Grand Design Spiral Arms in A Young Forming Circumstellar Disk

Kengo TOMIDA (Osaka), Masahiro N. Machida (Kyushu), Takashi Hosokawa (Kyoto), Yuya Sakurai (Tokyo), Chia Hui Lin (Osaka / National Taiwan University)

Reference: Tomida et al. 2017, ApJL, 835, L11

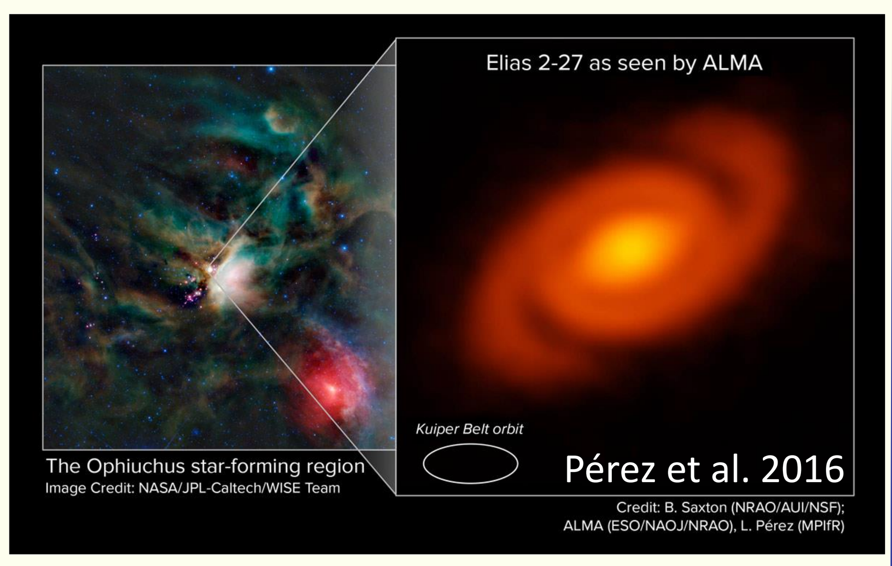
Background

Angular momentum transport is the key of star/disk formation and evolution.

- Magnetic braking and magnetically-driven outflows
- Gravitational torque by non-axisymmetric structures
- (turbulence, viscosity and other instabilities)

Grand design spiral arms are found around a young Class-II object Elias 2-27 (Pérez+ 2016), but the origin is unclear:

- Gravitational instability
  but spiral arms should disappear in a few orbits due to the differential rotation (?)
- Planet-disk interaction
  a planet may exist in the "gap", but it should produce non-axisymmetric arms (?)
- Density waves
  favored by elimination (?)



We perform a long-term MHD simulation until the end of the Class-I phase and compare our model with Elias 2-27.

