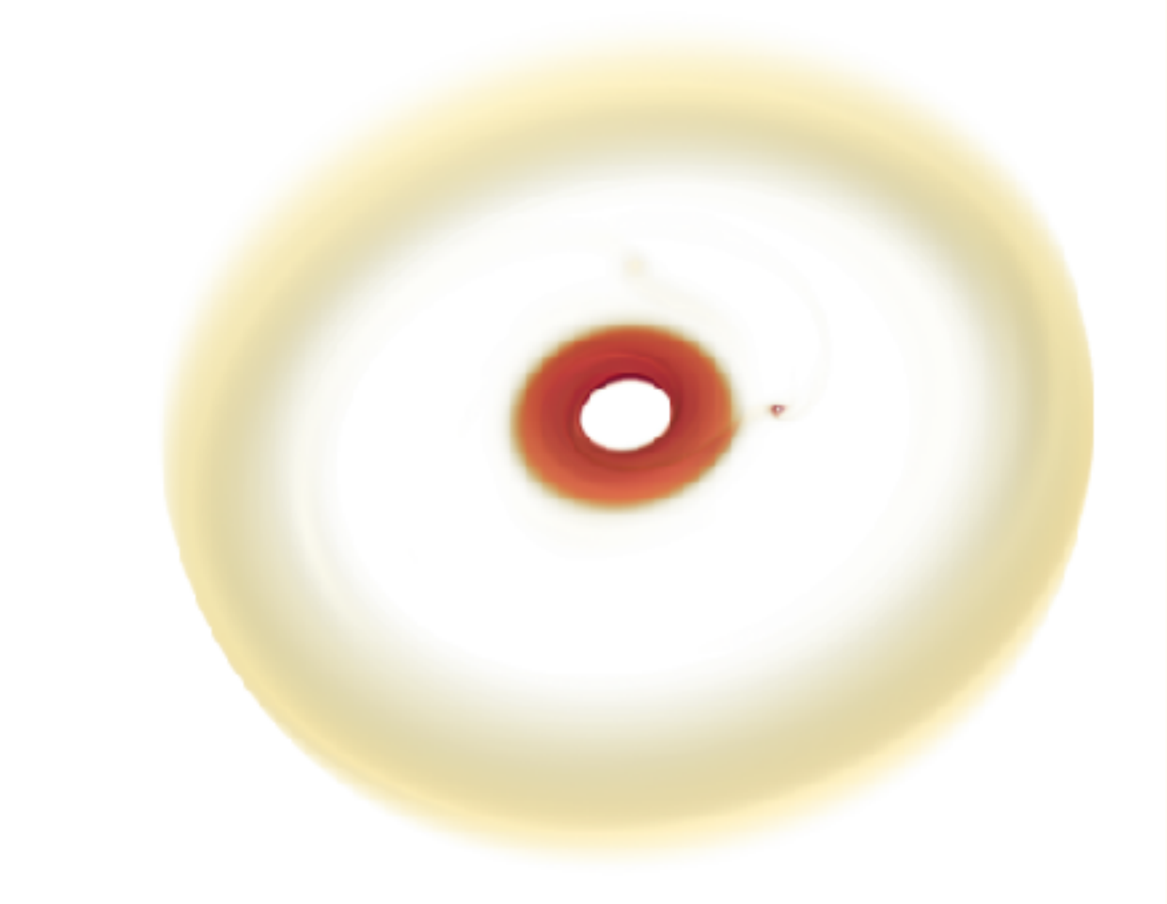
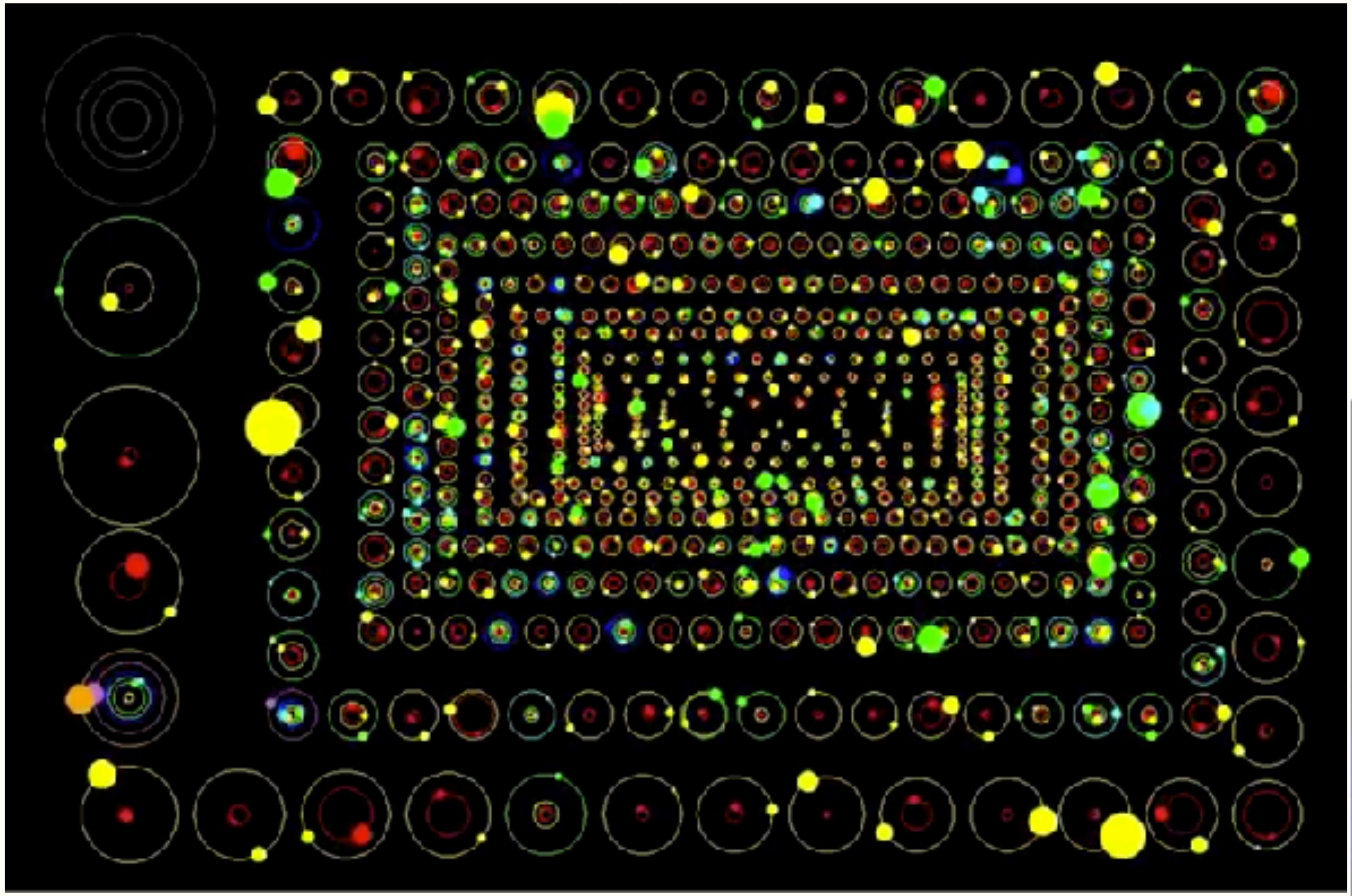
Indirect Observational Signatures of Young Planets

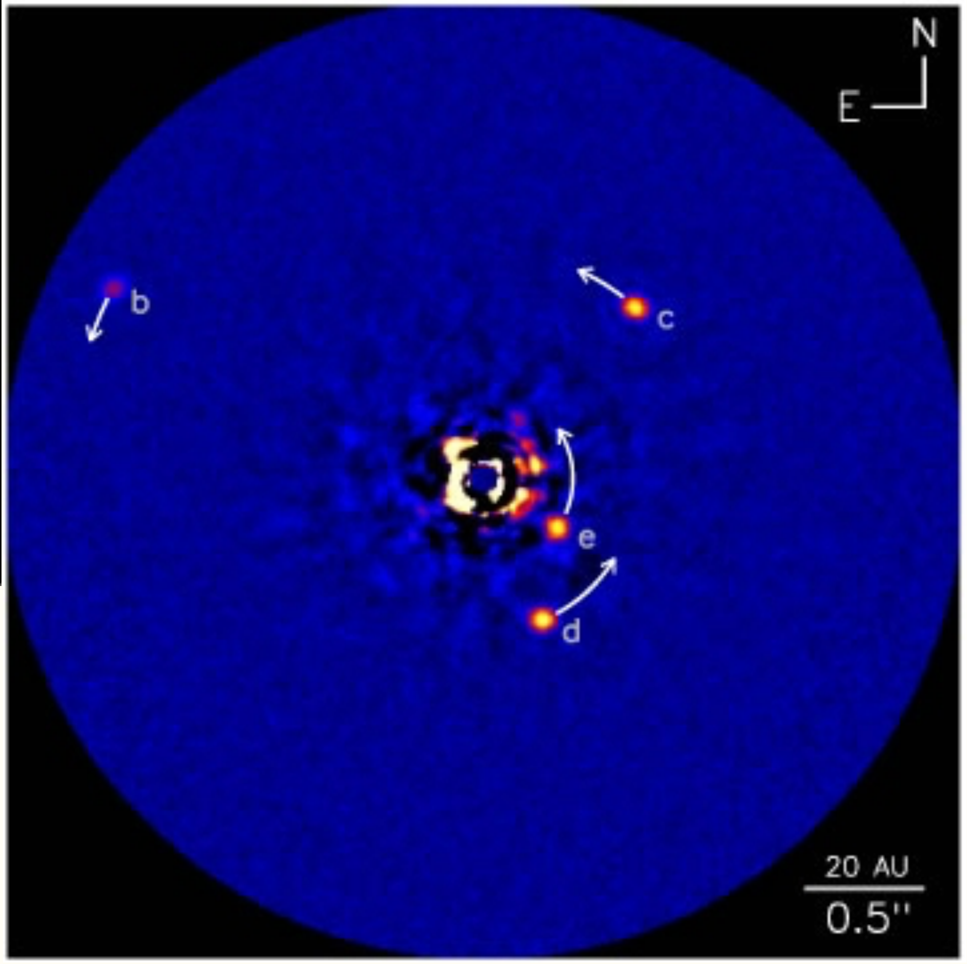
Myriam Benisty (U. Grenoble & U. Chile)
Zhaohuan Zhu (U. of Nevada, Las Vegas)



Exoplanets are **common** and **diverse**

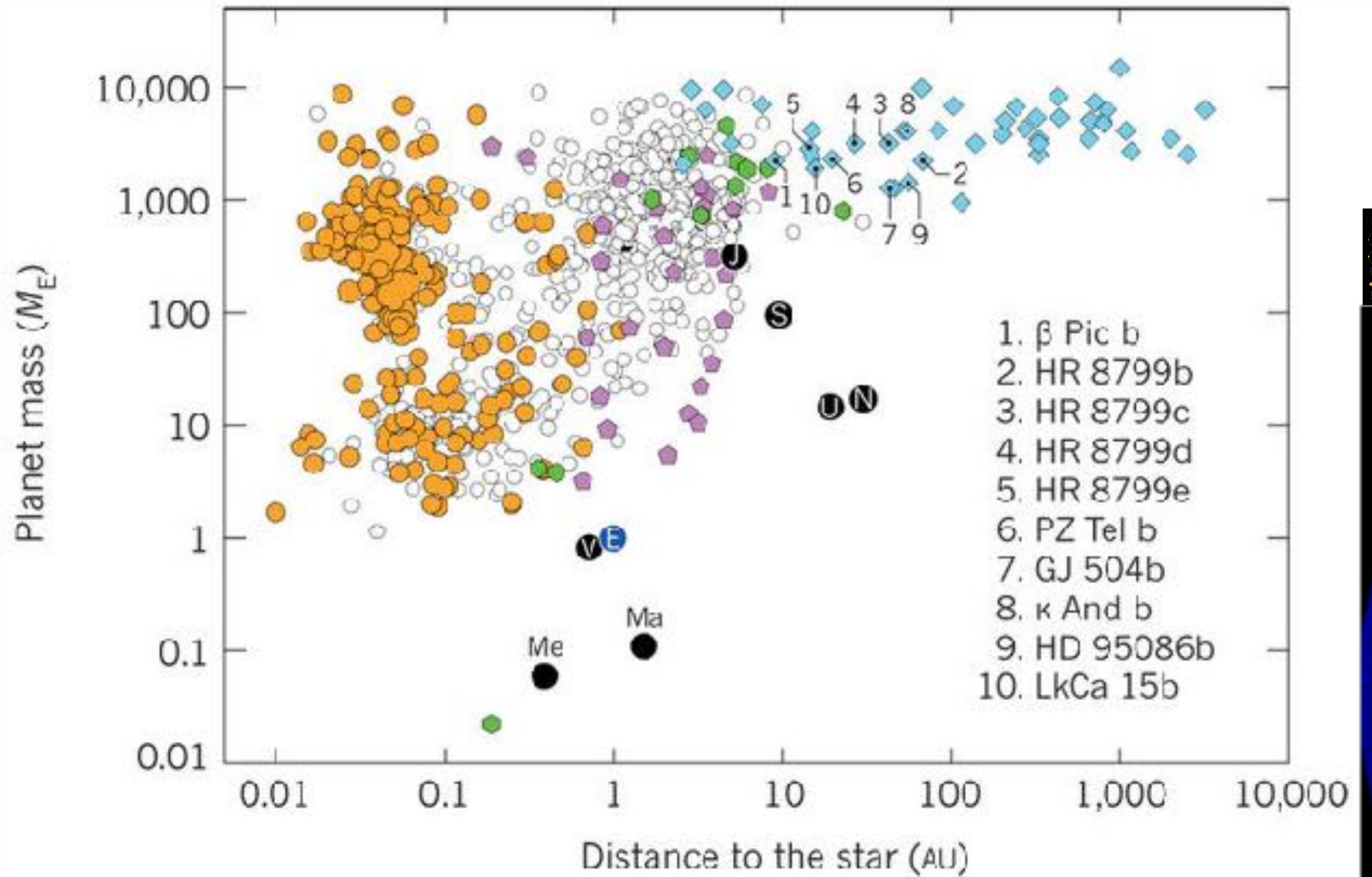


Kepler Orrery III by Daniel Fabrycky

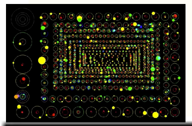


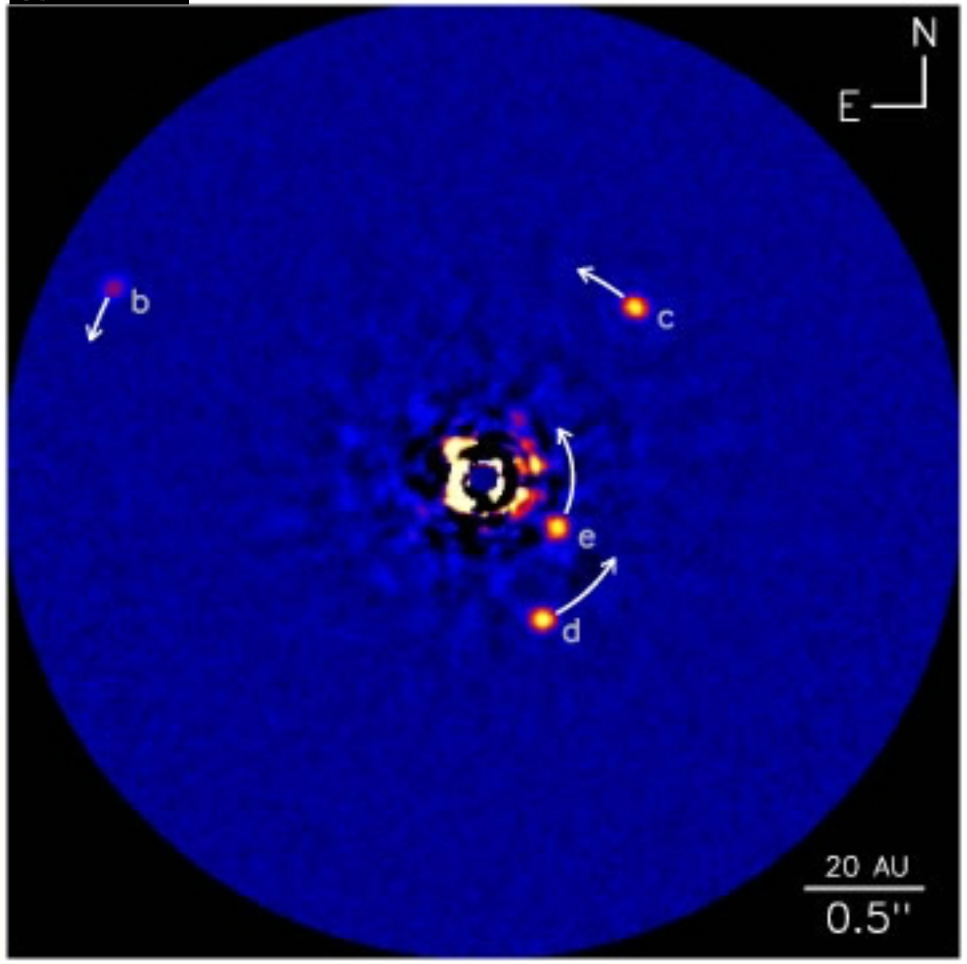
Credit: NRC/HIA, C. Marois, and Keck Observatory

Exoplanets are **common** and **diverse**



Pepe+ 2014



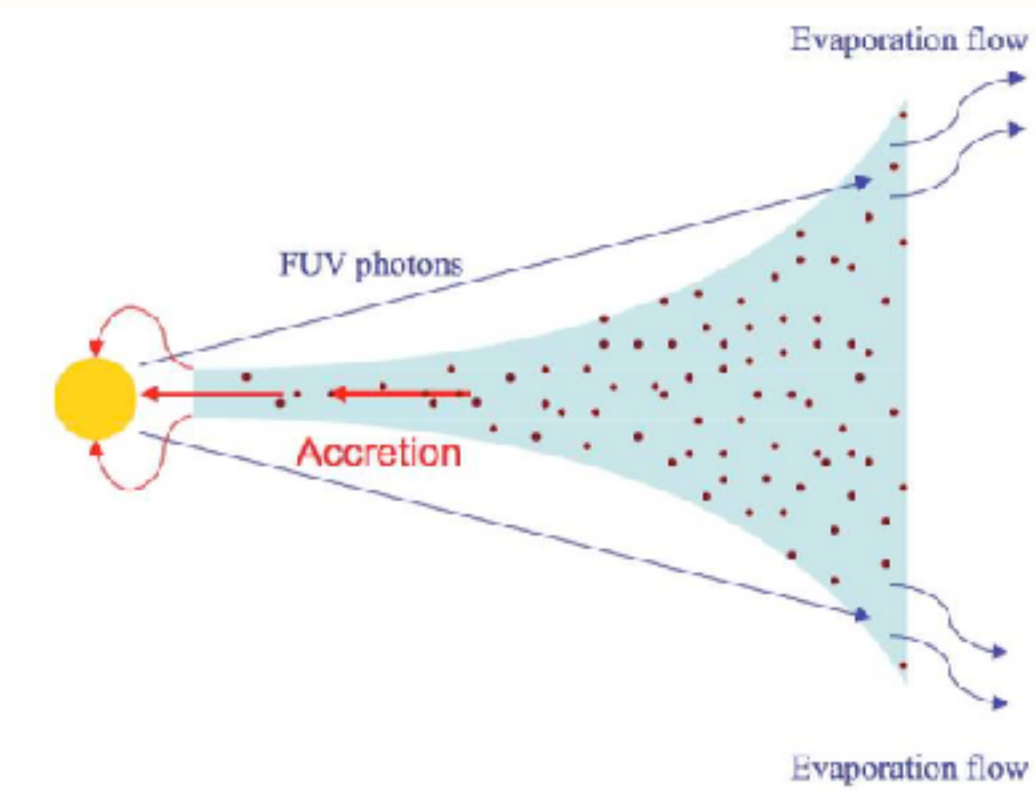


Credit: NRC/HIA, C. Marois, and Keck Observatory

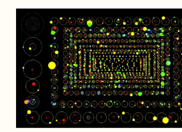
Disk evolution and planet formation

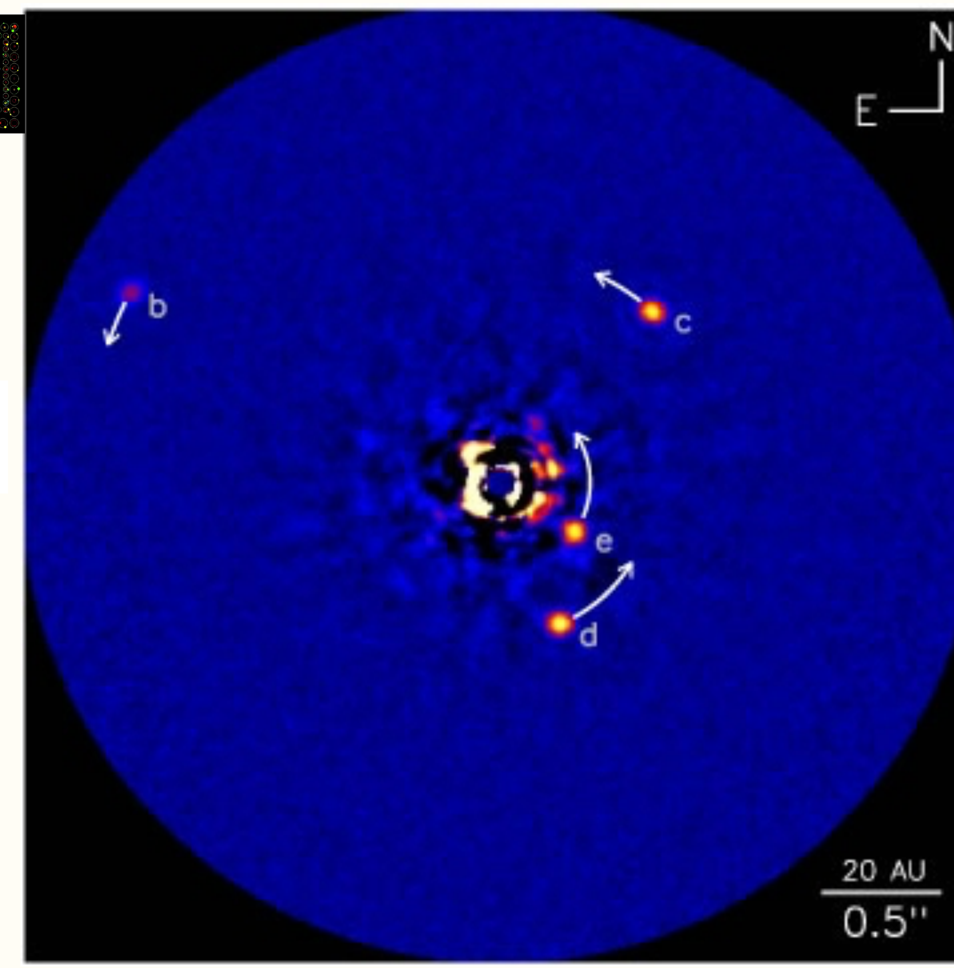
How do protoplanetary disks evolve to such diverse exoplanets?

- Look for disk structural change
- Look for signposts of planets



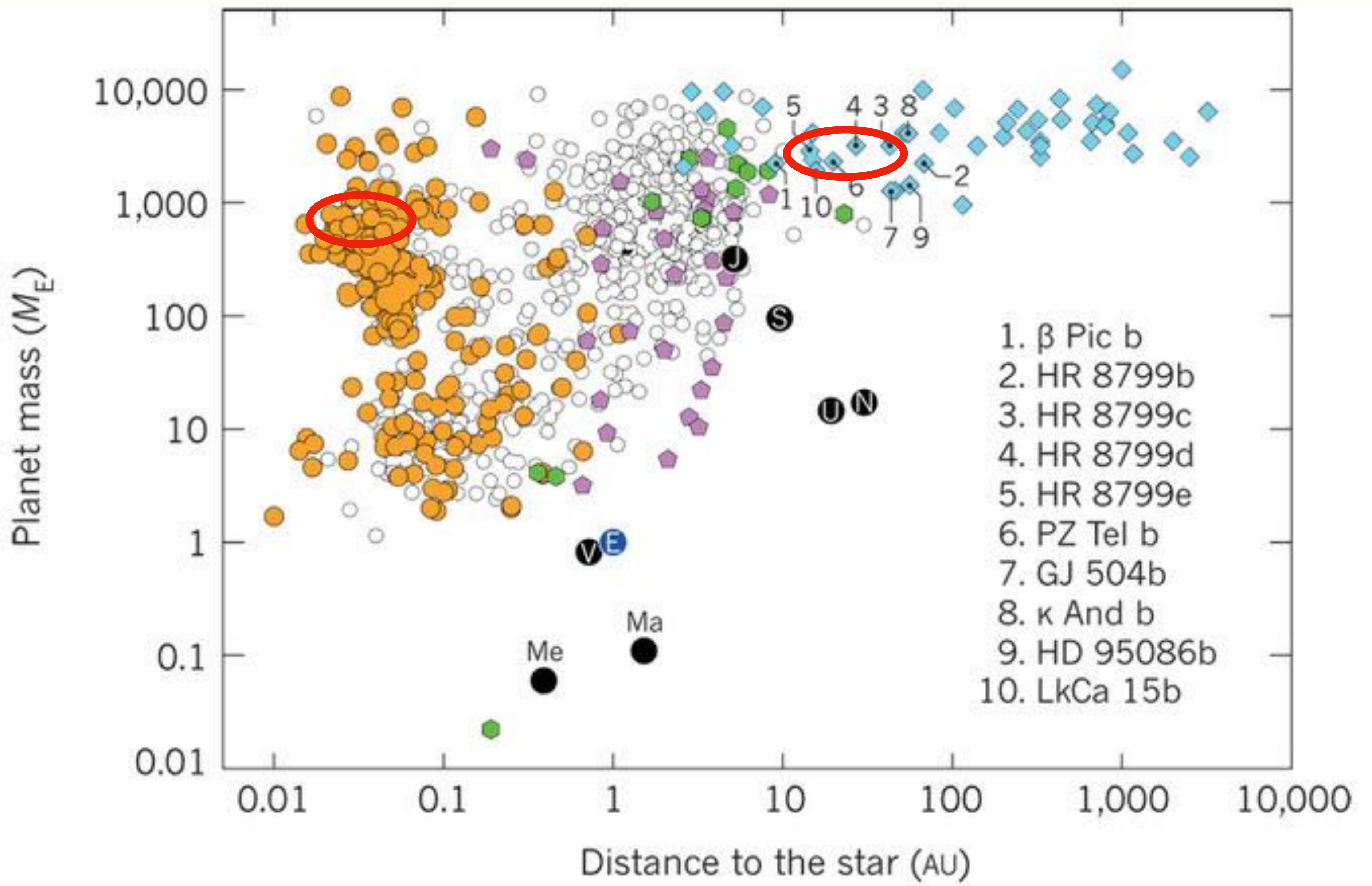
?





Credit: NRC/HIA, C. Marois, and Keck Observatory

Disk evolution and planet formation



Pepe+ 2014

Where are young planets on this plot?

Outline

- Disk Observations:

  Optical/Near-IR:

  Rings, Spirals, Disk shadowing

  Submm:

  Diverse features

  Synergy between Near-IR and Submm

- Planet-disk interaction theory:

  Gaps/rings

  Spirals

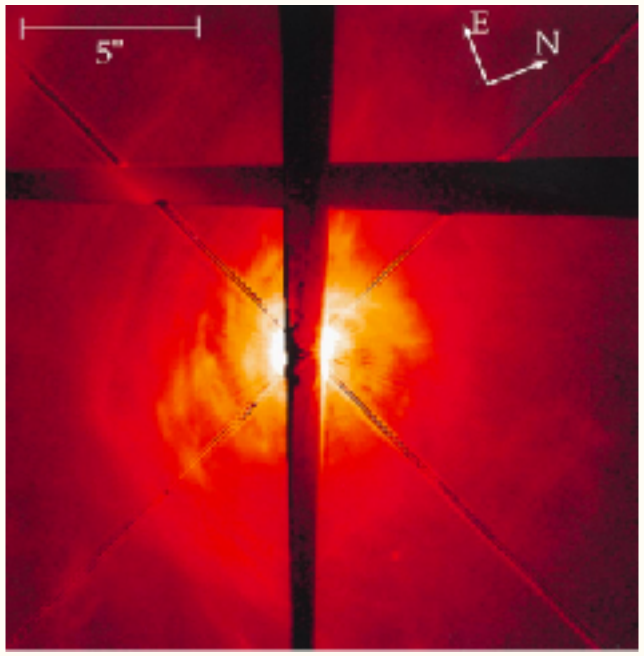
  Lopsided structures

  Shadows

  CPDs

Optical/Near-IR: scattered and polarized light

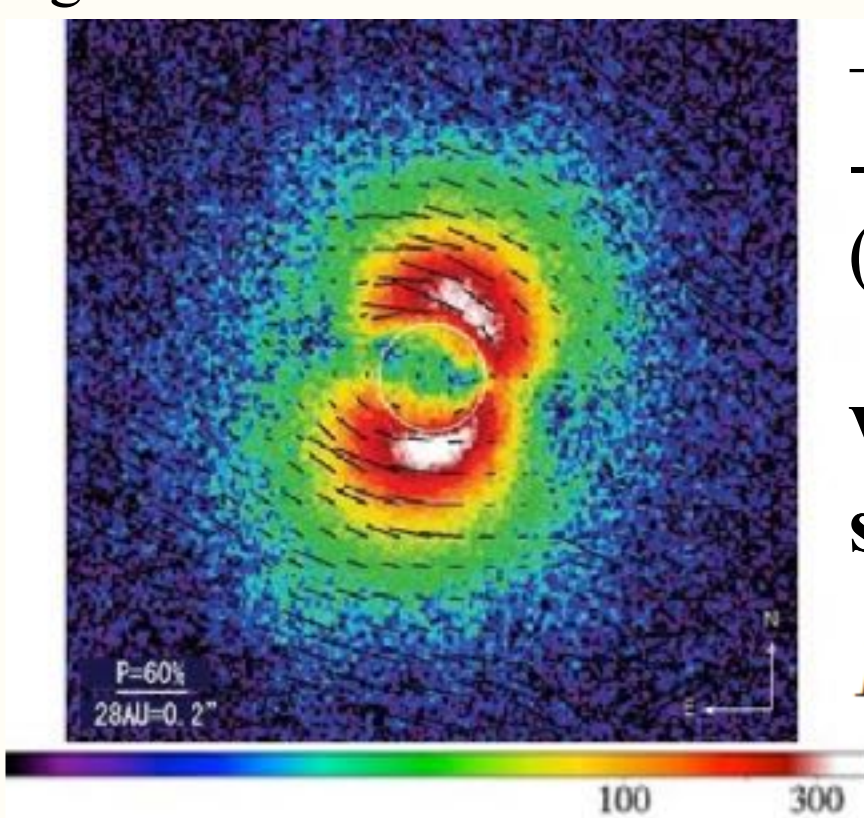
Full Intensity:



+ Full intensity
- But need a coronagraph
- the PSF halo of the star is hard to remove

AB Aur (Hubble)
Grady et al. 1999

Polarized light:



+ less contamination from the star
- Polarized light depends on lots of things (e.g. the scattering angle, inclination)

What we see is not what we think we are seeing!

$$PI = \sqrt{Q^2 + U^2}$$

UX Tau A (SEEDS)
Tanii et al. 2012

Polarization due to scattering

Scattering-induced polarization: simple illustration with oscillating dipoles

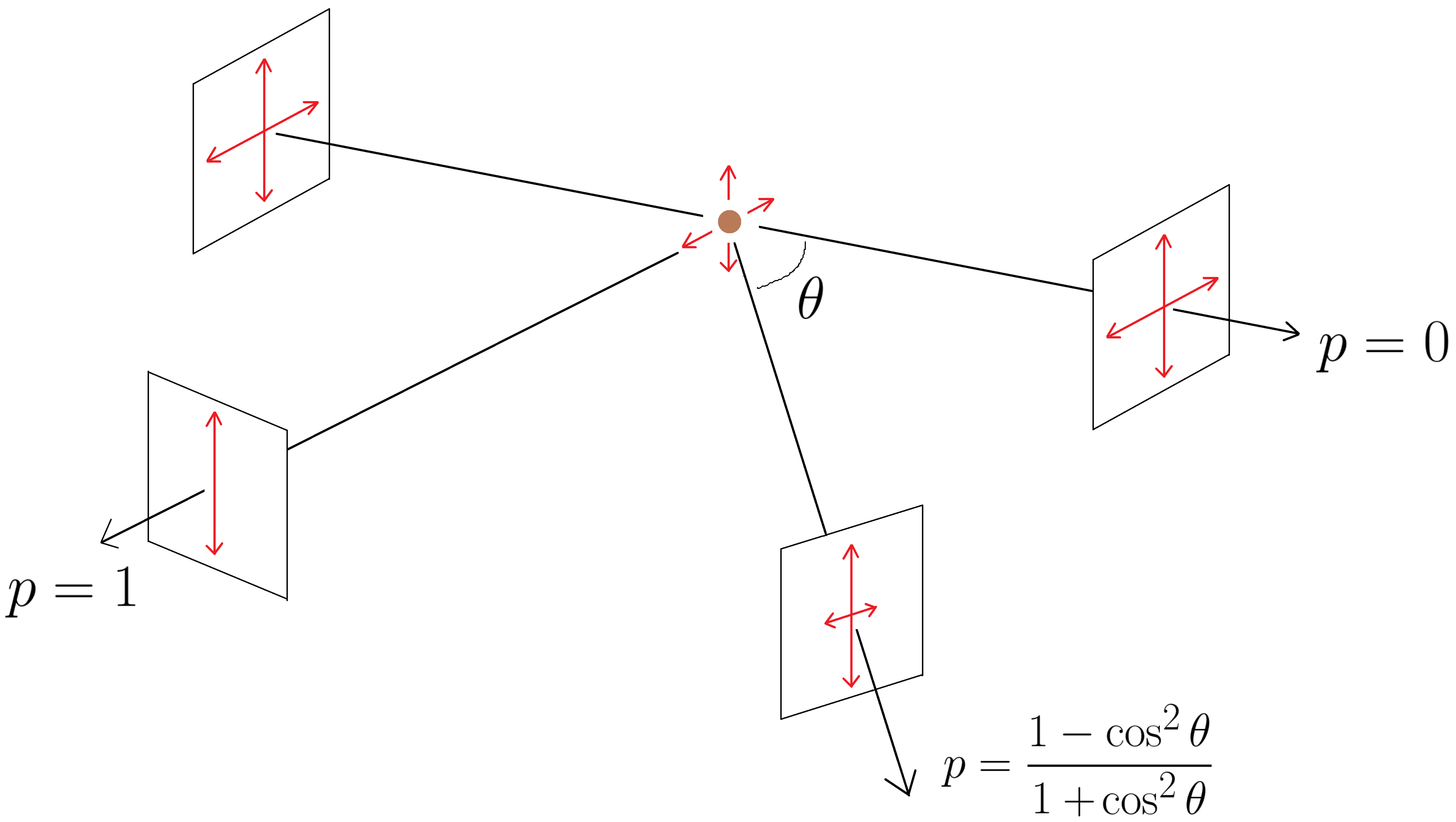


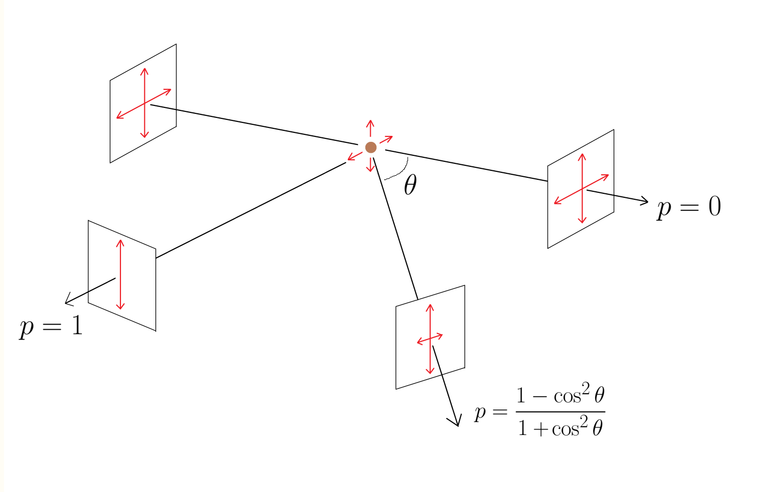
image: Zhi-Yun Li

No light with E field along direction of propagation (transverse wave)

Maximum (full) polarization for 90^0 scattering

Polarization (E field) perpendicular to scattering plane (incident + scattered light)

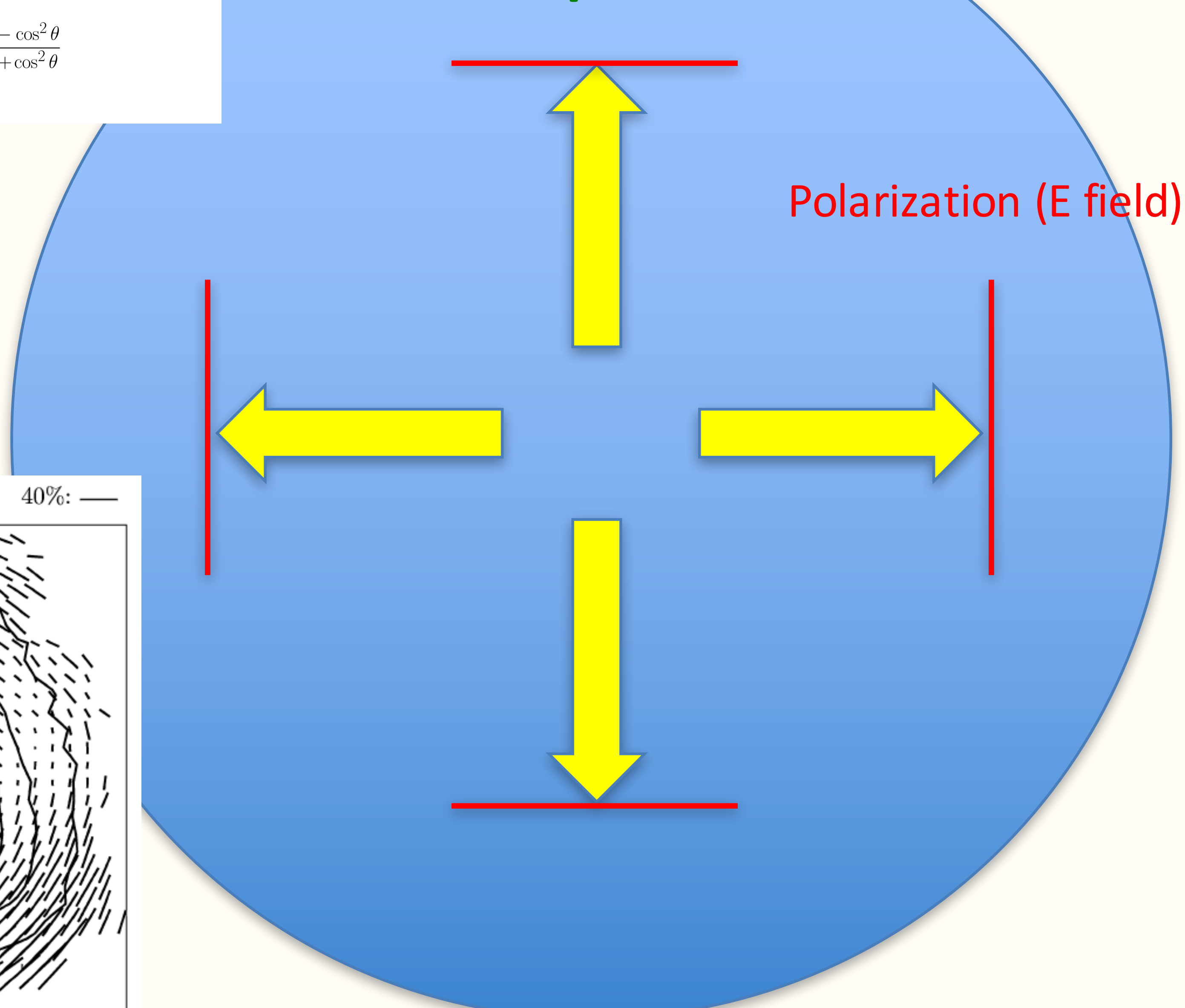
Polarization due to scattering



Simplest case: face-on disk

anisotropic radiation away from center

→ polarization after scattering



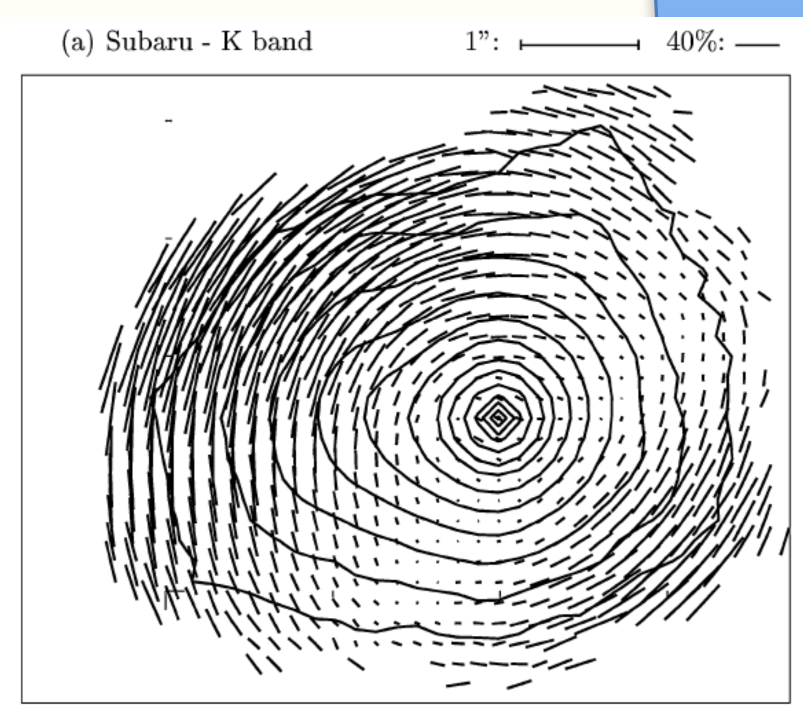
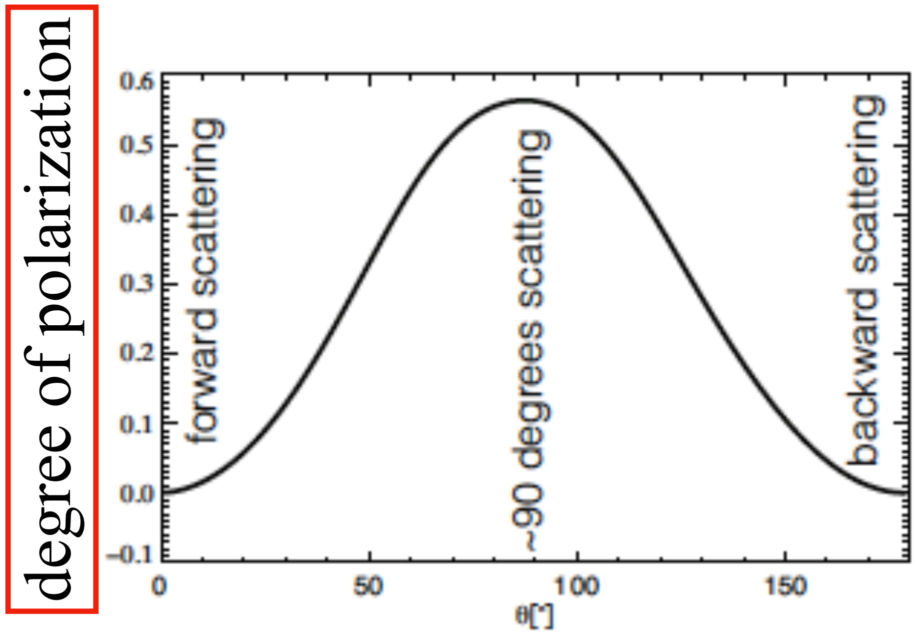
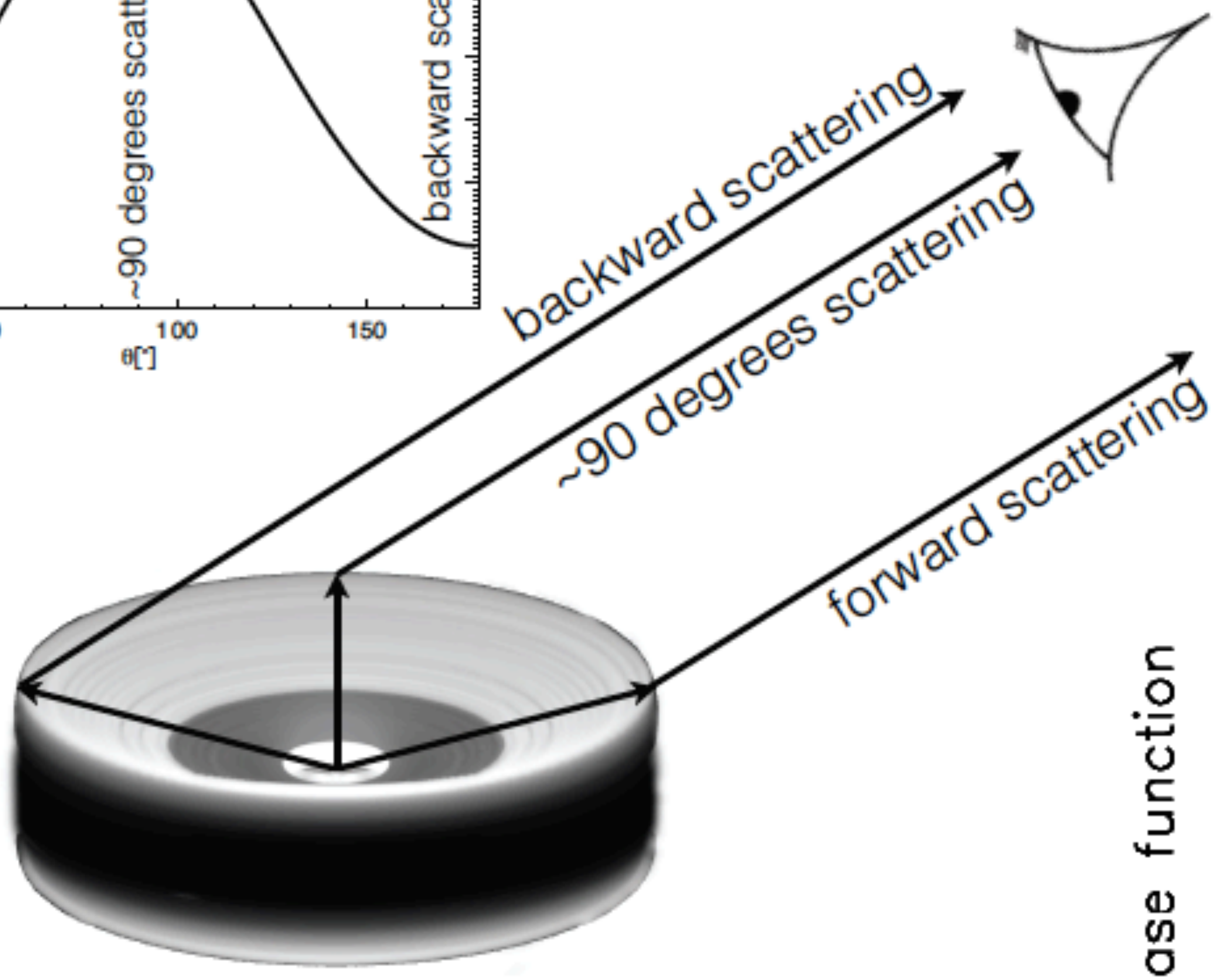


