Are star-forming molecular clouds really hierarchical and scale-free?

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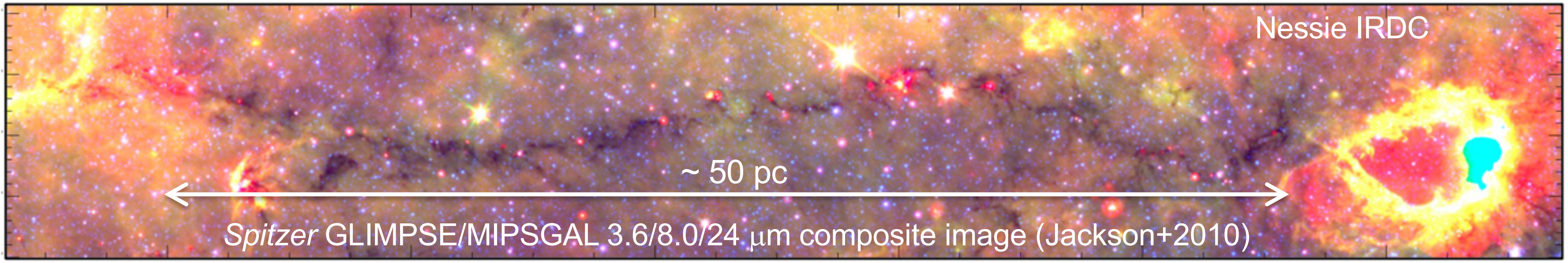
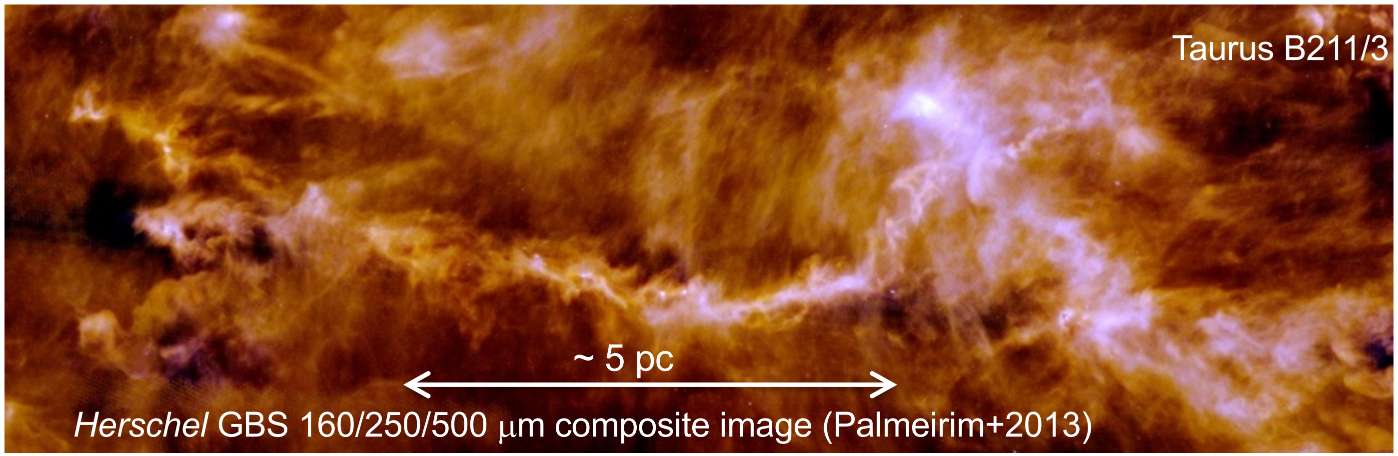
PoSFII: Puzzles of Star Formation – Ringberg, 4-7 May 2025



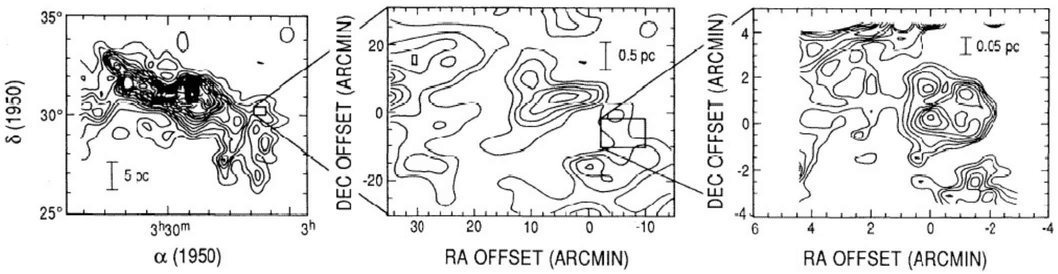
Spitzer GLIMPSE/MIPSGAL 3.6/8.0/24 μm composite image (Jackson+2010)



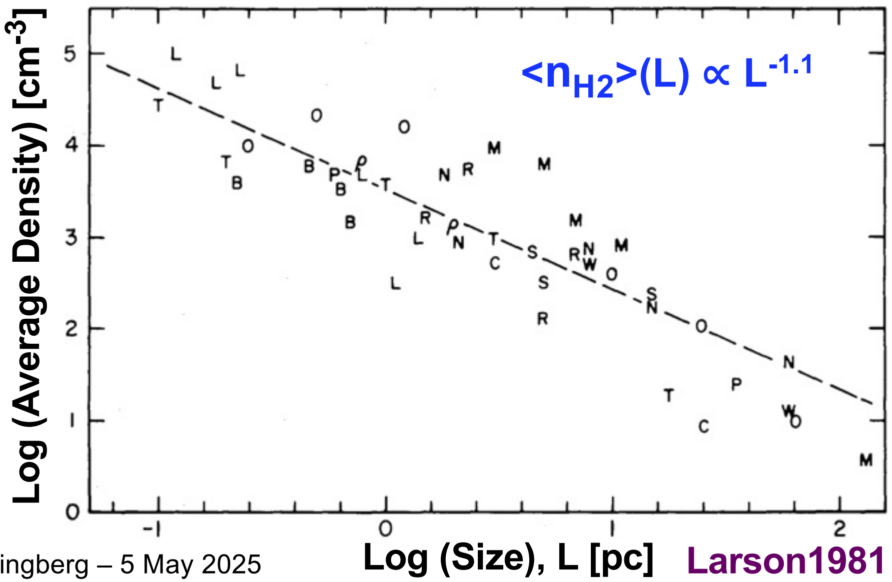
Herschel GBS 160/250/500 μm composite image (Palmeirim+2013)

The structure of molecular clouds is hierarchical and ~ scale-free over a wide range of scales

Scaling laws (Larson 1981) **and fractal structure**, often attributed to the effect of supersonic turbulence

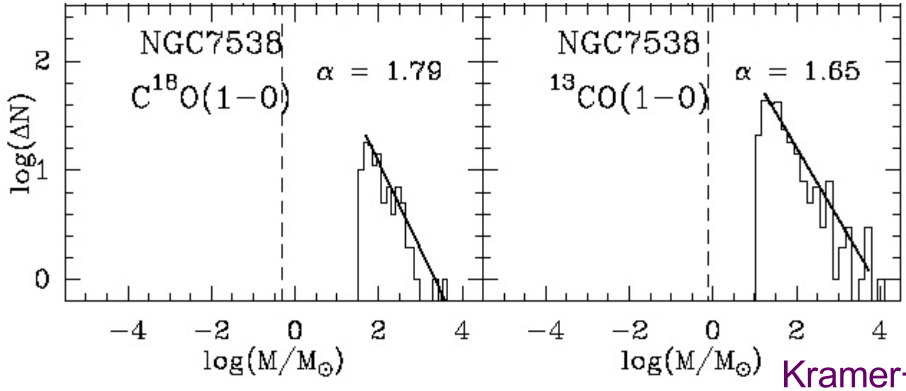


Falgarone+1991



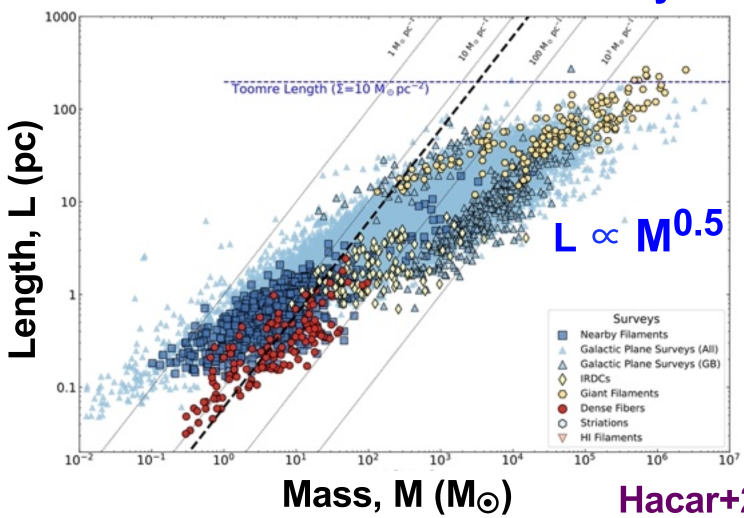
Larson1981

Cloud/clump mass spectrum: $dN/dM \propto M^{-1.6}$



Kramer+1998

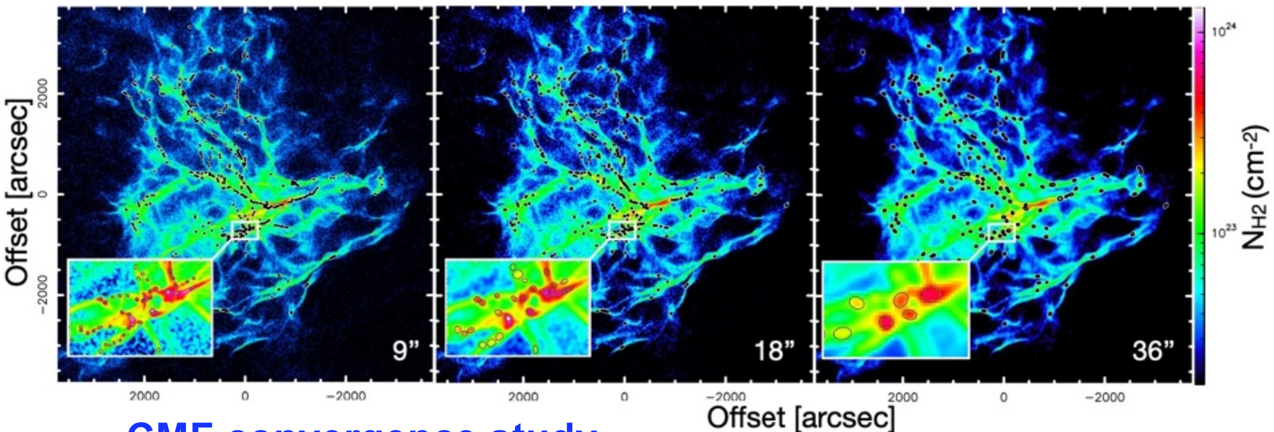
Self-similar behavior of ISM filamentary structure



