Star forming regions, clumps and cores

Alessio Traficante

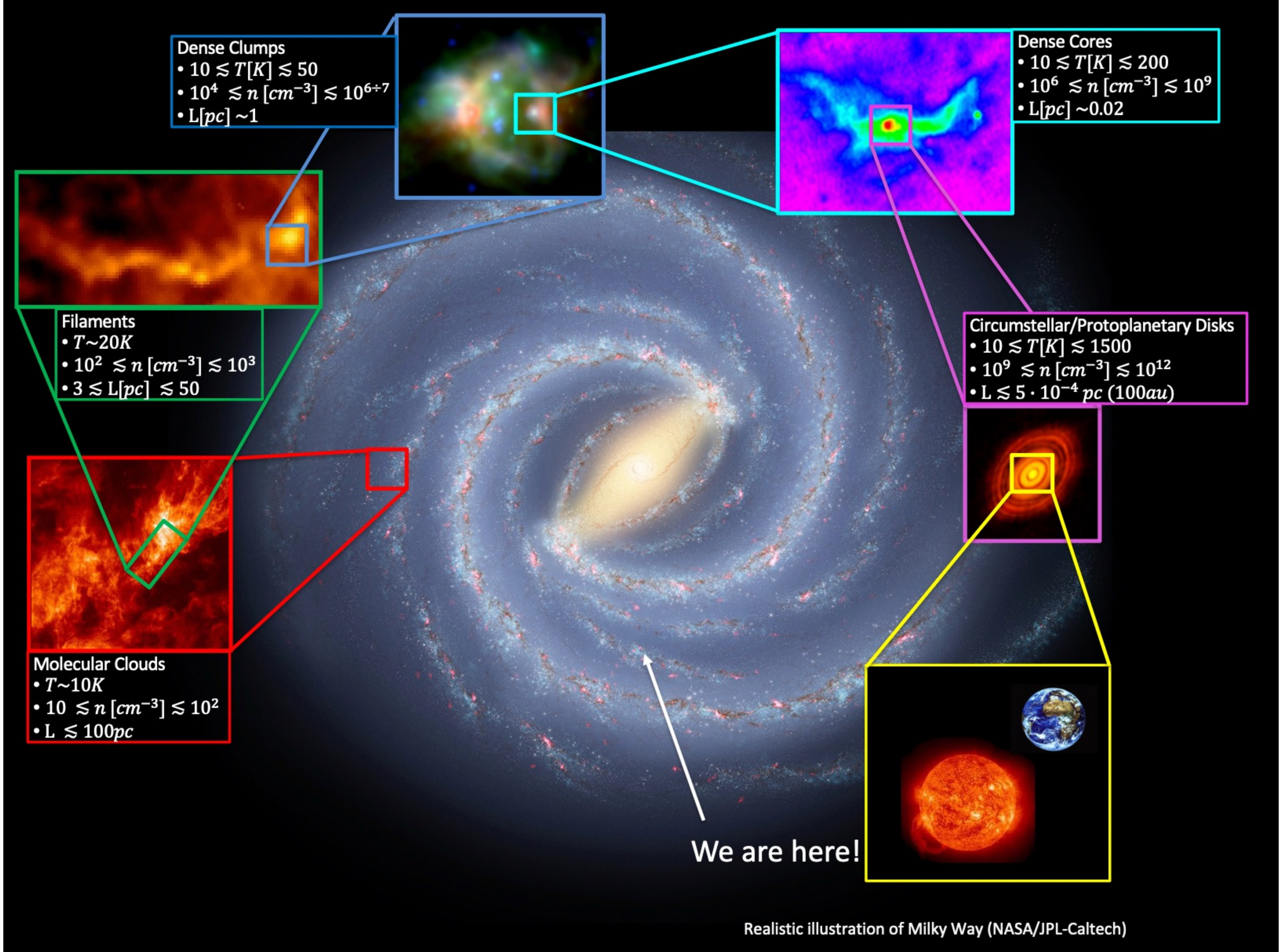
(INAF-IAPS, Rome, IT)

alessio.traficante@inaf.it

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
IAPS ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI

Completed by lectures of Frederique Motte

ECOGAL



Dense Clumps
- $10 \lesssim T[K] \lesssim 50$
- $10^4 \lesssim n\,[cm^{-3}] \lesssim 10^{6 \div 7}$
- $L[pc] \sim 1$

Dense Cores
- $10 \lesssim T[K] \lesssim 200$
- $10^6 \lesssim n\,[cm^{-3}] \lesssim 10^9$
- $L[pc] \sim 0.02$

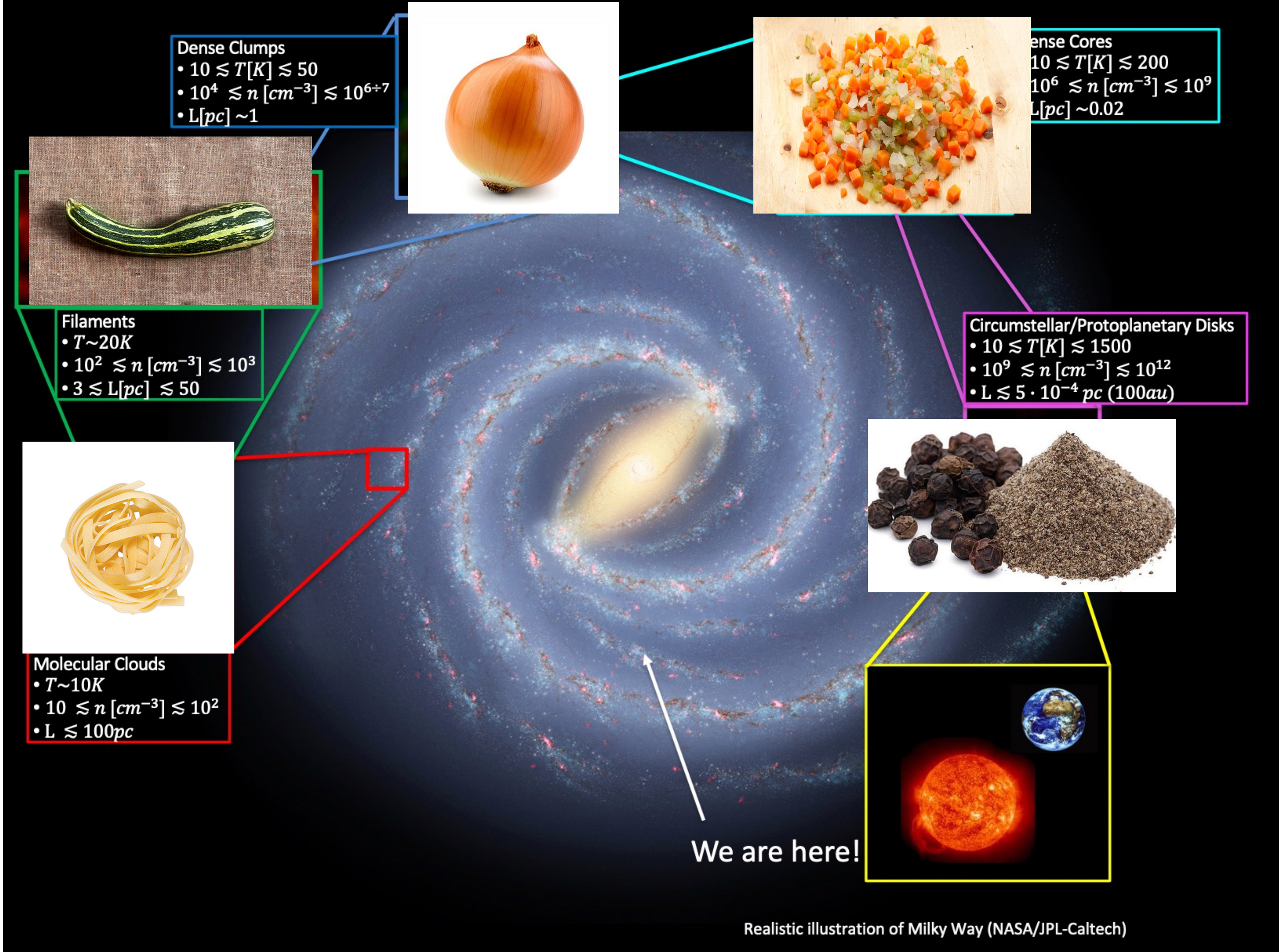
Filaments
- $T \sim 20K$
- $10^2 \lesssim n\,[cm^{-3}] \lesssim 10^3$
- $3 \lesssim L[pc] \lesssim 50$

Circumstellar/Protoplanetary Disks
- $10 \lesssim T[K] \lesssim 1500$
- $10^9 \lesssim n\,[cm^{-3}] \lesssim 10^{12}$
- $L \lesssim 5 \cdot 10^{-4}\,pc\ (100au)$

Molecular Clouds
- $T \sim 10K$
- $10 \lesssim n\,[cm^{-3}] \lesssim 10^2$
- $L \lesssim 100pc$

We are here!

Realistic illustration of Milky Way (NASA/JPL-Caltech)



Dense Clumps
- $10 \lesssim T[K] \lesssim 50$
- $10^4 \lesssim n\,[cm^{-3}] \lesssim 10^{6\div7}$
- $L[pc] \sim 1$

ense Cores

$10 \lesssim T[K] \lesssim 200$

$10^6 \lesssim n\,[cm^{-3}] \lesssim 10^9$

$L[pc] \sim 0.02$

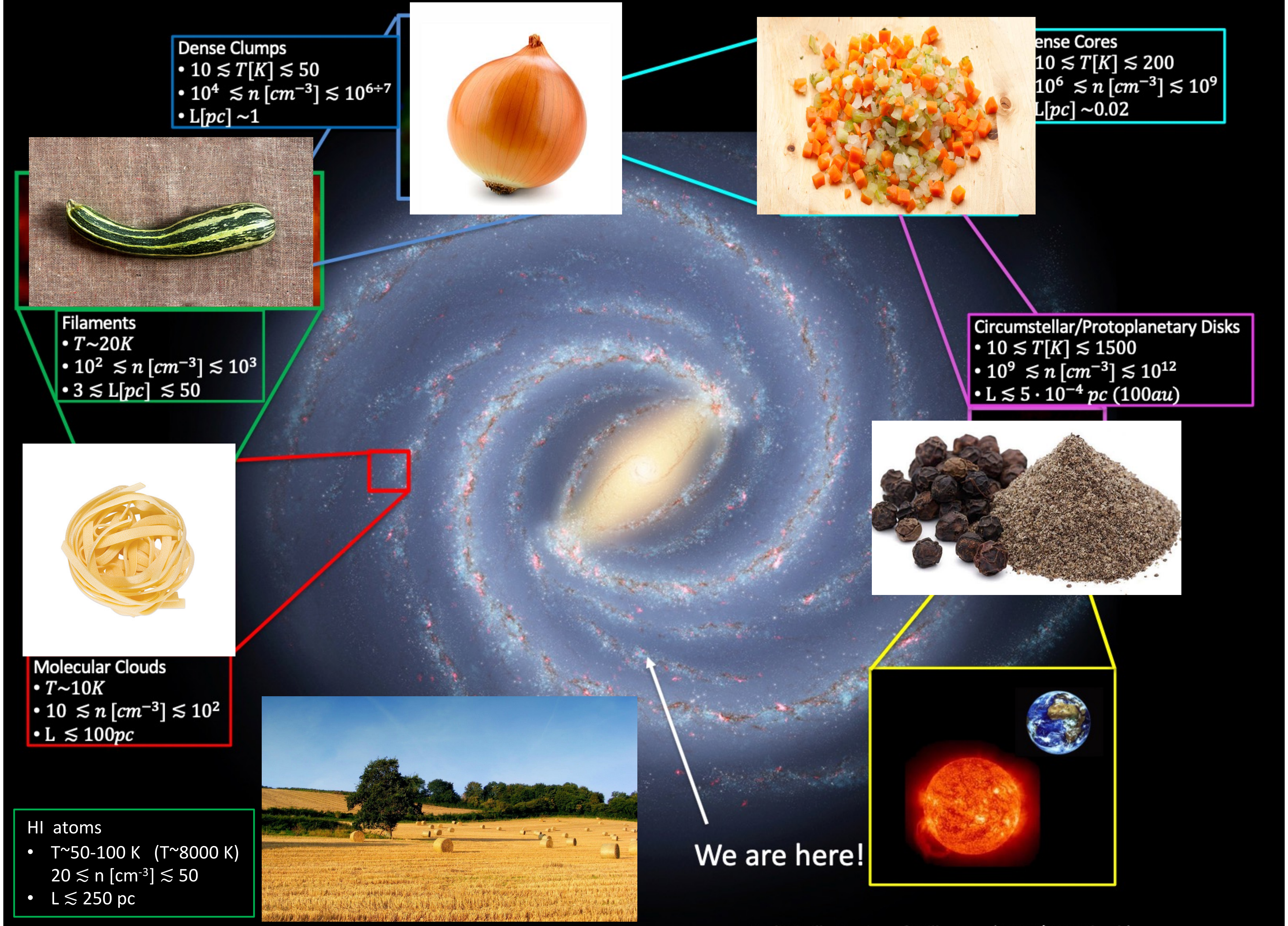
Filaments
- $T \sim 20K$
- $10^2 \lesssim n\,[cm^{-3}] \lesssim 10^3$
- $3 \lesssim L[pc] \lesssim 50$

Circumstellar/Protoplanetary Disks
- $10 \lesssim T[K] \lesssim 1500$
- $10^9 \lesssim n\,[cm^{-3}] \lesssim 10^{12}$
- $L \lesssim 5 \cdot 10^{-4}\,pc\ (100au)$

Molecular Clouds
- $T \sim 10K$
- $10 \lesssim n\,[cm^{-3}] \lesssim 10^2$
- $L \lesssim 100pc$

We are here!

Realistic illustration of Milky Way (NASA/JPL-Caltech)



Dense Clumps
- $10 \lesssim T[K] \lesssim 50$
- $10^4 \lesssim n\,[cm^{-3}] \lesssim 10^{6\div7}$
- $L[pc] \sim 1$

ense Cores
- $10 \lesssim T[K] \lesssim 200$
- $10^6 \lesssim n\,[cm^{-3}] \lesssim 10^9$
- $L[pc] \sim 0.02$

Filaments
- $T \sim 20K$
- $10^2 \lesssim n\,[cm^{-3}] \lesssim 10^3$
- $3 \lesssim L[pc] \lesssim 50$

Circumstellar/Protoplanetary Disks
- $10 \lesssim T[K] \lesssim 1500$
- $10^9 \lesssim n\,[cm^{-3}] \lesssim 10^{12}$
- $L \lesssim 5 \cdot 10^{-4}\,pc\;(100au)$

Molecular Clouds
- $T \sim 10K$
- $10 \lesssim n\,[cm^{-3}] \lesssim 10^2$
- $L \lesssim 100pc$

HI atoms
- T~50-100 K (T~8000 K)
  $20 \lesssim n\,[cm^{-3}] \lesssim 50$
- $L \lesssim 250$ pc

We are here!

Realistic illustration of Milky Way (NASA/JPL-Caltech)

Dense Clumps
- $10 \lesssim T[K] \lesssim 50$
- $10^4 \lesssim n\,[cm^{-3}] \lesssim 10^{6÷7}$
- $L[pc] \sim 1$

ense Cores
$10 \lesssim T[K] \lesssim 200$
$10^6 \lesssim n\,[cm^{-3}] \lesssim 10^9$
$L[pc] \sim 0.02$

Filaments
- $T \sim 20K$
- $10^2 \lesssim n\,[cm^{-3}] \lesssim 10^3$
- $3 \lesssim L[pc] \lesssim 50$

Circumstellar/Protoplanetary Disks
- $10 \lesssim T[K] \lesssim 1500$
- $10^9 \lesssim n\,[cm^{-3}] \lesssim 10^{12}$
- $L \lesssim 5 \cdot 10^{-4}\,pc\,(100au)$

Molecular Clouds
- $T \sim 10K$
- $10 \lesssim n\,[cm^{-3}] \lesssim 10^2$
- $L \lesssim 100pc$

HI atoms
- T~50-100 K (T~8000 K)
  $20 \lesssim n\,[cm^{-3}] \lesssim 50$
- L ≲ 250 pc

Realistic illustration of Milky Way (NASA/JPL-Caltech)

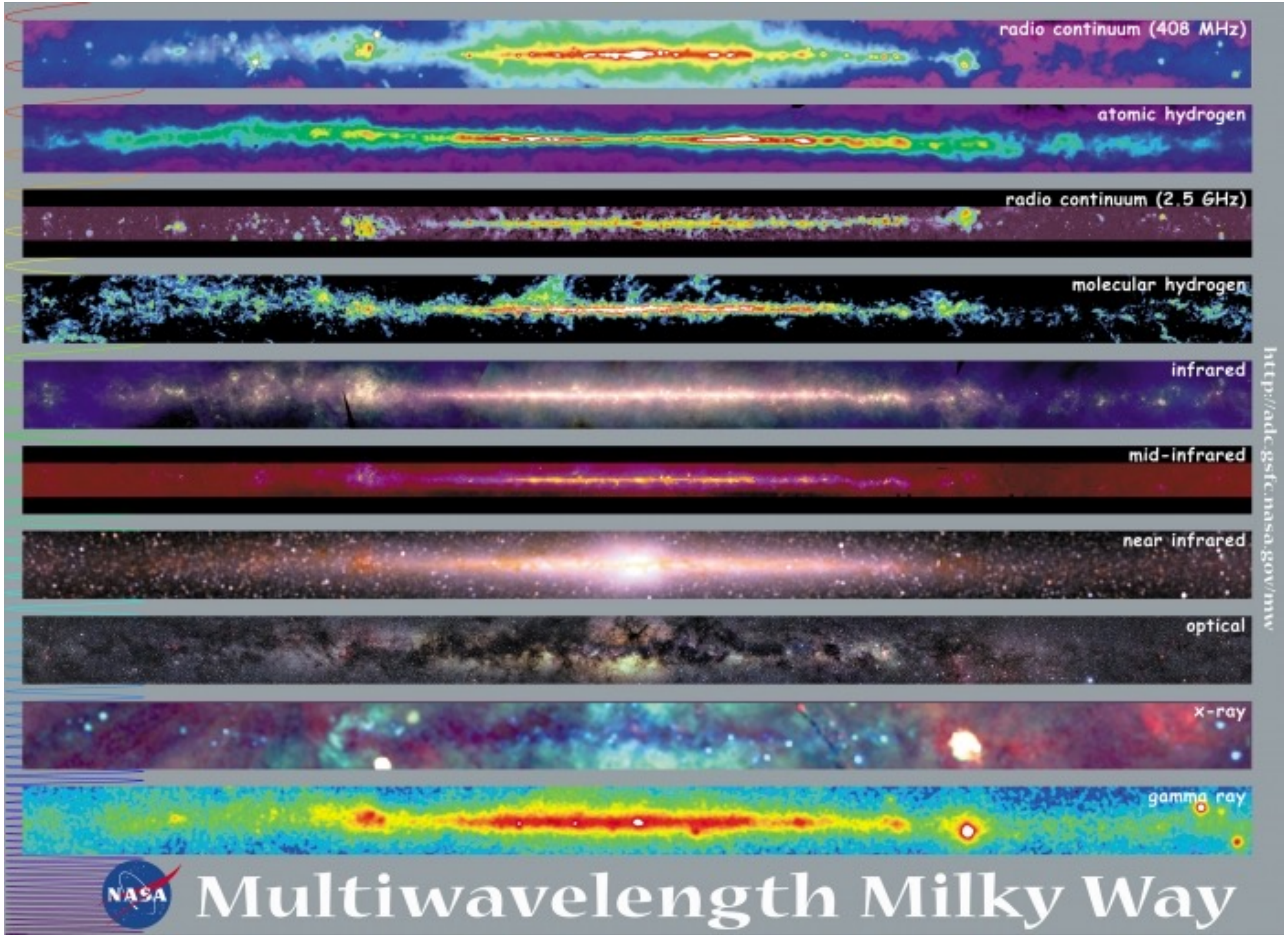
Star-forming regions, clumps and cores - outline

- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: physical properties, dynamics and (partial?) collapse
- From MCs to filaments: the densest regions of molecular clouds
- Pc-scales clumps: the nursery home of stars and protoclusters
- Gas dynamics in filament and clumps: the role of environment

Star-forming regions, clumps and cores - outline

- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: physical properties, dynamics and (partial?) collapse
- From MCs to filaments: the densest regions of molecular clouds
- Pc-scales clumps: the nursery home of stars and protoclusters
- Gas dynamics in filament and clumps: the role of environment

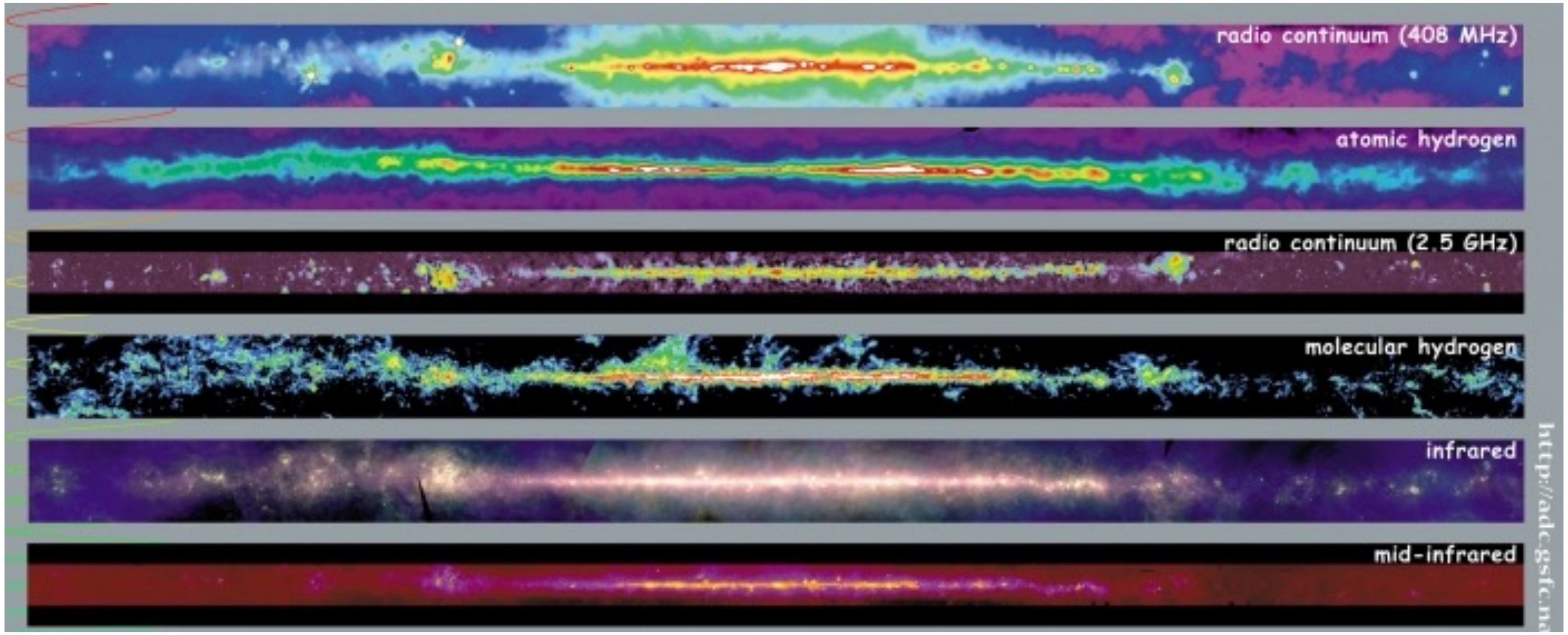
Our Milky Way: how to observe star-forming regions?



Our Milky Way: how to observe star-forming regions?

MIR/FIR regime:

cold dust



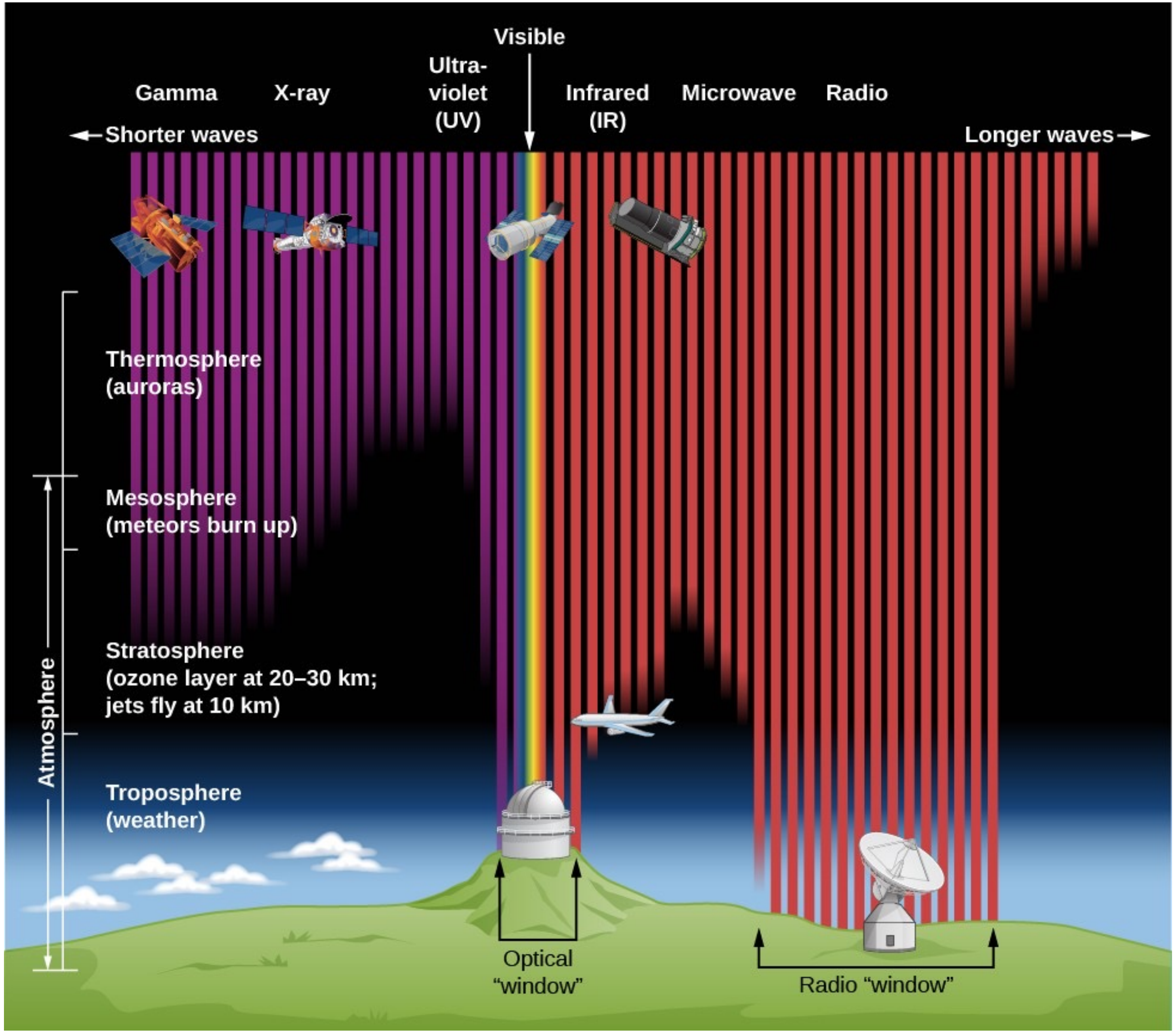
Radio regime:

Atoms + molecules

DUST can be seen in high density regions and it emits in the continuum. The cold dust (T~10-50K) associated with star-forming regions emits mostly in the Mid/Far-Infrared (MIR – FIR) regime: (~8 - ~3000μm)

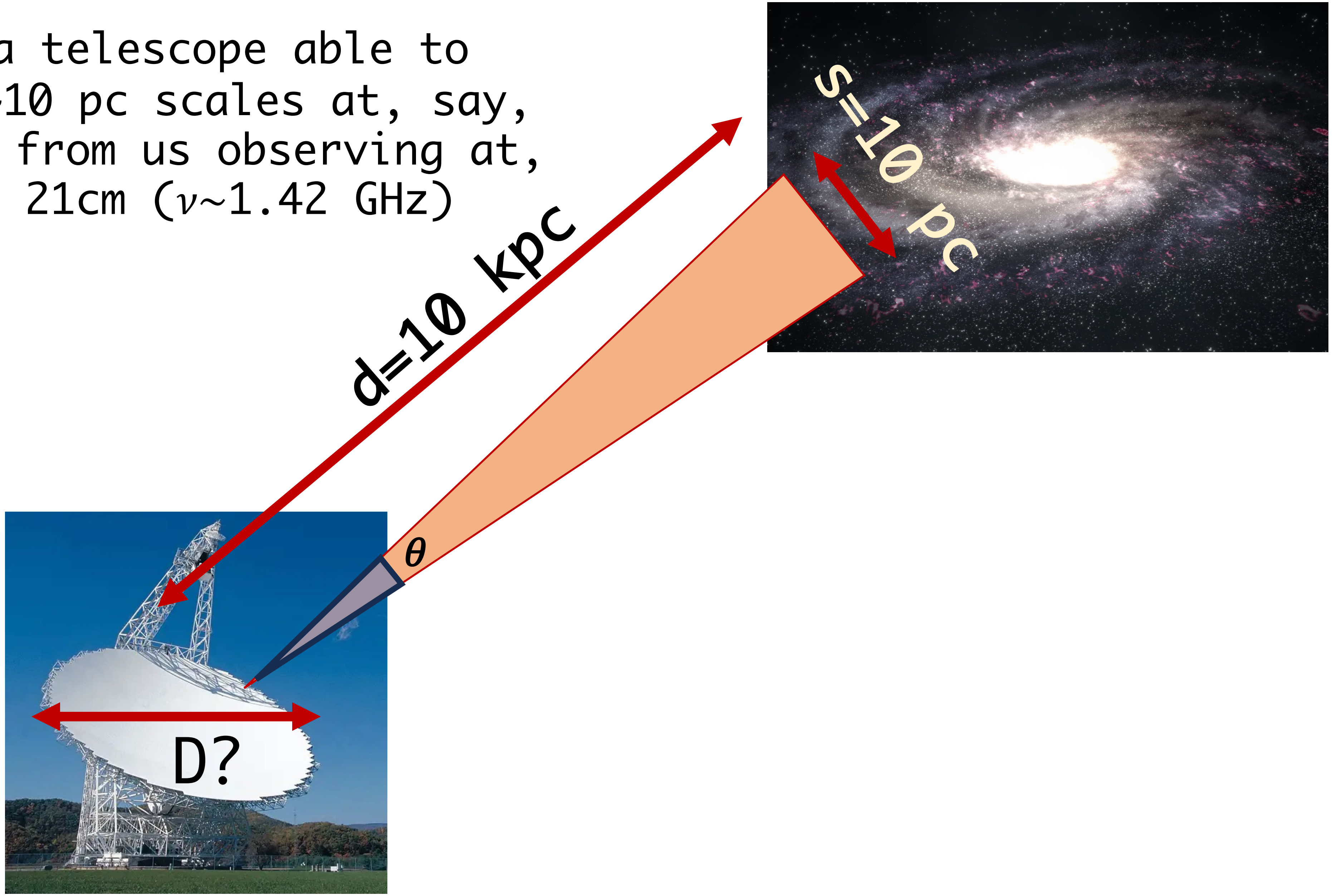
Molecules and atoms can be seen throughout the Interstellar Medium (ISM) of the Galaxy and they emit at specific frequencies. The simplest ones that we are interested in can be seen in the ~radio regime (~1mm – 30cm)

Our Milky Way: how to observe star-forming regions?



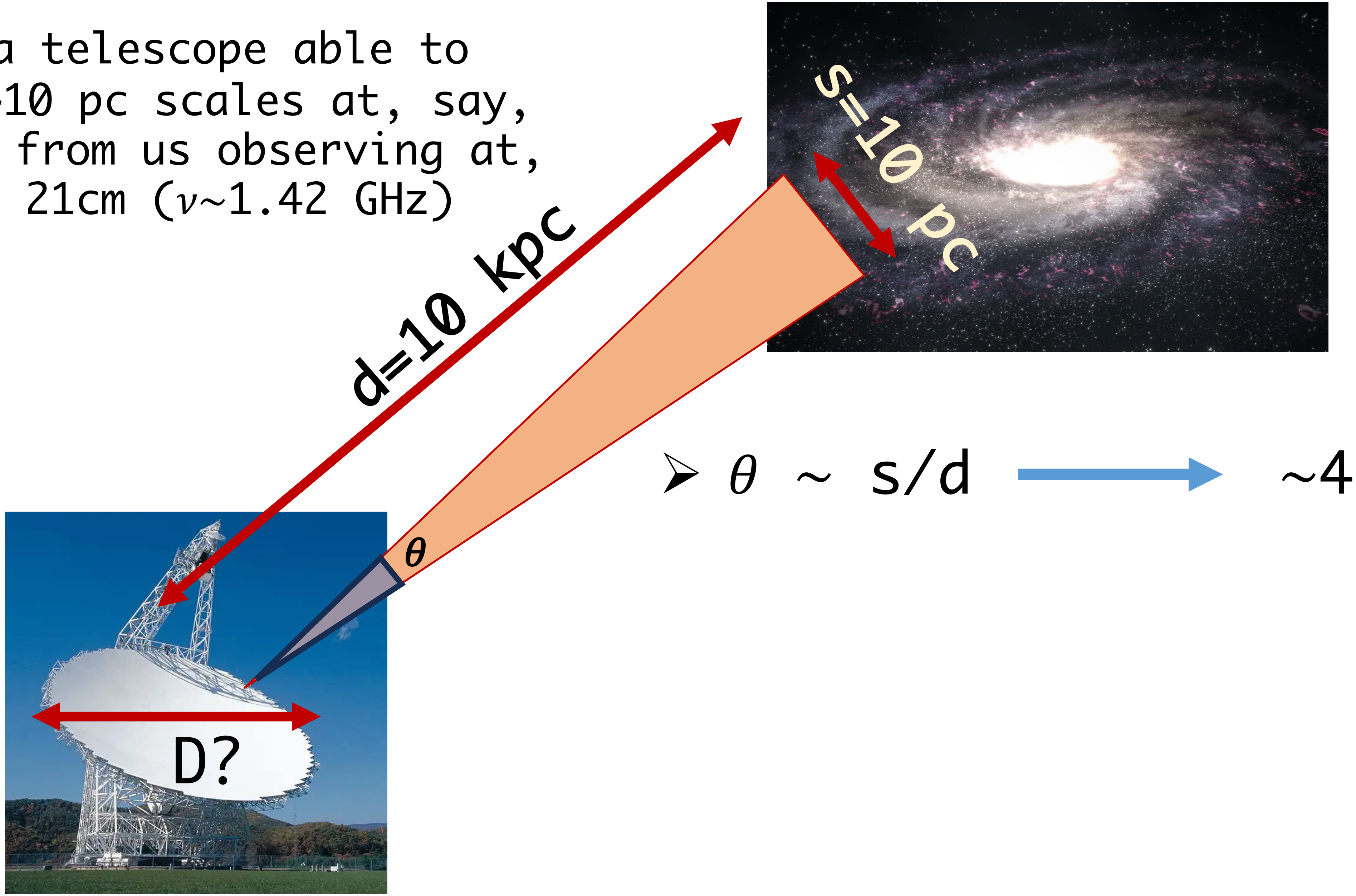
How do we observe atoms/molecules in the sky at radio wavelengths?

We need a telescope able to resolve a ~10 pc scales at, say, 10 kpc away from us observing at, say, λ = 21cm (ν~1.42 GHz)



How do we observe atoms/molecules in the sky at radio wavelengths?

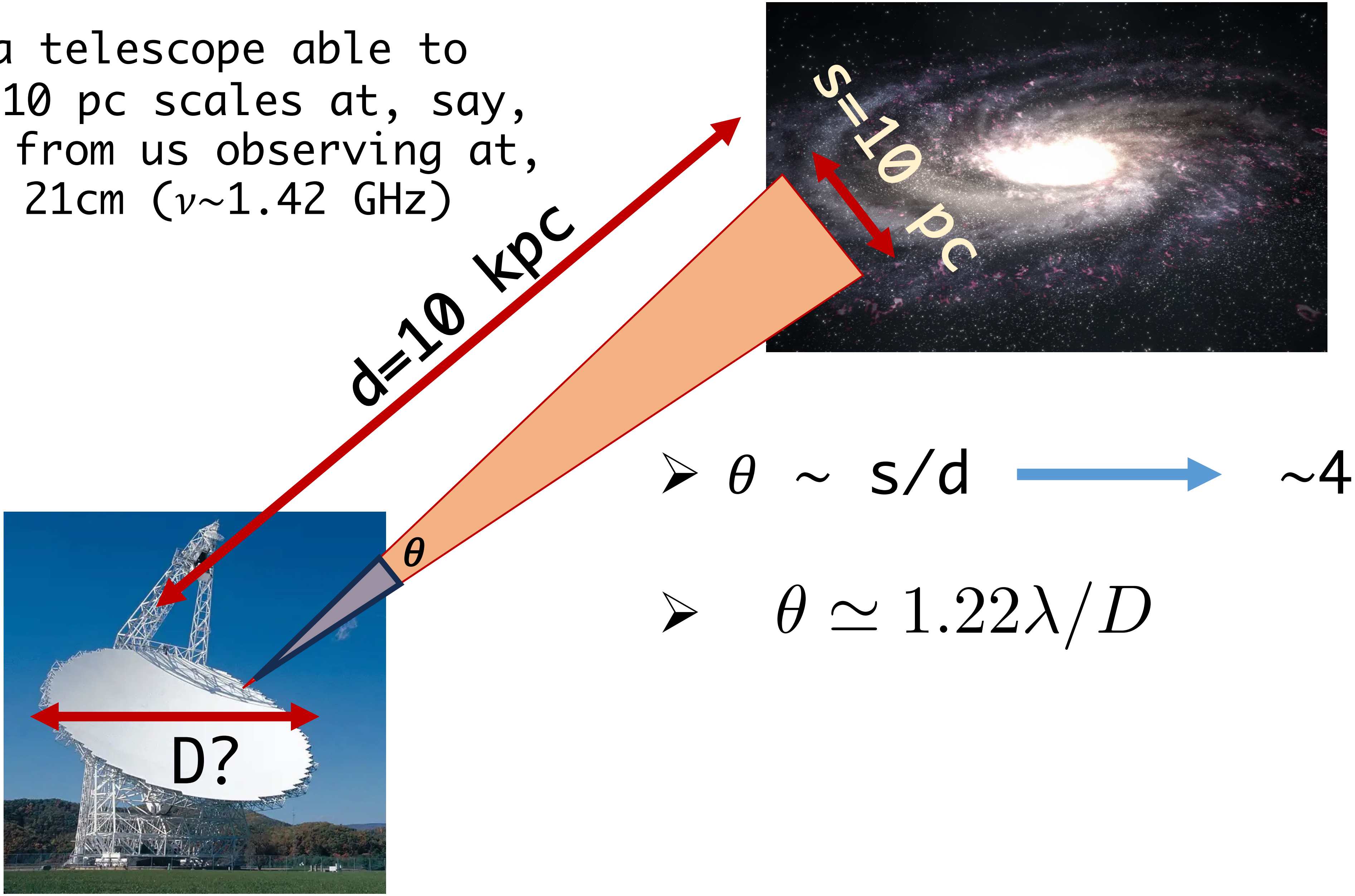
We need a telescope able to resolve a ~10 pc scales at, say, 10 kpc away from us observing at, say, λ = 21cm (ν~1.42 GHz)



- $\theta \sim s/d$ → ~4’

How do we observe atoms/molecules in the sky at radio wavelengths?

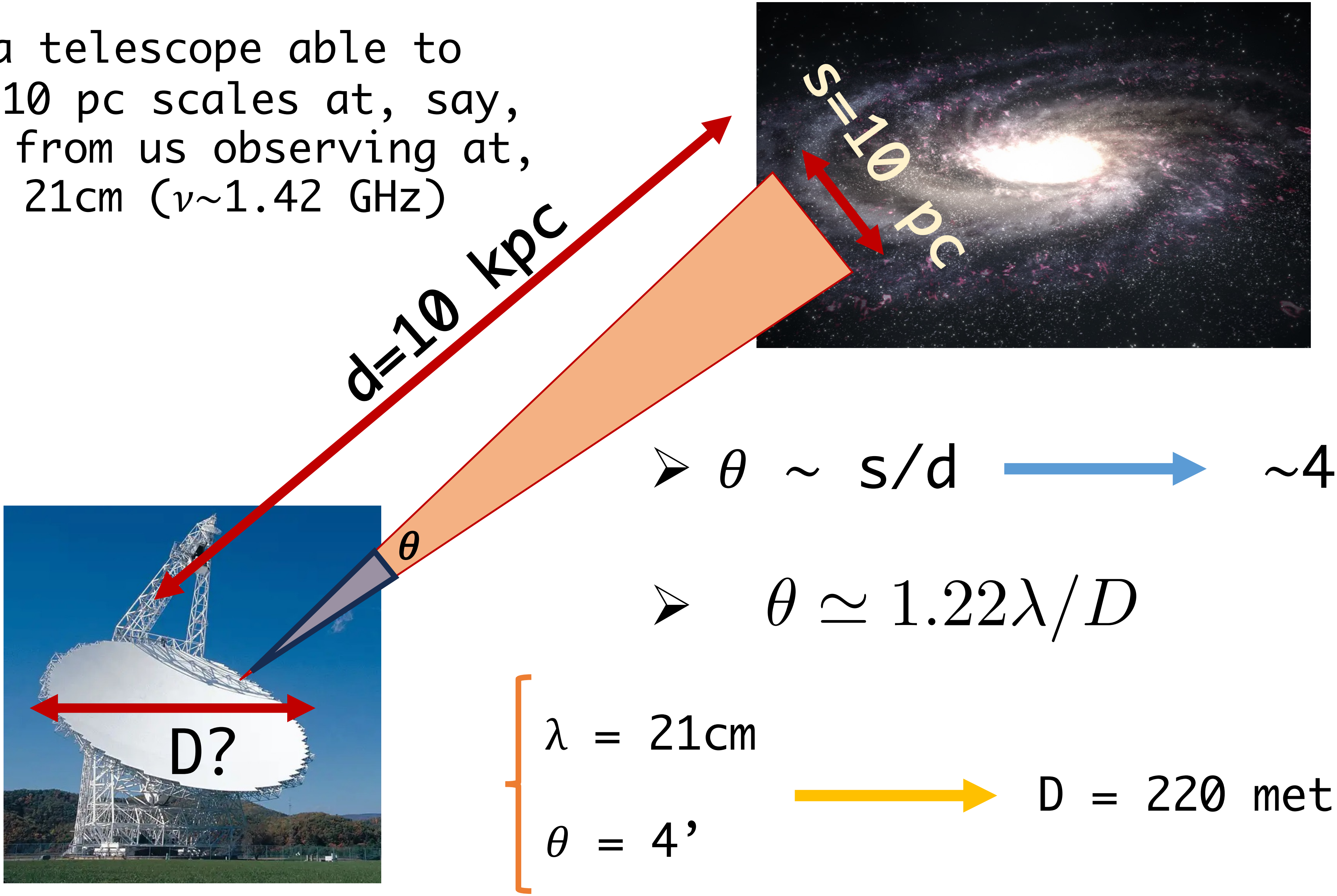
We need a telescope able to resolve a ~10 pc scales at, say, 10 kpc away from us observing at, say, λ = 21cm (ν~1.42 GHz)



- ➢ $\theta \sim$ s/d → ~4’
- ➢ $\theta \simeq 1.22\lambda/D$

How do we observe atoms/molecules in the sky at radio wavelengths?

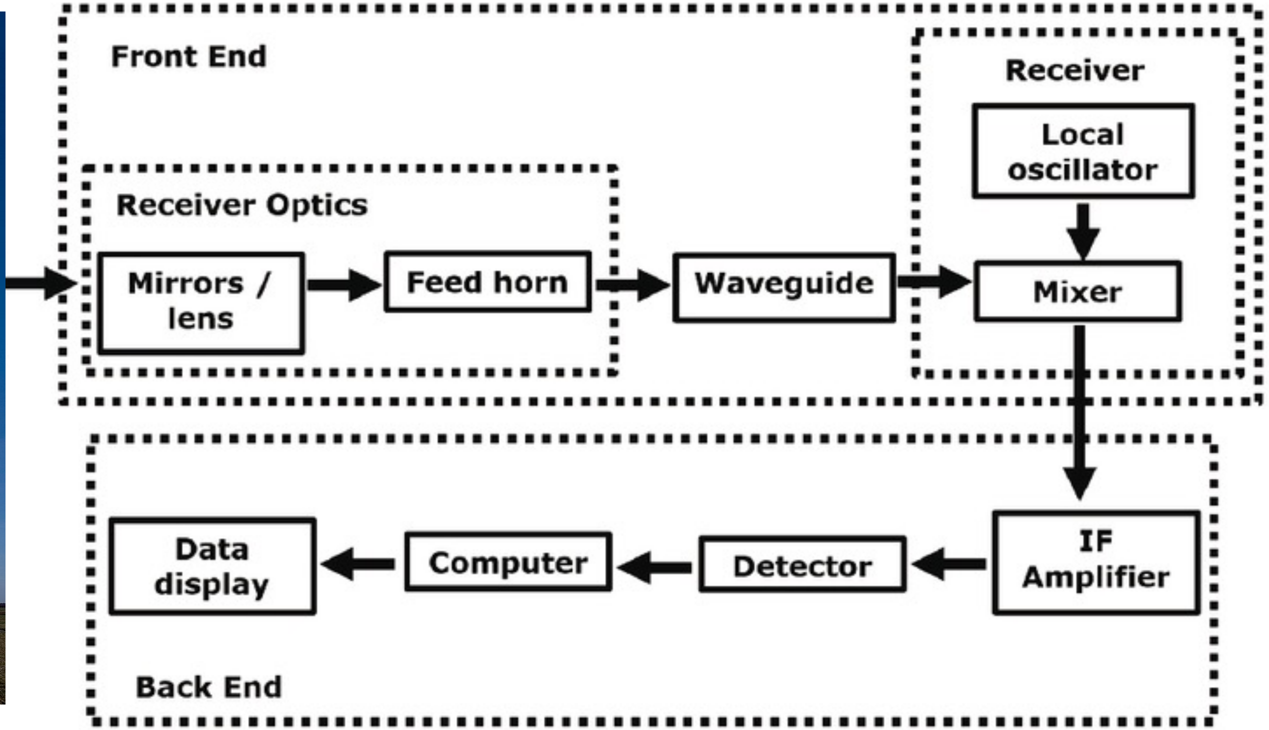
We need a telescope able to resolve a ~10 pc scales at, say, 10 kpc away from us observing at, say, λ = 21cm (ν~1.42 GHz)

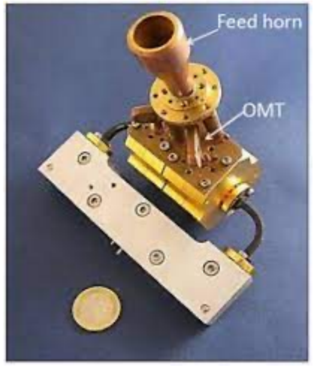


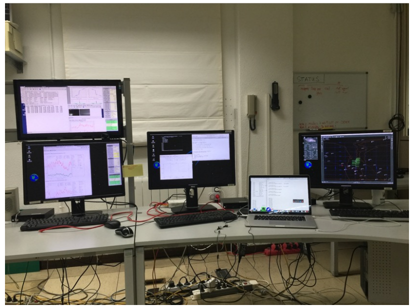
- $\theta \sim s/d$ → ~4’
- $\theta \simeq 1.22\lambda/D$

$$\left\{ \begin{array}{l} \lambda = 21\text{cm} \\ \theta = 4' \end{array} \right. \longrightarrow D = 220 \text{ meters…}$$

How do we observe atoms/molecules in the sky at radio wavelengths?







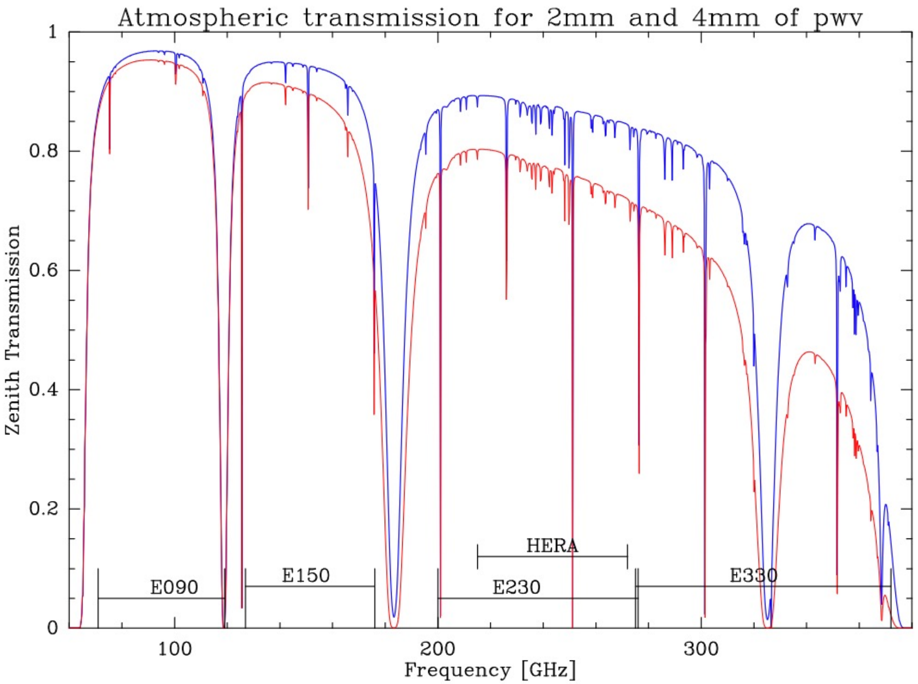
<u>**Front End**</u>: The front end components of the radio receiver systems are those where incoming radio waves are initially received.

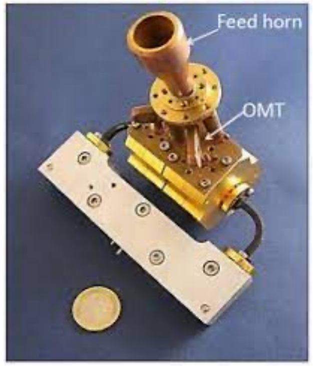
<u>**Back End**</u>: The back end instrument is used to determine the kind of signal we want to measure from the front end data. Usually offer a FIXED number of channels/bandwidth available to choose.

How do we observe atoms/molecules in the sky at radio wavelengths?

IRAM 30m telescope (Granada, SP)

Front end: EMIR

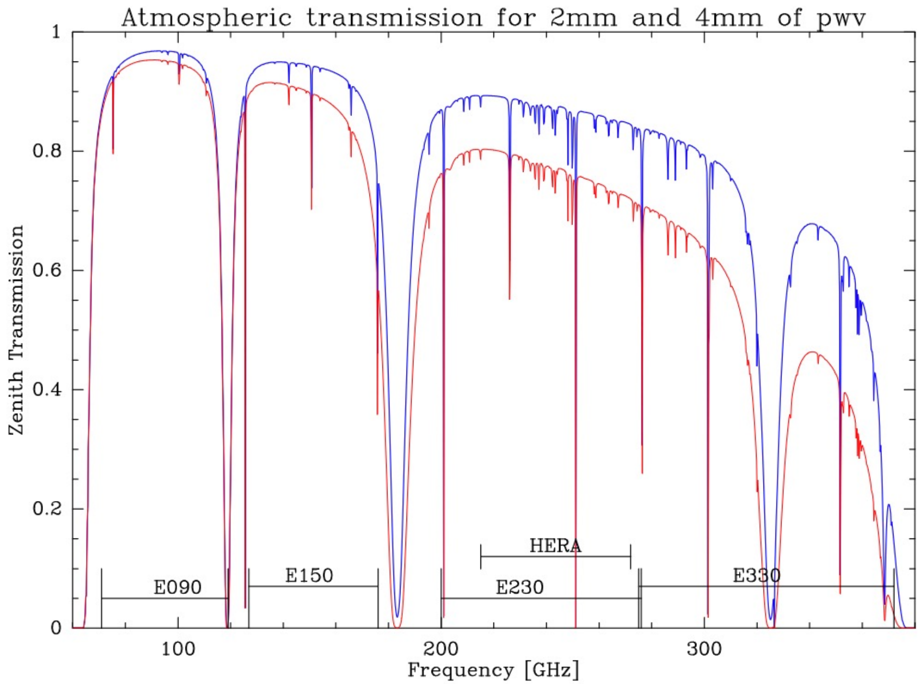


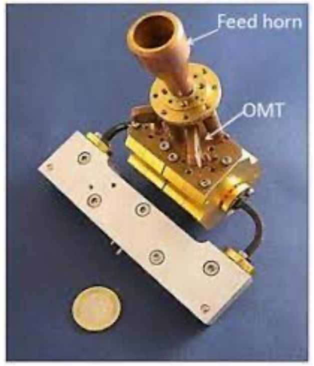


How do we observe atoms/molecules in the sky at radio wavelengths?

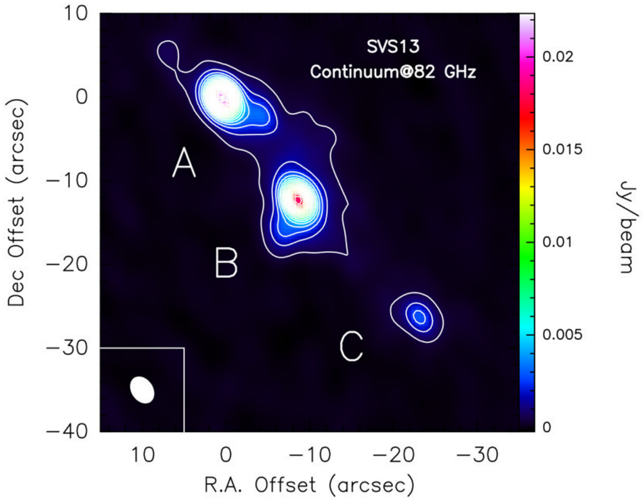
IRAM 30m telescope (Granada, SP)

Front end: EMIR





1. Do we want to observe the continuum **from dust** at e.g. E90 (~3mm)? We will use the bbc <u>**continuum**</u> back end

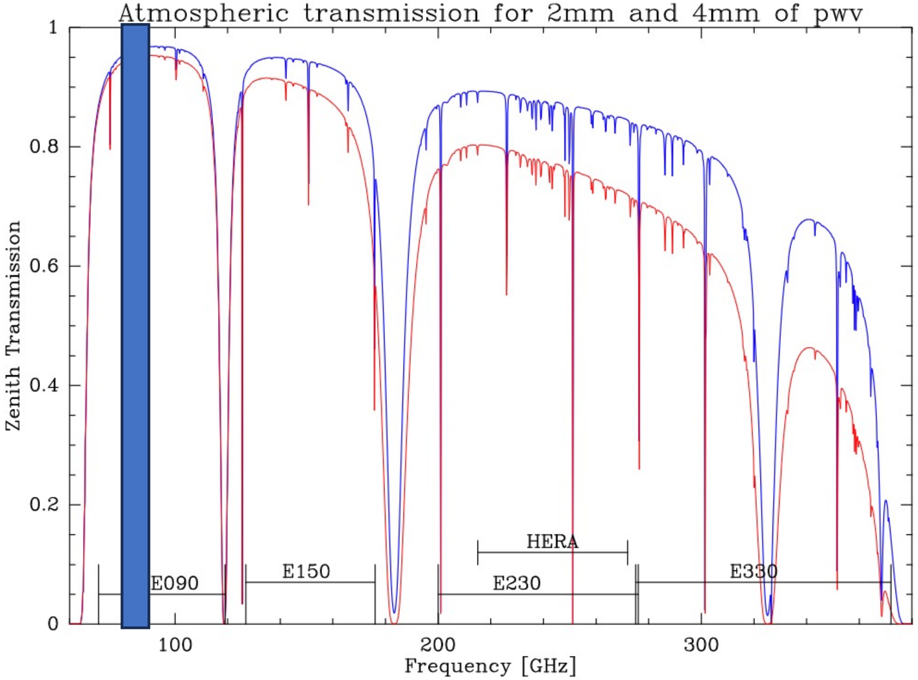


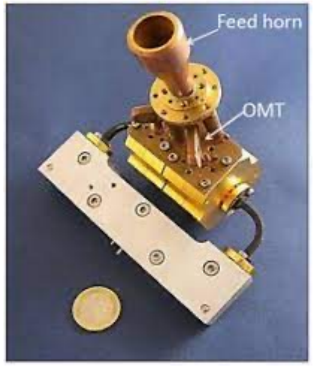
bandwidth
~1 GHz

How do we observe atoms/molecules in the sky at radio wavelengths?

IRAM 30m telescope (Granada, SP)

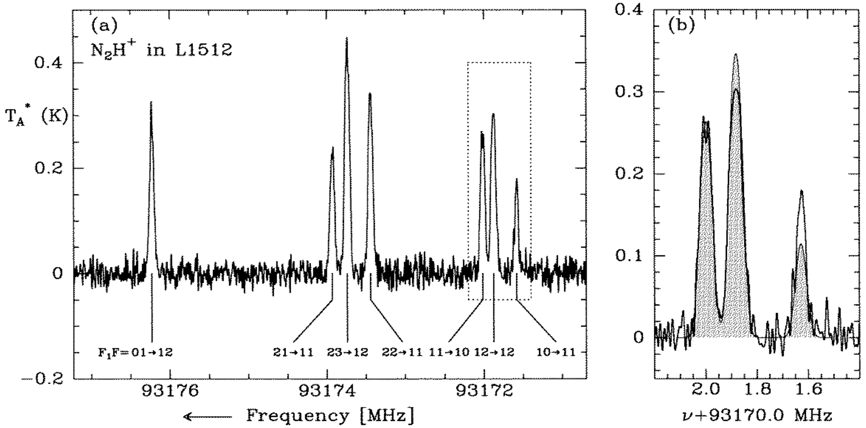
Front end: EMIR





1. Do we want to observe the continuum **from dust** at e.g. E90 (~3mm)? We will use the bbc **continuum** back end

2. Do we want to identify a spectral line transition with E90 such as, e.g., N_2H^+ (1-0) @93.3 GHz? We will use e.g. the FTS back end. He has ~20000 channels available. We can use it at **50 kHz** resolution

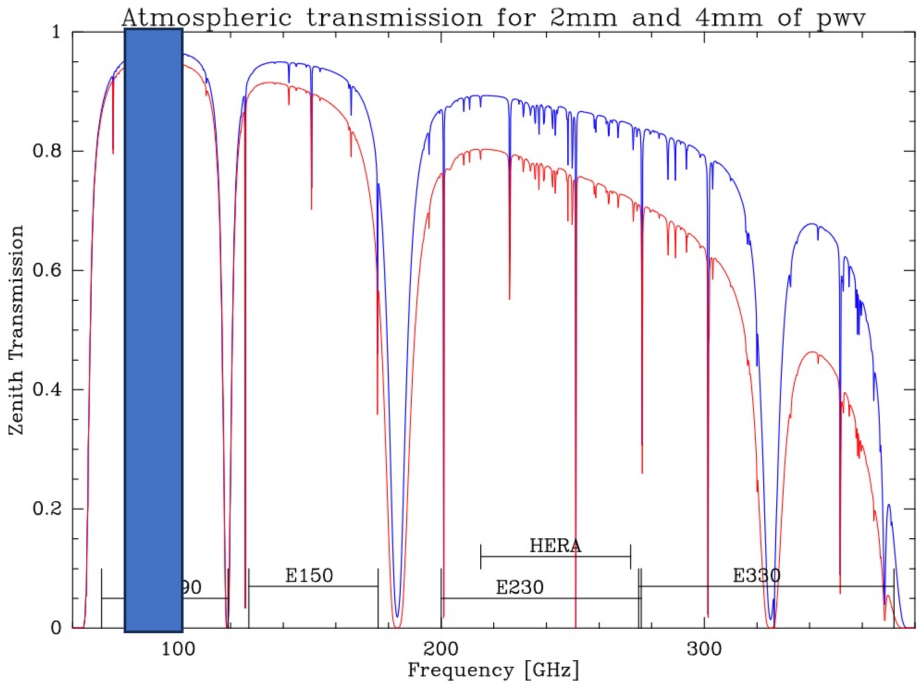


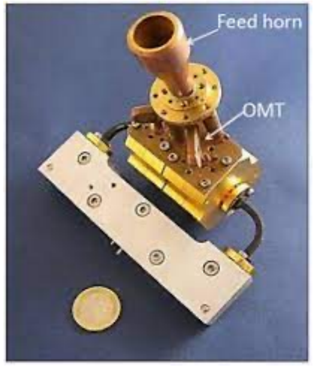
Good sampling (~1 GHz bandwidth)

How do we observe atoms/molecules in the sky at radio wavelengths?

IRAM 30m telescope (Granada, SP)

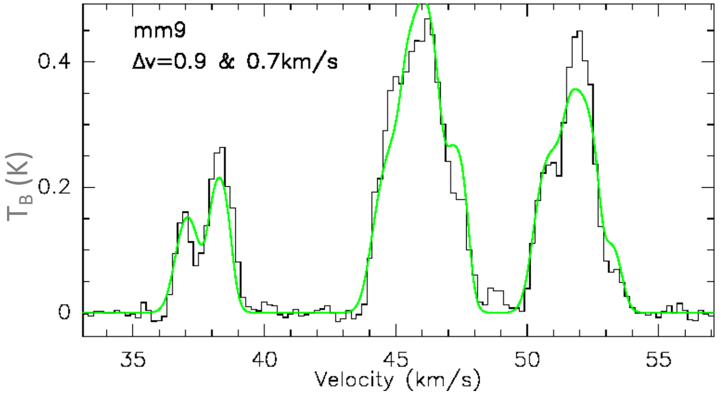
Front end: EMIR





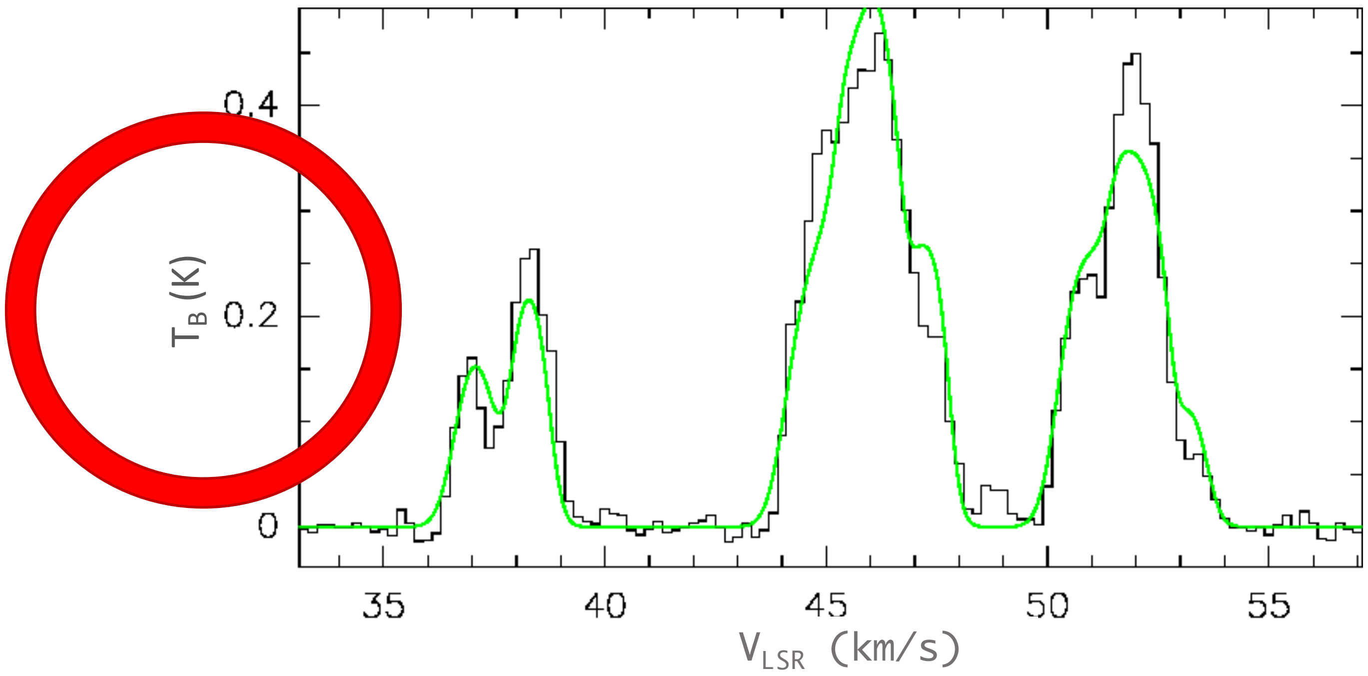
1. Do we want to observe the continuum **from dust** at e.g. E90 (~3mm)? We will use the bbc **continuum** back end

2. Do we want to identify a spectral line transition with E90 such as, e.g., N_2H^+ (1-0) @93.3 GHz? We will use e.g. the FTS back end. He has ~20000 channels available. We can use it at **200 kHz** resolution



Poor sampling (~4 GHz bandwidth)

How do we observe atoms/molecules in the sky at radio wavelengths?

