Disks with gaps

NBI Summer School Protoplanetary disks
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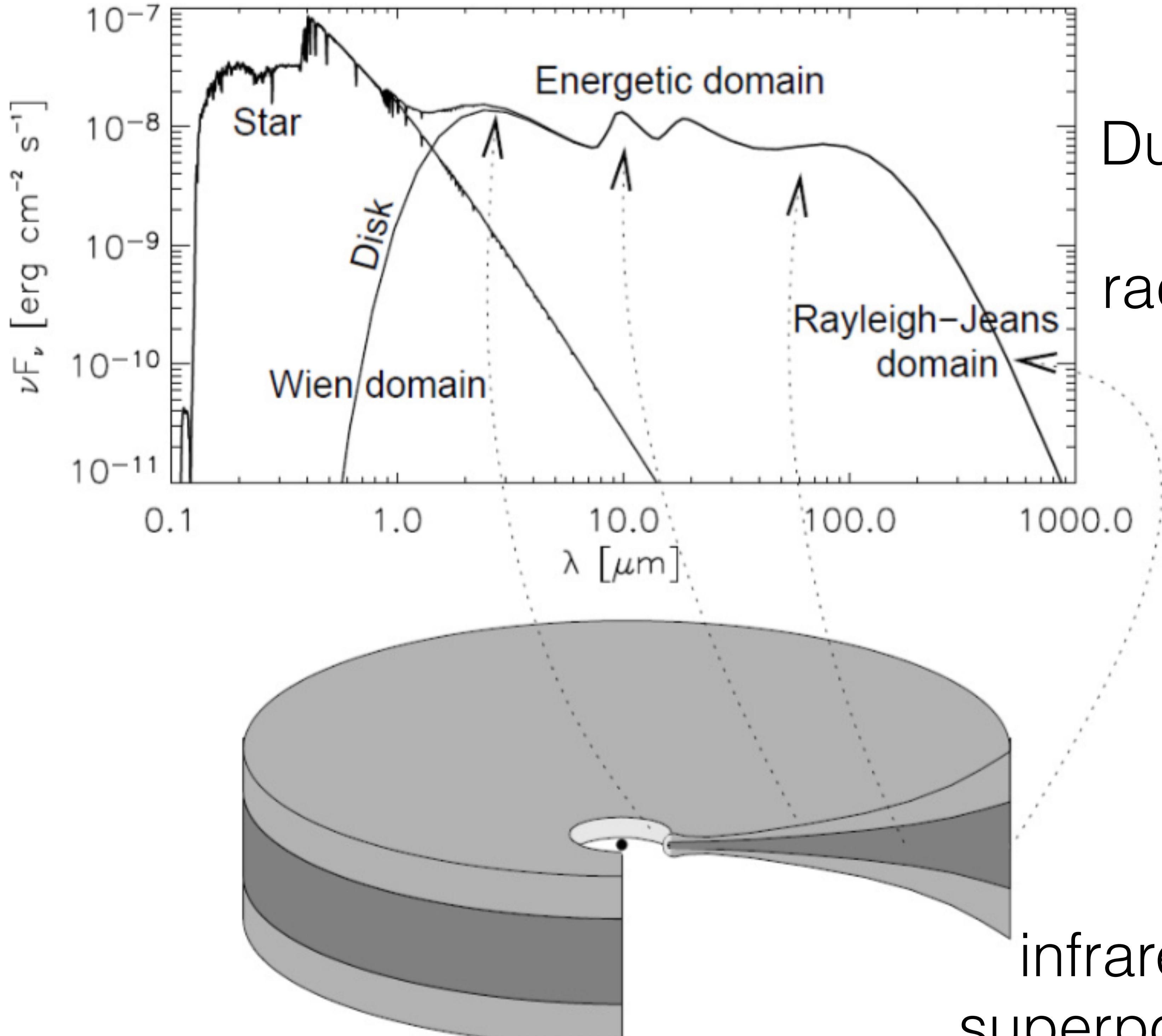
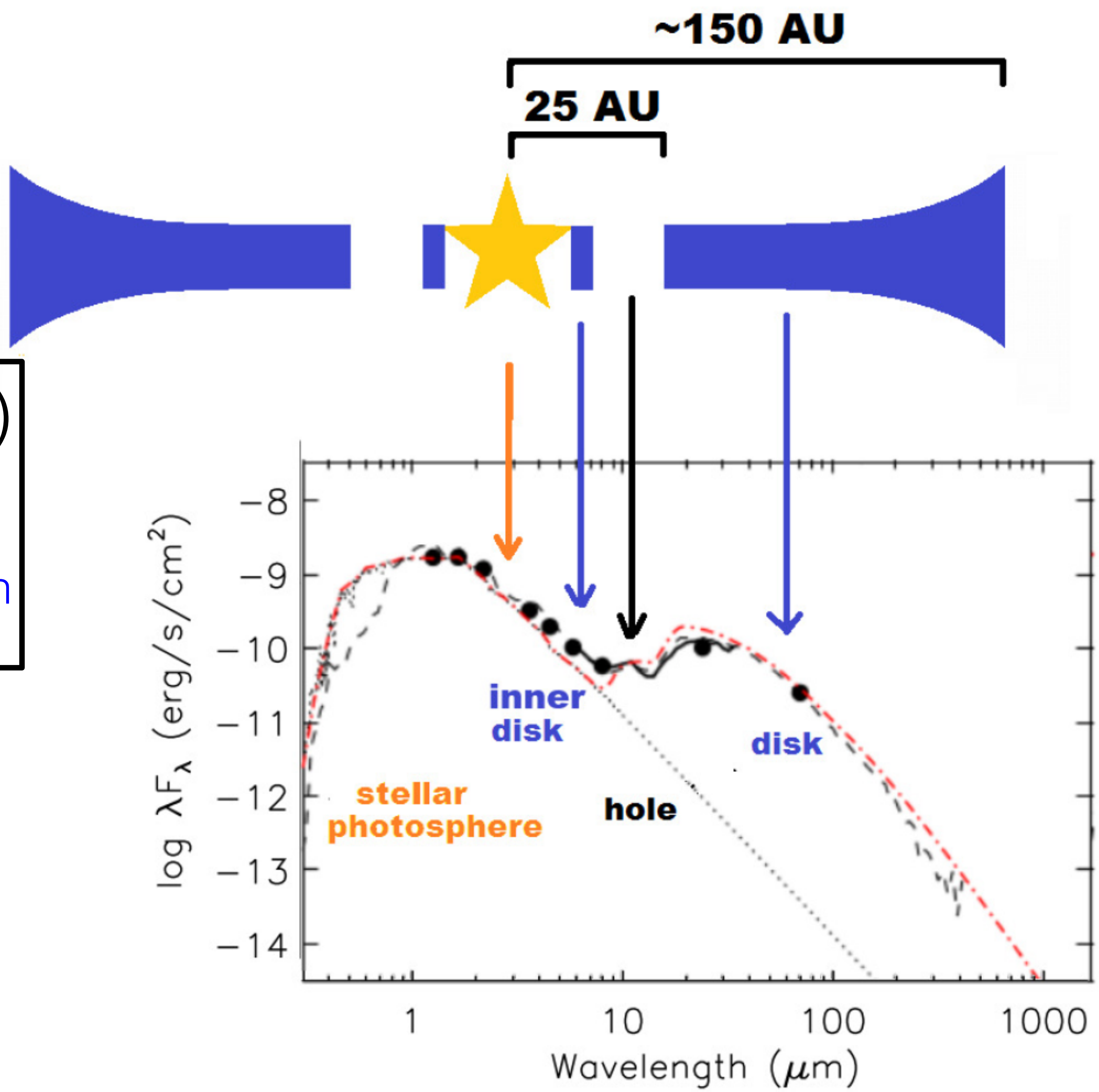
The SED



Dust in disk gets heated up by the star:
radial temperature gradient

infrared to mm emission:
superposition of blackbodies

Transition disks

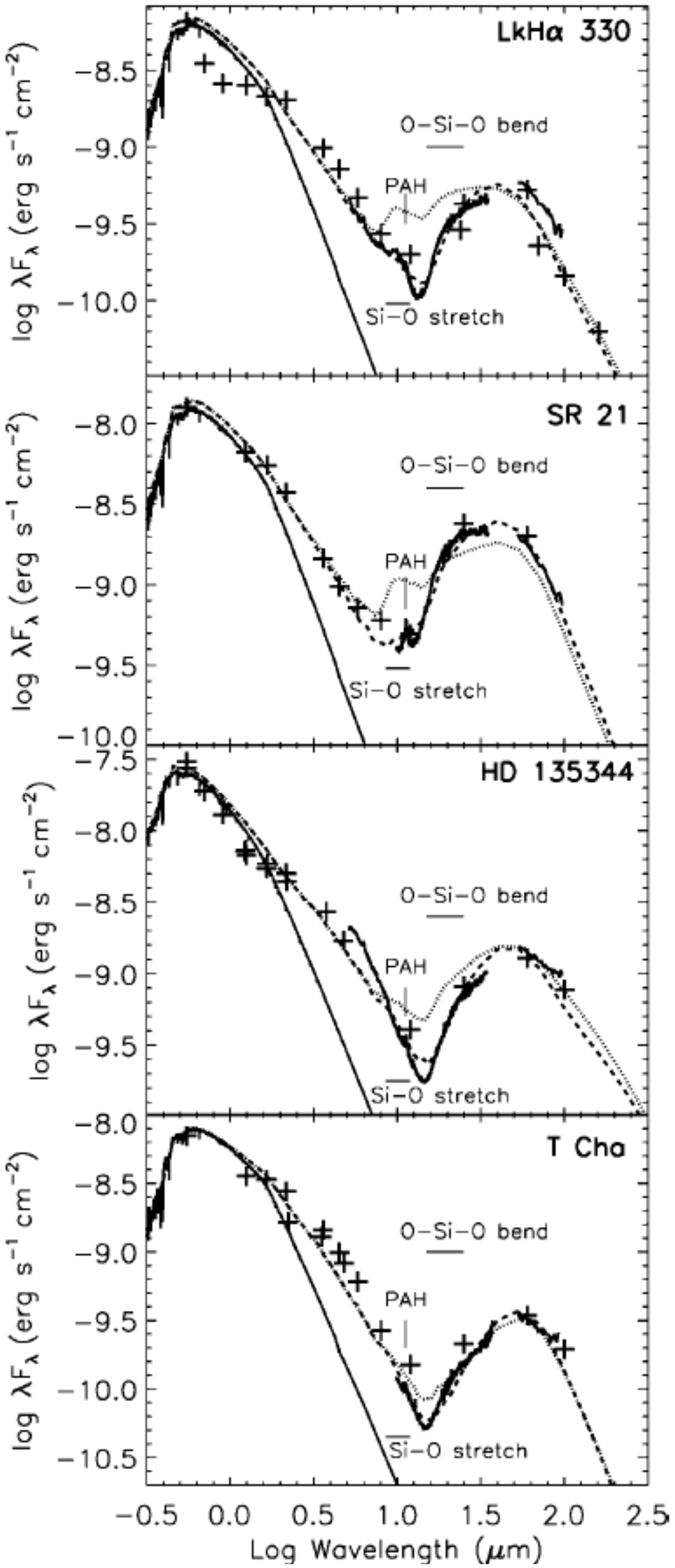


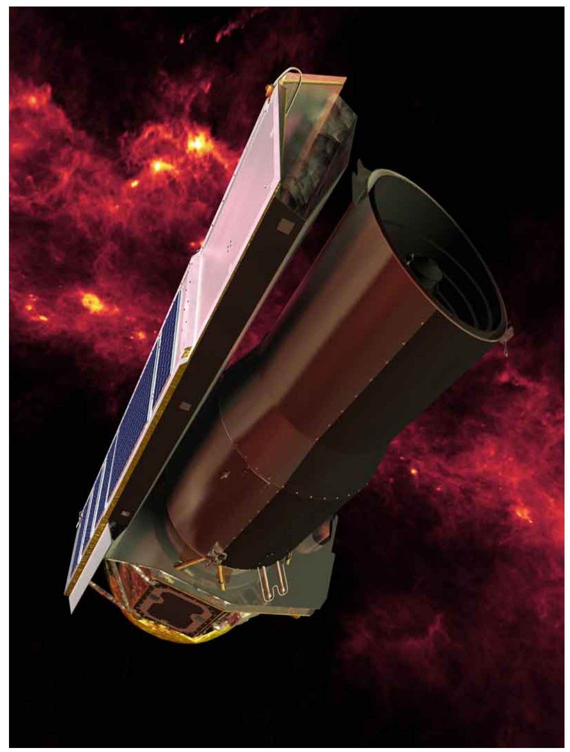
Transition(al) disks

Not necessarily an evolutionary term!

First discovery:
Strom et al. 1989

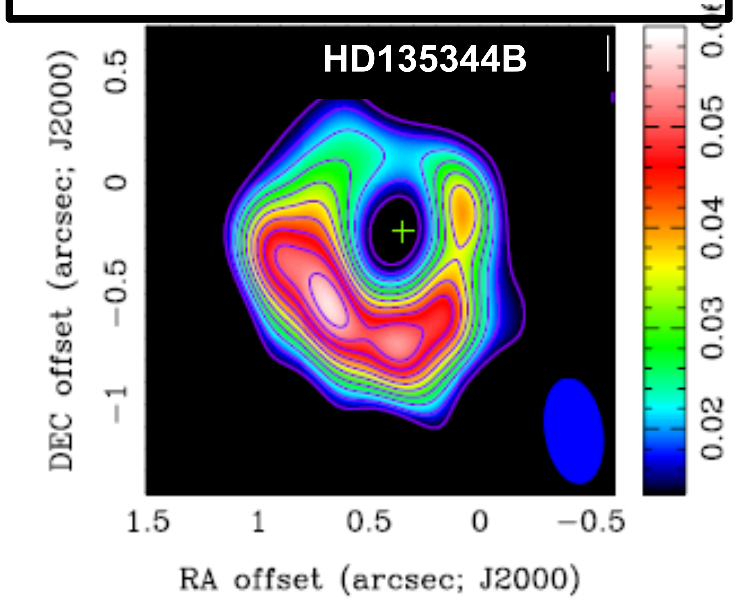
Transition disks

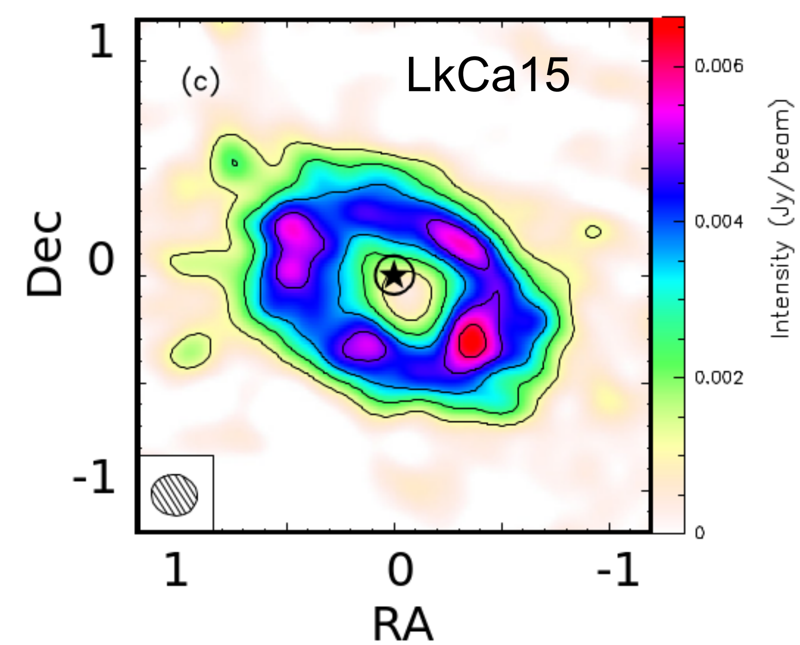




Spitzer infrared observations

Pioneering millimeter interferometry (SMA, CARMA,PdBI)

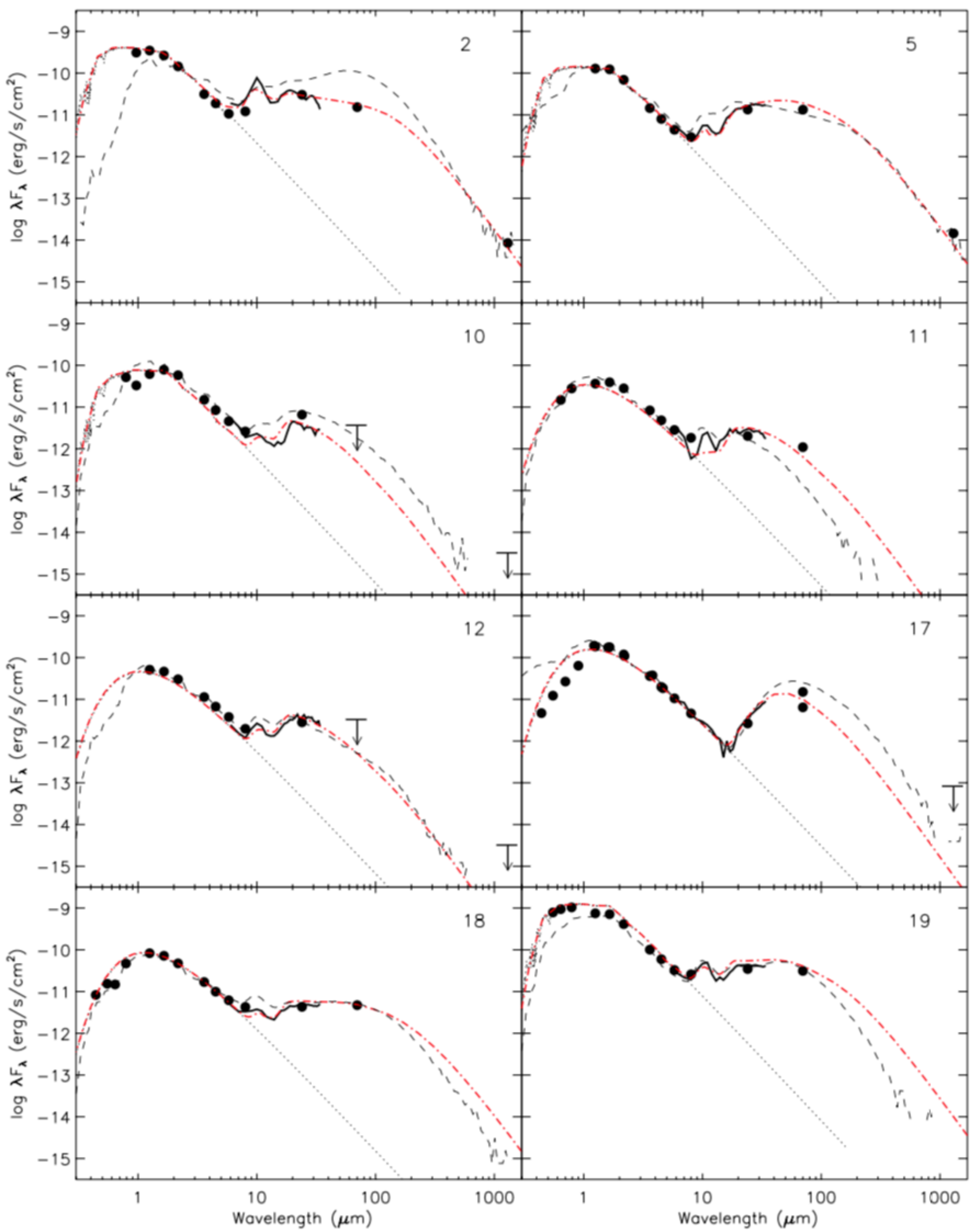




Link with planet formation?

