Planet-Forming Disks – A workshop to honor Antonella Natta
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# Planet-driven Spiral Waves in Protoplanetary Disks

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Why would you go back to the past?

Spiral waves have been studied for many decades…

THE EXCITATION AND EVOLUTION OF DENSITY WAVES*

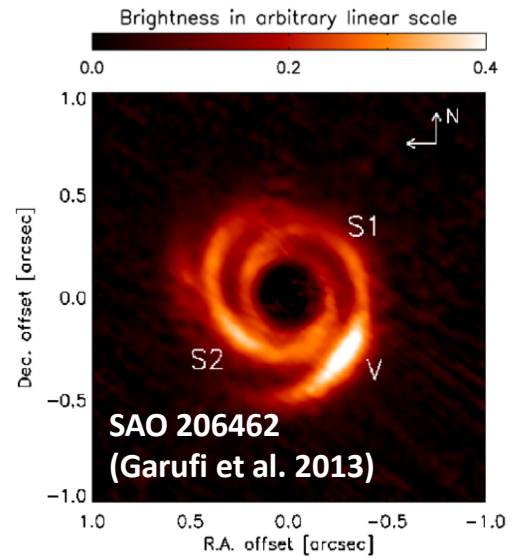
PETER GOLDREICH AND SCOTT TREMAINE
California Institute of Technology
*Received 1977 August 16; accepted 1978 January 4*

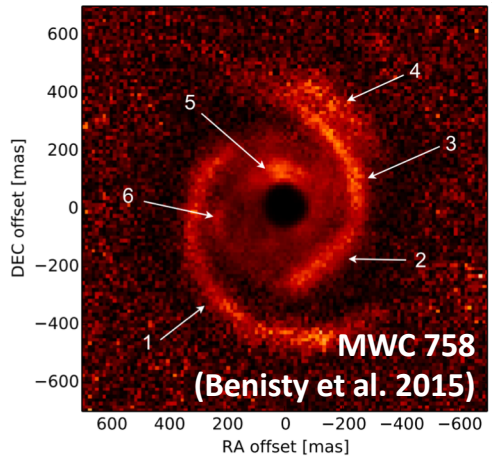
THE EXCITATION OF DENSITY WAVES AT THE LINDBLAD AND COROTATION RESONANCES BY AN EXTERNAL POTENTIAL[1]

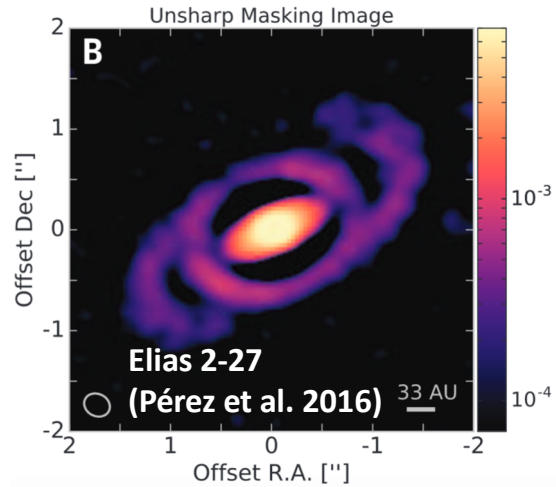
PETER GOLDREICH[2] AND SCOTT TREMAINE[3]
*Received 1978 September 22; accepted 1979 May 2*

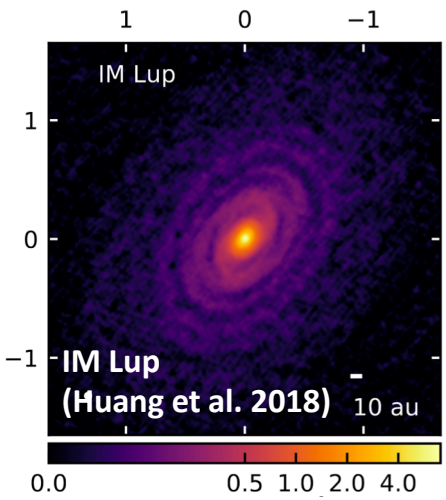
Six Decades of Spiral Density Wave Theory

