The role of magnetic fields in star formation

“The low metallicity ISM: chemistry,
turbulence, and magnetic fields”

Goettingen, Oct. 8-12, 2012

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Collaborators

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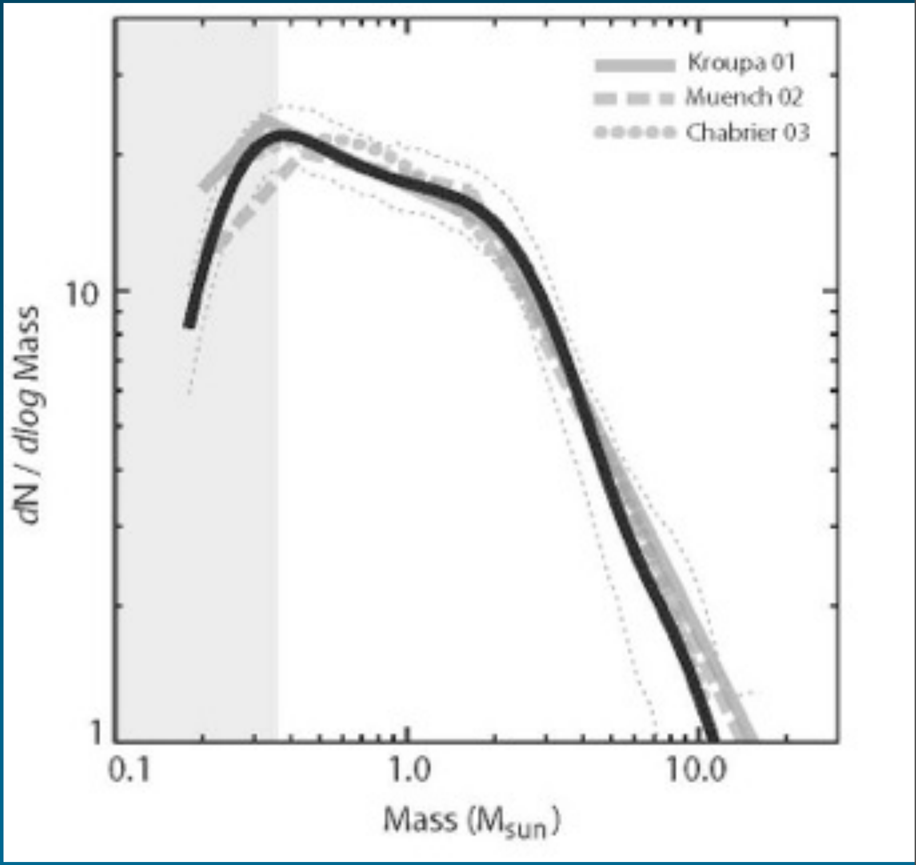
Star formation: IMF

- IMF well described as (eg. Chabrier 2005):

- Salpeter power law above 1 M_o
- Lognormal below this mass down to 10 Jupiter masses
- Characteristic mass at ~0.2 M_o.
- Evidence of universality: disk, spheroid, young and old globular clusters, … ?

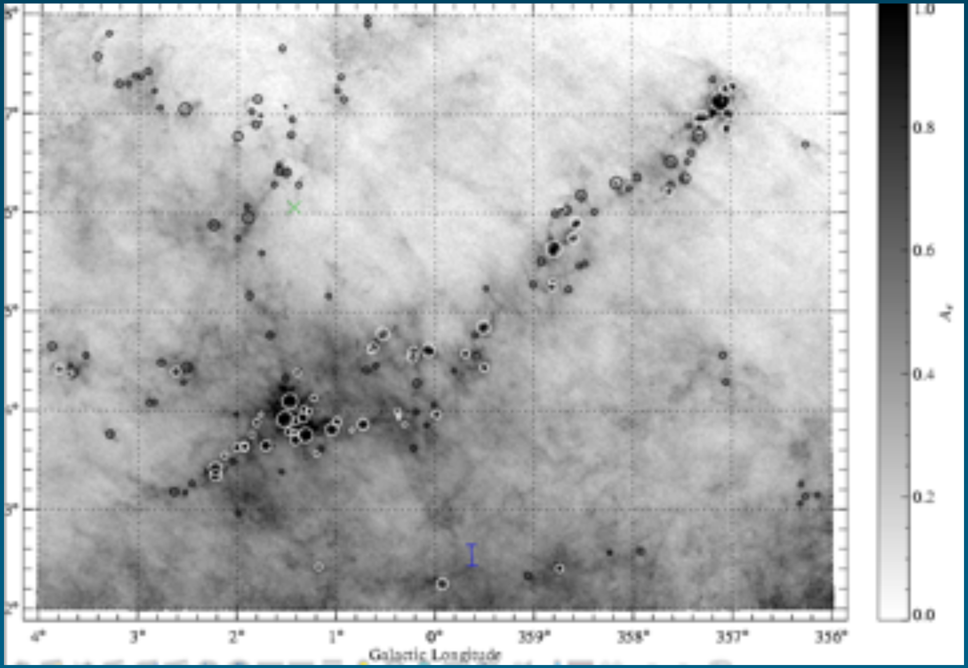
- Do B fields affect this?



Alves et al 2007

Star formation efficiency and rates:

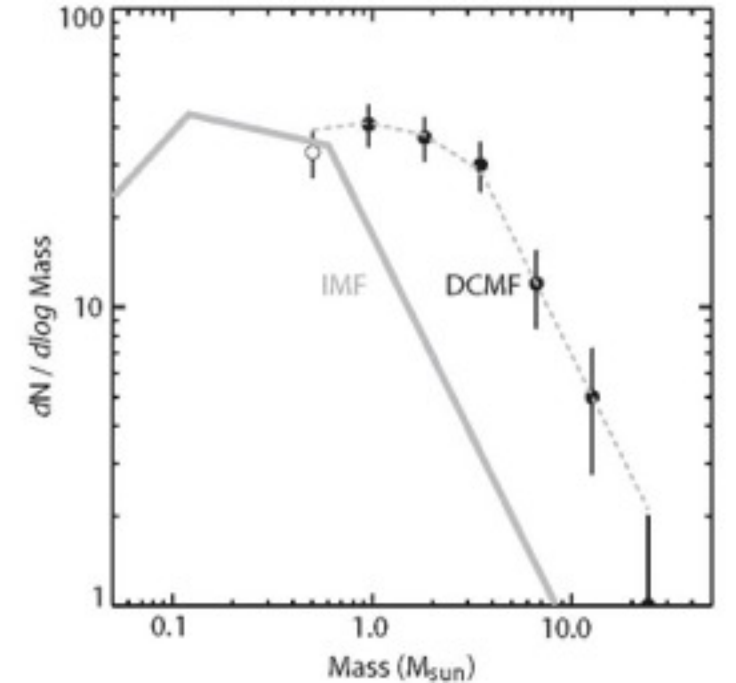
Do B fields affect relation between CMF and IMF?



Dense cores in the Pipe Nebula

Alves et al 2007 (Pipe Nebula)

Does MHD regulate this process? Eg. feedback effects of magnetized jets?



Similar distributions – shifted by factor of 3 in mass (Motte et al 1997, Testi & Sargent, Johnstone et al 2000, Andre et al 2010…)

How do magnetic forces work in fluids?

Magnetic force is the divergence (as in fluids) of “Maxwell stress tensor” - has 2 parts:

$$\boxed{\frac{B^2}{8\pi}\delta_{i,j} + \frac{B_i B_j}{4\pi}}$$

First term – B has a pressure:

- together with themal pressure, helps support gas, reduce fragmentation
- it is a “lighter” fluid -> magnetized fluid is buoyant
  (eg. the Solar field).

Second term – B exerts stress (torques) in different directions:

- transport of angular momentum on all scales; eg jets, magnetic “braking”, disk formation,
- tap energy in shearing flows (eg. disks) -> powering jets, MRI instability, dynamos

Physical processes in star formation influenced by MHD

I. Cloud to CMF.

- Galactic scale – building magnetized GMCs
- B and cloud structure
- Supersonic MHD turbulence
- Gravity and accretion
- Fragmentation – cores
- Disks and jets – disk formation / angular momentum flow

II. CMF to IMF: feedback modulated/driven by B

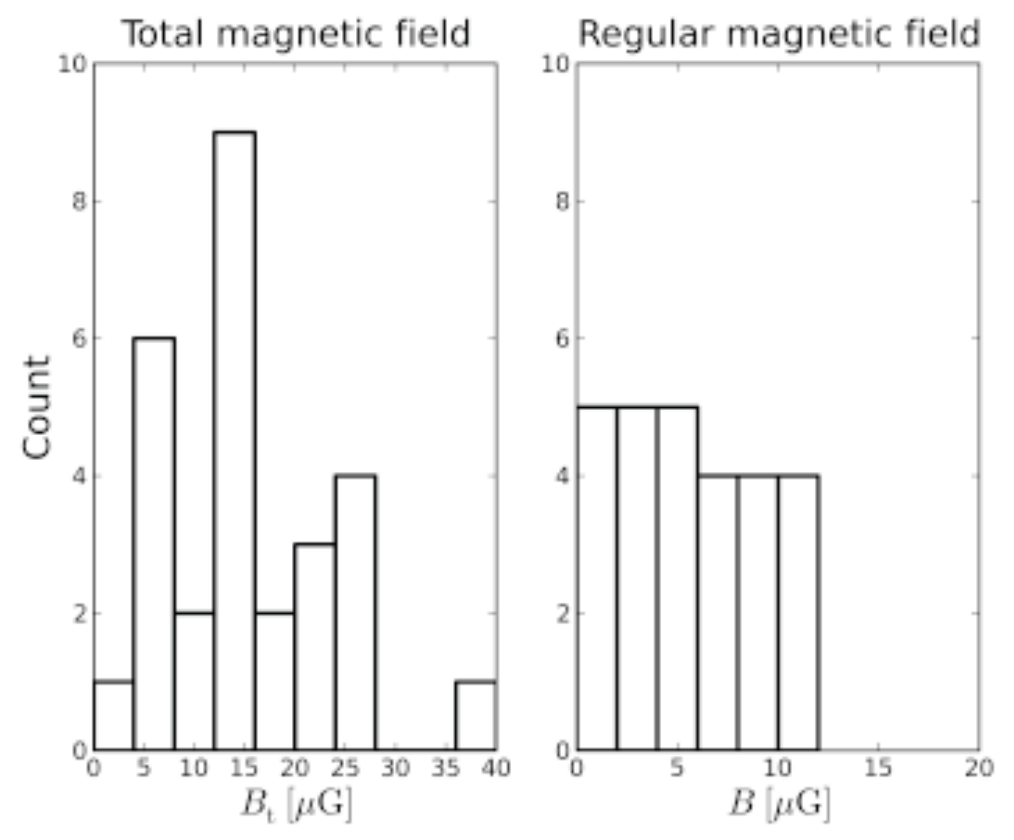
- Radiation / B connections for feedback
- Feedback from jets

III. Application to Pop III star formation?

B fields in spiral galaxies

- Resolution: several 10's of disk galaxies mapped RM ($B_{||}$) and polarizations (B_{perp})) -Beck et al 1996, Beck 2005, 2011, Fletcher 2011 – down to 100 pc.

- Equipartition: ISM, CR, and B fields on this scale (synchotron emission from CRs in B field)

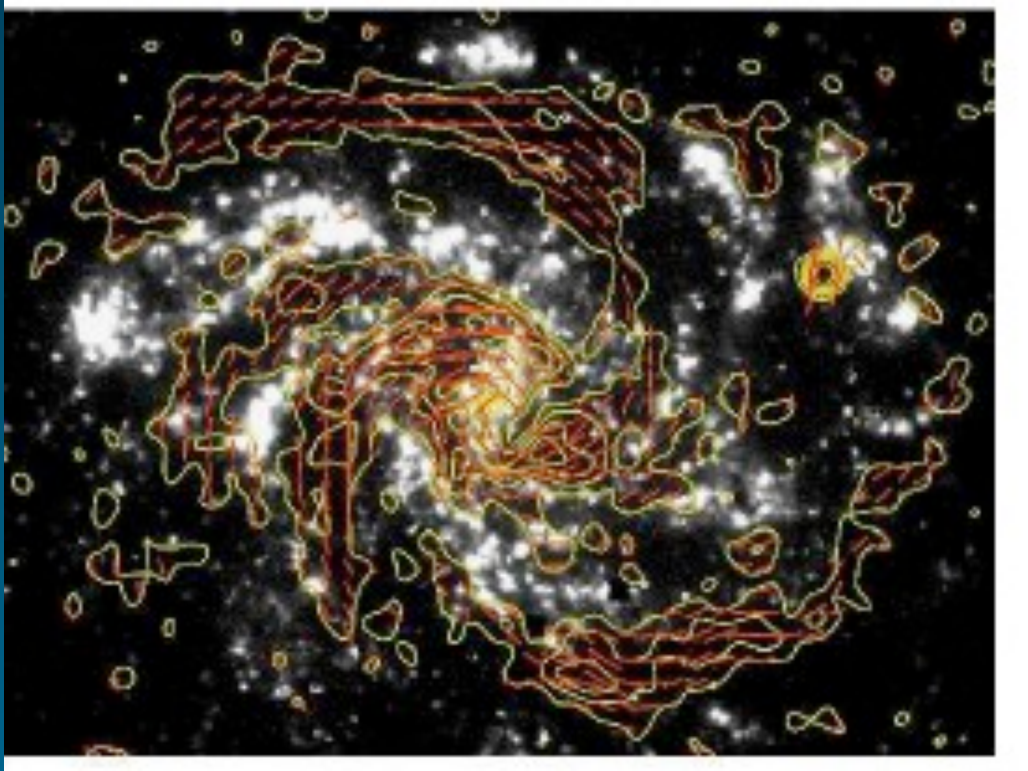


$$B_{tot} \cong 17 \pm 14 \mu G$$

$$B_{mean} \cong 5 \pm 3 \mu G$$

Fletcher, 2011

Large scale B fields in galaxies



Magnetic field in NGC 6946 :
contours – polarization
vectors – B field
background – H alpha

Ordered field parallel to arms:
10-15 micro-Gauss
- Galactic dynamo mode

(Beck 2010, Beck & Krause 2005)

6 cm image:
(Beck 2010)

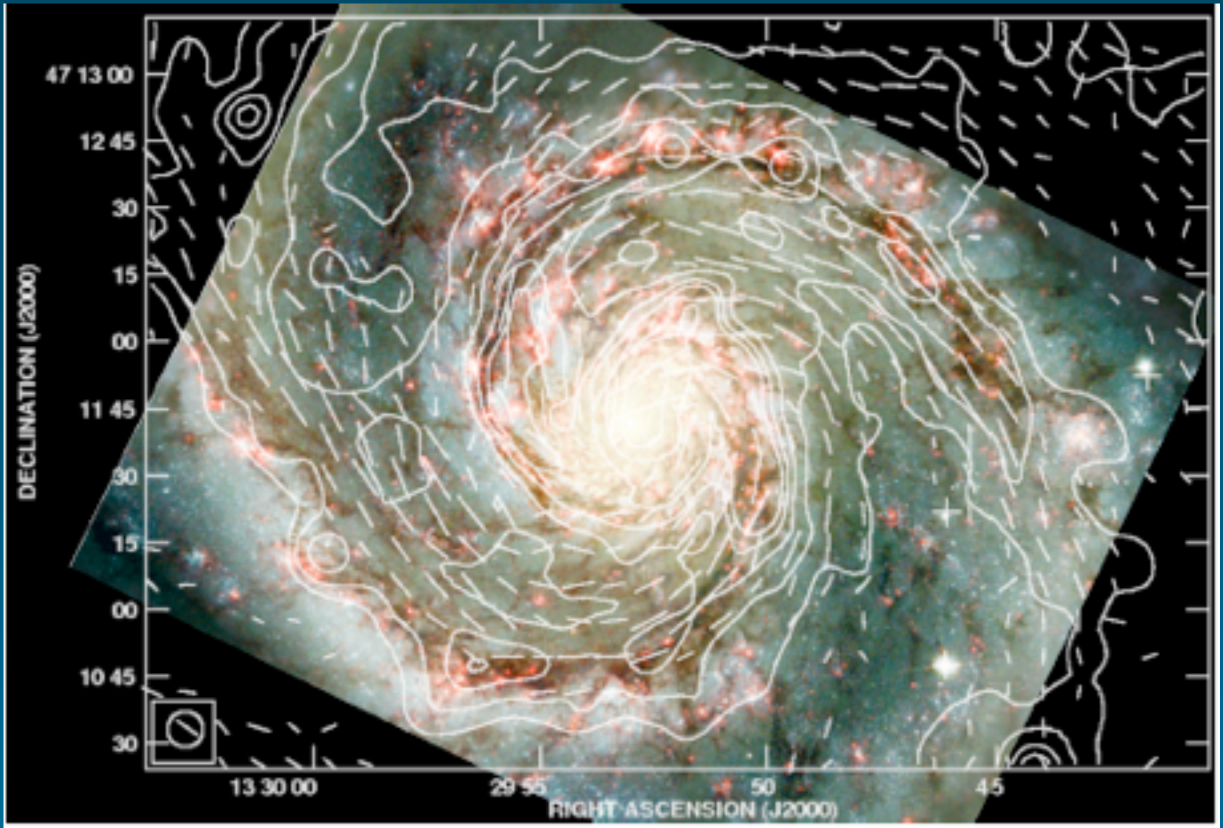
Magnetic fields in sprials – M51

Field compression:
spiral field along
density wave.