Hacar+2023 PPVII

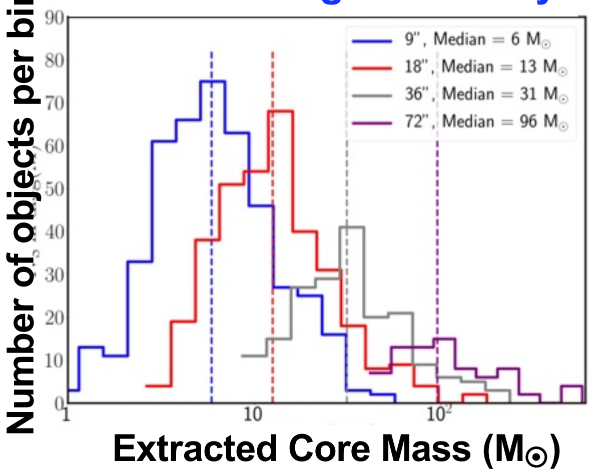
Hierarchical gravitational fragmentation and fragmentation "cascade" in molecular clouds

Example of a « fragmentation cascade » in *isothermal* hydro (M)HD simulations



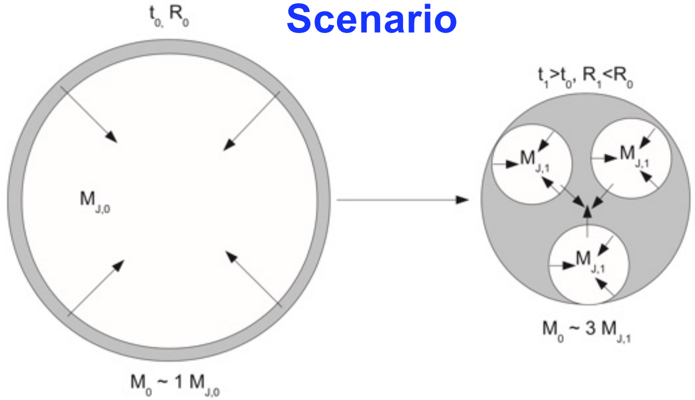
Louvet, Hennebelle+2021

CMF convergence study



- **In isothermal simulations, the median core mass (~ the CMF peak) tends to scale ~ linearly with numerical resolution**

Global Hierarchical Collapse/Fragmentation Scenario



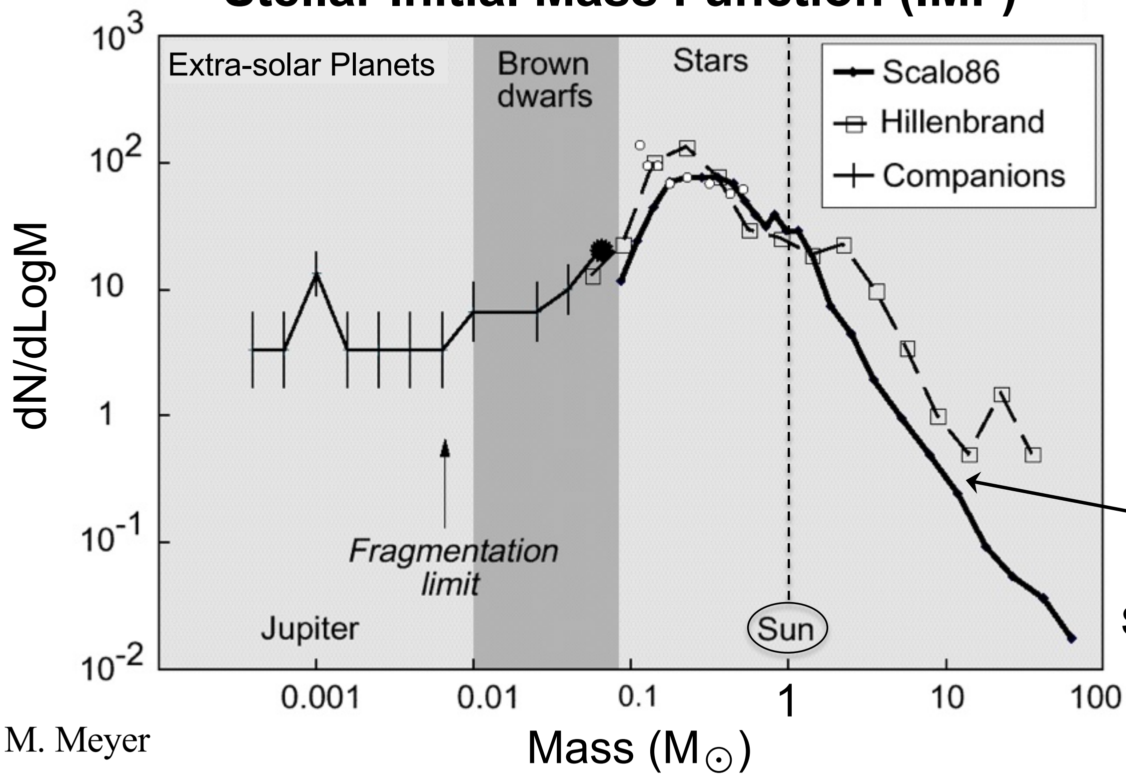
$M_J \propto \rho^{-1/2}\, T^{3/2}$ ↘ and $n_J = M/M_J$ during isothermal collapse

Hoyle 1953; Vazquez-Semadeni+2019

<u>Question</u>: In *real* clouds, does the fragmentation cascade continue all the way to the « opacity limit », i.e., « Larson first cores » (R ~ 5 a.u., M~0.01 M$_\odot$)?

But “universal” IMF suggests there is a mass scale in the SF process…

Stellar Initial Mass Function (IMF)



M. Meyer

dN/dLogM ∝ $M^{-1.35}$

Salpeter (1955)

See Bastian, Covey, Meyer ARA&A 2010

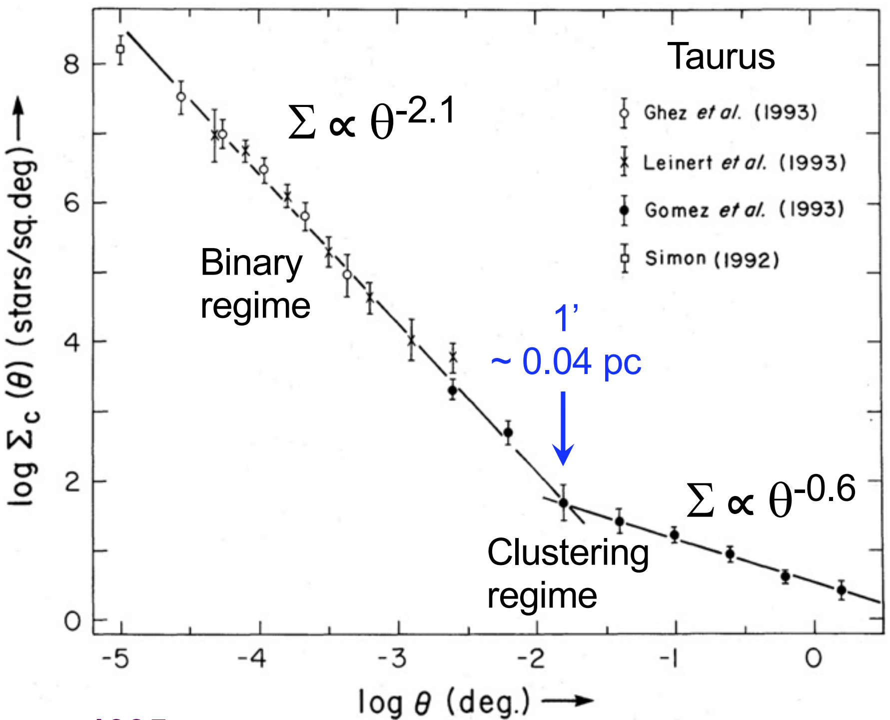
Also Kroupa 2002; Chabrier 2003

Offner+2014 …

- → **The self-similarity of SF clouds must break down at some scale**
- → **At what scale does this physical change occur?**

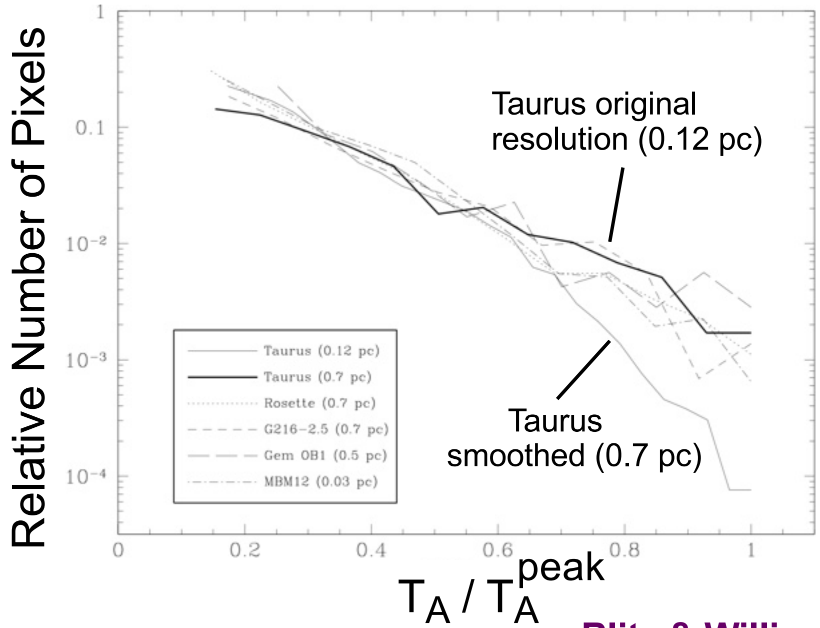
Observational evidence of departures from self-similarity in molecular clouds

Surface Density of Companions vs Separation



Larson 1995
(also Simon 1997; Bate+1998; Hartmann 2002)

