Clouds to Cores to Protostars: The Influence of Magnetic Fields

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The Origin of Stellar Masses
Tenerife, Canary Islands, Spain
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Western

Magnetic Field Effects

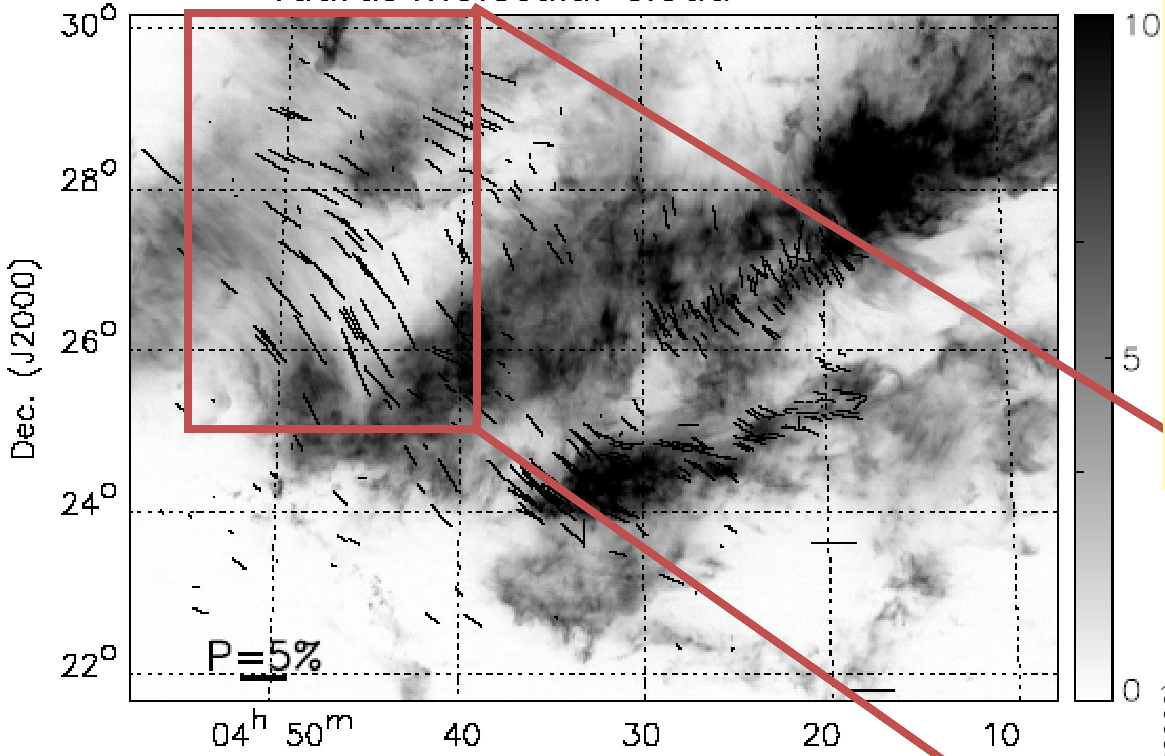
1. **LARGE SCALE (> 1 pc) :** Molecular cloud envelopes, where stars generally do not form. Large velocity dispersion. Also magnetically dominated?

2. **INTERMEDIATE SCALE (0.1 – 1 pc):** Regions of weak or strong clustering of YSOs and cores. Ambipolar-diffusion-driven, magnetically-diluted gravitational fragmentation, or turbulence-driven?

3. **SMALL SCALE (< 100 AU) :** Collapsing core. Magnetic fields drive angular momentum transport and jets. Major effect on disks? Magnetic braking catastrophe? Ohmic dissipation and ambipolar diffusion activated in innermost regions.

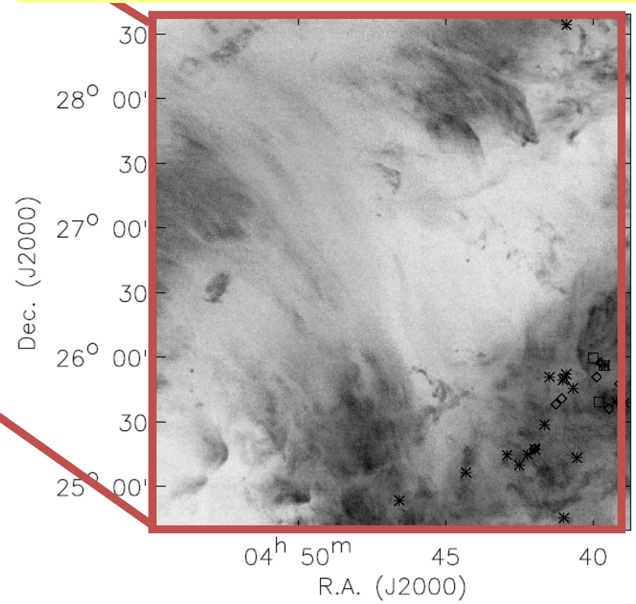
Taurus - low SFR and magnetically dominated envelope

Taurus Molecular Cloud



Goldsmith et al. (2008), ^{12}CO emission

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): Polarization of starlight plus velocity data → low density regions are magnetically dominated.



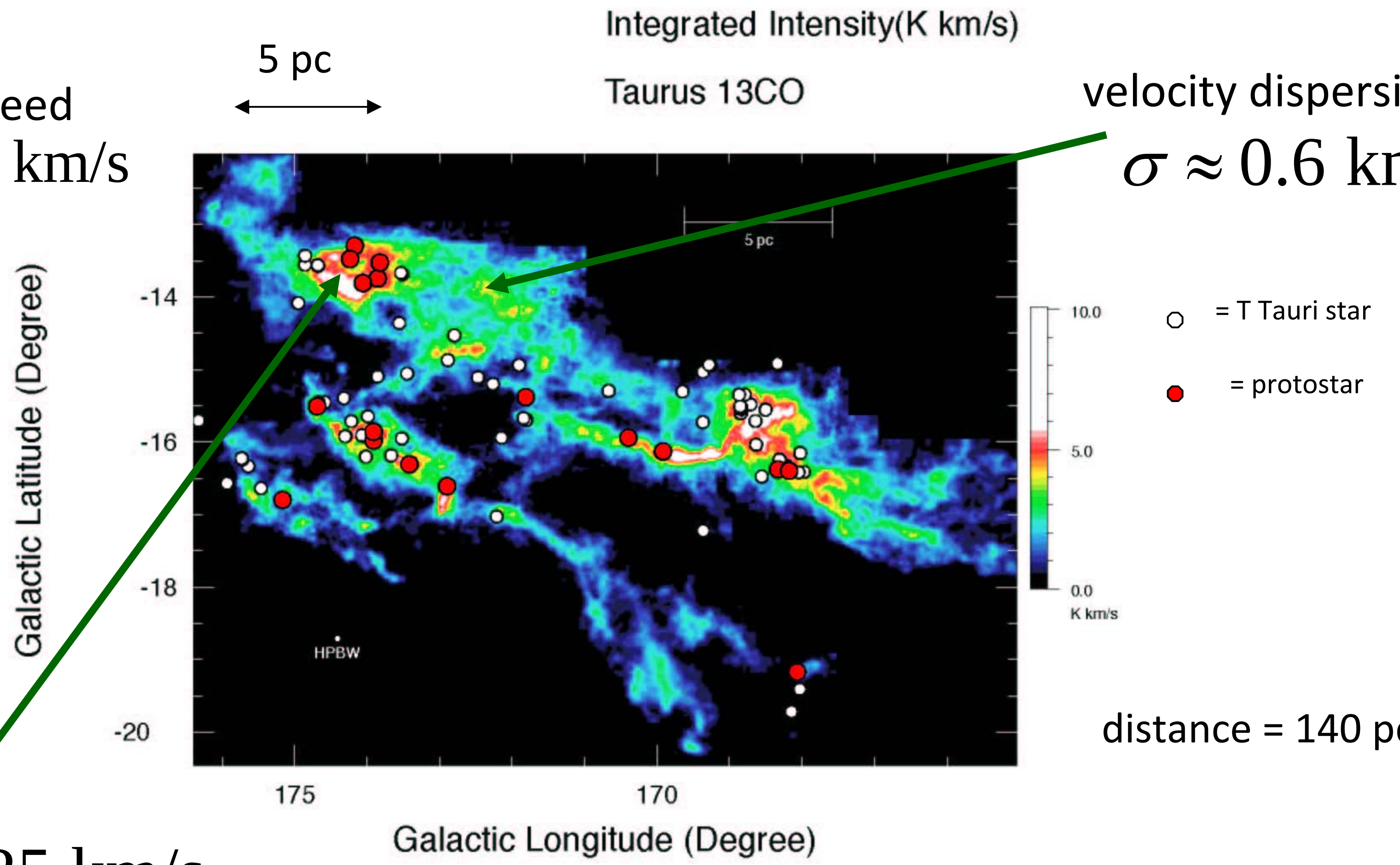
Star formation efficiency reflective of Galactic value. Magnetic dominated envelopes also inferred from global Galactic consideratons (e.g. Elmegreen 2007).

