Dynamical Modelling of Outflows/Jets, Disk Formation, and Dispersal

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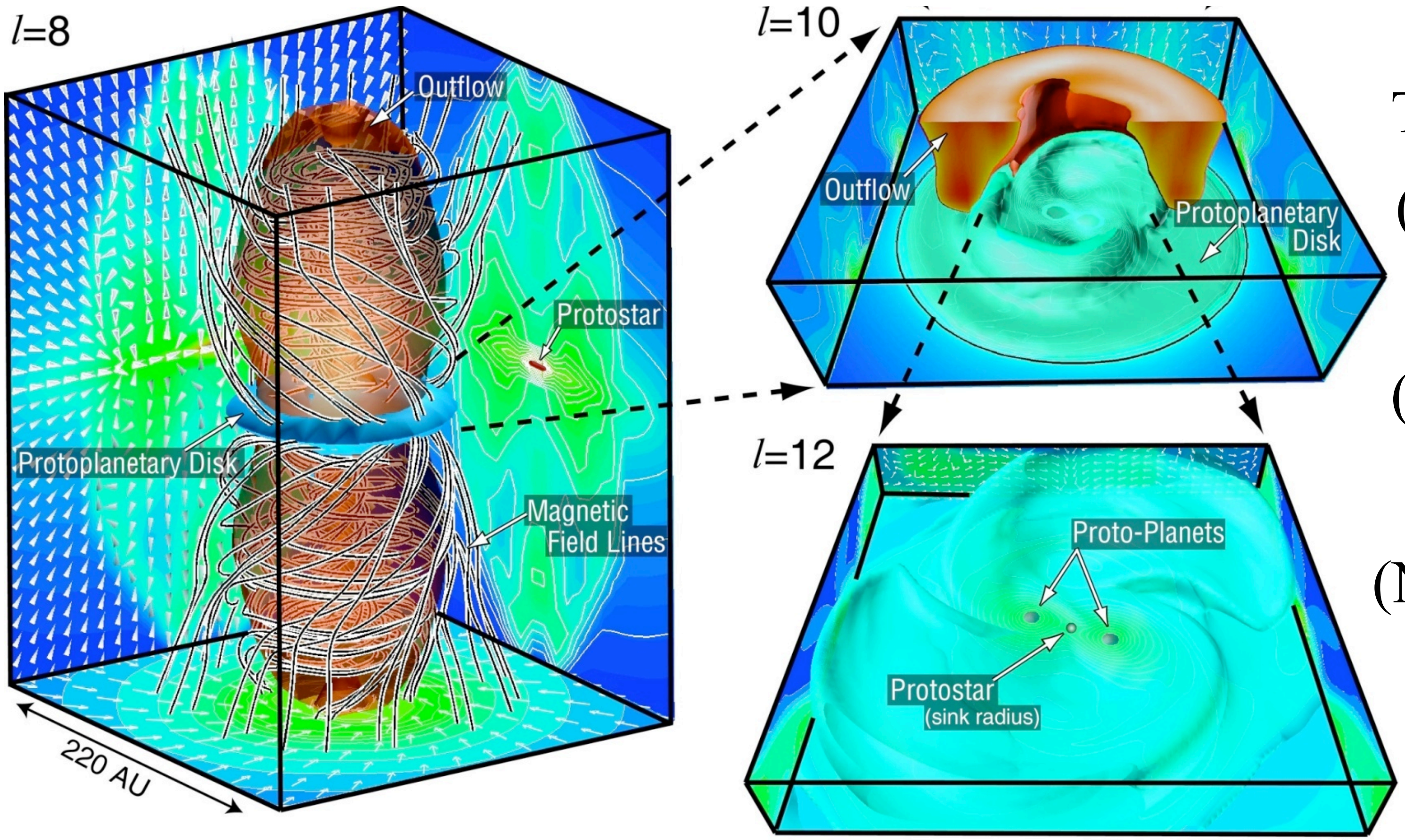


Outline

- Introduction: 2 Basic Problems in SF
- 1st Collapse ➔ 1st Core
  2nd Collapse ➔ 2nd Core=Protostar
- Outflows vs. Jets
  Properties & Driving Mechanism
  - Witnessing Magnetic Flux Loss
  - Formation of PPD and Fragmentation
  - Dispersal of PPD

Basic Problems in Star Formation

1. Angular Momentum Problem:

Protostar:

$$h_* = \Omega_* R_*^2 \sim (10^{11}\mathrm{cm})^2/(10^5\mathrm{s}) \sim 10^{17}\ \mathrm{cm}^2/\mathrm{s}$$

Molecular Cloud:

$$h_{\mathrm{core}} = \delta \mathrm{v}_{\mathrm{core}} R_{\mathrm{core}} \sim 0.1\mathrm{km/s} \times 10^{17}\mathrm{cm} \sim 10^{21}\ \mathrm{cm}^2/\mathrm{s}$$

$$\rightarrow \quad h_* \sim 10^{-4}\ h_{\mathrm{core}}$$

2. Magnetic Flux Problem

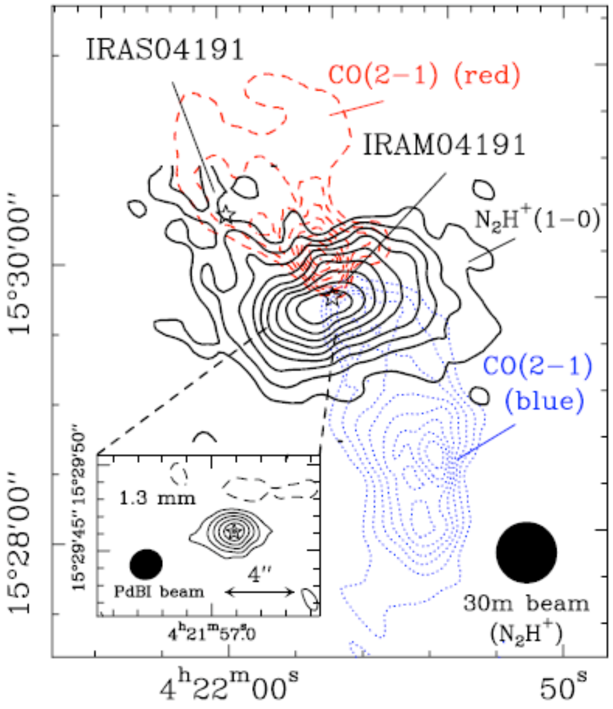
Protostar: $\Phi_* \sim B_* R_*^2 \sim \mathrm{kG} \times (10^{11}\mathrm{cm})^2$

Molecular Cloud: $\Phi_{\mathrm{core}} \sim B_{\mathrm{core}} R_{\mathrm{core}}^2 \sim 10\mu\mathrm{G} \times (10^{17}\mathrm{cm})^2$

$$\rightarrow \quad \Phi_* \sim 10^{-4}\ \Phi_{\mathrm{core}}$$

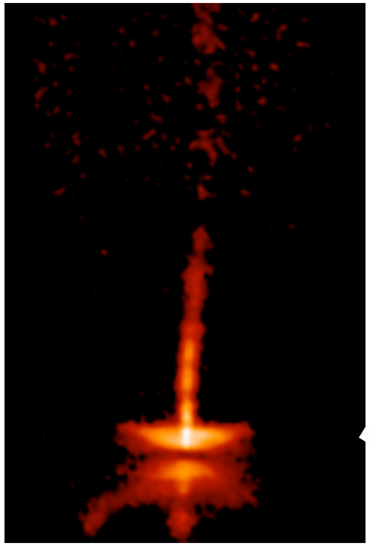
Outflows vs Jets

- Outflow and Jet are ubiquitous in the star-forming region.
  - **Outflow**: **low velocity** (~10 km/s), 10-1000 AU, **Wide opening angle**
  - **Jet**: **high velocity** (~100 km/s), 100-10^5 AU, **well-collimated structure**
- It is difficult to observe **the driving point.**
  - small scale, embedded in the dense cloud core

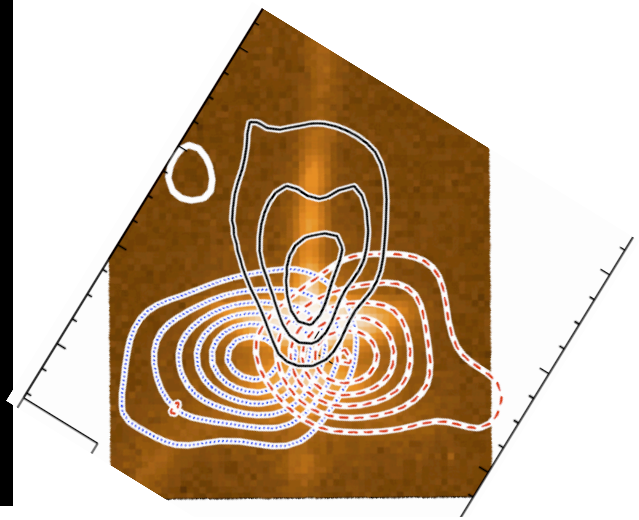


Outflow Belloche et al. (2002)

Jet

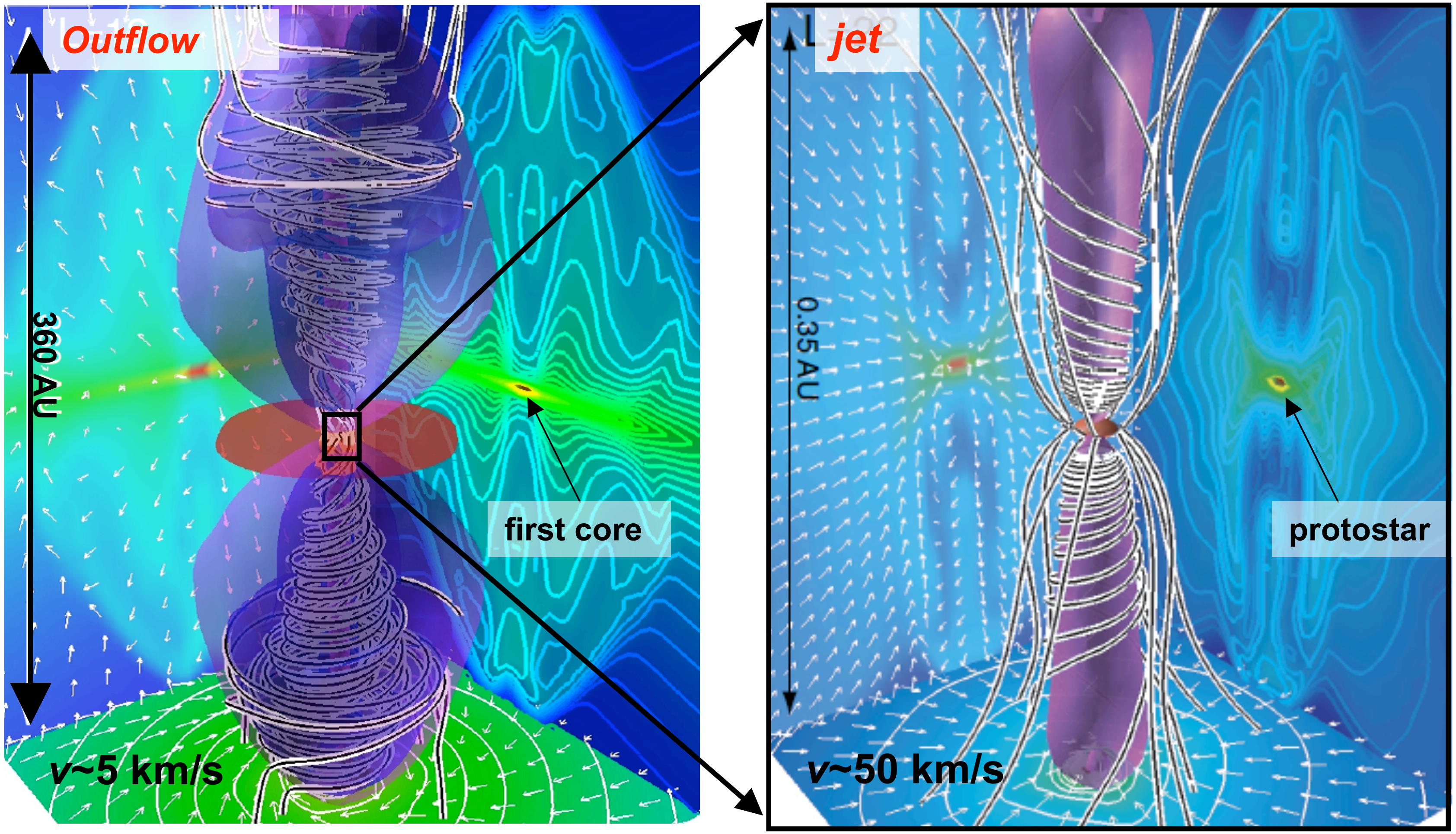


HST image



HH30, Pety et al. 2006

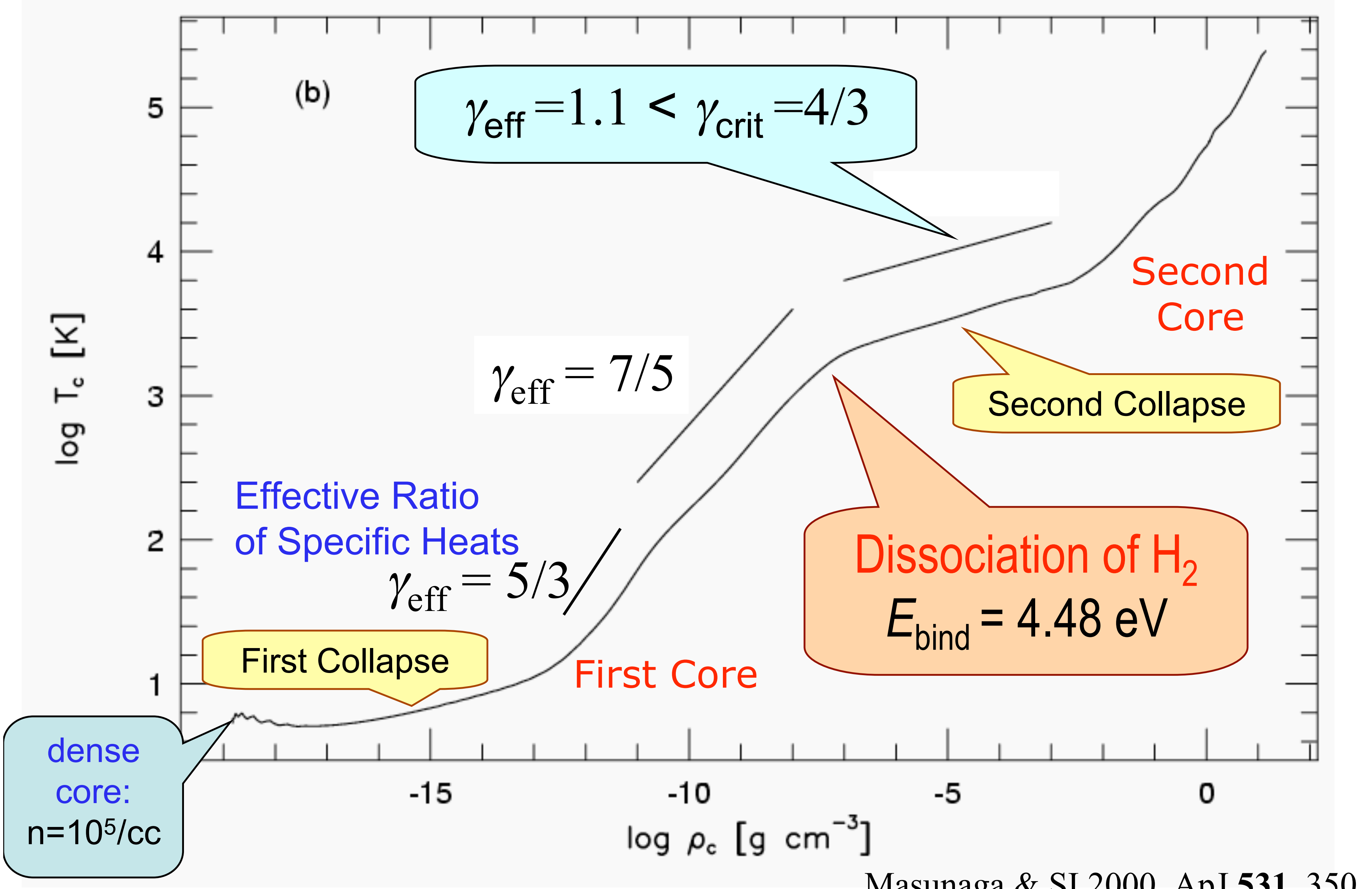
Early Phase of Protostar



Machida et al. (2006-2009), Banerjee & Pudritz (2006), Hennebelle & Fromang (2008)

Outflows & Jets are Natural By-Products!