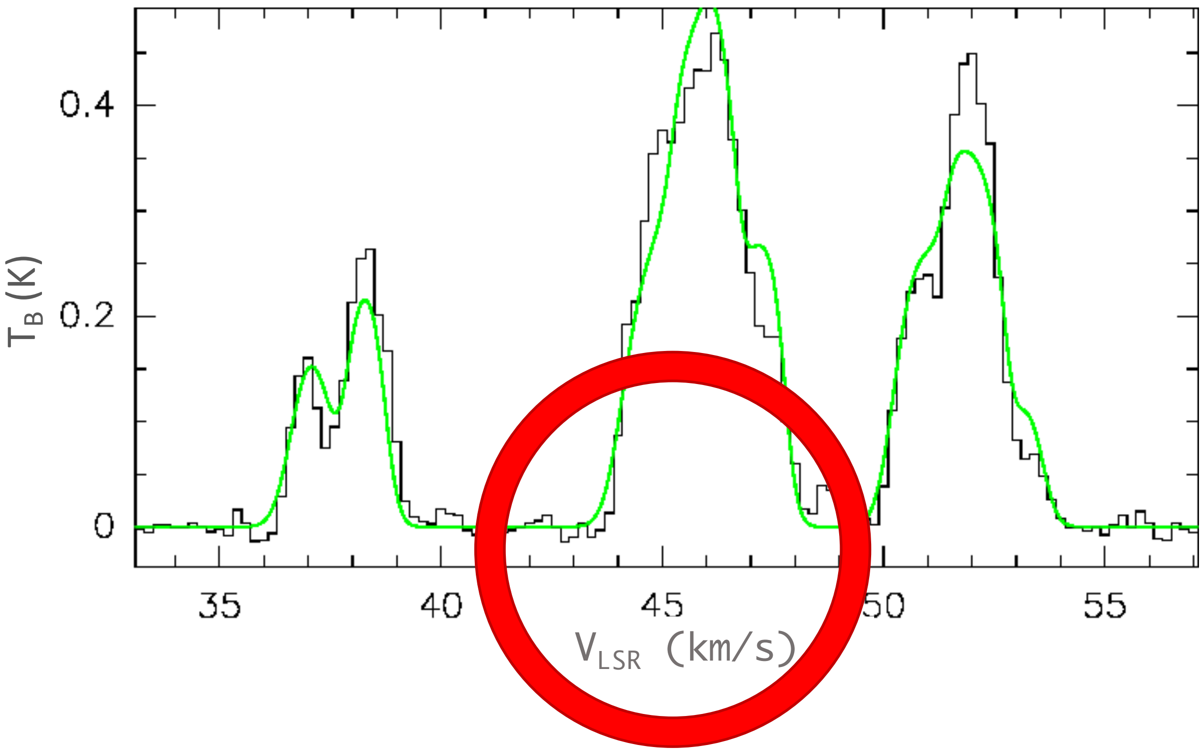


It is usually

- brightness temperature T_B(K)
- antenna temperature T_A(K)

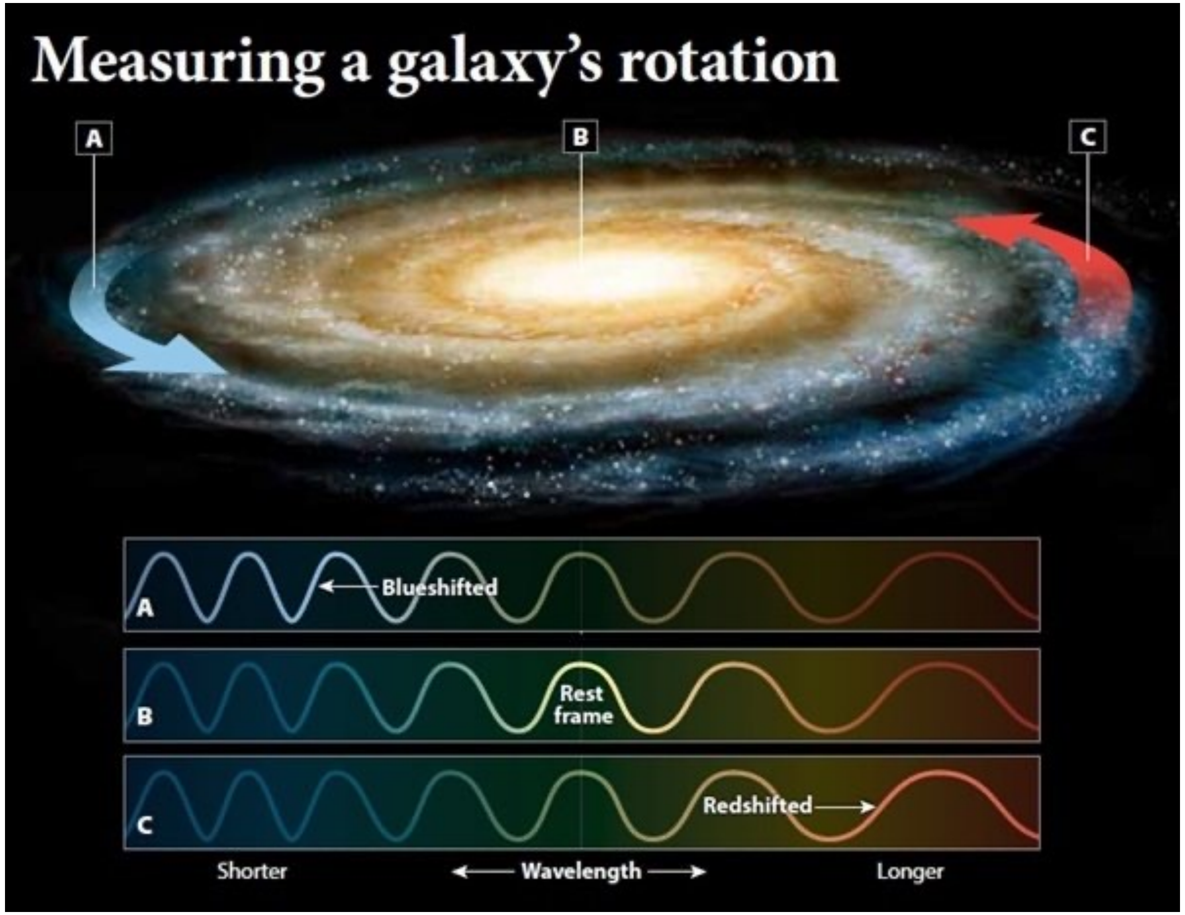
See lecture from Simon Glover

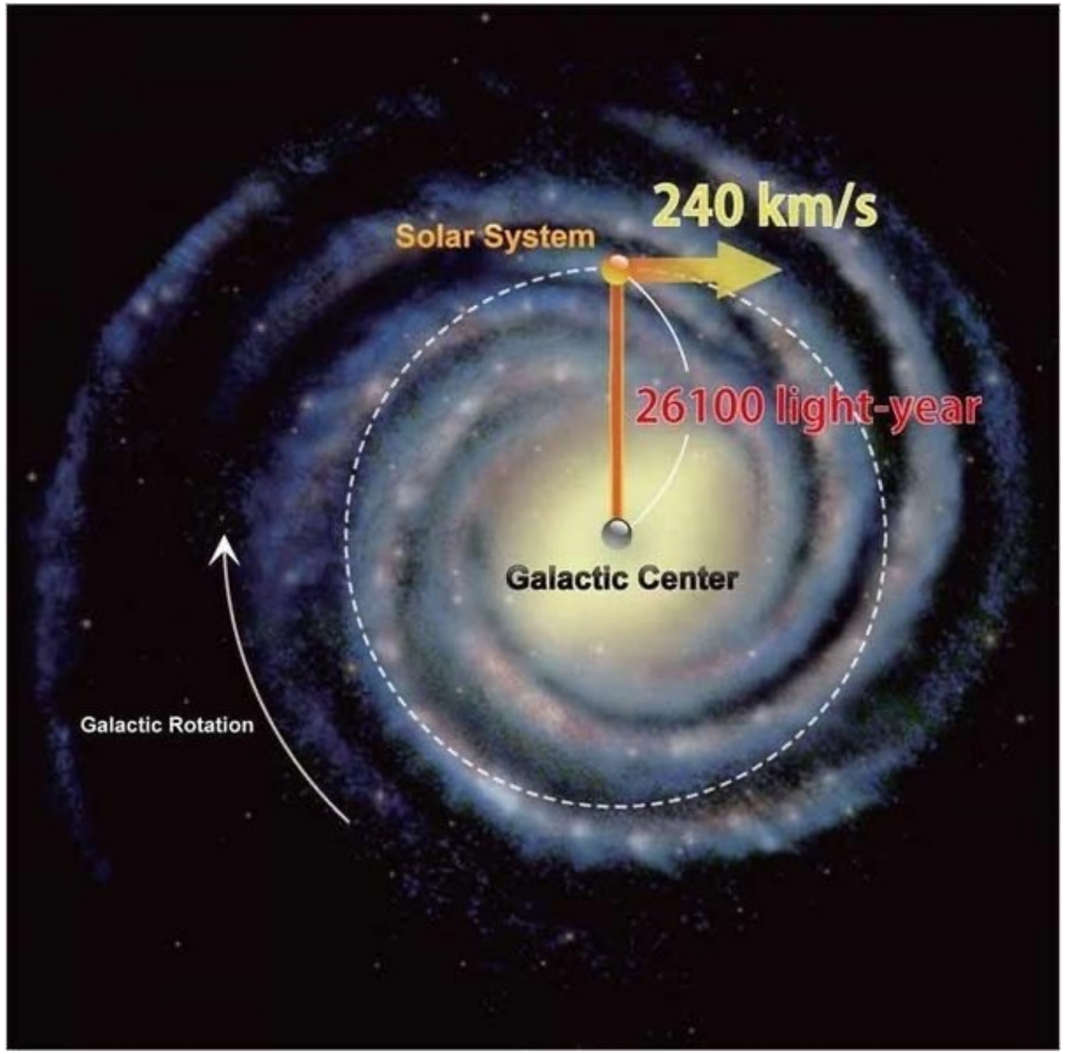
How do we observe atoms/molecules in the sky at radio wavelengths?



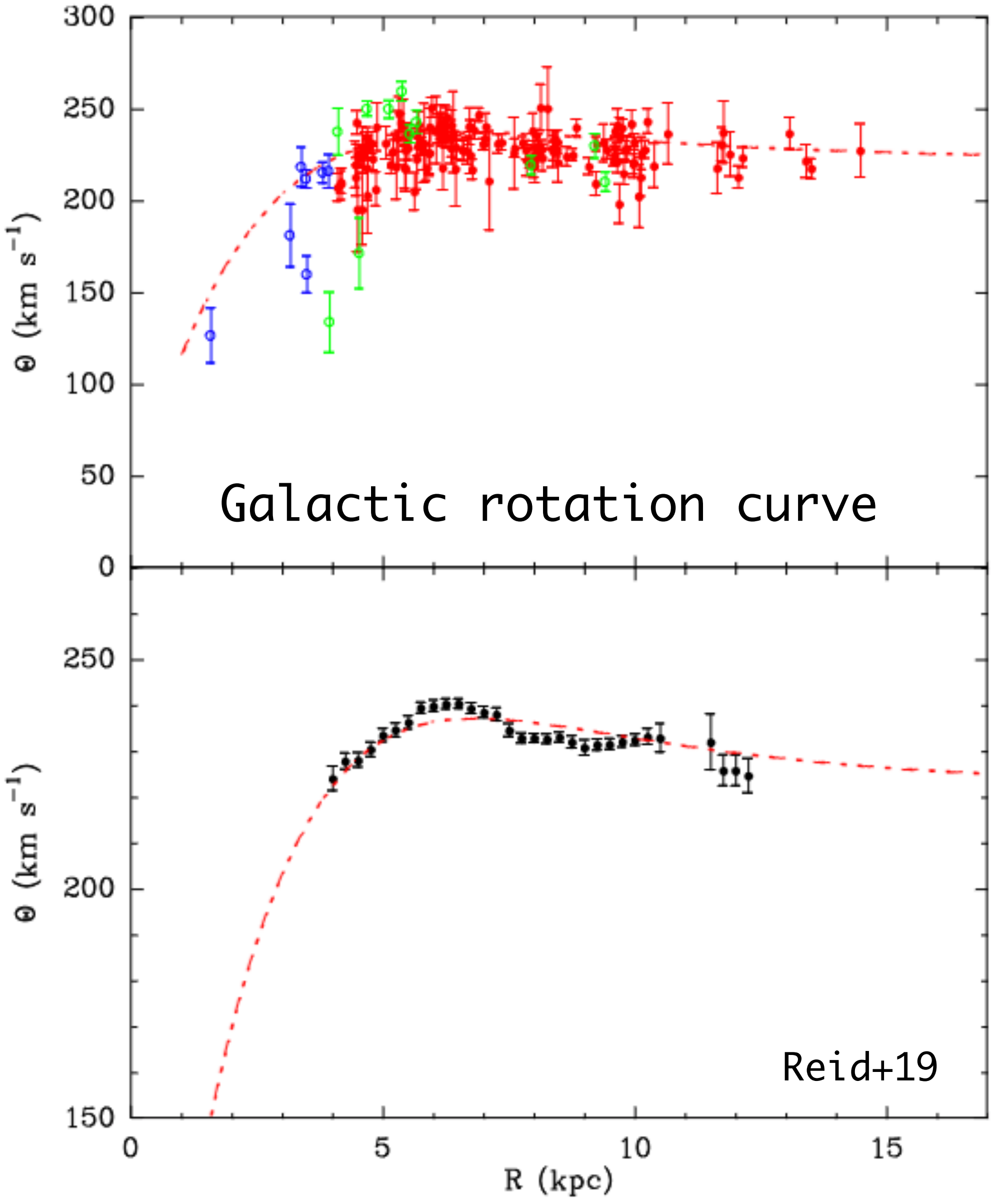
How do we observe atoms/molecules in the sky at radio wavelengths?

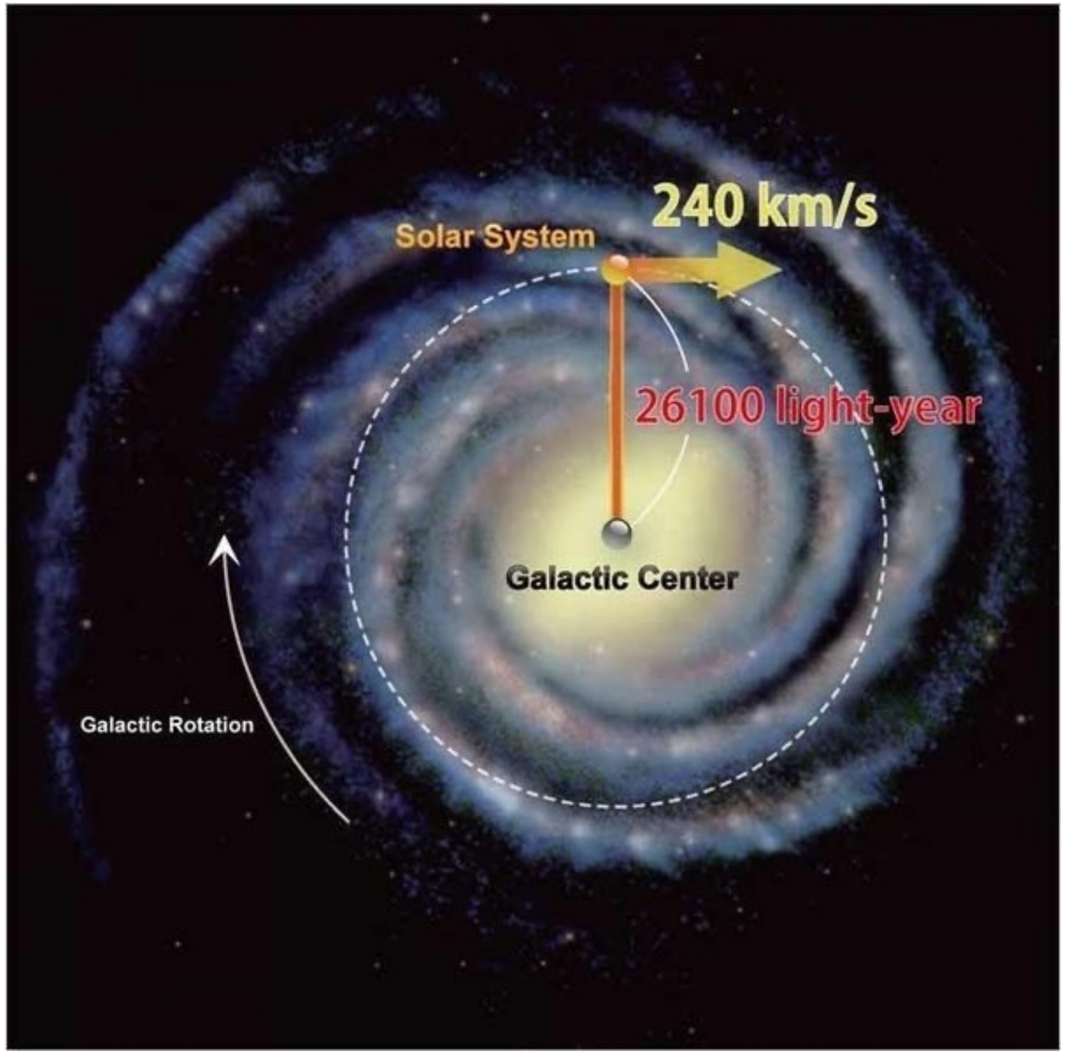
Remember the Doppler shift…the Galaxy is rotating!



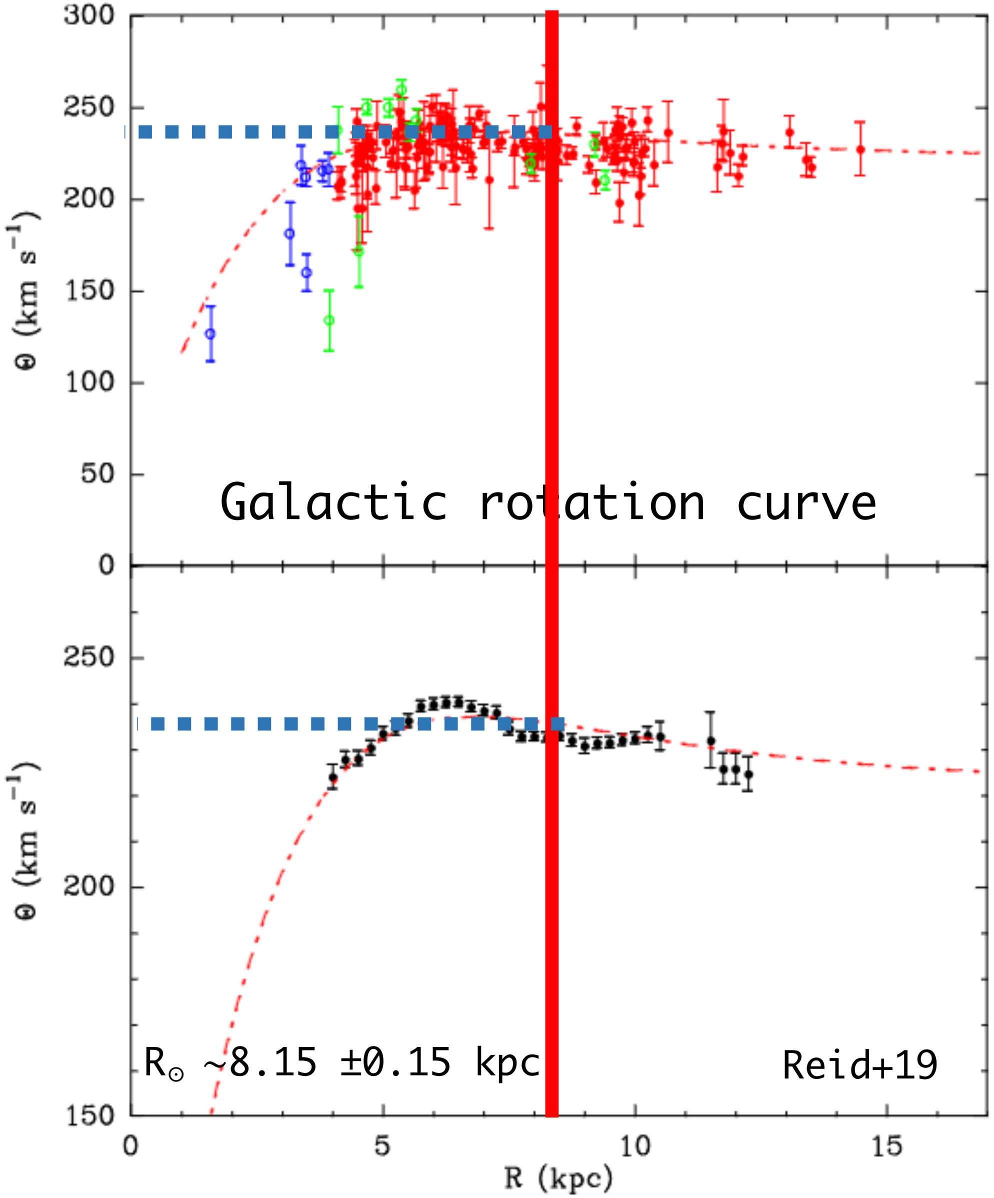


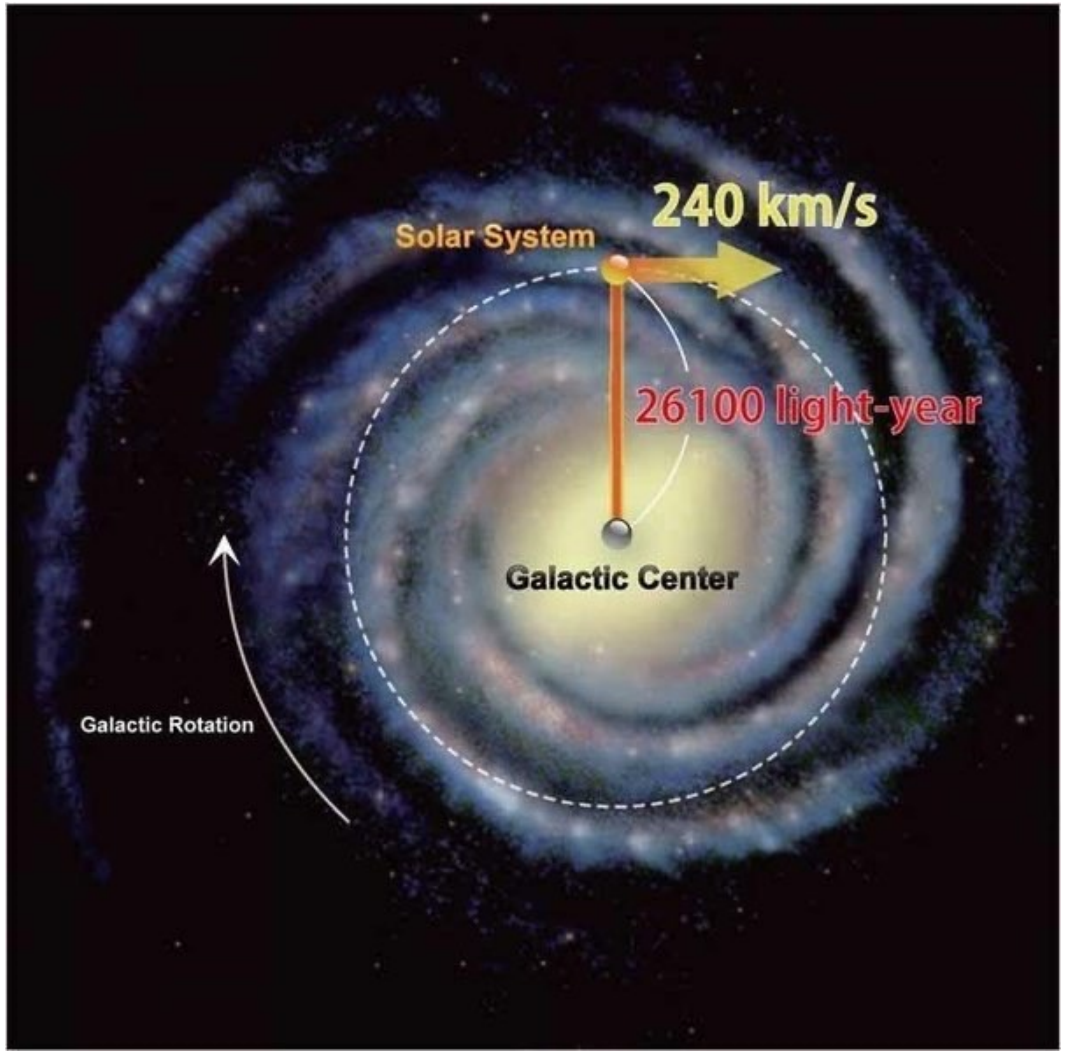
How do we observe atoms/molecules in the sky at radio wavelengths?



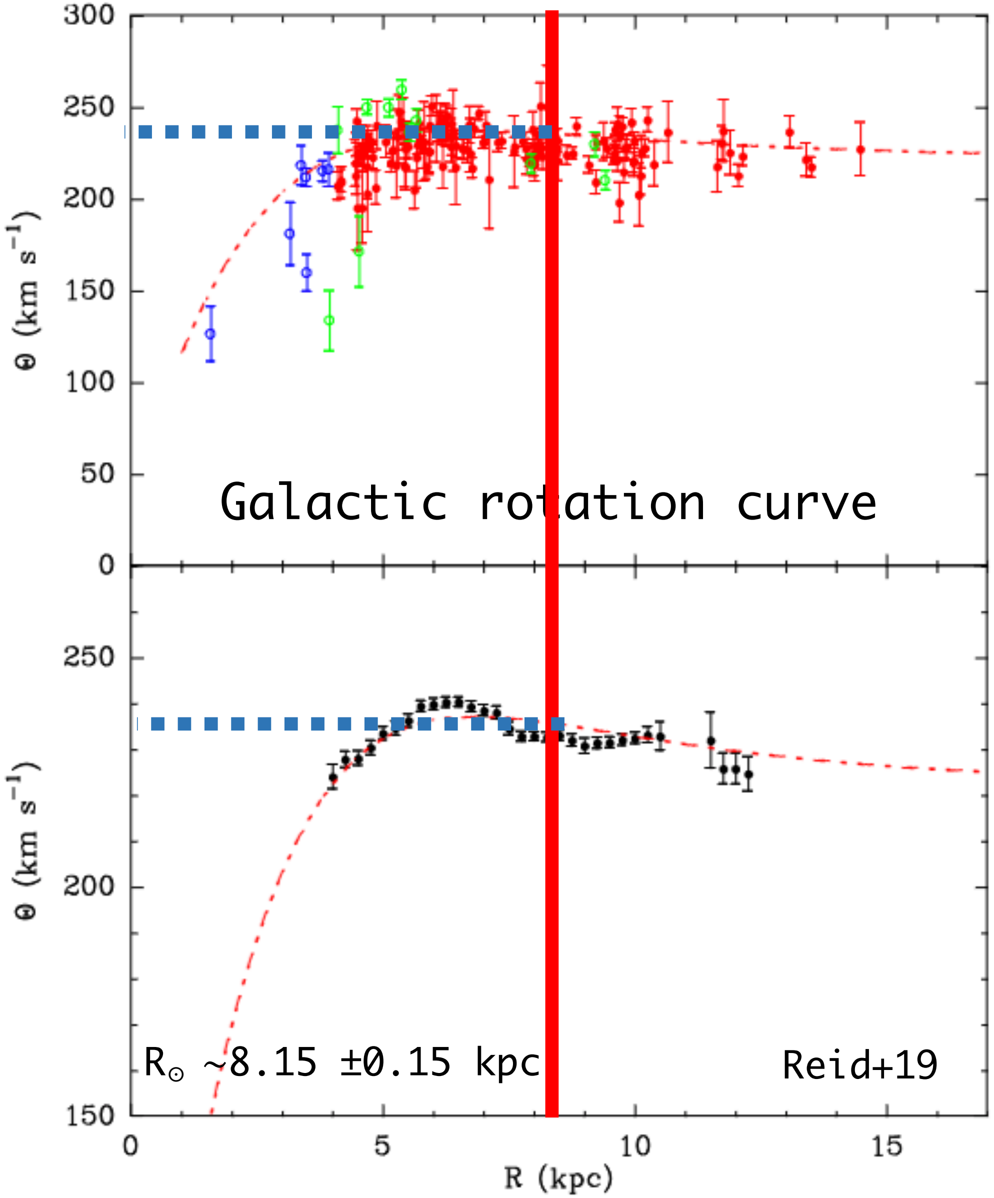


How do we observe atoms/molecules in the sky at radio wavelengths?





How do we observe atoms/molecules in the sky at radio wavelengths?



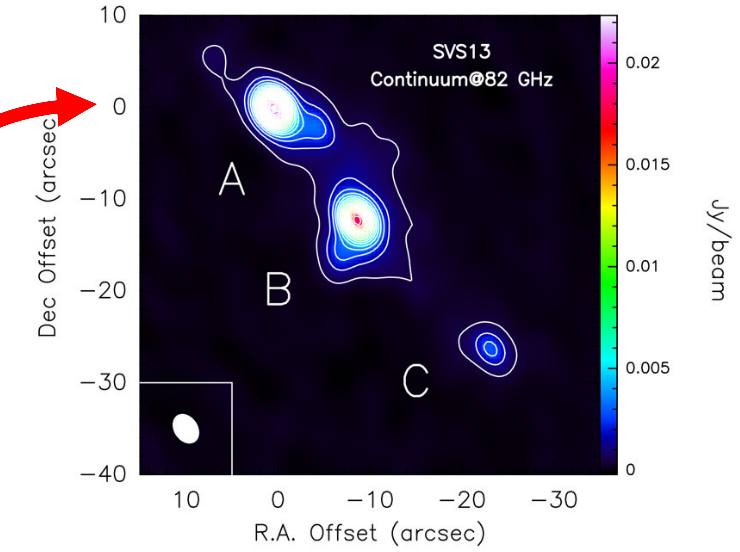
Within ± 250 km/s with respect to our Local Standard of Rest (LSR) velocity V we are able to cover almost all the emission from a specific line along any given line of sight

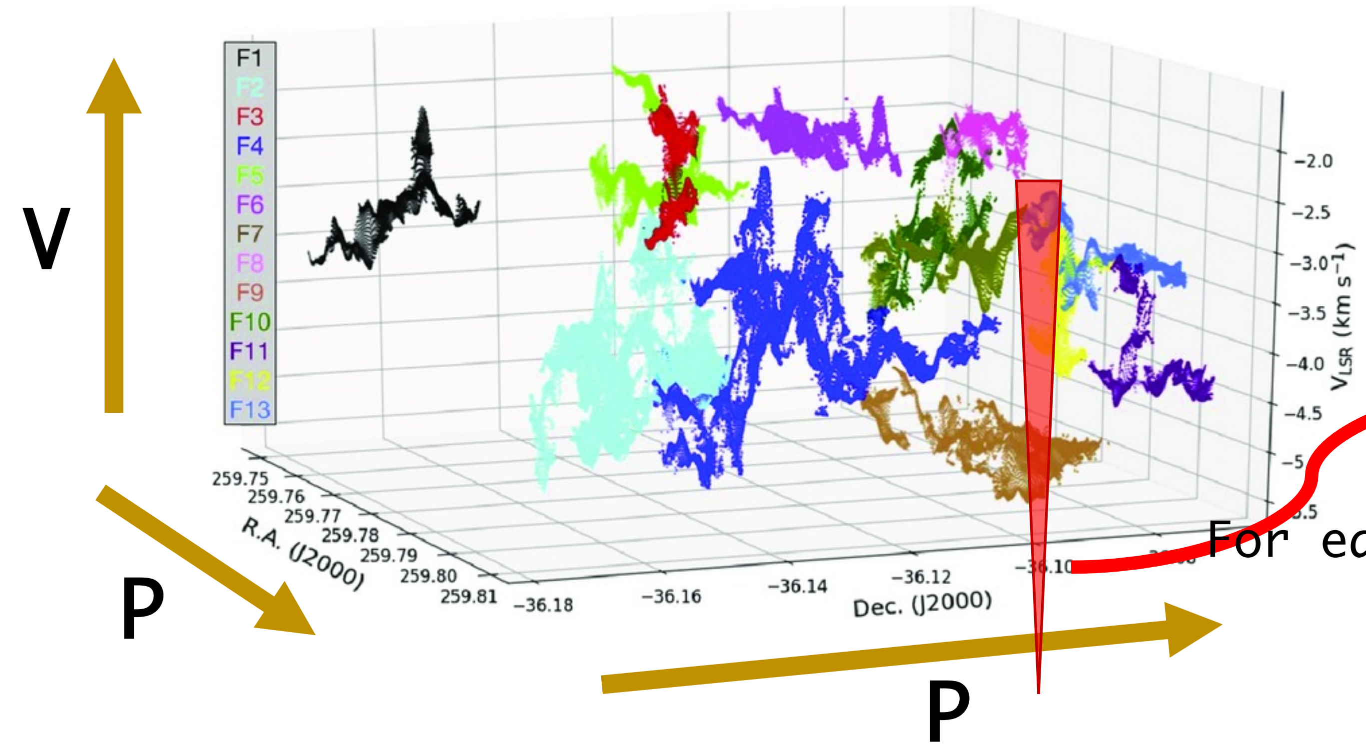
V_{LSR} can be used to define the **distance** of a given source, from a Galactic rotation curve (with many limits: e.g. Urquhart+18, see D. Elia's lecture)

How do we observe atoms/molecules in the sky at radio wavelengths?

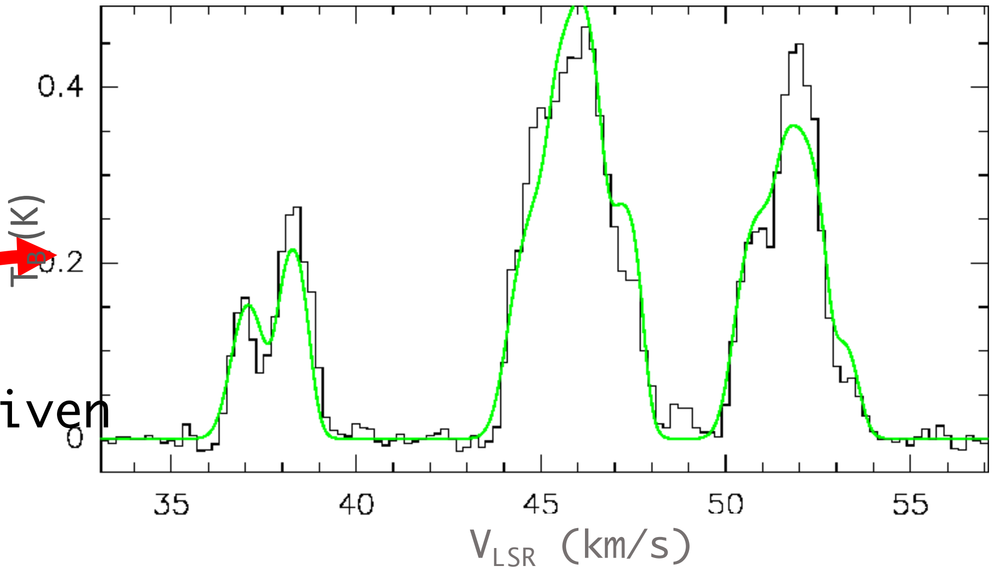
When you want to observe the sky you look for:

- **Continuum only**: Position-Position (PP) 2D maps
- **Spectral lines cube**: Position-Position-Velocity (PPV) datacube





For each given LOS



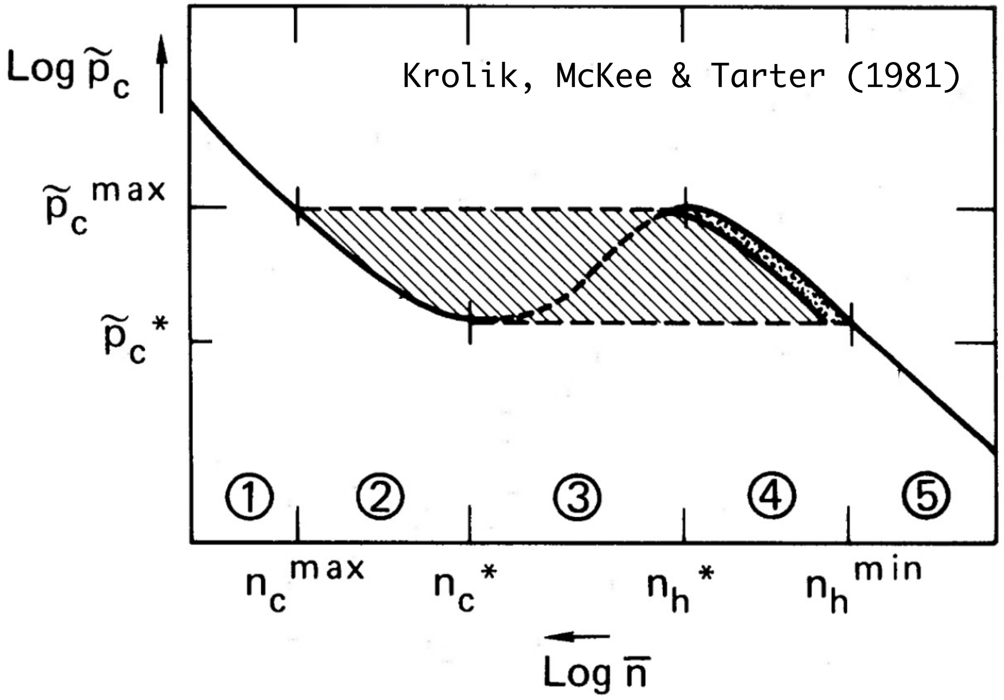
Star-forming regions, clumps and cores - outline

- ➢ How do we observe star-forming regions in our own Galaxy?
- ➢ Cold (and Warm) HI: the building blocks of star-forming regions
- ➢ From HI to H2: the transition phase to molecular clouds
- ➢ From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- ➢ (CO) Molecular clouds: physical properties, dynamics and (partial?) collapse
- ➢ From MCs to filaments: the densest regions of molecular clouds
- ➢ Pc-scales clumps: the nursery home of stars and protoclusters
- ➢ Gas dynamics in filament and clumps: the role of environment

HI: the building block of SF regions

HI is the main reservoir of gas which ultimately will form the molecular clouds

Simplest assumption: **2-phases neutral medium** (Cold and Warm)



Case 1: $n > n_c^{max}$

Dense, cold gas: CNM

Case 2-4: $n_c^{max} \leq n \leq n_h^{min}$

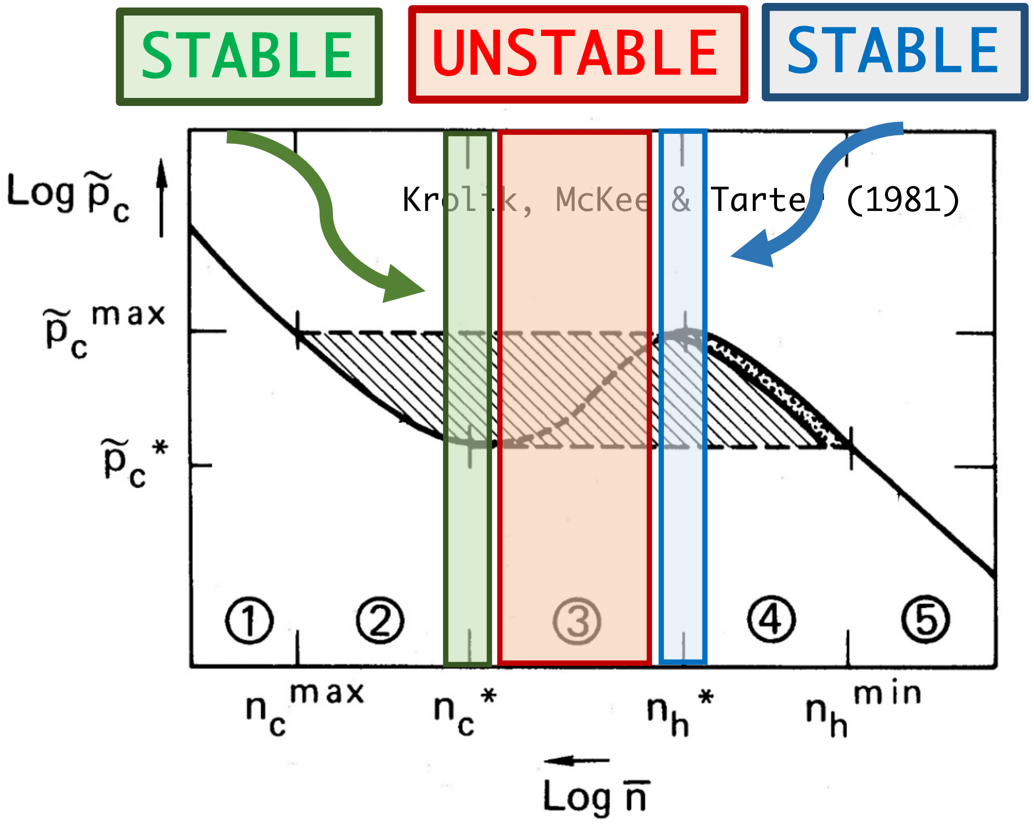
Case 5: $n < n_h^{min}$

Tenuous, warm gas: WNM

HI: the building block of SF regions

HI is the main reservoir of gas which ultimately will form the molecular clouds

Simplest assumption: **2-phases neutral medium** (Cold and Warm)



Krolik, McKee & Tarter (1981)

Case 1: $n > n_c^{max}$

Dense, cold gas: CNM

Case 2-4: $n_c^{max} \leq n \leq n_h^{min}$

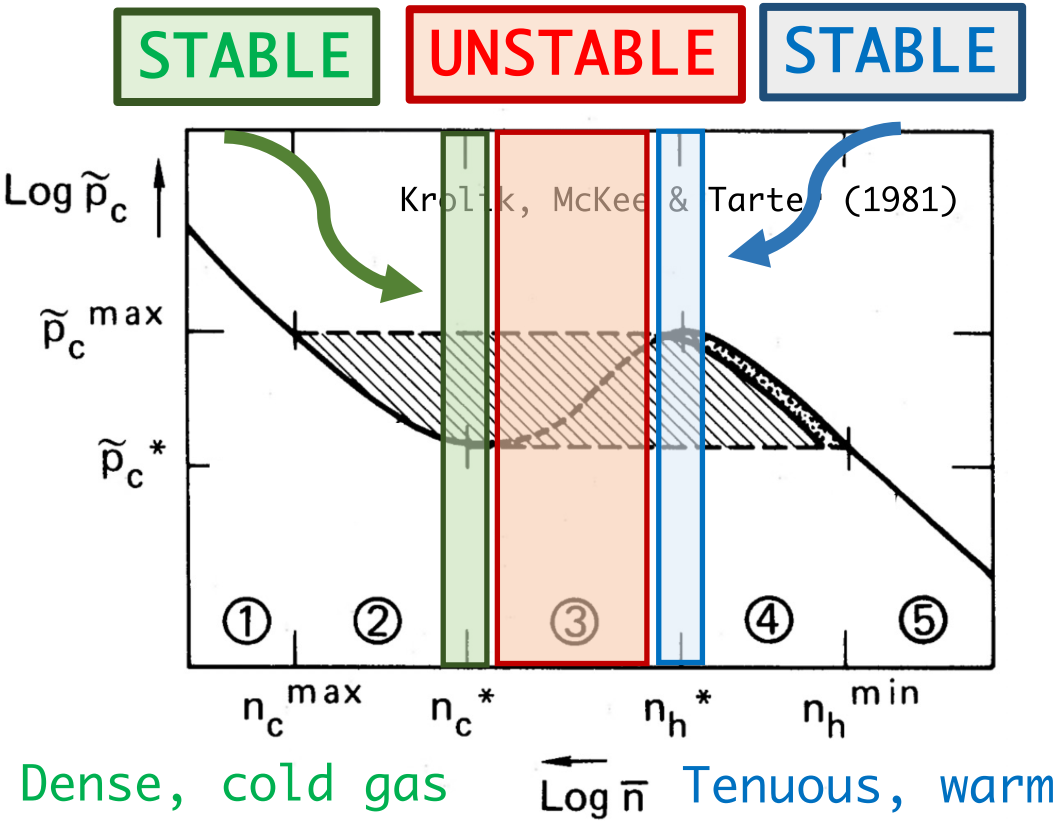
Case 5: $n < n_h^{min}$

Tenuous, warm gas: WNM

HI: the building block of SF regions

HI is the main reservoir of gas which ultimately will form the molecular clouds

Simplest assumption: **2-phases neutral medium** (Cold and Warm)



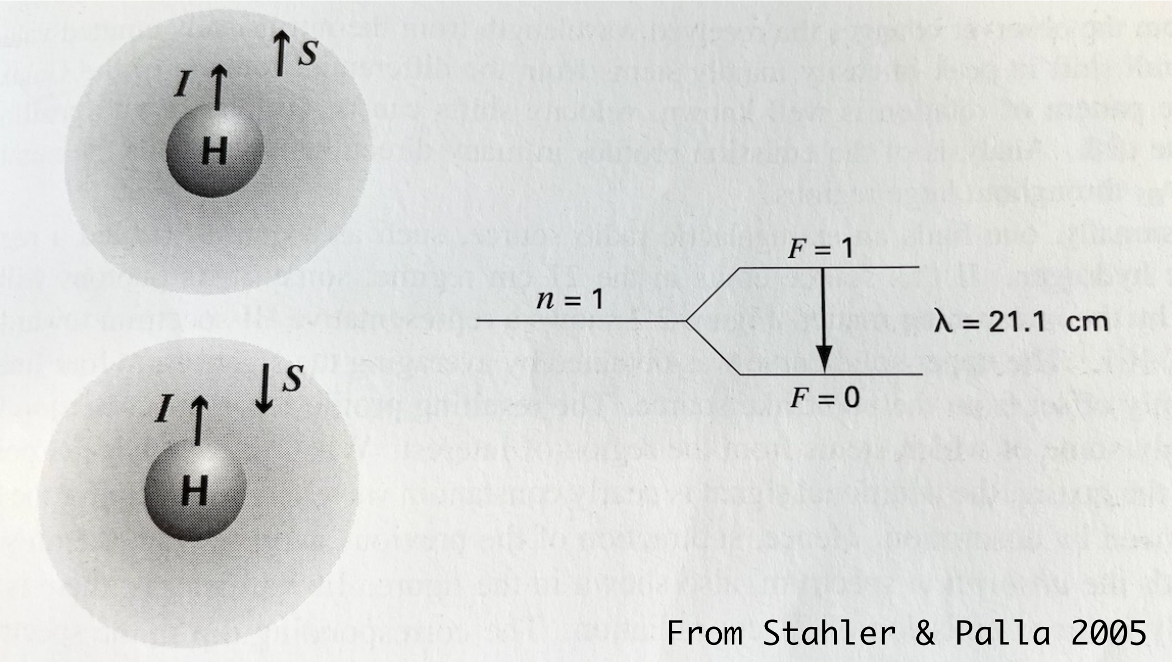
Dense, cold gas
CNM

Tenuous, warm gas
WNM

The gas is thermally unstable at intermediate densities
(1 – 20/30 cm^{-3})

- Cool down and get denser ->
  join the CNM (T~100 K, n~20-50 cm^{-3})
- Heat and become more tenuous ->
  join the WNM (T~8000 K n~0.2-0.5 cm^{-3})

HI: how do we observe it?



From Stahler & Palla 2005

The key observable: hyperfine transition at λ~21cm

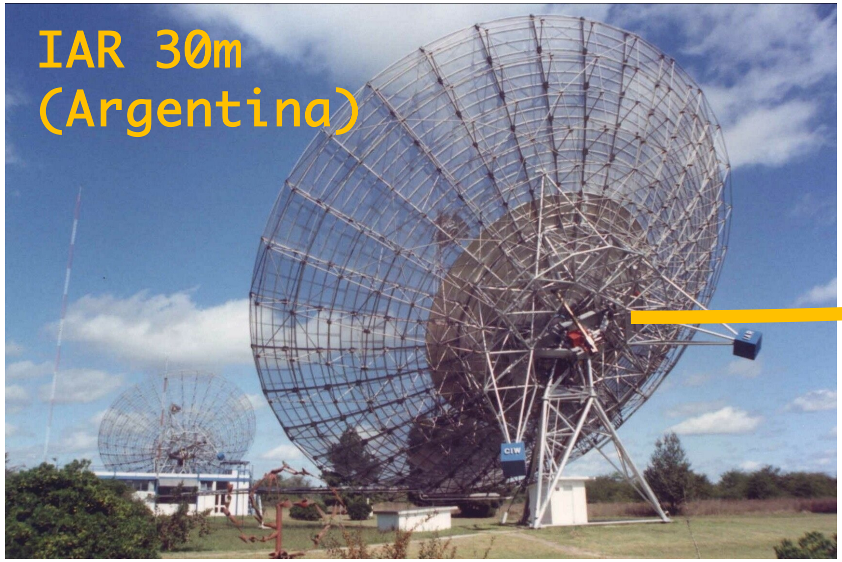
H atoms can be excited to the F=1 state by collision with neighbouring atoms. And deexcited by:

1) Collision with other H atoms

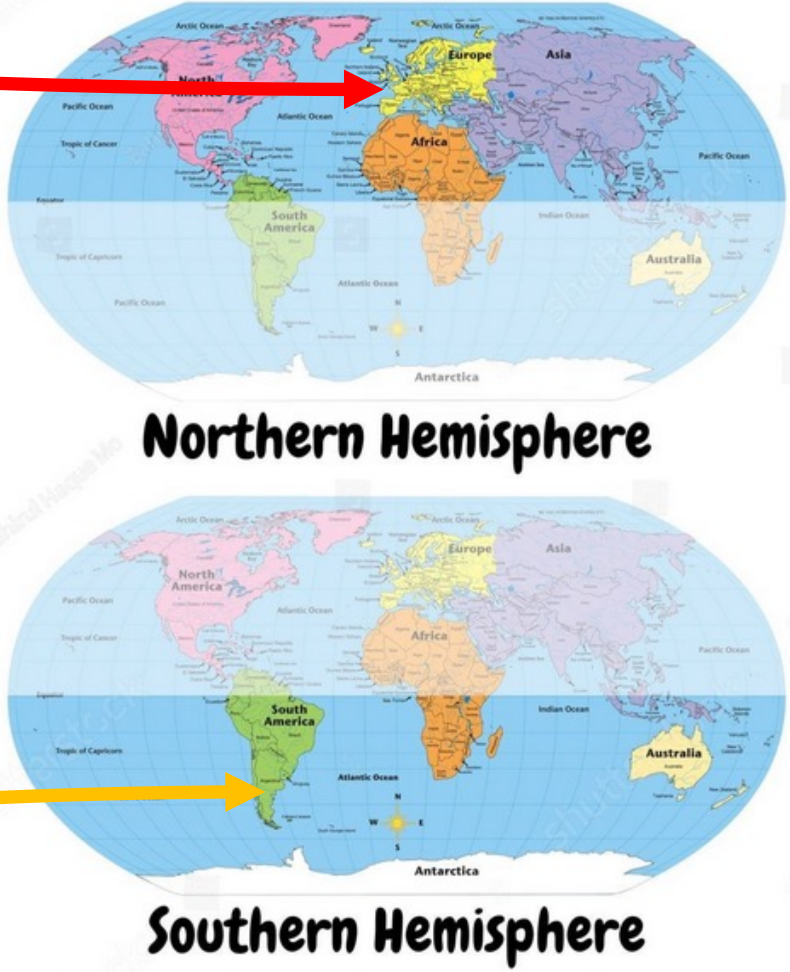
2) Emission of a ~21cm (~1.420 MHz) photon

HI: first all-sky survey (LAB survey, Kalberla+05)

Leiden 25m
(Netherlands)



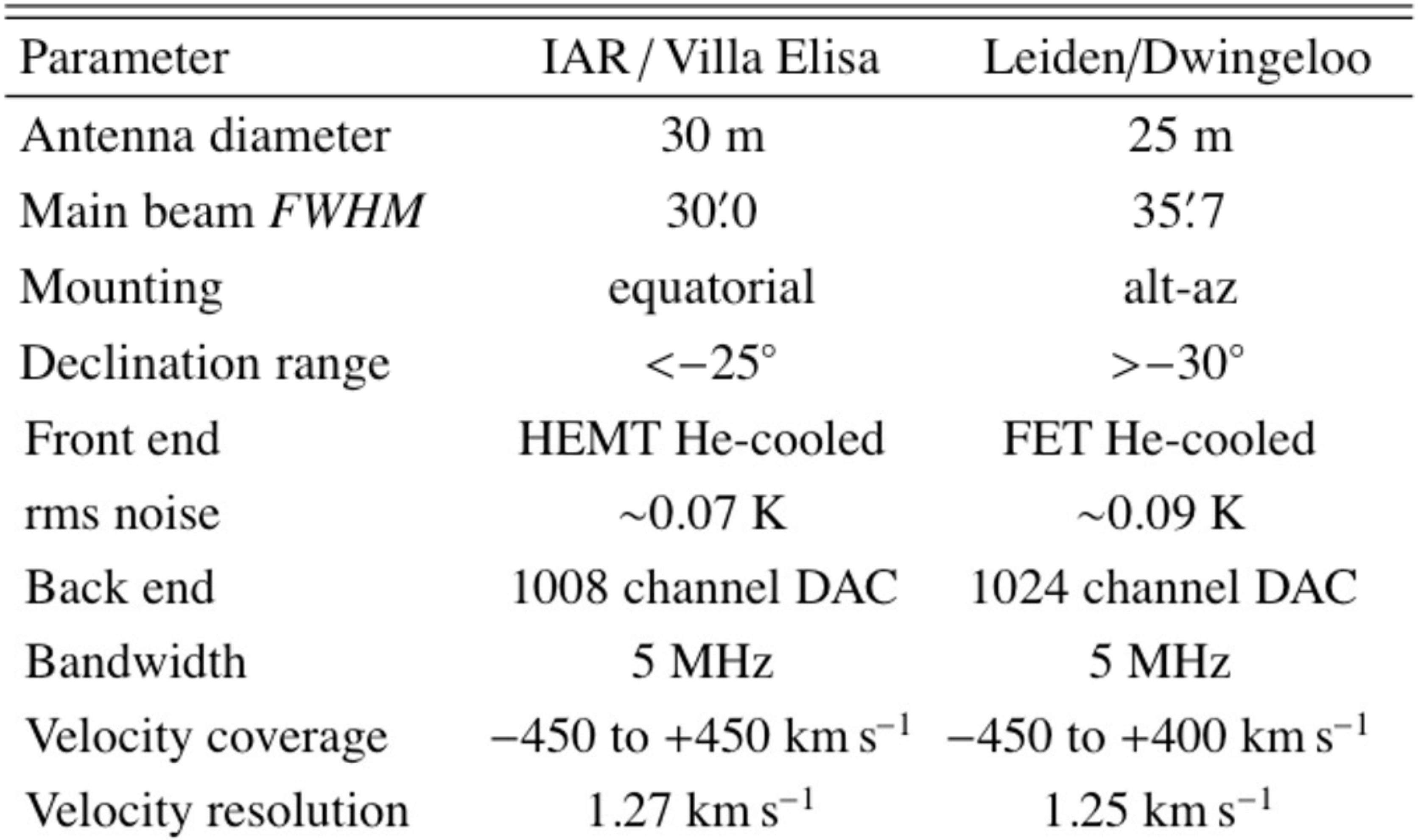
IAR 30m
(Argentina)



Northern Hemisphere

Southern Hemisphere

HI: first all-sky survey (LAB survey, Kalberla+05)



Parameter	IAR / Villa Elisa	Leiden/Dwingeloo
Antenna diameter	30 m	25 m
Main beam *FWHM*	30′.0	35′.7
Mounting	equatorial	alt-az
Declination range	<−25°	>−30°
Front end	HEMT He-cooled	FET He-cooled
rms noise	~0.07 K	~0.09 K
Back end	1008 channel DAC	1024 channel DAC
Bandwidth	5 MHz	5 MHz
Velocity coverage	−450 to +450 $\mathrm{km\,s^{-1}}$	−450 to +400 $\mathrm{km\,s^{-1}}$
Velocity resolution	1.27 $\mathrm{km\,s^{-1}}$	1.25 $\mathrm{km\,s^{-1}}$

HI: first all-sky survey (LAB survey, Kalberla+05)

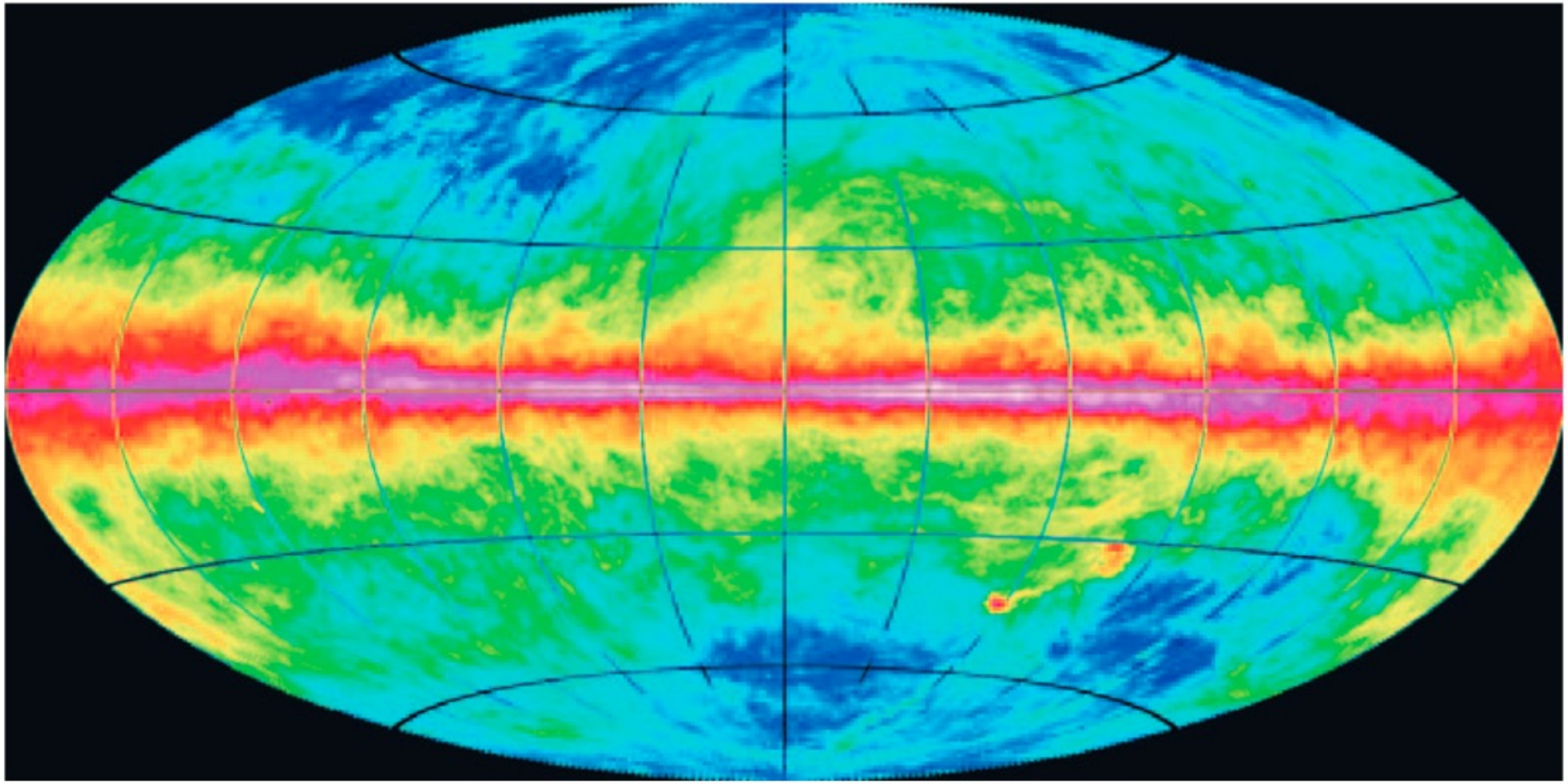
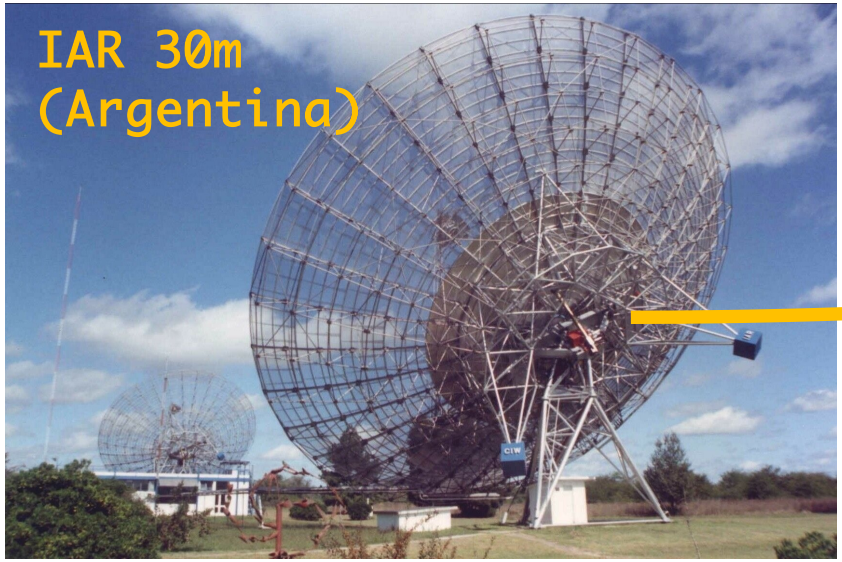


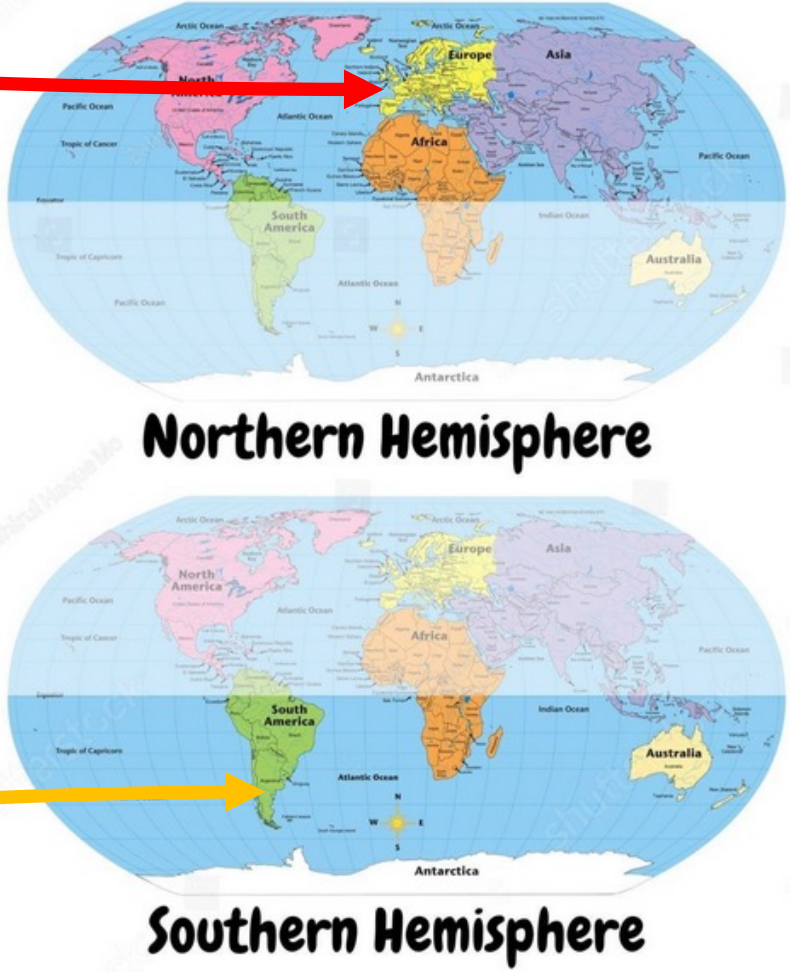
Fig. 3. H I emission integrated over the velocity range $-400 < v < +400$ km s^{-1} in the LAB dataset, shown in an Aitoff projection. The Galactic center is in the middle. The integrated emission ($0 < N_H < 2 \times 10^{22}$ cm^{-2}, logarithmic scale) yields column densities under the assumption of optical transparency; this assumption may be violated at latitudes within about 10° of the Galactic equator.