Normalized Antenna Temperature Histograms in ^{13}CO maps of molecular clouds

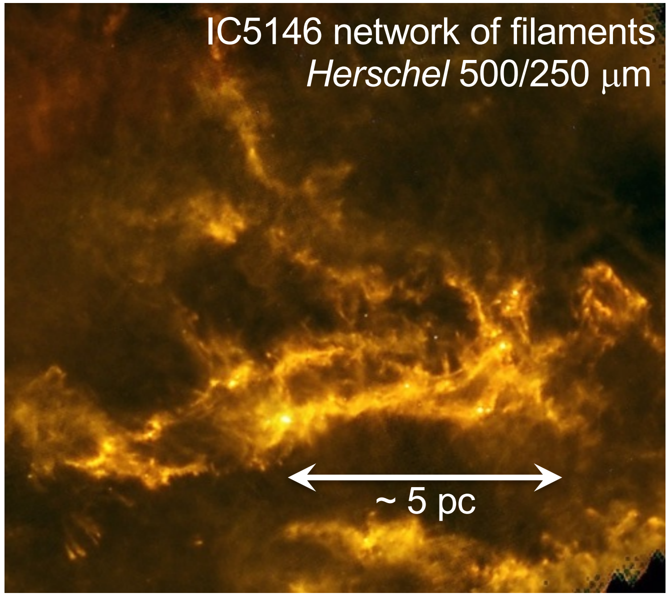


Blitz & Williams 1997

+ Transition to Coherence in Dense Cores

Goodman+1998; Pineda+2010

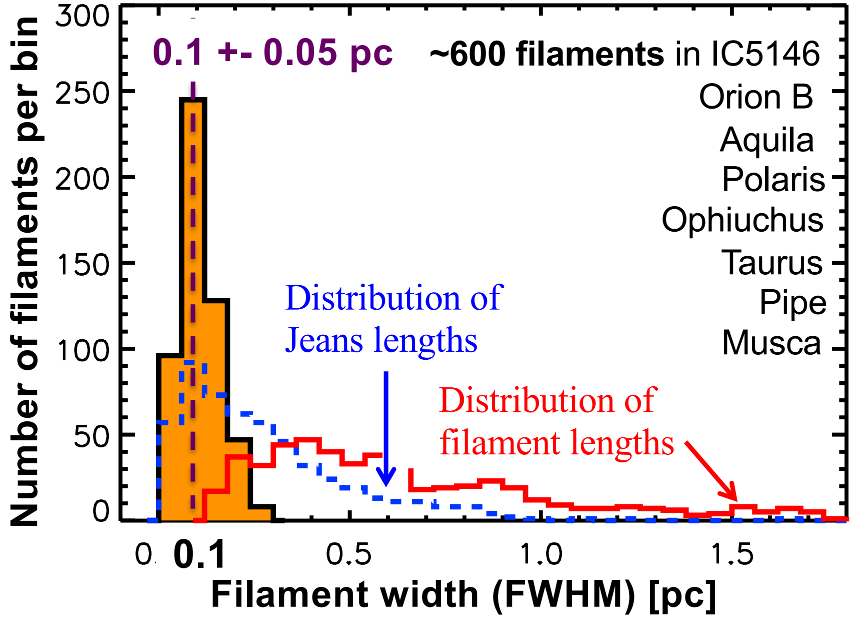
Herschel observations suggest that dense molecular gas is primarily structured in the form of filaments with typical half-power width ~0.1 pc



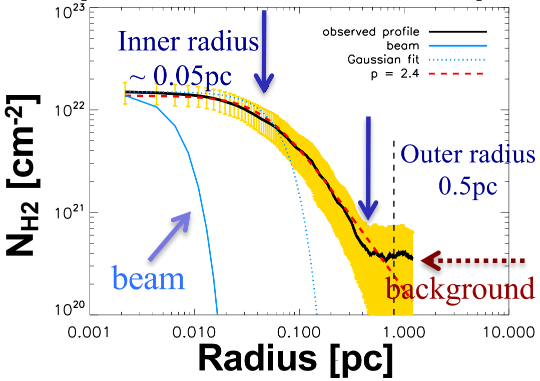
André+2010
Palmeirim+2013

A characteristic length/mass scale for SF and the IMF?

Nearby (< 500 pc) filaments have a common inner width ~ 0.1 pc



Example of a filament radial profile



D. Arzoumanian+2011 & 2019 [see also Koch & Rosolowsky 2015]

May correspond to the magneto-sonic scale of turbulence & turbulence correlation length (cf. Padoan+2001; Federrath 2016; Jaupart & Chabrier 2021)

Challenging for numerical simulations but very promising recent results
(cf. R. Smith+2014; Ntormousi+2016) (Abe, Inoue, Inutsuka+2024, 2025)

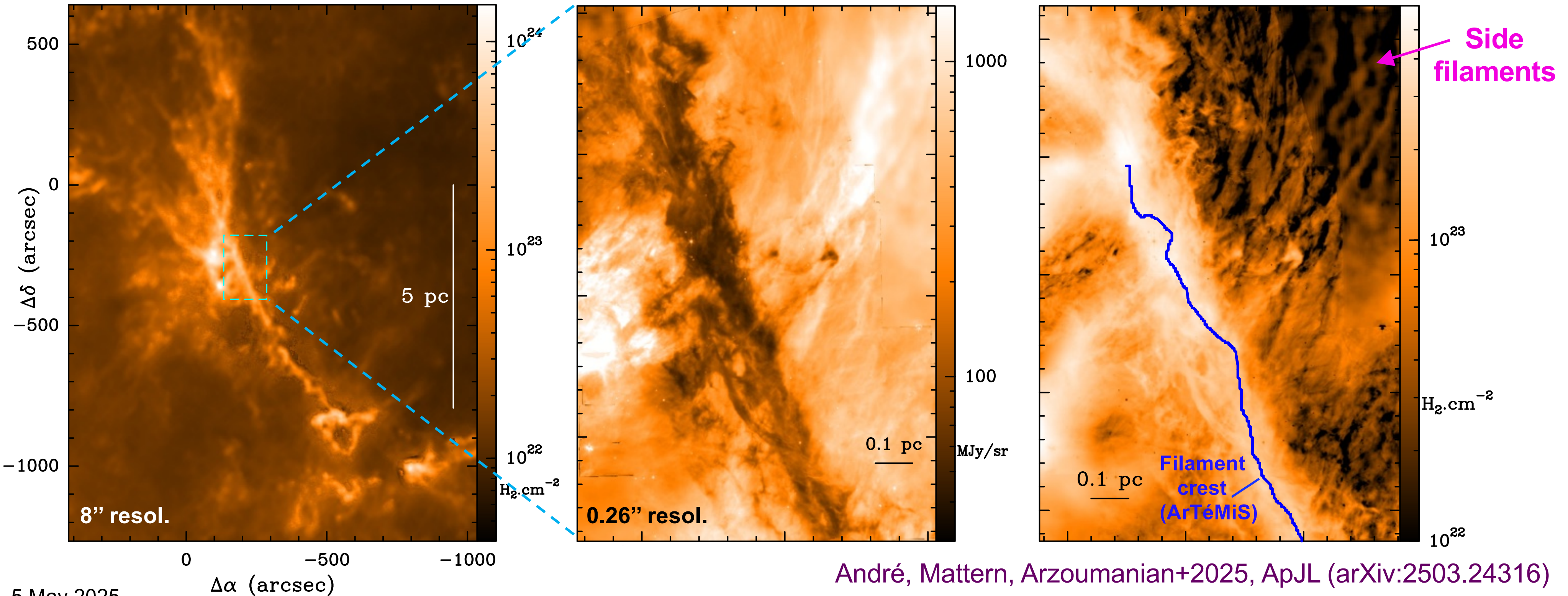
Recent JWST/MIRI observations of infrared-dark filaments suggest that this typical filament width ~0.1 pc is not restricted to nearby clouds

- **JWST has revealed the fine structure of the NGC6634M filament and the presence of (magnetically-aligned?) side filaments with a projected spacing of ~0.1 pc**

Herschel **+ APEX/ArTéMiS column density image of NGC 6334 (d ~ 1.5 kpc)**

JWST/MIRI 7.7 μm image → mid-IR-dark filament

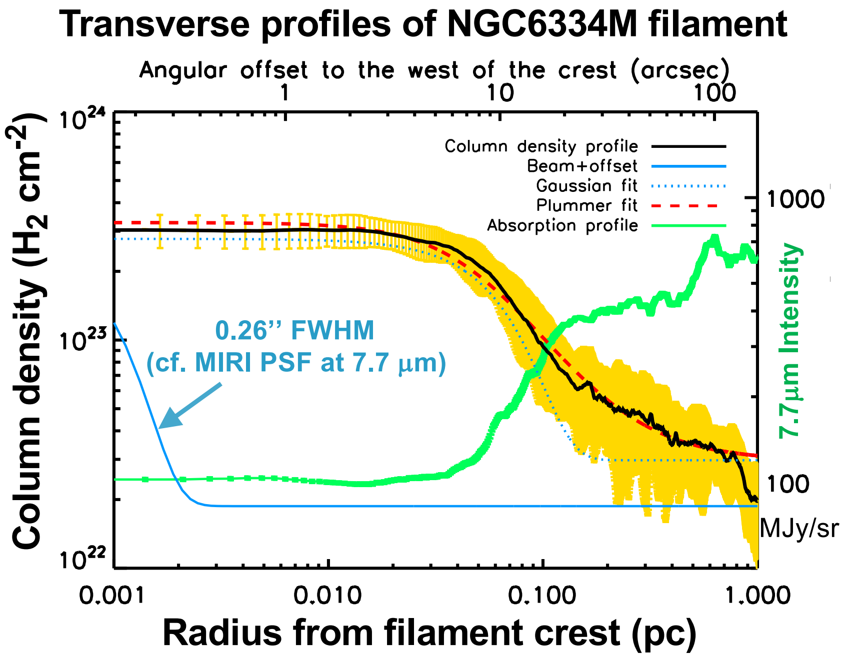
Column density image derived from JWST absorption

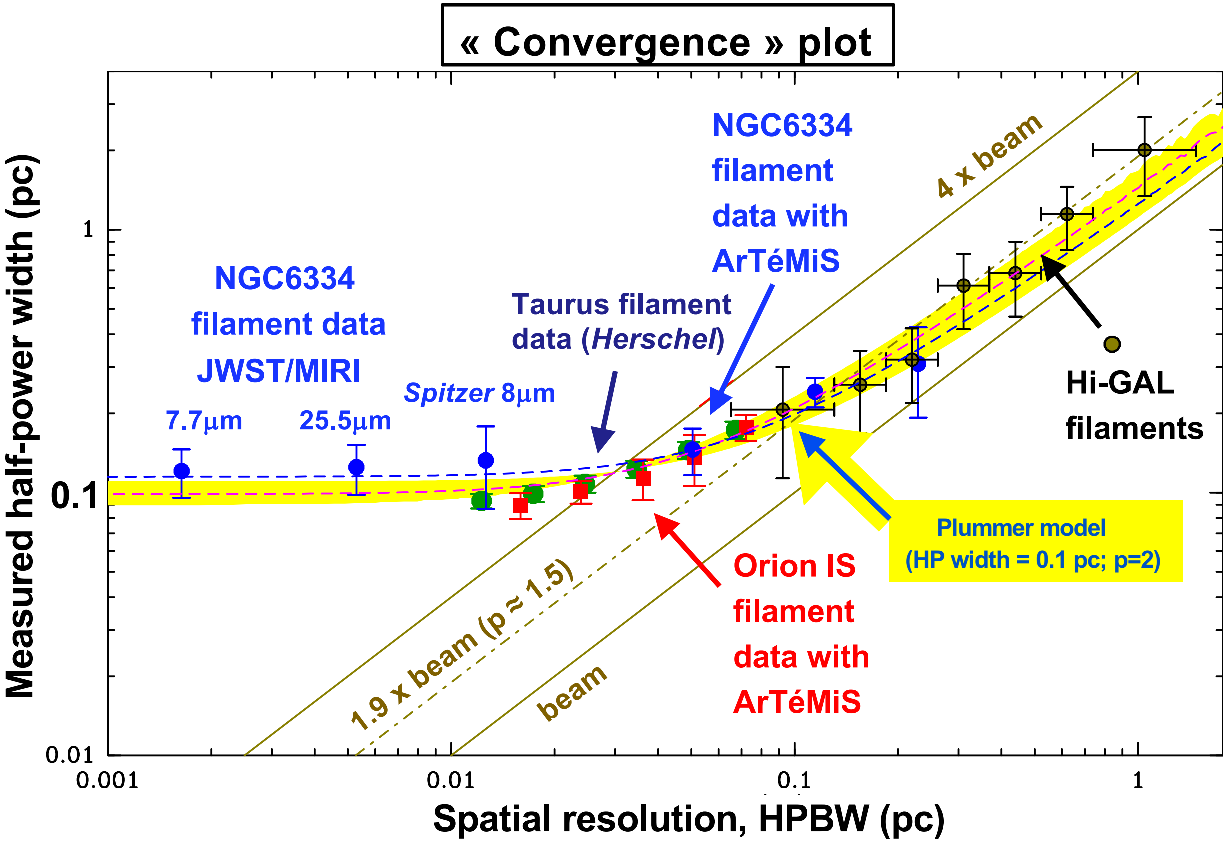


André, Mattern, Arzoumanian+2025, ApJL (arXiv:2503.24316)

