Gravitational Collapse and Disk Formation in Magnetized Cores

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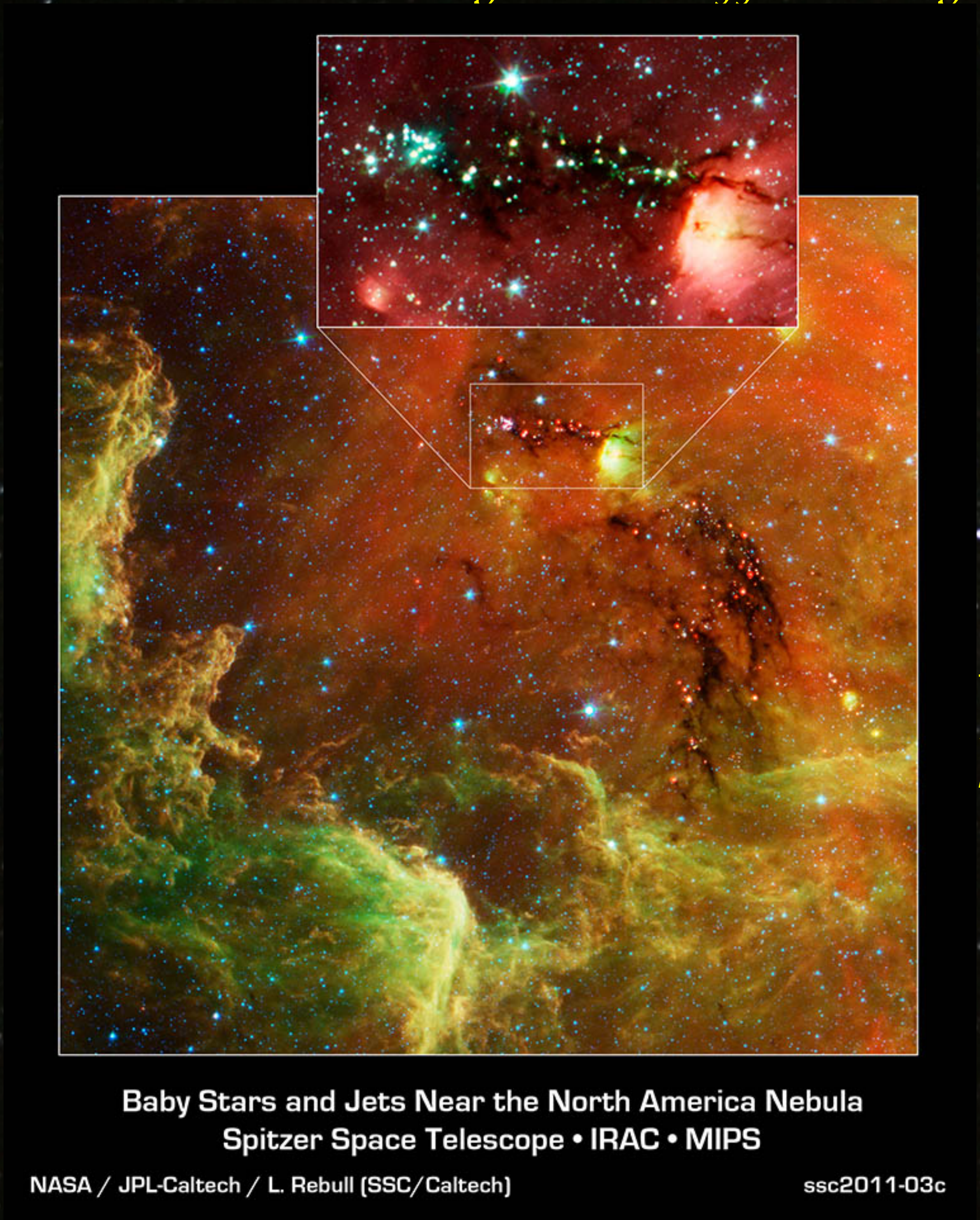
Transformational Science with ALMA: From Dust to Rocks to Planets, Formation and Evolution of Planetary Systems.

April 8-12, The Big Island of Hawaii

Dense cores in molecular clouds are the cradles of new stars in the Galaxy. Low efficiency of SF ~2-5%

e.g., Evans 2011.



Baby Stars and Jets Near the North America Nebula
Spitzer Space Telescope • IRAC • MIPS
NASA / JPL-Caltech / L. Rebull (SSC/Caltech) ssc2011-03c

Cores of low-mass stars have: sizes < 0.1 pc, T~ 10K, masses ~ few M_{sun} , Ω ~ few km s^{-1} pc^{-1} ,and $\sigma_{nt} < a$

e.g., Lada et al. 2008, Frau et al. 2010.

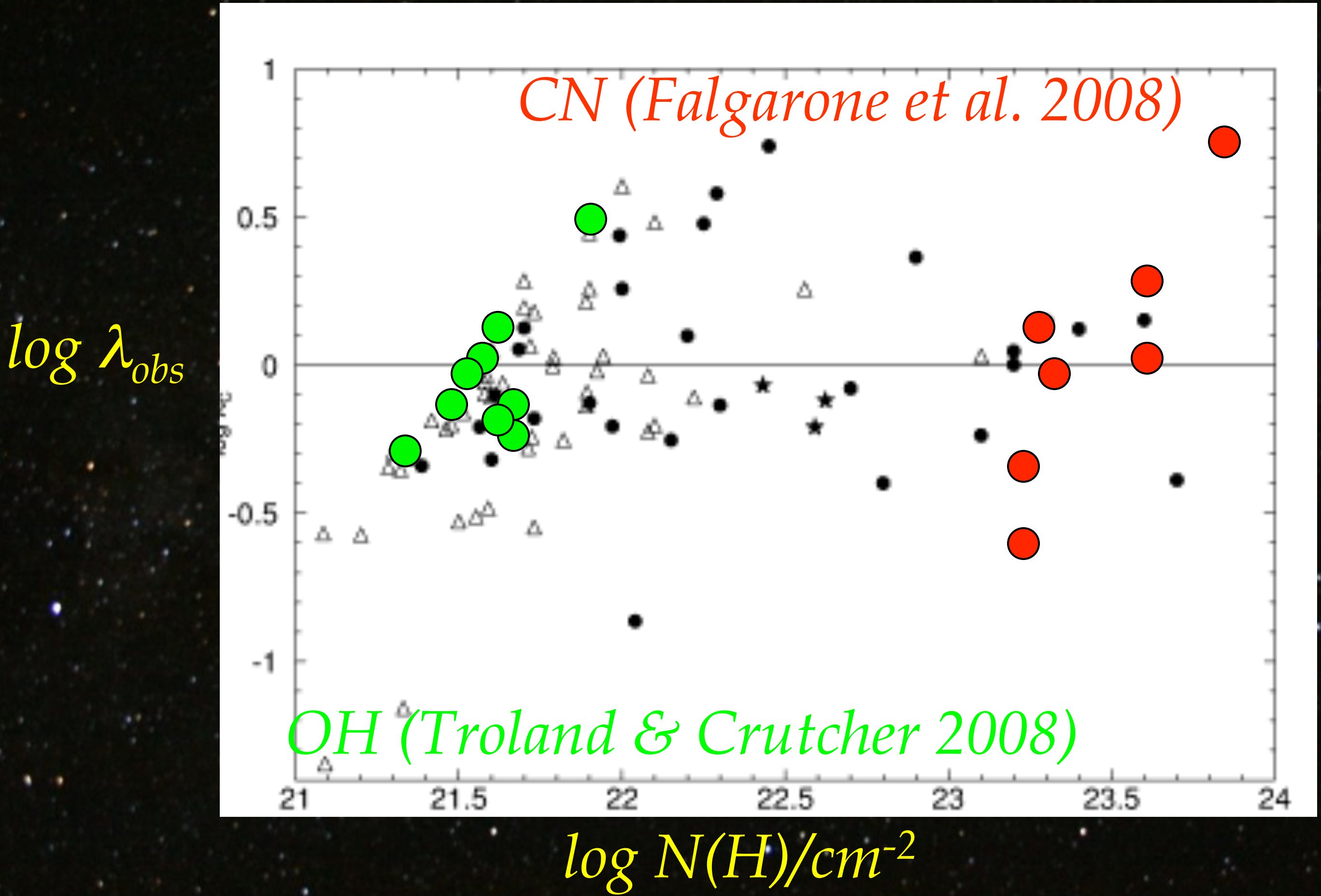
Rebull et al. 2011

- *It has been under debate if the origin of these dense cores is controlled by magnetic fields or by fast turbulent compression (e.g., Nakamura & Li 2008; Adams & Shu 2010 ; Ballesteros-Paredes et al. 2007; McKee & Ostriker 2007).*
- *Zeeman splitting observations of OH and CN give* $B_{l.o.s.}$ *~10 – 300 μG at gas densities* $n \sim 3 \times 10^3$ - 4×10^5 cm^{-3}*. These fields can provide support against gravitational collapse and there are difficult to get rid off (e.g., Troland & Crutcher 2008; Falgarone et al. 2008).*

The mass-to-magnetic flux ratio determines the relevance of magnetic support in cloud cores

$$\lambda = 2\pi G^{1/2} M/\Phi$$

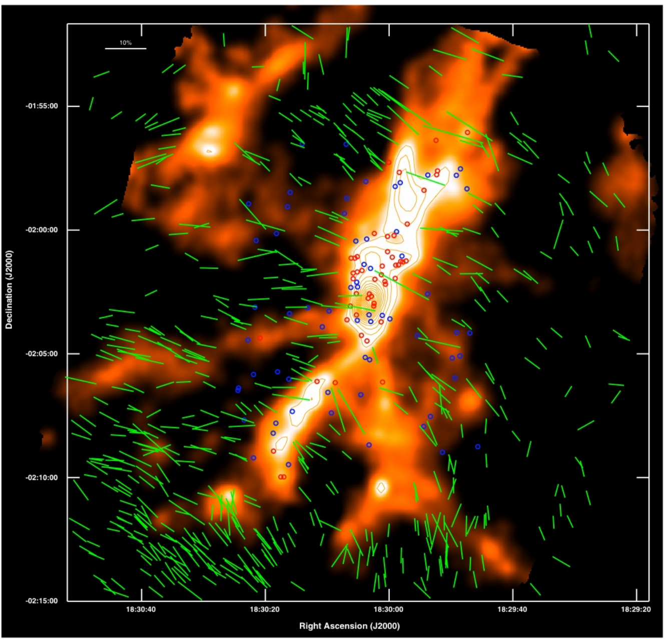
$\lambda > 1$ is necessary for instability.



After geometric corrections => λ~1-4

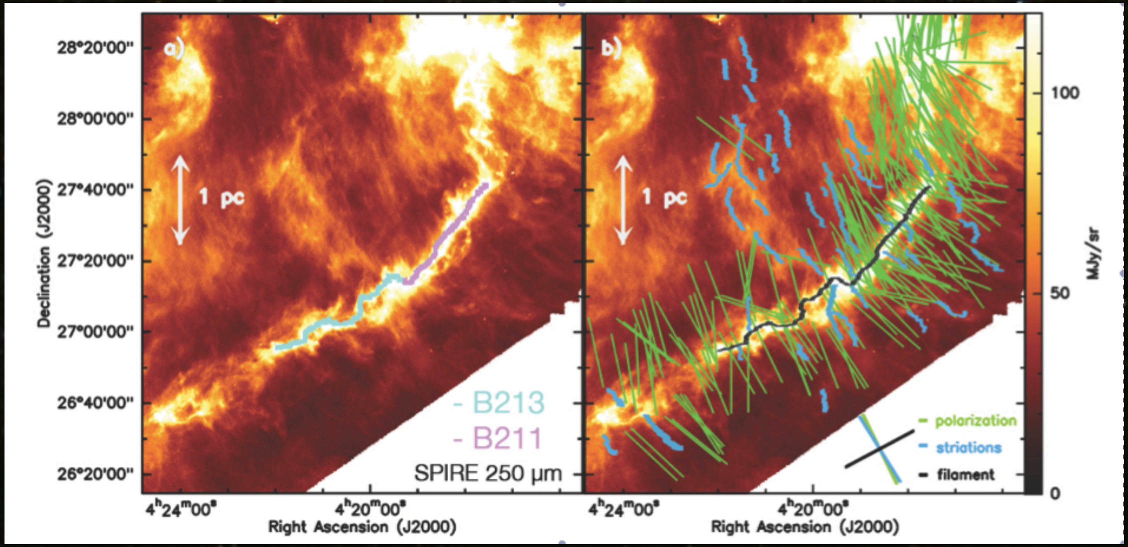
(Falgarone et al. 2008).

