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星形成過程の非理想輻射磁気流体シミュレーション：星周円盤の早期形成

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

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  - Ideal MHD
  - With Ohmic Dissipation
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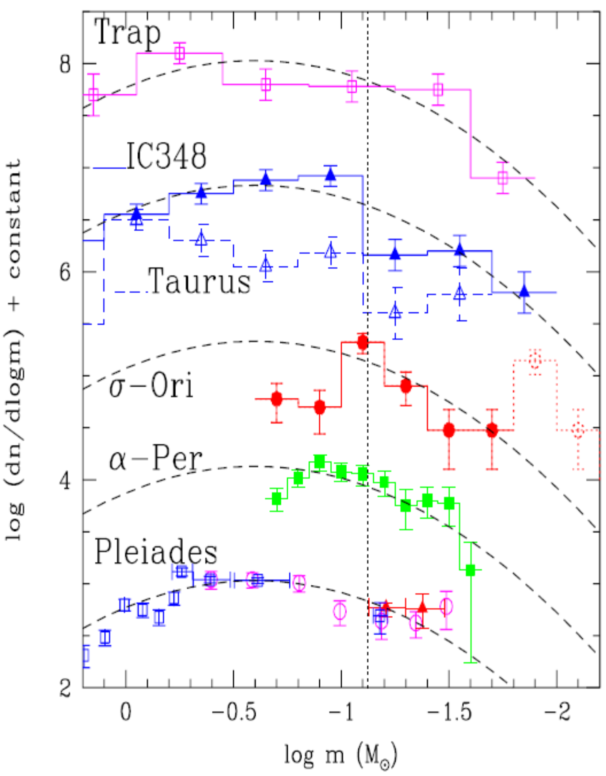
Introduction

Ultimate Goals of Star Formation Studies

(Chabrier 2005)



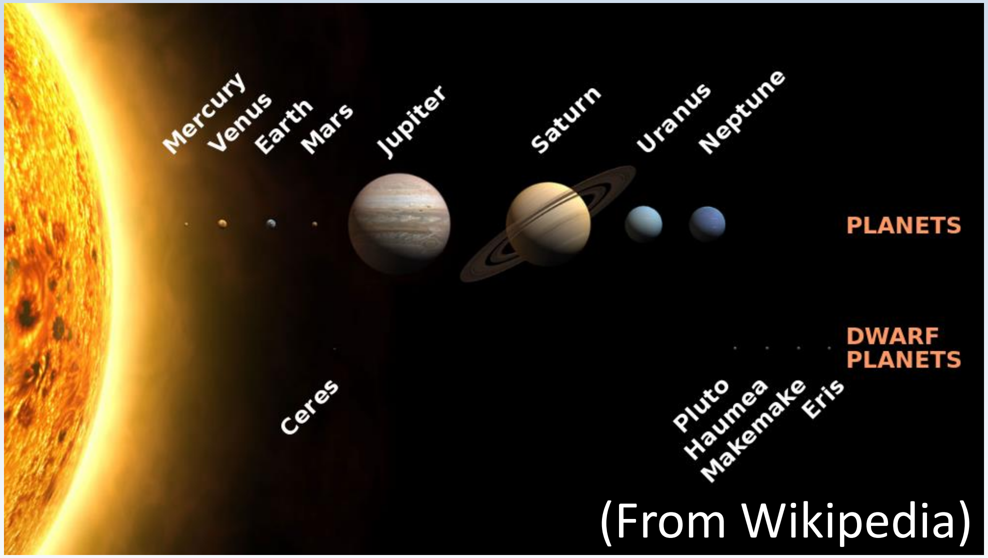
1. Stellar Initial Mass Function

Stellar mass determines stellar evolution

Chemical and Dynamical feedback from massive stars control the universe

→ Mass distribution of stars is crucial

⇒What is the origin of the IMF?



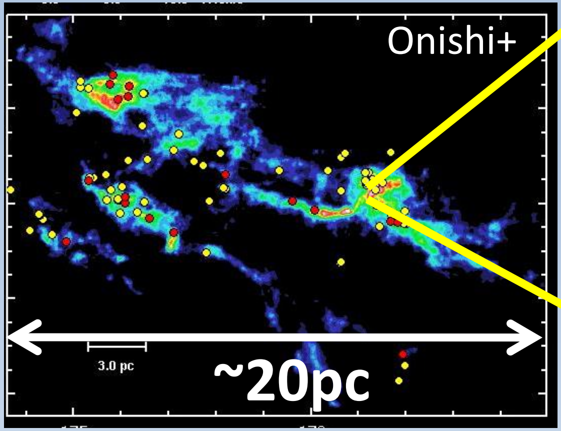
(From Wikipedia)

2. Origin of the Sun, Earth, other planets, and ourselves

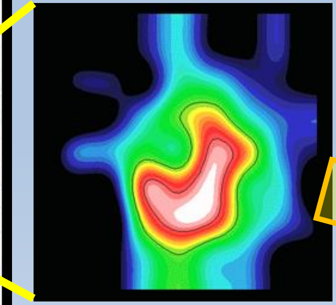
Formation of our solar system is still unclear, and now more than thousand exoplanets are found

⇒ Formation scenario of star, disk and planets = stellar system

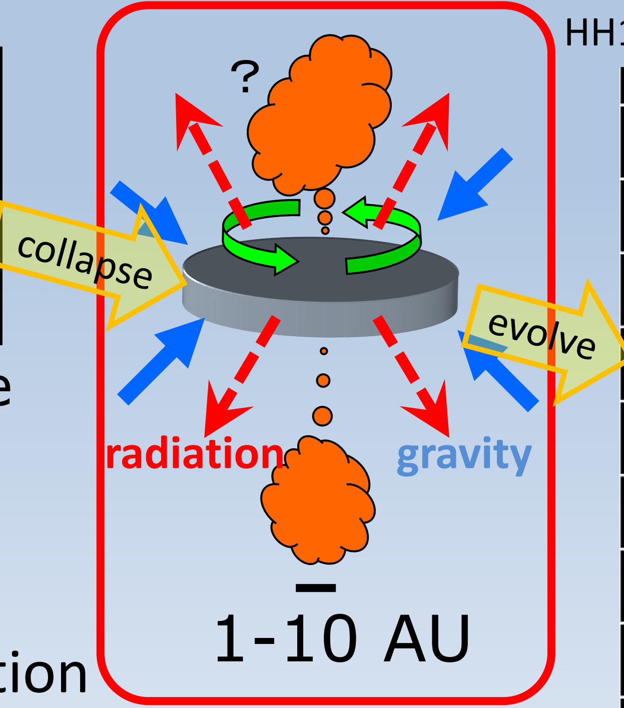
Protostellar Collapse



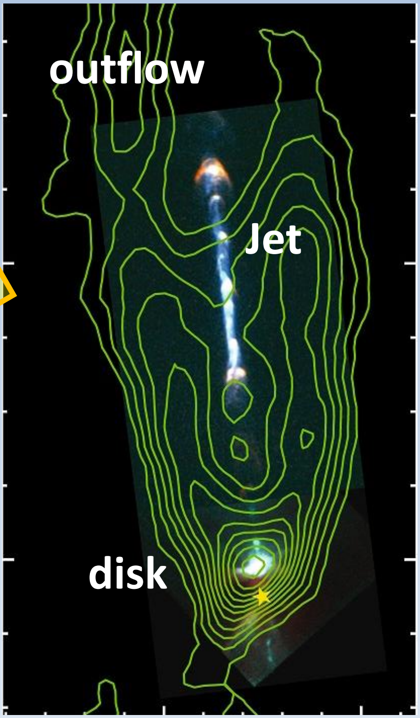
Taurus Molecular Cloud(Nagoya, 4m)



Cloud Core
∼0.1pc
n≳10^4/cc



Protostar, Disk, Outflow
HH111(Mckee&Ostriker 07)



- The site of disk & planet formation
- The origin of the IMF ← Star Formation Efficiency
- Many physical processes are involved here:

self-gravity, magnetic fields, radiation transfer, turbulence, chemistry, non-ideal MHD effects, etc…

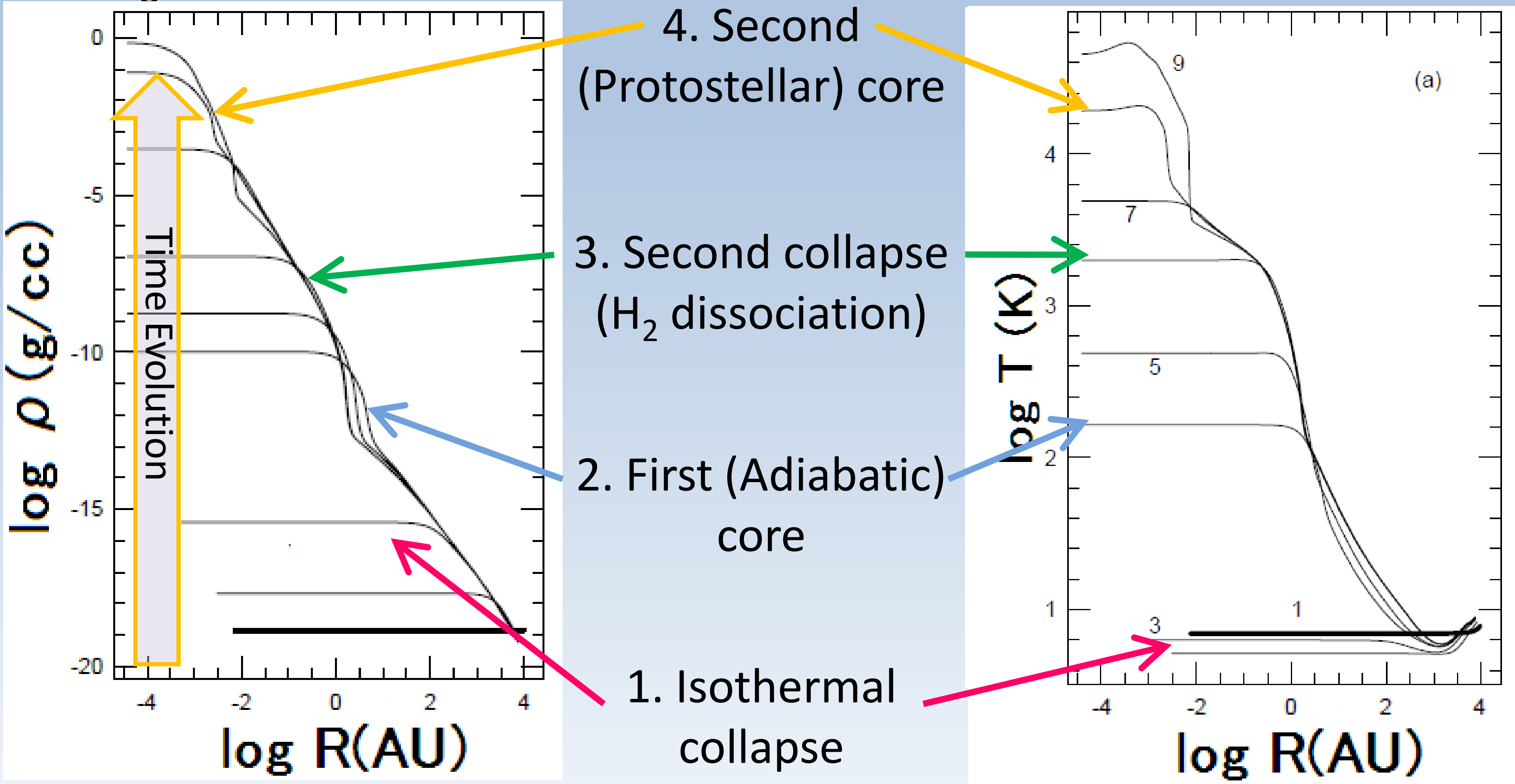
- Huge dynamic range: 0.1 pc / 1 Rs ∼4.5 x **10^6**

⇒Sophisticated numerical simulations are required

Protostellar Collapse: 1D RHD

Masunaga & Inutsuka 2000

(see also Larson 1969)