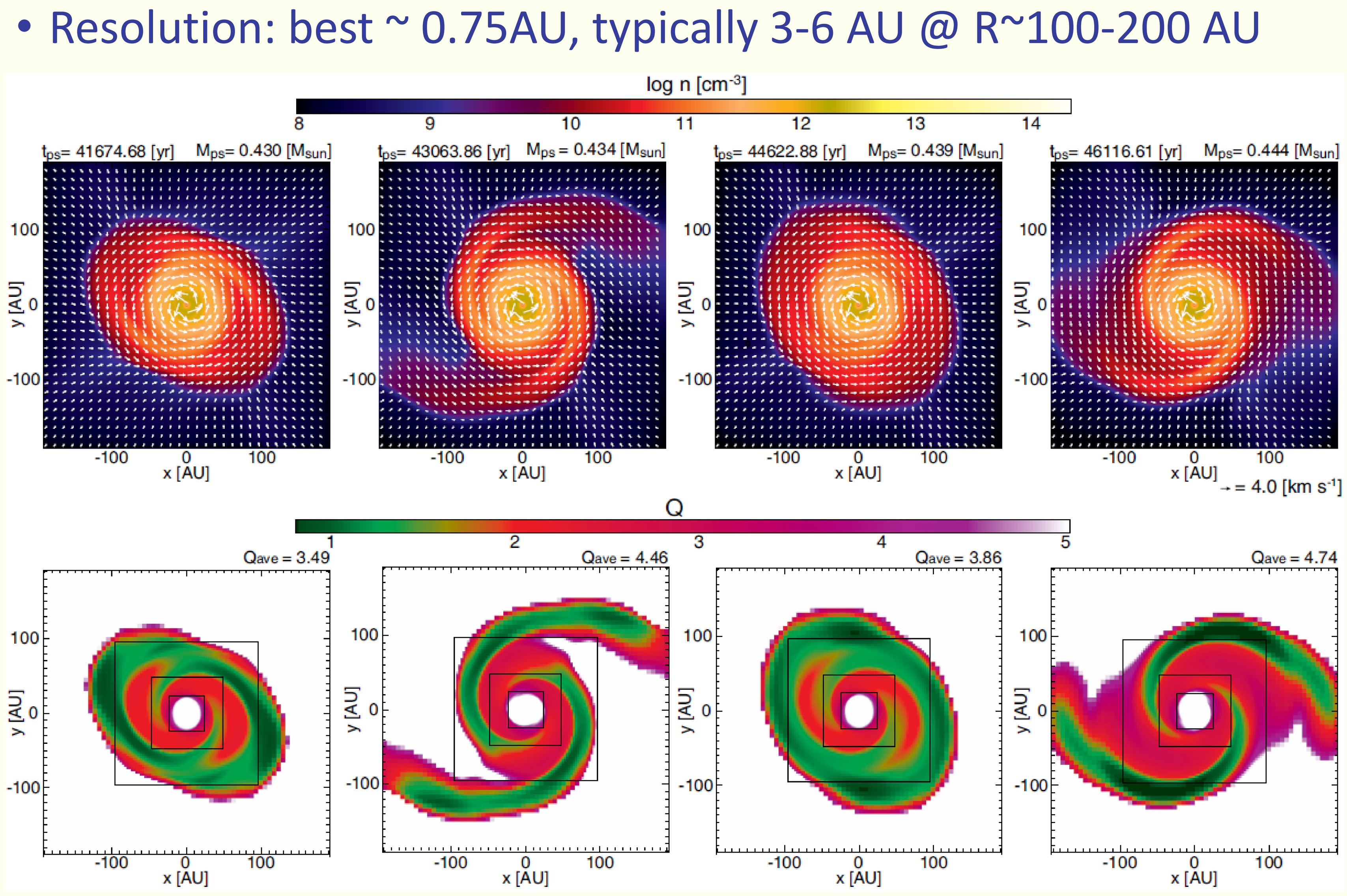
MHD Simulation

Simulation Method:

- 3D Nested-grid
- MHD + Ohmic dissipation
- Self-gravity
- A sink particle
- Barotropic approximation
- Resolution: best ~ 0.75AU, typically 3-6 AU @ R~100-200 AU

Initial condition:

