大阪大学
OSAKA UNIVERSITY

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Zooming in on Star Formation
Nafplio, Greece

Formation and Early Evolution of Circumstellar Disks

Kengo TOMIDA

Osaka University / Princeton University

Why Circumstellar Disks matter?

- They are the initial and boundary conditions of planet formation
  - Planetesimal formation, planet growth, migration, etc...
  - No reason to believe in the Minimum Mass Solar Nebula
- They are the plausible site of binary/multiple formation
  - Need to explain the origin of the high binary rate
  - The origin of the stellar initial mass function
- Stars acquire mass and ang. mom. by accretion through disks
  - Accretion rates and protostellar evolution
  - Observational signatures such as X-ray, UV, optical lines etc.
- Disks (and the interaction with stars) drive outflows and jets
  - Feedback impacts surrounding star forming environments
  - Star formation efficiency and the origin of the mass function

⇒ Study disk formation in the context of star formation

Key: Angular Momentum

- **Angular Momentum Problem**

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

→Efficient angular momentum transport during protostellar collapse
⇒Gravitational torque, magnetic braking, MHD outflows

- "**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.

STAR FORMATION IN MAGNETIC DUST CLOUDS

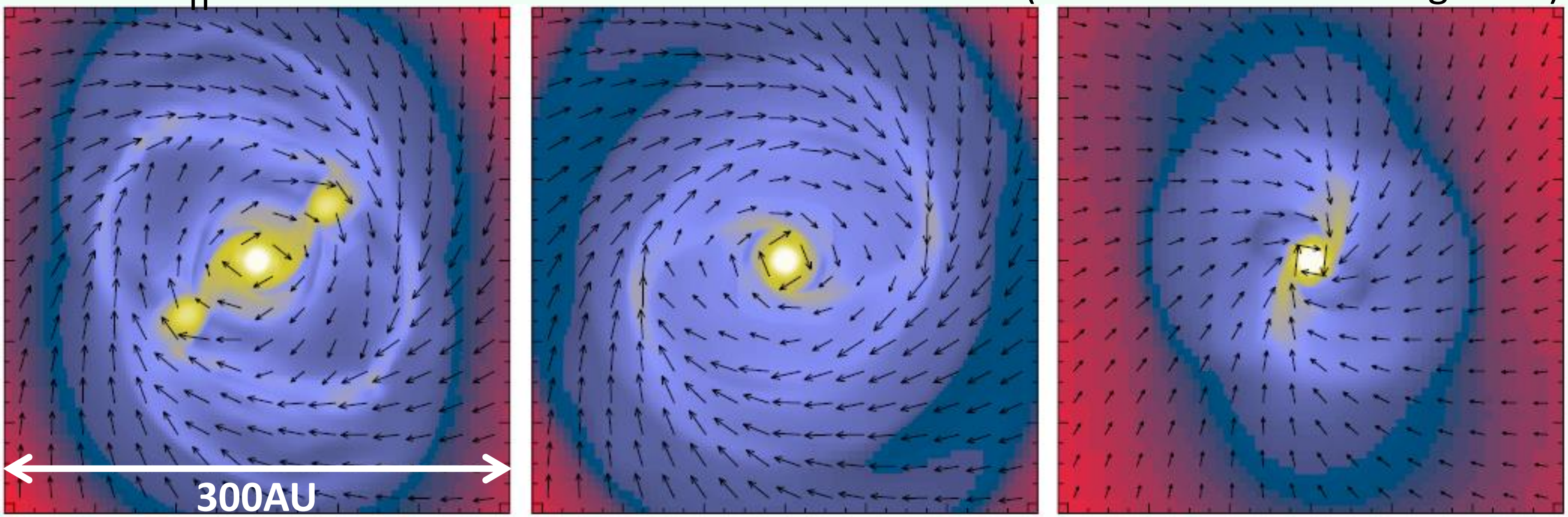
L. Mestel and L. Spitzer, Jr

(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.

Magnetic Braking Catastrophe / 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.

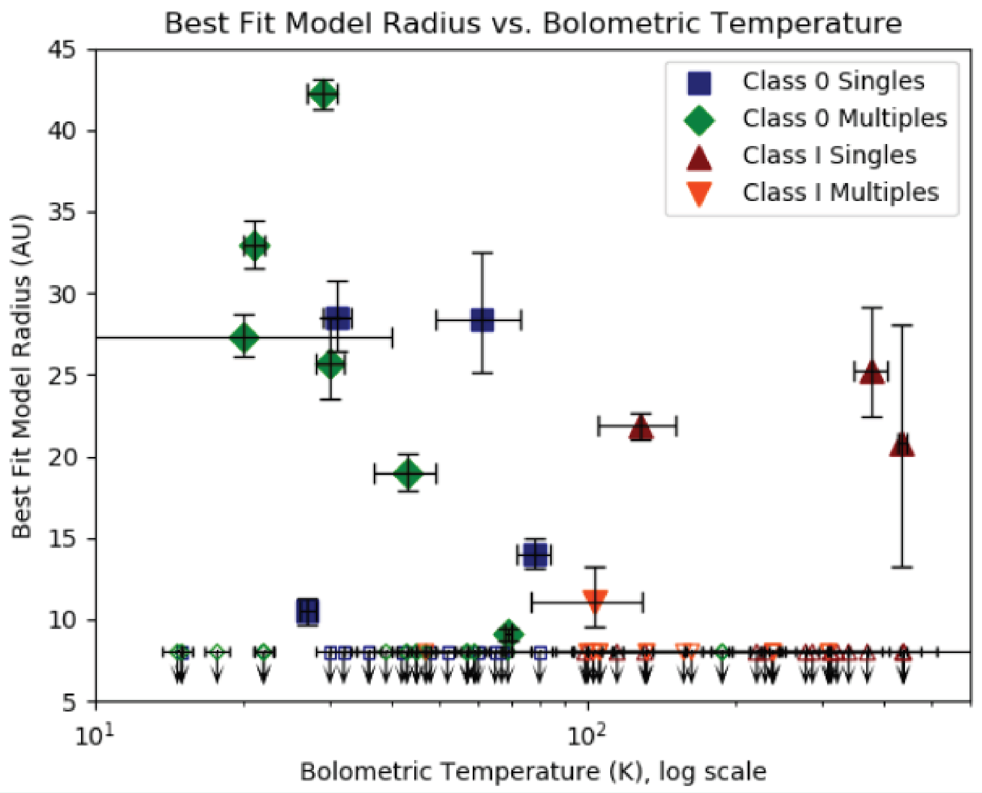
(see also, Mestel & Spitzer **1956**, Allen et al. 2003, Mellon & Li 08, 09, Li et al. 11, etc.)