Taurus in ^{13}CO plus YSOs

sound speed

$c_s \approx 0.2$ km/s

5 pc



velocity dispersion

$\sigma \approx 0.6$ km/s

distance = 140 pc

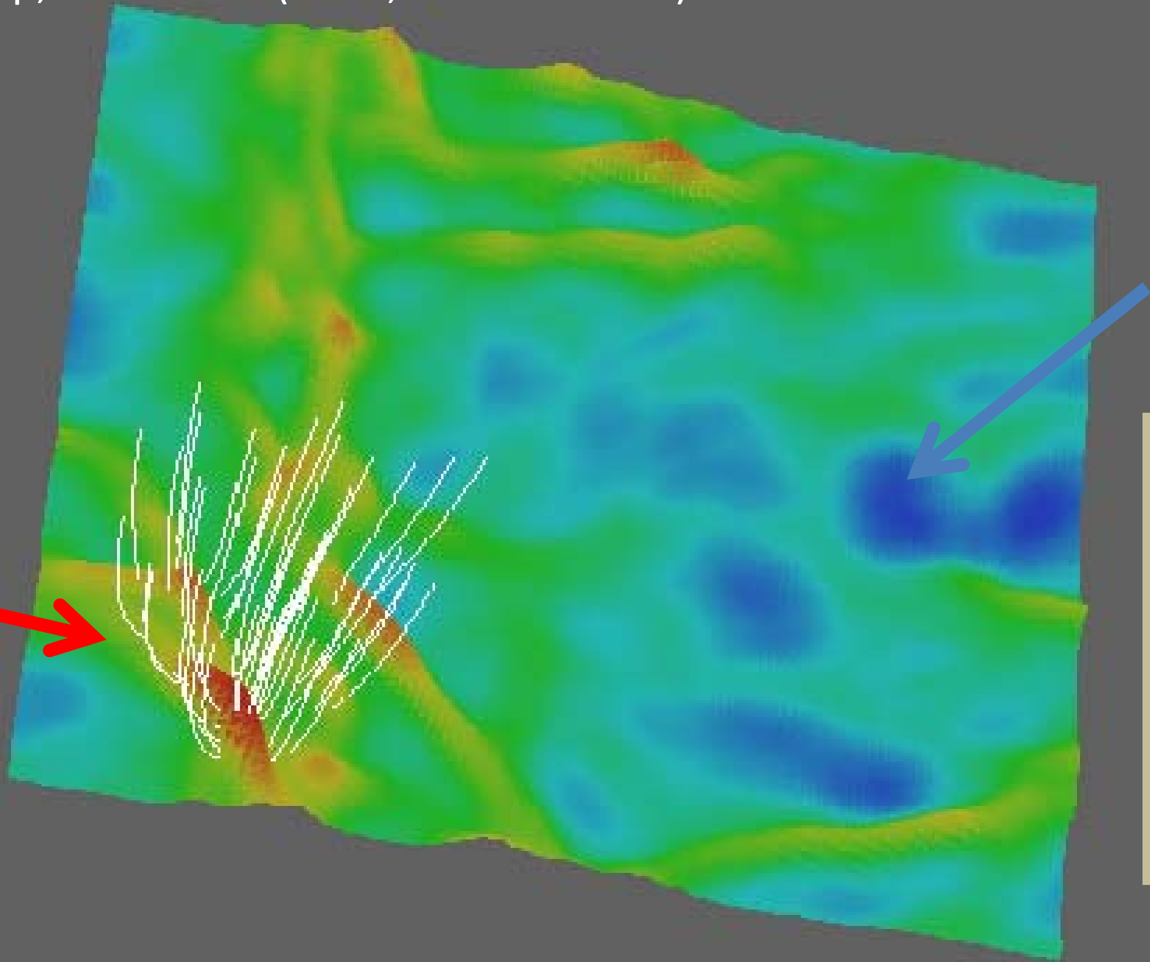
$\sigma \approx 0.25$ km/s

Onishi et al. (2002)

Scenario

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

Supercritical high-density regions assembled by nonlinear/ turbulent motions



Subcritical common envelope

Basu & Dapp (2010, ApJ, 716, 427) – large-scale modes may be very long lived

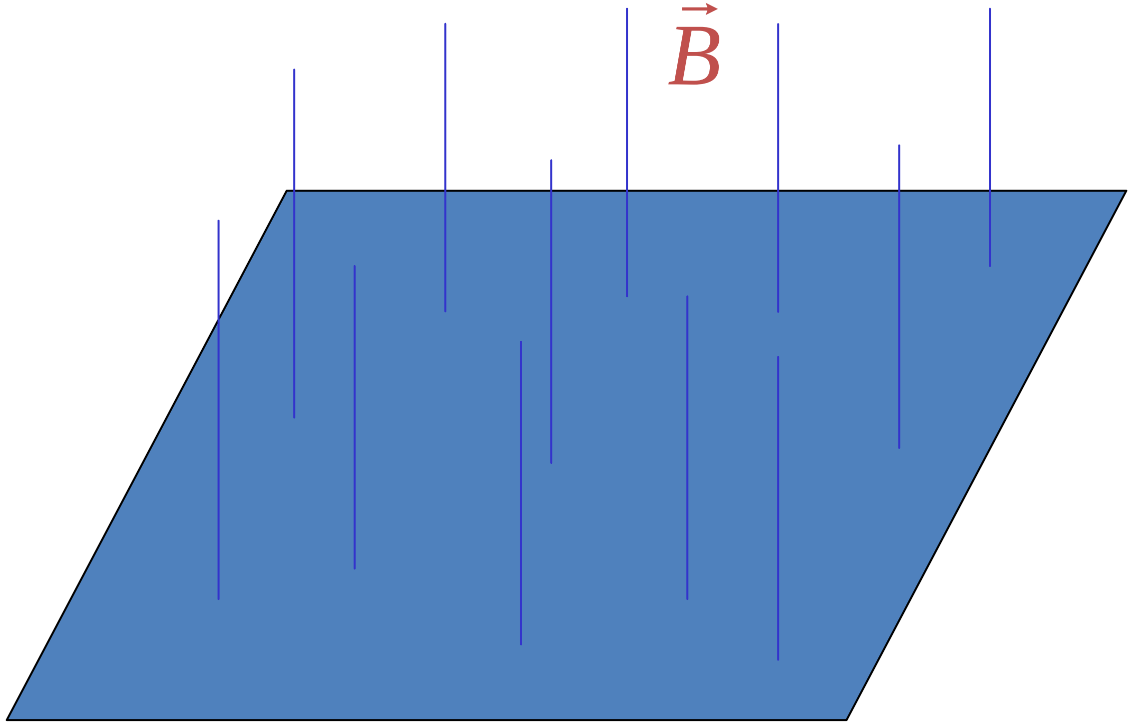
Stability Analysis with B

Critical magnetic field if

$$\frac{B^2}{8\pi} = \frac{\pi}{2} G\Sigma^2$$

↑ Magnetic pressure ↑ self-gravitational pressure

Σ = surface density of sheet



When magnetic flux-freezing applies:

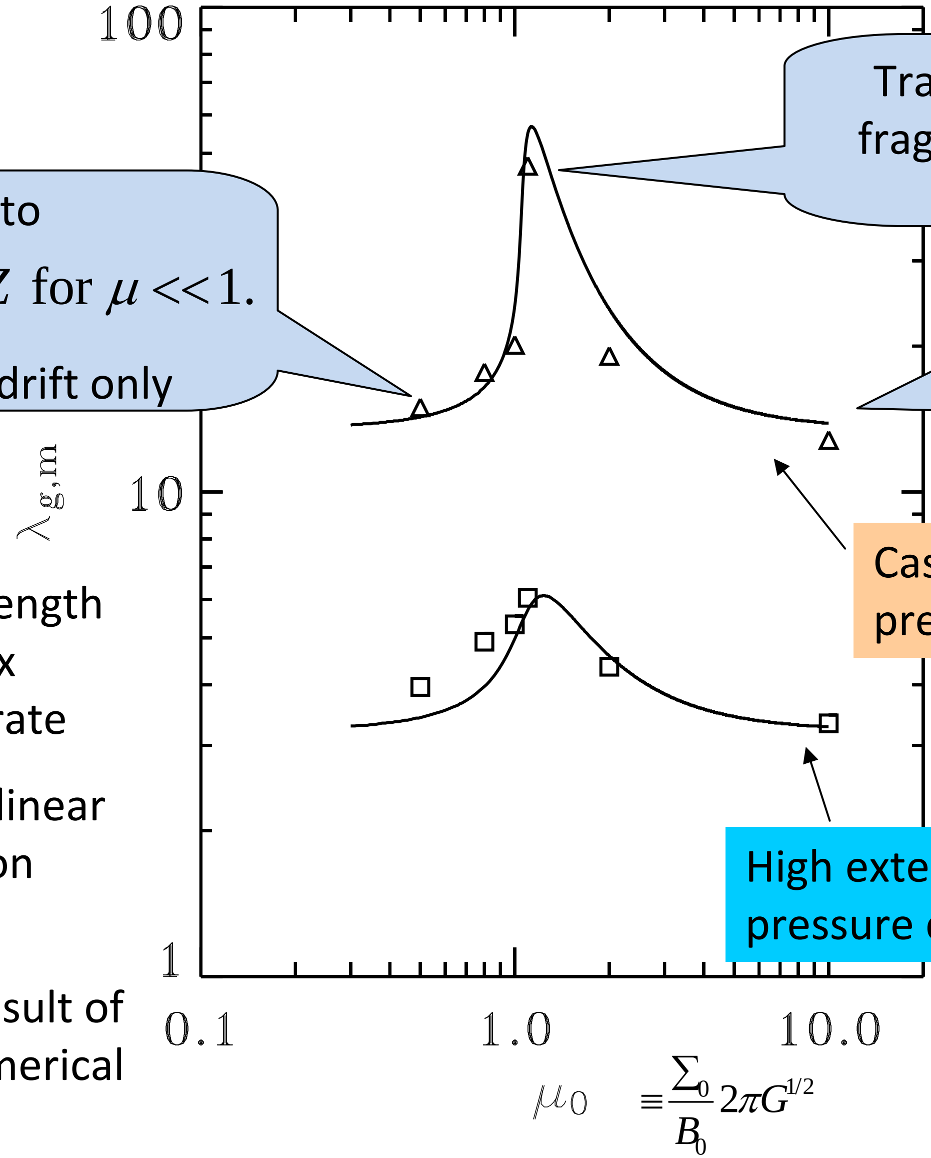
$$\mu = \frac{\Sigma}{B} 2\pi G^{1/2} < 1$$

Subcritical cloud No fragmentation occurs

$$\mu = \frac{\Sigma}{B} 2\pi G^{1/2} > 1$$

Supercritical cloud Fragmentation occurs

Magnetic Fields → broad CMF



Transcritical B yields largest fragmentation scales; AD and field dragging

Converges to $\lambda_{g,m} = 2\pi Z$ for $\mu << 1$. ambipolar drift only

Converges to $\lambda_{g,m} = 2\pi Z$ for $\mu >> 1$. B is negligible

Case of low external pressure on disk

High external pressure case

$\lambda_{g,m}$ is wavelength with max growth rate

Solid lines = linear fragmentation theory

Symbols = result of thin disk numerical simulations

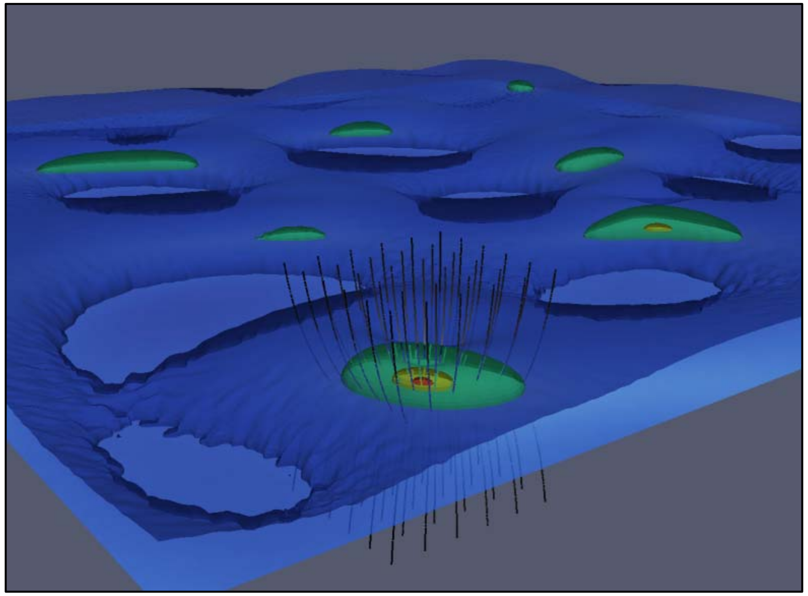
partial ionization

$$x_i = 10^{-7} \left(\frac{n}{10^4 \text{ cm}^{-3}} \right)^{-1/2}$$

Ciolek & Basu (2006),

Basu, Ciolek, & Wurster (2009)

Magnetic Model (Thin Disk Approx.)



Finite difference solution on (x,y) grid. Periodic BC's in (x,y) directions. Vertical (z) structure assumed to be in hydrostatic equilibrium. External magnetic field effects included. Model is "global" vertically, and "local" horizontally.

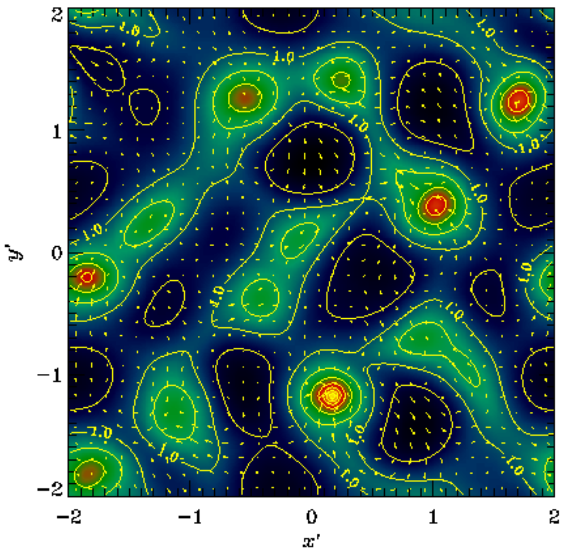
Start evolution by superposing either linear or nonlinear perturbations on uniform background state.

A non-ideal MHD code, i.e. partially ionized gas in which ambipolar diffusion can occur. Code described by Basu & Ciolek (2004), Ciolek & Basu (2006), Basu, Ciolek, & Wurster (2009).

