Formation, fragmentation and collapse of interstellar filaments

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Image credit: ESA/PACS & SPIRE Consortium, S. Molinari, Hi-GAL Project

The phases of the interstellar medium

+ cosmic rays
+ magnetic fields
+ interstellar dust

from McKee & Ostriker 1977

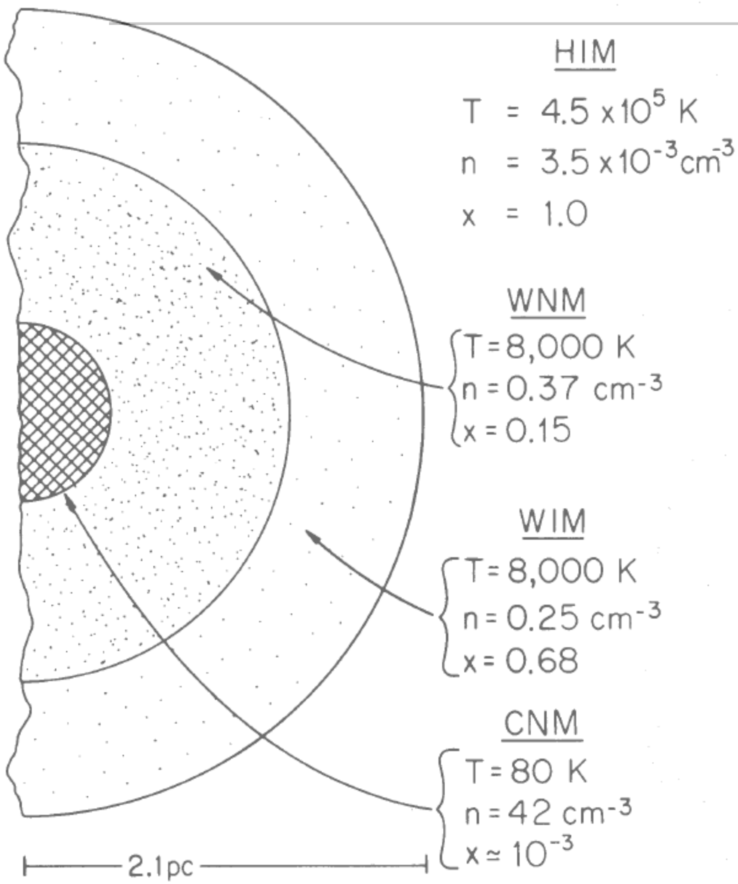


FIG. 1

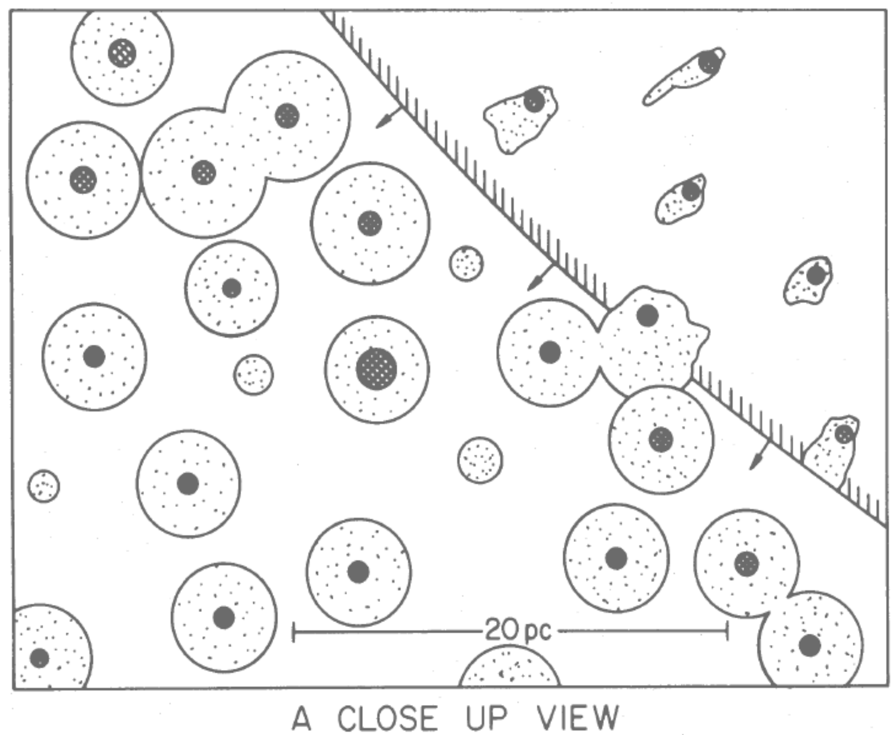
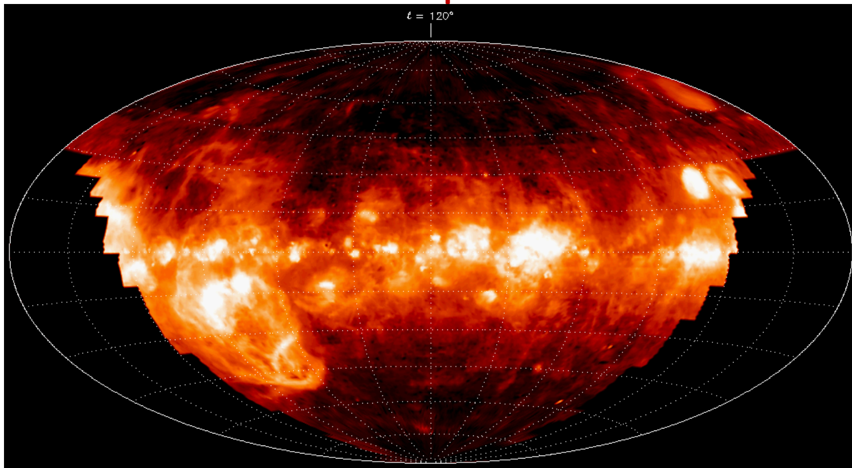
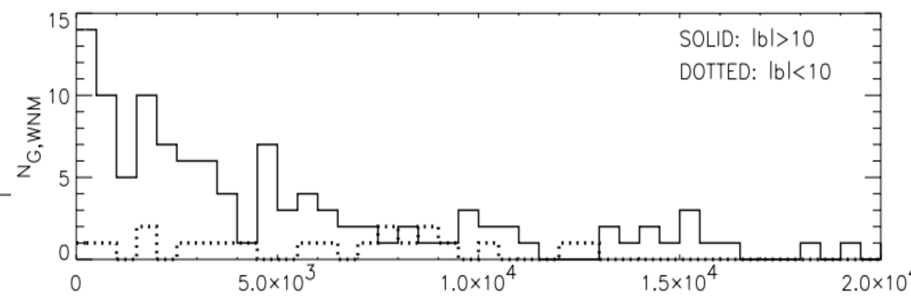


FIG. 2

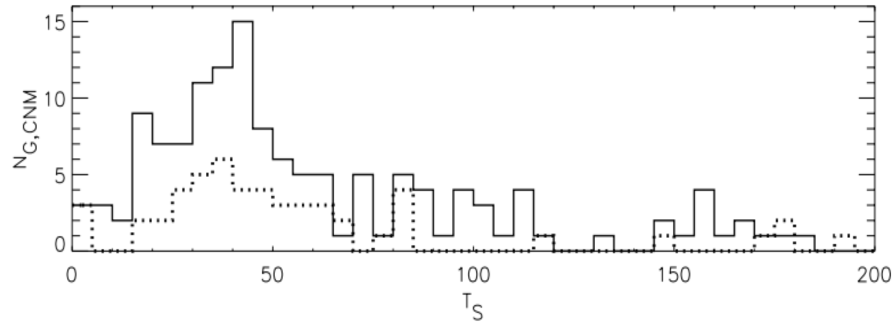
The phases of the interstellar medium

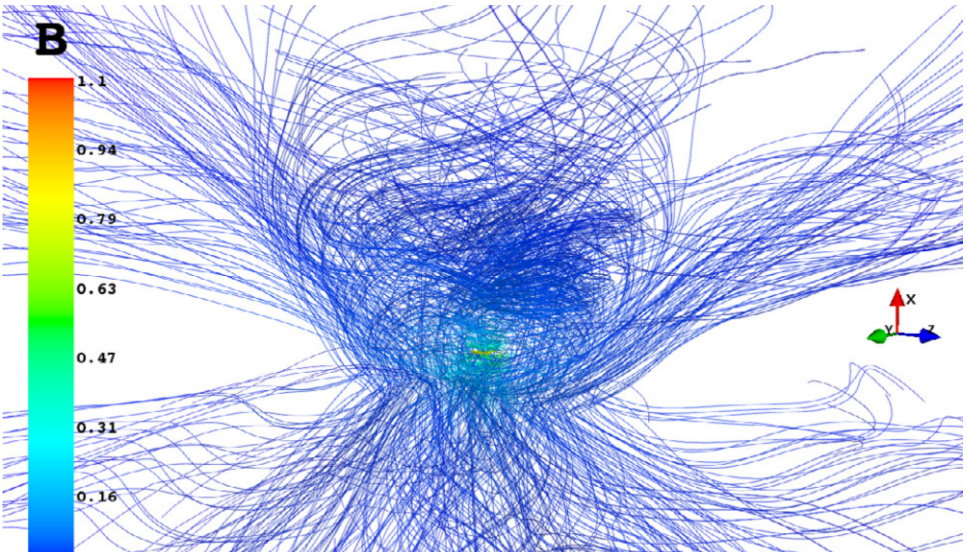


HII regions: regions where young stars have ionized their environment, are detected in Hα

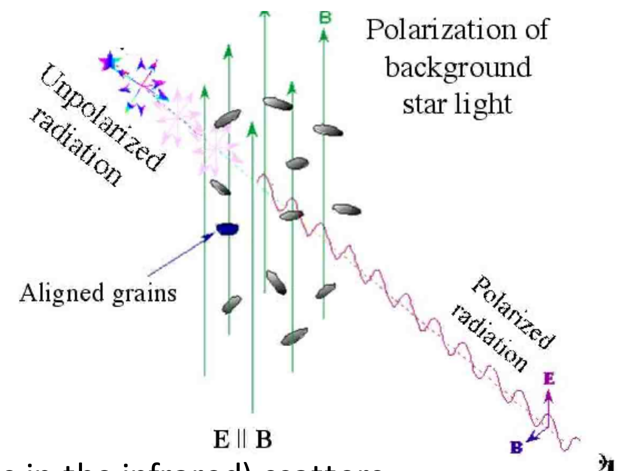


Heiles & Troland (2003) Arecibo HI survey





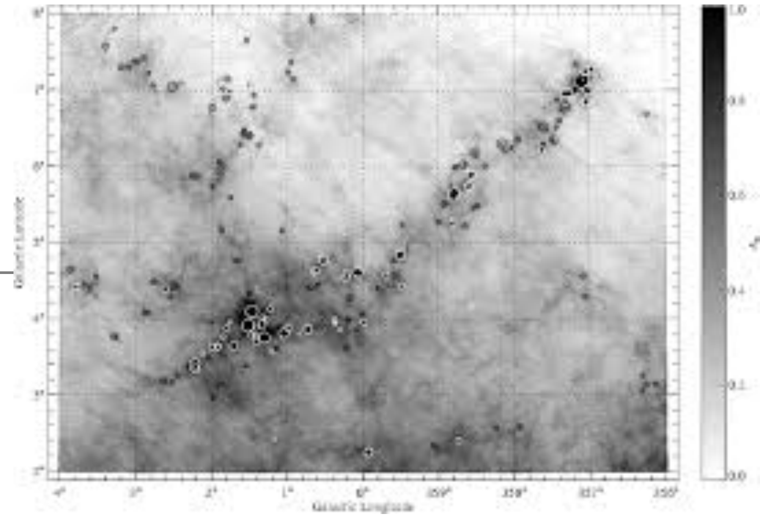
Cosmic ray propagation through a turbulent magnetic field (simulations by Padovani et al. 2013)

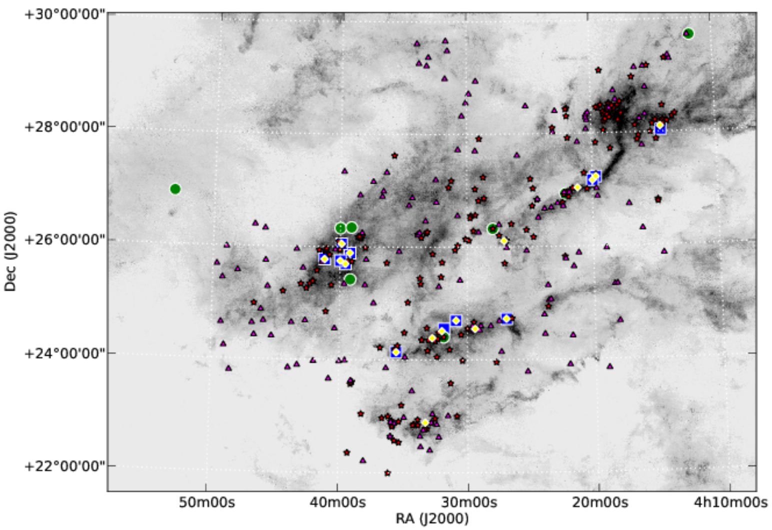


Dust (emits in the infrared) scatters and polarizes interstellar radiation

Molecular clouds

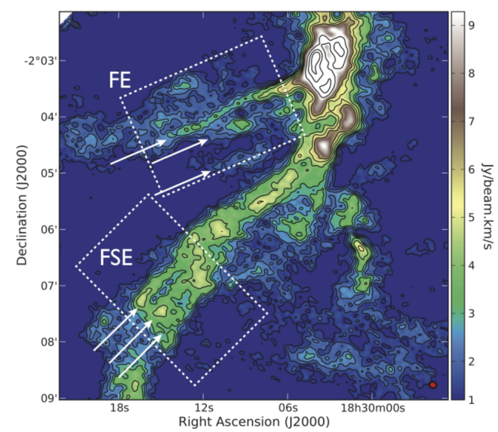
We know from observations that most, if not all stars, form out of dense cores made out of molecular hydrogen and other molecules. These cores are located in larger molecular clouds.

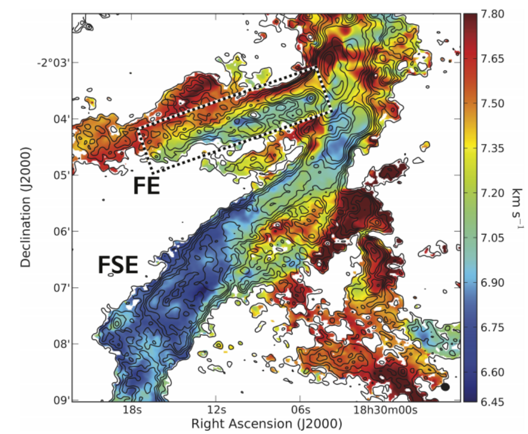




(Molecular clouds in dust extinction, from Lombardi et al. (2005). Overplotted are the locations of pre-stellar cores and young stellar objects)

Molecular clouds are very filamentary and have an almost self-similar structure. They also host supersonic motions, and are magnetized.





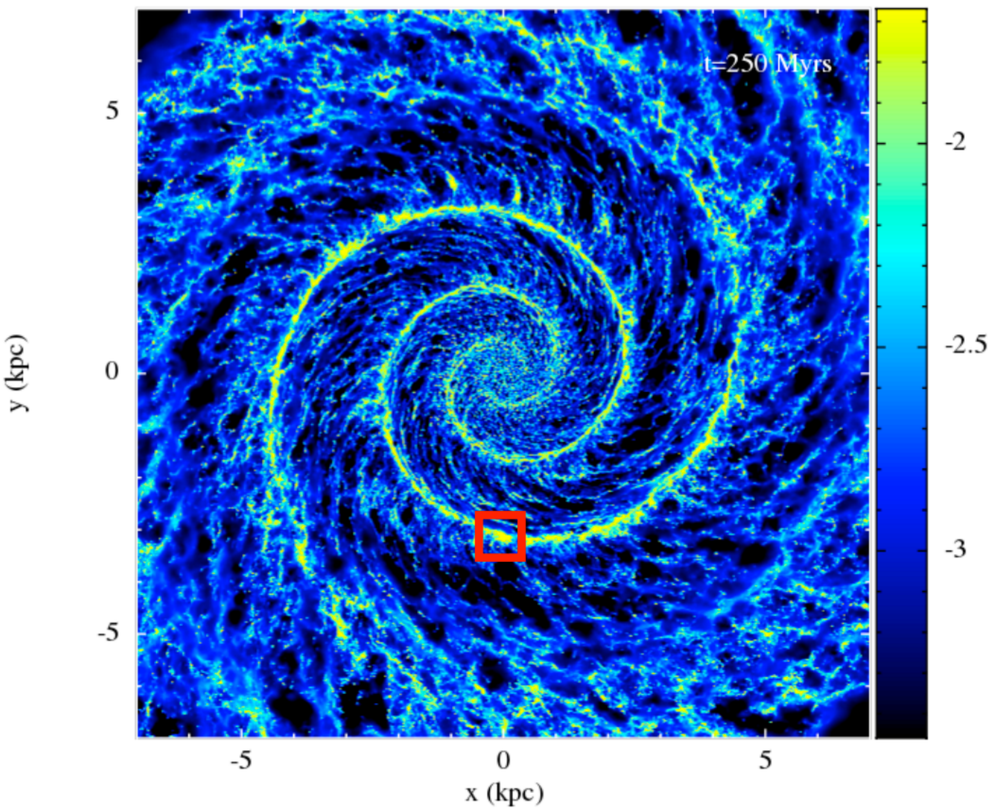
This very dynamical behavior is likely linked to the formation of the clouds themselves

Left: integrated line intensity, Right, centroid velocity (N2H+ ion) of the Serpens south star-forming cloud. CARMA survey (2015)

Part I

FORMATION OF MOLECULAR CLOUDS FROM SHOCK COLLISIONS (?)

(The main mode of) molecular cloud formation: Global gravitational instability of the galactic disk



Simulation of a gravitationally fragmenting disk with an epicycle perturbation of m=4 Dobbs & Pringle (2013)

The Toomre criterion for a disk to be stable can be expressed as

$$\frac{c_s \kappa}{\pi G \Sigma} > 1,$$

Where cs the speed of sound in the gas, κ the epicyclic frequency, G the gravitational constant and Σ the surface density of the gas.

