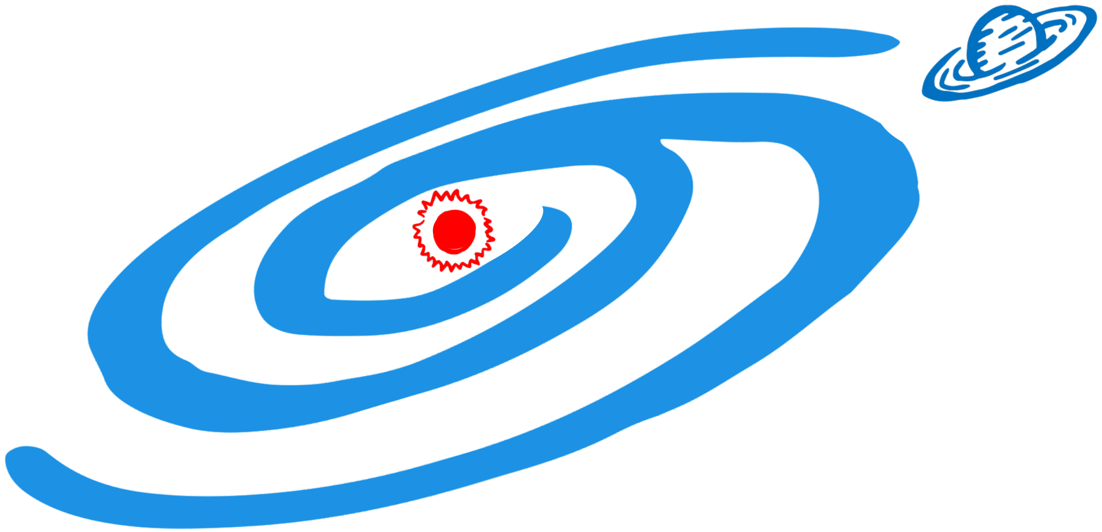
Structures in Disks and Planet-disk interactions



Jaehan Bae

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Carnegie Institution for Science

University of Florida starting Aug. 2021 (jbae@ufl.edu)

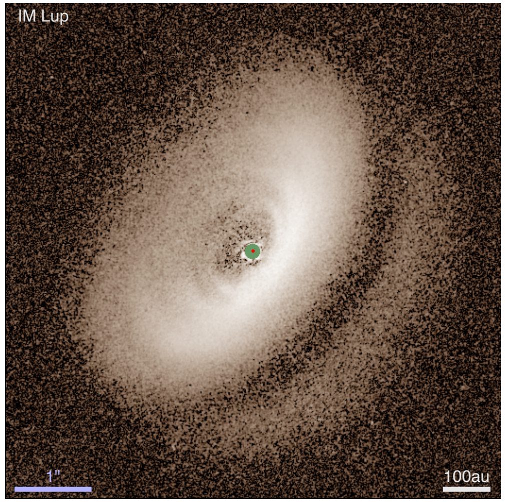
Circumstellar disk 101

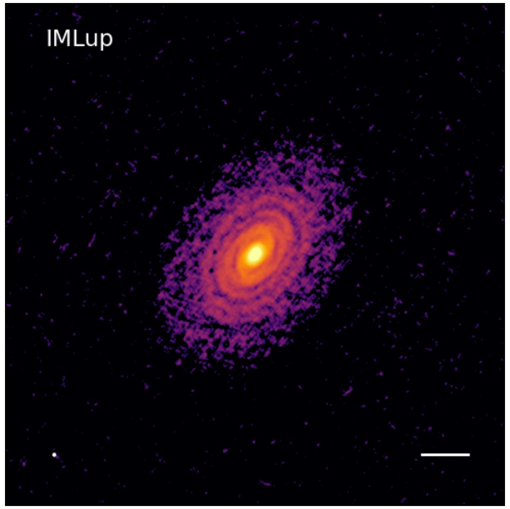
1. Circumstellar disks consist of 99 % gas + 1 % solids.

2. Most of the gas mass is in H_2 but they are poor emitters at typical circumstellar disk temperatures (a few x 10 – 100 K).

3. Circumstellar disks are three-dimensional objects.

4. Solid particles have different spatial distributions as a function of their sizes.





top: NIR scattered light (Avenhaus et al. 2018)
bottom: mm continuum (Andrews et al. 2018)

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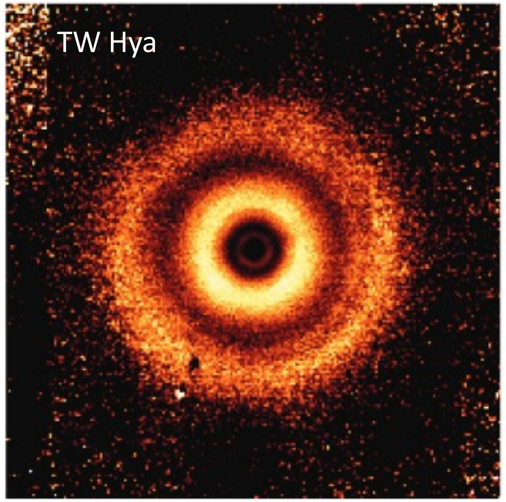

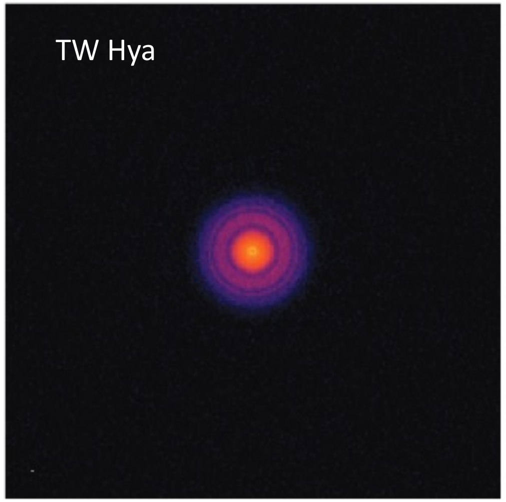

top: NIR scattered light (van Boekel et al. 2017)
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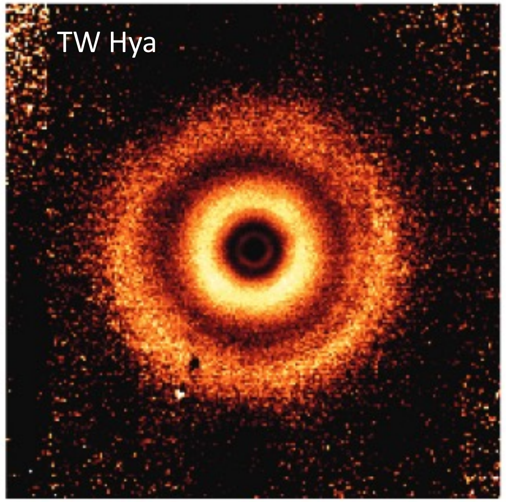
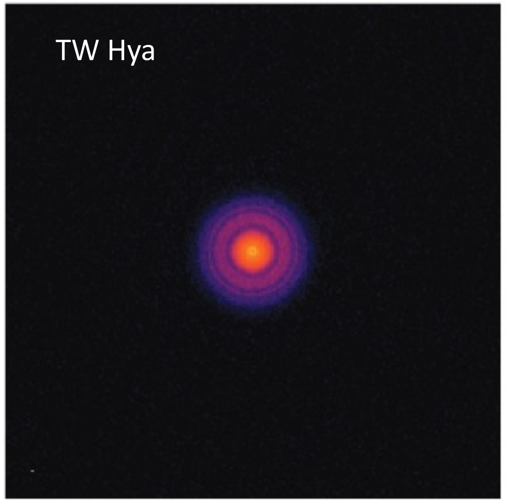
Depending on what wavelength/tracer you use, the same disk may look very different.

See Karin Öberg's talk for gas observations.





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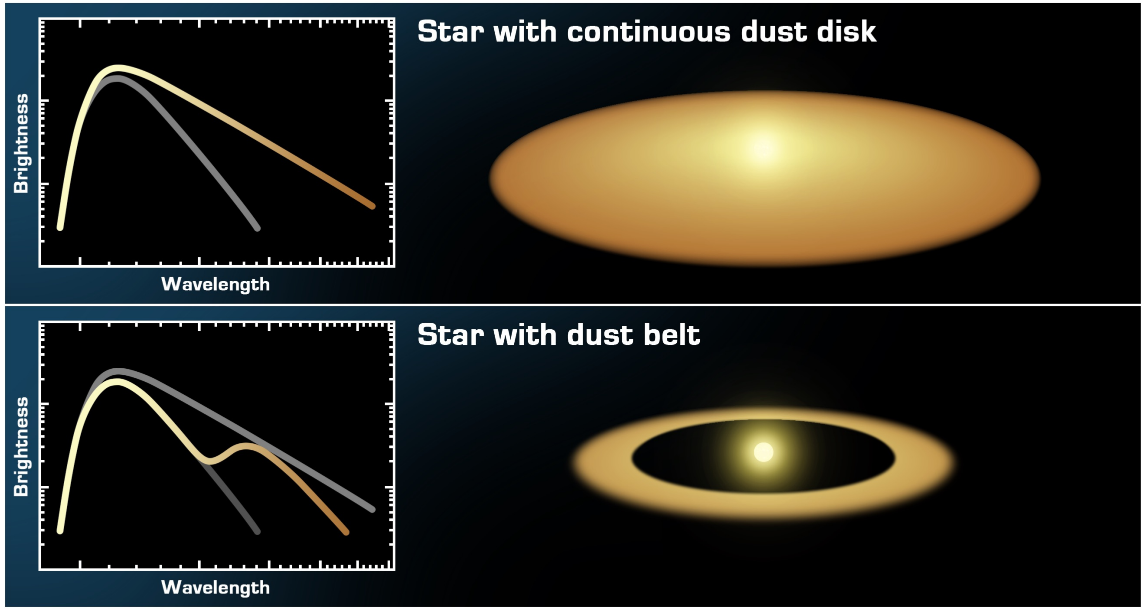
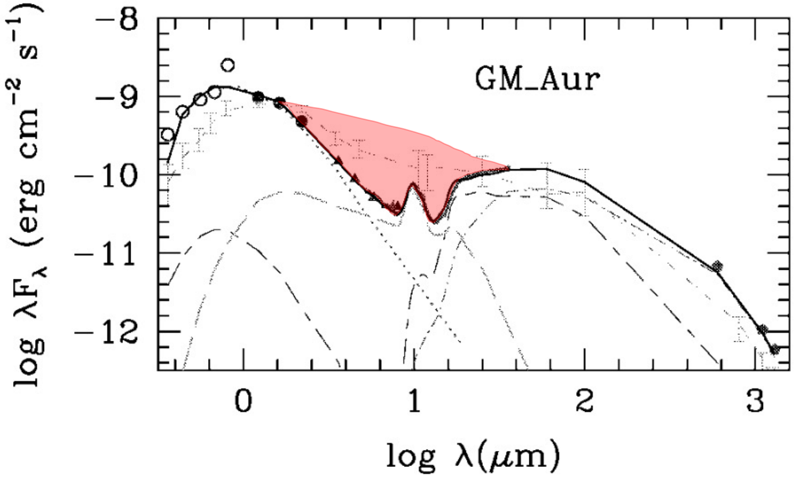
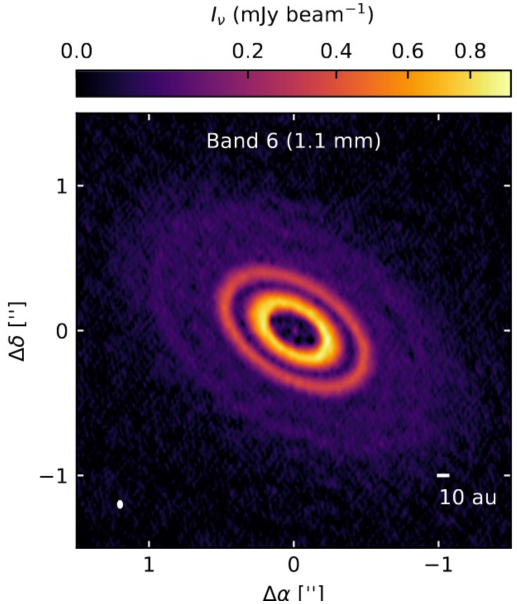
Disk substructures