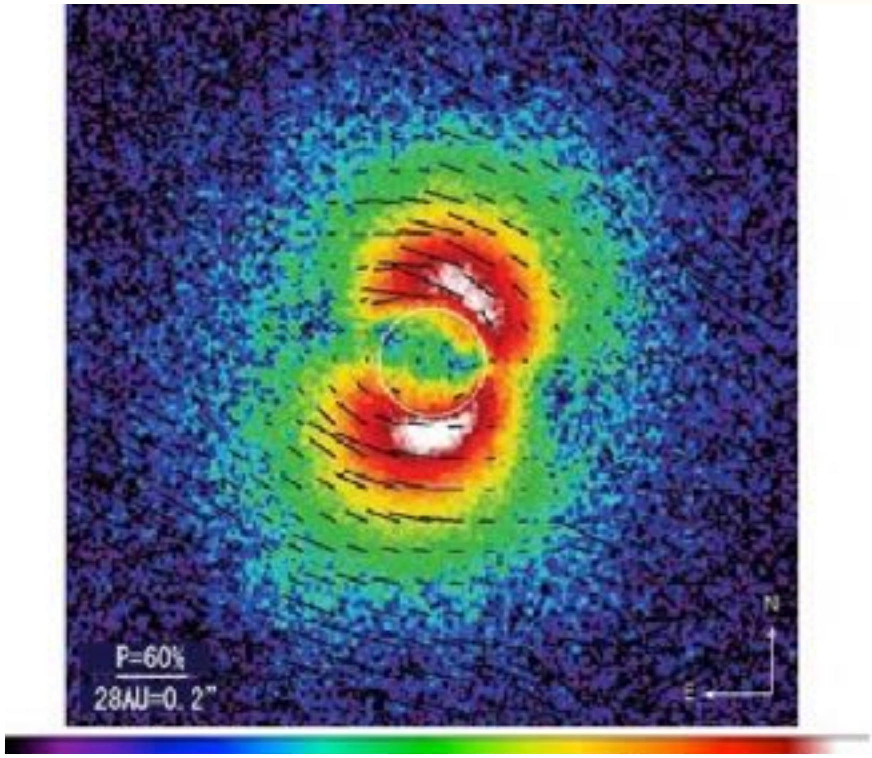
image: Zhi-Yun Li

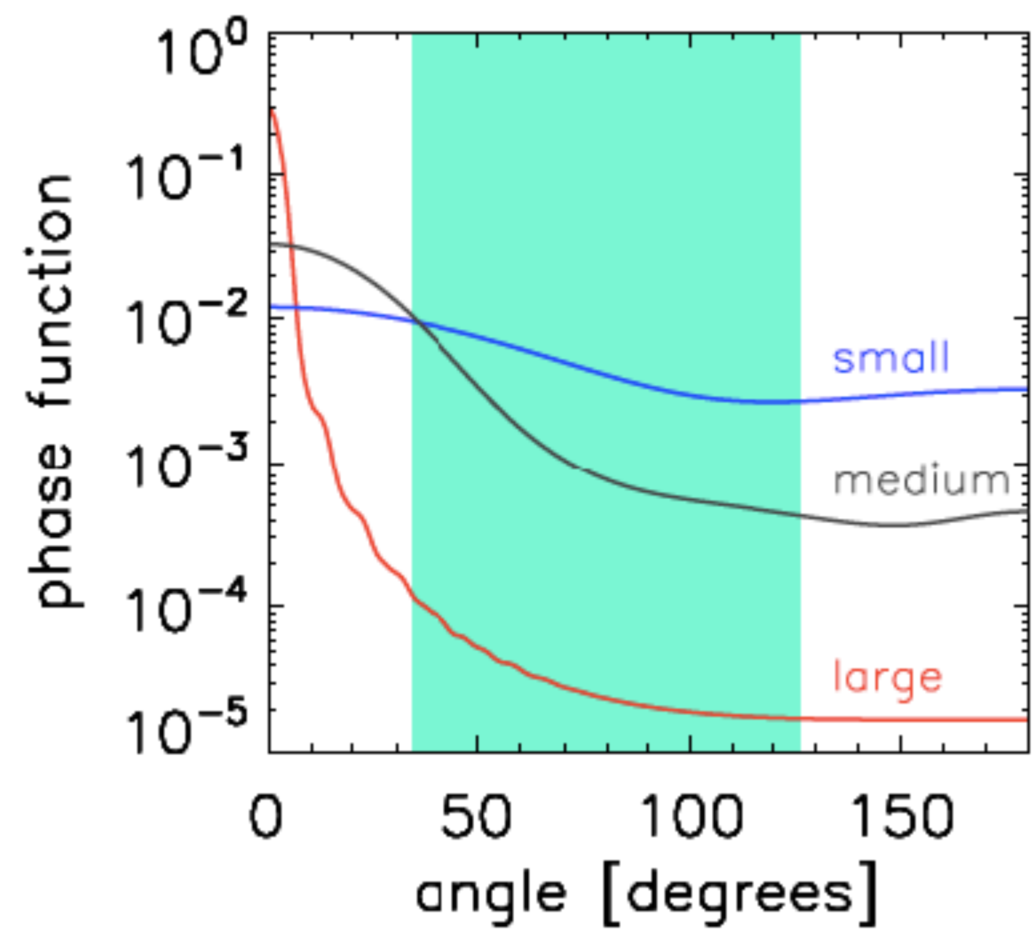
→ Azimuthal polarization pattern

Polarization due to scattering: Inclination





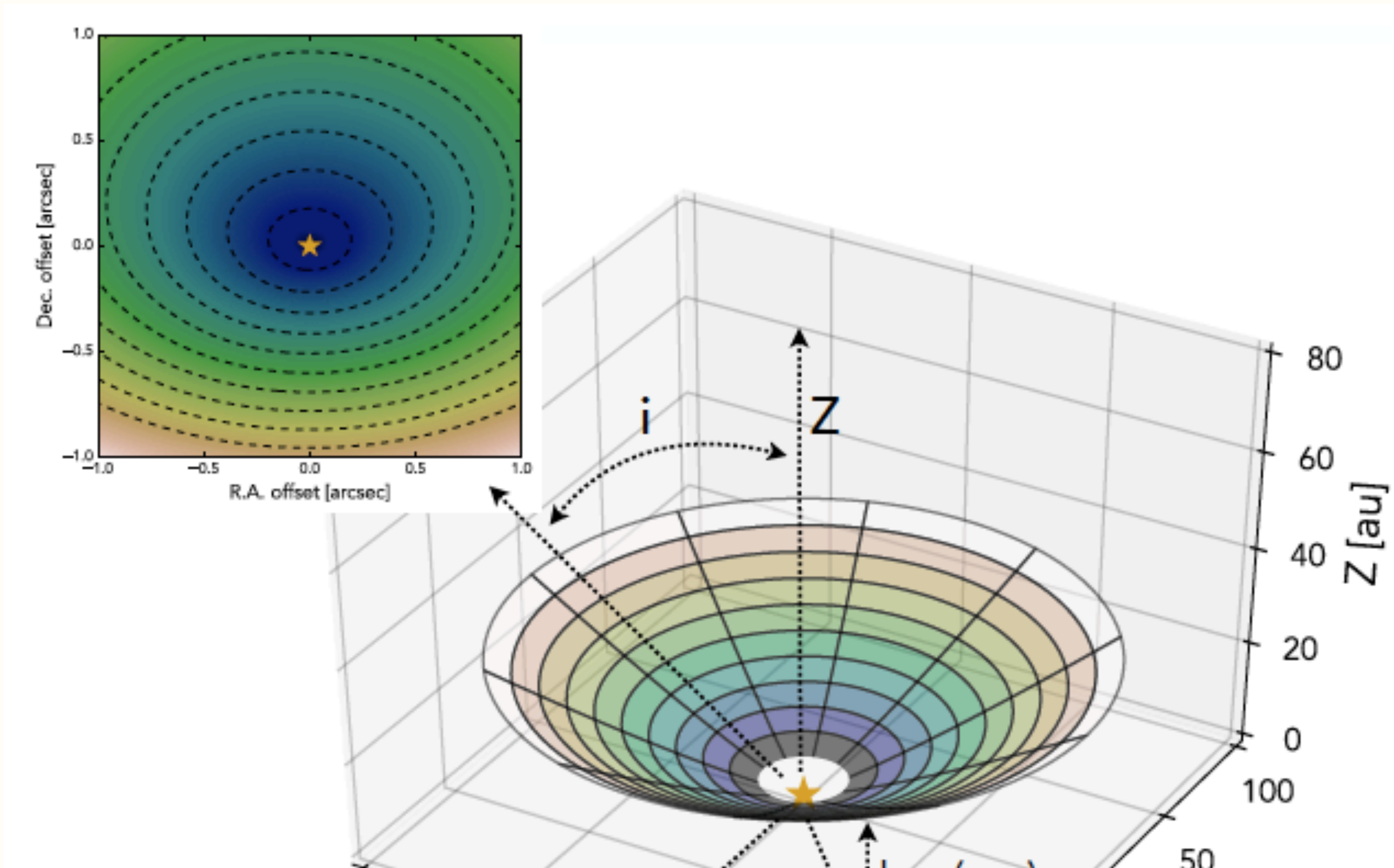


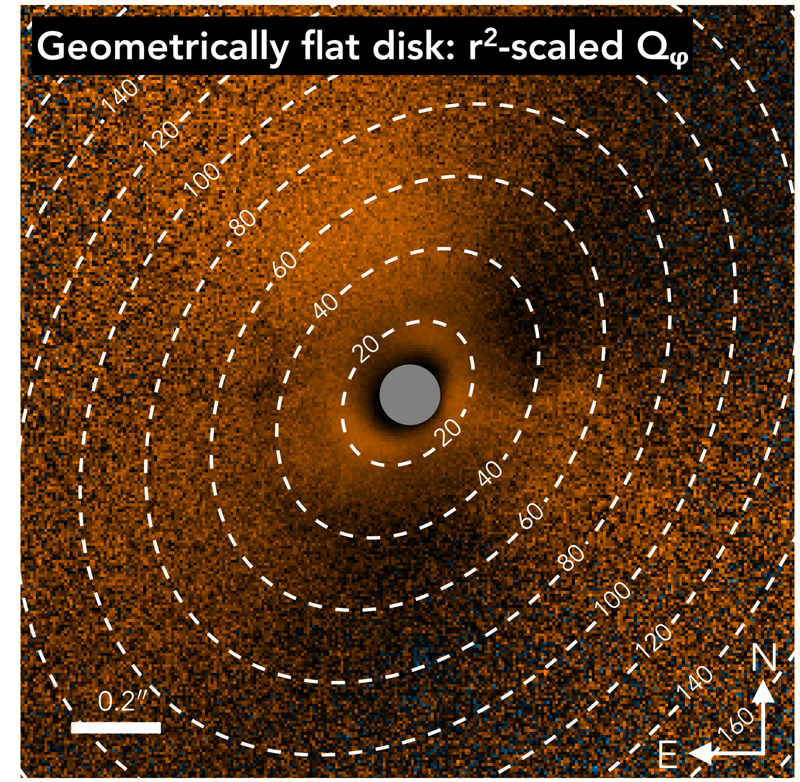


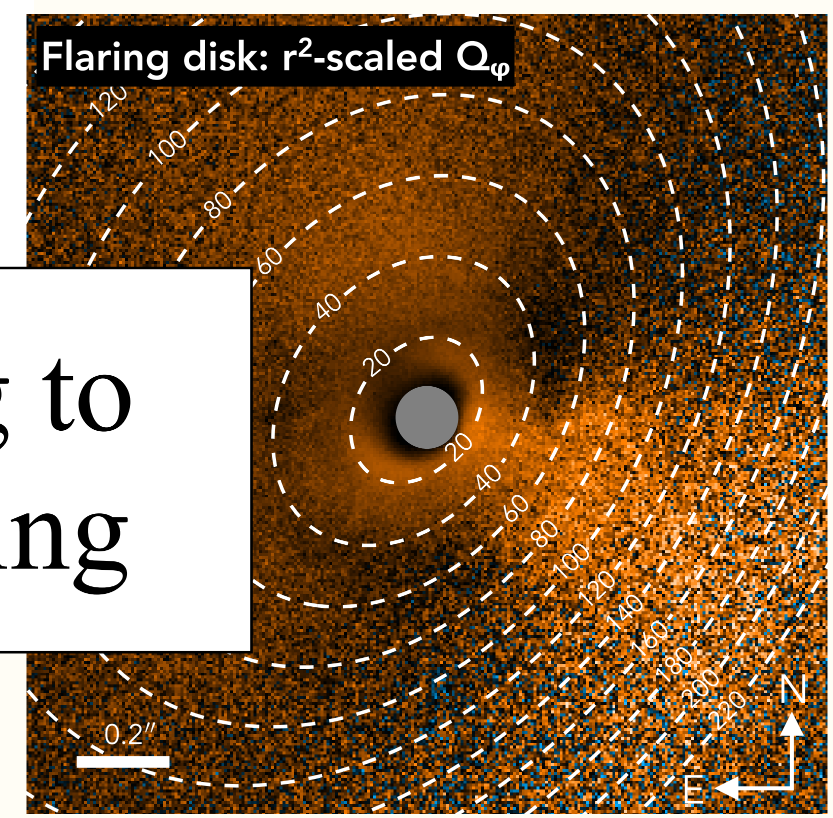
Min et al. 2015

… depends on grain size, composition, porosity…

Polarization due to scattering: Projection





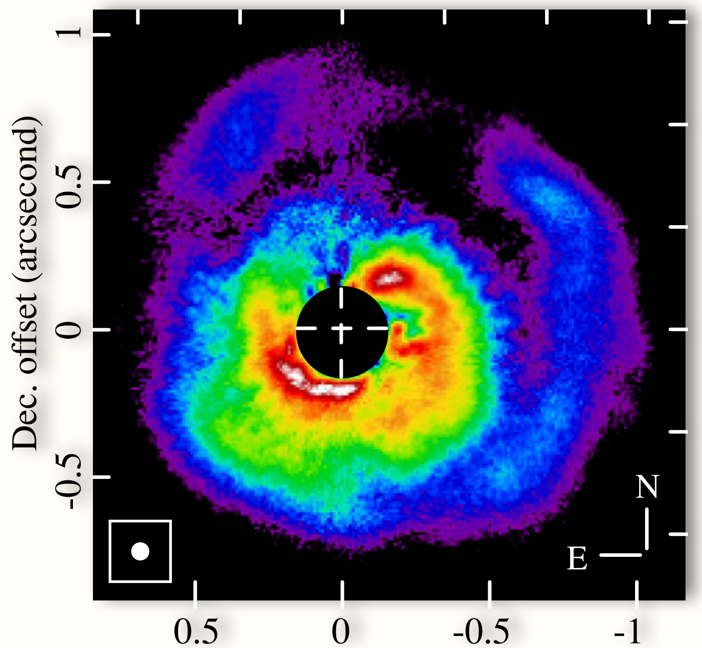


Need careful modeling to know what we are seeing

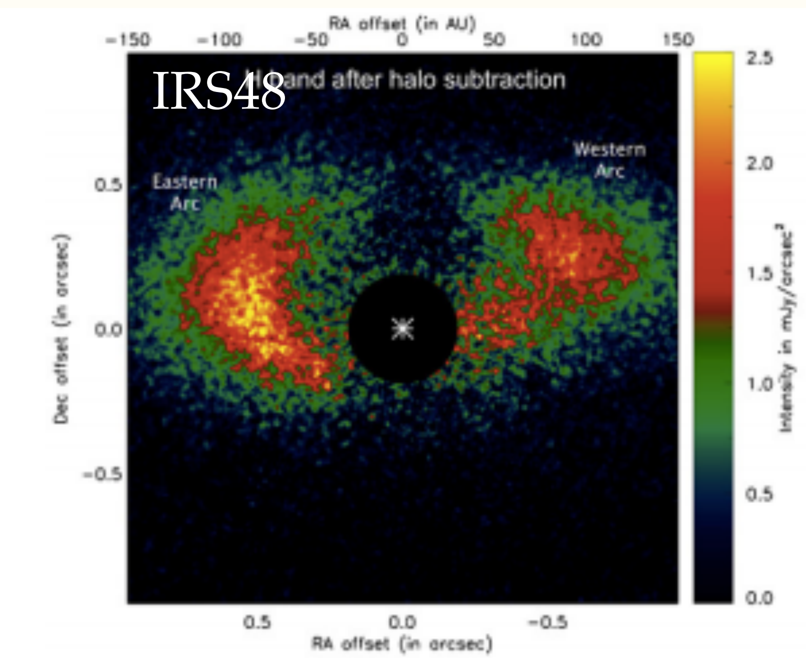
Stolker et al. 2016b. Also Mulders et al. 2013, Garufi et al. 2016

First PDI surveys

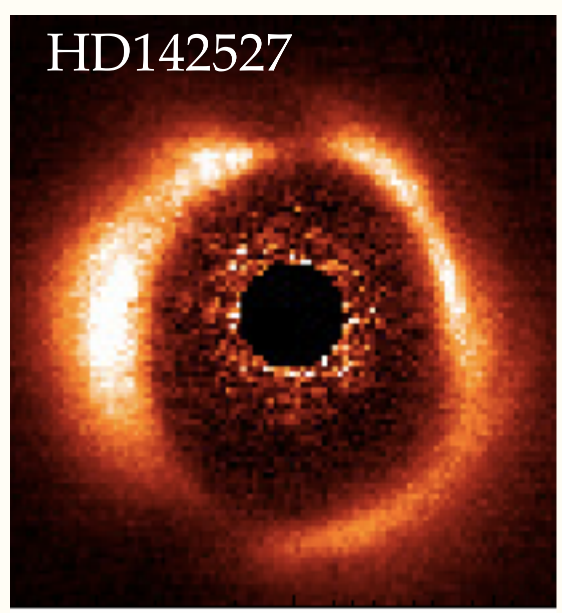
Observations of Herbig AeBe and TD with Naco/VLT and HiCIAO/Subaru at high resolution have shown more complex features.



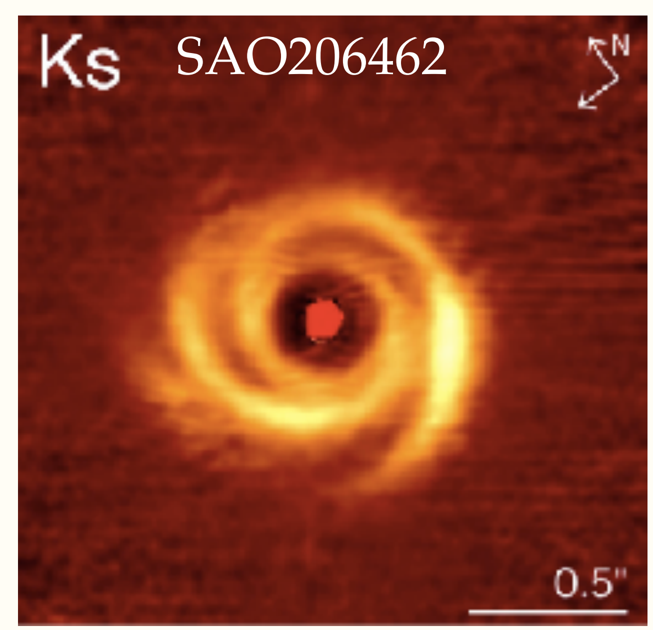
Hashimoto et al. 2011



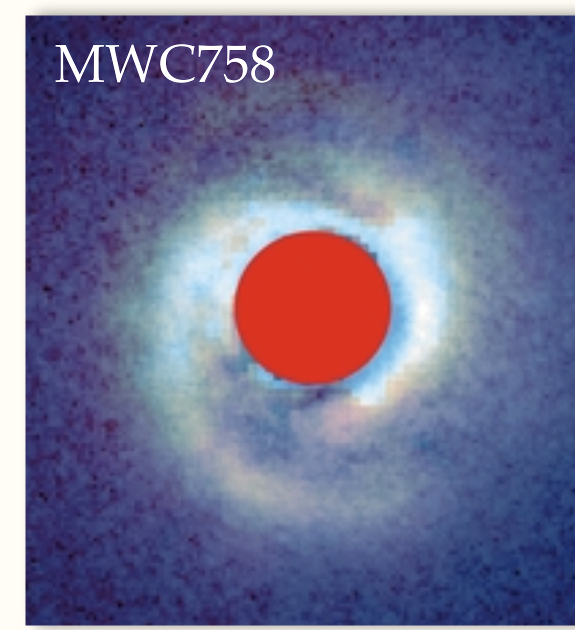
Folette et al. 2015



Canovas et al 2013



Garufi et al 2013



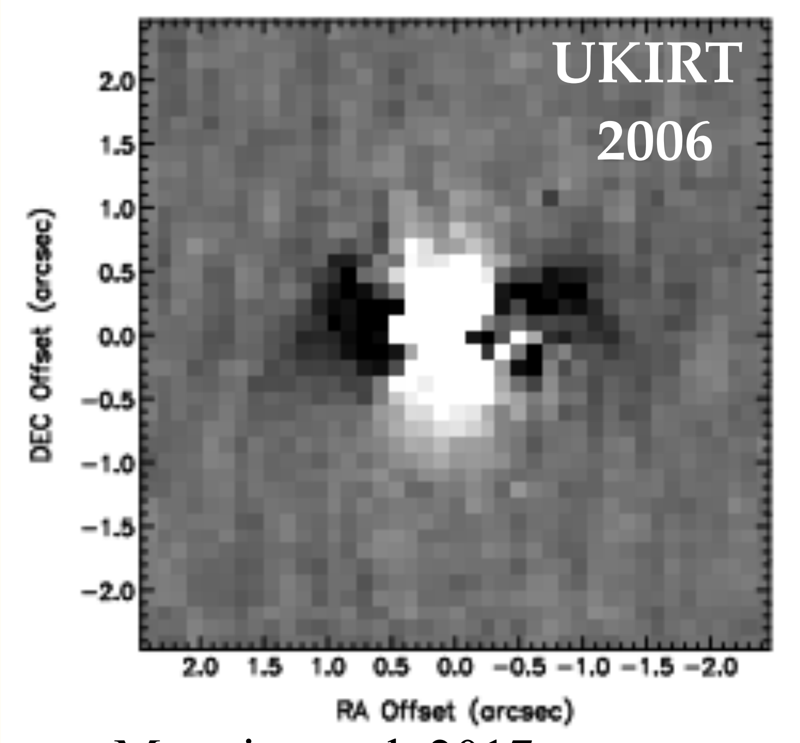
Grady et al 2013

Also Fukagawa et al. 2006; Hashimoto et al. 2011; Quanz et al. 2011,2012; Muto et al. 2012; Kusakabe et al 2012; Folette et al. 2013; Avenhaus et al. 2014; Garufi et al. 2014, and more.

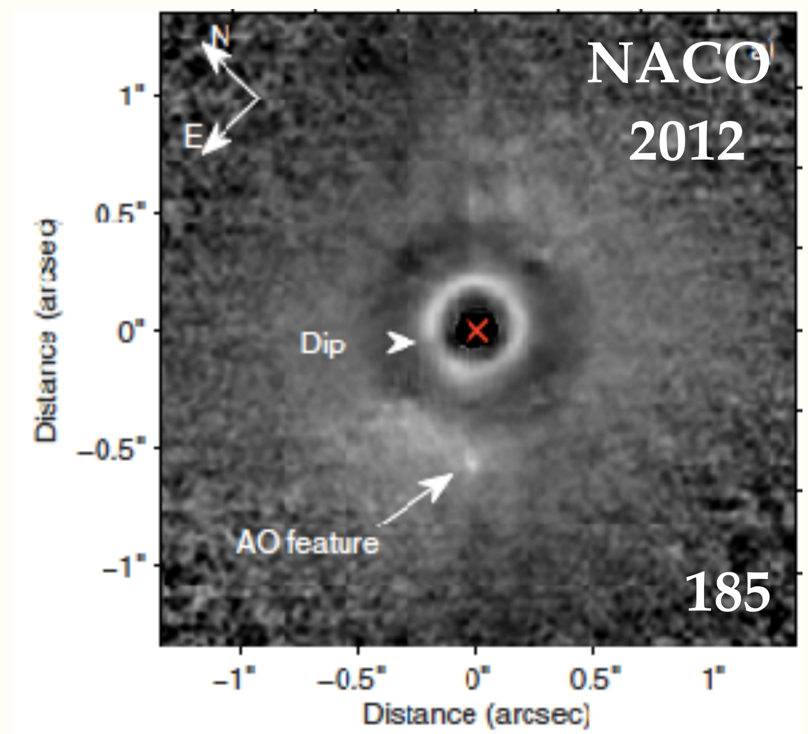
Evolution of AO

HD169142

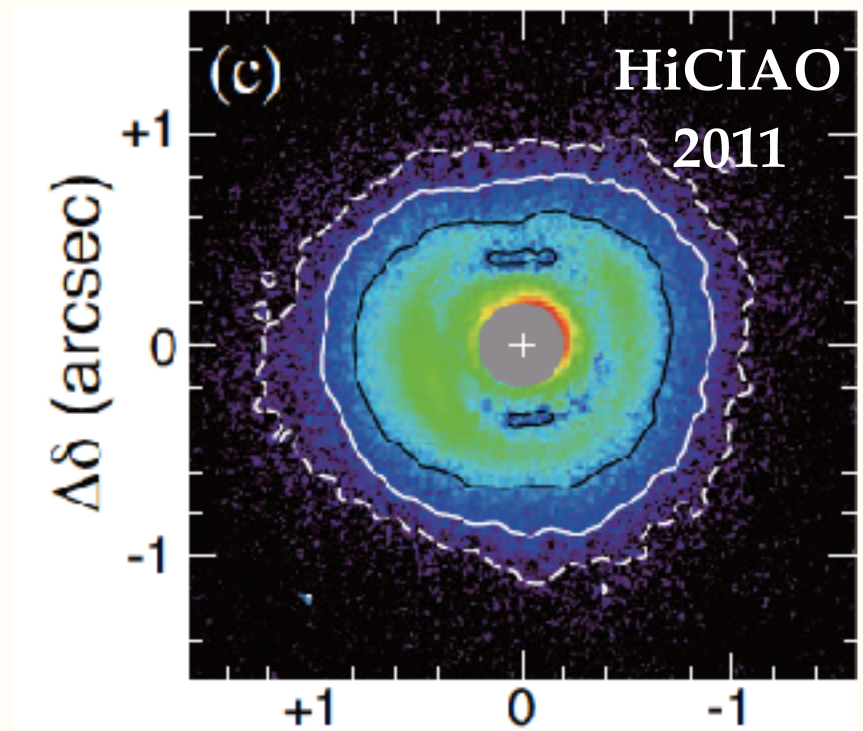
Hales et al. 2006



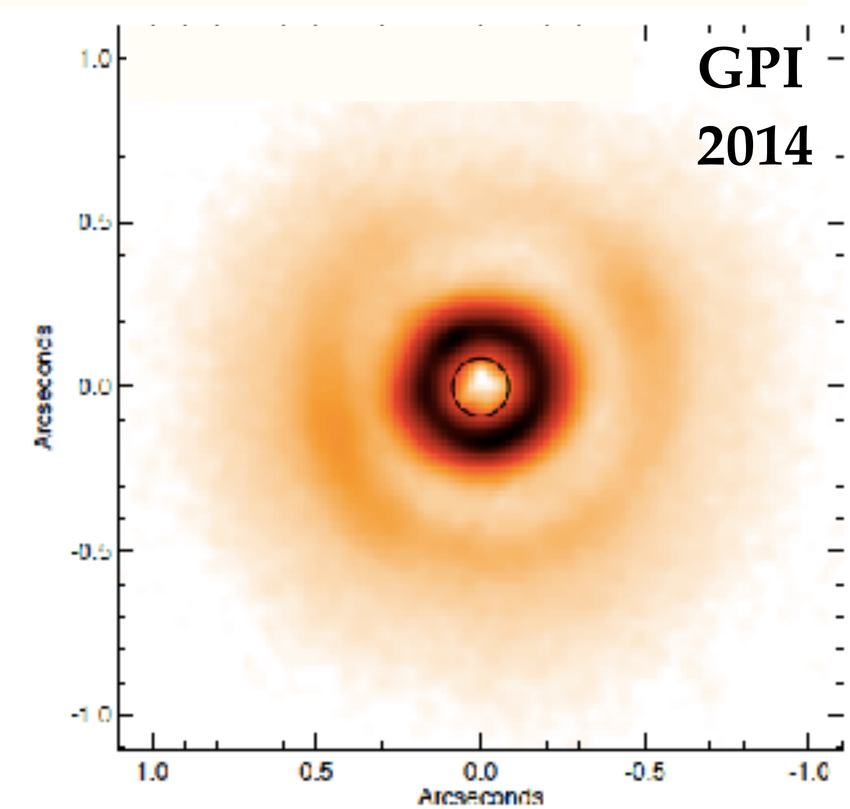
Quanz et al. 2013



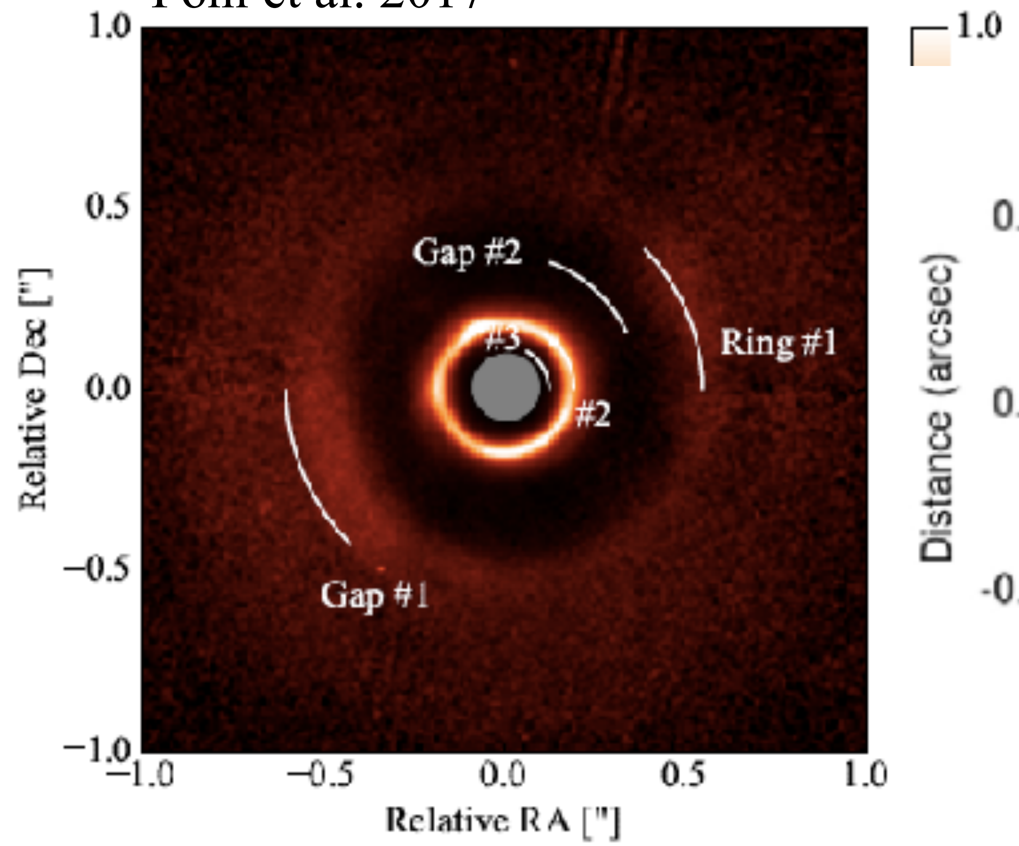
Momose et al.



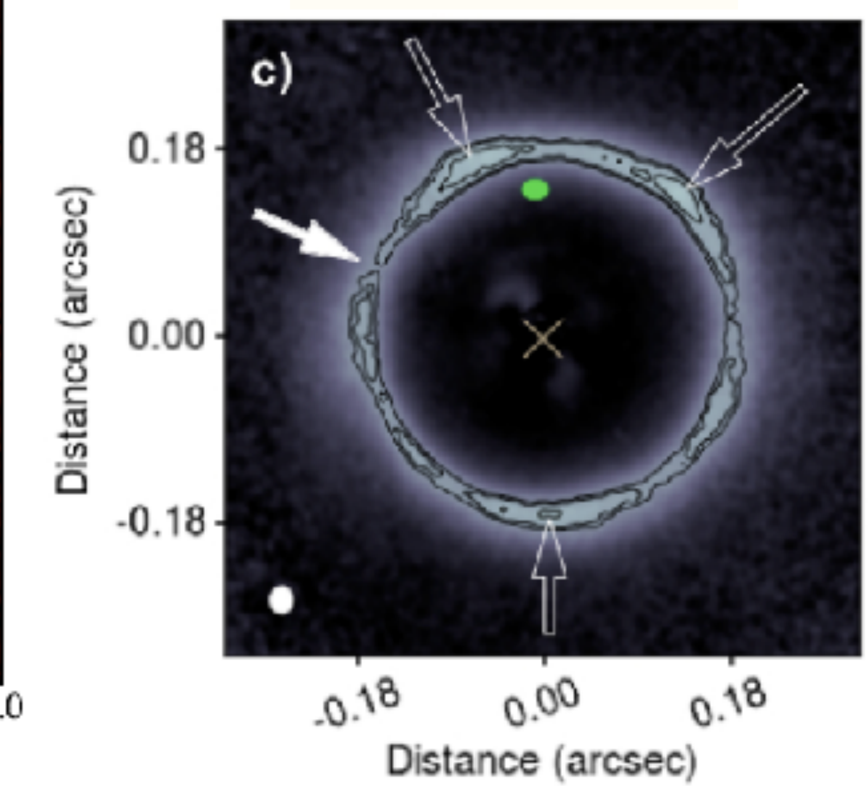
Monnier et al. 2017



Pohl et al. 2017



Bertrang et al. 2017



Outline

- Disk Observations:

  Optical/Near-IR:

    Rings, Spirals, Disk shadowing

  Submm:

    Diverse features

    Synergy between Near-IR and Submm

- Planet-disk interaction theory:

  Gaps/rings

  Spirals

  Lopsided structures

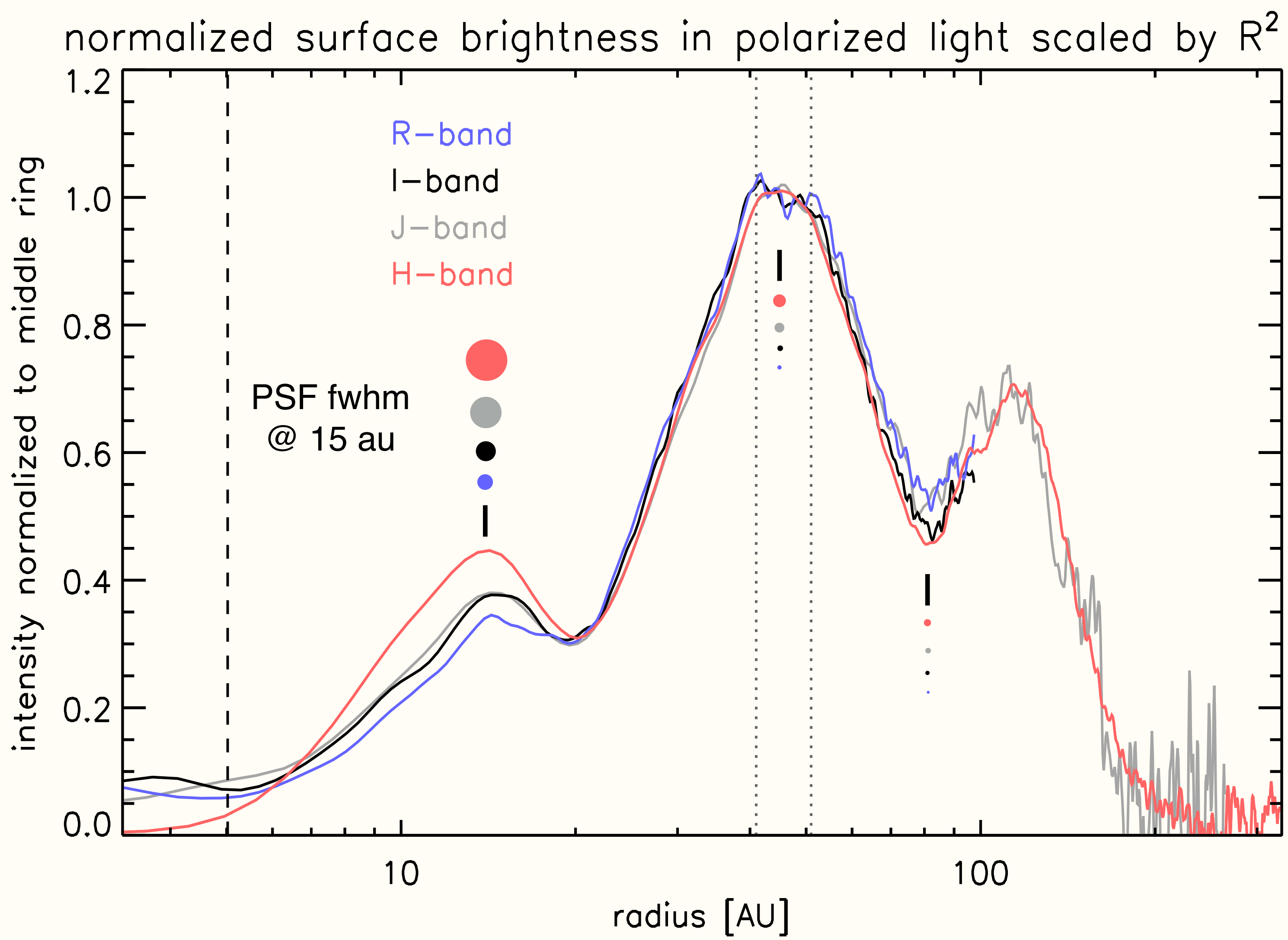
  Shadows

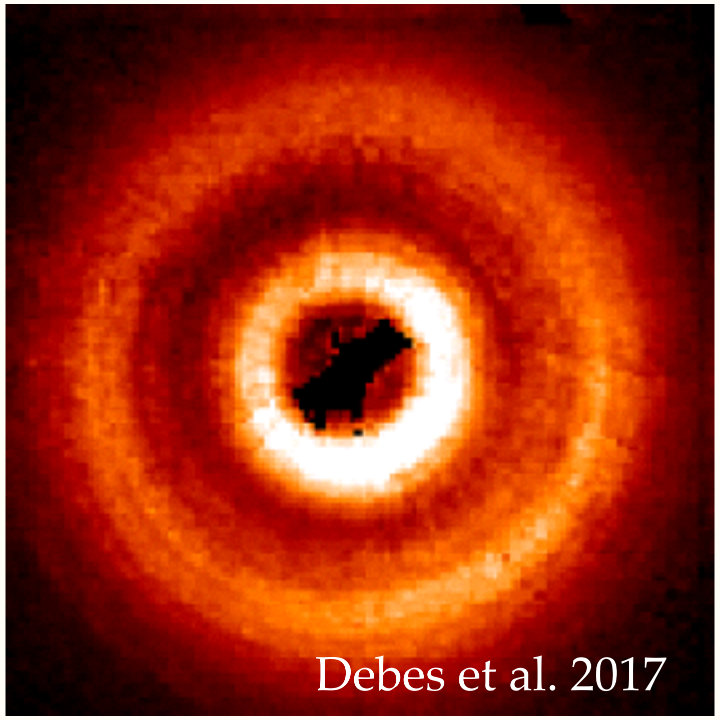
  CPDs

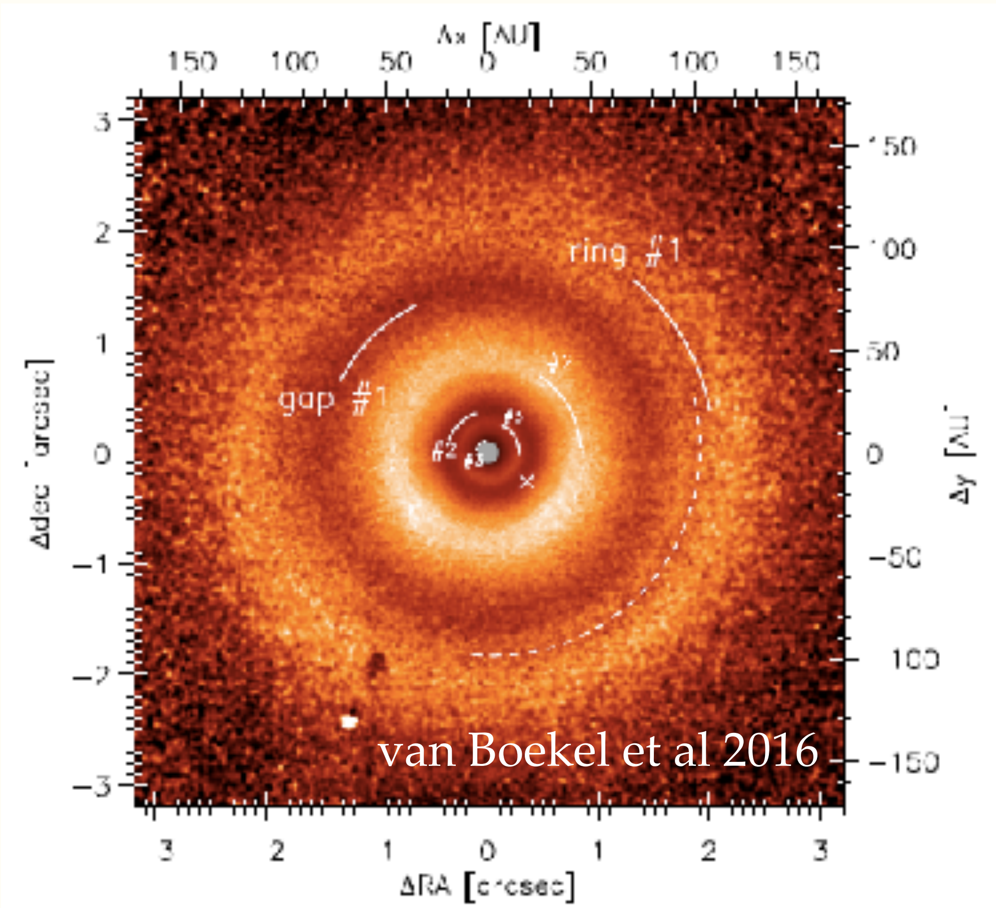
Rings

TW Hya

Gap @ 6 au, 20 au, 80 au

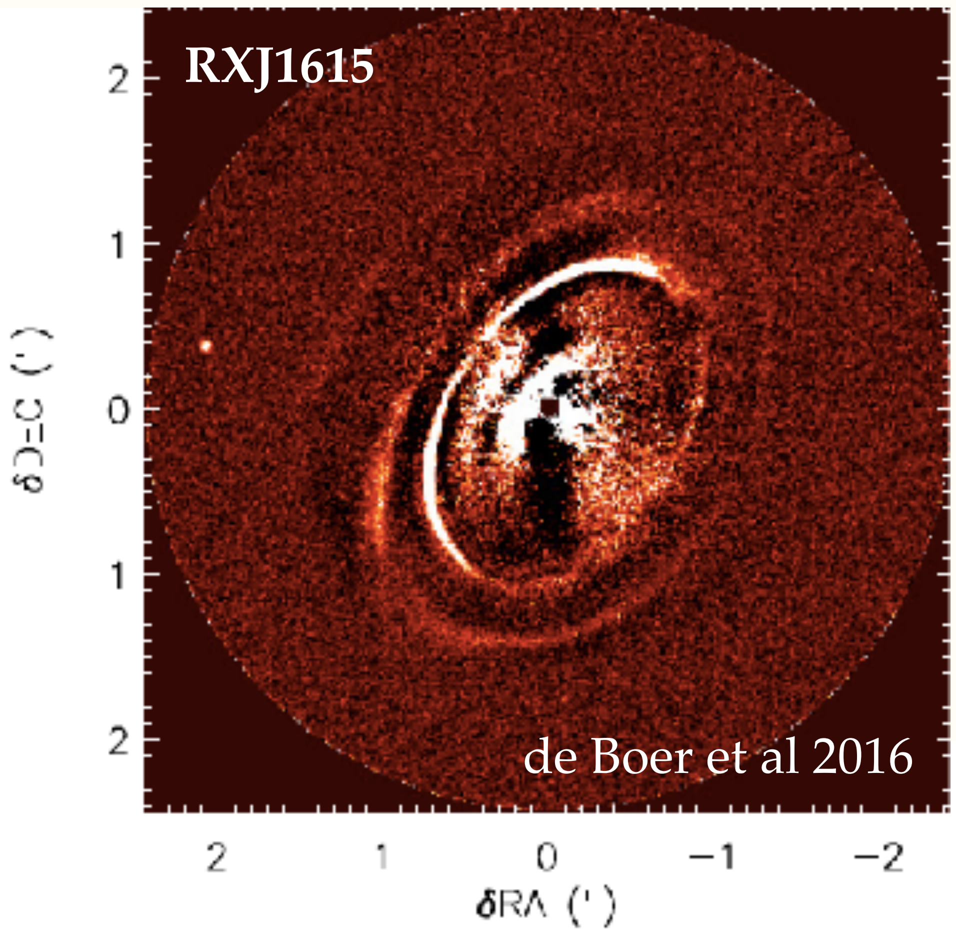




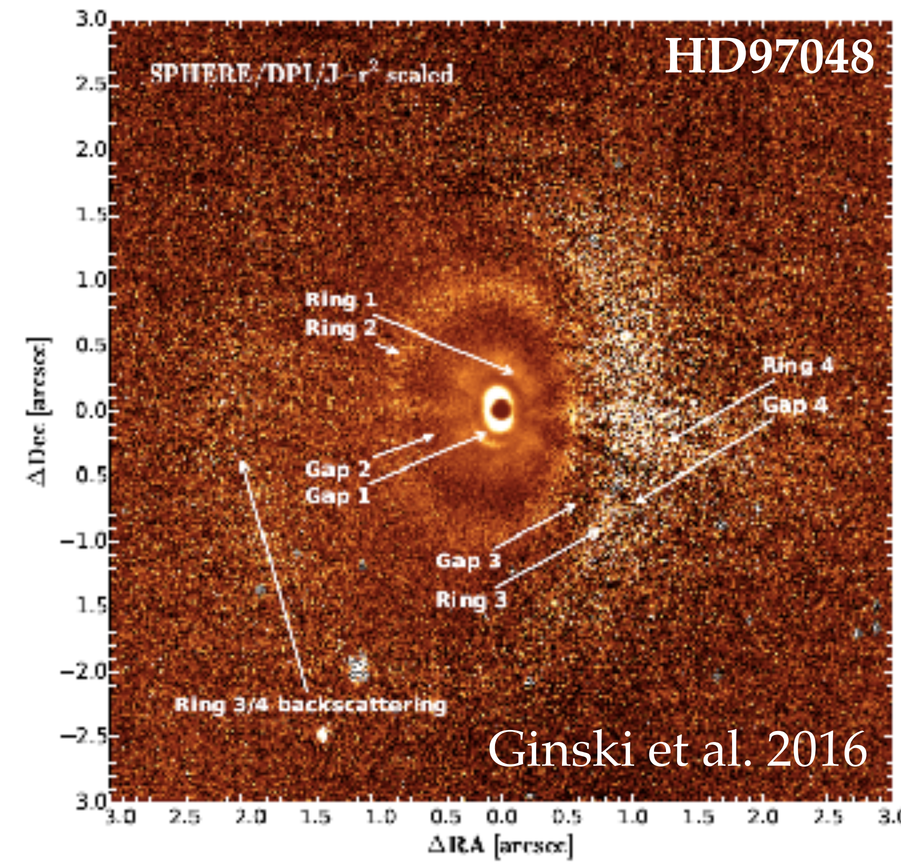


Also Debes et al. 2013, Akiyama et al. 2015, Rapson et al. 2015a,b.

