# Decifering the footprints of exoplanets in protoplanetary disks


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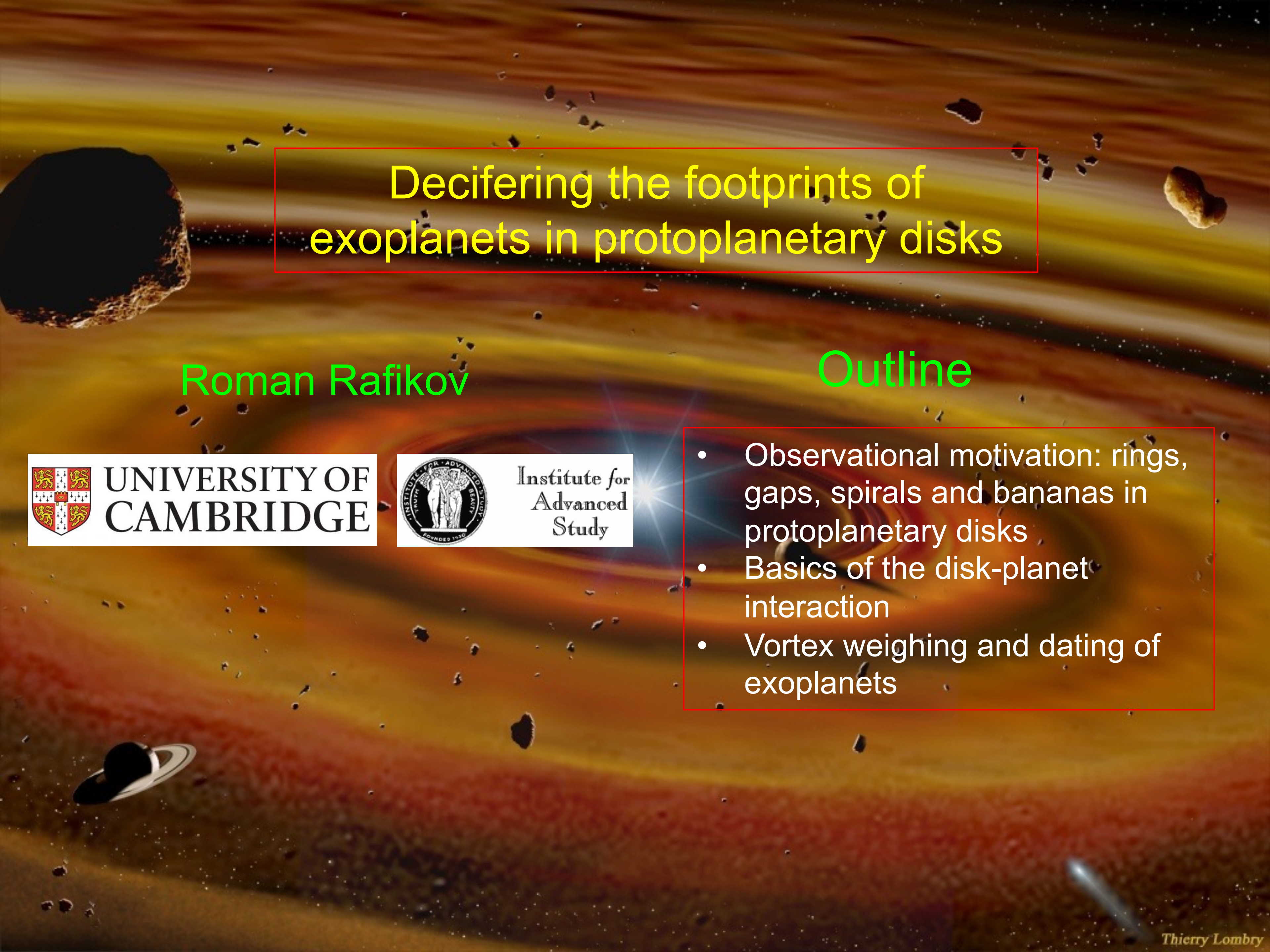
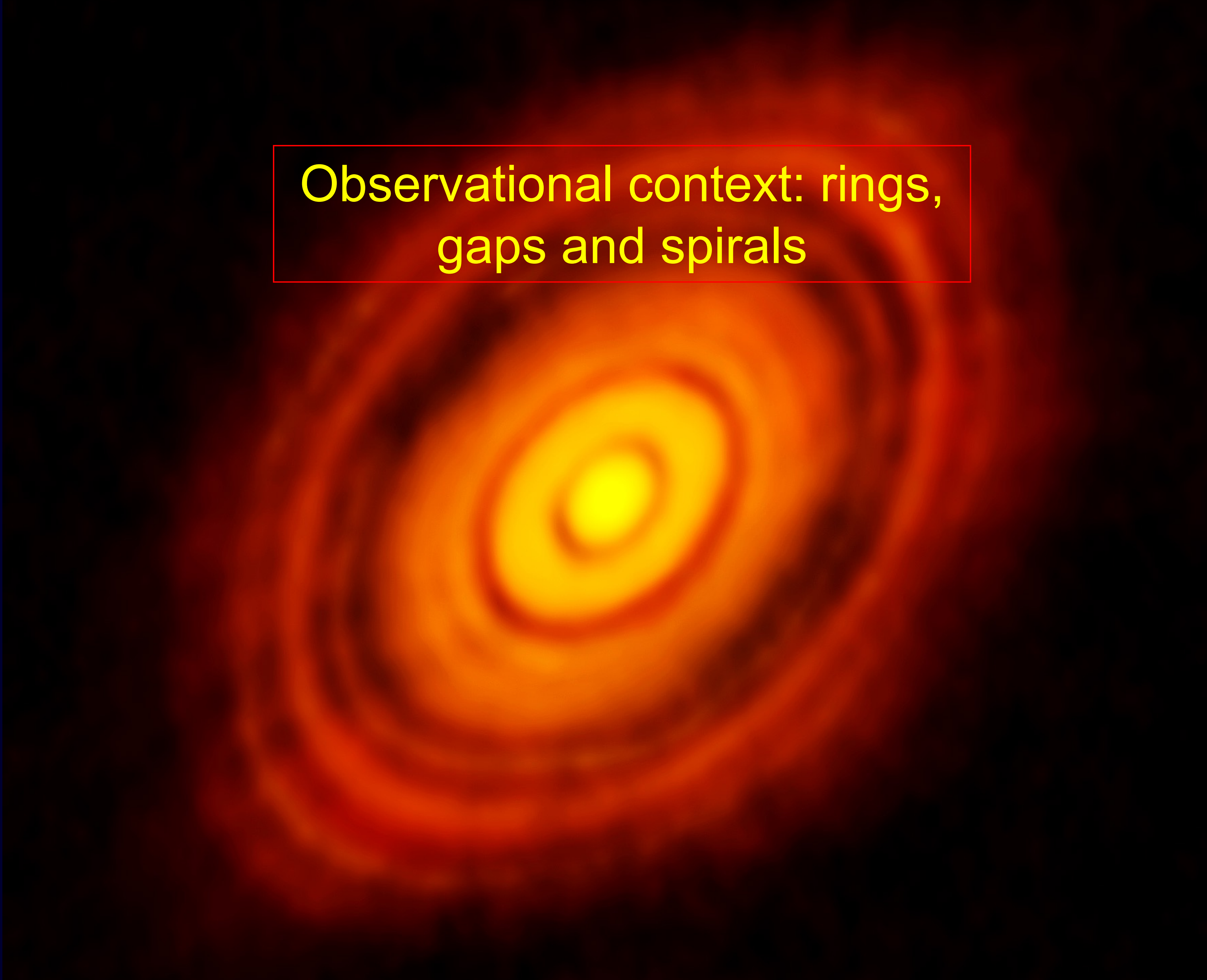
## Outline

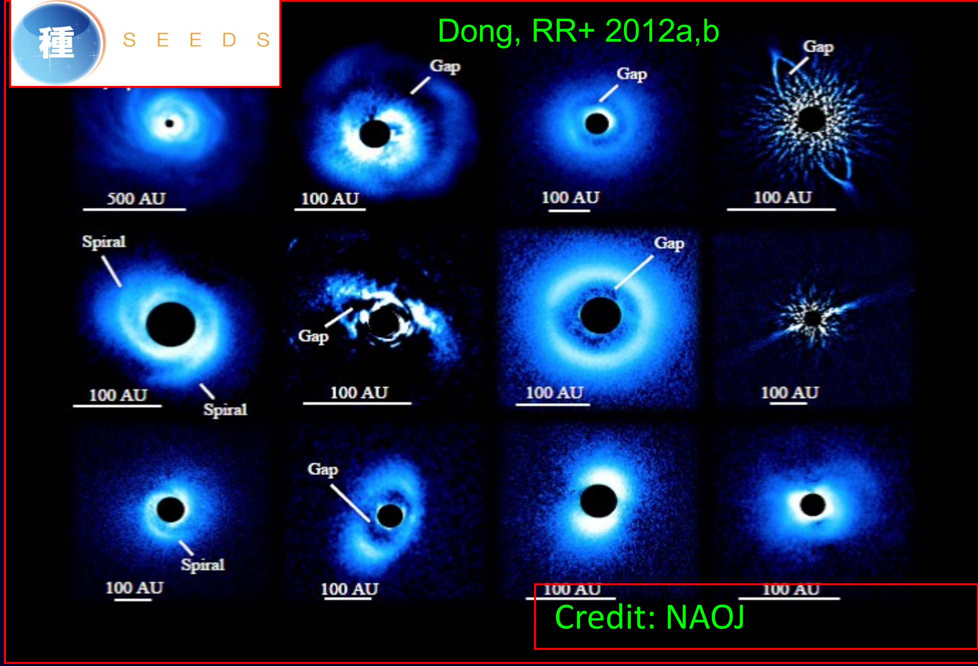
- Observational motivation: rings, gaps, spirals and bananas in protoplanetary disks
- Basics of the disk-planet interaction
- Vortex weighing and dating of exoplanets



# Observational context: rings, gaps and spirals

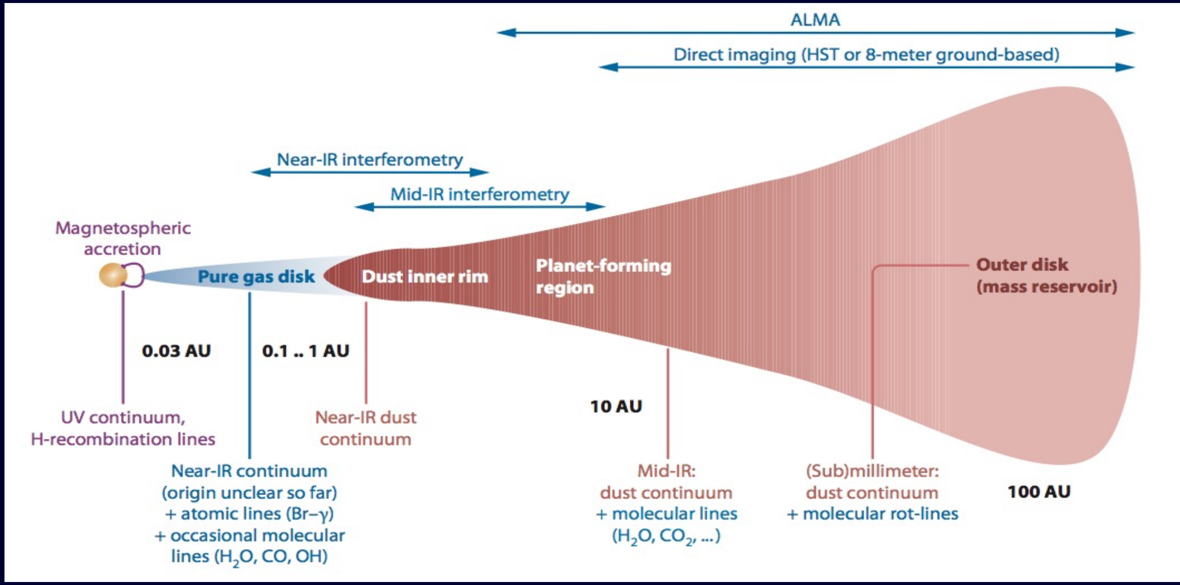


# Protoplanetary disks



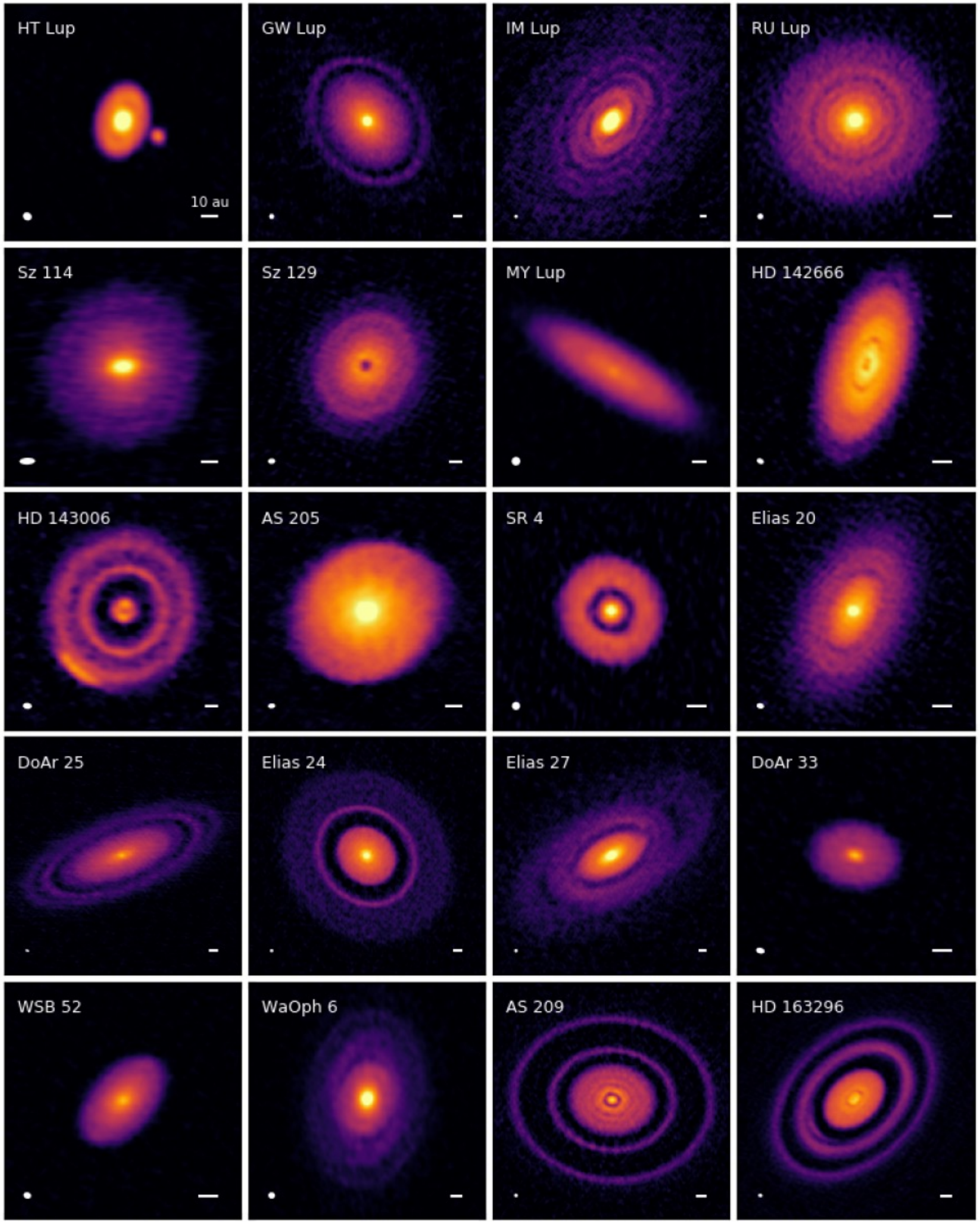

- Gaseous disks in differential rotation around parent stars, masses 0.1-10% of M_star
- Dust (about 1% by mass) is the material for planet building
- Sizes range from 100 to 1000 AU (AU – Sun-Earth distance)
- Disks last for 1-10 Myr
- Exhibit accretion with