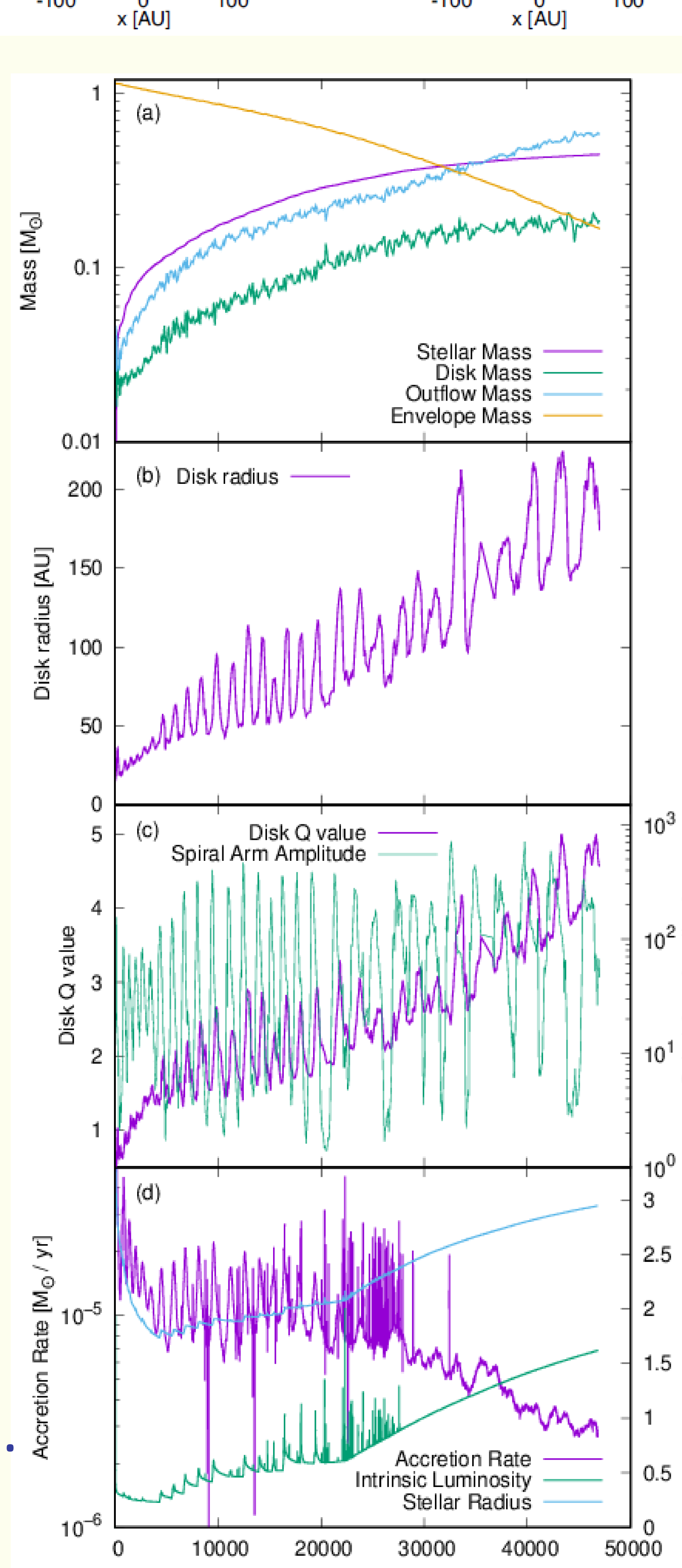
- unstable Bonnor-Ebert sphere
- T=10K, ρ_c=2.2x10^{-8} g/cc, 1.25Ms
- B=36μG, mass-to-flux ratio μ=3
- aligned rotation Ω=1.5 x 10^{-13}/s



- We run the simulation till the end of Class-I - almost all the gas was accreted or ejected.
- The disk mass is ~30% of the mass of the central protostar
- Magnetic braking becomes less efficient as the disk grows and as the envelope disperses.
- The disk gets gravitationally unstable and the spiral arms form, then the disk stabilizes and circularizes.

→ This occurs recurrently and its timescale is a few orbits.

- The disk oscillates as it grows - the radius correlates with Q.
- The disk radius reaches 200AU no magnetic braking catastrophe.
- The spiral arms persist through out class-0/I - reasonably likely in the visible state (∼50%)



Synthetic Observation

In order to compare our model directly with the observation, we calculate the dust continuum at 1.3mm.