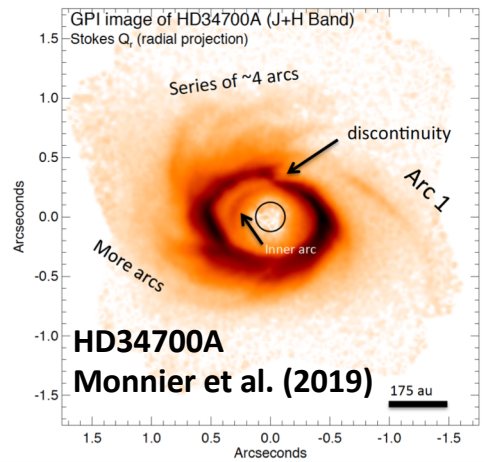
Frank H. Shu ARAA, 2016



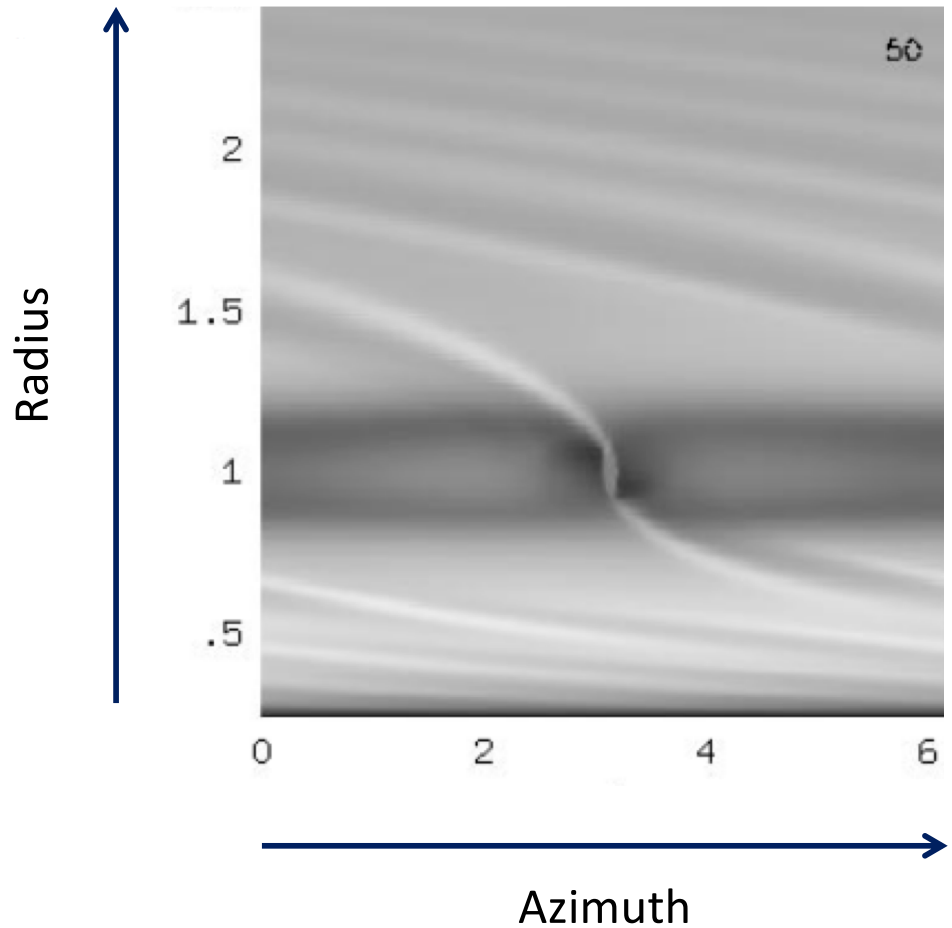



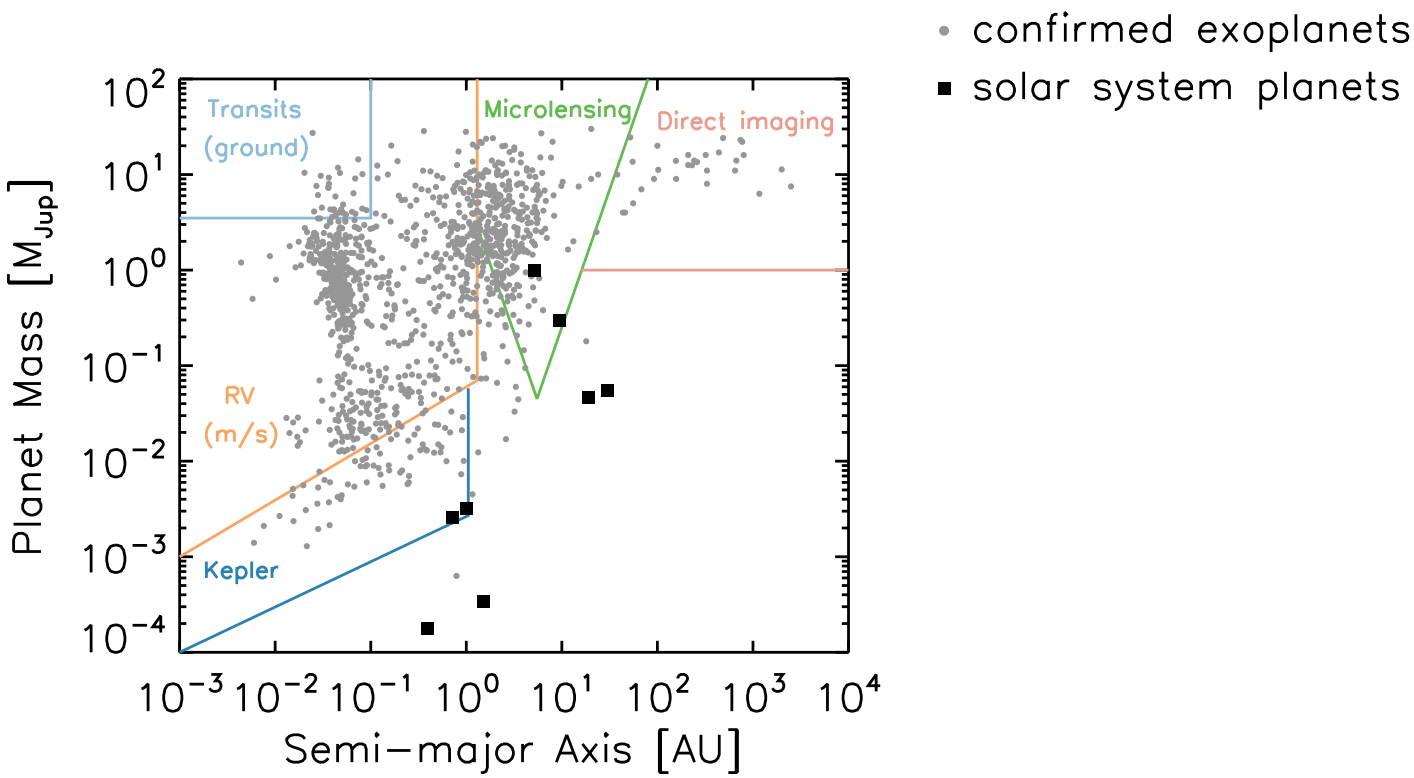

In most of the cases,
we see multiple spiral arms.