  Mdot ~ $10^{-10}$ - $10^{-5}$ Msun / yr
- Cold (10-100 K) – non-ideal MHD effects are very important



# Sub-mm observations: ALMA

- Atacama Large Millimeter Array
- Located at Chajnantor plateau (5 km altitude) in Chile
- 66 movable dishes, 12 m and 7 m in diameter
- Operates at wavelengths between 0.3 to 9.6 mm
- Interferometry with baselines between 150 m to 16 km
- 1.6 bn $$ - the most expensive ground based telescope



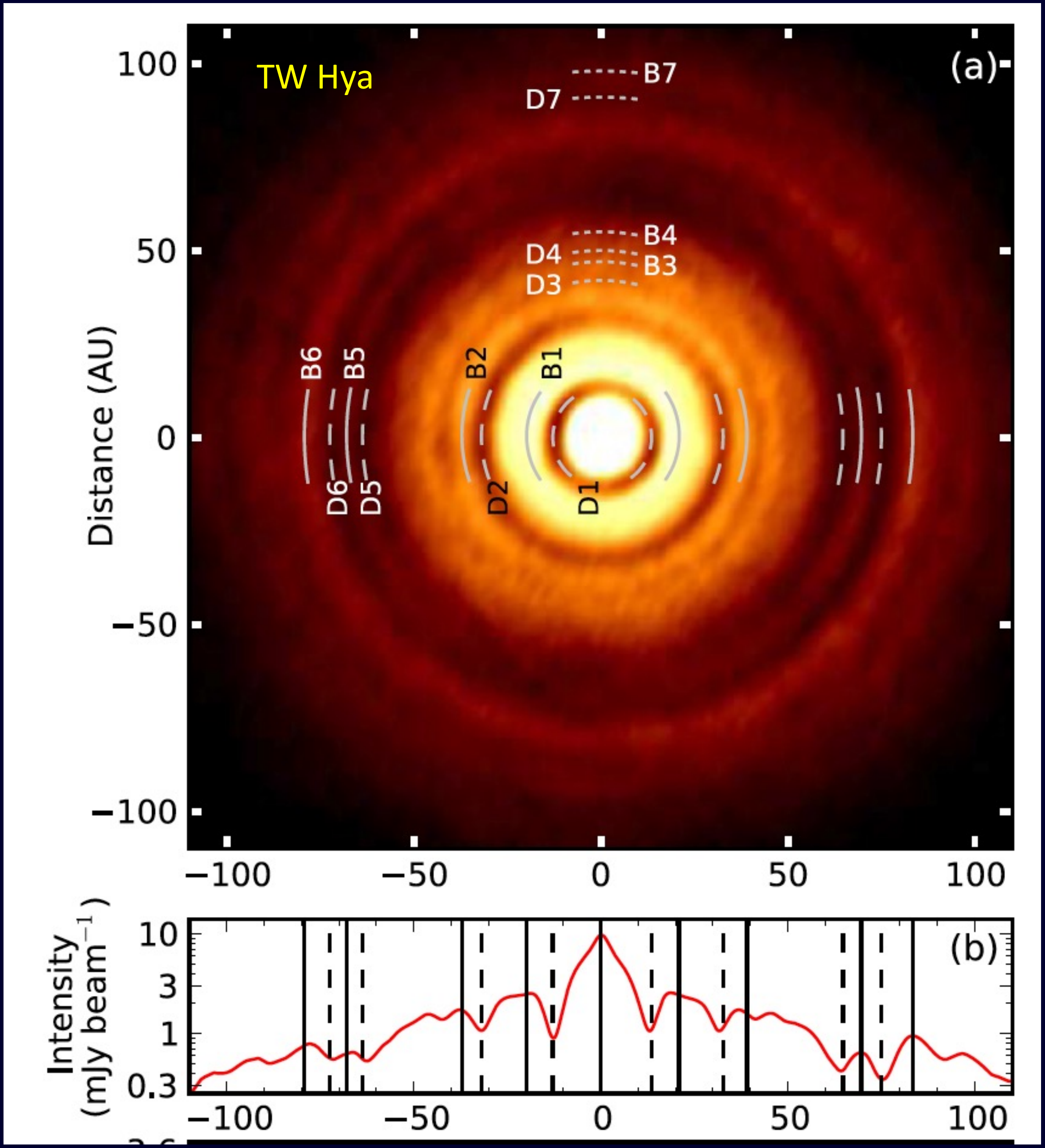

# The Disk Substructures at High Angular Resolution Project (DSHARP)

- Observations of thermal emission by large (~mm) dust particles
- Dramatically increased the number of disks with structures of all sorts
- Found spirals, multiple gaps, multiple rings, asymmetric features, etc.

Andrews et al 2018

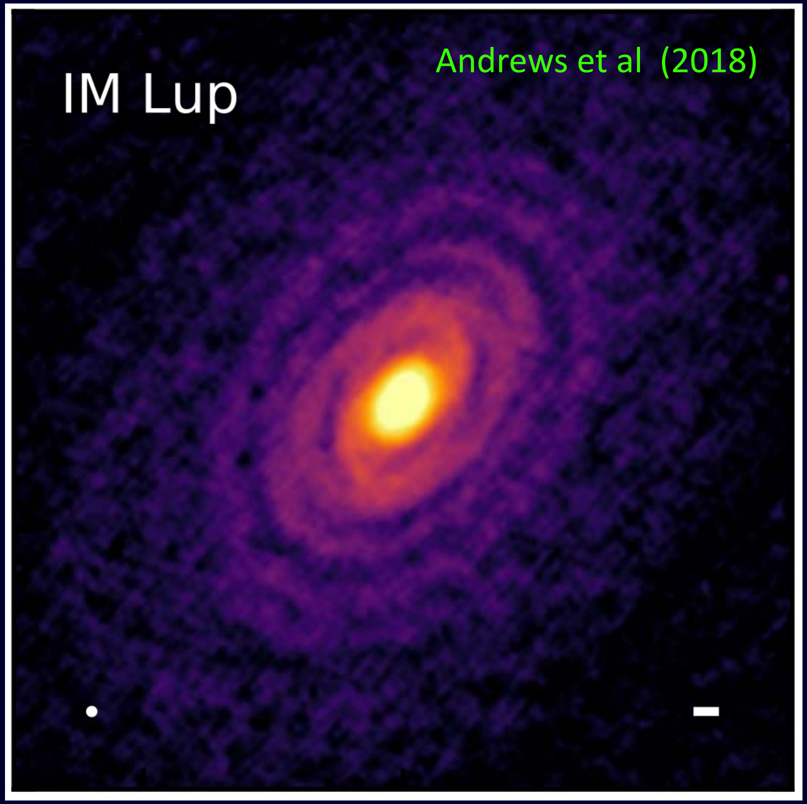
# Multiple rings/gaps

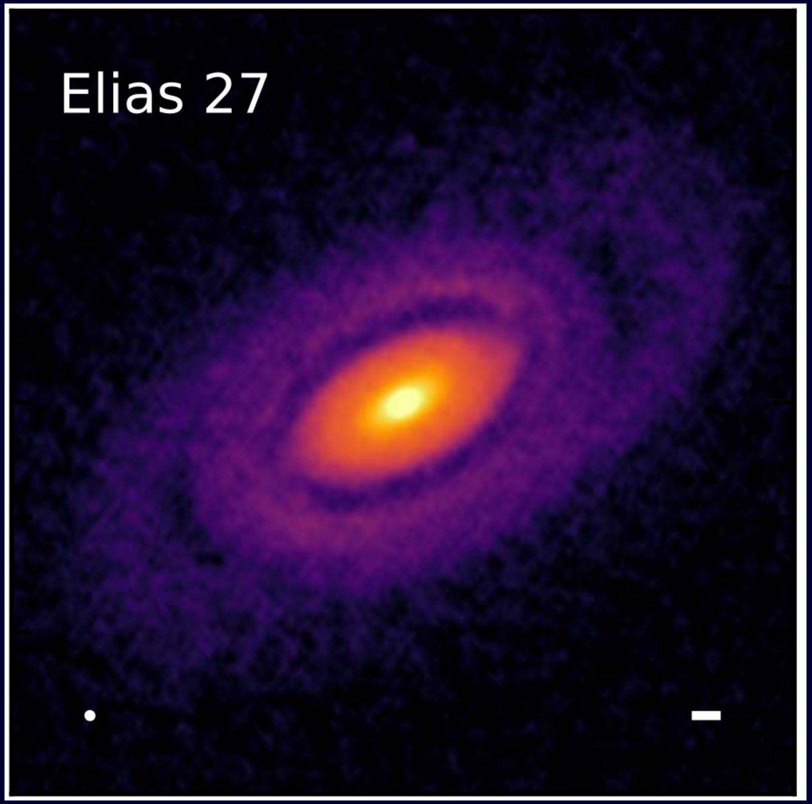
- Multiple annular gaps/rings are very ubiquitous and striking features
- Many ideas for their origin: snow lines, non-ideal MHD effects, etc.
- Gaps can also be naturally created by planets!



# Spiral arms

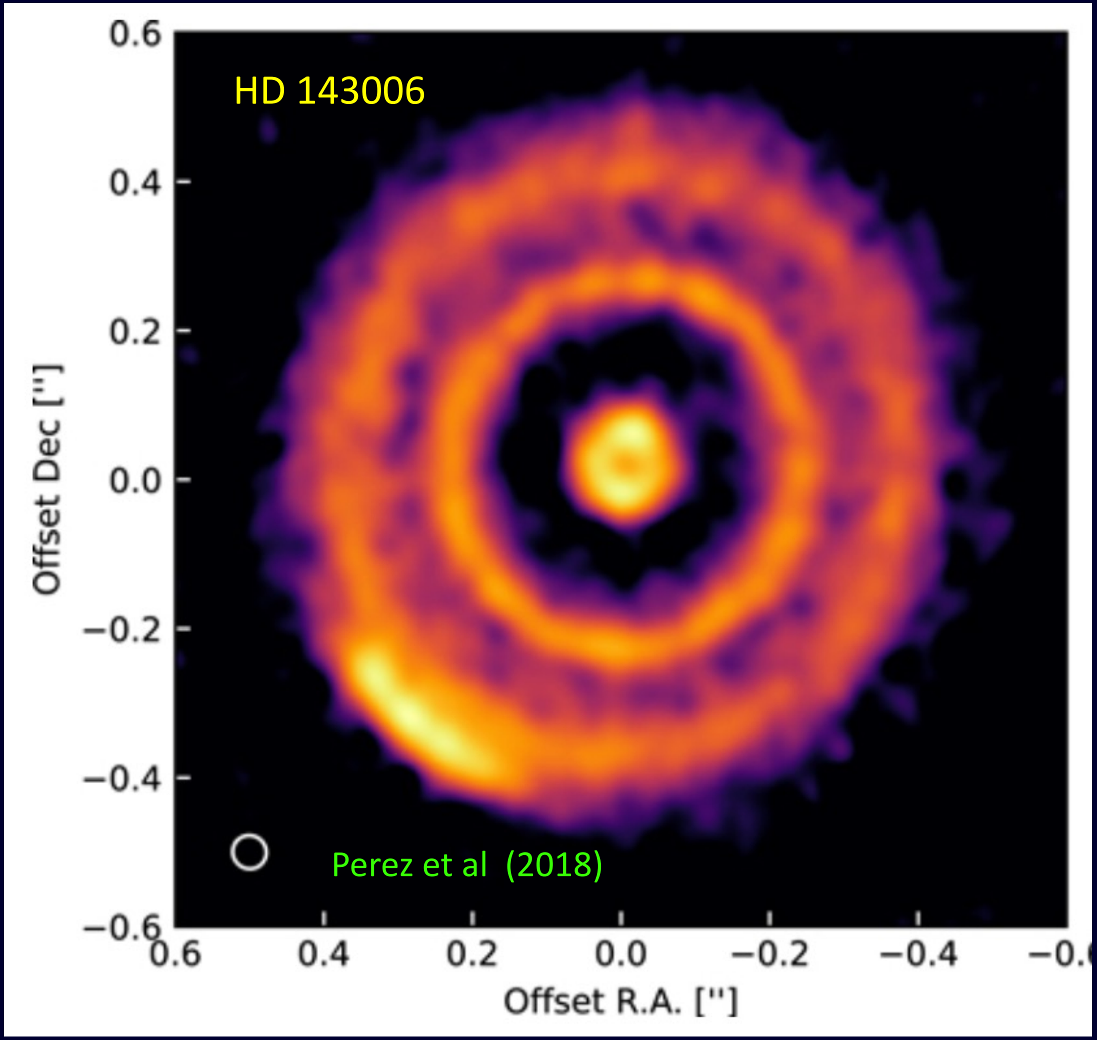
- Some disks show structures that look like spiral arms
- Sometimes visible in sub-mm dust emission with ALMA
- Even more often are seen in directly imaged (in near IR) disks
- Can also be induced by planets!