Brown et al. 2007, 2009, Isella et al. 2010

Transition disks



SEDs:

- Cavity sizes down to ~2 au from SEDs, but only largest cavities (>30 au) could be confirmed by mm interferometry
- Large range of color criteria used in the literature to identify transition disks and transition disk candidates (Spitzer): inconsistency
- SED analysis complex: extinction correction (spectral type), edge-on disks, radiative transfer effects
- Most TDs still accreting!

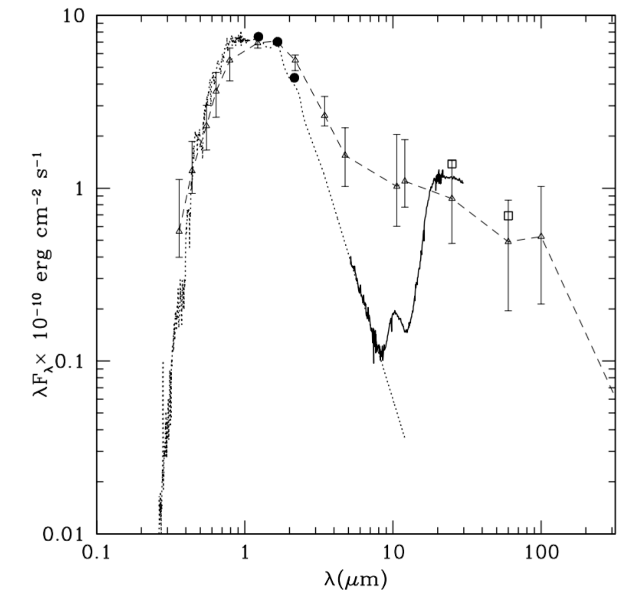
Origin transition disks

(Classical picture)

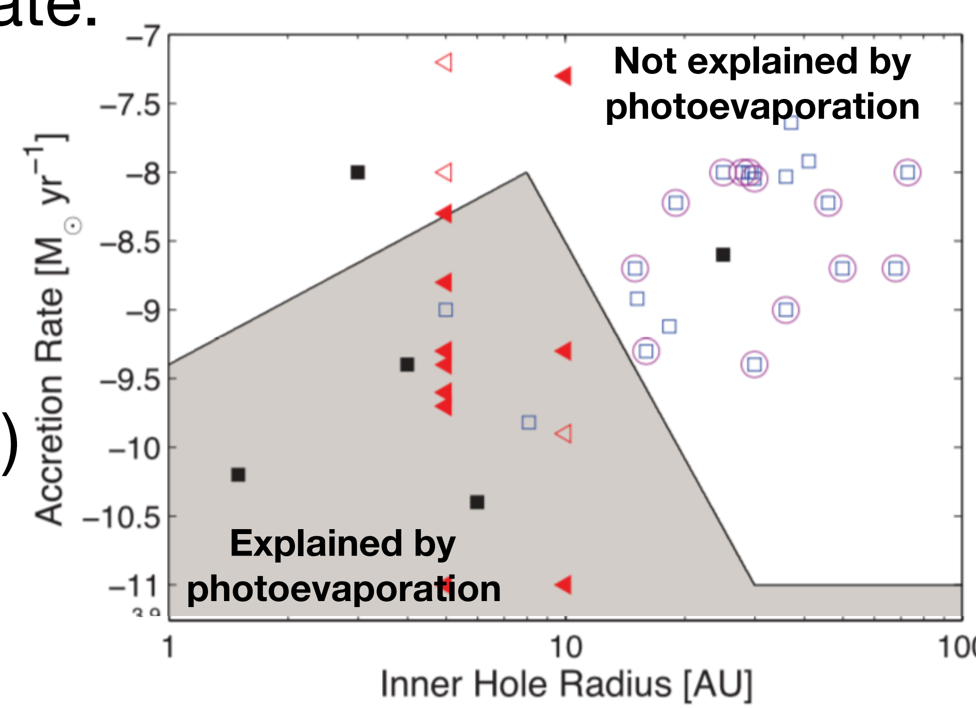
1. Circumbinary disk
   => famous example: Coku/Tau 4:
   10 au gap, but 8 au binary (Ireland & Kraus 2008)
   => but many TDs shown not to be binaries

2. Photoevaporation (e.g. Owen & Clarke 2012)
   => accretion drops below photoevaporative rate:
   inside out disk clearing
   => cannot explain large (>10 au) cavities
   (but debated)

3. Grain growth in inner disk (e.g. Birnstiel+2010)
   => remove small grains by growth
   => cannot explain mm-images cavities, only SEDs



d'Alessio et al. 2005



Owen & Clarke 2012

Lecture Ercolano
Thursday

Origin transition disks

(Classical picture)

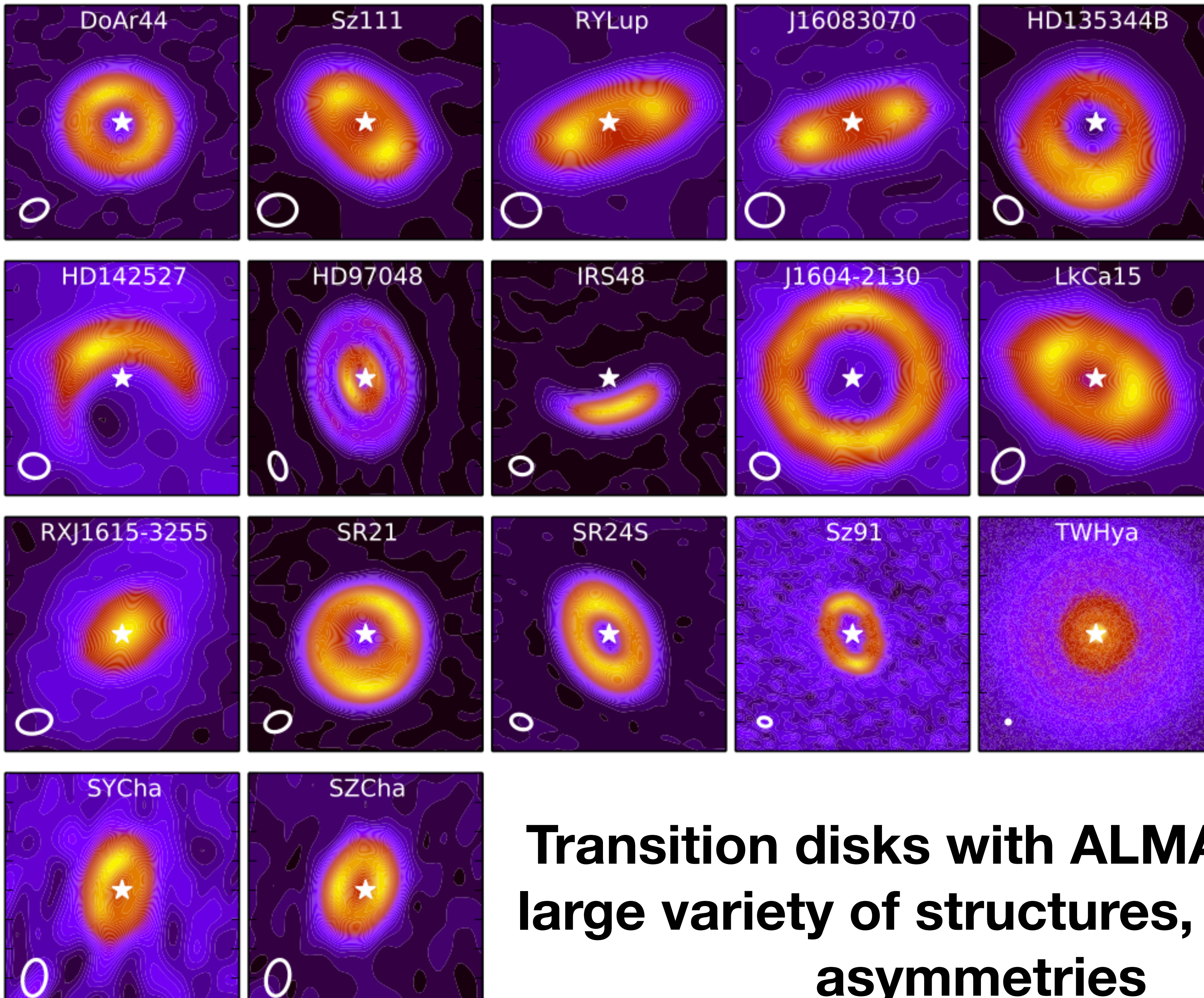
4. Dead zone (e.g. Regaly+2012)
   => region of low ionisation (in between radiative ionisation surface layer and collisional ionisation mid-plane): disruption of MRI creates pile-up material: dust ring

5. Planet clearing gap (e.g. Papaloizou+2007)
   => once a planet is formed, it clears out a large gap in gas and dust
   => needs large planets at wide orbits (10s of au), which are not detected in disks and are even rare in exoplanet demographics

6. Eccentric binary companion (new) (e.g. Ragusa+2016)
   => A binary companion (mass ratio q~0.1) on an eccentric orbit can carve out gaps at much larger radii
   => One clear example so far: HD142527 (Price+2018)

Lecture Benitez Friday

Transition disks with ALMA



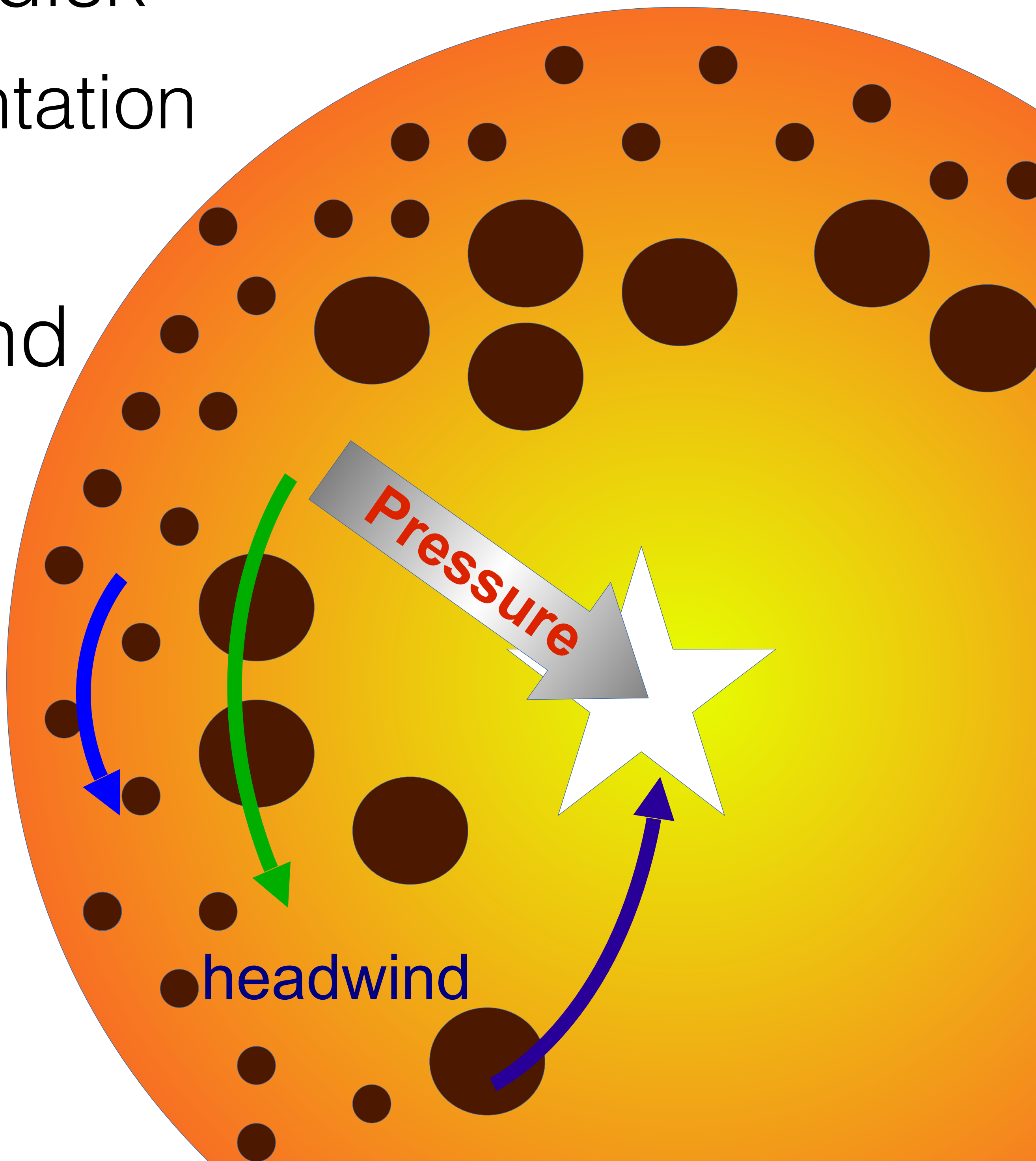
Gallery by van der Marel

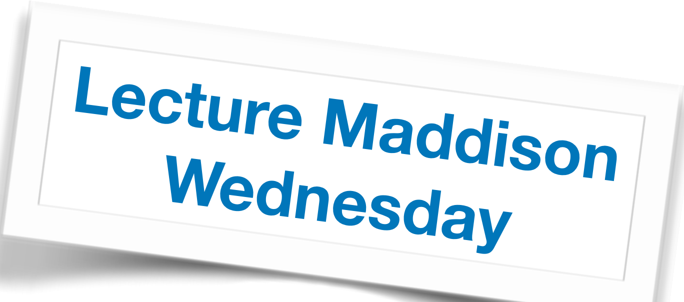
Transition disks with ALMA at 0.2” : large variety of structures, including asymmetries

Dust evolution

- Dust growth in a normal disk
  - Coagulation and fragmentation
  - Radial inward drift
- Dust can not grow beyond millimeter sizes?
- Large particles move towards high pressure