4. Second (Protostellar) core

3. Second collapse (H_2 dissociation)

2. First (Adiabatic) core

1. Isothermal collapse

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**, turbulence

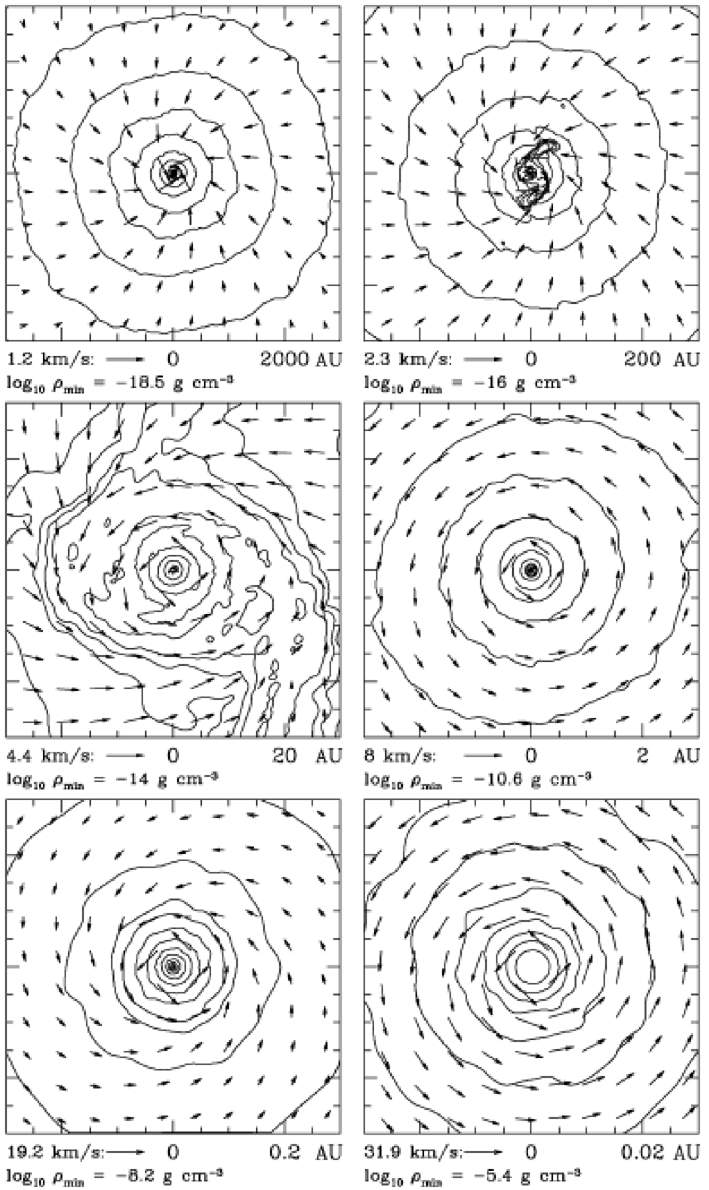
- “**Magnetic Braking Catastrophe**” (Mellon & Li 2008,09, Li+ 2011, etc.)

  Magnetic braking is too efficient; no circumstellar disk is formed

  ⇒B-Ω misalignment , turbulence, **non-ideal MHD effects**, etc.

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

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)

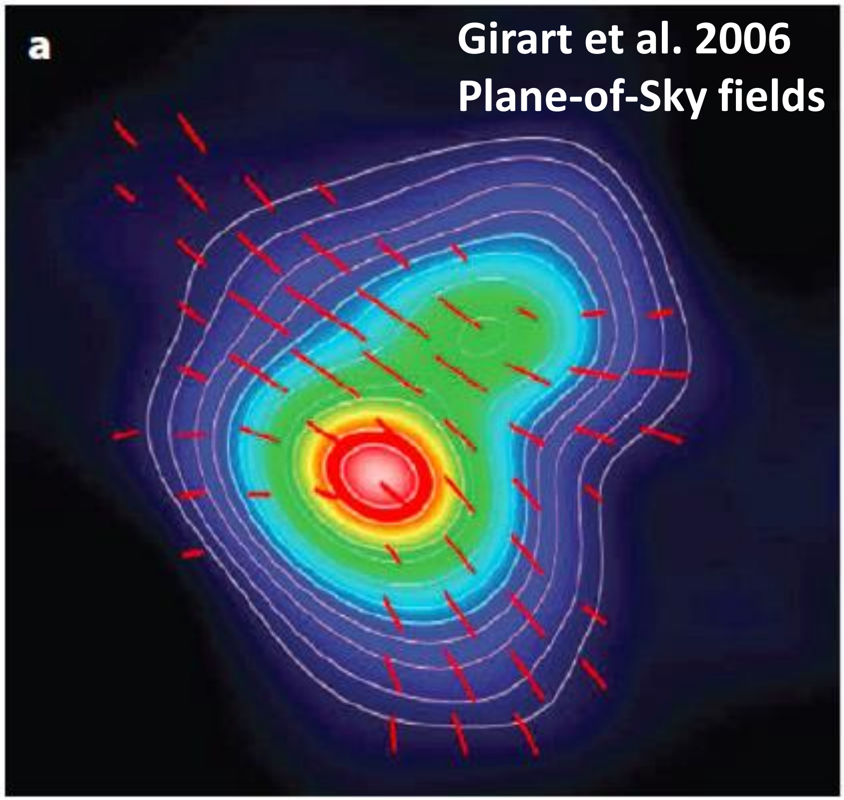
Collapse of a Molecular Cloud Core to Stellar Densities:

Rotational Instability of the First Hydrostatic Core

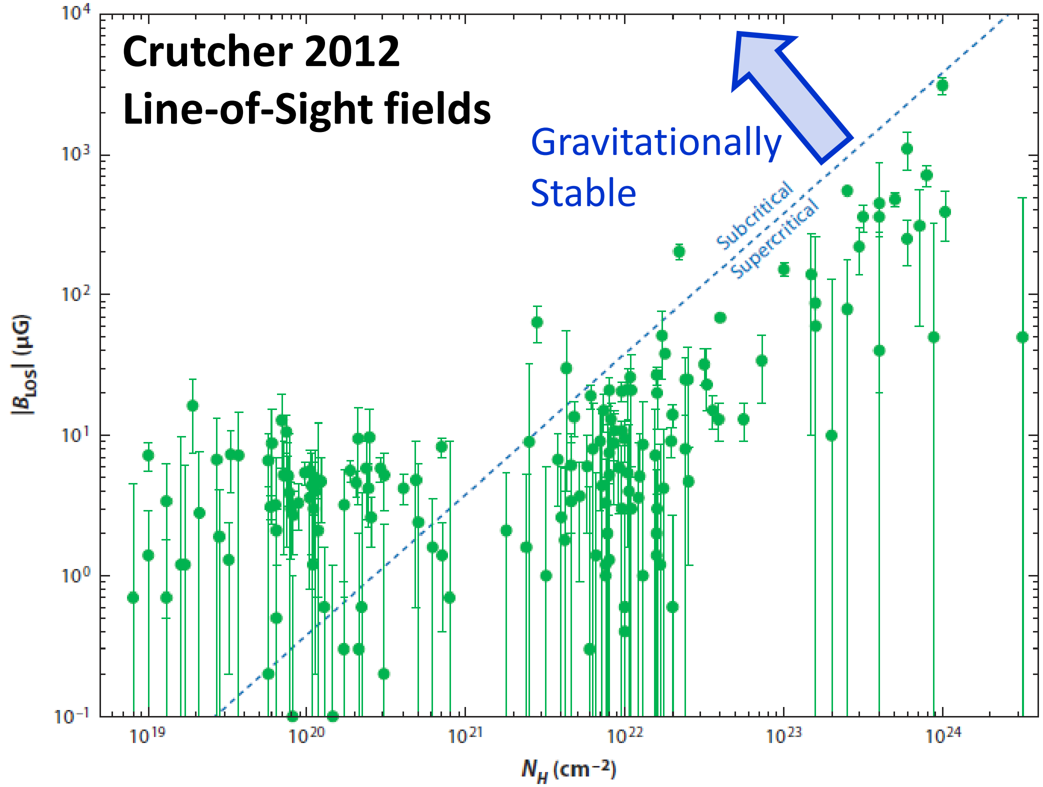
Matthew R. Bate
MPI für Astronomie, Heidelberg, Germany
Institute of Astronomy, Cambridge, U.K.

October 1998

Magnetic Fields



Girart et al. 2006
Plane-of-Sky fields



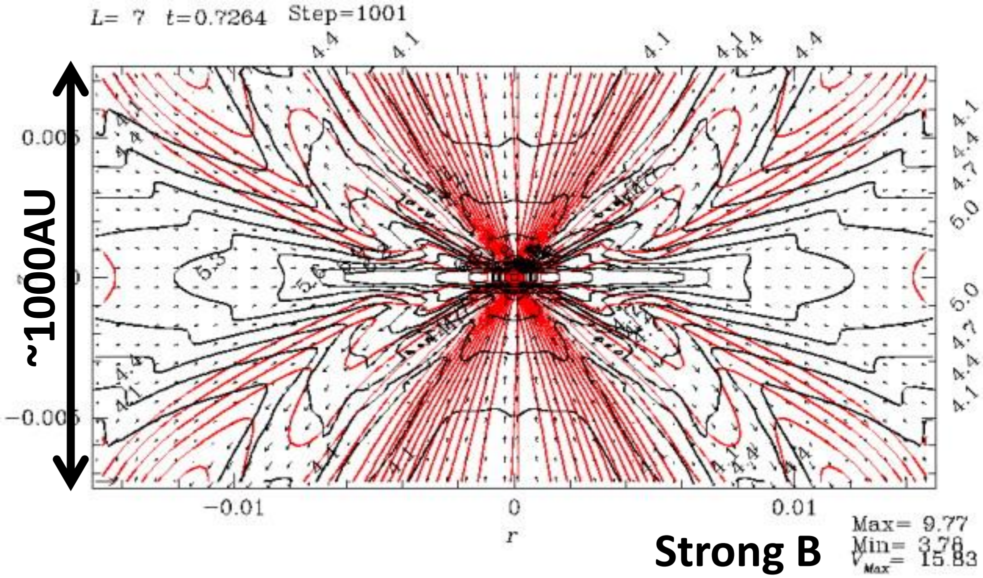
Crutcher 2012
Line-of-Sight fields

Gravitationally Stable

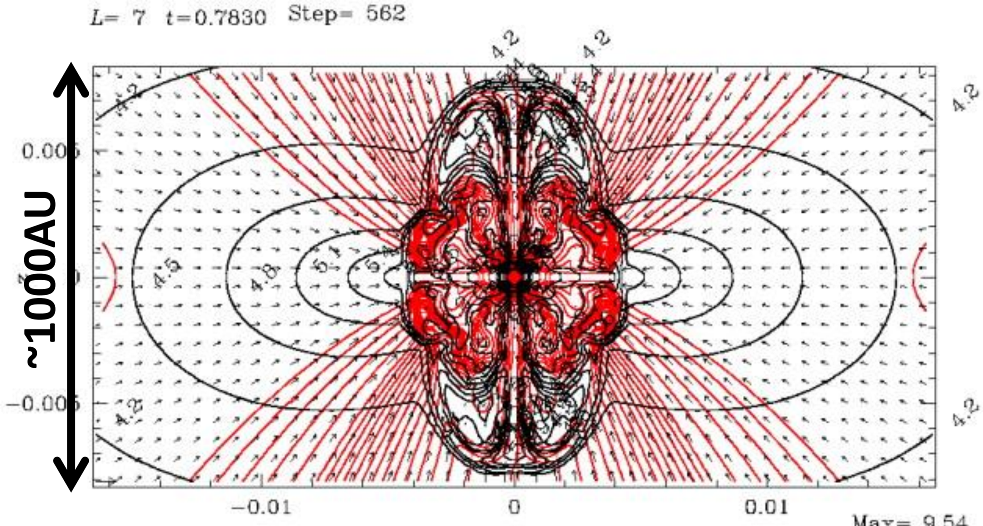
Observations suggest that cloud cores are considerably (supercritical to marginally subcritical) magnetized (μ～2-10). Therefore magnetic fields must have significant effects, actually even in the supercritical regime.

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.