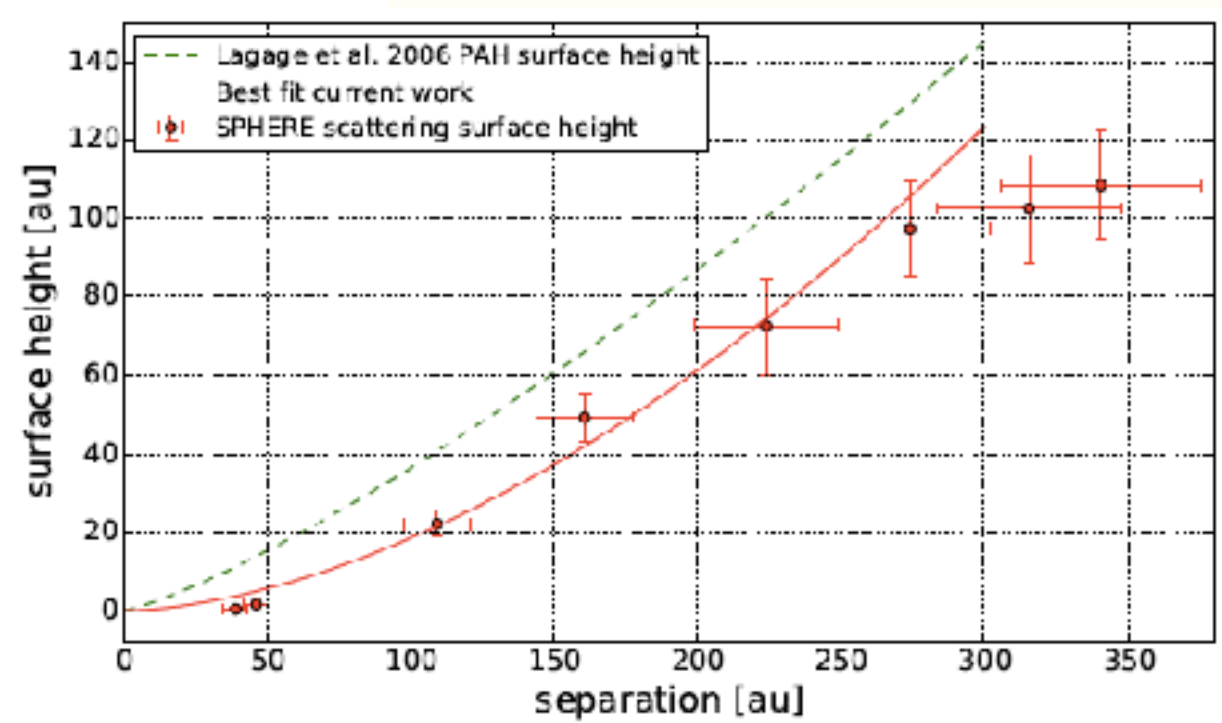
Using rings to constrain the disk surface



- An inner disk (up to ~56 au) and two rings (196 au; 278 au).
- Apparent offset provides the height of the scattering surface (H/R~0.15, 0.16)

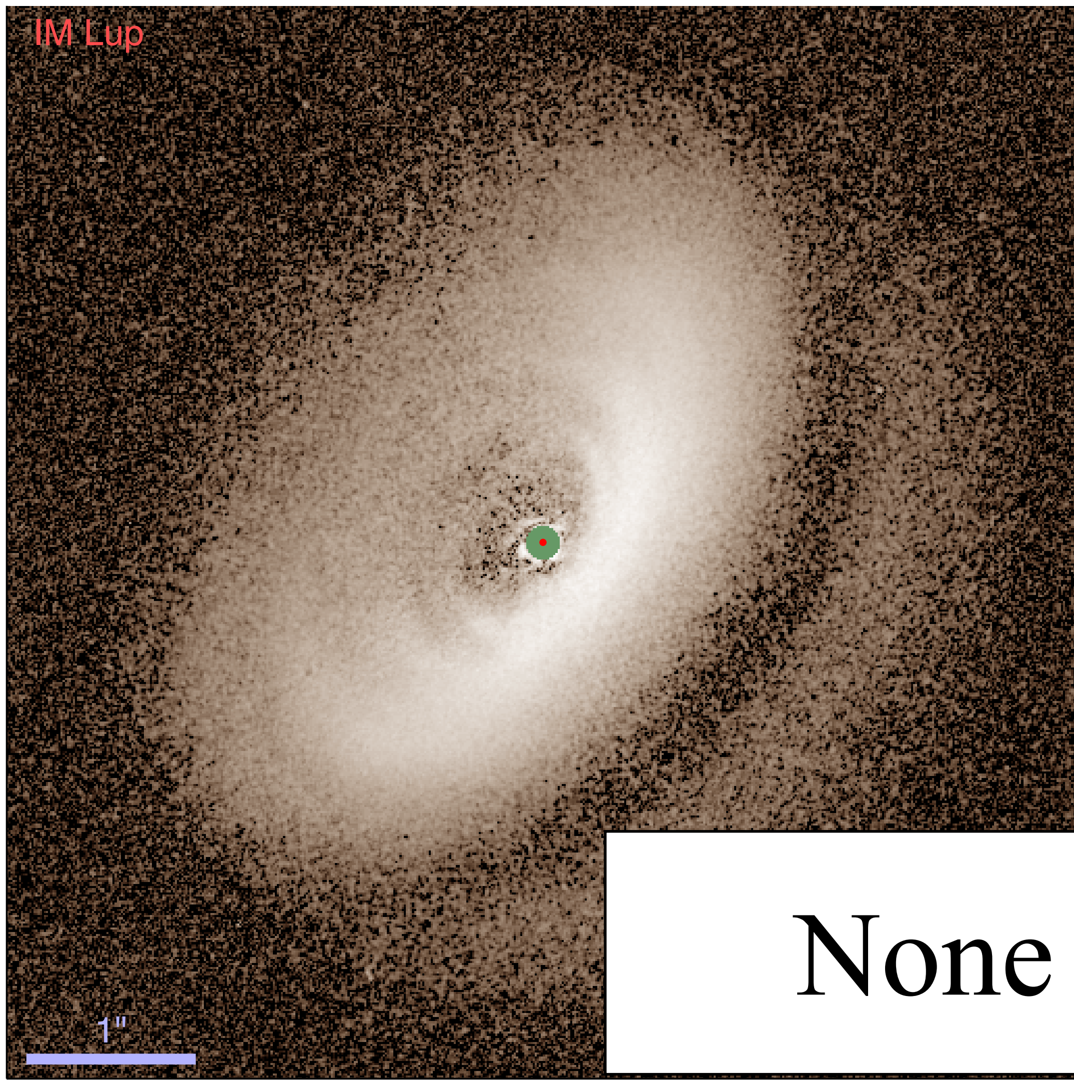


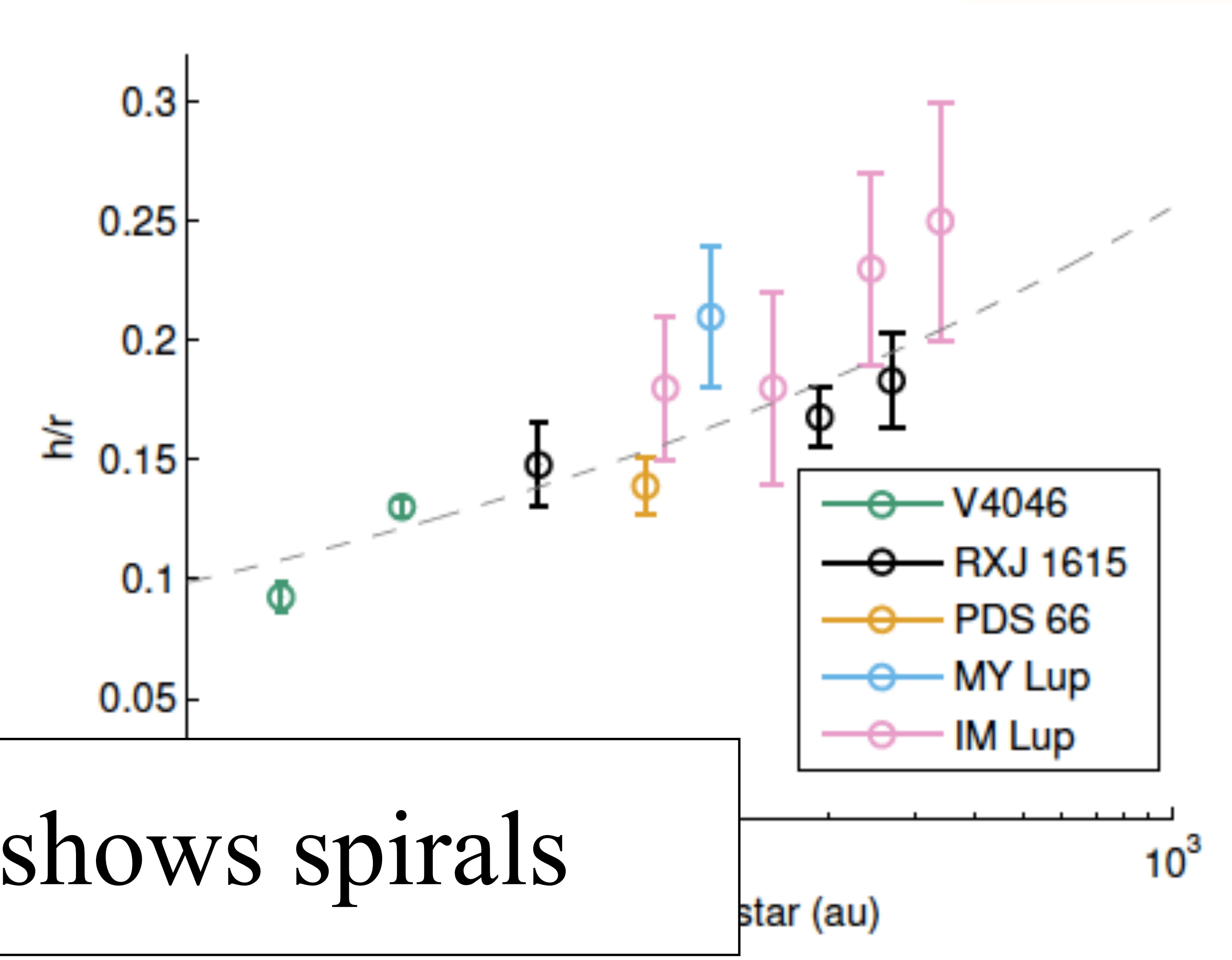
An inner disk (up to ~39 au) and 4 rings (46, 160, 274, 340 au)



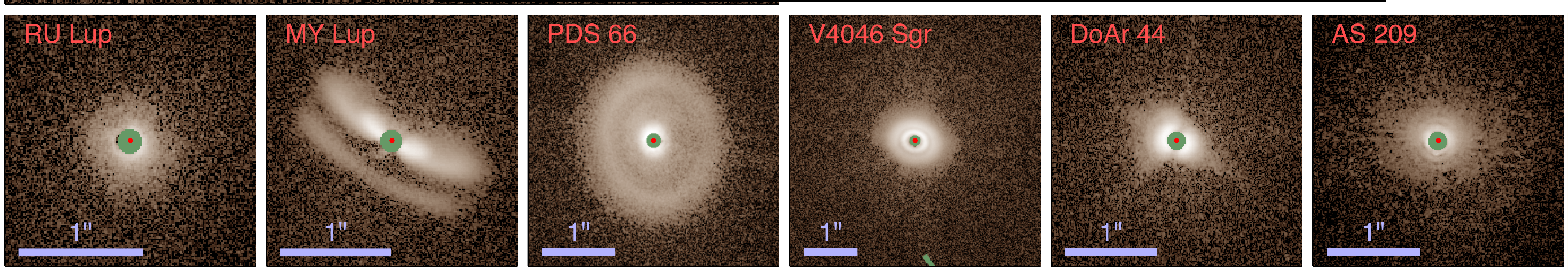
Using rings to constrain the disk surface

Recent survey of T Tauri stars





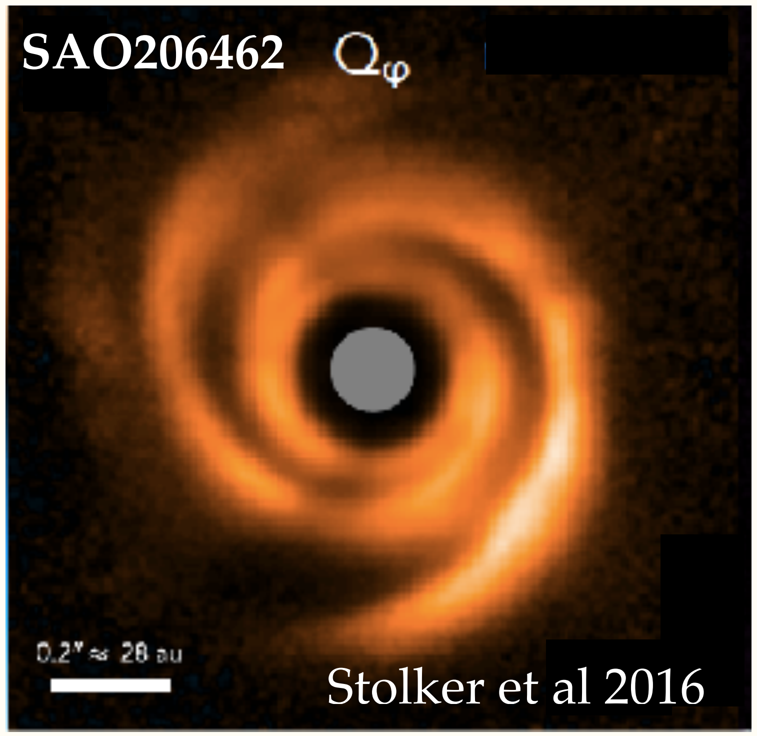
None shows spirals



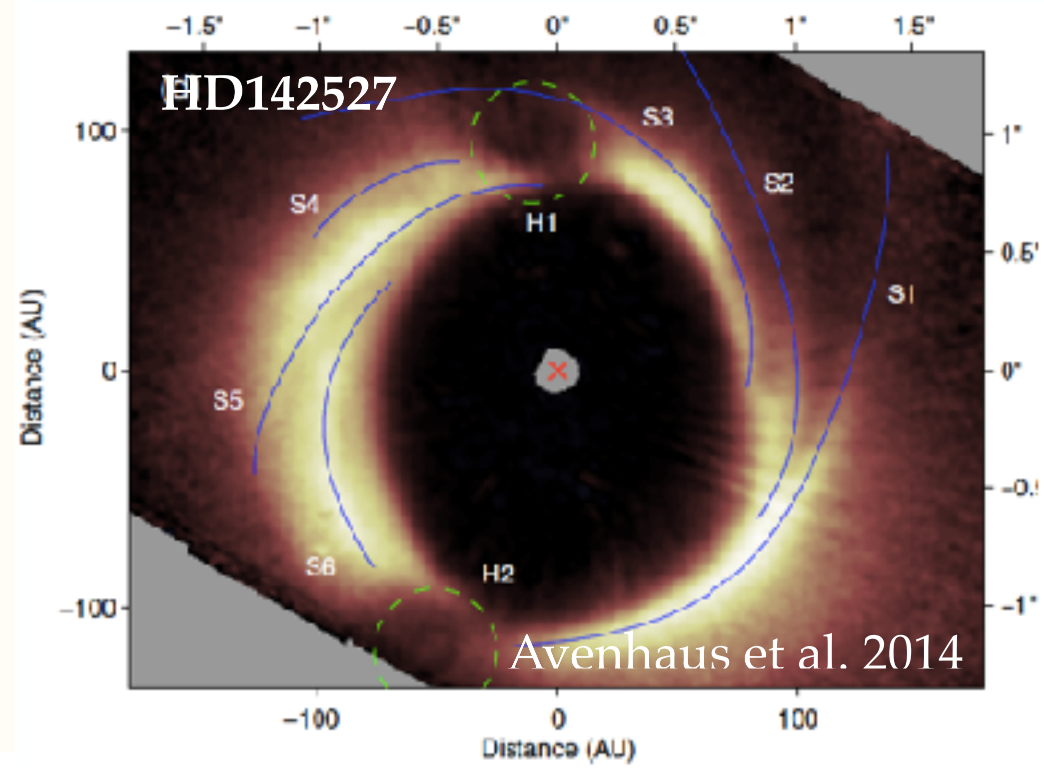
Survey of 8 T Tauri stars.

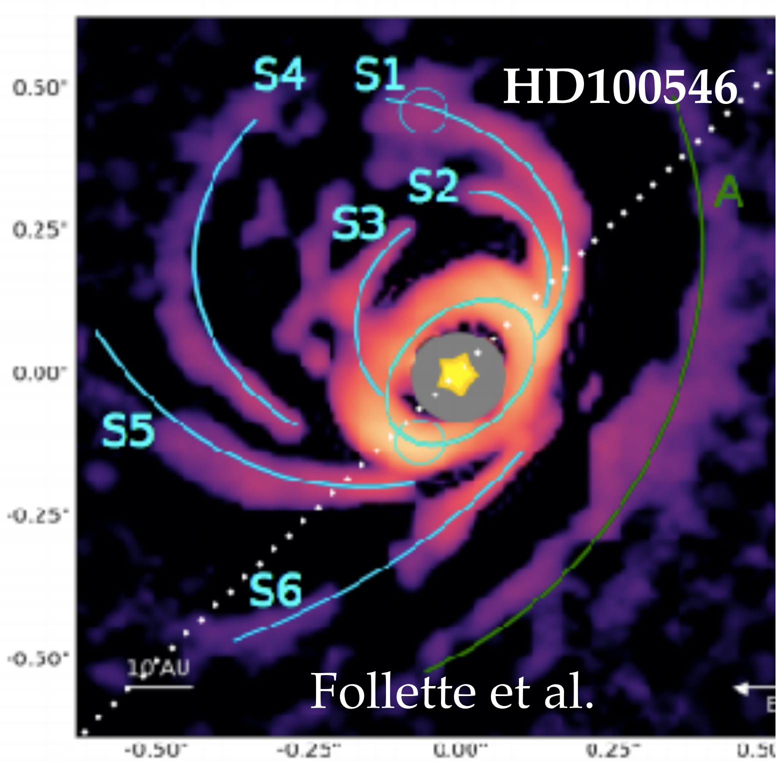
Avenhaus et al. 2018

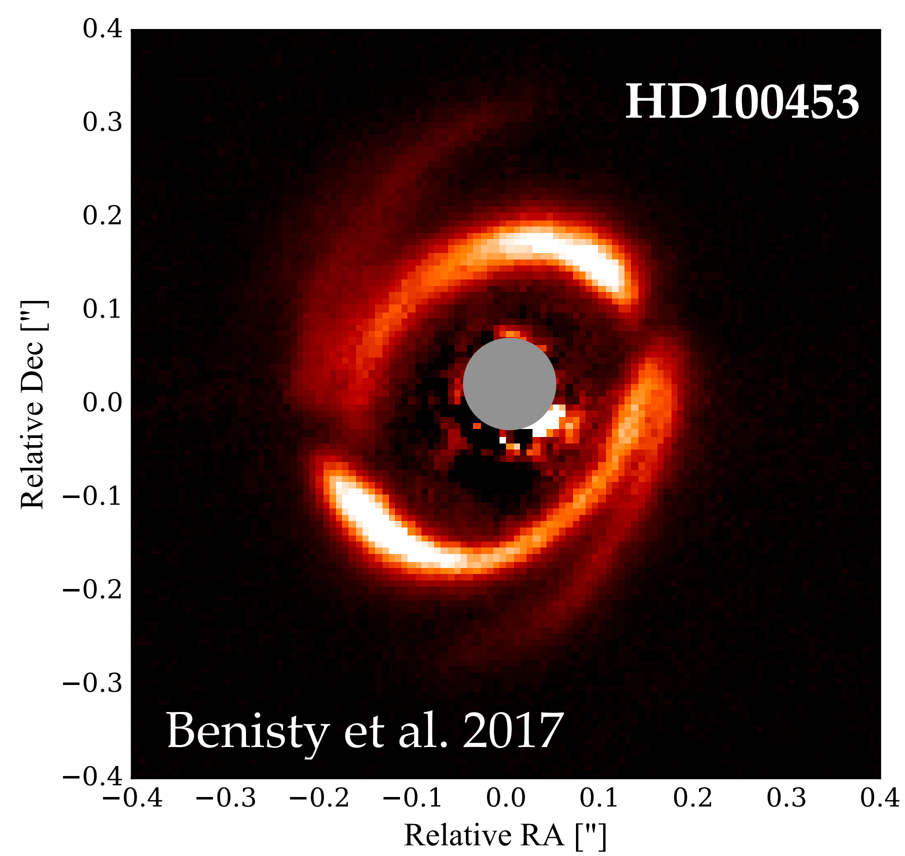
Multiple spiral arms

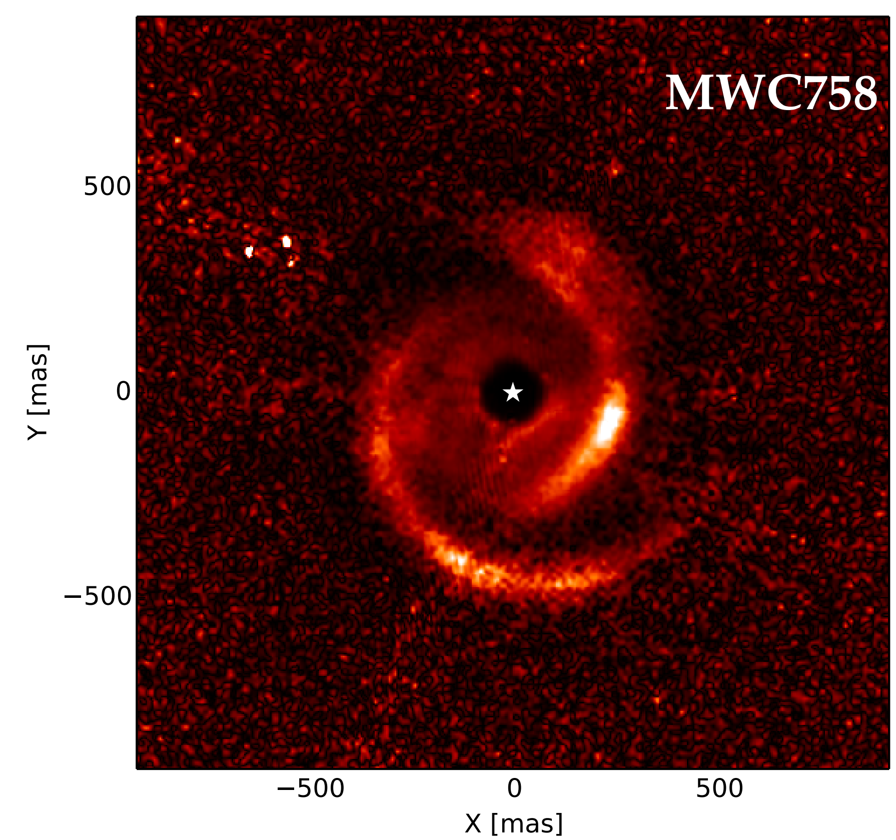


- 2 or more arms
- All Herbig transition disks
- Often with “shadows”



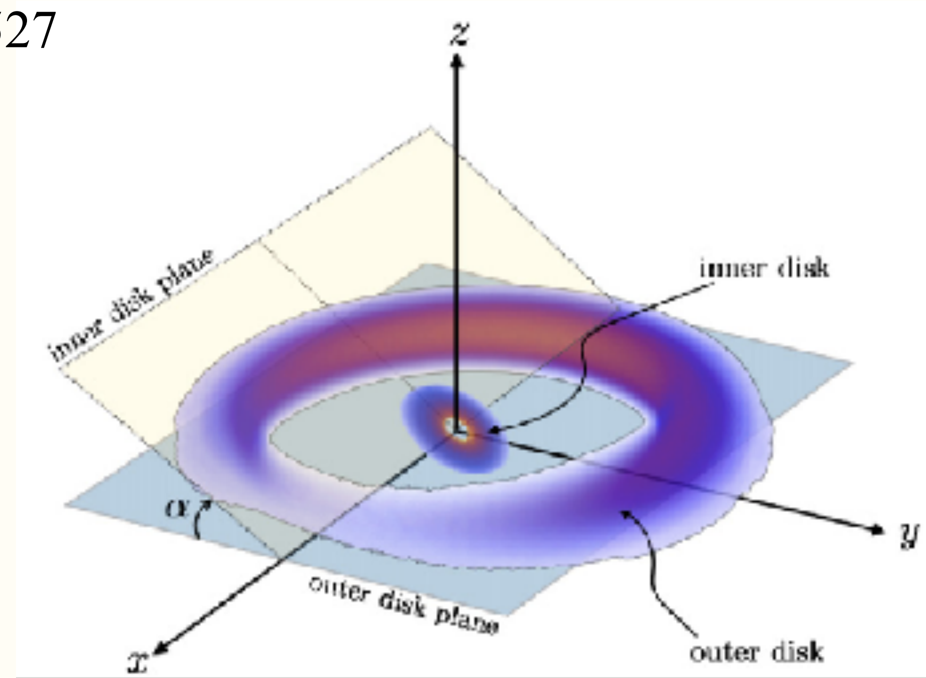


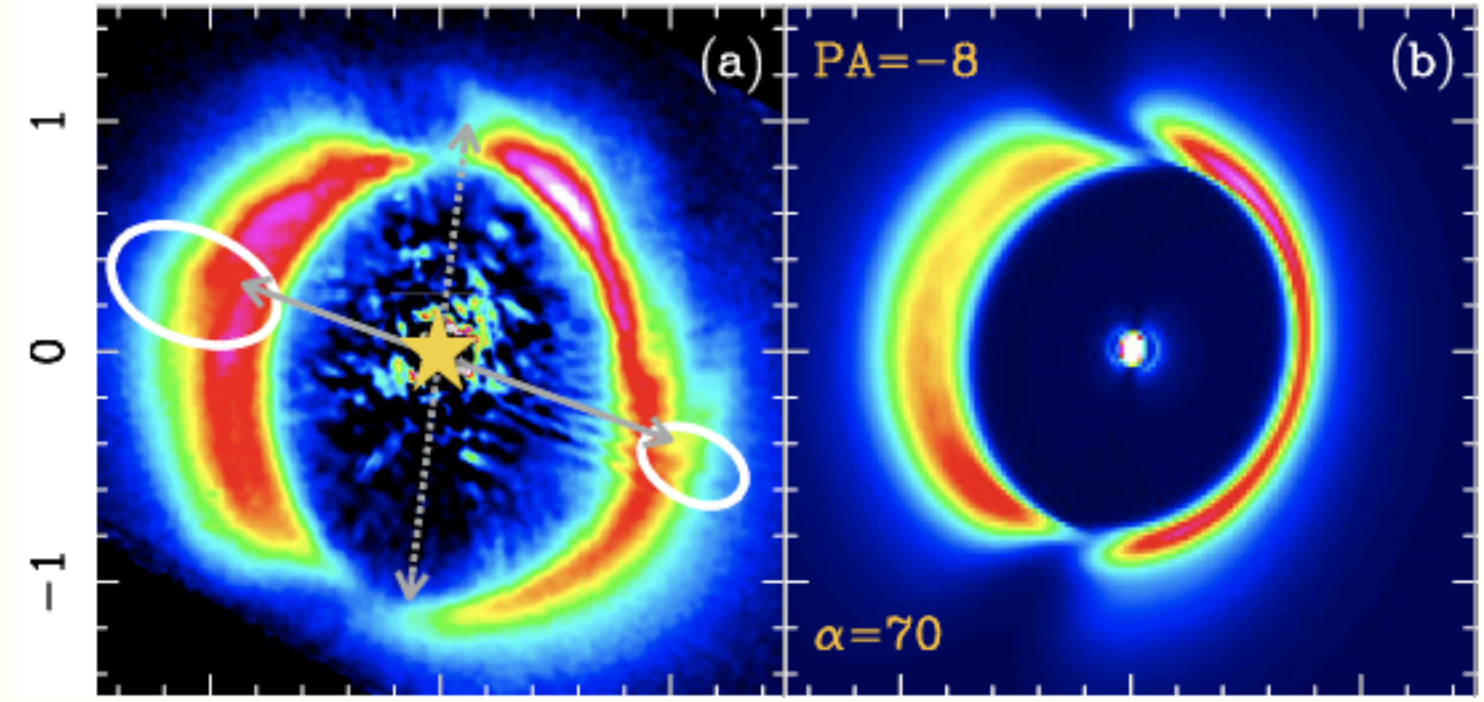




Disk shadows

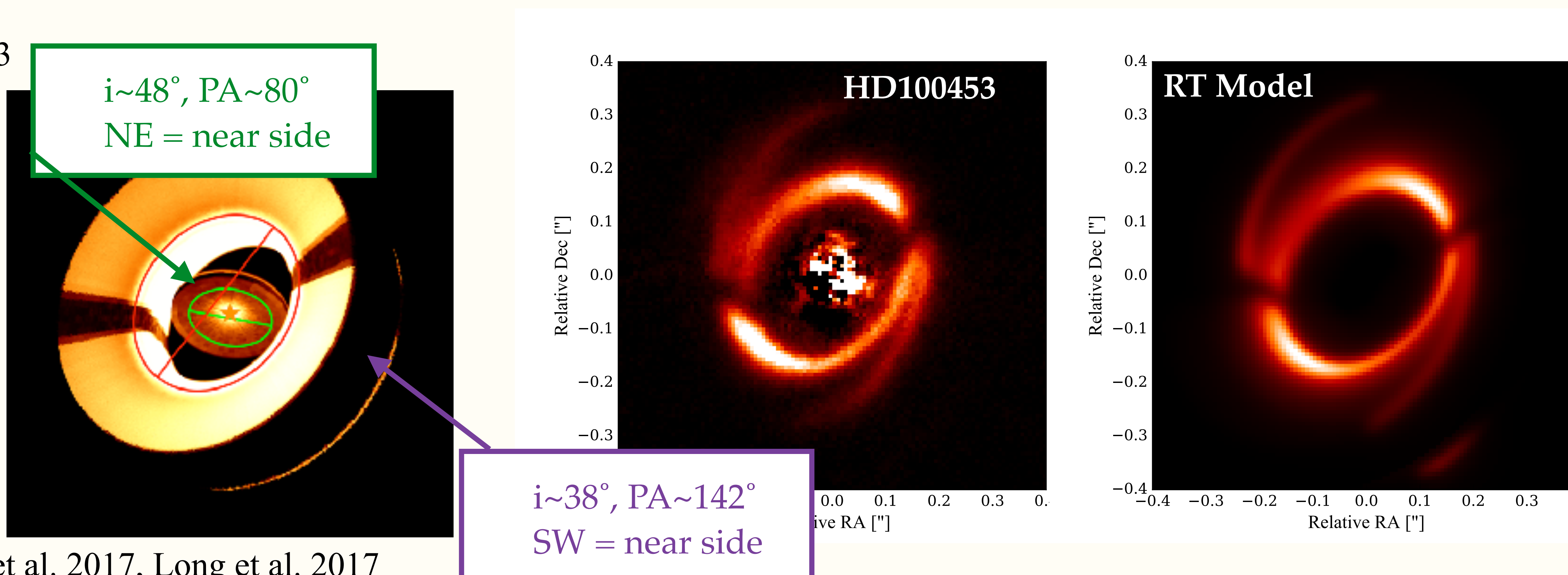
HD 142527





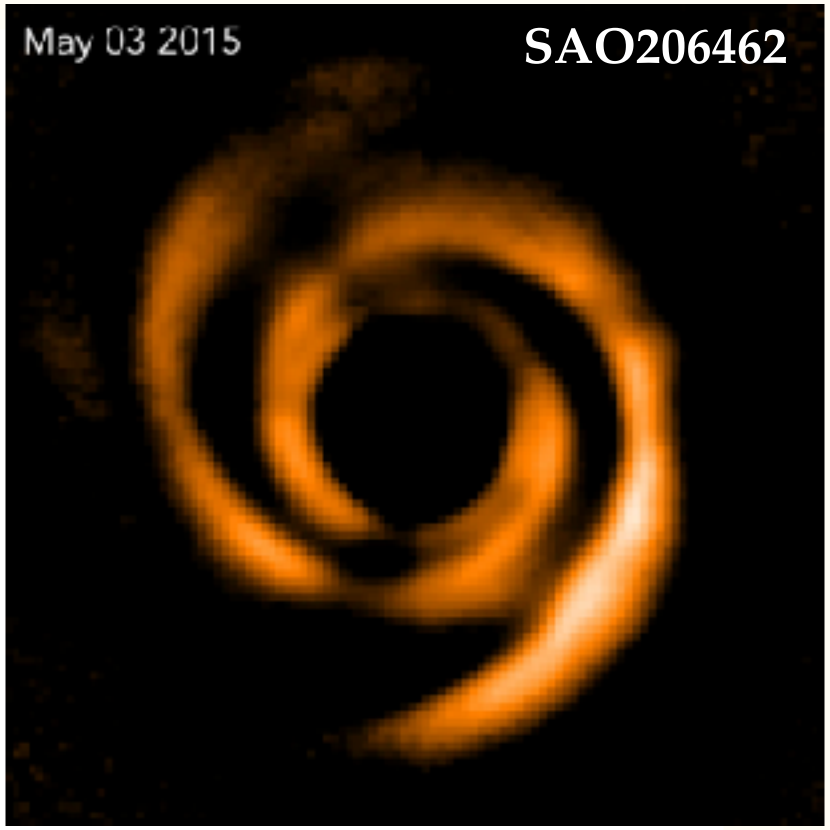
Marino et al. 2015

HD 100453

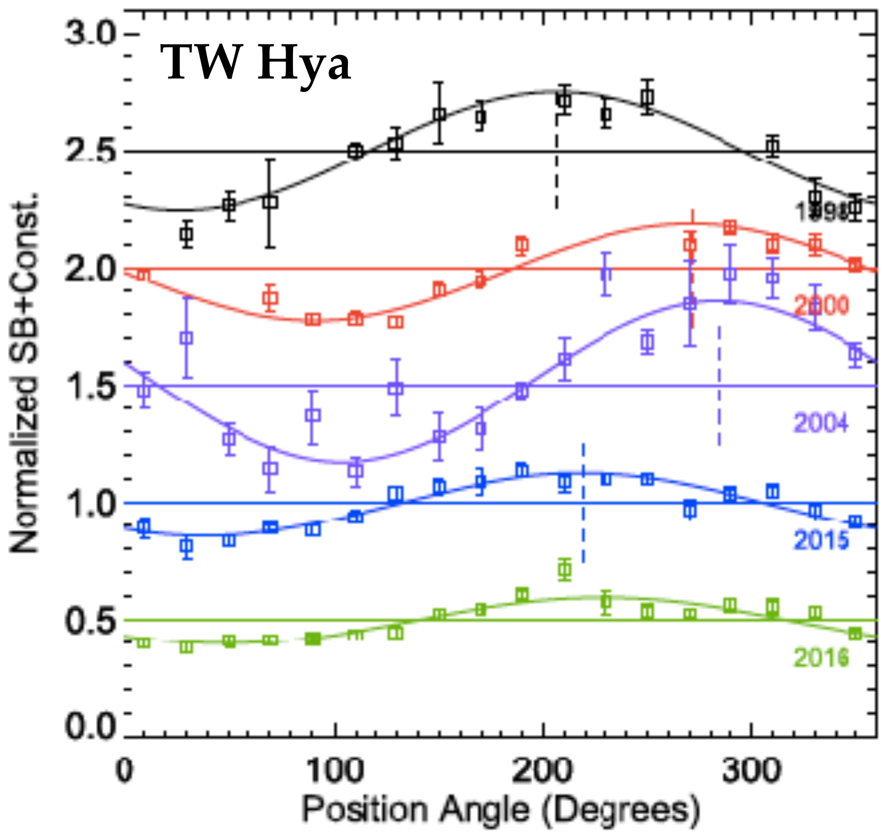


Min et al. 2017, Long et al. 2017

Variable disk shadows



Stolker et al. 2017b



Debes et al. 2017

- Strongly dynamic inner regions
- Significantly misaligned and optically thick dust in the inner(-most?) regions

An inclined inner disk < 1 au precessing with a period of ~16 yrs

Also Schneider et al. 2014, Wolff et al. 2016

Outline

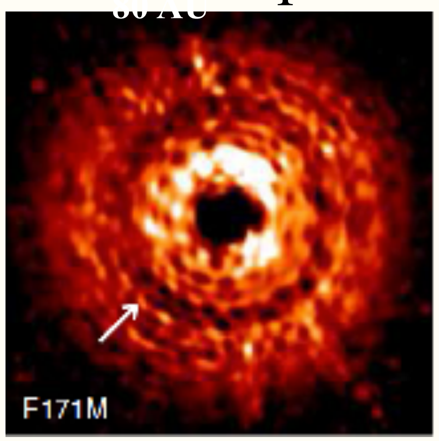
- Disk Observations:
  - Optical/Near-IR:
    - Rings, Spirals, Disk shadowing
  - Submm:
    - Diverse features
    - Synergy between Near-IR and Submm
- Planet-disk interaction theory:
  - Gaps/rings
  - Spirals
  - Lopsided structures
  - Shadows
  - CPDs

Diverse disk features too

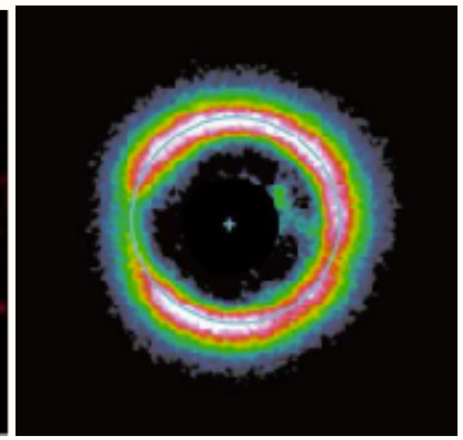
Optical/Near-IR

Radio

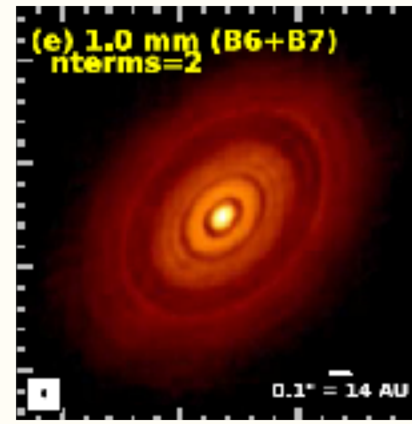
Axisymmetric
m=0



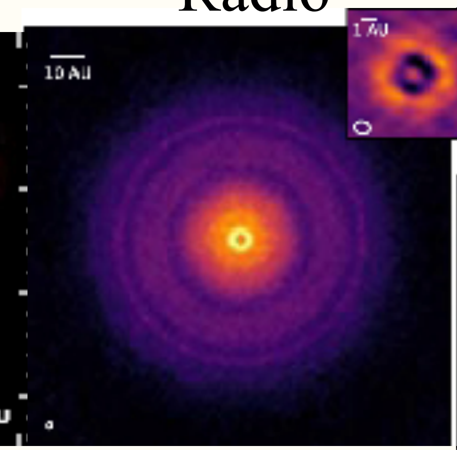
Debes+ 2013



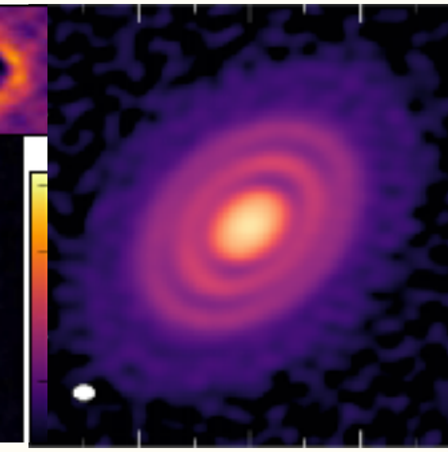
Mayama+ 2012



ALMA Partnership+ 2015



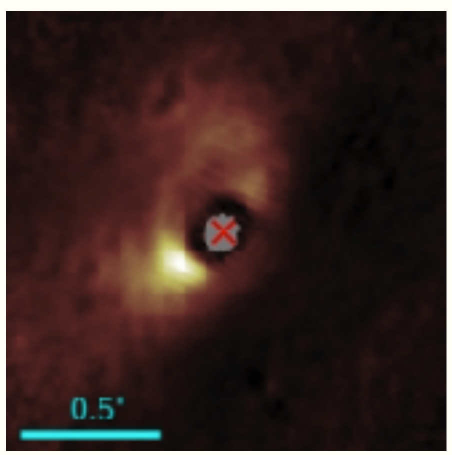
Andrews+ 2016



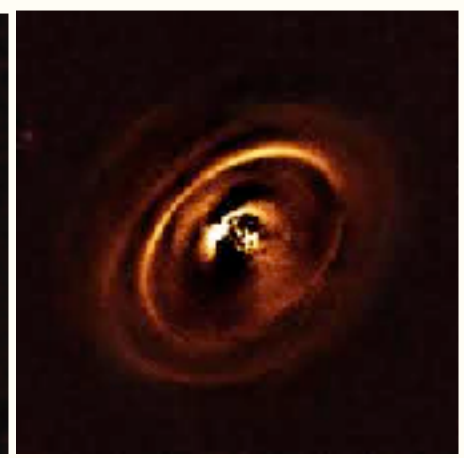
Isella+ 2016

nonaxisymmetric

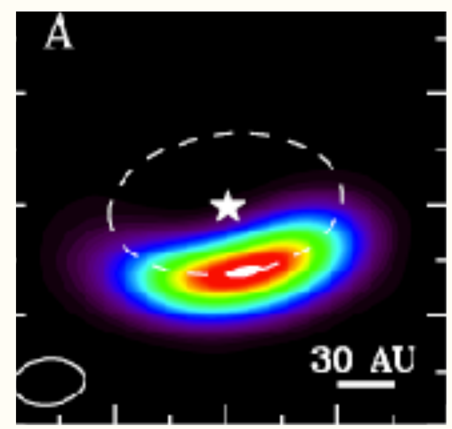
m=1



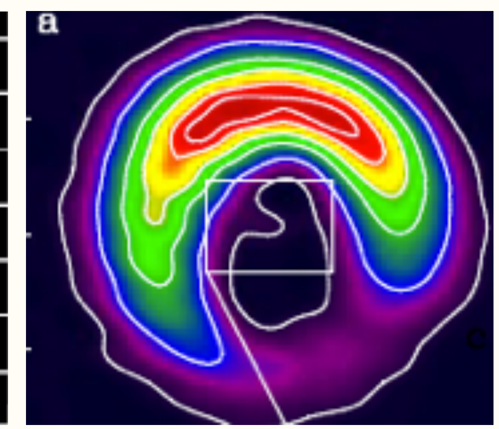
Avenhaus+ 2014



De Boer+ 2016

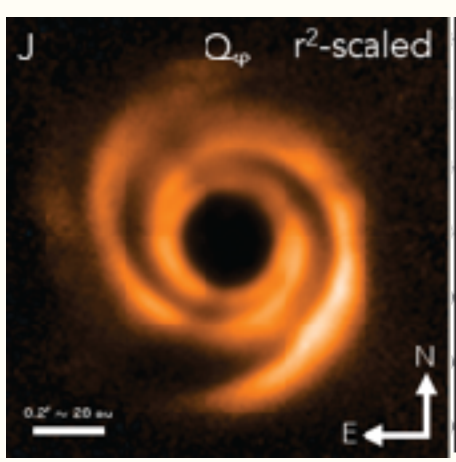


van der Marel+ 2013

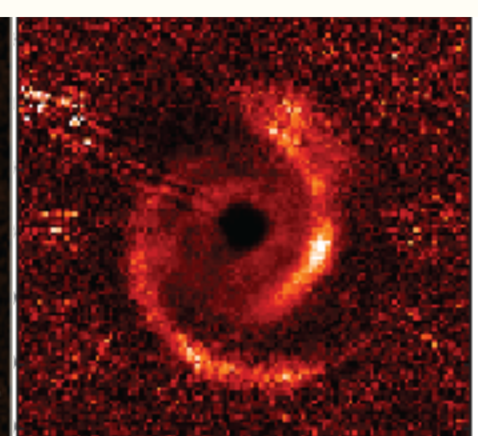


Casassus+ 2013

m=2



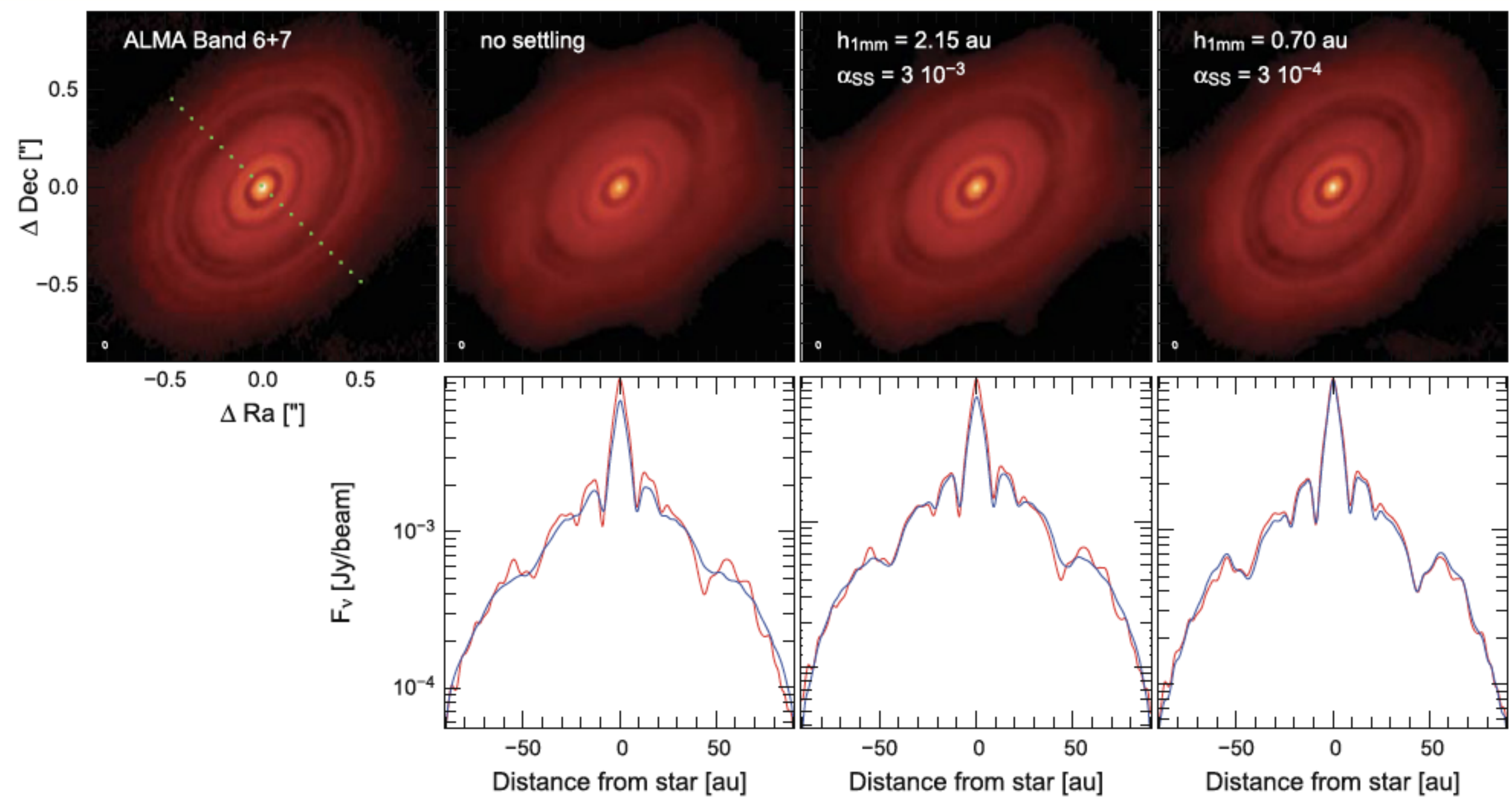
Garufi+ 2015



Benisty+ 2015

Pérez+ 2016

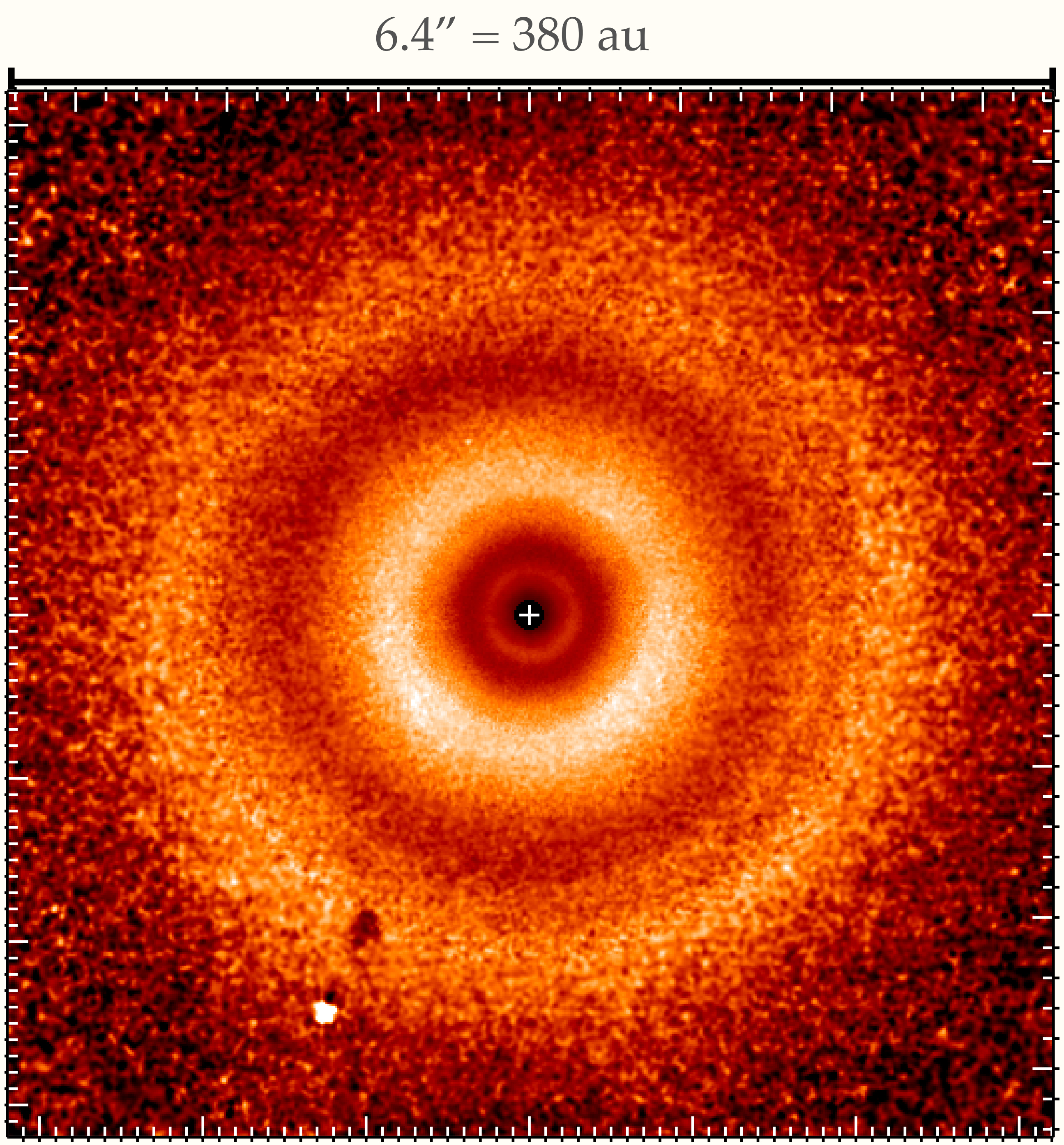
Constraints for disk surface and disk turbulence:

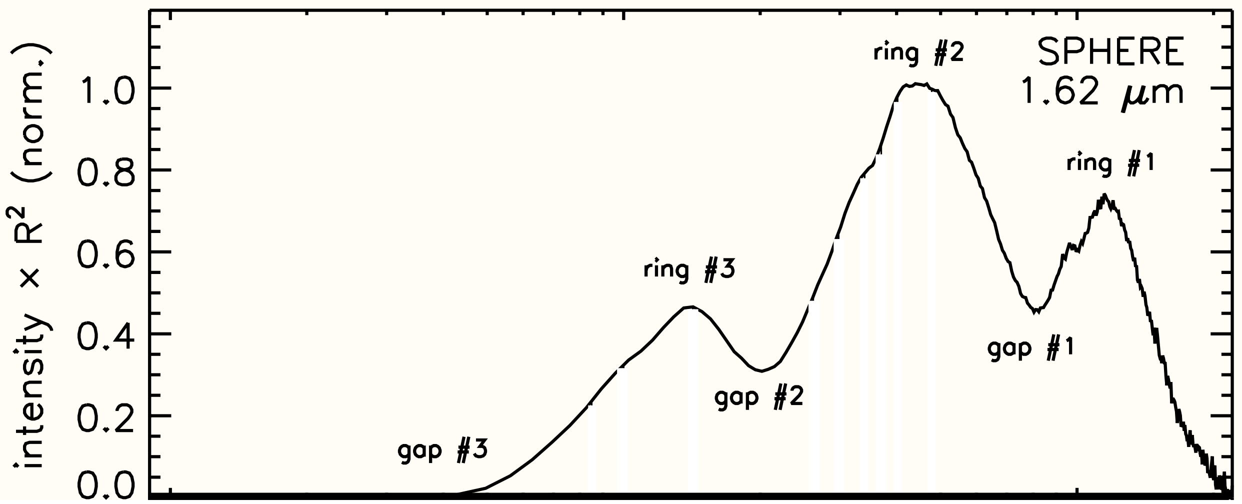


Pinte et al. 2016

$$H_d \sim \sqrt{\frac{\alpha}{T_s}} H$$

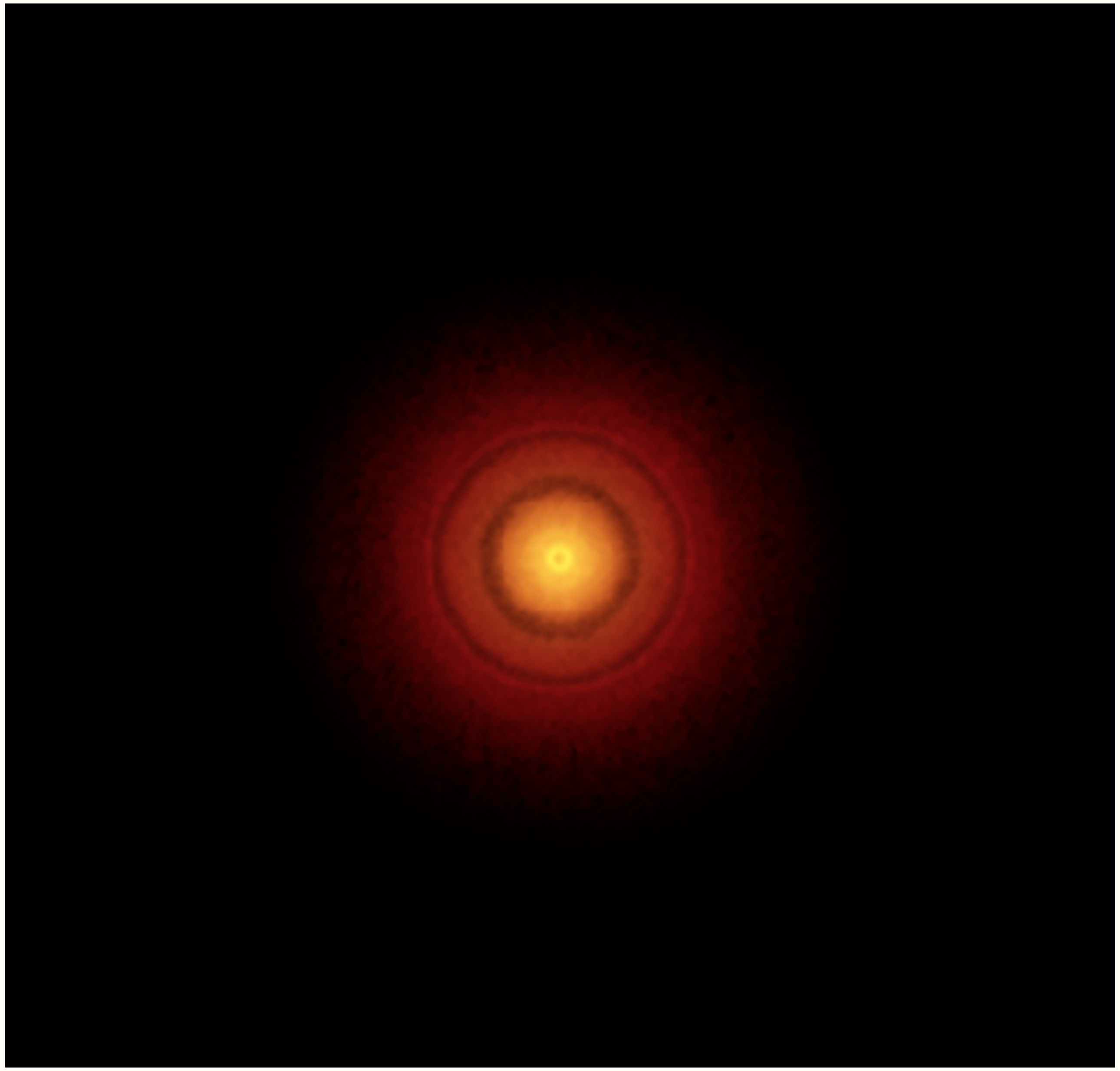
Synergy between Near-IR and Sub-mm

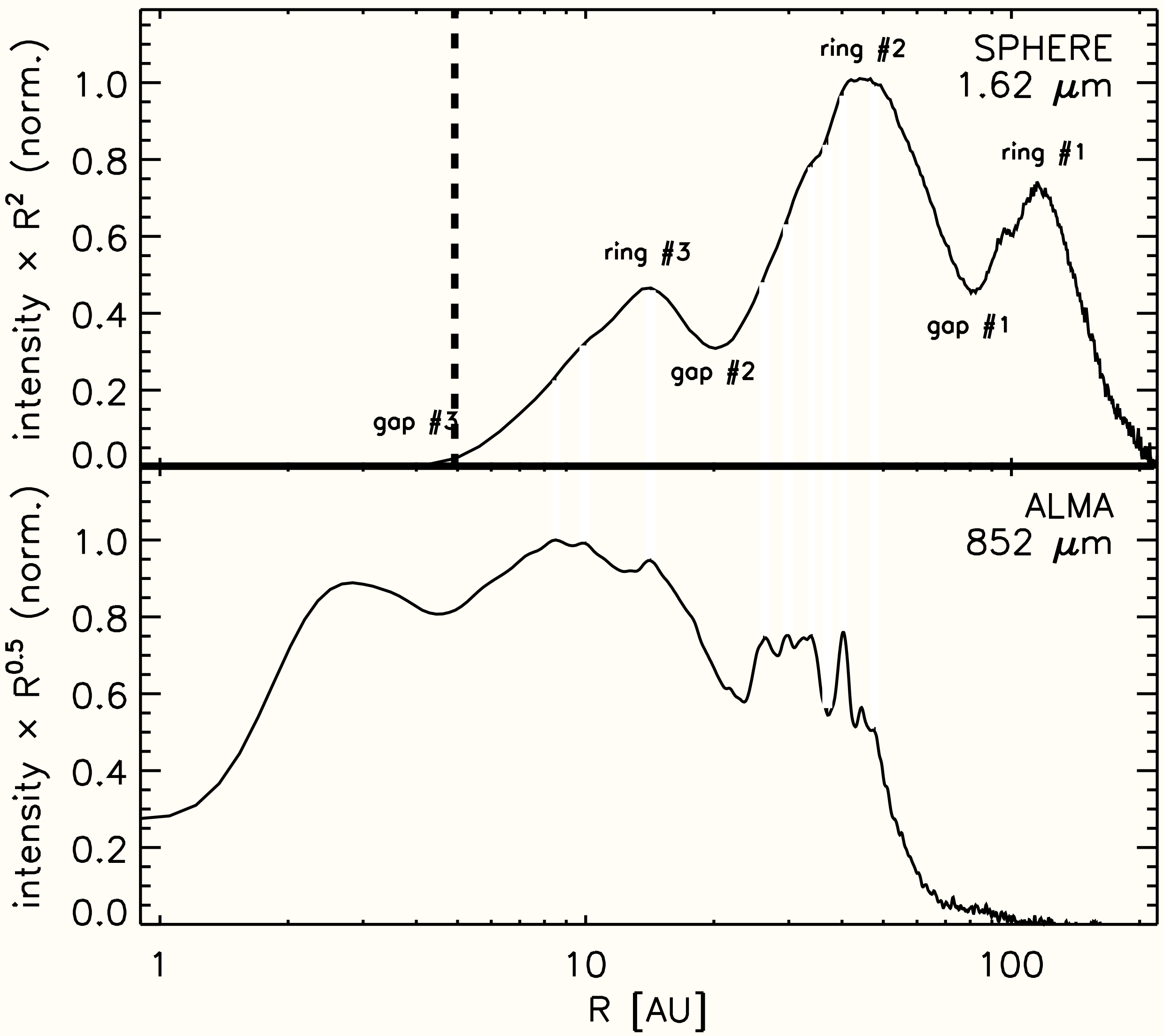




van Boekel et al. 2016

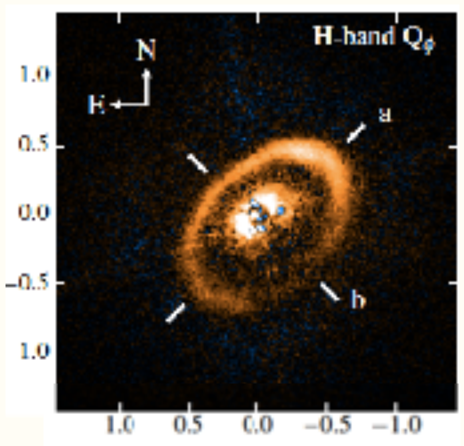
Near-IR and ALMA

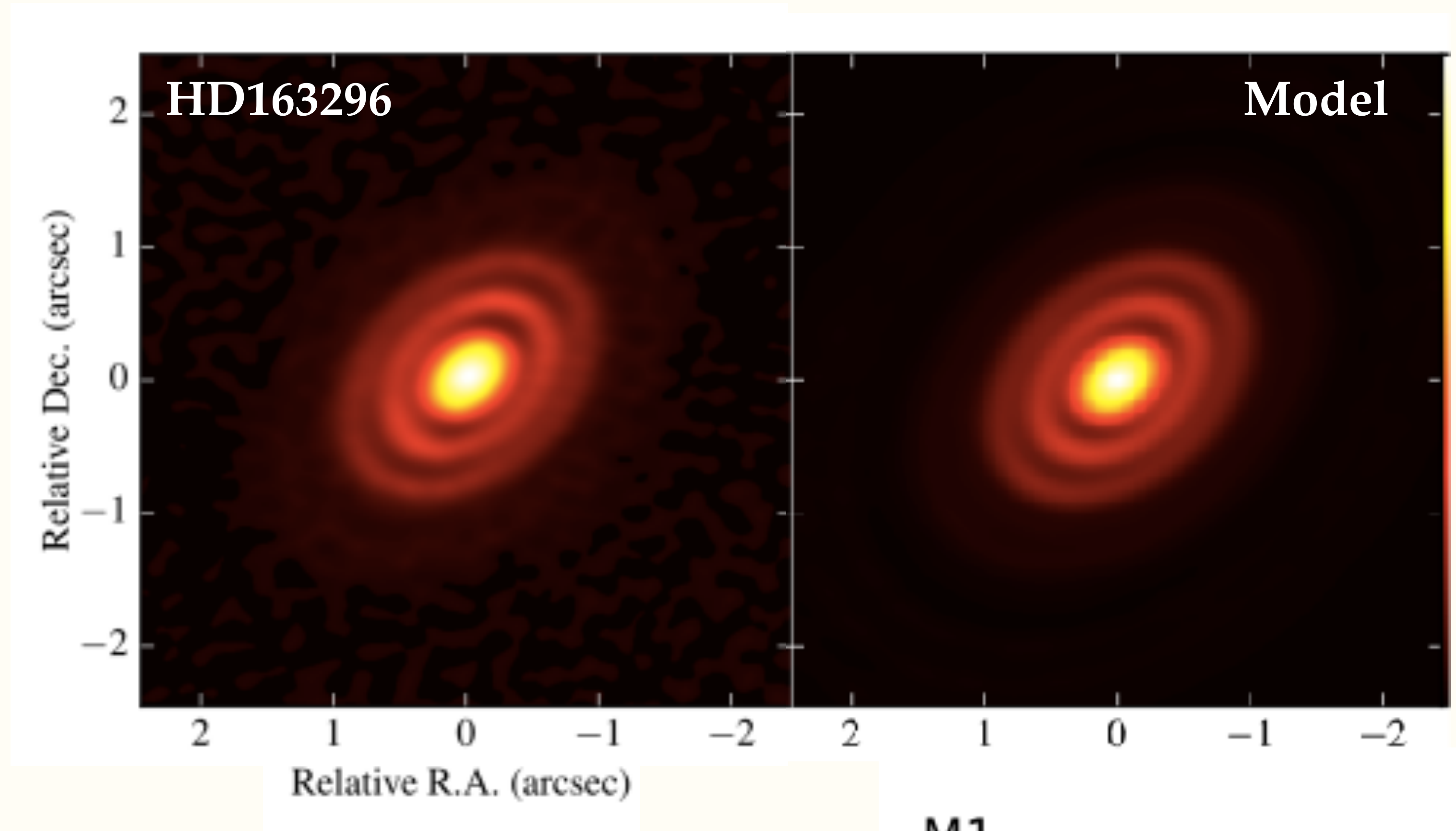




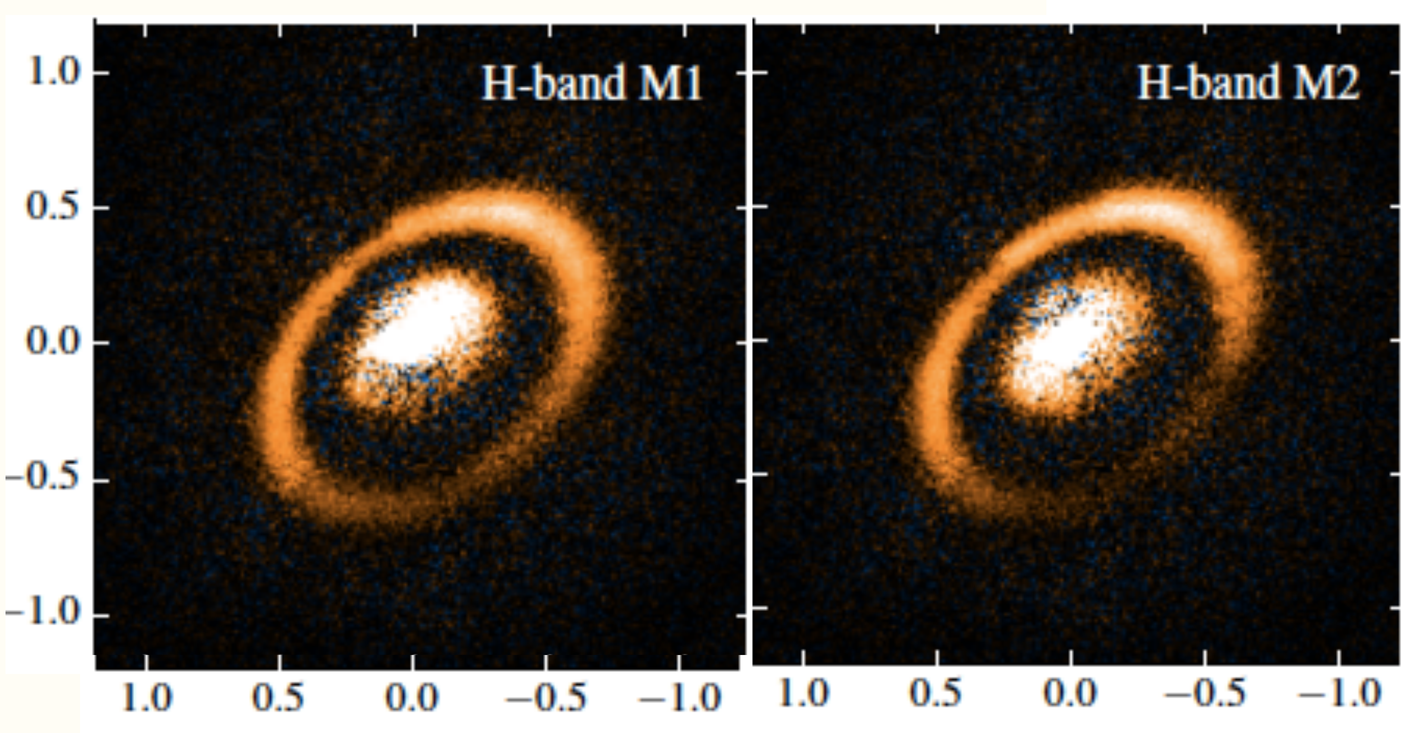
Andrews et al. 2016

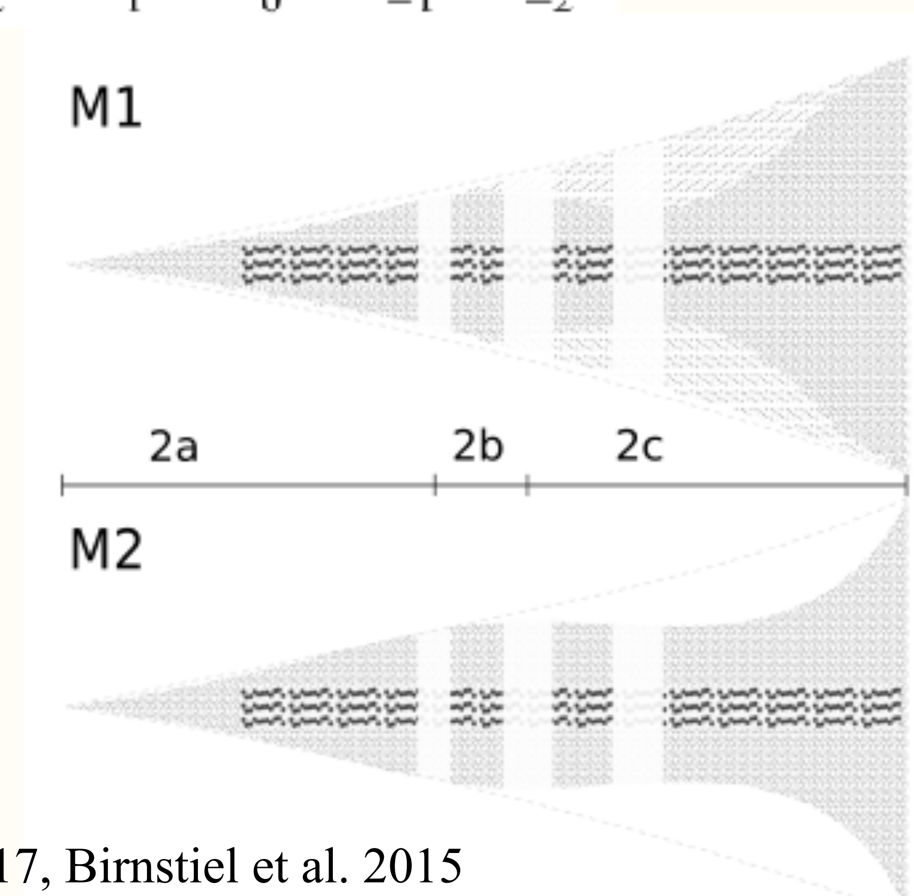
Vertical distribution of grains





Rings @ 80, 124, 200 au





Muro-Arena et al. 2018

see also Pohl et al. 2017, Birnstiel et al. 2015

Outline

- Disk Observations:

Optical/Near-IR...

1. Know the disk => Use disk features to probe the planets
   Disk features => Know the disk (e.g. turbulence, dust properties)

2. Can we model the disk with all constraints from different methods (imaging, SED), different wavelengths (near-IR, submm), techniques (ADI, PDI, sub-mm thermal/polarization), etc to build a complete disk picture?

3. Large sample now. Any trend with different samples?

-

Spirals

Lopsided structures

Shadows

CPDs

Outline

- Disk Observations:

  Optical/Near-IR:

  Rings, Spirals, Disk shadowing

  Submm:

  Diverse features

  Synergy between Near-IR and Submm

- Planet-disk interaction theory:

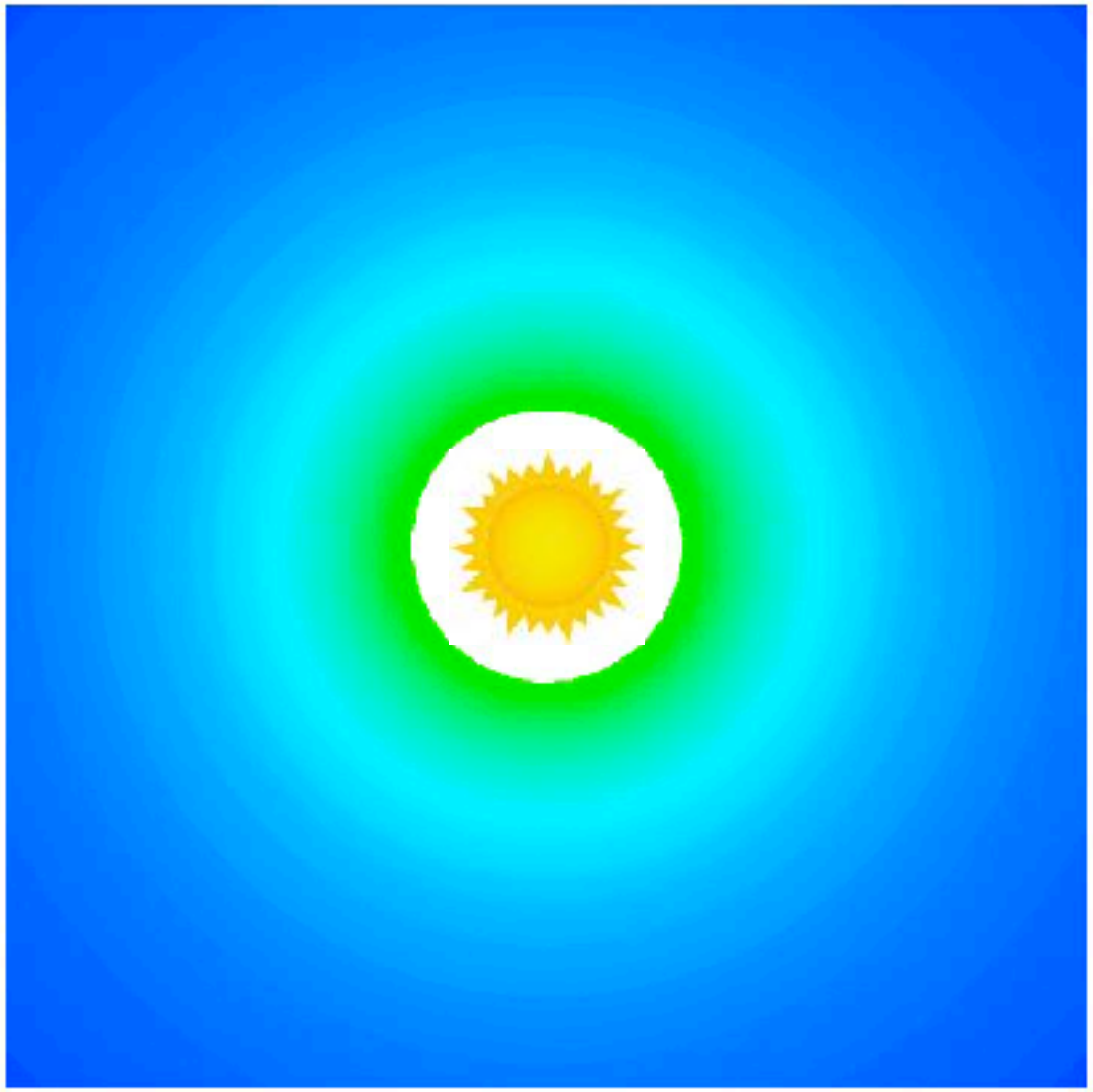
  Gaps/rings (basics, dust dynamics, gas dynamics)

  Spirals

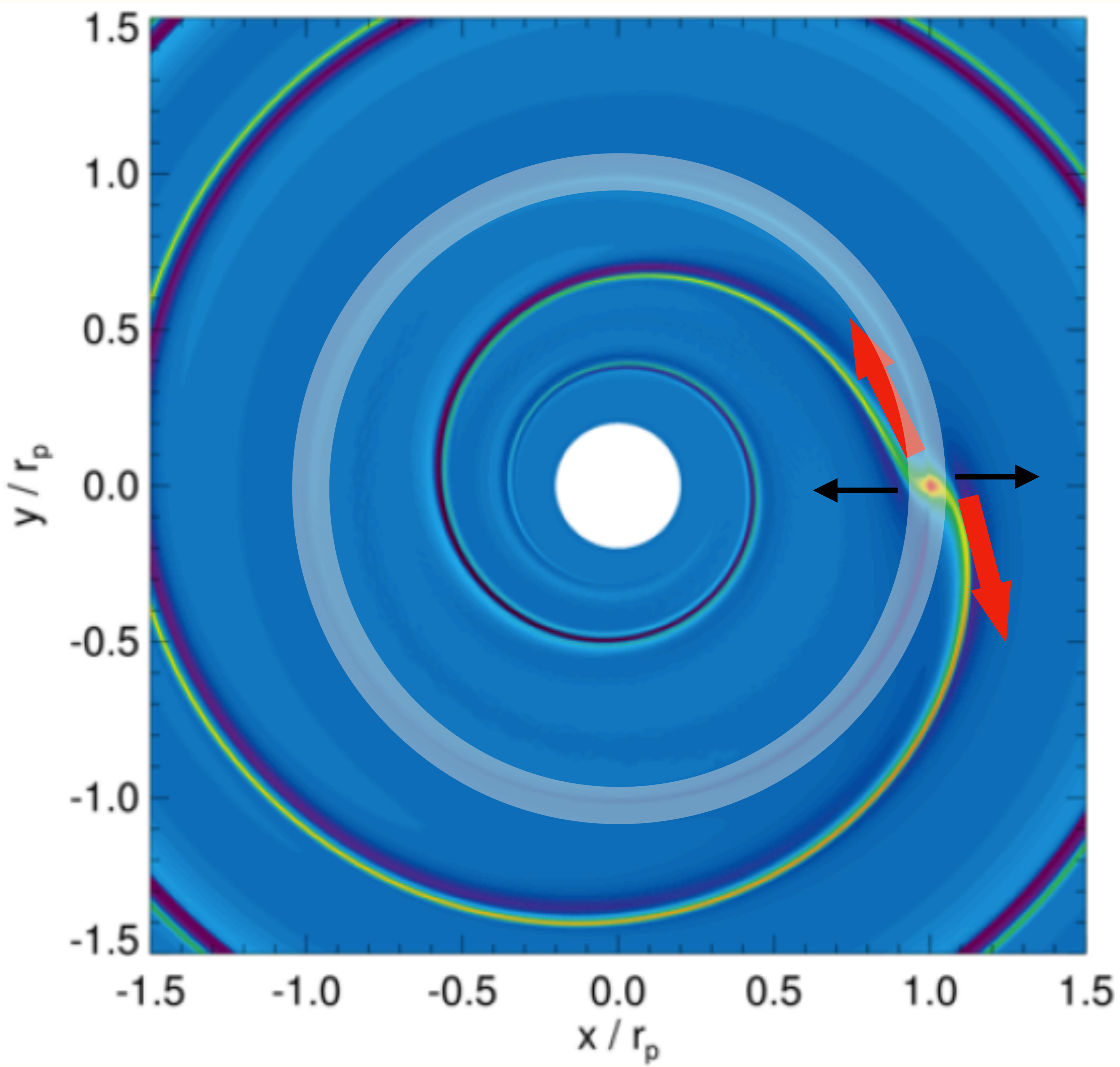
  Lopsided structures

  Shadows

  CPDs



Planet-disk interaction: migration



Baruteau+ 2014

Wave torque
(Lindblad Resonances)

(Goldreich & Tremaine 1979, Ward 1997, Tanaka et al. 2002)

migration timescale for both Earth and Neptune ~10^5 years

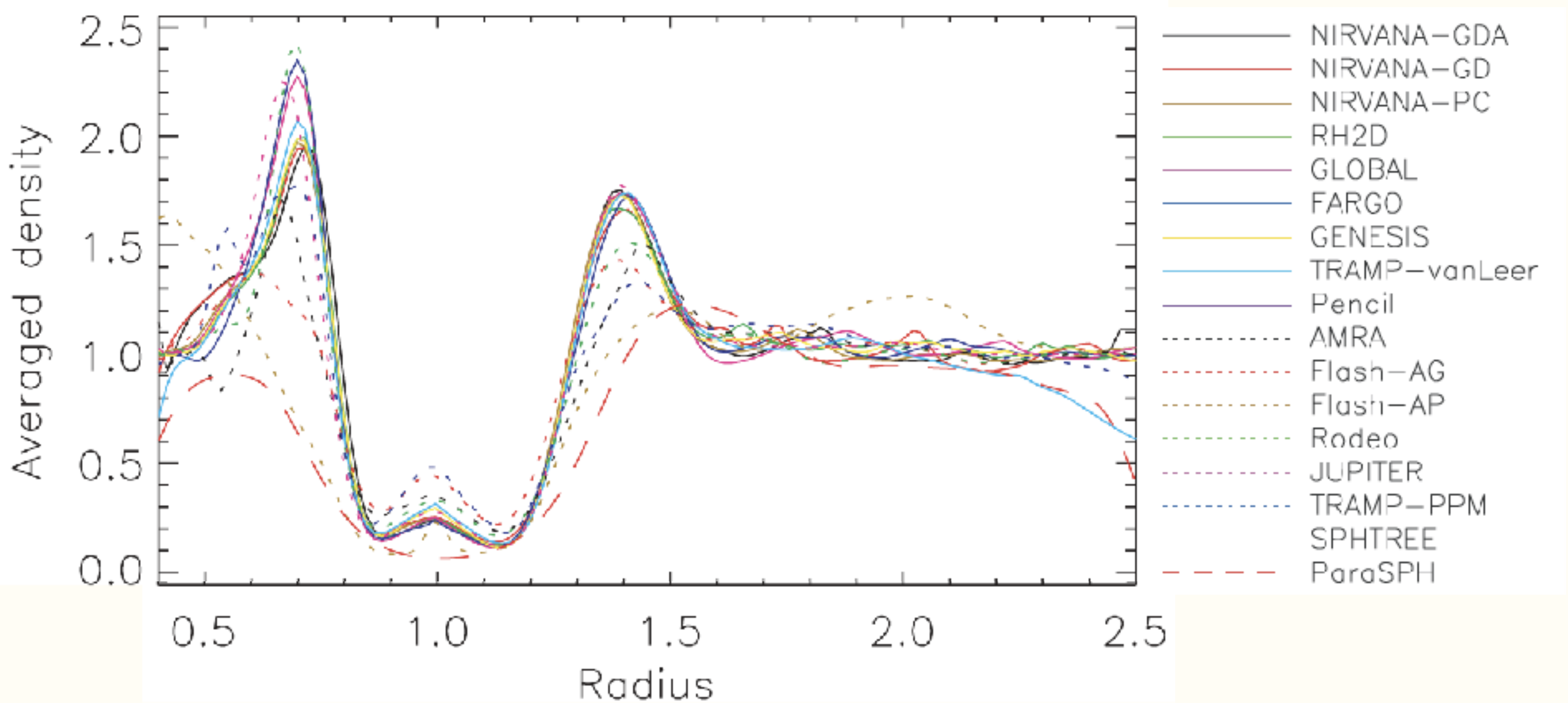
Corotation torque
(horseshoe drag or corotation resonances)

Planet-disk interaction: gap opening

When planetary torque > viscous torque, a gap is opened

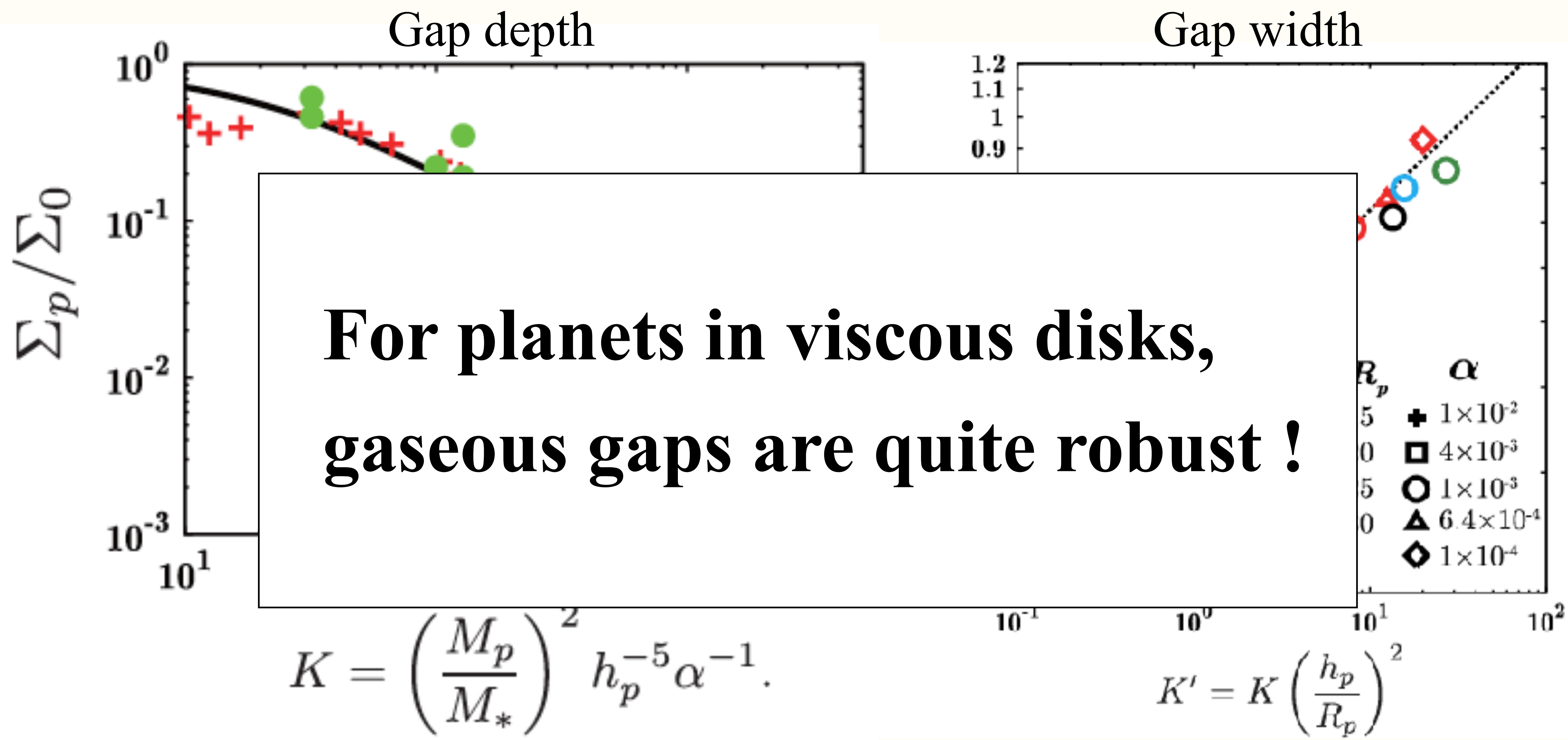
$0.1\ M_J$ in α=0.01, H/R=0.05 disks

Goldreich & Tremaine 1979, Lin & Papaloizou 1986, Crida et al. 2006



de Val-Borro et al. 2006

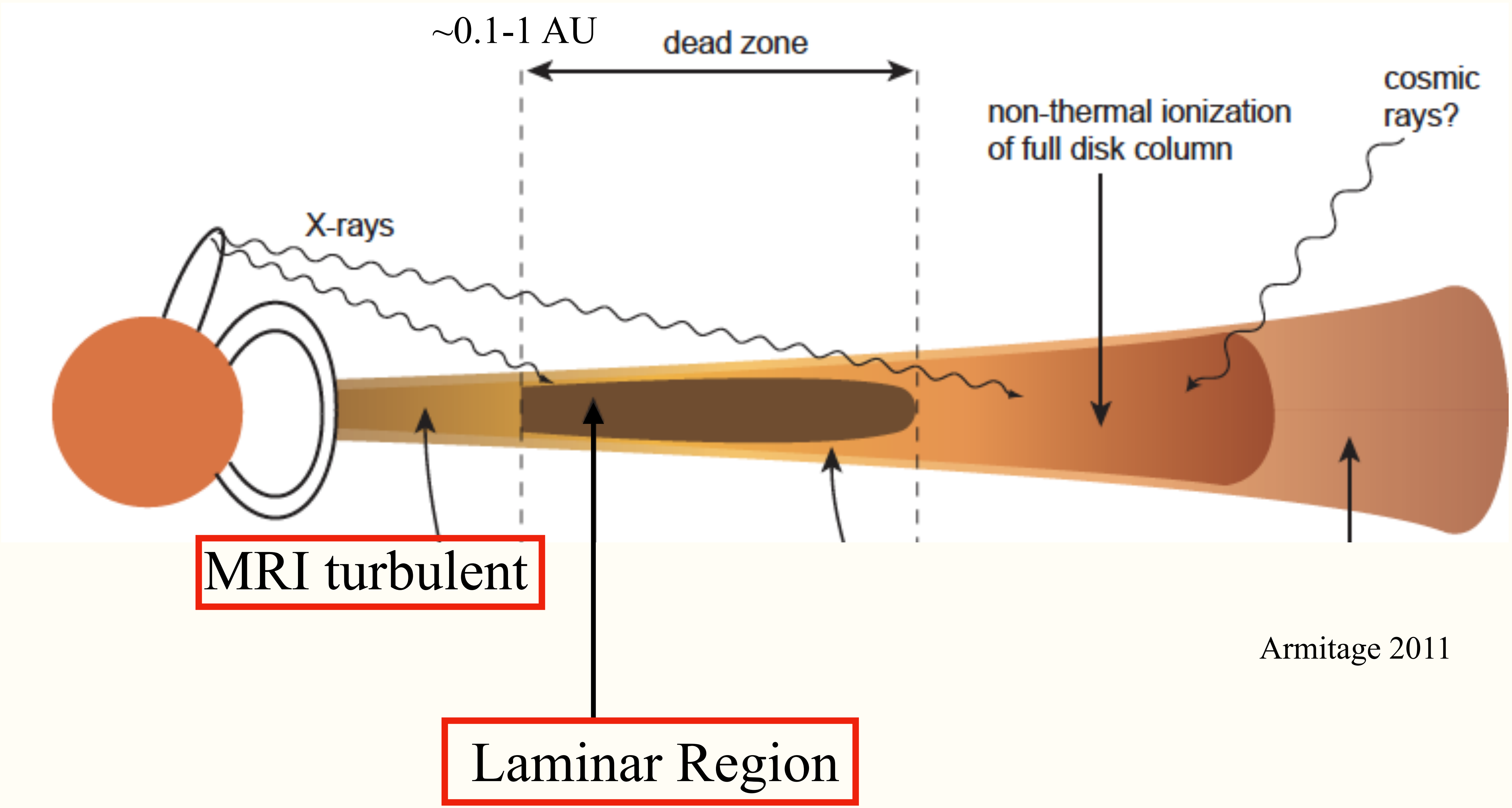
Gap opening in viscous disks



For planets in viscous disks, gaseous gaps are quite robust !

Kanagawa+2015, 2016
Ginzburg & Sari 2018

Gap opening in more realistic disks

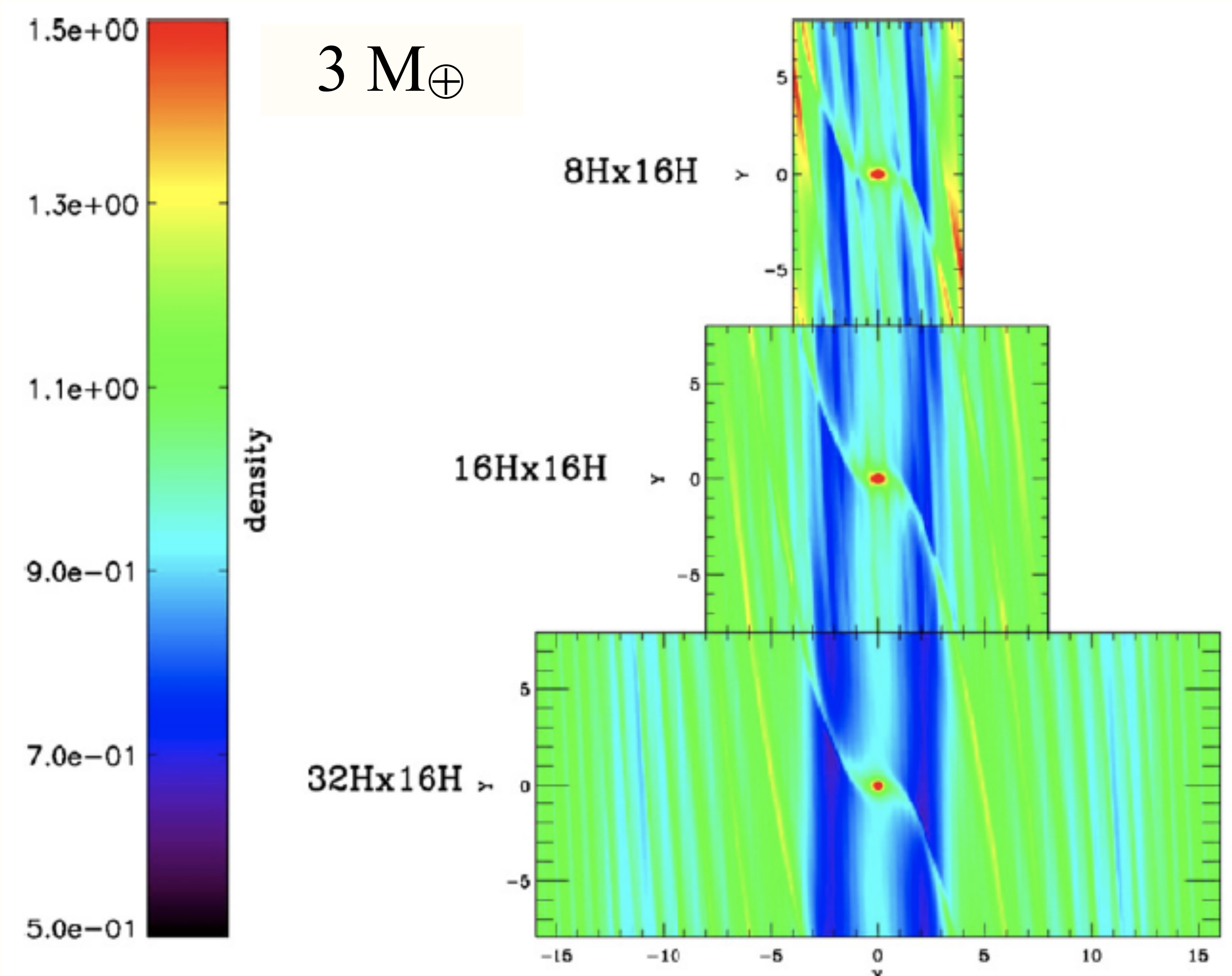


Armitage 2011

Gap opening in inviscid disks ("dead zone")

Gaps can be opened by any mass planets

Goodman & Rafikov 2001, Dong et al. 2009, Muto et al. 2010, Duffell & MacFadyen 2012, Dong et al. 2017, Bae et al. 2017

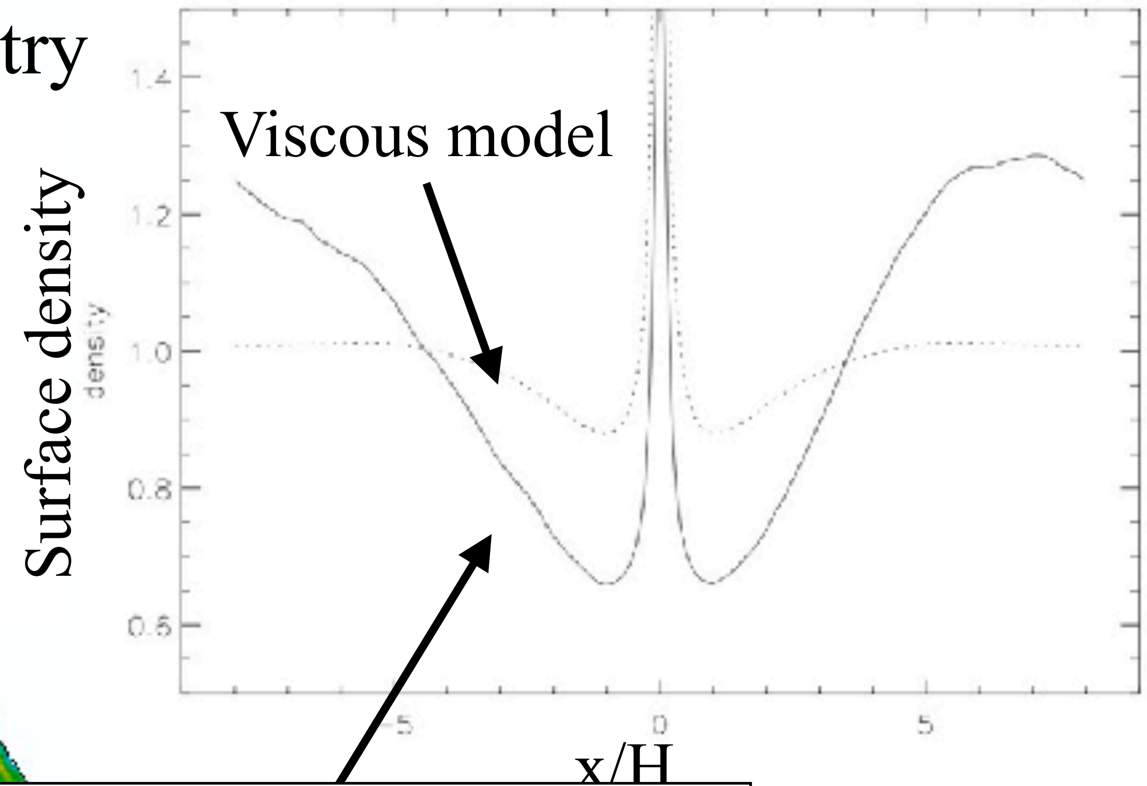


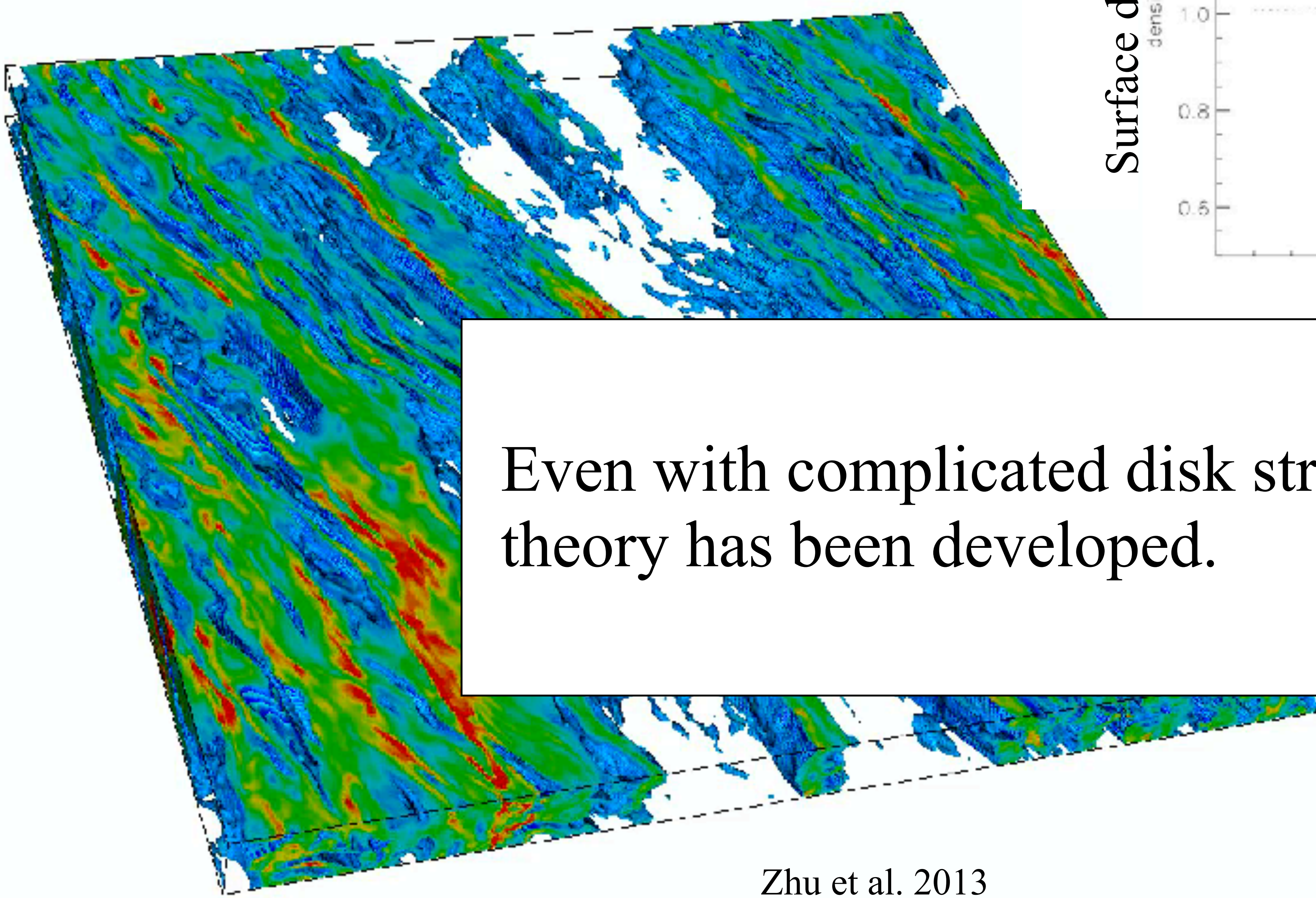
Zhu et al. 2013

Gap opening in turbulent disks

Gap depth depends on magnetic field geometry

Nelson & Papaloizou 2004, Nelson & Gressel 2010

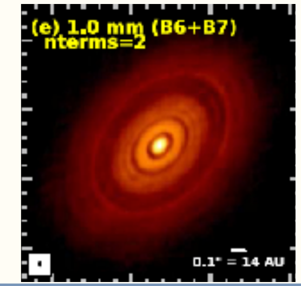




Even with complicated disk structure, theory has been developed.