**Mass flow and accretion through gaps in accretion discs**

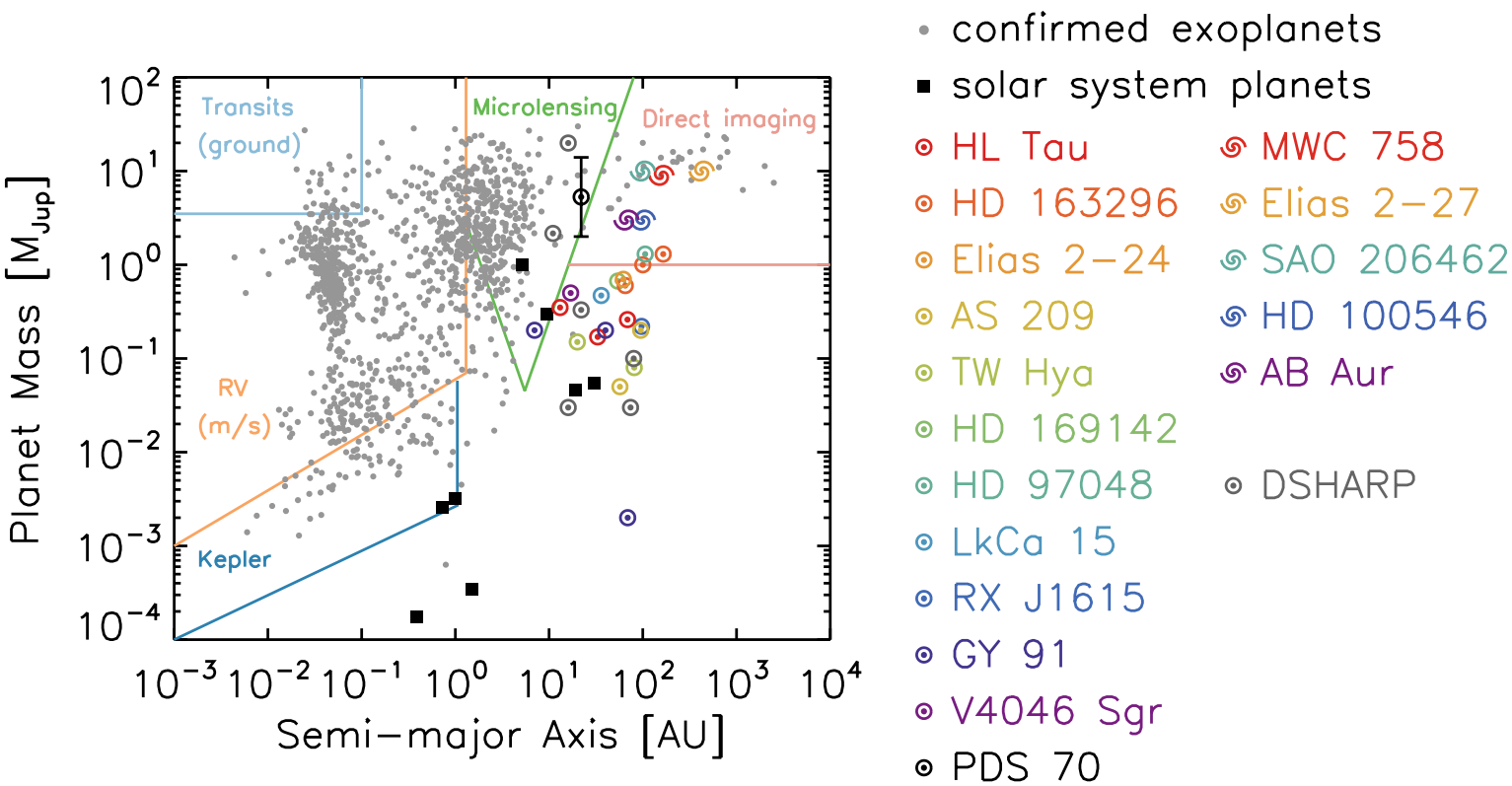
W. Kley* MNRAS, 1999

Planet-disk interaction simulations generally show that one planet launches multiple spiral arms.






exoplanets (NASA exoplanet archive, https://exoplanetarchive.ipac.caltech.edu/)




See Figure 1 of Bae, Pinilla & Birnstiel (2018) for the full reference list.

exoplanets (NASA exoplanet archive, https://exoplanetarchive.ipac.caltech.edu/)
DSHARP data (GW Lup, HD 142666, HD 143006, SR 4) from Zhang et al. (2018).