Temperature Evolution at Center



$\gamma_{\mathrm{eff}} = 1.1 < \gamma_{\mathrm{crit}} = 4/3$

$\gamma_{\mathrm{eff}} = 7/5$

Effective Ratio of Specific Heats

$\gamma_{\mathrm{eff}} = 5/3$

Second Core

Second Collapse

Dissociation of H_2

$E_{\mathrm{bind}} = 4.48$ eV

First Collapse

First Core

dense core: $n = 10^5$/cc

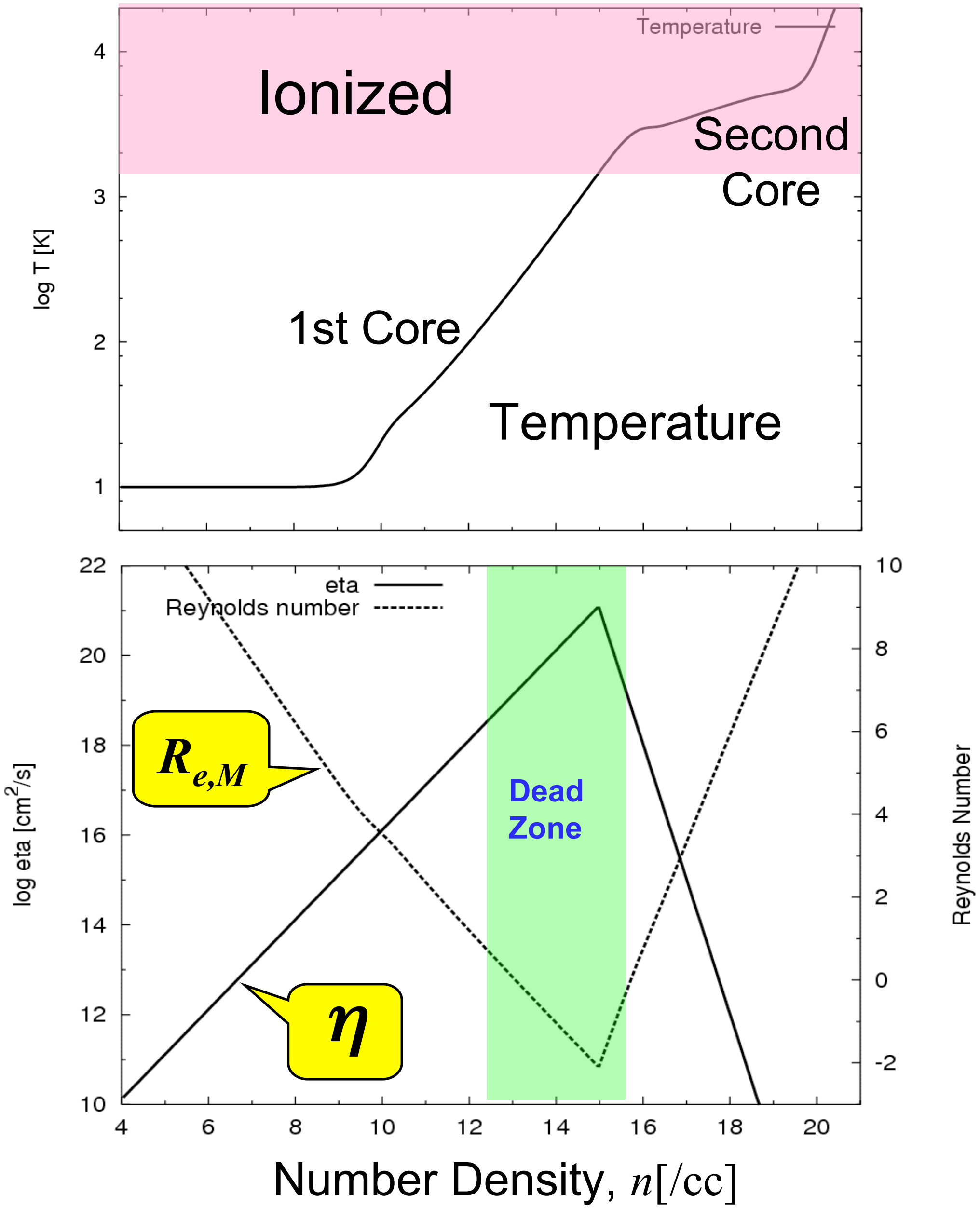
Masunaga & SI 2000, ApJ **531**, 350

Effect of Non-Ideal MHD

Weakly Ionized Gas

- Low density…
  Ambipolar Diffusion
- Intermediate…
  Hall Current Effect
- High density…
  Ohmic Dissipation

e.g., *Nakano, Mouchouvias, Wardle, etc.*



Stage 1: **Outflow** driven from the **first core**

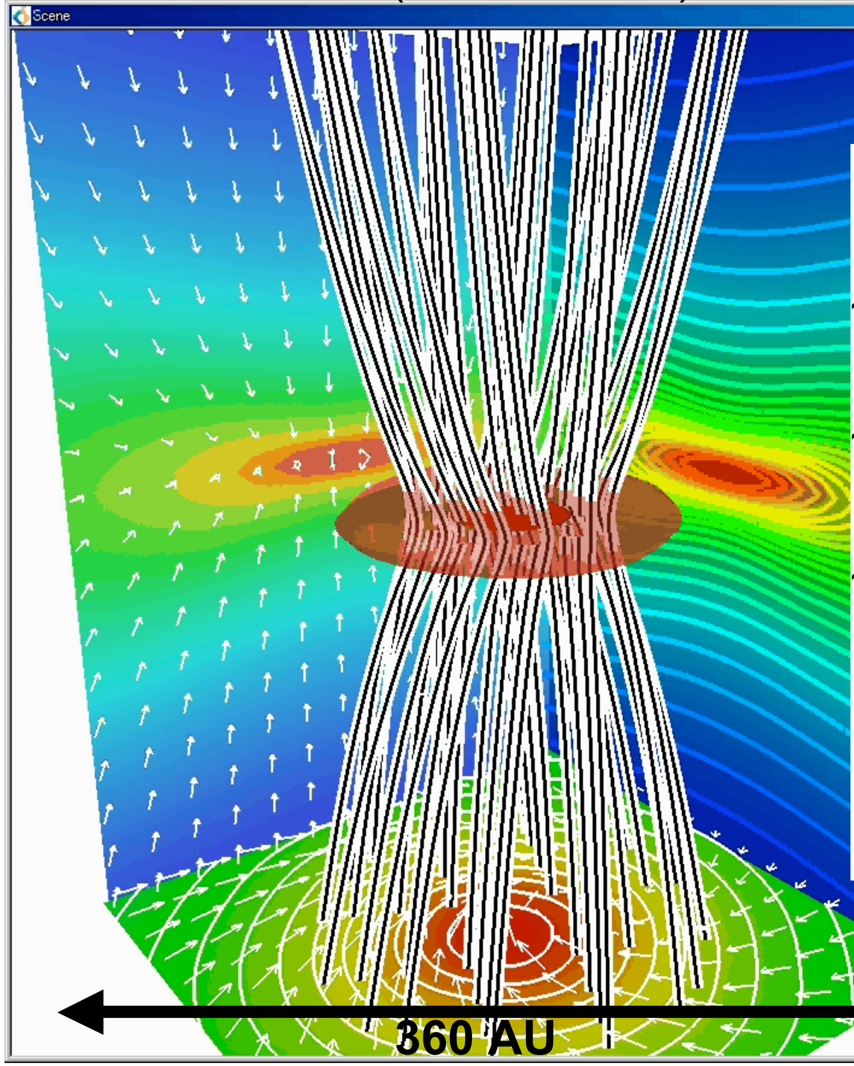
The evolution of the Outflow around the first core

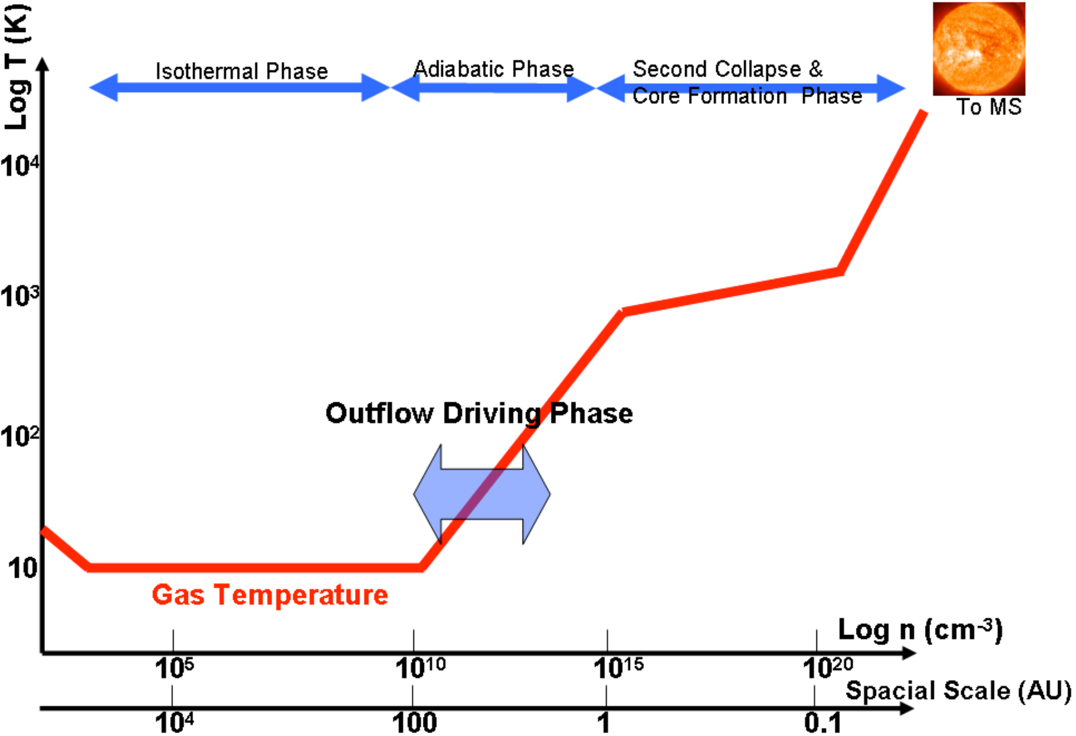
- This animation start after the first core is formed at n~10^{10} cm^{-3}

Model for
(α, ω)=1, 0.3

Grid level L =12 (Side on view)

Grid level L =12 (Top on view)





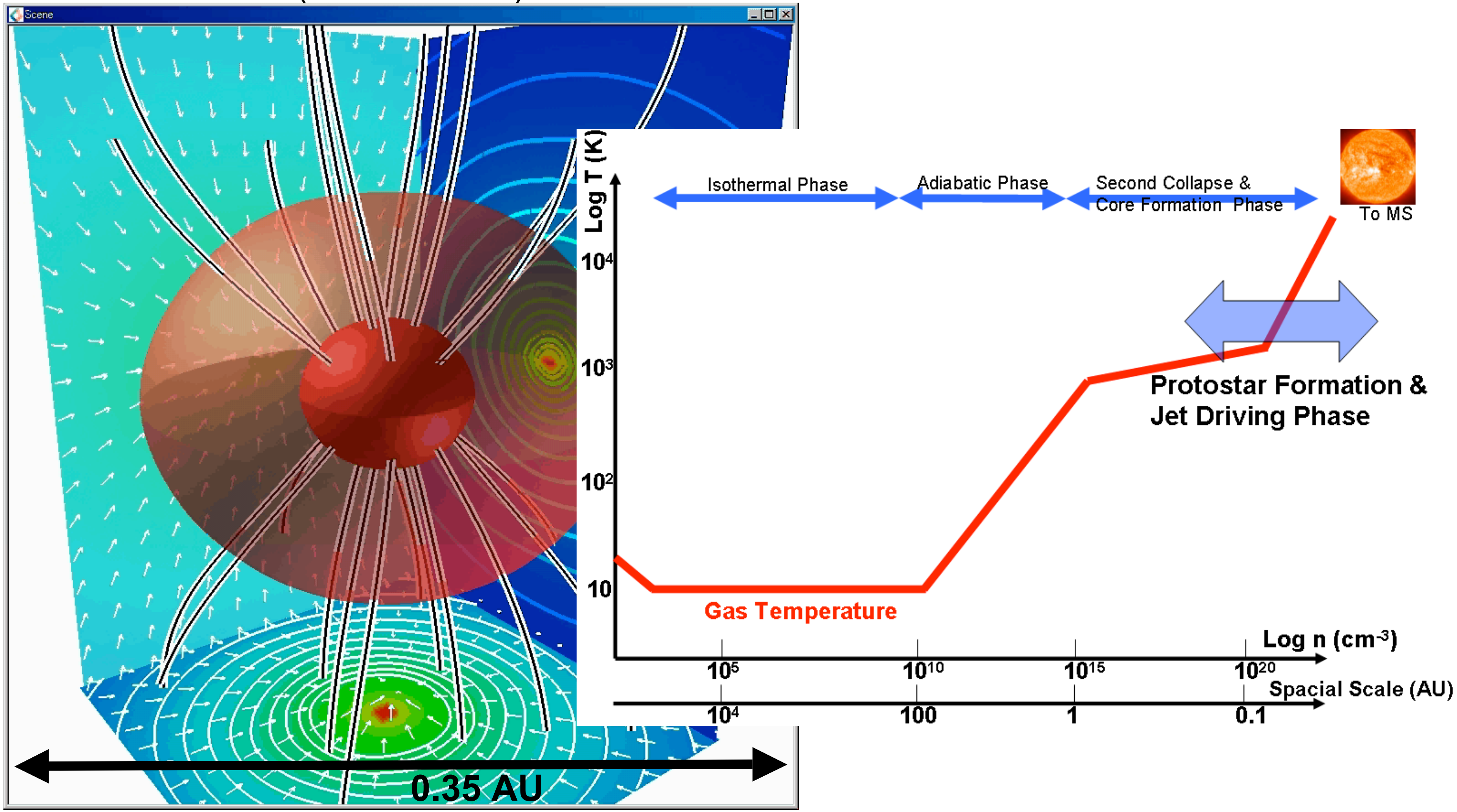
Stage 3: **Jet** driven from the **protostar**

The evolution of the Jet around the protostar

- This animation start before the protostar is formed at n~10^{19} cm^{-3}

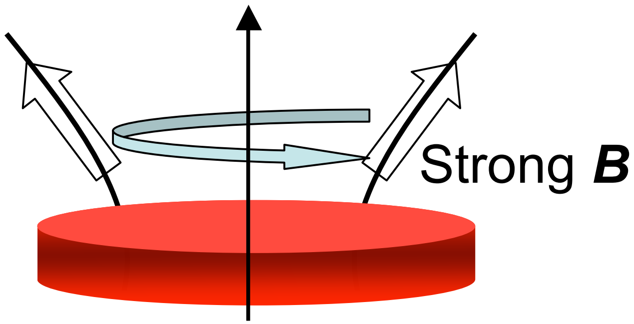
Model for
(α, ω)=1, 0.003

Grid level L =21 (Side on view)



Difference in Driving Mechanism

Magnetocentrifugally driven Wind

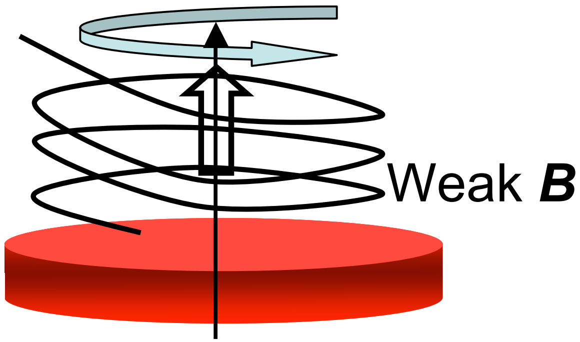


Wide Opening Angle

outflow around first core

$B_r \approx B_z \approx B_\phi$

Magnetic Pressure driven Wind



Narrow Opening Angle

jet around protostar

$B_z << B_\phi$

Discussion: Speeding-Up of Outflow/Jet

	Our results	Observation
■Outflow	: ~5 km/s	5—50 km/s
■Jet	: ~50 km/s	100—500 km/s

- These velocities correspond to escape velocity from the first core and protostar
  - ✓First core: ~0.01 M_{sun}, 1 AU (in our 3D calculation)
  - ✓Protostar: ~0.01 M_{sun}, ~1 R_{sun} (in our 3D our calculation)
- When the mass of each core increases up to 1 M_{sun}, the speed of the outflow and jet will increase by a factor 10 ($v_{kepler} \propto M^{1/2}$)... good agreement with obs.
  - ✓Outflow: ~5 km/s (0.01 Msun) ⇒ ~50 km/s (1 M_{sun})
  - ✓Jet: ~50 km/s (0.01 Msun) ⇒ ~500 km/s (1 M_{sun})

Differences of speeds are due to differences of escape velocities from the first core and protostar

Machida, SI, Matsumoto (2008) ApJ **676**, 1088

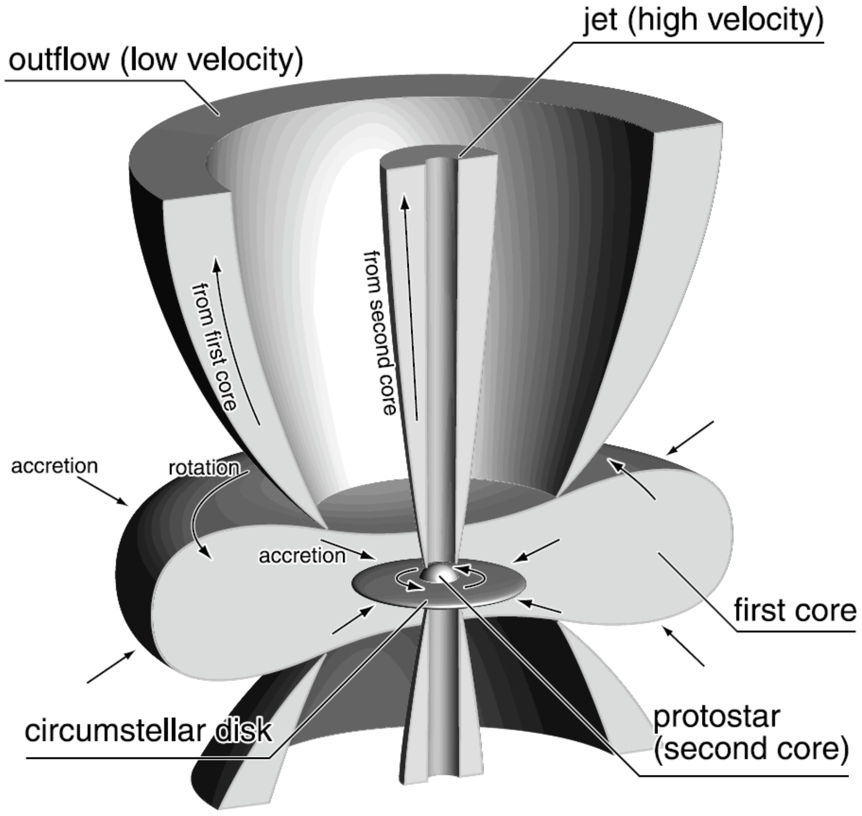
Summary of Our Theory

Evolution from $n = 10^4\ \mathrm{cm}^{-3}$ to $n \sim 10^{24}\ \mathrm{cm}^{-3}$.

◆Two different flows (outflow/jet) appear in the collapsing cloud owing to the Stiffening of EoS.

- ➢Outflow driven by the first core has wide opening angle and slow speed.
- ➢Jet driven by the protostar has well-collimated structure and high speed.

◆The velocities of the outflow and jet correspond to the escape speeds from the first core, and protostar.



