Star-forming regions, clumps and cores - outline

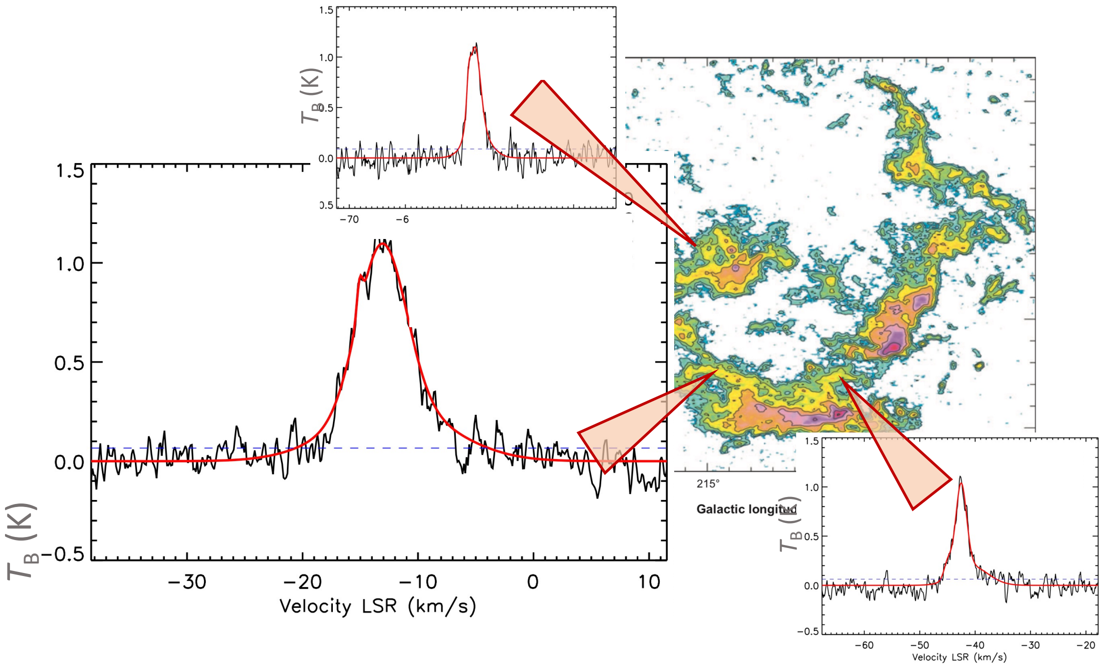
- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: 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: 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, n_{H2}**



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

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

Free-fall time

See lecture from Patrick Hennebelle

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

Virial parameter

See lecture from Ralf Klessen

Free-fall time and SFR

If all CO clouds are collapsing under their own gravity

$$\begin{cases} M_{\rm tot} \simeq 1.6 \times 10^9 \ \mathrm{M_\odot} \\ t_{\rm ff} = \sqrt{\dfrac{3\pi}{32 G\rho}} \simeq 1.0 \times 10^7 \ \mathrm{yr} \end{cases} \Longrightarrow \quad SFR = \frac{M_{\rm tot}}{t_{\rm ff}} \simeq 160 \ \mathrm{M_\odot \ yr^{-1}}$$

The **MEASURED** *SFR* across the Galaxy $\simeq 1 - 2 \ \mathrm{M_\odot \ yr^{-1}}$

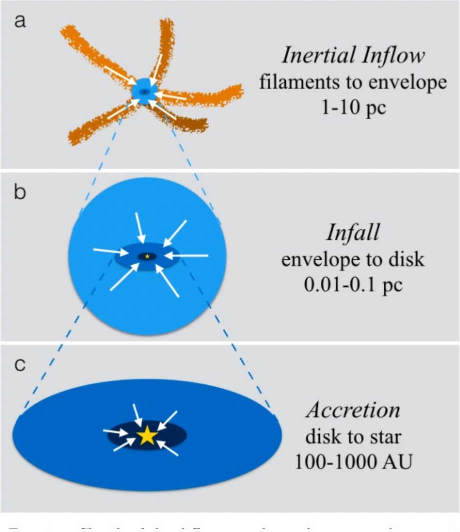
Which leads to a star formation efficiency SFE ~1%

What it slowing down the clouds gravitational collapse???

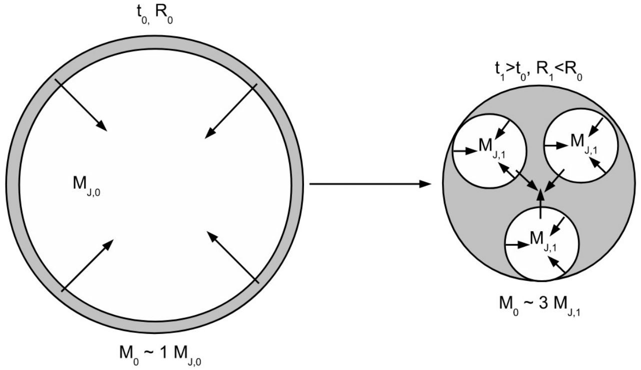
This question is <u>**THE** reason why we are still investigating the star formation mechanisms</u> in our Galaxy!!!

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?

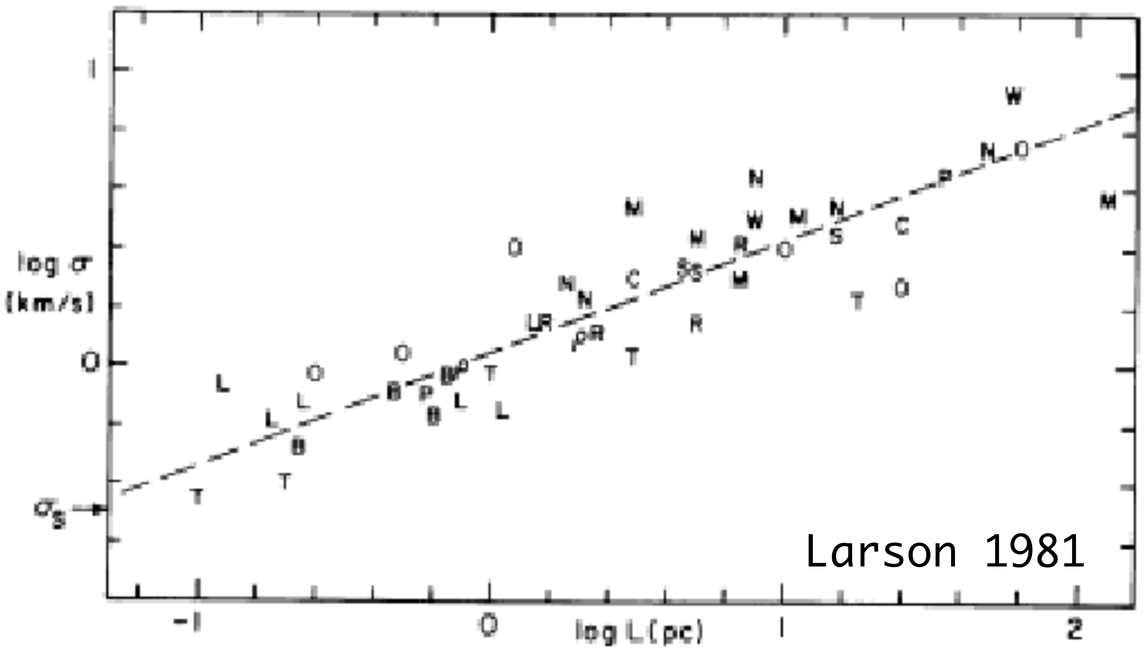
"Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls, and so on to viscosity"

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 turbulence we can measure:

- the (non-thermal) 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?

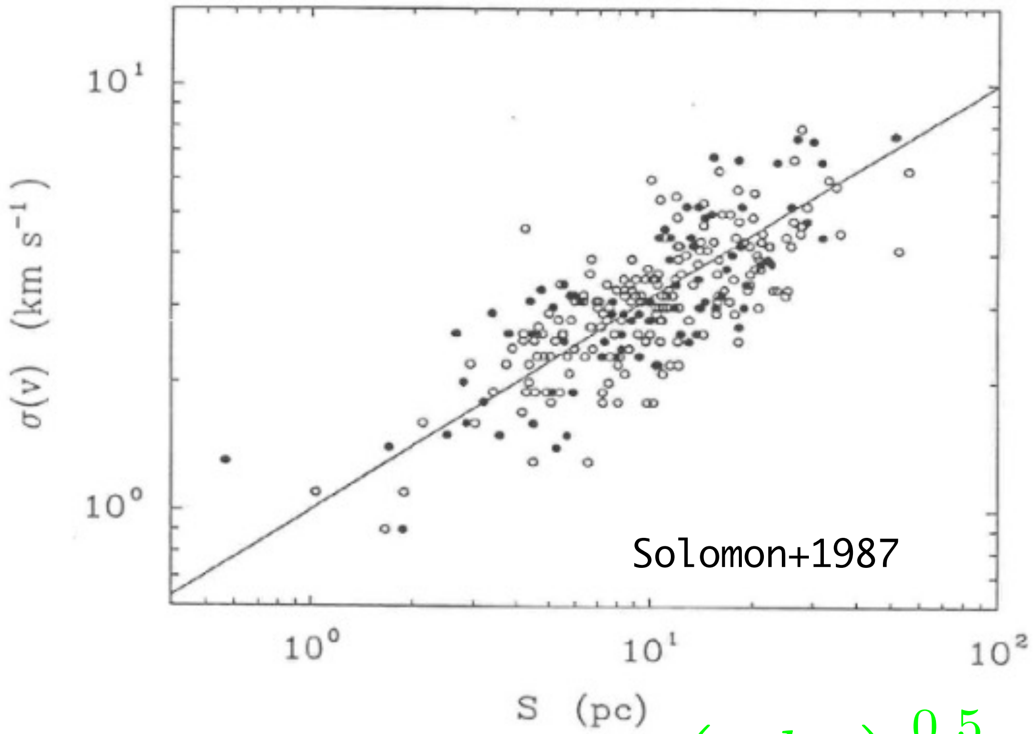
"Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls, and so on to viscosity"

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



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

Burgers turbulence

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

Also called **1st Larson 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 $a \sim 1$)

Virial parameter

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

See lecture from Ralf Klessen

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 is near virial equilibrium: it could slowly collapse

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Also called 2nd **Larson relation**

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

Are clouds nearby near virial equilibrium?

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1st Larson relation

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

2nd Larson relation

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

3rd Larson relation

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

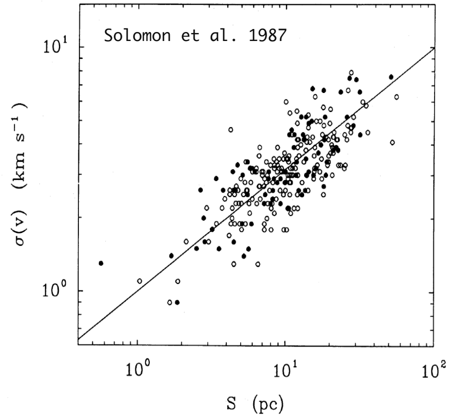
$$\frac{R^2}{M} = const. \Longrightarrow \frac{M}{R^2} \propto \Sigma = const.$$

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

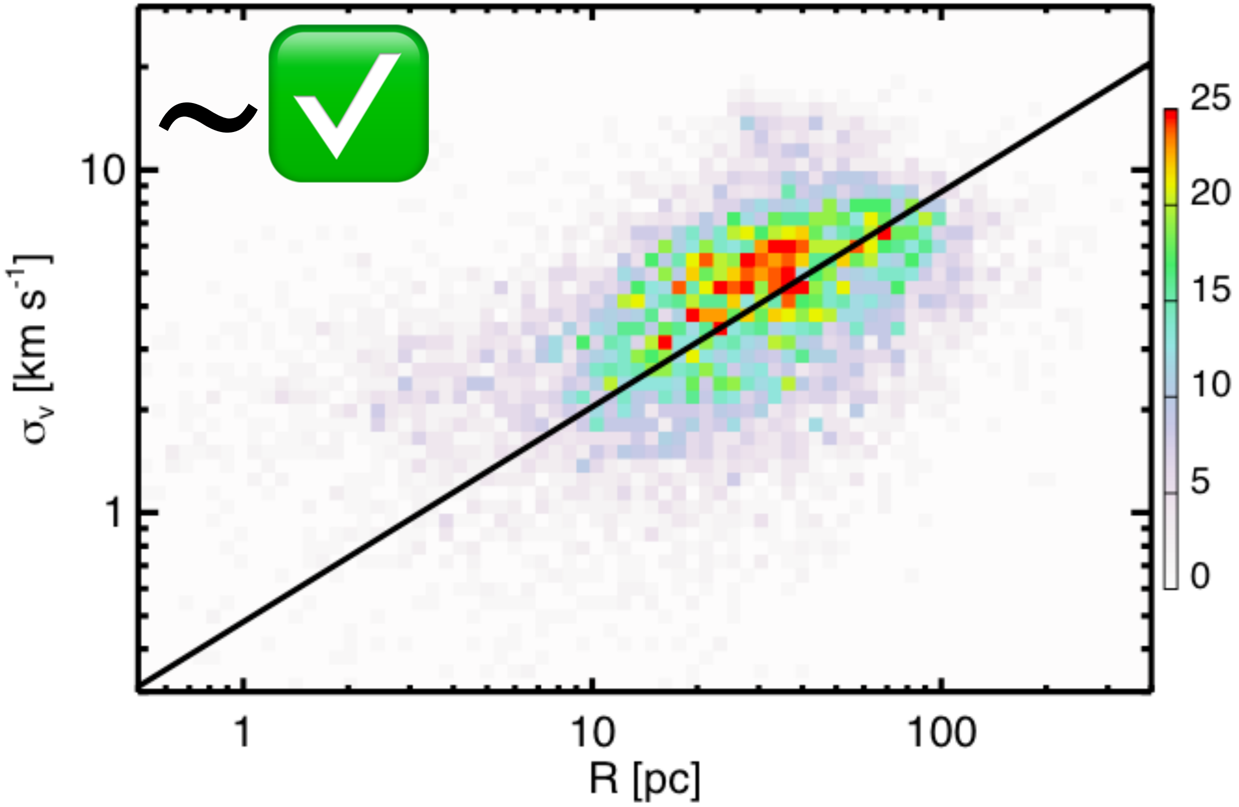
(Larson 81; Solomon+87; Heyer & Brunt 2004)



Molecular clouds from CO: physical and dynamical properties

1st Larson relation

Miville-Dechenes+17



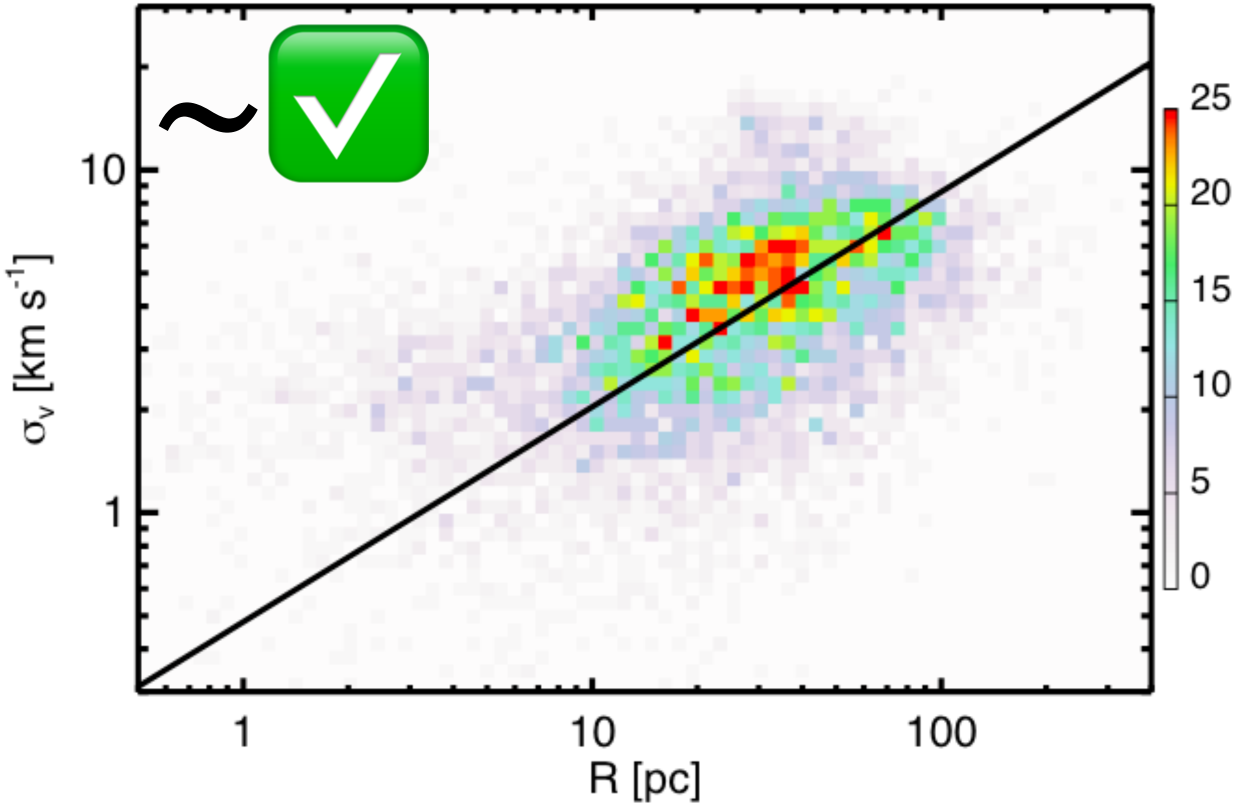
$$\sigma_v = 0.48\ R^{0.63 \pm 0.30}$$

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

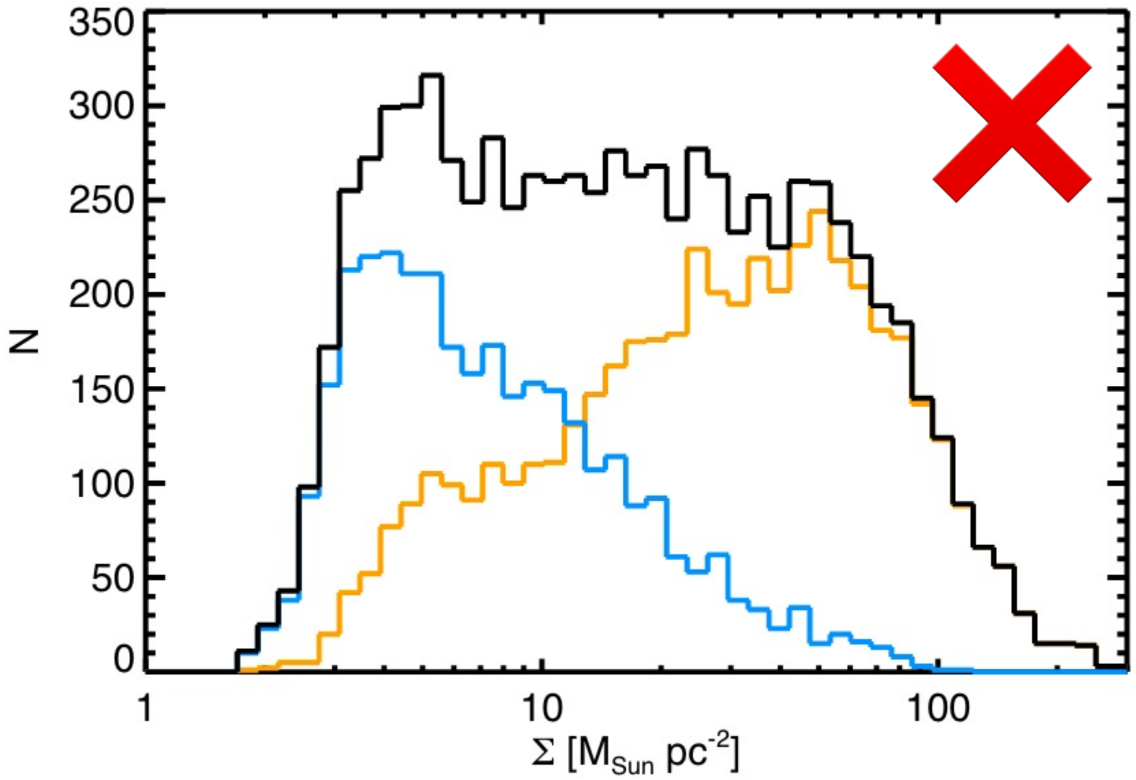
Molecular clouds from CO: physical and dynamical properties

Miville-Dechenes+17

1st Larson relation



3rd Larson relation

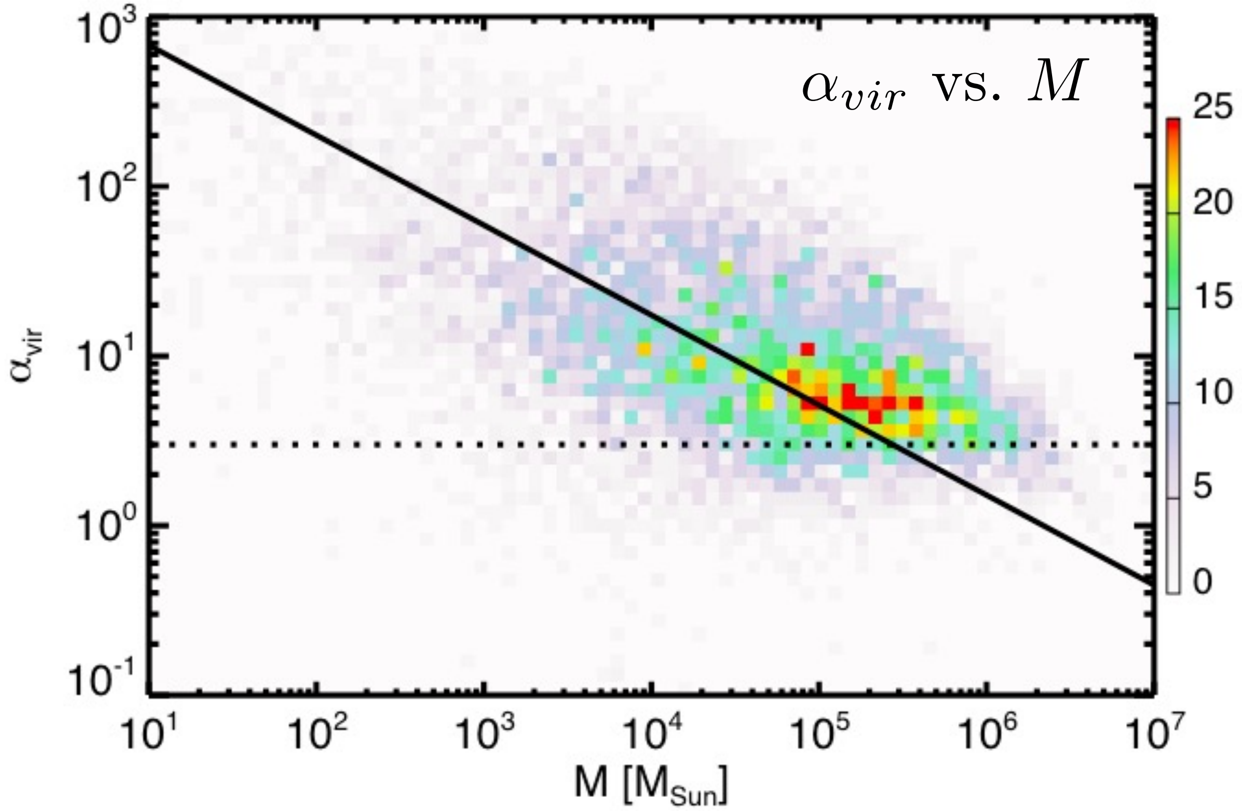


$$\sigma_v = 0.48\ R^{0.63\pm0.30}$$

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

Molecular clouds from CO: Mass – Radius relation

Miville-Dechenes+17



2nd Larson relation

Global $\alpha_{vir} \neq 1$

What are the implications?

