宇宙生命計算科学連携拠点
第3回ワークショップ
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原始惑星系円盤の形成と初期進化

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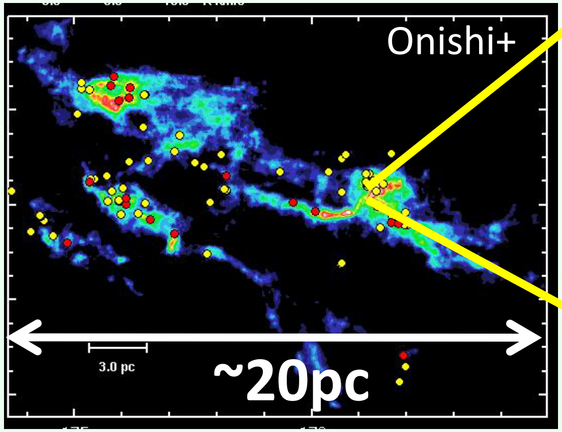
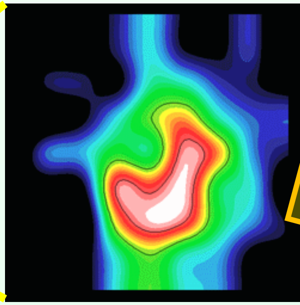
Disk Formation and Magnetic Braking Catastrophe

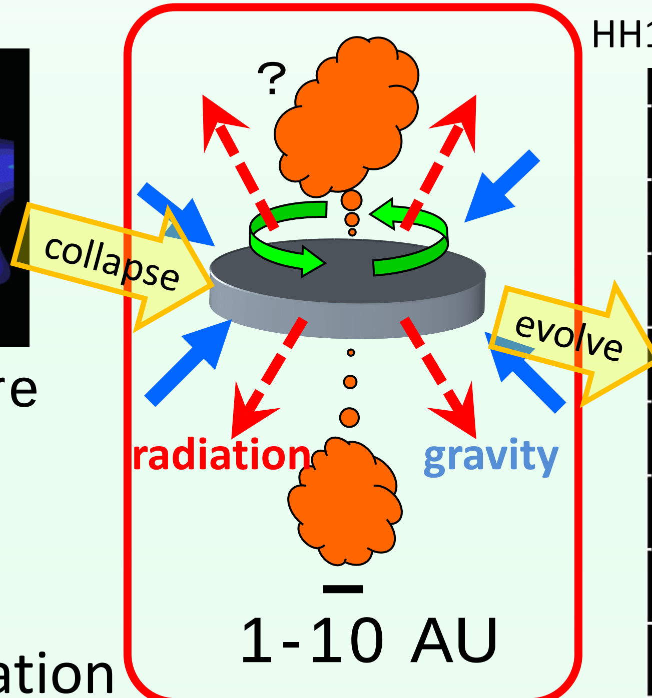
Protostellar Collapse



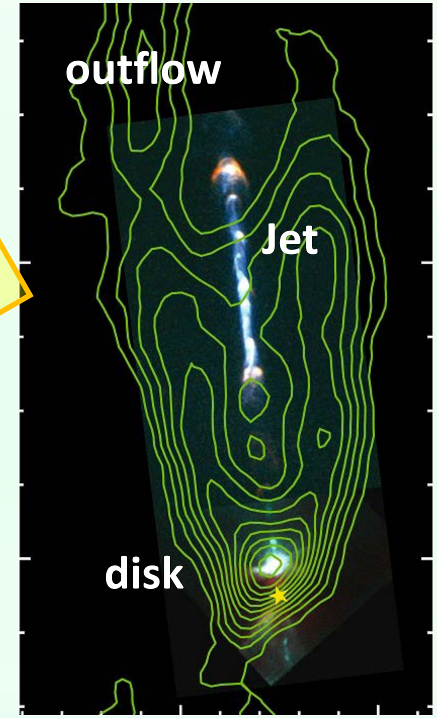
Taurus Molecular Cloud(Nagoya, 4m)



Cloud Core
∼0.1pc
n≳10⁴/cc



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

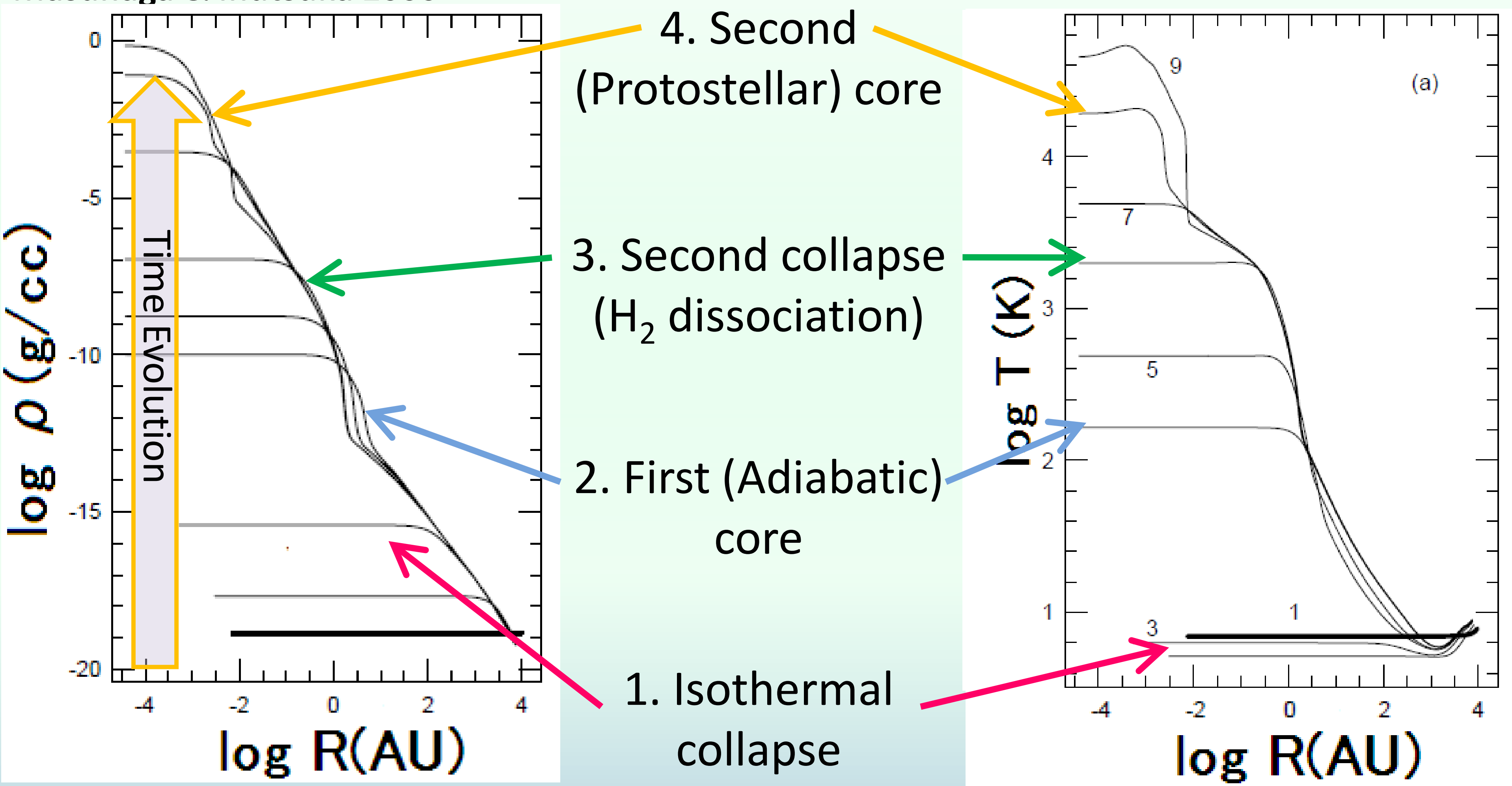


- The site of disk & planet formation
- The origin of the IMF ← Star Formation Efficiency
  Core Mass Function is similar to IMF, but shifted to higher mass.
- Many physical processes are involved here:
  self-gravity, magnetic fields, radiation transfer, turbulence, chemistry,...
- Huge dynamic range: 0.1 pc / 1 Rs ∼4.5 x **10^6**

⇒Sophisticated numerical simulations are required

Protostellar Collapse: 1D RHD

Masunaga & Inutsuka 2000



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 $j_{cl} \approx 5\times10^{21}\left(\frac{R}{0.1\mathrm{pc}}\right)^2\left(\frac{\Omega}{4\mathrm{km\,s^{-1}pc^{-1}}}\right)\mathrm{cm^2s^{-1}}$ **>>** $j_* \approx 6\times10^{16}\left(\frac{R_*}{2R_\odot}\right)^2\left(\frac{P}{10\mathrm{day}}\right)^{-1}\mathrm{cm^2s^{-1}}$ **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.)

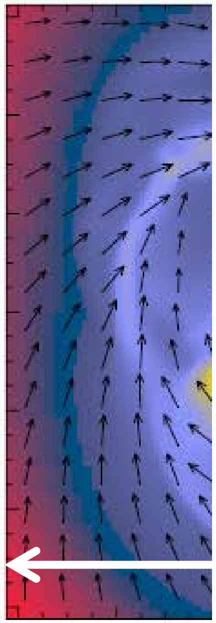
Magnetic braking is too efficient; no circumstellar disk is formed

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

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

Magnetic Braking Catastrophe and/or Fragmentation Crisis

t~ 1.2 t_{ff} (Hennebelle & Fromang 2008)

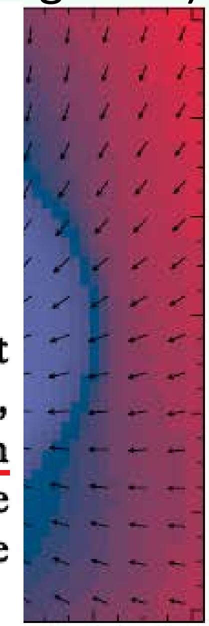


STAR FORMATION IN MAGNETIC DUST CLOUDS

L. Mestel and L. Spitzer, Jr

(Received 1956 July 27)*

(i) The angular momentum present leads to disk formation, and the subsequent evolution of the disk is slow enough for the field and plasma to diffuse outwards, in spite of the increased densities. The objection to this is that the strong frozen-in magnetic field will probably remove angular momentum too rapidly; the time of travel of a hydromagnetic wave across the cloud is of the same order as the time of free-fall, and so it is not obvious that a rotating disk will form.