HI – old generation telescopes

Leiden 25m
(Netherlands)

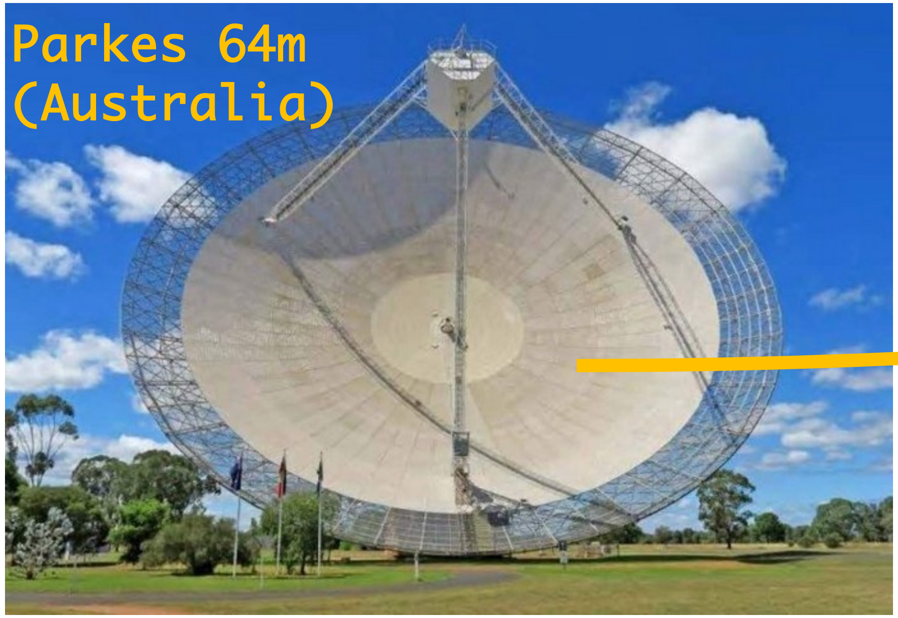


IAR 30m
(Argentina)



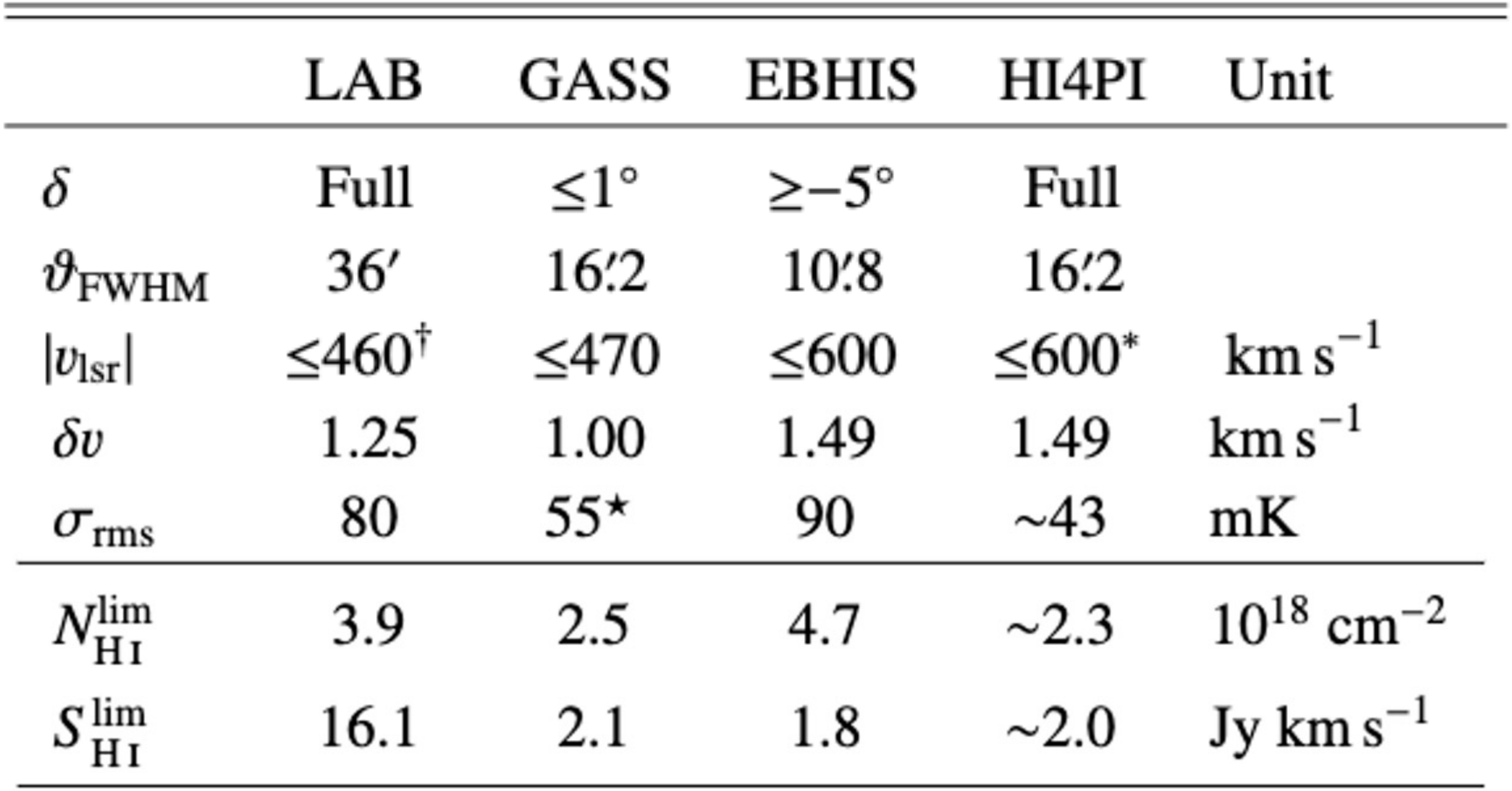
HI – NEW generation telescopes

Northern Hemisphere



Southern Hemisphere

HI: most recent all-sky survey (HI4PI survey, HI4PI coll. 2016)



	LAB	GASS	EBHIS	HI4PI	Unit
δ	Full	$\leq 1°$	$\geq -5°$	Full	
$\vartheta_{\mathrm{FWHM}}$	$36'$	$16'\!.2$	$10'\!.8$	$16'\!.2$	
$\lvert v_{\mathrm{lsr}} \rvert$	$\leq 460^{\dagger}$	≤ 470	≤ 600	$\leq 600^{*}$	$\mathrm{km\,s^{-1}}$
δv	1.25	1.00	1.49	1.49	$\mathrm{km\,s^{-1}}$
σ_{rms}	80	$55^{\star}$	90	~ 43	mK
$N_{\mathrm{H\,I}}^{\mathrm{lim}}$	3.9	2.5	4.7	~ 2.3	$10^{18}\,\mathrm{cm^{-2}}$
$S_{\mathrm{H\,I}}^{\mathrm{lim}}$	16.1	2.1	1.8	~ 2.0	$\mathrm{Jy\,km\,s^{-1}}$

HI: most recent all-sky survey (HI4PI survey, HI4PI coll. 2016)

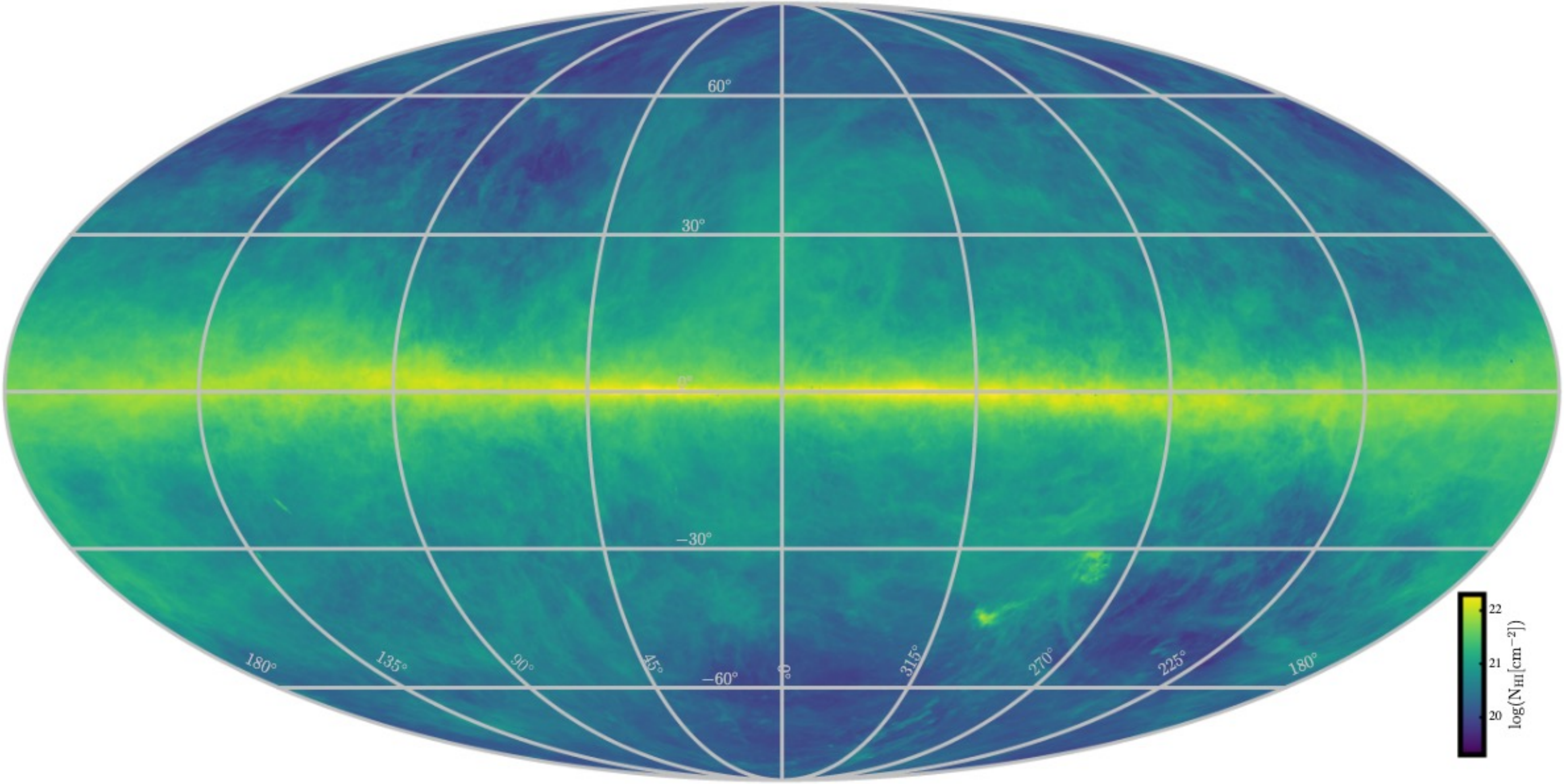
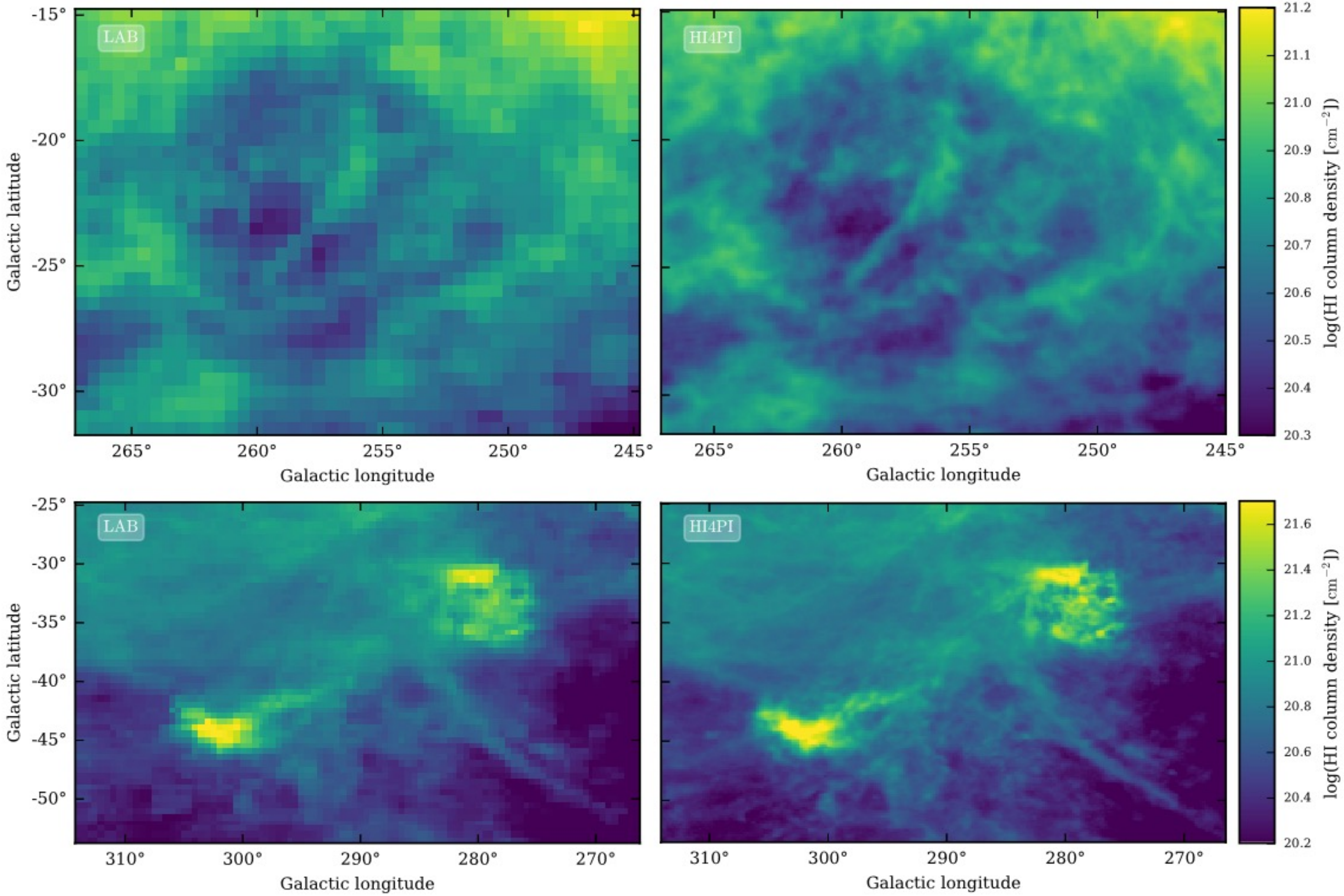
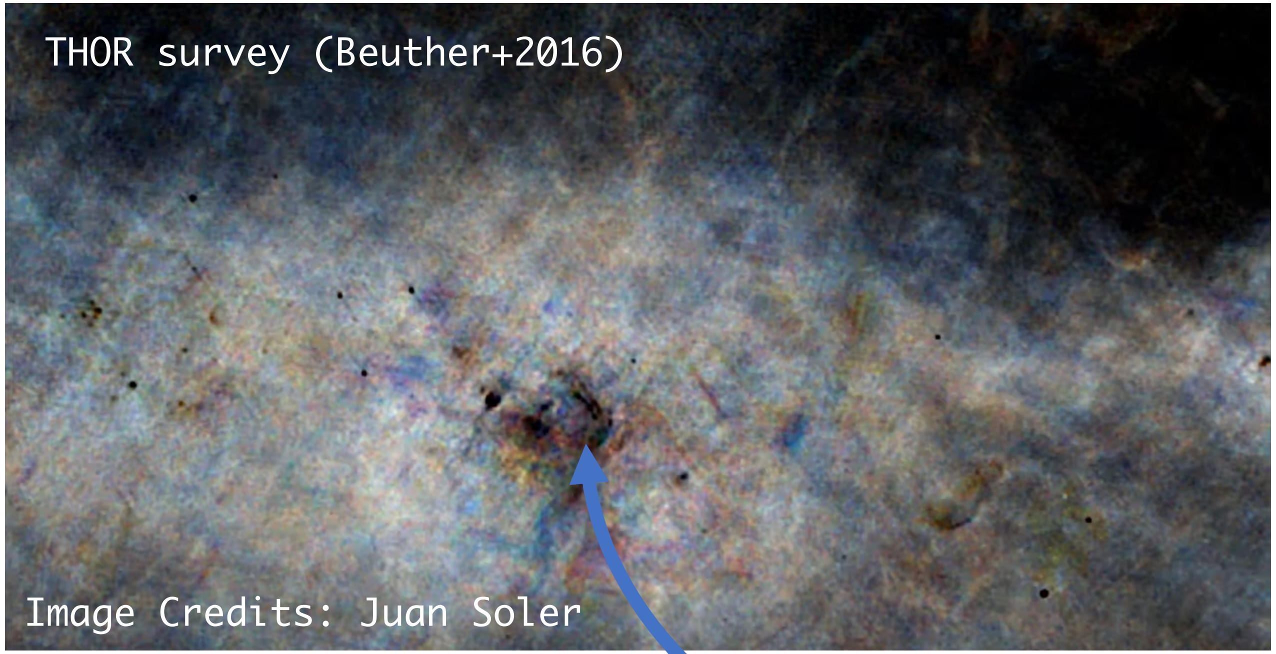


Fig. 2. HI4PI: all-sky column density map of H I gas from EBHIS and GASS data as integrated over the full velocity range $-600 \leq v_{\rm lsr} \leq 600\ {\rm km\,s^{-1}}$. The map is in Galactic coordinates using Mollweide projection.

HI: most recent all-sky survey (HI4PI survey, HI4PI coll. 2016)

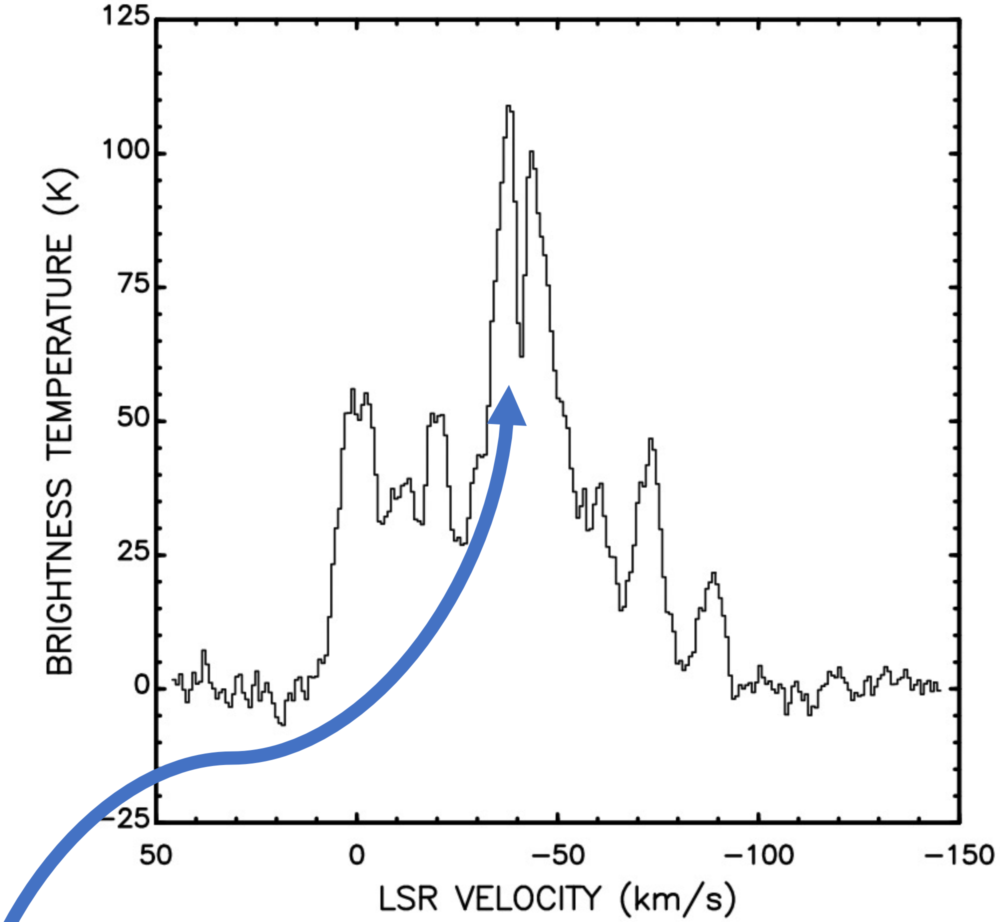


HI: HISA



THOR survey (Beuther+2016)

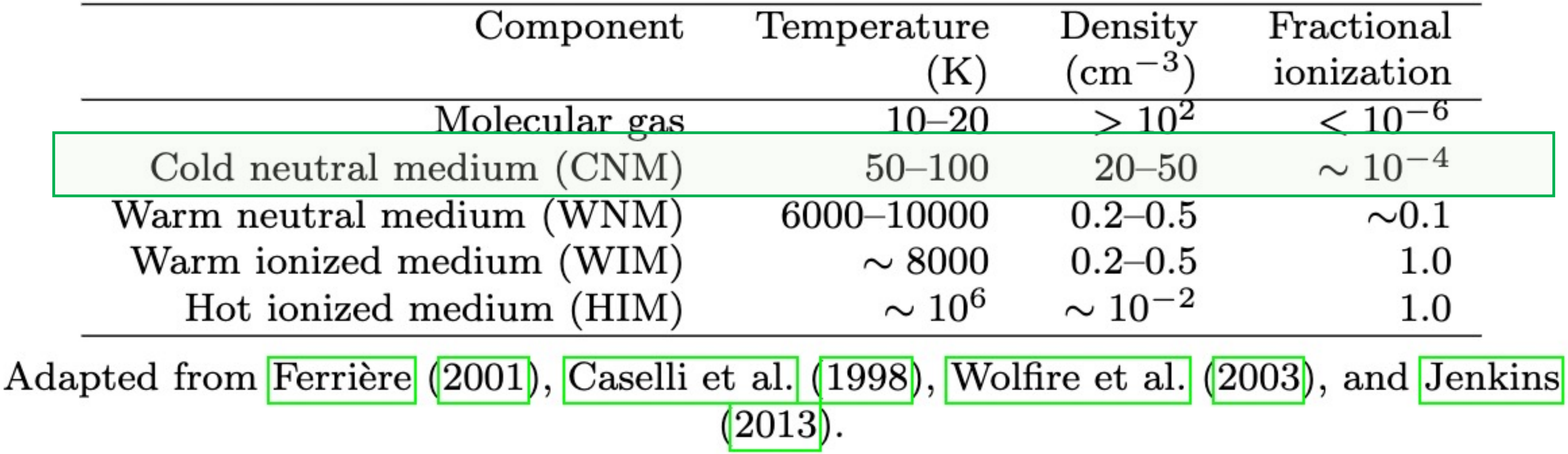
Image Credits: Juan Soler



HISA (HI Self-Absorption features)

Gas composition in the Milky Way

Girichidis+2020

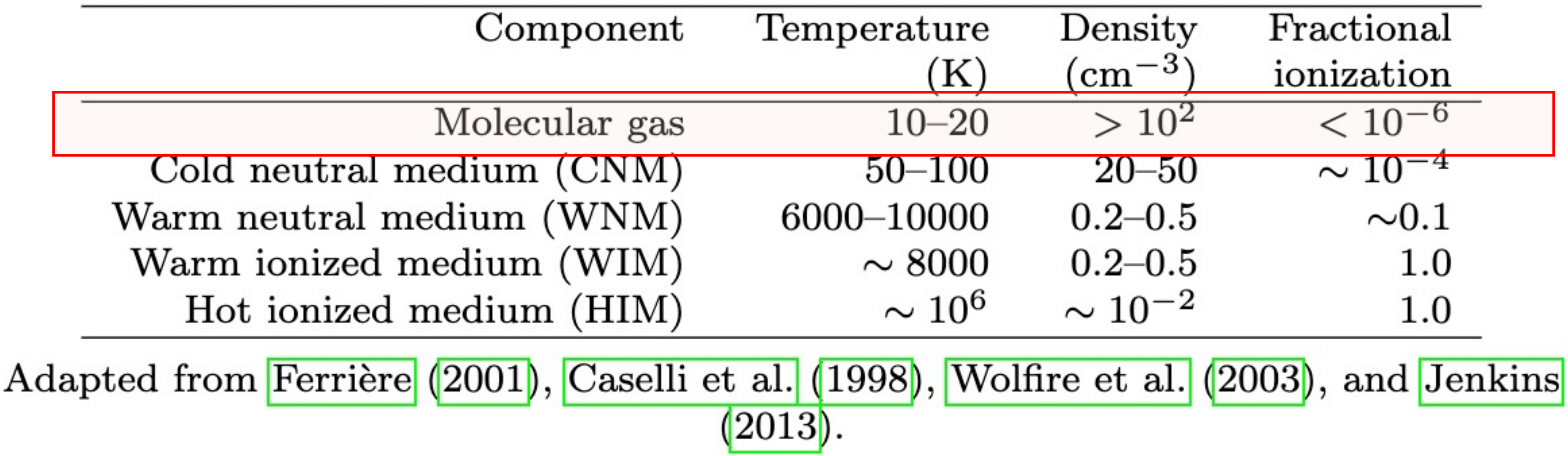


Component	Temperature (K)	Density (cm^{-3})	Fractional ionization
Molecular gas	10–20	$> 10^2$	$< 10^{-6}$
Cold neutral medium (CNM)	50–100	20–50	$\sim 10^{-4}$
Warm neutral medium (WNM)	6000–10000	0.2–0.5	$\sim$0.1
Warm ionized medium (WIM)	~ 8000	0.2–0.5	1.0
Hot ionized medium (HIM)	$\sim 10^6$	$\sim 10^{-2}$	1.0

Adapted from Ferrière (2001), Caselli et al. (1998), Wolfire et al. (2003), and Jenkins (2013).

Gas composition in the Milky Way

Girichidis+2020



Component	Temperature (K)	Density (cm^{-3})	Fractional ionization
Molecular gas	10–20	$> 10^2$	$< 10^{-6}$
Cold neutral medium (CNM)	50–100	20–50	$\sim 10^{-4}$
Warm neutral medium (WNM)	6000–10000	0.2–0.5	$\sim$0.1
Warm ionized medium (WIM)	~ 8000	0.2–0.5	1.0
Hot ionized medium (HIM)	$\sim 10^6$	$\sim 10^{-2}$	1.0

Adapted from Ferrière (2001), Caselli et al. (1998), Wolfire et al. (2003), and Jenkins (2013).

Star-forming regions, clumps and cores - outline

- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: physical properties, dynamics and (partial?) collapse
- From MCs to filaments: the densest regions of molecular clouds
- Pc-scales clumps: the nursery home of stars and protoclusters
- Gas dynamics in filament and clumps: the role of environment

Transition from H to H_2

There are several pathways:

1. $H + H \rightarrow H_2 + \gamma$

Radiative association of two H atoms

2a. $H + e^- \rightarrow H^- + \gamma,$
$H^- + H \rightarrow H_2 + e^-$

Ion-neutral reaction

2b. $H + H^+ \rightarrow H_2^+ + \gamma,$
$H_2^+ + H \rightarrow H_2 + H^+$

See lecture from Simon Glover

Transition from H to H_2

There are several pathways:

1. $H + H \rightarrow H_2 + \gamma$

Radiative association of two H atoms

2a. $H + e^- \rightarrow H^- + \gamma,$

$H^- + H \rightarrow H_2 + e^-$

2b. $H + H^+ \rightarrow H_2^+ + \gamma,$

$H_2^+ + H \rightarrow H_2 + H^+$

Ion-neutral reaction

Highly inefficient!!!

See lecture from Simon Glover

Under the ISM condition the best pathways the formation of H_2 occurs on the **surface of dust grains**

Star-forming regions, clumps and cores - outline

- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: physical properties, dynamics and (partial?) collapse
- From MCs to filaments: the densest regions of molecular clouds
- Pc-scales clumps: the nursery home of stars and protoclusters
- Gas dynamics in filament and clumps: the role of environment

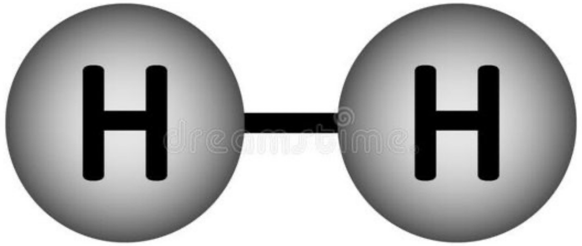
Molecular clouds: how do we observe them?

Molecular cloud is (theoretically) defined as **a region of gas and dust where most of the hydrogen is in form of H_2 rather than H**

Molecular clouds: how do we observe them?

Molecular cloud is (theoretically) defined as **a region of gas and dust where most of the hydrogen is in form of H_2 rather than H**

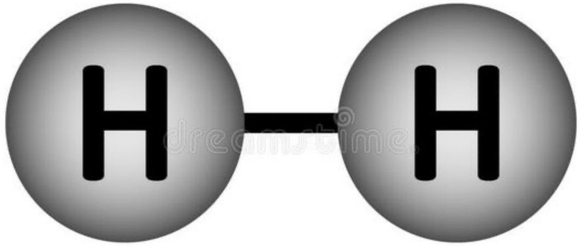
So let’s see which transition of H_2 we can use to observe molecular clouds…



Molecular clouds: how do we observe them?

Molecular cloud is (theoretically) defined as **a region of gas and dust where most of the hydrogen is in form of H_2 rather than H**

So let's see which transition of H_2 we can use to observe molecular clouds…

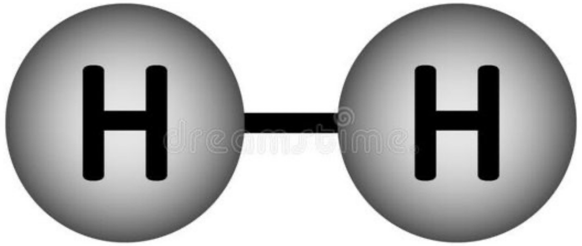


…and we got a problem here: H_2 is a symmetric molecule

It has no electric dipole transitions but only (forbidden) higher-order ones

It does **NOT** emit at the temperatures of a few 10 K to 100 K typical of Galactic clouds

Molecular clouds: how do we observe them?



…and we got a problem here: H_2 is a symmetric molecule

It has no electric dipole transitions but only (forbidden) higher-order ones

It does **NOT** emit at the temperatures of a few 10 K to 100 K typical of Galactic clouds

We need to use another tracer that must be

- Abundant enough to map the H_2 clouds
- With observable transitions at low temperatures (10K-50K)
- Exited at densities of 10^2 – 10^4 cm^{-3} (typical densities of molecular clouds)

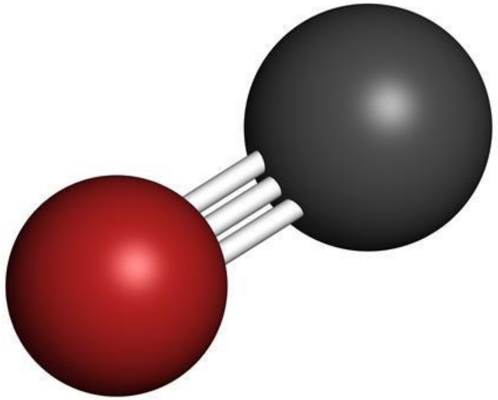
Molecular clouds: how do we observe them?

We need to use another tracer that must be

- Abundant enough to map the H_2 clouds
- With observable transitions at low temperatures (10K-50K)
- Exited at densities of $10^2 - 10^4$ cm^{-3} (typical densities of molecular clouds)

We have it!

Carbon Monoxide (CO)



✓ CO is the second most abundant molecular species after H_2 in the Galaxy

✓ CO has a significant dipole moment: it is rotationally excited even at very low gas temperatures, $T < 20$ K

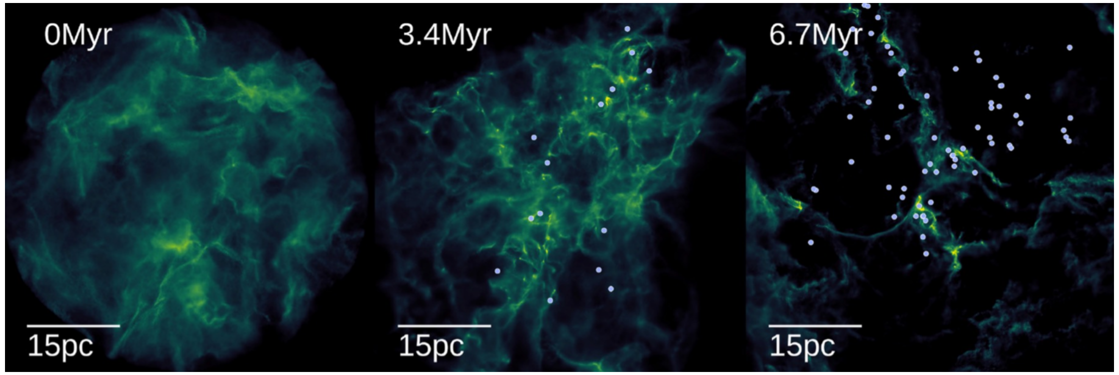
✓ It's critical density is ~10^3-10^4 cm^{-3} (i.e. ~ the expected cloud densities)

See lecture from Simon Glover

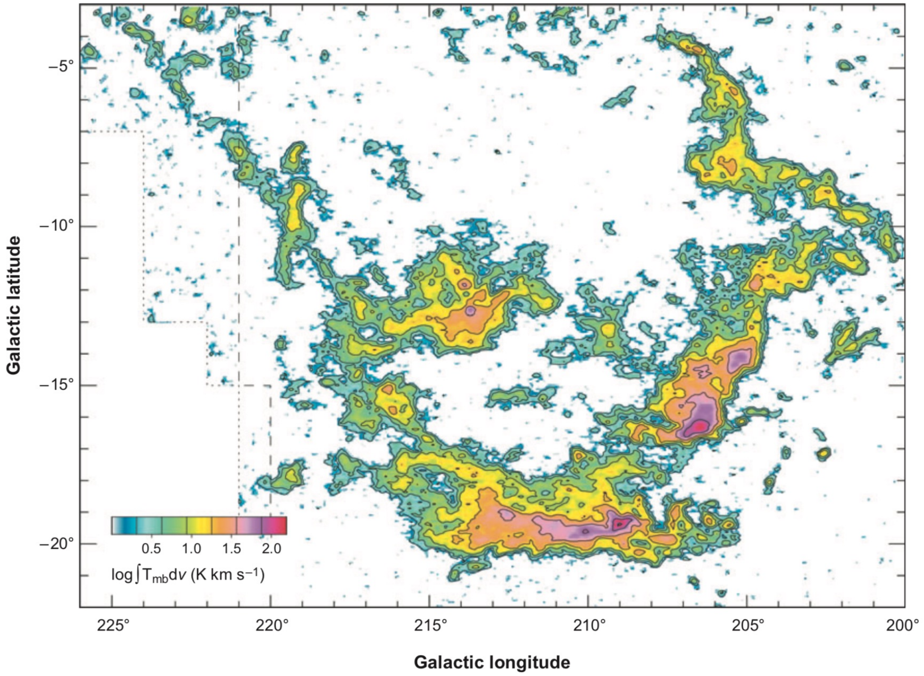
Molecular clouds: how do we observe them?

<u>**Theoretical**</u> definition of a molecular cloud: **an interstellar cloud of gas and dust where most of the hydrogen is in form of H_2 rather than H**

<u>**Operative**</u> definition of a molecular cloud: **a coherent structure in the sky identified in the CO spectrum above a certain noise level**



Simulation of a molecular cloud evolution

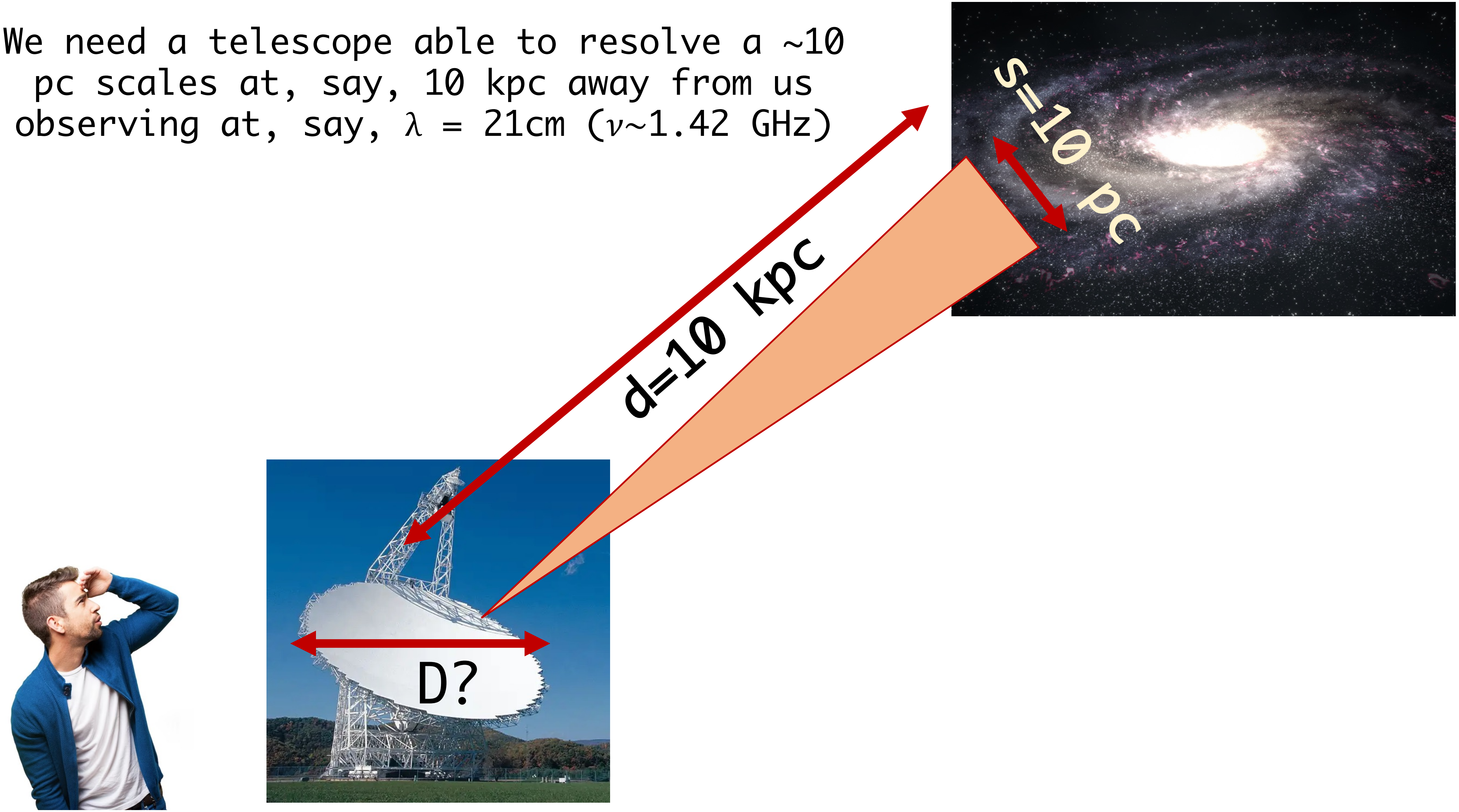


Orion-Monoceros molecular complex seen in ^{12}CO (1-0)

Wilson+05

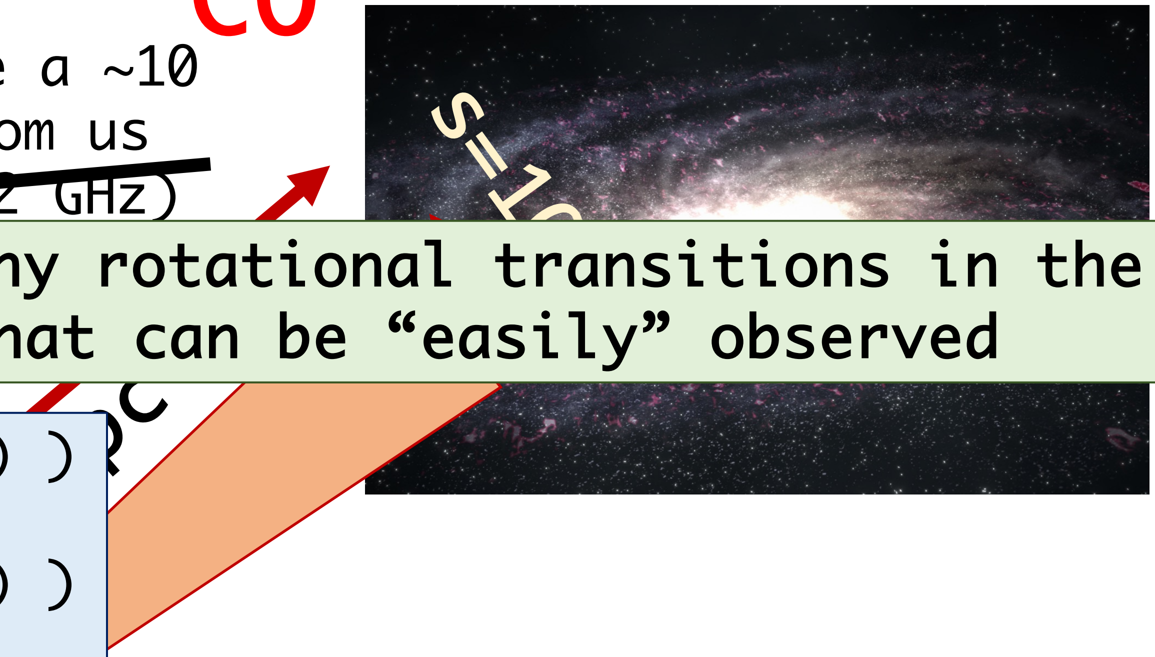
How do we observe HI in the sky?

We need a telescope able to resolve a ~10 pc scales at, say, 10 kpc away from us observing at, say, λ = 21cm (ν~1.42 GHz)



How do we observe ~~HI~~ CO in the sky?

We need a telescope able to resolve a ~10 pc scales at, say, 10 kpc away from us observing at, say, ~~λ = 21cm (ν~1.42 GHz)~~



CO (and CO isotopes) has many rotational transitions in the radio frequency range that can be "easily" observed

λ ~ 2.6mm (ν~115.3 GHz, ^{12}CO (1-0))

λ ~ 1.3mm (ν~230.5 GHz, ^{12}CO (2-1))

λ ~ 2.7mm (ν~110.2 GHz, ^{13}CO (1-0))

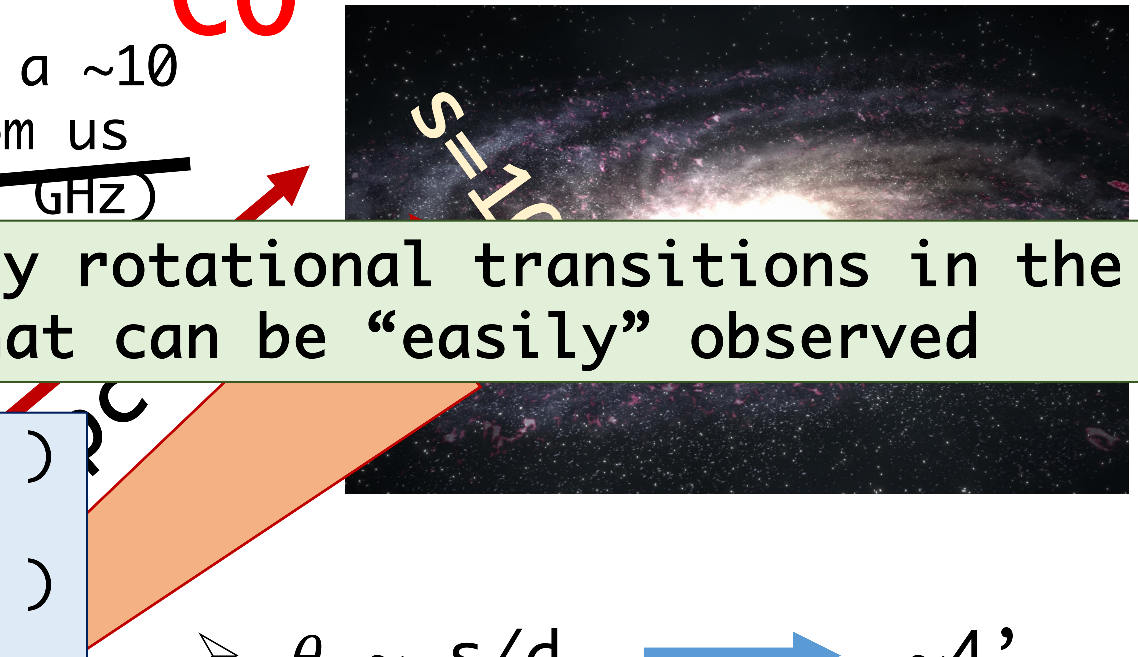
λ ~ 1.4mm (ν~220.4 GHz, ^{13}CO (2-1))

λ ~ 2.7mm (ν~109.8 GHz, C^{18}O (1-0))

… … …

How do we observe ~~HI~~ CO in the sky?

We need a telescope able to resolve a ~10 pc scales at, say, 10 kpc away from us observing at, say, ~~λ = 21cm (ν~1.42 GHz)~~



CO (and CO isotopes) has many rotational transitions in the radio frequency range that can be "easily" observed

λ ~ 2.6mm (ν~115.3 GHz, ^{12}CO (1-0))

λ ~ 1.3mm (ν~230.5 GHz, ^{12}CO (2-1))

λ ~ 2.7mm (ν~110.2 GHz, ^{13}CO (1-0))

λ ~ 1.4mm (ν~220.4 GHz, ^{13}CO (2-1))

λ ~ 2.7mm (ν~109.8 GHz, C^{18}O (1-0))

… … …

- $\theta \sim s/d$ → ~4'
- $\theta \simeq 1.22\lambda/D$

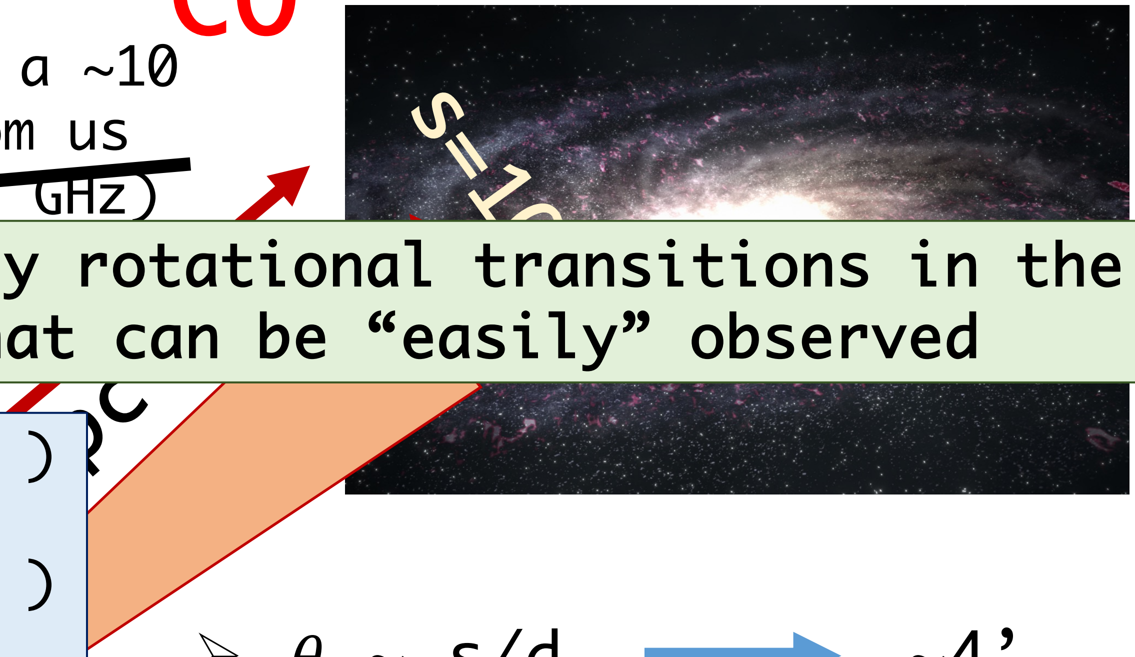
λ = 21cm

θ = 4' → D = 220 meters…

How do we observe ~~HI~~ CO in the sky?

We need a telescope able to resolve a ~10 pc scales at, say, 10 kpc away from us observing at, say, λ = ~~21cm (ν~1.42 GHz)~~

CO (and CO isotopes) has many rotational transitions in the radio frequency range that can be "easily" observed



λ ~ 2.6mm (ν~115.3 GHz, ^{12}CO (1-0))

λ ~ 1.3mm (ν~230.5 GHz, ^{12}CO (2-1))

λ ~ 2.7mm (ν~110.2 GHz, ^{13}CO (1-0))

λ ~ 1.4mm (ν~220.4 GHz, ^{13}CO (2-1))

λ ~ 2.7mm (ν~109.8 GHz, C^{18}O (1-0))

… … …

- $\theta \sim s/d$ → ~4'
- $\theta \simeq 1.22\lambda/D$

λ = ~~21cm~~ → 2.6mm

→ D = ~~220 meters…~~

θ = 4'

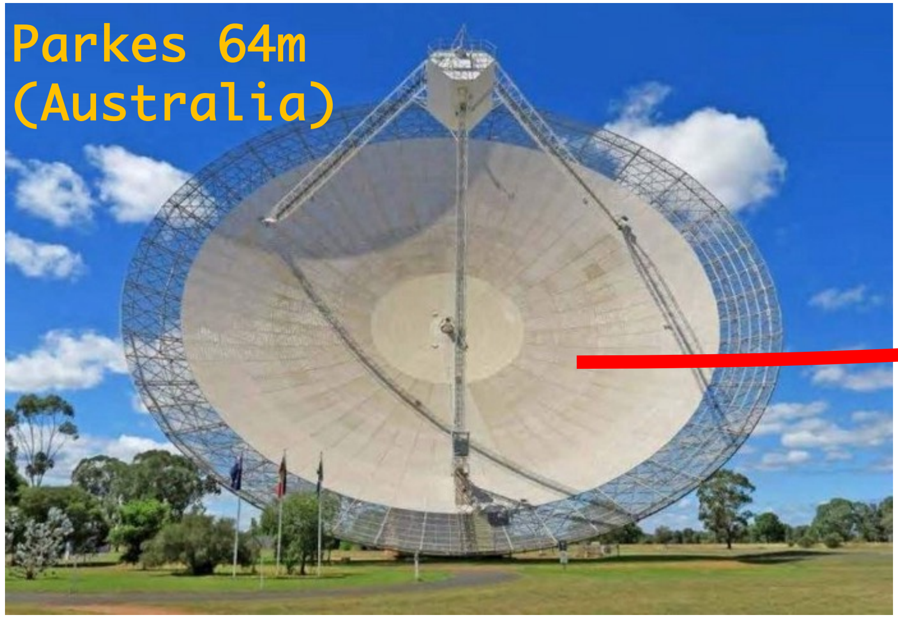
→

D = 2.7 meters…

HI – NEW generation telescopes

Effelsberg 100m
(Germany)

Northern Hemisphere

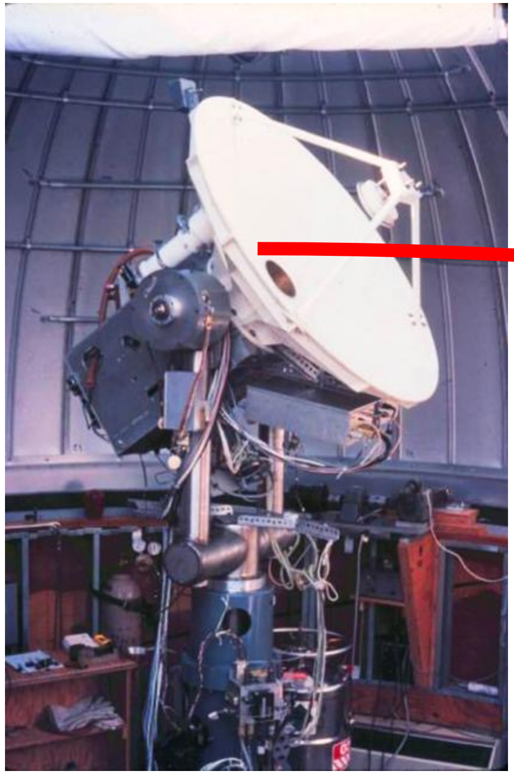


Parkes 64m
(Australia)

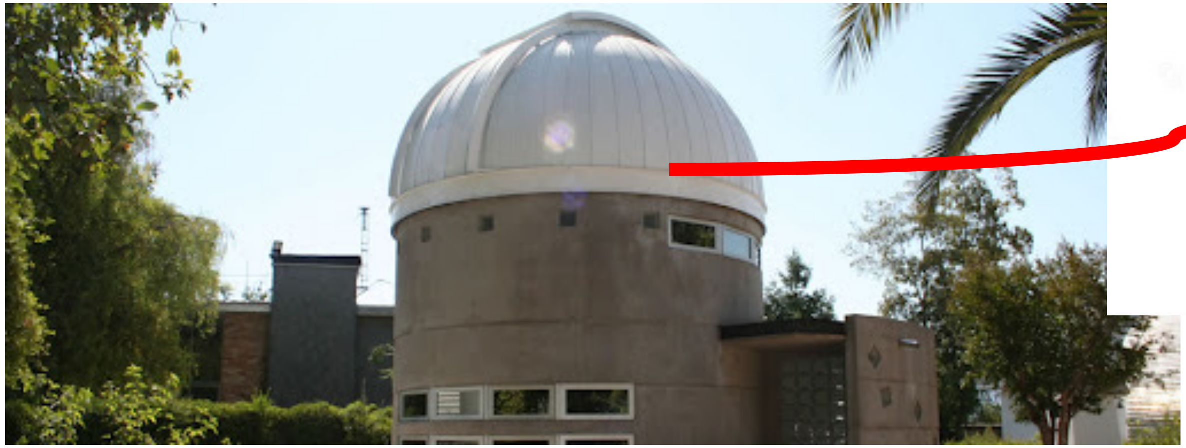
Southern Hemisphere

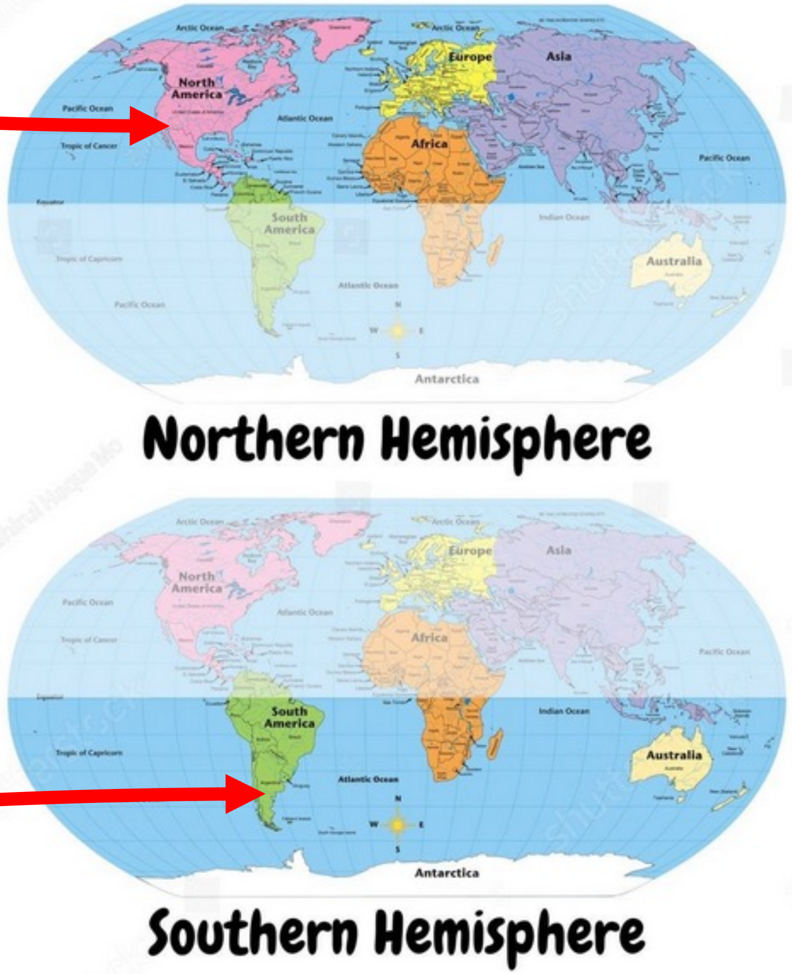
CO telescopes

1.2m CfA telescope (US)



1.2m Cerro Tololo telescope (Chile)





Molecular clouds: how do we observe them?

The first composite survey of ^{12}CO (1-0) across the Milky Way Galaxy
(Dame et al. 2001)

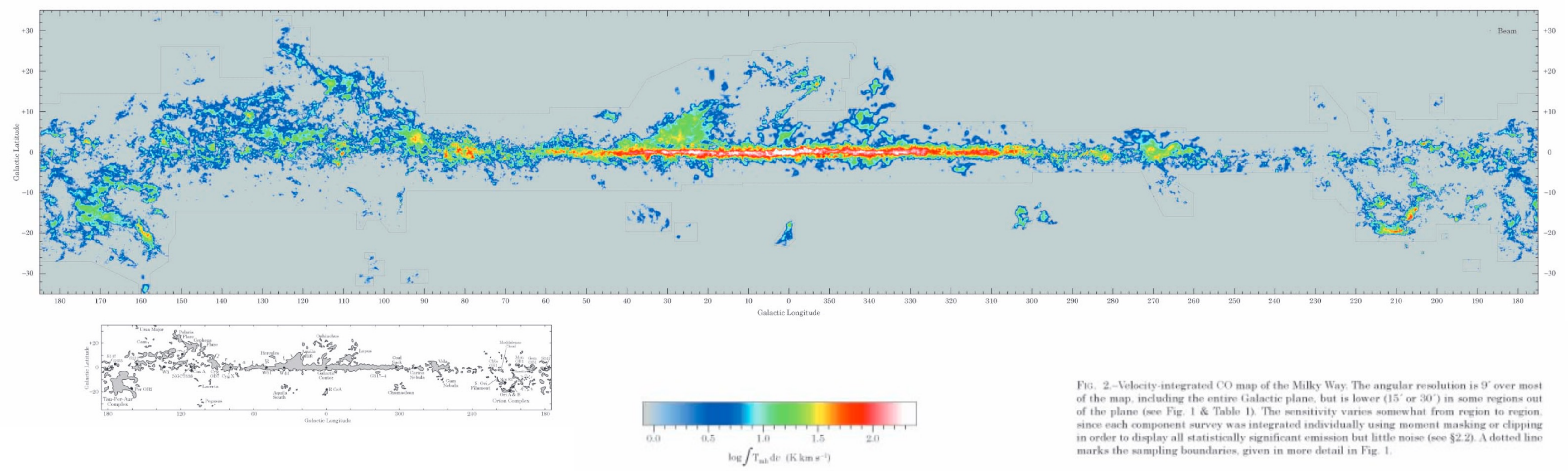
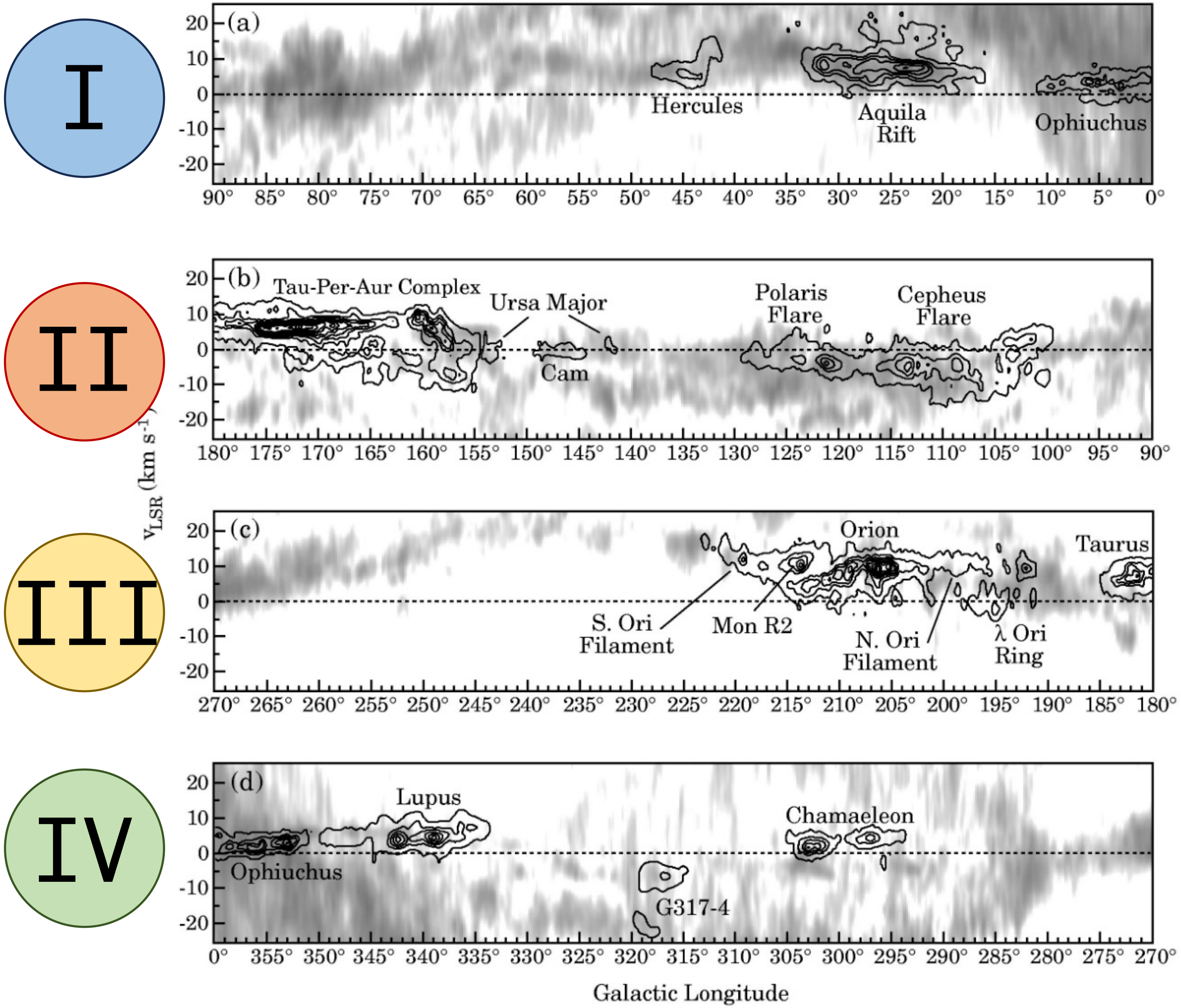
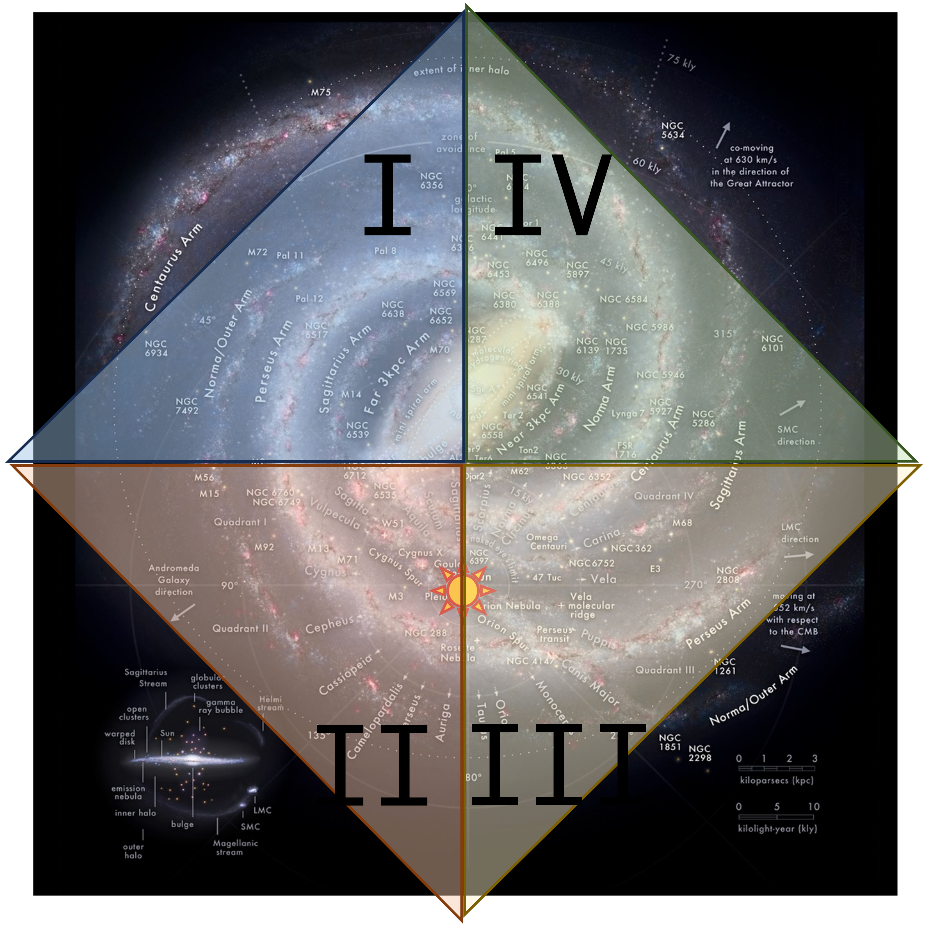


FIG. 2.—Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

Molecular clouds: how do we observe them?

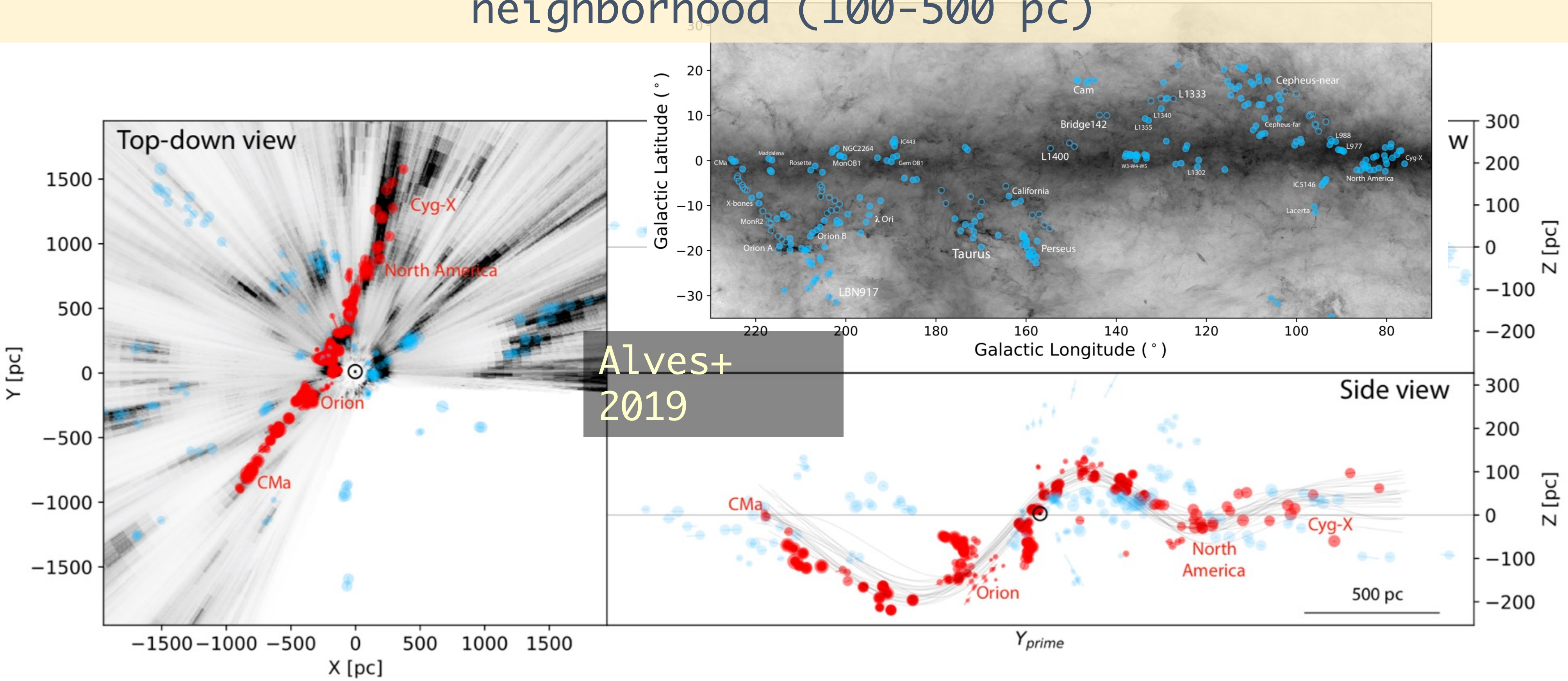




4 quadrants

Molecular clouds: how do we observe them?

Local system of clouds that form low-mass stars in the solar neighborhood (100-500 pc)



Alves+ 2019

Using photometric surveys and the Gaia astrometric survey, Alves+2019 found that the Gould Belt is NOT an expanding ring but a narrow arrangement of cloud: 160 pc x 2000 pc undulating like a “Radcliffe wave”

Slides courtesy of Frederique Motte

Molecular clouds: properties and caveats (that we have to deal with):

1. How to define the cloud boundaries (and how to disentangle different clouds along the LOS) from CO brightness temperature T_B maps?

2. How does the observed CO brightness temperature T_B convert in H_2 mass?

3. Does CO trace perfectly all the H_2 in a given line of sight?

Molecular clouds: properties and caveats (that we have to deal with):

1. How to define the cloud boundaries (and how to disentangle different clouds along the LOS) from CO brightness temperature T_B maps?

- **Clumpfind** algorithm

- **Dendrogram** analysis

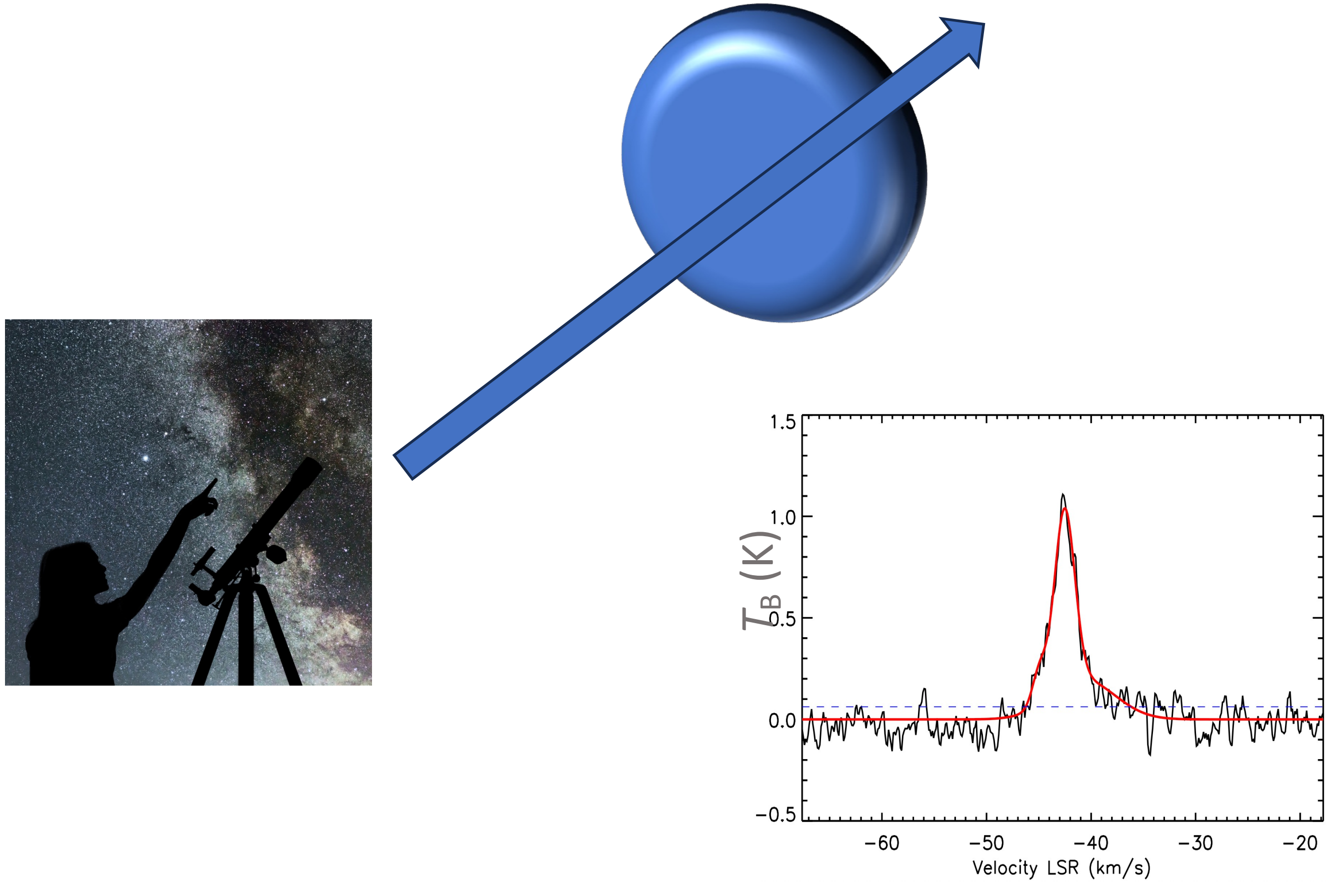
- **Gaussian** decomposition

See lecture from Frederique Motte

Molecular clouds: properties and caveats (that we have to deal with):

1. How to define the cloud boundaries (and how to disentangle different clouds along the LOS) from CO brightness temperature T_B maps?