Molecular clouds from CO: Heyer relation

1st Larson relation

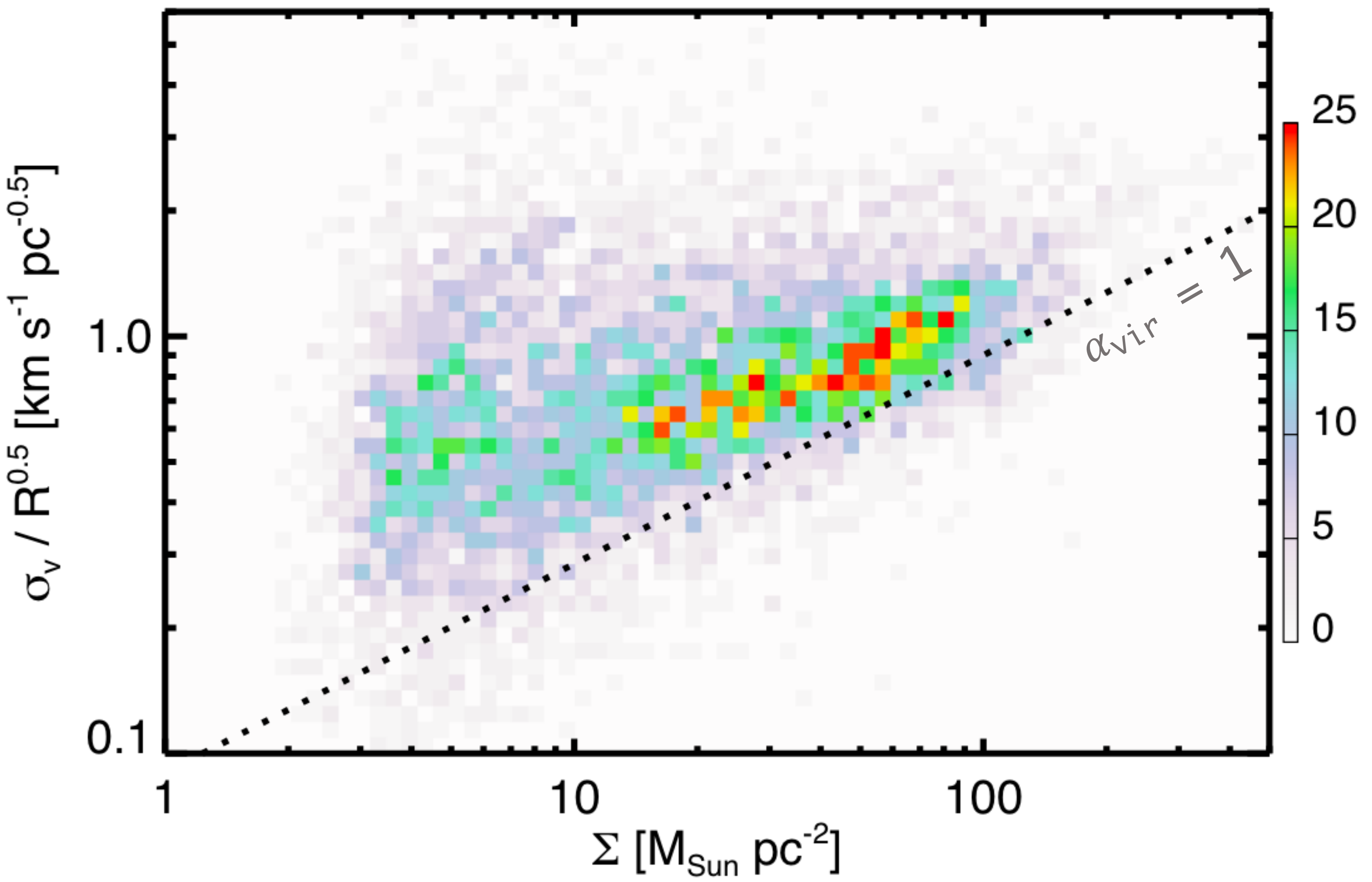
$$\sigma_v \propto R^{0.5}$$

2nd Larson relation

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

3rd Larson relation

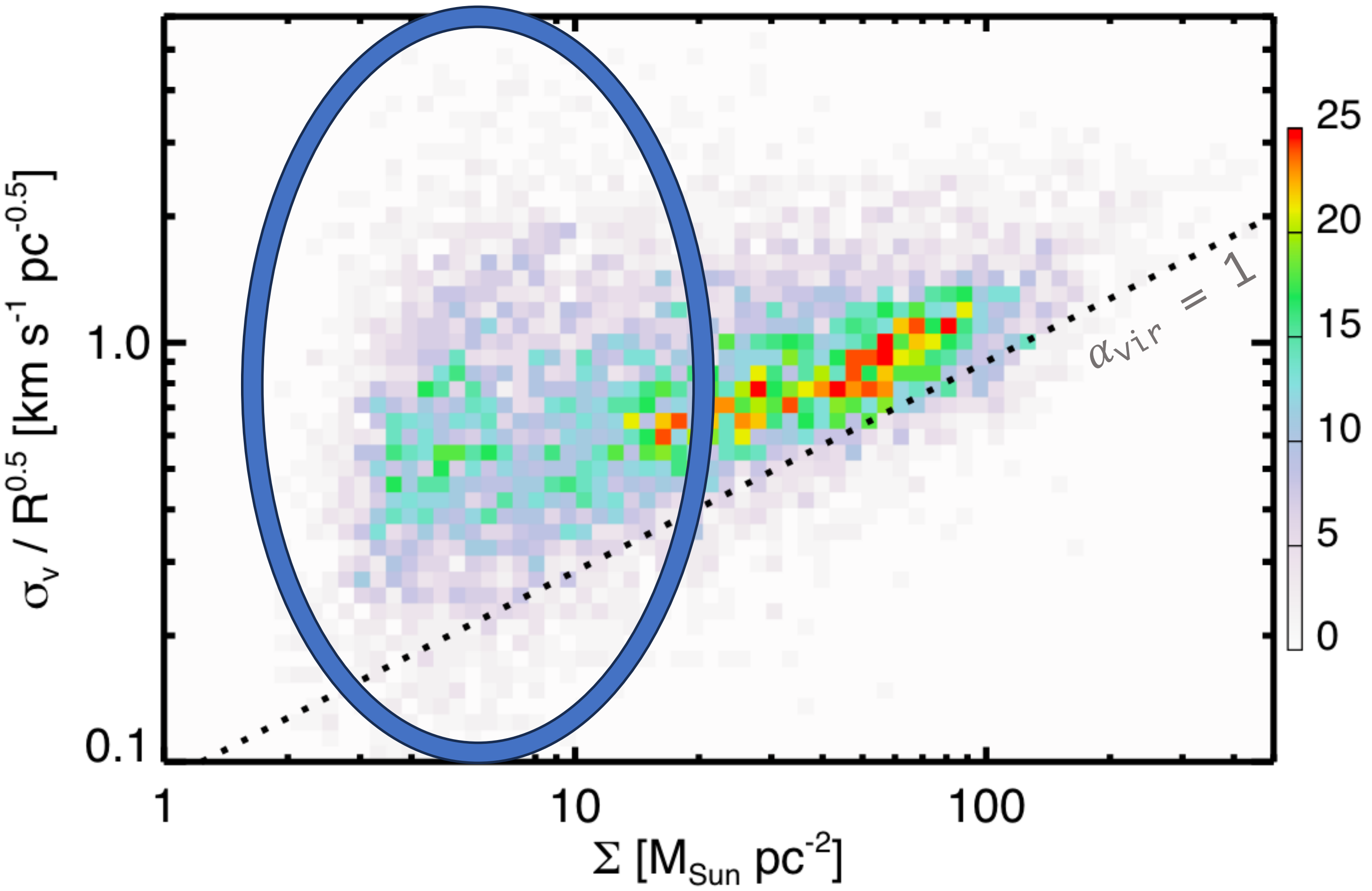
$$\frac{M}{R^2} \propto \Sigma = const.$$



The three Larson relations depend on each other:

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

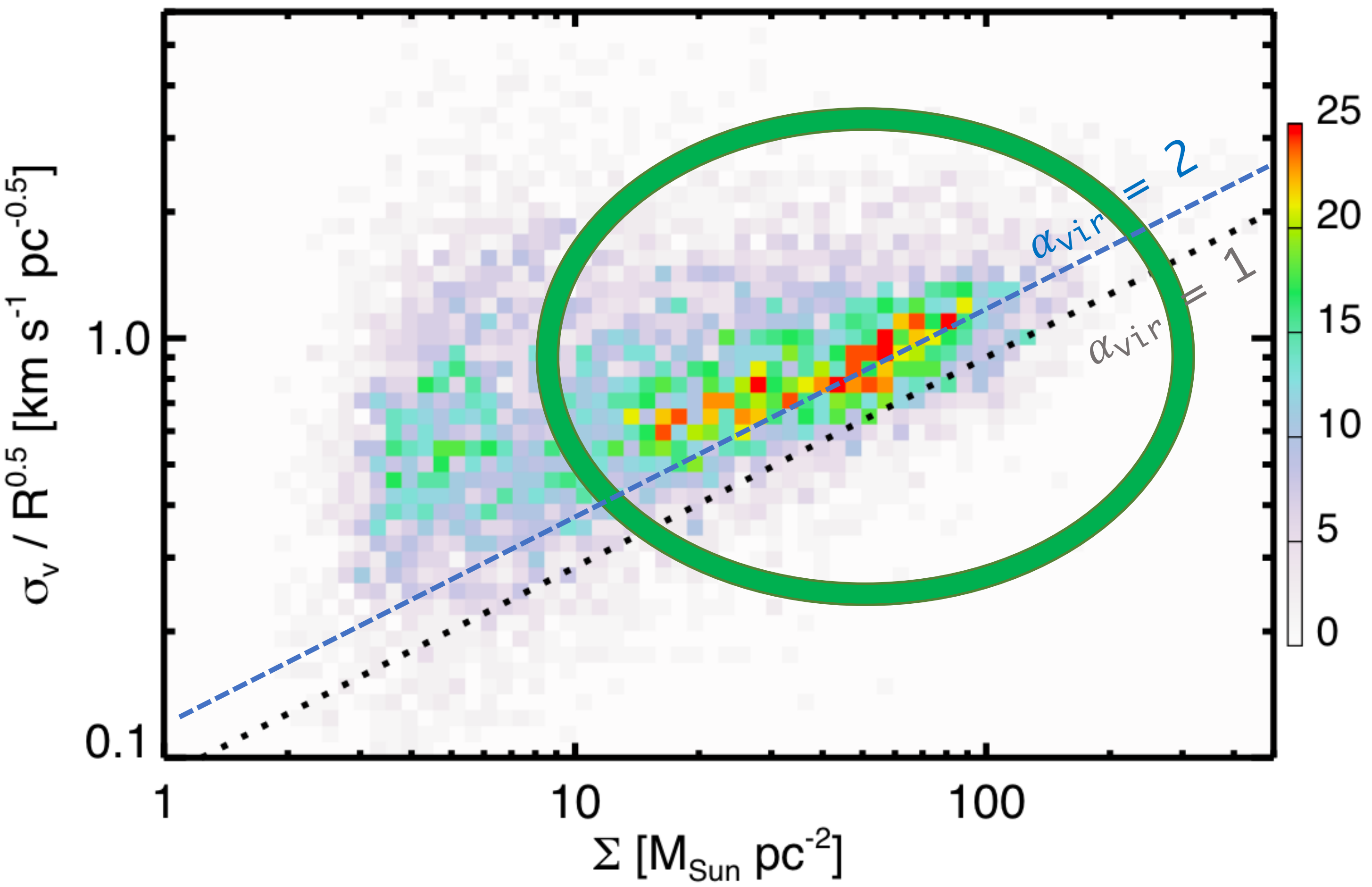
Molecular clouds from CO: Heyer relation



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

2 regimes?

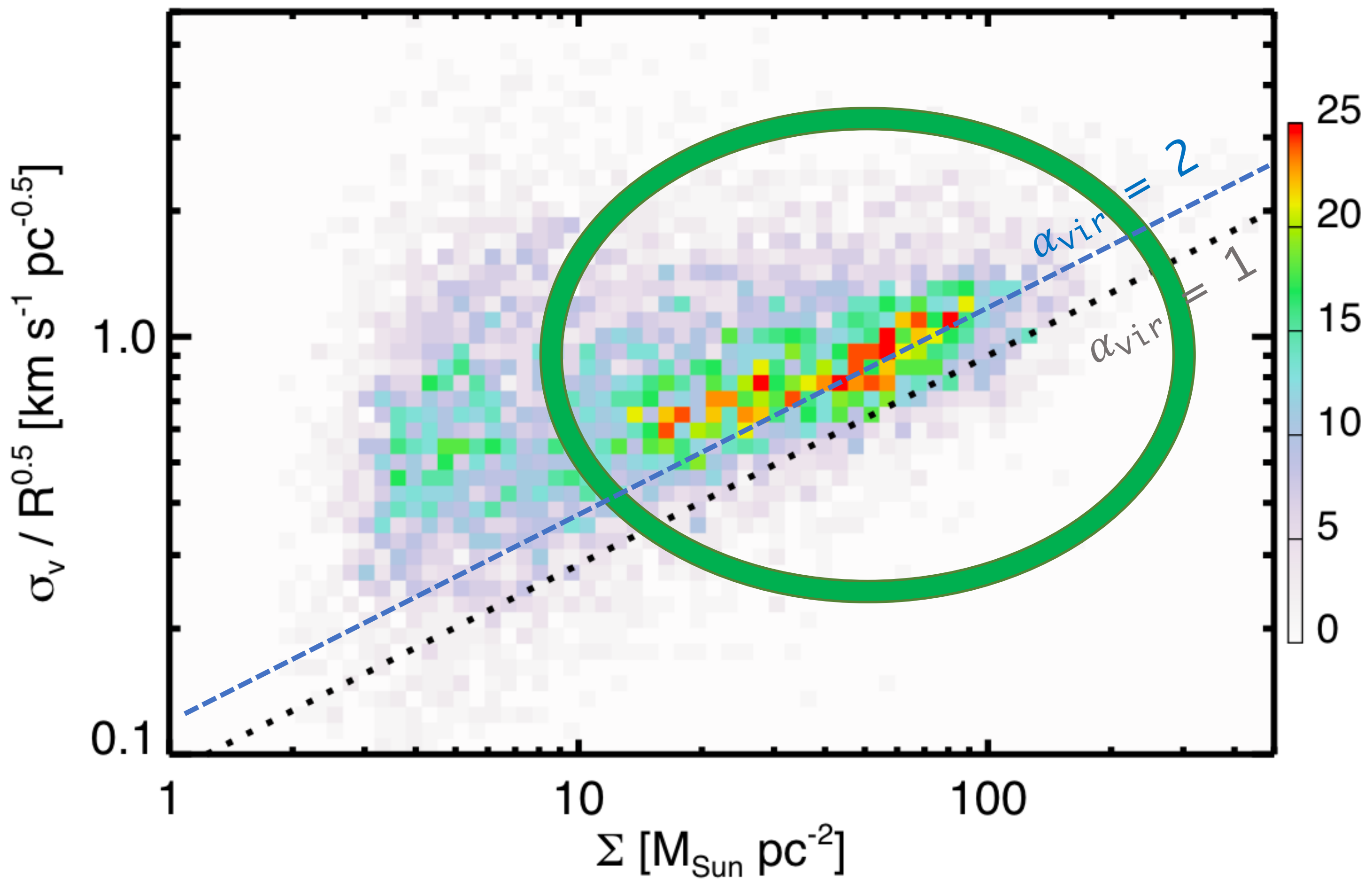
Molecular clouds from CO: Heyer relation



2 regimes?

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

Molecular clouds from CO: Heyer relation



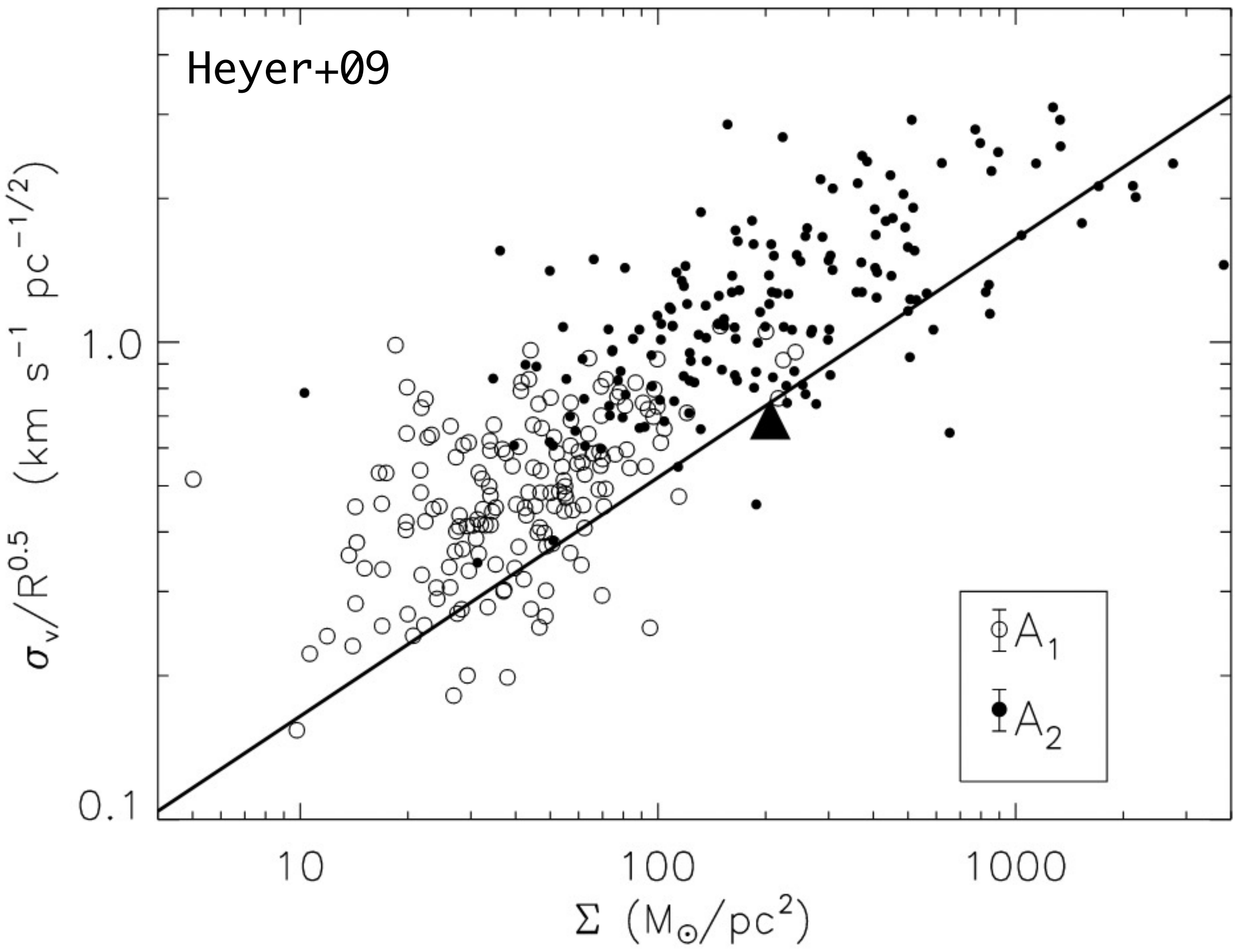
2 regimes?

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

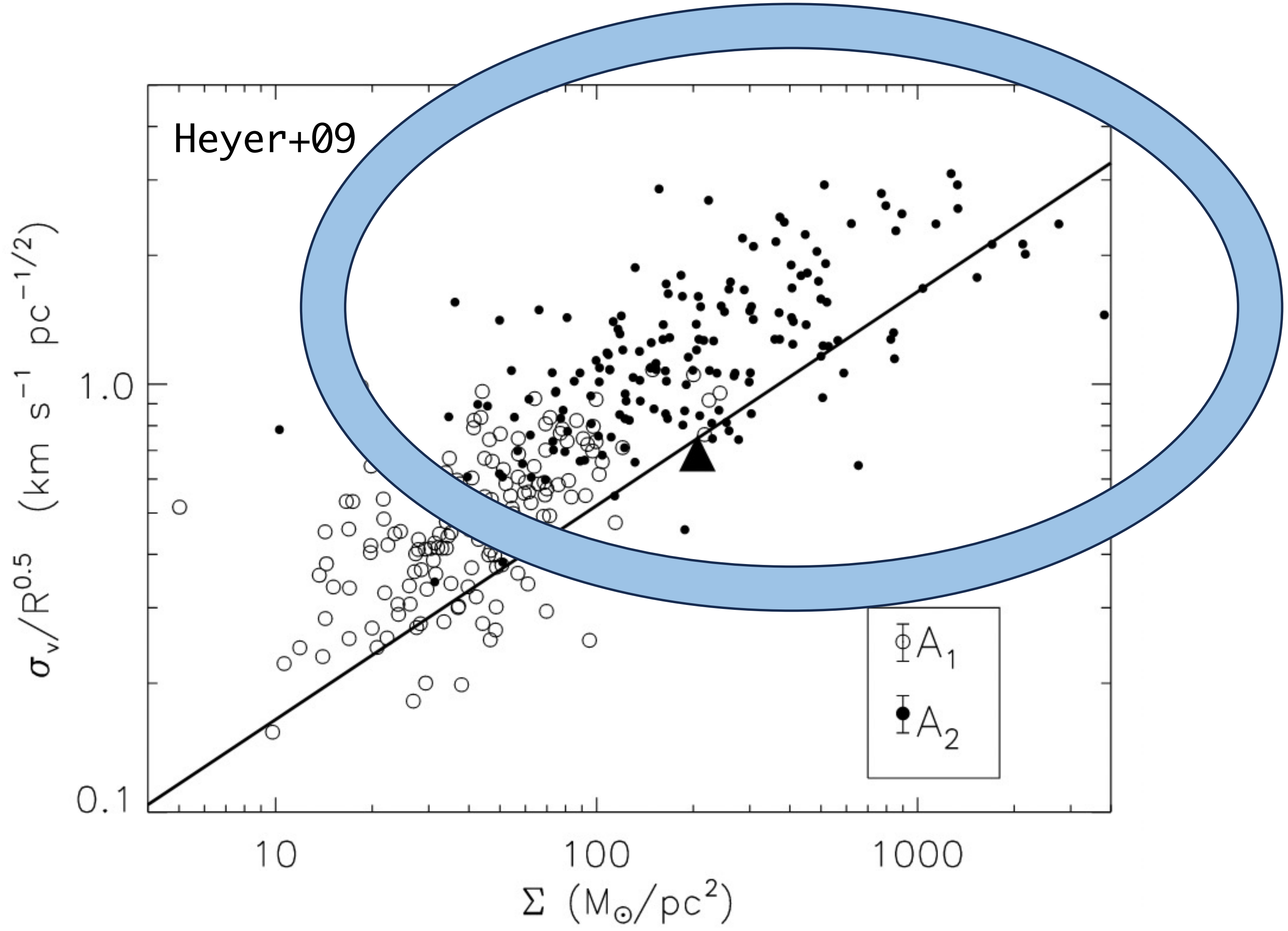
See Ballesteros-Paredes+2011

- 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>…

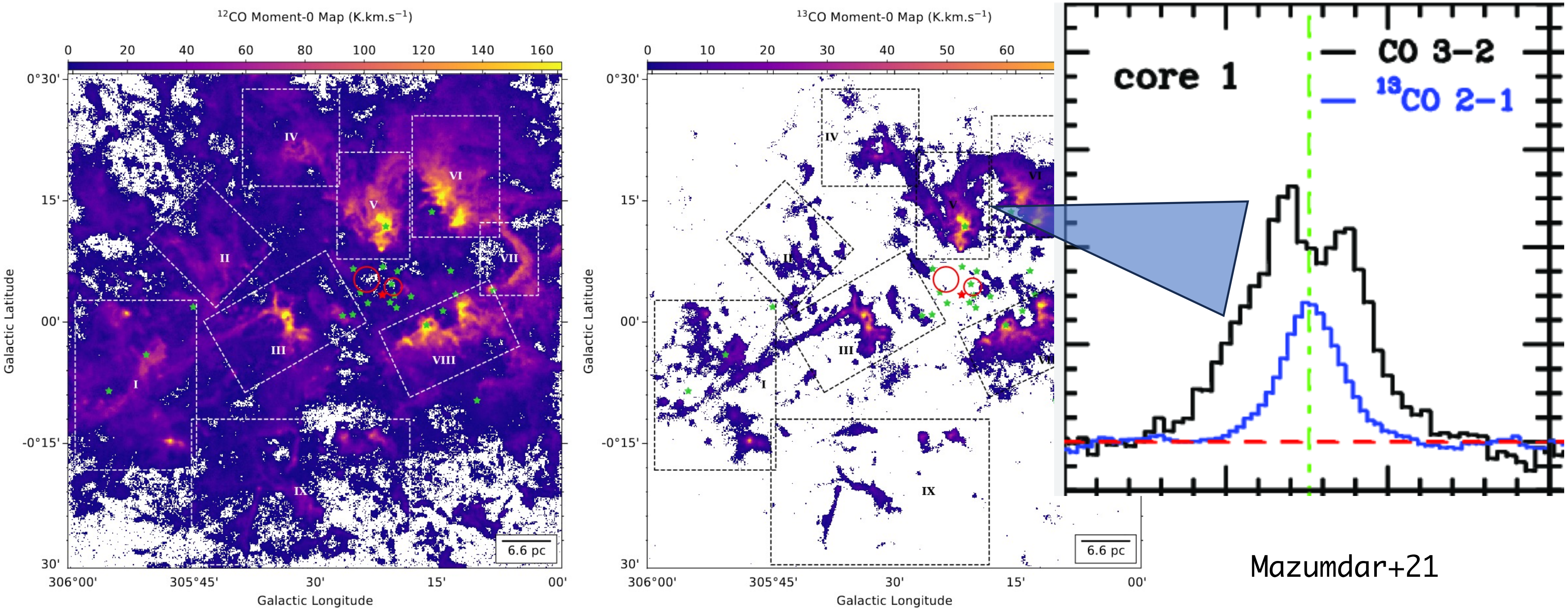
Which CO tracer?

^{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

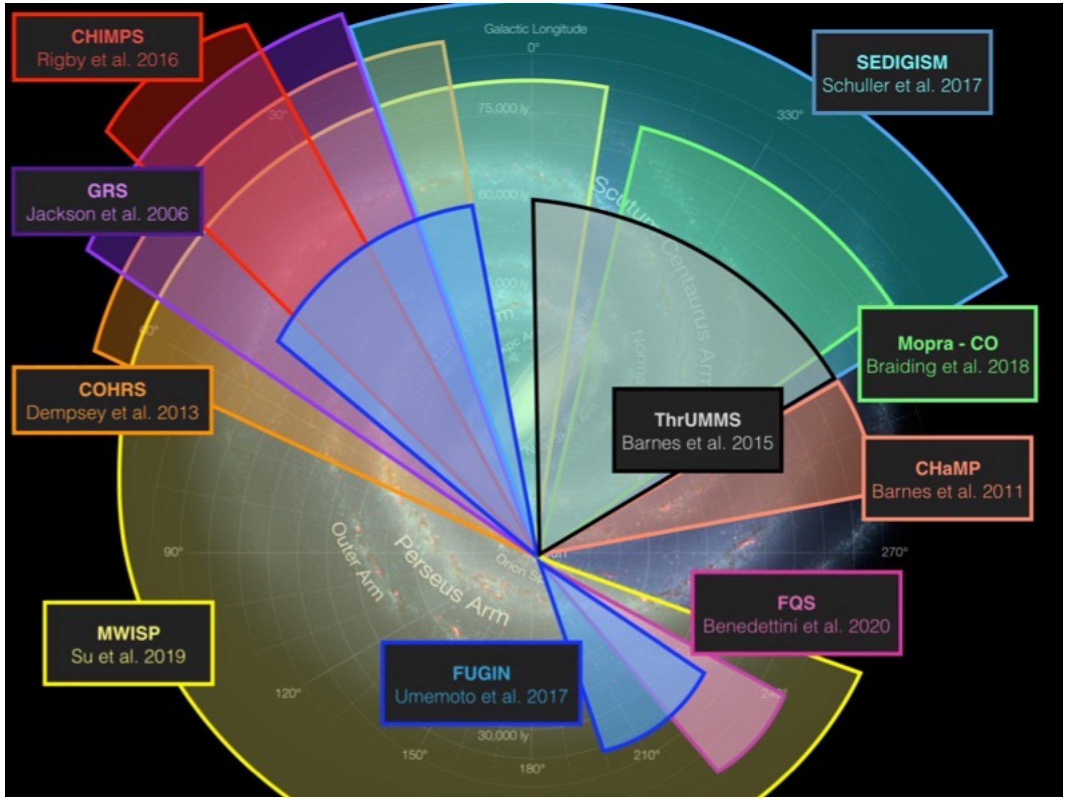
Other CO transition/isotopologues may be very useful to look INSIDE the "edges" of molecular clouds!!!