Machida, SI, Matsumoto (2008) ApJ **676**, 1088

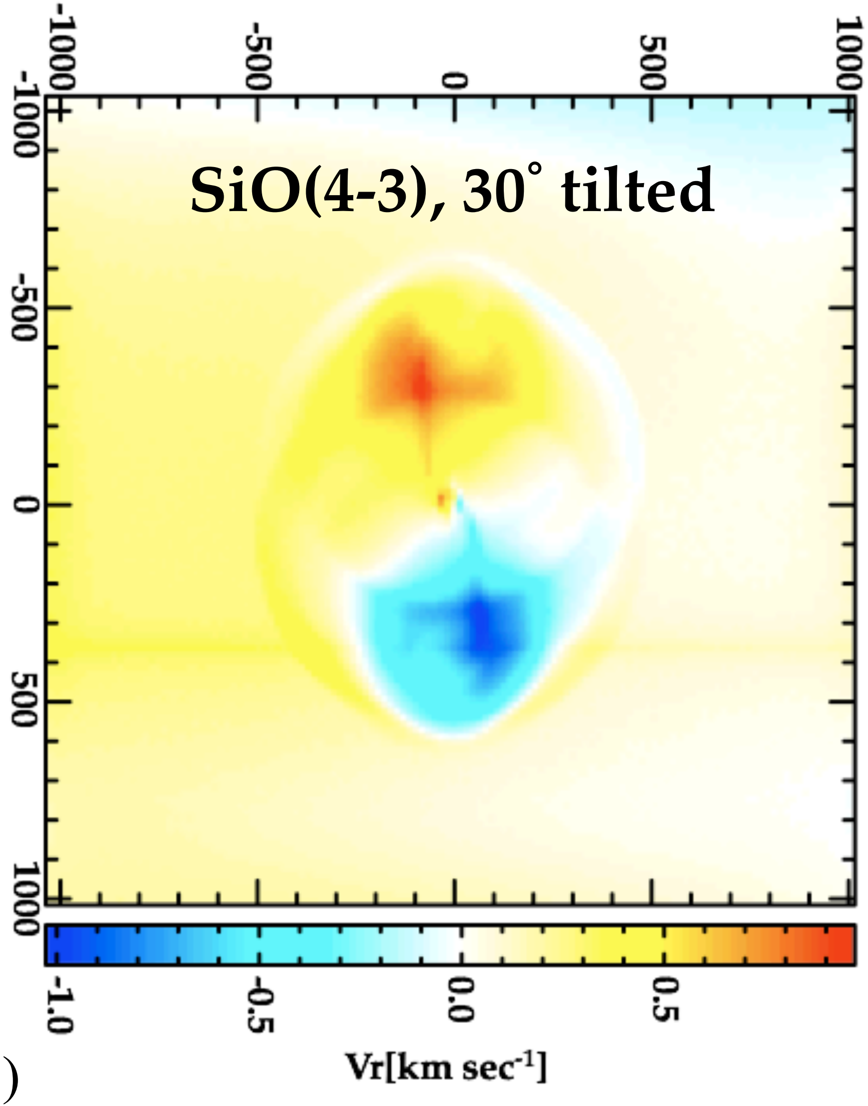
Q1:How to Measure Ang. Mom. Reduction

Non-LTE radiative transfer calc.

➔Comparison with ALMA Observation

➔Solution to Angular Momentum Problem in Star Formation

Non-LTE Radiative Transfer Calc.



SiO & CO…
Yamada, Machida, SI, & Tomisaka (2009)
ApJ **703**, 1141

We hope that

ALMA will determine launching points of outflows and jets, and testify evolutionary model and driving mechanism.

➔ Solution to Angular Momentum Problem in Star Formation

If yes,

what can we do next?

Rotation of Outflow Observed?

Launhardt et al.,: Rotating molecular outflow in CB 26 11

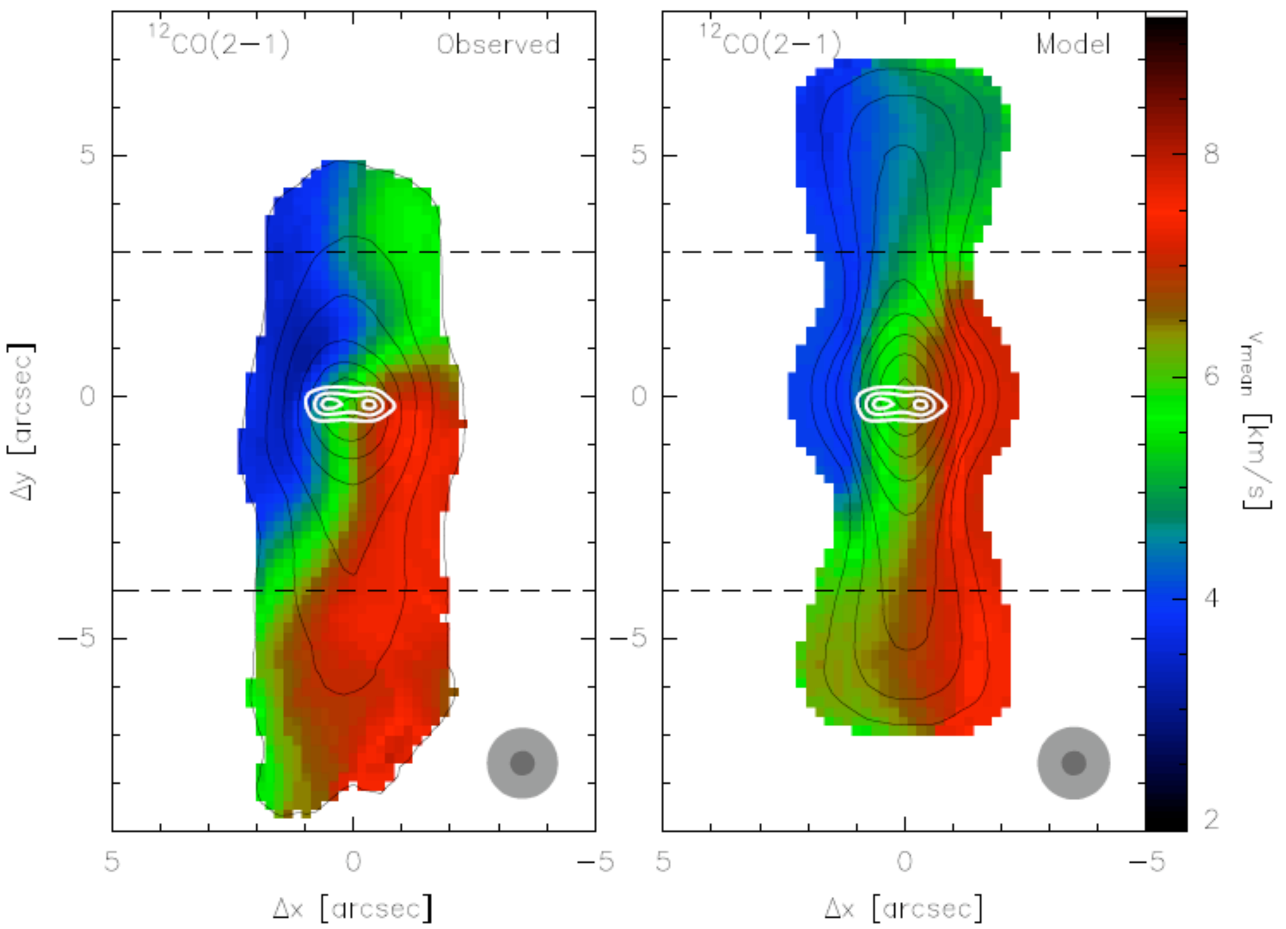
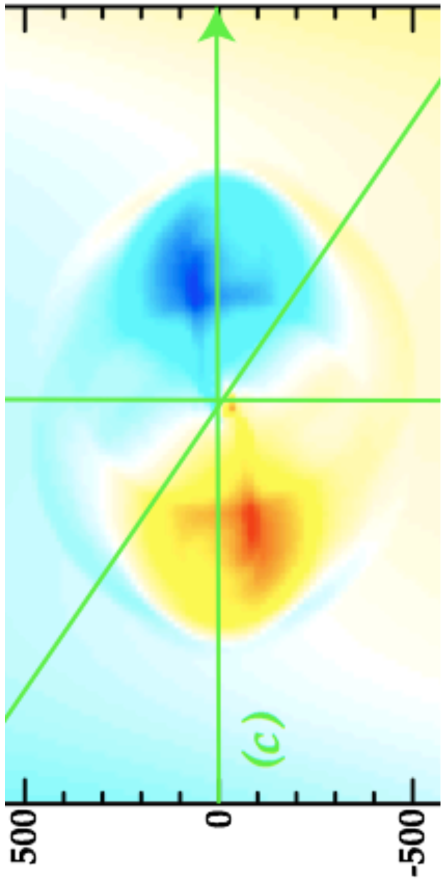


Fig. 3. ^{12}CO (2–1) integrated intensity maps (contours) and mean velocity field (1st moment map, color) of CB 26, rotated by 30°. White contours show the 1.1 mm dust continuum emission from the disk as observed with the SMA (contour levels same as Fig. 1). The ^{12}CO synthesized beam size is shown as large grey ellipse. The smaller and darker ellipse shows the 1.1 mm continuum beam. Left panel: observations. Right panel: best-fit model for ^{12}CO (2–1). Dashed lines refer to the y-coordinate of the position-velocity diagrams shown in Fig. 4

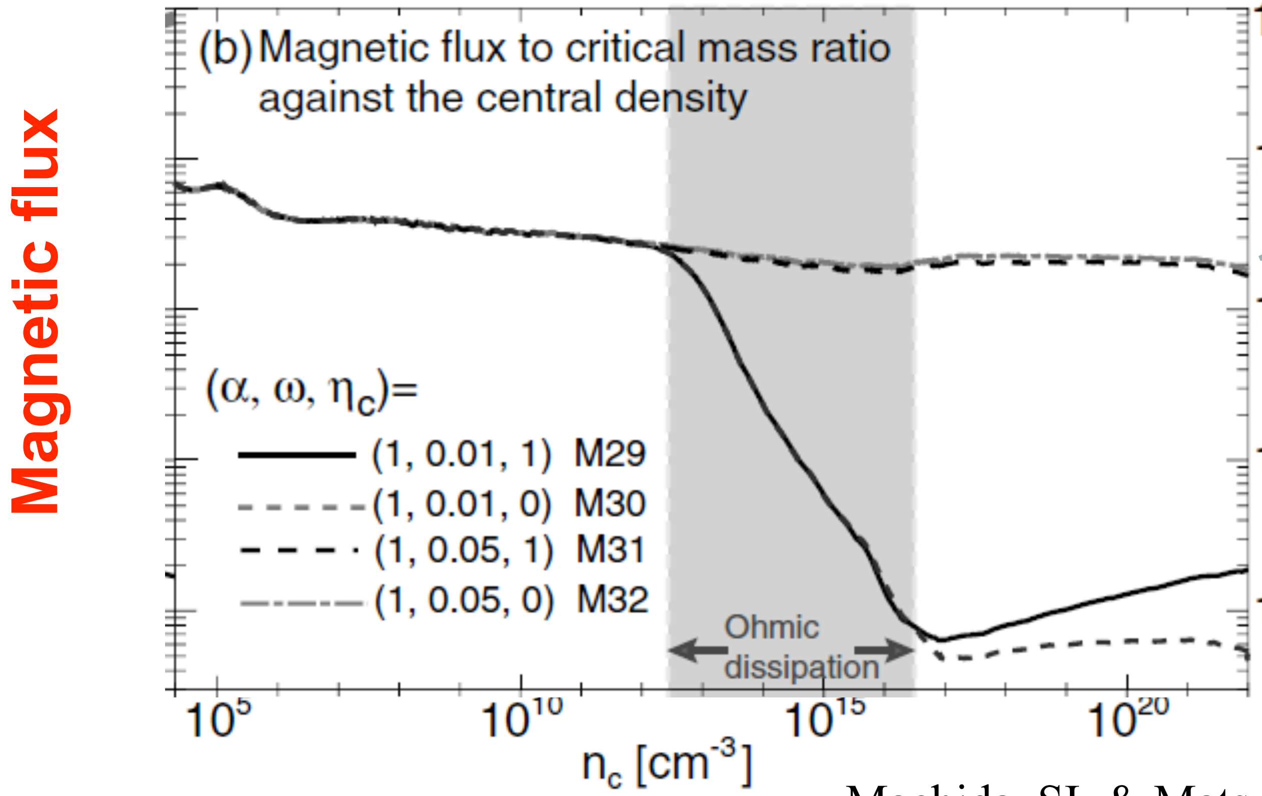
Launhardt et al. (2008, arXiv:08113910)



Transfer Calc. with Our Simulation, 30deg tilted

Q2: Obs of Magnetic Flux Loss?

Magnetic flux largely removed from First Core
when $n = 10^{12} \sim 10^{16}$ cm^{-3} ➔ B = kG or less



Ideal MHD

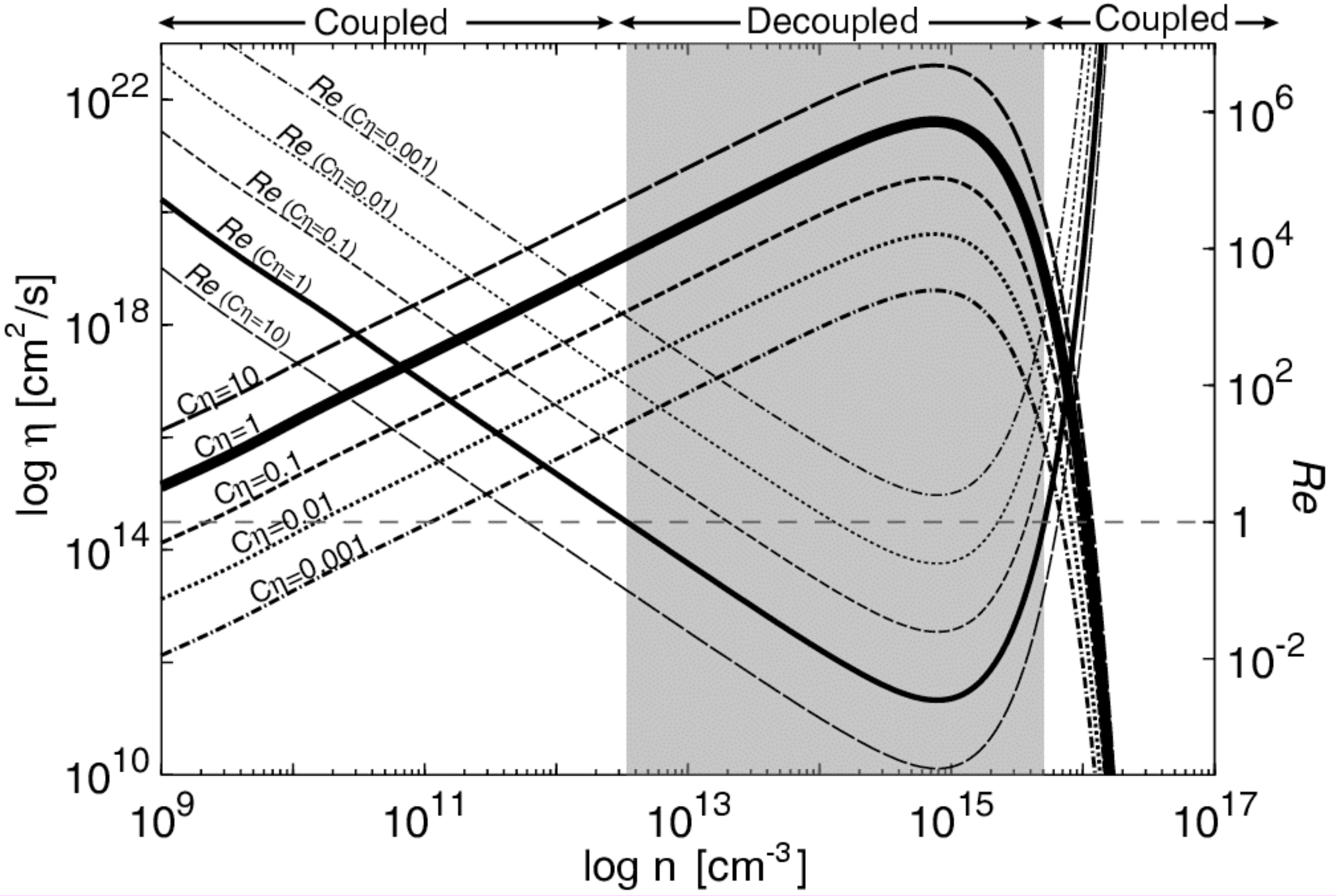
Resistive MHD

Machida, SI, & Matsumoto (2007) ApJ **670**, 1198

Can we observe this by ALMA?

History of Ionization Degree

Because of uncertainty of dust grain properties, we have parameterized resistivity.



