From Filaments to Stars: a Theoretical Perspective

NRAO Filaments.

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Collaborators

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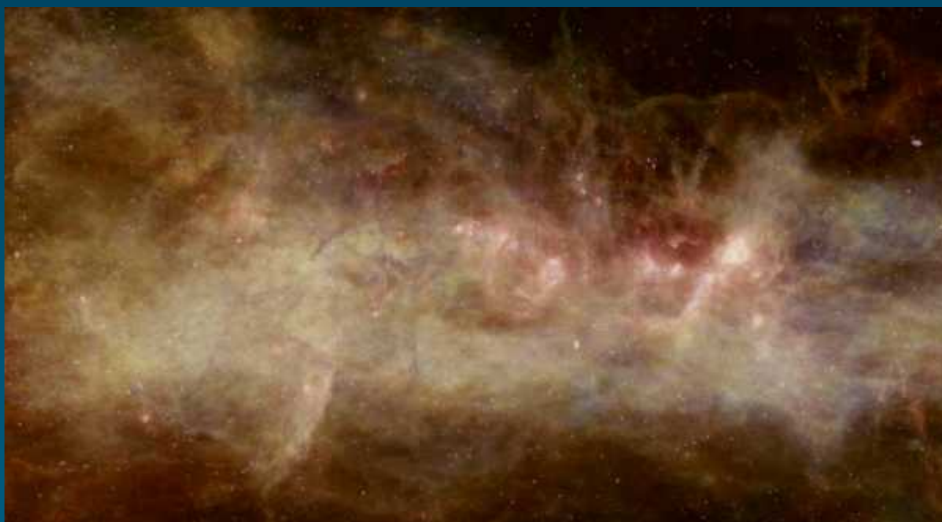
Ralf Klessen

… and PPVI Andre et al team

The observations: several complex processes in play:

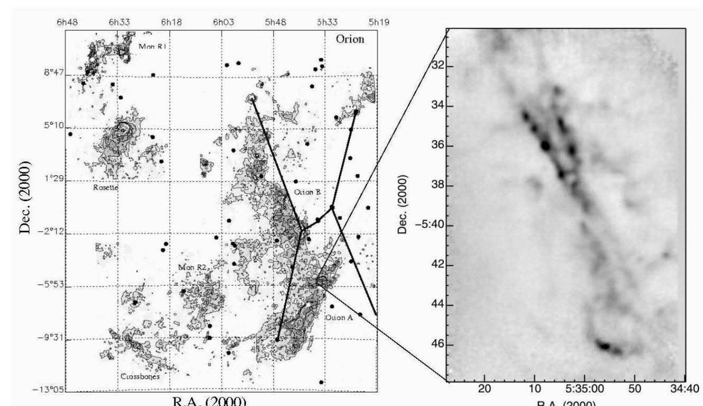
Turbulence controls structure formation ?



Diffuse Atomic Hydrogen in Milky Way (Canadian Galactic Plane Survey CGPS) near midplane towards Perseus.

Shocks and filaments on many scales, in diffuse and self-gravitating gas

Linked ?



Extinction map of Orion and Mon clouds (Cambresy 1998); right - Scuba continuum 850 micron map of 10 pc portion of cloud (Johnstone & Bally 2006)

Gravitational instability and star formation?

Herschel observations:
clouds are filamentary

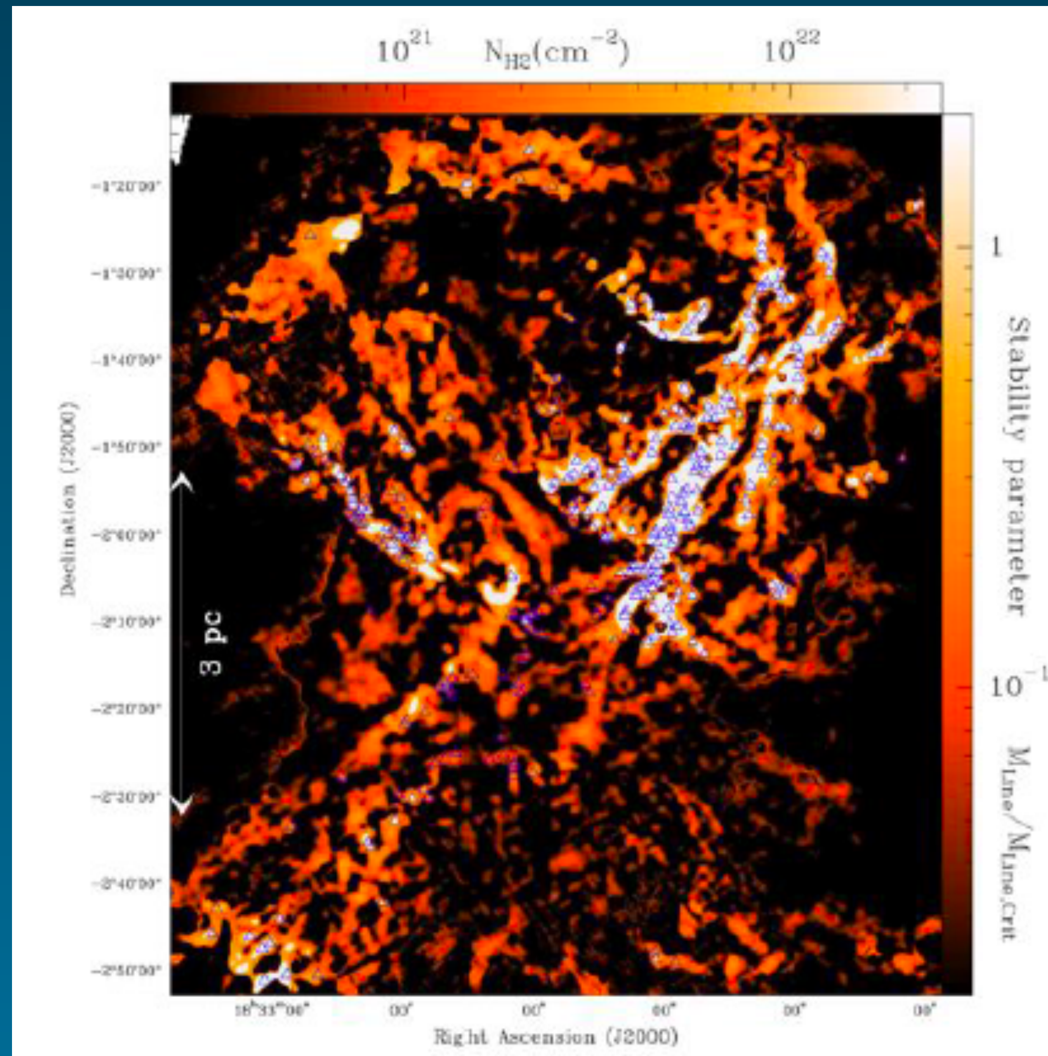
(Andre et al 2010, 2014 (PPVI)
Menshchikov et al 2011,
Henning et al 2010..)

- Cores are strongly associated with filaments

(> 70%; Polychroni et al 2013)

where

$$m > m_{crit} = 2\, c_s^2 / G$$

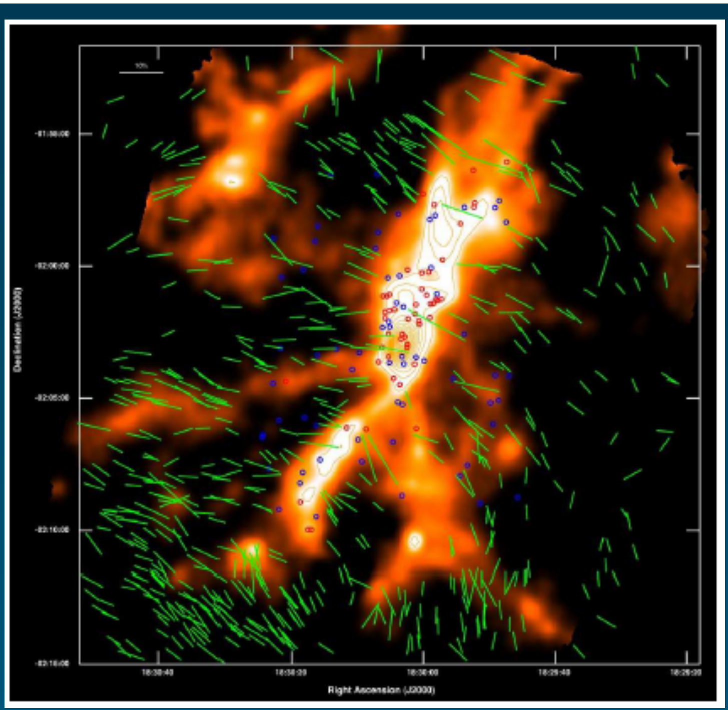


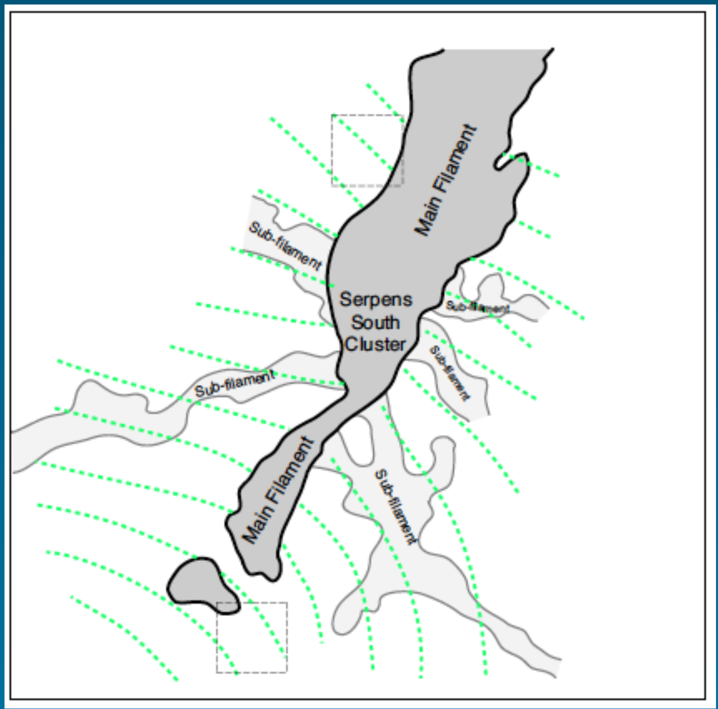
Aquila star forming cloud:
Andre et al 2010

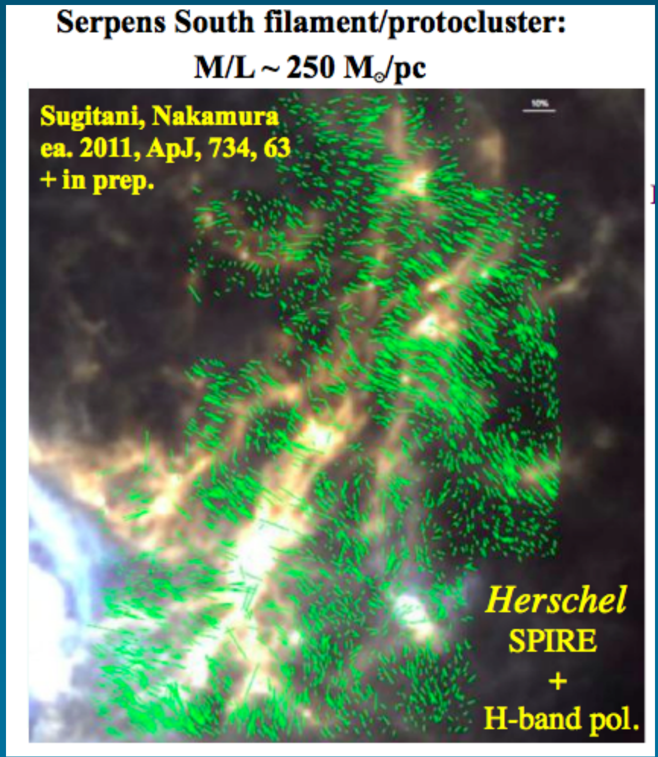
B fields - channel accretion flows or infall?