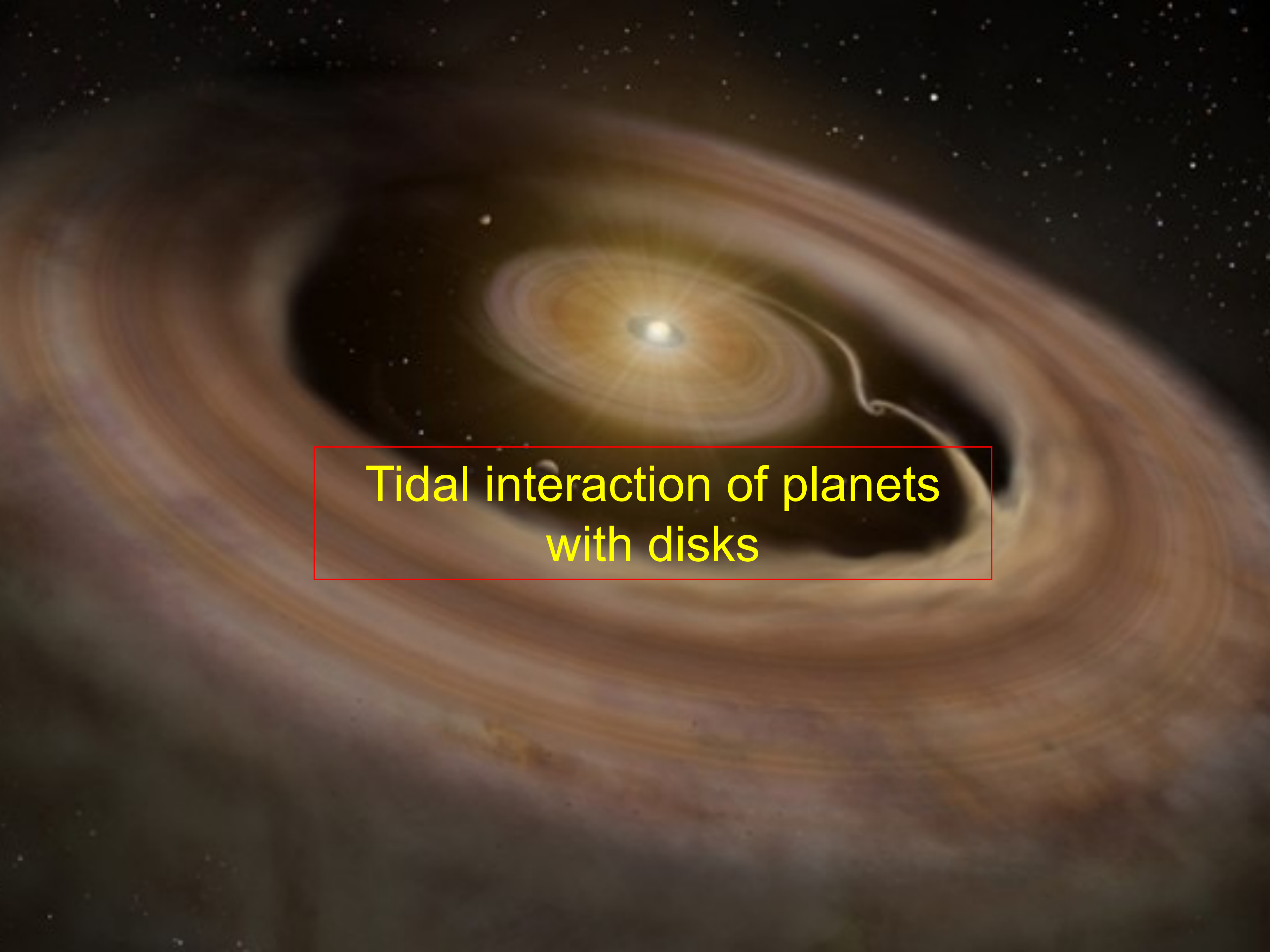



# Banana- or crescent- or clump-like features

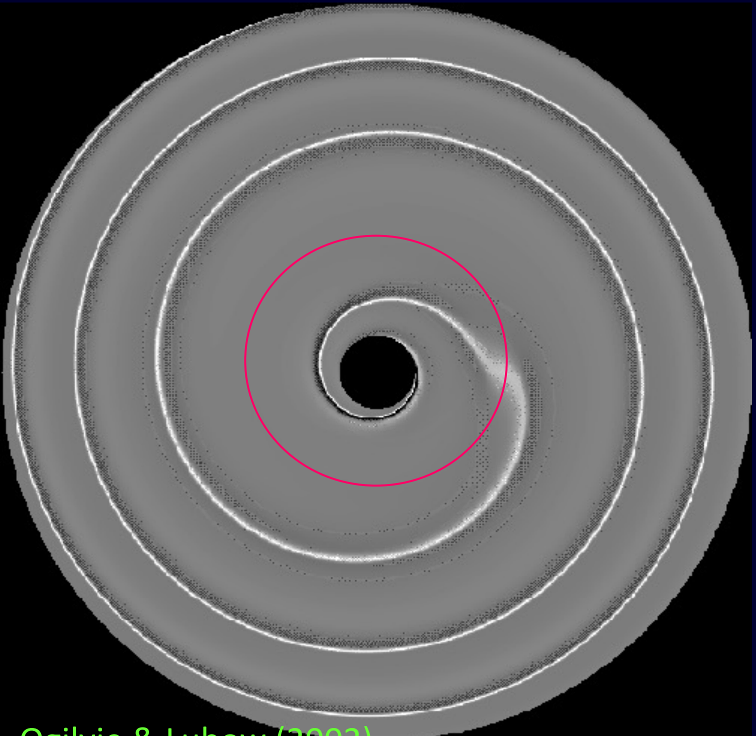
- Asymmetric features, look like a banana or a crescent
- Seen in sub-mm dust emission
- Often associated with rings/gaps
- Can be interpreted as dust concentrations inside fluid vortices that form in the disk
- Vortices can also be induced by planets!



# Tidal interaction of planets with disks



# Planet-disk interaction (Lin & Papaloizou 1979; Goldreich & Tremaine 1980)



Ogilvie & Lubow (2002)

- Tidal interaction of planet with the disk leads to the formation of spiral density perturbation – a density wave

- Sound wave modified by differential rotation; leads (trails) planet in the inner (outer) disk

- Dispersion relation neglecting disk self-gravity

$$\omega^2 = m^2[\Omega(r) - \Omega_p]^2 = \Omega^2 + c_s^2 k_r^2$$

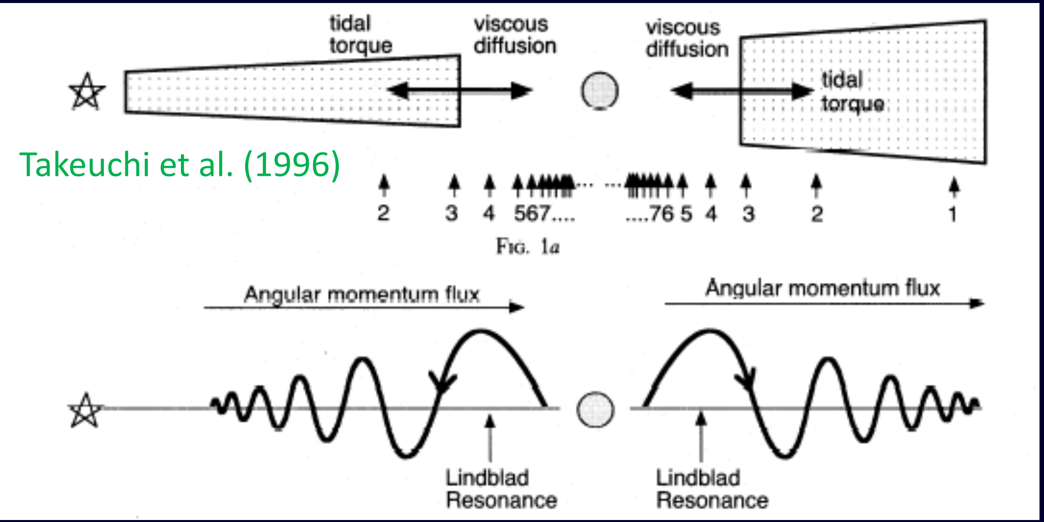
$$\delta f = C \exp\left[im(\phi - \phi_p) + i \int^r k_r(r')dr'\right]$$

- Excited at Lindblad resonances ($r=r_{LR}$) where $k_r=0$ and

$$m\,|\Omega(r_{\rm LR}) - \Omega_p| = \Omega(r_{\rm LR})$$

- Density wave (spiral) is a result of interference of many azimuthal harmonics, excited at different LRs

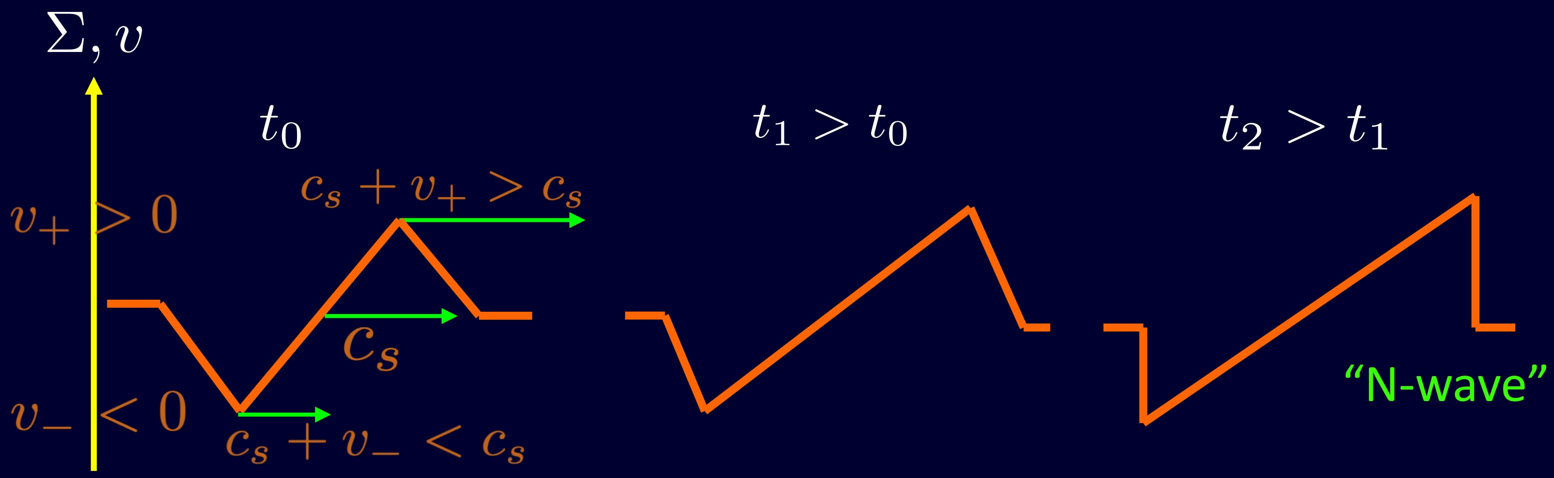
- One-armed spiral is expected to form (Ogilvie & Lubow 2002)




Takeuchi et al. (1996)

# Beyond linear

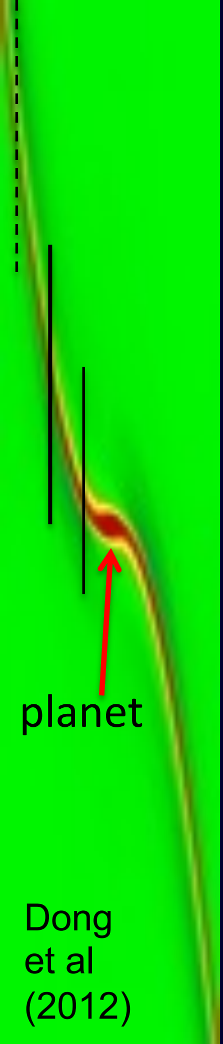
- As all sound waves, density waves exhibit non-linear evolution
  (Goodman & Rafikov 2001; Rafikov 2002)




- Propagation speed is different for different parts of the wave profile

- This leads to the wave profile steepening

- Eventually wave profile breaks → shock formation.



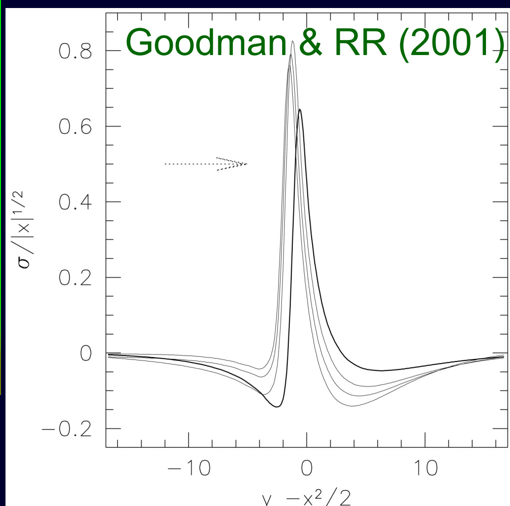

- Nonlinearity is weak when $M_p \lesssim M_{\rm th}$

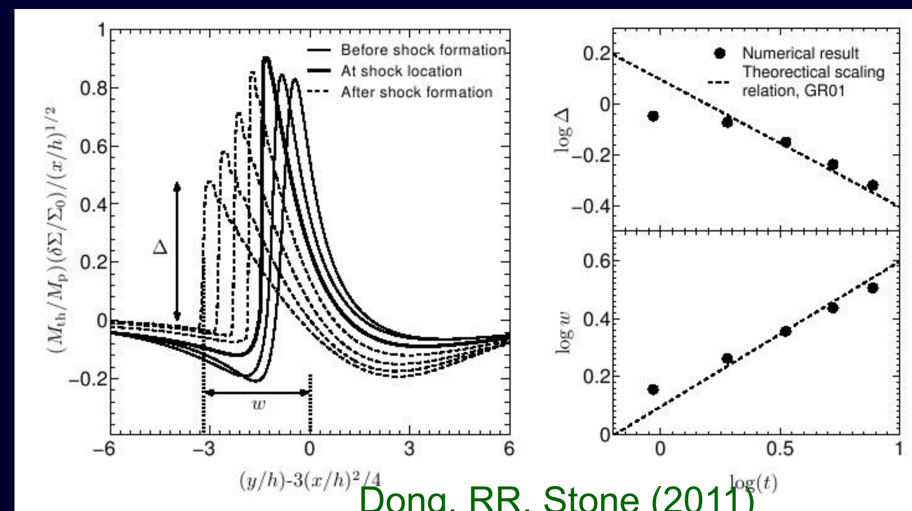
$$M_{\rm th} = \frac{c_s^3}{G\Omega_p} \approx 12\, M_\oplus \left(\frac{c_s}{1\ \mathrm{km\ s^{-1}}}\right)^3 \left(\frac{M_\odot}{M_\star}\right)^{1/2} \left(\frac{r_p}{\mathrm{AU}}\right)^{3/2}$$

- Can then separate linear excitation of the wave and its subsequent nonlinear propagation, shocking and damping (Goodman & Rafikov 2001)

Linear excitation, (1-2)h from the planet

Non-linear evolution: steepening, breaking -> dissipation and profile broadening

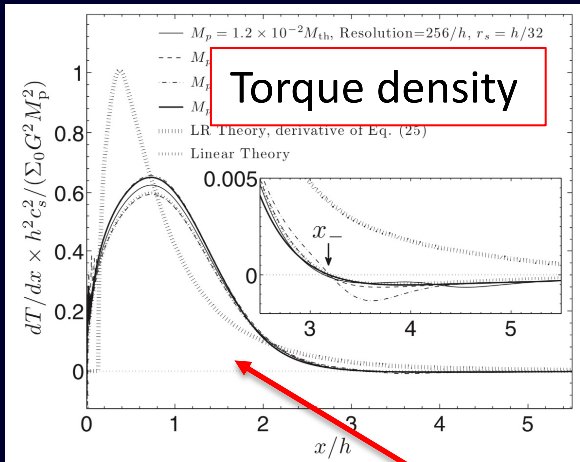



- Wave shocks after traveling a certain distance – shocking length - from the planet (Goodman & Rafikov 2001)

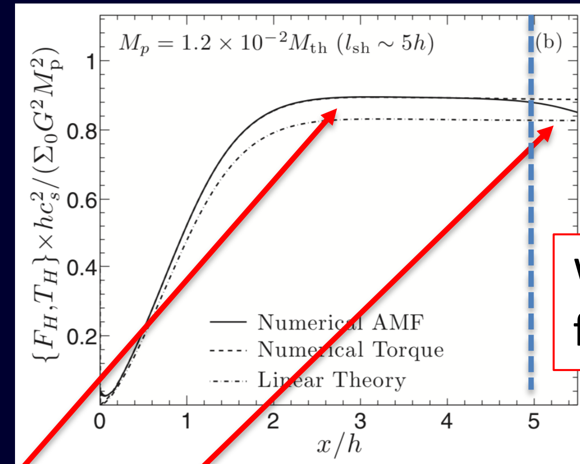
$$l_{\rm sh} \approx 0.8 \left(\frac{\gamma+1}{12/5}\frac{M_p}{M_{\rm th}}\right)^{-2/5} h$$

