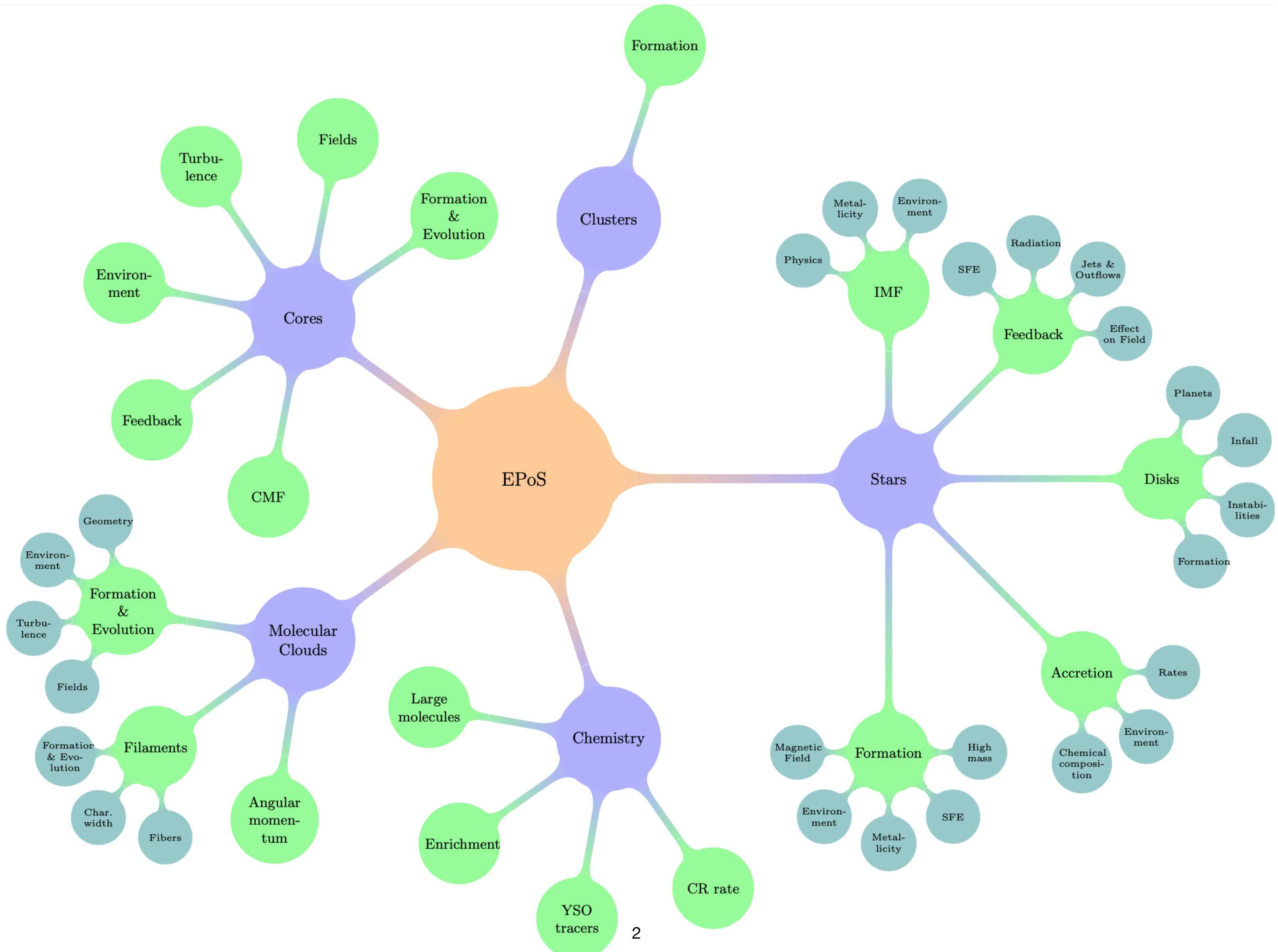
Answering the Big Questions: Are We Making Progress?

Part I: From Clouds to Cores

Understanding the formation pathways and excitation of large astronomical molecules, all the way to (pre)biotic molecules (section F-Q2.c in Astro2020).
How is the mass of a star assembled via an accretion disk?
How does the IMF depend on the environment?
Can dynamical mixing and dust transport via gas flows promote early planet formation within young discs?
What role does environment play in shaping the ISM and setting molecular cloud properties (and consequently star formation)?
How can we enhance our understanding of star-formation mechanisms in massive star-forming regions by bridging observations and numerical simulations?
How do low-mass protostars grow at the earliest stage?
What are the processes that form outflows and how do they impact stellar and planetary formation in young stars?
How does stellar feedback impact the star forming ability of molecular gas structures?
Which molecular tracers should be used to better understand the physics of Young Stellar Objects ?
Which physical processes regulate the star formation efficiency in galaxies?
What gives rise to the magnetic field-density relationship?
What are the initial conditions of cluster formation?
Is the cosmic ionisation rate constant at the different scales of the star formation process?
What is the nature of jets and outflows from low mass stars and brown dwarfs.
How do outflows affect the star formation process in the filament paradigm?
What are the accretion rates onto high-mass protostars?
What mechanism controls the fragmentation of molecular clouds and the formation of multiple stellar systems?
What role does the magnetic field play on envelope scales (few hundreds to thousands of au)?
What physics set the mass and size of gravitationally unstable clumps within molecular clouds?
What is the impact of turbulence in dense cores on the formation and evolution of disks?
What are the physical conditions during the early stages of protostellar evolution?
What is the role of magnetic fields in MC evolution and how can we test it observationally?
How does metallicity influence star formation and stellar feedback?
The role of magnetic fields in the transition stage between filaments to cluster formation
How do stars evolve from a clustered environment to the Galactic field?
What is the impact of radiative feedback on star formation?

How are highly chemically enriched star forming clouds formed?
The role of turbulence and magnetic fields in regulating gravitational contraction.
How do massive stars form?
How does accounting for a realistic turbulent magnetic field affect the existing picture of early star formation?
Can we observe ambipolar diffusion in prestellar cores?
What is the formation mechanism of the multiple close binary stars?
How do stars accrete their mass?
How and when do massive stars form?
How are molecular clouds shaped and how does their shape influence star formation within?
Which physical processes regulate the evolution of the filamentary ISM and its condensation into stars?
The role of magnetic fields in cloud and star formation.
Accretion bursts in massive stars
What is a mechanism of the angular momentum transfer in filamentary molecular clouds ?
Which mechanism is responsible for the observed outbursts in high-mass young stellar objects?
Cluster formation mechanisms and mass assembly process in giant molecular clouds.
How do binary and higher-order multiple system form in the protocluster?
How do protostars gain mass from their environment?
How high-mass stars keep accreting despite the onset of the ionizing radiation?
How do the initial conditions, and thresholds, for star formation vary with environment?
How do feedback effects from massive stars affect the surrounding magnetic field orientation and strength?
How does stellar feedback influence the star formation process within molecular clouds?
How and under which circumstances do circumstellar disks form?
What is the origin of stellar multiplicity?
Understanding the occurrence of 6.7 GHz methanol masers serves as a crucial element when examining the broader context of high-mass star formation on a larger scale
Which is the dominant mechanism that regulates the collapse and the fragmentation of massive regions in our Galaxy?
Does the magnetic field play a relevant role in regulating high-mass star formation at all scales, from large cloud scales to small circumstellar scales?
What mechanism solves the angular momentum problem at molecular cloud scales?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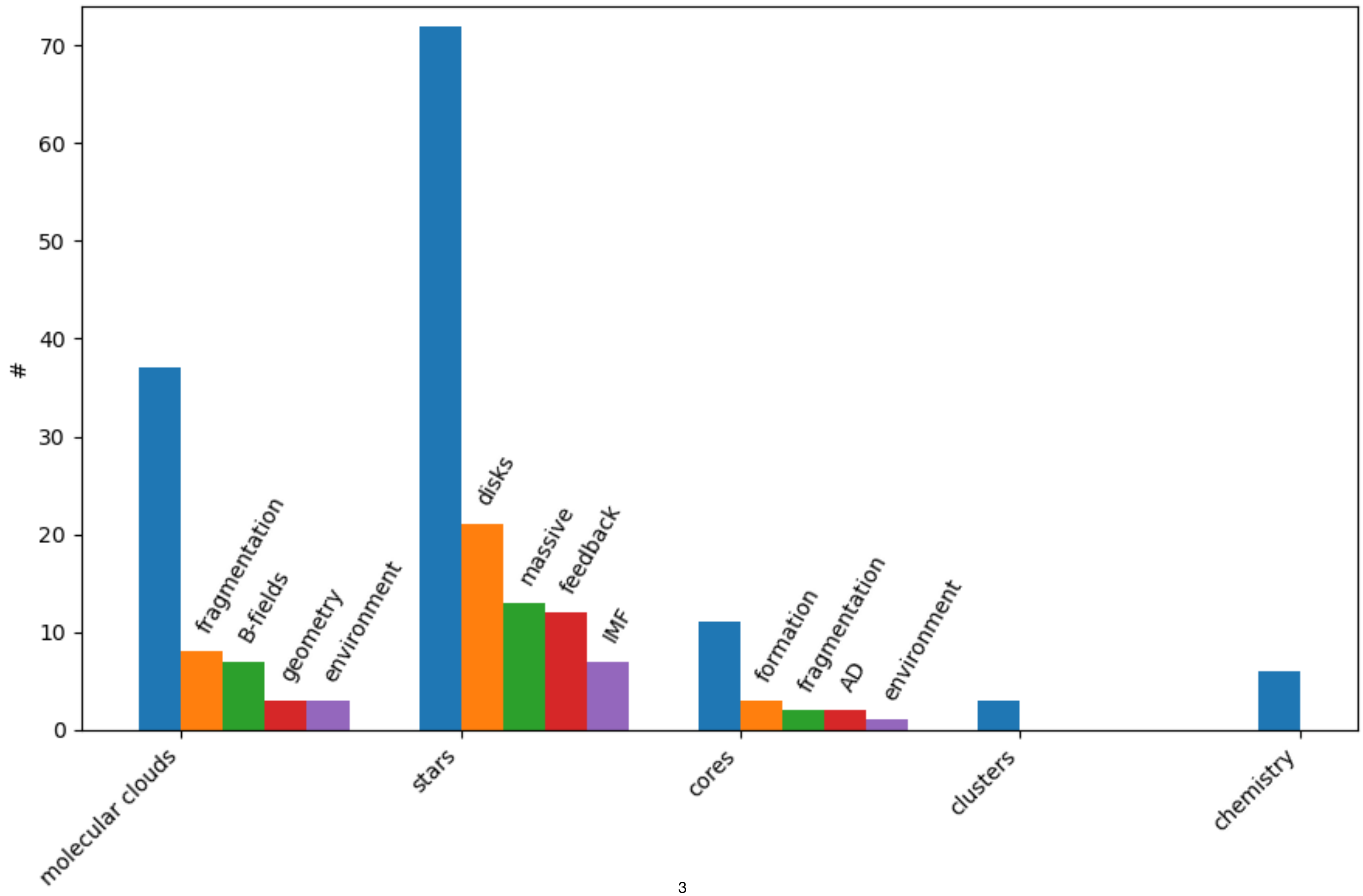
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environment
molecular clouds
stars
cores
clusters
chemistry

Questions:

1. How do filaments, cores and protostars assemble their mass?
2. What drives diversity in stellar mass?
3. How do feedback processes influence star formation?
4. How do magnetic fields in molecular clouds affect star formation?

Questions:

1. **How do filaments**, cores and protostars **assemble their mass?**
2. What drives diversity in stellar mass?
3. **How do feedback processes influence star formation?**
4. **How do magnetic fields in molecular clouds affect star formation?**

- “Nature” of Molecular Clouds: Process, not object
- Accretion: everywhere.
- Magnetic Fields: everywhere.
- Feedback: mostly everywhere **(but see J. Alves)**.

The Nature of "Giant Molecular Clouds": transient, subject to environmental effects

In summary, GMCs are observationally defined, in most cases as overdensities or bright, compact features. This identification is relative to the local medium, and the boundaries between GMCs and their surroundings are not clearly demarcated. Indeed, theoretical and observational work shows that GMCs are not isolated from their surroundings and evolve over a few crossing times (see Sections 3–5 below). *Thus, GMCs should not be regarded as a well-defined set of discrete entities.* Cloud properties must always be interpreted in the context of the object identification strategies that produced them. These properties are illuminating in comparative studies but the translation to any absolute measures requires care.

Chevance+2023, ASPC, 534, 1

We find that the velocity field is continuous across cloud boundaries for a hierarchy of clouds of progressively smaller sizes. Cloud boundaries defined by a density-threshold criterion are found to be quite arbitrary, with no correspondence to any actual physical boundary, such as a density discontinuity.

Ballesteros-Paredes, Vazquez-Semadeni, & Scalo 1999, ApJ, 515, 286

Molecular clouds should not be viewed as isolated clouds, but only as the opaque *regions* of more extended cloud complexes (Wannier et al. 1983)

Elmegreen 1985, PPII, UAz Press, 33

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Clouds are Flow Markers.

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Assembling Mass (I): $\partial_t \rho + \nabla \cdot \rho \mathbf{u} = 0$

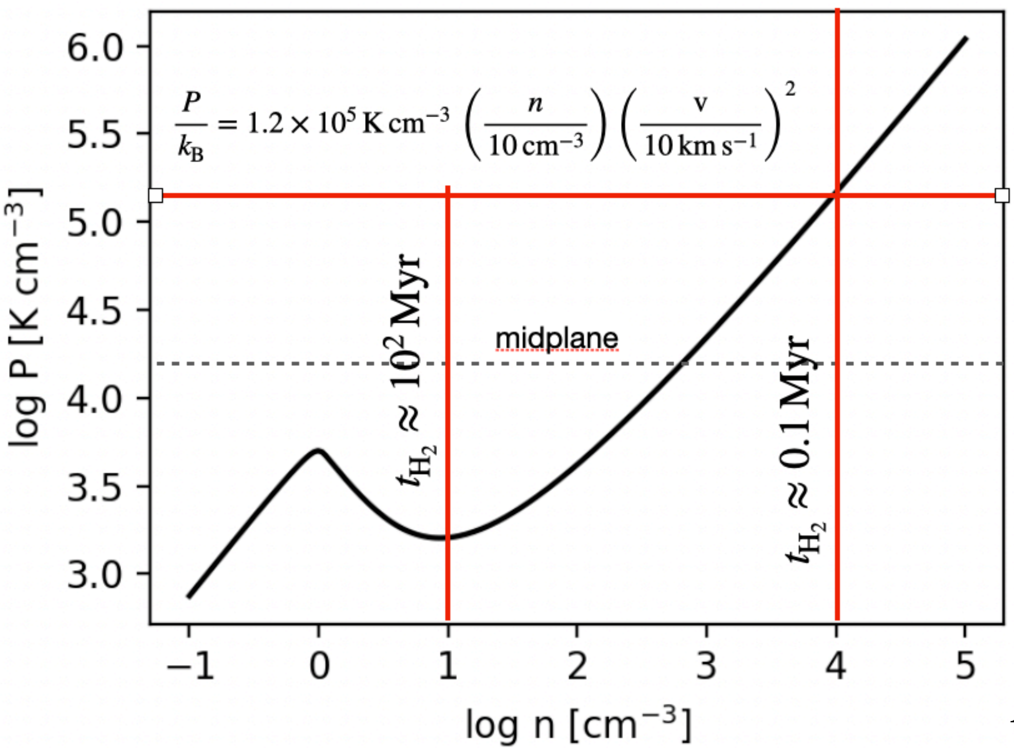
$$t_{sg} \approx 2.3\,\mathrm{Myr}\left(\frac{n}{10\ \mathrm{cm}^{-3}}\right)\left(\frac{\mathrm{v}}{10\,\mathrm{km}\,s^{-1}}\right)\left(\frac{P}{10^4\mathrm{K\,cm}^{-3}}\right)^{1/2}$$

$$t_{\mathrm{shield}} \approx 2.8\,\mathrm{Myr}\left(\frac{n}{10\ \mathrm{cm}^{-3}}\right)\left(\frac{\mathrm{v}}{10\,\mathrm{km}\,s^{-1}}\right)$$