Optical and NIR polarimetry of background starlight show well ordered fields.



Serpens South

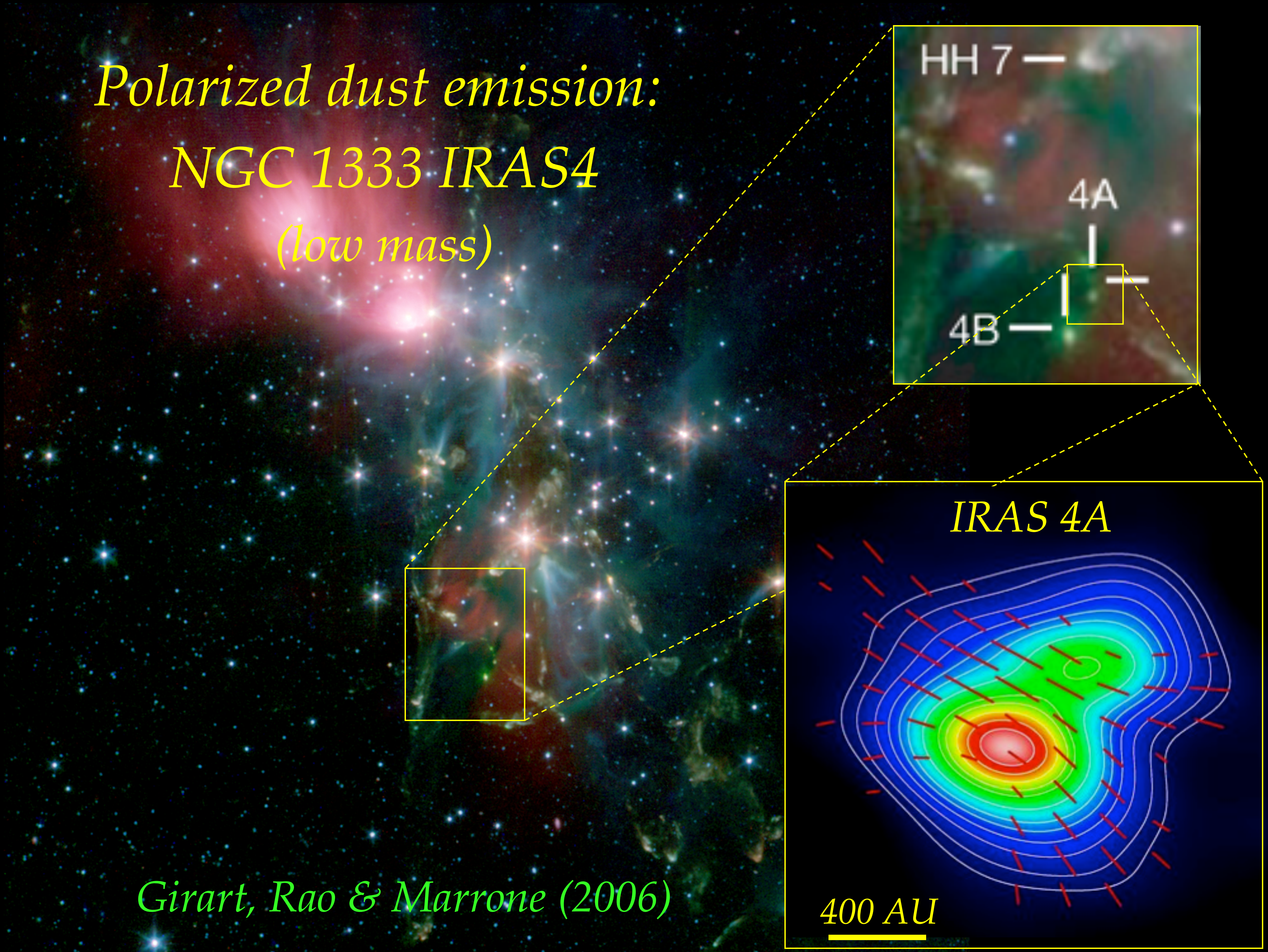
(Sugitani et al. 2011)



Taurus B213 and B212

(Palmeirim et al. 2012)

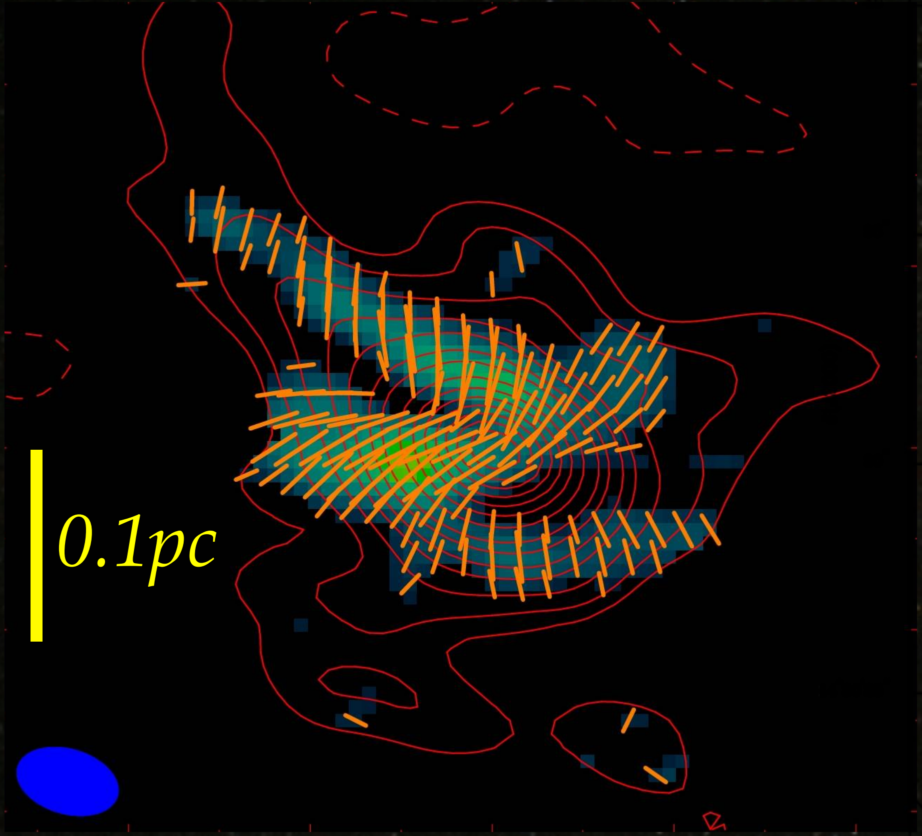
Polarized dust emission:
NGC 1333 IRAS4
(low mass)



Girart, Rao & Marrone (2006)

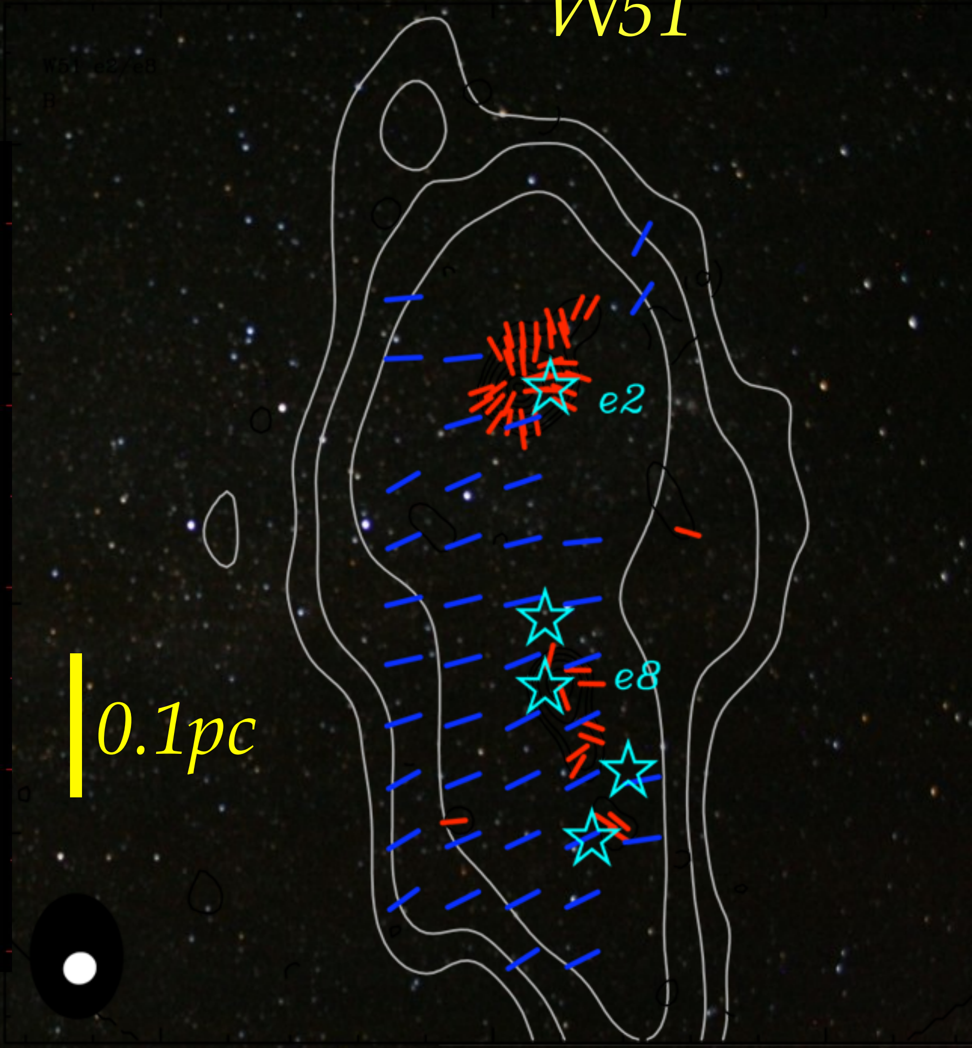
Massive stars

G31.41+0.31



Girart et al. (2009)

W51



Tang et al. (2009; 2012)

Discuss:

Effect of magnetic fields in the phase of gravitational collapse on disk formation, structure and stability

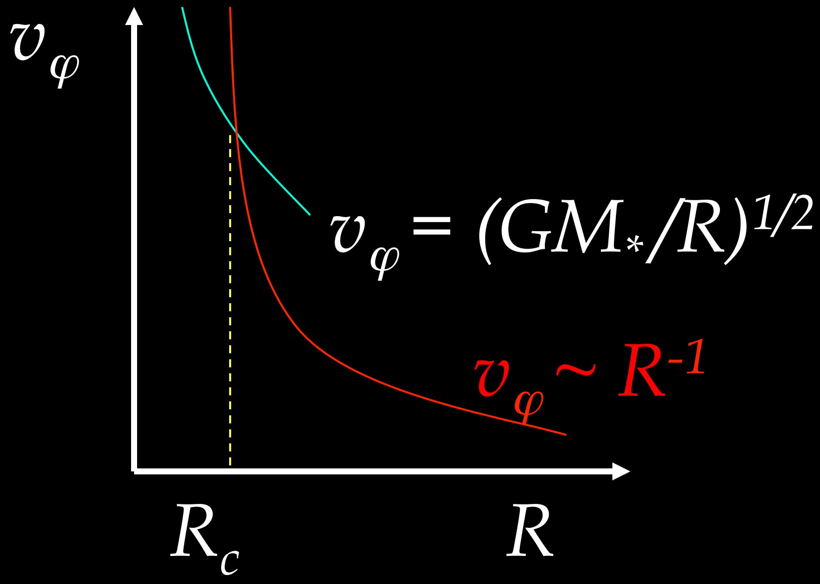
→

Magnetic fields are dynamically important for star and planet formation.

