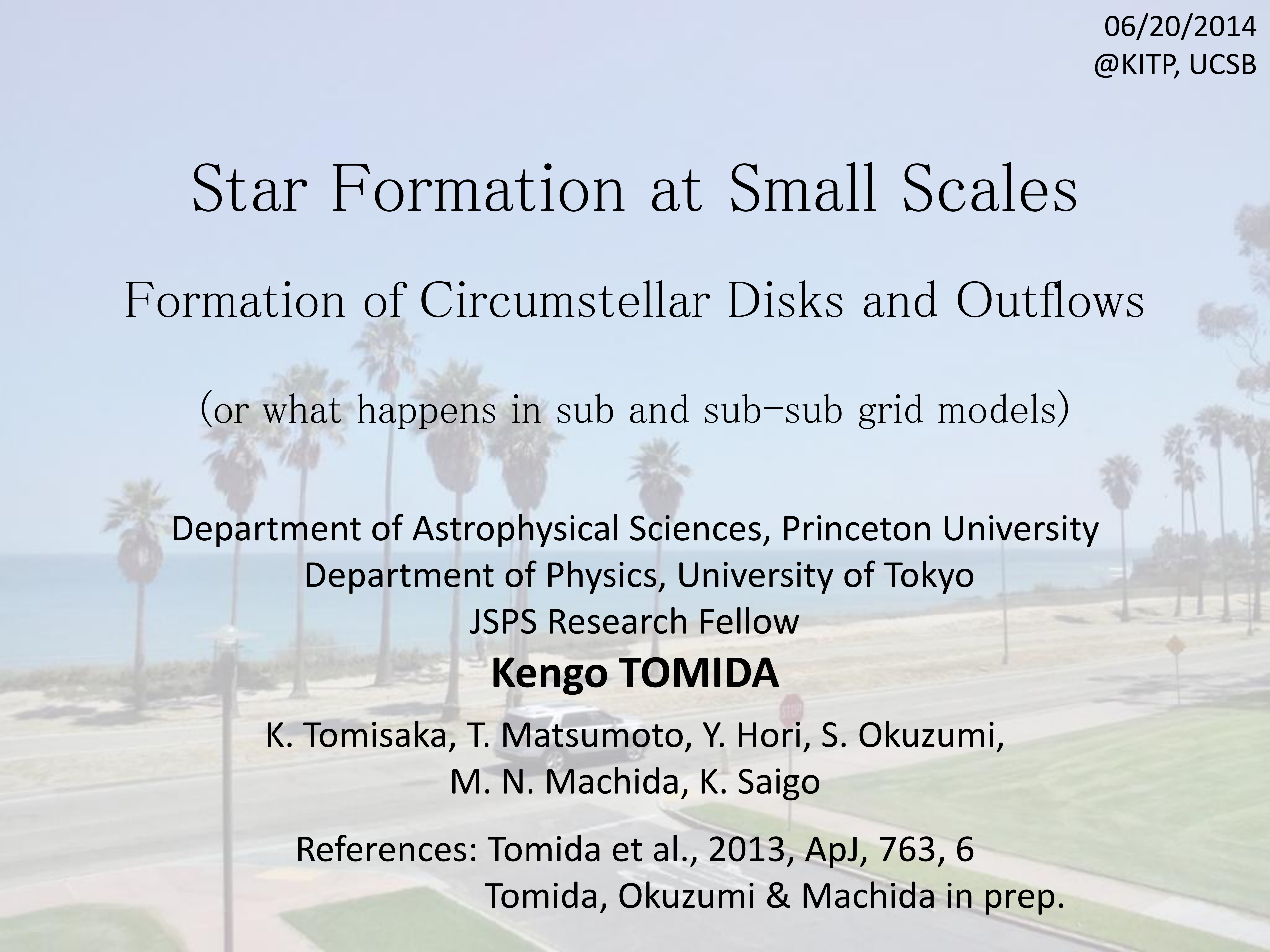

06/20/2014
@KITP, UCSB

Star Formation at Small Scales

Formation of Circumstellar Disks and Outflows

(or what happens in sub and sub-sub grid models)

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M. N. Machida, K. Saigo

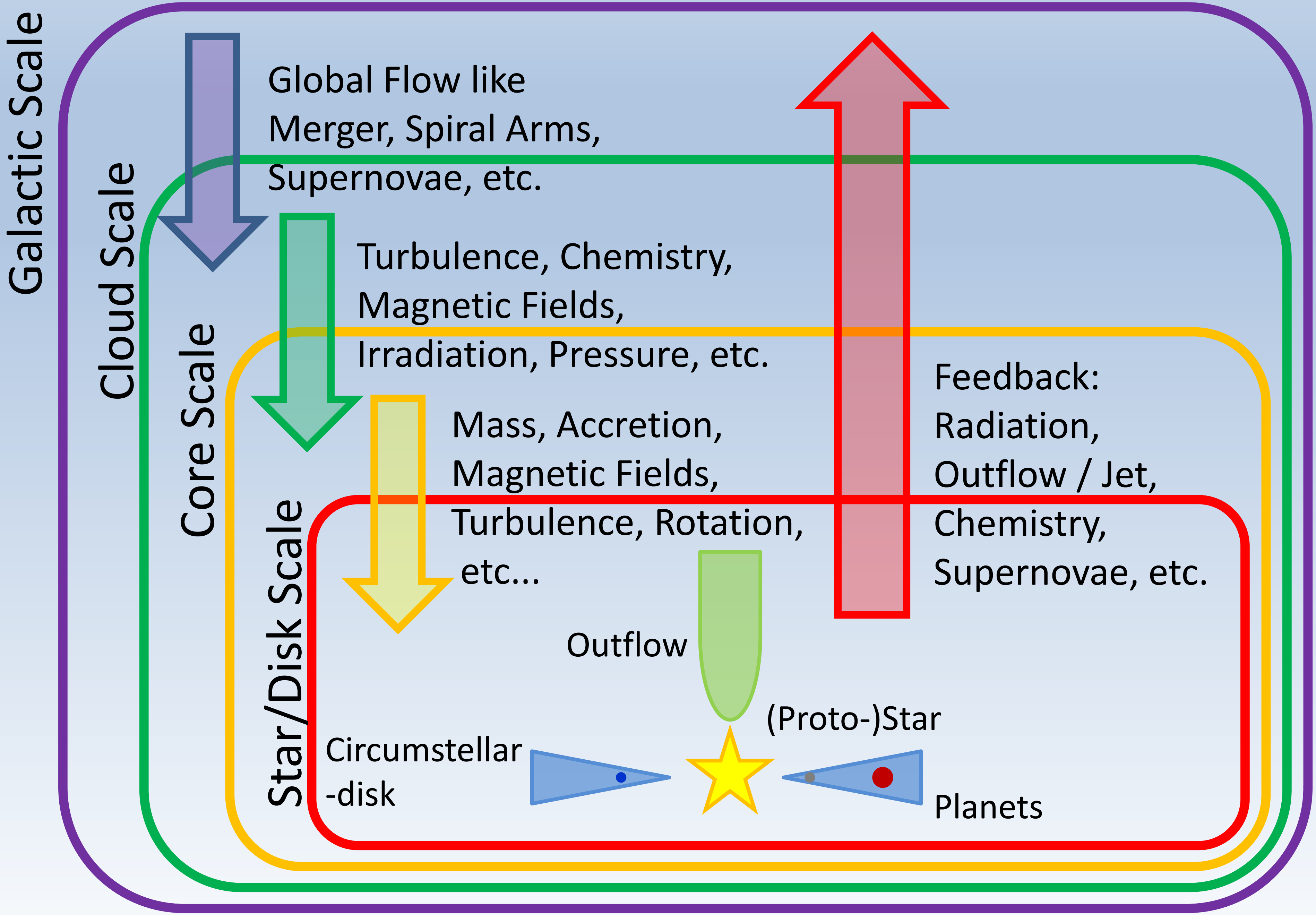
References: Tomida et al., 2013, ApJ, 763, 6
Tomida, Okuzumi & Machida in prep.

Topics

- Introduction
  - – Protostellar Collapse
  - – Angular Momentum Problem
  - – Magnetic Braking Catastrophe
- RMHD simulations of Protostellar Collapse
  - – Ideal RMHD
  - – Resistive RMHD
  - – Ambipolar Diffusion (very preliminary!)
- Observations
  - – Young Circumstellar Disks
  - – First Core Candidates
- Summary

Introduction

Multi-Scale, Multi-Physics nature of Star Formation



Galactic Scale

Cloud Scale

Core Scale

Star/Disk Scale

Global Flow like
Merger, Spiral Arms,
Supernovae, etc.

Turbulence, Chemistry,
Magnetic Fields,
Irradiation, Pressure, etc.

Mass, Accretion,
Magnetic Fields,
Turbulence, Rotation,
etc...

Feedback:
Radiation,
Outflow / Jet,
Chemistry,
Supernovae, etc.

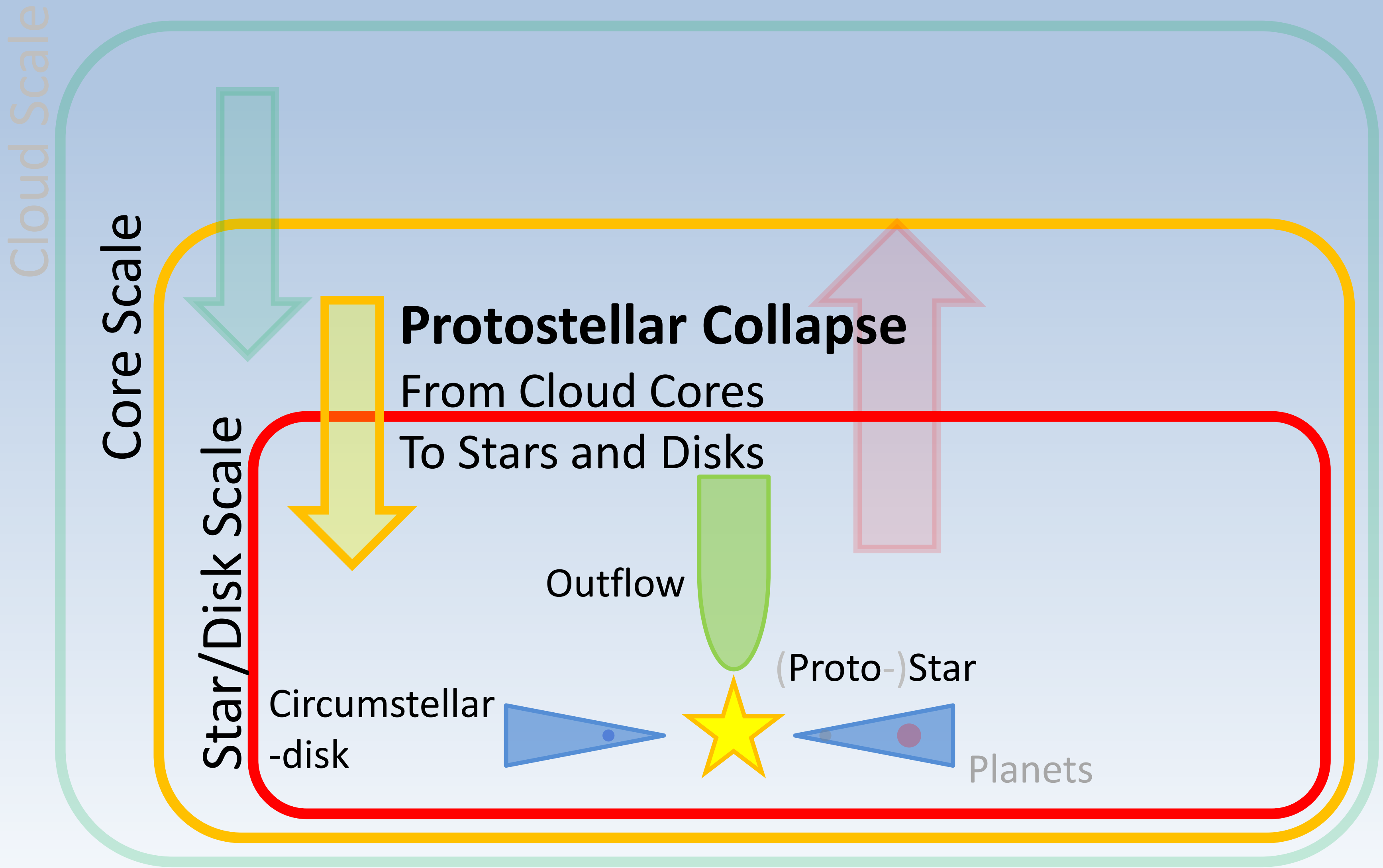
Outflow

(Proto-)Star

Circumstellar
-disk

Planets

What this talk covers



Cloud Scale

Core Scale

Star/Disk Scale

Protostellar Collapse

From Cloud Cores

To Stars and Disks

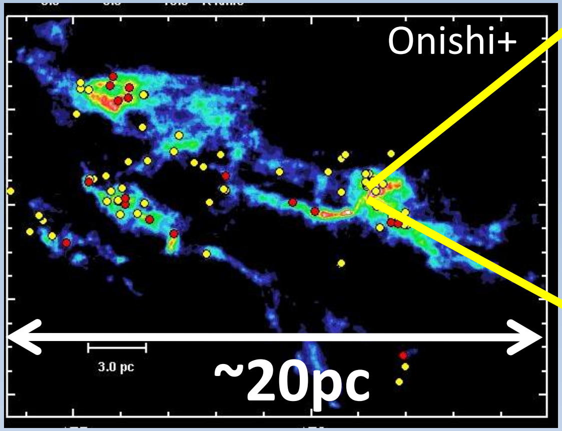
Outflow

(Proto-)Star

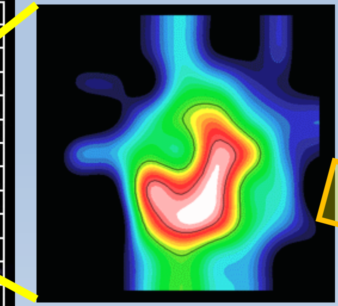
Circumstellar
-disk

Planets

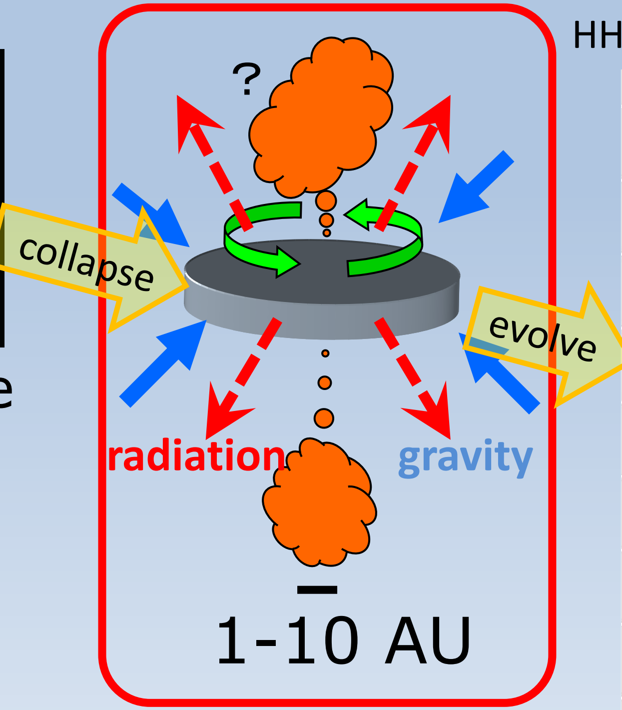
Protostellar Collapse



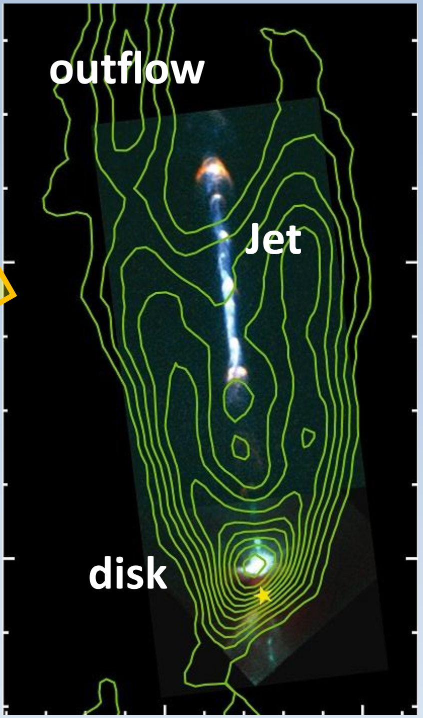
Taurus Molecular Cloud(Nagoya, 4m)



Cloud Core
∼0.1pc
n≳10^4/cc



Protostar, Disk, Outflow
HH111(Mckee&Ostriker 07



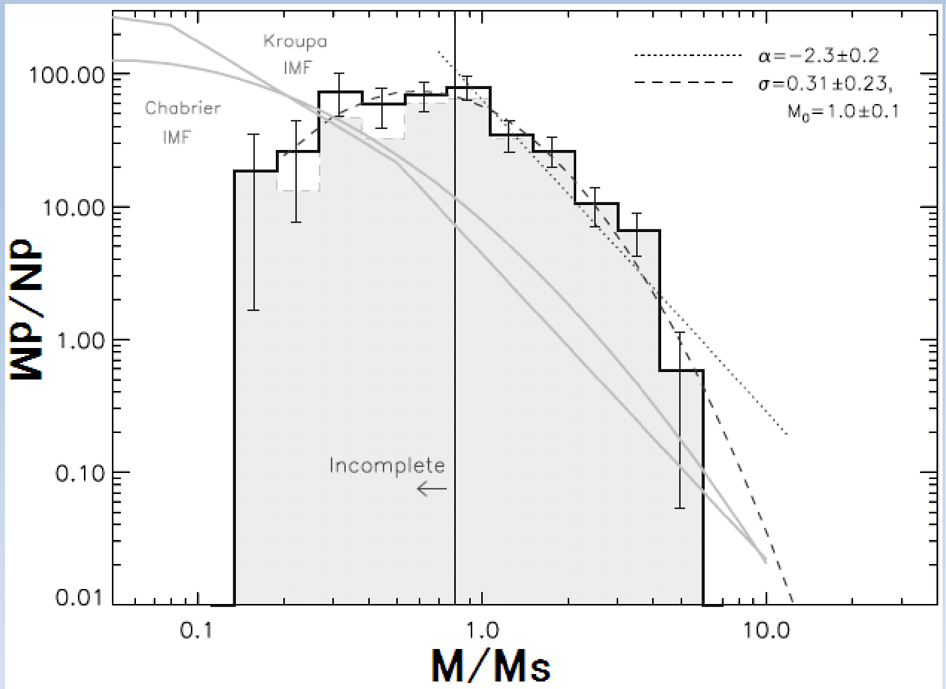
- Many physical processes are involved here: self-gravity, magnetic fields, radiation transfer, turbulence, chemistry, non-ideal MHD effects, etc…
- Huge dynamic range: 0.1 pc / 1 Rs ∼4.5 x **10^6**

⇒Sophisticated numerical simulations are required

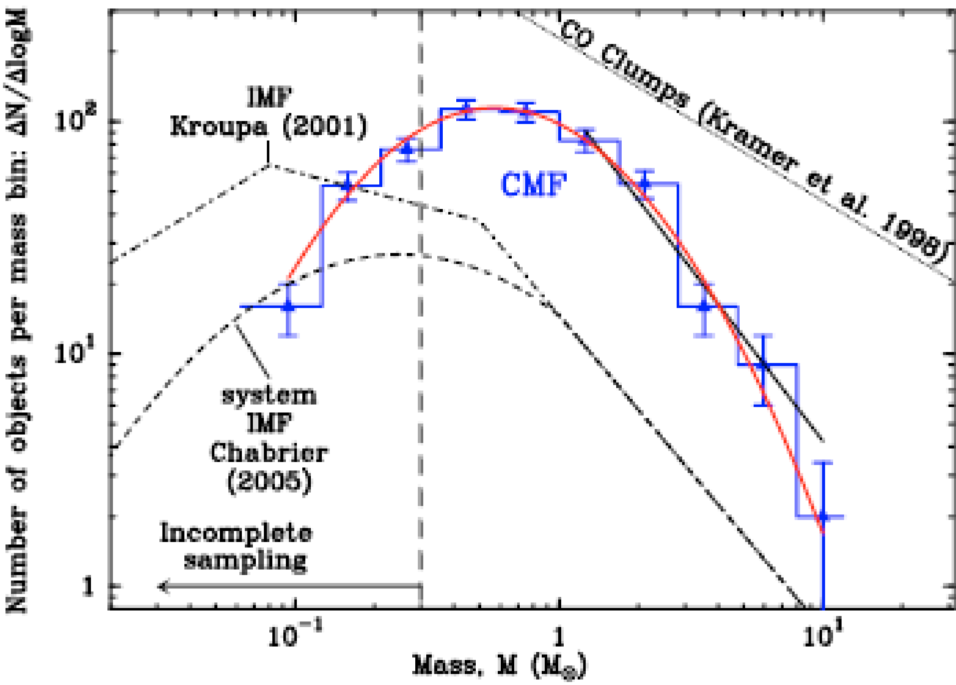
Why do we care such a small scale?

