Magnetic Fields from Cloud Fragmentation to Disks

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Key roles of interstellar B

- Low star formation efficiency by preventing SF in subcritical envelopes
- Maintaining (MHD) turbulence
- Filament formation
- Influencing core mass function
- Launching outflows
- Regulating star-disk interaction/accretion
- Providing fossil magnetic field to (at least) early type stars

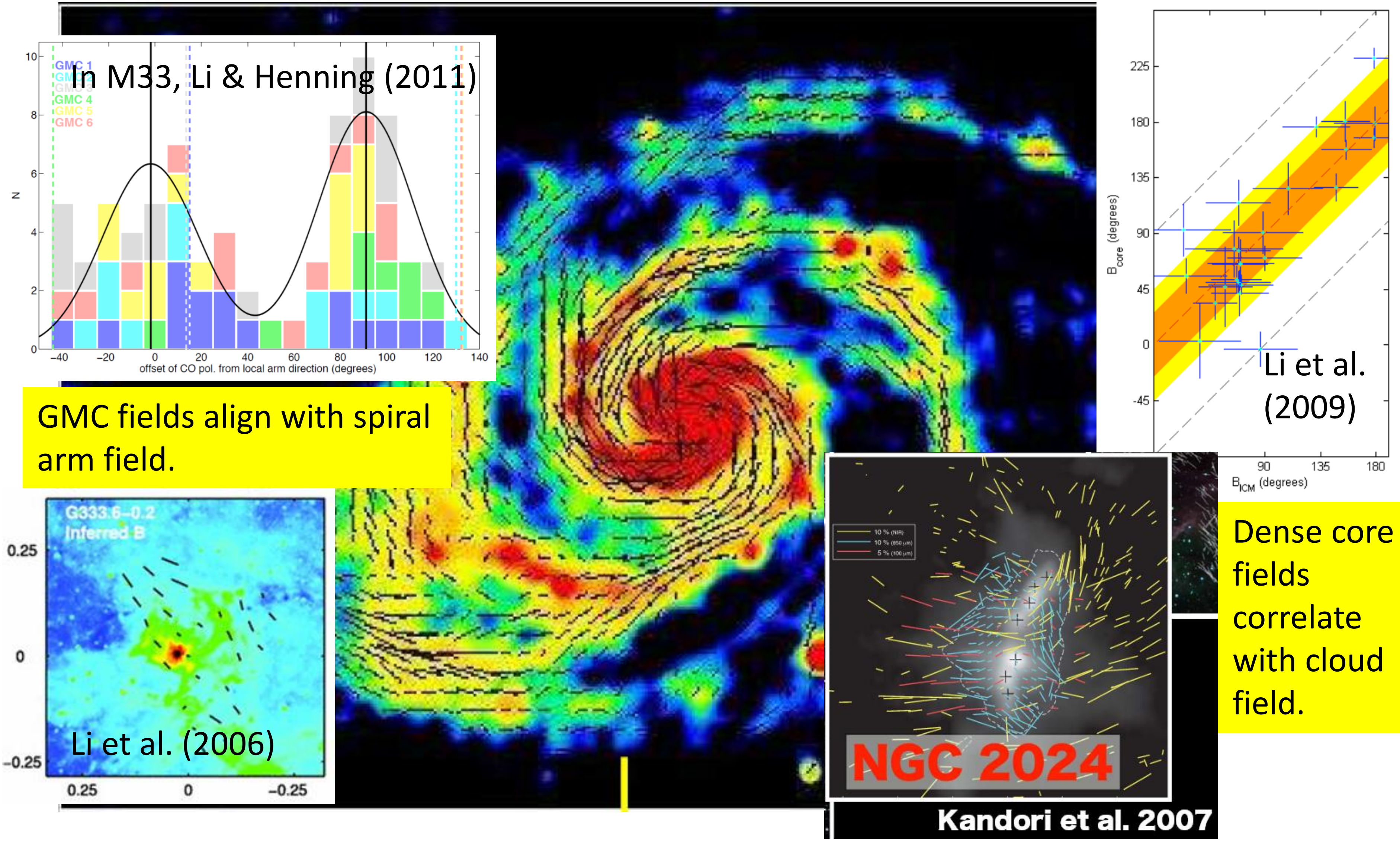
Today's key takeaway

- Magnetic Fields are complicated!

Key takeaways about B

- Recent observations reveal a connection between large and small scales. This supports the strong magnetic field scenario
- Filaments in molecular clouds have a LOT to do with magnetic fields
- Hourglass fields connect large and small scales. Observers see them, theorists fear them
- Disk formation is adventurous with B

A Magnetized Fluid



In M33, Li & Henning (2011)

GMC fields align with spiral arm field.

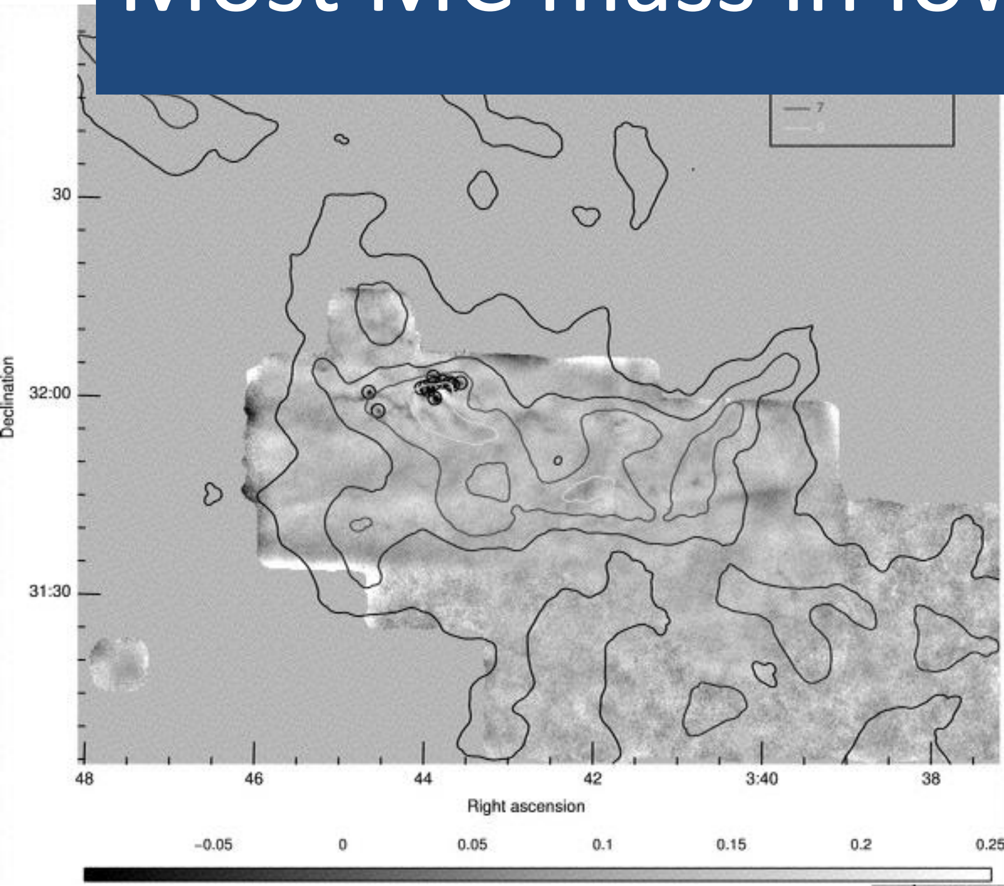
Li et al. (2009)

Dense core fields correlate with cloud field.

Li et al. (2006)

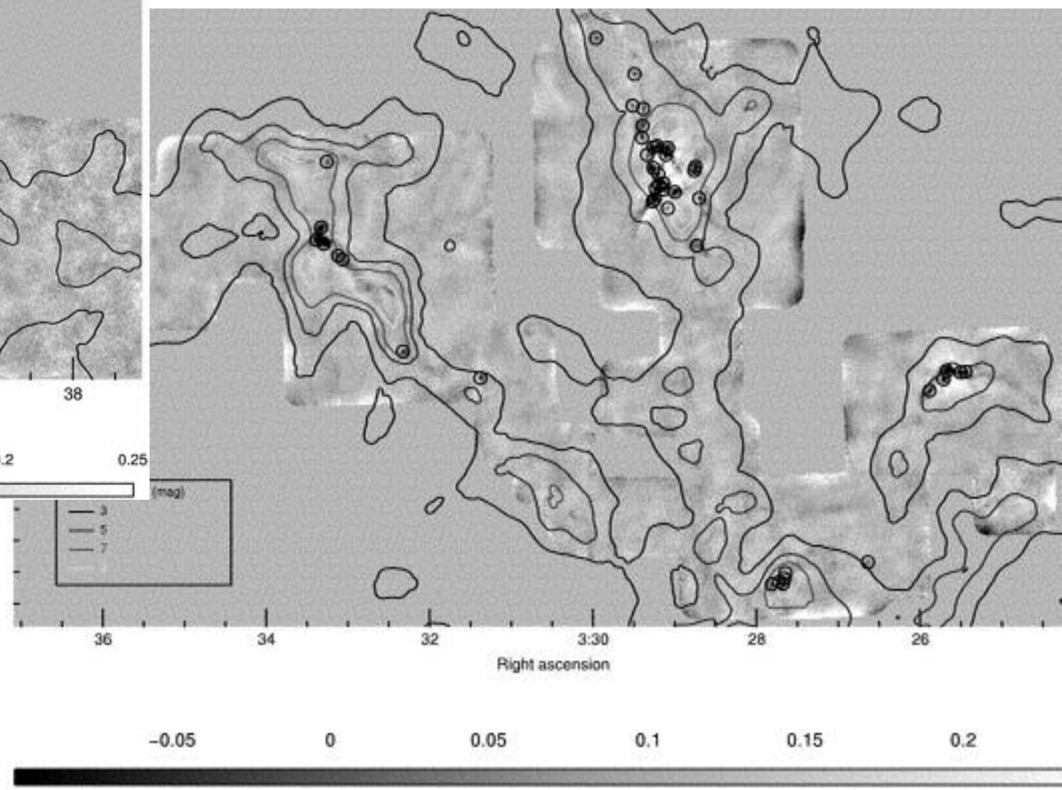
Kandori et al. 2007

Most MC mass in low density envelope



Perseus Molecular Cloud

Subcritical common envelope? Also turbulent. Highly ionized?

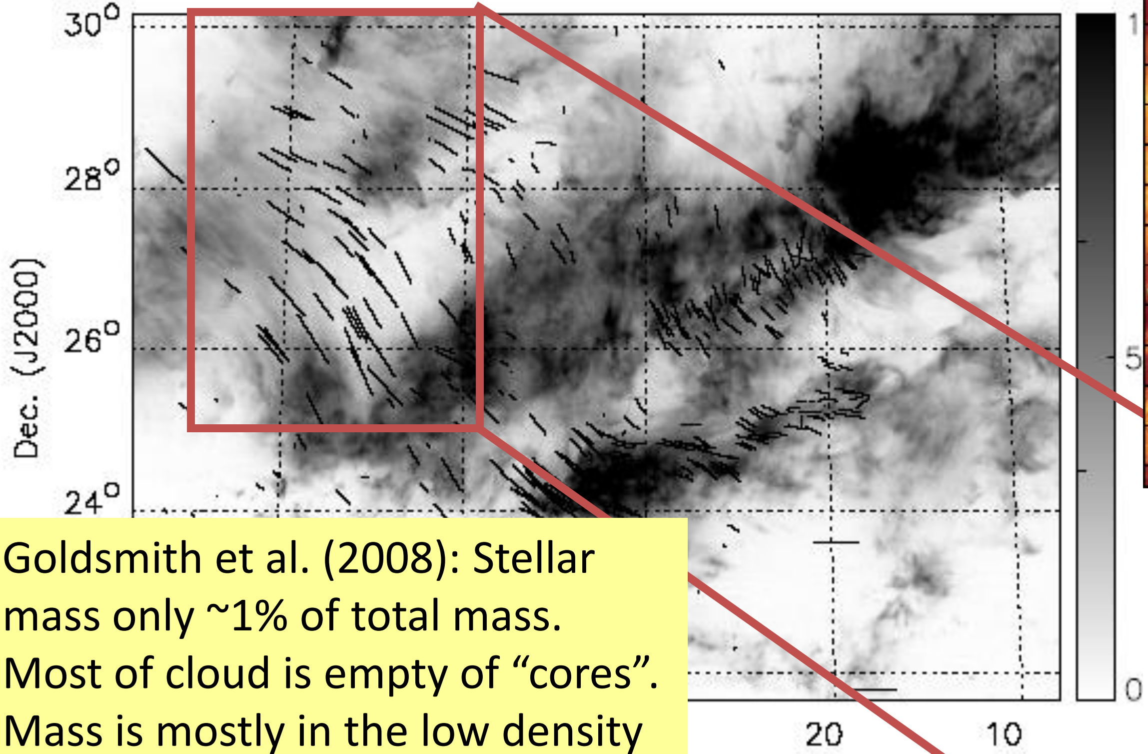


Kirk, Johnstone, & Di Francesco (2006)

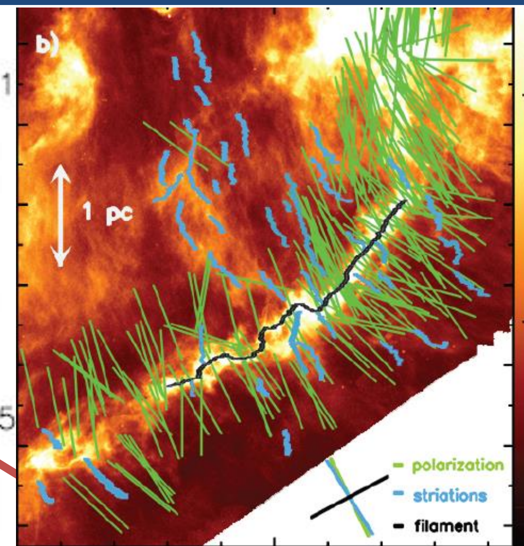
Cores only at $A_V > 5$ mag, threshold for shielding of UV?