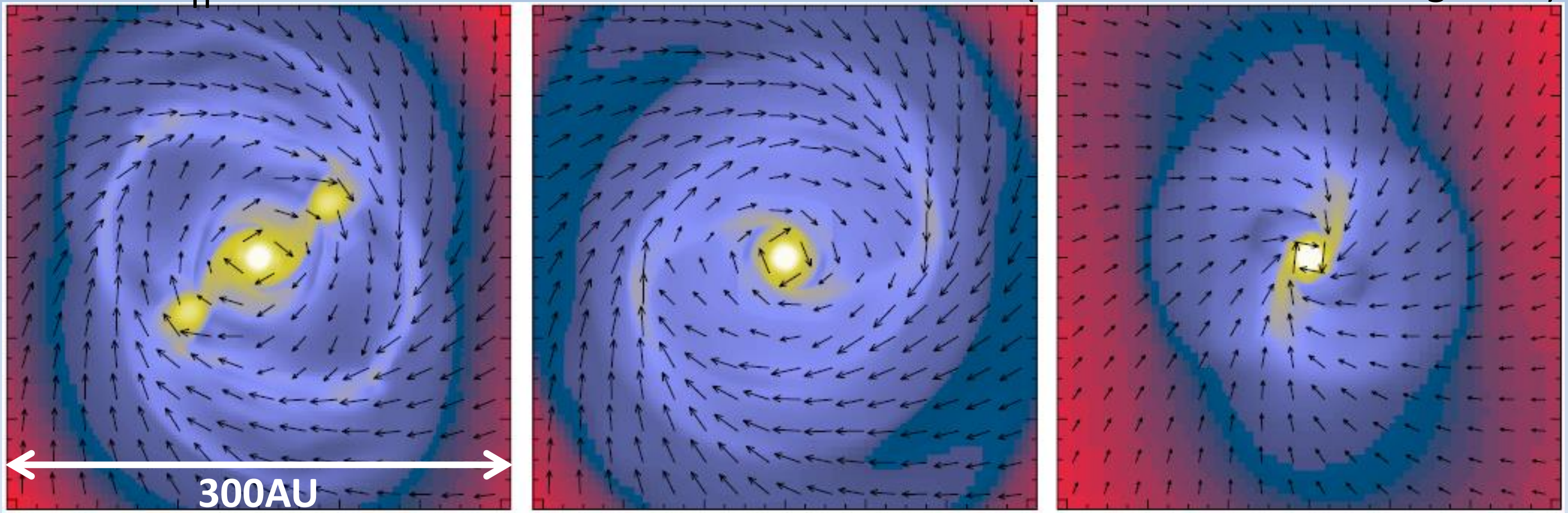
Two modes of outflows: Strong fields result in Magneto-centrifugal mode (Blandford & Payne 1982), while weak fields drive magnetic-pressure mode.

(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)



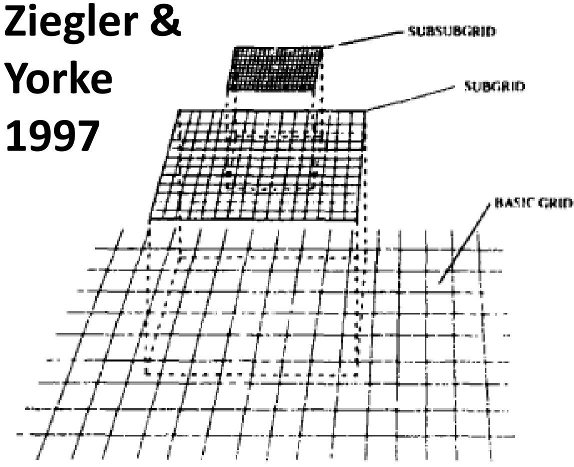
μ=M/Φ=50 (very weak) μ=20 (still modest) μ=5 (intermediate)

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.)

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→Mixed 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)
- **NEW Ambipolar Diffusion** (neutral-charged decoupling) with STS
- The code is optimized for a vector supercomputer (NEC SX-9).

⇒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

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

Eq. of motion

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times \left(\mathbf{v} \times \mathbf{B} \boxed{- \eta_O \mathbf{J}} \boxed{- \frac{\eta_A}{|\mathbf{B}|^2} \mathbf{B} \times \mathbf{F}} \right) = 0,$$

Induction eq.

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

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

Gas Energy Eq.

$$\mathbf{J} \equiv \nabla \times \mathbf{B}, \qquad \mathbf{F} \equiv \mathbf{J} \times \mathbf{B},$$

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

div B=0

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

Poisson's Eq.

$$\boxed{\begin{aligned} &\frac{\partial E_r}{\partial t} + \nabla \cdot [\mathbf{v} E_r] + \nabla \cdot \mathbf{F}_r + \mathbb{P}_r : \nabla \mathbf{v} = c\sigma_P (a_r T_g^4 - E_r), \\ &\mathbf{F}_r = \frac{c\lambda}{\sigma_R} \nabla E_r, \quad \lambda(R) = \frac{2 + R}{6 + 2R + R^2}, \quad R = \frac{|\nabla E_r|}{\sigma_R E_r}, \\ &\mathbb{P}_r = \mathbb{D} E_r, \quad \mathbb{D} = \frac{1 - \chi}{2} \mathbb{I} + \frac{3\chi - 1}{2} \mathbf{n} \otimes \mathbf{n}, \quad \chi = \lambda + \lambda^2 R^2, \quad \mathbf{n} = \frac{\nabla E_r}{|\nabla E_r|}, \end{aligned}}$$