- Large scale dynamo (Beck, Brandenburg, Moss, Shukurov, Sokolov 1996, ARAA):

dominant field is quadropolar type mode – includes vertical component wrt galactic plane

(Heeson et al 2009, Braum et a; 2010)



MHD Instabilities and GMC formation:

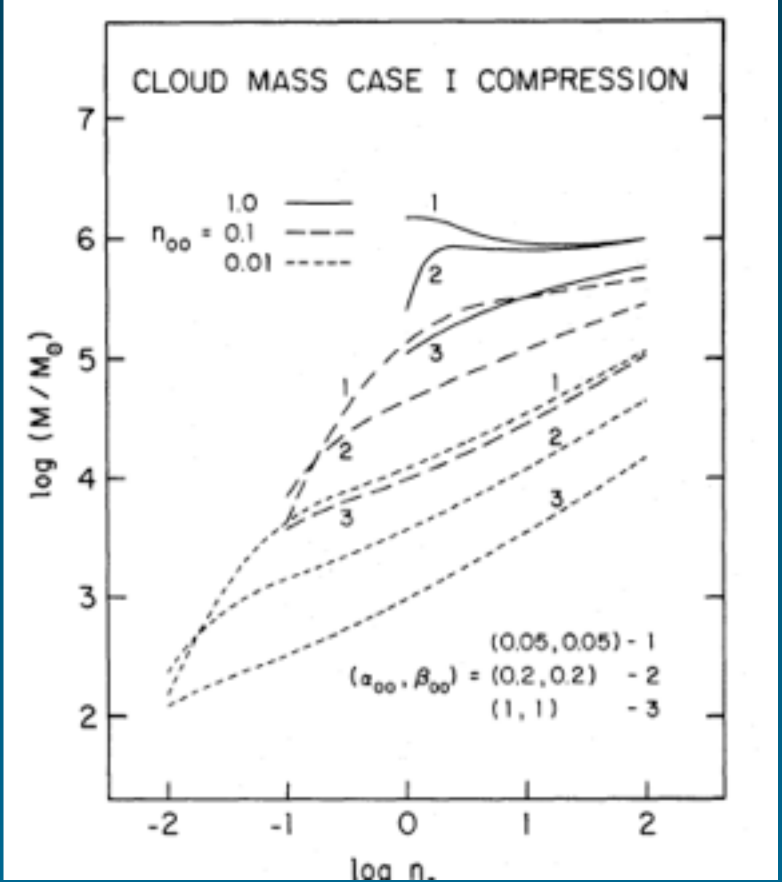
Parker- Jeans (Elmegreen 1982), MRI – gravity (Sellwood & Balbus 1999; Kim, Ostriker, & Stone 2003), ..

1. Parker-Jeans instability (Elmegreen 1982):

- gravity strongest in galactic plane, magnetic buoyancy peaks far from plane
  - -> finite value for growth rate
- Approaches Jeans time in higher density regions:

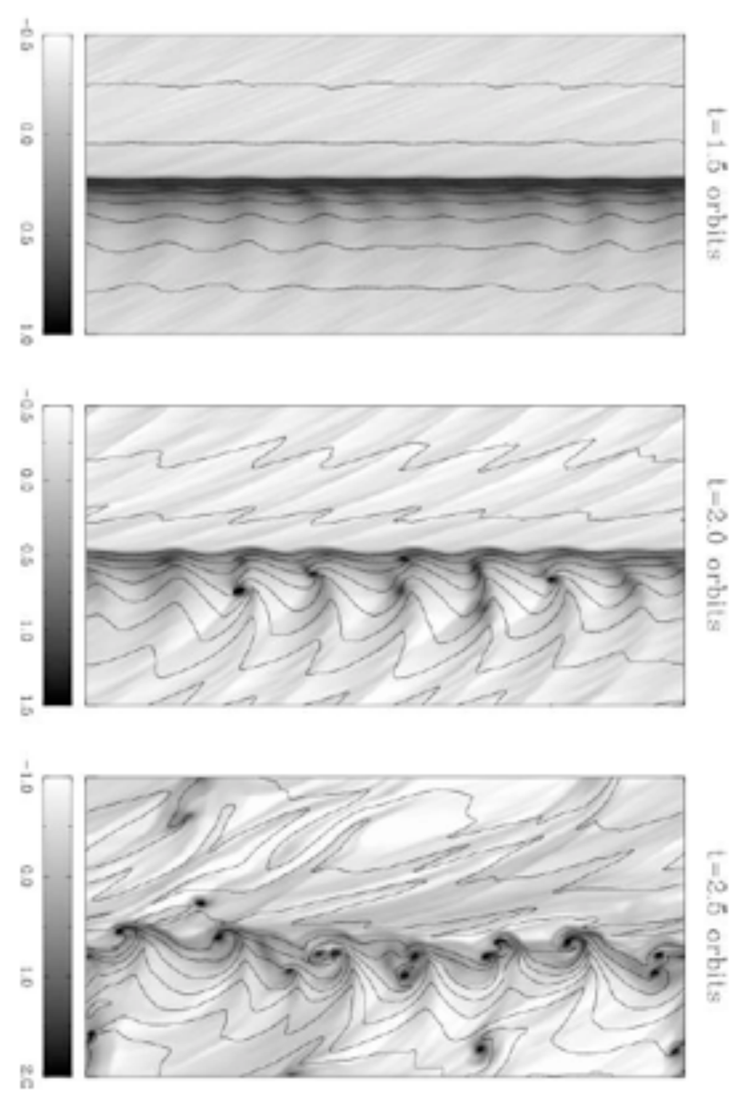
$$(4\pi G\rho_0)^{-1/2} = 23/n_0^{1/2} \text{ million years}$$

- Compression of cloud by spiral needed
- Find 10^6 solar mass GMCs in 10 Myr.



Solid curves, GI dominates
Small dash curves, Parker "

2. Local processes – MRI with no initial spiral arms

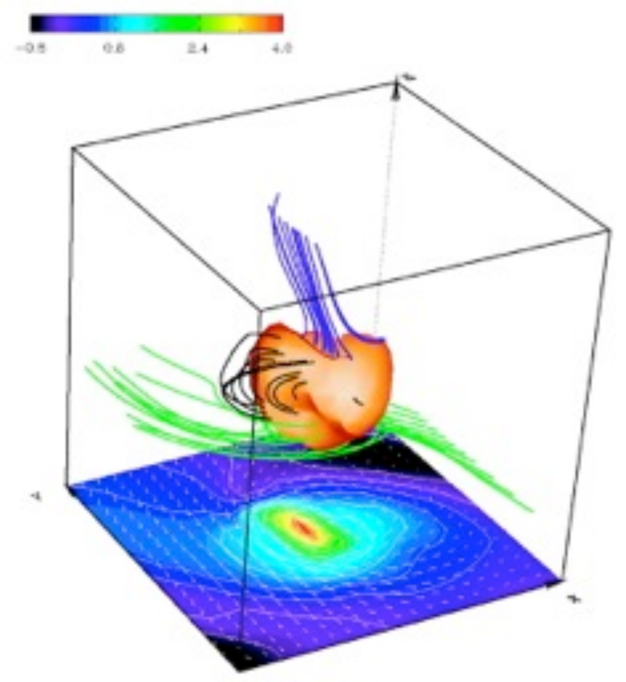


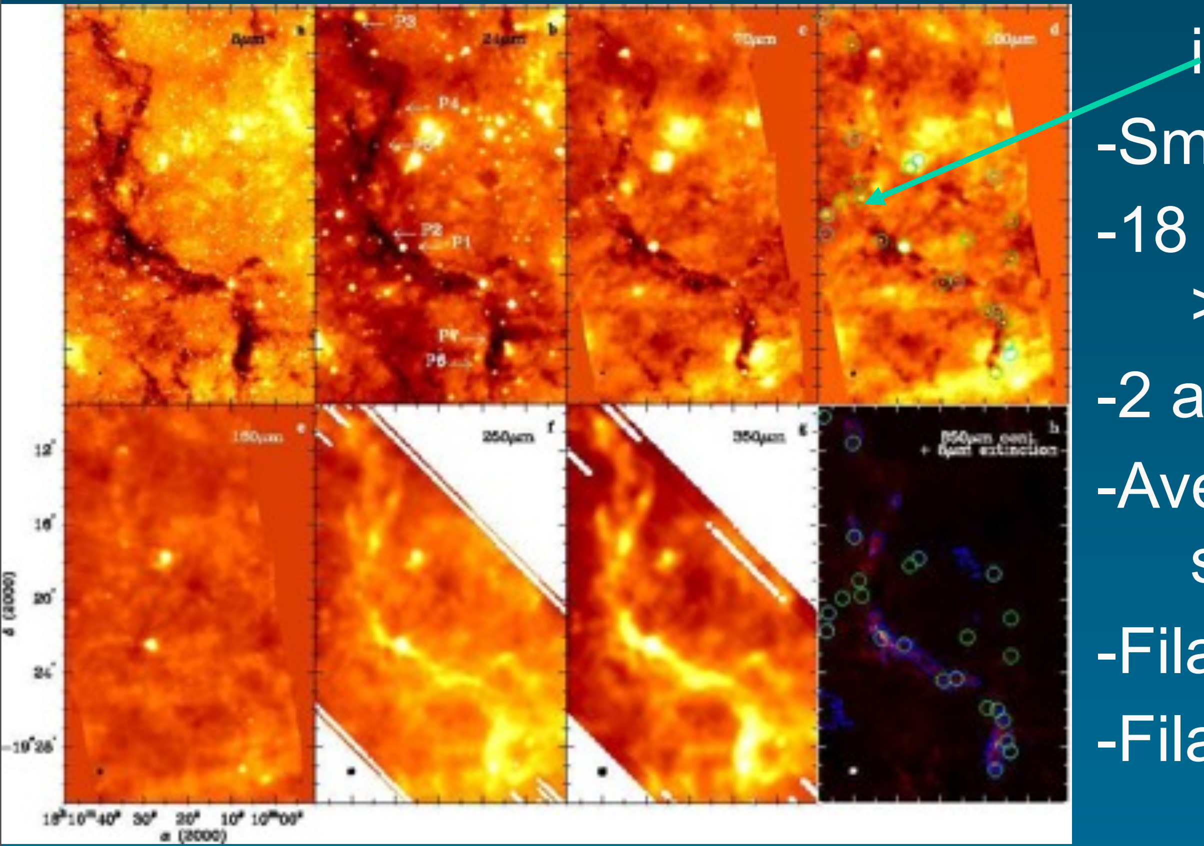
Ostriker & Kim 2001, B ~ 2microG. GMCs @ Toomre Q < 1.6

MRI to start and run turbulence in shearing box,

GI – Toomre swing amplifier– acts on larger scale fluctuations - build self-gravitating objects 10^7 solar masses (Kim, Ostriker & Stone 2003)

- GMC field lines shown below





Henning et al 2010

- -Thousands of solar masses in filaments
- -Smaller amount in cores
- -18 of 24 cores on filament -> fragmentation
- -2 are 50 solar masses
- -Average core mass 24 solar masses
- -Filament temperature 12 K.
- -Filament density

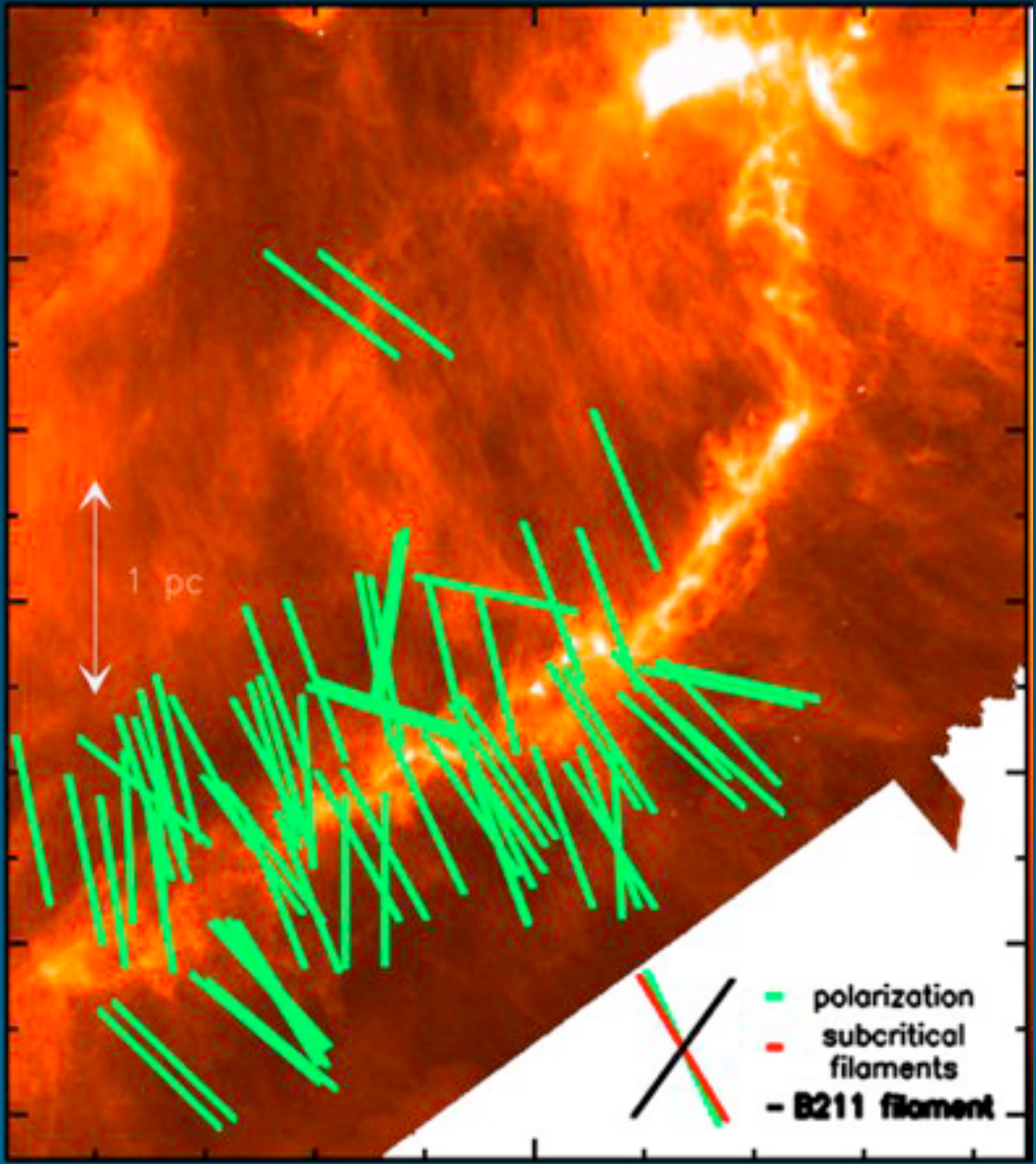
$$10^4 - 10^5$$

B and cloud structure

Optical polarization in filamentary clouds: optical polarization by Hyer al al 2008, Heiles 2000.

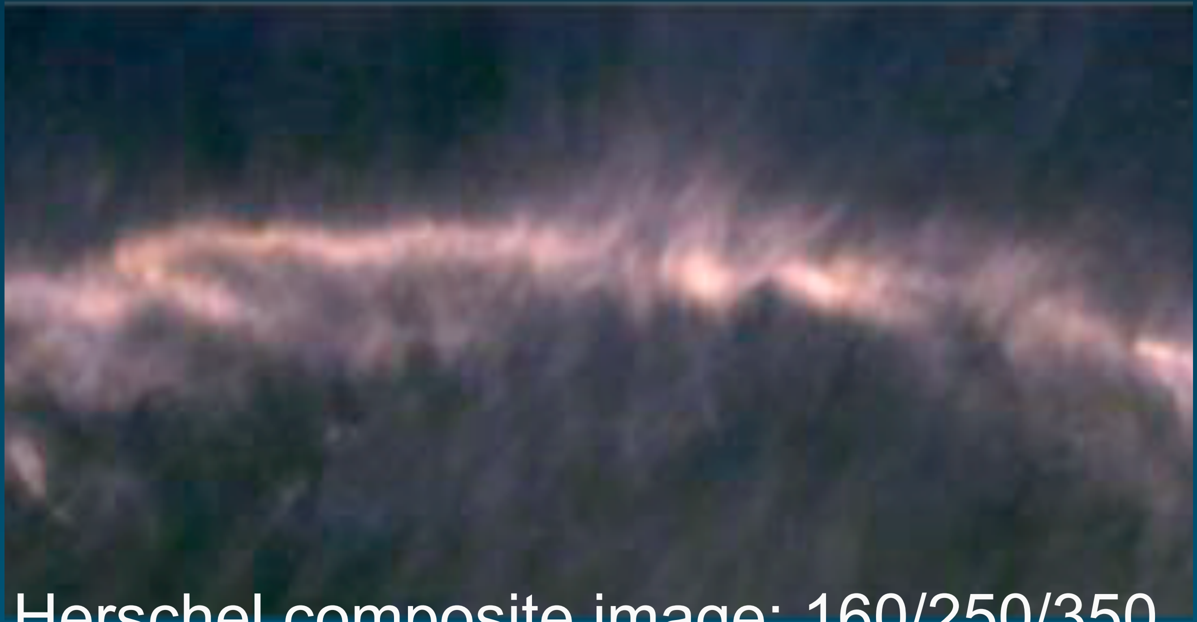
Traces more diffuse gas – magnetic field dominates diffuse ISM

- Field perp to filament : channeled collapse?