Taurus - low SFE and magnetic striations

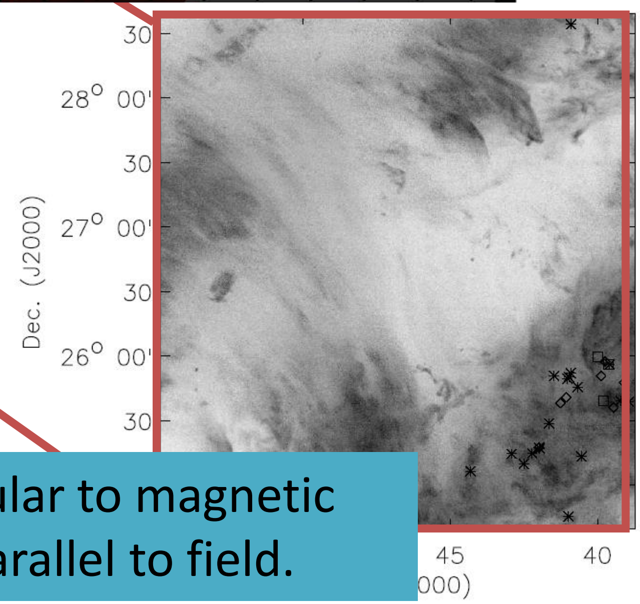
Taurus Molecular Cloud



^{12}CO emission



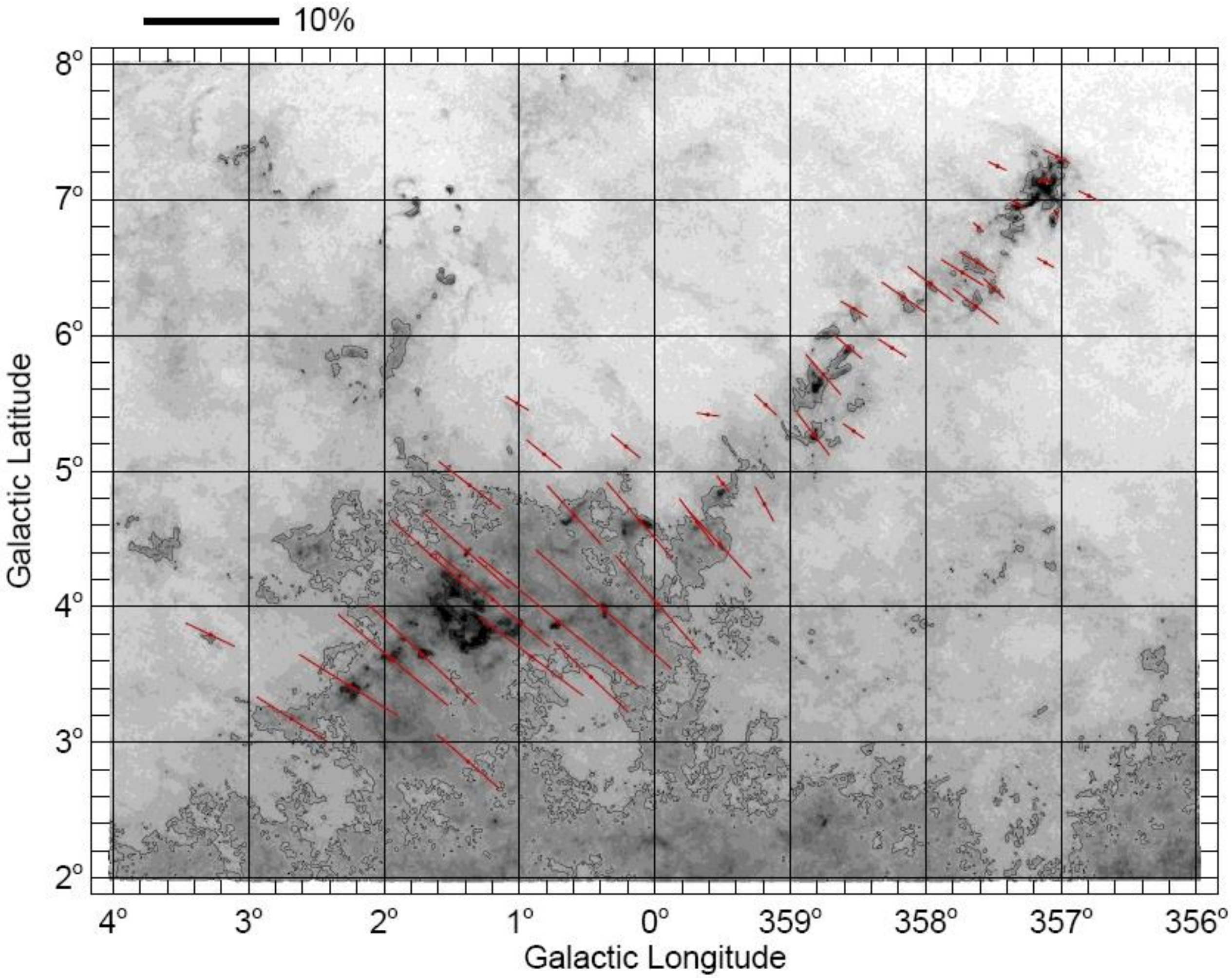
Palmierim et al (2012)



Goldsmith et al. (2008): Stellar mass only ~1% of total mass. Most of cloud is empty of “cores”. Mass is mostly in the low density “envelope”. Heyer et al. (2008) use velocity information to conclude low plasma β in envelope → subcritical?

Main filaments perpendicular to magnetic field while striations are parallel to field.

Pipe Nebula



Alves, Franco, & Girart (2008)

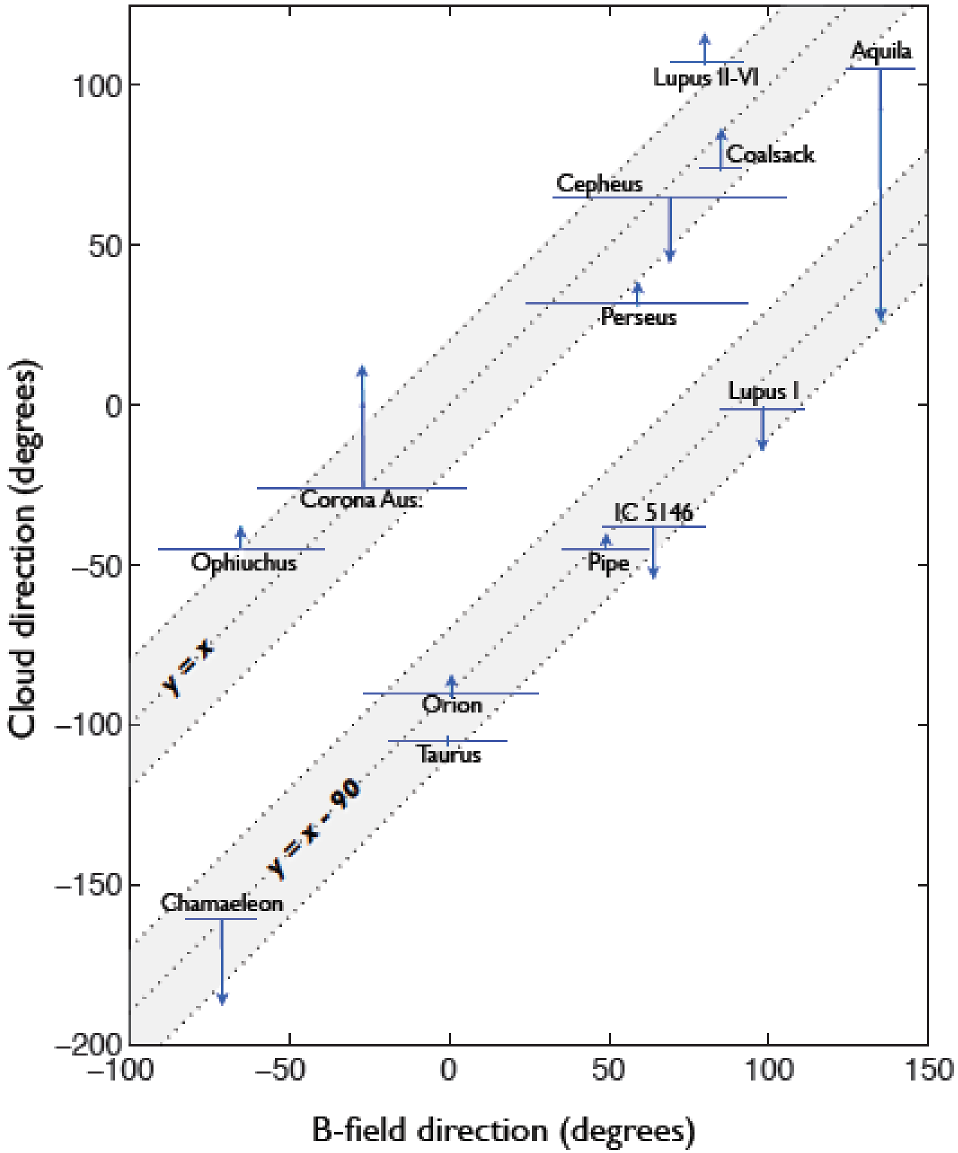
More evidence of cloud formation by flow or contraction along B.

See posters on polarimetry:

Poster 10 – Josep Girart: Magnetic Fields in Massive Star Forming Regions

Poster 13 – Chat Hull: Multi Scale View of Magnetized Star Formation

A two state system?



H-B Li et al. (2013)

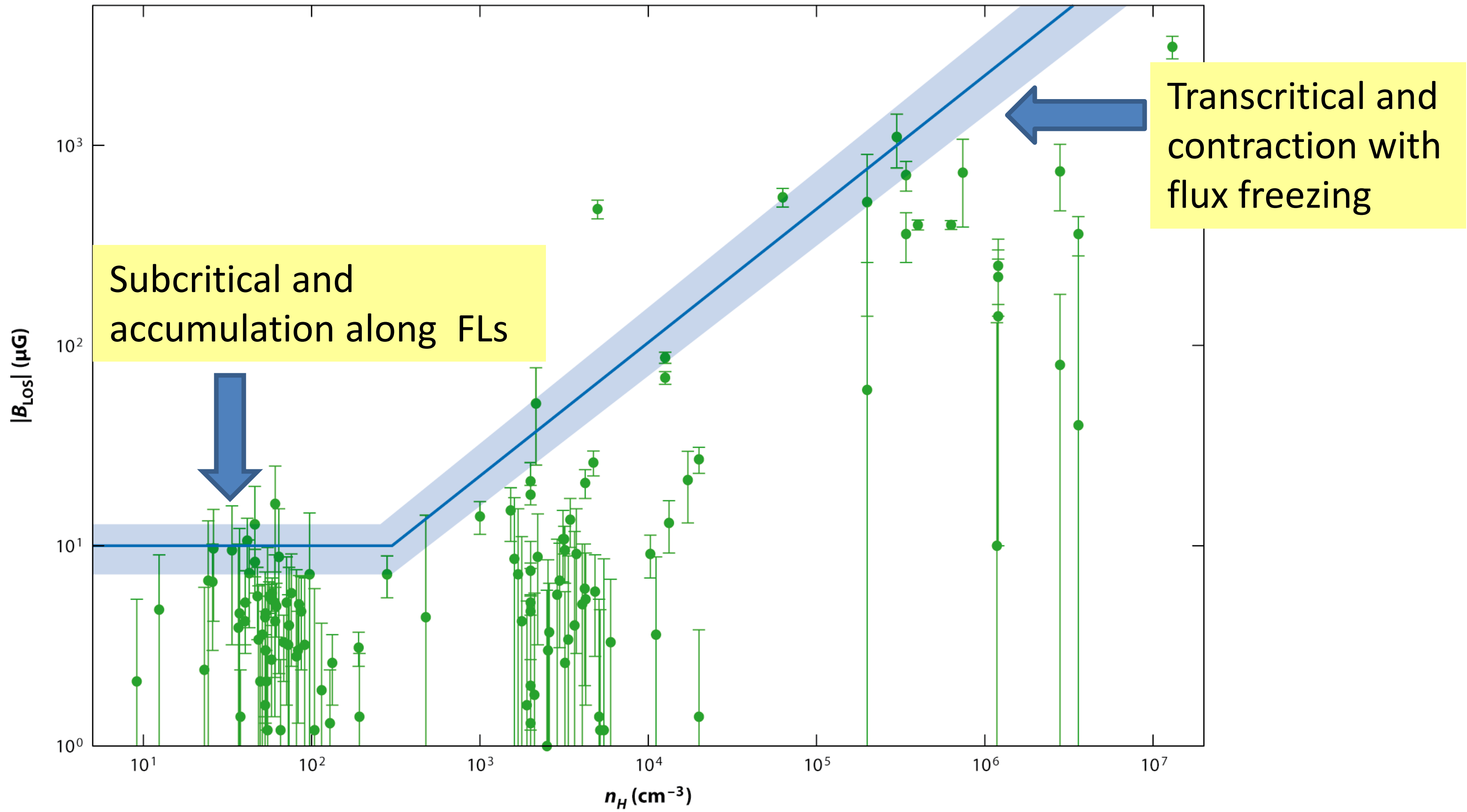
Magnetic field invariably either perpendicular or parallel to filament.