When a disk is close to instability, (which means the above ratio >1) the disk fragments.
The Milky Way has a Toomre Q ratio almost equal to 1

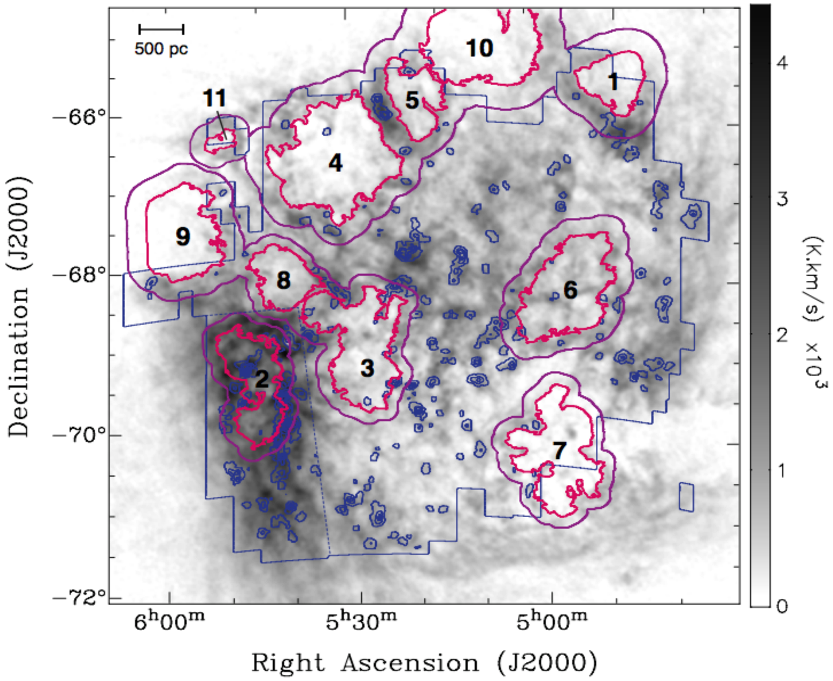
Superbubbles and Supershells

Superbubbles are large cavities of hot gas created by the combined wind and supernova feedback of several OB stars.

Supershells are shocks of hundreds of parsecs size, usually associated with superbubbles.

(Image from Gemini. Violet corresponds to Hα)

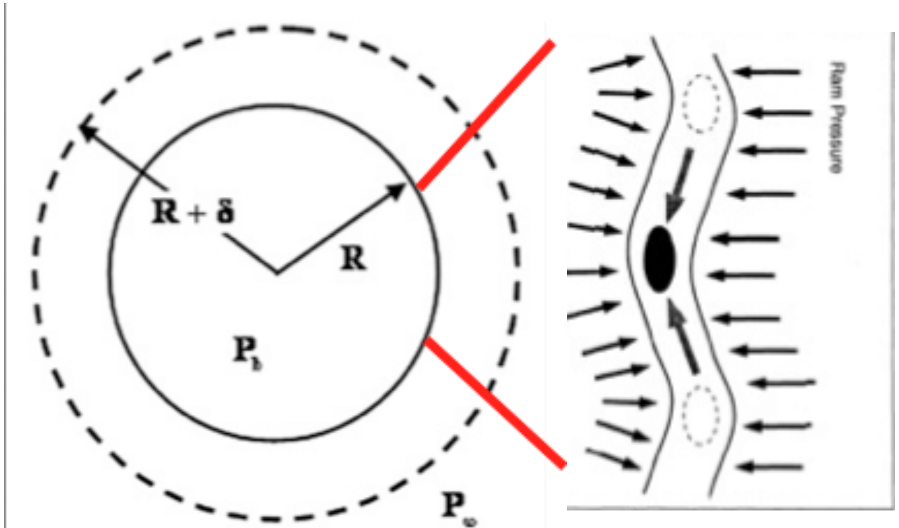
(Superbubbles in the LMC from Dawson et al. 2012)



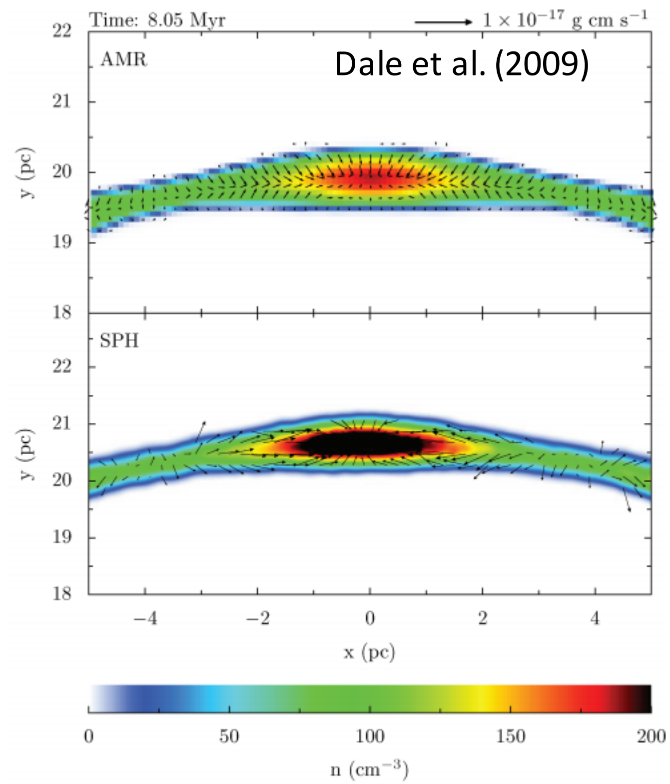
Enhanced molecular gas content and young stars are often found around them

Supershell fragmentation and molecular cloud formation

It is theorized that molecular gas forms around superbubbles due to the dynamical and/or gravitational instability of decelerating spherical shocks.



Dynamical Instability of the shell (Vishniac 1983) due to the different natures of the pressure on either side of the shock

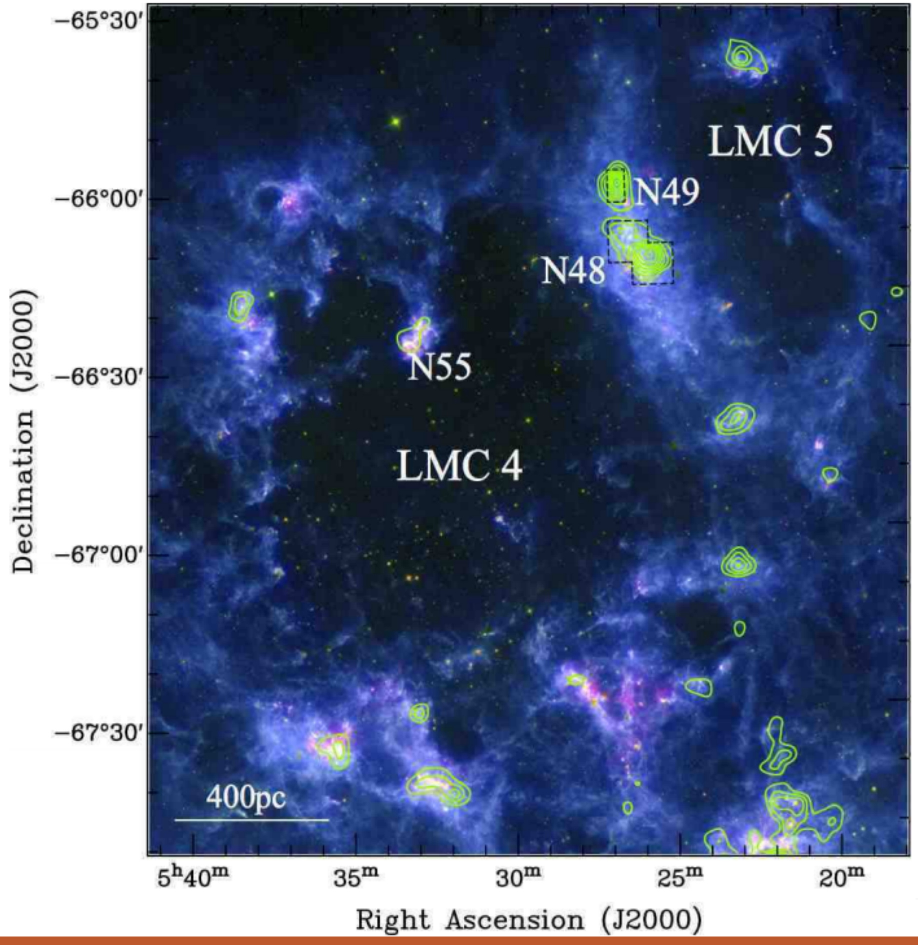


"collect and collapse" model for star formation

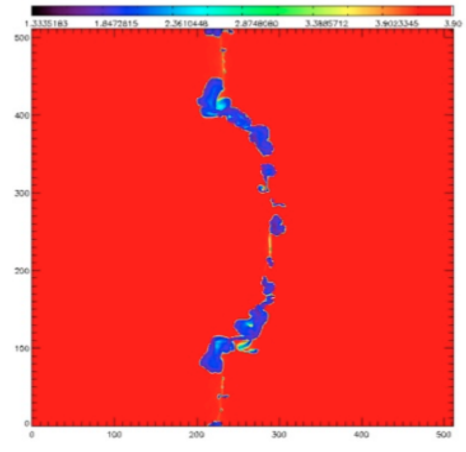
Magnetic fields have so far only been considered in terms of their effect on the shock thickness, but so far not of their effect on the shell stability.

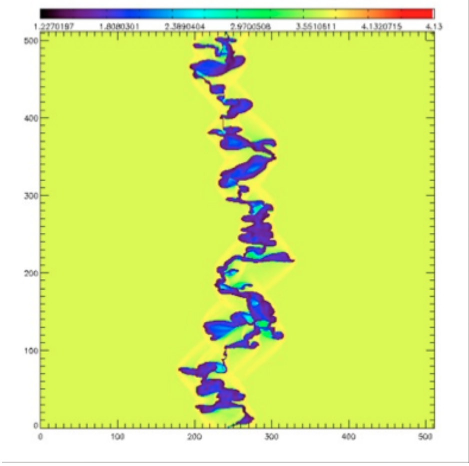
Supershell interactions

Fujii et al. (2014) colliding shells in the LMC



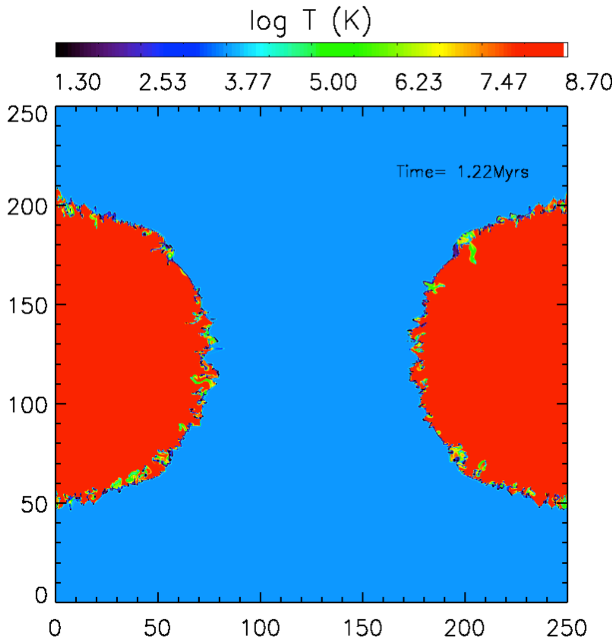
Whenever supershells are observed to interact, there is either an enhanced molecular gas content or young stars at the collision interface.
Does this mean that supershell collisions are even more efficient in forming molecular gas than the simple "collect and collapse" process?

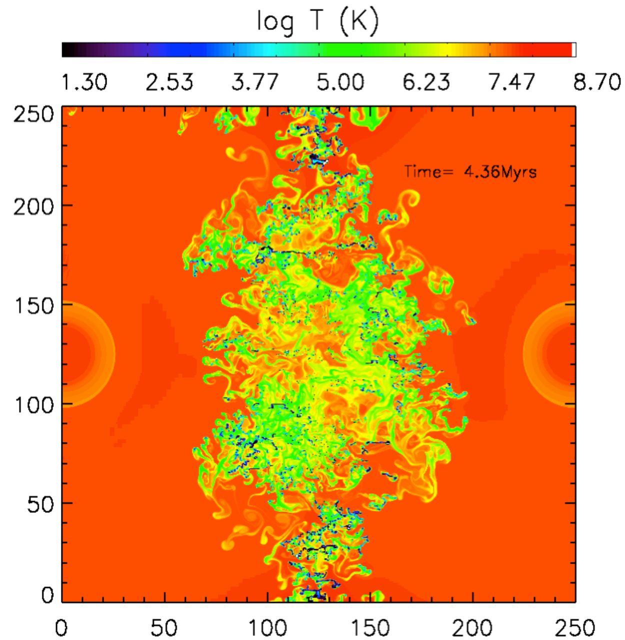


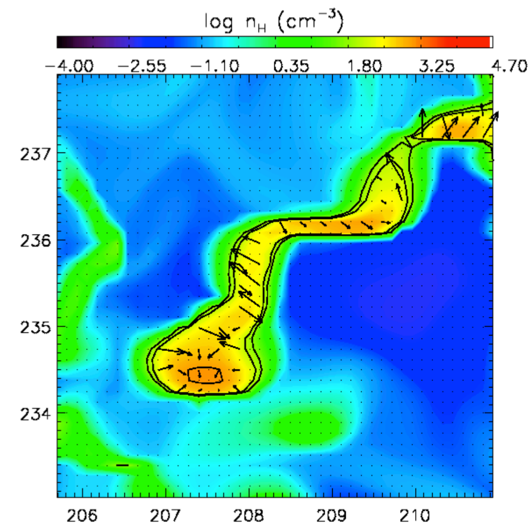


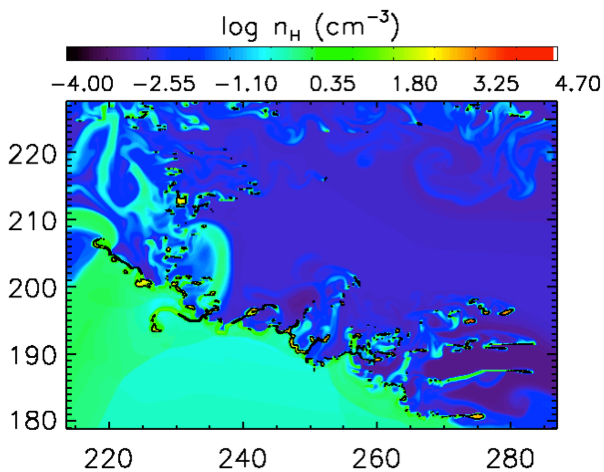
2D models of supershell collisions (EN+11)

2D simulations of OB associations comprising 50 stars each



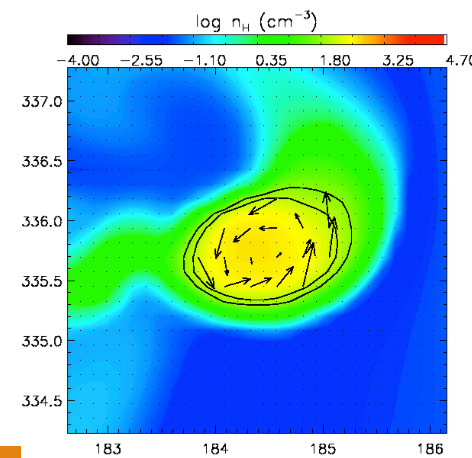






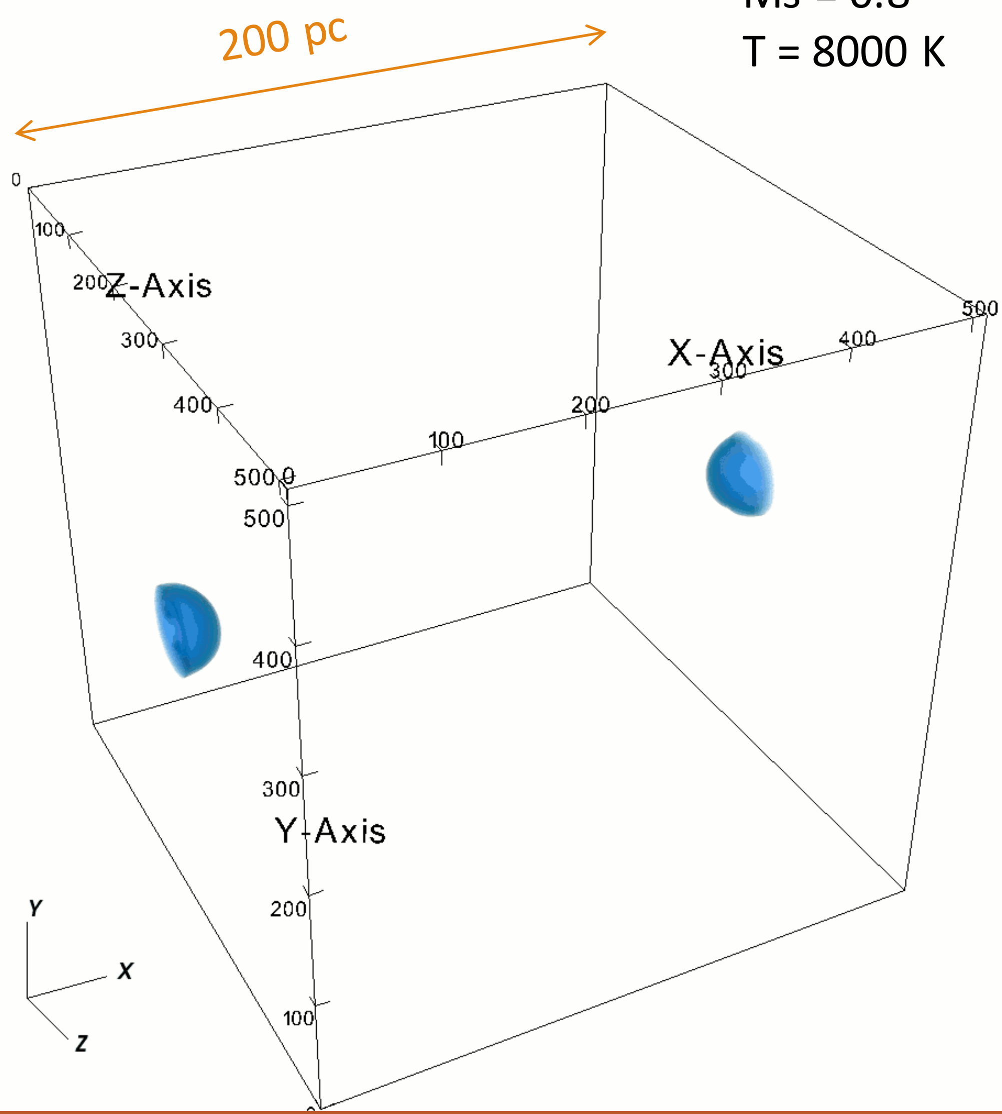
Feedback regions positioned 500 pc apart in a warm, turbulent interstellar medium