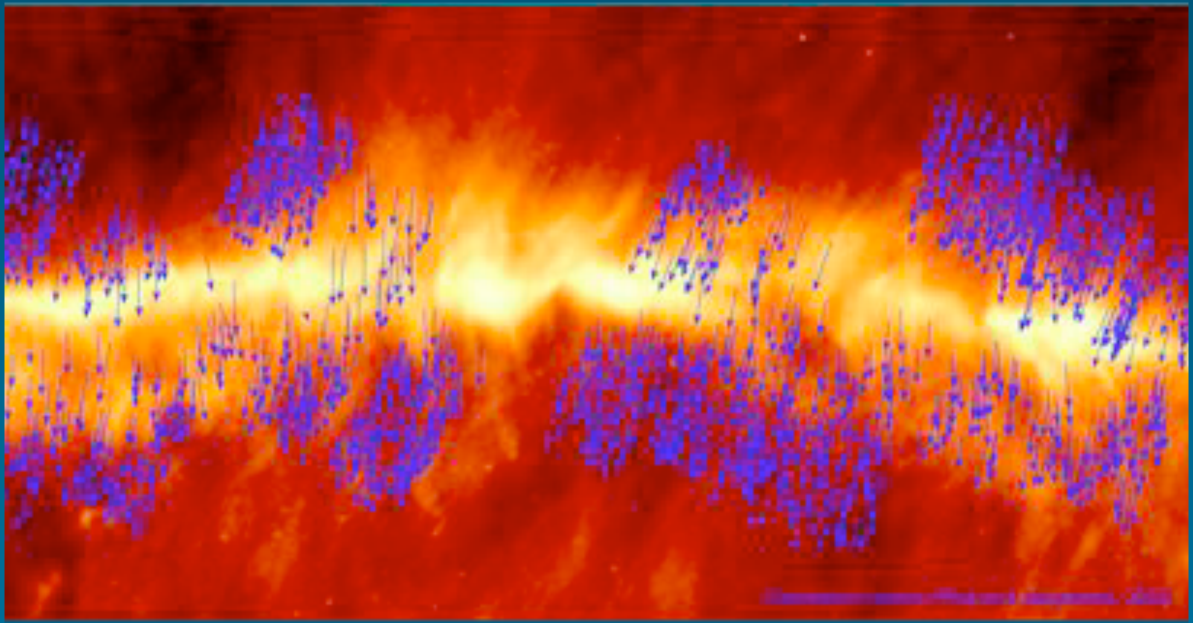


Optical polarization, Taurus B211 filament; Palmeirim et al 2012

Filaments and polarization measured with Herschel observatory.



Herschel composite image: 160/250/350 microns of Musca filament

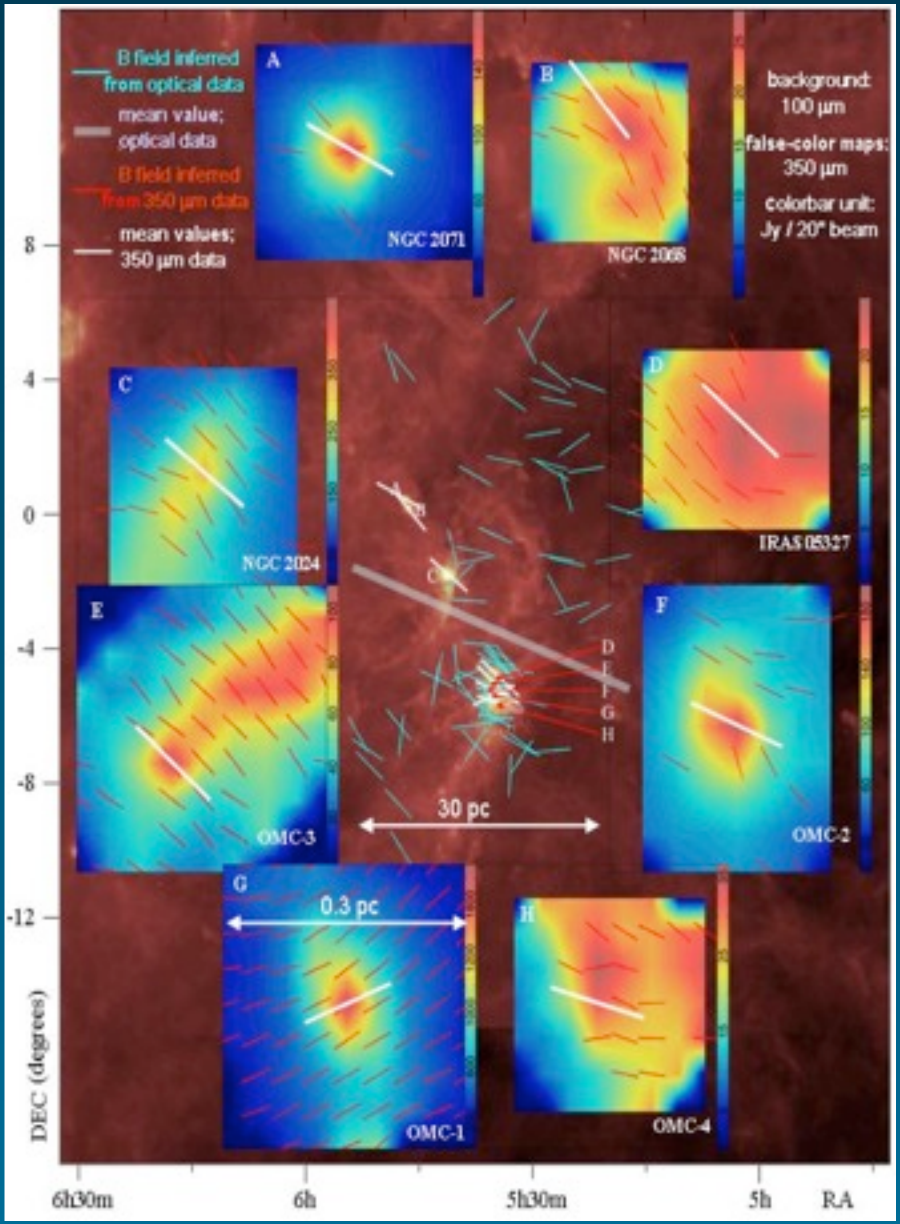


SubmmPolarization vectors overlaid: N. Cox in prep

Large scale (core to core) ordered field

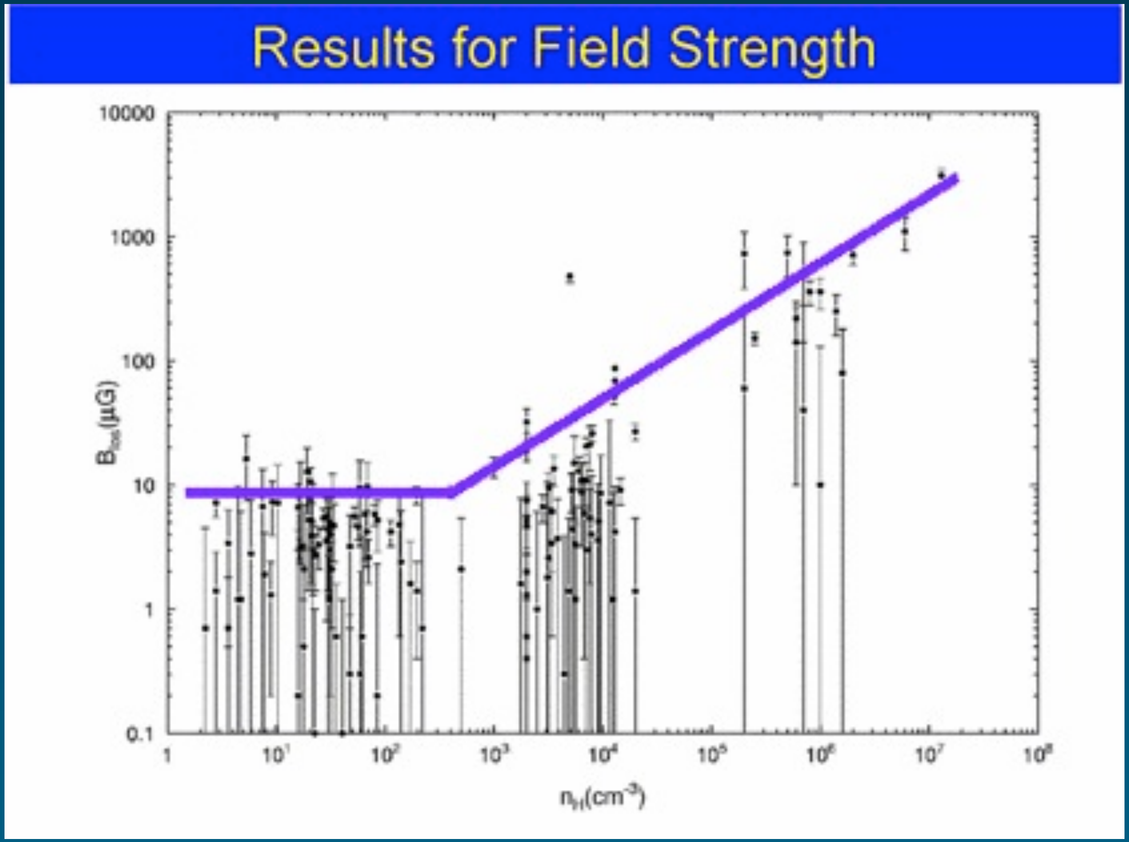
- Magnetic fields in 8 dense cores in Orion region.

- Measured using submm polarimetry at SMA (H-B Li et al 2009)



Zeeman measurements:

distribution of B field strenths measured in cores (Crutcher et al 2010)

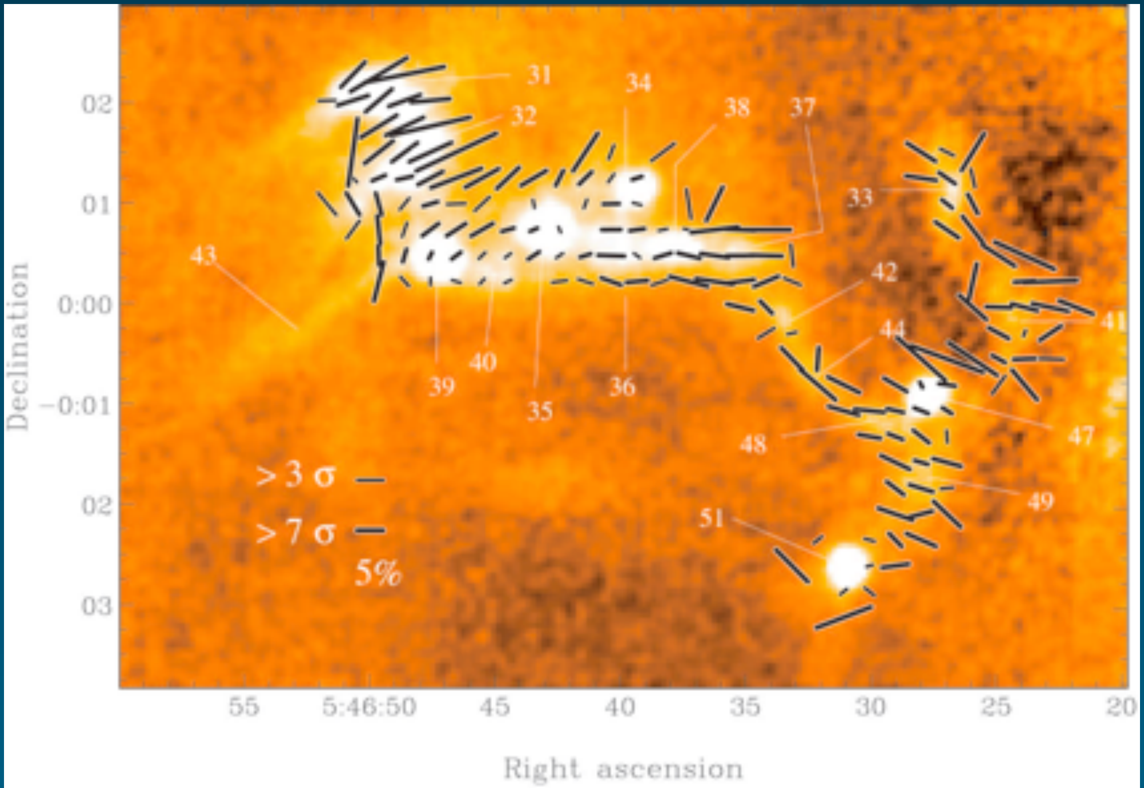


- Low density medium: constant field
- Dense medium, many clumps supercritical – get distribution of core magnetization, some become strongly magnetized, others not: (eg. Padoan & Nordlund 2002, Tilley & Pudritz 2007)

Submm (JCMT) map of polarization of Orion, NGC 2068 filament

(Matthews & Wilson 2002, Matthews, Wilson & Fiege 2003),

- Single field direction does not fit data for this filament: variable field direction along filament.
- Strong correlation of axis and B in OMC-3



Mathews & Wilson (2002)

Evidence for helically wound field?

(eg. Fiege & Pudritz, 2000)

Virial theorem for magnetized filaments :

Twisting a mean field (eg., filaments formed in oblique shocks) -> both field along filament B_p and wrapping filament $B_{toroidal}$ contribute

(Fiege & Pudritz 2000a)

$$\frac{P_S}{\langle P \rangle} = 1 - \frac{m}{m_{\rm vir}} \left(1 - \frac{\mathcal{M}}{|\mathcal{W}|} \right)$$

$$\mathcal{M} = \frac{1}{4\pi} \int B_z^2 \, d\mathcal{V} - \left(\frac{B_{zS}^2 + B_{\phi S}^2}{4\pi} \right) \mathcal{V}$$

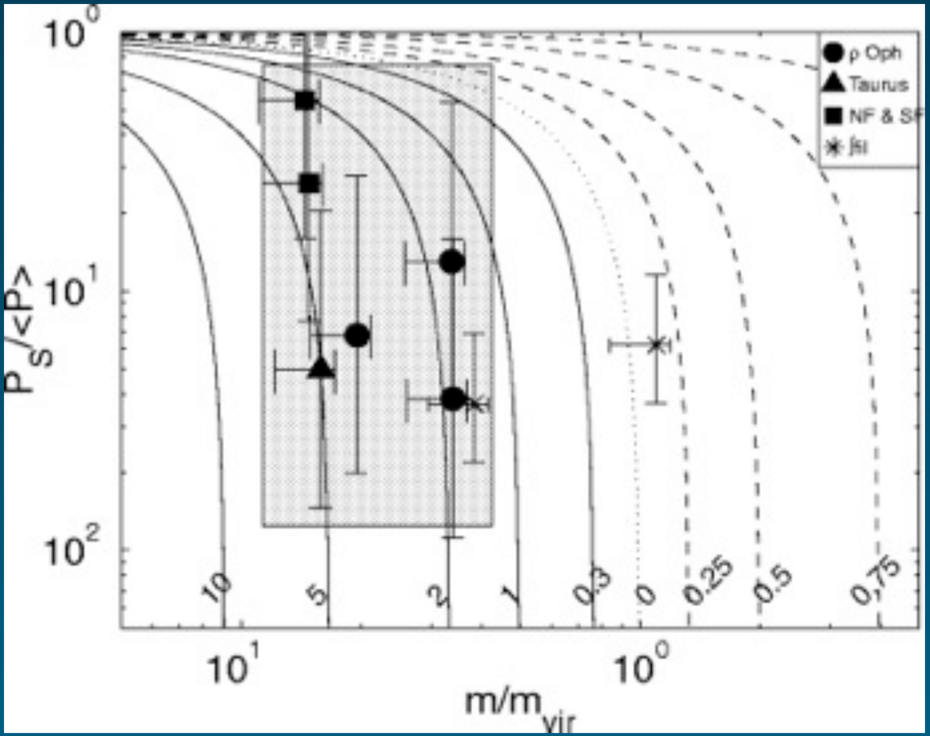
Filaments and gravity: Mass per unit length (m) is critical instability criterion; $m > m_{vir}$ not pressure!