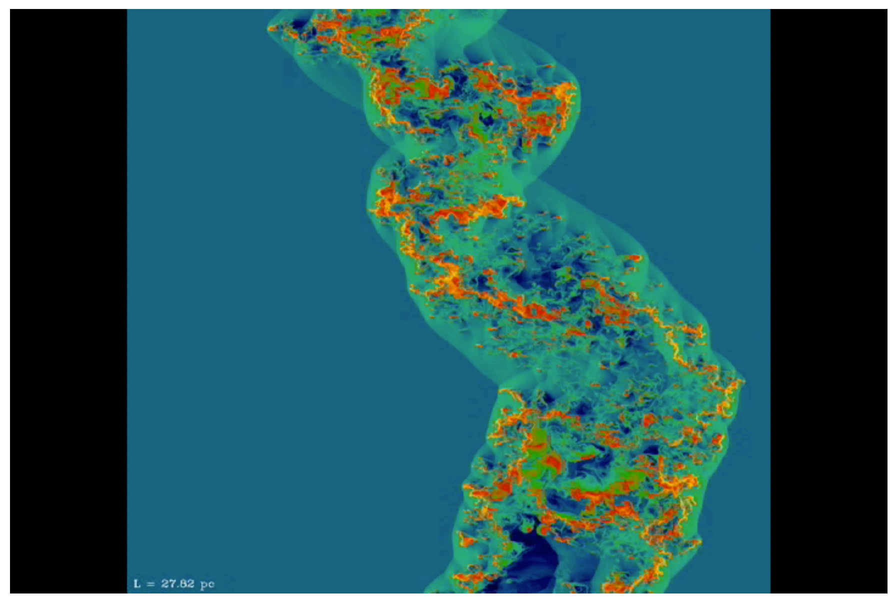
$$\longleftrightarrow \quad t_{\mathrm{H}_2} \approx 10^2\,\mathrm{Myr}\left(\frac{n}{10\,\mathrm{cm}^{-3}}\right)^{-1}$$

$$\Rightarrow \quad t_{\mathrm{H}_2} \approx 10^{-1}\,\mathrm{Myr}\left(\frac{n}{10^4\,\mathrm{cm}^{-3}}\right)^{-1}$$

Bergin+2004, ApJ, 612, 921
Glover & Mac Low, 2006, ApJ, 659, 1317
Seifried+2020, MNRAS, 492, 1465



Heitsch+2011, MNRAS, 415, 271



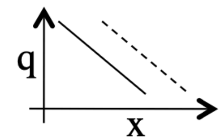
Assembling Mass (I): $\partial_t \rho + \nabla \cdot \rho \mathbf{u} = 0$

How does Turbulence arise? ("How is turbulence driven?")

Hydrodynamic instabilities: Non-linearity of momentum equation

$$\partial_t \rho + \nabla \cdot (\rho \mathbf{u}) = 0$$

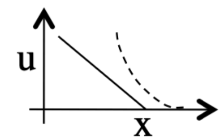
: linear in u



$\nabla \times$

$$\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\frac{1}{\rho}\nabla P + \frac{1}{\rho}\nabla \cdot \boldsymbol{\tau}$$

: non-linear in u

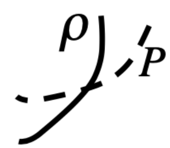


Not only compression: vorticity $\omega \equiv \nabla \times \mathbf{u}$

$$\partial_t \omega + (\mathbf{u} \cdot \nabla)\omega = (\omega \cdot \nabla)\mathbf{u} - \omega(\nabla \cdot \mathbf{u}) + \frac{1}{\rho^2}\nabla \rho \times \nabla P + \nabla \times \left(\frac{1}{\rho}\nabla \cdot \boldsymbol{\tau}\right)$$

velocity tilt/shear

angular momentum conservation



Assembling Mass (I): $\partial_t \rho + \nabla \cdot \rho \mathbf{u} = 0$

How does Turbulence arise? ("How is turbulence driven?")

Hydrodynamic instabilities: Non-linearity of momentum equation

Turbulence for free.

∇

Molecular hydrogen "fast".

Not only compression: vorticity $\omega \equiv \nabla \times \mathbf{u}$

$$\partial_t \omega + (\mathbf{u} \cdot \nabla)\omega = (\omega \cdot \nabla)\mathbf{u} - \omega(\nabla \cdot \mathbf{u}) + \frac{1}{\rho^2} \nabla \rho \times \nabla P + \nabla \times \left(\frac{1}{\rho} \nabla \cdot \boldsymbol{\tau} \right)$$

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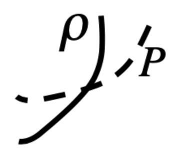
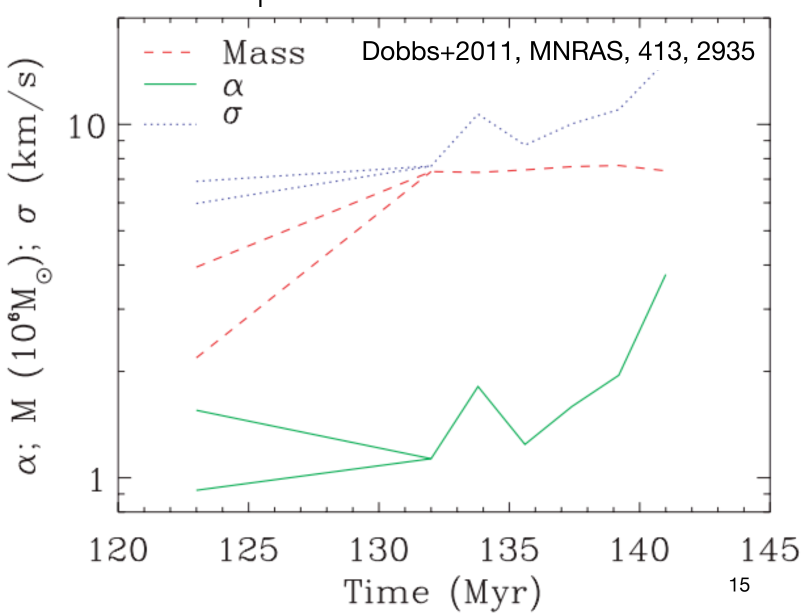
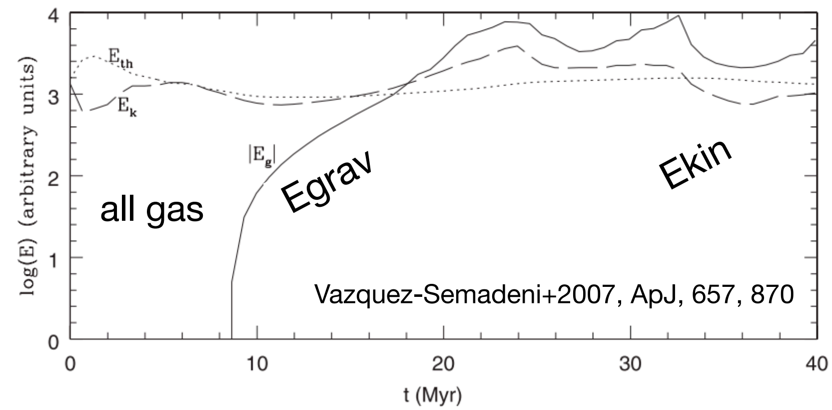
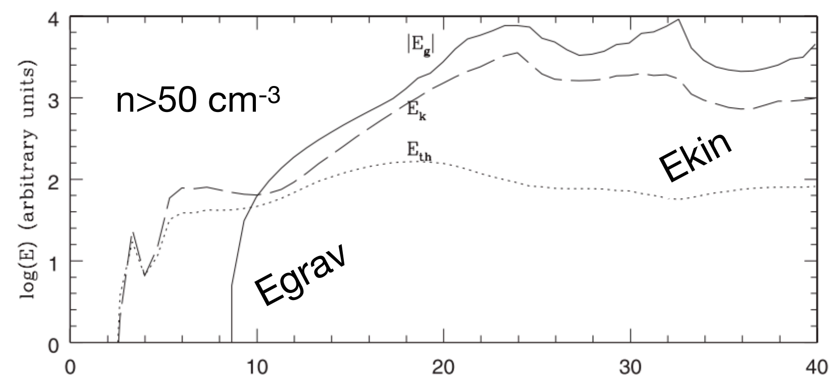


Assembling Mass (II): Local vs Global Collapse?

	local collapse	global (hierarchical) collapse
VT/energies	$2T + V = \mathrm{const}$	$T + V = \mathrm{const}$
dispersions	$\frac{\sigma^2}{R} = G\Sigma$	$\frac{\sigma^2}{R} = 2G\Sigma$







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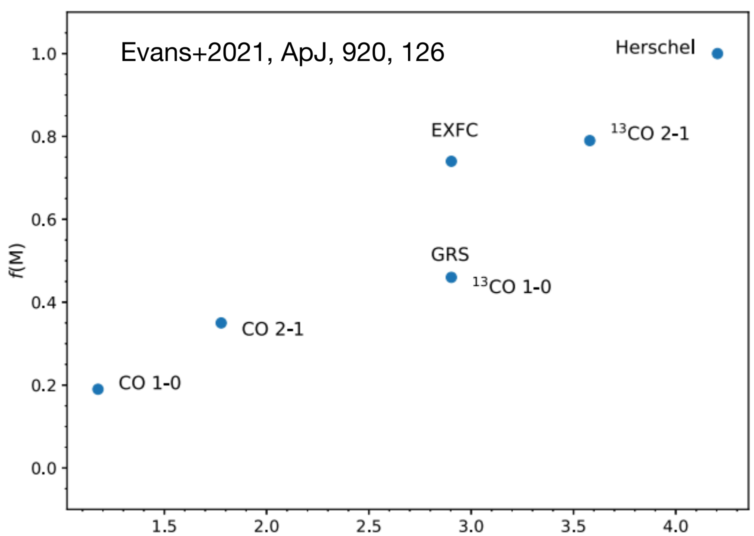
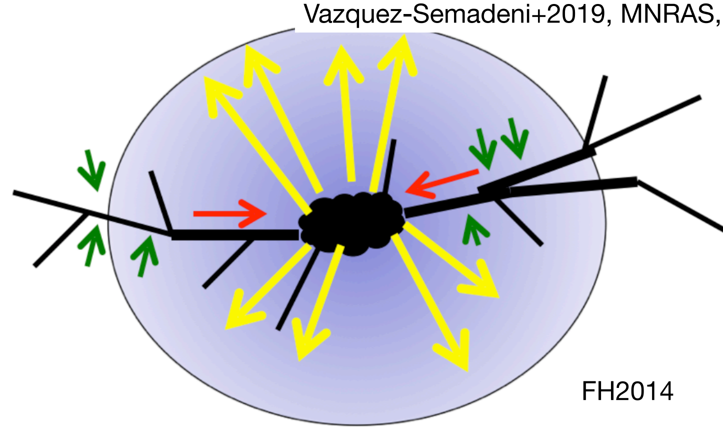
low SFE	most gas unbound	fragmentation & feedback



collapse (e.g. Galván-Madrid et al. 2009; Peretto et al. 2013; Beuther et al. 2015; Liu et al. 2015, 2016a; Friesen et al. 2016; Jin et al. 2016; Csengeri et al. 2017; Hacar et al. 2017; Yuan et al. 2018; Barnes et al. 2019; Jackson et al. 2019), with the filaments in particular exhibiting longitudinal flow (e.g. Sugitani et al. 2011; Kirk et al. 2013; Fernández-López et al. 2014; Jiménez-Serra et al. 2014; Motte et al. 2014; Peretto et al. 2014; Tackenberg et al. 2014; Hajigholi et al. 2016; Wyrowski et al. 2016; Juárez et al. 2017; Rayner et al. 2017; Baug et al. 2018; Dutta et al. 2018; Gong et al. 2018; Lu et al. 2018; Ryabukhina et al. 2018; Chen et al. 2019a) that feeds central 'hubs', the sites where the filaments converge (Myers 2009).

Vazquez-Semadeni+2019, MNRAS, 490, 3061



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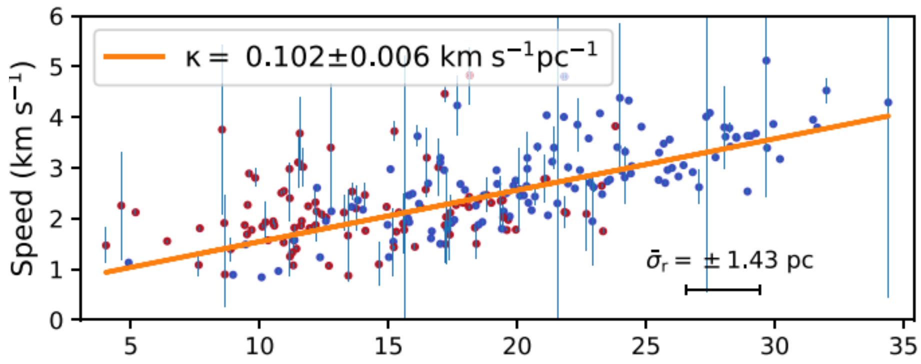
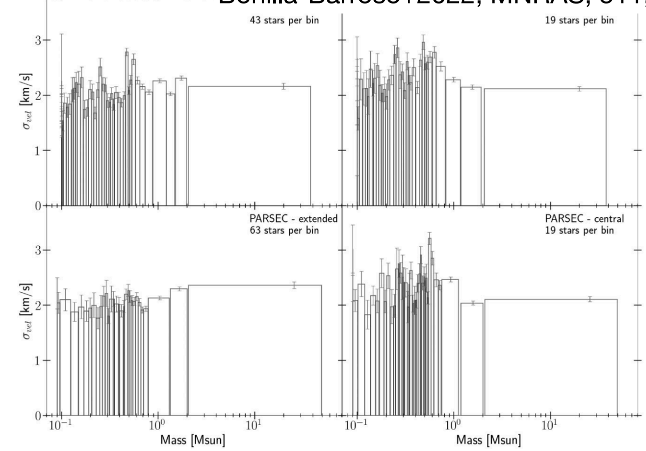


Swiggum+2021, ApJ, 917, 21

Bonilla-Barroso+2022, MNRAS, 511, 4801



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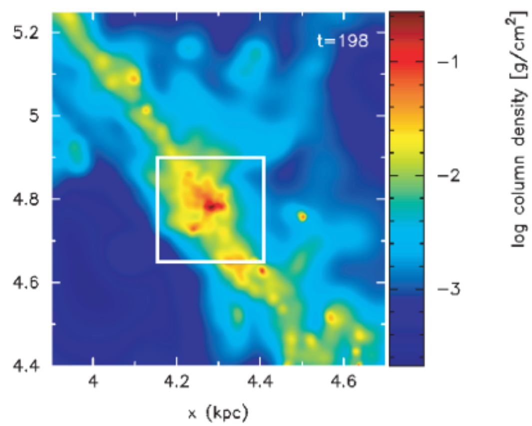
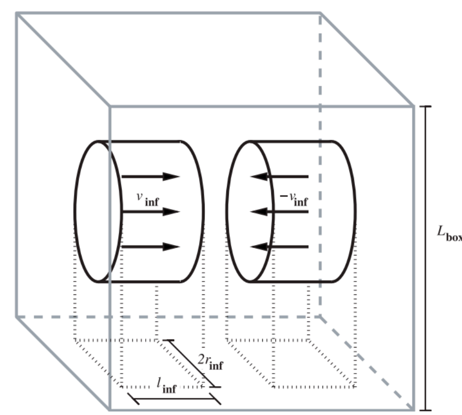
assumption?