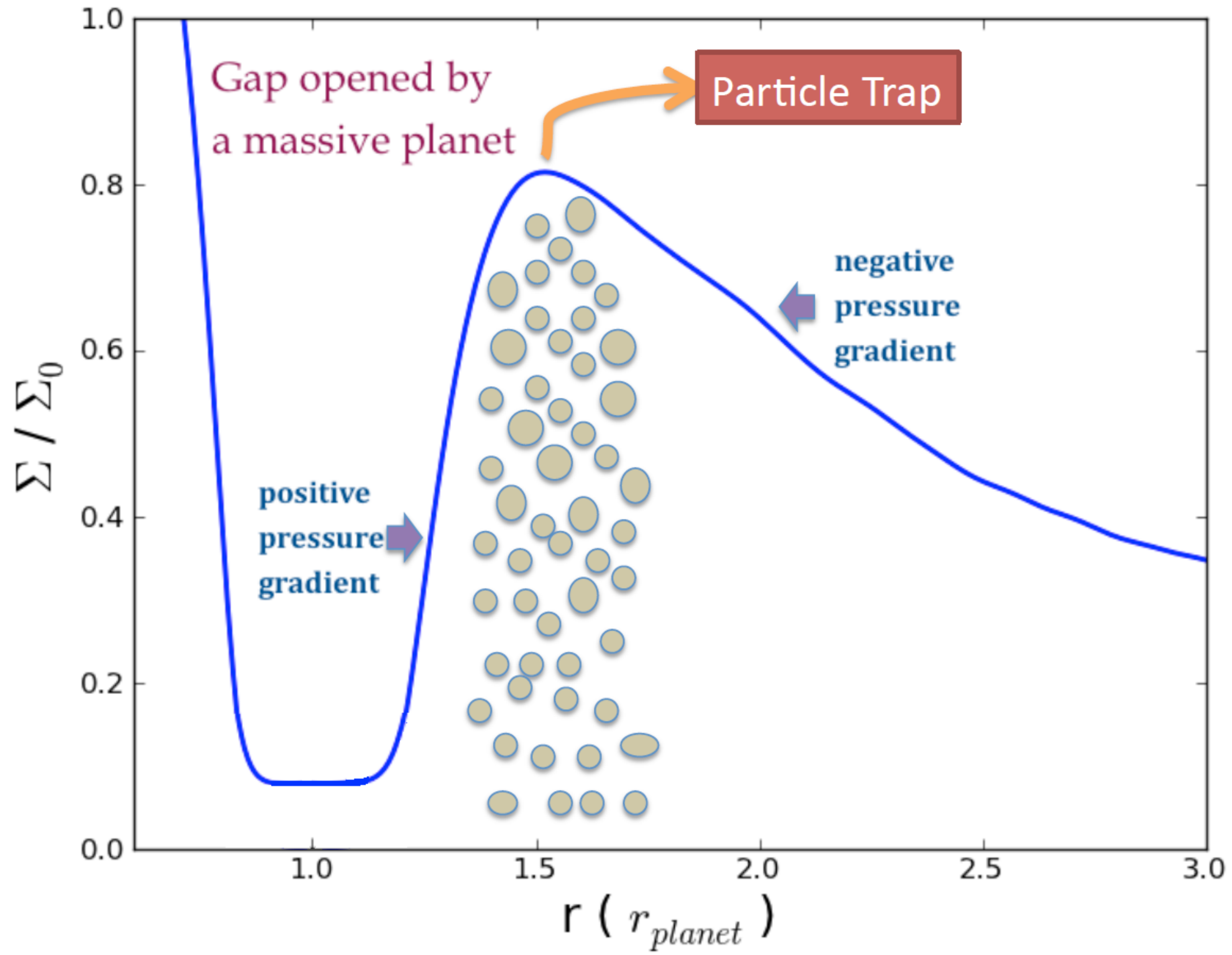
=> Pressure bump?





Dust trapping

- Pressure bump in outer disk
  => through drag forces, large dust gets trapped
  - density gradient (planet)
  - viscosity gradient or dead zone: local low ionization (most of the disk is ionized by either collisions or radiation)

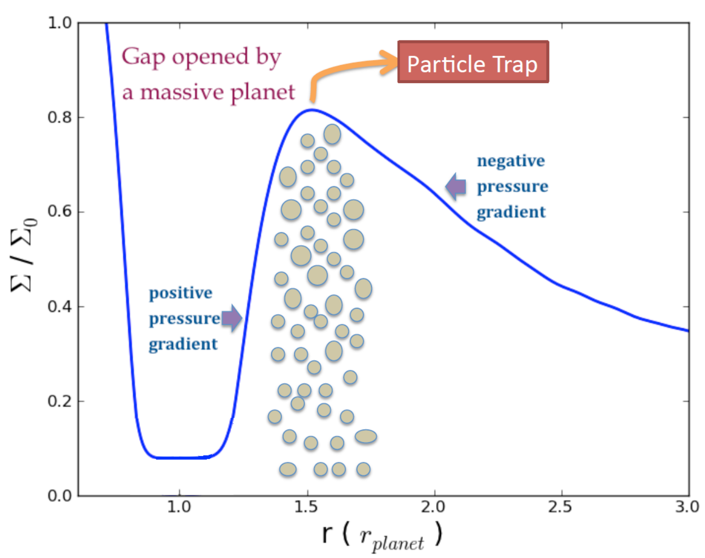


=> Transition disk as pressure bump!

Varniere et al 2007
Pinilla et al. 2012
Zhu et al. 2012

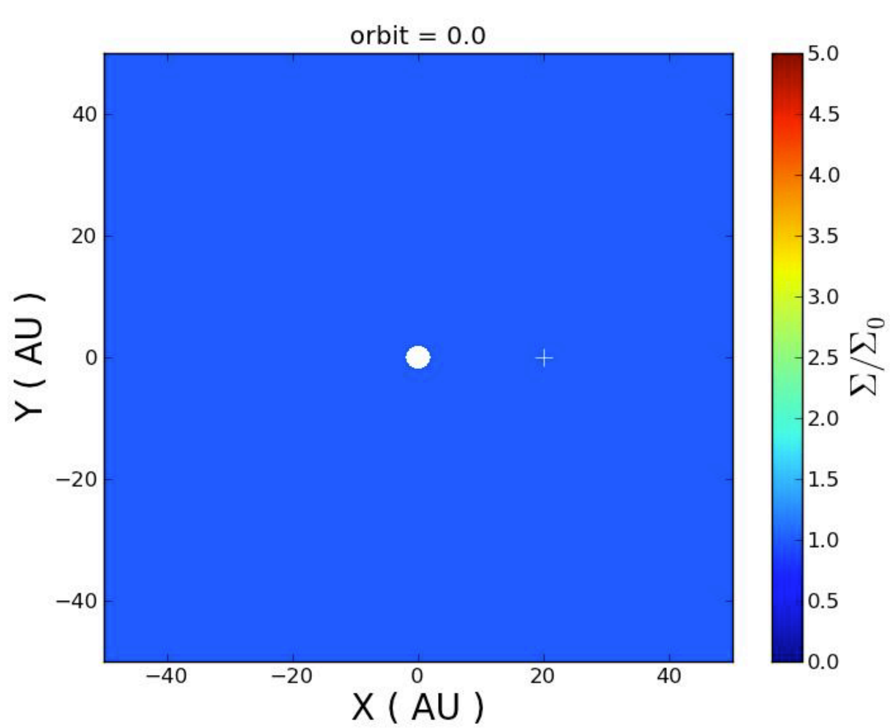
Dust trapping

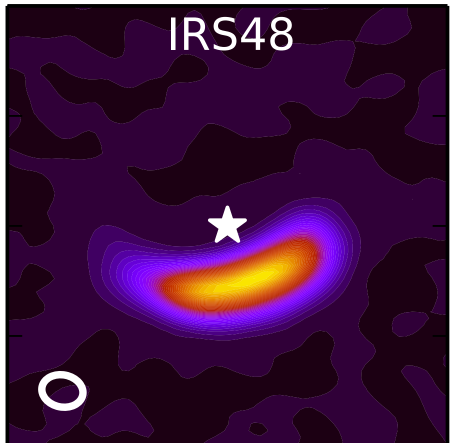
- What is the origin of the azimuthal asymmetries?
- Steep drop & low viscosity
  => pressure bump develops Rossby instability (Kelvin-Helmholtz instabity)
  => forms long-lived vortices => azimuthal trapping

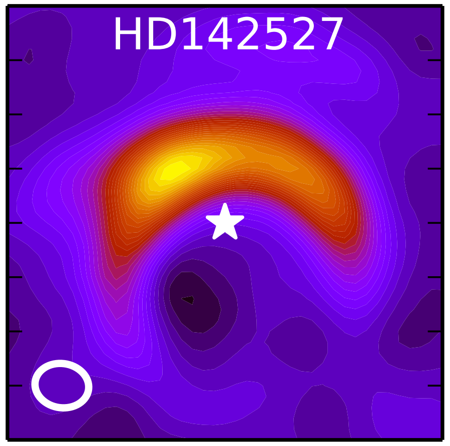


Barge & Sommeria 1995
Klahr & Henning 1997
Birnstiel et al. 2013
Lyra & Lin 2013
Zhu & Stone 2014

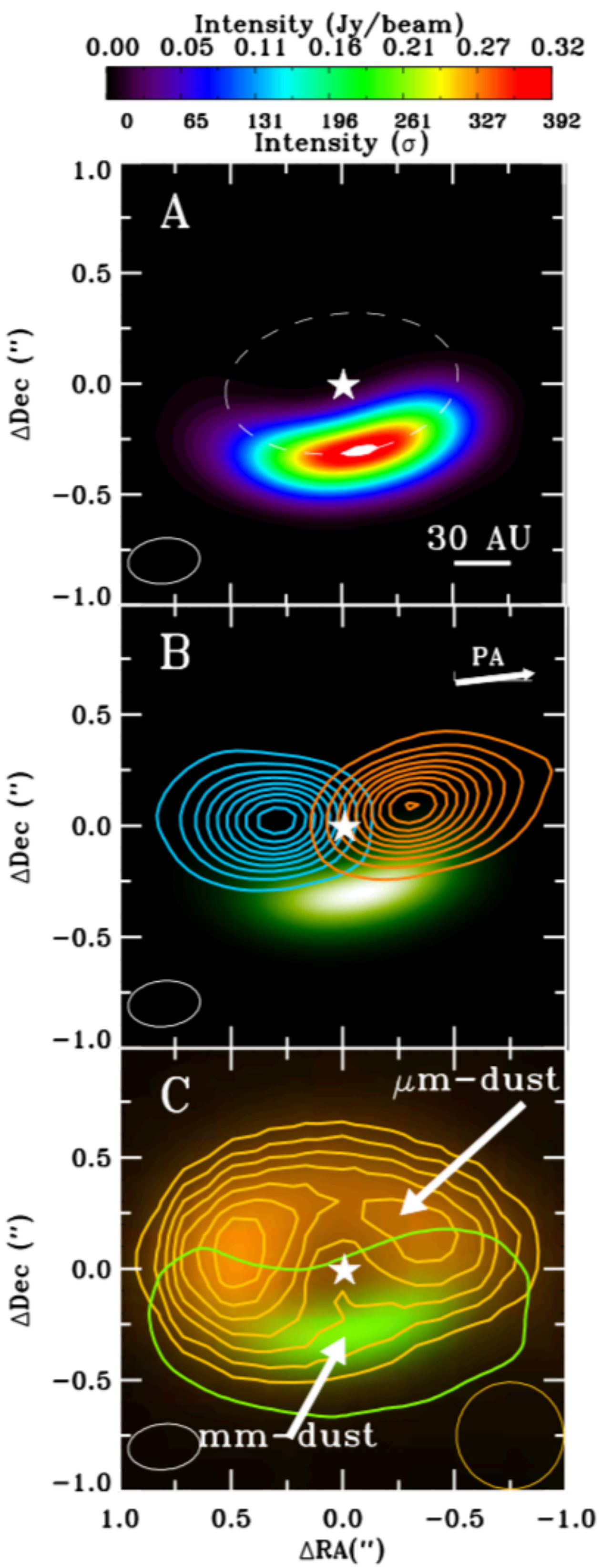
gas simulation



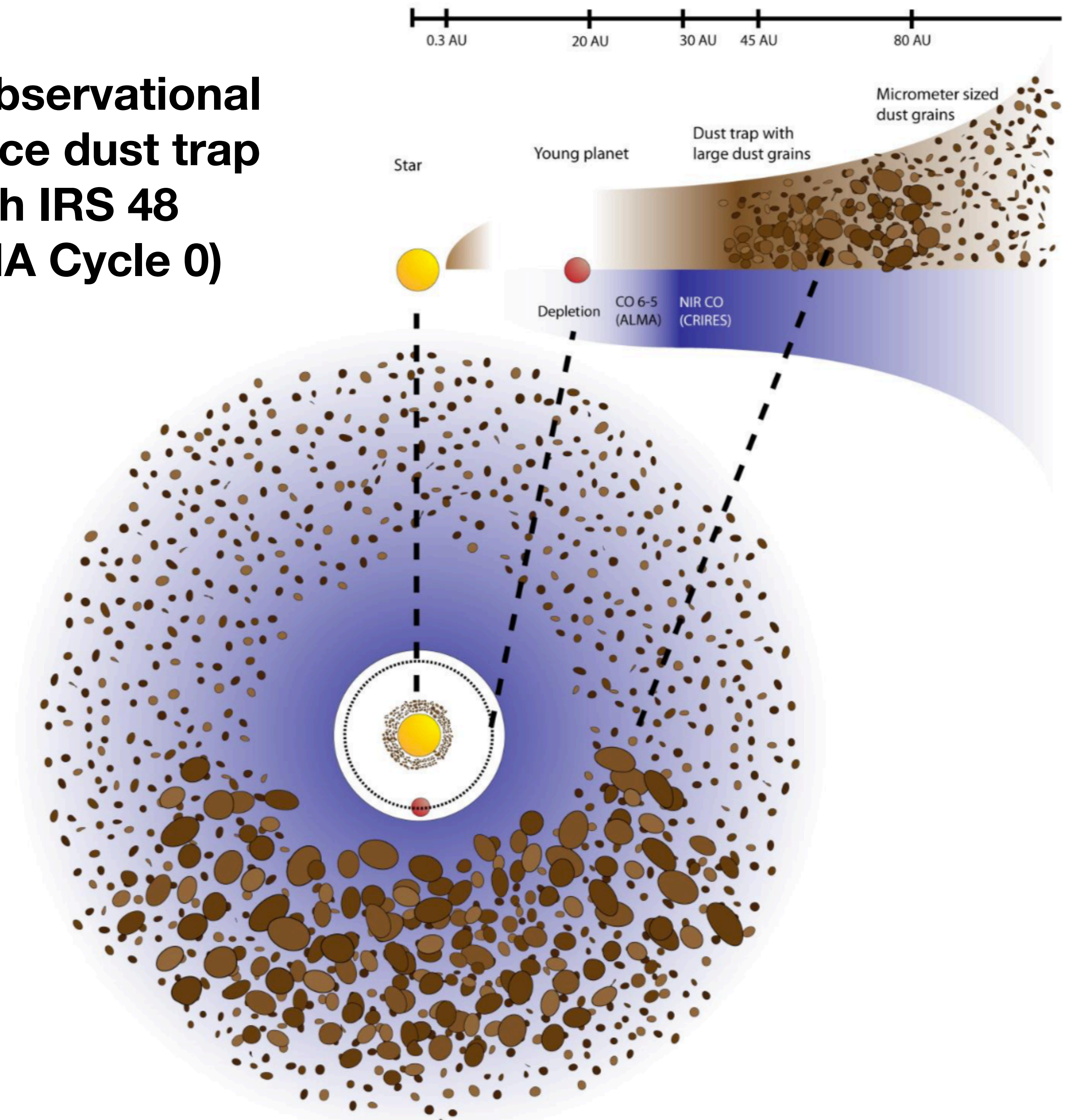




Dust trapping



First observational evidence dust trap Oph IRS 48 (ALMA Cycle 0)

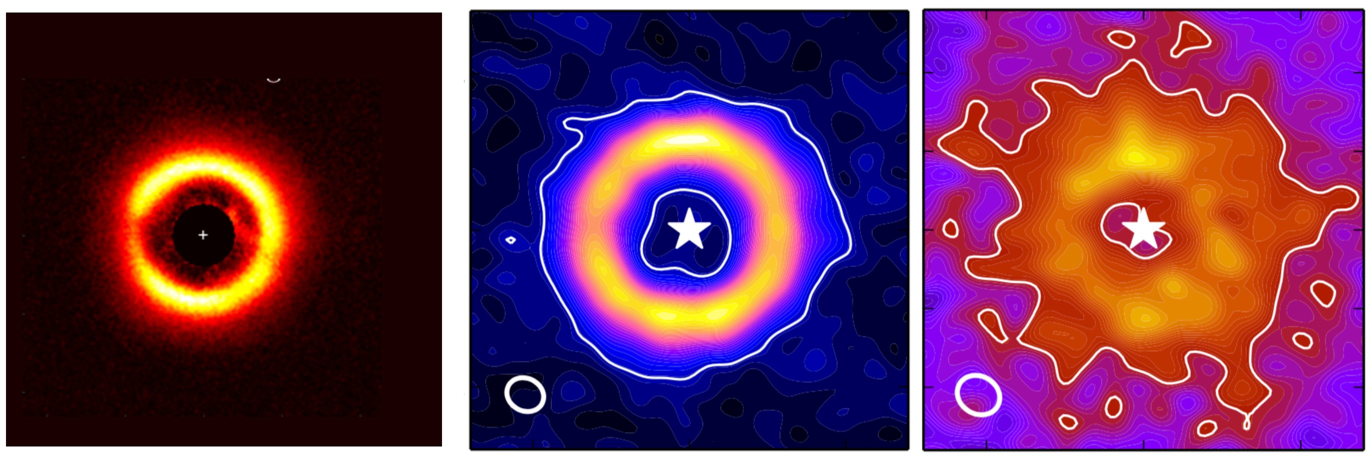


Van der Marel et al. 2013, *Science*

Dust trapping in transition disks

Small dust | **Large trapped dust** | **Gas**

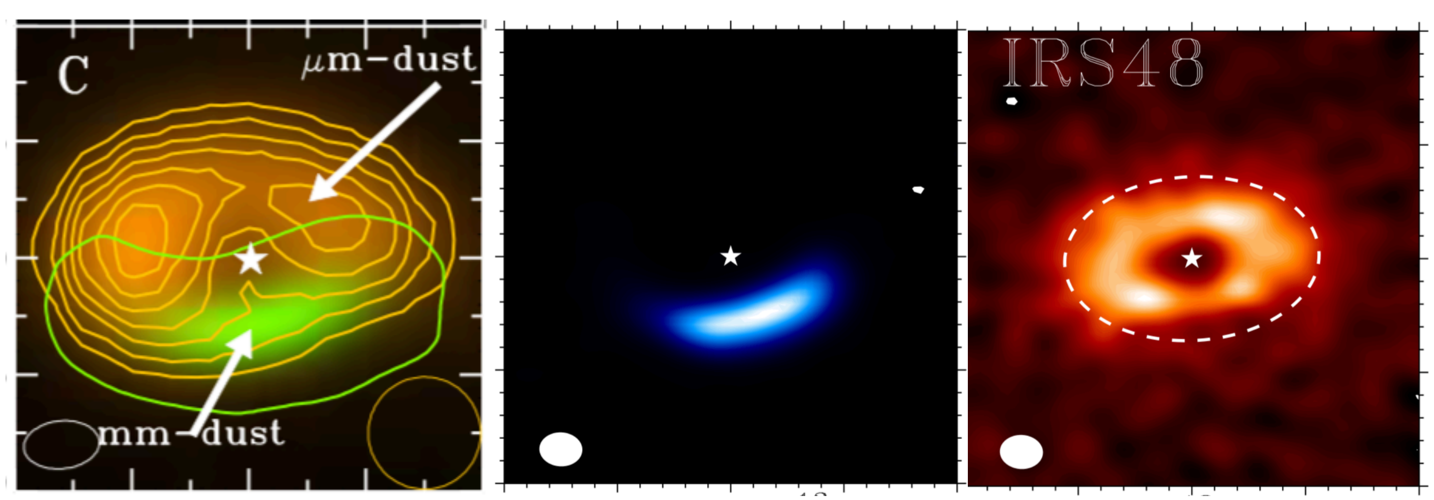
J1604-2130



NIR (Subaru) | 1.3mm (ALMA) | ^{13}CO (ALMA)

Radial trapping

IRS48



MIR (VISIR) | 0.5mm (ALMA) | ^{13}CO (ALMA)

Distinct distribution of mm-dust and gas/small grains shows trapping!