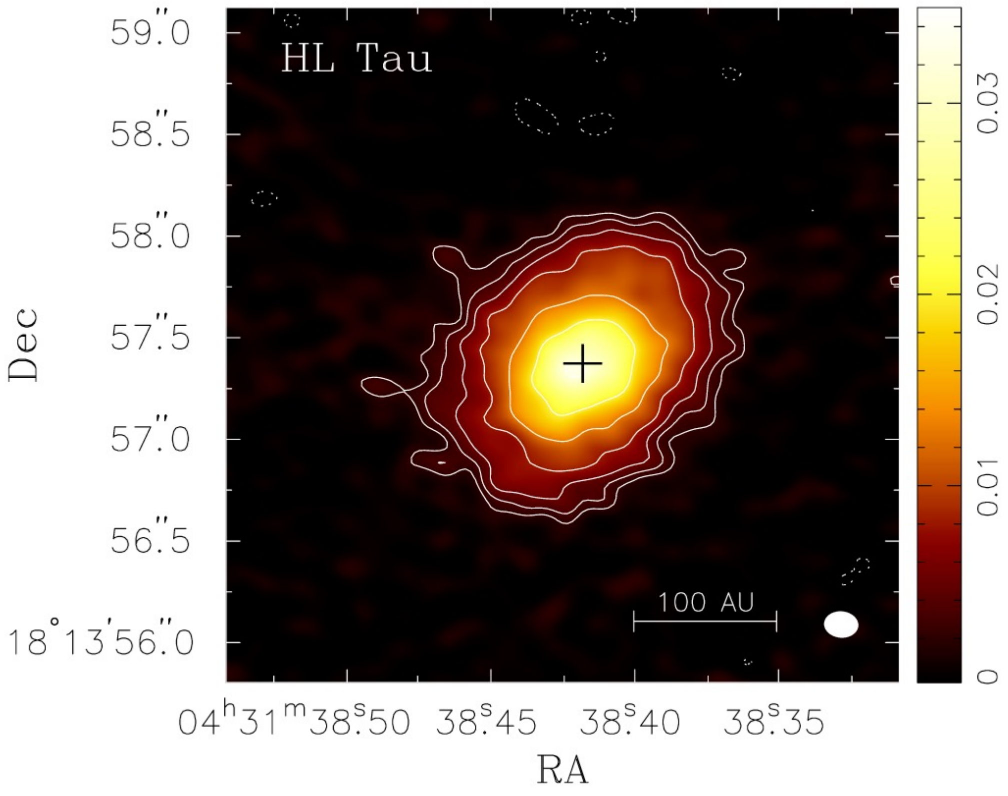
NASA/JPL-Caltech/T. Pyle (SSC)





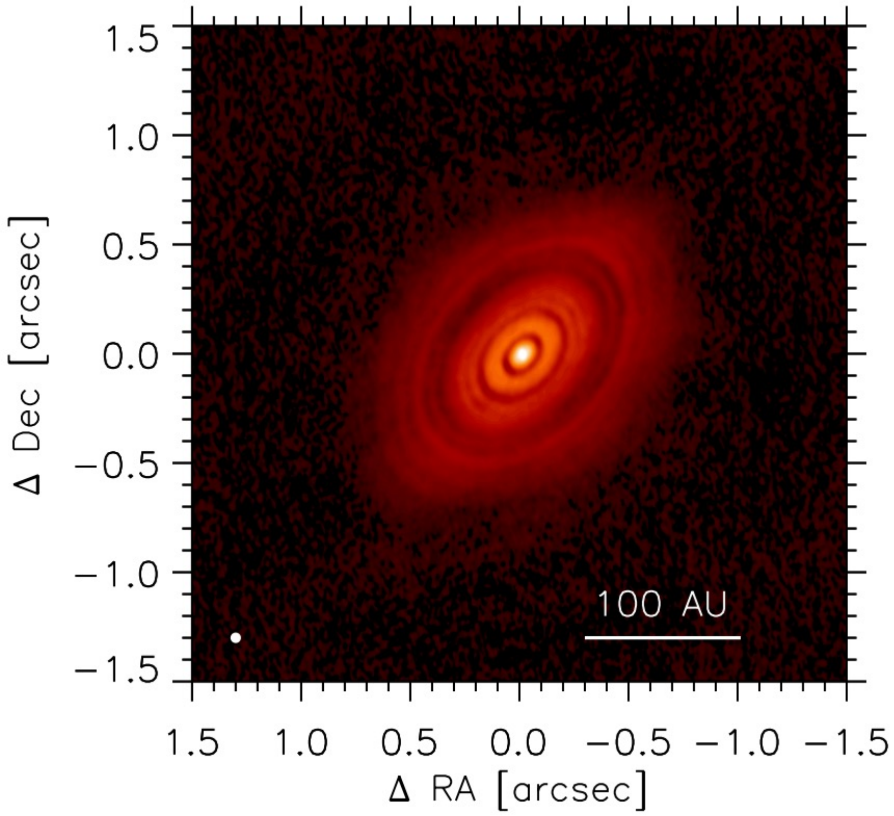
Top: Calvet et al. (2005); see also Strom et al. (1989)
Bottom: Huang et al. (2020)

Disk substructures



Kwon et al. (2011) with CARMA

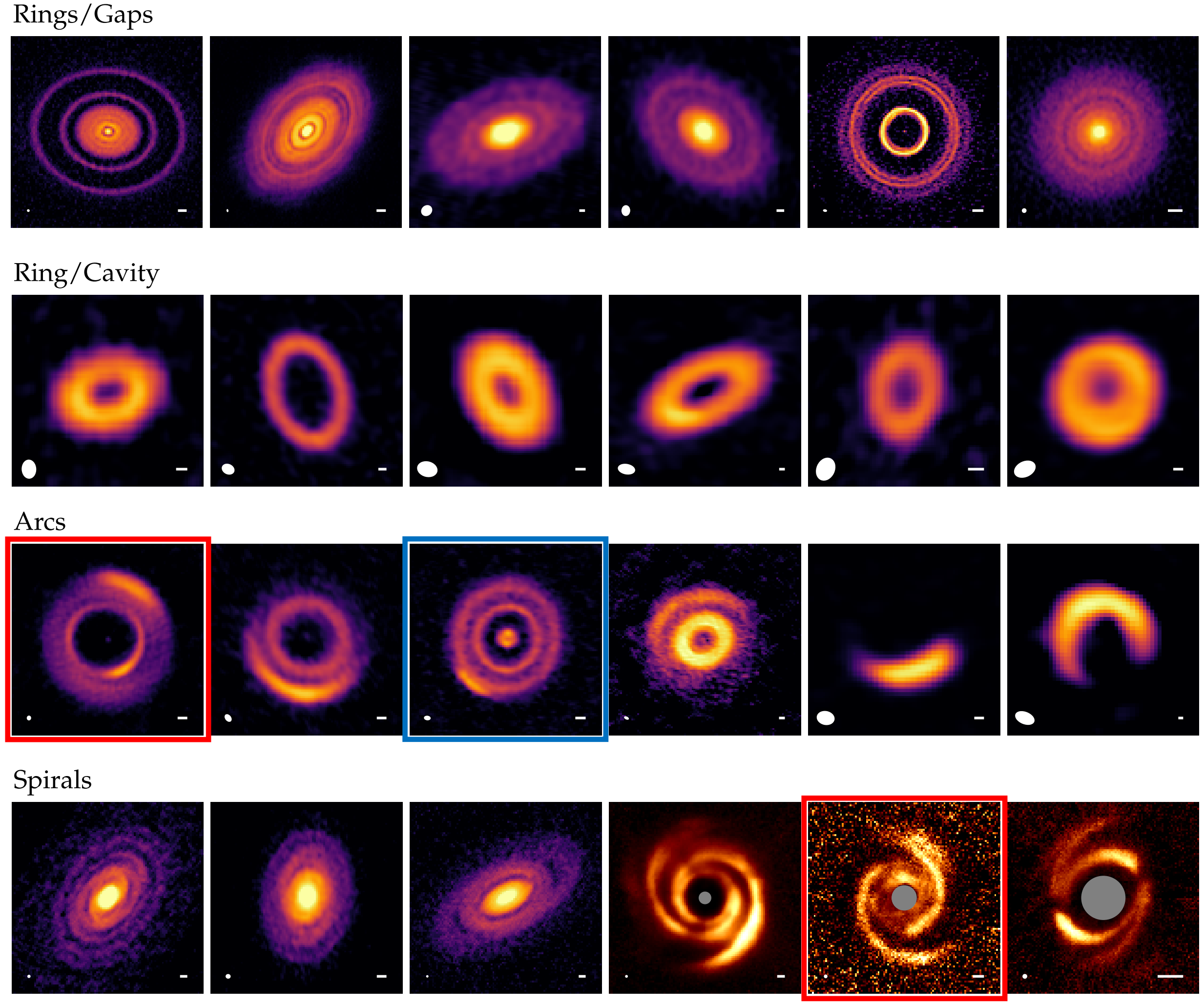
0."17 x 0."13 (≃ 24 AU x 18 AU) resolution



ALMA Partnership et al. (2015) with ALMA

0."03 x 0."02 (≃ 4 AU x 3 AU) resolution

Disk substructures

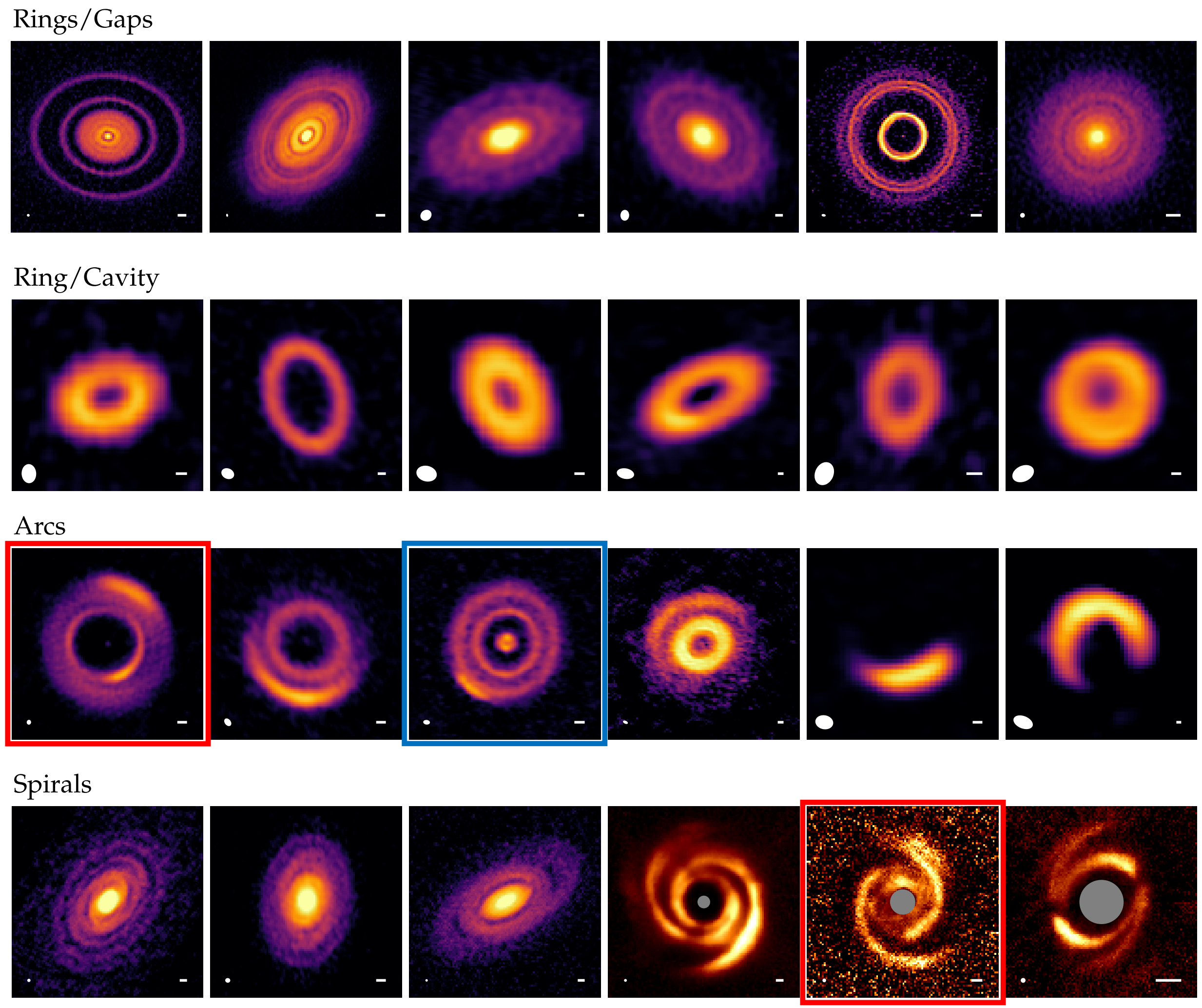


Andrews (2020)

- What have created disk substructures?
  - Planet-disk interaction
  - Ice lines
  - Vertical shear instability
  - Magnetic zonal flows
  - Photoevaporative winds
  - Magnetohydrodynamic winds
  - Self-induced dust traps
  - Streaming instability
  - Gravitational instability
  - Stellar flyby
  - Infall
  - Eccentric disks
  - Rossby wave instability
  - Convective overstability
  - Subcritical baroclinic instability
  - Zombie vortex instability
  - …

See Protostar and Planets VII review chapter
"A Theoretical Perspective of Structured Distribution of the Gas and Solids in Protoplanetary Disks" by Bae et al. (in prep.)

