The Earliest Stages of Star and Planet Formation: Core Collapse, and the *Formation of Disks* and Outflows

Zhi-Yun Li (Virginia)
Robi Banerjee (Hamburg)
Ralph Pudritz (McMaster)
Jes Jorgensen (Copenhagen)
Sienny Shang (ASIAA)
Ruben Krasnopolsky (ASIAA)
Anaelle Maury (CfA)

Outline

I. Difficulty with disk formation in ideal MHD limit

magnetic fields in dense cores; magnetic flux freezing; magnetic split monopole; excessive magnetic braking

II. Can non-ideal MHD effects save disk in 2D?

ambipolar diffusion; Ohmic dissipation; Hall effect

III. Can 3D effects save the disk?

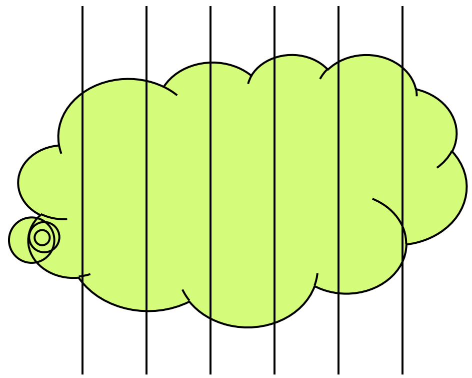
magnetic interchange instability in inner protostellar accretion flow

IV. How to form rotationally supported disks?

review proposed mechanisms and some speculations

I. Difficulty with disk formation in the ideal MHD limit

• Dynamical importance of the magnetic field measured by the mass-to-flux ratio



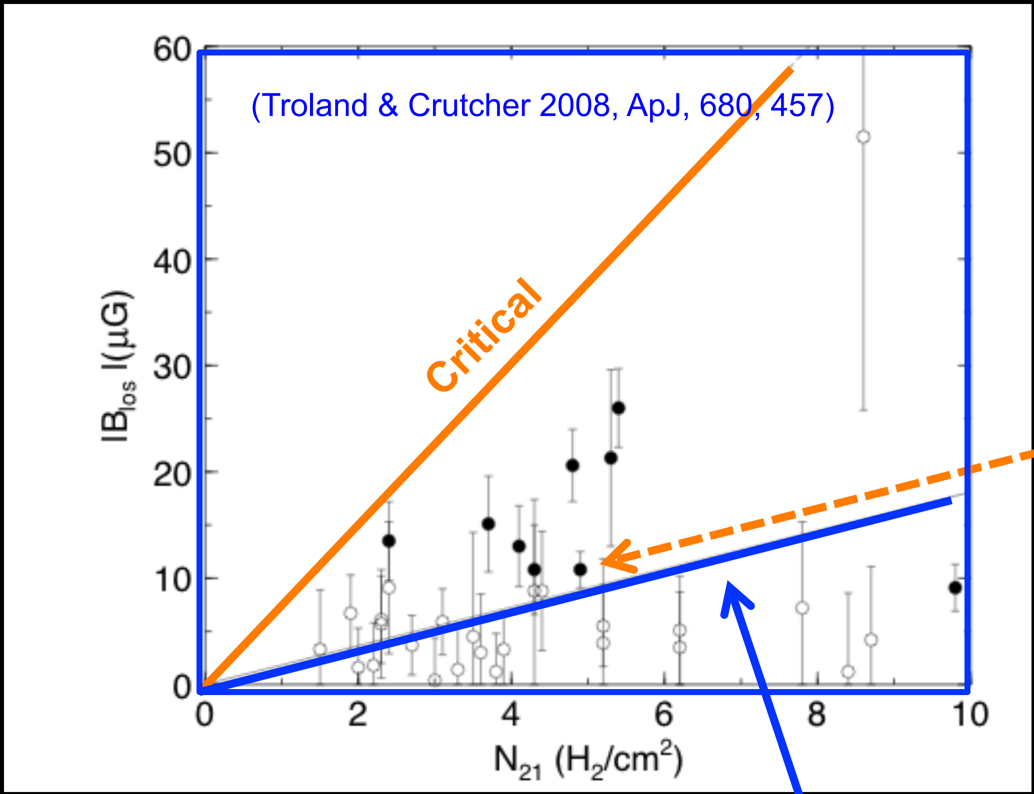
$$\lambda = \frac{\left(\frac{M}{\Phi}\right)}{\left(\frac{1}{2\pi G^{1/2}}\right)} = \frac{\left(\frac{\Sigma}{B}\right)}{\left(\frac{1}{2\pi G^{1/2}}\right)}$$

(Nakano & Nakamura 1978, PASJ, 30, 671)

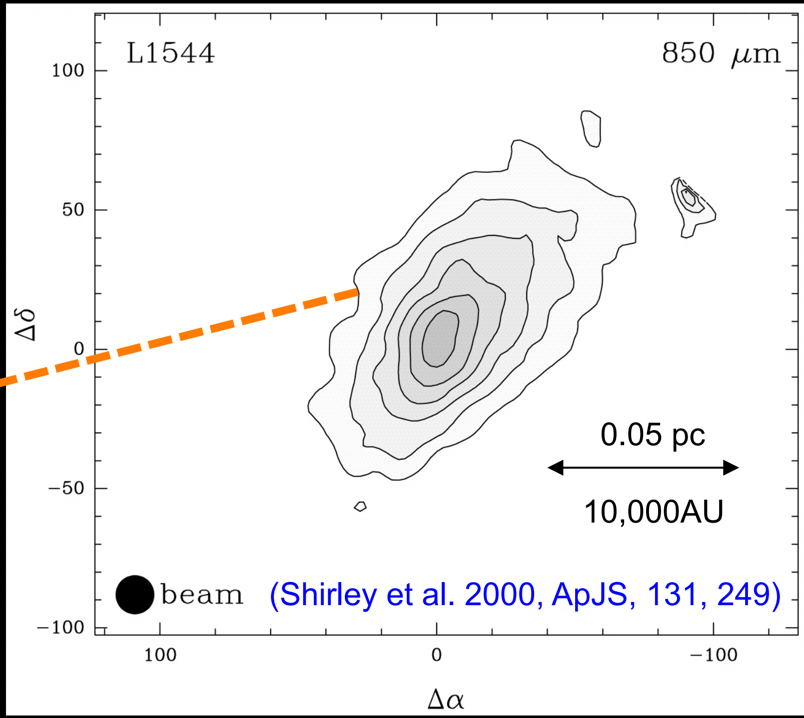
(Can the magnetic field support a core against the gravity?)

• Supercritical if λ > 1, subcritical if λ < 1 (larger λ, weaker B field)

Magnetic Field Strength in Cores: Observations



Prestellar core L1544



OH Zeeman survey of dark cloud cores using Arecibo telescope (Troland & Crutcher 2008)

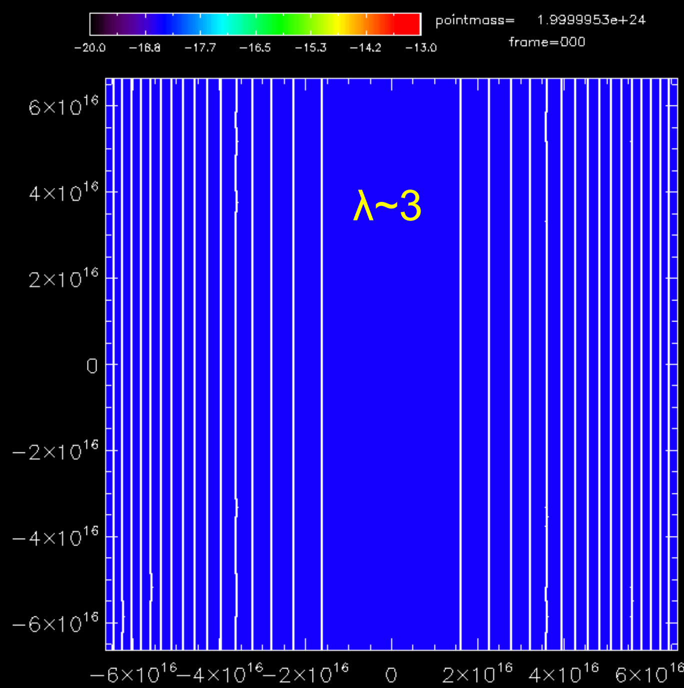
mean mass-to-flux ratio $\lambda_{core,los} \approx 4.8 \pm 0.4$ without geometric corrections

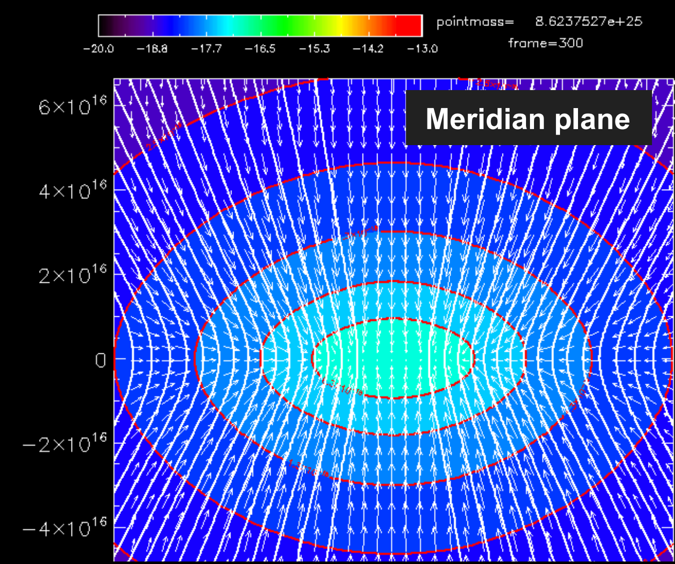
Geometric corrections reduce the ratio by a factor of 2-3, to $\lambda \sim 2$

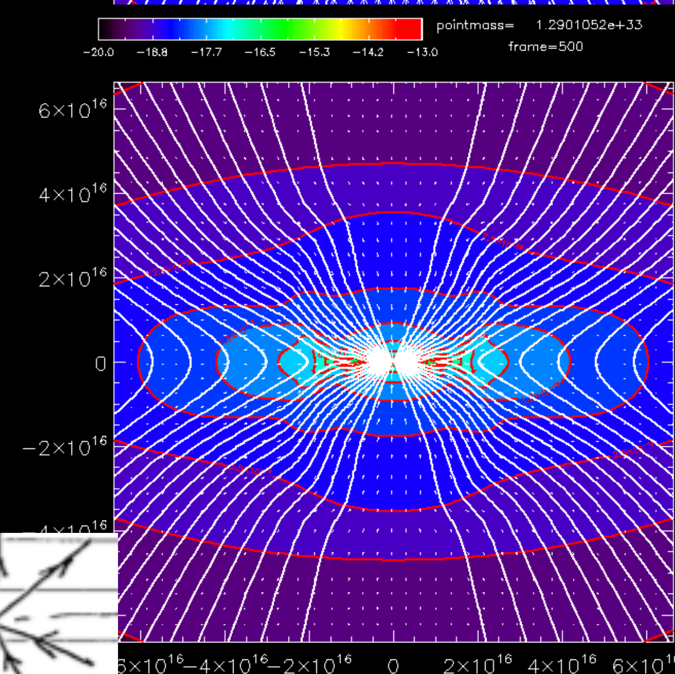
(magnetic/gravitational ~λ^{-2} ~ tens of percent >> rotational/gravitational ~ a few%)

Not strong enough to prevent collapse, but strong enough to affect disk formation

Magnetic core collapse in ideal MHD: split monopole





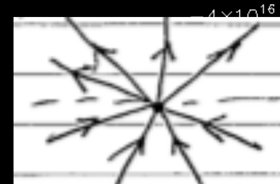


Collapse of 1 $M_{\odot}$ core w/ uniform B, no Ω

Flux freezing during collapse (pinched B)

Flattened mass distribution (pseudodisk)
(Galli & Shu 1993, ApJ, 417, 243)

Split magnetic monopole near origin
(making disk formation difficult)



Magnetic braking catastrophe in ideal MHD limit

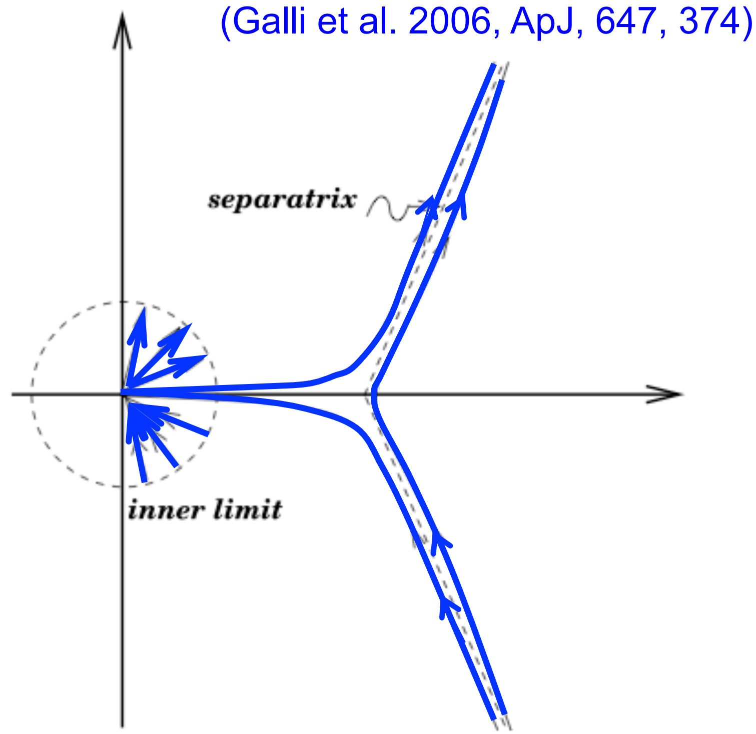


FIG. 1.—Geometry of the magnetic field in a collapsing magnetized cloud. The separatrix (dashed curve) separates field lines that have been pulled into an accreting protostar (at the origin of the coordinate system) from field lines tied to matter in the infalling envelope. A dashed circle indicates the inner region with nondimensional radius $x \ll 1$ studied in this paper, where magnetic field lines are asymptotically radial.