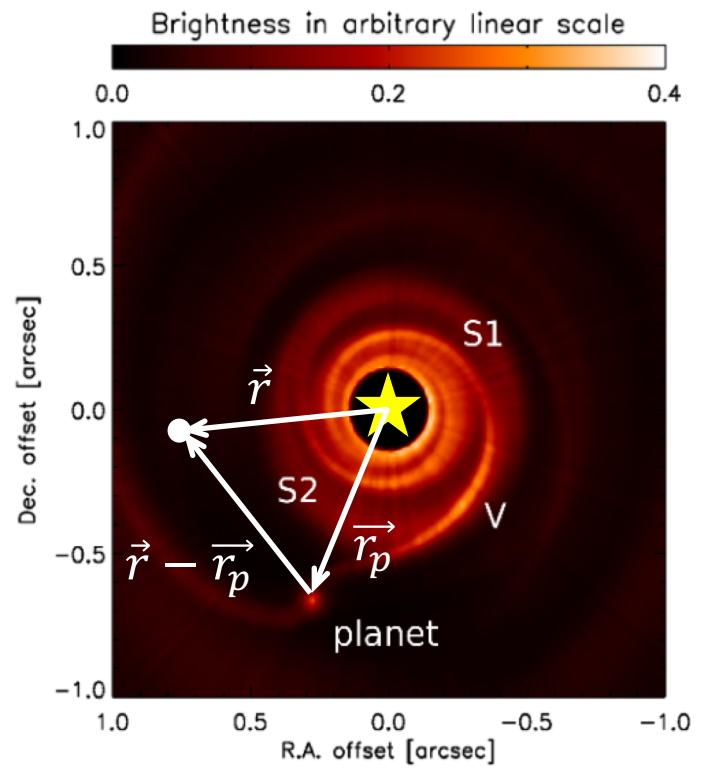
# Outline

1. How does a planet excite multiple spiral arms?

2. What are the implications?

3. Effects of disk thermal properties on the planet-driven spiral arm formation.

How does a planet excite multiple spiral arms?



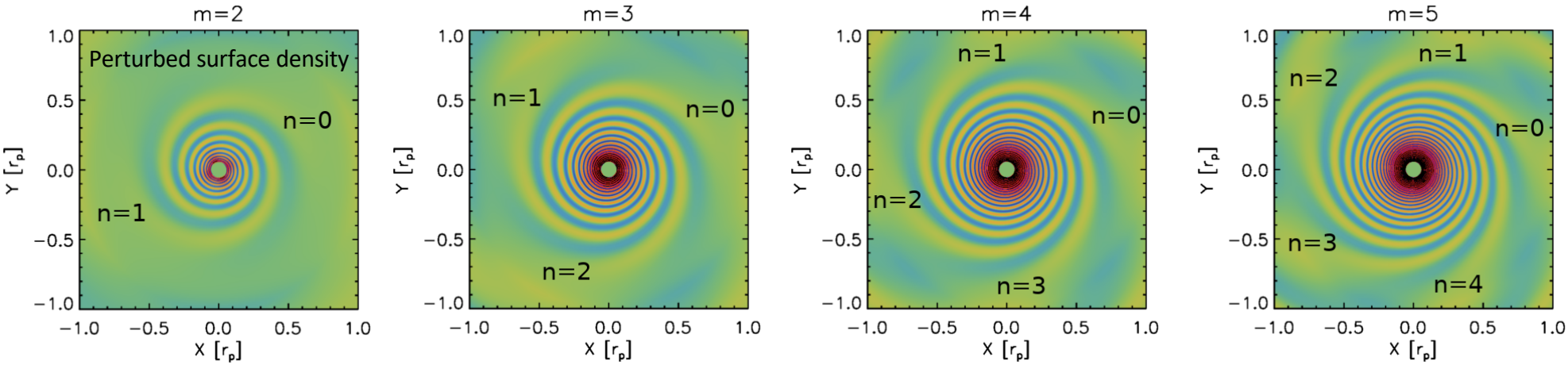

A simulated J band scattered light image of SAO 206462 based on the model presented in Bae, Zhu & Hartmann (2016).

$$\Phi_p(r,\phi) = -\frac{GM_p}{|\vec{r} - \vec{r_p}|}$$

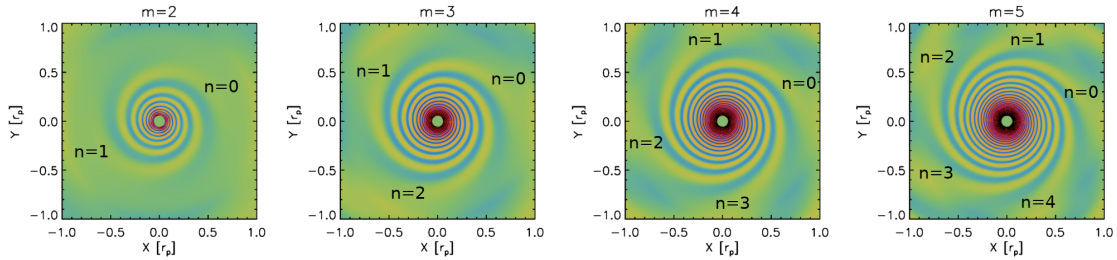
$$\Phi_p(r,\phi) = \sum_{m=0}^{\infty} \Phi_m(r)\cos(m\phi)$$

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

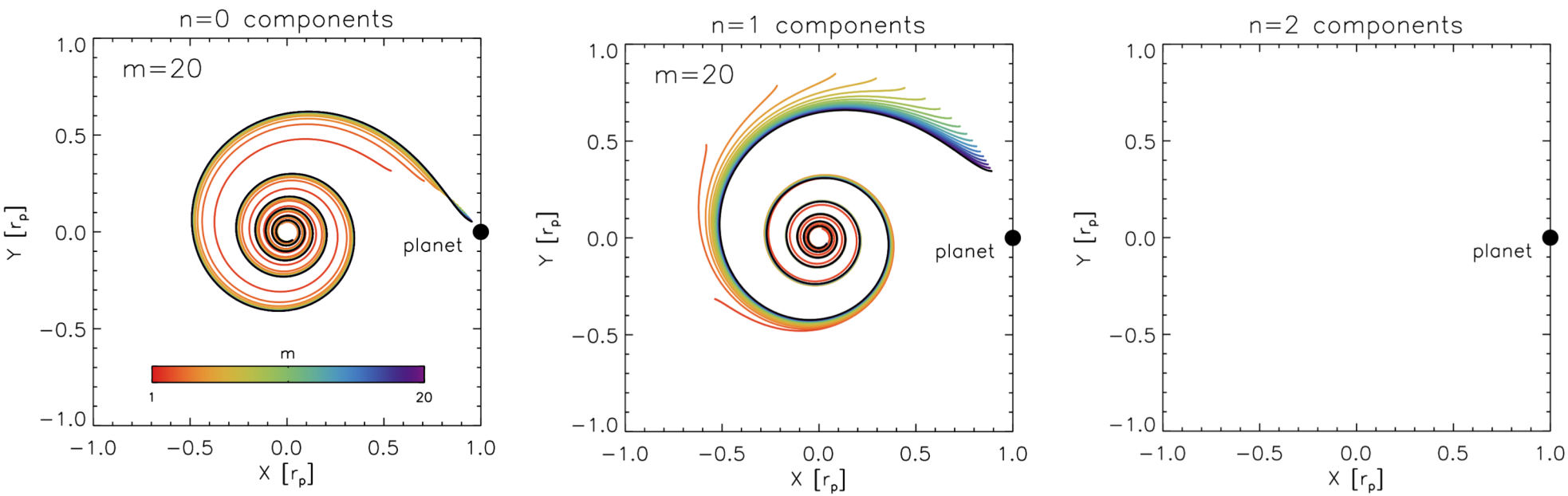
$\Phi_2(r)\cos(2\phi)$ $\Phi_3(r)\cos(3\phi)$ $\Phi_4(r)\cos(4\phi)$ $\Phi_5(r)\cos(5\phi)$