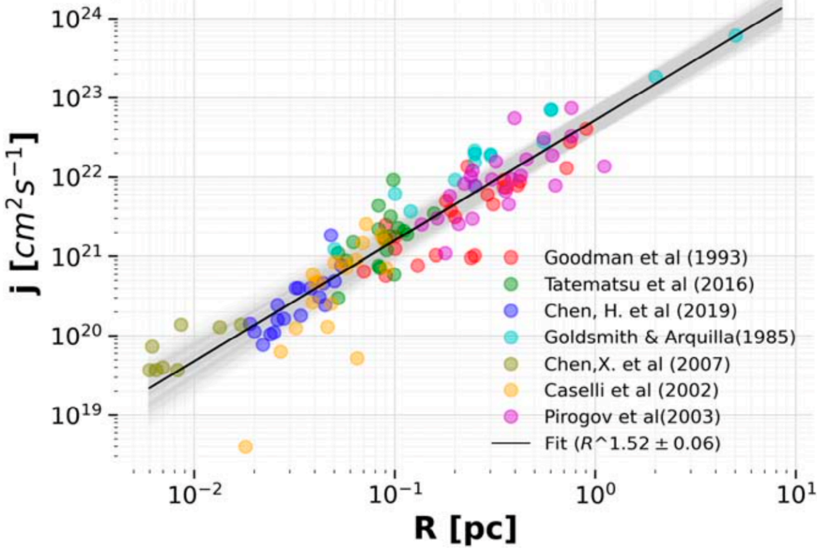
Dobbs+2011, MNRAS, 413, 2935

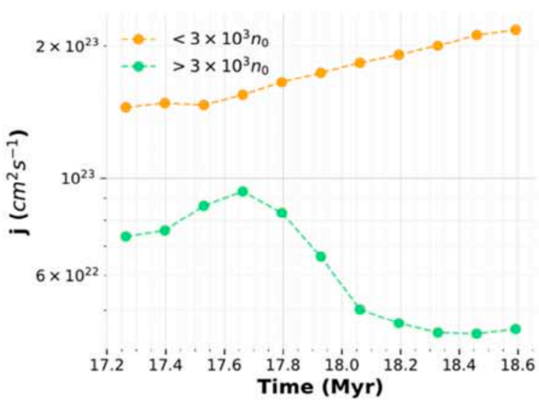


Vazquez-Semadeni+2007, ApJ, 657, 870

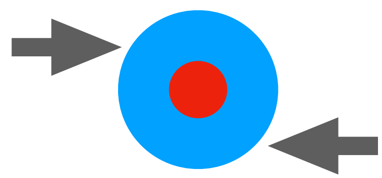
Assembling Mass (III): Angular Momentum

Arroyo-Chavez & Vazquez-Semadeni 2022, ApJ, 925, 78





$$\frac{e_r}{e_g} \propto \frac{1}{R}\Big|_{j=\mathrm{const}}$$



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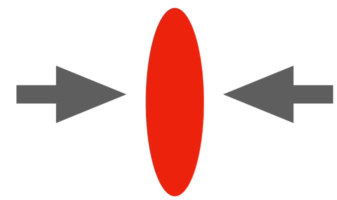


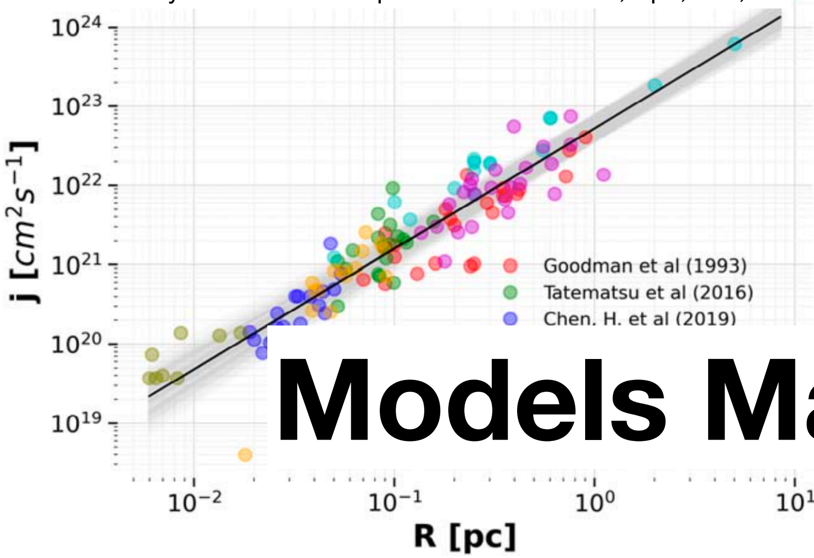
j increases in envelope and decreases in core.

Loss of high-j material?

Loss of j via turbulent viscosity?

Assembling Mass (III): Angular Momentum

Arroyo-Chavez & Vazquez-Semadeni 2022, ApJ, 925, 78



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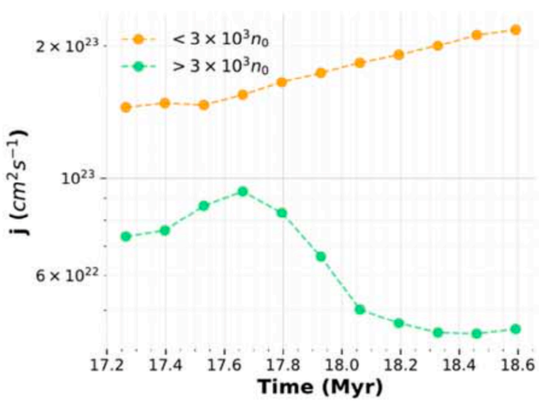
Models Maketh Theories?



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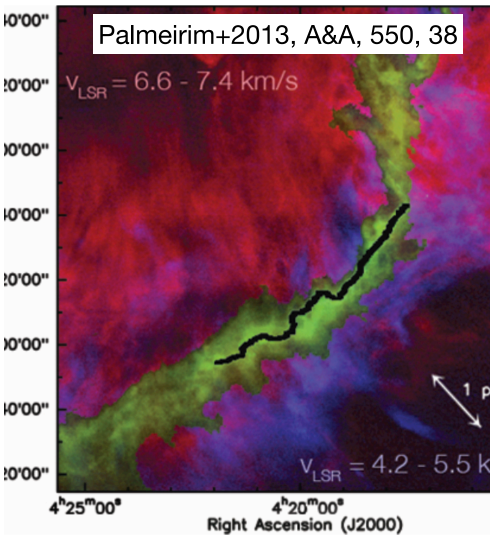
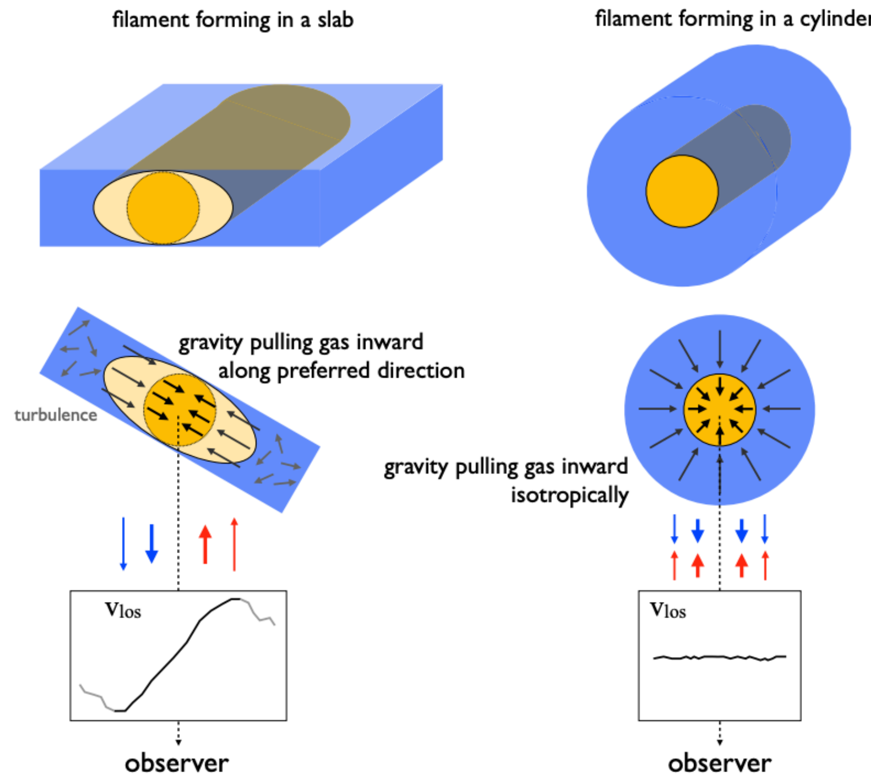
Accretion (I): “Radial” Flows

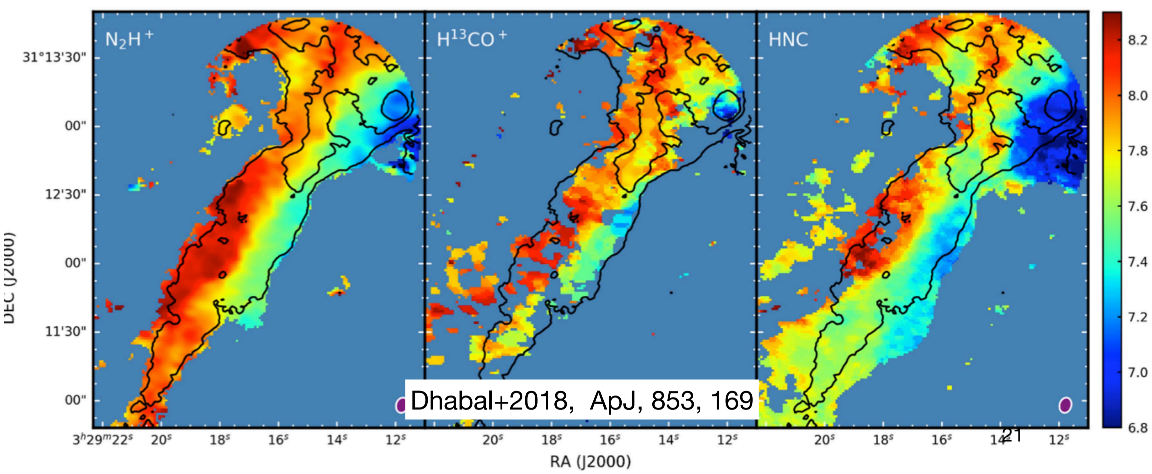


Palmeirim+2013, A&A, 550, 38

$$\mathrm{v}_{\mathrm{ff}}^{\mathrm{fil}} \equiv 2\left(Gm\,\ln\frac{R_{\mathrm{ref}}}{R}\right)^{1/2} \approx 0.8\,\mathrm{km\,s^{-1}}\left(\frac{m}{16\,\mathrm{M_{\odot}pc^{-1}}}\right) \quad @\;\; R_{\mathrm{ref}} = 1\,\mathrm{pc}$$

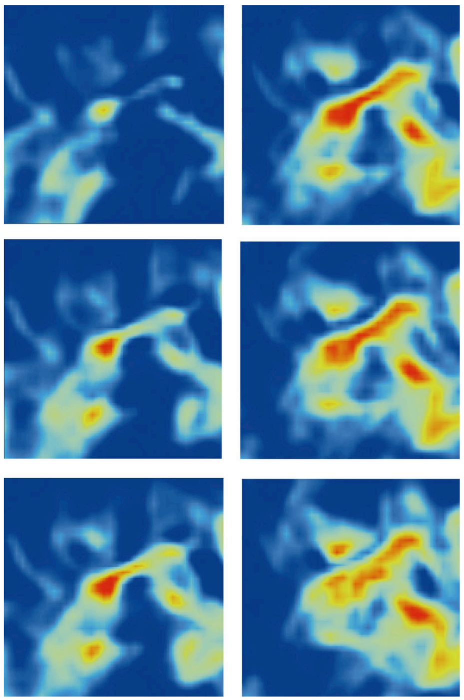


Chen+2020, MNRAS, 494, 3675

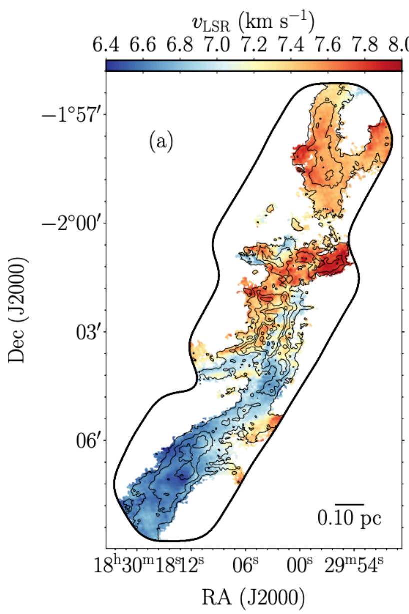


Dhabal+2018, ApJ, 853, 169

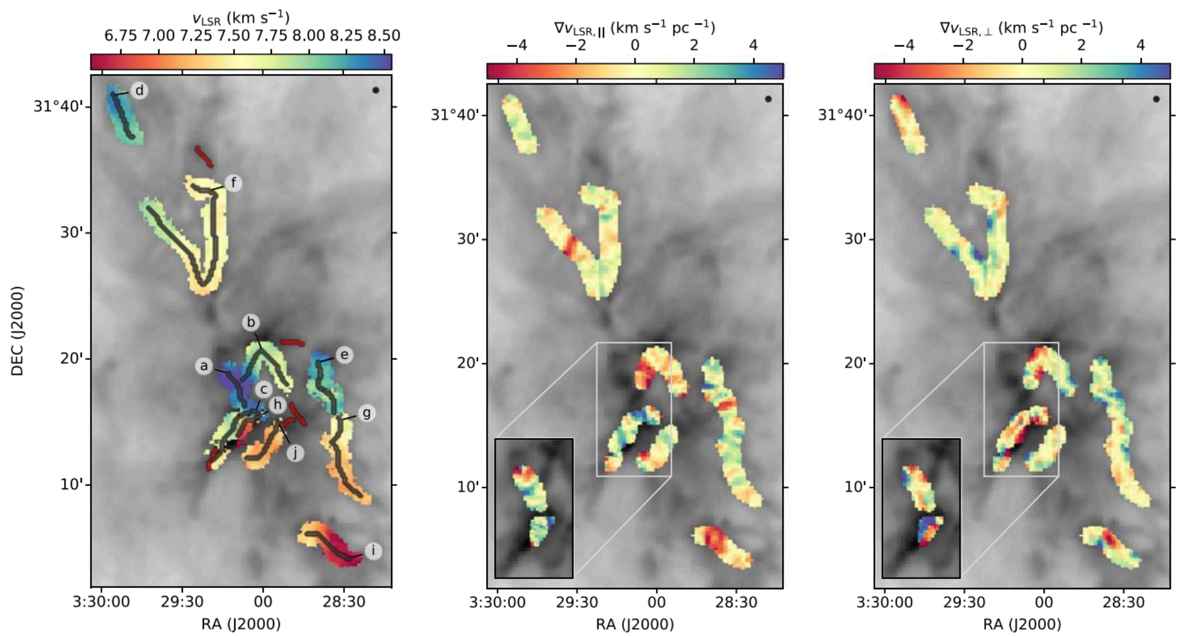
Accretion (II): Onto and Along Filaments