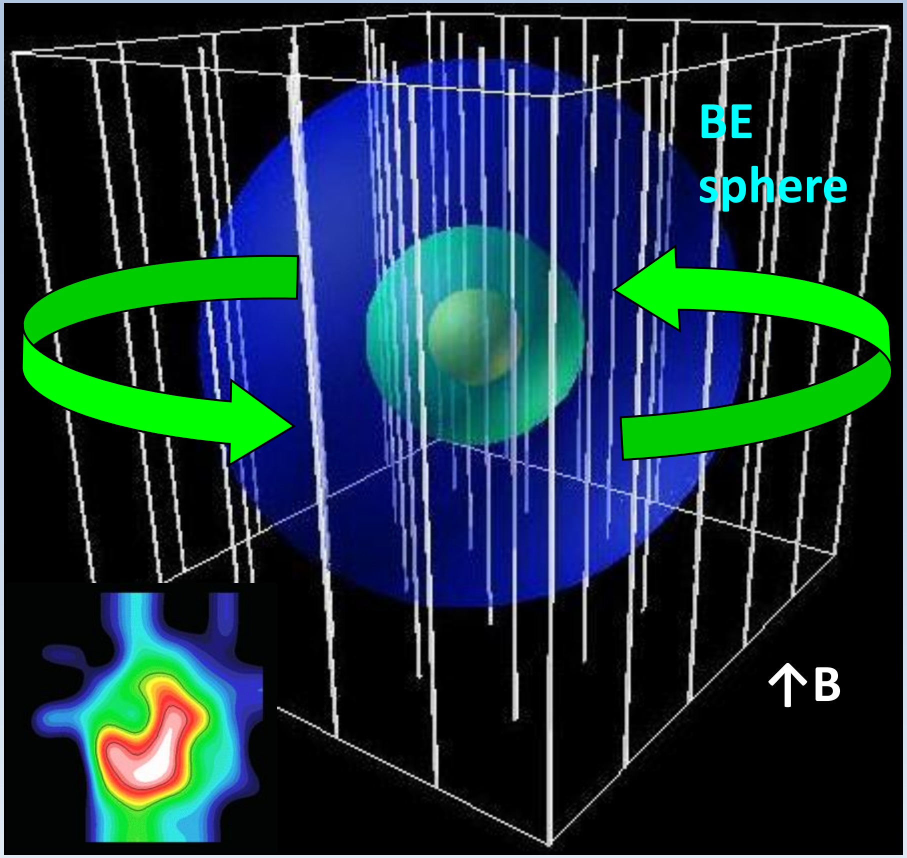
Radiation Transfer

+ **Eq. of state**

+ **AD & OD rates**

+ **Opacities**

Simulation Setup



Nested-grid RMHD simulations with ngr^{3}mhd code

- Ideal MHD model
- With Ohmic Dissipation
- Plus Ambipolar Diffusion

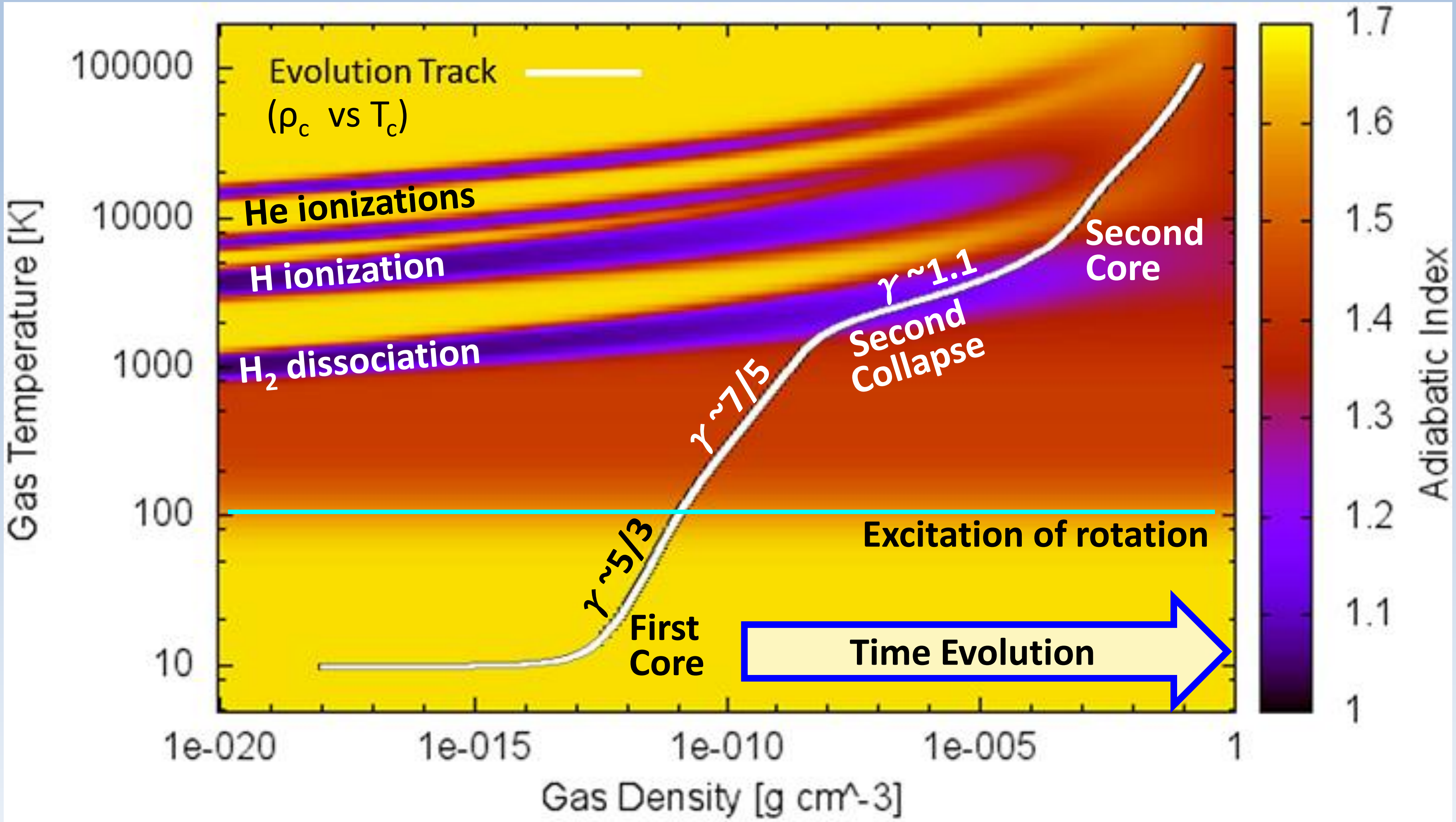
Resolution: >16 cells / λ_{Jeans}

64^3 x 15 levels at the end of FC

Typical resolution @ FC～ 0.1 AU

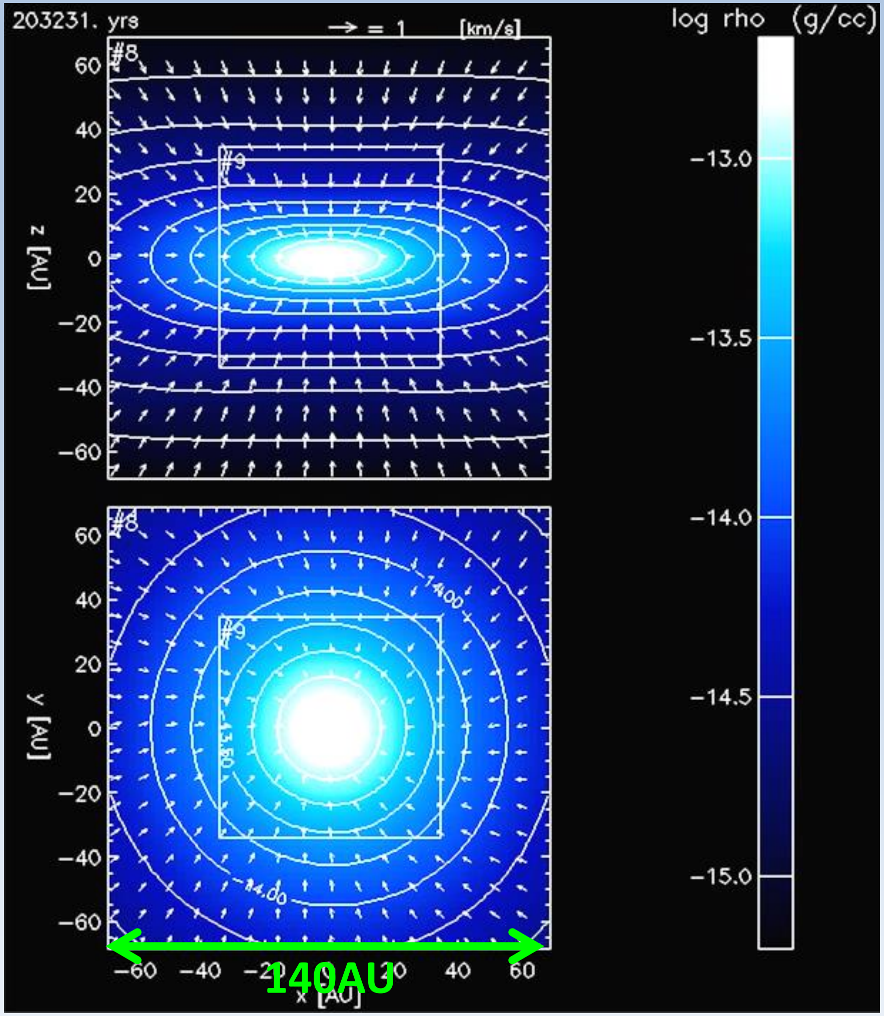
- 1Ms unstabilized BE sphere（ρ_c=1.2 x 10^{-18} g/cc, T=10K, **R=8800AU**）
- Bz=20μG (μ～3.8), Ω=0.046/t_{ff} ～2.4 x 10^{-14} s^{-1} , aligned rotator
- 10% m=2 density perturbation
- Opacity: Semenov+ 2003 (dust), Ferguson+ 2005, Seaton+ 1994 (OP)

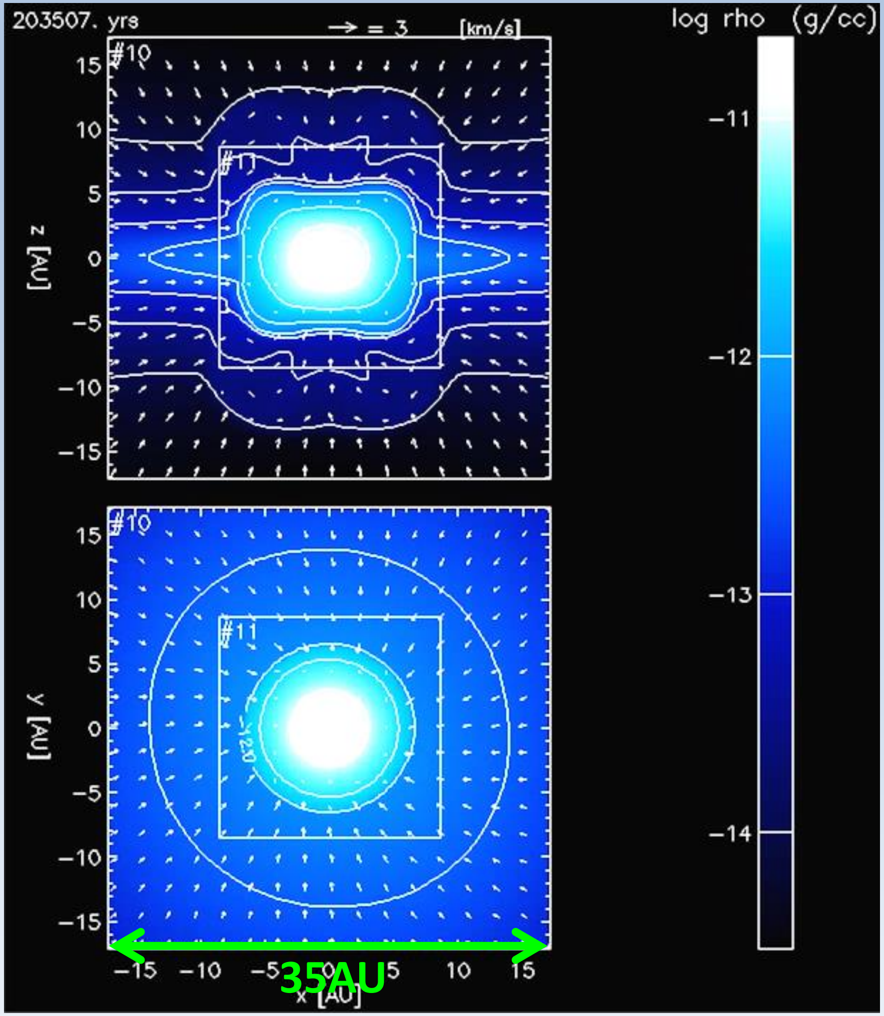
Thermal Evolution (spherical case)



The central gas element evolves following EOS in $\rho > 10^{-12}$ g /cc.
The evolution is consistent with MI2000, except for details of EOS.

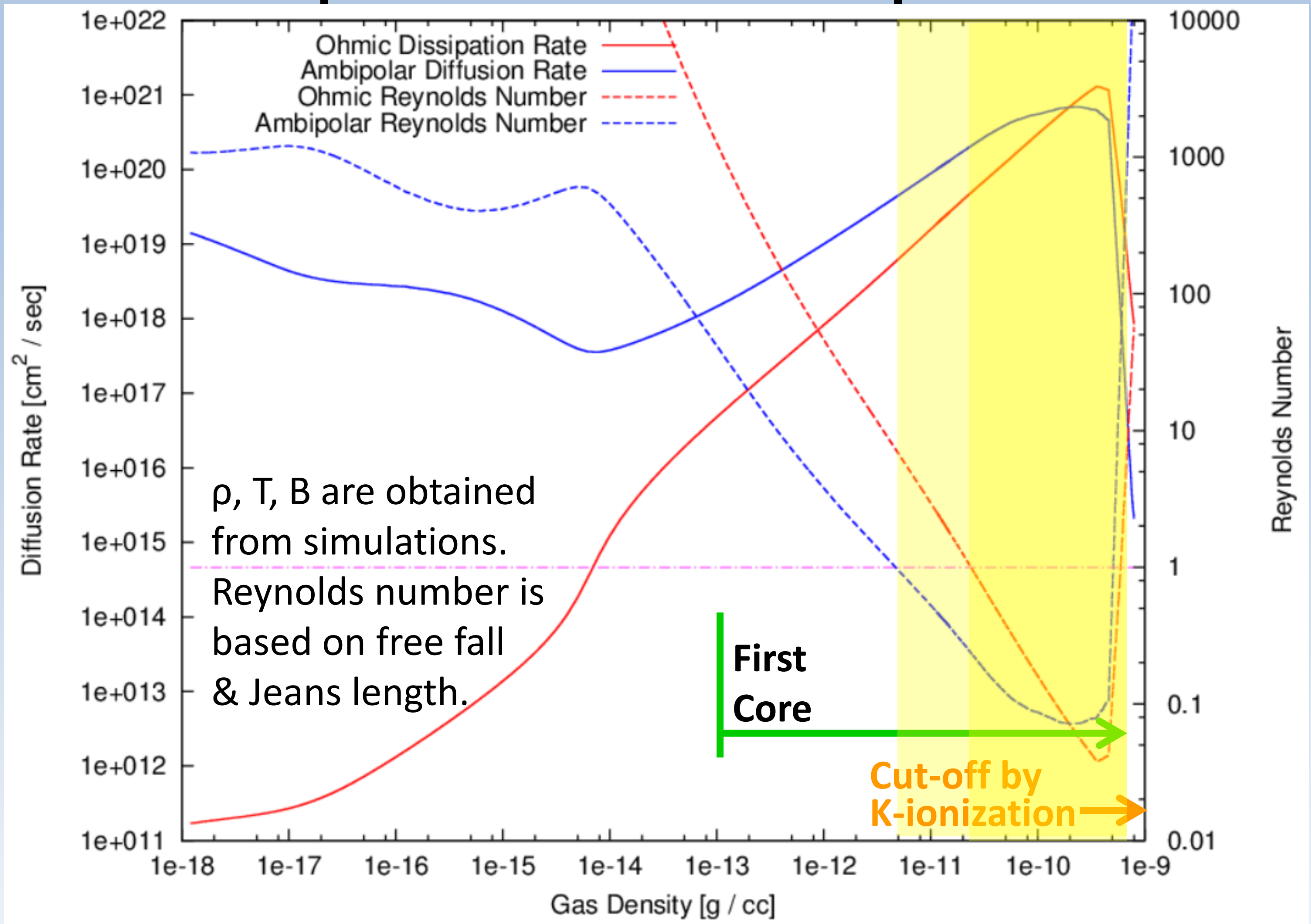
Ideal MHD Model





Magnetic Braking (+Outflow) is so efficient that the FC is not supported by rotation = Magnetic Braking Catastrophe (at least in the early phase)

Ohmic Dissipation & Ambipolar Diffusion



ρ, T, B are obtained from simulations. Reynolds number is based on free fall & Jeans length.