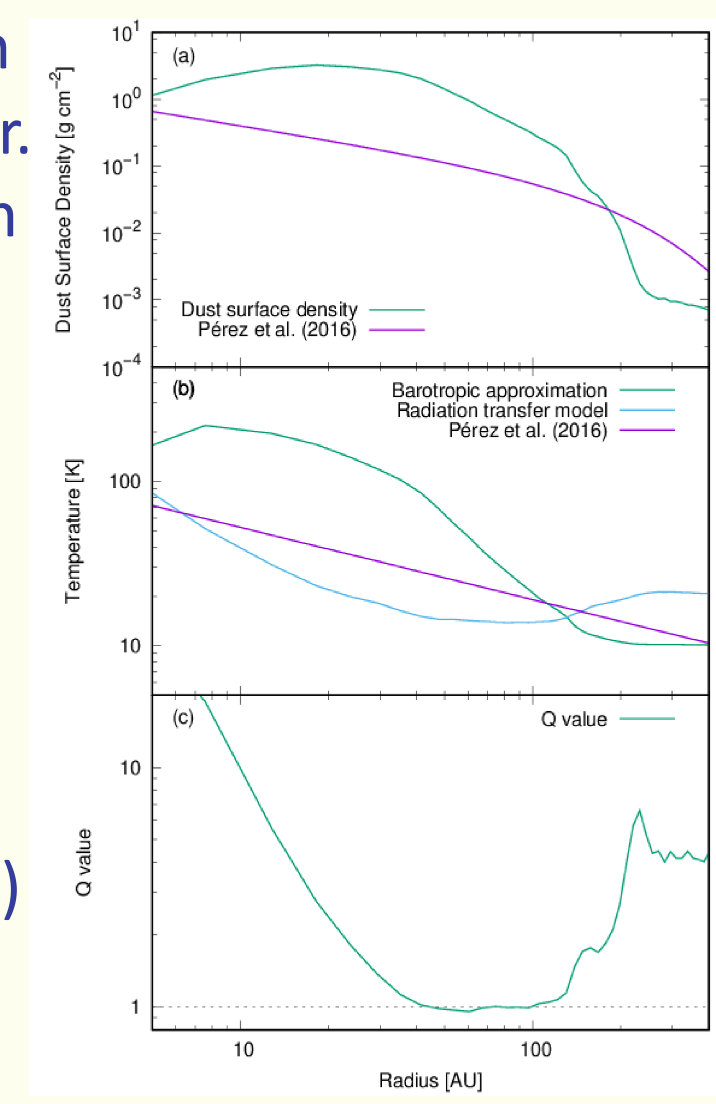
1. Calculate evolution of the star (the STELLAR code, Yorke & Bodenheimer 2008, Hosokawa et al. 2013)
2. Recalculate the temperature assuming that the temperature is in equilibrium under the stellar irradiation using RADMC-3D (Dullemond 2012) and the opacities of Semenov et al. (2003)
3. Calculate the intensity distribution with RADMC-3D
4. Simulate ALMA observation using CASA

Obtained stellar properties at the end of the simulation:
Mass: 0.444$M_\odot$, Radius: 2.935 $R_\odot$, Luminosity: 1.604 $L_\odot$

