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Department of Astronomy, Tsinghua University

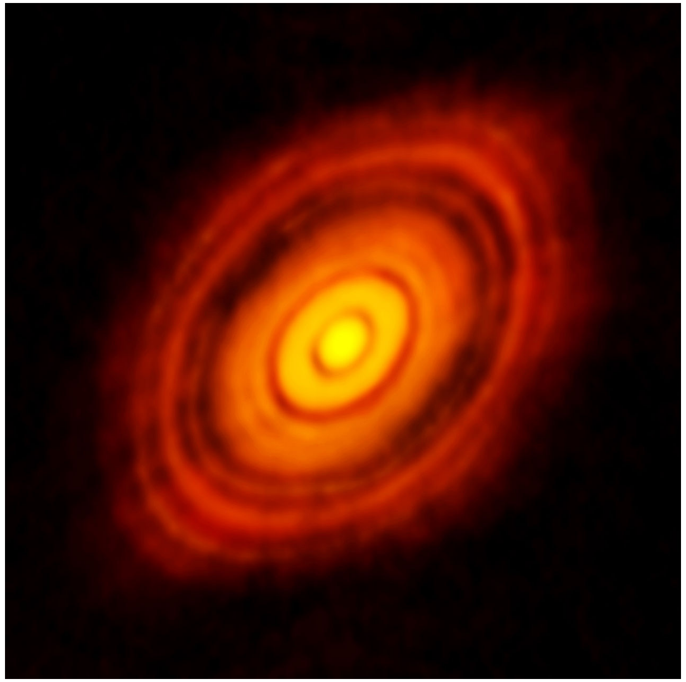
Origin of spirals in protoplanetary disks

Changxing Zhou, Jiahui Huang, Tao Jing

2022/06/10

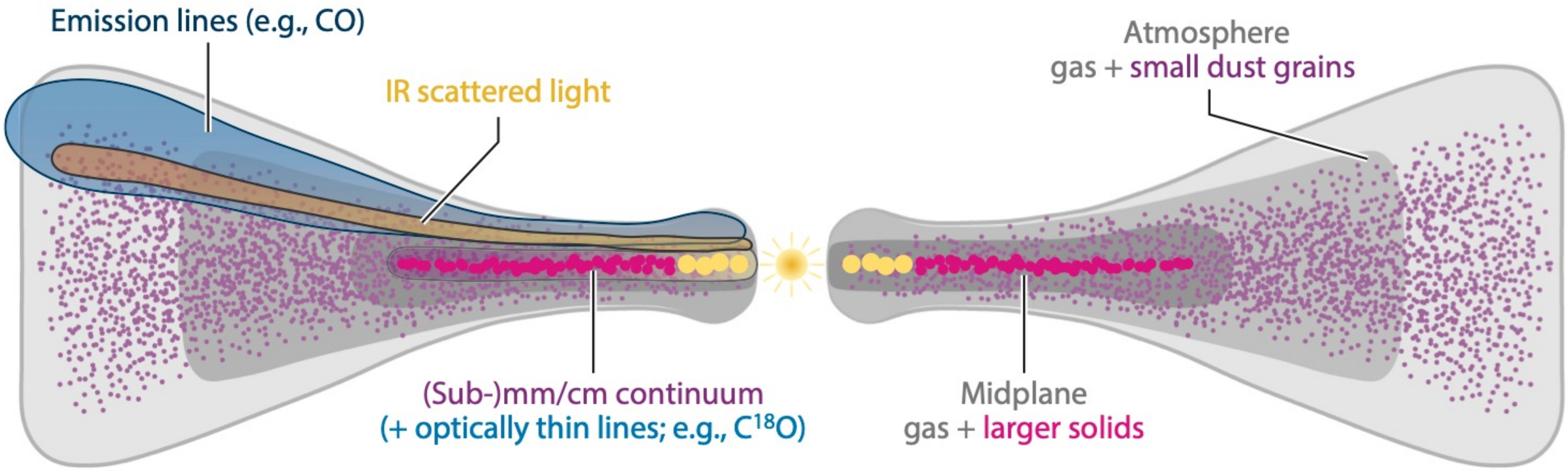
Protoplanetary disk

- Protoplanetary disk:
  - disk of dense gas and dust surrounding a young newly formed star



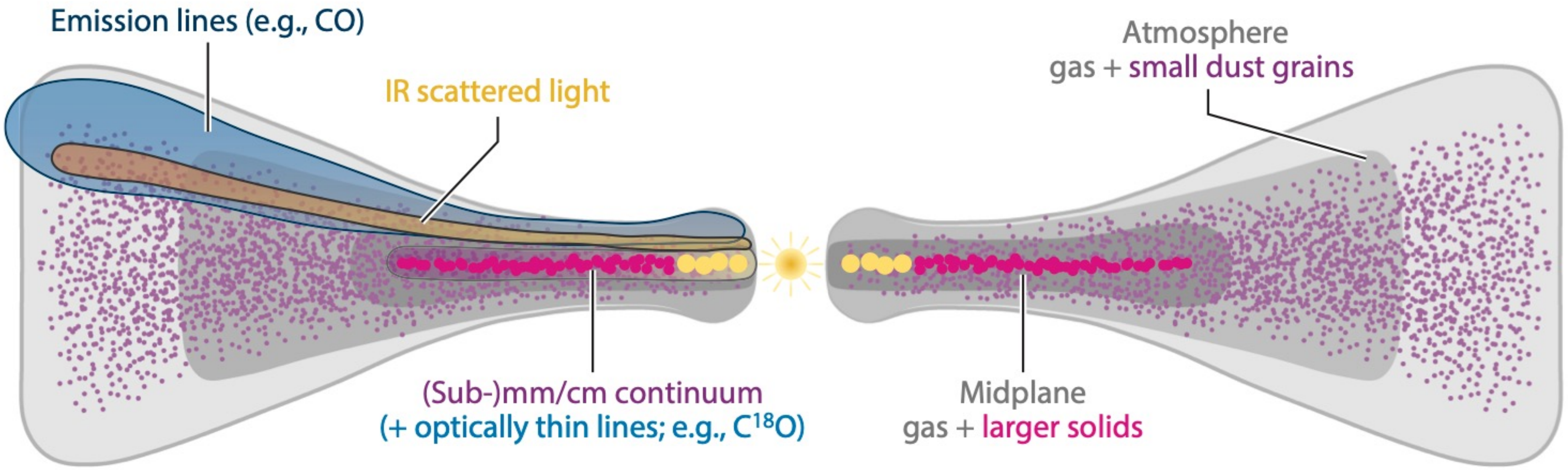
A protoplanetary disc has formed around the young star HL Tau (Webb 2014)

Disk structure



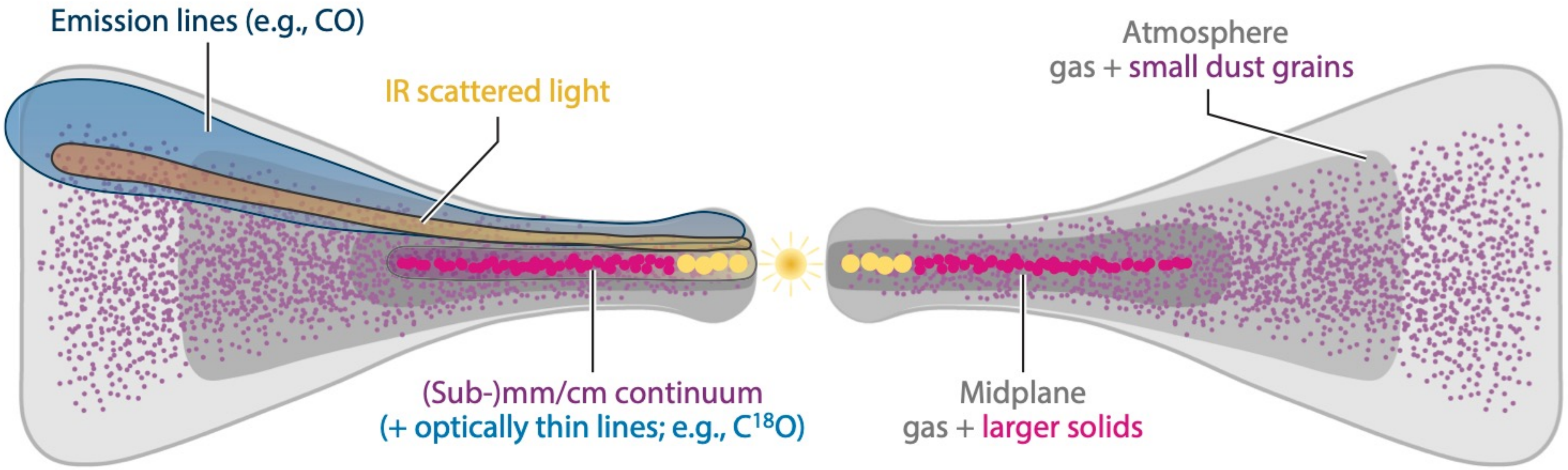
A diagram of a disk structure viewed in cross-section. The gas is denoted in grayscale, and solids are marked with exaggerated sizes and colors. (Andrews 2020)

Infrared (IR) scattered light



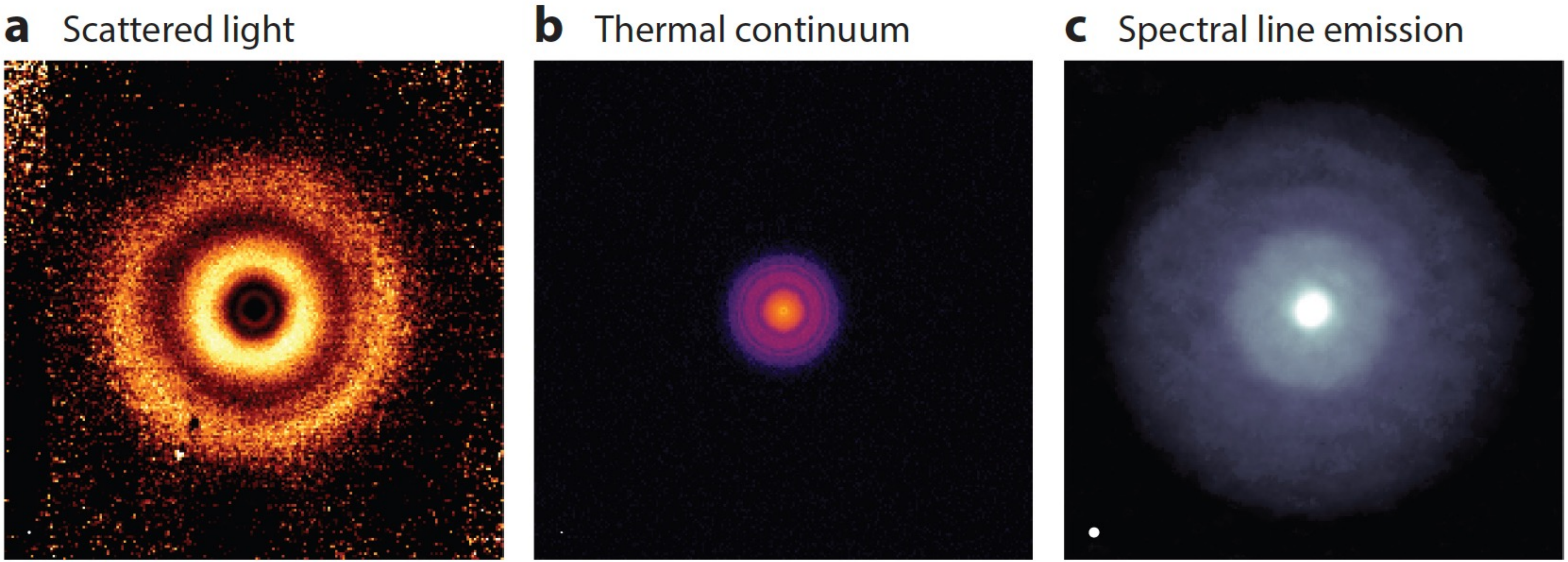
- The host star (protostar): By shrinking, convert the gravitational potential energy into radiation emission (optical and infrared)
- Small (~micrometer-sized) dust grains: well coupled to gas, scattering the radiation emitted by the host star.