Infrared (H band) polarization overlaid on column density map + young stellar cluster

- Orientation – often perp to filament?
- Field strength ~ 100 μG





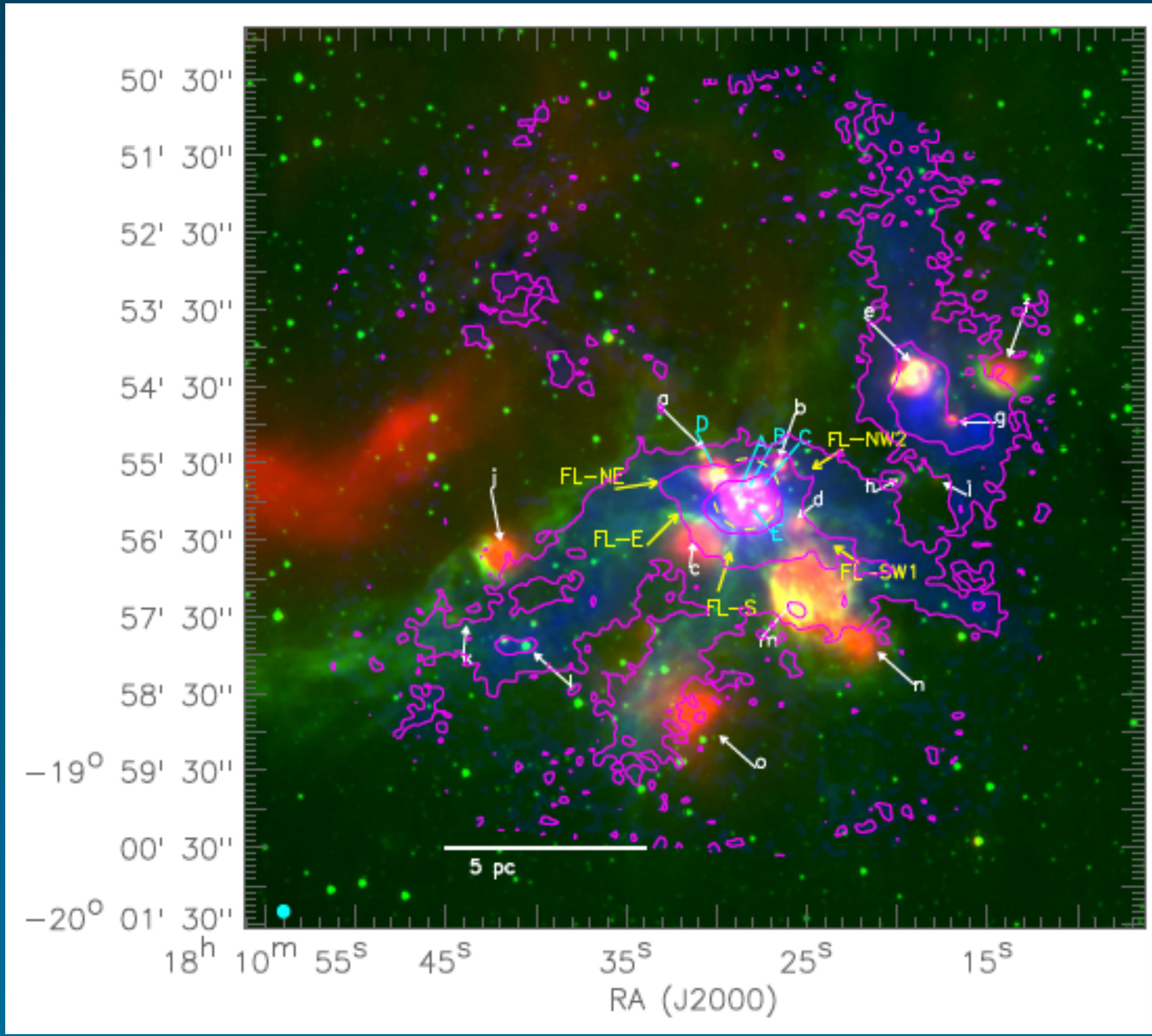


Radiative feedback from massive stars in young clusters – affect filaments? IMF?

Filaments and OB clusters, and HII regions in G10.6-0.4

(IRAM 30m MAMBO-2 bolometer array + SMA)

- 200 $M_{\odot}$ OB cluster
- Ultracompact HII regions: A-E



H.B. Liu et al 2011

I Equilibria and Their Fragmentation

Radial force balance for infinite cylinders with constant line mass

$m \sim \rho\, r^{-2} \sim \text{const}$:

The gravitational force: $F_g = 2Gm / r \sim r^{-1}$

Balance with pure radial (thermal) pressure gradient for polytropic gas (index γ)

$$F_p = \rho^{-1}\, dP/dr \sim r^{1-2\gamma}$$

So: radial pressure / gravitational force ~ $r^{2(1-\gamma)}$

POINT: $\gamma > 1$ stable (pressure wins for small r)

Y<1 unstable (pressure loses to gravity ultimately)

Thermal gas properties, filaments, and fragmentation

Fitting polytropic equation of state to different parts of the cooling curve: 2 states, low and high density

(Larson 1985, 2005; Koyama & Inutsuka 2000; low density – Benson & Myers 1989, Evans 1999)…

$$T \propto \rho^{-0.27} \quad \rho < 10^{-18} gcm^{-3} \quad (\gamma = 0.73)$$

$$\propto \rho^{+007} \quad \rho > 10^{-18} \quad (\gamma = 1.03)$$

Fragmentation depends on polytropic index:

$P \sim \rho^{\gamma}$ implies scaling $T \sim \rho^{(\gamma-1)}$

Cools as gas gets denser for $\gamma < 1$: Prone to fragmentation

Heats as gas gets denser for $\gamma > 1$: Stable to fragmentation

Consequences for molecular clouds:

Critical indices:	Geometry	γ_{crit}
	Sphere	4/3
	Sheet	0
	Filament	1

$\gamma = 1$ isothermal case: Can define critical mass per unit length for hydrostatic equilibrium:

$$m_{crit} = 2c_s^2 / G = 16\ (T/10\ K)\quad M_\odot\ pc^{-1}$$

(Stodolkiewicz 1963; Ostriker 1964, Inutsuka &Miyama 1997, Fiege & Pudritz 2000a,),

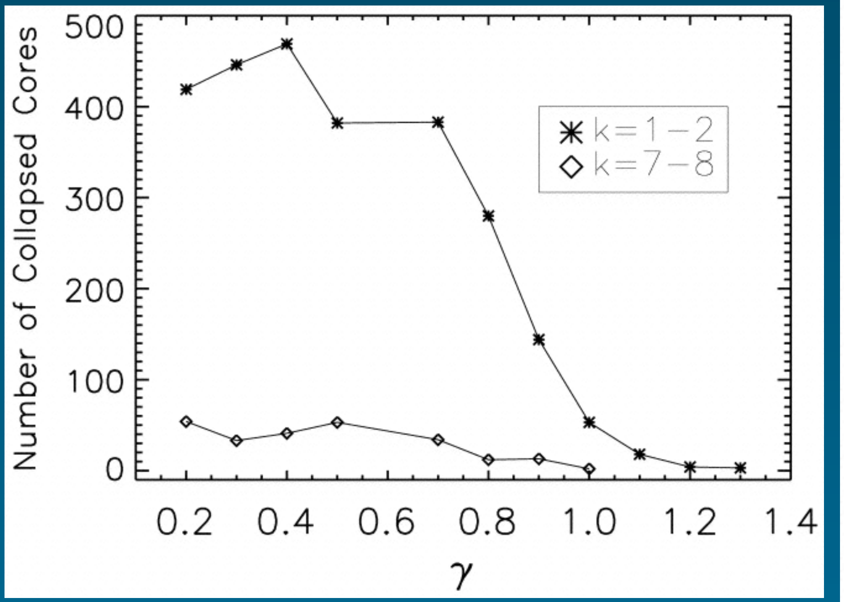
Highly filamentary molecular clouds – consequence of

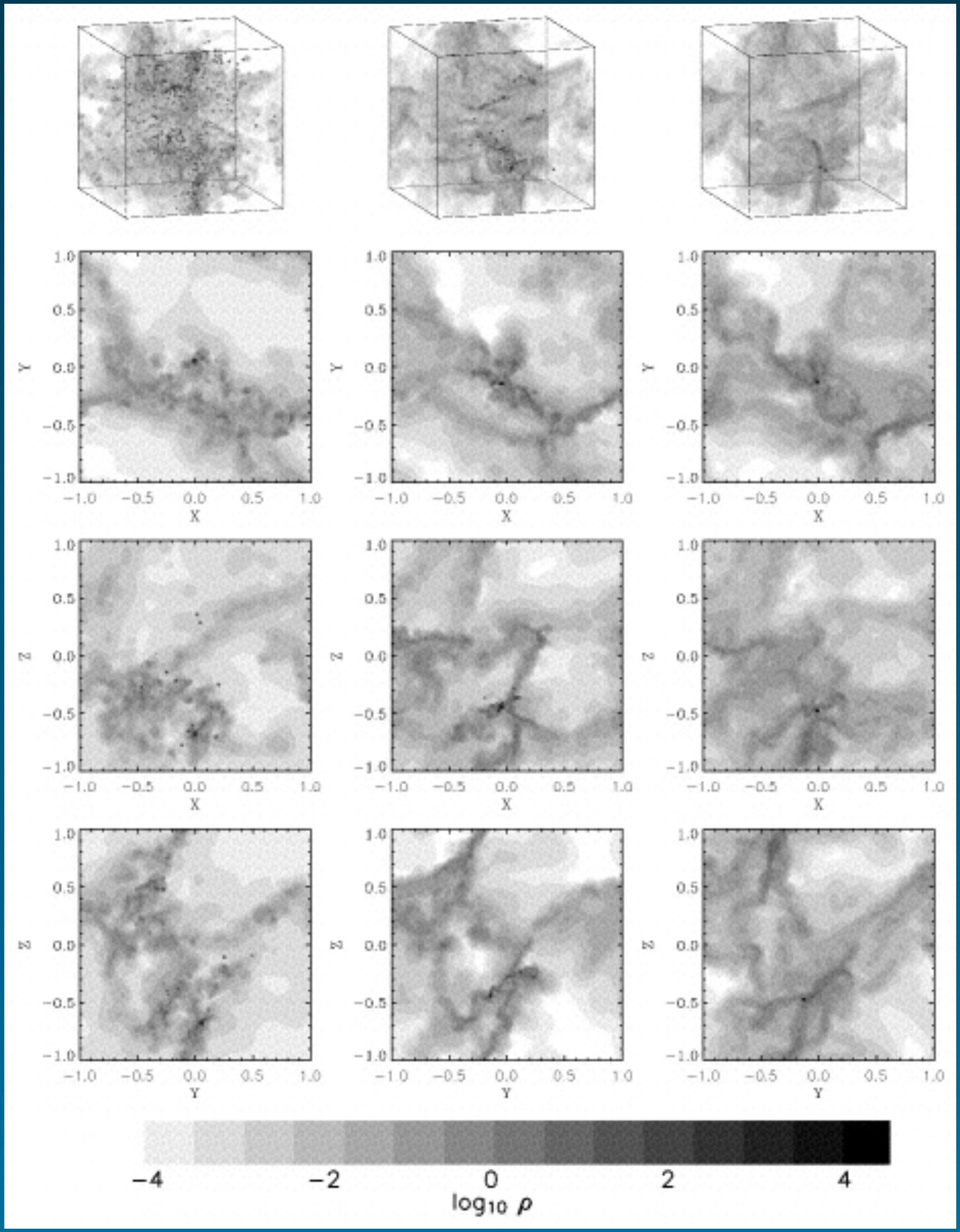
$$\gamma_{effective} < 1 \quad ?$$

(Koyama & Inutsuka 2000, Larson 2005, Andre et al PPVI review,…)