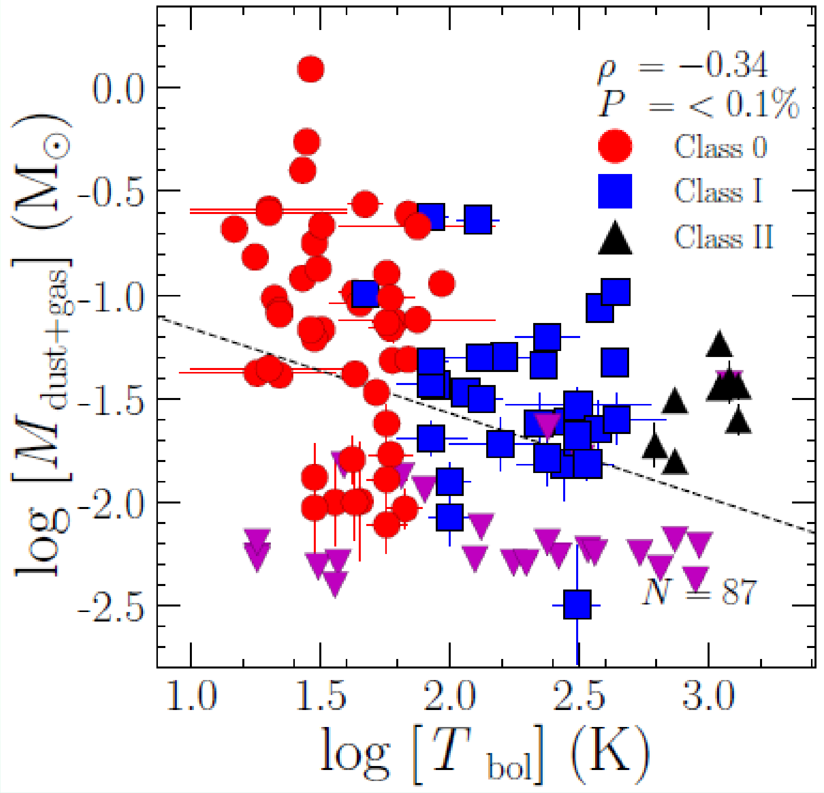
Solutions to the Catastrophe

- **Non-ideal MHD effects**
  - **Ohmic Dissipation and Ambipolar Diffusion**
    (Inutsuka et al. 2010, Li et al. 2011, Machida et al. 2011, Dapp et al. 2012, Tomida et al. 2015, Tsukamoto et al. 2015, Wurster et al. 2015, Masson et al. 2016, Vaytet et al. 2018, etc…)
  - **Hall Effect** (→ James Wurster's poster)
    (Li et al. 2011, Tsukamoto et al. 2015, Wurster et al. 2016, Marchand et al. 2018, etc.)
- **Rotation-magnetic field misalignment**
  (Matsumoto & Tomisaka 2004, Hennebelle & Ciardi 2009, Joos+ 2012, Krumholz+ 2013, **... however, this depends on initial cond. and non-ideal MHD; Tsukamoto et al. 2018**)
- **Turbulence**
  - Enhances magnetic diffusion by reconnection (Santos-Lima et al. 2012, 13)
  - Induces rotation-magnetic field misalignment (Joos et al. 2013)
  - Reduces magnetic braking efficiency (Seifried 2013, 14)
  - Turbulence itself introduces angular momentum in the small scale
  - Misaligned pseudo-disk reduces B-field accumulation (Li et al. 2014)

NOTE: these are NOT EXCLUSIVE - probably all of them work together.

Observations of Young Disks



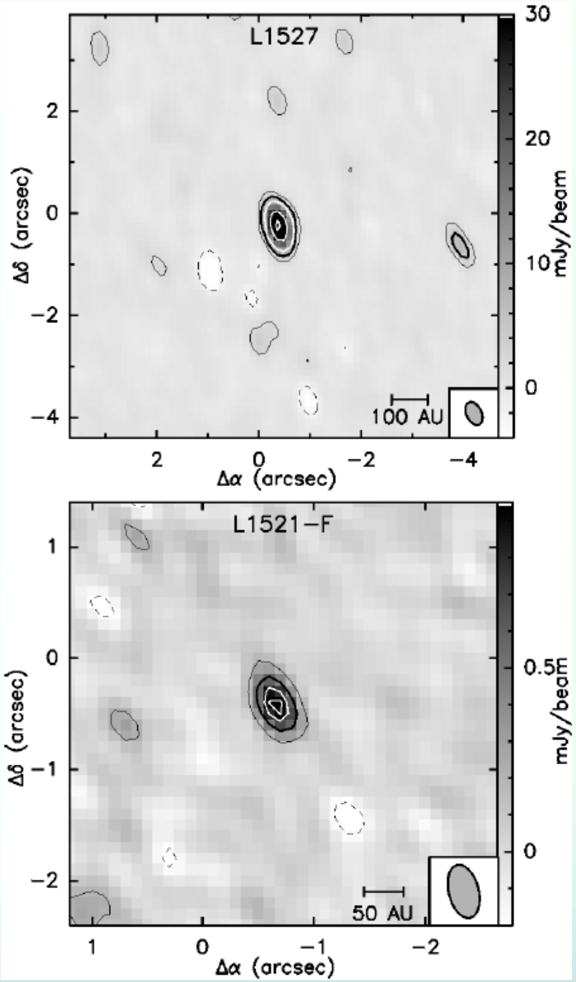


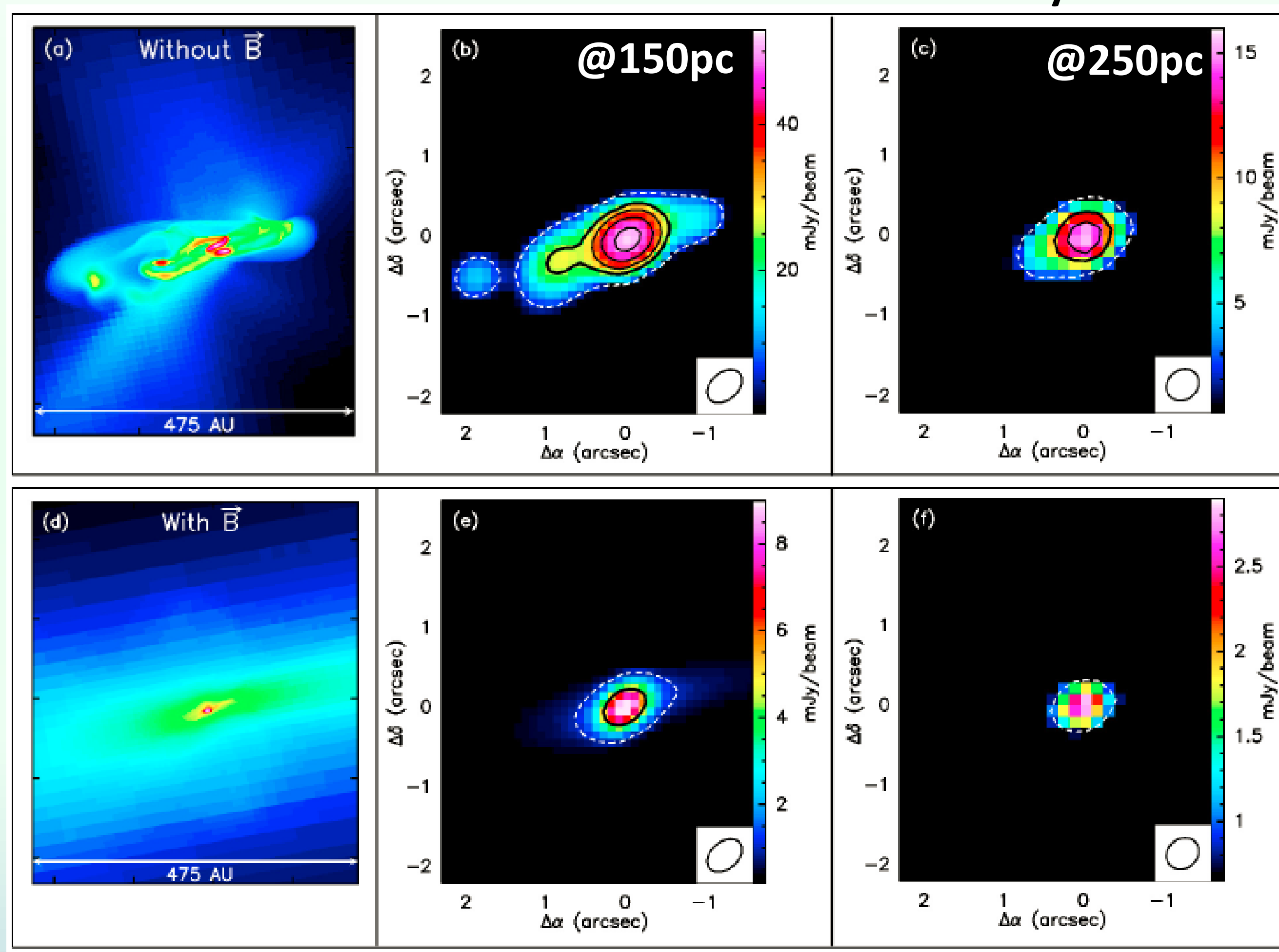
VANDAM survey (JVLA 8mm) - left: Segra-Cox+ 2018, right: Tychoniec+ 2018
Also Jørgensen+ 2009, Andersen+ 2019 (SMA) and Williams+ 2019 (ALMA)