Convergence tests suggest that Galactic SF filaments have a common density profile with a typical half-power width ~0.1 pc

➤ **A single model density profile (in blue/yellow) can account for nearby filaments (e.g, Taurus/Orion) and Galactic Plane filaments (e.g., N6334, Hi-GAL)**

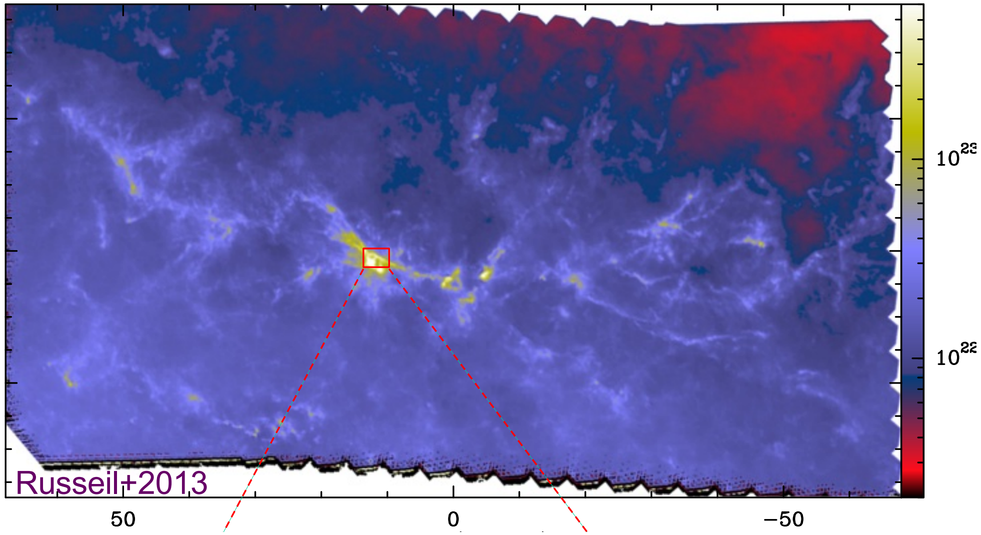




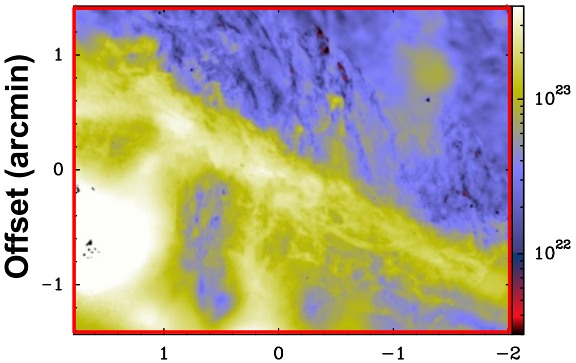
André+2022, 2025

Comparison of JWST and *Herschel* results in NGC 6334 indicates a clear departure from self-similarity at a scale comparable to the filament width

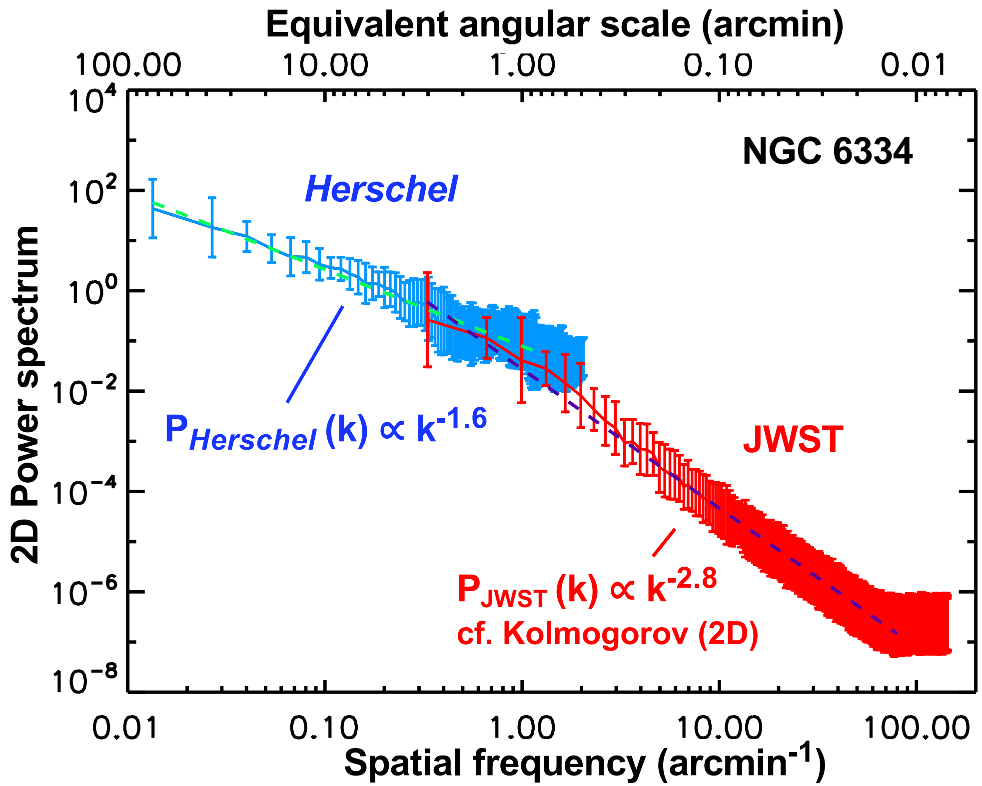
NGC6334: *Herschel*/HOBYS column density map



JWST column density map

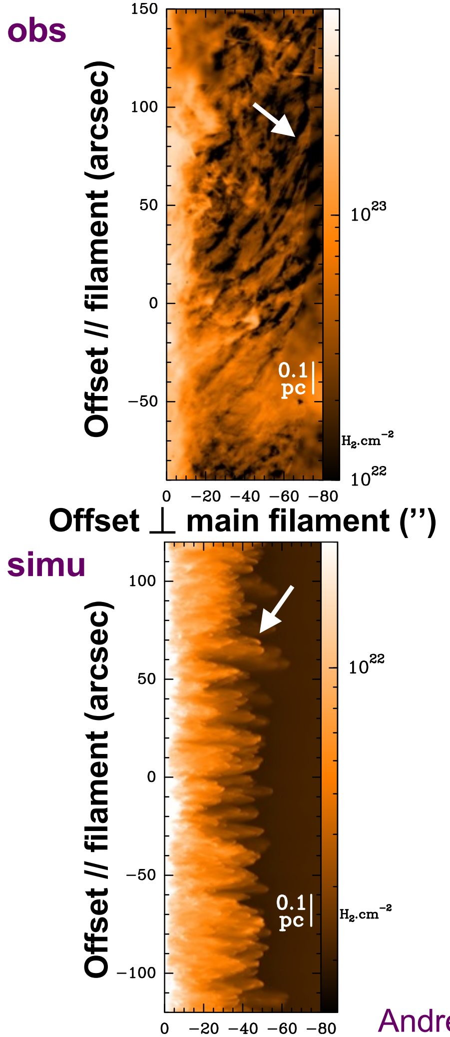


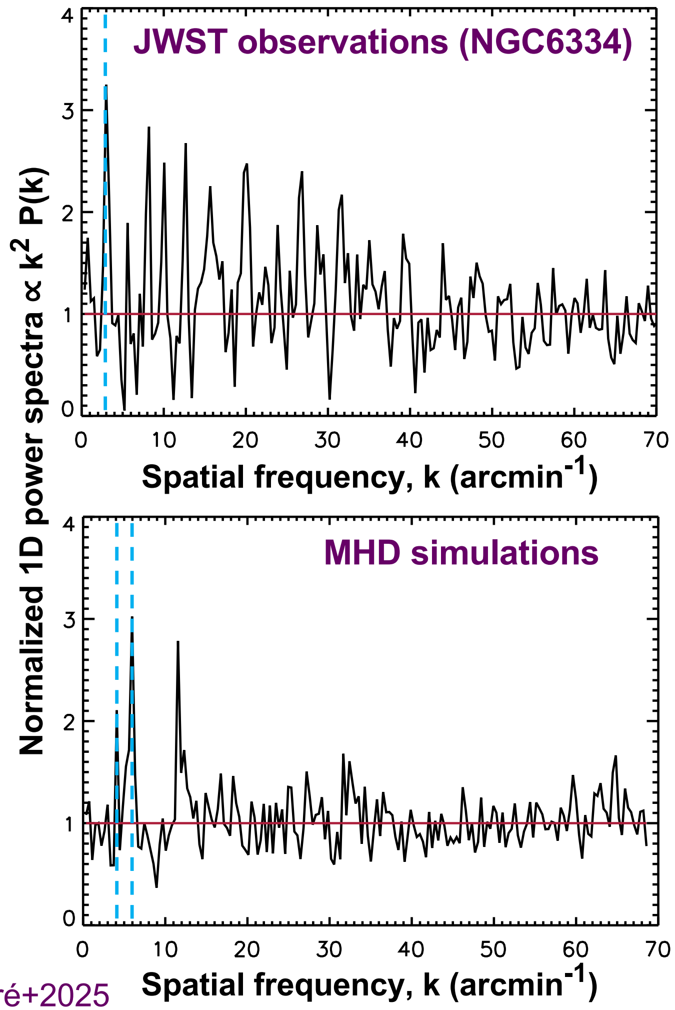
Change in the slope of the power spectrum of (N_{H2}) density fluctuations at about ~0.1-0.2 pc