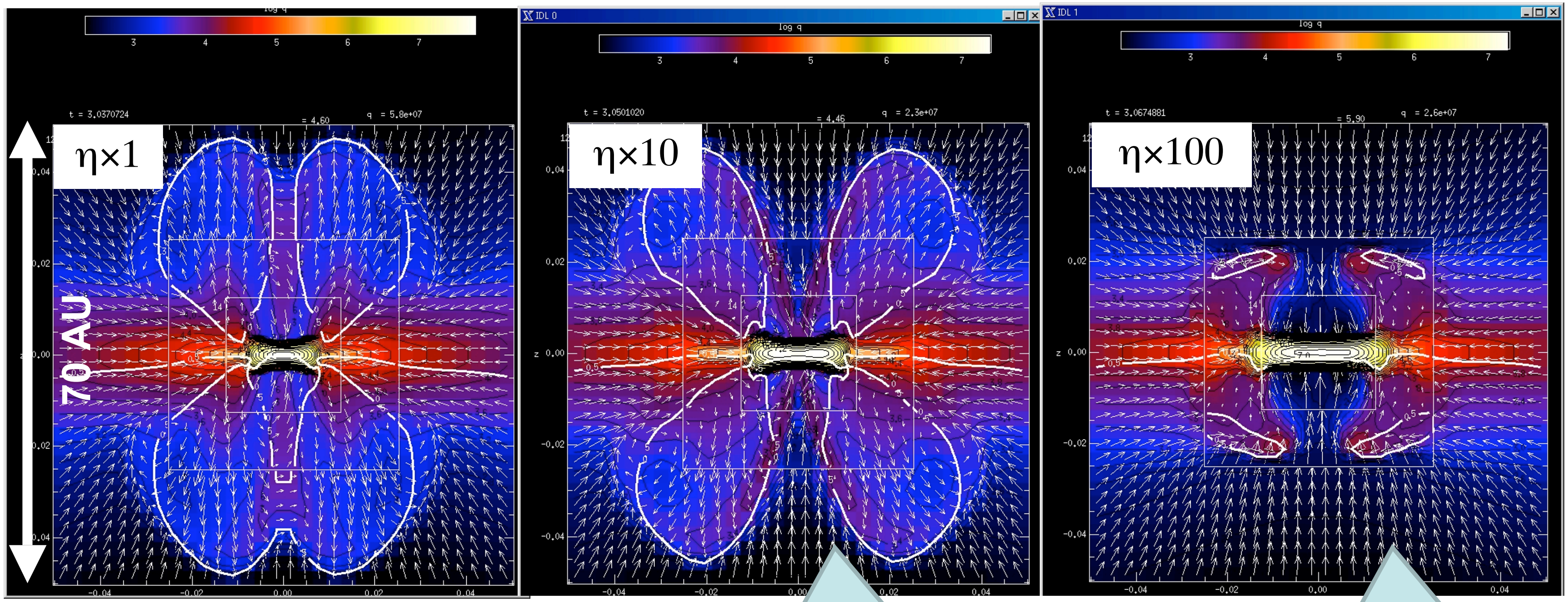
Machida, SI,
& Matsumoto
(2007) ApJ
670, 1198

Changing resistivity results in different morphology of

Effect of Changing Resistivity Parameter

density snapshot at very early phase of outflow in 3 models

Increasing Resistivity Parameter



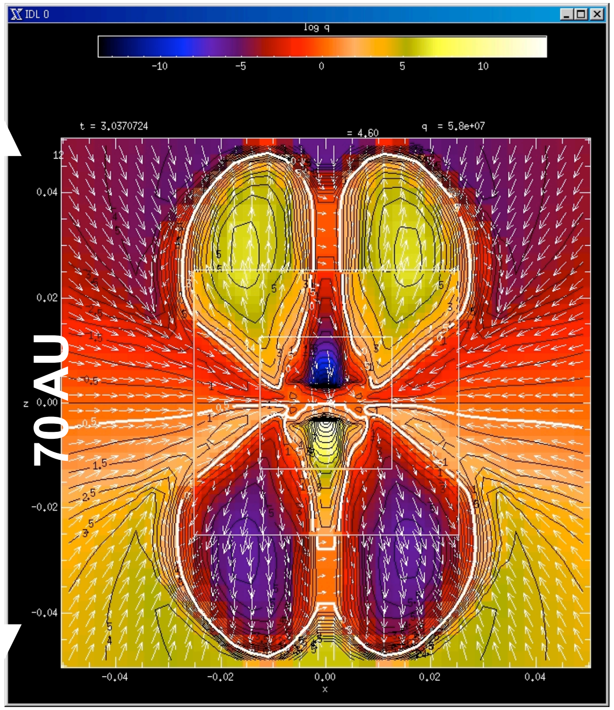
Wider Opening Angle of Outflow

Almost No Outflow

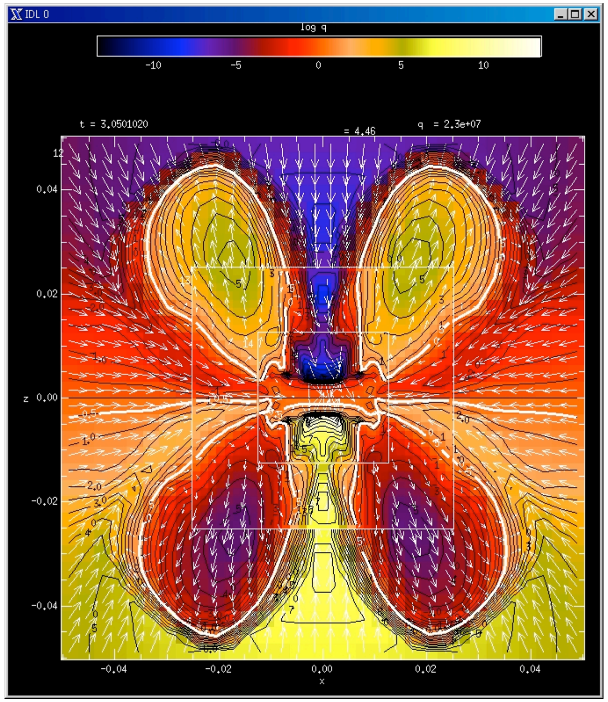
Effect of Changing Resistivity Parameter

Velocity Profile (V_z)

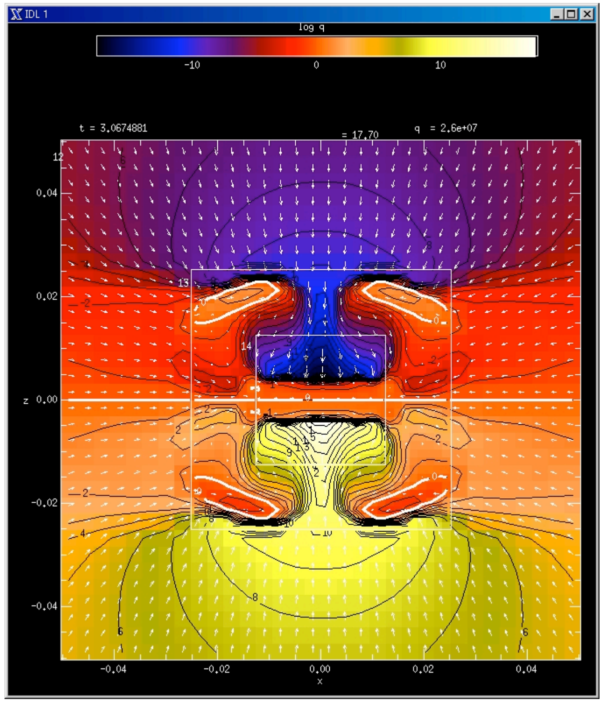
Increasing Resistivity Parameter →



η x 1



η x 10



η x 100

Proposals for ALMA Obs.

● Outflow from First Core

Launch at large radius ←→ Other Models

● Fast Jet from Second Core

Reduced Magnetic Flux → Winding-Up

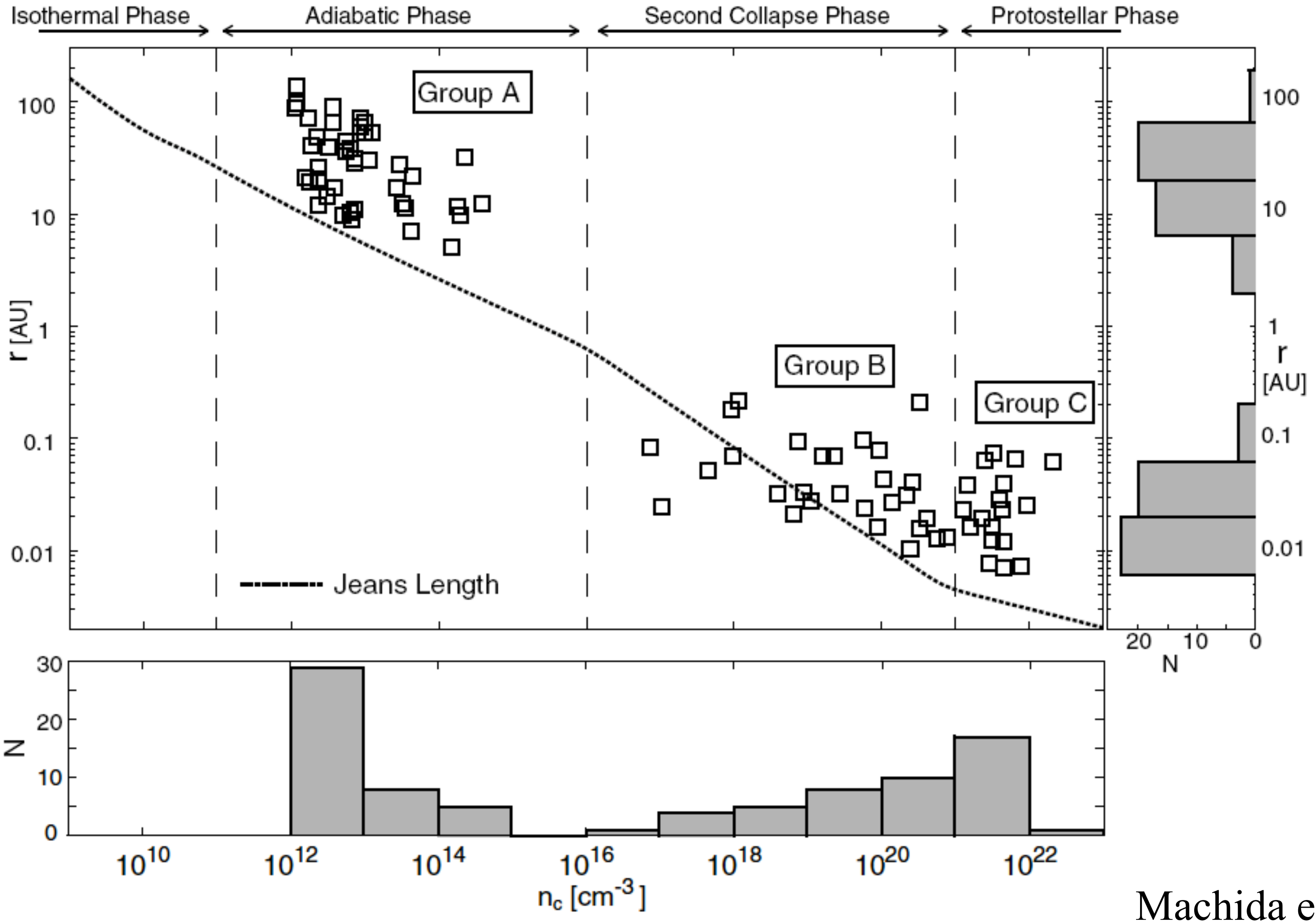
Well-Collimated from The Beginning

←→ Magneto-Centrifugally Driven Model

● Detailed Comparison with Simulations

→ Witnessing Magnetic Flux Loss from Central Object

Bimodal Binary Formation



distance from primary star

Machida et al. (2008)
ApJ **677**, 327

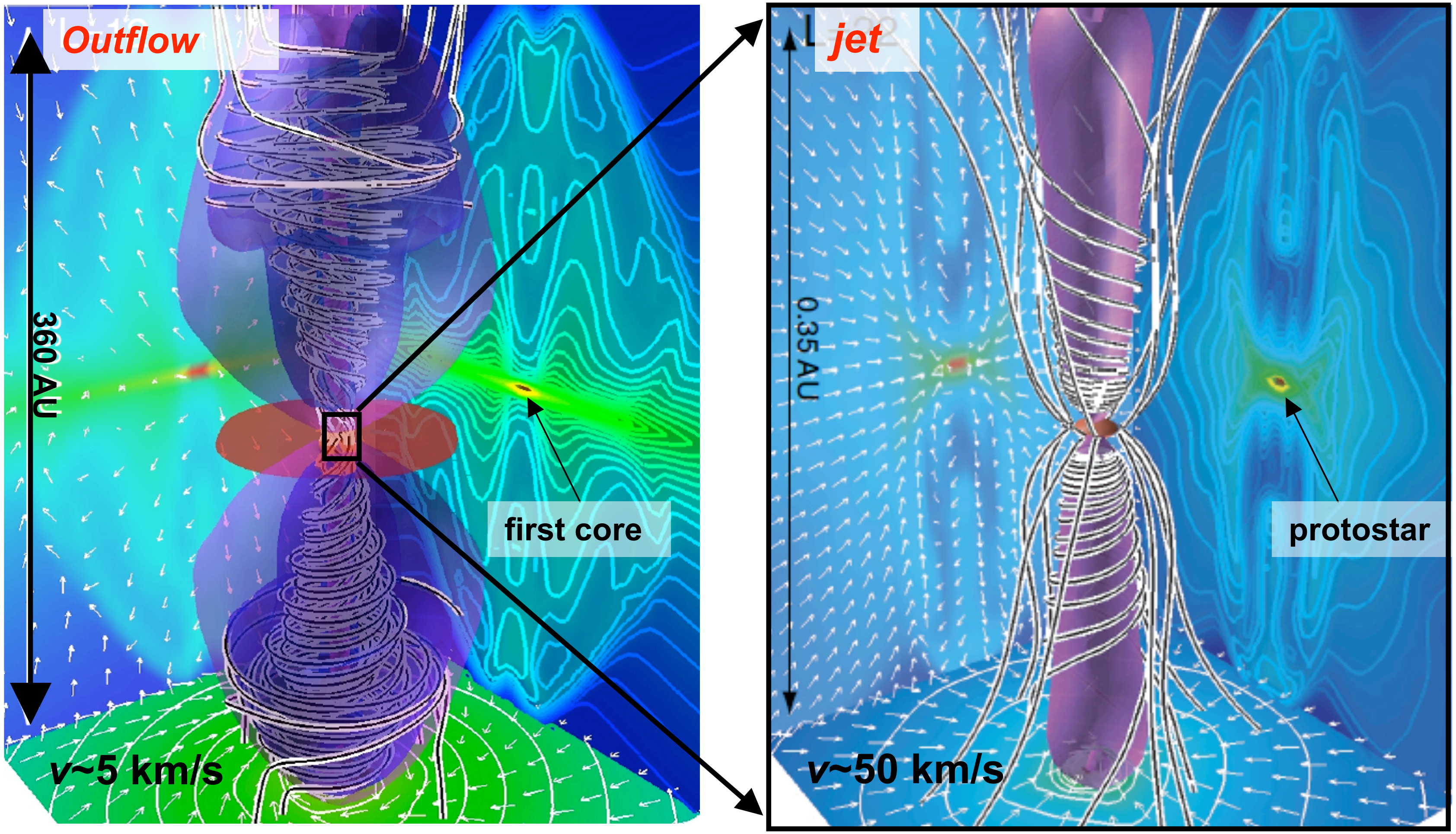
Star Formation Theory Extended

Rapid Progress in Our Understanding of Formation of Protostars

→ Further Evolution to Formation/Evolution of Protoplanetary Disks

→ Star formation process determines Initial Condition of Planet Formation!

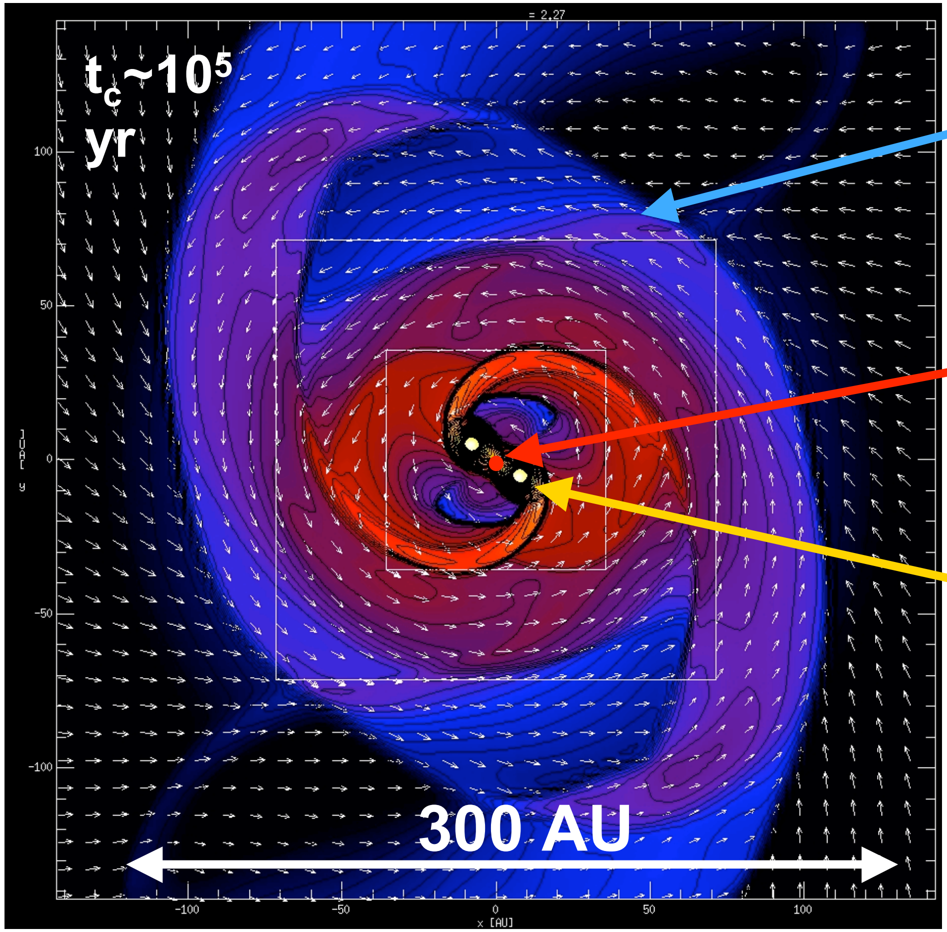
Early Phase of Protostar



Machida et al. (2006)

We have good understanding up to $M = 0.1\ M_{\odot}$!