See posters on magnetized filaments:

Poster 15 – Eric Keto: Filaments by reconnection in magnetized sheets

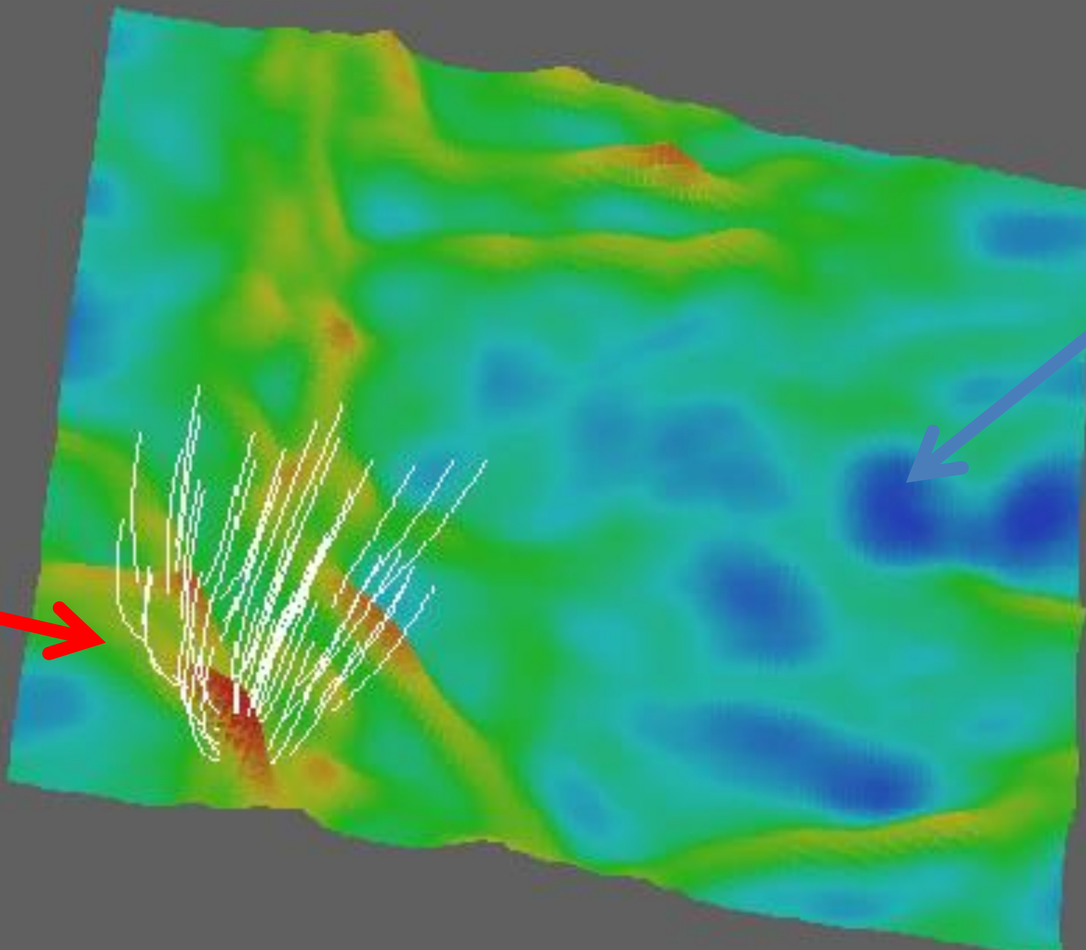
Next talk + Poster 31 – Kohji Tomisaka: MHS equilibria of Filamentary Cloud with Lateral Magnetic Field

Zeeman measurements B_{los}



Crutcher RM. 2012.
Annu. Rev. Astron. Astrophys. 50:29–63

B-dominated scenario for low SFE

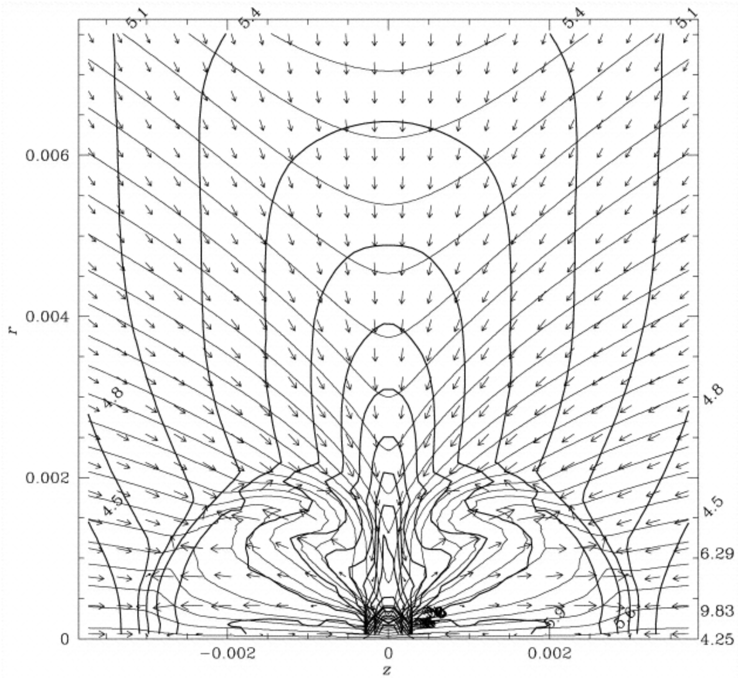


Subcritical common envelope

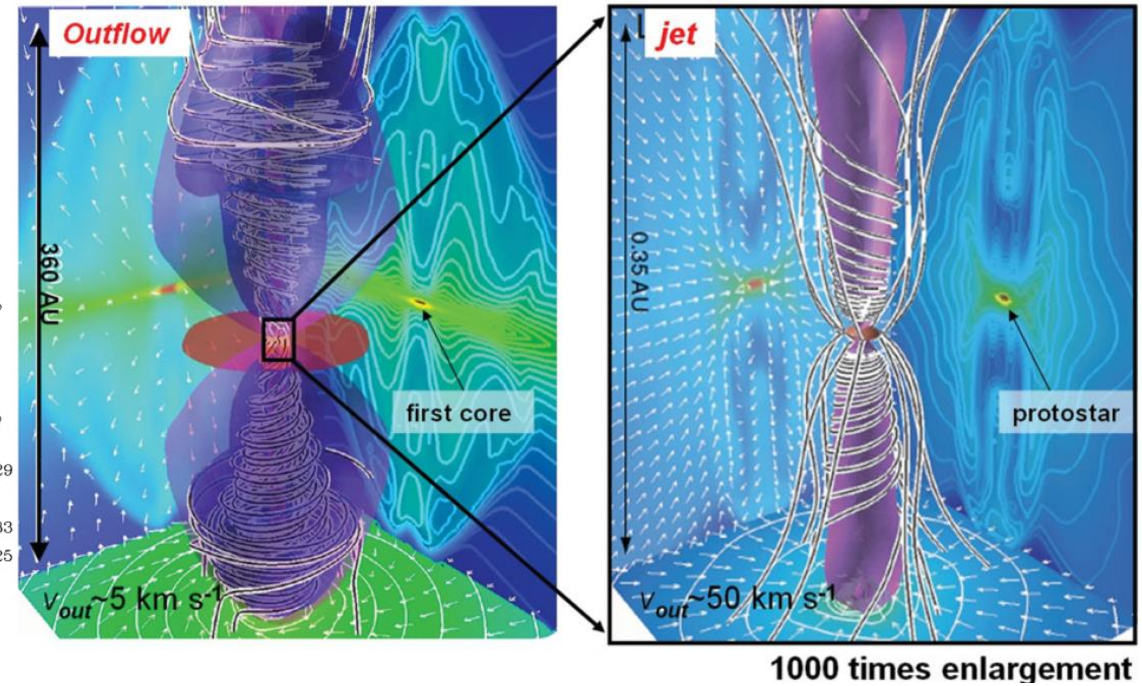
Supercritical high-density regions assembled by large scale flows/turbulence

cf. Nakamura & Li (2005), Elmegreen (2007), Kudoh & Basu (2008, 2011), Nakamura & Li (2008), Basu , Ciolek, Dapp, & Wurster (2009; model shown above).

Late phase: collapse → outflow/jet



Tomisaka (1998)

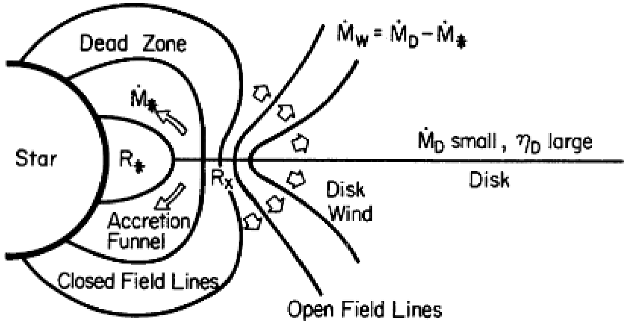


Machida et al. (2006, 2007)

See Poster 13 – Chat Hull: Multi Scale View of Magnetized Star Formation for polarimetry of outflow regions

Even later: Star-Disk Phase

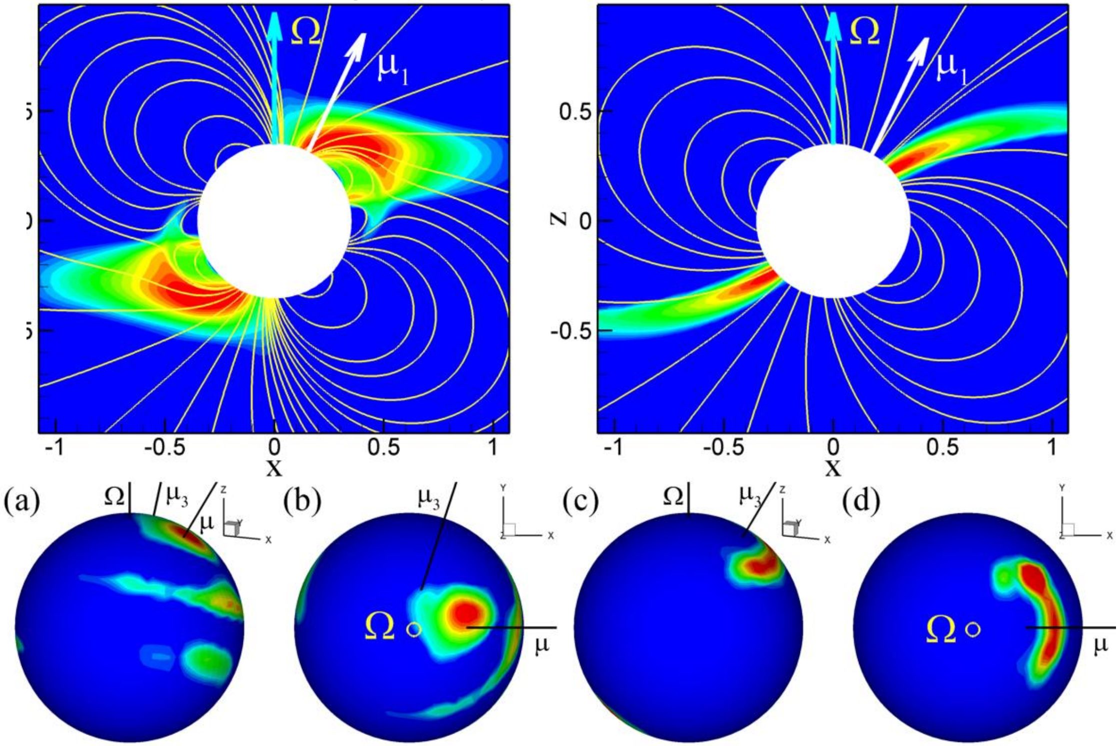
Stellar/disk wind/jet



Shu et al. (1994)