- Ultimate goal: the origin of the initial mass function
  - ➢ Relation between CMF and IMF (?)
    - Star Formation Efficiency (at core scale)
    - Binary / Multiple Formation

Core and Stellar Mass Functions



(Enoch et al. 2008, Bolocam 1.1mm)



(Andre et al. 2010, Herschel)

Mass Function of Dense Cores looks like the IMF -- with some shift.

- Is there such a simple relation? Is **IMF** imprinted in **CMF**? If so …
- What is the origin of the CMF?
- What is the origin of the shift, or **efficiency**? How about **binaries**?

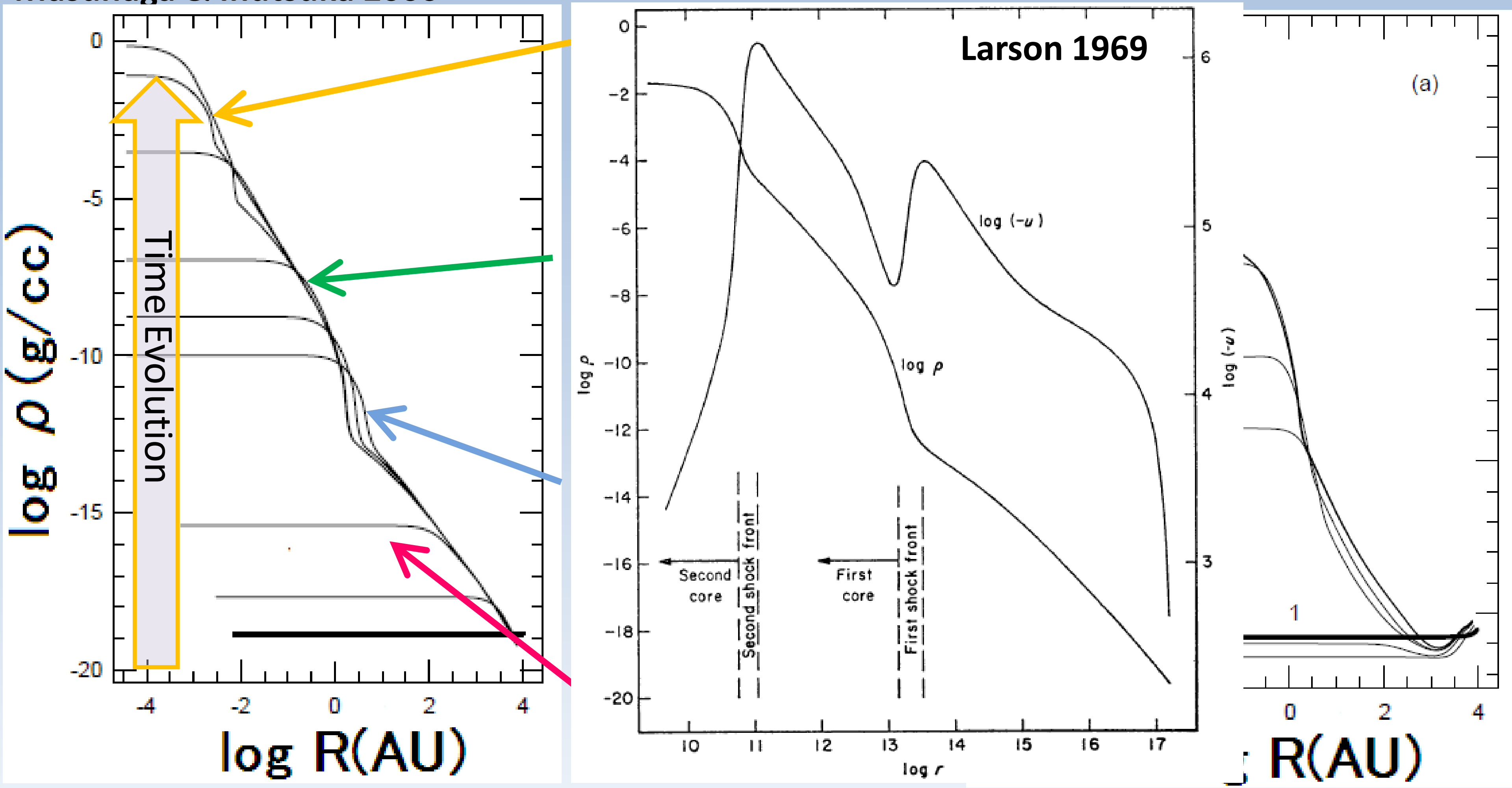
To understand this relation, we have to study protostellar collapse.

Why do we care such a small scale?

- Ultimate goal: the origin of the initial mass function
  - Relation between CMF and IMF (?)
    - Star Formation Efficiency (at core scale)
    - Binary / Multiple Formation
- Goal of this talk: the origin of circumstellar disks
  - Angular momentum redistribution
  - Binary / Multiple / Planet Formation
  - Outflow driving
  - Feedback: anisotropic radiation, outflows
    - “Flash light effect” (Yorke & Bodenheimer 1999)
    - Disks can be optically thick without dust (Vaidya+ 2009)
- Significant progress in observations with ALMA
- I have a bad allergy to small particles, like pollen & sink particles

Protostellar Collapse: 1D RHD

Masunaga & Inutsuka 2000



Larson 1969

Radiation transfer and chemical reactions control the evolution.

This scenario is well established based on 1D RHD simulations.

“Problems” in Protostellar Collapse

- **Angular Momentum Problem**

Cloud Cores $j_{cl} \approx 5\times 10^{21}\left(\frac{R}{0.1\,\mathrm{pc}}\right)^{2}\left(\frac{\Omega}{4\,\mathrm{km\,s^{-1}pc^{-1}}}\right)\mathrm{cm^{2}s^{-1}}$ **>>** $j_{*} \approx 6\times 10^{16}\left(\frac{R_{*}}{2R}\right)^{2}\left(\frac{P}{10\,\mathrm{day}}\right)^{-1}\mathrm{cm^{2}s^{-1}}$ **Stars**

→Efficient angular momentum transport during protostellar collapse

⇒Gravitational torque, magnetic braking, outflows

- **Magnetic Flux Problem**

  Similarly, magnetic flux in cloud cores >> stellar magnetic flux

→Magnetic fields must dissipate during the collapse

⇒Ohmic dissipation, ambipolar diffusion, (Hall effect), turbulence

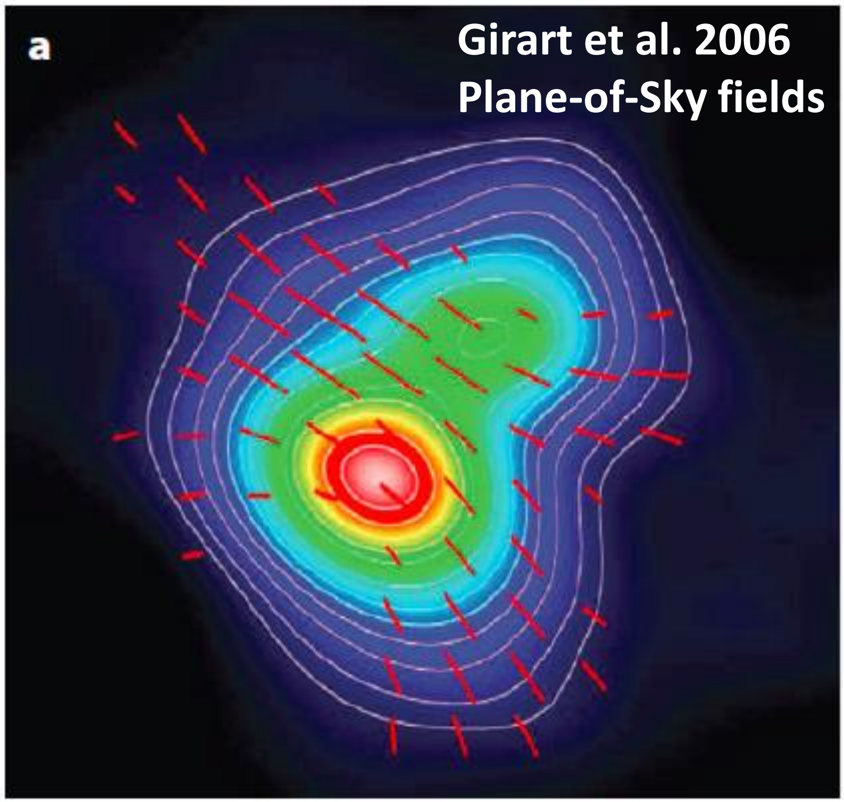
- “**Magnetic Braking Catastrophe**” (Mellon & Li 2008,09, Li+ 2011, etc.)

  Magnetic barking is too efficient; no circumstellar disk is formed

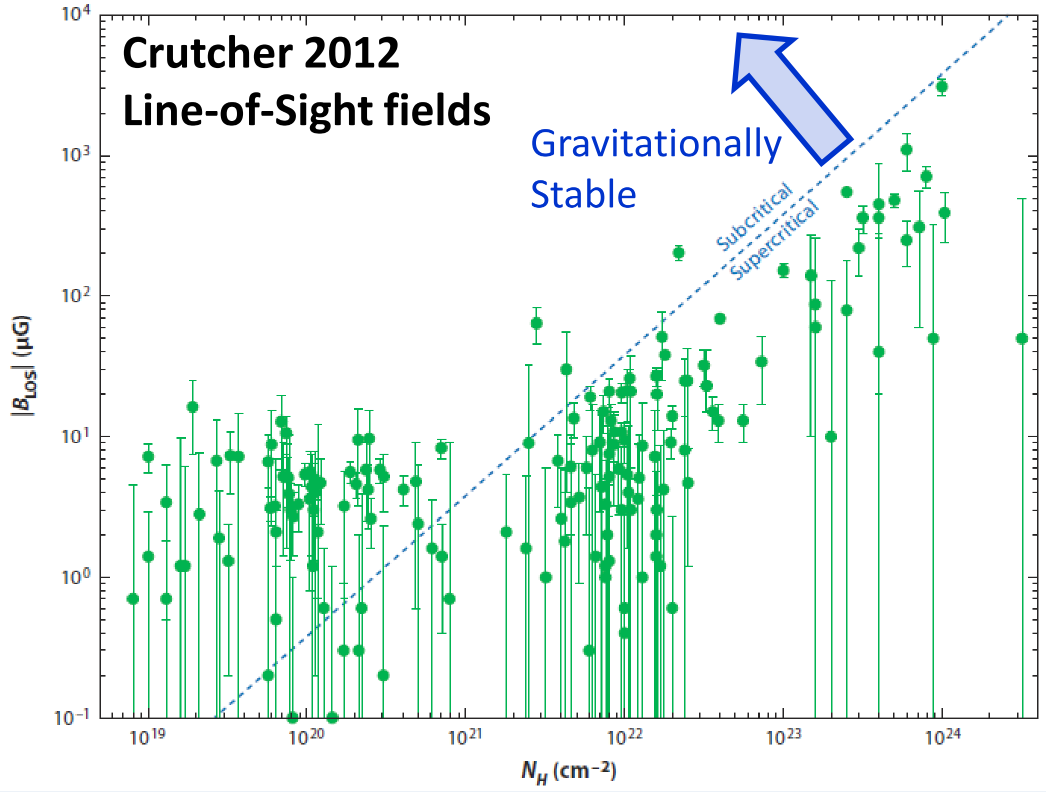
  ⇒Long-term accretion, non-ideal MHD effects, turbulence

⇒Realistic **3D simulations with many physical processes**

Magnetic Fields



Girart et al. 2006
Plane-of-Sky fields



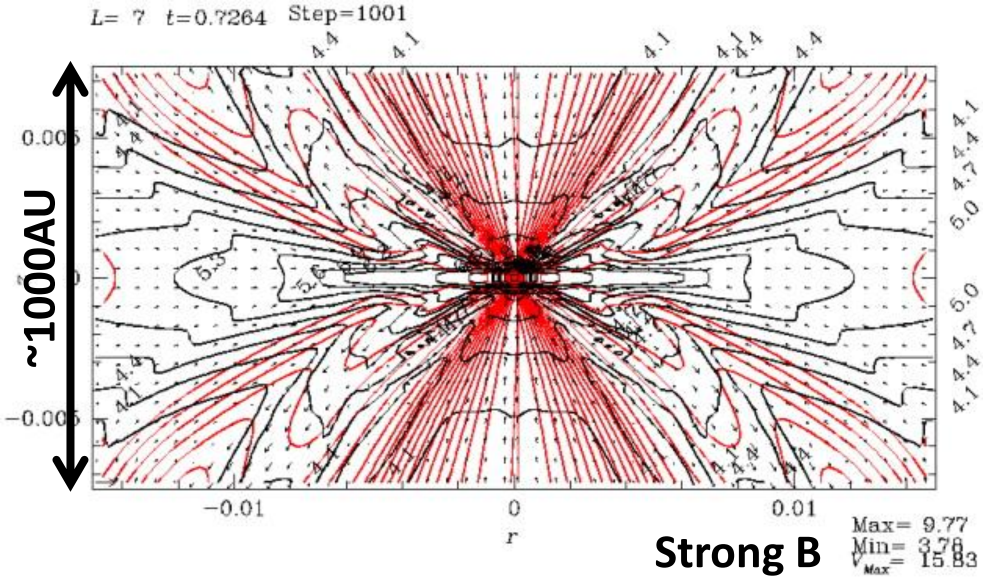
Crutcher 2012
Line-of-Sight fields

Gravitationally
Stable

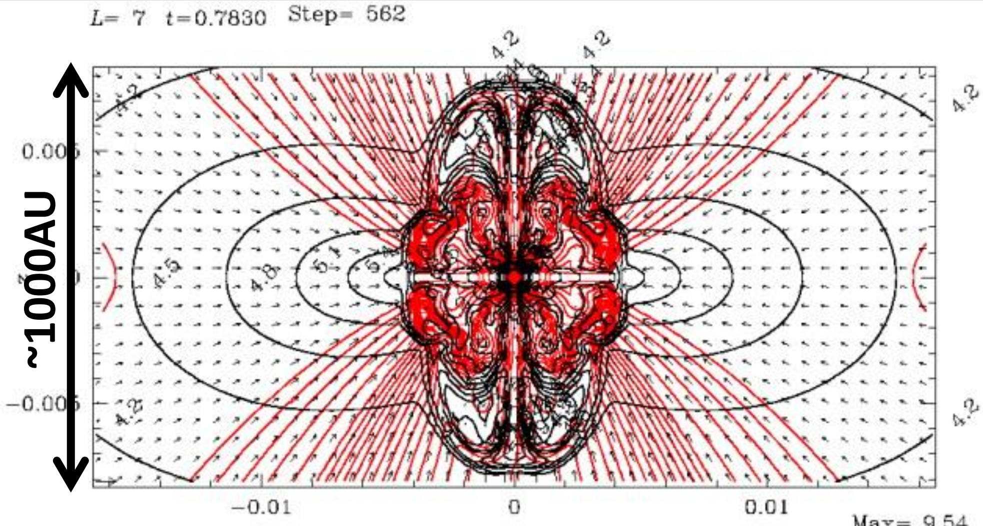
Observations suggest that cloud cores are considerably (supercritical to marginally subcritical) magnetized (μ∼2-10). Therefore magnetic fields must have significant effects, actually even in the supercritical regime.

NOTE: these observations are difficult and can have large uncertainties.

Magnetic Braking and Outflows



Strong B



(Tomisaka 1998,2000,2002) **Weak B**

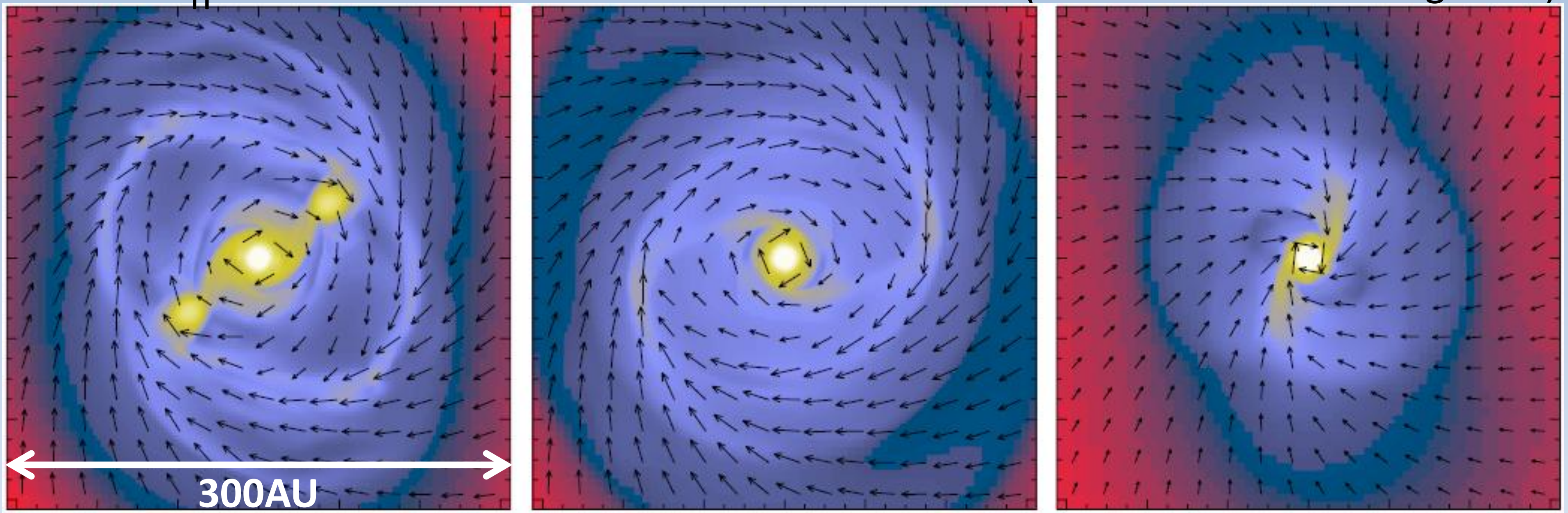
As a result of interaction between magnetic fields and rotation, bipolar outflows are launched from the collapsing cloud. Those outflows and **magnetic braking** transport angular momentum very efficiently.

Two modes of outflows:
Strong fields result in Magneto-centrifugal mode (Blandford & Payne 1982), while weak fields drive magnetic-pressure mode.

(see also, Mouschovias, & Paleologou 1979, 80, Kudoh et al. 1998, etc.)

Magnetic Braking Catastrophe and/or Fragmentation Crisis

$t\sim 1.2\ t_{ff}$ (Hennebelle & Fromang 2008)



$\mu=M/\Phi=50$ (very weak) $\mu=20$ (still modest) $\mu=5$ (intermediate)

Magnetic fields actually transport angular momentum “**too efficiently**”.