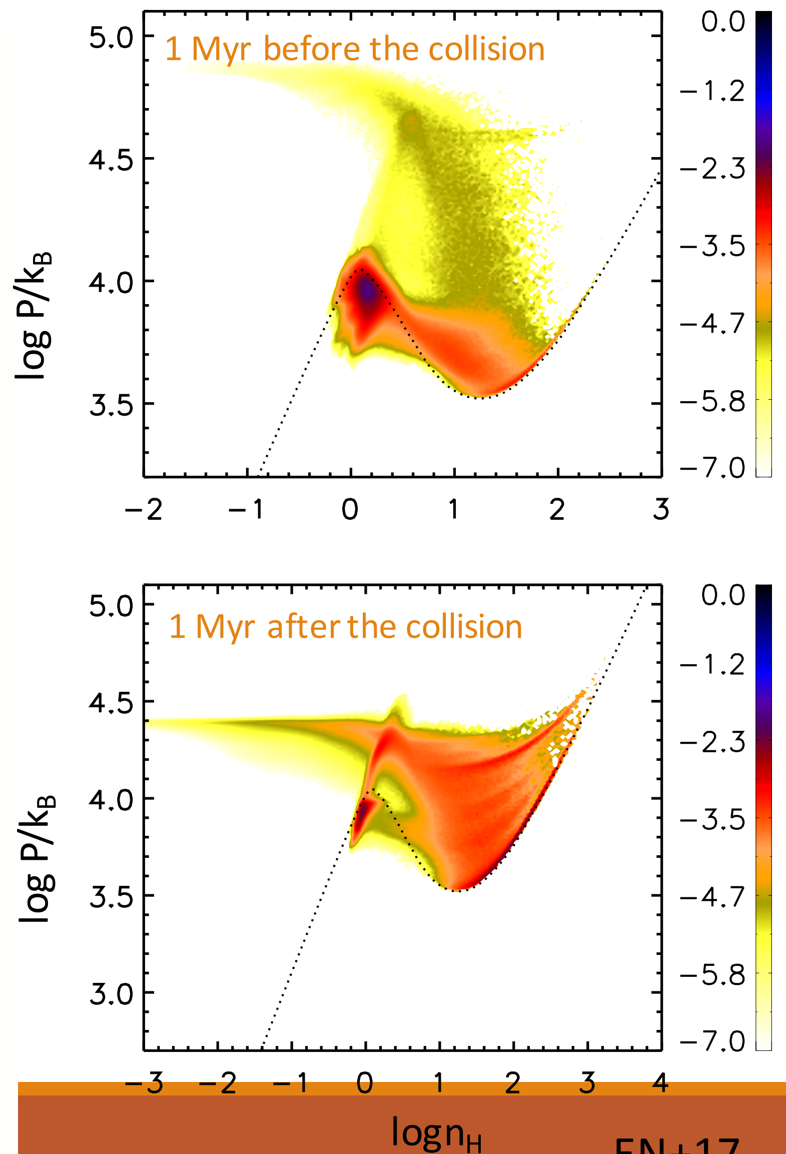
Internal structure of the clouds is resolved: rotating, turbulent or quiescent clouds



Numerical simulation of two colliding supershells: hydrodynamical case

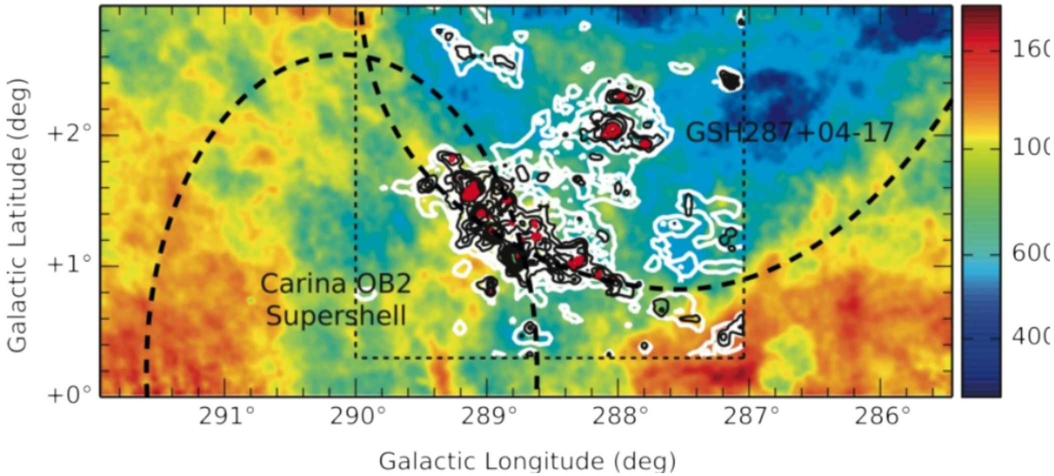
n_0 = 1 cm^{-3}
Ms = 0.8
T = 8000 K

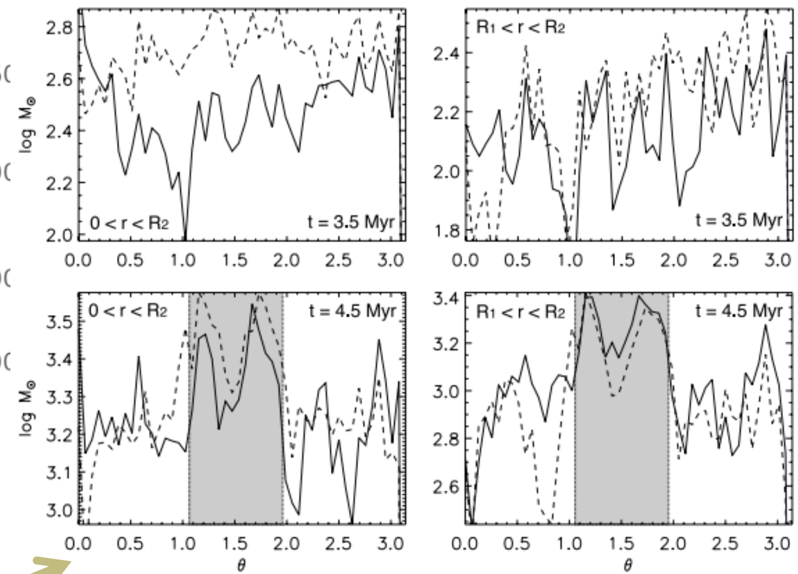




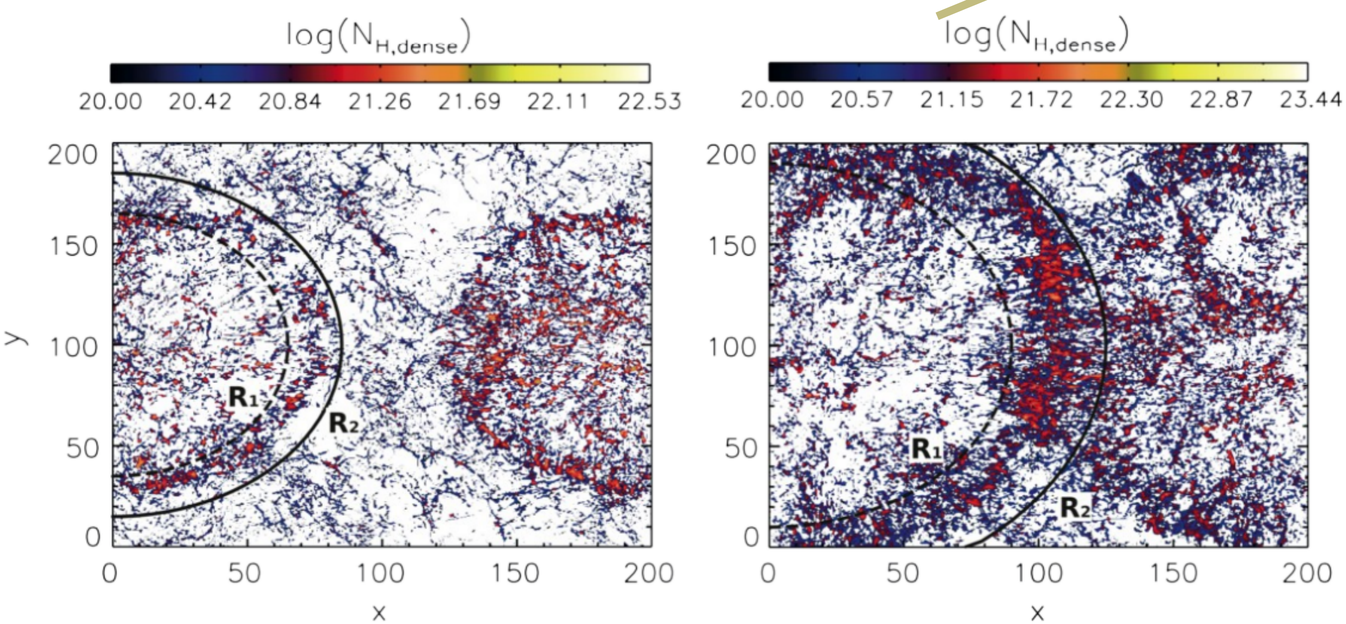
EN+17

Interacting shells: Observations meet simulations





Dawson et al. (2015)

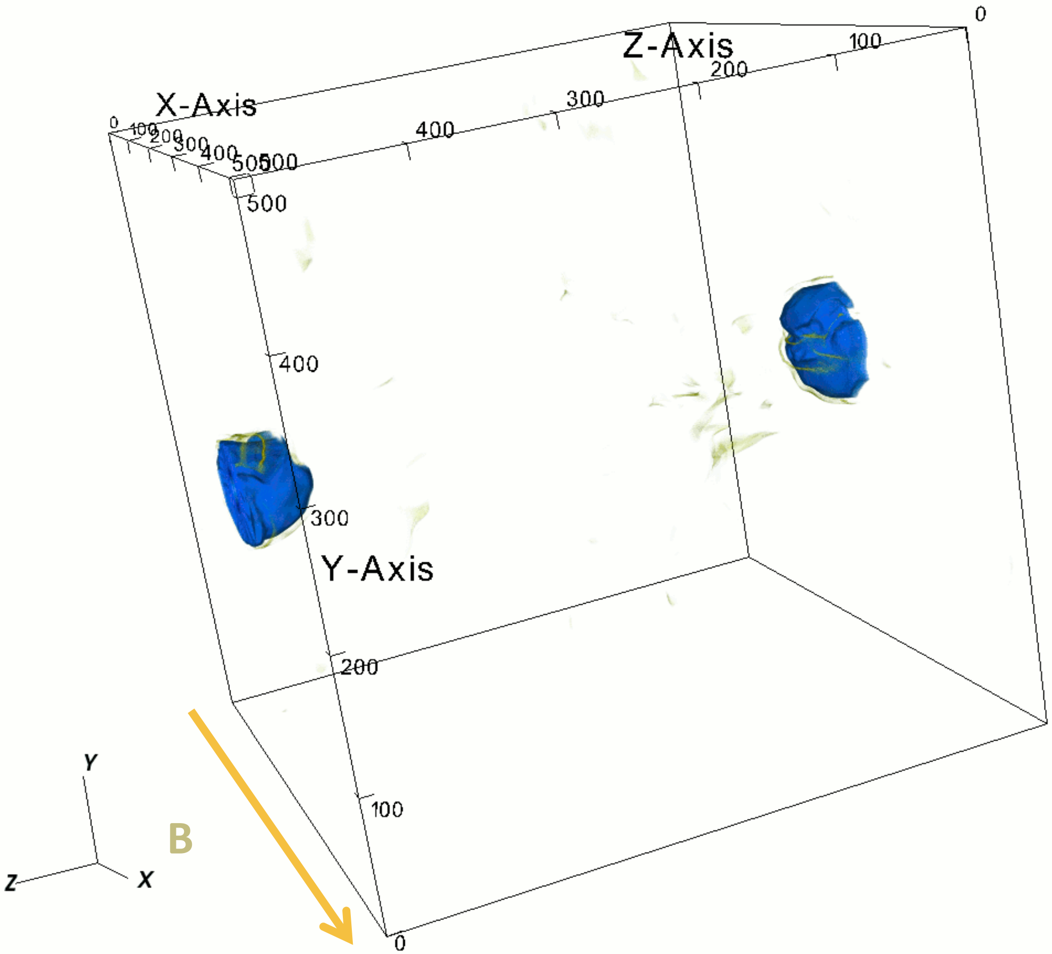


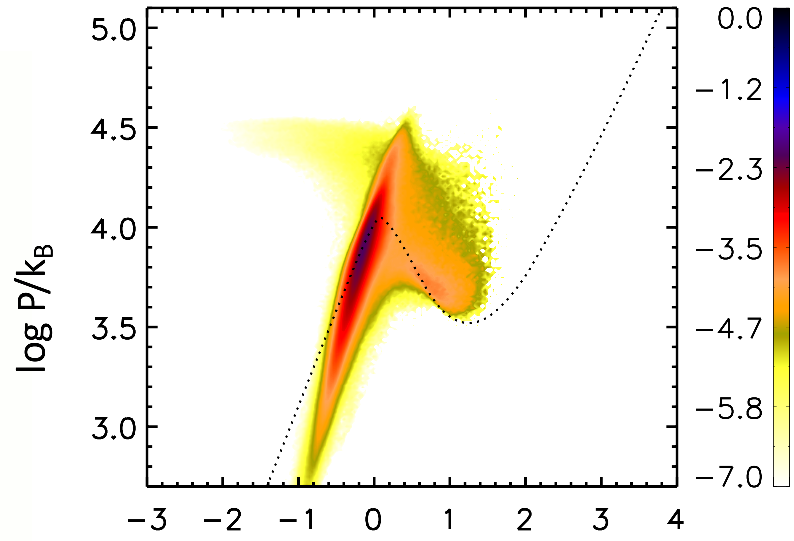
Comparison between hydro simulations and observations of a GMC between two Galactic supershells:

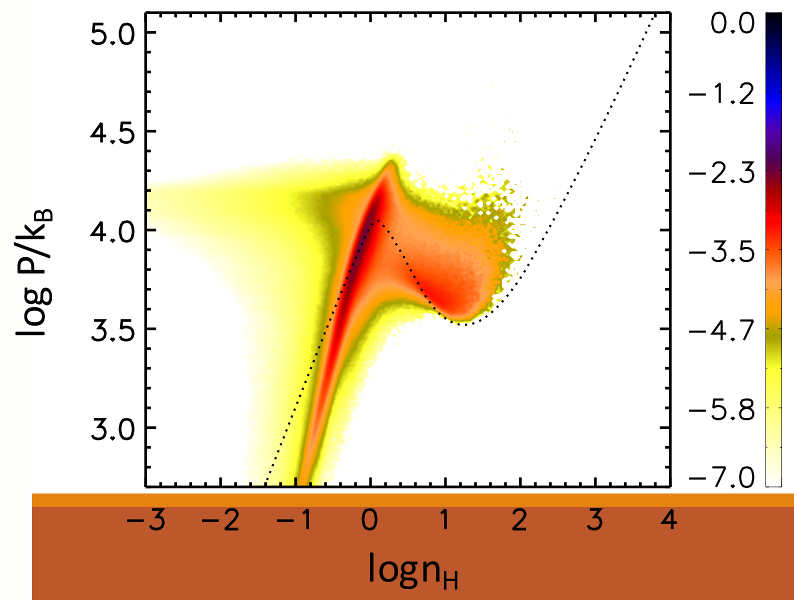
No additional dense gas due to the shell collision!

MHD case with mean field perpendicular to the collision axis

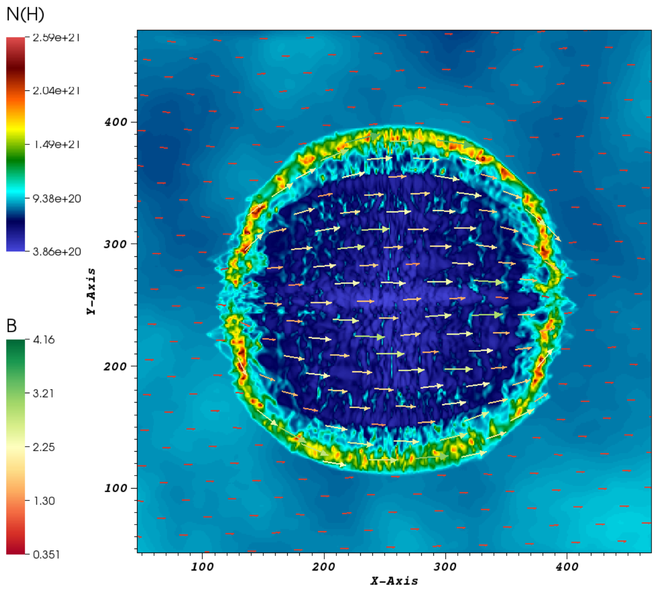
Magnetic field initiated with a 5μG strength, oriented along x.