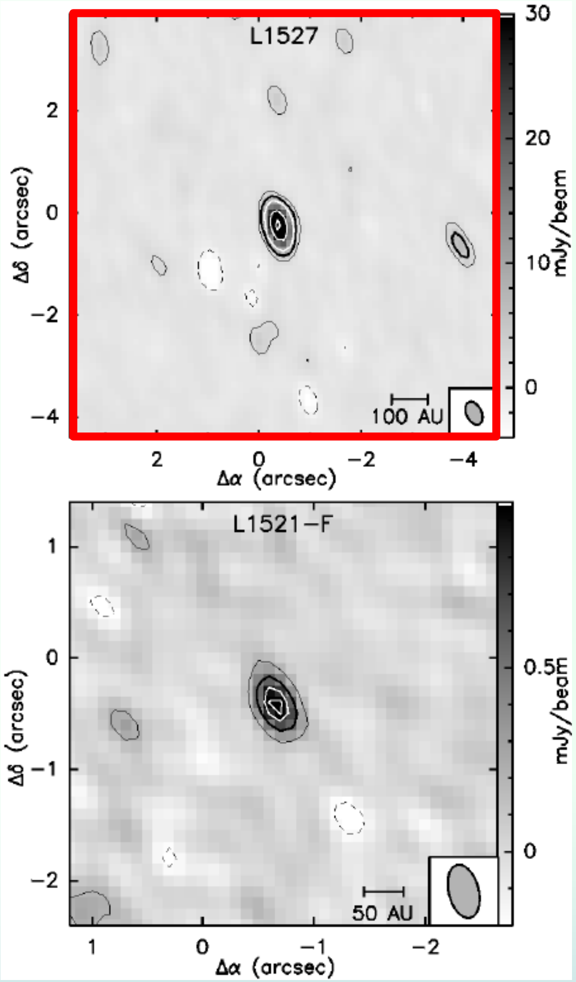
μ=M/Φ=50 (very weak) μ=20 (still modest) μ=5 (intermediate)

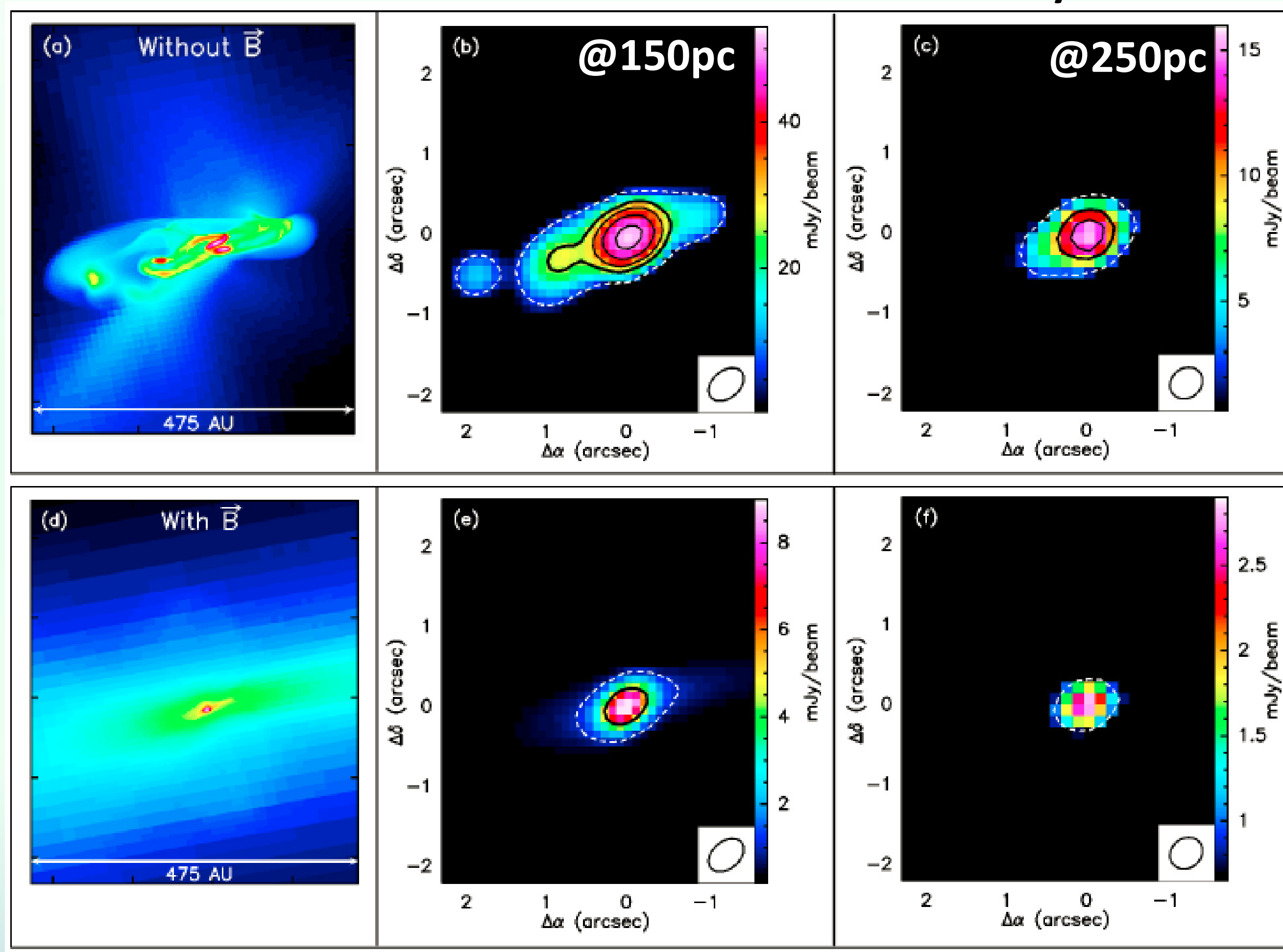
Magnetic fields actually transport angular momentum “**too efficiently**”. Circumstellar disks are not formed, fragmentation is strongly suppressed. This is a serious problem: Binary rate is known to be high (M: >30% G : >50%, A: ~80%), and we know lots of circumstellar disks and planets exist.

(see also, Mestel & Spitzer **1956**, Allen et al. 2003, Mellon & Li 08, 09, Li et al. 11, etc.)

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.

So, what is the problem?

Magnetic fields play crucial roles in star and disk formation
→ Strongly suppress disk formation and fragmentation

However, they can not be too efficient

- Circumstellar disks need to be formed even in the early phase of star formation (Class-0 phase)
- Binary/multiples/planets are common

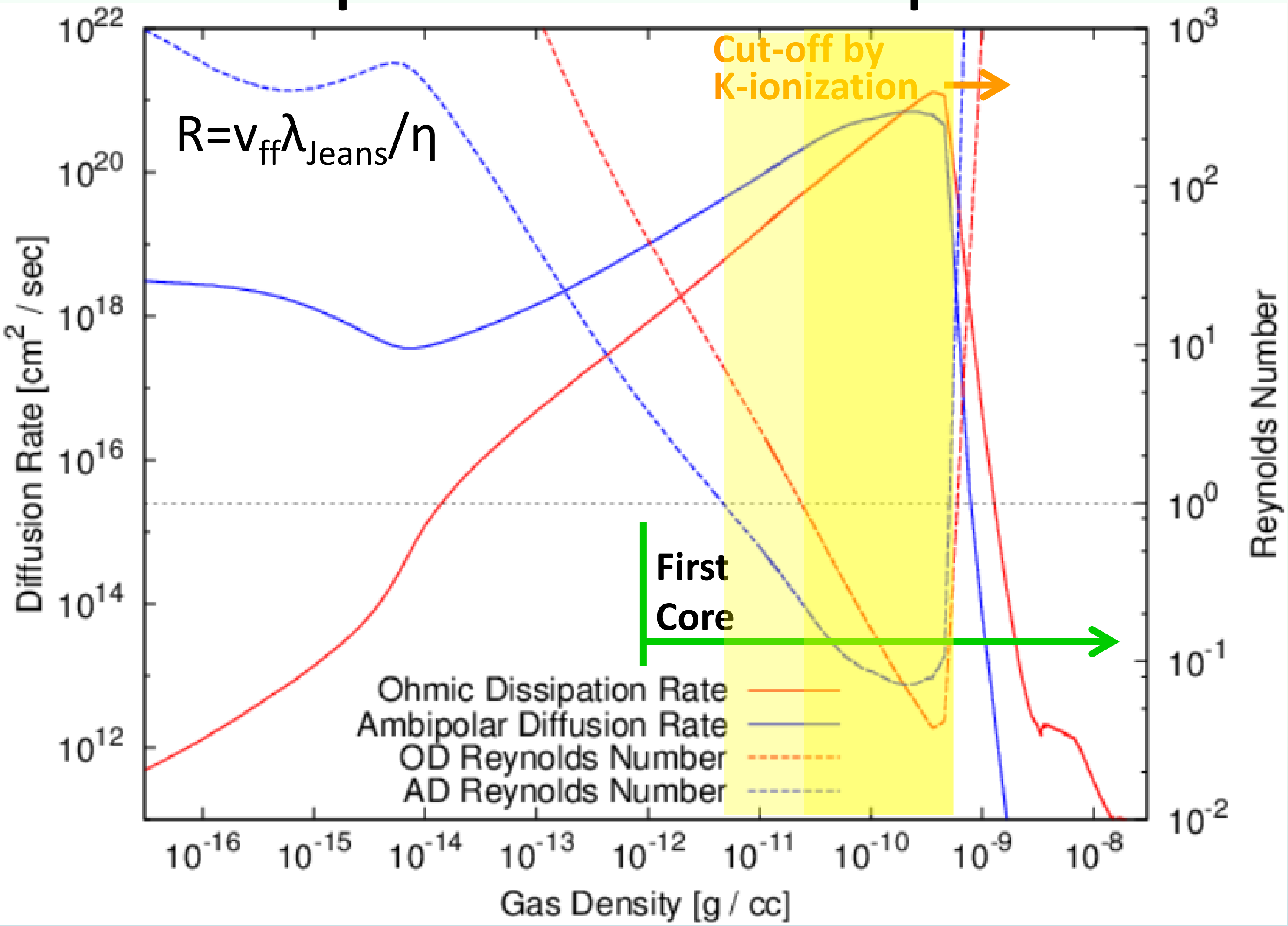
→ Ang. mom. transport should be suppressed in the small scale

Solutions proposed:

- Non-ideal MHD (Li et al. 2011, Dapp et al. 2012, Tomida+ etc.)
- Hall effect (Li et al. 2011, Tsukamoto et al., Wurster et al. 2015)
- B-Ω misalignment (Joos et al. 2012, Krumholz et al. 2013, etc.)
- Turbulence (Santos-Lima et al. 2012, Seifried et al. 2013, etc.)

Note: these are not exclusive; probably all of them work together.