André, Mattern, Arzoumanian+2025, ApJL (arXiv:2503.24316)

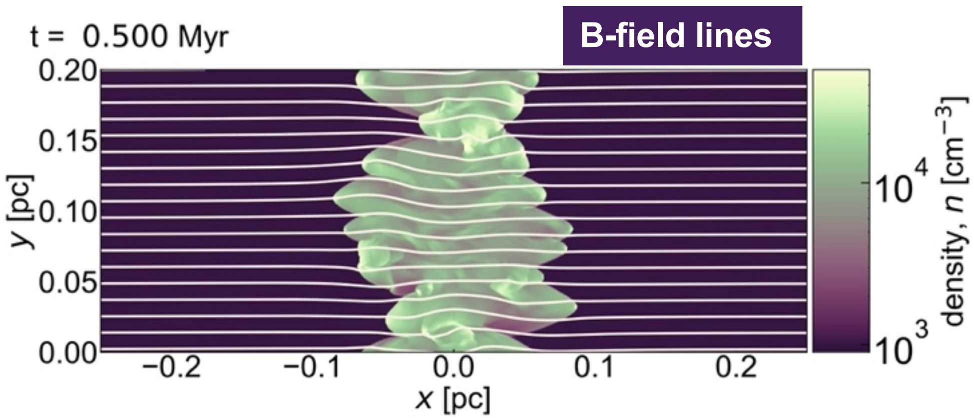
Hints that B fields and non-ideal MHD effects (e.g., ambipolar diffusion) may play a key role in setting this typical filament width scale





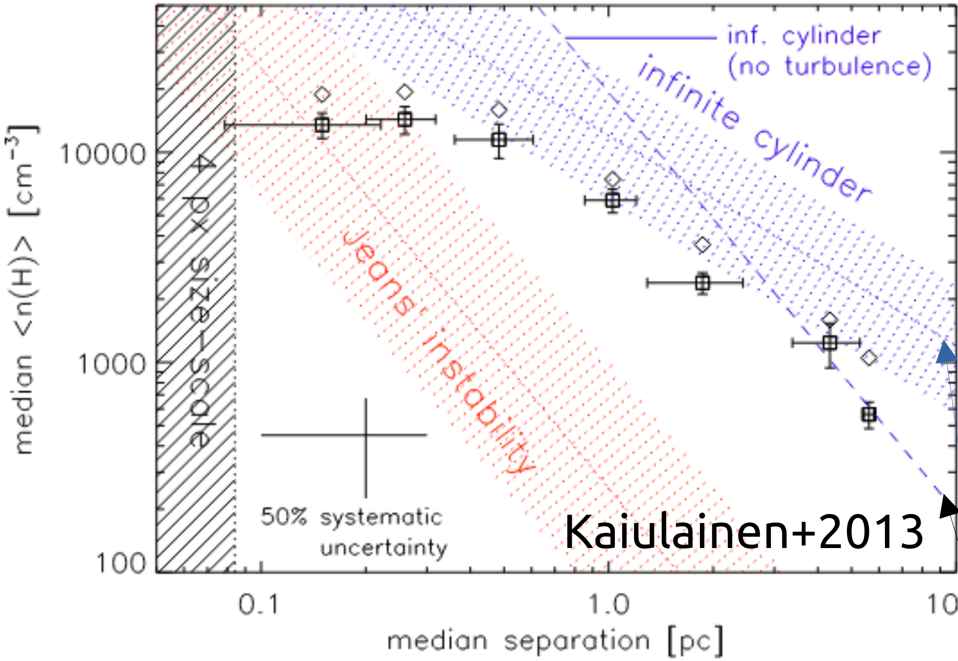
André+2025

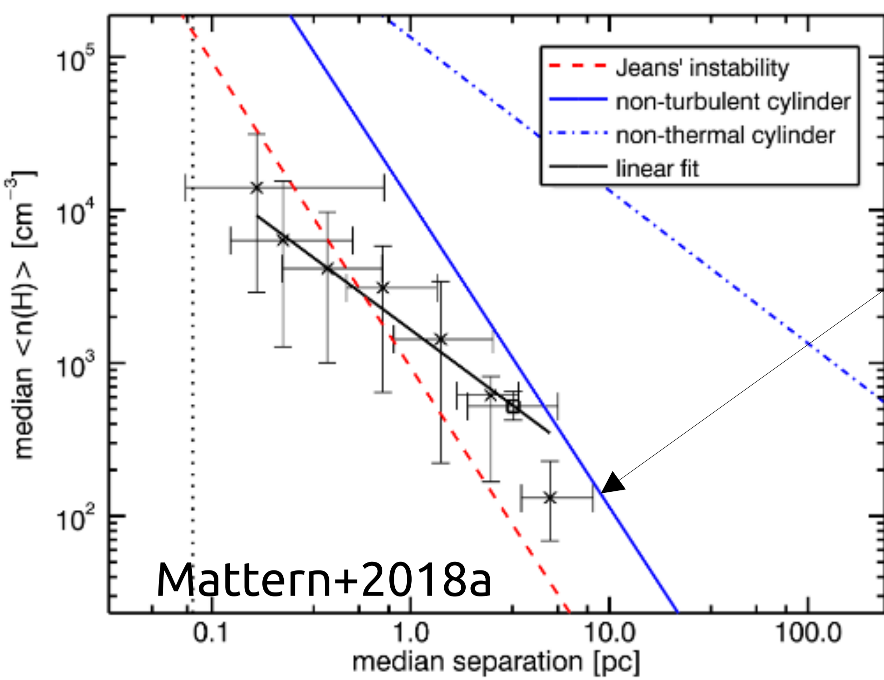
- → **Non-ideal MHD simulations show that the combination of the slow-shock MHD instability and ambipolar diffusion (AD) allow massive accreting filaments to retain a HP width ~ 0.1 pc (~ AD scale) while evolving.**
- → ***Magnetic fields are key in this process***



Abe, Inoue, Inutsuka+2025, ApJ

Fragmentation and Turbulence in Filaments





Isothermal Jeans fragmentation
(Jeans 1902)

$$\lambda_J = c_s \left(\frac{\pi}{G\rho}\right)^{0.5}$$

$$c_s = \sqrt{\frac{kT}{\mu m_p}}$$

Cylindrical fragmentation
(Nagasawa 1987)

Isothermal

$$\lambda \approx 22 \cdot c_s (4\pi G \rho_c)^{-0.5} \approx 4 \cdot w_{\mathrm{fil}}$$

Turbulent

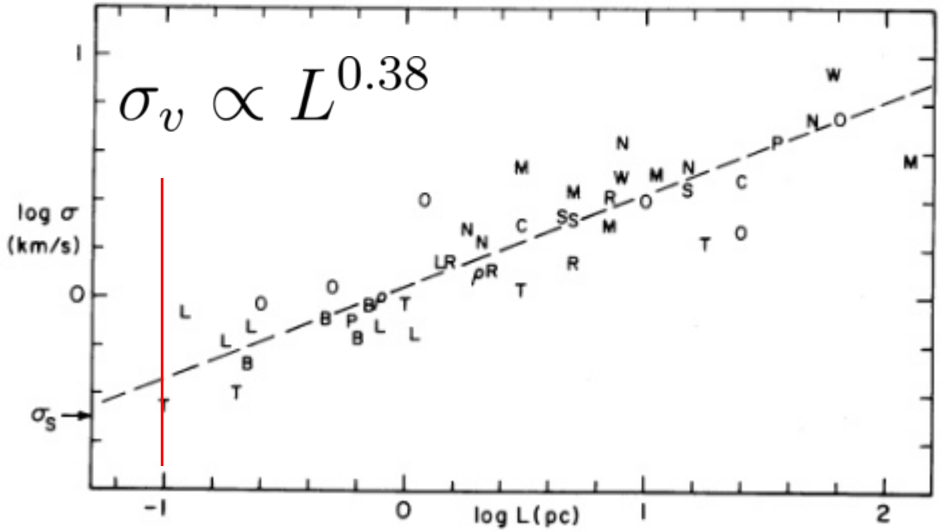
$$\lambda \approx 22 \cdot \sigma_v (4\pi G \rho_c)^{-0.5}$$

$$\sigma_v = A \cdot \lambda^{0.5}$$ Linewidth-Size Relation

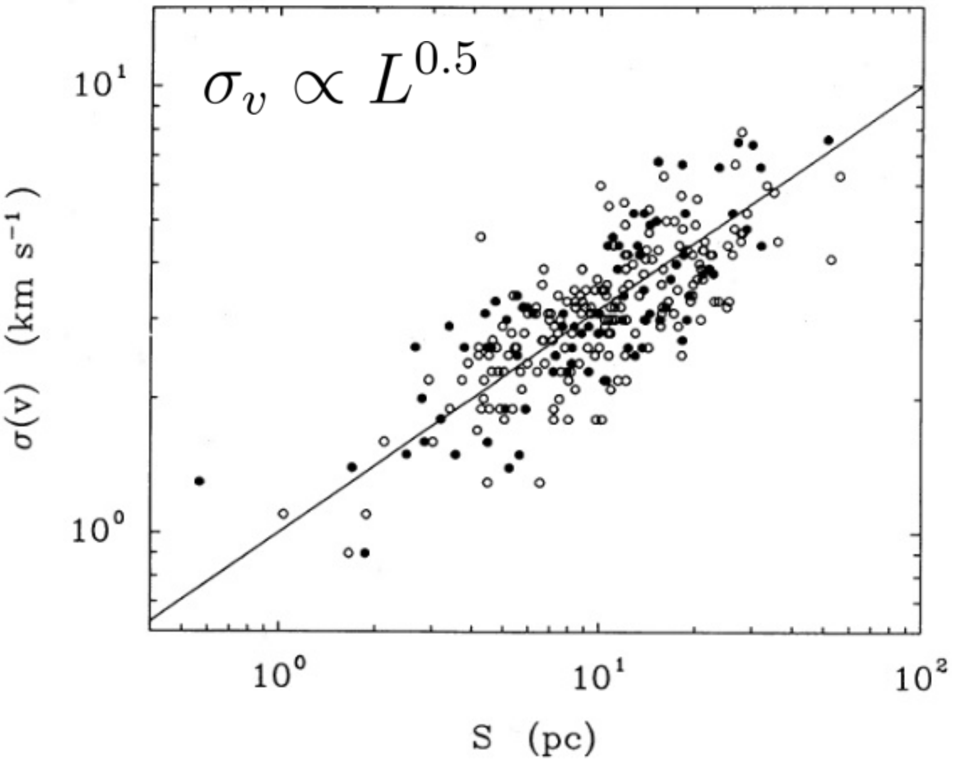
$$\lambda^{0.5} \approx 22 \cdot A (4\pi G \rho_c)^{-0.5}$$