G305
molecular
cloud
clomplex



Mazumdar+21

Which CO tracer?

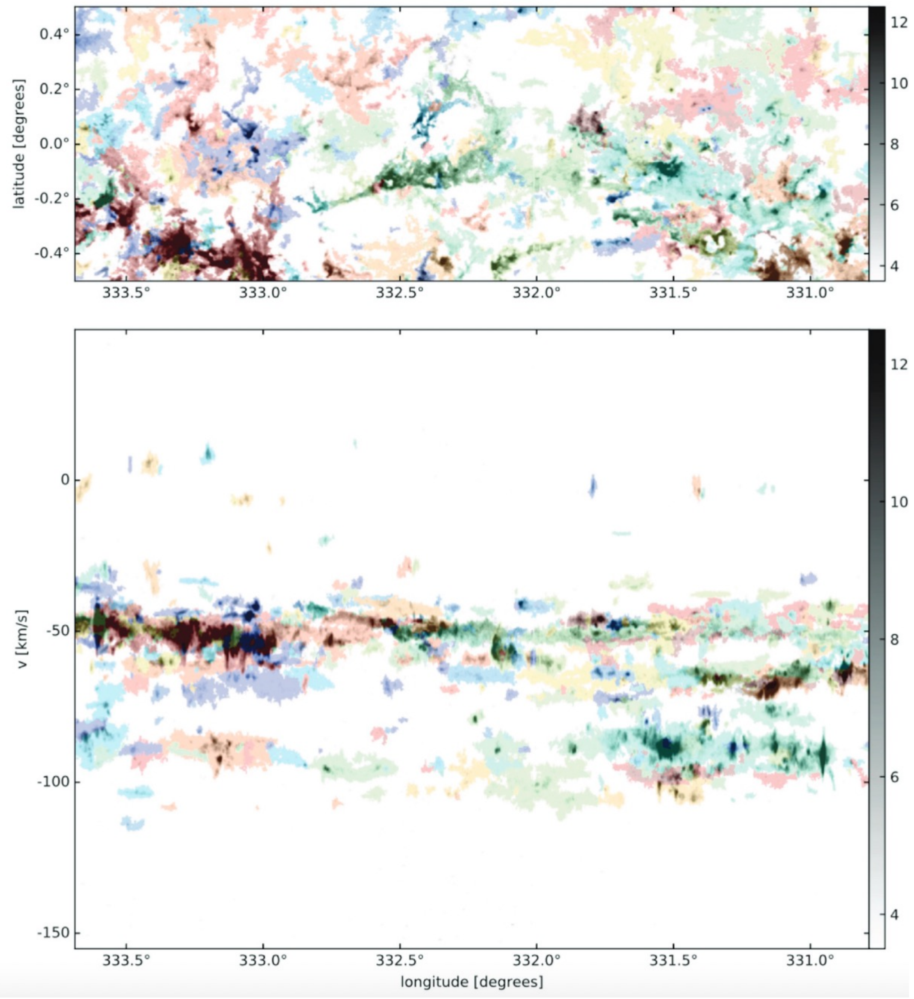


Credits: D. Colombo & J. Urquhart

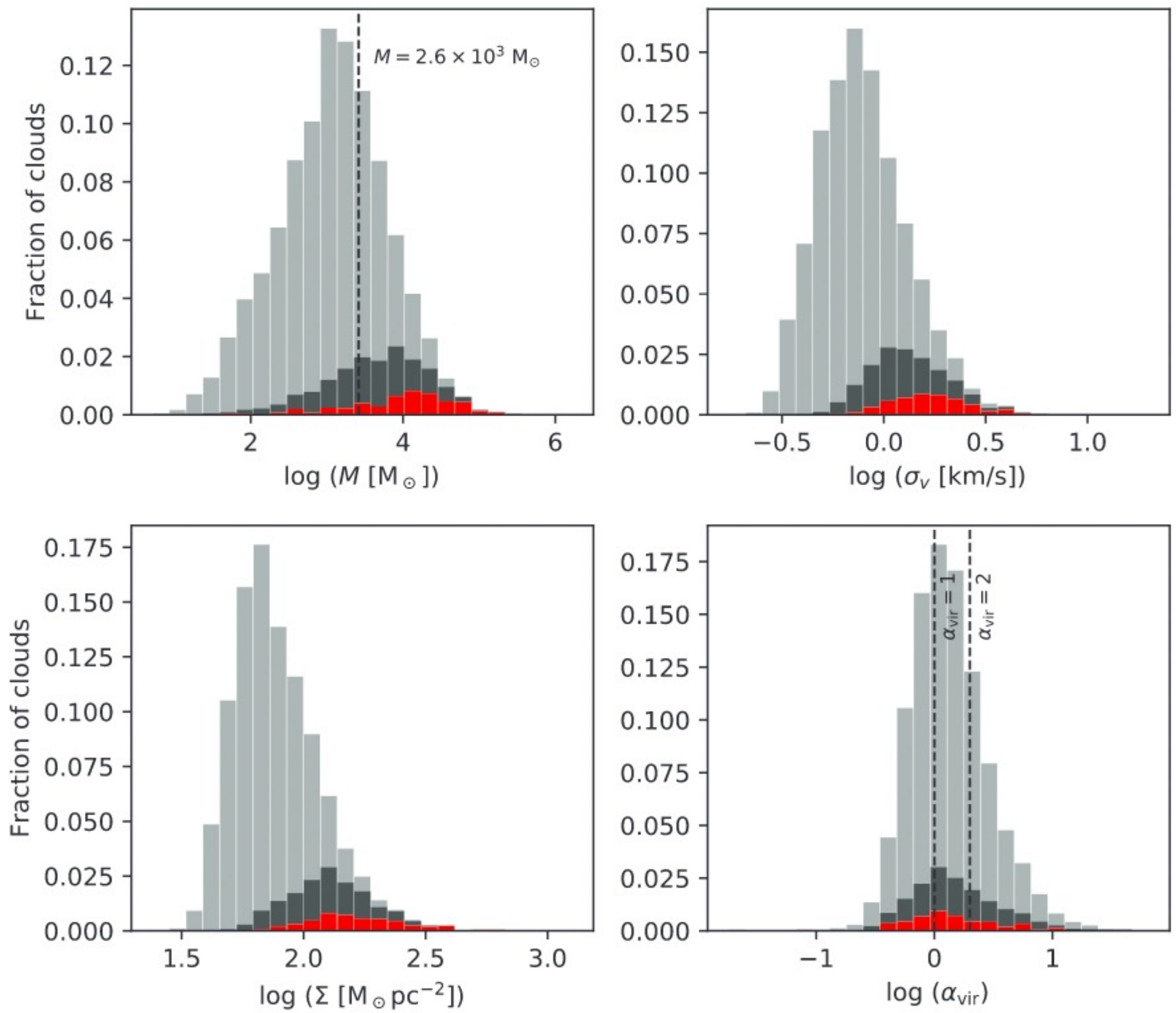
Survey	Transition	Coverage
GRS	^{13}CO (1-0)	15º < l < 55º
ThrUMMS	^{12}CO (1-0) ^{13}CO (1-0) C^{18}O (1-0)	-60º < l < 0º
FUGIN	^{12}CO (1-0) ^{13}CO (1-0) C^{18}O (1-0)	10º < l < 50º
SEDIGISM	^{13}CO (2-1) C^{18}O (2-1)	-60º < l < 18º
COHRS	^{12}CO (3-2)	10º < l < 55º
CHIMPS	^{13}CO (3-2) C^{18}O (3-2)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

…and more!

Molecular clouds in ^{13}CO (2-1): SEDIGISM



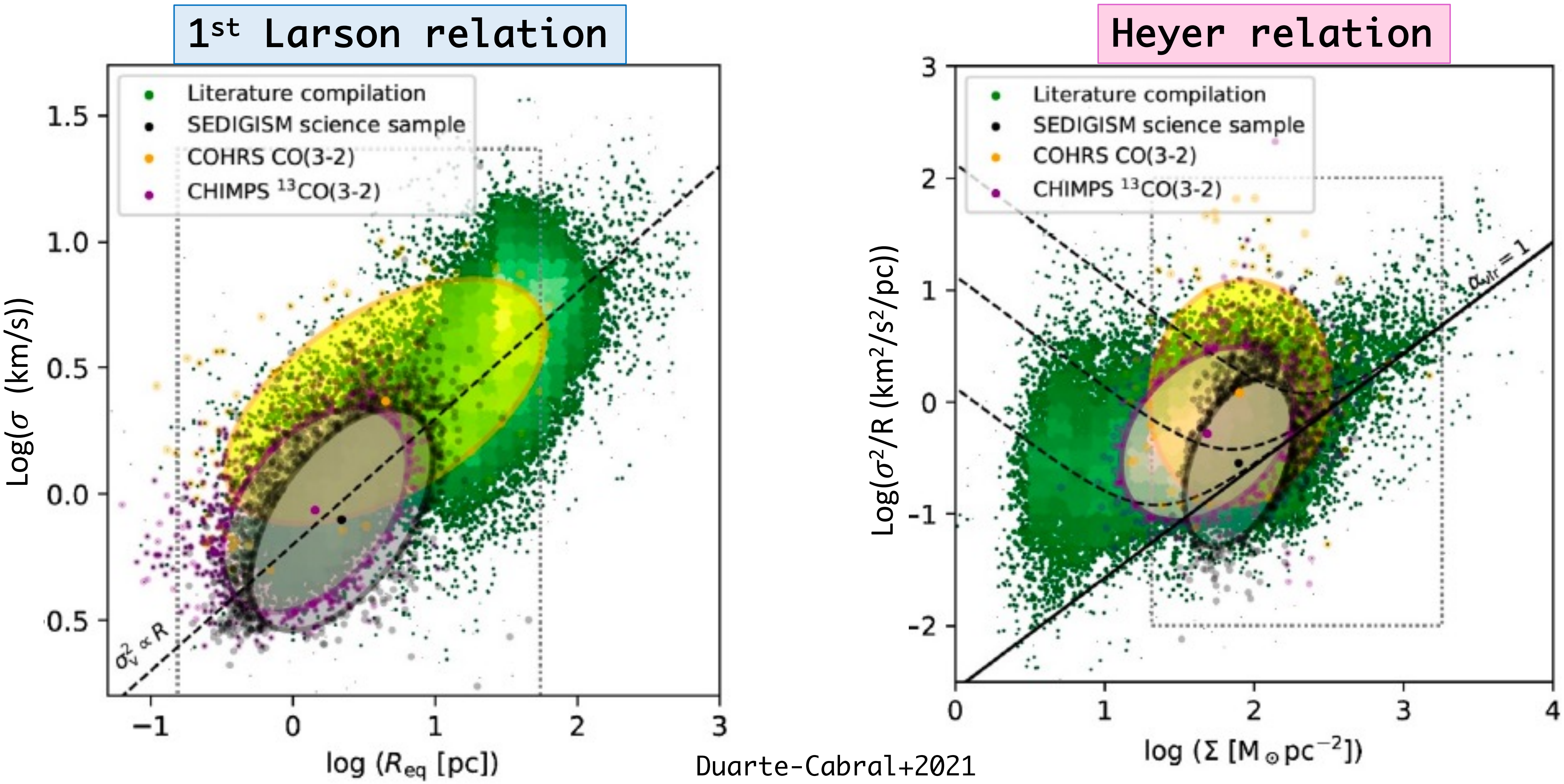
Clouds identified and separated with SCIMES algorithm (Colombo+15)



6664 clouds with well defined physical and dynamical properties

Duarte-Cabral+21

Larson & Heyer relations in ^{13}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…)
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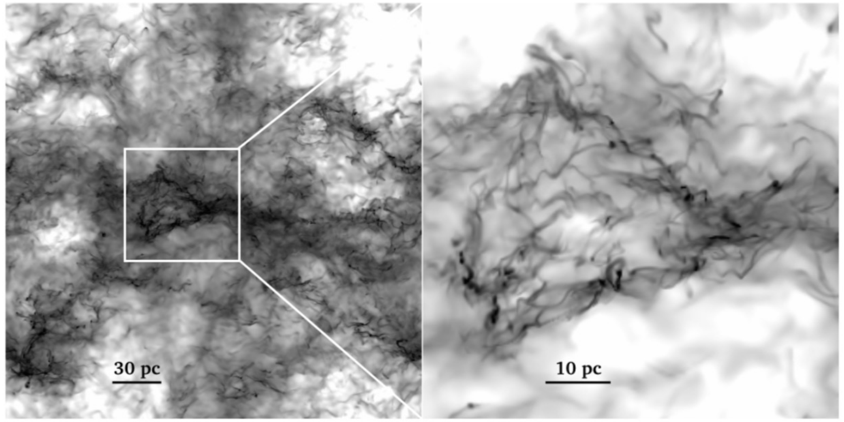
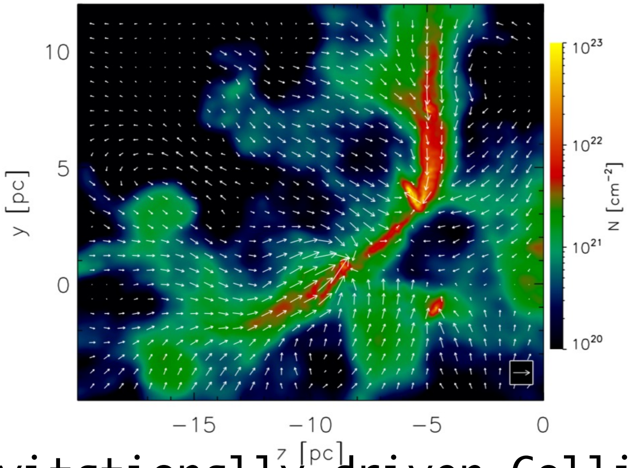
- Gas dynamics in filament and clumps: the role of environment

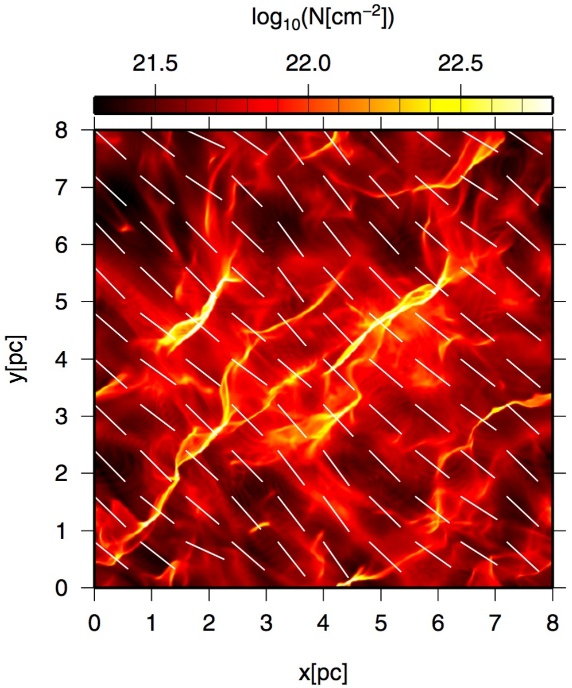
Denser regions in CO molecular clouds: (Galactic scale) FILAMENTS



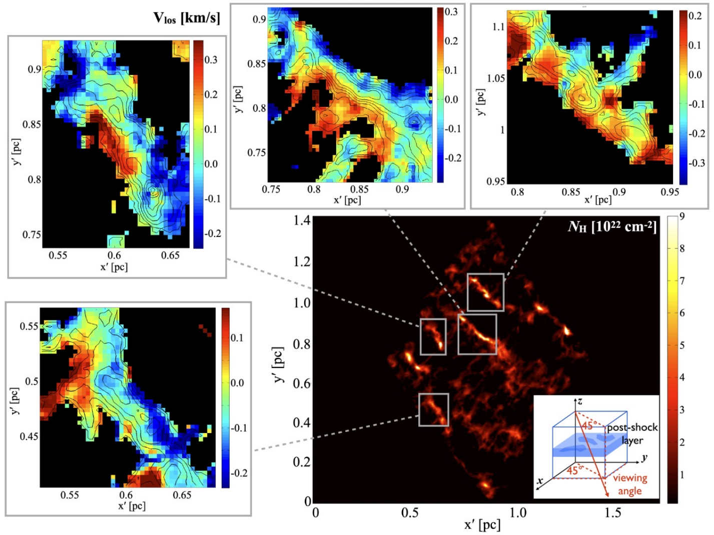
Turbulent fragmentation
Padoan+15



Gravitationally driven Colliding flows
Gomez & Vaquez-Semadeni 14

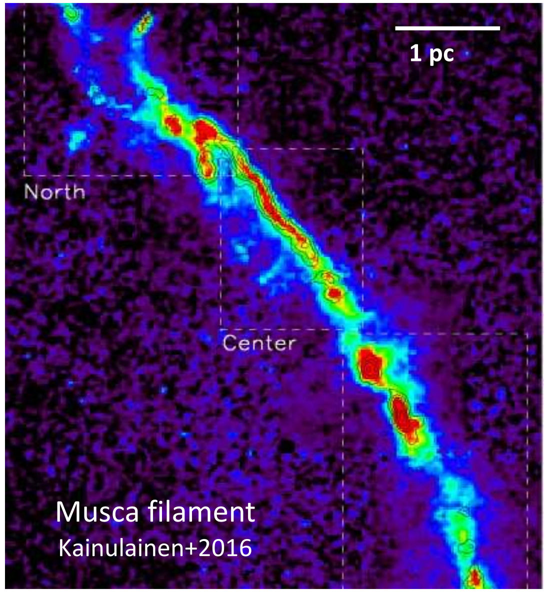


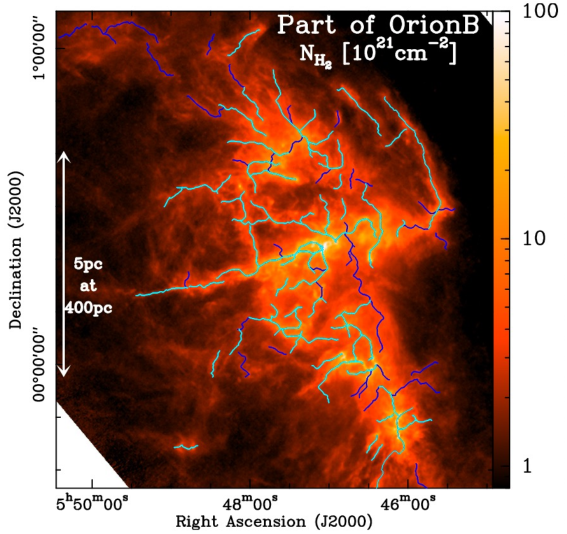
Shock-wave passage
Inutsuka+15

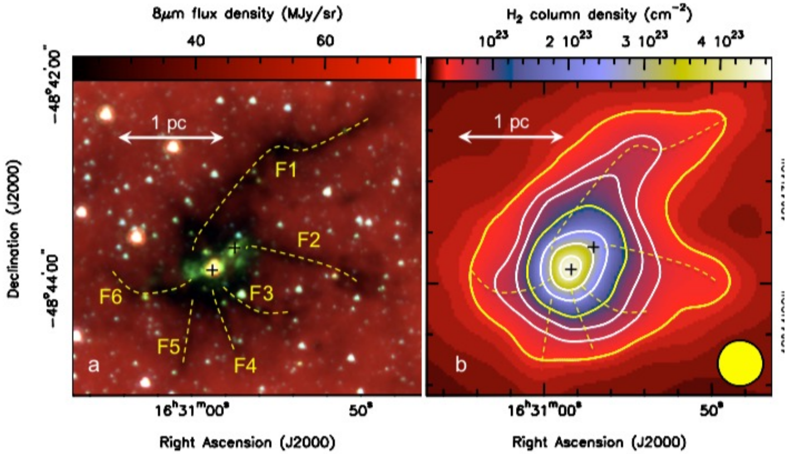


Turbulent, self-gravitating, magnetized converging flow (Chen+20)

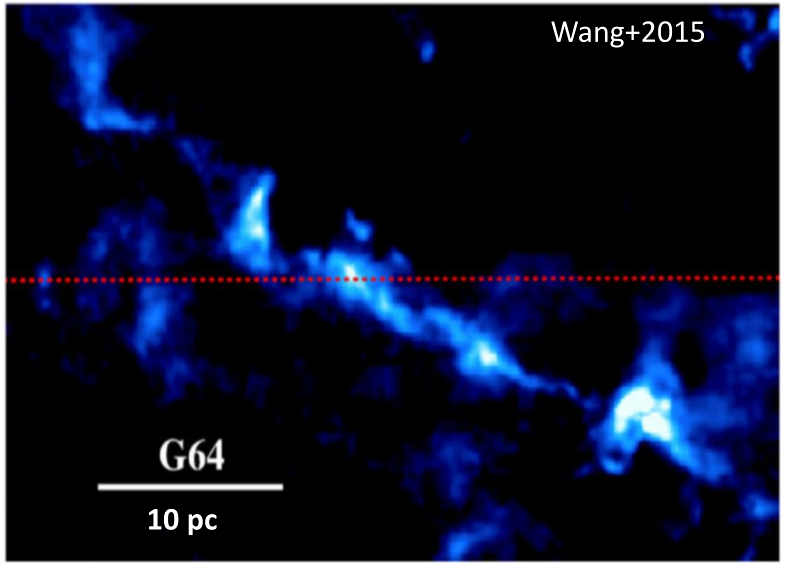
Denser regions in CO molecular clouds: (Galactic scale) FILAMENTS

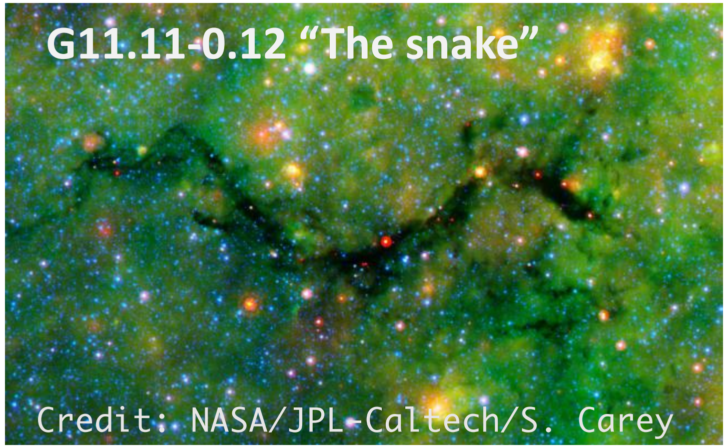






SDC335 Peretto+13





Filaments are denser than CO clouds

Can also be seen in DUST emission (or absorption in the MIR, e.g. IRDCs)

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

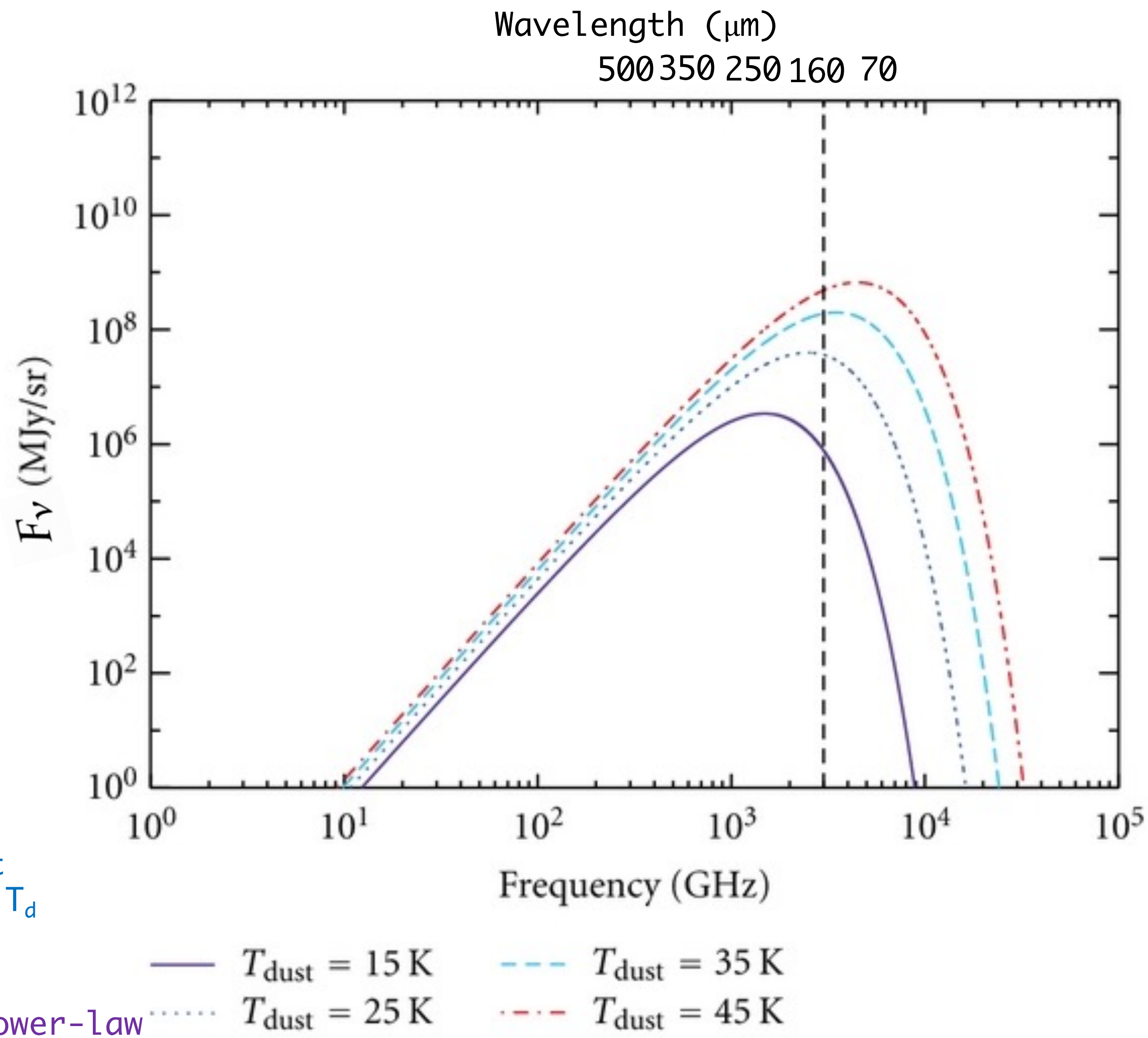
$$F_\nu = \frac{M\kappa_{\rm ref}}{d^2}\left(\frac{\nu}{\nu_{\rm ref}}\right)^\beta B_\nu(T_d)$$