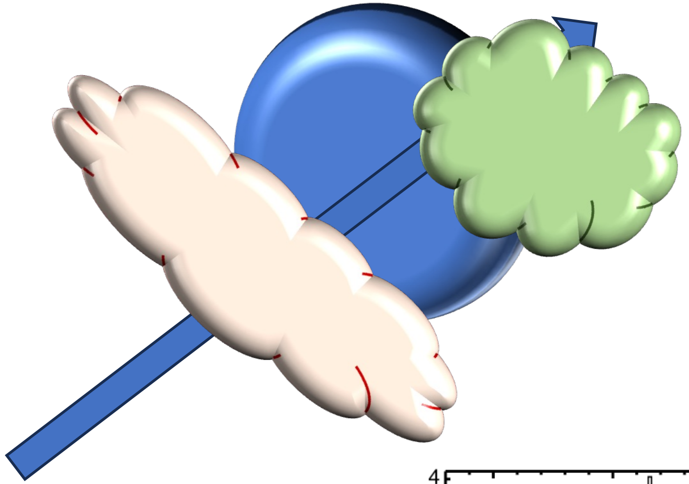
- **Clumpfind** algorithm
- **Dendrogram** analysis
- **Gaussian** decomposition

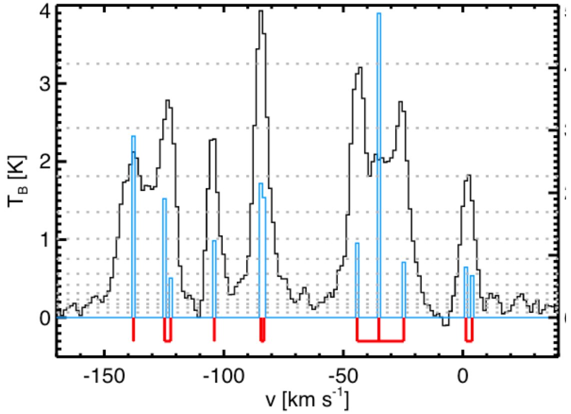


Molecular clouds: properties and caveats (that we have to deal with):

1. How to define the cloud boundaries (and how to disentangle different clouds along the LOS) from CO brightness temperature T_B maps?

- **Clumpfind** algorithm
- **Dendrogram** analysis
- **Gaussian** decomposition





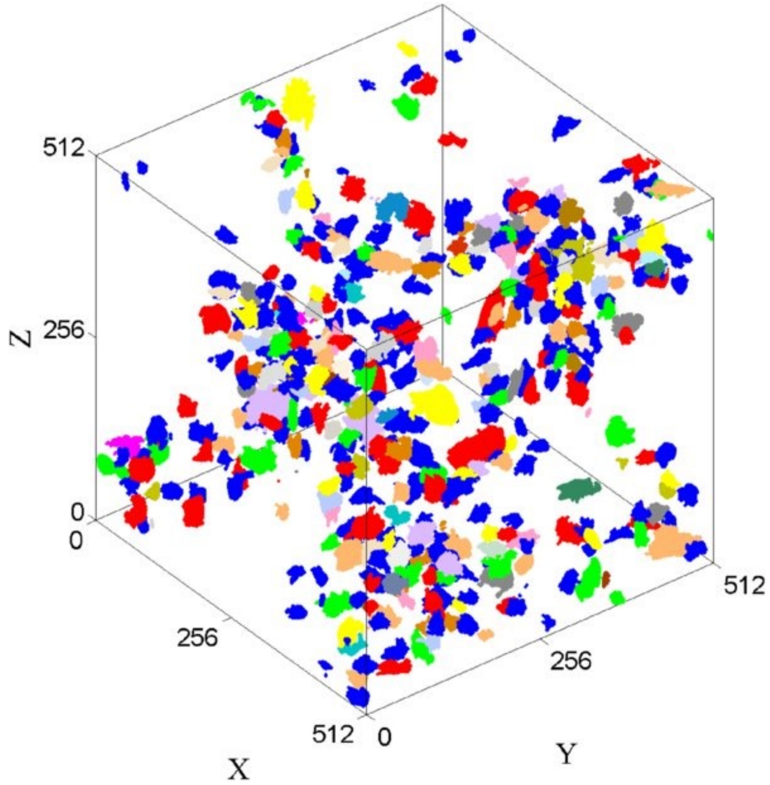
Molecular clouds: properties and caveats (that we have to deal with):

1. How to define the cloud boundaries (and how to disentangle different clouds along the LOS) from CO brightness temperature T_B maps?

- **Clumpfind** algorithm

The algorithm works by first contouring the data at a multiple of the rms noise of the observations, then searches for peaks of emission which locate the clumps, and then follows them down to lower intensities. No a priori clump profile is assumed

Williams+94



Molecular clouds: properties and caveats (that we have to deal with):

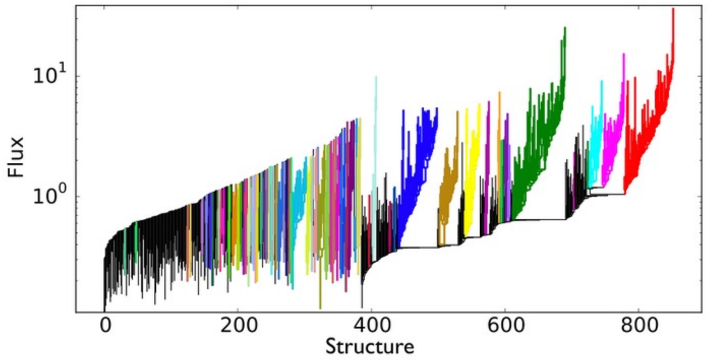
1. How to define the cloud boundaries (and how to disentangle different clouds along the LOS) from CO brightness temperature T_B maps?

- **<u>Dendrogram</u>** analysis

Dendrogram is a diagram that shows the hierarchical relationship between objects. The analysis utilizes spectral clustering to find discrete regions with similar emission properties

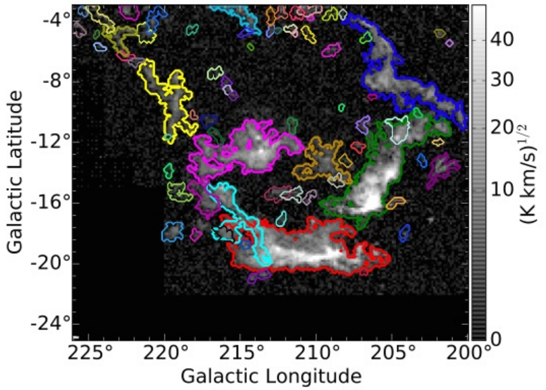
Rosolowsky+08, Colombo+15

***Clustered* dendrogram**



The figure shows the final product of `SCIMES`: the *clustered* dendrogram. Each color indicates a relevant branch (i.e. *cluster*) within the dendrogram, according to the chosen affinity criterion. In this case, the clusters are selected based on their similar maximal volume. Affinity criteria can be based upon virtually any observable property of the ISM.

Giant Molecular Clouds in Orion-Monoceros



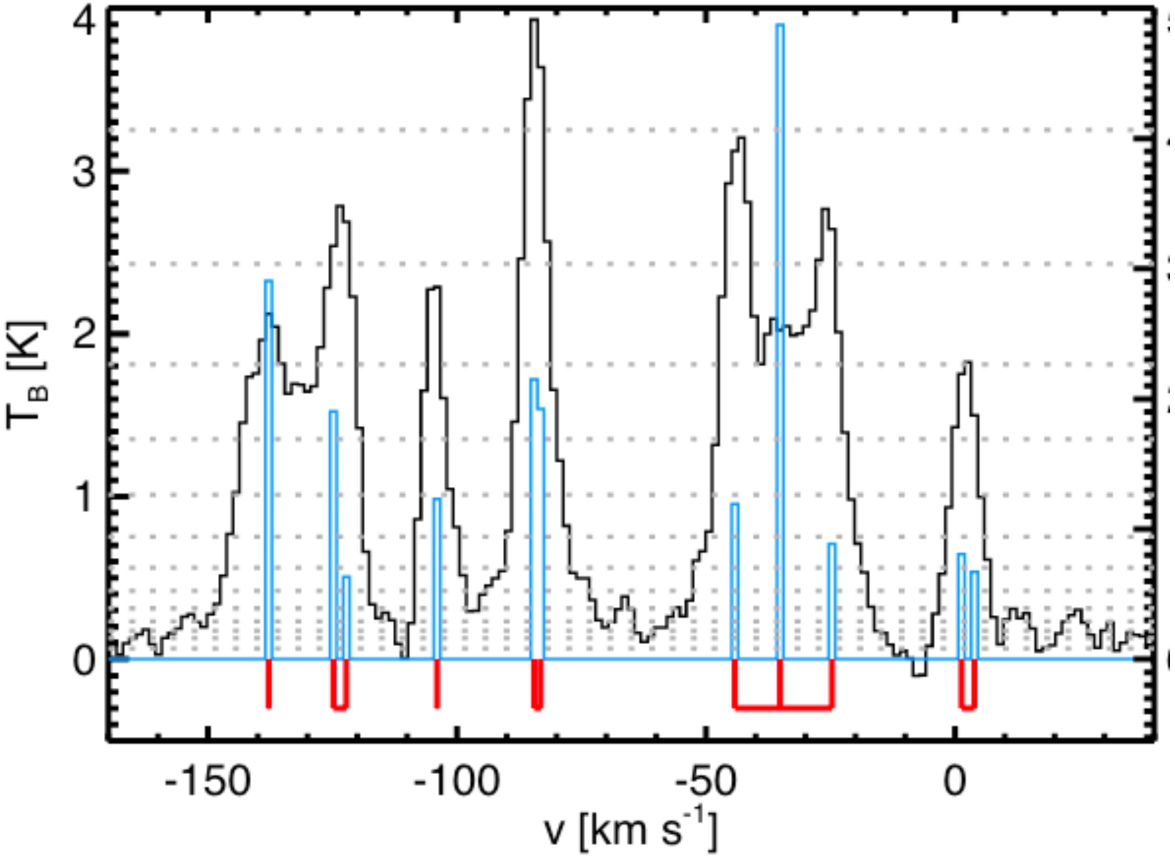
Molecular clouds: properties and caveats (that we have to deal with):

1. How to define the cloud boundaries (and how to disentangle different clouds along the LOS) from CO brightness temperature T_B maps?

- **<u>Gaussian</u>** decomposition

First, the entire data cube is decomposed into a set of Gaussian functions.
Second, coherent structures are identified using a hierarchical cluster analysis scheme

Miville-Dechenes+17

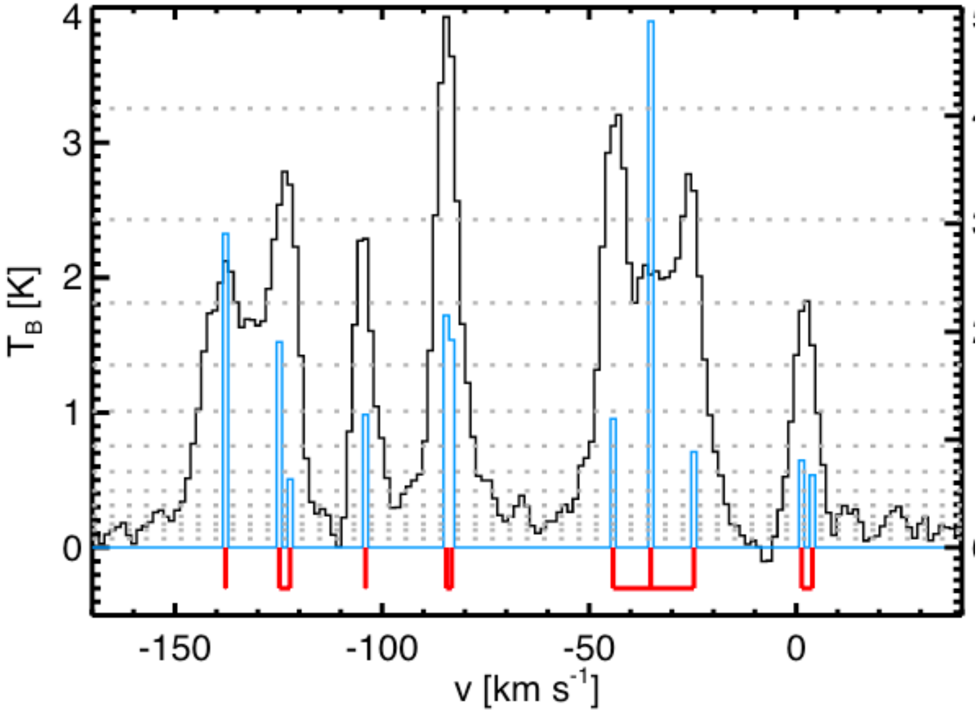


Molecular clouds: properties and caveats (that we have to deal with):

2. How does the observed CO brightness temperature T_B convert in H_2 mass?

for each given
LOS position *(l,b)* the CO spectrum is described
as a sum of *i* Gaussian components:

$$T_{\rm B}(v) = \sum_{i=1}^{N} A_i \, \exp((v - v_i)^2/2\sigma_i^2) \quad \text{(K)}$$



Molecular clouds: properties and caveats (that we have to deal with):

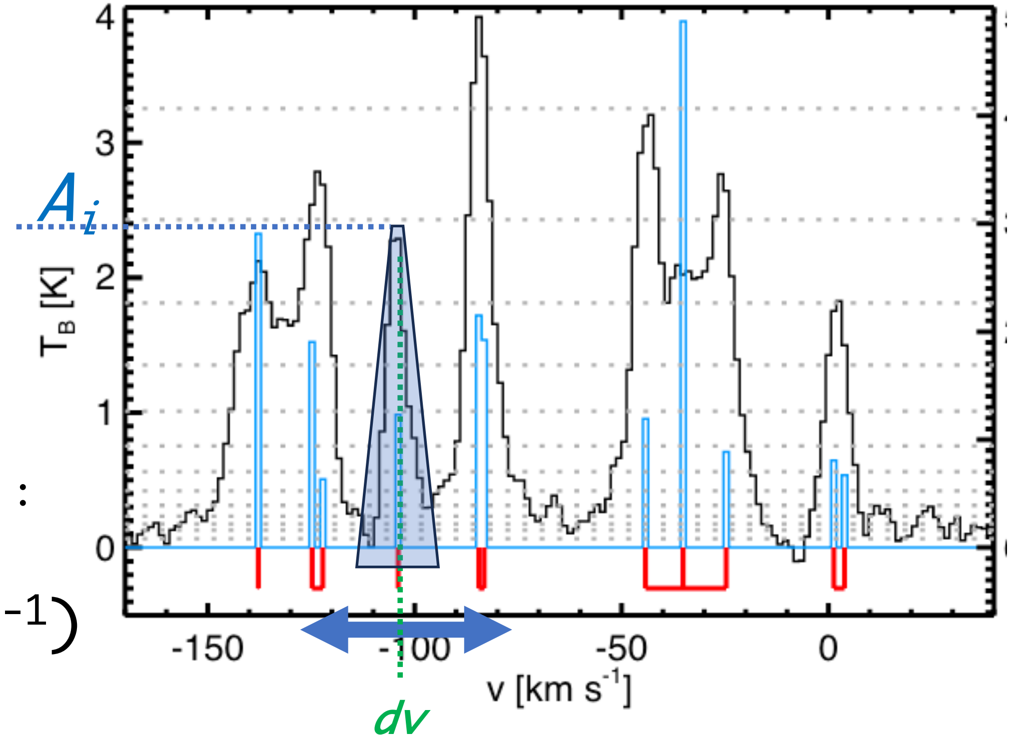
2. How does the observed CO brightness temperature T_B convert in H_2 mass?

for each given
LOS position *(l,b)* the CO spectrum is described
as a sum of *i* Gaussian components:

$$T_\mathrm{B}(v) = \sum_{i=1}^{N} A_i \exp((v - v_i)^2/2\sigma_i^2) \quad \text{(K)}$$

The integrated intensity for each LOS *(l,b)* of a given Gaussian *i* :

$$W^i_\mathrm{CO}(l,b) = \sqrt{(2\pi)} A_i \sigma_i \; dv \quad (\mathrm{K\ Km\ s^{-1}})$$



Molecular clouds: limitations (that we have to deal with):

2. How does the observed CO brightness temperature T_B convert in H_2 mass?

for each given LOS position *(l,b)* the CO spectrum is described as a sum of *i* Gaussian components:

$$T_{\rm B}(v) = \sum_{i=1}^{N} A_i \exp((v - v_i)^2/2\sigma_i^2) \quad \text{(K)}$$

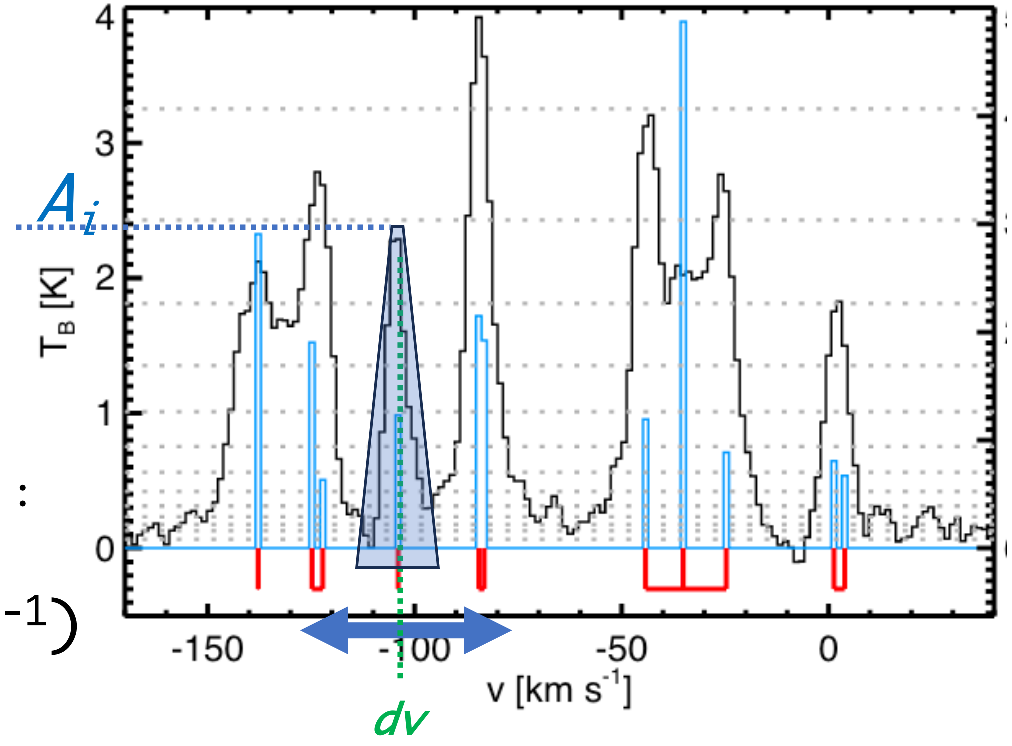
$$\downarrow$$

The integrated intensity for each LOS *(l,b)* of a given Gaussian *i* :

$$W^i_{\rm CO}(l,b) = \sqrt{(2\pi)} A_i \sigma_i \; dv \quad \text{(K Km s}^{-1}\text{)}$$

$$\downarrow$$

$$W^{tot}_{\rm CO} = \sum_{l,b,v} W_{\rm CO}(l,b,v) \quad \text{(K Km s}^{-1}\text{)}$$



Integrated intensity of a given cloud (also called **Moment 0**)

Molecular clouds: limitations (that we have to deal with):

2. How does the observed CO brightness temperature T_B convert in H_2 mass?

$$W_{\mathrm{CO}}^{tot} = \sum_{l,b,v} W_{\mathrm{CO}}(l,b,v)$$ (K Km s^{-1})

↓

$$N_{\mathrm{H}_2} = \frac{W_{\mathrm{CO}}^{tot}\ X_{\mathrm{CO}}}{N_{pix}}$$

Molecular clouds: limitations (that we have to deal with):

2. How does the observed CO brightness temperature T_B convert in H_2 mass?

$$W_{\mathrm{CO}}^{tot} = \sum_{l,b,v} W_{\mathrm{CO}}(l,b,v)$$ (K Km s^{-1})

$$\Big\downarrow$$

$$N_{\mathrm{H}_2} = \frac{W_{\mathrm{CO}}^{tot} X_{\mathrm{CO}}}{N_{pix}}$$

Molecular clouds: limitations (that we have to deal with):

2. How does the observed CO brightness temperature T_B convert in H_2 mass?

$$W_{\rm CO}^{tot} = \sum_{l,b,v} W_{\rm CO}(l,b,v)$$ (K Km s^{-1})

The conversion factor

$X_{\rm CO}$ = 2 x 10^{20} cm^{-2} (k km s^{-1} $)^{-1}$

For every LOS !!!

(Bolatto+13)

$$N_{\rm H_2} = \frac{W_{\rm CO}^{tot} X_{\rm CO}}{N_{pix}}$$

Molecular clouds: limitations (that we have to deal with):

2. How does the observed CO brightness temperature T_B convert in H_2 mass?

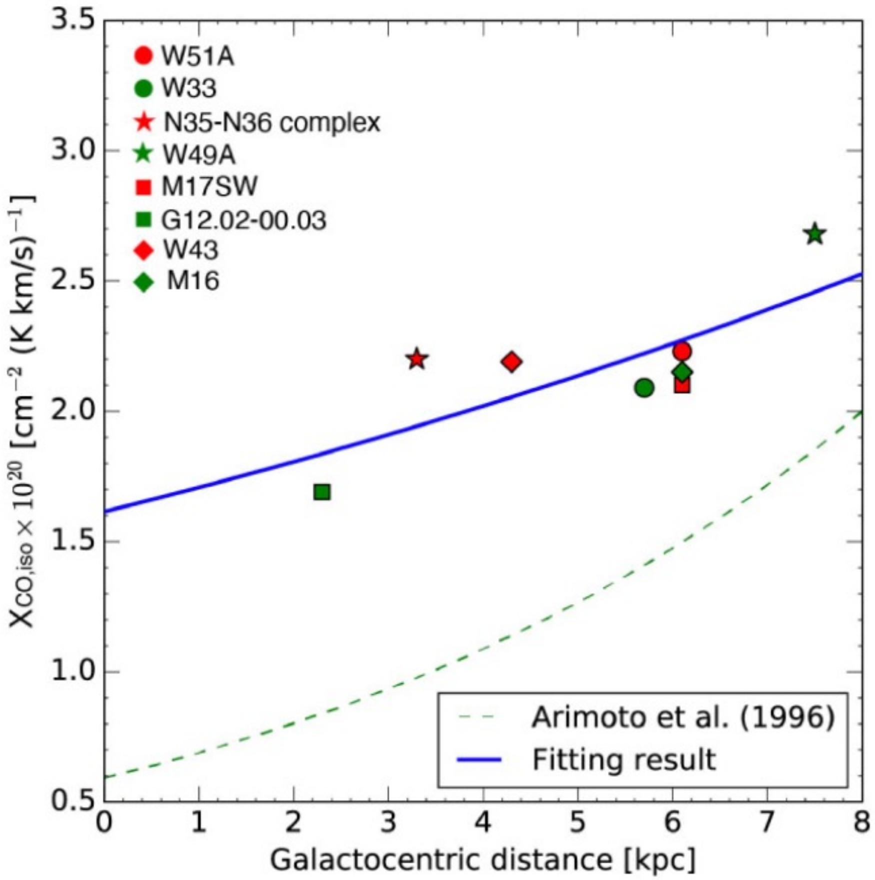
The conversion factor

$$X_{CO} = 2 \times 10^{20}\ \mathrm{cm}^{-2}\ (\mathrm{k\ km\ s}^{-1})^{-1}$$

For every LOS !!!

It varies:

- With the Galactocentric radius (metallicity gradient)



Kohno & Sufue 24

Molecular clouds: limitations (that we have to deal with):

2. How does the observed CO brightness temperature T_B convert in H_2 mass?

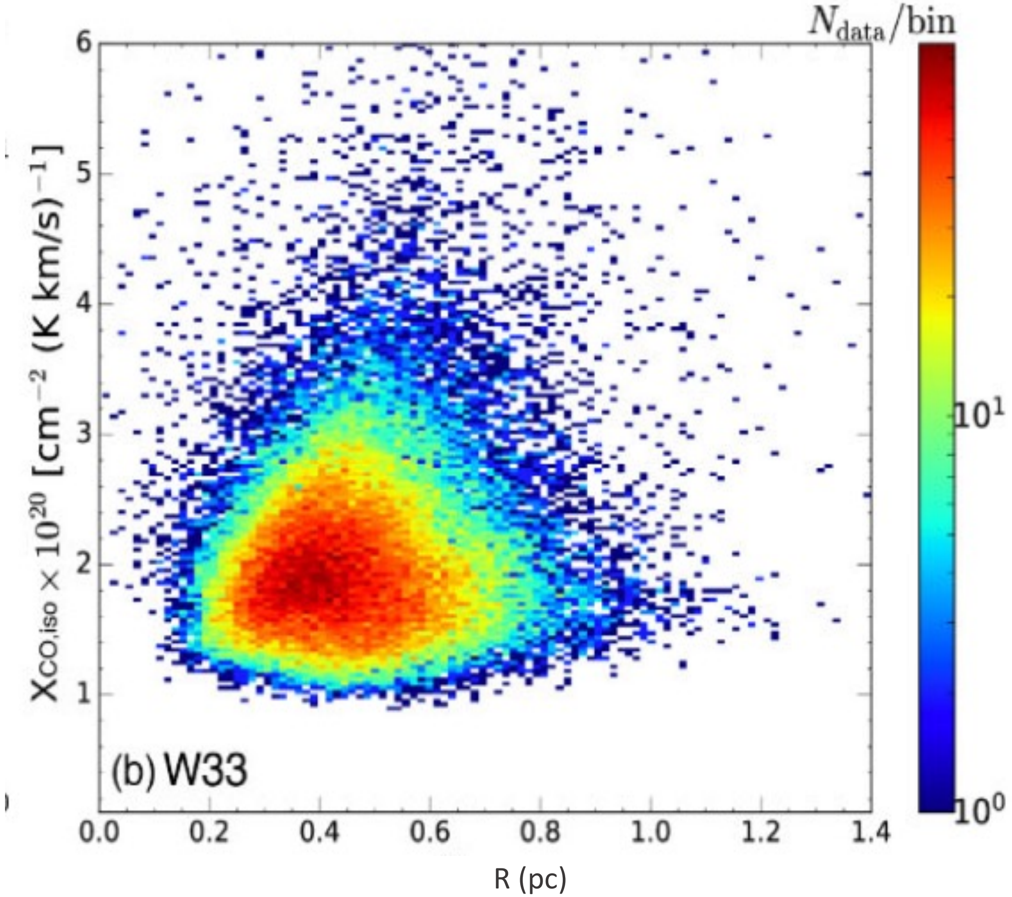
The conversion factor

$$X_{CO} = 2 \times 10^{20} \text{ cm}^{-2} (\text{k km s}^{-1})^{-1}$$

For every LOS !!!

It varies:

- With the Galactocentric radius (metallicity gradient)
- Locally within clouds



Kohno & Sufue 24

Molecular clouds: limitations (that we have to deal with):

2. How does the observed CO brightness temperature T_B convert in H_2 mass?

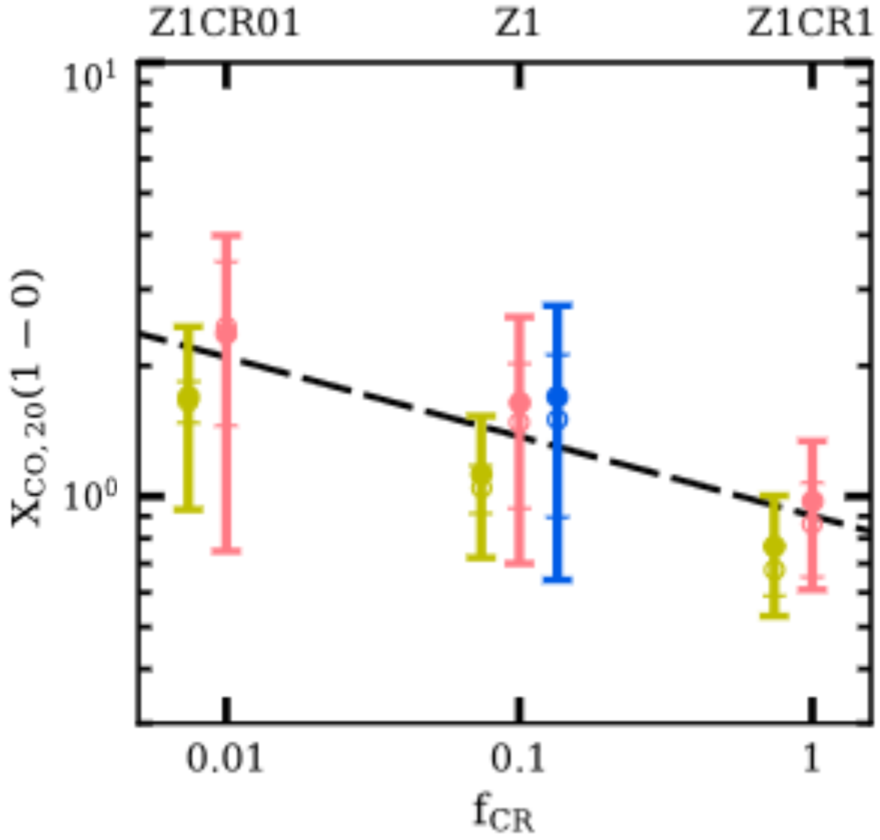
The conversion factor

$$X_{CO} = 2 \times 10^{20}\ \text{cm}^{-2}\ (\text{k km s}^{-1})^{-1}$$

For every LOS !!!

It varies:

- With the Galactocentric radius (metallicity gradient)
- Locally within clouds
- Cosmic Rays (CR) intensity…



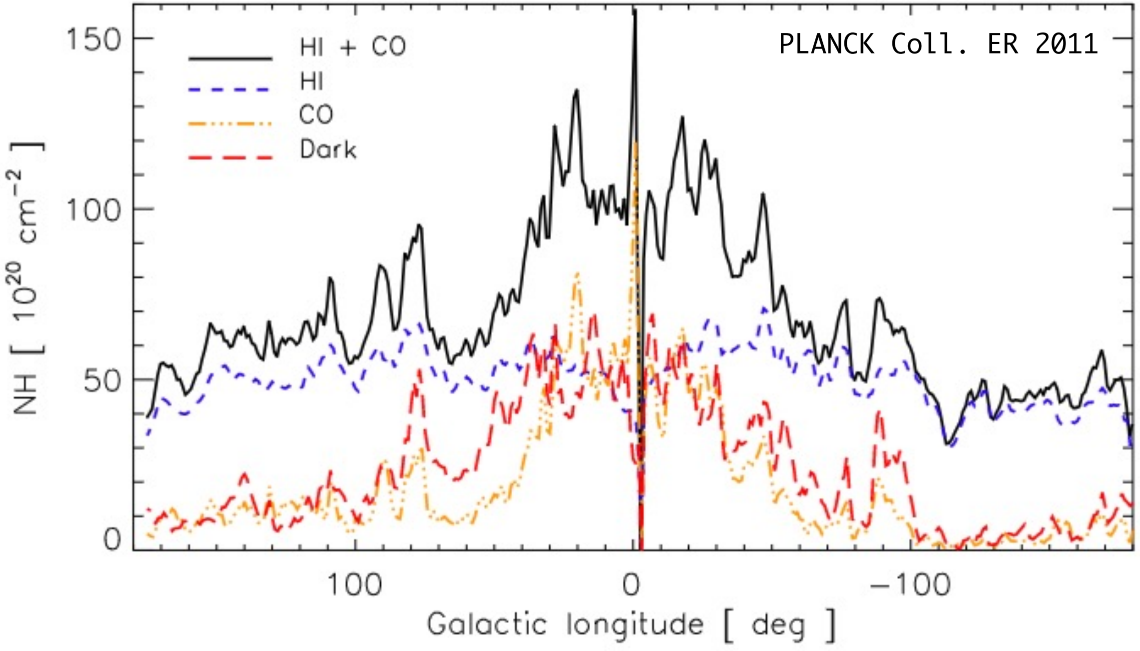
Gong+18 (sims.)

Molecular clouds: limitations (that we have to deal with):

3. Does CO trace perfectly all the H_2 in a given line of sight?

"A significant H_2 mass may lie outside the CO region, in the outer regions of the molecular cloud where the gas phase carbon resides in C or C^+. Here, H_2 self-shields or is shielded by dust from UV photodissociation, whereas CO is photodissociated. **This H_2 gas is "dark" in molecular transitions** because of the absence of CO and other trace molecules." (Wolfire+10)

This fraction can be even more abundant than CO-traced H_2 (along specific LOS)!!!



PLANCK Coll. ER 2011

See lecture from Simon Glover

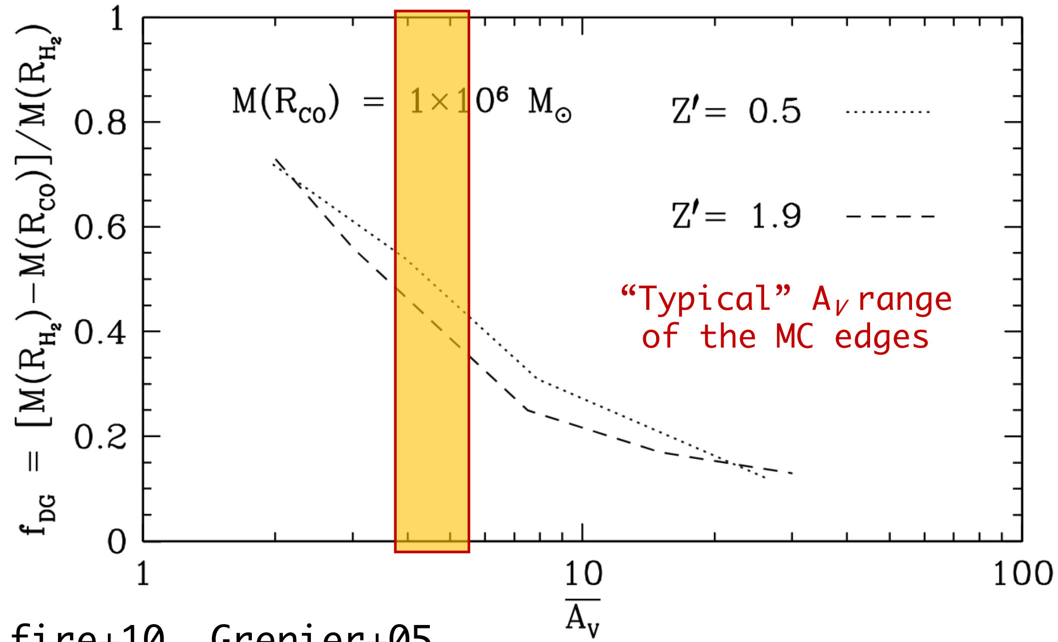
Molecular clouds: limitations (that we have to deal with):

3. Does CO trace perfectly all the H_2 in a given line of sight?

“A significant H_2 mass may lie outside the CO region, in the outer regions of the molecular cloud where the gas phase carbon resides in C or C^+. Here, H_2 self-shields or is shielded by dust from UV photodissociation, whereas CO is photodissociated. **This H_2 gas is “dark” in molecular transitions** because of the absence of CO and other trace molecules.” (Wolfire+10)

This fraction can be even more abundant than CO-traced H_2 (along specific LOS)!!!

However, this is highly dependent to the density of the region: high density (high visual extinction A_V) are less affected



“Typical” A_V range of the MC edges

Wolfire+10, Grenier+05

Molecular clouds: limitations (that we have to deal with):

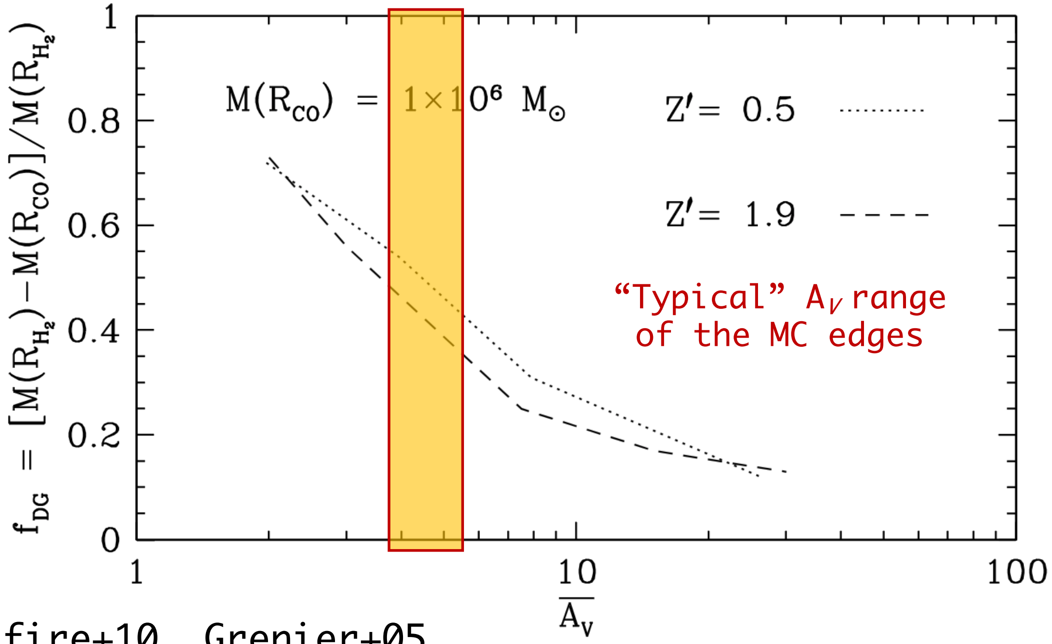
3. Does CO trace perfectly all the H_2 in a given line of sight?

"A significant H_2 mass may lie outside the CO region, in the outer regions of the molecular cloud where the gas phase carbon resides in C or C^+. Here, H_2 self-shields or is shielded by dust from UV photodissociation, whereas CO is photodissociated. **This H_2 gas is "dark" in molecular transitions** because of the absence of CO and other trace molecules." (Wolfire+10)

This fraction can be even more abundant than CO-traced H_2 (along specific LOS)!!!

However, this is highly dependent to the density of the region: high density (high visual extinction A_V) are less affected

Of course, these studies must assume a ~X_{CO} conversion factor…



Wolfire+10, Grenier+05

Molecular clouds: how do we observe them?

However, given all the limitations and assumptions:

1. algorithm used to extract clouds in T_B
2. X_{CO} conversion factor
3. CO-dark gas

We can now:

- identify CO molecular clouds

- estimate the H_2 clouds physical (e.g. mass, radius column density) and dynamical (e.g. velocity dispersion, virial parameter) properties

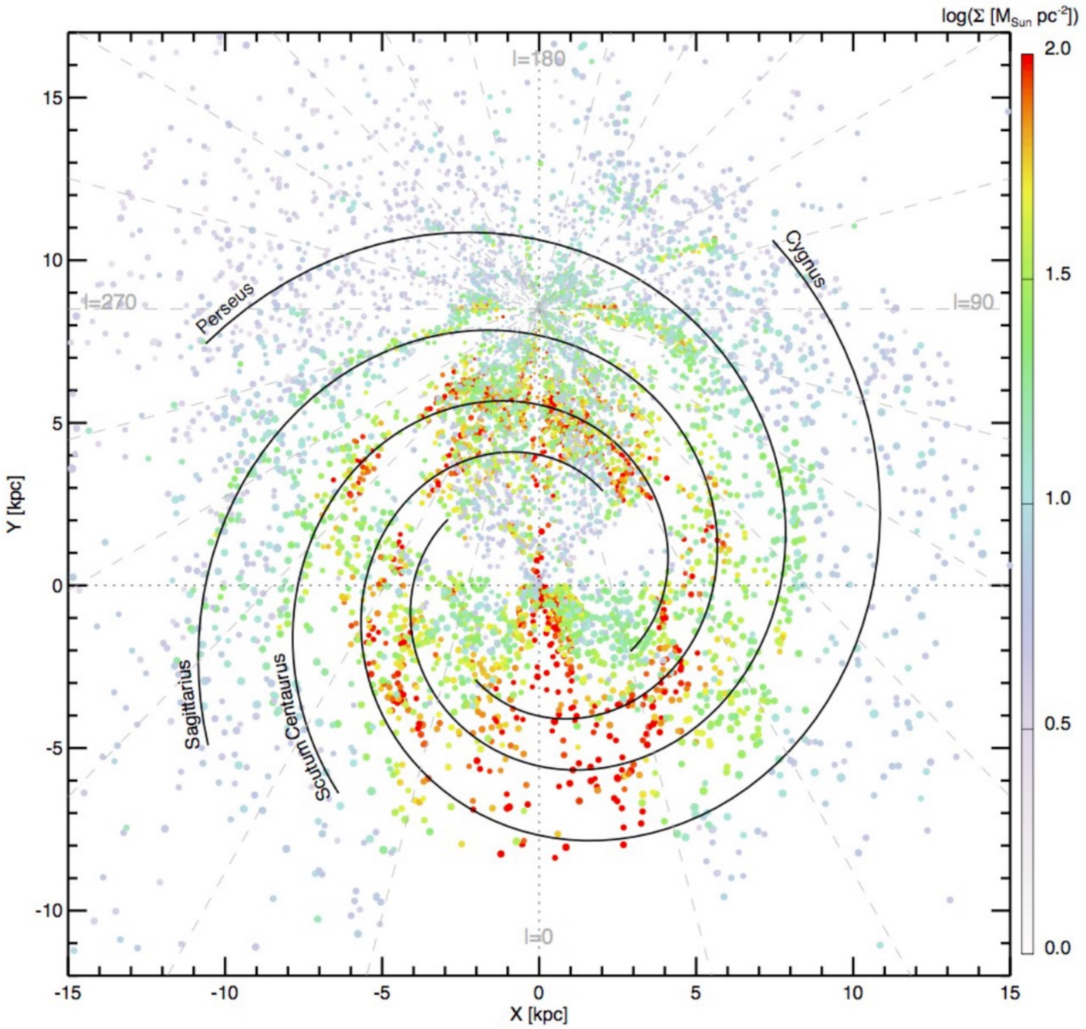
- derive the physics of the formation at the cloud scales

Star-forming regions, clumps and cores - outline

- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: physical properties, dynamics and (partial?) collapse
- From MCs to filaments: the densest regions of molecular clouds
- Pc-scales clumps: the nursery home of stars and protoclusters
- Gas dynamics in filament and clumps: the role of environment

Molecular clouds from CO: physical properties

The **most complete** composite survey of ^{12}CO (1-0) across the Milky Way Galaxy to date (Miville-Deschenes+17, using the same dataset of Dame+01)



8107 “molecular clouds”

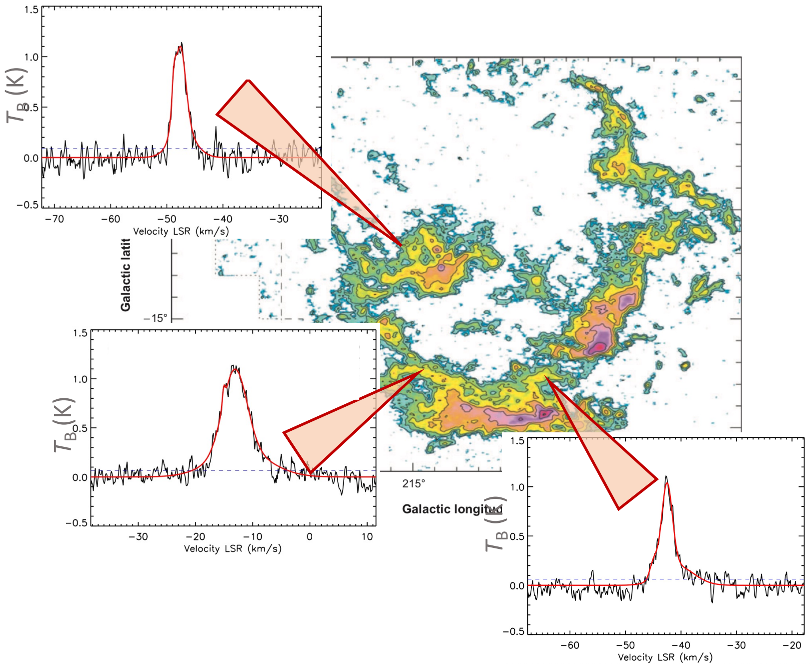
Observational properties	Values
Beam	~8.5’
Coverage	b ± 5°
V_{lsr} range	~ ±165 km/S
R.M.S.	~0.1 K
Δv	~1.3 km/s

Dame+01; Miville-Deschenes+17

Molecular clouds from CO: physical properties

For each cloud we now know

- W_{CO} (per pixel and tot)
- total # pixels N_{pix}
- brightness temperature T_{B}



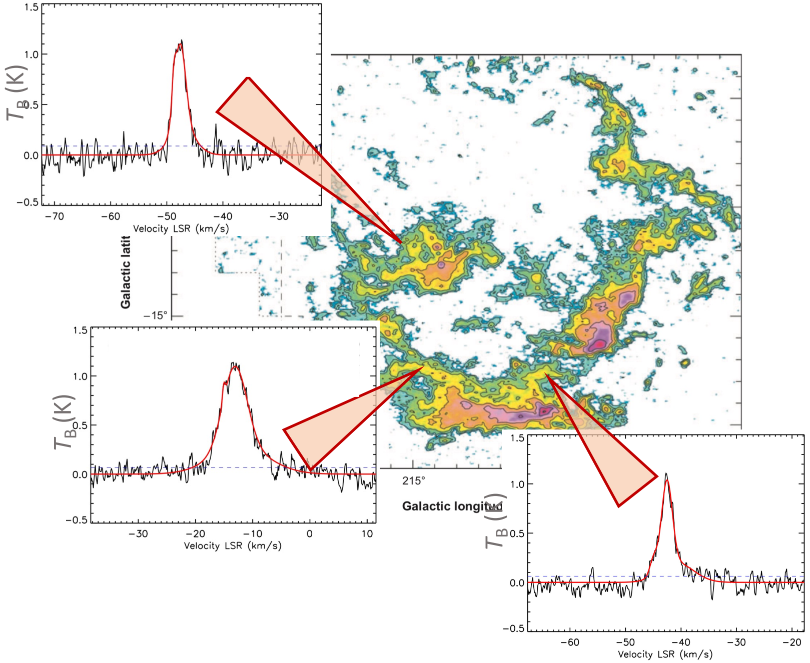
Molecular clouds from CO: physical properties

For each cloud we now know

- $W_{\rm CO}$ (per pixel and tot)
- total # pixels $N_{\rm pix}$
- brightness temperature $T_{\rm B}$

$$N_{\rm H_2} = \frac{W_{\rm CO}^{tot}\, X_{\rm CO}}{N_{pix}} \qquad \mathrm{cm}^{-2}$$

$$\Sigma = N_{\rm H_2} 2 \mu m_{\rm H} \qquad M_\odot\ \mathrm{pc}^{-2}$$



See lecture from Ralf Klessen

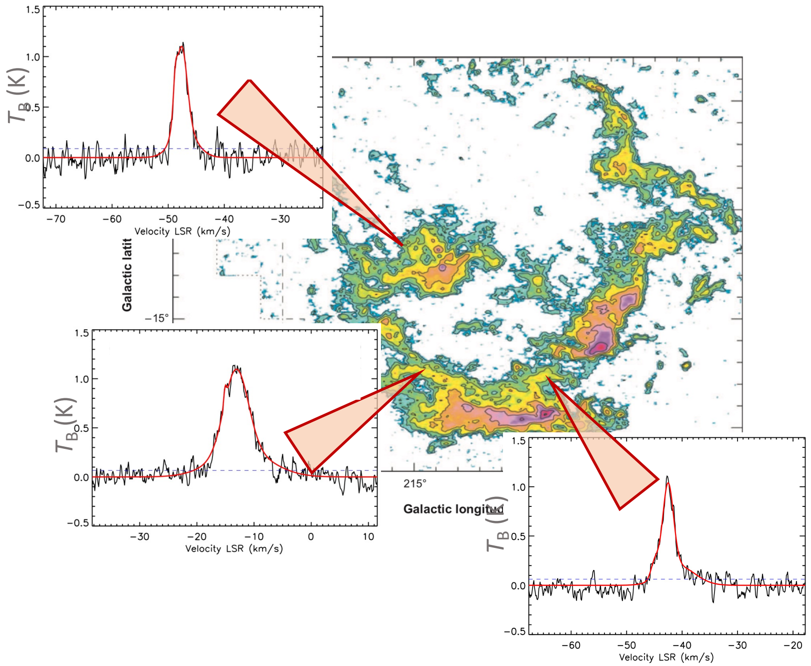
$$R_{\rm ang} = \sqrt{A/\pi} \qquad \text{Rad}$$

$$A = N_{\rm pix} d\Omega \qquad \text{area of the clouds}$$

Molecular clouds from CO: physical properties

For each cloud we now know

- $W_{\rm CO}$ (per pixel and tot)
- total # pixels $N_{\rm pix}$
- brightness temperature $T_{\rm B}$



$$N_{\rm H_2} = \frac{W_{\rm CO}^{tot}\, X_{\rm CO}}{N_{pix}}$$ cm^{-2}

$$\Sigma = N_{\rm H_2} 2\mu m_{\rm H}$$ $M_\odot$ pc^{-2}

See lecture from Ralf Klessen

$$M = \Sigma\, N_{\rm pix}\, D^2\, d\Omega$$ $M_\odot$

$$R_{\rm ang} = \sqrt{A/\pi}$$ Rad

If we know the **distance *D*** of a given cloud (…)

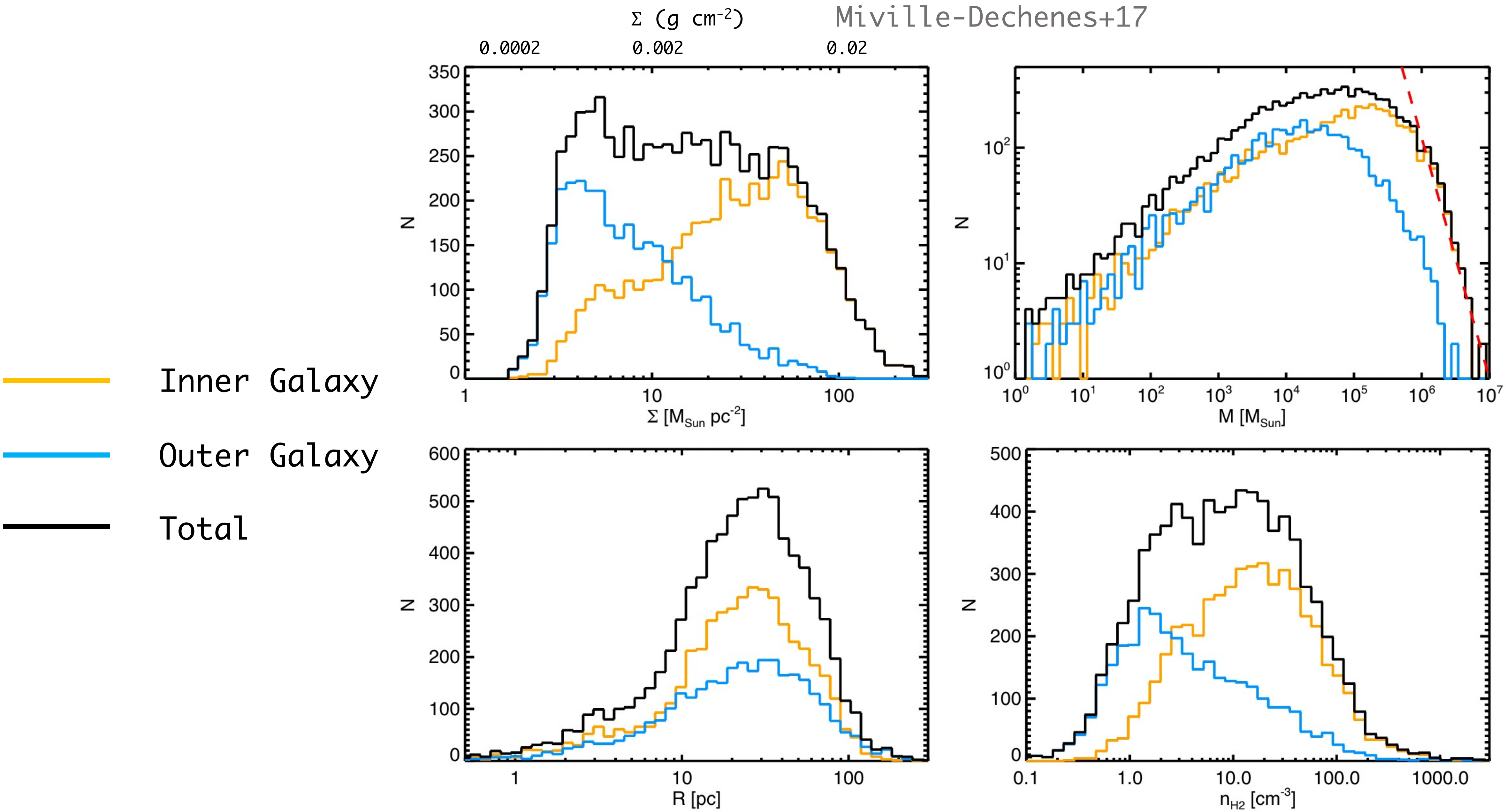
$$R = D\, \tan(R_{\rm ang})$$ pc

$$A = N_{\rm pix} d\Omega$$ area of the clouds

$$n_{\rm H2} = \frac{3\, M}{4\, \pi\, \mu\, R^3}$$ cm^{-3}

$$\rho = \mu 2 m_p n_{\rm H_2}$$ $M_\odot$ pc^{-3}

Molecular clouds from CO: physical properties

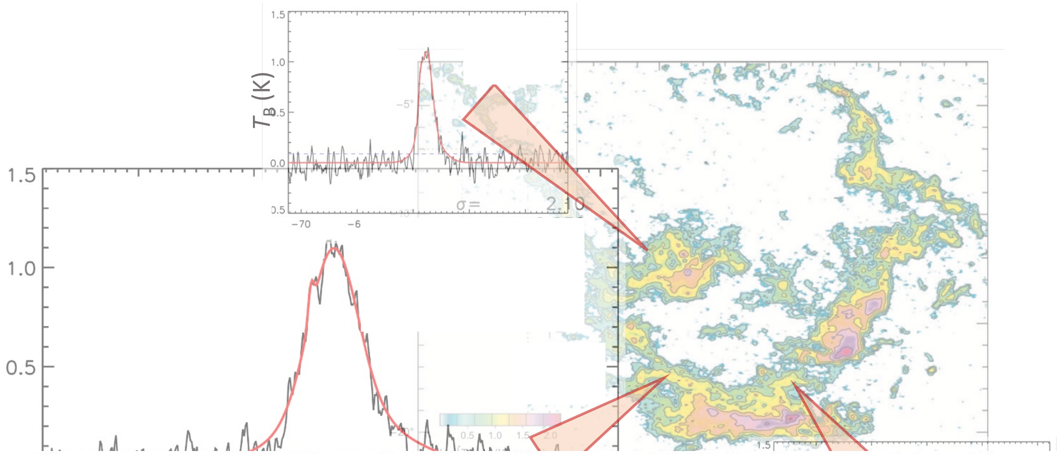


Miville-Dechenes+17

Molecular clouds from CO: kinematic properties

For each cloud we now know

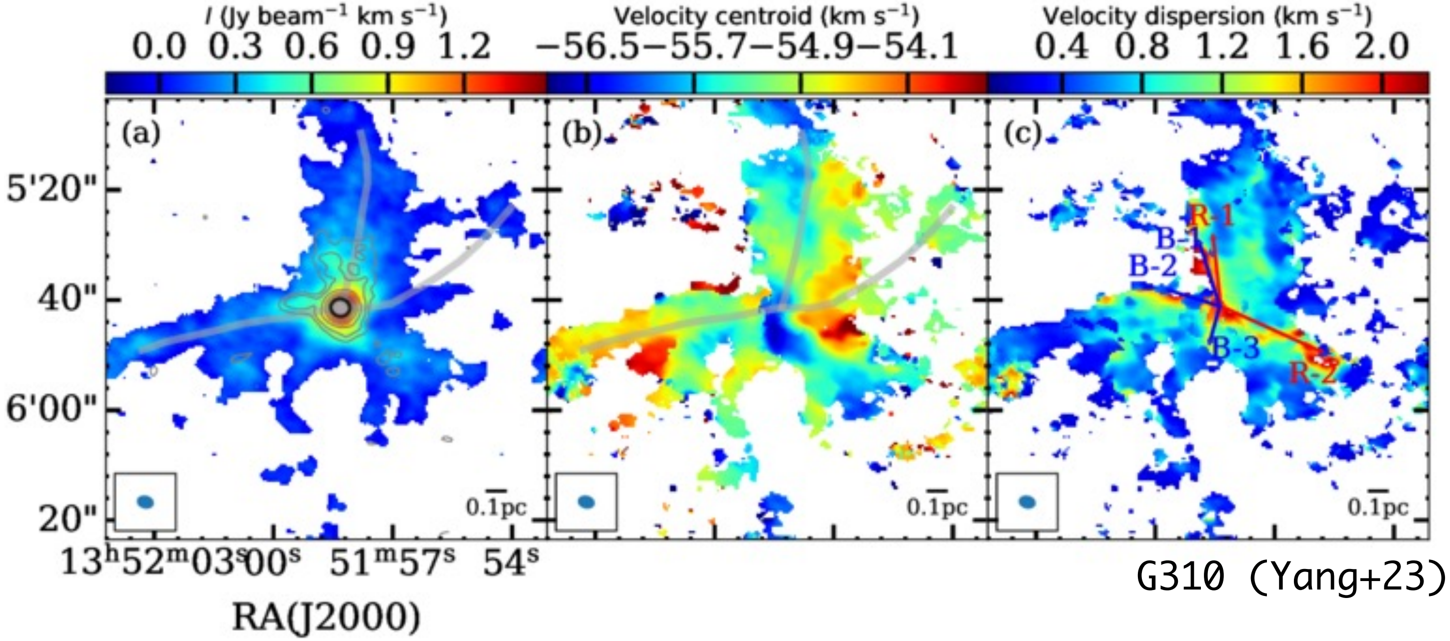
- $W_{\rm CO}$ (per pixel and tot)
- total # pixels $N_{\rm pix}$
- brightness temperature $T_{\rm B}$



$$W^{i}_{\rm CO}(l,b) = \sqrt{(}2\pi)A_i\sigma_i\;dv$$

$$\langle v\rangle = \frac{1}{W^{\rm tot}_{\rm CO}}\sum_v v\,T^{\rm tot}_{\rm B}(v)\,dv$$

$$\sigma^2{}_{\rm tot} = \frac{1}{W^{\rm tot}_{\rm CO}}\sum_v v^2\,T^{\rm tot}_{\rm B}(v)\,dv - \langle v\rangle^2$$



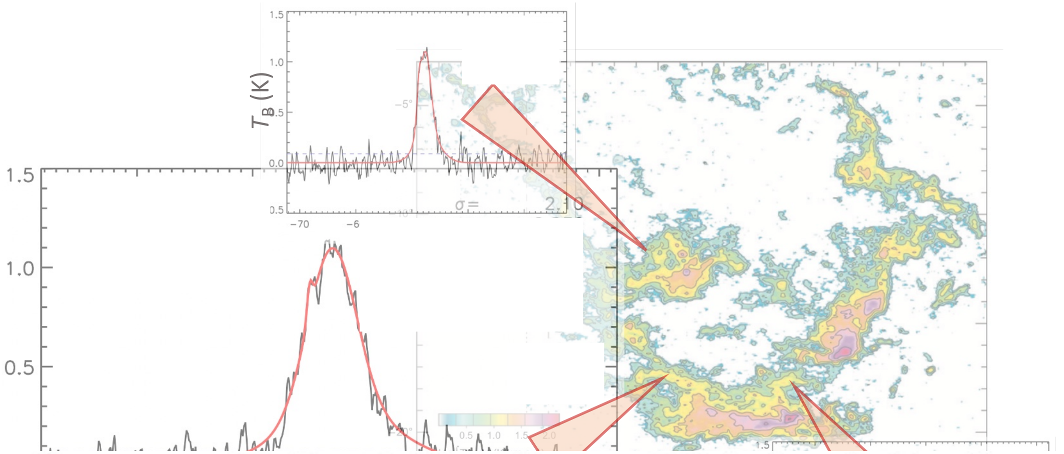
G310 (Yang+23)

Moment 0 **Moment 1** **Moment 2**

Molecular clouds from CO: kinematic properties

For each cloud we now know

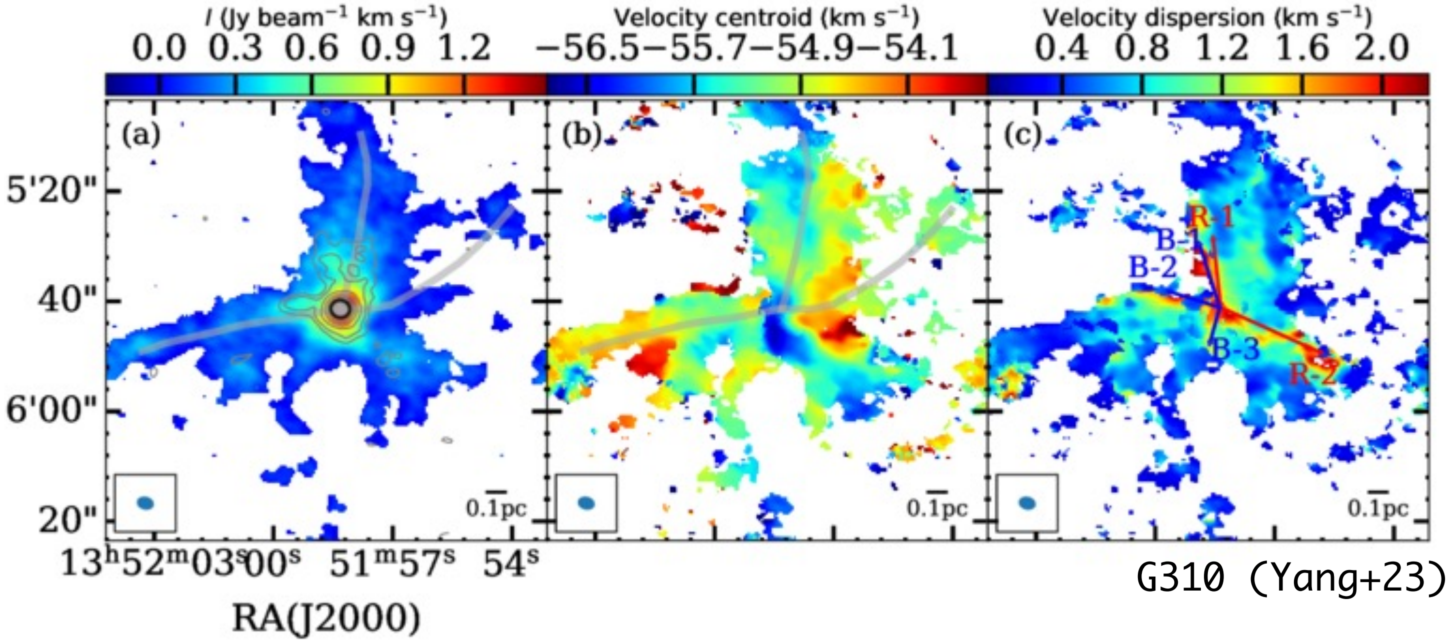
- $W_{\rm CO}$ (per pixel and tot)
- total # pixels $N_{\rm pix}$
- brightness temperature $T_{\rm B}$



$$W^i_{\rm CO}(l,b) = \sqrt(2\pi)A_i\sigma_i\ dv$$

$$\langle v\rangle = \frac{1}{W^{\rm tot}_{\rm CO}}\sum_v v\,T^{\rm tot}_{\rm B}(v)\,dv$$

$$\sigma^2{}_{\rm tot} = \frac{1}{W^{\rm tot}_{\rm CO}}\sum_v v^2\,T^{\rm tot}_{\rm B}(v)\,dv - \langle v\rangle^2$$



G310 (Yang+23)

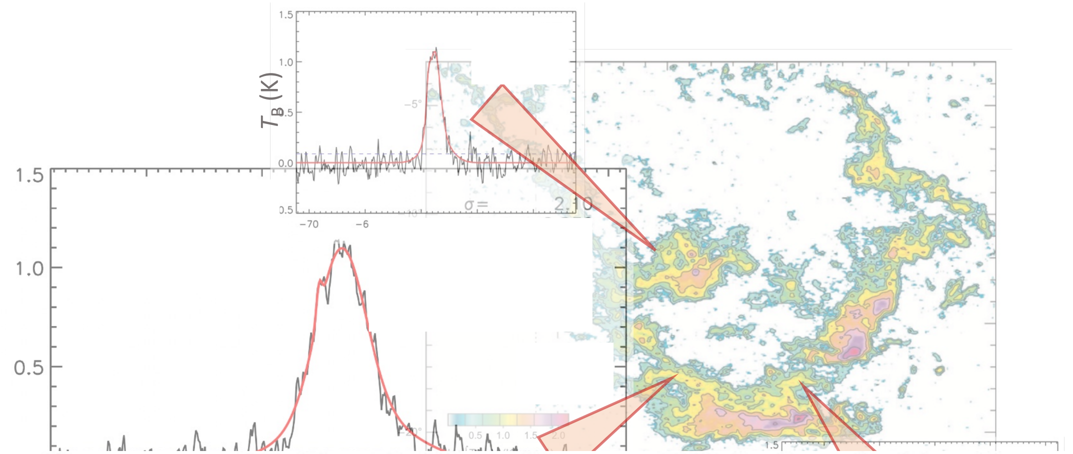
$$\sigma^2_{\rm tot} = \ ?$$

Moment 0 **Moment 1** **Moment 2**

Molecular clouds from CO: kinematic properties

For each cloud we now know

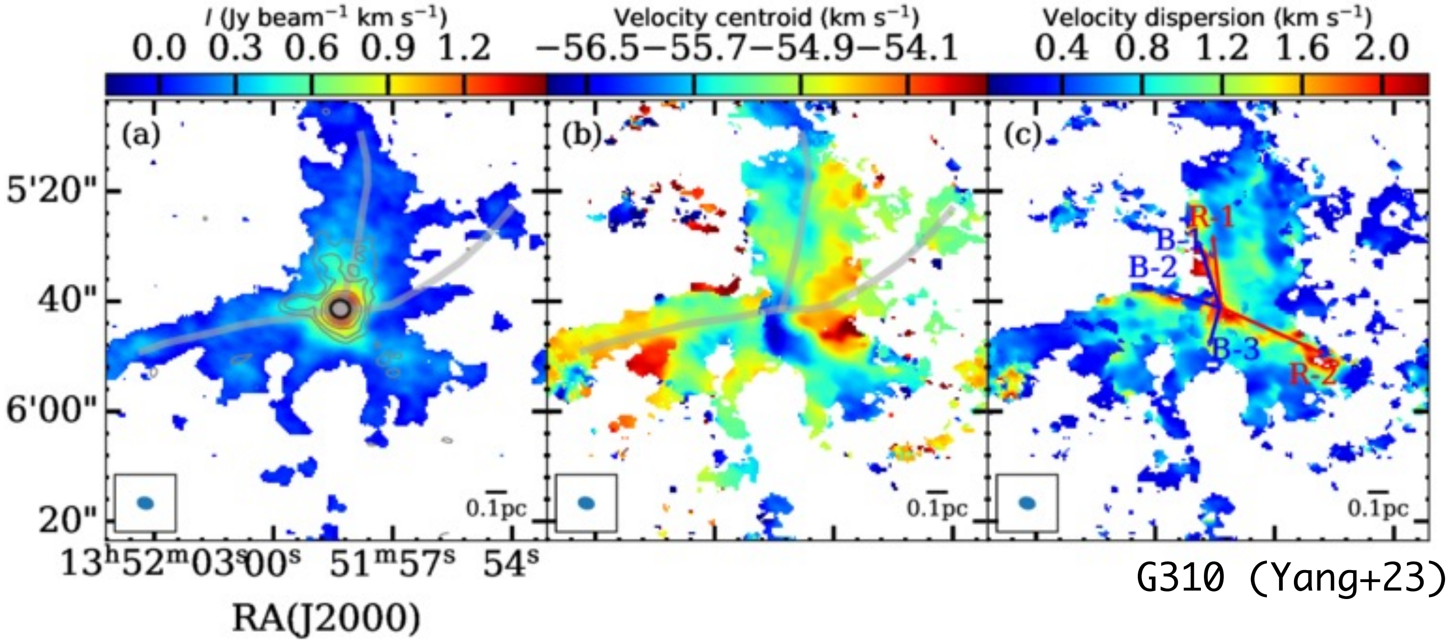
- $W_{\rm CO}$ (per pixel and tot)
- total # pixels $N_{\rm pix}$
- brightness temperature $T_{\rm B}$



$$W^i_{\rm CO}(l,b) = \sqrt{(2\pi)} A_i \sigma_i \; dv$$

$$\langle v \rangle = \frac{1}{W_{\rm CO}^{\rm tot}} \sum_v v \, T_{\rm B}^{\rm tot}(v) \, dv$$

$$\sigma^2{}_{\rm tot} = \frac{1}{W_{\rm CO}^{\rm tot}} \sum_v v^2 \, T_{\rm B}^{\rm tot}(v) \, dv - \langle v \rangle^2$$