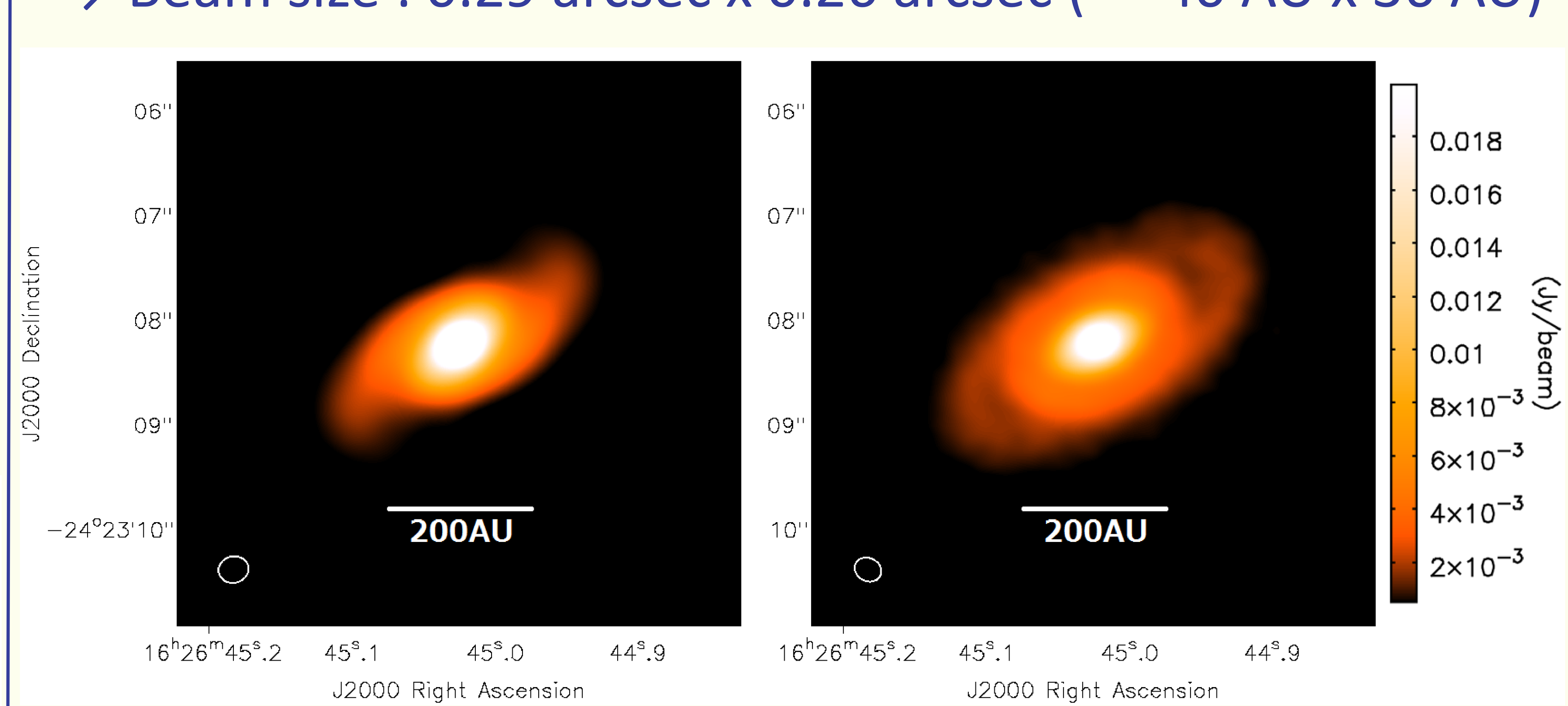
The time-averaged accretion rate in the simulation is high: ∼10^{-6} $M_\odot$/yr. Considering the luminosity problem and episodic accretion, we use the observed accretion rate 8x 10^{-8} $M_\odot$/yr (Najita et al. 2015).

→ Accretion luminosity: 0.379 $L_\odot$,
Total luminosity: 1.98 $L_\odot$,
Effective temperature: 4,000 K,
Spectral type: ~ M0
(good agreement with Elias 2-27)

The protostar age: ~ 5 x 10^4 yrs
Elias 2-27: ~ 10^5 yrs (isochrone)



Parameters of the ALMA simulation (based on Pérez+ 2016):
Position: RA = 16h26m45.024s, Dec = -24d23m08.250s
Distance and Inclination: 139pc, 55.8°
Array configuration: alma.cycle4.5.cfg
Integration time: 12.5 minutes on the source
Wavelength and Bandwidth: 1.3mm, 6.8GHz
CLEAN: the Briggs waiting, robustness = 0.5
→ Beam size : 0.29 arcsec x 0.26 arcsec (∼ 40 AU x 36 AU)



Left: synthetic observation (Tomida et al. 2017)
Right: actual ALMA observation (Pérez et al. 2016)
They are in good agreement (I mean, "astrophysically")
→ the gravitational instability model works well!

Conclusions and Discussions

- Young circumstellar disks become massive, and spiral arms form recurrently by the gravitational instability
- Our model successfully reproduces most of Elias 2-27

→ Gravitational instability scenario can explain spiral arms

- Slow molecular outflows (1~2 km/s, Gurney+ 2008) and the age (observation: ~10^5 yrs vs model: ~5 x 10^4 yrs) are also consistent with the observation
- If such spiral arms are common in young circumstellar disks, it means that young circumstellar disks are massive.

→ This is consistent with the observed high binary rate.
→ Also important as the environment of planet formation