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

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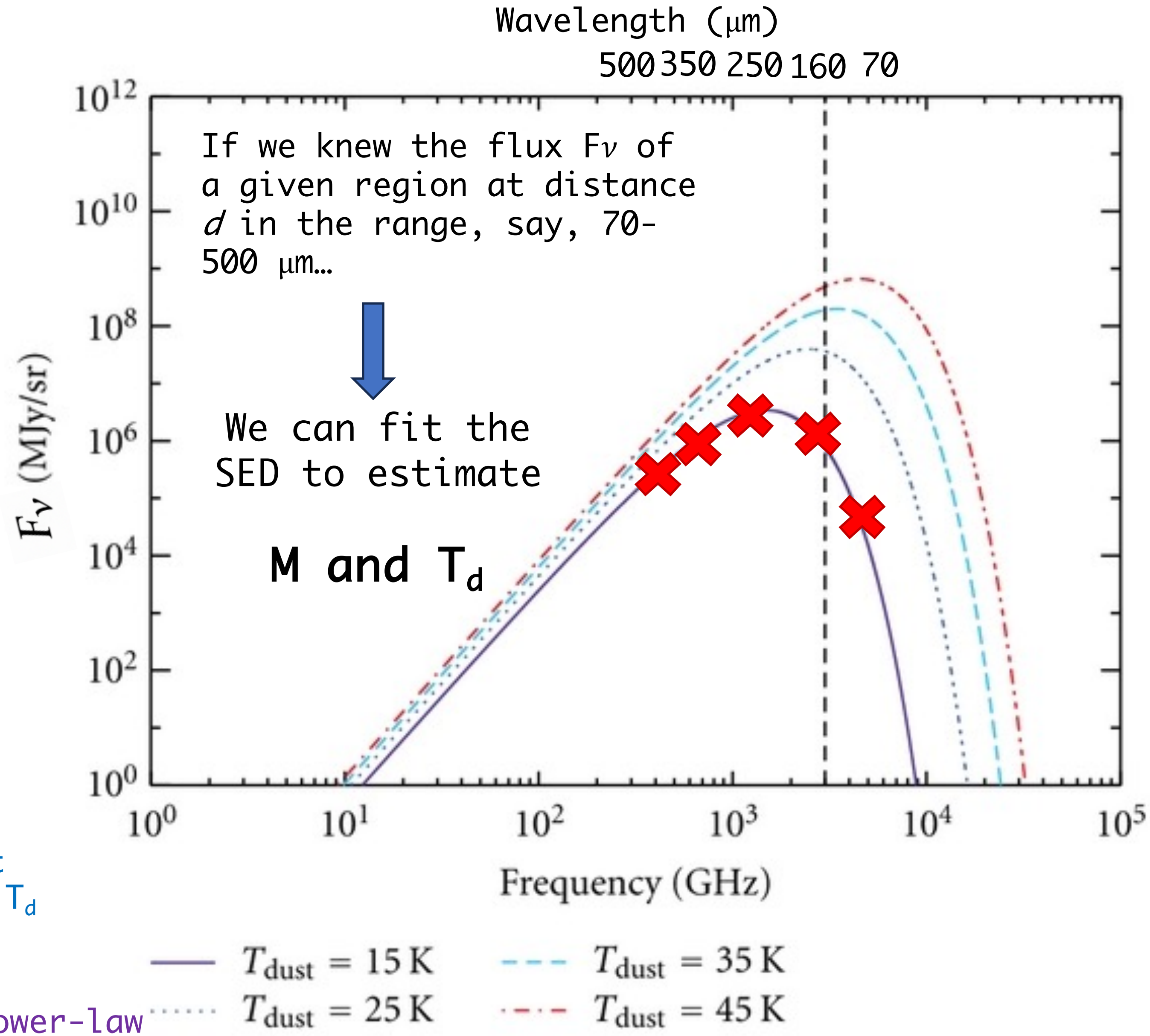
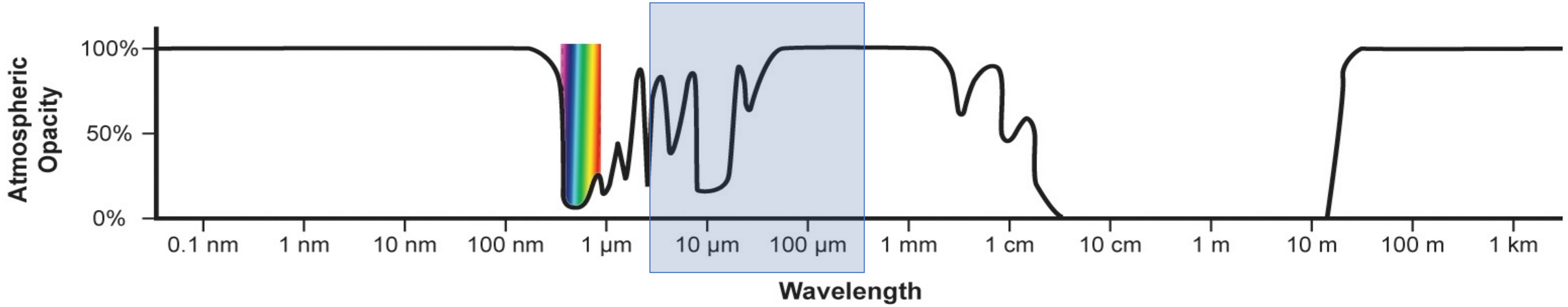
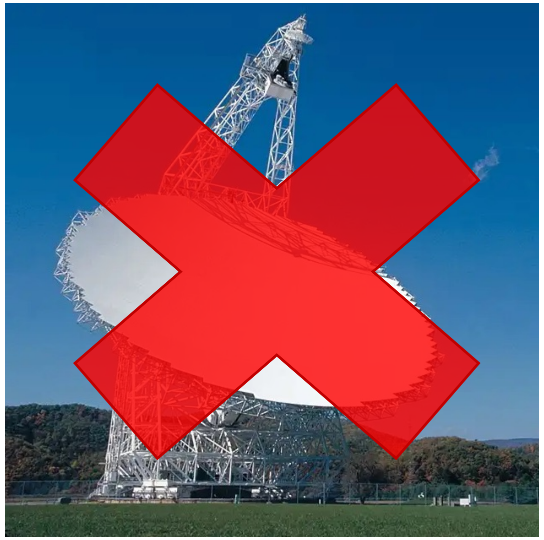


See lecture from Karine Demyk

Observing dust emission in the NIR/MIR/FIR/sub-mm





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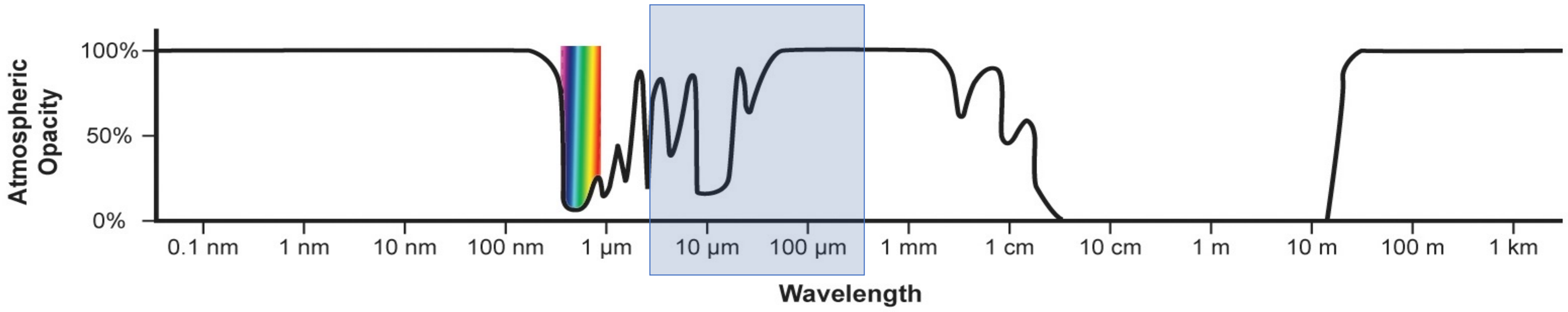
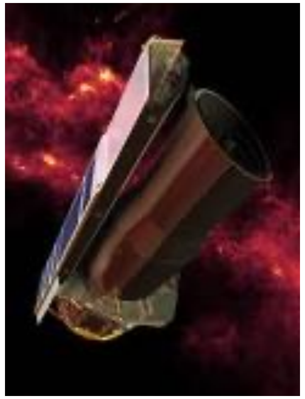


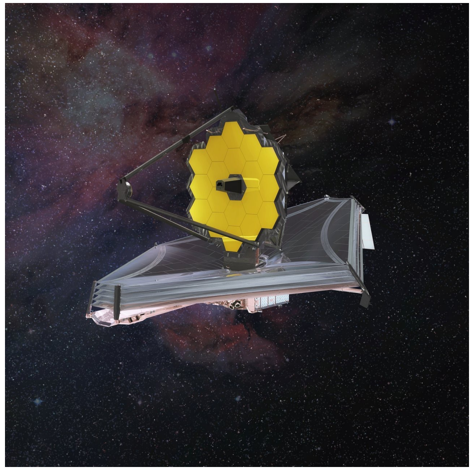
IRAS (1983)
12 ≤ λ ≤ 100 µm

ISO (1995)
2.5 ≤ λ ≤ 240 µm

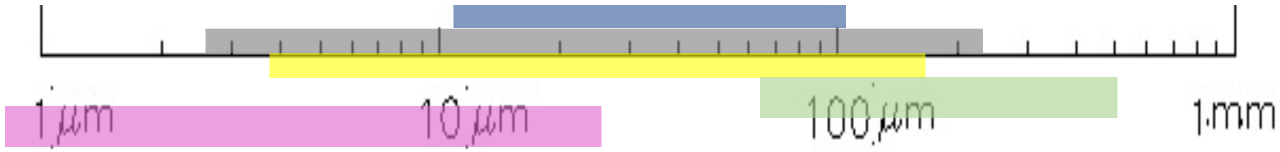


Spitzer (2003)
3.6 ≤ λ ≤ 160 µm

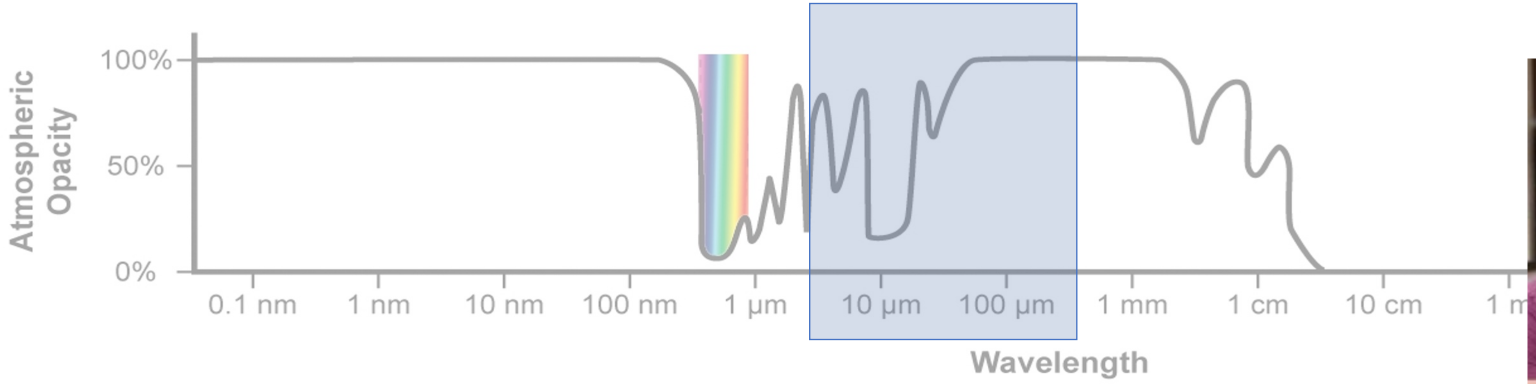
Herschel (2009)
70 ≤ λ ≤ 500 µm



JWST (2022)
0.6 ≤ λ ≤ 28 µm



Observing dust emission in the NIR/MIR/FIR/sub-mm



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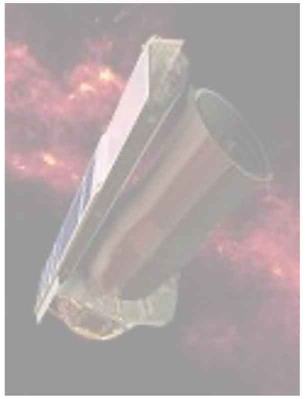

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You are here!!!

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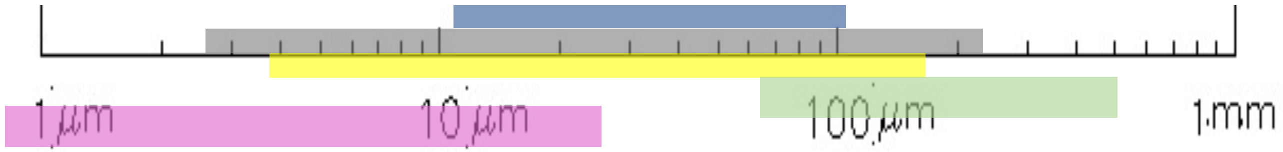
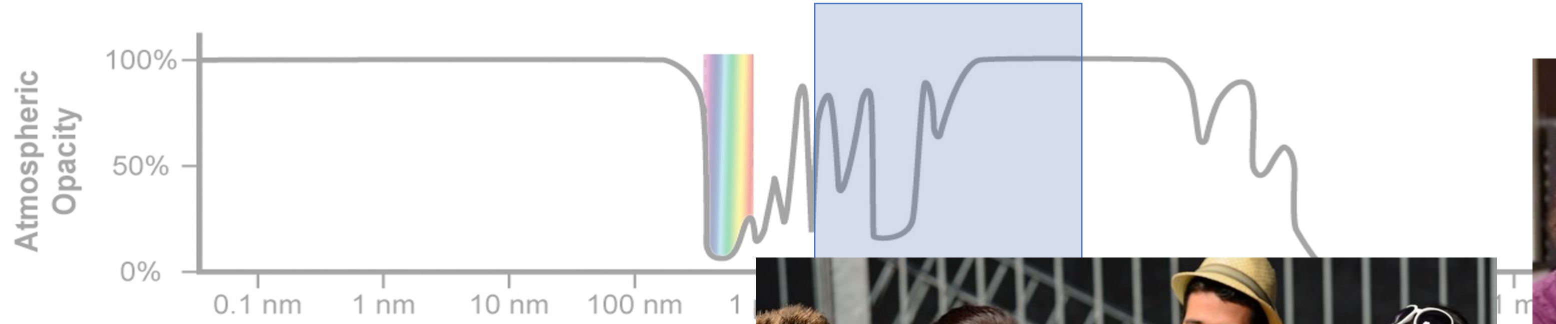
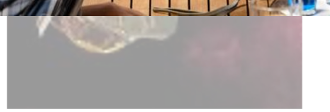


Observing dust emission in the NIR/MIR/FIR/sub-mm





IRAS (1983)
12 ≤ λ ≤ 100 μm

ISO (1995)
2.5 ≤ λ ≤ 240 μm

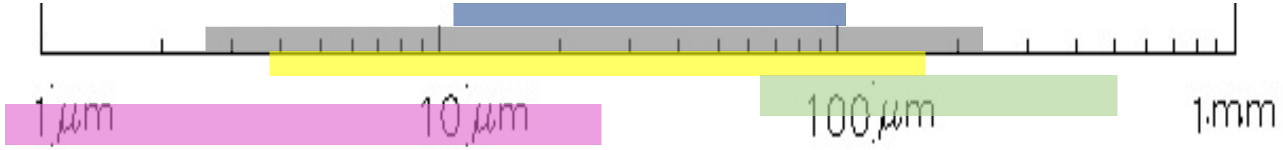
Spitzer (2003)
3.6 ≤ λ ≤ 160 μm

I started here…

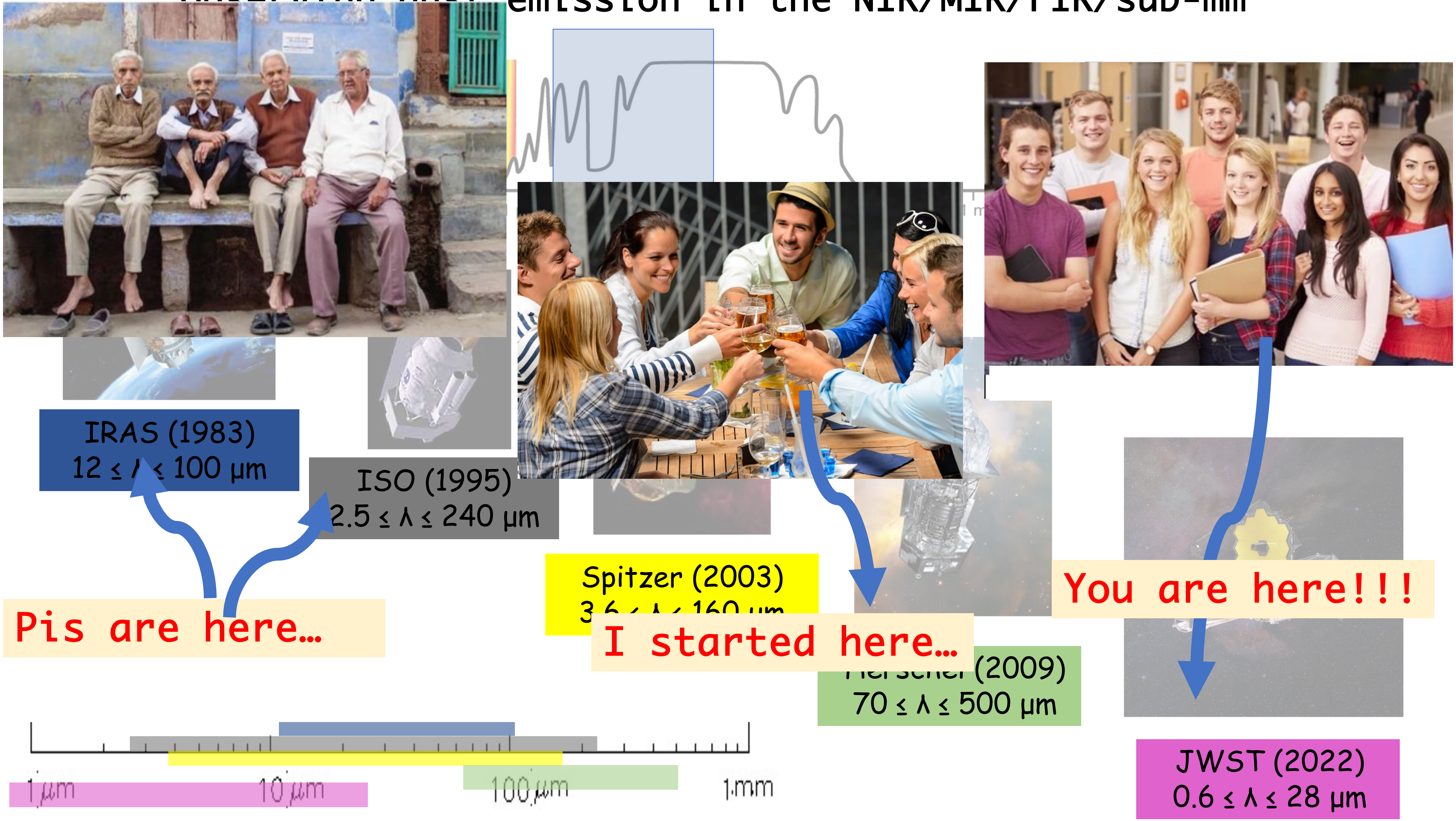
Herschel (2009)
70 ≤ λ ≤ 500 μm

You are here!!!

JWST (2022)
0.6 ≤ λ ≤ 28 μm



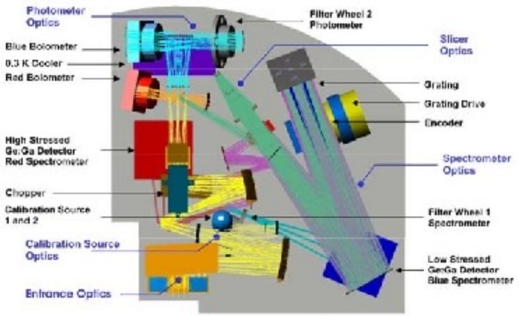
Observing dust emission in the NIR/MIR/FIR/sub-mm

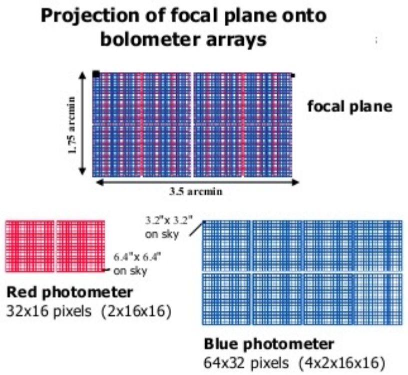


The Herschel FIR/sub-mm observatory

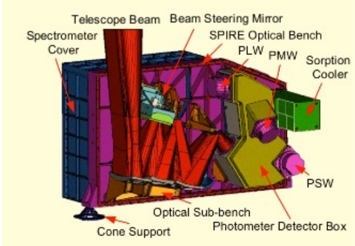
Band (μm)	Bolometers	Beam size (arcsec)	Sensitivity (mJy)
PACS 70	2048	3.2	5.0
PACS 160	512	6.4	10.0
SPIRE 250	139	18.1	7.0
SPIRE 350	88	25.2	7.0
SPIRE 500	43	36.6	7.0

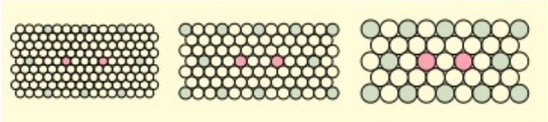
PACS: 70 – 160 μm (Poglitsch et al. 2010)





SPIRE: 250 – 350 - 500 μm (Griffin et al. 2010)