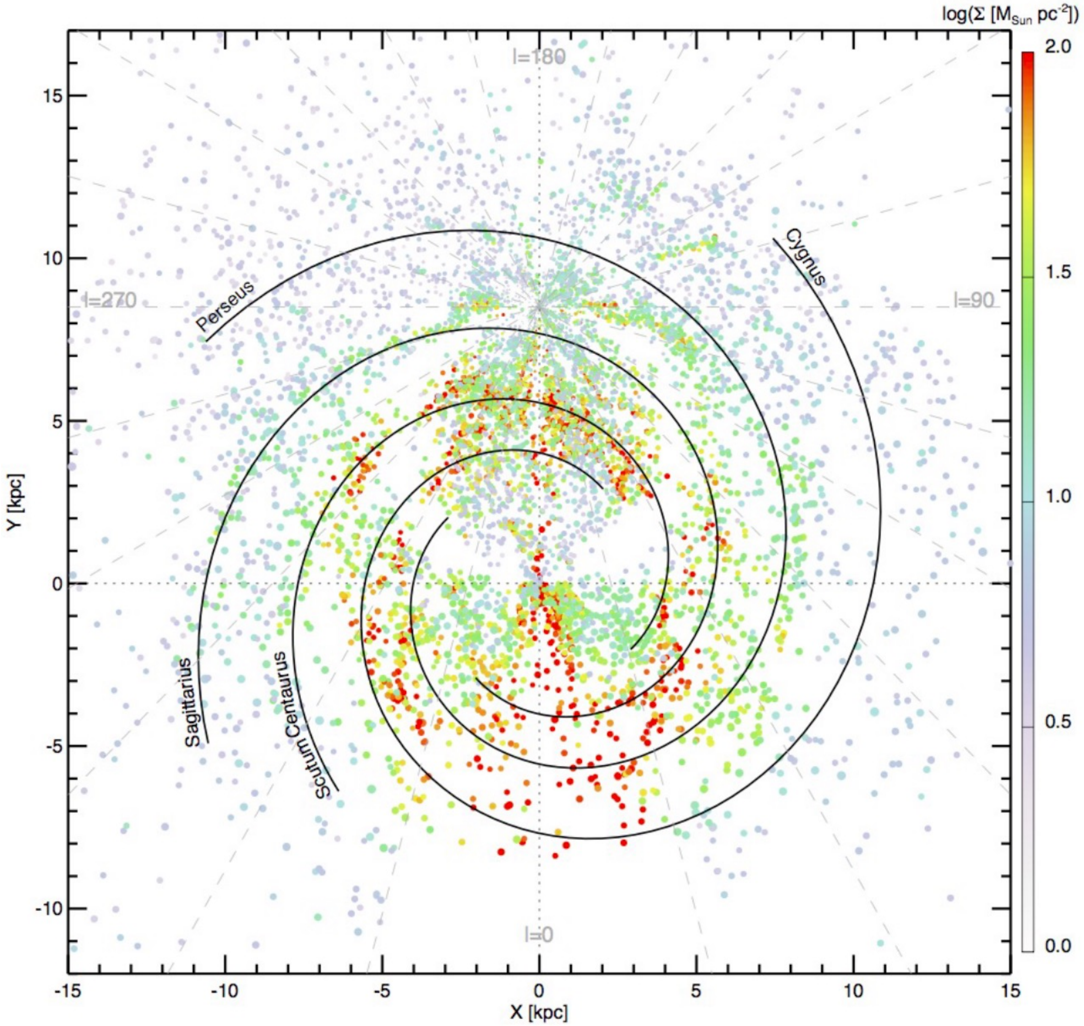


G310 (Yang+23)

$$\sigma^2_{\rm tot} = \sigma^2_{\rm nth} + \sigma^2_{\rm th}$$

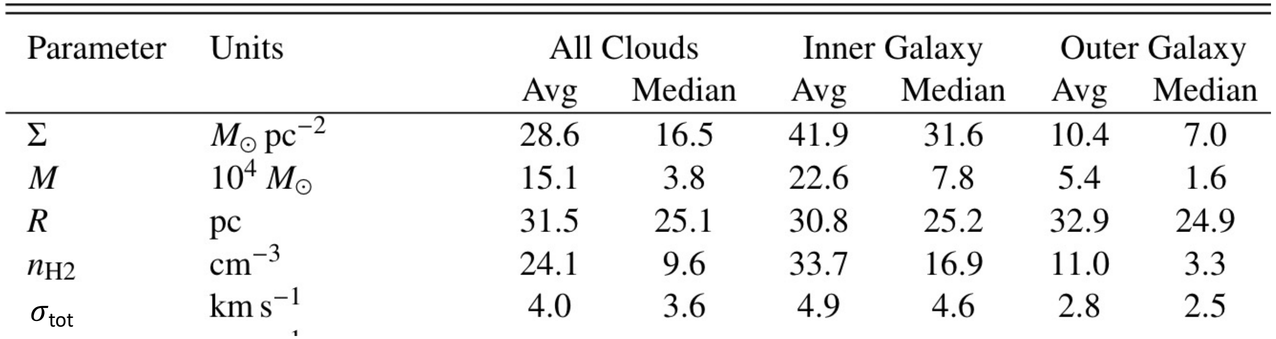
Moment 0 **Moment 1** **Moment 2**

Molecular clouds from CO: physical and kinematic properties



8107 “molecular clouds”

Miville-Dechenes+17



Parameter	Units	All Clouds		Inner Galaxy		Outer Galaxy	
		Avg	Median	Avg	Median	Avg	Median
Σ	$M_\odot$ pc^{-2}	28.6	16.5	41.9	31.6	10.4	7.0
M	$10^4\ M_\odot$	15.1	3.8	22.6	7.8	5.4	1.6
R	pc	31.5	25.1	30.8	25.2	32.9	24.9
n_{H2}	cm^{-3}	24.1	9.6	33.7	16.9	11.0	3.3
σ_{tot}	km s^{-1}	4.0	3.6	4.9	4.6	2.8	2.5

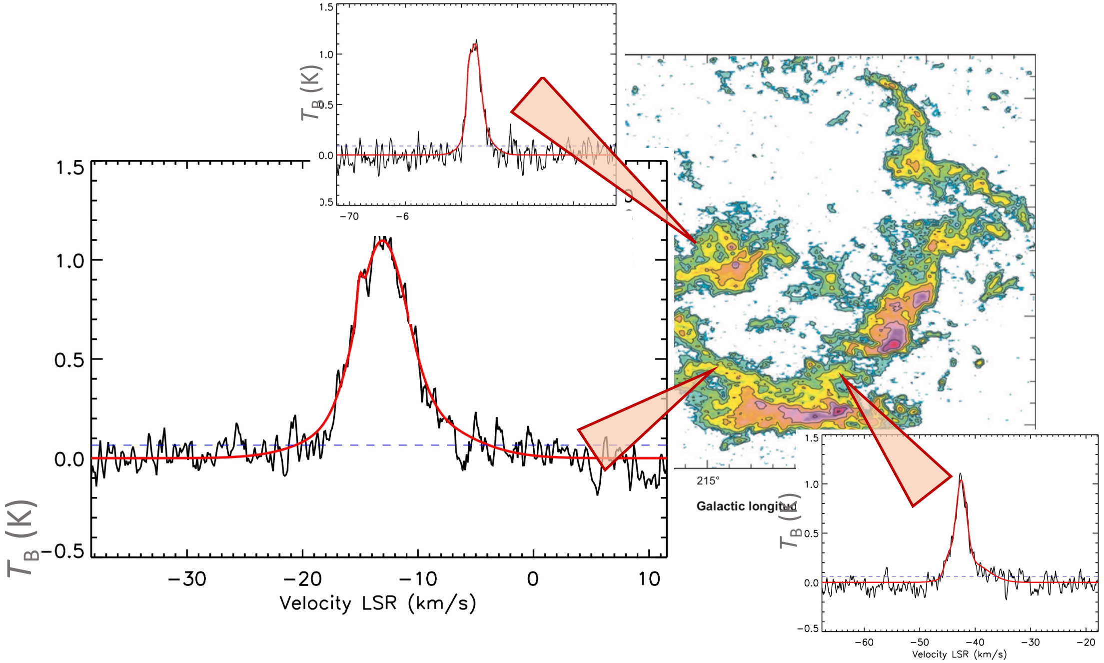
For T = 10 K ➡ σ_{th} ~ 0.1 km/s

Molecular clouds from CO: dynamical properties

For each cloud we now know

- W_{CO} (per pixel and tot)
- total # pixels N_{pix}
- brightness temperature T_{B}

- **M, R, σ → Σ, ρ, $\mathbf{n_{H2}}$**



We can now estimate parameters that correlate these quantities, among which the most important to us are:

$$t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G\rho}}$$

Free-fall time

$$\alpha_{vir} = \frac{5\sigma_v^2 R}{GM}$$

Virial parameter

See lecture from Patrick Hennebelle

See lecture from Ralf Klessen

Free-fall time and SFR

$t_{\rm ff}$ is defined as the time needed for a cloud of mass M to collapse entirely under the only action of its own gravitational force. For all our CO clouds therefore:

$$\left\{\begin{array}{l} M_{\rm tot} \simeq 1.6 \times 10^9 \ {\rm M}_\odot \\ t_{\rm ff} = \sqrt{\dfrac{3\pi}{32 G\rho}} \simeq 1.0 \times 10^7 \ {\rm yr} \end{array}\right.$$

We can introduce the total star formation rate (*SFR*) of our Galaxy

if all CO clouds are collapsing under their own gravity

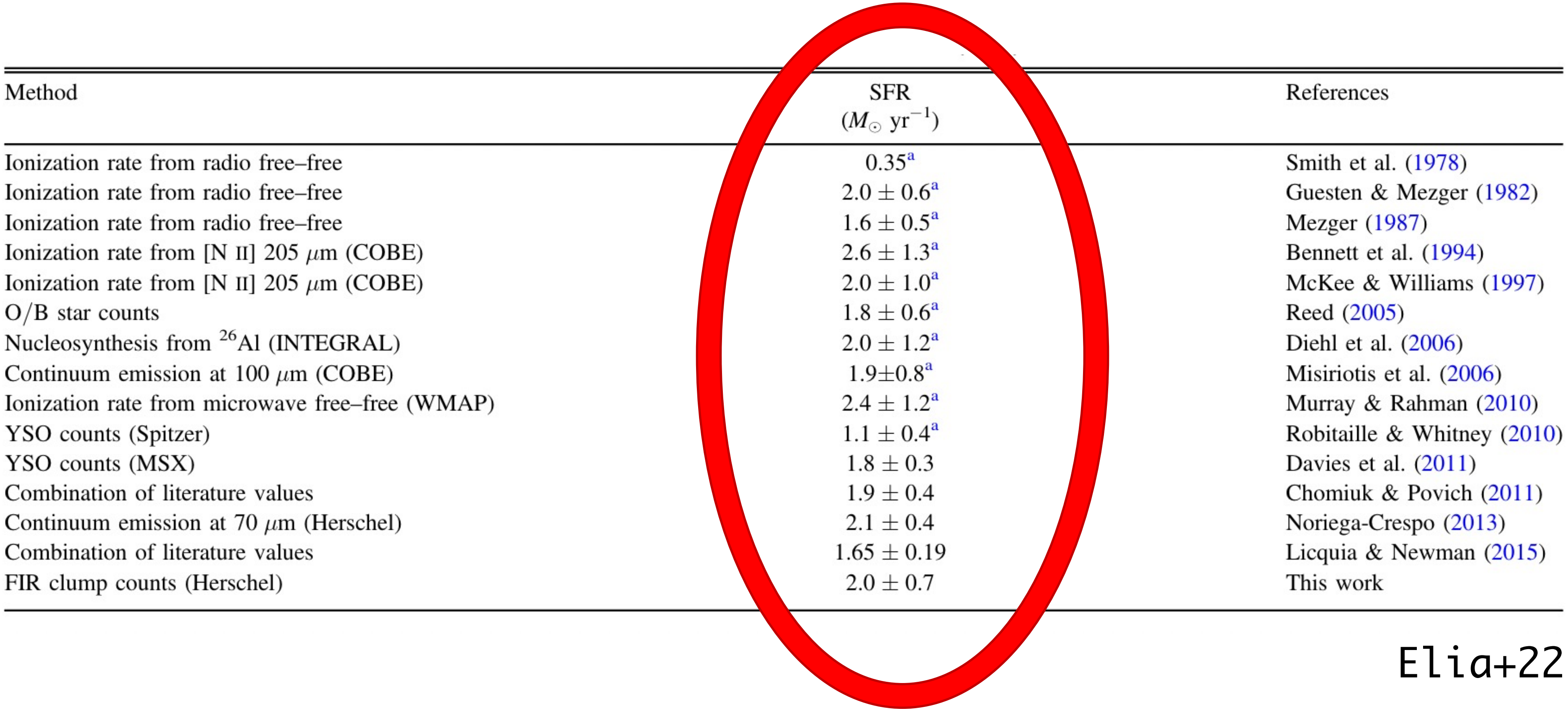
$$SFR = \frac{M_{\rm tot}}{t_{\rm ff}} \simeq 160 \ {\rm M}_\odot \ {\rm yr}^{-1}$$

Free-fall time and SFR

If all CO clouds are collapsing under their own gravity

$$SFR = \frac{M_{\rm tot}}{t_{\rm ff}} \simeq 160 \ {\rm M_\odot \ yr^{-1}}$$

The MEASURED *SFR* across the Galaxy



Method	SFR ($M_\odot$ yr^{-1})	References
Ionization rate from radio free–free	0.35[a]	Smith et al. (1978)
Ionization rate from radio free–free	2.0 ± 0.6[a]	Guesten & Mezger (1982)
Ionization rate from radio free–free	1.6 ± 0.5[a]	Mezger (1987)
Ionization rate from [N II] 205 μm (COBE)	2.6 ± 1.3[a]	Bennett et al. (1994)
Ionization rate from [N II] 205 μm (COBE)	2.0 ± 1.0[a]	McKee & Williams (1997)
O/B star counts	1.8 ± 0.6[a]	Reed (2005)
Nucleosynthesis from ^{26}Al (INTEGRAL)	2.0 ± 1.2[a]	Diehl et al. (2006)
Continuum emission at 100 μm (COBE)	1.9±0.8[a]	Misiriotis et al. (2006)
Ionization rate from microwave free–free (WMAP)	2.4 ± 1.2[a]	Murray & Rahman (2010)
YSO counts (Spitzer)	1.1 ± 0.4[a]	Robitaille & Whitney (2010)
YSO counts (MSX)	1.8 ± 0.3	Davies et al. (2011)
Combination of literature values	1.9 ± 0.4	Chomiuk & Povich (2011)
Continuum emission at 70 μm (Herschel)	2.1 ± 0.4	Noriega-Crespo (2013)
Combination of literature values	1.65 ± 0.19	Licquia & Newman (2015)
FIR clump counts (Herschel)	2.0 ± 0.7	This work

Elia+22

See lecture from Patrick Hennebelle Davide Elia

Free-fall time and SFR

If all CO clouds are collapsing under their own gravity

$$SFR = \frac{M_{\rm tot}}{t_{\rm ff}} \simeq 160 \ {\rm M_\odot \ yr^{-1}}$$

The **<u>MEASURED</u>** *SFR* across the Galaxy $\simeq 1 - 2 \ {\rm M_\odot \ yr^{-1}}$

Which leads to a star formation efficiency SFE ~1%

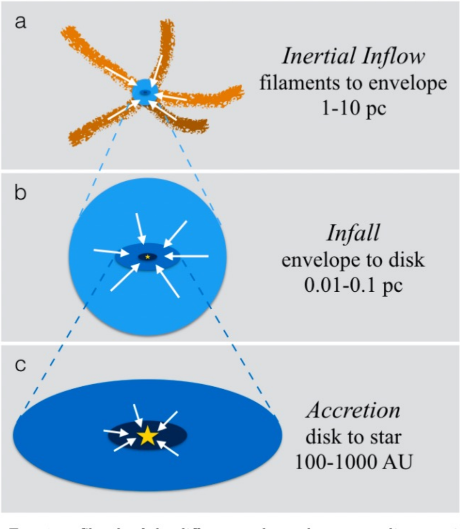
What it slowing down the clouds gravitational collapse???

This question is <u>**THE** reason why we are still investigating the star formation mechanisms</u> in our Galaxy!!!

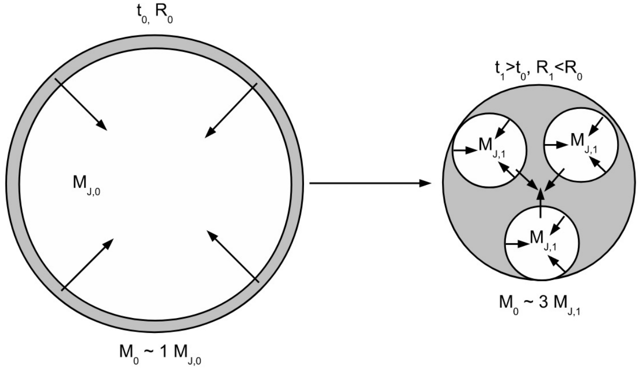
Turbulence in the ISM?


100% turbulence

100% gravity



Padoan+2020



Vazquez-Semadeni+2019

There must be some **interplay between gravity (sustained by feedback mechanisms) and turbulence** to slow-down the collapse

Turbulence in the ISM?

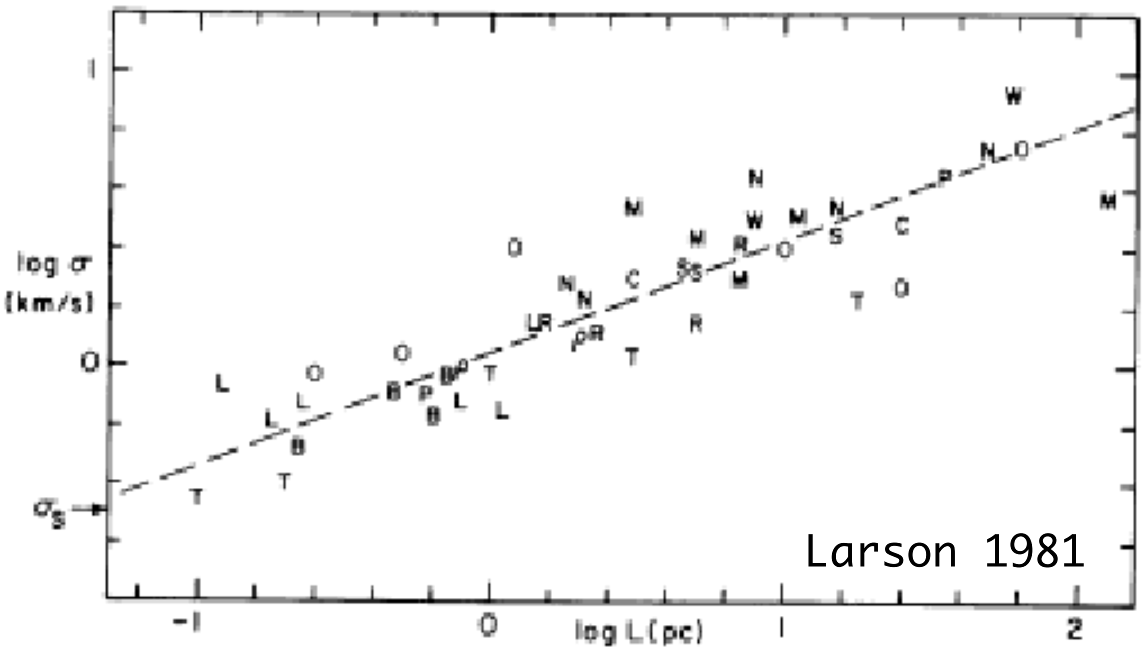
“Turbulence is characterised by chaotic motions in a fluid that lead to diffusion of matter and dissipation of kinetic energy” Falceta-Goncalves+14

“Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls, and so on to viscosity” Richardson 1922

See lectures from
Jennifer Schober - Blakesley Burkhart - Sébastien Galtier

If we assume that the (non-thermal) motions of the (incompressible) ISM are driven by large-scale Galactic turbulence we can measure:

- the velocity dispersion σ of the molecular clouds estimated from the CO spectra
- l (or R) as the size of the CO molecular cloud



Larson 1981

$$\sigma \simeq R^{1/3}$$

Kolmogorov turbulence

$$\sigma \simeq 1.1 \text{ km s}^{-1} \left(\frac{l}{1 \text{ pc}}\right)^{0.38}$$

Turbulence in the ISM?

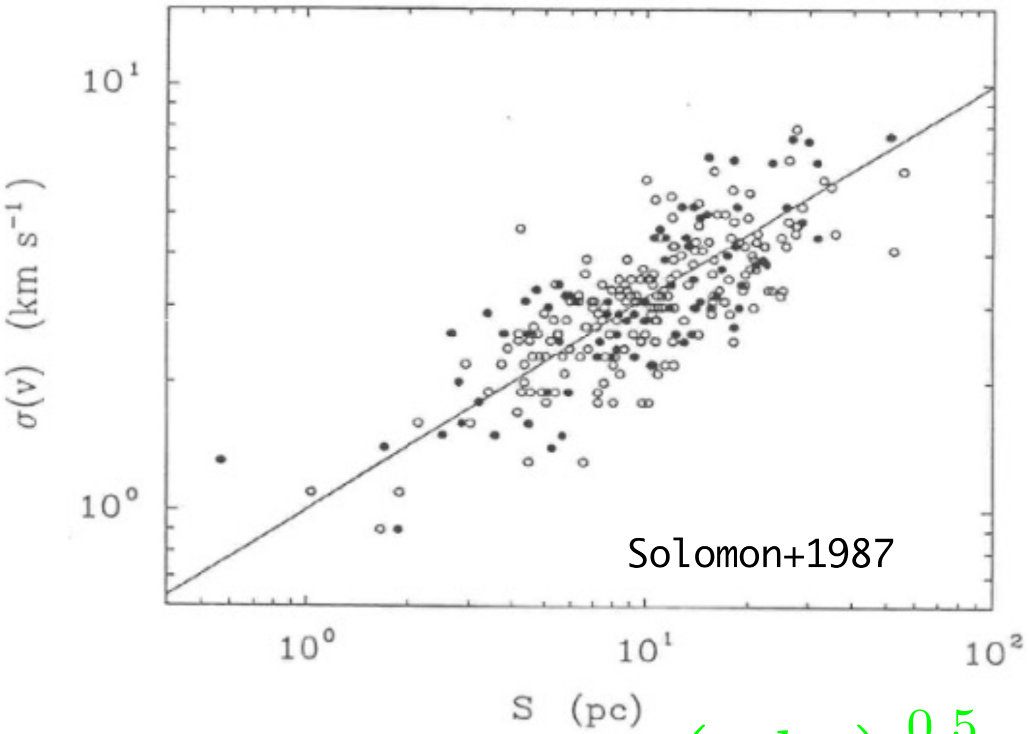
"Turbulence is characterised by chaotic motions in a fluid that lead to diffusion of matter and dissipation of kinetic energy" Falceta-Goncalves+14

"Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls, and so on to viscosity" Richardson 1922

See lectures from
Jennifer Schober - Blakesley Burkhart - Sébastien Galtier

If we assume that the (non-thermal) motions of the ISM are driven by large-scale Galactic supersonic motions under shocks we can measure:

- the velocity dispersion σ of the molecular clouds estimated from the CO spectra
- l (or R) as the size of the CO molecular cloud



Solomon+1987

$$\sigma \simeq R^{1/2}$$

Burgers turbulence

$$\sigma \simeq 1 \text{ km s}^{-1} \left(\frac{l}{1 \text{ pc}}\right)^{0.5}$$

Also called **Larson 1st relation**

Virial parameter

The virial parameter derives from the virial theorem, which (in our case) relates the total kinetic energy with the gravitational energy of a cloud with mass M, radius R and velocity dispersion σ

See lecture from Ralf Klessen

The virial parameter is defined as (Bertoldi & McKee 1992):

Kinetic energy ($\propto \sigma^2$)

$$\alpha_{vir} = \frac{5\sigma_v^2 R}{GM} = 2a\frac{E_{kin}}{E_G}$$

Gravitational energy

The factor a accounts for non-uniform density and for the cloud's ellipticity (usually a~1)

Virial parameter

$$\alpha_{vir} = \frac{5\sigma_v^2 R}{GM} = 2a\frac{E_{kin}}{E_G}$$

IF the kinetic energy is generated by a force that acts as a support against the (global) collapse e.g. ISM turbulence →

E_{kin} and E_G are in competition within each cloud:

Very naively speaking:

- $\alpha_{vir} << 1$ — E_{kin} << E_G the cloud is globally prone to the gravitational collapse
- $\alpha_{vir} >> 1$ — E_{kin} << E_G the turbulent motions are dominating. The cloud is not bound and may dissolve
- $\alpha_{vir} \sim 1$ — E_{kin} ~ E_G the cloud are near virial equilibrium: it could slowly collapse

See lecture from Ralf Klessen

Are clouds nearby near virial equilibrium?

$$\sigma_v \propto R^{0.5}$$

1st Larson relation

$$\alpha_{vir} = \frac{5\sigma_v^2 R}{GM} = 1$$

2nd Larson relation

$$\Downarrow$$

$$\frac{R^2}{M} = const. \Longrightarrow \frac{M}{R^2} \propto \Sigma = const.$$

3rd Larson relation

Molecular clouds from CO: Mass – Radius relation

$$\sigma_v \propto R^{0.5}$$

1st Larson relation

$$\alpha_{vir} = \frac{5\sigma_v^2 R}{GM} = 1$$

2nd Larson relation

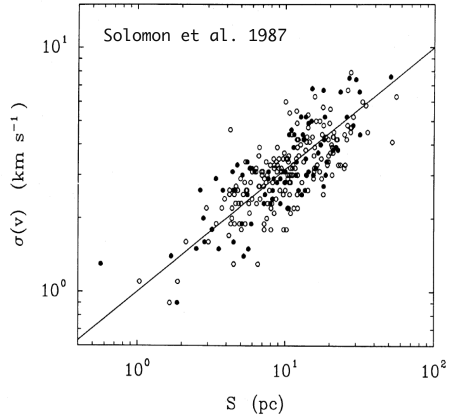
$$\frac{M}{R^2} \propto \ \Sigma = const.$$

3rd Larson relation

Do they correctly describe the interplay between gravity and turbulence in MCs?

First works in ^{12}CO (1-0) seemed to confirm that

(Larson 81; Solomon+87; Heyer & Brunt 2004, …)



Molecular clouds from CO: Mass – Radius relation

$$\sigma_v \propto R^{0.5}$$

1st Larson relation

$$\alpha_{vir} = \frac{5\sigma_v^2 R}{GM} = 1$$

2nd Larson relation

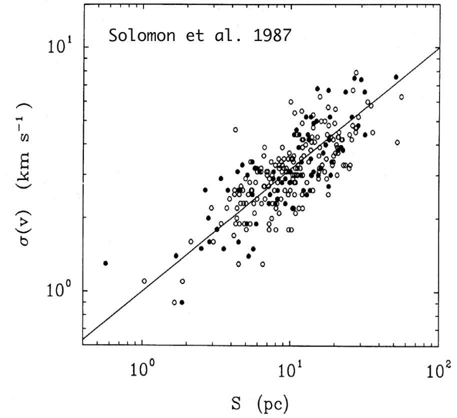
$$\frac{M}{R^2} \propto \ \Sigma = const.$$

3rd Larson relation

Do they correctly describe the interplay between gravity and turbulence in MCs?

First works in ^{12}CO (1-0) seemed to confirm that

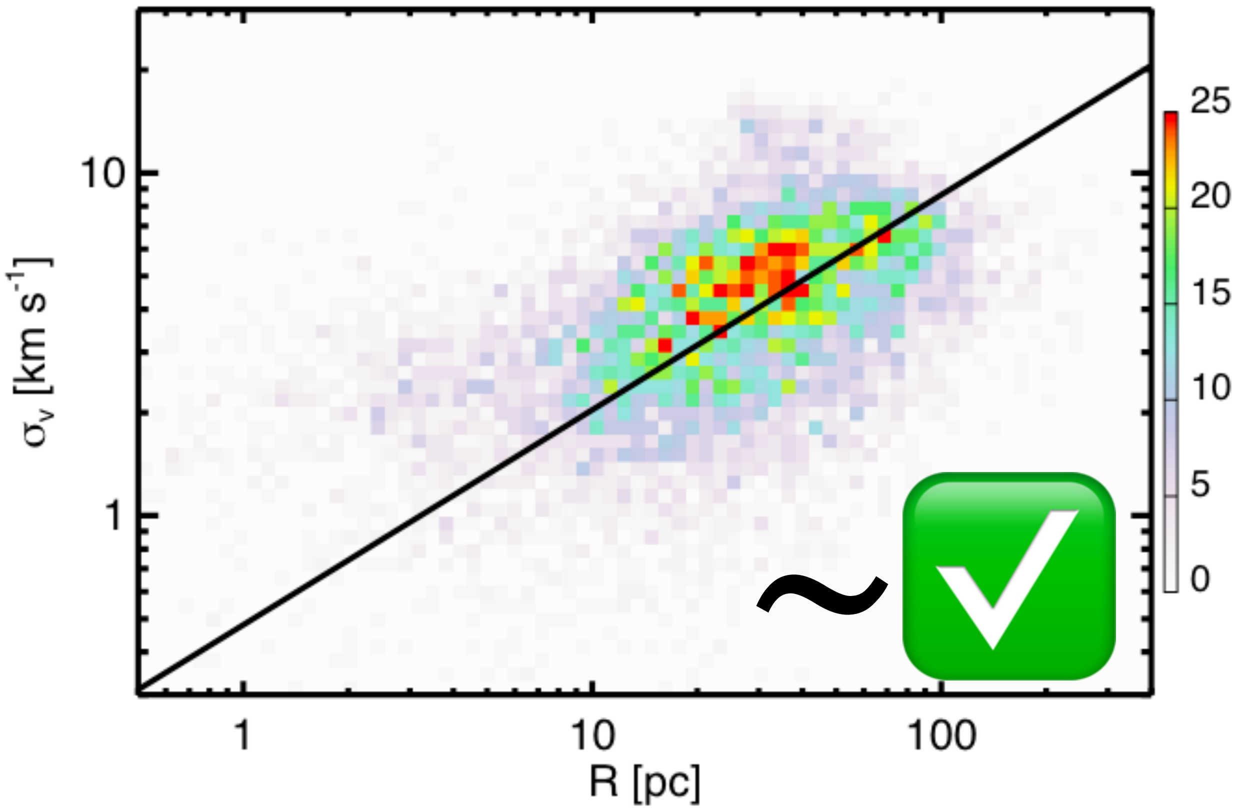
(Larson 81; Solomon+87; Heyer & Brunt 2004, …)



Molecular clouds from CO: physical and dynamical properties

Miville-Dechenes+17

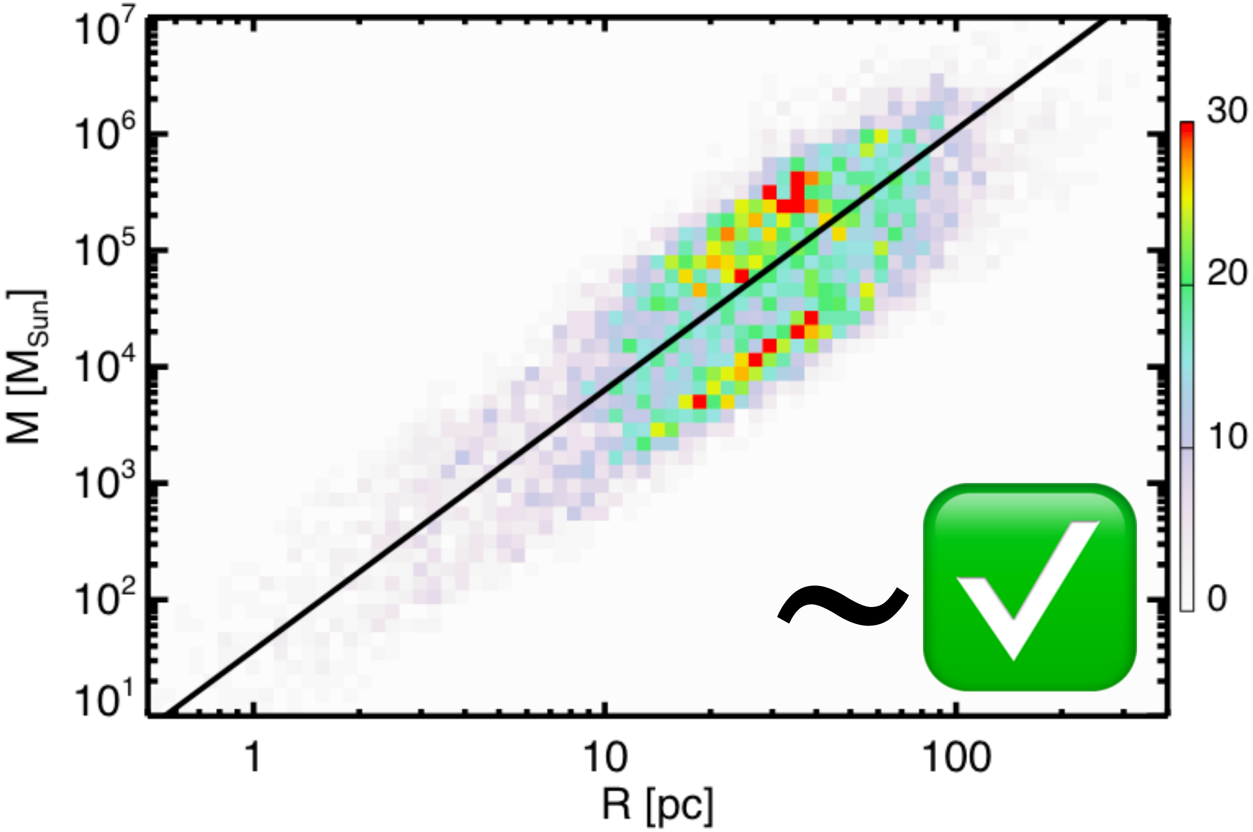
1st Larson relation



$$\sigma_v = 0.48\ R^{0.63\pm0.30}$$

$$\sigma_v \propto R^{0.5}$$

3rd Larson relation



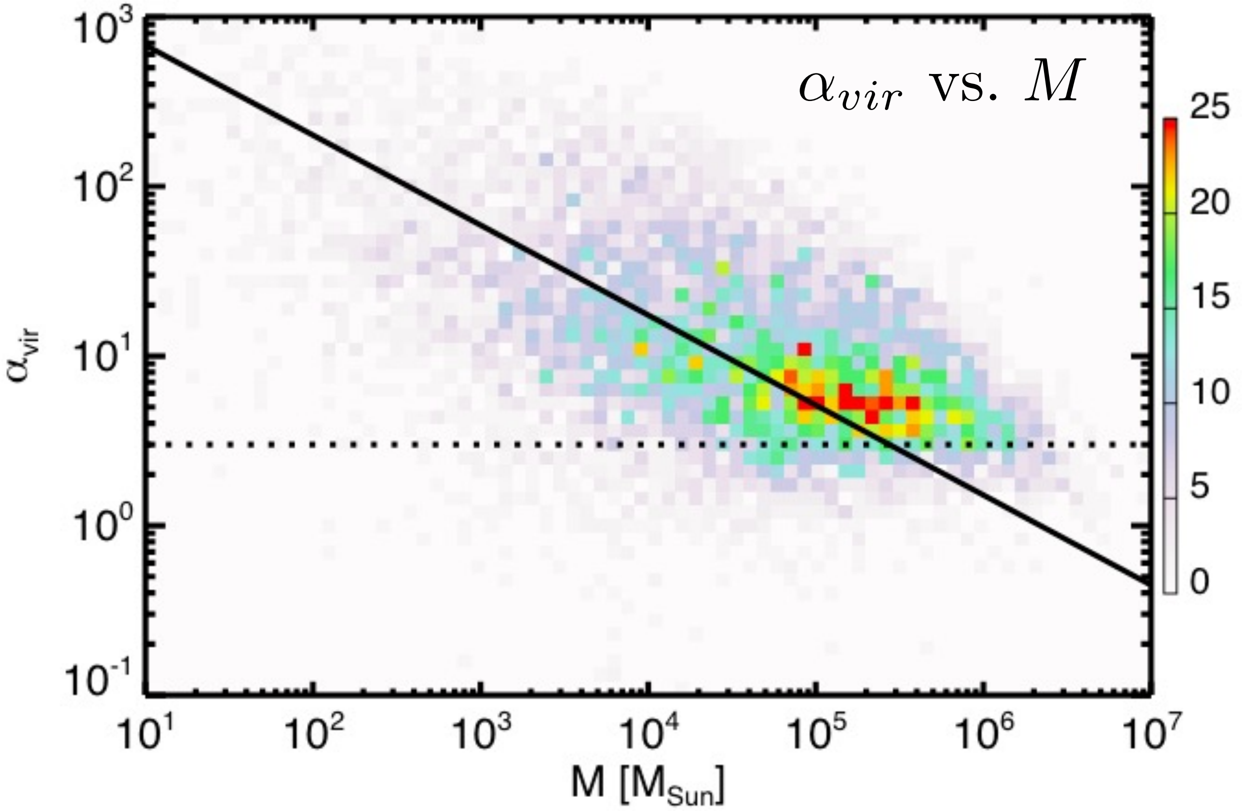
$$M = 36.7\ R^{2.2\pm0.2}$$

$M \propto R^2 \longrightarrow \Sigma(\propto M/R^2) \sim$ const.

Molecular clouds from CO: Mass – Radius relation

Miville-Dechenes+17

2nd Larson relation



Global $\alpha_{vir} \xcancel{=} 1$

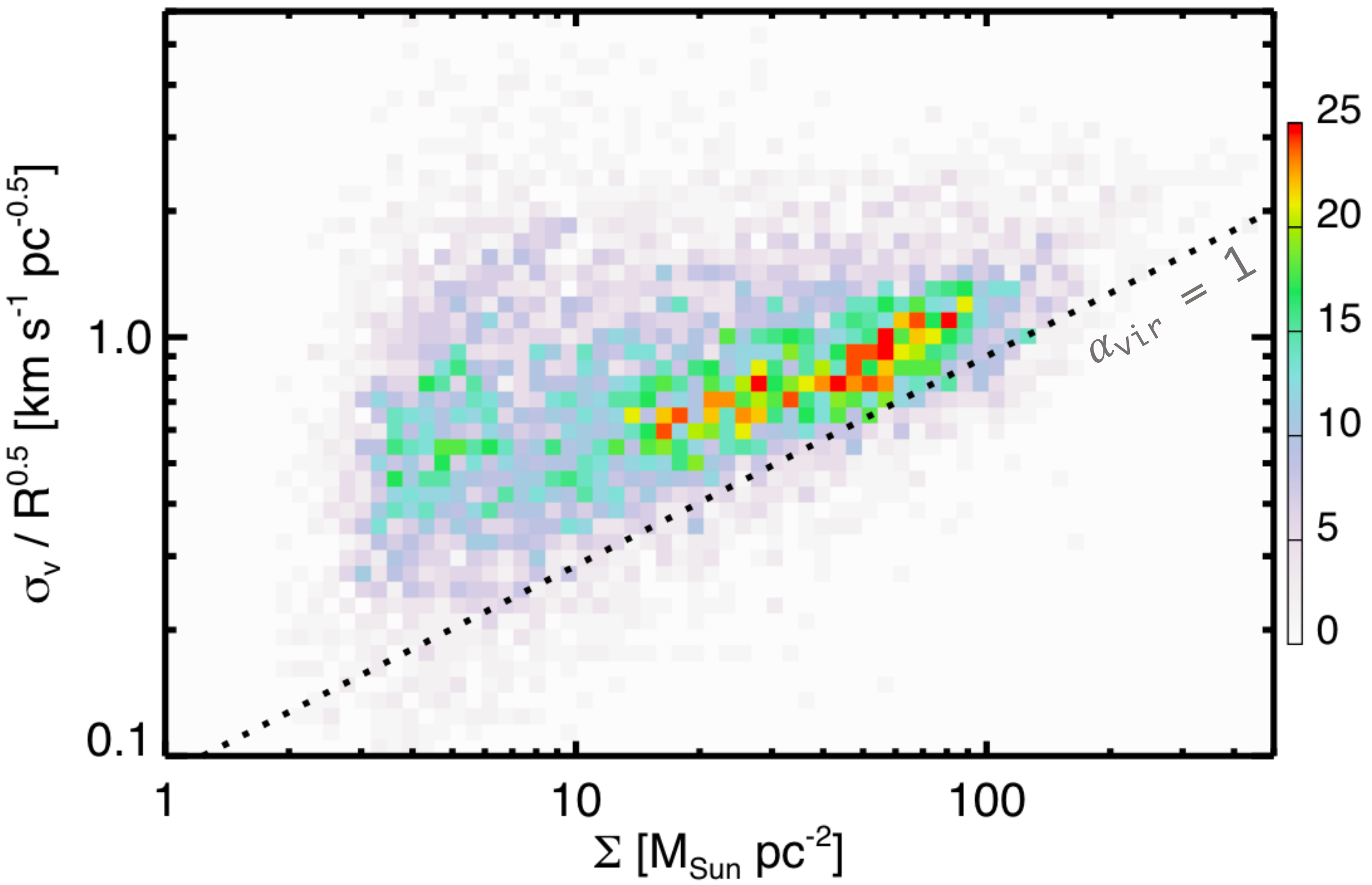
What are the implications?

Molecular clouds from CO: Heyer relation

$$\sigma_v \propto R^{0.5}$$

$$\alpha_{vir} = \frac{5\sigma_v^2 R}{GM} = 1$$

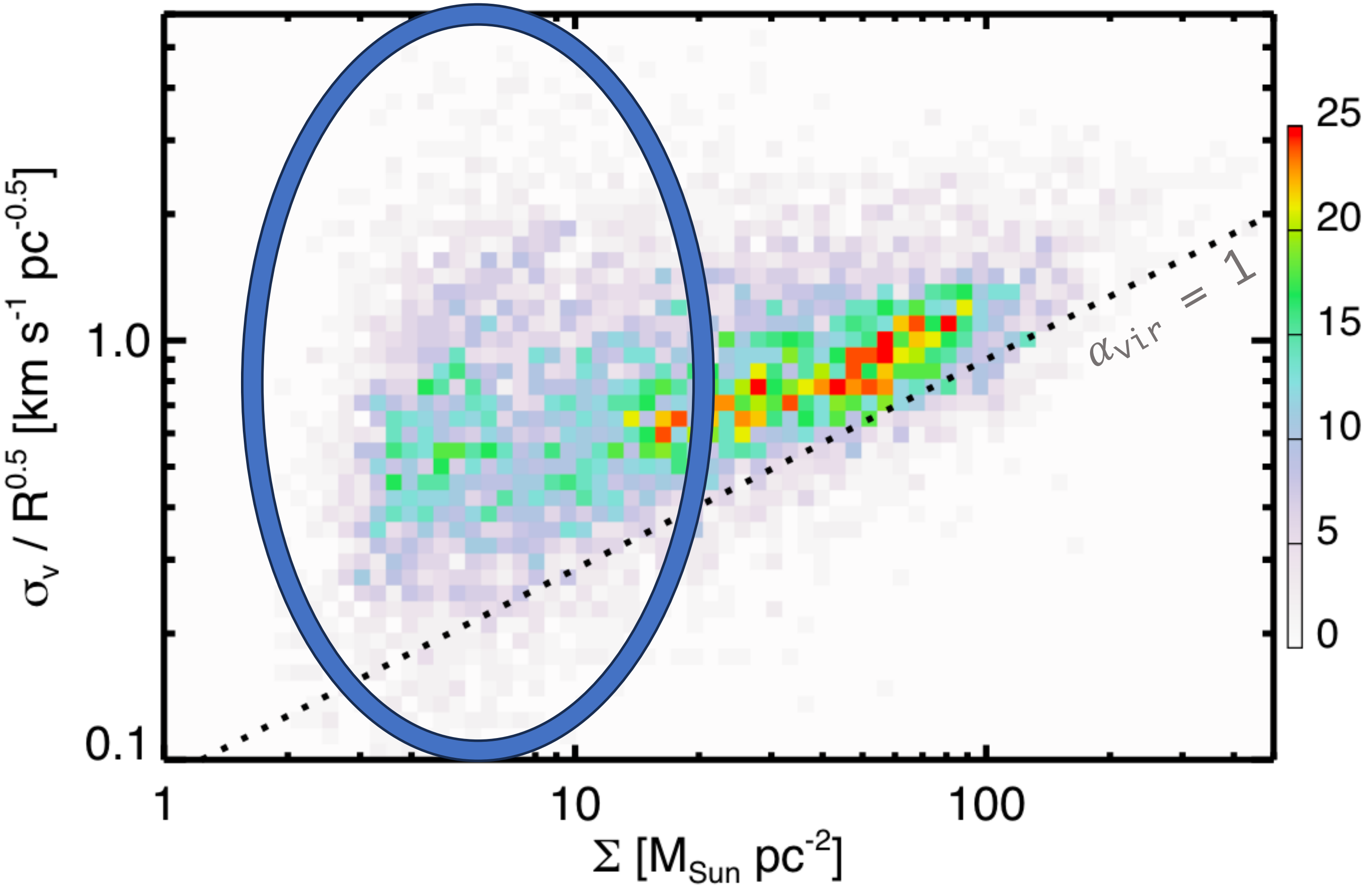
$$\frac{M}{R^2} \propto \Sigma = const.$$



The three Larson relations depend on each other:

$$\alpha_{vir} \propto \frac{\sigma_v^2}{R}\frac{R^2}{M} \propto \frac{\sigma_v^2}{R\Sigma} = \cancel{const.}$$

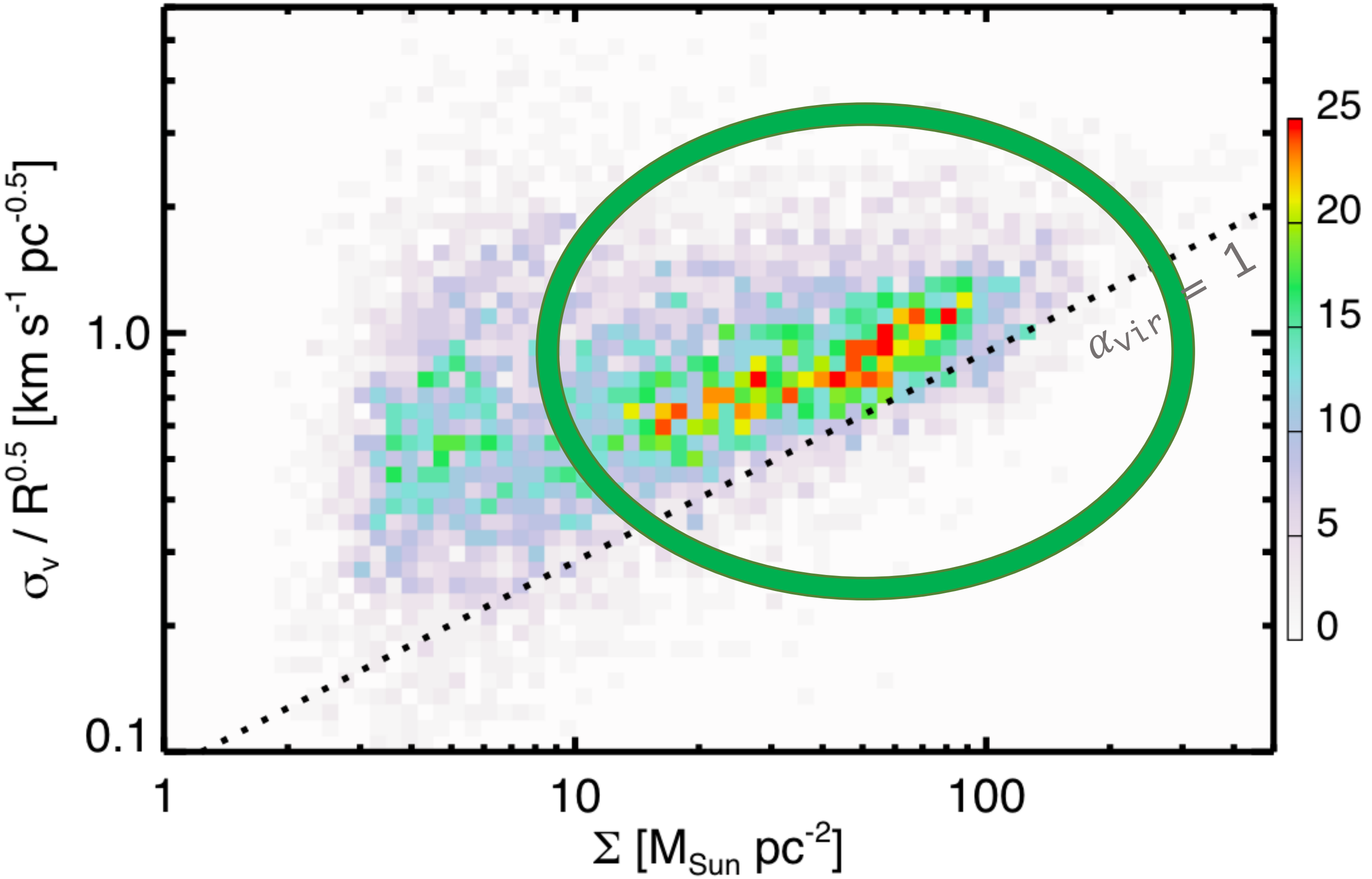
Molecular clouds from CO: Heyer relation



- The kinetic energy E_k dominates over the gravitational term → Clouds mostly unbound

2 regimes?

Molecular clouds from CO: Heyer relation



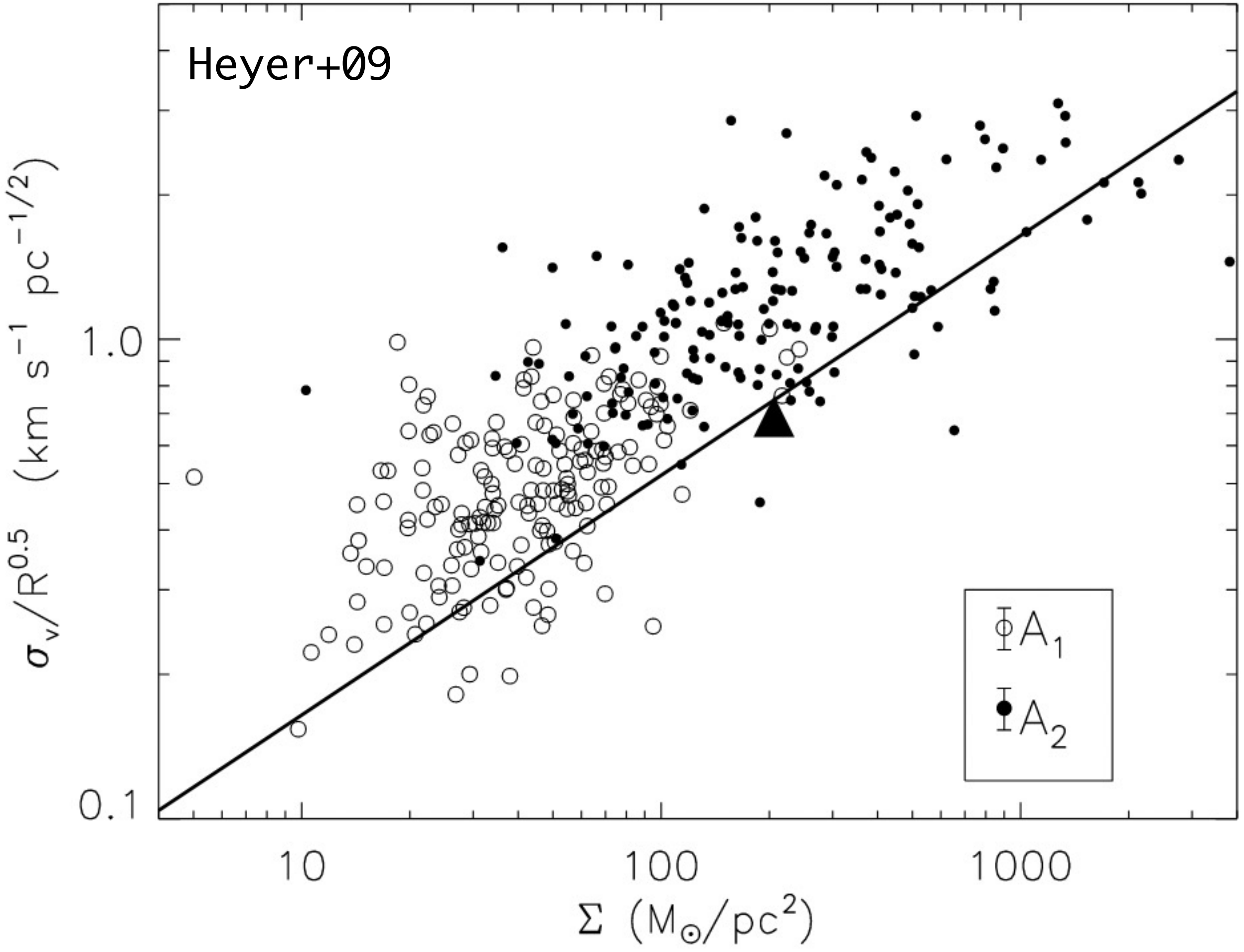
2 regimes?

- The kinetic energy E_k dominates over the gravitational term → Clouds mostly unbound

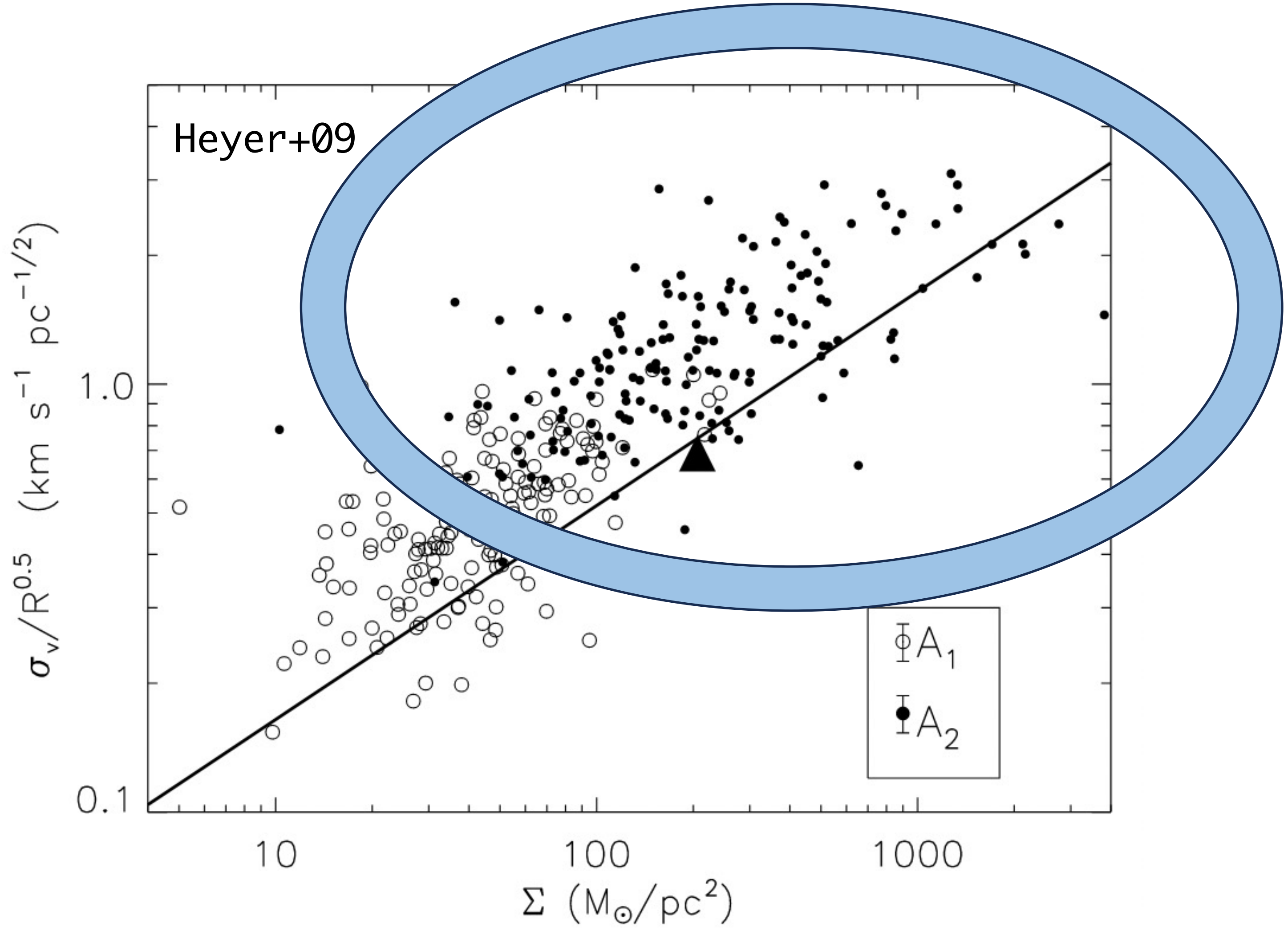
See Ballesteros-Paredes+2011

- The kinetic energy E_k correlates with Σ → E_k may be driven by gravity itself → Clouds mostly (or partially) bound!!

Are molecular clouds self-gravitating?



Are molecular clouds self-gravitating?



Those points are from a <u>^{13}CO (1-0) survey</u>…

Which CO tracer?

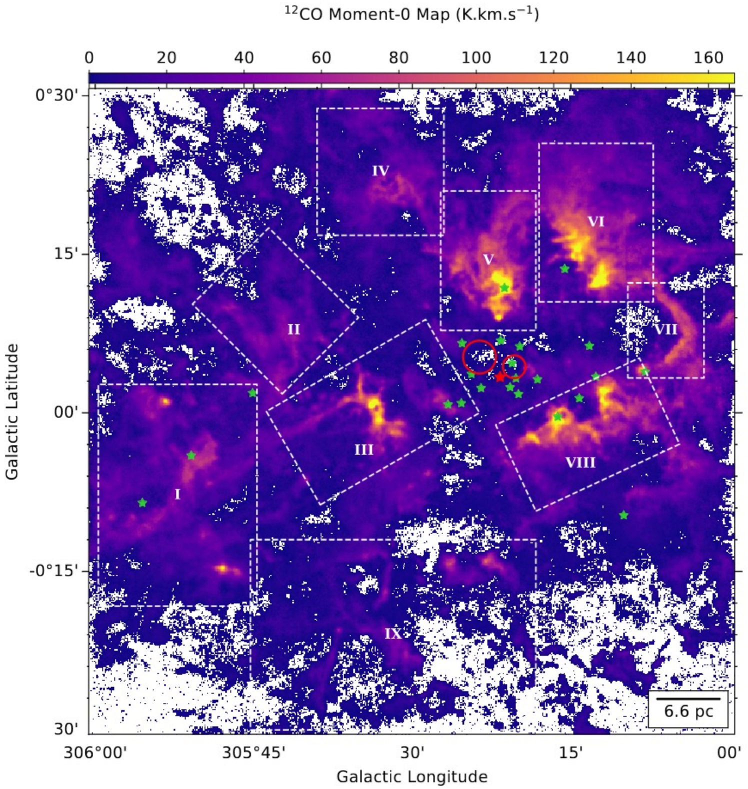
^{12}CO (1-0) is THE most abundant CO in the Galaxy

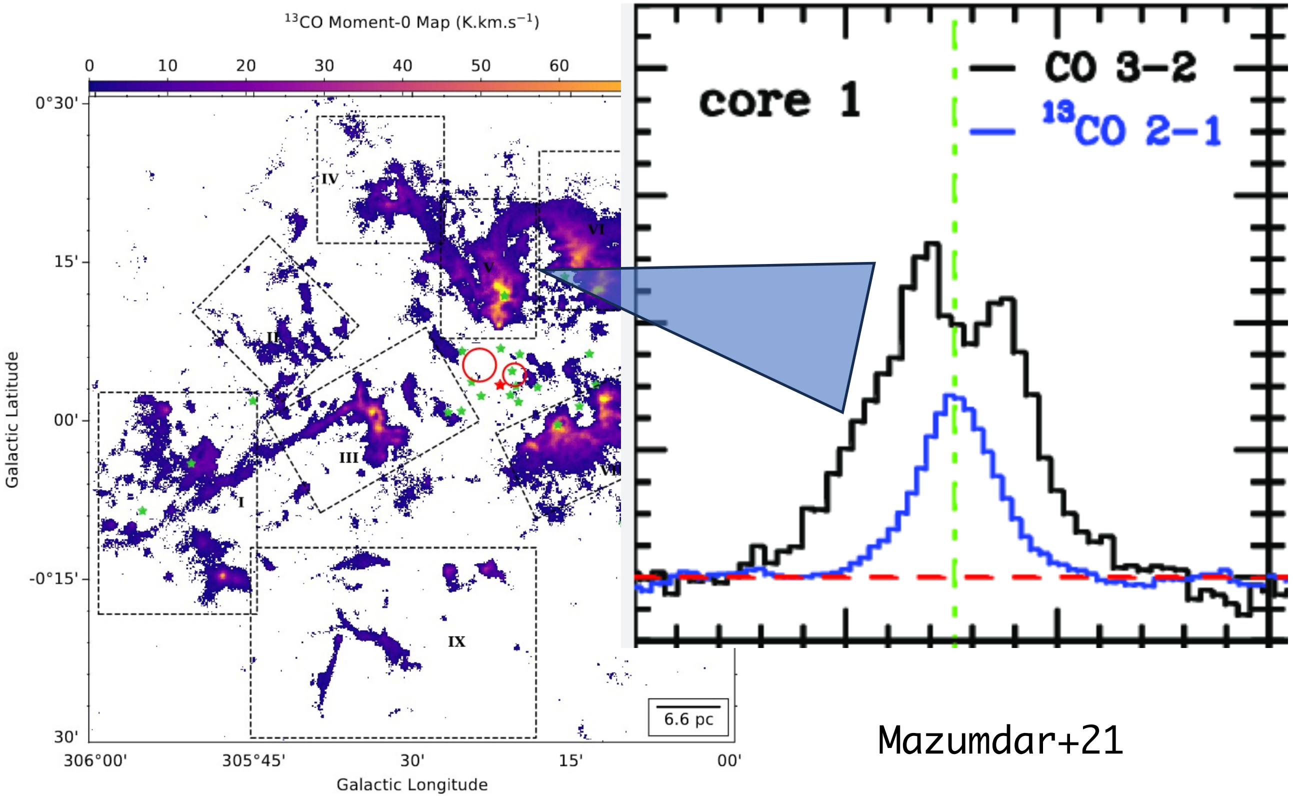
⬇

at “high densities” (n_{H2} ~ 10^3 - 10^4 cm^{-3}) it becomes optically THICK

Other CO transition/isotopologues may be very useful to look INSIDE the “edges” of molecular clouds!!!

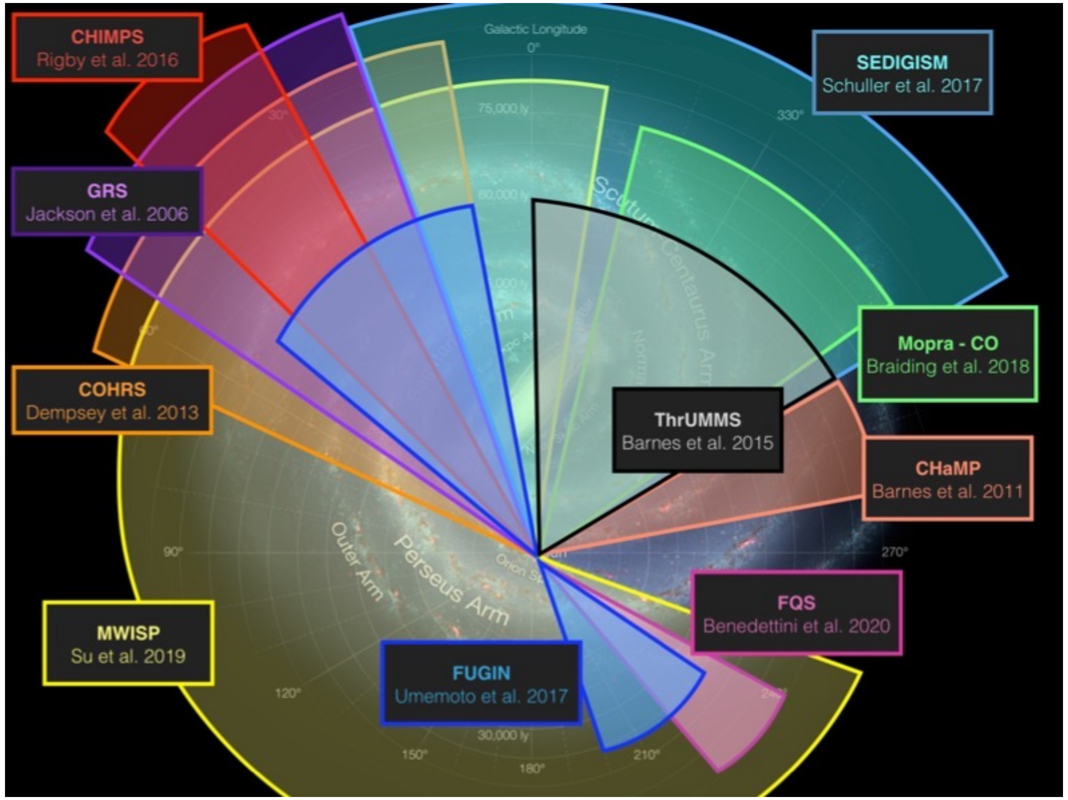
G305
molecular
cloud
clomplex





Mazumdar+21

Which CO tracer?