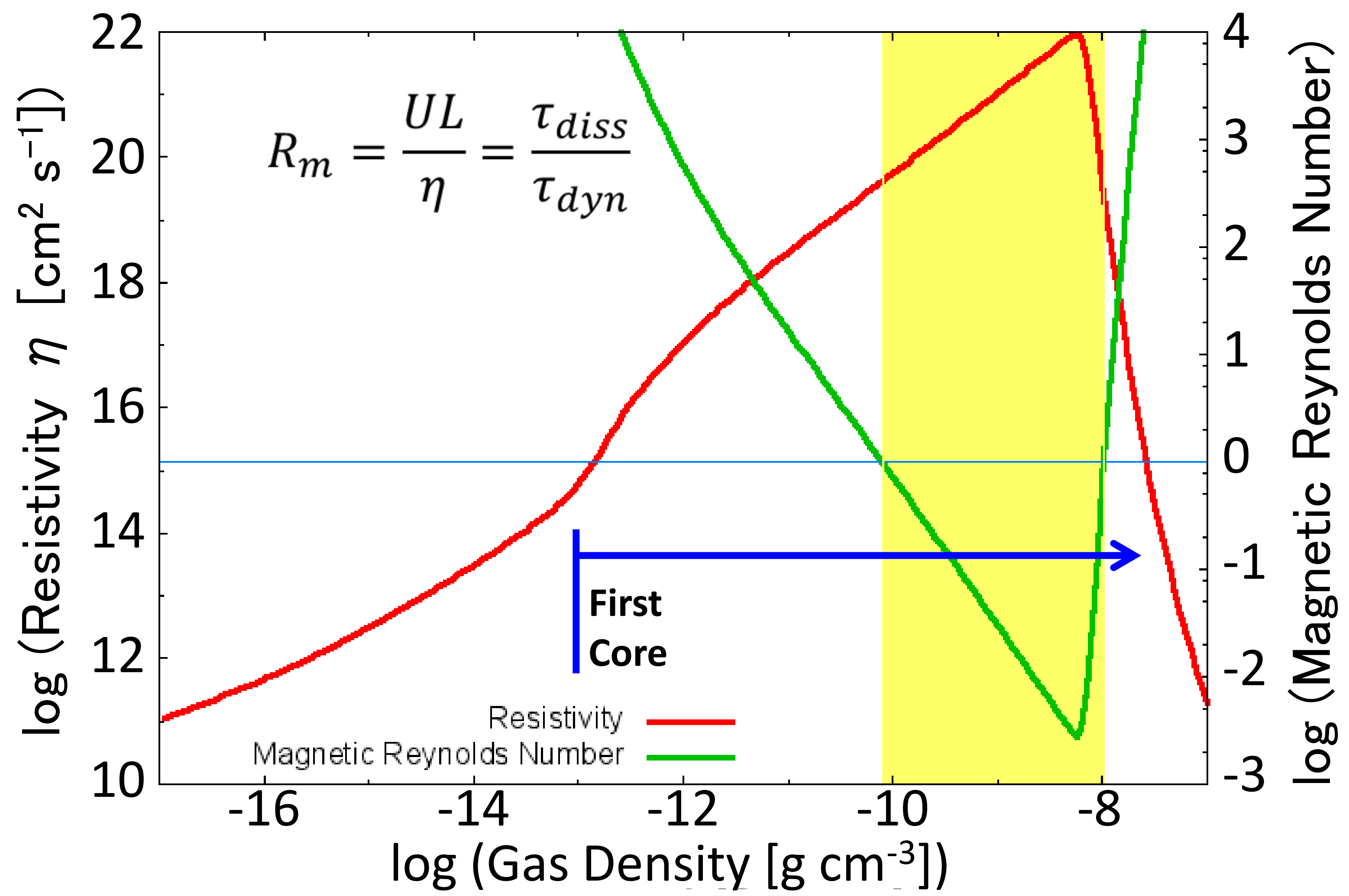
Circumstellar disks are not formed, fragmentation is strongly suppressed.

This is a serious problem: Binary rate is known to be high (M: >30% G : >50%, A: ~80%), and we know lots of circumstellar disks and planets exist.

(see also, Mestel & Spitzer **1956**, Mellon & Li 08, 09, Li et al. 11, Hennebelle & Ciardi 09, etc.)

Non-Ideal MHD effects

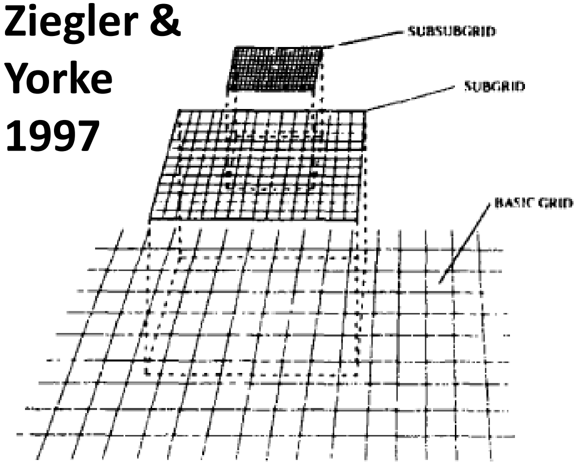
(Tomida et al. 2013)



Ohmic resistivity with $\xi=10^{-17}$ s^{-1} (neglecting Cosmic Ray shielding)
Significant flux loss occurs in the first core. (cf. Kunz & Mouschovias 09, 10)

RMHD Simulations of Protostellar Collapse

ngr^{3}mhd code


Ziegler & Yorke 1997

- Huge dynamic range: 3D nested-grids
- MHD → HLLD (Miyoshi & Kusano 2005)
  (+ Carbuncle care→shock detection + HLLD-)
  - ✓ Fast, robust and as accurate as Roe's solver
  - ✓ Independent from the details of EOS
- div **B**=0 constraint→Hyperbolic cleaning (Dedner+ 2002)
- Self-gravity→Multigrid (Matsumoto & Hanawa 2003)
- Radiation→Gray Flux Limited Diffusion (Levermore & Pomraning 1981)
  +Implicit (BiCGStab + ILU decomposition (0) preconditioner)
- EOS including chemical reactions (H_2, H, H^+, He, He^+, He^{2+} and e^-)
- Ohmic dissipation→Super Time Stepping (Alexiades+ 1996)
- (preliminary!) Ambipolar Diffusion with STS
- OD & AD tables are derived using a chemical network with dusts

⇒The latest version of Larson's protostellar collapse simulation.

Basic Equations (w/o div **B** cleaning)

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{v})=0,$$

Mass Conservation

$$\frac{\partial\rho\mathbf{v}}{\partial t}+\nabla\cdot\left[\rho\mathbf{v}\otimes\mathbf{v}+\left(p+\frac{1}{2}|\mathbf{B}|^2\right)\mathbb{I}-\mathbf{B}\otimes\mathbf{B}\right]=-\rho\nabla\Phi+\underline{\frac{\sigma_R}{c}\mathbf{F}_r},$$

Eq. of motion

$$\frac{\partial\mathbf{B}}{\partial t}-\nabla\times(\mathbf{v}\times\mathbf{B}-\underline{\eta\nabla\times\mathbf{B}})=0,$$

Induction eq.

$$\nabla\cdot\mathbf{B}=0,$$

div B=0

$$\frac{\partial e}{\partial t}+\nabla\cdot\left[\left(e+p+\frac{1}{2}|\mathbf{B}|^2\right)\mathbf{v}-\mathbf{B}(\mathbf{v}\cdot\mathbf{B})-\underline{\eta\mathbf{B}\times(\nabla\times\mathbf{B})}\right]=$$

Gas Energy Eq.

$$-\rho\mathbf{v}\cdot\nabla\Phi\underline{-c\sigma_P(aT^4-E_r)+\frac{\sigma_R}{c}\mathbf{F}_r\cdot\mathbf{u}},$$

$$\nabla^2\Phi=4\pi G\rho,$$

Poisson's Eq.

$$\underline{\frac{\partial E_r}{\partial t}+\nabla\cdot[\mathbf{u}E_r]+\nabla\cdot\mathbf{F}_r+\mathbb{P}_r:\nabla\mathbf{u}=c\sigma_P(a_rT_g^4-E_r)},$$

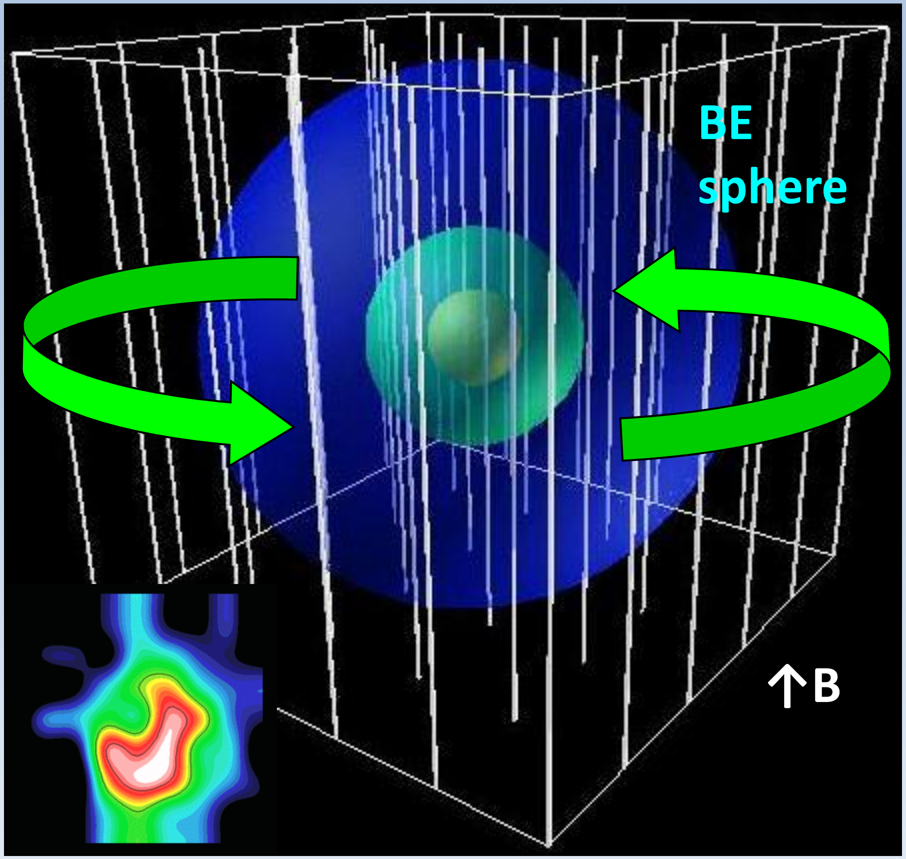
Radiation Transfer

$$\mathbf{F}_r=\frac{c\lambda}{\sigma_R}\nabla E_r,\quad\lambda(R)=\frac{2+R}{6+2R+R^2},\quad R=\frac{|\nabla E_r|}{\sigma_R E},$$

+ **Eq. of state**

$$\mathbb{P}_r=\mathbb{D}E_r,\quad\mathbb{D}=\frac{1-\chi}{2}\mathbb{I}+\frac{3\chi-1}{2}\mathbf{n}\otimes\mathbf{n},\quad\chi=\lambda+\lambda^2R^2,\quad\mathbf{n}=\frac{\nabla E_r}{|\nabla E_r|}.$$

Simulation Setup



Two rotating models:

- Ideal MHD model
- Resistive MHD model

64^3 x 23 levels, 16 cells / λ_{Jeans}

min(Δx)～**6.6 x 10^{-5}AU**～0.014Rs

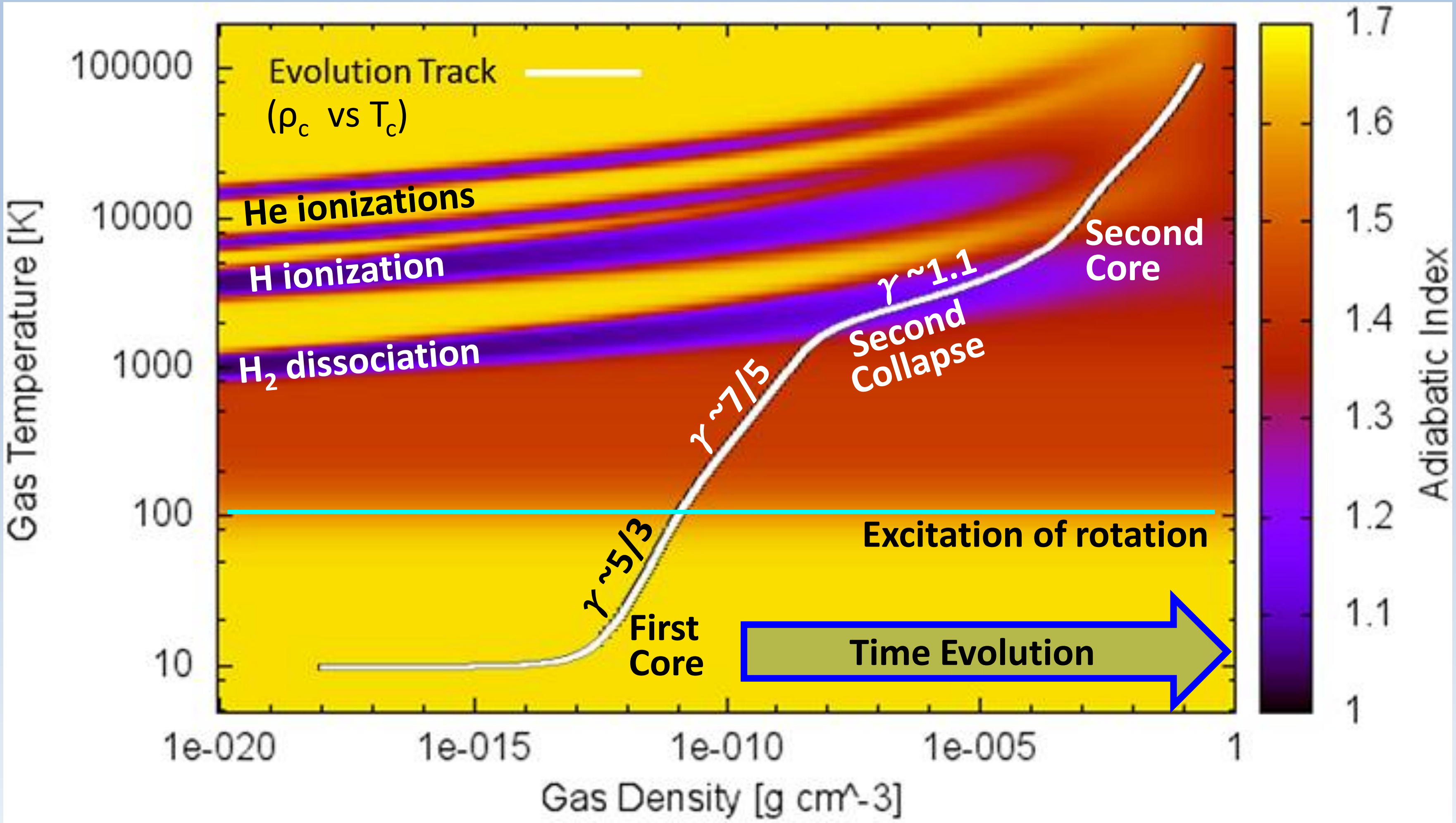
End of simulations: Tc～10^5 K,

~1 yr after 2nd core formation

Huge dynamic range > 10^8 !

- 1Ms unstabilized BE sphere（ρ_c=1.2 x 10^{-18} g/cc, T=10K, **R=8800AU**）
- Bz=20μG (μ～3.8), Ω=0.046/t_{ff} ～2.4 x 10^{-14} s^{-1} , aligned rotator
- 10% m=2 density perturbation
- Opacity: Semenov+ 2003 (dust), Ferguson+ 2005, Seaton+ 1994 (OP)

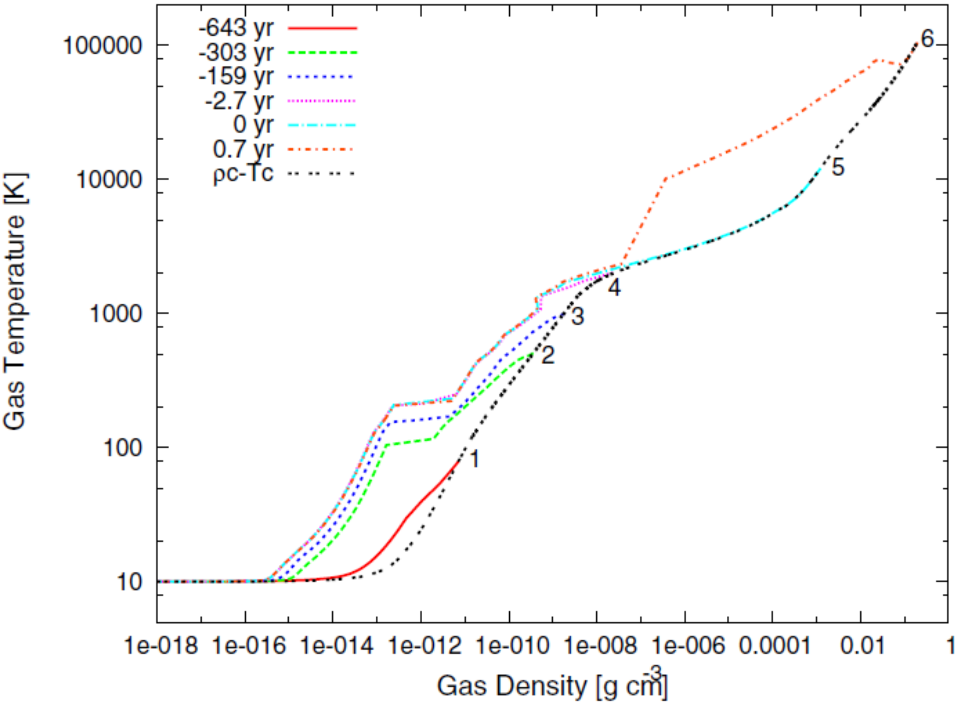
Thermal Evolution



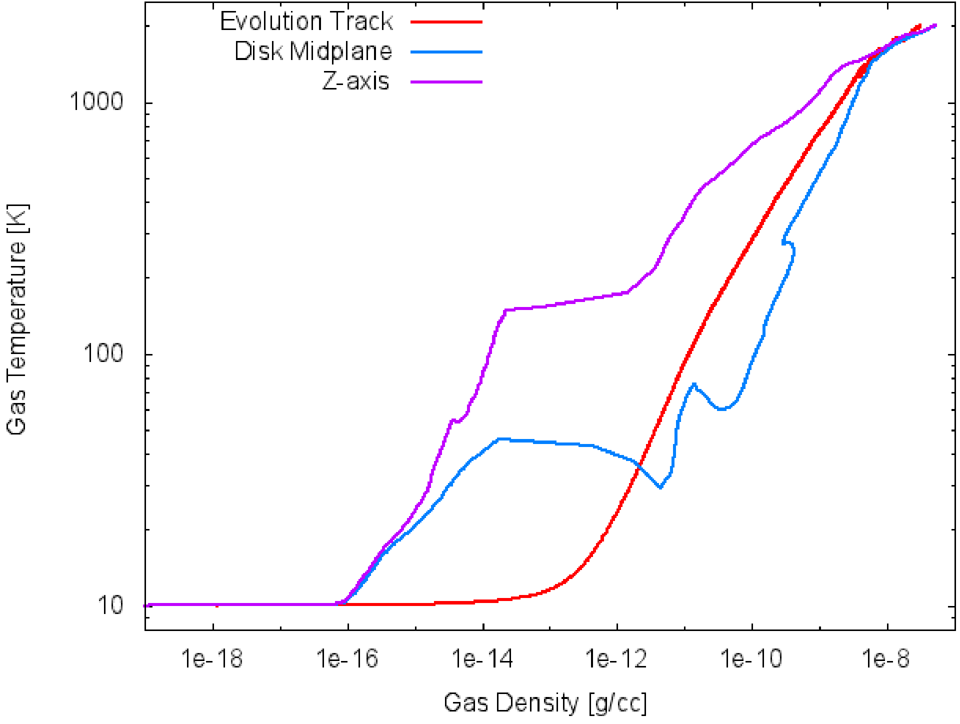
The central gas element evolves following EOS in $\rho > 10^{-12}$ g /cc.