also
Uchida & Shibata 1985
Camenzind 1990
Konigl 1991
Lovelace et al. 1995

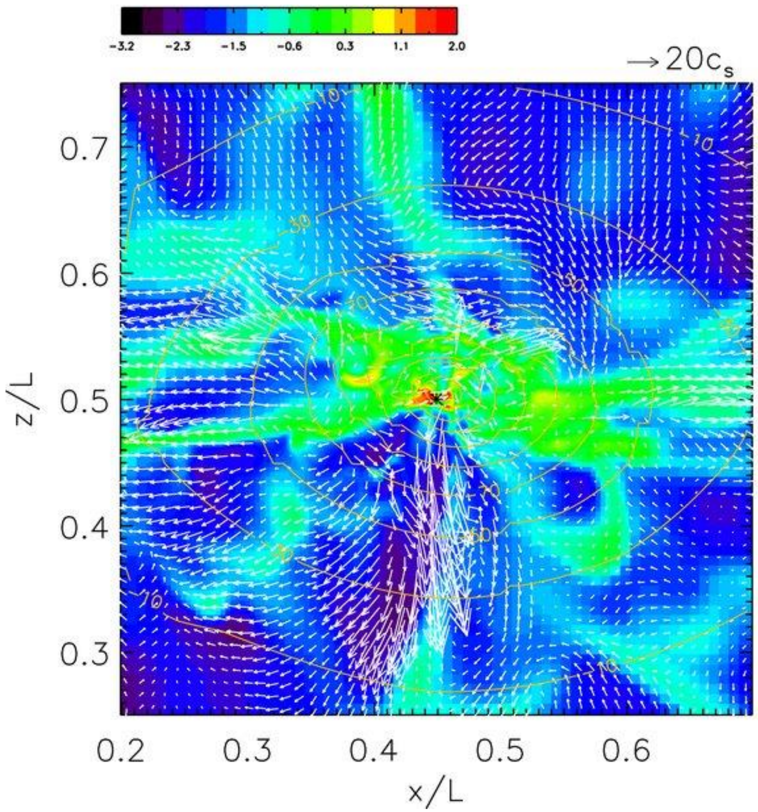
Magnetospheric accretion



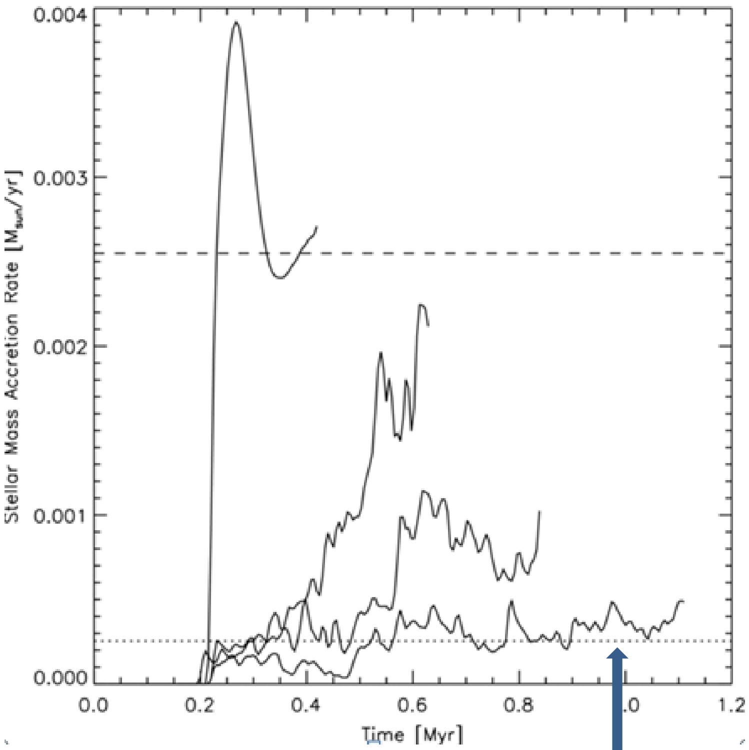
Romanova et al. (2009)

Talks by H. Arce, C. Fendt. See also poster 06 – Turlough Downes : MRI in weakly ionized disks

Maintaining Turbulent Energy



Wang, Li, Abel, & Nakamura (2010)

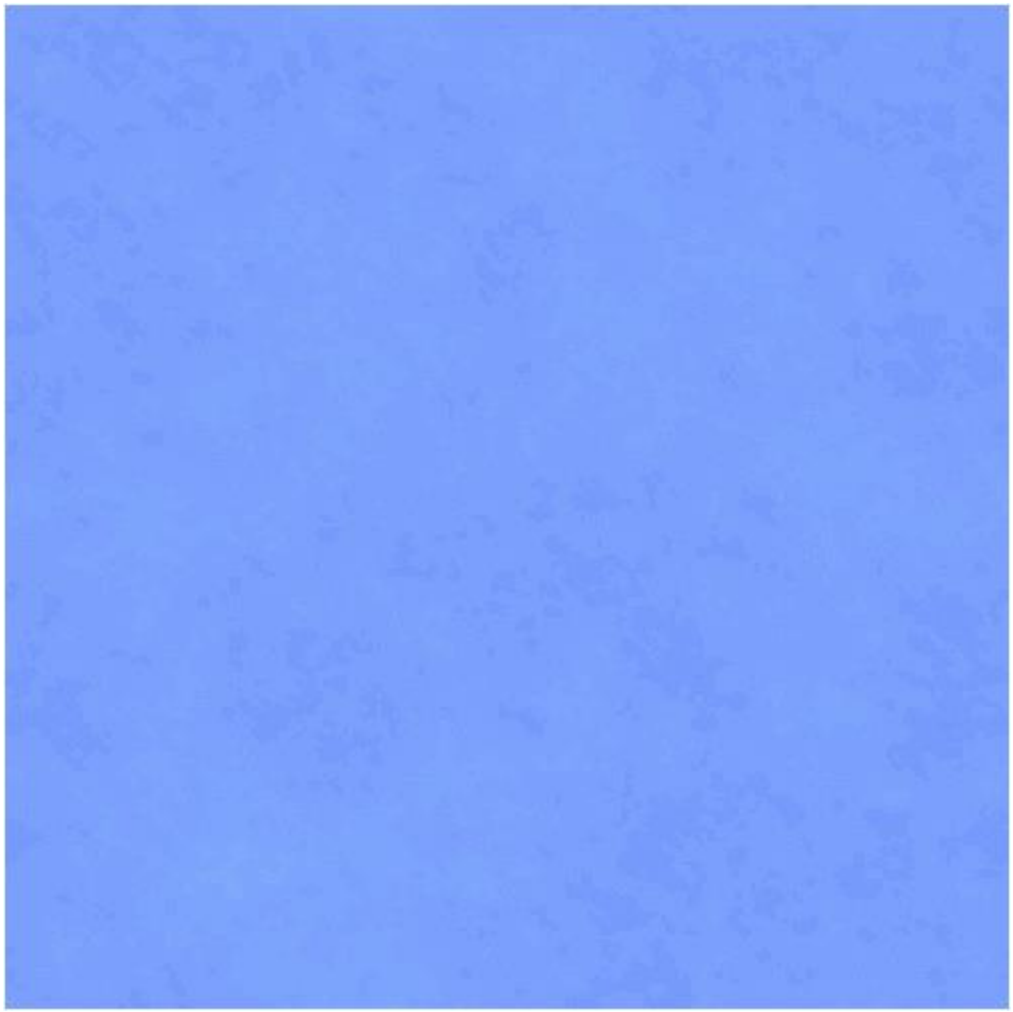


Mass accretion onto sink particles reduced significantly when both magnetic field and outflow driving are present.

Subcritical turbulent cloud with flux-freezing

Initially turbulent ($v_k^2 \sim k^{-4}$) thin disk model. Magnetic field perpendicular to layer. Supersonic motions continue without local collapse.

$$\mu_0 \equiv 2\pi G^{1/2} \frac{\Sigma_0}{B_0} = 0.5$$

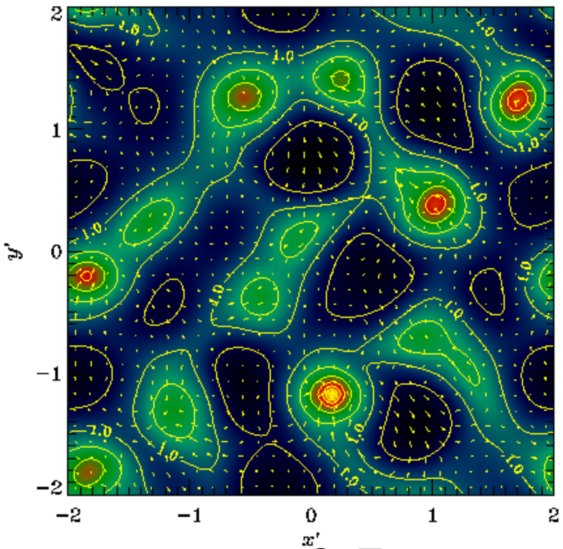


Animation (not available in pdf version)

Basu & Dapp (2010, ApJ, 716, 427)

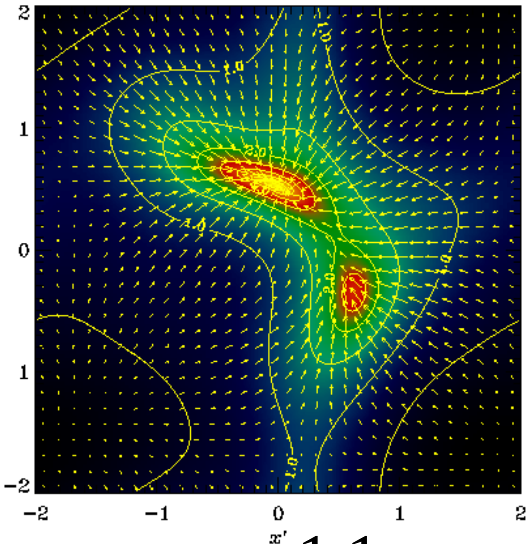
Magnetic Fields, Ambipolar Diffusion, and a modified Jeans mass

Basu, Ciolek & Wurster (2009, NewA, 14, 221)



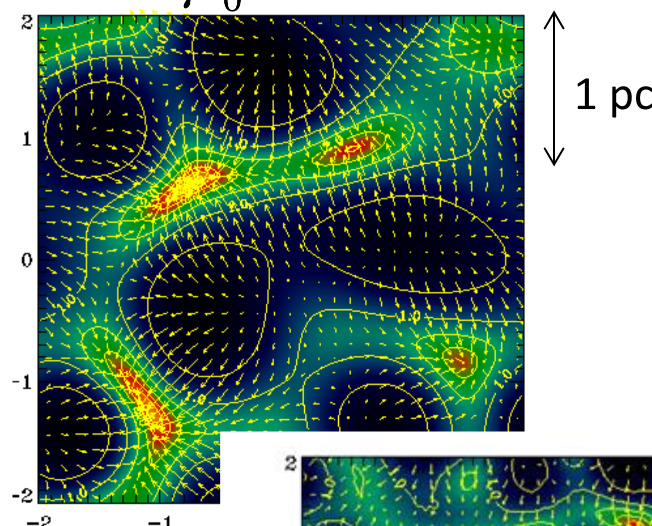
$\mu_0 = 0.5$

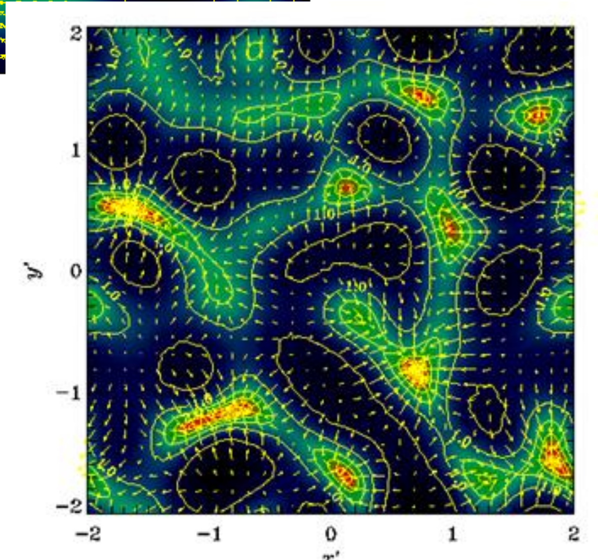
$x' = x/(2\pi Z_0)$, etc.