Collapse of a rotating cloud

Centrifugal radius

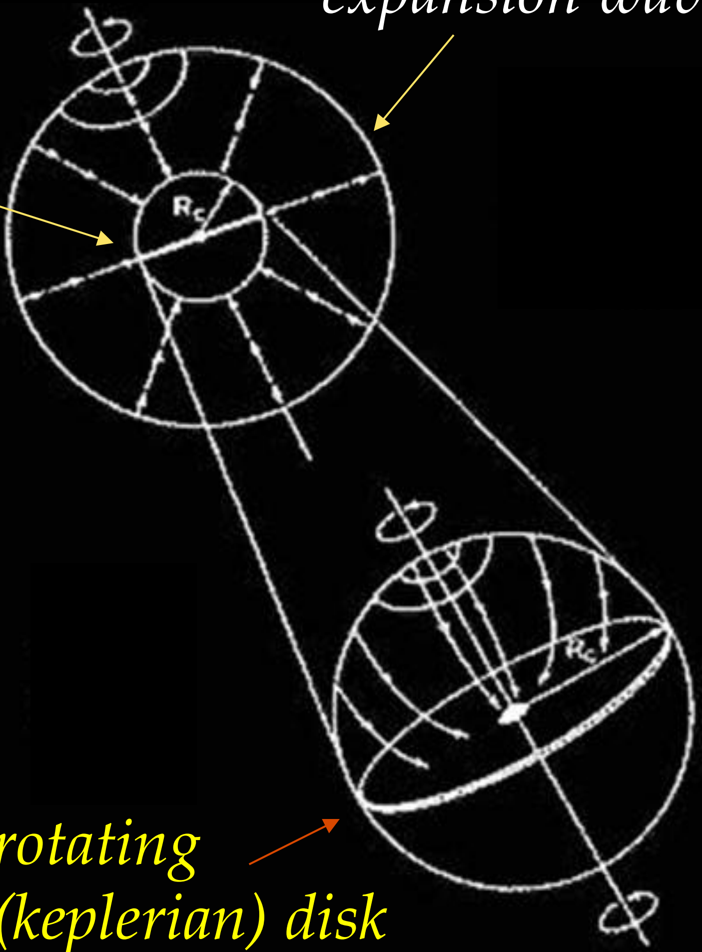
$R_c = G^3 M_*^3 \Omega^2 / 16\, a^8$



$v_\varphi = (GM_*/R)^{1/2}$

$v_\varphi \sim R^{-1}$

expansion wave

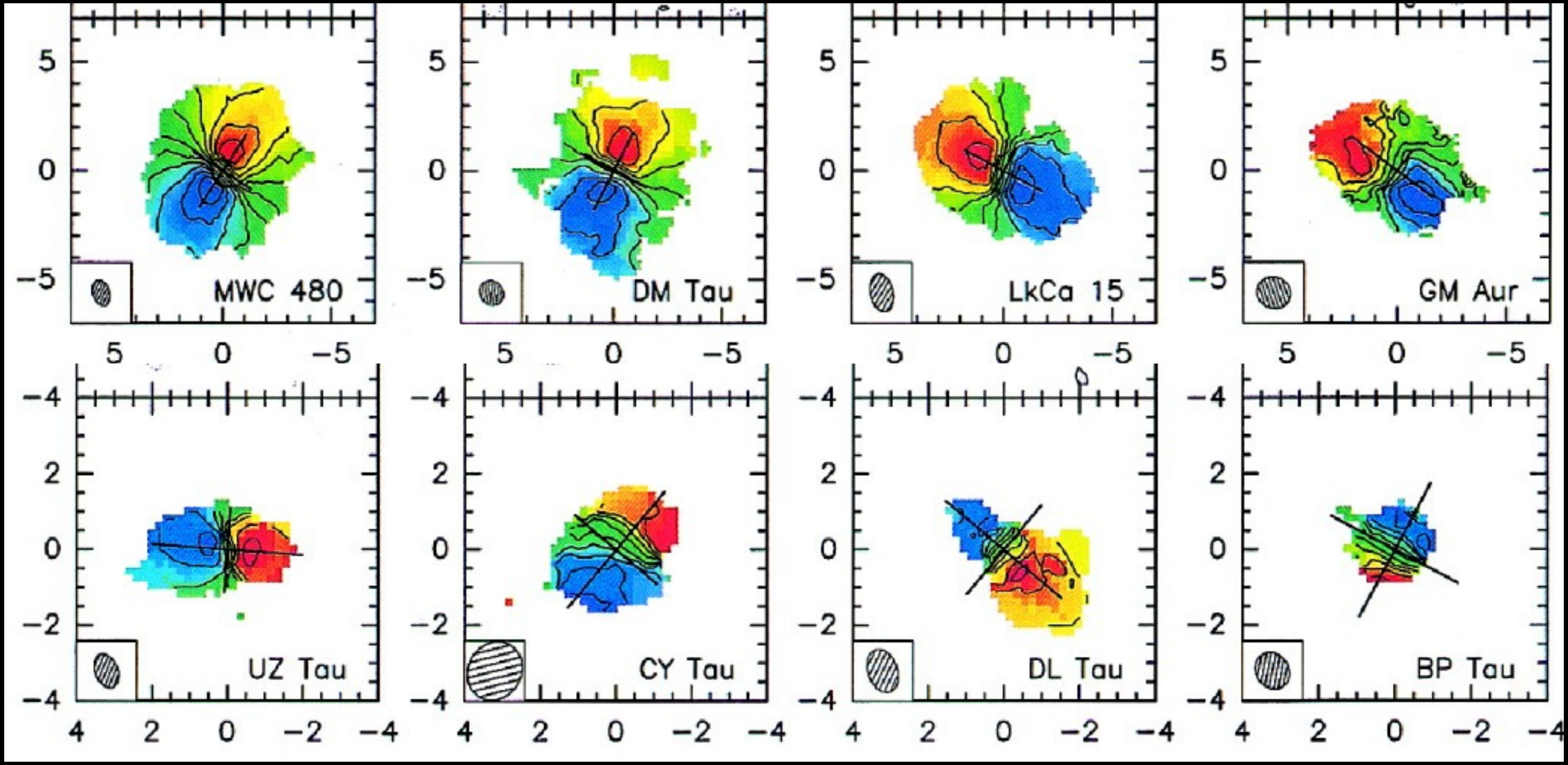


rotating (keplerian) disk

Shu, Terebey & Cassen (1984)

Disks around T Tauri stars

$M_{*} \approx 0.5\ M_{o}$, $dM_{*}/dt \approx 10^{-8}\ M_{o} yr^{-1}$



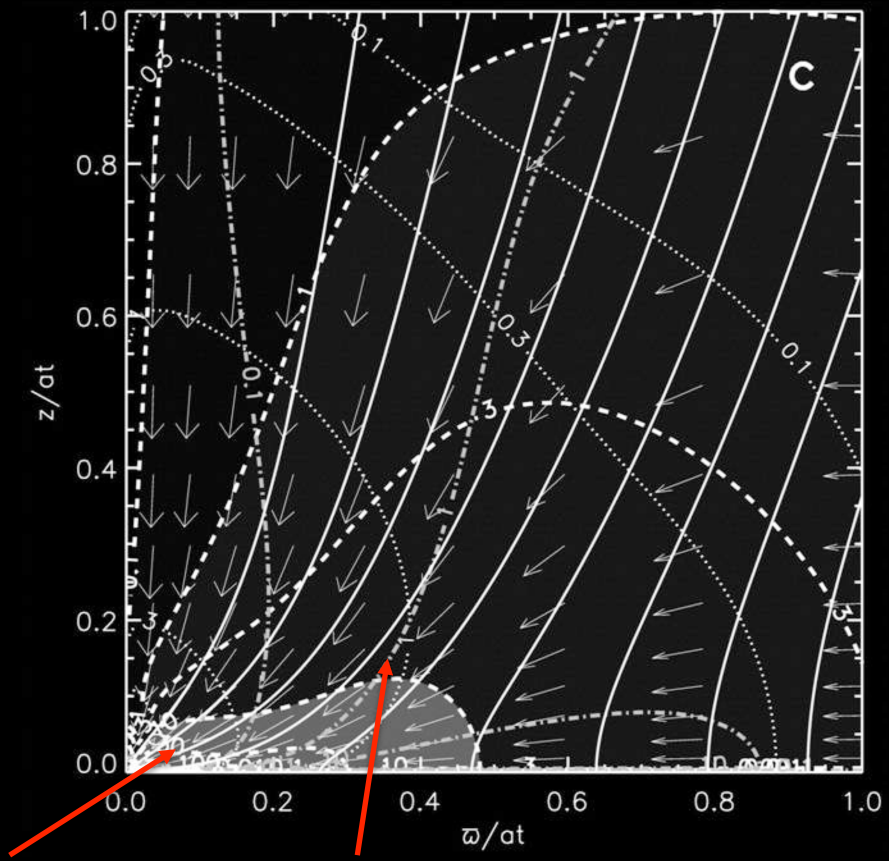
Simon et al. (2000)

Collapse of a non-rotating magnetized cloud

Galli & Shu (1993)
semi-analytical

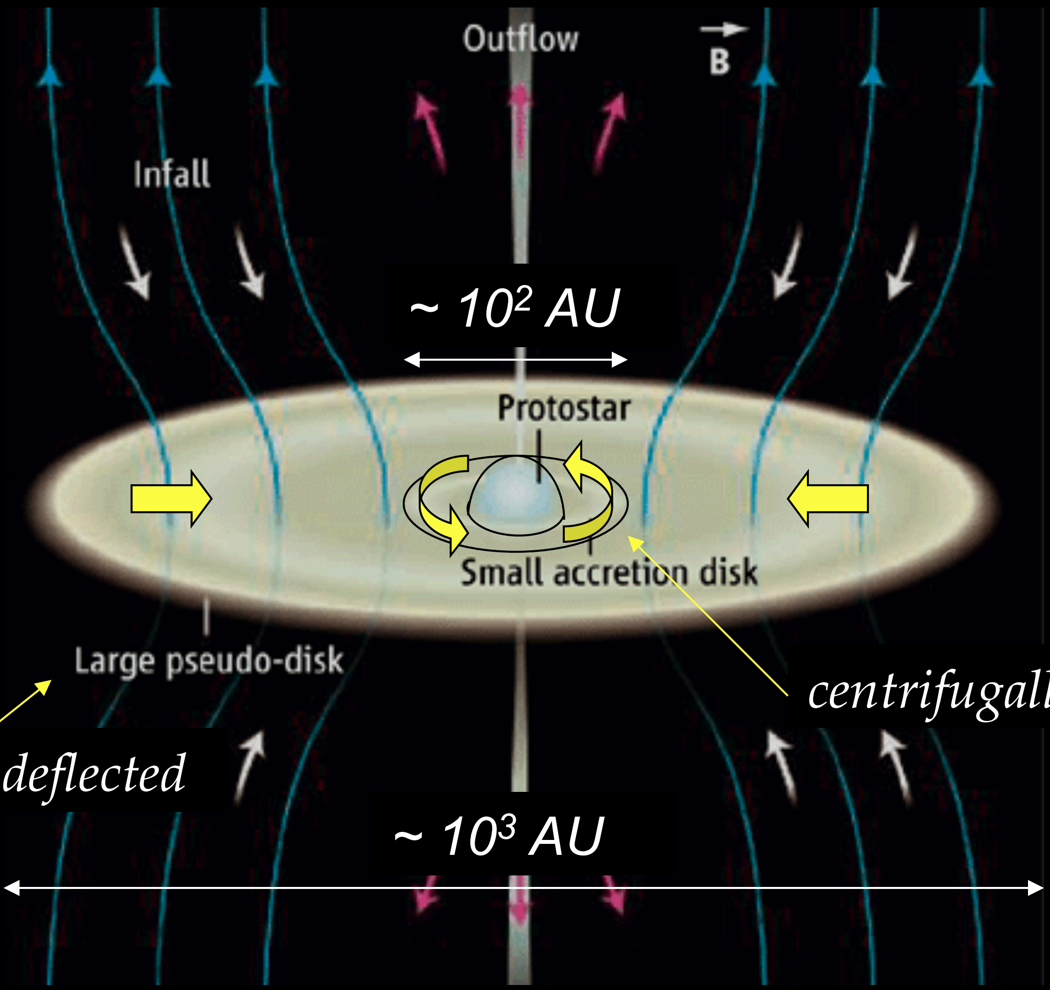
Allen, Li & Shu (2003)
ZEUS-2D

Strong magnetic pinching forces deflect infalling gas toward the equatorial plane to form a flattened structure the ``pseudo-disk'' not in equilibrium