Only 10-30% have large (>10AU) disks (sensitivity limited?)
Class-0/I disks are not very large but massive (beware of large uncertainties)

Young Disks Are Small

Maury et al. 2010

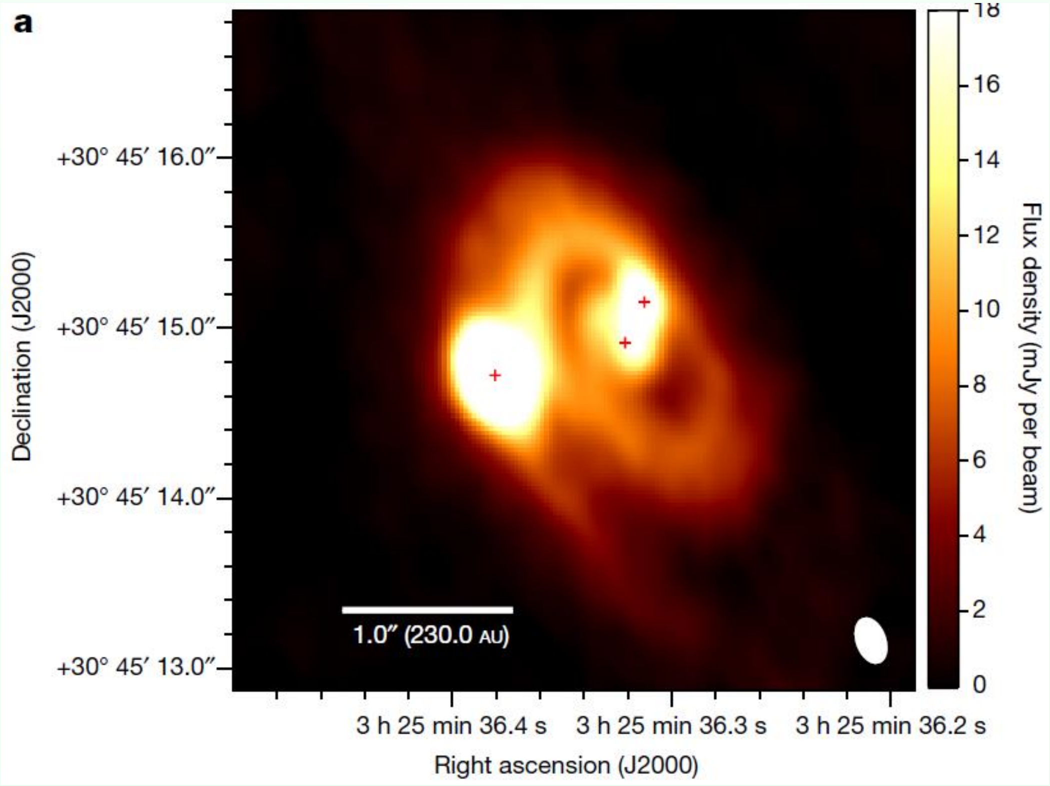


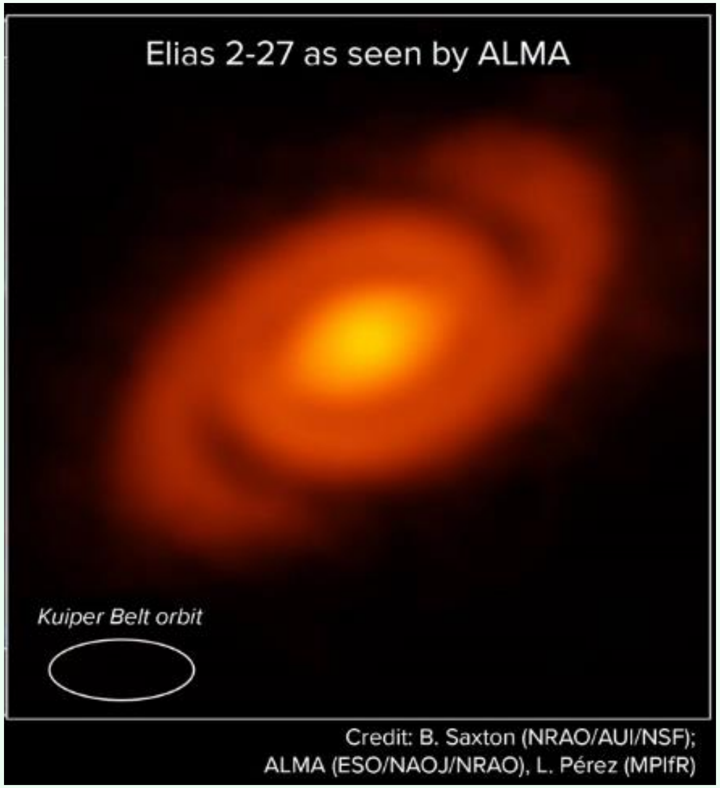


1.3mm Dust continuum observations of Class-0 sources with PdBI.