(sub-)mm/cm continum



- Large solids: thermal continuum (λ ≈ 1 μm – 1 cm). Tracing surface density variations in the midplane

Disk compared in different tracers

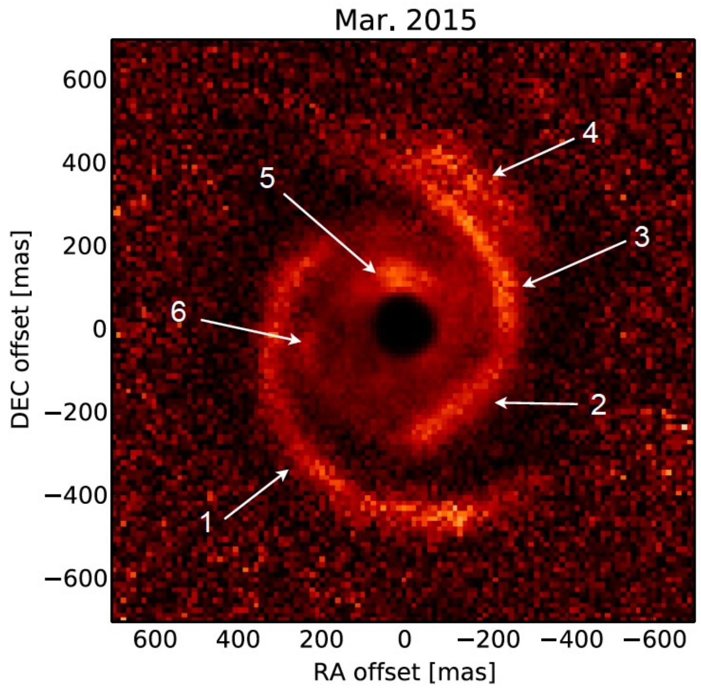


The morphology of the TW Hya disk is compared in three different tracers: (a) λ = 1.6-μm scattered light from small dust grains (van Boekel et al. 2017), (b) λ = 0.9-mm continuum from pebble-sized particles (Andrews et al. 2016), and (c) the CO J = 3–2 spectral line emission tracing the molecular gas (Huang et al. 2018a). (Andrews 2020)

Protoplanetary disk

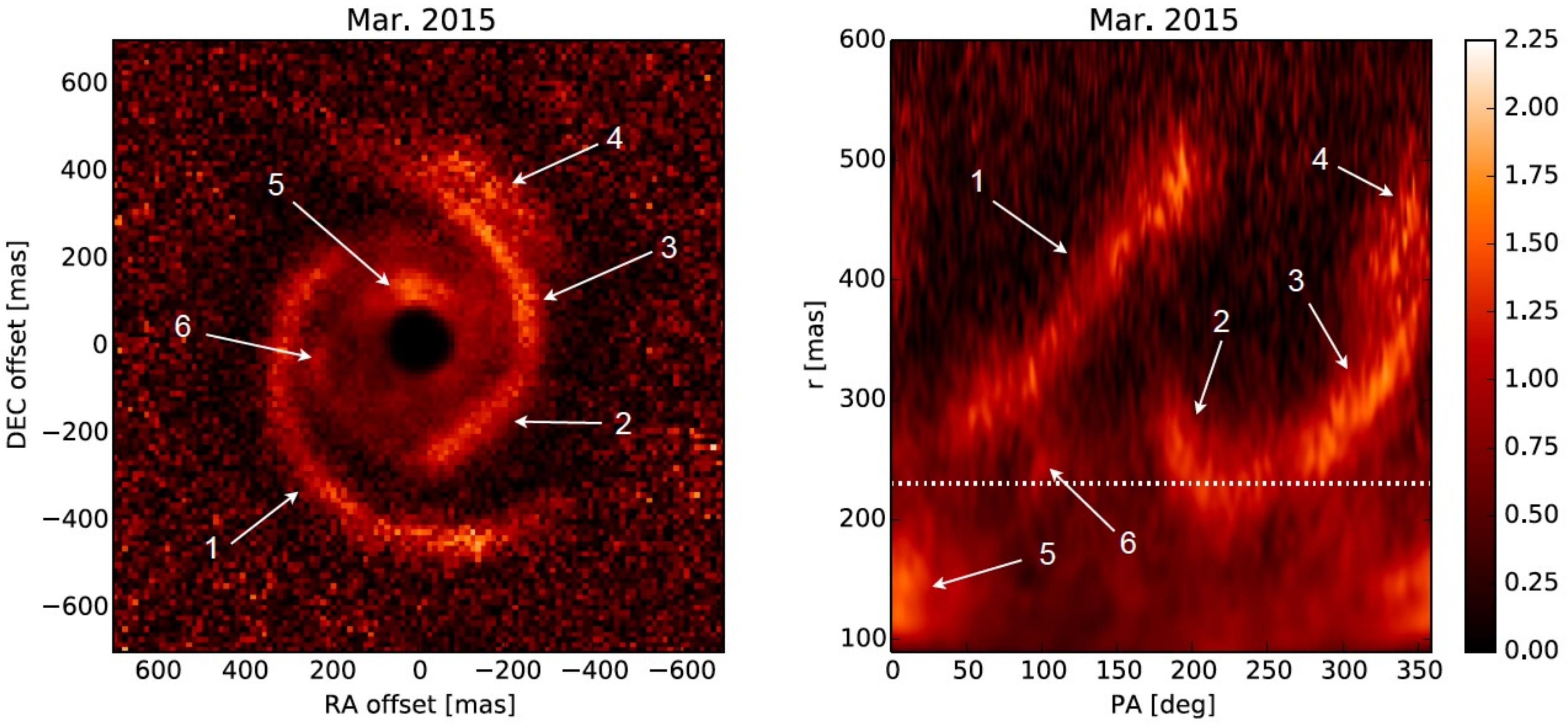
- Differential polarimetric imaging (DPI)

- spiral substructures are observed in a few protoplanetary disks



MWC 758 Polarized intensity image Q_ϕ (Benisty et al. 2015)

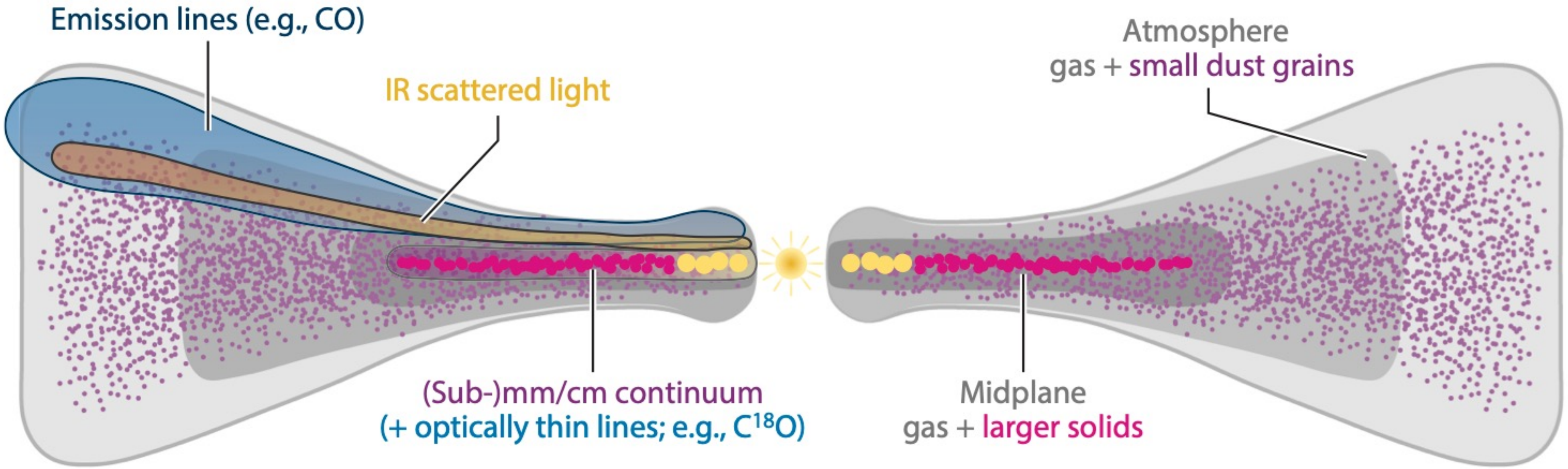
Differential polarimetric imaging



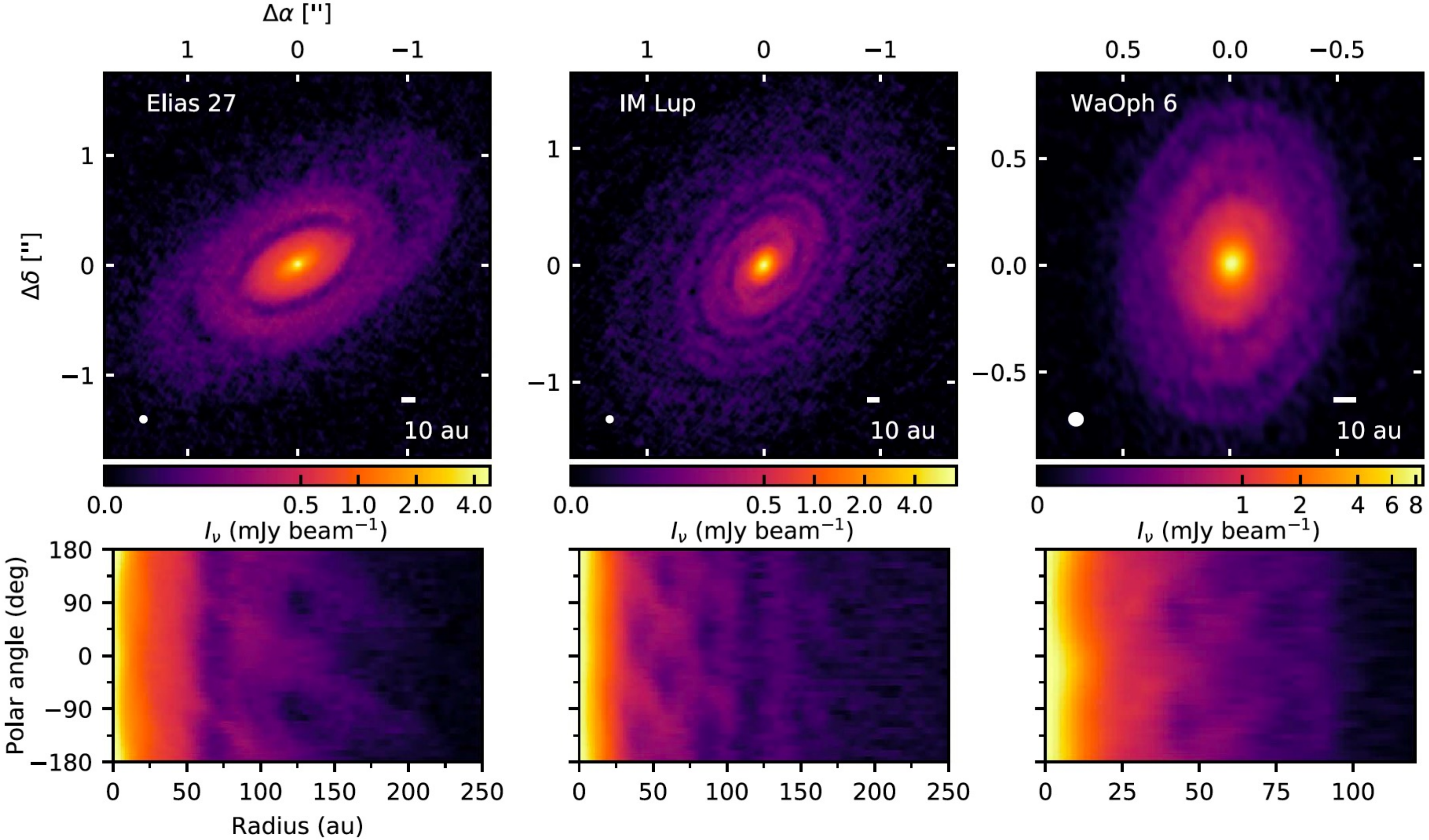
Left: MWC 758 polarized intensity images (Q_ϕ), East is toward the left. **Right:** radial map of the deprojected Q_ϕ image using $i = 21°$ and $\mathrm{PA} = 65°$. The dashed line indicates a radius of $0.23''$ (Benisty et al. 2015).

Millimeter continuum emission observations

- Millimeter continuum emission:
  - Tracing surface density variations in the midplane

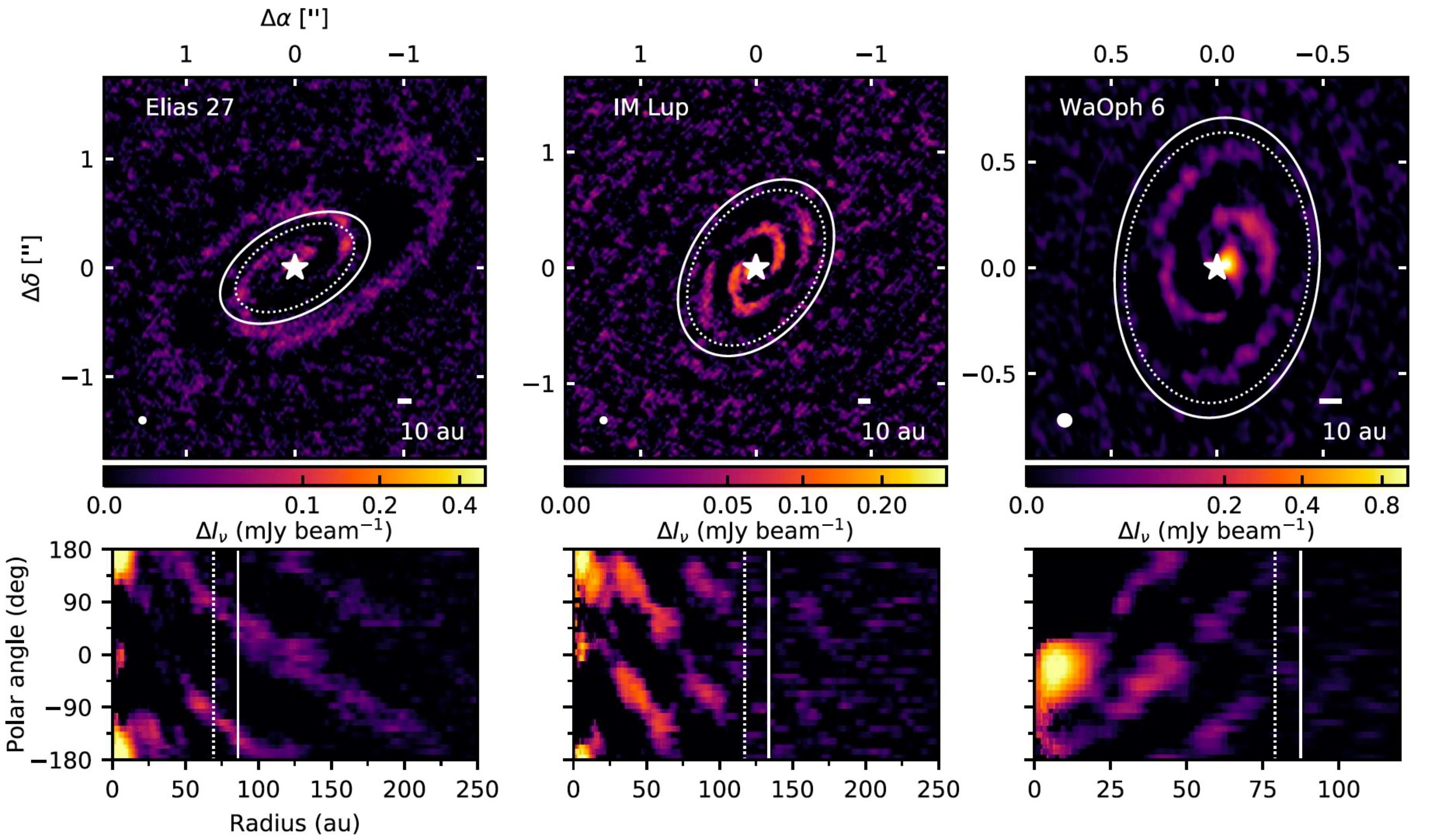


Millimeter continuum emission images



Top: ALMA 1.25 mm continuum images of the Elias 27, IM Lup, and WaOph 6 disks.
Bottom: the continuum emission deprojected and replotted as a function of disk radius and polar angle (Huang et al. 2018).