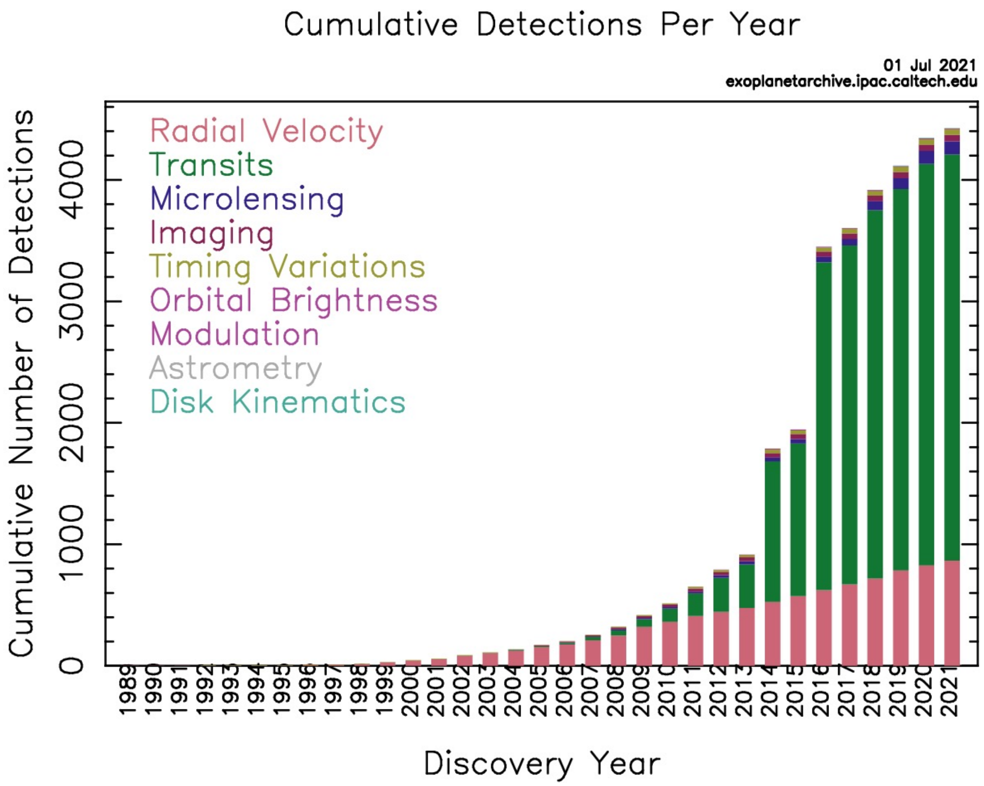
Disk substructures



Andrews (2020)

- What have created disk substructures?
- If substructures are created by (yet-unseen) planets in the disk, they can provide important information on
  - planets' properties
  - how/where/when planets form
  - how planets interact with their parental disks
- Even if substructures are not created by planets, they can provide important information on
  - initial conditions of planet formation
    (!= smooth disk density/temperature profiles)

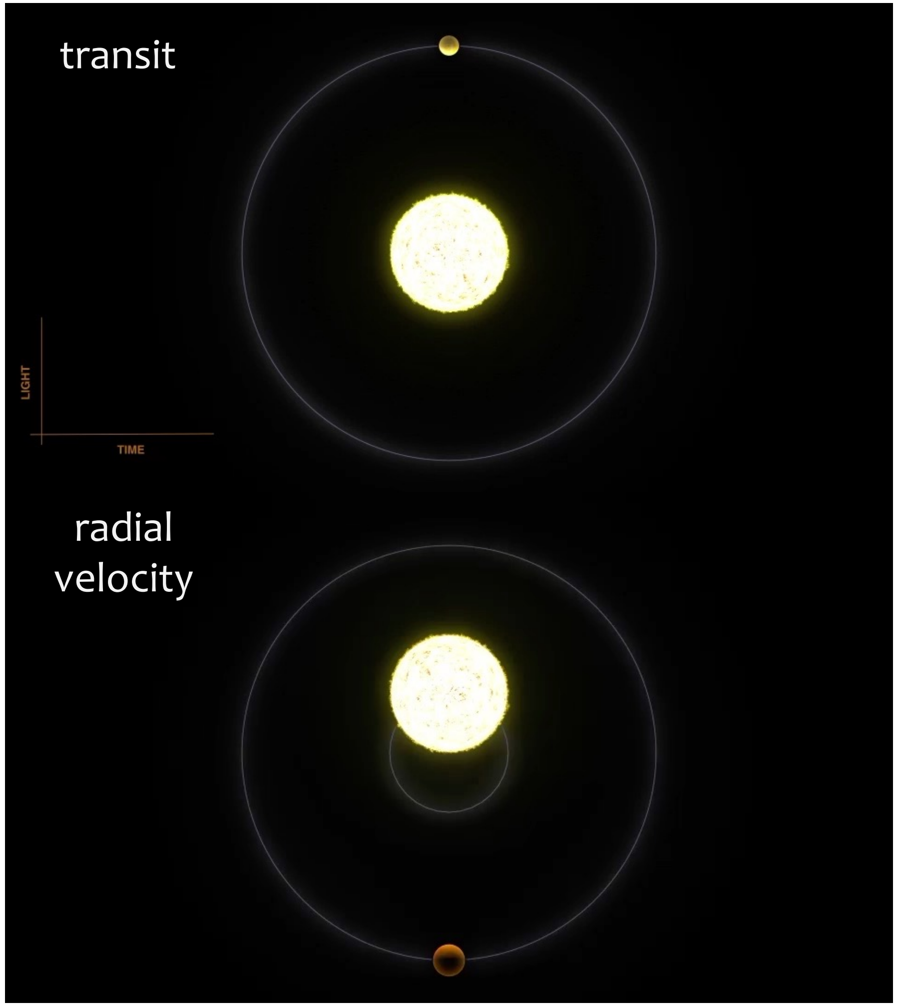
Why can’t we simply use well-established exoplanet detection techniques to find young planets?



See talks by Anne-Marie Lagrange, Arpita Roy, Mathias Nowak, Andrew Mann

Why can't we simply use well-established exoplanet detection techniques to find young planets?

- We need to "see" the star.
- We need stable stellar flux.
- (radial velocity) We need bright stars.



video credit: NASA Exoplanet Exploration Program

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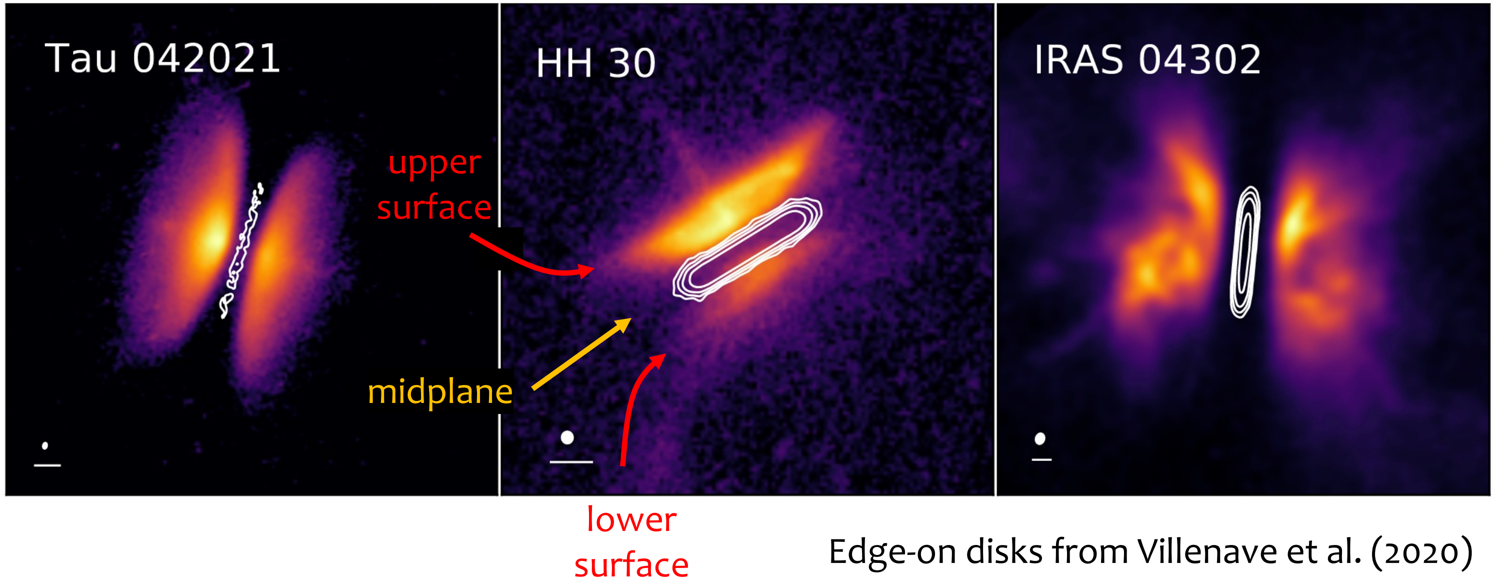

Edge-on disks from Villenave et al. (2020)

Background color: NIR scattered light

White contours: mm continuum

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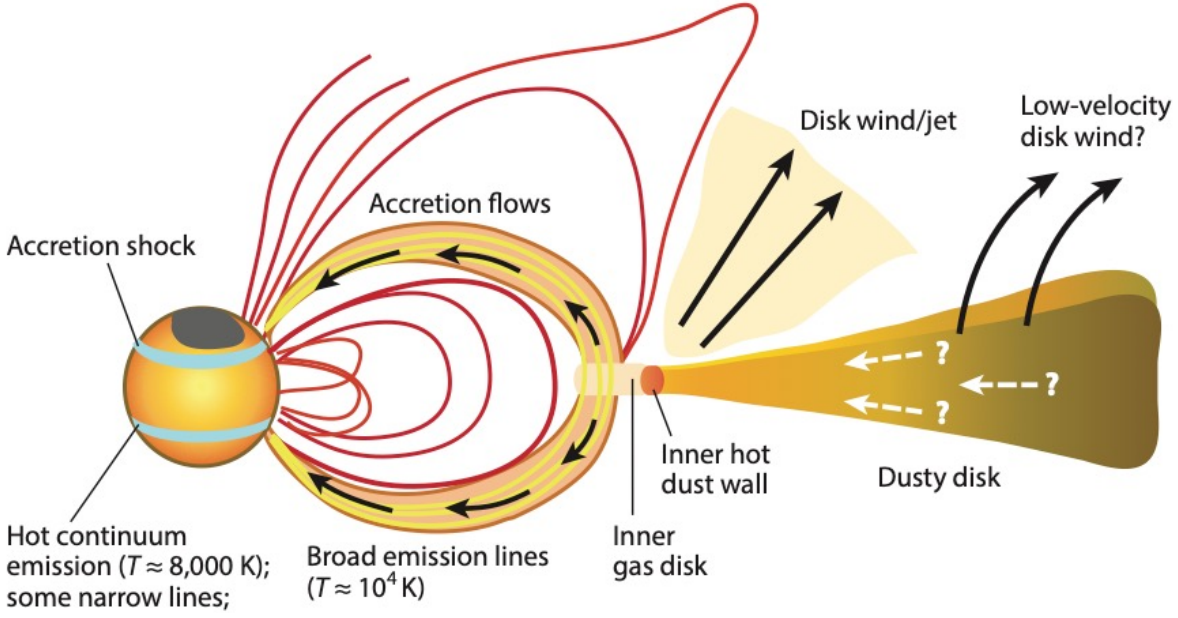

Hartmann et al. (2016)