Young disks around Class-0 objects should not be too large (R ≲ 100AU)

Fragmentation / Spiral Arms





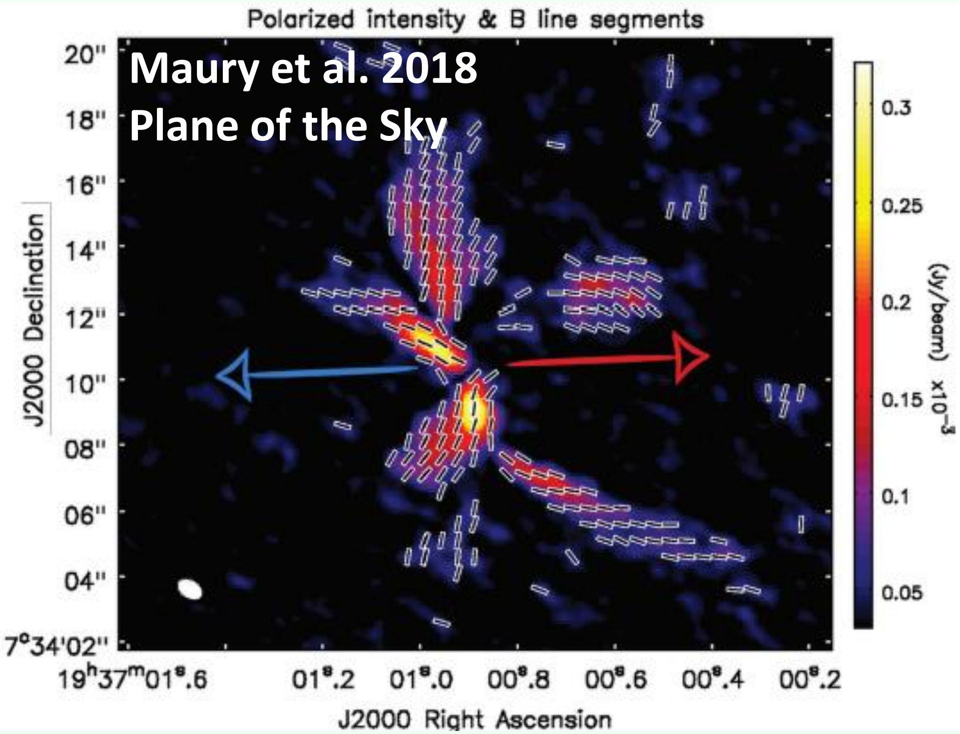
L1448 IRS3B (Class-0, Tobin et al. 2016)

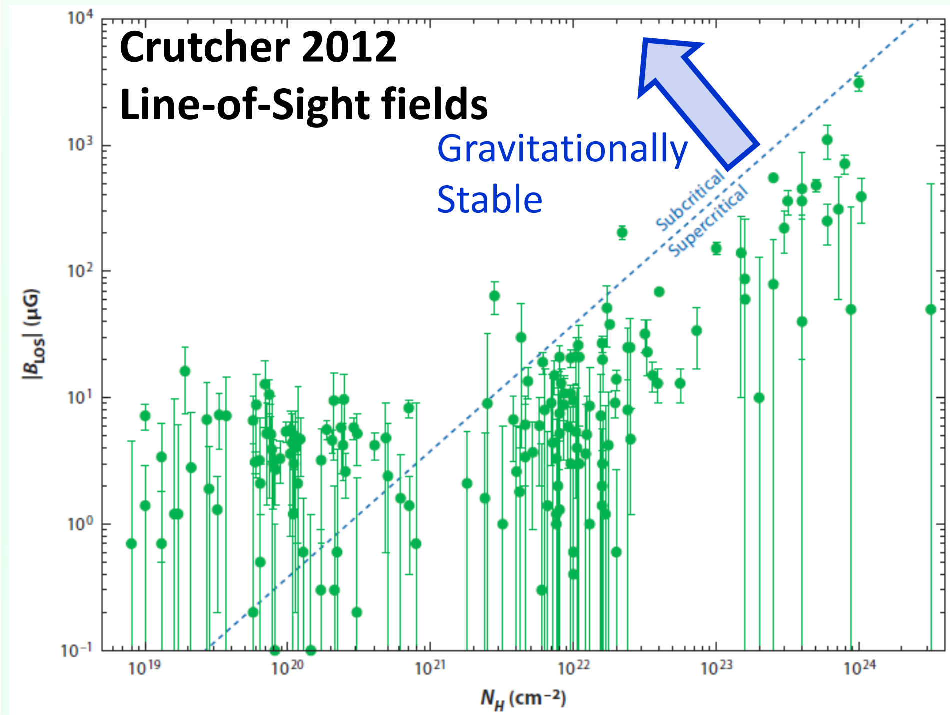
Elias 2-27 (Class-II?, Perez et al. 2016)

Some (more evolved) objects show fragmentation and/or spiral arms – indication of massive disks (L1448: M_s~1, M_d~0.3, Elias 2-27: M_s~0.4, M_d~ 0.16).
If these are produced by gravitational (Toomre-like) instability, there must be sufficient mass and angular momentum.

Clouds are Strongly Magnetized

(see also H.-B. Li et al. 2014, PPVI review)





Magnetic fields measured by dust polarization and the Zeeman effect. Observations suggest that cloud cores are considerably (supercritical to marginally subcritical) magnetized (μ～a few). Therefore magnetic fields must have significant effects, actually even in the supercritical regime.

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

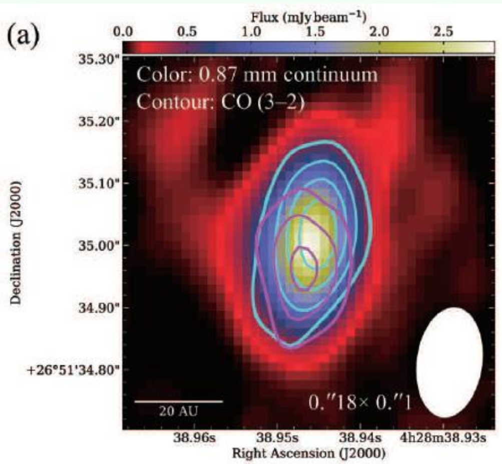
So Observations Tell Us...

- Protoplanetary disks are small in the early (Class-0/I) phase, and should grow later (in the late Class-I to Class-II phase).
- There is plenty of mass in the small scale in the early phase, and the disks get less massive as they grow.
- Some disks can be massive enough to be gravitationally unstable and may fragment (c.f. the high binary rate)
- Star forming clouds are considerably magnetized, not enough to prevent collapse but sufficient to affect dynamics.

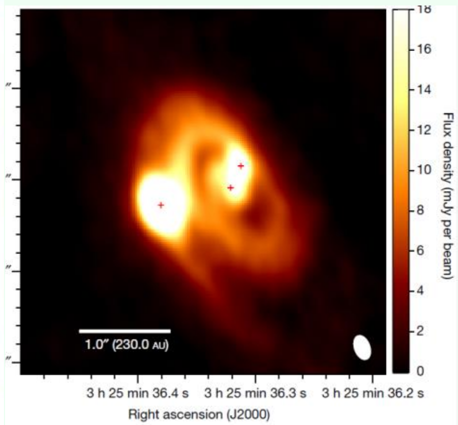
$\downarrow$

- Angular momentum must be removed in the early phase, probably by B-field, but it can’t be too efficient in the small scale.
- In the disk scale, the mass and angular momentum should be redistributed while accretion continues