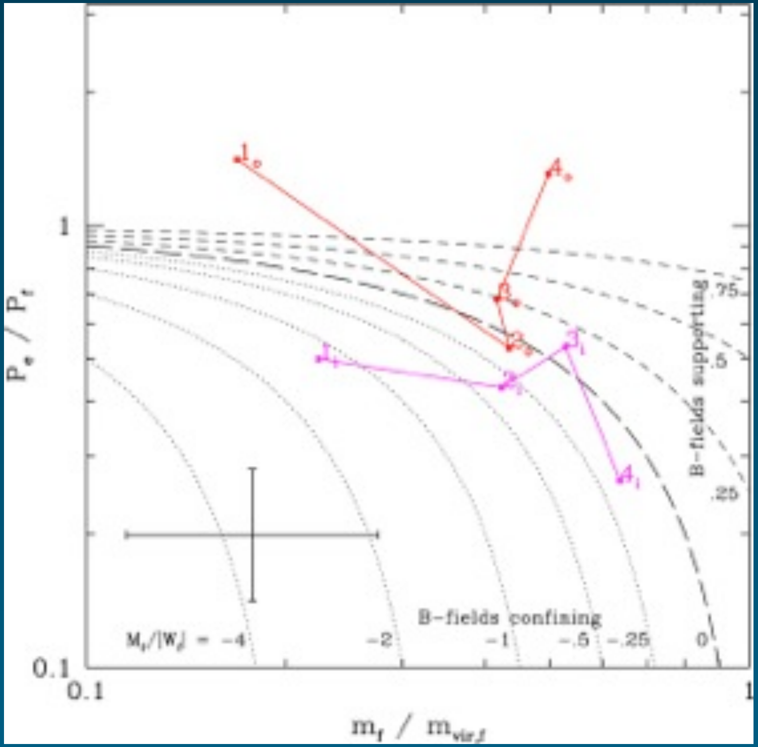
$$m_{\rm vir} = \frac{2\langle \sigma^2 \rangle}{G}.$$

Magnetic contribution postive: poloidal field supports filament

Magnetic contribution negative: toroidal field compresses filament

The data: connections to large scale filaments





Pressure – m curves + data for filaments.
Solid curves – toroidal field dominates, confinement
Dashed curves – poloidal field dominates, supports filament
Dotted curves – net mag energy = 0
Fiege & Pudritz 2000

MIREX N + near IR maps of infrared dark cloud (IRDC) filament – several 10^3 M_{solar} along 4 pc: nearly zero net mag energy (Hernandez, Tan, et al 2012)

Other tests of B and filament structure:

Radial density structure of equilibrium filaments with helical fields (Fiege & Pudritz 2000):

$$\boxed{\rho \propto r^{-2}}$$

- Matches many observations (Johnstone & Bally 1999, Alves et al 1999, Lada et al 1999), but not all (Johnstone, Fiege, et al 2003)

- not isothermal self gravitating, hydro filaments (Ostriker 1964):

$$\boxed{\rho \propto r^{-4}}$$

MHD Turbulence and star formation

- Supersonic turbulence compresses gas into sheets, filaments.
- Turbulent “fragmentation” drives CMF?
- Clouds have abundant B field – does this affect fragmentation?

Source 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),
- NEW: GI instabilities and small scale dynamos (following talks!)

Does 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,…

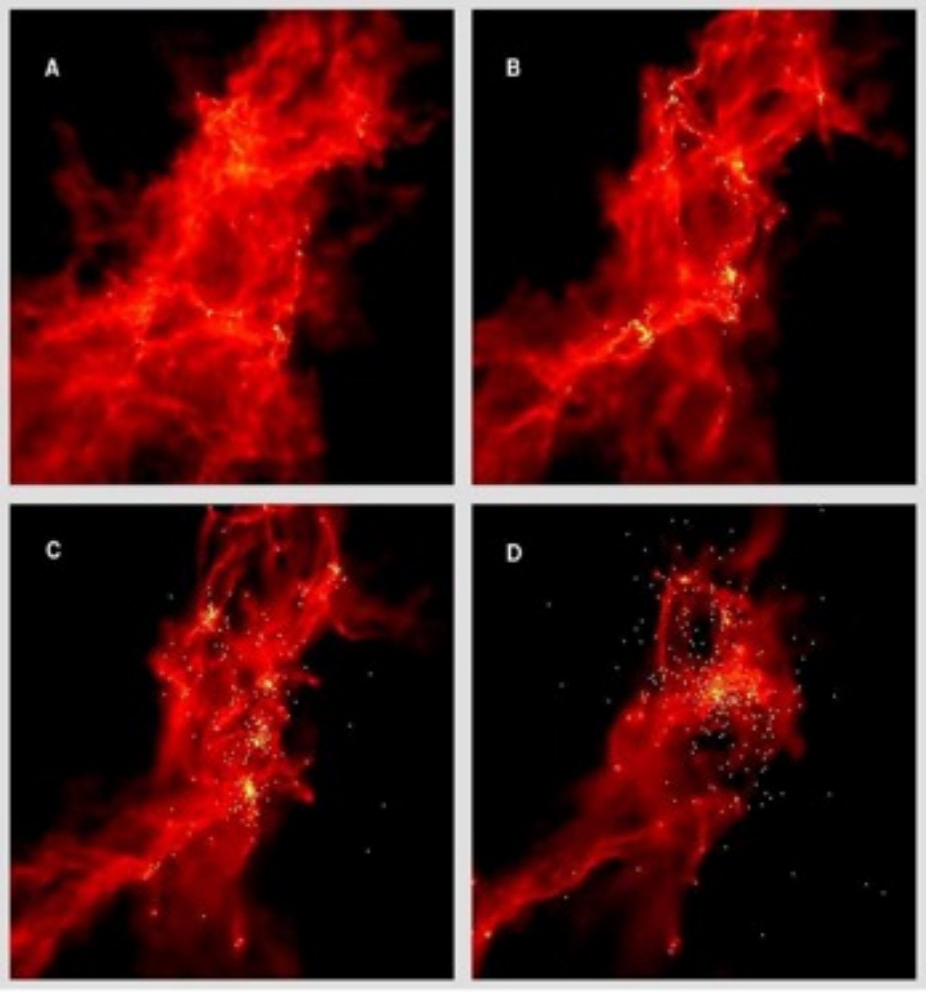
Making filaments and clusters:

Hydro + gravity:

Shocks produce filaments (eg. Inutsuka & Miyama 1998, Klessen & Burkert 2000, Bonnell et al 2003, Bate 2012,..)

Shocks dissipate turbulent support (eg. Ostriker 2001) as t^{-1}

Gas flows along filaments into local potential minima – cluster formation regions (eg. R. Smith et al 2012



Bonnell et al (2003)

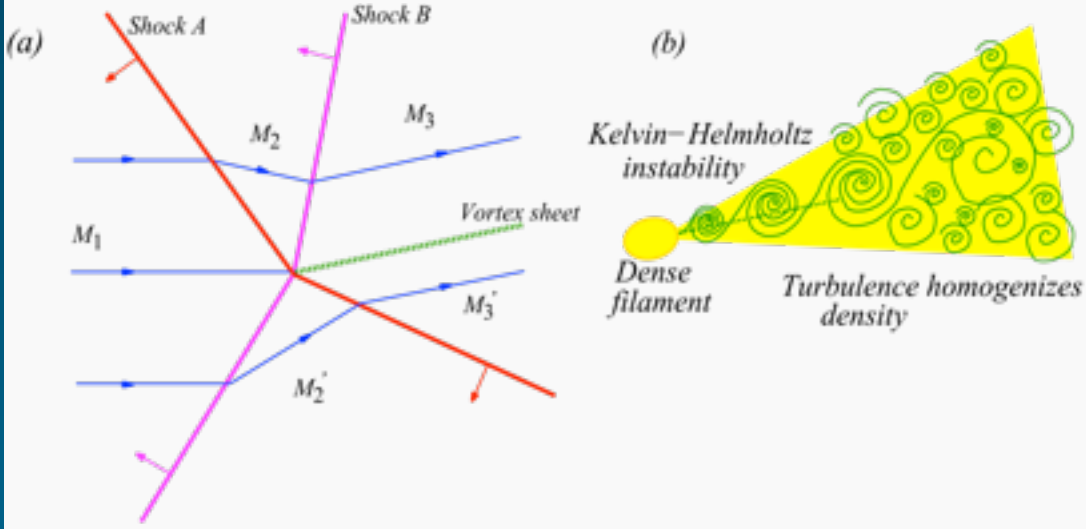
Creating filaments in shock-dominated media

Intersection of 2 planar hydro shocks of unequal strength:

- streamlines rotated, - vortex sheet generated, filament out of plane

- Instability of vortex sheet produces turbulence downstream

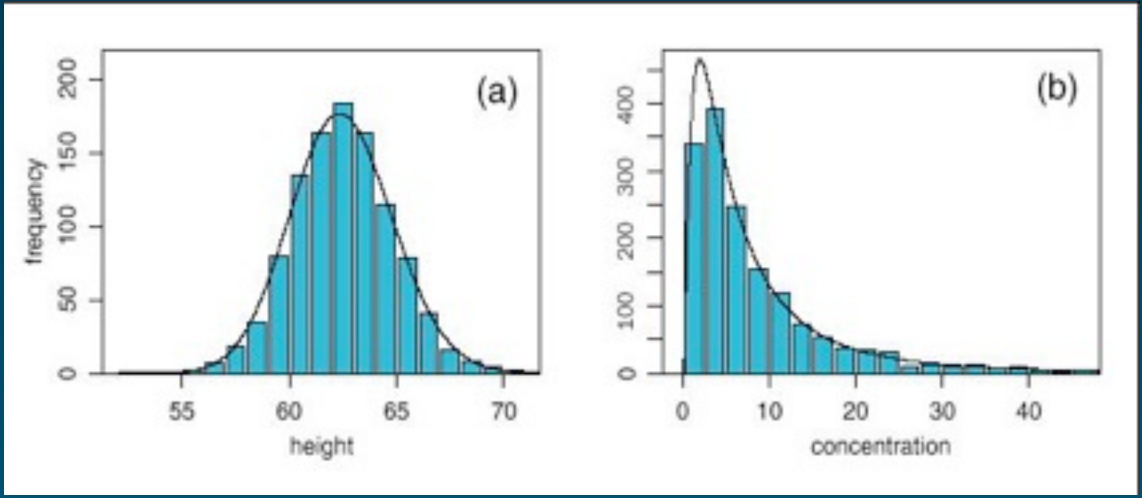
- What is net B geometry within filament?



Pudritz & Kevlahan 2012

IMF: Origin of lognormals:

Limpert et al 2001



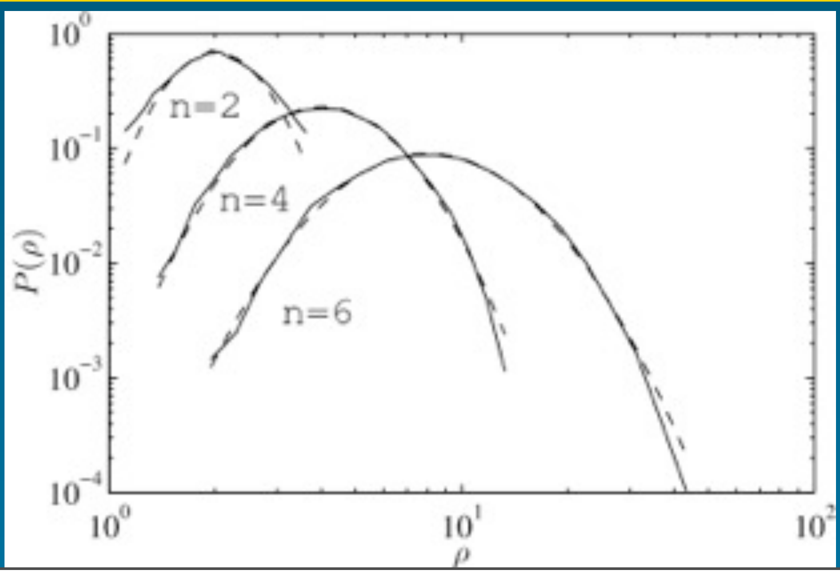
Normal: (“Bell Curve”)

Additive process

(Limpert et al – review)

Lognormal:

Multiplicative process



Shocks and lognormals

- Assume density changes primarily due to shock compression – after n shock passages:

$$\rho^{(n)} = \prod_{j=0}^{n}(1+\mu^{(j)}(x));\ \text{normalized to } \rho_o$$

- Consider shock strengths to be identically distributed random variables, in interval

$$\mu \in [0, 2/(\gamma - 1)]$$

- Take log of both sides, apply central limit theorem. Get a log-normal distribution for density PDF (n related to RMS Mach no.):

$$P(\rho) = \frac{1}{\sqrt{2\pi\sigma\rho}} \exp\left(- \frac{(\log(\rho) - \overline{\log \rho})^2}{2\sigma^2} \right)$$

$$\overline{\log \rho} = \frac{n}{2} \ln \frac{\gamma + 1}{\gamma - 1},$$

$$\sigma^2 = \frac{n}{12} \ln \frac{\gamma + 1}{\gamma - 1}$$

MHD produces similar result:

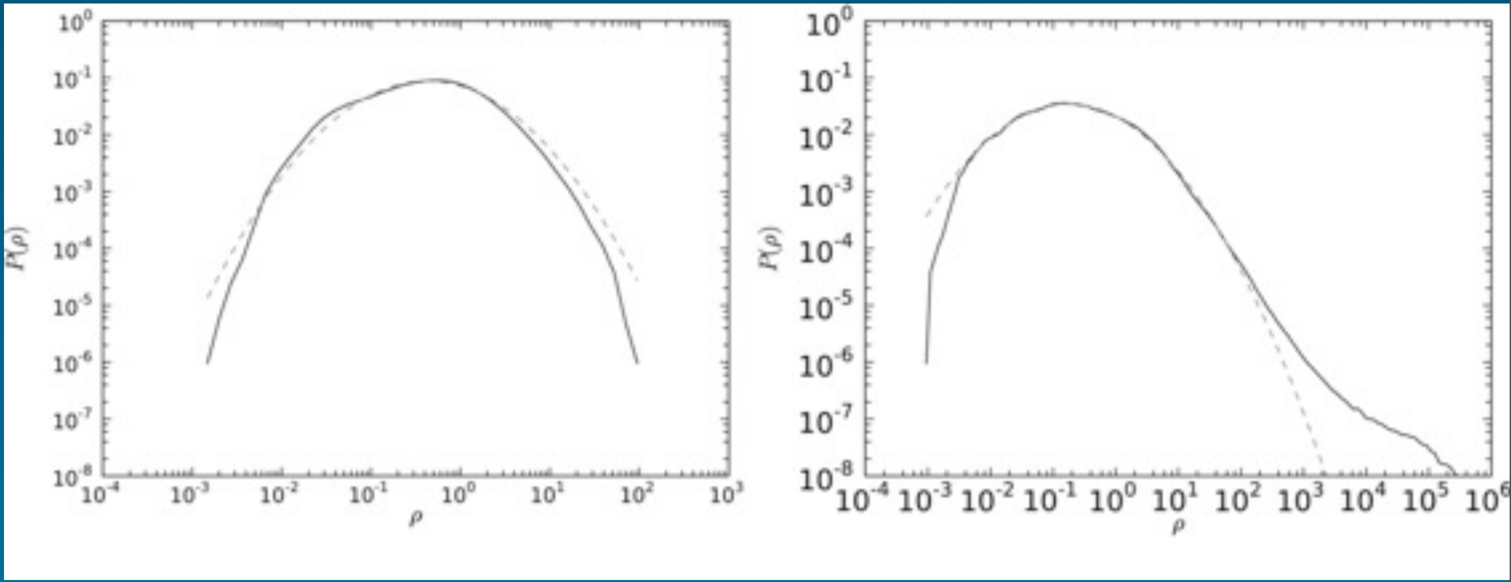
(Li et al 2004, Lemaster & Stone 2008, Kritsuk et al 2009)

- Change: Broader FWHM for driven turbulence (Lemaster & Stone 2008) - not sensitive to Alfvenic Mach numbers

$$\sigma_{hydro} = \sqrt{\ln(1 + b^2 M^2)}$$

$$\sigma_{MHD} = \sqrt{\left|-0.72\ln(1 + 0.5M^2) + 0.20\right|}$$

For full hydro + gravity + MHD: lognormal with tail – initial state and after 0.75 t



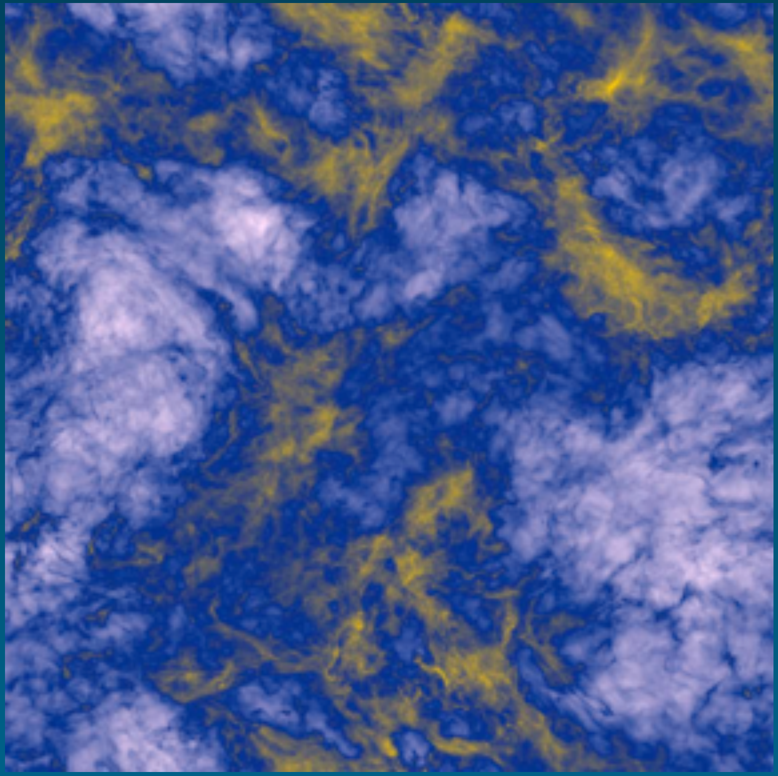
Collins, Kritsuk, Norman, & Xu 2010

Supersonic turbulence in magnetized clouds

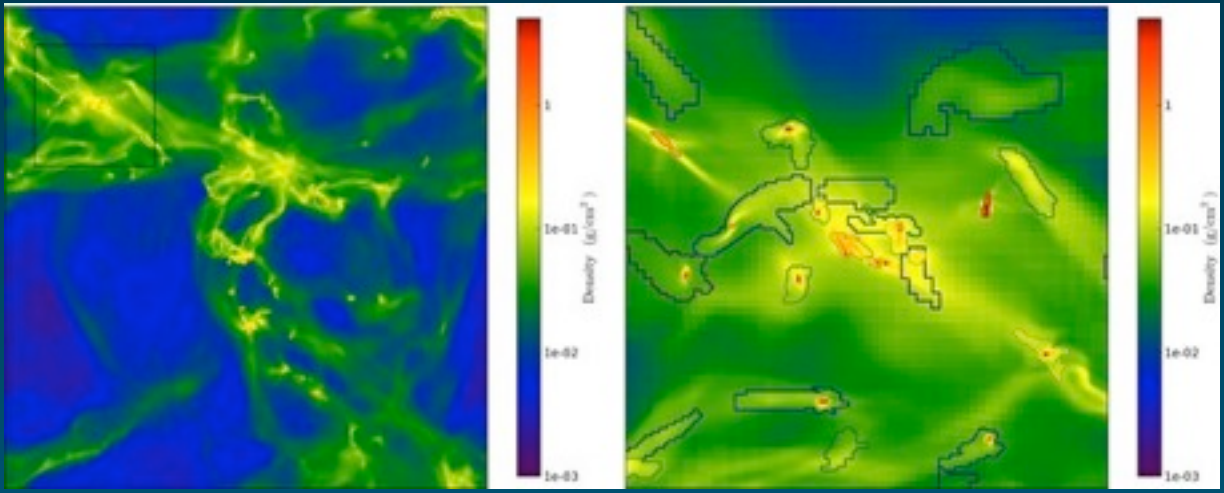
3D, turbulence with resolution 1024^3

M_s = 10
M_A= 3

Broad range in density enhancements, several orders of magnitude.