✓ *m*th Fourier component of the planet's potential excites *m* axisymmetric spiral wave modes at the Lindblad resonance (Goldreich & Tremaine 1978a,b,1979).



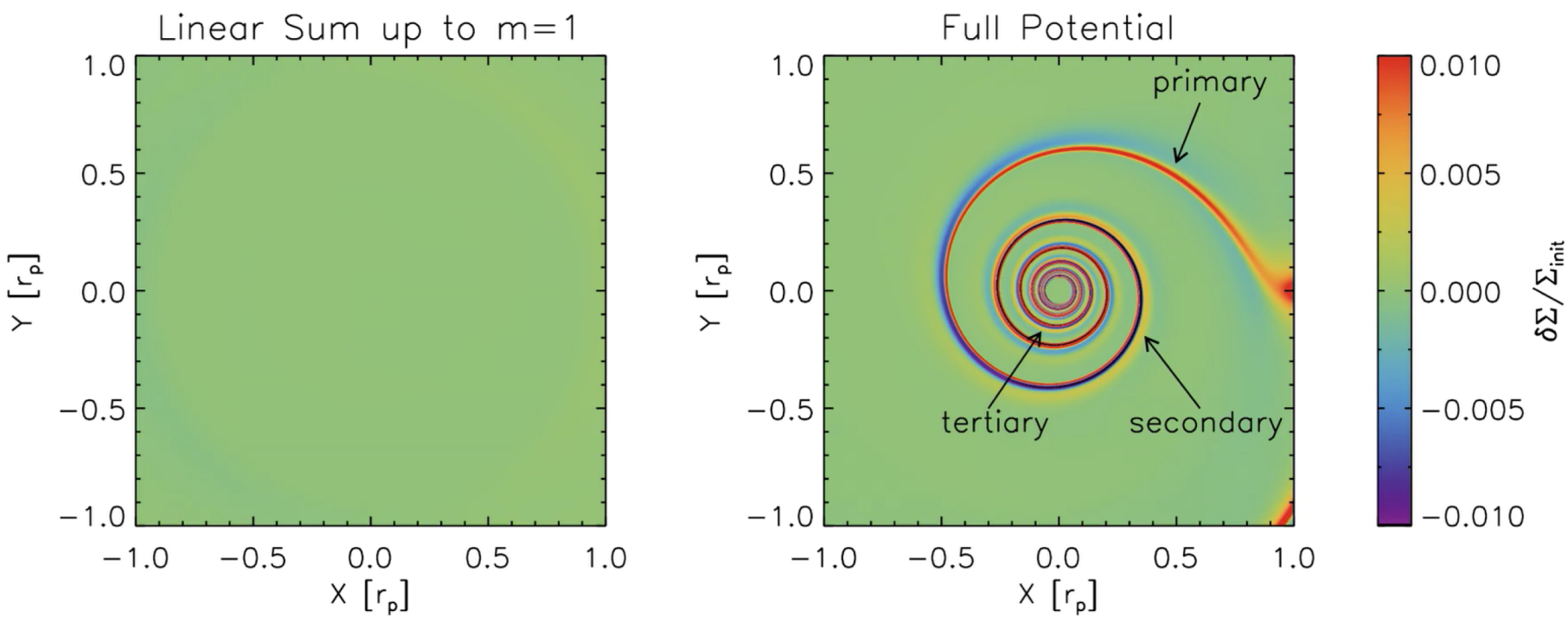

The propagation of waves depends on their azimuthal wavenumber *m* such that **constructive interference** becomes available.