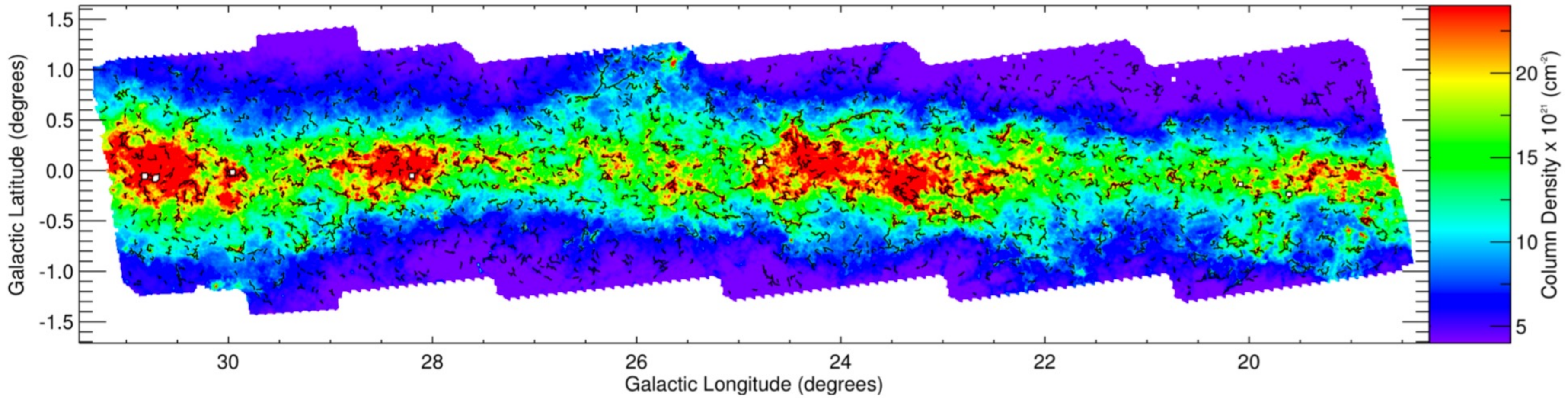


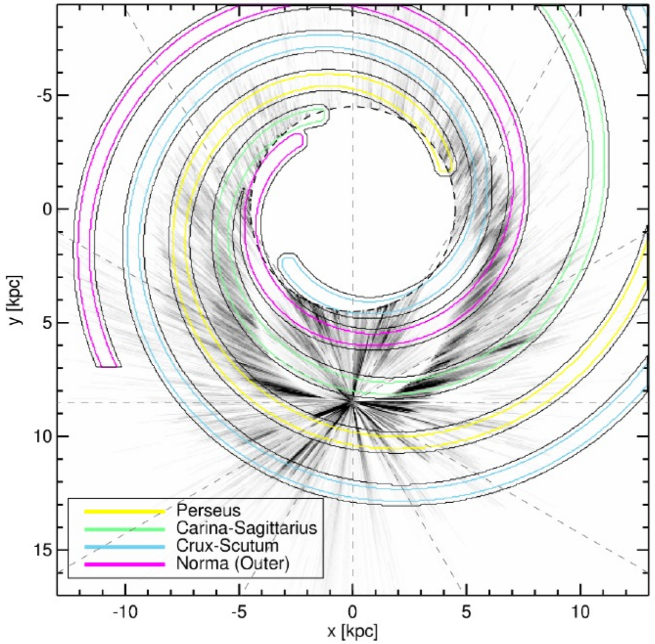


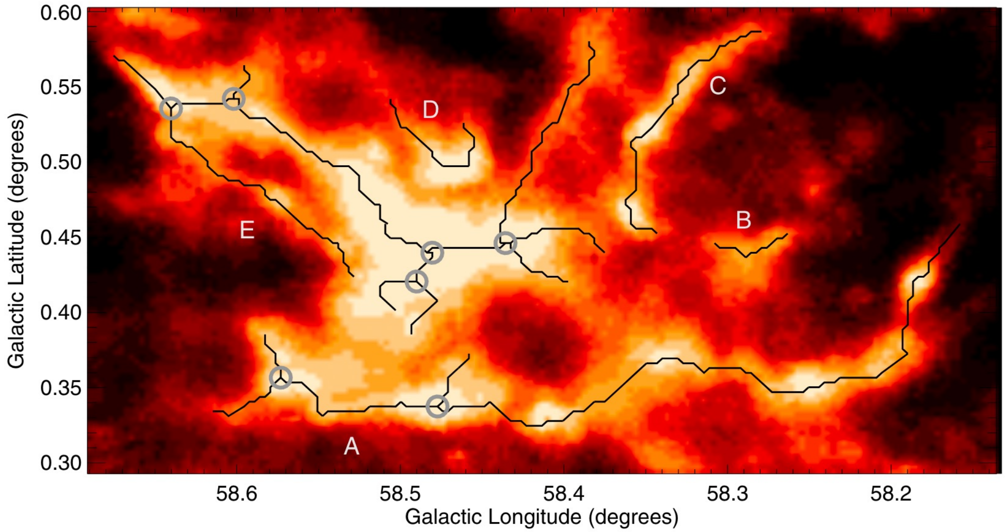
Hi-GAL: the Herschel Galactic Plane survey of the Milky Way in the FIR / sub-mm

Filaments

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







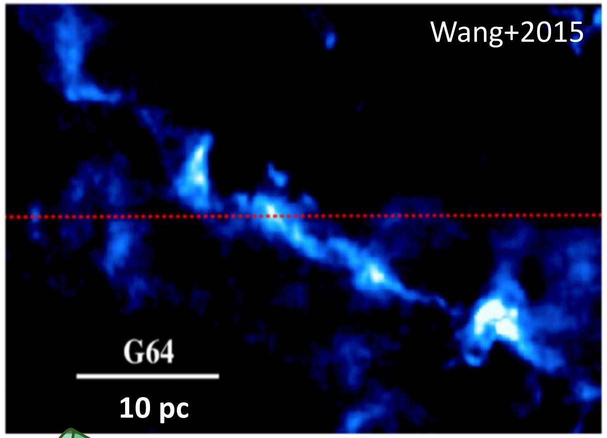
Schisano+14, 20

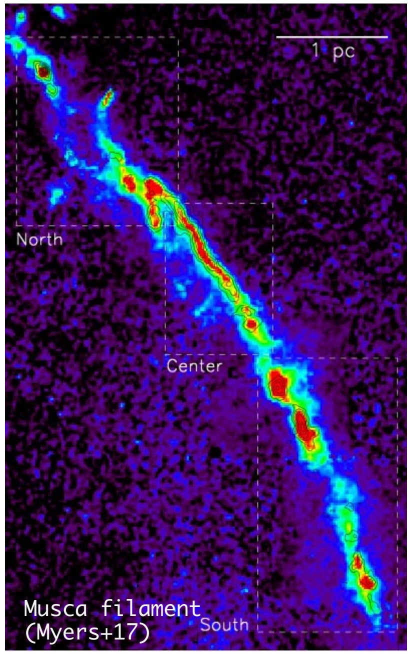
How to characterize filaments from observations

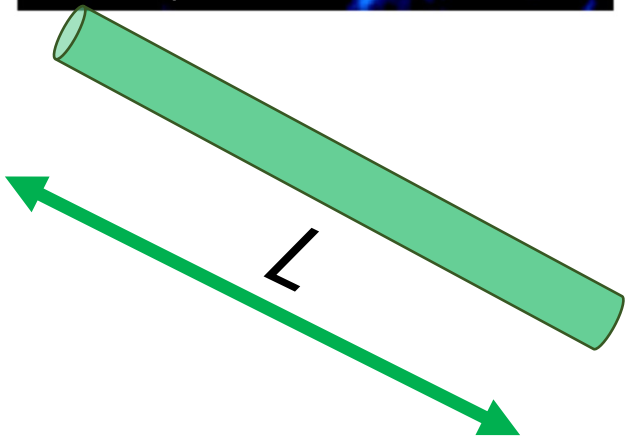
Filaments are elongated, dense, cold structures. The simplest (and more effective) approach to model them is the

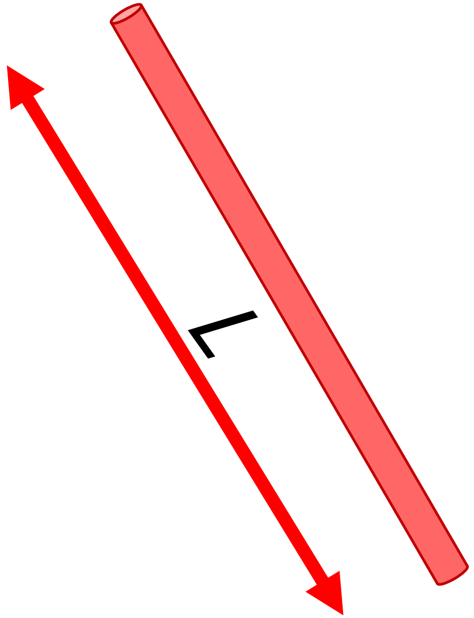
Hydrostatic, isothermal cylinder model

(Ostriker 1964)



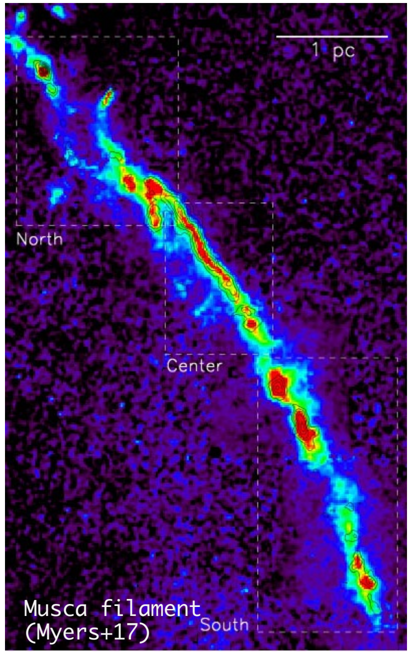






- Mass M, Length L (derived from dust emission)
- Velocity dispersion σ_{tot} (derived from CO transitions)

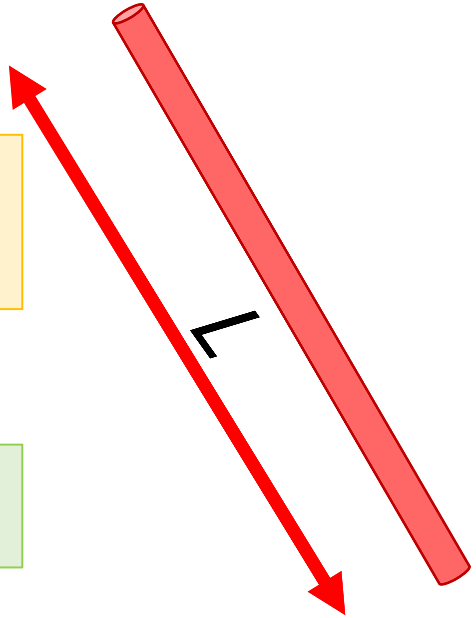
How to characterize filaments from observations



- 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)



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

$f > 1 \rightarrow$ (supercritical)

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

$f < 1 \rightarrow$ (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

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

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

$\Downarrow$

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

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

Under the assumption that **ALL** σ_{tot} works to support the filament against the collapse

How to characterize filaments from observations

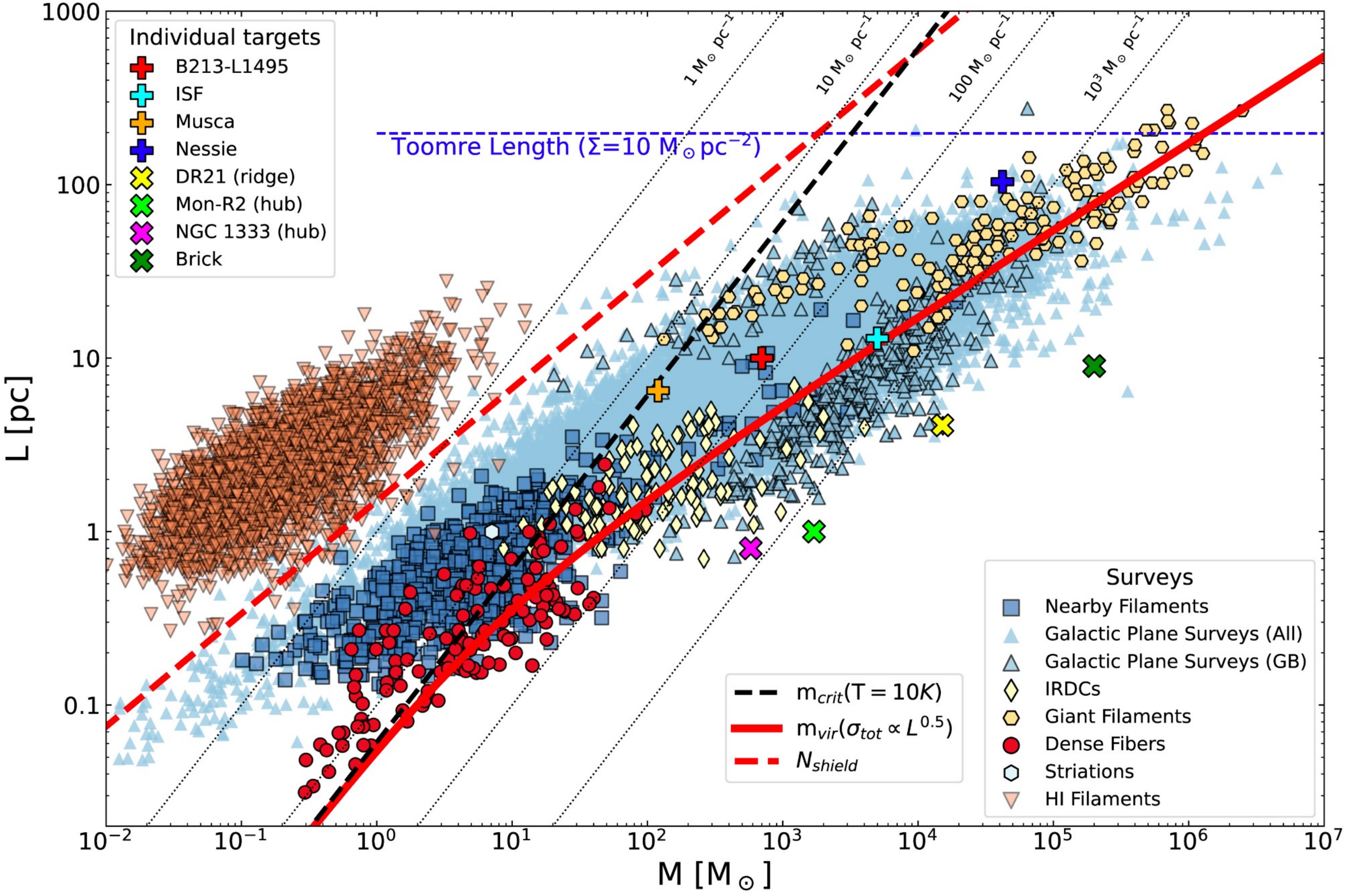
$$m_{\rm crit}(T) = \frac{2\sigma_{\rm th}^2}{G} \qquad \longrightarrow \qquad m_{\rm vir}(\sigma_{\rm tot}) = \frac{2\sigma_{\rm tot}^2}{G}$$

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

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

How to characterize filaments from observations

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

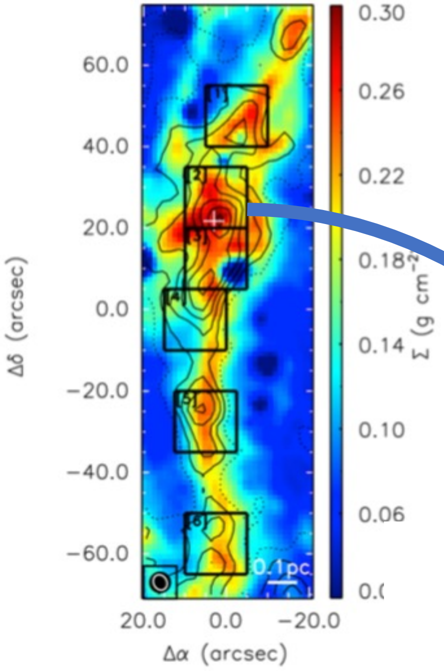


Star-forming regions, clumps and cores - outline

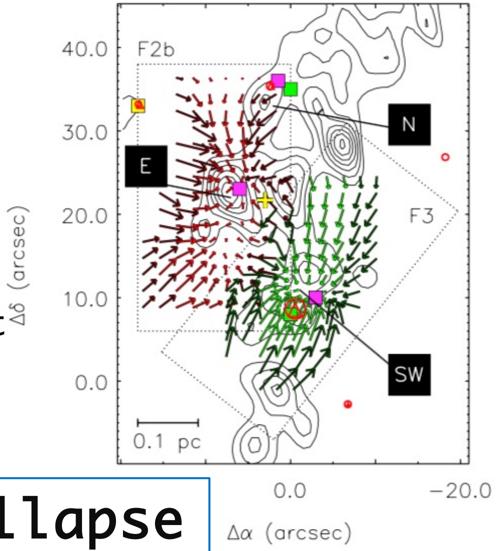
- How do we observe star-forming regions in our own Galaxy?
- Cold (and Warm) HI: the building blocks of star-forming regions
- From HI to H2: the transition phase to molecular clouds
- From H2 to CO: why this molecule is so crucial for observations (and all the limitations…)
- (CO) Molecular clouds: 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}

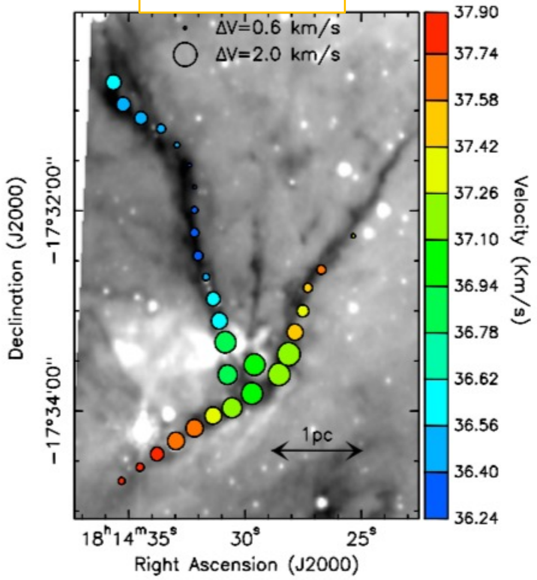


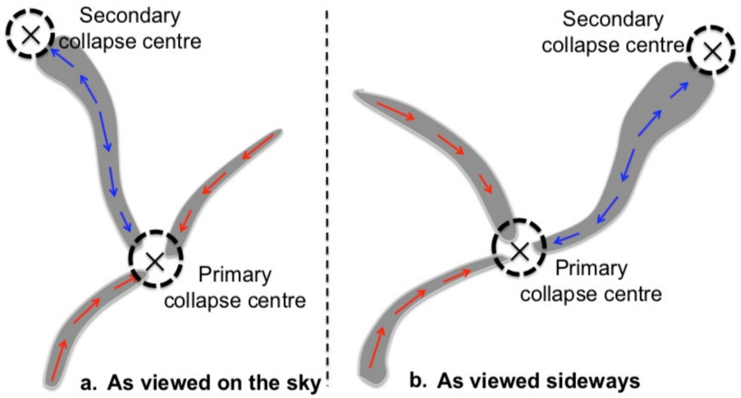
Local
velocity gradient
~ 1.5-2.5 km s^{-1}

Local collapse

Henshaw+14

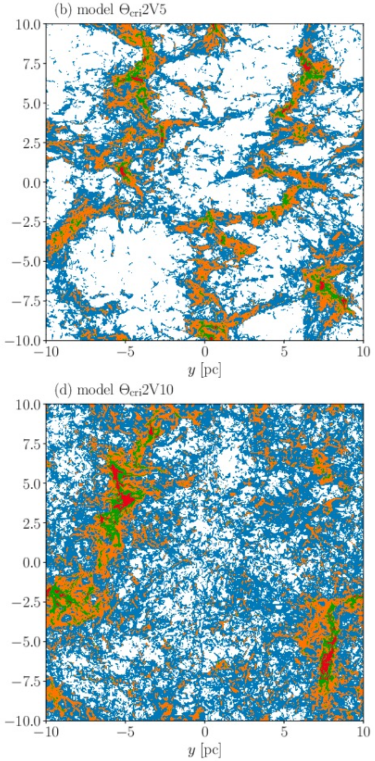
SDC13





Global collapse

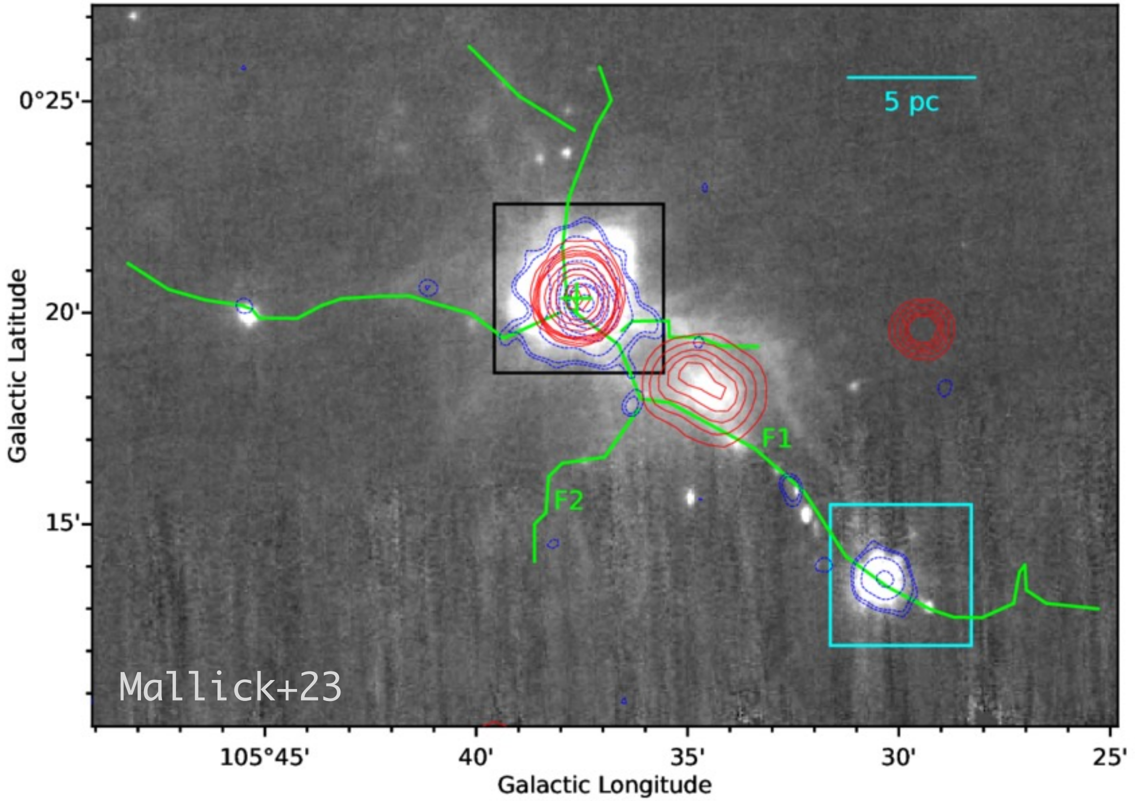
Peretto+14



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

Iwasaki & Tomida 2022

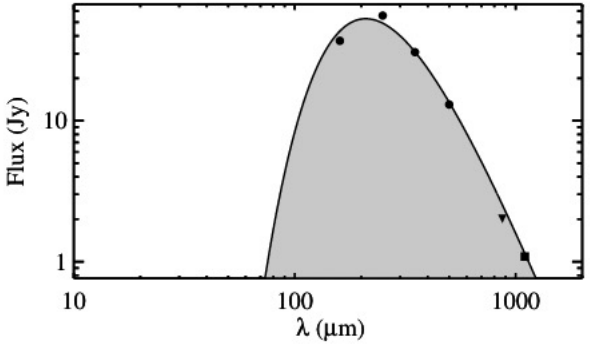
Super-critical filaments: the nursery home of pc-scales clumps



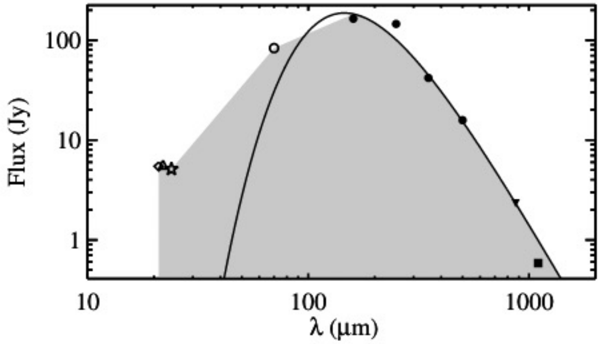
These are the most common structures where you form **clumps**
(pc-scale condensations with ~spherical shape)

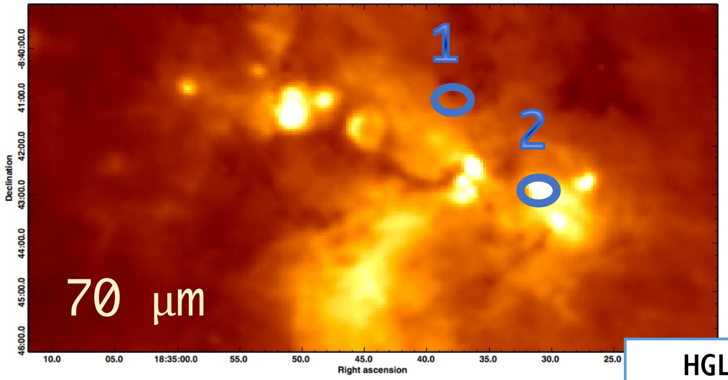
Clumps physical properties

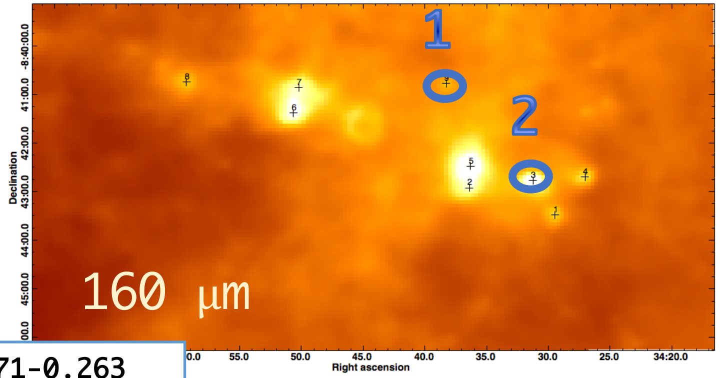
“pre-stellar”