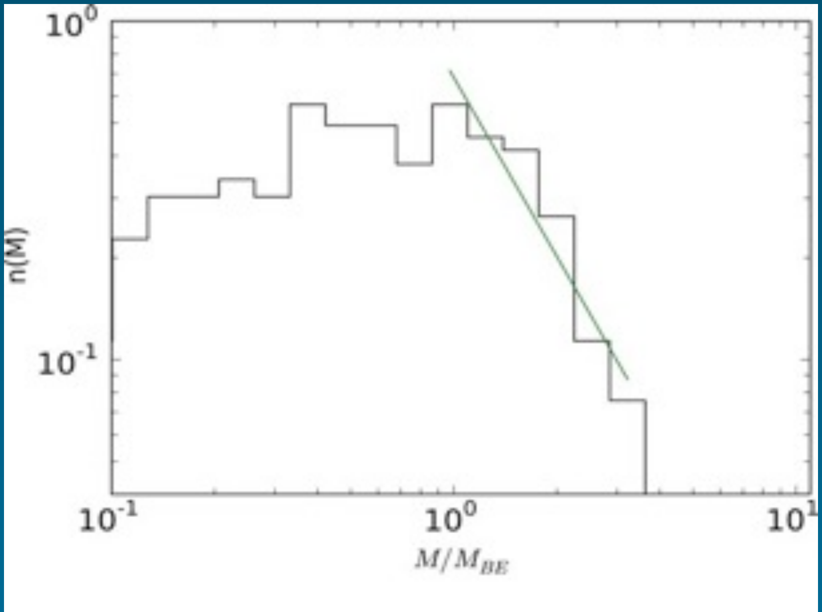


Projected column density:
Kritsuk et al 2009

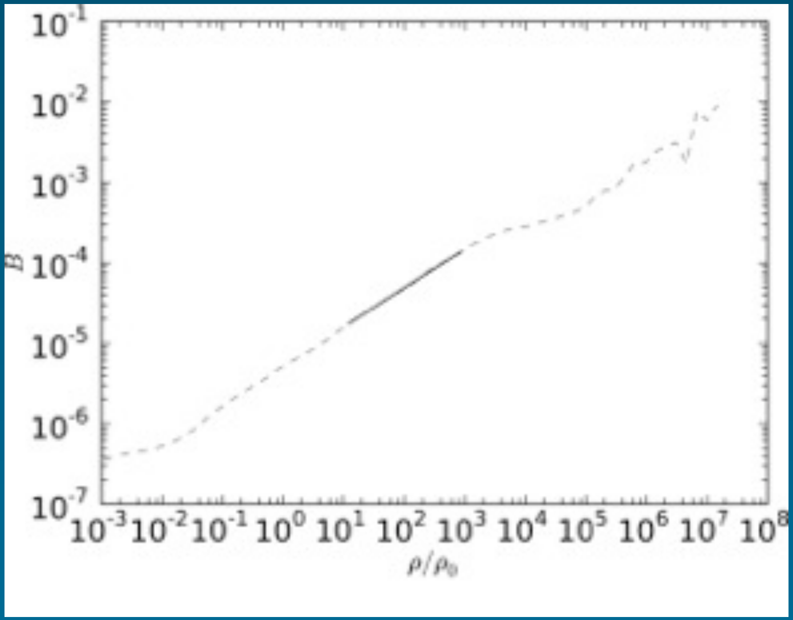


Gravity + turbulence + MHD

Filaments, core mass function, and mass weighted B



$$N(M) \propto M^{-2.1\pm0.6}$$



$$B \propto \rho^{0.48}$$

Turbulence + Gravity

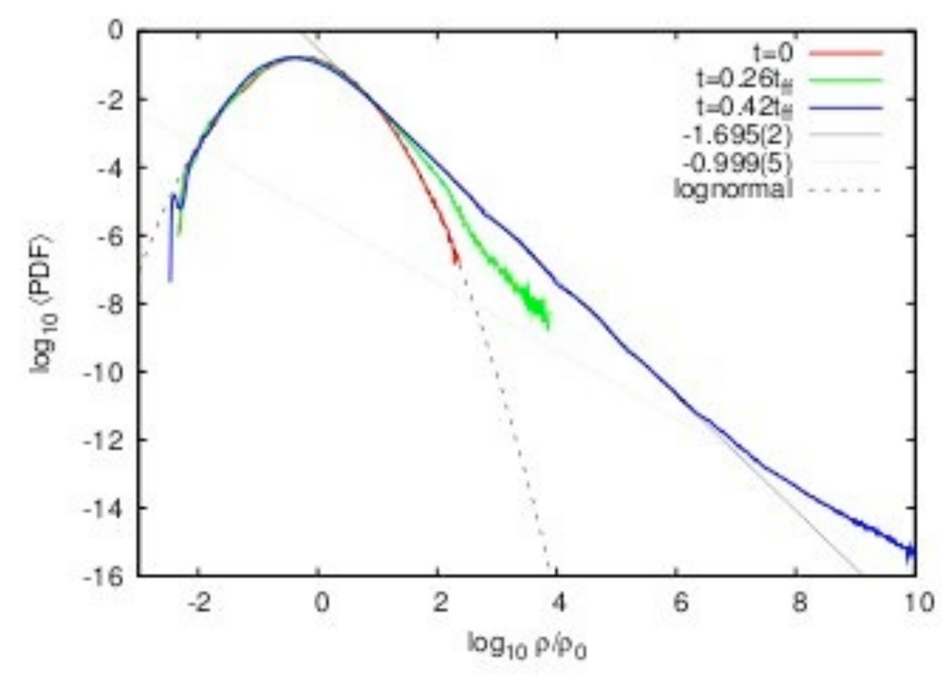
Matching Kainulainen et al (20 column density pdf for clouds.

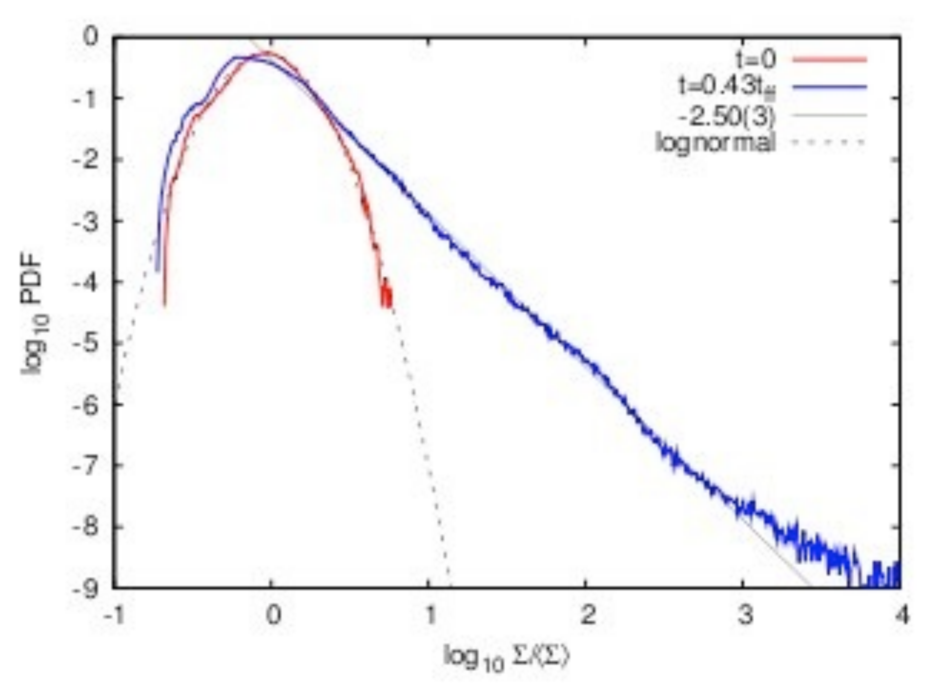
High resolution turbulent box: 5pc down to 5 AU (eg. Kritsuk et al 2011) - ENZO AMR code

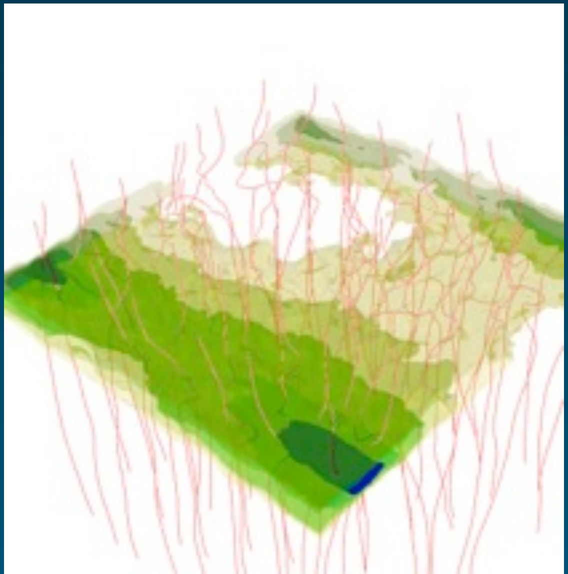
- Periodic box stirred for 4.8 t_ff, and then system allowed to evolve with gravity.

- Initial state- lognormal

- Gravitational collapse of subregions produces power-law tail (see poster – Girihidis et al)







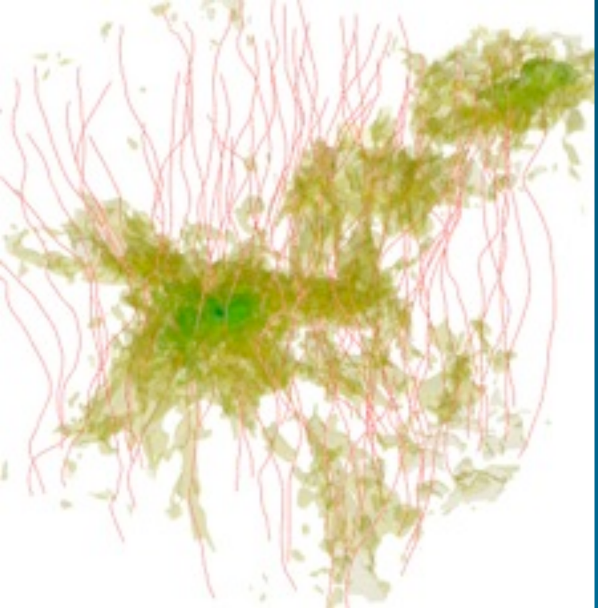
Completely suppress fragmentation in subcritical clouds (mass to flux < 1) – GMCs are supercritical (~ 2 -3?)

$$\Gamma = 2\pi\sqrt{G}\Sigma / B = 1.4\beta^{1/2} n_J^{1/3}$$

Nearly supercritical clumps:
Top: near critical – collapse along field line into sheet structure.

Filament by fragmentation of magnetized sheet?

Bottom: modestly supercritical, turbulence breaks up collapse into more distributed clump structures.



(Tilley & Pudritz 2007)

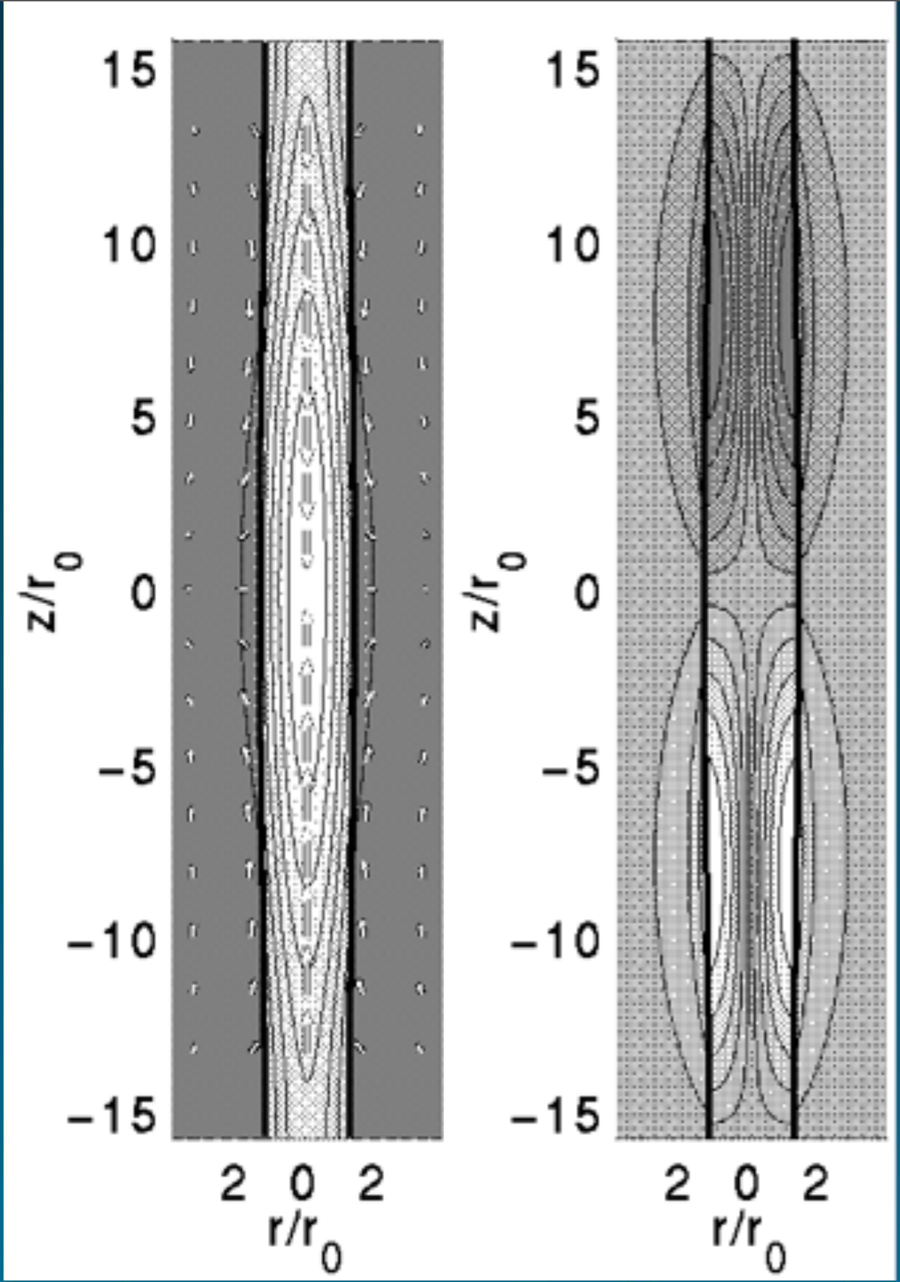
Fragmenting filaments

GI of magnetized filaments first studied: Chandrasekhar & Fermi 1953! B fields decrease growth rate.

Early studies poloidal field: Nakamura et al 1993, Tomisaka 1996, Gehman 1996,..)