"pseudo-disk" + "hourglass" field

The naive expectation



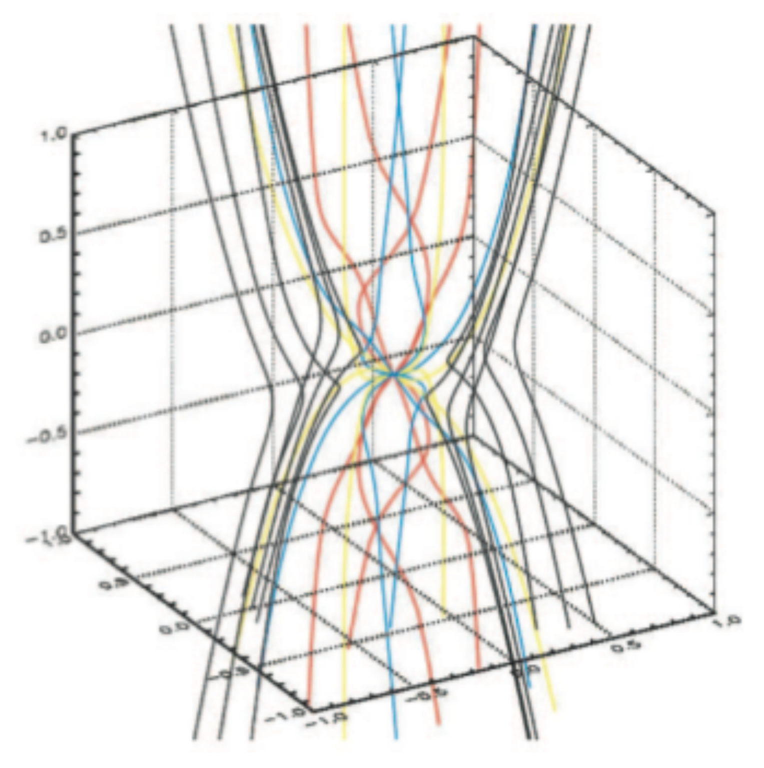
centrifugally supported

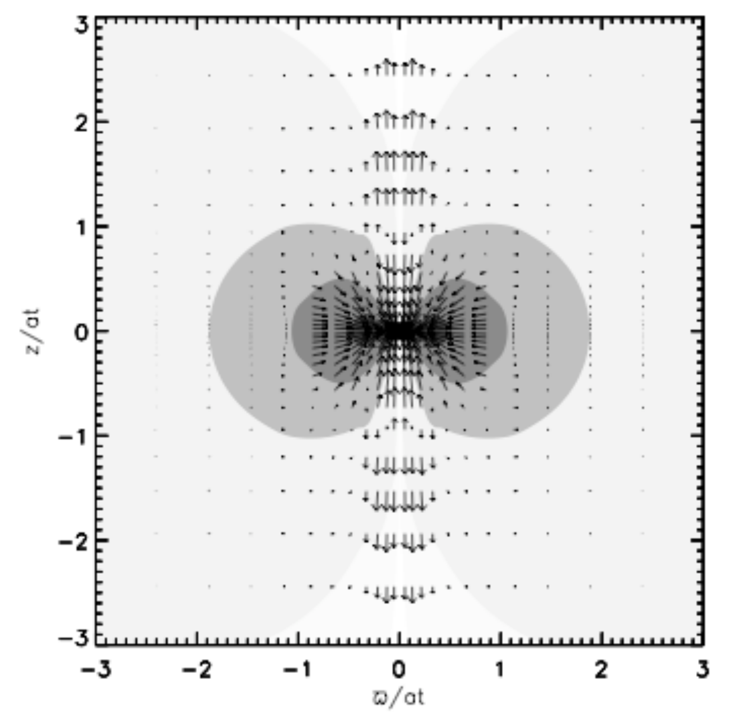
Magnetically deflected

from Crutcher (2006)

The problem….

In ideal MHD the collapse of a magnetized rotating core does not form a rotationally supported disk *Allen et al. (2003).*

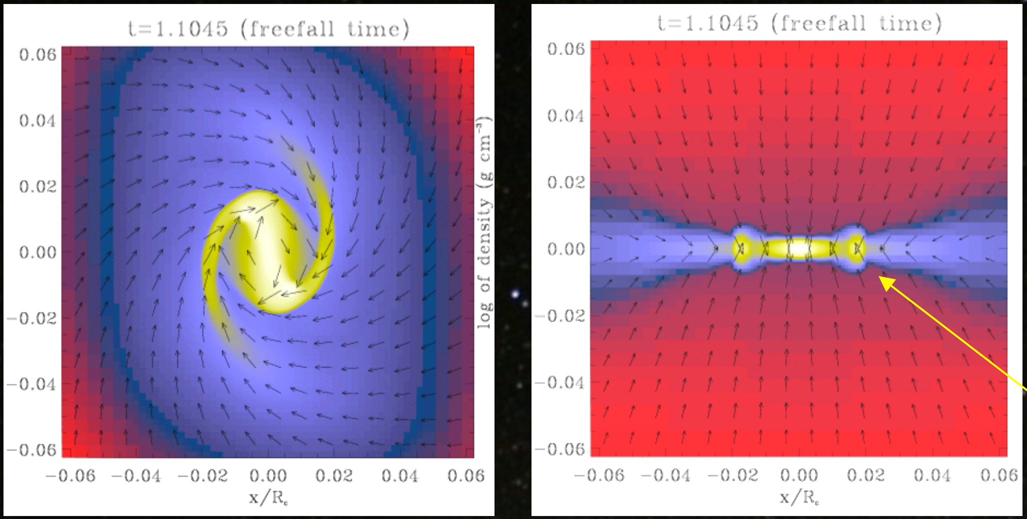




Magnetic braking: torsional Alfven waves in twisted field lines carry away angular momentum and produce slow outflows (v~few km/s) *Mestel (1985).*

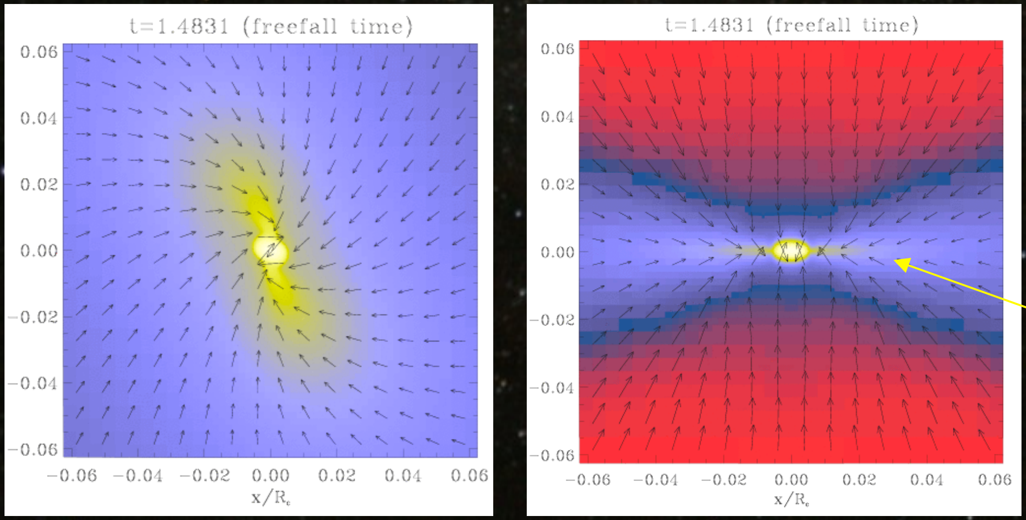
Fromang et al. (2006)

no B field ($\lambda = \infty$)



centrifugal disk

with B field ($\lambda = 2$)

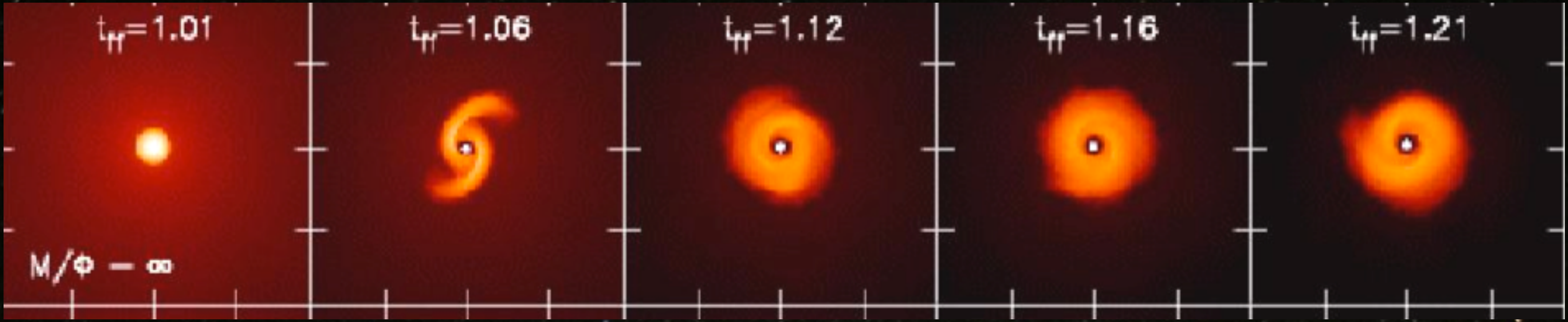


magnetic pseudo-disk (not supported centrifugally)

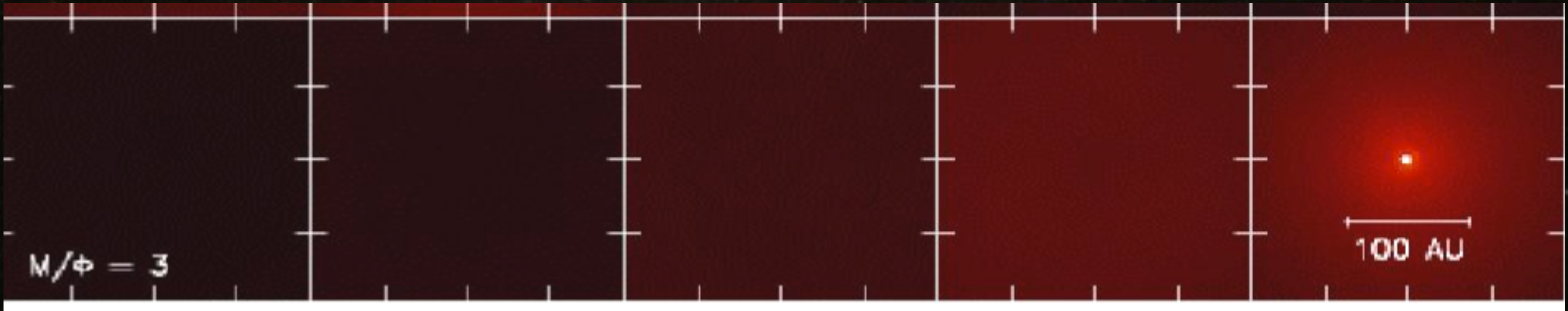
top view

side view

no B field ($\lambda = \infty$)



with B field ($\lambda = 3$), in ideal MHD



Price & Bate (2007)

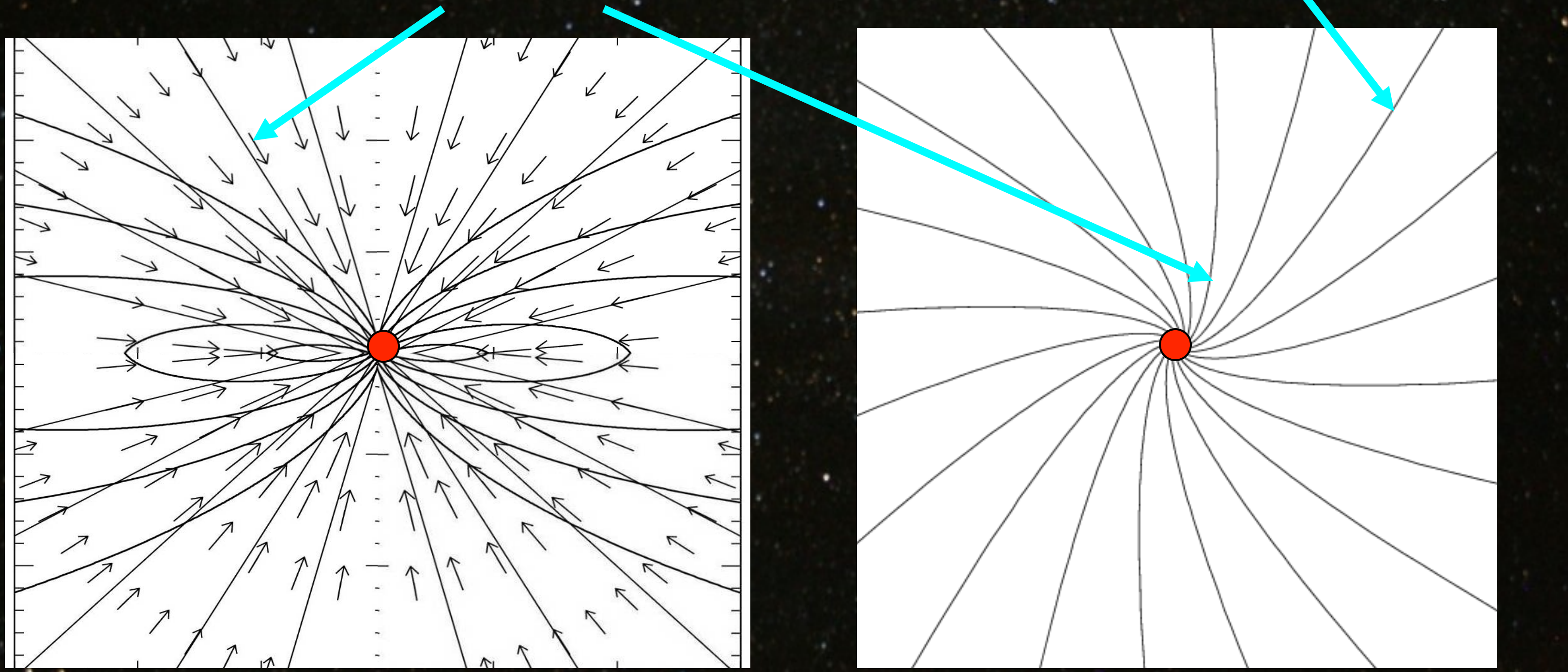
The explanation

During gravitational collapse, B trapped in the central star creates a split monopole => catastrophic magnetic braking!