- Flow dynamics near split monopole

  $B_r \sim r^{-2}$, $v_r \sim v_{ff} \sim r^{-1/2}$, $\rho \sim \rho_{ff} \sim r^{-3/2}$

- Magnetic energy density

  $B^2 \sim r^{-4}$

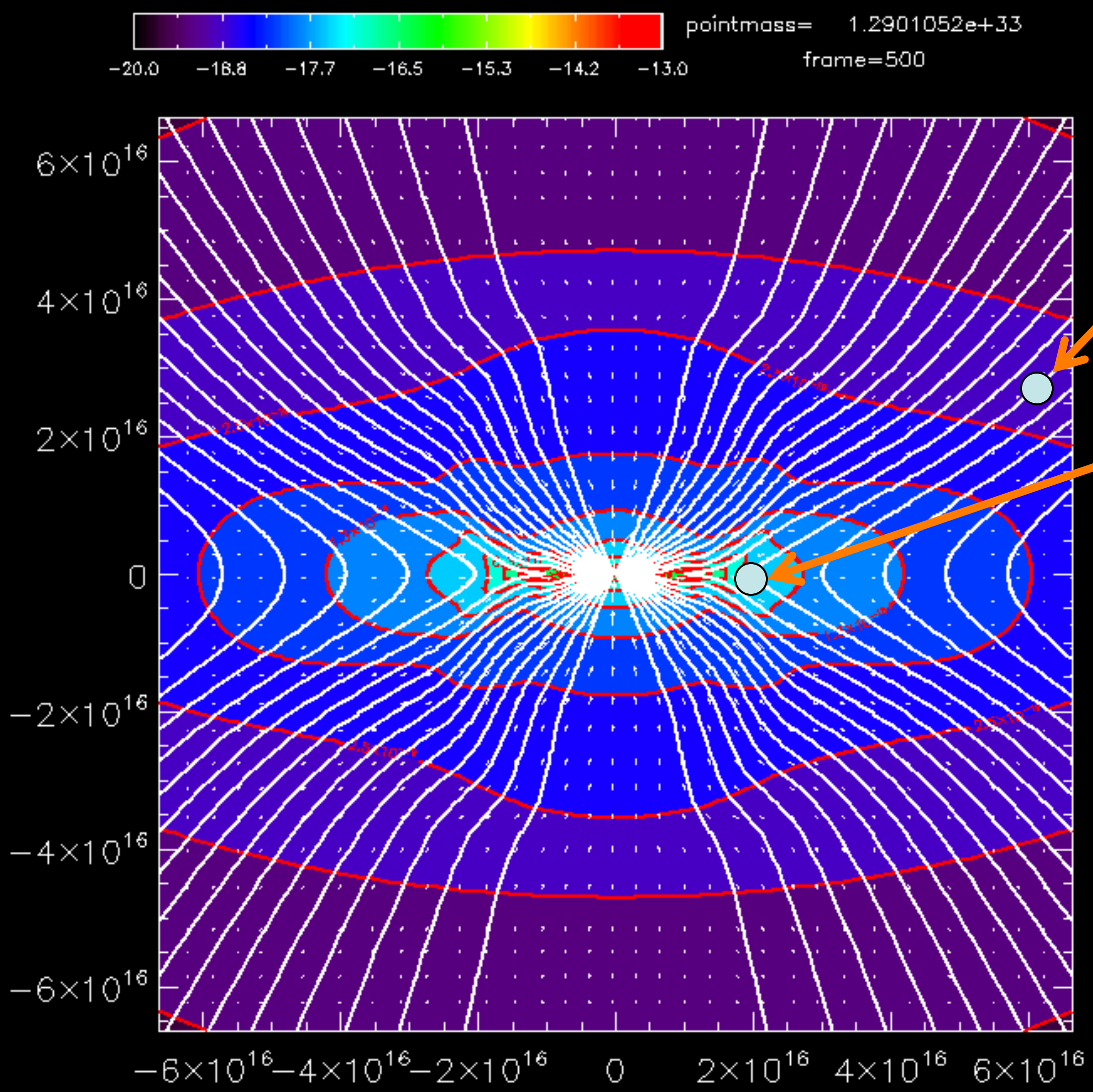
- Flow energy density

  $\rho\, v^2 \sim r^{-5/2}$

- Flow completely magnetically dominated as $r \rightarrow 0$

  $v_\varphi \rightarrow 0$ as $r \rightarrow 0$ (no RSD)

Magnetic Braking & Disk Formation

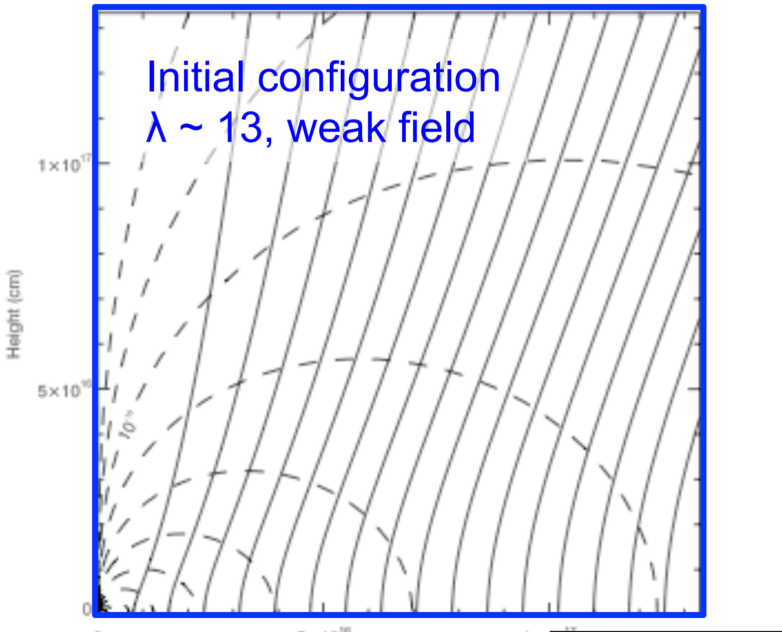


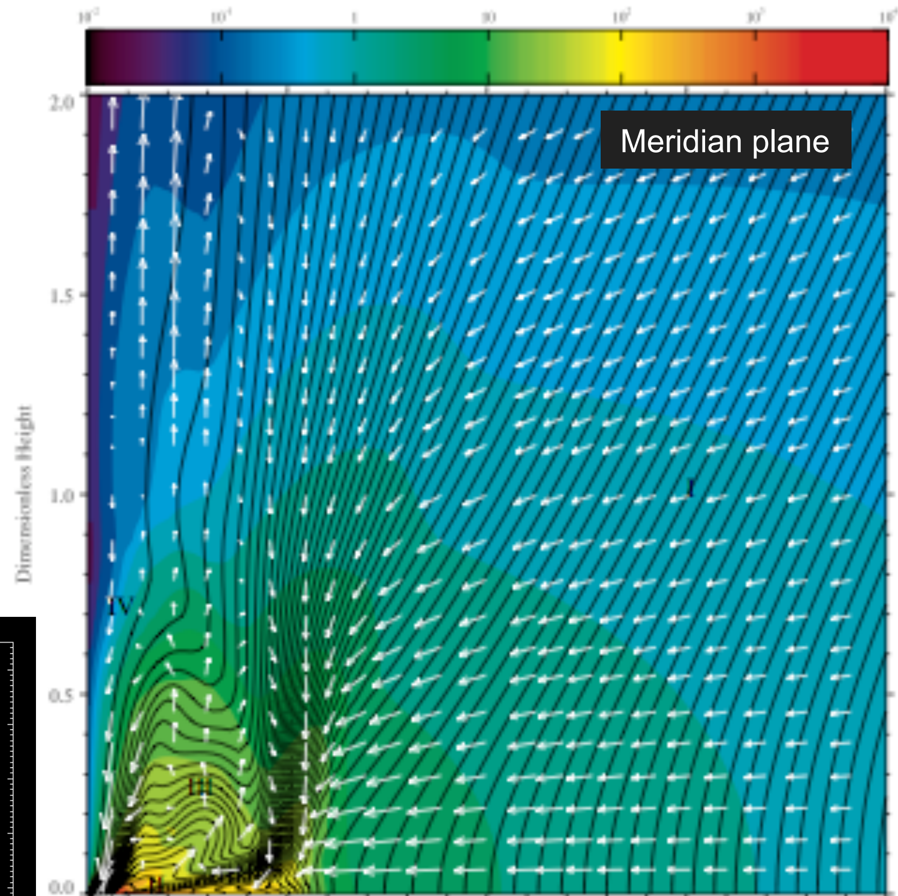
Slower rotation

Faster rotation

- Differential twist of field lines generates a toroidal magnetic field
- Magnetic tension of twisted field yields a braking torque on the faster rotating, inner material
- Braking rate ~ B_p x $B\varphi$
- Stronger field, harder to form disk

Magnetic braking catastrophe in ideal MHD: 2D numerical example with ZeusMP (Mellon & Li 2008, ApJ, 681, 1356)





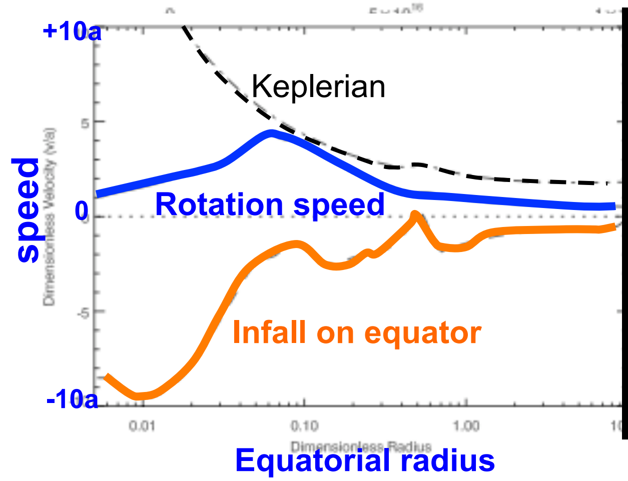
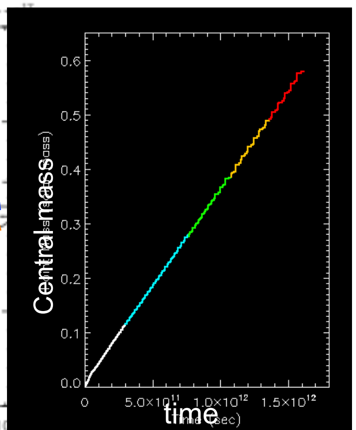


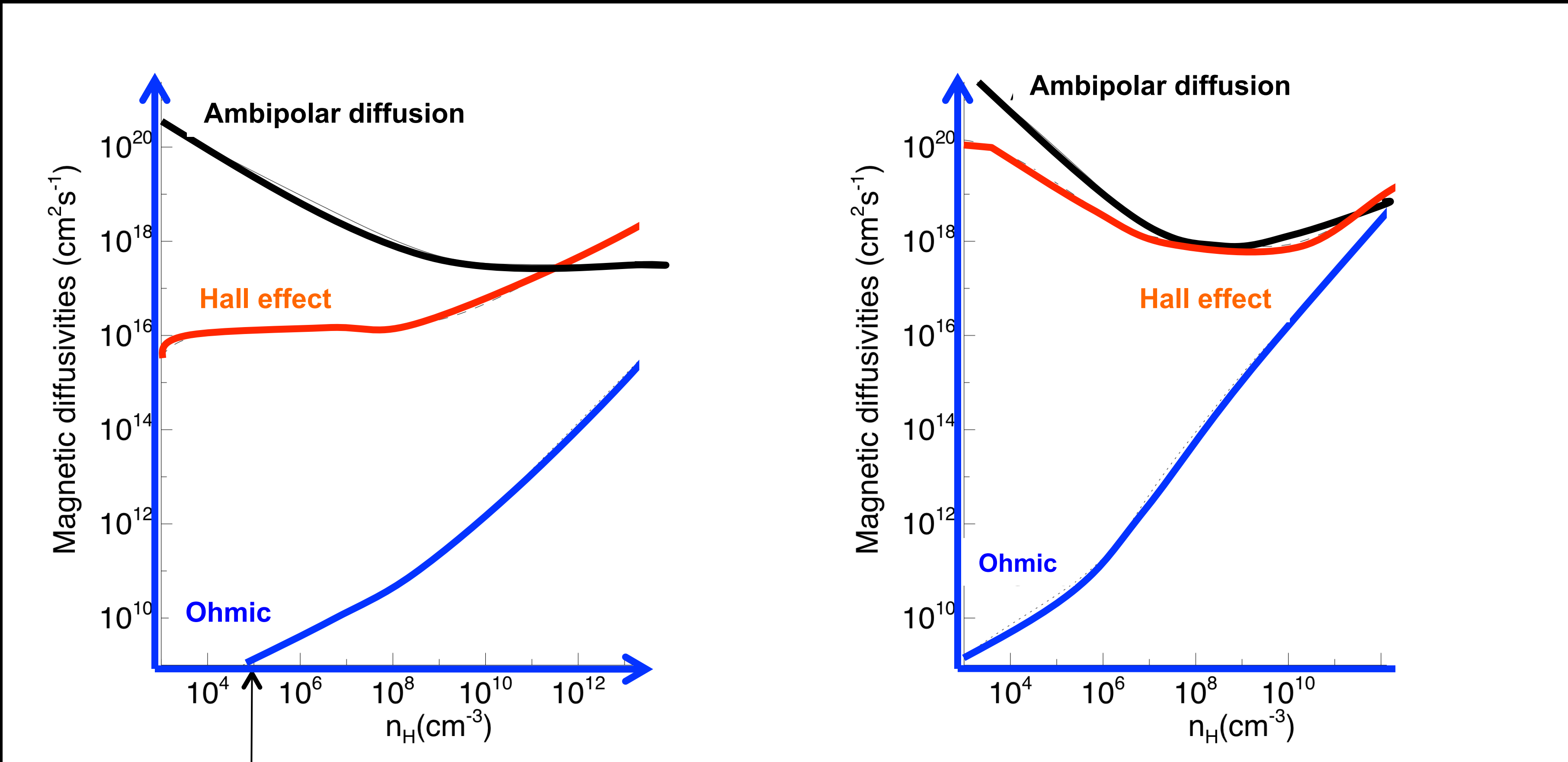
FIG. 4.—Velocity distribution of the standard model on the equator. Plotted are the radial (*dashed line*) and rotational (*solid line*) speeds of the fluid, and the rotation speed needed for support against gravity (*dot-dashed line*).



(see also, e.g., Allen et al. 2003, Machida et al. 2005, Banerjee & Pudritz 2006, Price & Bate 2007, Hennebelle & Fromang 2008, Duffin & Pudritz 2009, Seifried et al. 2012, Santos-Lima et al. 2012)

➡ Disk formation suppressed for λ ~ a few in ideal MHD aka “magnetic braking catastrophe”

II. Can non-ideal MHD effects save the disk in 2D? (Li, Krasnopolsky & Shang 2011, ApJ, 738, 180)



Typical core density

Large grain size: 1 μm

AD dominates over most densities

Power-law size distribution w/ small grains (MRN) (Mathis, Rumpl & Nordsieck 77)