Azimuthal trapping

Unclear why only some disks (~10%) are asymmetric…

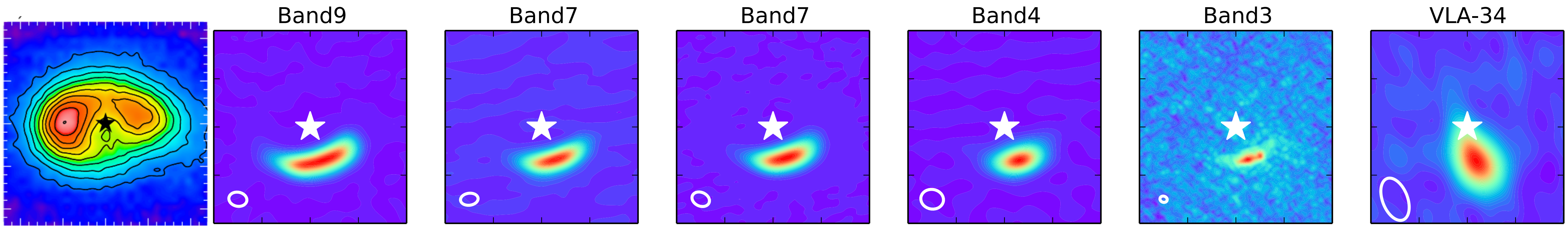
Van der Marel et al. 2013, 2016
Dong et al. 2017

Multi-wavelength observations

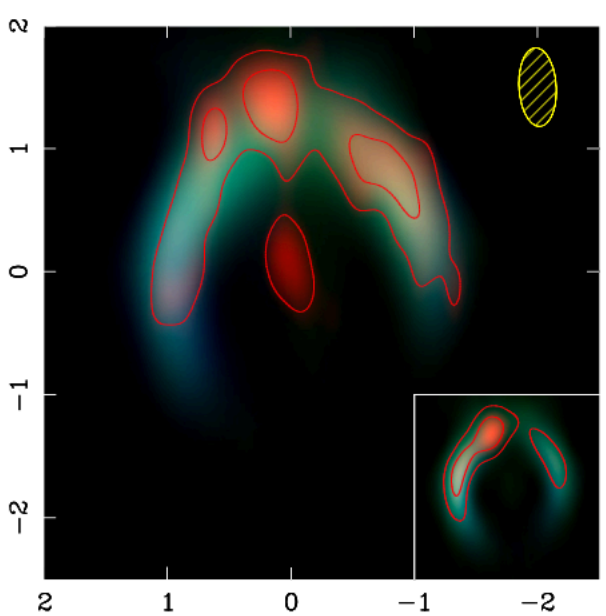
λ ~ particle size and larger particles are more efficiently trapped

IRS48

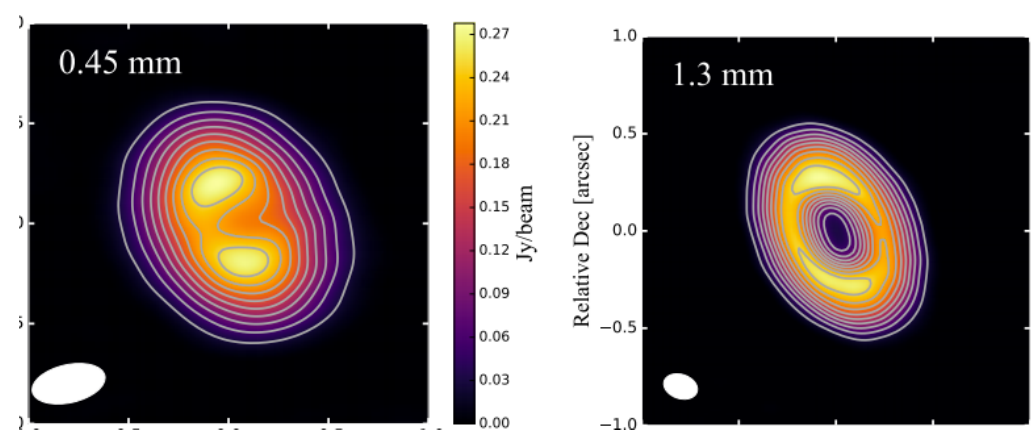
18 micron | 0.45mm | 0.85mm | 0.9mm | 2mm | 3mm | 9mm



HD142527



SR24S



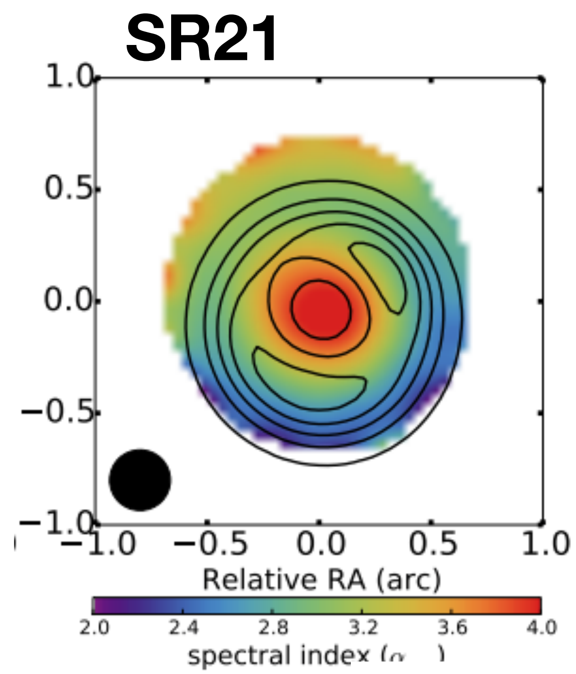
Multi-wavelength observations show evidence trapping

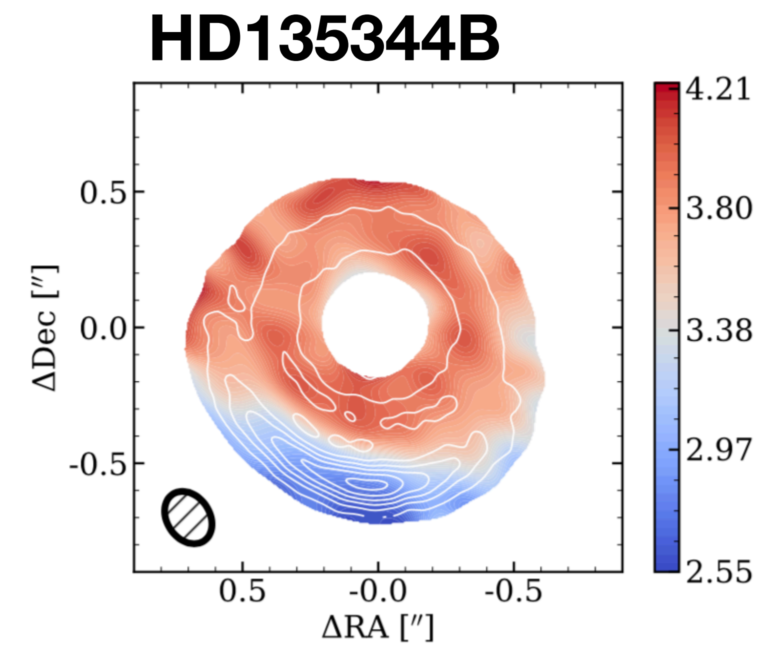
Casassus et al. 2015
Pinilla et al. 2015
van der Marel et al. 2013,2015,in prep.

Multi-wavelength observations

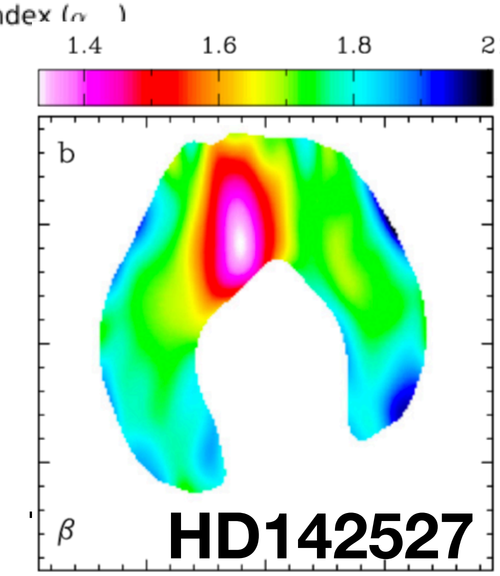
Spectral index (α) maps:

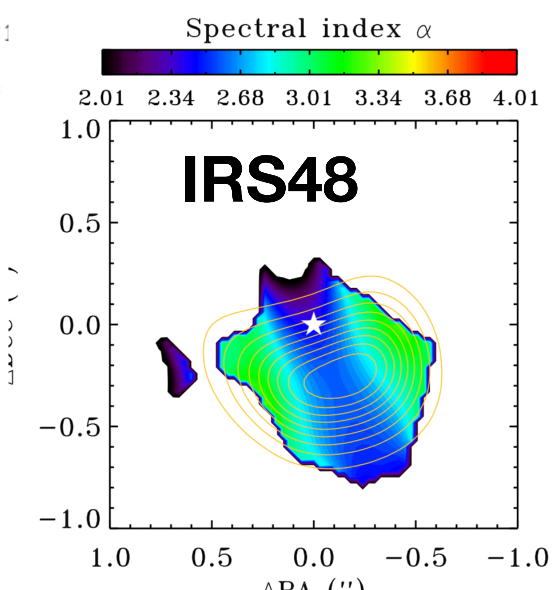
- Flux $F_\nu \sim \nu^\alpha$
- Spectral index $\alpha \sim 2+\beta$
- Dust opacity $\tau_\nu \sim \kappa_\nu \sim \nu^\beta$
- κ_ν ~ grain size distribution
  ($n(a) \sim a^{-p}$, a_{max}, a_{min})





- α ~ 3.7: ISM grains
- 2 < α < 3: grain growth
- But also α < 3: optically thick



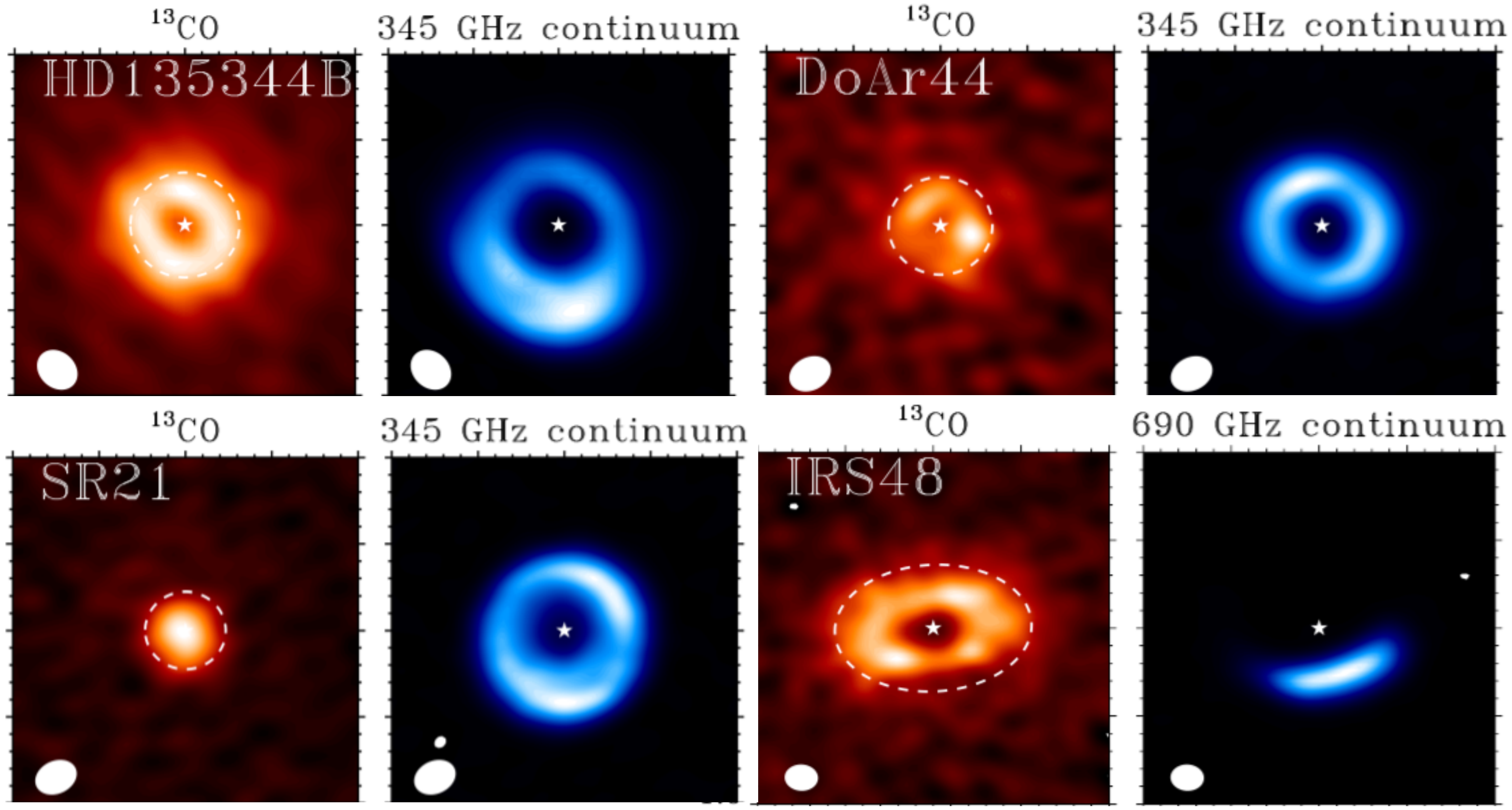


=> So spectral index maps can be used to trace grain growth, but careful with optical depth effects

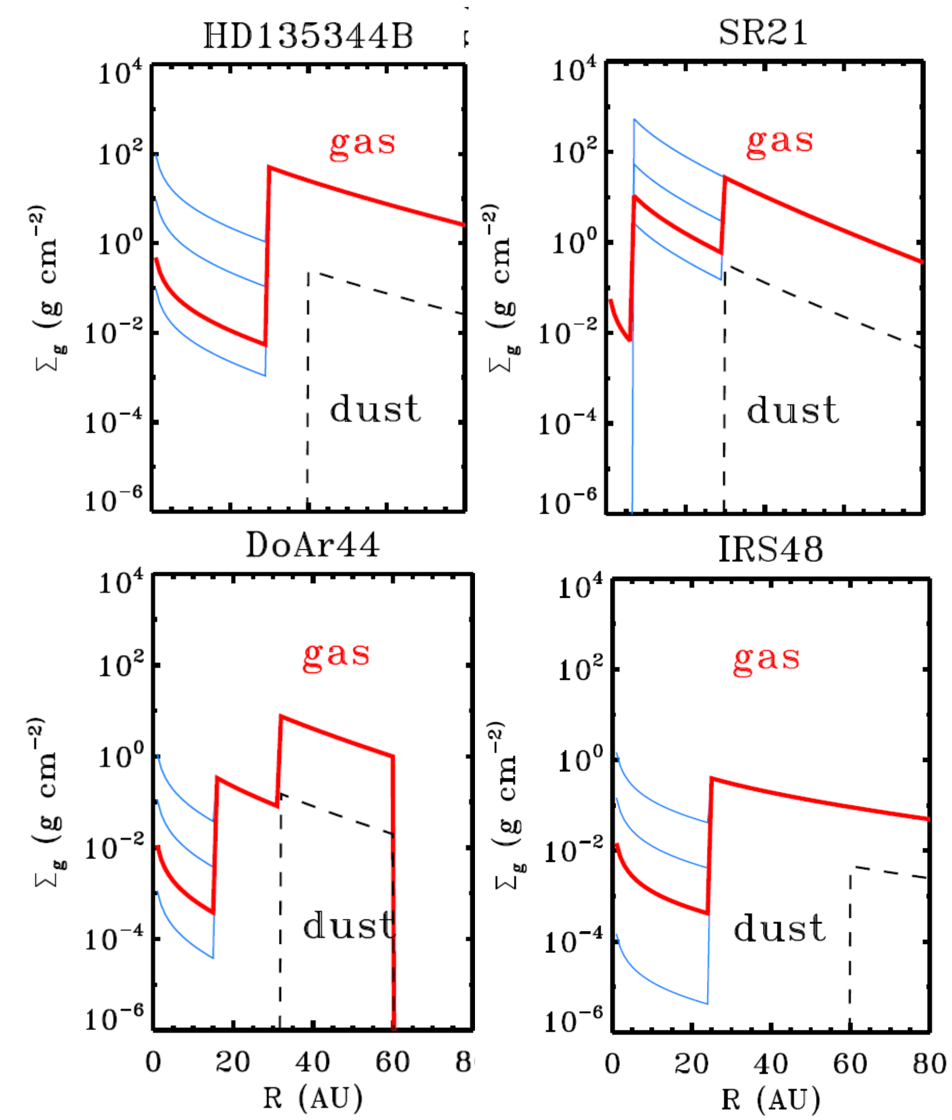
Casassus et al. 2015
Pinilla et al. 2014
Cazzoletti et al. 2018
Van der Marel et al. 2015

Origin TDs: planets?