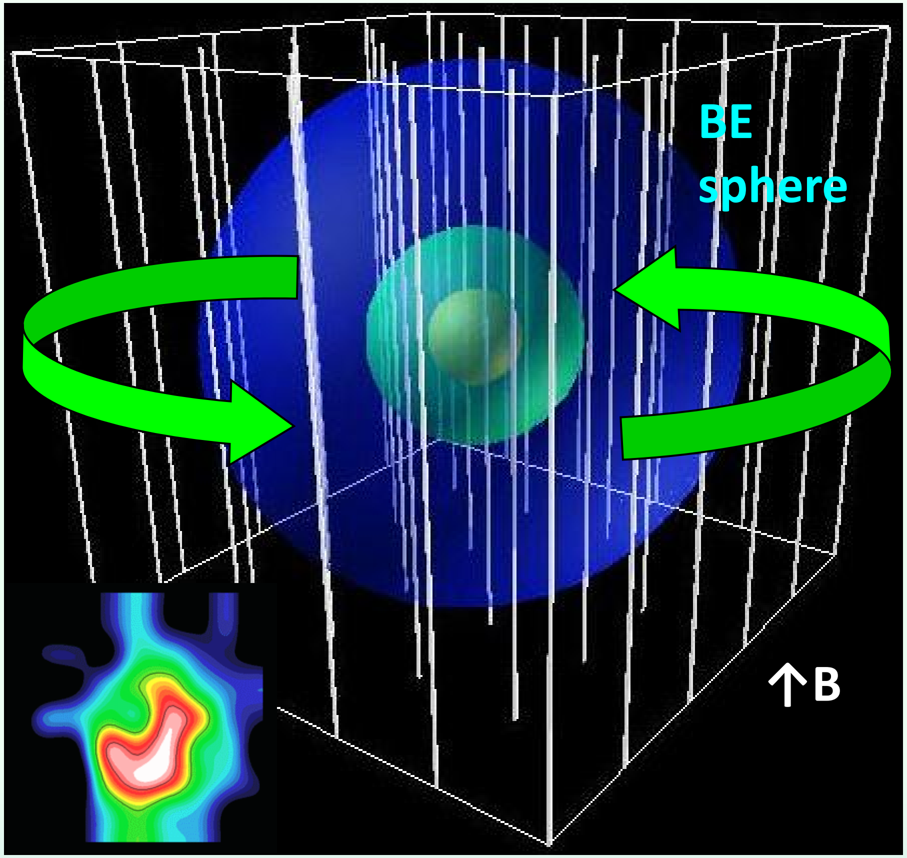
Ohmic Dissipation & Ambipolar Diffusion



Ohmic Dissipation: Effective in the high density region within FC

Ambipolar Diffusion: More effective in the lower density region

Simulation with ngr^{3}mhd



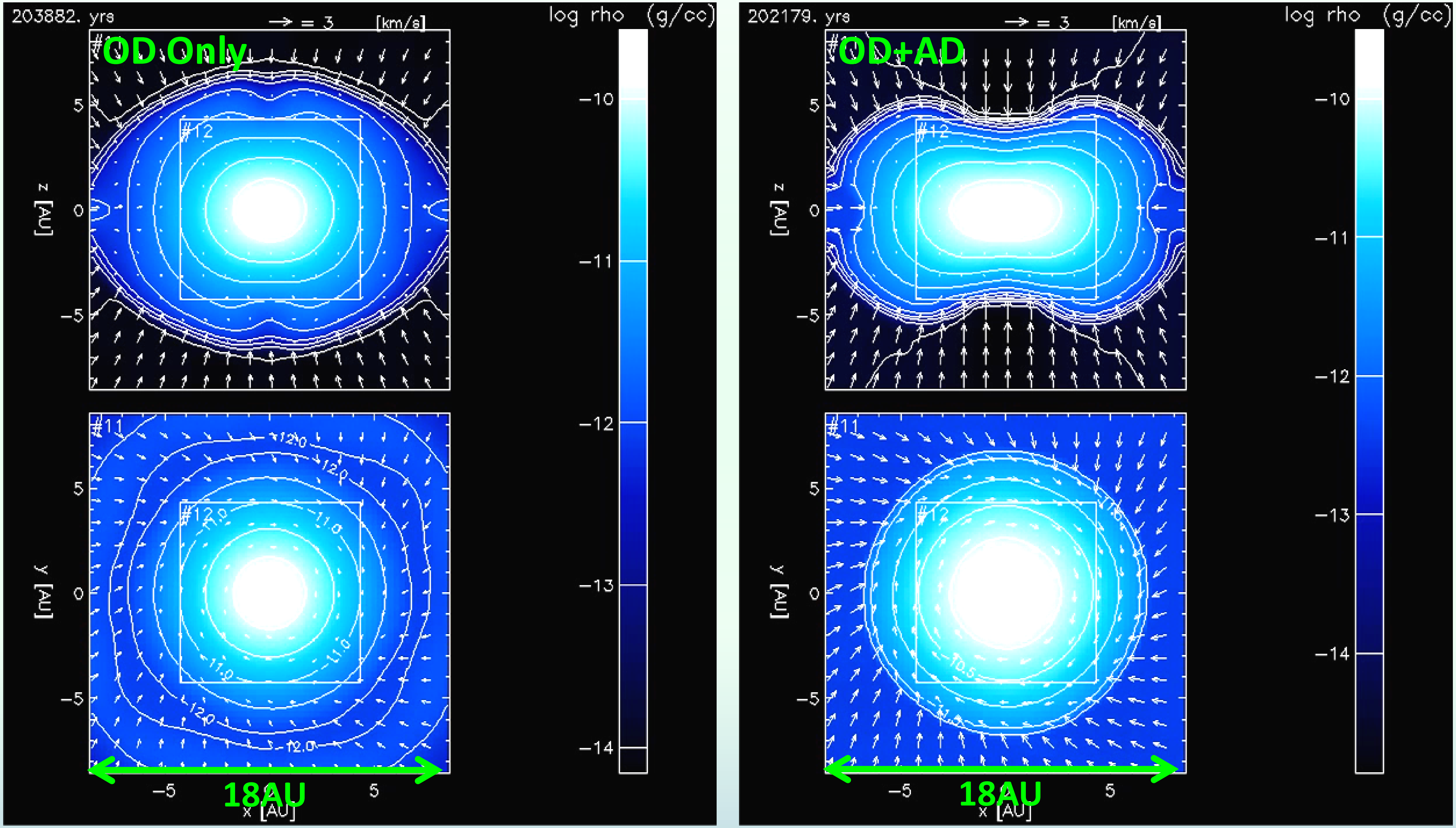
Nested-grid RMHD simulations with ngr^{3}mhd code

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

Resolution: >16 cells / λ_{Jeans}
64^3 x 14 levels (FC), 22 levels (SC)
Typical resolution @ FC～ 0.1 AU

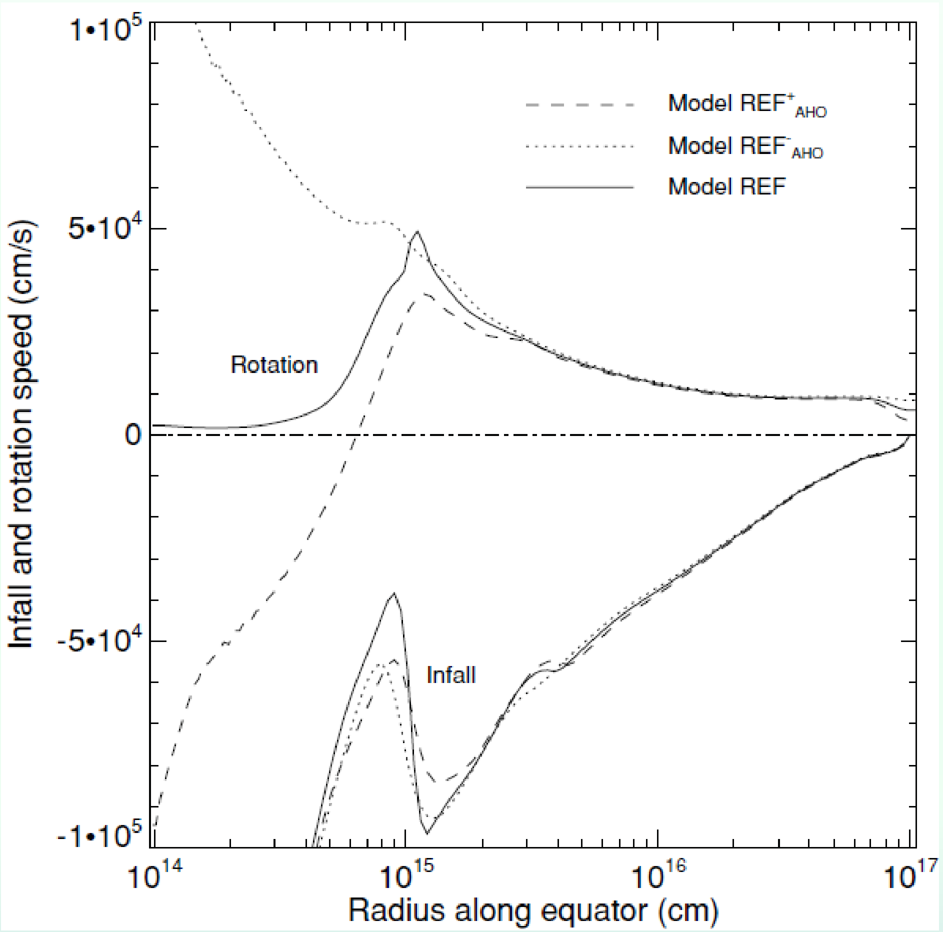
- 1Ms unstabilized BE sphere（ρ_c=1.2 x 10^{-18} g/cc, T=10K, **R=8800AU**）
- Bz=20μG (μ～3.8), Ω=0.046/t_{ff} ～2.4 x 10^{-14} s^{-1} , aligned rotator
- 10% m=2 density perturbation
- Opacity: Semenov+ 2003 (dust), Ferguson+ 2005, Seaton+ 1994 (OP)

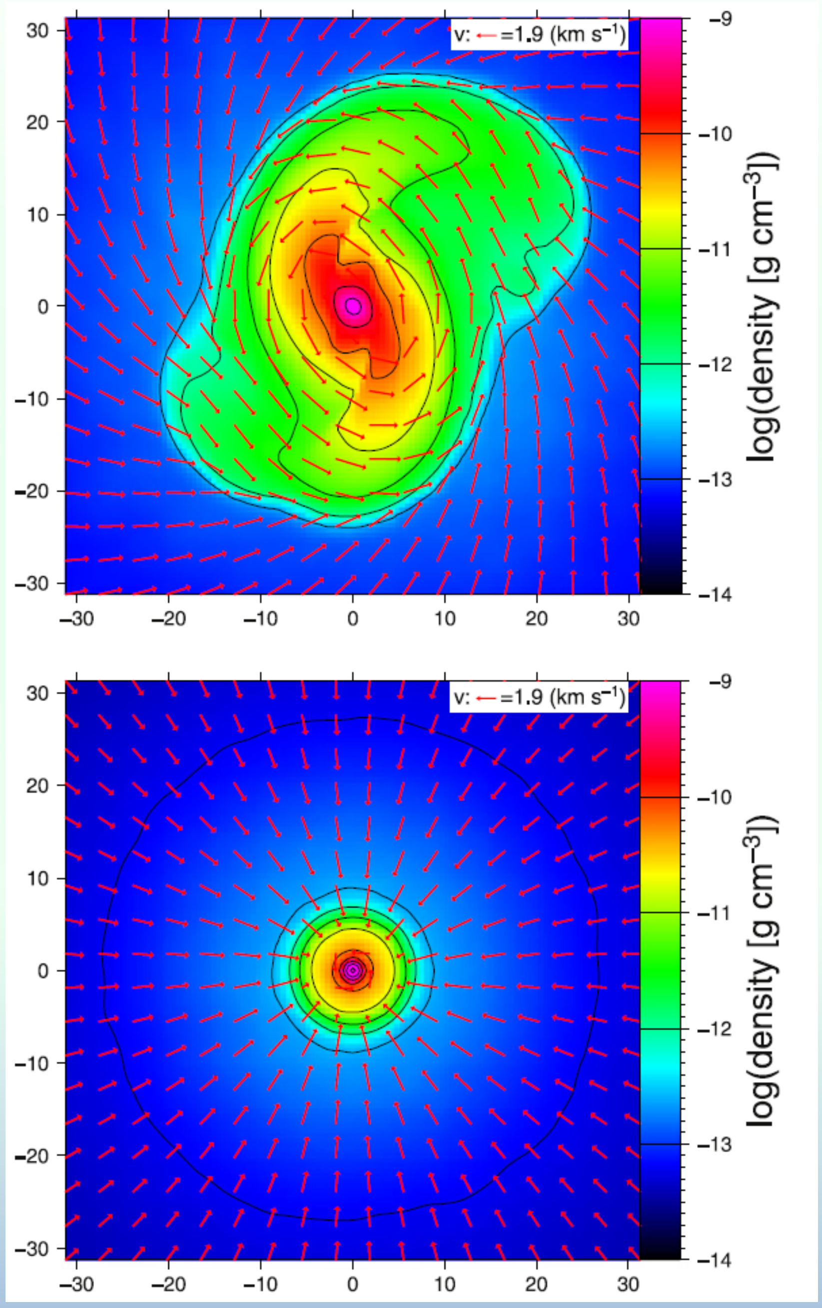
Non-ideal MHD Models: First Cores



OD: Slow-rotating FC, small disk and jet formation after second collapse
AD: Supported by rotation, gravitationally unstable, but still small

The Hall Effect





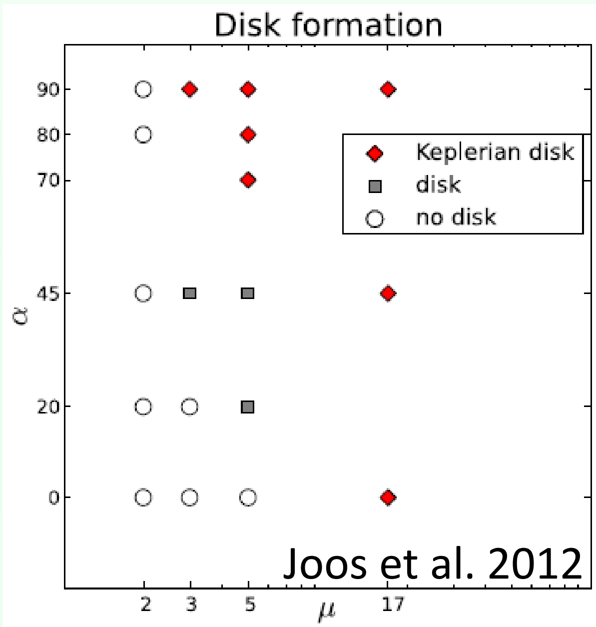
The Hall effect can spin up / down the disk depending on the sign of B・Ω.