Formation of Planetary Mass Companions in Protoplanetary Disk



Protoplanetary Disk

Protostar

- $\sim 0.1\ M_{sun}$

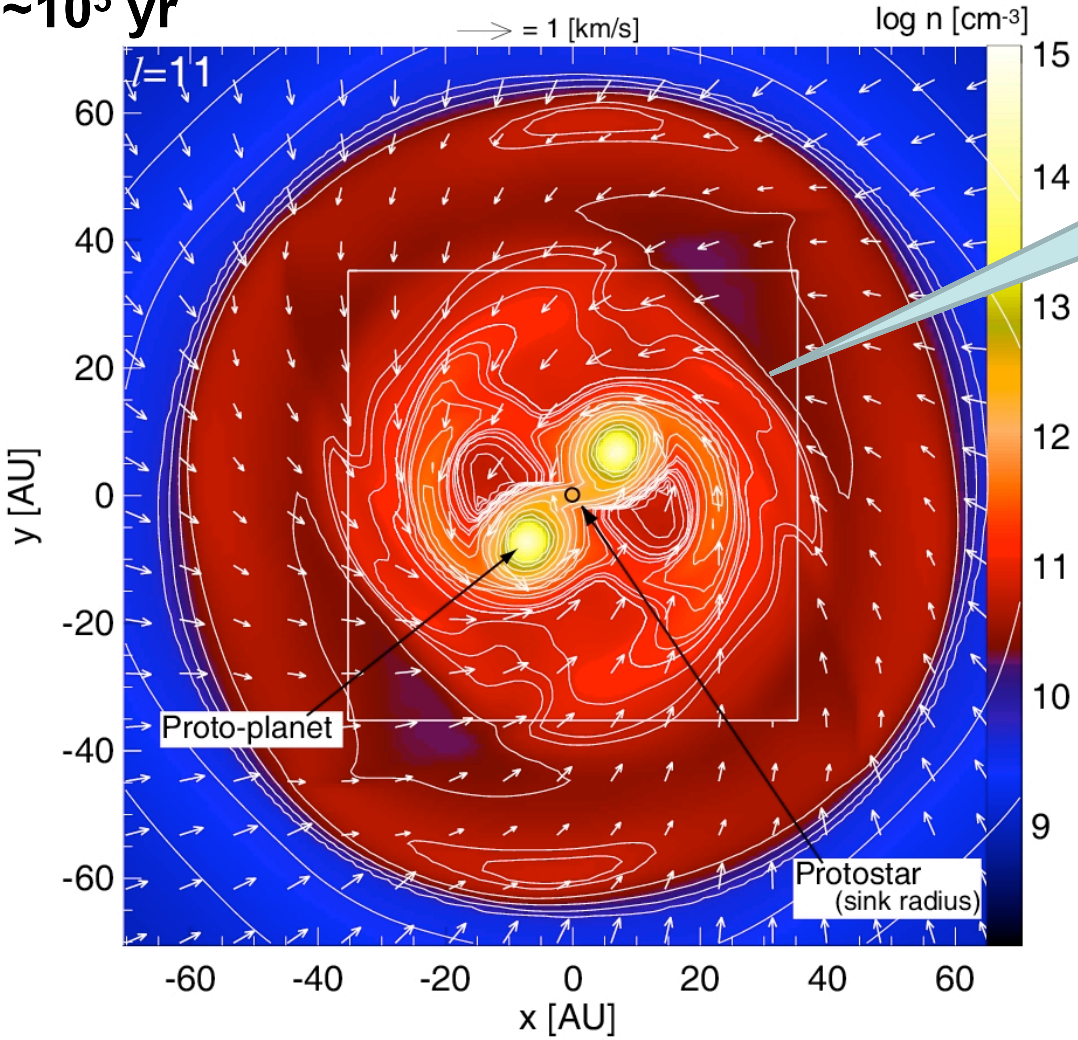
Protoplanet

- $M \sim 8\ M_{Jup}$
- $R_{sep} \sim$ 10-20 AU

Machida, SI, Matsumoto (2009)

Formation of Planetary Mass Companions in Protoplanetary Disk

$t_c \sim 10^5$ yr



Protoplanetary Disk

Protostar

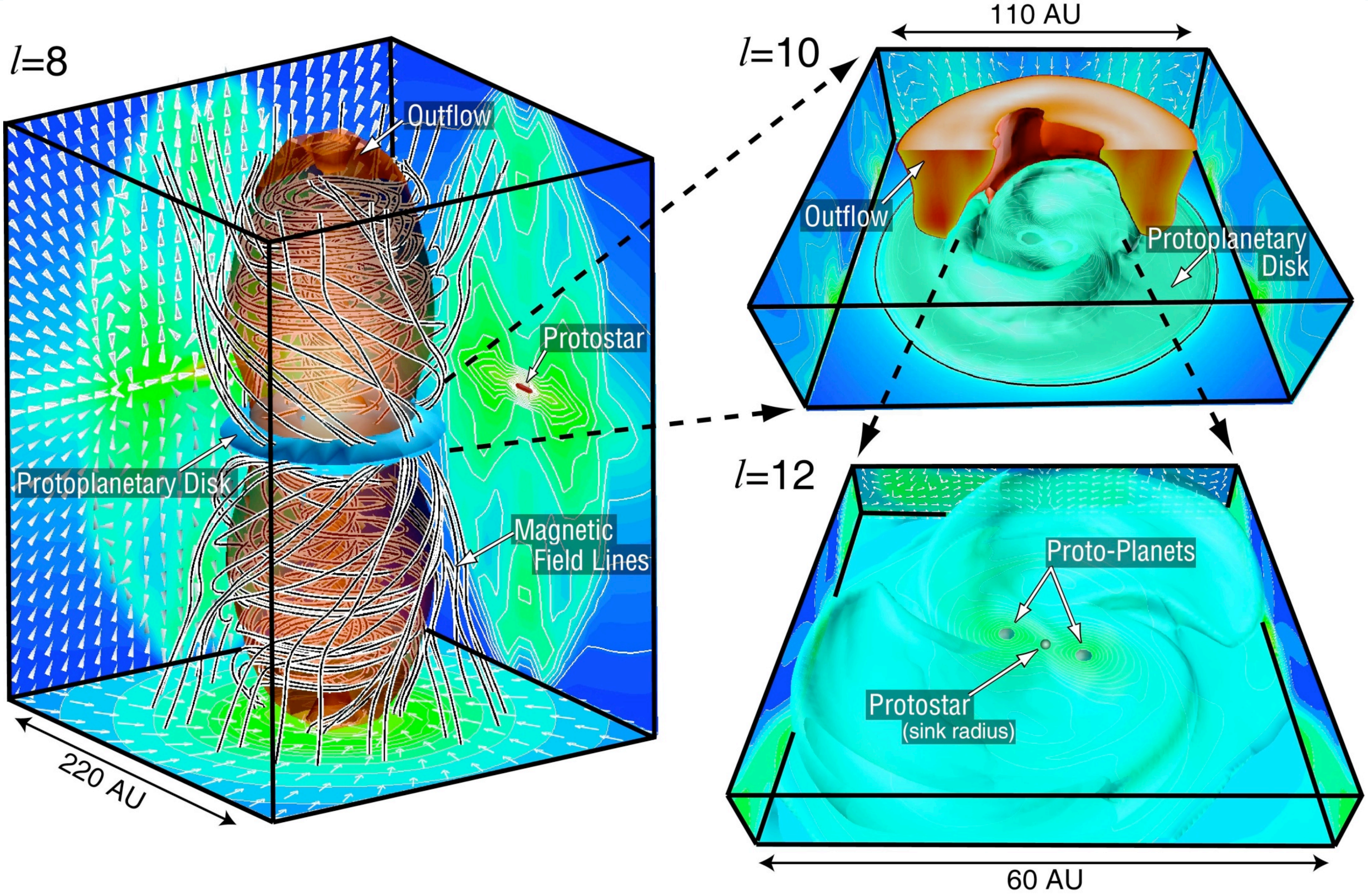
- ~0.1 M_{sun}

Protoplanet

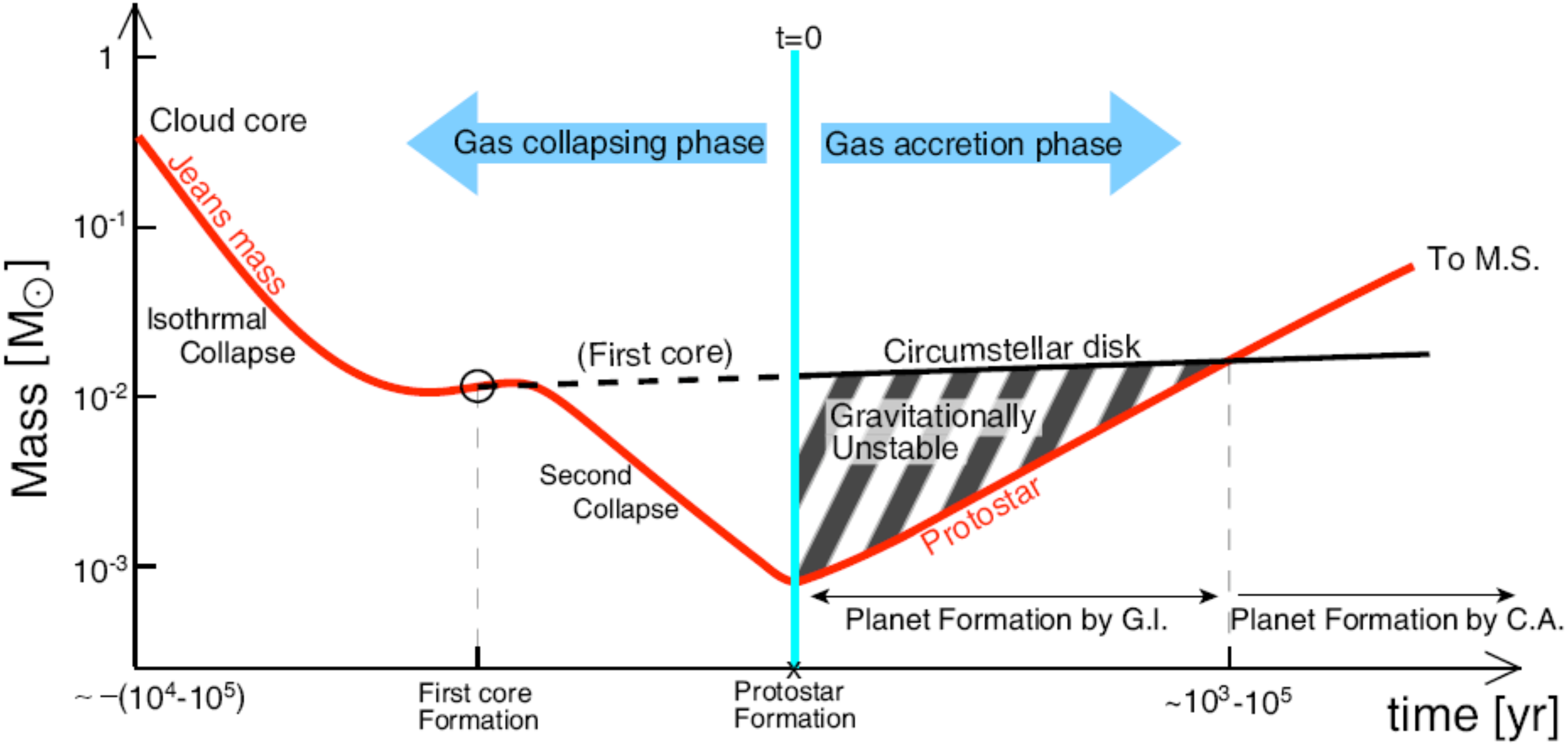
- M~8 M_{Jup}
- R_{sep}～10-20 AU

Machida, SI, Matsumoto (2009)

Resistive MHD Calc. from Mole. Cloud Core

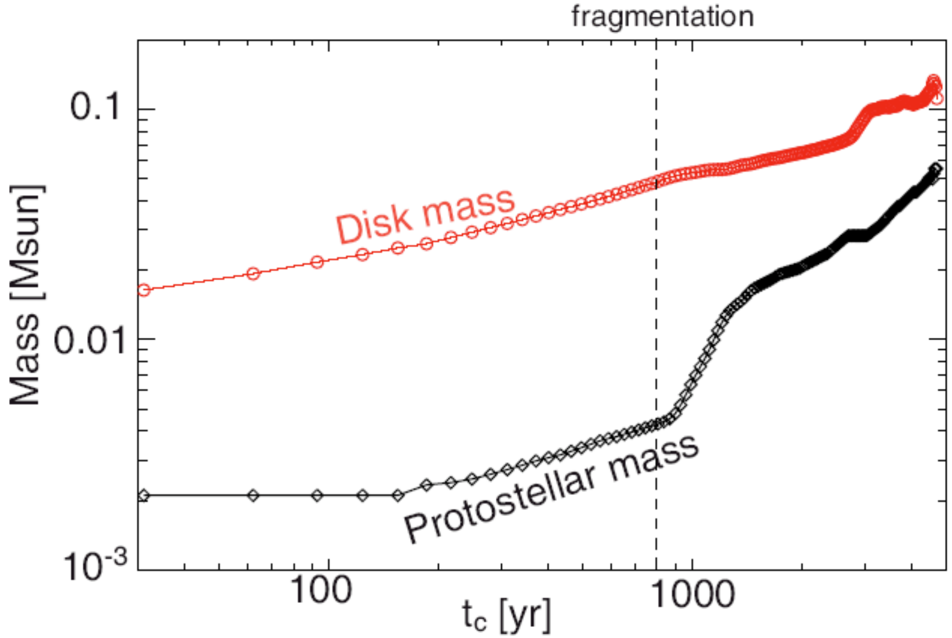


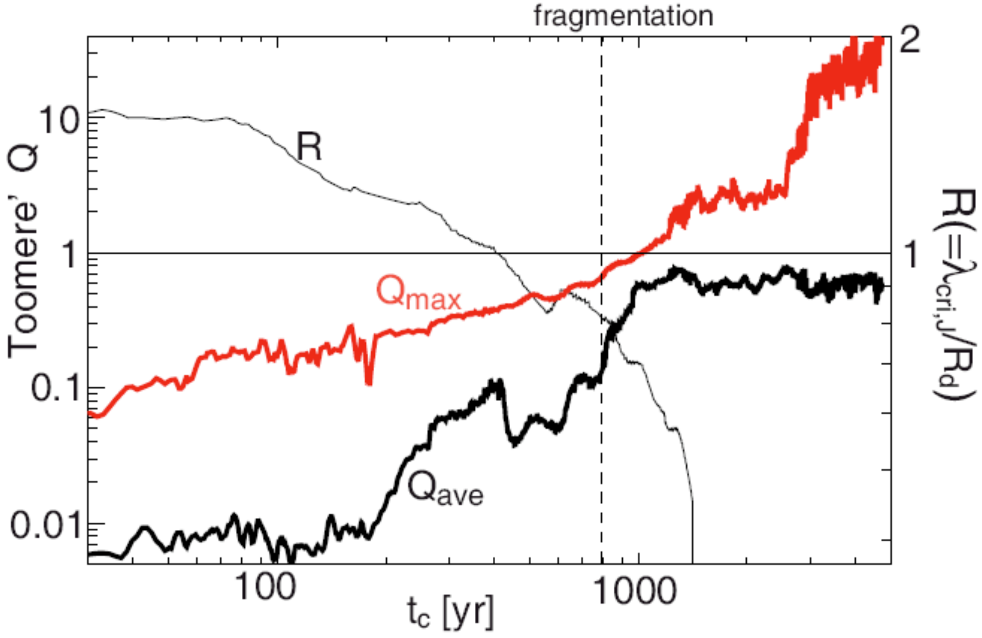
Formation of Planetary Mass Companions in Protoplanetary Disk



SI, Machida, & Matsumoto (2009)

Evolution of Stellar Mass & Disk Mass





Local Criterion for Gravitational Instability:

$$Q \equiv \kappa\, C_s /(\pi G \Sigma)$$

SI, Machida, & Matsumoto (2009)

Gap in Mass Distribution?

Brown Dwarf Desert:

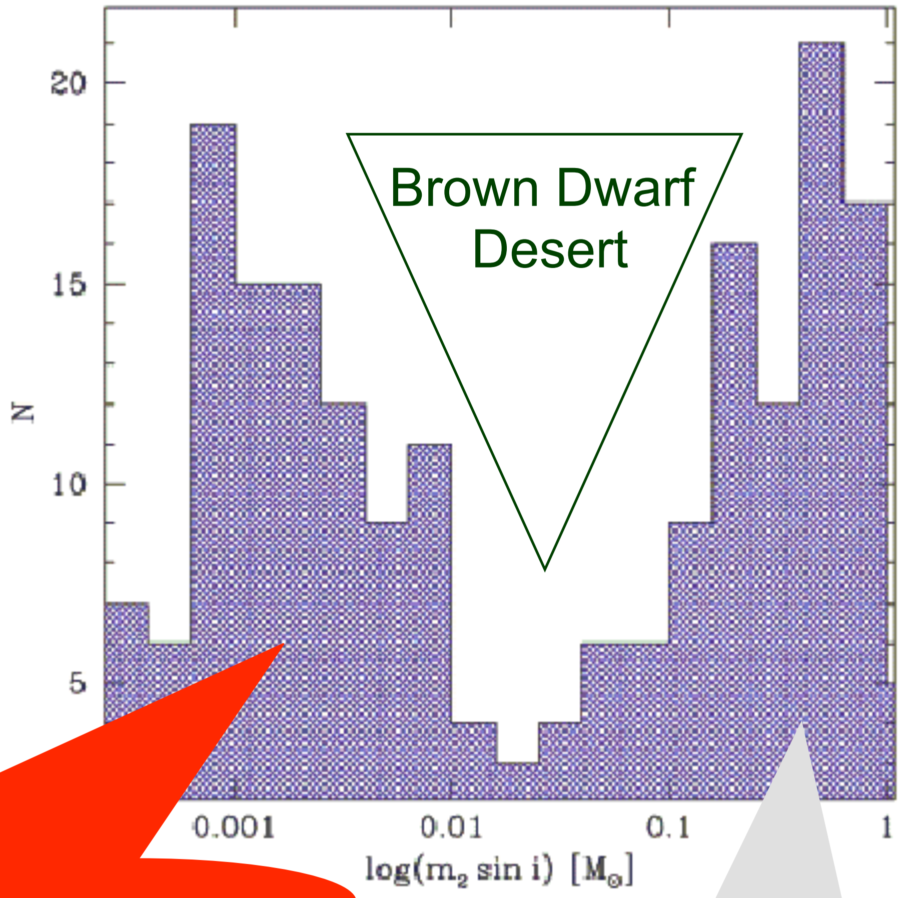
$M \sin(i) < 0.01\,M_{\odot}$

$M \sin(i) > 0.01\,M_{\odot}$

➔ different formation mechanism?