Millimeter continuum emission images

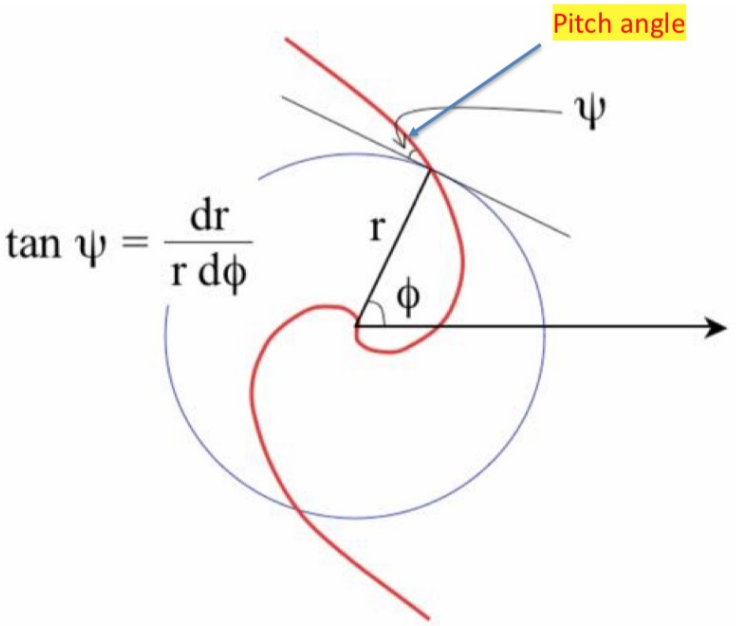


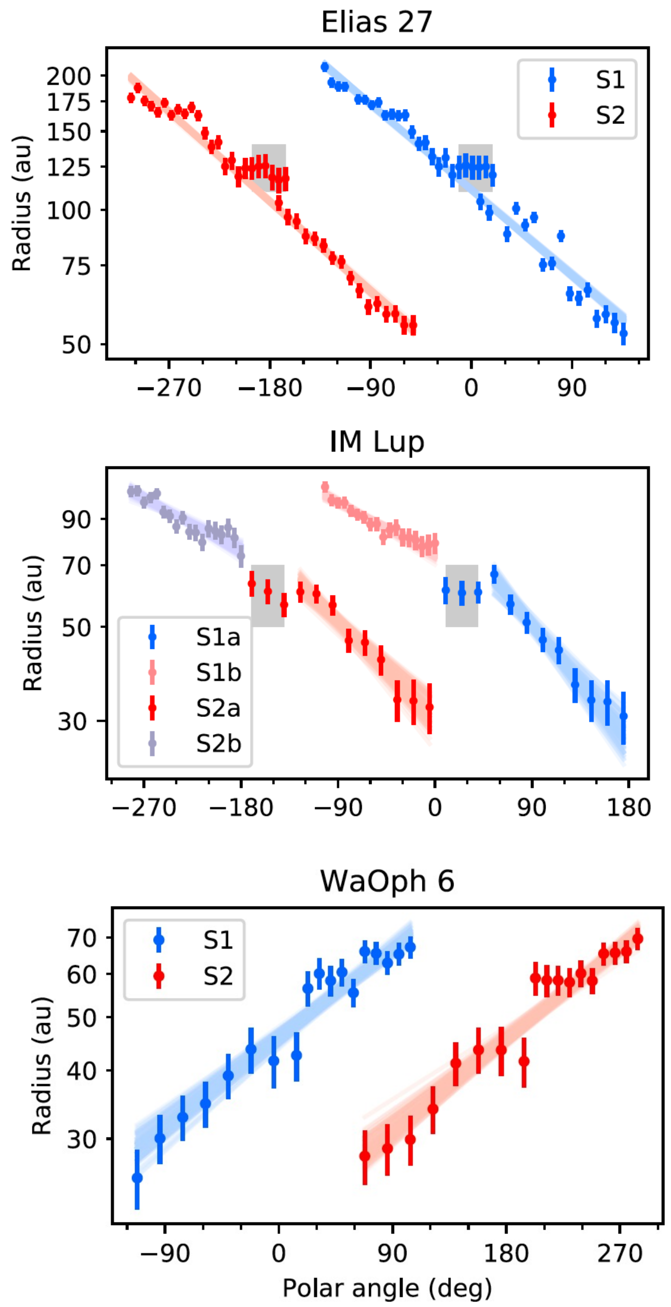
Top: residual emission after subtracting the median radial intensity profile. White stars mark the continuum emission peaks. Dotted ellipses correspond gaps, Solid ellipses correspond to bright rings.

Bottom: residual emission replotted as a function of disk radius and polar angle (Huang et al. 2018).

Logarithmic Spiral Fits

- $r(\phi) = r_0 e^{b\phi}$, pitch angle $\psi = \arctan|b|$
- For all disks, the arms appear to be symmetric
- IM Lup: a clear decrease in pitch angle





Comparison of logarithmic spiral fits to the data (Huang et al. 2018)

Possible Origins of Spiral Structure

- Spiral arms induced by a perturber
    - Stellar and planetary companions are expected to trigger spiral density waves in protoplanetary disks.

    - The massive objects could be directly imaged in the near-infrared.

Possible Origins of Spiral Structure

- Gravitational Instability (GI)
  - Large and cold disk: conditions for triggering GI

  - **GI**: symmetric, logarithmic spiral arms,

  - **companions**: spiral arms with variable pitch angles

Summary

- The spiral structures in protoplanetary disks have been mapped scattered-light observations and millimeter continuum emission

- The two ways above trace different regions of the disks, and their maps may be quite different

- There are some explanations for the origin of spirals, mainly spiral density waves and gravitational instability

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Two Possible Ways of the Formation of Spiral Structures

Name: Jiahui Huang

2022.06.10

Observational Signatures

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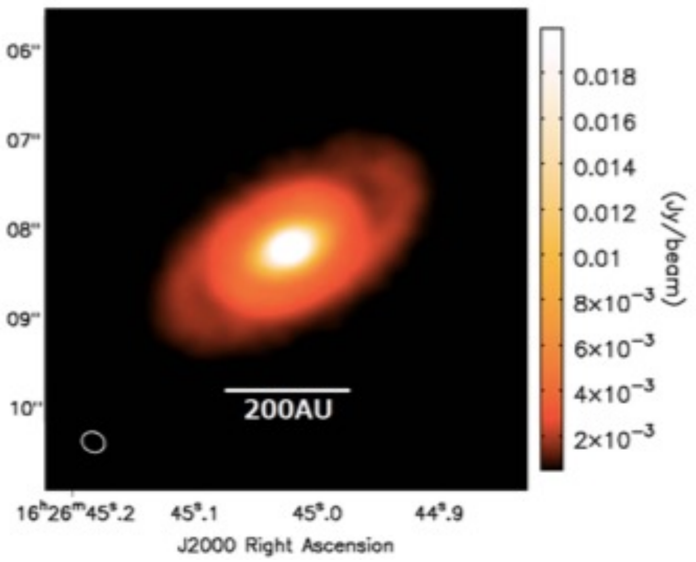
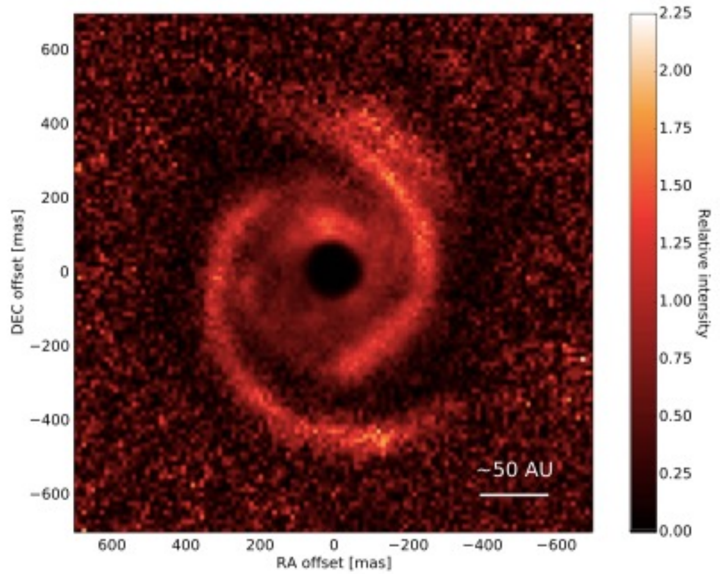
- Circumstellar disk provides initial and boundary conditions for planet formation
- High angular resolution near-IR imaging shows spiral-arm-like features in PP-disks



Elias 2-27

Tomida et al. 2017



MWC 758

Dong et al. 2015

Two Ways of Formation

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- Material spiral arms of gravitational instability
  - Condition: Unstable disks where Toomre's Q parameter is low $Q = \frac{c_S \kappa}{\pi G \Sigma}$
  - Problem: The material arms wind up and disappear
- Density waves excited by unseen planets
  - Problem: The density wave is too small to be visible; need 2 companian
- Hydro simulations can help us to understand the way of their formation

Resistive MHD Simulation

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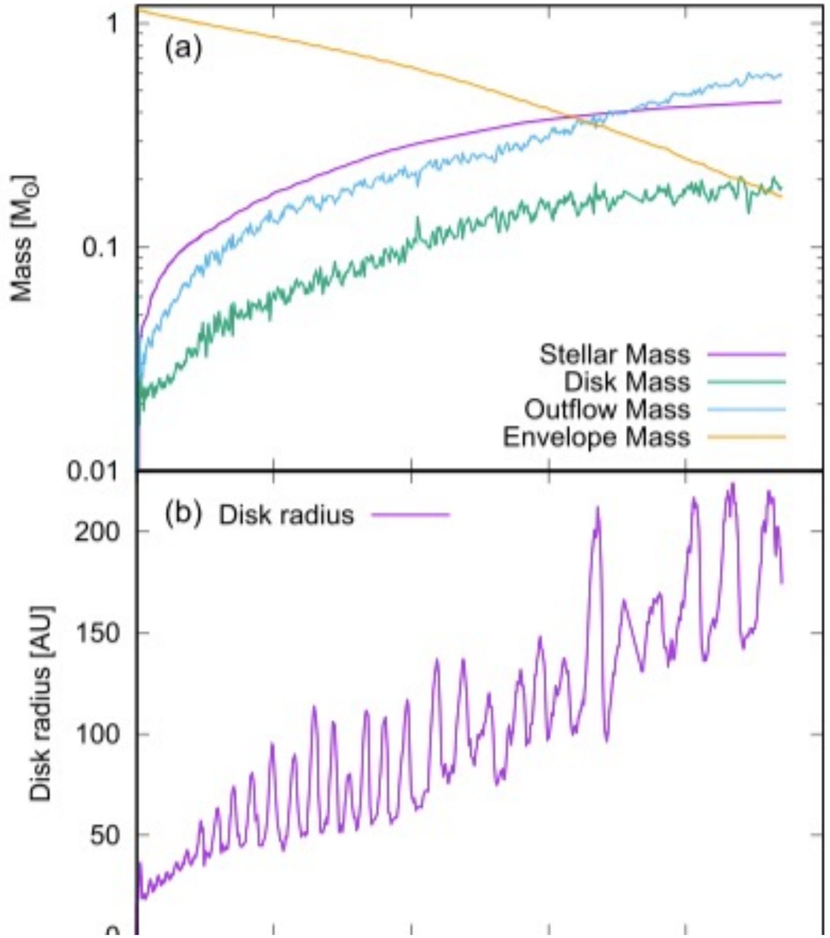