The evolution is consistent with MI2000, except for details of EOS.

Importance of Radiation (M)HD



Spherical Model



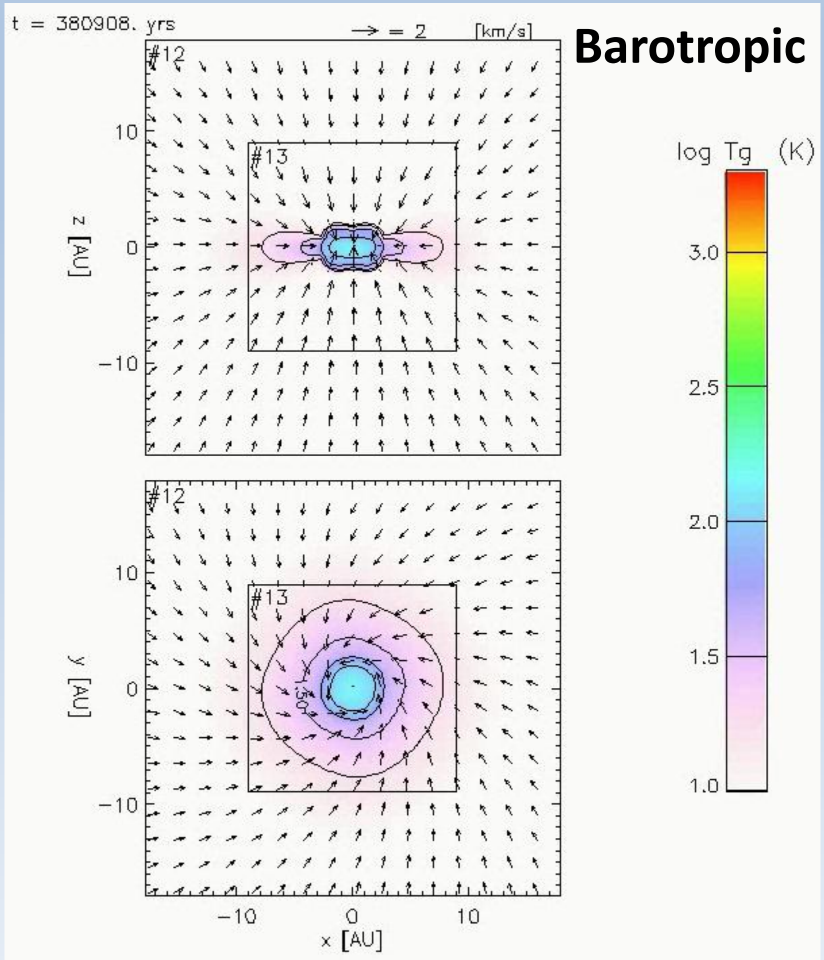
Non-magnetized Rotating Model

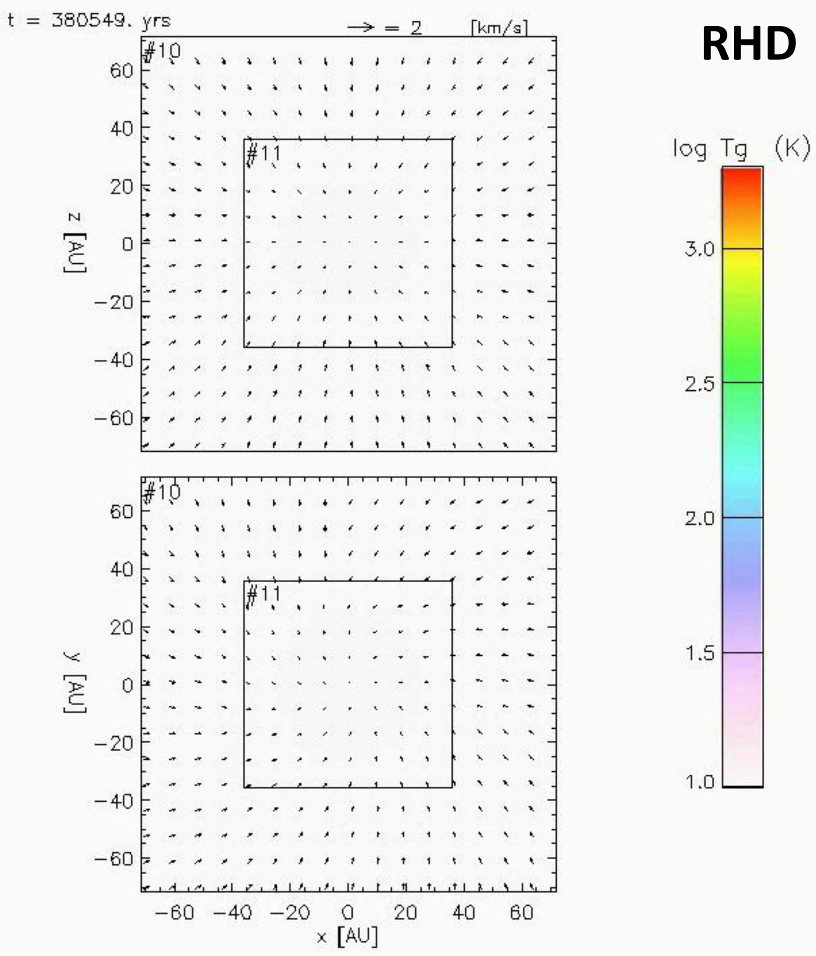
Barotropic approximation can under/overestimate the temperature.

- Non/weakly rotating cases: the temperature tend to be underestimated because shock and radiation heating are neglected.
- More complicated in rotationally-supported disks

∼ x5 difference in T ⇒ x10 difference in Jeans Mass, and stability

RHD Sims with Gray FLD Approx.

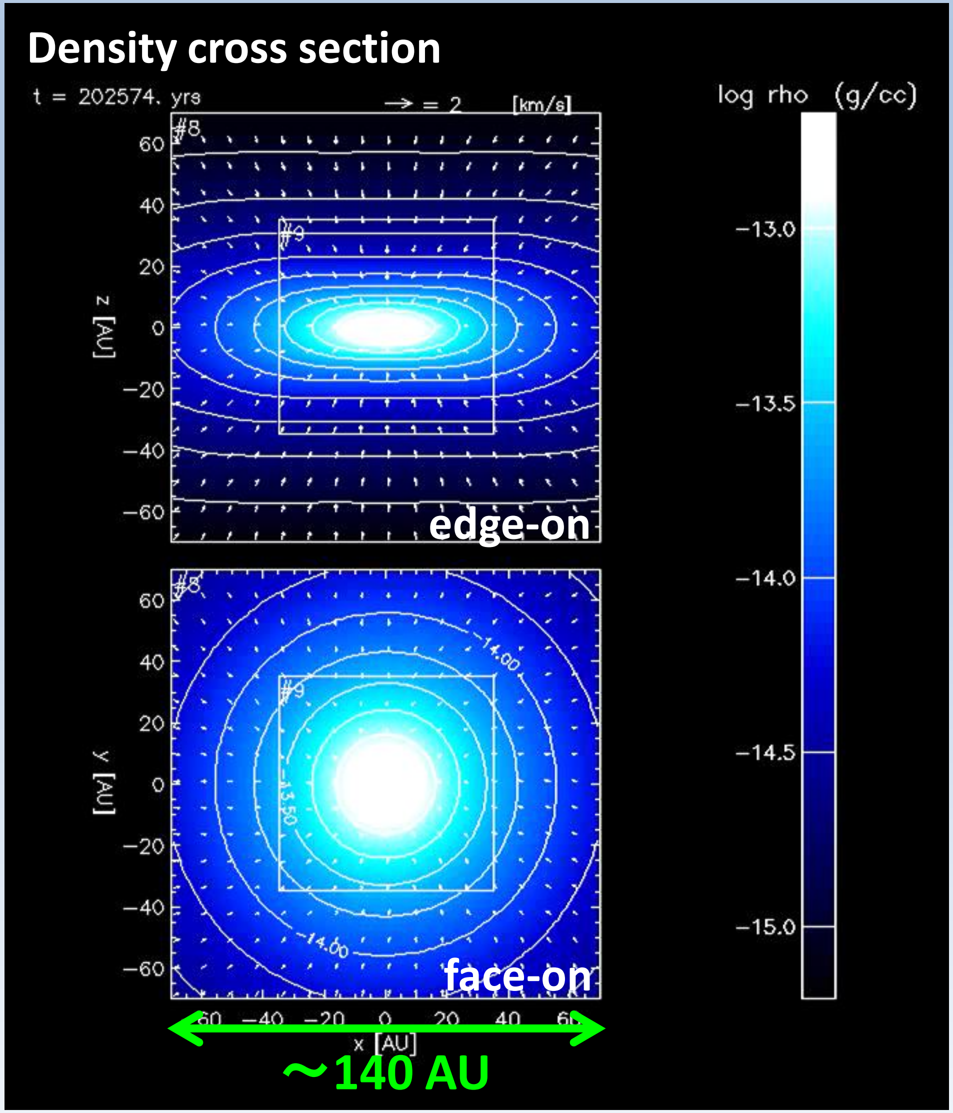




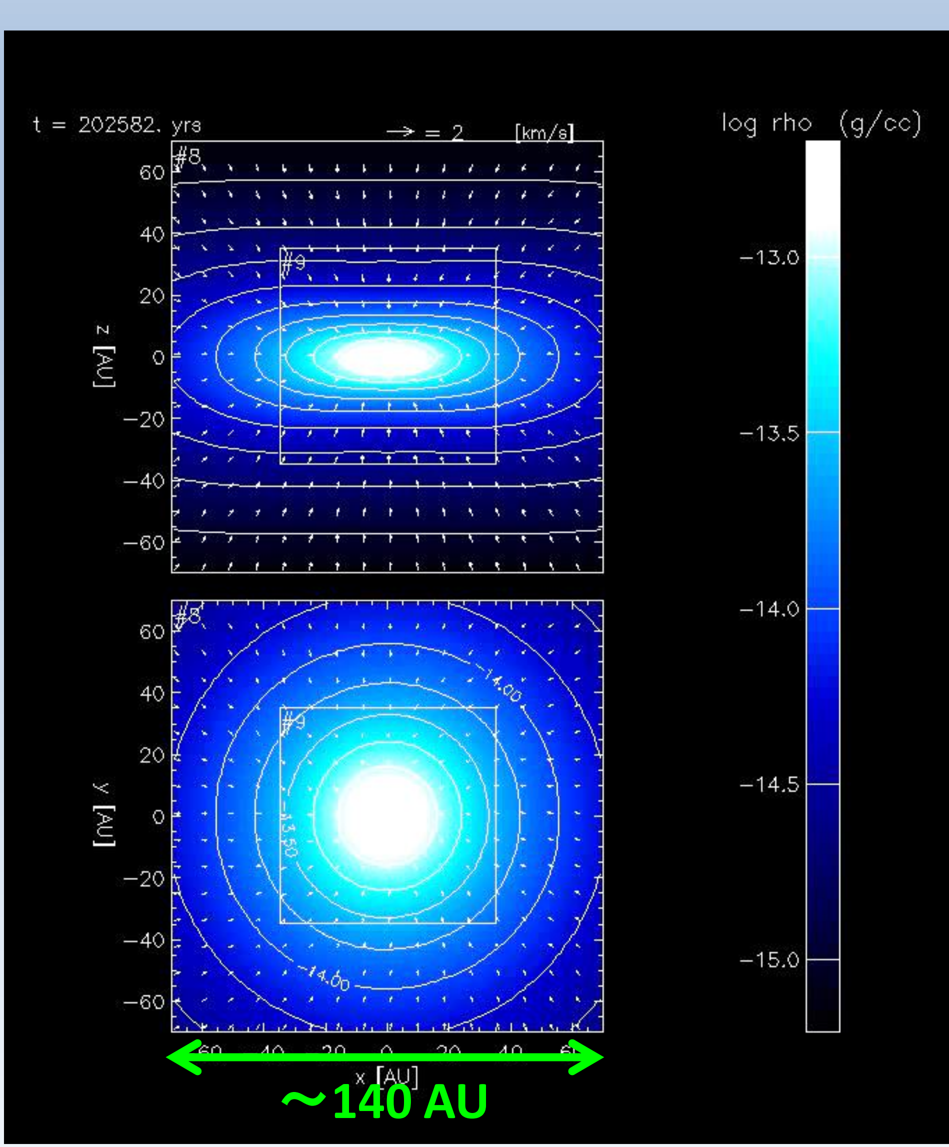
Thicker disks, spiral arms, larger first core mean that RHD is more stable. This also has a significant impact on prediction for observations.

(see, Offner et al. 09, Commercon et al. 10, 11, Tomida et al. 10a,b, Bate 10, 11, etc.)