Fragmentation and Equations of State

- Strong fragmentation γ≤1
- Suppressed for γ>1, and ceases for γ>1.4





Result of thermodynamics + stability properties of filaments (Larson 2005)

Li, Klessen, & MacLow (2003)

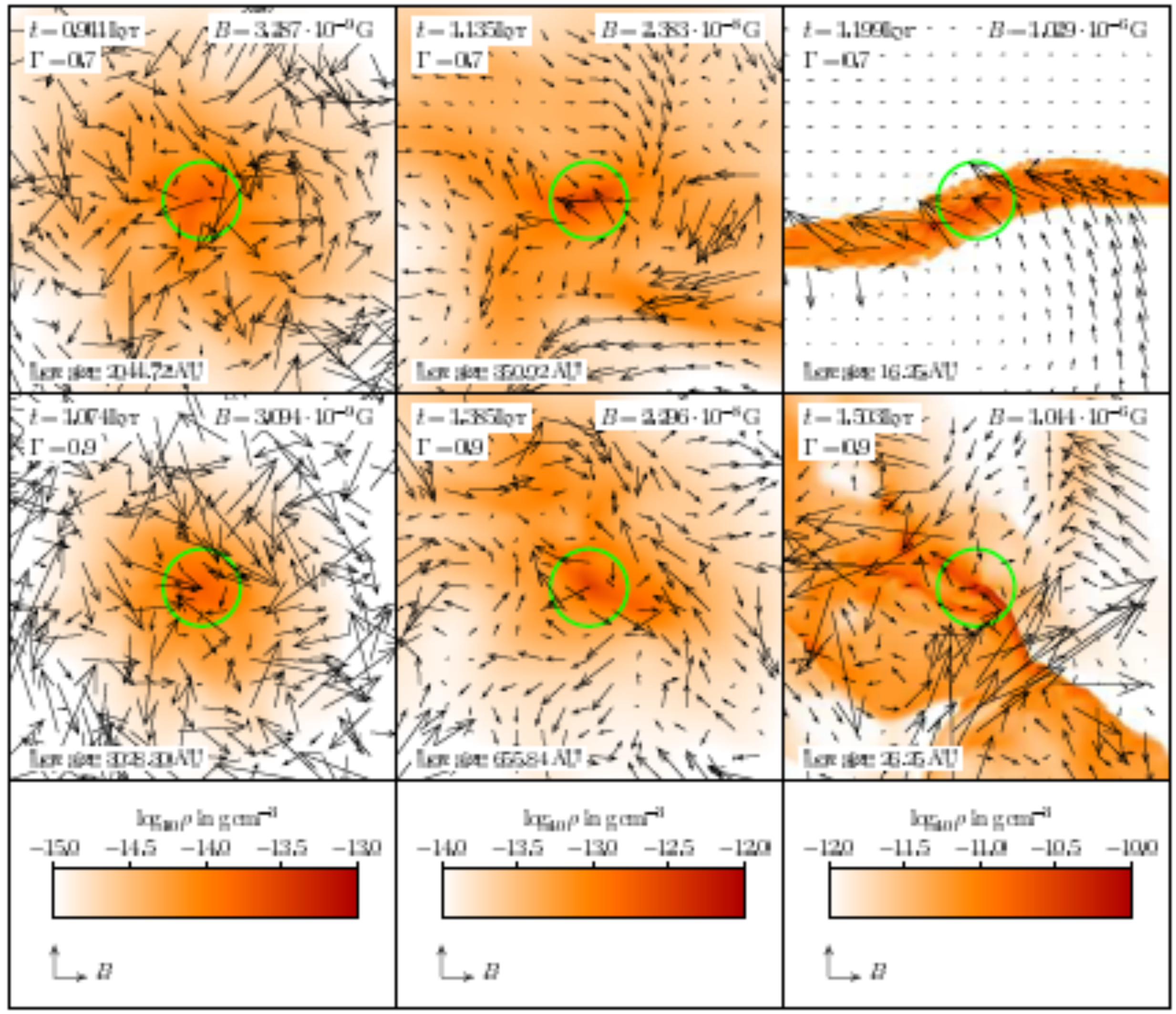
Filament formation: γ < 1

Top = 0.7

Bottom = 0.9

Filament forms more clearly for lower value

- Flow has strong shocks, intersecting sheets, and filaments
- B more ordered,
- More turbulence



Peters et al 2012

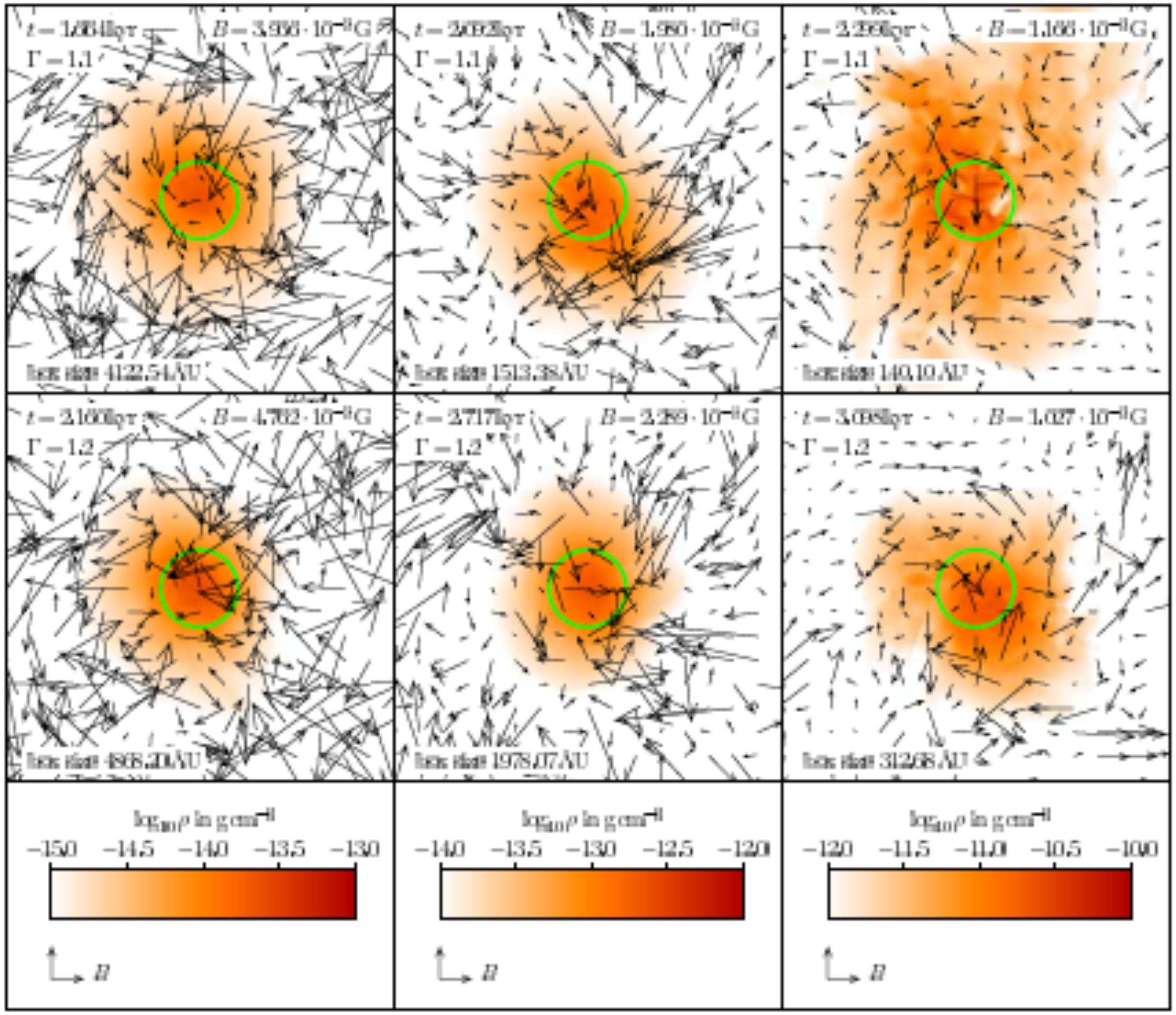
Filaments for γ > 1 ?

Top = 1.1

Bottom = 1.2

Pressure gradients slow the contraction

- Produces virialized core
- B more tangled
- Less turbulent



Complications – other forces.

Radial density profiles do not follow isothermal filaments (r^{-4})

MHD: Poloidal field supports cylinder against collapse – but a toroidal component (wrapping filament) *squeezes it*. (Fiege & Pudritz 2000)

-> Net magnetic contribution could be positive, *or negative*

Radial density profiles: $r^{-1.5} – r^{-2}$

Accretion: Filaments result of shock intersection – dynamic accretion not static equilibria. Get r^{-2} (simulations, Fabian's talk)

Turbulence: Changes the critical mass to

$$m_{crit} = 2\sigma^2 / G \; ; \quad \sigma^2 = c_s^2 \; (1 + M^2/3)$$

-> LARGE critical line mass until turbulence damps

Cores and stars from GI?

Polytropes:

- Radial collapse wins

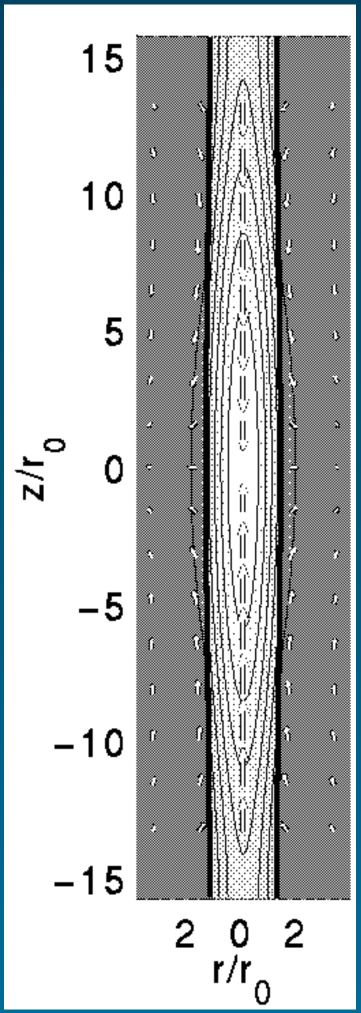
– halted as γ increases… then slower fragmentation

- Smaller than preferred mode in linear instability analysis.