$\mu_0 = 1.1$

$\mu_0 = 2.0$



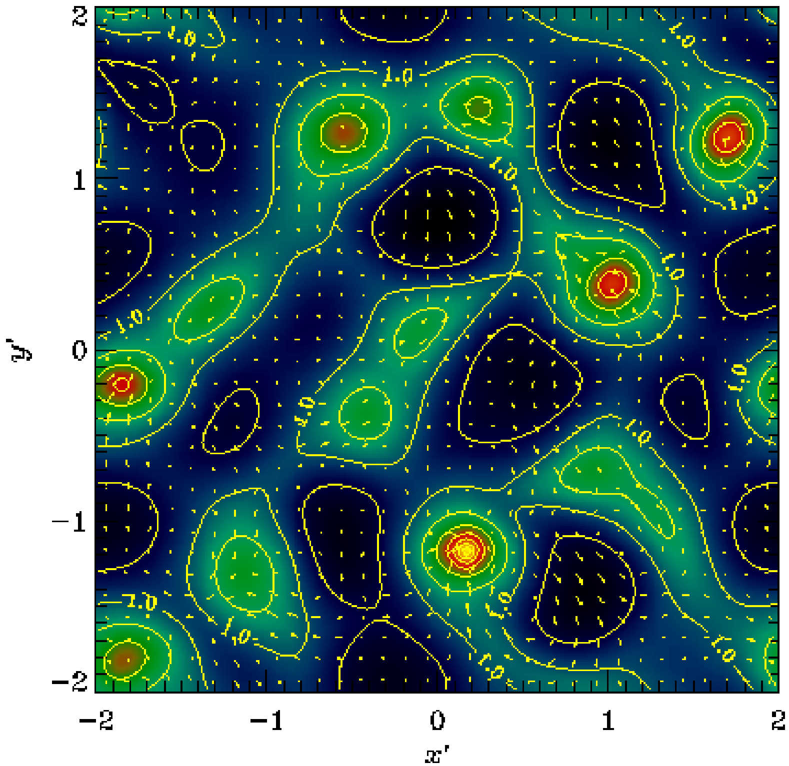


$\mu_0 = 10$

Periodic isothermal thin-sheet model. Initial small amplitude perturbations. B is initially normal to sheet. Ambipolar diffusion is active.

Column density and velocity vectors (unit 0.5 c_s)
Note sensitivity to magnetic field strength and super-Jeans transcritical fragmentation.

Subcritical Fragmentation

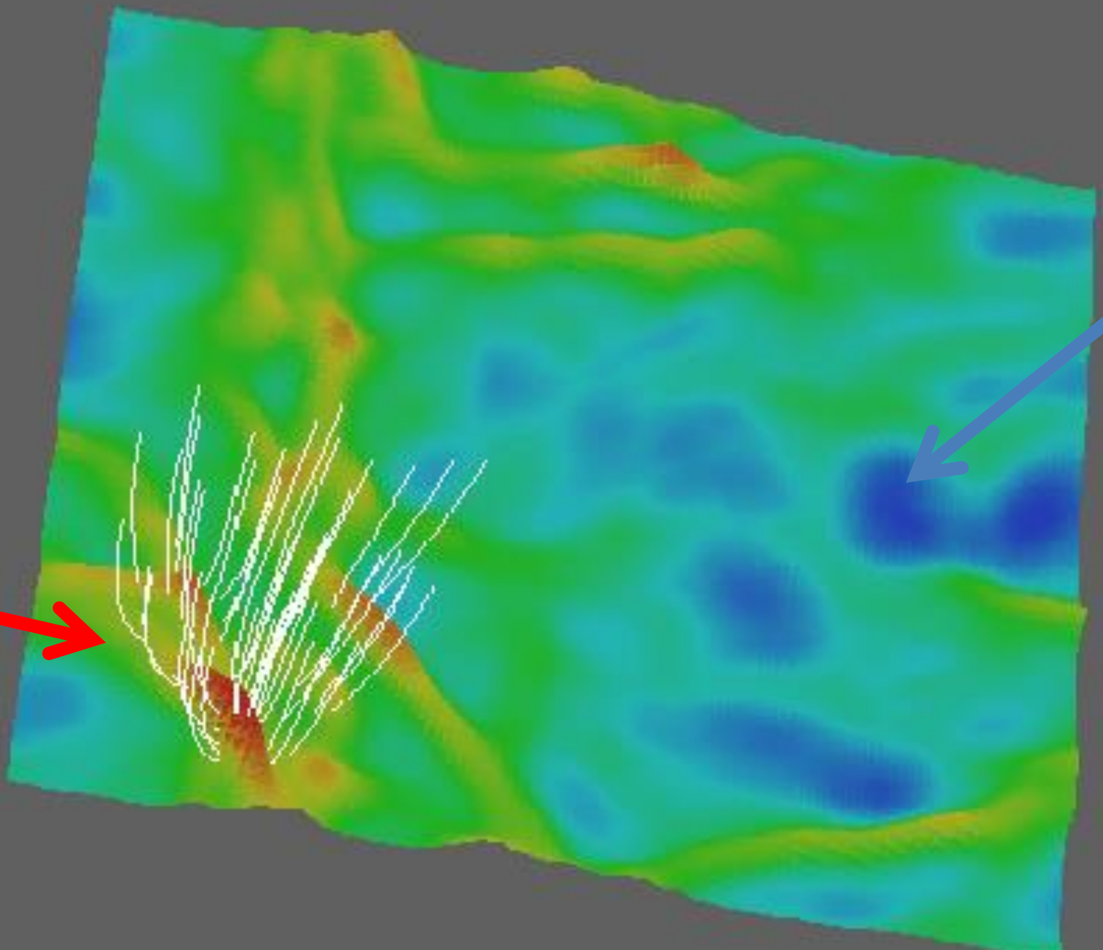


$\mu_0 = 0.5$ fragmentation

- Direct fragmentation due to ambipolar diffusion from a decidedly subcritical common envelope
- Protocores are still subcritical
- Collapsing cores are already supercritical
- Gestation time and age spread can be ~ 10^7 yr for typical ionization fraction
- No direct observational evidence of this mode so far (Crutcher, Hakobian, & Troland 2009), i.e., a subcritical intercore medium

Basu, Ciolek & Wurster (2009)

Other paths in B-dominated scenario



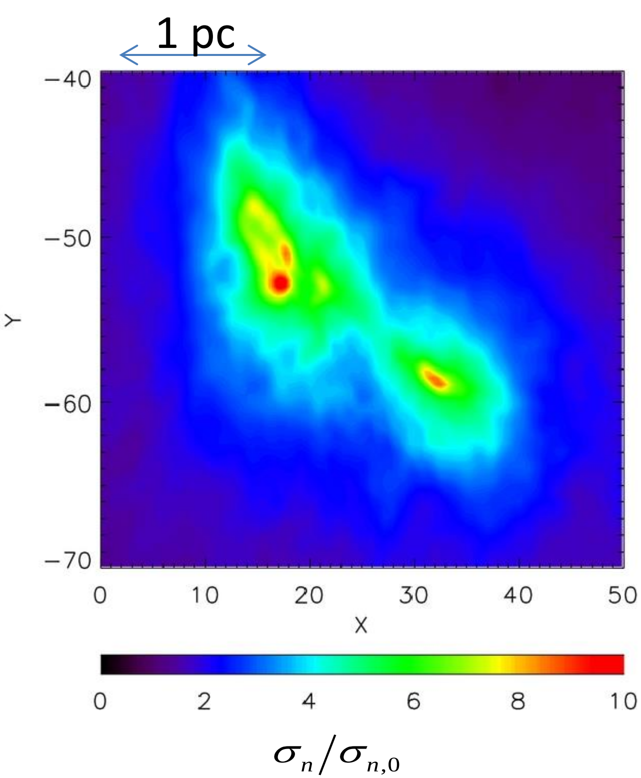
Subcritical common envelope

Supercritical high-density regions assembled by large scale flows/turbulence

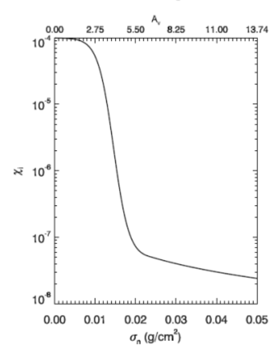
cf. Nakamura & Li (2005), Elmegreen (2007), Kudoh & Basu (2008, 2011), Nakamura & Li (2008), Basu , Ciolek, Dapp, & Wurster (2009; model shown above).

Transcritical Fragmentation

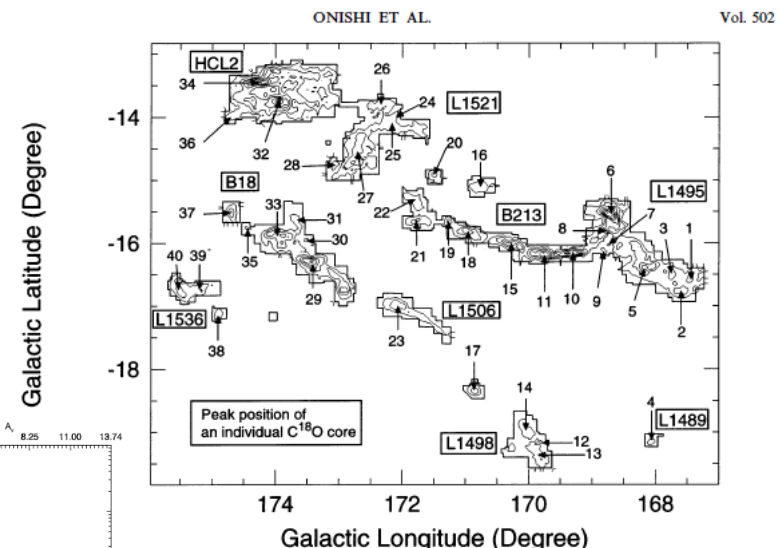
Flows along field lines build up molecular cloud. Region that becomes transcritical is first to fragment on a reasonably short timescale. Initial fragment is pc scale clump. As ionization fraction drops, fragmentation scale drops and continued small amplitude perturbations lead to a second stage of fragmentation.



Two stage fragmentation of transcritical clump (Bailey & Basu 2014, ApJ, 780, 40) driven by drop in ionization fraction from UV level to CR level.



Ionization fraction

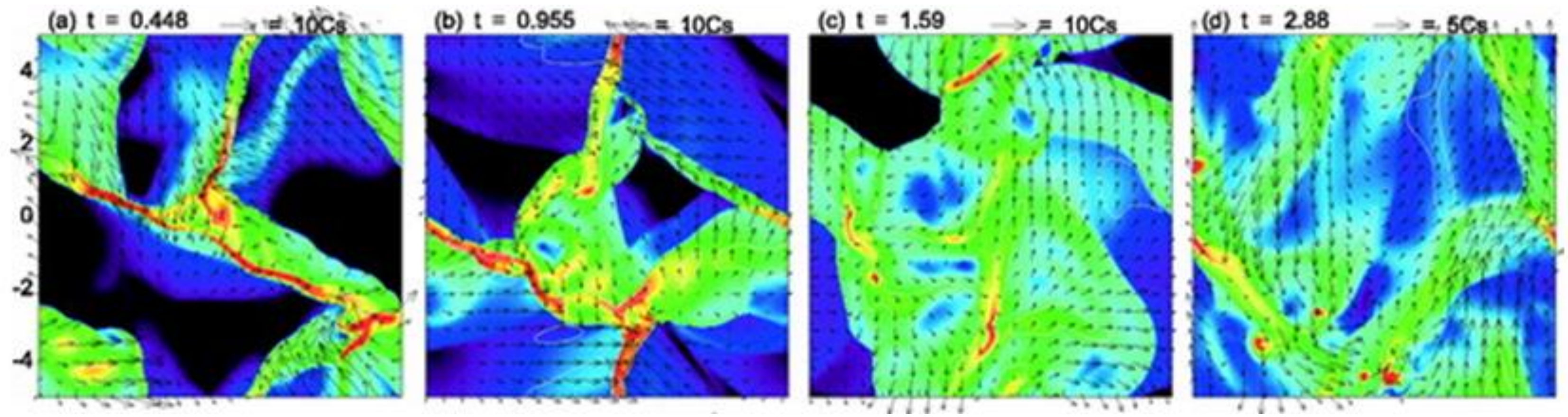


Taurus Molecular Cloud (Onishi et al. 1998)

Turbulence Accelerated Star Formation

Thin disk approximation

Li & Nakamura (2004)



subcritical ($\mu_0 = 0.83$) model

$v_k^2 \sim k^{-4}$ spectrum

Note filamentarity of column density.