# Angular momentum transport

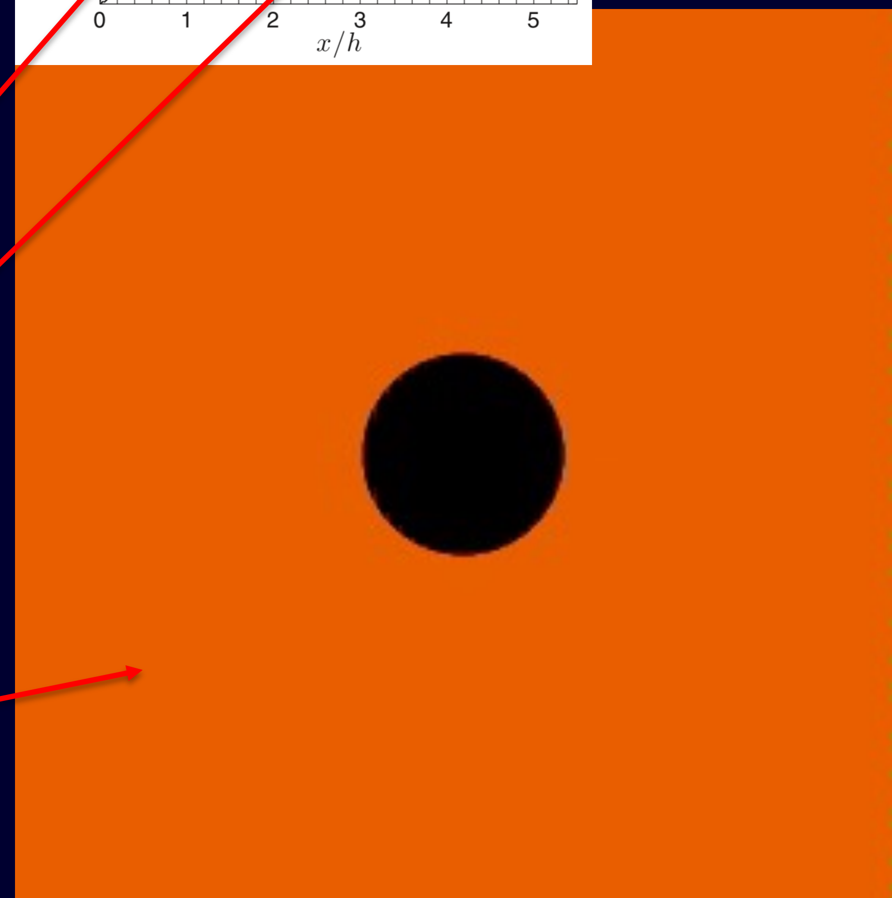



Dong et al (2012)

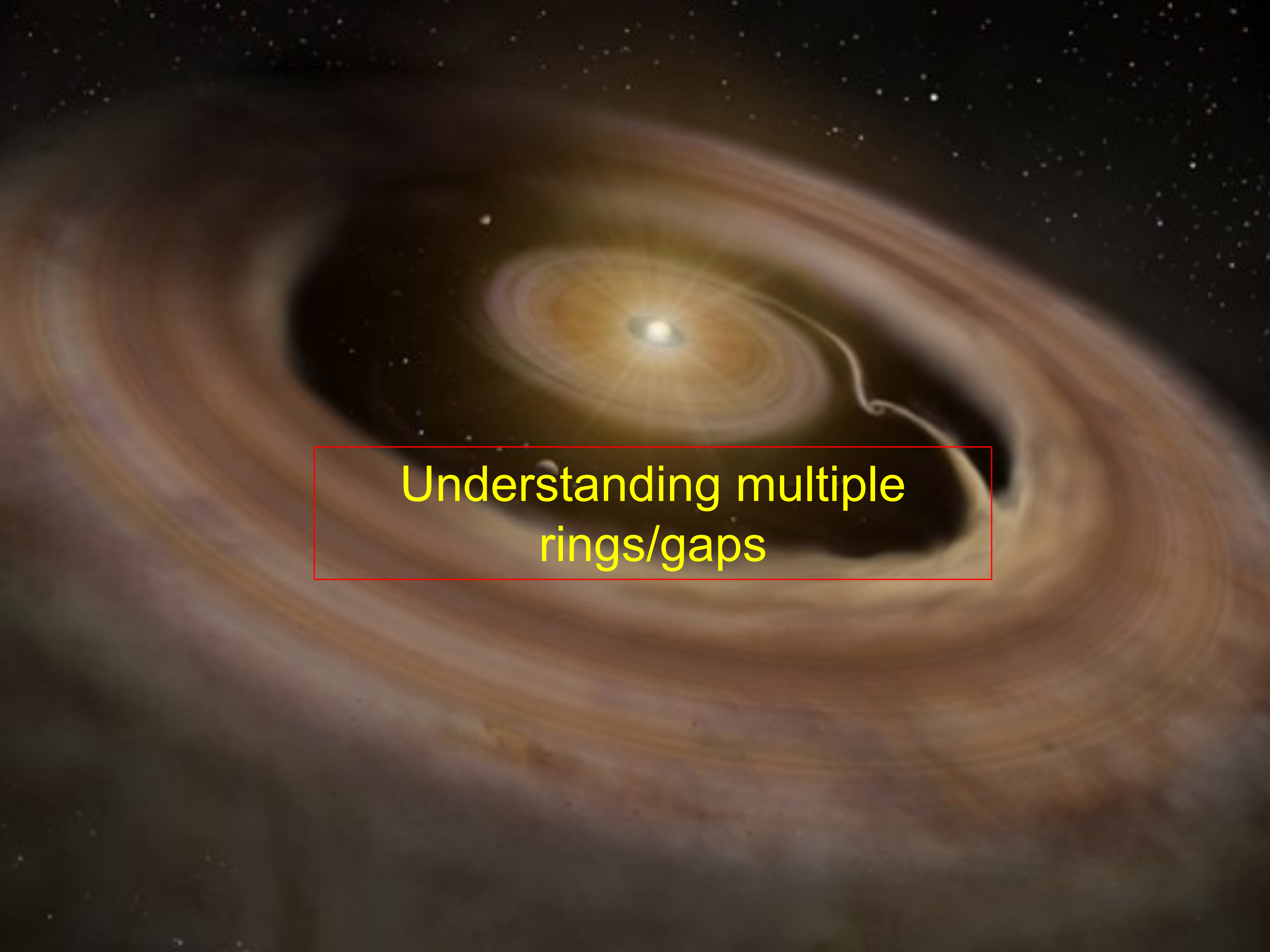
Linear excitation




Dong et al (2012)



- Planetary torque injects angular momentum into the density wave
- Without dissipation, wave preserves its AM flux
- After shock forms, wave dissipates, transfers its AM to the disk fluid
- Only then can affect the disk – gas gets repelled away from the planetary orbit
- This leads to gap formation

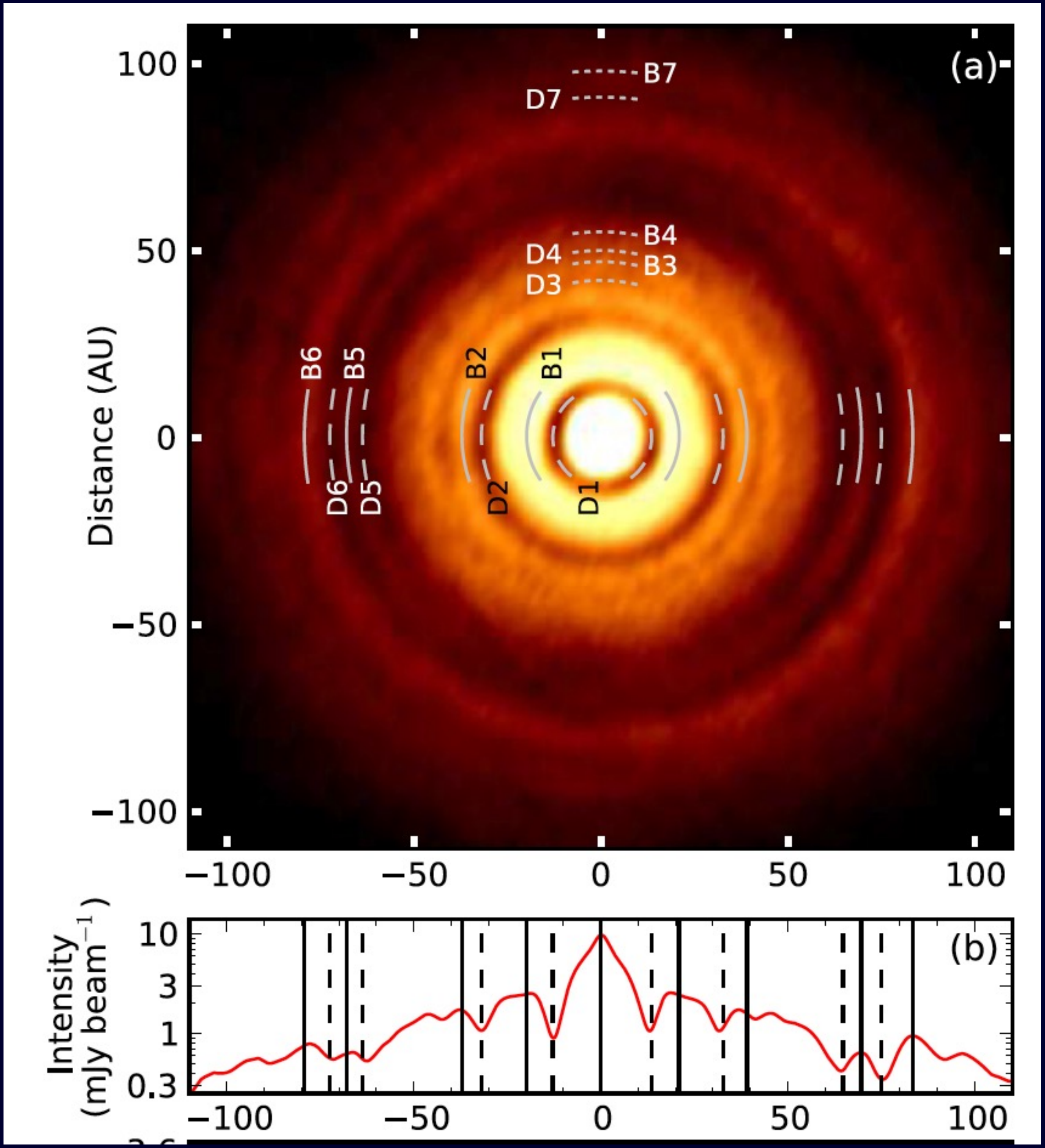

Understanding multiple
rings/gaps

- Multiple annular gaps/rings are very ubiquitous and striking features

- Many ideas for their origin: snow lines, non-ideal MHD effects, etc.

- Gaps can also be naturally created by planets!

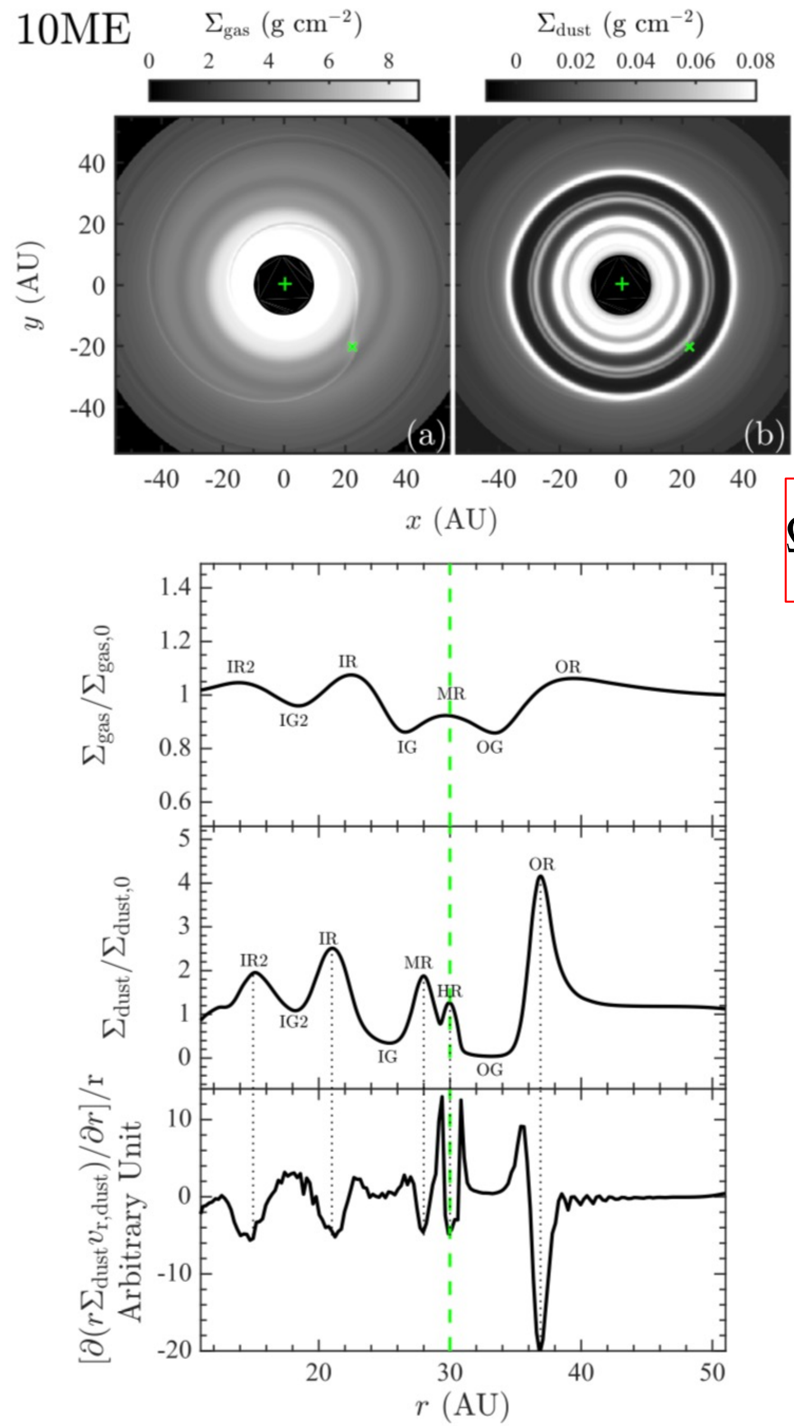
Does one need multiple planets to create multiple gaps?



# Not necessarily!

- Simulations show that even a single low-mass planet can produce multiple annular perturbations of gas density
- Gas pressure maxima are natural trapping sites for dust grains
- This leads to high-contrast annular concentrations of dust grains - multiple rings/gaps!

But what is causing gas density perturbations in the first place?