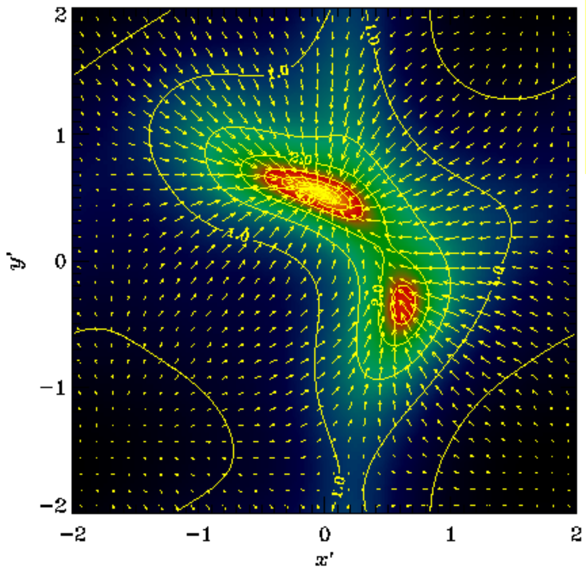
Magnetic Fields and Origin of the CMF

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

Column density and velocity vectors (unit 0.5 c_s)
Note variation in sizes, shapes, velocity fields.

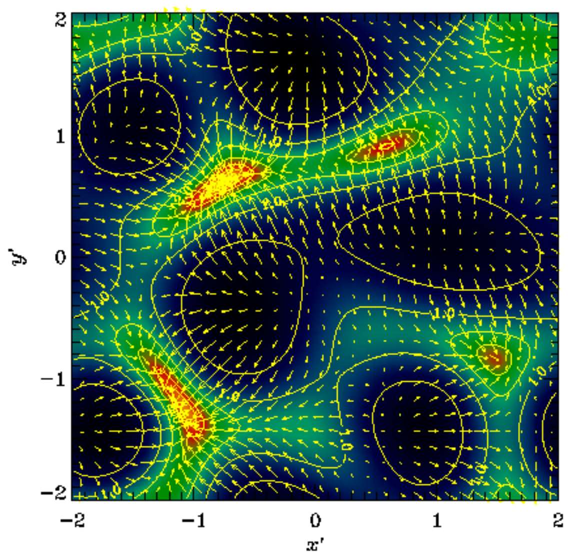


$$\mu_0 = 0.5$$



$$\mu_0 = 1.1$$

$$\mu_0 = 2.0$$

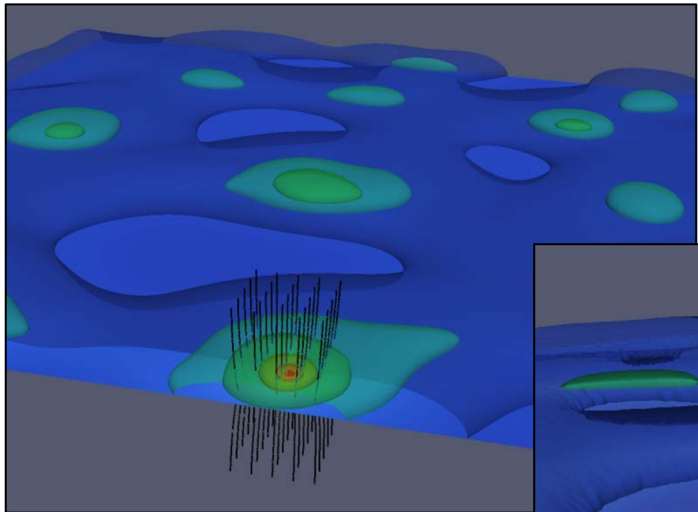


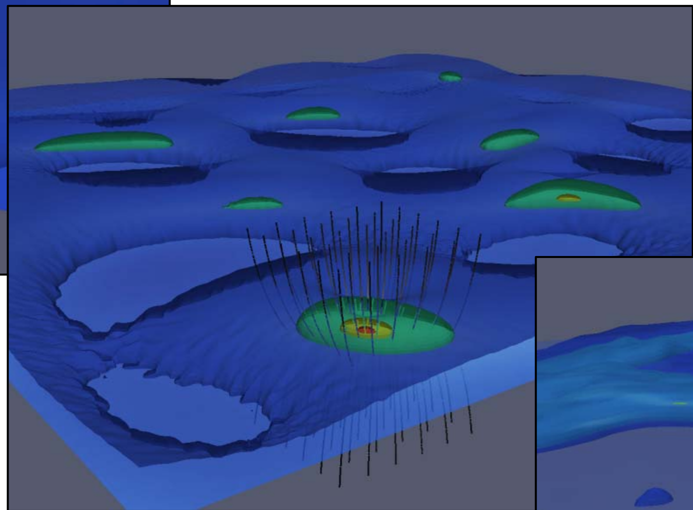
$$x' = x/(2\pi Z_0), \text{ etc.}$$

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

Magnetic Field Geometry reveals Ambient Conditions

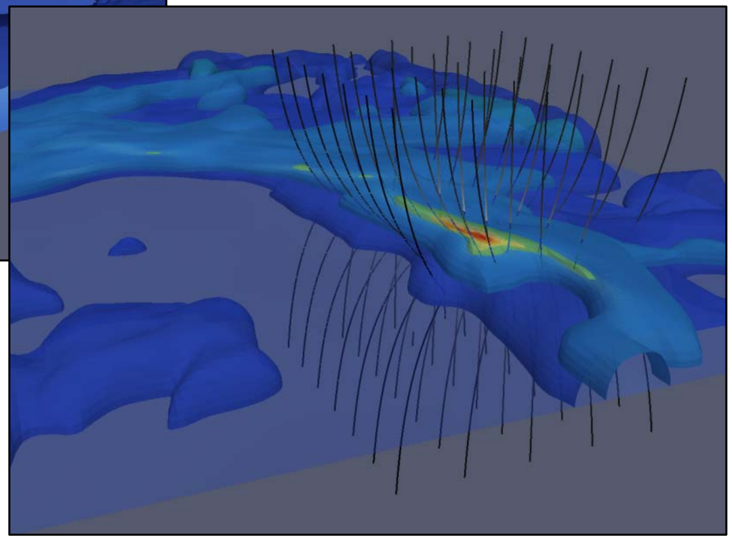
Extensive parameter study in two papers:
Basu, Ciolek & Wurster (2009, NewA, 14, 221)
Basu, Ciolek, Dapp, & Wurster (2009, NewA, 14, 483)





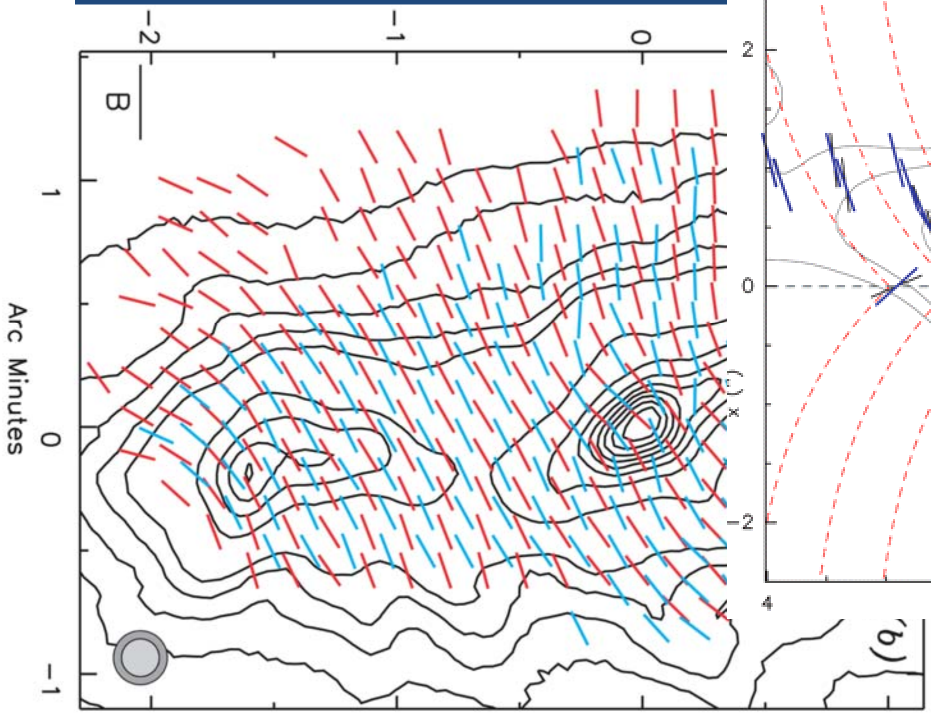
Above: strong B model.
Right: moderate B model