Zhu et al. 2013

Gaps/Rings: dust dynamics



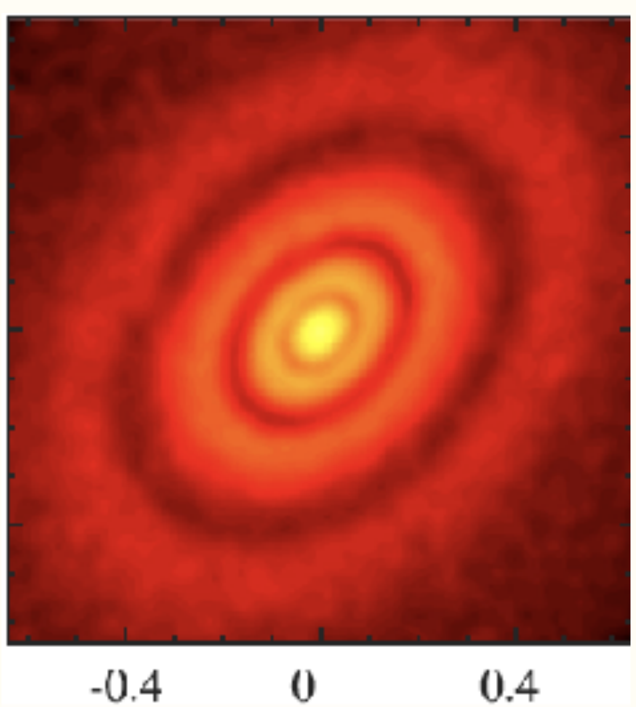
Theory: dust particles drift to gas pressure maximum due to aerodynamic drag

Paardekooper & Mellema 2004, 2006, Rice et al. 2006, Fouchet et al. 2007, ...12, Zhu et al. 2012, ...12, Dipierro & Laibe ... al. 2018

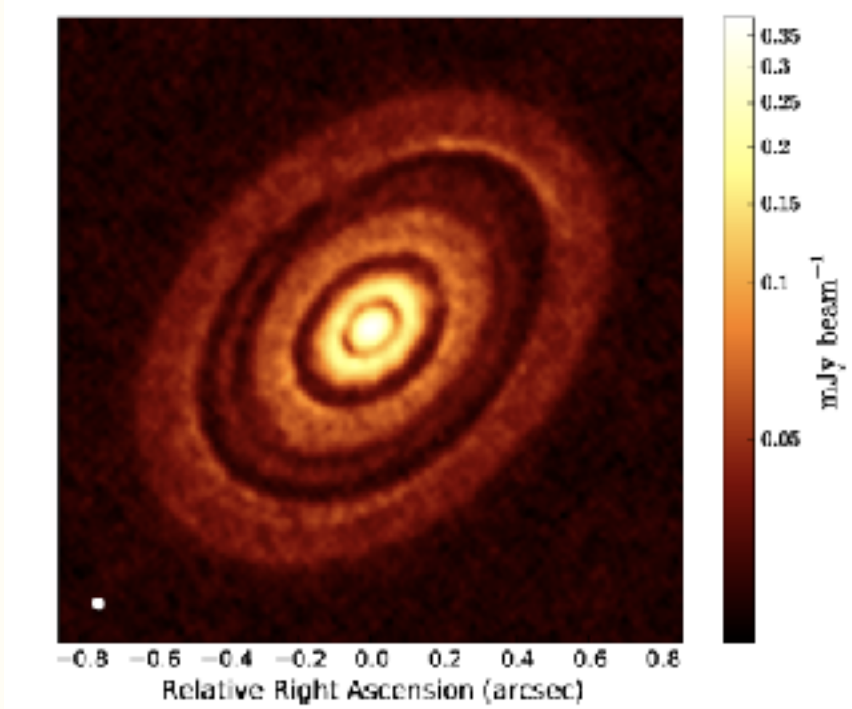
+Most sensitive indirect method ($M_\oplus$)

- Other ways to make gaps/rings
- Even it is by planets, huge degeneracy

Observations ... th MCRT:



Dong et al. 2015



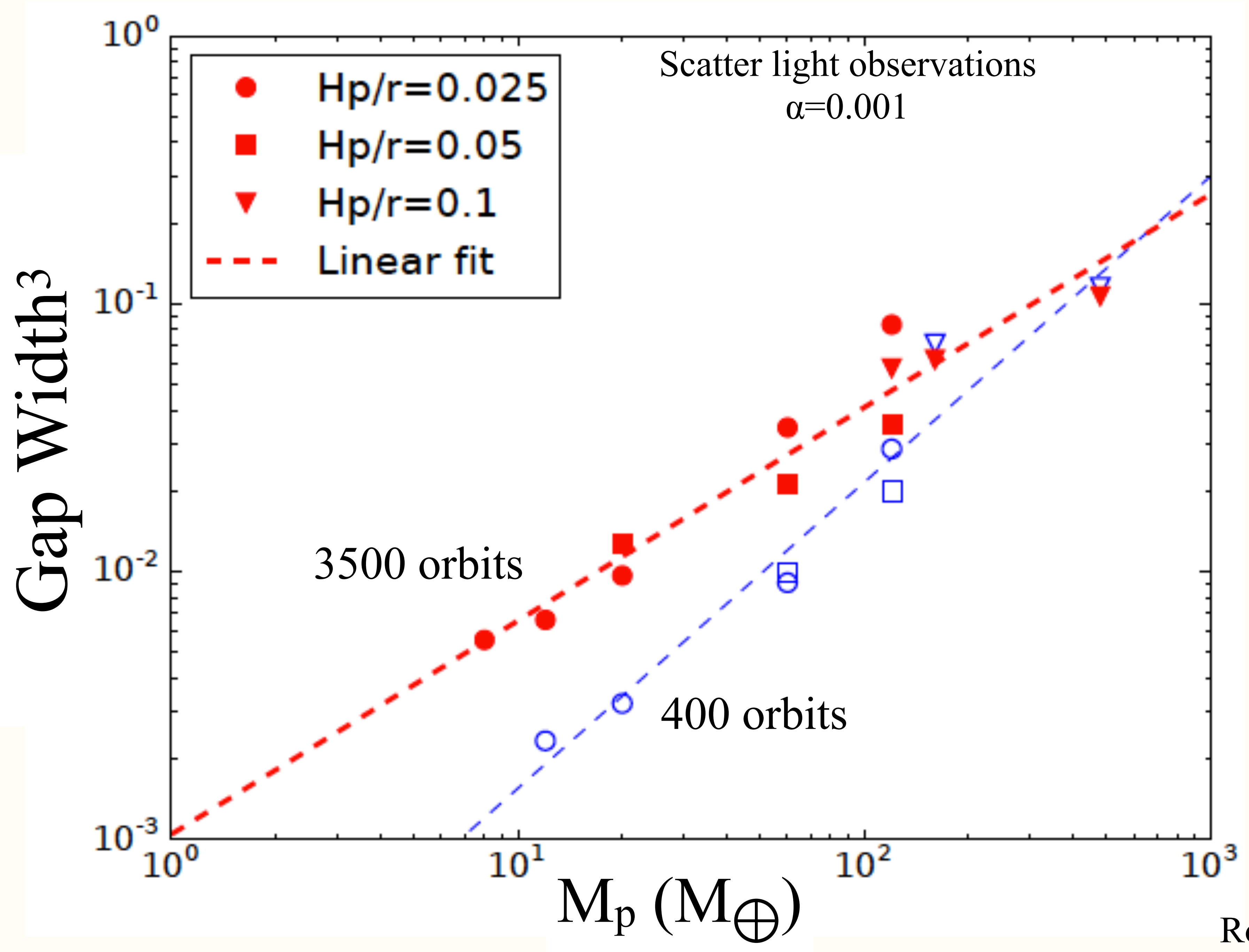
Dipierro et al. 2016

De Juan Ovelar et al. 2013, Garufi et al. 2013, Dong et al. 2013, Benisty et al. 2015, Picogna & Kley 2015, Dipierro et al. 2016, Dong & Fung 2017, Hornbeck et al. 2018, Boehler et al. 2018

0.2, 0.27, 0.55 M_J

Gaps/Rings: degeneracy

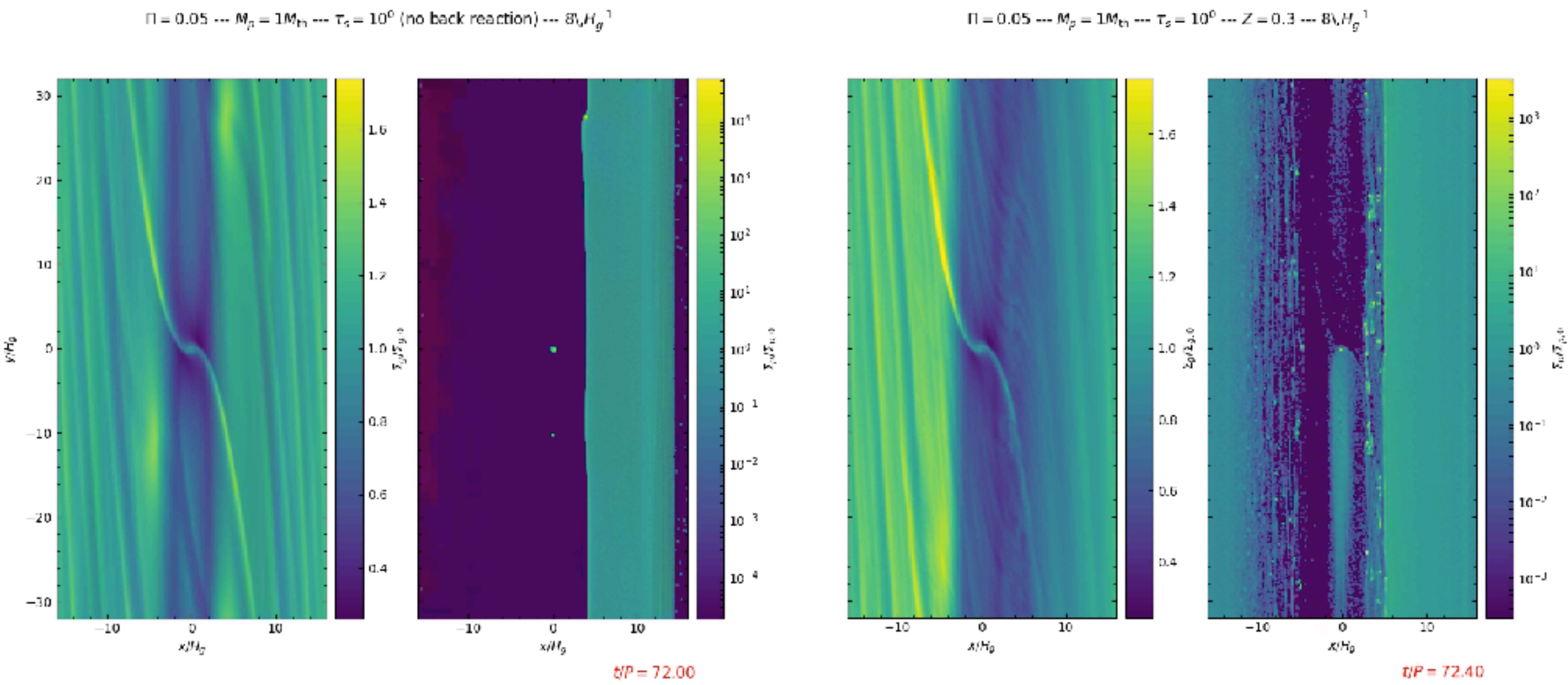
- Uncertain particle size distribution
- Time dependent



Rosotti+ 2016

Gaps/Rings: including dust's back reaction to gas

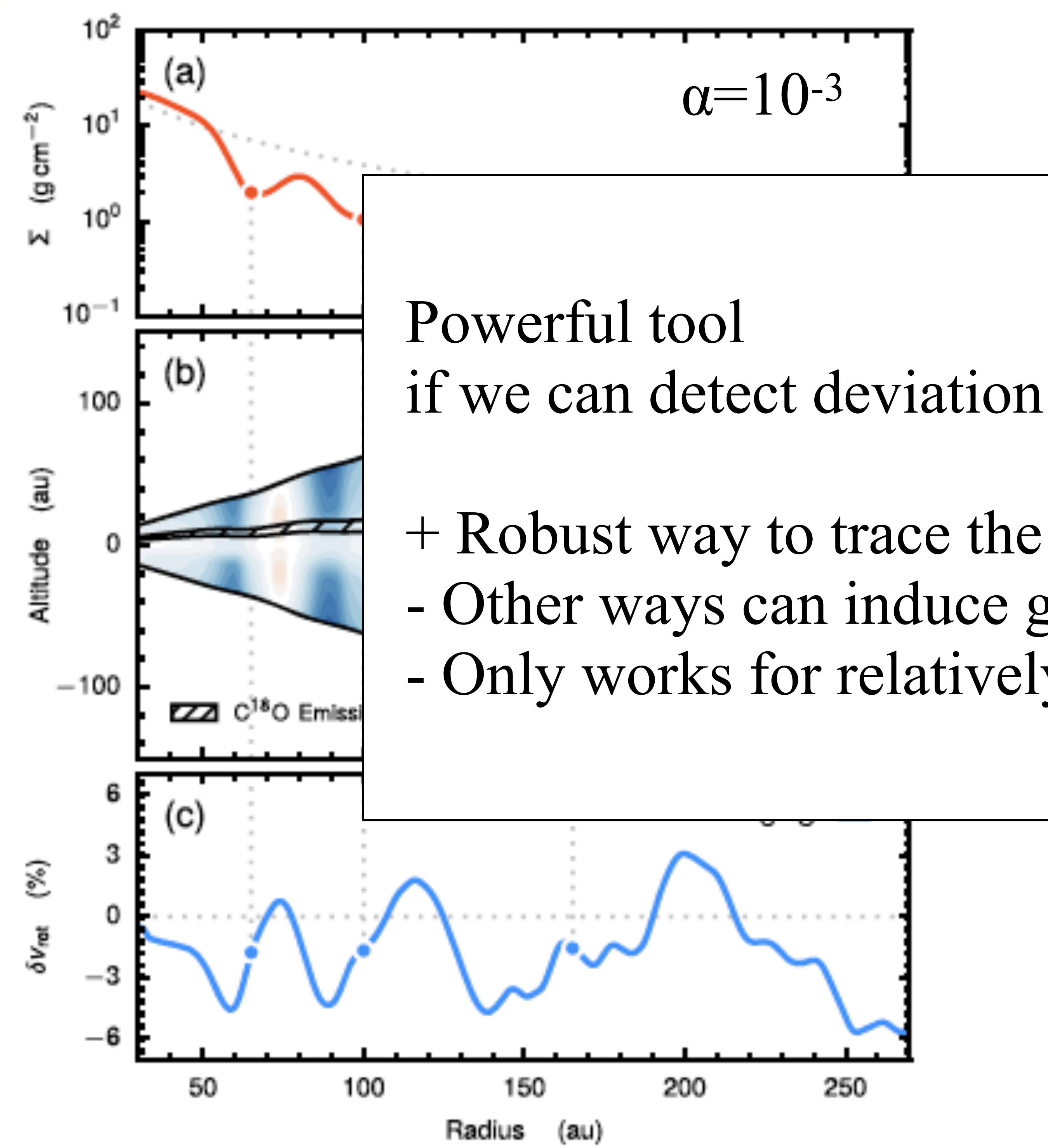
No back-reaction　　　　　　　　　　Z=0.3 back-reaction

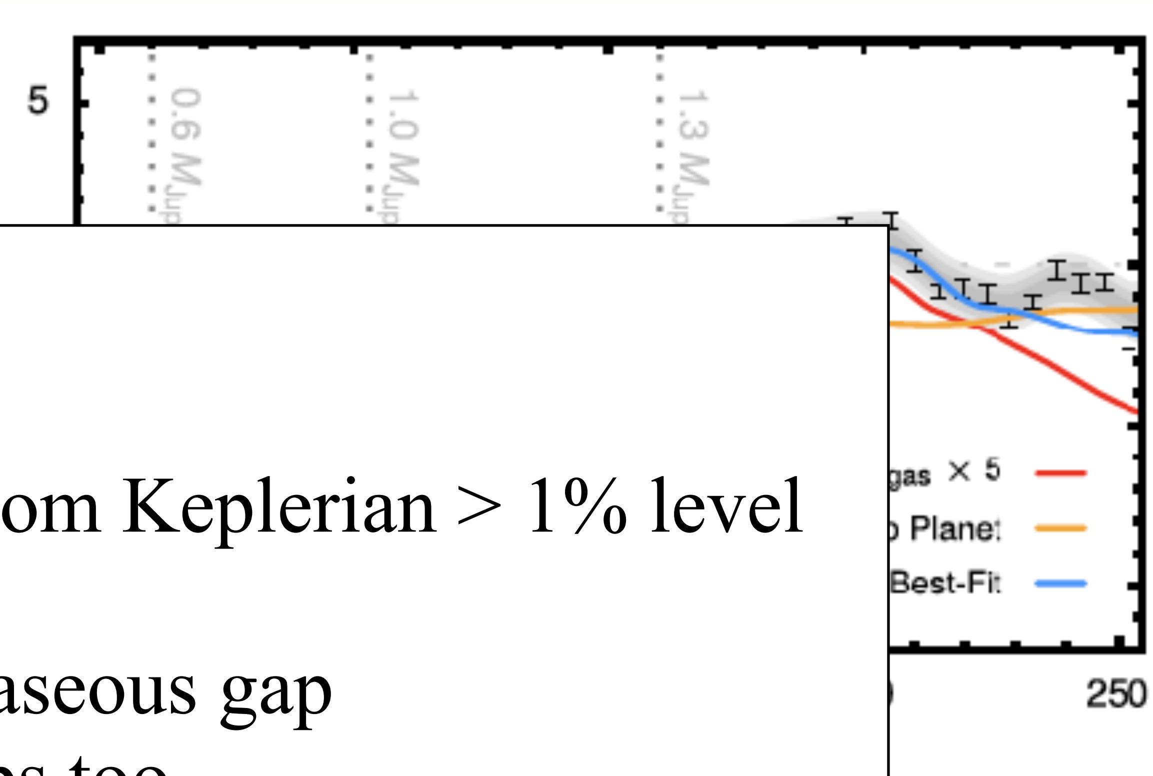


Yang & Zhu in prep.

- Particle filtration efficiency is significantly reduced.
- Gas is accumulated at the inner gap edge.

Gaps/Rings: gas dynamics





Powerful tool
if we can detect deviation from Keplerian > 1% level

+ Robust way to trace the gaseous gap
- Other ways can induce gaps too
- Only works for relatively massive planets (>0.1 M_J)

0.6, 1.0, 1.3 M_J

Teague et al. 2018

Outline

- Disk Observations:

  Optical/Near-IR:

    Rings, Spirals, Disk shadowing

  Submm:

    Diverse features

    Synergy between Near-IR and Submm

- Planet-disk interaction theory:

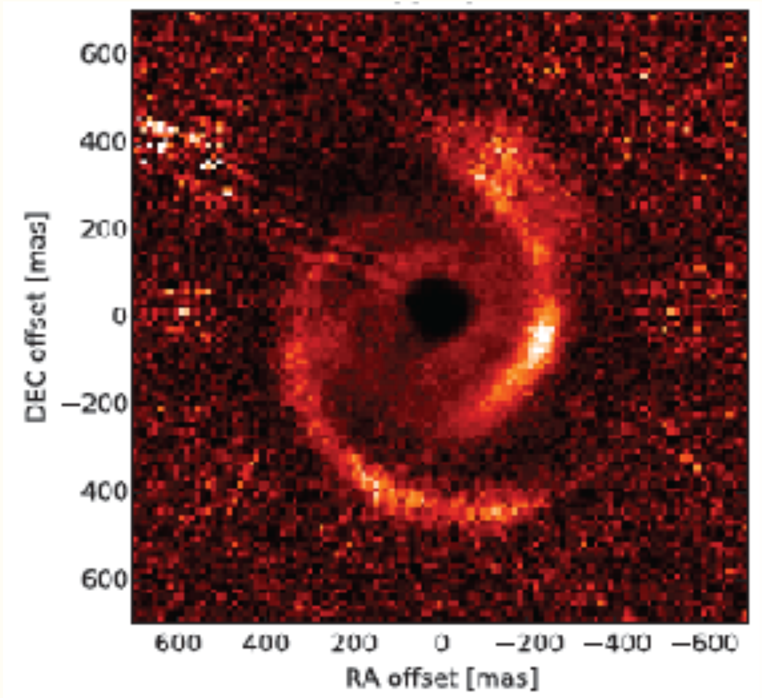
  Gaps/rings

  Spirals (theory, test theory, spirals lead to gaps)

  Lopsided structures

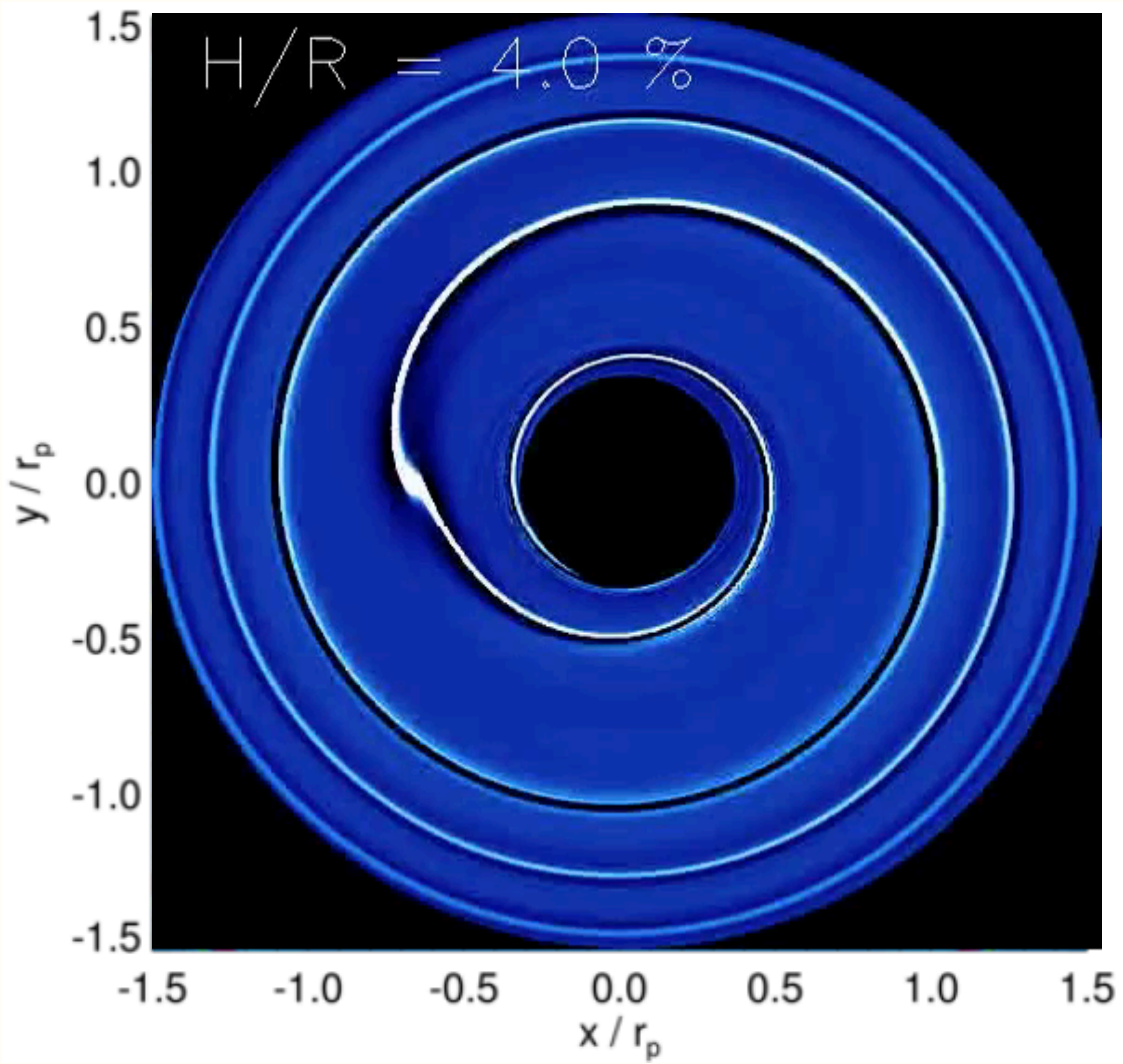
  Shadows

  CPDs



Benisty+ 2015

Sound waves in disks



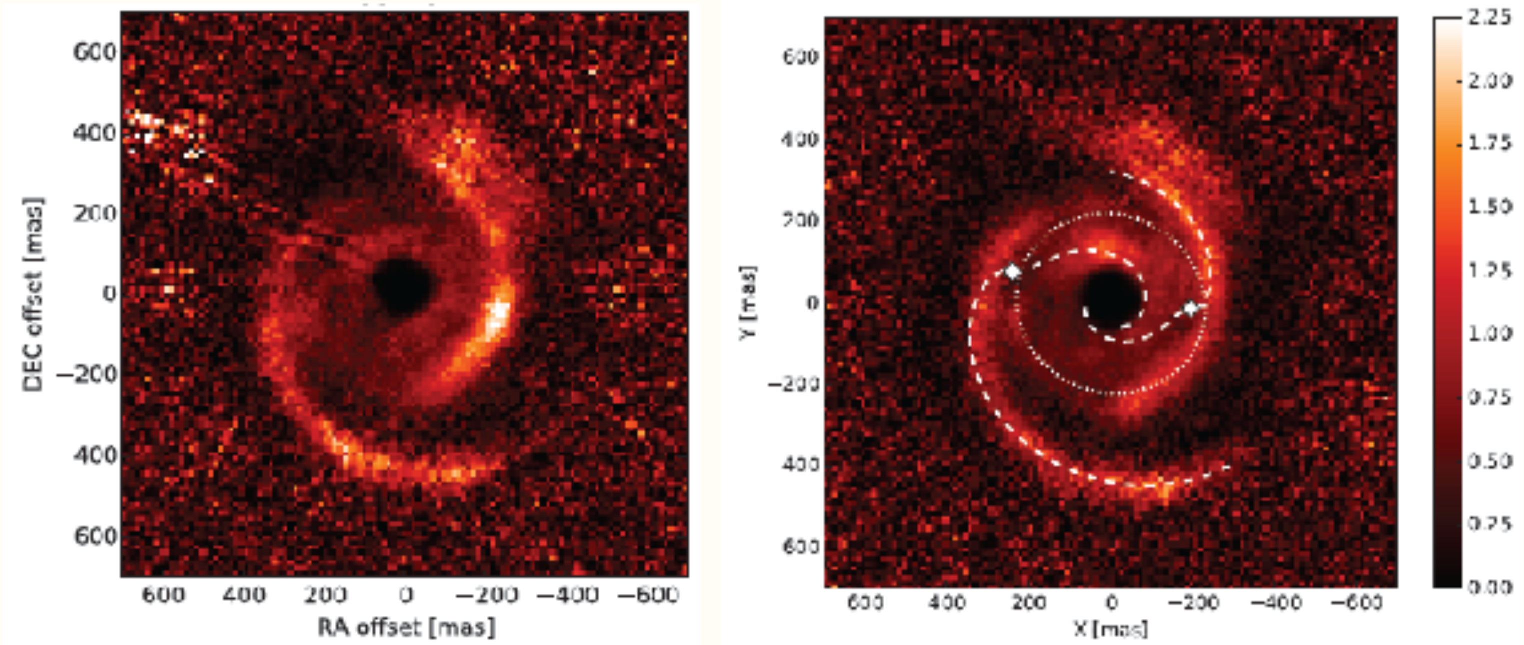
The pitch angle β

$$\tan \beta = \frac{c_s}{R|\Omega - \Omega_p|}$$

Explaining observations is difficult

1. Fitting the pitch angle suggests a too hot disk

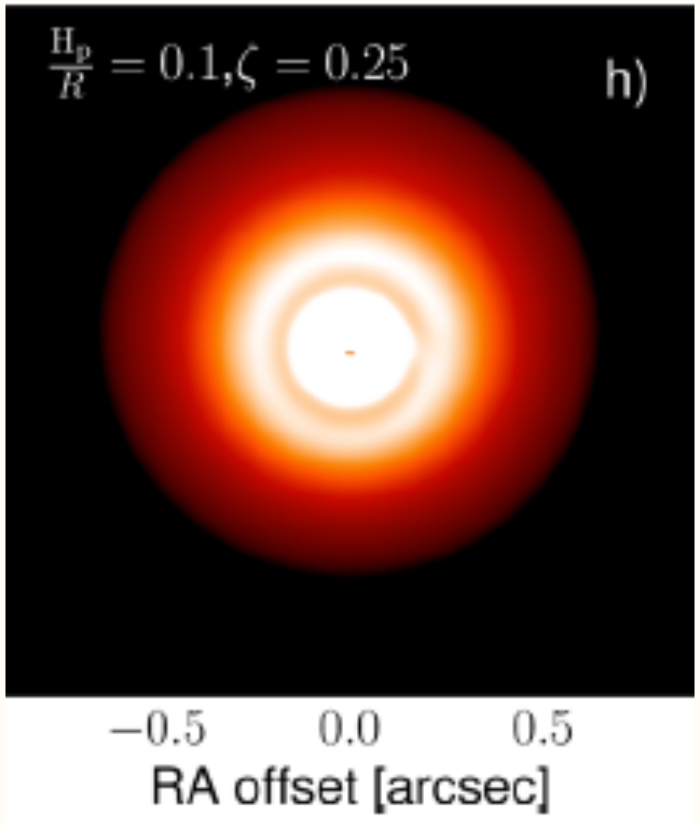
MWC 758



Benisty et al. 2015

At 50 AU, T~300 K

2. Planet-induced spiral arms are too weak



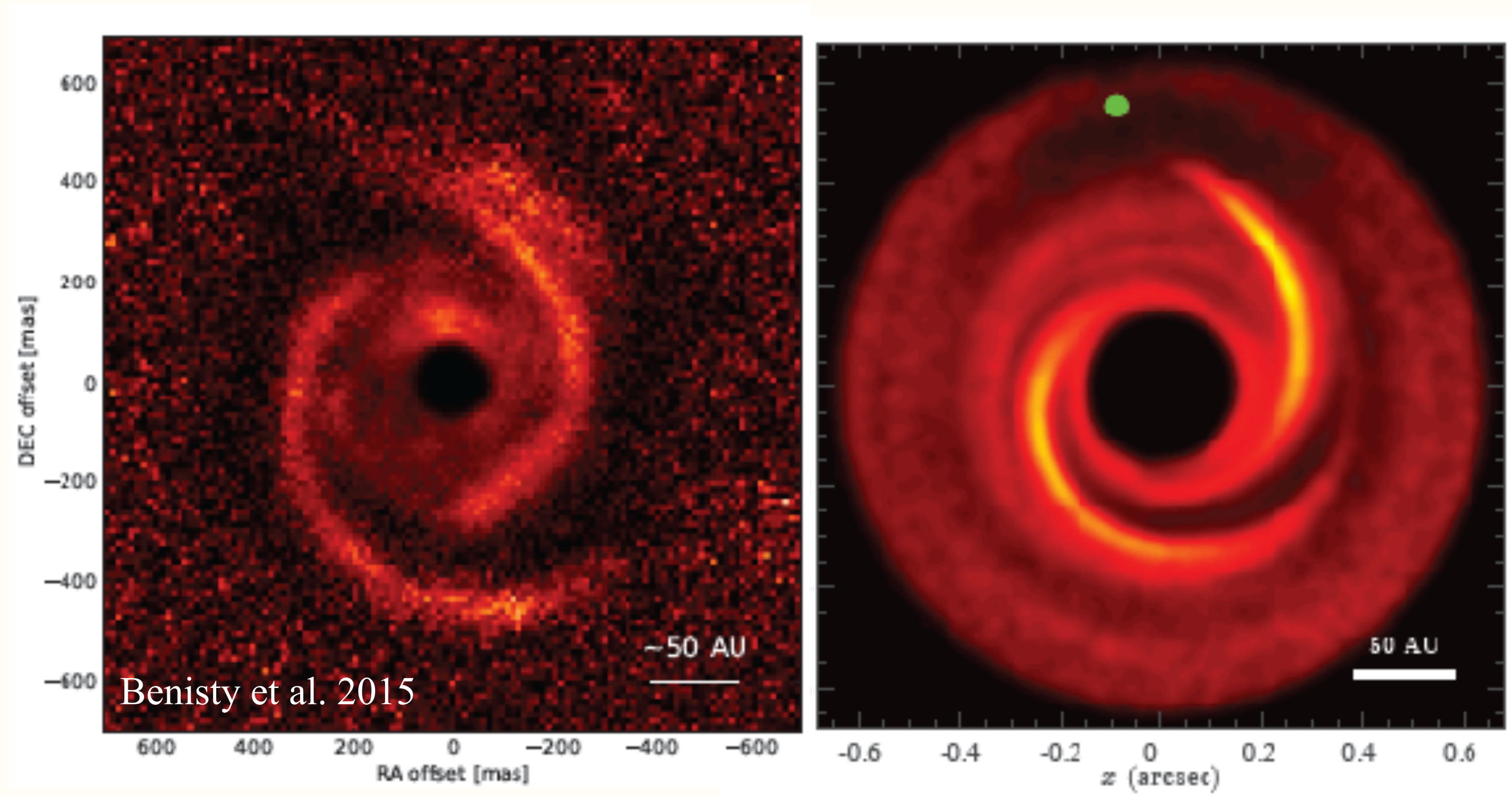
Juhasz et al. 2015

Spirals: Grand design

M51

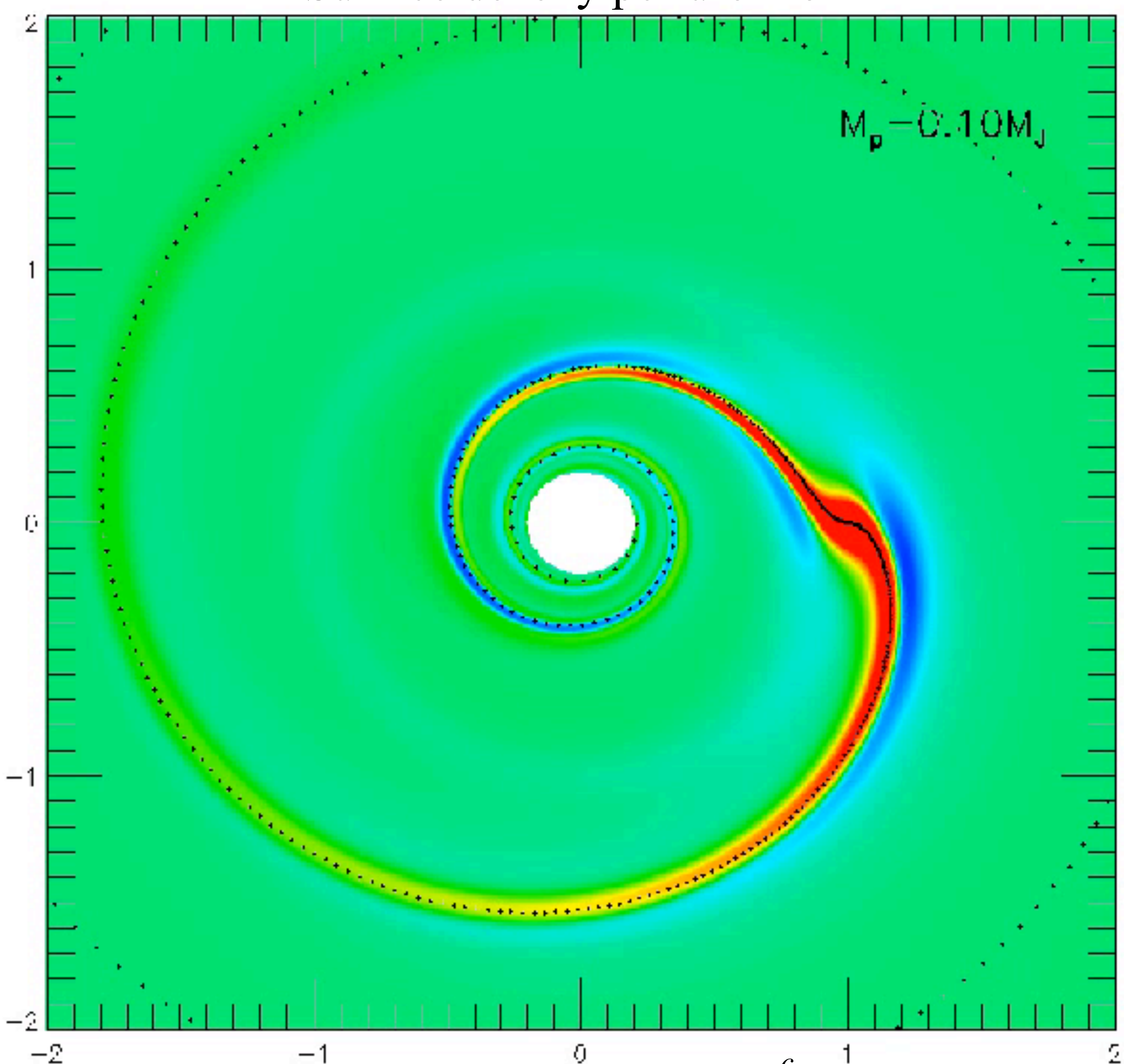
What if the planet is outside the spirals?

(Dong et al. 2015, Zhu et al. 2015)



Athena++

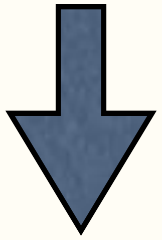
Surface density perturbation



dotted curve: linear theory $\tan\beta = \dfrac{c_s}{R|\Omega - \Omega_p|}$

When the planet mass increases:

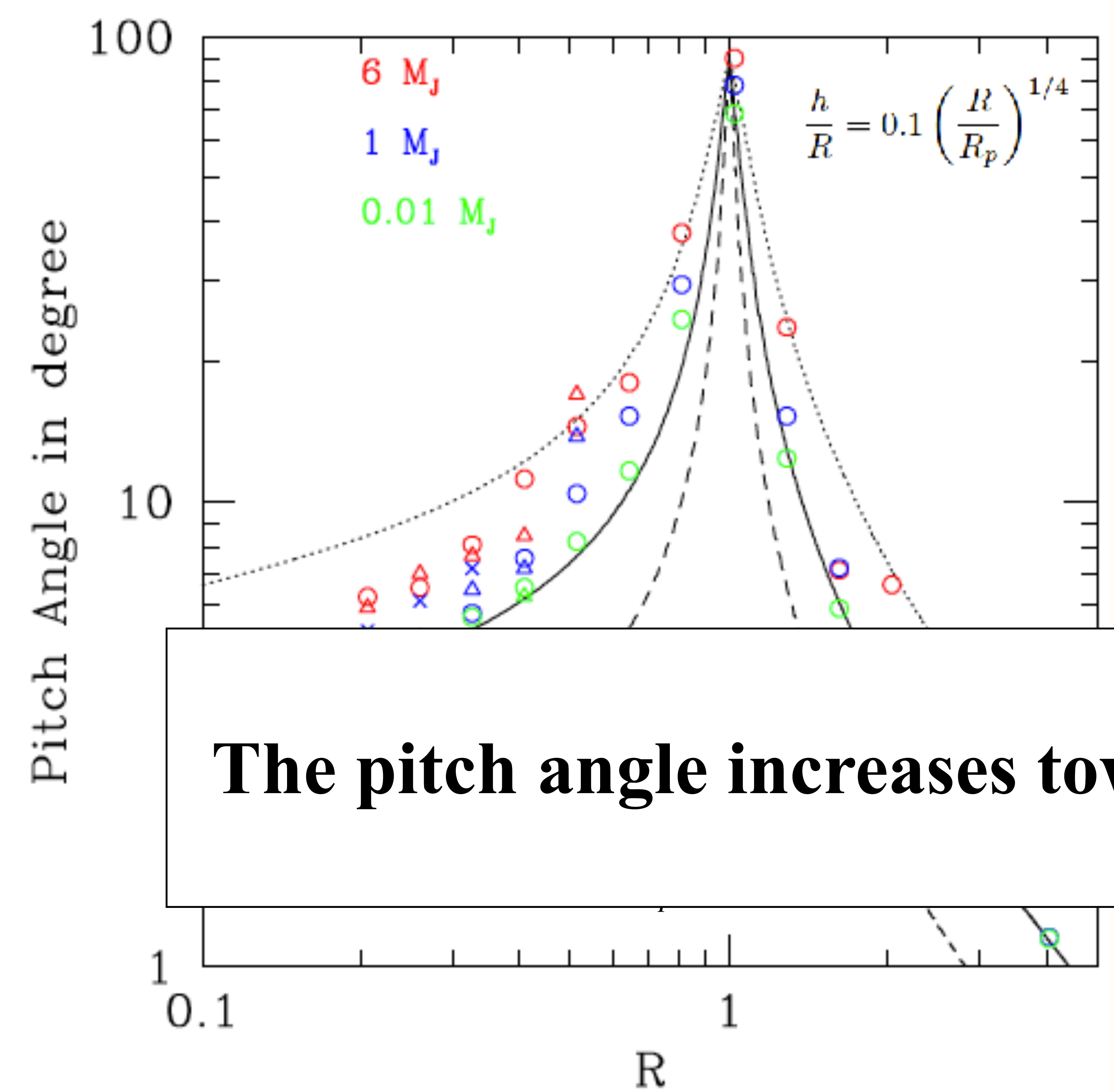
- **The pitch angle increases**
- The secondary arm becomes apparent and **the separation between two arms increases**
- **Amplitude of shocks becomes larger**



Use spiral arms to estimate planet mass

Zhu et al. 2015

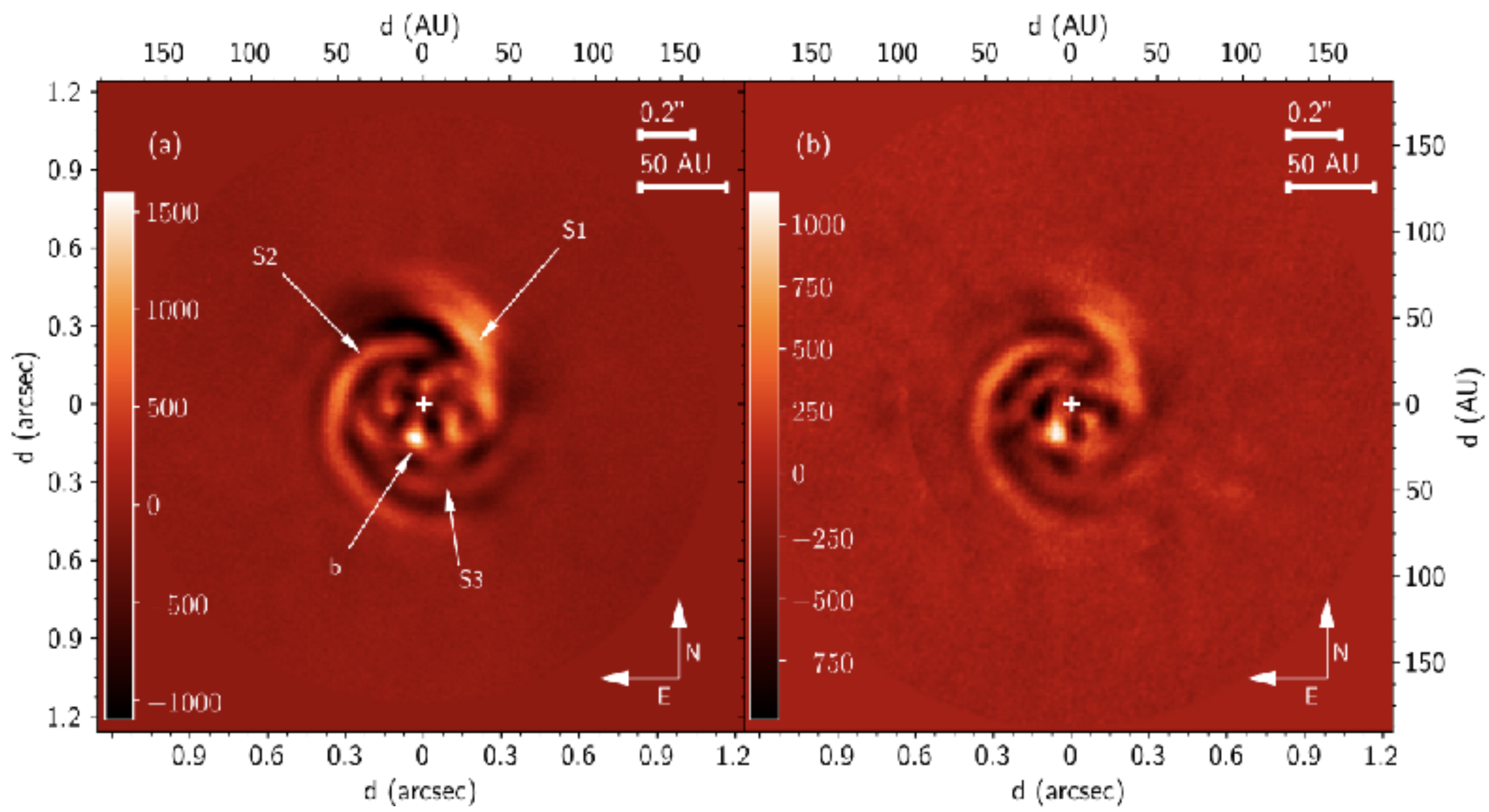
Spirals: pitch angle

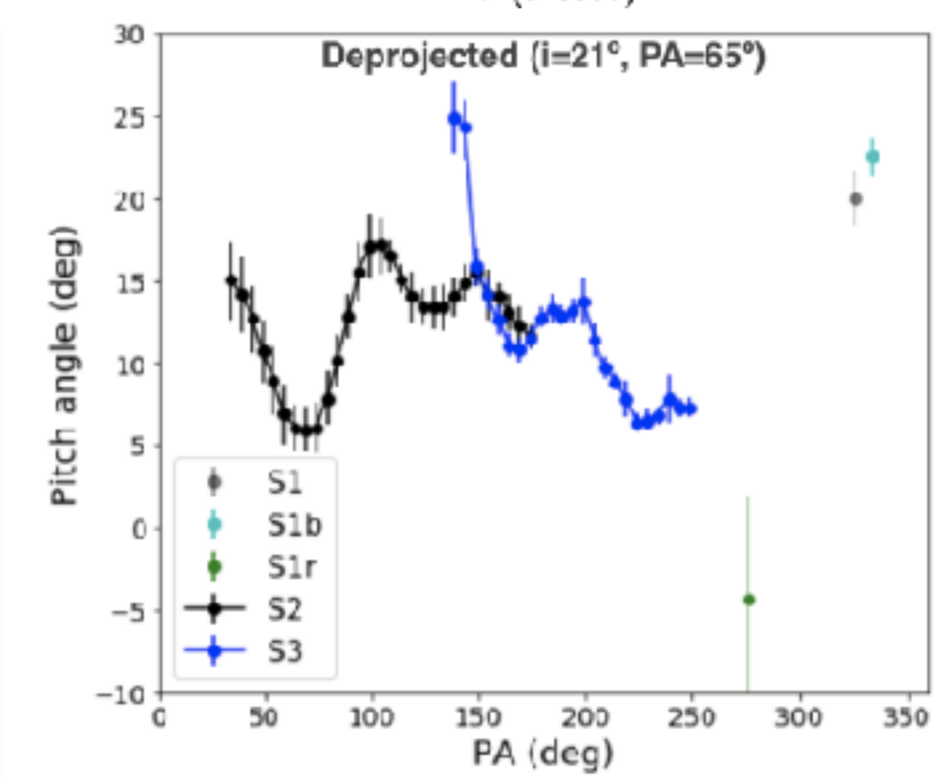


The pitch angle increases towards the planet

Zhu+ 2015

New Observations: Reggiani+ 2017



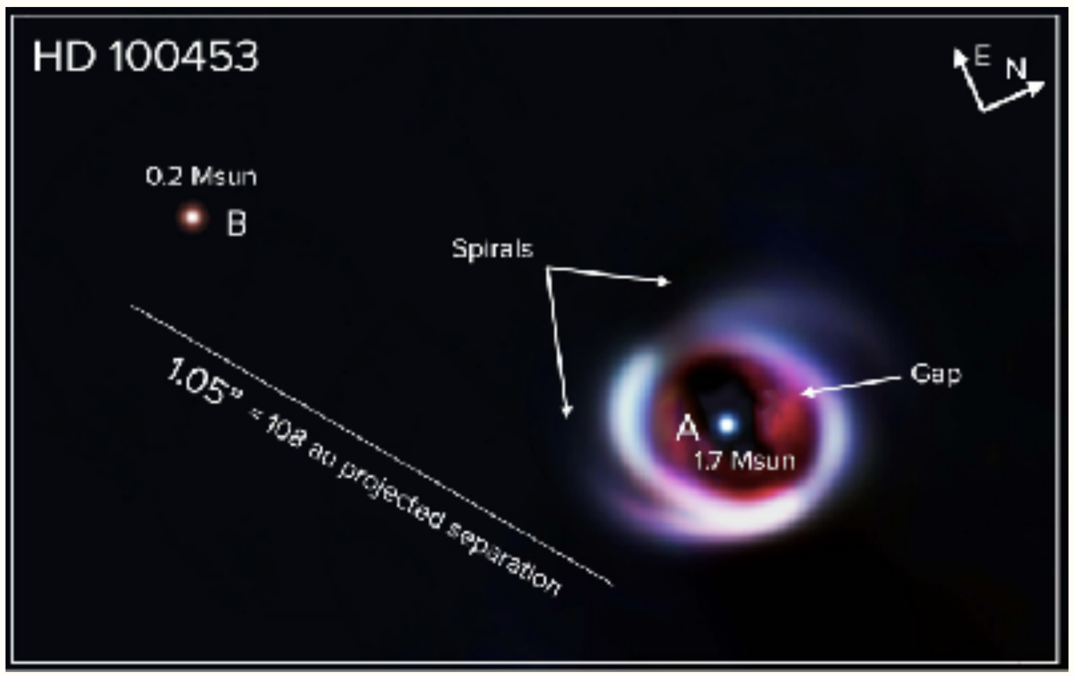


New developments:

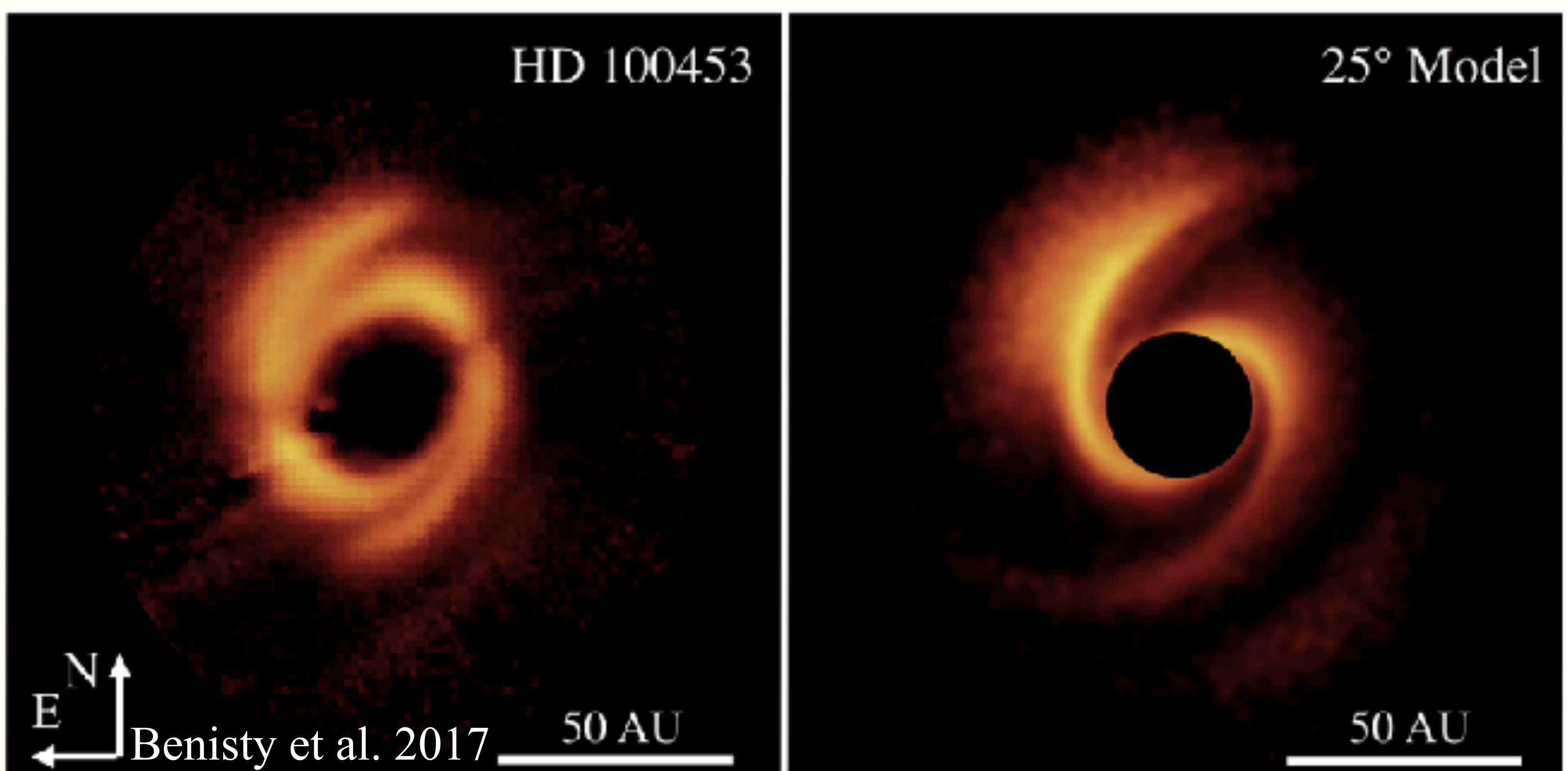
Fung & Dong 2015, Lyra et al. 2016, Bae et al. 2016ab, Dong &Fung 2017, Hord et al. 2017, Juhasz & Rosotti 2018

How to test the theory?

1. Use binaries as a test



Wagner et al. 2015

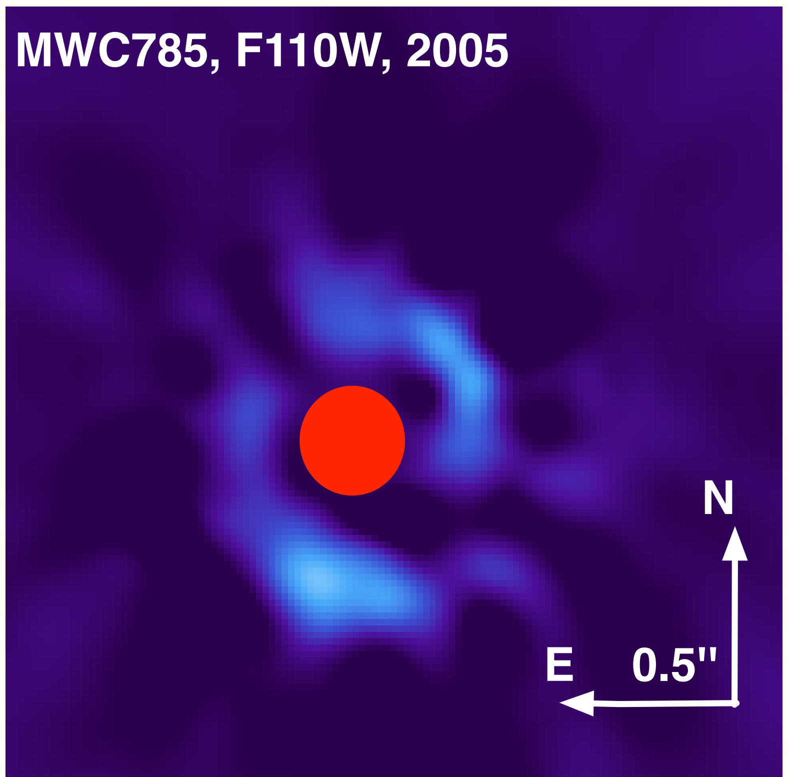


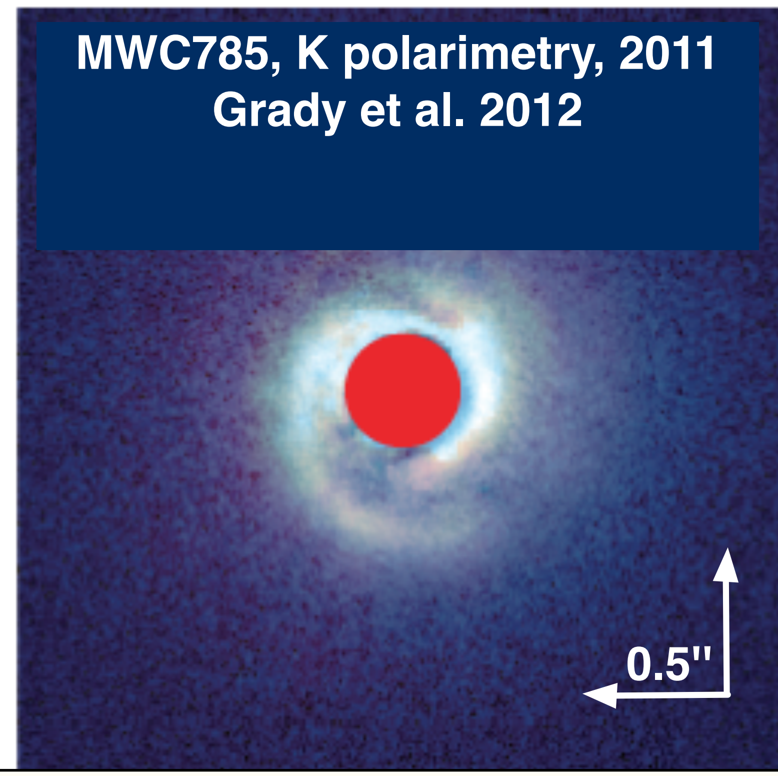
Benisty et al. 2017

Wagner et al. 2018

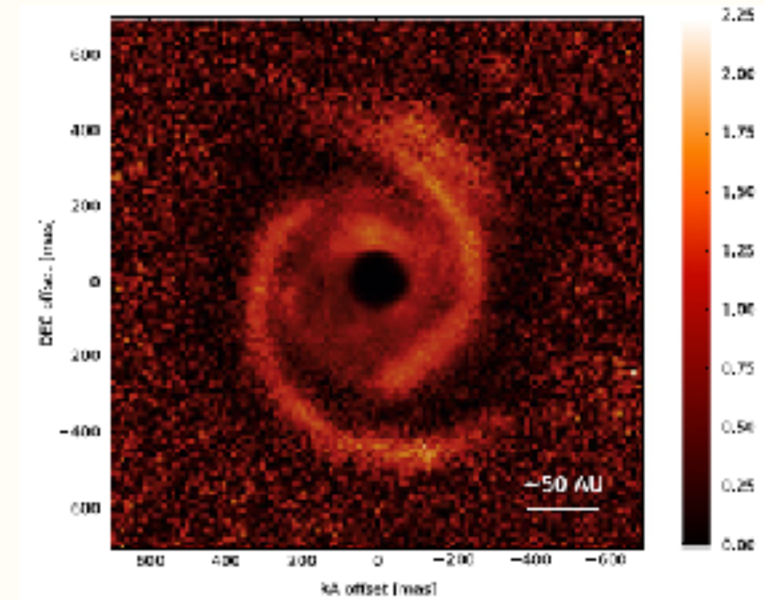
How to test the theory?