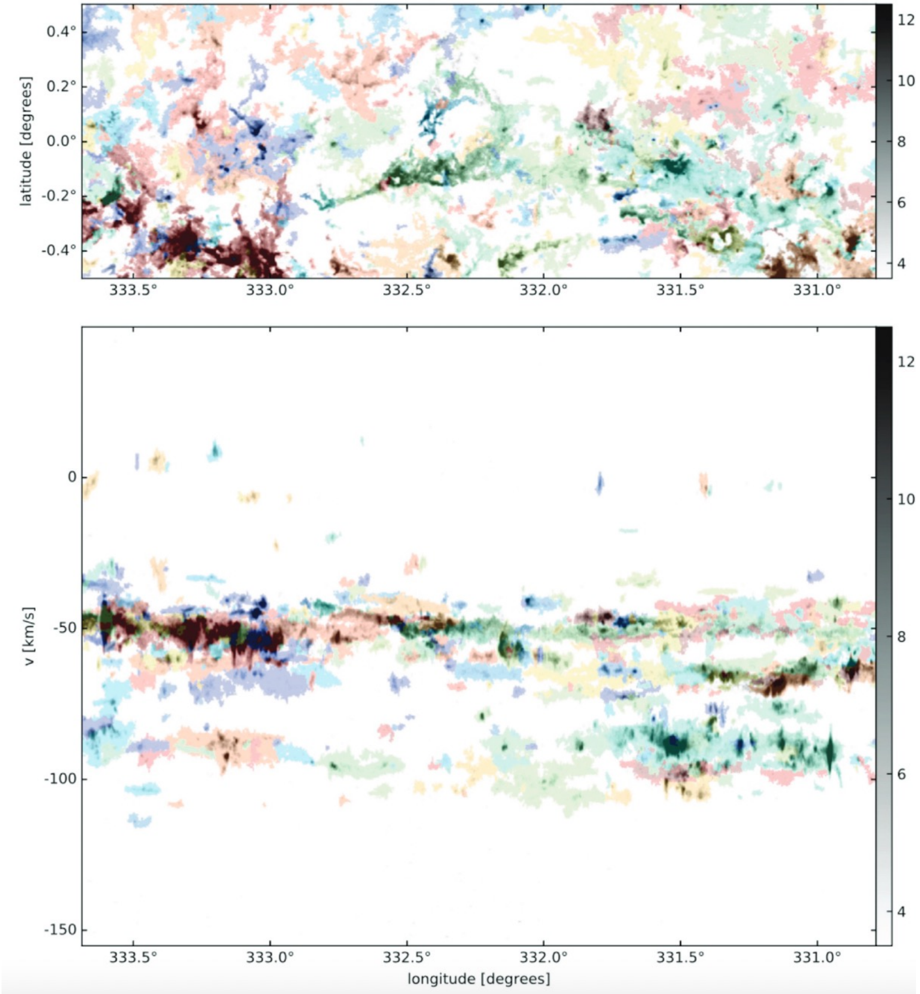


Credits: D. Colombo & J. Urquhart

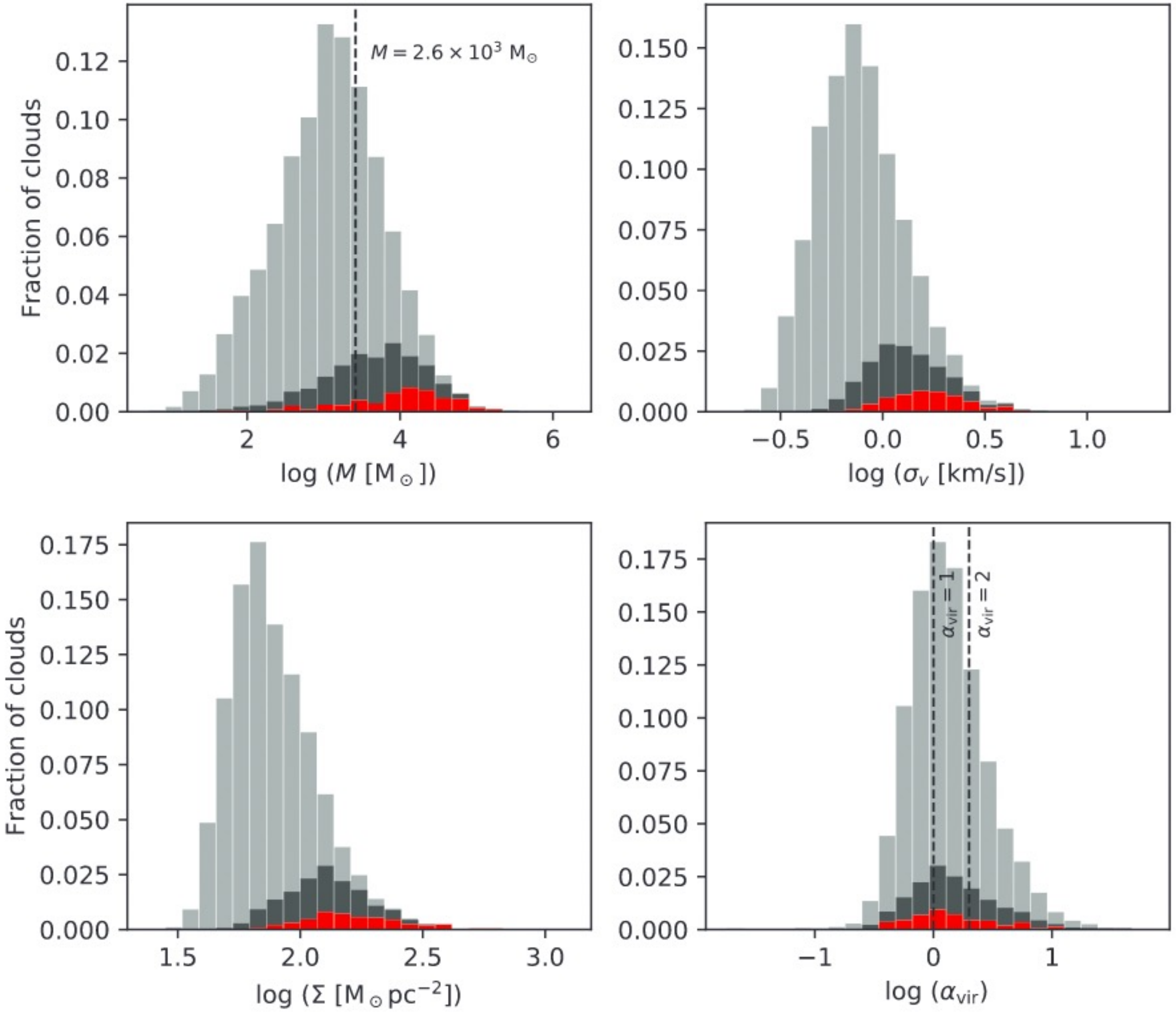
Survey	Transition	Coverage
GRS	^{13}CO (1-0)	$15^{\circ} < l < 55^{\circ}$
ThrUMMS	^{12}CO (1-0) ^{13}CO (1-0) C^{18}O (1-0)	$-60^{\circ} < l < 0^{\circ}$
FUGIN	^{12}CO (1-0) ^{13}CO (1-0) C^{18}O (1-0)	$10^{\circ} < l < 50^{\circ}$
SEDIGISM	^{13}CO (2-1) C^{18}O (2-1)	$-60^{\circ} < l < 18^{\circ}$
COHRS	^{12}CO (3-2)	$10^{\circ} < l < 55^{\circ}$
CHIMPS	^{13}CO (3-2) C^{18}O (3-2)	$28^{\circ} < l < 46^{\circ}$
CHIMPS2	^{12}CO (3-2) ^{13}CO (3-2) C^{18}O (3-2)	$-5^{\circ} < l < 28^{\circ}$

…and more!

Molecular clouds in CO (2-1): SEDIGISM



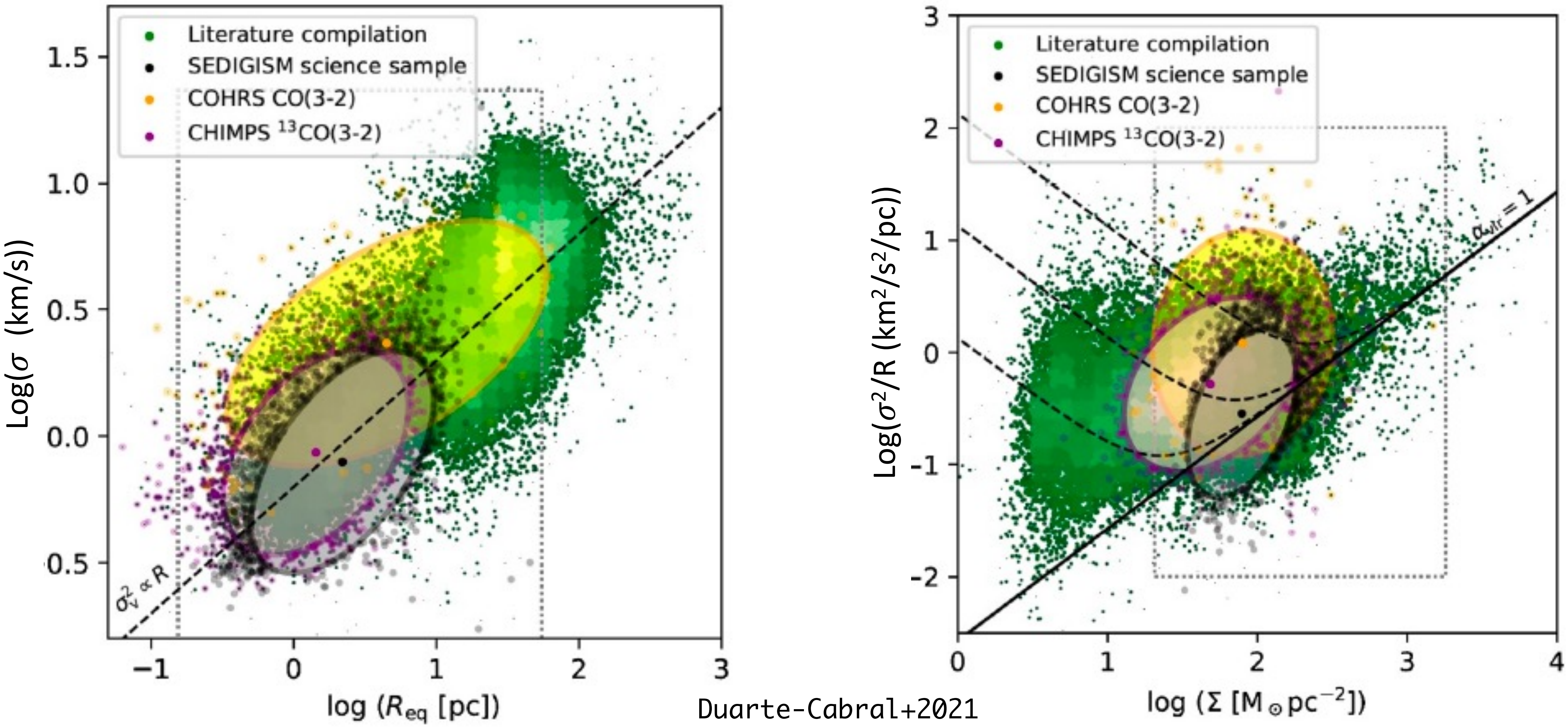
Clouds identified and separated with SCIMES algorithm (Colombo+15)



6664 clouds with well defined physical and dynamical properties

Duarte-Cabral+21

Larson & Heyer relations in CO (2-1) & CO (3-2)



Duarte-Cabral+2021

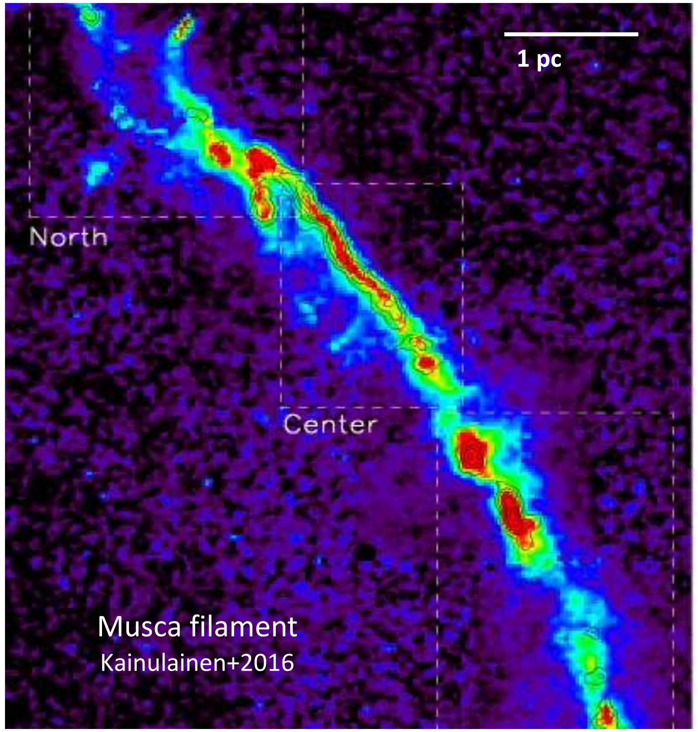
The inner, denser part of a molecular cloud could be bound. How do they look like?

Star-forming regions, clumps and cores - outline

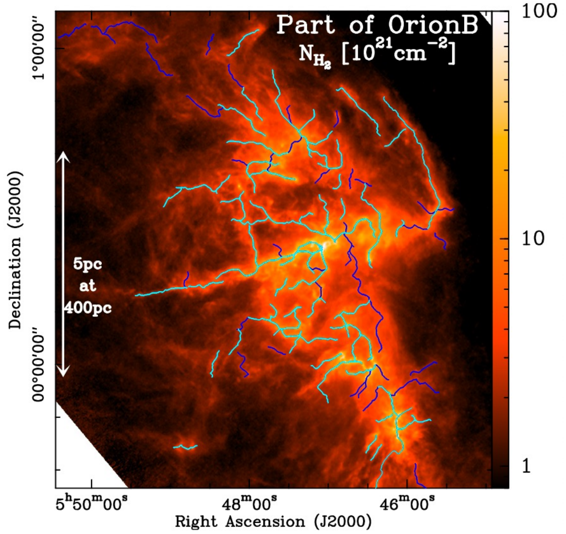
- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: physical properties, dynamics and (partial?) collapse
- From MCs to filaments: the densest regions of molecular clouds
- Pc-scales clumps: the nursery home of stars and protoclusters
- Gas dynamics in filament and clumps: the role of environment

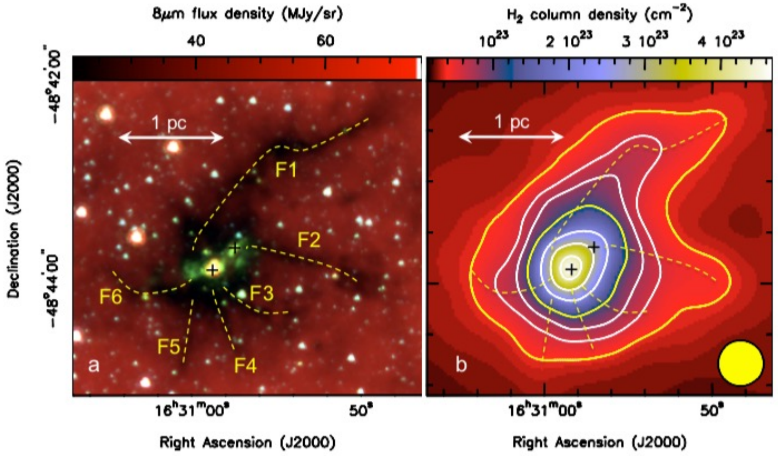
Denser regions in CO molecular clouds: (Galactic scale) FILAMENTS

Filaments are elongated, cold structures thought to be the birthplace of stars

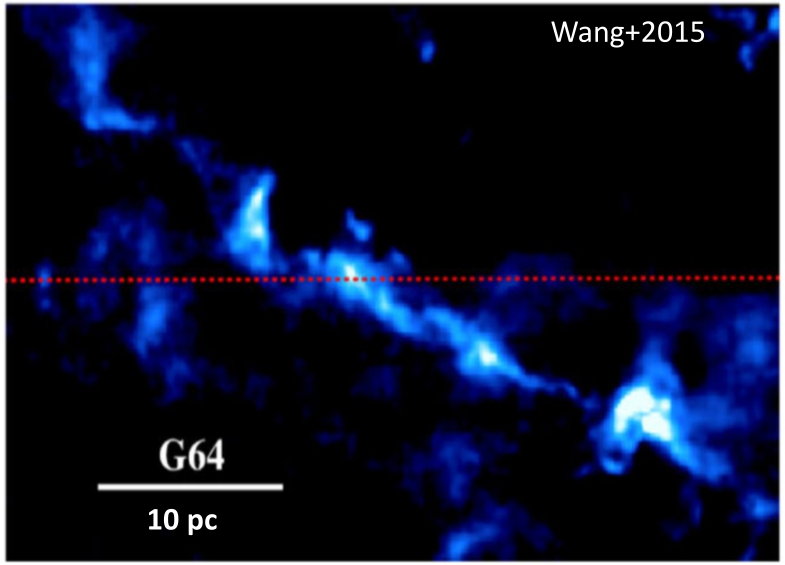


Musca filament
Kainulainen+2016

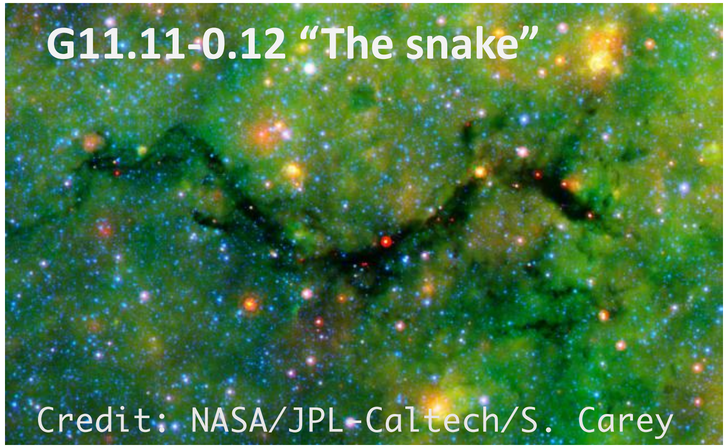




SDC335 Peretto+13



Wang+2015



G11.11-0.12 "The snake"

Credit: NASA/JPL-Caltech/S. Carey

Galactic scale FILAMENTS main properties

Filaments are denser than CO clouds

Can be seen in DUST emission!

Properties	CO clouds	Filaments
Length (pc)	up to 150	up to 100
Temperature (K)	~ 10-30	~ 10-35
Mass $(M_\odot)$	up to few 10^6	up to few 10^5
Surf. density (g/cm^2)	~0.0004-0.06	~0.0005 - 0.5

Schisano+2020

Physical properties (M, R, Σ)
Cold dust emission
Continuum IR / sub mm surveys

Gas kinematics (σ)
various CO
transitions

Filaments in dust emission

The Spectral Energy Distribution of the cold (T~10-40K) dust emission associated with filamentary structures can be approximated with a modified greybody function

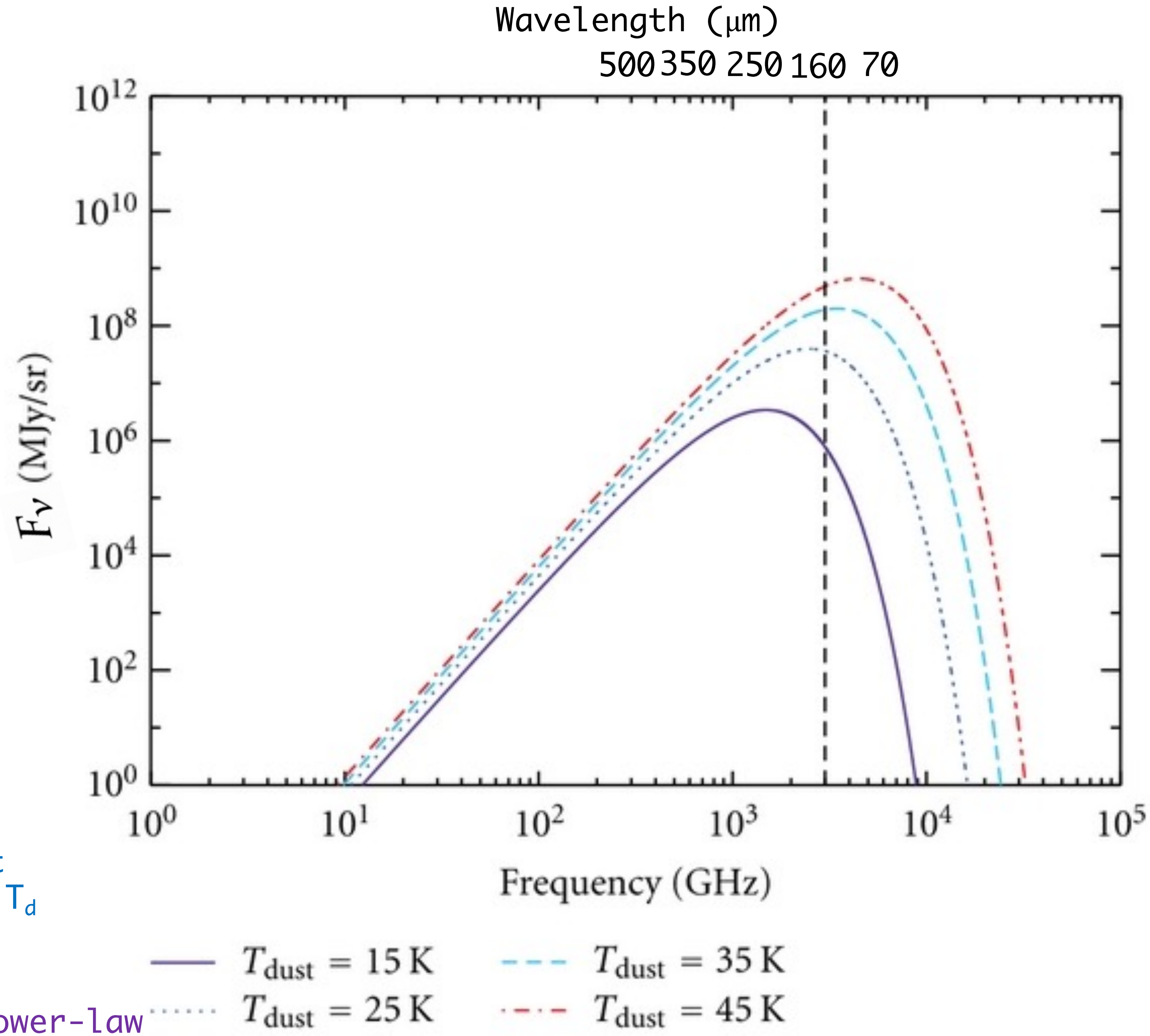
$$F_{\nu} = \frac{M\kappa_{\mathrm{ref}}}{d^2}\left(\frac{\nu}{\nu_{\mathrm{ref}}}\right)^{\beta} B_{\nu}(T_d)$$

Flux at frequency ν

Opacity at a given frequency ν_{ref}

exponent of the power-law dust emissivity at large wavelengths

Blackbody at temperature T_d



See lecture from Karine Demyk

Filaments in dust emission

The Spectral Energy Distribution of the cold (T~10-40K) dust emission associated with filamentary structures can be approximated with a modified greybody function

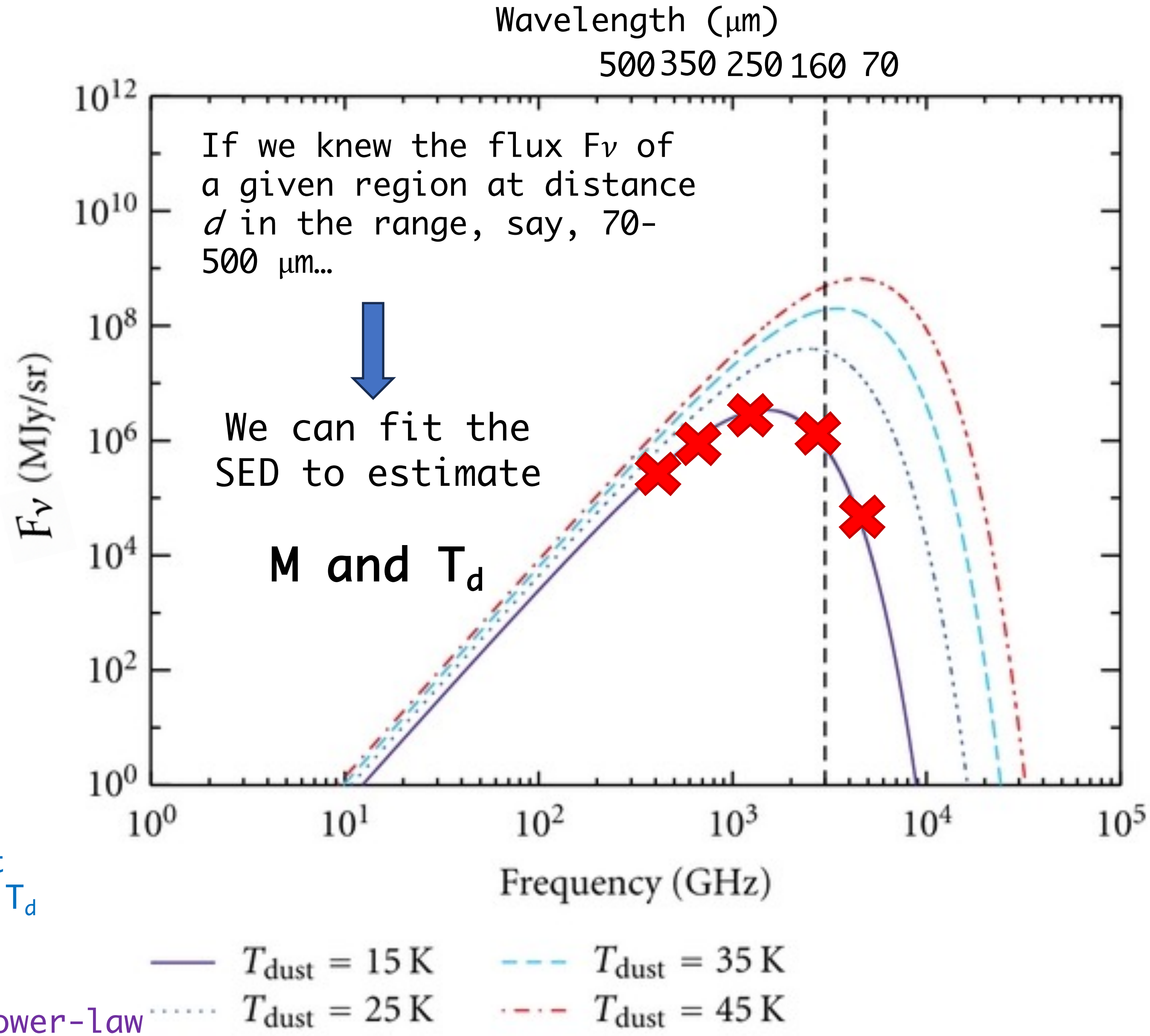
$$F_\nu = \frac{M\kappa_{\mathrm{ref}}}{d^2}\left(\frac{\nu}{\nu_{\mathrm{ref}}}\right)^\beta B_\nu(T_d)$$

Flux at frequency ν

Opacity at a given frequency ν_{ref}

exponent of the power-law dust emissivity at large wavelengths

Blackbody at temperature T_d



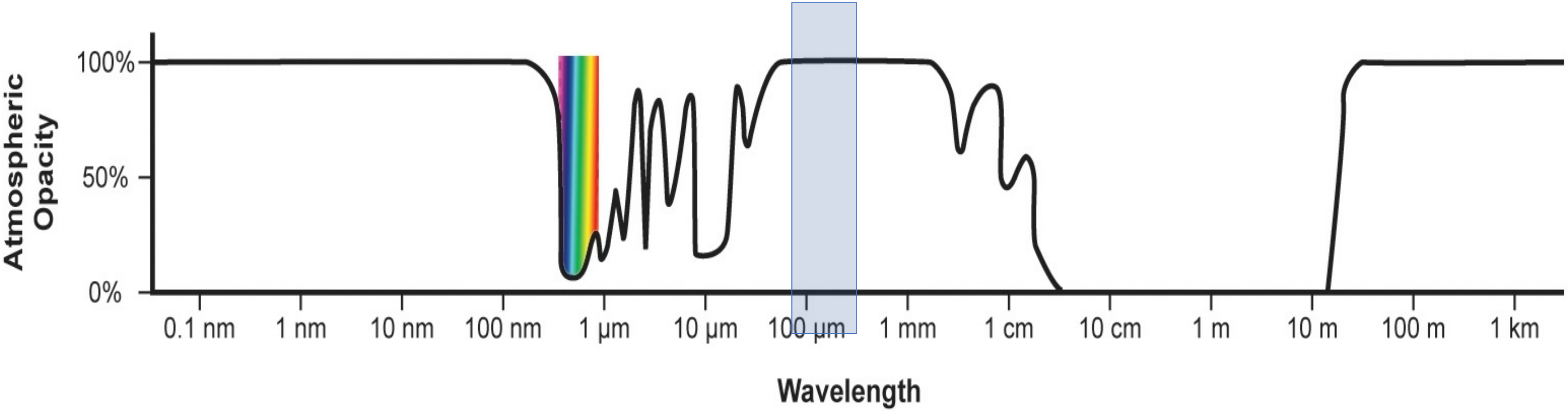
If we knew the flux F_ν of a given region at distance *d* in the range, say, 70-500 μm…

We can fit the SED to estimate

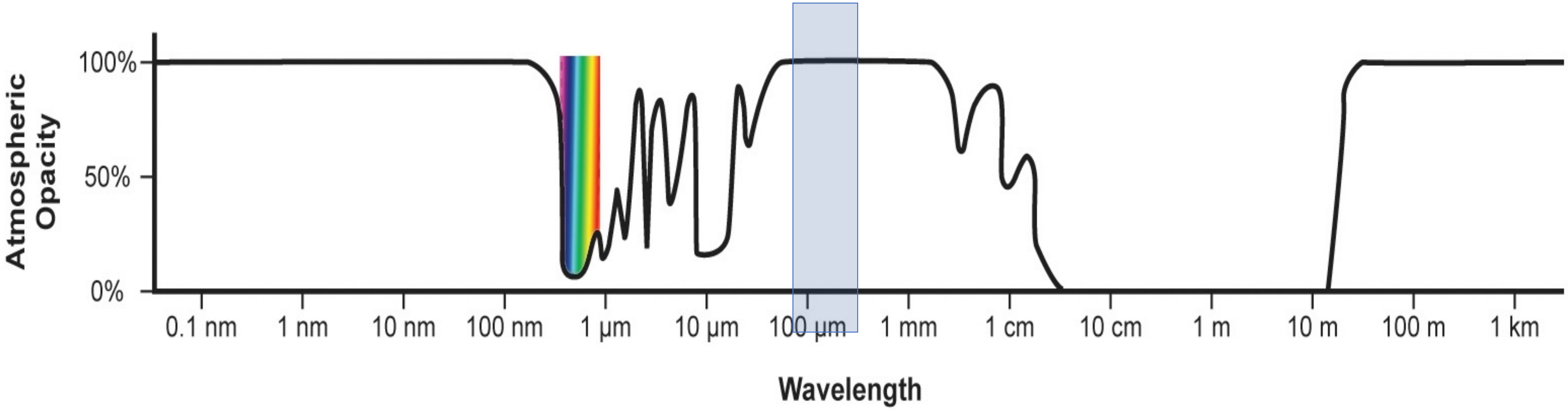
M and T_d

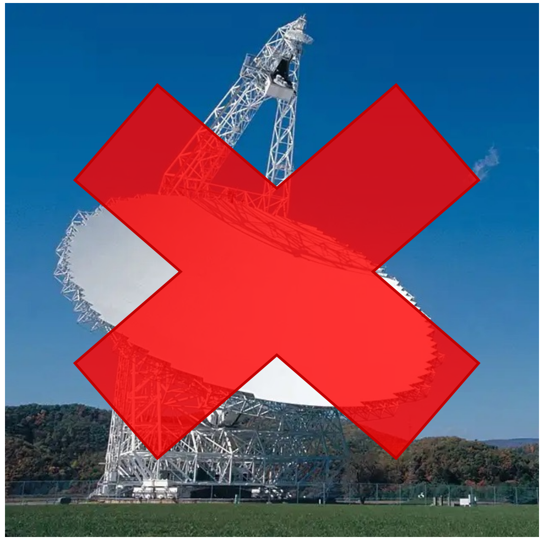
See lecture from Karine Demyk

Observing dust emission in the FIR/sub-mm



Observing dust emission in the FIR/sub-mm





Herschel (2009)
70 ≤ λ ≤ 500 μm

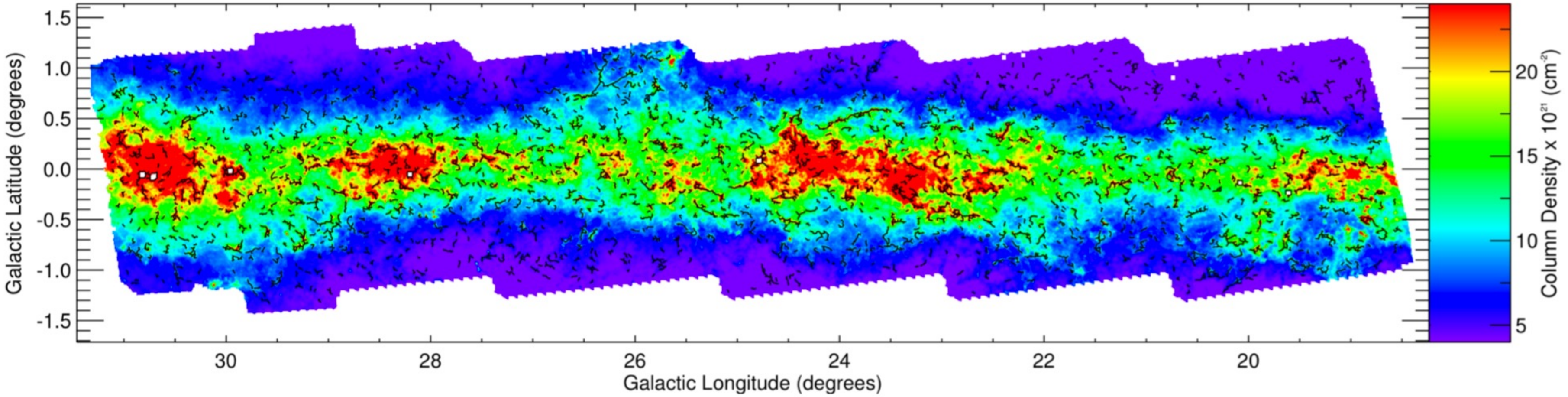
Hi-GAL: the Herschel Galactic Plane survey of the Milky Way in the FIR / sub mm

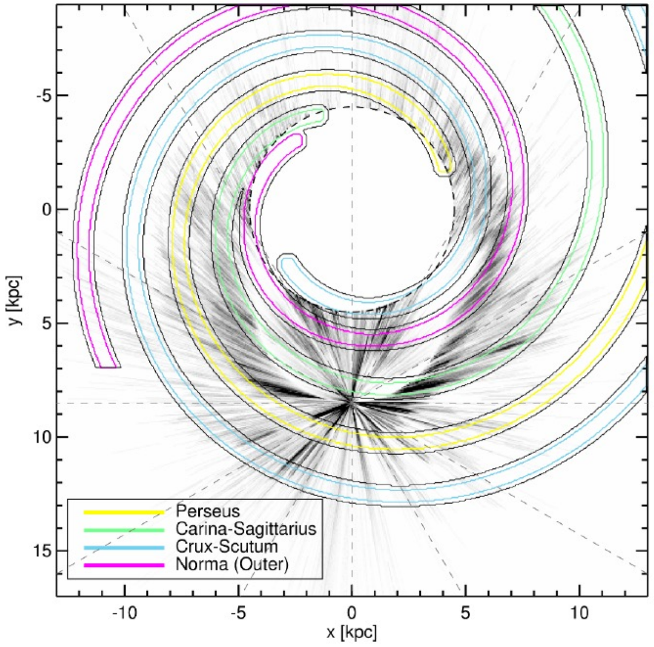
Credits: Gianluca Li Causi (INAF-IAPS)

Molinari+ 2010, 2016

Filaments

> 30000 Hi-GAL candidate filaments across the Galactic Plane!!!





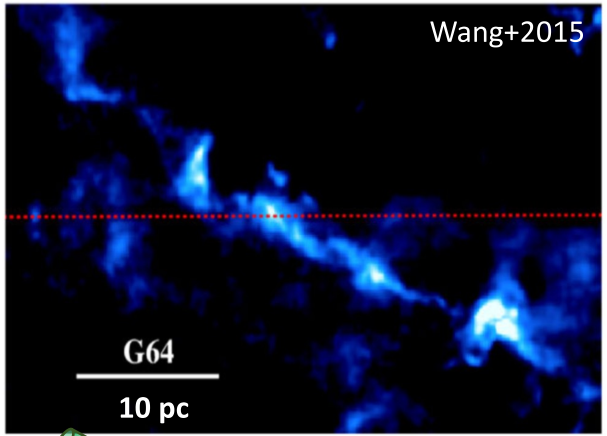
Schisano+2020

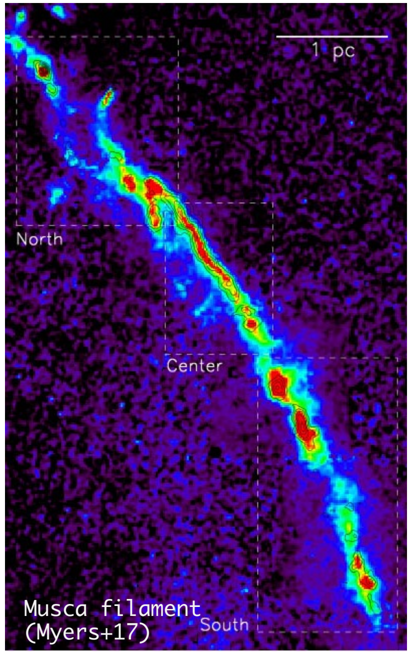
How to characterize filaments from observations

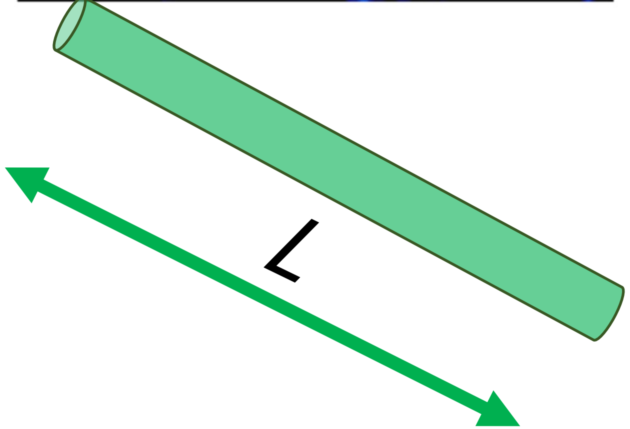
Filaments are elongated, dense, cold structures. The simplest (and more effective) approach to model them is the

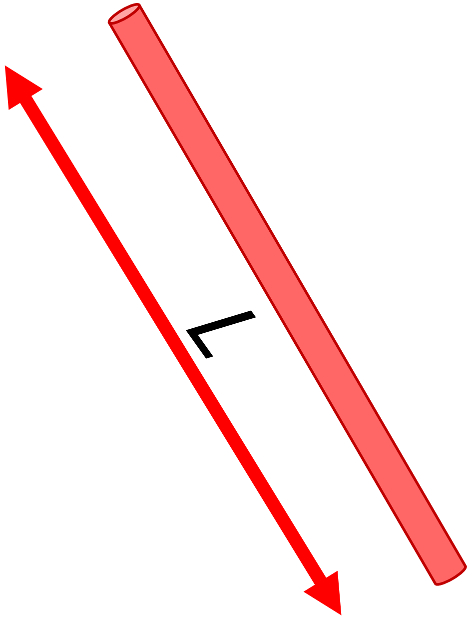
Hydrostatic, isothermal cylinder model

(Ostriker 1964)



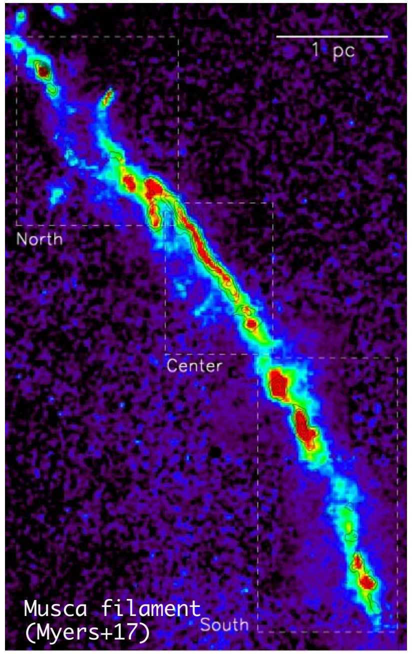






- Mass *M*, Length *L* (derived from dust emission)
- Velocity dispersion σ_{tot} (derived from CO transitions)

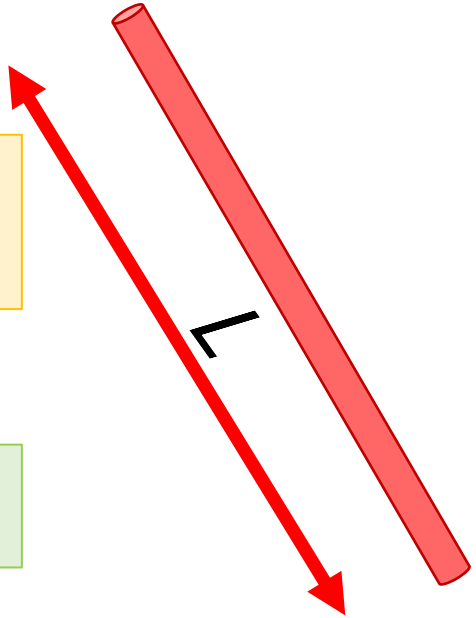
How to characterize filaments from observations



- Linear mass m (mass per unith length): $$m = \frac{M}{L}$$

- A critical line mass $m_{\rm crit}$: $$m_{\rm crit}(T) = \frac{2\sigma_{th}^2}{G} = \frac{2k_BT}{\mu m_p G}$$

(From the integration of the mass per unit length of an isothermal cylinder of (infinite) length. For details see Ostriker 1964)



$$f = \frac{m}{m_{\rm crit}}$$

f > 1 → (supercritical)

Radially unstable and **<u>should collapse</u>** under their own gravity

f < 1 → (subcritical)

<u>Can remain</u> in hydrostatic equilibrium

How to characterize filaments from observations

Remember however that we observe **supersonic, non-thermal motions** σ_{nth} that dominates the velocity fields of our star-forming regions

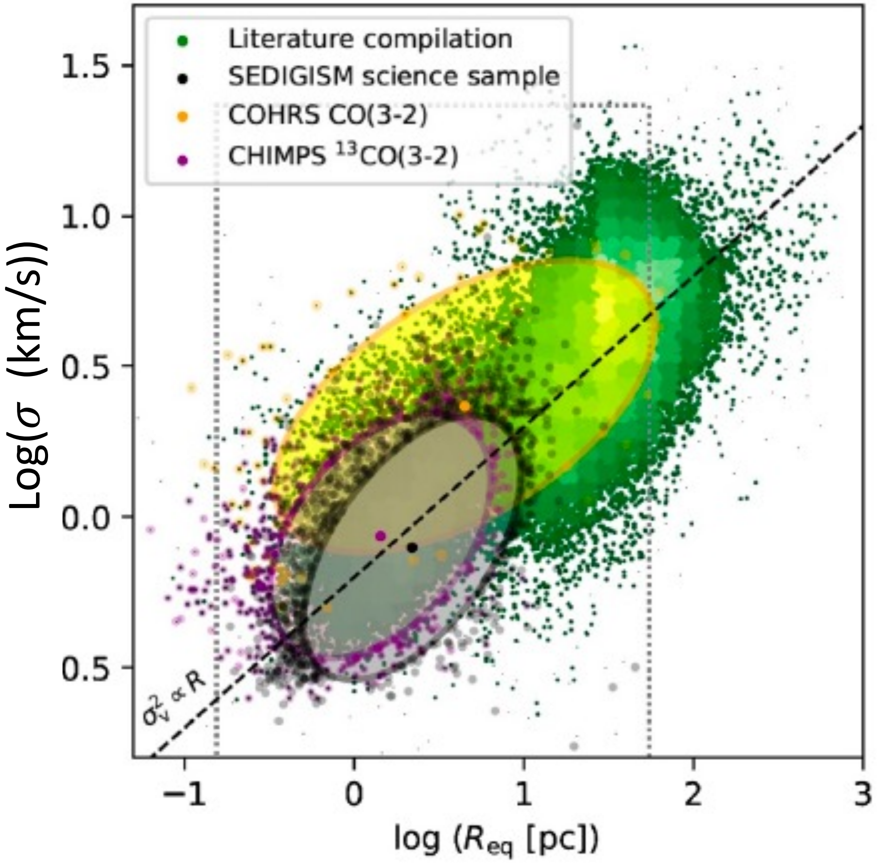
$$m_{\text{crit}}(T) = \frac{2\sigma_{\text{th}}^2}{G}$$

For T = 10 K $\rightarrow$ σ_{th} ~ 0.1 km/s

$$m_{\text{vir}}(\sigma_{\text{tot}}) = \frac{2\sigma_{\text{tot}}^2}{G}$$

With $$\sigma_{\text{tot}}^2 = \sigma_{\text{nth}}^2 + \sigma_{\text{th}}^2$$

Under the assumptions that ALL σ_{th} works to support the filament against the collapse



Log(σ_{th} ~ 0.1) ~-1 km/s

How to characterize filaments from observations

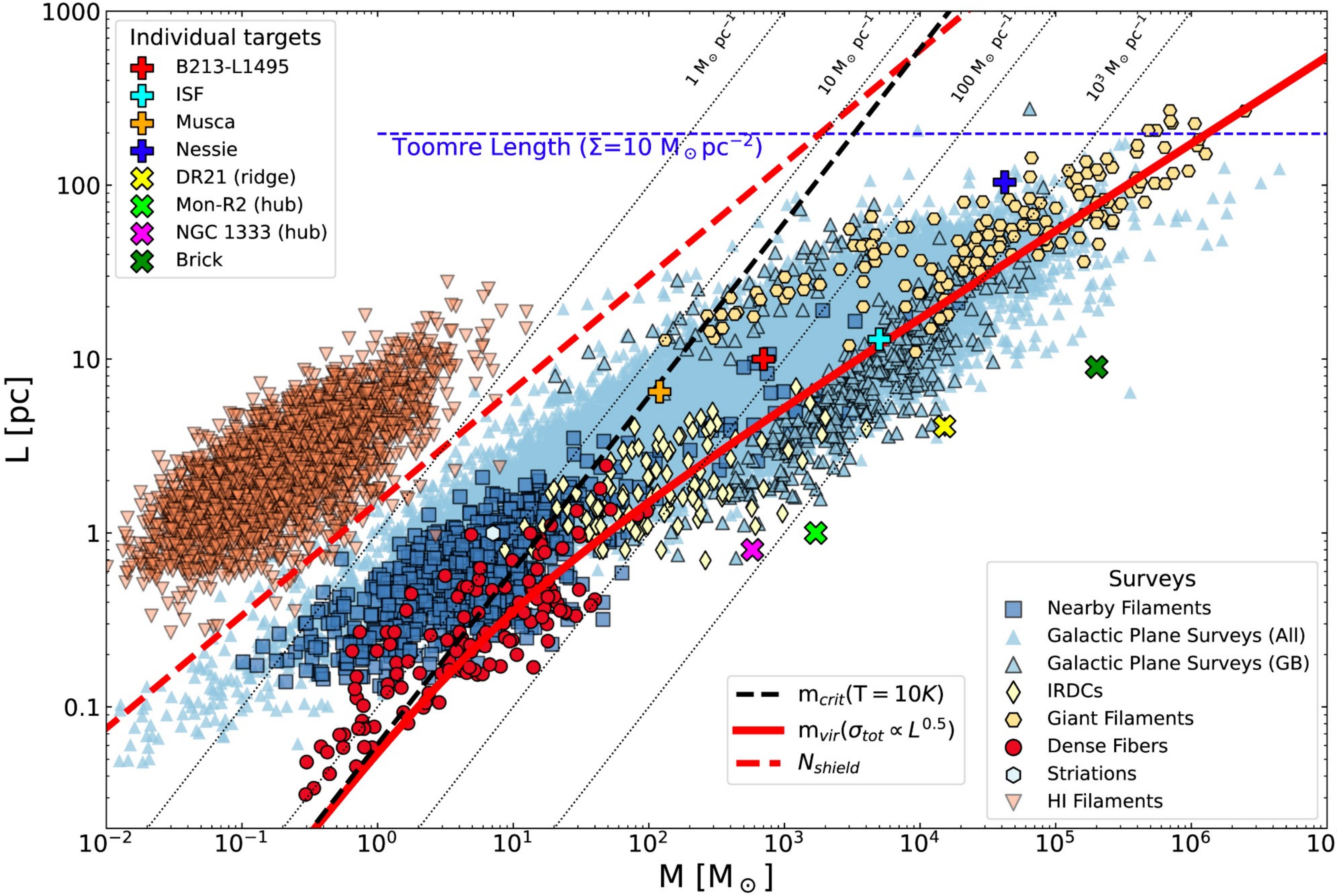
$$m_{\rm crit}(T) = \frac{2\sigma_{\rm th}^2}{G} \qquad \longrightarrow \qquad m_{\rm vir}(\sigma_{\rm tot}) = \frac{2\sigma_{\rm tot}^2}{G}$$

Combining the LARGEST sample of filaments structures to date from several different surveys, observationally we found (Hacar+23):

$$m_{\rm vir} = \frac{M}{L} \simeq \frac{2c_s^2}{G}\left(1 + \frac{L}{0.5\ {\rm pc}}\right)$$

How to characterize filaments from observations

Combining the LARGEST sample of filaments structures to date from several different surveys, observationally we found (Hacar+23):

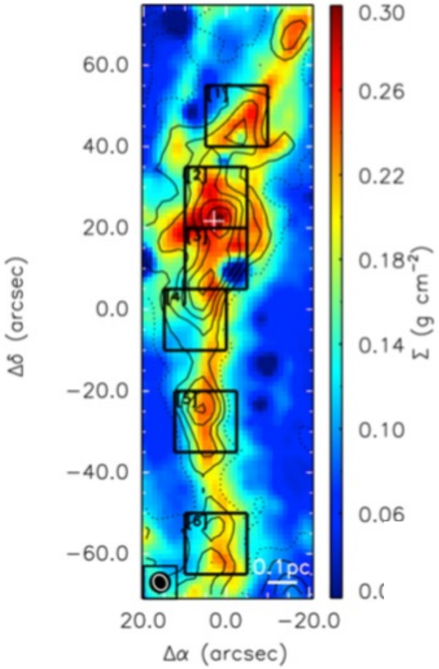


Star-forming regions, clumps and cores - outline

- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: physical properties, dynamics and (partial?) collapse
- From MCs to filaments: the densest regions of molecular clouds
- Pc-scales clumps: the nursery home of stars and protoclusters
- Gas dynamics in filament and clumps: the role of environment

Super-critical filaments: the nursery home of pc-scales clumps

G035

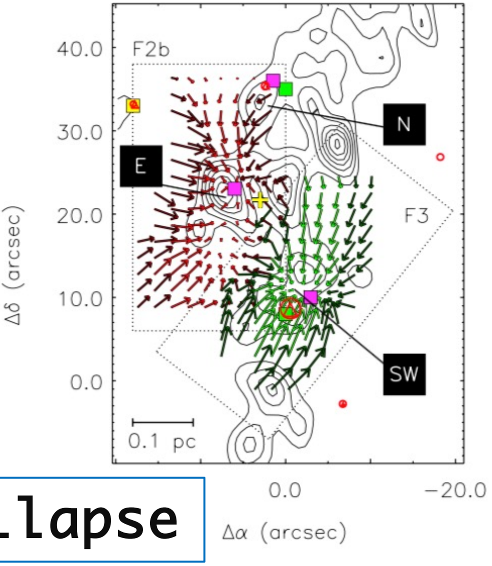


Global

velocity gradient
~ 0.7 km s^{-1}

Local

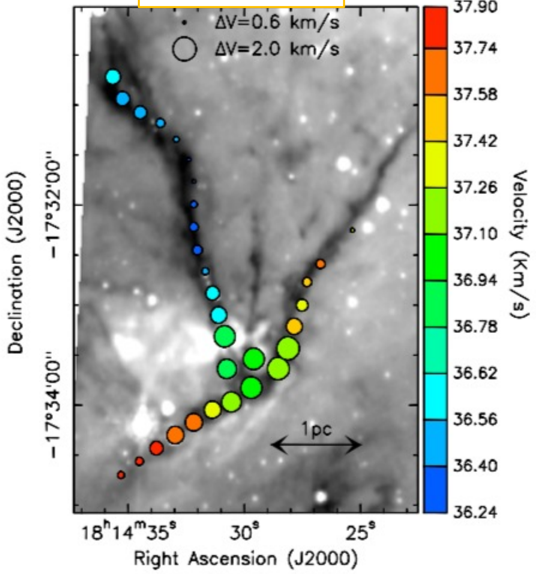
velocity gradient
~ 1.5-2.5 km s^{-1}

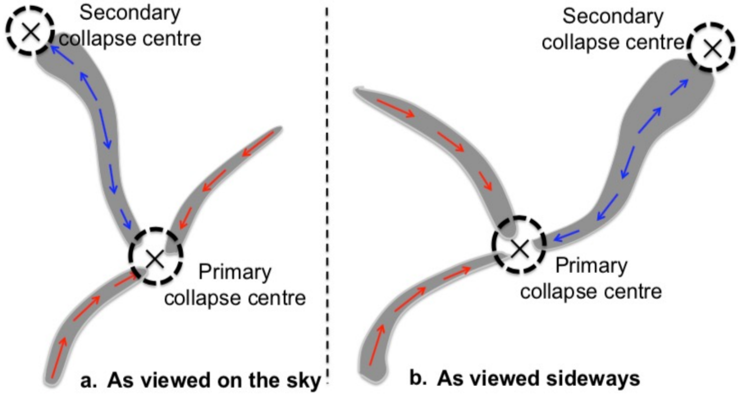


Local collapse

Henshaw+14

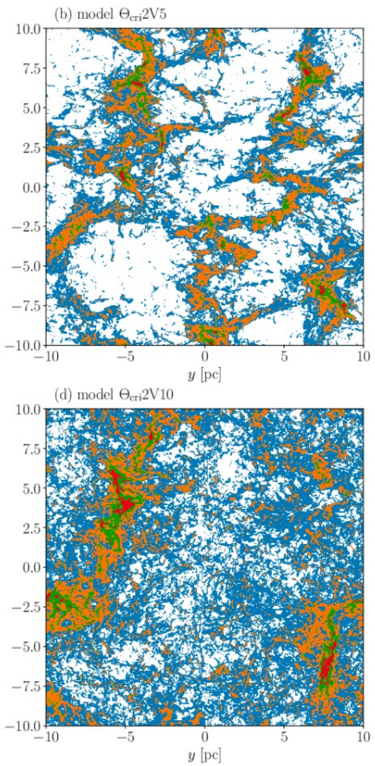
SDC13





Global collapse

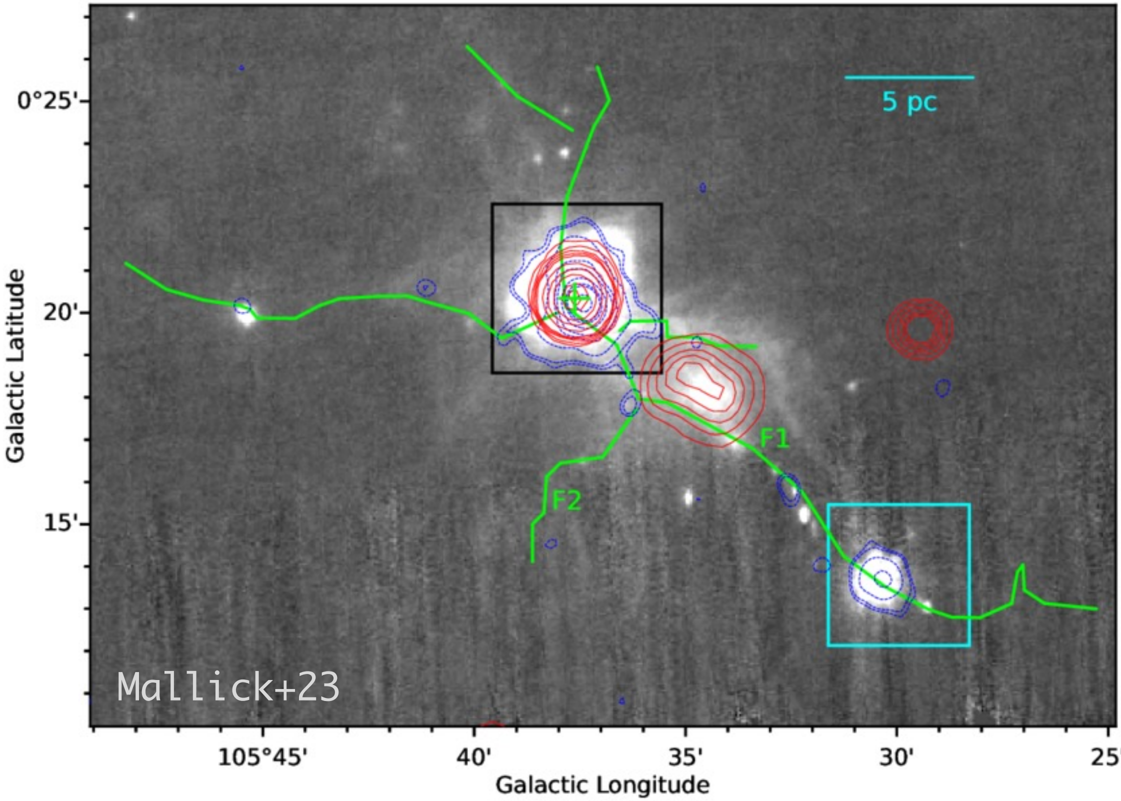
Peretto+14



Inner properties inherited from the collision of the two-phases flow?

Iwasaki & Tomida 2022

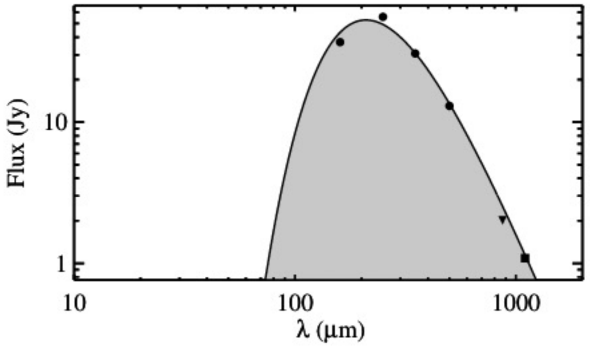
Super-critical filaments: the nursery home of pc-scales clumps



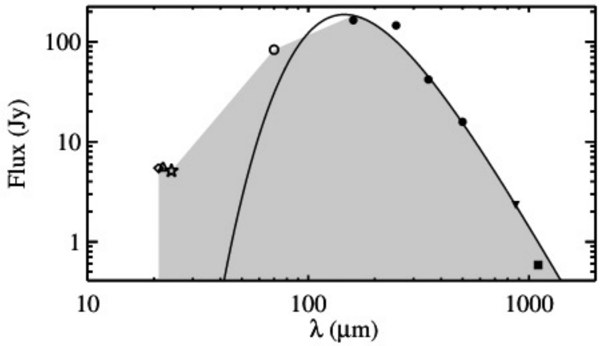
These are the most common structures where you form **clumps** (pc-scale condensations with ~elliptical shape)

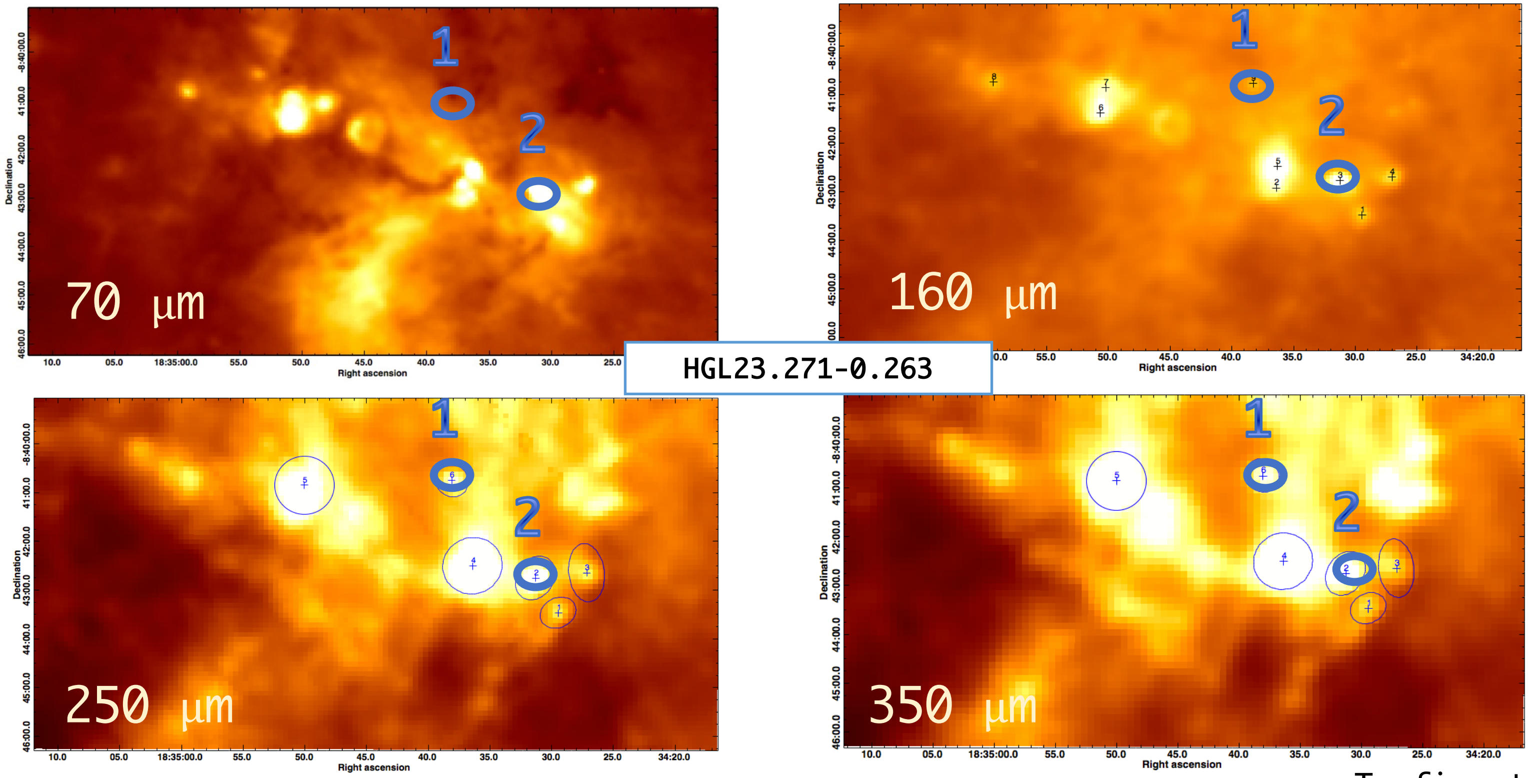
Clumps physical properties

“starless”



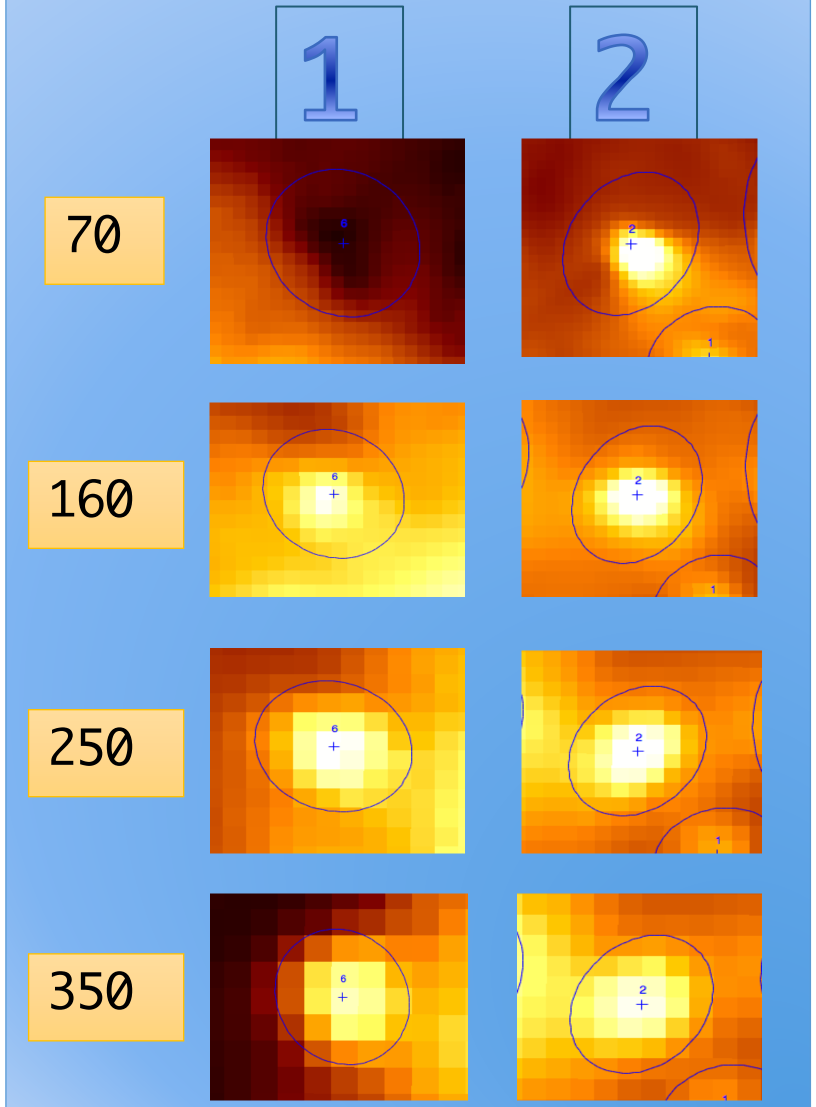
protostar





“starless”

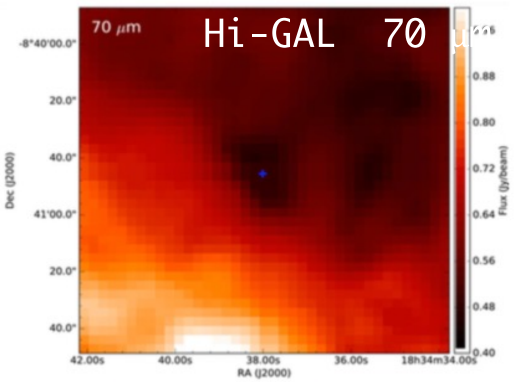
protostar

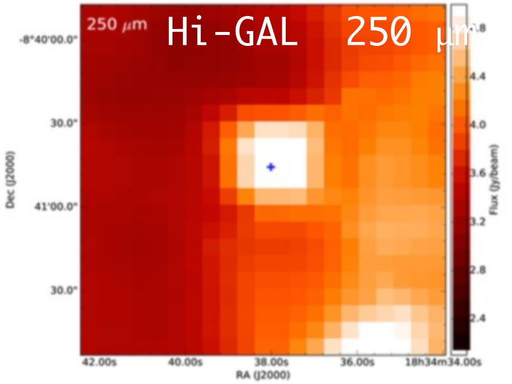


Traficante+15

Clumps in the Galaxy

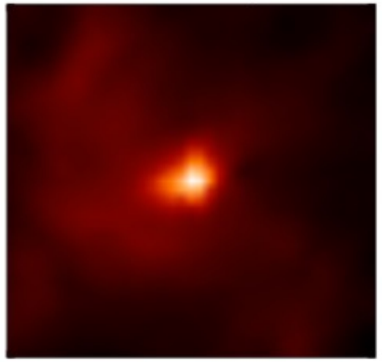
SDC23271-0263



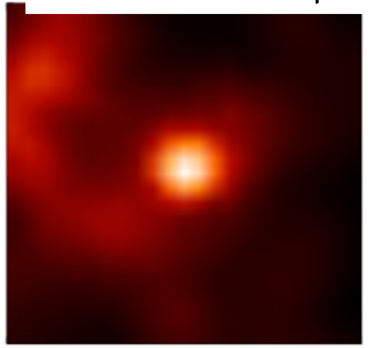


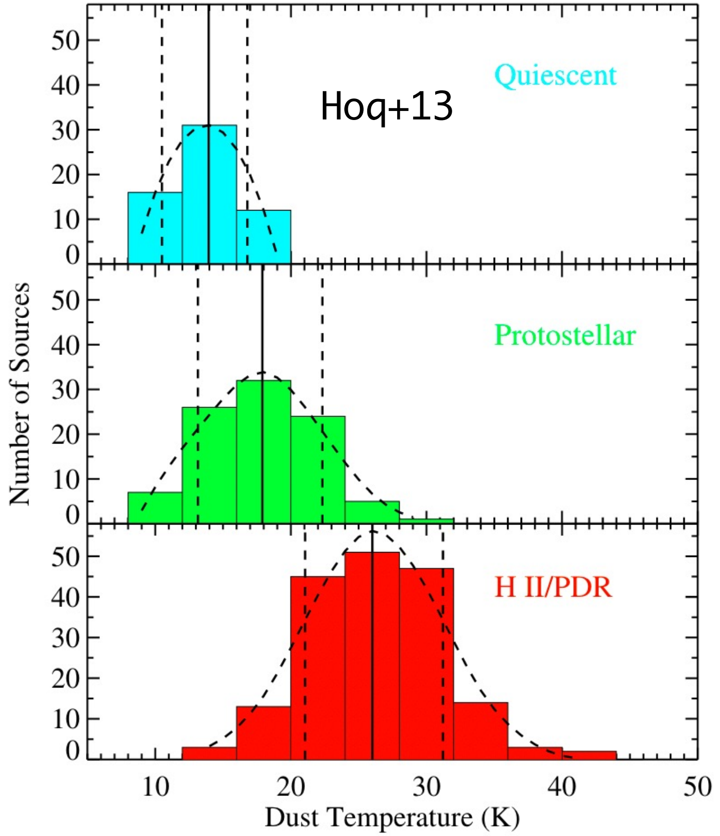
Hi-GAL #110522

Hi-GAL 70 µm



Hi-GAL 250 µm





starless/
pre-stellar
(70 µm-quiet)

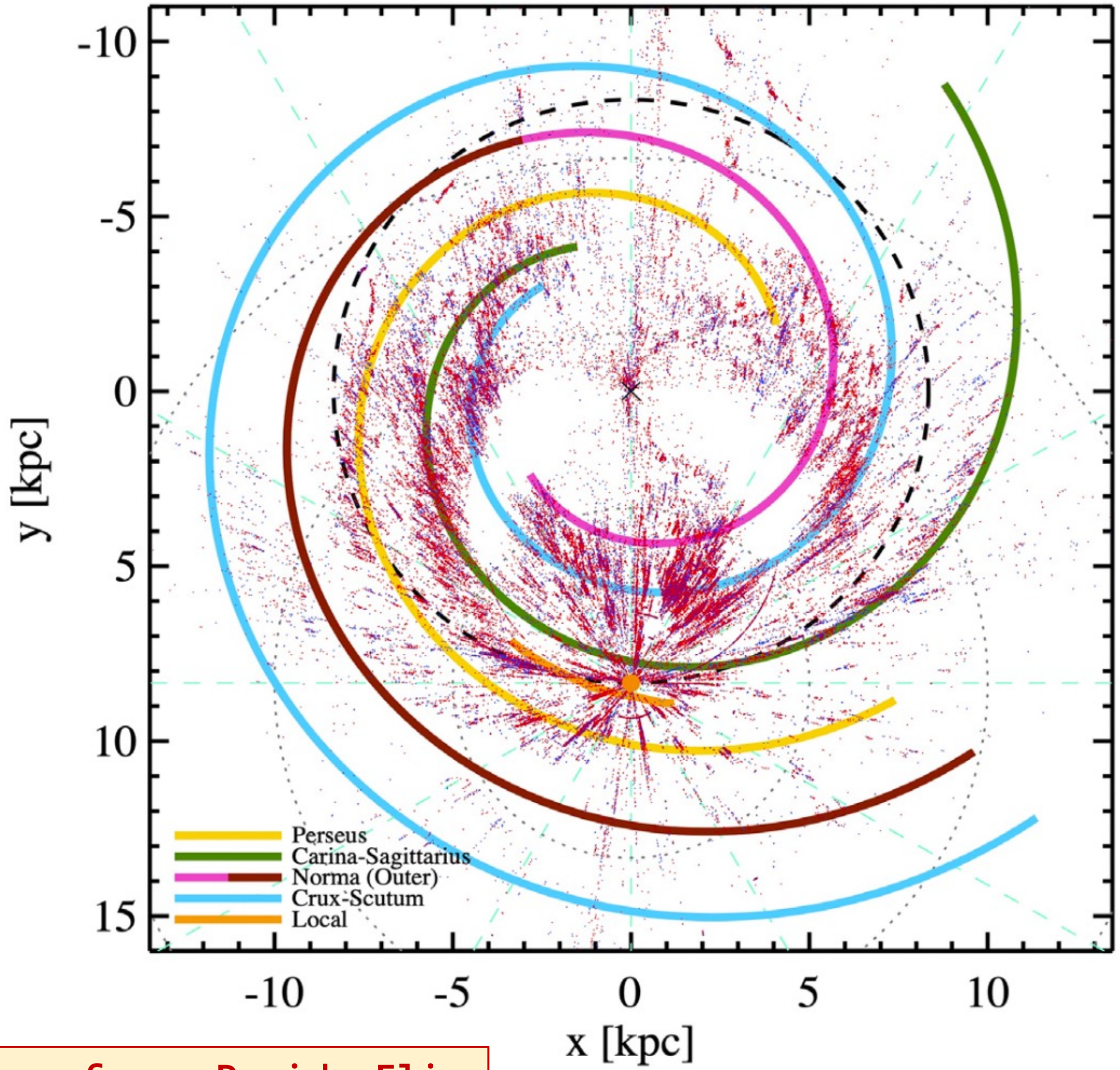
Protostellar
(70 µm-bright)

See lecture from Davide Elia

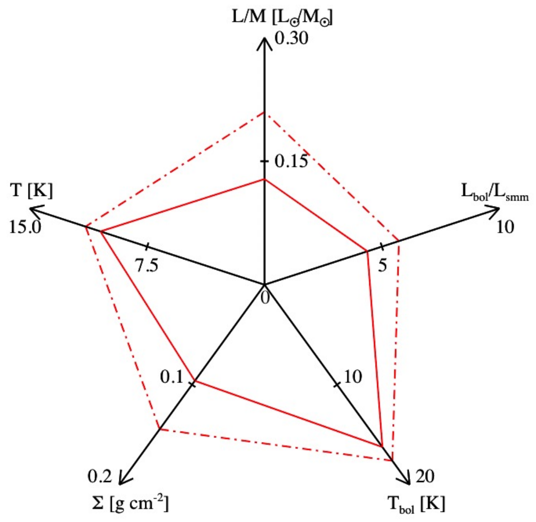
{
MIR dark
MIR/NIR bright
PDR/HII regions

Hoq+13; Urquhart+14; Svoboda+16; Traficante+18; Merello+19

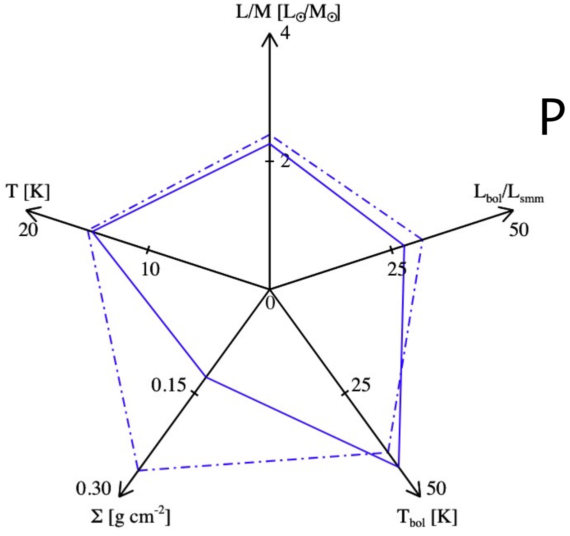
Clumps in the Galaxy



Pre-stellar



Protostellar



See lecture from Davide Elia

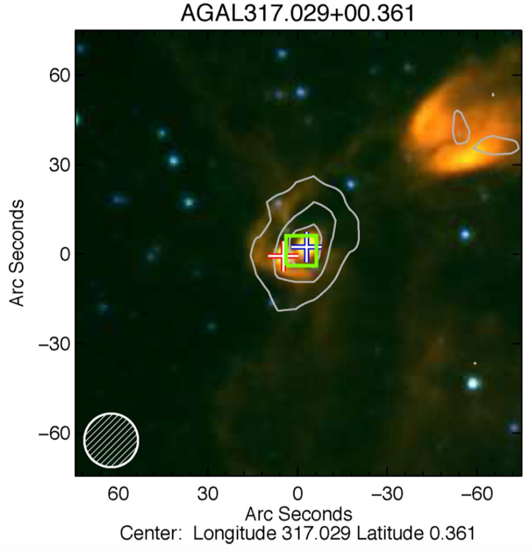
~150000 in the inner Galaxy (~200000 in the Galactic disk) !!!