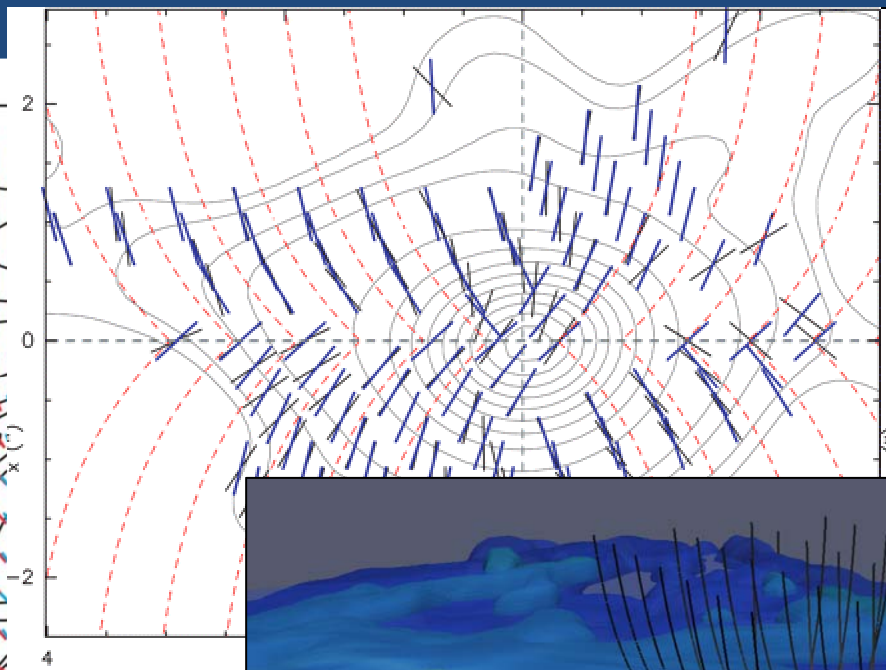
Below: moderate field with nonlinear flow IC's



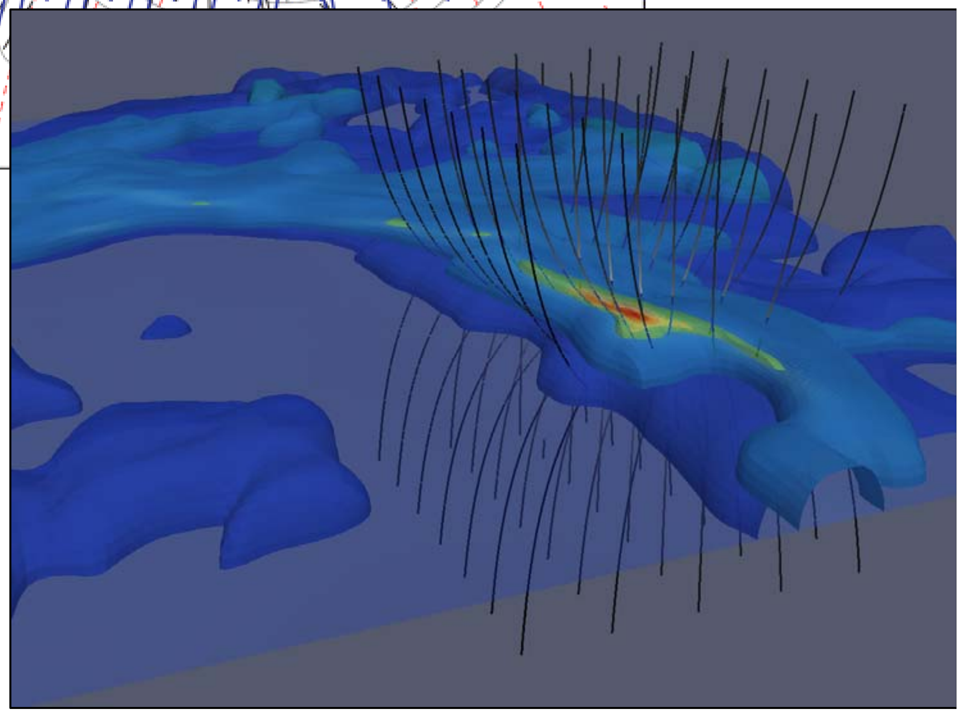
Fully 3D fragmentation models (Kudoh et al. 2007, Kudoh & Basu 2008, 2010) confirm these basic features of the thin-disk models.

Field Line Shapes Reveal Dynamics





G31.41: Girart et al. (2009, Science)



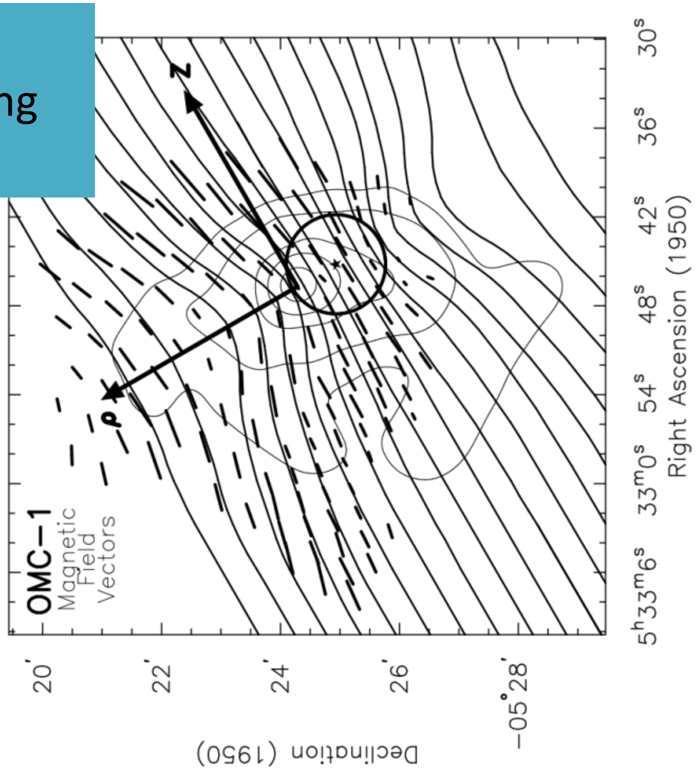
OMC 1: Vaillancourt et al. (2008)

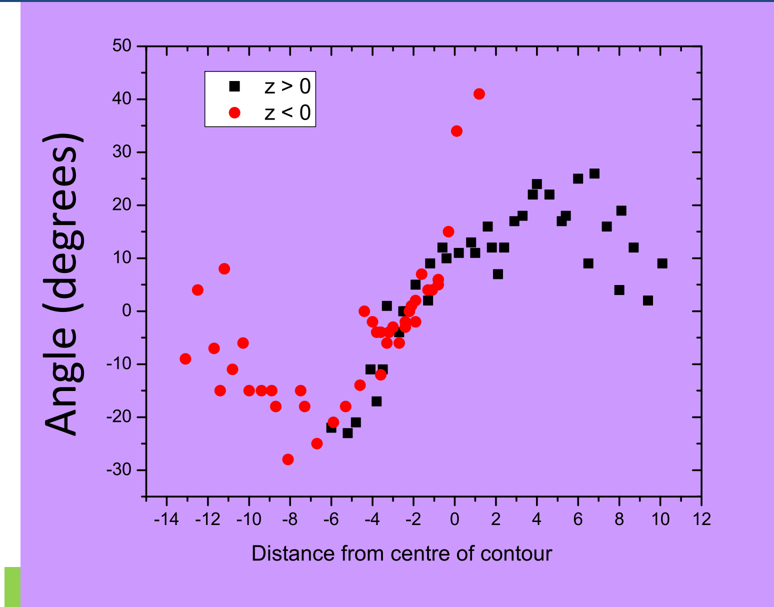
Dust polarization traces shape of the magnetic field. Viewing angle and field *strength* are unknown.

