A Unifying and biased observational overview from the Galactic Disk to Protoplanetary Disks

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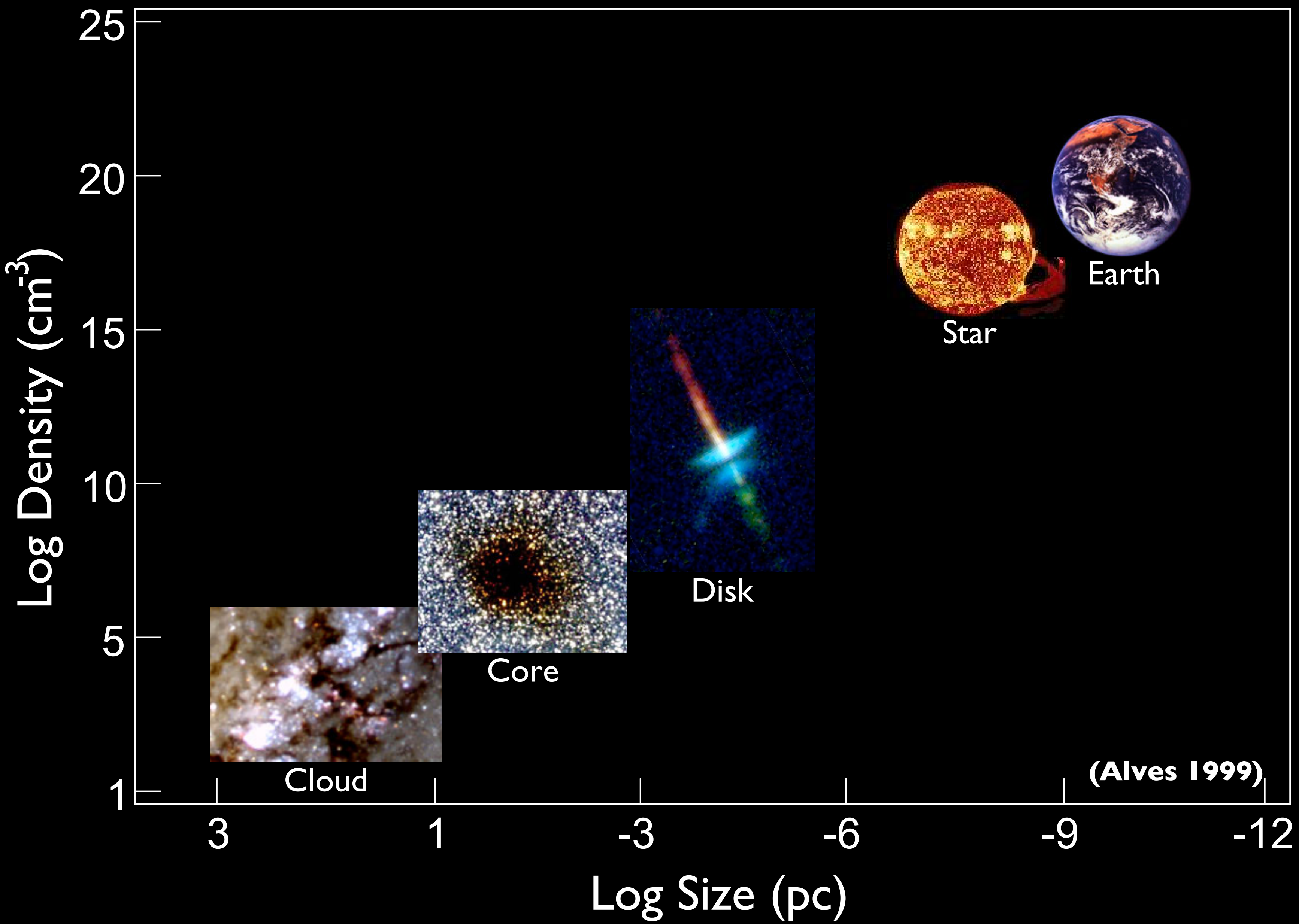
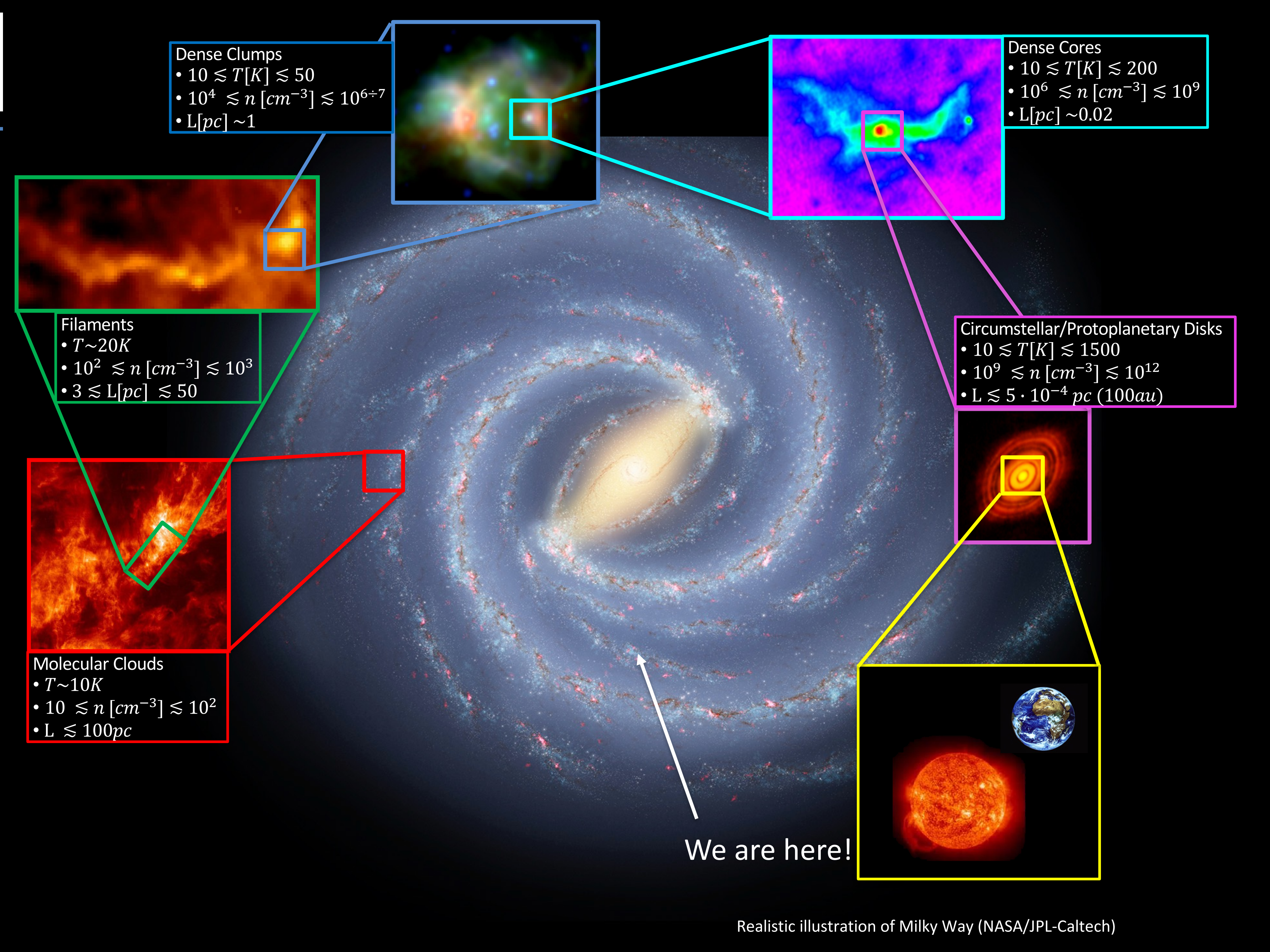
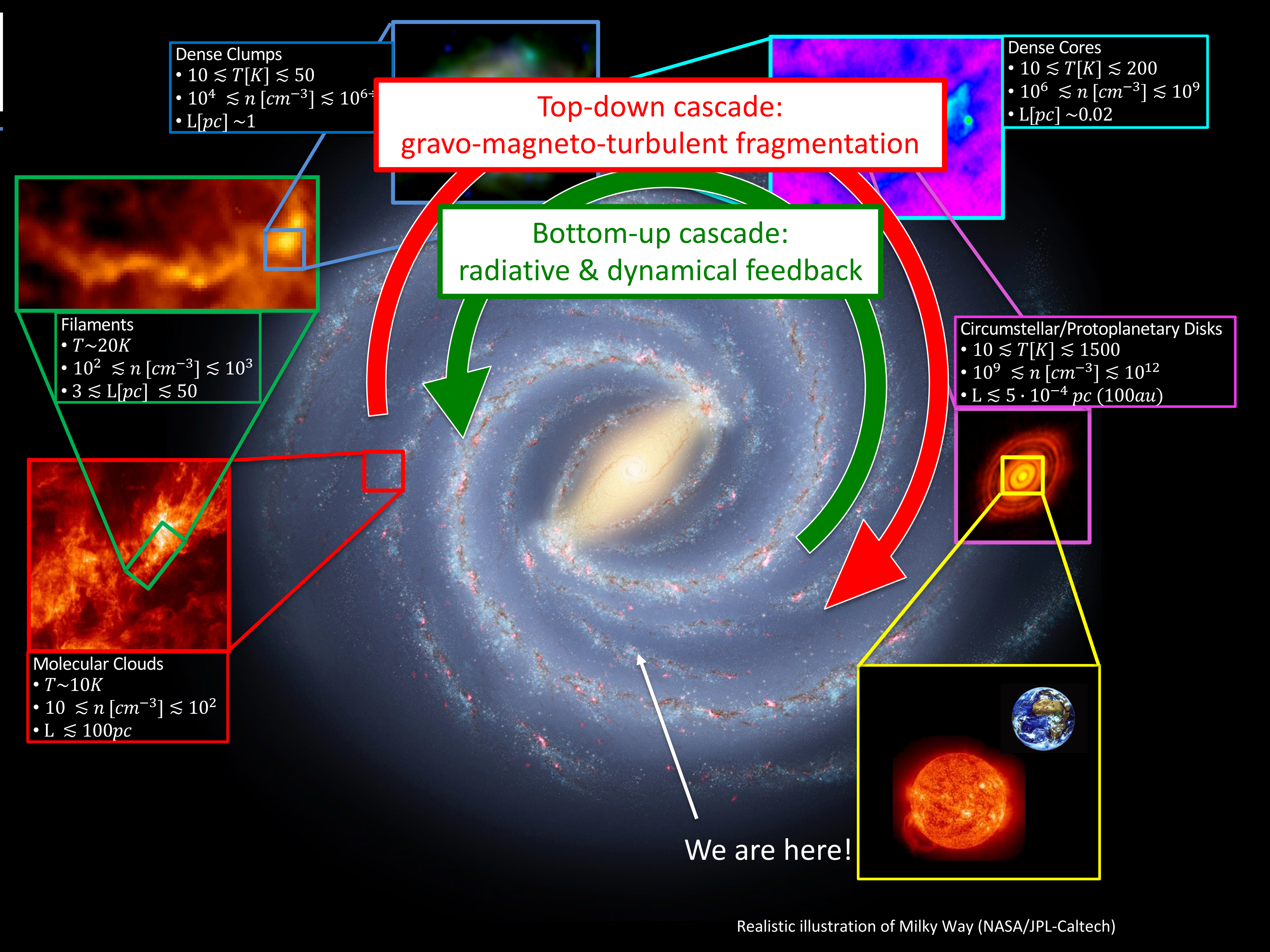
From diffuse gas to Stars and Planets





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



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Top-down cascade:
gravo-magneto-turbulent fragmentation
Bottom-up cascade:
radiative & dynamical feedback
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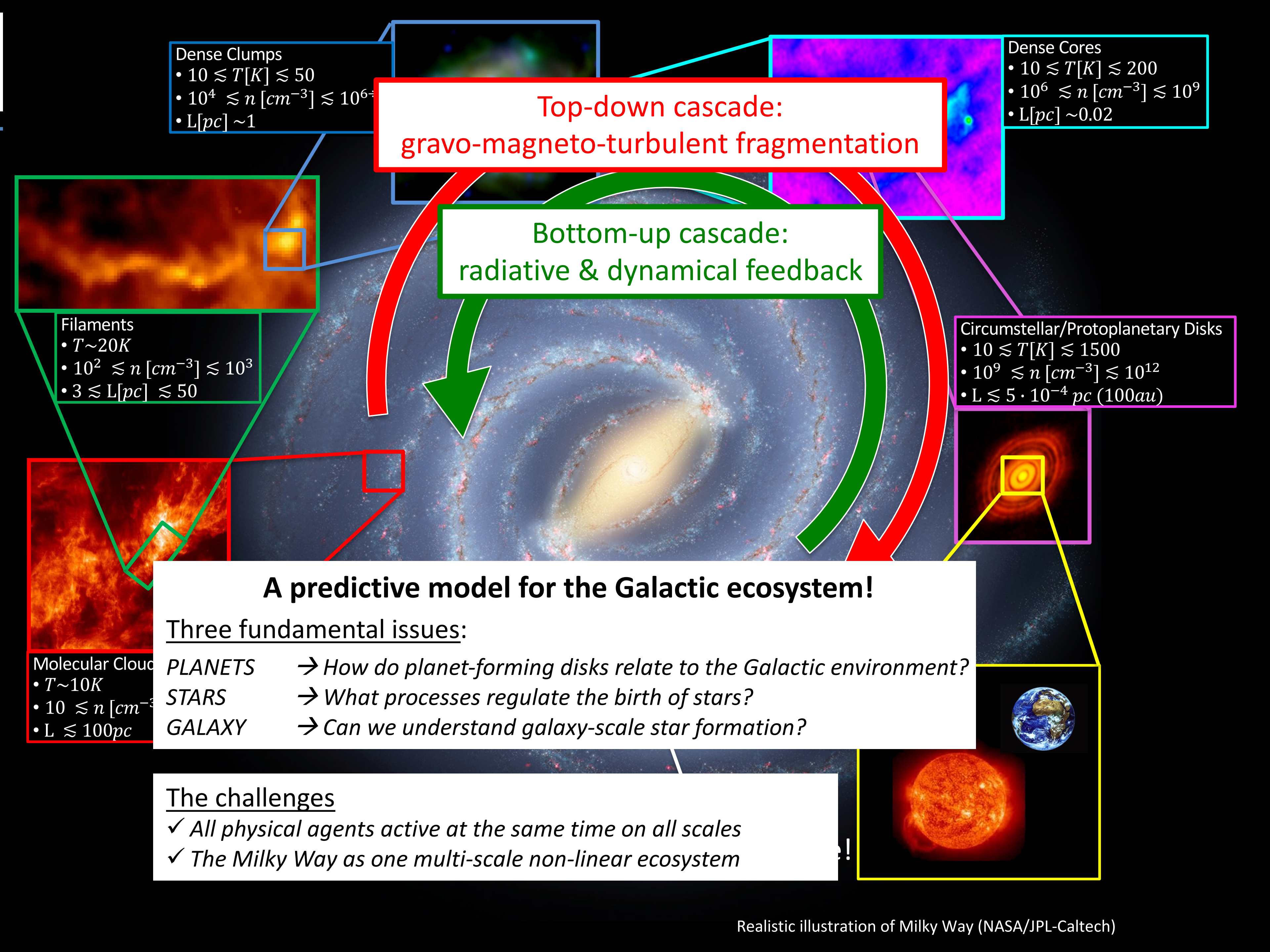
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A predictive model for the Galactic ecosystem!
Three fundamental issues:
PLANETS → How do planet-forming disks relate to the Galactic environment?
STARS → What processes regulate the birth of stars?
GALAXY → Can we understand galaxy-scale star formation?
The challenges
✓ All physical agents active at the same time on all scales
✓ The Milky Way as one multi-scale non-linear ecosystem
Realistic illustration of Milky Way (NASA/JPL-Caltech)

Wouldn't this be ideal ….?

Mapping the Milky Way in any possible way

Table 1: List of most representative surveys covering the Galactic Plane

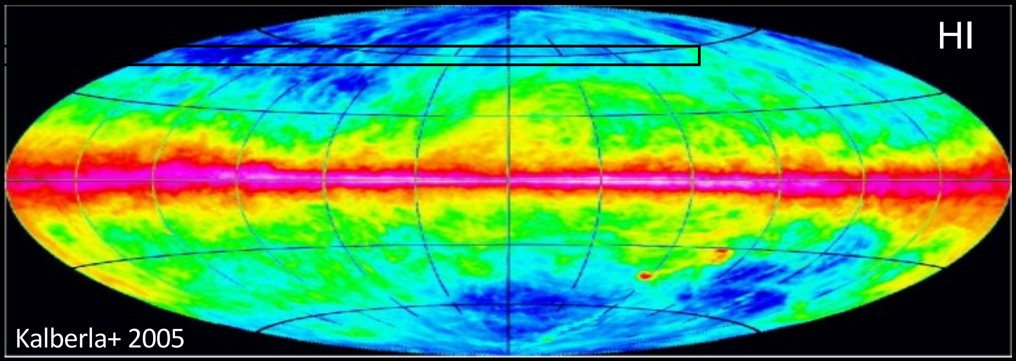
Surveys facilities	λ or lines	Surveys notes
		Ground-based
Columbia/CfA	CO, ^{13}CO	9 - 25′ resolution (*Dame et al.*, 2001)
DRAO/ATCA/VLA	HI-21 cm OH/Hα-RRL/1-2GHz cont. 5GHz cont.	IGPS: unbiased HI-21cm 255°$\leq l \leq$ 357° and 18°$\leq l \leq$ 147° (*McClure-Griffiths et al.*, 2001; *Gibson et al.*, 2000; *Stil et al.*, 2006) + THOR: unbiased HI-21cm/OH/Hα-RRLs/1-2GHz cont. 15°$\leq l \leq$ 67° (Beuther et al. in prep.)+ CORNISH: 5GHz continuum 10°$\leq l \leq$ 65° (*Hoare et al.*, 2012)
FCRAO 14 m	CO, ^{13}CO	55″ resolution. Galactic Ring Survey (*Jackson et al.*, 2006) + Outer Galaxy Survey (*Heyer et al.*, 1998)
Mopra 22 m	CO, ^{13}CO, N_2H^+, (NH_3 + H_2O) maser, $HCO^+/H^{13}CO^+$ + others	HOPS: (*Walsh et al.*, 2011; *Purcell et al.*, 2012), MALT90: ∼ 2000 clumps 20° $\geq l \geq -60$° (*Foster et al.*, 2013), Southern GPS CO: unbiased 305°$\leq l \leq$ 345° (*Burton et al.*, 2013), ThrUMMS: unbiased 300°$\leq l \leq$ 358° (*Barnes et al.*, 2013), CMZ: (*Jones et al.*, 2012, 2013)
Parkes	CH_3OH maser	Methanol MultiBeam Survey (*Green et al.*, 2009)
NANTEN/ NANTEN2	CO, ^{13}CO, $C^{18}O$	NGPS: unbiased, 200° $\leq l \leq$ 60° (*Mizuno and Fukui*, 2004) + NASCO: unbiased in progress, 160° $\leq l \leq$ 80°
CSO 10 m	1.3 mm continuum	Bolocam Galactic Plane Survey (BGPS), 33″ (*Aguirre et al.*, 2011)
APEX 12 m	870 μm continuum	ATLASGAL, 60°$\geq l \geq -80$° (*Schuller et al.*, 2009)
		Space-borne
IRAS	12, 25, 60 and 100 μm cont.	3-5′, 96% of the sky
MSX	8.3, 12.1, 14.7, 21.3 μm cont.	Full Galactic Plane (*Price et al.*, 2001)
WISE	3.4, 4.6, 11, 22 μm continuum	All-sky (*Wright et al.*, 2010)
Akari	65, 90, 140, 160 μm continuum	All-sky (*Ishihara et al.*, 2010)
Spitzer	3.6, 4.5, 6, 8, 24 μm continuum	GLIMPSE+GLIMPSE360: Full Galactic Plane (*Benjamin et al.*, 2003), (*Benjamin and GLIMPSE360 Team*, 2013) + MIPSGAL, 63°$\geq l \geq -62$° (*Carey et al.*, 2009)
Planck	350, 550, 850, 1382, 2098, 3000, 4285, 6820, 10^4 μm cont.	All-sky, resolution ≥5′ (*Planck Collaboration et al.*, 2013a)
Herschel	70, 160, 250, 350, 500 μm cont.	Hi-GAL: Full Galactic Plane (*Molinari et al.*, 2010a)

Molinari+ 2014, PP VI

Multiphase ISM in the Milky Way

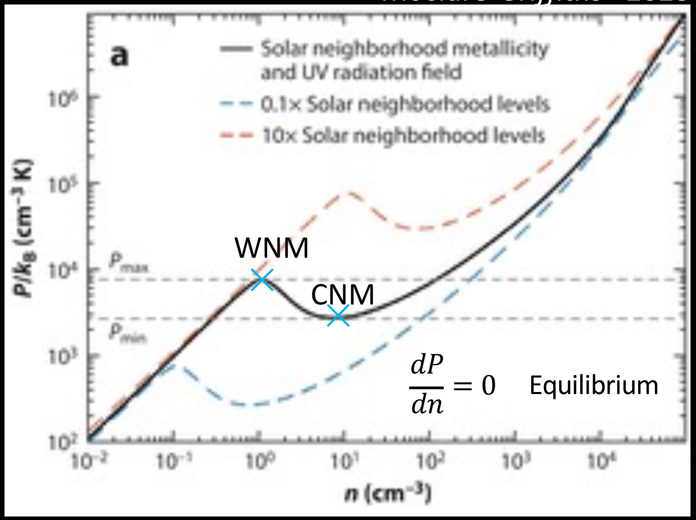
Atomic material is found spread over the Galaxy disk

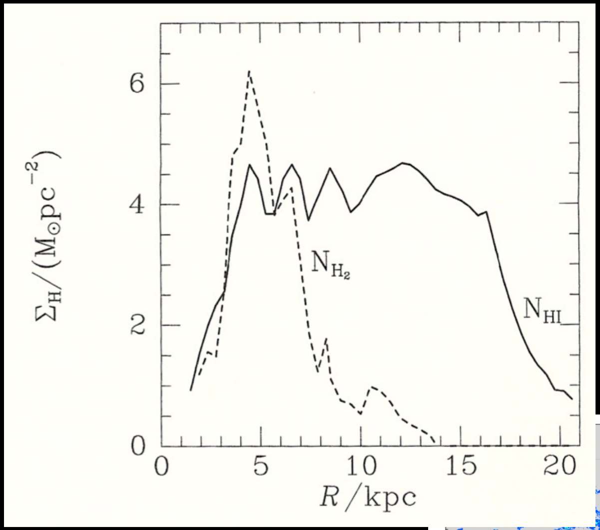
- Cold Neutral Medium (CNM) → T ~ 100 K
- Warm Neutral Medium (WNM) → T ~ 8000 K



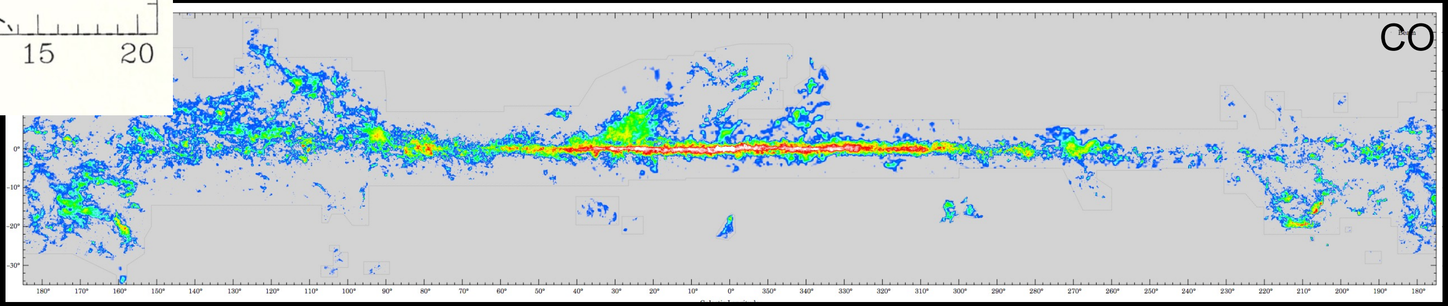
Heating *vs* Cooling

McClure-Griffiths+ 2023



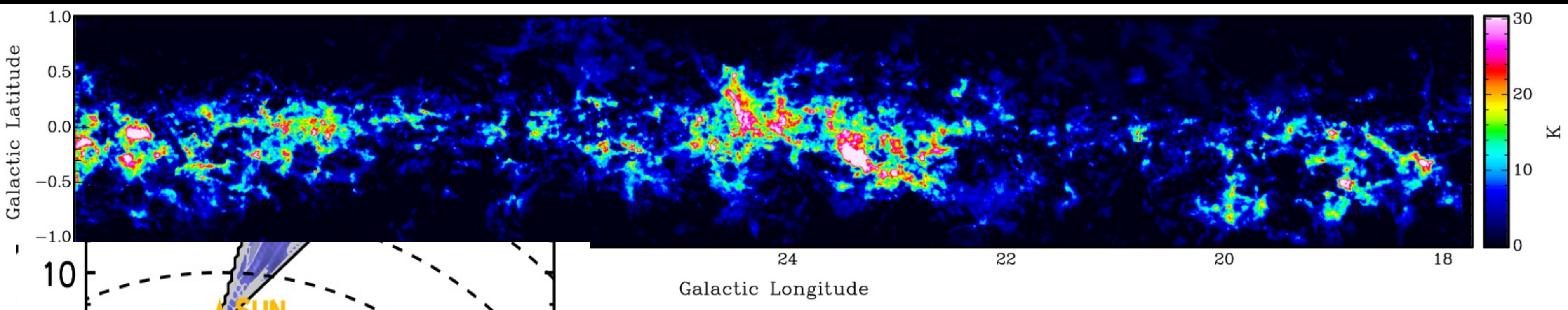


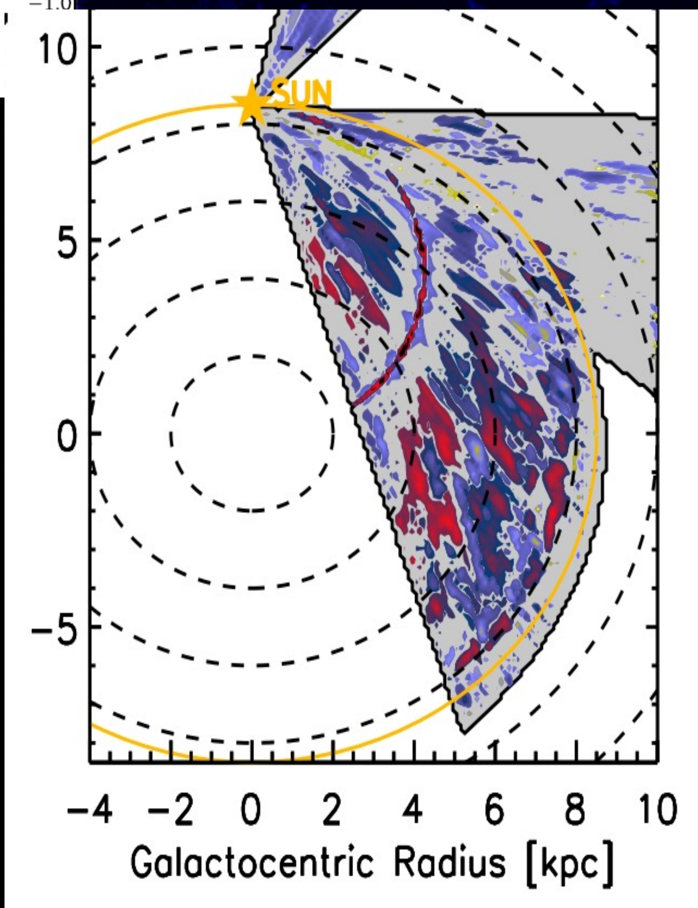
- Molecular material is mostly concentrated within a few degrees of the Galactic Plane
- Similarly different trends in Galactocentric radial profiles