Balsara+2001, MNRAS, 327, 715



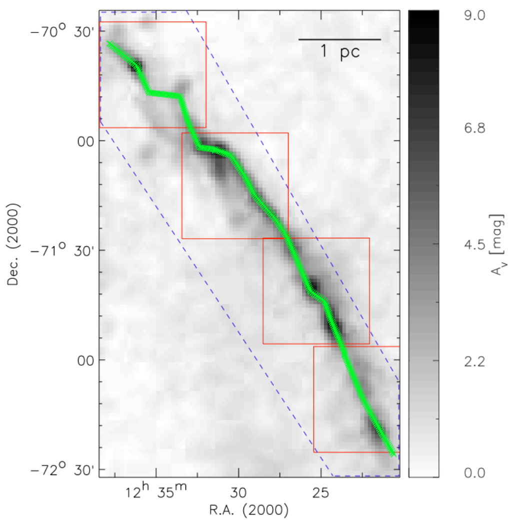
Friesen & Jarvis 2024, arxiv

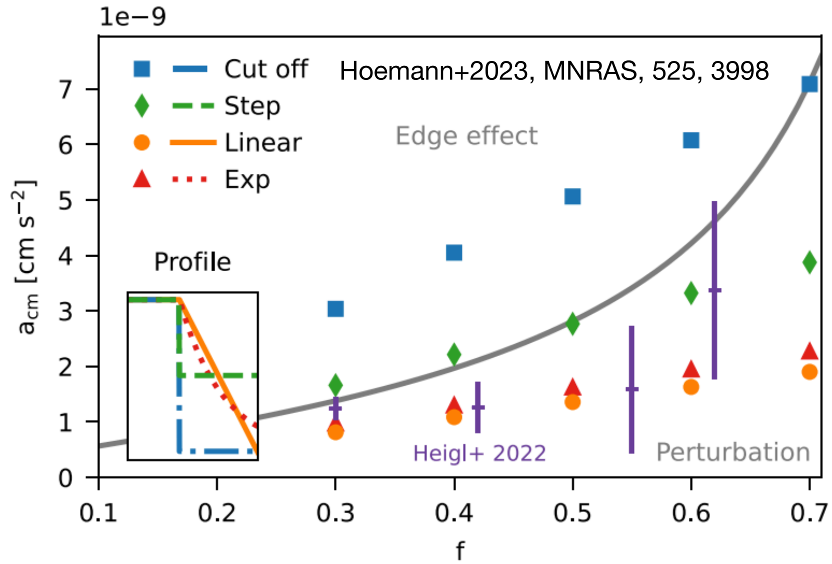


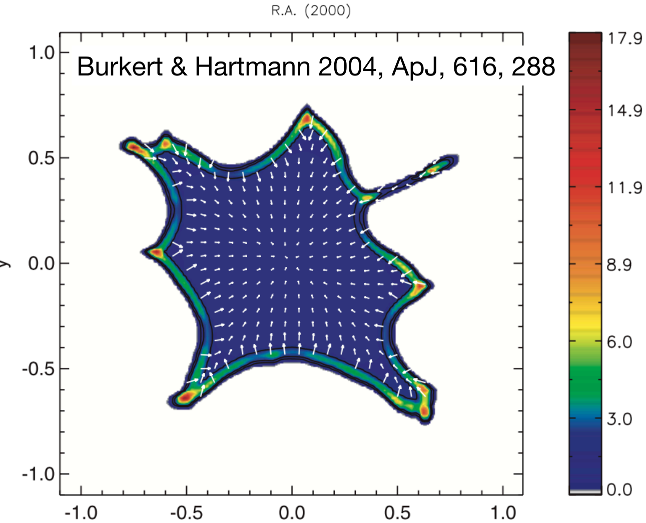
Chen+2020, ApJ, 891, 84

Accretion (III): Does geometry beat linear effects?

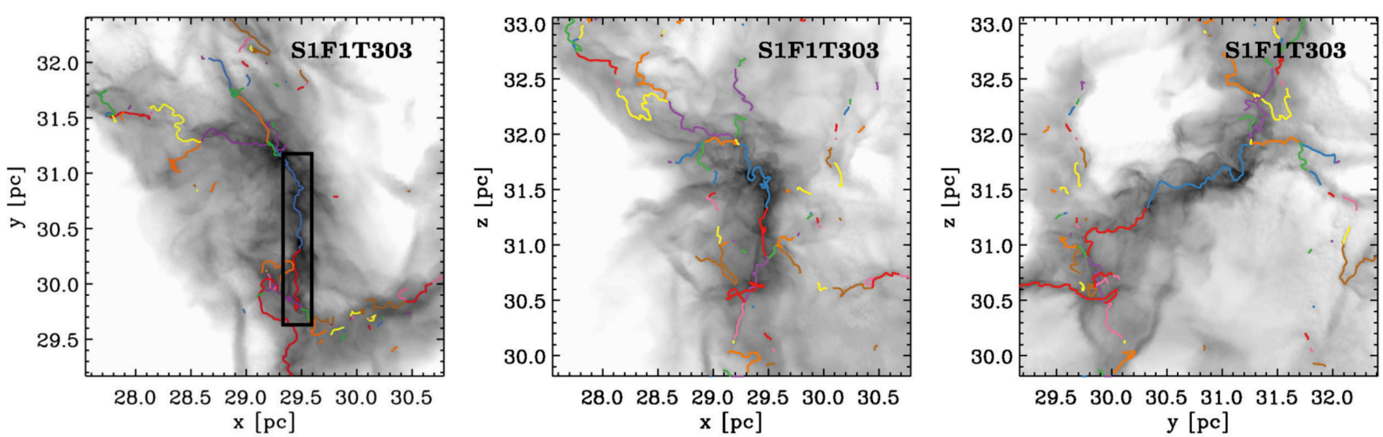
Kainulainen+2016, A&A, 586, 27







Smith+2016, MNRAS, 455, 3640



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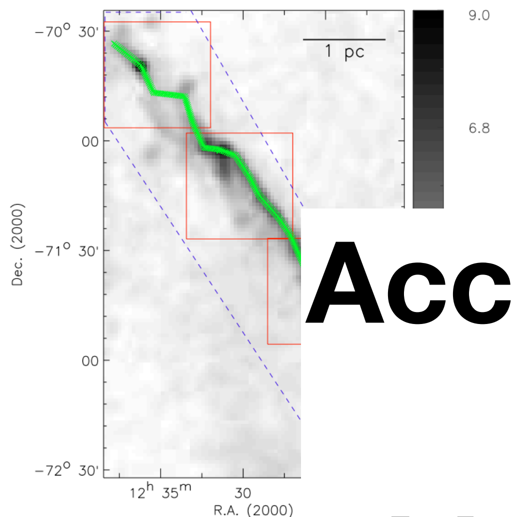
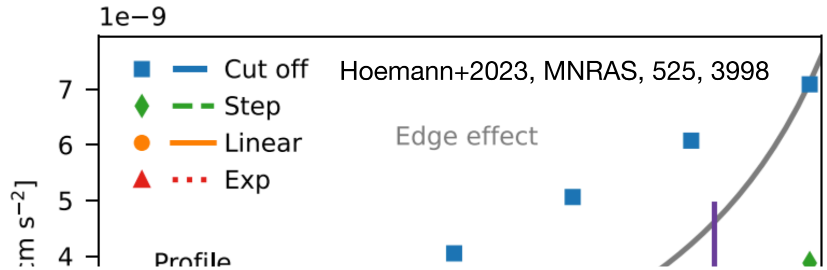
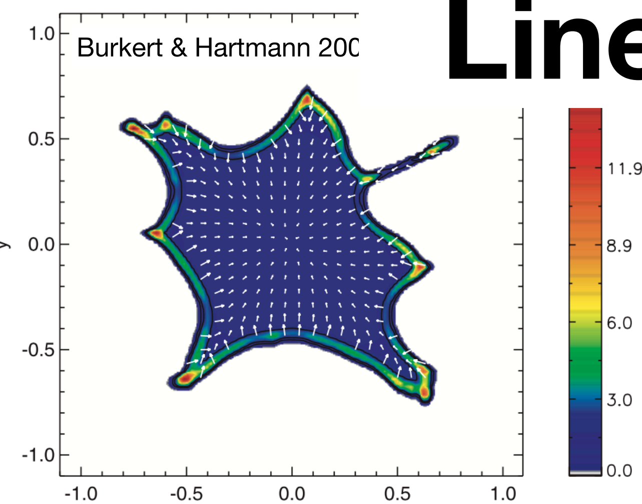




Accretion and Geometry
vs
Linear Fragmentation



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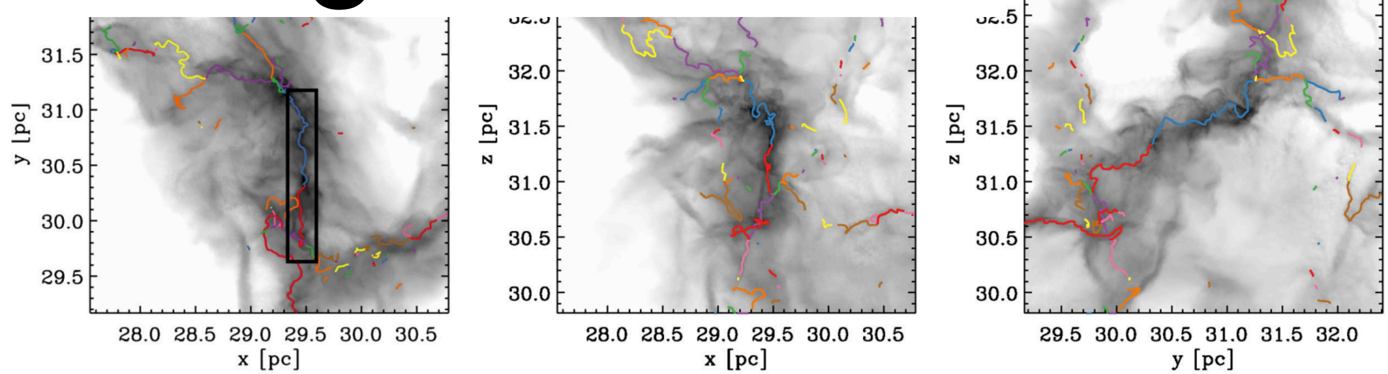
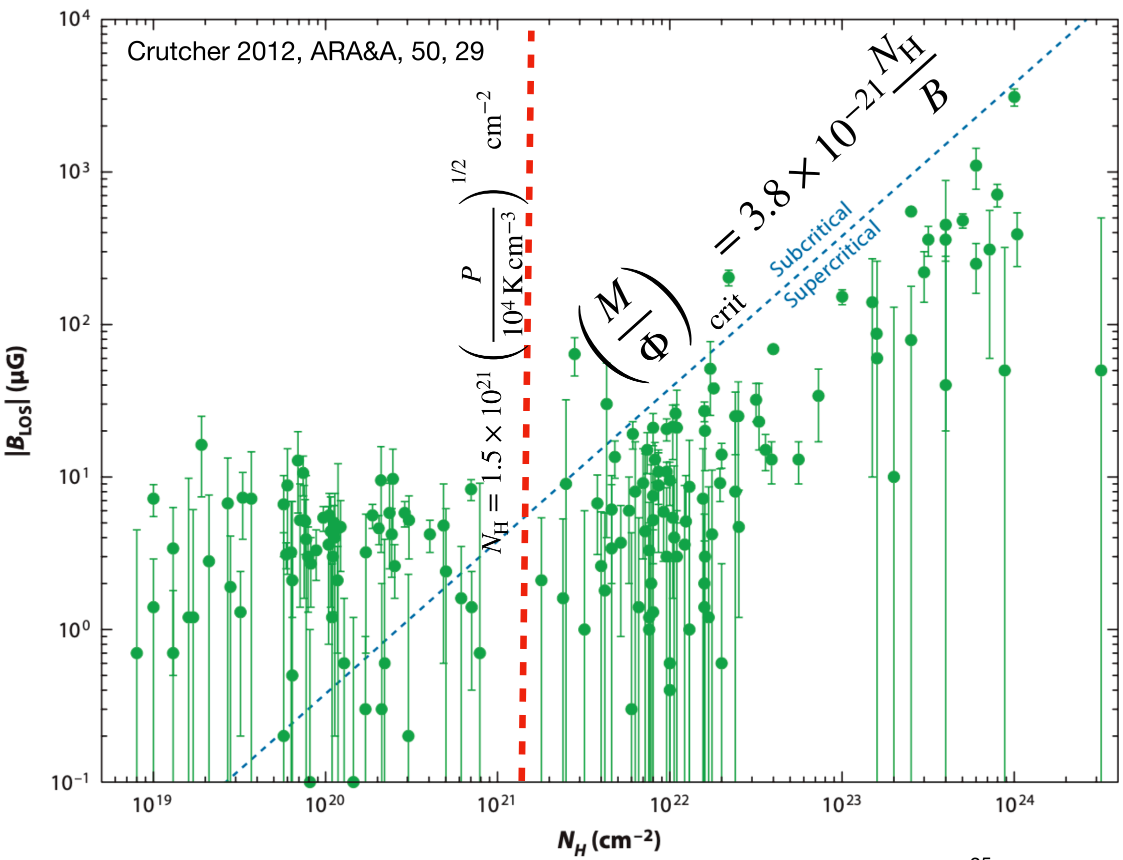
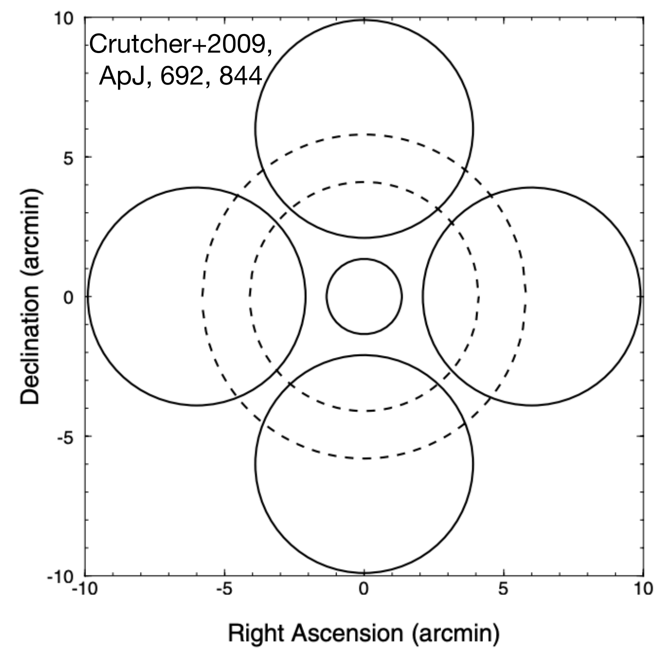