Observations

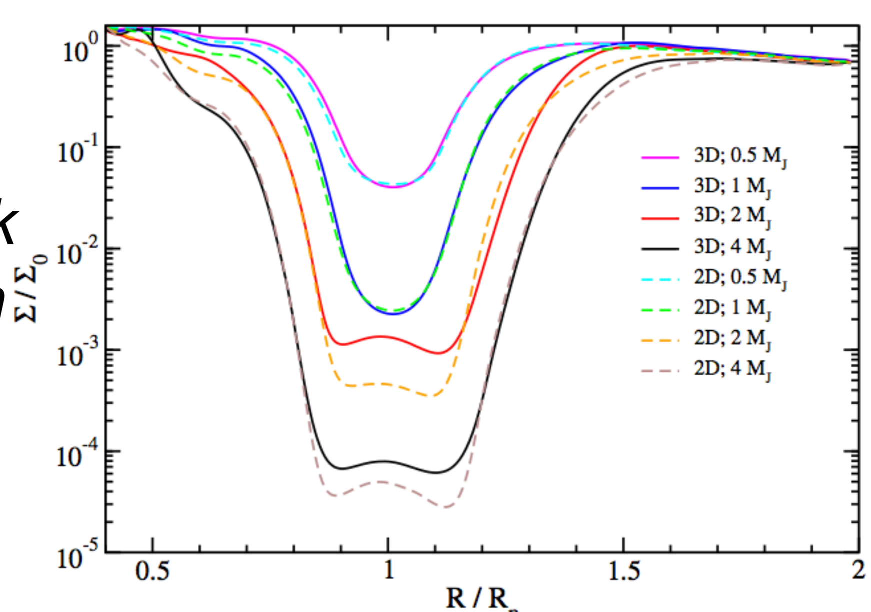


Derived surface density



ALMA CO maps reveal deep gas gaps, consistent with clearing by Jupiter-mass planets

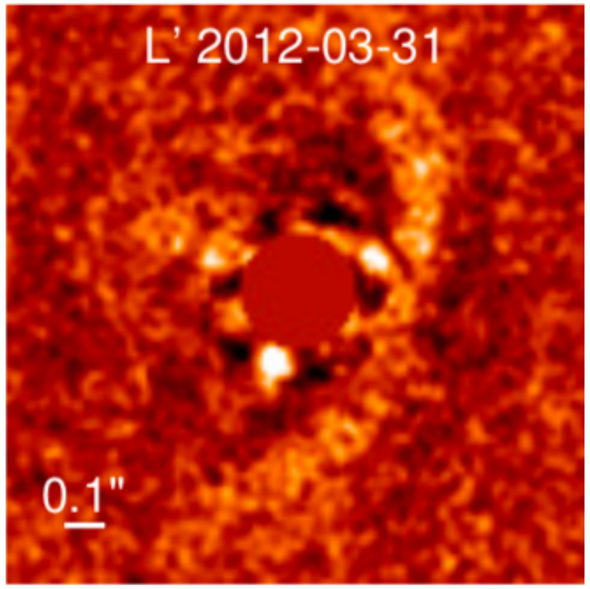
Planet-disk interaction model



Dead zone excluded!

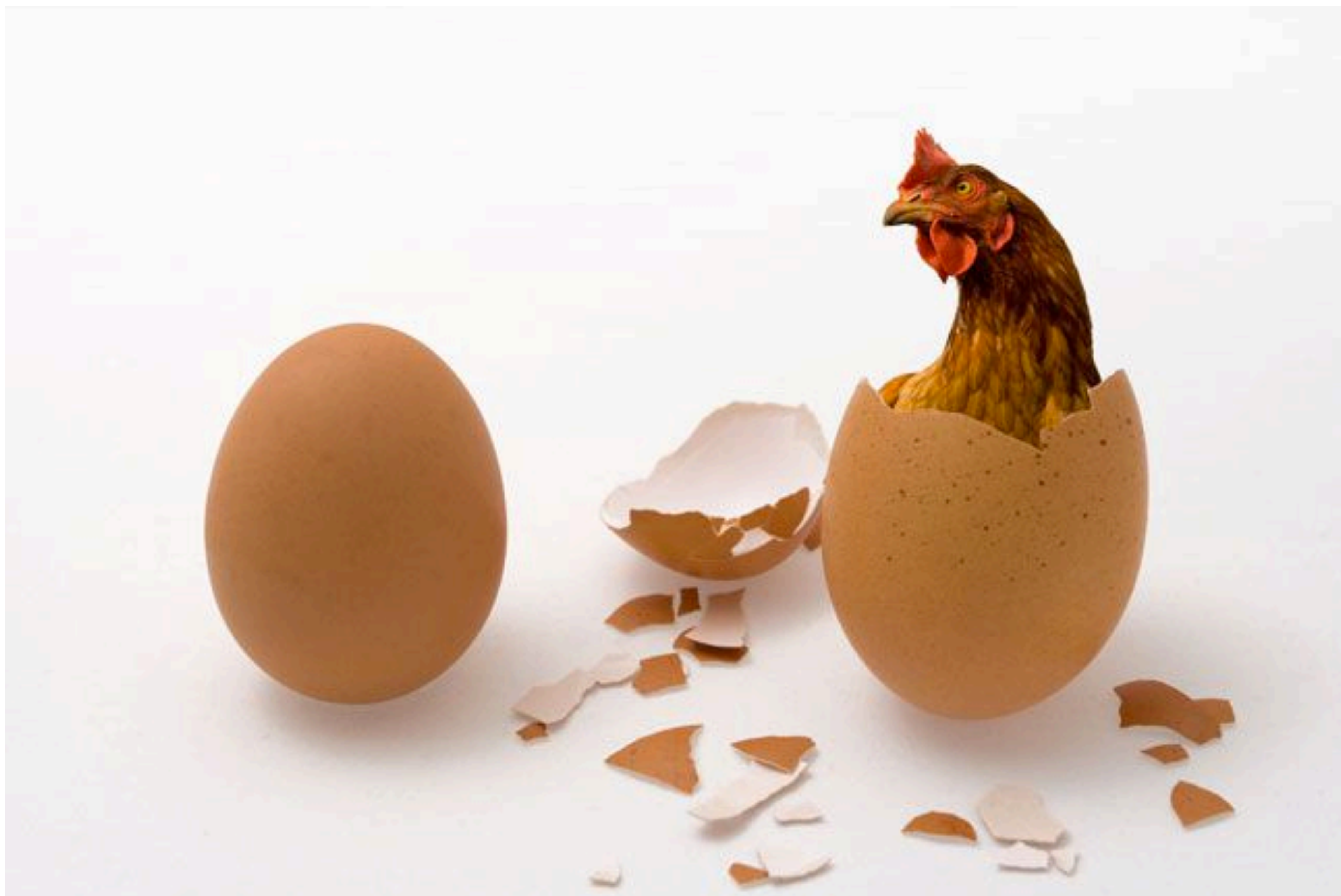
Van der Marel et al. 2016
Fung & Chiang 2016

Origin TDs: planets?



1. Only one transition disk has a planet detection (PDS70, Keppler+2018)
   => but close to detection limit (see end lecture)
2. Difficult to form planets at tens of au
   => but lots of debate on initial conditions planet formation
3. Low frequency giant planets at wide orbits in exoplanet demographics
   => but strong bias due to exoplanet demographics
4. Large separation between gas cavity radius (planet location) and dust cavity radius
   => but possible with eccentric companion
5. Problem to explain dust trapping as origin planet formation…

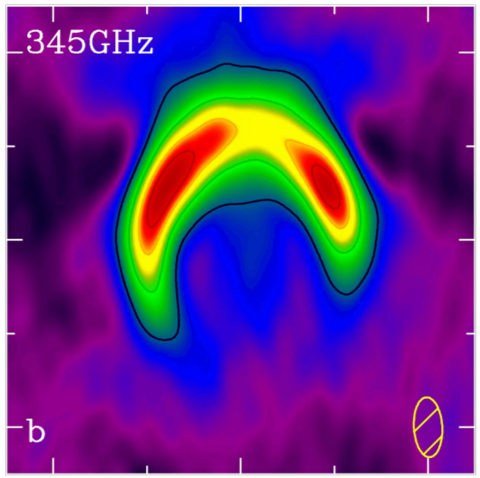
Dust gaps and traps due to planets?



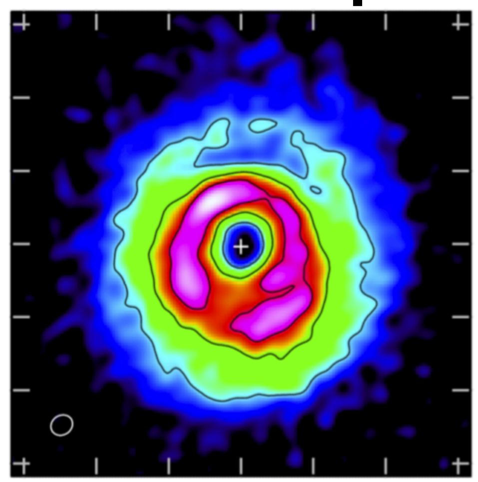
Origin TDs: eccentric companion?