Star Formation: the classical conundrum

^{13}CO FCRAO Galactic Ring Survey (Jackson+ 2006)





The dense phase of the Galactic ISM traced by CO is mostly concentrated in the Spiral Arms

$$M_J \sim 8\, M_\odot \sqrt{T^3 / \rho_{H_2}\, [cm^{-3}]}$$

Typical conditions in molecular clouds:

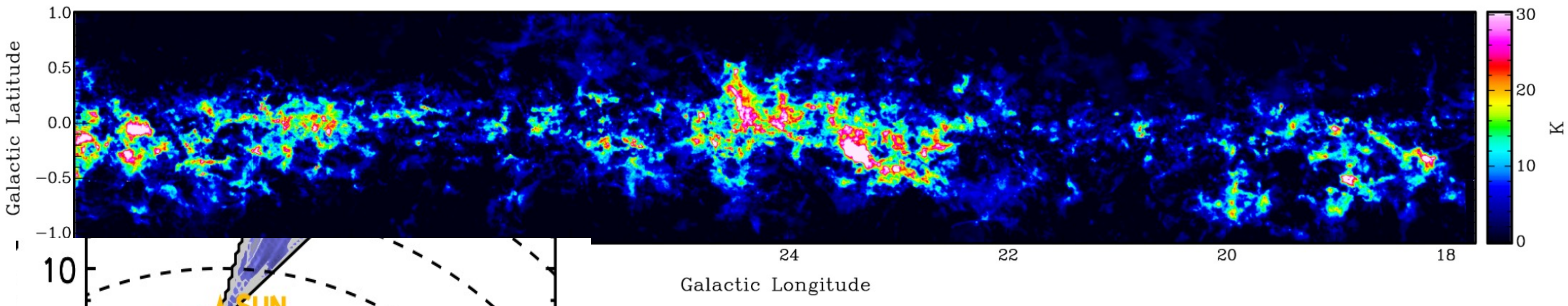
$T \sim 10\ K, \rho \sim 10^3\ cm^{-3}$ ⟶ $M_J \sim 3\ M_\odot$!!

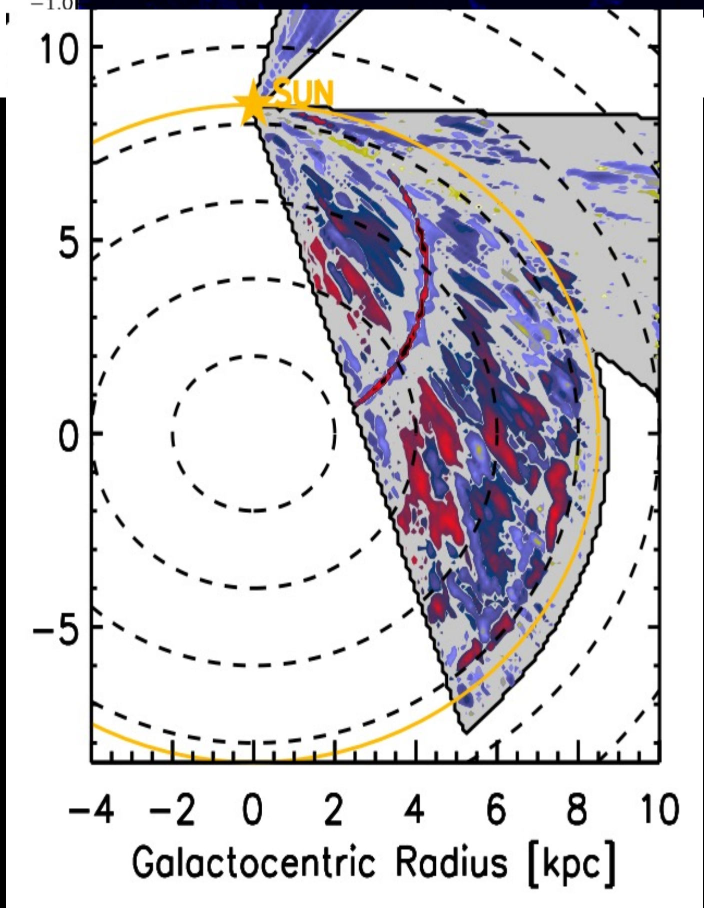
MC masses $10^4 M_\odot \leq M \leq 10^6\ M_\odot$

A Molecular Cloud should be forming stars like crazy!!
…..it does not. Why ?

Support in Molecular clouds

^{13}CO FCRAO Galactic Ring Survey (Jackson+ 2006)





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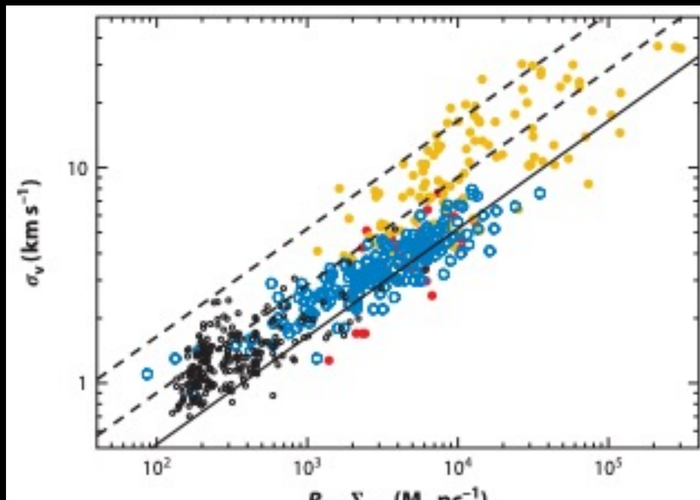
<u>Virial considerations</u>

In equilibrium (equipartition) status

$$\frac{GmM_{Cl}}{R_{Cl}} = \frac{1}{2}m < v >^2$$

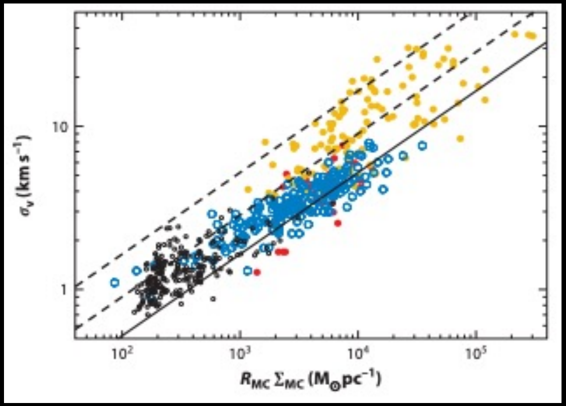
$$\sigma_v \quad = 2G\, \Sigma_{Cl}^{1/2}\, R_{Cl}^{1/2}$$

What is responsible for σ_v?



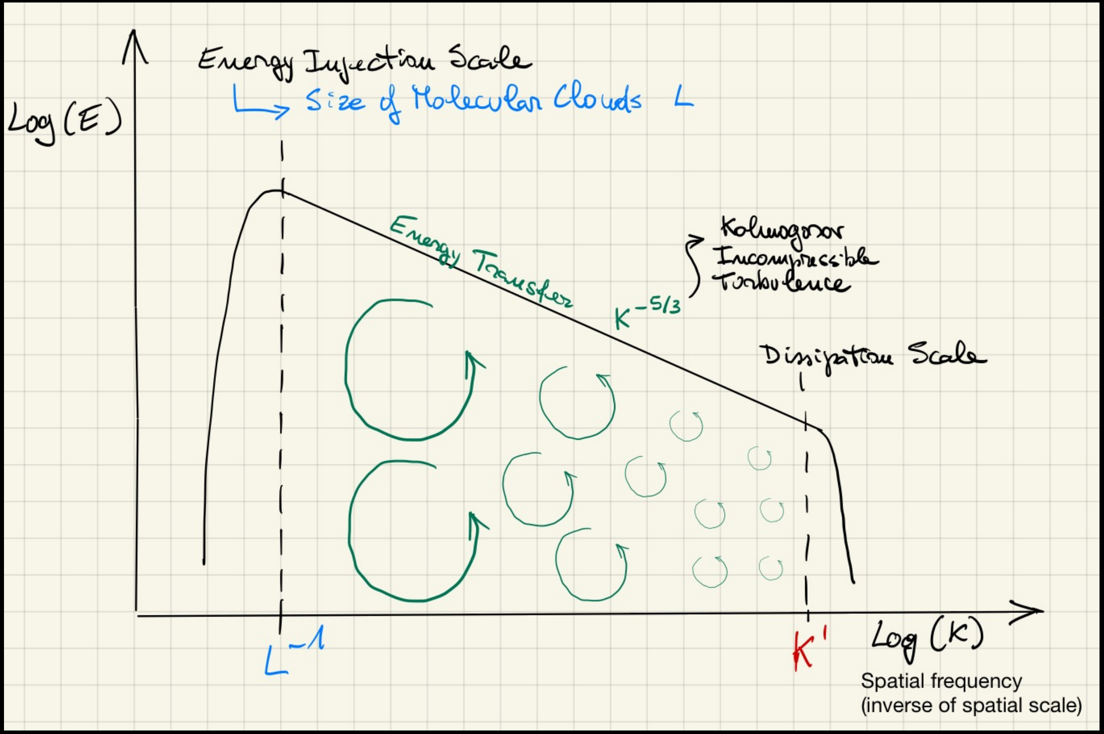
Heyer & Dame (2015)

Turbulence Support



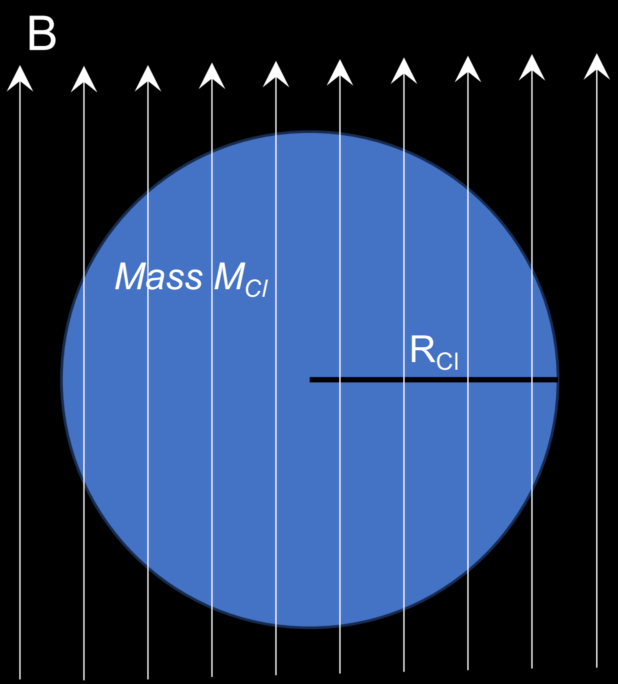
Molecular Clouds are not globally collapsing

Turbulent support



- CO linewidth in molecular clouds are largely non-thermal: $\Delta v \approx 10$ km s^{-1}
  (thermal linewidth for T=10K → 0.1 km s^{-1})
- What is injecting turbulence at the cloud scale?
  - Slow gravitational contraction
  - Large-scale flows
  - SN shocks
  - …

Magnetic Support: Clouds to Filaments



Magnetic support

Gravitational Energy

$$\frac{3GM^2}{5R}$$

Magnetic Energy

$$\frac{|B|^2 V}{8\pi} = \frac{|B|^2 R^3}{6}$$

$$=$$

$$M_{cr} = 0.13 \frac{\Phi}{G^{1/2}}$$

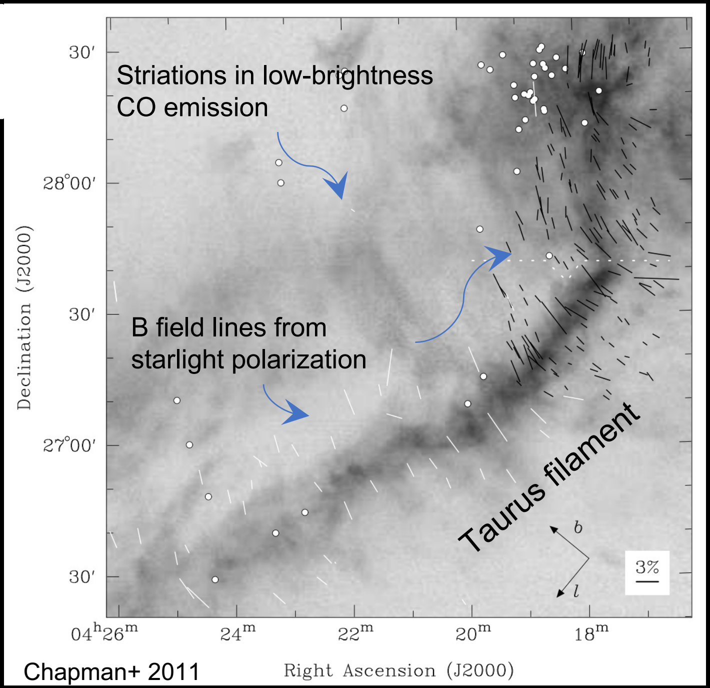
e.g. Mouschovias & Spitzer 1976
Shu, Adams & Lizano 1987

In molecular clouds, a very small fraction ($\sim 10^{-7}$) of the cloud is ionised due to Cosmic Rays.
In flux-freezing conditions, ions are bound to B lines and the ion-neutral drag acts to allow gas flow along B lines and oppose flow across B lines.

→ Natural formation of flattened structures

Role of Magnetic Field ?

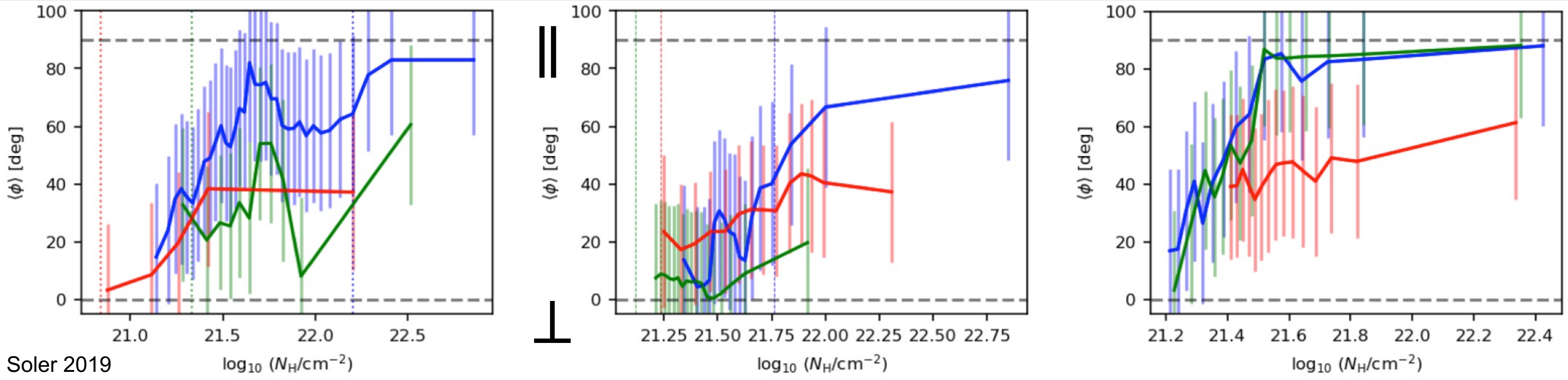
Morphology of low-density medium in molecular clouds is aligned with magnetic field



Chapman+ 2011

Magnetic field and density structure of ISM clouds are related, but what is the role of magnetic field ?

Magnetic field changes orientation w.r.t. filaments: from ⊥ in the low-density ISM to ∥ in the high-density filament gas



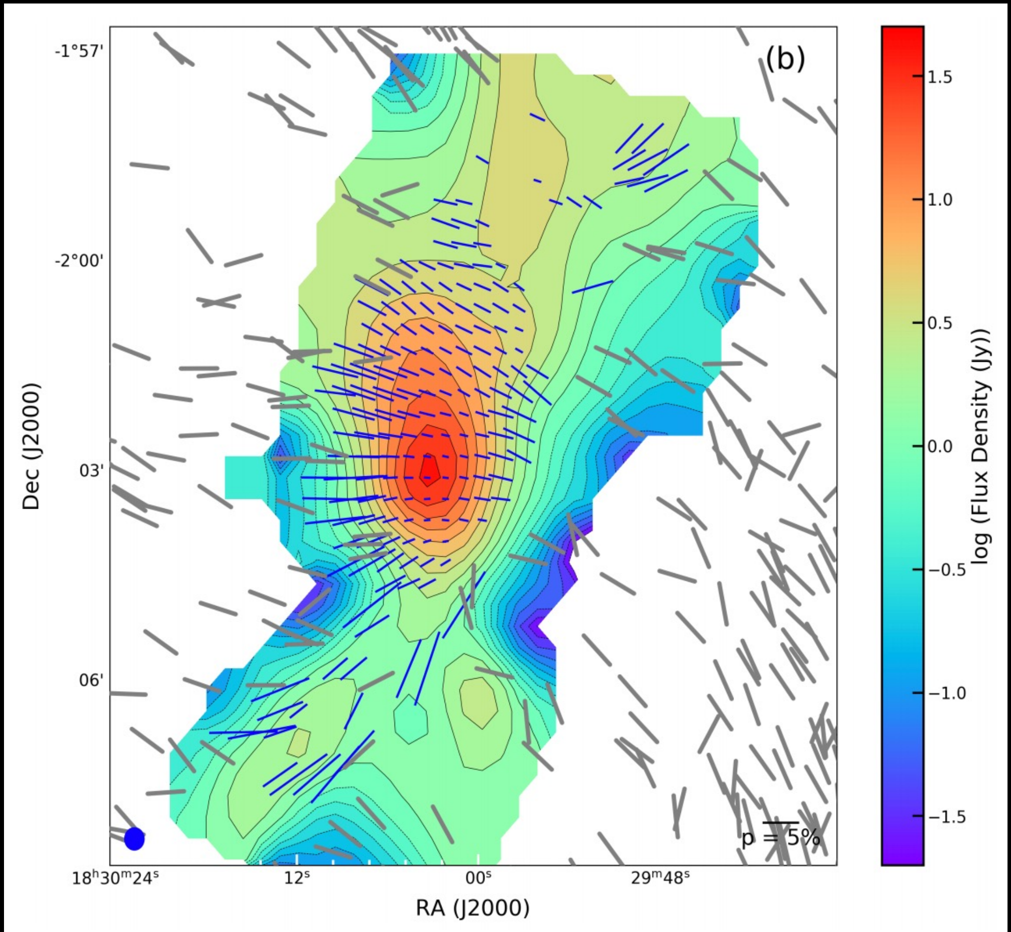
Soler 2019

B-*vs*-filament alignment in 9 star forming regions (based on Planck satellite polarization maps)

Role of Magnetic Field ?

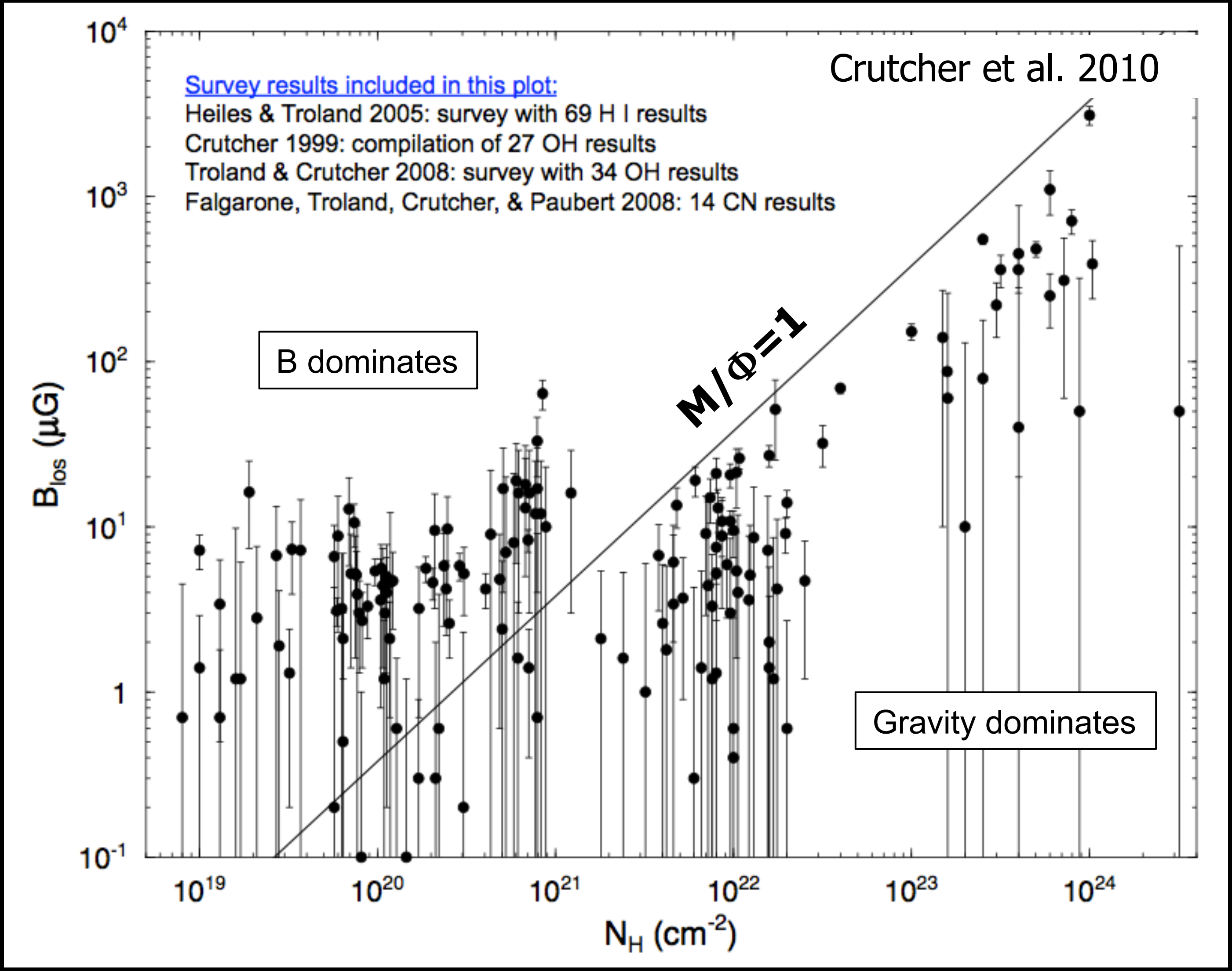
- Thresholds for twofold B-ρ directional transitions: A_V~3 to A_V~20
- Evidence of B entrained from accretion flows
- Role of B
  - Facilitator ?
  - Regulator ?
  - Passive ?
- *vs* different mass regimes ?
- *vs* different evolutionary stages ?
- *vs* ambient shear (e.g., R_{GAL})