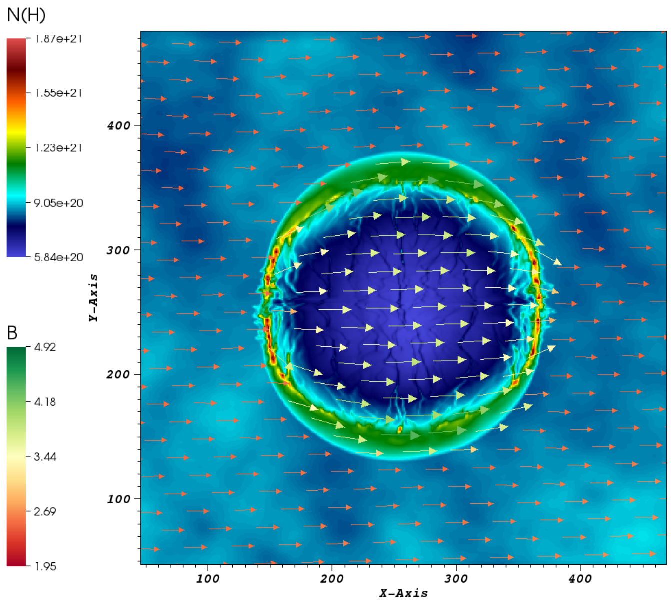




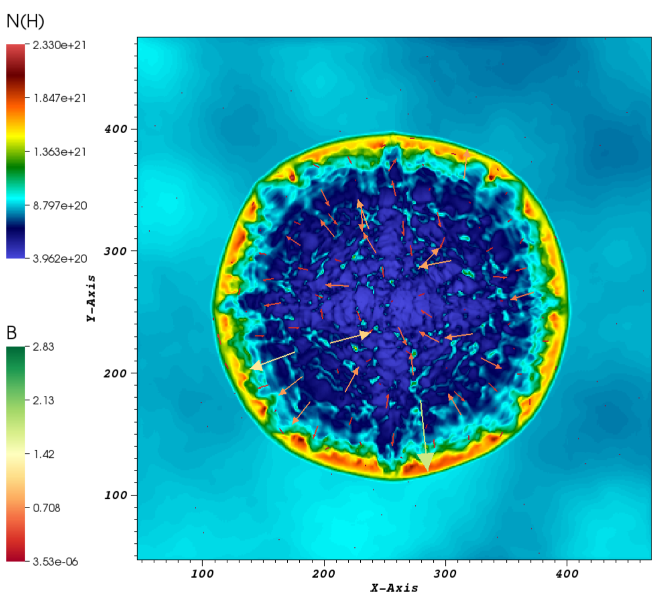


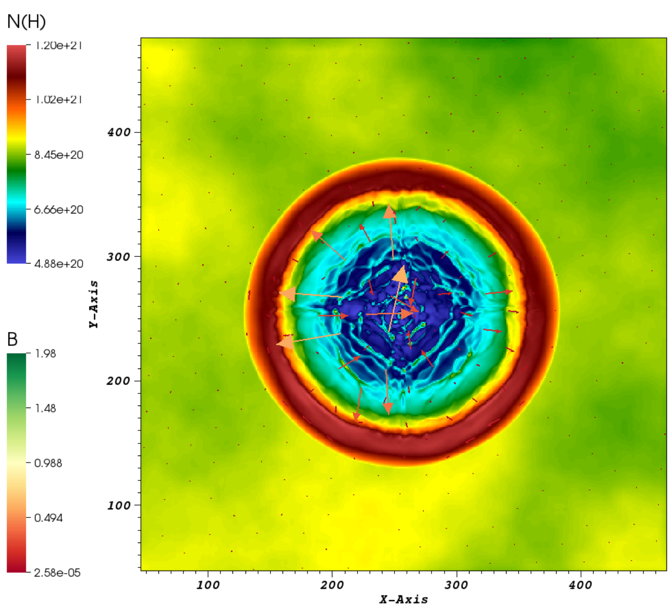
A single bubble in a magnetic field





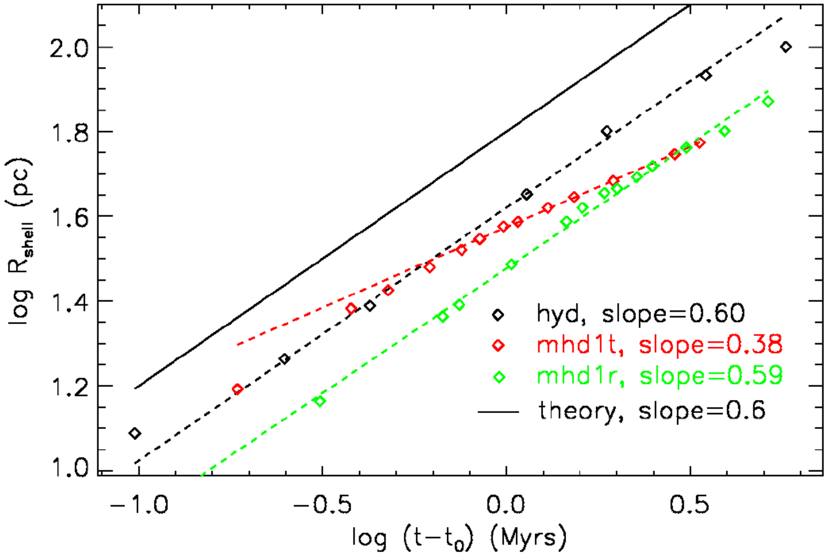
Increasing the magnetic field strength broadens the shell perpendicular to the mean field direction.





It also causes more filamentary fragments to form on the shock surface

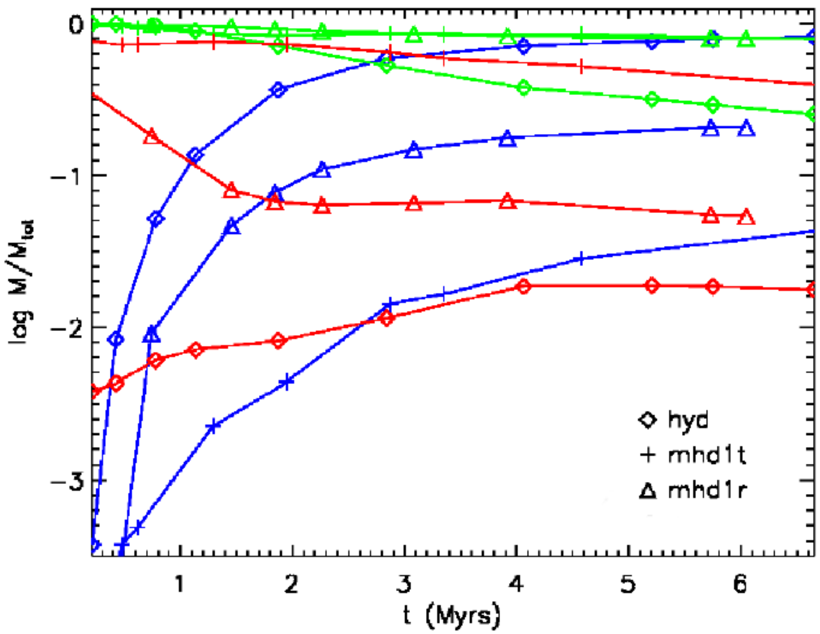
Expansion laws and gas phases

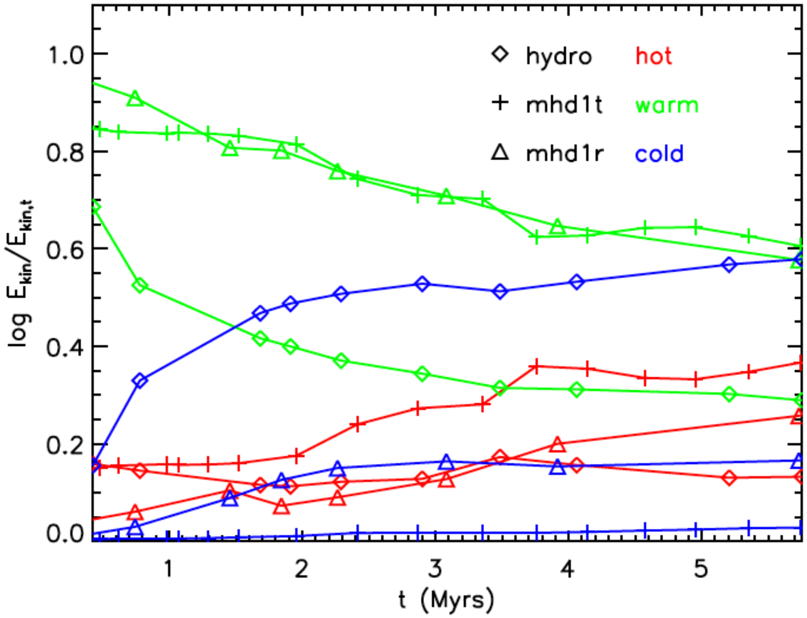


(Analytic wind similarity solution: $R \sim t^{0.6}$)

A magnetic field oriented along the collision axis doesn't alter the expansion law with respect to the hydro case.

However, the formation of dense gas is greatly affected, as well as the momentum carried by each phase.





Open questions I

Cold dense clouds form naturally around expanding supershells due to a combination of fluid instabilities. However, neither a single shock nor a shock collision can accumulate enough mass from the WNM to create a molecular cloud:

Are multiple shock compressions necessary to form molecular clouds?

The magnetic field changes the expansion law of the superbubbles, reduces the amount of dense gas formed and modifies the morphology of the cold clouds.

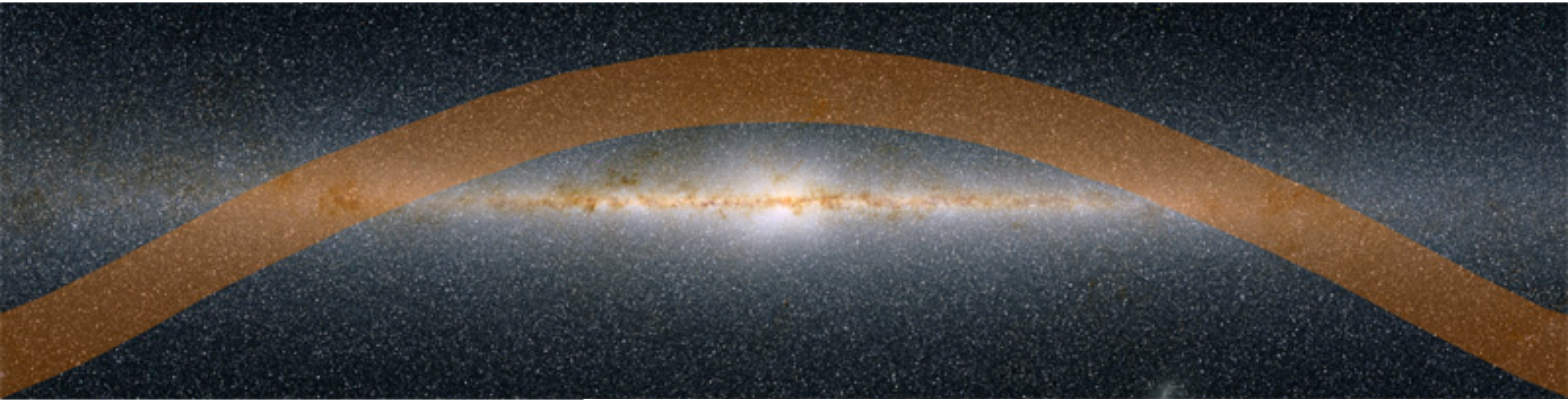
In hydro simulations most of the wind momentum is transferred to the cold gas. In MHD simulations the momentum is carried principally by the warm gas.

Do magnetic fields regulate the cycle of dense gas formation in the galaxy?

Part II

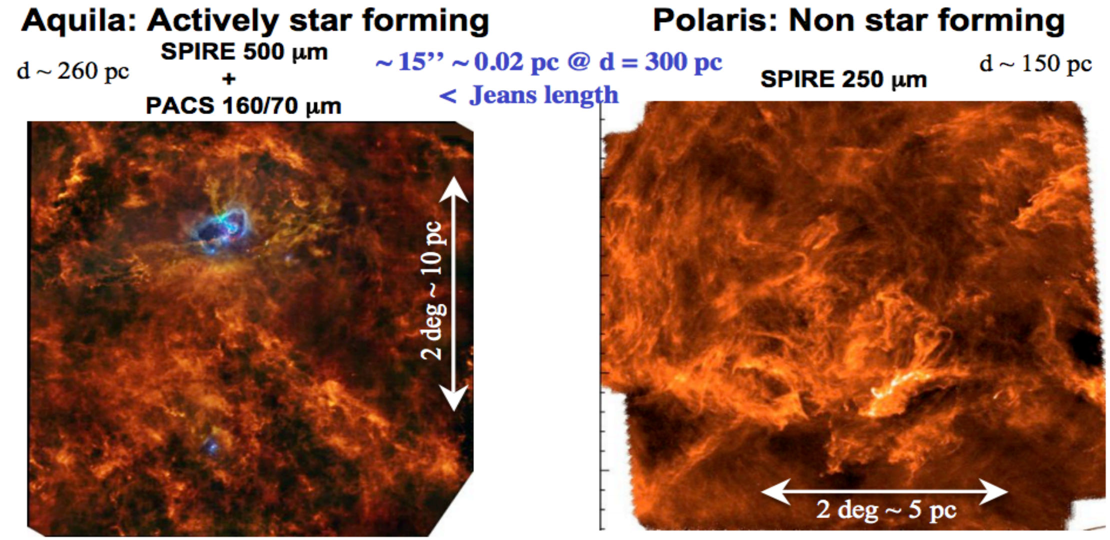
FILAMENT FORMATION IN MHD TURBULENCE

Interstellar filaments from the Herschel Gould Belt Survey



The Gould Belt survey, aimed at studying local star formation in the Galaxy, included several molecular cloud regions such as Taurus, Polaris, Musca, Aquila, and others, observed by Spitzer, JCMT, and Herschel.

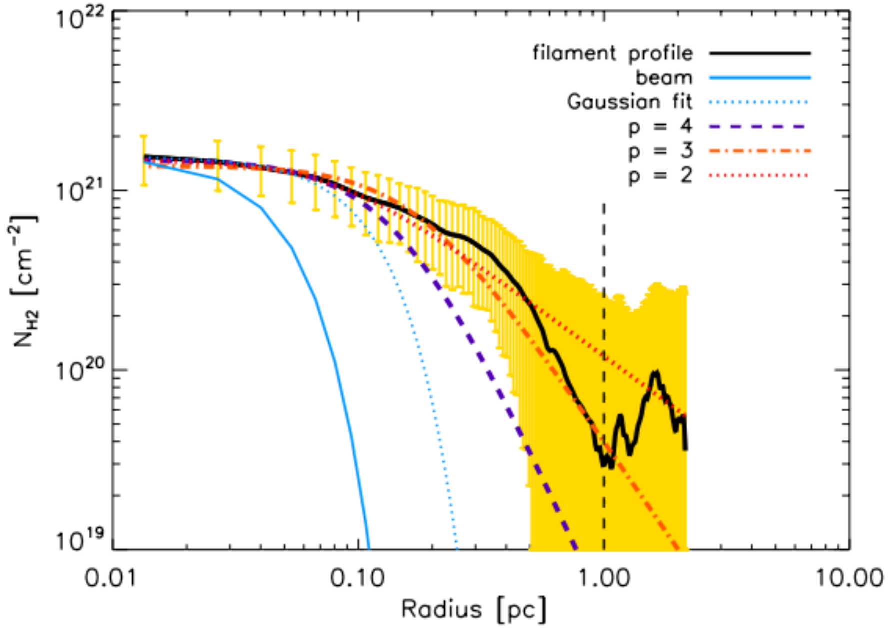
A series of interesting results came out of the Herschel observations of local molecular filaments.

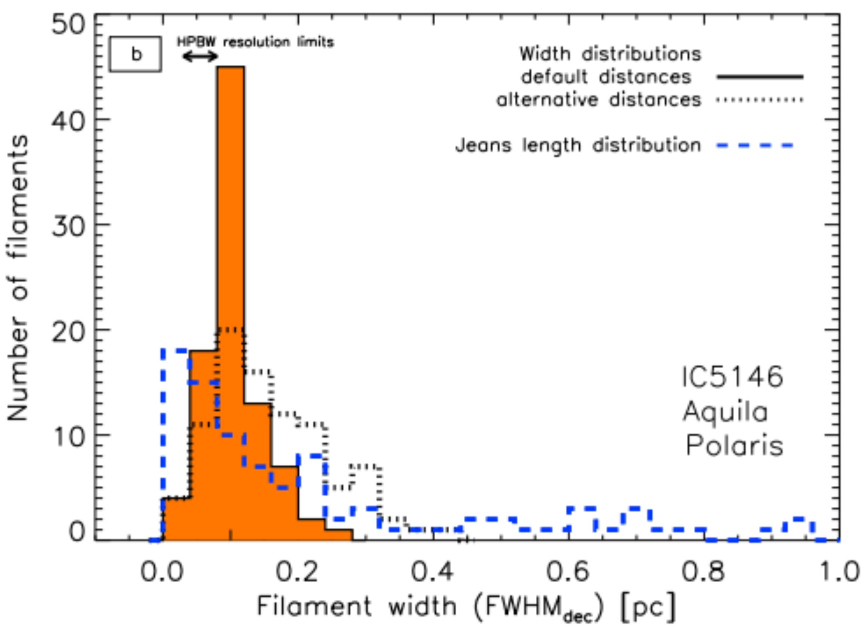


Aquila Rift
André et al. 2010,
Bontemps et al. 2010,
Konyves et al. 2010

Polaris flare
Men'shchikov et al. 2010,
Miville-Deschênes et al 2010,
Ward-Thomson et al. 2010

Image credit: 2MASS/ J.Carpenter, T.H. Jarett & R. Hur



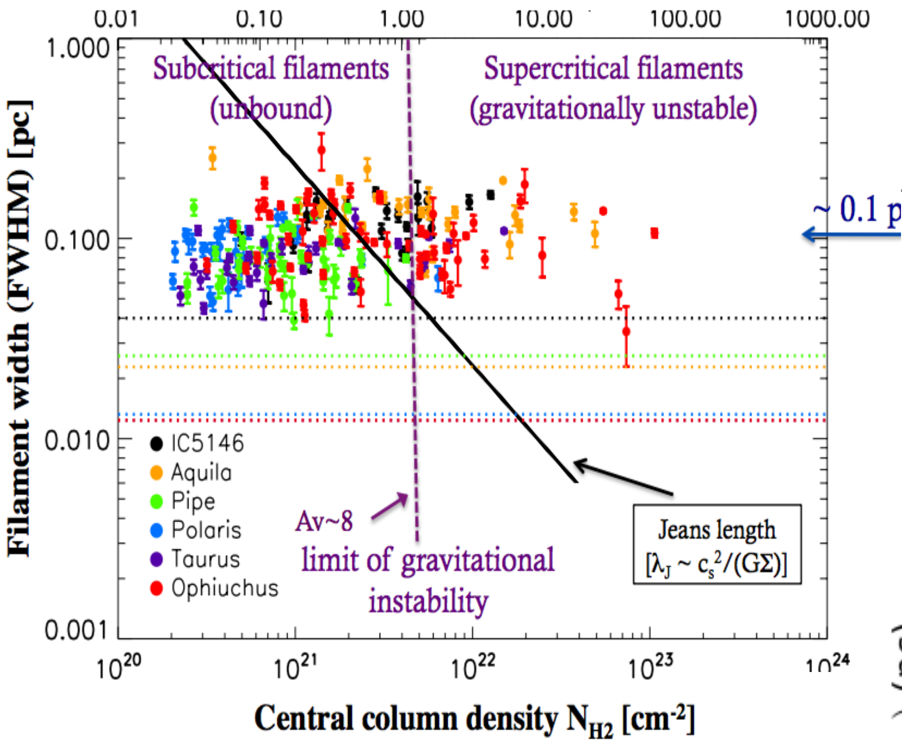


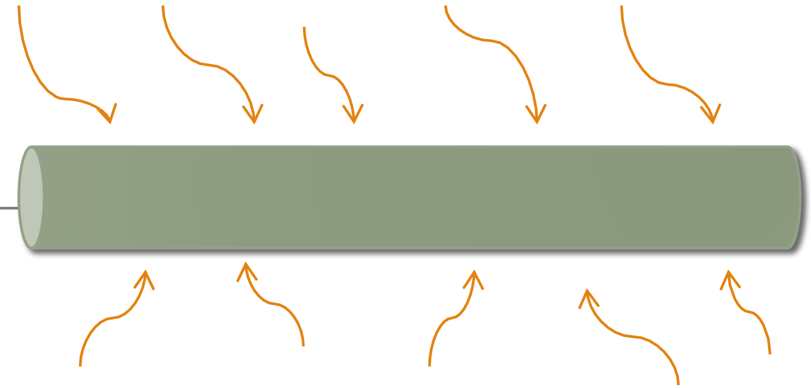
Arzoumanian et al. (2011) fitted the Gould Belt survey filaments with Plummer-like profiles
and found that the thickness of the central parts remained constant and equal to 0.1 pc

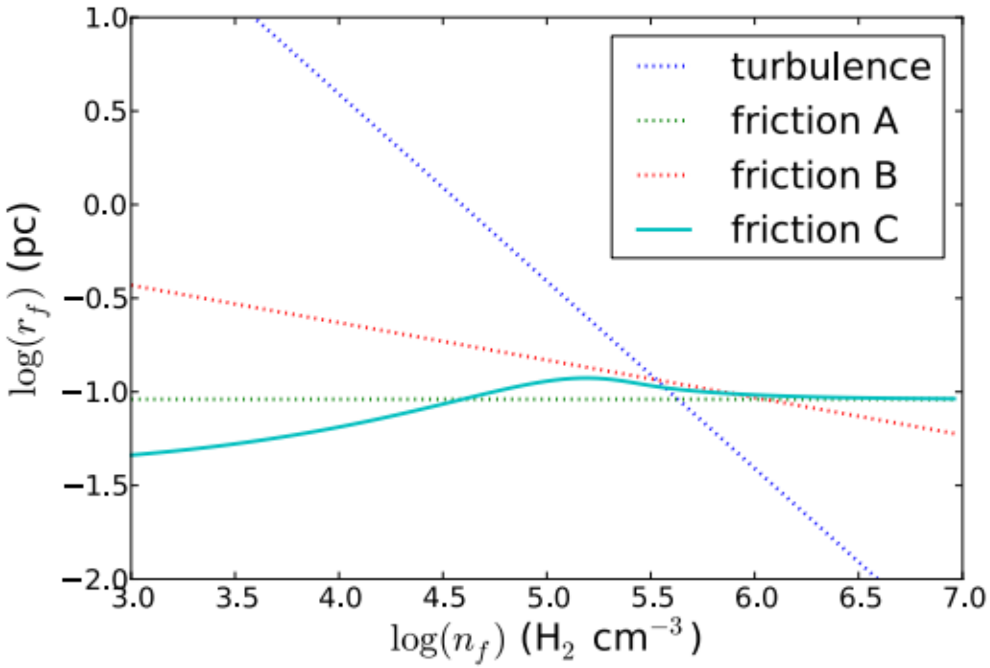
In an environment dominated by scale-free processes such as gravity and turbulence, one expects the filaments to go thinner and thinner as they collapse and condense.