Dong et al (2017)

see also Zhu et al (2014), Bae et al (2016)

$$\Omega^2 = \Omega_K^2 + \frac{1}{\rho}\frac{dP}{dr}$$

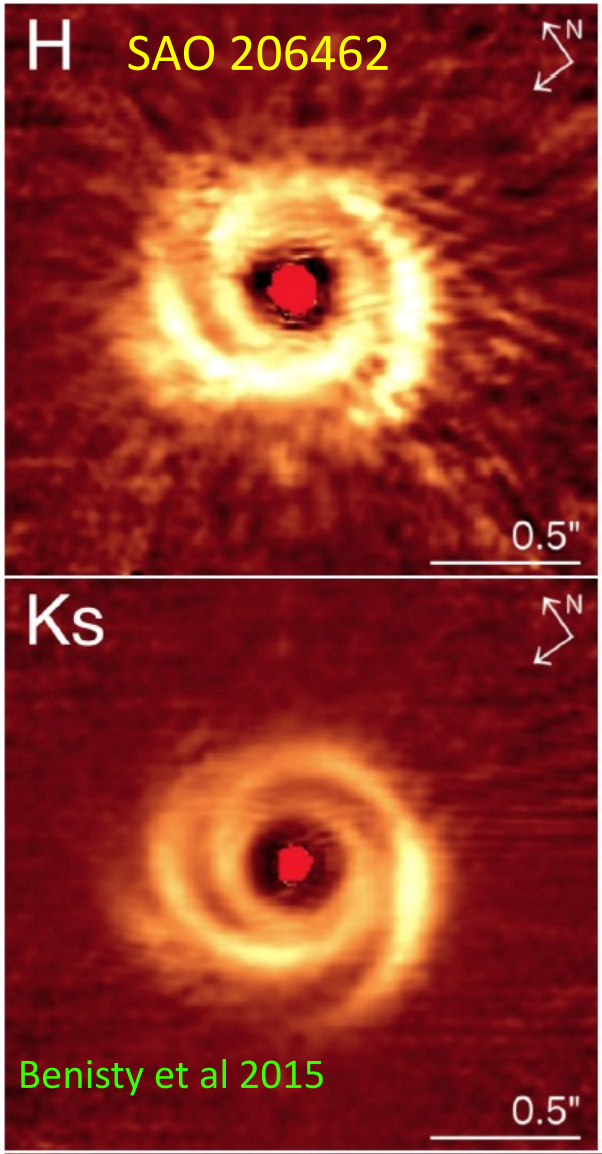
Small perturbations of gas density

Very significant perturbations of dust density

# Another observational puzzle: multiple spirals

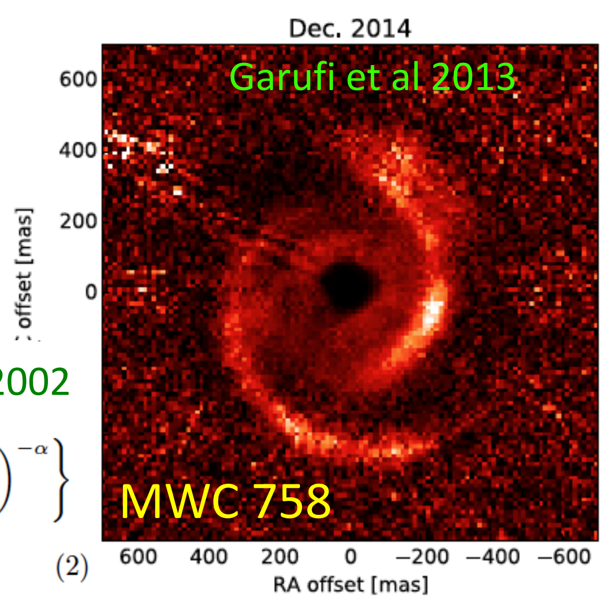
Spirals in near-IR due to scattering by small (~micron) dust grains

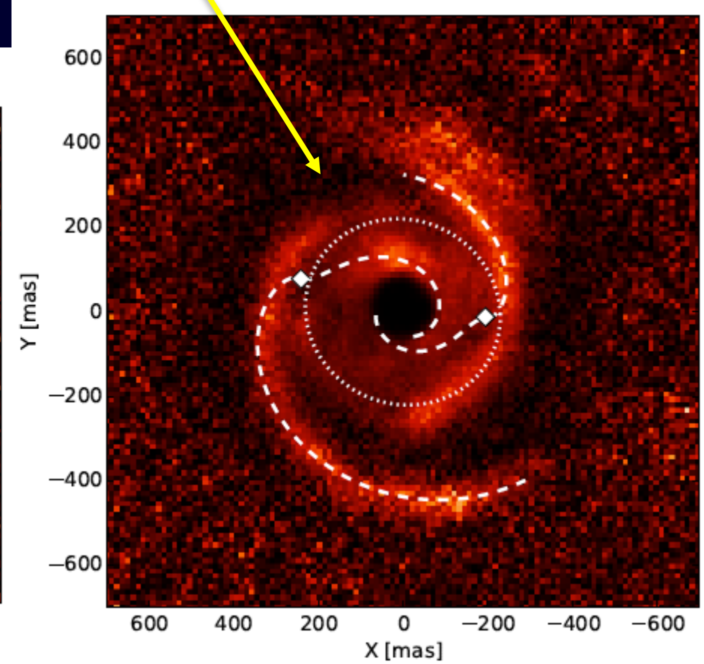
- Strong m=2 spirals, quite open
- Reflect structure of the disk surface
- Can't be naturally explained by the classical linear theory of planet-driven density waves




Rafikov 2002

$$\phi(R)=\phi_p-\frac{\mathrm{sgn}(R-R_p)}{h_p}\times\left[\left(\frac{R}{R_p}\right)^{1+\beta}\left\{\frac{1}{1+\beta}-\frac{1}{1-\alpha+\beta}\left(\frac{R}{R_p}\right)^{-\alpha}\right\}-\left(\frac{1}{1+\beta}-\frac{1}{1-\alpha+\beta}\right)\right] \qquad (2)$$

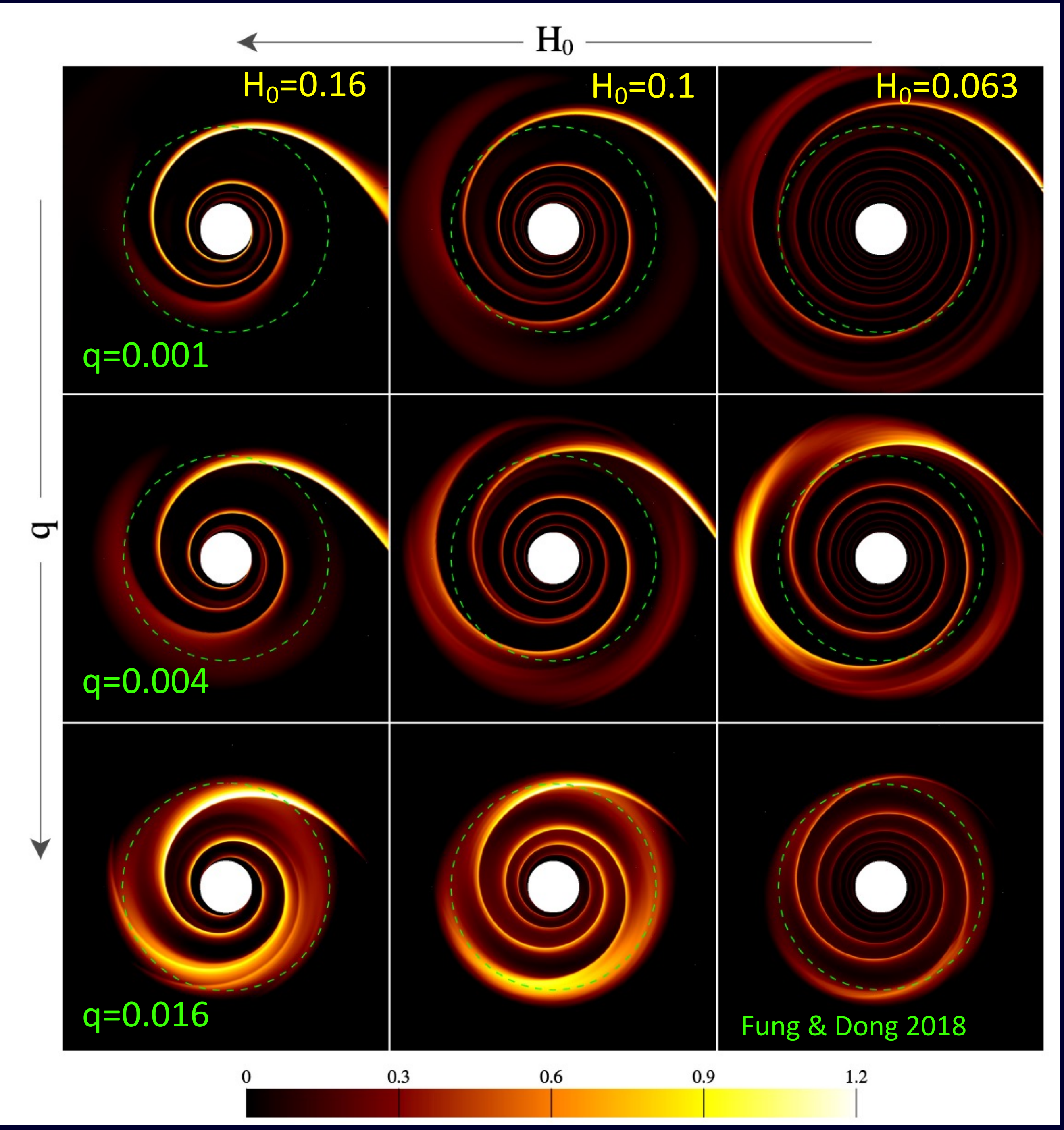


Multiple spirals are also seen in simulations

- Largely support observations. At odds with linear theory.
- Simulations fully account for the nonlinear effects

Does this suggest an important role of the density wave nonlinearity for the production of multiple spirals?



# Multiplicity of spirals

- Initially, multiplicity was believed to be caused by the nonlinear effects (Fung & Dong 2018) – natural in light of the simulation results

- Bae & Zhu (2018) suggested, based on numerical experiments (simulations), that higher order spirals may be driven by the intricate interference pattern of different perturbation harmonics excited in the disk by the planet.

- But interference is a linear phenomenon! Miranda & Rafikov (2019) re-evaluated the problem in a fully linear setup, using semi-analytical theory

$$k_r \approx \pm m \frac{\Omega - \Omega_p}{c_s}, \quad \text{thus}$$

$$\exp\left[im(\phi - \phi_p) + i\int^r k_r(r')dr'\right] \rightarrow$$

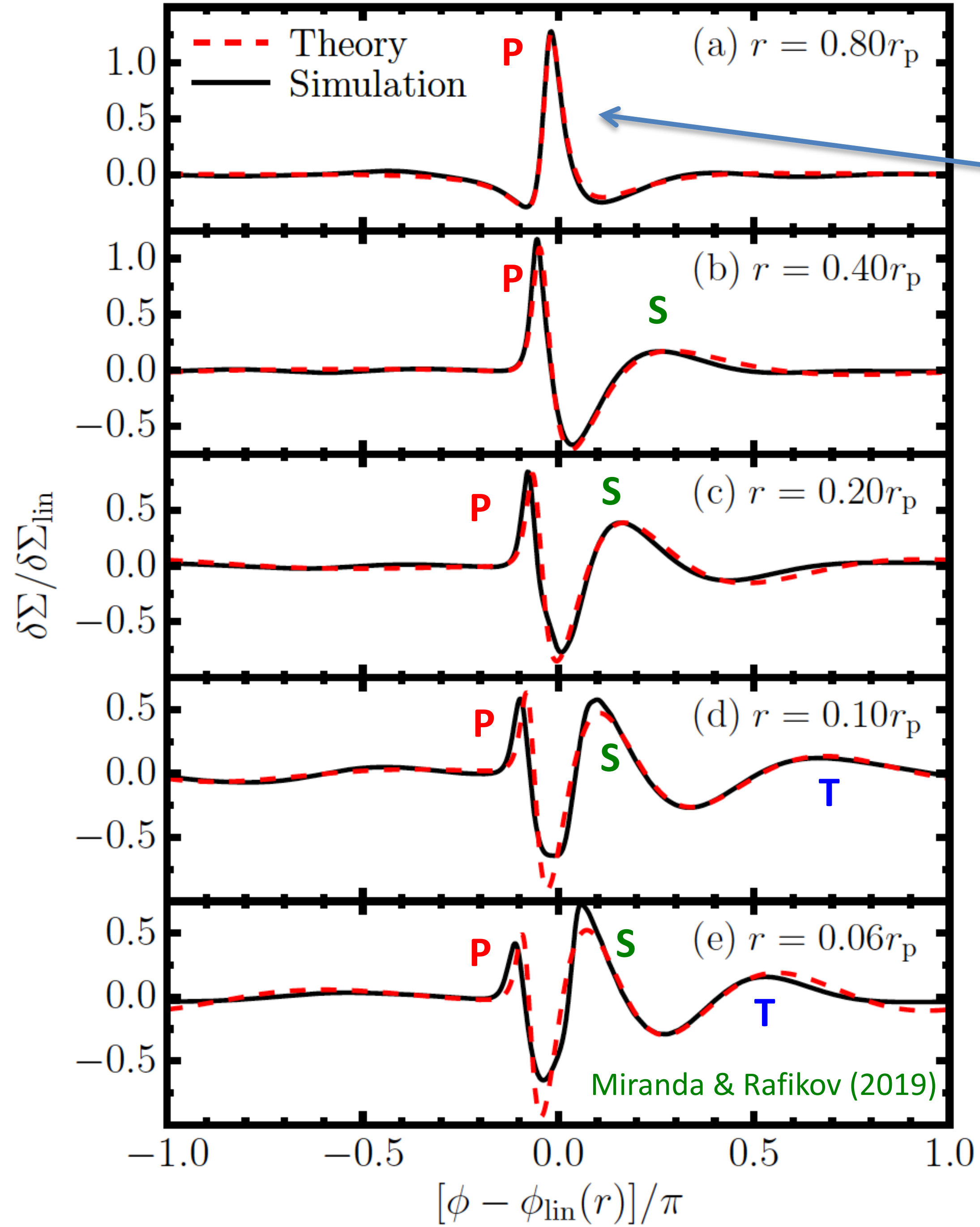
$$\exp\left[im\left(\phi - \phi_p - \int^r \frac{\Omega(r') - \Omega_p}{c_s(r')}dr'\right) + i\psi_m(r)\right]$$

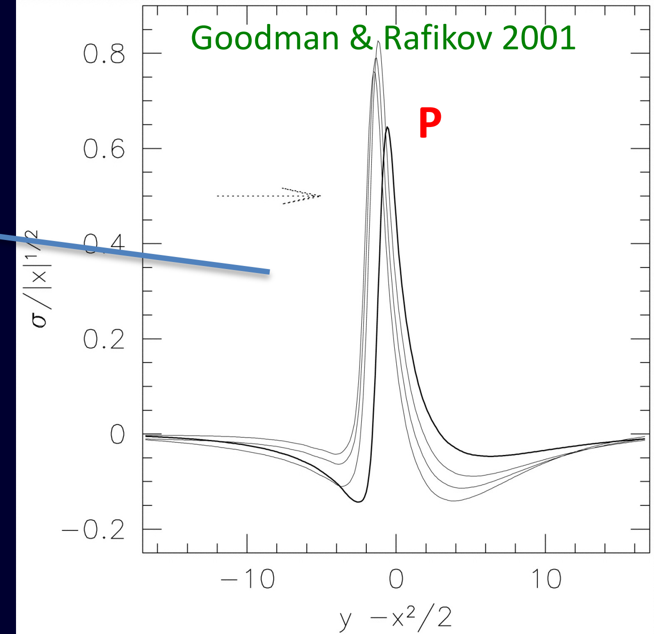
Phase residual

Classical prediction for spiral shape

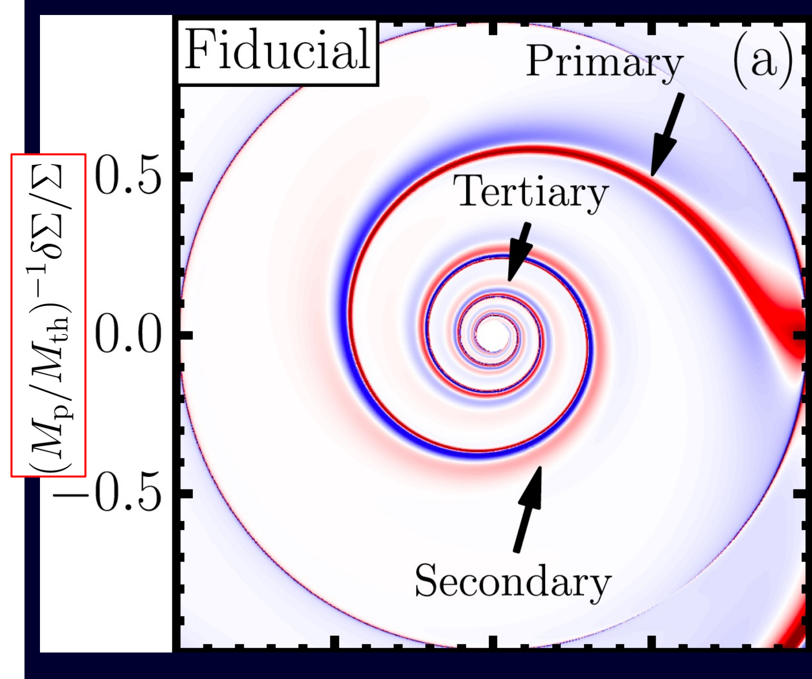
- Found the emergence of multiple arms in purely linear regime – nonlinearity is not the primary cause of these structures