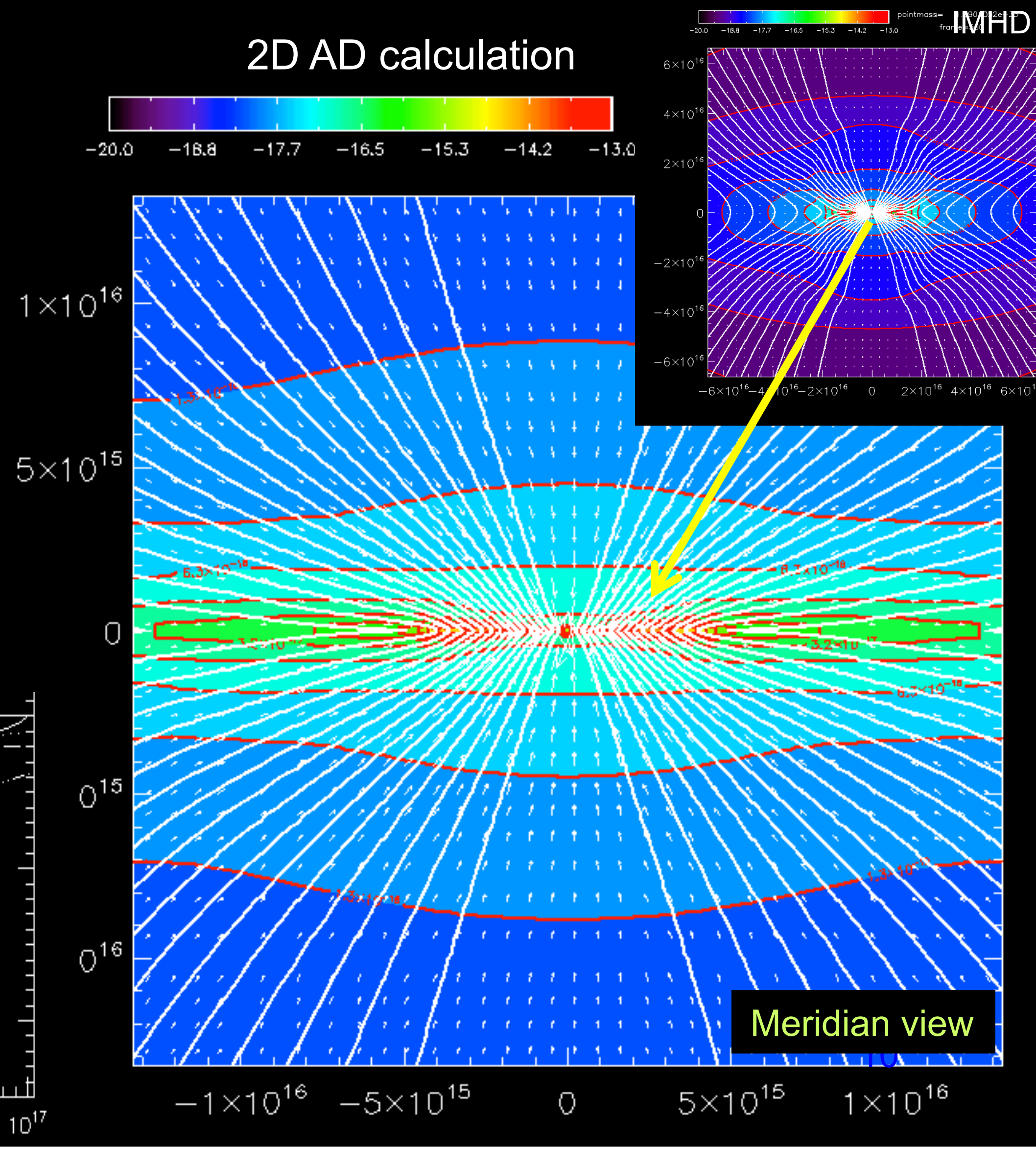
Smaller grain, Hall more important

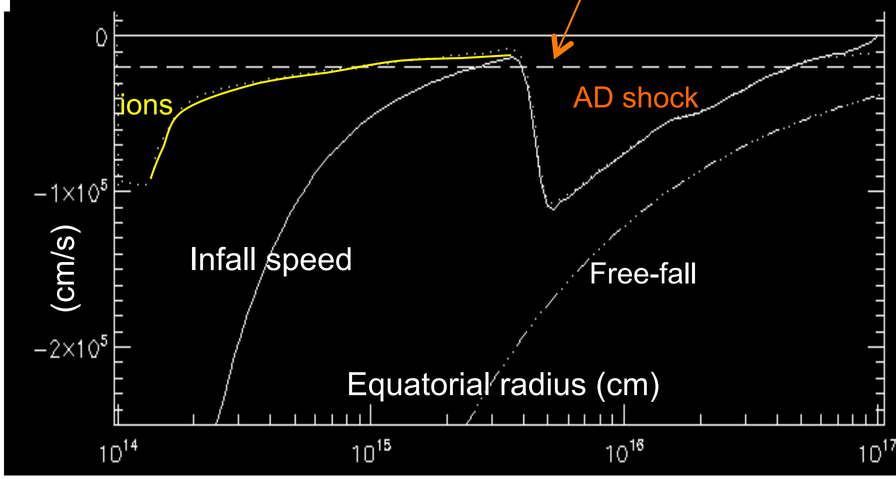
Ambipolar diffusion & magnetic flux redistribution

(Li, Krasnopolsky & Shang 2011, ApJ, 738, 180)

- 2D (axisymmetric) collapse of initially uniform, λ=2.9 non-rotating core, with only AD (including MRN grains), in spherical coordinate system using ZEUS–TW

- Magnetic flux piles up outside star (high magnetic pressure, slowing down collapse) (Li & McKee 1996, also Ciolek & Konigl 1998, Krasnopolsky & Kronigl 2002, Tassis & Mouschovias 2007)

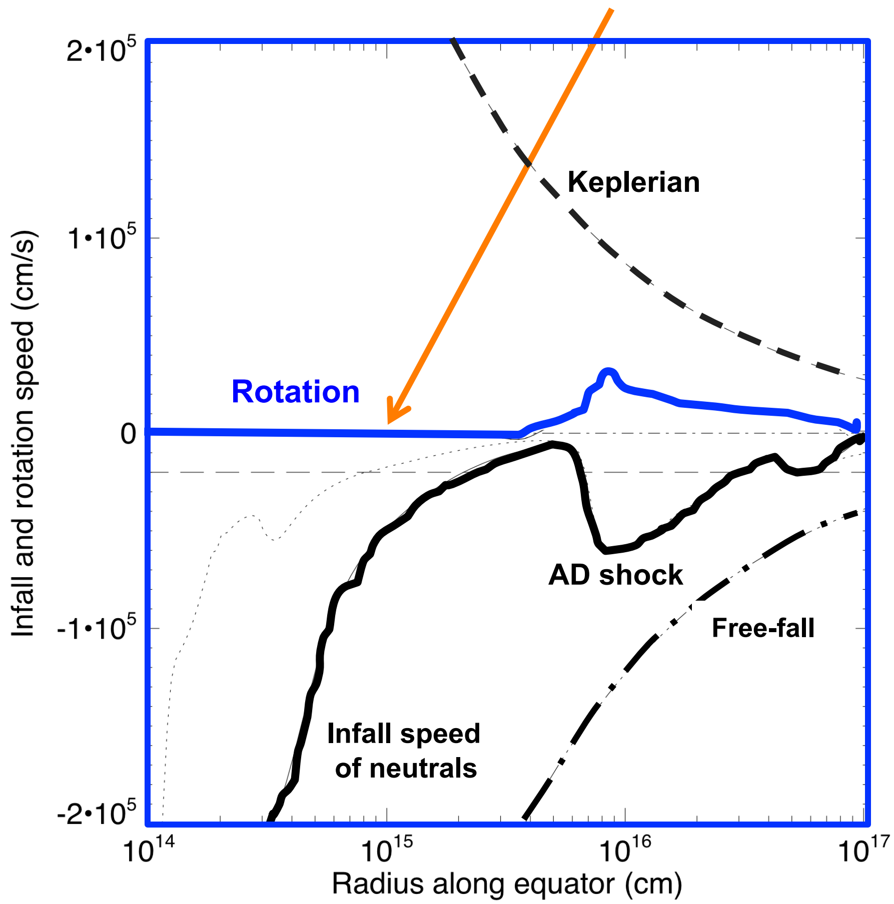


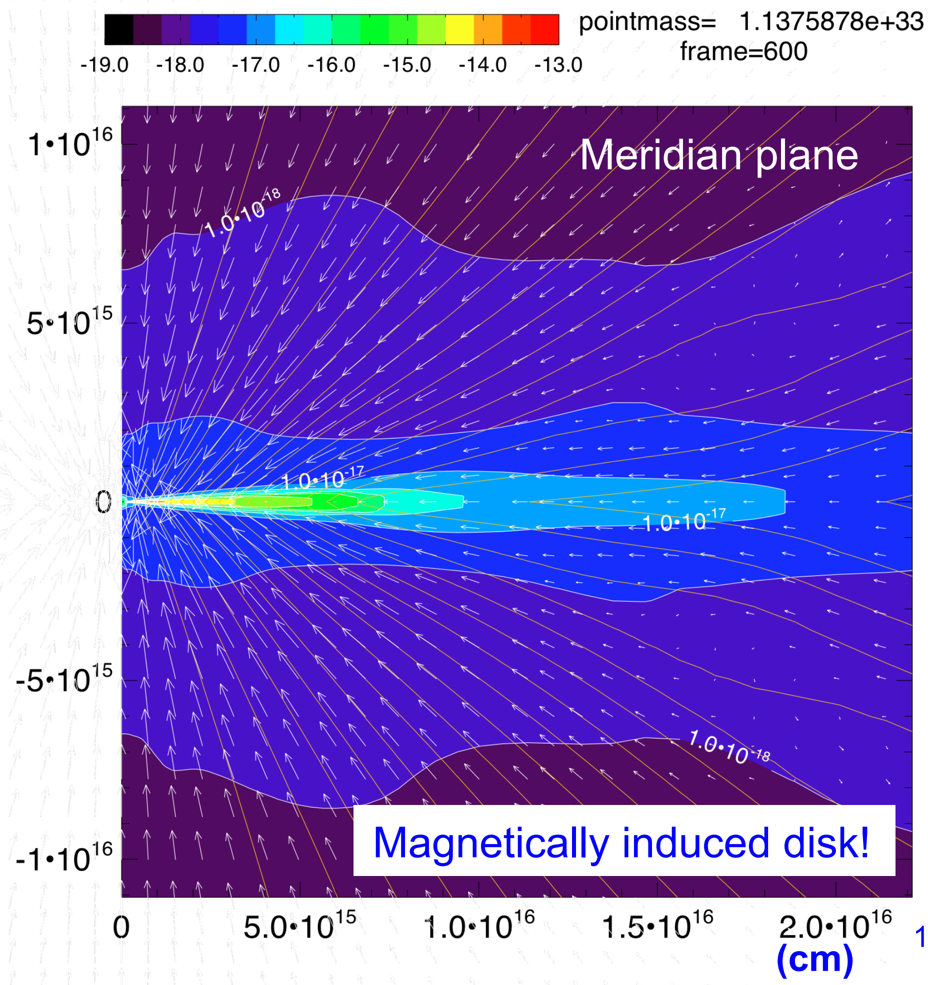


Can ambipolar diffusion save the *rotationally supported* disk (RSD)?

• No! No rotationally supported disk (see also Krasnopolsky & Konigl 2002, ApJ, 580, 987)

Almost complete braking of rotation





Can ambipolar diffusion, Ohmic dissipation & Hall effect save the *rotationally supported* disk (RSD)?

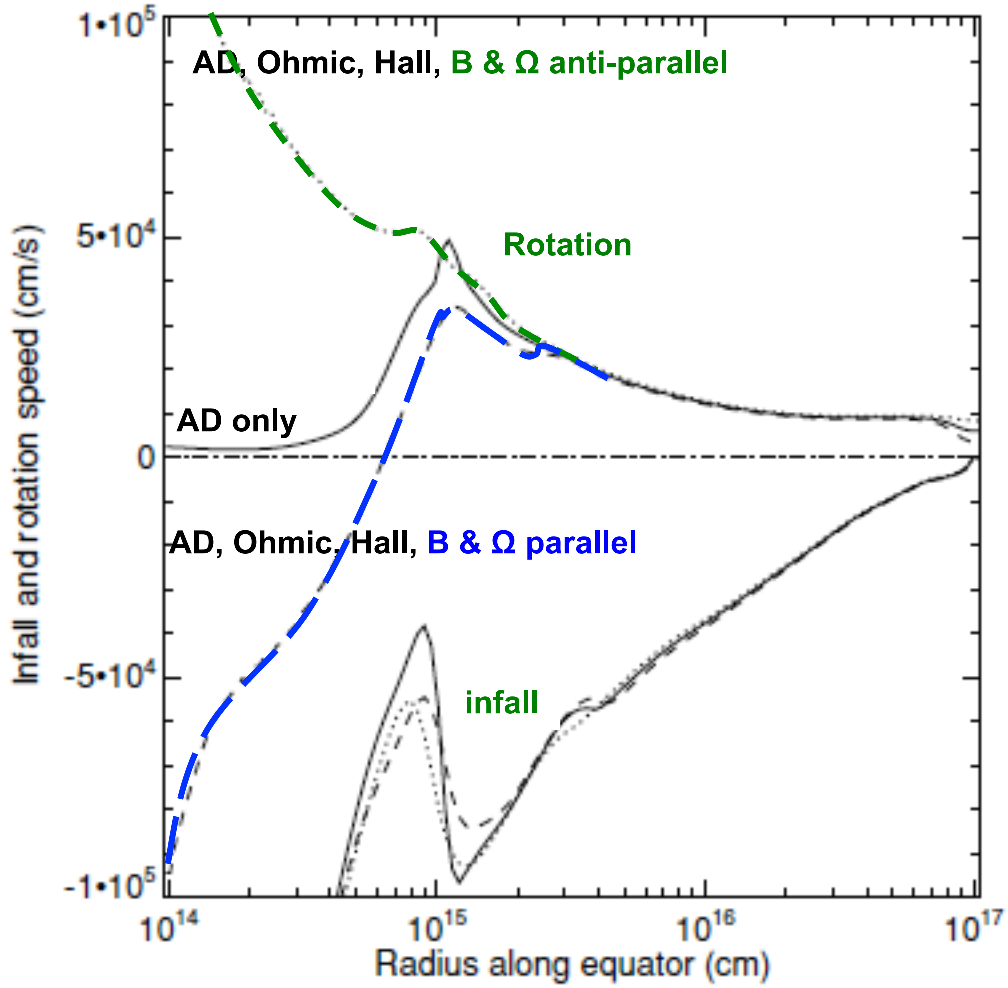
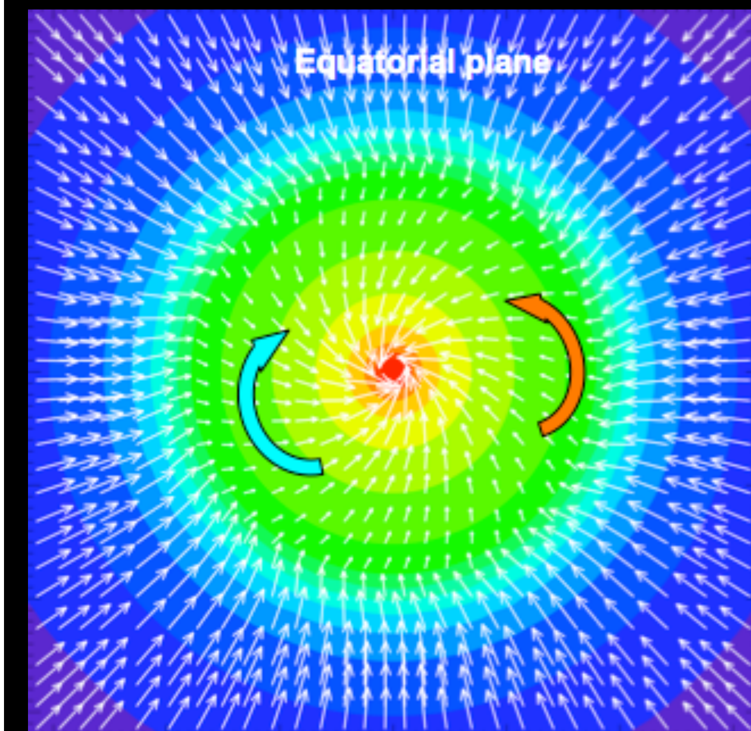


Figure 12. Infall and rotation speeds along the equator for two models of opposite initial magnetic orientation, Model $\mathrm{REF}^{+}_{\mathrm{AHO}}$ (dashed lines) and Model $\mathrm{REF}^{-}_{\mathrm{AHO}}$ (dotted), at $t = 4.55 \times 10^{12}$ s. The reference model (solid) without the Hall effect is also plotted for comparison.