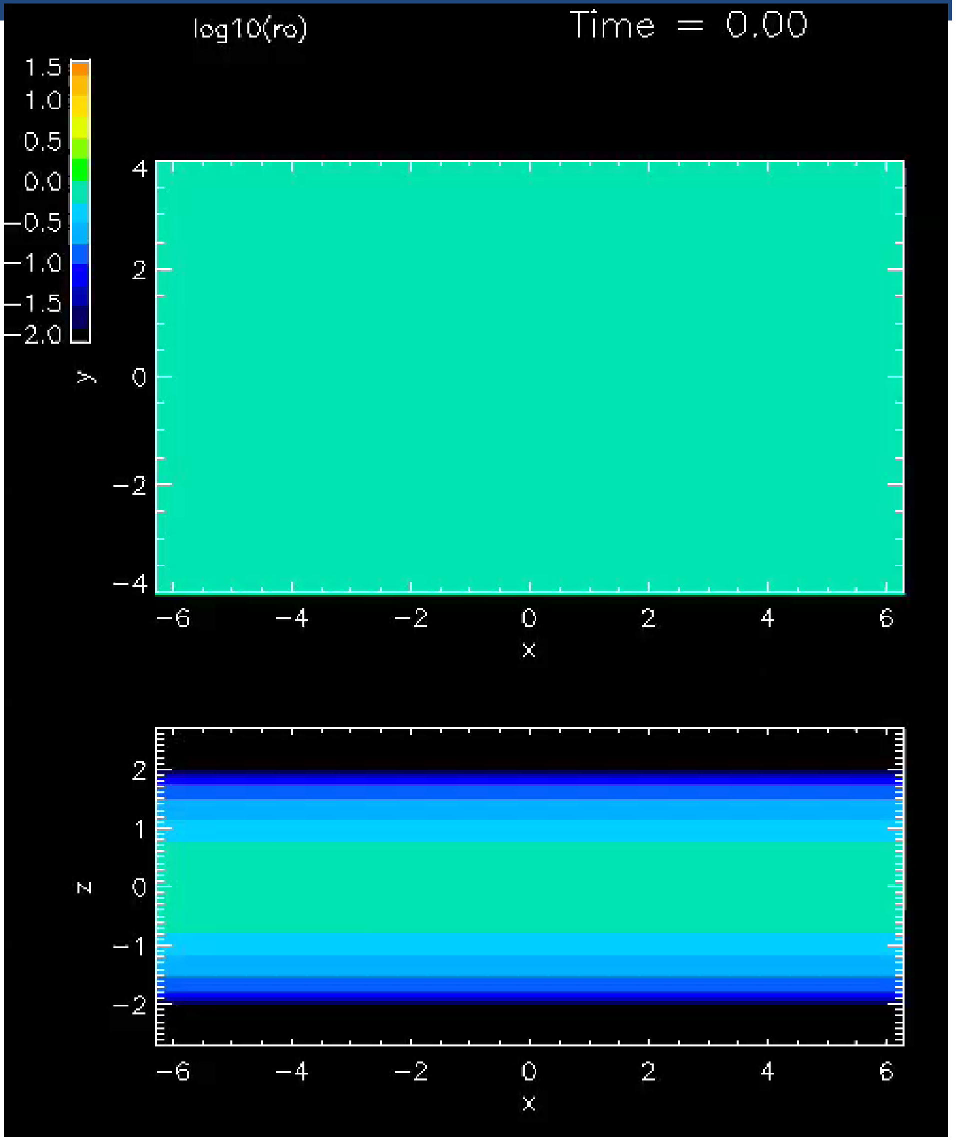
TASF Simplified – Filament Formation

Capture essence of TASF and filament formation by introducing 1D flow in x-y plane. Subcritical initial condition and Mach 5 flow. Animation (not visible in pdf version).

B_0 in z-direction.
Time unit = 2.5 x 10^5 yr.

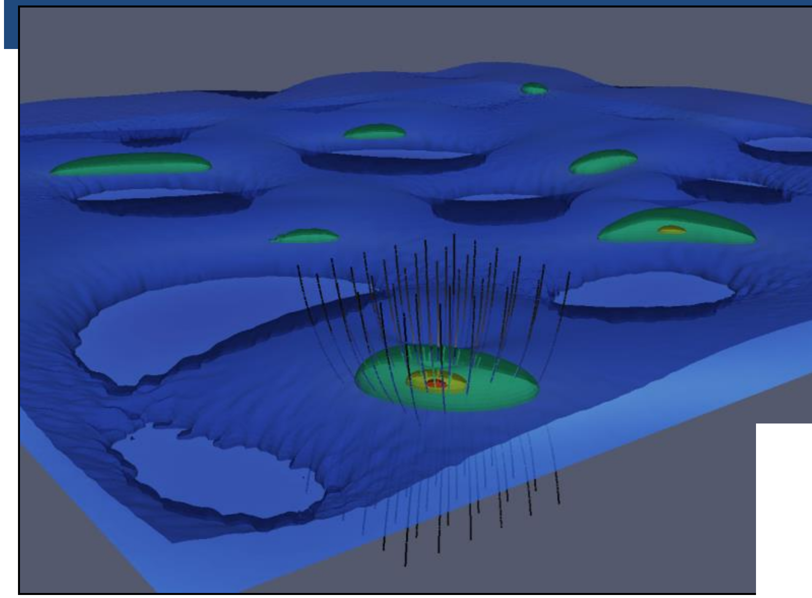
$$\tau_{AD} \simeq \frac{1}{3}\tau_{AD,0} \simeq \frac{1}{3}\frac{\tau_{ff}^2}{\tau_{ni}}$$

$$\text{when} \quad v_{flow} = v_{A,0}$$



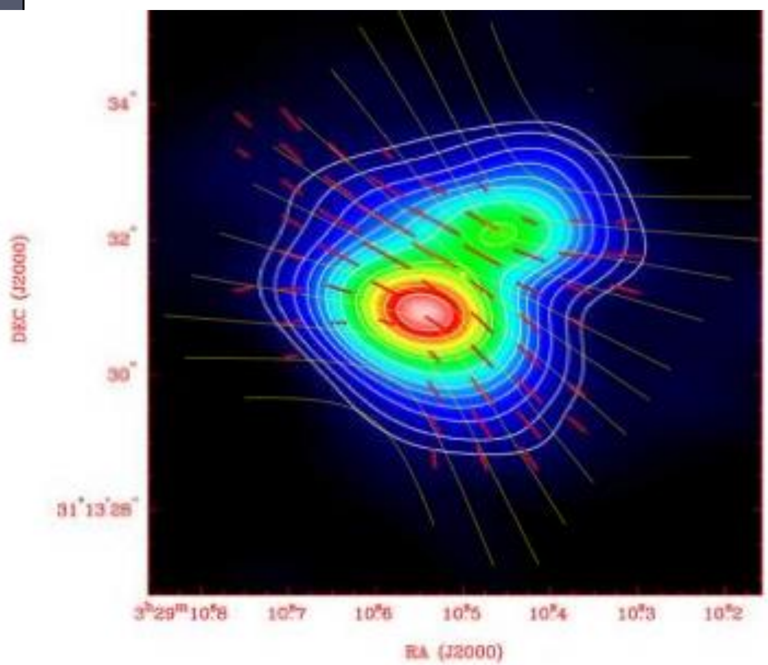
Kudoh & Basu (2014, submitted)

Local hourglass B-field



See Poster 10 – Josep Girart:
Magnetic Fields in Massive
Star Forming Regions

Smooth hourglass from **either subcritical fragmentation or mildly supercritical fragmentation** with low turbulence. Degree of curvature can reveal background mass-to-flux ratio (Basu et al. 2009, NewA, 14, 221)

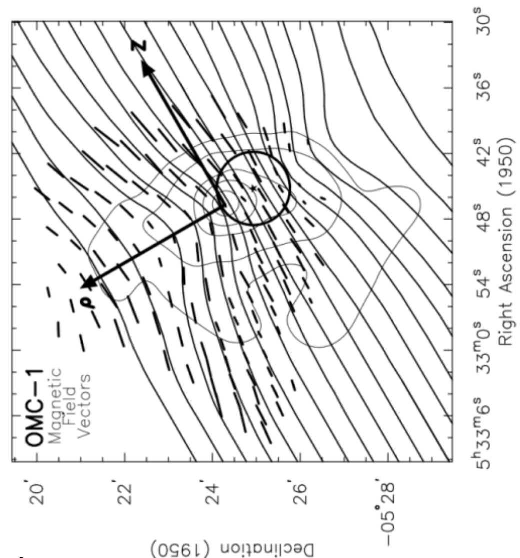


NGC 1333 IRAS 4A, Girart et al. (2006)

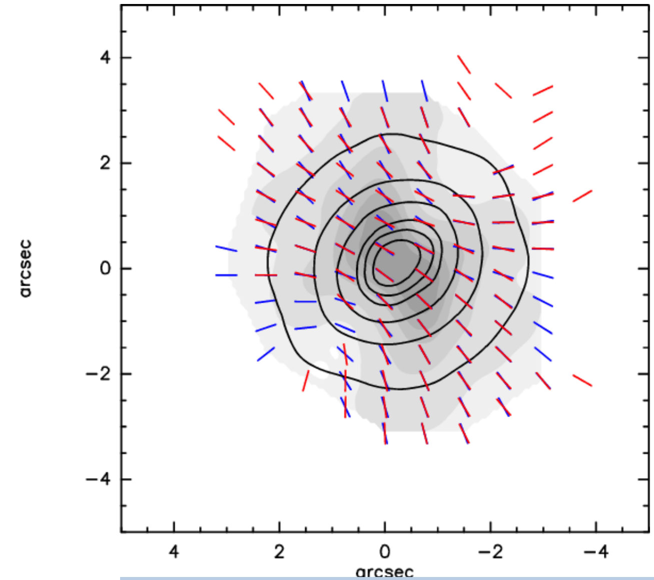
Hourglass Patterns Carry Information

Scheluning (1998)

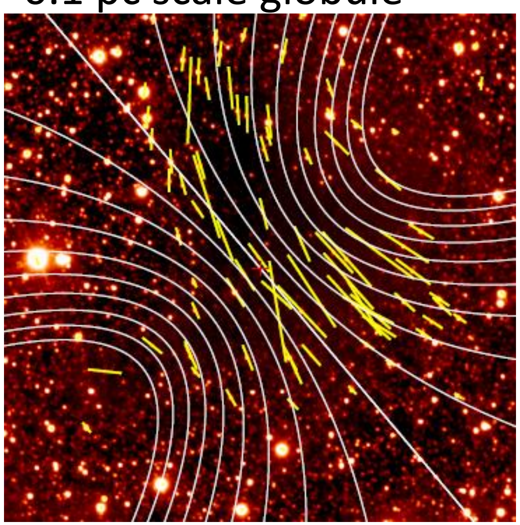
pc scale clump



Scale is 100s AU



0.1 pc scale globule

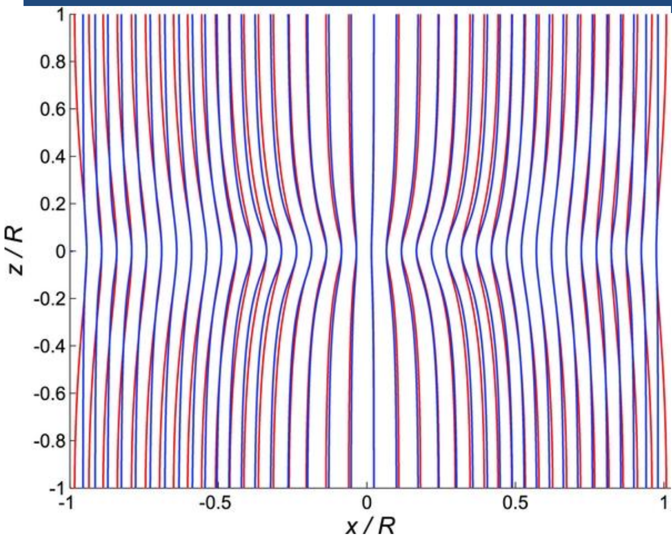


Both OMC 1 and B68 have enough curvature to imply mildly supercritical contraction.

B68, image courtesy R. Kandori

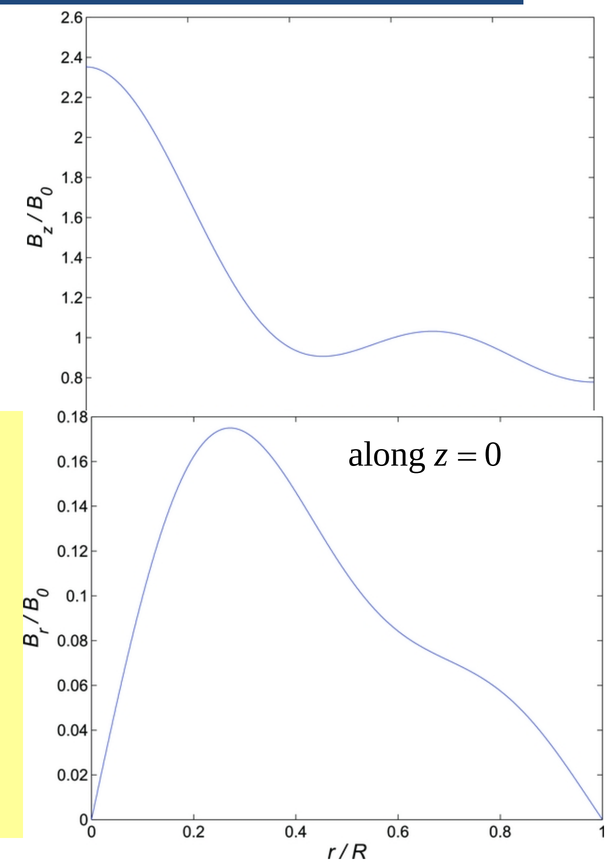
NGC 1333 IRAS 4A, Gonçalves, Galli, & Girart (2008). Data red, model blue. Small pinch at this scale not consistent with flux freezing. Model allows resistivity estimate.