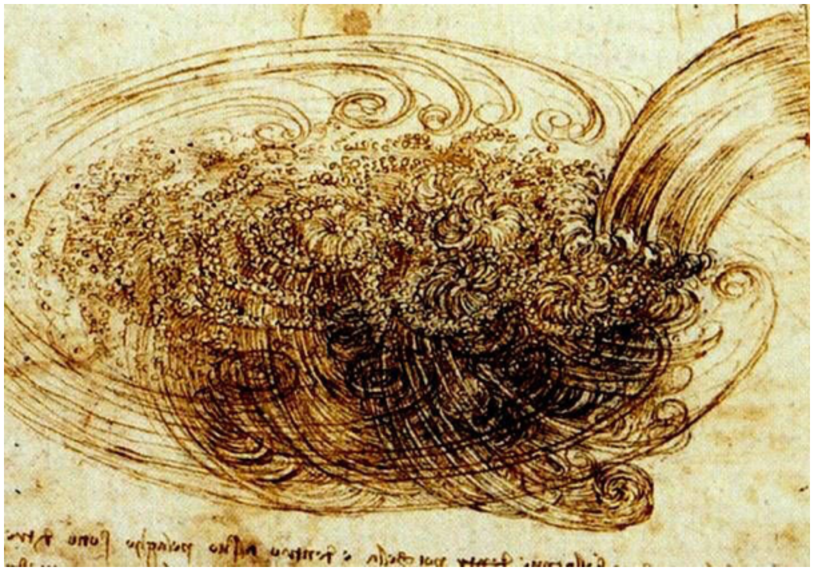
Linewidth – Size Relation

Larson+1981



Solomon+1987





Da Vinci 1500s

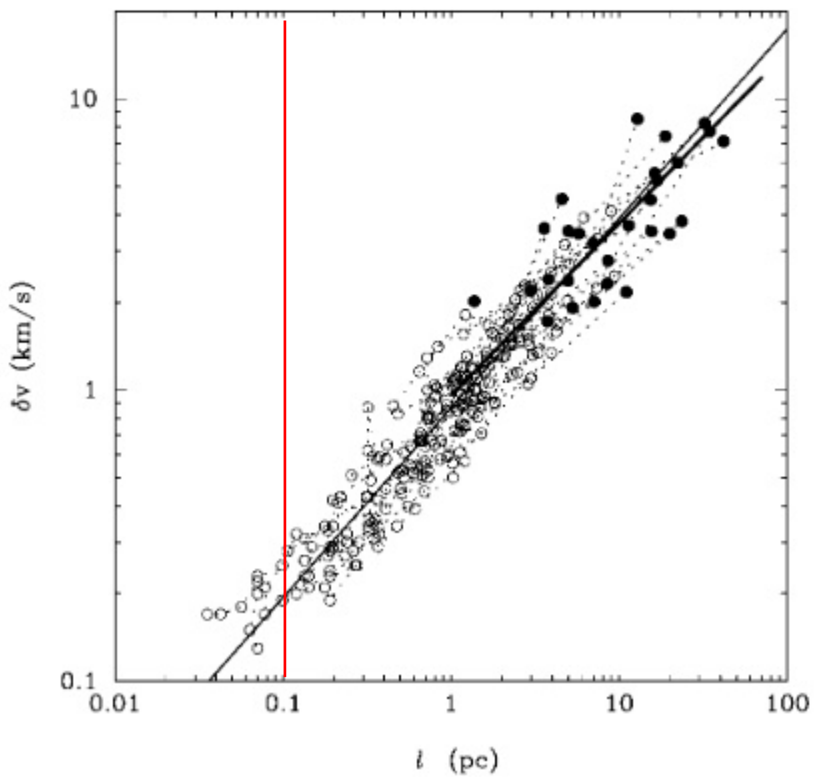
The incompressible energy cascad model of Kolmogorov (1941) predicts a linewidth-size relation:

$$\sigma_v \propto L^{0.33}$$

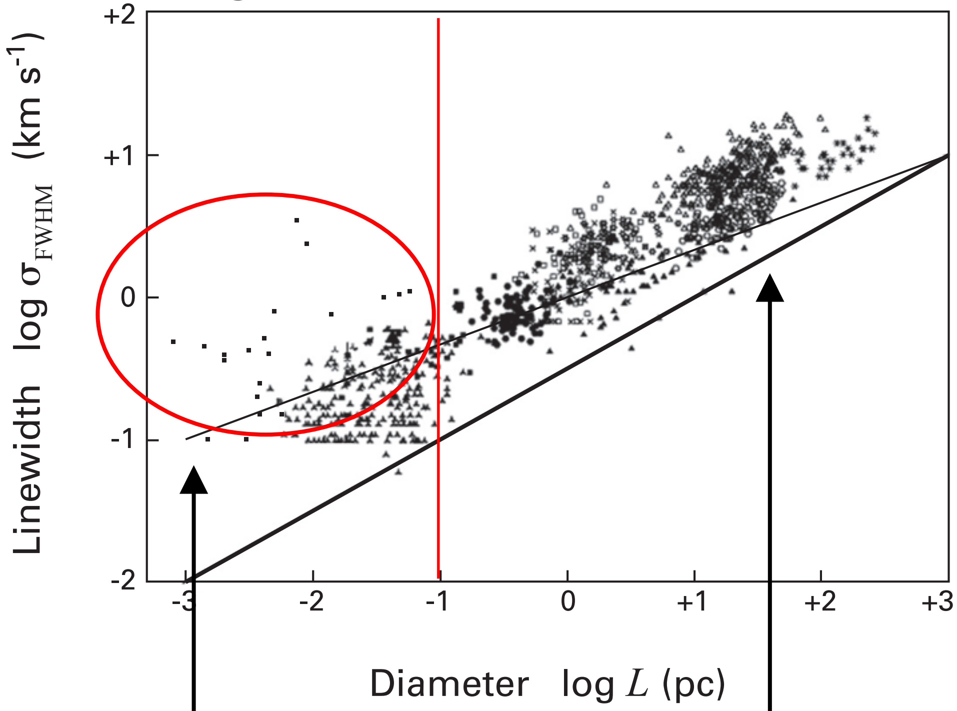
Observational results show a steeper relation.

Linewidth – Size Relation

Heyer&Brunt 2004



Falgarone+2009



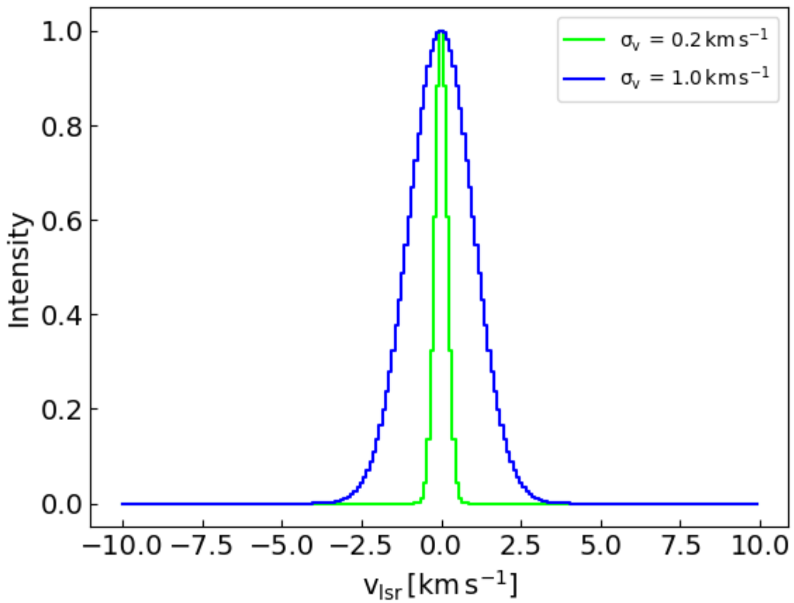
$\sigma_v \propto L^{0.33}$ $\sigma_v \propto L^{0.5}$

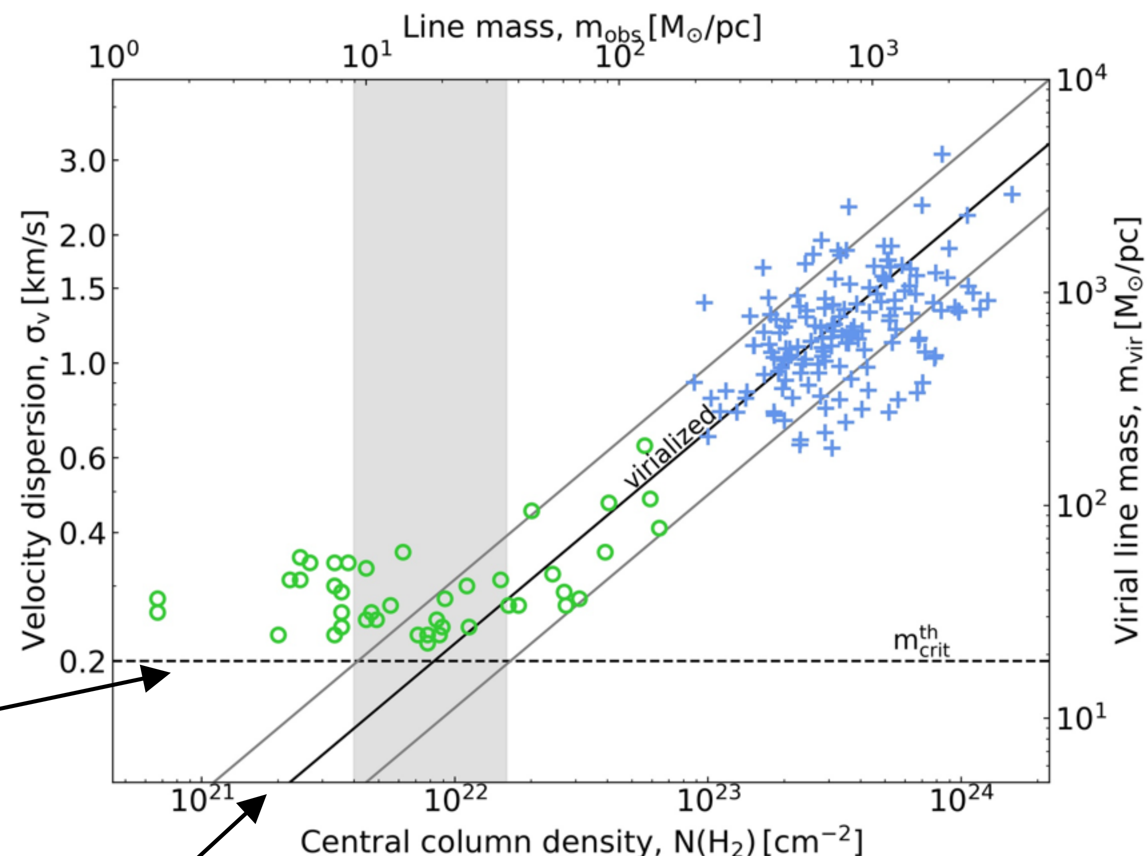
- The relations of single clouds show a similar behavior.
- The cloud to cloud variations are small.
- This suggest similar processes within the clouds.