HAWC+ Serpens South Pillai+ 2020



Larger mapping areas + Many more clouds/filaments

Magnetic Field vs Gravity

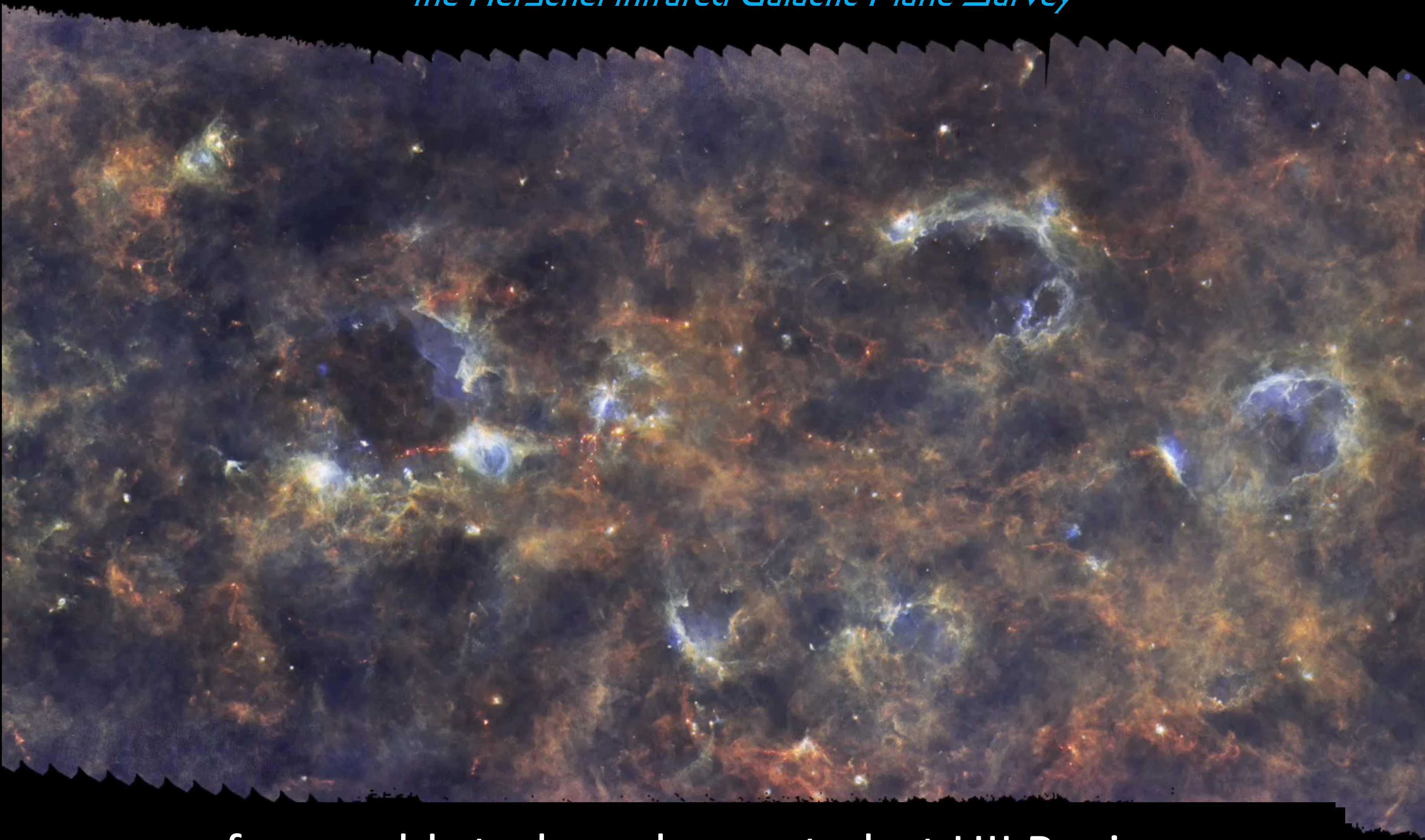


Molinari et al. 2016

Hi-GAL

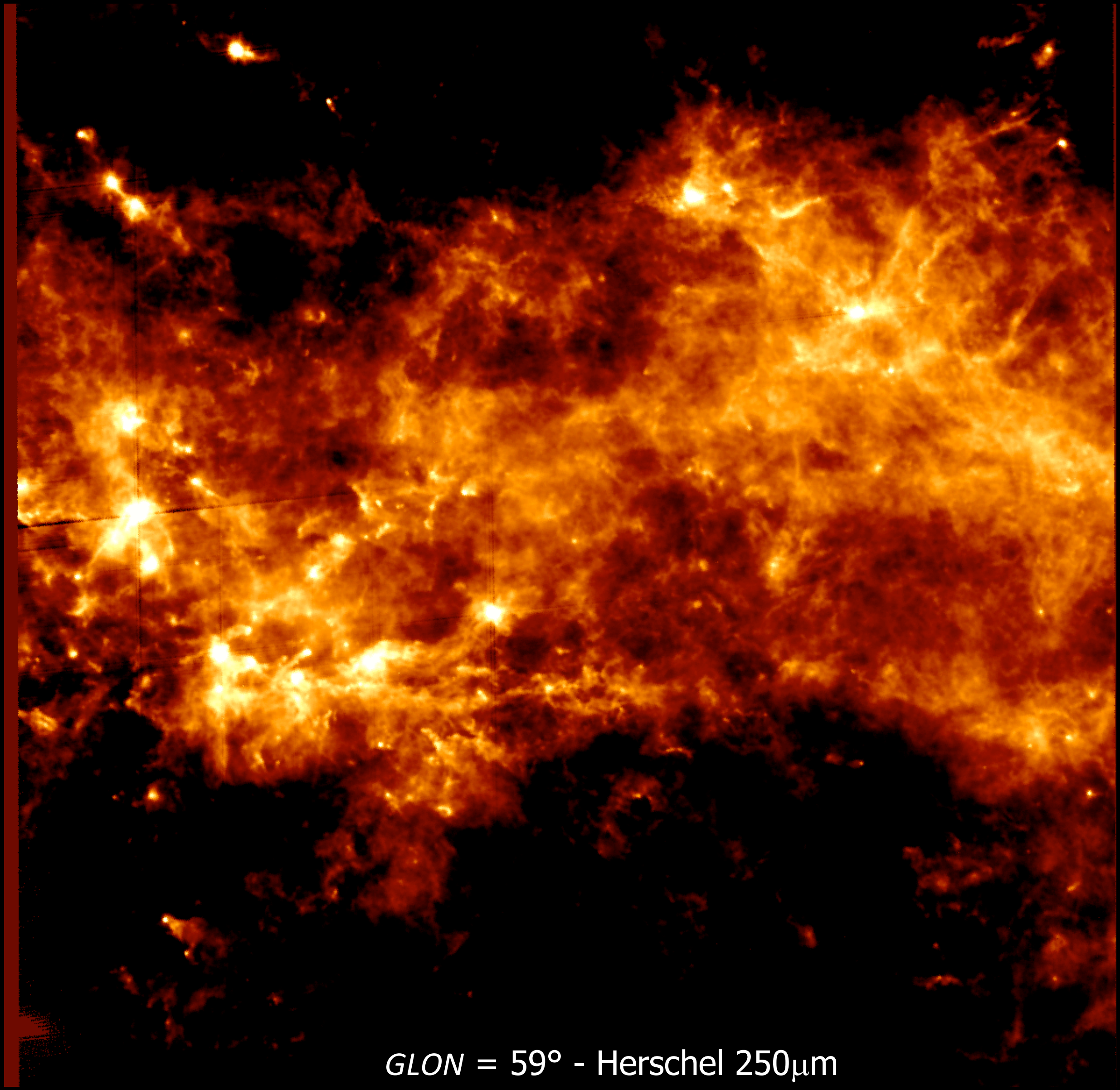
70-160-250μm composite

the Herschel infrared Galactic Plane Survey



from cold starless clumps to hot HII Regions

Filamentary Clouds



GLON = 59° - Herschel 250μm

- The denser part of the molecular clouds on teh Galactic Plane is organised in networks of filamentary structures
- The dense clumps that are sites of protocluster formation are for a large fraction distributed along these filaments
- The counterpart of this phenomenology in nearby (local) star forming regions exists; in this case the compact sources found on filaments are «cores», or sites of formation of single stars

Molinari+ 2010, Schisano+ 2014, 2020

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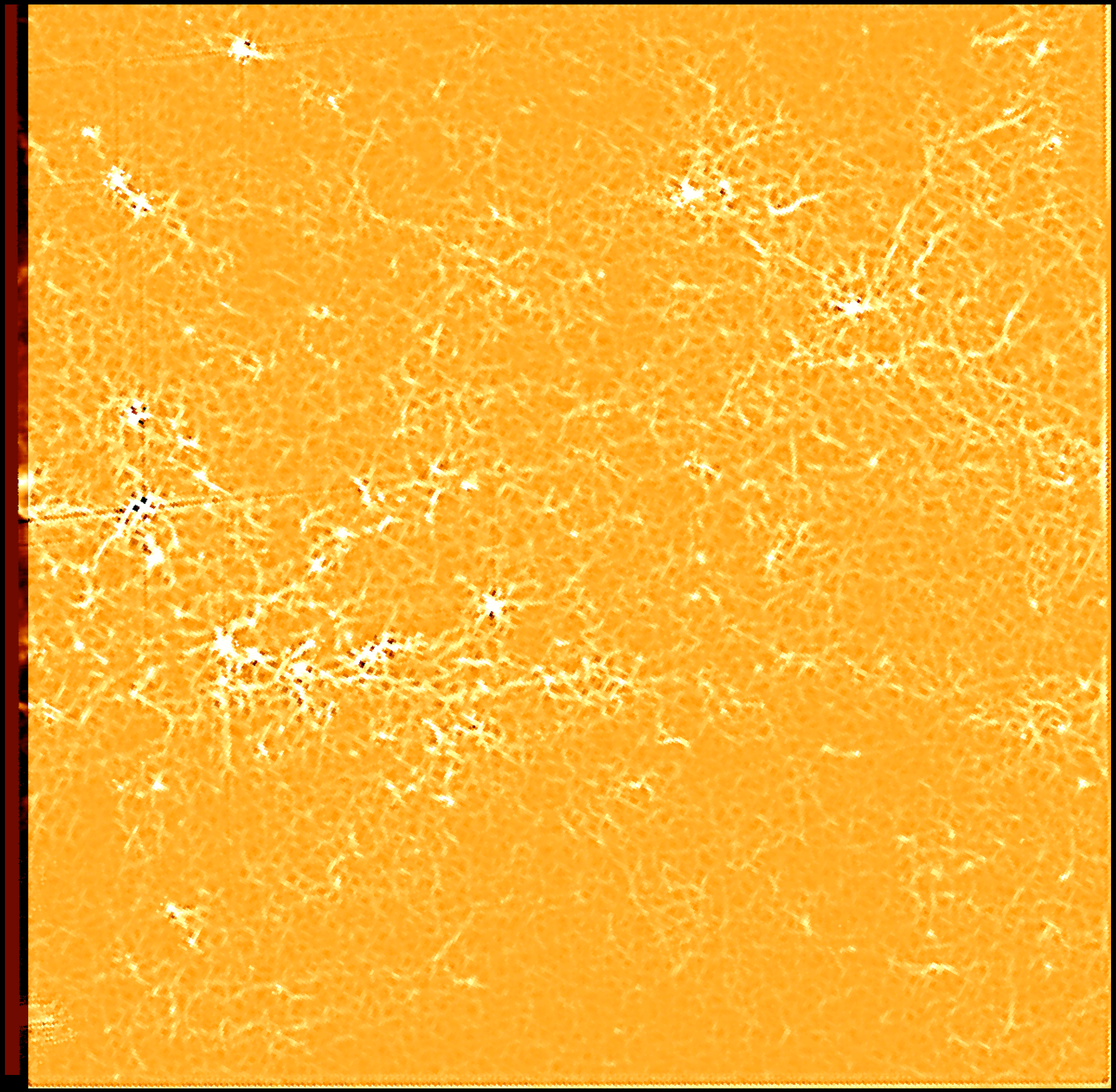

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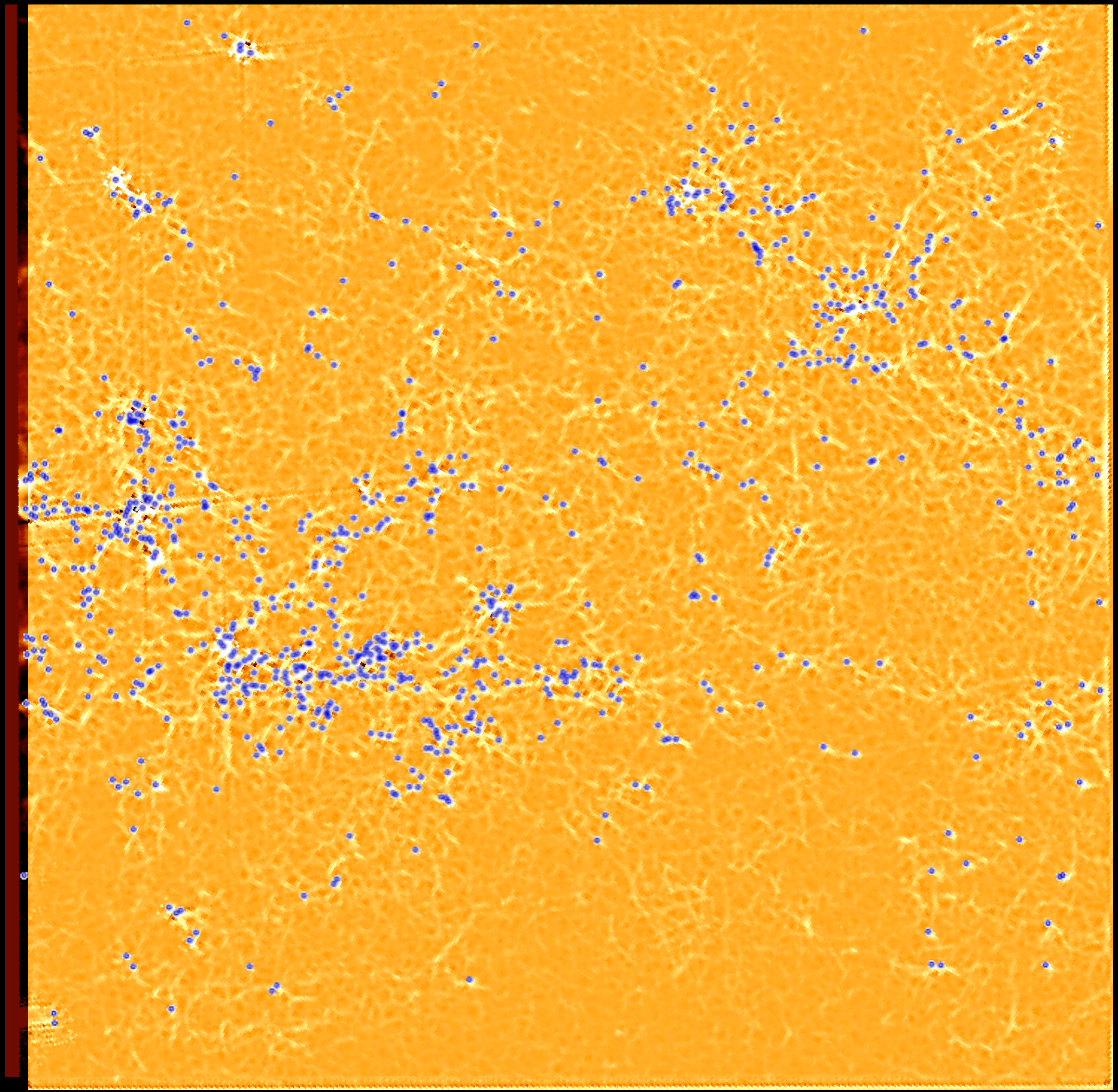

Molinari+ 2010, Schisano+ 2014, 2020

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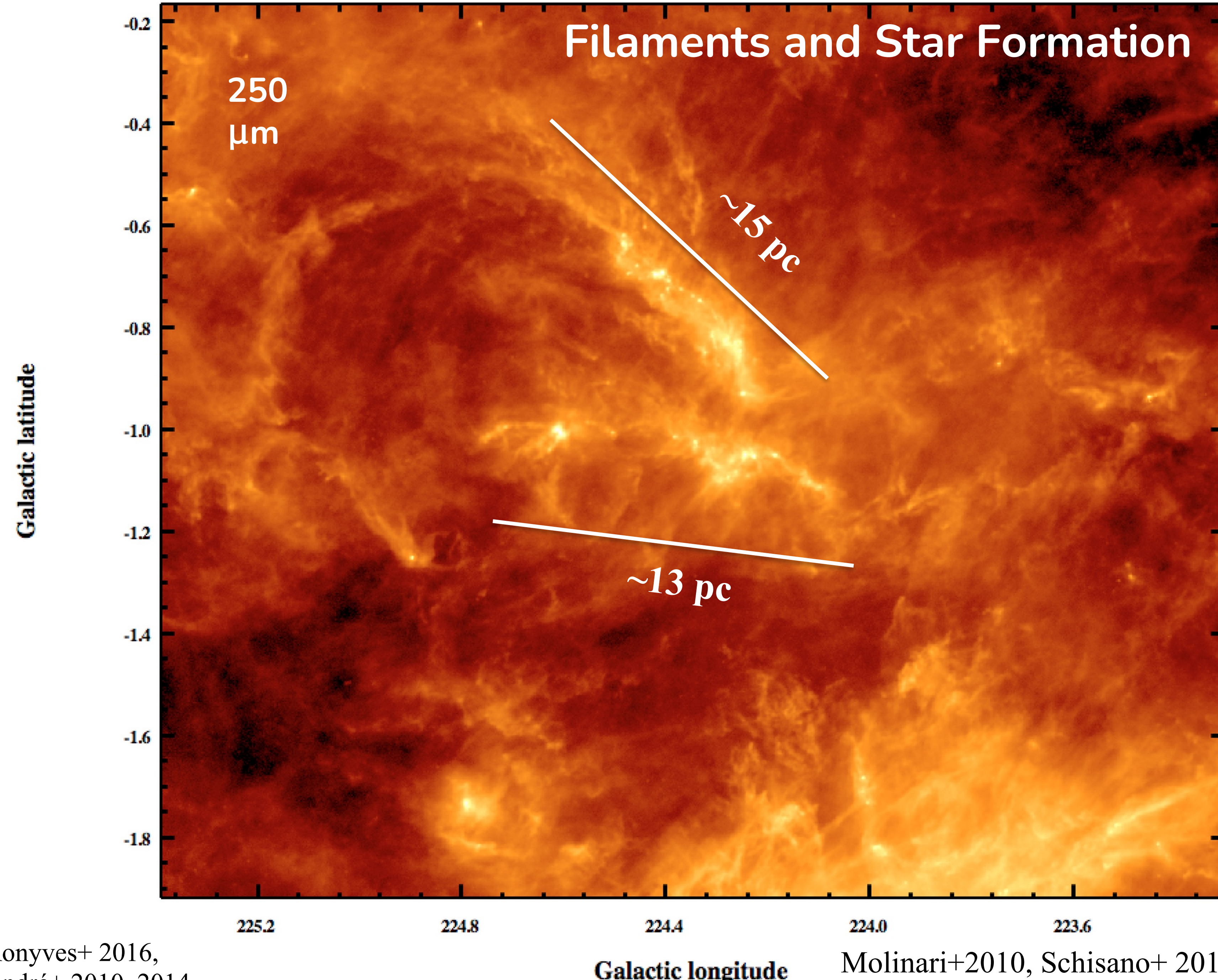
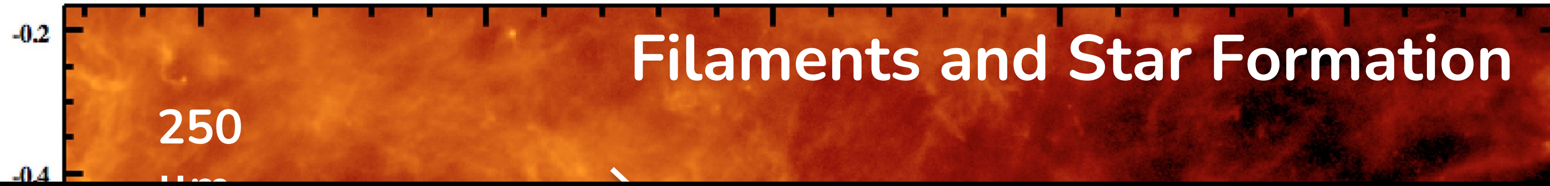
Filaments and Star Formation



Konyves+ 2016, André+ 2010. 2014

Molinari+2010, Schisano+ 2014

Filaments and Star Formation



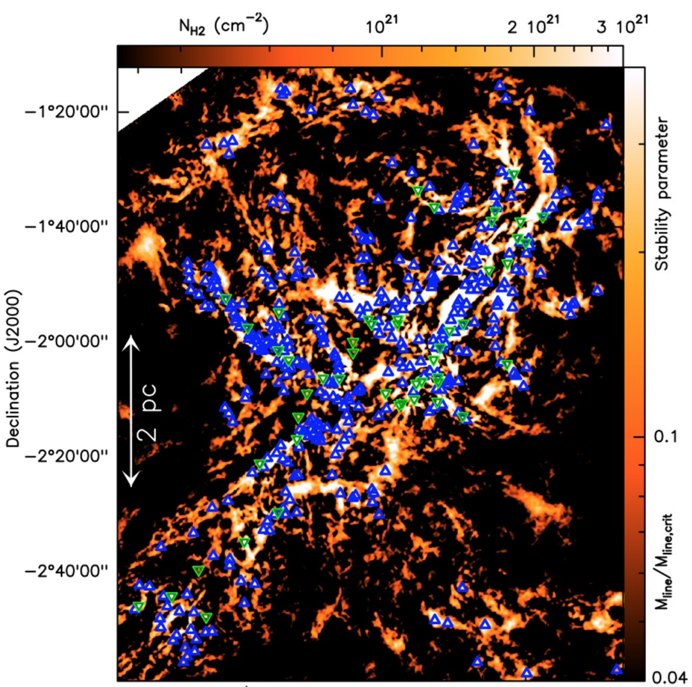
Star formation is mostly associated with filaments

(reported for young stars back to Schneider & Elmegreen 1979)

But also primordial condensation ($\tau^{pre} \leq 1$ Myr) are located on filaments

On situ formation $\geq 75\%$ early objects

Not all filaments are star forming



Konyves+ 2016,
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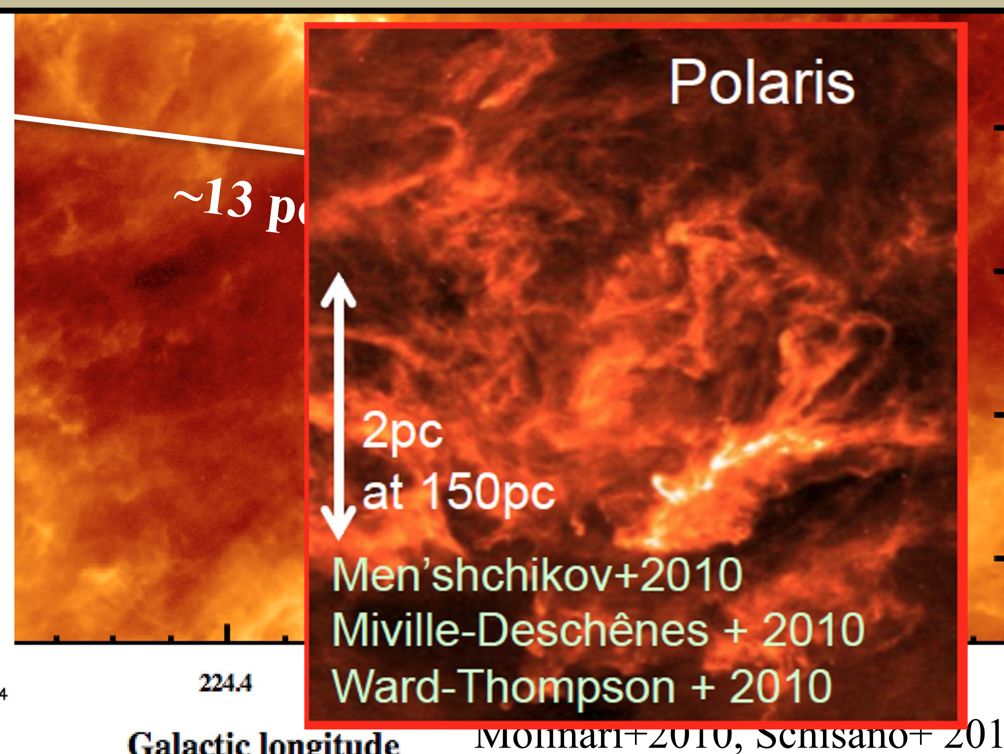
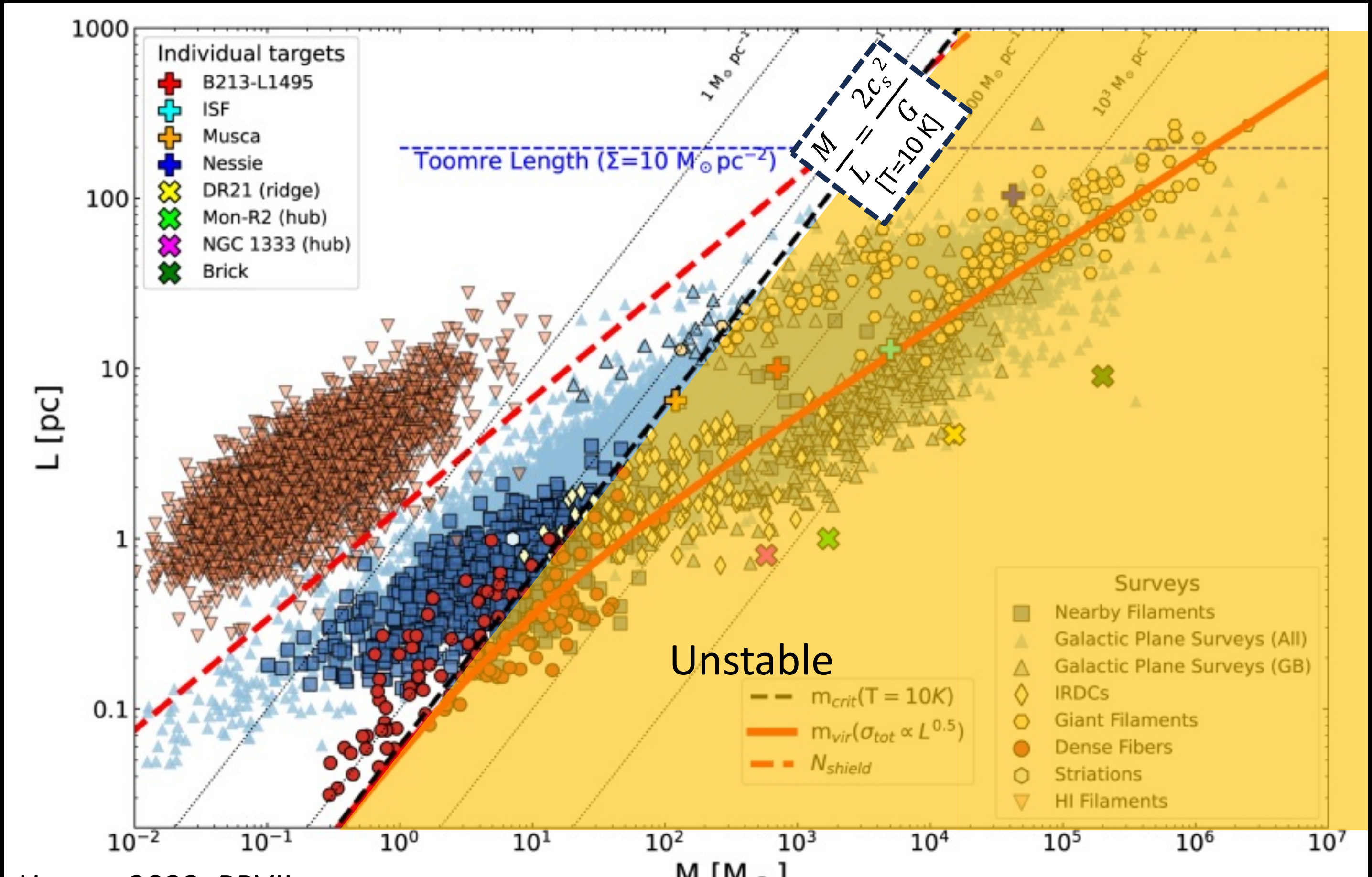