Analytic Hourglass Model



Simulation: Kudoh & Basu (2008)

Analytic model: Ewertowski & Basu (2013)



$$B_r = \sum_{m=1}^{\infty} k_m \sqrt{\lambda_m} J_1(\sqrt{\lambda_m}\, r) \left[\mathrm{erfc}\left(\frac{\sqrt{\lambda_m}\, h}{2} - \frac{z}{h} \right) e^{-\sqrt{\lambda_m}\, z} - \mathrm{erfc}\left(\frac{\sqrt{\lambda_m}\, h}{2} + \frac{z}{h} \right) e^{\sqrt{\lambda_m}\, z} \right], \quad (45)$$

$$B_z = \sum_{m=1}^{\infty} k_m \sqrt{\lambda_m} J_0(\sqrt{\lambda_m}\, r) \left[\mathrm{erfc}\left(\frac{\sqrt{\lambda_m}\, h}{2} + \frac{z}{h} \right) e^{\sqrt{\lambda_m}\, z} + \mathrm{erfc}\left(\frac{\sqrt{\lambda_m}\, h}{2} - \frac{z}{h} \right) e^{-\sqrt{\lambda_m}\, z} \right] + B_0. \quad (46)$$

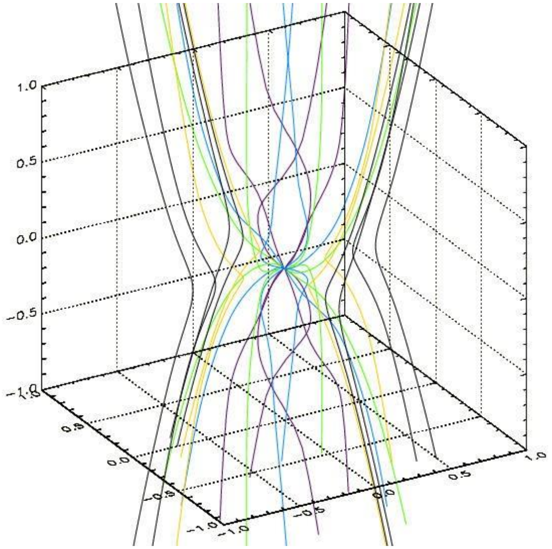
Keep first few terms of series expansion to get a good fit to data or simulation.

Best fit → $B_{\mathrm{central}} / B_0$. Estimate degree of flux freezing by comparing to density ratio.

Ewertowski & Basu (2013, ApJ, 767, 33)

Catastrophic Magnetic Braking

A connection of small scales to large scales!



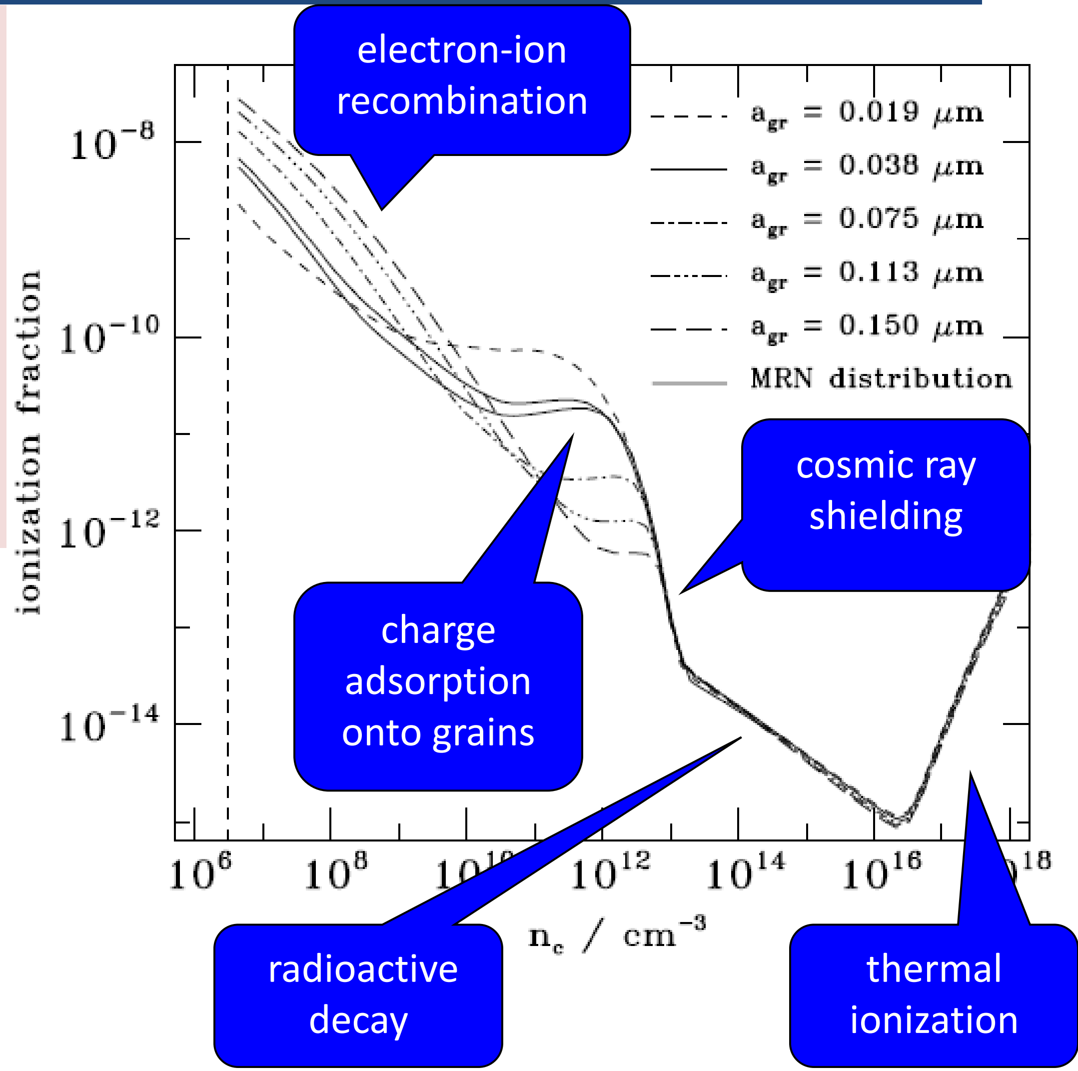
Allen, Li, & Shu (2003) first pointed this out. Subsequently shown by
Galli et al. (2006)
Mellon & Li (2008)
Hennebelle & Fromang (2008)
and others.

In protostellar phase (but not prestellar phase), flux-frozen and extremely flared magnetic field with large lever arm leads to extreme angular momentum loss → no centrifugal disk is formed!

Chemistry → Ionization balance

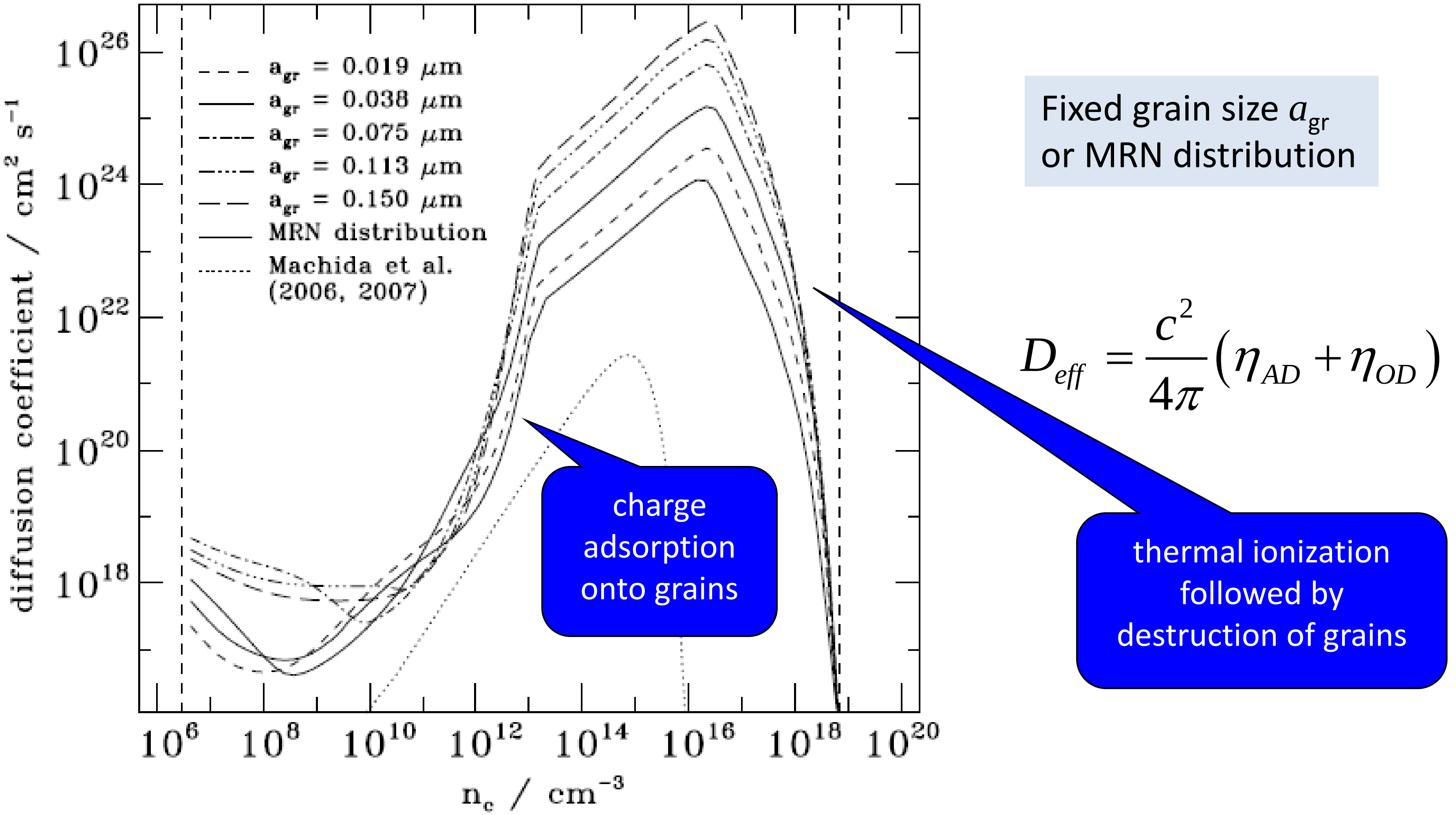
Detailed chemical network with at least nine charged species including grains and the effects of radiative and dissociative recombination of ions and electrons, charge exchange b/w atomic and molecular ions, adsorption of charge onto grains, and charge exchange b/w grains. Ionization sources are:

1. UV ionization
2. cosmic ray ionization
3. ionization due to radiation liberated in radioactive decay
4. thermal ionization through collisions



Kunz & Mouschovias (2009, ApJ, 693, 1895), Dapp, Basu, & Kunz (2012, A&A, 541, A35)

Effective (total) diffusion coefficient



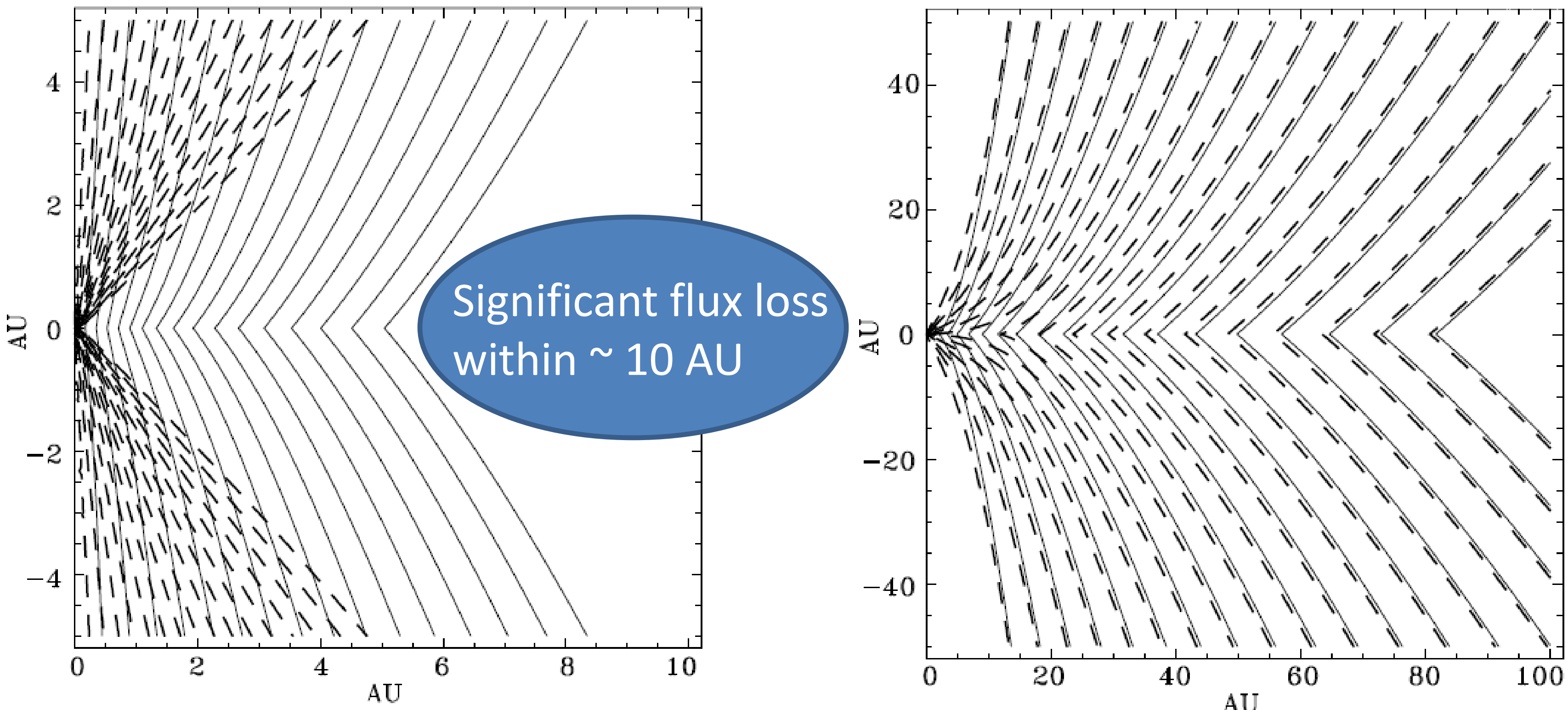
Fixed grain size a_{gr} or MRN distribution

$$D_{eff} = \frac{c^2}{4\pi}\left(\eta_{AD} + \eta_{OD}\right)$$

Figure from Dapp, Basu, & Kunz (2012, A&A, 541, A35)