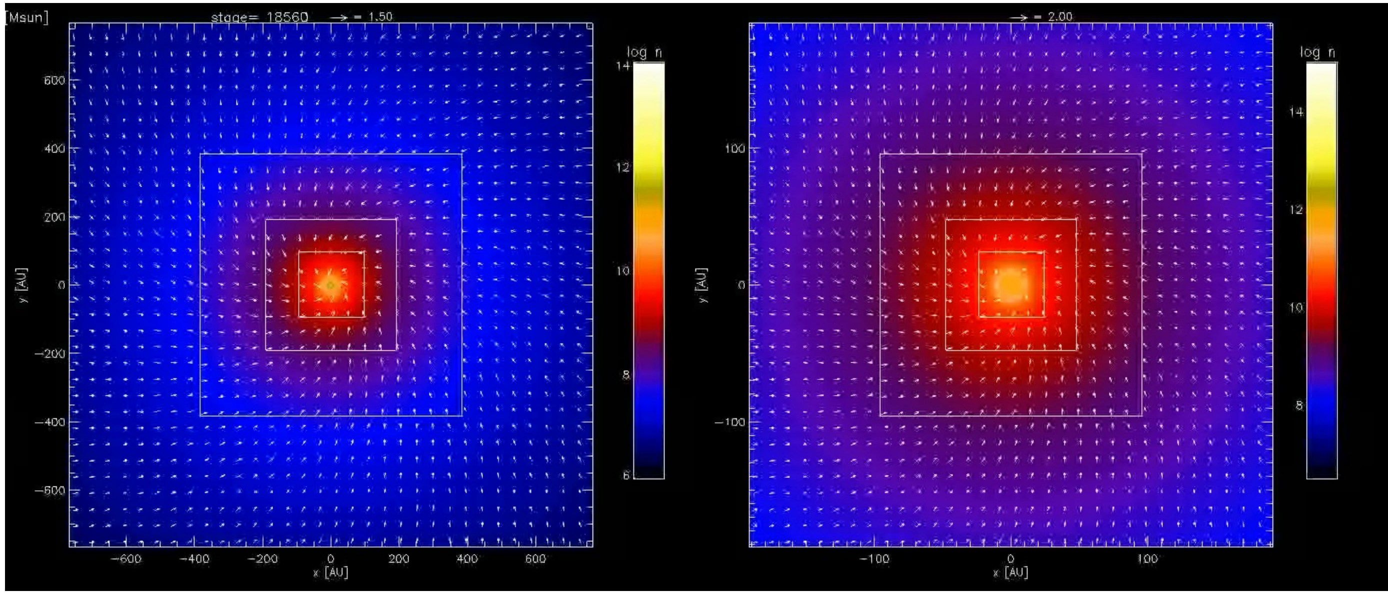

Tomida et al. 2017

- The disk mass and radius increases
- The spiral arms form repeatedly as radius oscillates

Spiral Arm of Gravitational Instabi

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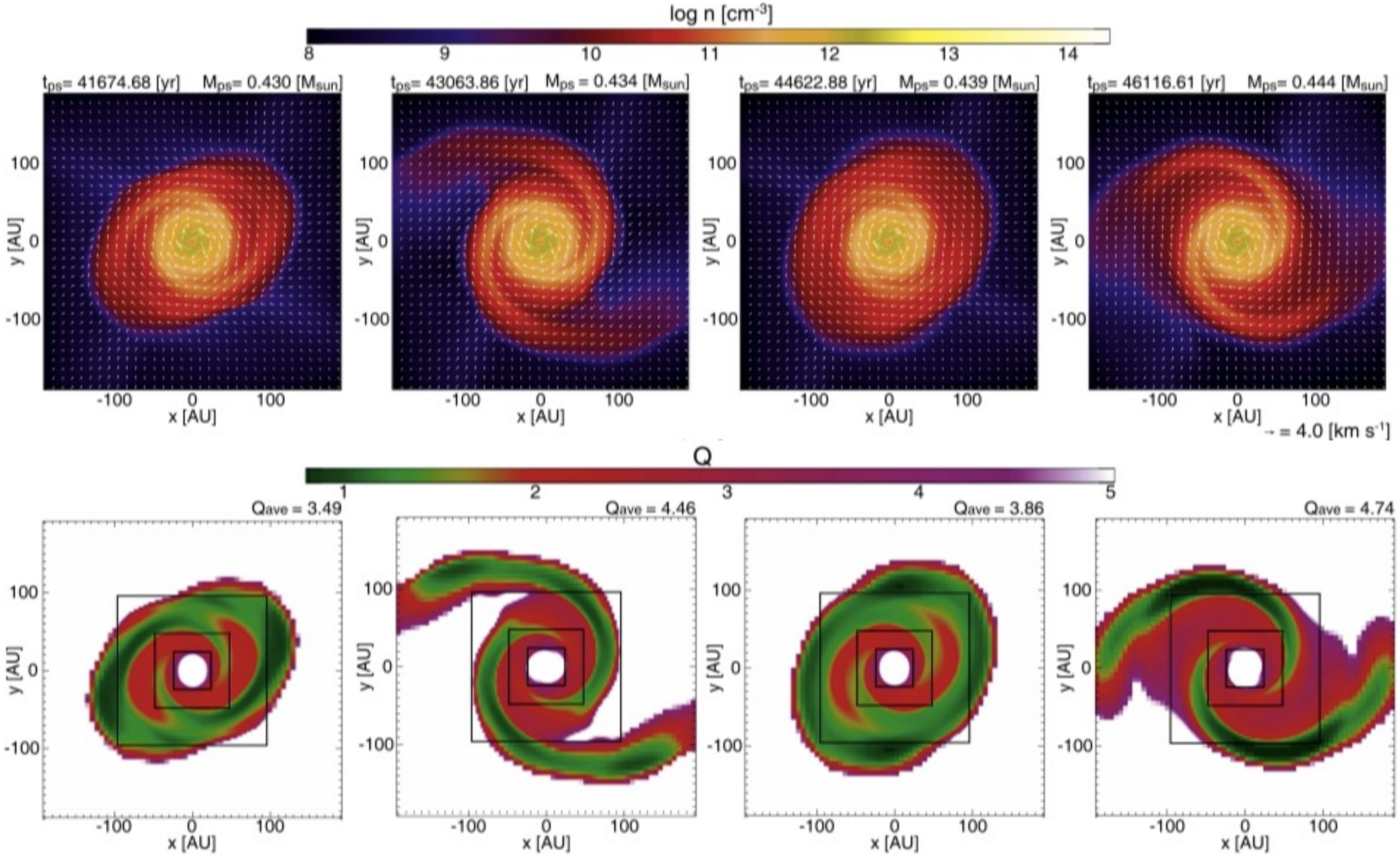

- Q value is less than 1 in the spiral arms
- The spiral arms are formed by gravitational instability

Tomida et al. 2017

Spiral Arm of Gravitational Instabi

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Q value decreases

↓

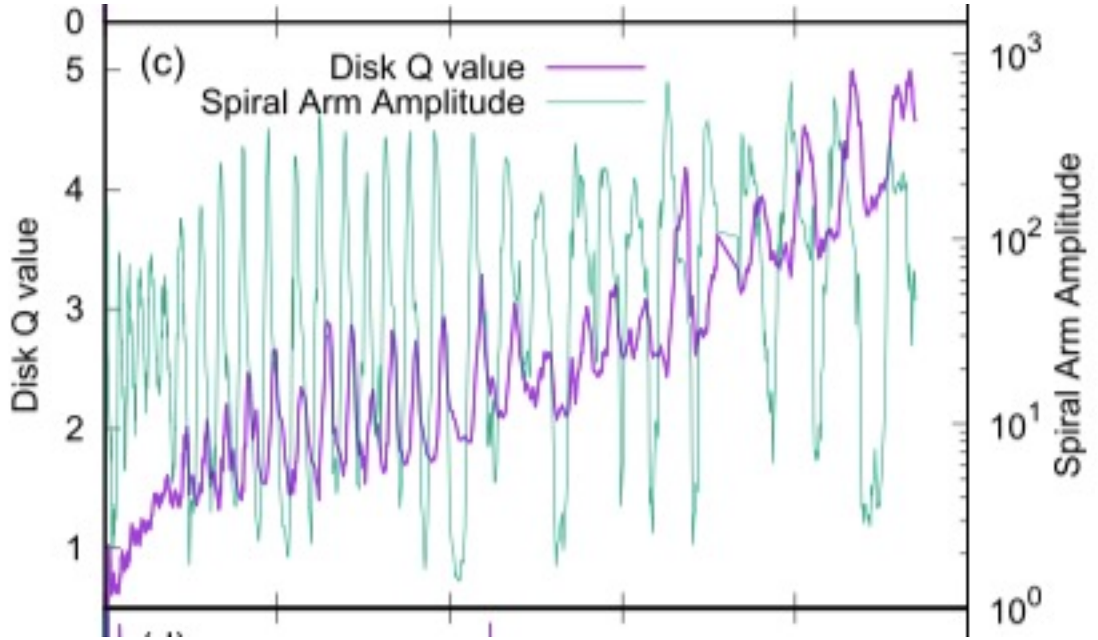
unstable disk forms spiral arms

↓

transfer angular momentum

↓

disk stabilizes, Q value increases



Tomida et al. 2017

➢ The oscillation explains the wind-up problem

Comparison with Observation

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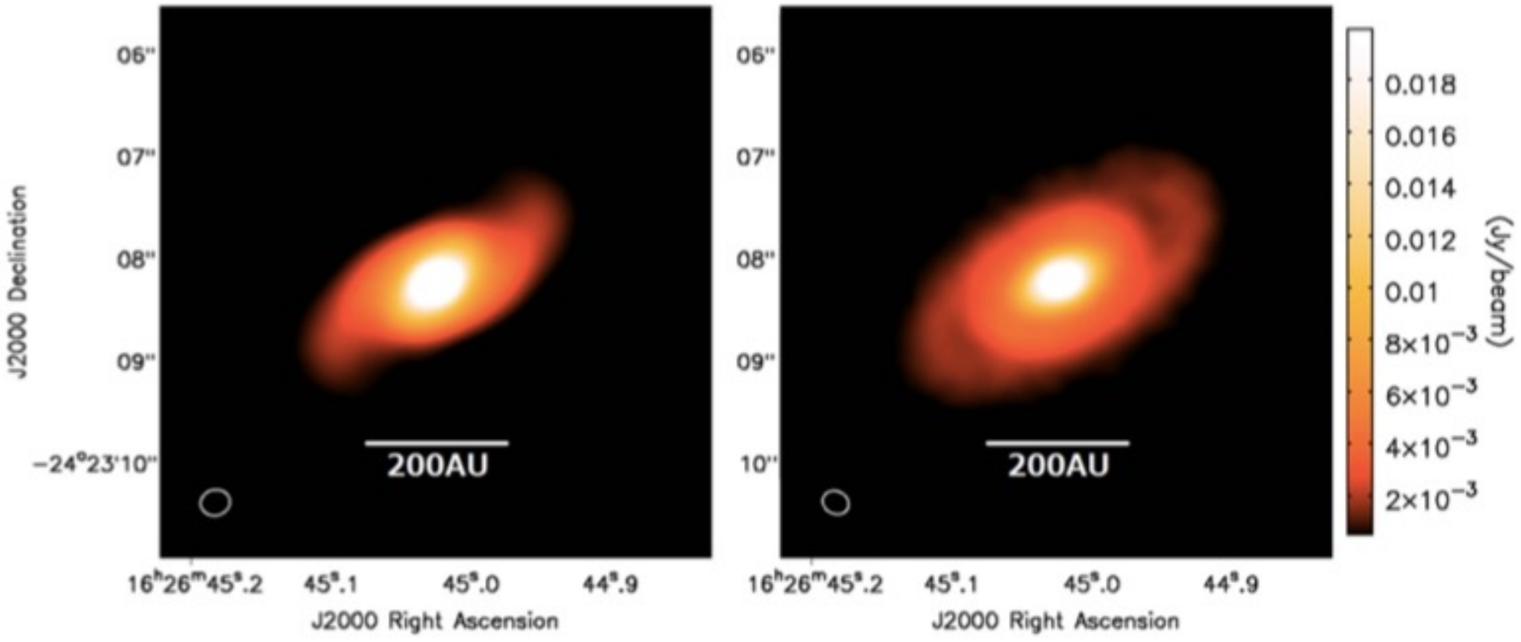
simulation



Elias 2-27

Tomida et al. 2017

- The disk size, brightness and thickness of spiral arms are consistent
- Gap like structures may be explained by the low-density region between spiral arms