$B_r \sim a^3 t / (G^{1/2} r^2)$ Galli et al. (2006)

split monopole

streamlines and fieldlines

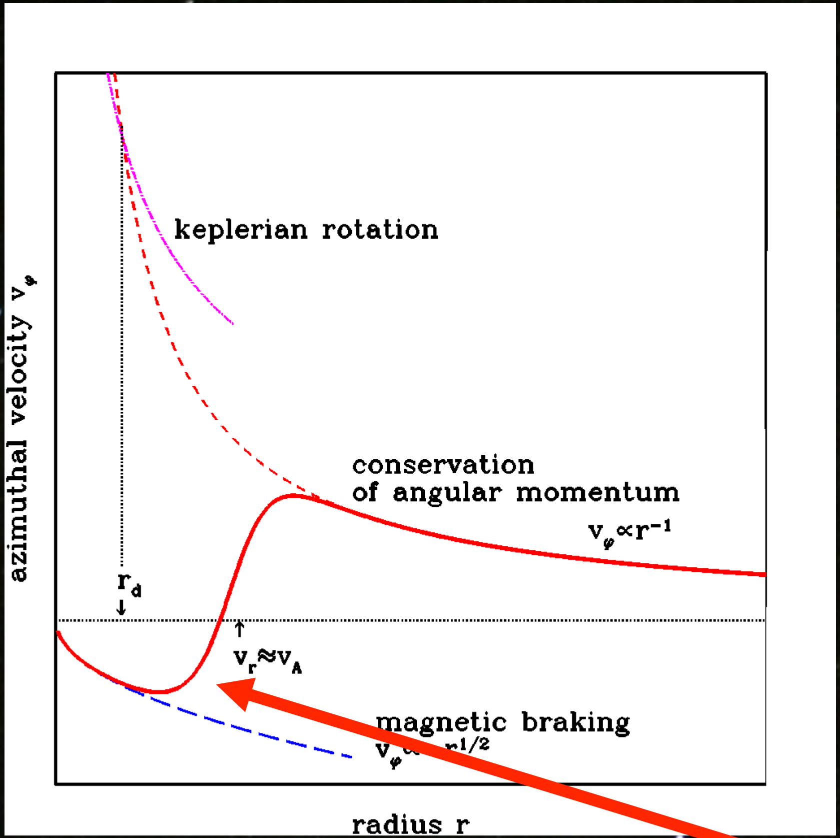


side view: pseudodisk

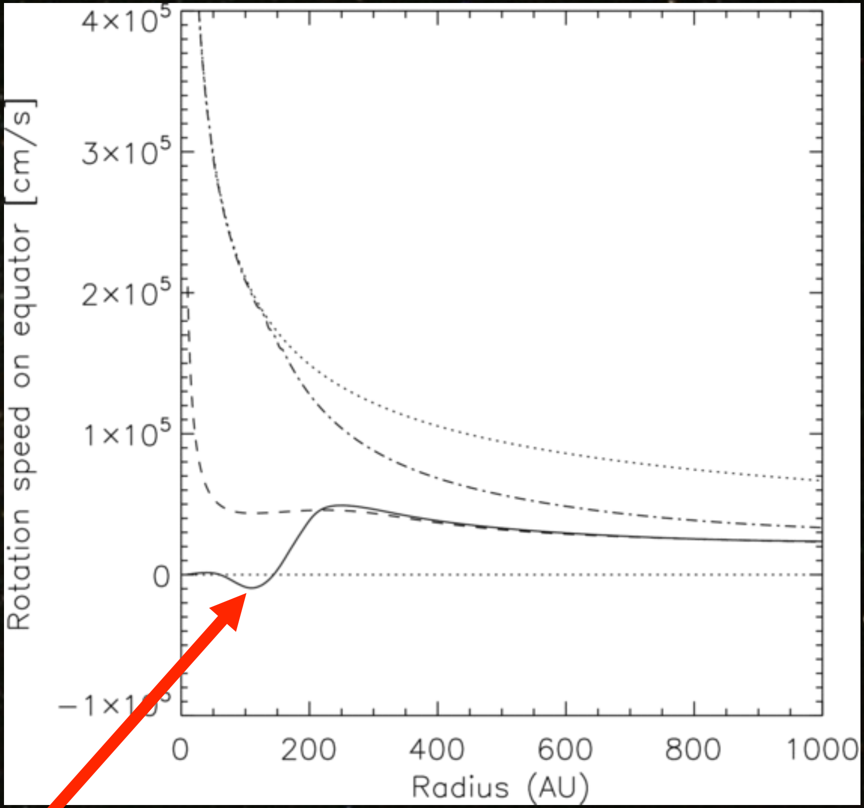
top view: no centrifugal disk

Catastrophic magnetic braking Galli et al. 2012

Analytic solution

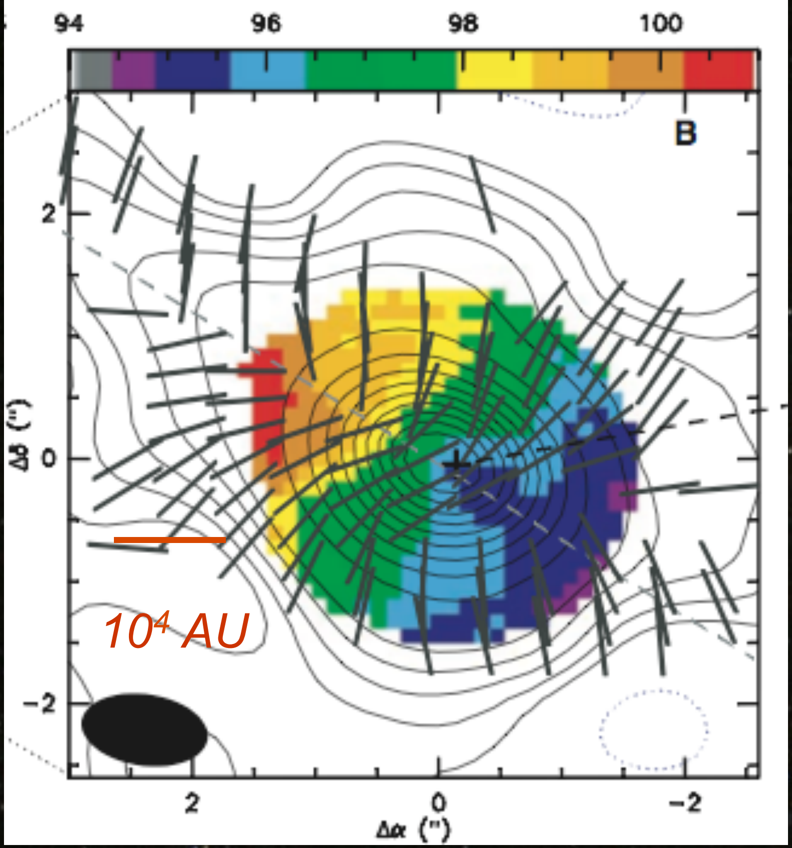


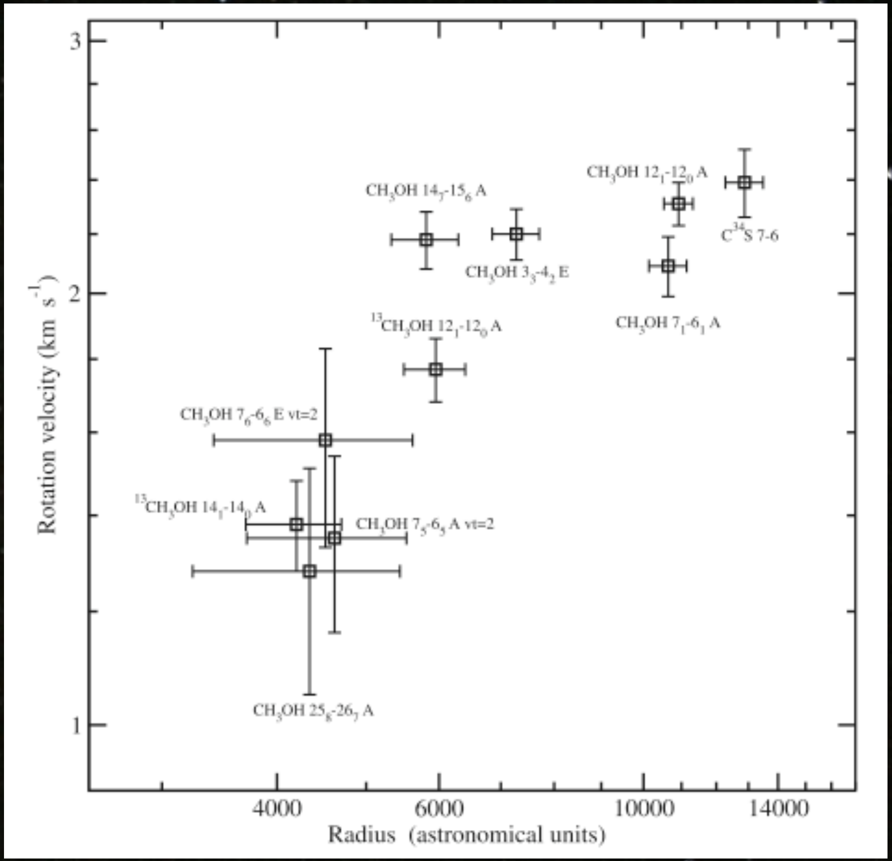
Krasnopolsky et al. (2010)



counter rotation: $v_\varphi \sim -r^{1/2}$

Magnetic braking in the hot molecular core G31.41+0.31 *(Girart et al. 2009).*





Magnetic Braking and disk formation

- *Suppression of disk formation by catastrophic magnetic braking in ideal MHD (Galli et al. 2006).*

- *Disk formation with field-freezing possible only for clouds with $\lambda > 10$-80, or $\lambda > 3$ when the magnetic and rotation axis are perpendicular (Mellon & Li 2008; Hennebelle & Fromang 2007; Seifried et al. 2011; Hennebelle & Ciardi 2009).*

- *But $\lambda \approx 1$-4 in molecular cloud cores*

→ field-freezing must be violated, field dissipation is necessary! Also required to solve the magnetic flux problem.

Magnetic flux problem for collapse with field-freezing (Mestel & Spitzer 1956).