In this context a characteristic scale can only appear if there is a dissipation mechanism acting on the 0.1 pc scale

"Supercritical" filaments



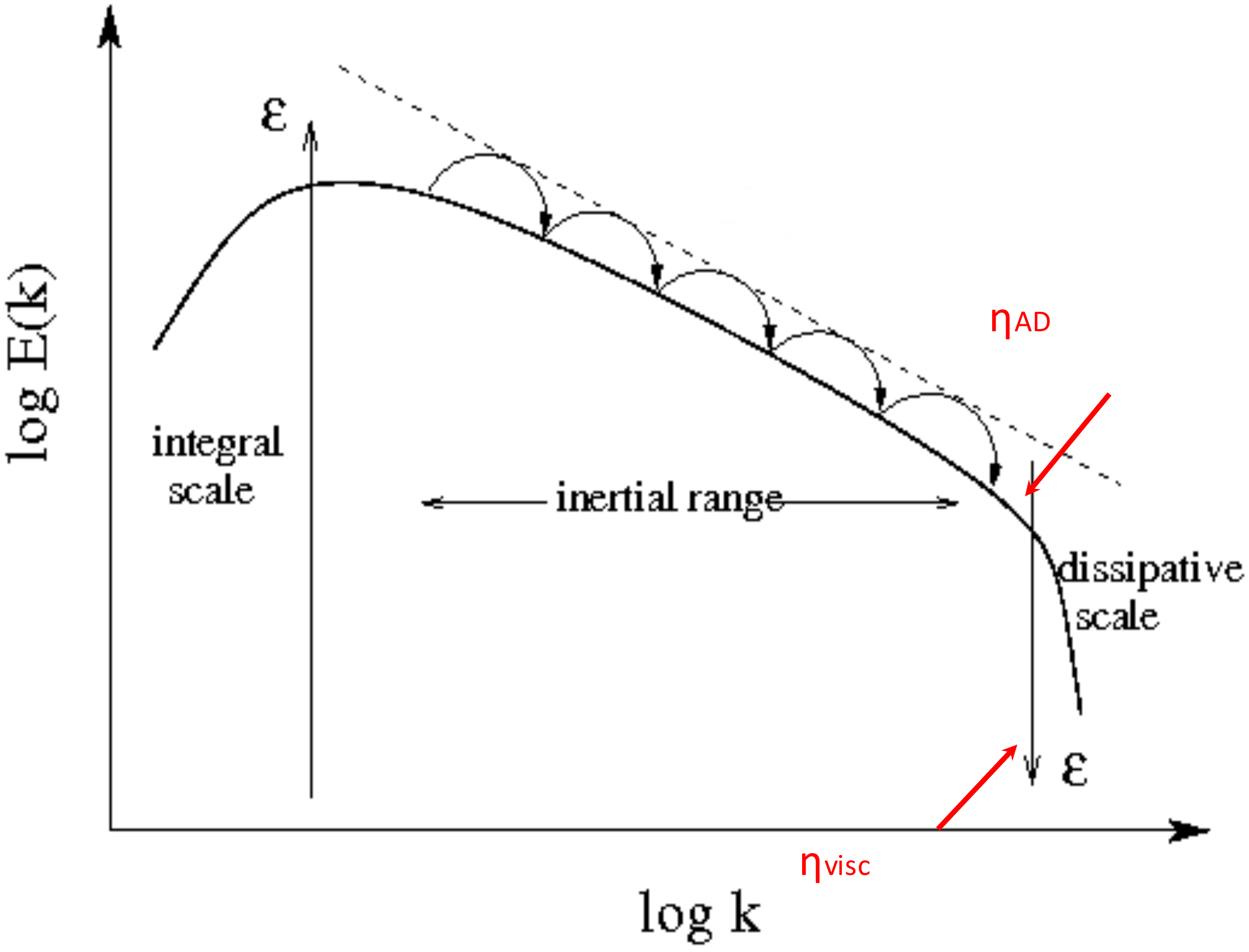




Hennebelle & André (2013) proposed that the balance between accretion-driven turbulence and dissipation through ambipolar diffusion is what maintains the supercritical filaments 0.1 pc thick.

Does this work for low-mass filaments?

The critical length scale for damping Alfvén waves through ambipolar diffusion is (Kuslrud & Pierce (1969))



$$\lambda_d = \frac{\pi v_A}{\gamma_{AD}\rho_i}$$

For molecular clouds u_A=1 km/s, $\rho_i \approx \sqrt{\rho_n}$

This gives a $\lambda_d \approx 0.07$ pc

Non-ideal MHD equations

Two-fluid MHD equations (valid for scales r > r_{gyr})

$$\frac{\partial \rho_n}{\partial t} = -\nabla(\rho_n v_n)$$

$$\frac{\partial \rho_i}{\partial t} = -\nabla(\rho_i v_i)$$

+ EOS for each species
+ Poisson equation for self - gravity
+ $\nabla \cdot \vec{B} = 0$

$$\rho_n \frac{\partial v_n}{\partial t} = -\rho_n(v_n \cdot \nabla)v_n - \nabla P_n - \rho_n g + F_{fri}$$

$$\rho_i \frac{\partial v_i}{\partial t} = -\rho_i(v_n \cdot \nabla)v_i - \nabla(P_i + P_e) - \rho_i g - F_{fri} + \frac{1}{4\pi}(\nabla \times B \times B)$$

$$\frac{\partial B}{\partial t} = \nabla \times (v_i \times B)$$

The strong coupling approximation

When the ion density in the plasma is low and the collision timescale between ions and neutrals is short compared to typical timescales of the problem, then the Lorenz force exerted on the ions is almost equal to the drag force from the neutrals, leading to a strong coupling between the neutral fluid and the magnetic field and the plasma can be described by one fluid.

$$v_i - v_n = \frac{1}{4\pi\gamma_{cpl}\rho_n\rho_i}(\nabla \times B) \times B$$

The above relation comes from equating these two terms and can be replaced in the equation for the neutrals to give a one-fluid set of equations with a momentum equation:

$$\rho_n \frac{\partial v_n}{\partial t} = -\rho_n(v_n \cdot \nabla)v_n - \nabla P_n - \rho_n g + \frac{1}{4\pi}(\nabla \times B) \times B$$

Non-ideal MHD turbulence simulations

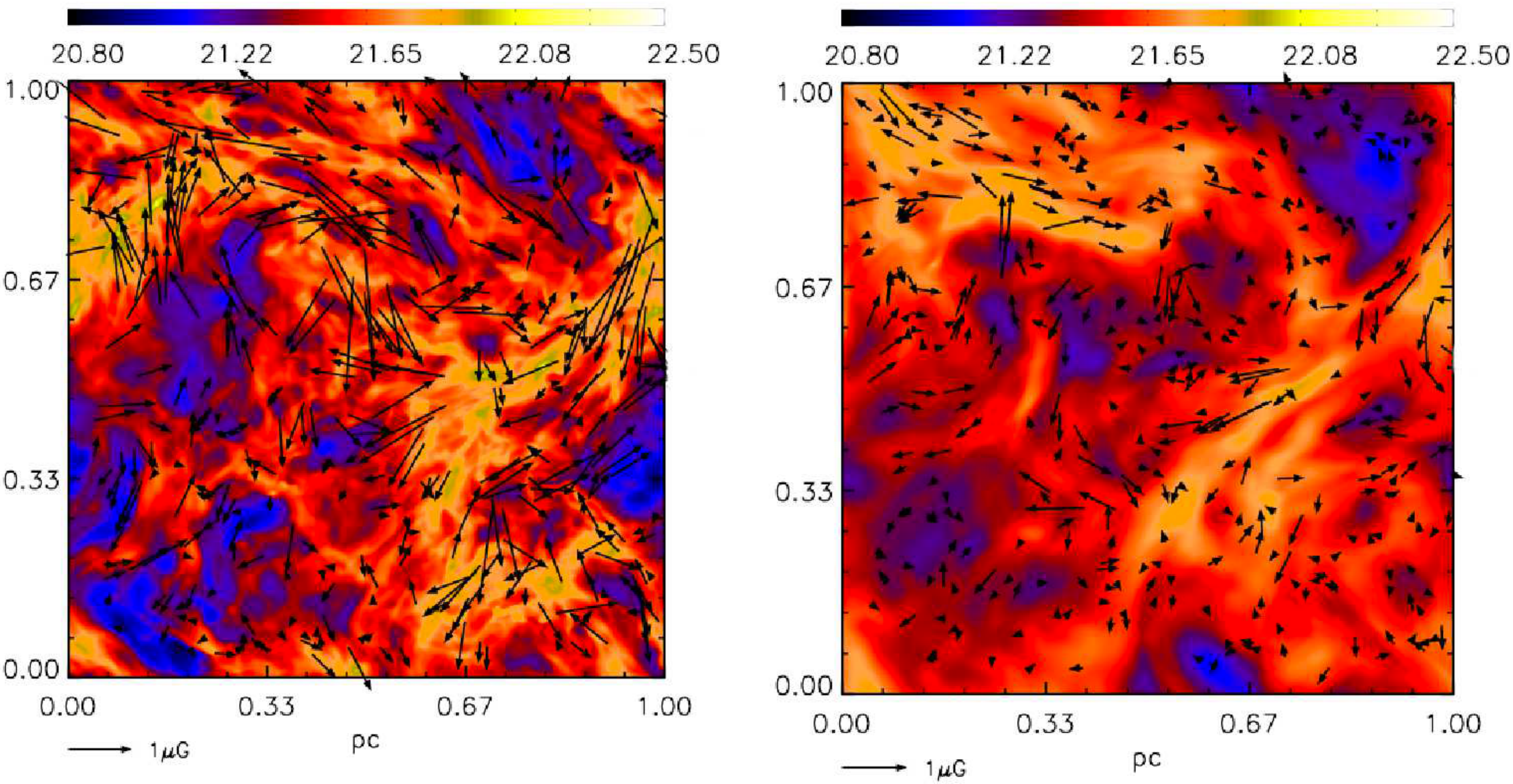
1 pc box with a 512^3 or 1024^3 coarse resolution (no AMR)

$n_0 = 500\ cm^{-3}$ and T=10K, with a plasma β=0.1

No self-gravity, isothermal eos

Decaying turbulence starts with an rms Mach number 10, driven is at Mach 4

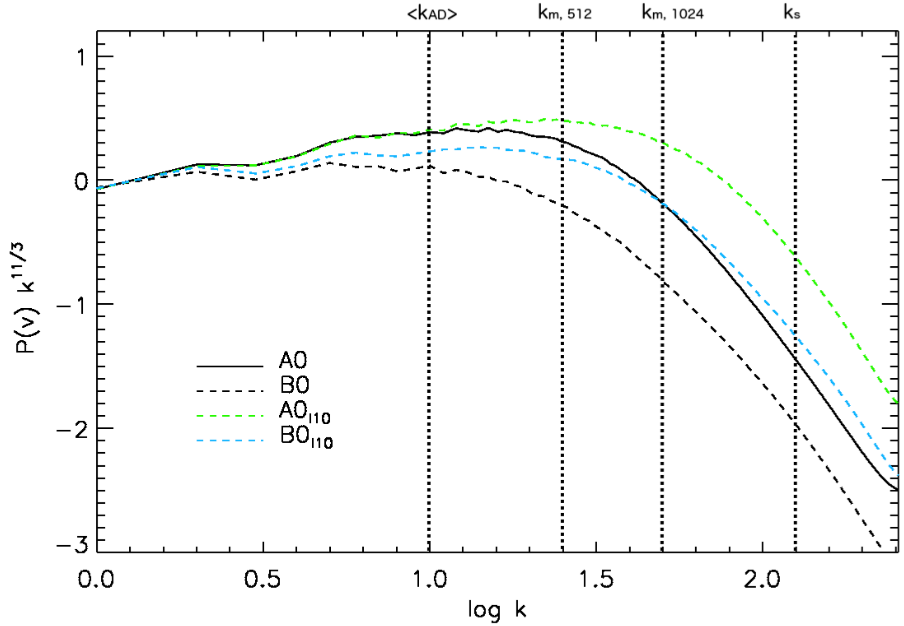
Two decaying runs after one rms crossing time (sonic M=3.5)



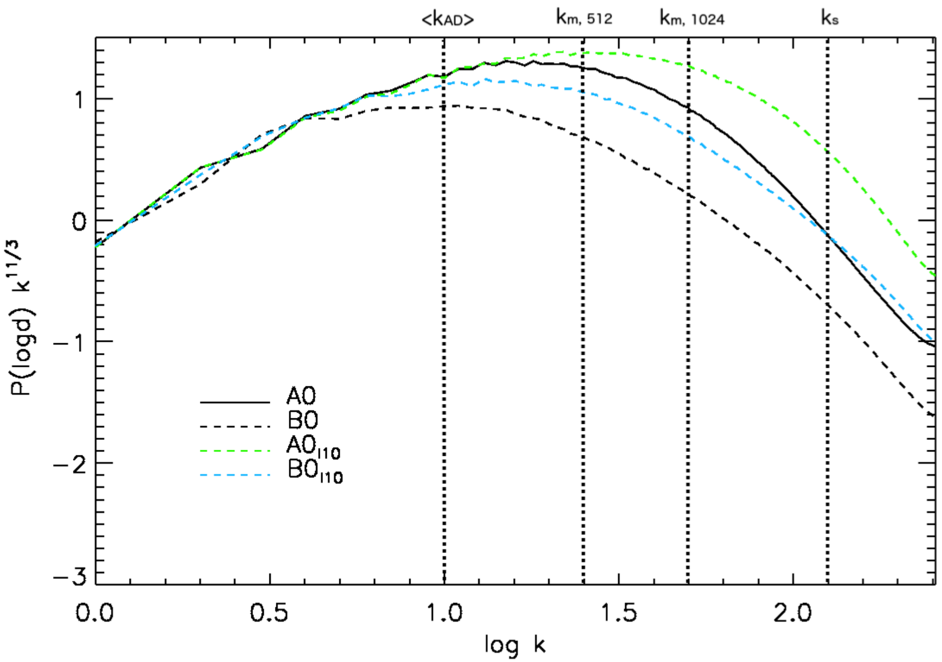
Ideal MHD

Ambipolar diffusion MHD

EN+16



Power spectra of the velocity (left) and the log of the density (right) in the decaying runs.