*not to scale

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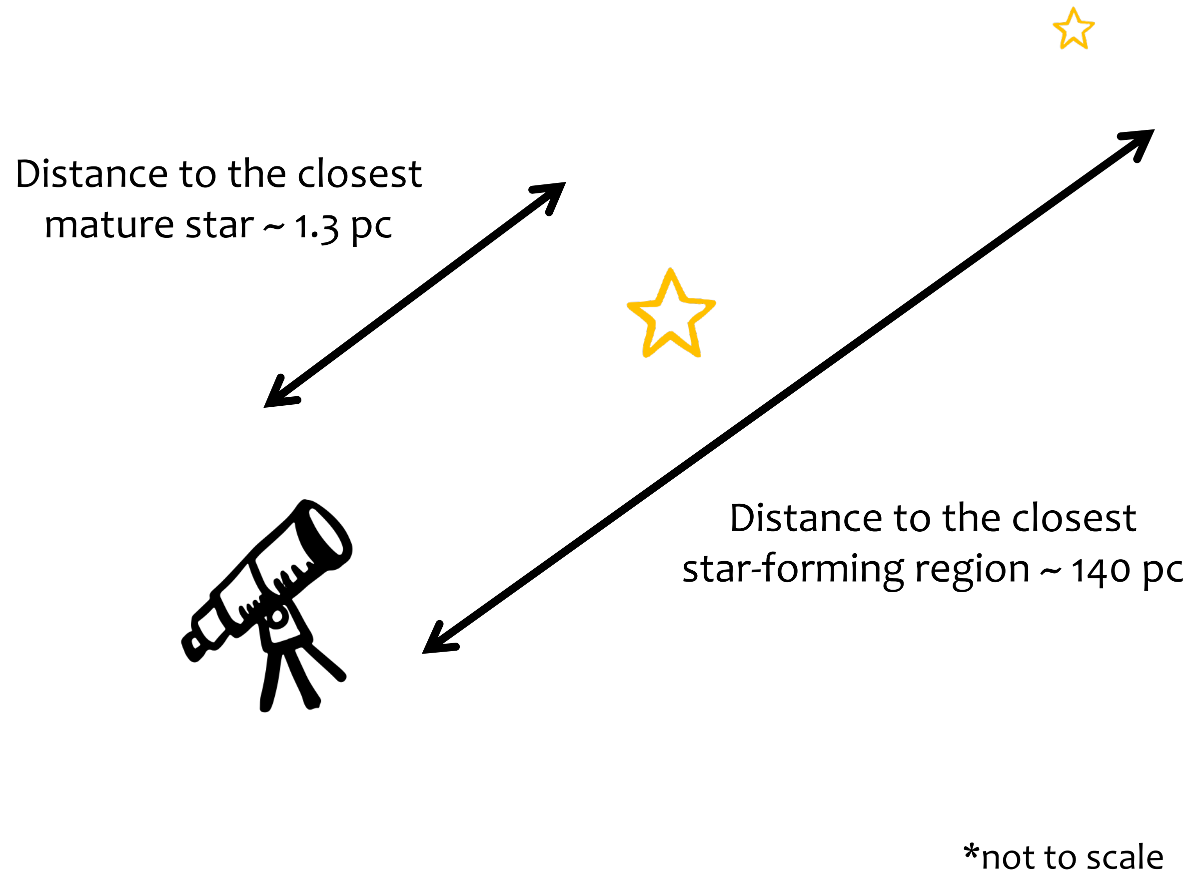

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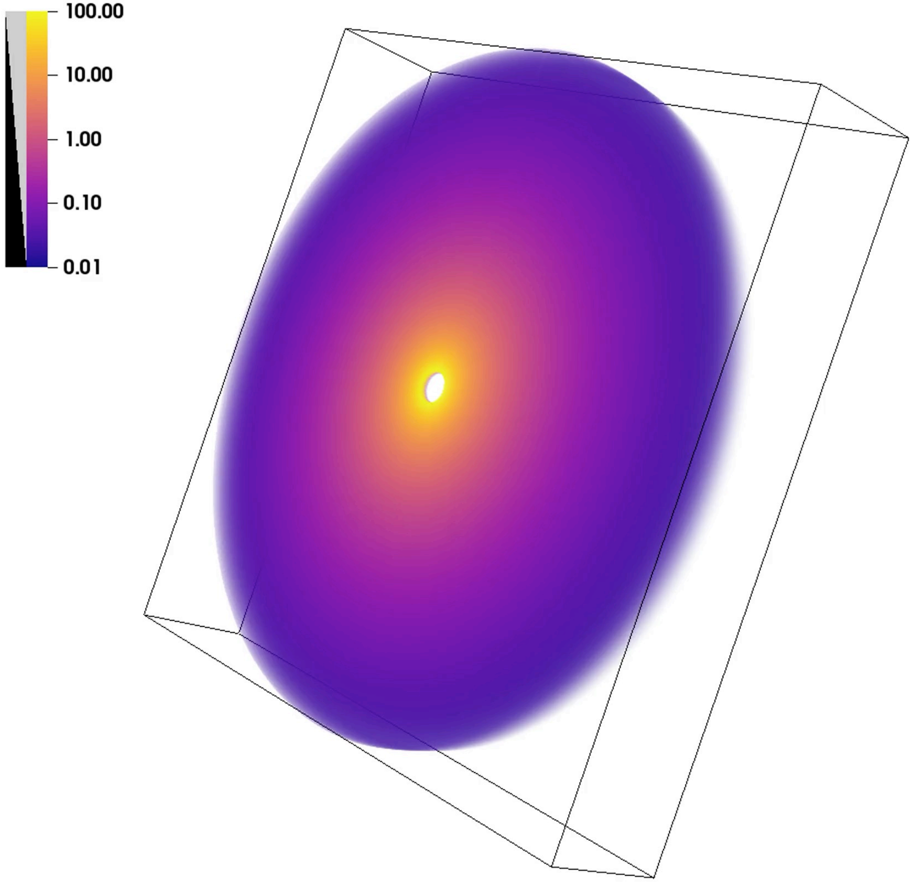
The most successful exoplanet detection techniques cannot be applied to finding young planets!

Disk substructures: signpost of planet-disk interaction



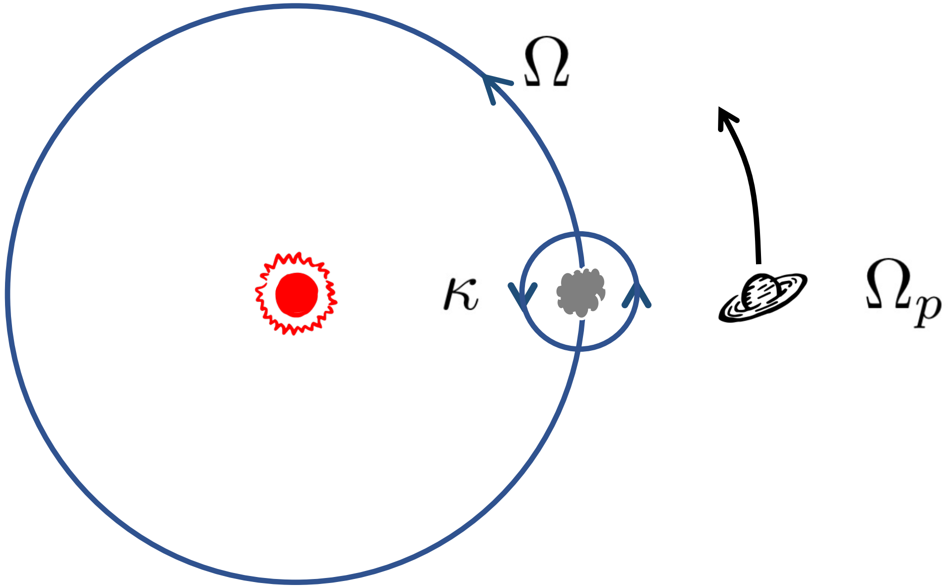
Theories of planet-disk interaction

First step: Lindblad resonances excite spirals

epicyclic frequency

= planet's Doppler-shifted orbital frequency

$$m|\Omega - \Omega_p| = \kappa$$



Lindblad resonance

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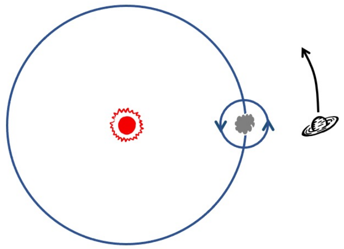
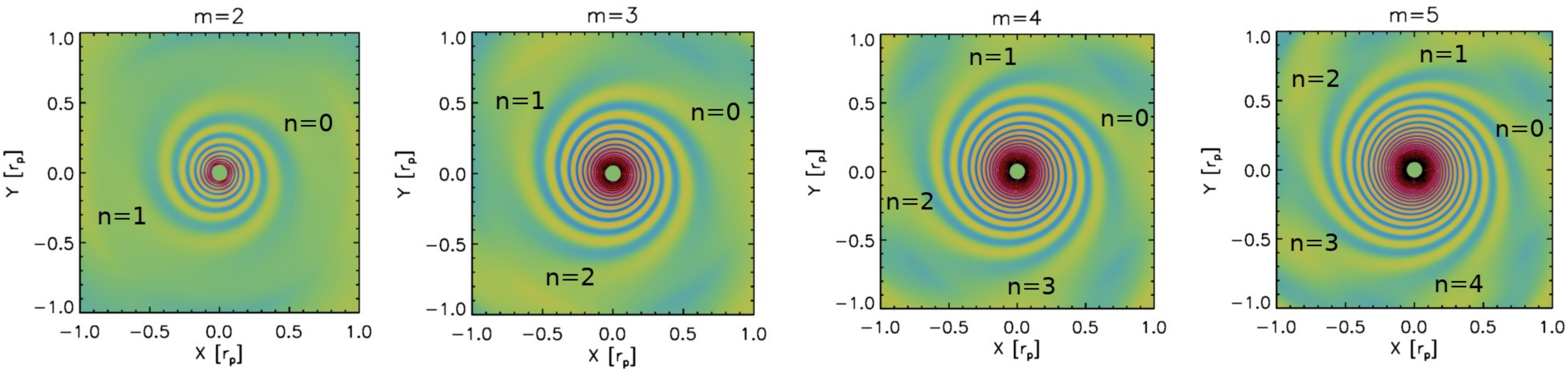


First step: Lindblad resonances excite spirals

*m*th Fourier component of the planet's potential excites *m* axisymmetric spiral wave modes at the

Lindblad resonance (Goldreich & Tremaine 1978a,b,1979).



$$\Phi_p(r,\phi) = -\frac{GM_p}{|\vec{r}-\vec{r_p}|} = \sum_{m=0}^{\infty} \Phi_m(r)\cos(m\phi) = \Phi_0(r) + \Phi_1(r)\cos(1\phi) + \Phi_2(r)\cos(2\phi) + \cdots$$

$$\Phi_p(r,\phi) = \sum_{m=0}^{\infty} \Phi_m(r)\cos(m\phi)$$

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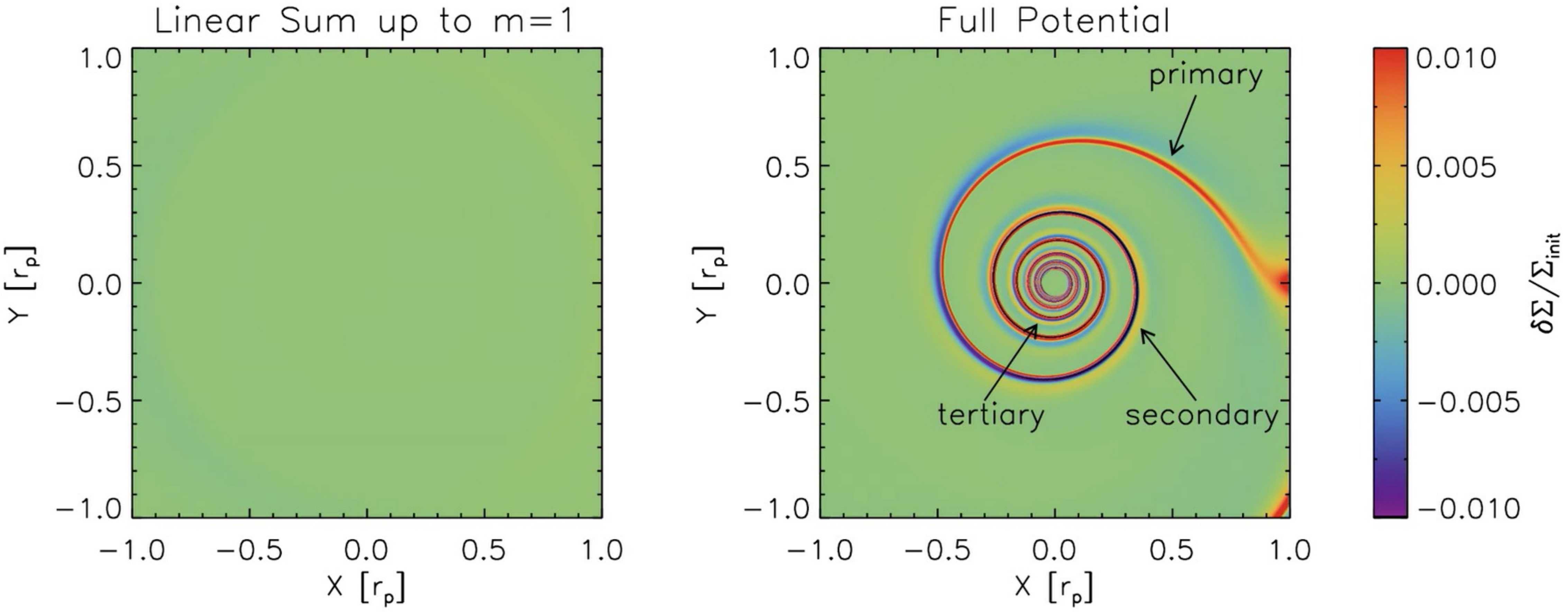

Spiral arm formation is a ***linear*** process: constructive interference among spiral waves having different azimuthal wavenumbers.