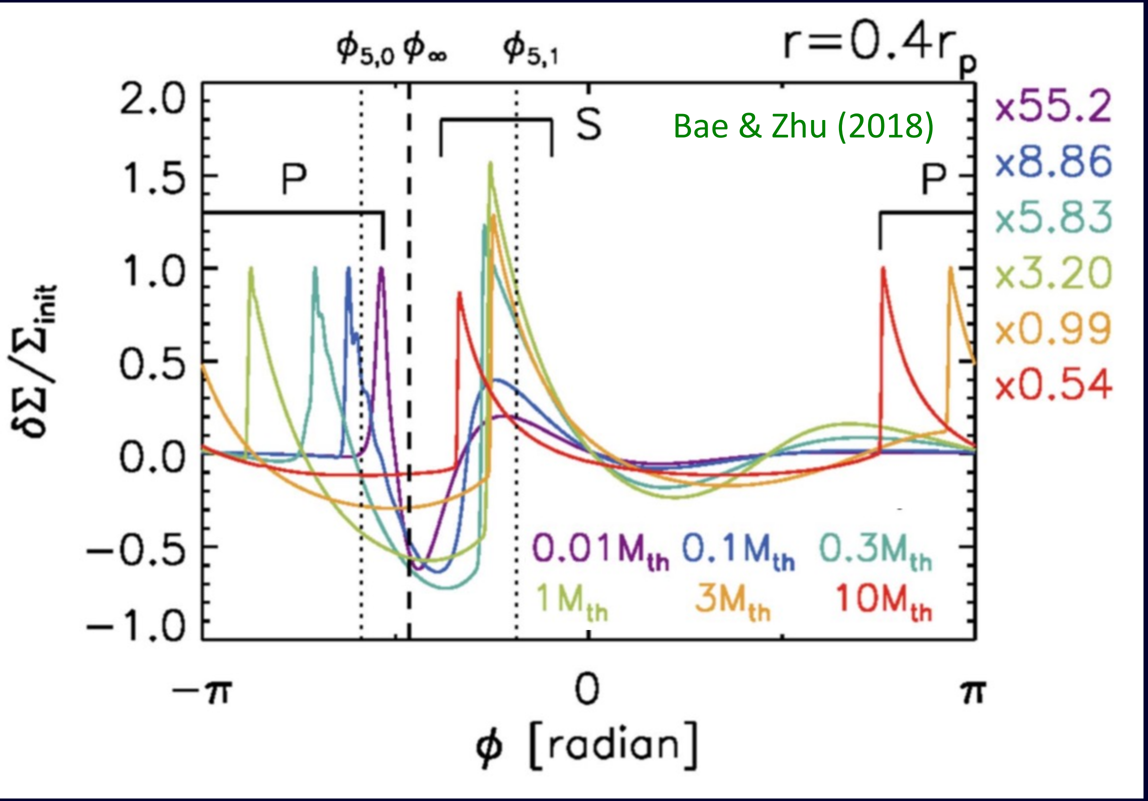
- Can demonstrate the prevalence of multiple spirals in the inner disk




Linear calculation

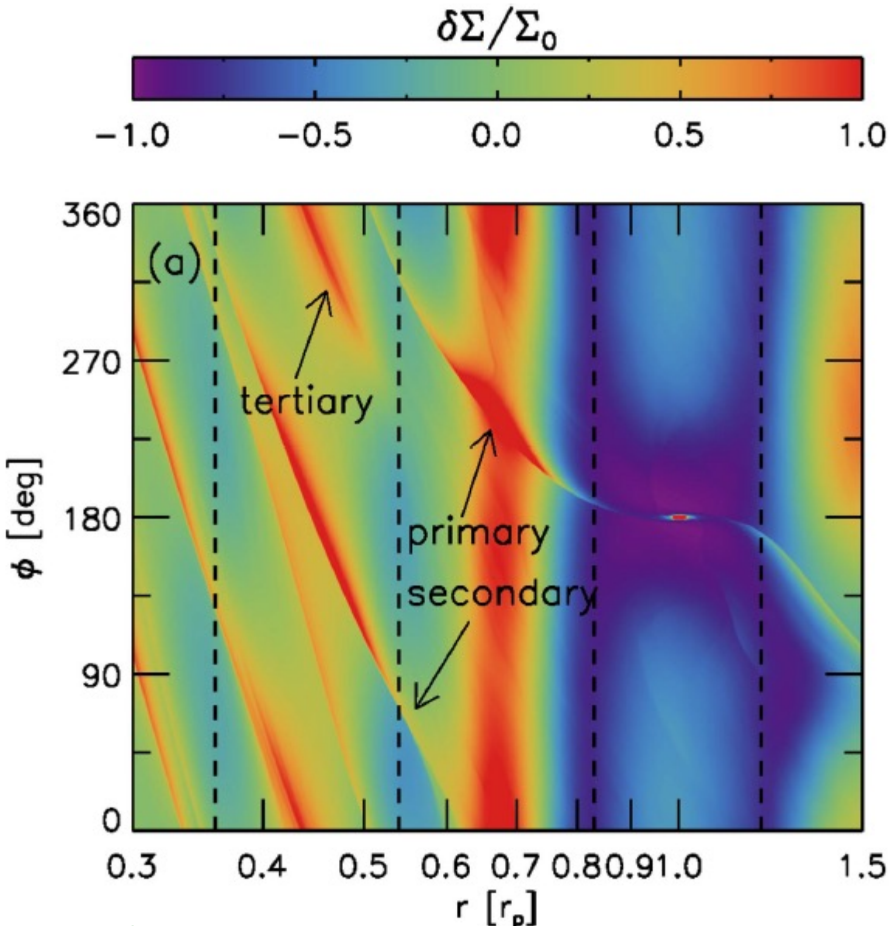




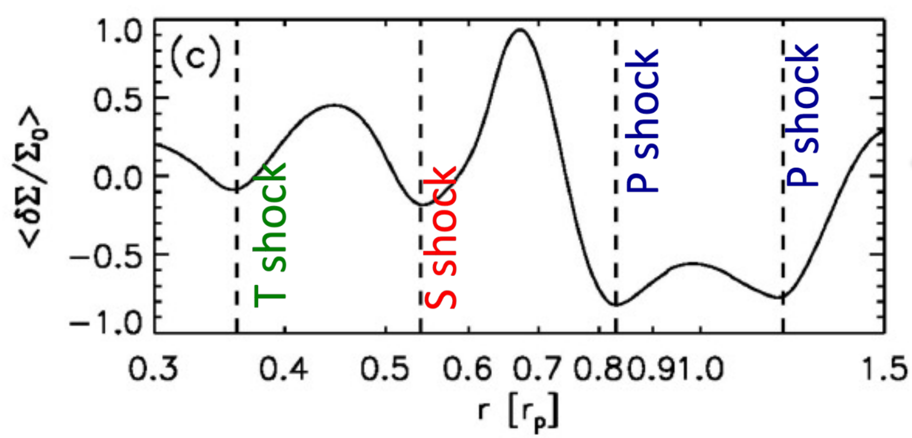

- Linear genesis of multiple spiral arms is a robust process (works just as well for passive, i.e. not planet-driven, density waves, Arzamasskiy & Rafikov 2017)
- Causes redistribution of angular momentum between the different arms
- Then nonlinear effects start developing on top of the linear perturbation pattern – individual arms steepen and eventually shock

Formation of multiple spiral arms - linear effect

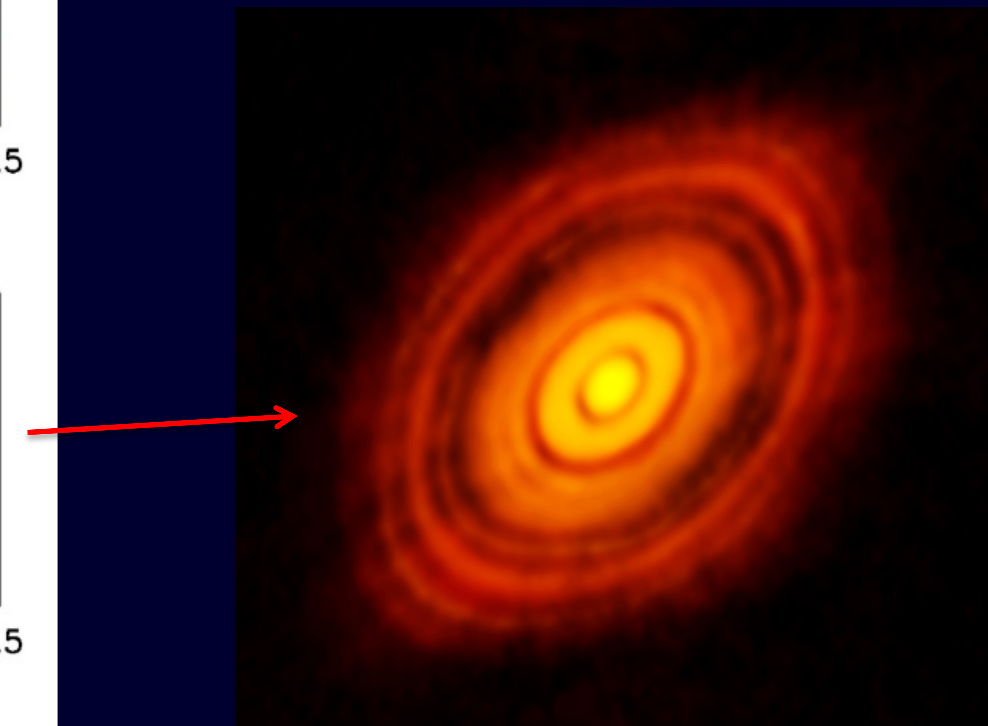
Their shocking, broadening, damping - nonlinear effect



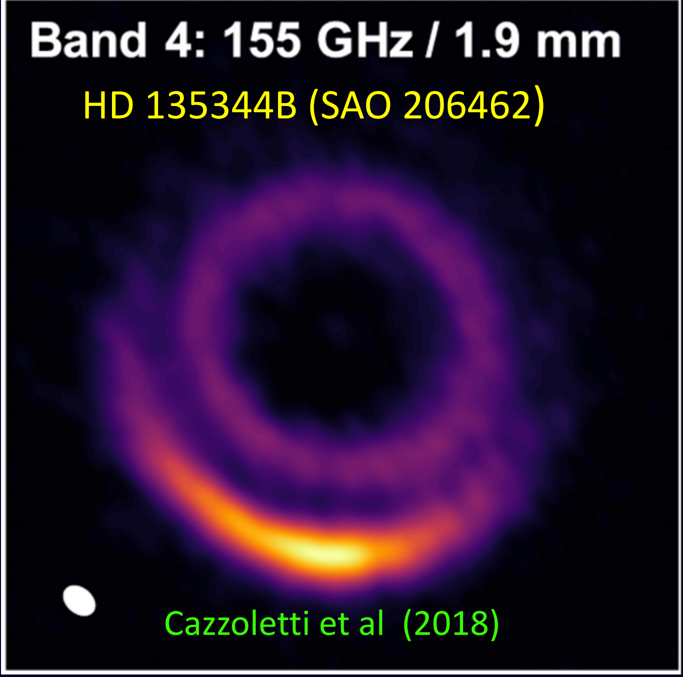

Bae et al 2017




- Shocks produced by the multiple spirals (due to a single planet) cause annular perturbations of gas density
- Dust concentrates at pressure maxima, giving rise to corresponding multiple concentric ring-like features in dust emission
- Makes it possible for a single planet to produce multiple rings/gaps!

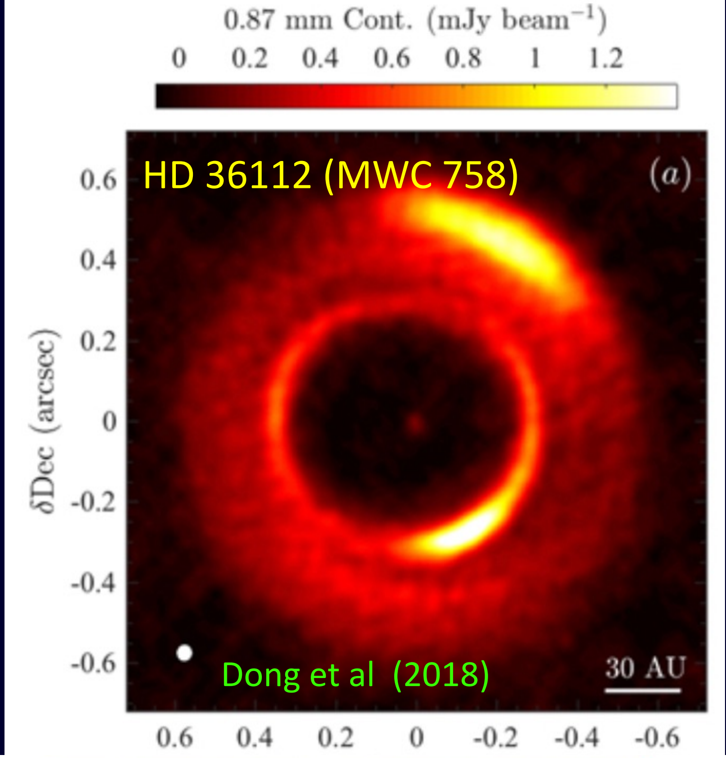


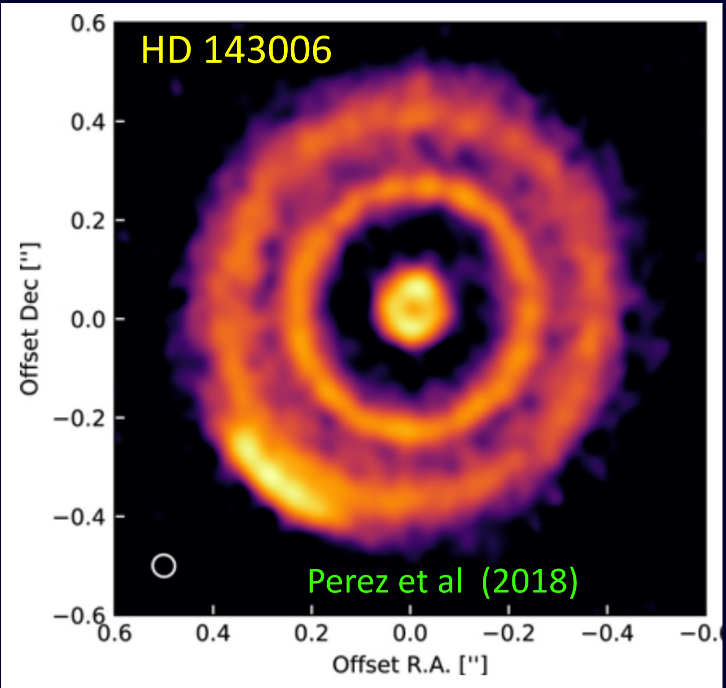
# Vortex weighing and dating of planets in protoplanetary disks