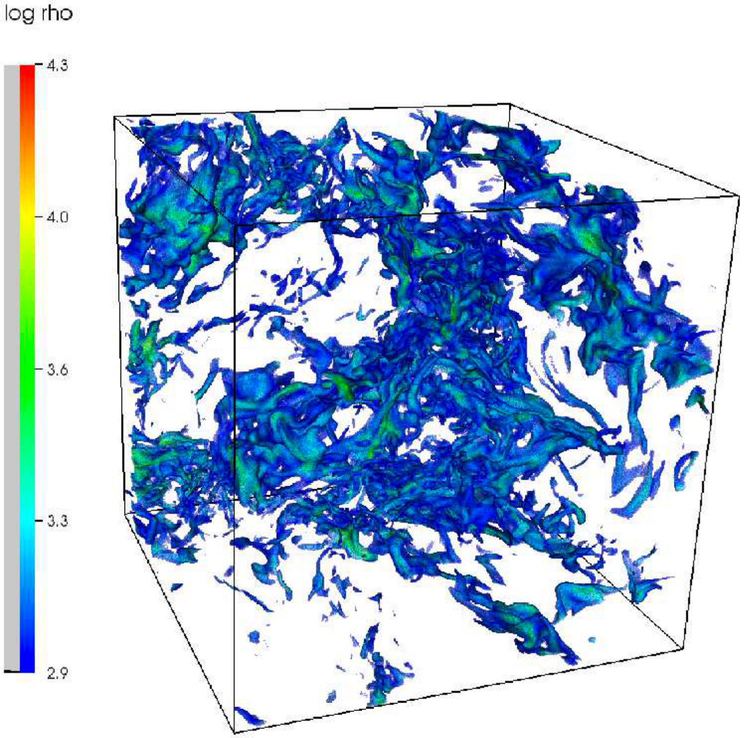


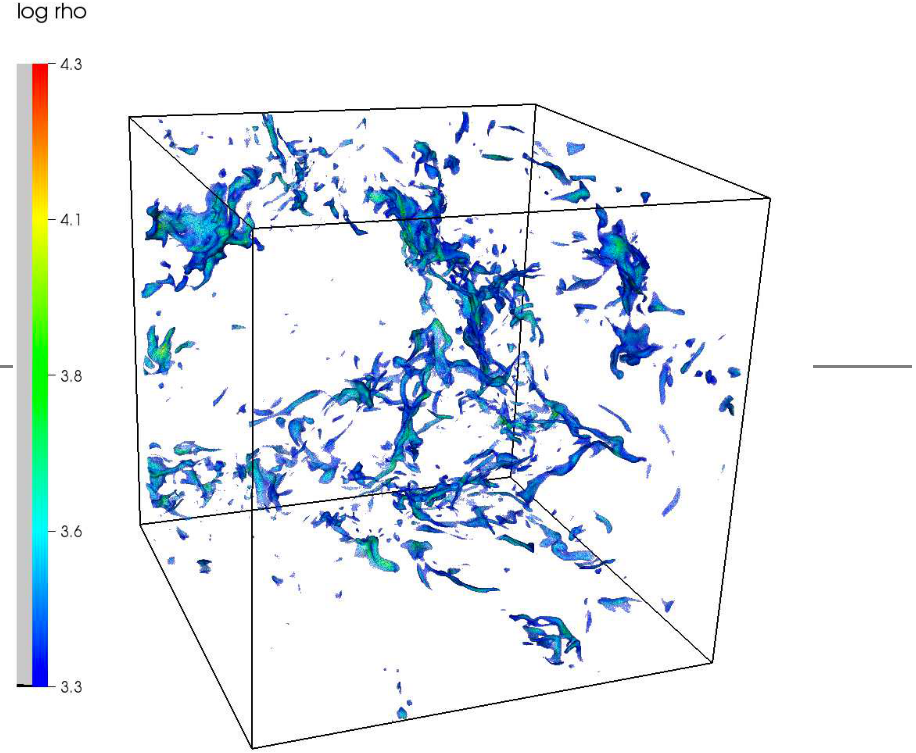
Black solid lines: 512^3 ideal run

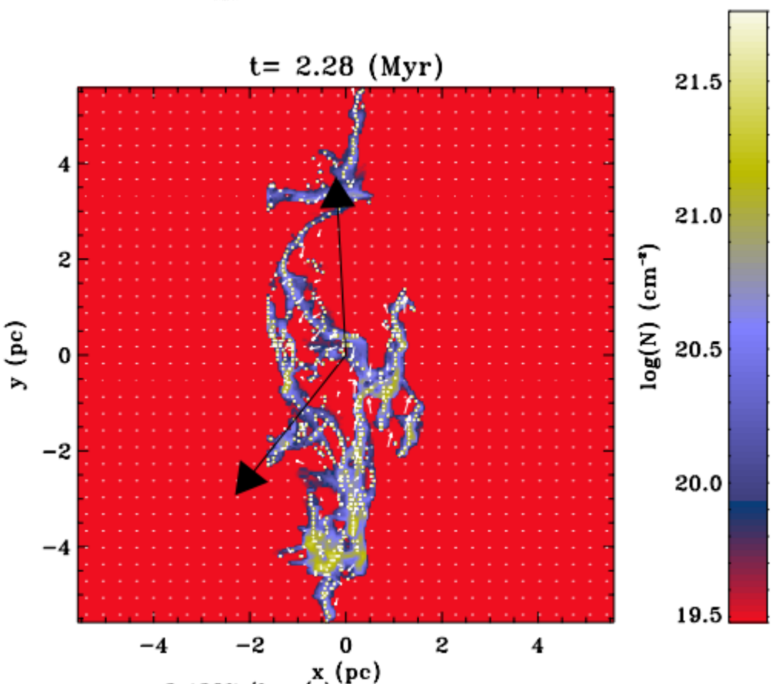
Black dashed lines: 512^3 AD run

Green dashed lines: 1024^3 ideal run

Blue dashed lines: 1024^3 AD run

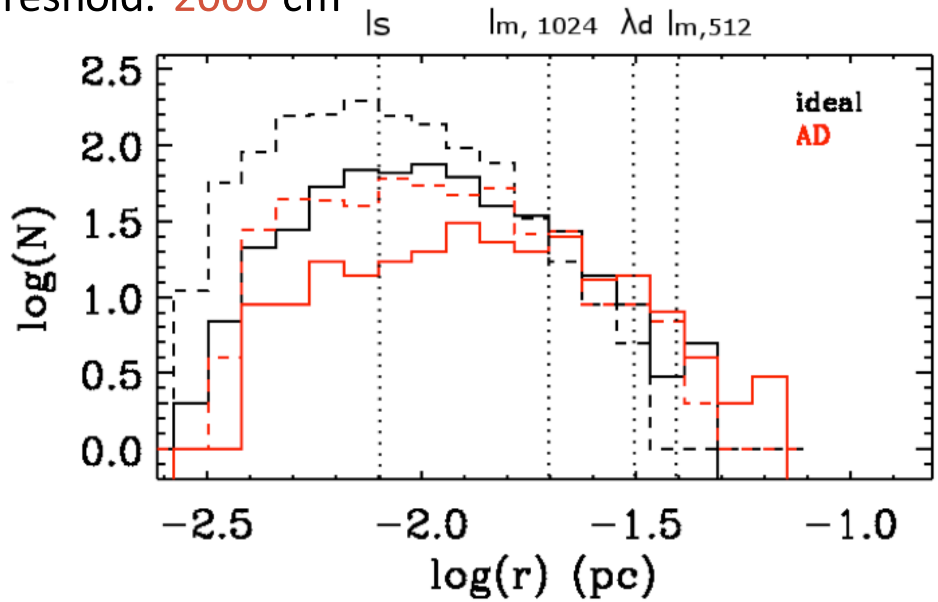




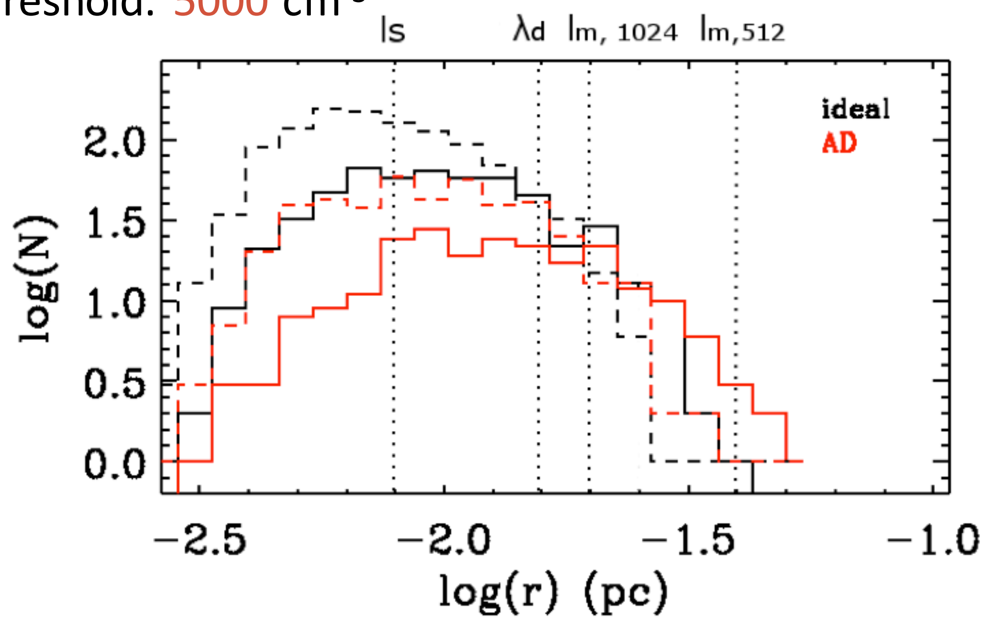


1. Put a threshold in density to select densest locations
2. Apply a friends-of-friends algorithm to identify filaments
3. Solve for the eigenvectors of the inertia matrix to find the filament's principal directions
4. Find the local centers of mass along the longest axis and calculate local properties

Threshold: 2000 cm^{-3}



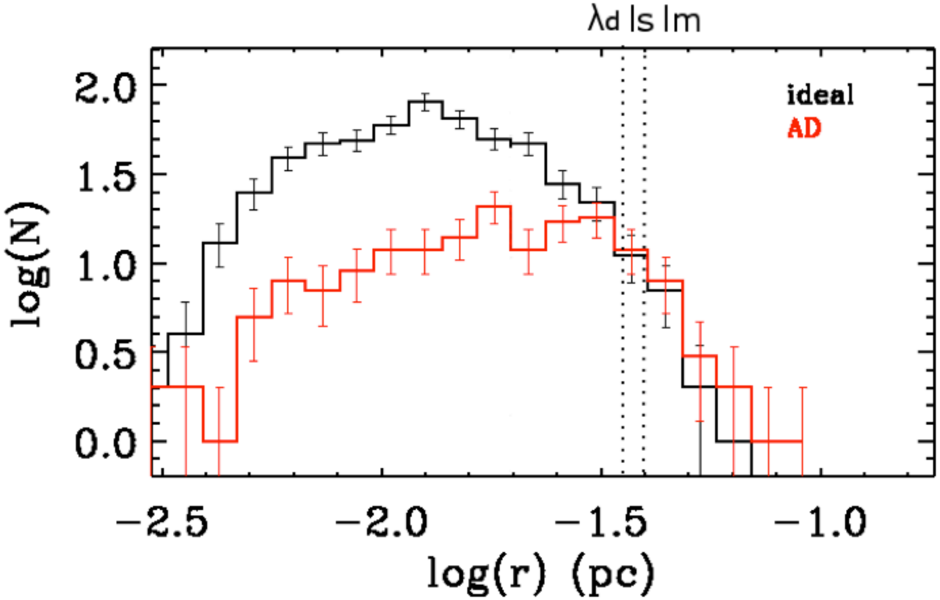
Threshold: 5000 cm^{-3}

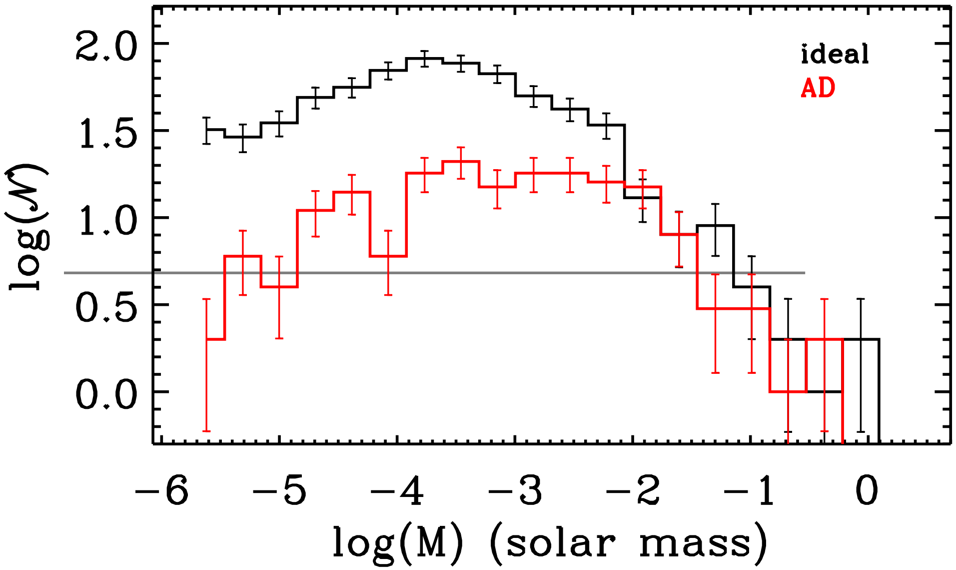


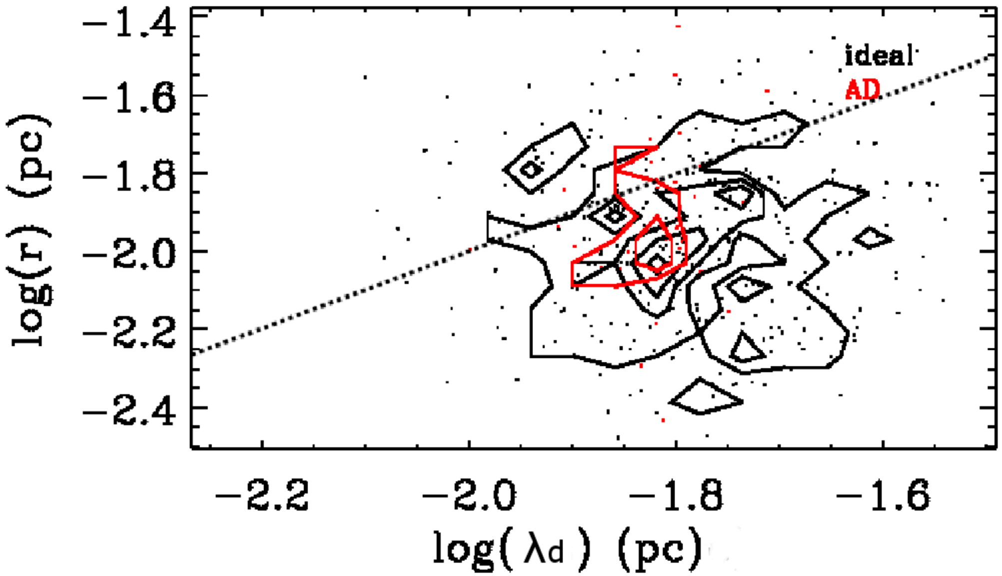
Early-phase comparison

Thickness distributions in different simulations:
dashed lines indicate the 1024^3 runs, vertical dotted lines show the different dissipation lengths

Late-phase comparison (1 crossing time)







The ambipolar diffusion critical length λd is calculated locally with the estimates of the ion fraction and the Alfvén speed for each location.

Open questions II

In MHD turbulence with ion-neutral friction included:

- Filaments appear broader, and
- The magnetic field within them is less tangled

compared to ideal MHD conditions.

Ion-neutral friction clearly modifies the properties of MHD turbulence. But:

Is this process responsible for the 0.1 pc thickness observed in local filaments?

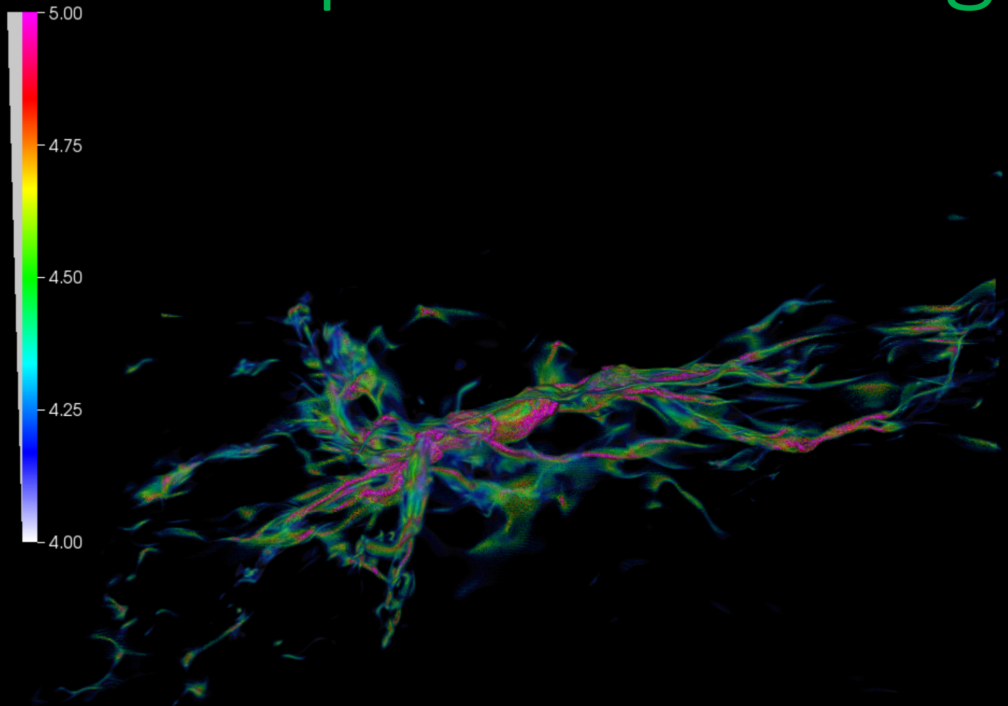
and

What happens to self-gravitating structures?

Part III

FRAGMENTATION AND COLLAPSE OF TURBULENT ISOTHERMAL FILAMENTS

Collapse of an elongated cylinder



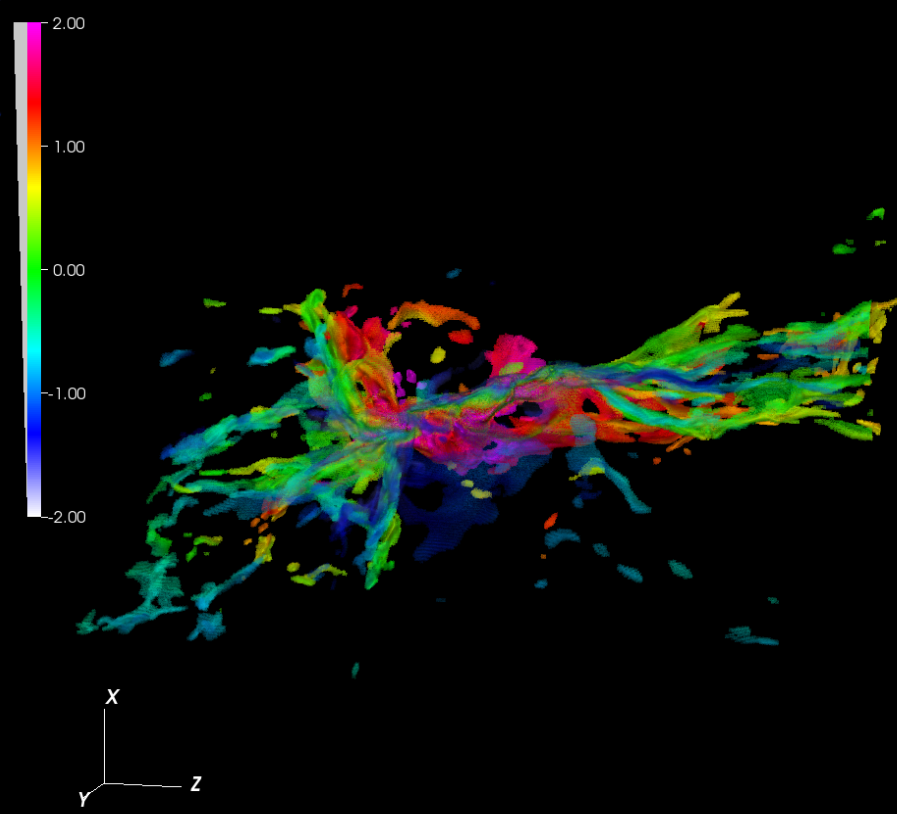
A gravitationally unstable cloud with different initial magnetic field and turbulence strengths