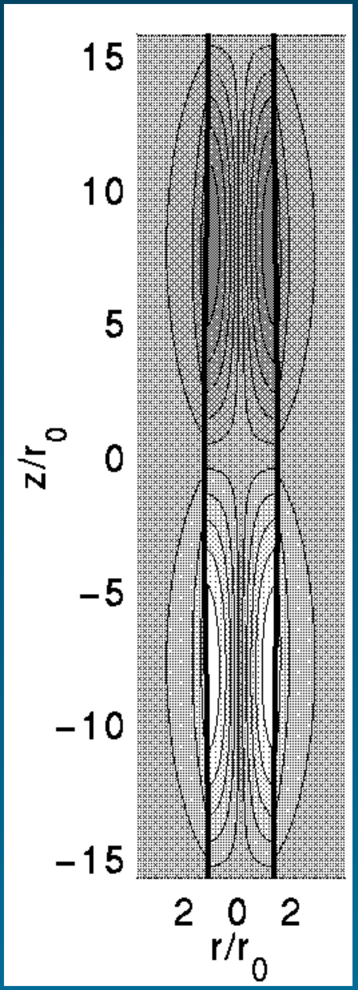
(Inutsuka & Miyama 1992, 1997)

** What determines fragmentation spectrum? IMF? **

General B field; induce twisting motions as well (Fiege & Pudritz, 2000b)



Density + Poloidal velocity



Toroidal velocity

II Making filaments and clusters

Clouds are not likely to be equilibria.   Dynamical process:

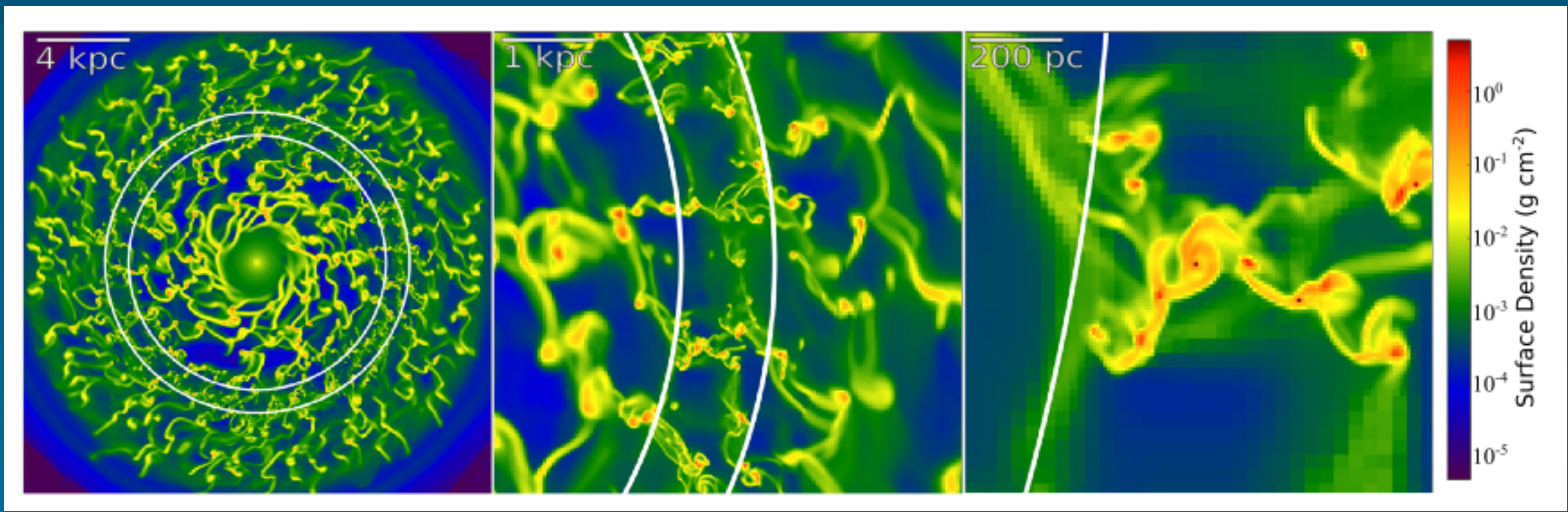
- Gravitational instability
  (galactic dynamics, filaments (nonlinear evolution),….)
- Turbulence
- Shocks (compression, vorticity generation,…)
- Magnetic fields (channeling, squeezing,…)

Filaments (large scale) connected with GMC formation

- Colliding flows (Heitsch et al 2008, Banerjee et al 2009,..) produce highly turbulent, filamentary clouds

- GI via Toomre instability (Tasker 2011, Dobbs et al 2011, Bournaud et al 2010, Agertz et al 2009, Benincasa et al 2013);

Long filaments from shear + cloud-cloud tidal interaction



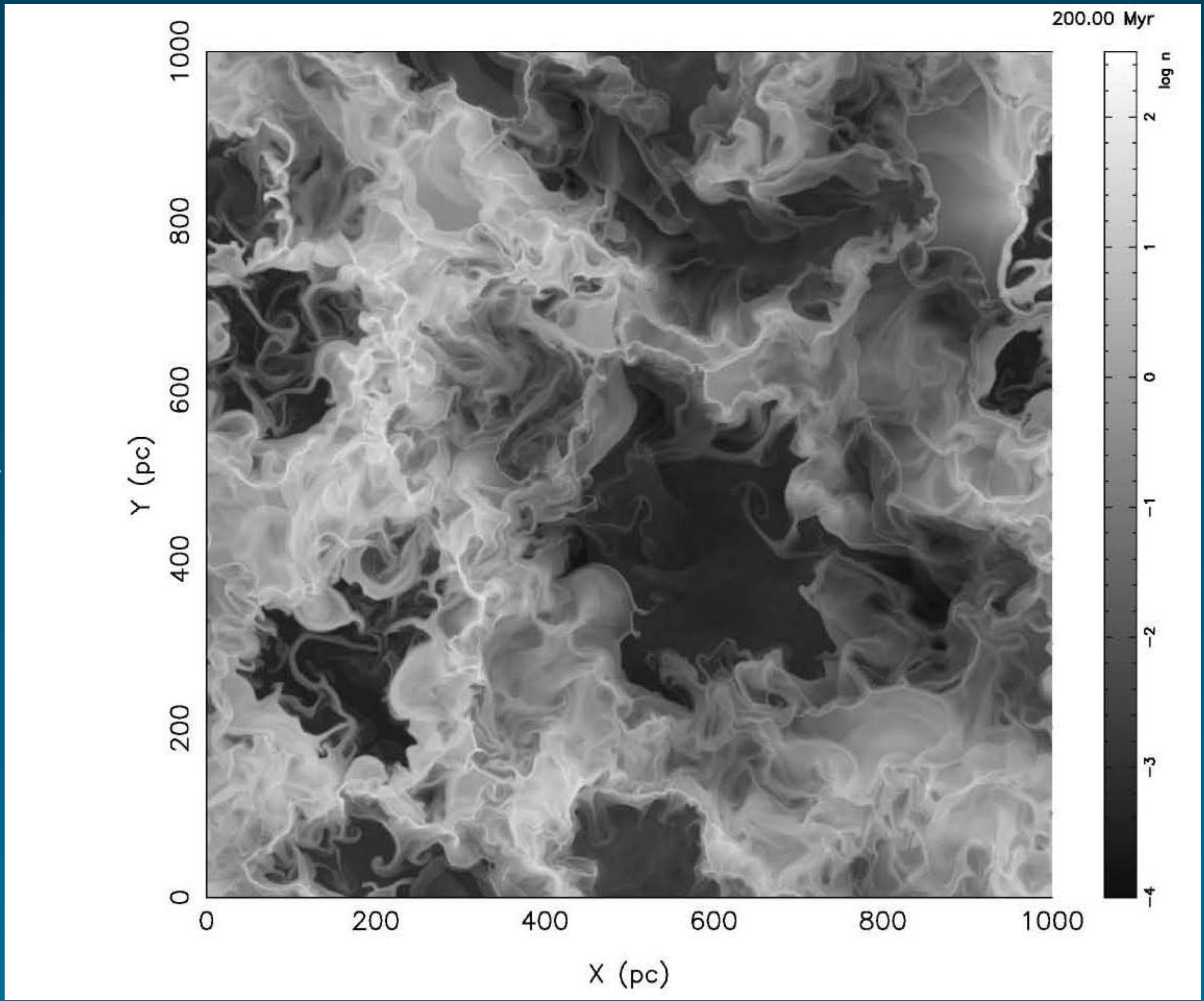
Benincasa, Tasker, Pudritz, & Wadsley 2013, ApJ : (No Feedback)

Super Nova driven structure and turbulence in the galactic disk

3D, SN driven shocks:

Simulations done for galactic disk with numerical resolution 1.25 pc

Broad range in density enhancements, several orders of magnitude



Avillez & Breitschwerdt (2003) – density contrast

Turbulence

Turbulence, filaments, and turbulent fragmentation

-Theory; eg. Larson 1981; Elmegreen & Scalo (2003)

-Reviews: eg. MacLow & Klessen 2004; McKee & Ostriker 2007; Bonnell et al 2007

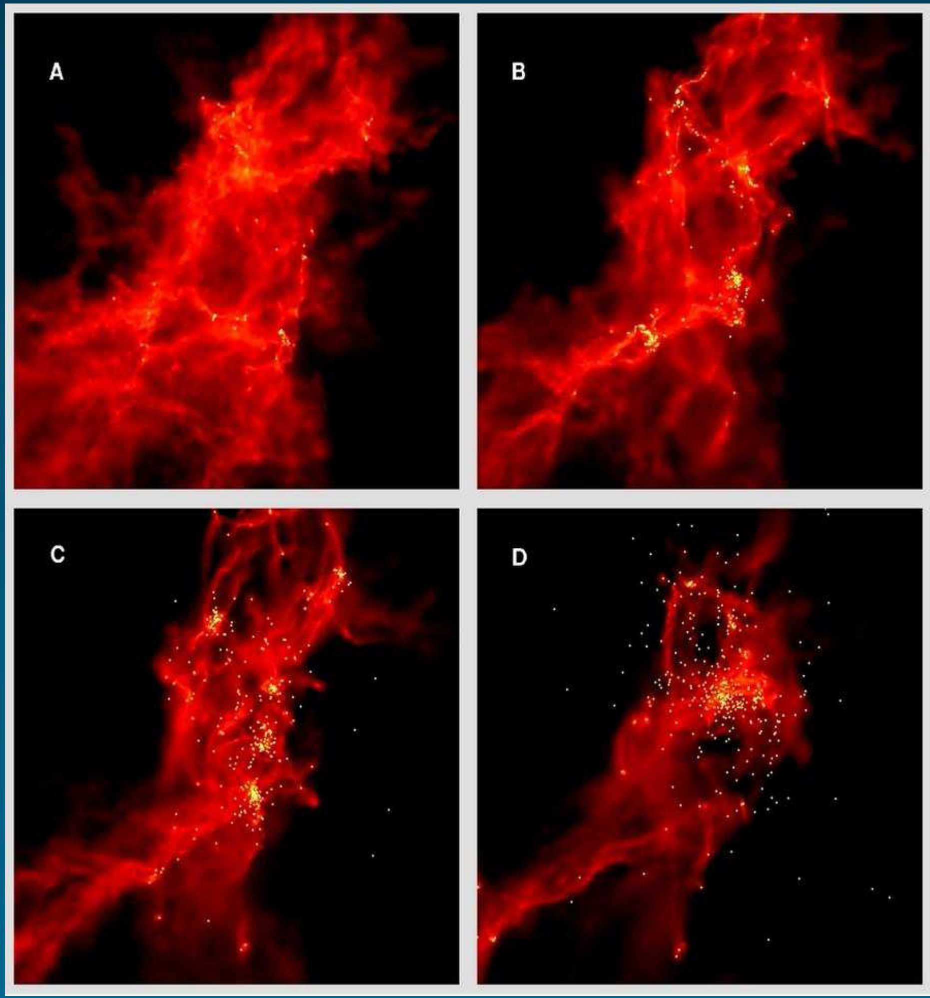
- Simulations; Porter et al 1994; Vazquez-Semadeni et al 1995, Bate et al 1995, Klessen & Burkert 2001; Ostriker et al 1999, Padoan et al 2001; Tilley & Pudritz, 2004,2007; Krumholz et al 2007, Federrath et al 2010,…

Shocks dissipate turbulent support as t^{-1}

(eg. Ostriker 2001)

Gas flows along filaments into local potential minima – cluster formation regions

(eg. Banerjee et al 2006, R. Smith et al 2012, Kirk et al 2012,..)



Bonnell et al (2003)

QUESTIONS:

Turbulent “fragmentation” drives CMF (eg. Padoan & Nordlund)
– or gravitational fragmentation of filaments?

Sources of “turbulence” in molecular gas

- galactic spiral shocks, supernovae, cosmic ray streaming, expanding HII regions, K-H and R-T instabilities, gravitational and thermal instabilities, … (eg. review Elmegreen & Scalo 2004)

Does the source of turbulence matter?