Molinari+2010, Schisano+ 2014

Mass-Size relationship of filamentary dust clouds



Hacar+ 2023, PPVII

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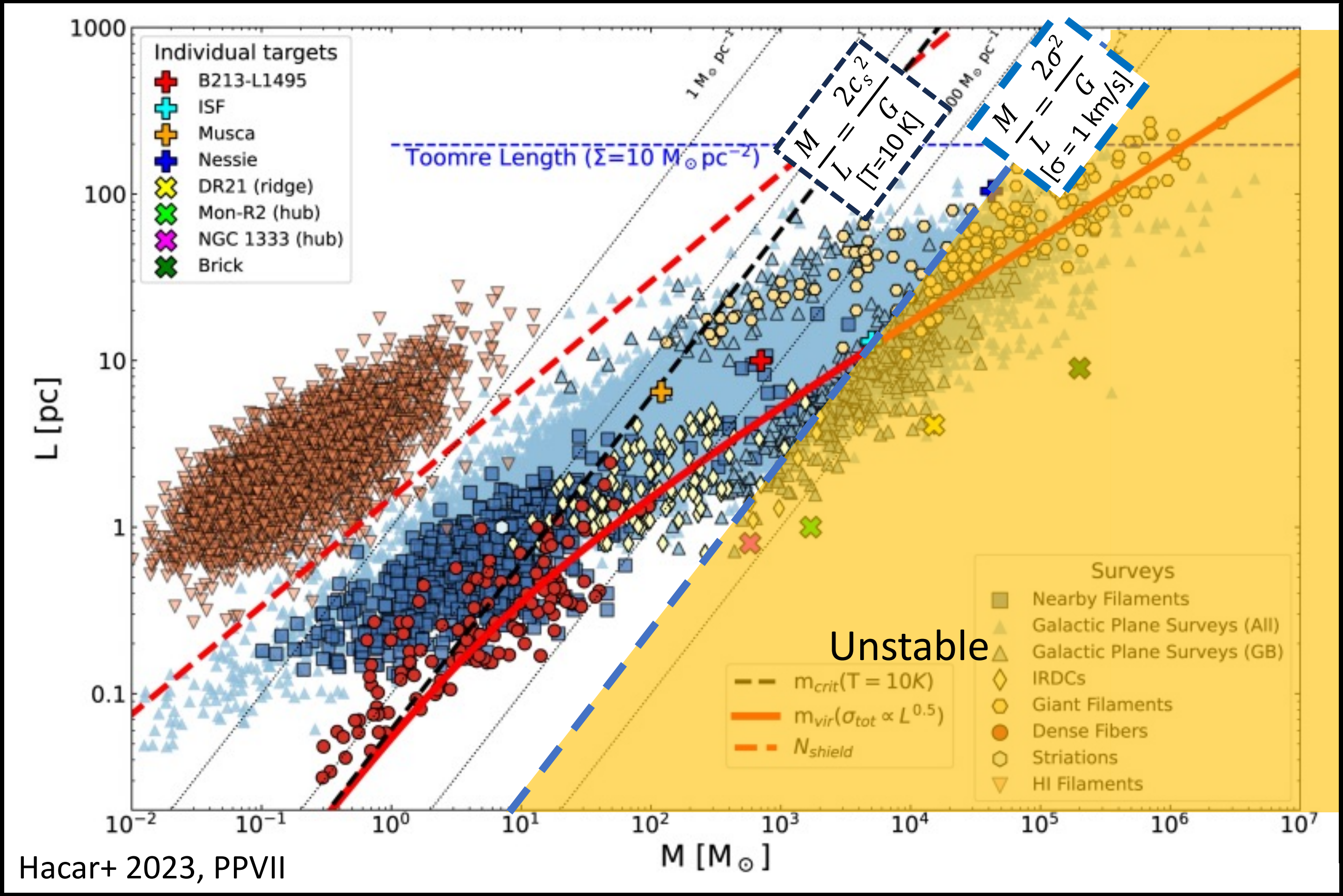
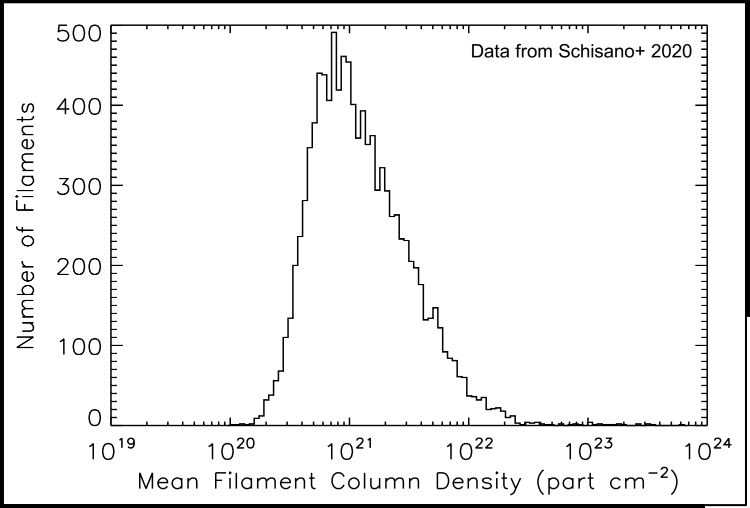
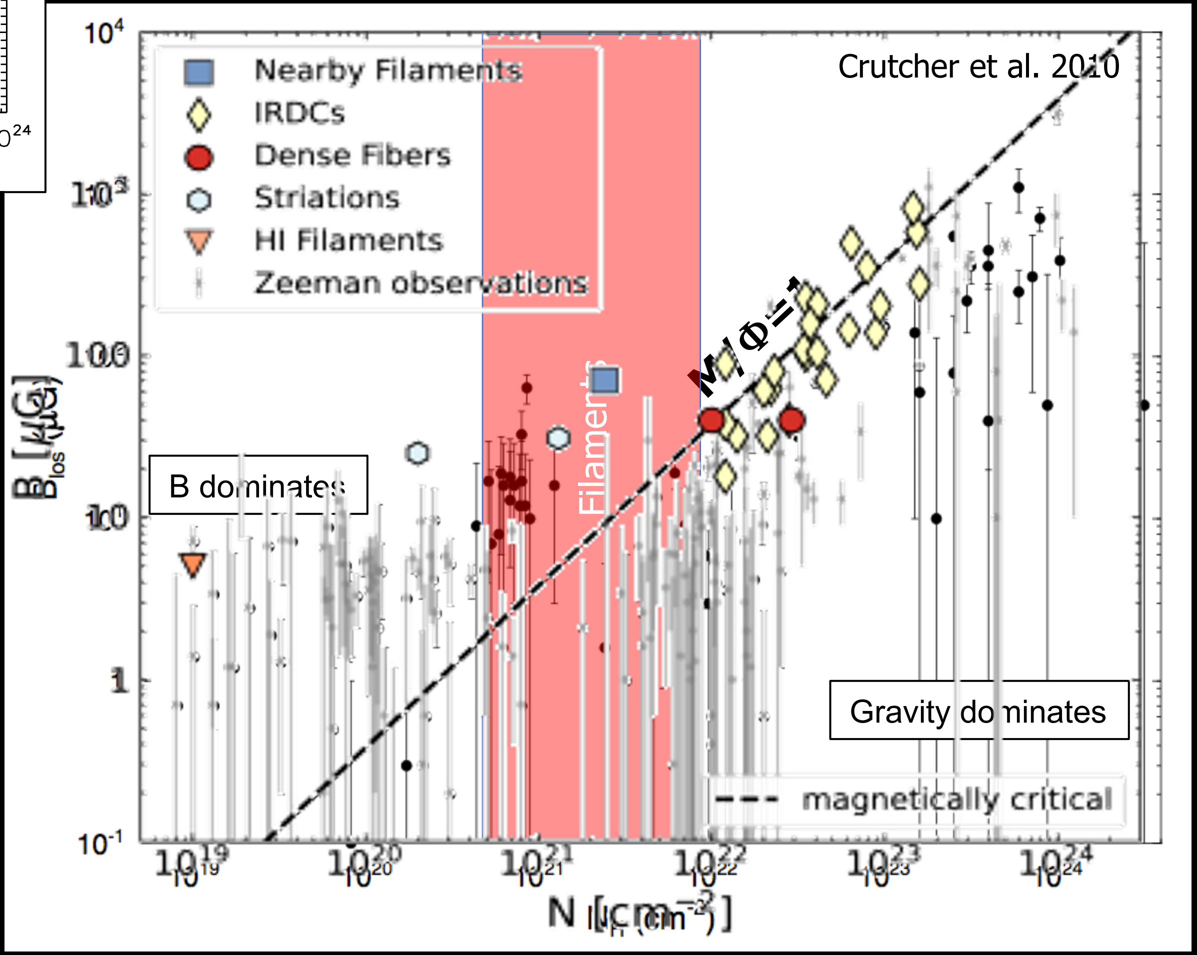


Supersonic non-thermal velocity dispersions $\sigma \sim 1\ km/s$ are compatible with measurements on large Galactic filaments, providing dynamical support.

Magnetic support in filaments



Dense Filaments span an average N(H_2) range that is compatible with structures on the verge of losing magnetic support



Dust polarization measurement, provide estimates of B intensity via the Davis-Chandrasekhar-Fermi method.

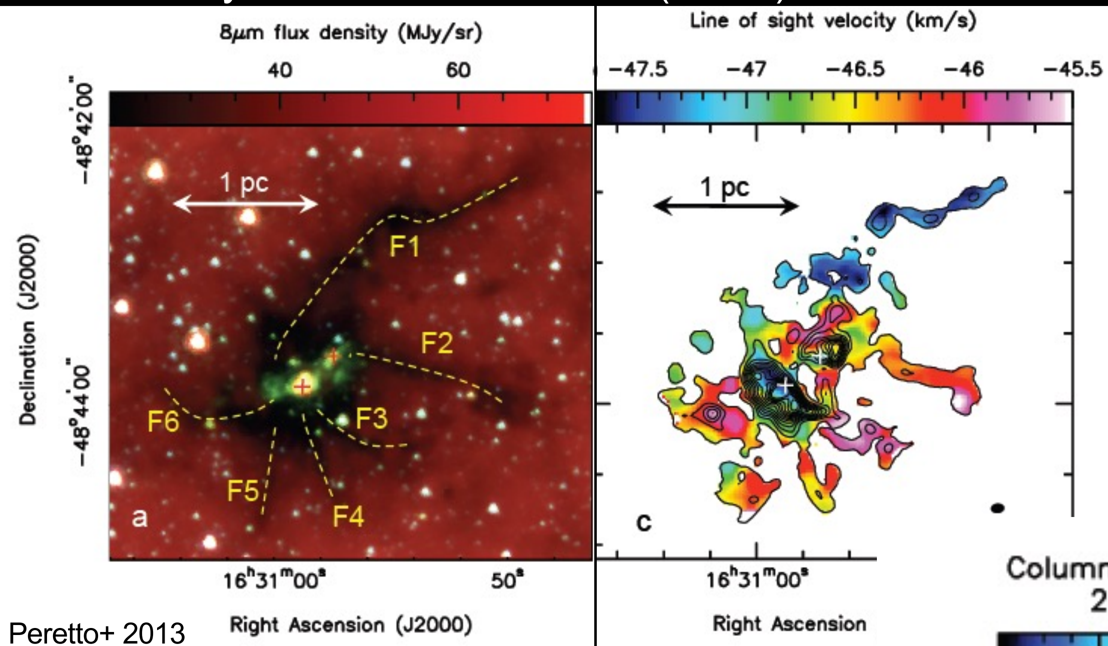
HI filaments and "striations" ISM are magnetically supported

Dense filaments like IRDC distribute on an equilibrium/equipartition

B drawn and amplified by gravity ?

Kinematics in filamentary clouds

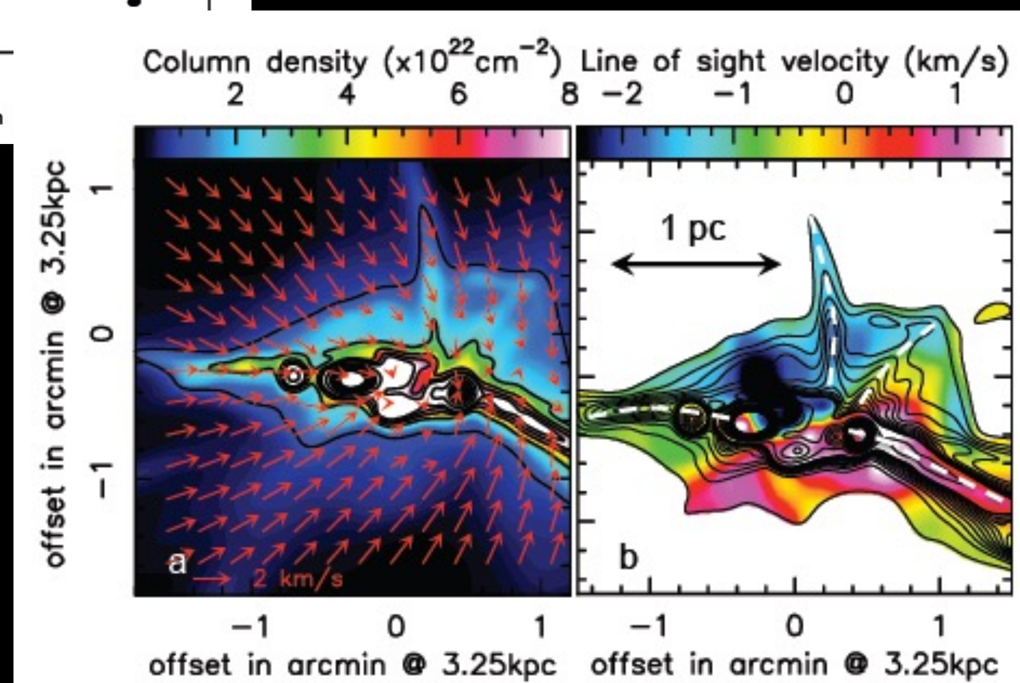
Filamentary *InfraRed Dark Cloud* (IRDC) SDC335



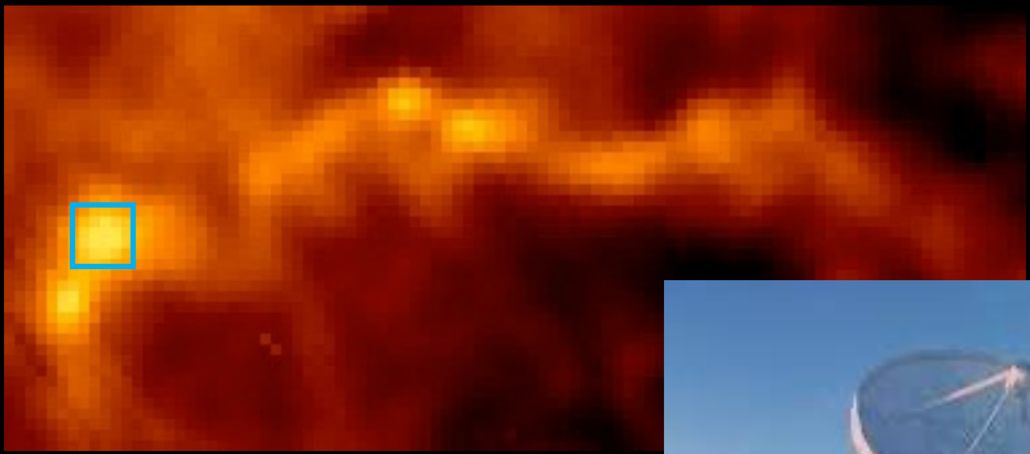
Peretto+ 2013

CH_3OH and N_2H^+ with ALMA (3mm band) reveal ordered motions along the filaments: filament accretion onto the central massive cores

Single-dish millimeter spectroscopy (HCO^+ 1-0) suggests global collapse: clump accretion onto the filaments.



When gravity takes over: the Dense Clumps



CLUMPS → Compact dense structures, generally poorly resolved by single-disk facilities both in dust and gas. Clumps are sites of protocluster formation

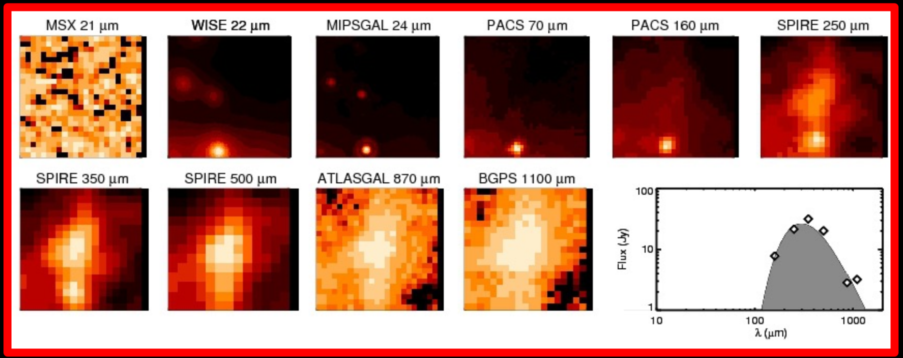
IRAM 30m – 1-3mm

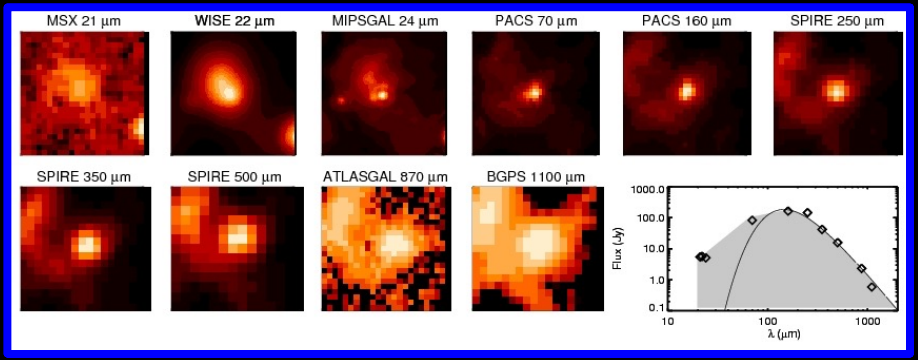
Herschel 3.5m – 70-500μm

Typical parameters:

- $0.1pc \leq R \leq 1.5pc$ → These are protoclusters formation sites
- $100M_{\odot} \leq M \leq 5000M_{\odot}$
- $n \geq 10^4\ cm^{-3}$
- Temperature, Luminosity and the shape of the Spectral Energy Distribution (SED) dramatically change with evolution

Dense Clumps in the infrared

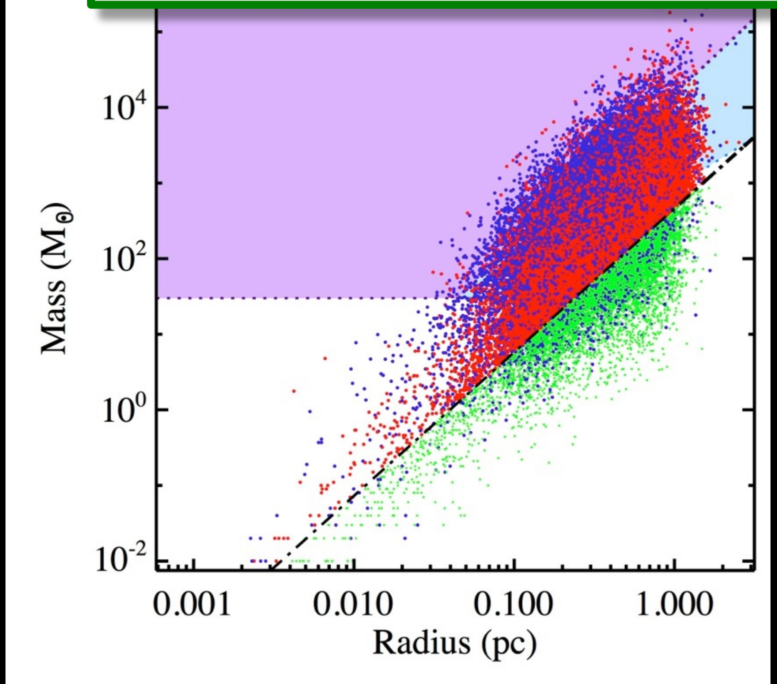


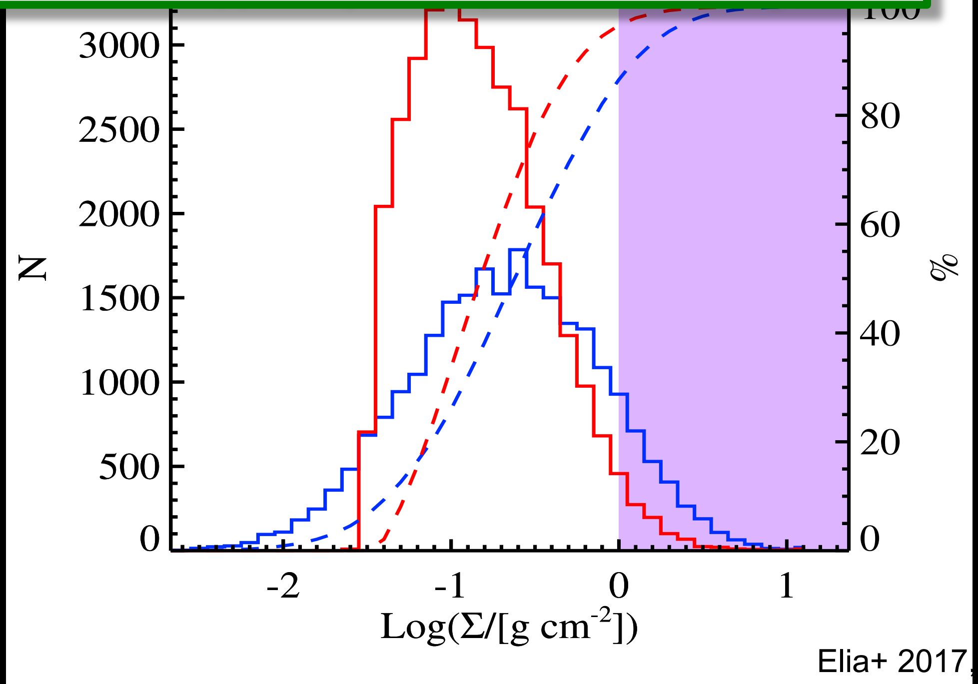


Proto-stellar sources

Pre-stellar sources

Nearly 150,000 compact clumps revealed by Herschel/Hi-GAL (Elia+ 2017, 2021)
Each source in Far-IR/submm single-dish surveys is a dense clump potentially hosting a protocluster in the making