Ogilvie & Lubow (2002); Bae & Zhu (2018a)

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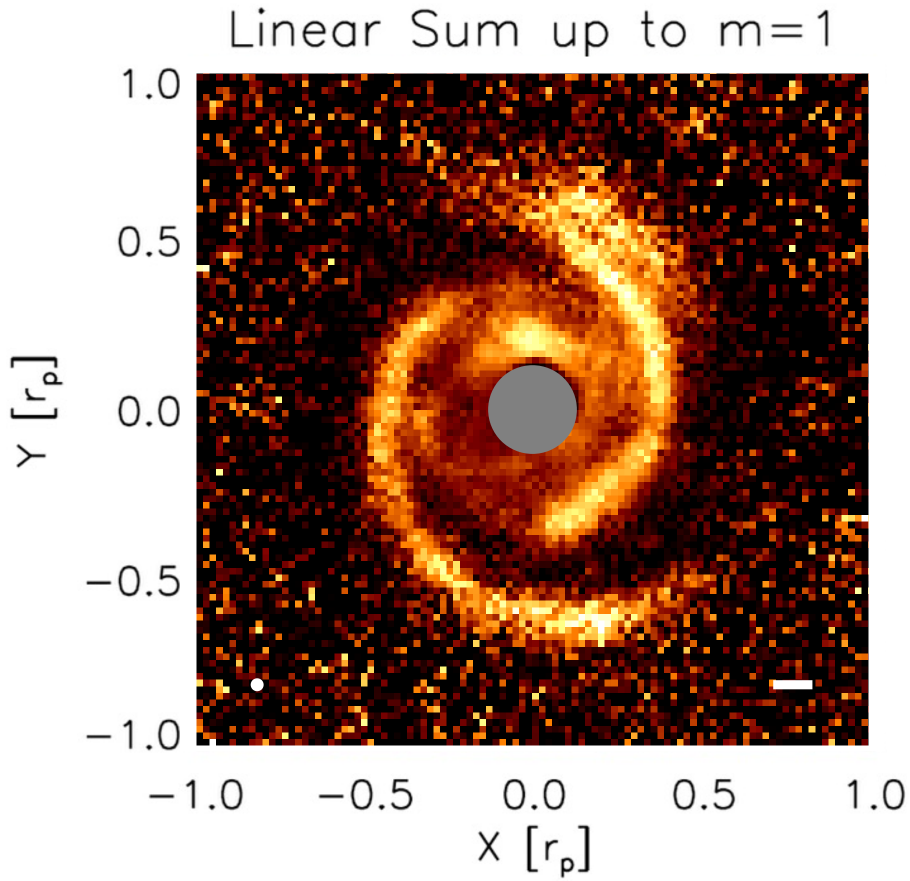

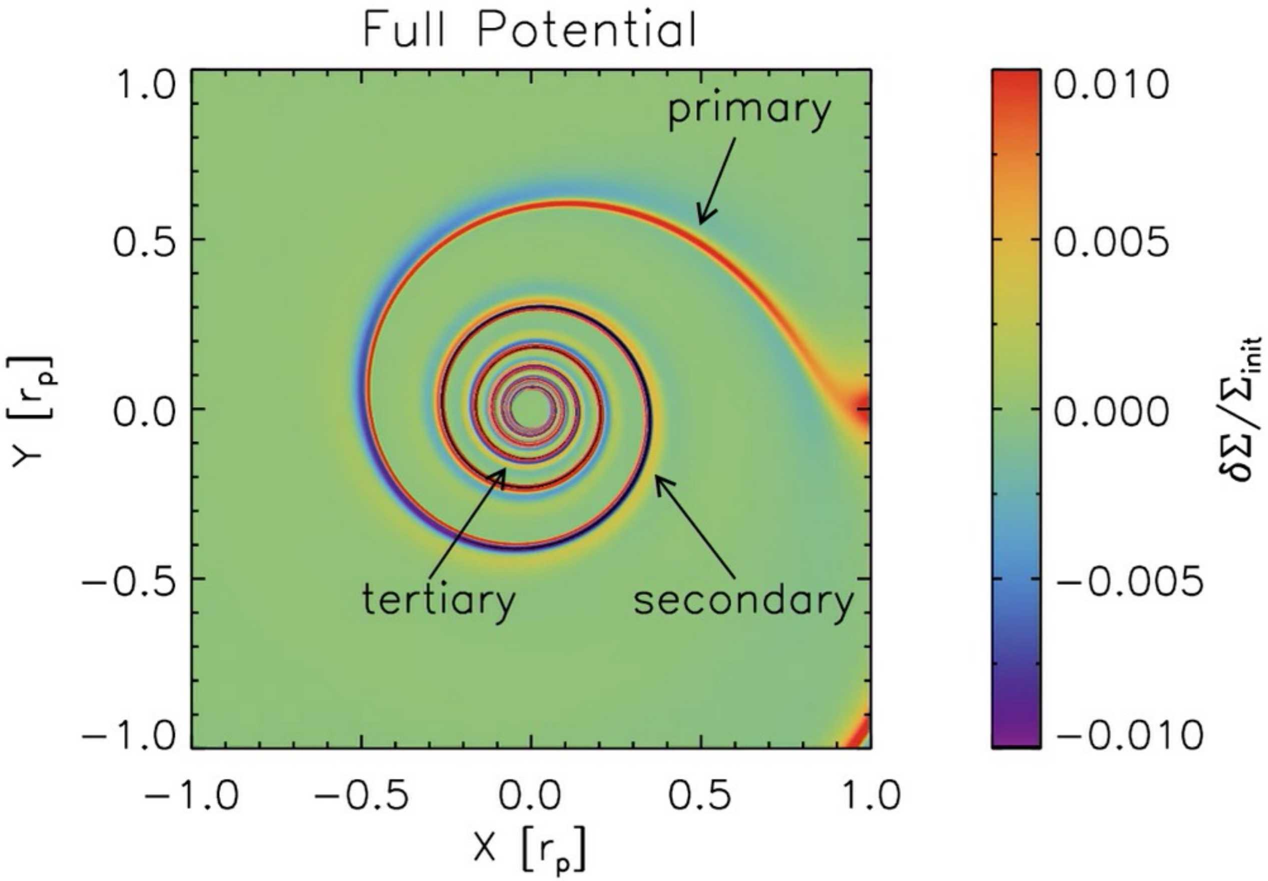

Spiral arm formation is a ***linear*** process: constructive interference among spiral waves having different azimuthal wavenumbers.

Ogilvie & Lubow (2002); Bae & Zhu (2018a)

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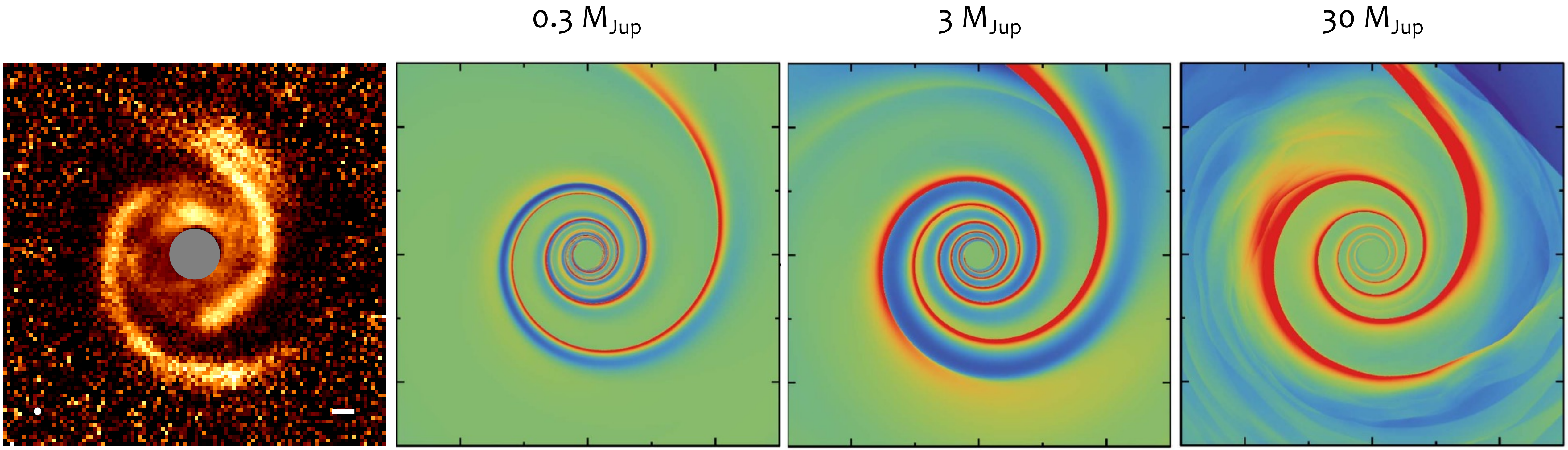
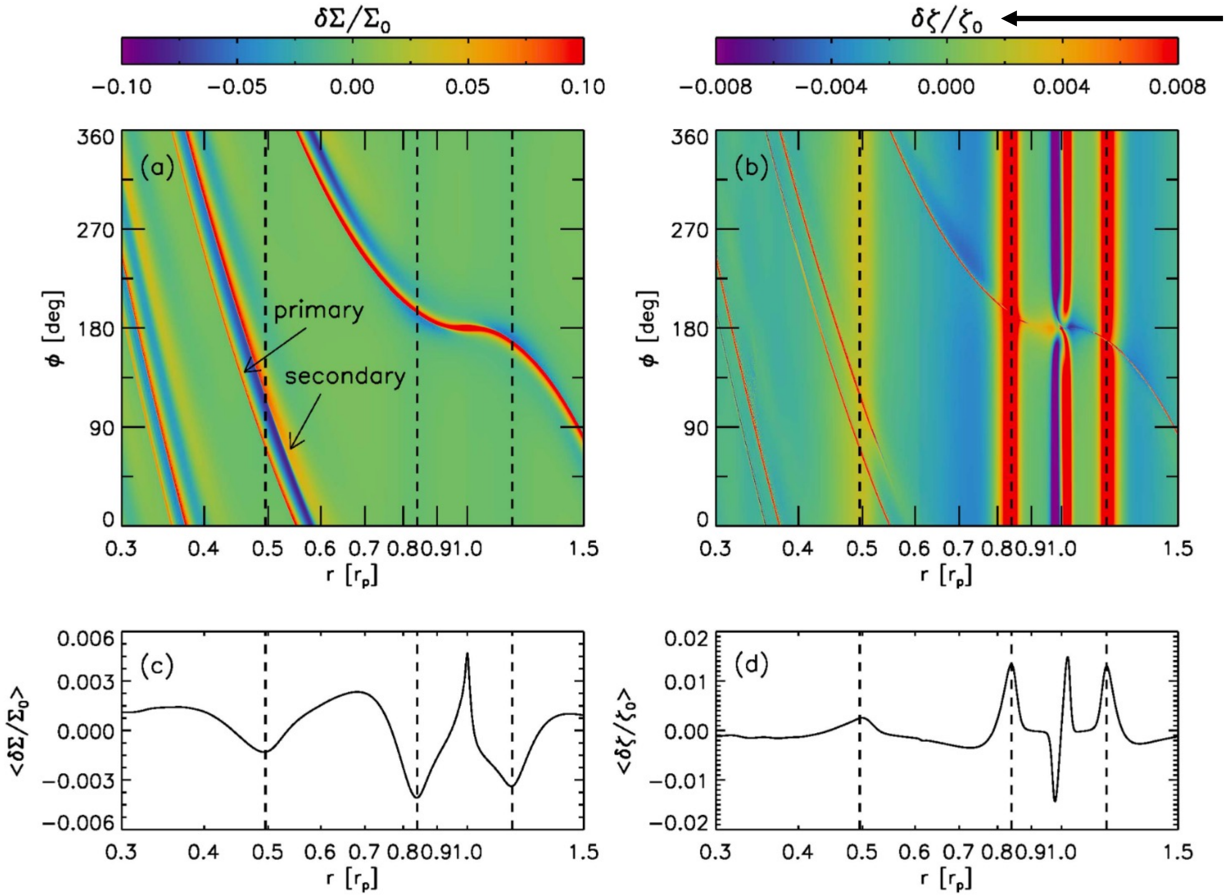


Propagation of waves can be ***non-linear*** when the planet is massive.

more massive planets = stronger shocks = more opened spirals

Spirals can create <u>gaps/rings</u>.