Role of Magnetic Fields (I): Strengths



$$\left(\frac{M}{\Phi}\right)_{env} \gtrsim \left(\frac{M}{\Phi}\right)_{core}$$



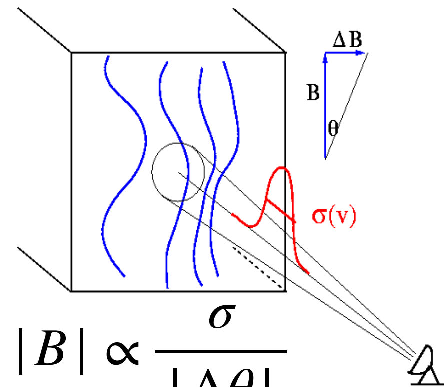
Role of Magnetic Fields (I): Strengths

- improved DCF consistent with Zeeman

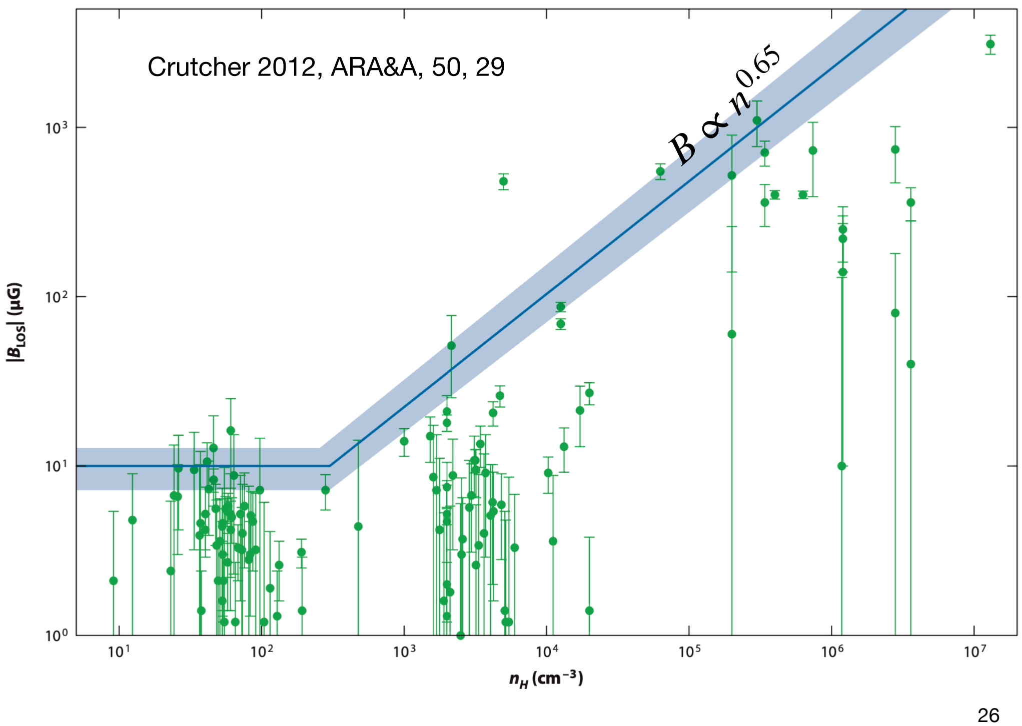
Ostriker+01, Heitsch+01, Padoan+01, Falceta-Goncalves+08, Pillai+15, Pattle+17, Cho & Yoo 16, Lazarian+20

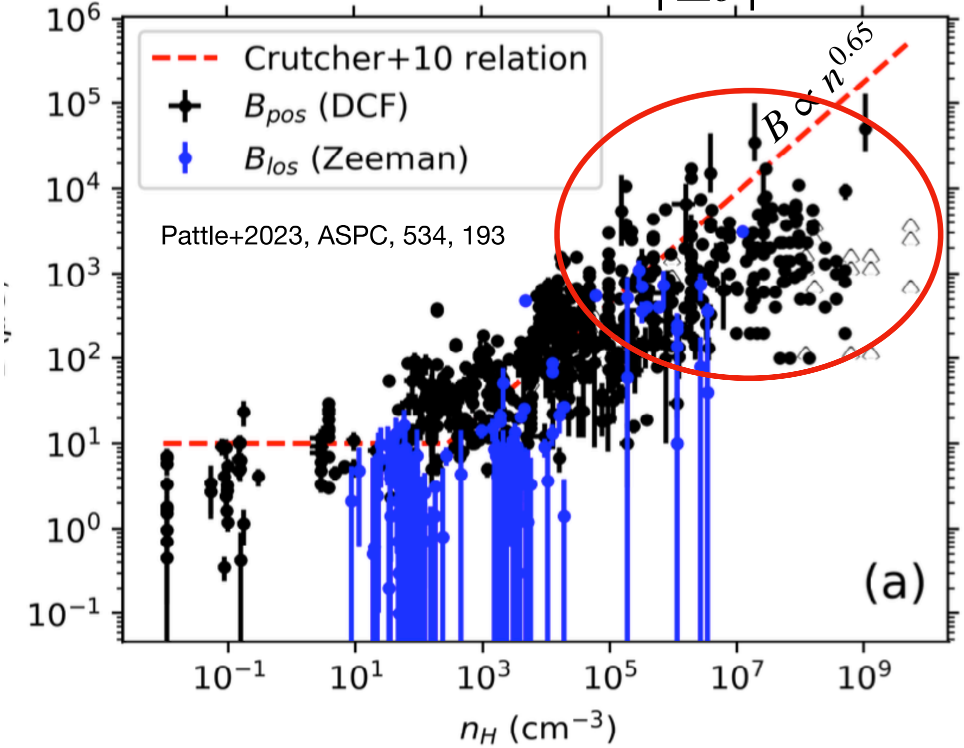
- DCF slope < Crutcher slope (0.65) for high density