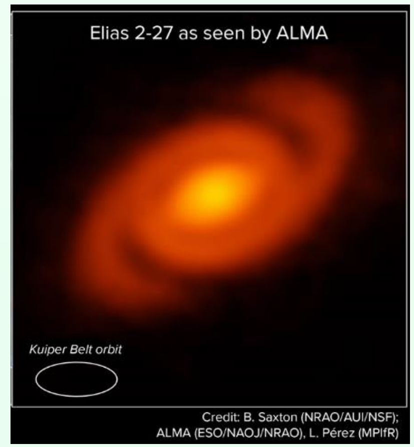
Disk Evolution / Diversity



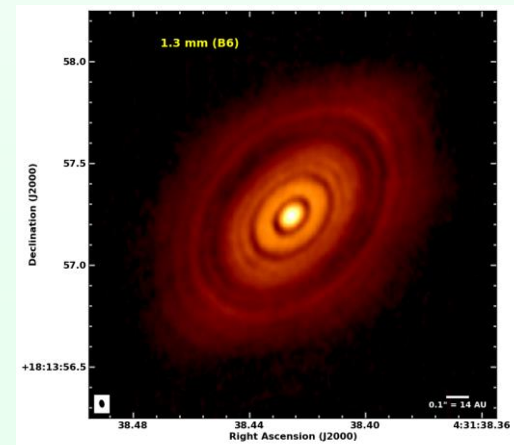
L1521-F (Tokuda+)



L1448 IRS3B (Tobin+)



Elias 2-27 (Perez+)



HL Tau (ALMA SV)

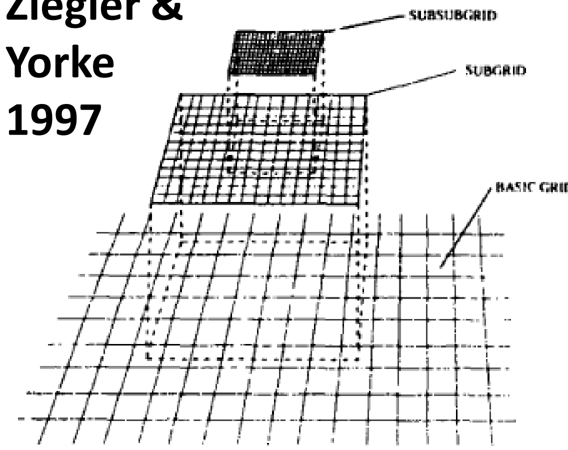
←Young Age (?) Old→

Young (Class-0/I) disks are small but grow later (Class-I/II)
Young disks can 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 Simulation

Ziegler & Yorke 1997

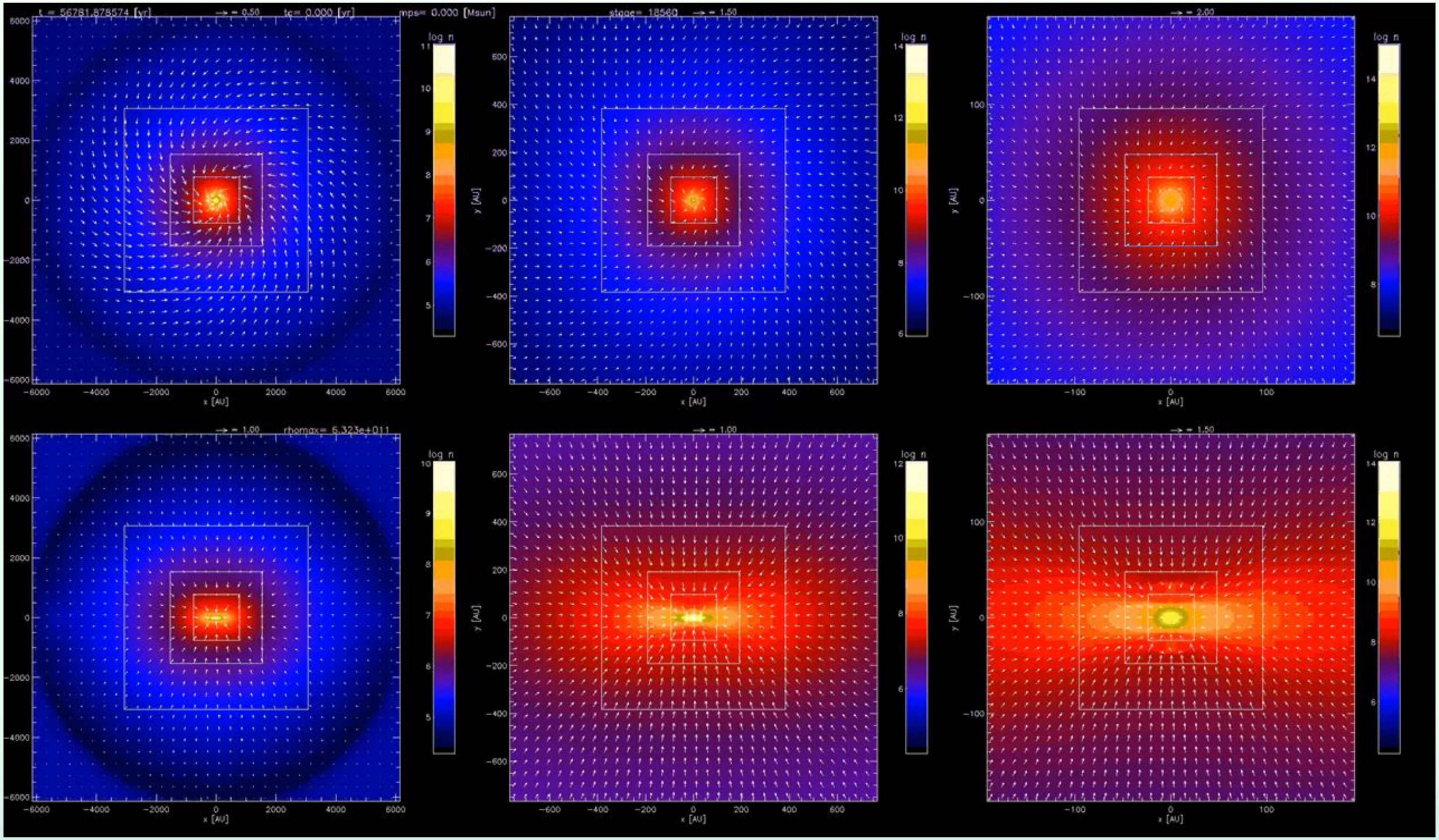


- 3D nested-grids (64x64x32, z-mirror)
- div **B**=0 → Mixed cleaning (Dedner+ 2002)
- Self-gravity→Multigrid (Matsumoto & Hanawa 2003)
- Non-ideal MHD: **only Ohmic dissipation**
- **Barotropic approximation** - isothermal in low density
  - adiabatic in high density
- **Sink particle**, accretion radius ~ 1AU
- Stellar Evolution model (Hosokawa et al. 2013)

Initial conditions:

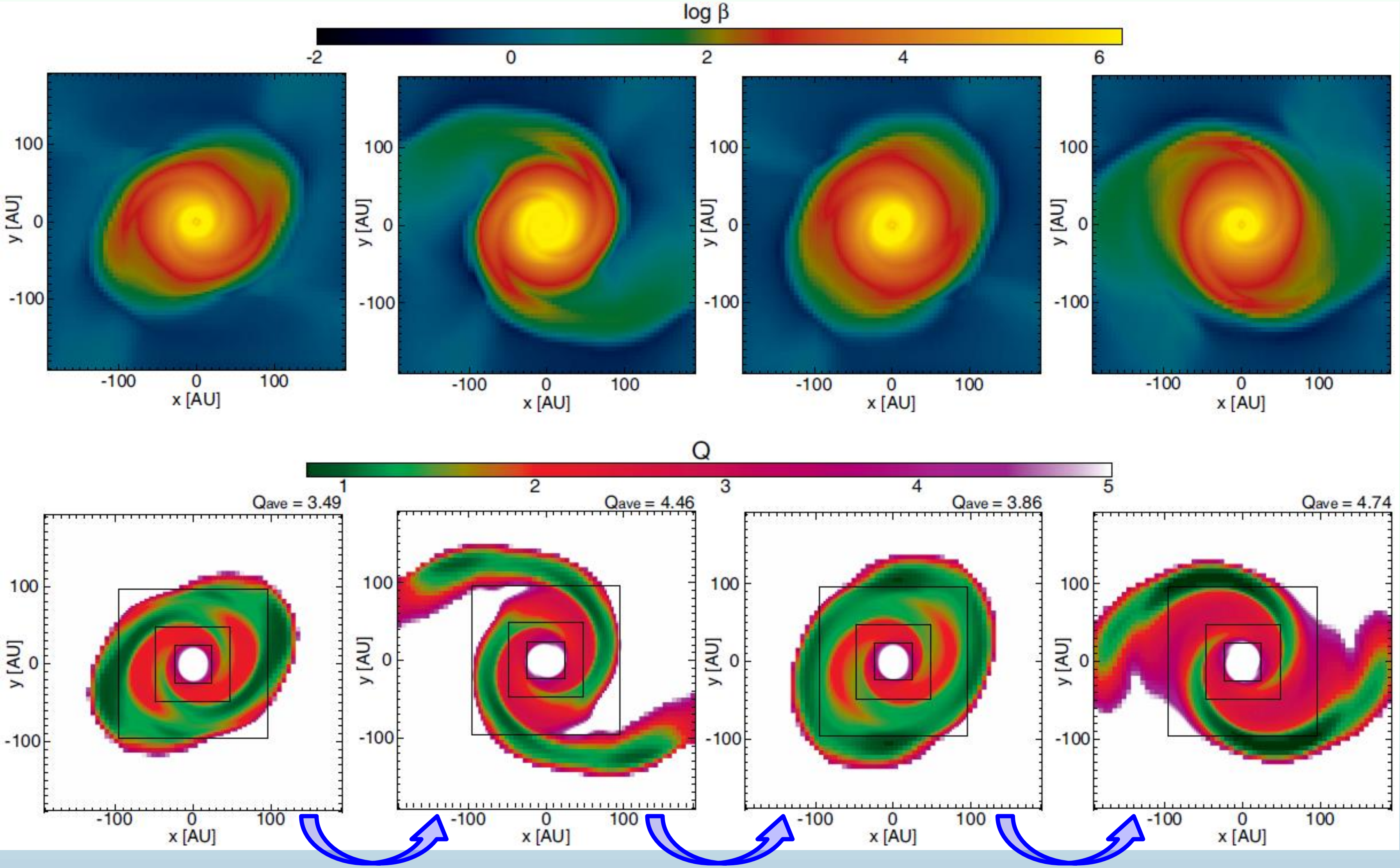
- $1.25M_{\odot}$ BE sphere, $\rho_c=2.2\times10^{-18}$ g/cc, T=10K, $R=6.1\times10^3$ AU
- Bz=50.65μG → normalized mass-to-flux ratio $\mu/\mu_{crit} \sim 3$
- Rigid-body rotation $\Omega=2.1 \times 10^{-13}$ sec^{-1}