M = 1000 Msol

a_{turb} = Eturb/Egrav

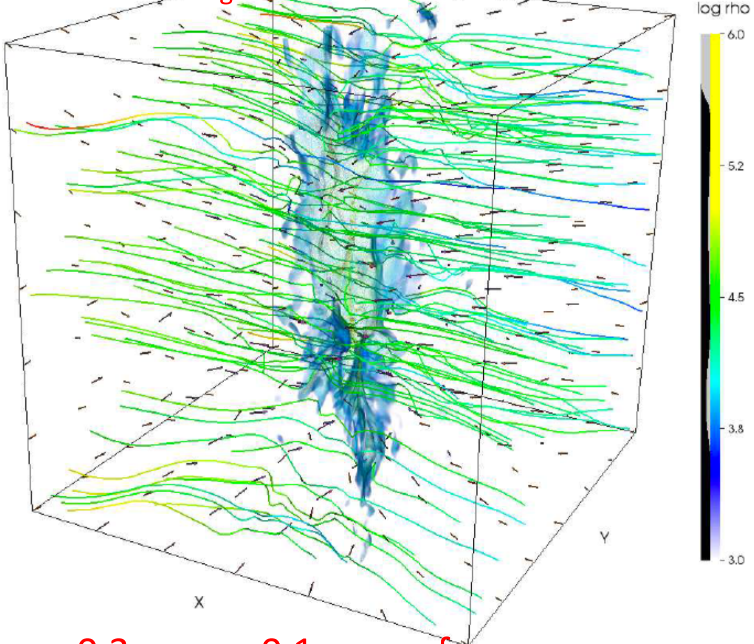
a_{mag} = Emag/Egrav

No sink formation/ no feedback

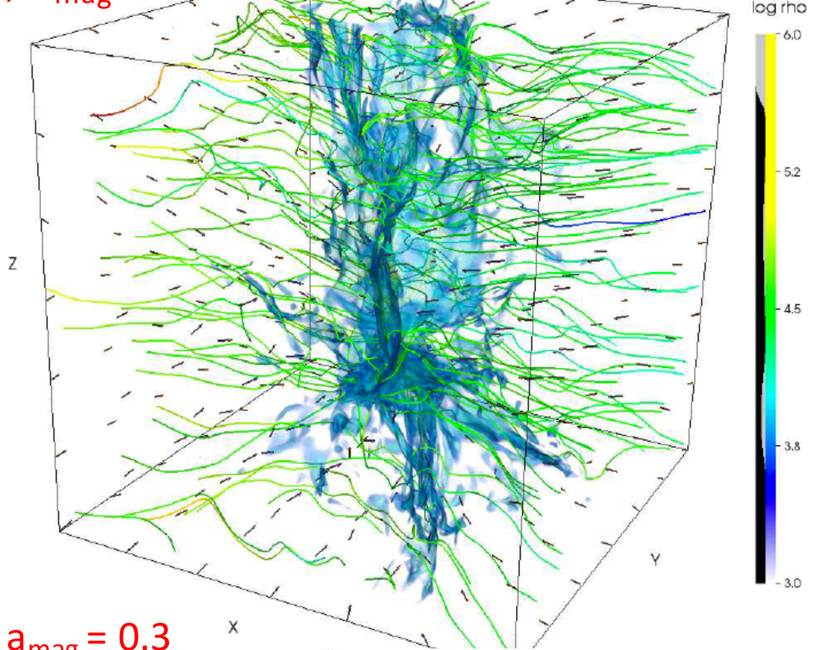


The filament collapses, fragments, and forms complex density and velocity structures.

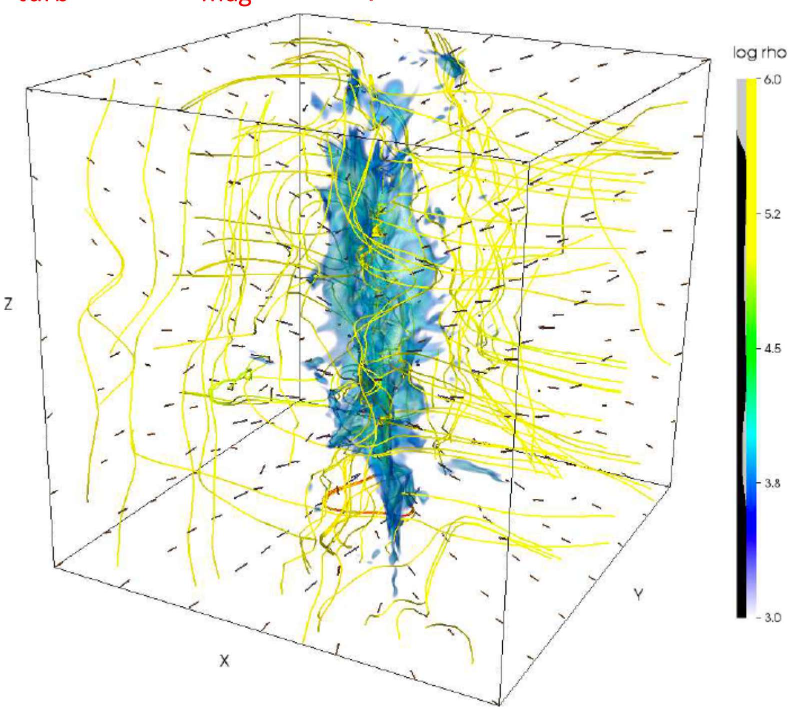
$a_{turb} = 0.3$, $a_{mag} = 0.1$, perp mf



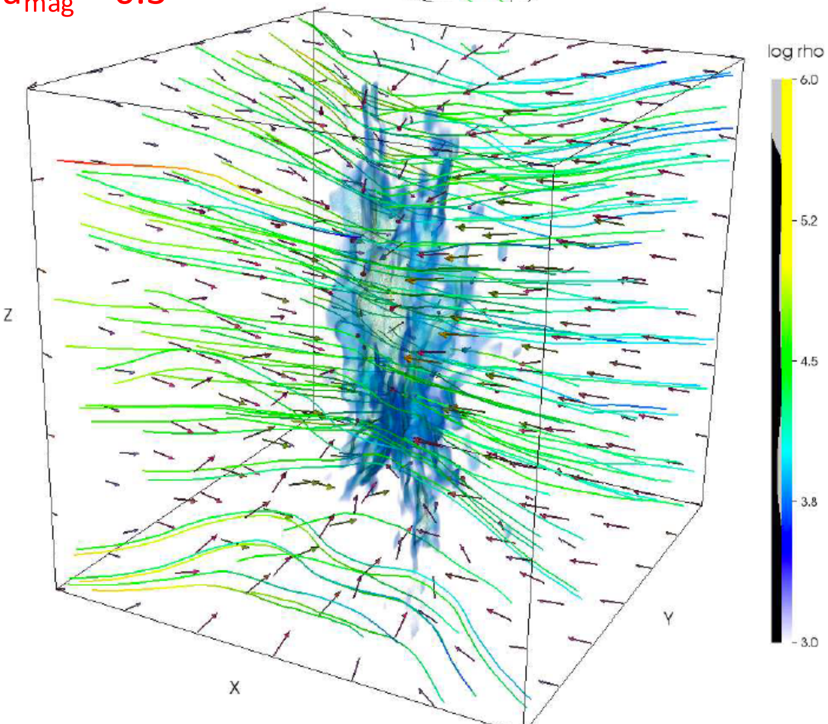
$a_{turb} = 0.5$, $a_{mag} = 0.1$

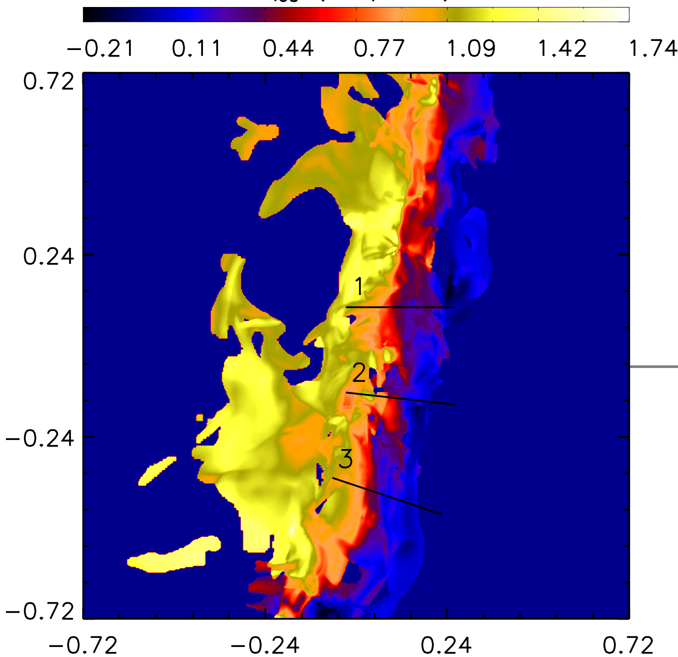


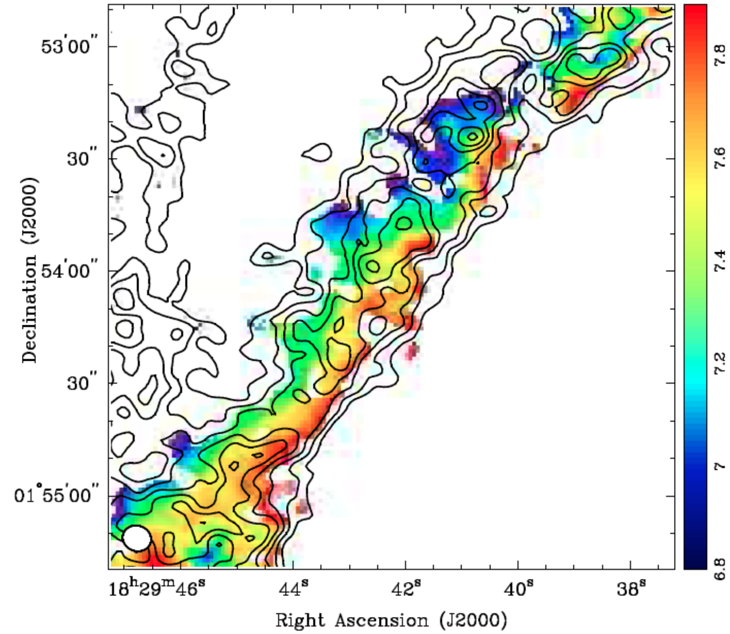
$a_{turb} = 0.3$, $a_{mag} = 0.1$, par mf

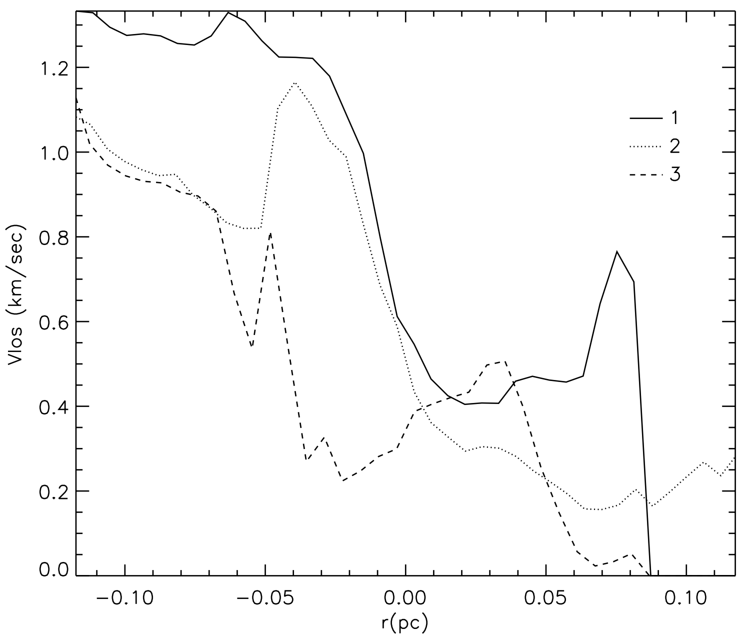


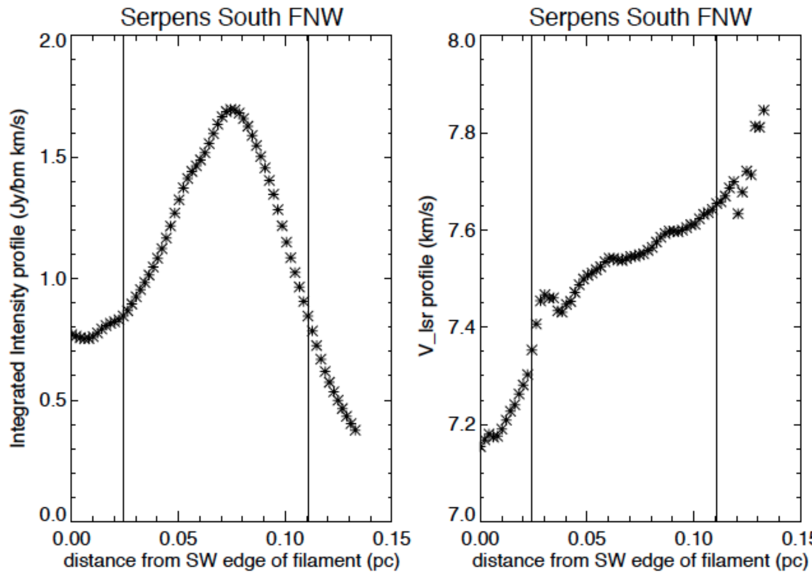
$a_{turb} = 0.7$, $a_{mag} = 0.3$





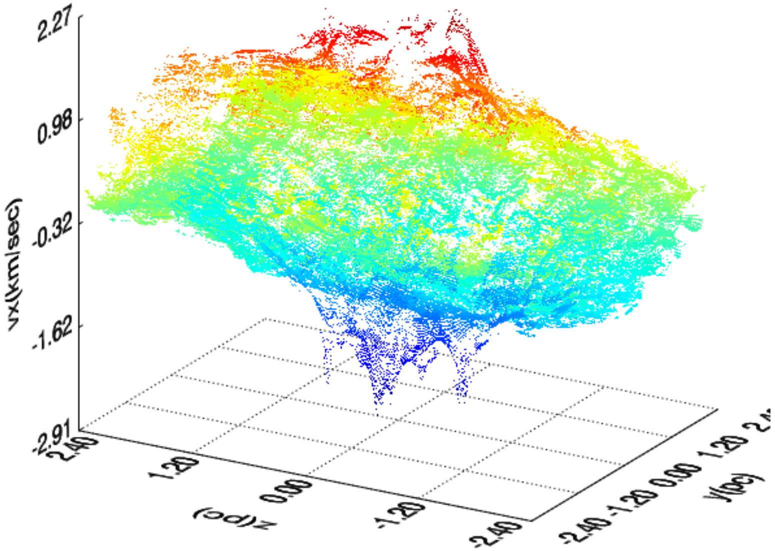




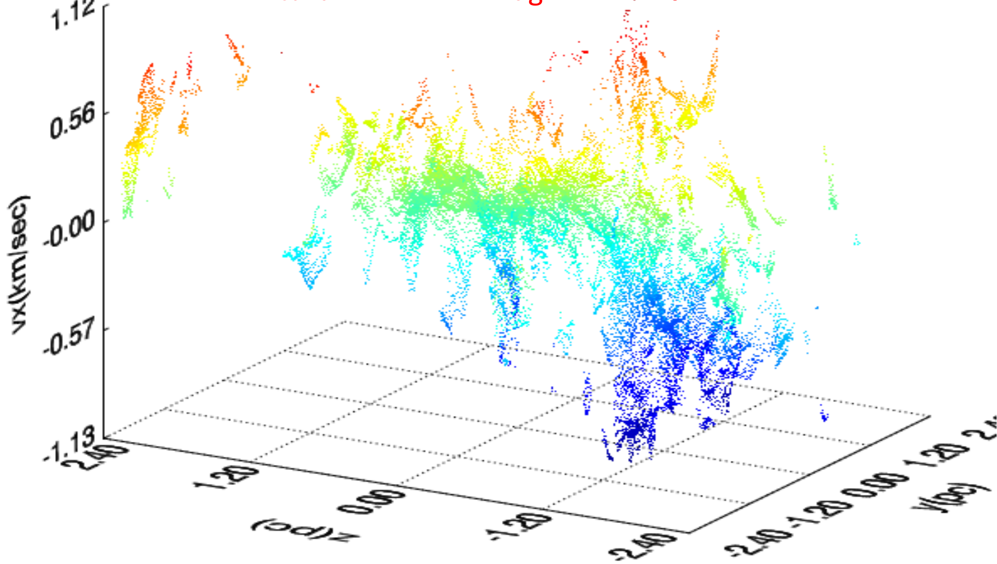


A relatively good fit to Serpens south: cloud with aturb=0.5, amag=0.1

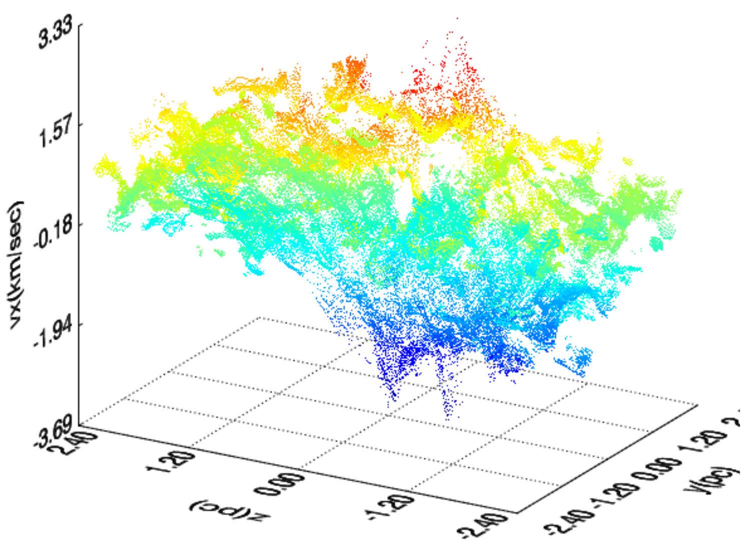
a_{turb} = 0.3, a_{mag} = 0.1, , perp mf