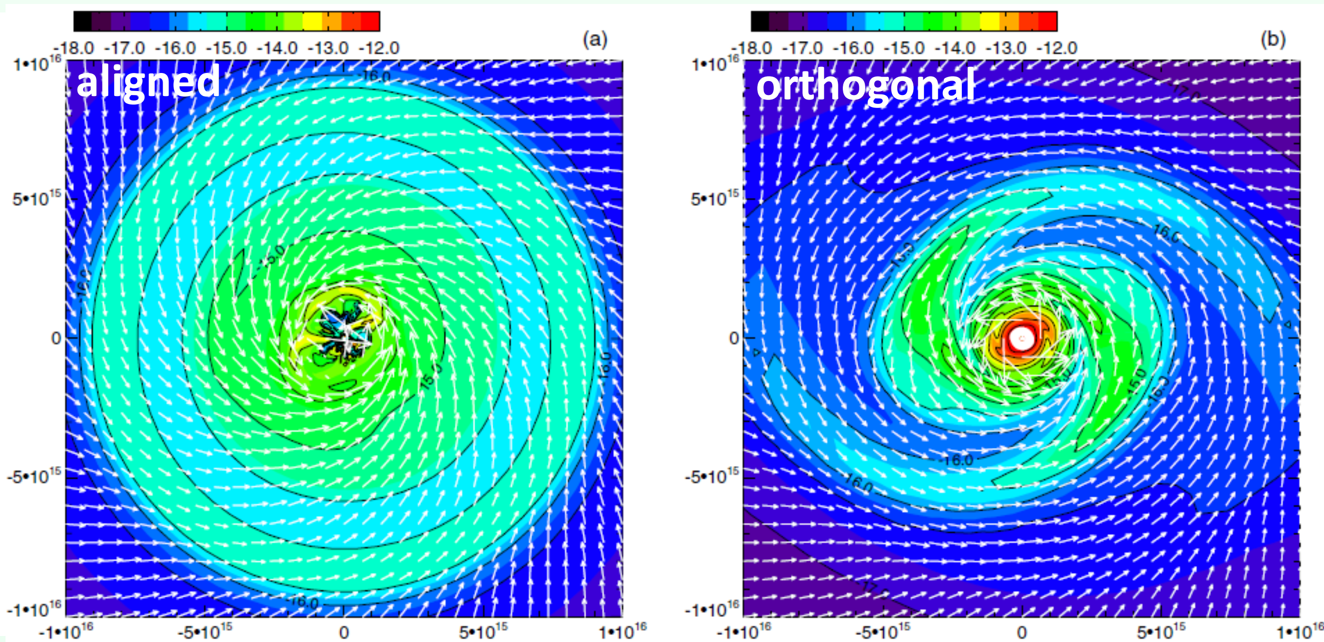
↑Li+ 2011 →Tsukamoto+ 2015

See also Wurster et al. 2015

Rotation-magnetic field misalignment

Li et al. 2013





Observationally, no clear correlation btw rotation axis & magnetic fields.

Misaligned magnetic fields are less effective in ang. mom. transport.

Outflows are less significant in misaligned cases (Li et al. 2013)

It may explain 10-50% disk fraction in the early phase (Krumholz+ 2013)

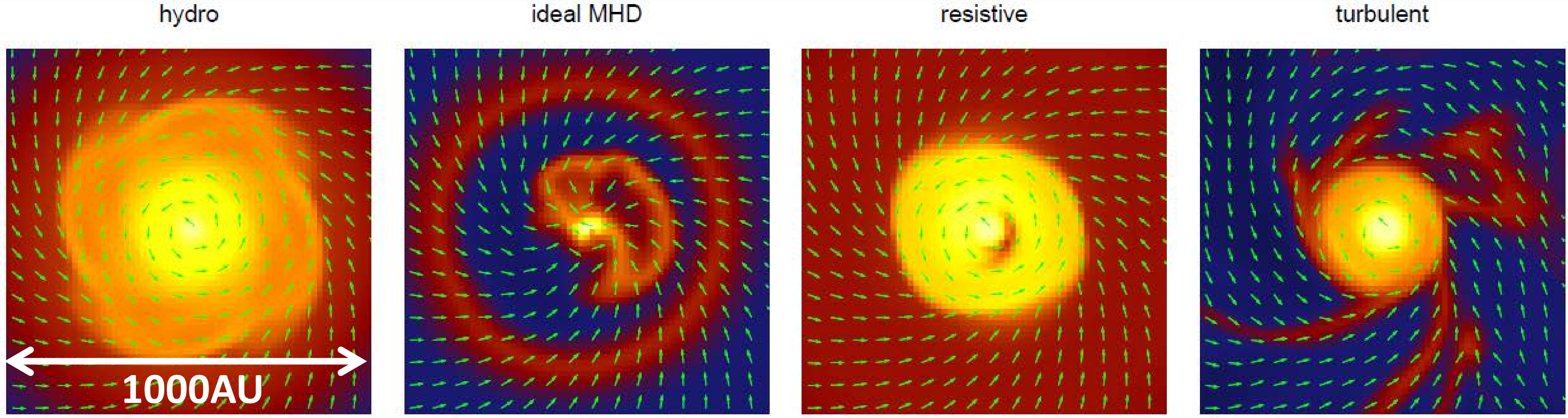
(see also: Matsumoto & Tomisaka 2004, Ciardi & Hennebelle 2009, etc.)

Note1: numerical convergence is difficult in misaligned simulations

Note2: It depends on the initial condition if this effect is positive/negative. (Tsukamoto+)

Turbulence

(Santos-Lima et al. 2012)



Turbulence is another solution, but its interpretation varies:

- turbulence can enhance magnetic diffusion by reconnection
- turbulence can induce misalignment between B and Ω and suppress angular momentum transport
- misaligned pseudo-disk reduces B-field accumulation
- turbulence itself has additional (local) angular momentum

So, is the Catastrophe resolved?

QUALITATIVELY, **YES**, but there remain many QUANTITATIVE problems-

- When the disk should be formed? What are typical size and mass?
  - First core phase? Class-0? → need systematic survey (Segura-Cox+ 2016)
  - Some Class-0 objects already have disks (e.g. L1527, Ohashi et al. 2014, R~60AU), but some do not (B335, Yen et al. 2014, R<10AU)
- What about Fragmentation Crisis?

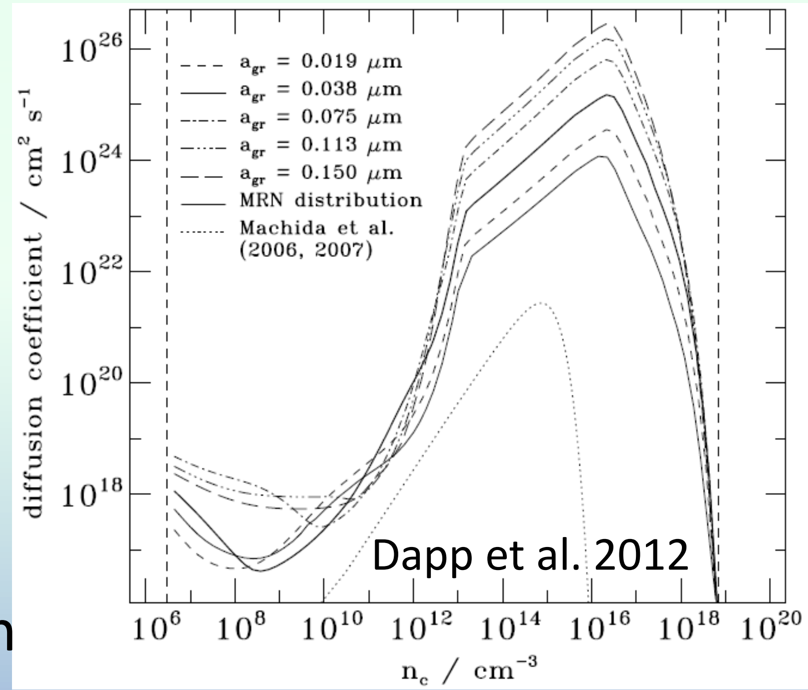
→ Some works show gravitational instab. Perhaps not too serious…

- Do we have realistic parameters?

→ e.g. magnetic diffusion rates can vary 5 orders of magnitude due to cosmic-ray, dust, and ^{26}Al (Zhao et al. 2016, Küffmeier+ 2016)

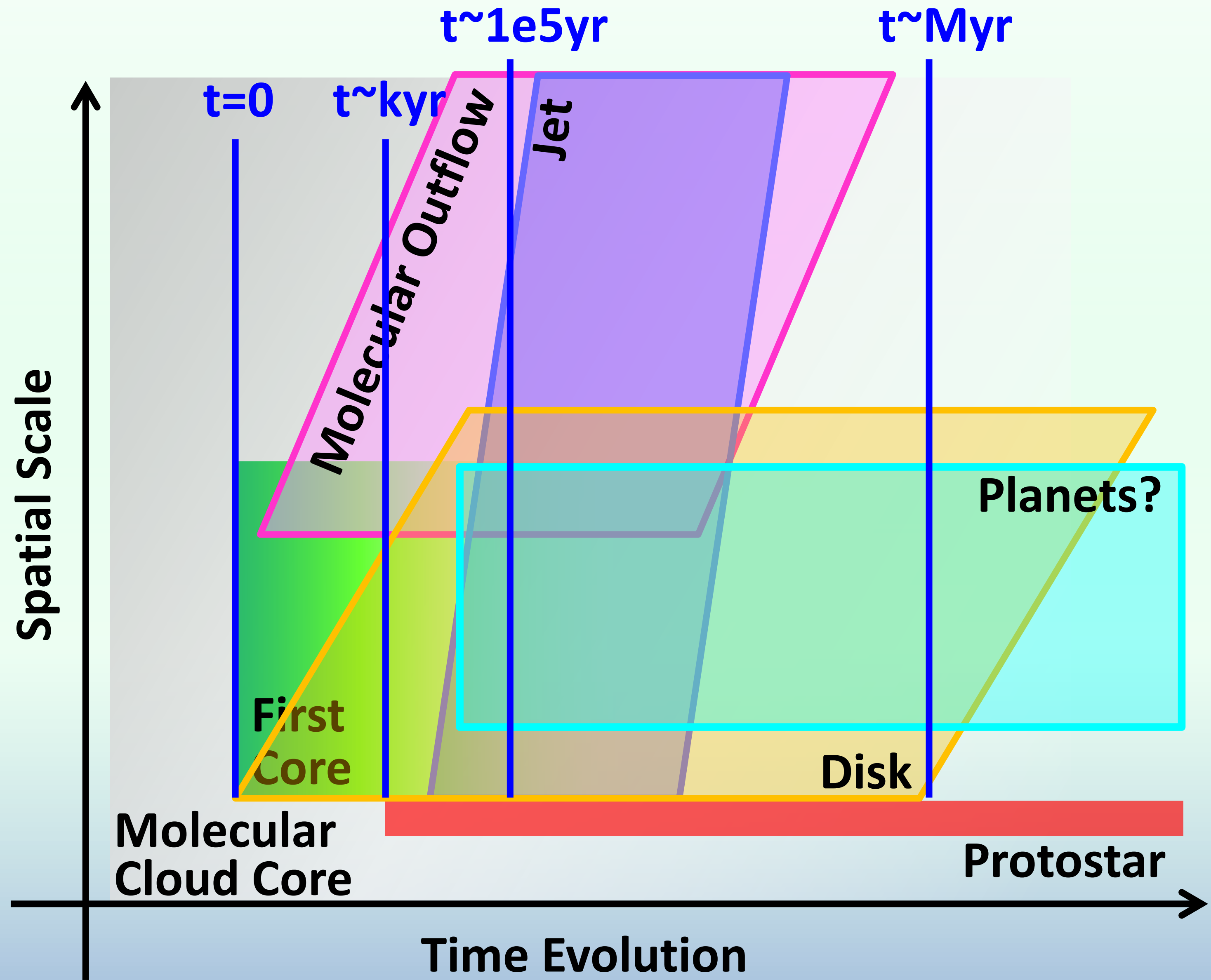
- Can we distinguish these processes?