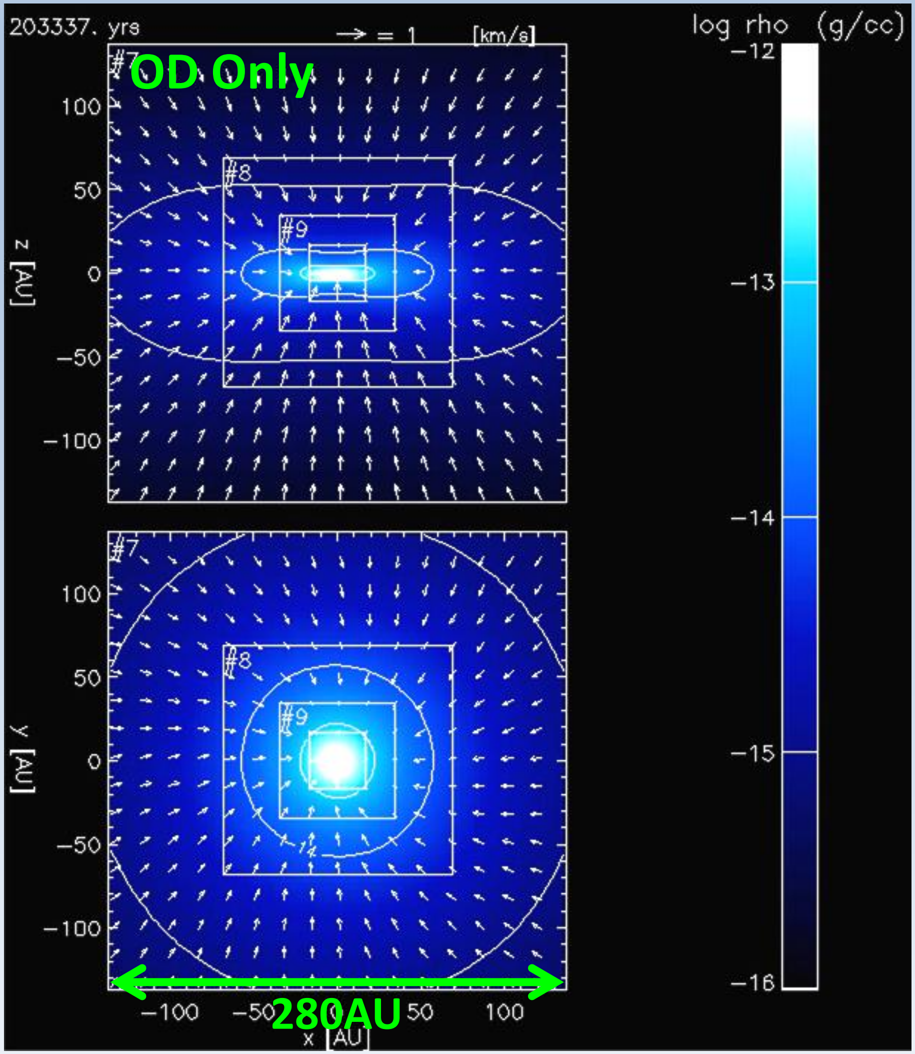
First Core

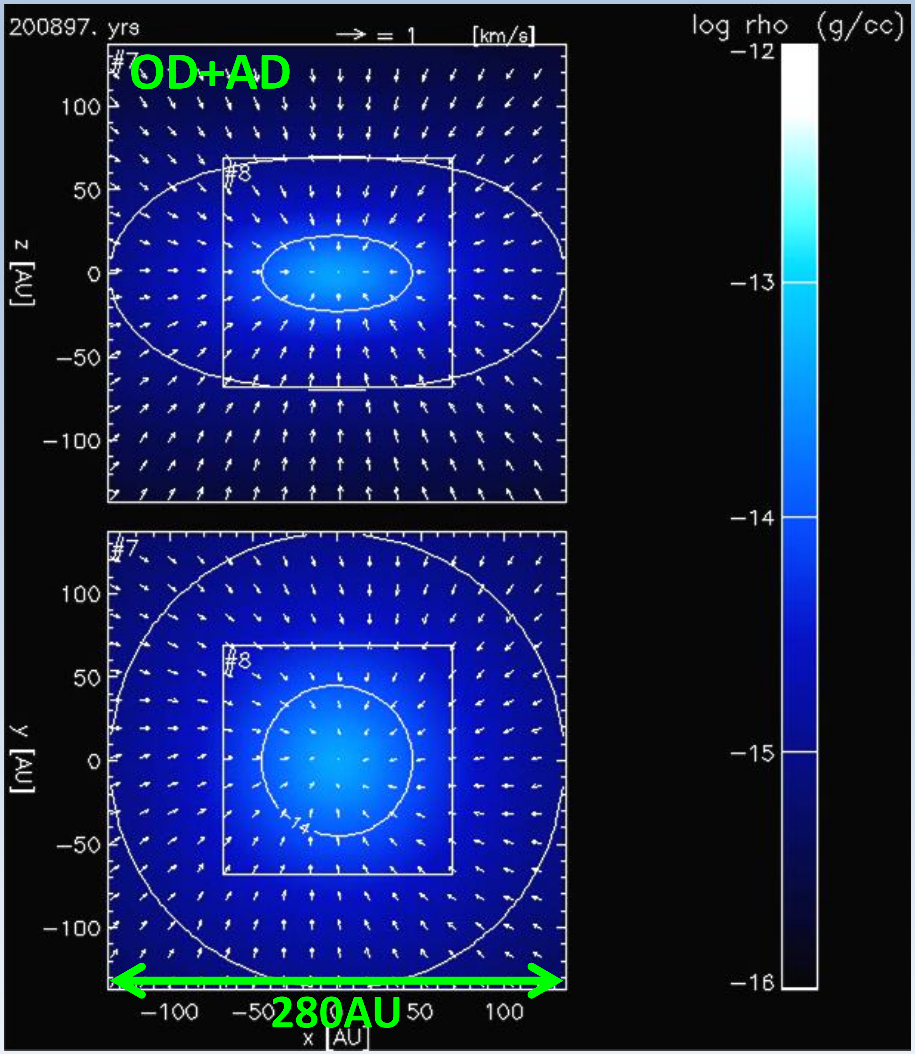
Cut-off by K-ionization

Ohmic Dissipation: Effective in the high density region

Ambipolar Diffusion: More effective in the lower density region

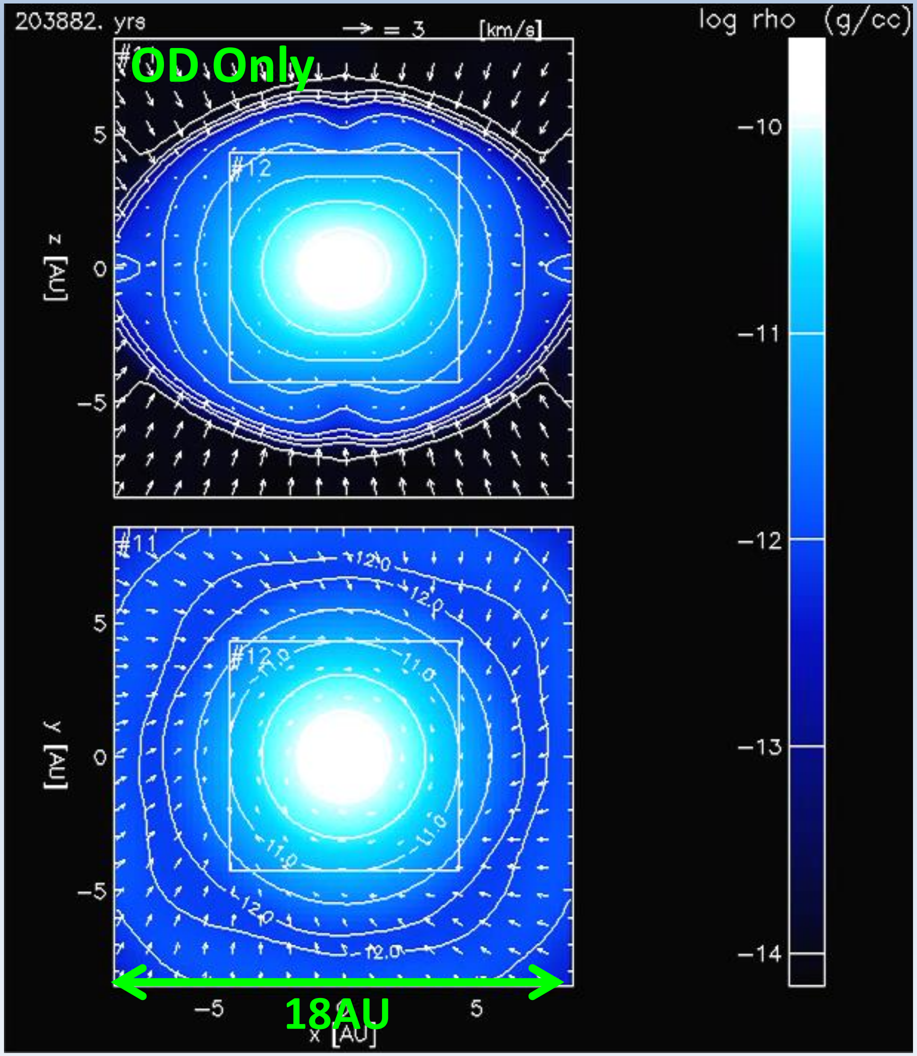
Non-ideal MHD Models: Outflows

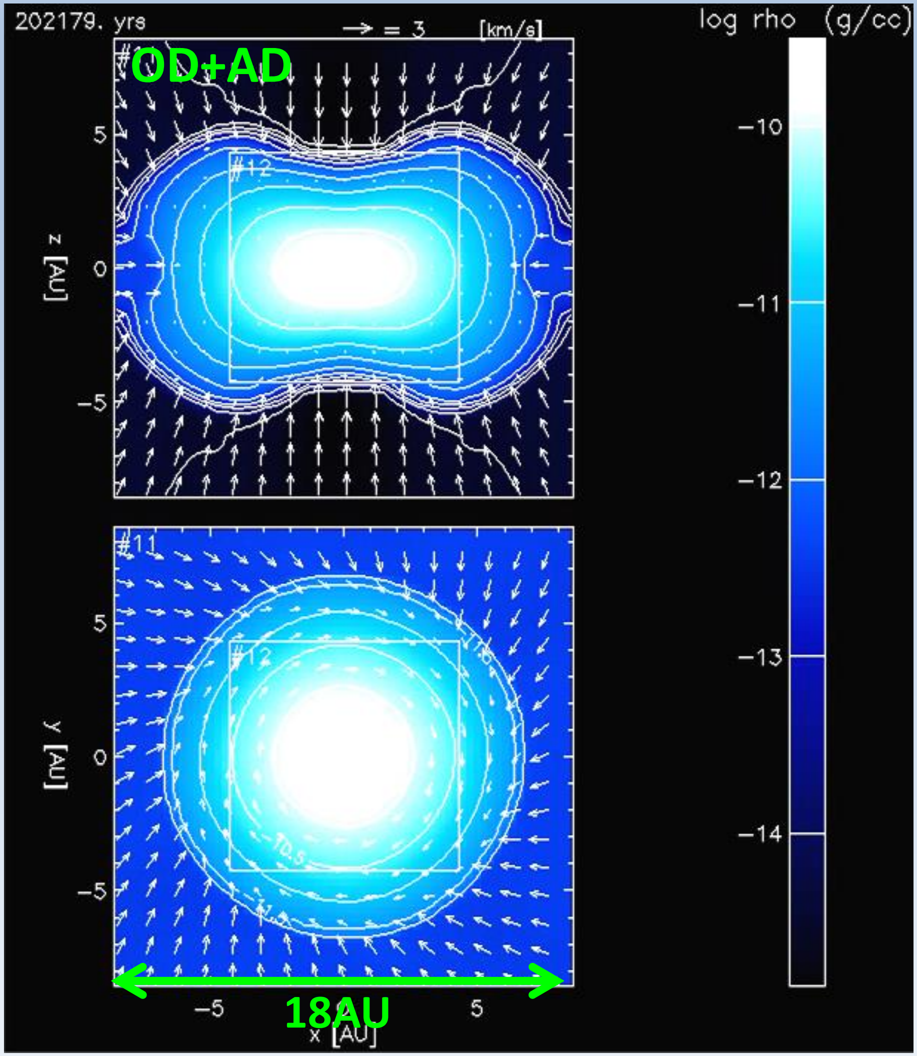




Outflows are not affected by non-ideal MHD effects; they simply travel further because of the longer lifetime of the first cores.