Outflows

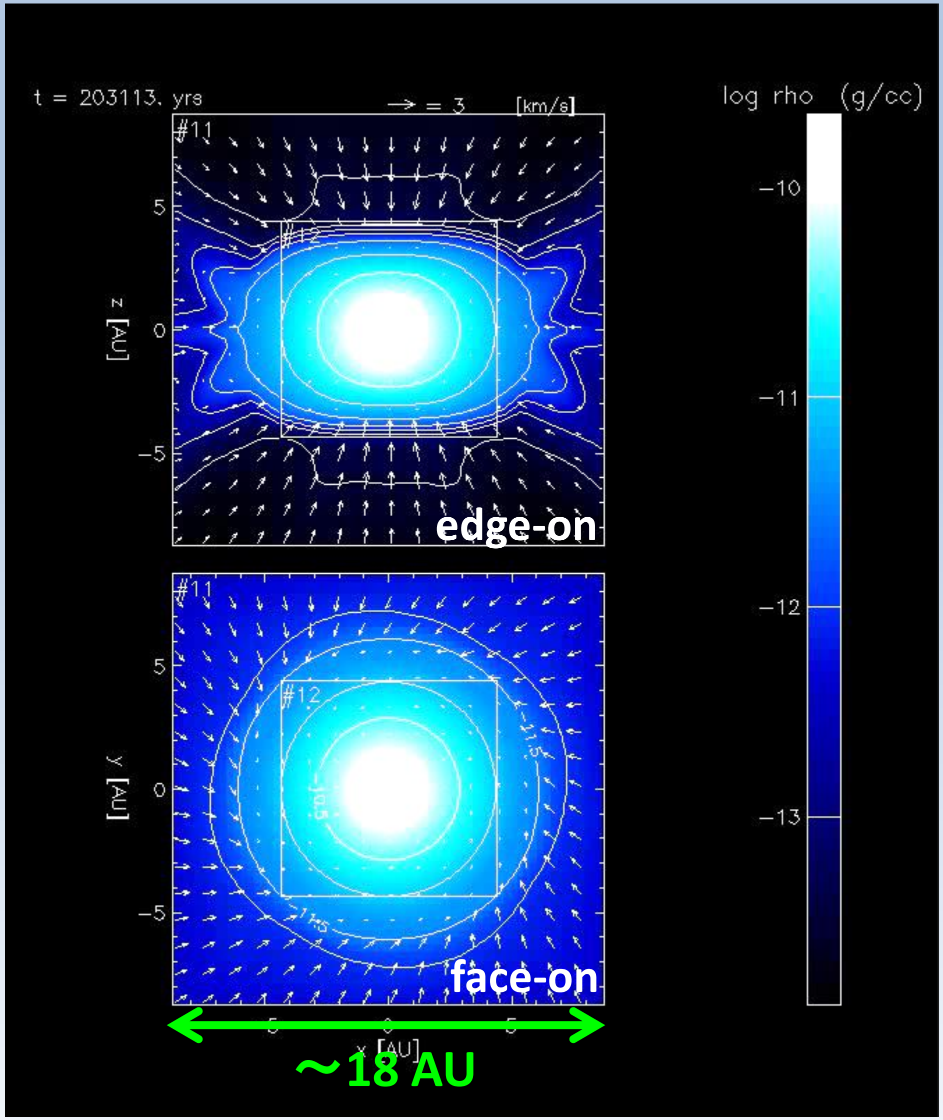


Ideal MHD

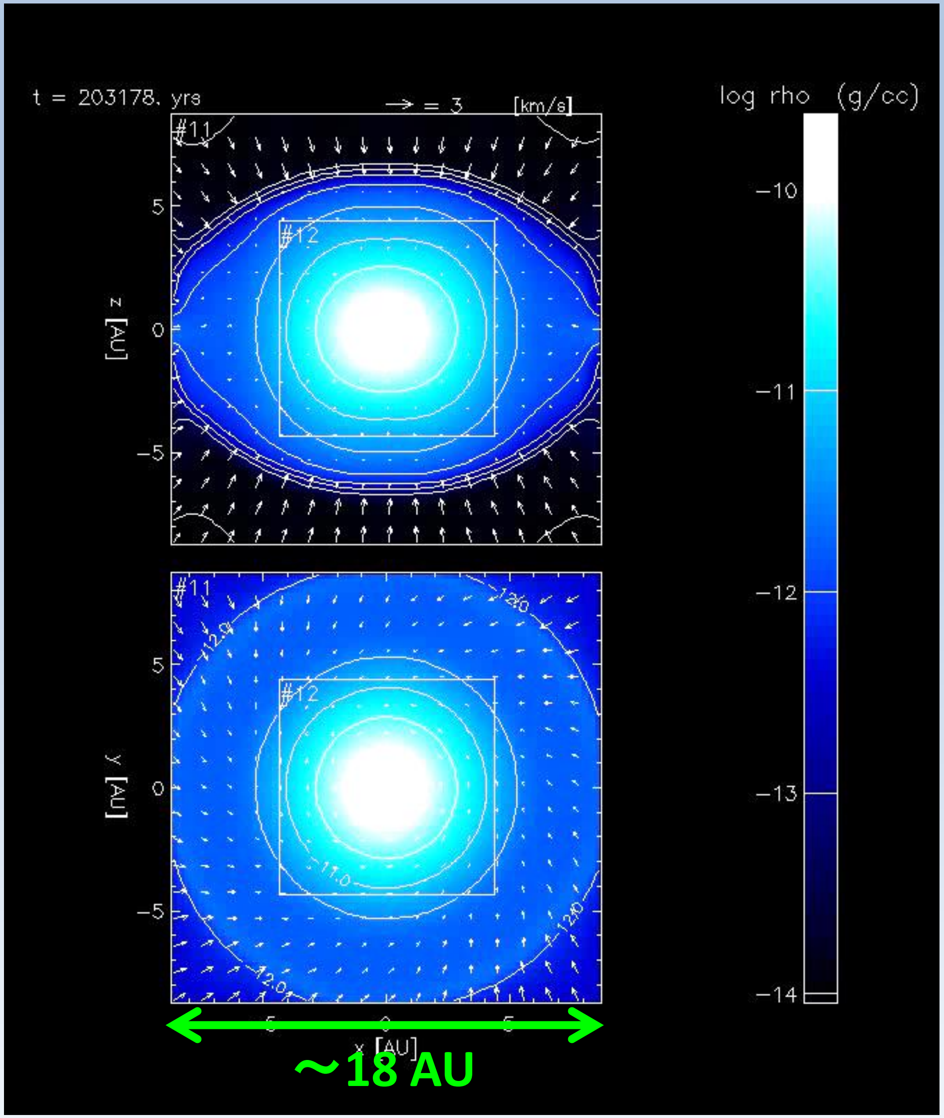


Resistive MHD

First Cores

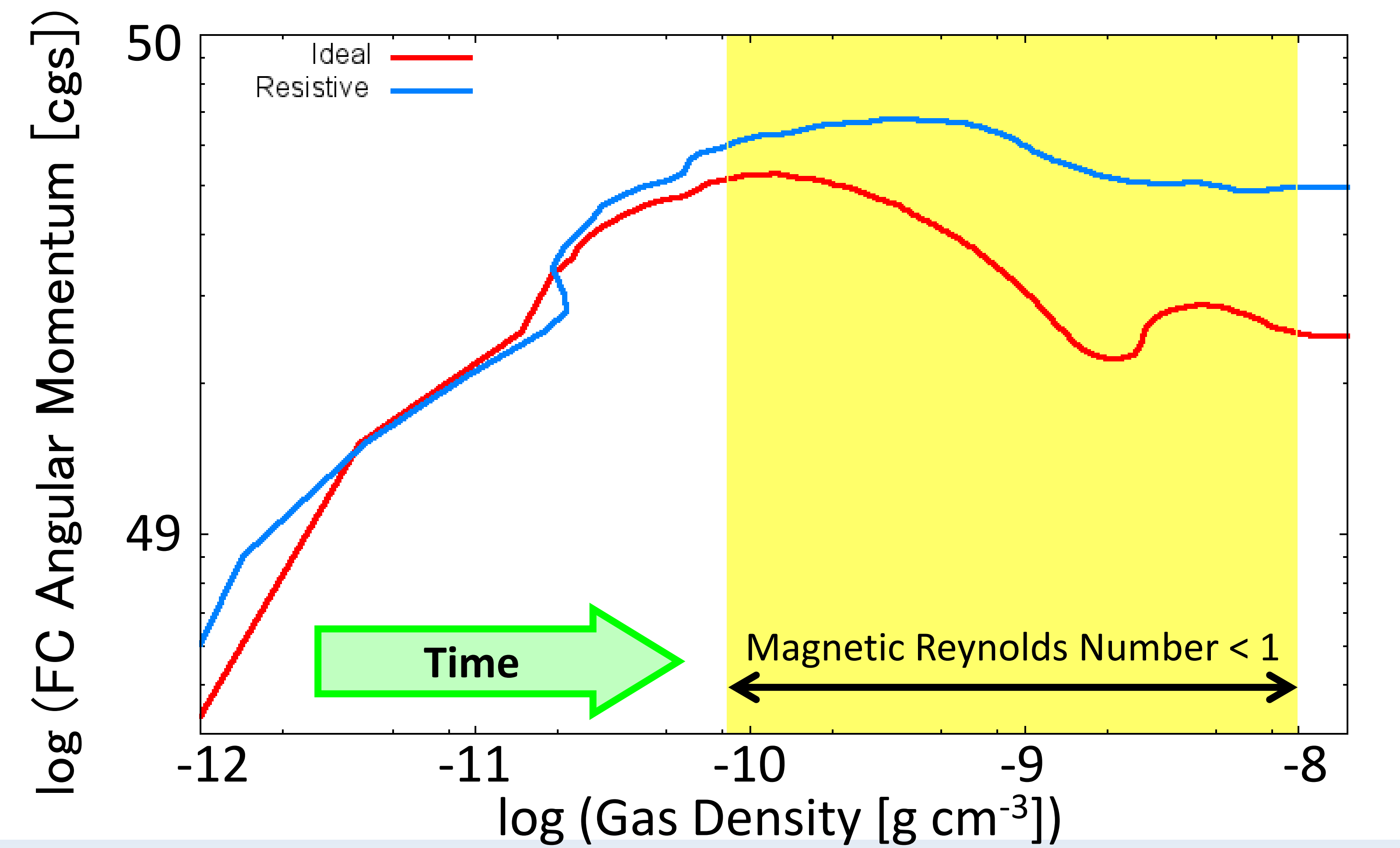


Ideal MHD



Resistive MHD

First Core Angular Momentum

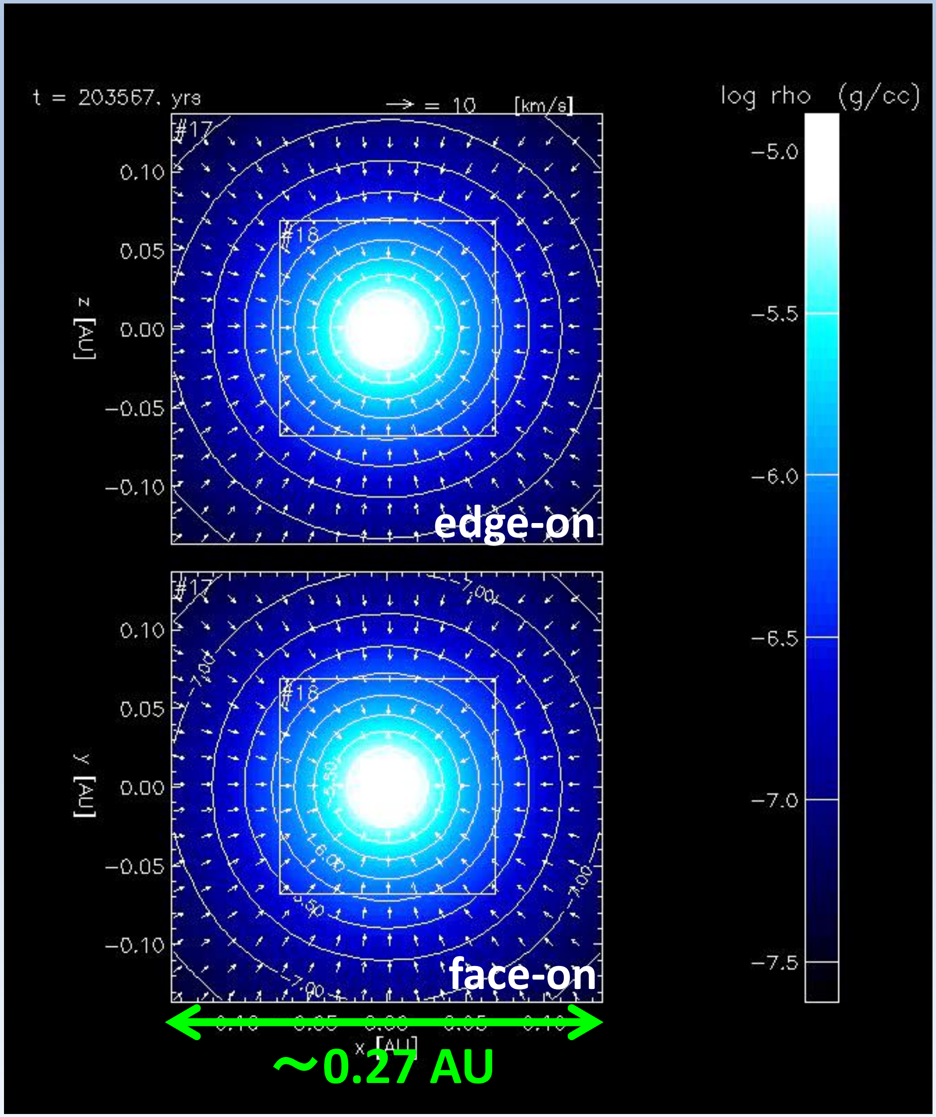


Angular momentum transport is suppressed when resistivity works.

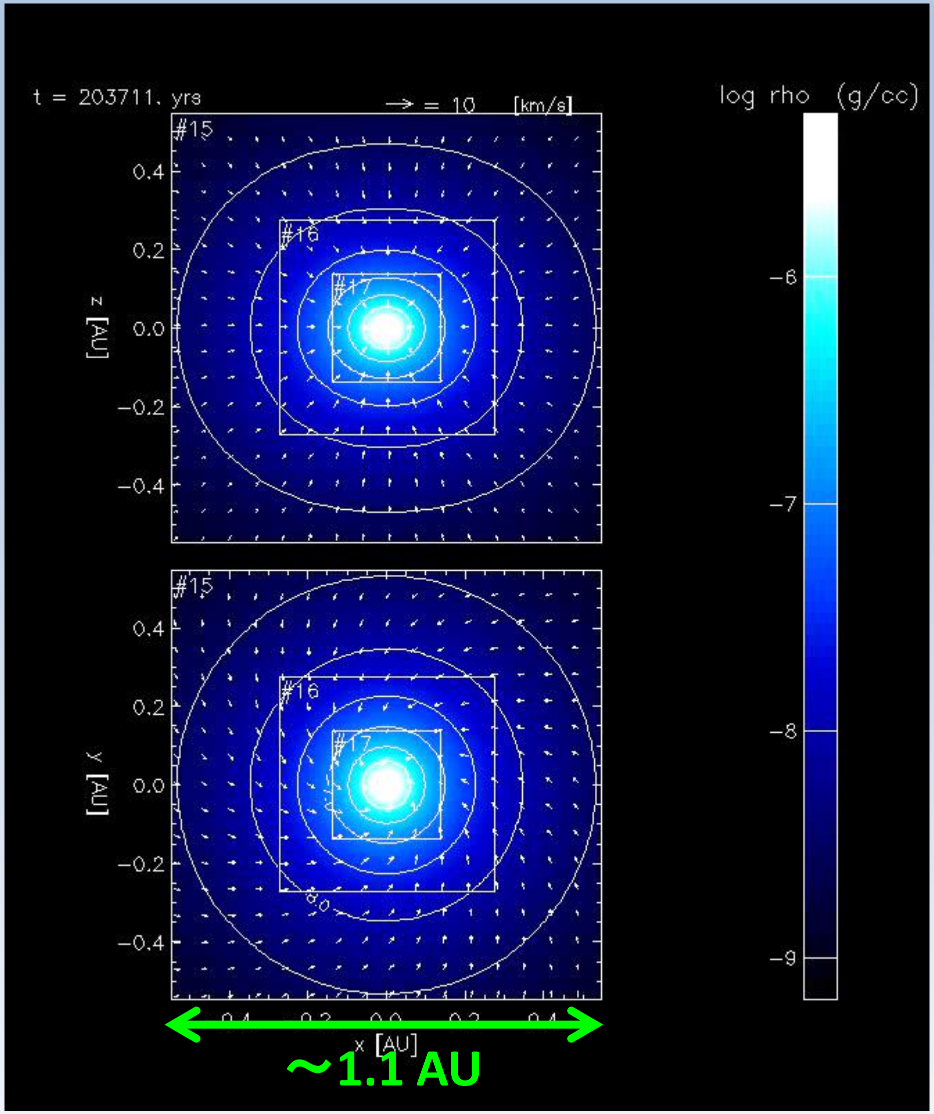
Twice larger angular momentum in FC (more significant in PC)

Longer lifetime due to rotational support:Ideal 800yrs→Resistive 950yrs

Protostellar Cores, Disk and Jet



Ideal MHD



Resistive MHD

Protostellar Cores

Radii, Masses, Angular momenta⇒

PCs acquire ~0.02 Ms in ~ 1yr

Ideal MHD model = virtually spherical

←very low angular momentum

Circumstellar disk is not formed

“**Magnetic Braking Catastrophe**”

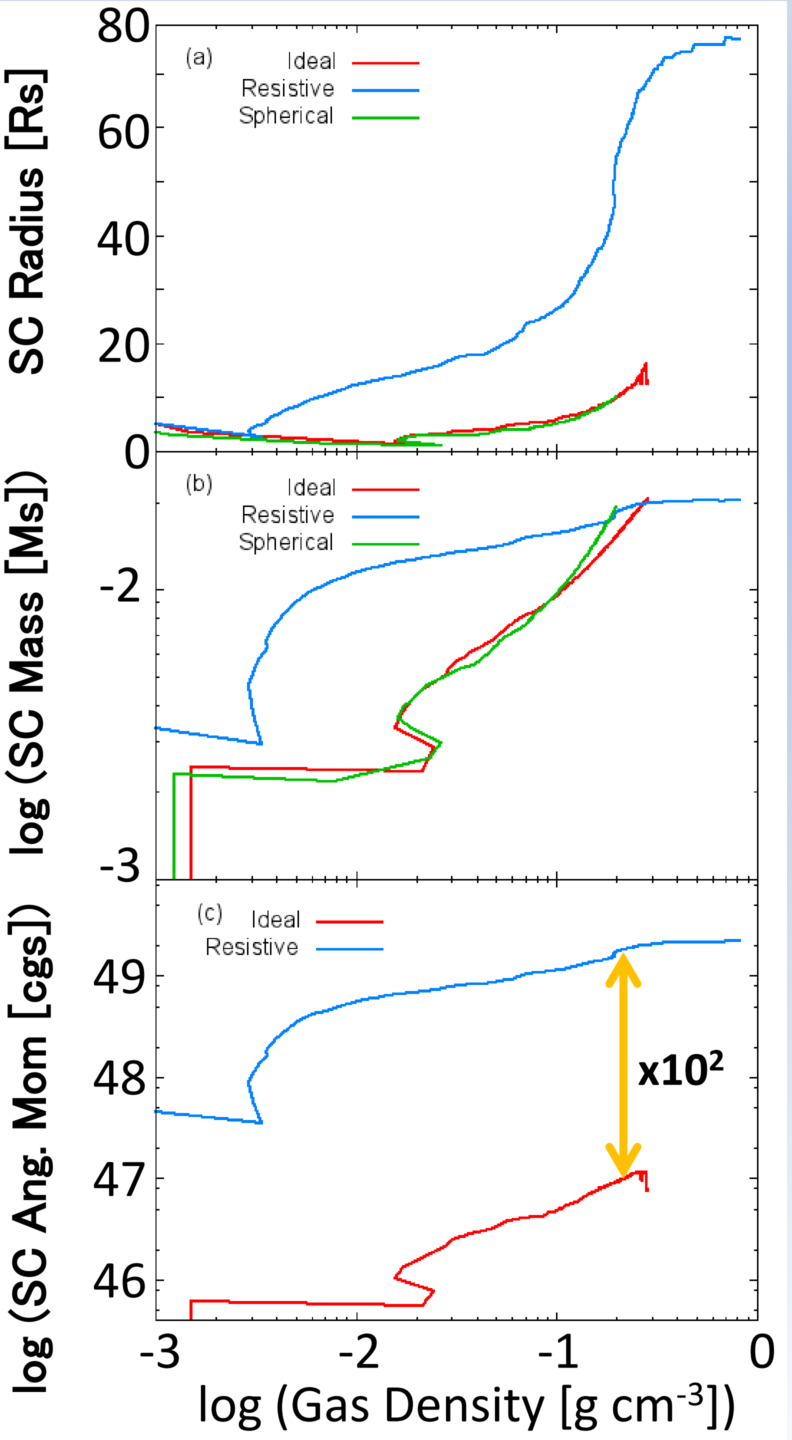
Resistive MHD: large ang. momentum

→rotationally supported disk is formed

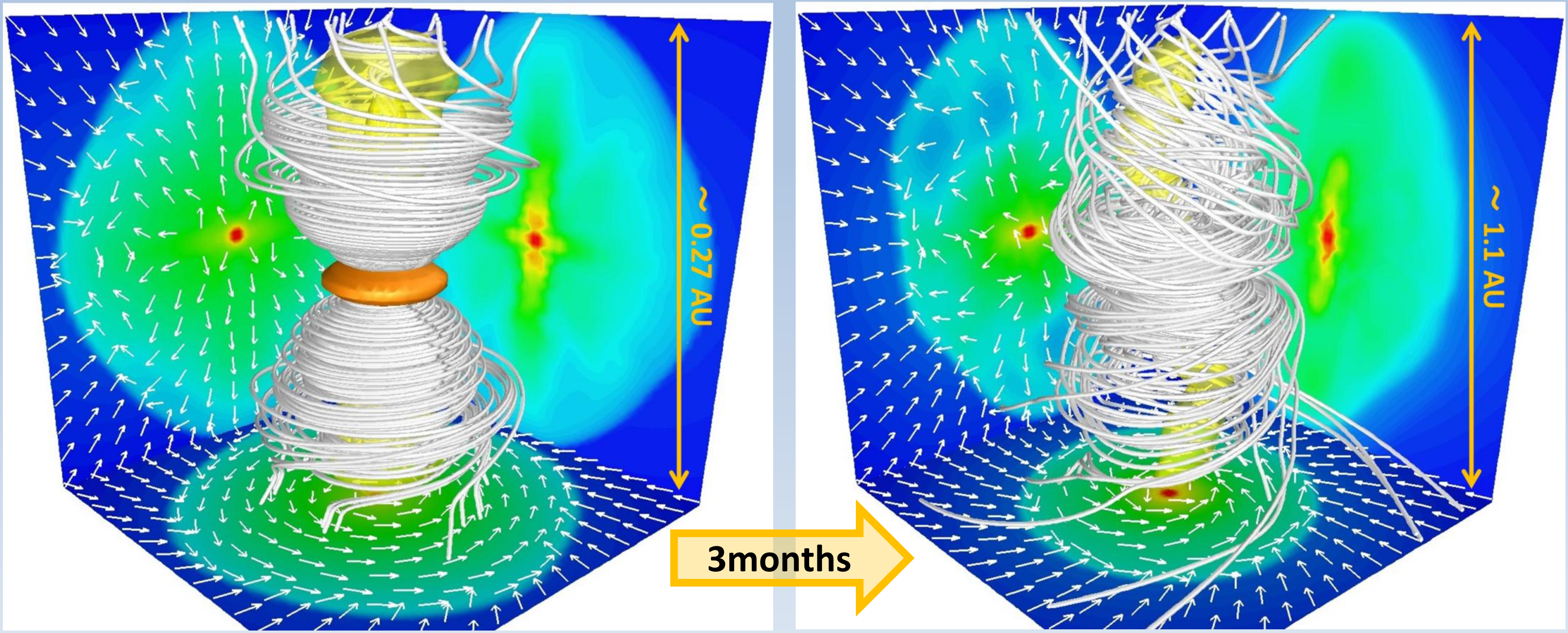
Rdisk ~ 0.3 AU at the end of simulation

It will continuously grow via accretion

⇒**NO Magnetic Braking Catastrophe**



Fast outflow from protostellar core



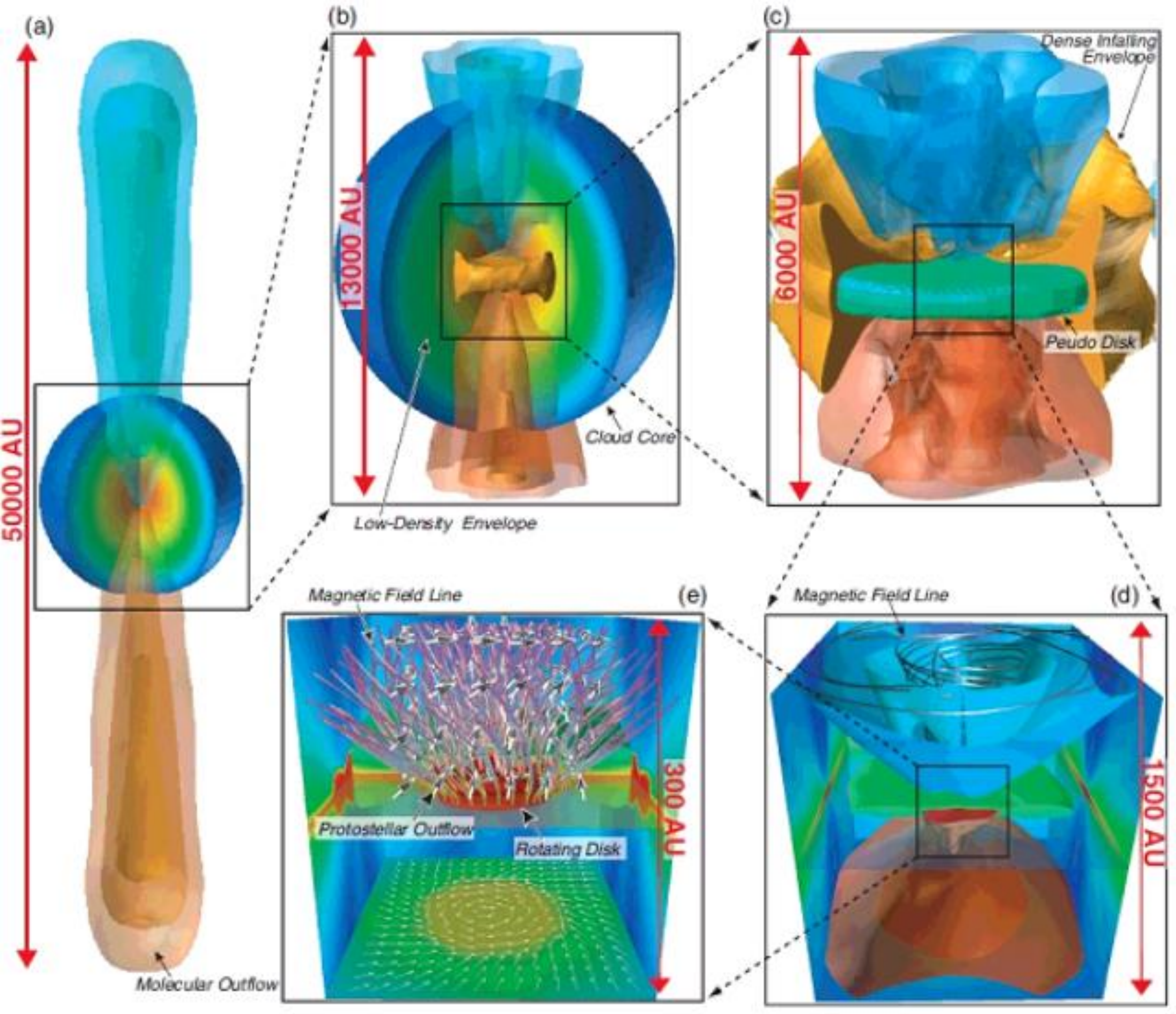
Toroidal fields are rapidly amplified by rotation in resistive case.