Theory; eg. Larson 1981; Elmegreen & Scalo (2003)

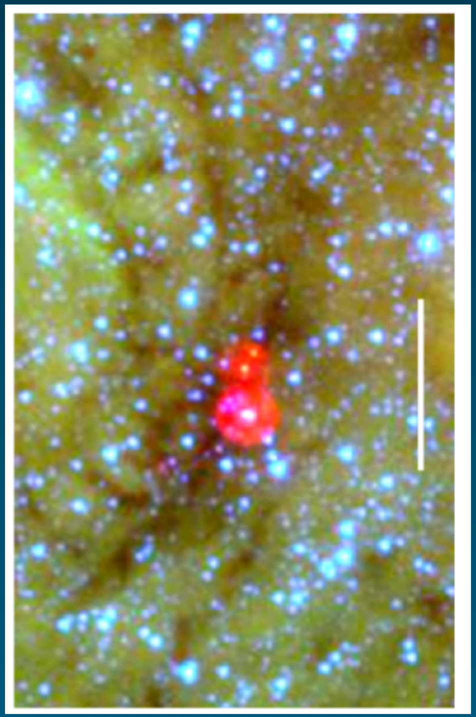
Reviews: eg. MacLow & Klessen 2004; McKee & Ostriker 2007; Bonnell et al 2007

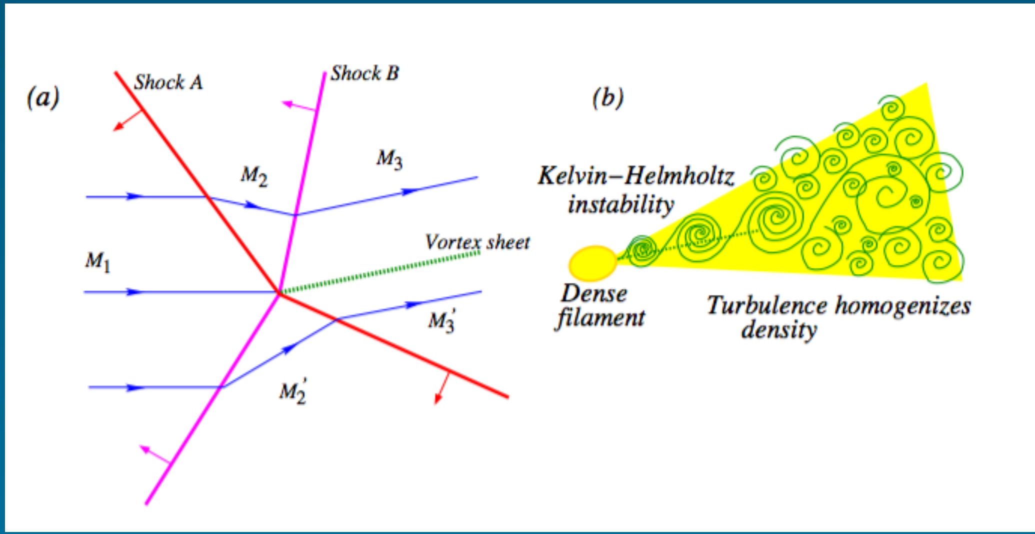
Simulations; Porter et al 1994; Vazquez-Semadeni et al 1995, Bate et al 1995, Klessen & Burkert 2001; Ostriker et al 1999, Padoan et al 2001; Tilley & Pudritz, 2004,2007; Krumholz et al 2007, Federrath et al 2010,…

Shocks:

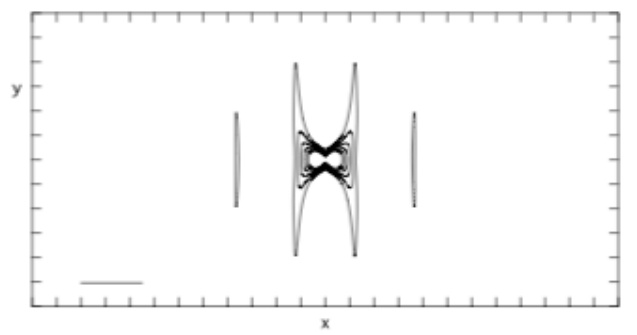
Shock produced sheets fragment into filaments. -> Filament/ hub systems and cluster formation (Myers 2009)

Intersecting oblique shocks produce filaments, sheets (MacLow & Klessen review 2004)





Pudritz & Kevlahan 2012



Myers 2009

Initial conditions matter!

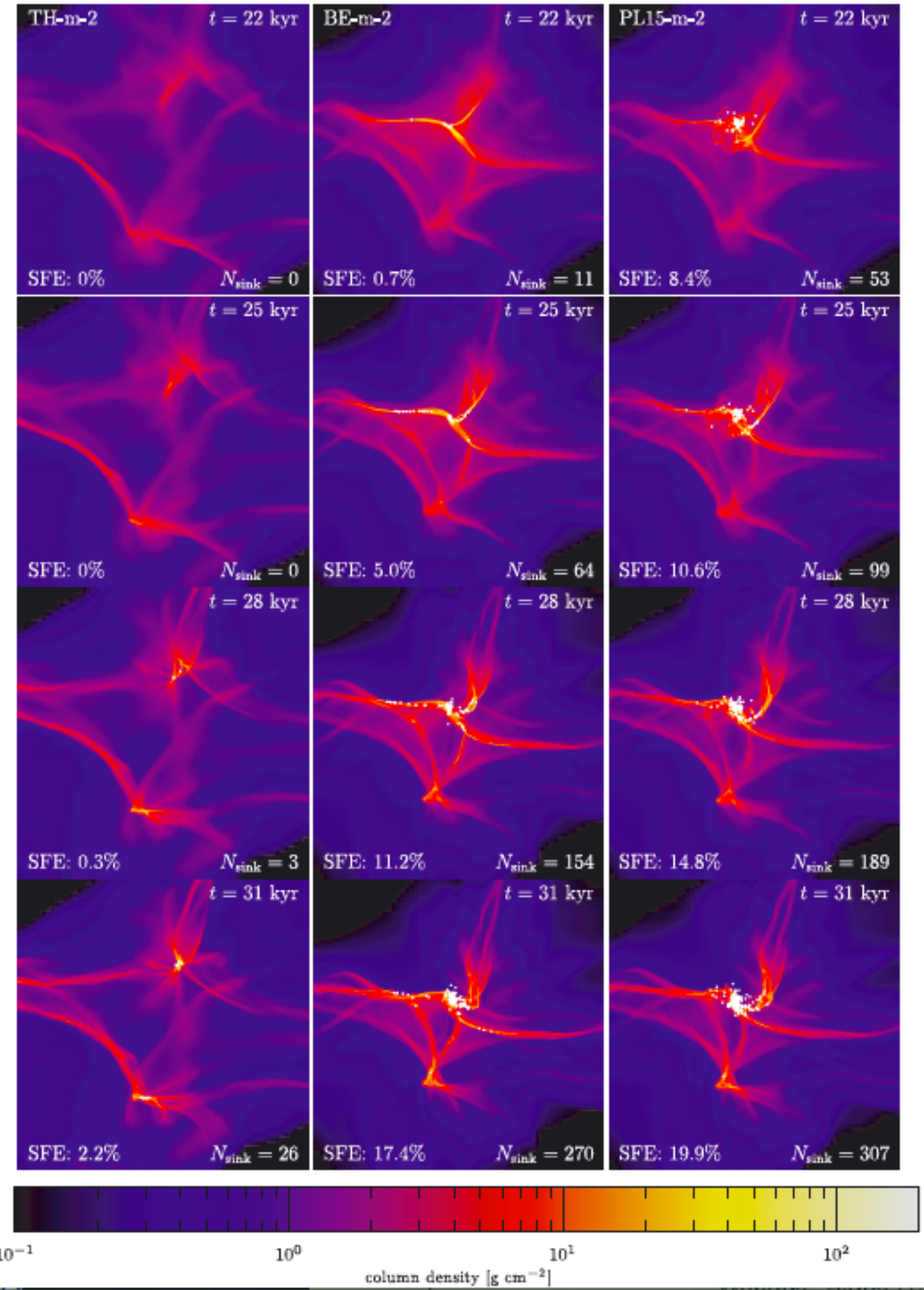
Different cloud density profiles are *most important factor*

TH = top hat: many sinks in filaments, subclusters and merging in outskirts, few high mass stars

PL15 = r $^{-1.5}$: one massive sink in centre in early stage, becomes most massive particle