2. Spiral Patterns over Time

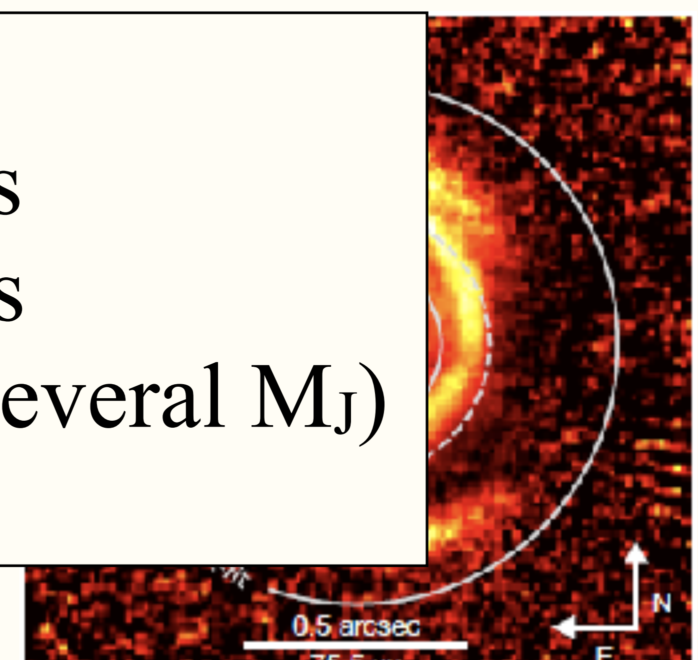




MWC 758



VLT Observations
by Benisty et al. 2015



Ren + 2018

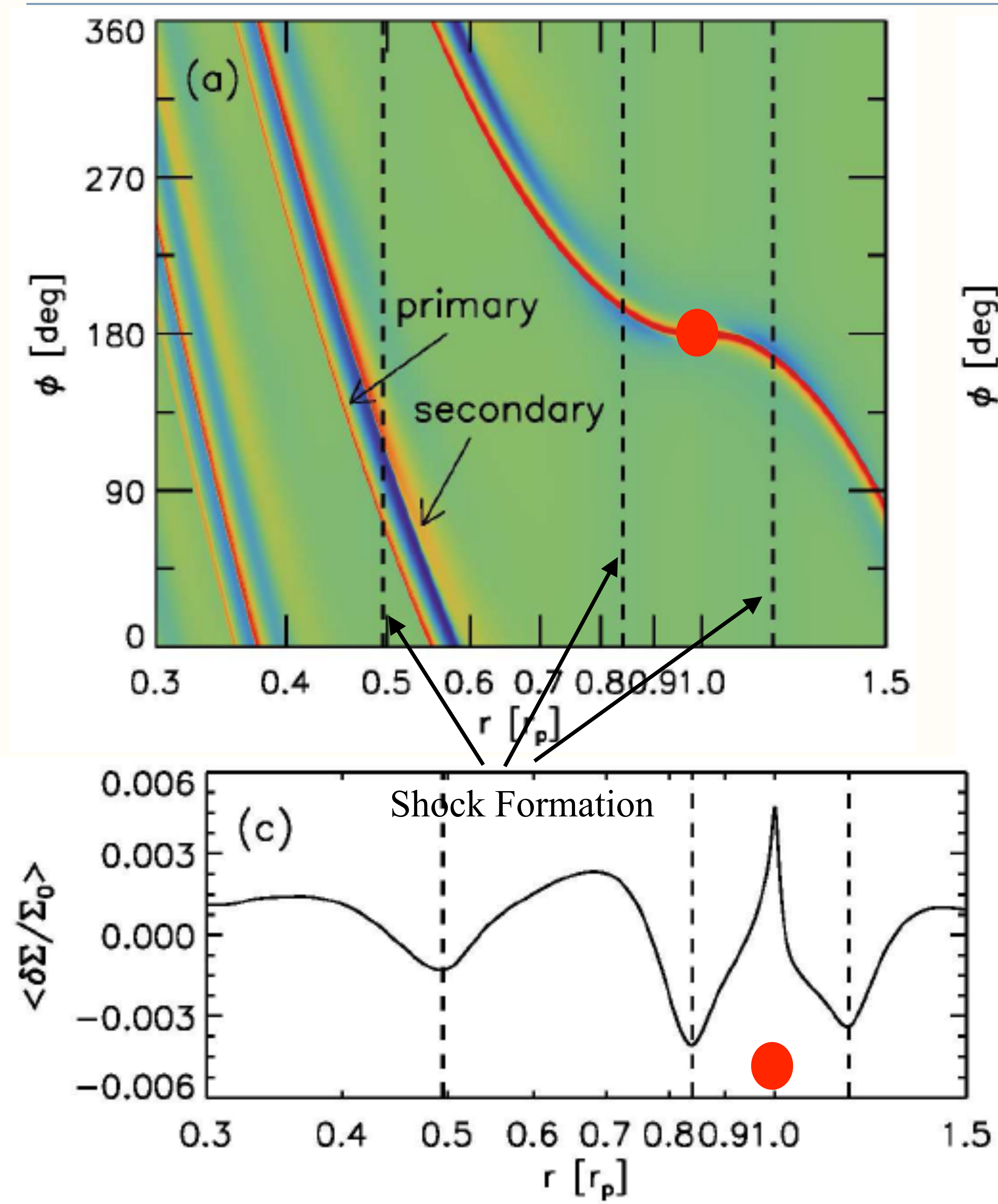
2005 Hubb

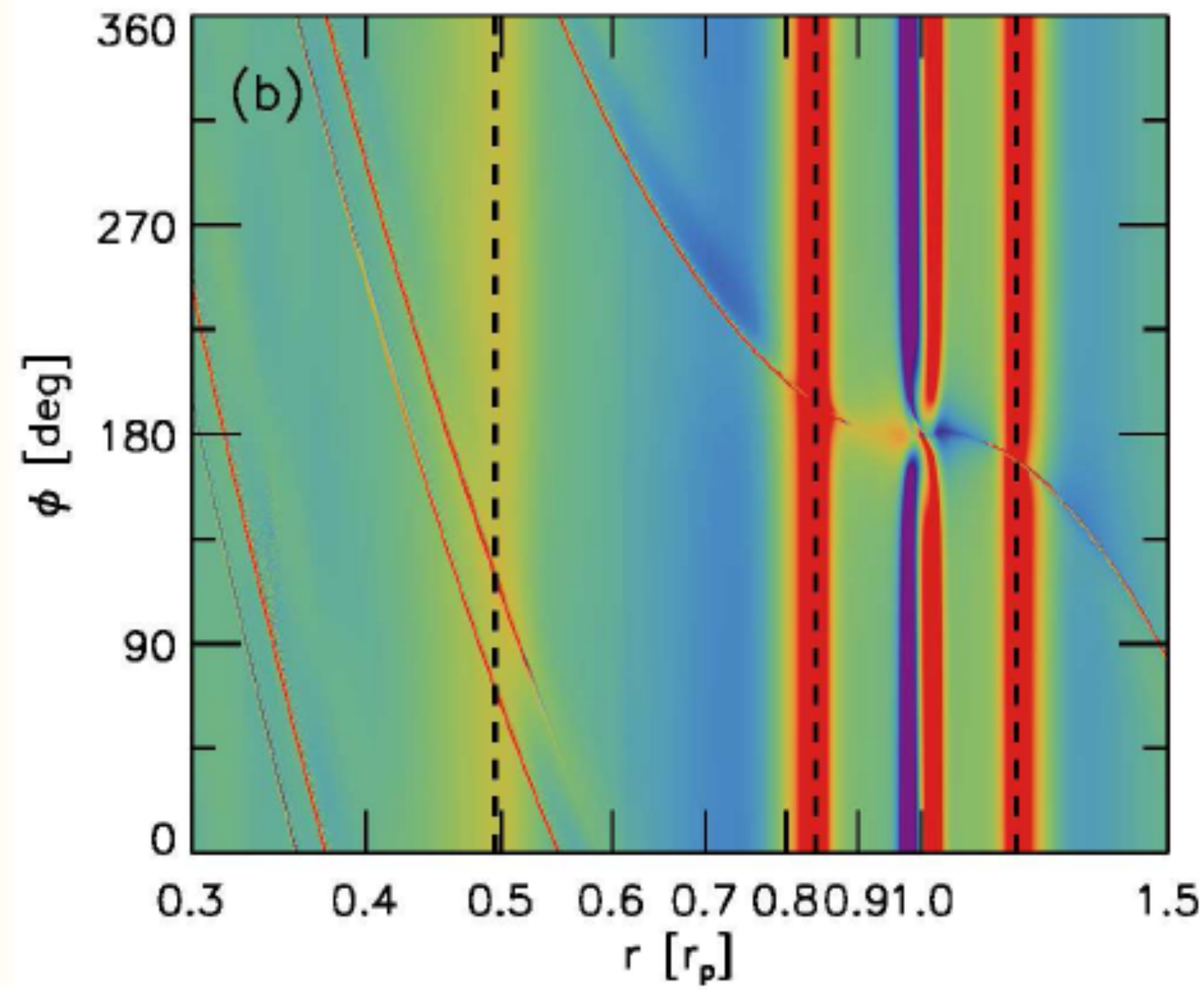
+Can trace planet position and mass
+Not many other ways to get spirals
- Only works for massive planets (several M_J)

Planets

Planets

Multiple spirals with multiple gaps



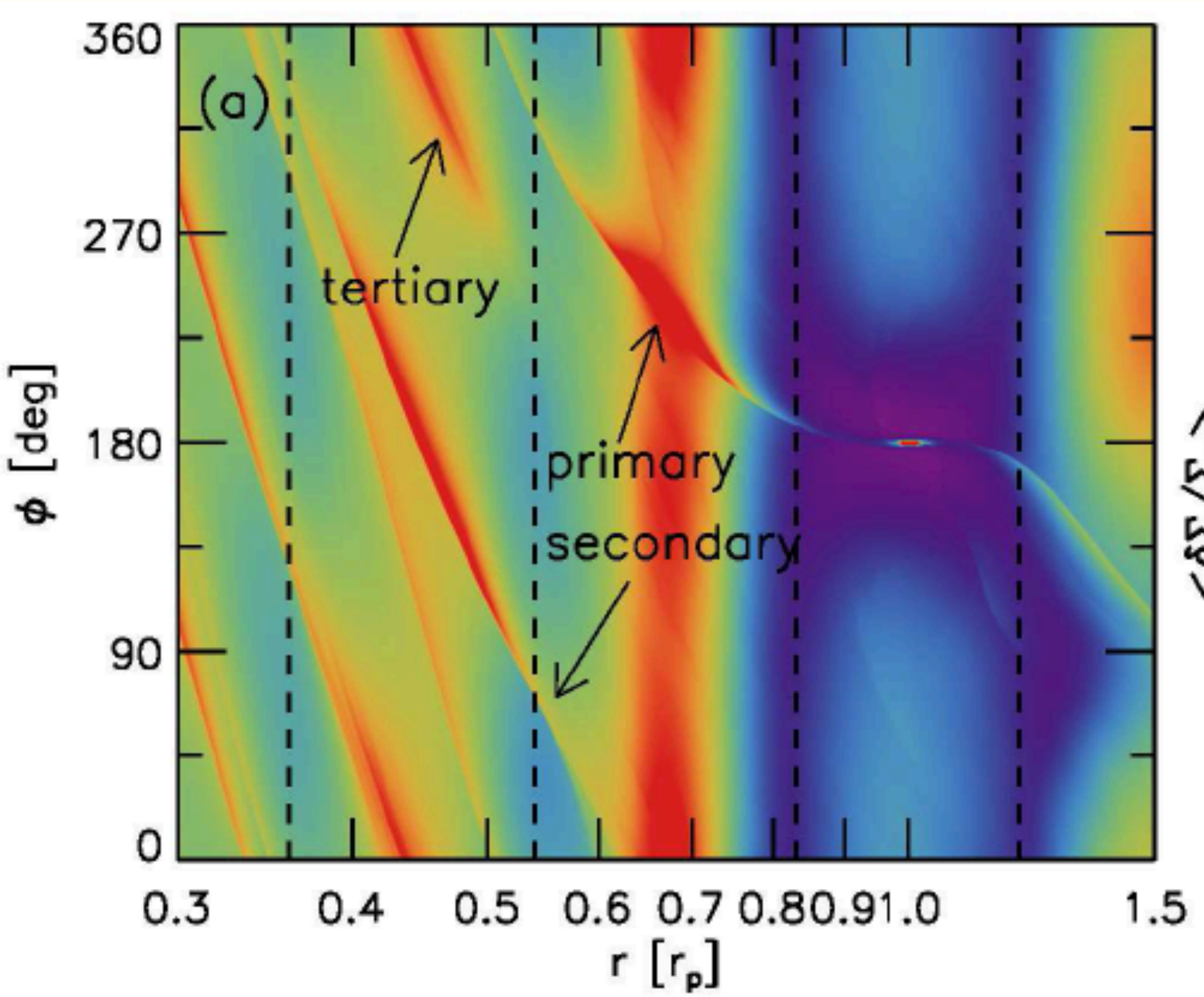


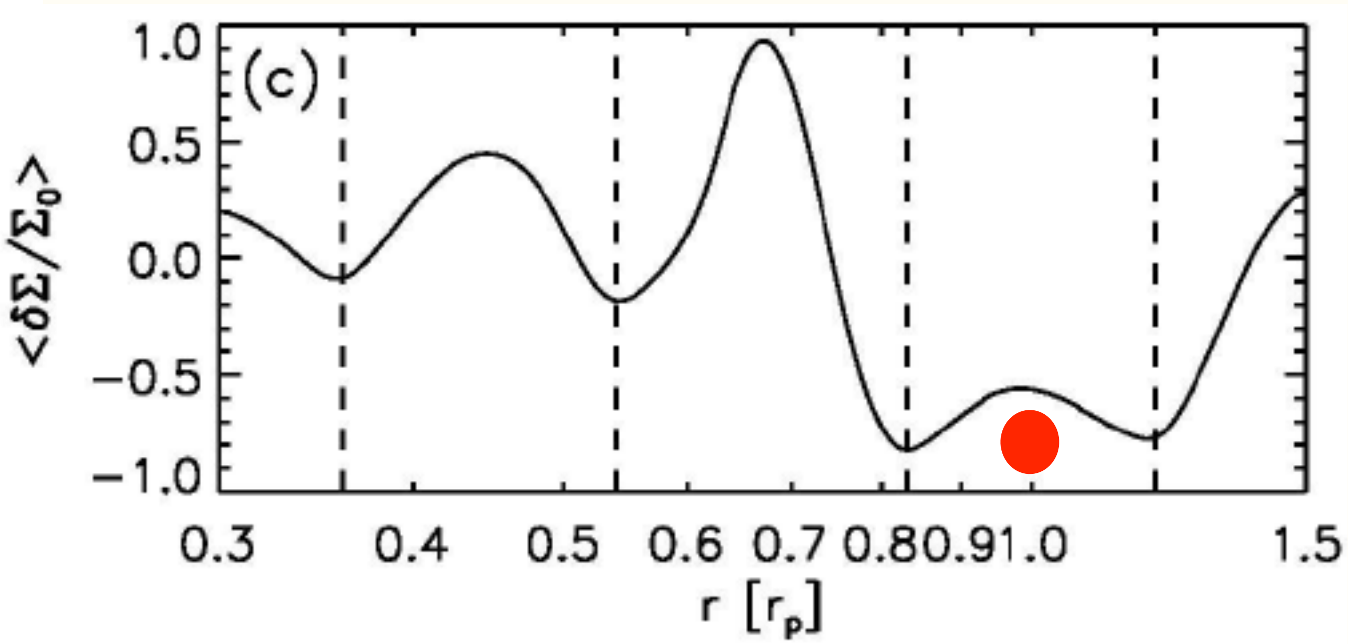
Potential Vortensity:

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

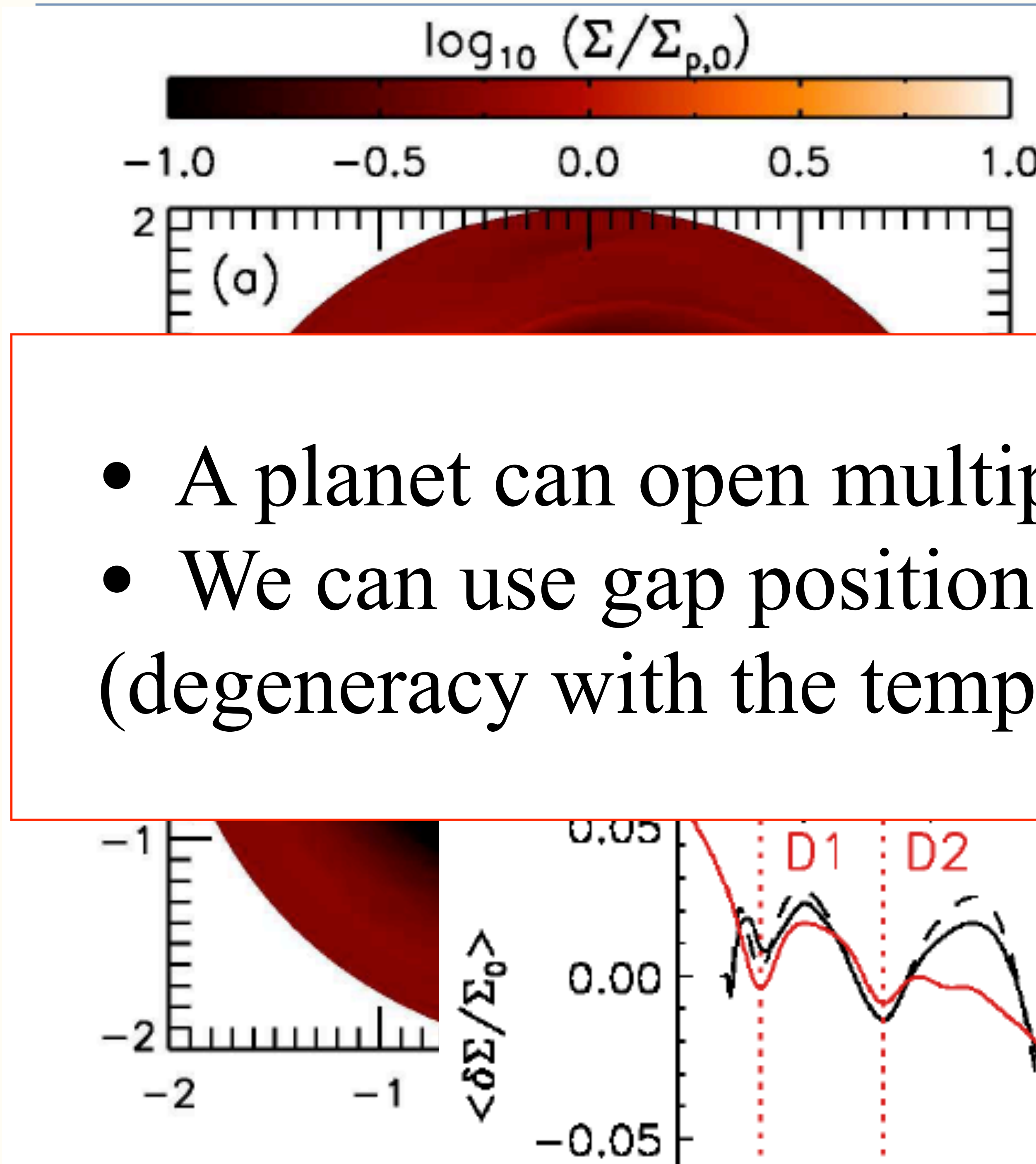
Bae, Zhu, Hartmann 2017

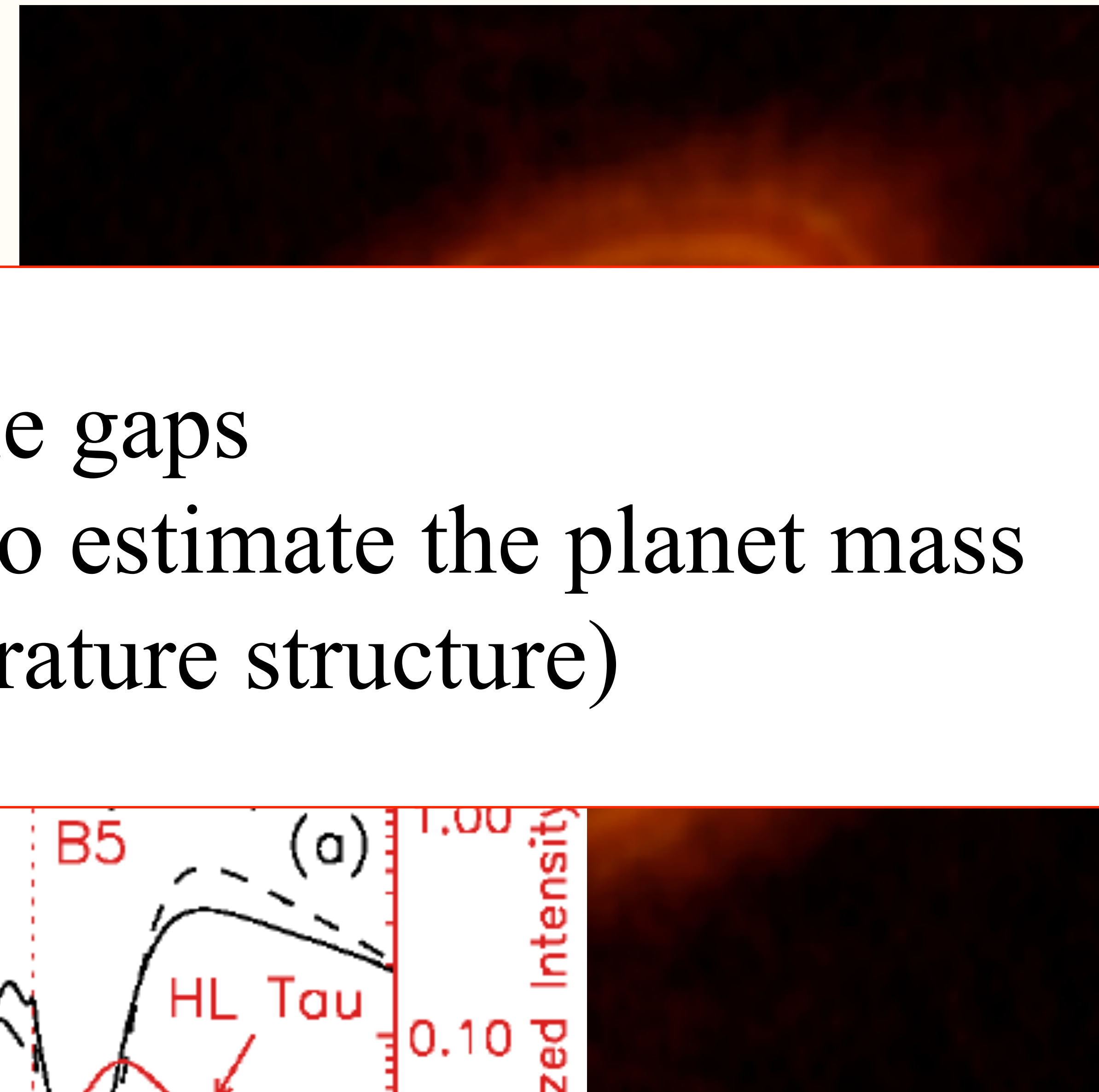
Each spiral can open its own gap





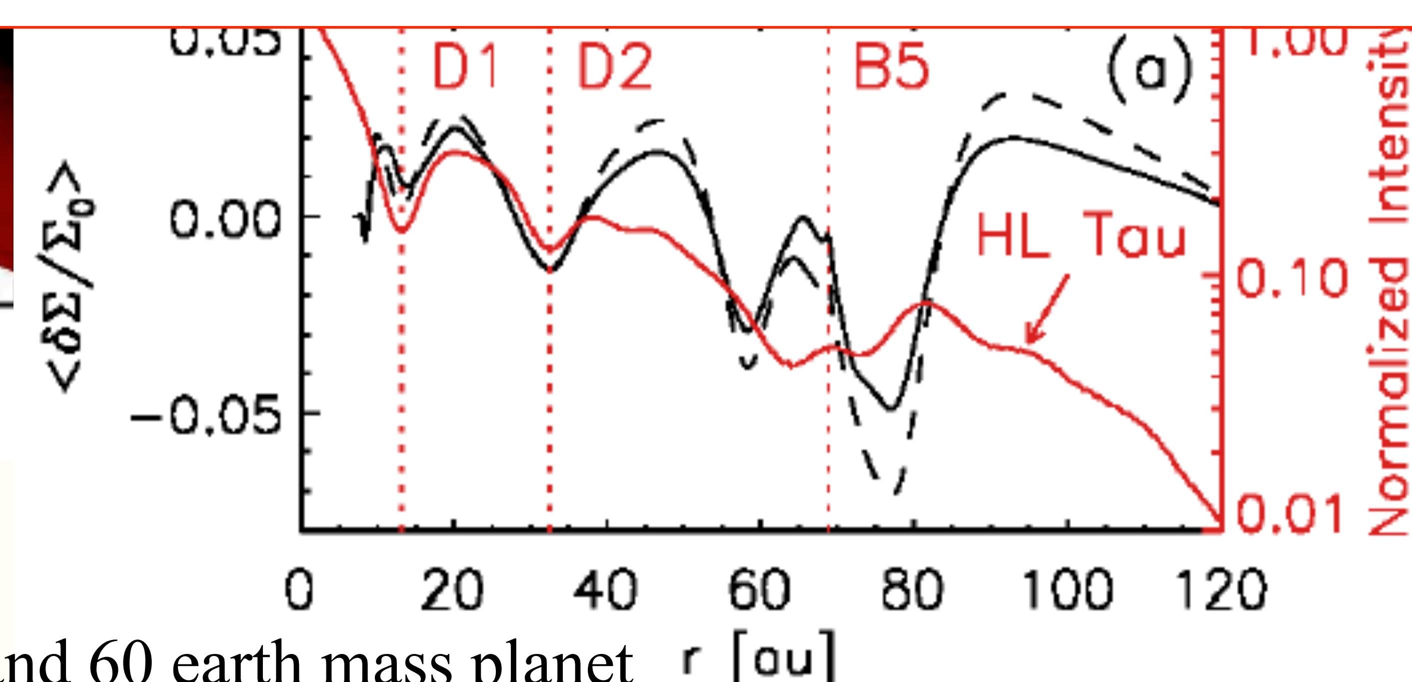
Multiple gaps by one planet





- A planet can open multiple gaps
- We can use gap position to estimate the planet mass

(degeneracy with the temperature structure)



Bae, Zhu, Hartmann 2017
Dong et al. 2017

30 and 60 earth mass planet

Outline

- Disk Observations:

  Optical/Near-IR:

    Rings, Spirals, Disk shadowing

  Submm:

    Diverse features

    Synergy between Near-IR and Submm

- Planet-disk interaction theory:

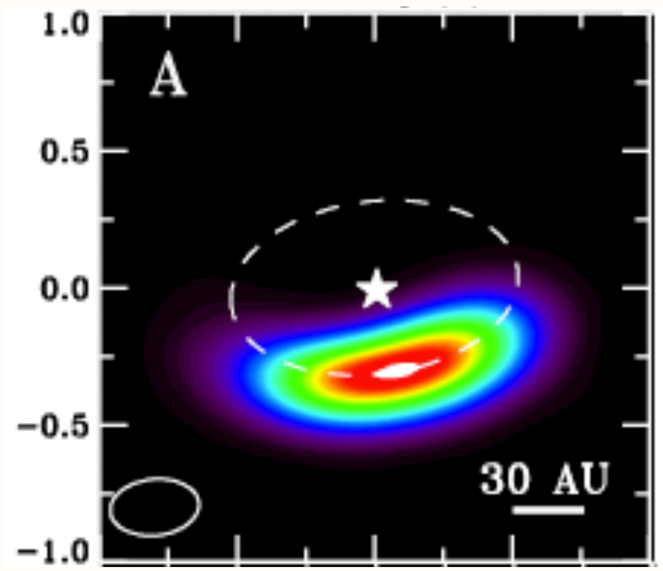
  Gaps/rings

  Spirals

  Lopsided structures (theory, test theory, spirals lead to gaps)

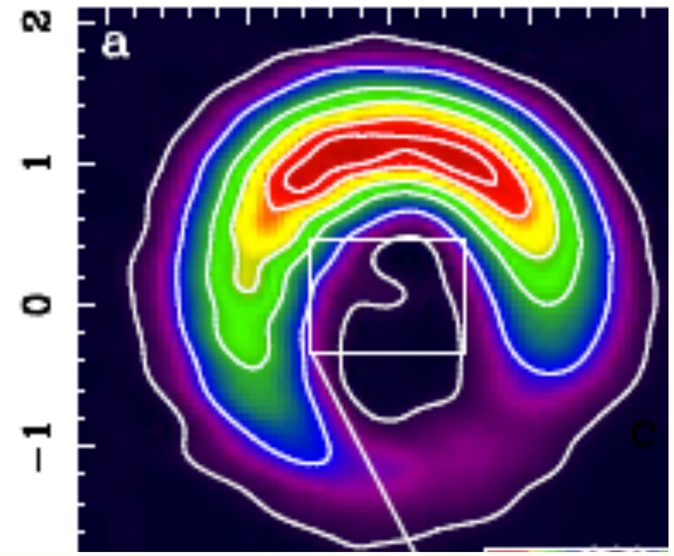
  Shadows

  CPDs

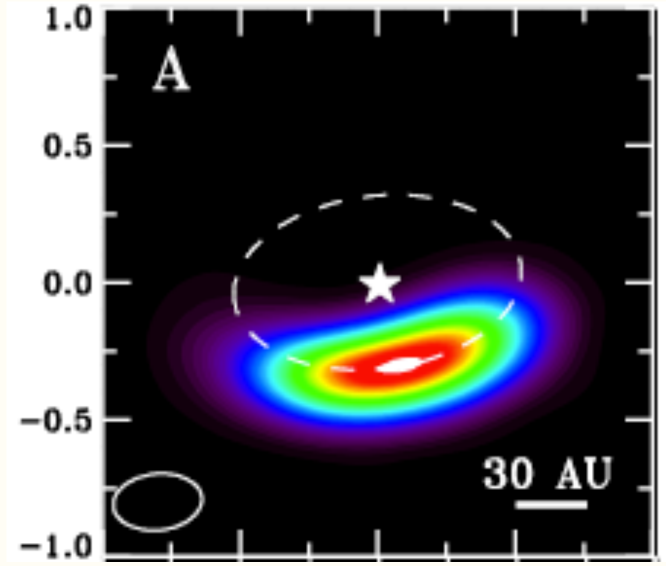


van der Marel+ (2013)

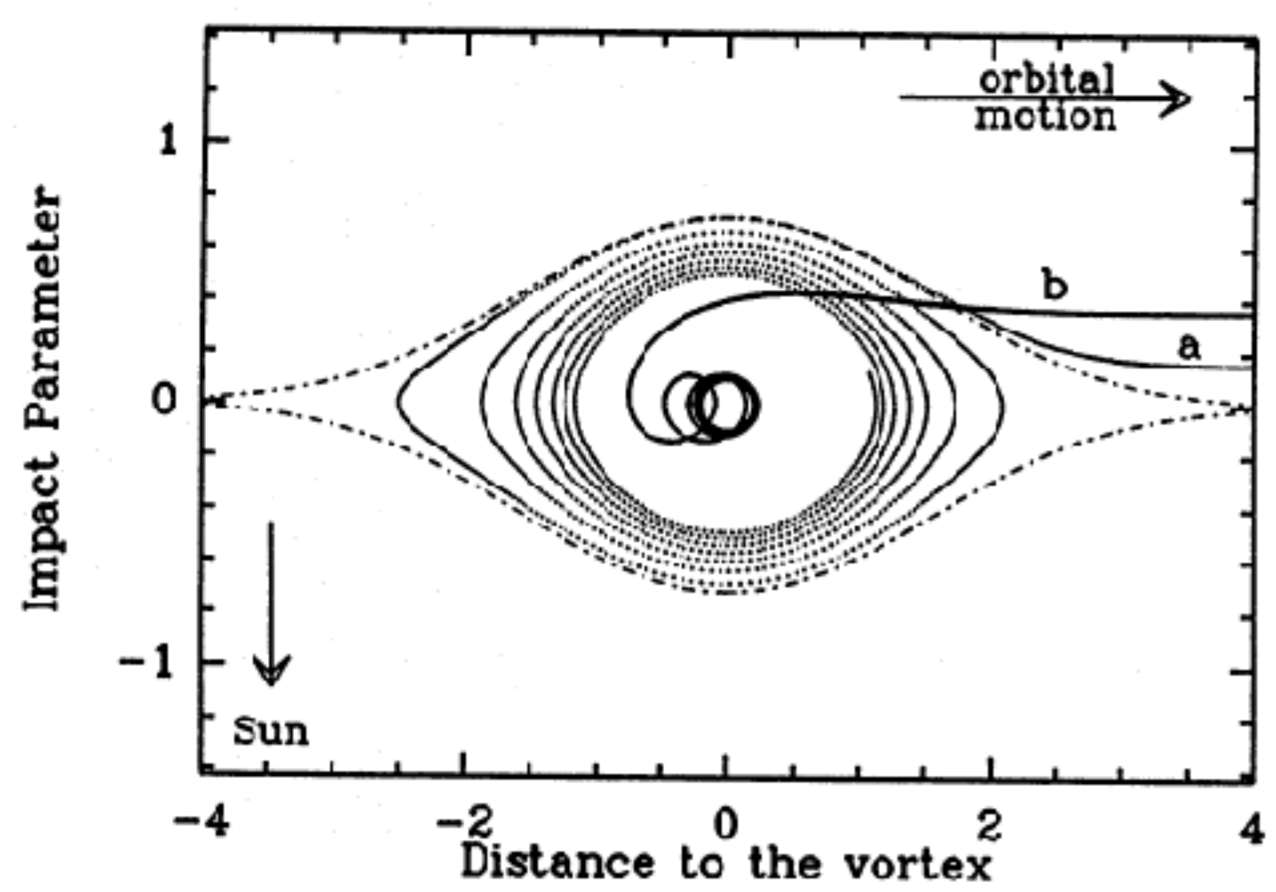
Lopsided structure: vortex



Casassus+ (2013)



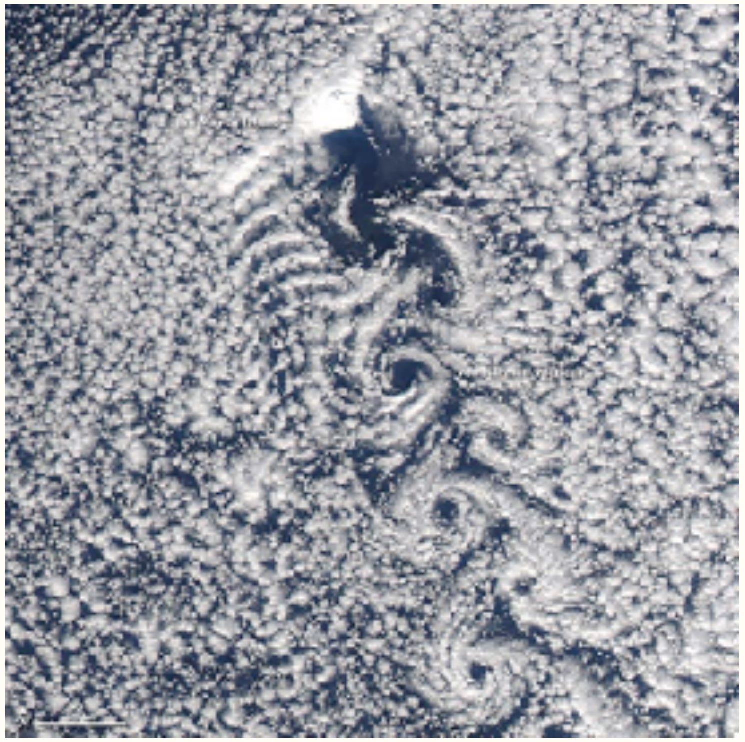
van der Marel+ (2013)



Barge & Sommeria (1995)

Vortex does not have to be associated with planets

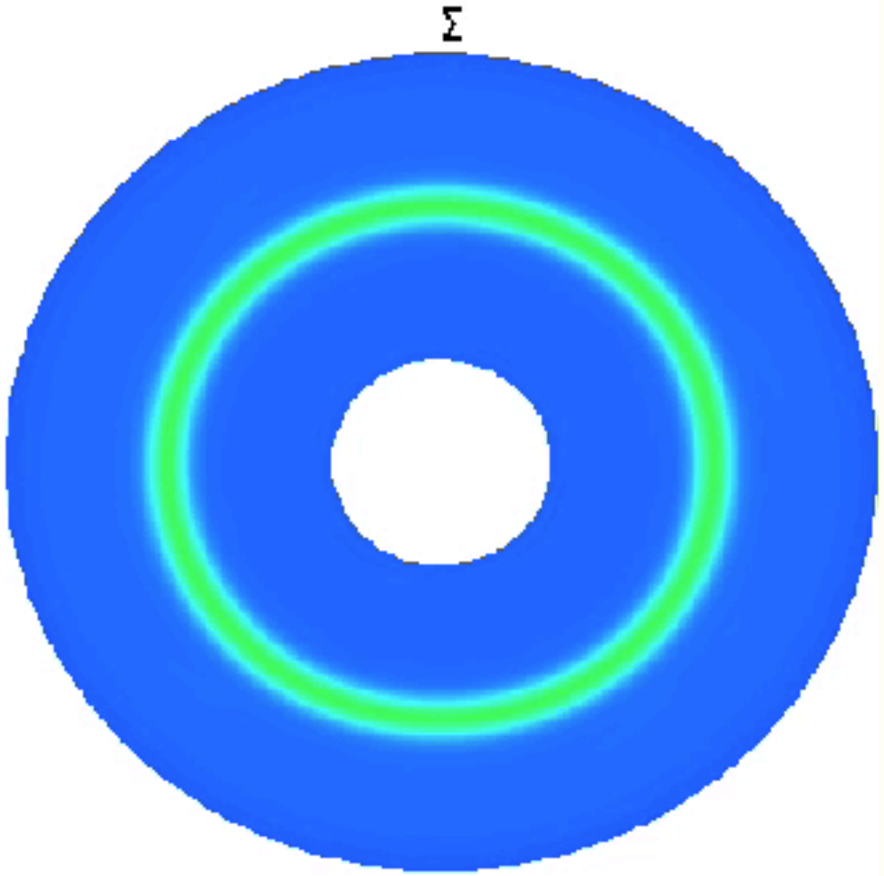
- Vortices are natural outcomes of fluid instabilities.



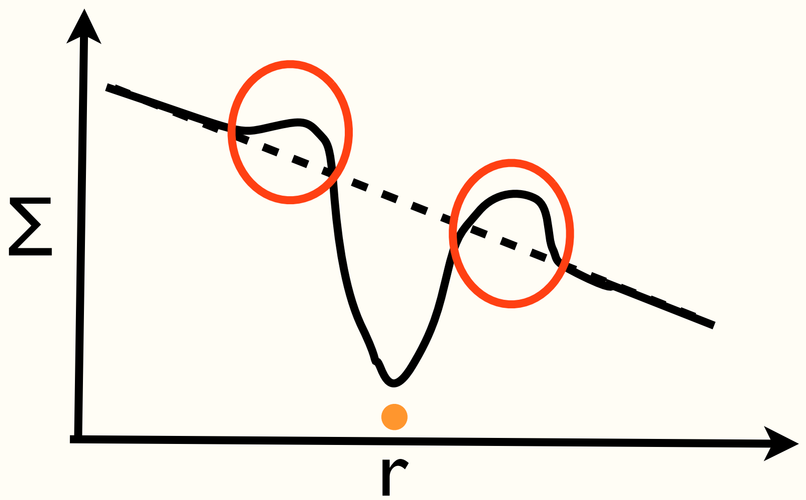
- In protoplanetary disks:

  MRI, baroclinic instability,
  Rossby wave instability

Papaloizou & Pringle 1984,1985
Lovelace+ 1999, Li+ 2000, 2001
Meheut+ 2010, Yu & Lai 2013

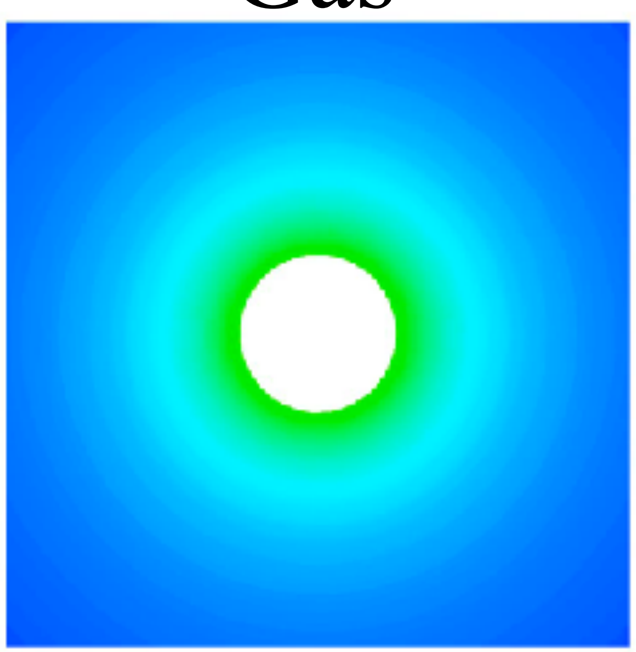


Planet-induced gap edge instability

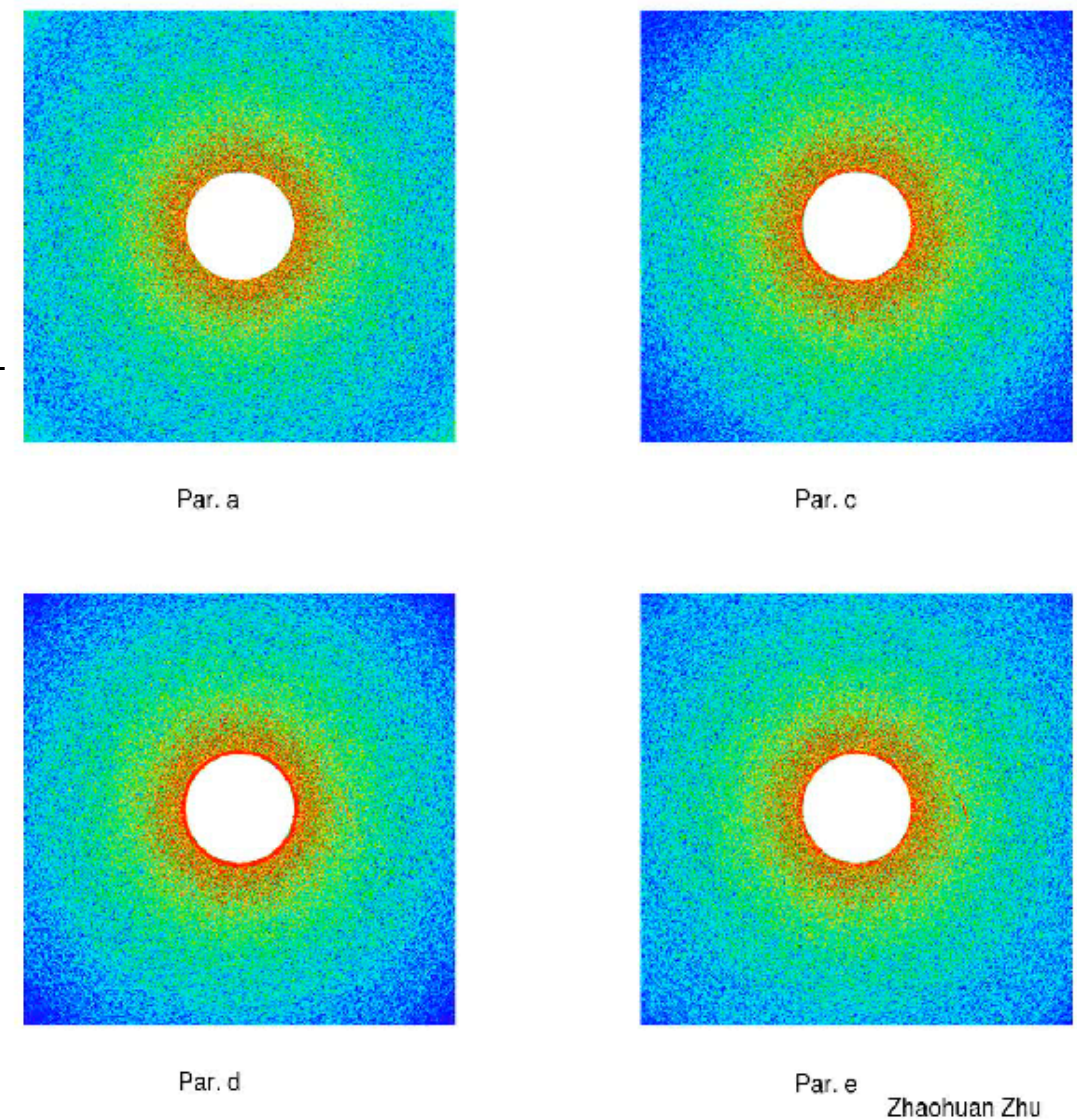


Papaloizou & Pringle 1984,1985 Lovelace et al. 1999, Li et al. 2000, 2001, Li et al. 2005, De Val-Borro 2007, Lyra et al. 2009, Meheut et al. 2010, Lin 2012, Altaiee et al. 2013, Zhu et al. 2014, Fu et al. 2014, Surville et al. 2016, Regaly et al. 2012, 2017

Gas



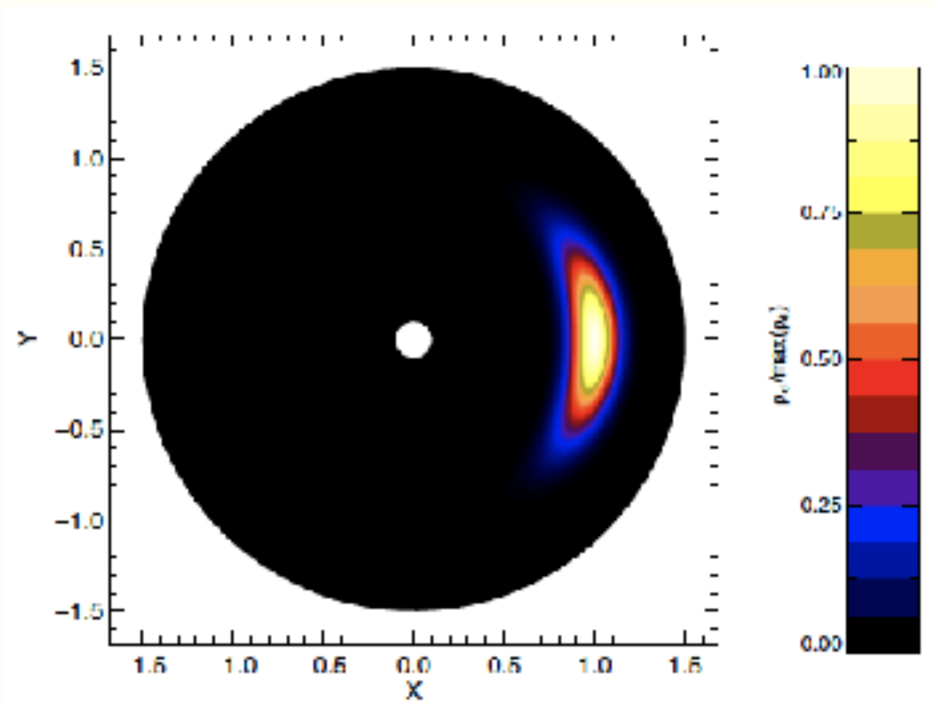
Dust particles



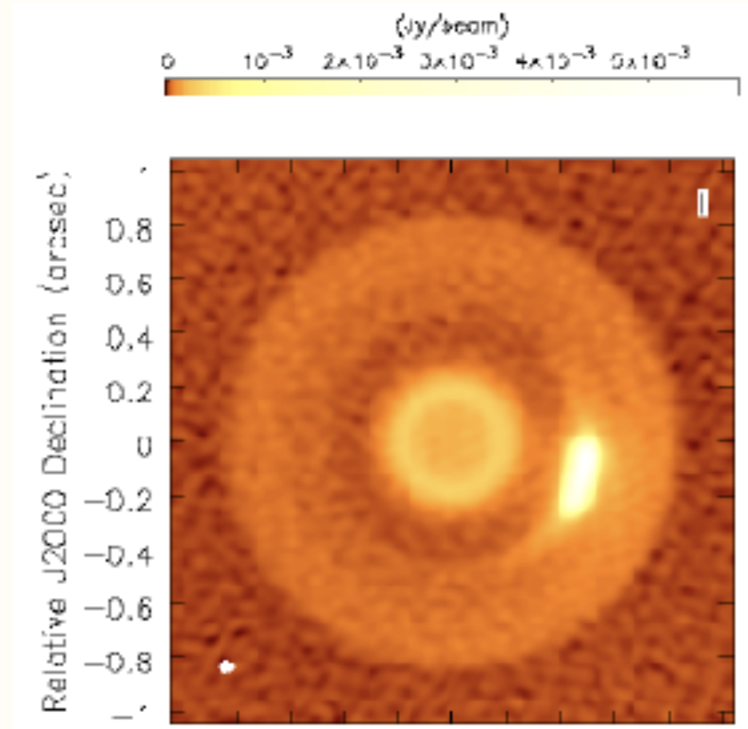
Compared with observations

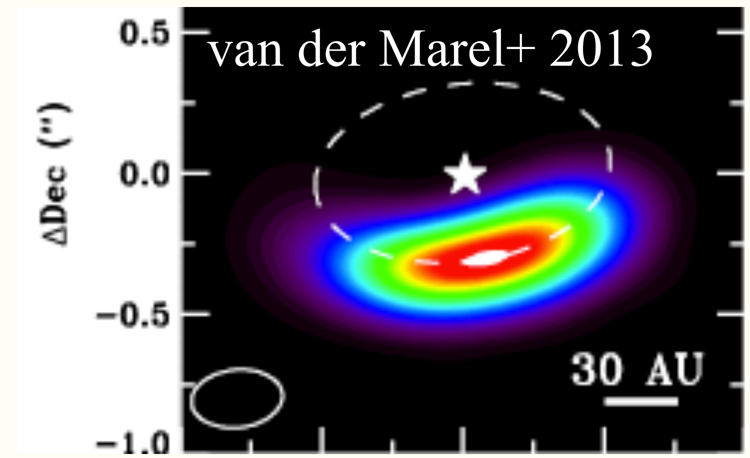
Analytical Model

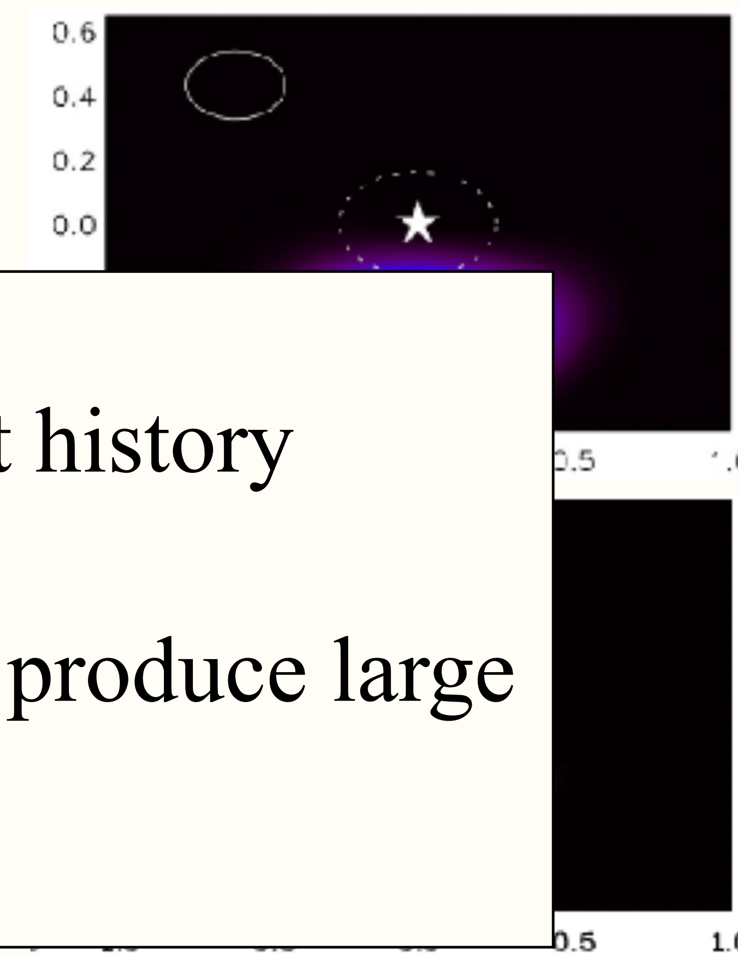
Simulation+post processing



Lyra & Lin







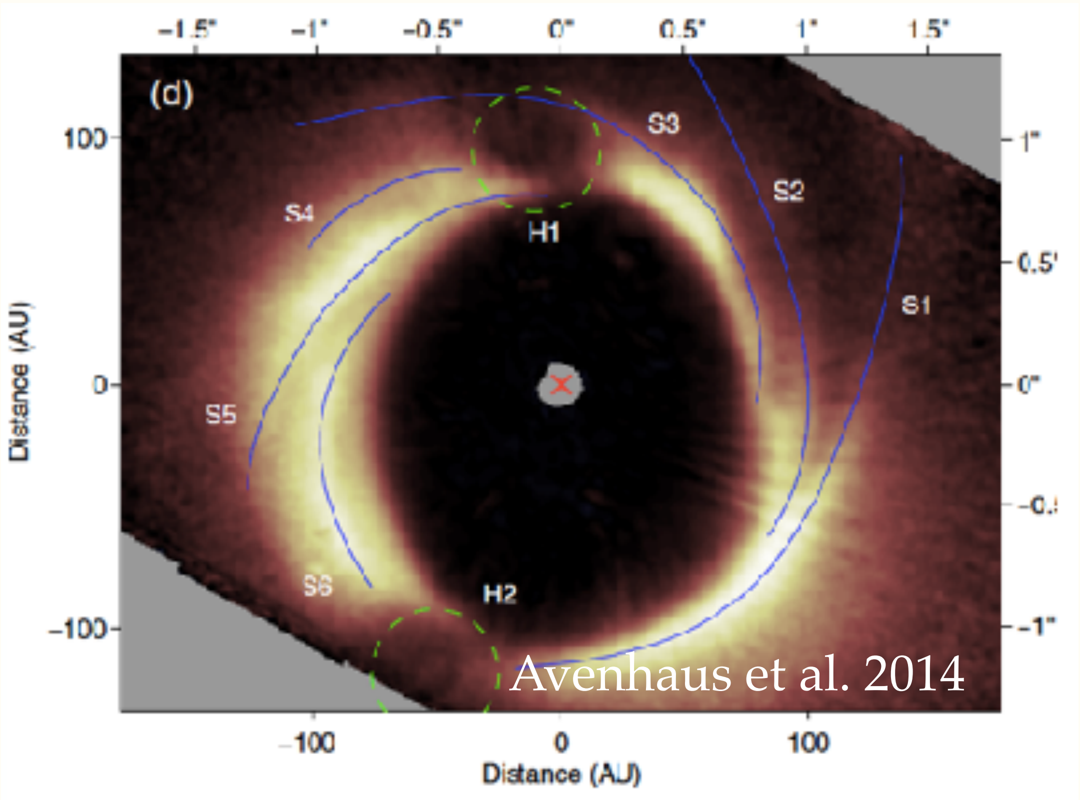
- Too many disk parameters, planet history
(Hammer, Kratter, Lin 2018)

+ Vortex is the only known way to produce large scale disk asymmetry at submm.