→ Need Class-0,1 survey incl. polarization



Long-term Evolution and Synthetic Observations

A Schematic Picture



What Do We Need Next?

We reasonably understand "**physics**" of disk formation/evolution.
But we need more quantitative theory – which process is most important, when/how they work, how they depend on parameters?

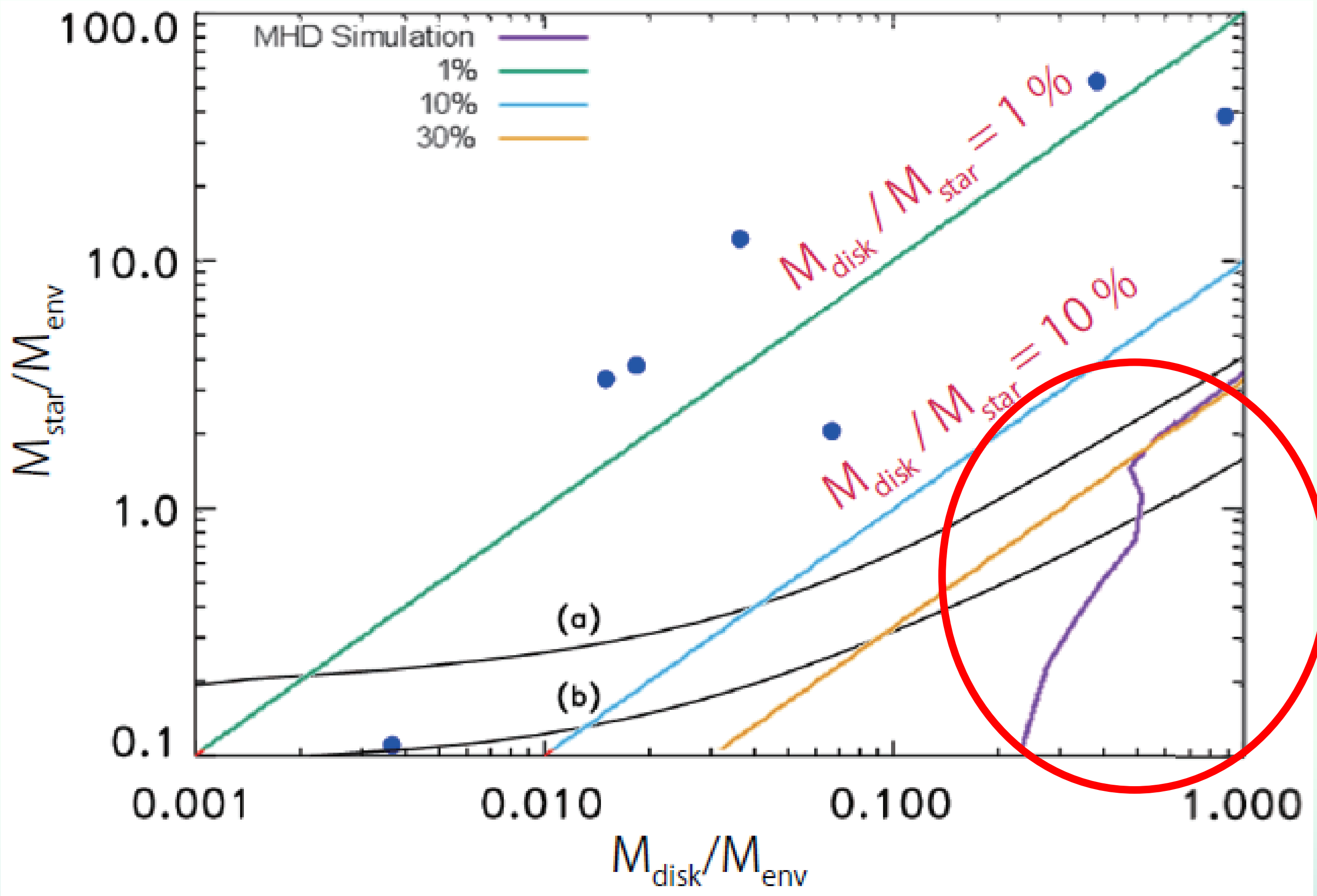
Also, binary / multiple formation is another big question
– When / how binaries are formed? Is there fragmentation crisis?
• Disk fragmentation (require massive disks)
• Core / turbulent fragmentation (expect various fragmentations)

To understand real systems quantitatively, we need to compare simulations and observations directly → **synthetic observations**

Also, observations are limited to the late phase (Class-1 or later)
→ **Long-term evolution** till the end of the accretion phase
⇒ Toward complete understanding through direct comparison

Disk Mass Problem?

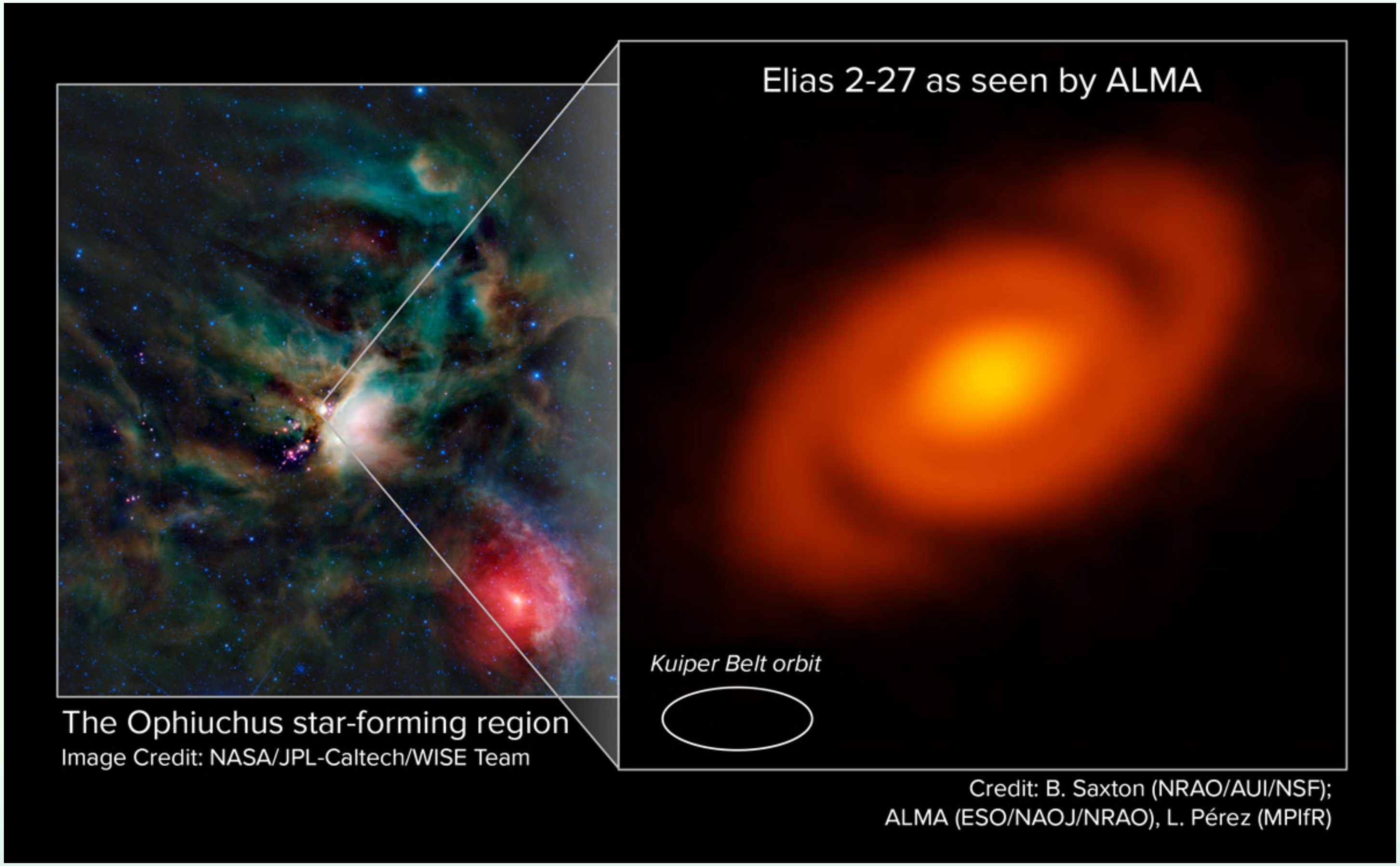
Observations: Jorgensen et al. 2009, Takakuwa et al. 2012, Tobin et al. 2012
MHD sim: Machida & Hosokawa 2013



MHD simulations tend to produce a massive disk (M_{disk}/M_{star} ~ 30%)
Observational uncertainties: dust growth, filtration, disk temperature
Missing physics? Radiation feedback? MRI? Initial/Boundary conditions?