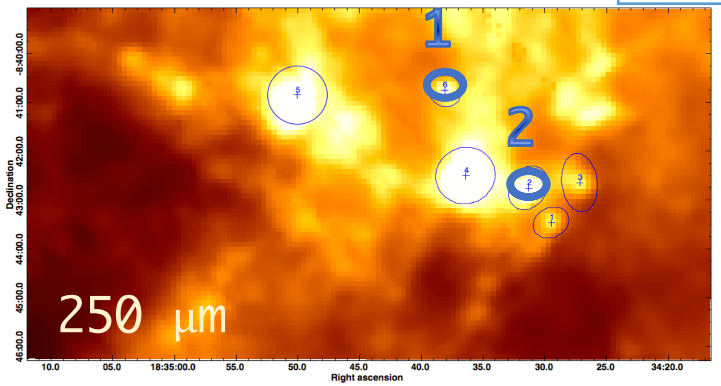
protostar

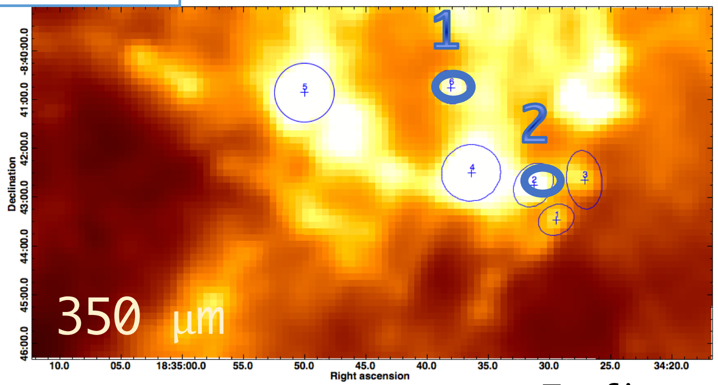




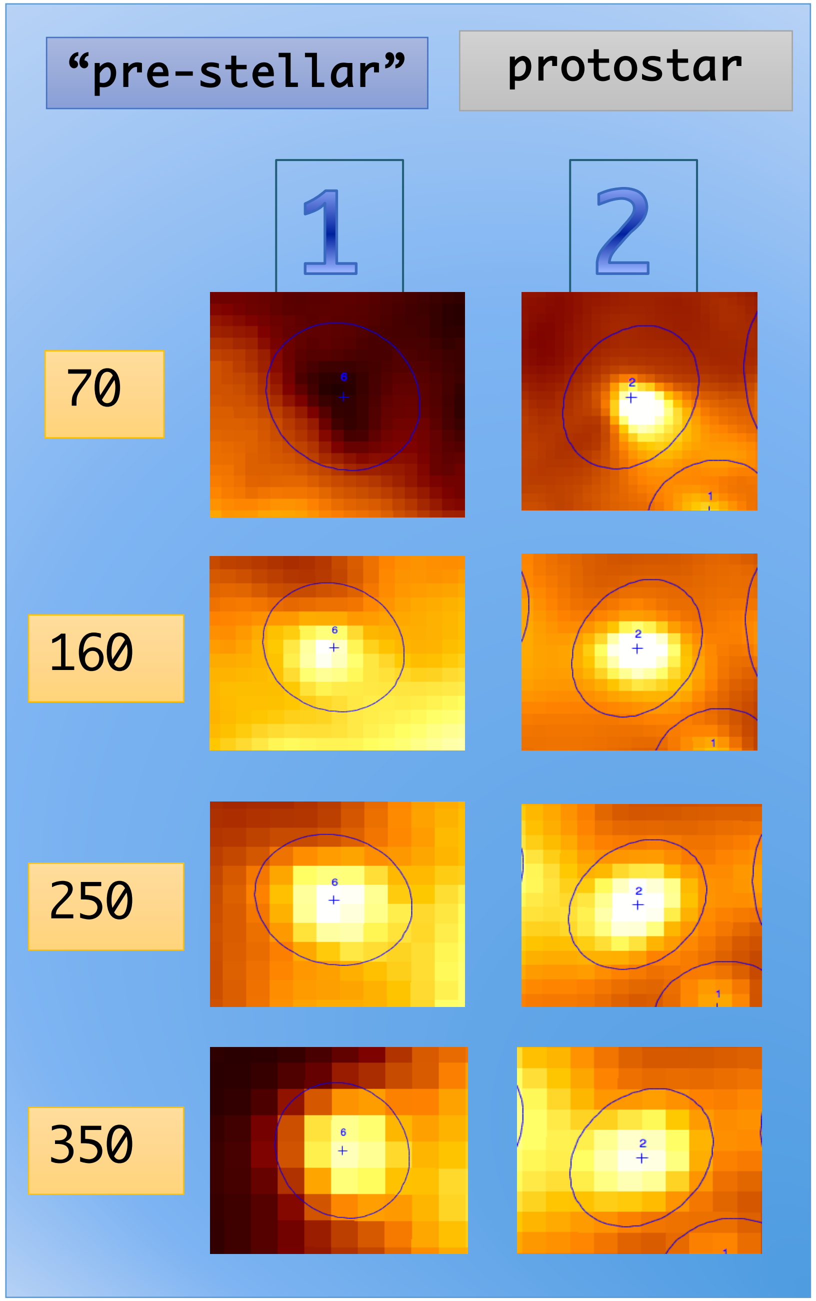


HGL23.271-0.263

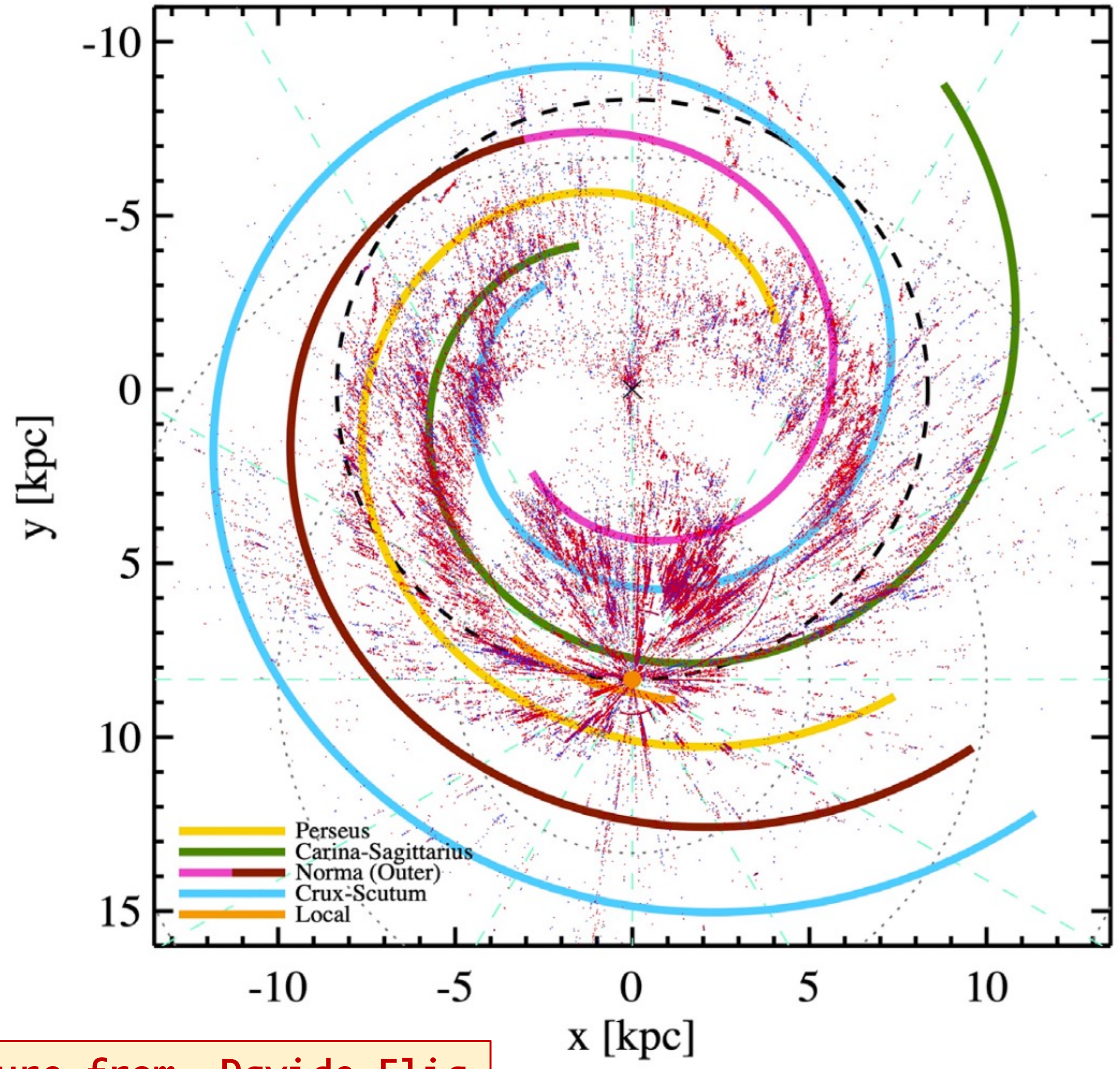




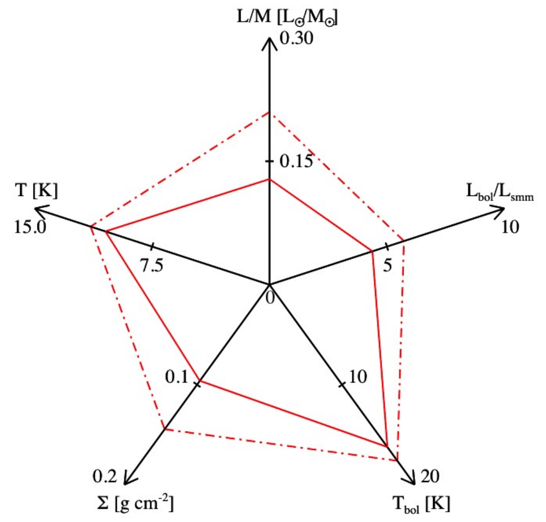
Traficante+15



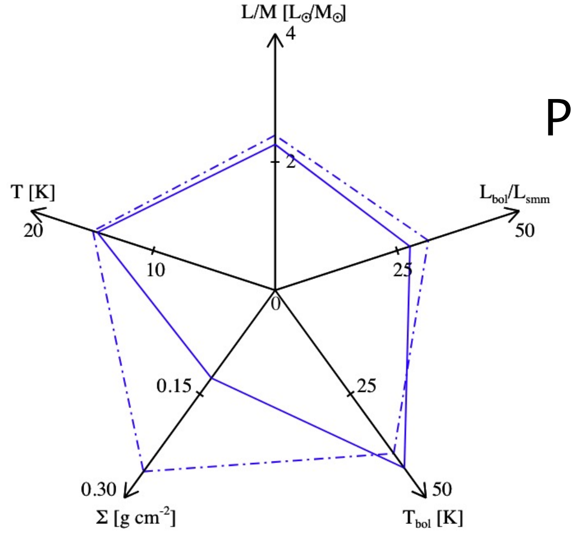
Clumps in the Galaxy



Pre-stellar



Protostellar



See lecture from Davide Elia

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

Elia+21

Clumps physical properties

Properties	Molecular clouds	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

Miville-Dechenes+17
Duarte-Cabral+21

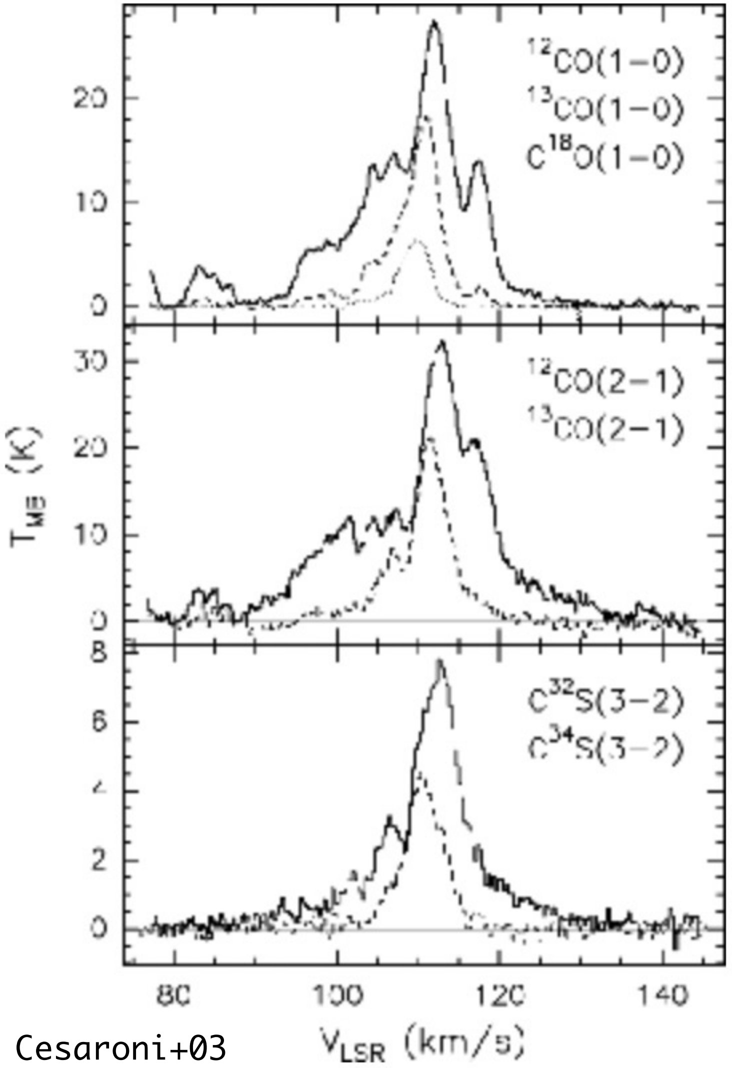
Schisano+14, 20
Hacar+23

Urquhart+14
Traficante+15
Elia+17, 21

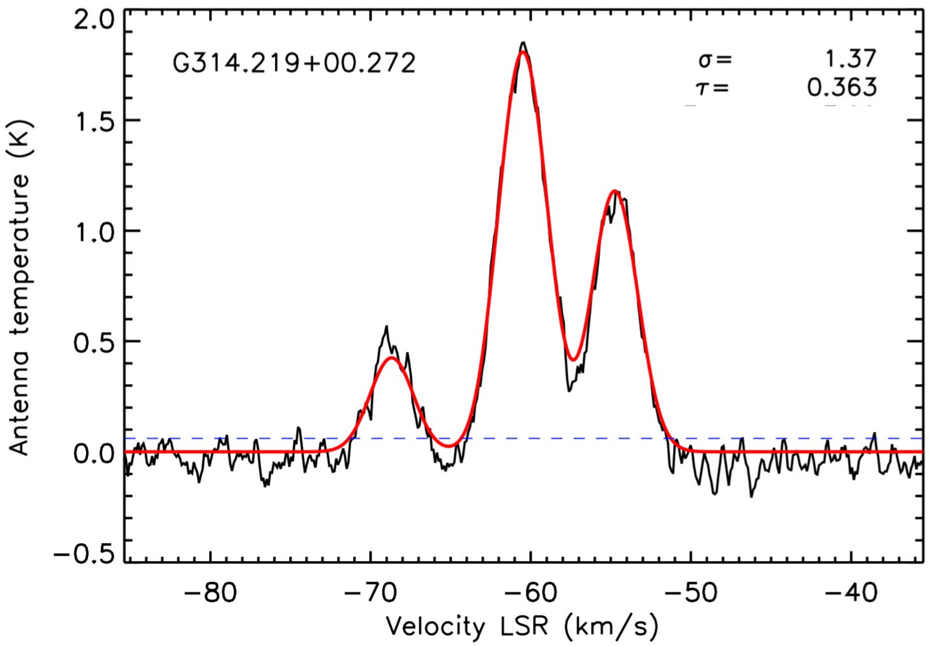
Clumps kinematics

Higher surface density compared to filaments/clouds

CO is not anymore an optically thin tracer



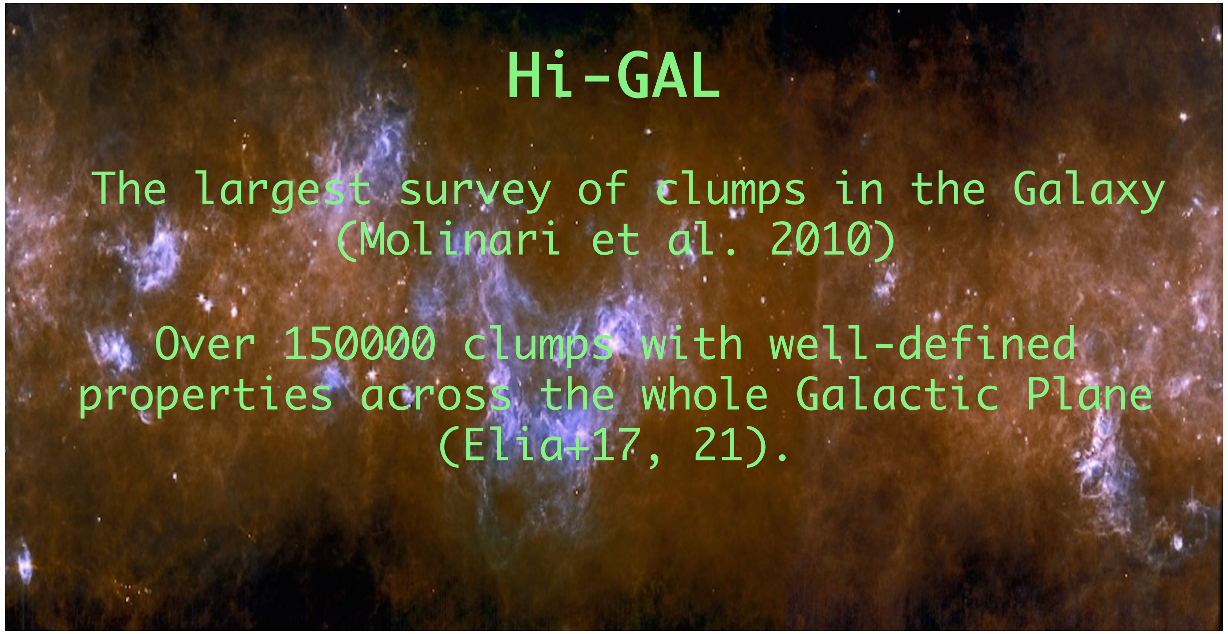
Cesaroni+03



N_2H^+ (1-0)

To get velocity dispersion σ, v_{LSR}

Clumps dynamics

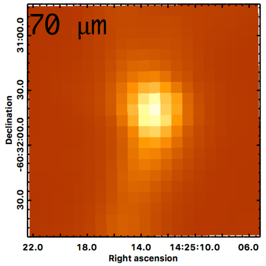


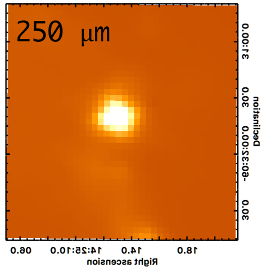
MALT90

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)

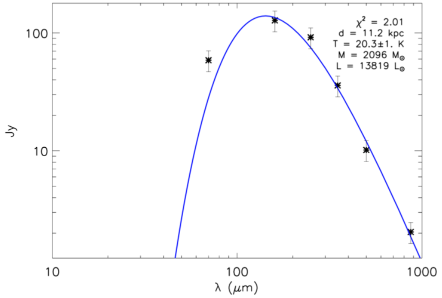
- All MALT90 clumps (2012)
- MALT90 clumps with good N_2H^+ (1-0) spectra (S/N≥5)
- MALT90 clumps with well-defined Hi-GAL distances (l≥10°)
- Hi-GAL clumps with well defined dust SED (24≤λ≤870) µm and gas emission properties