Hall spin-up (Wardle & Ng 1999)



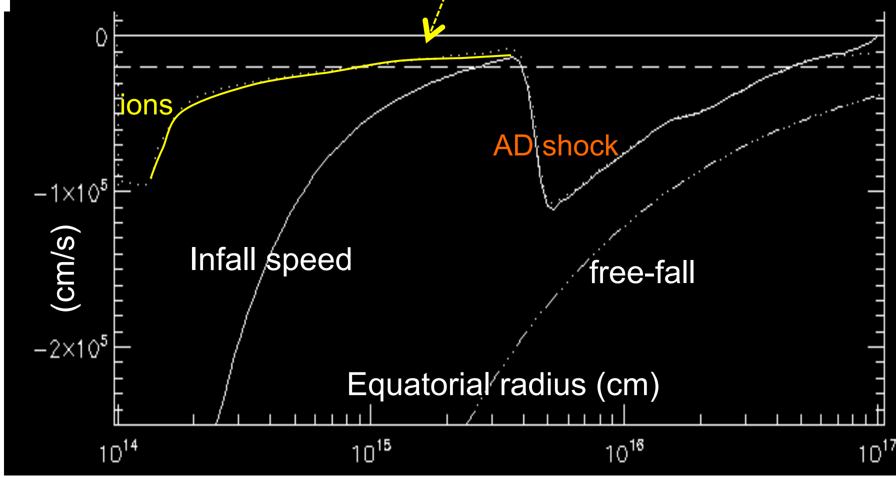
➡ unable to save disks, at least in 2D

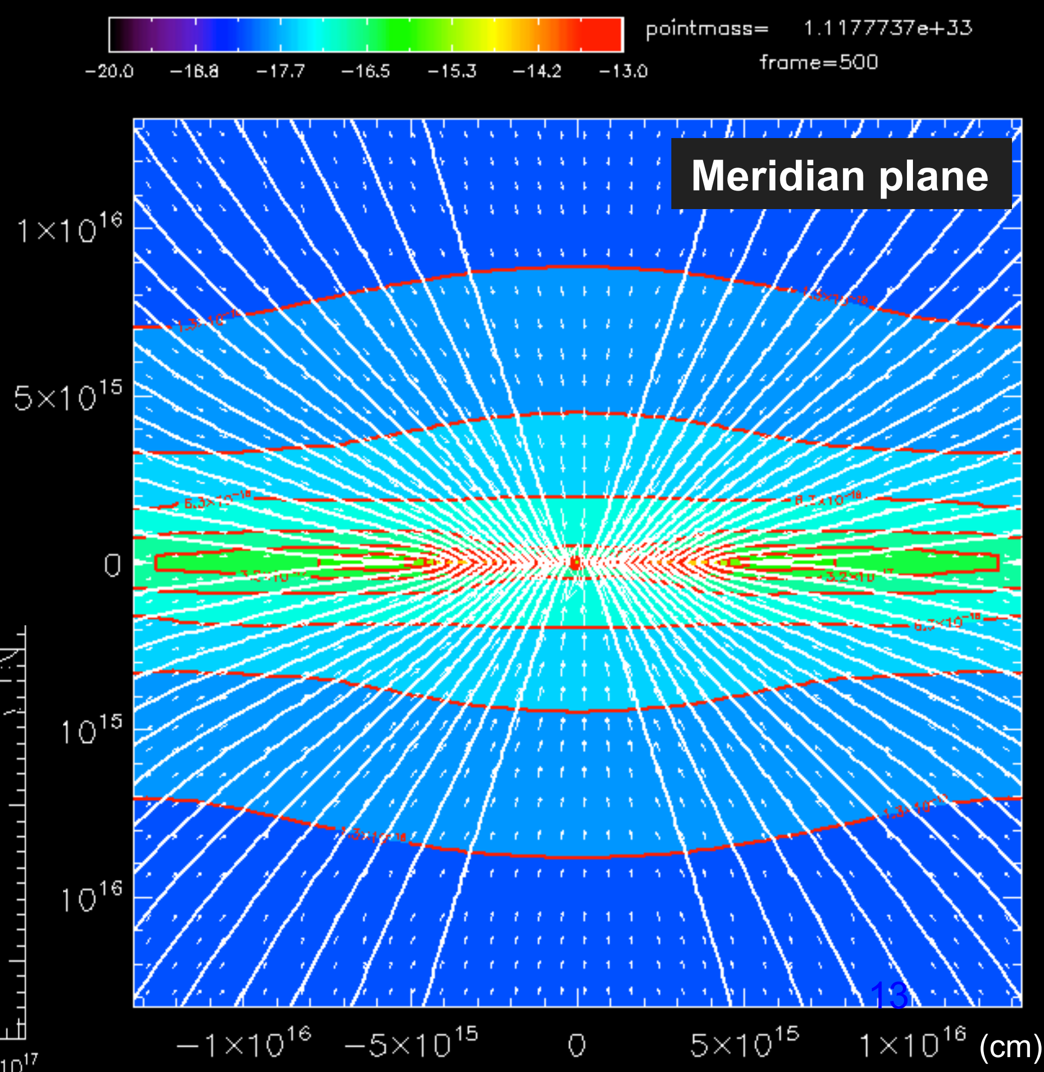
III. Can 3D effects save the disk?

2D accretion flows expected to be unstable

- Magnetically supported post-AD shock region expected to be unstable to magnetic interchange instability (Li & McKee 1996, Krasnopolsky & Konigl 2002)

- What happens in 3D?



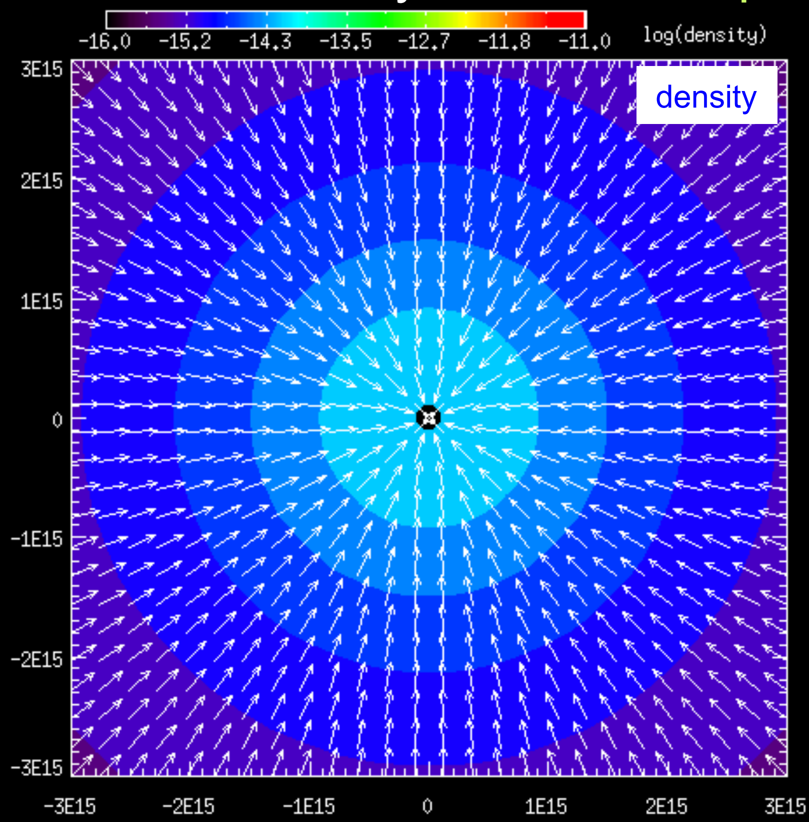


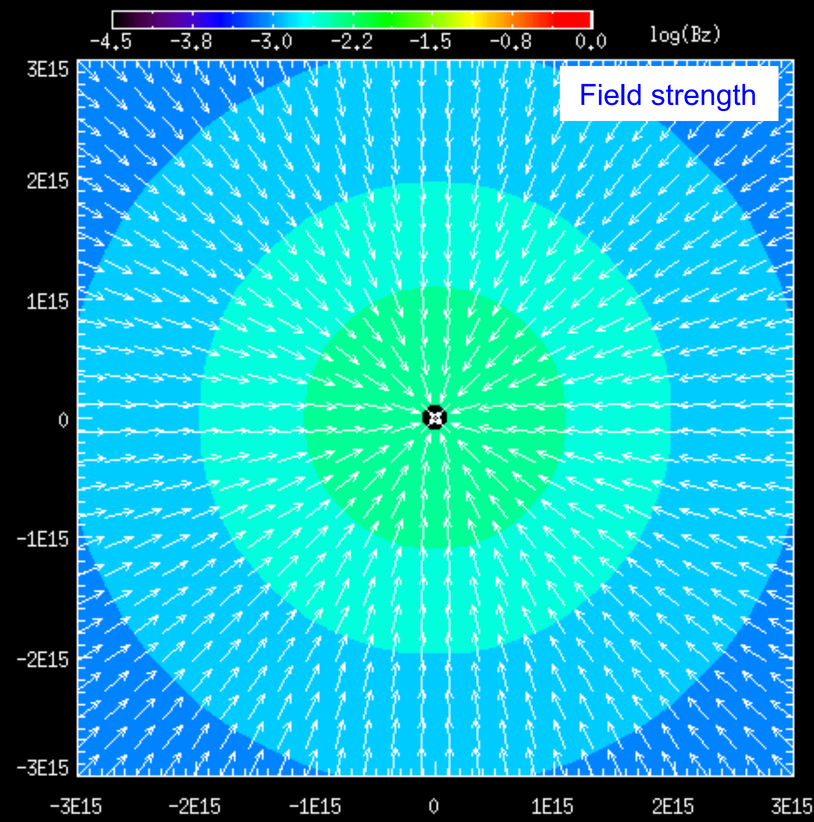
III. Can 3D effects save the disk?

(Krasnopolsky, Li, Shang & Zhao 2012, ApJ, 757, 77)

Non-rotating collapse in 3D with AD and localized Ohmic dissipation

- 3D collapse of initially uniform, non-rotating dense core of λ=2.9 (late times)
- Shown are density and Bz on equatorial plane, simulated with ZEUS-TW





•Instability driven by magnetic flux decoupled from matter going into the central object

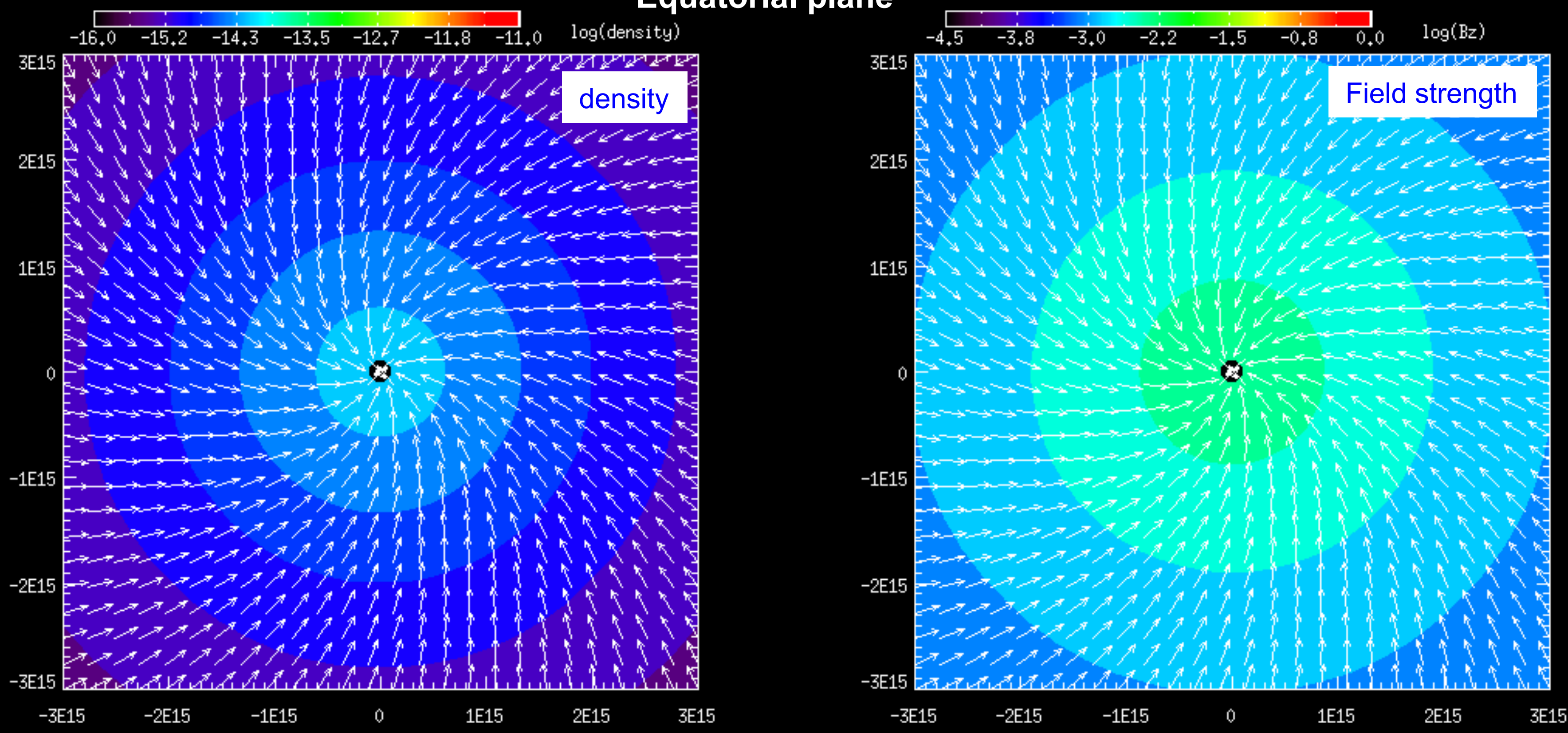
(also B. Zhao+2011, with ENZO AMR MHD code, Seifried+2011 with FLASH, & Cunningham+2012,Joos+2012 with RAMSES)

•Magnetically dominated circumstellar region, potentially making disk formation difficult

III. Can 3D effects save the disk?

Rotating collapse in 3D with AD and localized Ohmic dissipation

Equatorial plane



- Rotationally supported disk does not appear to form in 3D during the protostellar accretion phase
- Instability alleviated but not eliminated the obstacle to disk formation – strong circumstellar field

➡ 3D instabilities unable to save disks

IV. How to form rotationally supported disks (RSDs)?

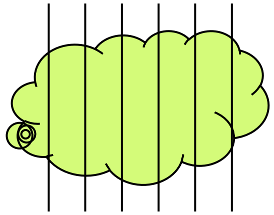
(1) Simplest resolution: most dense cores weakly magnetized?

unlikely for the following reason

Consider a uniform core of 1 M_{sun} and $n(H_2)=10^4 cm^{-3}$, radius=2.17×10^{17}cm

For a dimensionless mass-to-flux ratio of λ, the core field strength must be

$$B = \frac{2\pi G^{1/2} M}{\lambda\,(\pi r^2)} = 4.4\mu G \left(\frac{5}{\lambda}\right)$$



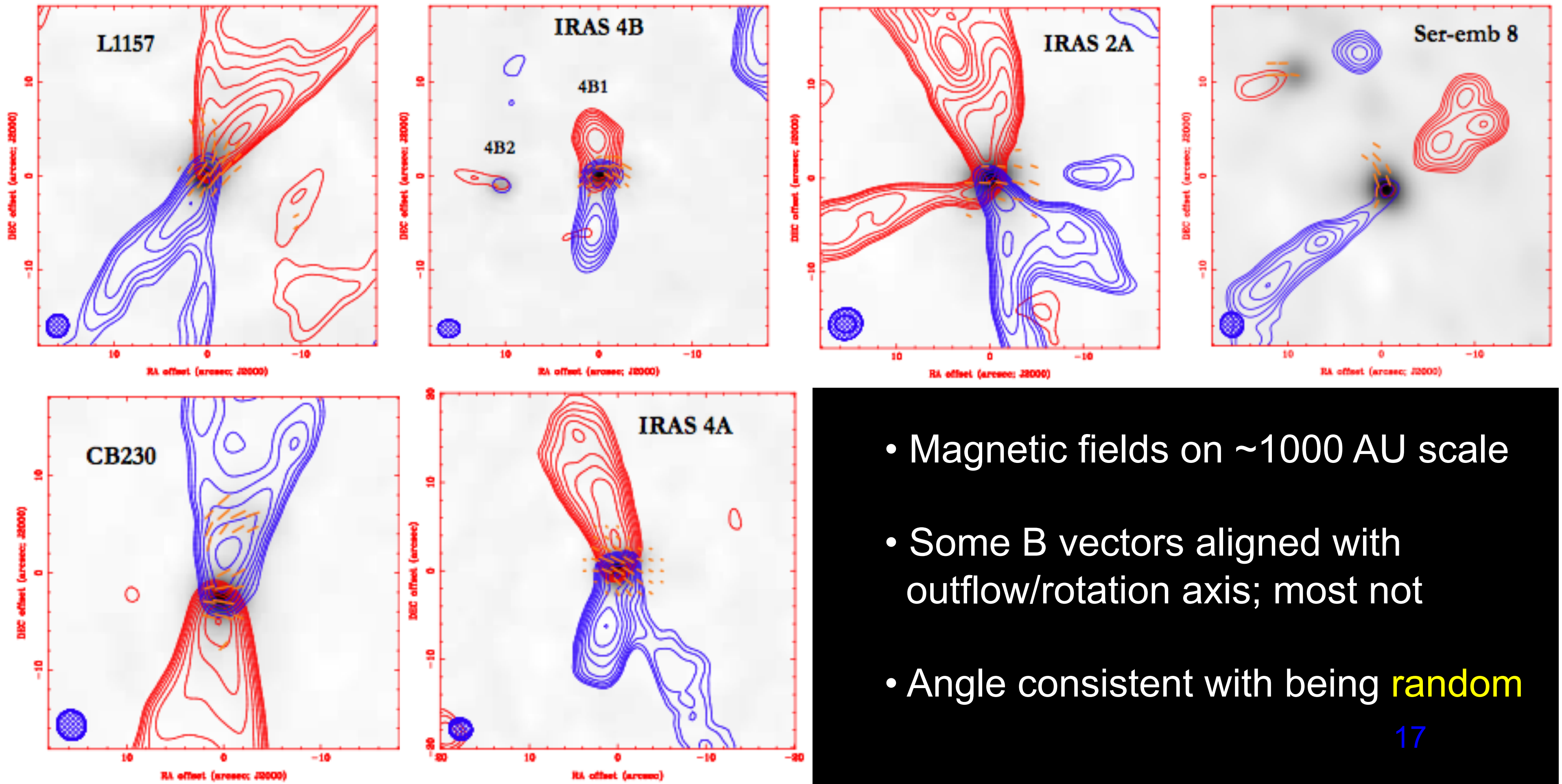
4.4μG is less than median field strength inferred for atomic CNM of ~6μG!
(Heiles & Troland 2005; see also Troland's results for B field of GMC envelope, ~10μG)

>> $\lambda_{core} \lesssim 5$ may be enough to make formation of large-scale rotationally supported disk difficult during protostelllar accretion phase

IV. How to form rotationally supported disks?

(2) Disk formation through misaligned rotation & magnetic axes?