Elias 2-27

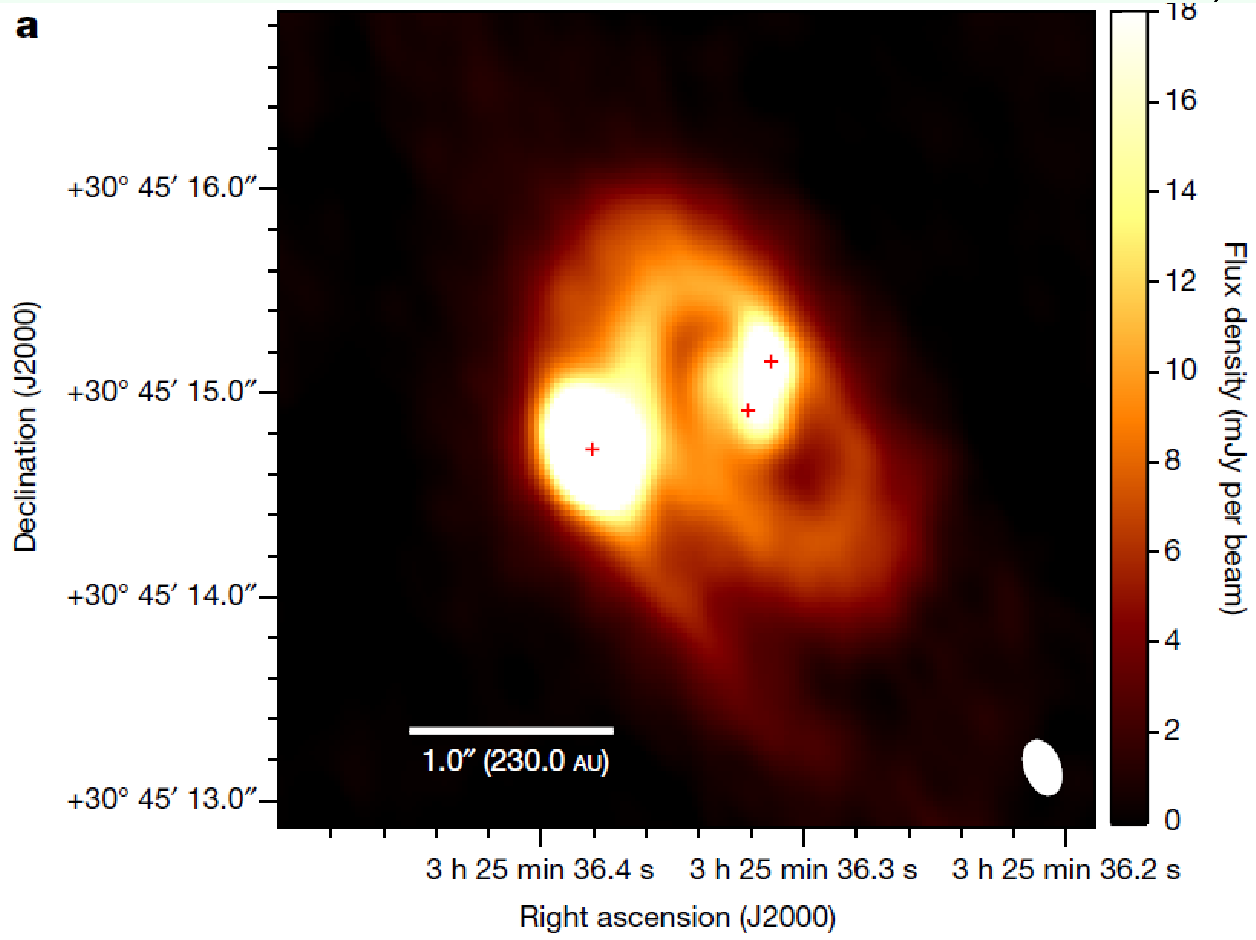
Pérez et al. 2016 Science



Beautiful grand-design spiral arms are found in a young protoplanetary disk around Elias 2-27 (a young Class II, but A_V~14 - possibly late Class I). Gravitational instability? Planet-disk interaction? Density waves? (Relatively high Q value(?), **winding problem**, good symmetry, etc…)

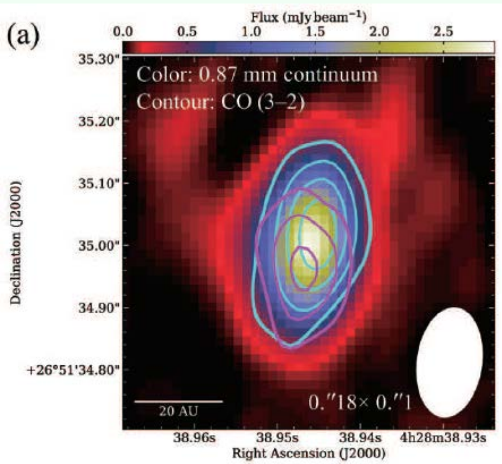
Another Example: L1448 IRS3B

Tobin et al. 2016, Nature

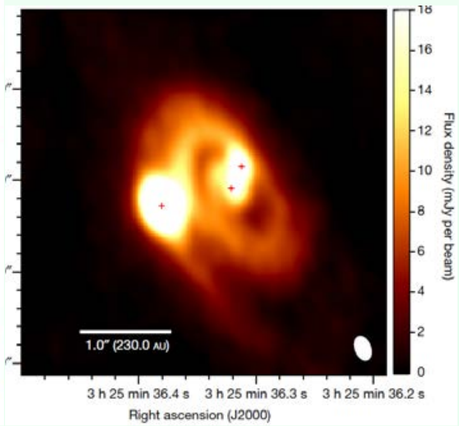


Young Class-0 disk undergoing fragmentation
→ Implies that young circumstellar disks can be massive

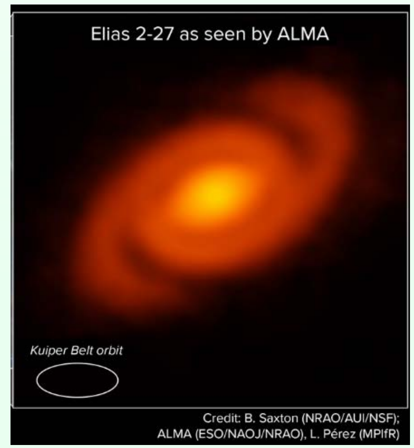
Disk Evolution / Diversity



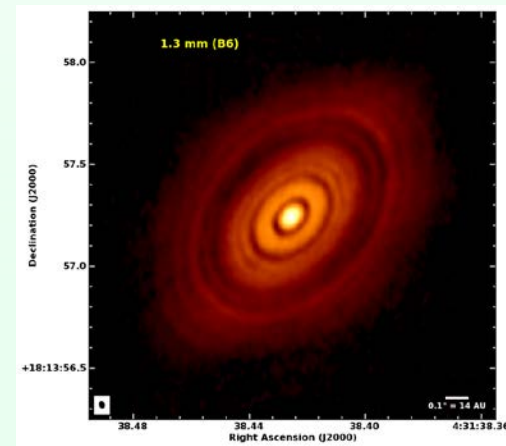
L1521-F (Tokuda+)



L1448 IRS3B (Tobin+)



Elias 2-27 (Perez+)



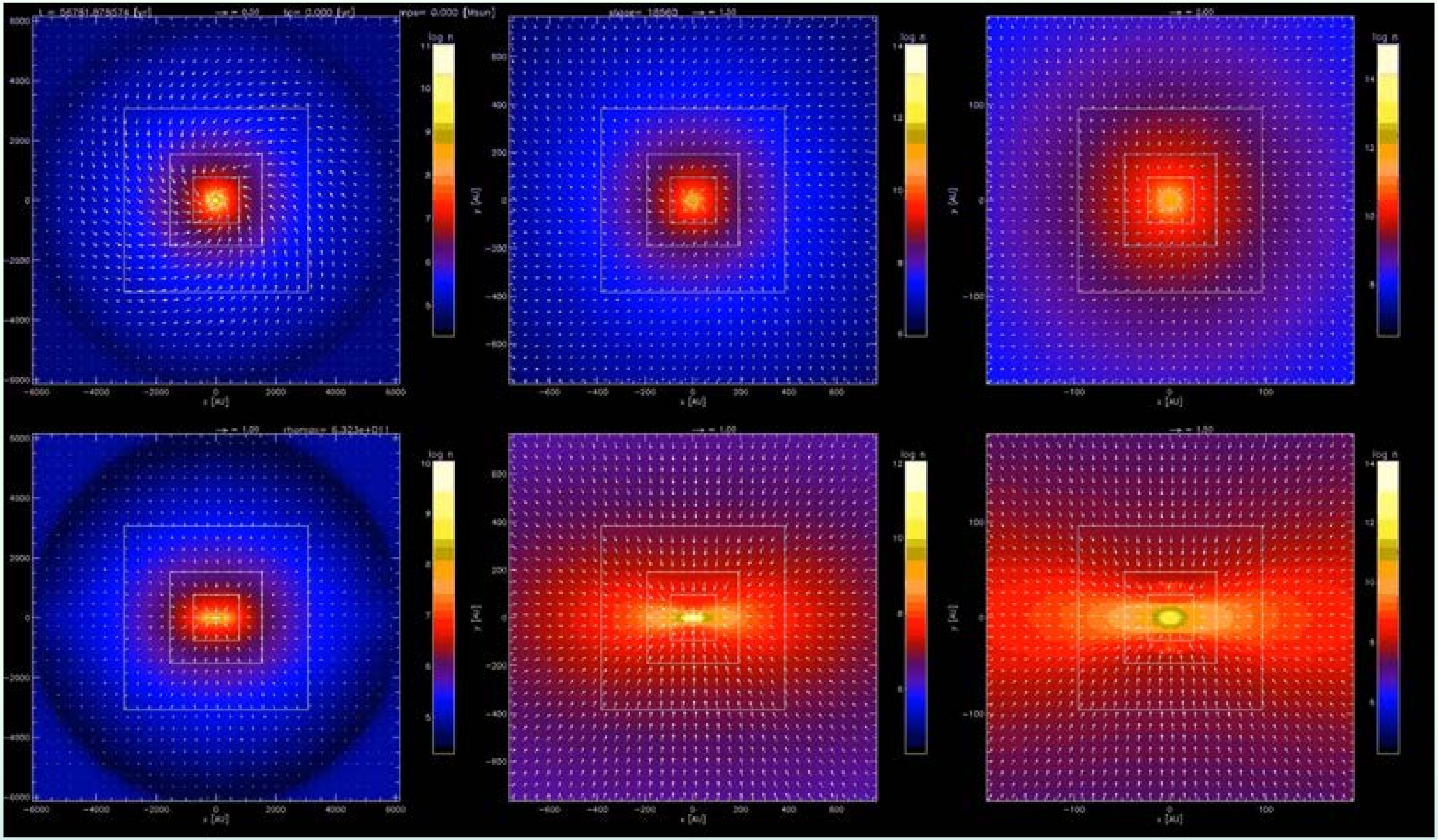
HL Tau (ALMA SV)

←Young Age Old→

Young disks are small but grow via gas accretion
Young disks tend to be gravitationally unstable - spiral arms
Sometimes they fragment and form binaries (gas giants?)
As accretion declines, the disk evolves and stabilizes (?)