Liu+21, 22

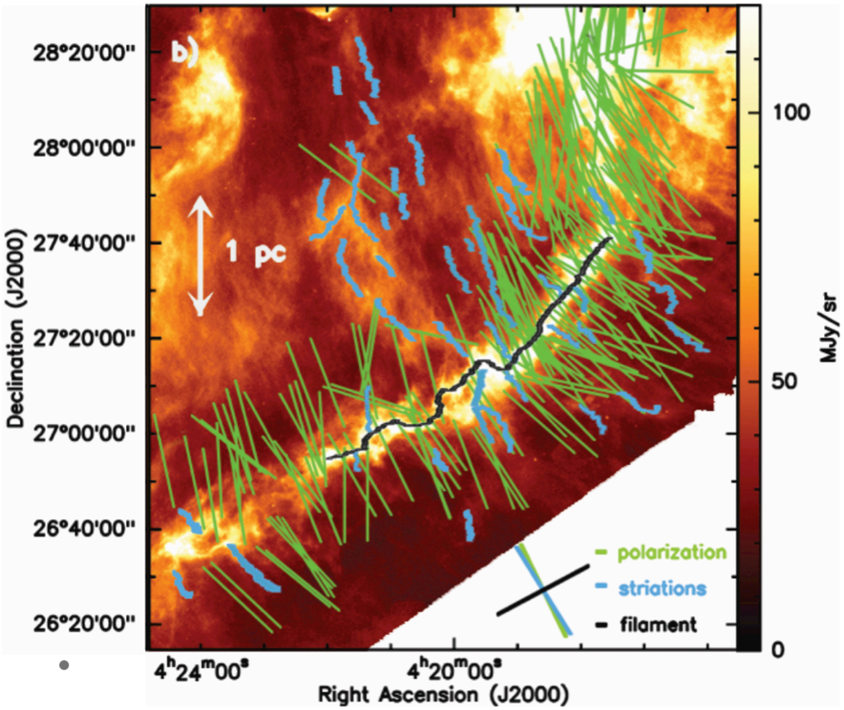


$$|B| \propto \frac{\sigma}{|\Delta\theta|}$$



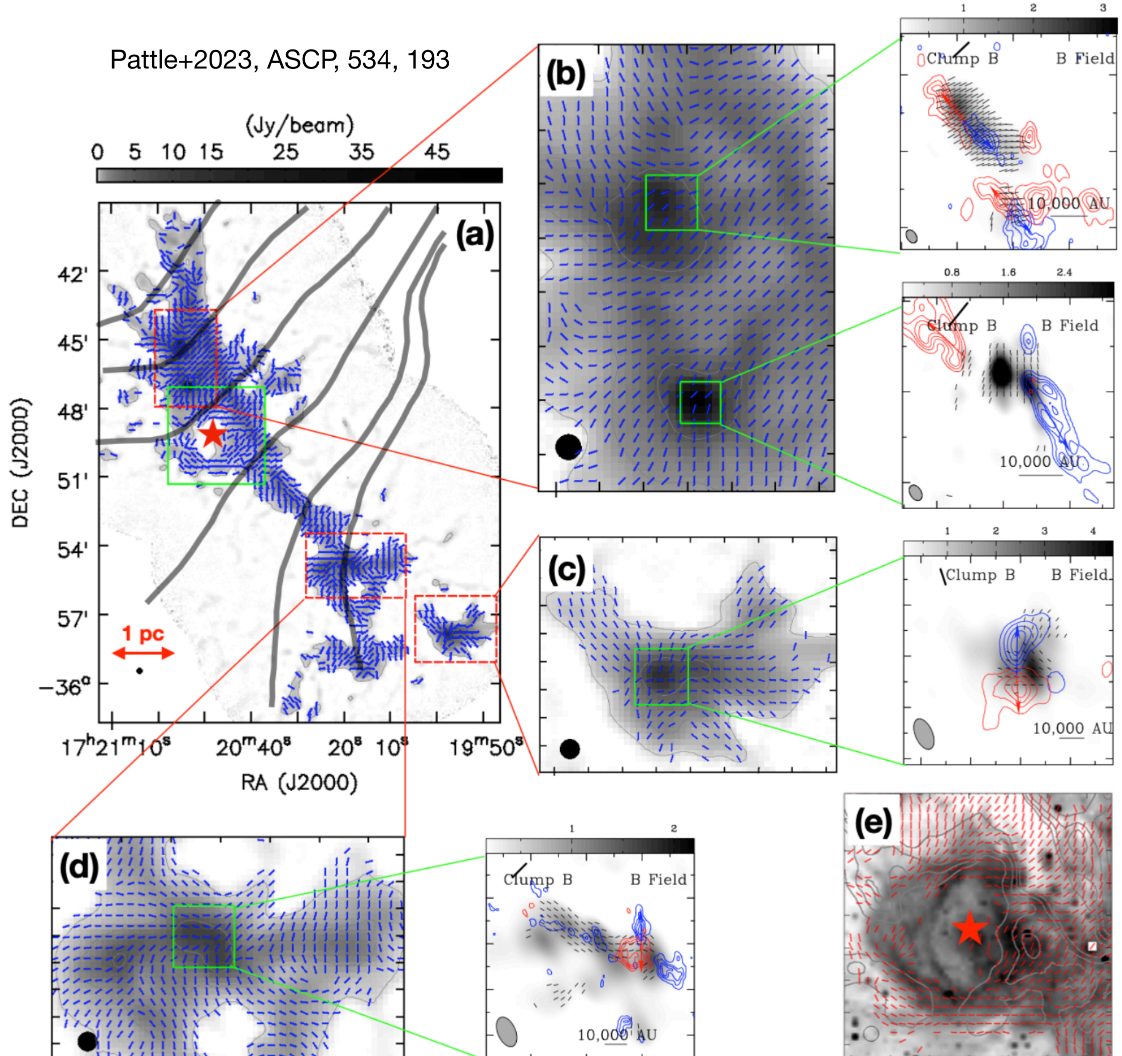


Role of Magnetic Fields (II): Geometry

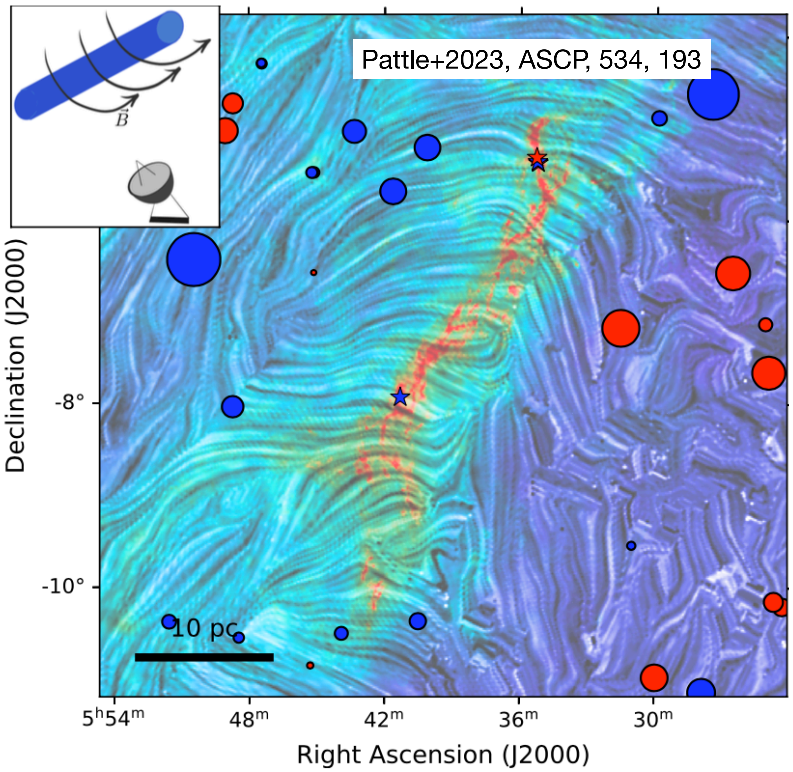


Palmeirim+2013, A&A, 550, 38

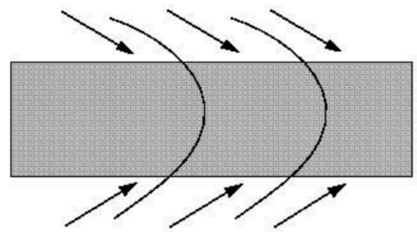
Pattle+2023, ASCP, 534, 193



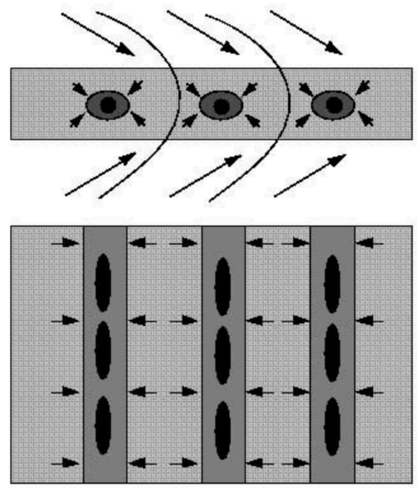
Role of Magnetic Fields (II): Geometry

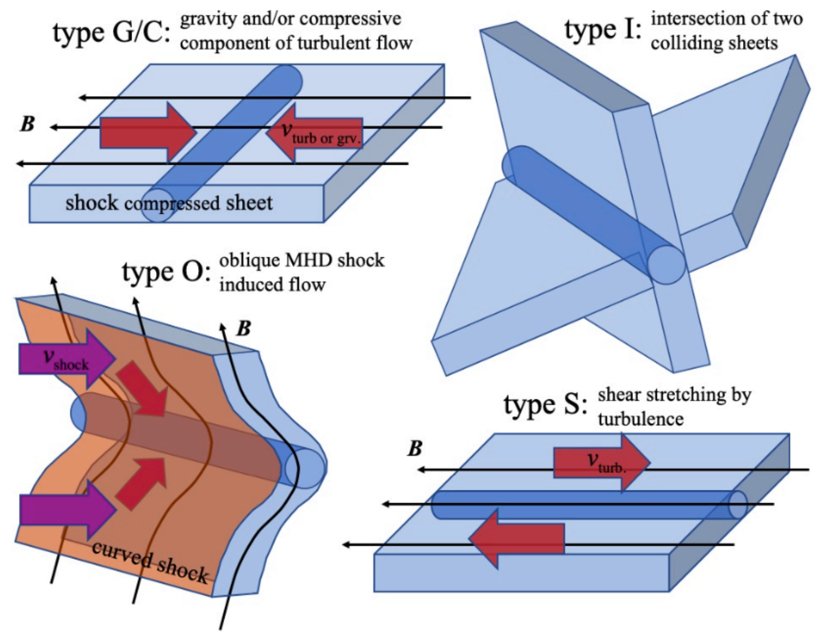


Pattle+2023, ASCP, 534, 193



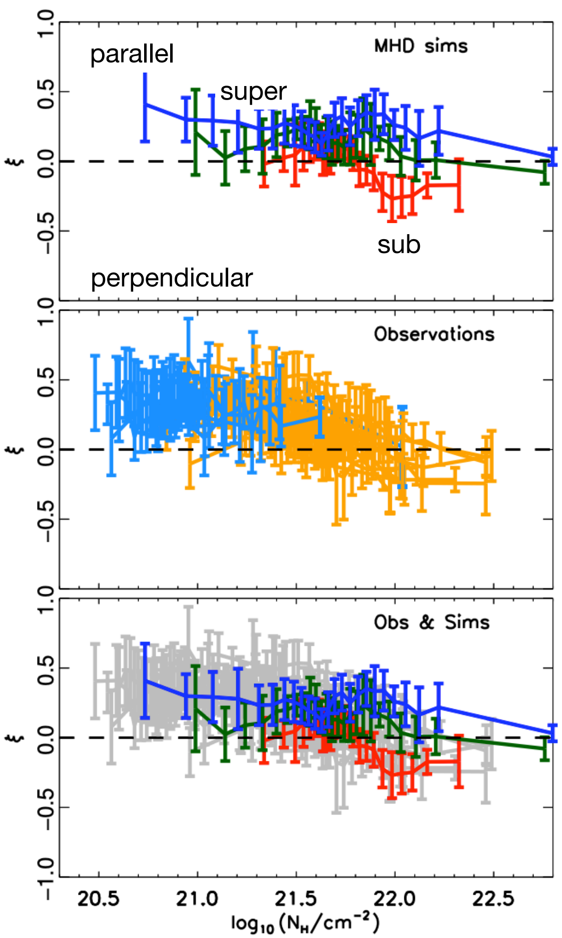
Hartmann 2002, ApJ, 578, 914



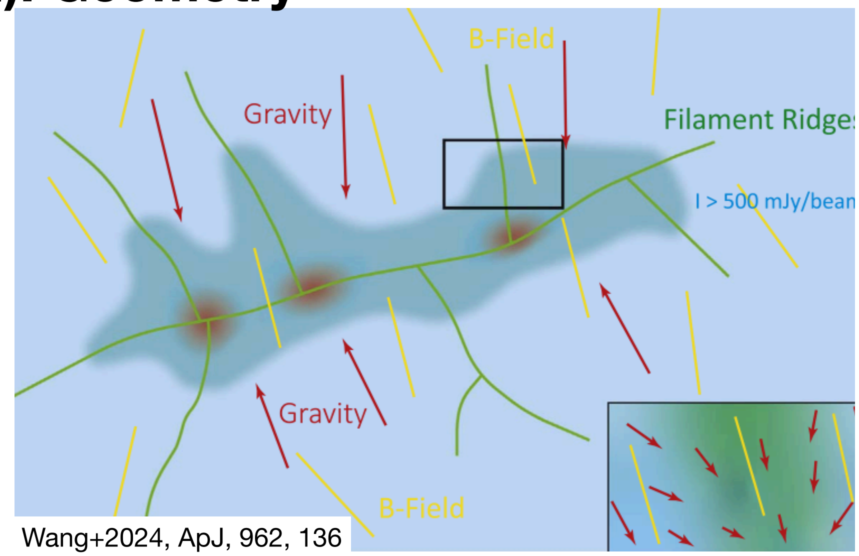


Pineda+2023, ASPC, 534, 233

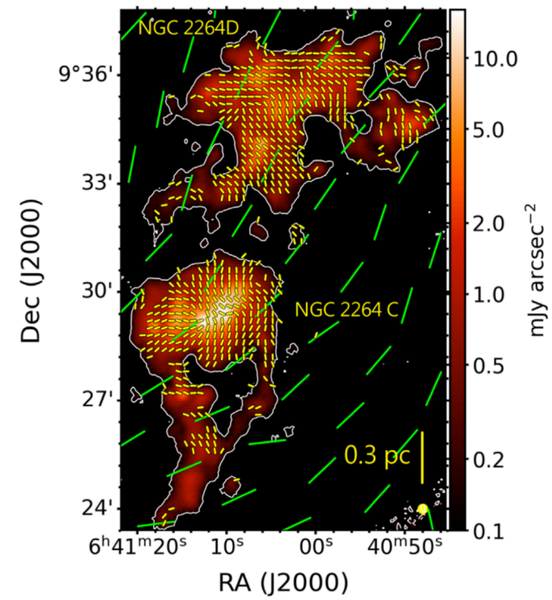
Role of Magnetic Fields (II): Geometry

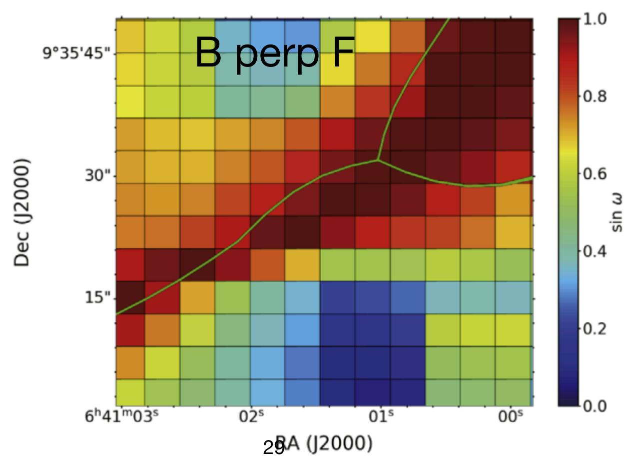


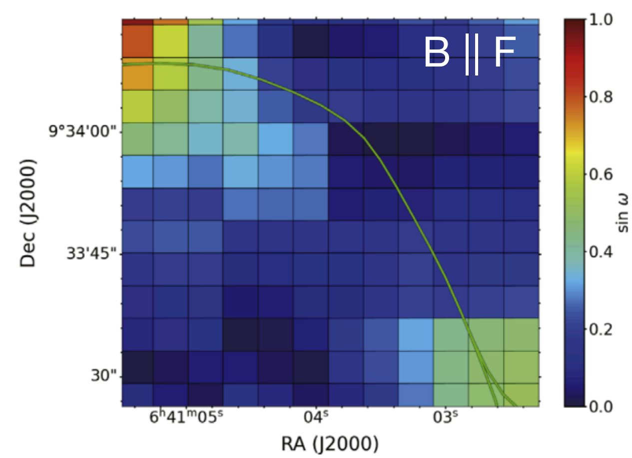
Planck XXXV 2016, A&A, 586, 138



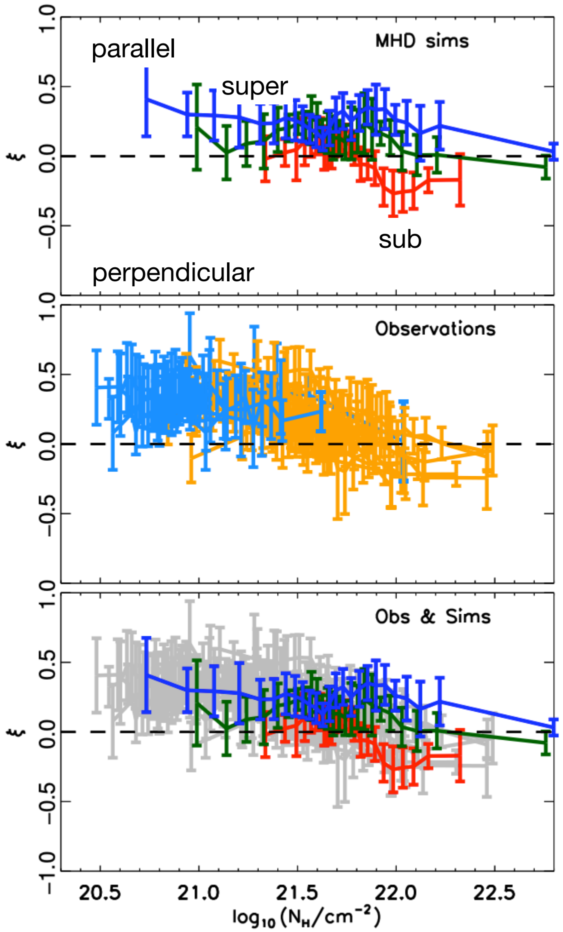
Wang+2024, ApJ, 962, 136



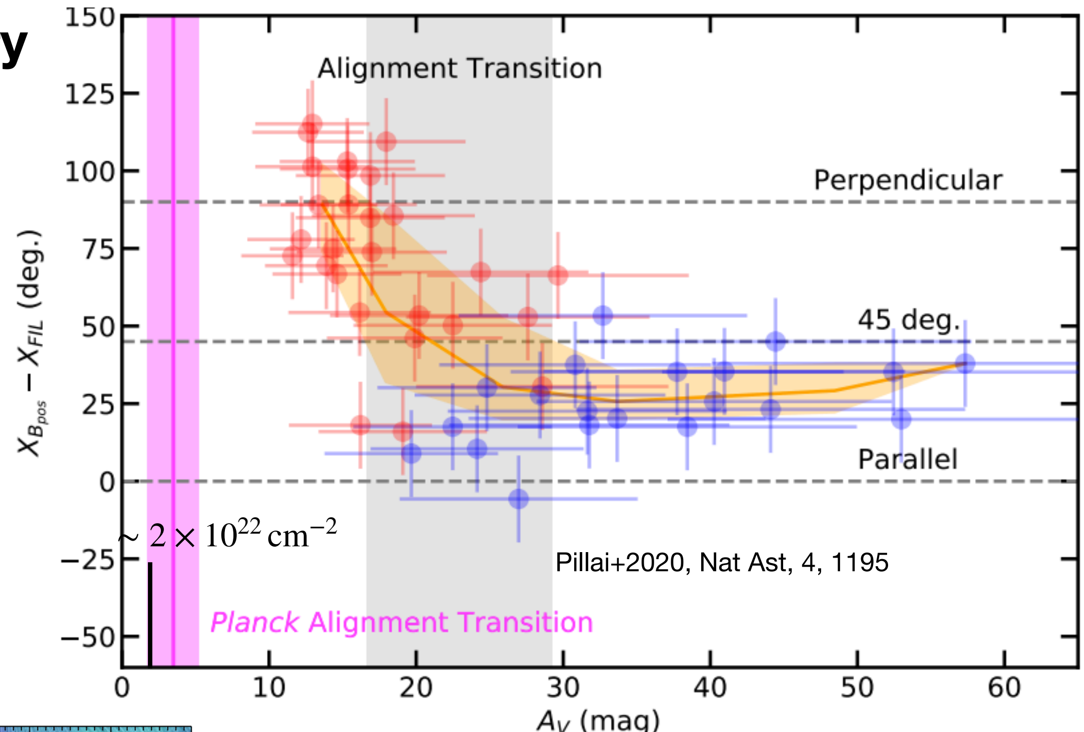




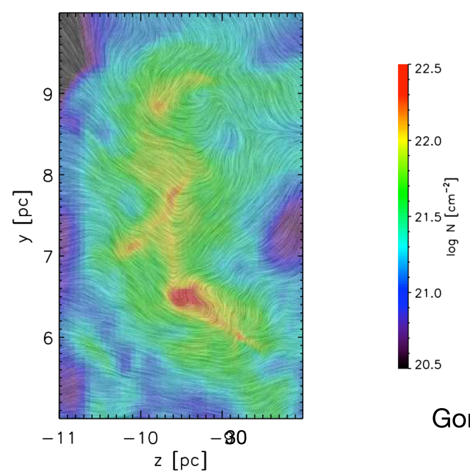
Role of Magnetic Fields (II): Geometry

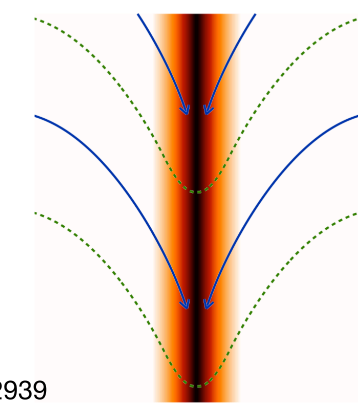


Planck XXXV 2016, A&A, 586, 138



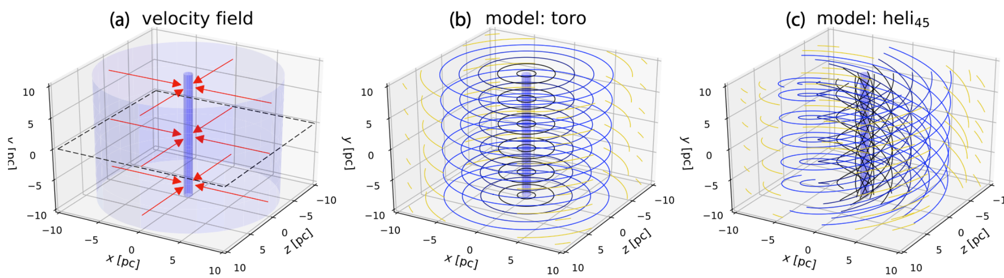
Pillai+2020, Nat Ast, 4, 1195



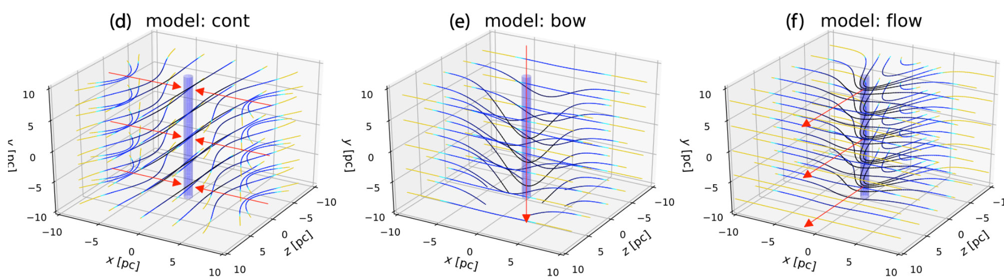


Gomez+2018, MNRAS, 480, 2939

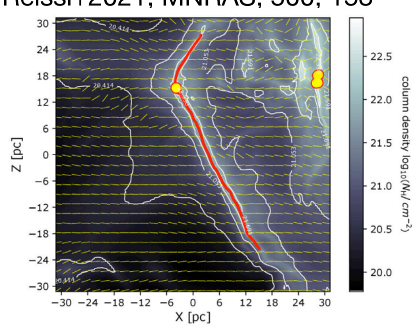
Role of Magnetic Fields (III): 3D Reconstruction