BE= rescaled Bonner-Ebert – one central particle

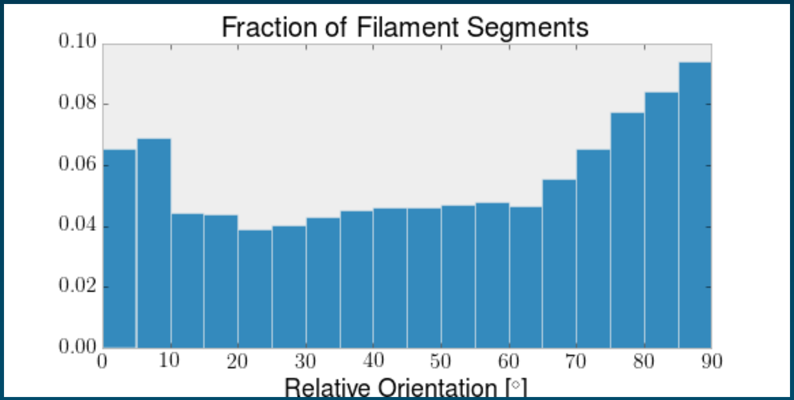
Initially: 100 $M_{\odot}$ of gas

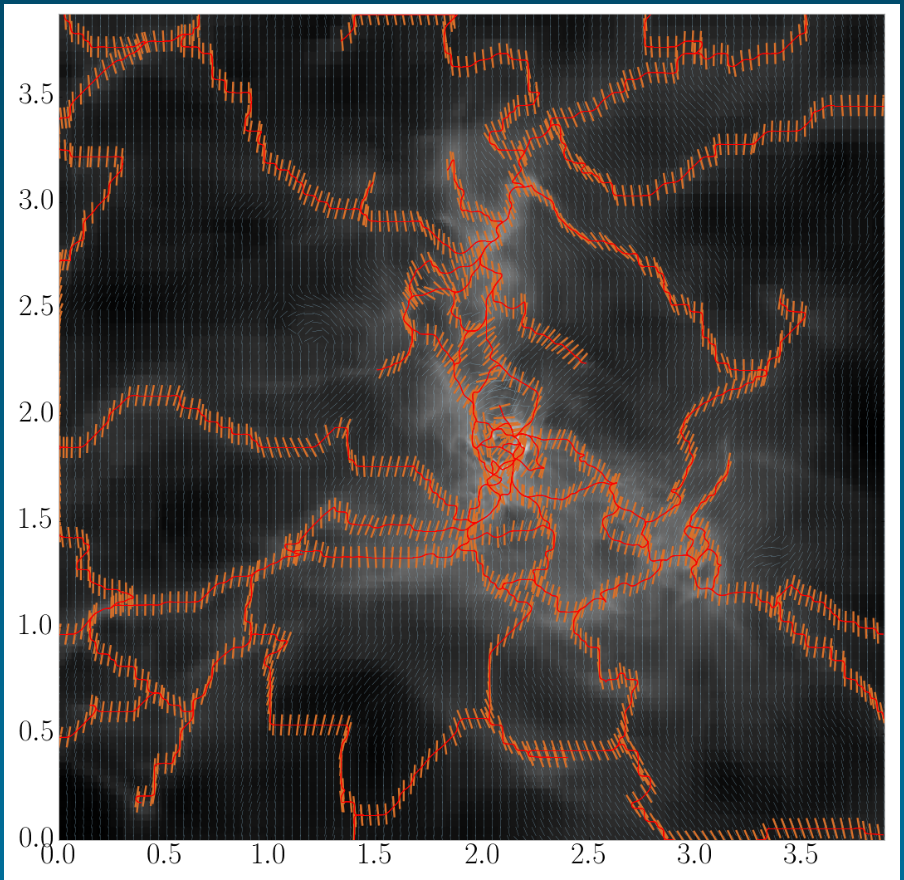


Girihidis et al 2011

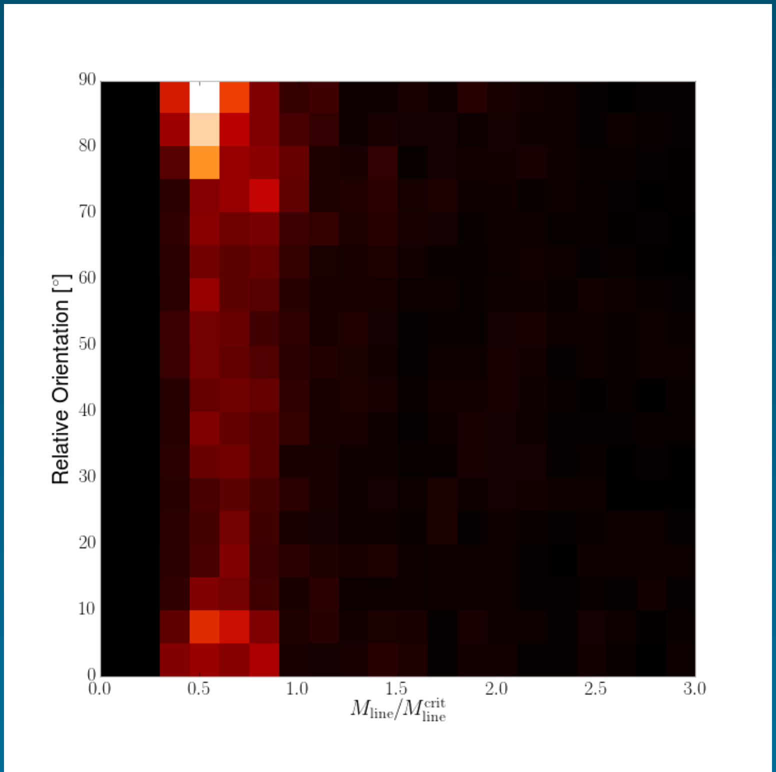
B and filaments

Look at B relative to filaments identified by DisPerse (Klassen, Pudritz, & Kirk, 2014) – 2 peaks, but broad band too…





Filaments as in Kirk et al 2014

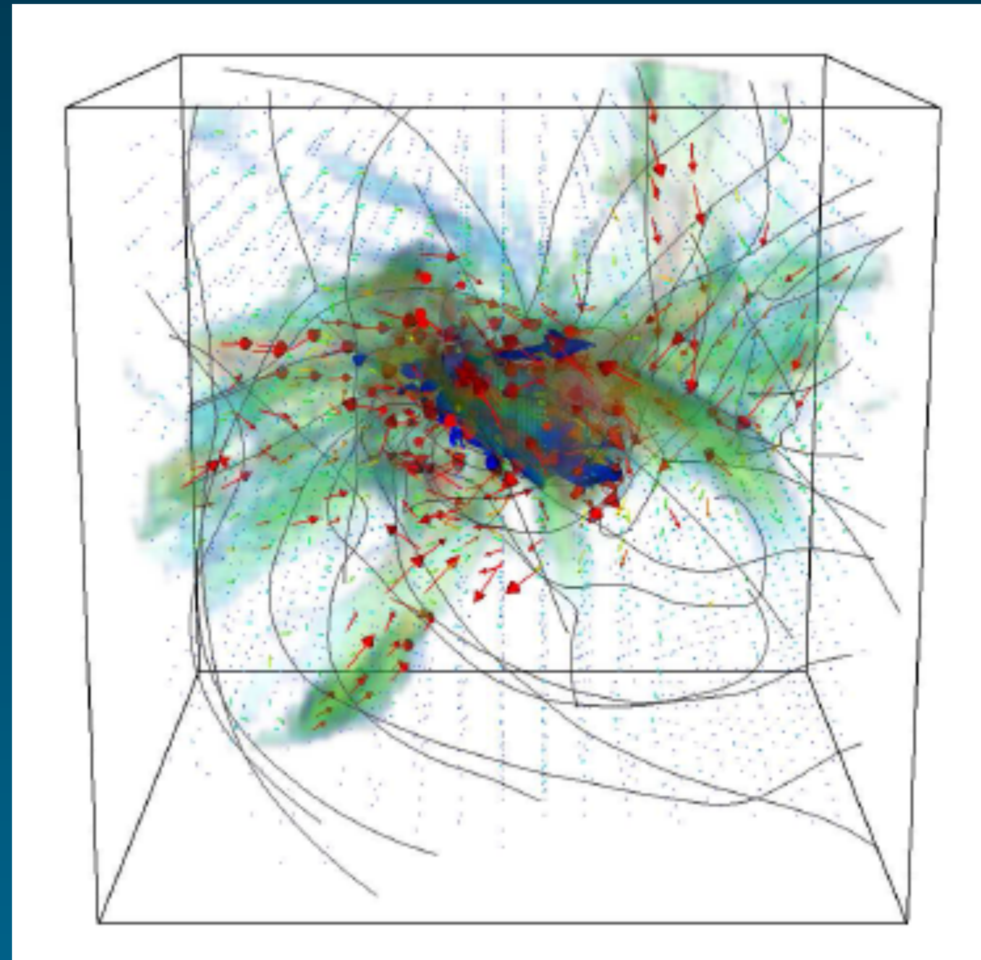


Angles vs m/m_{crit}

Getting down to stellar scales – filamentary flow and disk formation

-large scale filamentary
 flow onto disk: links
 0.1pc to sub AU
 scales (Banerjee, Pudritz, & Anderson 2006):

Multiple filaments and disk formation
(Seifried, Banerjee, Pudritz, & Klessen 2014, astro-ph)



1300 AU scale, 100 $M_{\odot}$, no initial rotation, velocity vectors, B (black lines), forming Keplerian disk (blue), filaments (green)

III. Radiative Feedback

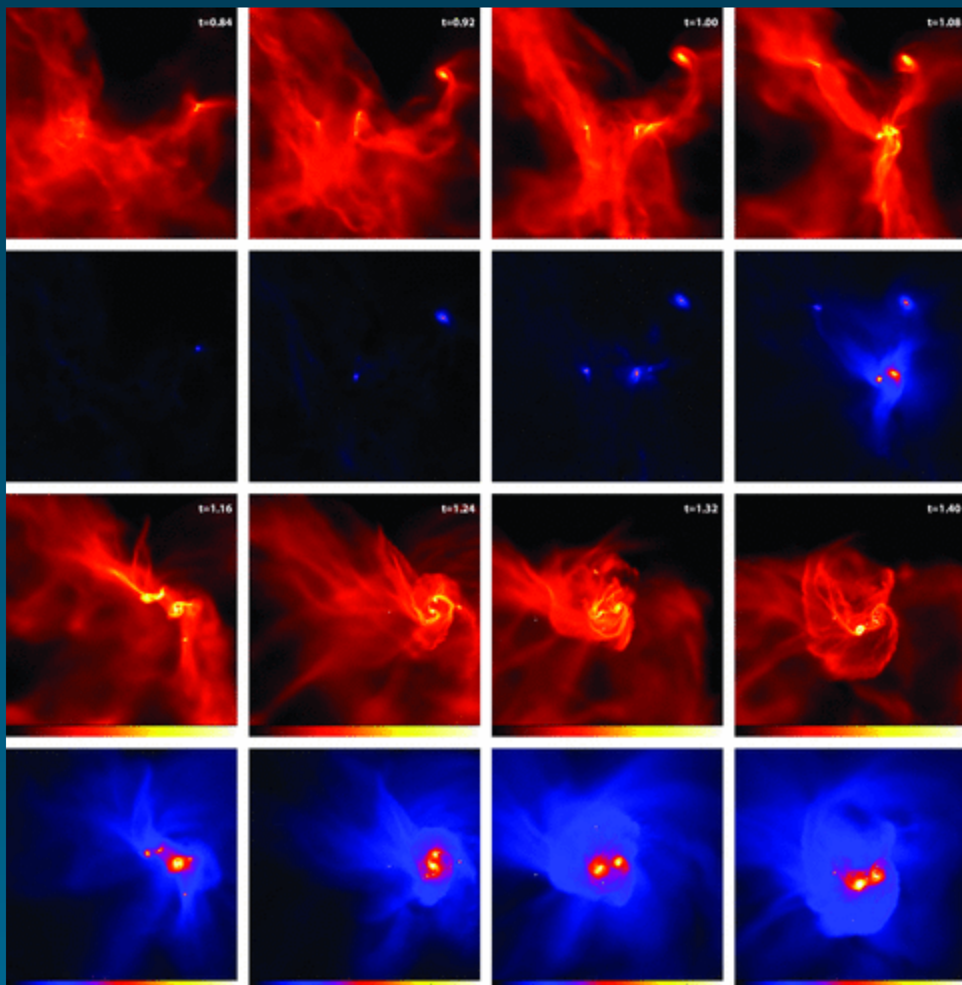
Radiative effects in 2D; Yorke & Bodenheimer, 1999, Yorke & Sonnhalter (2003)

Need to prevent excessive fragmentation found in standard turbulence + cooling simulations (3D turbulent dynamics: Krumholz et al 2007)

- Important source of energy – accretion luminosity
- radiative feedback from massive stars: raises Jeans Mass

$$M_J \propto T^{3/2}$$

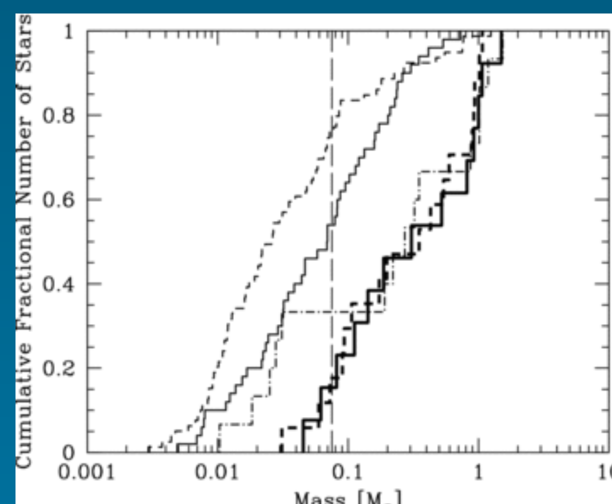
- filaments don't fragment – gas drains into primary and its disk
- prevent fragmentation out to 1000 AU scales



Bate (2009)

Radiation heating in a cluster environment:

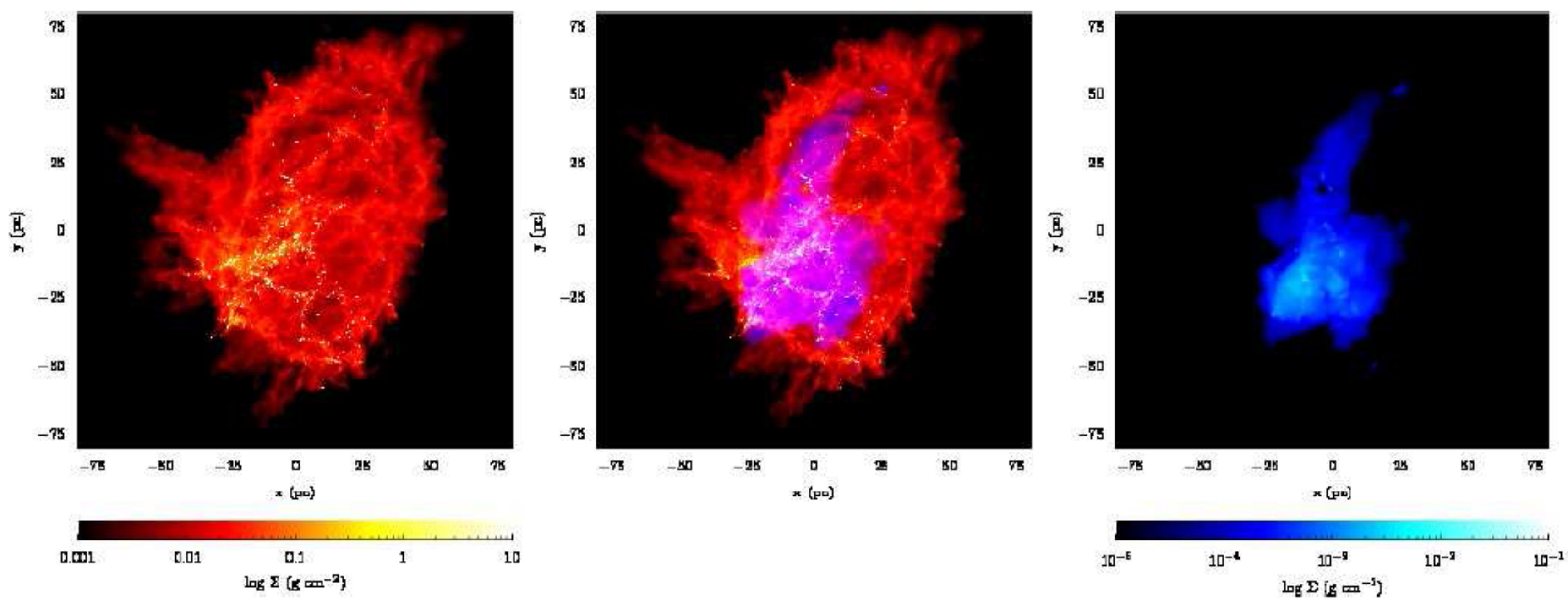
- Filaments drain material into central region
- Feedback from forming stars affects dense material in central region
- Suppression of objects by factor 4; produces stars/ brown dwarfs = 5



Problem - ionization does not erode dense cold filaments (Dale & Bonnell, 2011)….. how does accretion stop?

Ionize diffuse gas in the voids instead – filamentary structure has major implications for efficiency of feedback, and therefore SFR

Break the filaments with outflows? (Wang et al 2010, poster paper yesterday by Adele Plunkett)



(b) Column density plots of cold neutral gas and stars (left panel), cold neutral gas and hot ionized gas (centre panel) and hot ionized gas alone (left panel) 1.08 Myr after ionization was turned on.

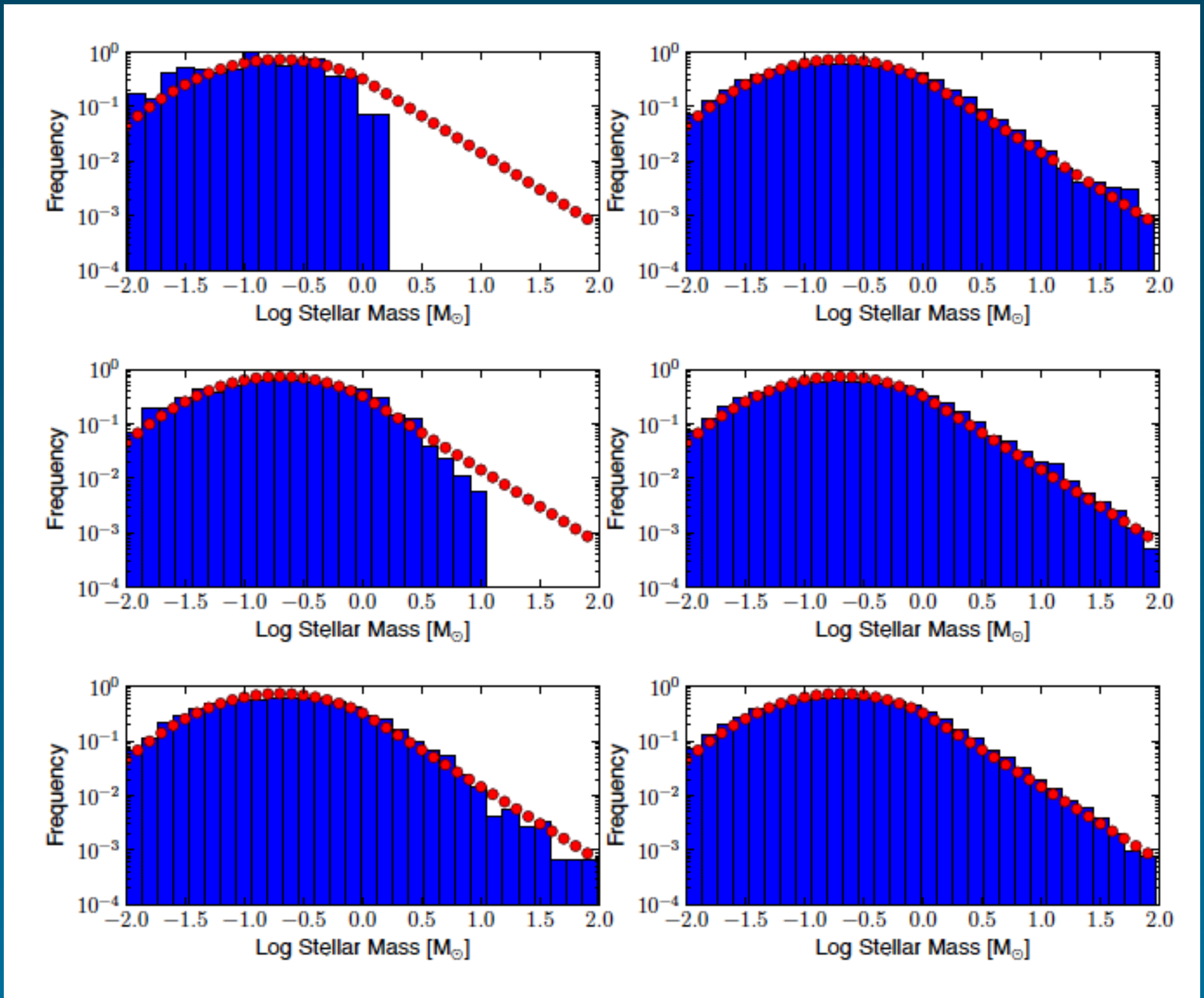
Cluster formation: stellar populations, star formation rates, and ionizing radiation

(Howard, Pudritz, & Harris 2013)

Subgrid model for cluster: random sampling of IMF – in clumps (sinks) with initial mass, and ongoing accretion

Columns (M_o yr^{-1})
Left = 0
Right = 2.8 x 10^{-2}

Rows, initial gas: 10^2, 10^3, 10^4 M_o



Cluster L, ionizing flux, and SFR

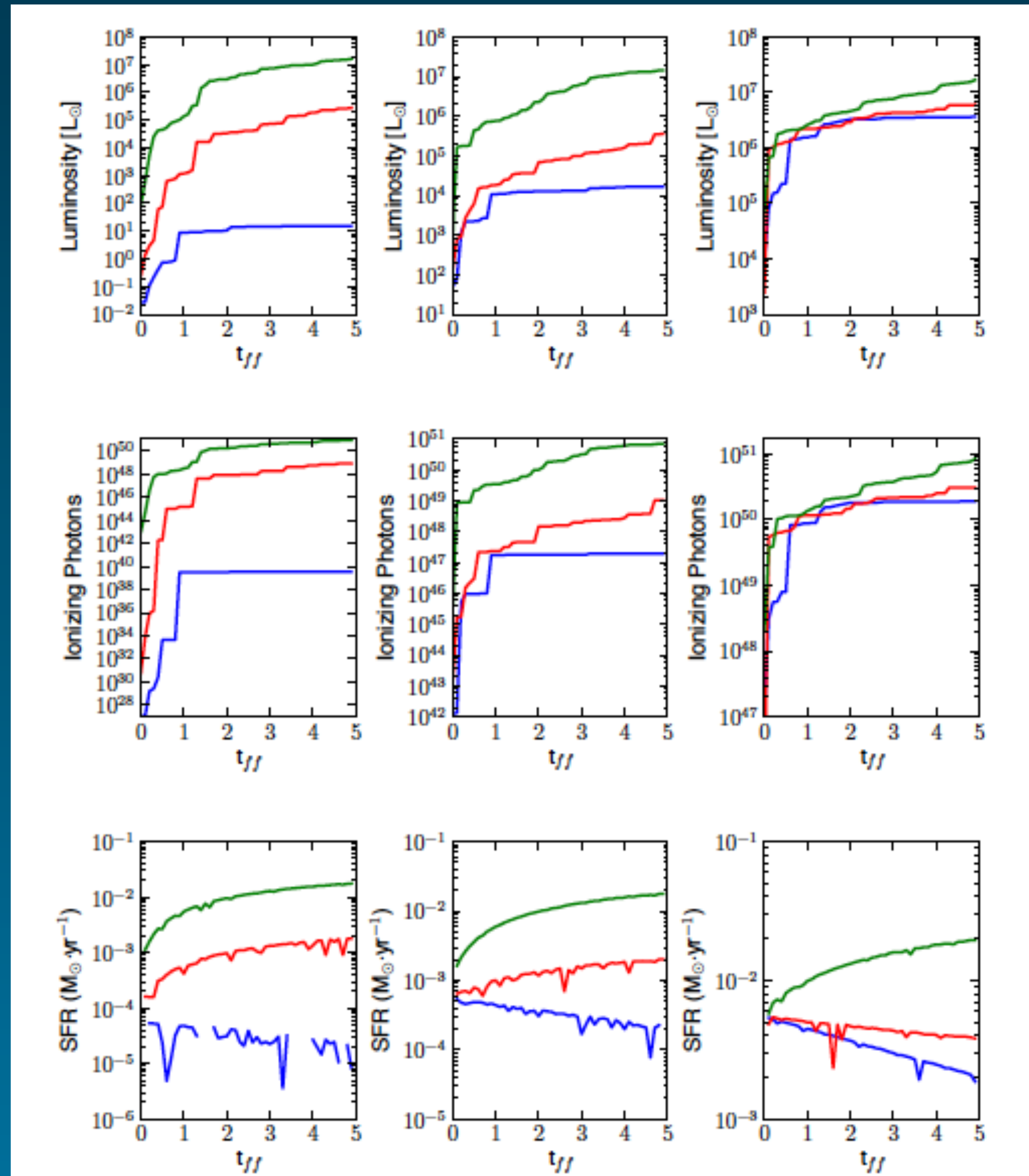
Columns: Initial masses of gas 10^2, 10^3, 10^4 M_o

Accretion rates (fixed) onto sinks: (M_o yr^{-1})