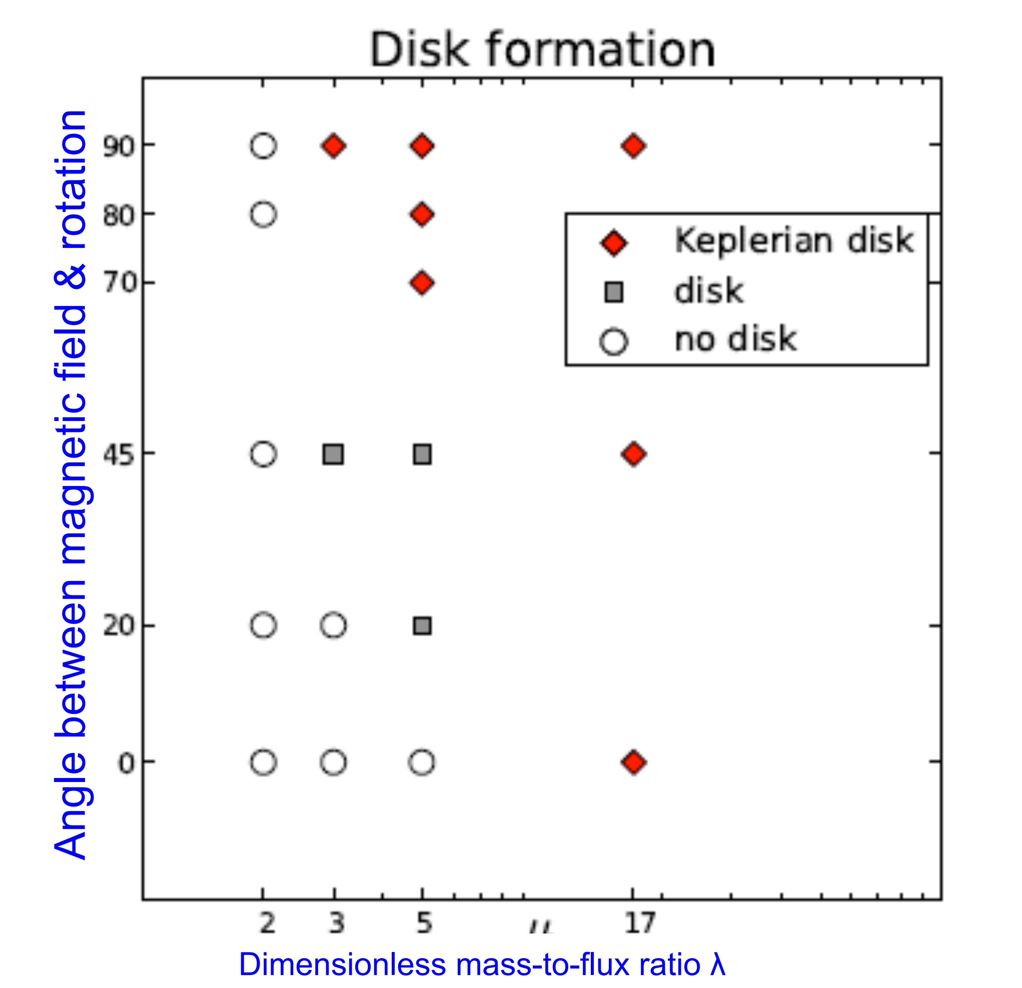
- Possible motivation: CARMA observations (Hull et al. 2013, 768, 159)



- Magnetic fields on ~1000 AU scale
- Some B vectors aligned with outflow/rotation axis; most not
- Angle consistent with being random

Can magnetic field-rotation axis mis-alignment enable large-scale disk formation?

- Joos, Hennebelle & Ciardi (2012, AA, 543, 128)



(also Price & Bate 2007; Hennebelle & Ciardi 2009)

- Disks form in weakly magnetized cores of λ~17 for all angles, but not for λ~2, median value inferred by Troland & Crutcher (2008)

- For intermediate cases of λ~3-5, large misalignment enables disk formation

Illustration: Li et al 2013, ApJ, in press, λ~14 (weak B), density map & velocity vectors on **equatorial** plane

Aligned case

Orthogonal case

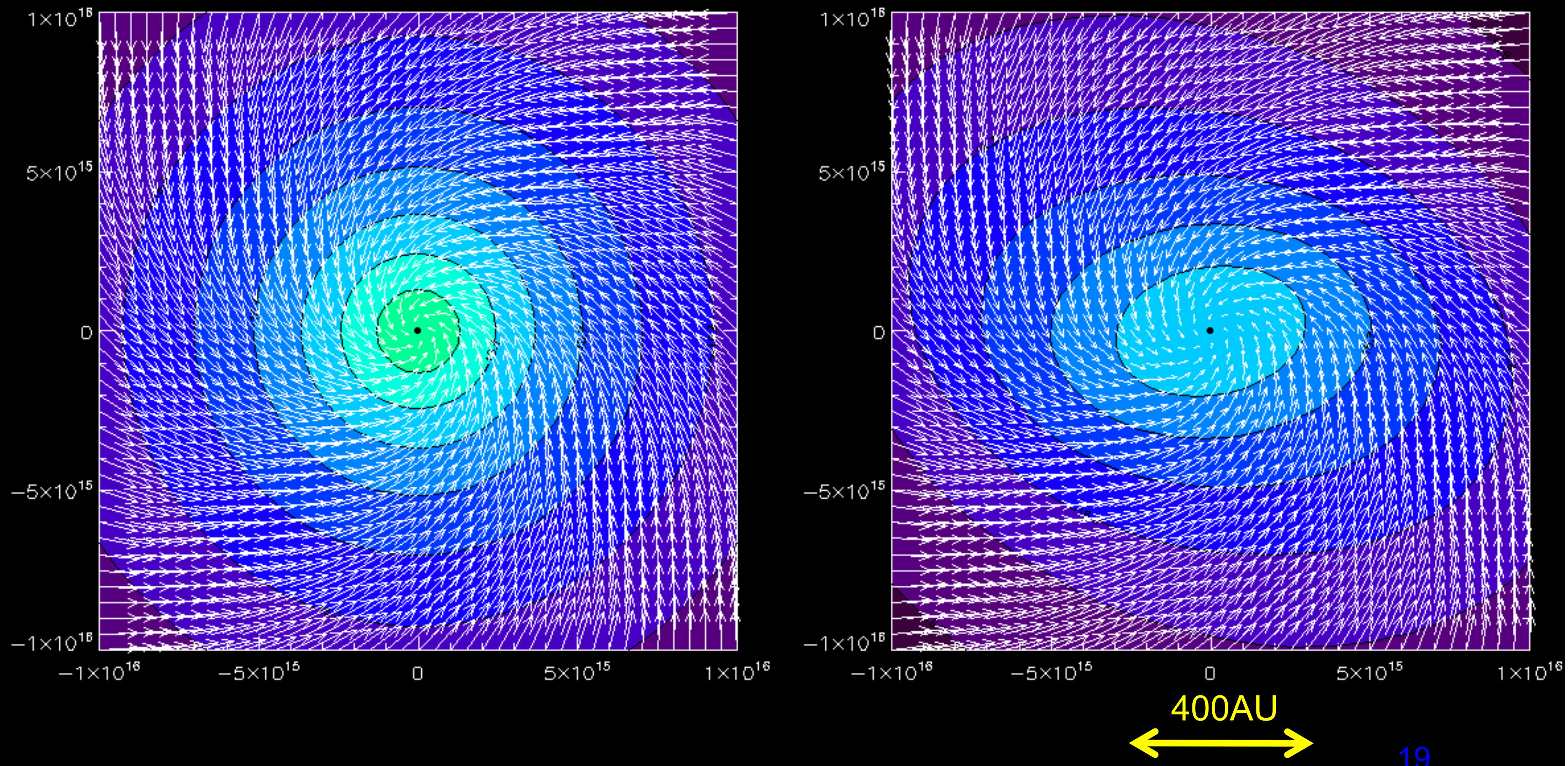
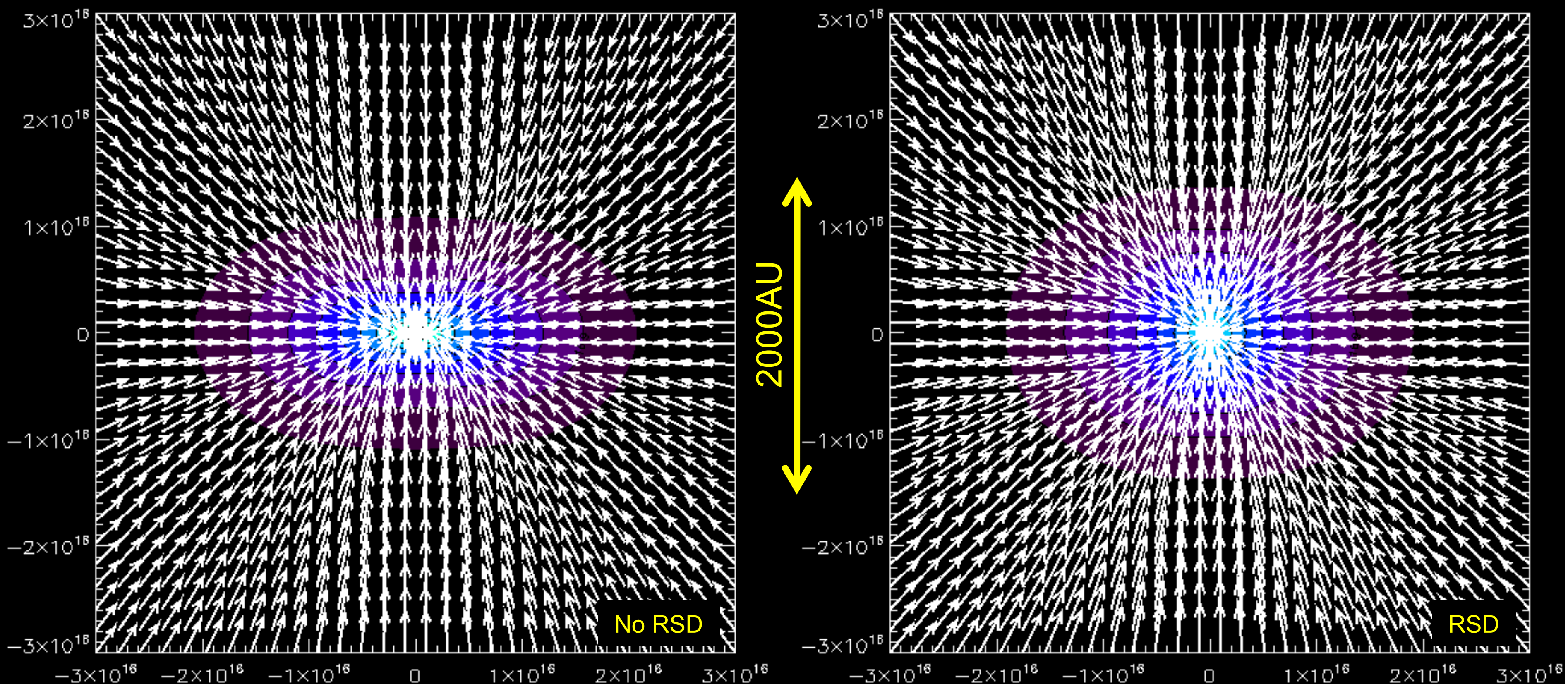


Illustration: Li et al 2013, ApJ, in press, λ~14 (weak B), density map & velocity vectors on a **meridian** plane

Aligned case

Orthogonal case

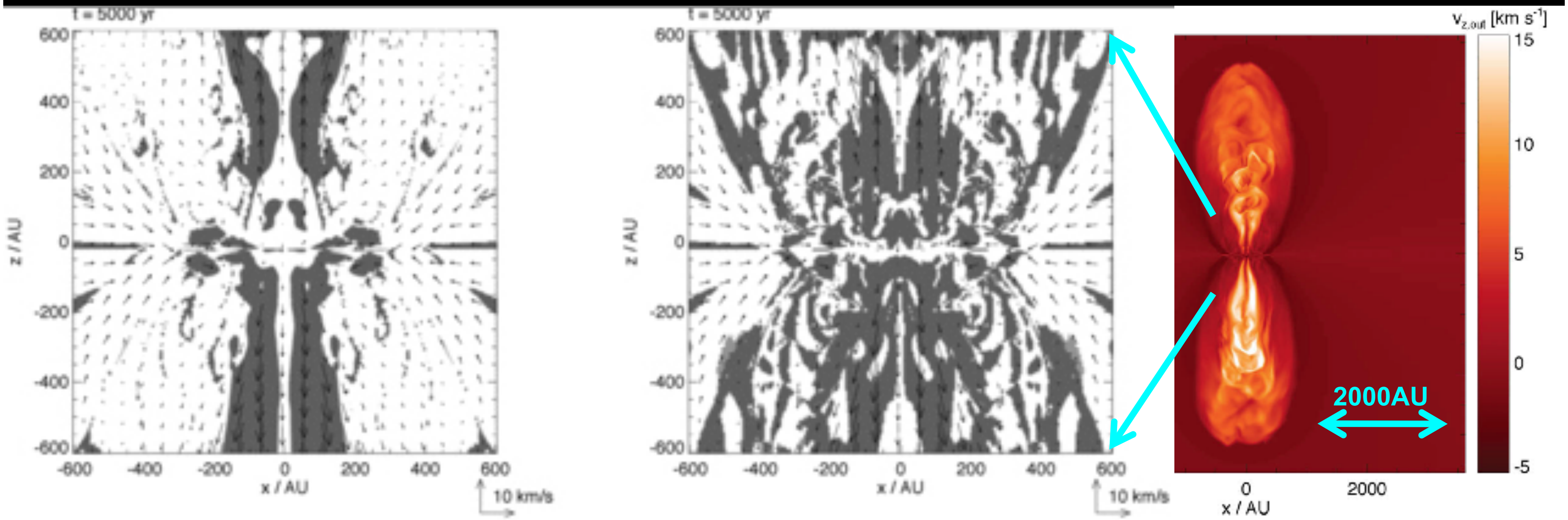


Outflow is a key difference! (see also Ciardi & Hennebelle 2010)

Early outflows in collapse simulations

(Tomisaka 1998, ApJL, 502, 163 & many later MHD simulations)