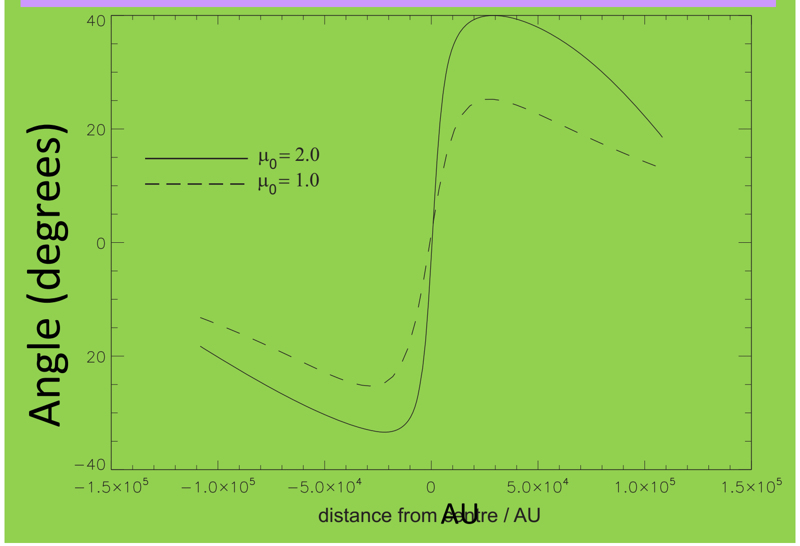
Model: Basu, Ciolek, Dapp, & Wurster (2009)

Preliminary Fit – OMC 1

OMC-1
Schleuning
(1998)





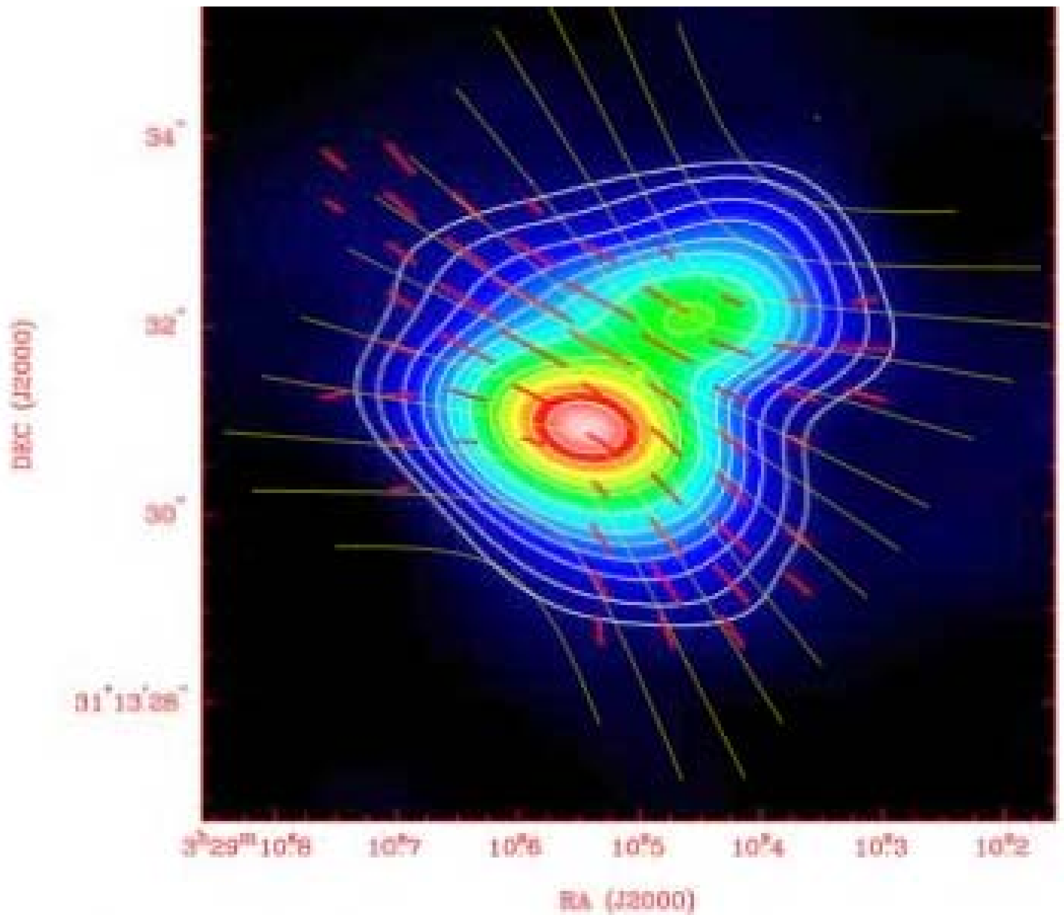


This massive star forming region fit by **mildly supercritical** model.

$$1.0 < \mu_0 < 2.0$$

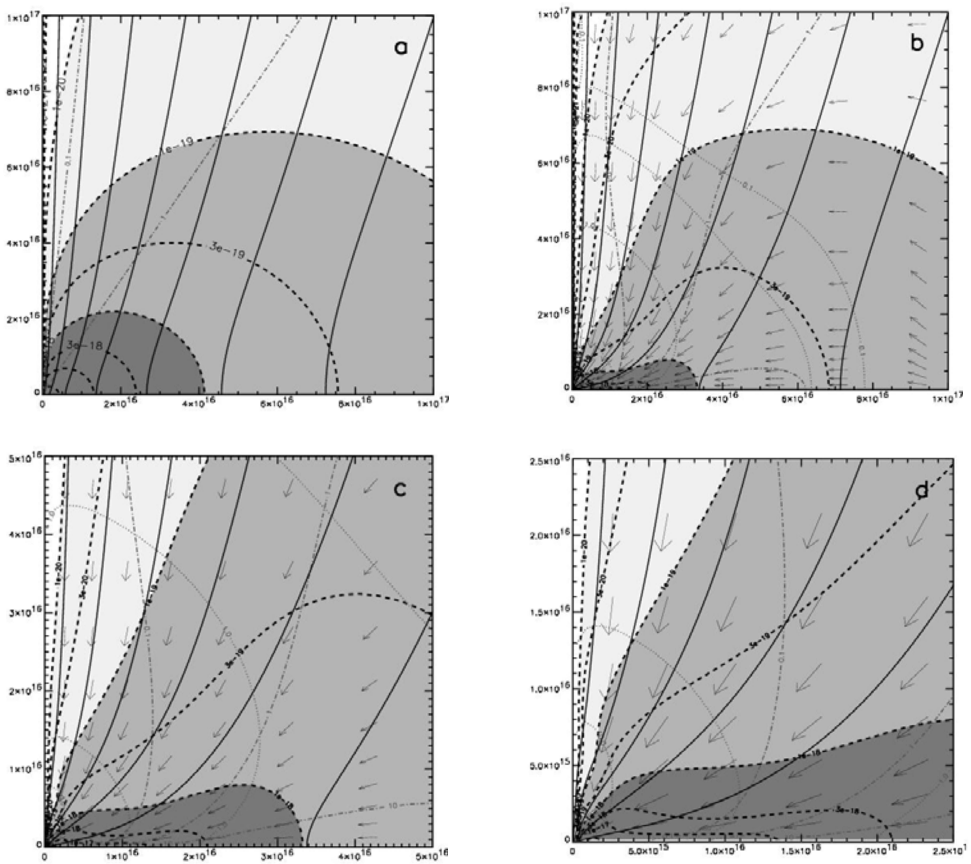
Wolf Dapp & S. Basu

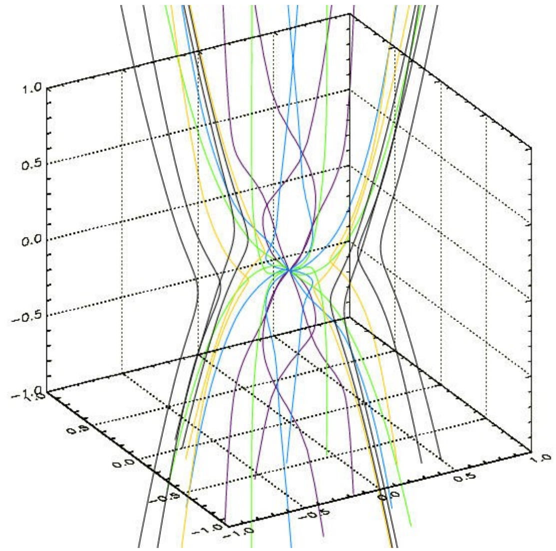
The Later Stage of Core Collapse



Girart, Rao, &
Marrone (2006)