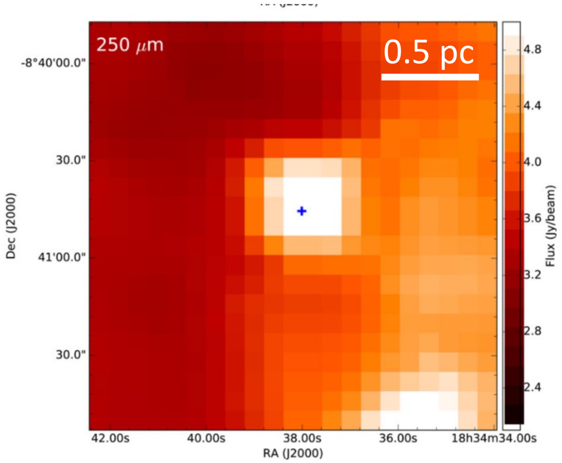
Elia+21

Clumps physical properties

GLIMPSE composite
(4.5, 5.8, 8.0 μm)
Contour:
ATLASGAL 870 μm

Urquhart+14





Hi-GAL 250 μm

Traficante+15

Properties	**GMCs**	**Filaments**	**Clumps**
Radius/Length (pc)	up to 150	up to 100	**~0.05-1**
Temperature (K)	~ 10-30	~ 10-35	**~ 10-40**
Mass ($M_\odot$)	up to few 10^6	up to few 10^5	**up to few 10^4**
Surf. density (g/cm^2)	~0.0004-0.06	~0.0005 - 0.5	**~0.01 - 10**

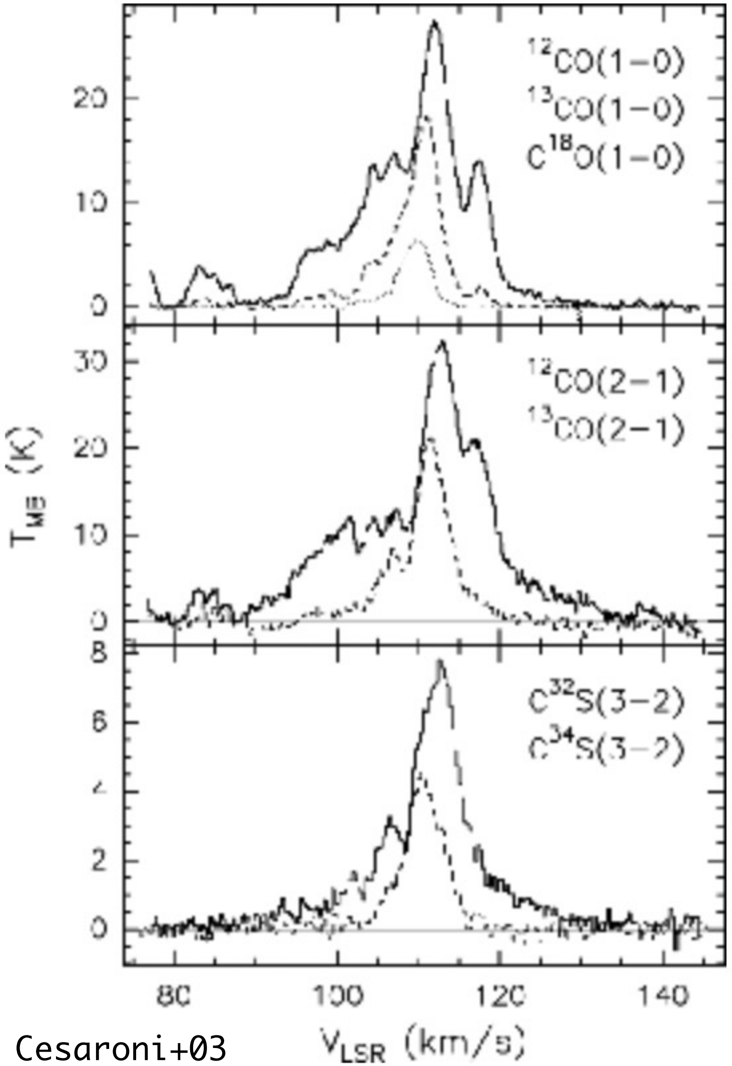
See lecture from
Davide Elia

Urquhart+14
Traficante+15
Elia+17, 21

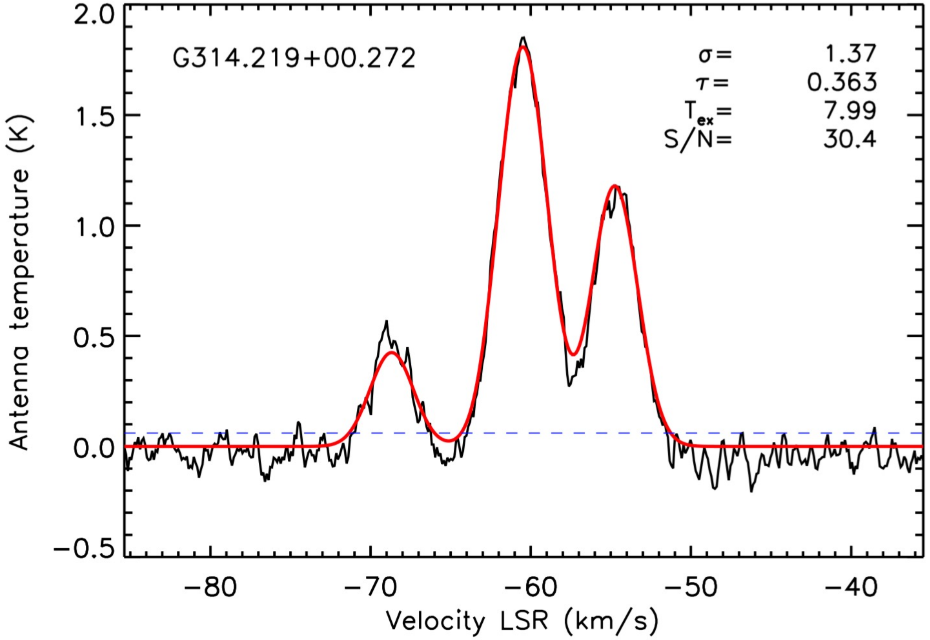
Clumps kinematics

Higher surface density compared to filaments/clouds

CO is not anymore an optically thin tracer



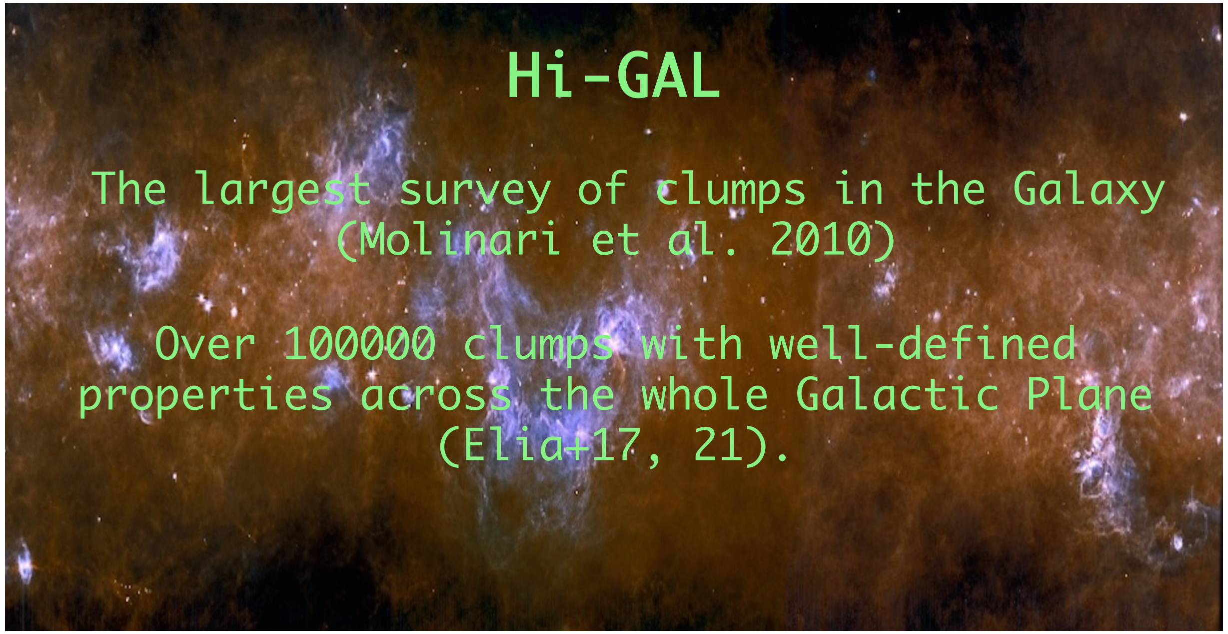
Cesaroni+03



N_2H^+ (1-0)

To get velocity dispersion σ, v_{LSR}

Clumps dynamics



Hi-GAL

The largest survey of clumps in the Galaxy (Molinari et al. 2010)

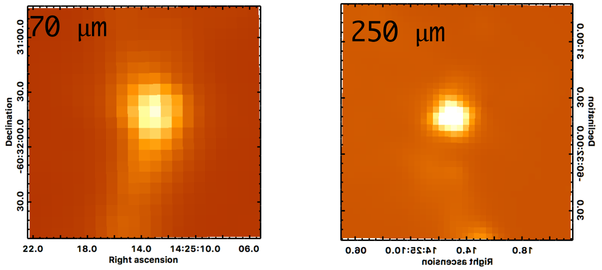
Over 100000 clumps with well-defined properties across the whole Galactic Plane (Elia+17, 21).

MALT90

The largest 90 GHz survey aimed to characterize the physical and chemical evolution of high-mass star-forming clumps

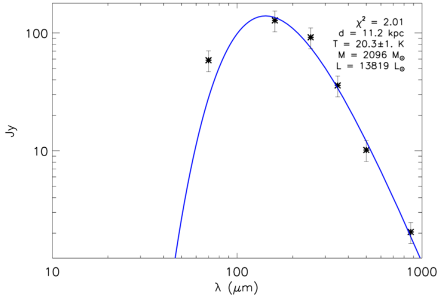
Over 2000 clumps observed in 16 molecular transitions Including N_2H^+ (1-0) and HCO^+ (1-0) (Jackson+13)

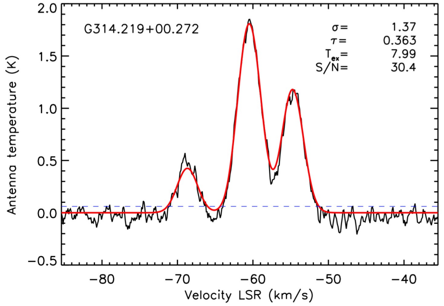
- All MALT90 clumps (2012)
- MALT90 clumps with good N_2H^+ (1-0) spectra (S/N≥5)
- MALT90 clumps with well-defined Hi-GAL distances (l≥10°)
- Hi-GAL clumps with well defined dust SED ($24 \leq \lambda \leq 870$) µm and gas emission properties



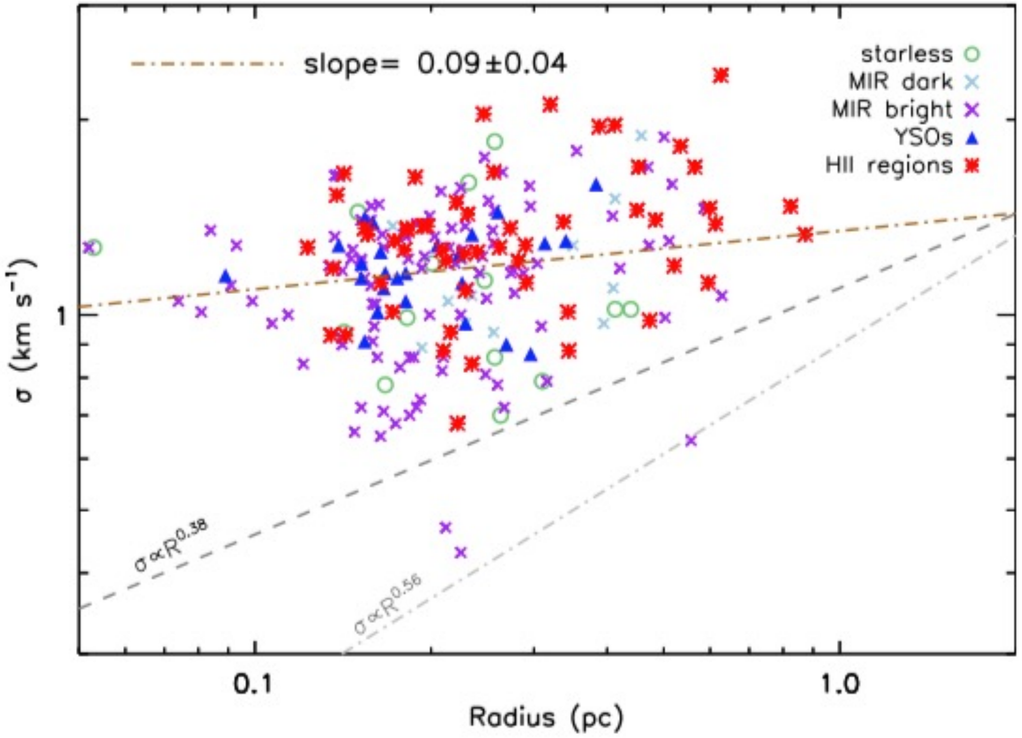
213 clumps

Traficante+18b





Clumps dynamics

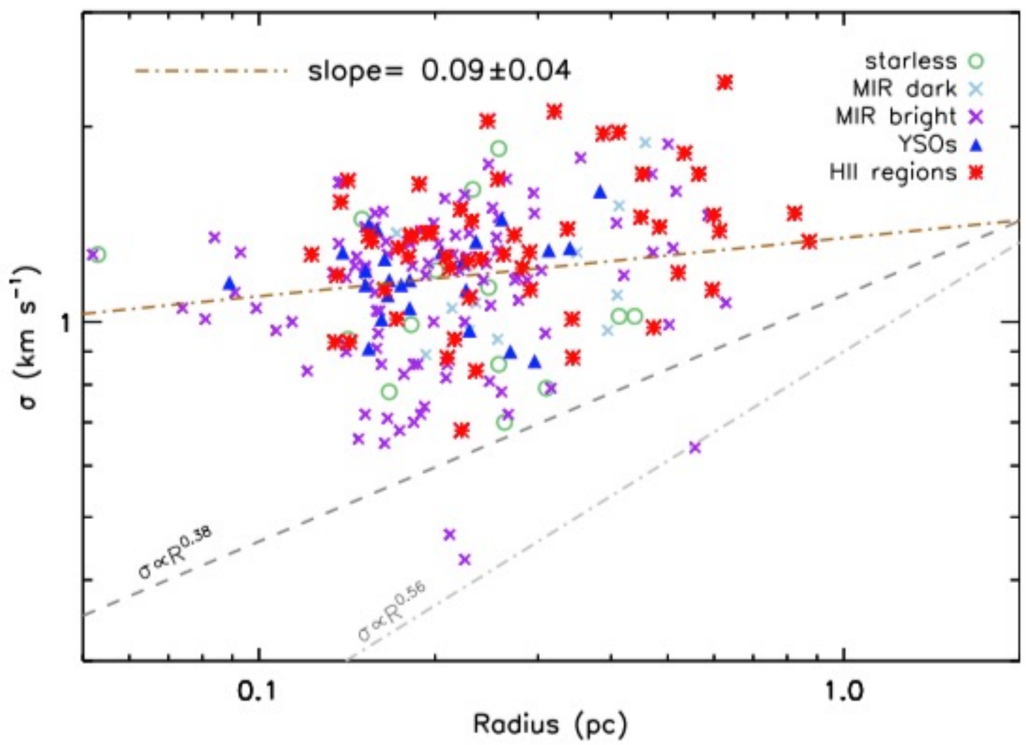


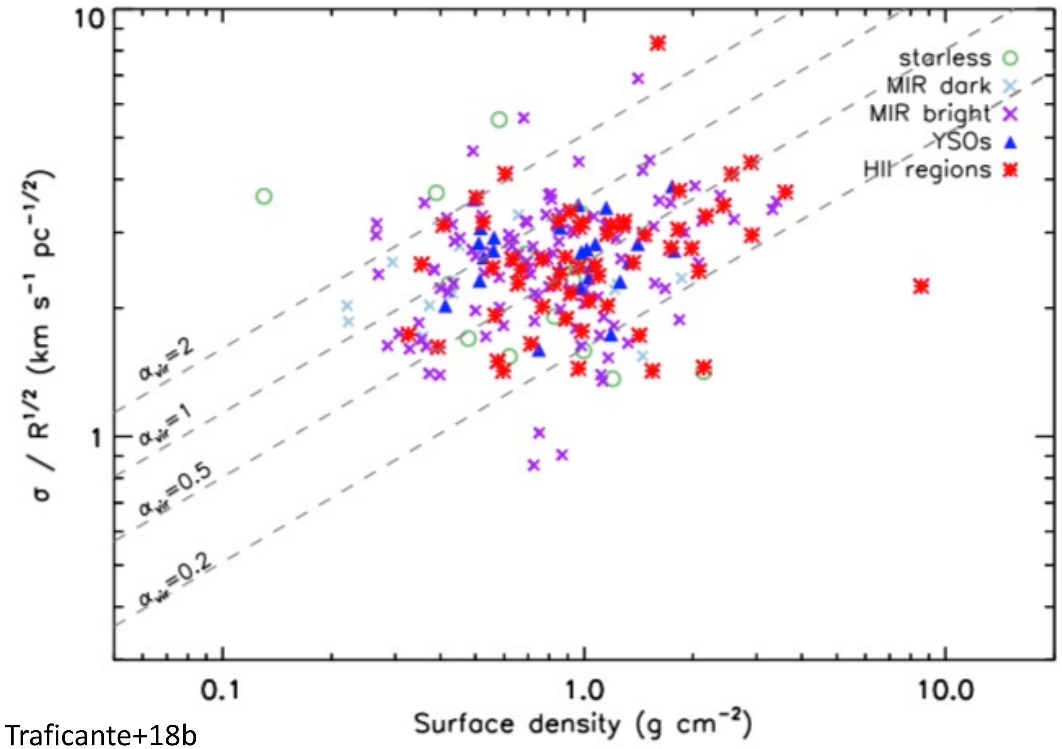
Traficante+18b

$\sigma \cancel{\propto} R$

Traficante+18b

Clumps dynamics





Traficante+18b

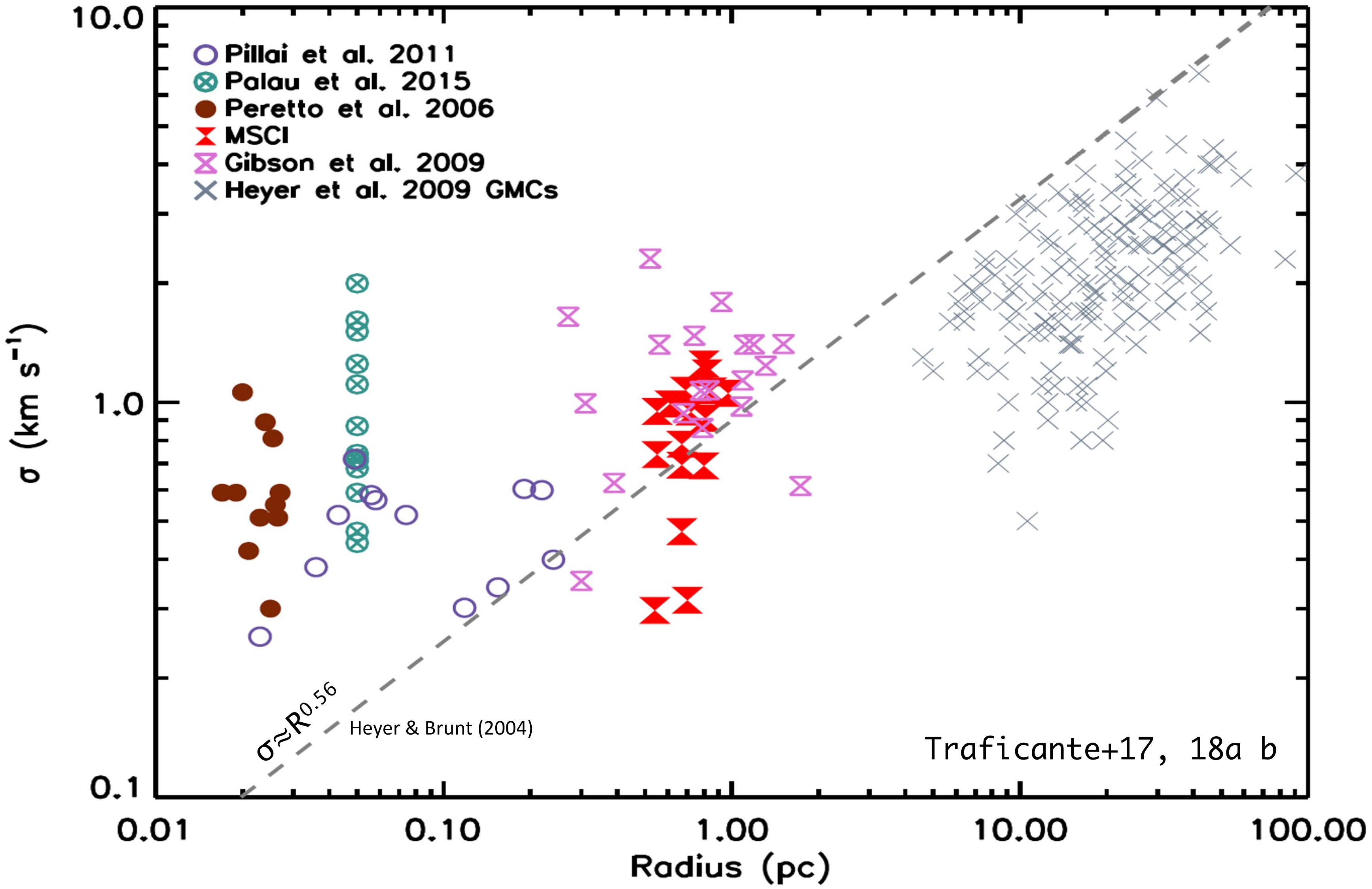
$\sigma \cancel{\propto}$ R and σ/R $\not\propto$ Σ in massive clumps at all evolutionary phases

Traficante+18b

Star-forming regions, clumps and cores - outline

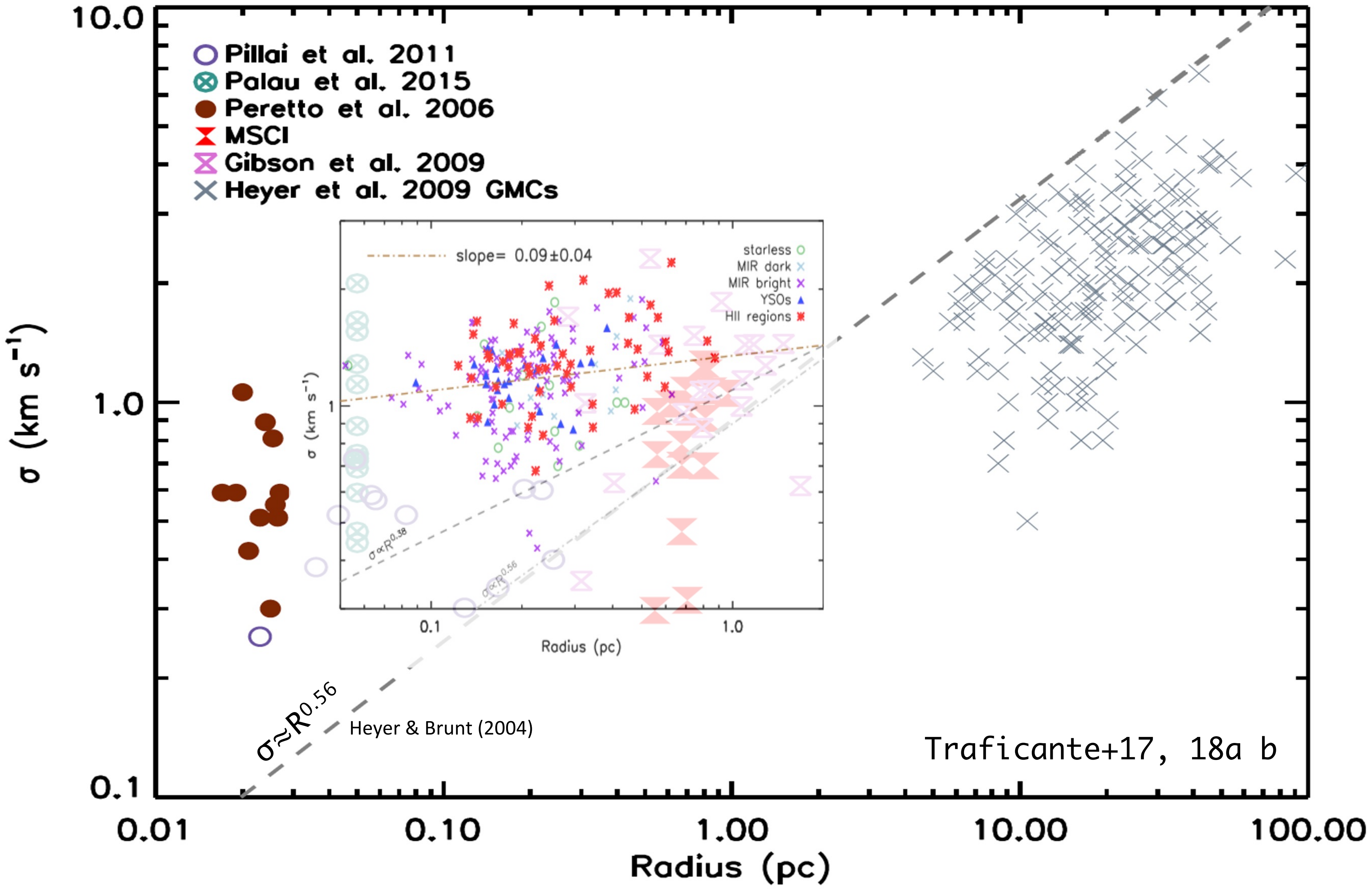
- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: physical properties, dynamics and (partial?) collapse
- From MCs to filaments: the densest regions of molecular clouds
- Pc-scales clumps: the nursery home of stars and protoclusters
- Gas dynamics in filament and clumps: the role of environment

Clumps dynamics in context

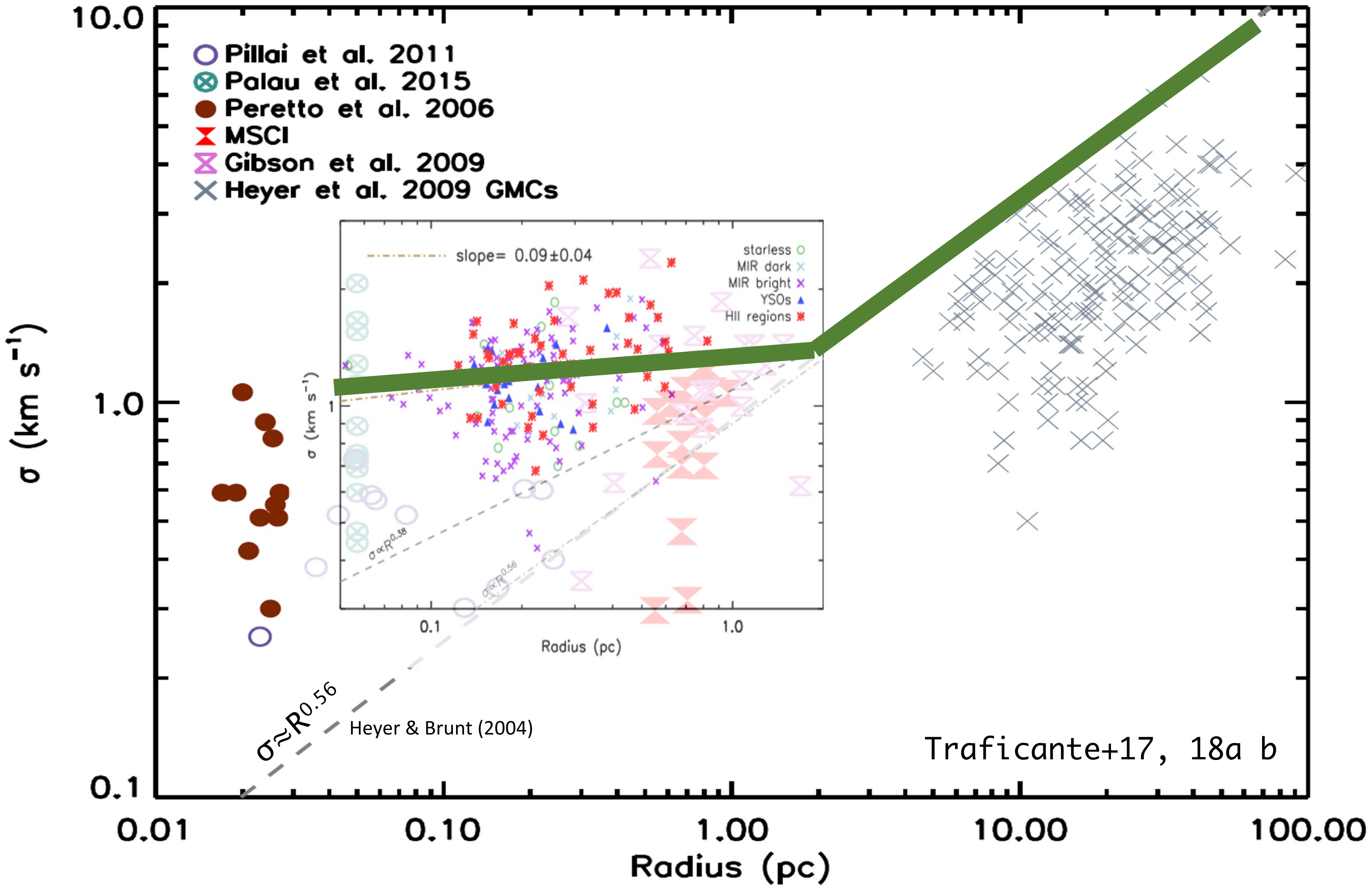


Traficante+17, 18a b

Clumps dynamics in context



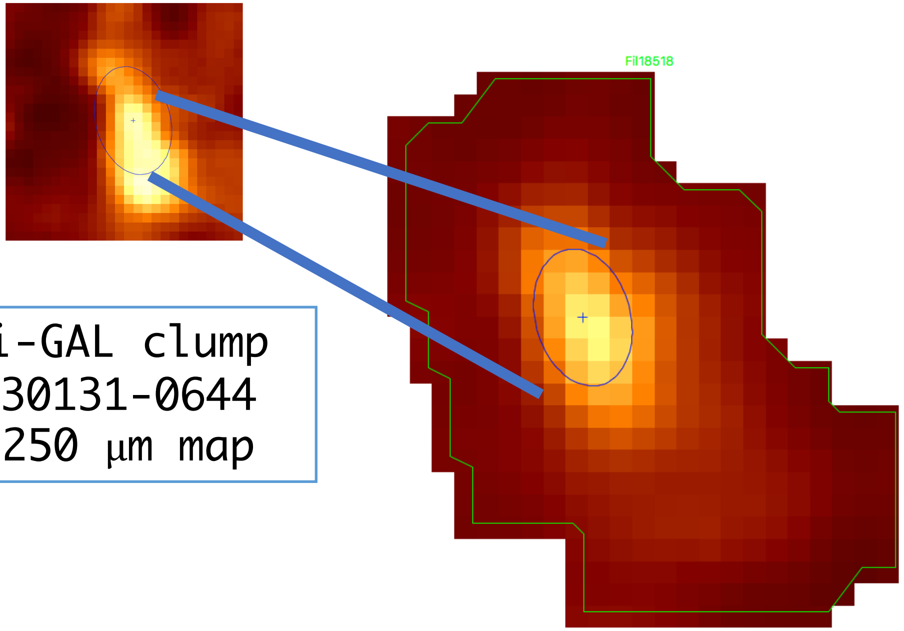
Clumps dynamics



But such a scatter…could it be the role of environment?

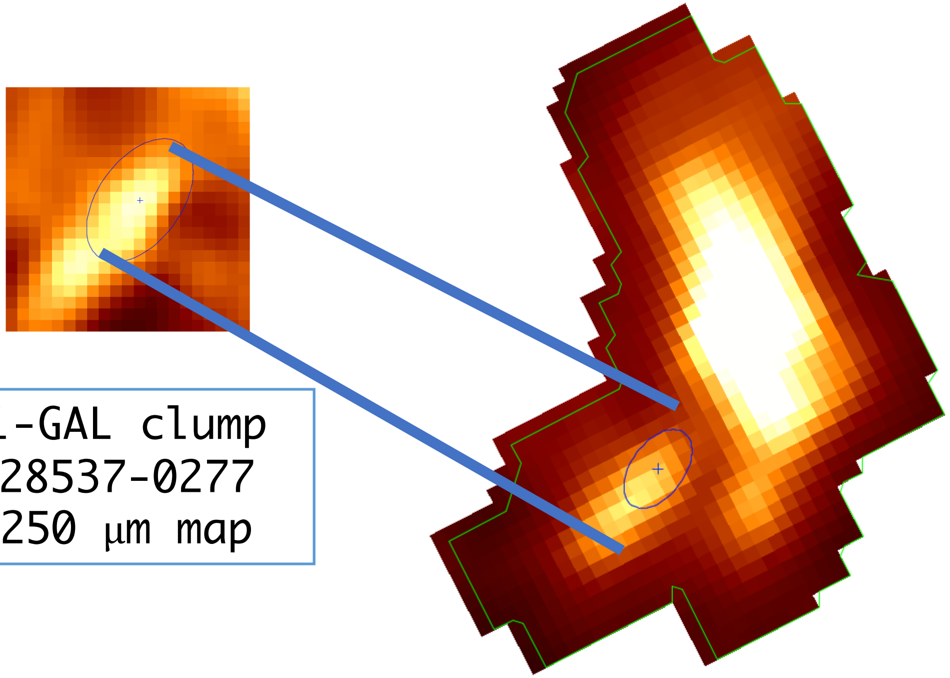
Filament to clumps dynamics

- **Hi-GAL clumps** in the Traficante+17, 18a, Elia+17 catalogues
- **Hi-GAL filaments** in the Schisano+20 catalogue



Hi-GAL clump
30131-0644
250 μm map

Hi-GAL filament Fil18518
Column density map

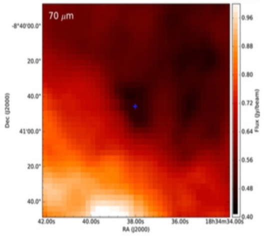


Hi-GAL clump
28537-0277
250 μm map

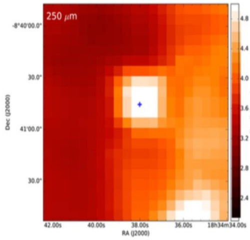
Hi-GAL filament Fil20491
Column density map

Filament to clumps dynamics

70µm-quiet
clumps

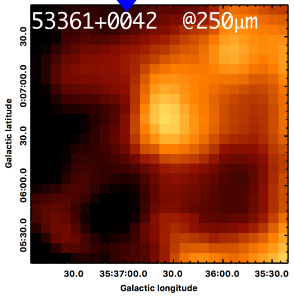


70 µm



250 µm

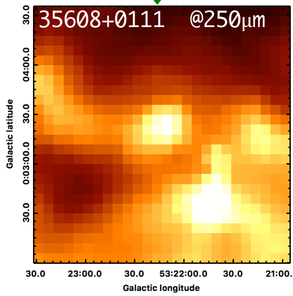
- L/M < 1
- ~NO feedback



6 clumps

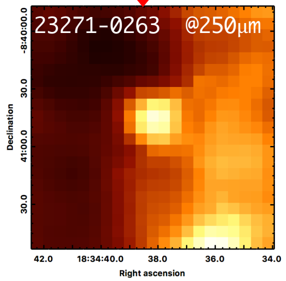
$\Sigma_l < 0.05$ g cm^{-2}
Low

e.g. Urquhart+ 2014



7 clumps

$0.05 \leq \Sigma_i \leq 0.1$ g cm^{-2}
Int

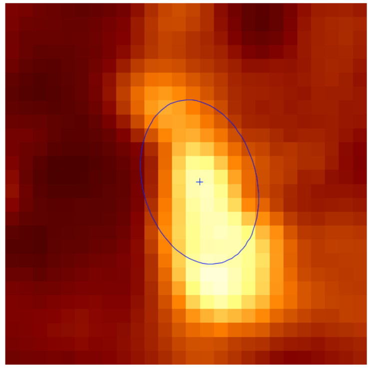


11 clumps

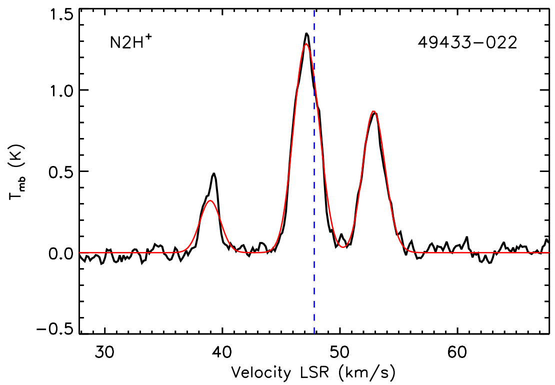
$\Sigma_h > 0.1$ g cm^{-2}
High

e.g. Tan+ 2014

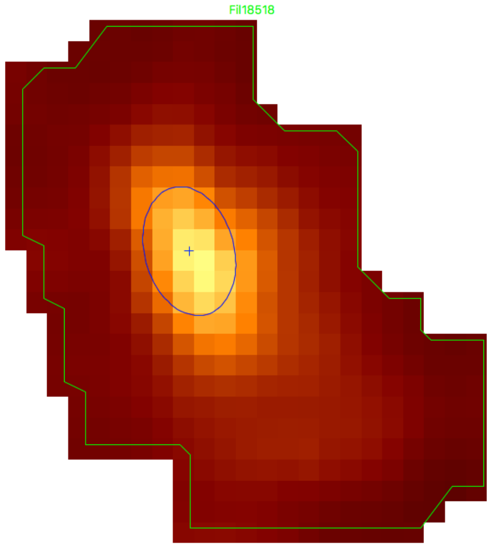
Filament to clumps dynamics



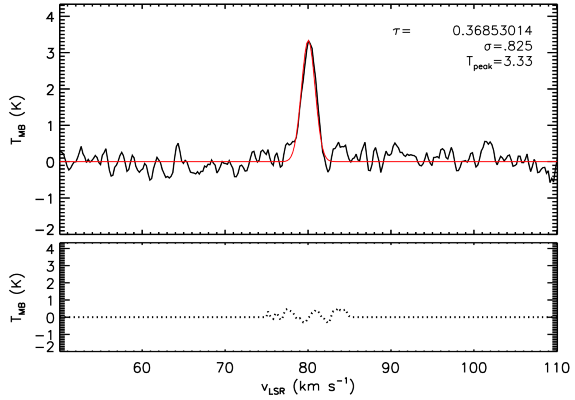
Clump-scale kinematics from N_2H^+ (1-0) observations



IRAM 30m, Traficante+17, 18a



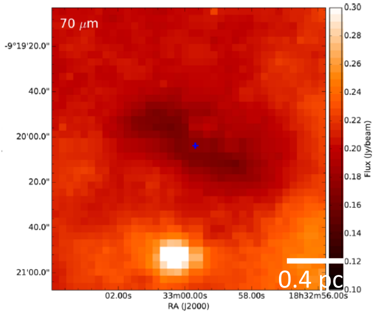
Cloud-scale kinematics from ^{13}CO (1-0) observations



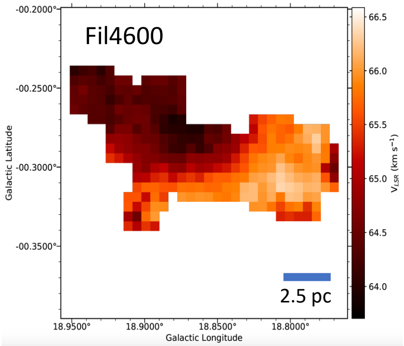
(GRS, Jackson et al. 2013)

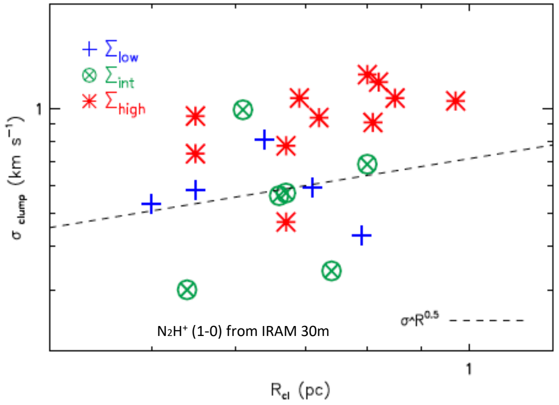
1st and 2nd moment of the map spectrum → $\langle v_{lsr} \rangle$ and $\langle \sigma \rangle$

Filament to clumps dynamics: the role of environment

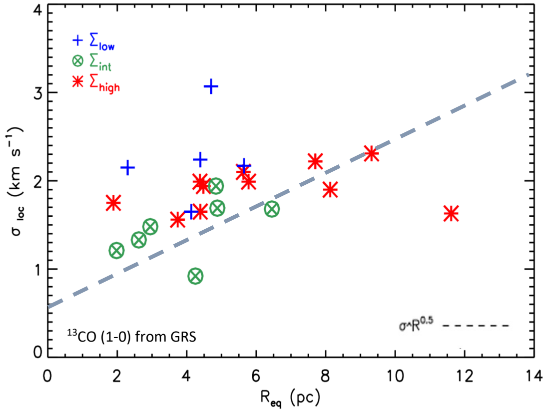


+

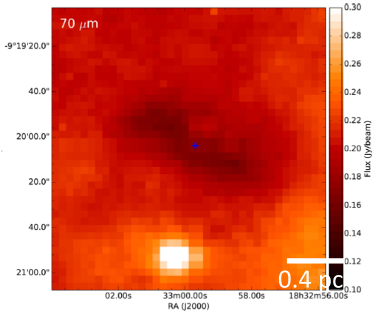




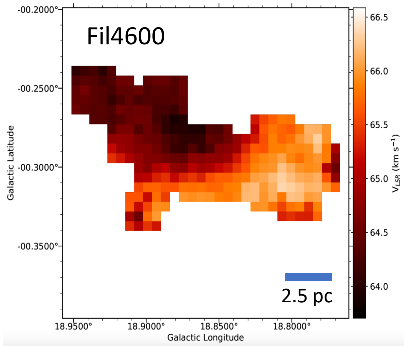
+

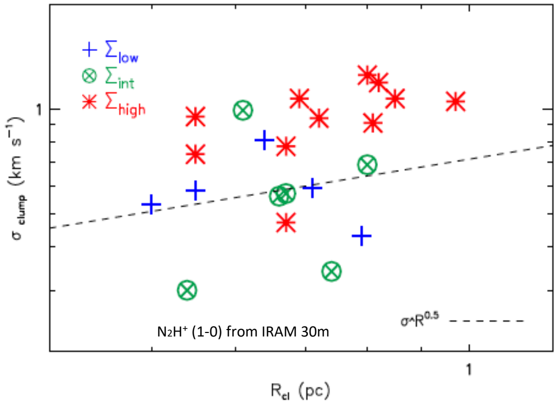


Filament to clumps dynamics: the role of environment

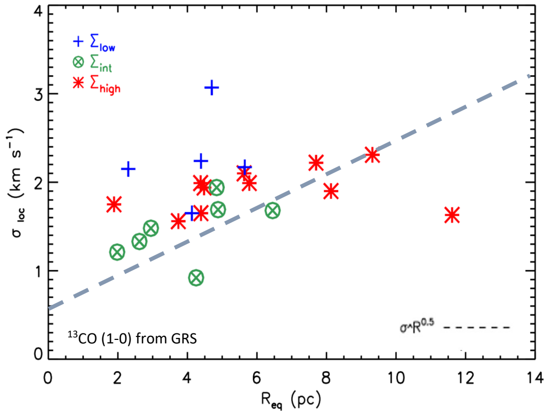


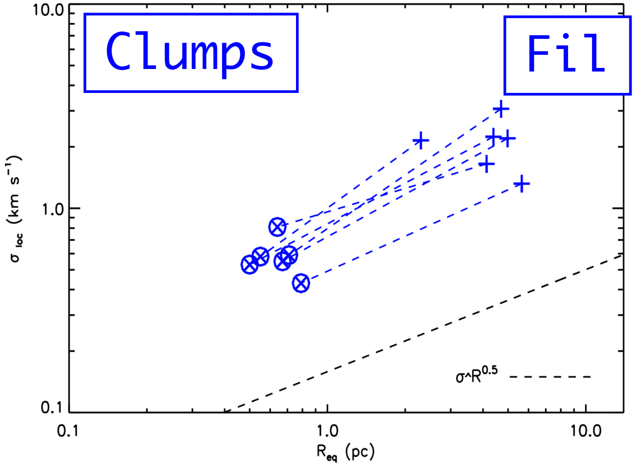
+



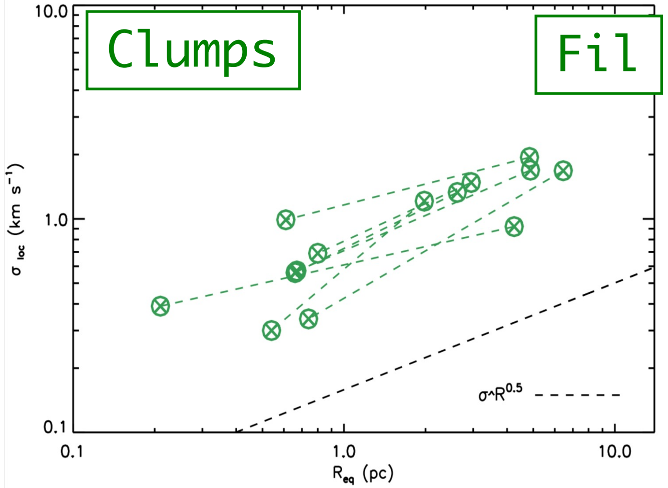


+

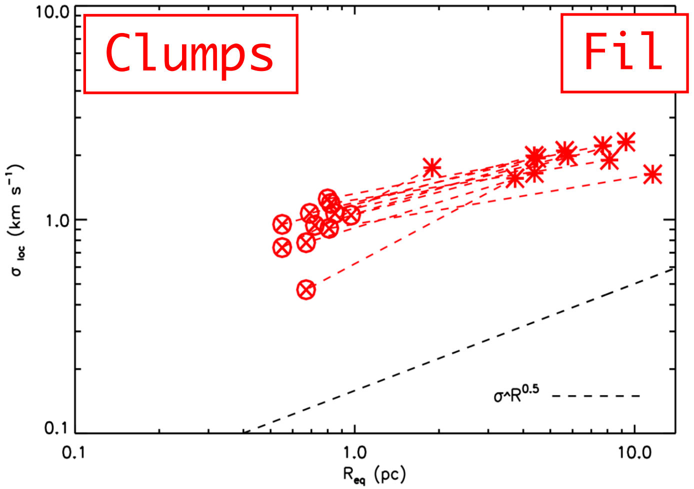




$\sigma \sim R^{0.68}$



$\sigma \sim R^{0.60}$

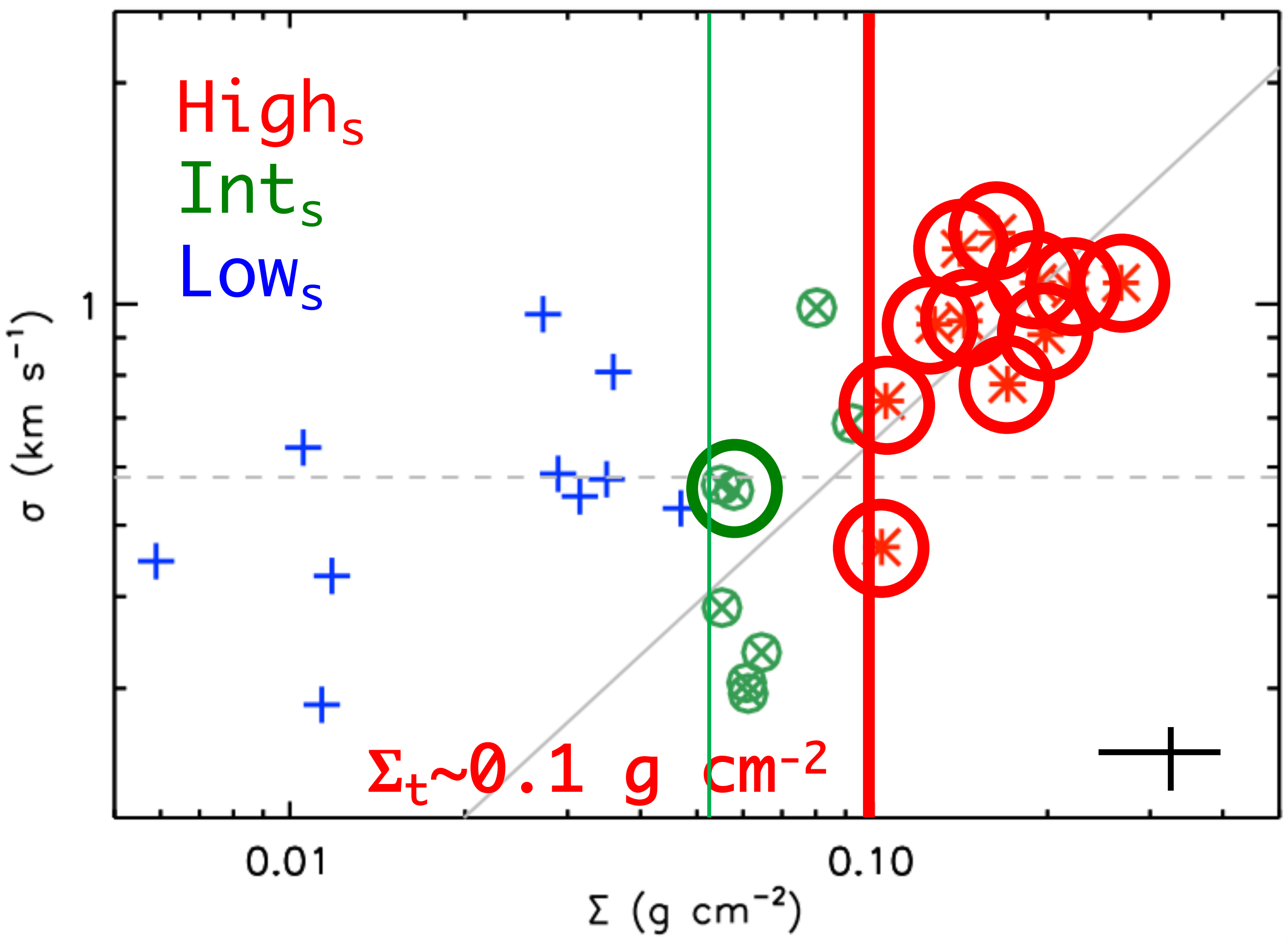


$\sigma \sim R^{0.38}$

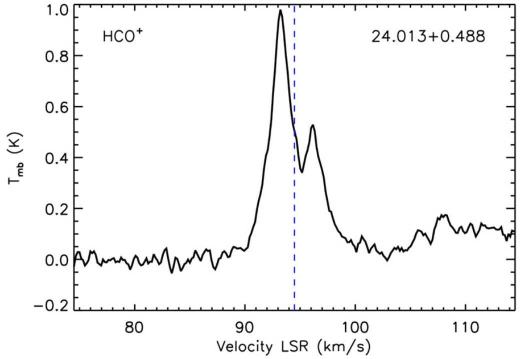
$\sigma \sim R^{0.7}$ in Taurus region
Fuller & Myers (1992)

Traficante+2020

Filament to clumps dynamics: the role of environment

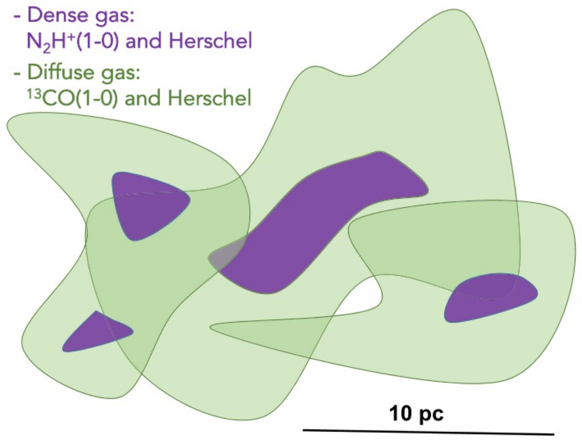


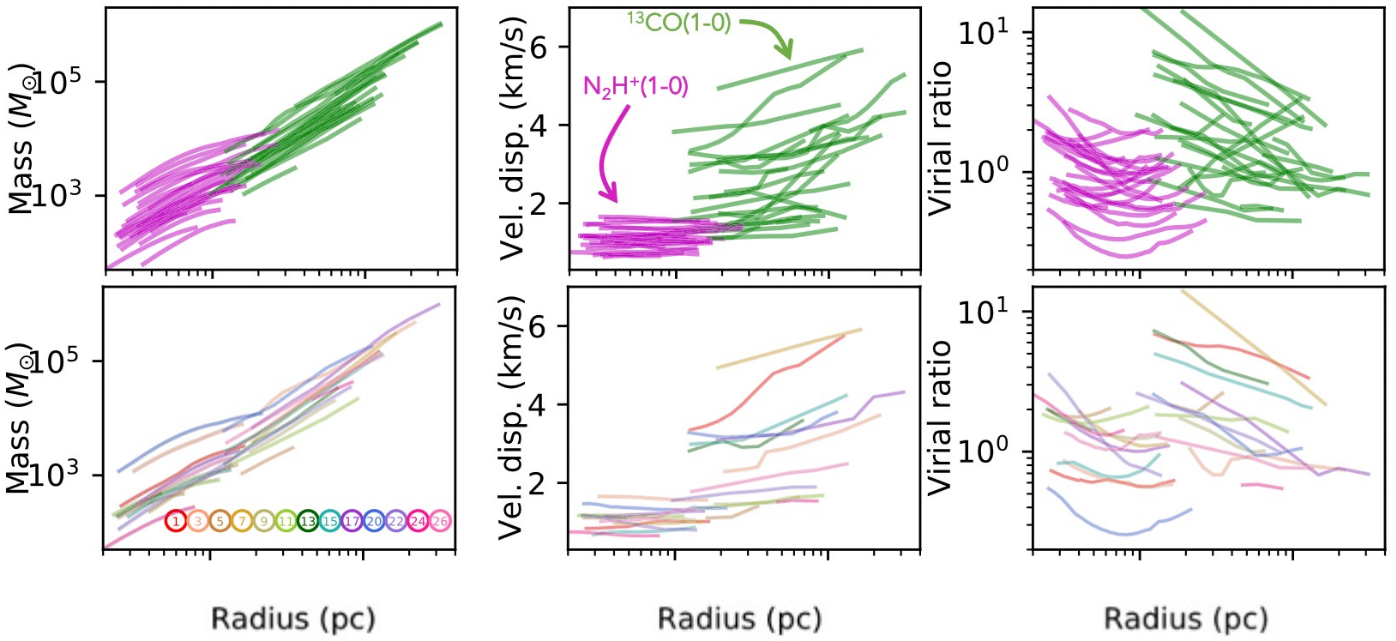
Traficante+20



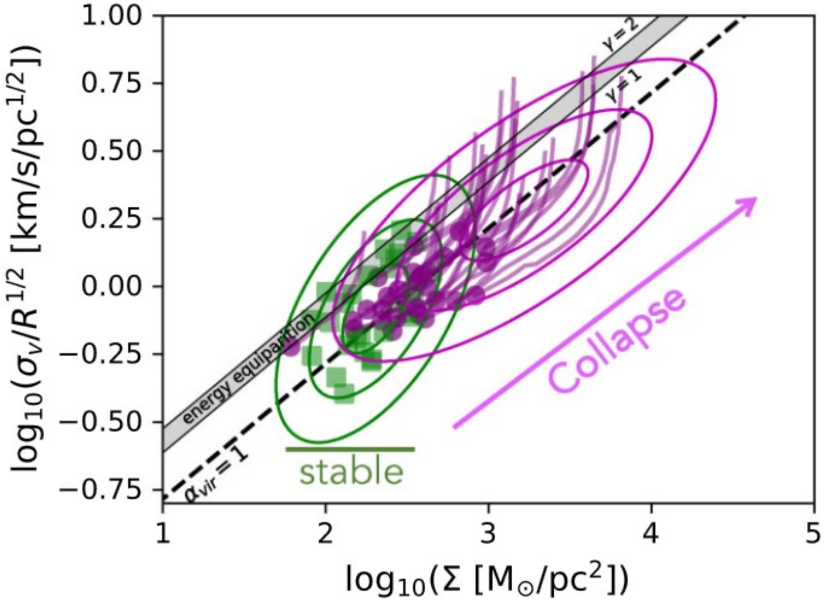
○ Clumps with evidence of dynamical activity and/or gravitationally driven motions (**infall**) at the pc scales (asymmetric HCO$^+$ spectra)

Filament to clumps dynamics: the role of environment



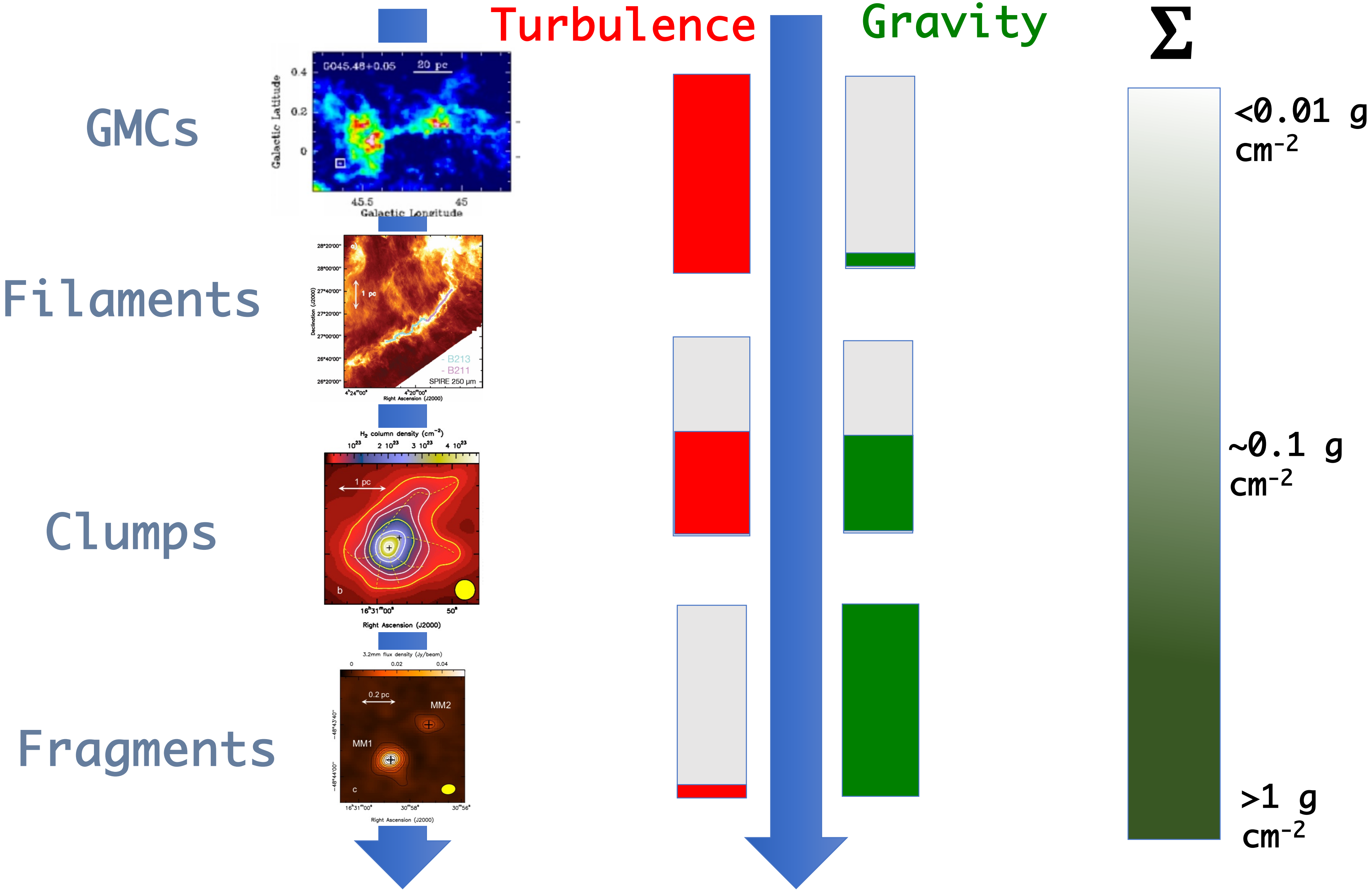


Dynamically decoupled clumps from progenitor IRDCs



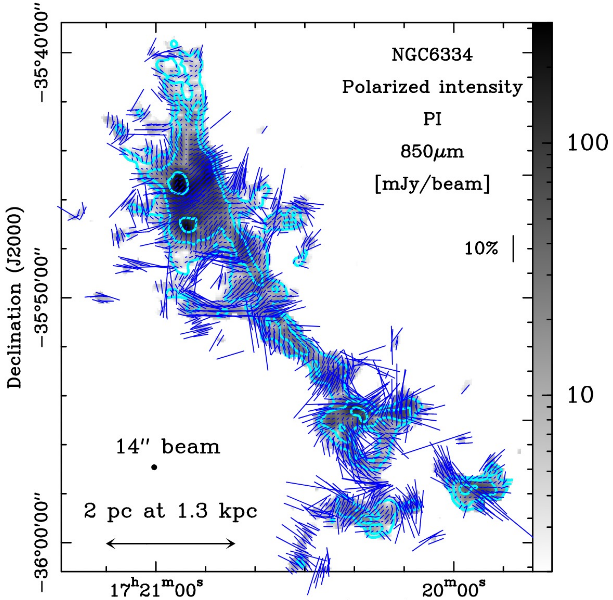
Peretto+23

On the interplay between gravity and turbulence

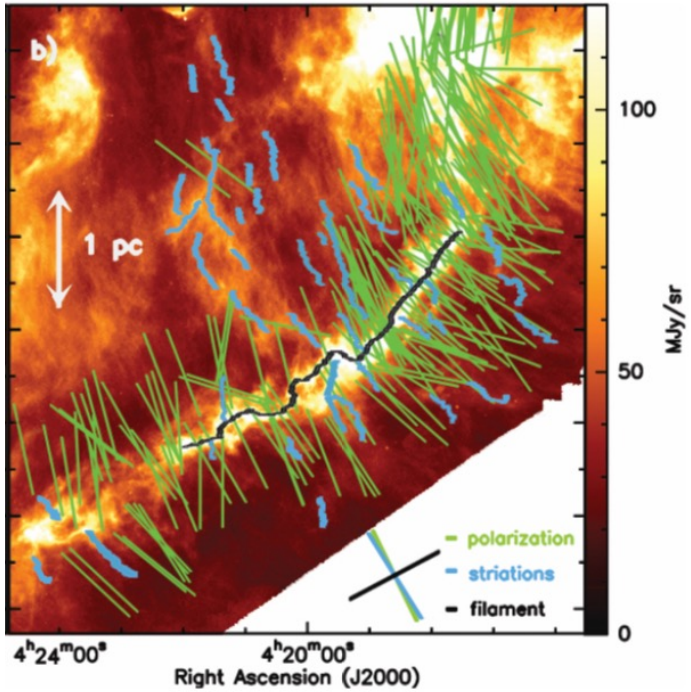


Traficante+2020

The elephant in the room: magnetic fields



Arzoumanian+21, NGC6334 (BISTRO survey)



Palmeirim+13, Taurus B211

Changing of orientation with column density (e.g. Soler+19) or above certain spatial scales (Doi+20), from = to mostly ⊥

Does the orientation correlate with SFR?