Two Ways of Formation

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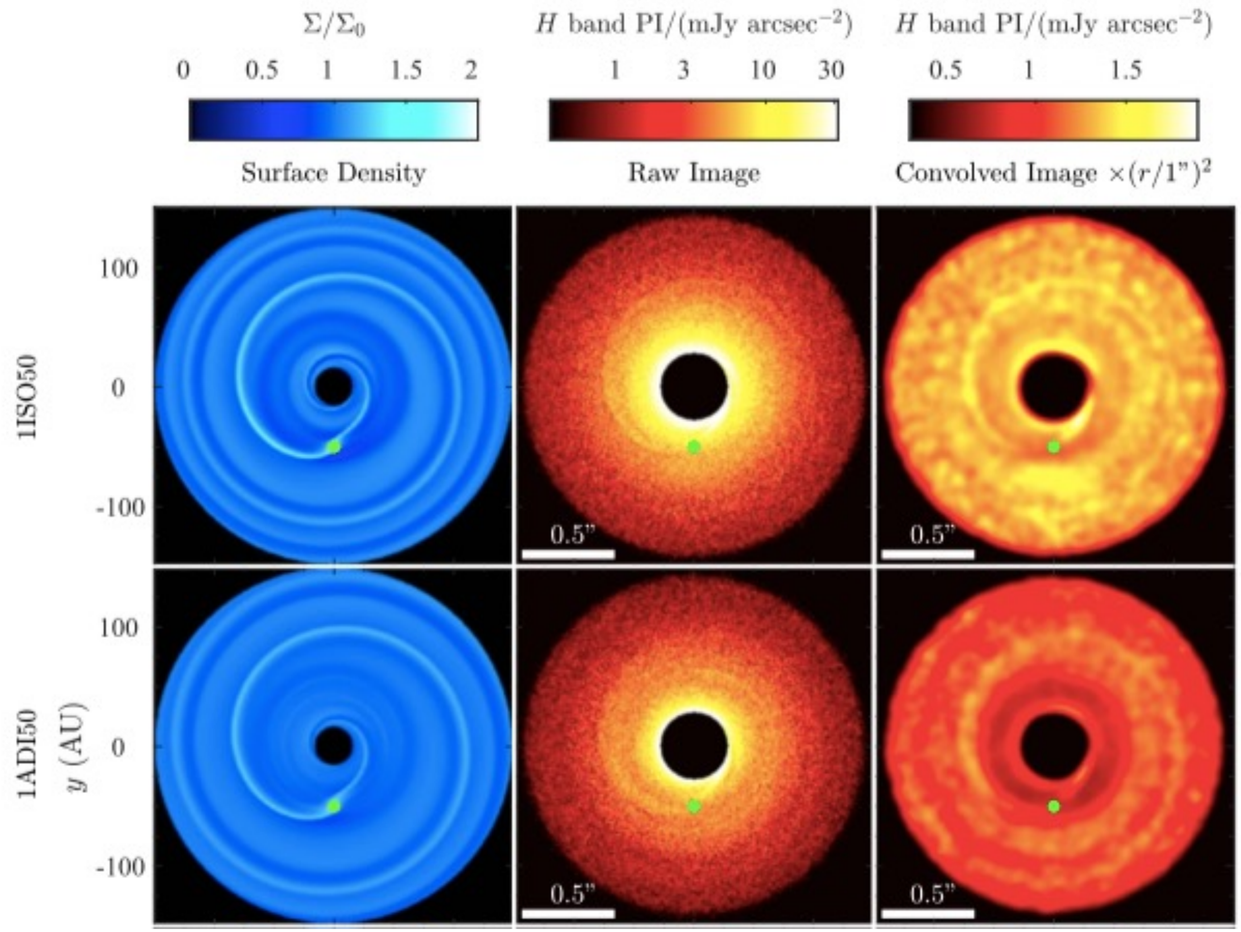
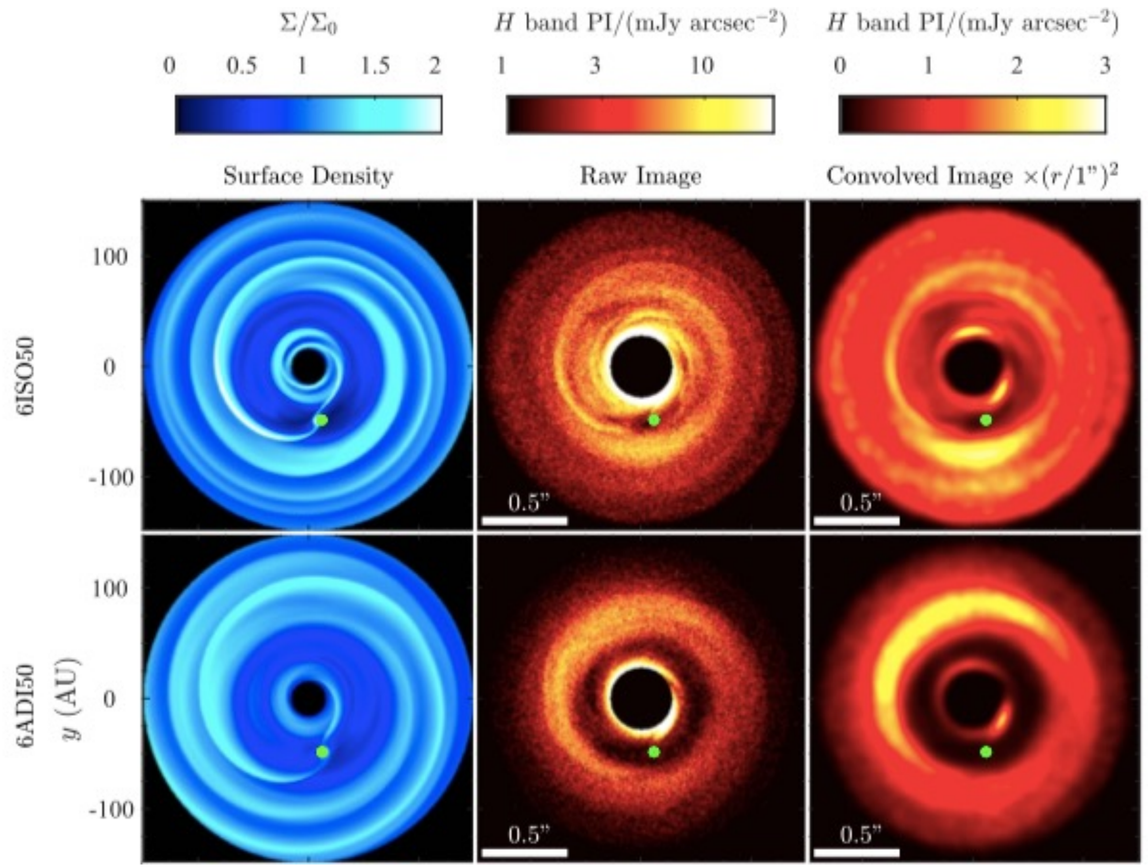
Outer Arms



- The outer spiral arm of $1M_J$ is not traceable in the simulated H band image

Dong et al. 2015

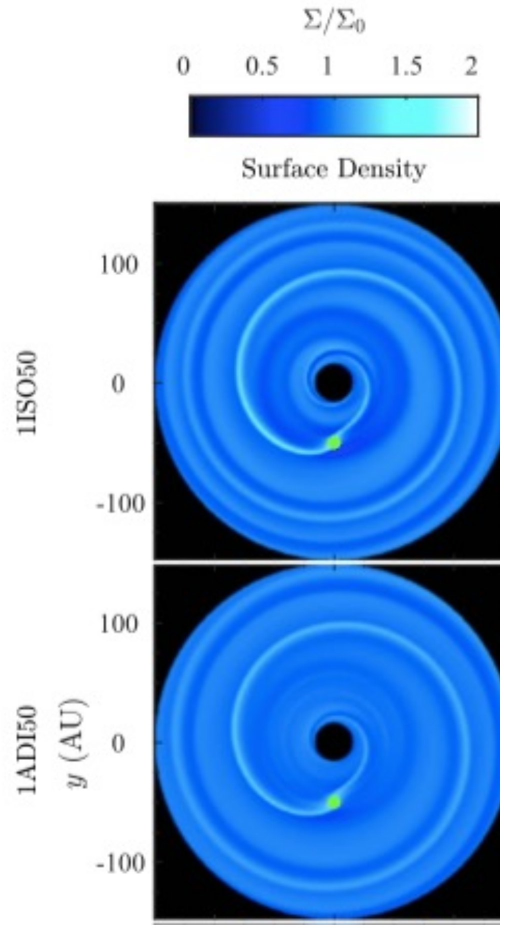
Outer Arms

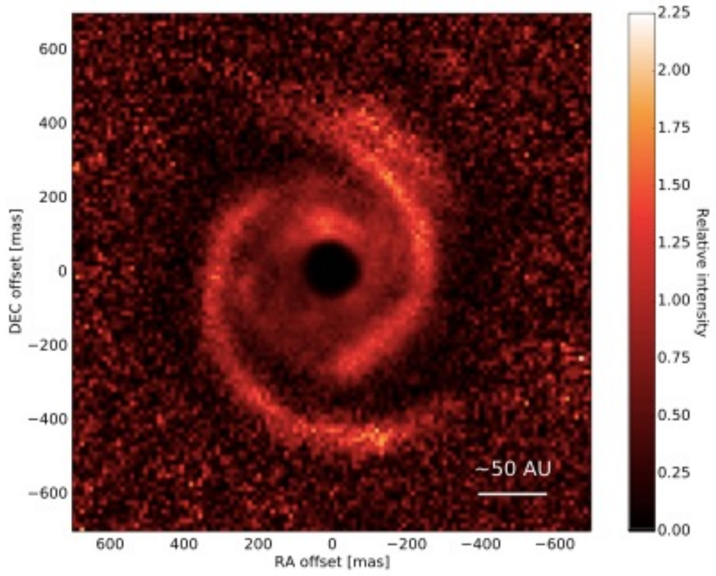


- The outer arm of $6M_J$ can be 2 times of the background
- Pitch angle < 6°, not distinguishable from ring

Dong et al. 2015

Outer Arms





MWC 758

- ➢2 planets needed

Dong et al. 2015

Density Structure

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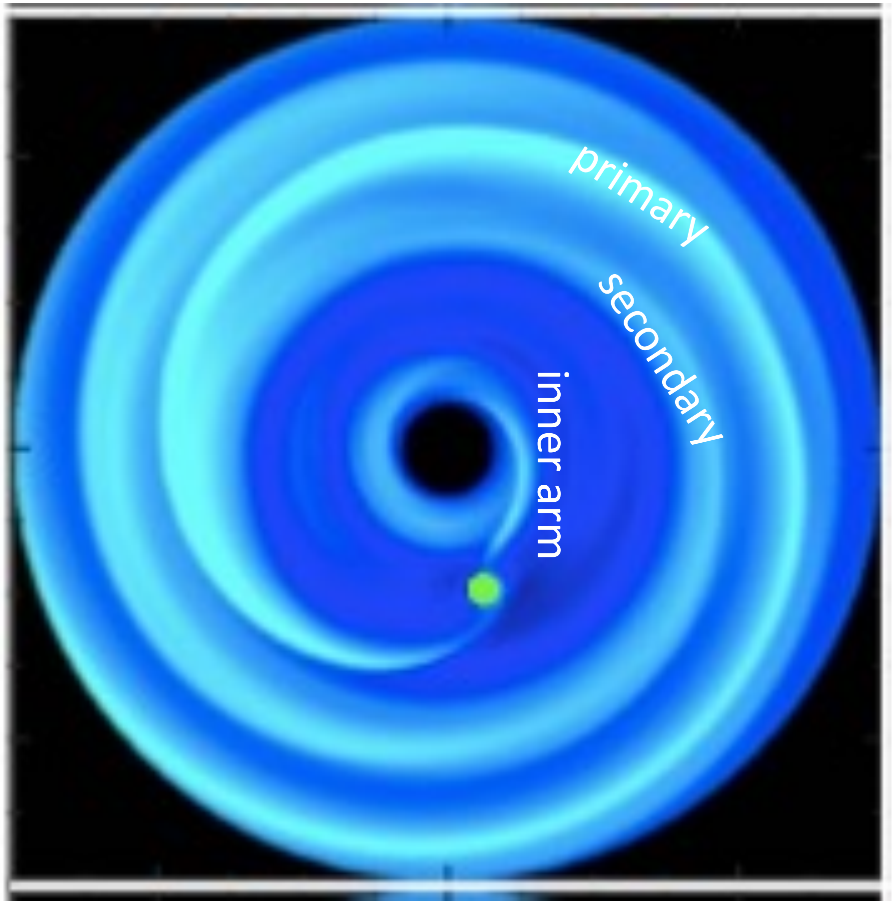