$\Phi_* \approx 1/4\ \Phi_{core}$

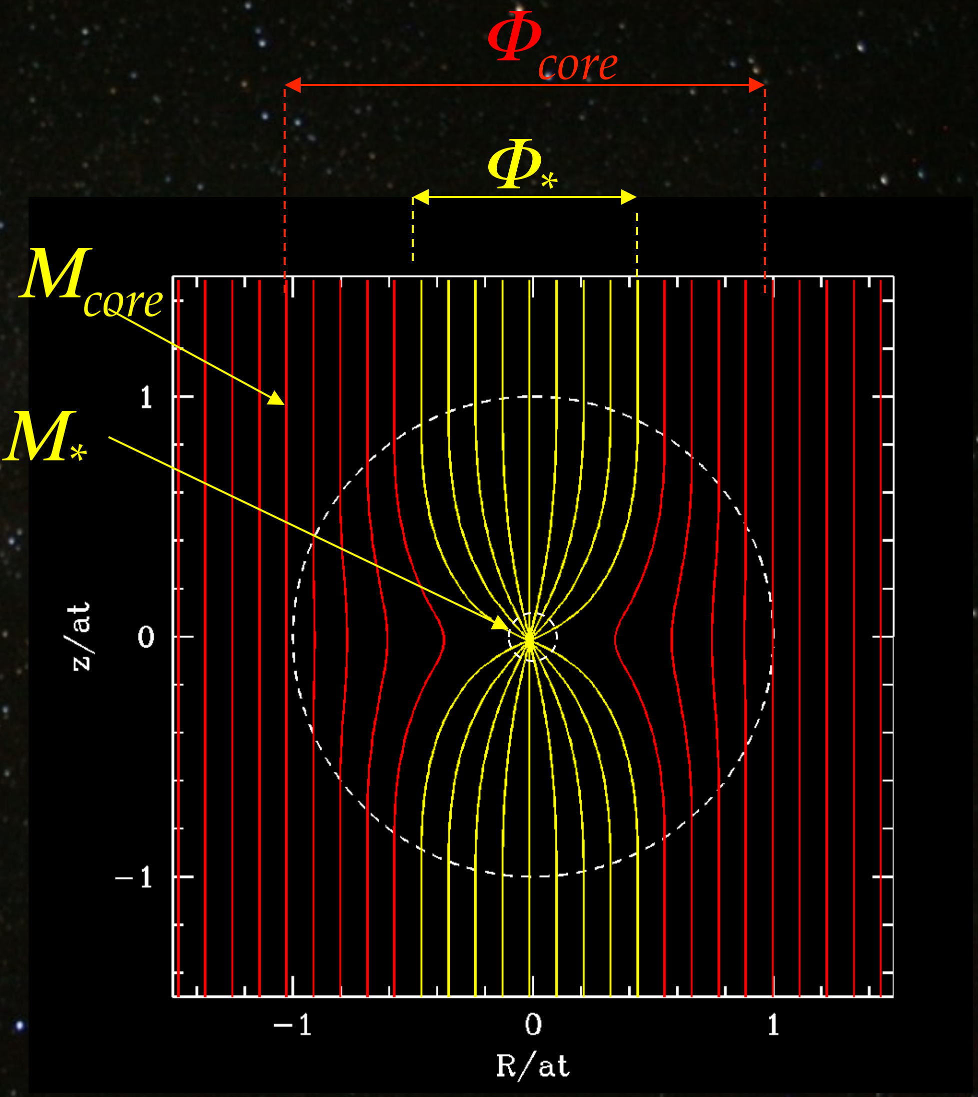
$M_* \approx 1/2\ M_{core}$

=> $\lambda_* \approx 2\ \lambda_{core}$ (B_*~MG)!!

Observationally

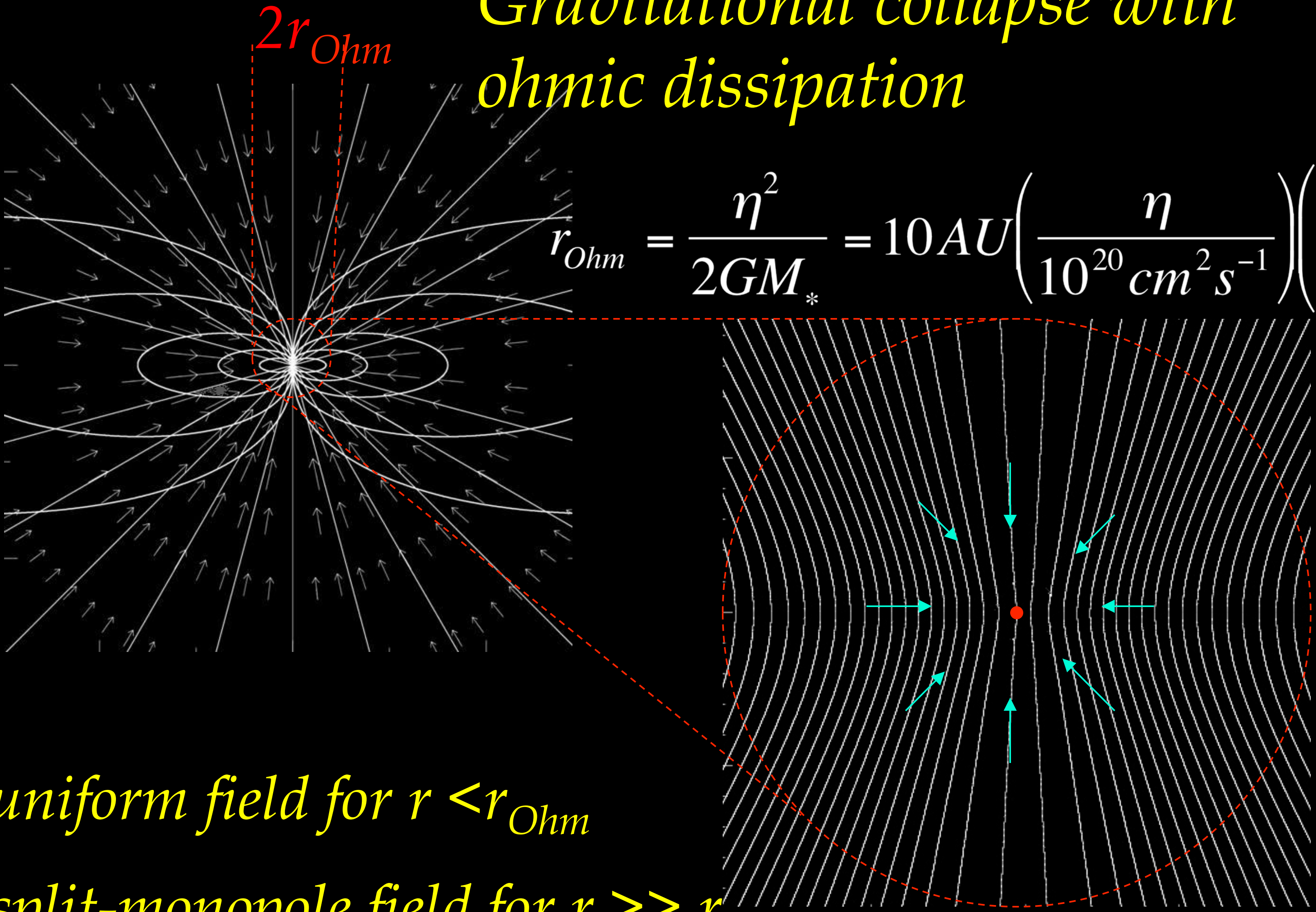
$\lambda_* \approx 10^3$-10^4 (B_*~KG)

=> *field dissipation must occur during the gravitational collapse of the dense core*



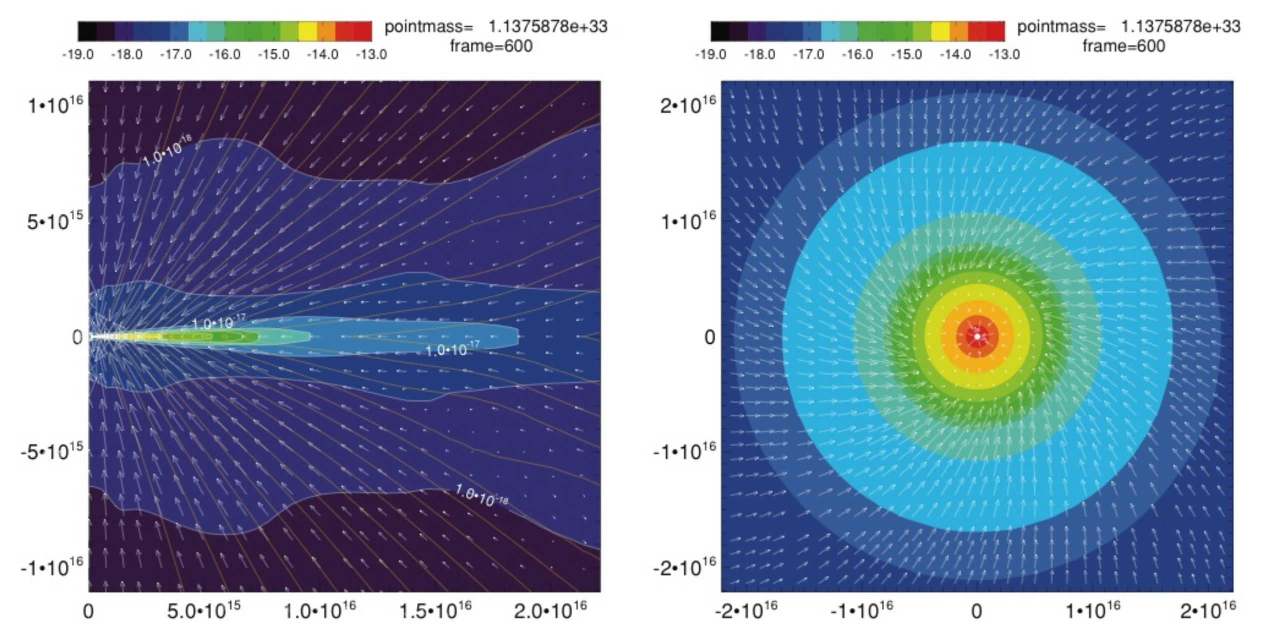
Gravitational collapse with ohmic dissipation

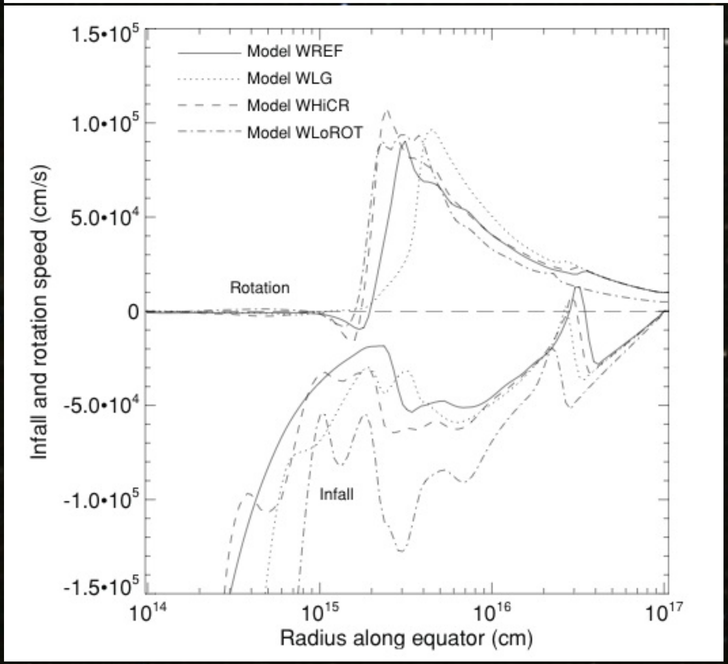
$$r_{Ohm} = \frac{\eta^2}{2GM_*} = 10\,AU\left(\frac{\eta}{10^{20}\,cm^2 s^{-1}}\right)\left(\frac{M}{M_o}\right)^{-1}$$



- *uniform field for* $r < r_{Ohm}$
- *split-monopole field for* $r >> r_{Ohm}$

Shu et al. (2006)



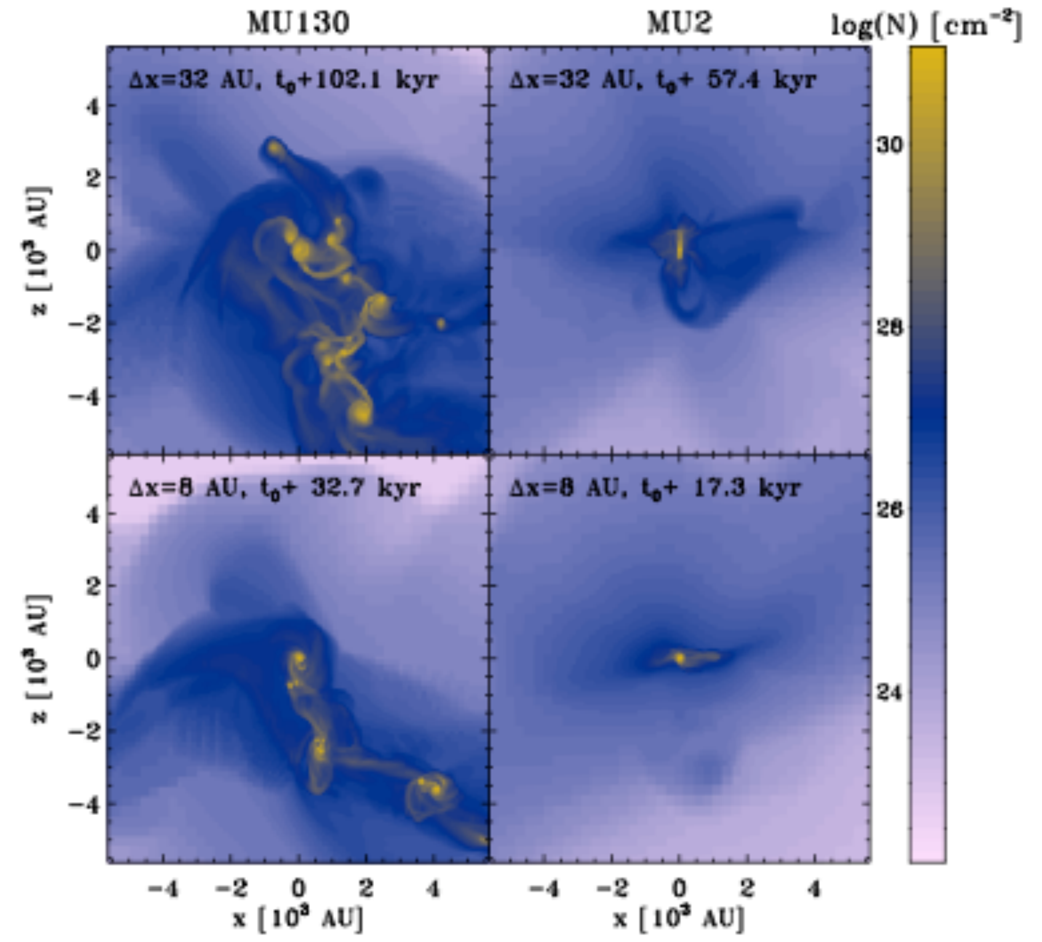


Gravitational collapse with ambipolar diffusion, Ohmic dissipation and Hall effect (e.g., Li et al. 2011).