Zhu & Stone 2014

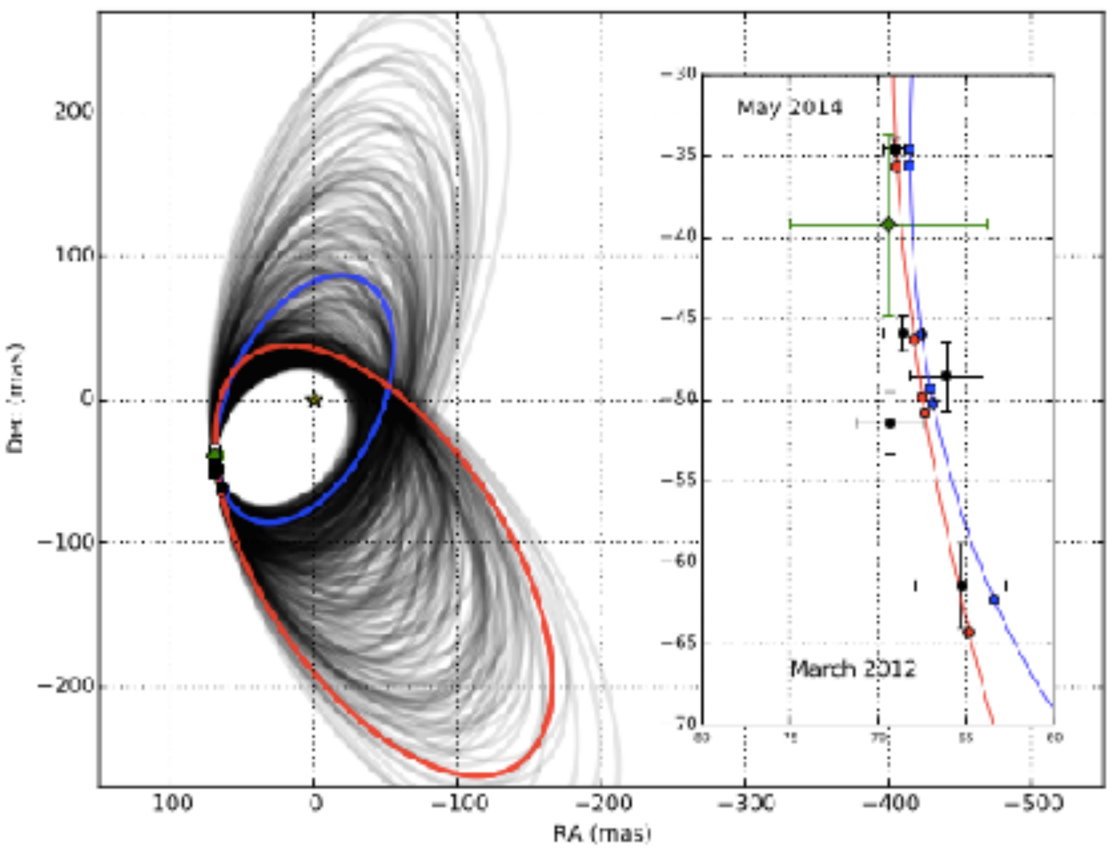
Outline

- Disk Observations:
  - Optical/Near-IR:
    - Rings, Spirals, Disk shadowing
  - Submm:
    - Diverse features
    - Synergy between Near-IR and Submm
- Planet-disk interaction theory:
  - Gaps/rings
  - Spirals
  - Lopsided structures
  - Shadows
  - CPDs

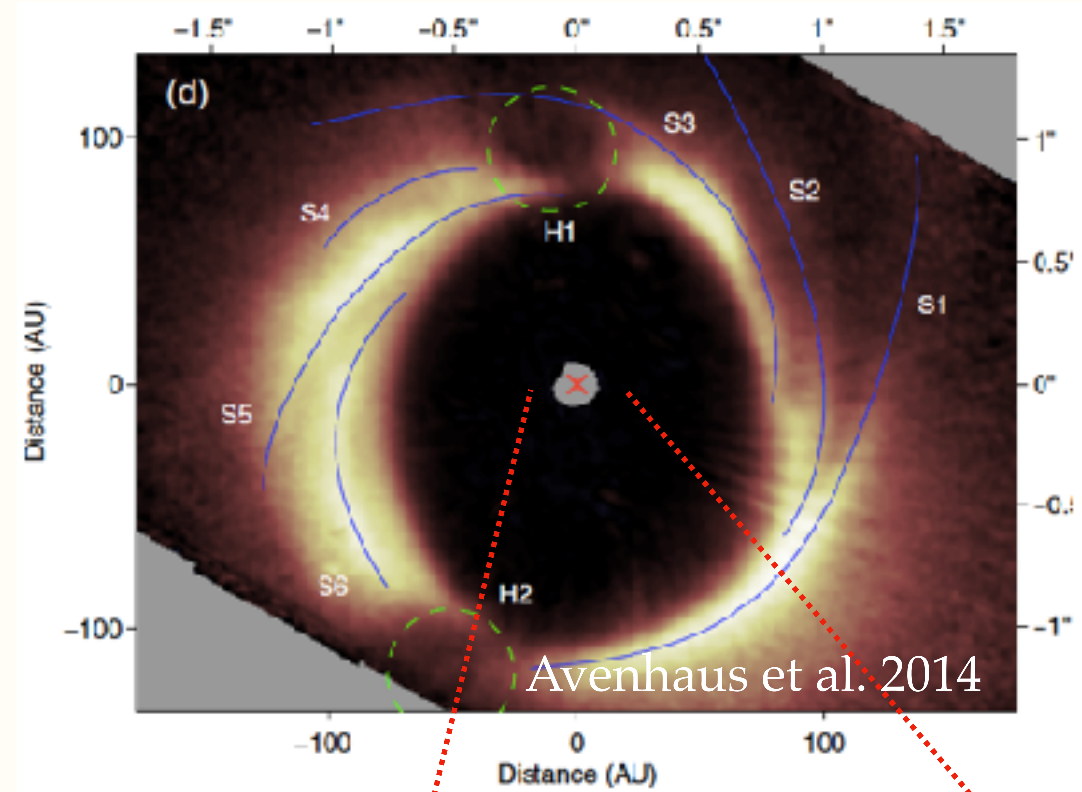


Avenhaus et al. 2014

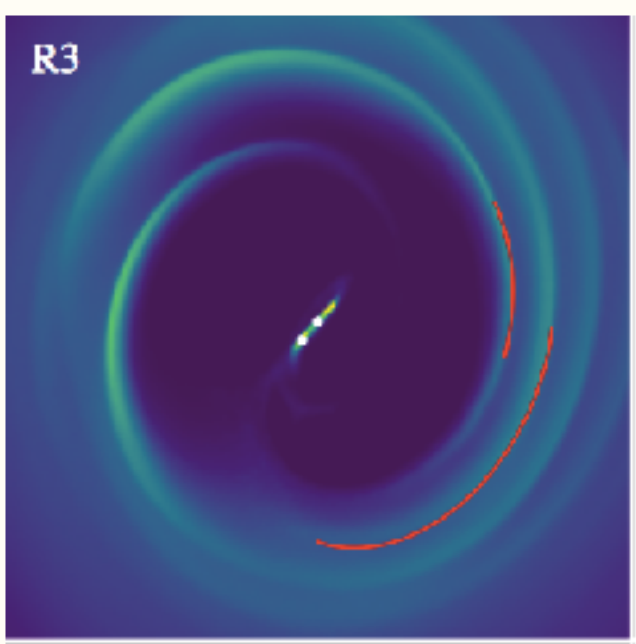
Inner/outer disk misalignment



Lacour et al. 2016

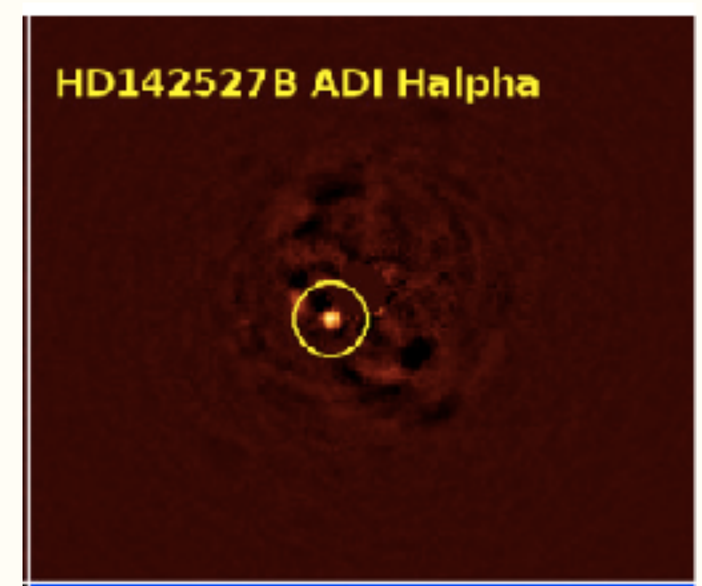


Avenhaus et al. 2014



Price at al. 2018

- 0.2 $M_\odot$ companion at ~ 12 au projected separation [Biller et al. 2012]
- ~40-50 au semi major axis, e~0.6-0.7, almost polar inclination [Price et al. 2018]

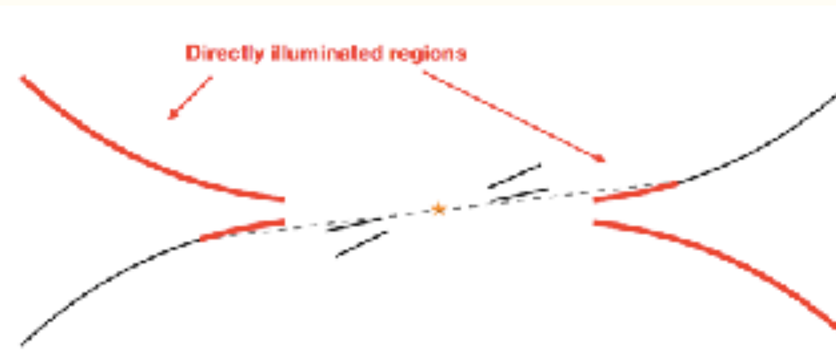


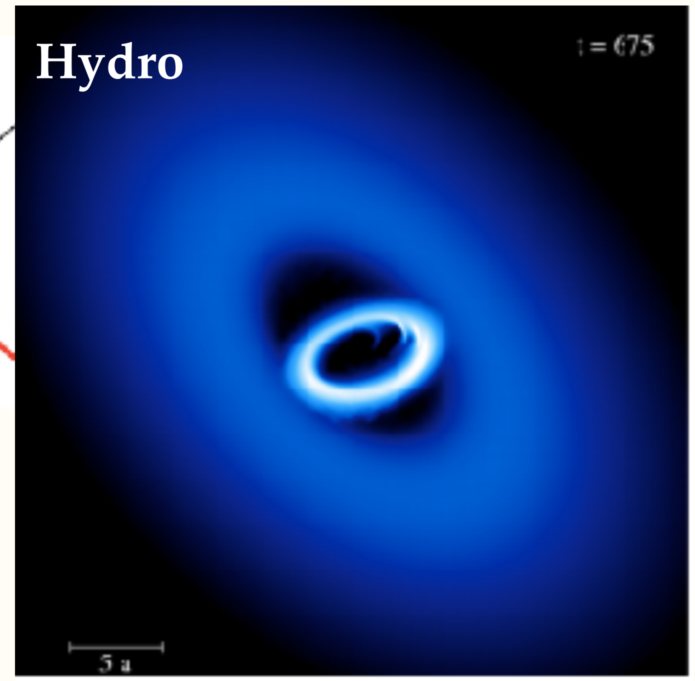
Close et al. 2014

Also Marino et al. 2015

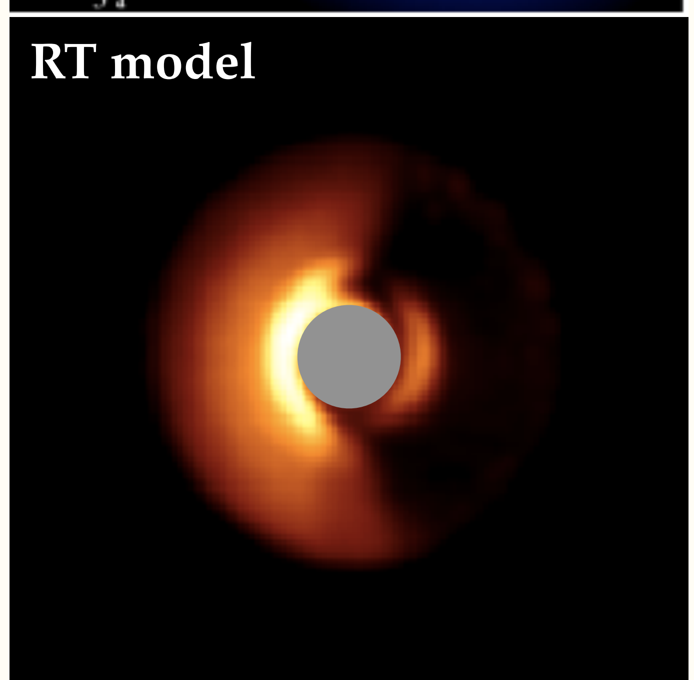
Inner/outer disk misalignment

Inclined binary torques the circumbinary disk



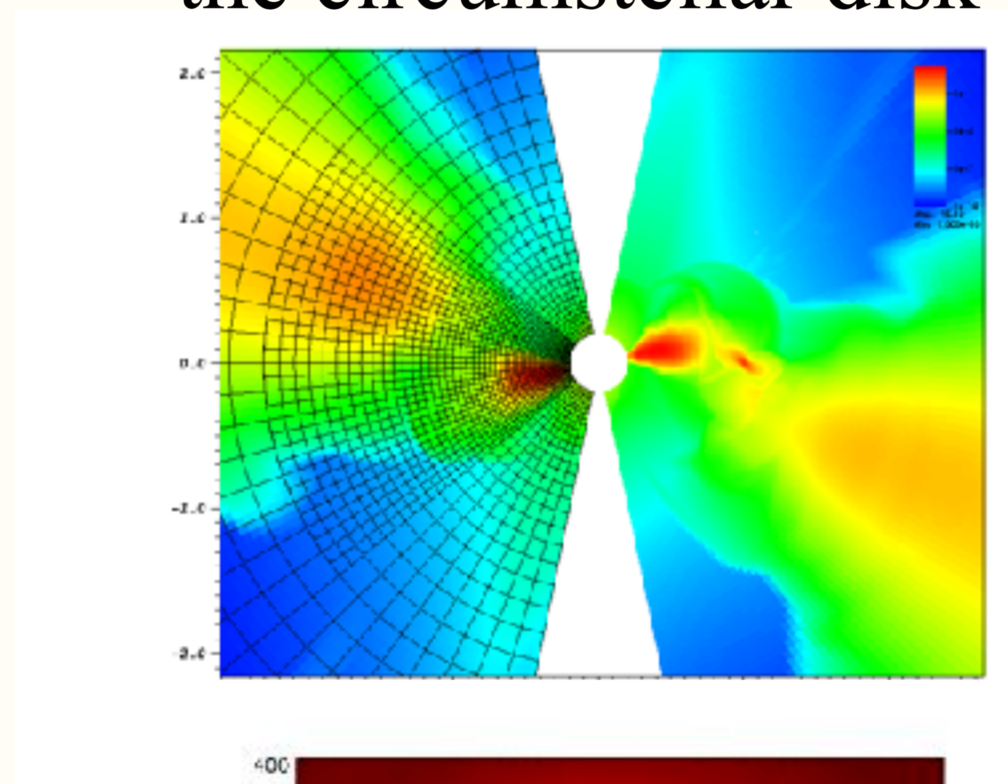


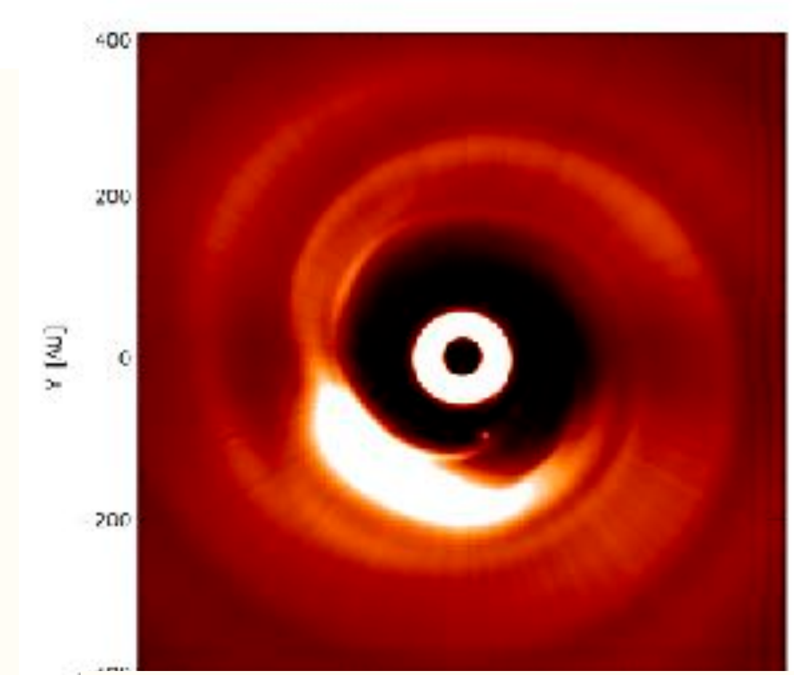
- An equal mass binary, inclined by 60°, breaks the disk.
- A misalignment of ~30 deg (from VLTI, ALMA)



Facchini et al. 2018
Juhasz & Facchini 2017

Inclined planet torques the circumstellar disk





Arzamasskiy, Zhu, Stone 2018
Zhu et al. In prep

Outline

- Disk Observations:

  Optical/Near-IR:

  Rings, Spirals, Disk shadowing

  Submm:

  Diverse features

  Synergy between Near-IR and Submm

- Planet-disk interaction theory:

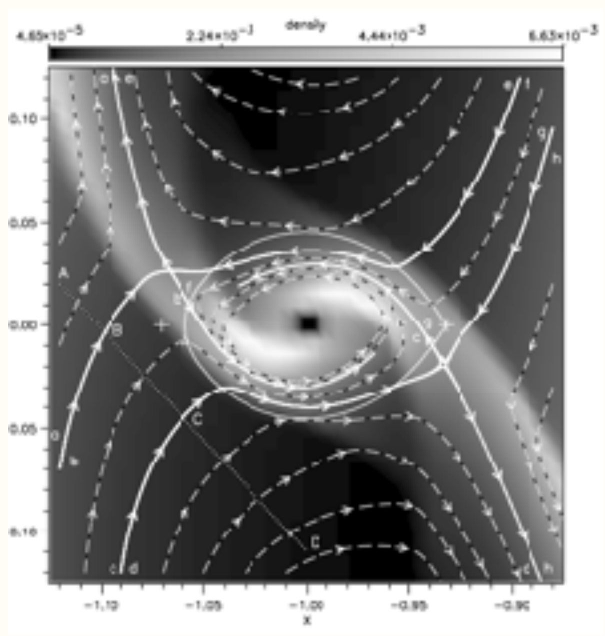
  Gaps/rings

  Spirals

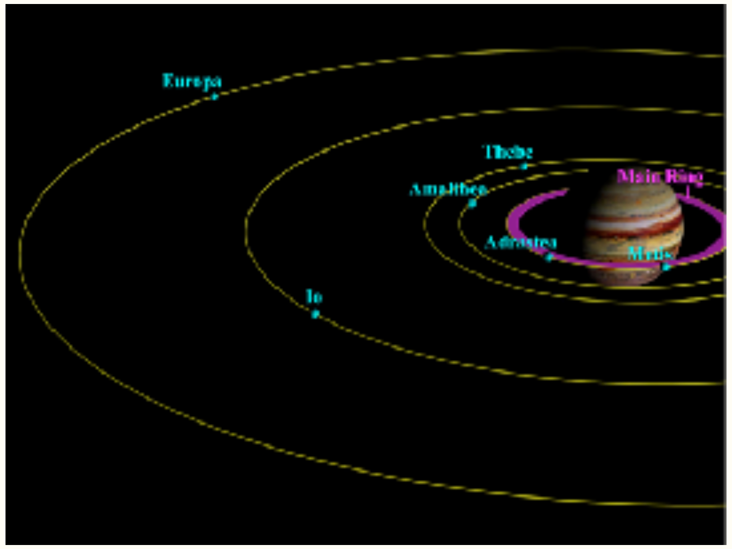
  Lopsided structures

  Shadows

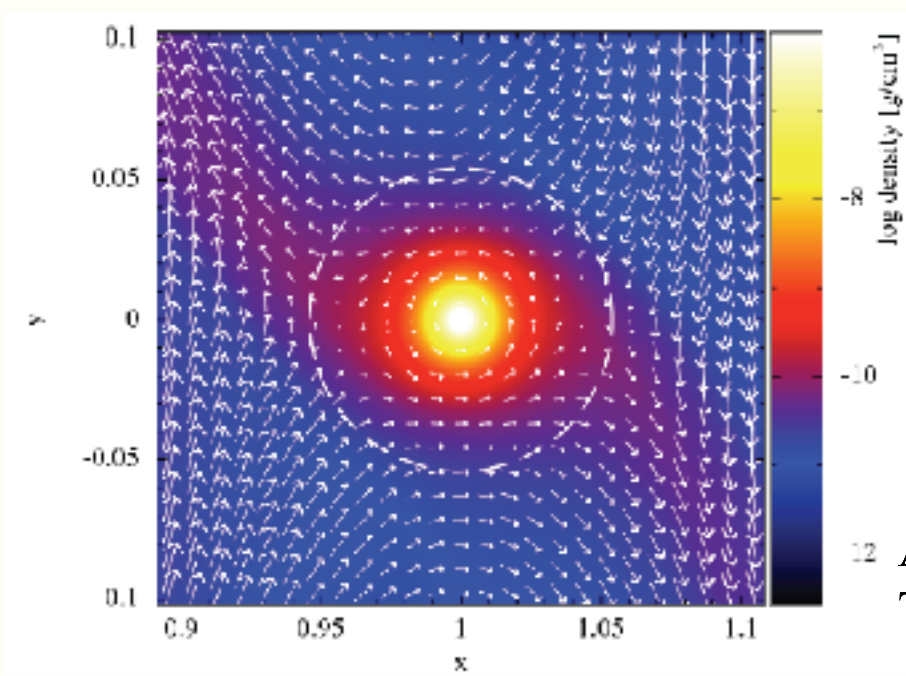
  CPDs



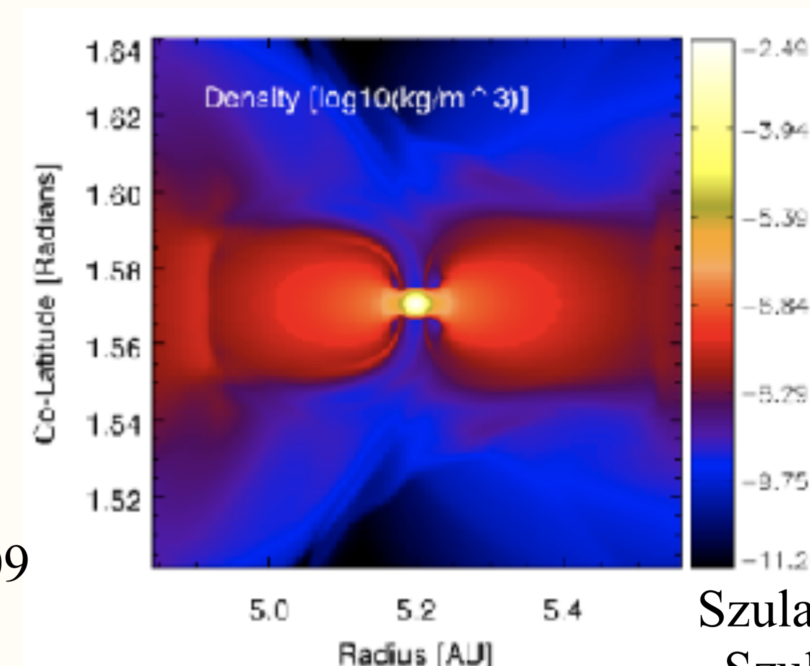
Circumplanetary Disks (CPD)



- Viscous model:



Ayliffe & Bate 2009
Tanigawa+ 2012



Szulagyi & Mordasini 2017,
Szulagyi et al. 2014, 2016

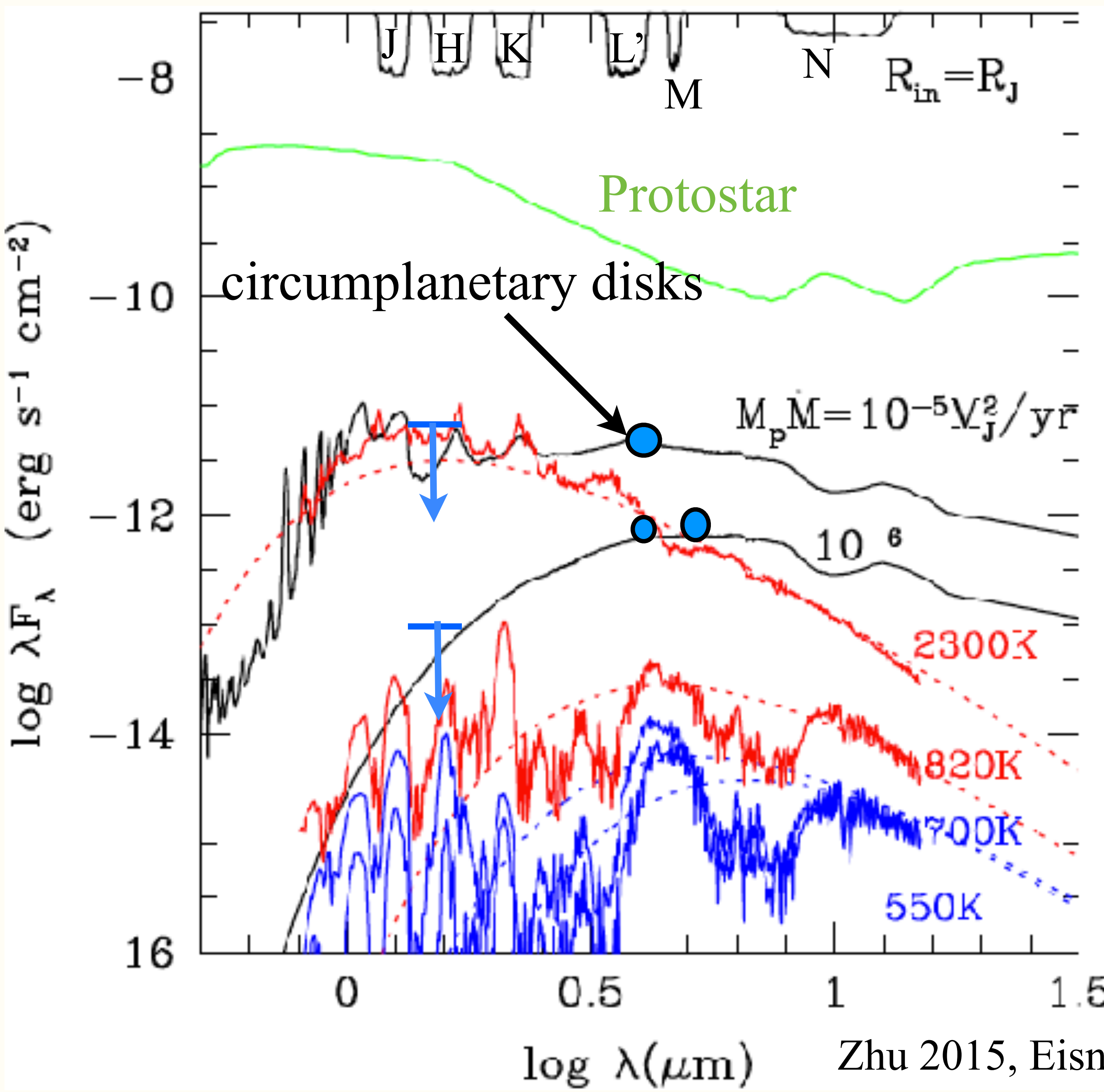
- Wind, non-ideal MHD: Turner et al. 2014, Fujii et al. 2014, Keith & Wardle 2015, Gressel et al. 2015
- Shock driven accretion: Zhu et al. 2016

CPD should be bright

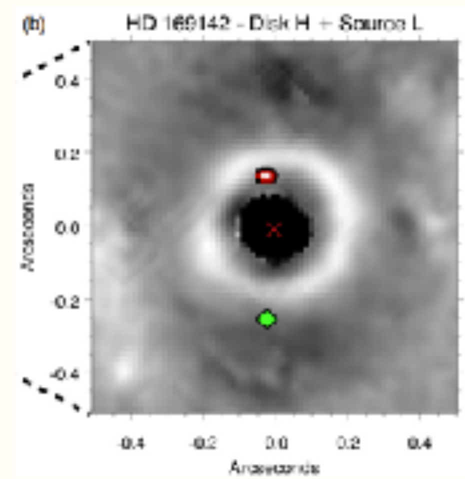
If Jupiter is accreting at $\dot{M}=10^{-5}\ M_{Jupiter}/yr$

$L_{accretion}=0.5\ GM_{Jupiter}\dot{M}/R_{Jupiter}=1.5\times10^{-3}\ L_{sun}$

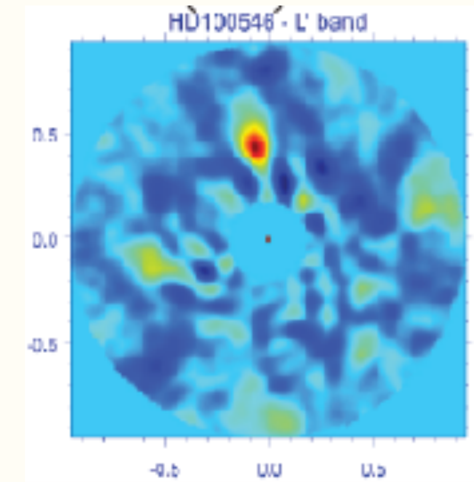
As bright as M type brown dwarfs!



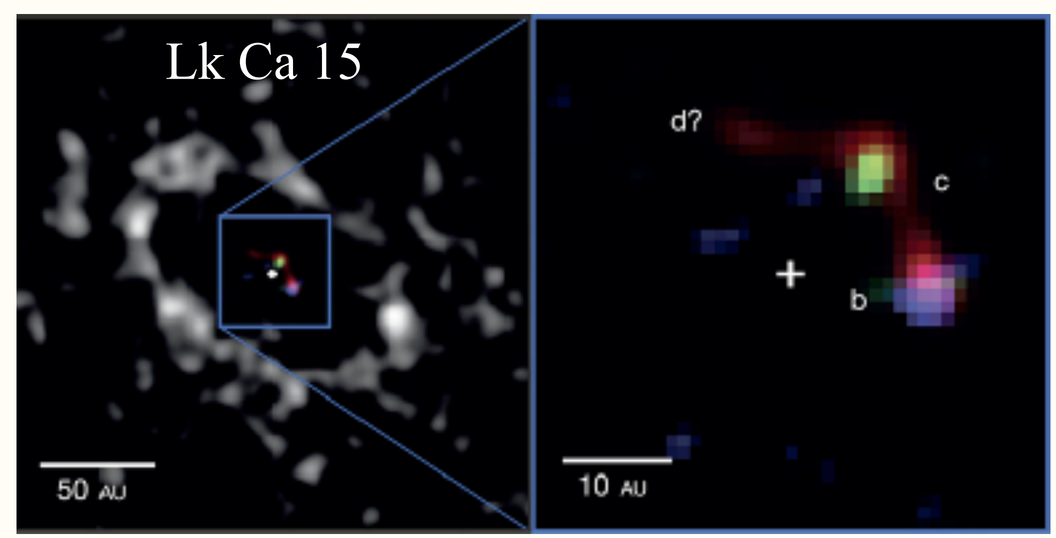
Zhu 2015, Eisner 2015



Reggiani et al. 2014
Biller et al. 2014



Currie et al. 2014
Quanz et al. 2014
Follette et al. 2017

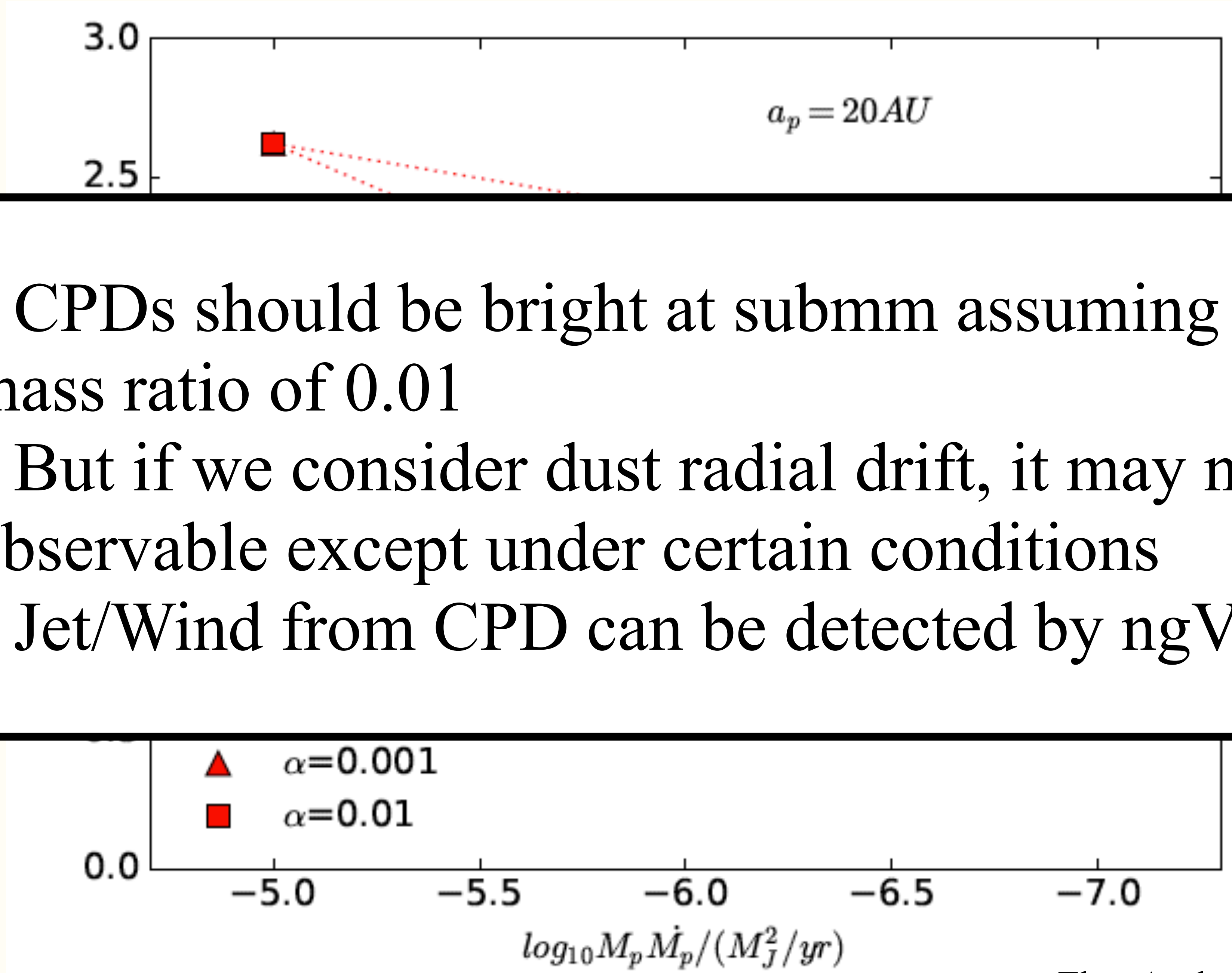


Sallum+ 2015

CPD should be bright at submm

Isella et al. 2014, Zhu, Andrews & Isella, 2018, Szulagyi et al 2018

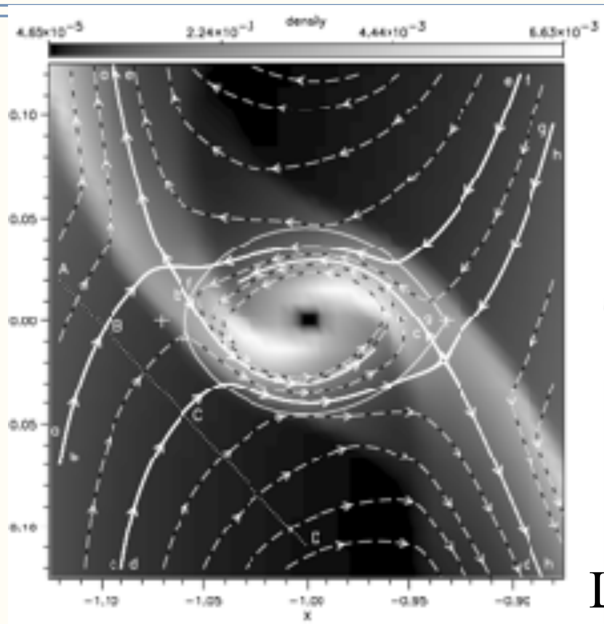
submm flux from CPDs at 20 AU, assume dust-to-gas ratio 0.01



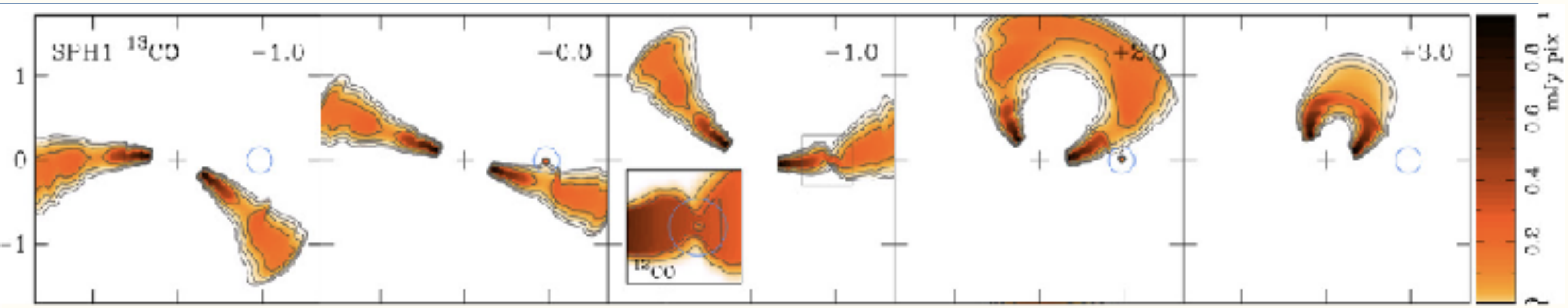
- CPDs should be bright at submm assuming dust-to-gas mass ratio of 0.01
- But if we consider dust radial drift, it may not be observable except under certain conditions
- Jet/Wind from CPD can be detected by ngVLA

Zhu, Andrews & Isella, 2018

CPD kinematics

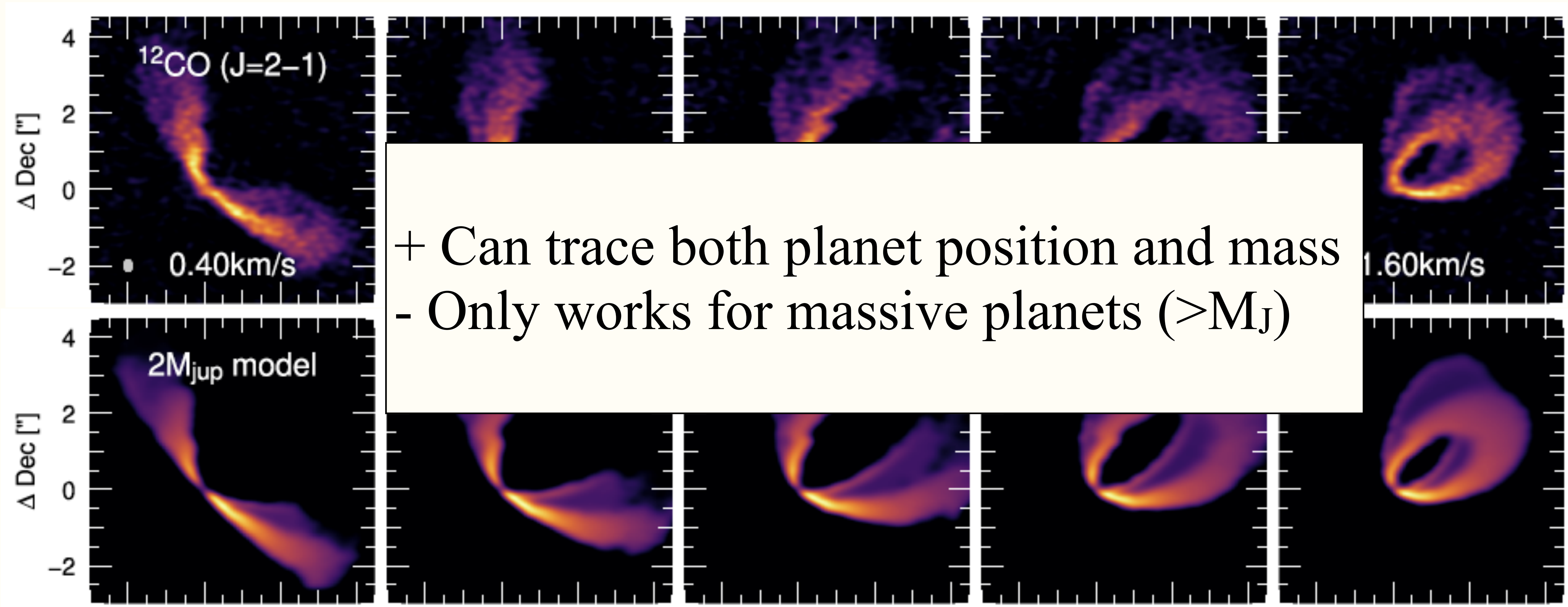


Lubow et al. 1999



Perez et al. 2015

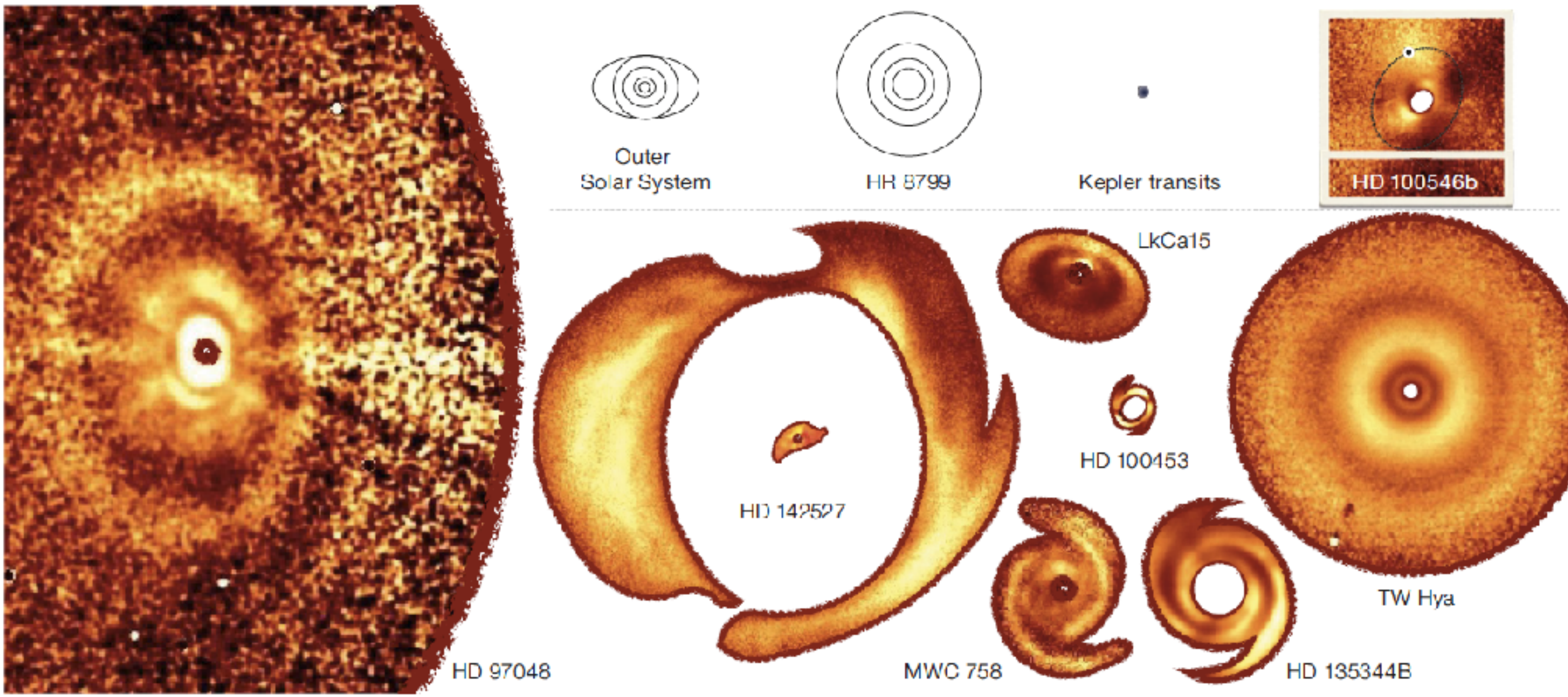
A 2 M_J planet at 260 AU



+ Can trace both planet position and mass
- Only works for massive planets (>M_J)

Pinte et al. 2018

Overview: observations



Garufi et al. 2018

Overview: planet-disk interaction

h/r=0.05 h/r=0.1

Zhang in prep.