→Fast outflow（≳15km/s）is driven by magnetic pressure

Consistent w/ previous MHD sims（Machida et al. 08 etc.）

The magnetic tower is disturbed by the kink instability.

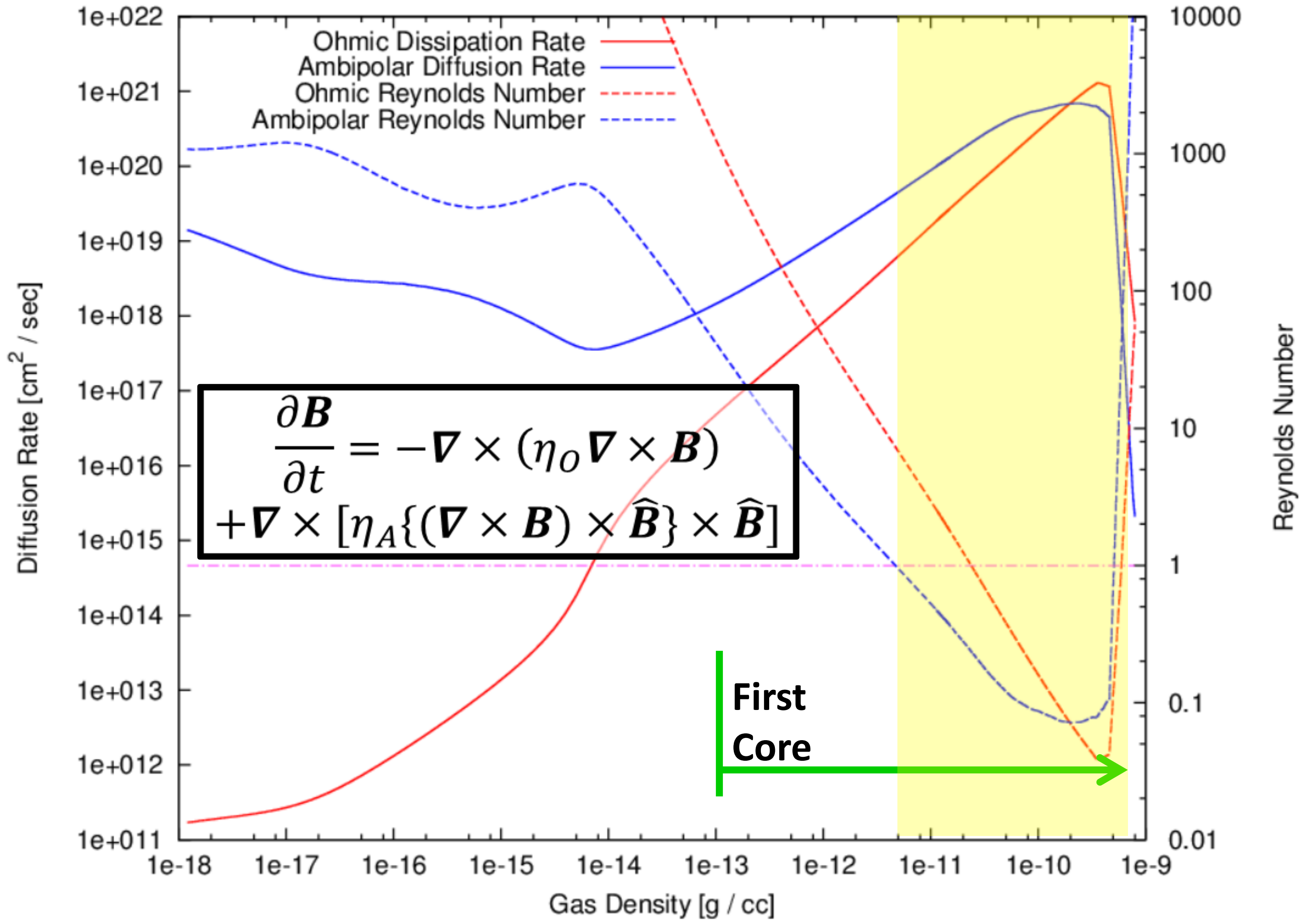
Fate of the disk and outflows



Machida & Hosokawa 13
(they are not
allergic.)

Long-term (till class-I phase) MHD simulation using a sink particle.
Outflows and disks grow continuously, $R_{disk}\sim100$ AU

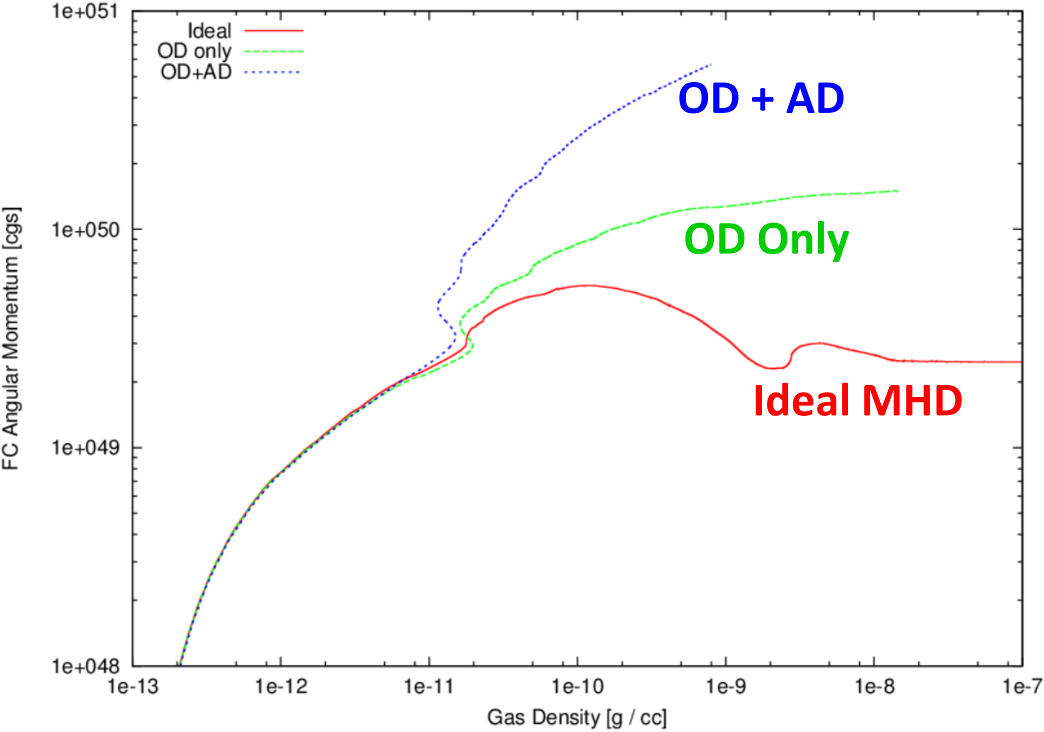
Preliminary: Ambipolar Diffusion



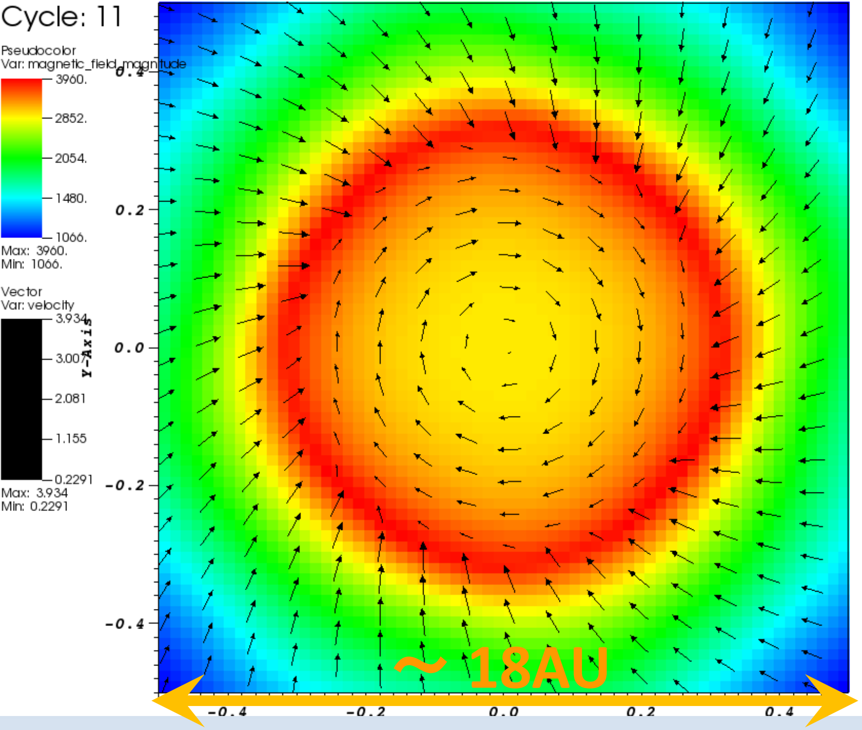
$$\frac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times (\eta_O \boldsymbol{\nabla} \times \boldsymbol{B})$$
$$+\boldsymbol{\nabla} \times [\eta_A\{(\boldsymbol{\nabla} \times \boldsymbol{B}) \times \hat{\boldsymbol{B}}\} \times \hat{\boldsymbol{B}}]$$

Ambipolar diffusion rate is very high and works in a relatively low density region ⇒ more magnetic flux loss will occur.

Angular Momentum in FC



Color = B-field

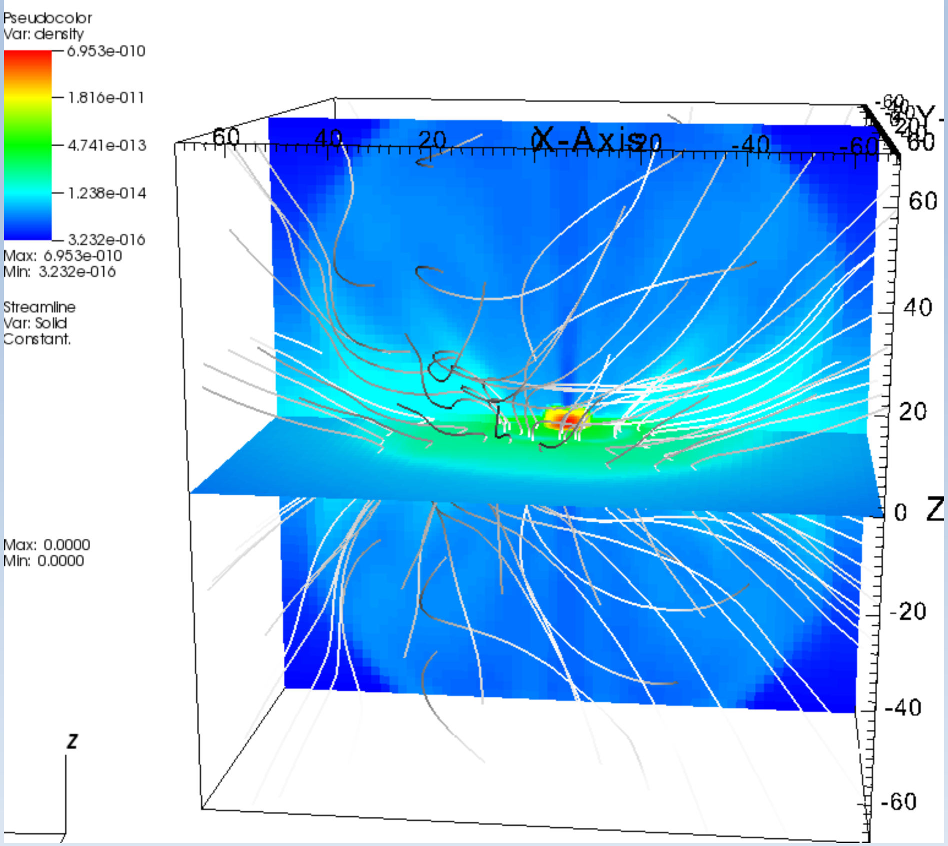


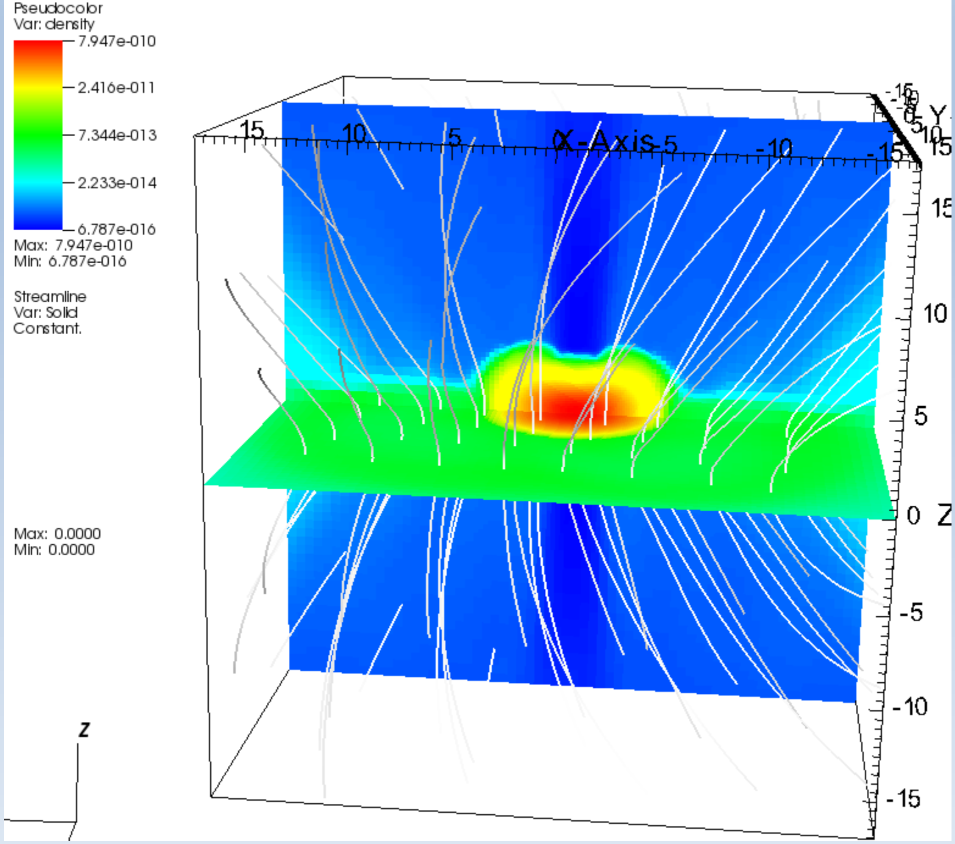
(in the middle of the first core phase, Tc～800K)

Large angular momentum remains in the FC ⇒ earlier disk formation.

The rotating disk is resistive: magnetic flux is removed from the dense central region and piles up outside the disk.

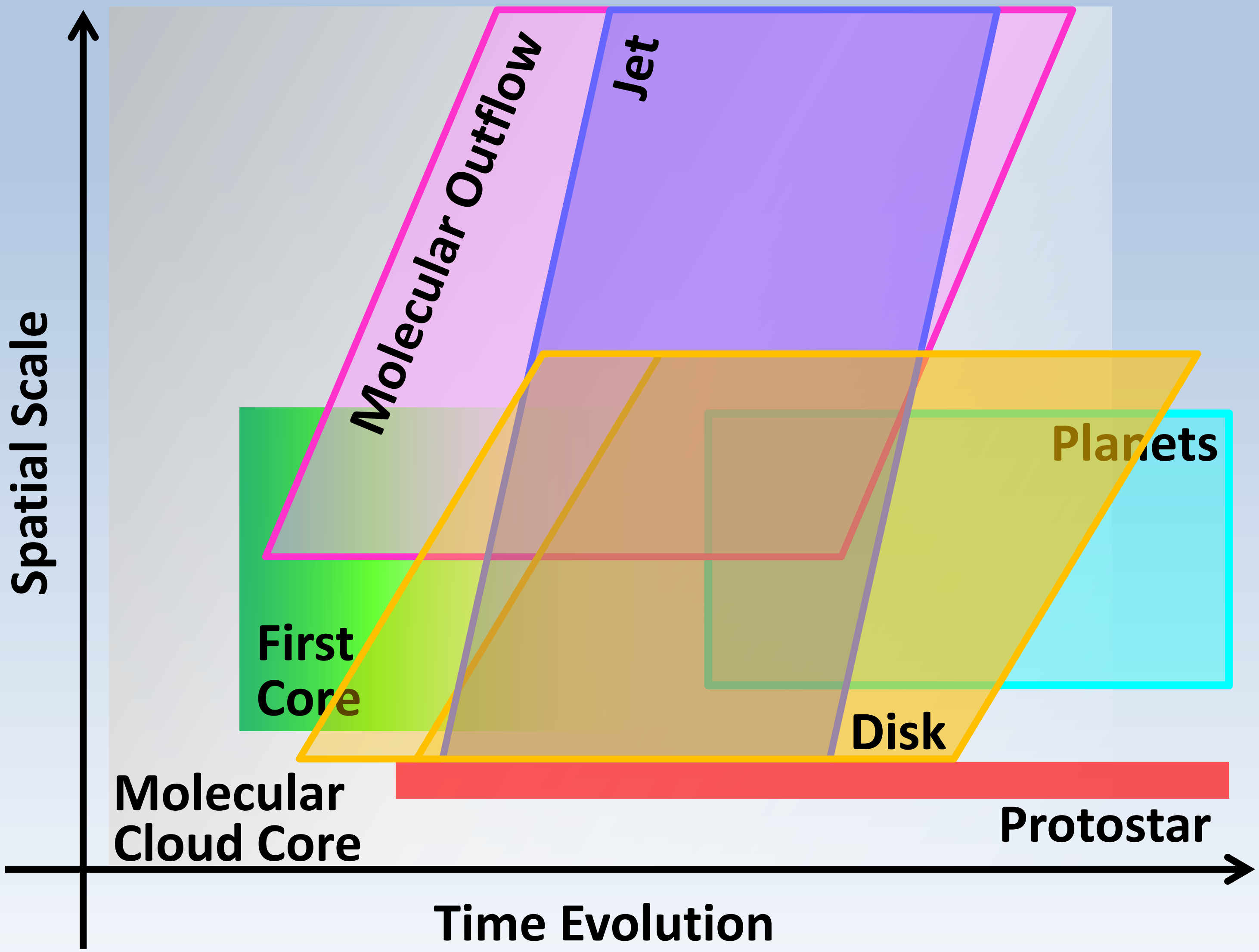
Outflows and First Core with AD





The bipolar outflows are very similar to the previous cases.
First core becomes disk-like because of rotational support.
However, the disk radius is still small, about 5 AU.