- Spiral arms transport angular momentum as they shock the disk gas, **opening gaps** (Goodman & Rafikov 2001, Rafikov 2002).



$$\zeta \equiv \frac{\nabla \times \boldsymbol{v}}{\Sigma}$$

<u>potential vorticity</u>: strictly conserved in the absence of shocks under a barotropic setup.

Bae et al. (2017)

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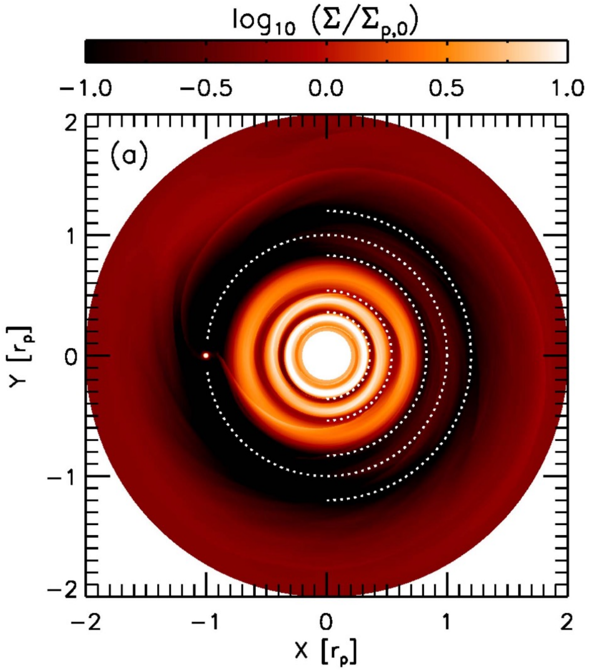
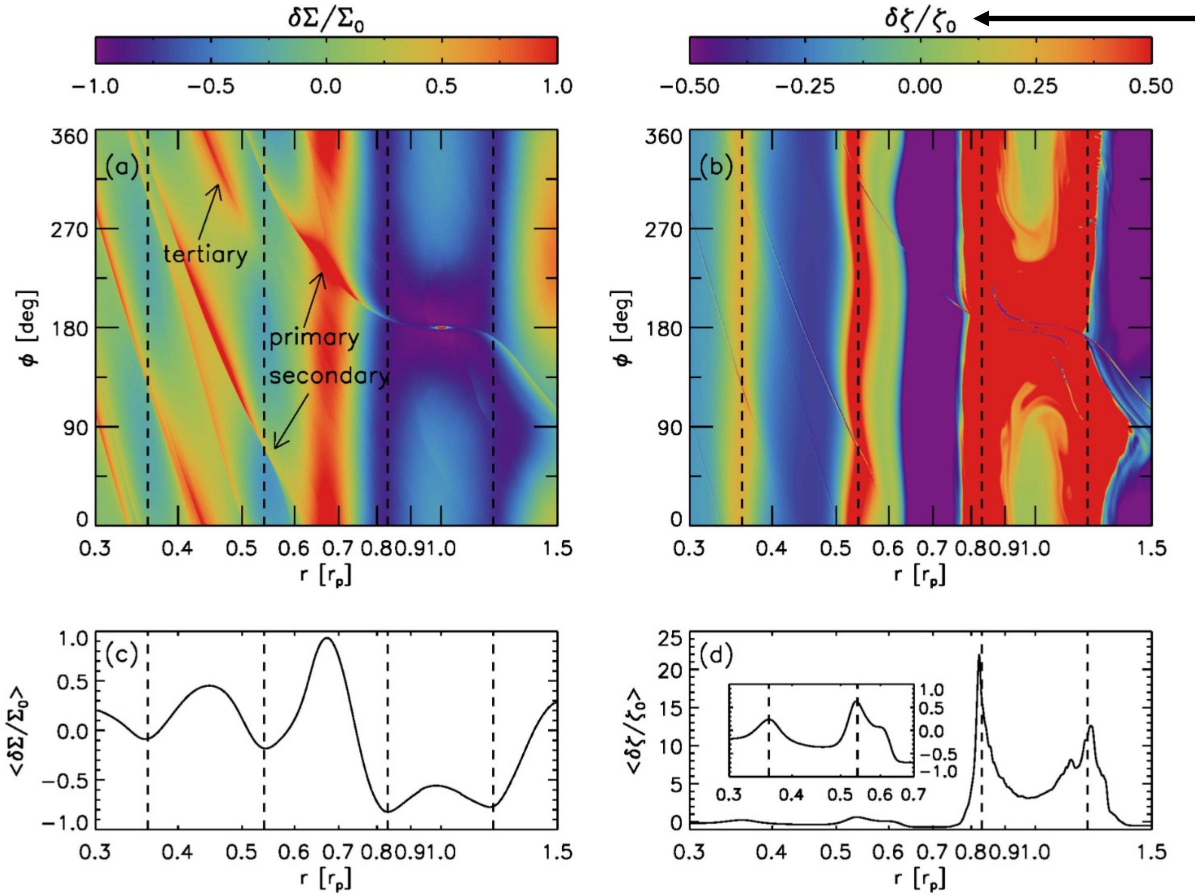
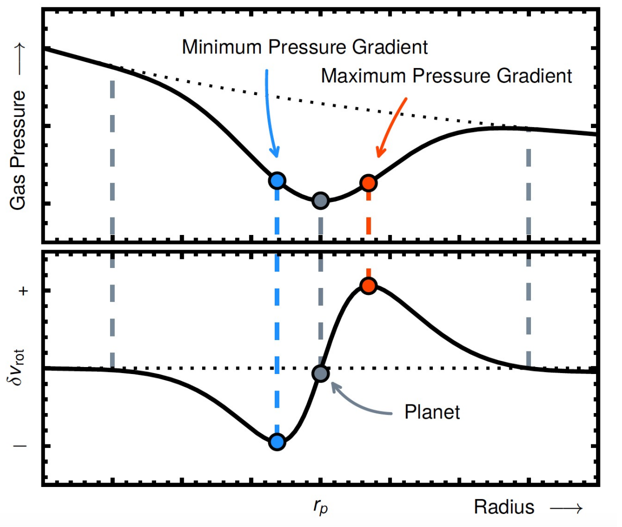




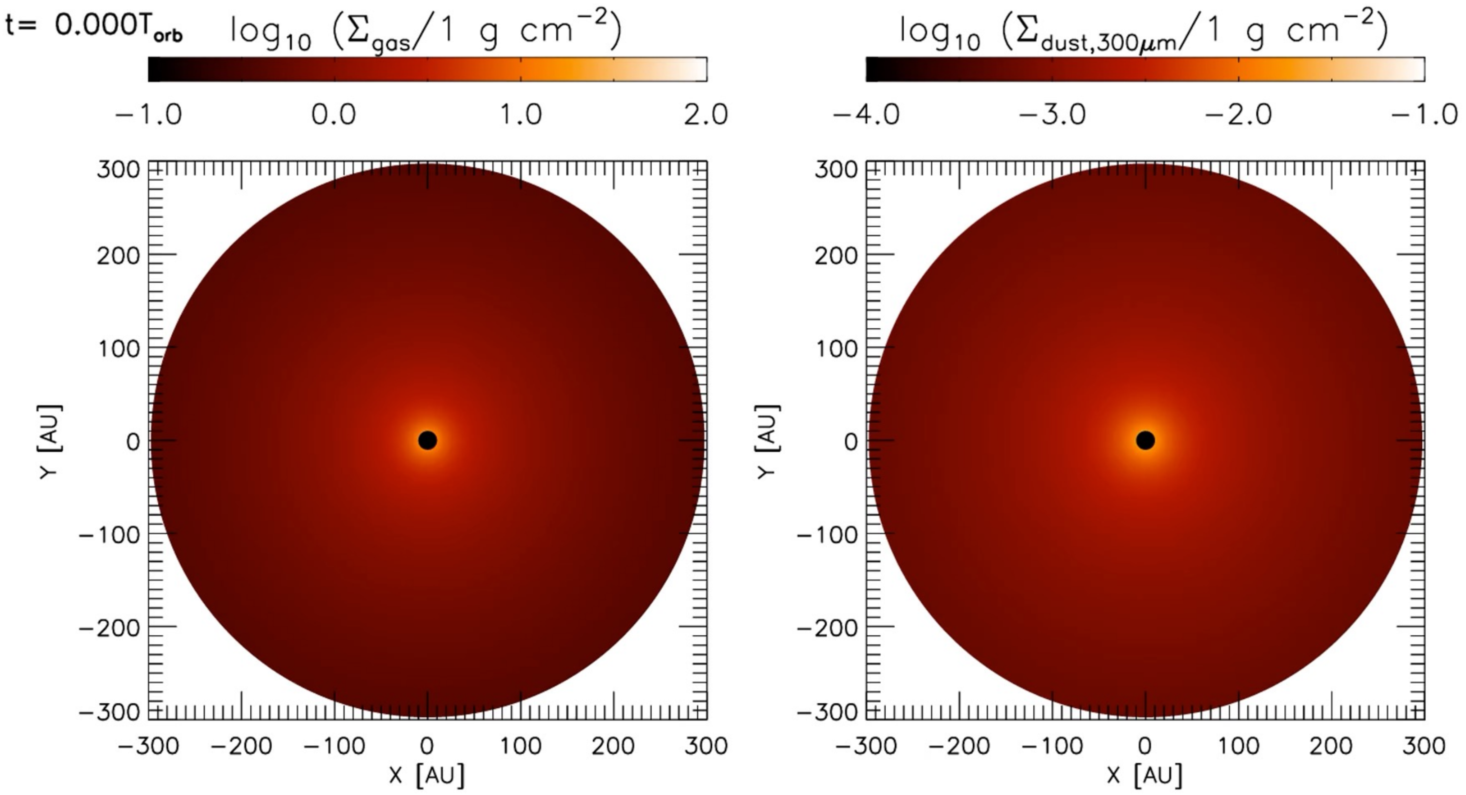
Bae et al. (2017)

Vortices can form at the gap edge.

- Steep rotational velocity gradients at the gap edge can lead to the Rossby wave instability (Lovelace et al. 1999).