Magnetic Fields during Core Collapse

At the time of second core (stellar core) formation

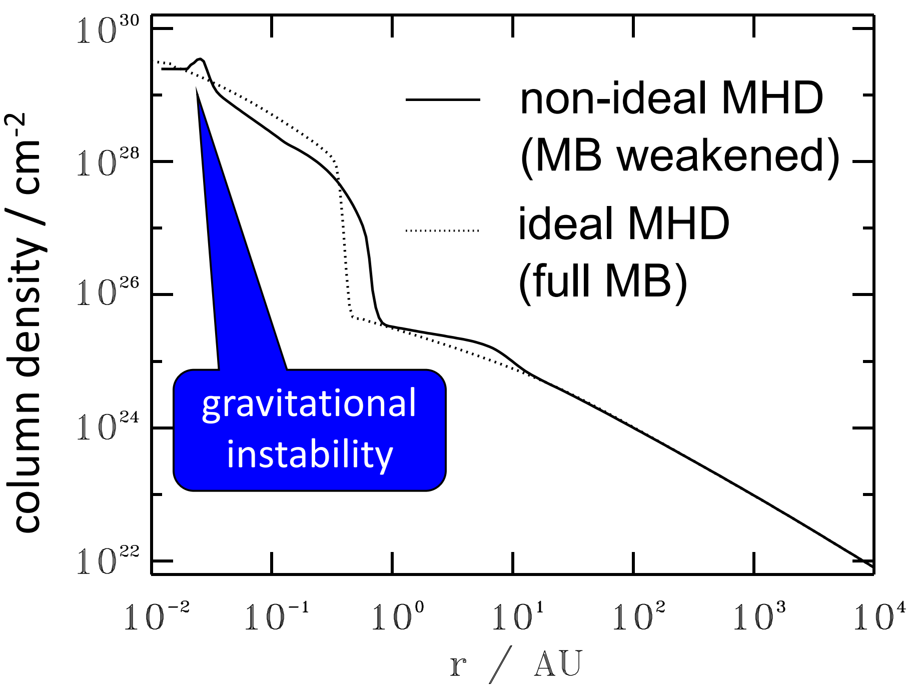


Dashed lines are for flux-frozen model (extreme flaring of FL's leads to braking catastrophe).
Solid lines are for non-ideal MHD model (note relaxation of FL shapes within 10 AU).

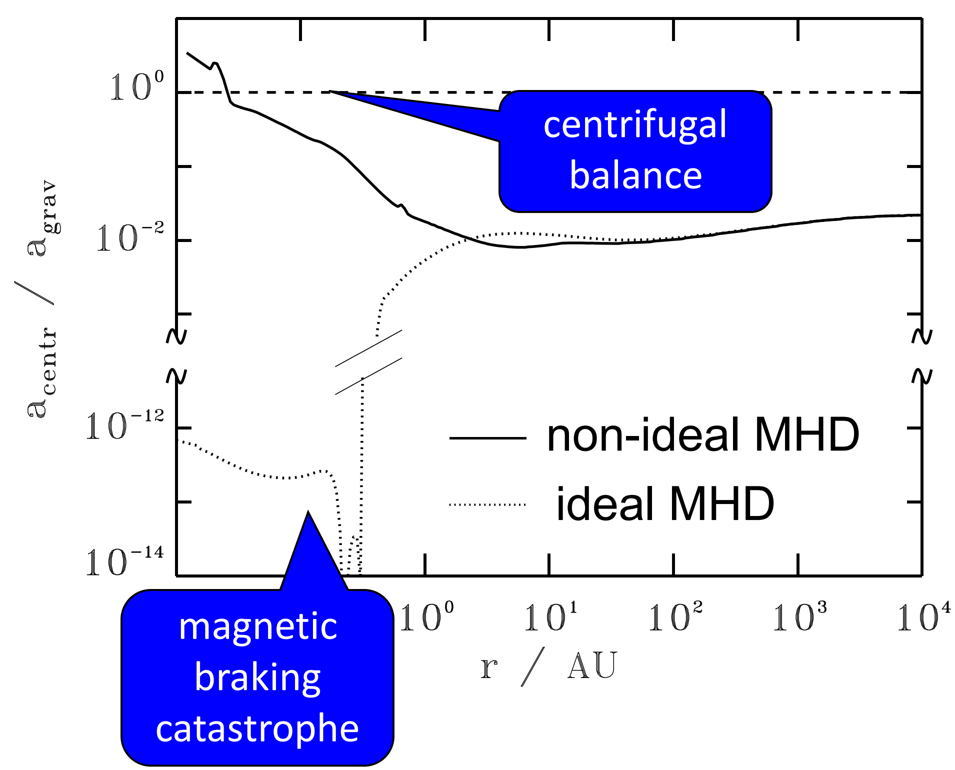
Dapp, Basu, and Kunz (2012) employ thin-disk approximation, detailed chemical network for partial ionization and non-ideal MHD coefficients, and resolve second core in radial direction.

Disk formation

- introduction of sink cell after 2nd core formation (few R_{sun})
- centrifugal balance is achieved, and disk fragments into ring



Dapp, Basu, & Kunz (2012)



Small Class 0 disks?

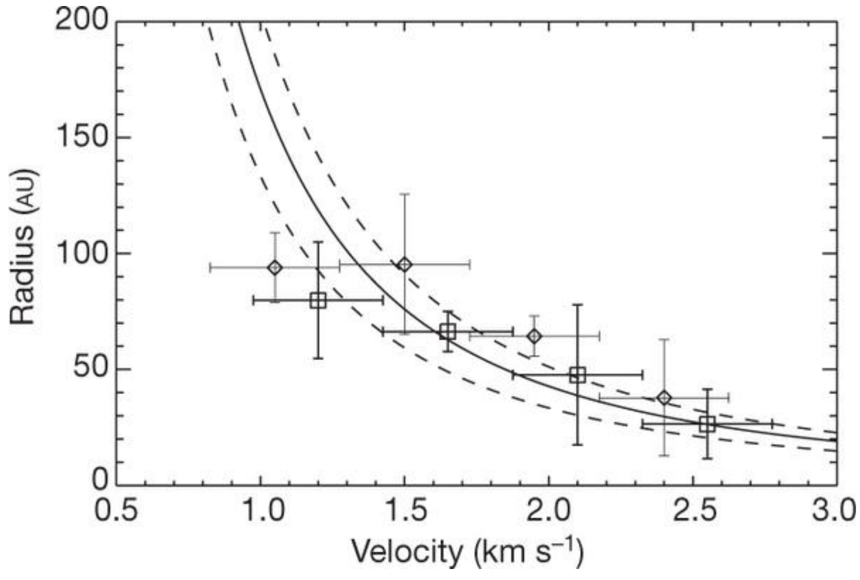
- Resolution of CMB with classical resistivity alone will result in a small AU scale initial disk
- If this small "initial" disk is also massive ($M_{disk,\,init} \sim 0.1\ M_{star}$) it will expand in size as it becomes a lower mass disk.

$$R_{disk,\,final} \simeq R_{disk,initial} \left(\frac{M_{disk,init}}{M_{disk,\,final}} \right)^2$$ if angular momentum conserved

- For $R_{disk,\,initial} \sim 3$ AU, could end up with $R_{disk,final} \sim 300$ AU for "final" disk mass to star mass ratio $M_{disk,final}/M_{star} \sim 0.01$

Small Class 0 disks? v2

- A study of 5 class 0 objects down to a ~ 50 AU finds no evidence for disks down to this scale (Maury et al. 2010)
- Large (~ 100 AU) Keplerian disks found around L1527 IRS (Tobin et al. 2012) and VLA 1623A (Murillo et al. 2013). Only two known class 0 disks to date.



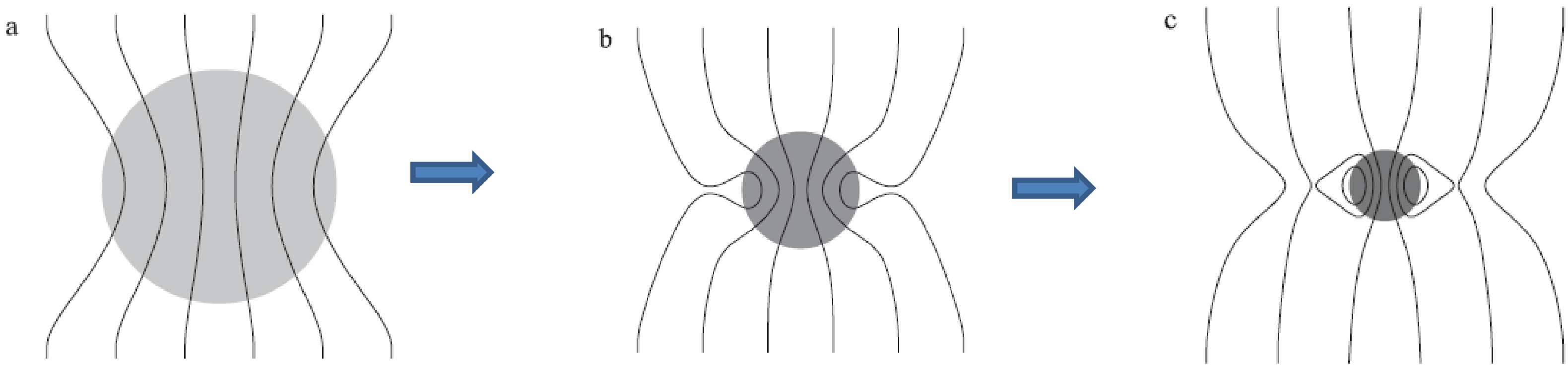
Keplerian motions in L1527 IRS, Tobin et al. (2012)

Possible resolutions to CMB

- Classical resistivity: implies small initial disk (Dapp et al. 2012)
- Misalignment of magnetic axis and rotation axis (Hennebelle & Ciardi 2009; Joos, Hennebelle & Ciardi 2012)
- Depletion of core envelope matter shuts down magnetic braking (Machida et al. 2011)
- Interchange instability redistributes flux (Krasnopolsky et al. 2012)
- Turbulence in core breaks coherence of magnetic field (Seifried et al. 2013; Santos-Lima et al. 2013)

Zhi-Yun Li 's talk on Thursday will address many of these and other ideas.

To the final stellar B-field



Images: Braithwaite (2012)

Resistivity: fine tuning needed?

- Great enough to allow disk formation
- Small enough to allow outflow launching
- Small enough at very late stage to allow for pinched configuration and detachment of field lines

Conclusions

There is likely no unique value for mass-to-flux ratio in ISM, however:

- Zeeman and **especially** polarimetry data from ISM to molecular clouds yield evidence for subcritical molecular cloud envelope
- Core formation may be within transcritical clumps/filaments created by flows or turbulence rather than by direct growth from subcritical envelope
- Degree of pinching in hourglass patterns carries extractable information about physical conditions
- Extreme hourglass field leads to catastrophic magnetic braking (CMB). Non-ideal MHD resolves this problem on AU scales
- Size of disk in class 0 phase predicted to be very small for aligned rotator. Other situations may allow for larger young disk
- Cloud magnetic field remains crucial at later stages for outflow driving, turbulent energy transport, disk accretion, and supplying a fossil field to stars