- Accelerated by a combination of centrifugal forces & magnetic pressure gradient (e.g., Seifried, Pudritz, Banerjee et al. 2012, MNRAS, 422, 347)



centrifugal acceleration

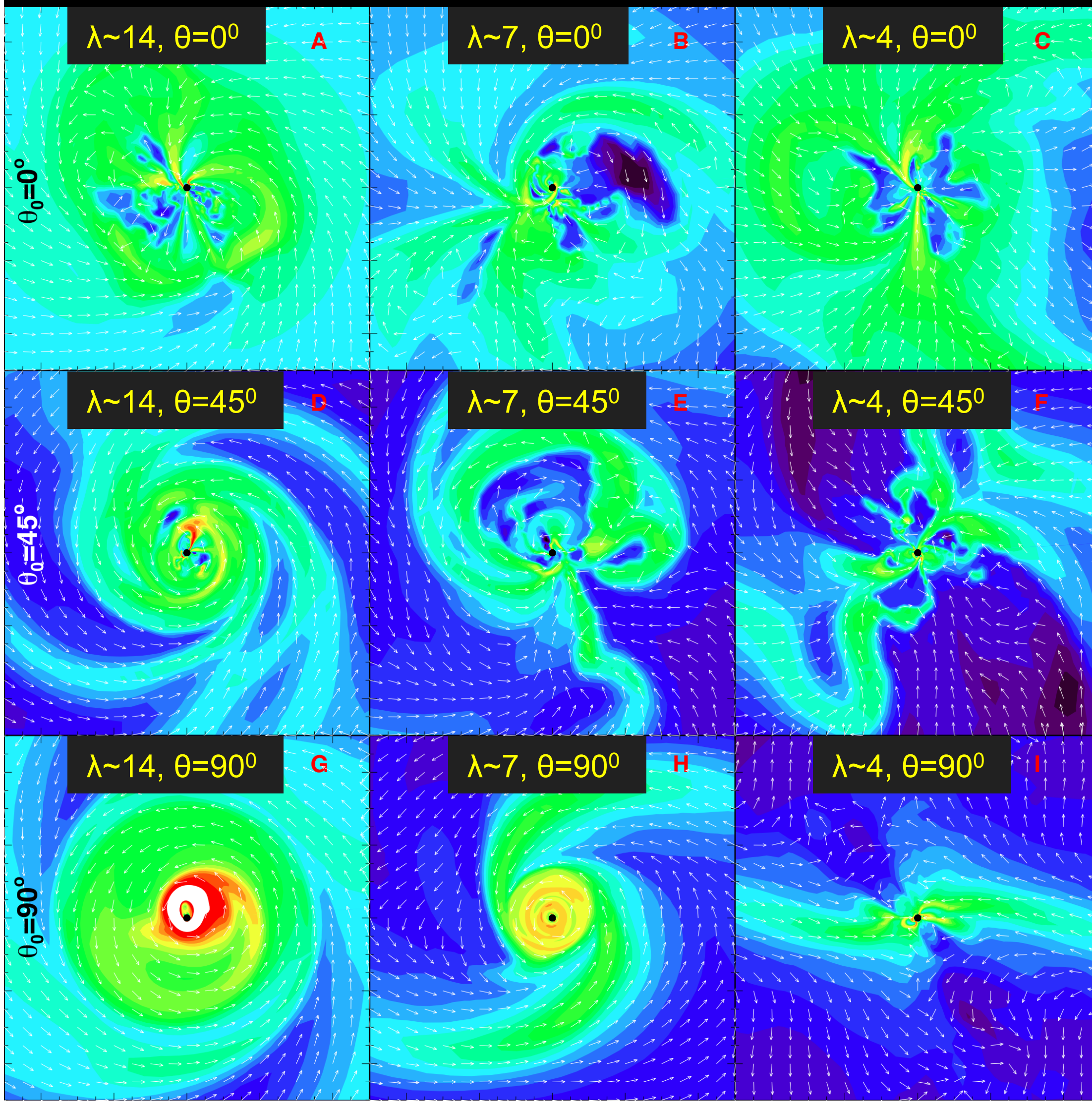
generalized acceleration criterion satisfied

(see Thursday's outflow talk by Cabrit)

IV. How to form rotationally supported disks (RSDs)?

(2) Disk formation through misaligned rotation & magnetic axes?

(Li, Krasnopolsky & Shang 2013, ApJ, in press)



- Yes, for weak-field cases of λ~14 and 7, where disk formation is enabled by large tilt, in broad agreement with Joos et al. (2012)

- No, for moderately strong-field case of λ~4 (B field two times weaker than inferred value), where there is NO disk even in the orthogonal case!

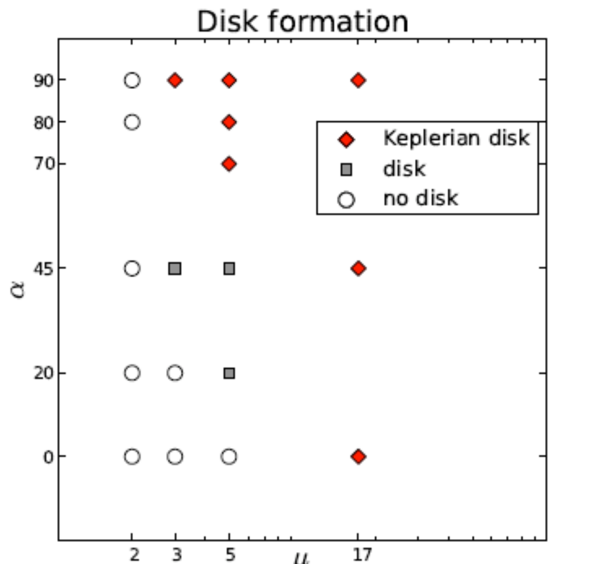
Dual requirement for large disks:

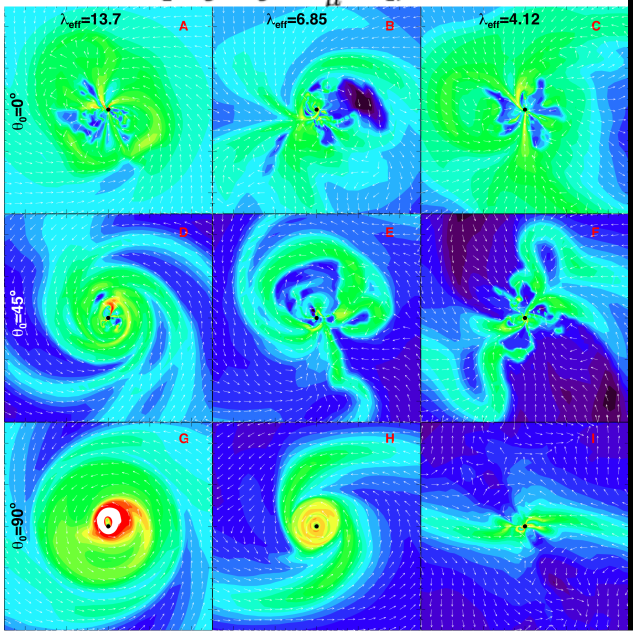
Rather weak B AND large misalignment

Unlikely for the majority of cores

Rough estimate of the fraction of dense cores with misalignment-enabled large-scale disks

(Krumholz et al. 2013, ApJL, 767, L11; Li et al. 2013, ApJ, in press)





- Median λ~2 for dense cores (Troland & Crutcher 2008)
- Half cores with λ>2, capable of disk formation for large

  misalignment according to Joos et al. 2012
- If misalignment random (Hull et al. 2013), half cores θ>60^0

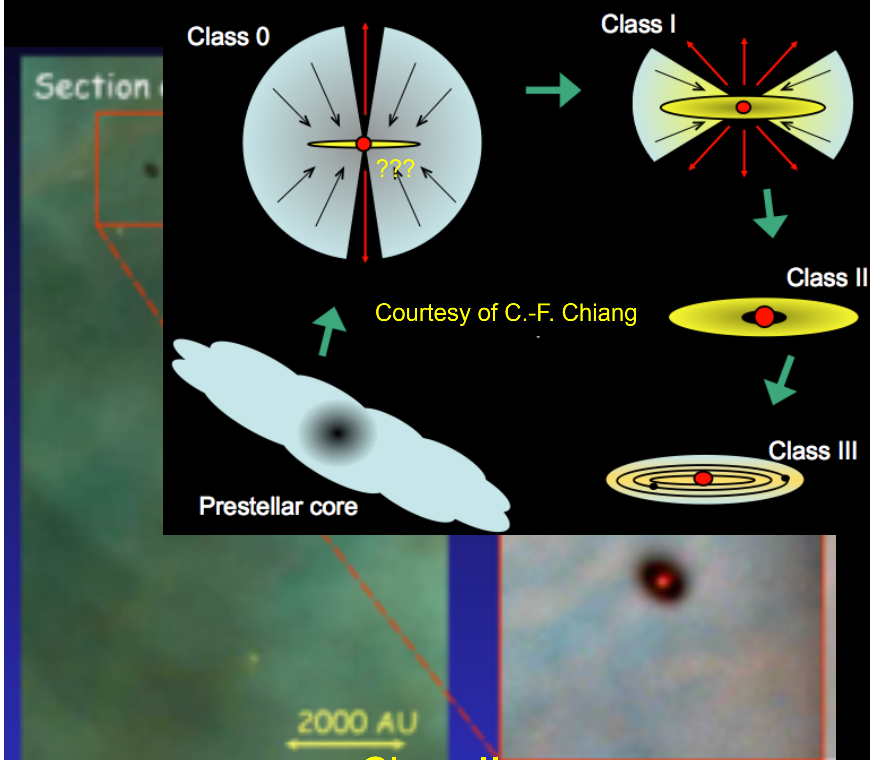
  → disk fraction ~ ½ x ½ ~ ¼
- However, if only λ>4 cores form disks (Li et al. 2013)

  disk fraction reduced by a factor of ~2

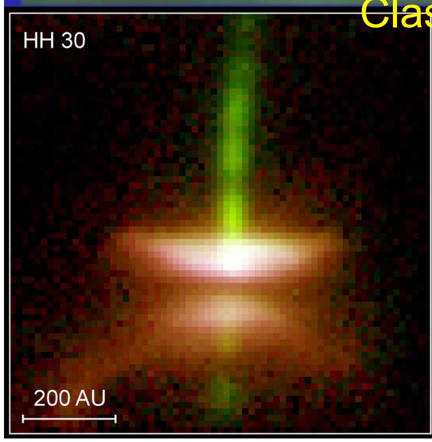
  → disk fraction ~10%

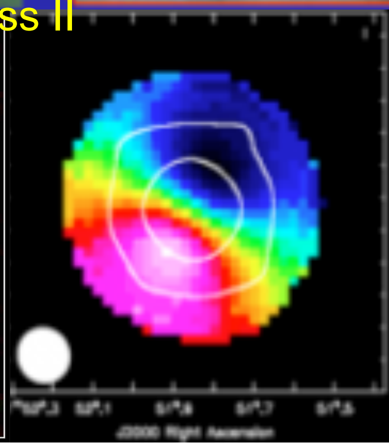
→ *majority of cores may not produce large disks during the protostellar accretion phase?*

Comparison with observations: what fraction of protostars have large, 100AU-scale RSDs?



Class II

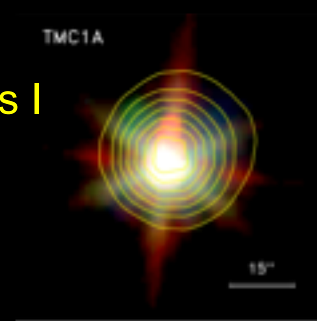


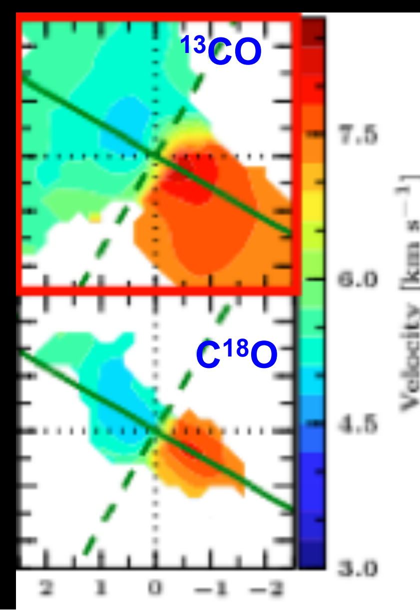


Direct evidence for large disks around

- many evolved “Class II” YSOs (little envelope)
- increasing number of “Class I” YSOs (some envelope, transition from deeply embedded to revealed)
- “Class 0” protostars?? (deeply embedded within a massive envelope) – objects to compare with simulations

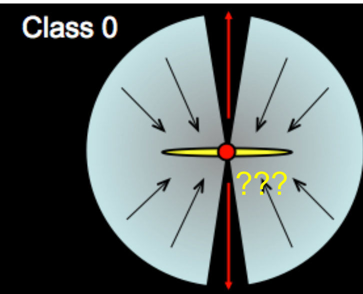
Class I



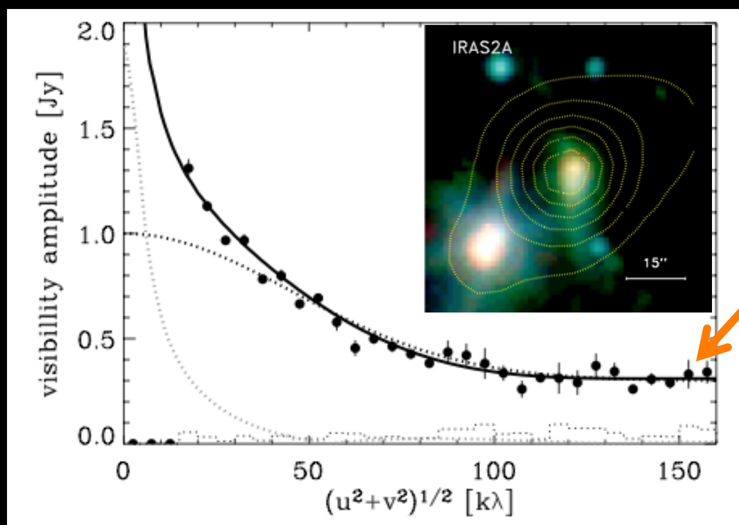


Class I object TMC1A observed with PdBI in ^{13}CO and $C^{18}O$ (2-1) (Harsono et al. 2013, in prep)

What fraction of protostars have large, 100AU-scale RSDs?