Asymmetric dust gap + gas gap

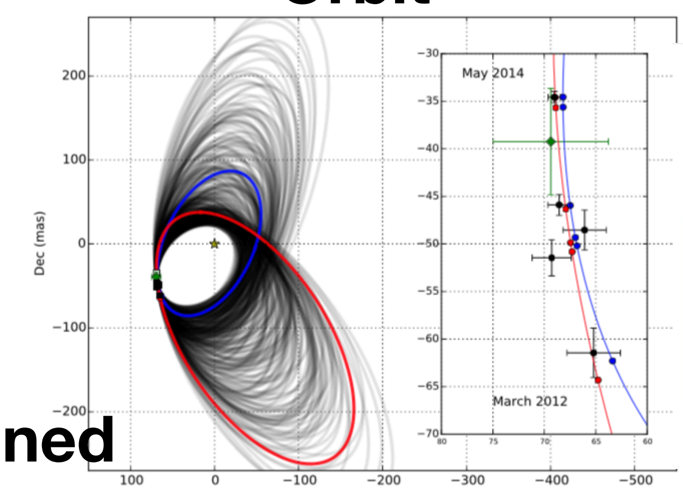
Mm-dust



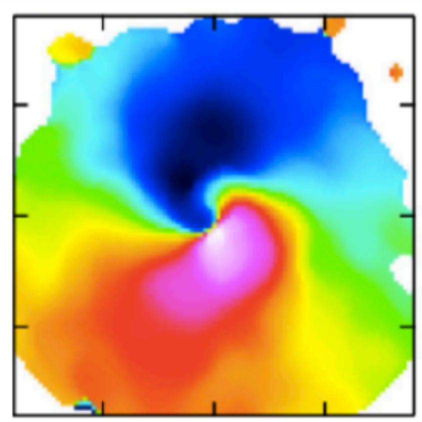
^{13}CO map



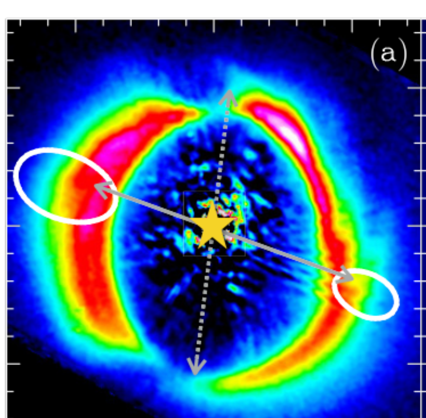
Orbit



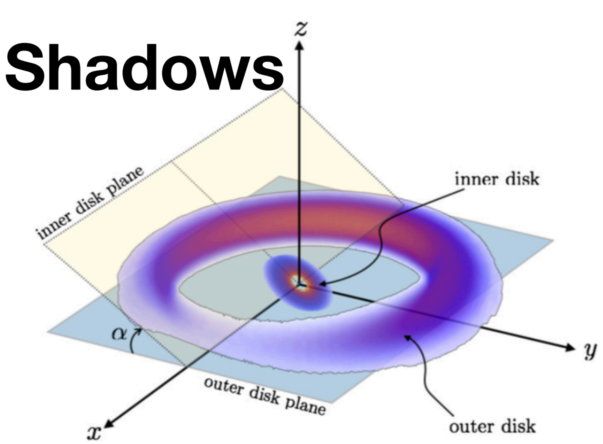
HCO+ velocity



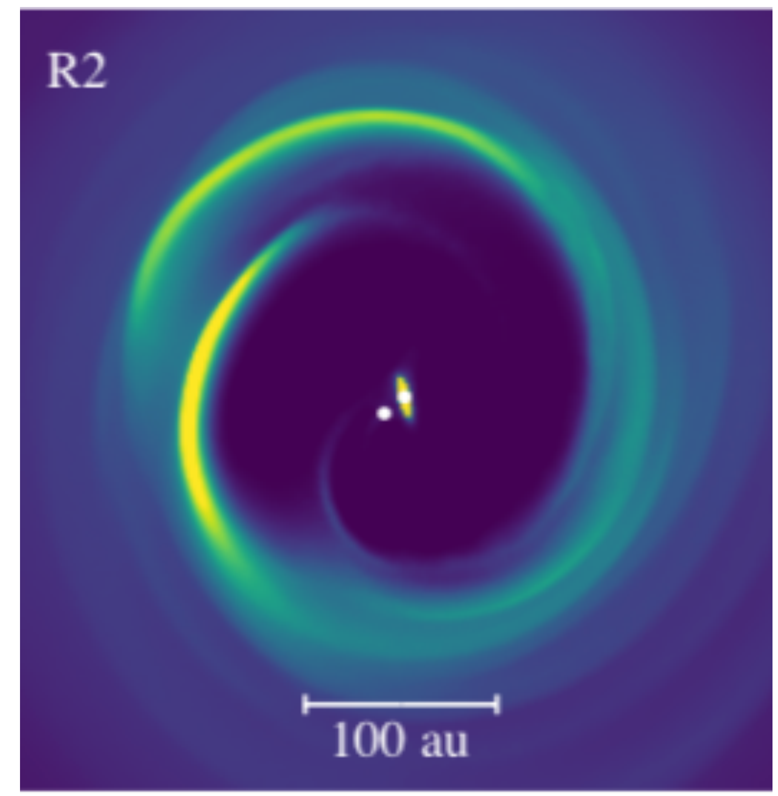
Misaligned eccentric companion



Shadows



HD142527: a circumbinary disk

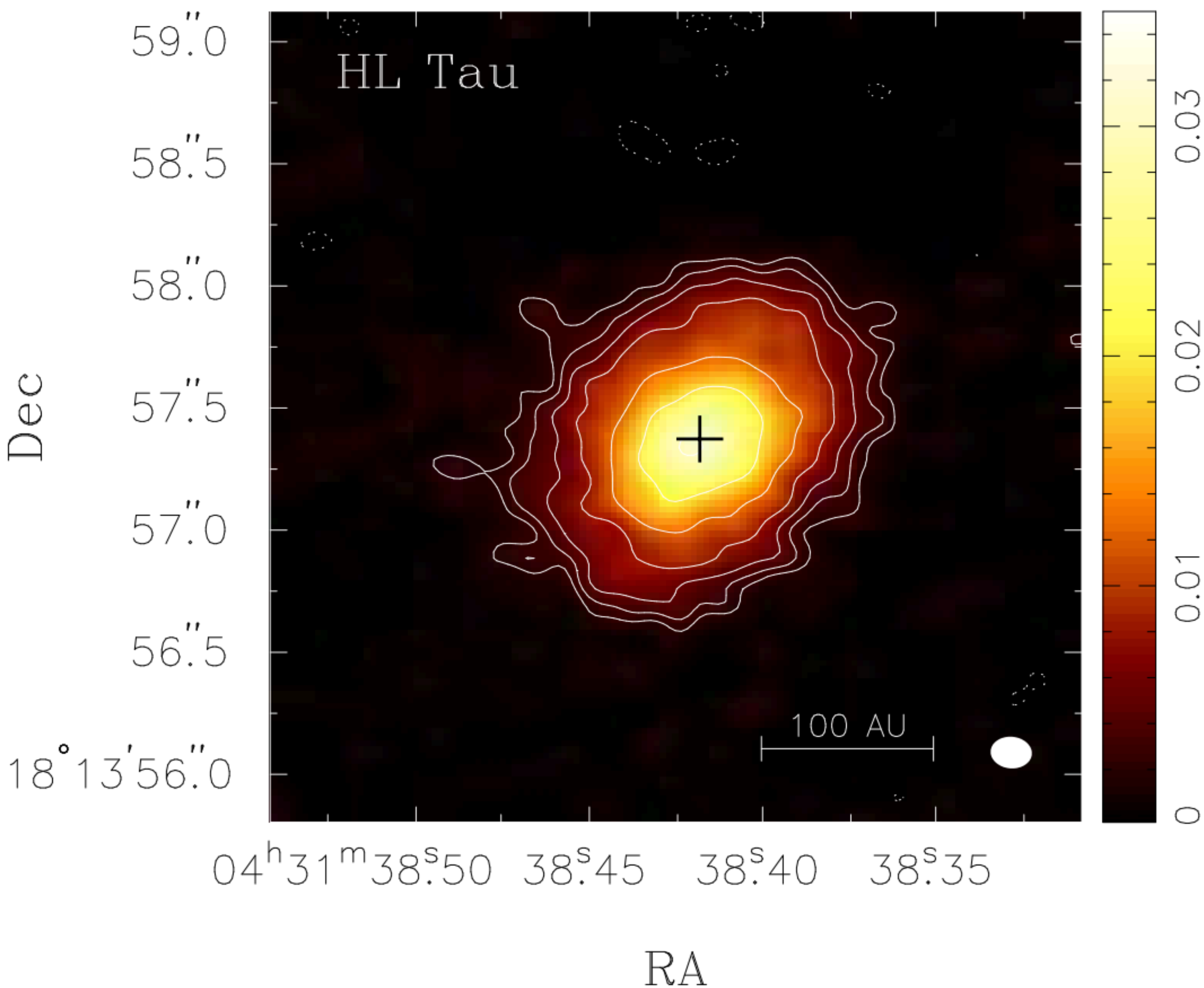


Full simulation of disk-binary interaction induces 'bananas' due to Lindblad resonance: reproduce all observations of HD142527

Price et al. 2018 (and references therein)

Origin of transition disks remains a hot topic of on-going research!

‘Full’ disks: no inner cavity



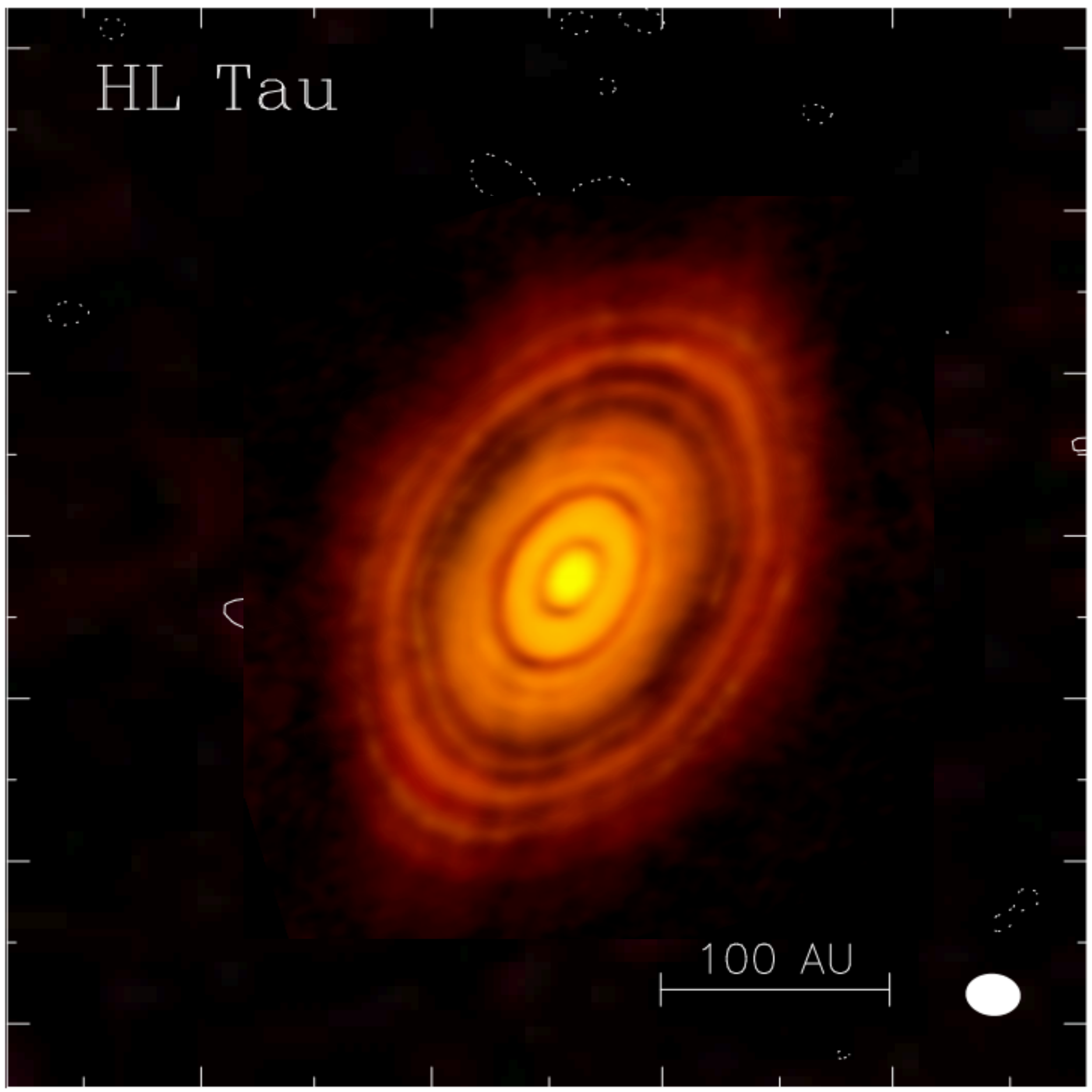
Smooth disk, following viscous disk model

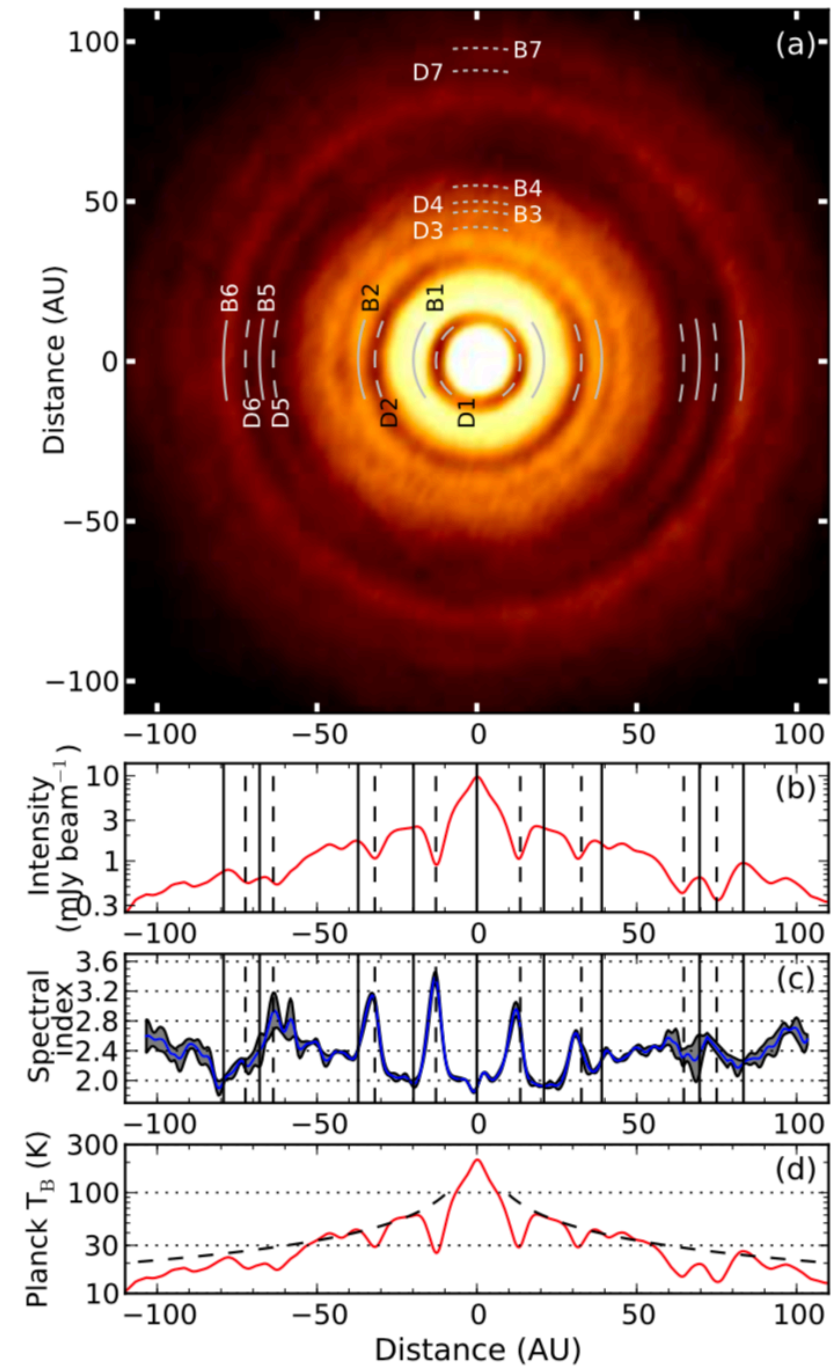
Also called primordial disk

Kwon et al. 2011

‘Full disks’ => Ring disks!

ALMA image 2015: Long Baseline Campaign, 0.03” resolution



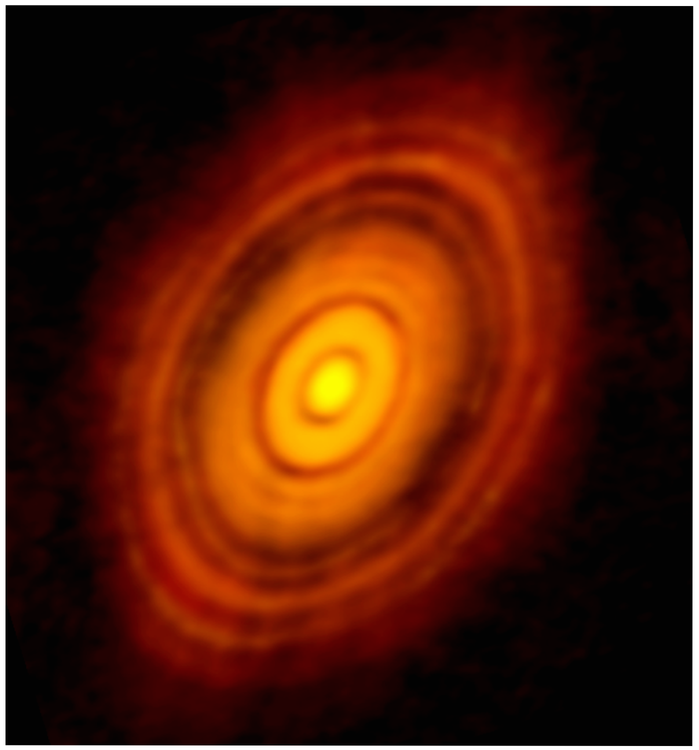


Big surprise! Not a smooth disk, but many gaps and rings!