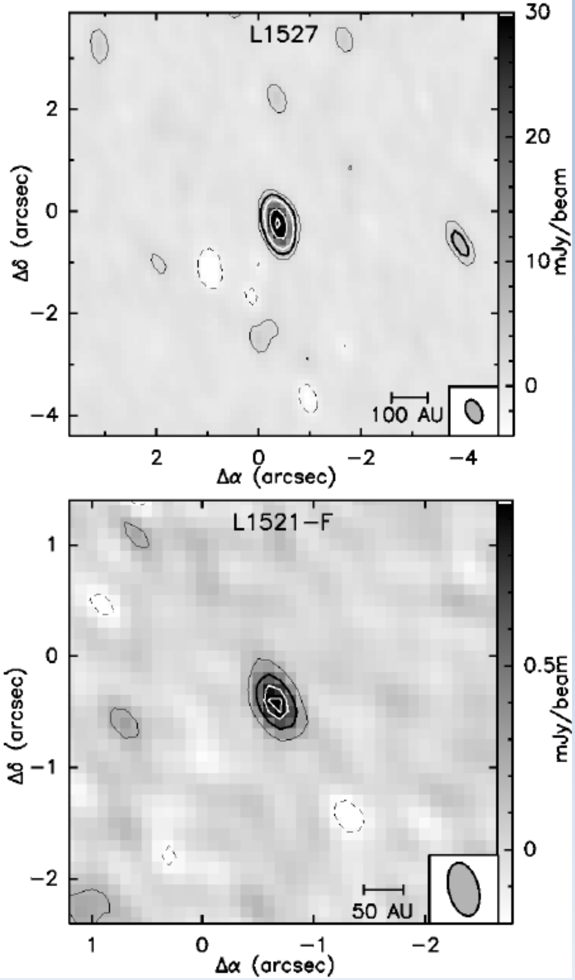
To Summarize: A Schematic Picture

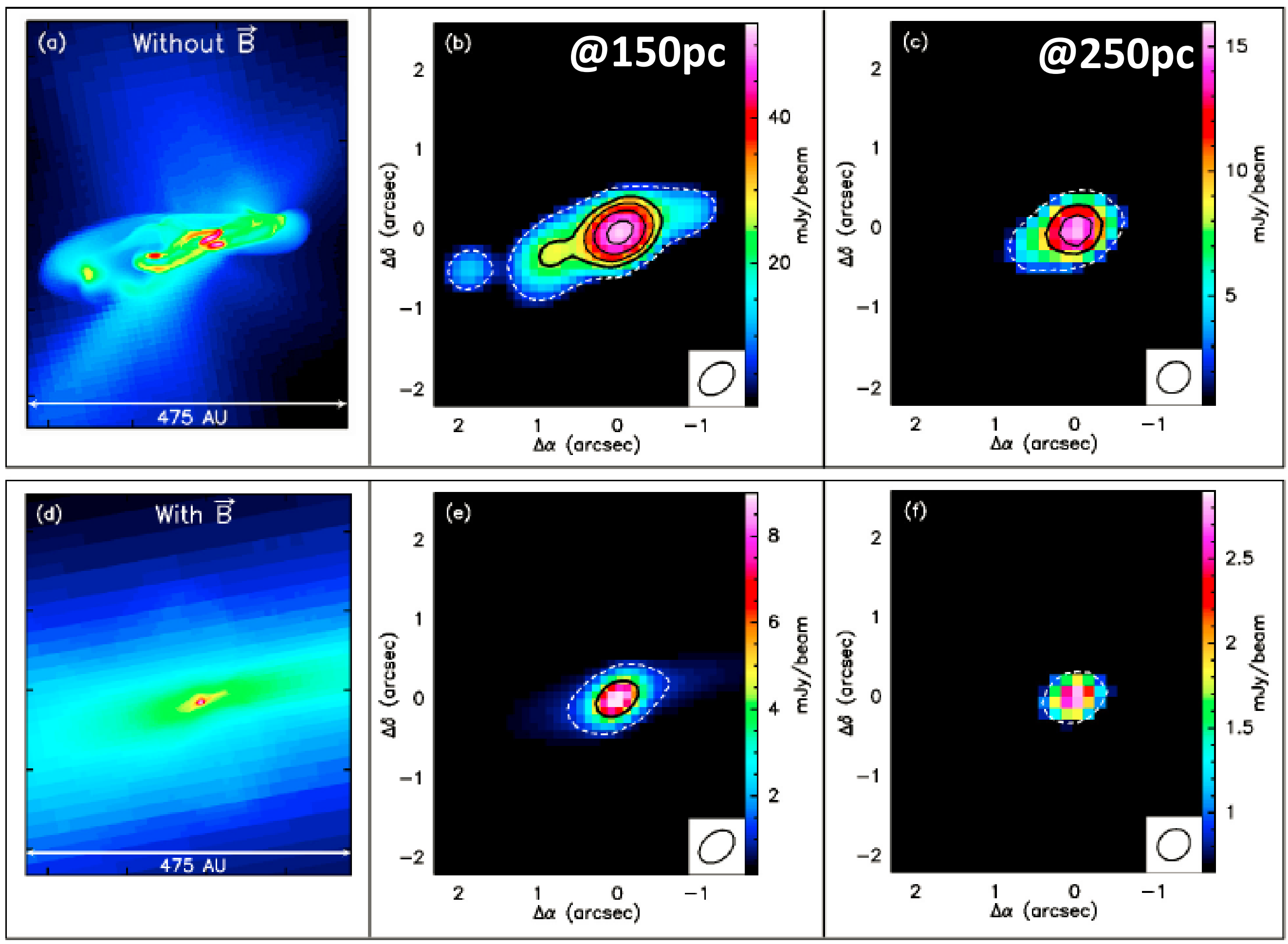


Implications from / for Observations

Observations of Young Disks

Maury et al. 2010

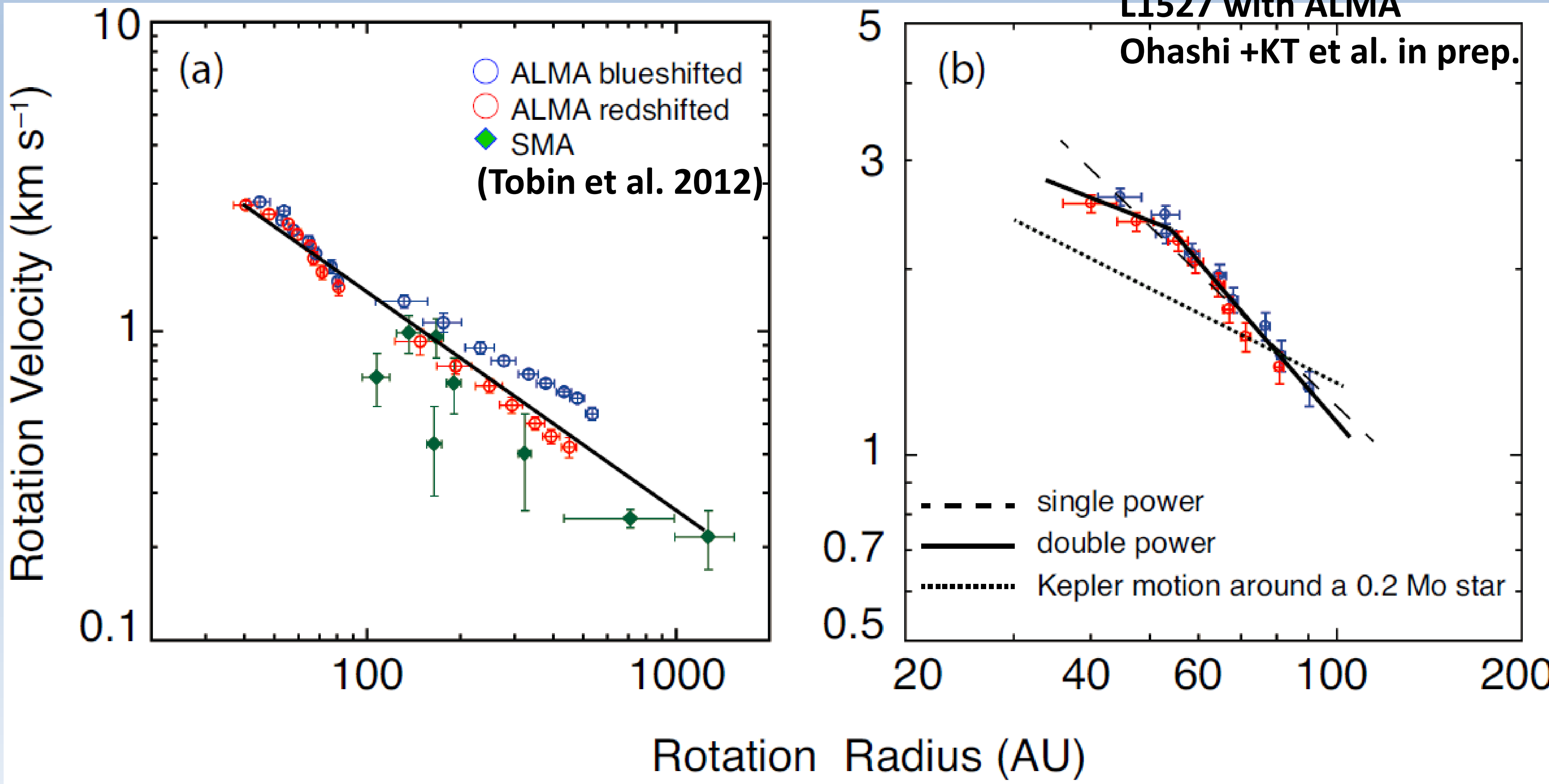




1.3mm Dust continuum observations of Class-0 sources with PdBI.

The observed disks are small and more consistent with the MHD models.

A well-studied example: L1527 IRS



(Tobin et al. 2012)

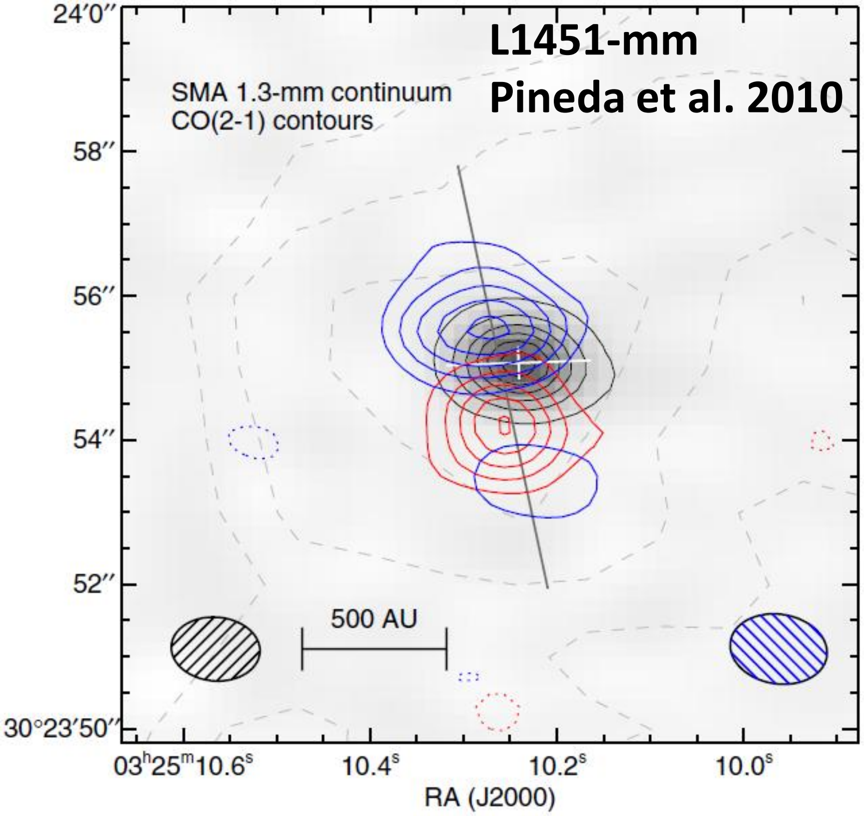
L1527 with ALMA
Ohashi +KT et al. in prep.

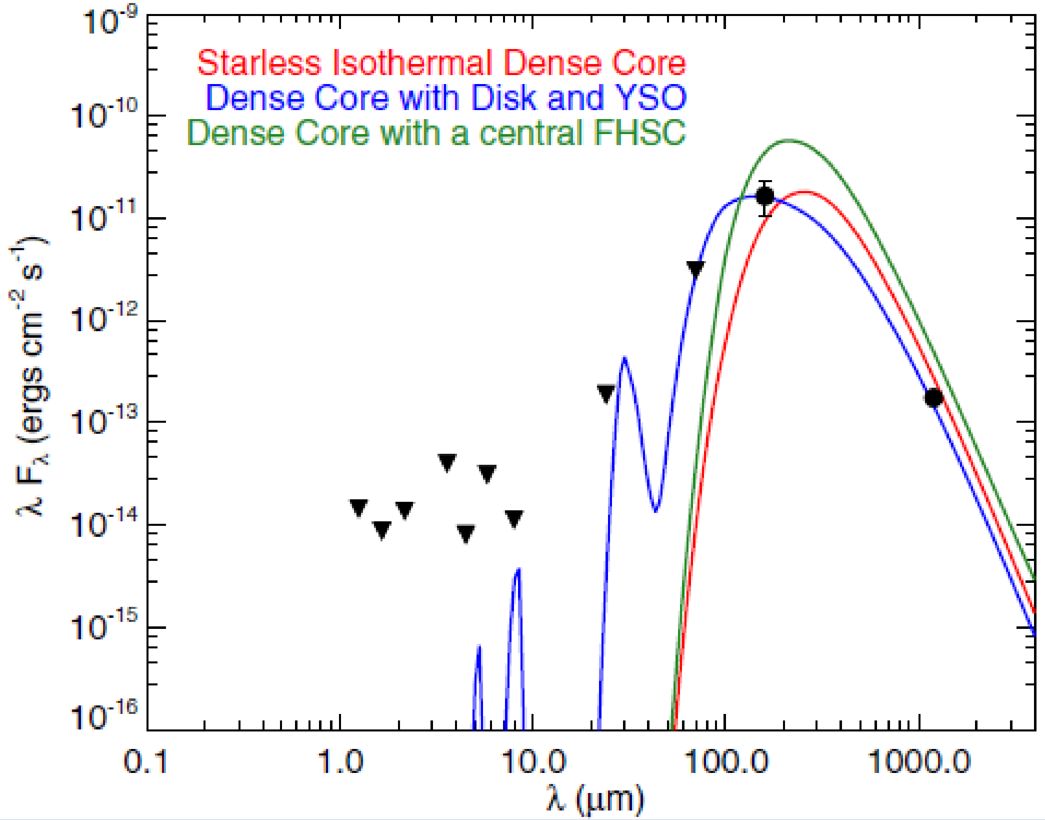
Tobin+ 2012 (SMA & CARMA): R～120 AU disk around 0.2 Ms protostar

Ohashi+ in prep. (ALMA Cycle-0): R＜60AU disk around 0.3 Ms protostar

⇒Disks can be formed early, but should be small in the early phase

Even Younger: First Core Candidates

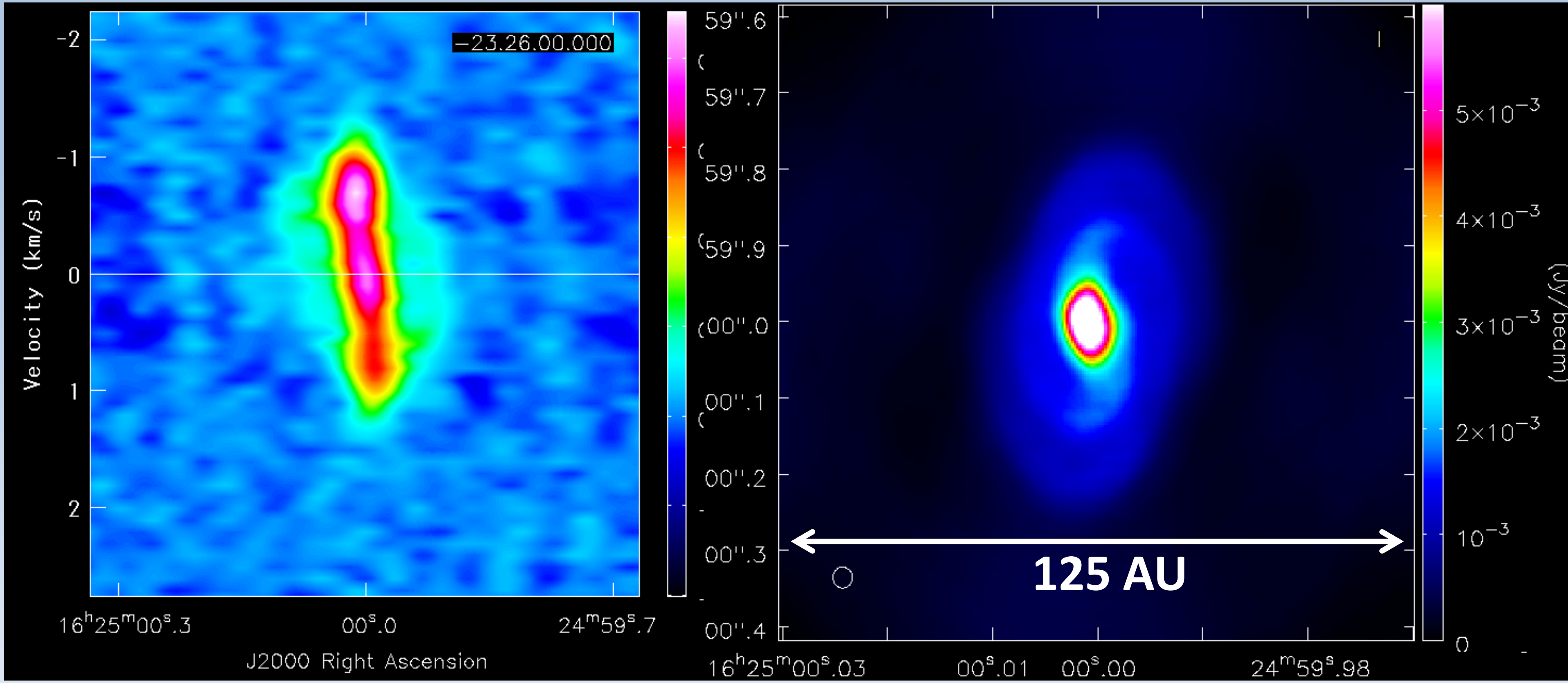

L1451-mm
Pineda et al. 2010



Recent first core candidates: L1451-mm, Barnard 1-bN, Per-Bolo 58 etc.

- Faint compact molecular cores without stellar NIR emission
- Associated with compact, slow outflows without fast jet
- However: it must be rare: ～1 FC in 100-1000 molecular cloud cores
- Predicted in Larson 1969 but not confirmed observationally yet

Synthetic Observations



Left: $C^{34}S$(5-4), Cycle-0, extended, 0.5arcsec, 4h, P-V diagram
Right: 345GHz continuum, Full ALMA, 0.02arcsec, 4h (Tomida, PhD Thesis)

Motivated by ALMA, theoretical predictions based on the results of R(M)HD simulations are actively performed. (especially for first cores.)