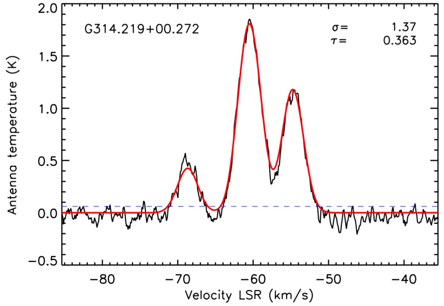




213 clumps

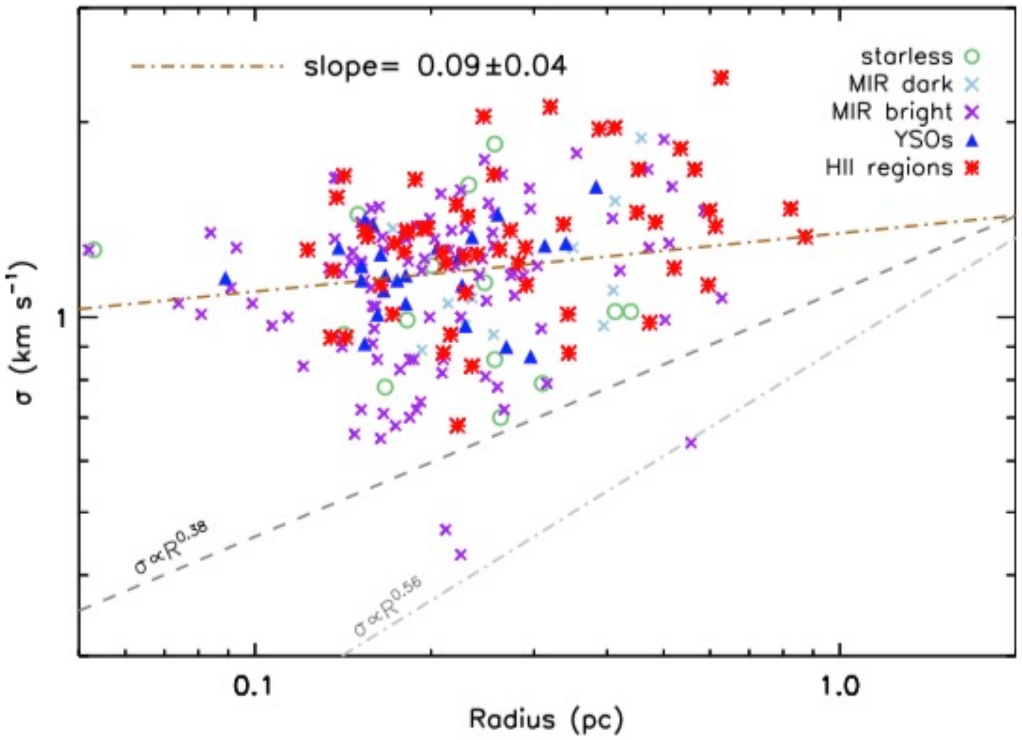
Traficante+18b





Clumps dynamics

1st Larson relation

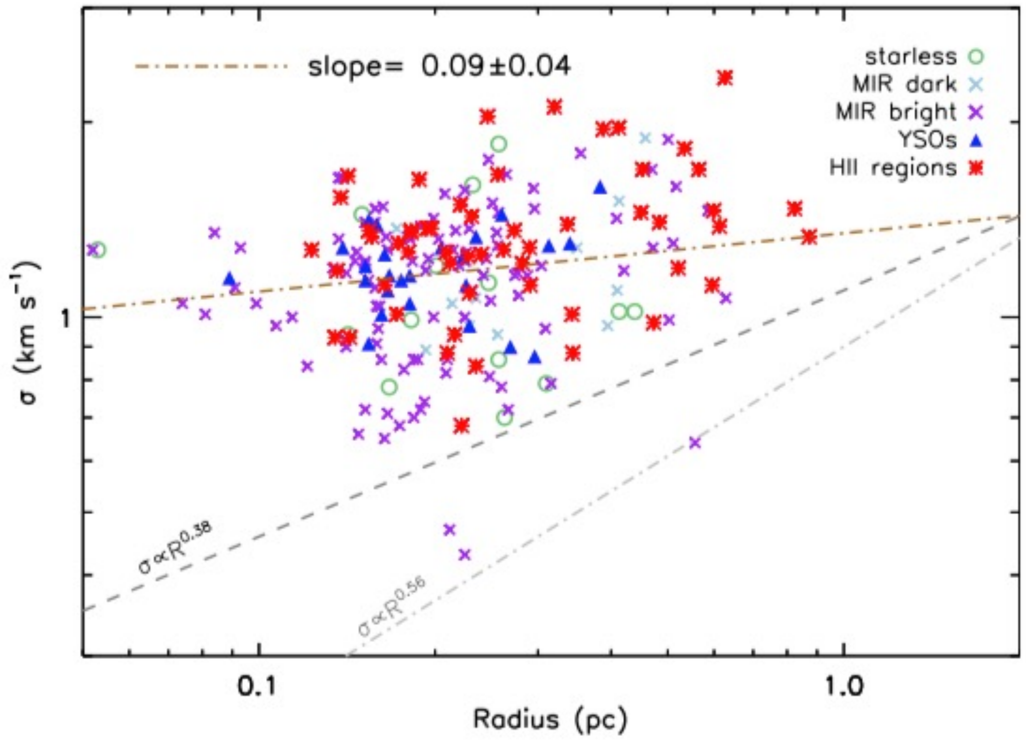


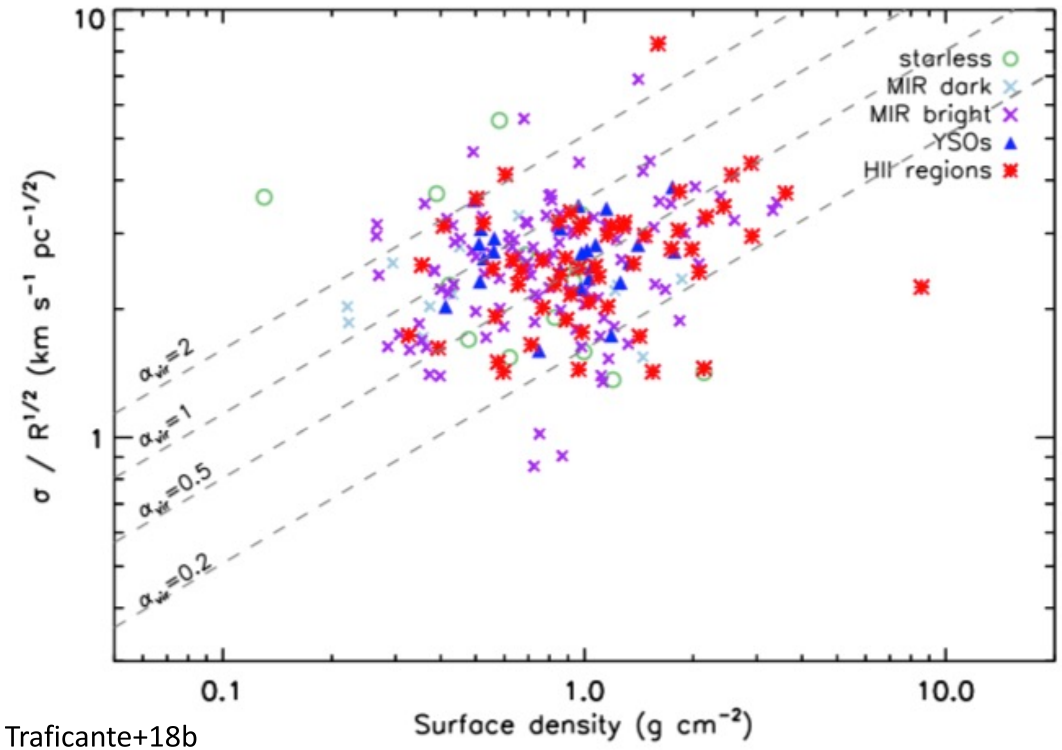
$\sigma \cancel{\propto} R$

Traficante+18b

Clumps dynamics

1st Larson relation





Traficante+18b

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

Traficante+18b

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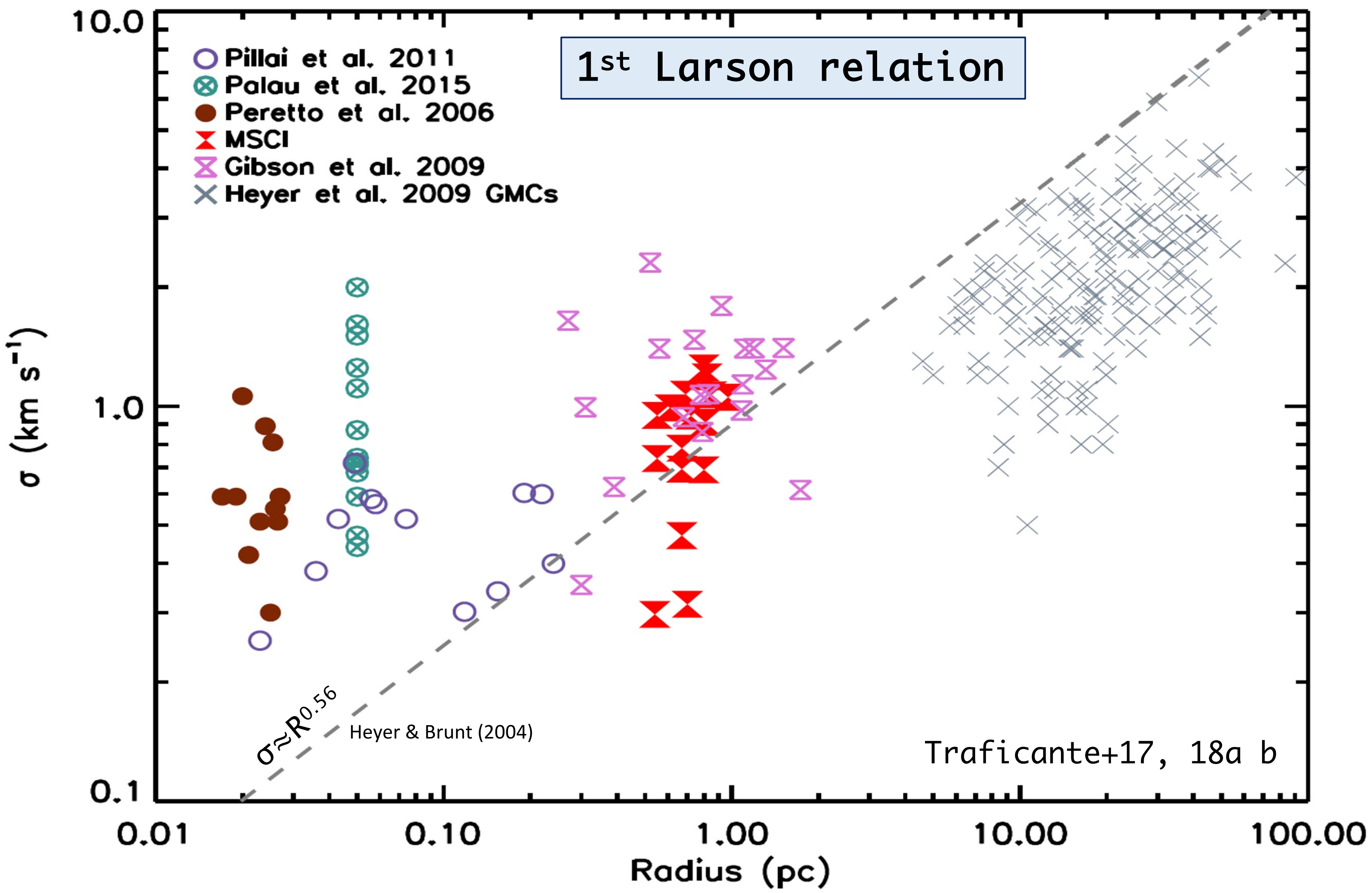
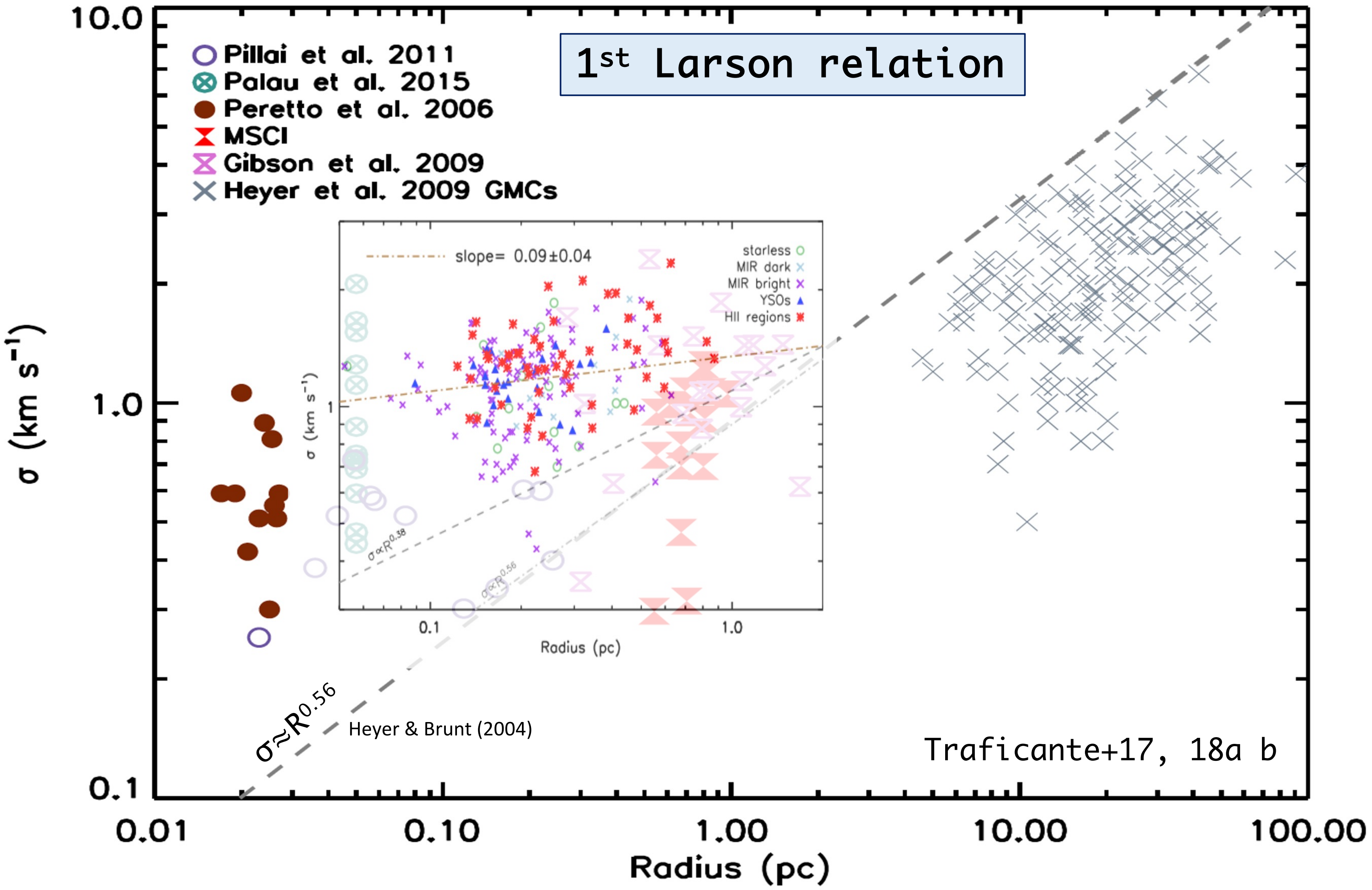
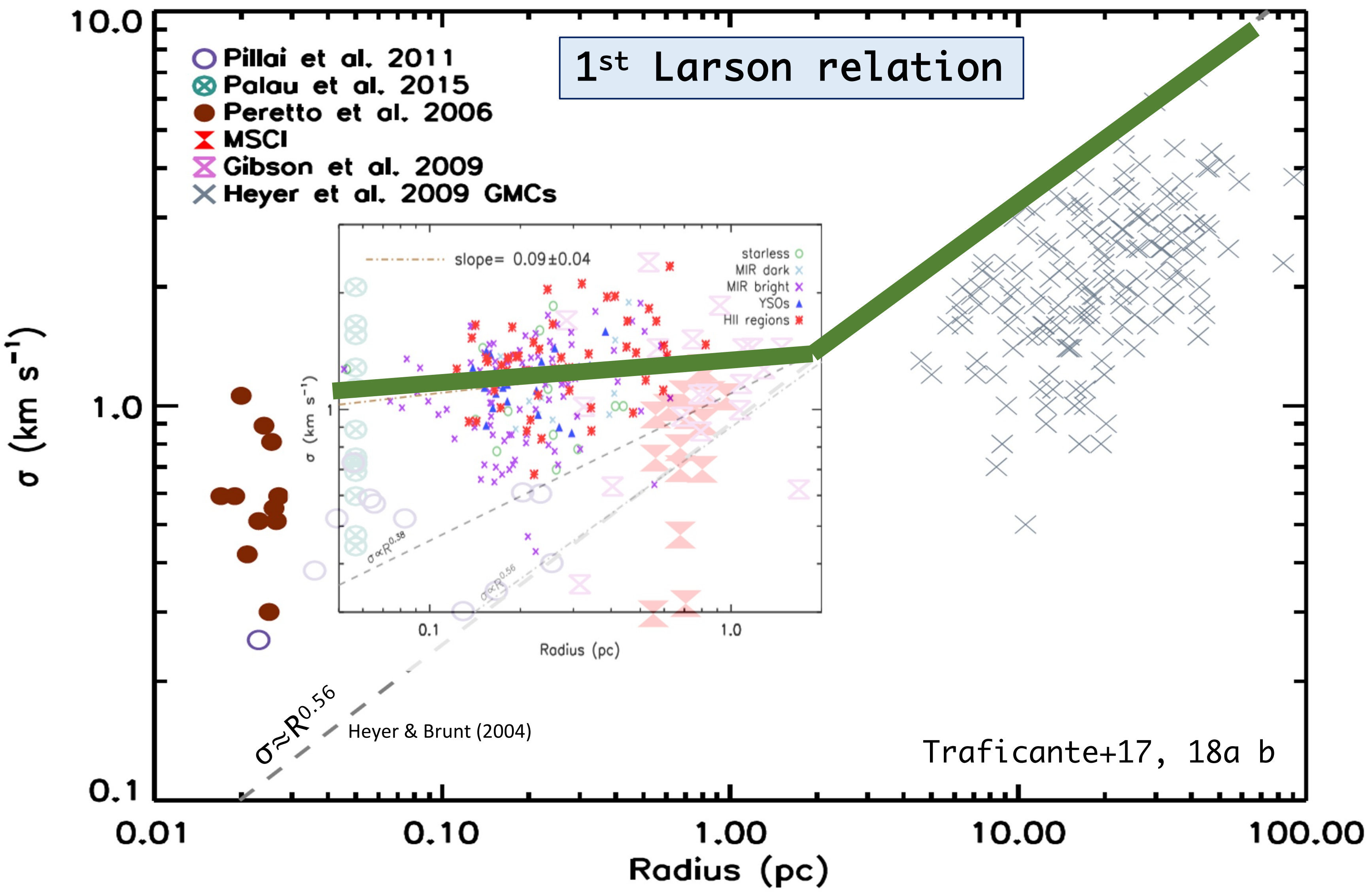
Clumps dynamics in context



Clumps dynamics in context



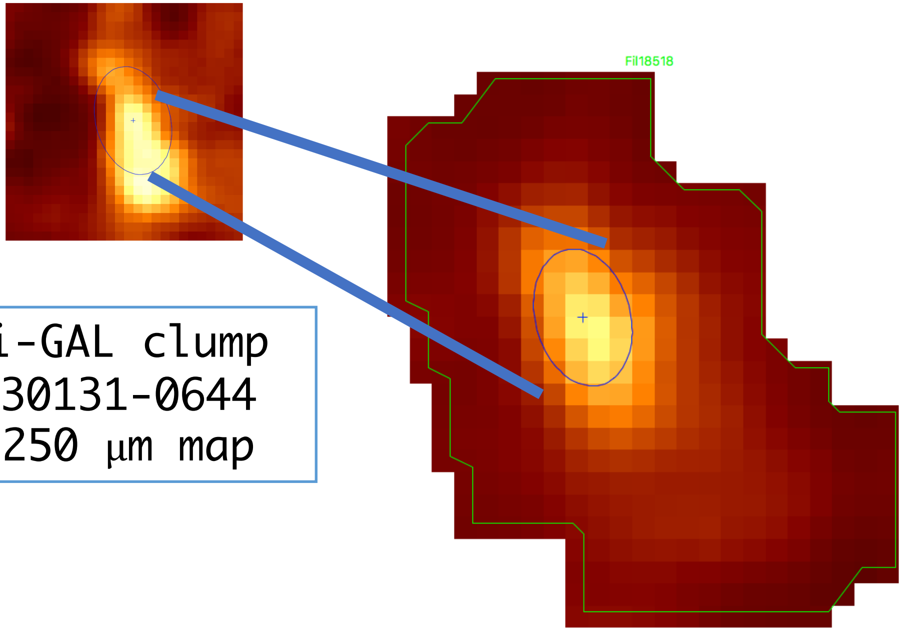
Clumps dynamics in context



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

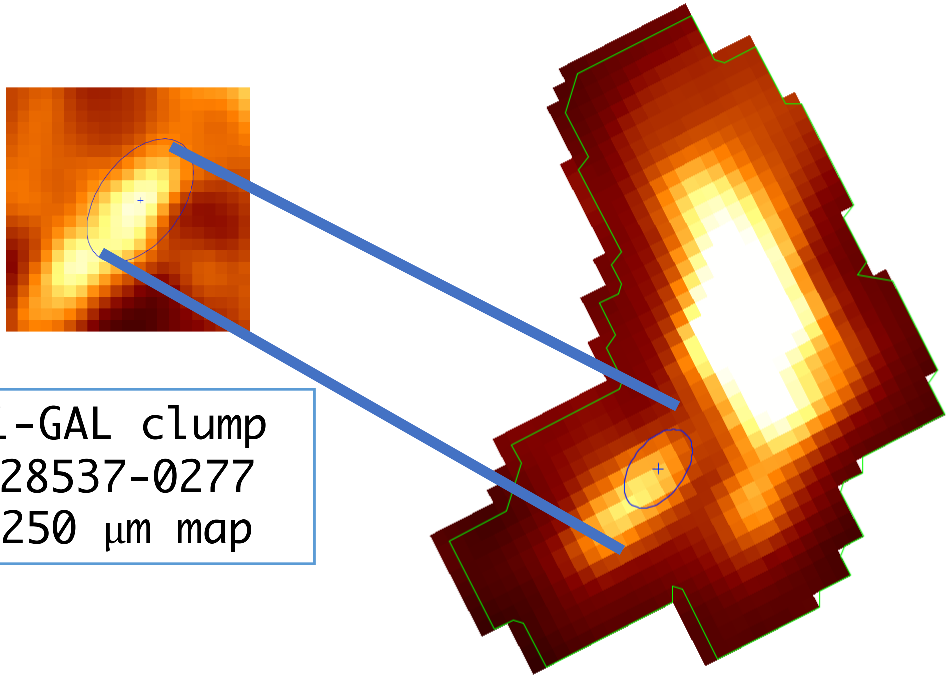
Filament to clumps dynamics

- **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

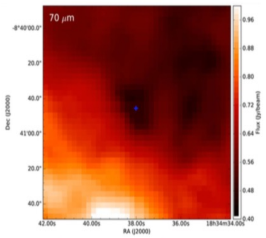


Hi-GAL clump
28537-0277
250 μm map

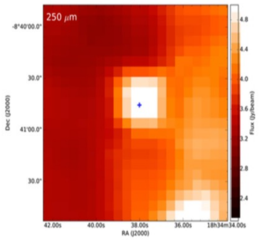
Hi-GAL filament Fil20491
Column density map

Filament to clumps dynamics

70µm-quiet clumps

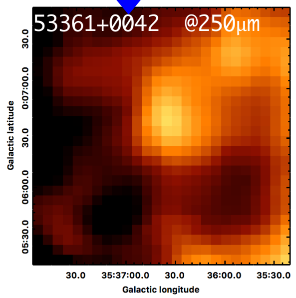


70 µm

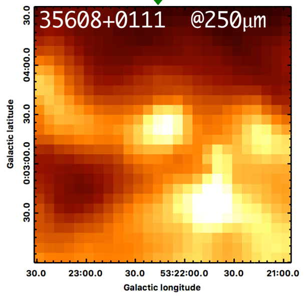


250 µm

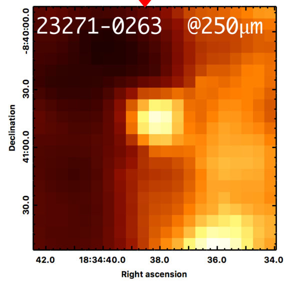
~NO feedback



6 clumps



7 clumps



11 clumps

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

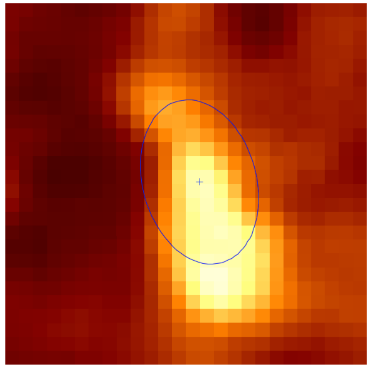
e.g. Urquhart+ 2014

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

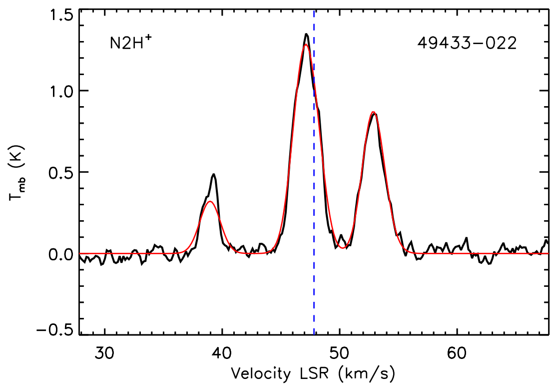
$\Sigma_h > 0.1$ g cm^{-2}
High

e.g. Tan+ 2014

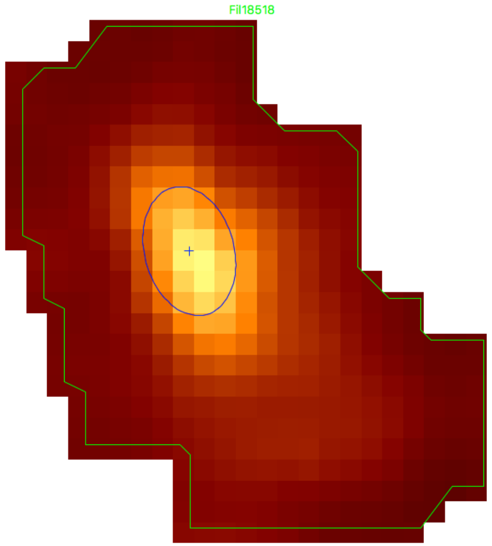
Filament to clumps dynamics



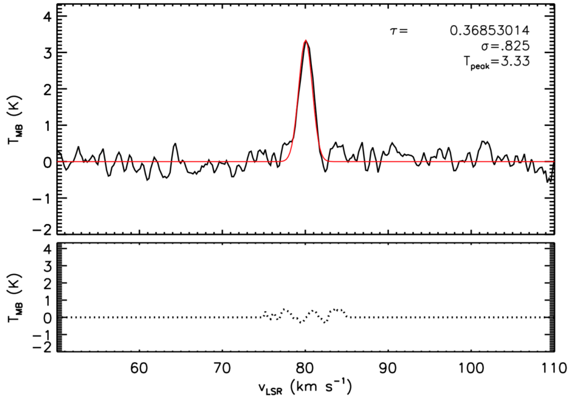
Clump-scale kinematics from N_2H^+ (1-0) observations



IRAM 30m, Traficante+17, 18a



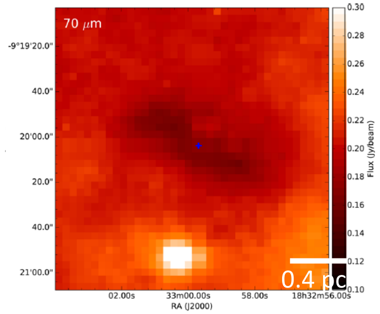
Filament-scale kinematics from ^{13}CO (1-0) observations

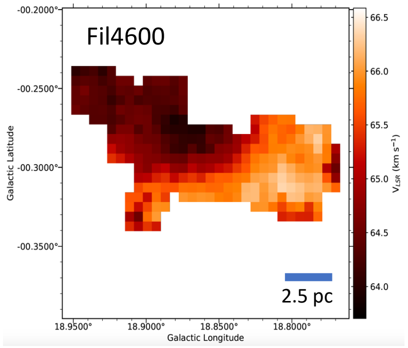


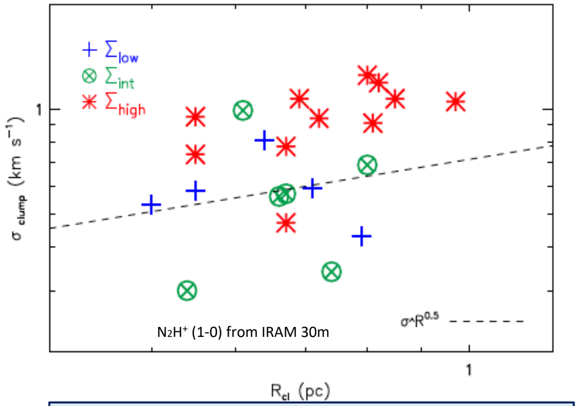
(GRS, Jackson et al. 2013)

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

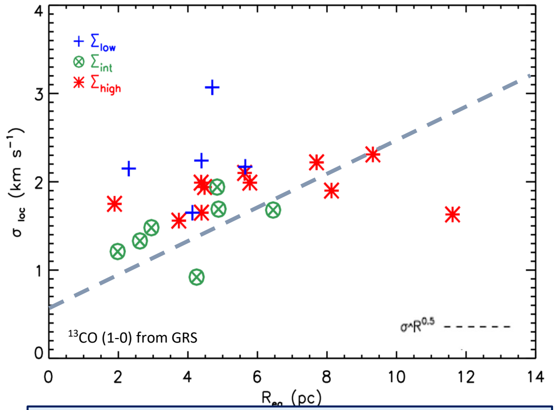
Filament to clumps dynamics: the role of environment





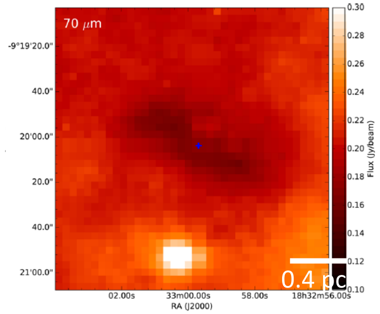


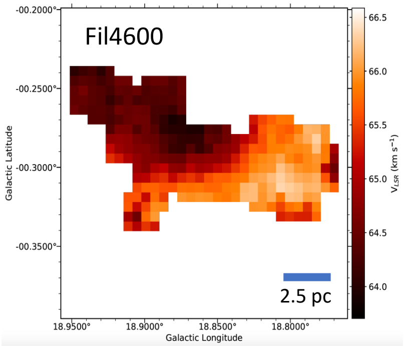
1st Larson relation in clumps

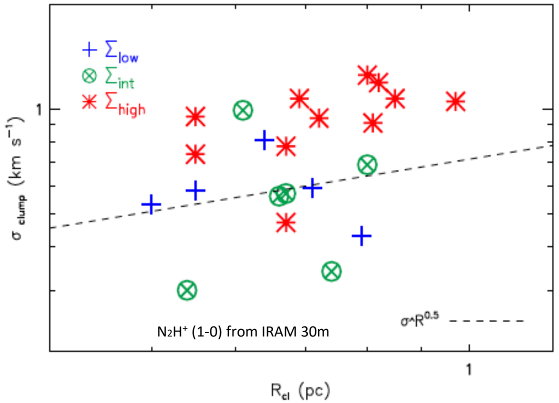


1st Larson relation in filaments

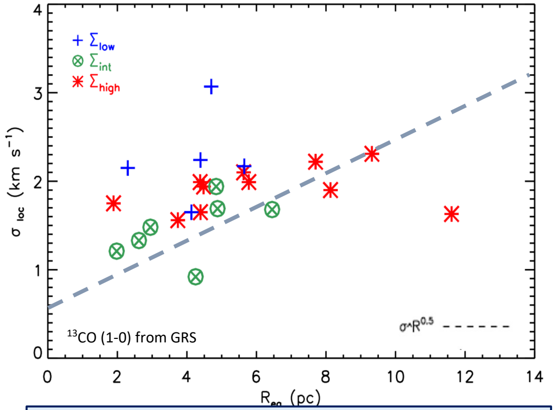
Filament to clumps dynamics: the role of environment