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



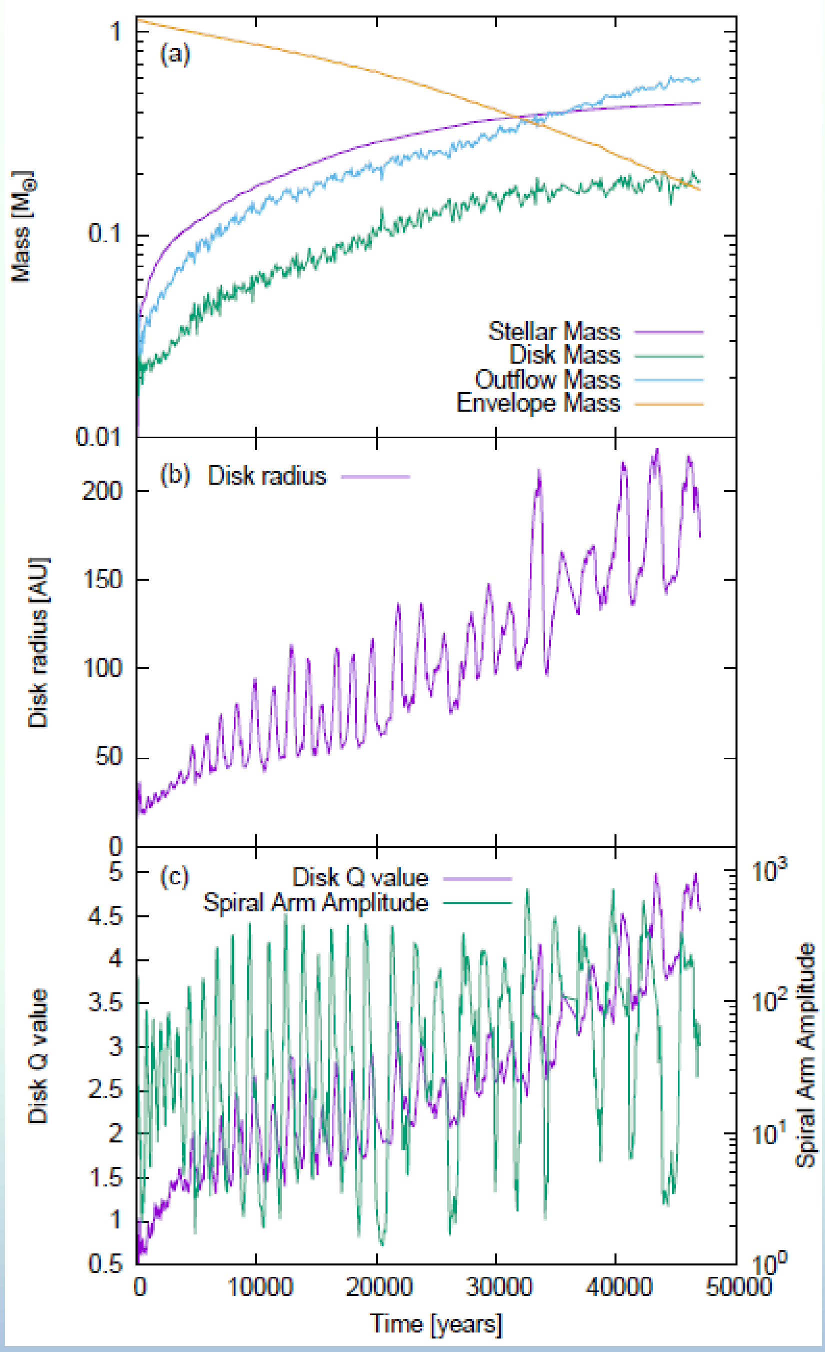
1500 yrs 1500 yrs 1500 yrs

Disk Evolution

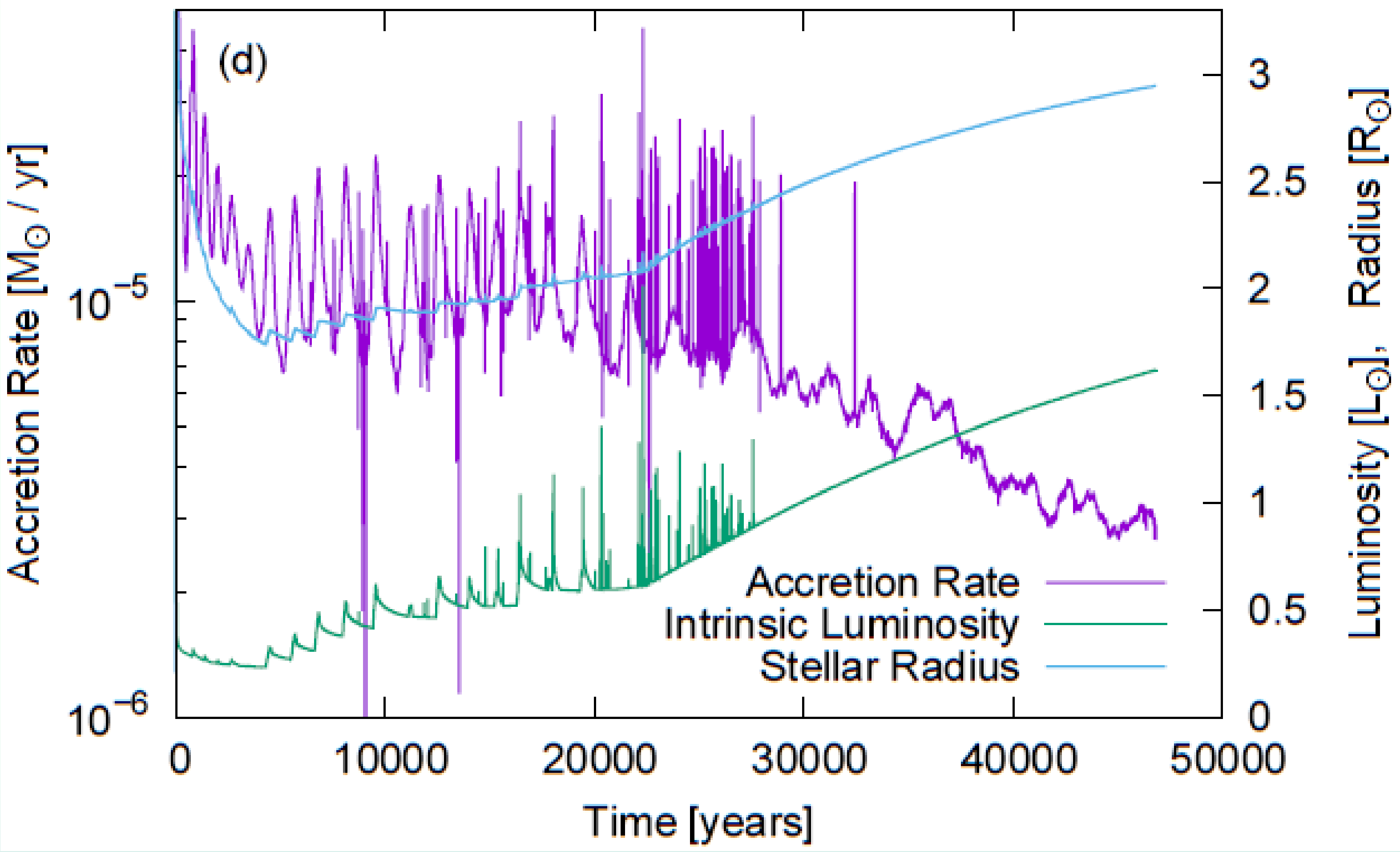
1. The disk becomes gravitationally unstable by accretion
2. Spiral arms form and transfer angular momentum by gravitational torque
3. The disk stabilizes and circularize.
4. Go back to 1 - **1cycle ~ a few orbits**

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

- Young circumstellar disks should be massive, 30-40% of the central star
- Outflows carry away ~50% of mass
- Spiral arms form by gravitational inst.
- Probability of spiral arms ≳ 50%
- Global Q~4 is not too high to kill GI



Protostar Evolution

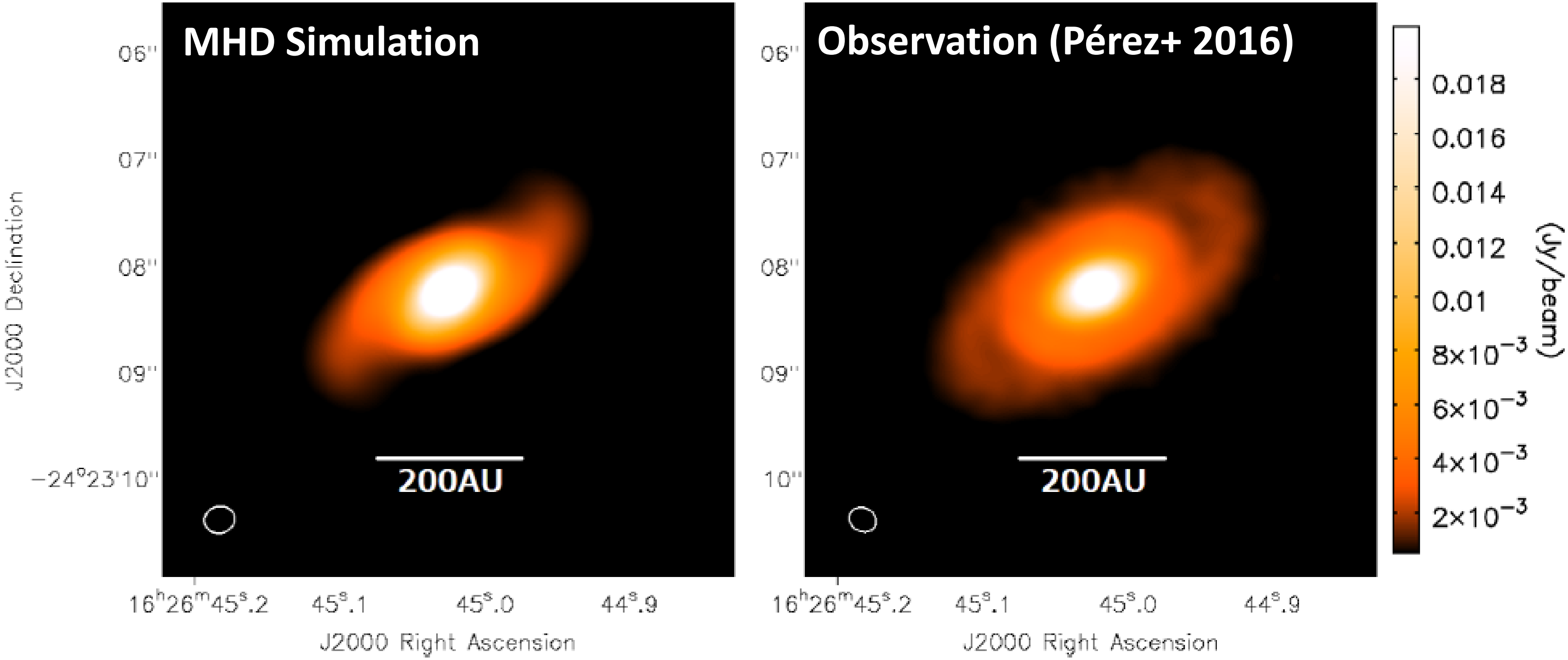


(Time-averaged) Accretion Rate is high: $10^{-5} \rightarrow$ a few 10^{-6} $M_{\odot}$ / yr

This accretion rate is too high - observationally it is only 8 x 10^{-8} $M_{\odot}$ / yr

Probably related to the luminosity problem and episodic accretion

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

→We attribute this to the luminosity problem / episodic accretion.