Non-ideal MHD Models: First Cores



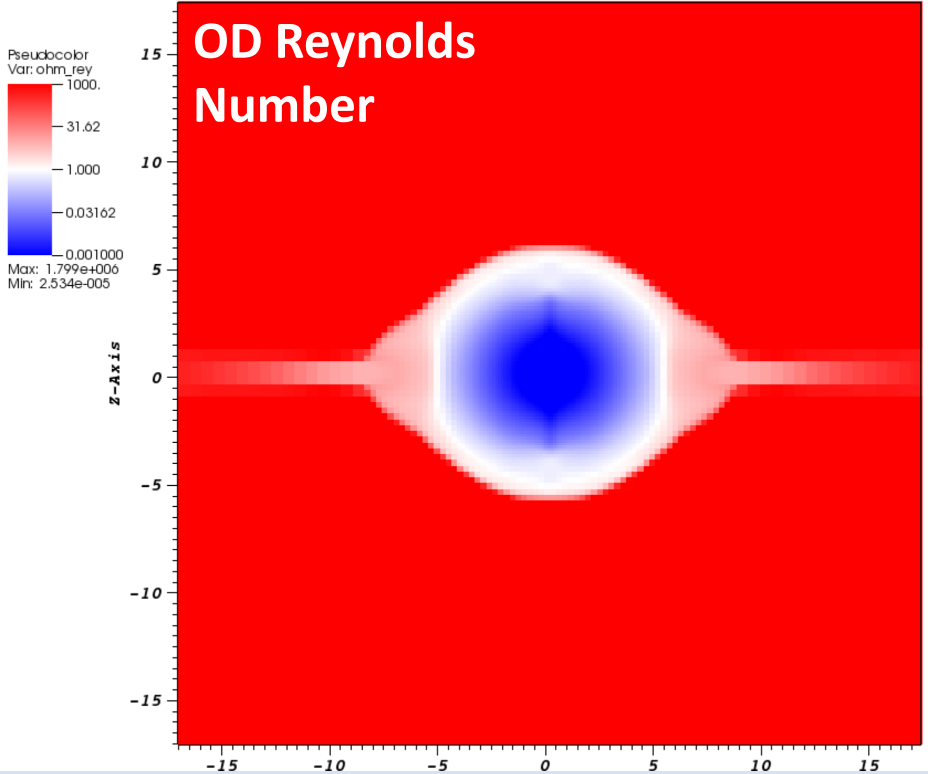


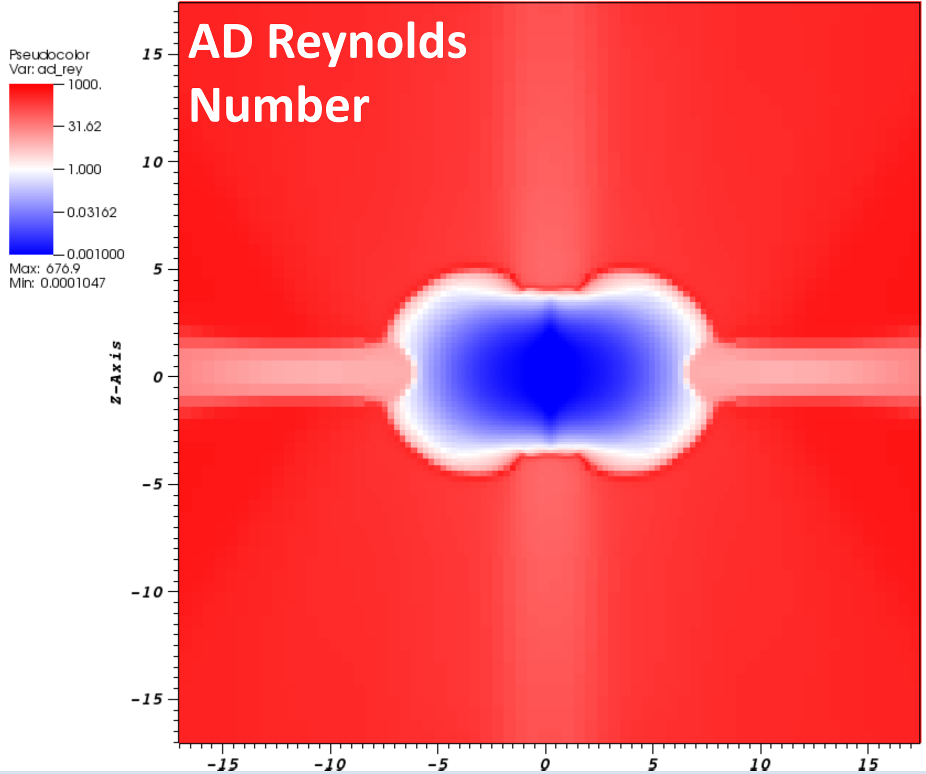
OD: Slow-rotating, vertical inflation by heating from second core

AD: Supported by rotation, non-axisymmetric (GI), but size is still small

Dissipation of Magnetic Fields

Tc=600K





Magnetic Reynolds Number=VL/η : dimension-less indicator of dissipation

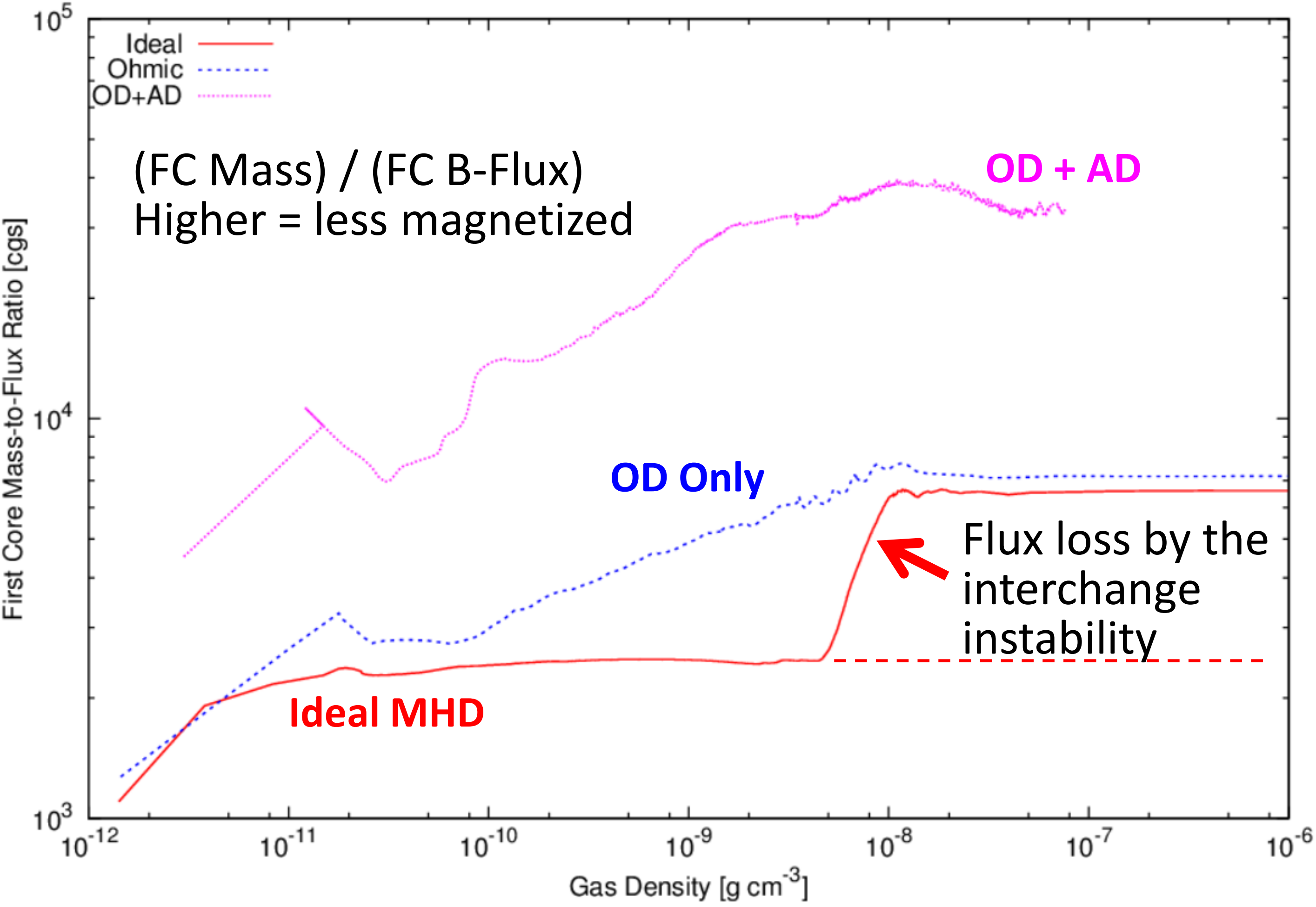
Red = ideal → White(∼1) = marginal → Blue = highly dissipative

OD only: only central region becomes dissipative

OD+AD: almost the whole first core becomes dissipative

AD works in more extended region and extract magnetic flux from FC

Magnetic Flux Loss

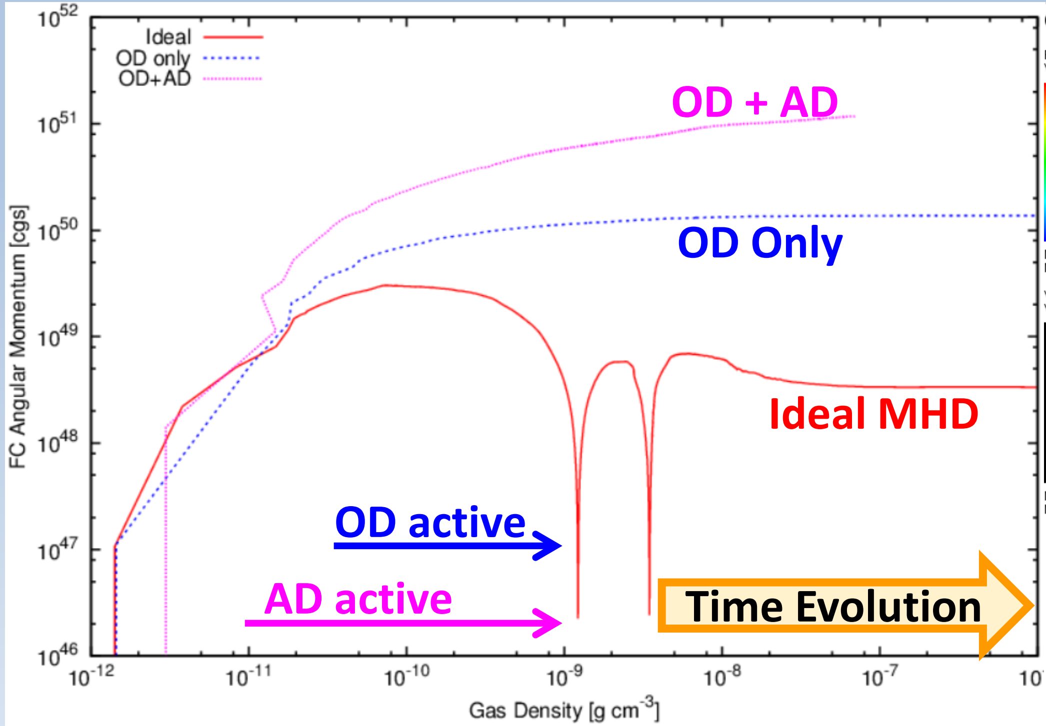


(FC Mass) / (FC B-Flux)
Higher = less magnetized

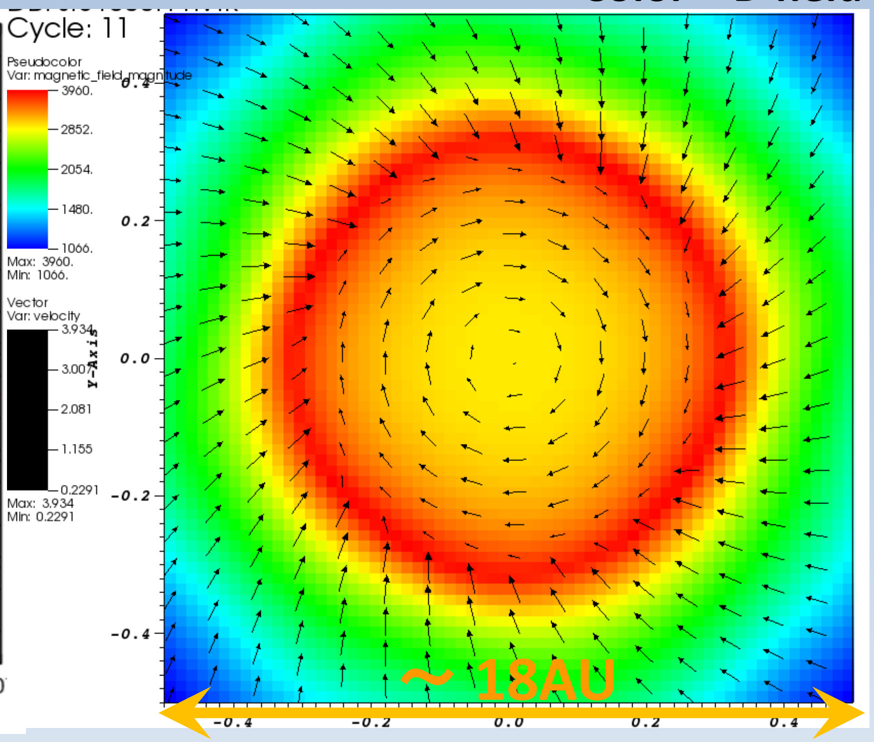
Flux loss by the interchange instability

OD+AD model is significantly less magnetized from the beginning, while OD model lose the magnetic flux gradually later in the FC phase. At the end, OD+AD is x15, OD is x3 weakly magnetized than the Ideal.