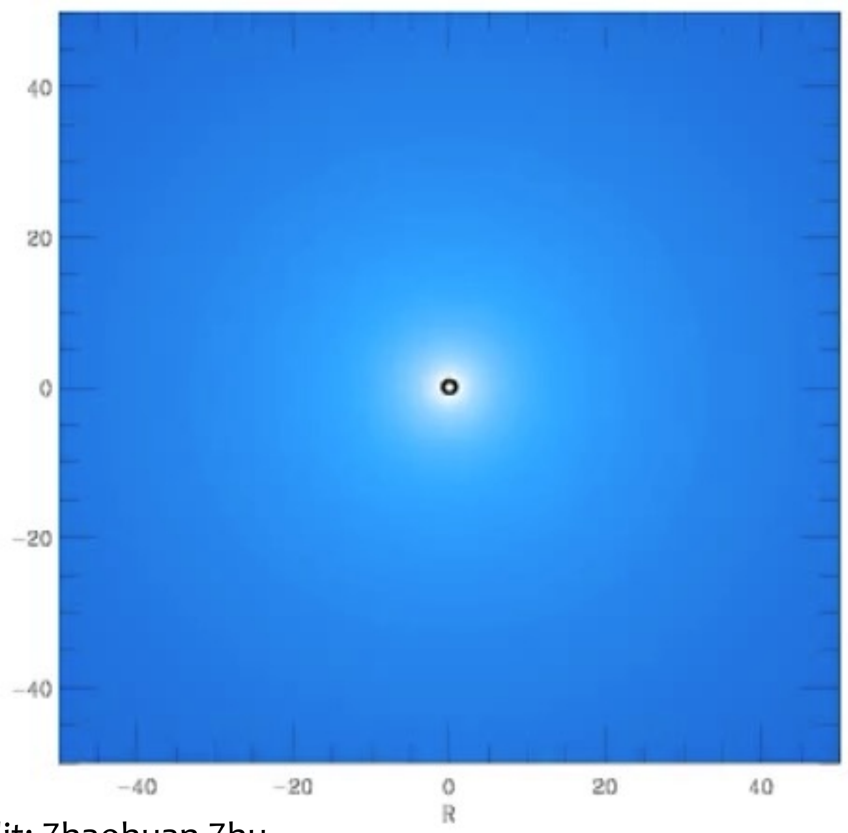


$$\frac{v_{\rm rot}^2}{r} = \frac{GM_\star r}{(r^2+z^2)^{3/2}} + \frac{1}{\rho_{\rm gas}}\frac{\partial P}{\partial r}$$



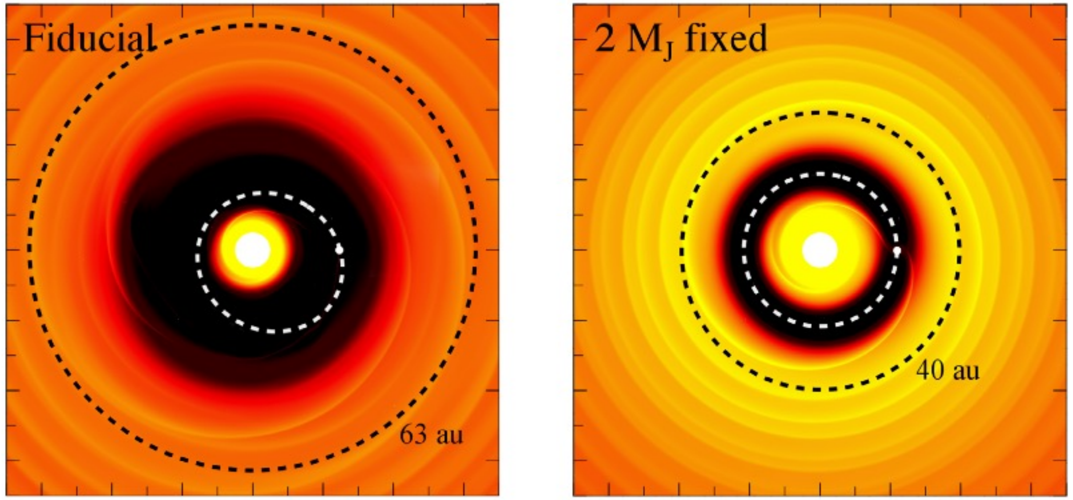
Planets can create a <u>cavity</u>.

- When there are multiple planets (e.g., Zhu et al. 2011)



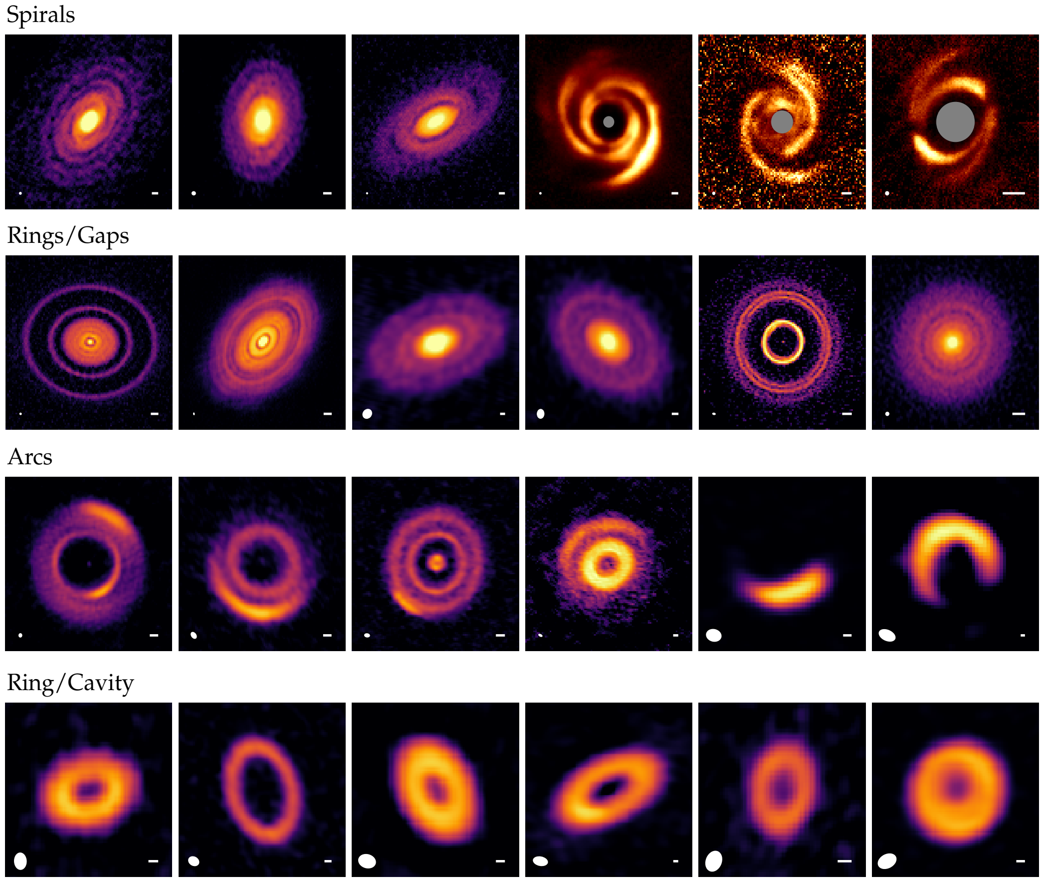
video credit: Zhaohuan Zhu

- When a planet has a large orbital eccentricity (e.g., Muley et al. 2019)



To summarize, planets can create

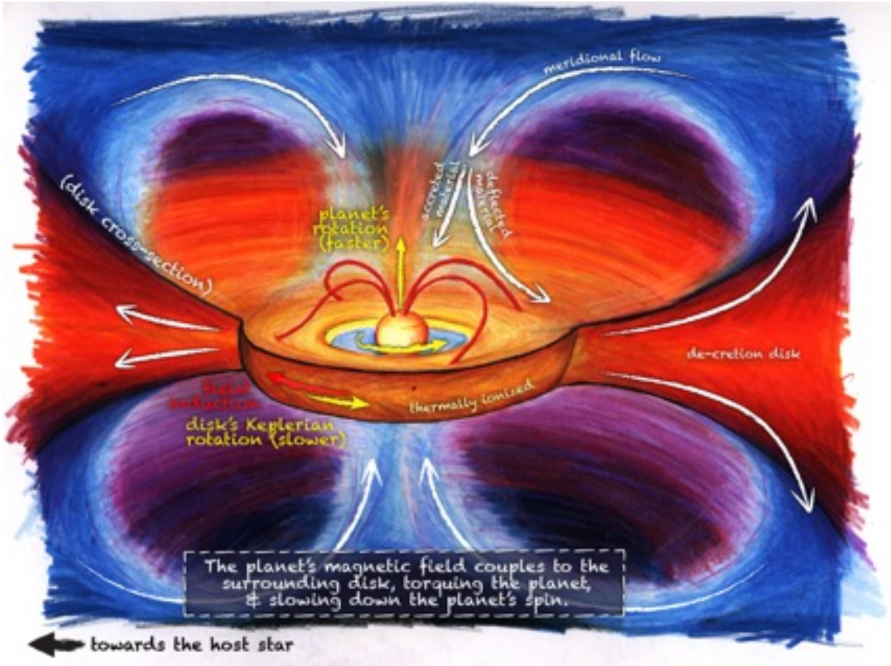
- **<u>spirals</u>** through Lindblad resonances,
- **<u>gaps</u>** as spirals shock the disk gas and exchange angular momentum,
- **<u>vortices/arcs</u>** as the gap edge becomes unstable to the Rossby wave instability.
- **<u>inner cavities</u>** when there are multiple planets in the disk or when a planet has a large orbital eccentricity,



Disk substructures = planets?

We need more direct evidence of planets.

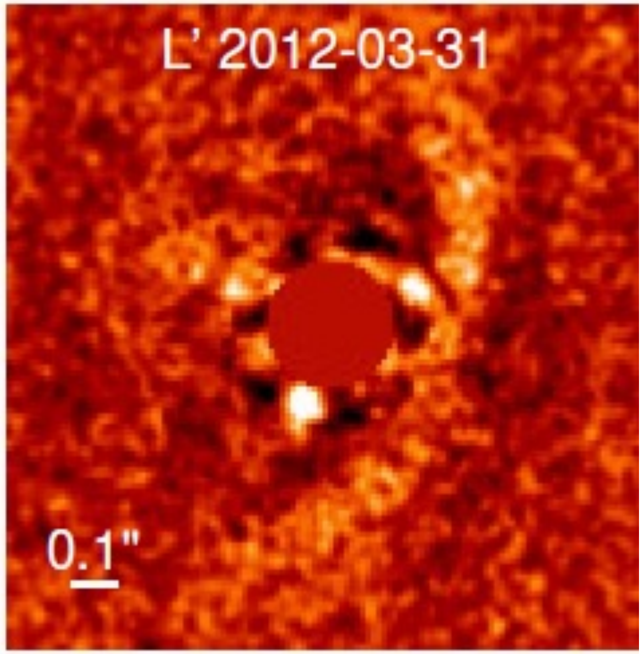
- Thermal emission from the planet
- Circumplanetary disk (CPD)
- Accretion shocks (e.g., Hα)



Batygin (2018)

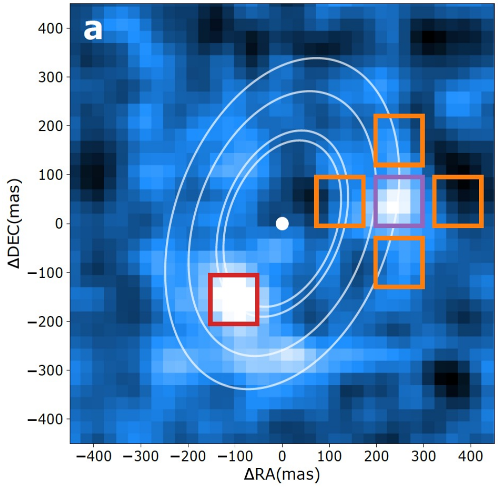
Direct detection of young planets: PDS 70b & c

thermal emission (3.5 μm)



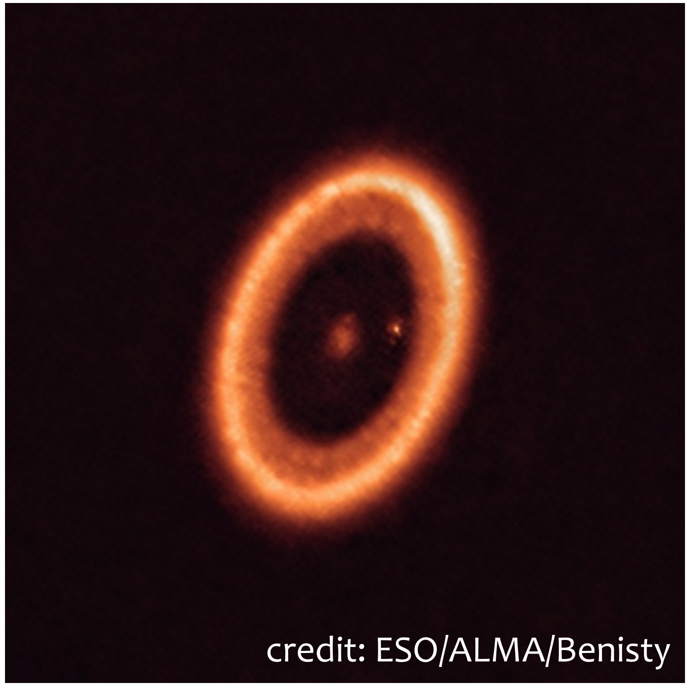
Keppler et al. (2018)

Hα (6563Å)



Haffert et al. (2019)