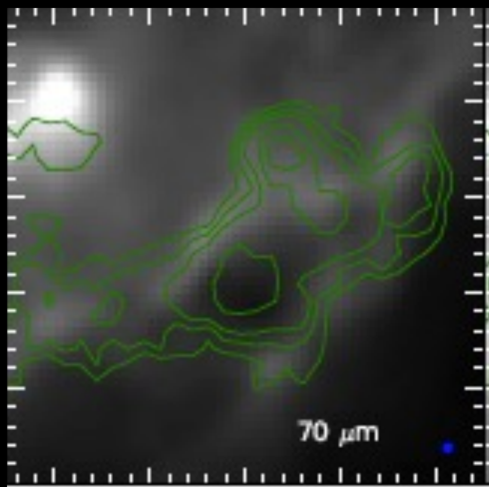


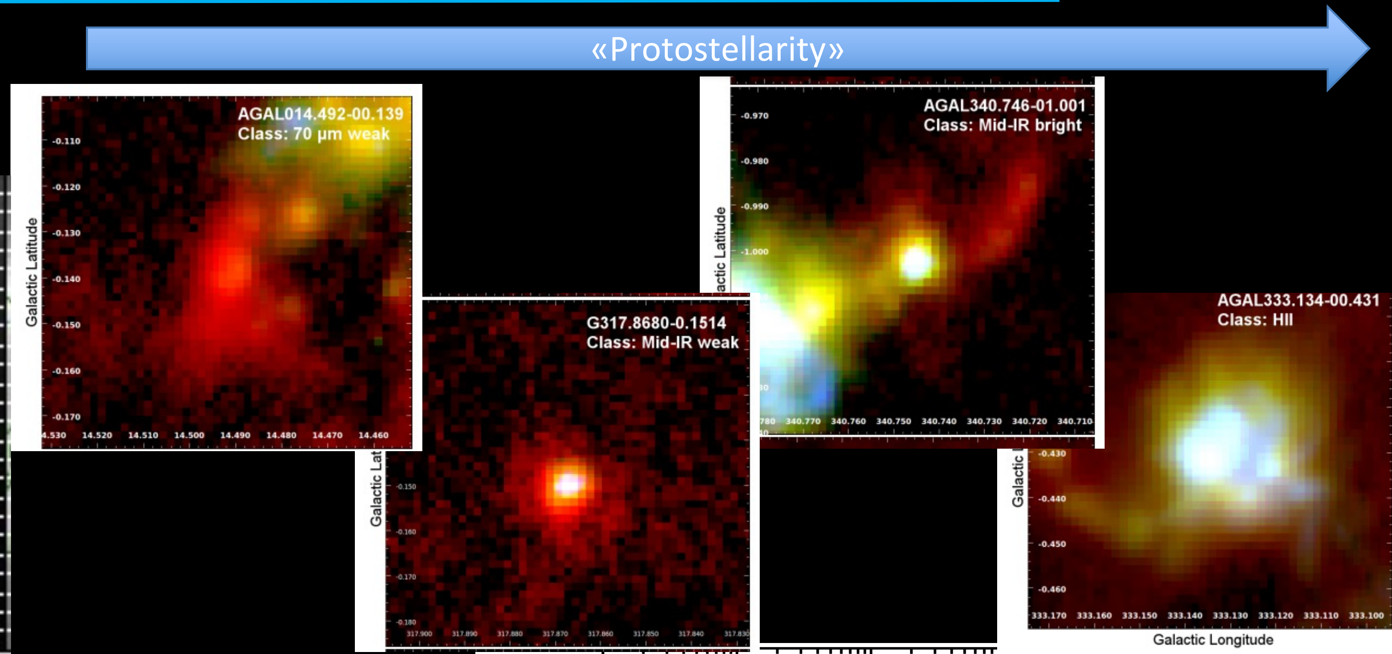


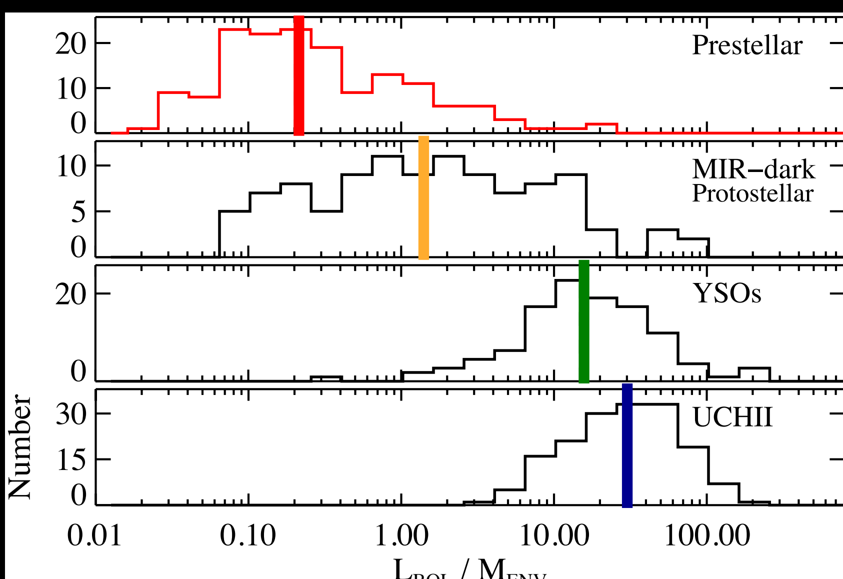
Elia+ 2017

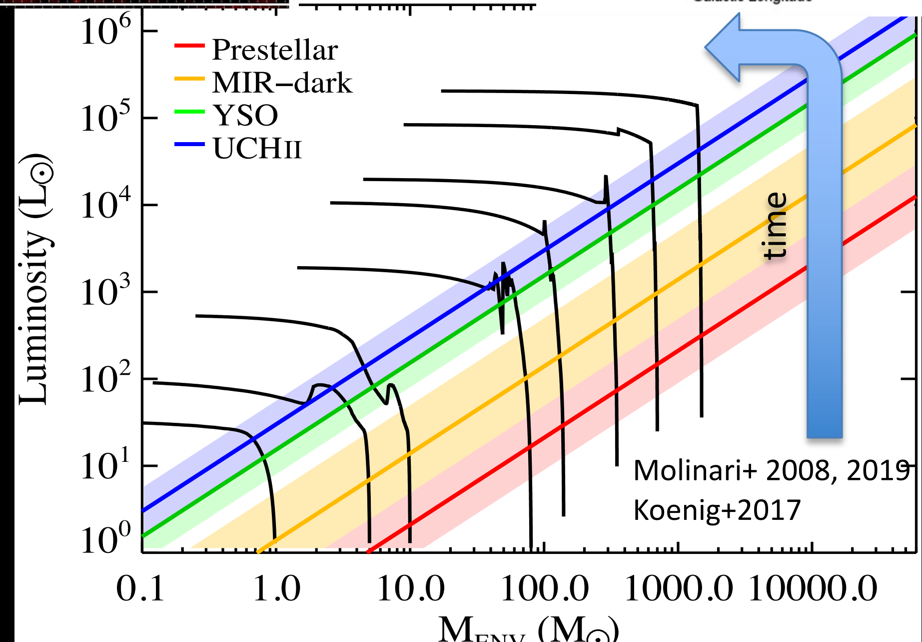
Tracing the evolution of Dense Clumps

«PreStellar» – 70μm dark
[no, or low, star formation ongoing





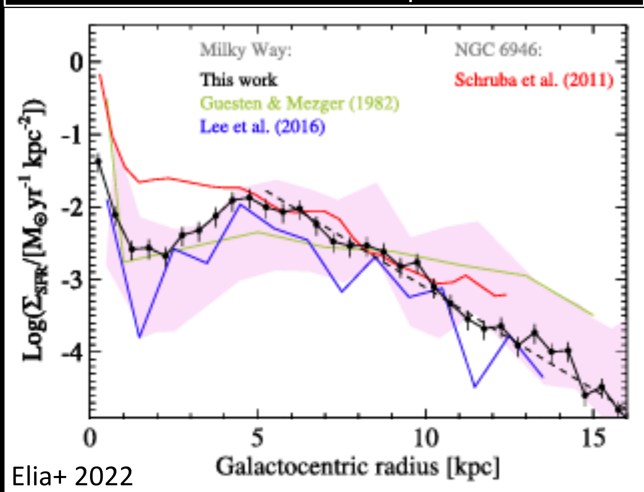




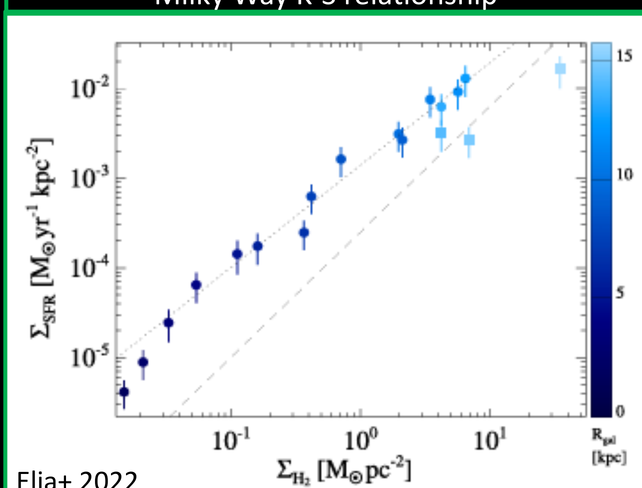
Back to the Galaxy: Star Formation Rates

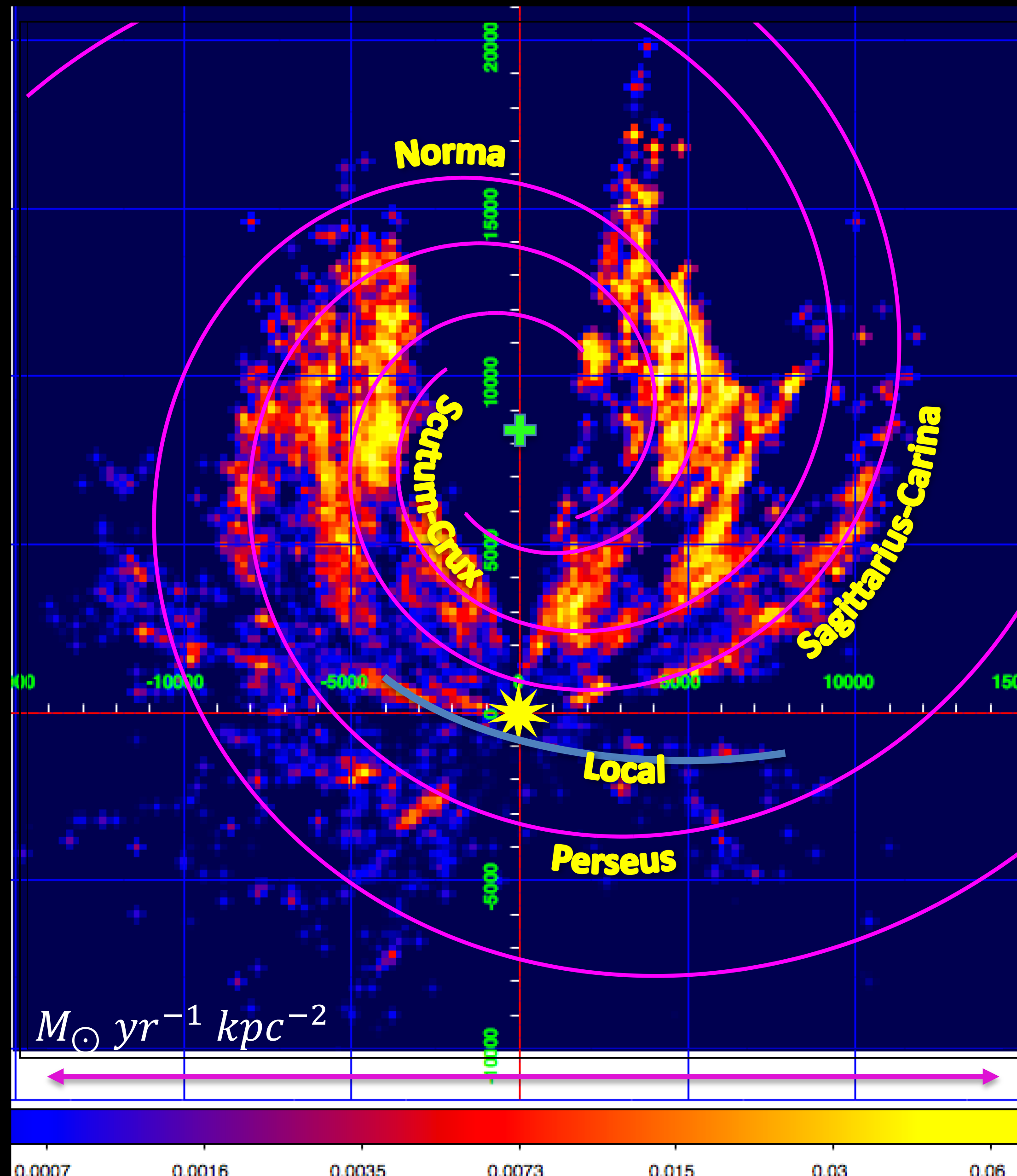
$$\iint \Sigma_{SFR} \sim 2.0 \pm 0.7\ M_{\odot} yr^{-1}$$

Galactocentric SFR profile

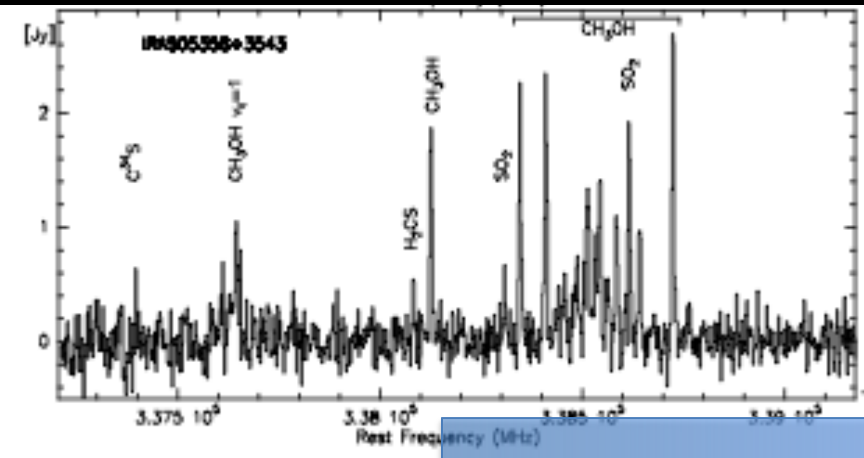


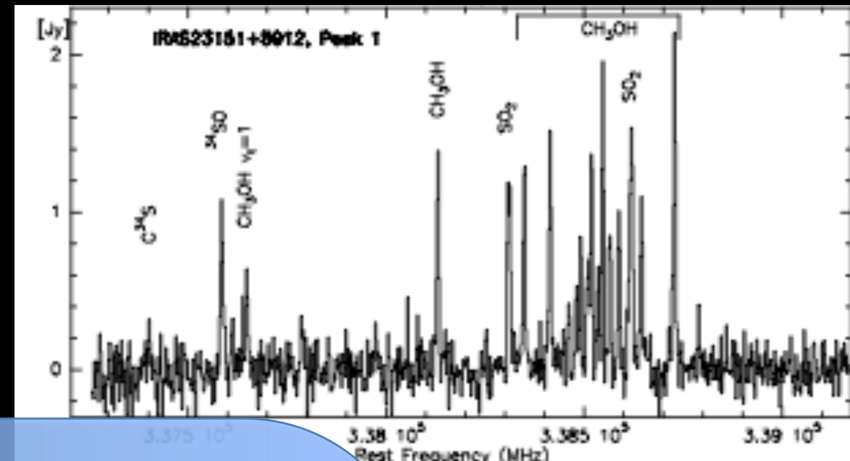
Milky Way K-S relationship





Star-forming Clumps as Chemistry Labs

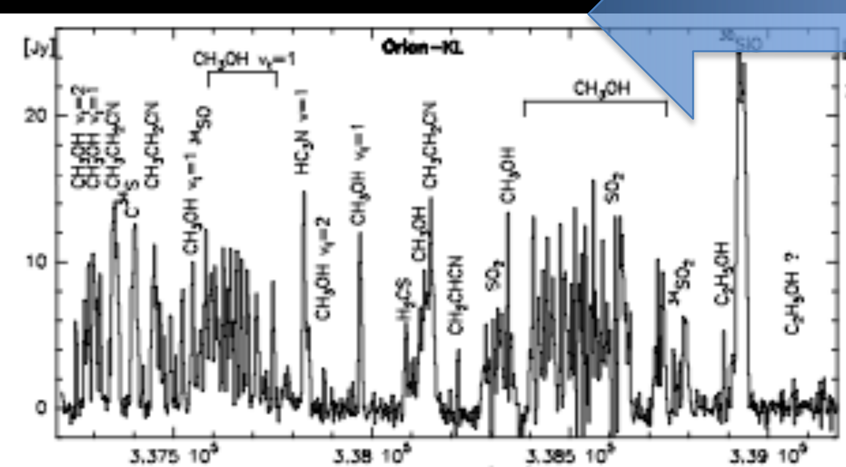


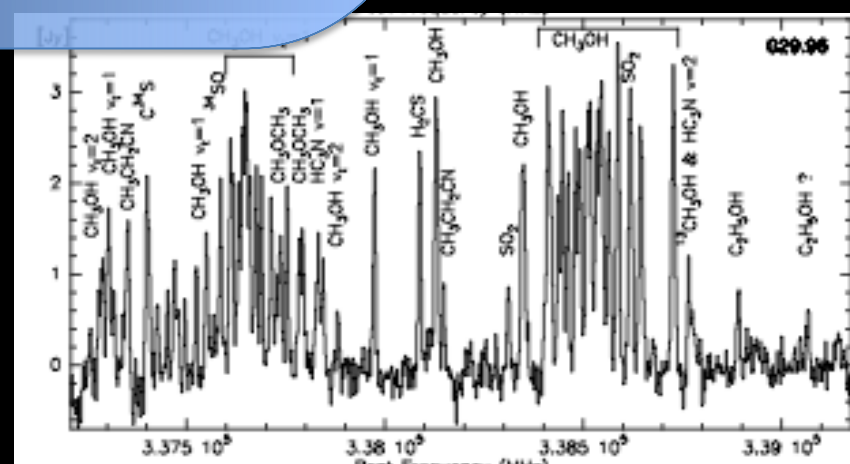


Rich photochemistry triggered by intense UV field from newborn massive stars

Evolution

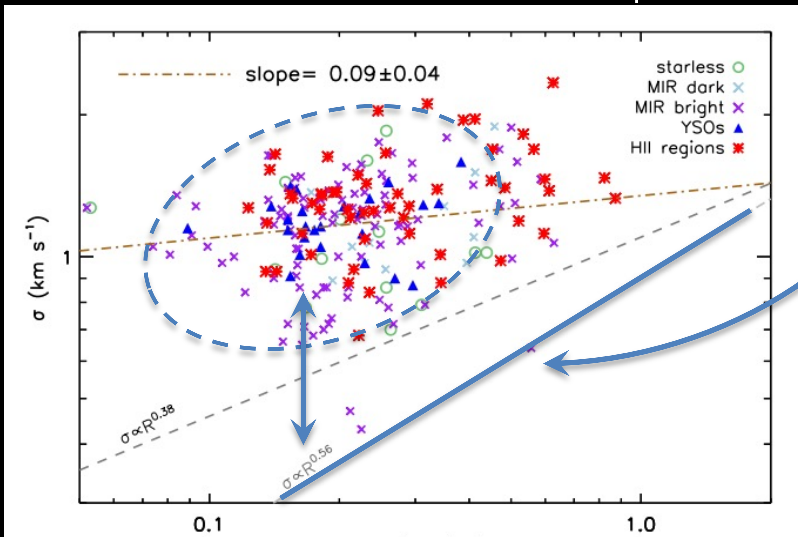
Sublimation of dust grain ice mantles (rich in molecules)





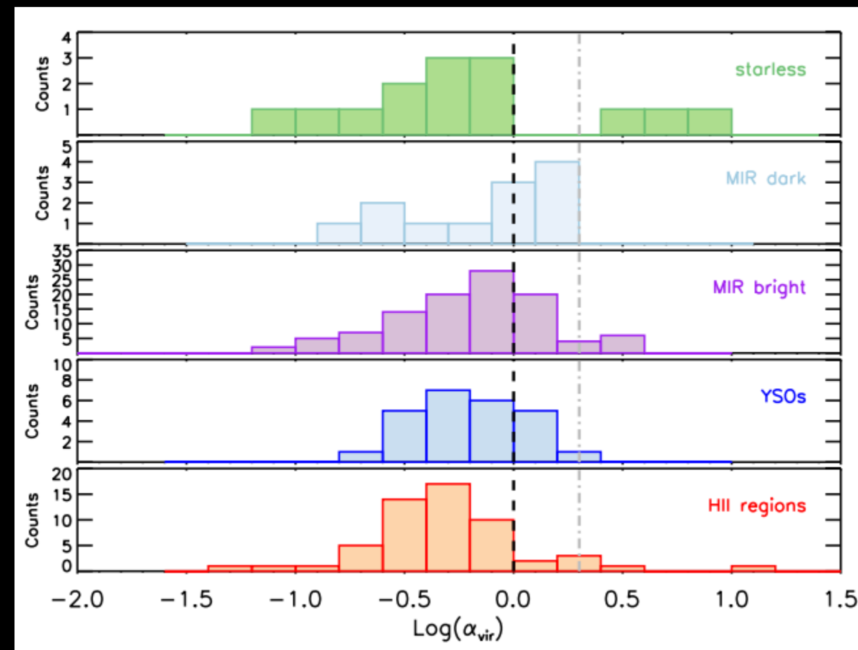
Dynamical State of Massive Clumps

Hi-GAL/MALT90 massive clumps



Traficante+ 2018

Massive Clumps depart from the Larson's relation $\sigma_v \propto R^{0.5}$ typical of turbulent support

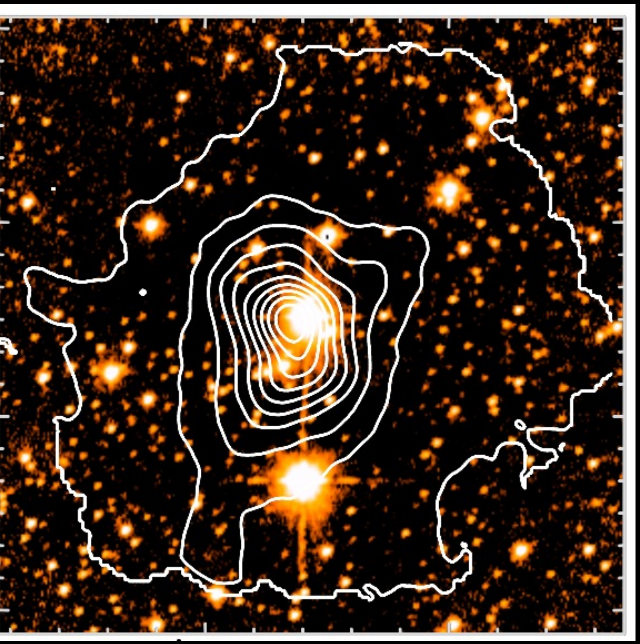


The excess of velocity dispersion at any given Clump radius (w.r.t. expectations for turbulent support) may be due to gravity-driven turbulence that does not oppose collapse, because it dissipates faster than it is injected

Virial parameters are for the most part α<1, suggesting a state of unsupported collapse
Caution in interpreting α_{vir}: equipartition may not mean stable equilibrium

Star Formation Histories in Dense Clumps

(image: Ks – contours: cold dust)



Strong ZAMS source and YSO cluster coincident with the peak of dense gas → well evolved system

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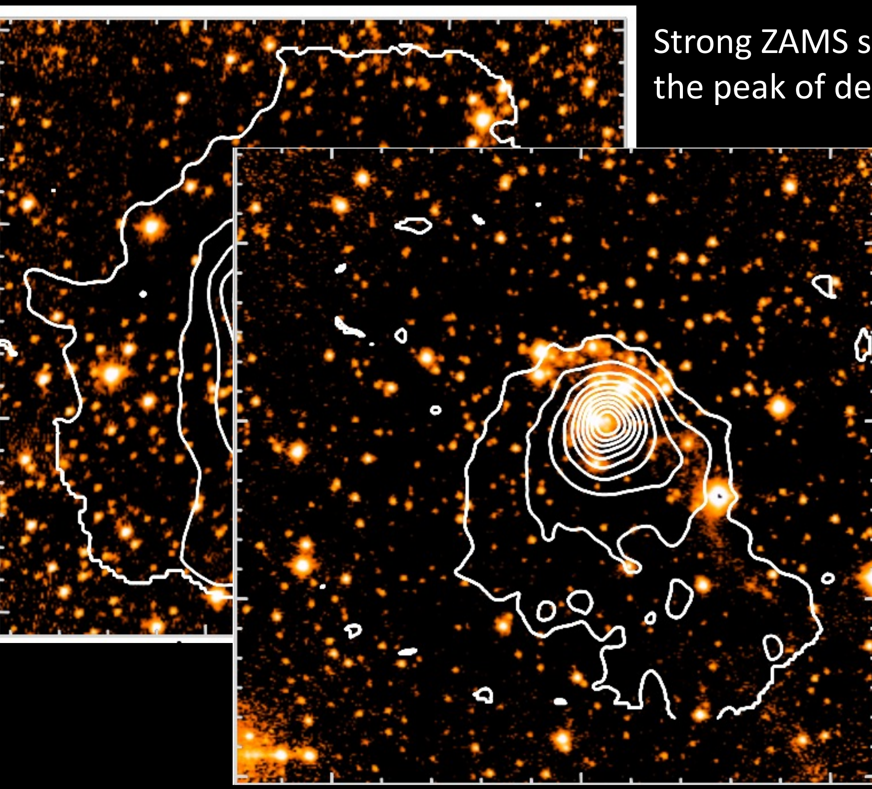

Strong ZAMS source and YSO cluster coincident with the peak of dense gas → well evolved system

Rich YSO cluster coincident with the peak of dense gas → massive ZAMS likely not yet there