- Disks difficult to observed in deeply embedded objects; confused with inner envelope
- Continuum interferometer data often reveal compact emission indicating significant mass concentration on small scales



•Example: SMA data on NGC1333-IRAS2A (Jorgensen et al. 2005, ApJ, 632, 973)

→Compact component of 0.02 $M_\odot$ or more

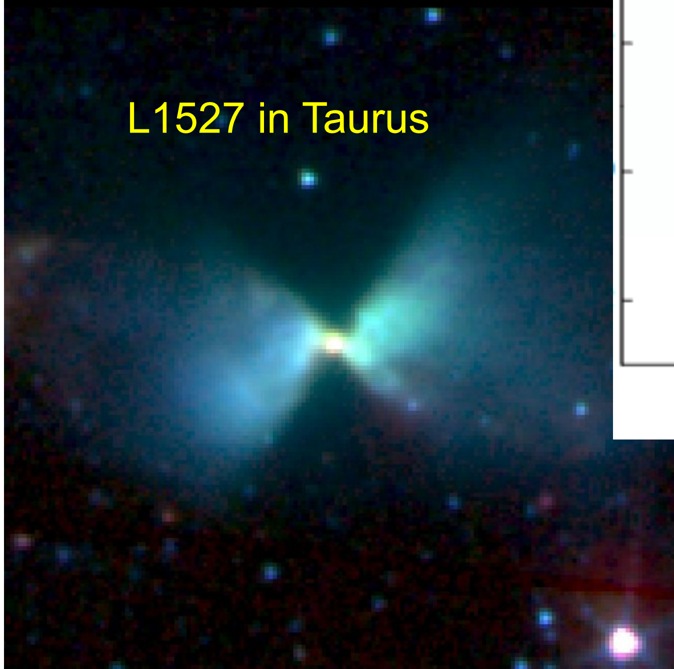
•Unbiased CARMA survey of protostars in Serpens reveals that 6 out of 9 have compact emission (Enoch et al. 2011, ApJS, 195, 21)

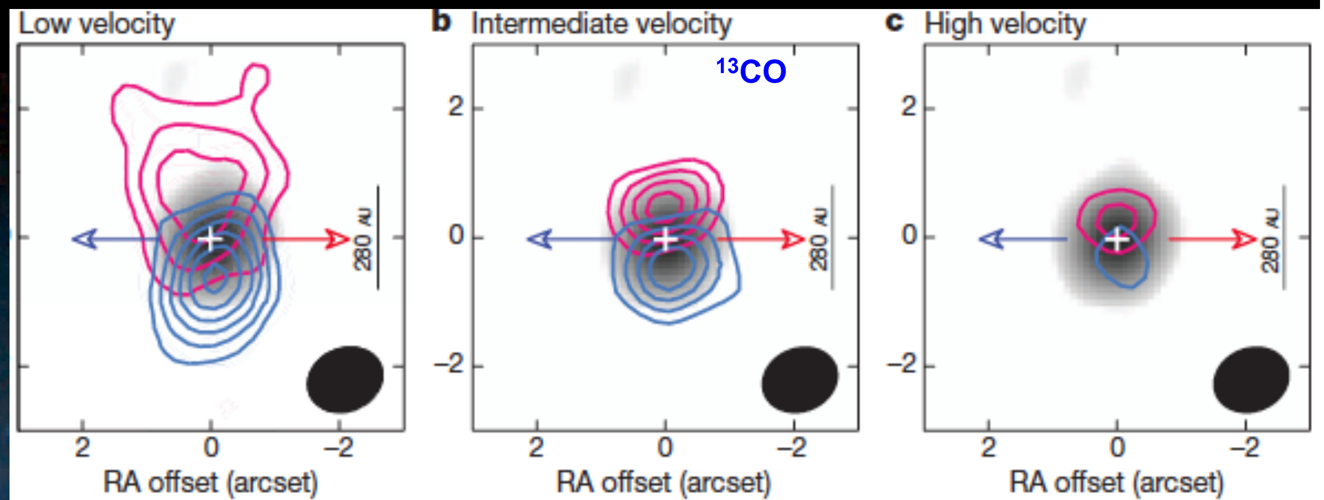
→Compact component appears common

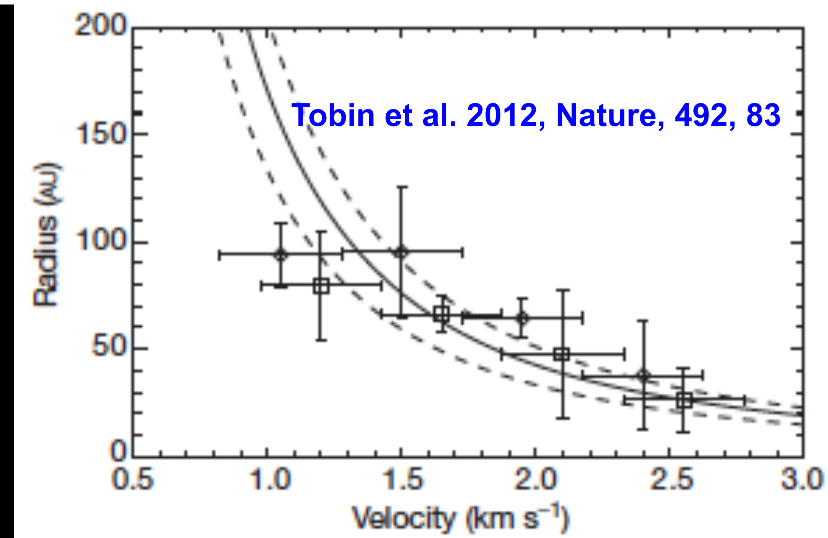
- Maury et al. (2010, AA, 512, A40) surveyed 5 “Class 0” objects w/ PdBI at 0.3-0.5” resolution & found no evidence for large-scale (~100 AU) RSDs
- Kinematic information on small scales needed

Comparison with observations: what fraction of “Class 0” protostars have large, 100AU-scale RSDs?

• Using CARMA, Tobin et al. (2012) detected in L1527 a roughly Keplerian disk





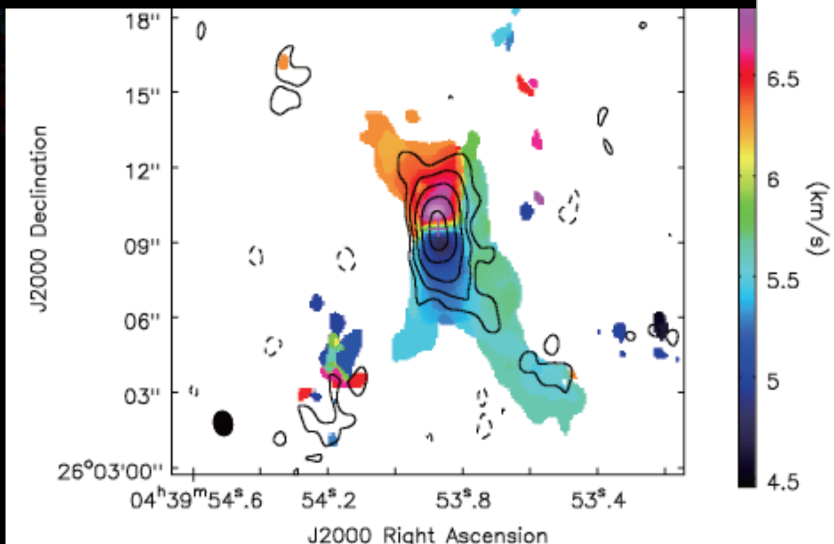


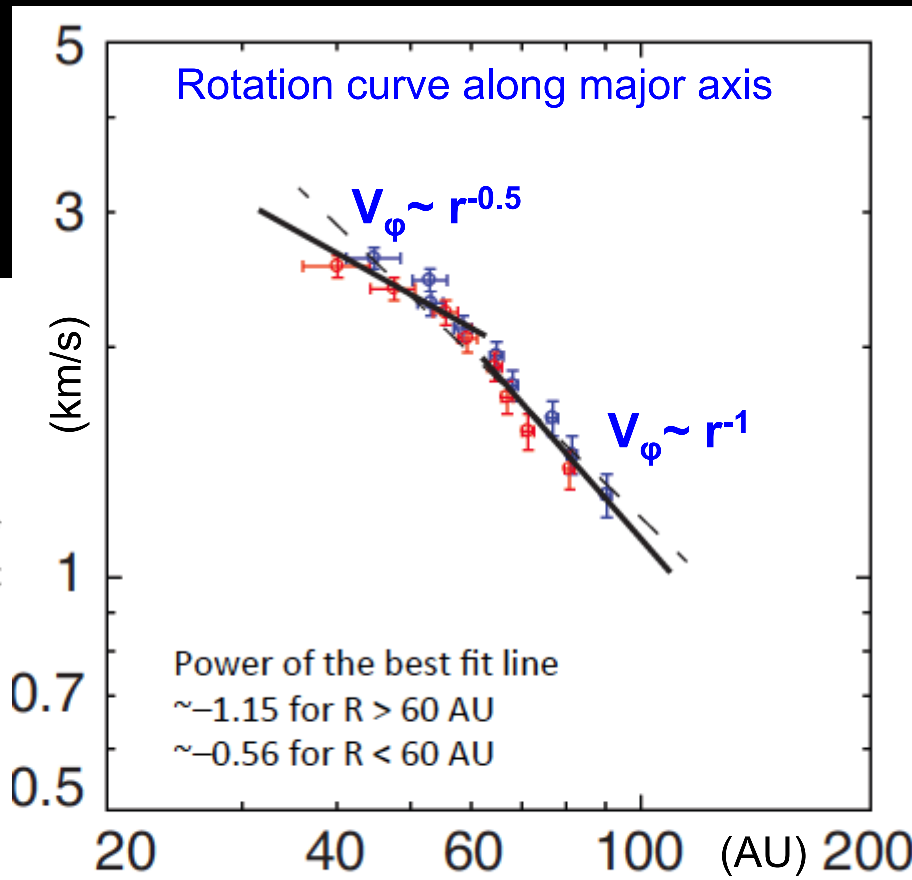
• L1527: a case for large rotationally supported “Class 0” disk?

•ALMA observations…

What fraction of “Class 0” protostars have large, 100AU-scale RSDs? ALMA observations of L1527

Courtesy N. Ohashi, $C^{18}O$ 2-1, velocity map



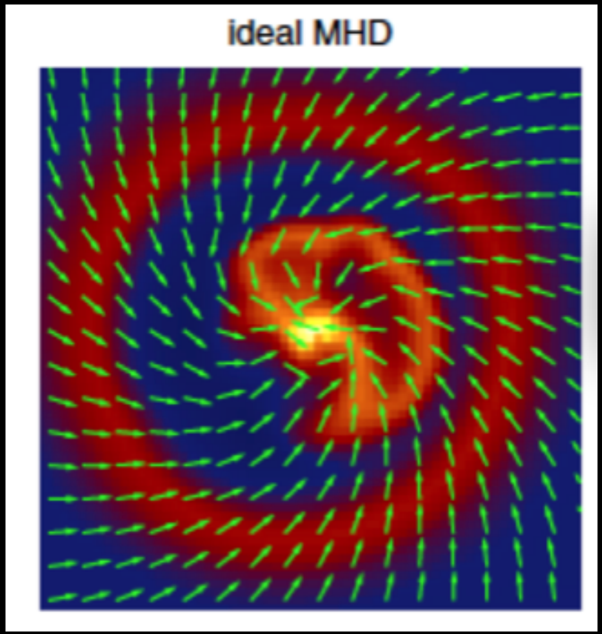


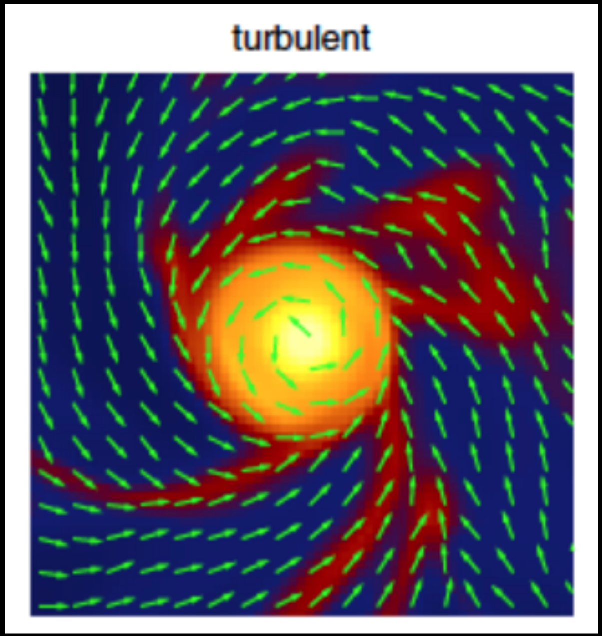
- Keplerian-like inside ~60 AU, case for rotationally supported “Class 0” disk strengthened
- Unclear how common such relatively large Keplerian disks are around protostars…AMLA!
- If rare, strong magnetic braking may be ok or even desirable
  - L1527: perhaps a rare case of BOTH weak magnetic field AND large B-rotation misalignment?
- If common, key ingredient missing?

IV. How to form rotationally supported disks?

(3) turbulence-enabled large disk formation?

- Plausibility first demonstrated numerically by Santos-Lima et al. (2012, ApJ, 747, 21)





- Confirmed and extended by Seifried et al. (2012, 2013), Myers et al. (2013), Joos et al. (2013) & Li et al. (2013, in prep.)

Example of turbulence-enabled disk formation

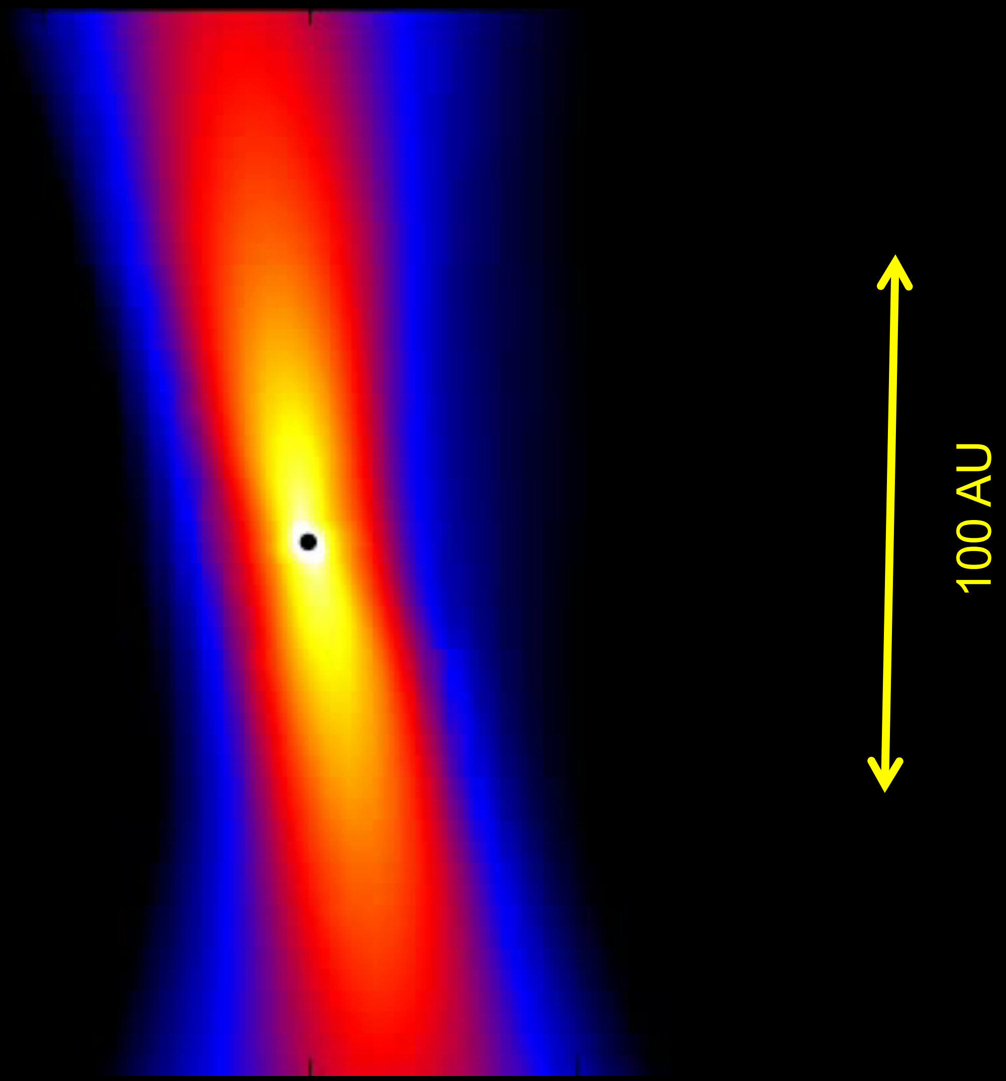
(Seifried, Banerjee, Pudritz & Klessen 2013, MNRAS, 432, 3320)

Core mass $2.6 M_{\odot}$

Mass-to-flux ratio
$\lambda \sim 2.6$

Turbulence with rms
Mach number ~ 0.74

Global rotation
$\Omega \sim 2.2 \times 10^{-13}\ s^{-1}$



Turbulence-enabled disk formation: reasons debated

- Magnetic flux loss from central region due to turbulence-induced reconnection (Santos-Lima et al. 2012, 2013, motivated by Lazarian & Vishniac 1999)
- Tangling of field lines and strong shear conducive to disk formation (Seifried et al. 2012, 2013)
- Turbulence induces magnetic flux loss & B-rotation misalignment (Joos et al. 2013; Myers et al. 2013)
- Caveat: turbulence-accelerated numerical reconnection (Li et al. 2013)