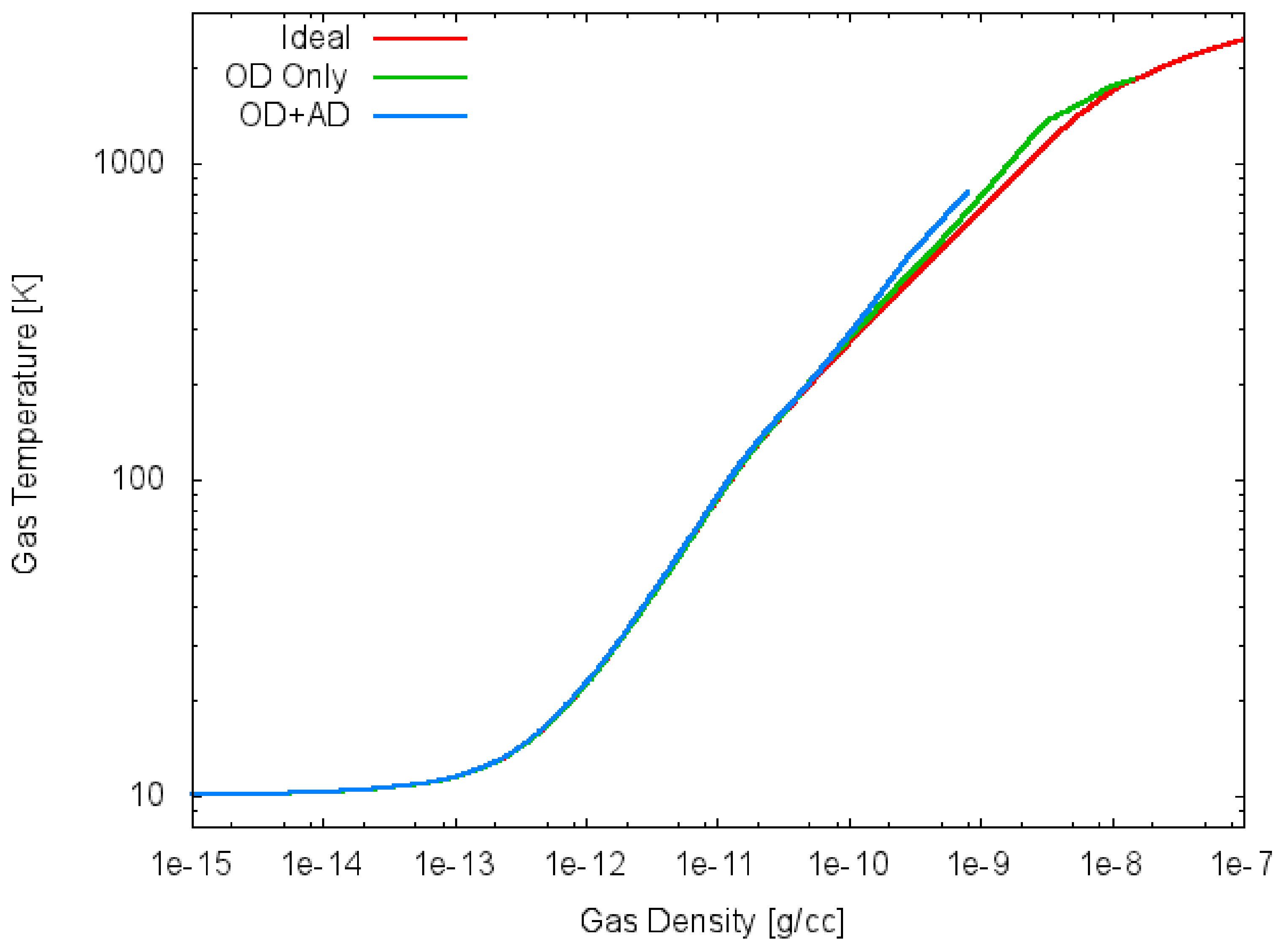
Summary

RMHD simulations of protostellar collapse with non-ideal MHD

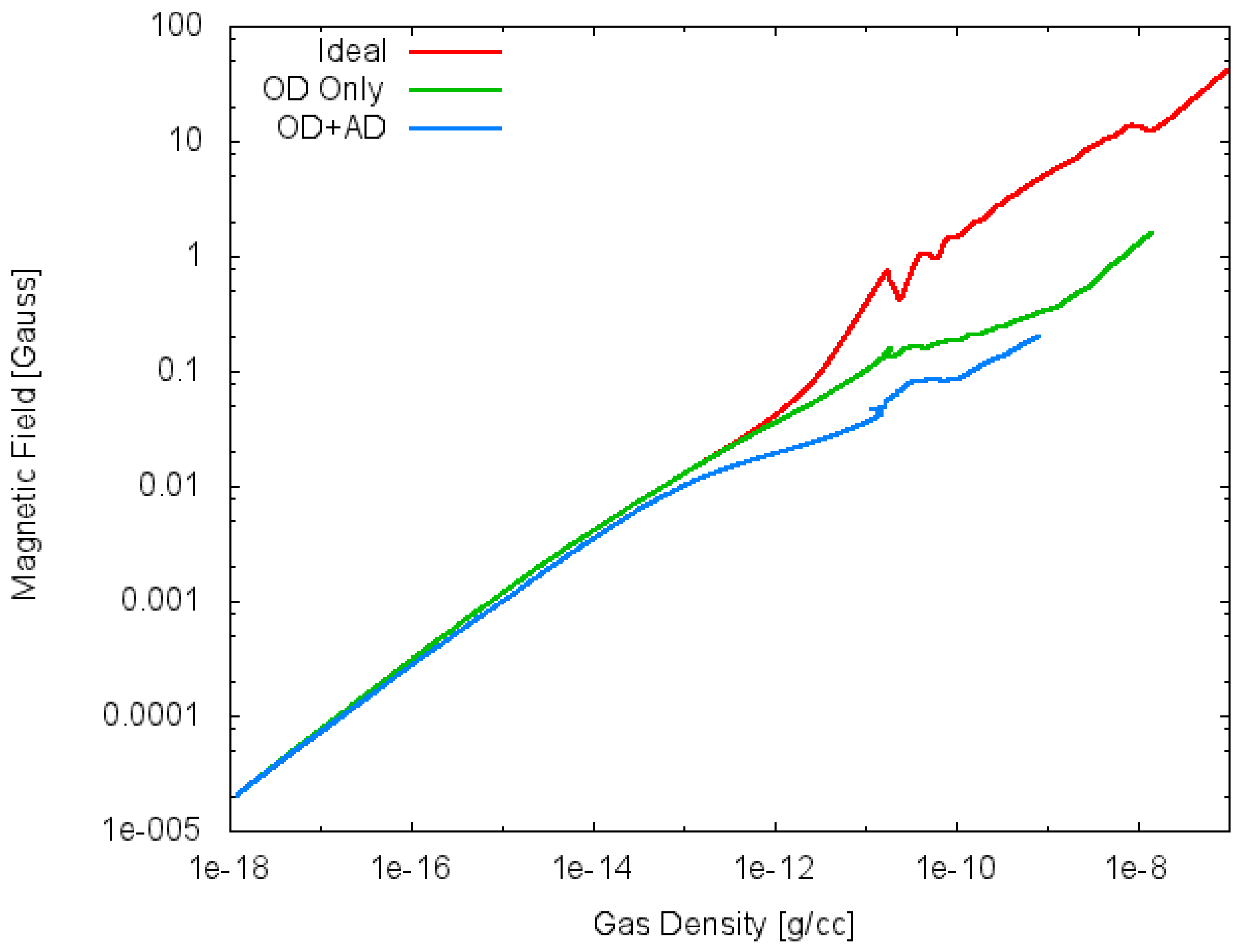
- Radiation transfer and realistic thermodynamics are important
- Magnetic braking is so efficient in the ideal MHD case that no rotationally-supported disks can be formed in the early phase
- Ohmic dissipation enables early formation of disks
- As natural byproducts, two different outflows are launched: slow, loosely collimated outflows from the first core scale and fast, well collimated jets from the protostellar core scale
- (preliminary!) With ambipolar diffusion, disk formation can be possible even before the second collapse (= birth of a star)
- Disks can be formed early, but should be small, will grow later
- Magnetic Braking Catastrophe is not so catastrophic as it sounds, rather a quantitative question: how, when, and how massive?
- ALMA observations of young disks will be crucial

Thank you!

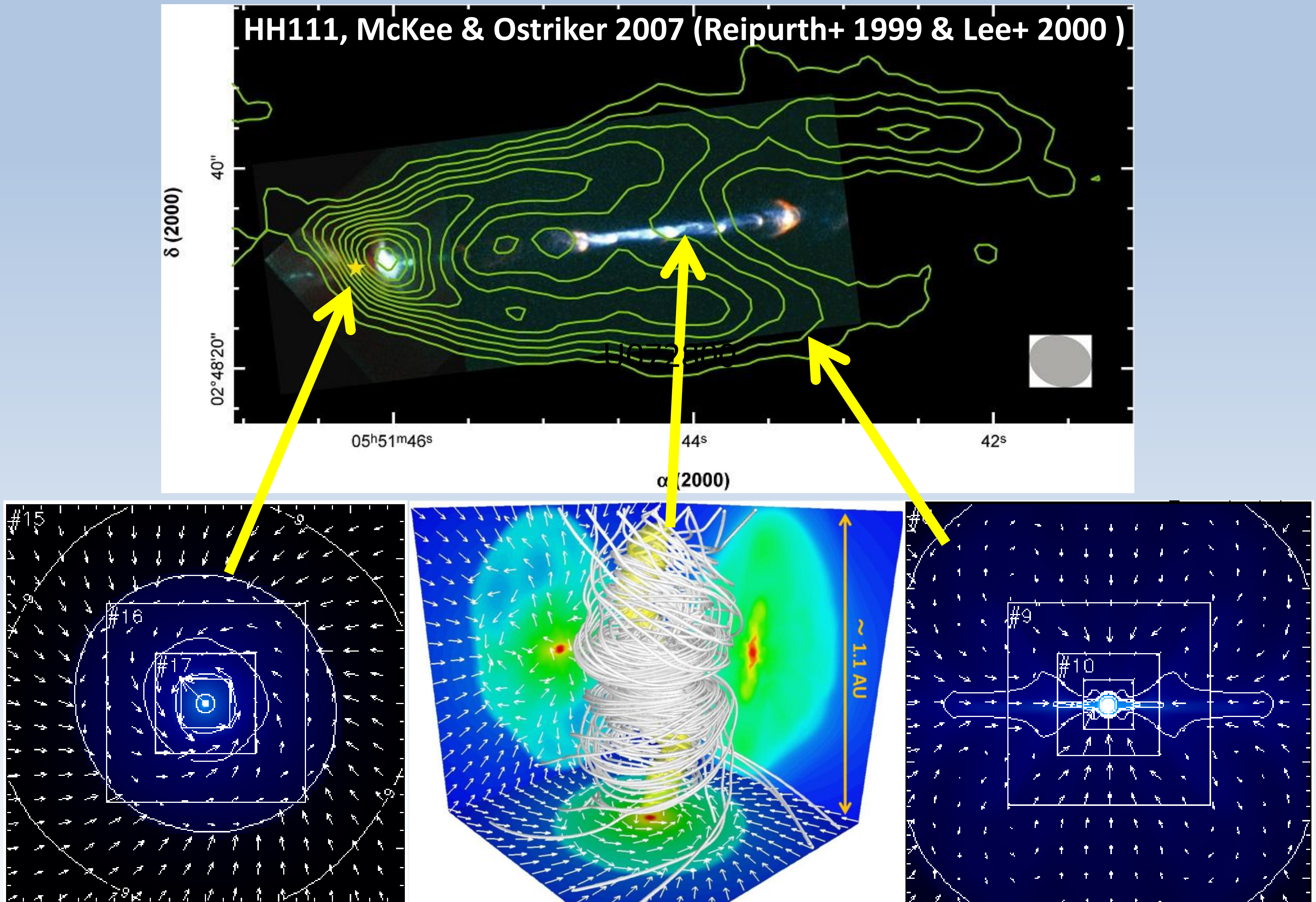
Thermal Evolution



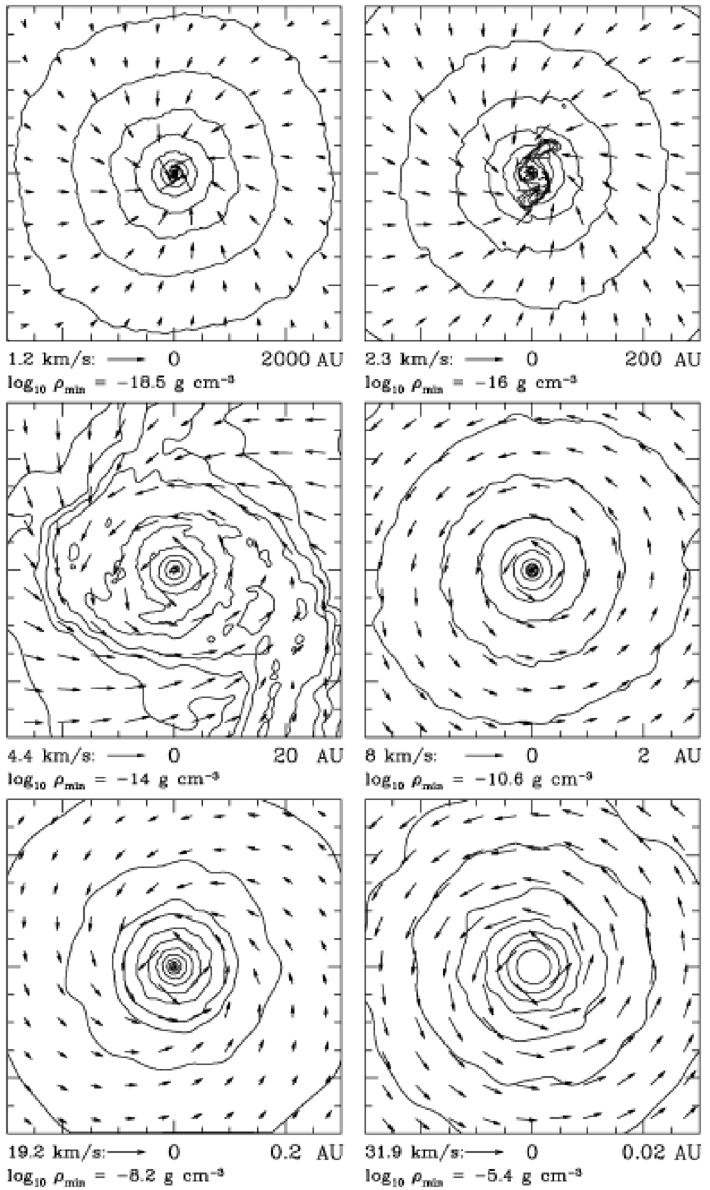
Magnetic Field



With some “imagination”…


HH111, McKee & Ostriker 2007 (Reipurth+ 1999 & Lee+ 2000)

Gravitational Torque

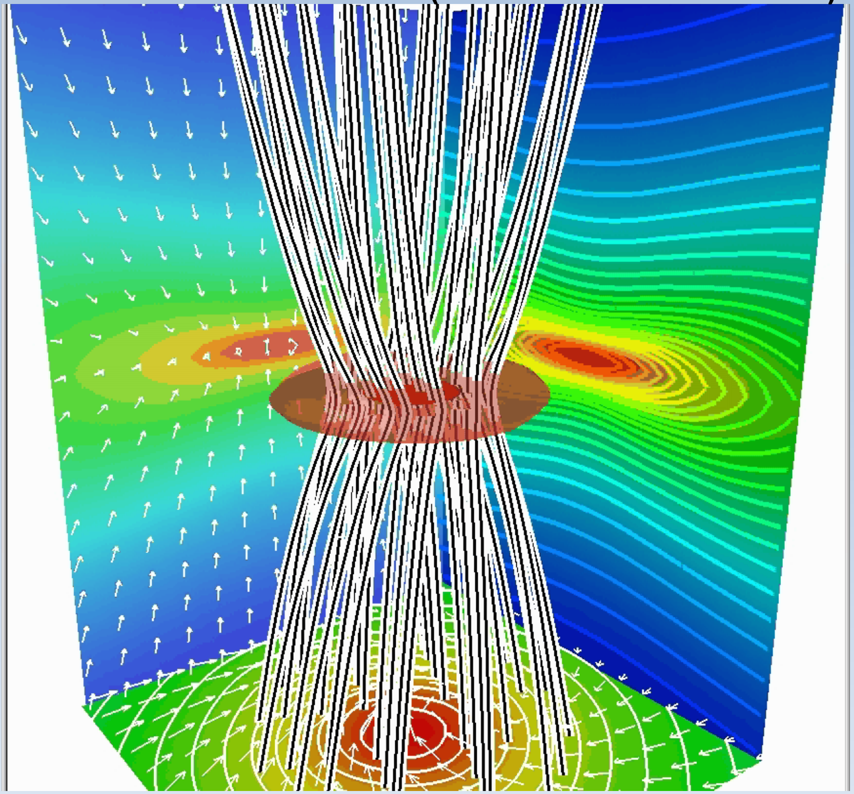


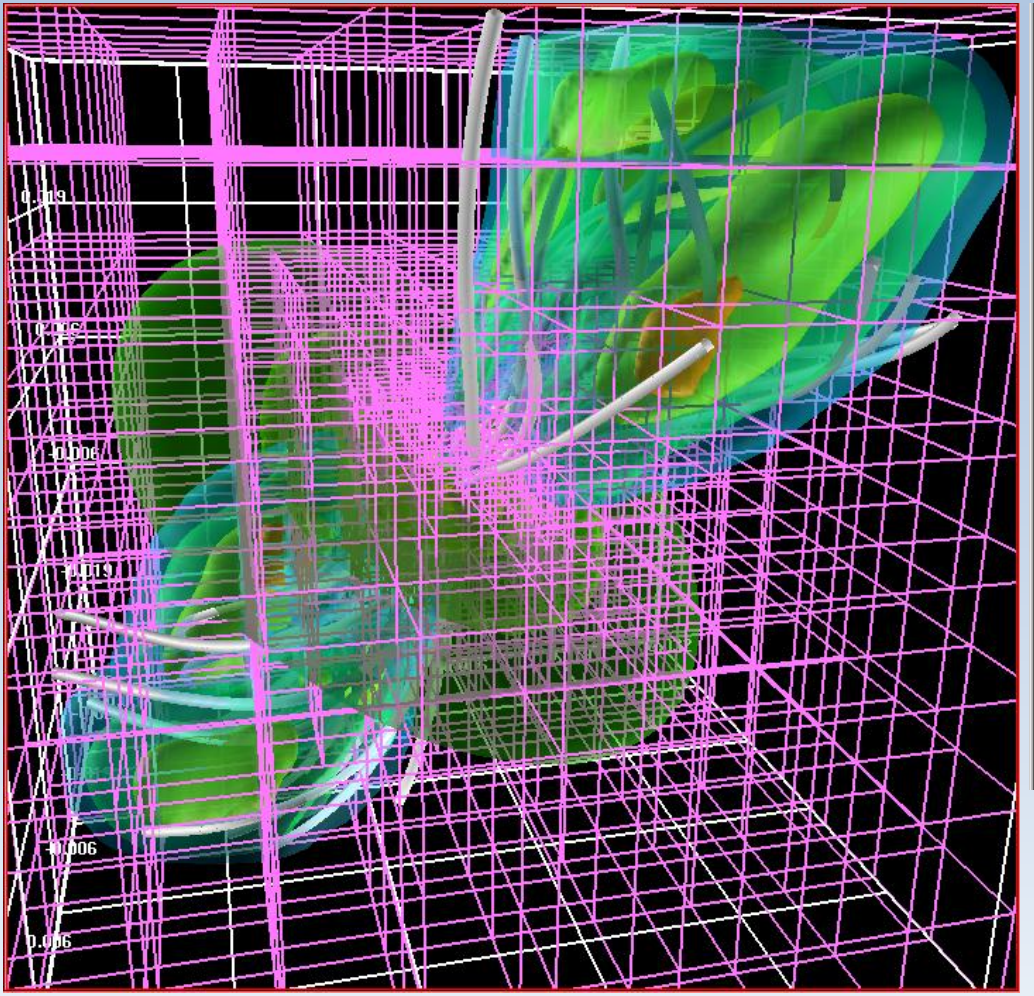
Bate (1998) first performed 3D SPH simulations of protostellar collapse and showed that the rotationally-supported disk becomes unstable and spiral arms are formed.
These non-axis-symmetric structure can transport ang. mom. efficiently and finally a protostar is formed.
(see also Matsumoto & Hanawa 03, Saigo et al. 08, Commercon et al. 08, etc.)

Note: Thermodynamics (radiation transfer) is modeled using a fitting formula based on 1D RHD simulations (so-called barotropic approximation)

3D MHD Protostellar Collapse

(Machida et al. 2008)





(Matsumoto 2007, SFUMATO AMR MHD code)

3D simulations show that magnetic fields transport ang. mom. efficiently.

(see also, Matsumoto & Tomisaka 04,Banerjee & Pudritz 06, Hennebelle & Fromang 08, Hennebelle & Teyssier 08, Duffin & Pudritz 09, Hennebelle & Ciardi 09, etc., etc…)