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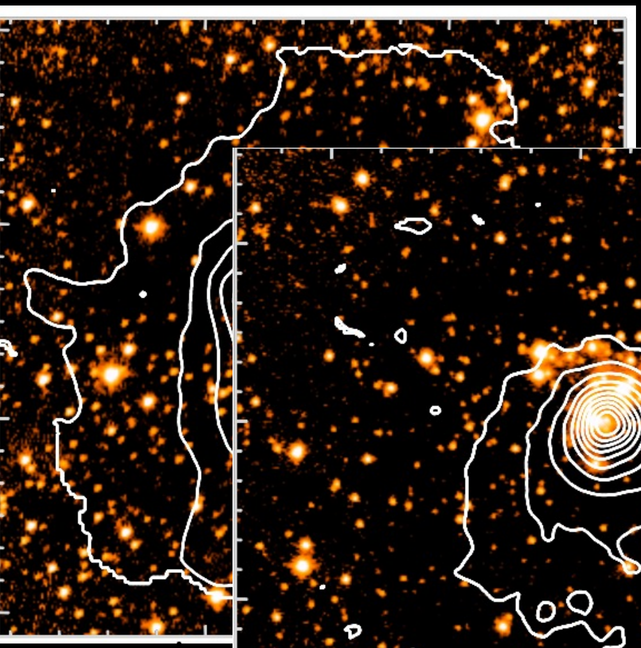

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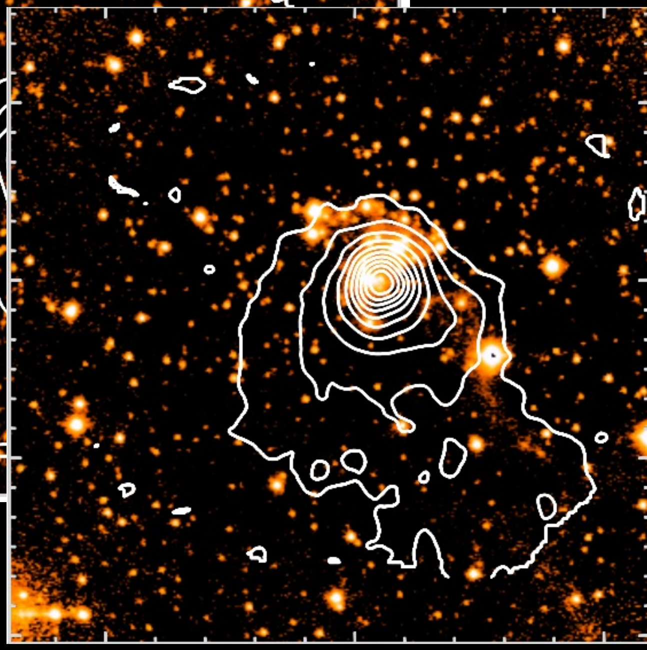

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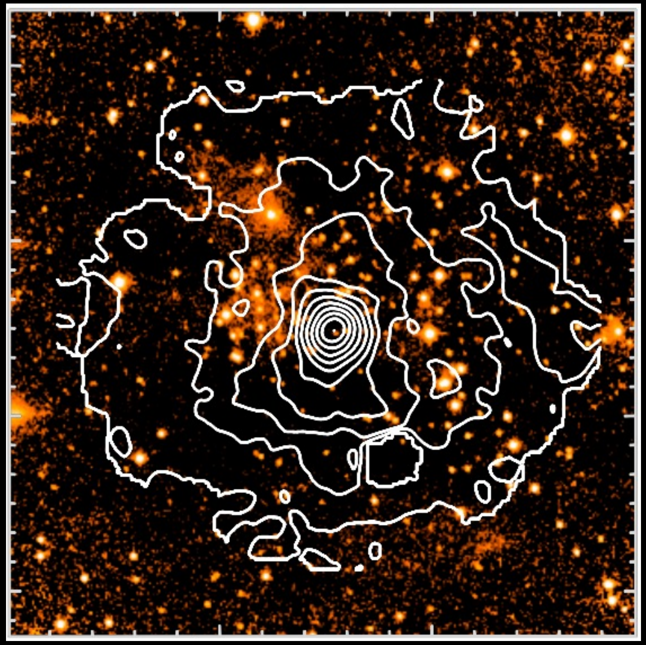

Rich YSO cluster AROUND the peak of dense gas → seed of massive stars not yet there, but still part of the same Star Formation event

Star Formation Histories in Dense Clumps

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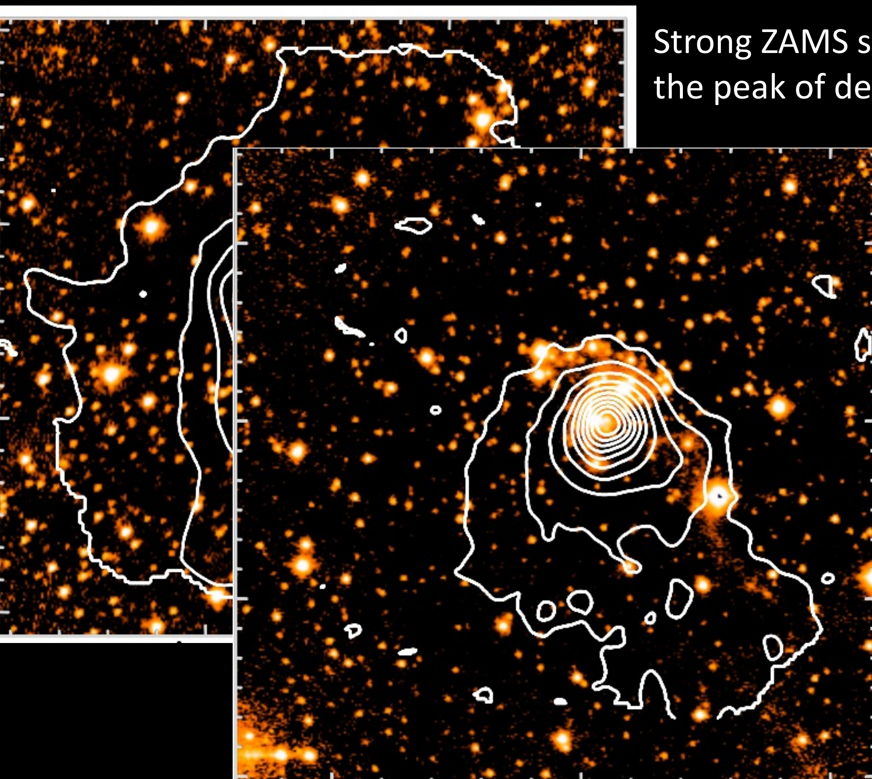

Strong ZAMS source and YSO cluster coincident with the peak of dense gas → well evolved system

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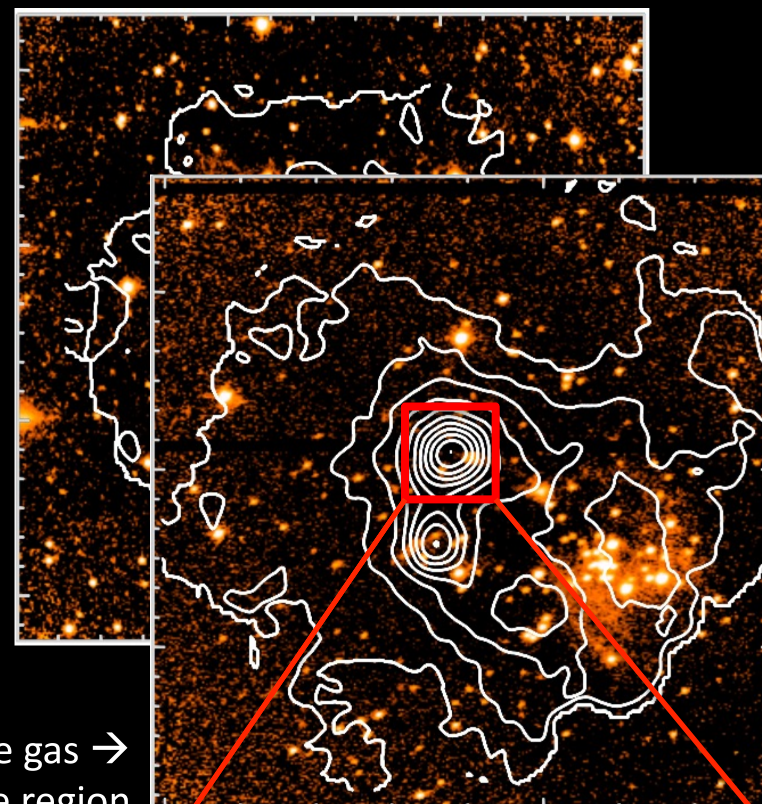


Rich YSO cluster AROUND the peak of dense gas → seed of massive stars not yet there, but still part of the same Star Formation event

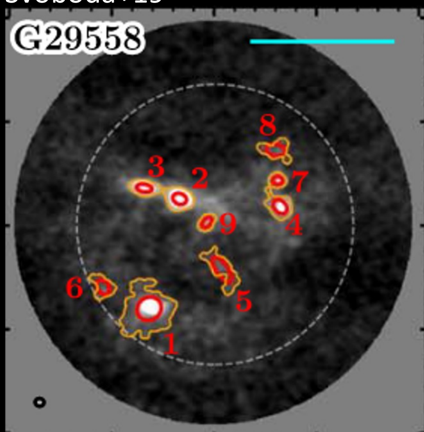
Rich YSO cluster OFFSET with the peak of dense gas → two distinct star formation events in the same region

Resolve the dense clumps into cores, a.k.a., the YSO progenitors

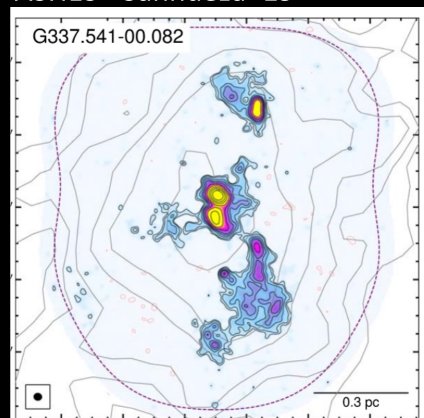
Cores-clusters overview with ALMA/NOEMA

70μm-dark — Evolution → $L \geq 10^4\ L_\odot$

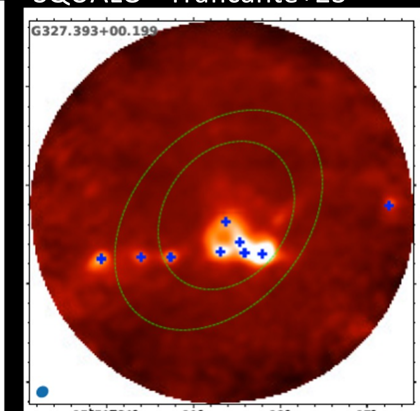
Svoboda+19



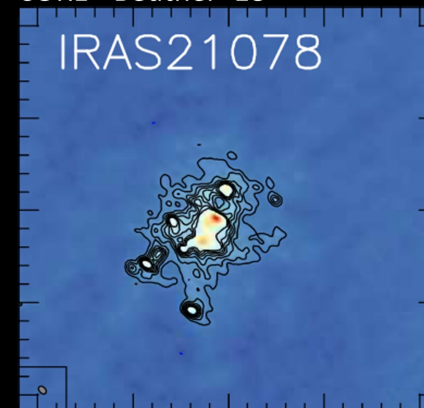
ASHES - Sanhueza+19



SQUALO - Traficante+23



CORE - Beuther+18



- Variable but relatively high degree of fragmentation (up to 40-ish) in all evolutionary stages
- Hierarchical sub-clustering, with fragments separation ~ thermal Jeans length
- Hints of cores separation decreasing with evolution

However: 10-20 massive clumps for each program - Physical resolutions between 1000 and 5000 au

→ poor statistics

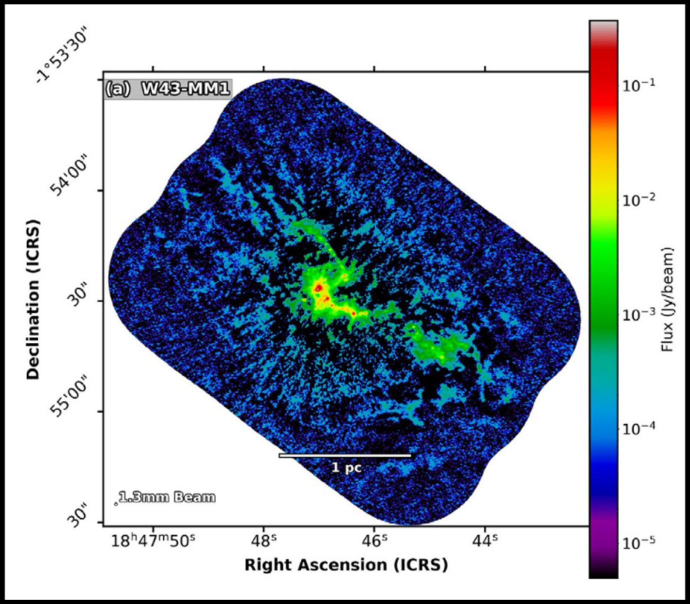
- Mapping of entire star-formation complexes
- Statistical target samples ($\sim 1000s$)
- Chemistry

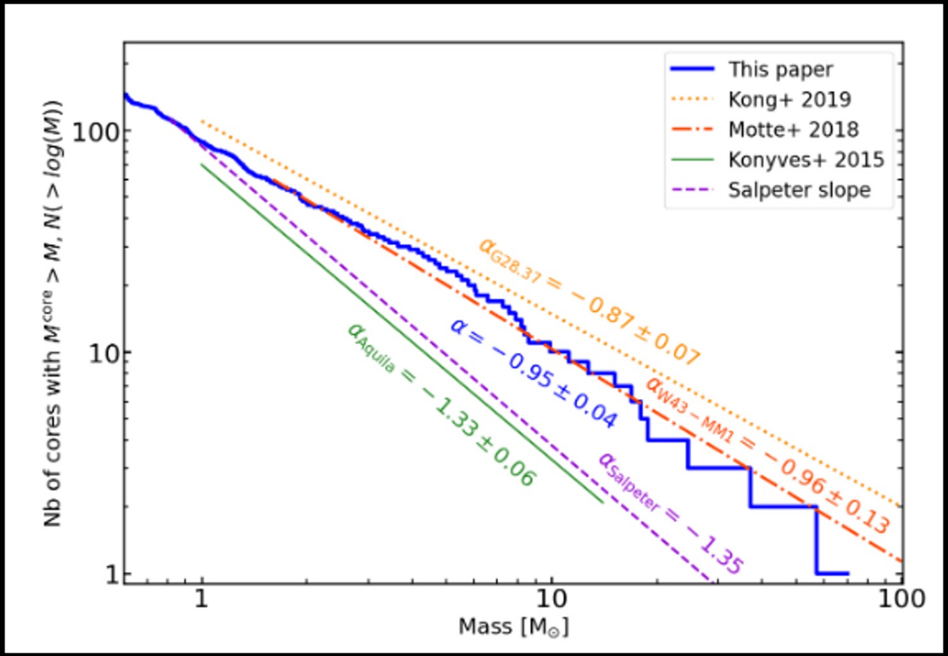
Large ALMA Programs:
ALMA-IMF & ALMAGAL

ALMA-IMF: Star-Forming Complexes

Large ALMA Program: ALMA-IMF: Investigating the origin of stellar masses (Motte+2022)

- 15 extreme protoclusters (2500 ≤ M ≤ 33000 $M_\odot$) mapped at 1mm and 3mm, including e.g. the W43 mini-starbust complex
- Sensitivity down to ~0.5 $M_\odot$ and spatial resolution of ~2000 AU





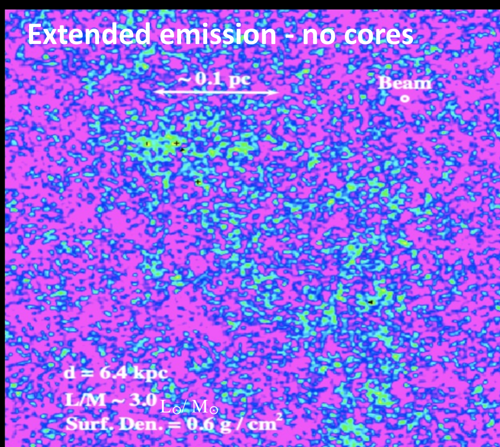
FIRST RESULTS

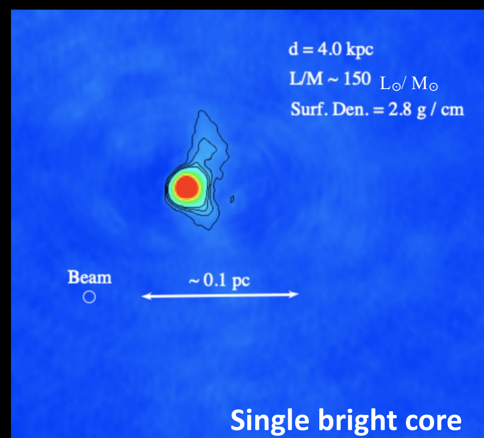
- ~700 cores with masses 0.15 ≤ M ≤ 250 $M_\odot$ (Motte+22; Ginsburg+22)
- Evidence of top-heavy core mass function in W43-MM2/MM3 (Pouteau+22)
- Similar chemical composition and excitation of most of the COMs in W43-MM1 hot cores (Brouillet+22)

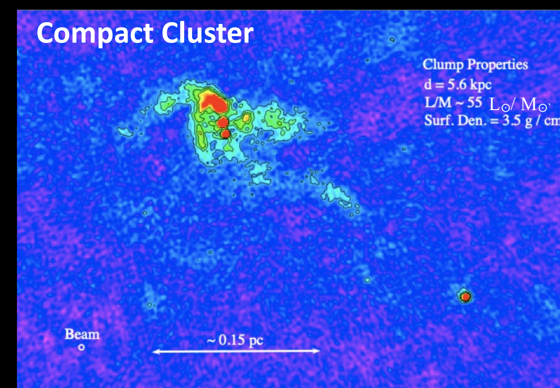
ALMAGAL: Statistical Galaxy-Wide Surveys

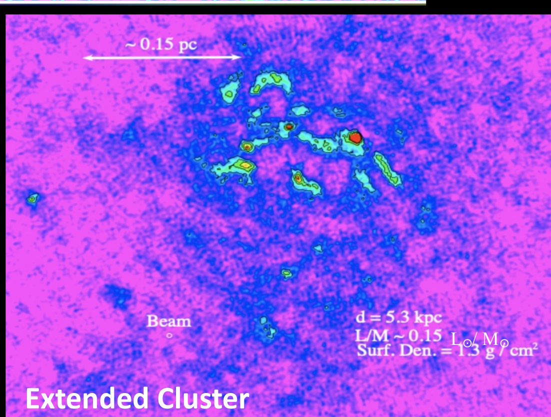
Large ALMA Program ALMAGAL: a **statistically significant and complete survey** of massive star-forming clumps in our Galaxy (Molinari+ 2024, in prep.)

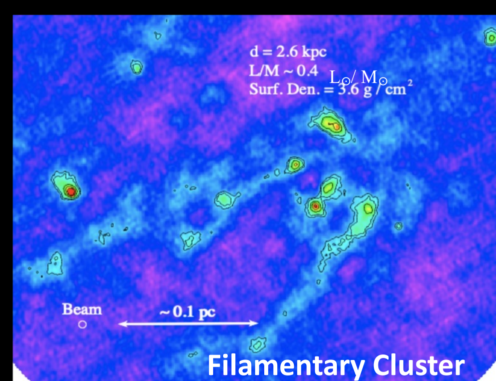
1017 clumps: **M** ≥ 500 $M_\odot$, $10^{-2} \lesssim$ **L/M** $\lesssim 10^{3}$ $L_\odot/M_\odot$
ALMA Band 6 (1.3mm), 1000au spatial resolution, 0.3 $M_\odot$ mass limit

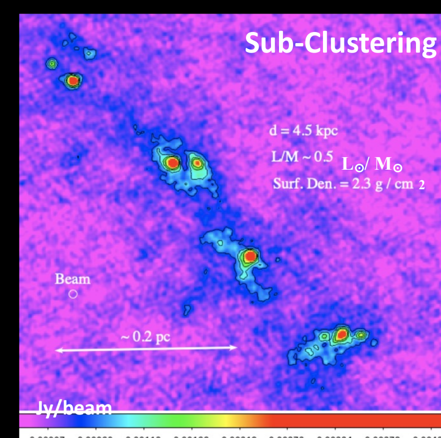




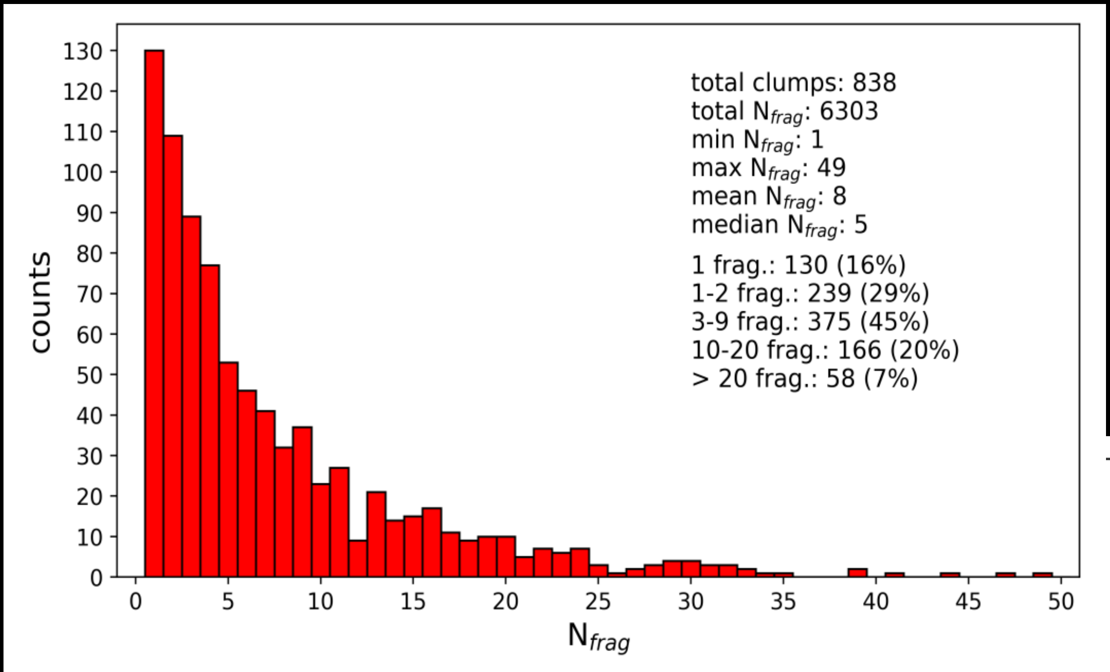




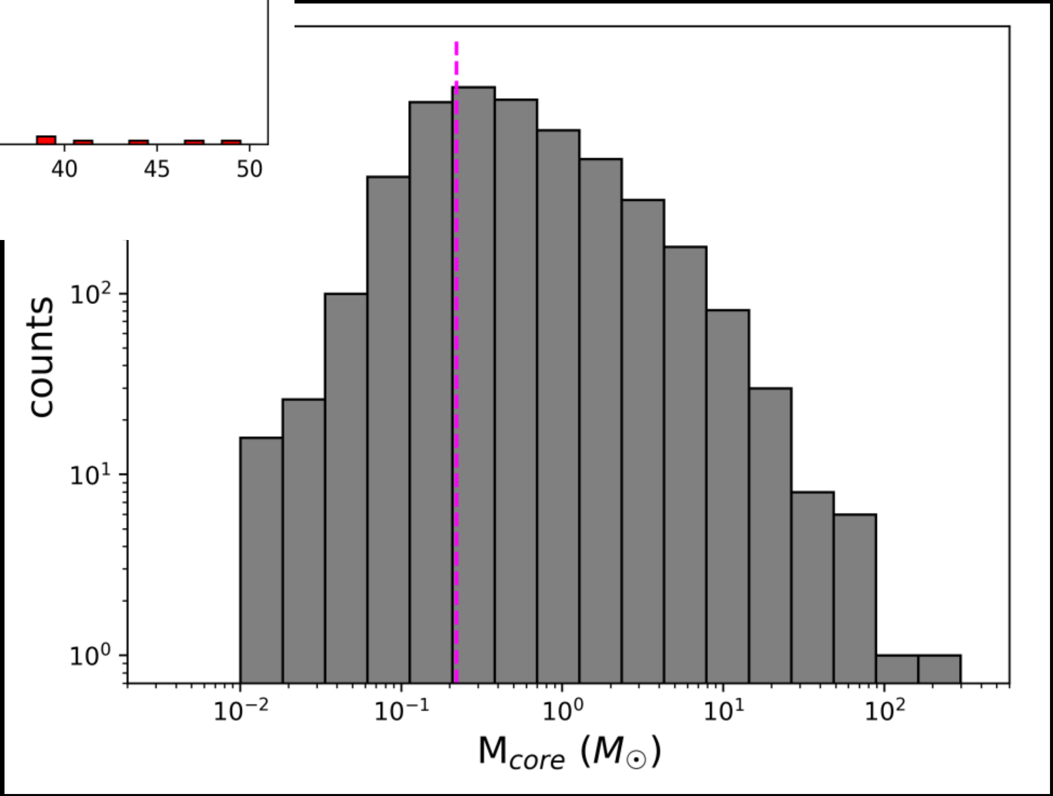




ALMAGAL: Fragmentation Statistics



Coletta+ 2024, in prep.