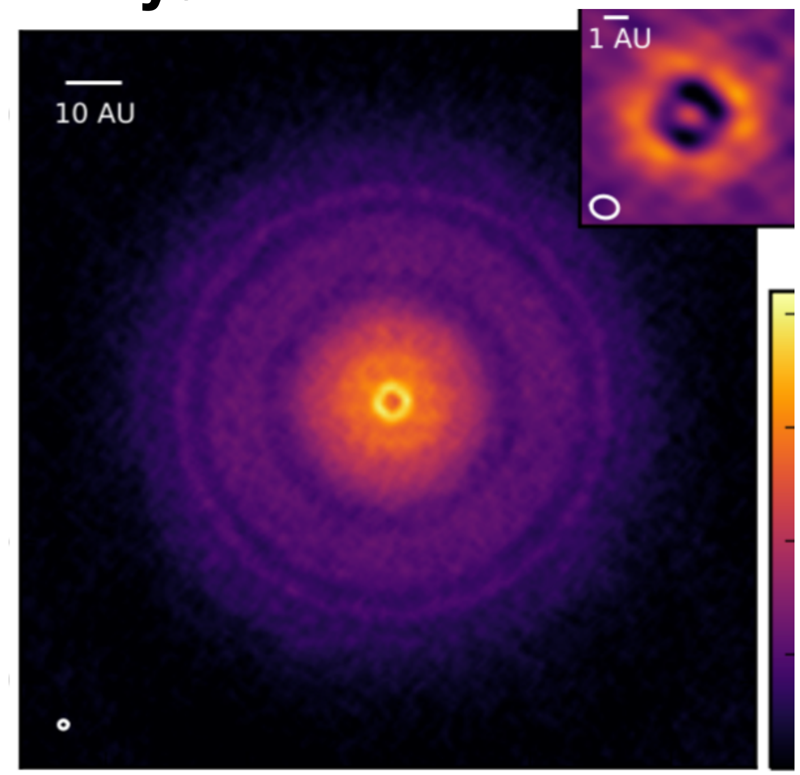
ALMA consortium et al. 2015

More ring disks

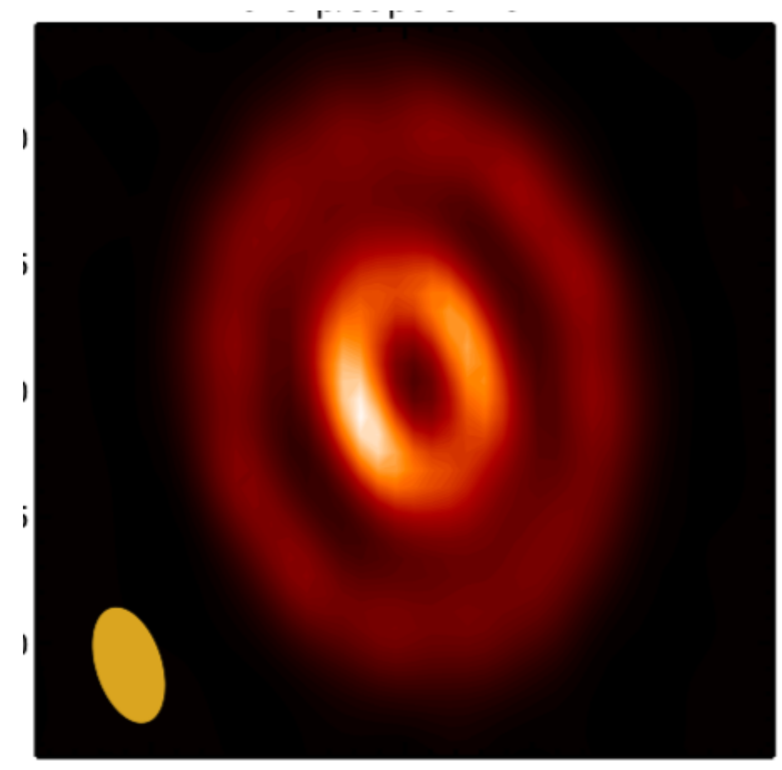
HL Tau

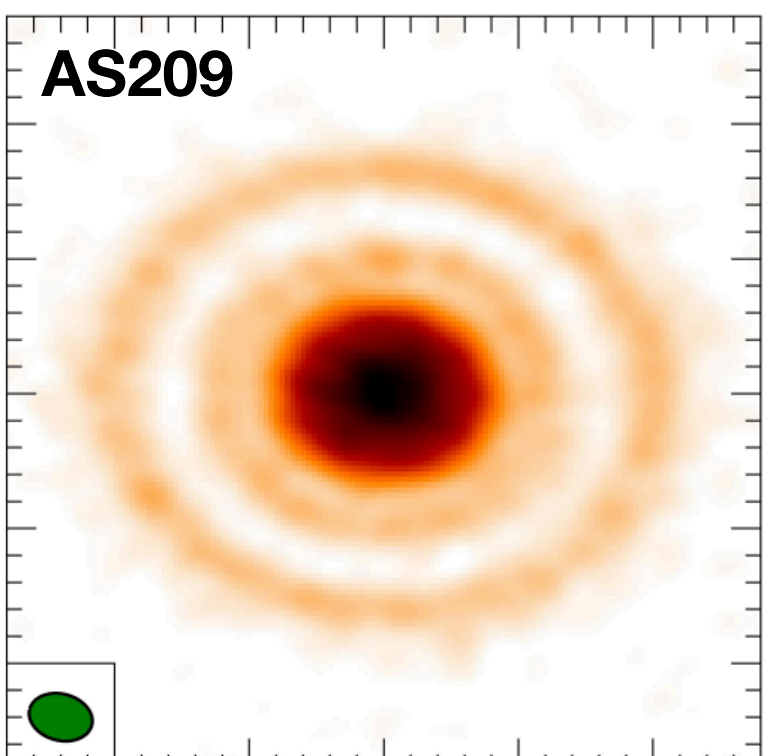


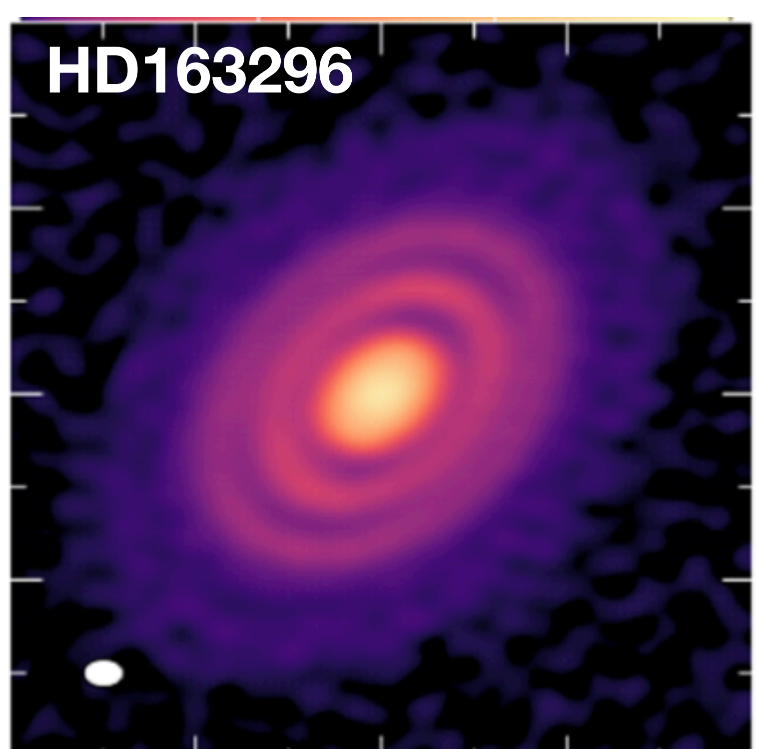
TW Hya

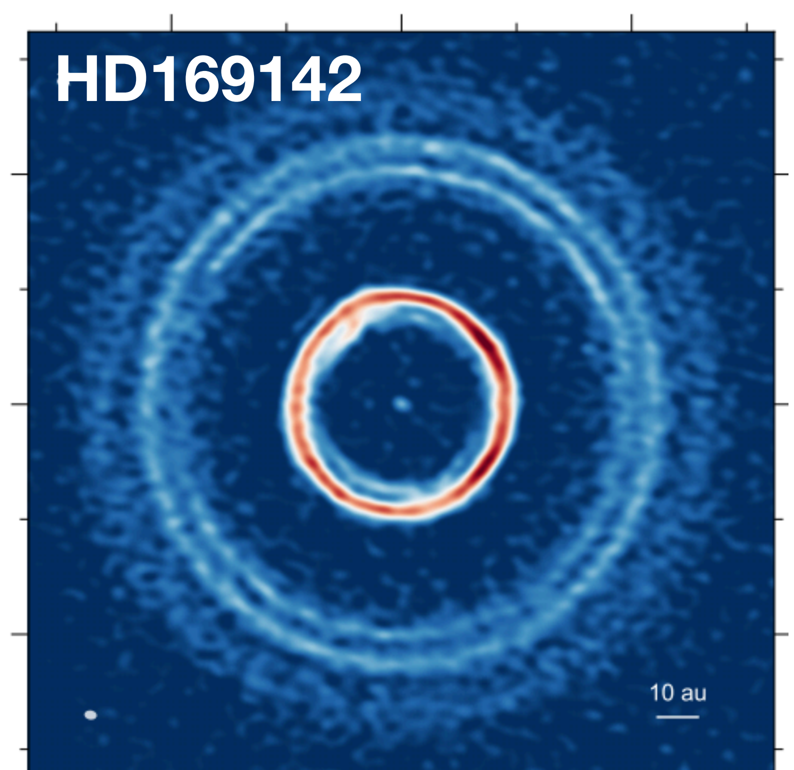


HD97048







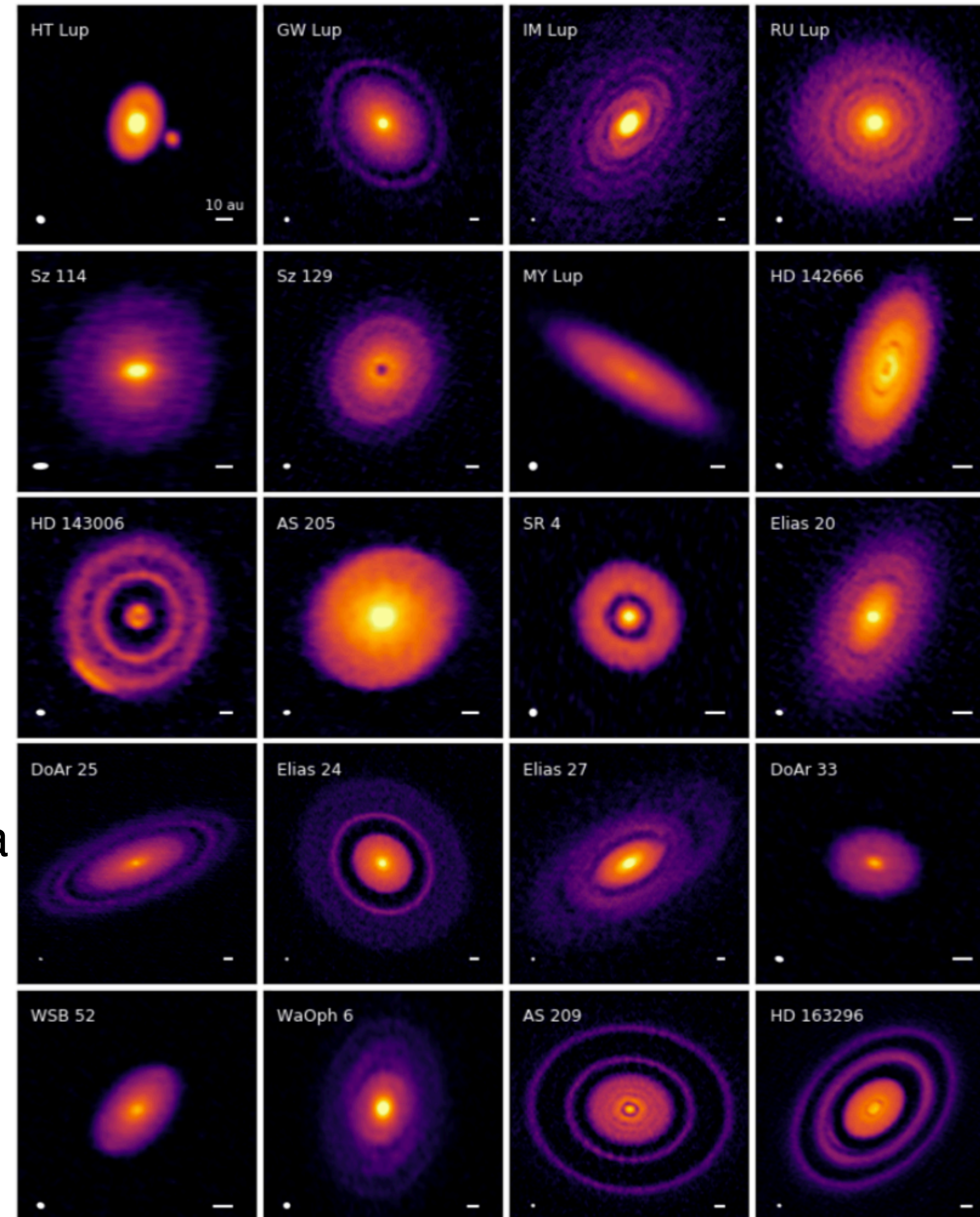


Also transition disks with multiple rings!

And more ring disks

- ALMA Large Program 2016 (Cycle 4), PI Sean Andrews
- Resolving 20 ‘full’ disks at 0.04”
- Distances 100-165 pc
- Dust continuum (1.3mm) + ^{12}CO 2-1
- Range of stellar masses (spectral types)
- Every disk has substructure: primarily rings, but also asymmetries, spiral arms
- Structures on scales of tens of au
- Selection bias: bright (large) disks with previous ALMA data

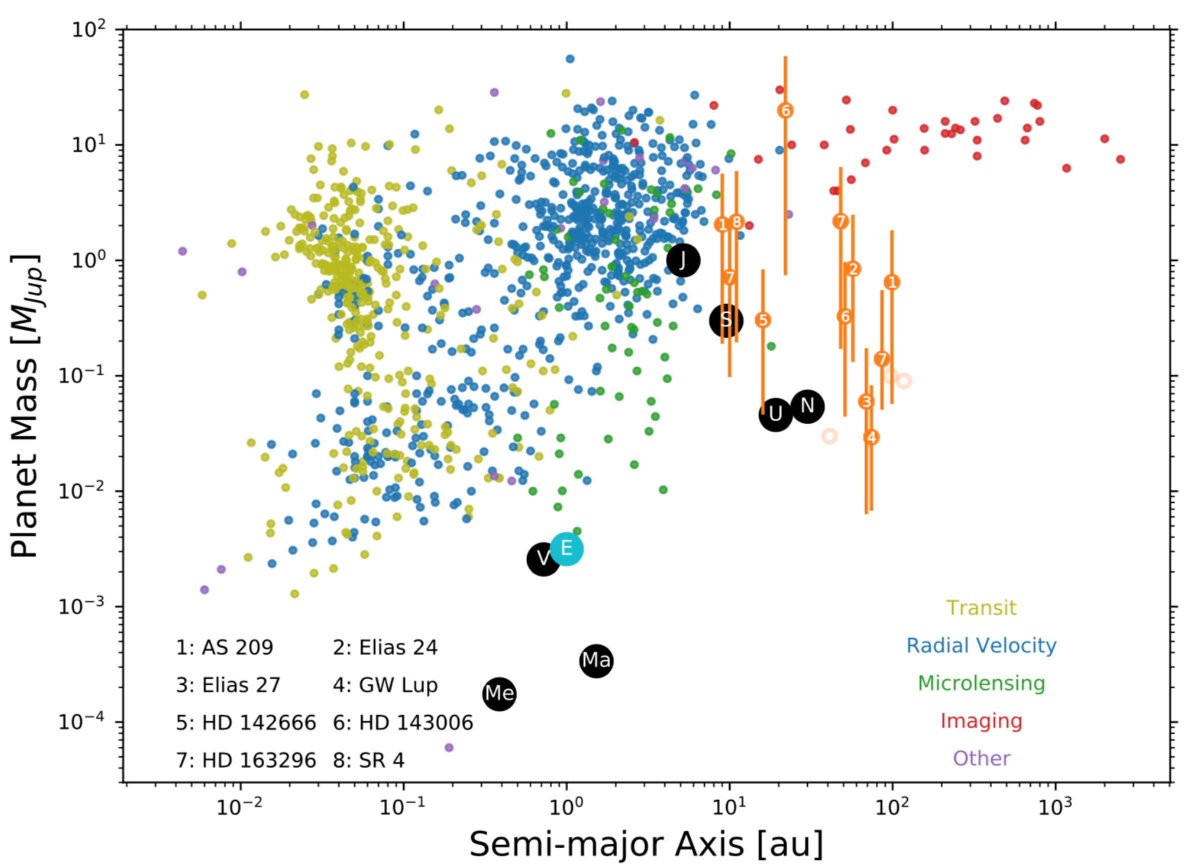
DSHARP

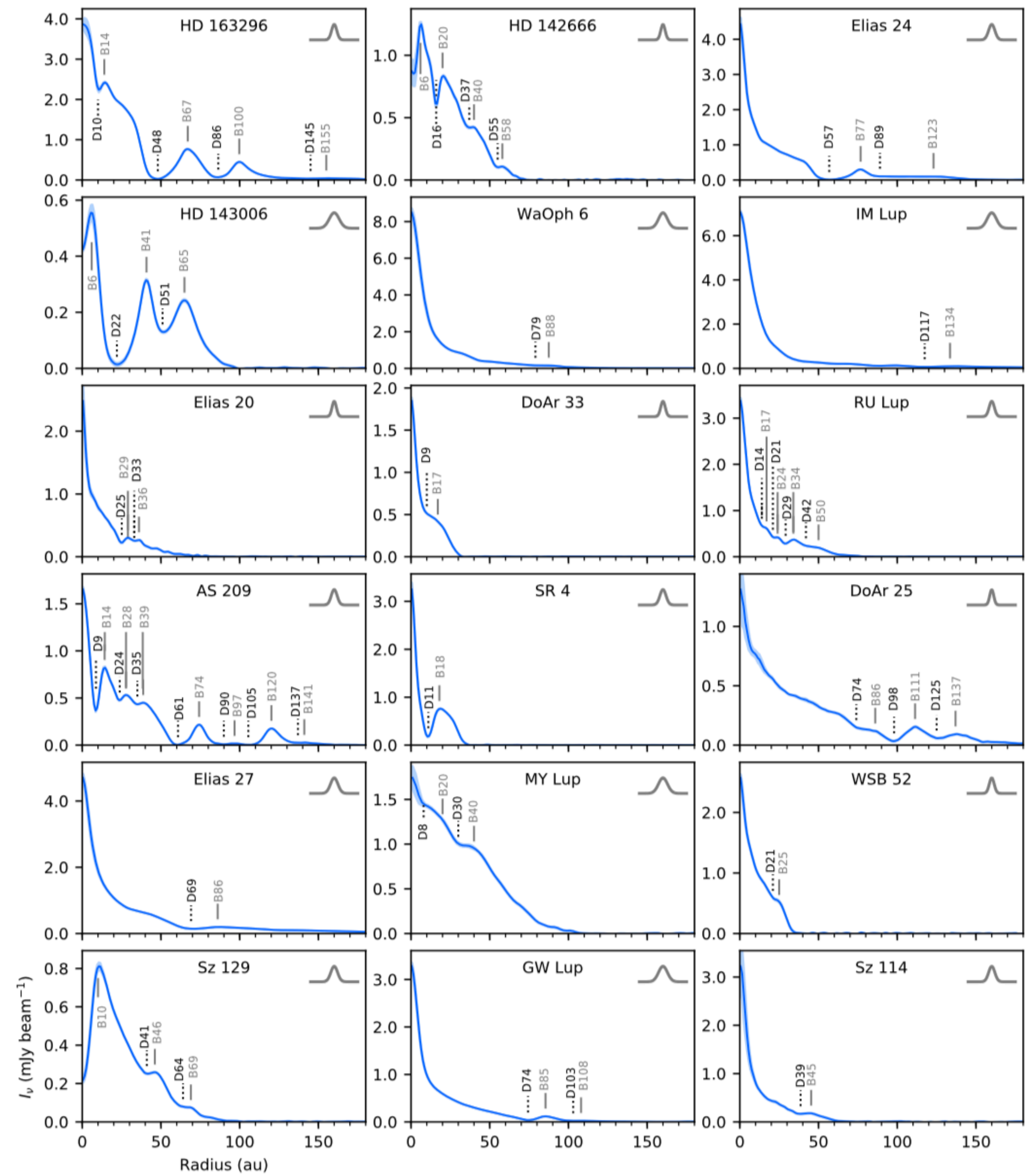


Andrews et al. 2018
Huang et al. 2018

And more ring disks

- Rings and gaps are commonly found at a wide range of radii, up to ~150 au
- Many features are narrow, down to ~<5 au (close to resolution)
- No correlation ring/gap locations with stellar properties
- Derived exoplanet locations/mass in non-detectable range (current techniques)