Comparison with Elias 2-27

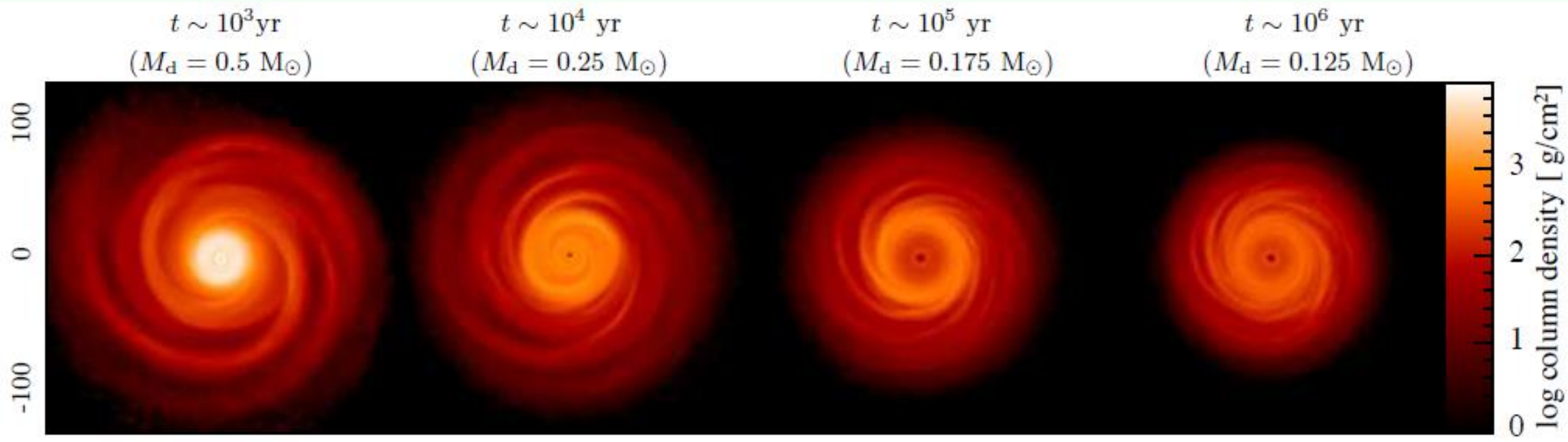
	Elias 2-27	**Our Model**
Stellar Mass	～0.4 $M_\odot$	～0.444 $M_\odot$
Accretion Rate	8 x 10^{-8} $M_\odot$ / yr	← (a few x 10^{-6} $M_\odot$ / yr)
Stellar Type	M0 (~4000 K), L_*=1.3$L_\odot$	M0 (~4000K), L_*=1.6$L_\odot$
Stellar Age	～100,000 yrs (Isella+ 2009)	～47,000 yrs
Disk Mass	～0.16 $M_\odot$	～0.18 $M_\odot$
Disk Radius	～300 AU	～250 AU
Spiral Arms	m=2 grand design	m=2 grand design
Outflows	slow outflow (Gurney+ 2008) but not in the disk scale	slow (~1km/s) outflow but not in the disk scale

We conclude that the spiral arms in Elias 2-27 can be well explained by the spiral arms formed by the gravitational instability.

Note: we did not tune the model - the simulation started way before the observation.

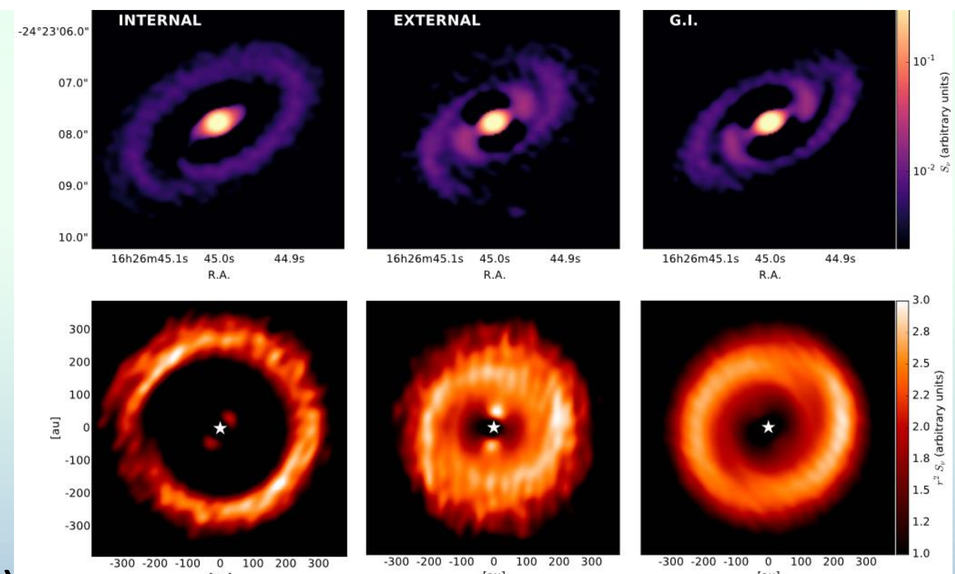
Comparison with Similar Works

(Hall et al. 2019)



- Meru et al. agreed GI can explain the spiral arms, while other process (companion) is possible.
- Hall et al. criticized GI cannot maintain spiral arms long enough.

Note that these works **do not consider accretion** which makes disks unstable repeatedly (& B-field).



(Meru et al. 2017)

Summary

From our long-term non-ideal MHD simulations...

- Protoplanetary disk should be small in the early phase but grow as accretion continues and mass/ang. mom. are redistributed.
- Magnetic braking is important in the large scale / early phase
- Gravitational instability is important in the late phase of disk formation and in the small (disk) scale

→ Similar trend in zoom-in simulations(→Michael Kűffmeier's talk)

- Outflow ejects half of the mass, disk/star ratio remains 30-40%.
- Spiral arms form recurrently as accretion keeps the disk unstable.

→ The spiral arms of Elias 2-27 can be explained well by GI

⇒Magnetic fields and self-gravity work together to transport angular momentum in different scales.

⇒Massive disks can be important for binary/planet formation

⇒Stars and disks (possibly planets) form together and coevolve


Protostars and Planets VII
April 1-7, 2021, Kyoto, Japan
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Protostars and Planets VII

Please mark your calendar!

Venue: Kyoto International Conference Center, Kyoto, Japan

Editors: S. Inutsuka, M. Tamura, Y. Aikawa, T. Muto, K. Tomida

Dates: April 1st-7th, 2021

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