Alternative solutions:

- *Misalignement B and Ω reduces braking torque (Hennebelle & Ciardi 2009; Joos et al. 2012) → requires strong misalignement and low magnetization*
- *The disk could grow when the envelope has been depleted and magnetic braking becomes inefficient (e.g., Machida et al. 2011).*
- *Turbulence enhances the rate of field reconnection and diffusion (e.g., Seifried et al. 2012, Santos-Lima et al. 2012-13) → requires high levels of turbulence, caution with numerical diffusion.*

Numerical simulations of gravitational collapse also show that B suppresses fragmentation for $\lambda < 20$ unless initial density perturbations are large (50%).



e.g., Hennebelle & Teyssier 2008; Duffin & Pudritz 2009; Commerc,on et al. 2010, 2011; Myers et al. 2013

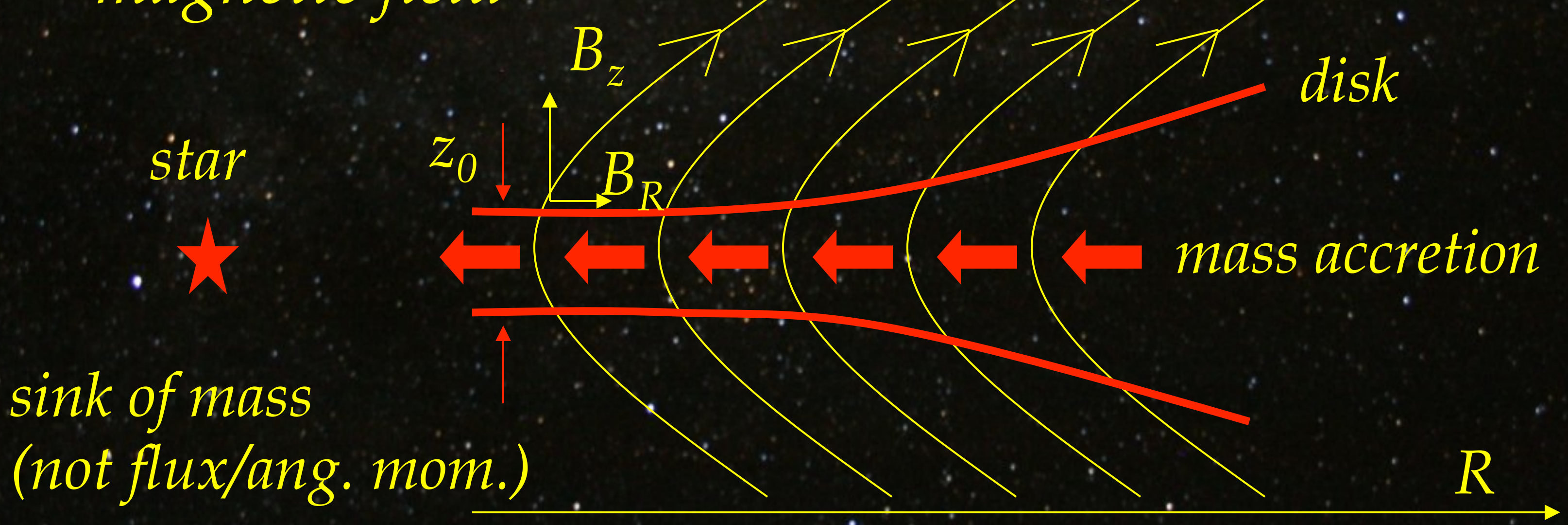
B can change the orbital separation and evolution of protobinaries (Zhao & Li 2013).

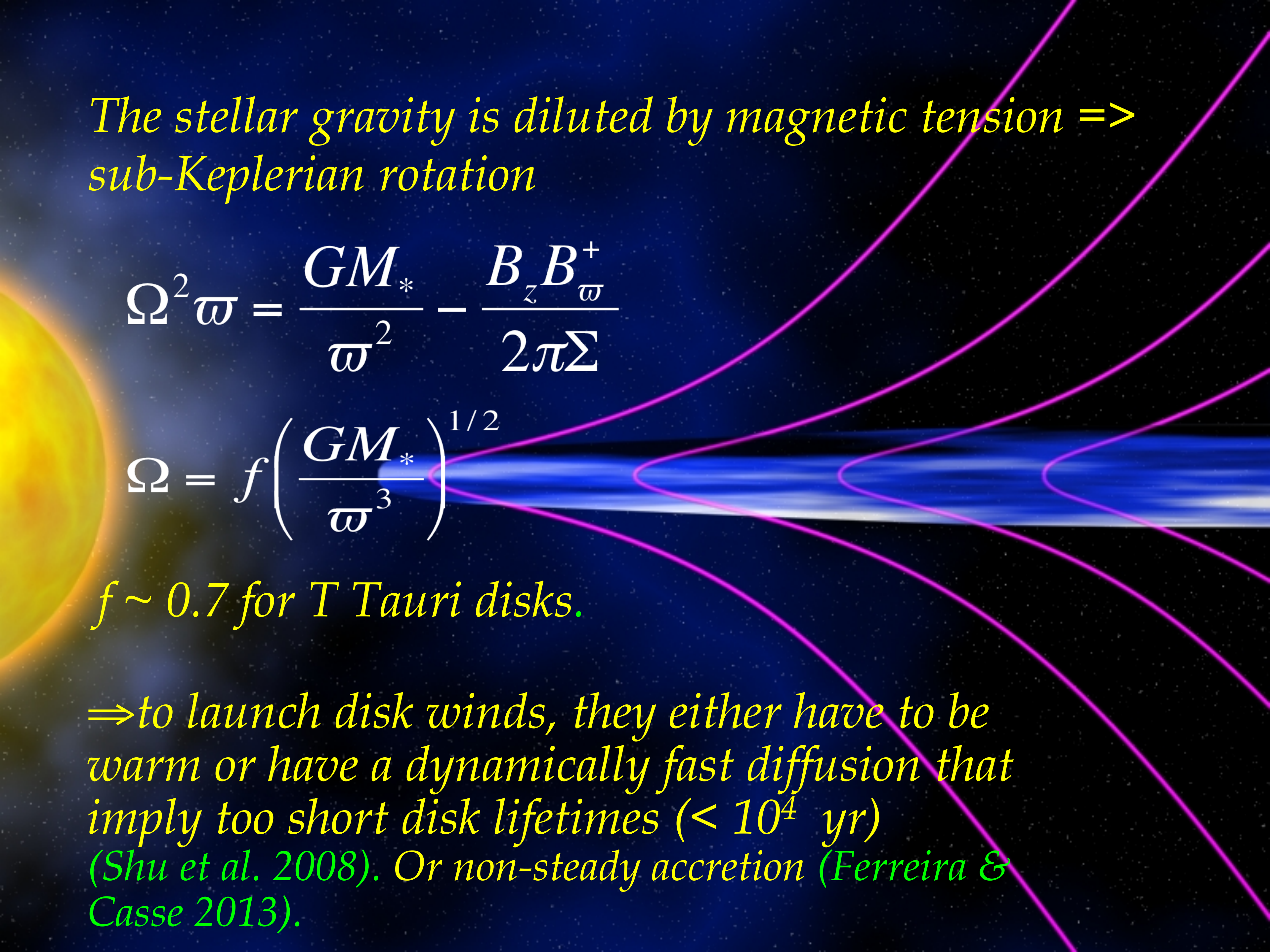
Magnetized accretion disks

$\vec{B}$ *modifies the structure and dynamics of accretion disks* (*Shu et al 2007*).

Two diffusive processes:

- *Viscosity* ν → *allows matter to accrete (MRI)*
- *Resistivity* η → *allows matter to slip through the magnetic field*





The stellar gravity is diluted by magnetic tension => sub-Keplerian rotation

$$\Omega^2 \varpi = \frac{GM_*}{\varpi^2} - \frac{B_z B_\varpi^+}{2\pi\Sigma}$$

$$\Omega = f\left(\frac{GM_*}{\varpi^3}\right)^{1/2}$$

$f \sim 0.7$ *for T Tauri disks.*

⇒to launch disk winds, they either have to be warm or have a dynamically fast diffusion that imply too short disk lifetimes (< 10^4 *yr) (Shu et al. 2008). Or non-steady accretion (Ferreira & Casse 2013).*

Planet migration

More than 800 exoplanets are known today.*

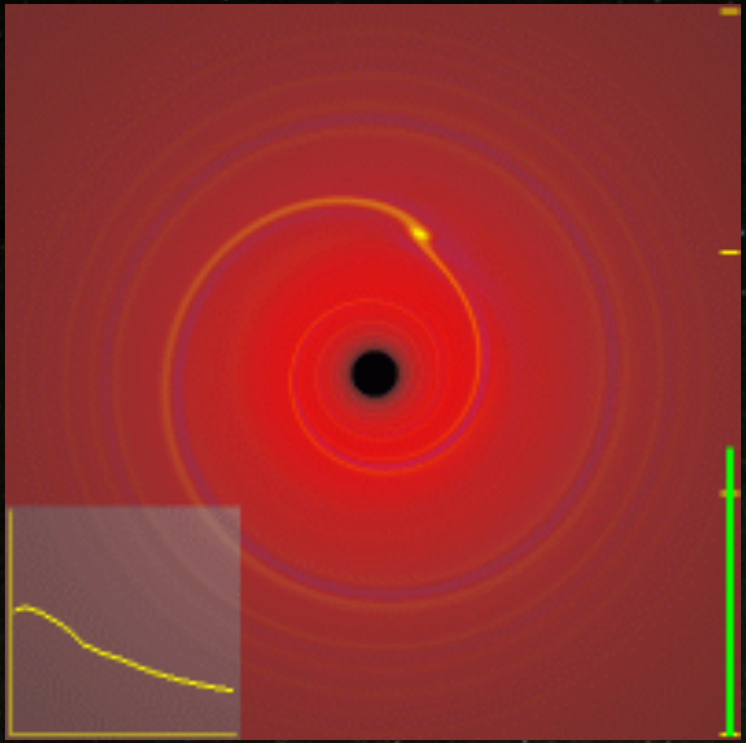
- *There is a population of close orbit giant planets with a < 0.1 AU, the so-called ``hot Jupiters'' (Udry et al. 2007).*

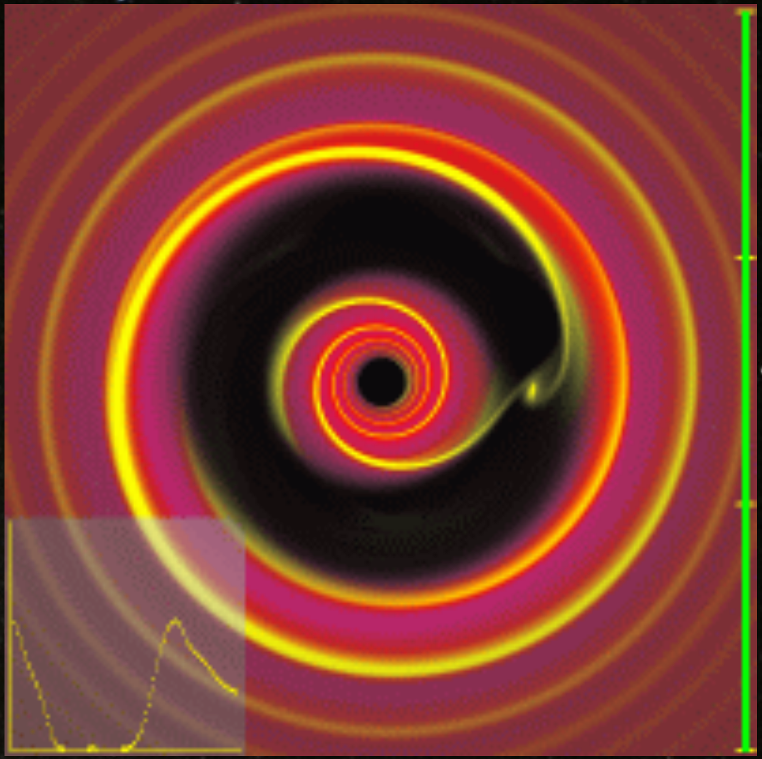
Planet migration: planets and planitesimals form in the outer regions of the circumstellar disk and then migrate inwards because of the gravitational interaction with the disk (e. g., Papaloizou et al. 2007).