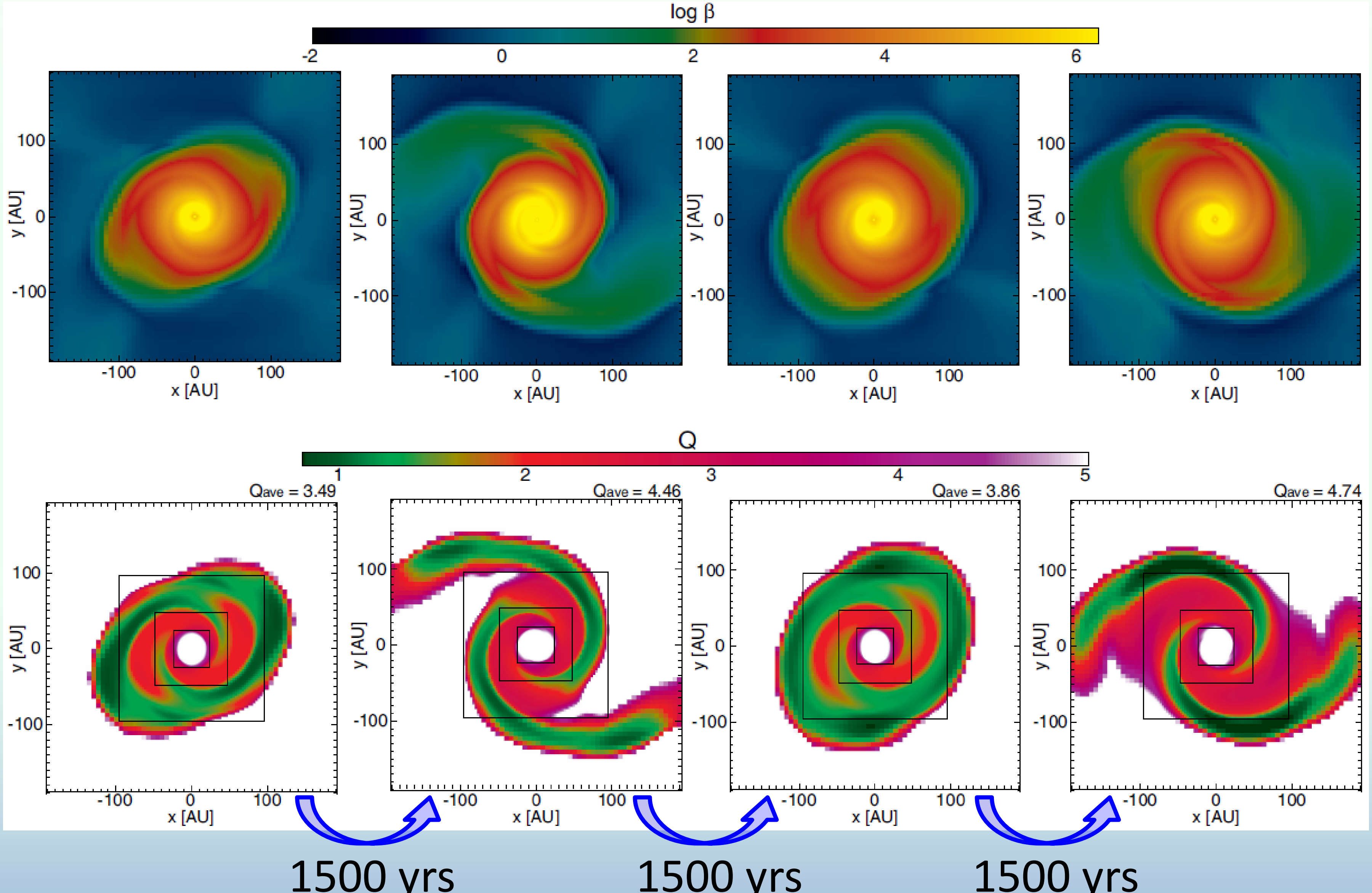
⇒ Can we explain such a long-term evolution with simulations?

Long-Term Evolution



Long-term resistive MHD simulation until the end of Class-I phase.
As accretion continues, the disk acquires more mass and angular mom.
The disk becomes gravitationally unstable, spiral arms form recurrently.

Plasma Beta and Toomre's Q value

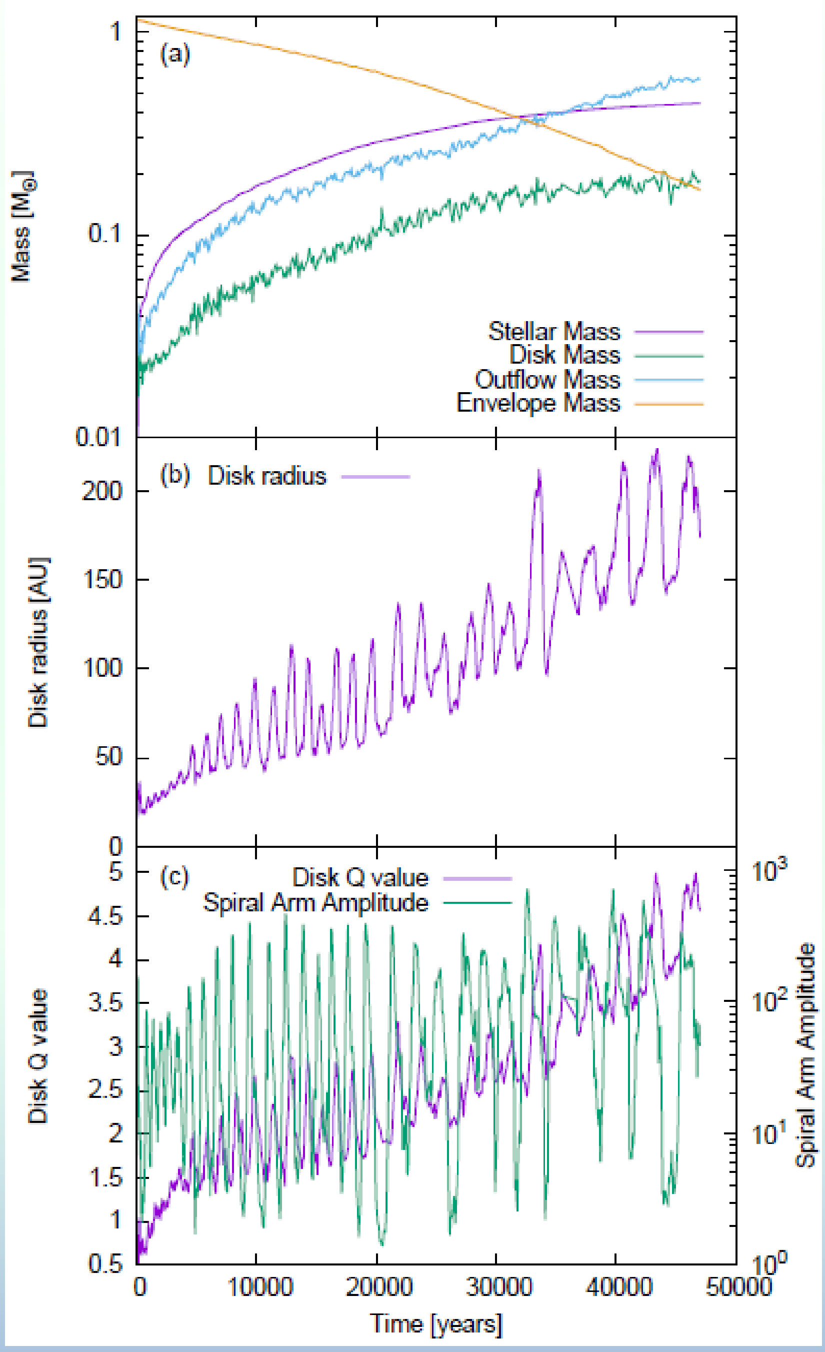


Disk Evolution

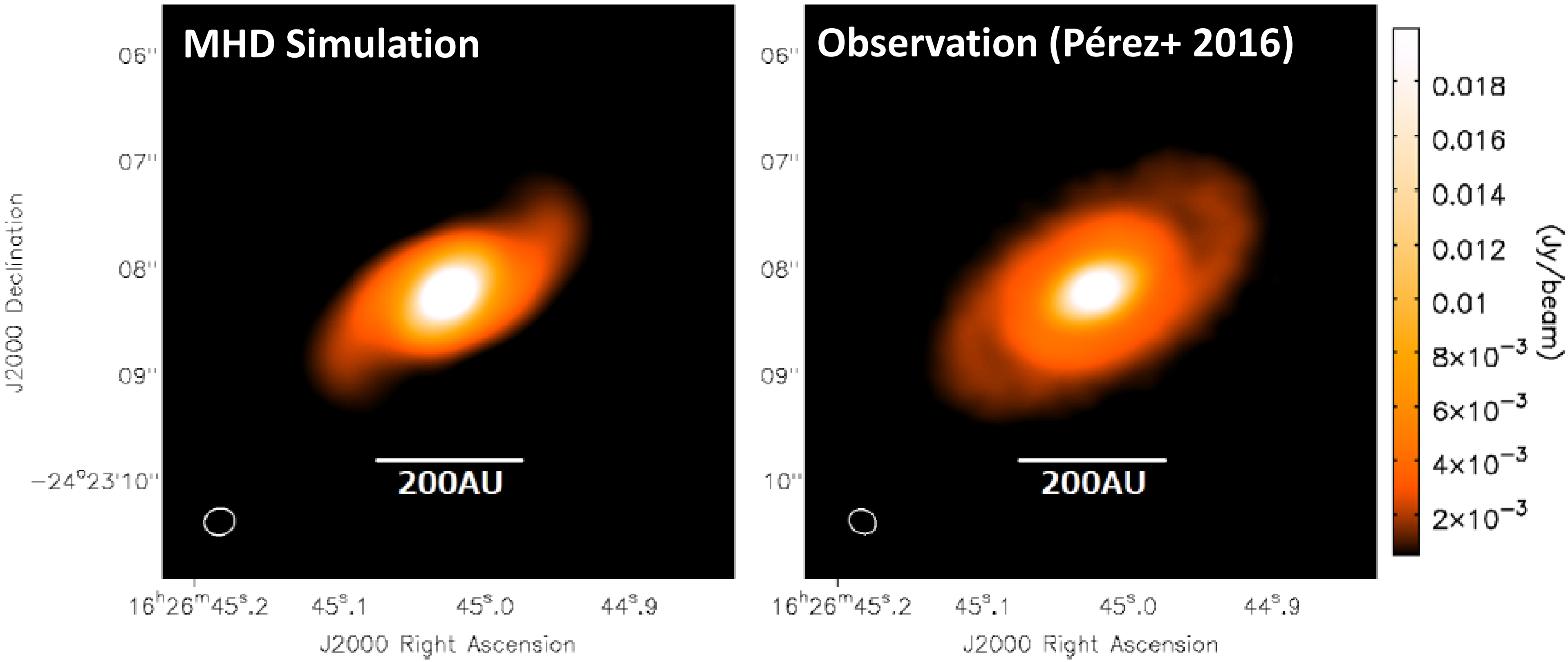
1. The disk becomes gravitationally unstable by accretion
2. Spiral arms form and transfer angular momentum by gravitational torque
3. The disk stabilizes and circularize.
4. Go back to 1 - **1cycle ~ a few orbits**

The disk radius reaches about 200 AU - magnetic braking is not serious

- Young circumstellar disks should be massive, 30-40% of the central star
- Spiral arms form by gravitational inst.
- Probability of spiral arms $\gtrsim$ 50%



Synthetic Observation



Synthetic Observation using RADMC-3D (Dullemond 2012) & CASA

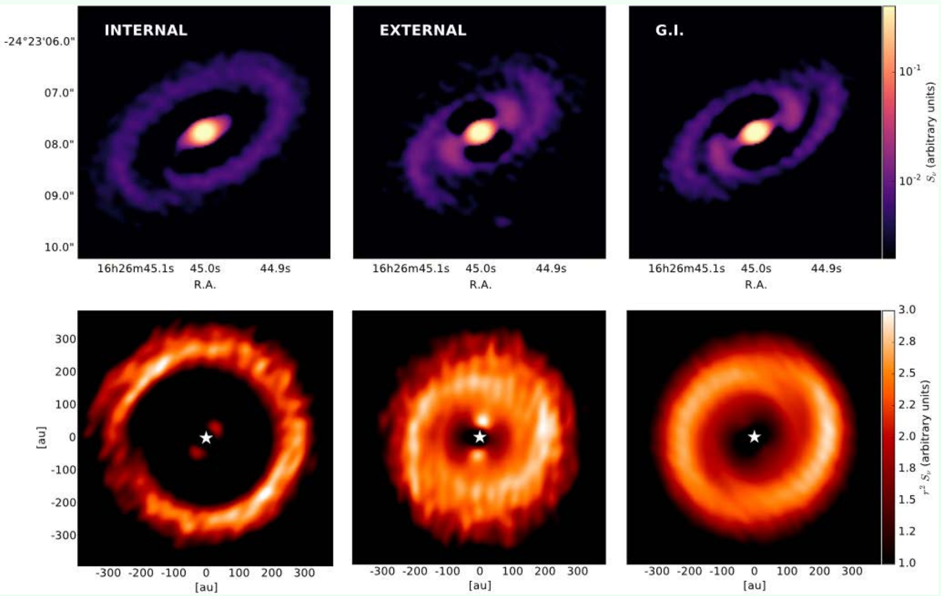
Opacities: Semenov et al. 2003, composite aggregate (incl. evaporation)