Self-gravitating filaments beyond critical mass / unit length dominant gravity (slow-mode) fragmentation scale (Fiege & Pudritz 2000b):

$$\lambda_{\max} = 2.8\left(\frac{k_{\max}}{0.2}\right)^{-1}\left(\frac{\sigma_c}{-.5\,km s^{-1}}\right)\left(\frac{n_c}{10^4\,cm^{-3}}\right)^{-1/2}$$



Density + Poloidal velocity

Toroidal velocity (spin reversals)

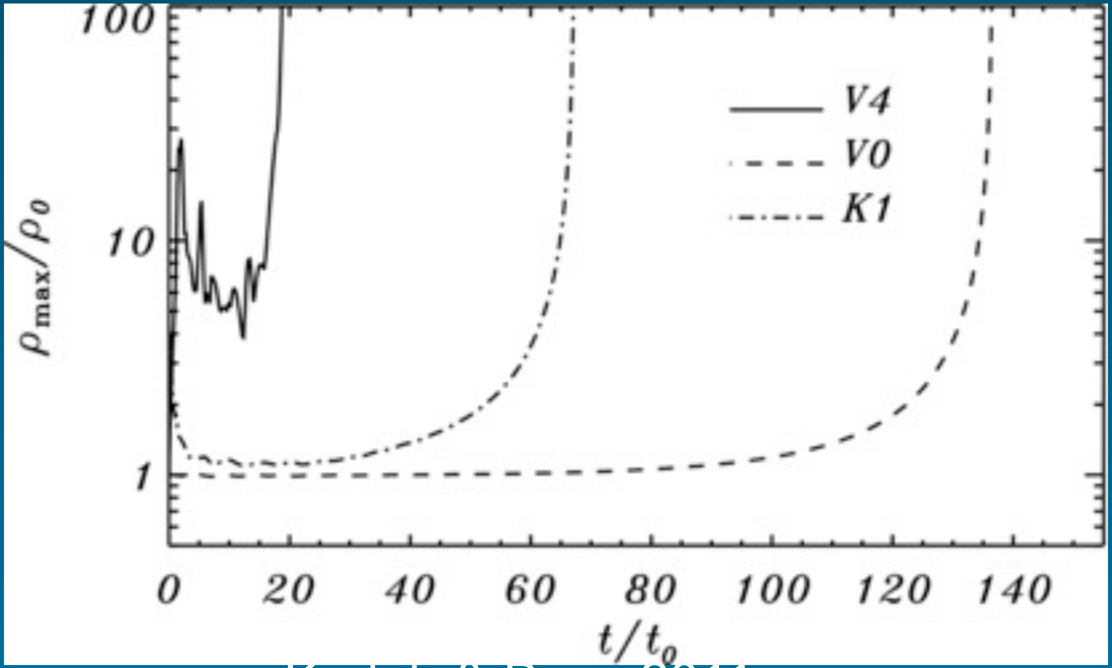
SFR in magnetized clouds – non ideal MHD:

Slip of field in poorly ionized media (ambipolar diffusion) in time (neutral-ion collision time) proportional to free fall time:

$$\tau_{ni} = \gamma\rho^{-1/2}$$

$$\gamma = 170(gcm^{-3})^{1/2}$$

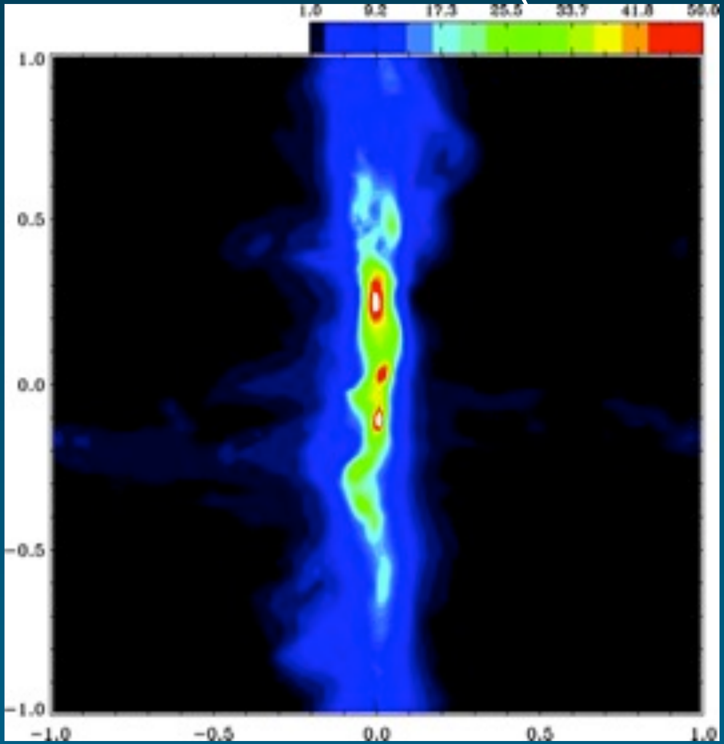
AD and growth times of cores in 3D MHD – with turbulence imposed…
V4 = super Alvenic
V0 strongly Sub Alfvenic



Kudoh & Basu 2011

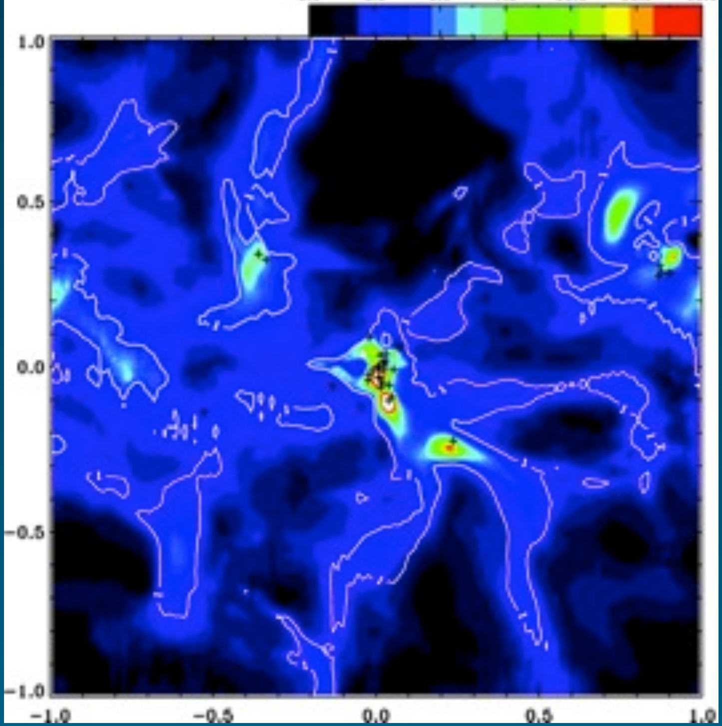
Making cores – ambipolar diffusion in turbulence

(Nakamura & Z-H Li , 2008)



Subcritical simulation – edge on and face on views

Contours: supercritical regions

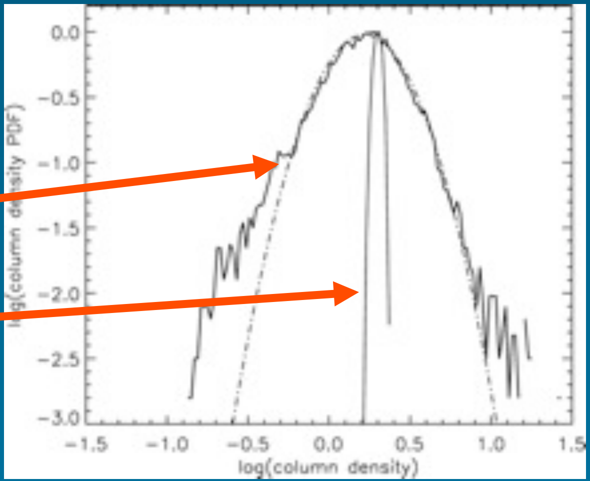


Column density PDF:

lognormal – but broadens...

AD MHD

ideal MHD



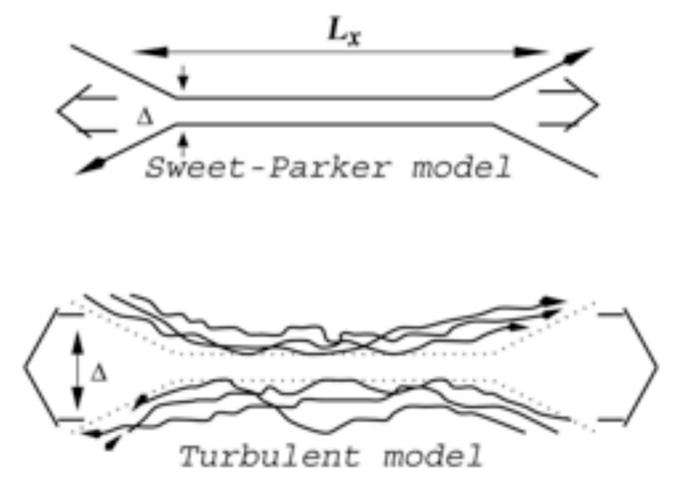
“Old picture” of star formation: slow growth of cores as field dissipates by AD in subcritical clouds (eg. reviews, Shu et al 1987)

– takes too long & depends totally on assumed “start density”

- AD cannot predict what initial density fluctuations are for models – only rate of growth of initial magnetized fluctuations -> turbulence, not AD, predicts CMF

Faster field dissiation:

turbulent reconnection?



Lazarian, Esquivel, Crutcher 2012

Angular Momentum

Distribution of specific angular momentum of cores

Spin arises in oblique shocks

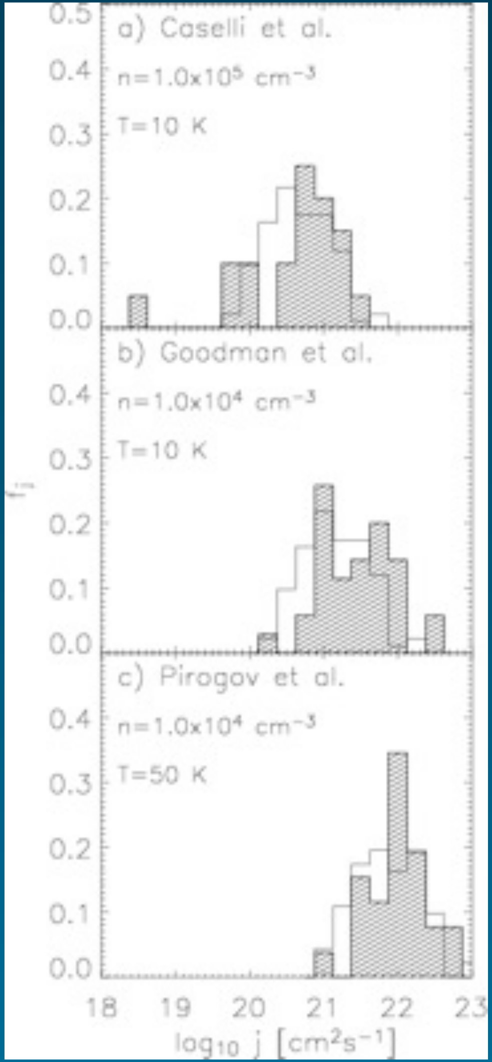
- natural scale indep of M:

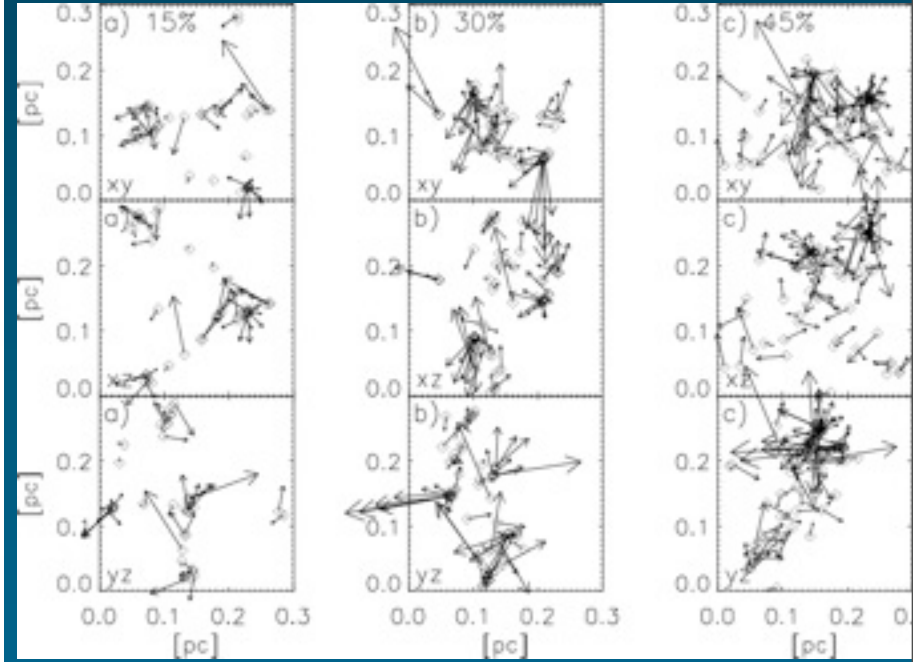
$$j \cong c_s (L/4)$$

- determines disk fragmentation into multiple stars:

(eg. Value of Ωt_{ff})

- Vector related to outflows?

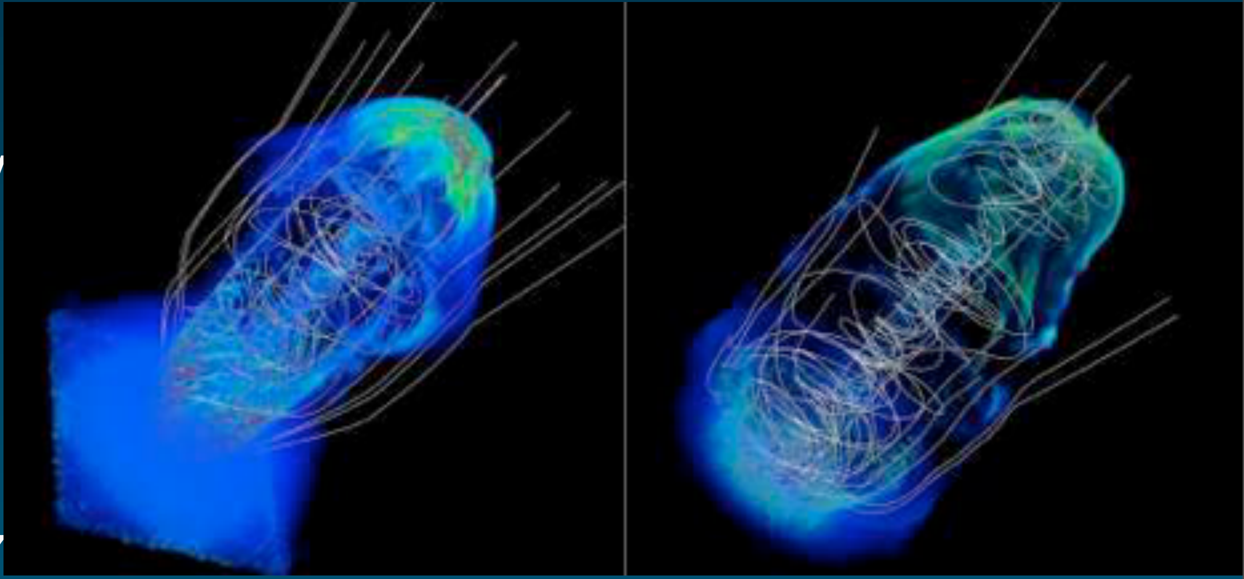




Core angular momentum distribution and directions – Jappsen et al 2004

Jets / outflows

Outflow models all rely on magnetic field + rotation + gravity



- Disk wind; (eg. review Pudritz et al 2007)

-X-winds (Shang et al 2007

3D MHD simulations of disk winds – 2 models, Blanford & Pane (1981) to right Poloidal field on axis, torodal field further out (Staff et 2010).