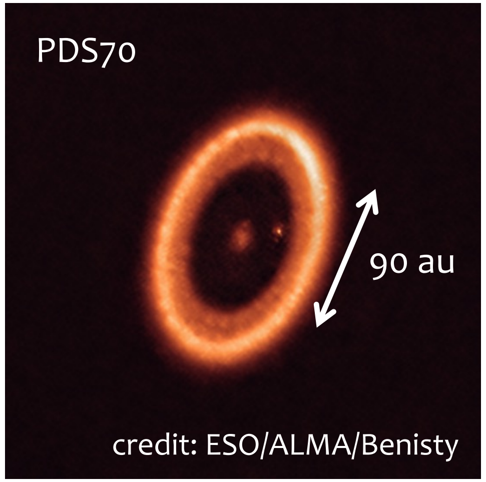
mm continuum (855 μm)

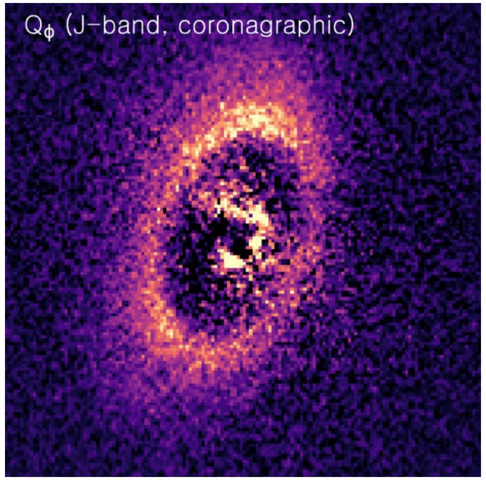


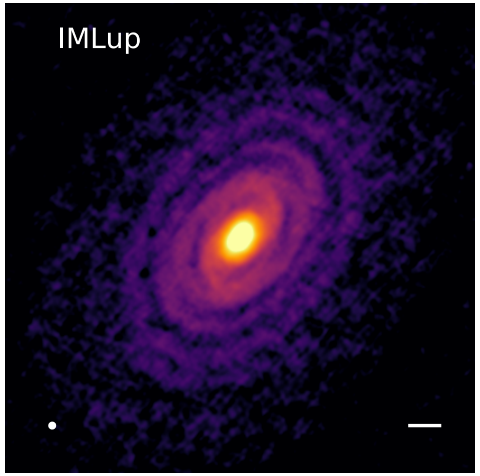
Isella et al. (2019)

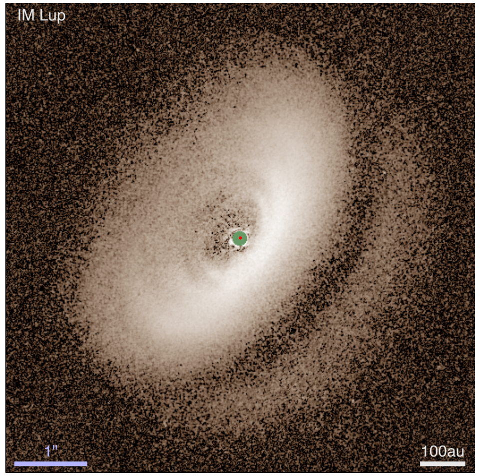
Benisty et al. (in press)

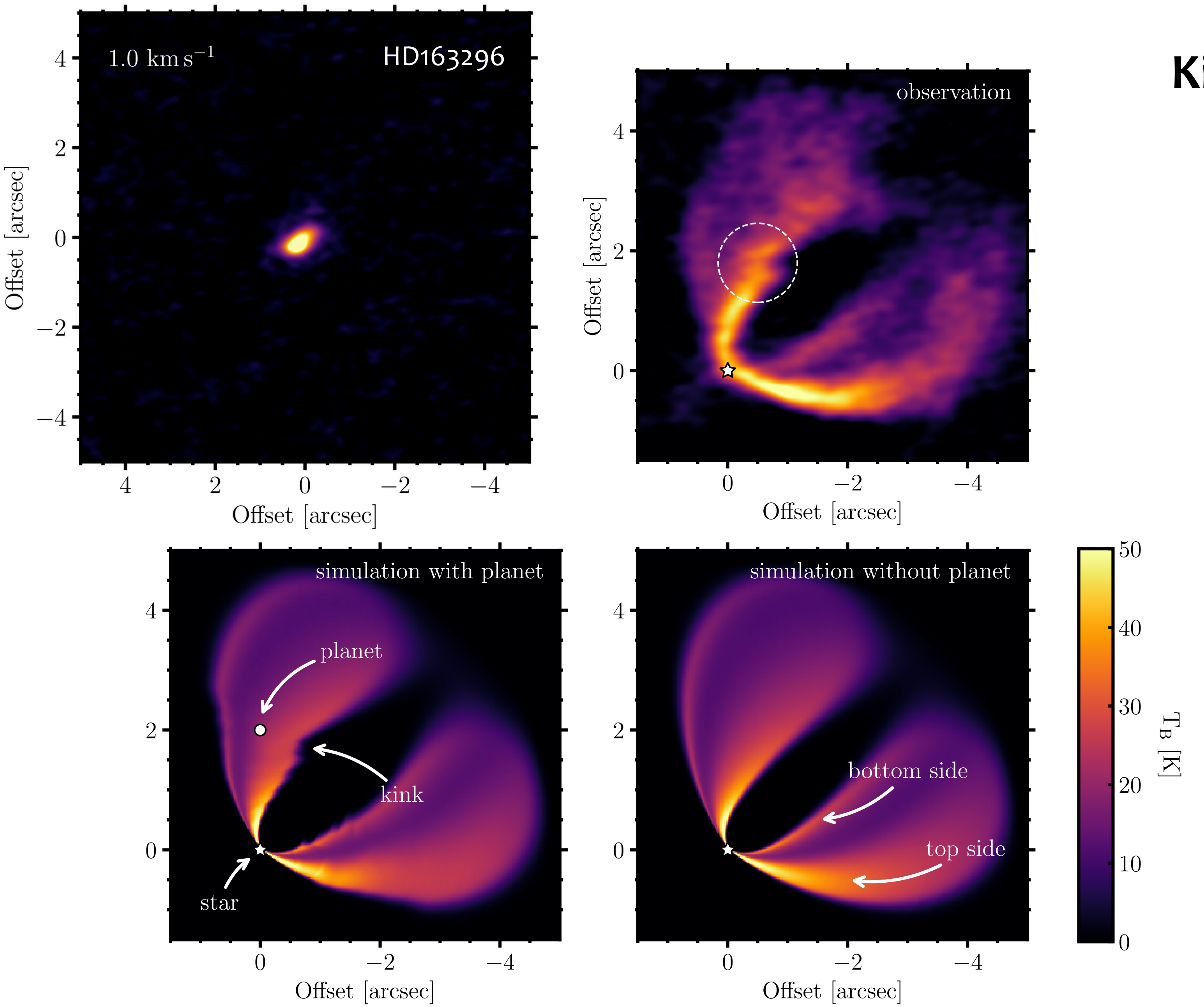
PDS 70 has a favorable condition.











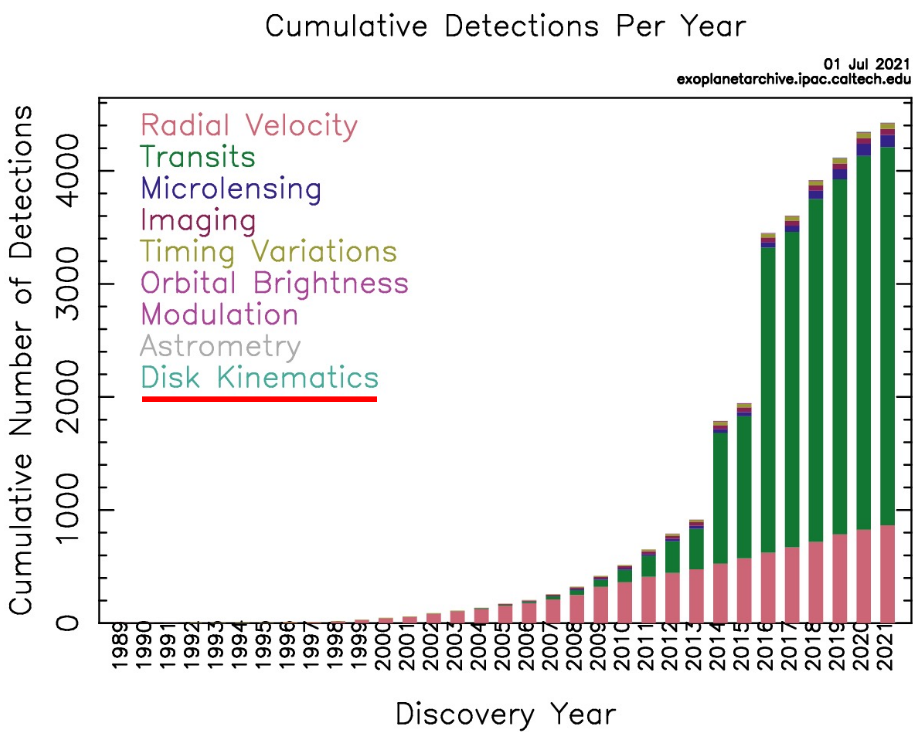
Kinematic Planetary Signature (KPS)

localized velocity perturbations in

ALMA molecular line observations

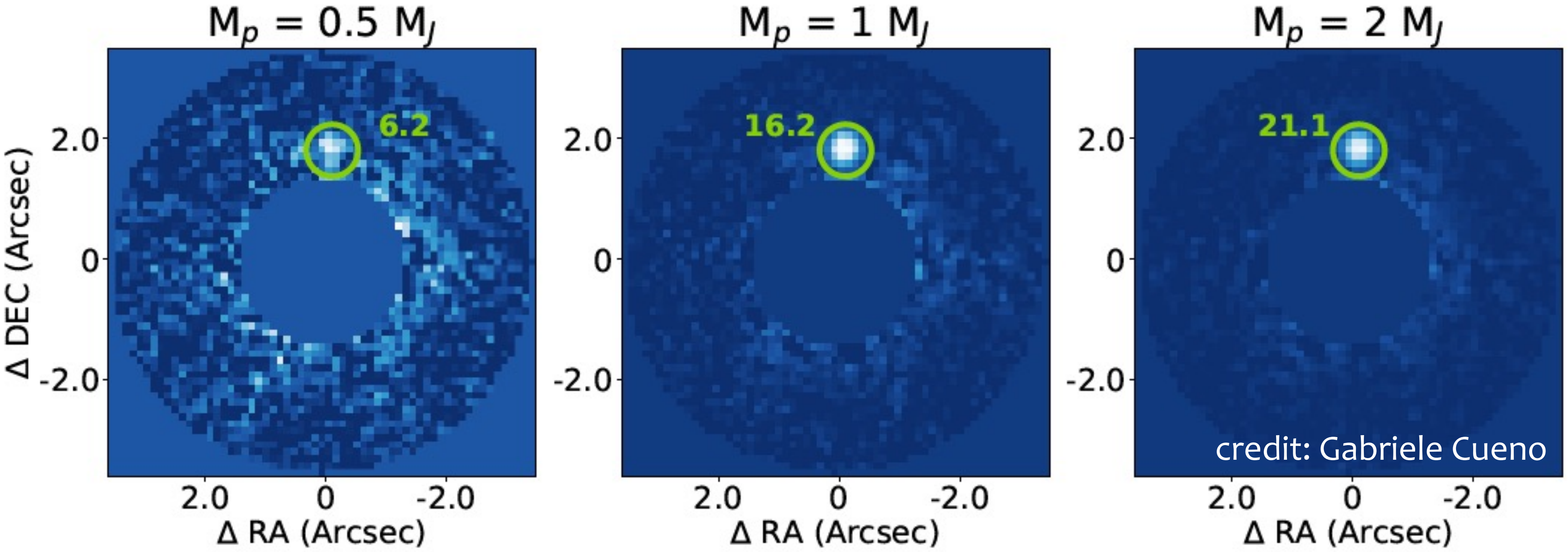
Pinte et al. (2018, 2019, 2020)

Disk Dynamics Collaboration et al. (2020)



Direct detection of young planets with JWST

- JWST 11 μm simulated observation for HD 163296



Summary

- High-resolution observations have revealed various types of substructures in circumstellar disks, reshaping the field.

- Planet-disk interactions offer an intriguing, yet inconclusive explanation to the observed disk substructures.

- More direct detection of planets will help build an unambiguous connection between planets and substructures, but also will help calibrate/improve planet-disk interaction theories.

Questions?

- Live talk on Tuesday July 20 at 10:25 am PT
- Lunch with speakers on Friday July 23 at 2:00 pm PT
- Slack message
- email to jbae@ufl.edu