Angular Momenta in FCs



Color = B-field



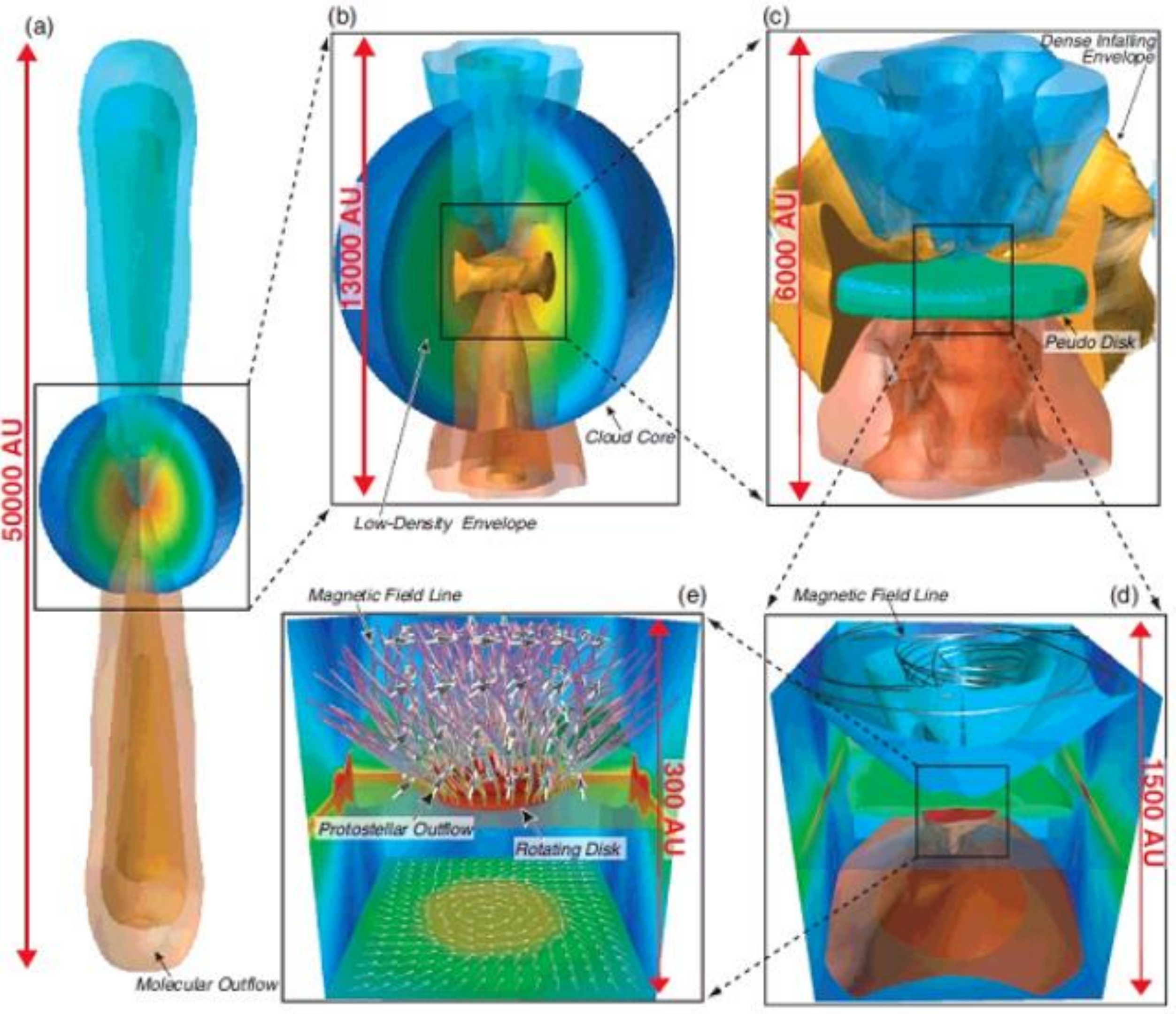
FC in OD+AD model has significantly larger angular momentum (∼x300 larger than ideal model, ∼x10 larger than OD model)

Almost the whole first core disk becomes dissipative in the OD+AD case

→ Magnetic angular momentum transport is strongly suppressed

But the disk size remains almost unchanged, ∼5AU → regulated by B?

Fate of the disk and outflows



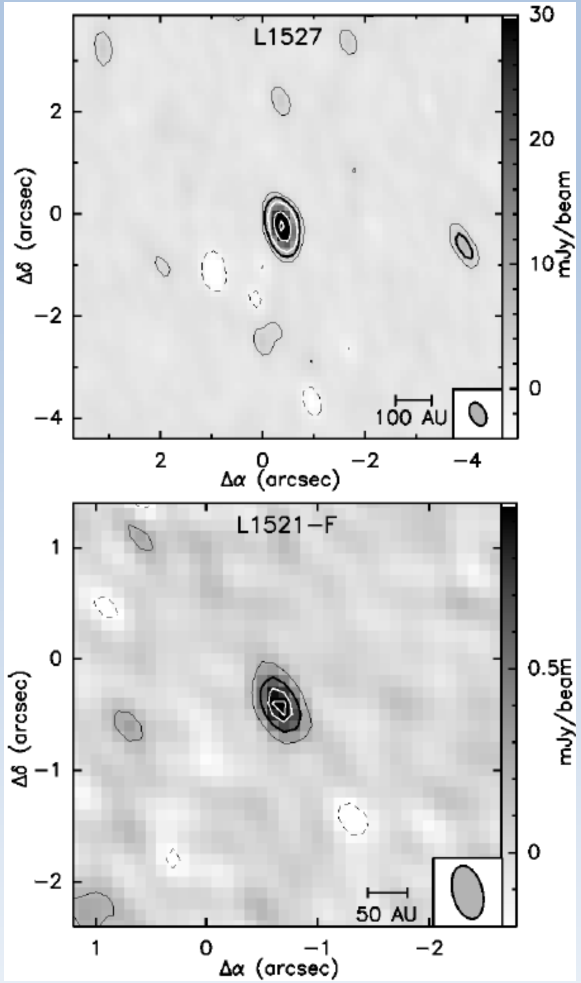
Machida & Hosokawa 13

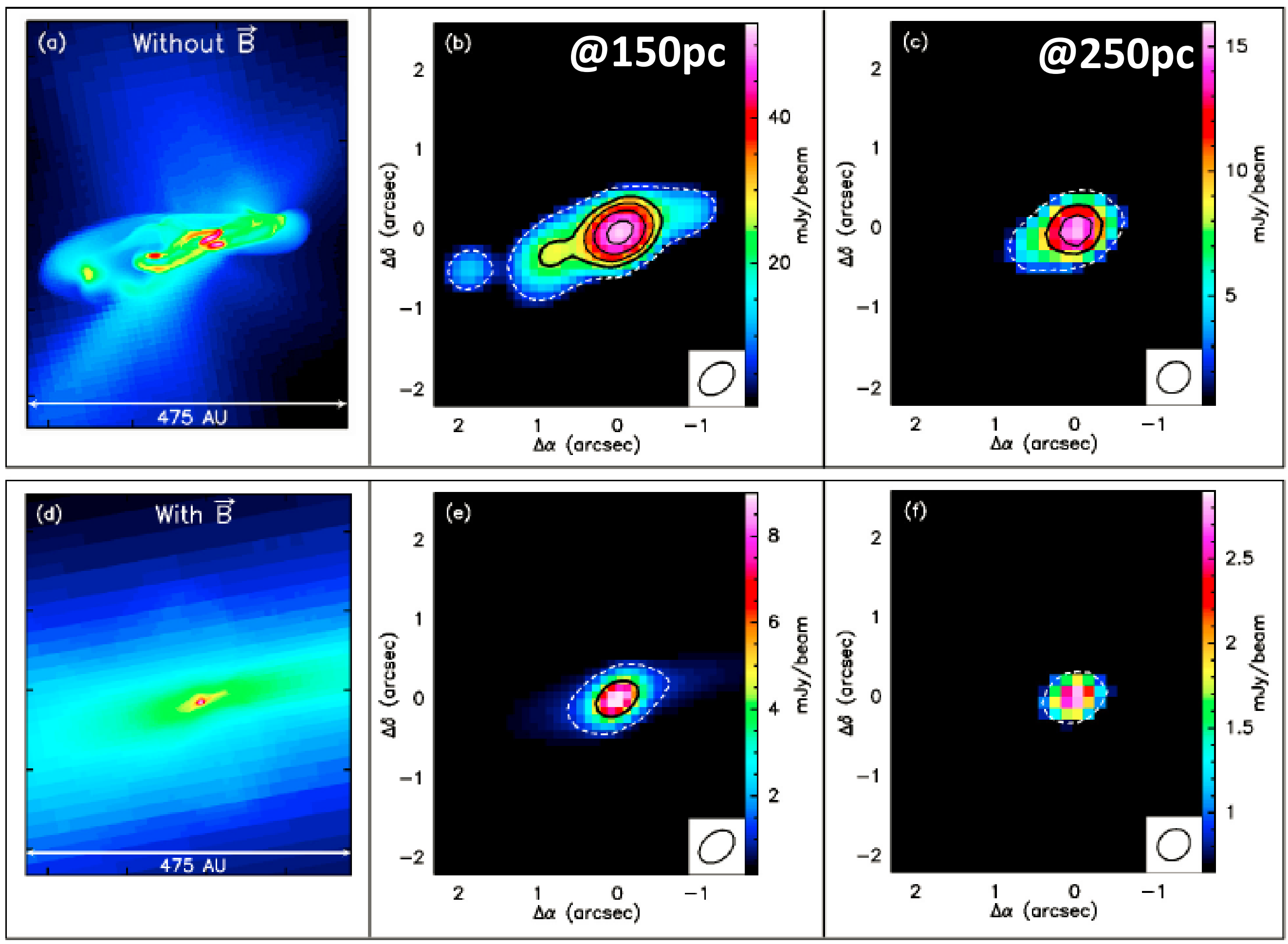
Long-term (till class-I phase) MHD simulation using a sink particle.
Outflows and disks grow continuously, $R_{disk} \sim 100$ AU