**http://planetquest.jpl.nasa.gov*

http://exoplanets.org/

Armitage





Type I : a small protoplanet perturbs the disk producing density waves that carry away angular momentum.

Type II : : a massive planet opens a gap; the time evolution is set by the disk viscosity.

Planet migration in sub-keplerian disks

In sub-Keplerian disks, embedded planets orbit with keplerian speeds. Thus, they experience a headwind from the slower gaseous disk. The velocity mismatch results in energy loss from the planet orbit and inward migration (Adams et al. 2009).

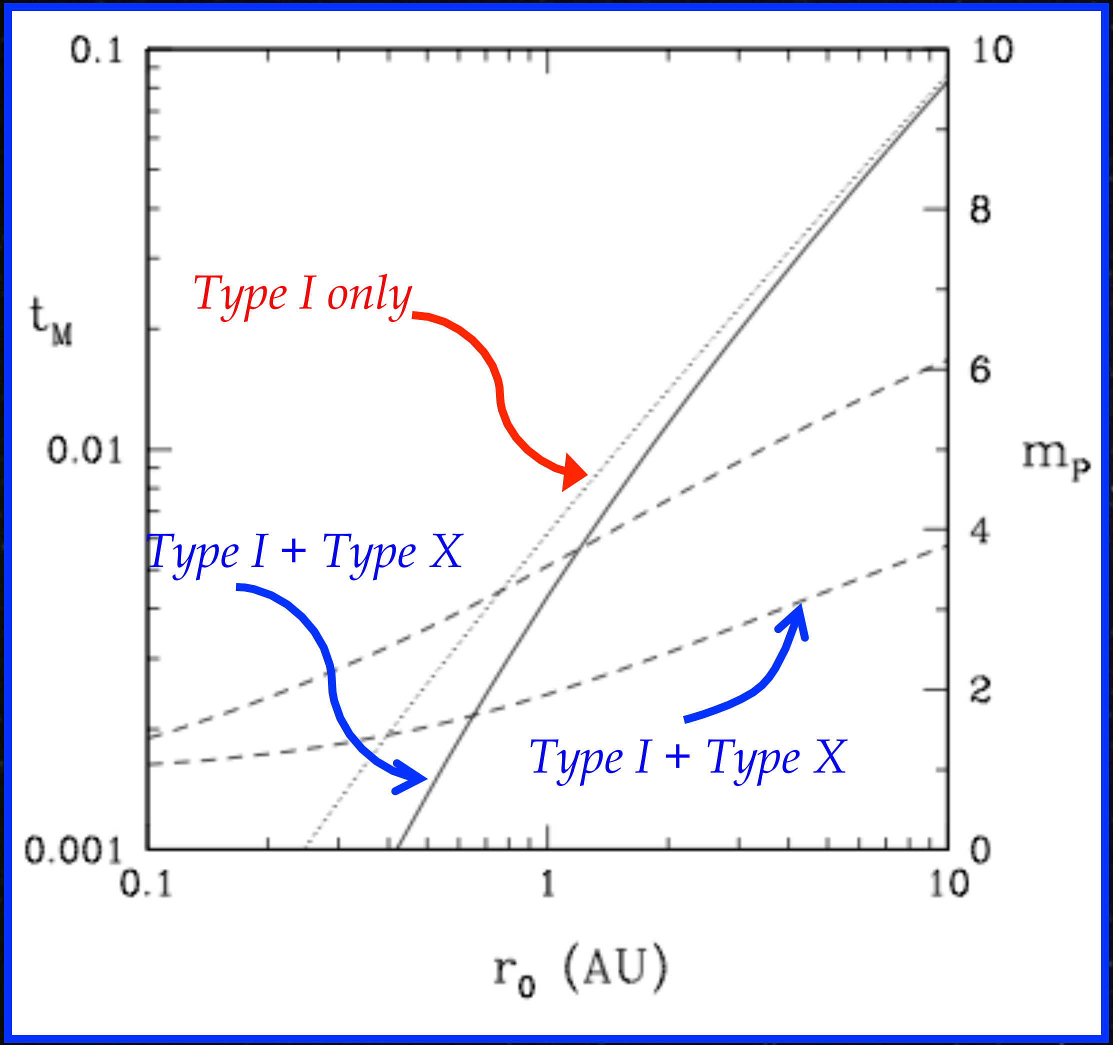
Time evolution of the semi-major axis:

$$\frac{1}{r}\frac{dr}{dt} = \frac{2T_X}{m_p \Omega r^2}$$

where

$$T_X = C_D \pi R_p^2 r \rho_{gas} v_{rel}^2 \quad \textit{and} \quad v_{rel} = (1-f)\left(\frac{GM_*}{r}\right)^{1/2}$$

Migration time (Myr) and final planetary core mass $m_p(M_\oplus)$ versus starting radius r_0(AU)



- *Subkeplerian migration dominates over Type I migration inside ~1 AU. The mass accreted by the core is reduced.*

Disk stability: the modified Toomre Q parameter (Lizano et al. 2011)

$$Q_M = \frac{\Theta^{1/2} a \kappa}{\pi \varepsilon G \Sigma}$$

$\Theta = 1 + \frac{v_A^2}{a^2}$ *magnetosonic speed*

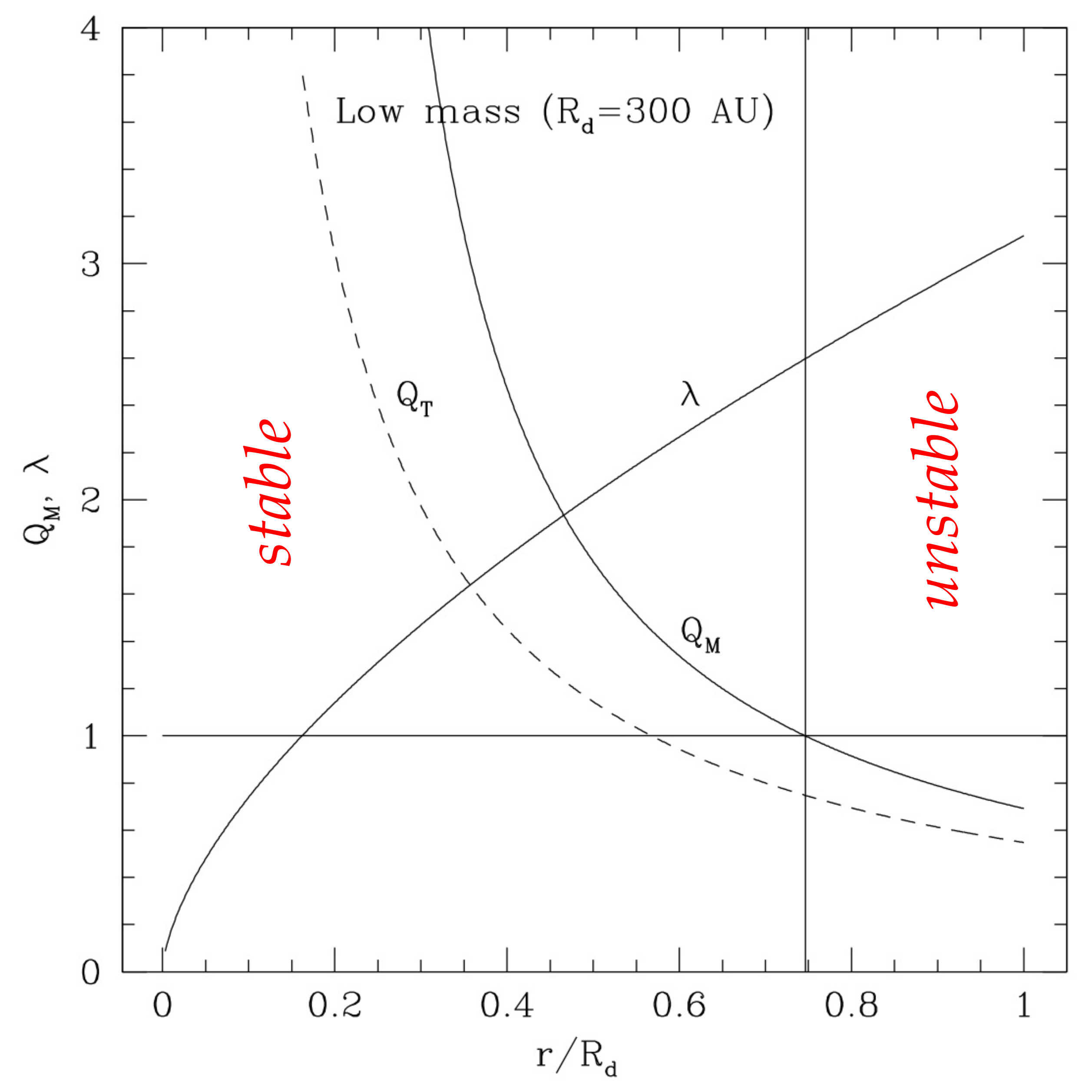
$\varepsilon \equiv 1 - \frac{1}{\lambda^2}$ *magnetic tension dilutes gravity*

$\kappa = f\Omega_K ; f < 1$ *Sub-Keplerian rotation*

=> *competing effects:*

- *Strong B enforce sub-keplerian flow:* $Q_M \downarrow$
- *Magnetic tension and pressure:* $Q_M \uparrow$

→ *magnetized disks around YSOs are* *<u>more stable</u>* $Q_M > 1$



Stability of magnetized disks models of Shu (2006)

Formation of giant planets via gravitational instability in magnetized disks.

- $Q_M < 1; \lambda > 1$
- *Short cooling times:* $\Omega_K \tau_{cool} \leq 3$ *Gammie (2001)*
- *Get rid of the magnetic flux:*

$Q_M < 1; \lambda > 1$

$$\tau_{diff} \sim \frac{l^2}{\eta} \leq \tau_{cool} \Rightarrow \eta > 2.5 \times 10^{18}\, cm^2 s^{-1}$$

These coupled constraints make it more difficult to form planets this way and limit their formation to take place at large radii.

l^2

Summary

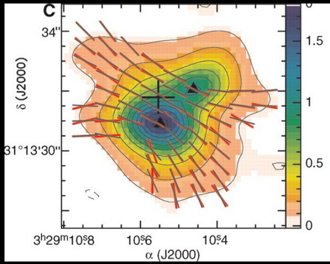
- *Magnetic fields are observed in molecular clouds and it is difficult to get rid of them.*
- *Magnetic field dissipation is needed to avoid catastrophic braking and form disks and normal stars.*
- *B fields dragged in the disks produce sub-Keplerian rotation which affects the ejection of winds and planet migration.*
- *B fields increase disk stability => more difficult to form giant planets via grav. instability.*

ALMA will be able to measure B and rotation curves with unprecedent spatial resolution and test these theories.

- *Measure the mass-to-flux ratio of dense cores as a function of radius (Zeeman CN @ 3mm).* *
- *Measure rotation in cores (magnetic braking).*
- *Measure disk rotation curves and stellar mass independently: magnetized disks should be sub-Keplerian; also magnetic support increases with system age.*

[B estimated from C-F method or polarization-intensity gradient method (Koch et al. 2012)].*

NGC 1333 IRAS4



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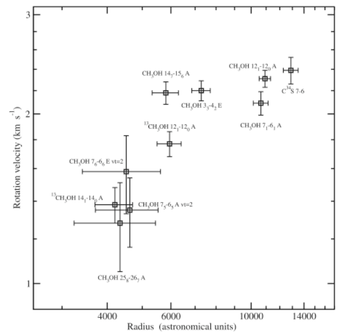

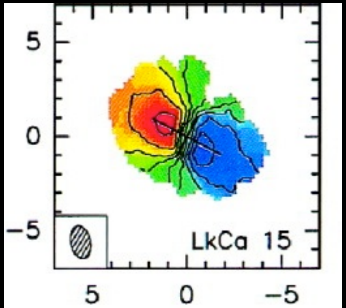

ALMA can test if magnetic fields are dynamically important for star and planet formation.

Thank you!