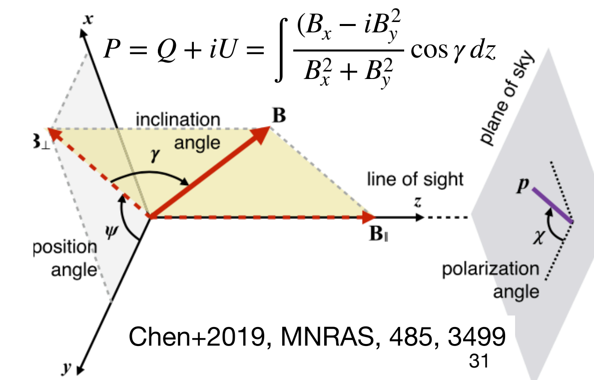


Reissl+2018, MNRAS, 481, 2507



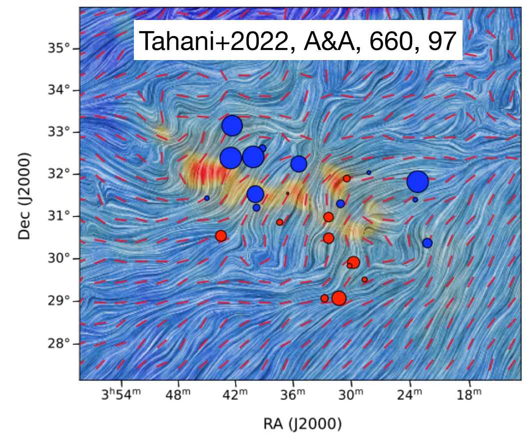
Reissl+2021, MNRAS, 500, 153

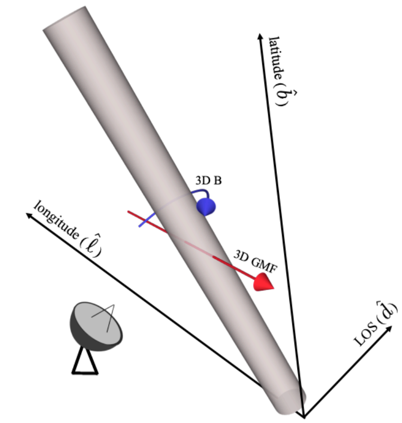


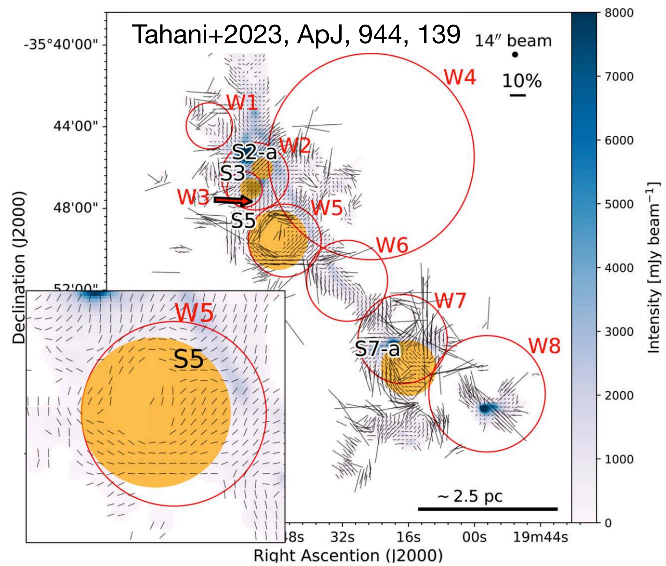


$$P = Q + iU = \int \frac{(B_x - iB_y^2}{B_x^2 + B_y^2} \cos\gamma \, dz$$

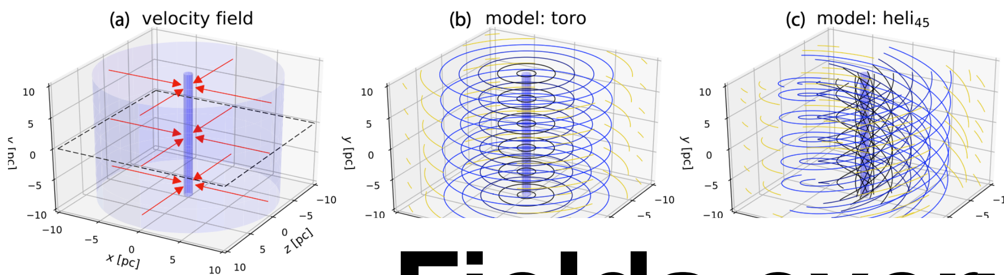
Chen+2019, MNRAS, 485, 3499

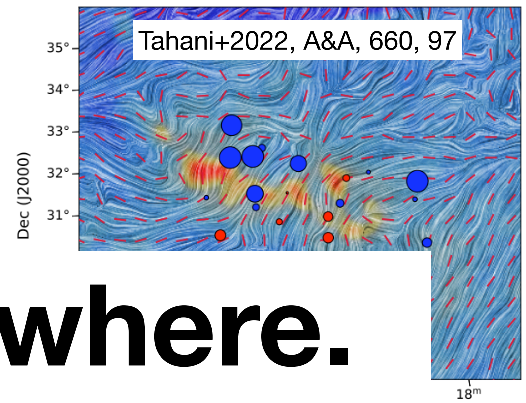


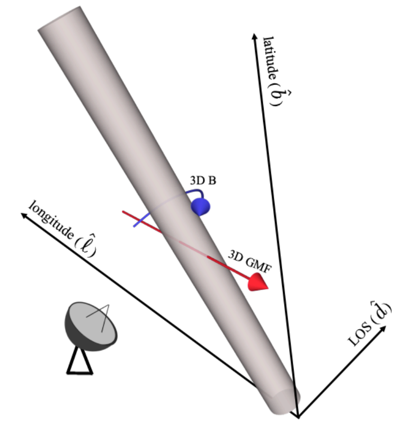




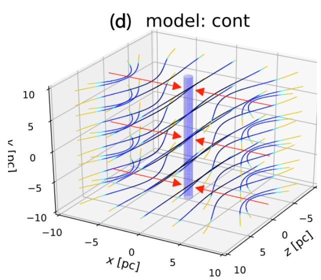
Role of Magnetic Fields (III): 3D Reconstruction







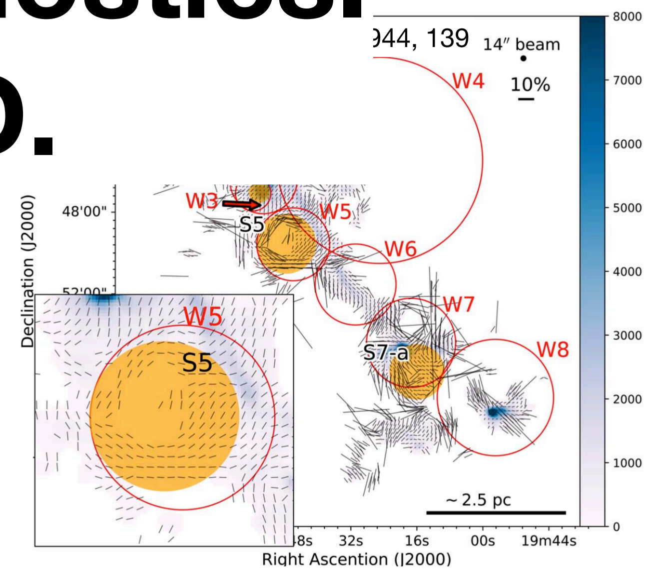
Reiss



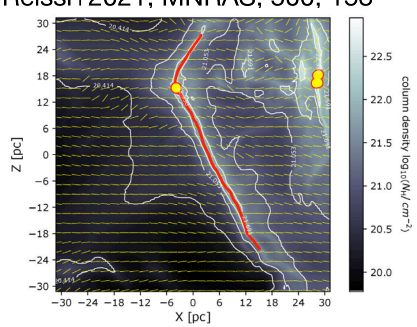
Fields everywhere.

Detailed Diagnostics.

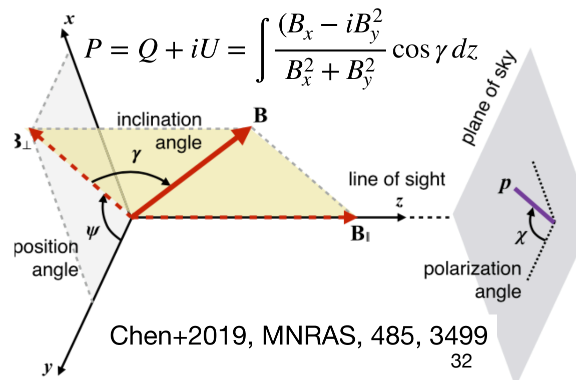
Going 3D.



Reissl+2021, MNRAS, 500, 153



$$P = Q + iU = \int \frac{(B_x - iB_y)^2}{B_x^2 + B_y^2} \cos\gamma \, dz$$



Chen+2019, MNRAS, 485, 3499

Feedback (I)

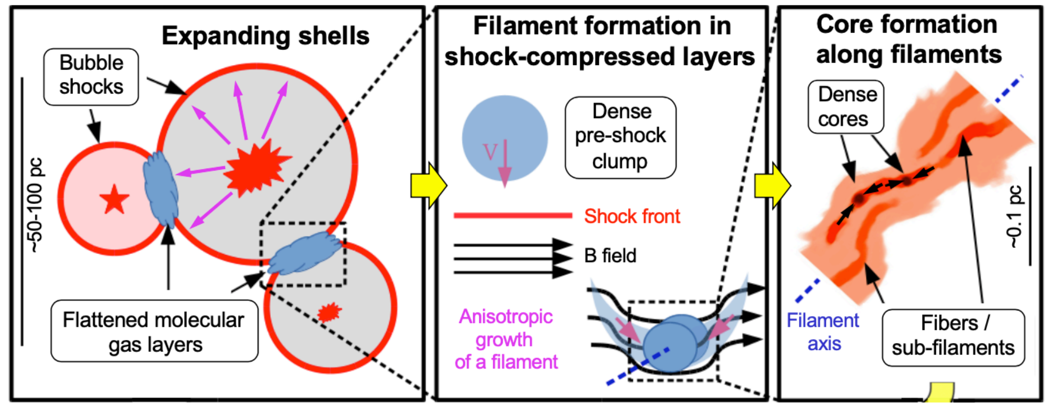
SEQUENTIAL FORMATION OF SUBGROUPS IN OB ASSOCIATIONS

BRUCE G. ELMEGREEN AND CHARLES J. LADA
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory
Received 1976 May 26; revised 1976 October 26

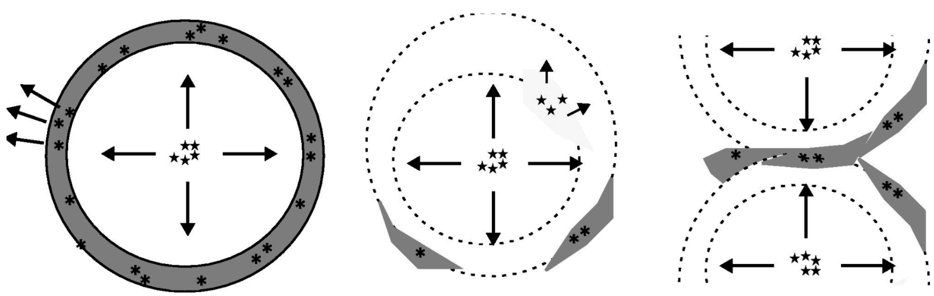
ABSTRACT

We reconsider the structure and formation of OB associations in view of recent radio and infrared observations of the adjacent molecular clouds. As a result of this reexamination, we propose that OB subgroups are formed in a step-by-step process which involves the propagation of ionization (I) and shock (S) fronts through a molecular cloud complex. OB stars formed at the edge of a molecular cloud drive these I-S fronts into the cloud. A layer of dense neutral material accumulates between the I and S fronts and eventually becomes gravitationally unstable. This process is analyzed in detail. Several arguments concerning the temperature and mass of this layer suggest that a new OB subgroup will form. After approximately one-half million years, these stars will emerge from and disrupt the star-forming layer. A new shock will be driven into the remaining molecular cloud and will initiate another cycle of star formation.

Several observed properties of OB associations are shown to follow from such a sequential star-forming mechanism. These include the spatial separation and systematic differences in age of OB subgroups in a given association, the regularity of subgroup masses, the alignment of subgroups along the galactic plane, and their physical expansion. Detailed observations of ionization fronts, masers, IR sources, and molecular clouds are also in agreement with this model. Finally, this mechanism provides a means of dissipating a molecular cloud and exposing less massive stars (e.g., T Tauri stars) which may have formed ahead of the shock as part of the original cloud collapsed and fragmented.