Implications from / for Observations

Observations of Young Disks

Maury et al. 2010

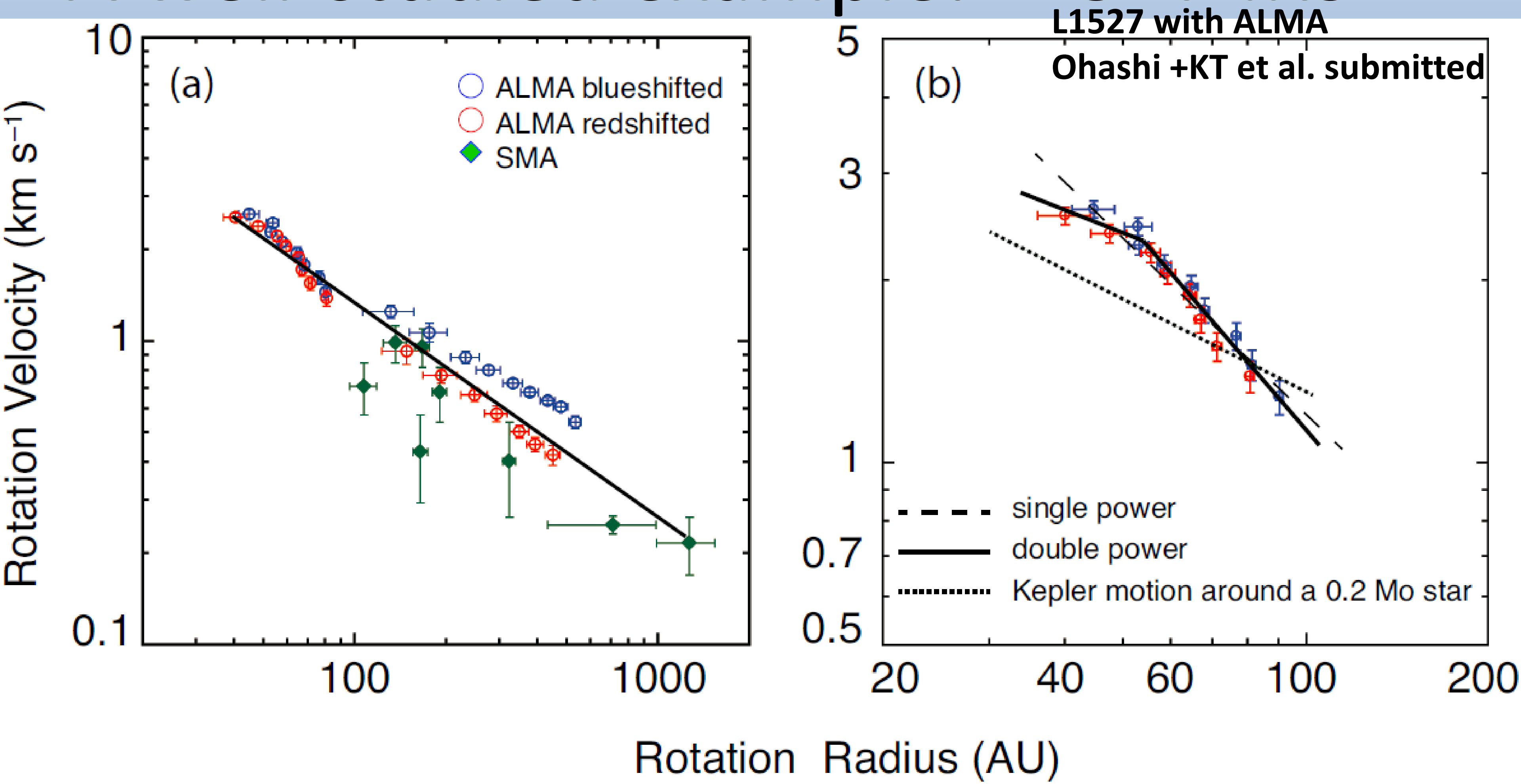




1.3mm Dust continuum observations of Class-0 sources with PdBI.

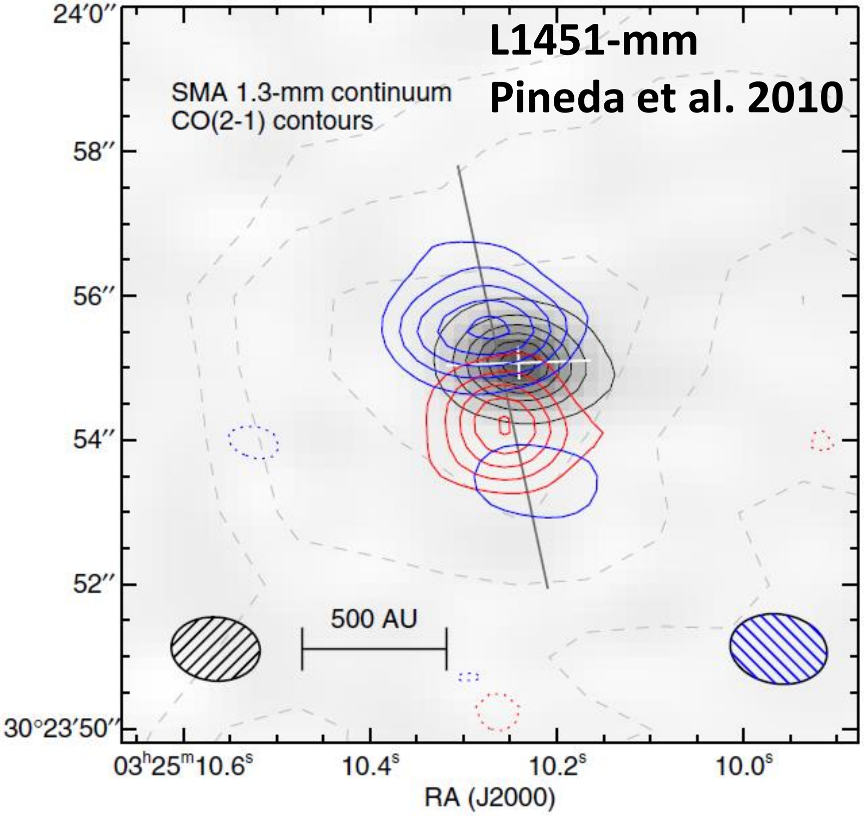
The observed disks are small and more consistent with the MHD models.

A well-studied example: L1527 IRS

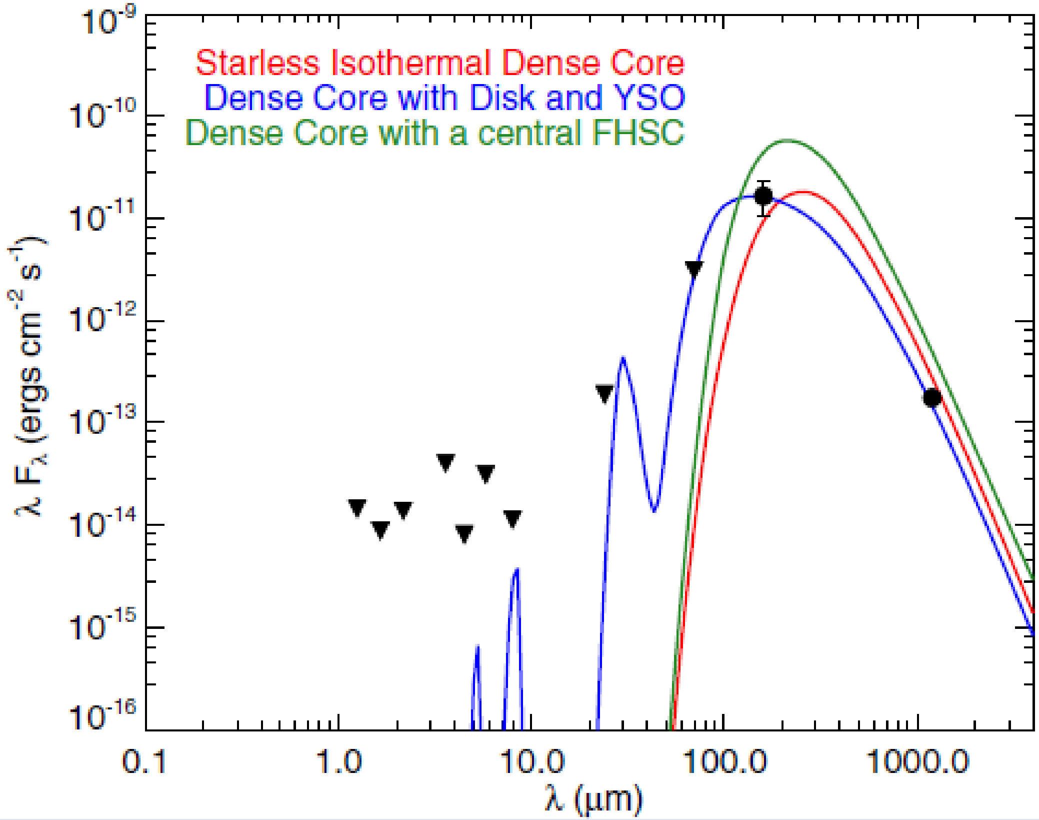


Tobin+ 2012 (SMA & CARMA): R～120 AU disk around 0.2 Ms protostar
Ohashi+ submitted. (ALMA Cycle-0): R＜60AU around 0.3 Ms protostar
⇒Disks can be formed early, but should be small in the early phase

Even Younger: First Core Candidates



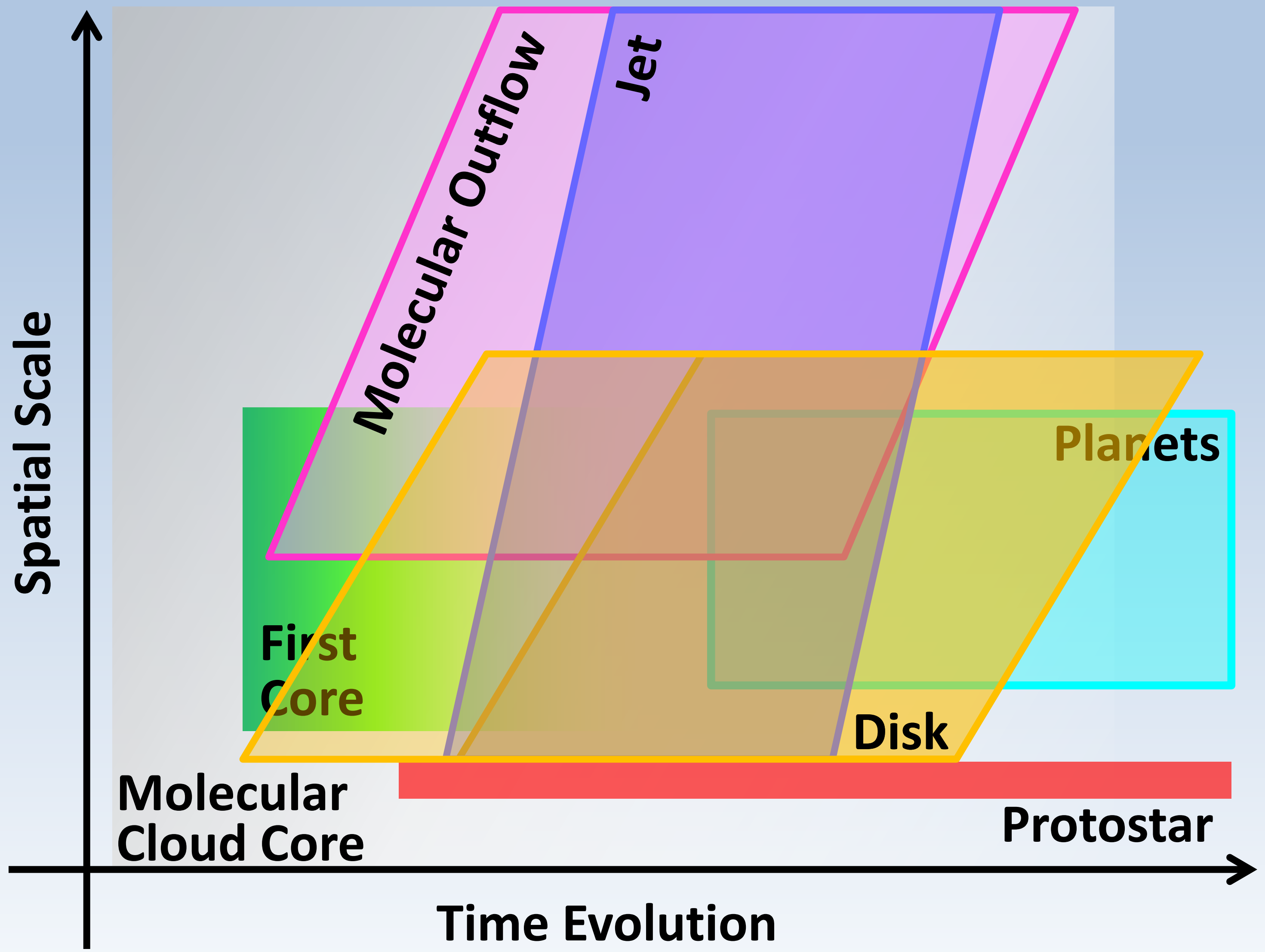
L1451-mm
Pineda et al. 2010



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

To Summarize: A Schematic Picture



Summary

RMHD simulations of protostellar collapse with non-ideal MHD

- 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
- 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?
- Unfortunately, it sensitively depends on microphysics (i.e. dust grain properties). Broad parameter survey is needed.

Thank you!