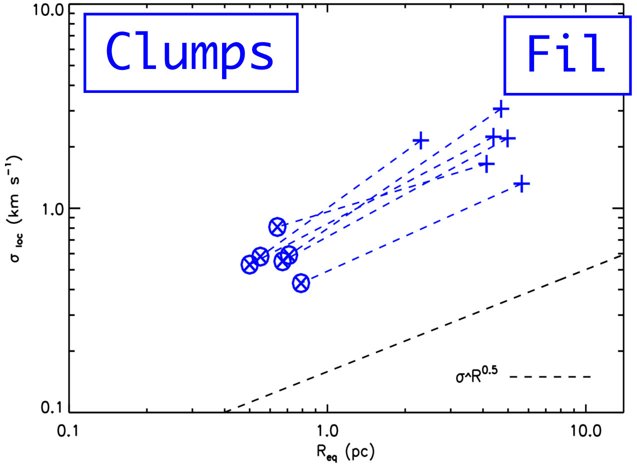




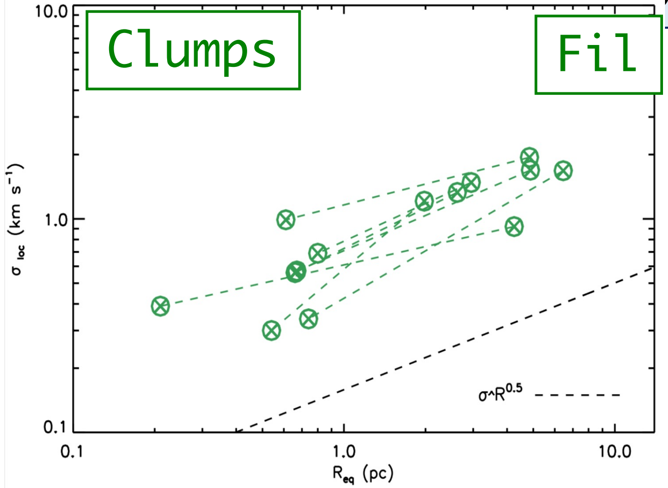
1st Larson relation in clumps



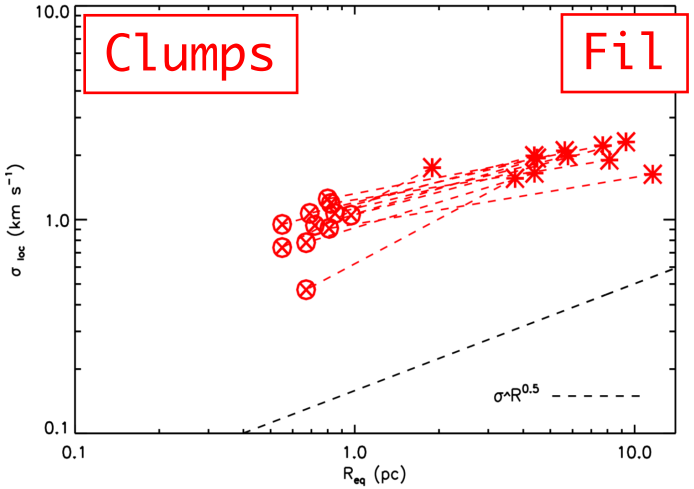
1st Larson relation in filaments



$\sigma \sim R^{0.68}$



$\sigma \sim R^{0.60}$

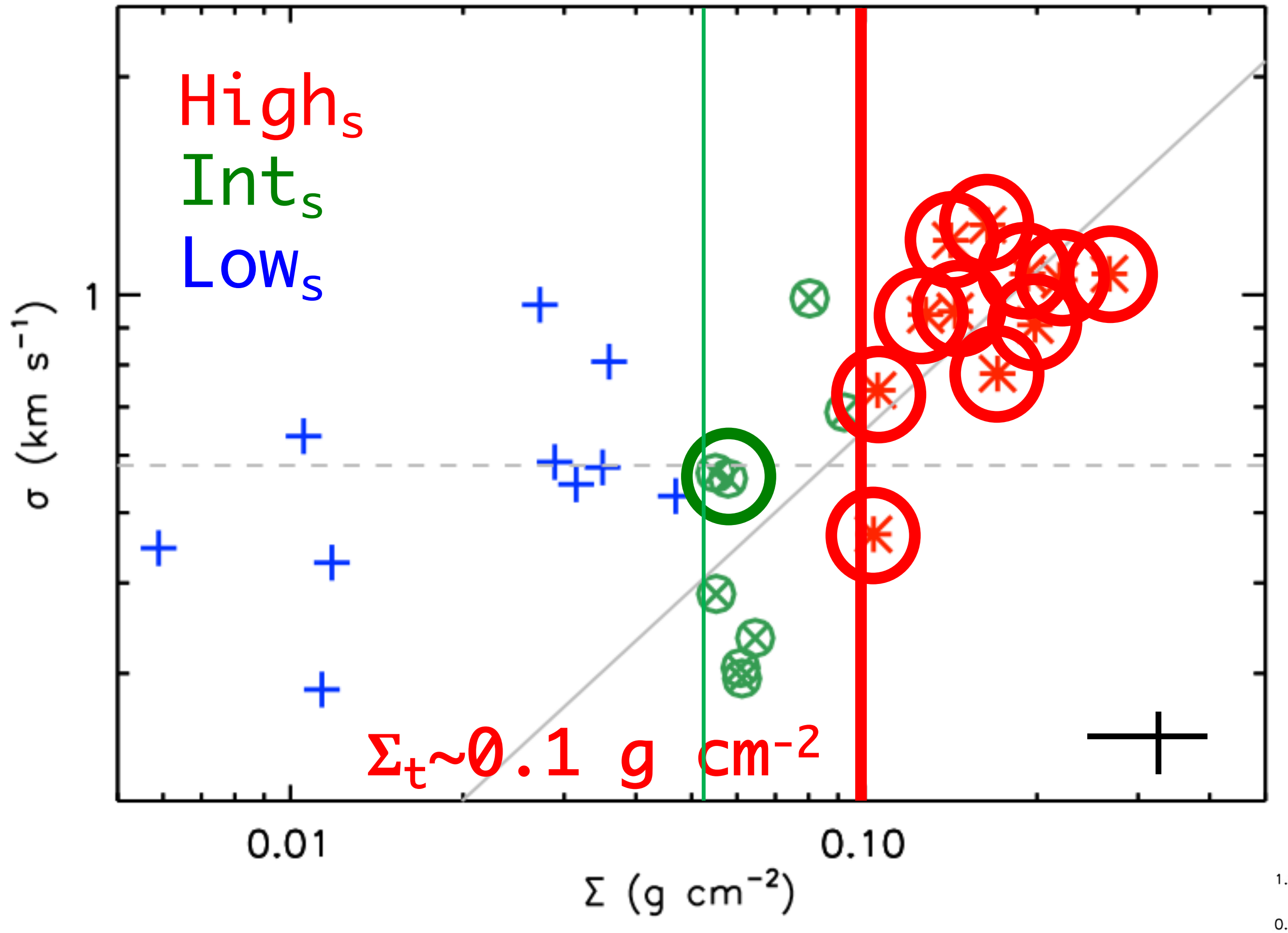


$\sigma \sim R^{0.38}$

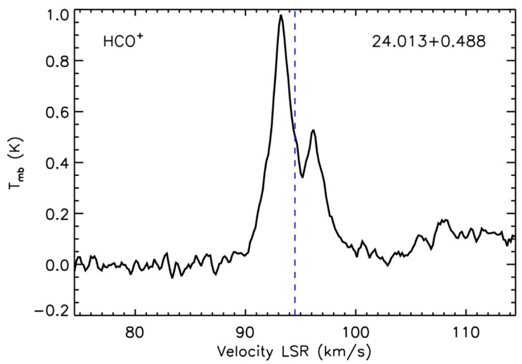
$\sigma \sim R^{0.7}$ in Taurus region
Fuller & Myers (1992)

Traficante+2020

Filament to clumps dynamics: the role of environment

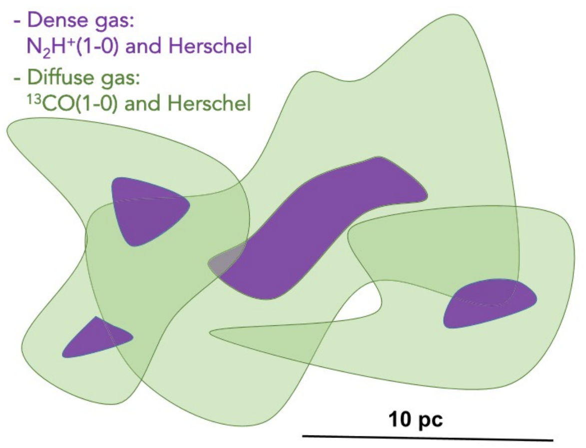


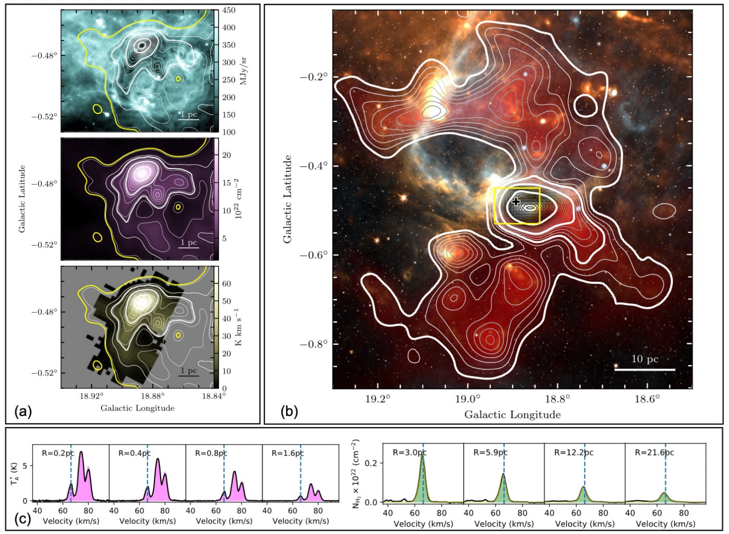
Traficante+20



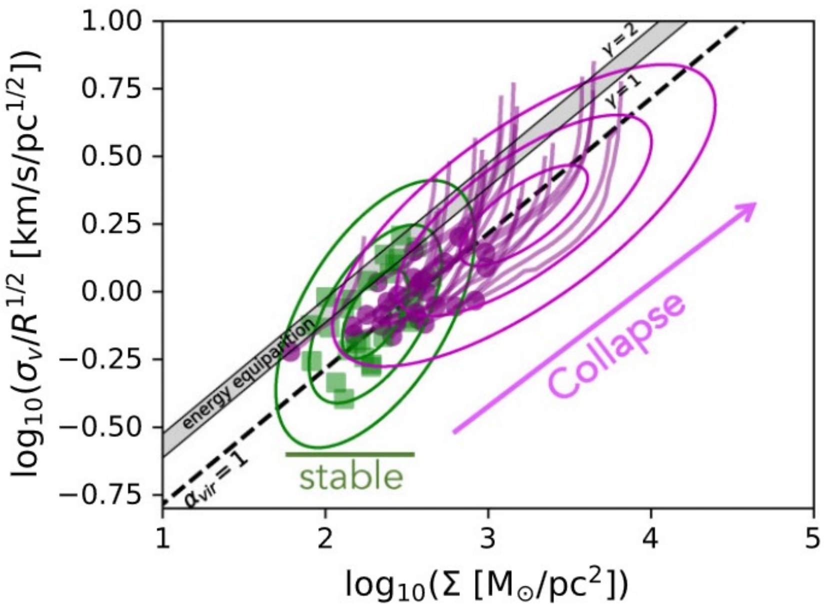
Clumps with evidence of dynamical activity and/or gravitationally driven motions (**infall?**) at the pc scales (asymmetric HCO+ (1-0) spectra)

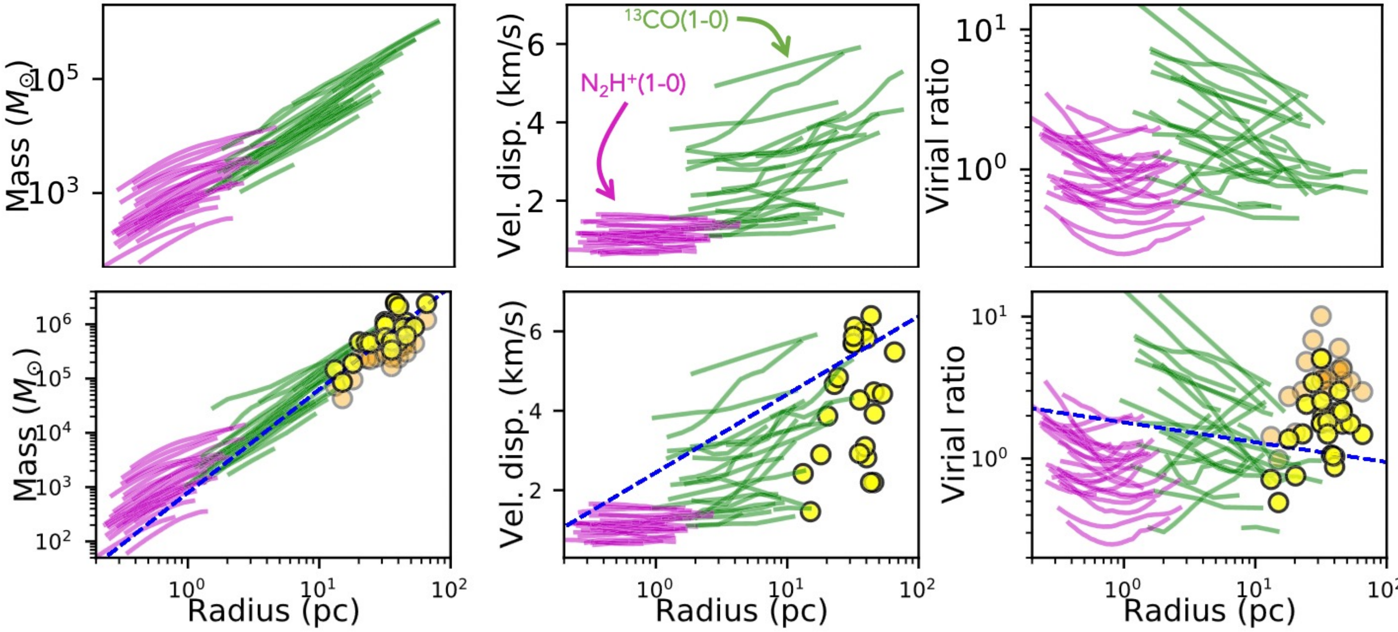
Filament to clumps dynamics: the role of environment





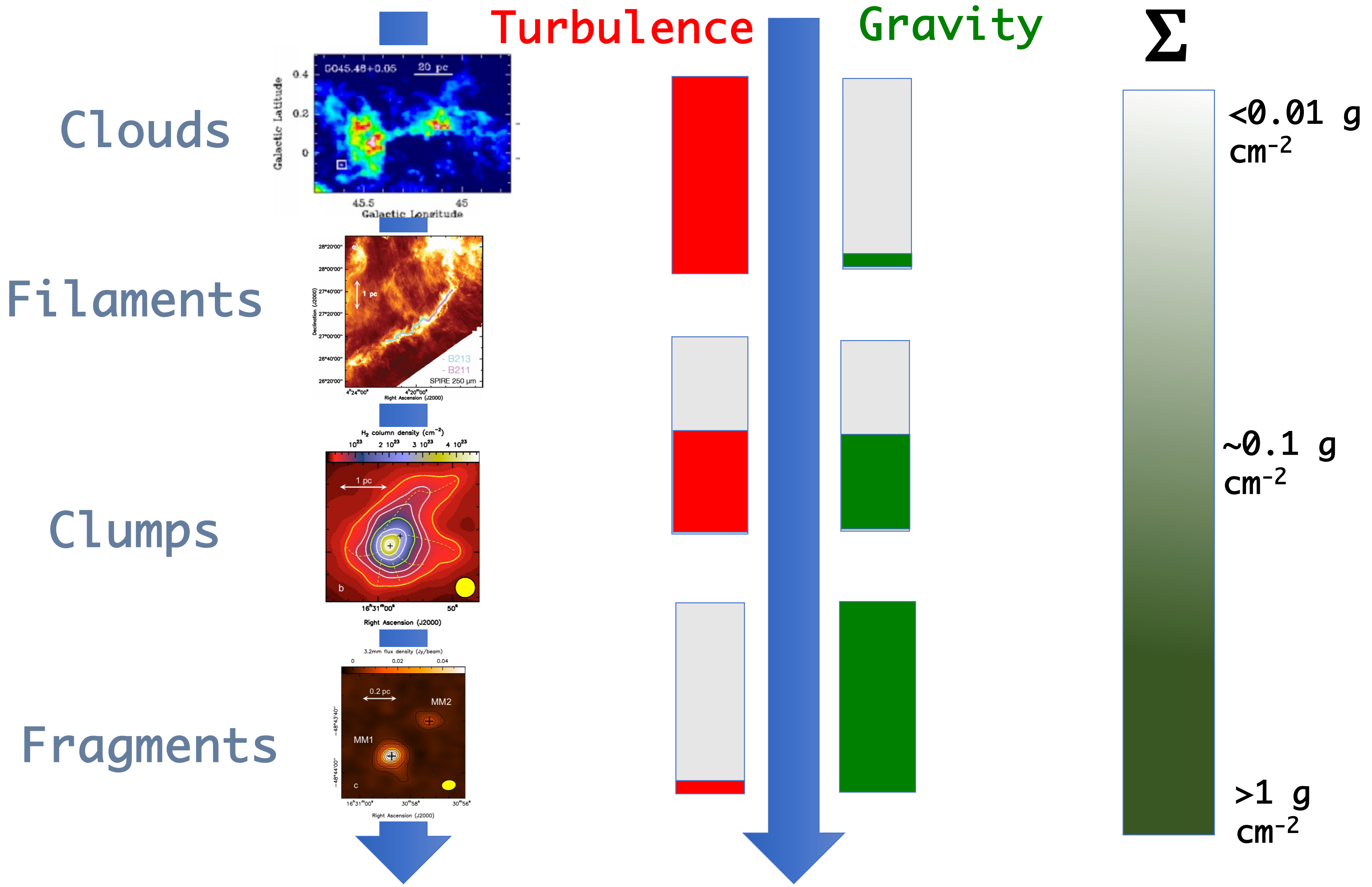
Dynamically decoupled clumps from progenitor IRDCs (27)





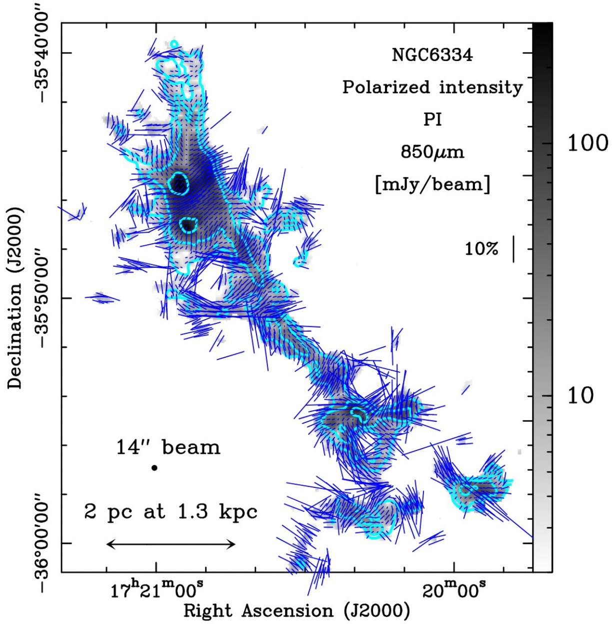
Peretto+23

On the interplay between gravity and turbulence

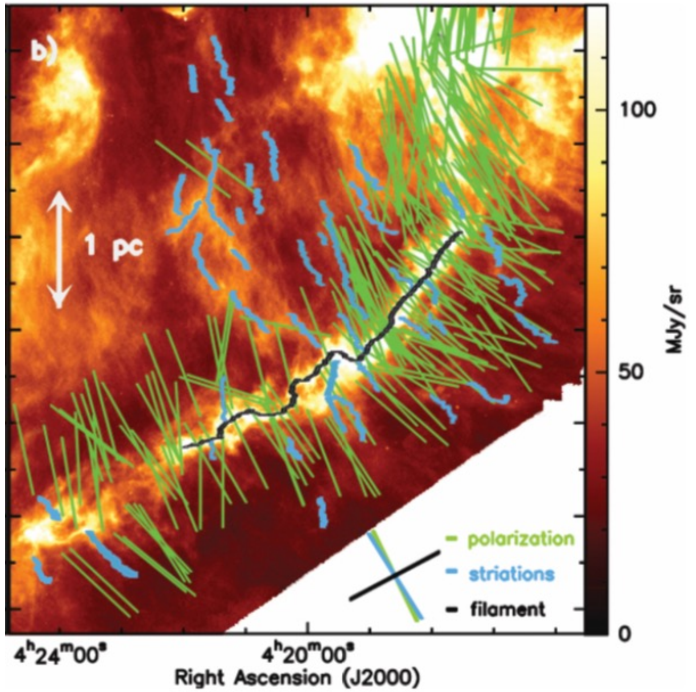


Traficante+2020

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 $\perp$

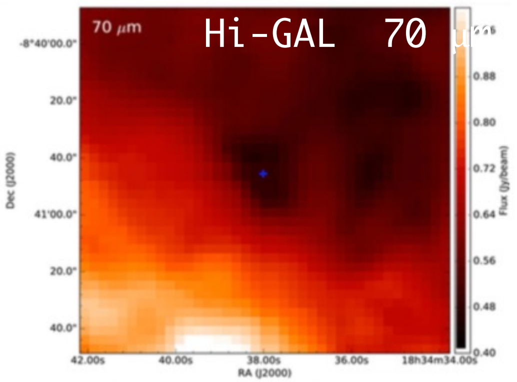
Does the orientation correlate with SFR? $\left\{ \begin{array}{l} \text{YES (Li+17)} \\ \text{NO (Soler+19)} \end{array} \right.$

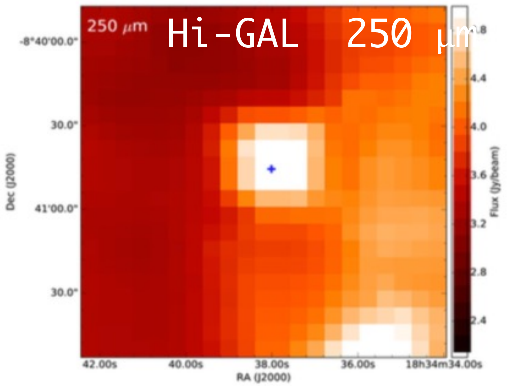

Dense Clumps
• $10 \lesssim T[K] \lesssim 50$
• $10^4 \lesssim n\,[cm^{-3}] \lesssim 10^{6\div7}$
• $L[pc] \sim 1$
ense Cores
$10 \lesssim T[K] \lesssim 200$
$10^6 \lesssim n\,[cm^{-3}] \lesssim 10^9$
$L[pc] \sim 0.02$
Filaments
• $T \sim 20K$
• $10^2 \lesssim n\,[cm^{-3}] \lesssim 10^3$
• $3 \lesssim L[pc] \lesssim 50$
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
FETTUCCINE
We are here!
Realistic illustration of Milky Way (NASA/JPL-Caltech)

Extra slides

Clumps in the Galaxy

SDC23271-0263

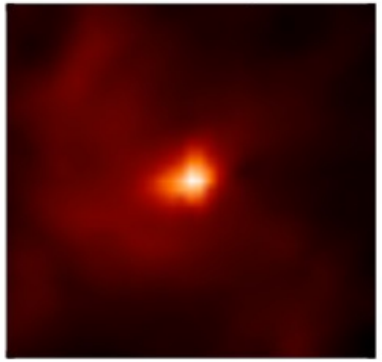




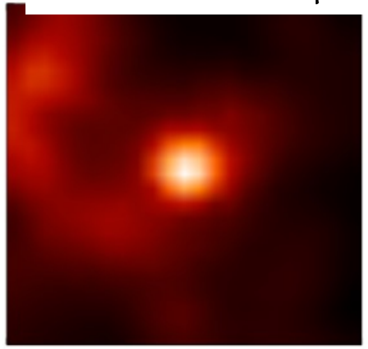
(70 µm-quiet)

Hi-GAL #110522

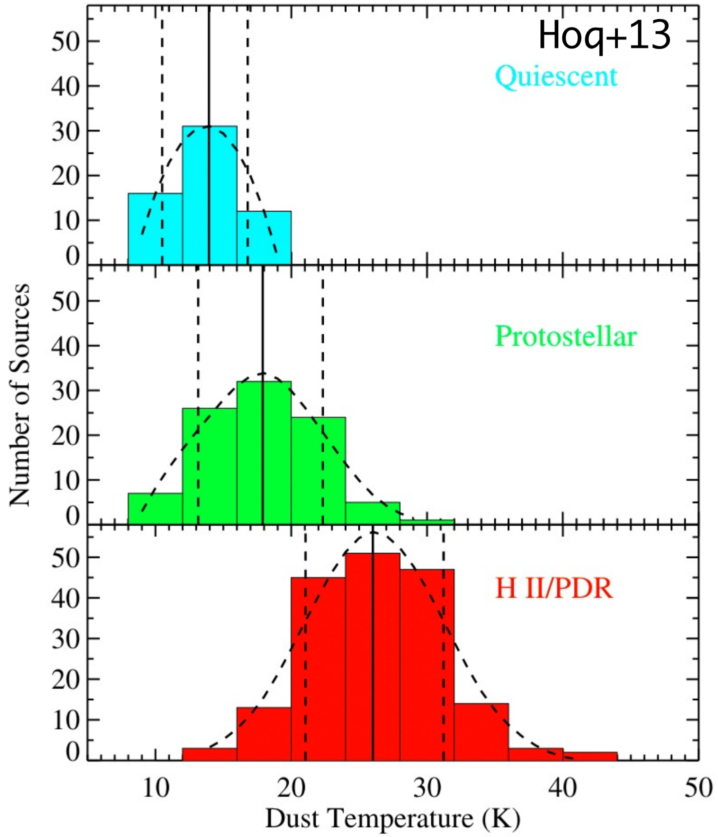
Hi-GAL 70 µm



Hi-GAL 250 µm



(70 µm-bright)



MIR dark
MIR/NIR bright
PDR/HII regions

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

See lectures from Frederique Motte & Davide Elia