α=10^{-4} α=10^{-3} α=10^{-2}

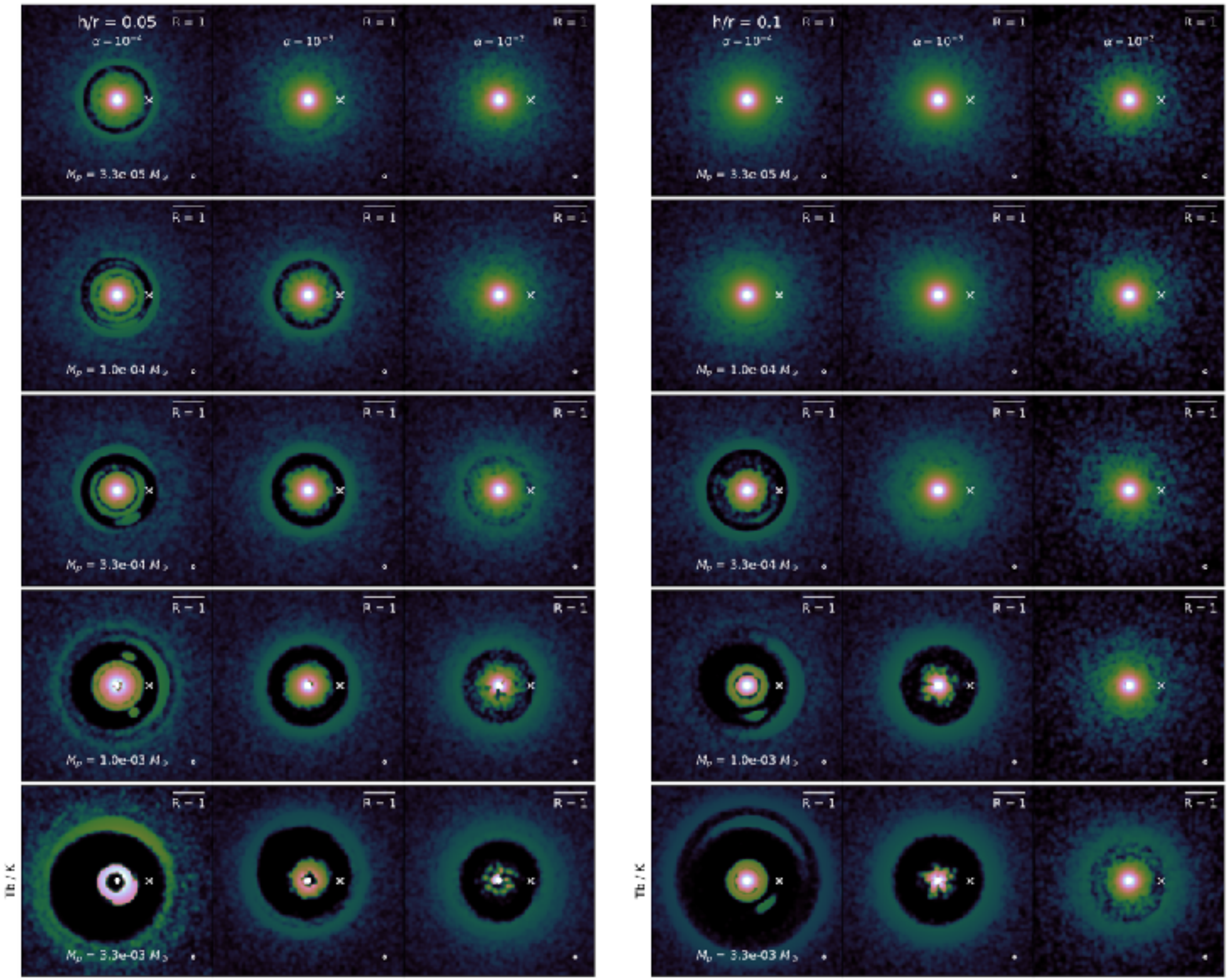
M_p=10 M⊕

M_p=30 M⊕

M_p=100 M⊕

M_p=1 M_J

M_p=3 M_J



Overview: indirect methods

Gaps/rings:

Depth/width at near-IR or submm

Deviation from Keplerian motion at the gap edge

Spirals:

Using spiral features (arm separation, contrast, opening angle)

Using pattern speed

Lopsided structures:

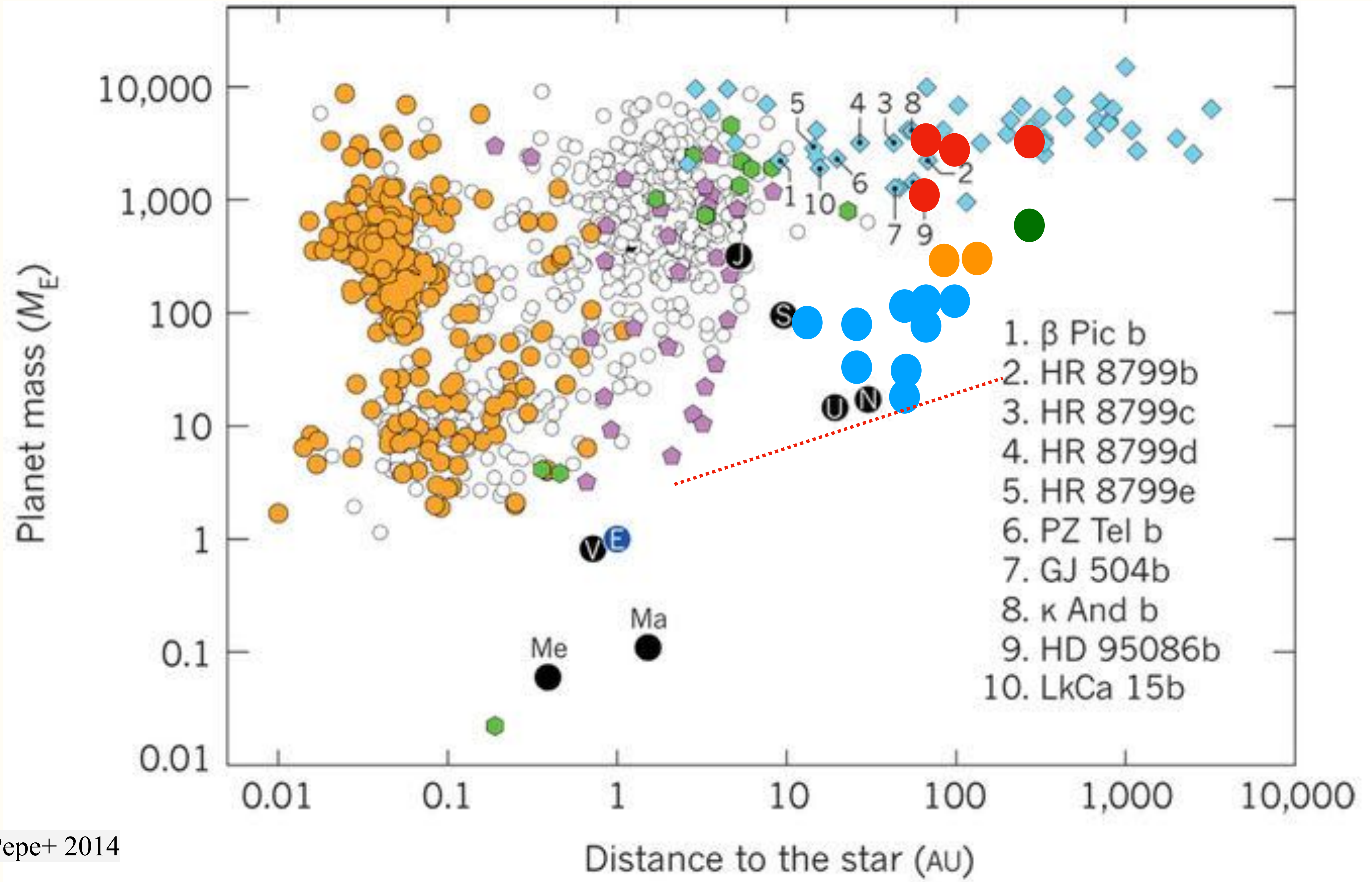
Vortex is the only known mechanism but may not be associated with planets

Shadows: misalignment

CPDs:

near-IR, Hα, submm

Kinematics

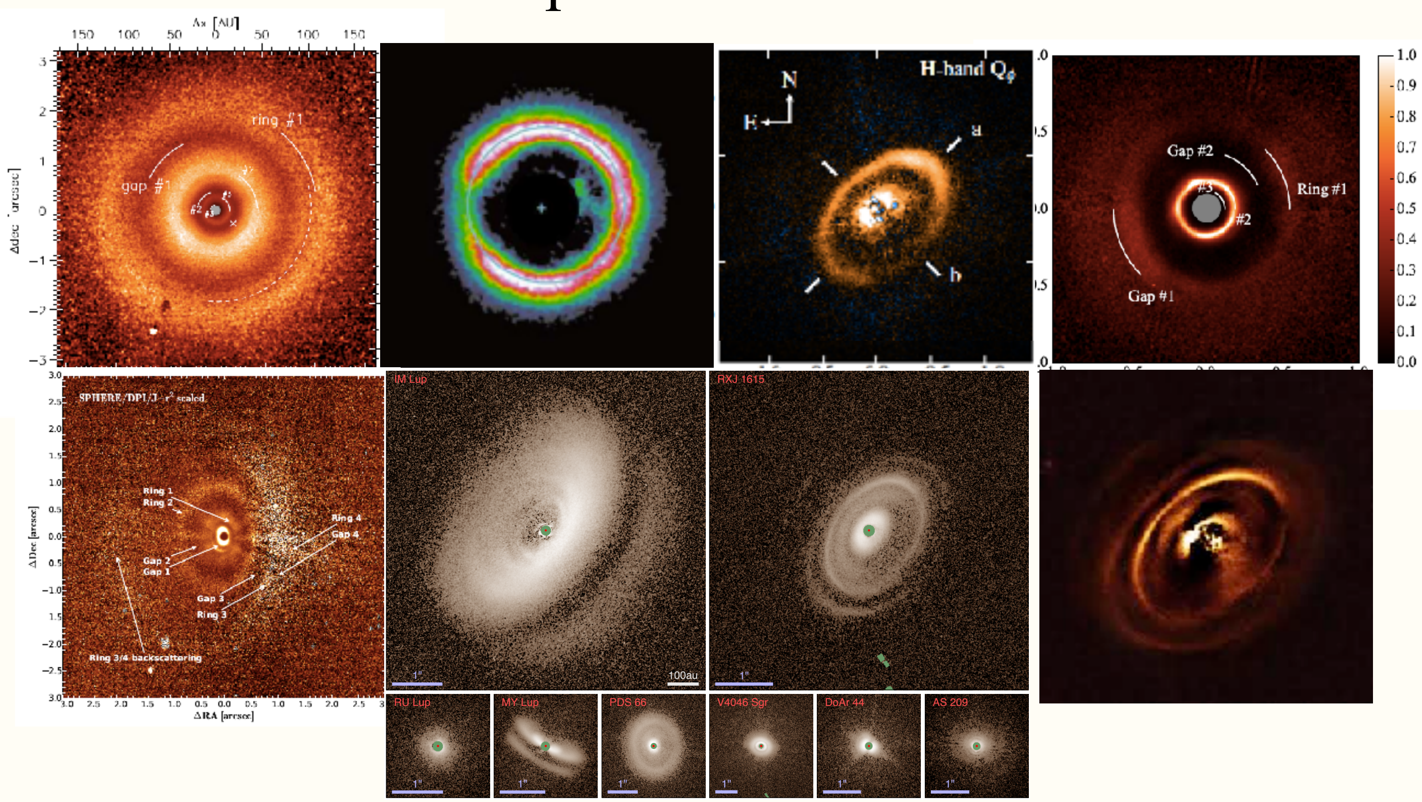


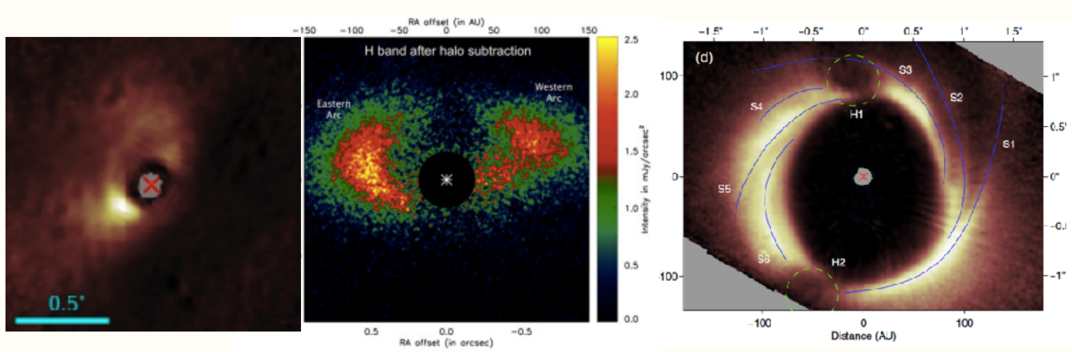
Pepe+ 2014

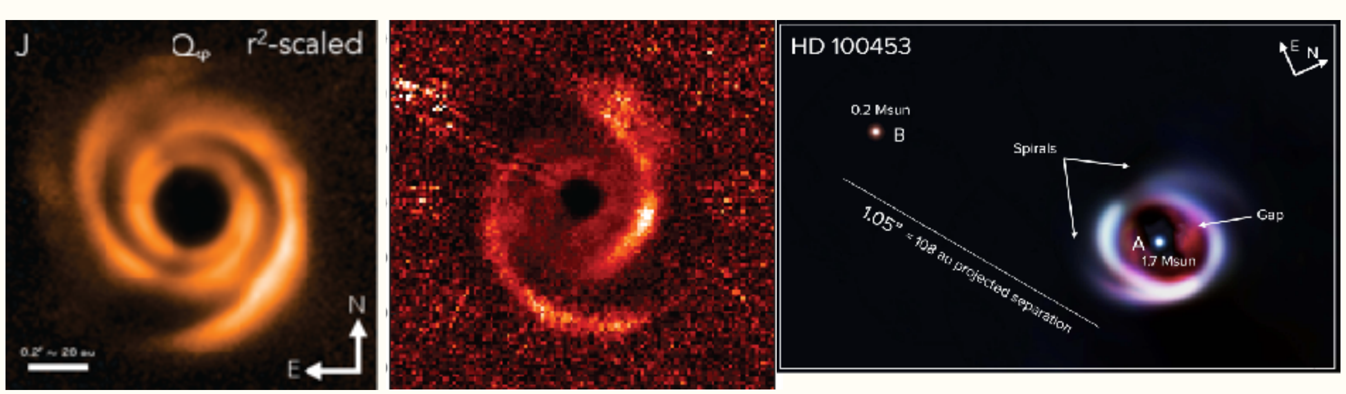
Dong+ 2015, Bae+ 2016, Isella+ 2016 Meru+ 2017, Dipierro+ 2018, Fedele+ 2018, Teague+ 2018, Pinte+ 2018

A lot more to come (ALMA large program PI: Sean Andrews)

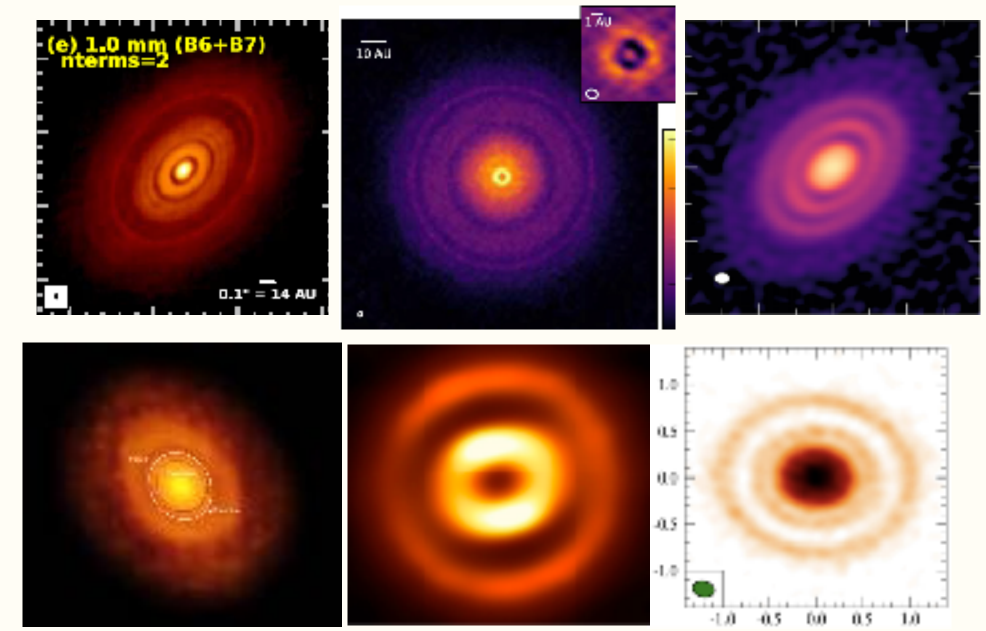
Optical/Near-IR



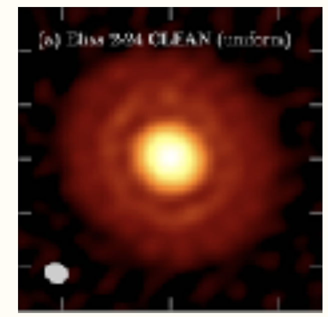




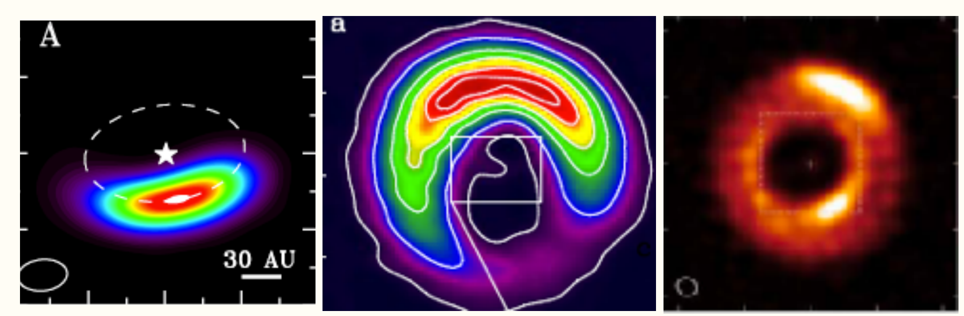
Radio



Fedele et al. 2017, 2018



Cieza et al. 2017



Boehler et al. 2017

Outline

- The traditional interests in planet-disk interaction

  Migration

  Gap opening

- New interests in planet-disk interaction

  1. The imprints on the circumstellar disks

     Spiral Wakes

     Gaps/rings

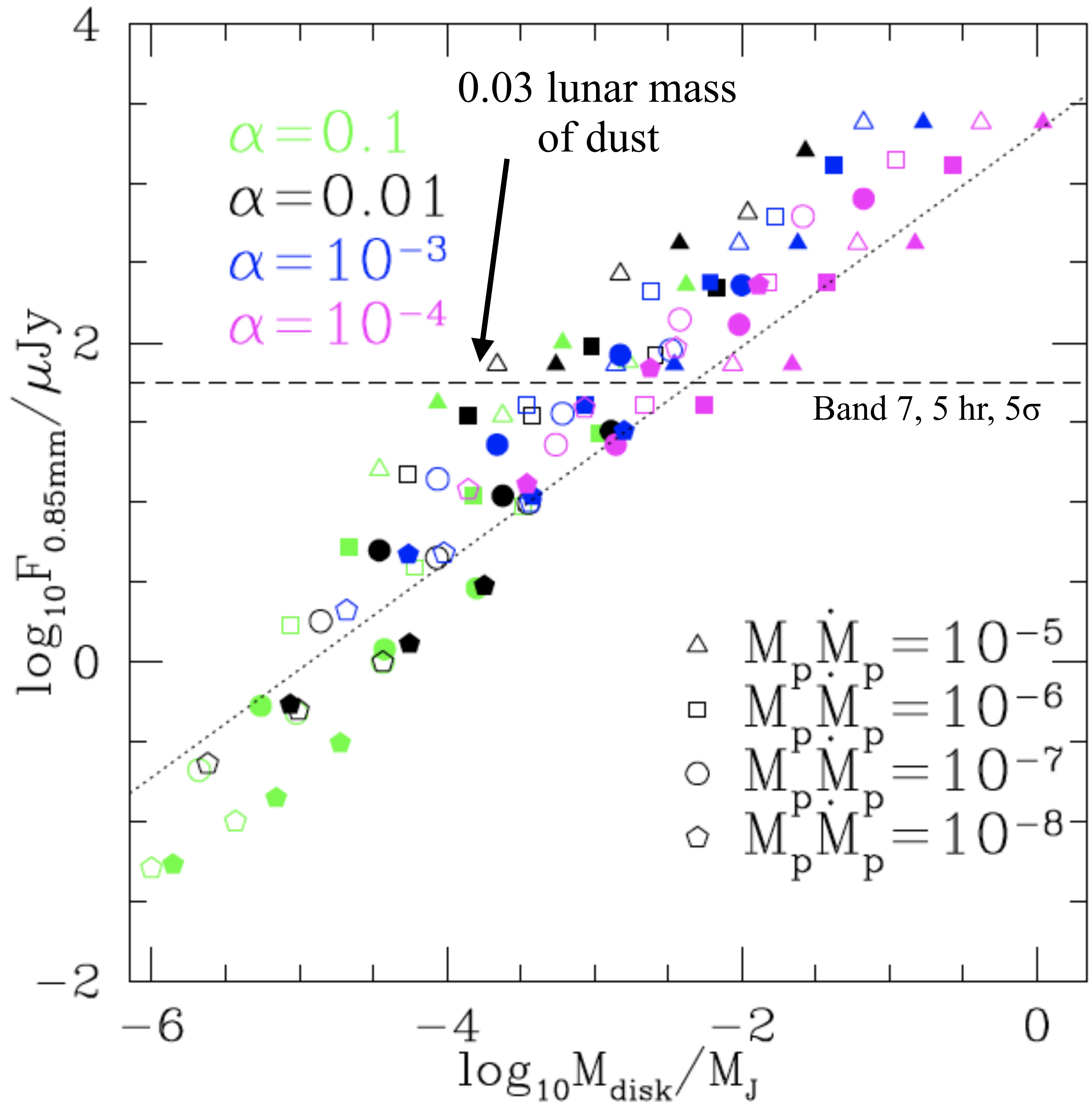
     Vortices

  2. Circumplanetary disks

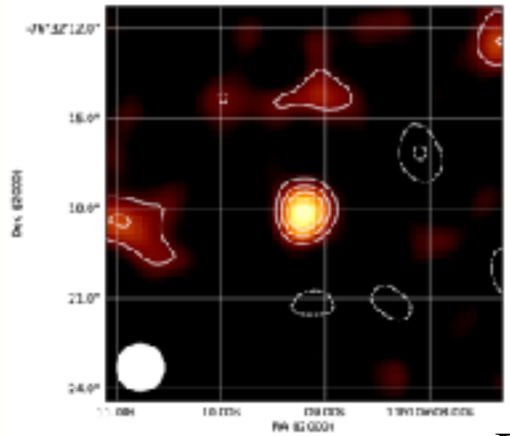
Summary

- Migration and gap opening depend on the disk property
- Planet-disk interaction can explain a lot of disk features (spirals, vortices, gaps/rings)
- Spirals to estimate planet mass/position
- Dust dynamics is the key for gaps/rings. Dust-to-gas feedback starts to be considered
- Vortices imply disk viscosity, mass, particle size
- CPD should be bright at near-IR to submm. We don't see many. Maybe radial drift, too compact ?
  - **Where are the planets in protoplanetary disks ?**

Detection of dust emission in CPD by ALMA



OTS 44, 12 M_J

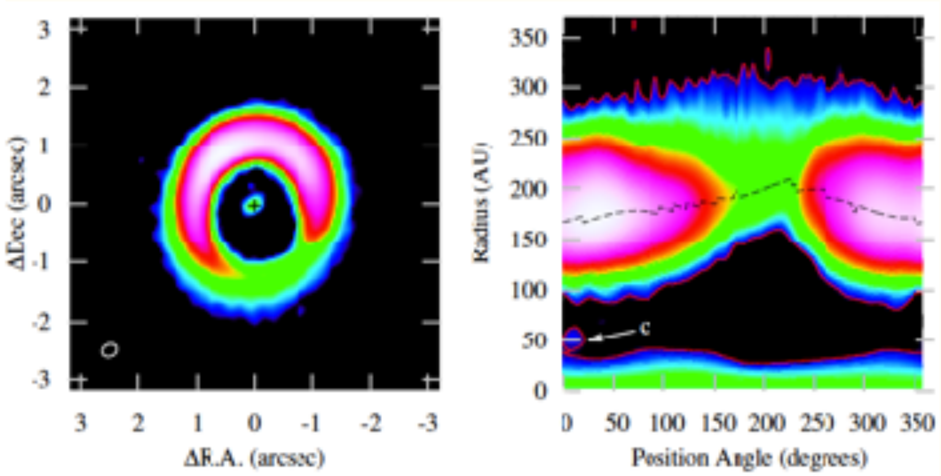


Bayo+ 2017

$M\dot{M}\sim10^{-7}\ M_J^2/yr$

F=100 μJy

HD 142527

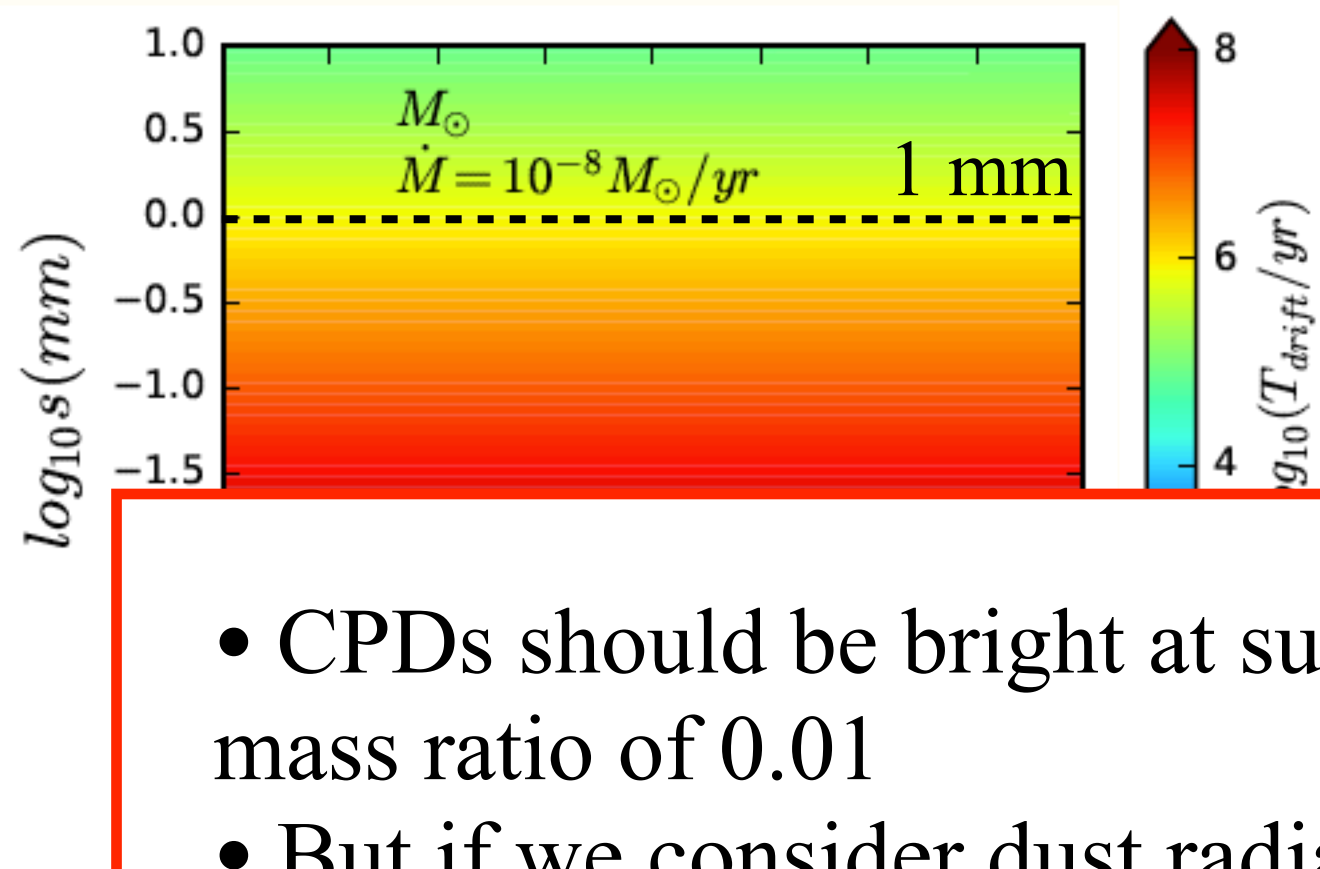


Boehler+ 2017

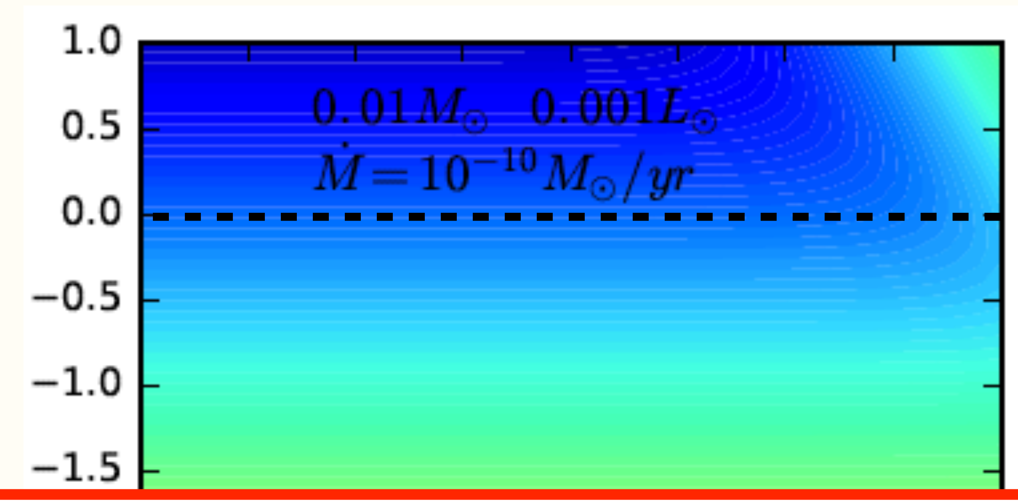
50 AU, 0.8 mJy

Dust drifts very fast in CPDs

Dust drift timescale in circumstellar disks



Dust drift timescale in CPDs



- CPDs should be bright at submm assuming dust-to-gas mass ratio of 0.01
- But if we consider dust radial drift, it may not be observable except under certain conditions
- Jet/Wind from CPD can be detected by ngVLA

In order to be detected at mm:

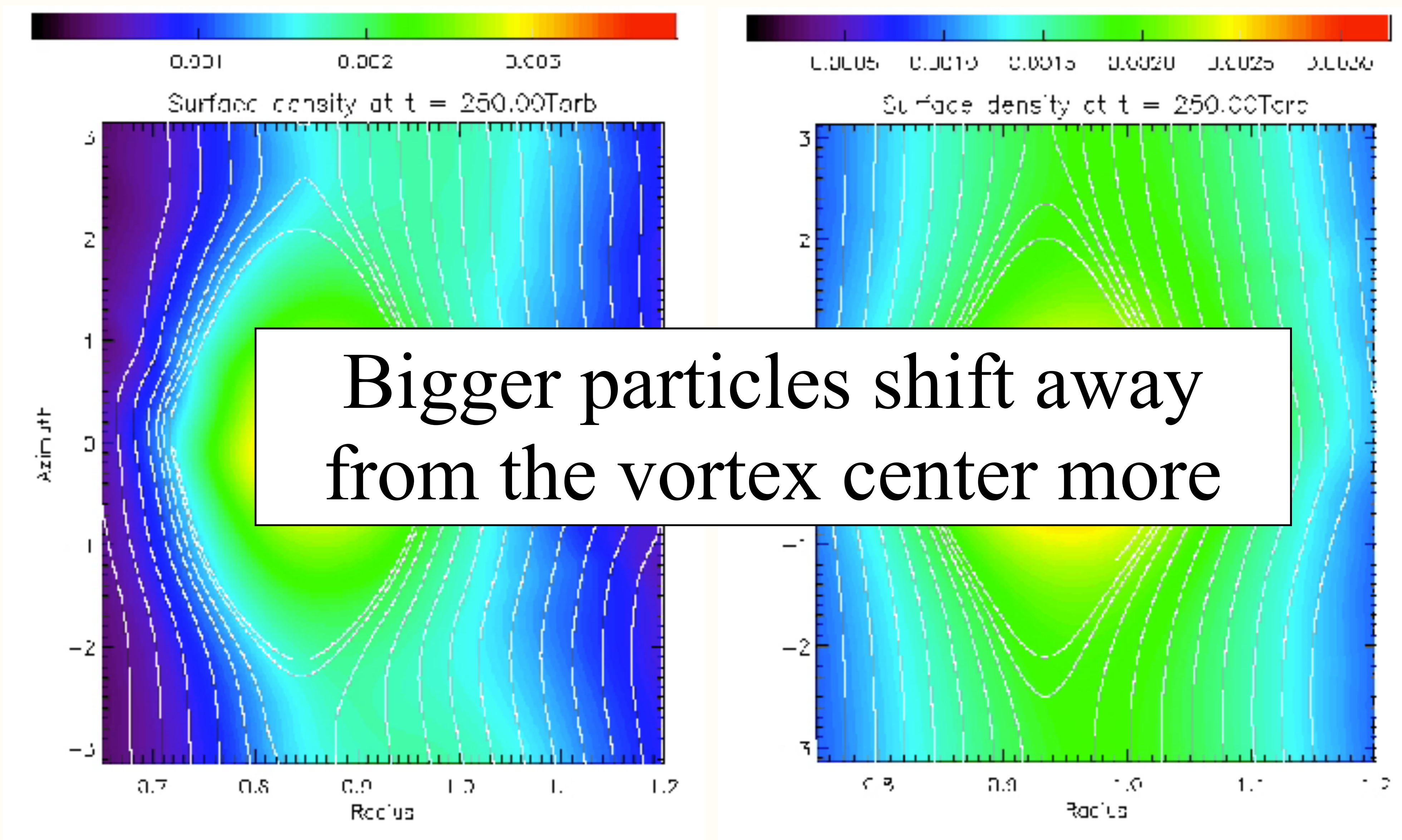
1) dust are micron sized
2) high gas surface density
3) substructures in CPD (HL Tau in HL Tau)

Vortex: gravity from gas to dust

No gravity from gas to dust

With gravity from gas to dust

Q=13

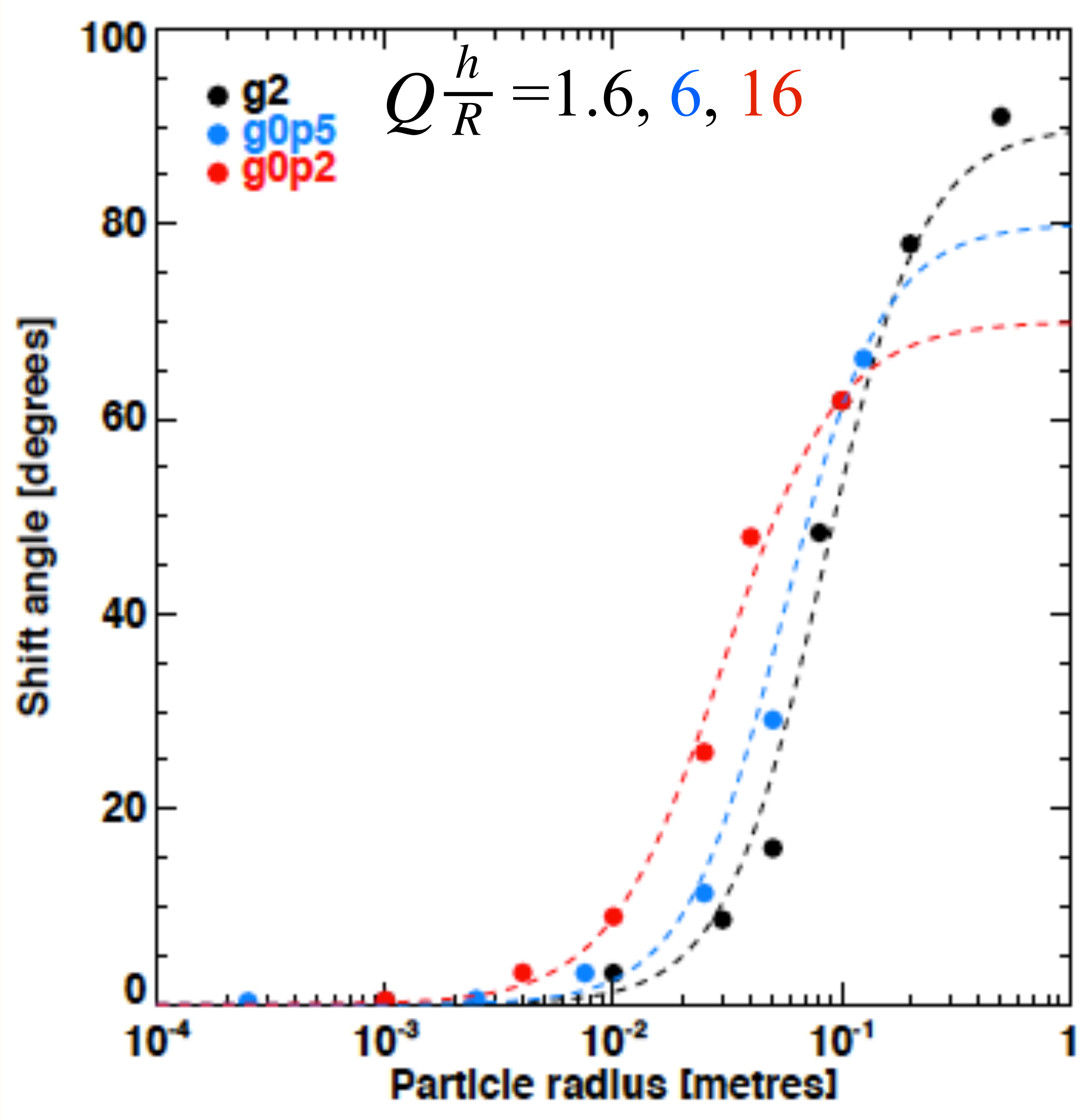


Bigger particles shift away from the vortex center more

Baruteau & Zhu 2015

Applications

Planetesimal Formation

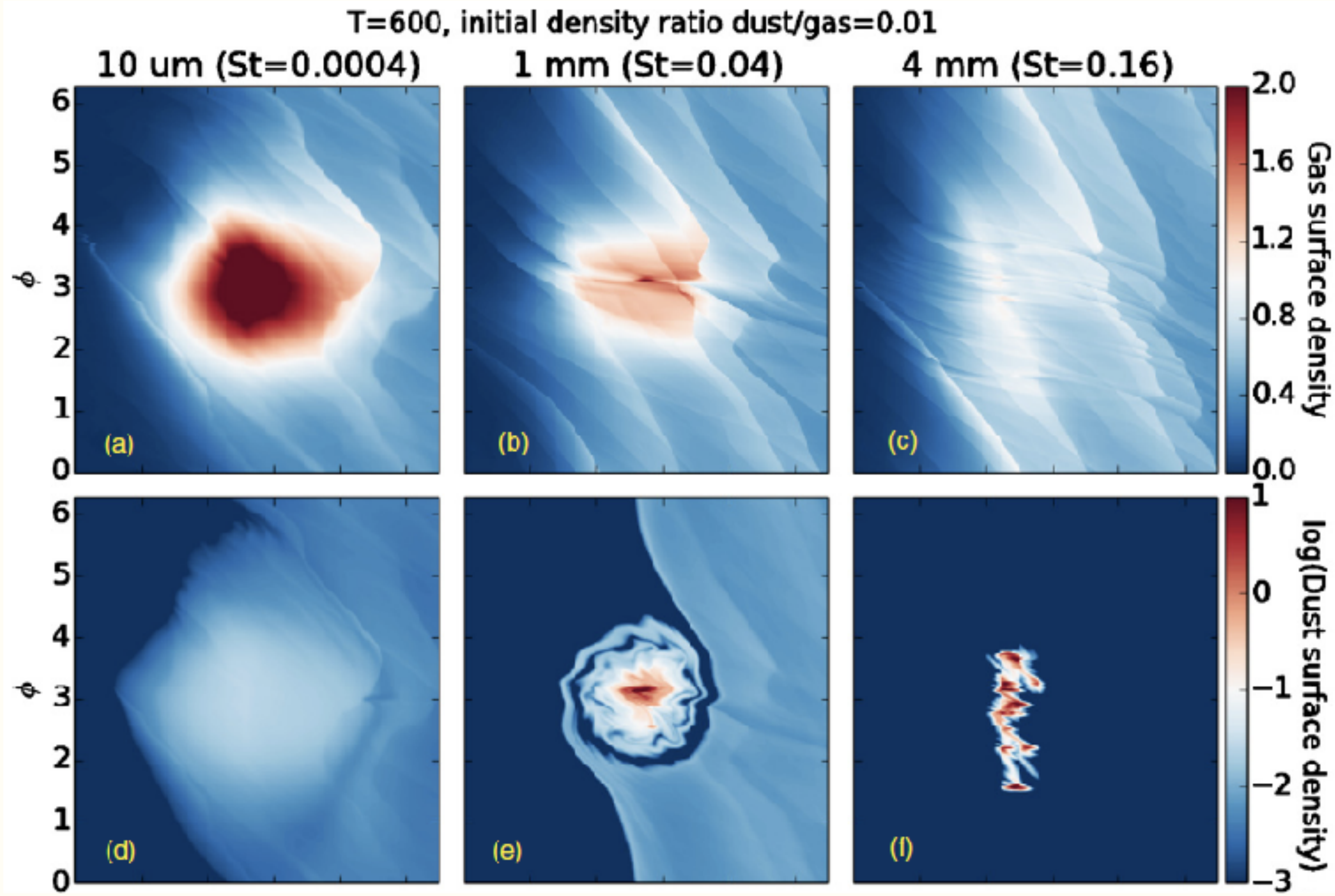


Baruteau & Zhu (2015)

Vortex: including dust-to-gas feedback

Gas

Dust

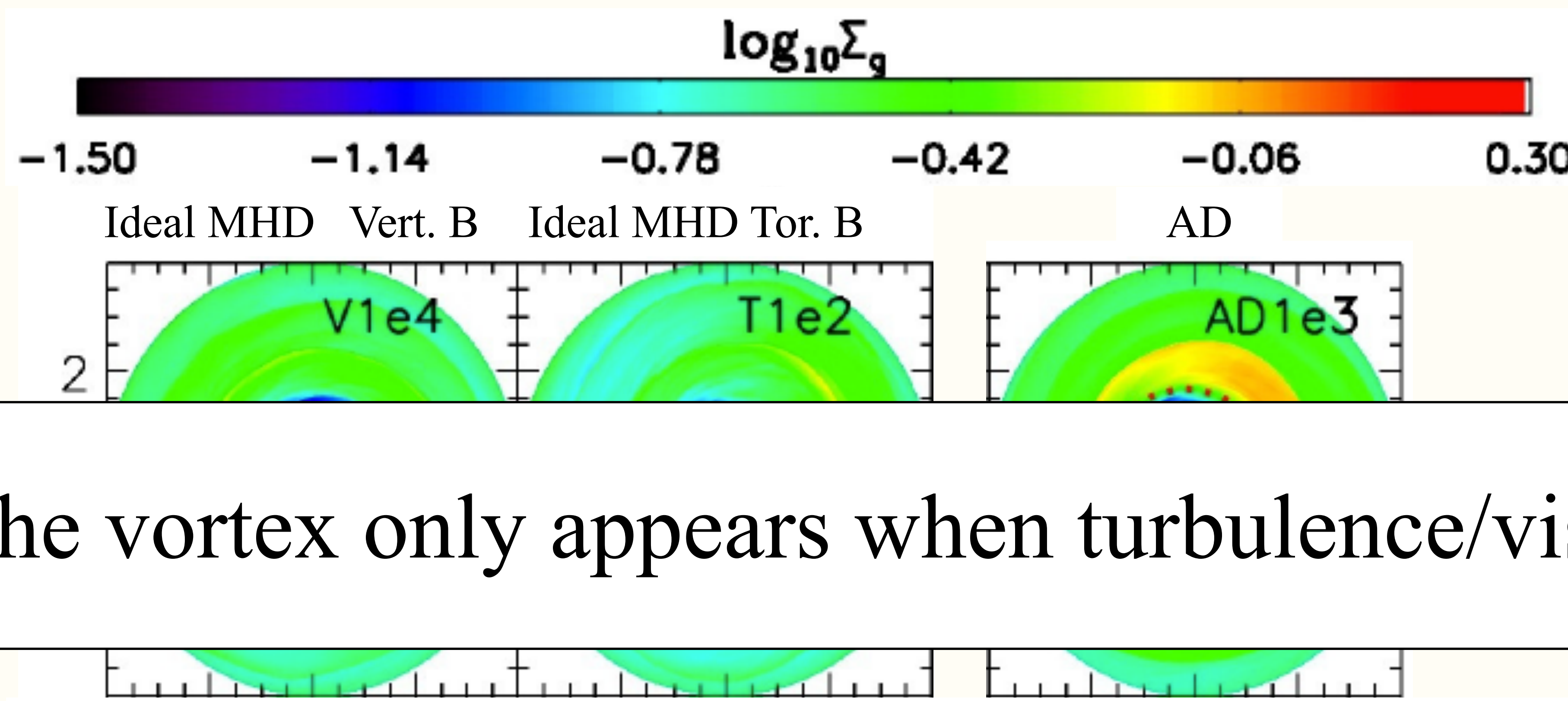


Fu et al. 2014
Crnkovic-Rubsamen et al. 2014

- Locally, dust can have higher density than gas
- signs of instability (Lesur & Papaloizou 2009, Chang & Oishi 2010, Railton & Papaloizou 2014)

Ring or vortex ?

- If a gap edge is optically thick, a vortex will not show up
- For a shallow gaseous gap edge, it is more likely to be a ring !
- If you have turbulence/viscosity, it forms a ring !



The vortex only appears when turbulence/viscosity is weak!

Turbulence is strong
α~0.01

Turbulence is weak
α~0.001

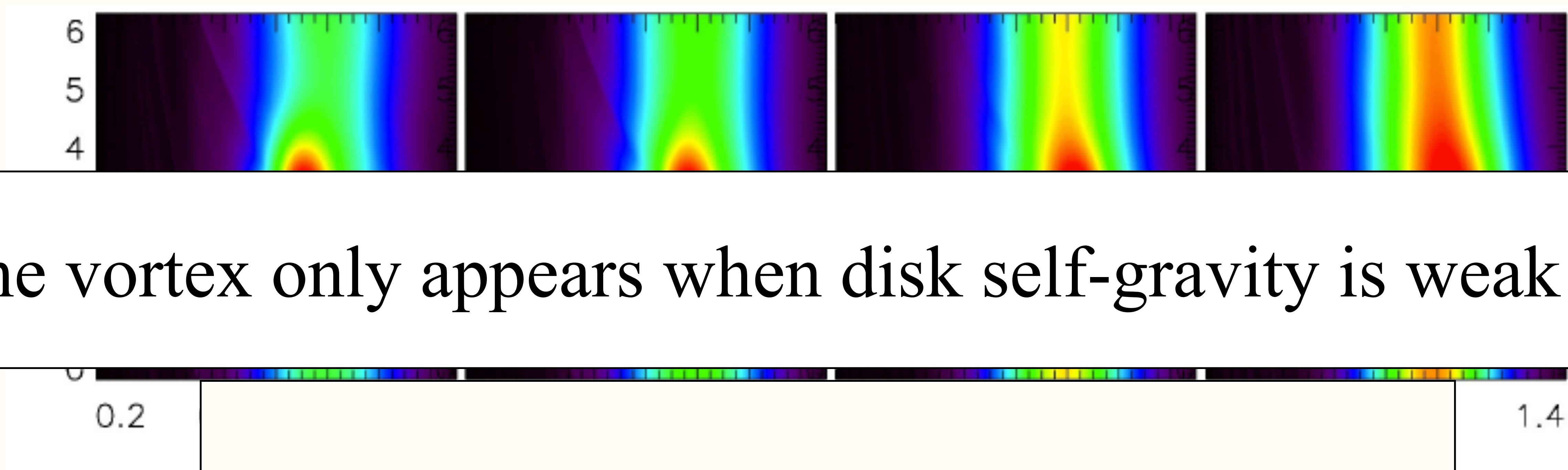
Zhu & Stone 2014
Fu et al. 2014
Hammer et al. 2017

Ring or vortex ?

- Gas self-gravity suppresses instability (Lin et al. 2011, Lovelace & Hohlfeld 2013)

$Q\frac{h}{R} < 1$

$Q\frac{h}{R}$ 15 1.5 0.6 0.3



The vortex only appears when disk self-gravity is weak!

iang 2015)

van de

- Too many disk parameters, planet history
(Hammer, Kratter, Lin 2018)

+ Vortex is the only know way to produce large scale disk asymmetry at submm.

Q~4000

Q~1