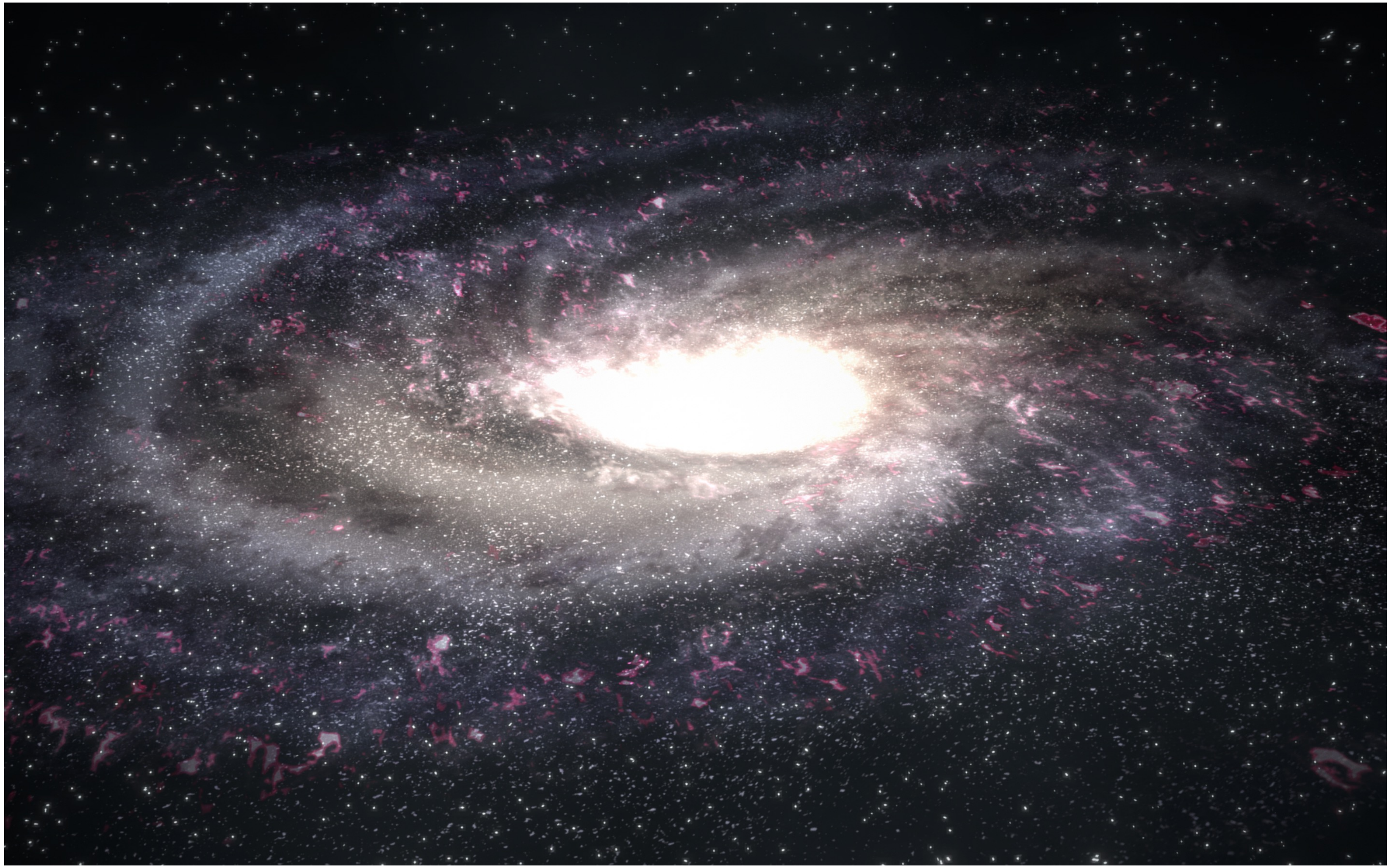
YES (Li+17)

NO (Soler+19)

EXTRA slides

Molecular clouds in free-fall?

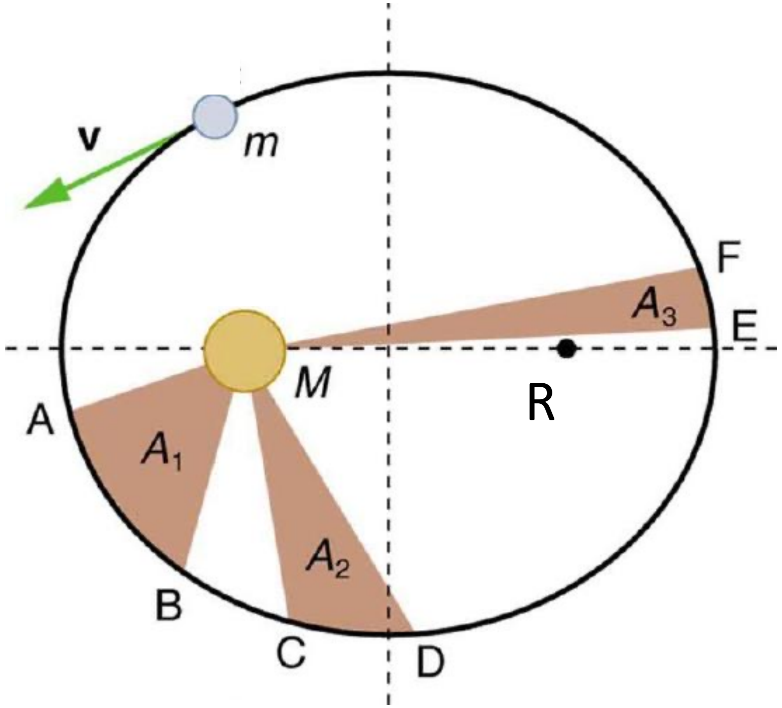
Our Milky Way



Molecular clouds from CO: physical an dynamical properties

<u>Kepler's third law</u>: The ratio of the **square** of an object's orbital period T with the **cube** of the semi-major axis R of its orbit is the same for all objects orbiting the same primary.

$$\frac{R^3}{T^2} =\simeq \frac{GM}{4\pi^2}$$



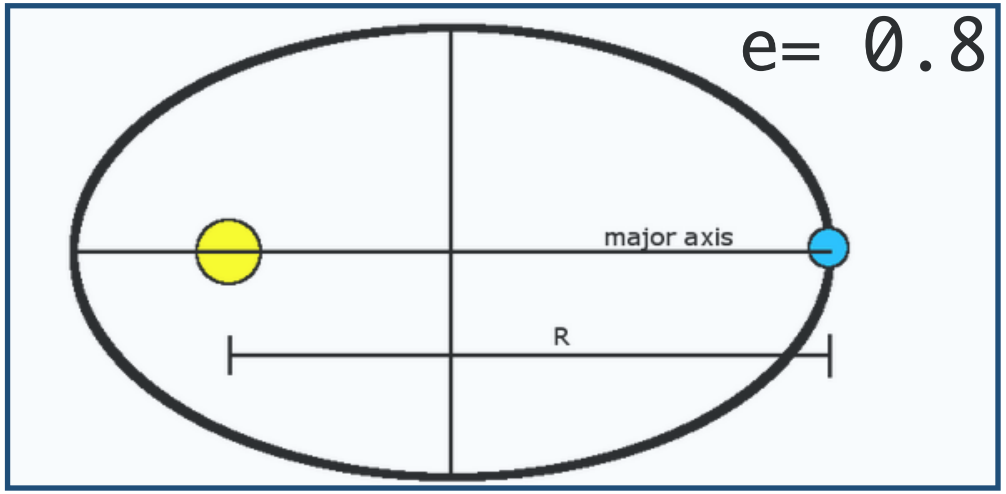
Molecular clouds from CO: physical an dynamical properties

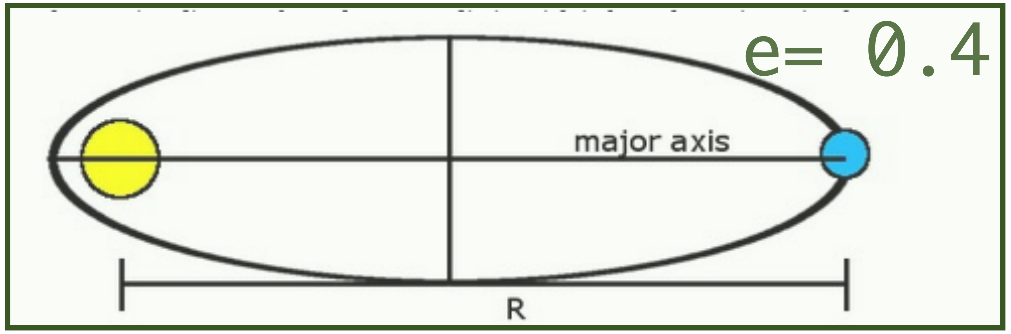
Kepler's third law: The ratio of the **square** of an object's orbital period T with the **cube** of the semi-major axis R of its orbit is the same for all objects orbiting the same primary.

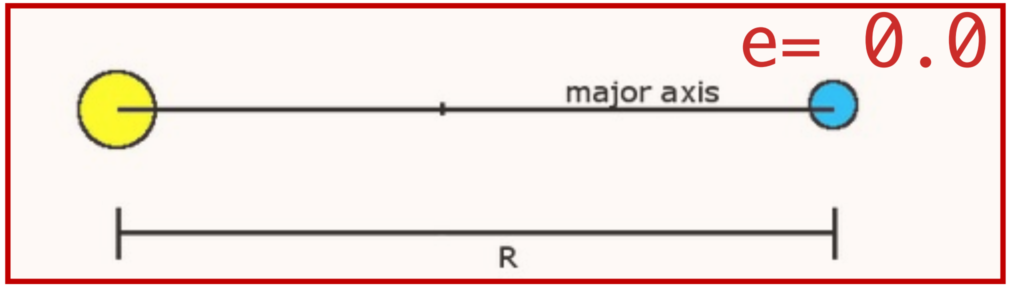
$$\frac{R^3}{T^2} =\simeq \frac{GM}{4\pi^2}$$

This law does NOT depend on the eccentricity "e" of the orbit. Therefore, in case of e = 0:

Semi-major axis = R/2







Molecular clouds from CO: physical an dynamical properties

Kepler's third law: The ratio of the **square** of an object's orbital period T with the **cube** of the semi-major axis R of its orbit is the same for all objects orbiting the same primary.

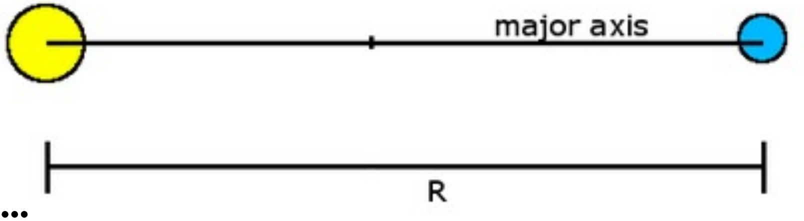
$$\frac{R^3}{T^2} =\simeq \frac{GM}{4\pi^2}$$

This law does NOT depend on the eccentricity "e" of the orbit. Therefore, in case of e = 0:

Semi-major axis = *R/2*

T = t_{orbit} and free-fall time t_{ff} = T/2

e= 0.0



If we substitute these values in the Kepler's third law…

Molecular clouds from CO: physical an dynamical properties

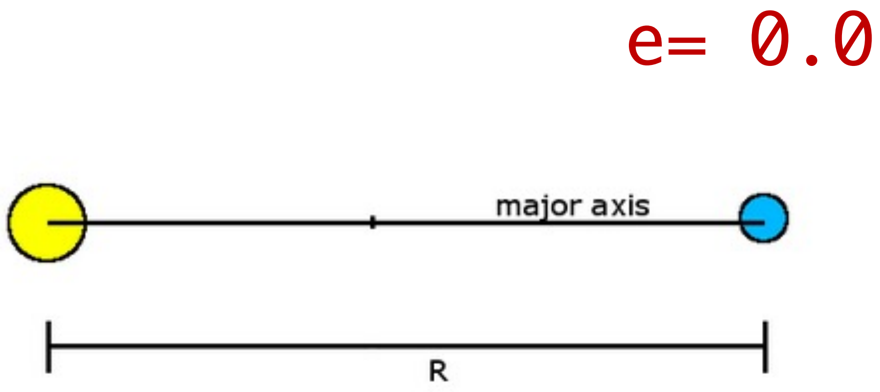
Kepler’s third law: The ratio of the **square** of an object’s orbital period T with the **cube** of the semi-major axis R of its orbit is the same for all objects orbiting the same primary.

$$\frac{R^3}{T^2} \simeq \frac{GM}{4\pi^2}$$

$$\frac{(R/2)^3}{4t_{\mathrm{ff}}^2} \simeq \frac{GM}{4\pi^2}$$

$$\boxed{t_{\mathrm{ff}} \simeq \frac{\pi}{2}\frac{R^{3/2}}{\sqrt{2GM}}}$$

Semi-major axis = R/2
free-fall time t_{ff} = T/2



Molecular clouds from CO: physical an dynamical properties

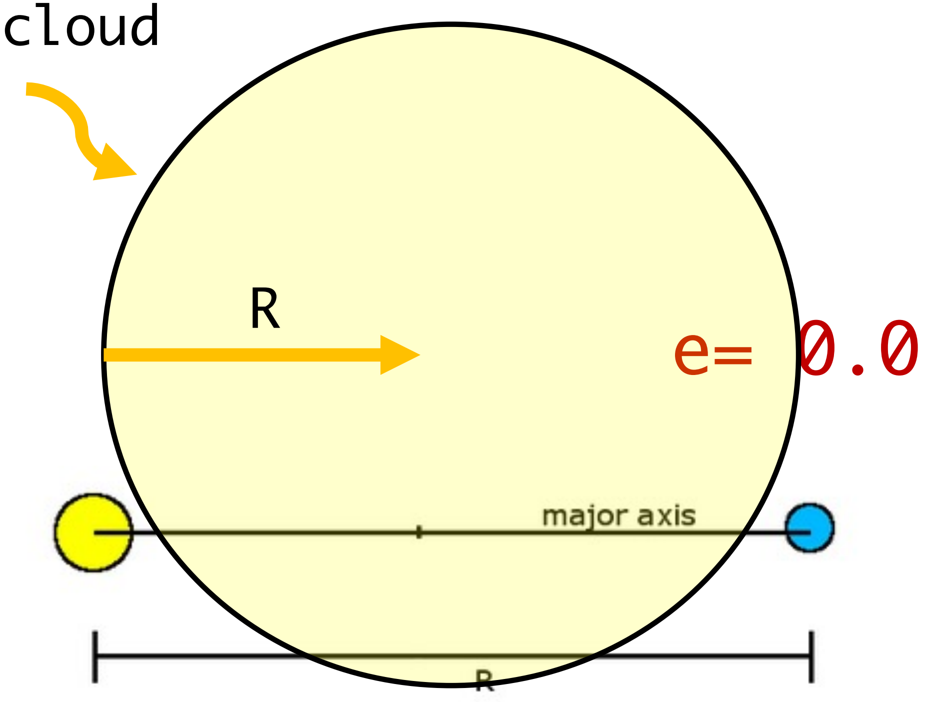
Kepler's third law: The ratio of the **square** of an object's orbital period T with the **cube** of the semi-major axis R of its orbit is the same for all objects orbiting the same primary.

$$\left\{\begin{aligned} &\frac{R^3}{T^2} \simeq \frac{GM}{4\pi^2} \\ &\frac{(R/2)^3}{4t_{\rm ff}^2} \simeq \frac{GM}{4\pi^2} \\ &\boxed{t_{\rm ff} \simeq \frac{\pi}{2}\frac{R^{3/2}}{\sqrt{2GM}}} \end{aligned}\right.$$

Semi-major axis = R/2
free-fall time t_{ff} = T/2

Gravity only is acting

Our cloud



Molecular clouds from CO: physical an dynamical properties

Kepler's third law: The ratio of the **square** of an object's orbital period T with the **cube** of the semi-major axis R of its orbit is the same for all objects orbiting the same primary.

$$\frac{R^3}{T^2} \simeq \frac{GM}{4\pi^2}$$

Semi-major axis = R/2
free-fall time t_{ff} = T/2

Gravity only is acting

$$\frac{(R/2)^3}{4t_{\mathrm{ff}}^2} \simeq \frac{GM}{4\pi^2}$$

$$\boxed{t_{\mathrm{ff}} \simeq \frac{\pi}{2}\frac{R^{3/2}}{\sqrt{2GM}}}$$

The total mass M contained in a radius R gives a density ρ

$$\rho = \frac{3M}{4\pi R^3}$$

Molecular clouds from CO: physical an dynamical properties

Kepler's third law: The ratio of the **square** of an object's orbital period T with the **cube** of the semi-major axis R of its orbit is the same for all objects orbiting the same primary.

$$t_{\rm ff} \simeq \frac{\pi}{2}\frac{R^{3/2}}{\sqrt{2GM}} \quad + \quad \rho = \frac{3M}{4\pi R^3}$$

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho}}$$

The free-fall time $t_{\rm ff}$ of a cloud with mass M and radius R depends ONLY on its mean density ρ

HI: the building block of SF regions

HI is the main reservoir of gas which ultimately will form the molecular clouds

If the atomic ISM is in:

- thermal equilibrium
- pressure balance

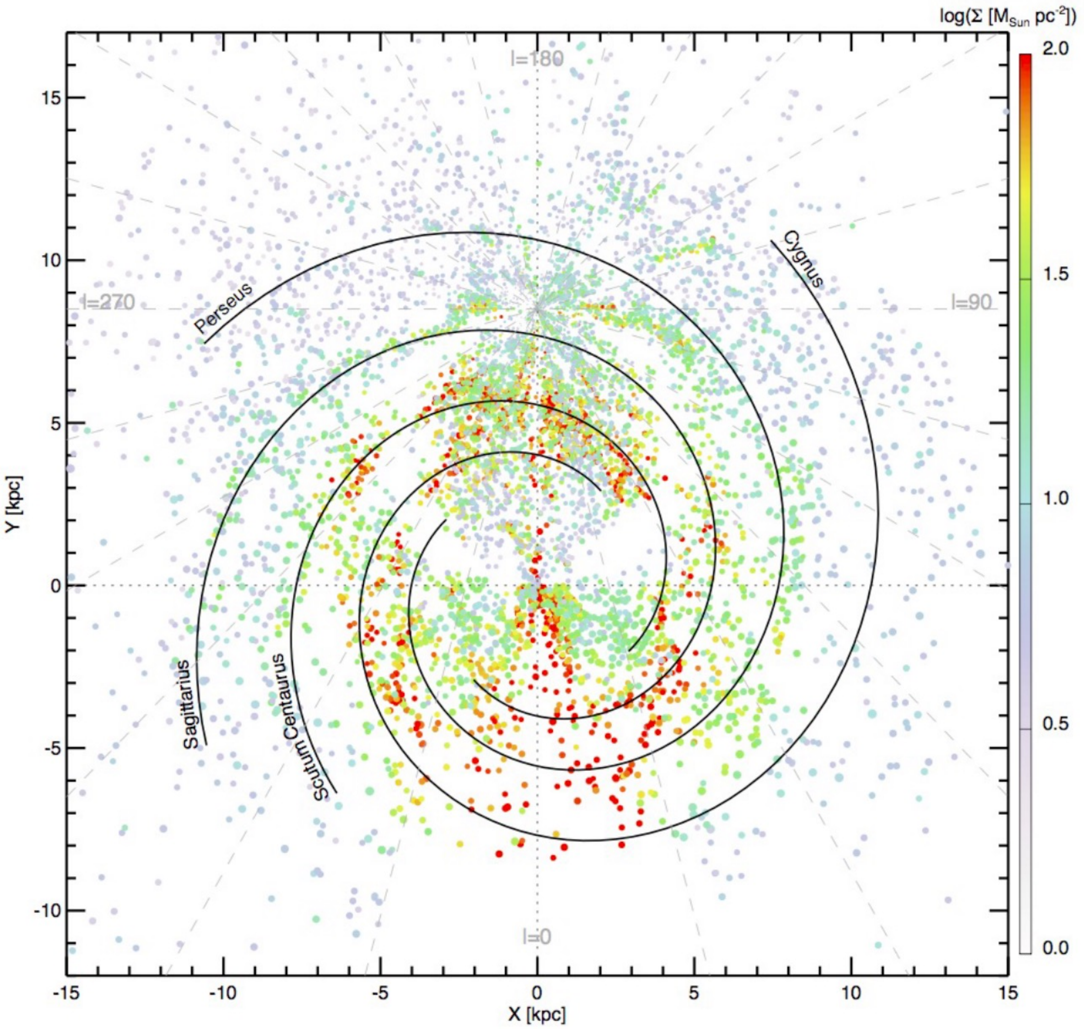
→

2 thermally **stable** solutions (for a range of pressure):

Cold neutral medium (CNM) T~100 K

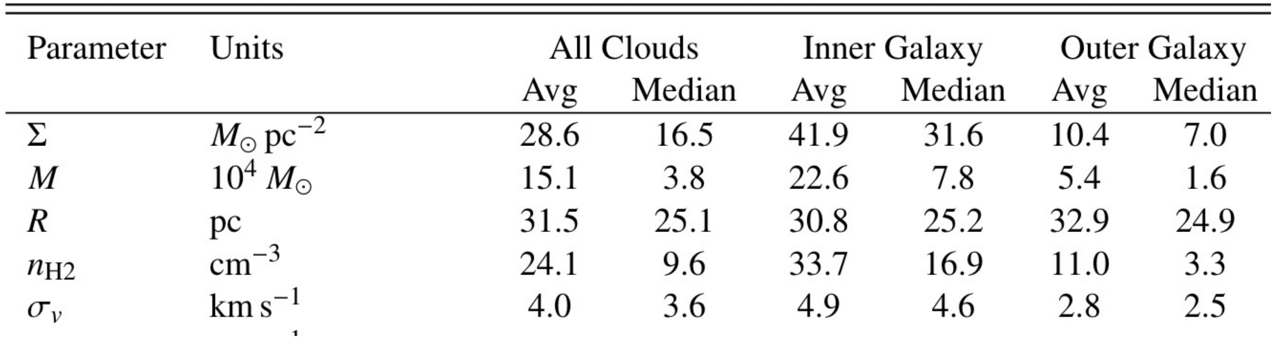
Warm neutral medium (WNM) T~8000 K

Molecular clouds from CO: physical and dynamical properties



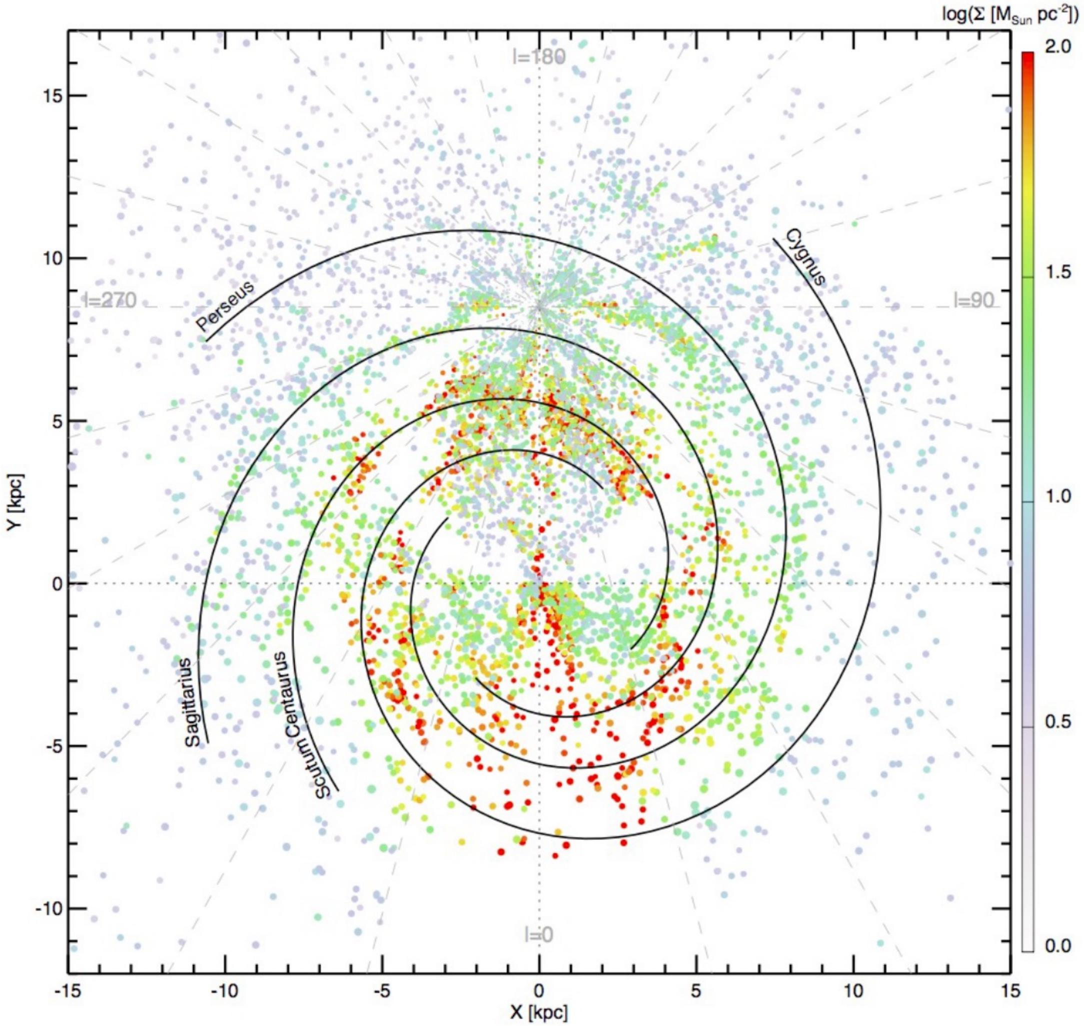
8107 “molecular clouds”

Miville-Dechenes+17



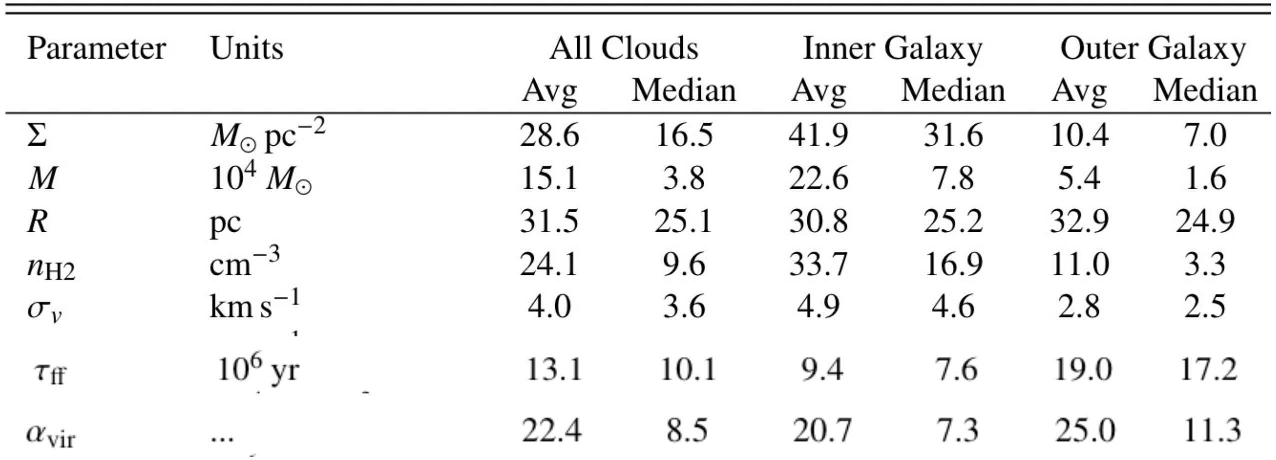
Parameter	Units	All Clouds		Inner Galaxy		Outer Galaxy	
		Avg	Median	Avg	Median	Avg	Median
Σ	$M_\odot$ pc^{-2}	28.6	16.5	41.9	31.6	10.4	7.0
M	$10^4\ M_\odot$	15.1	3.8	22.6	7.8	5.4	1.6
R	pc	31.5	25.1	30.8	25.2	32.9	24.9
$n_{\rm H2}$	cm^{-3}	24.1	9.6	33.7	16.9	11.0	3.3
σ_v	km s^{-1}	4.0	3.6	4.9	4.6	2.8	2.5

Molecular clouds from CO: physical and dynamical properties



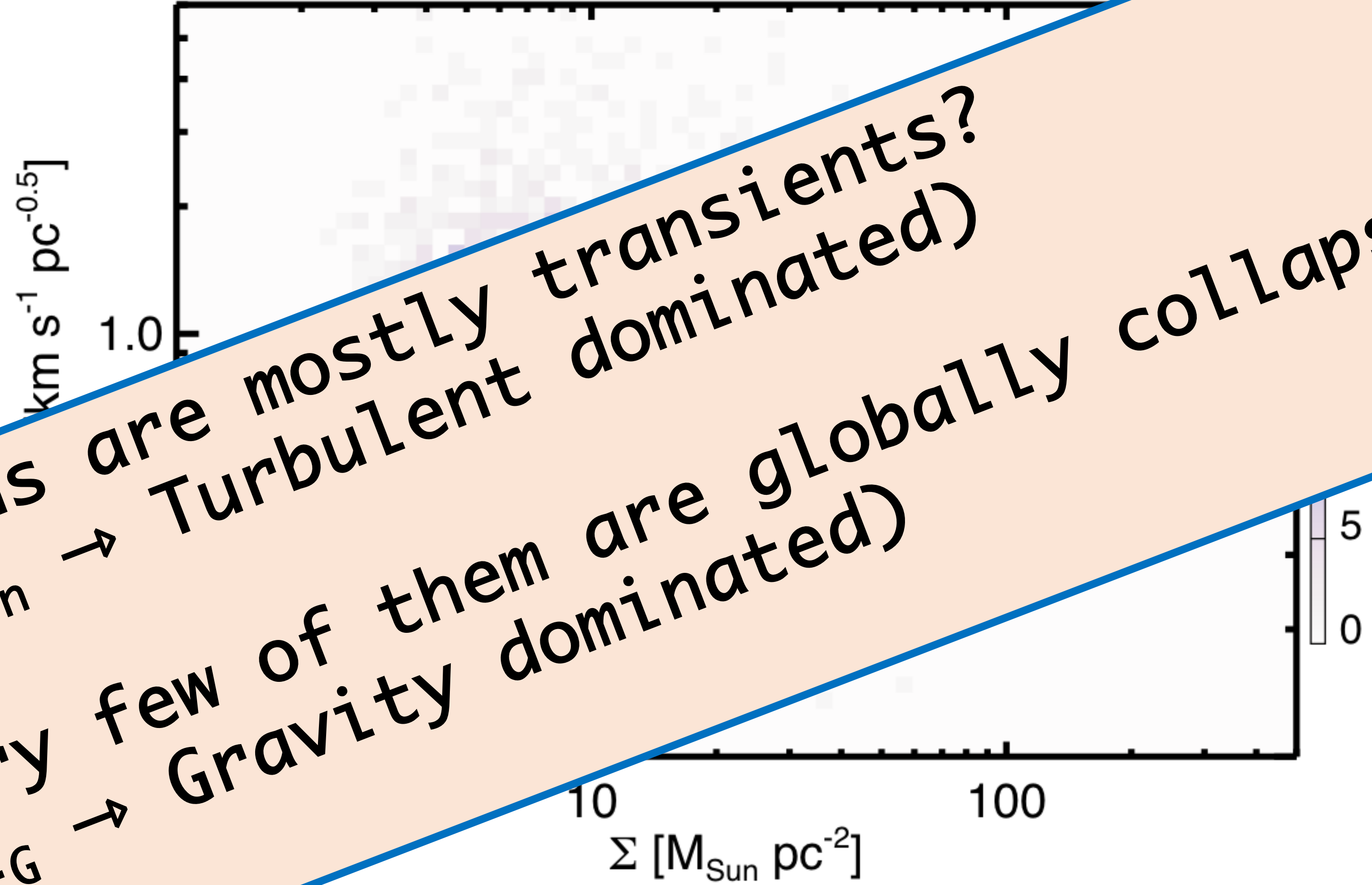
8107 “molecular clouds”

Miville-Dechenes+17



Parameter	Units	All Clouds		Inner Galaxy		Outer Galaxy	
		Avg	Median	Avg	Median	Avg	Median
Σ	$M_\odot$ pc^{-2}	28.6	16.5	41.9	31.6	10.4	7.0
M	$10^4\ M_\odot$	15.1	3.8	22.6	7.8	5.4	1.6
R	pc	31.5	25.1	30.8	25.2	32.9	24.9
$n_{\rm H2}$	cm^{-3}	24.1	9.6	33.7	16.9	11.0	3.3
σ_v	km s^{-1}	4.0	3.6	4.9	4.6	2.8	2.5
$\tau_{\rm ff}$	10^6 yr	13.1	10.1	9.4	7.6	19.0	17.2
$\alpha_{\rm vir}$	...	22.4	8.5	20.7	7.3	25.0	11.3

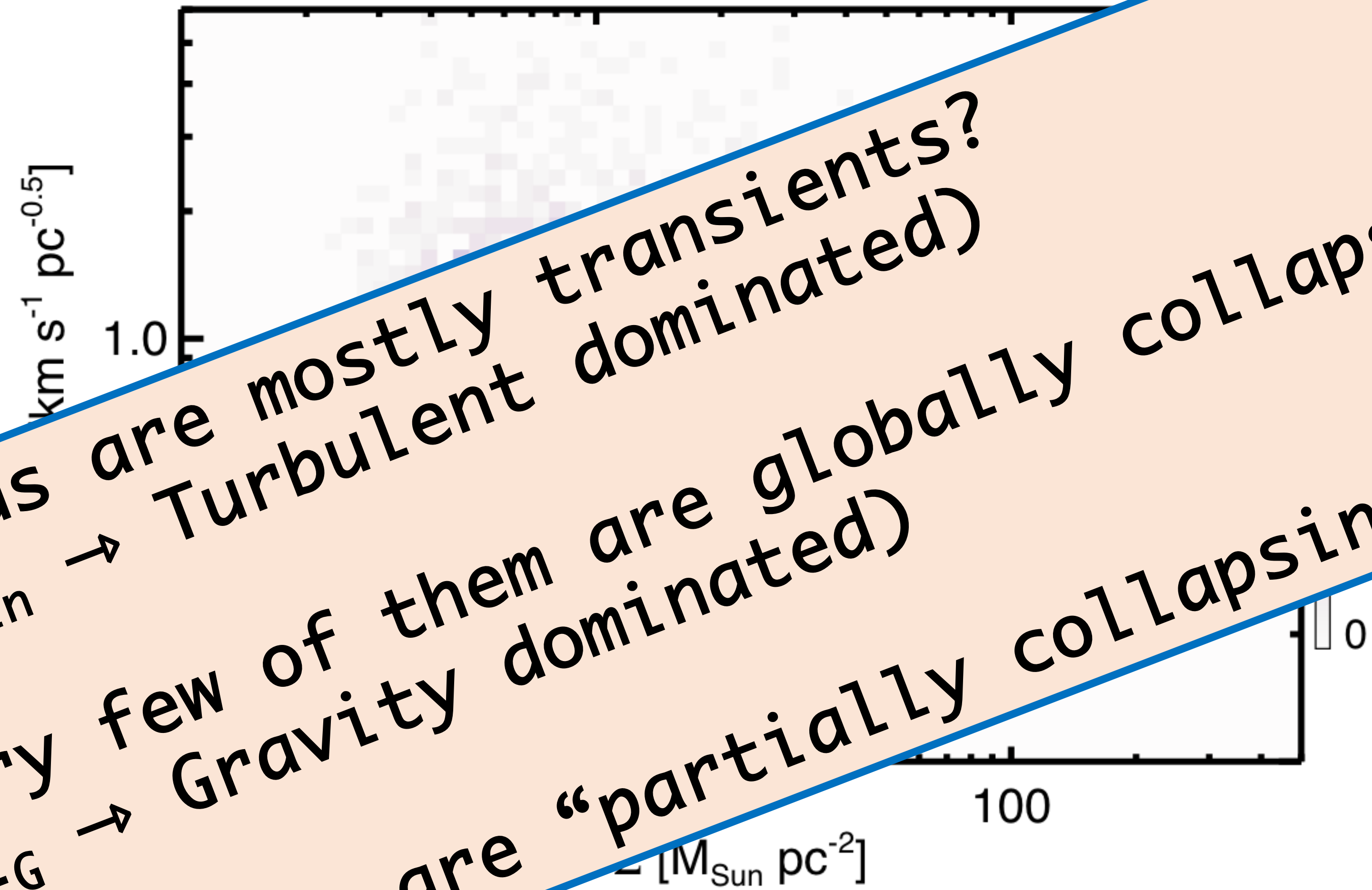
Molecular clouds from CO: Mass – Radius relati



- Clouds are mostly transients?
  (E_{kin} → Turbulent dominated)
- Very few of them are globally collapsing?
  (E_G → Gravity dominated)

$$\alpha_{vir} \propto \frac{E_{kin}}{E_G} \propto \frac{\sigma_v^2}{R}\frac{R^2}{M} \propto \cancel{\frac{\sigma_v^2}{R\Sigma}} = const.$$

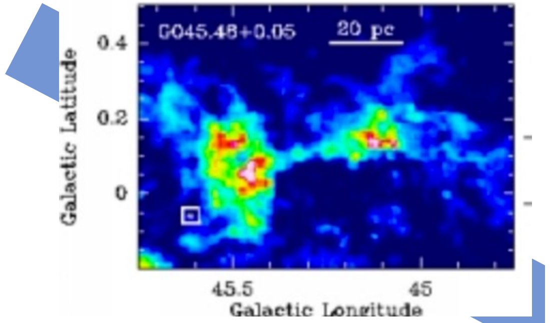
Molecular clouds from CO: Mass – Radius relati



- Clouds are mostly transients?
  (E$_{kin}$ → Turbulent dominated)
- Very few of them are globally collapsing?
  (E$_G$ → Gravity dominated)
- Or…clouds are “partially collapsing”!!!

$$\propto \frac{E_{kin}}{E_G} \propto \frac{\sigma_v^2}{R}\frac{R^2}{M} \propto \cancel{\frac{\sigma_v^2}{R\Sigma}} = const.$$

The multi-scale Milky Way

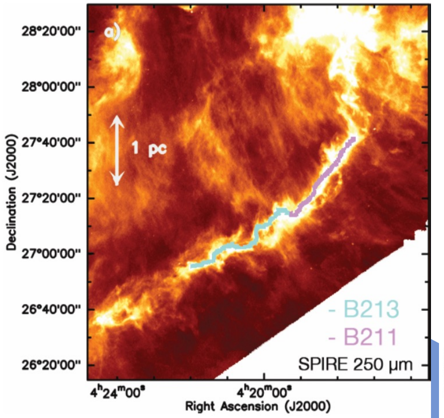


GMCs

10 ≤R ≤150 pc

Σ~0.0004-0.06 (g/cm²)

Palmeirin+13

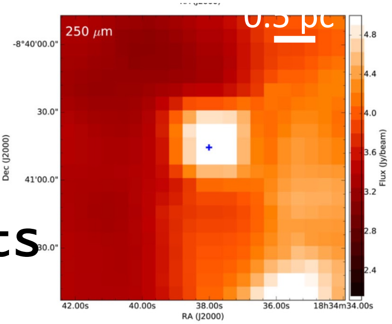


Galactic filaments

1 ≤R ≤100 pc

Σ~0.0005-0.5 (g/cm²)

Traficante+15

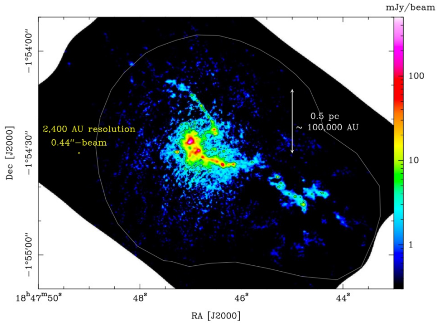


Clumps

0.2 ≤R ≤1 pc

Σ~0.1-5 (g/cm²)

Motte+18

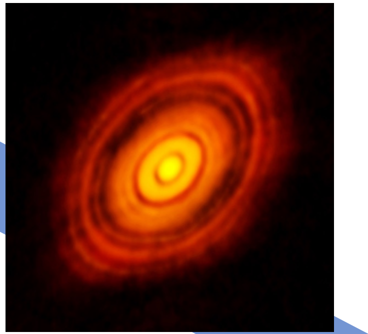


Fragments

0.5 ≤R ≤0.1 pc

Σ ~1-20 (g/cm²)

ALMA (ESO/NAOJ/NRAO)



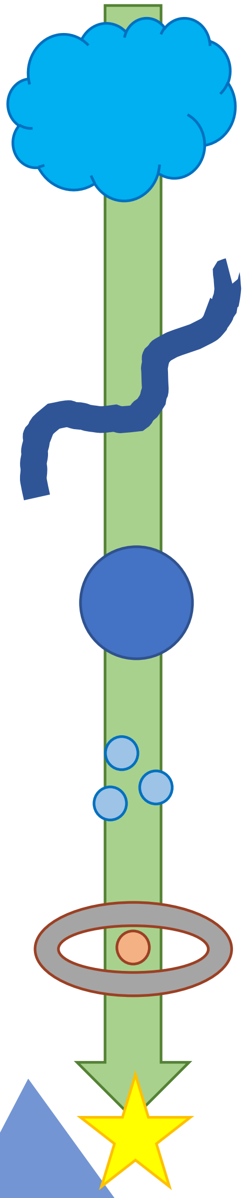
Disks/stars

R <<0.01 pc

Σ >>10 (g/cm²)

n ~100 cm^{-3}

R ~ 100 pc



n ~ 10^{15}-10^{20} cm^{-3}

R ~ 500 AU

How do we observe atoms/molecules in the sky at radio wavelengths?

When you want to observe the sky you look for:

- <u>Continuum only</u>: Position-Position (PP) 2D maps

<u>DUST</u> emits in the continuum!!!

- <u>Spectral cubes</u>: Position-Position-Velocity (PPV) datacubes

<u>Molecules</u> emit at specific frequency!!!

In both cases with a **given resolution** driven by the telescope size and the wavelength you want to observe

Transition from H to H_2

Under the ISM condition the best pathways the formation of H_2 occurs on the **surface of dust grains**

The formation rate R_{H2} is therefore driven by the rate at which H atoms are absorbed onto the grain surface

In typical Milky Way conditions $R_{H2} \sim 3 \text{ x}10^{-17}\ n n_H\ s^{-1}cm^{-3}$

Jura 1975

Total number density of gas particles

Number density of atomic hydrogen

Transition from H to H_2

In typical Milky Way conditions

$$R_{H2} \sim 3 \text{ x}10^{-17} \, n n_{H} \, s^{-1}cm^{-3}$$

Total number density of gas particles

Number density of atomic hydrogen

Jura 1975

This rate translates in a H_2 formation timescale $t_{\rm form}$ of

$$t_{\rm form} = \frac{n_{\rm H}}{R_{\rm H_2}} \simeq 10^9 n^{-1} {\rm yr}$$

Girichidis+20

~1 order of magnitude (or more) larger than estimated (e.g. Inutsuka+12) and measured in e.g. the Large Magellanic Cloud (e.g. Kawamura+09), and larger than the gravitational free-fall time.

The intermittent compression of gas due to **supersonic turbulent gas motions** can shorten $t_{\rm form}$ (Glover & Mac Low 2007)

Turbulence in the ISM?

Which leads to a star formation efficiency SFE ~1%

What it slowing down the clouds gravitational collapse???

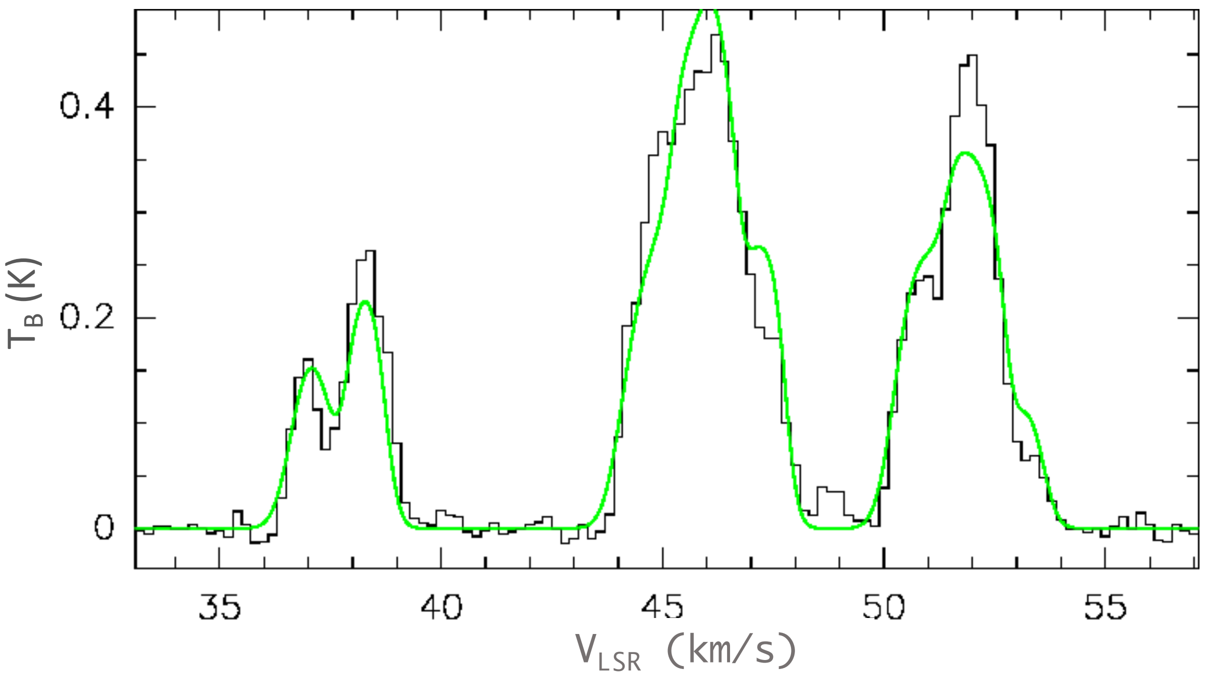
This question is **THE** reason why we are still investigating the star formation mechanisms in our Galaxy!!!

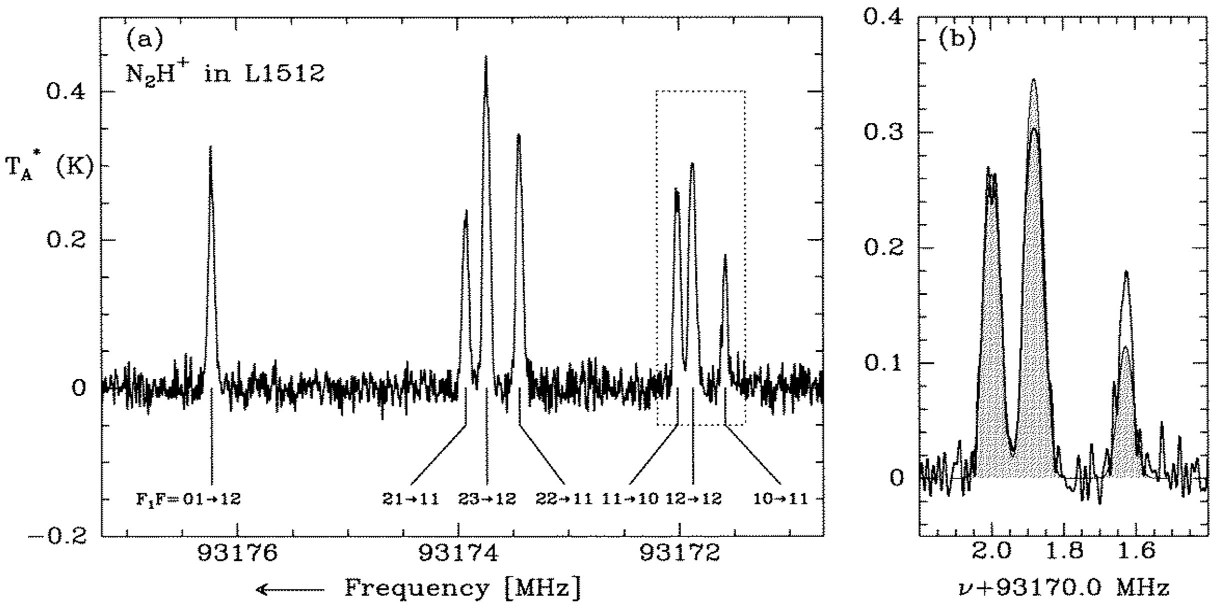
The main suspect is the **turbulence** in the interstellar medium

“Turbulence is characterised by chaotic motions in a fluid that lead to diffusion of matter and dissipation of kinetic energy”

Falceta-Goncalves+14

How do we observe atoms/molecules in the sky at radio wavelengths?





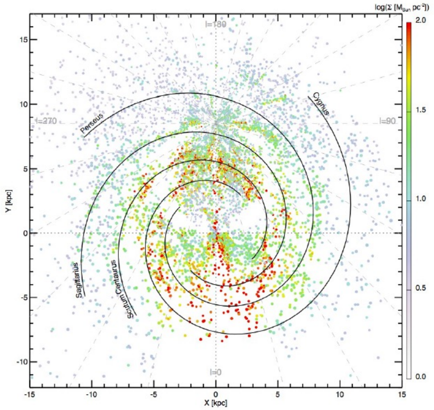
The velocity resolution Δv is given by the frequency resolution and the observed frequency

$$\Delta v = c * \frac{\Delta\lambda}{\lambda}$$

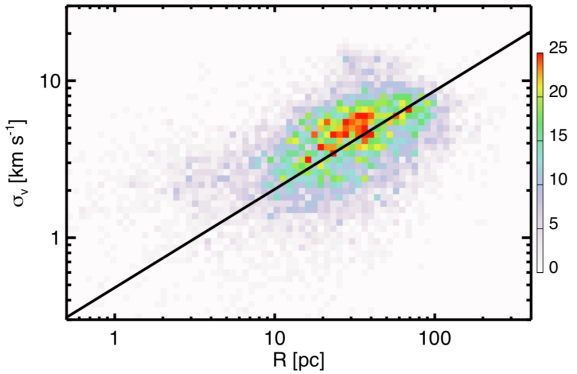
$\lambda = 93.2$ GHz

$\Delta\lambda = 200$ kHz → $\Delta v \simeq 0.6$ Km/s

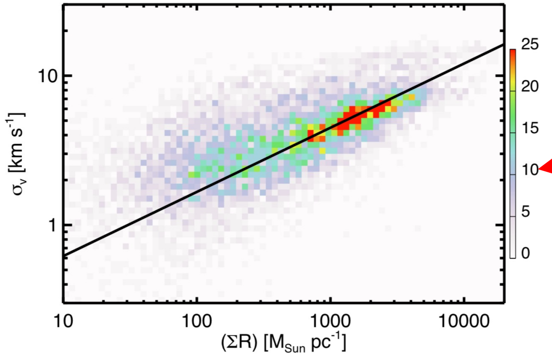
$\Delta\lambda = 50$ kHz → $\Delta v \simeq 0.15$ Km/s



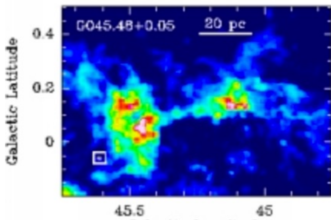
Larson relation

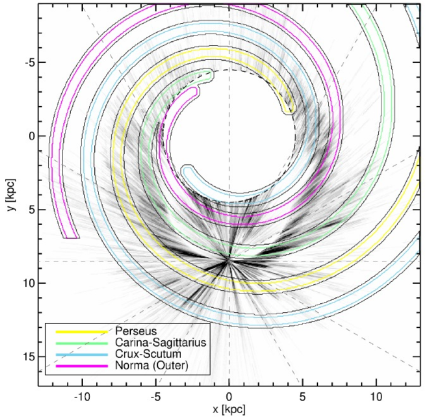


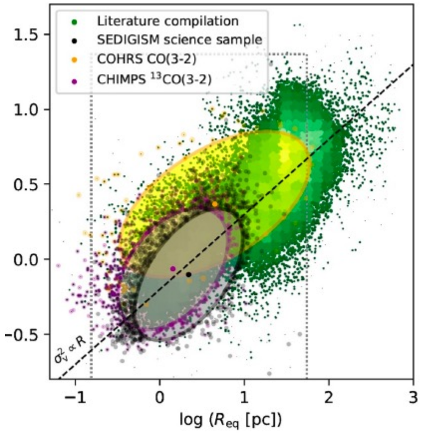
Heyer relation

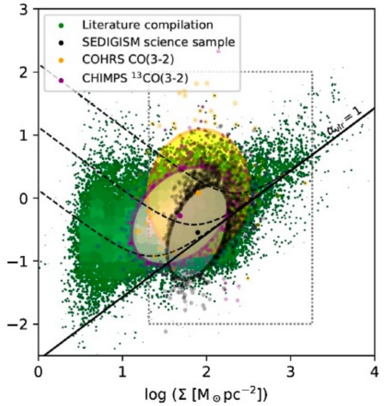


GMCs

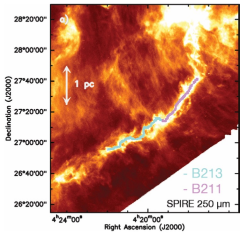


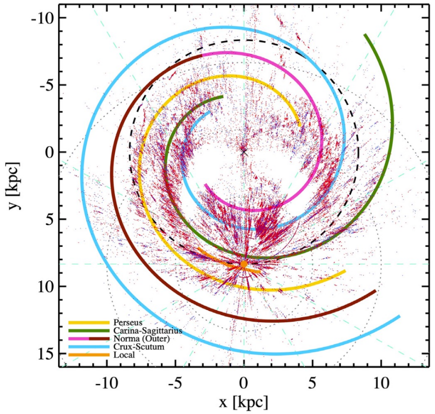


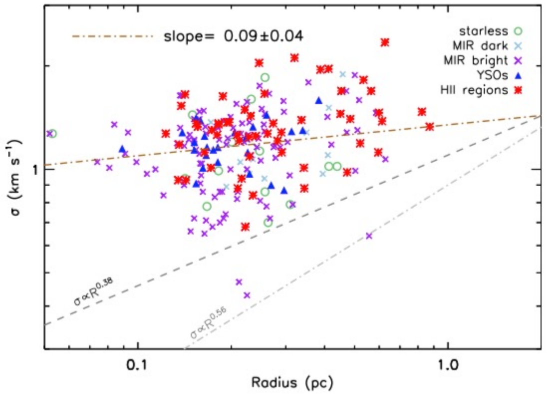


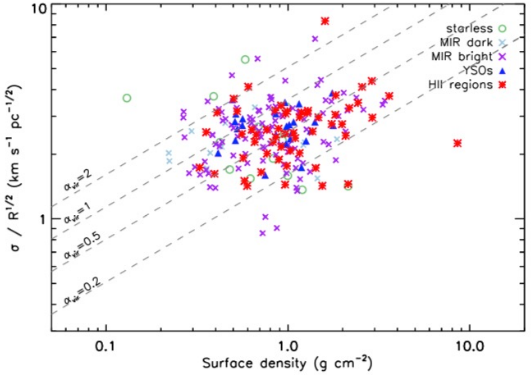


Dense clouds/ filaments

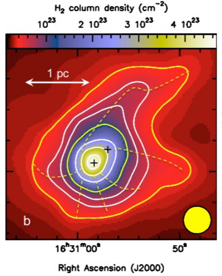








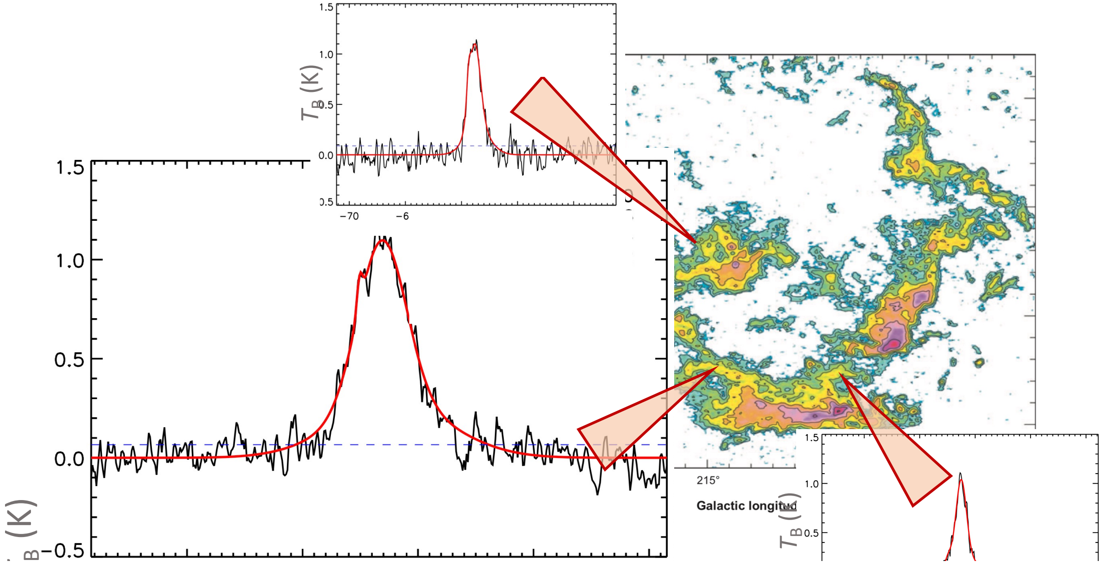
Clumps



Molecular clouds from CO: kinematic properties

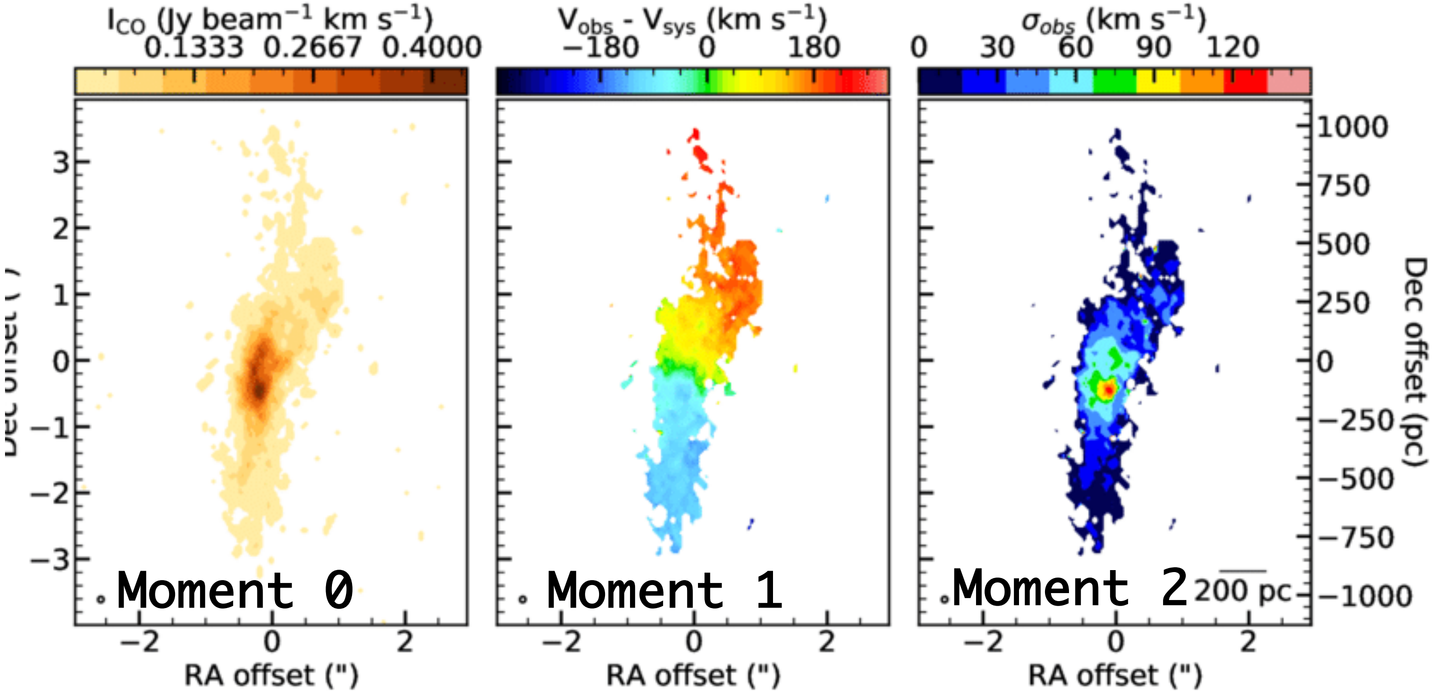
For each cloud we now know

- $W_{\rm CO}$ (per pixel and tot)
- total # pixels $N_{\rm pix}$
- brightness temperature $T_{\rm B}$



$$\langle v\rangle = \frac{1}{W_{\rm CO}^{\rm tot}} \sum_v v\, T_{\rm B}^{\rm tot}(v)\, dv$$

$$\sigma_v^2 = \frac{1}{W_{\rm CO}^{\rm tot}} \sum_v v^2\, T_{\rm B}^{\rm tot}(v)\, dv - \langle v\rangle^2$$



How to characterize filaments from observations

Combining the LARGEST sample of filaments structures to date from several different surveys, observationally we found (Hacar+23):

$$m_{\rm crit}(T) = \frac{2c_{\rm s}^2}{G} \sim 16.6 \left(\frac{T}{10\,{\rm K}}\right) M_\odot\,{\rm pc}^{-1}$$

$$m_{\rm vir}(\sigma_{\rm tot}) = \frac{2\sigma_{\rm tot}^2}{G} \sim 465 \left(\frac{\sigma_{\rm tot}}{1\,{\rm km\,s}^{-1}}\right)^2 M_\odot\,{\rm pc}^{-1}$$

$$m_{\rm vir} = \frac{M}{L} \simeq \frac{2c_s^2}{G}\left(1 + \frac{L}{0.5\ {\rm pc}}\right)$$