Dong et al. 2015

- Two arms shifted by 180°, inner arm

Inner Arms

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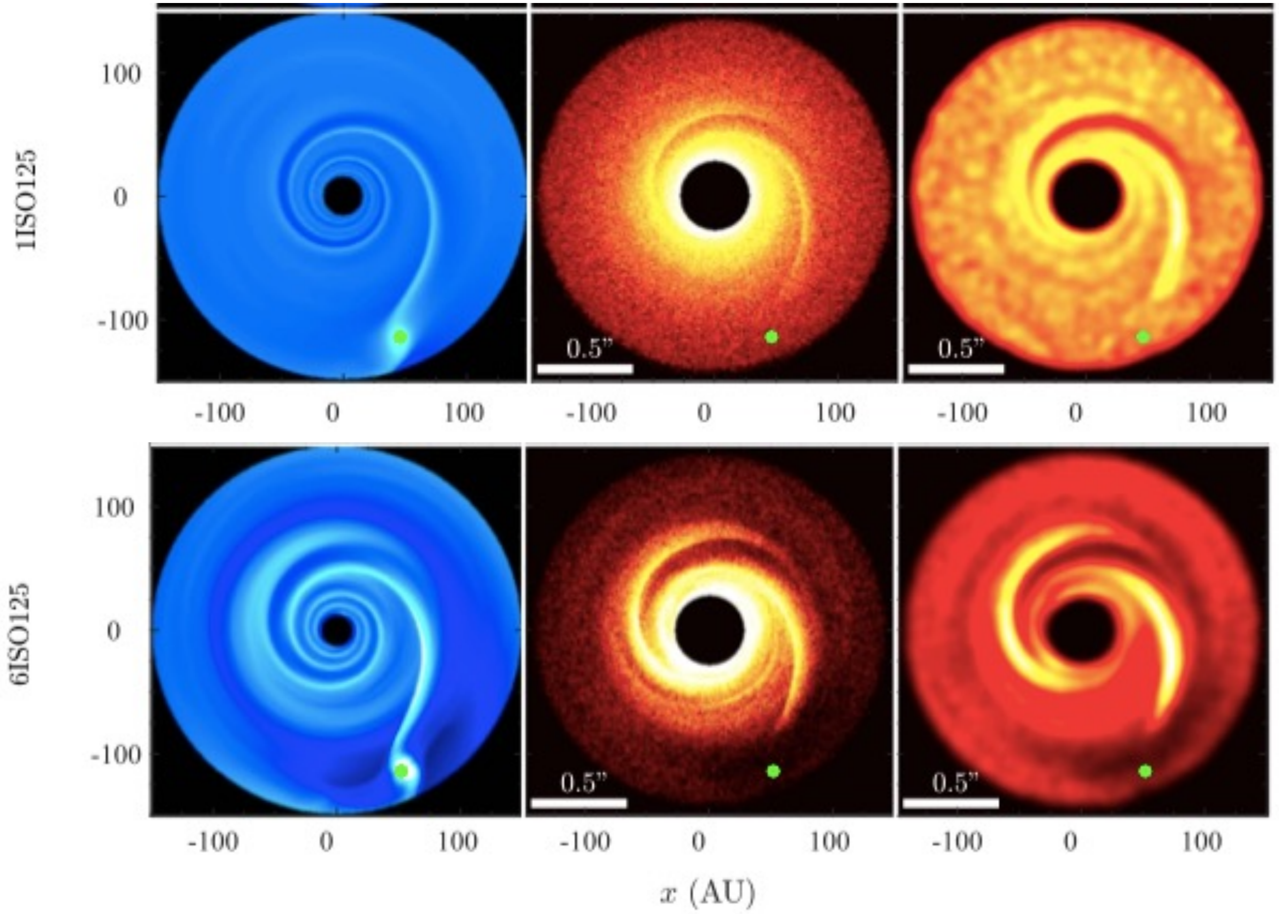
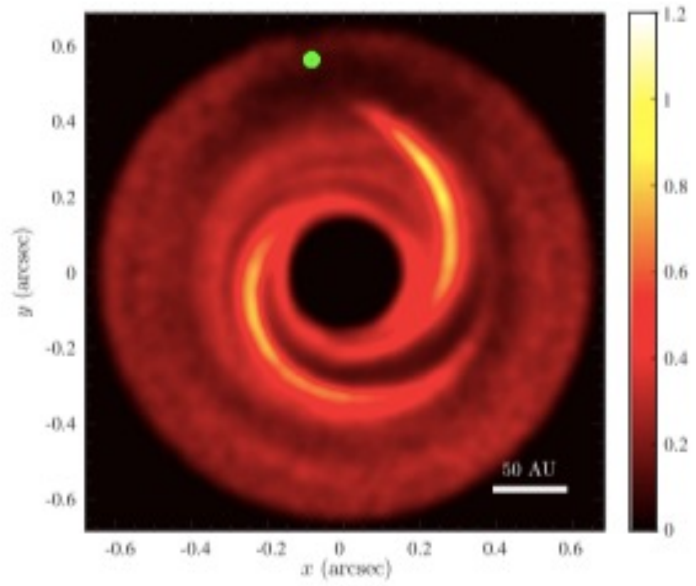


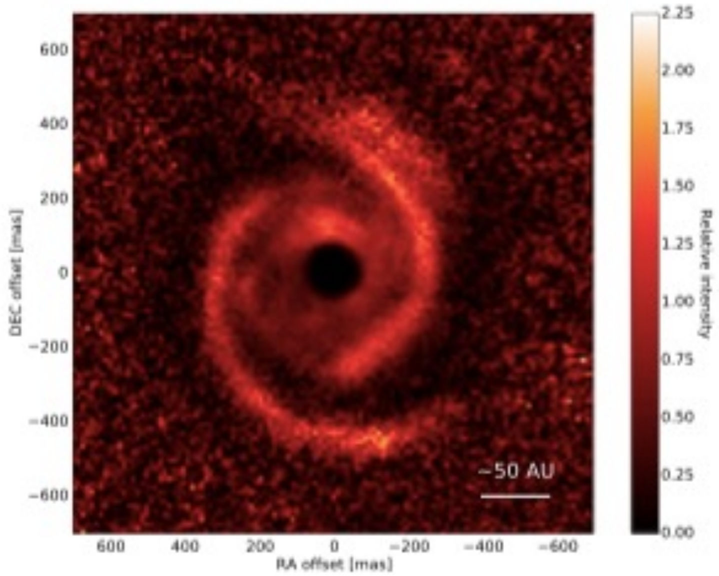
- 30%-40% brighter for $1M_J$, 150%-160% brighter for $6M_J$
- The secondary arm is equally bright to primary

Dong et al. 2015

Inner Arms vs. Observation

observation





MWC 758

Dong et al. 2015

- Both have rough m=2 symmetry
- Both have pitch angle 10-15°

Summary (take-home message)

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- The gravitational instability can form material spiral arms in PP-disk
- The material spiral arms will wind up and disappear after several thermal timescales, but will show up repeatedly
- Inner density wave of far away giant planet will form visible spiral arms in PP-disk
- Outer density wave of small planet will not be visible, and the outer density wave of giant planet may explain the ring structure

References

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[1] Tomida, K., Machida, M.N., Hosokawa, T., Sakurai, Y., Lin, C.H. Grand-design Spiral Arms in a Young Forming Circumstellar Disk. The Astrophysical Journal 835. doi:10.3847/2041-8213/835/1/L11

[2] Dong, R., Zhu, Z., Whitney, B. Observational Signatures of Planets in Protoplanetary Disks I. Gaps Opened by Single and Multiple Young Planets in Disks. The Astrophysical Journal 809. doi:10.1088/0004-637X/809/1/93

Origin of spirals in PPD III:

Distinguish two models via pattern speed

Speaker: Tao Jing

Groupmates: Jiahui Huang, Changxing Zhou

Advisor: Prof. Bai

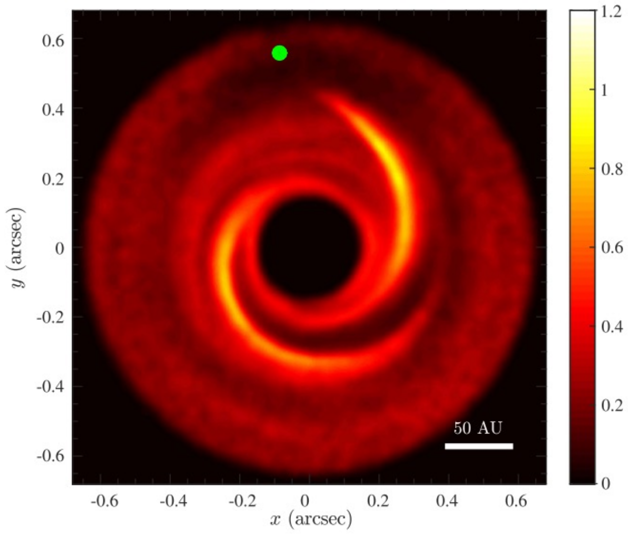
Take home message

- The measurement of pattern speed of spiral in MWC 758 (Ren et al. 2020) and SAO 206462 (Xie et al. 2021) prefer the companions induced spiral model.

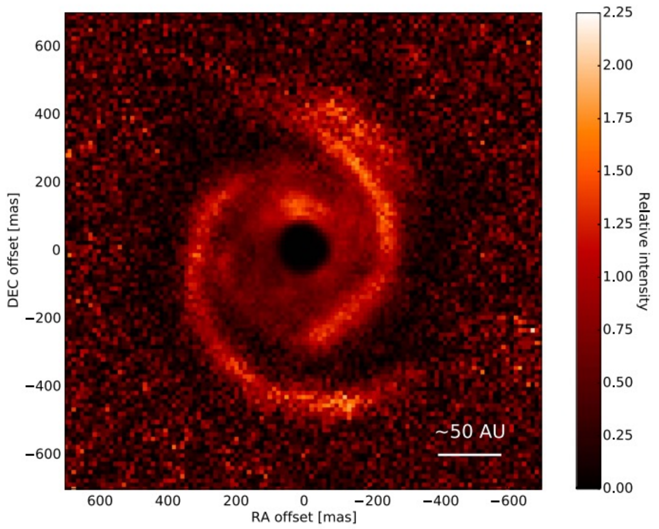
Outline

- How to measure the spiral arm pattern speed, and how to select the models based on this measurement?
- The limitation and the systematics of current results.
- The next to do, larger sample and new method.

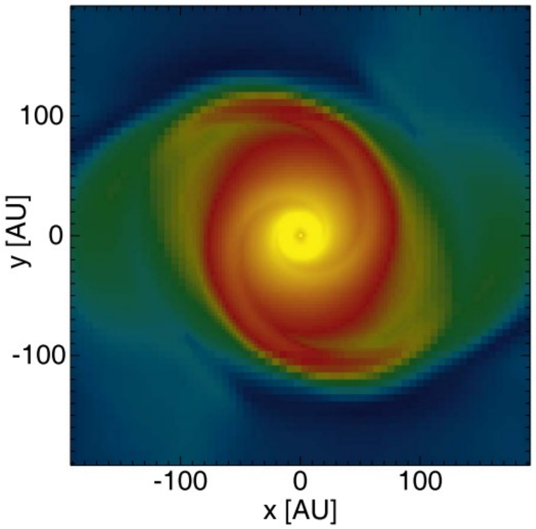
Gravitational instability vs. Companion



Companion



Observation



Gravitational instability

Both of these two models are designed for one-snapshot observational results. It is hard to distinguish them by such observation.

So we need **test these two models by measuring pattern speed of the spiral arm**.

left, Tomida et al. 2017; right, Dong et al. 2015

How to measure the spiral arm pattern speed?

Let’s firstly think about how to measure the rotation speed of the spinning top (陀螺)?

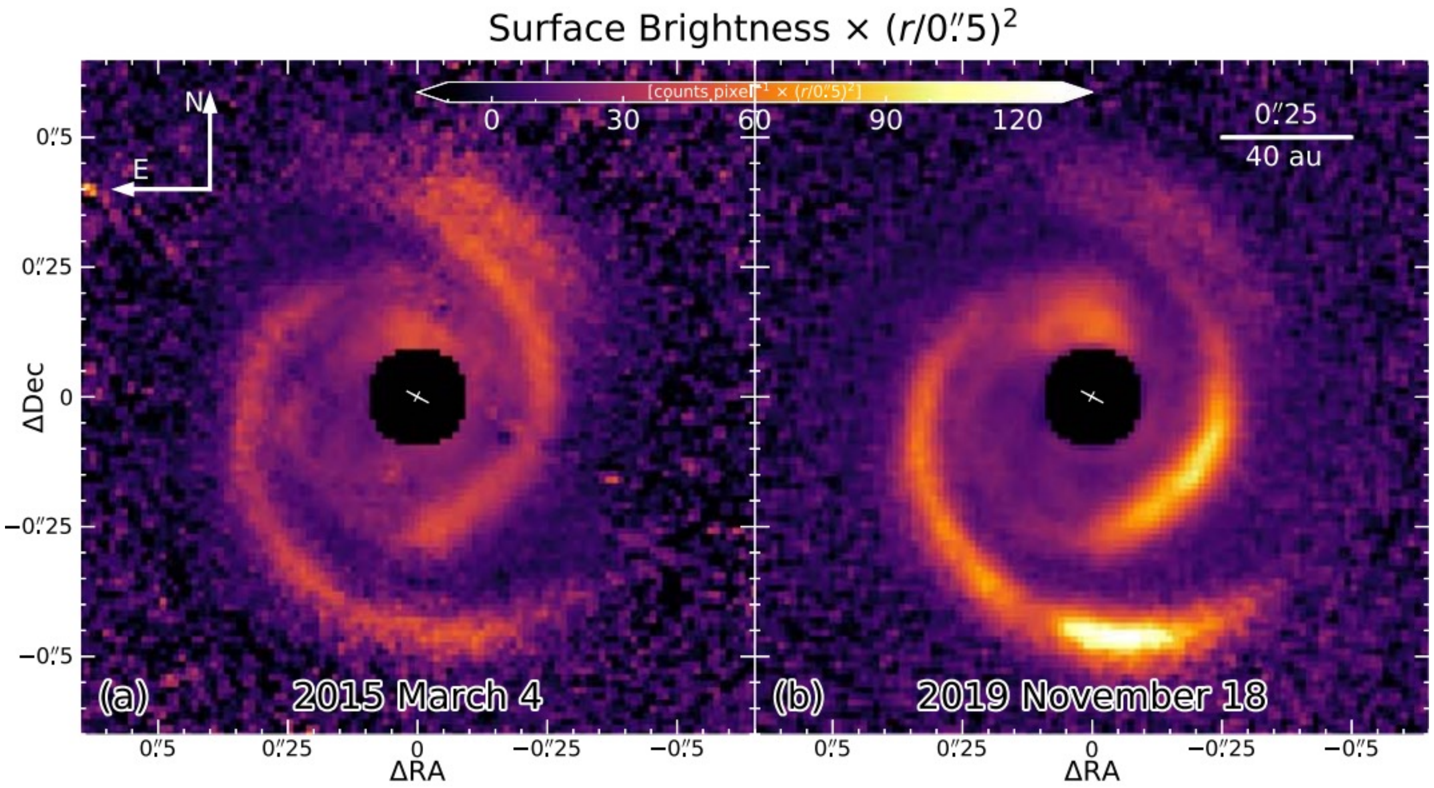
$\pi/2$

t = t0

t = t1

$$\omega = \frac{\frac{\pi}{2}}{t1 - t0}$$

How to measure the spiral arm pattern speed?