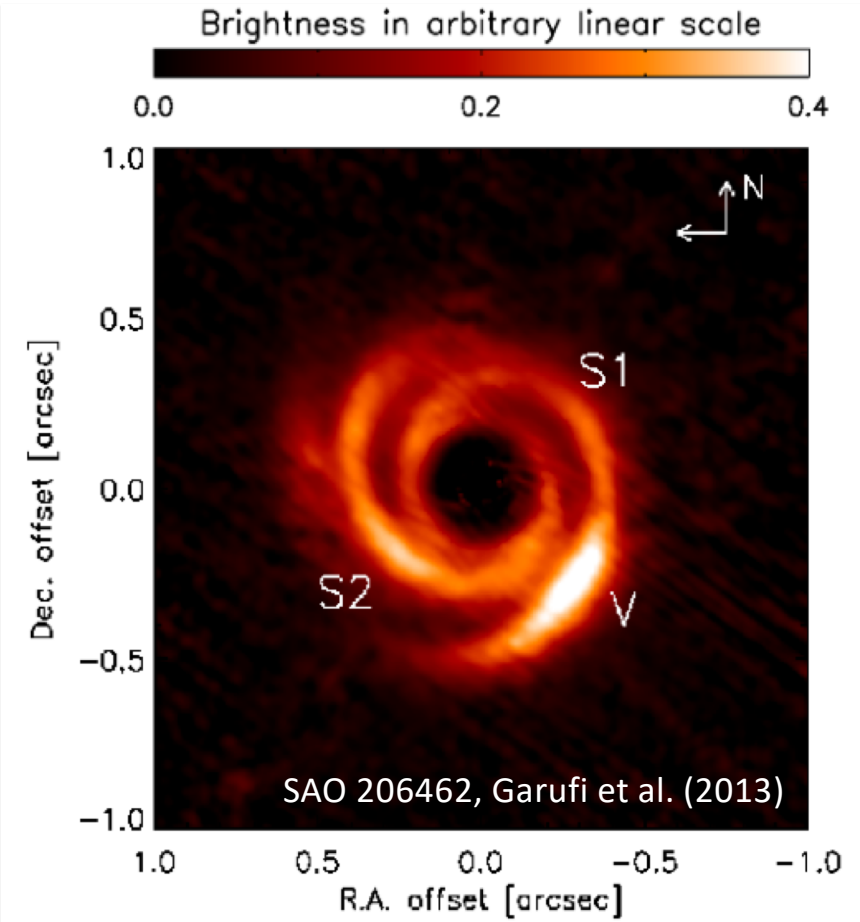

Bae & Zhu (2018a)

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

$$\Phi_p(r,\phi) = -\frac{GM_p}{|\vec{r} - \vec{r_p}|}$$




Bae & Zhu (2018a)

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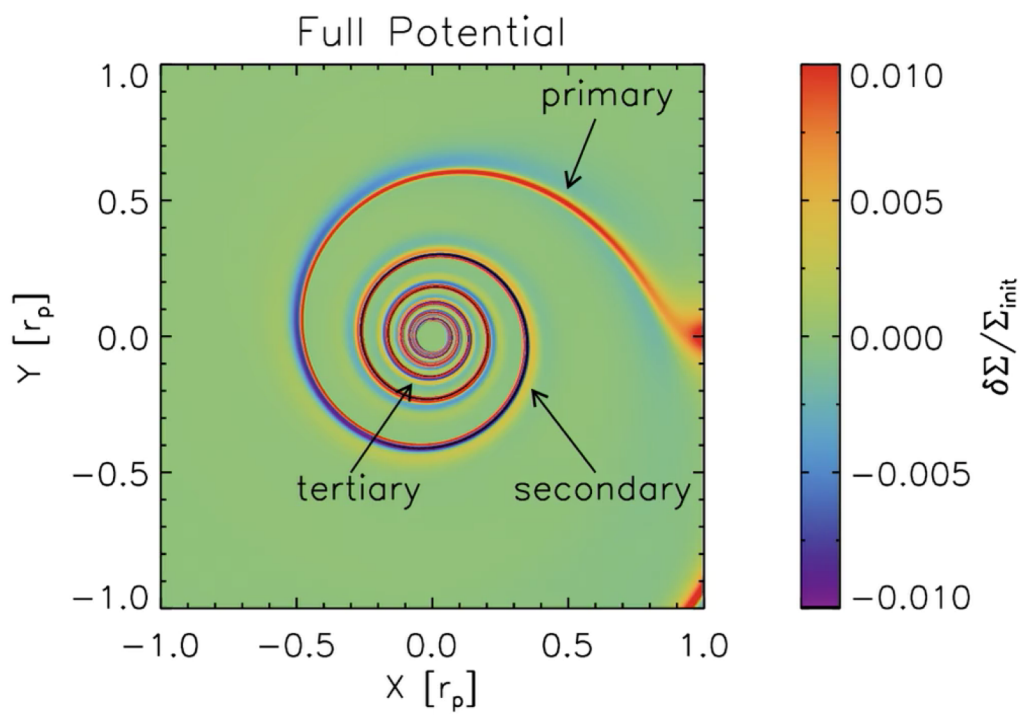
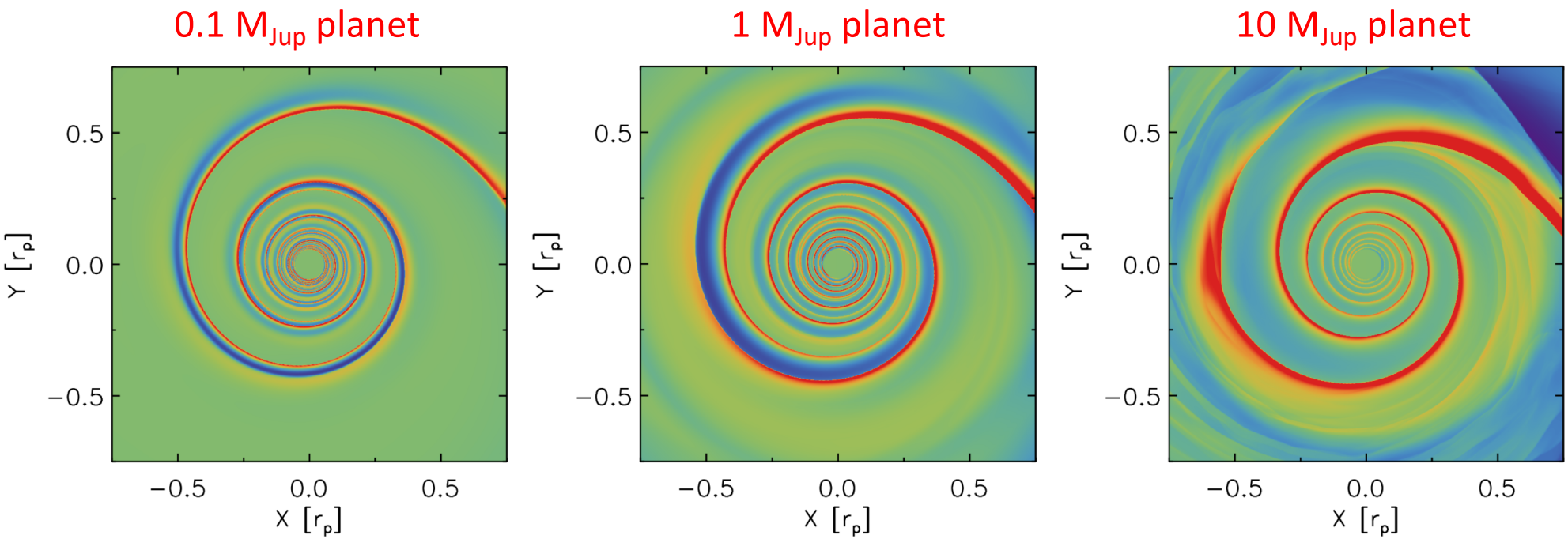