Blue - 0

Red - 2.8×10^{-3}

Green - 2.8×10^{-2}

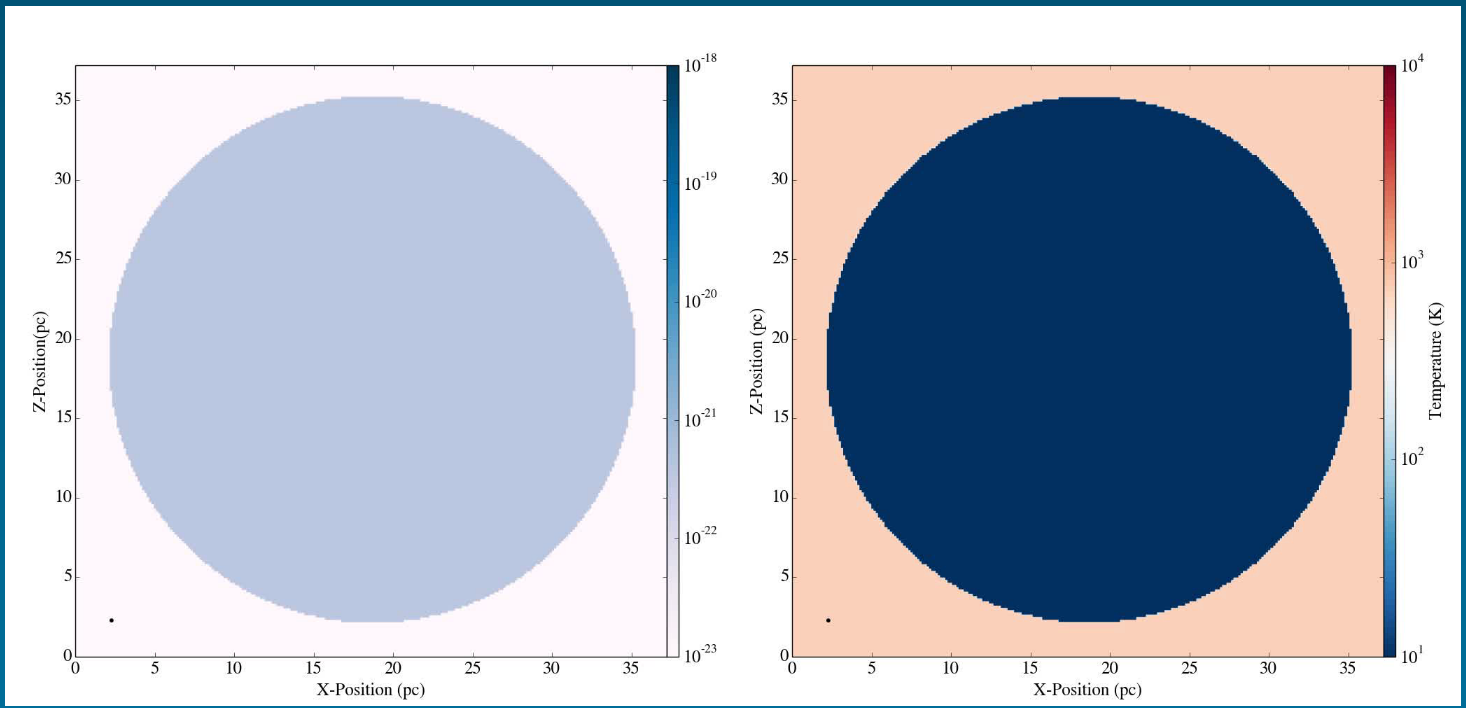


Cluster Formation and Feedback in a GMC - links to filaments

Radiative feedback from evolving IMF in cluster sink particles – using ray tracing from sources, not FLD…

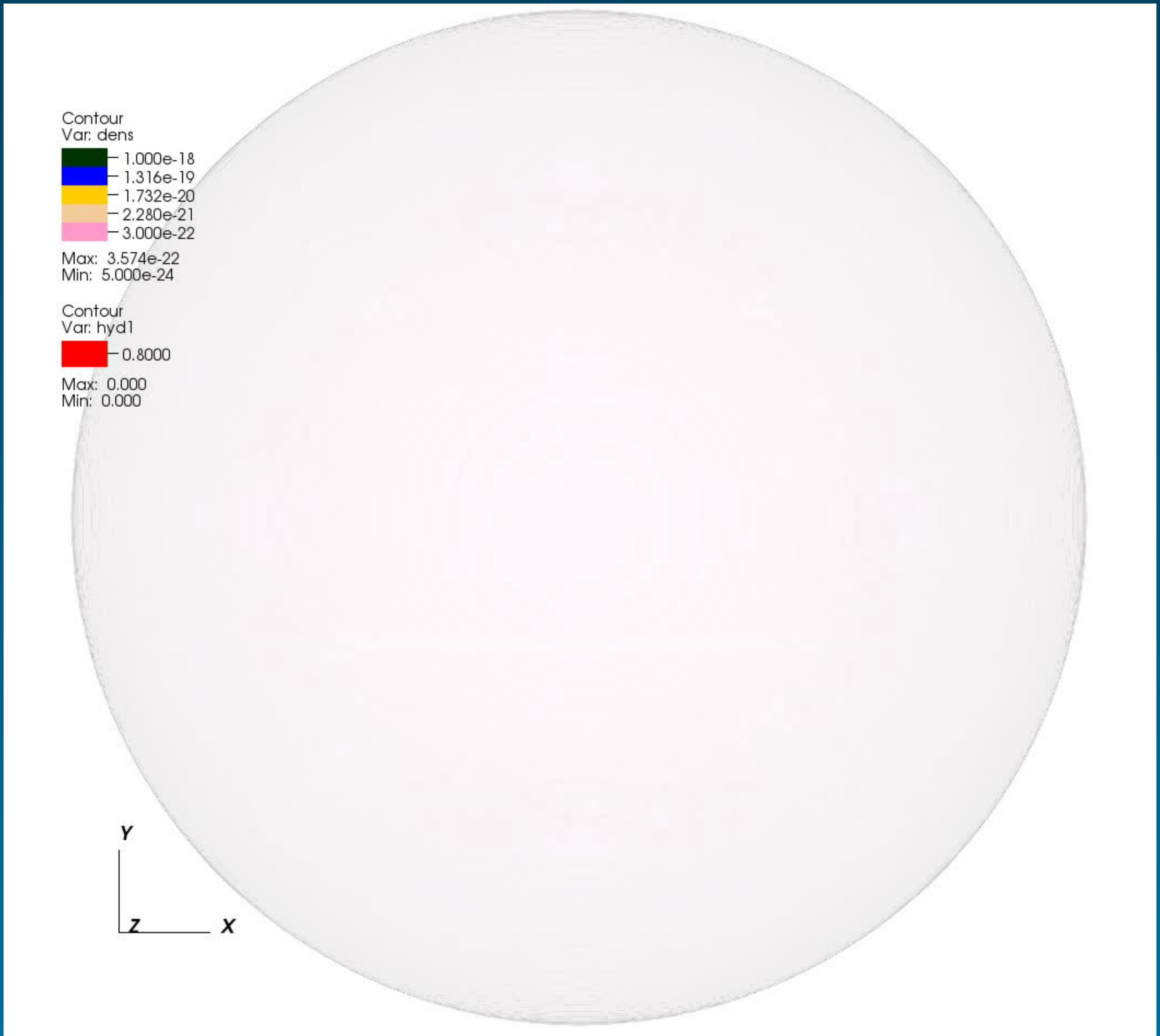
- Cloud: virial parameter = 1, n=100 cm^{-3}, box 32 pc, profiles flattop, powerlaws; low rotation (2 %), mass 10^5 $M_\odot$
- Ionization, thermal heating, radiative momentum..

Howard, Pudritz, & Harris 2014, in prep



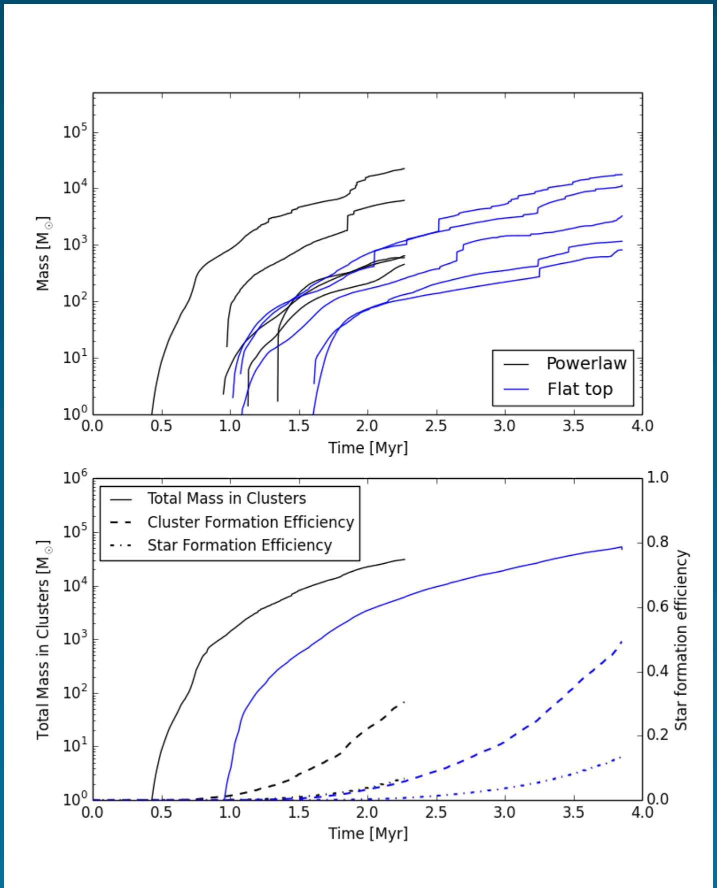
Density Temperature

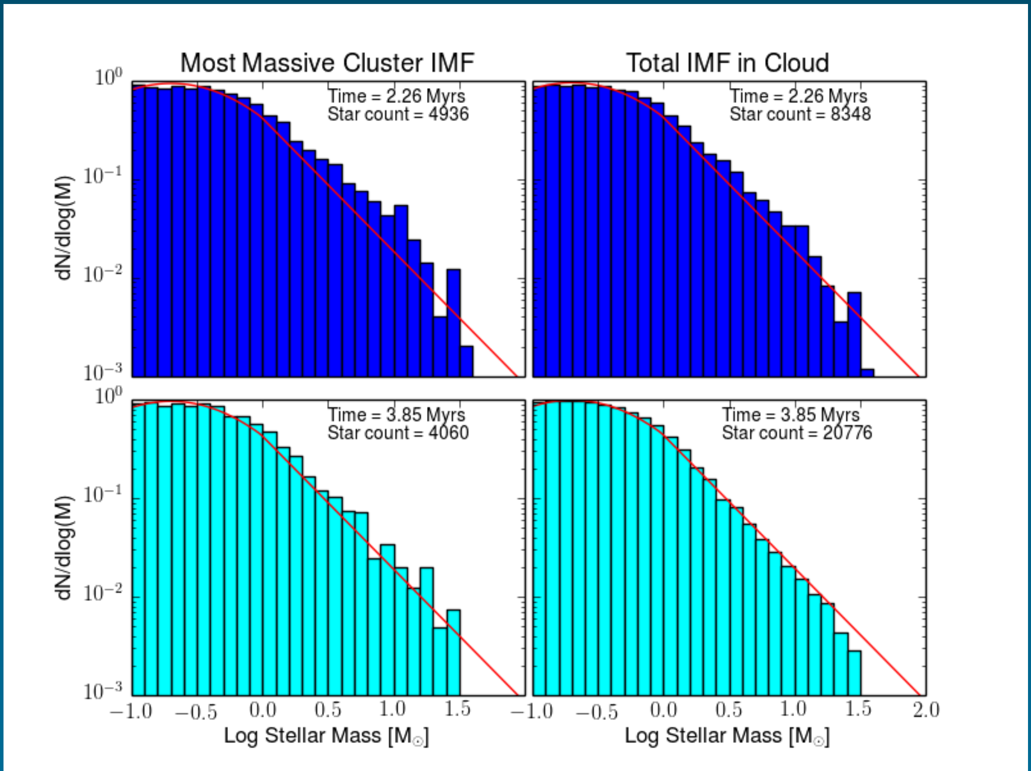
3D Visualization: filaments, HII regions



Heirarchical formation of larger clusters –

- many subclusters merge
- initial conditions matter (eg. flat topped vs power law)
- radiative feedback not sufficient to prevent high star formation efficiency..





Power-law (blue), flat top (cyan)

Summary

- How filaments change our ideas of star formation:

  - a physical mechanism for core formation (GI)
  - a new way of understanding accretion processes – large scales essential for the story
  - multiscale connectivity in density, velocity, B, – clouds to stars
  - challenge for feedback – how do you turnoff accretion? If by outflows – then B is fundamental since outflows are hydromagnetic.

- Filament formation: thermodynamics, turbulence, gravity, B, shocks - what is essential ?
-