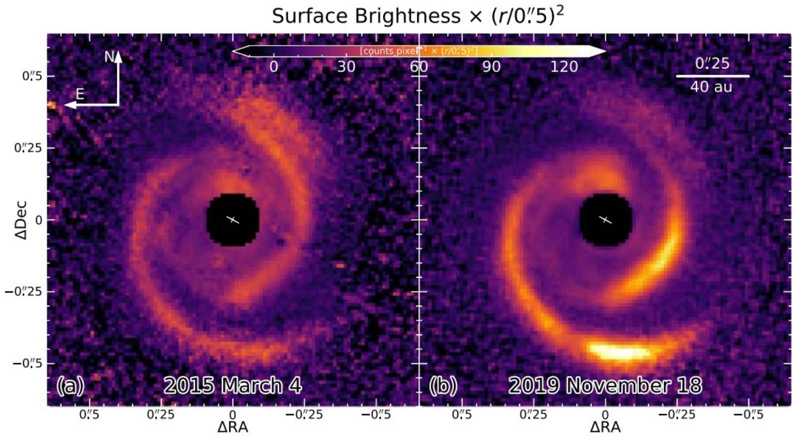
MWC 758

Challenges:

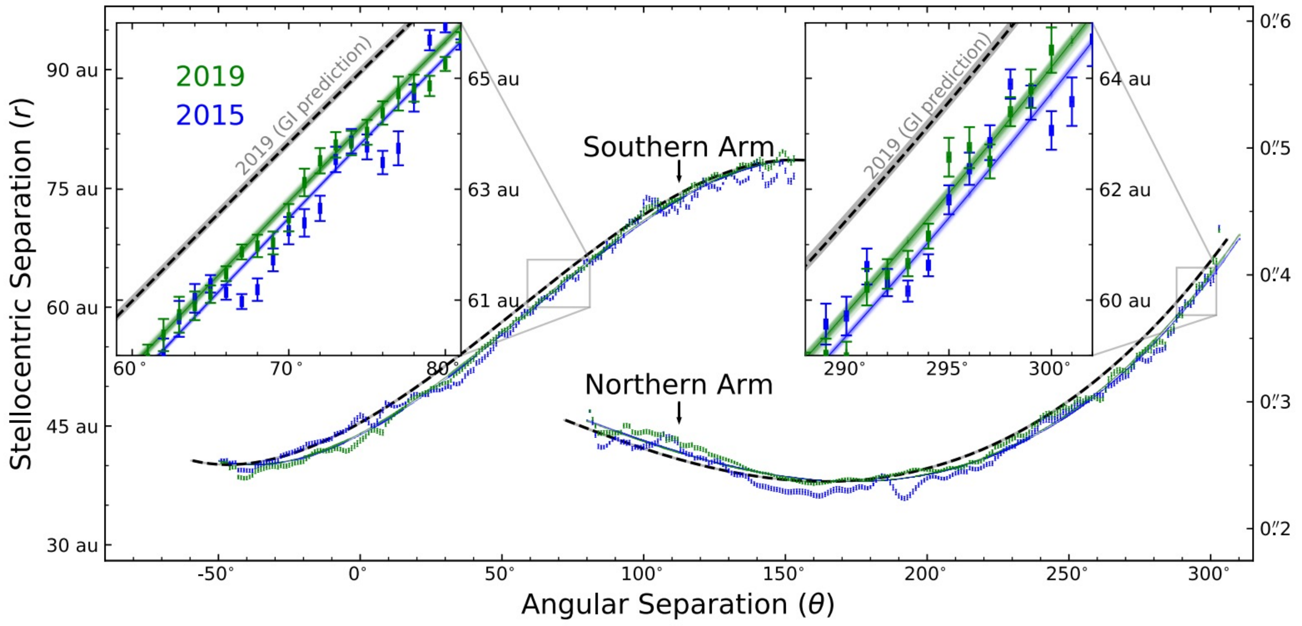
- The central star is too bright
  - Coronagraph + polarization
- The rotation is not significant for eyes
  - Fitting

Ren et al. 2020

How to measure the spiral arm pattern speed?



Deprotect



It is better to deal with the rotation in **polar coordinates**

Ren et al. 2020

How to select the models based on this measurement?

- Gravitational instability case

$$\Delta\theta \propto r^{-\frac{3}{2}}$$

- Companion case

$$\Delta\theta \propto const.$$

- The pattern of spiral arm is fitted by p-degree polynomials

How to select the models based on this measurement?

Related to the mass of central star

- Gravitational instability case

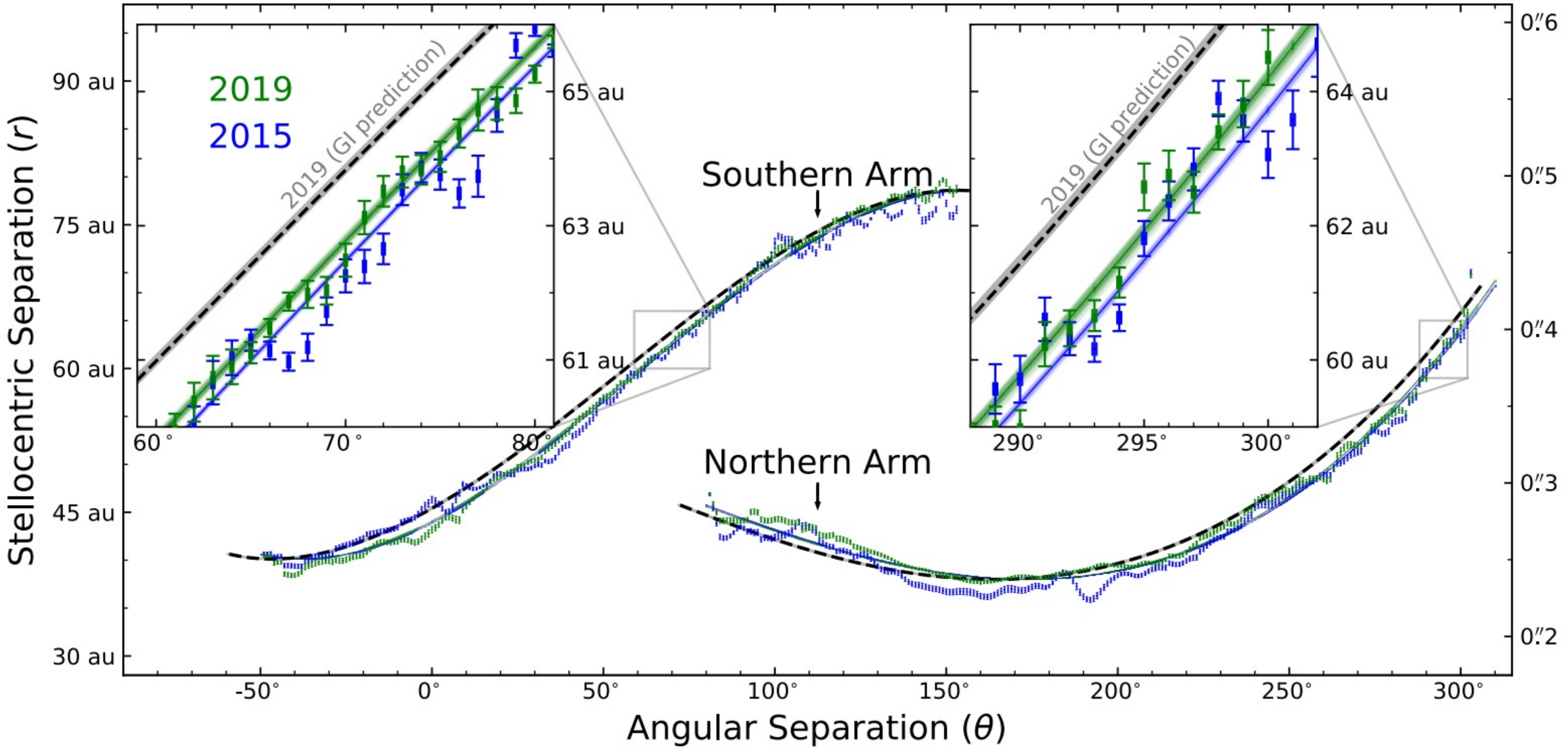
$$\Delta\theta \propto r^{-\frac{3}{2}} \qquad t_0: r = Poly(\theta), t_1: r = Poly\left(\theta - k_1 r^{-\frac{3}{2}}\right)$$

- Companion case

$$\Delta\theta \propto const. \qquad t_0: r = Poly(\theta), t_1: r = Poly(\theta - k_2)$$

How to select the models based on this measurement?

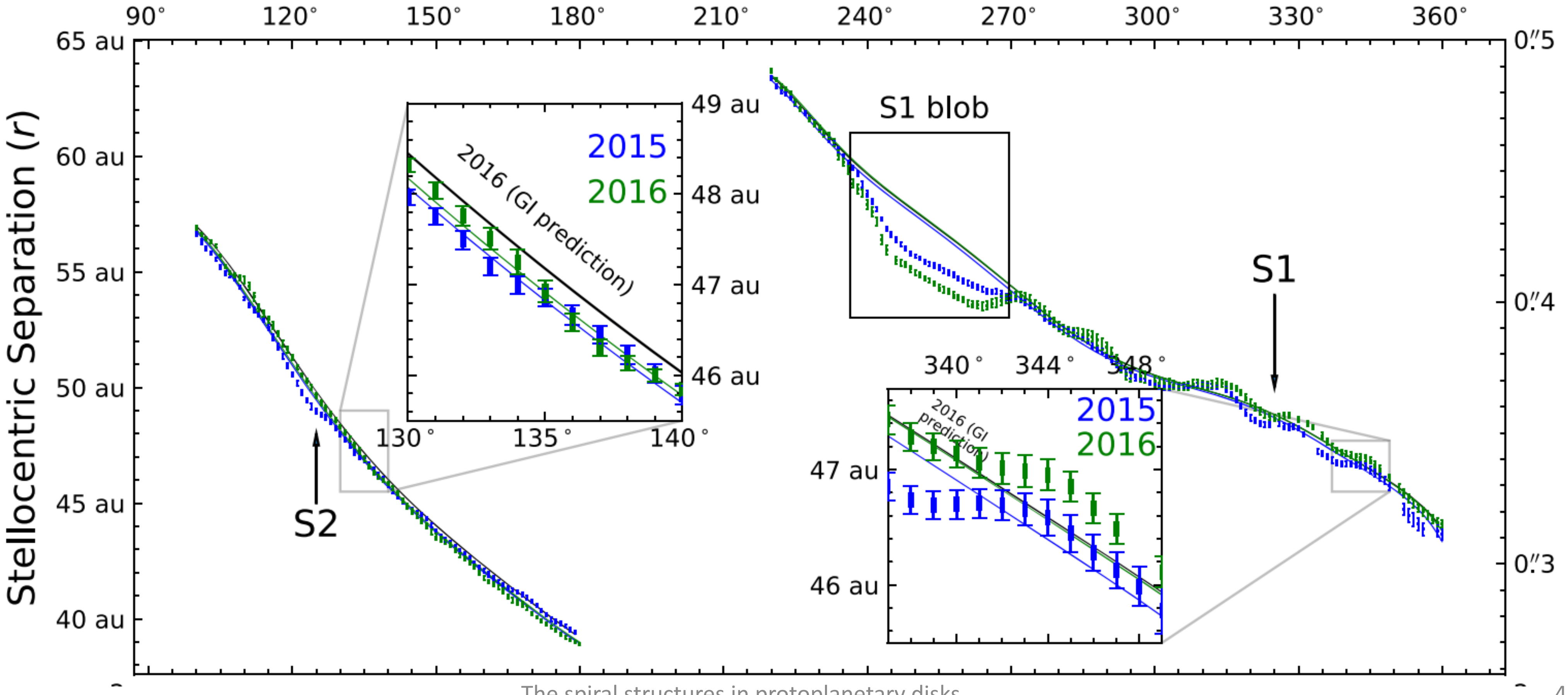
MWC 758



Ren et al. 2020

How to select the models based on this measurement?

SAO 206462



Xie et al. 2021

The limitation and the systematics of current results.

- Where are companions?
- Too small samples.
- The spiral arm pattern is not actually well fitted.