➔ Smaller mass objects are formed by <u>core accretion model?</u>

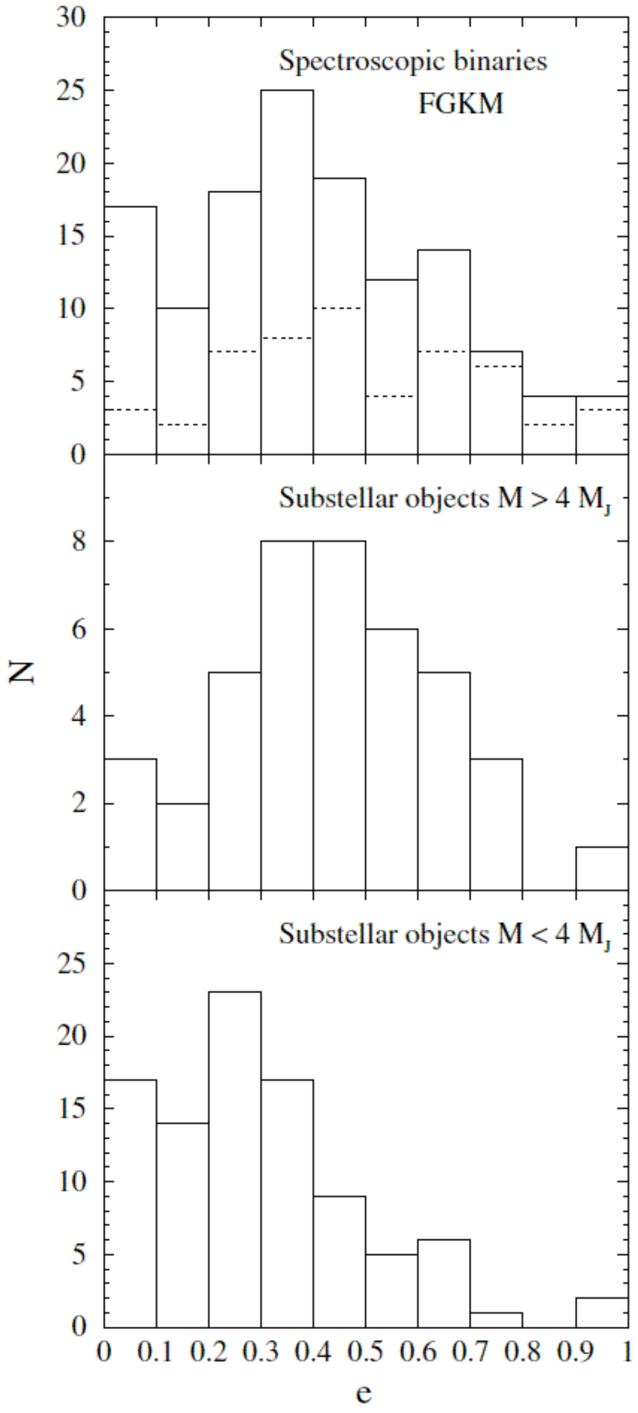
Mass Function of Companions



Fragmentation in Protoplanetary disk

Fragmentation

Eccentricity Distribution of Exo-Planets



Ribas &
Miralda-Escudé
(2007)

Metallicity Dependence?

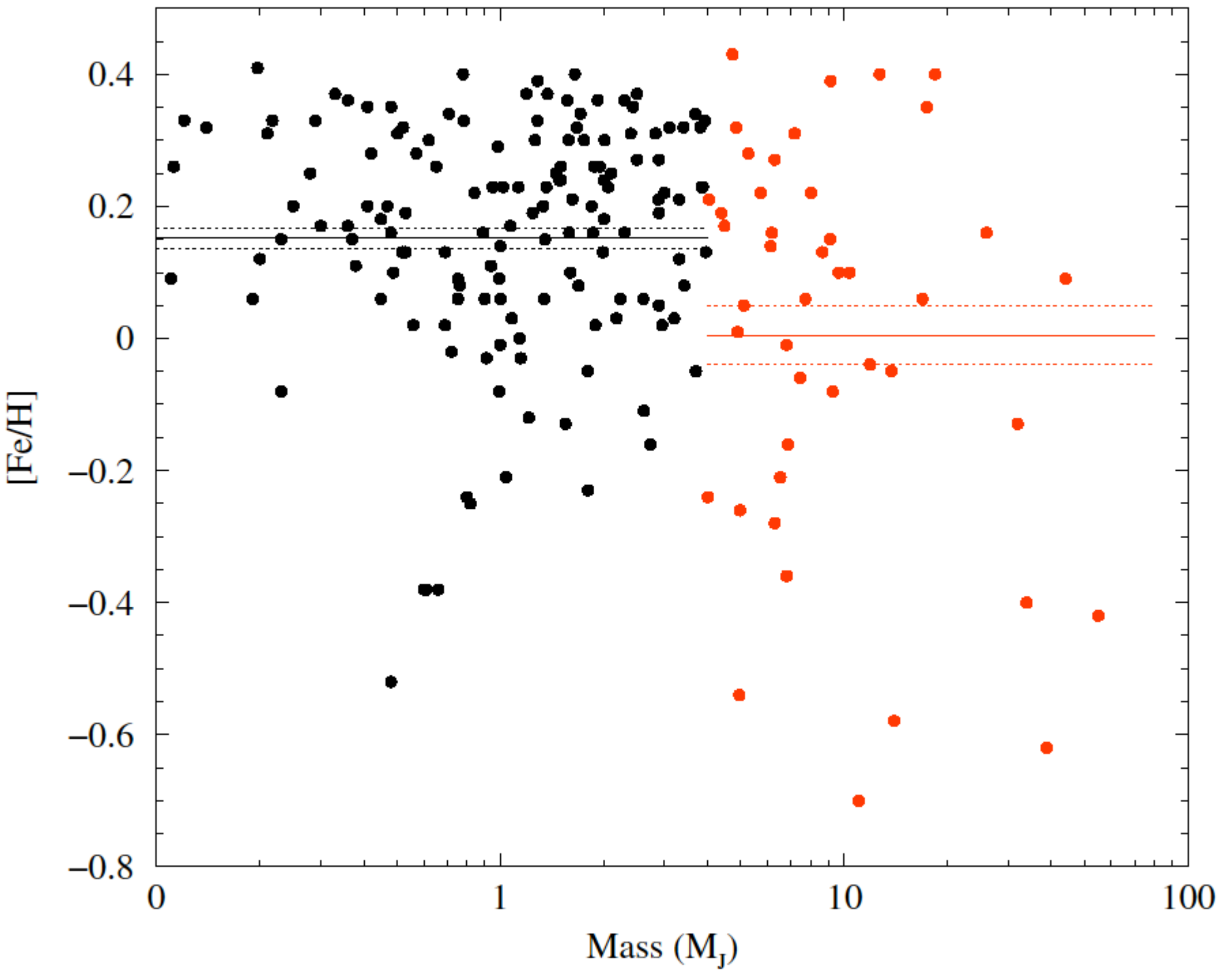


Fig. 4. Mass versus metallicity for the substellar objects in the sample. Mean metallicity values for the two proposed populations (minimum mass above and below 4 M_J) are represented by the horizontal lines (with the corresponding error bars shown as dotted lines).

Ribas & Miralda-Escudé (2007)

Gap in Mass Distribution?

Brown Dwarf Desert:

$M \sin(i) < 0.01\ M_\odot$

$M \sin(i) > 0.01\ M_\odot$

➔ different formation mechanism?

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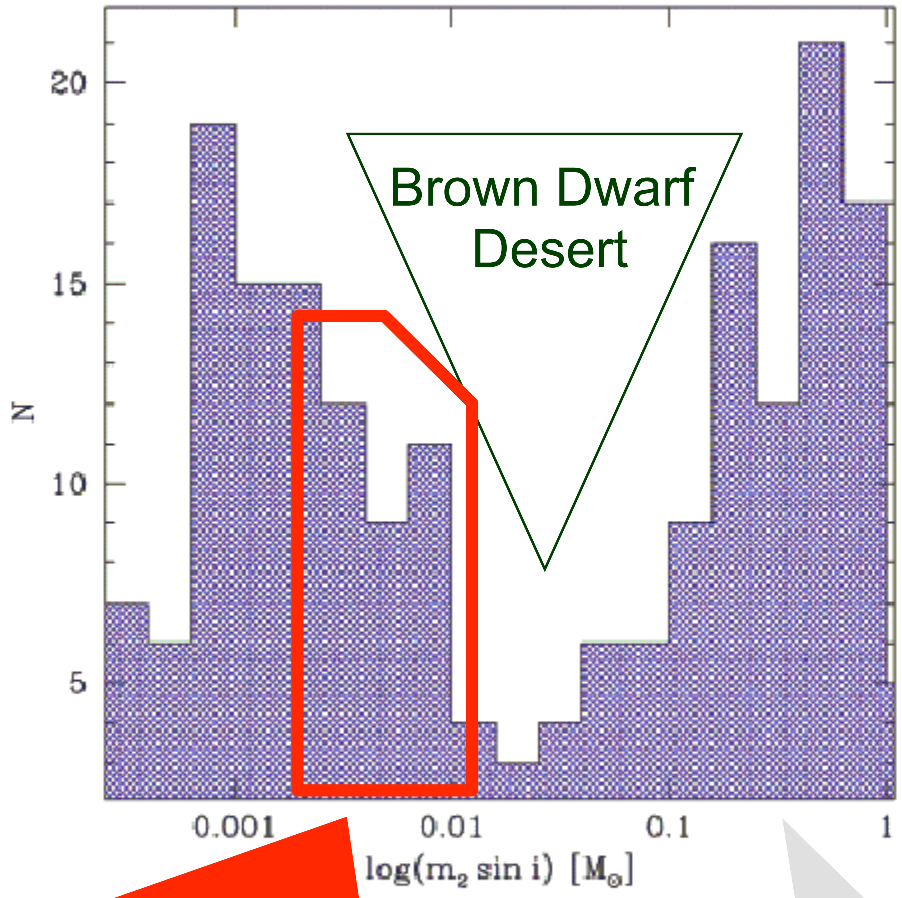
Good Interpretation?

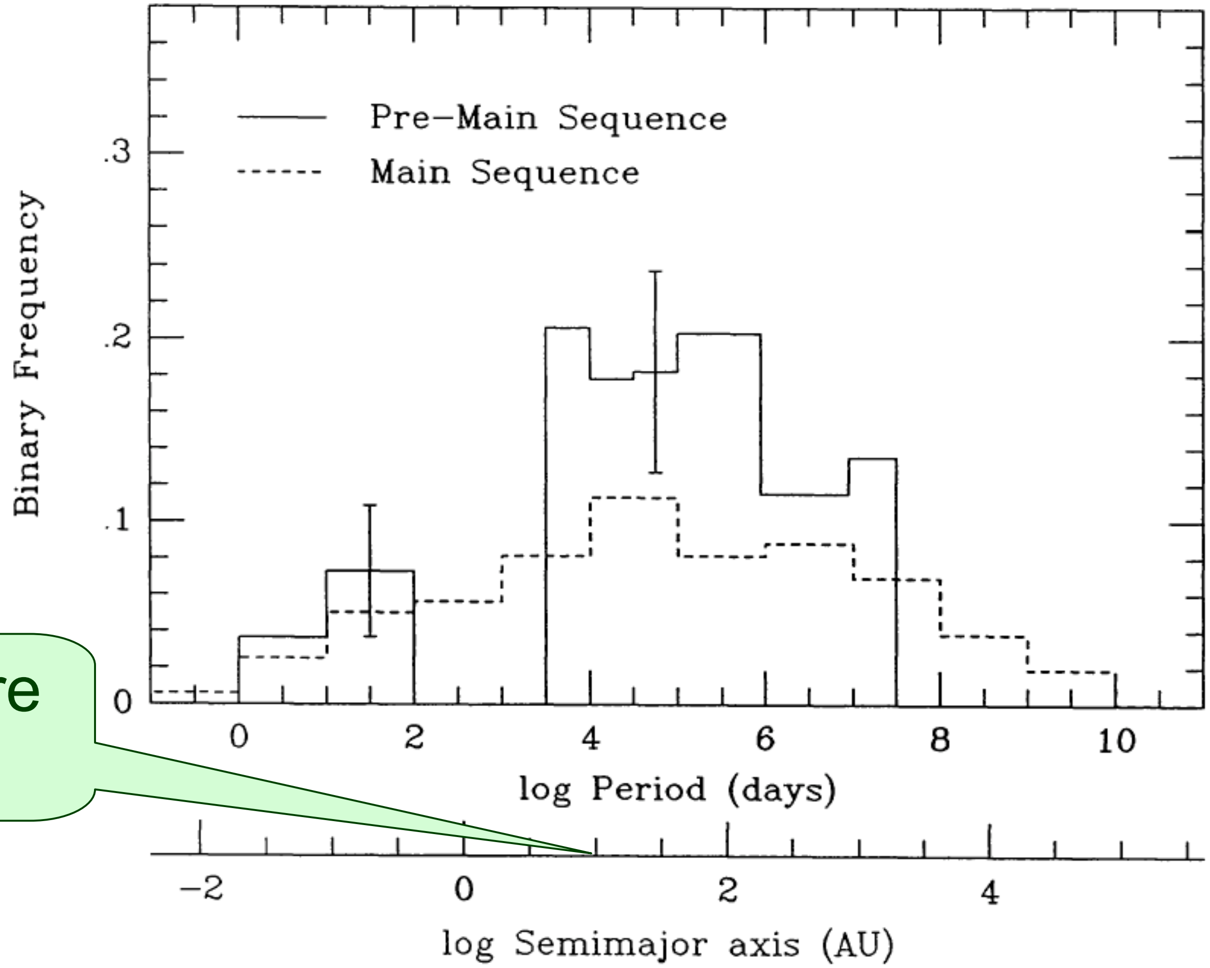
Mass Function of Companions



Fragmentation in Protoplanetary disk

Binaries

Binary Frequency

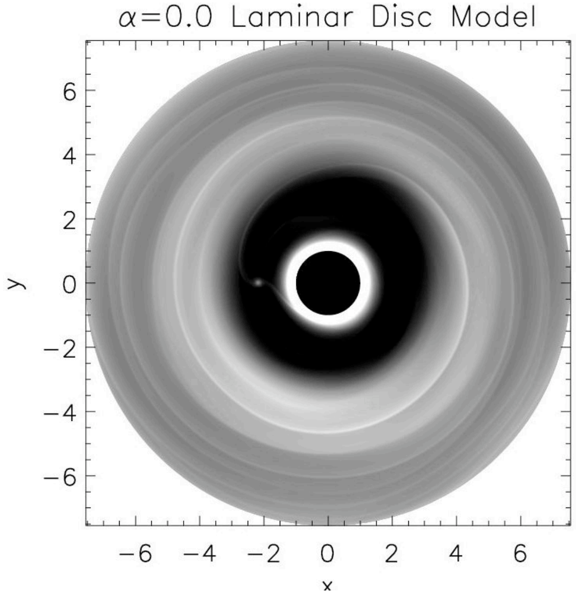


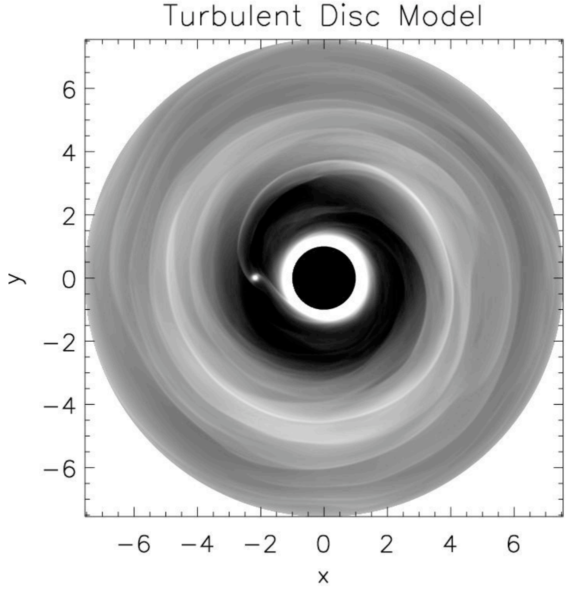
First Core
Radius

Mathieu
1992

Fragmentation after 2nd Collapse!!!