Drive outflows starting in earliest phases of collapse – feedback

(Tomisaka 2002, Banerjee & Pudritz 2006, Machida et al Duffin& Pudritz 2009, Seifried et al 2012,)

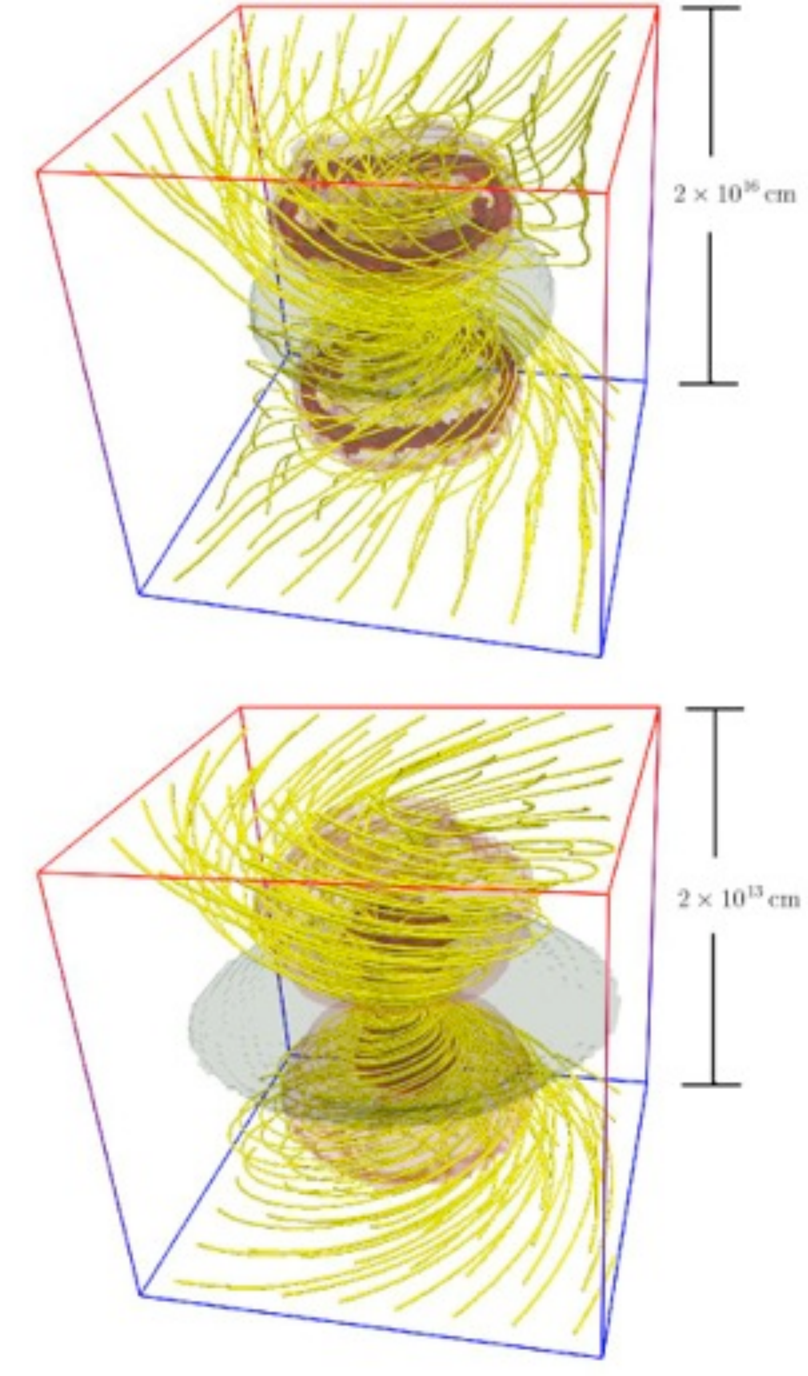
Measured B by synchotron emission from HH 80-81 jet! B ~ 0.2 milliGauss,

(Carrasco-Gonzalez et al 2010).

Outflows and collapse

Gravitational collapse of rotating, magnetized cores produces disks and disk winds

2 components of the flow – outer magnetic tower, inner disk wind



3D Visualization of field lines, disk, and outflow (Banerjee & Pudritz 2006):

Magnetic Braking and Disk Formation

Extract angular momentum from pre-collapse cores by magnetic braking (eg Mouschovias & Paleogolou 1980, Basu & Mouschovias 1994).

Inhibits disks formation in early infall – even in weakly ordered magnetized systems (Mellon & Li 2008, Hennebelle & Fromang 2008…)!

Jets - in later phase – most disk ang momentum carried by jet ~ 60% of disk (Anderson et al 2003, Bacciotti et al 2002)

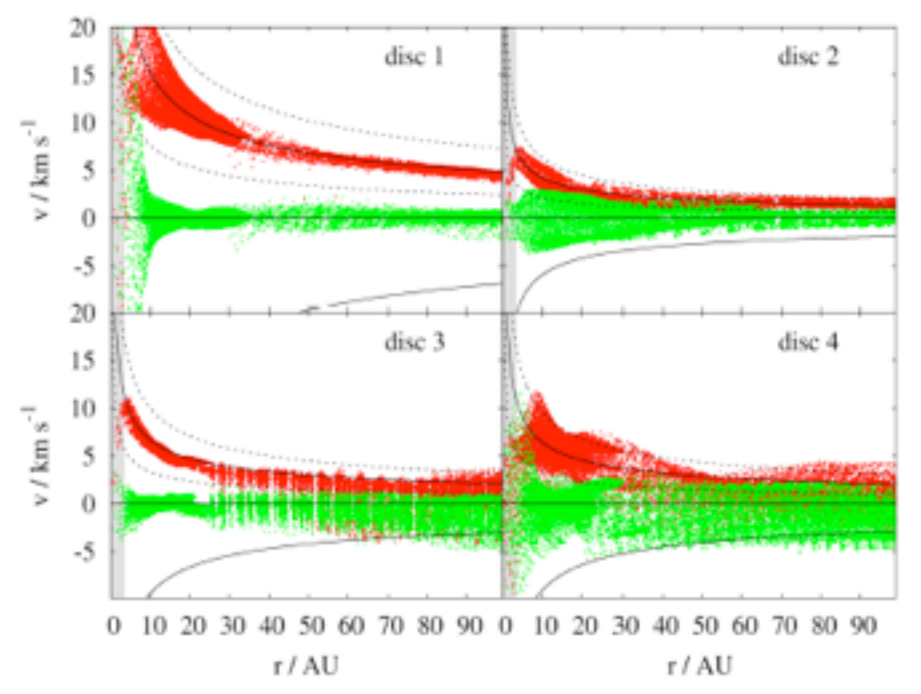
Solutions to “braking catastrophe” formation problem

Strongly reduce braking if field is disordered.

Massive star formation regions highly turbulent:

Turbulence scrambles field -> magnetic torques much lower, disk can form

(Seifried, Banerjee, Pudritz, & Klessen 2012)



Red = rotation speed of disk with disk radius

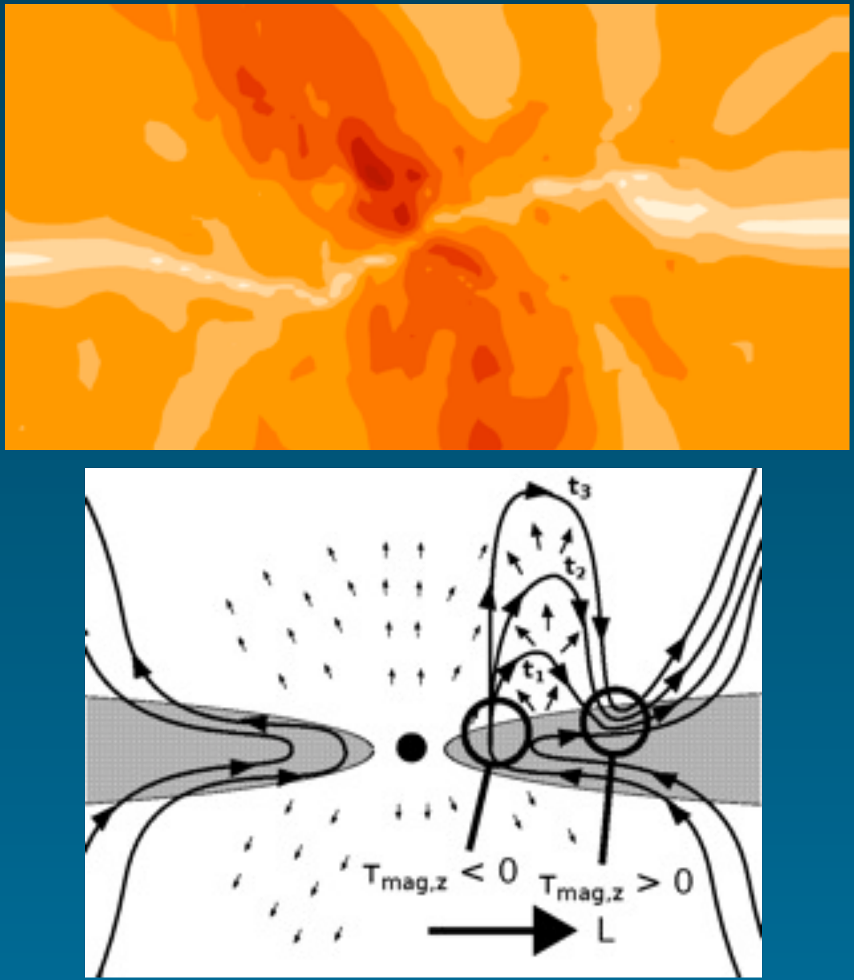
Contours – Kepler profiles

Green – radial velocities

Low mass cores and disk formation – buoyancy

- Form warped, disk and precessing outflow
- Disk near Kepler rotation out to 100 AU.
- Disk warp by magnetic torque (Lai, 1985)

Explanation: degrade mean torque by buoyant magnetic loops generated by flattened object



Duffin, Pudritz, Seifried, Banerjee, & Klessen 2012 (submitted)

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II. Feedback

Radiation

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

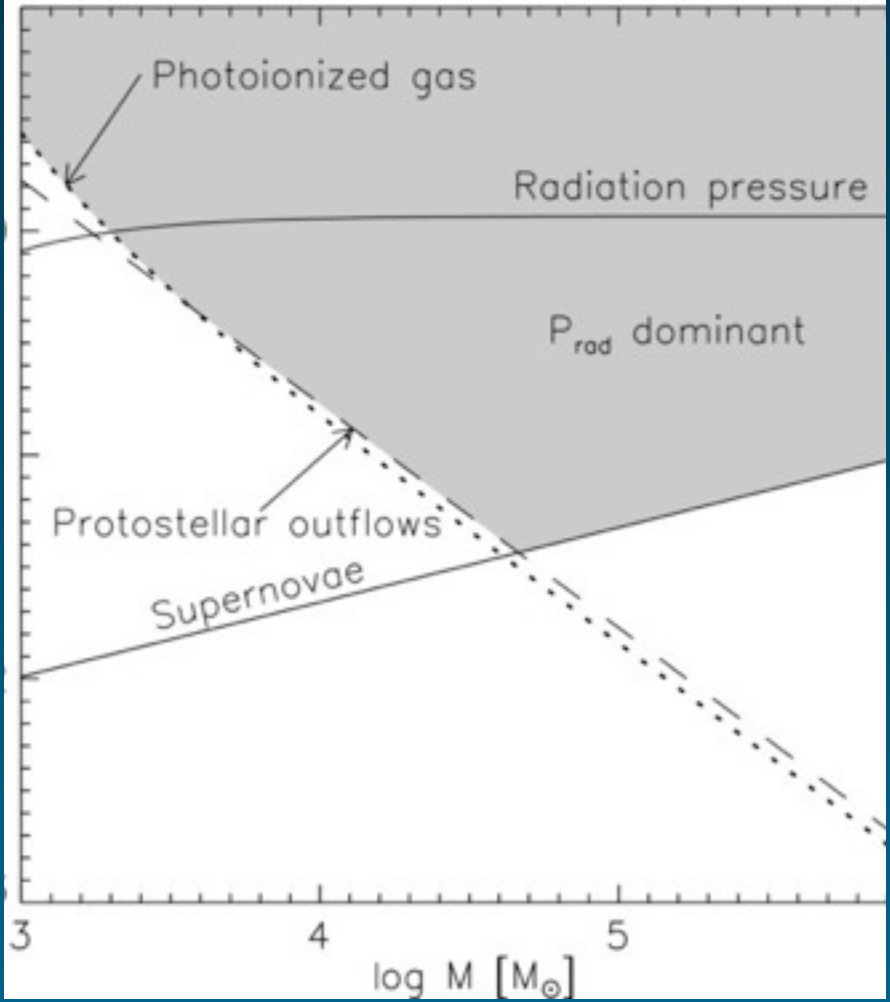
$$M_J \propto T^{3/2}$$

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

The feedback landscape: ten thousand solar masses a threshold…

Feedback sources: -
supernovae (beyond 3.6 Myr Krumholtz & Matner 2009),

- MS winds (leaks in bubbles reduce effectiveness),
- photoionization: important when gas pressure > radiation pressure
- protostellar jets: not effective for large masses..
- radiation pressure: dominate above 10^4 solar masses



Fall, Krumholtz, Matzner 20102

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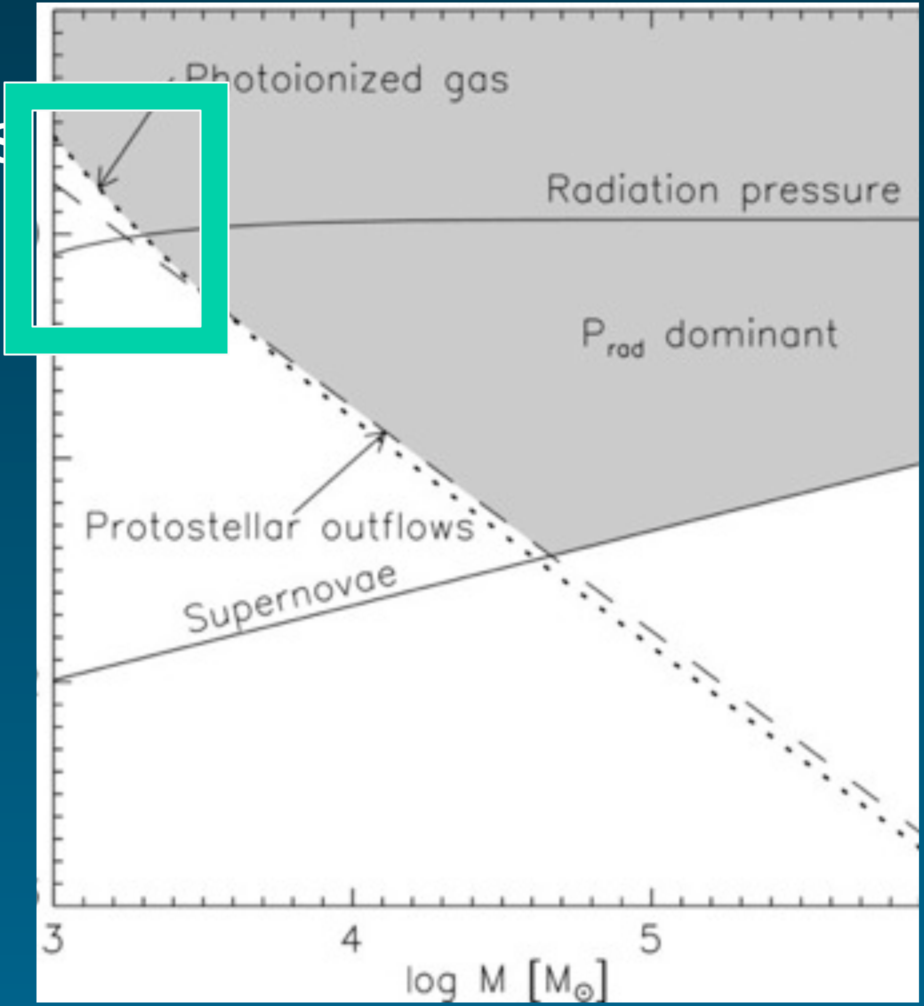