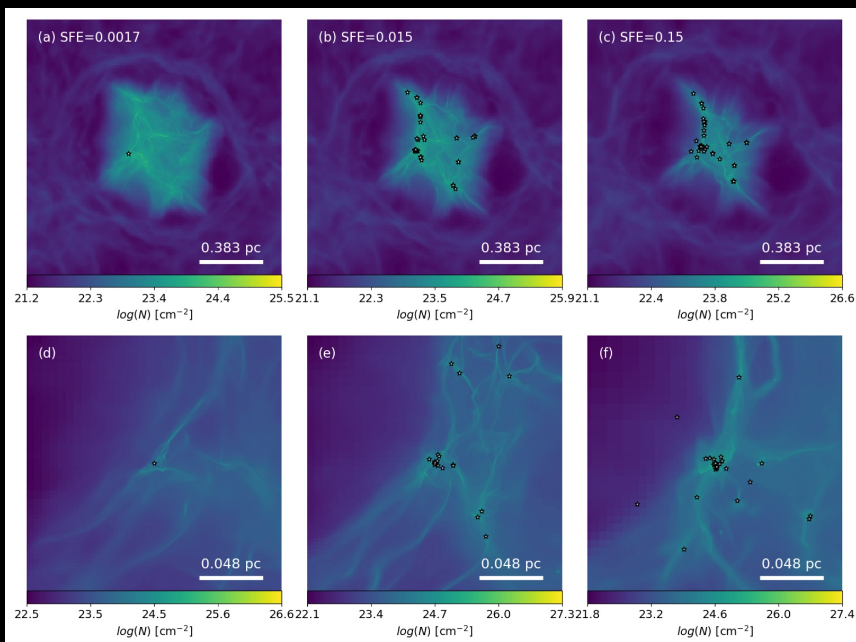


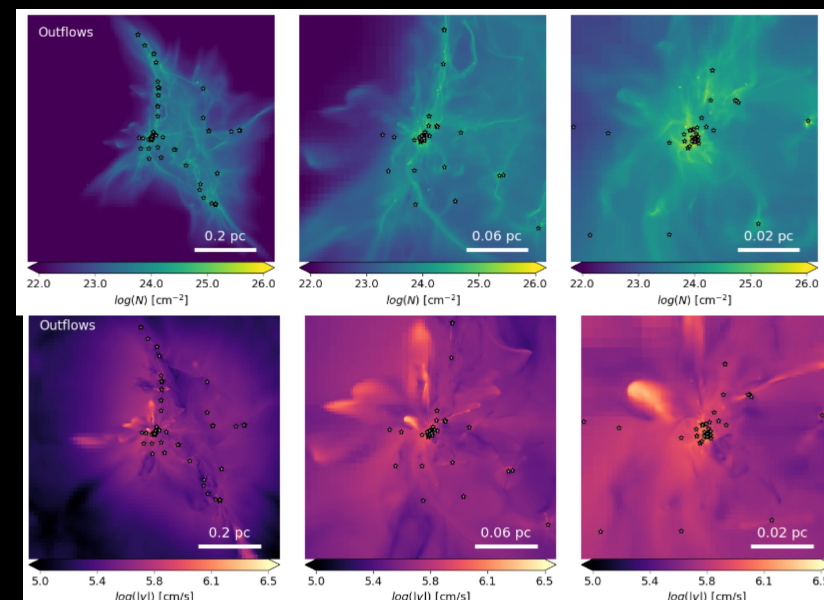
Careful with Core mass estimates

→ Dust Temperature
→ Dust Opacity
→ Free-free contamination

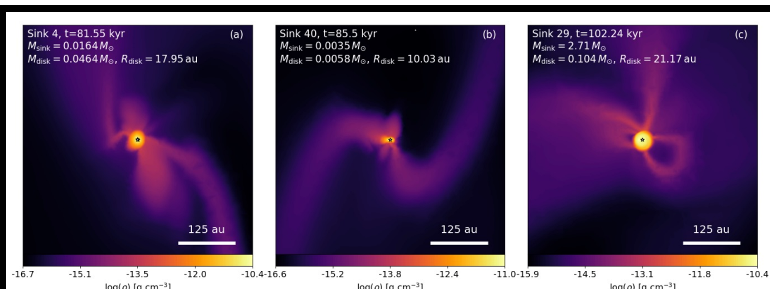
From Cores to Disks

Simulations show that new/different physics affects the process of clump fragmentation and disk formation. Simulations alone cannot allow us to derive quantitative conclusions without the ground truth provided by observations. A meaning full detailed comparison is essential!





(Lebreuilly et al. 2022, 2023)



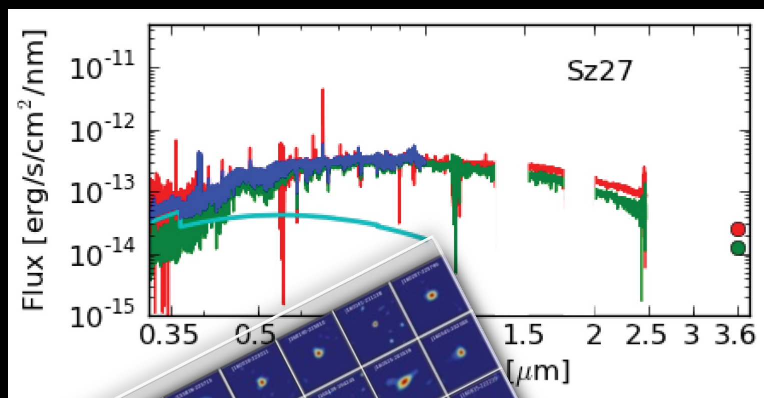
<= Individual disks, fed by streamers

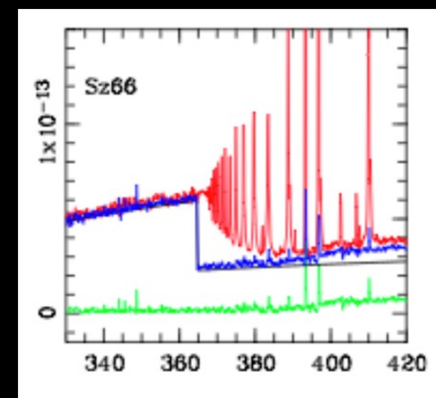
ALMA and VLT observations of disks populations

The past decade has produced a revolution in our understanding of protoplanetary disk populations using ALMA and VLT.

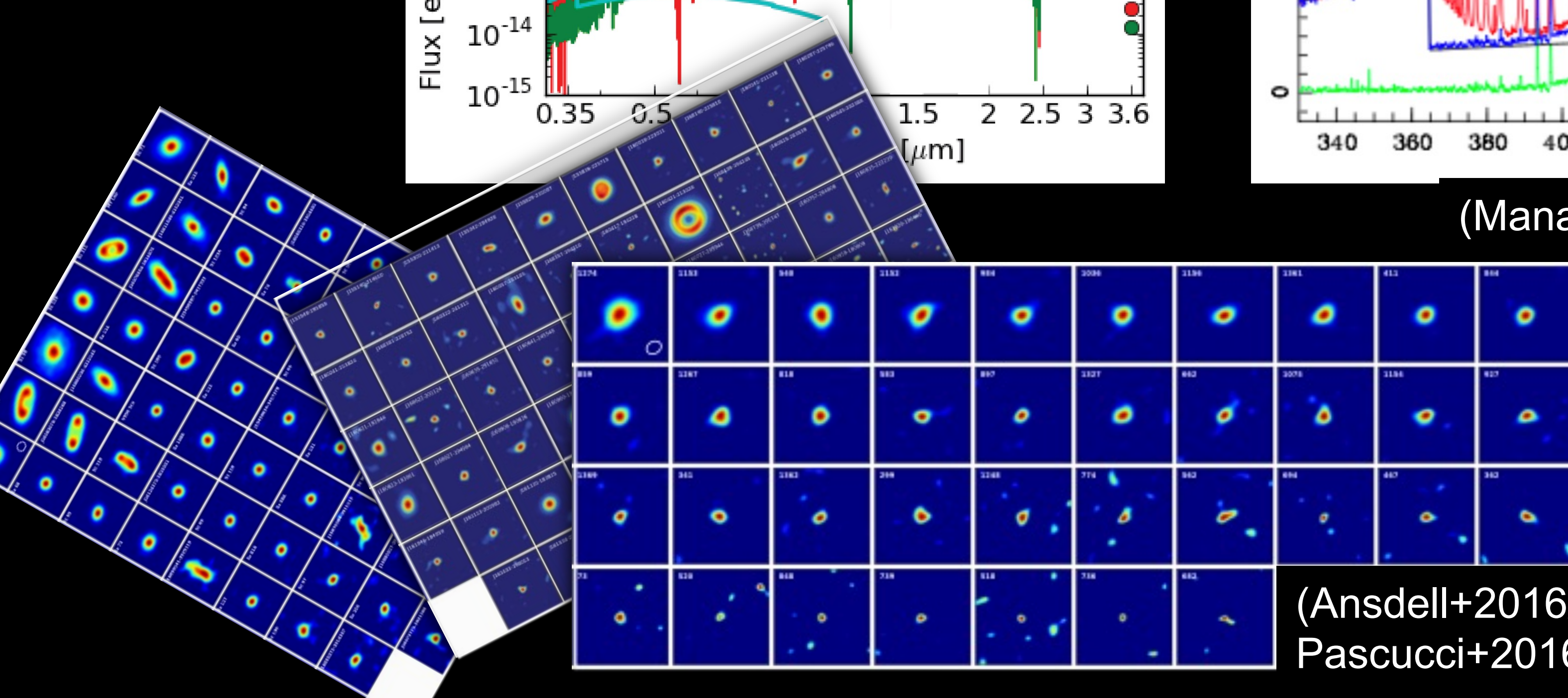
Disk masses, sizes and accretion rates have been the prime observables used to constrain disk physics during planet formation

VLT/XSHOOTER





(Manara+2014, 2023)



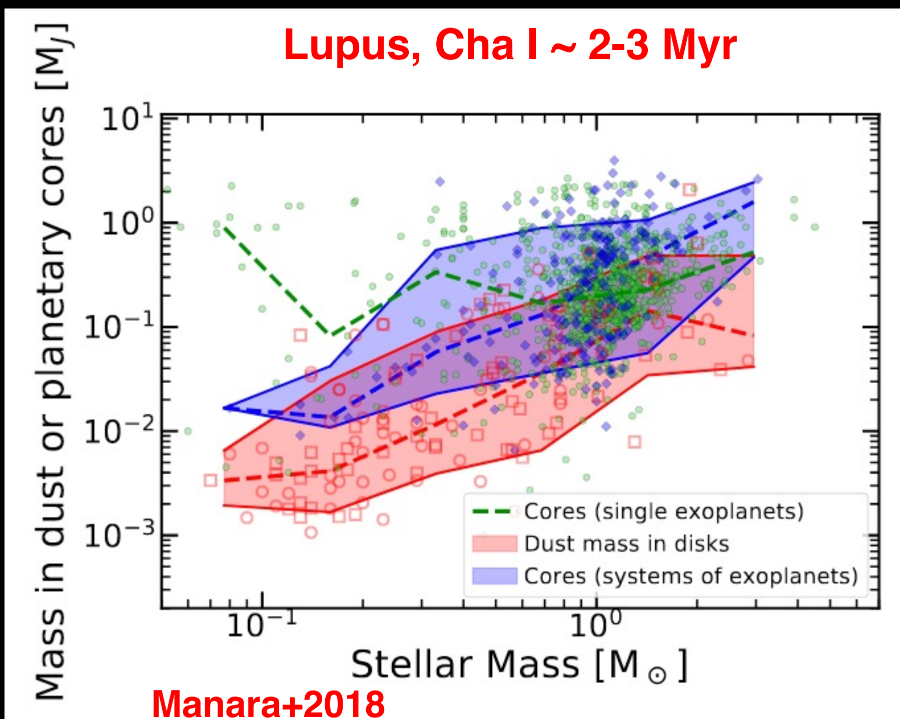
ALMA/B6/B7

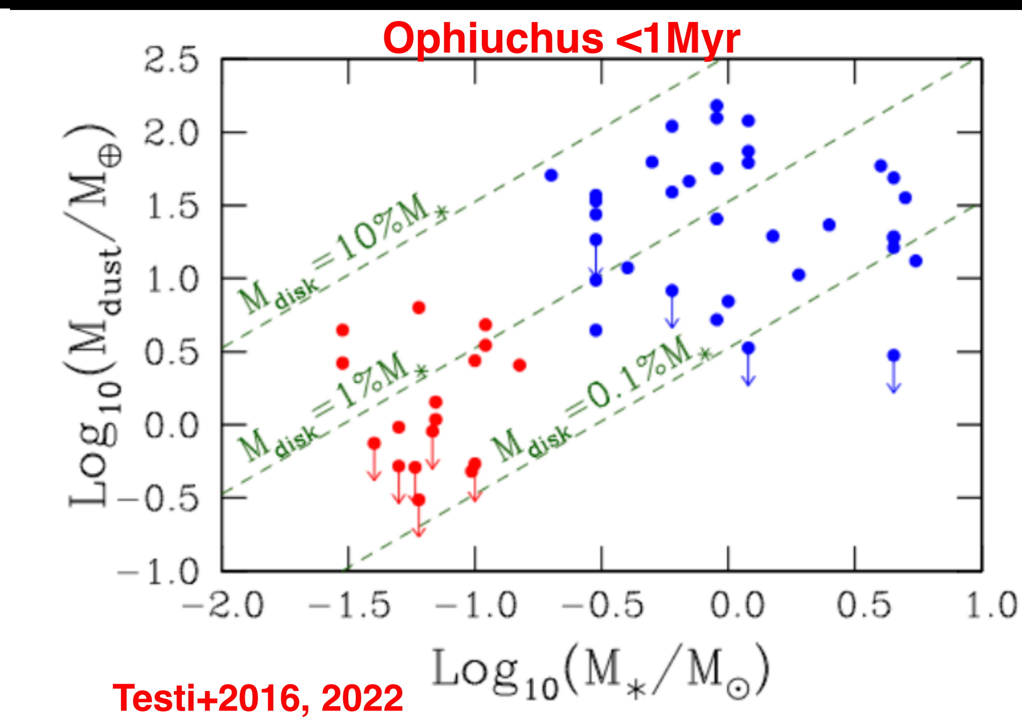
(Ansdell+2016/2017, Pascucci+2016, Testi+2022)

« Protoplanetary » vs. « Planet hosting » disks

”protoplanetary” disks @1Myr seem to contain too little mass to form planetary systems.

Planet formation has to happen at early stages of evolution implying that constraining initial conditions is essential

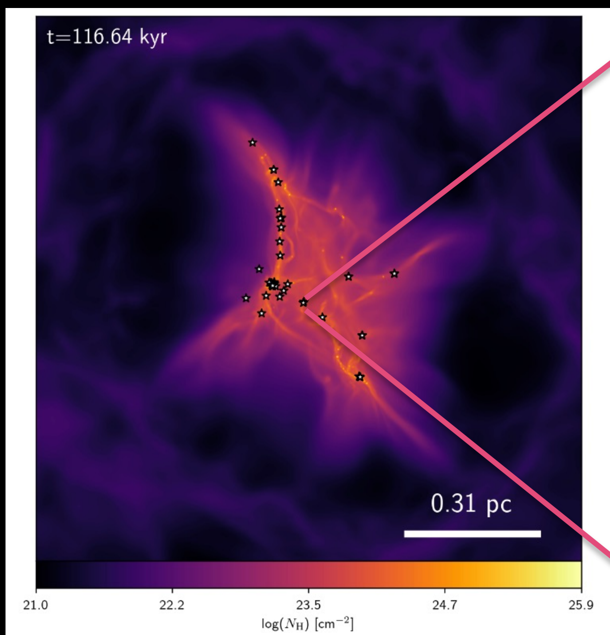




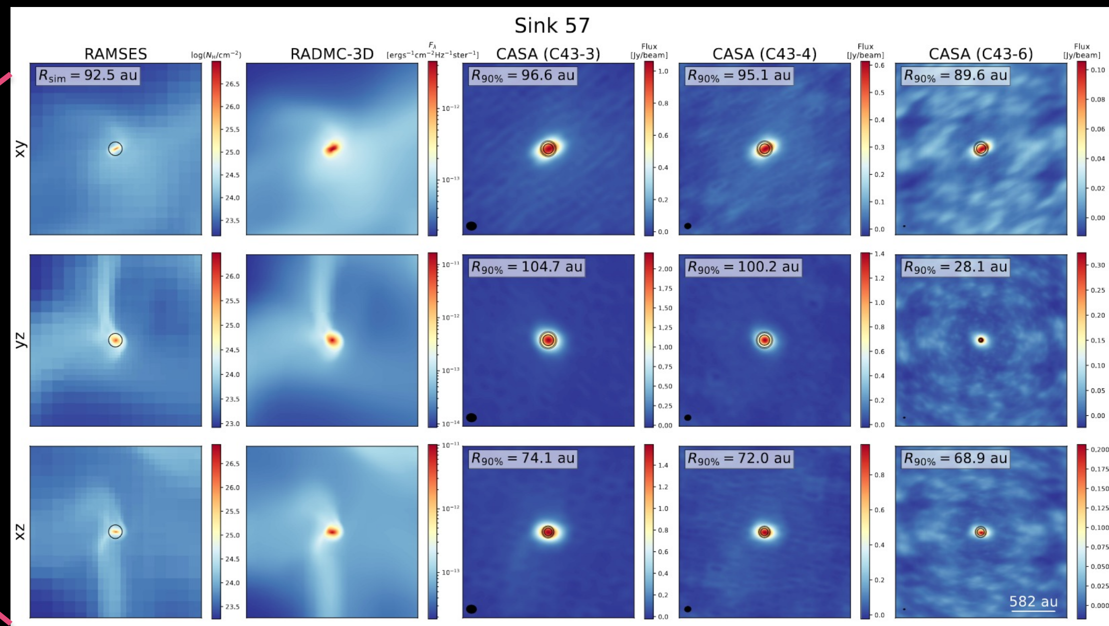
Are young disk masses and sizes reliable?

Measuring disk radii and masses at young ages is not easy

Detailed comparison with simulations show systematic bias with measurements done at 1mm with ALMA



(Lebreuilly et al. 2022, 2023)



Simul RT ALMA Observations 0.9mm

(Ngo et al. 2024)

Basic comparison framework Simulations ⇔ Observations

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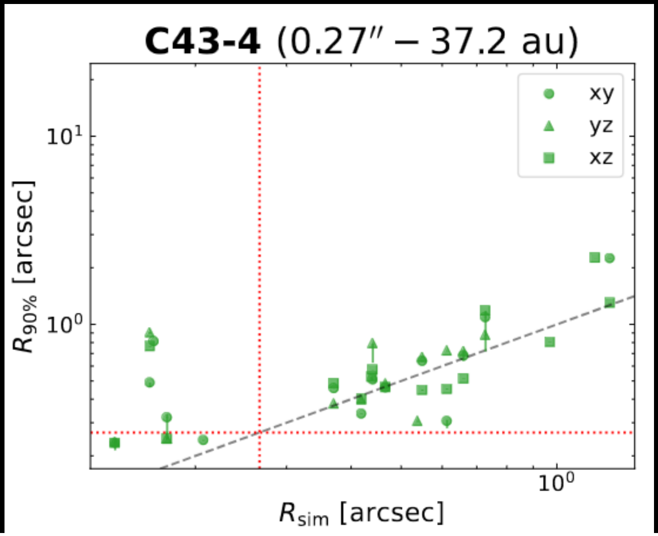
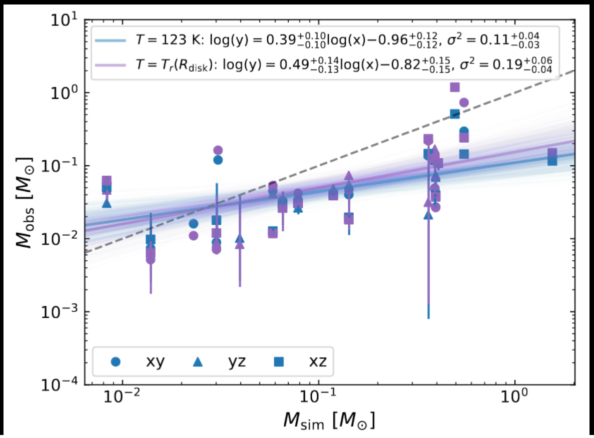


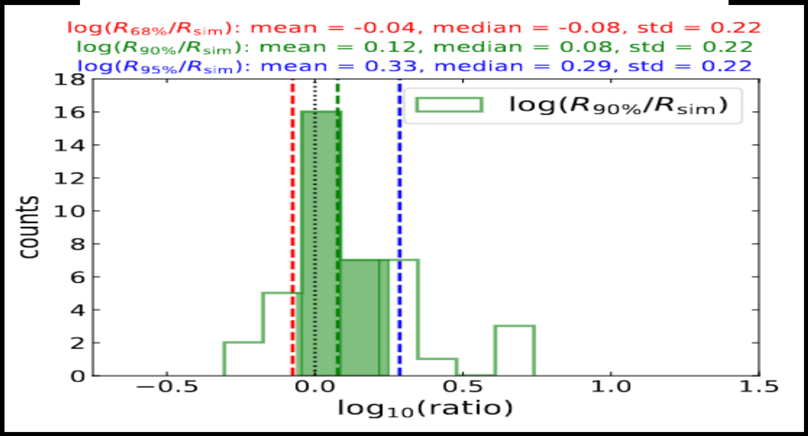
(Ngo et al. 2024)

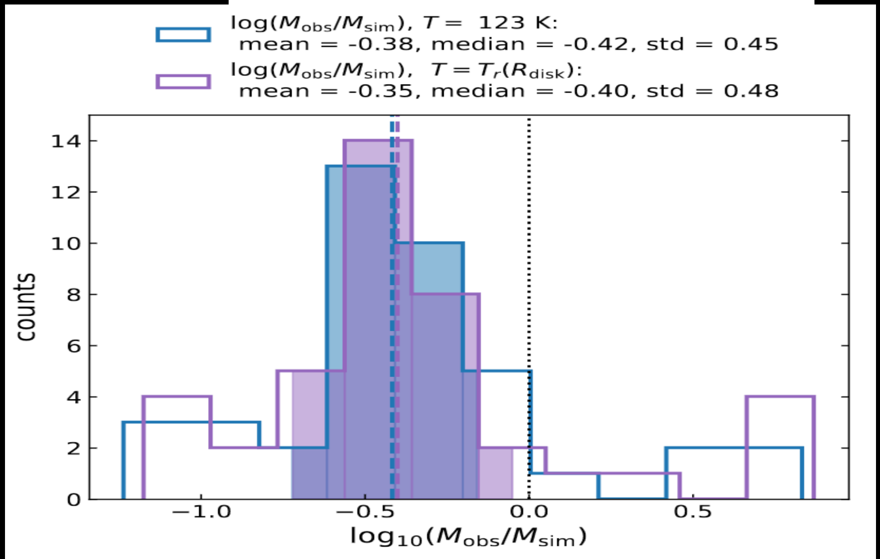


Disk radii - Ok

Disk mass – No!

Optical depth!

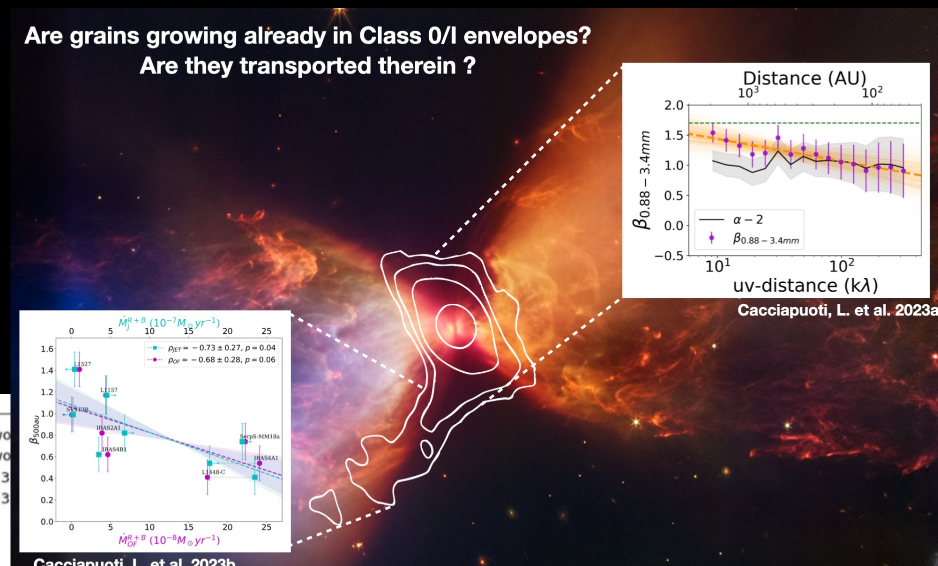




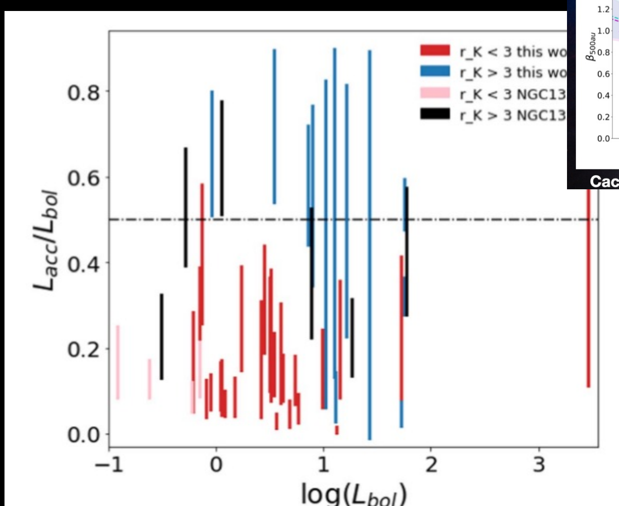
How to progress?