Effect of Giant Planets in PP Disks





In Laminar Disk: **Shepherding** of Dust Grains

➔Formation of Planetesimals by GI

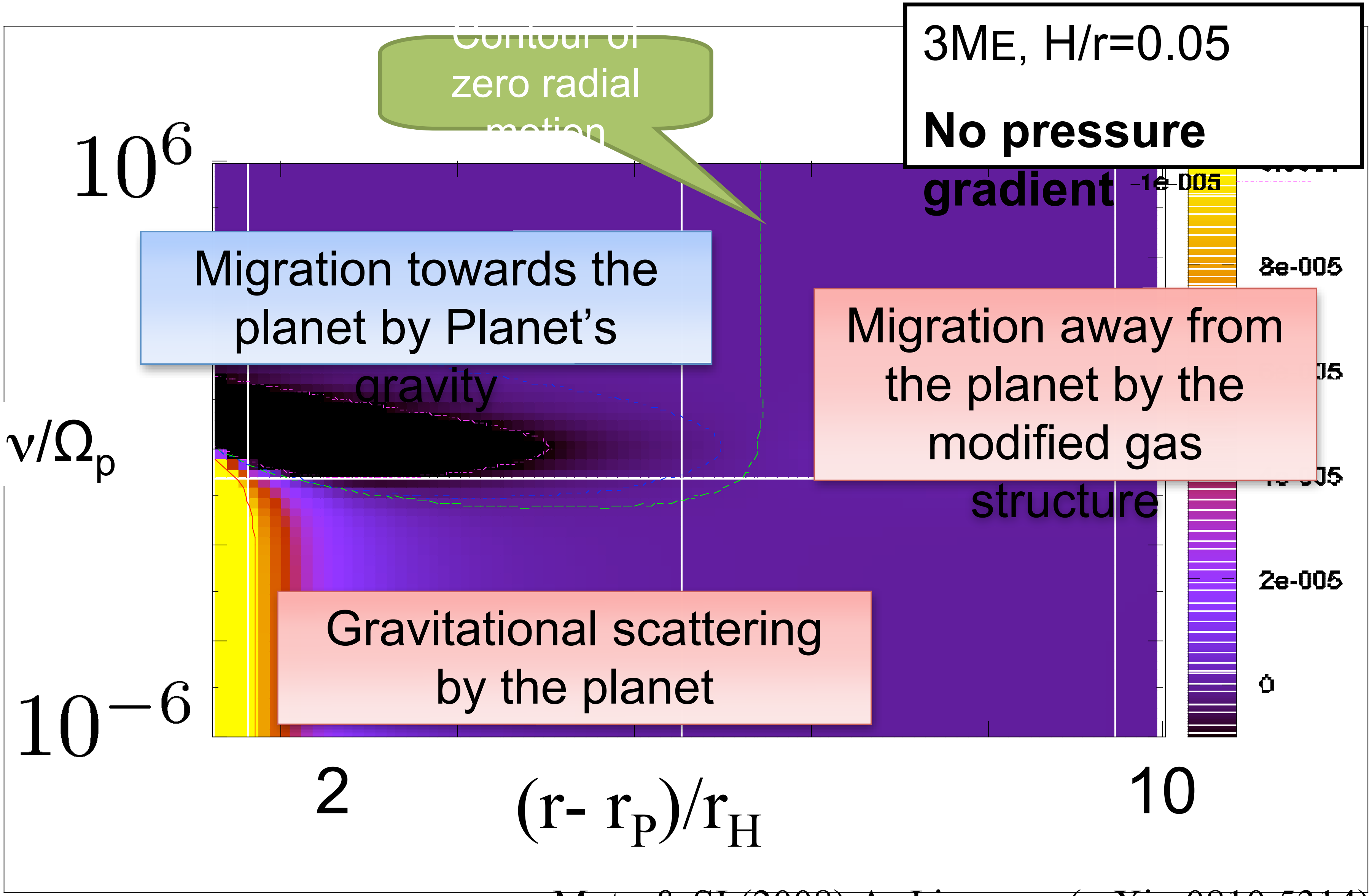
➔Proceed to **Core Accretion Scenario** in Region Outside Giant Planet

In Turbulent Disk:

➔Formation by Grain Coagulation?

c.f. Johansen et al. (2007) Nature

Shepherding of Dust Grains



3ME, H/r=0.05

No pressure gradient

Contour of zero radial motion

Migration towards the planet by Planet's gravity

Migration away from the planet by the modified gas structure

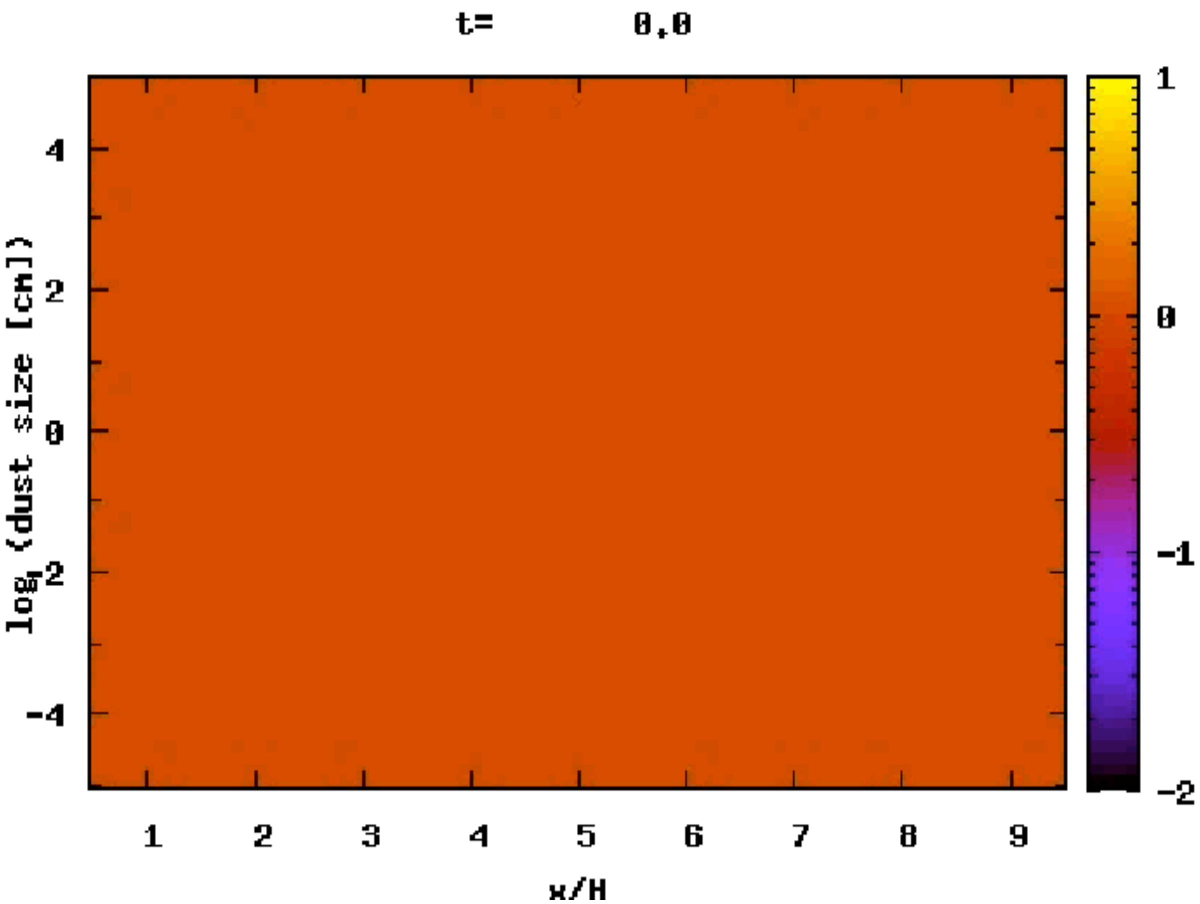
Gravitational scattering by the planet

Muto & SI (2008) ApJ in press (arXiv:0810.5314)

Shepherding of Dust Grains

Evolution of Dust Distribution with Various Sizes

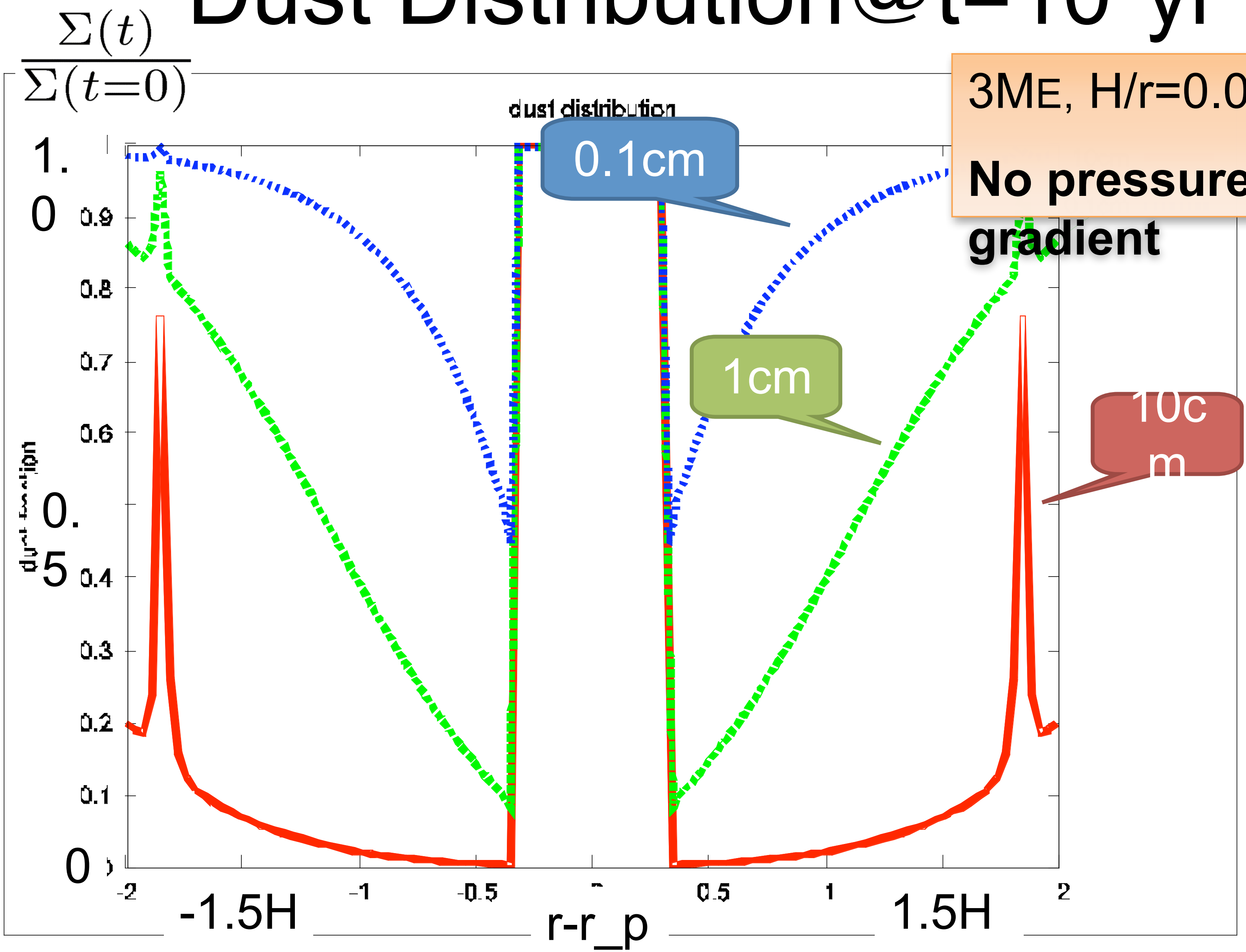
($3M_E$, $\eta = 0$)



Dust grains outside of “planet” do not fall onto the central star!

Muto & SI (2009) ApJ **695**, 1132

Dust Distribution@t=10^6yr

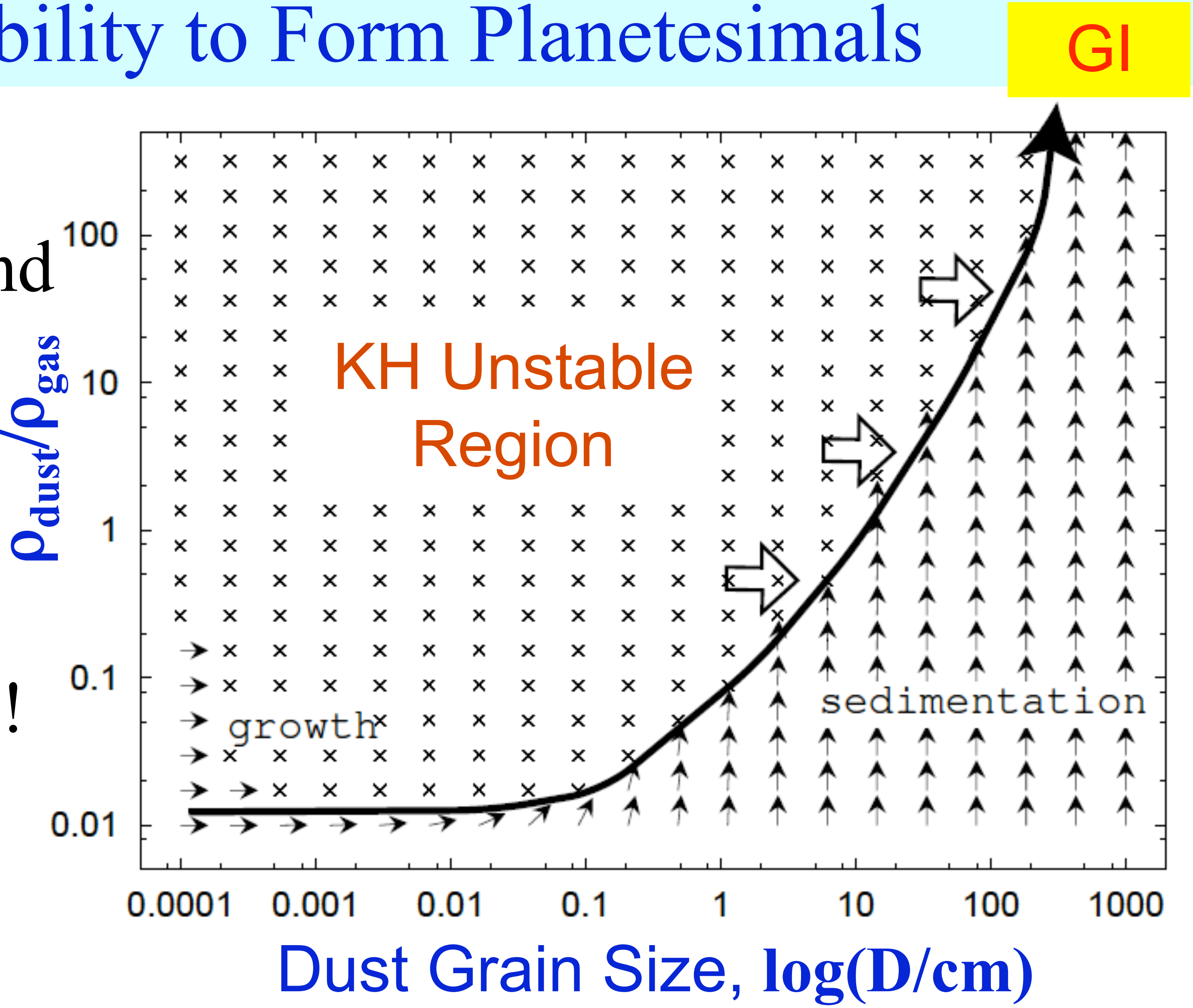


3ME, H/r=0.05

No pressure gradient

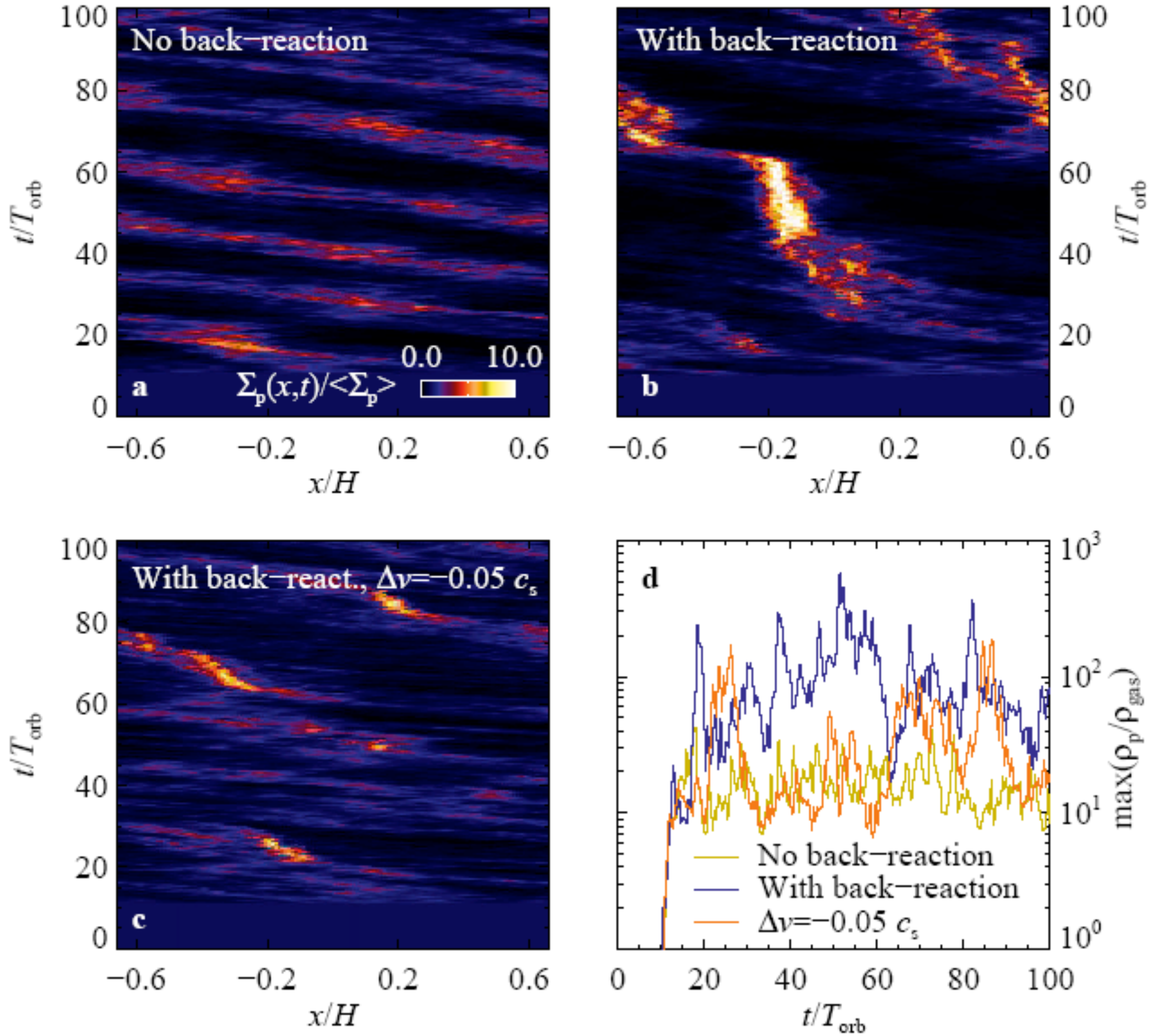
A Possible Path Toward Gravitational Instability to Form Planetesimals

Big Grains Avoid KHI and Enable Gravitational Instability to Form Planetesimals!



Michikoshi & SI (2006) ApJ **641**, 1131

Growth of Boulders to Planetesimals in MHD Turbulence



NB) D_{dust} is large initially.

Johansen et al. (2007) Nature

“Hybrid Scenario”

Scenario 1: Giant planets fall onto the central star.

➔ Remnant Planetesimals may proceed to

(classical) core accretion scenario.

Scenario 2: Giant planets survive gas dispersal.

➔ Giant Planets (no core) & Rocky Planets

NB: This can be a formation scenario even for our solar system, if M_{core} of Jupiter is very small.

Dispersal of Protoplanetary Disks?