- A more massive planet creates stronger spiral shocks (= faster propagation), so the spirals have more opened shapes (Bae & Zhu 2018b; see also Zhu et al. 2015, Fung & Dong 2015).

- This may explain why we need multi-Jupiter-mass planets to reproduce the observed grand-design m=2 spiral arms.

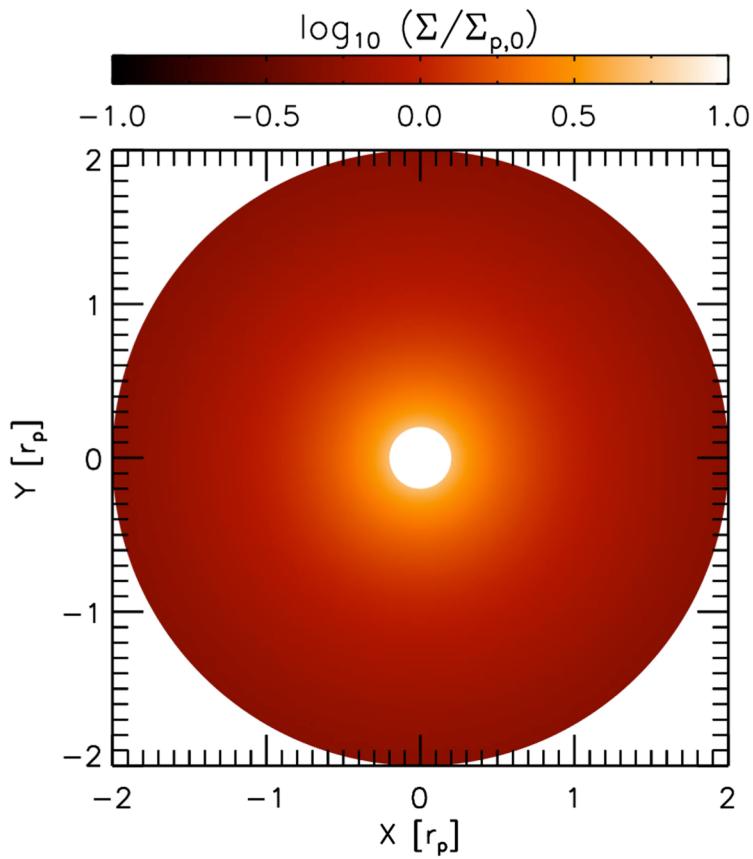
Q: What can a spiral arm do?

A: It transports angular momentum as it shocks the disk gas, **opening a gap** (Goodman & Rafikov 2001, Rafikov 2002).

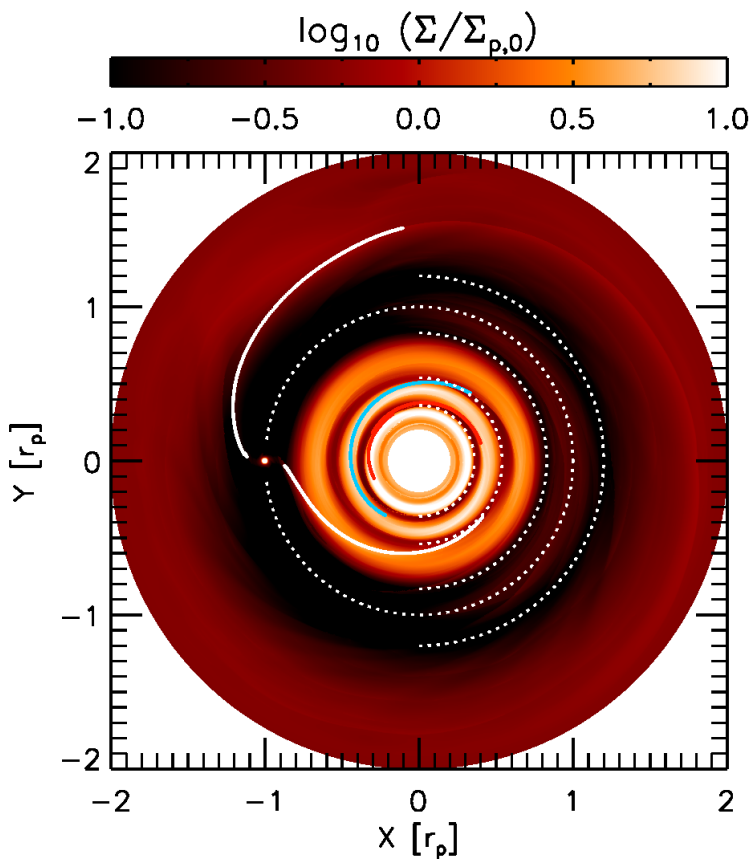
Q: What happens when a planet excites multiple spiral arms?