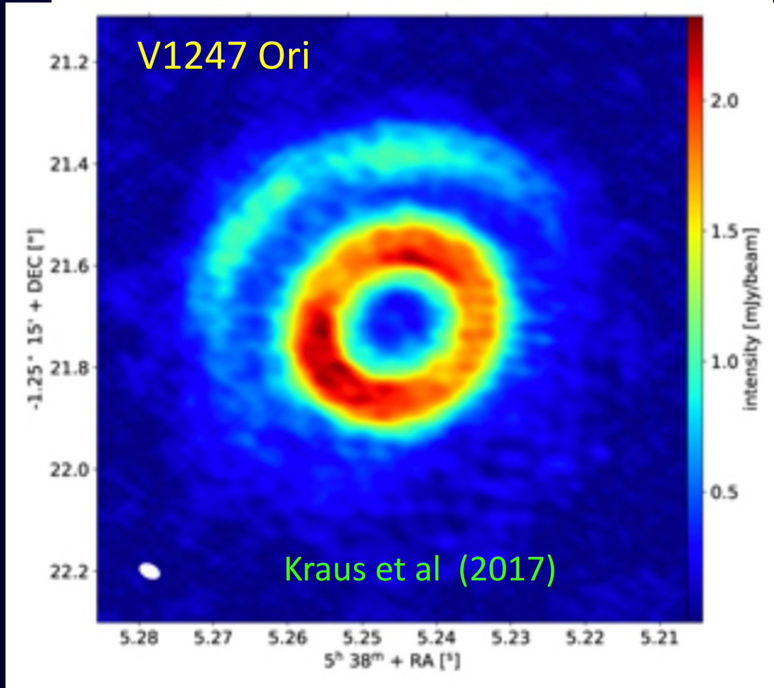



# Vortices in disks

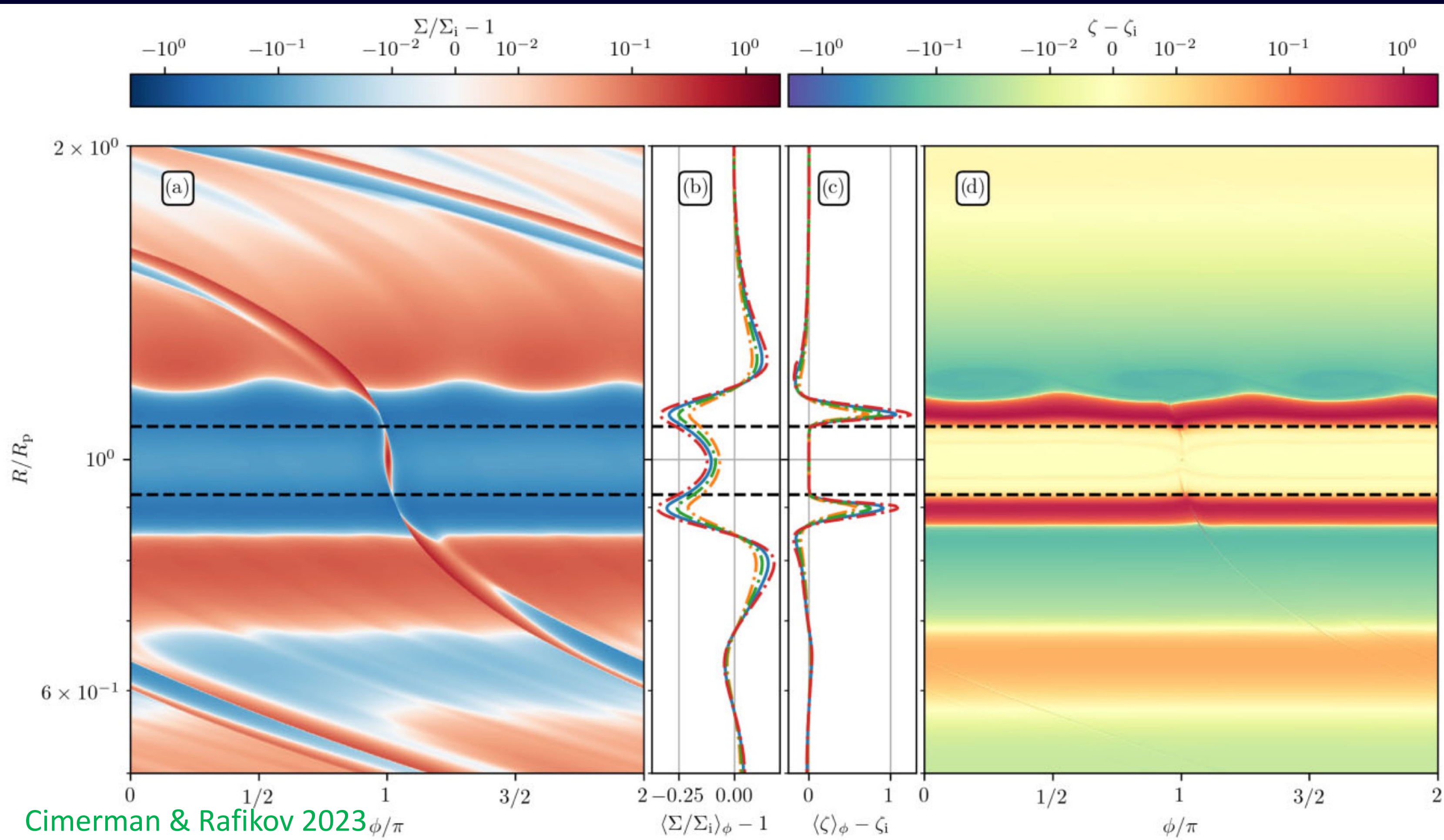
- Dust can be very efficiently trapped inside the vortices in disks
- This makes vortices easily visible



# Production of vortices by planets

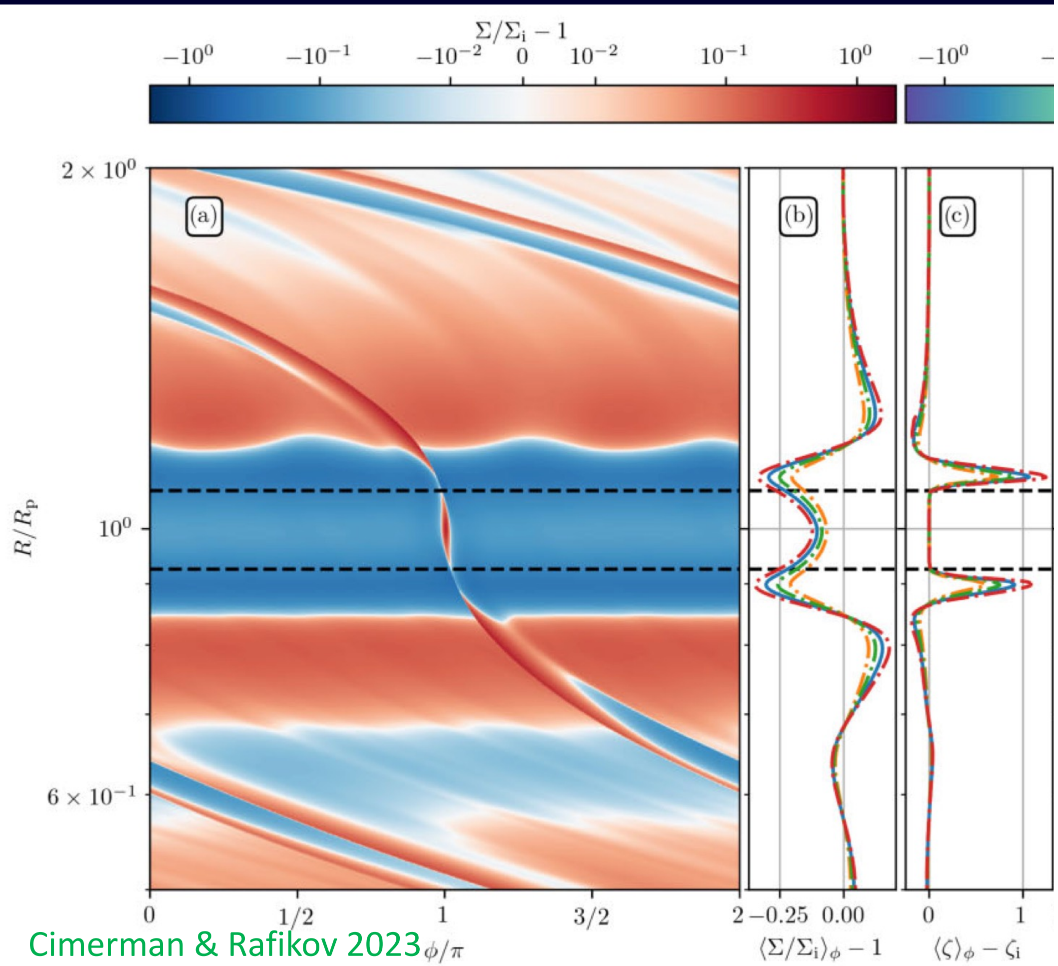



Cimerman & Rafikov 2023

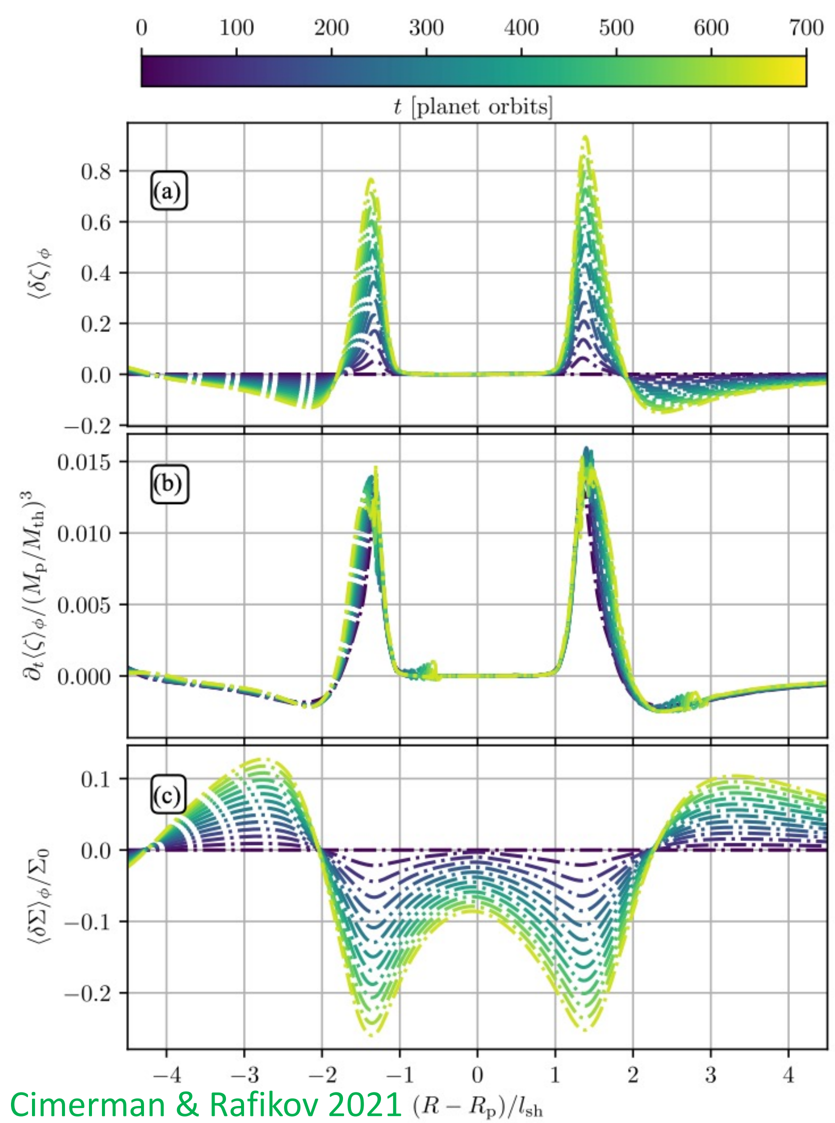
$$\zeta = \frac{\nabla \times \mathbf{v}}{\Sigma}$$

- Vortensity (potential vorticity)
- Conserved quantity, but shocks violate its conservation

# Production of vortices by planets




Cimerman & Rafikov 2023



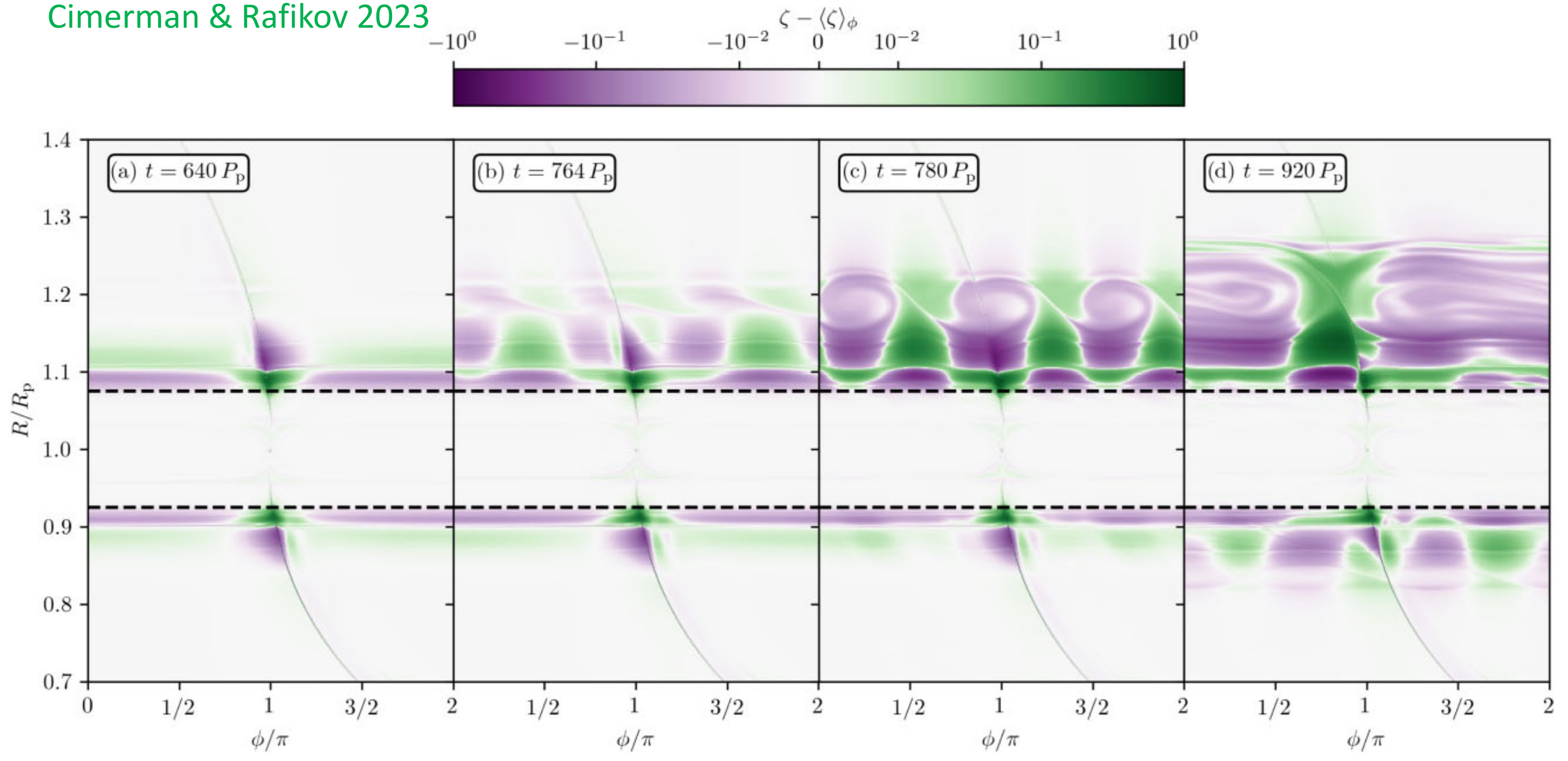

Cimerman & Rafikov 2021

$$\zeta = \frac{\nabla \times \mathbf{v}}{\Sigma}$$

- Vortensity (potential vorticity)
- Conserved quantity, but shocks violate its conservation