Trace the material that is feeding the young disk (gas and dust properties)

Trace the physical conditions in the disk



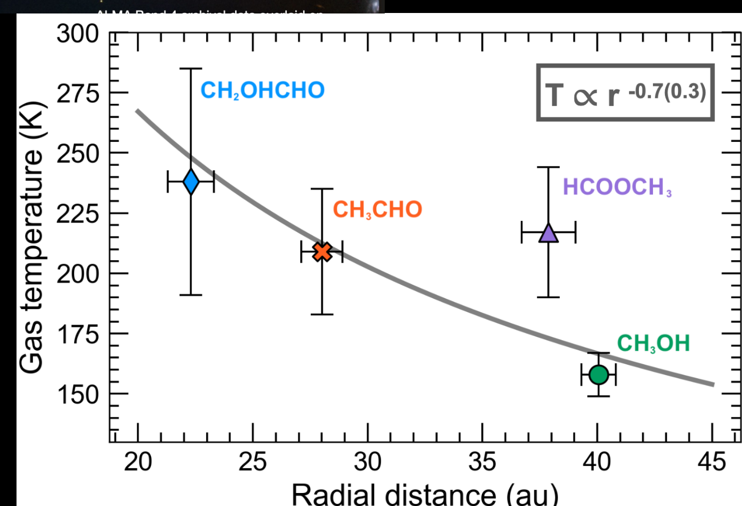
Dust properties
And recycle
In Class 0/I
Envelopes
(Miotello+2014;
Galametz+2019;
Cacciapuoti+2023ab)



Accretion rates in
Class I protostars
(Fiorellino+2023)

Class 0
Temperature profile at
planet-forming scales

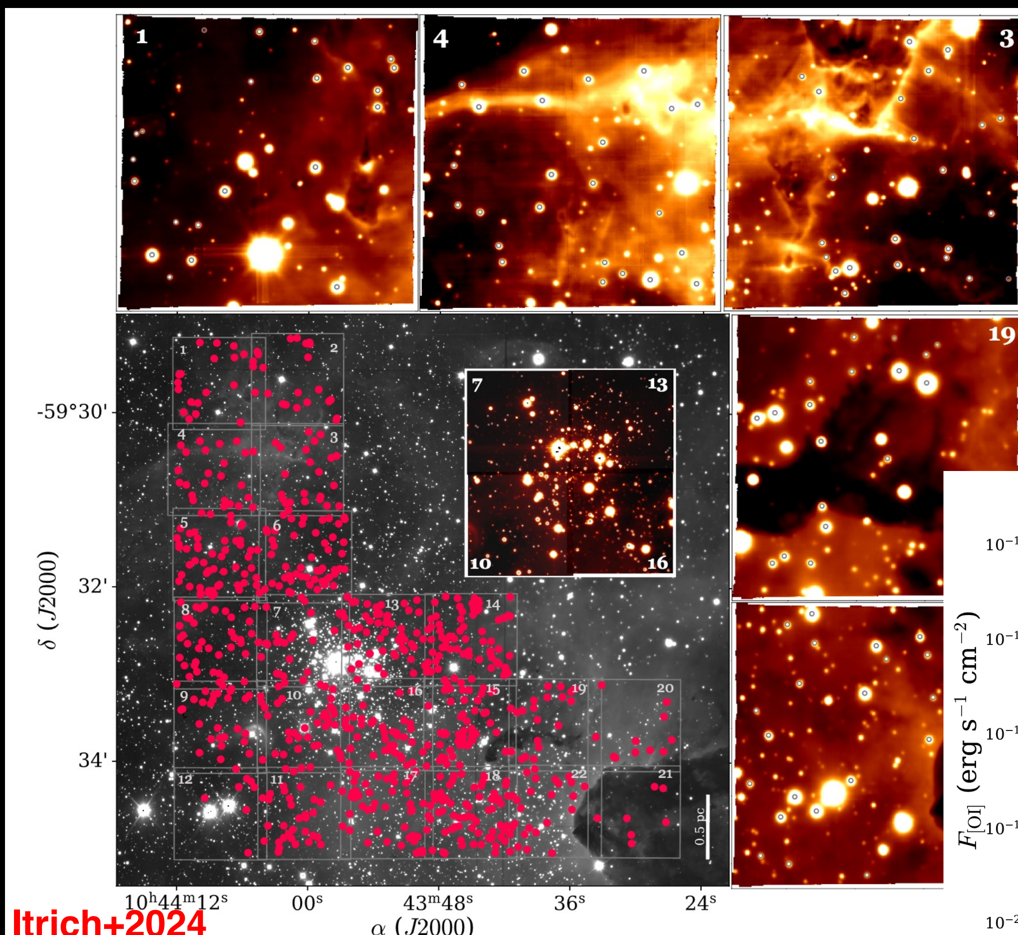
(Frediani+2024)

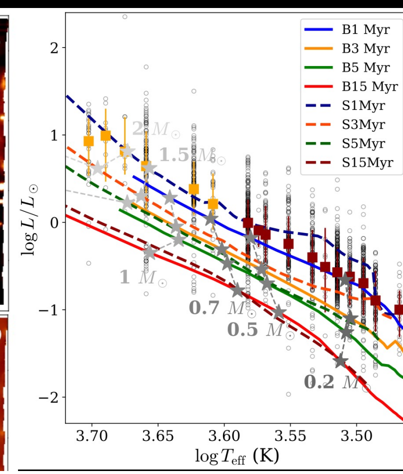


Effect of environment on disk properties and lifetimes

Most of what we know of disk evolution is based on nearby SFR

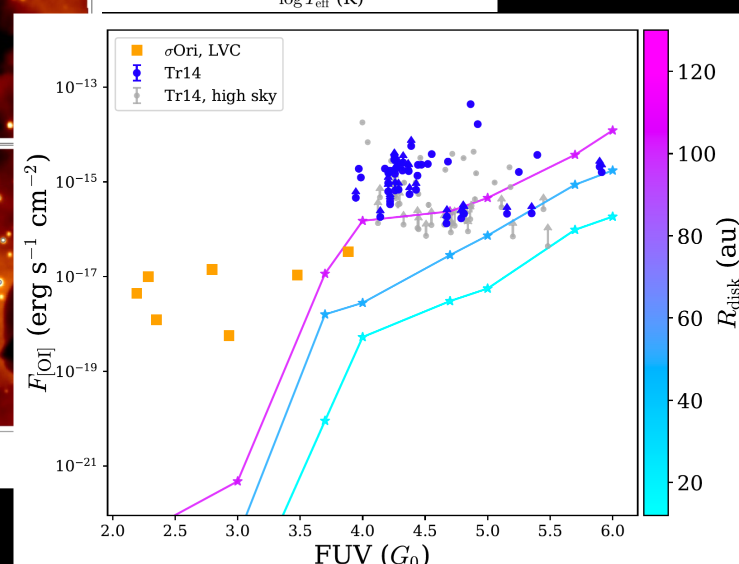
This is an anomaly in the galactic context, and for the Solar System, which may have formed in a clustered environment





Effect of external photoevaporation on disk mass and accretion

(Itrich+2024ab, Kang+2023,2024)



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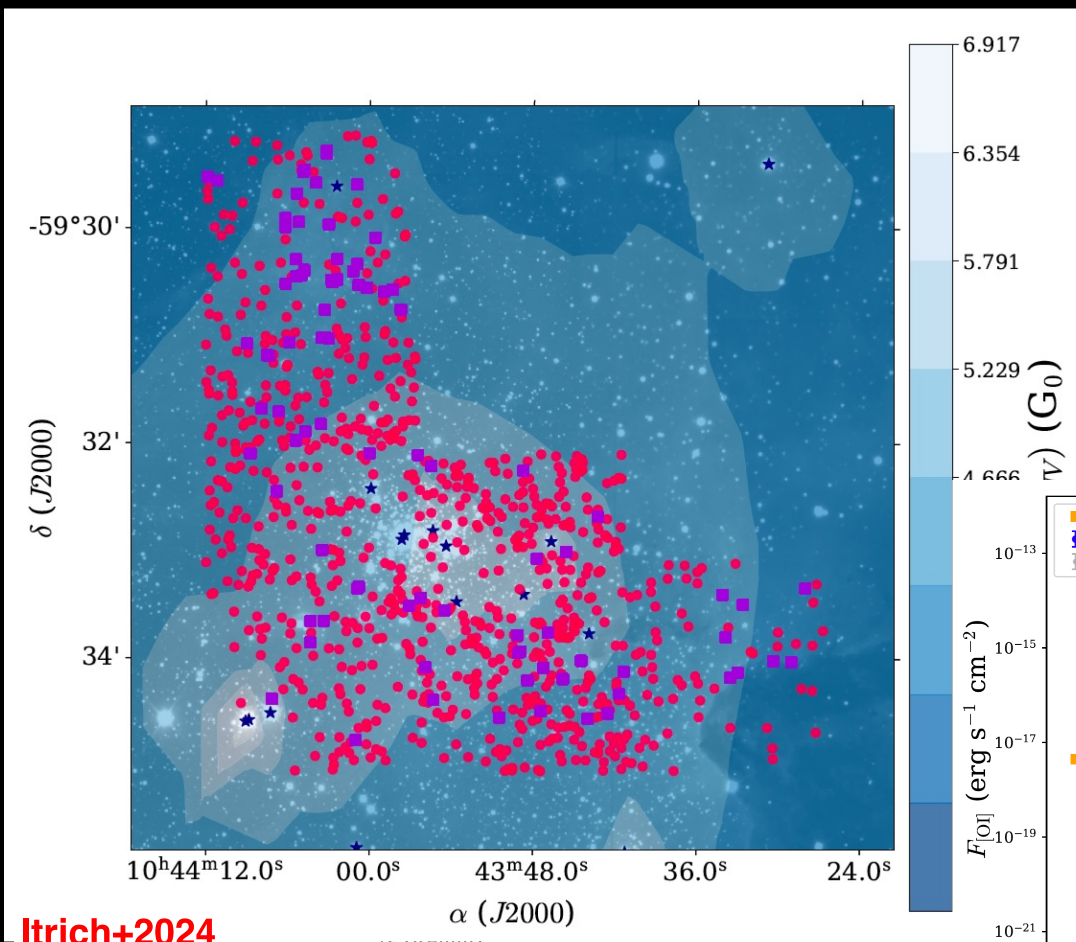

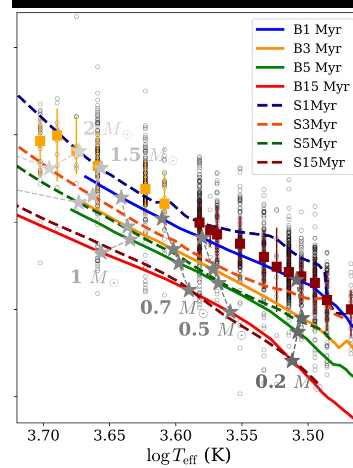

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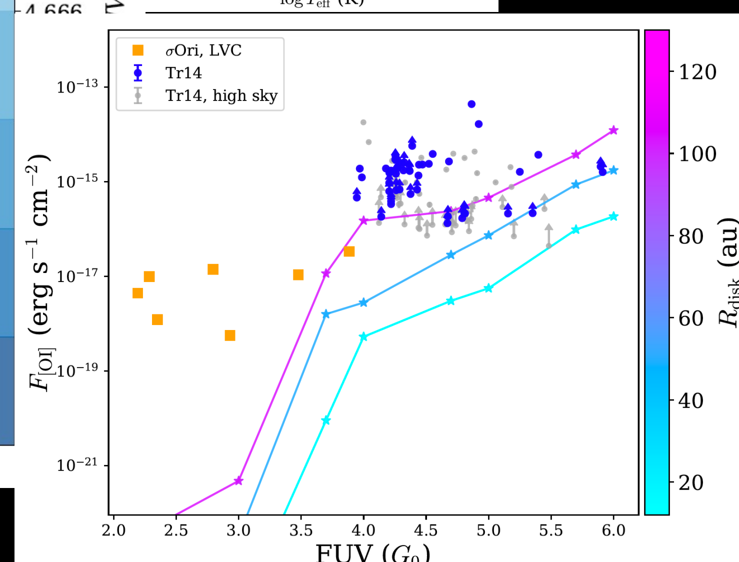
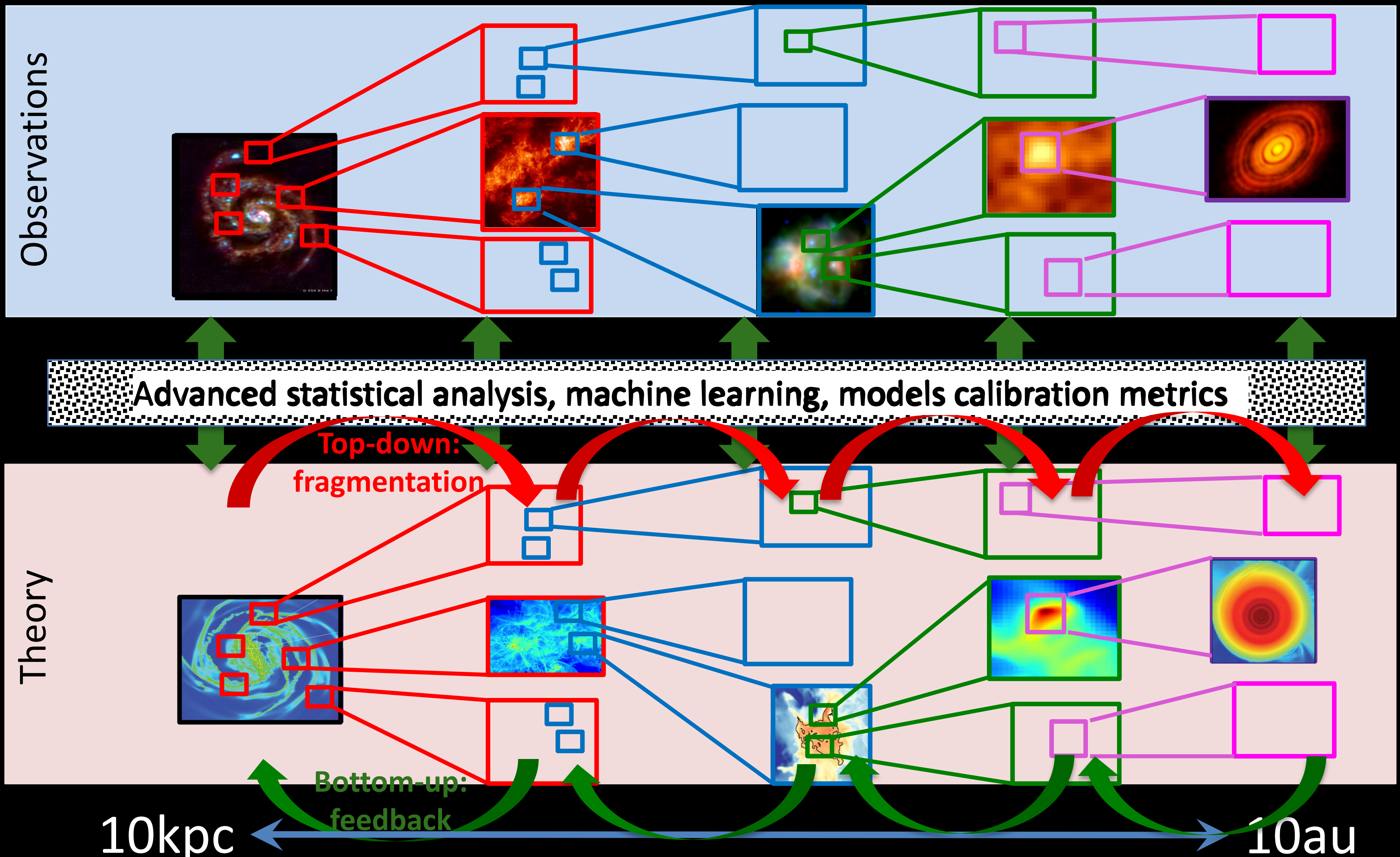


The ECOGAL challenge: Putting everything together



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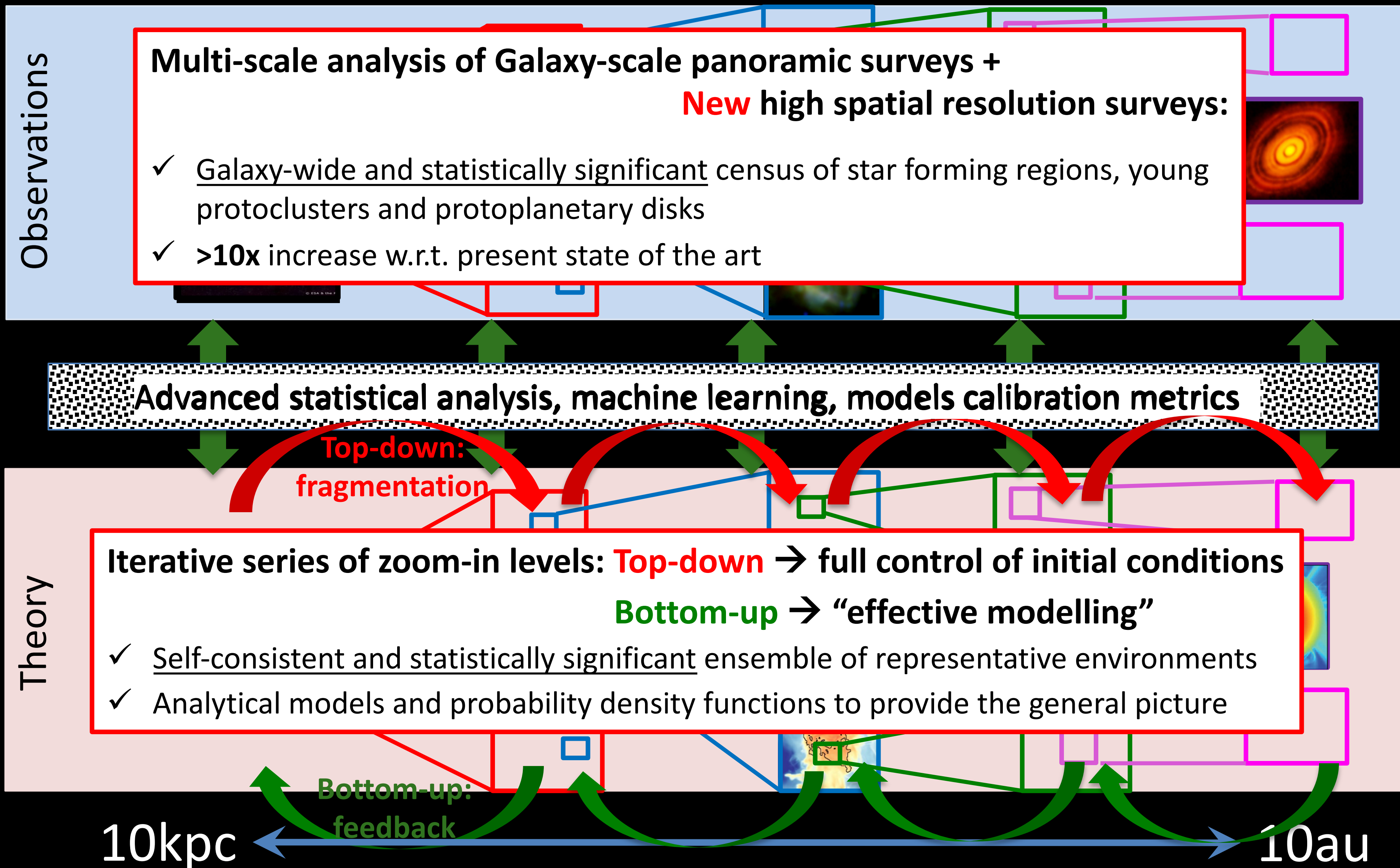
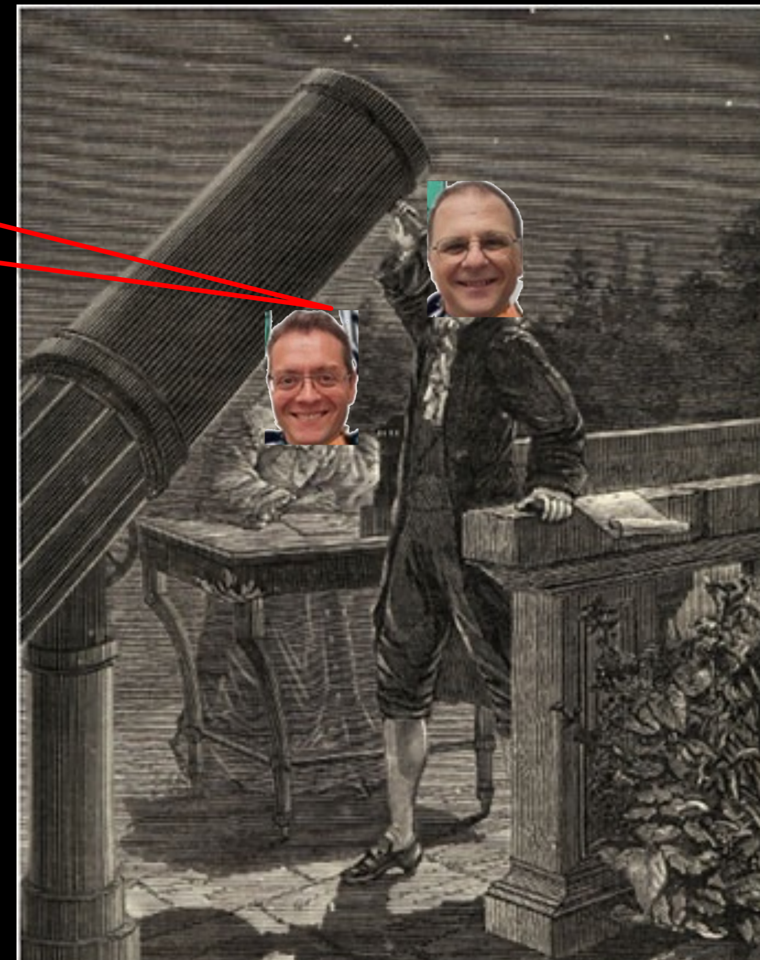


The «real» ECOGAL challenge

''we switched-off gravity'' ?? WHAT???



''clumps'' ? ''filaments'' ? ''cores'' ?
How much crap do you think you see ?

The Sins you will do

''the p-Whatthefuckov tes

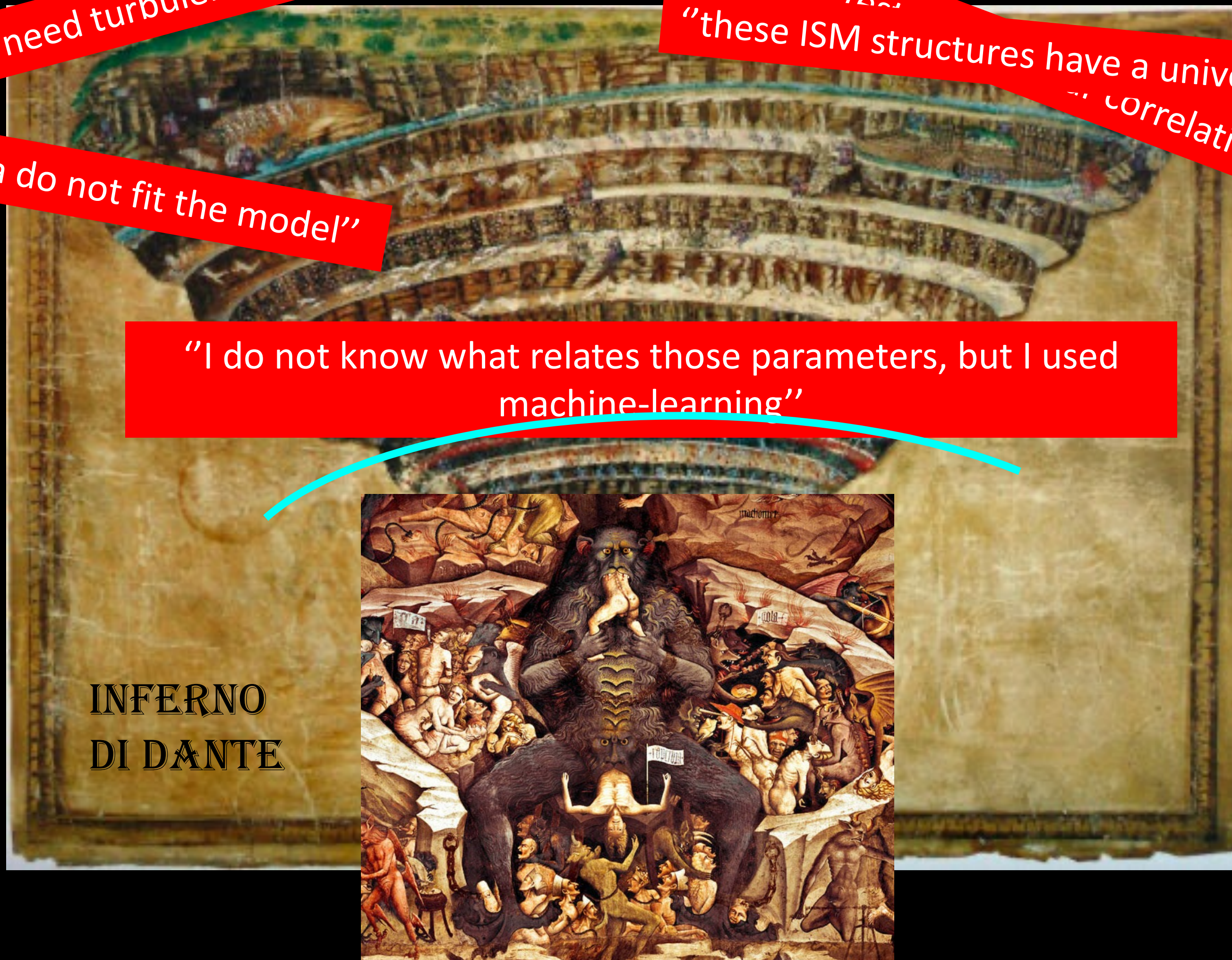
''these ISM structures have a universal size!''

correlation at the 99.5% level''

''we only need turbulence!''

''the data do not fit the model''

''I do not know what relates those parameters, but I used machine-learning''



''Lucifer eating Cosmologists''
Giovanni da Modena, Basilica di S. Petronio

Let's learn a lot of things!

Question everything!

Lecturers are at your disposal: use them!

ENJOY THE PHYSICS OF STAR FORMATION SCHOOL!!

Welcome to Les Houches

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