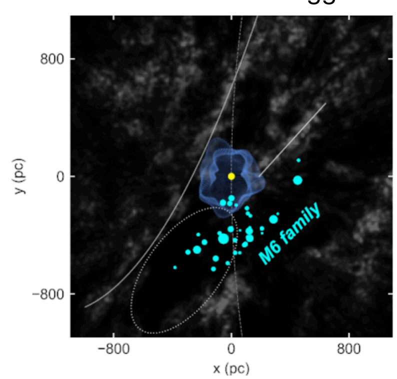


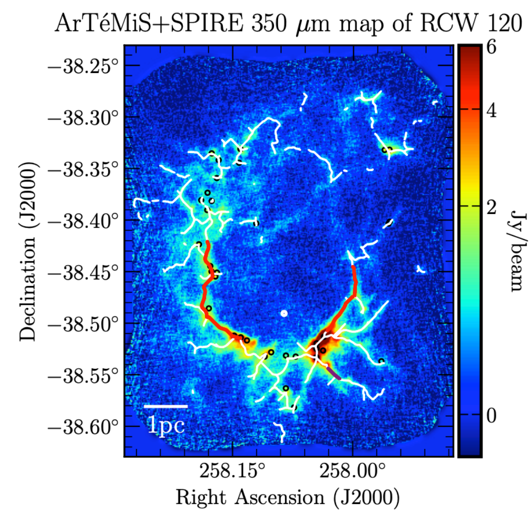
Pineda+2023, ASPC, 534, 233



Hartmann+2001, ApJ, 562, 852

P01 Ahmad Ali
P11 Wonju Kim
P13 Rolf Kuiper
P26 Cameren Swiggum



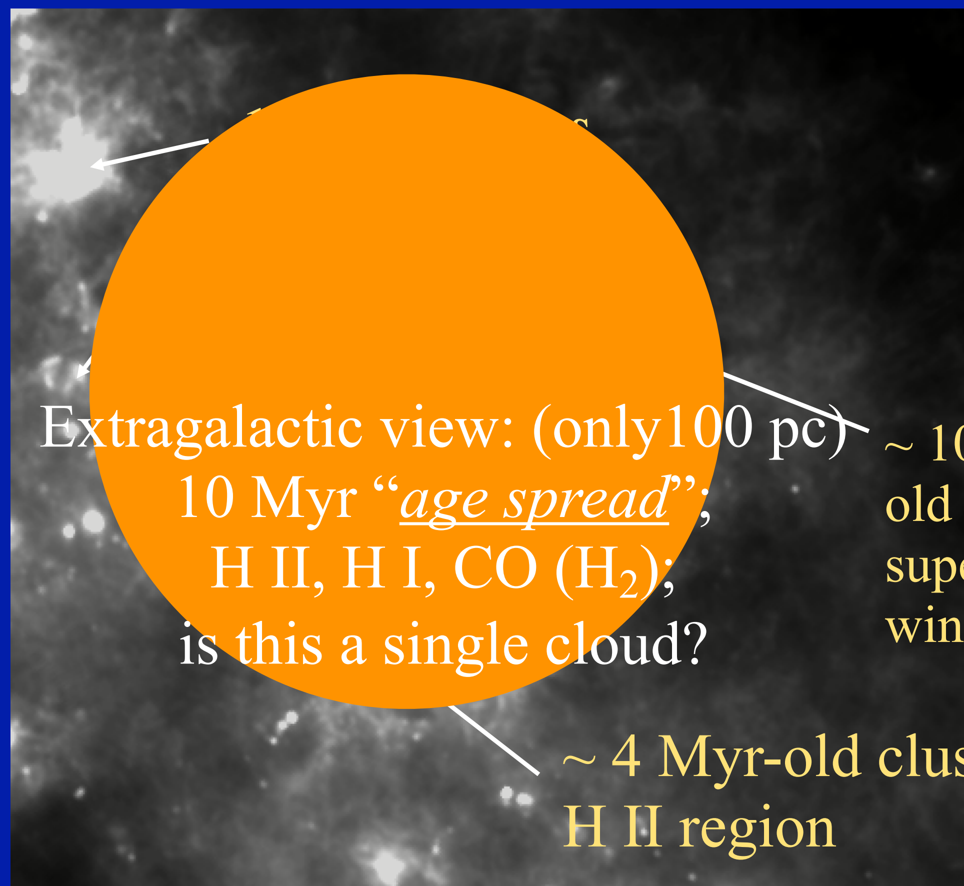


Zavagno+2020, A&A, 638, 7

Cep OB2: supernova, H II region-driven bubbles

courtesy of Lee Hartmann

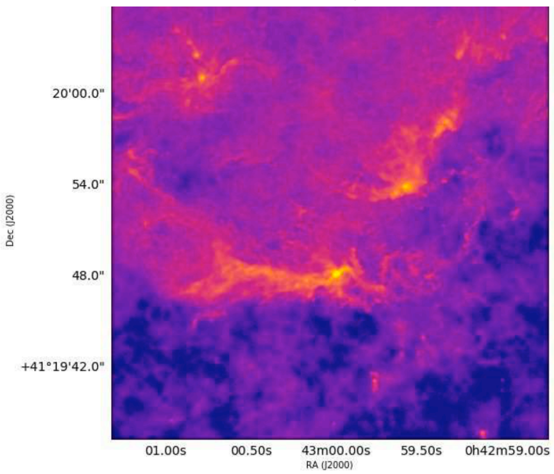
50 pc

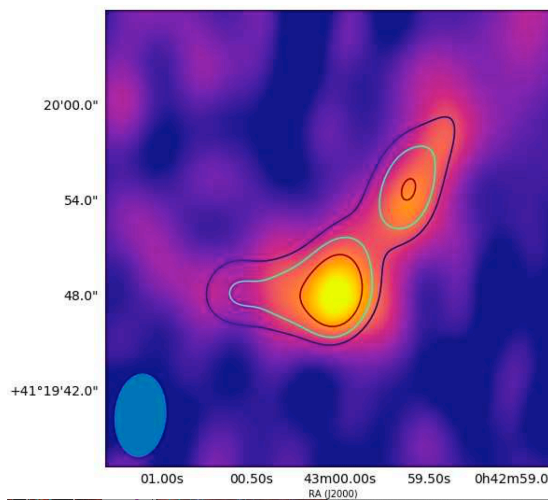


100 μm IRAS dust emission

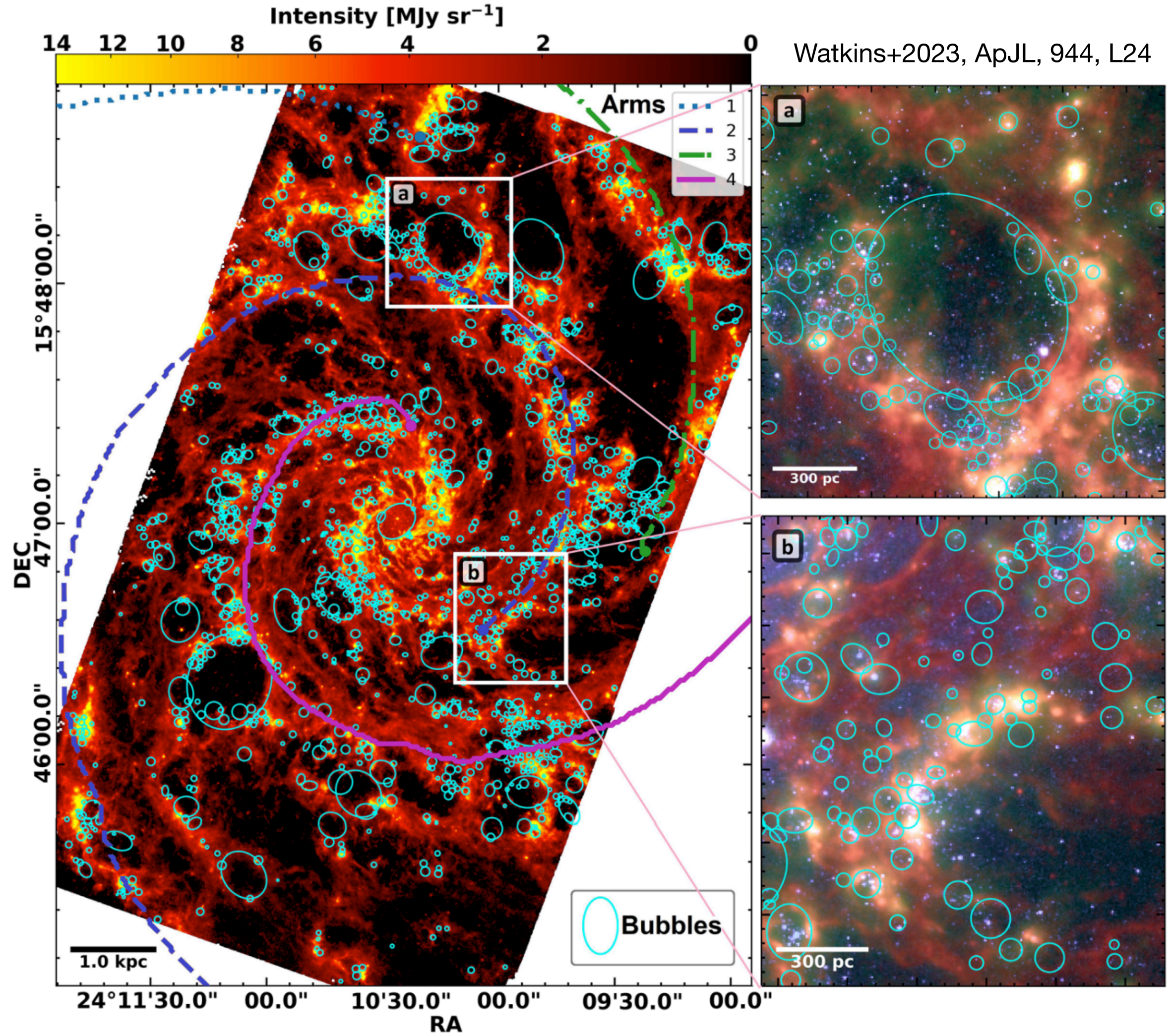
Feedback (III)

courtesy of J. Forbrich's talk



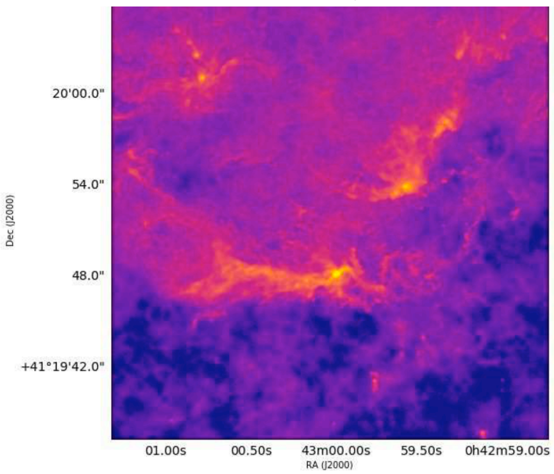


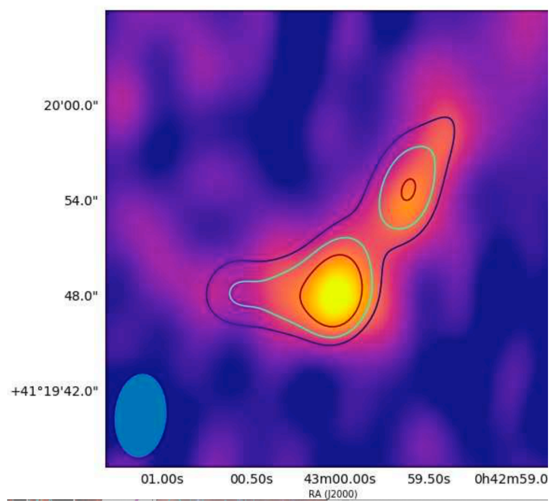
Watkins+2023, ApJL, 944, L24



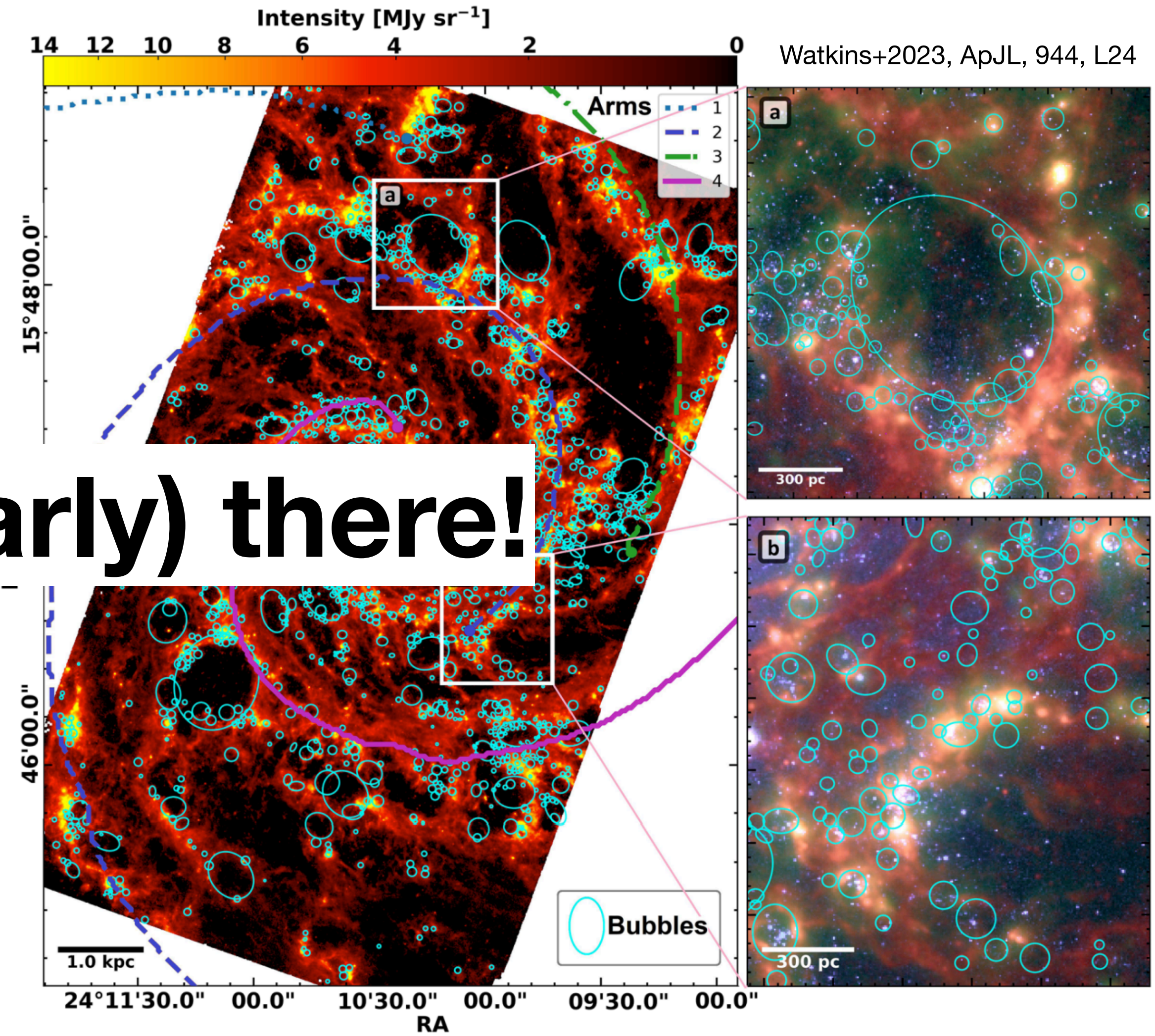
Feedback (III)

courtesy of J. Forbrich's talk





Watkins+2023, ApJL, 944, L24



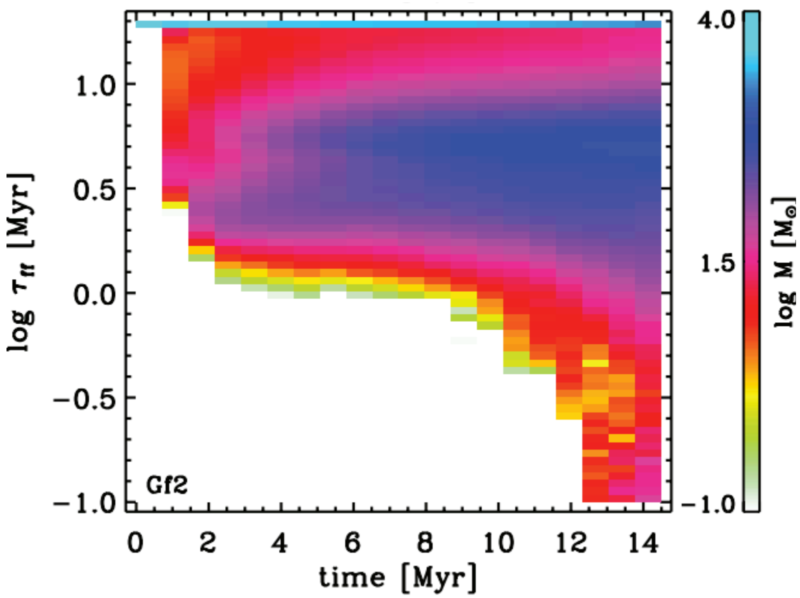
(Nearly) there!

Which Freefall Time?

$$\epsilon_{ff} \equiv \frac{\dot{M}_* t_{\rm ff}}{M_{\rm gas}}$$ star formation rate per free fall time

$$\epsilon_{sf} \equiv \frac{M_*}{M_{\rm gas}}$$ efficiency

$$\epsilon_* \equiv \frac{M_*}{M_{\rm gas,0} + \int \dot{M}_{\rm acc} dt}$$ net SF efficiency

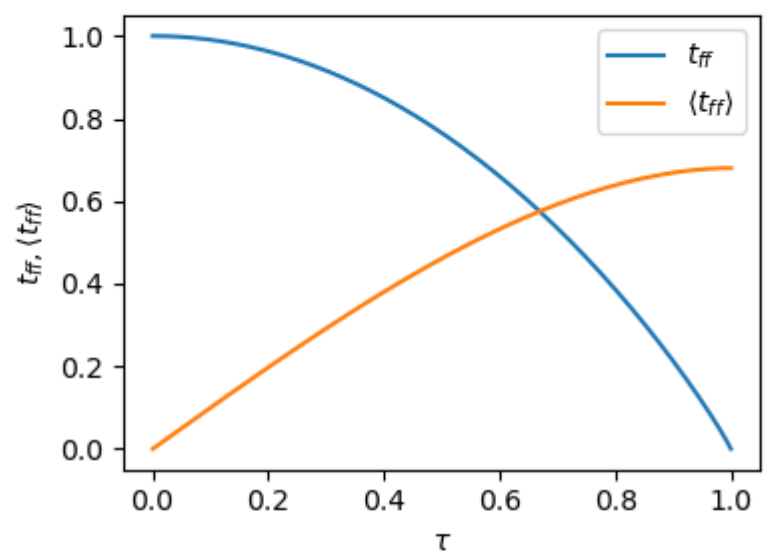


Heitsch & Hartmann 2014, ApJ, 689, 290

$$\frac{t_{\rm ff}(\tau)}{t_{\rm ff,0}} = \left(1 - \tau^2\right)^{a/2} \xrightarrow[\tau\to1]{} 0$$

$$\left\langle \frac{t_{\rm ff}}{t_{\rm ff,0}} \right\rangle_\tau = \int_0^\tau \left(1 - \tau'^2\right)^{a/2} d\tau' \xrightarrow[\tau\to1]{} 0.68$$

Vazquez-Semadeni+2019, MNRAS, 490, 3061



Summary:

Cloud formation: Angular momentum role and evolution?

Filaments: Accretion and Geometry.

Magnetic Fields: Going 3D.

Extragalactic Star Formation: Pushing the boundary.