- Accumulation of vortensity at the edges of the planetary gaps eventually leads to an instability – Rossby Wave Instability (RWI), Lovelace et al (1999)
- RWI produces multiple vortices in disks, which merge into larger banana-shaped vortices

Cimerman & Rafikov 2023




$$\tau_\mathrm{vrt} \approx 10^5\mathrm{yr}\left(\frac{M_\mathrm{p}}{10^2\,\mathrm{M}_\oplus}\right)^{-2.7}\left(\frac{R_\mathrm{p}}{50\,\mathrm{au}}\right)^{1.5}\left(\frac{h_\mathrm{p}}{0.1}\right)^{7.2}\left(\frac{M_\star}{M_\odot}\right)^{2.2}$$

Development of vortices may take rather long time

- Accumulation of vortensity at the edges of the pla
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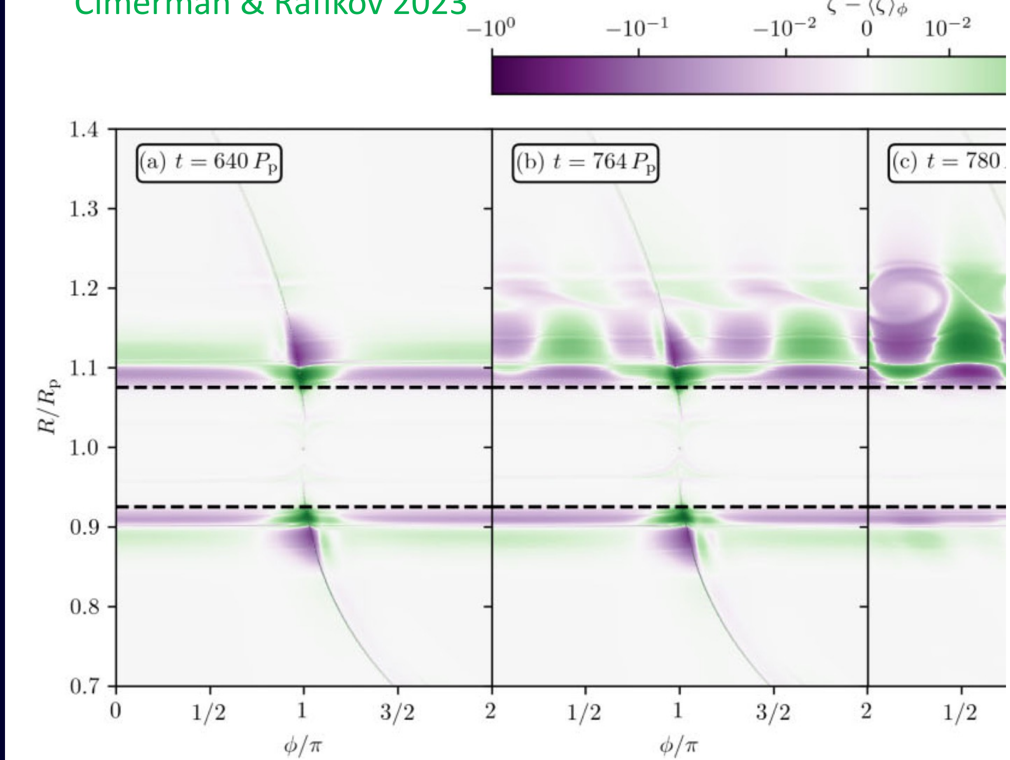
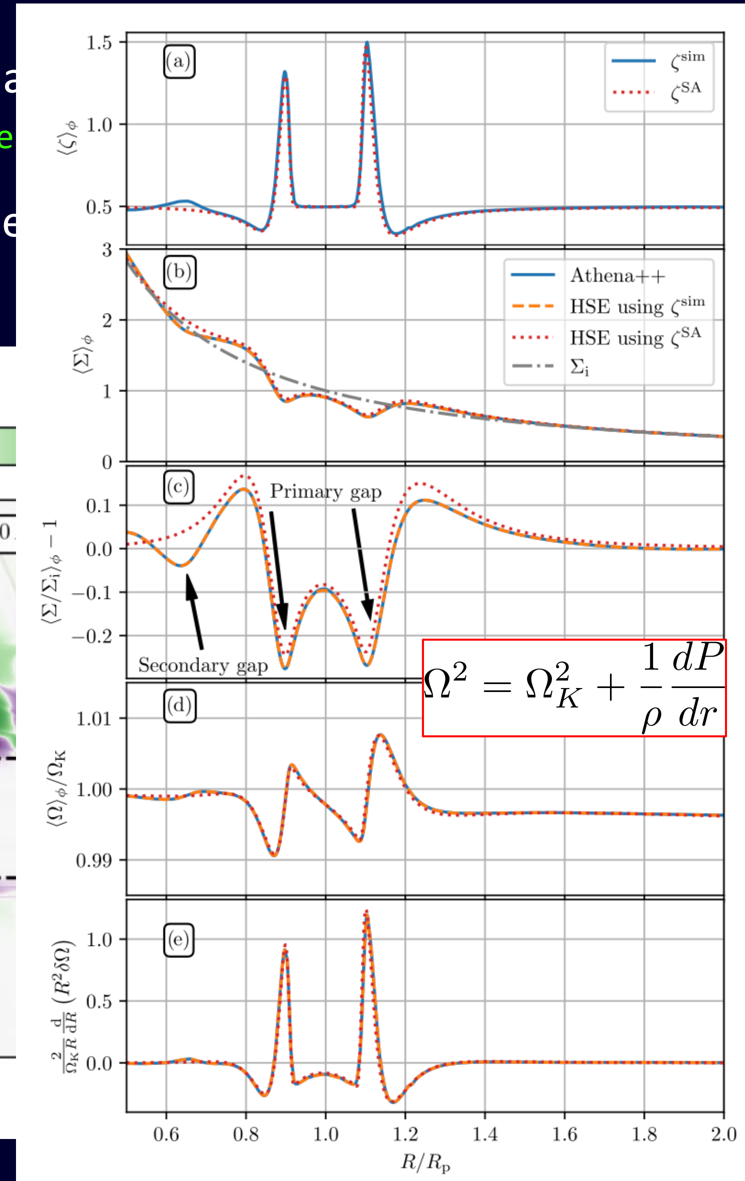
Cimerman & Rafikov 2023




$$\Omega^2 = \Omega_K^2 + \frac{1}{\rho}\frac{dP}{dr}$$

$$\tau_{\rm vrt} \approx 10^5 {\rm yr} \left(\frac{M_{\rm p}}{10^2\,M_\oplus}\right)^{-2.7} \left(\frac{R_{\rm p}}{50\,{\rm au}}\right)^{1.5} \left(\frac{h_{\rm p}}{0.1}\right)^{7.2} \left(\frac{M_\star}{M_\odot}\right)^{2.2}$$

Development of vortices may take rather long time

# Vortex dating of planets

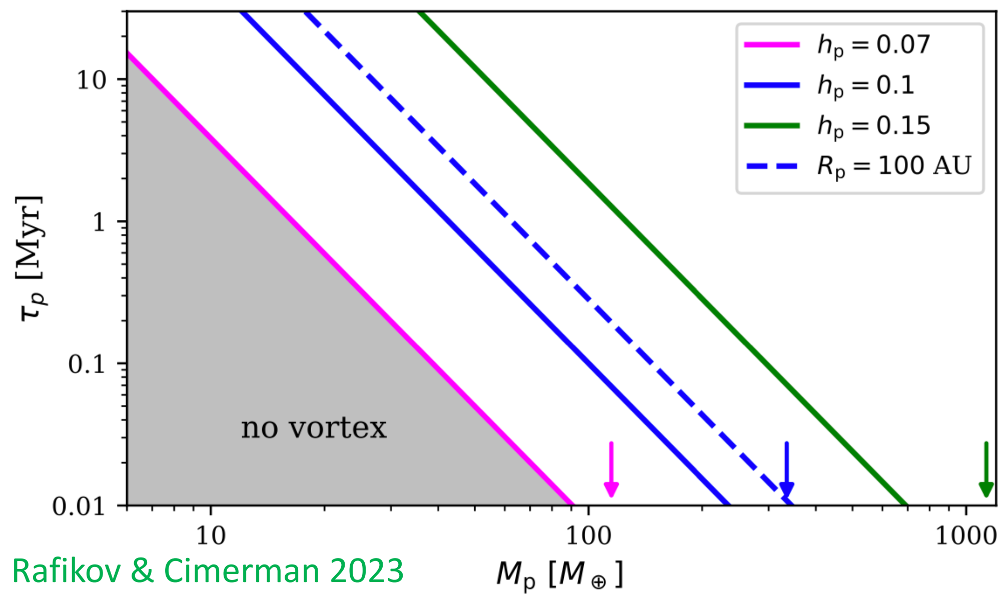
- Suppose that we know planet mass $M_p$
- Age of the planet $\tau_p$ must satisfy

$$\tau_p > \tau_{vrt}$$

or vortex won't have time to develop

- Get a lower limit on $\tau_p$

$$\tau_{vrt} \approx 10^5 \mathrm{yr} \left(\frac{M_p}{10^2\, M_\oplus}\right)^{-2.7} \left(\frac{R_p}{50\,\mathrm{au}}\right)^{1.5} \left(\frac{h_p}{0.1}\right)^{7.2} \left(\frac{M_\star}{M_\odot}\right)^{2.2}$$



Rafikov & Cimerman 2023

# Vortex weighing of planets

- Suppose that we know the age of the system $\tau_{sys}$
- It must satisfy

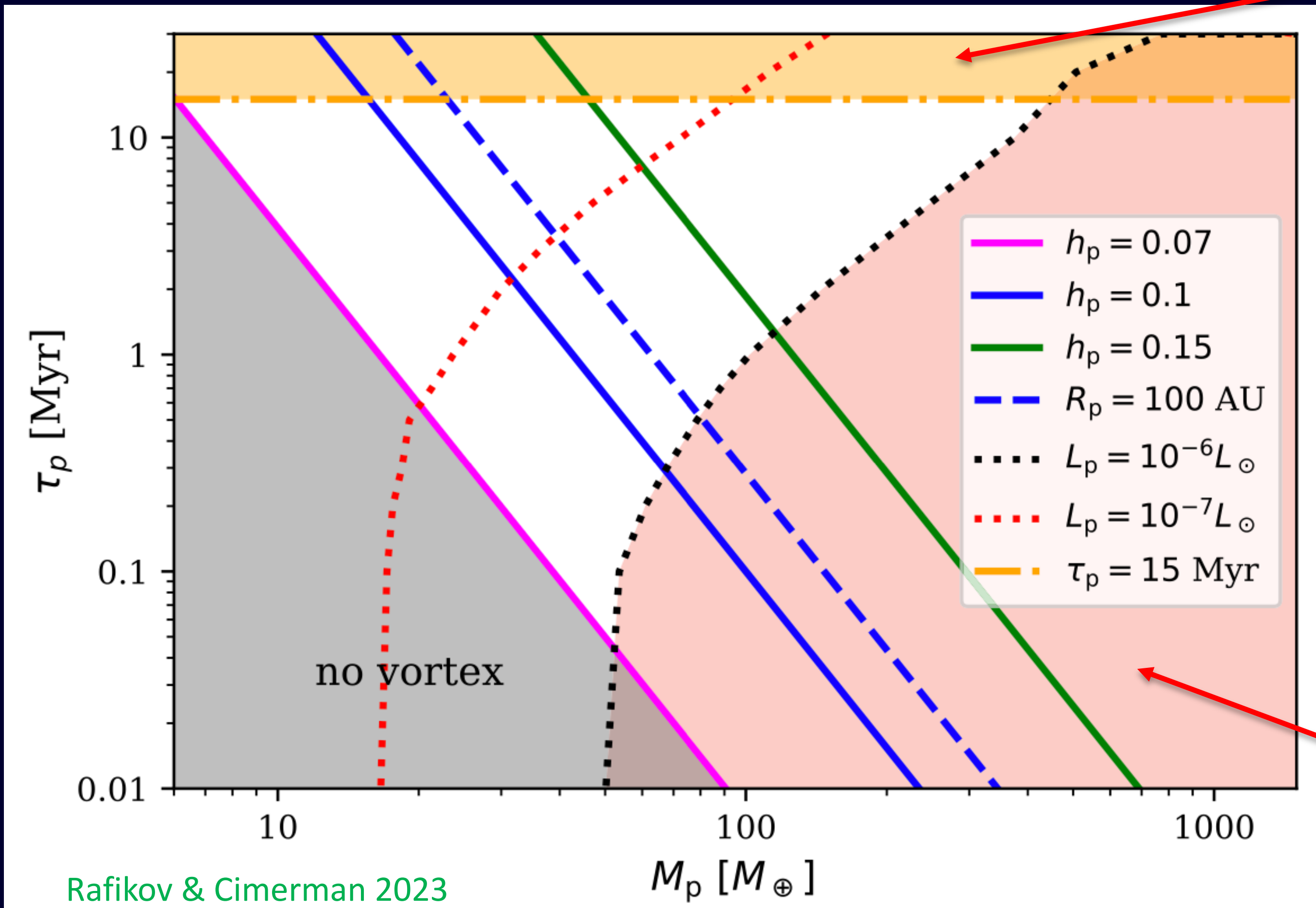
$$\tau_{sys} > \tau_{vrt}$$

- Get a lower limit on the planetary mass $M_p$

$$M_p > M_{vrt} \approx 40\, M_\oplus \left(\frac{\tau_{sys}}{\mathrm{Myr}}\right)^{-0.37} \left(\frac{R_p}{50\,\mathrm{au}}\right)^{0.56} \left(\frac{h_p}{0.1}\right)^{2.7} \left(\frac{M_\star}{M_\odot}\right)^{0.81}$$

# Combination of constraints

Upper limit on the disk age




Rafikov & Cimerman 2023

Planet young and massive enough to be hot and directly visible

# Summary

- Sub-mm interferometry with ALMA and direct imaging revealed a plethora of structures in protoplanetary disks: gaps, rings, spirals, banana-shaped clumps
- All of them may be linked to presence of planets in protoplanetary disks
- Even low-mass planets can produce multiple gaps/rings in a disk – a process related to splitting of planet-driven density waves int multiple spiral arms
- Nonlinear effects play a very important role in the evolution of planet-driven density waves
- Thermodynamics of the disk (the way it cools) is another key ingredient determining the evolution of density waves and their effect on the disk
- Fluid vortices can be naturally produced at the edges of planet-driven gaps as a result of Rossby Wave Instability
- They can efficiently trap dust and be visible as asymmetric clumps
- Detection of vortices in disks allow one to set indirect constraints on the properties of planets that cause them: planetary mass (‘vortex weighing’) and age (‘vortex dating’)