A: The planet can **open multiple gaps**!

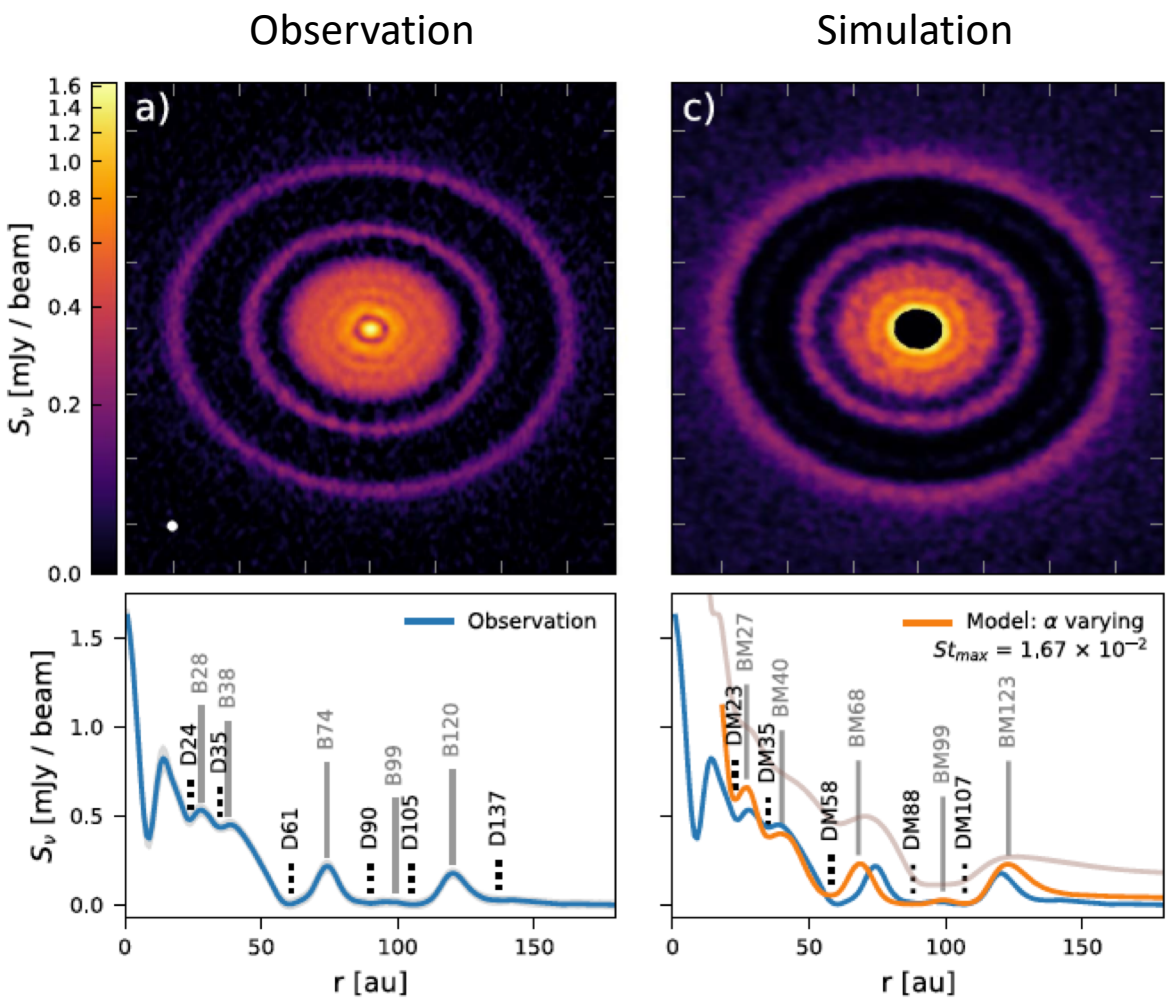
# Multiple rings/gaps formed by “one” planet




Bae, Zhu & Hartmann (2017)




Gaps open at the radial locations each spiral arm shocks the disk gas.

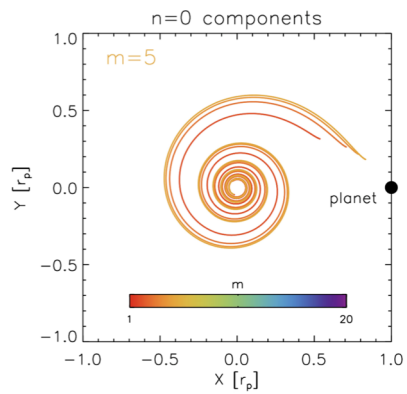



A 0.1 Jupiter-mass planet at 99 AU can explain many of the observed continuum gaps and rings in the AS 209 disk (Zhang et al. 2018).

Secondary spiral arm formation prefers a low disk viscosity ($\alpha \lesssim 10^{-3}$ for a Jupiter-mass planet; Bae, Zhu & Hartmann 2017).

# Summary

- ✓ ***One planet can launch more than one spiral*** through constructive interference among wave modes having different azimuthal wavenumbers.




- ✓ ***One planet can create multiple rings and gaps*** as its spiral arms shock the disk gas.
  - ✓ Number of observed gaps ≠ number of planets
  - ✓ We need more direct, localized evidence of planets in order to link disk substructures to planets.