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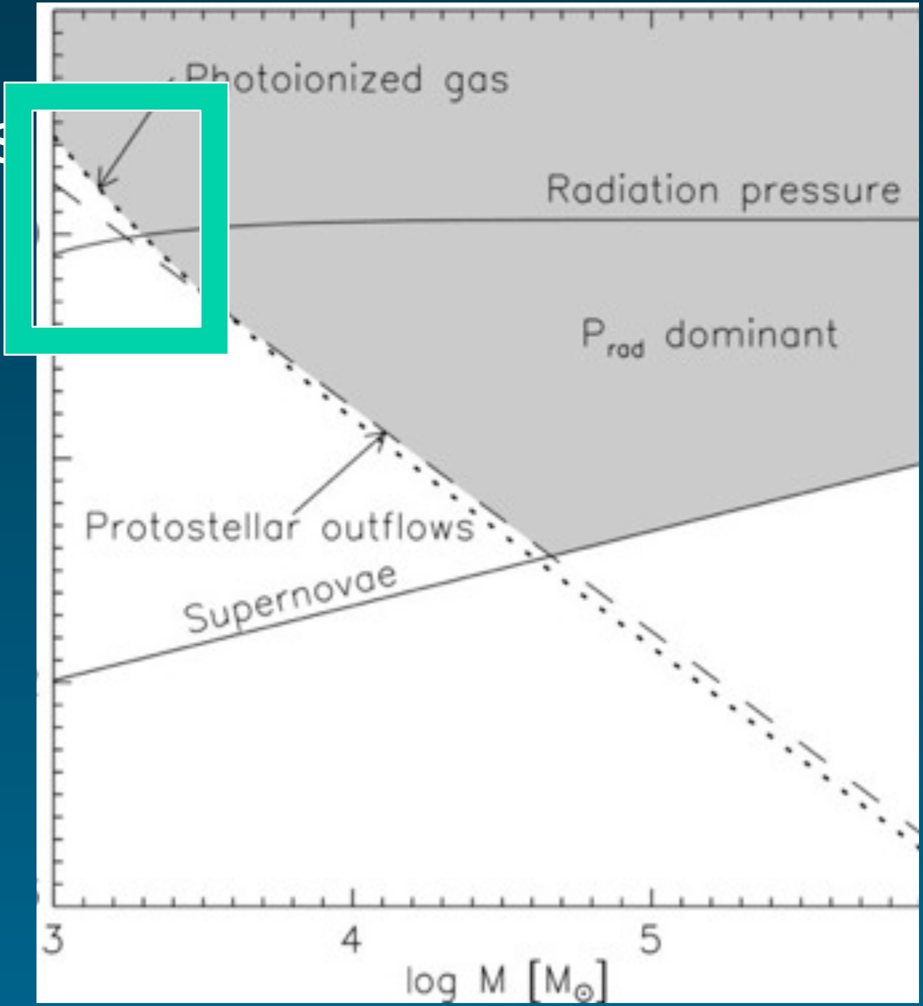
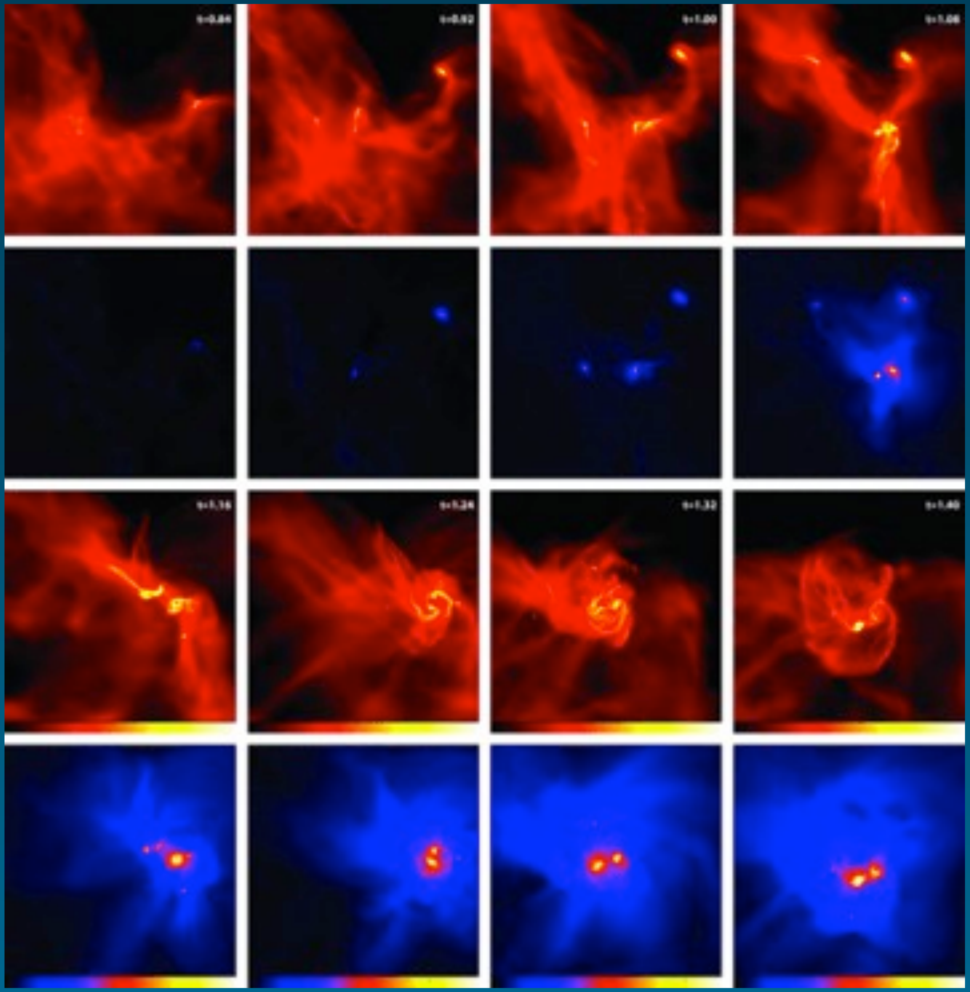


Fall, Krumholtz, Matzner 20102

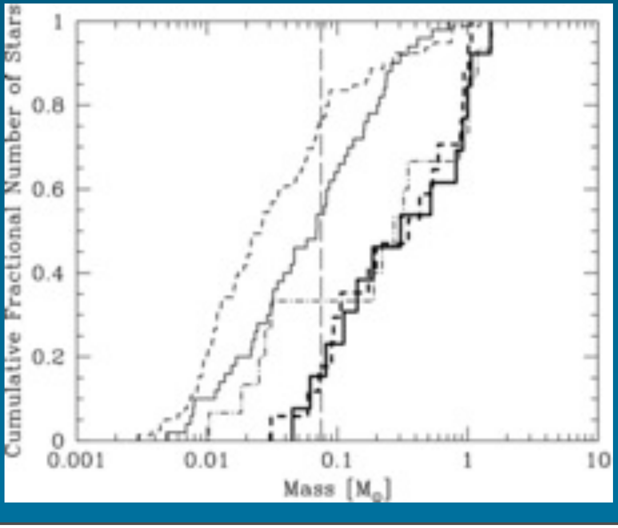
Regime in which jets important - B matters for feedback in low mass systems



Bate (2009)

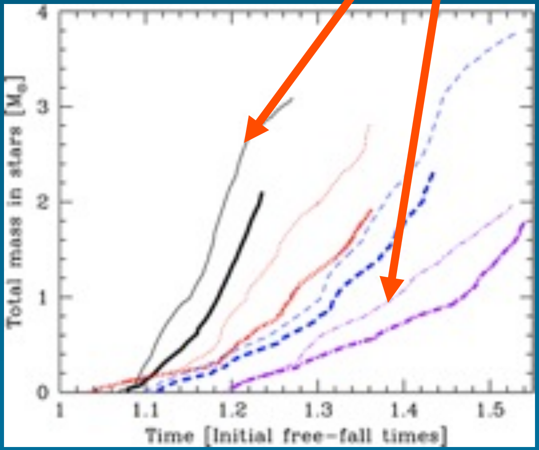
Radiation heating in a cluster environment:

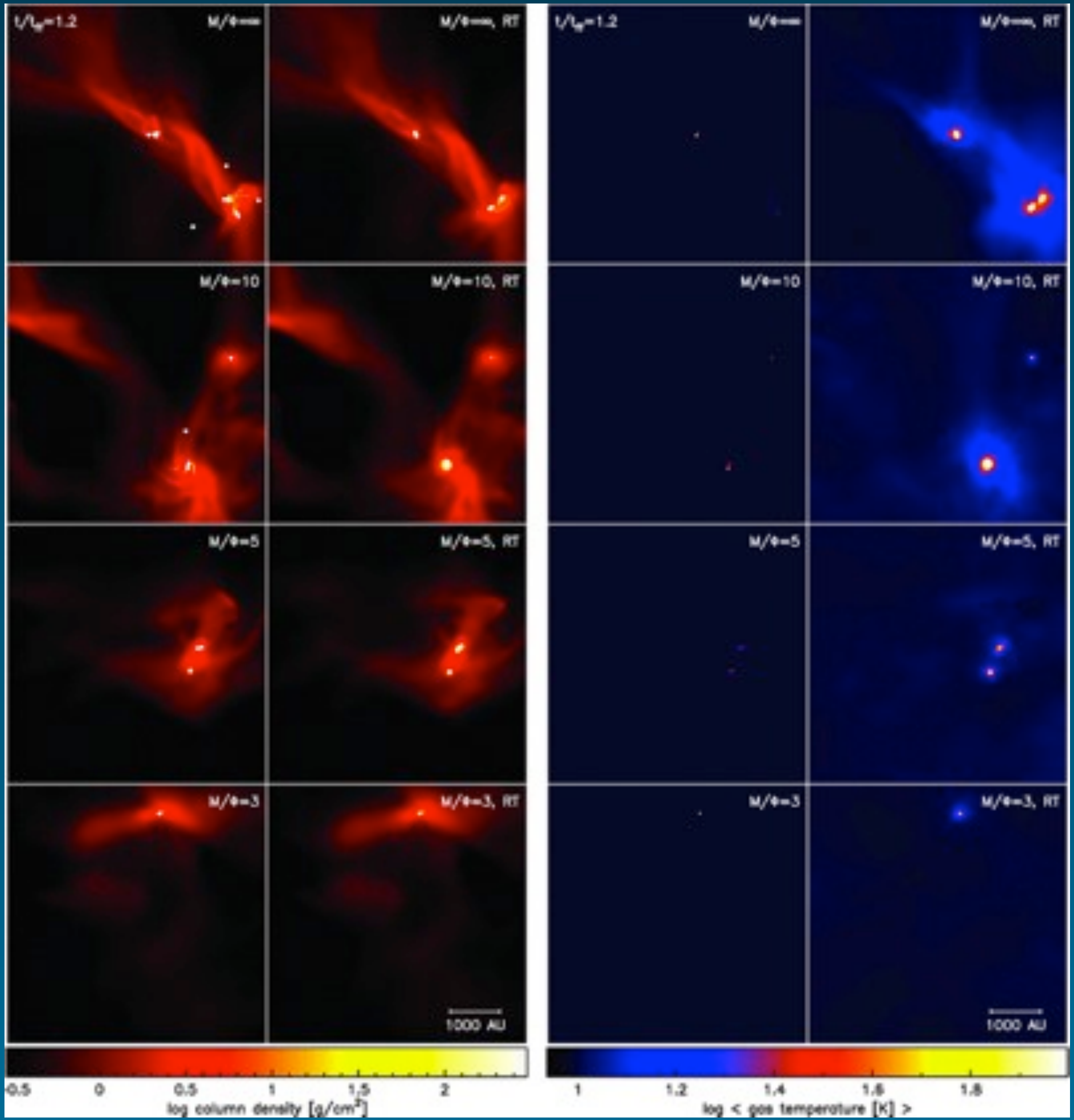
- Filaments drain material into central region
- Feedback from forming stars affects dense material in central region
- Suppression of objects by factor 4; produces stars/brown dwarfs = 5



MHD in SPH: combined with RT

- MHD with Euler potentials (eg. Price & Bate 2009) but see 2012 paper where this is removed
- RT suppresses fragmentation – small scales
- MHD suppresses larger scales
- MHD has strong suppressive effect compared to hydro for supercritical cloud Γ=3?



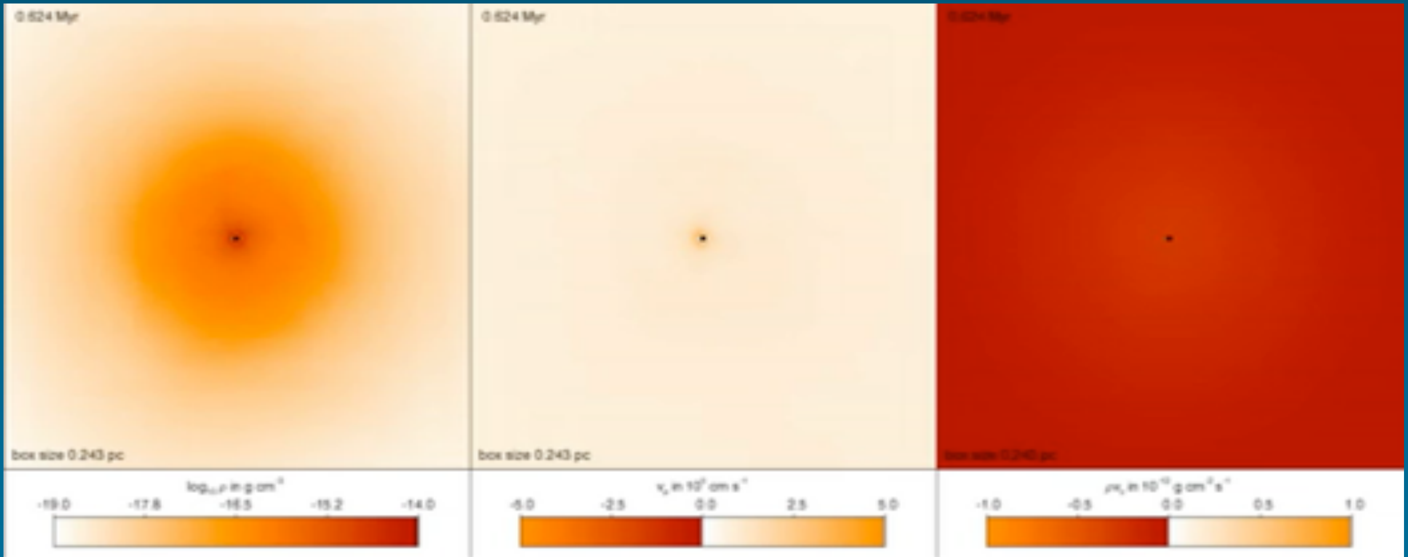


Barotropic RT

RMHD and formation of massive stars and clusters:

Simulations of B and ionizing radiation. Collapse of 1000 M rotating Ω at typical rate (Peters et al 2010)

B field suppress fragmentation
➜ longer accretion time onto fragments ➜ more massive star created.



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Add in turb + B: Klassen, Pudritz, et al, in prep

1000 M_{sun} clump
rho ~ 10^{-17} g/cm^3 at the centre
rho ~ $r^{-1.5}$ power law profile
mass-to-flux ratio ~ 3.5
flux ~ 10 uG uniform in the z-direction
turbulence RMS

~ Mach 5
turbulent power spectrum: P(k) ~ k^(-2) (Burger's Turbulence)
rigid body rotation: beta ~5% of the gravitational potential

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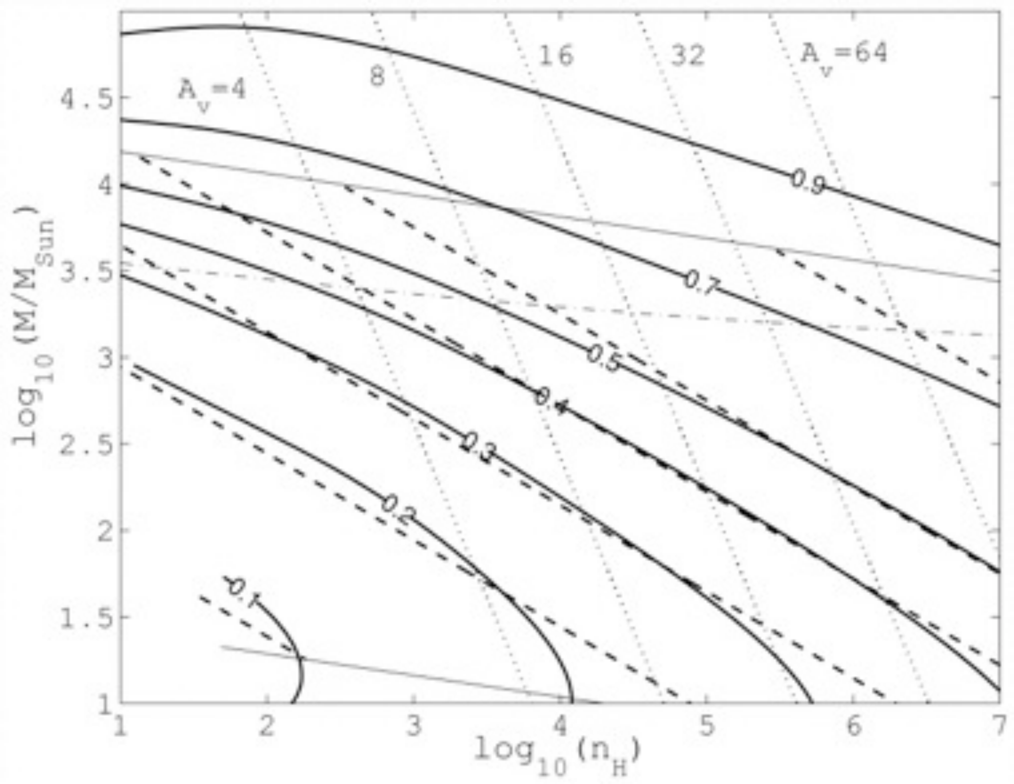
Feedback by Outflows: Efficiency of low mass star formation - MHD outflow

Neglect effects of massive stars

- Use X-wind models (wide opening angles, momentum up the axis



Find 30-50% efficiencies: Duffin et al find higher efficiencies (70%) –> more matter gets into disk before outflow starts

Matzner & McKee 2000

$$\varepsilon = m_* / (m_* + M_{eject})$$

Outflows feedback:

Does energy in outflows couple into clump to excite turbulence – regulate star formation? (Norman & Silk 1980)

Uncertain: Banerjee et al 2008 vs Wang et al 2009

Put in outflow feedback as “subgrid” in larger simulations

III. Application to Pop III ?

- B in current clouds, flux rich

  - in primordial gas, B assumed totally negligible (eg. Abel et al 2002)

  - turbulent dynamos: rapidly generate small scale field (Kazanstev 1968, Boldyrev & Cattaneo 2004, Sur et al 2010, Federrath et al 2011, Schober et al 2011…)

  - seed field for dynamo (eg. Brandenburg & Subramanian 2005)

- Collapse in minihaloes generates turbulence

  ->drives small scale dynamos for strong local fields:

  Schleicher,Banerjee, etal 2010,

  - implications: disk/jet paradigm, jet feedback and mass of PopIII stars, B influences fragmentation, ….

Score card: – role of B fields in star formation?

1. Lognormal part of CMF/IMF from shocks: independent of origin.

2. High mass power-law of CMF: gravity?

3. GI in magnetized filaments as a formation mechanism of cores and CMF?

4. Radiative / outflow feedback essential to suppress too much fragmentation

5. MHD turbulence essential for early formation of disks (essentially Keplerian). B fields critical for jets / angular momentum.

6. B makes Pop III star formation like current paradigm: jets and disks, star formation efficiency, …