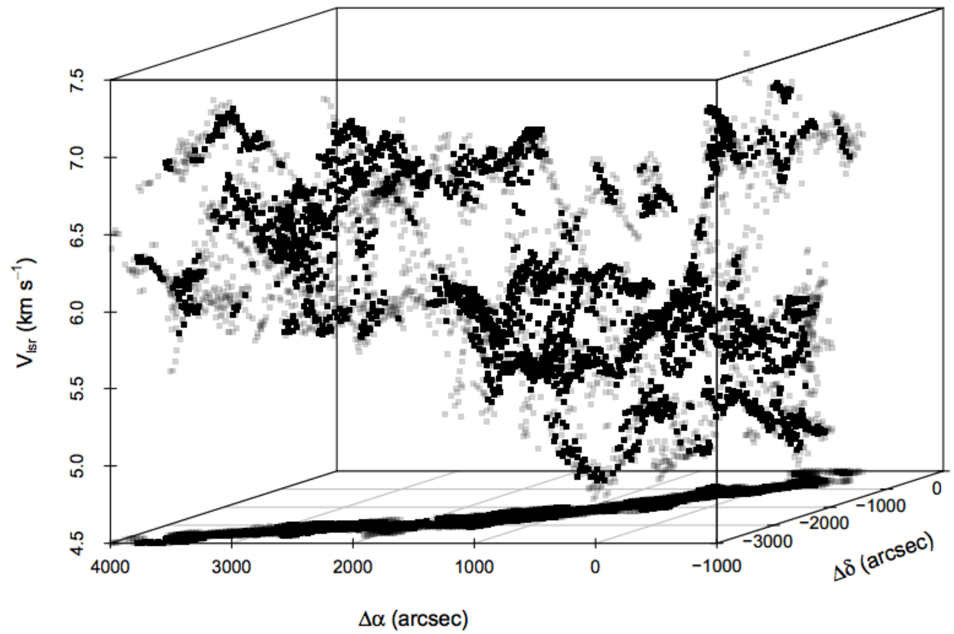


a_{turb} = 0.5, a_{mag} = 0.5, parallel mf

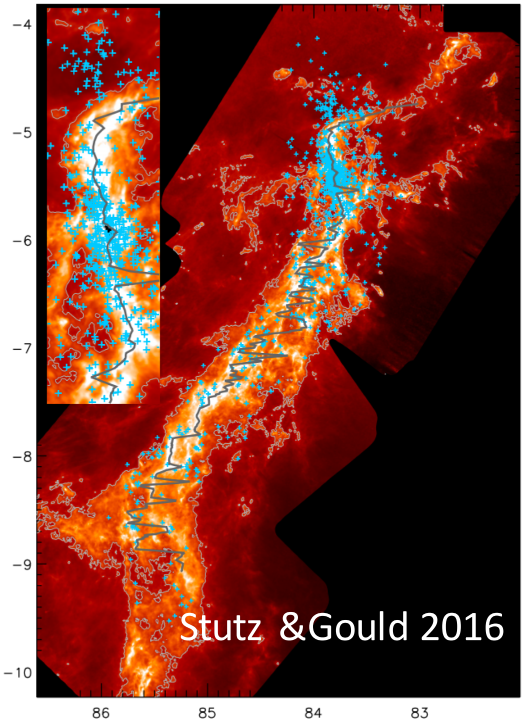


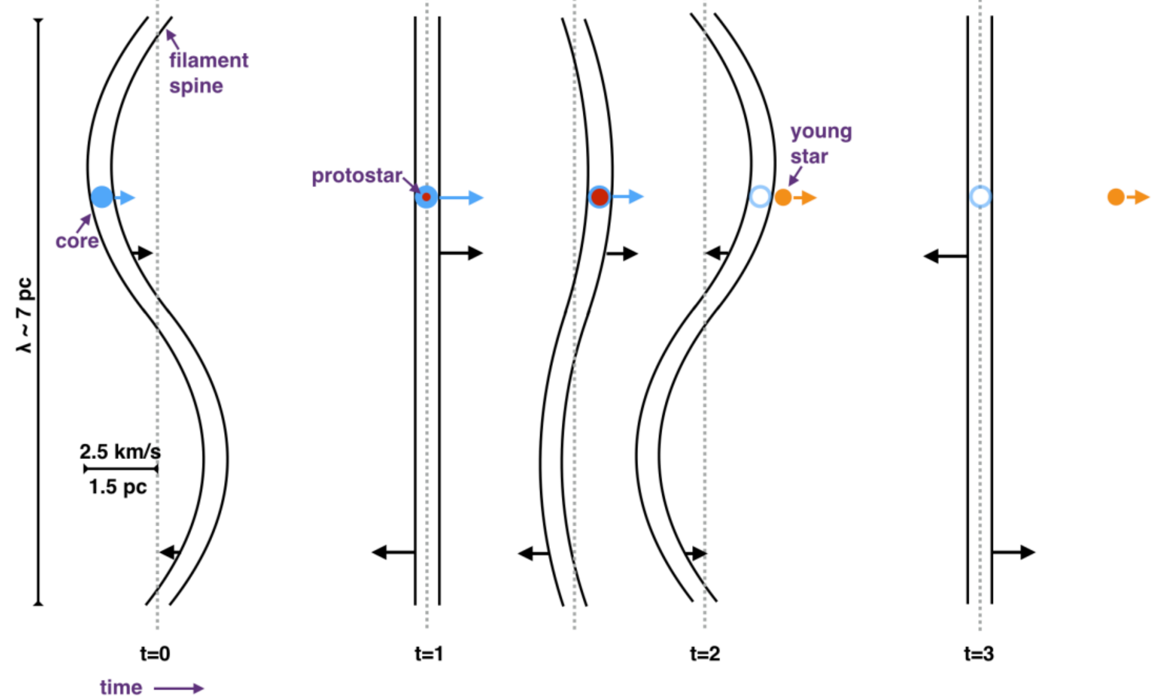
a_{turb} = 0.5, a_{mag} = 0.1, perp mf

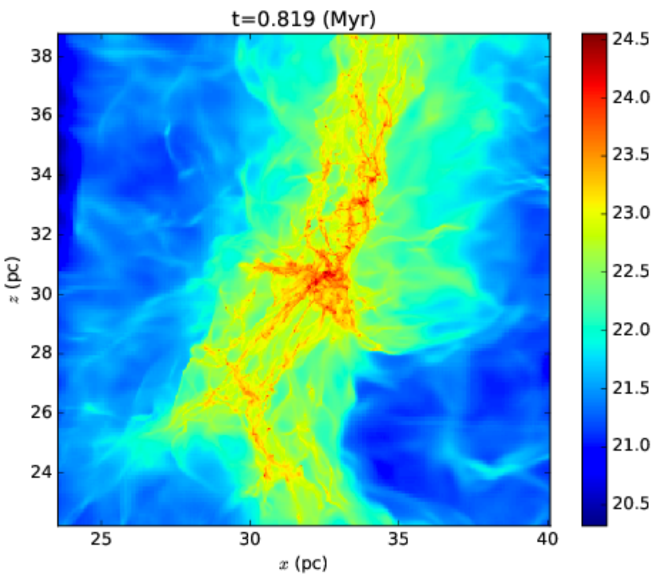


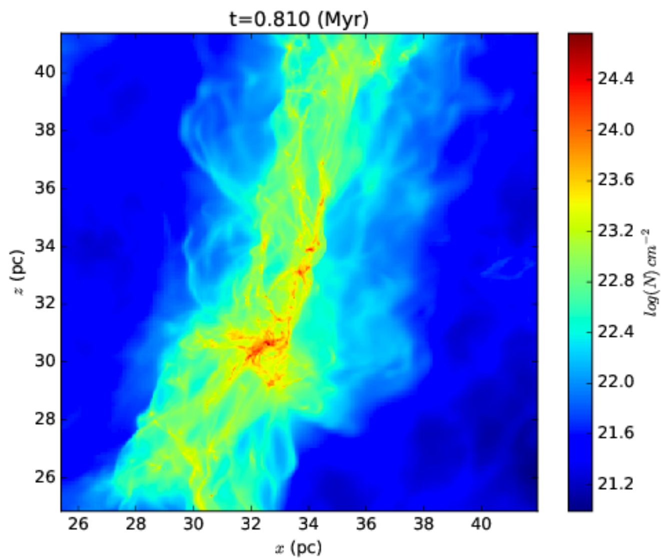


Velocity-coherent “fibers” in Taurus (Hacar+ 2013)









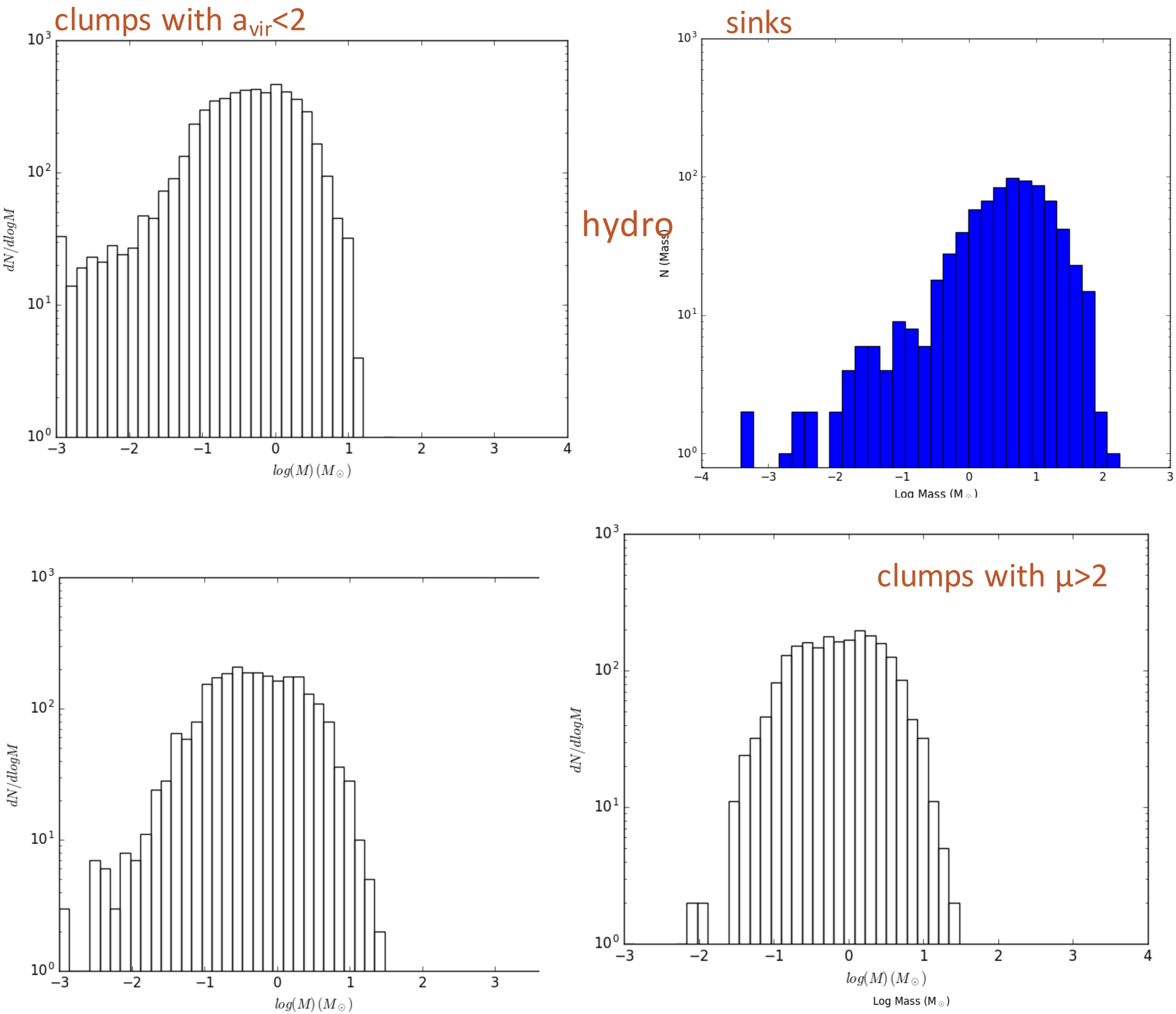
The simulation:

M = 10^5 Msol

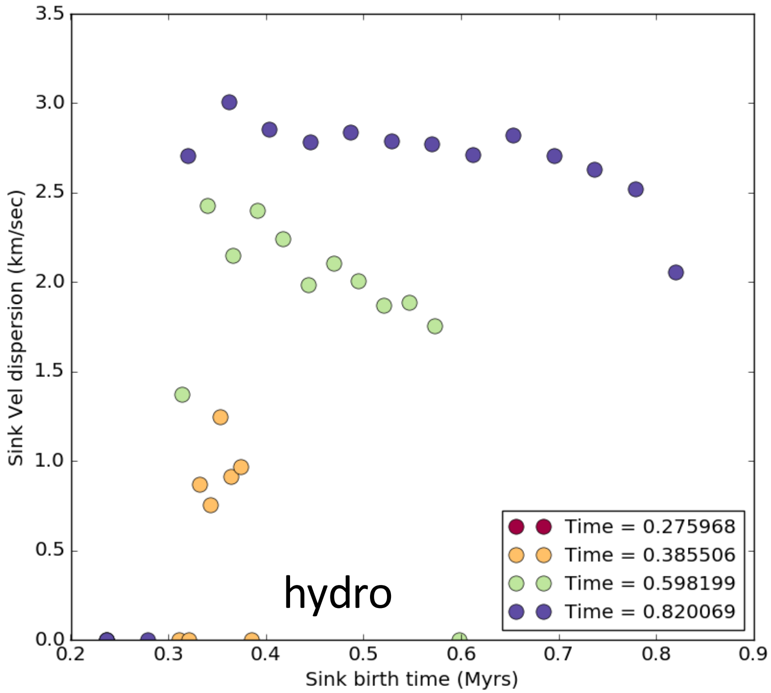
a_{turb} = 1

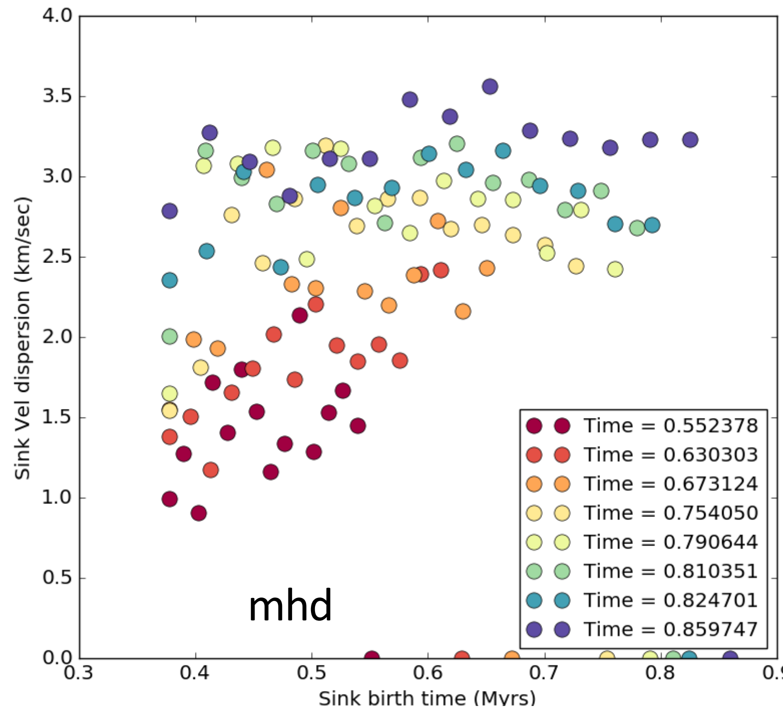
a_{mag} = 0.0 / 0.2

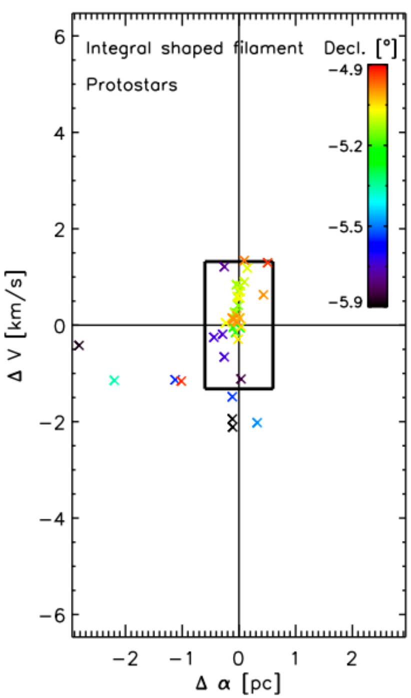
Sink formation above 10^8 cm^{-3} No feedback

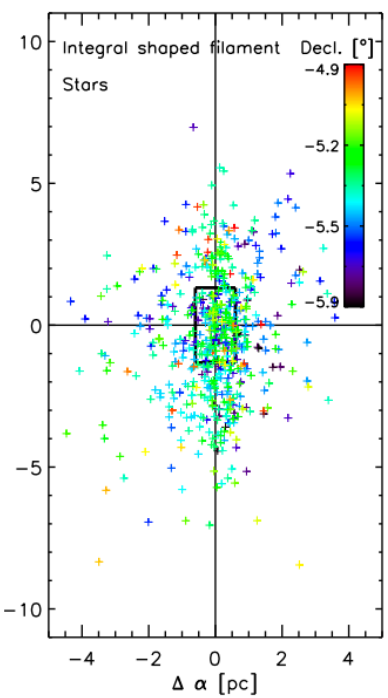


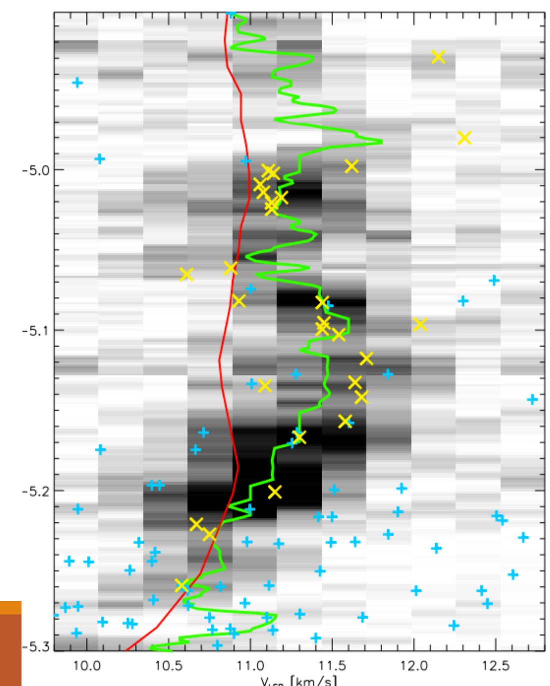
clumps with a_vir<2
sinks
hydro
clumps with μ>2
dN/dlogM
log(M) (M☉)
N (Mass)
Log Mass (M☉)


Sink Vel dispersion (km/sec)
Sink birth time (Myrs)
Time = 0.275968
Time = 0.385506
Time = 0.598199
Time = 0.820069
hydro


Sink Vel dispersion (km/sec)
Sink birth time (Myrs)
Time = 0.552378
Time = 0.630303
Time = 0.673124
Time = 0.754050
Time = 0.790644
Time = 0.810351
Time = 0.824701
Time = 0.859747
mhd


Integral shaped filament
Protostars
Decl. [°]
Δ V [km/s]
Δ α [pc]


Integral shaped filament
Stars
Decl. [°]
Δ α [pc]


V_{LSR} [km/s]

Open questions III

Many observed regions, like Serpens South, show evidence of gravitational collapse, which are easily reproduced by a simple model o an initially elongated, gravitationally unstable cloud, with a magnetic field and turbulence.

Can this initial condition just set from interstellar turbulence?

The observed velocity structures can only be reproduced by a narrow range of turbulence and magnetic field parameters.

Which properties are inherited from large scales during the phase transition?

Magnetic fields do not seem to affect the density profiles of the filaments, the stellar clustering, or the sink velocity dispersion, but the do affect the core and sink mass functions.

How is the stellar IMF related to the local magnetic field conditions?