We can reproduce the Elias 2-27 system **except the accretion rate**

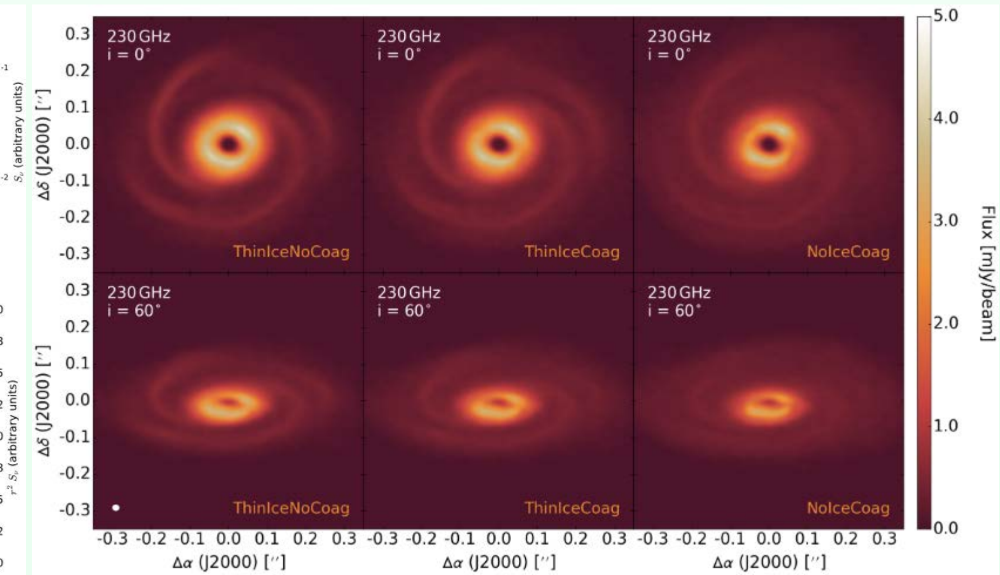
Observation: $8 \times 10^{-8} M_\odot$ / yr ↔ Model: a few x $10^{-6} M_\odot$

→this is probably related to the luminosity problem / episodic accretion

More Synthetic Observations



Meru et al. 2017



Evans et al. 2017

Meru et al. studied companions as another possible origin

Evans et al. studied the effects of different dust models

They all agree that the gravitational instability can explain Elias 2-27.

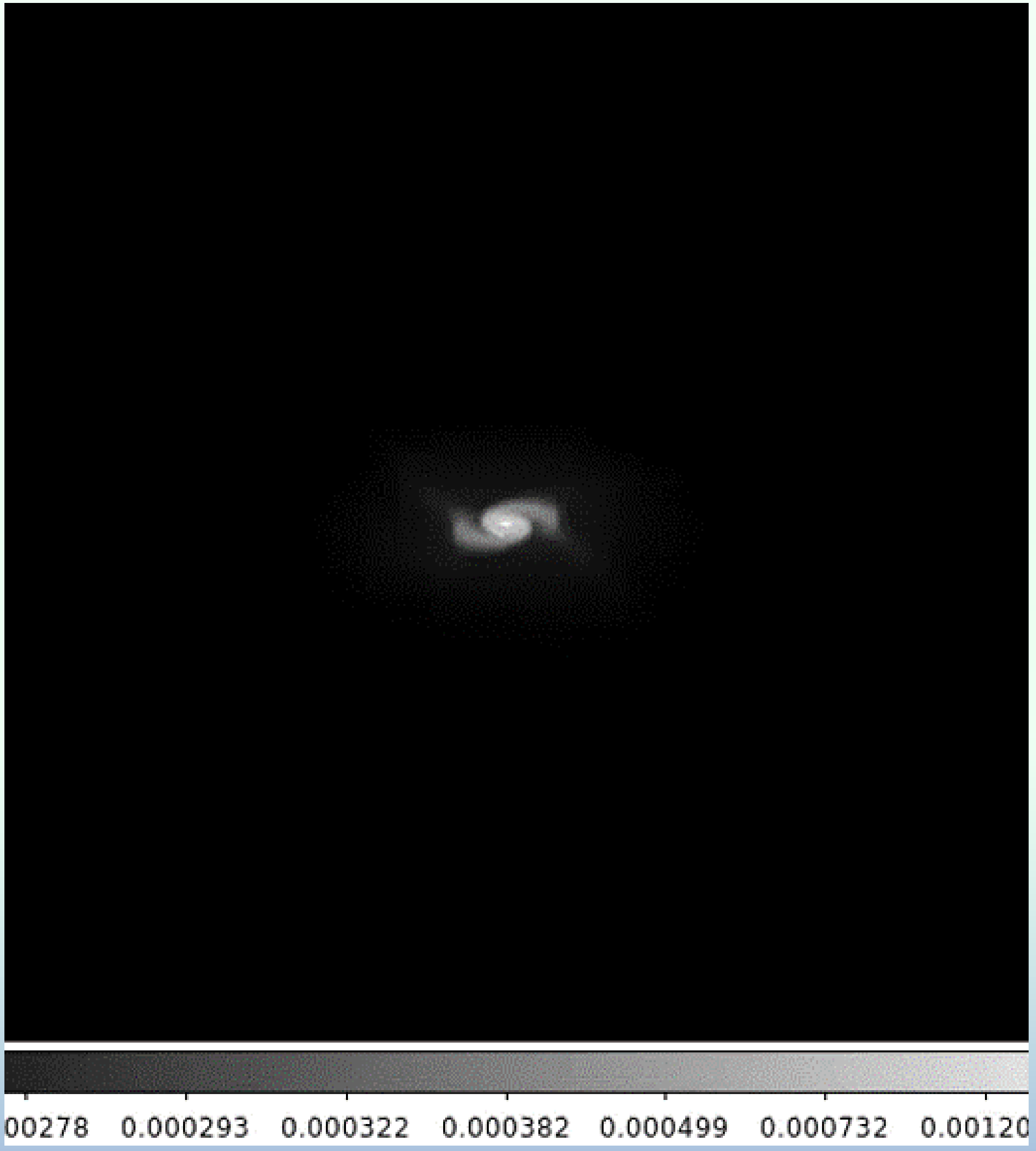
However, they both start simulations from gravitationally unstable disks.

Only our group performed consistent simulations from star formation!

Next: Molecular line Simulations

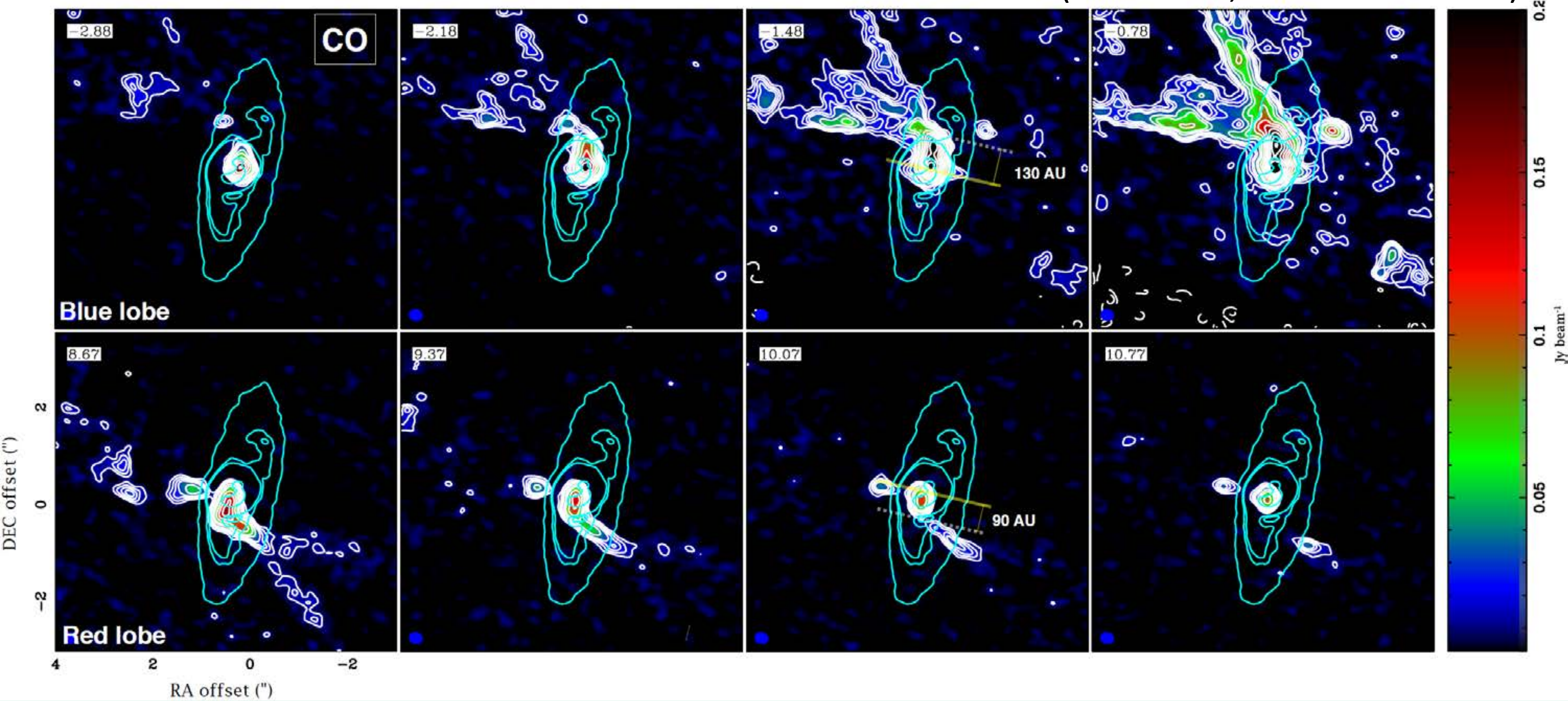
Setup:
Local Thermodynamic Eq.
Molecules: **^{12}CO**, ^{13}CO, C^{18}O
Abundance: 3.3e-7, **1.6e-7**,
4.5e-8
Lines: J=**2-1**, 3-2
Microturbulence: 0.19km/s
Inclinations: 0, 30, **60**, 90
Spatial resolution: 1AU
Spectral resolution 0.1km/s

C^{18}O: disk and pseudo-disk
^{13}CO: dense core + outflows
^{12}CO: outflows and envelope



Outflow Observations

(BHB07-11, Alves et al. 2017)



Some molecular outflows are rotating and asymmetric.

Out simulation model may be able to explain these structures.

Rotation: angular momentum transport by the magnetically driven wind

Asymmetry: absorption by the infalling envelope

Summary

Synthetic observations based on MHD simulations
→ Now we can ***observe*** and compare the simulations with observations, and derive some physical properties and implications directly.

Most properties of Elias 2-27 are successfully reproduced (luckily)
- Disk radius, disk mass, protostar spectral type, age, image, etc…

• Magnetic braking is important in the large scale / early phase
• Gravitational instability is important in the late phase of disk formation. (i.e. During the Class 0/I and earliest Class II phases, still accreting)
• The spiral arms form recurrently as the disk remains unstable.
→ the spiral arms of Elias 2-27 are explained well by material arms formed by gravitational instability.

If such spiral arms are common in young disks, it means that young disks are massive - which is important as planet formation environment.