Catastrophic Magnetic Braking if (even weak) B is Frozen-in





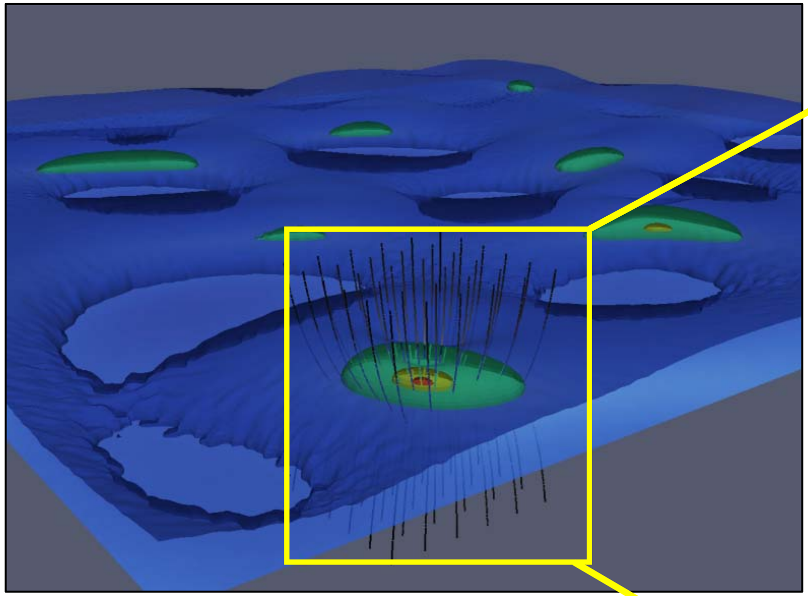
Lever arm is very BIG!

No Keplerian disk forms!!

Allen, Li, & Shu (2003)

More recent work by Mellon & Li (2008,2009), Galli et al. (2009), Hennebelle & Ciardi (2009)

High resolution collapse model

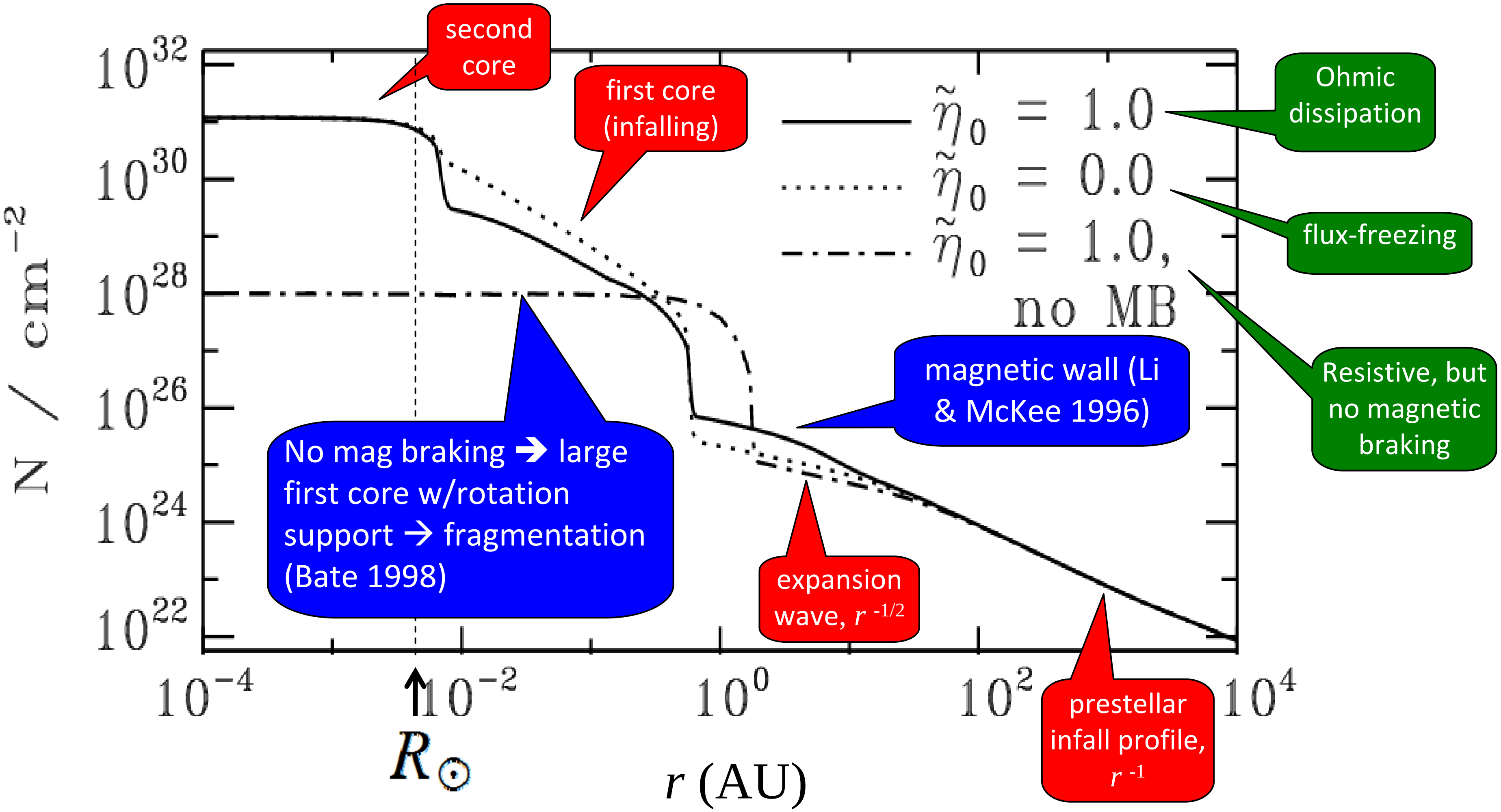


Start with collapsing core profile and follow with axisymmetric thin-disk adaptive mesh refinement code to resolve formation of stellar core and beyond. Barotropic equation of state, and prescription for magnetic braking

Objective: resolve stellar core formation and evolve until disk formation in a non-ideal MHD calculation.

Dapp & Basu (2010, A&A Letters)