Xie et al. 2021

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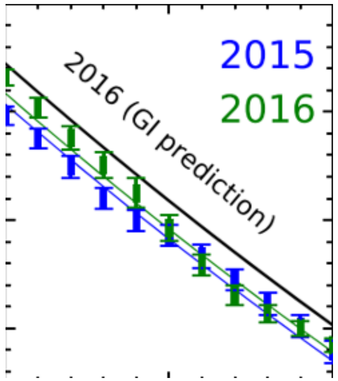
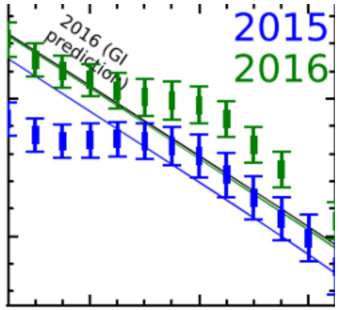


S2 @ SAO 206462



S1 @ SAO 206462

Xie et al. 2021

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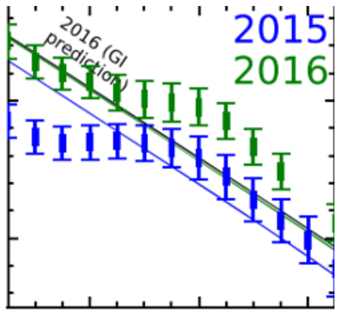
- Where are companions?
- Too small samples.
- The spiral arm pattern is not actually well fitted.
- Deprojection problem leads to $2\,\sigma$ difference.
- The center of the disk leads to $1\,\sigma$ difference.
- Flaring of the disk (disk is not flat) leads to $2\,\sigma$ difference.

S2 @ SAO 206462



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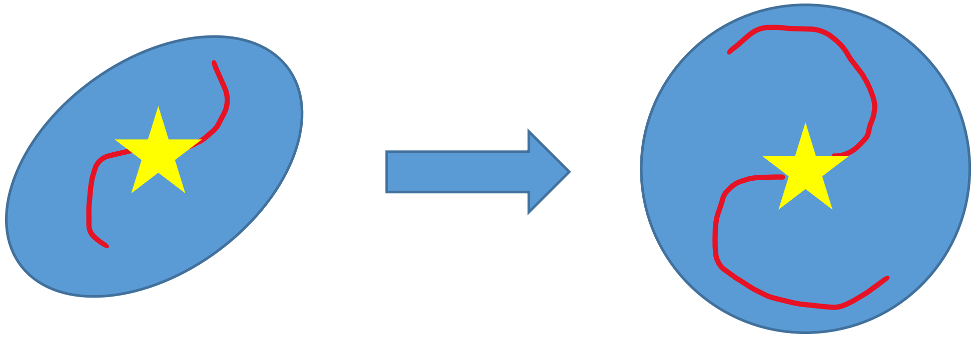

Xie et al. 2021

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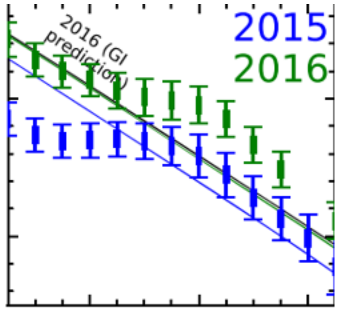

S2 @ SAO 206462 **S1 @ SAO 206462**

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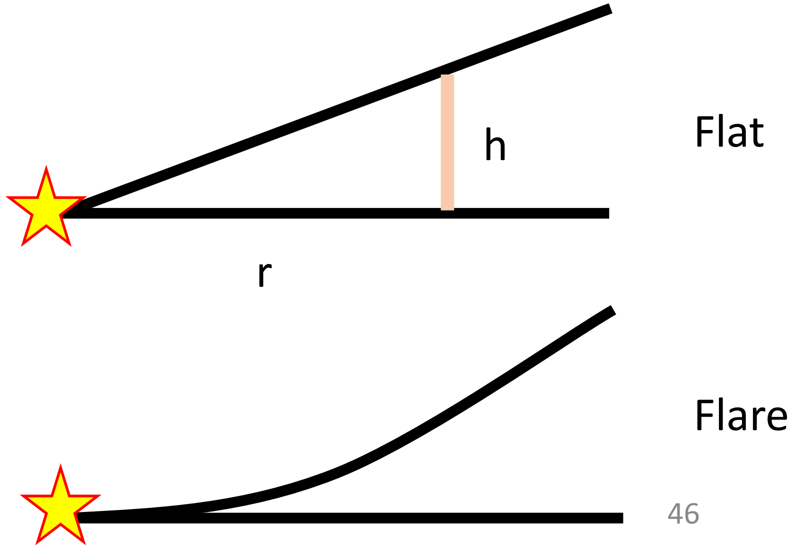


Xie et al. 2021

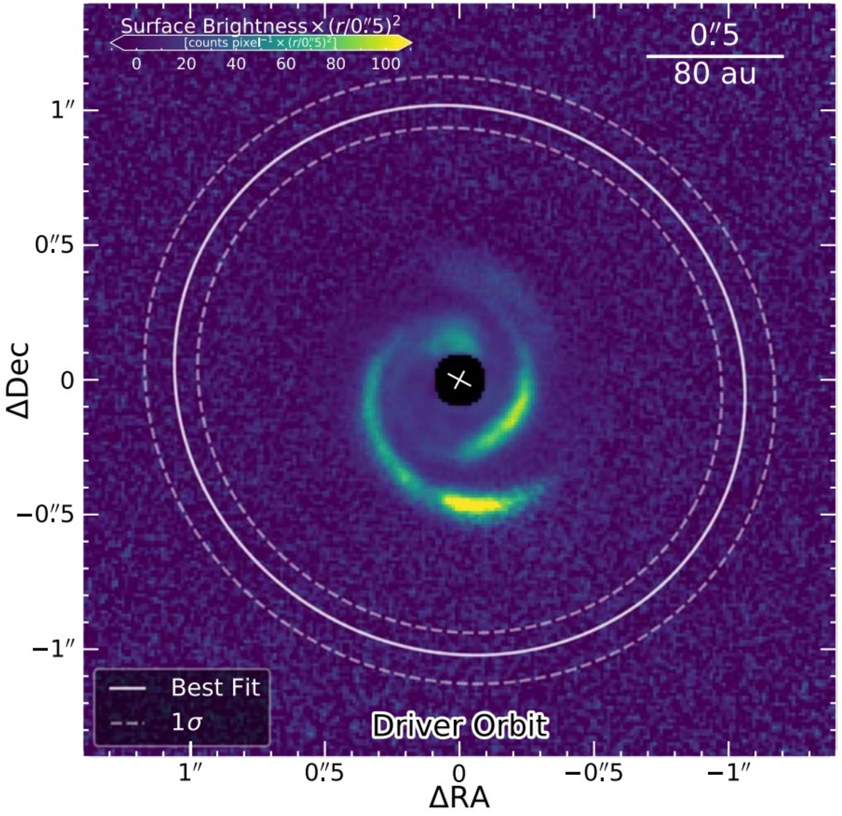
The next to do, larger sample and new method.

- Where are companions?
  - Direct detection
  - Try their best to observe but no detection up to now

- Too small samples

- The spiral arm pattern speed is not actually well fitted.

MWC 758

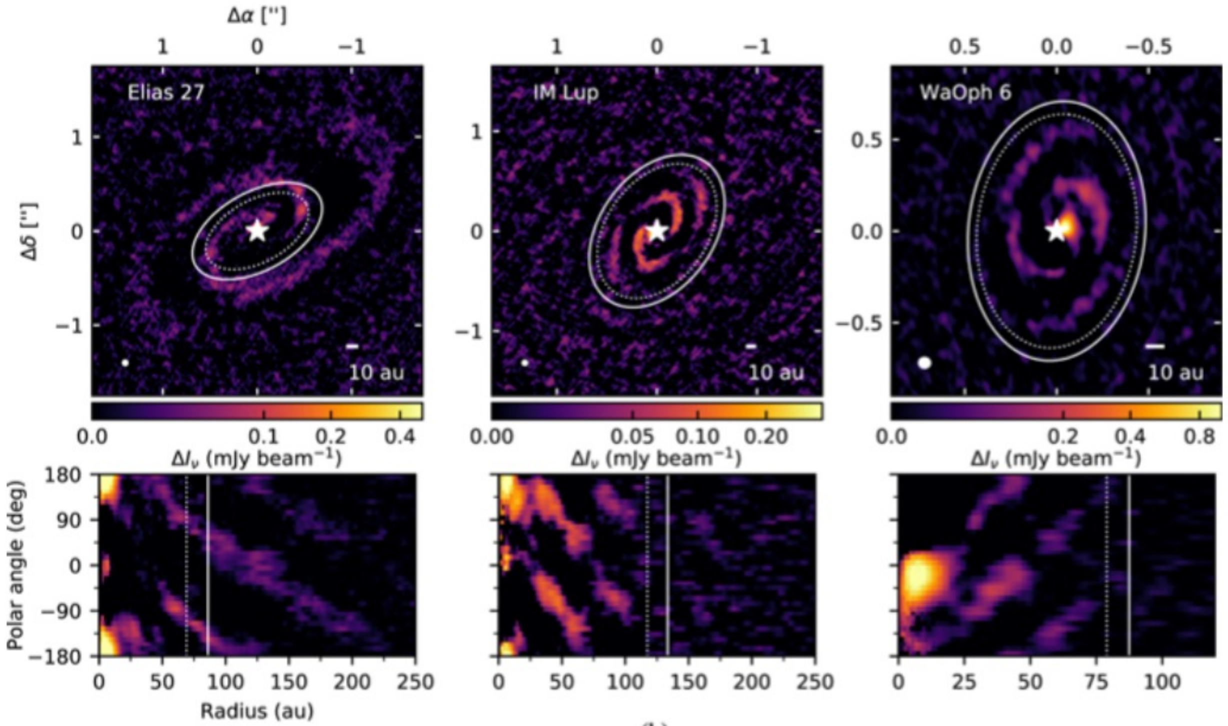


"Can be detected at 5σ level if it is a **hot-start planet** using four half-nights of NIRC2 Ms-band high contrast imaging observations"

Ren et al. 2020

The next to do, larger sample and new method.

- Where are companions?
- Too small samples
  - Hard to extend
  - < 200 pc
  - No significant shadowing effect
- The spiral arm pattern is not actually well fitted.

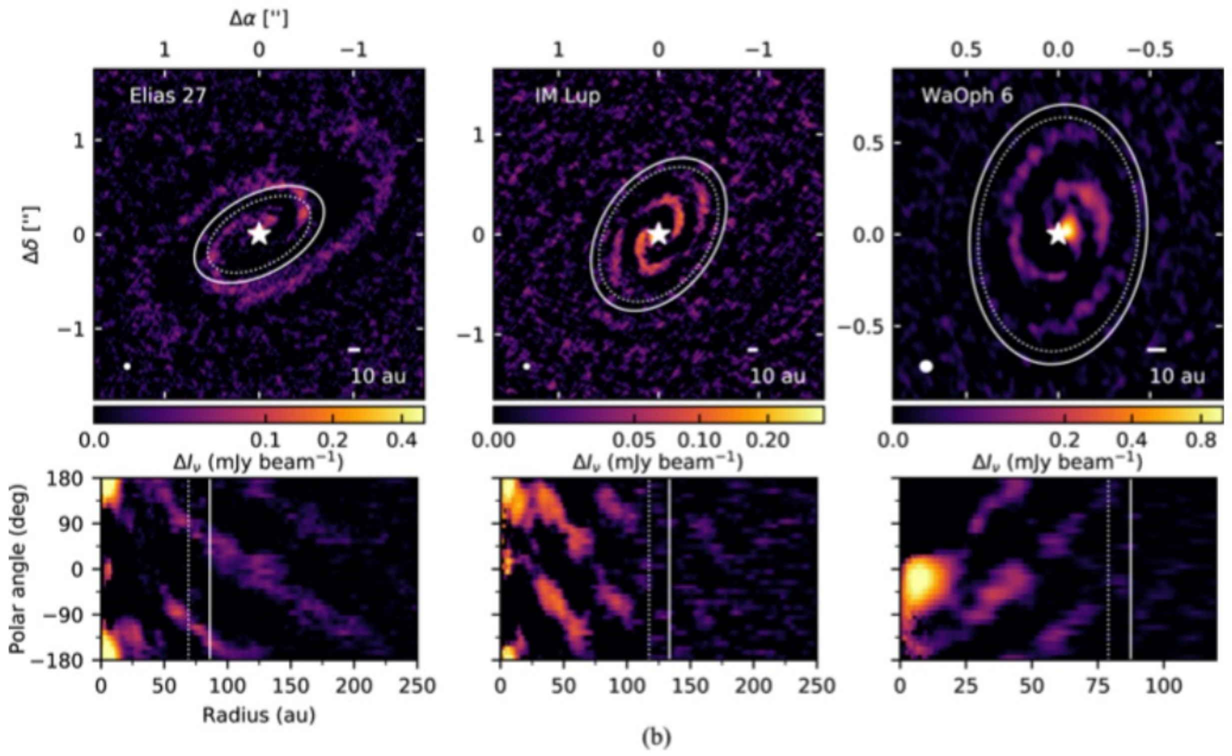


(b)

Huang et al. 2018

The next to do, larger sample and new method.

- Where are companions?
- Too small samples
- The spiral arm pattern is not actually well fitted.
  - Simulations are struggling to reproduce what we observed.



Huang et al. 2018

Summary

- The pattern speed measurement of spiral arm prefer companion case in SAO 206462 and MWC 758.
- The results are not very sensitive to deprojection, center of the disk, and flaring of the disk.
- The more effects should be made in both observation (detect the planet, extend the sample) and theory (better simulation) aspects to further understand such spiral arms.