Deviation from the Linewidth-Size relation?

Thin (~mpc) layers of gas seen in ^{12}CO in the Polaris flare.

Turbulent – Thermal transition





Mattern+2018b

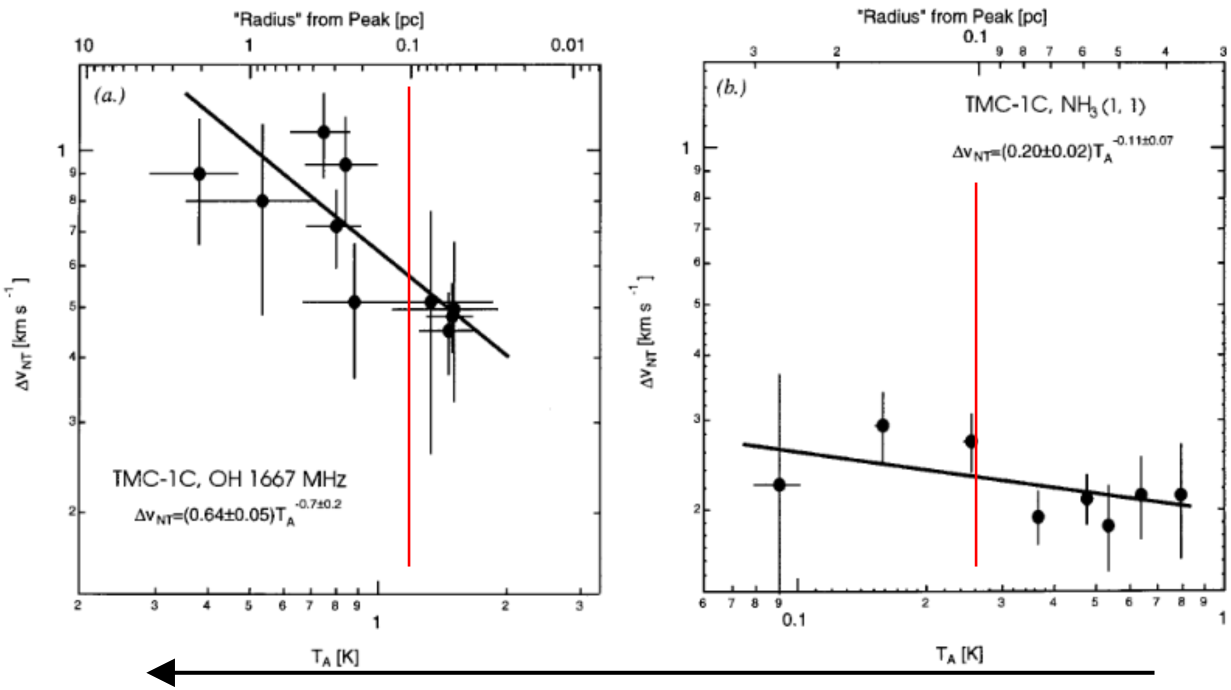
$$m \equiv \frac{M}{l} \qquad m_{\rm crit}^{\rm th} = \frac{2c_s^2}{G}$$

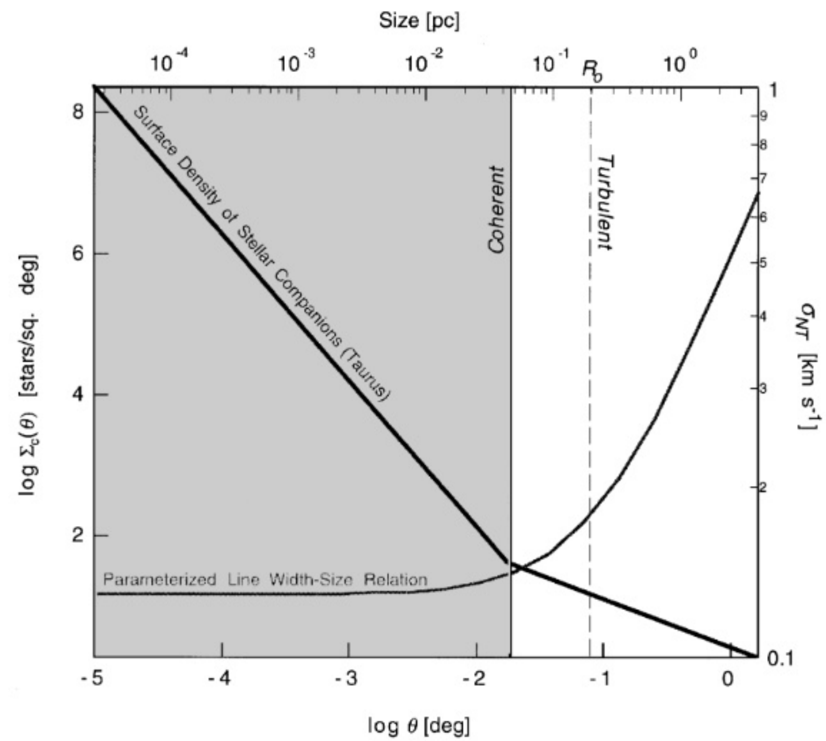
$$m_{\rm crit}^{\rm turb} = \frac{2\sigma_v^2}{G}$$

The kinetic energy support against gravity for filaments changes from turbulent to thermal.

Turbulent – Thermal transition

Goodman+1998



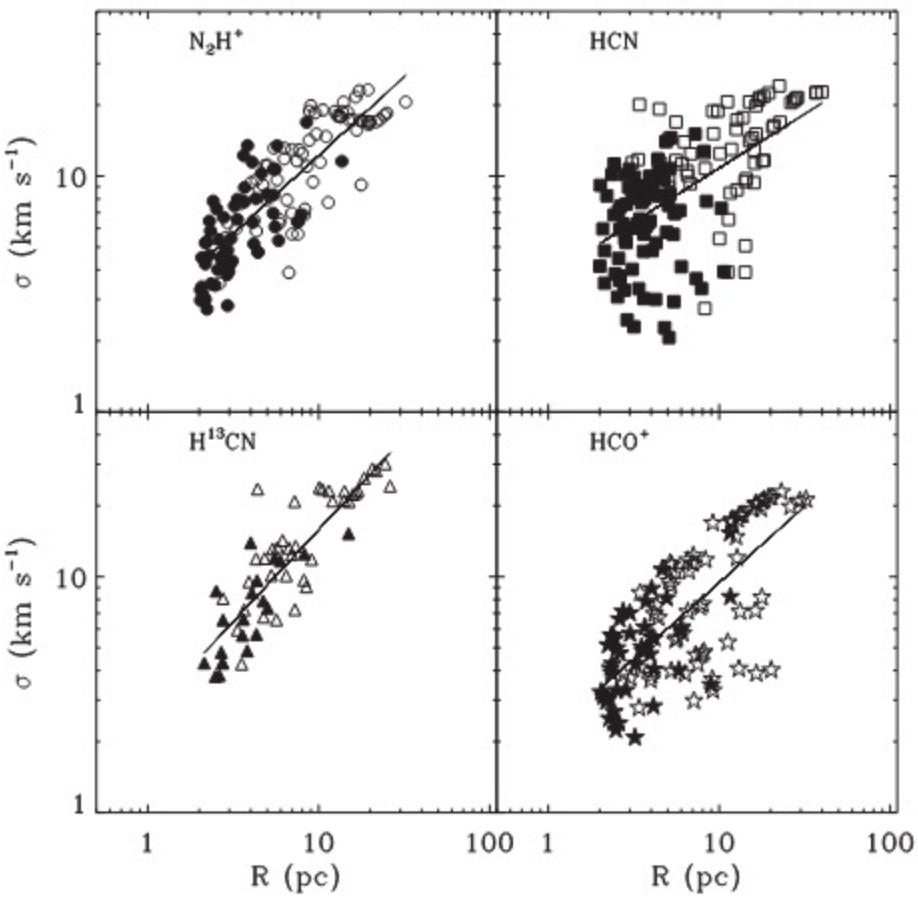


Scale-size

- Star forming cores have a coherent velocity, e.g. are dominated by thermal motion
- Different density regimes are traced only by specific molecules.
- The transition scale is around 0.1 pc

Linewidth – Size Relation

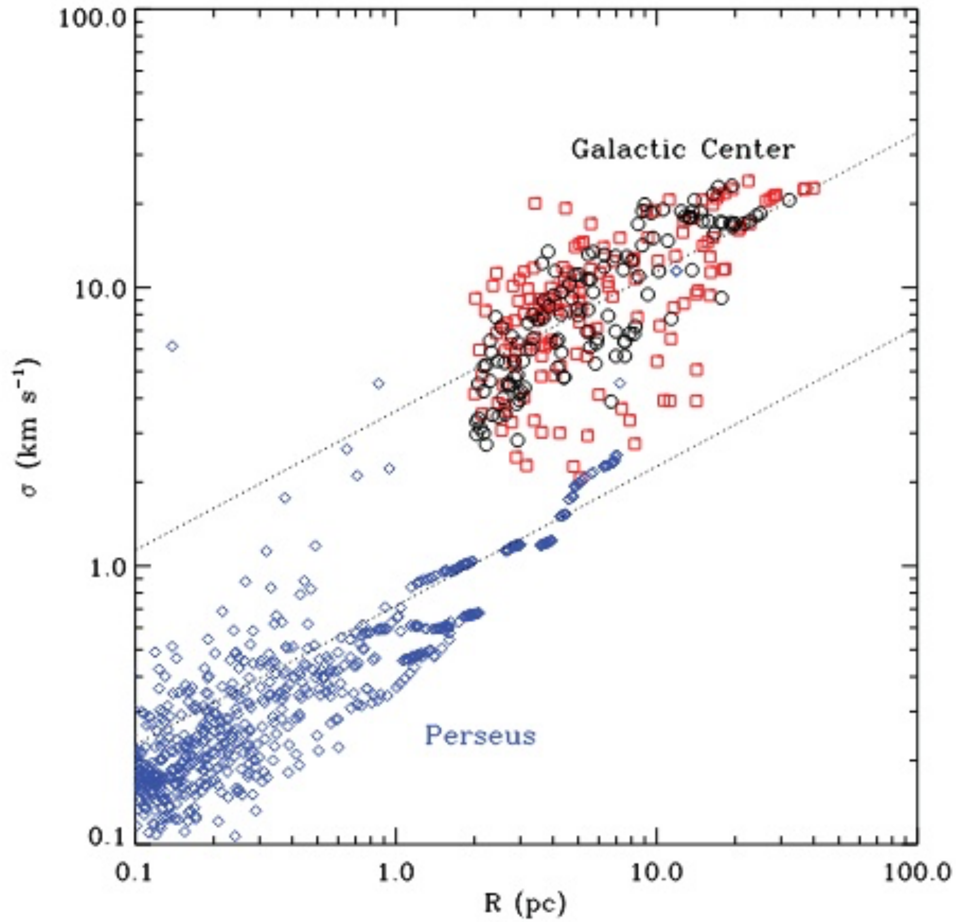
Shetty+2012



$$\sigma_v = A \cdot L^b$$

Tracer	N_2H^+	HCN	$H^{13}CN$	HCO^+
Power-law index b	0.67	0.46	0.78	0.64
Coefficient A	2.6	3.8	2.6	2.1

[a]The formal 1σ errors in b and A are all $\lesssim 0.06$ and 1.2, respectively.