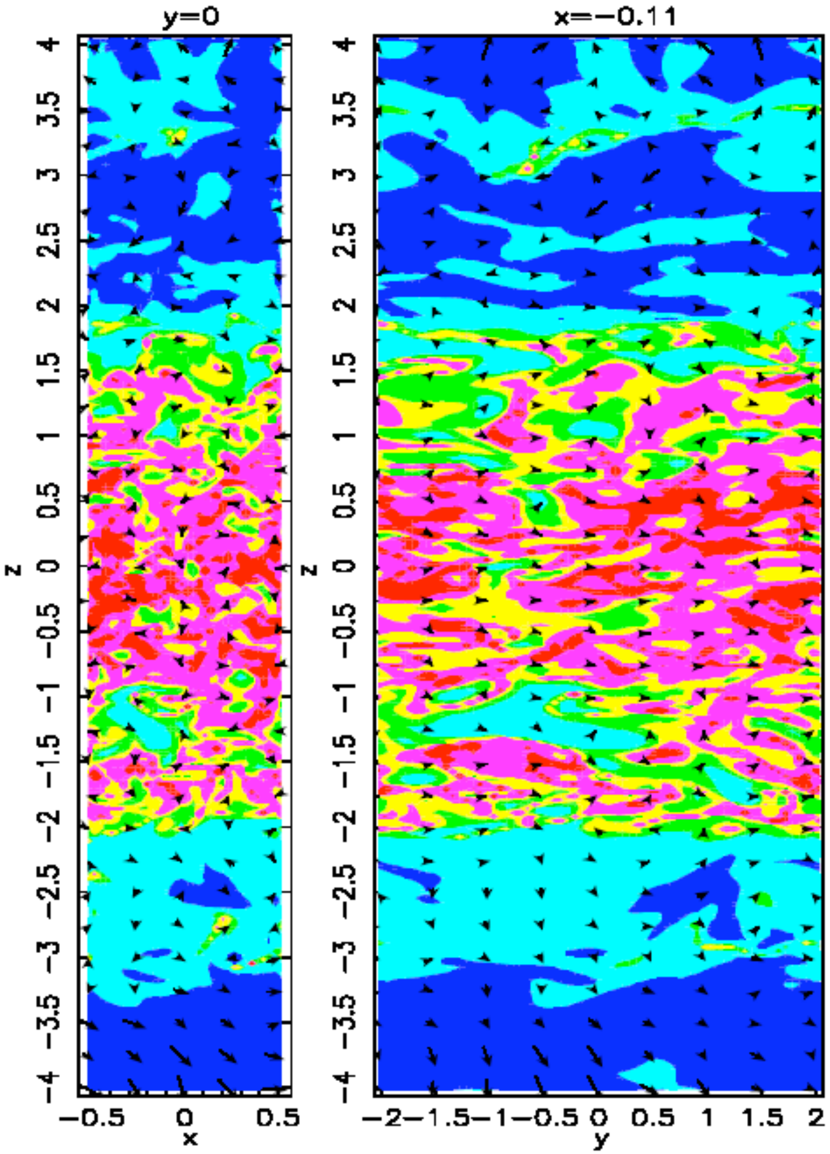
- Accretion by MRI
- Photoevaporation: good for outer regions

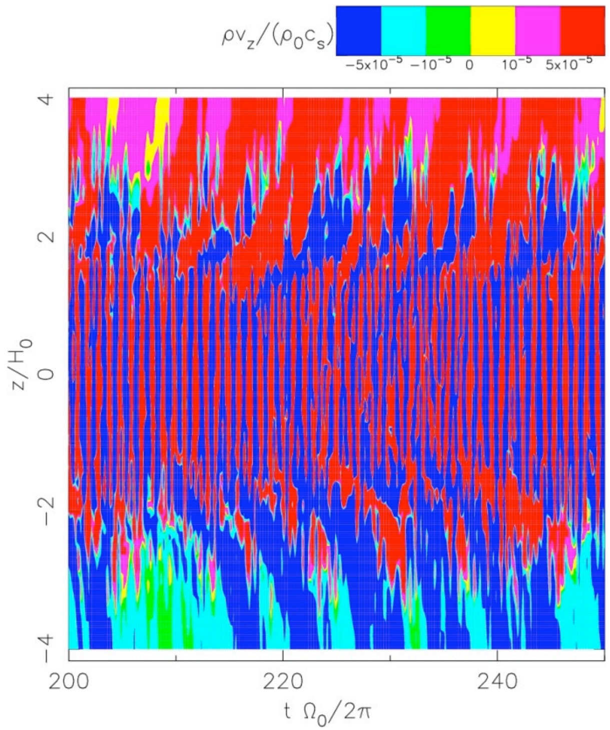
something missing?

Many Observations of Inner Holes in PPDs

Powerful Quasi-Steady Disk Wind

after 210 rotations





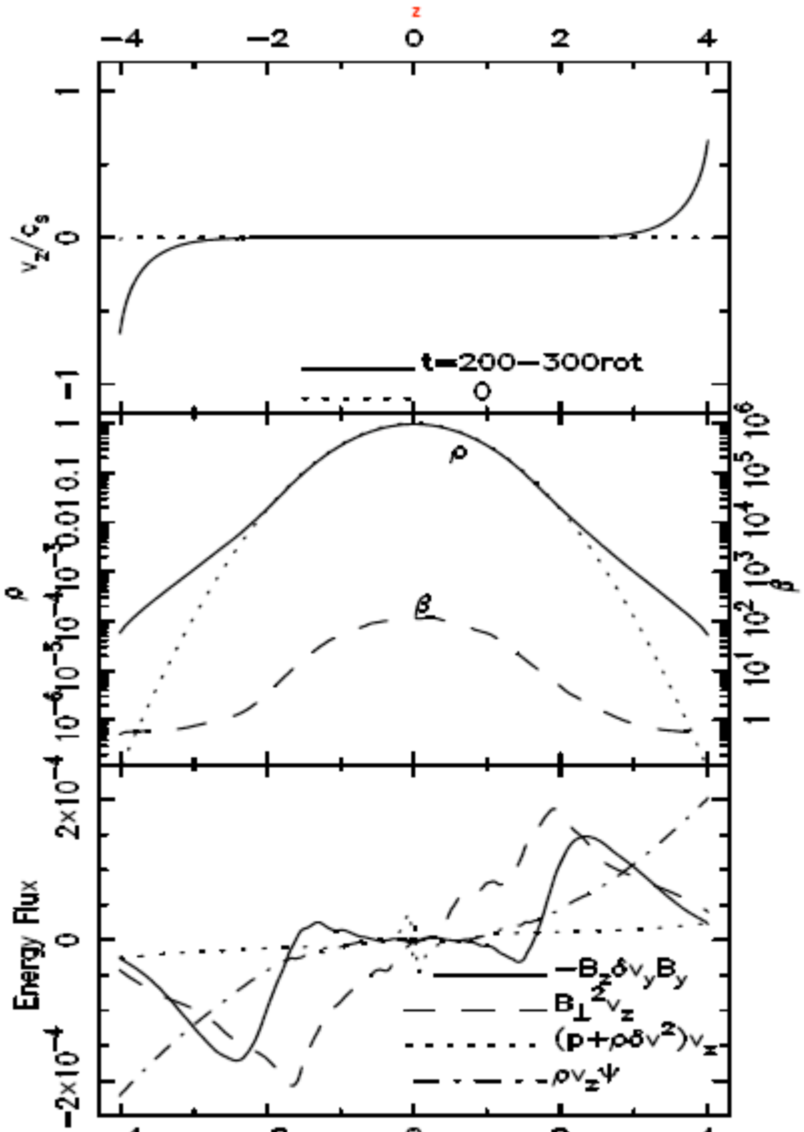
Powerful MHD Wind from Disk

just like Solar Wind

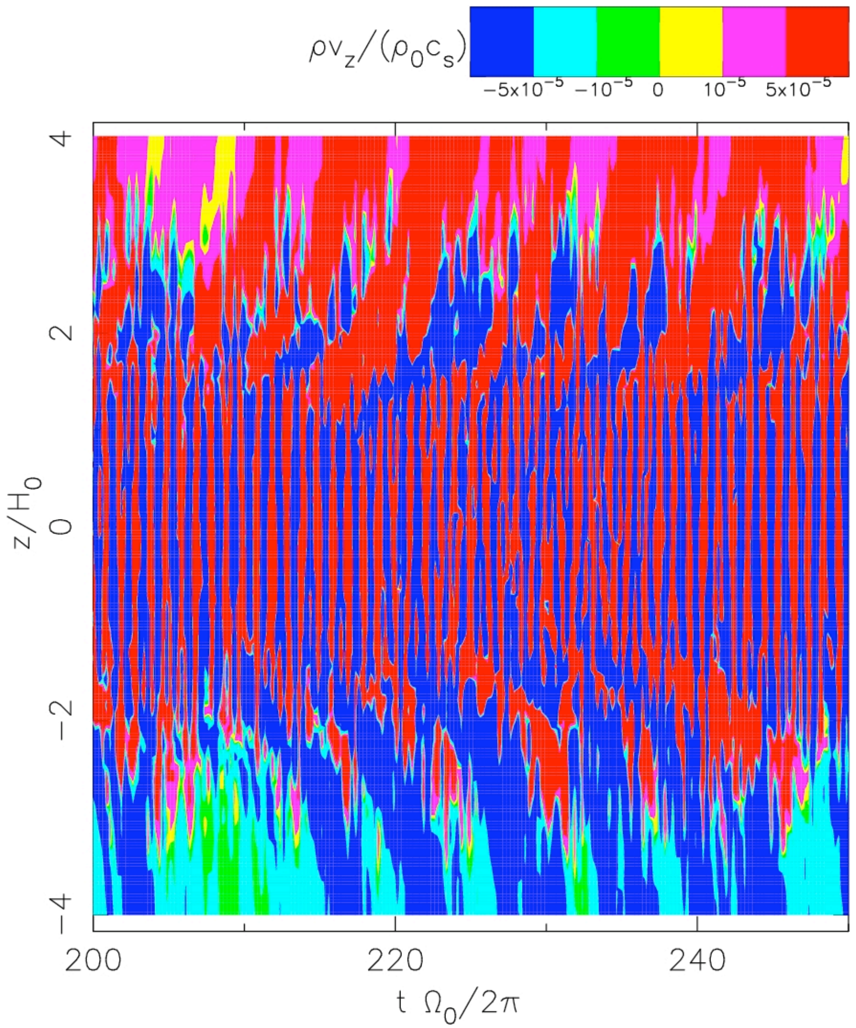
Suzuki & SI (2009) ApJ **691**, L49

cf. Turner et al. (priv.comm.)

Powerful Quasi-Steady Disk Wind



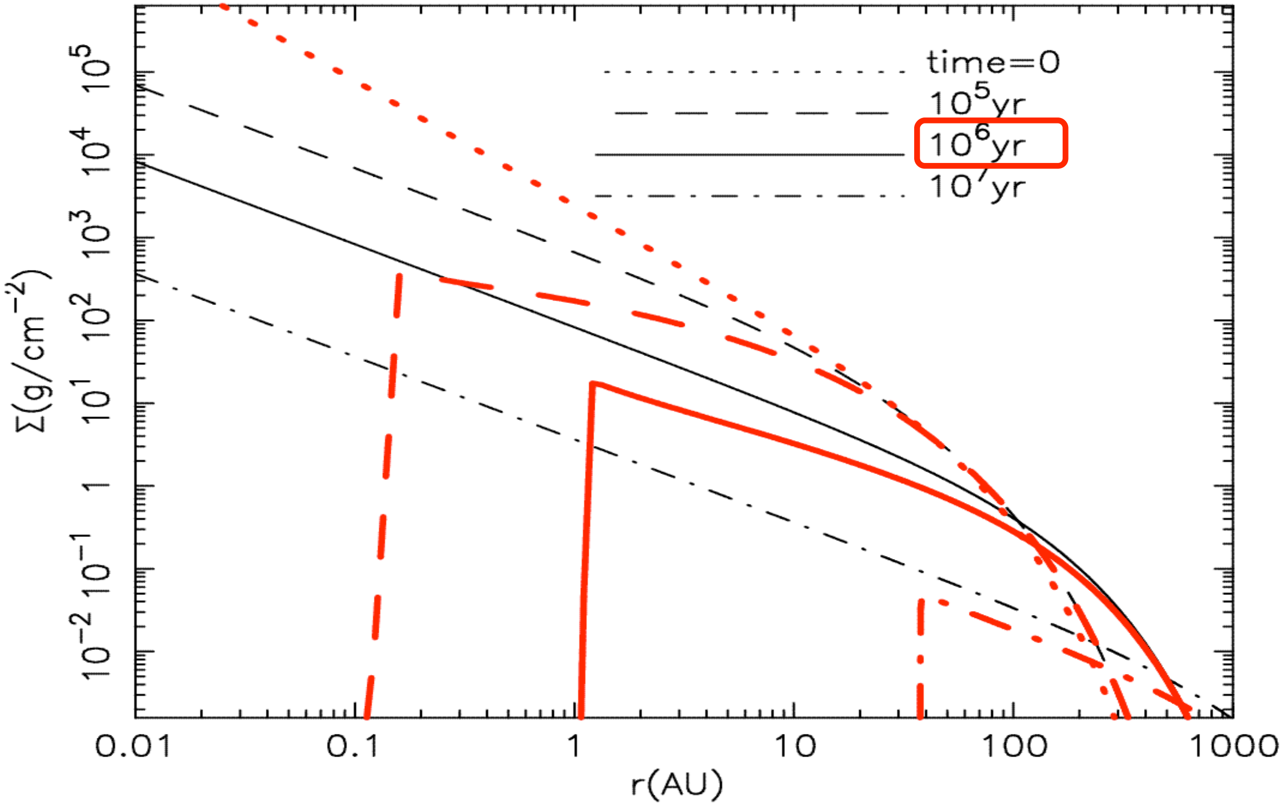
Distance from Midplane, Z



Suzuki & SI (2009) ApJ **691**, L49

Suzuki, Muto, & SI (2009) arXiv:0911.0311

Inner Hole Creation and Dispersal



Distance from Central Star

Dispersal Timescale ~ a few Myr

for typical disk models in Ideal MHD

Suzuki, Muto, & SI (2009) arXiv:0911.0311

Ionization Degree in PP Disks

neutral gas + ionized gas
+ dust grains

$\zeta_{CR} = 10^{-17}\ s^{-1}$

cosmic ray ionization
⇒ resistivity

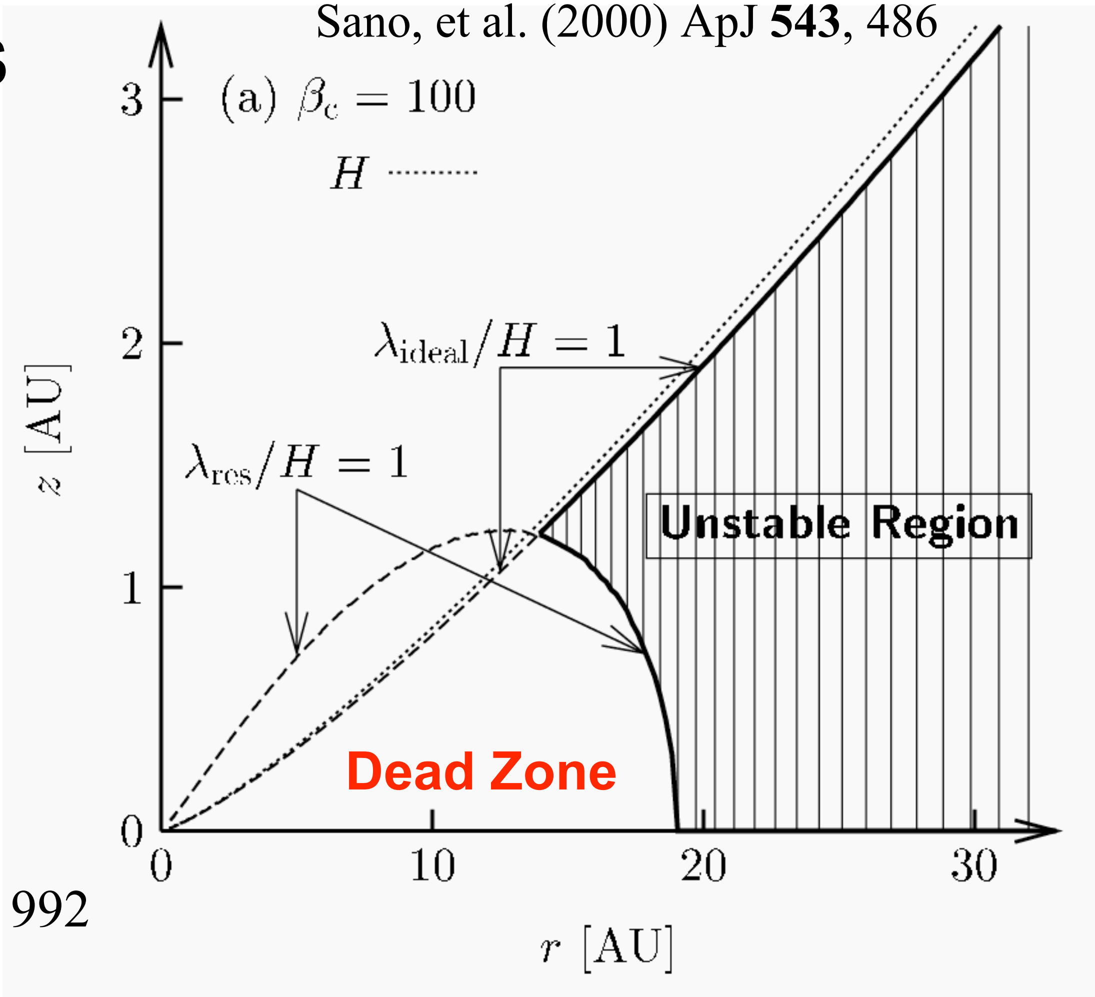
Classical Models:

Sano et al. 2000, ApJ **543**, 486

Glassgold et al. 2000, PPIV

Fromang et al. 2002, MN **329**, 18

Salmeron & Wardle 2003, MN **345**, 992



Sano, et al. (2000) ApJ **543**, 486

"Dead Zone" can be removed by self-sustained ionization!

SI & Sano (2005) ApJ **628**, L155

Summary

Outflows from First Core & Jets from Protostar

→ ALMA Observations of Early Phase

→ Ang. Mom. & Mag. Flux Problem

The First Core becomes Protoplanetary Disk!

Planetary Mass Companions in PP Disks

Shepherding for Dust Grains

→ Formation of Planetesimals in Outer Region

→ Natural *Hybrid Scenario*