→ *Promising mechanism but better understanding needed*

IV. How to form rotationally supported disks?

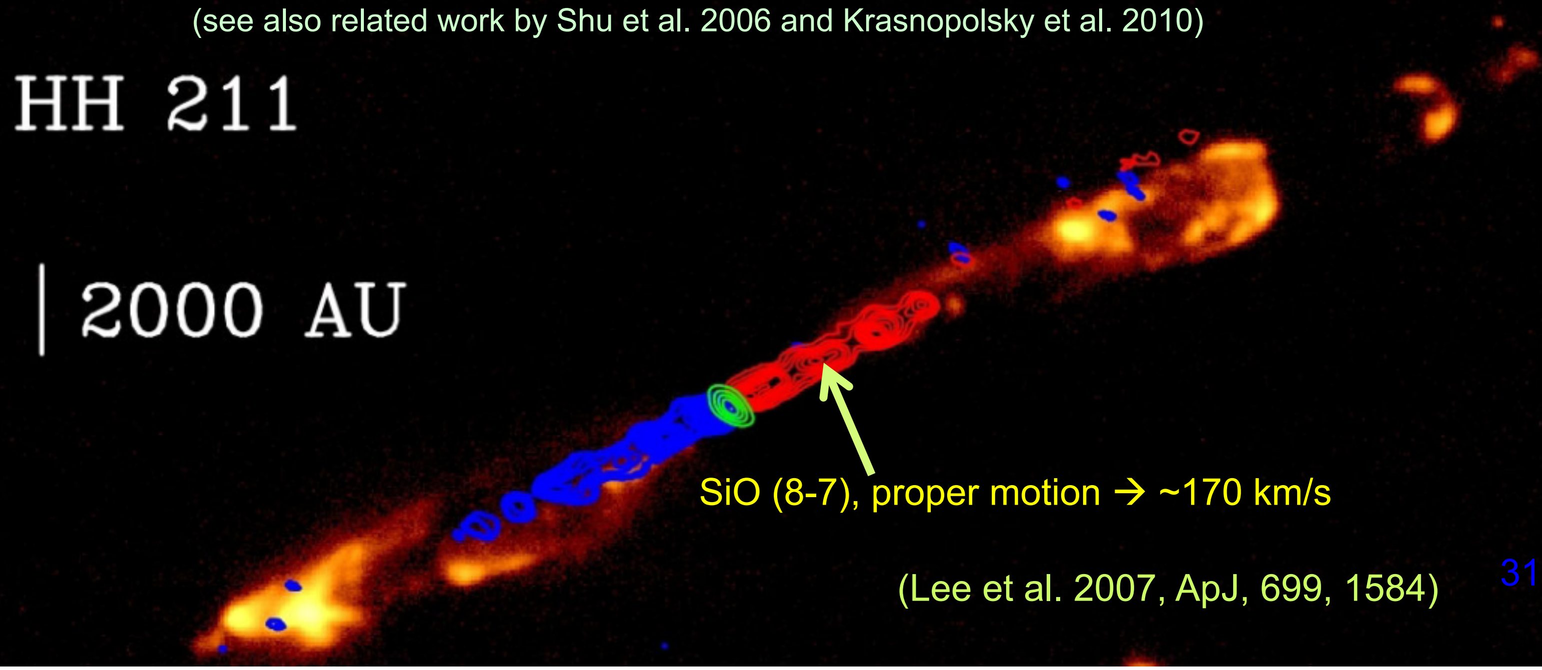
(4) Ohmic dissipation-enabled small disk formation

• Outflow a defining characteristic of “Class 0” objects (Andre et al. 1993, ApJ, 406, 122)

• Fast (~100 km/s) jets (e.g., HH211) most likely driven by disks on sub-AU scale

• Small, AU-scale rotationally supported disks can form through Ohmic dissipation, the dominant non-ideal MHD effect at highest densities

demonstrated semi-analytically by Dapp & Basu (2010) and Dapp et al. (2012)
numerically by Machida et al. (2010) and Tomida et al. (2013)
(see also related work by Shu et al. 2006 and Krasnopolsky et al. 2010)

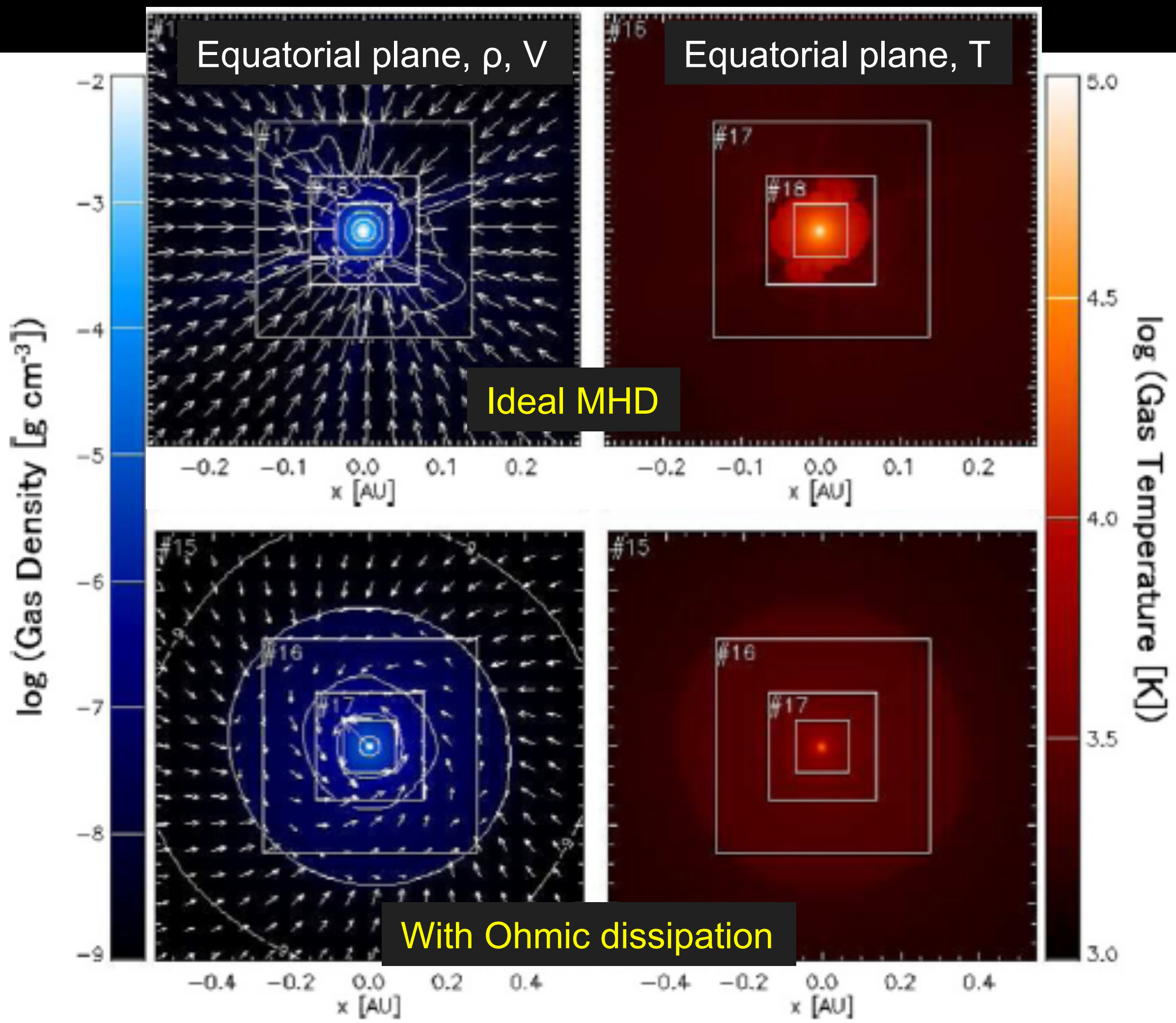


(Lee et al. 2007, ApJ, 699, 1584)

IV. How to form rotationally supported disks?

(4) Ohmic dissipation-enabled small disk formation

• Example of small disk formation: radiative MHD simulations with nested grid
(Tomida et al. 2013, ApJ, 763, 6)



•Include both first & second (stellar) core

•Challenging simulations, stopped ~ 1yr after 2nd core

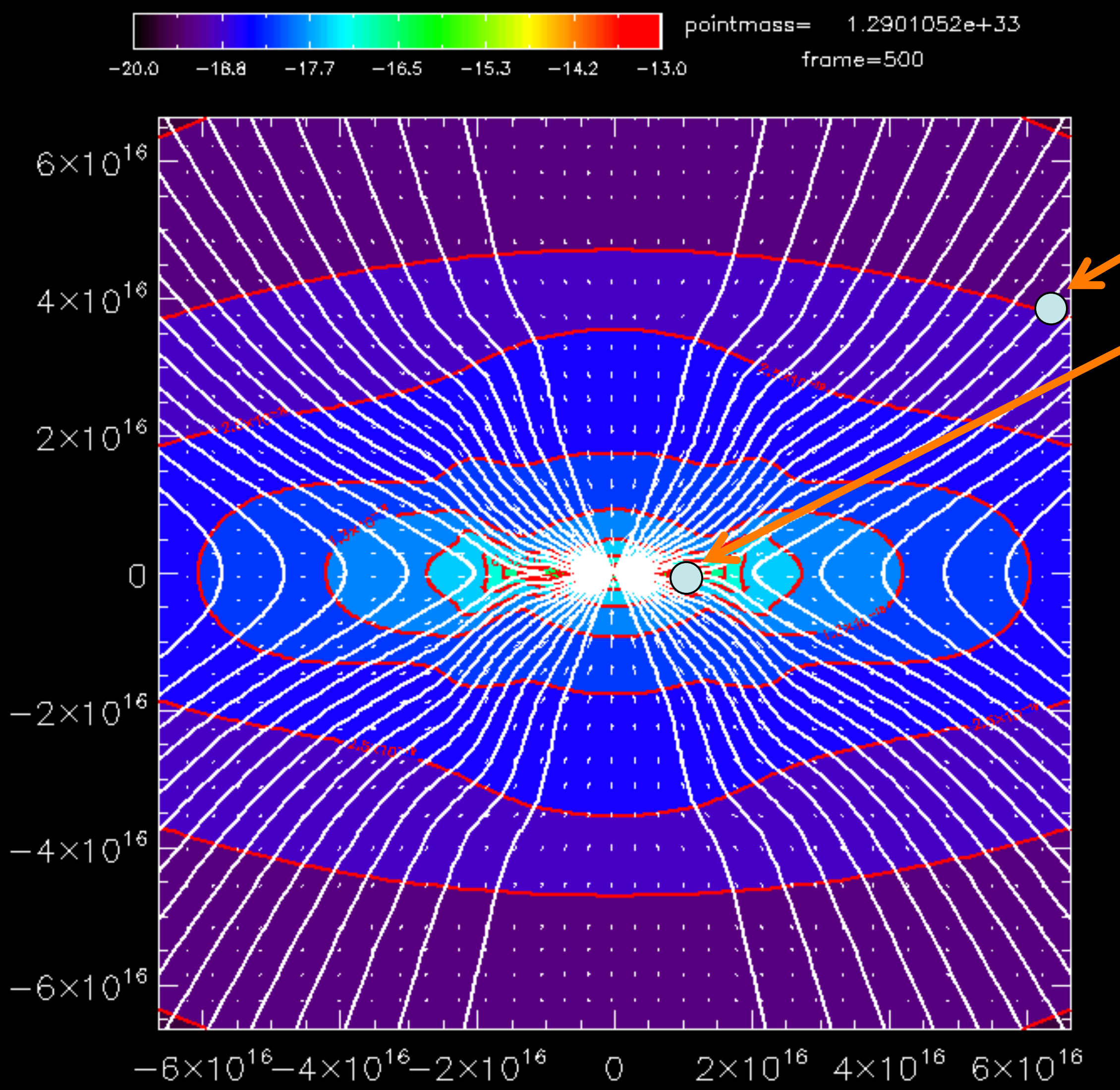
•No RSD in ideal MHD

•Small (0.35AU) RSD with Ohmic dissipation

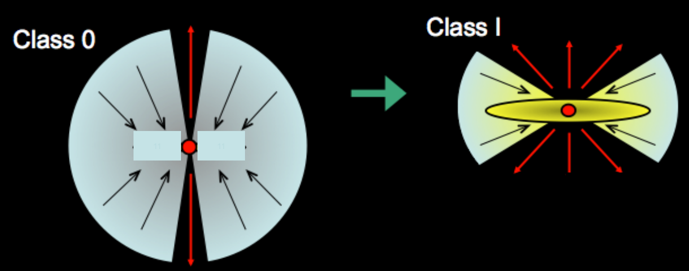
→How does the small disk grow in time, in presence of AD & Hall effect?

IV. How to form rotationally supported disks?

(5) Late formation of large disks from envelope depletion?



- IF the slowly rotating envelope is removed, the braking may become inefficient → rapid disk growth?
- By outflows? (Mellon & Li 2008)

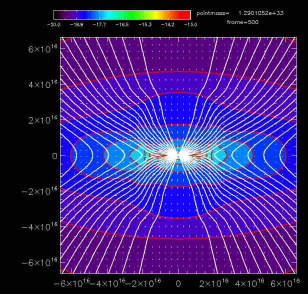


(rapid disk growth during Class 0→ I?)

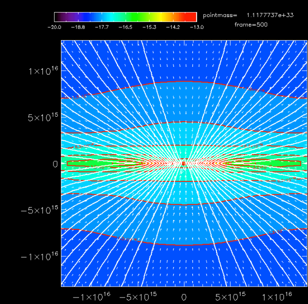
- By accretion? (Machida et al. 2010)

Summary: difficulties with disk formation

- Disk formation suppressed in the ideal MHD limit for realistically magnetized dense cores



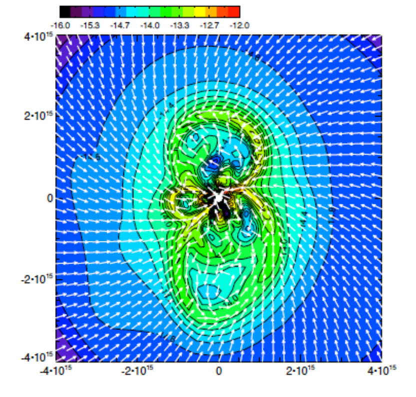
- Microscopic non-ideal effects (AD, Ohmic, Hall) do not appear to enable large disk formation in 2D



- Protostellar accretion flows unstable to magnetic interchange instability driven by flux redistribution

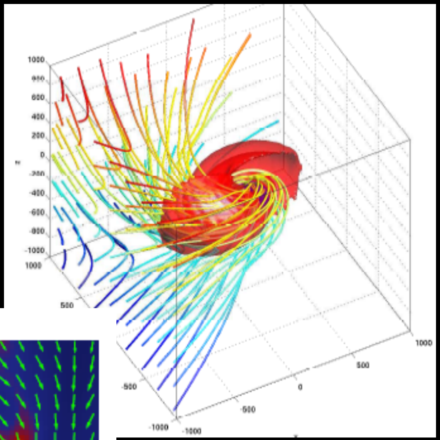
→ Disk formation not as simple as generally believed

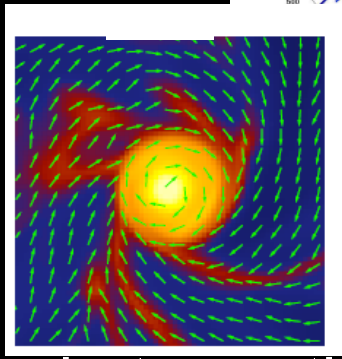
(basic problem: magnetic flux concentration by accretion)

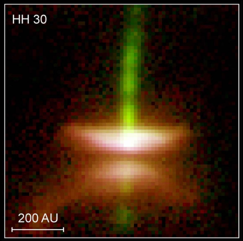


Summary: Possible Resolutions

- Weak core magnetization probably not consistent with available data
- Misalignment weakens magnetic braking but may not enable large disk formation in majority of dense cores
- Turbulence is found to facilitate disk formation, but details debated
- Ohmic dissipation enables small disks, but growth uncertain
- Outflow may weaken magnetic braking through envelope stripping, yet to be quantified







→ *Problem of disk formation not yet resolved definitively*