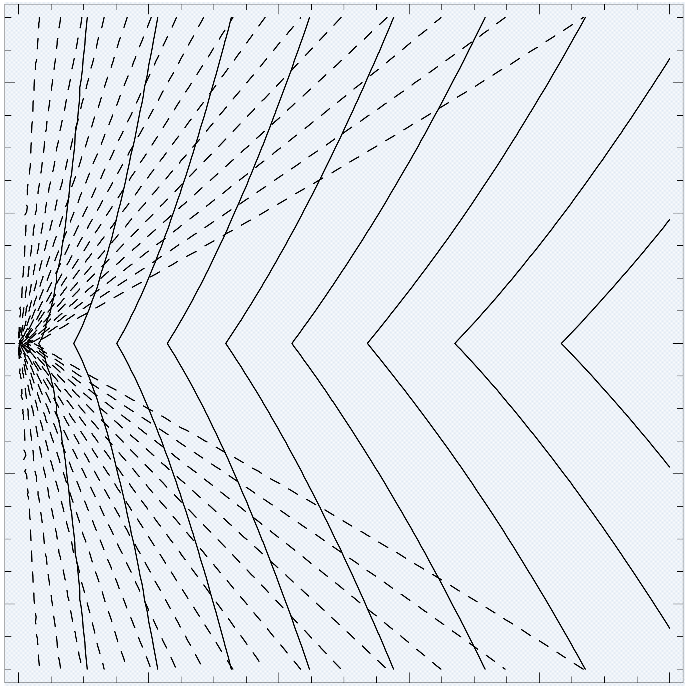
Magnetic collapse to high densities



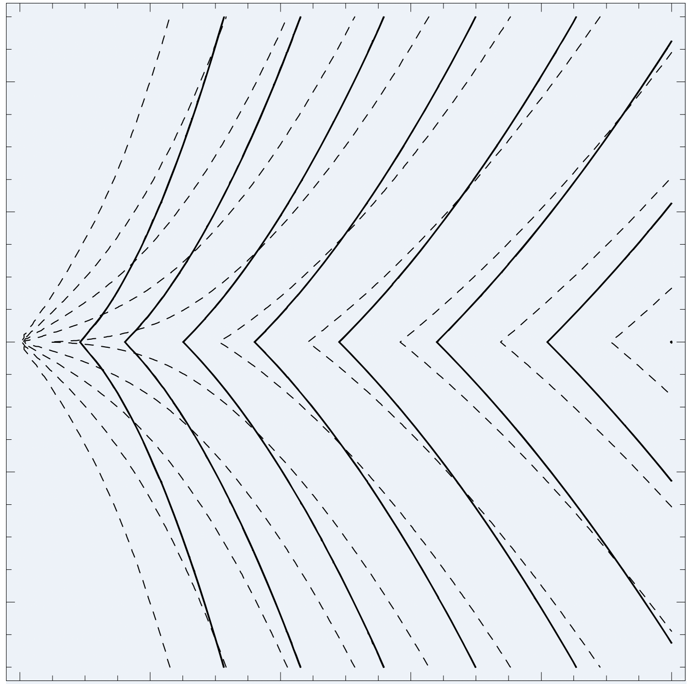
Dapp & Basu (2010)

Hourglass on small scales

At the time of second core (stellar core) formation



10 AU box size



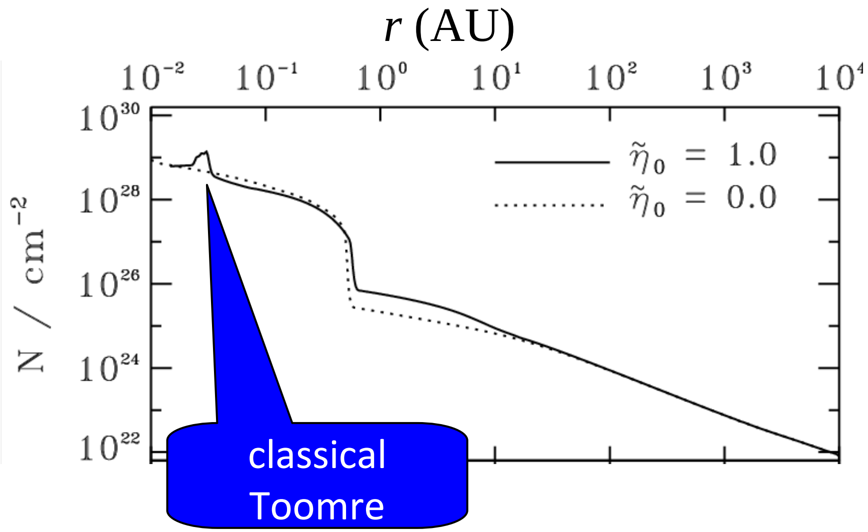
100 AU box size

Dashed lines are for flux-freezing model (extreme flaring of FL's leads to MB catastrophe).
Solid lines are for standard resistive model (note relaxation of FL shapes).

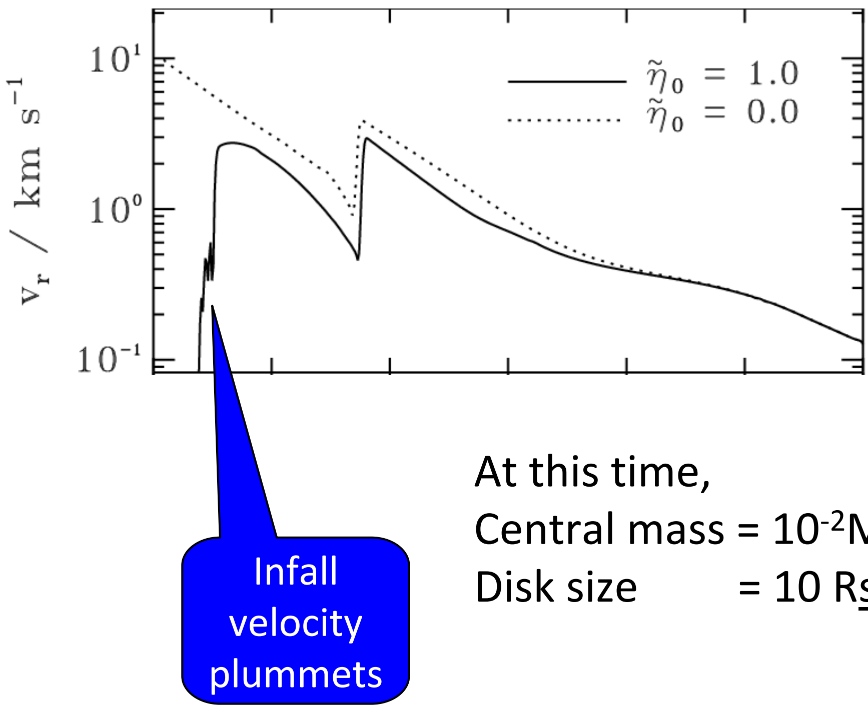
Dapp & Basu (2010)

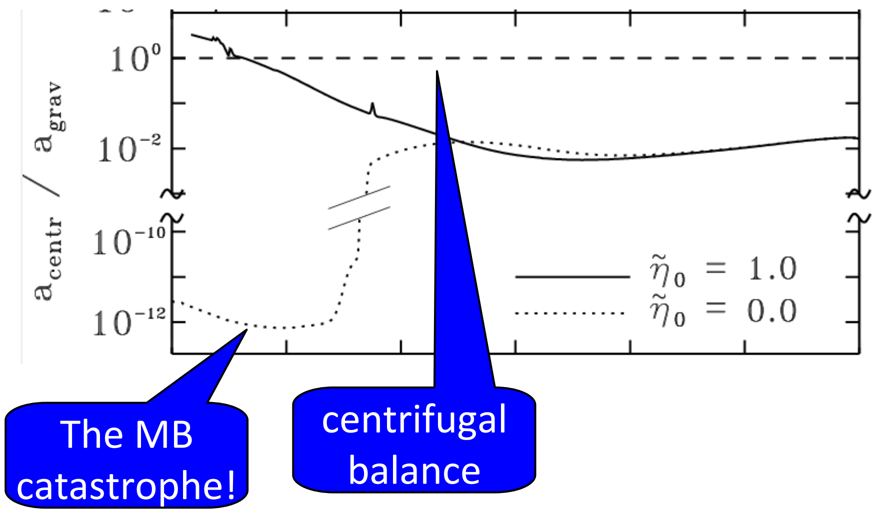
Subsequently, a disk forms

Dapp & Basu (2010)



Inner sink, = Rsun introduced at this stage





At this time,

Central mass = 10^{-2}Msun

Disk size = 10 Rsun

Summary

- On largest scales, molecular cloud envelopes expected to be magnetically dominated, with long-lived supersonic motions
- Core mass function expected to be broad simply due to a narrow range of ambient mass-to-flux ratios
- Magnetic field line curvature from polarimetry as a new proxy for measuring magnetic field strength on intermediate scales – cluster-forming region OMC1 appears supercritical as a whole
- Non-ideal MHD (Ohmic dissipation) leads to rapid flux loss within the original 1st core, allowing (small) disk formation around the 2nd core – no magnetic braking catastrophe
- Early phase disks will be compact. Need to understand larger sizes during Class II phase