The normalization coefficient is dependent on the column density of the cloud

$$A = \sigma_v / L^{0.5} = (\pi G \Sigma / 5)^{0.5}$$

(Heyer+2009)

Line-of-sight velocities

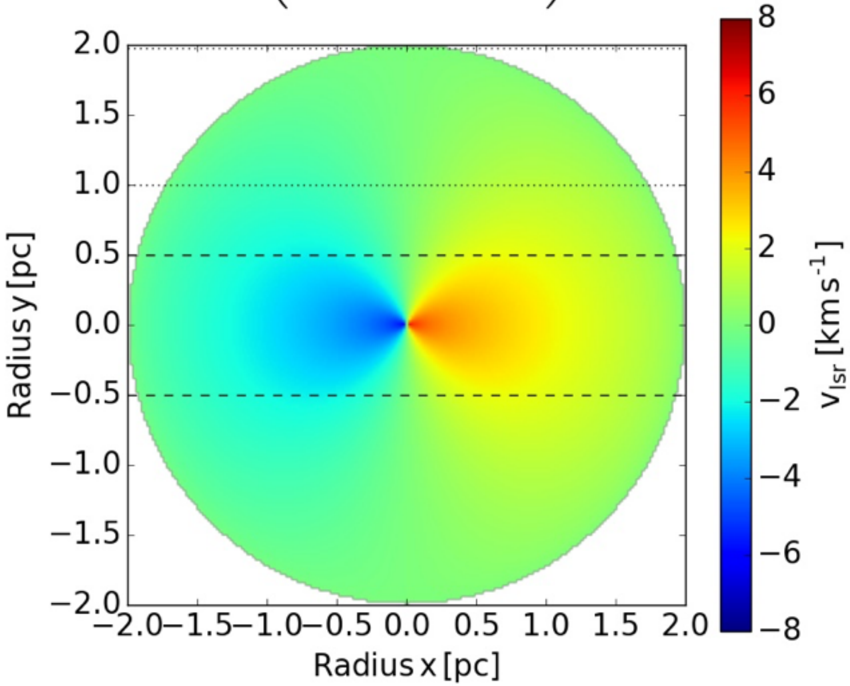
Fig. 24	m $M_\odot\,pc^{-1}$	p	position	σ_v $km\,s^{-1}$	$\sigma_{crit,nt}$ $km\,s^{-1}$
a	100	1.5	all	1.03	0.46
b	500	1.5	all	2.29	1.04
c	1000	1.5	all	3.23	1.47
d	500	2.0	all	2.65	1.04
e	500	3.0	all	3.24	1.04
f	500	1.5	middle	2.86	-
g	500	1.5	edge	0.62	-

$$m \propto \sigma^2$$

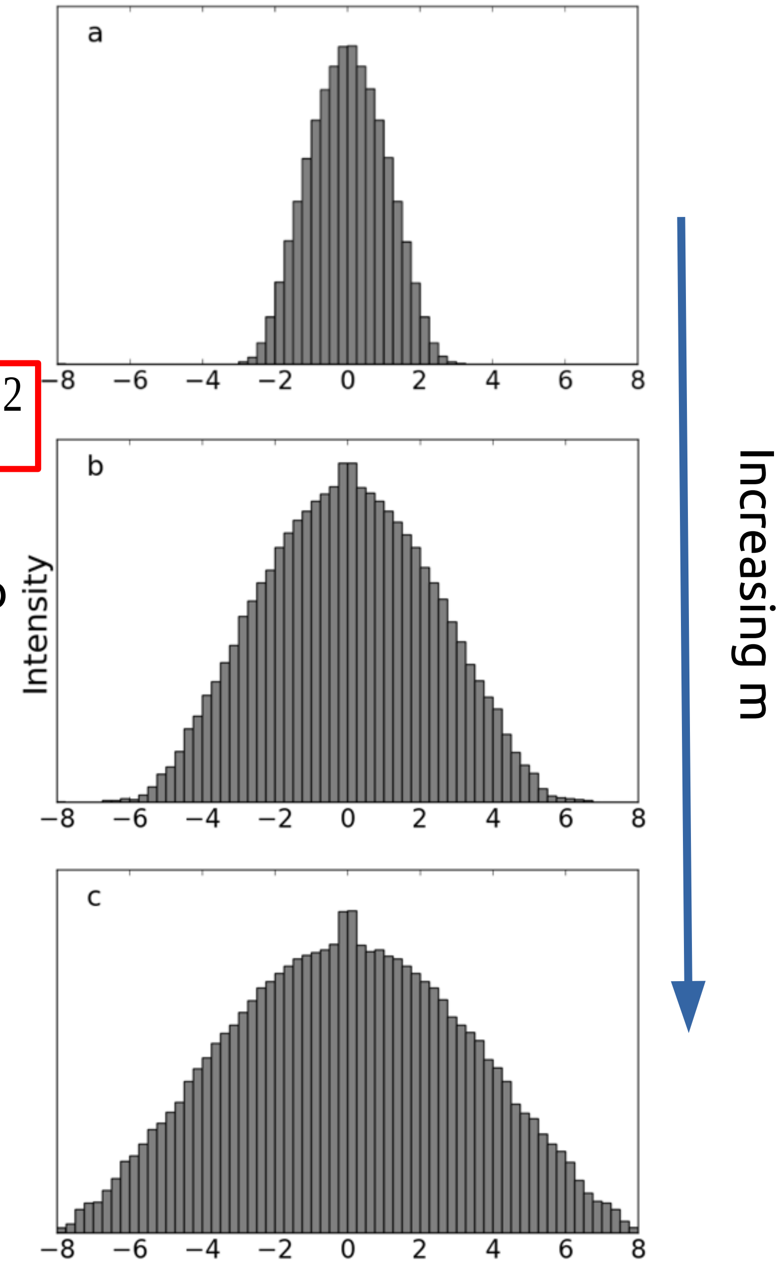
(Heitsch+ 2009, 2013)

$$v_R = 2\left(Gm \ln \frac{R_{ref}}{R}\right)^{1/2}$$

Mattern+2018b

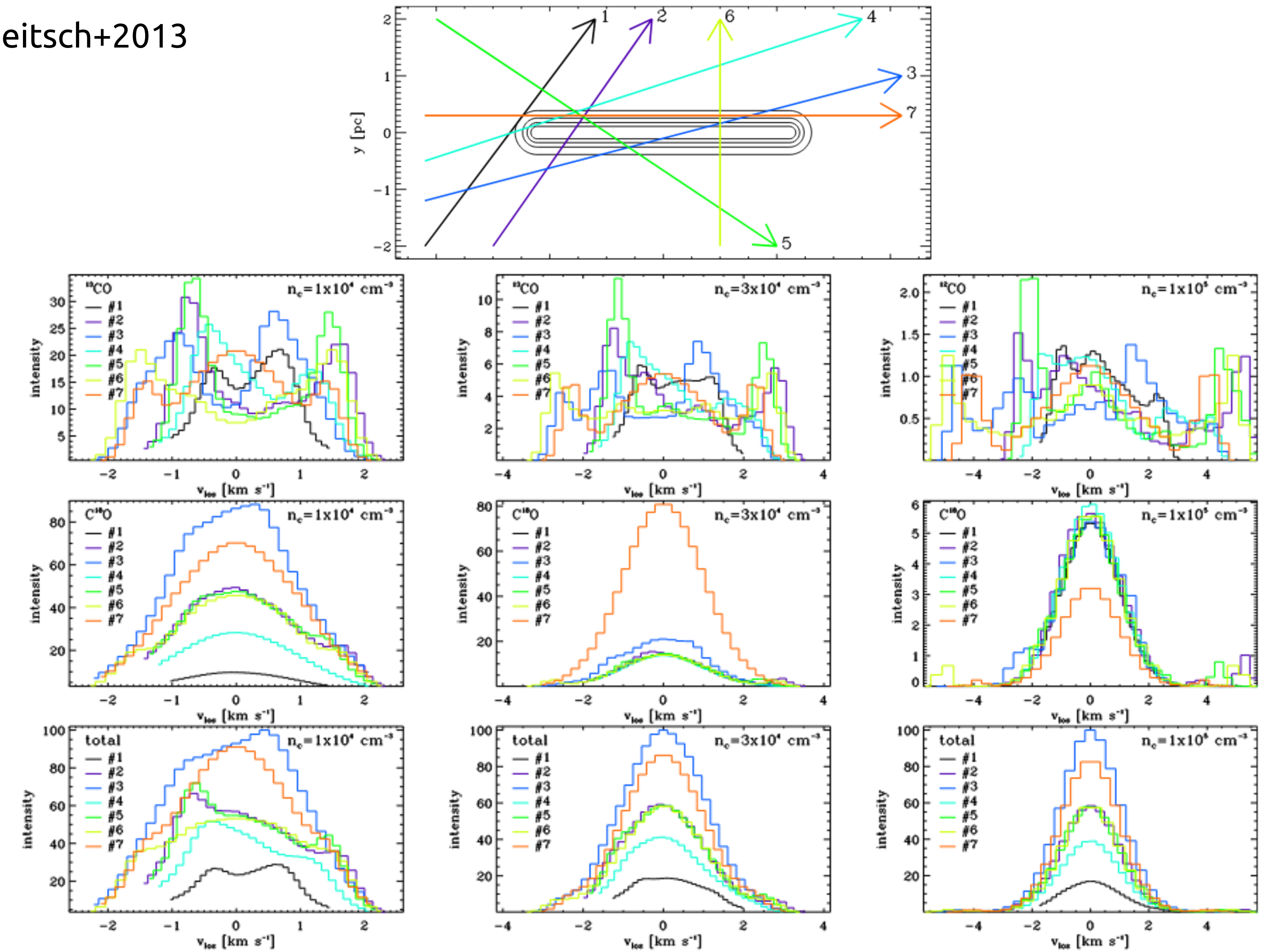


Observer



Line-of-sight velocities

Heitsch+2013



Summary and key questions for discussion

- The density/velocity of the cold ISM is hierarchical and ~scale-free over wide range of scales, from ~ 100 pc to ~ 0.1 pc or less
- At what scale does the self-similarity of ISM structures break down?
  At a few a.u. (opacity limit for fragmentation) or at the larger ~0.1 pc scale of dense cores / typical filament transverse size?
- What is/are the physical reason(s) for the observed departures from self-similarity?
- Transition from supersonic to subsonic turbulence at the sonic scale?
- Ambipolar diffusion scale below which short-wavelength MHD waves can no longer propagate in the mostly neutral gas?