Huang et al. 2018
Zhang et al. 2018

Origin rings and gaps

1. Planet-disk interaction

2. Snowlines: see next slide

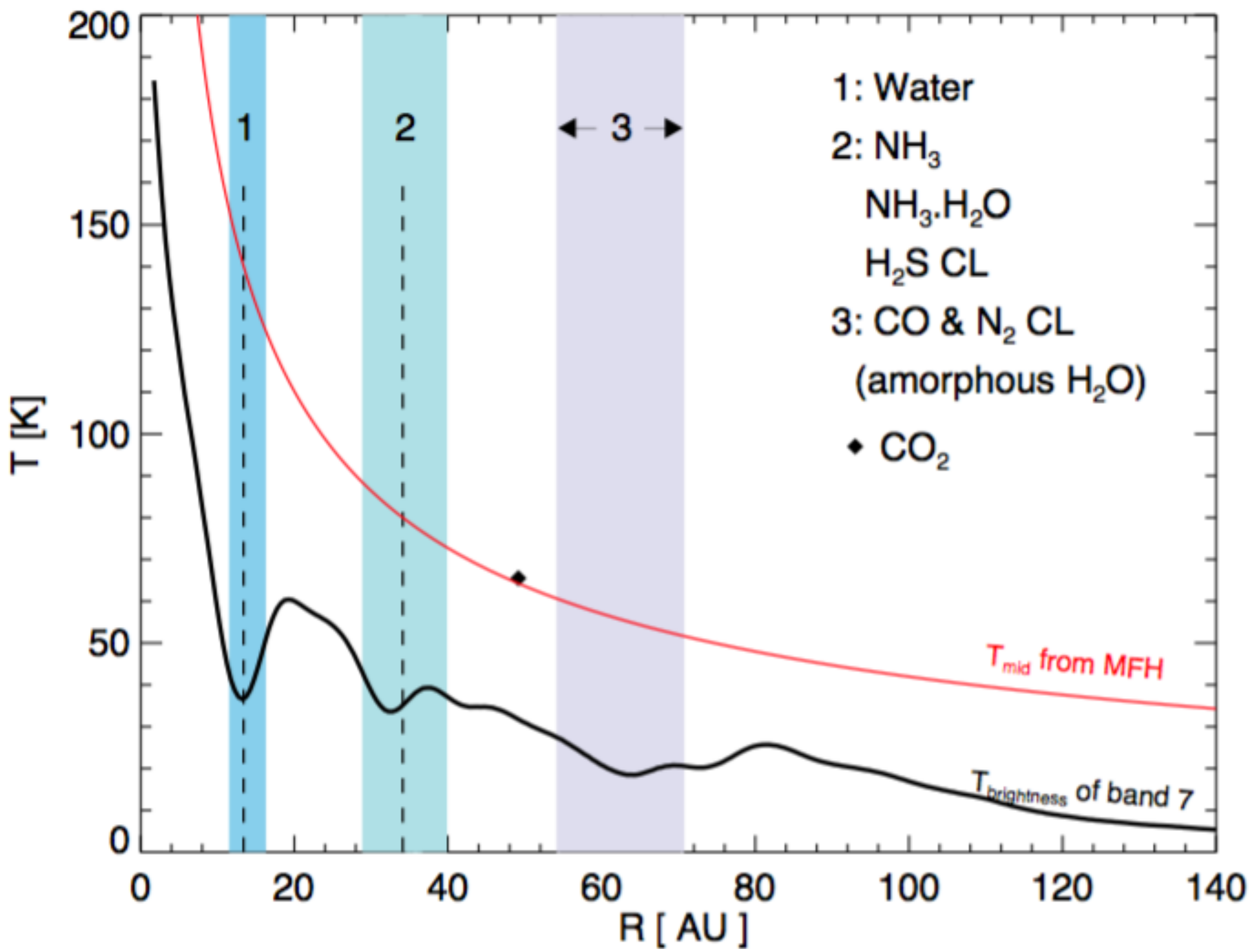
3. Hydrodynamic instabilities: vertical shear, dust-driven viscous ring, secular gravitational instability

4. Magnetohydrodynamic instabilities, related to MHD winds, dead zones, MRI turbulence

} **Difficult to test observationally**

Snow lines

Basic idea: freeze-out of various molecules at various radii, depending on the temperature => increase stickiness dust grains => change dust growth at radii => rings/gaps



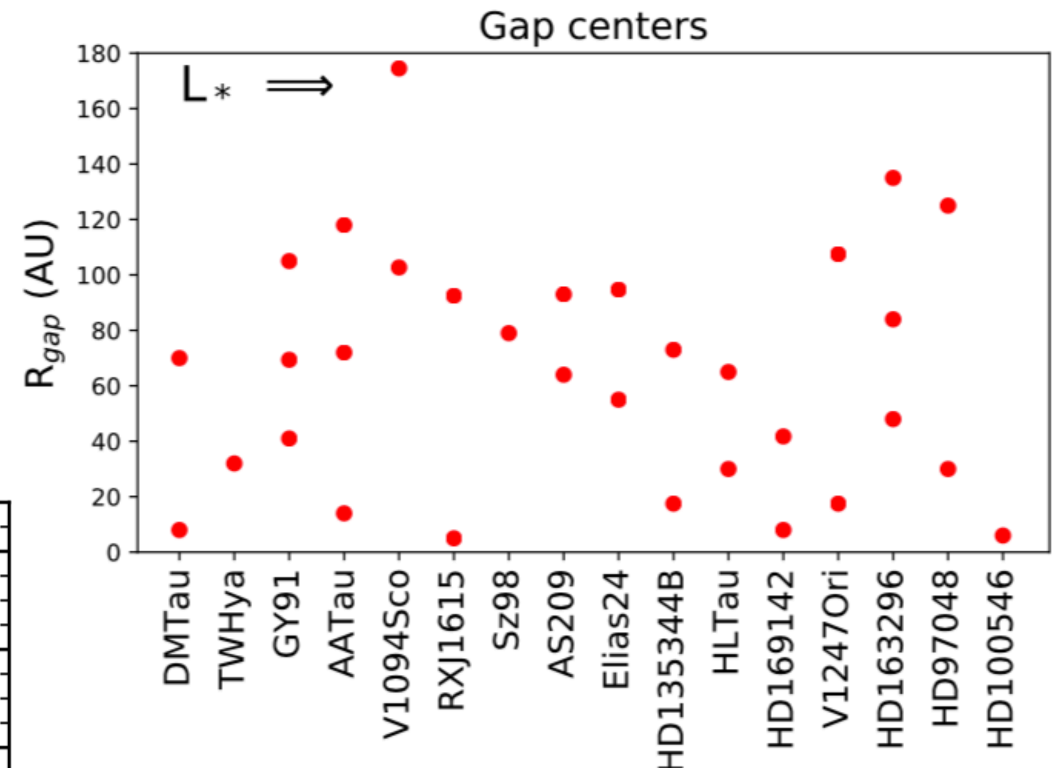
Reasonable fit for HL Tau!

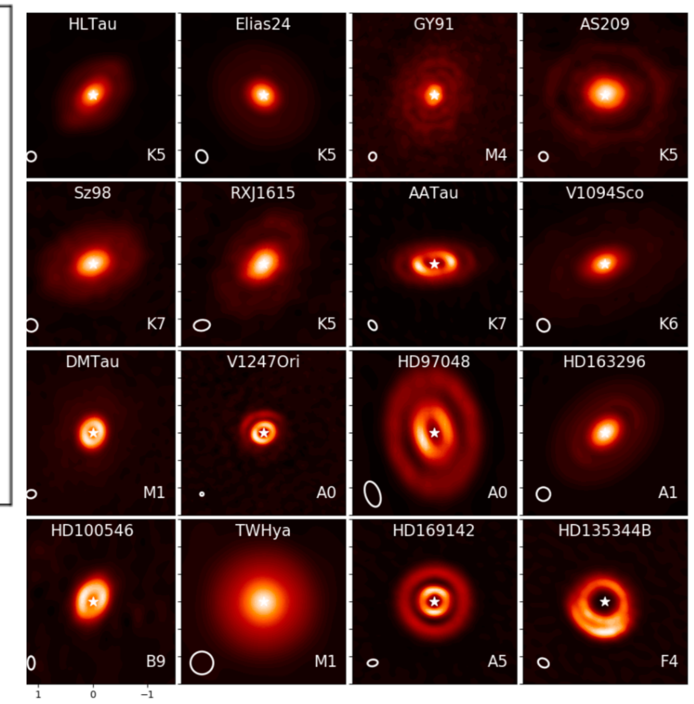
Zhang et al. 2015

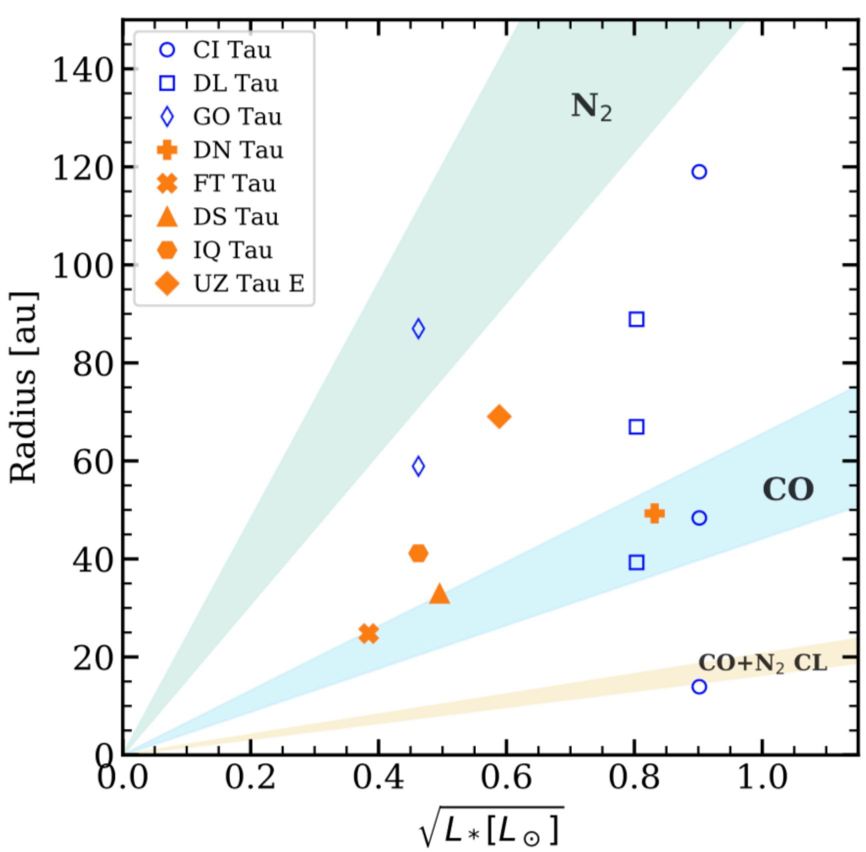
Snow lines

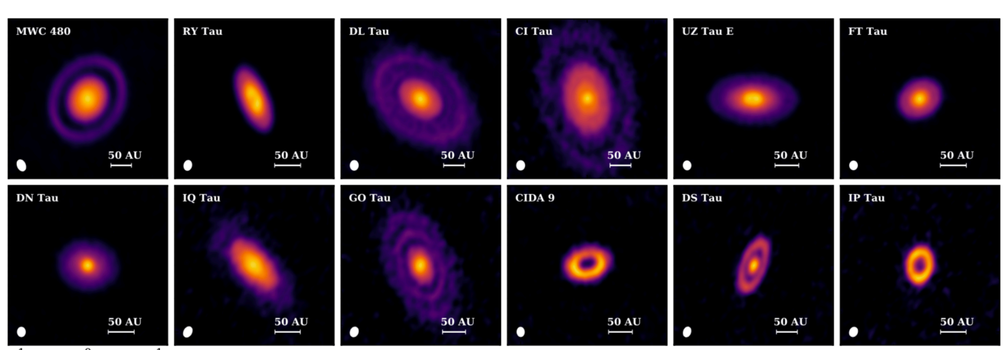
Three independent sample studies of ring disks (December 2018):

NO correlation between stellar luminosity and gap radii, so snow line scenario is unlikely









+ DSHARP!

Long et al. 2018
Huang et al. 2018
Van der Marel et al. 2019

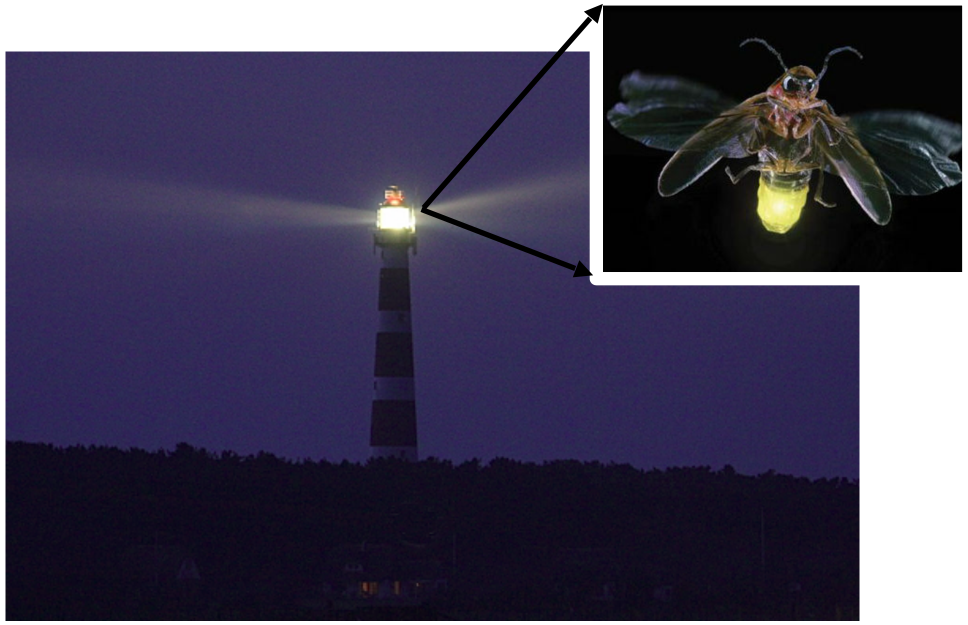
Planets

If planets are responsible for ring disks:

- Planets must be relatively massive (Saturn-Jupiter)
- Planets must form early (rings and gaps found in systems that are <1 Myr old)
- Jupiter-mass planets must form easily at tens of au
- Planets do not migrate inwards significantly after formation

Detecting planets

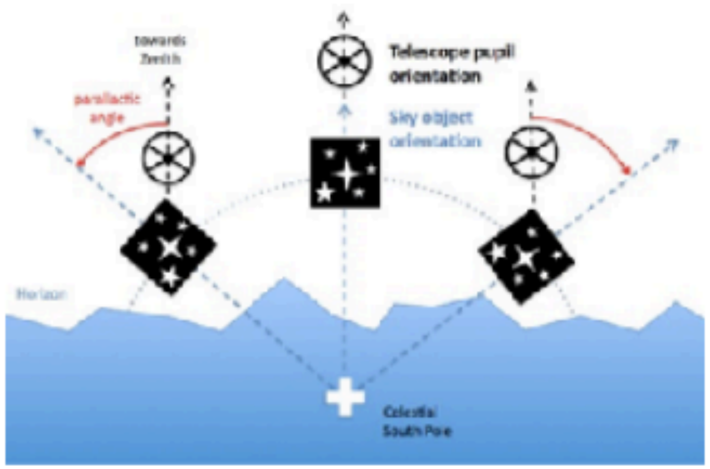
- Common techniques exoplanets (radial velocity, transits) not possible as young stars are intrinsically variable
- Direct imaging
  - Near infrared (lower contrast from ~10^{-8} to 10^{-4} wrt optical): => J/H/K/L' (1.2/1.7/2.2/3.8 μm)
  - Adaptive Optics for high resolution (bright objects only)
  - Coronagraph to block star (sometimes)
  - Remove diffraction pattern:
    - Angular differential imaging (ADI)
    - Spectral differential imaging (SDI)
    - Reference star differential imaging (RDI)
    - (Polarized differential imaging (PDI)) => not for disks



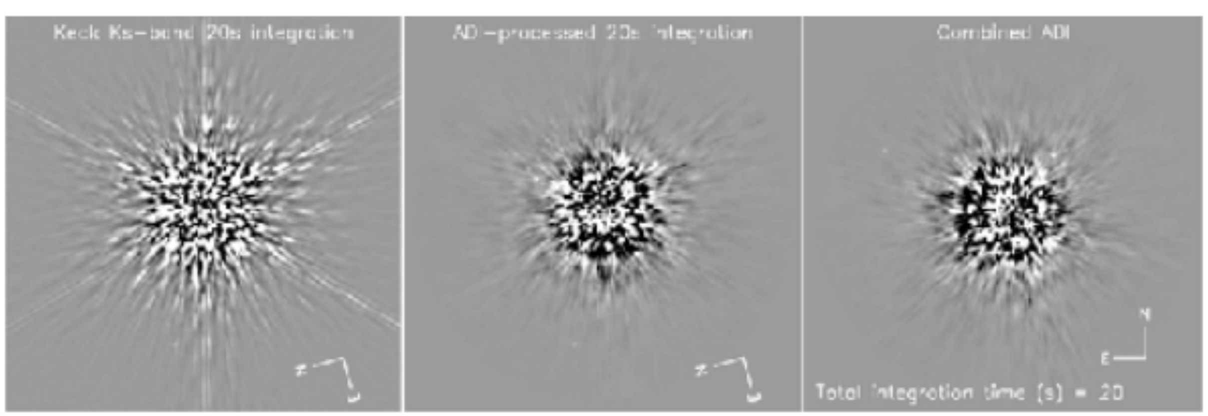
Detecting planets

Angular Differential Imaging (ADI)

(Marois+2006)



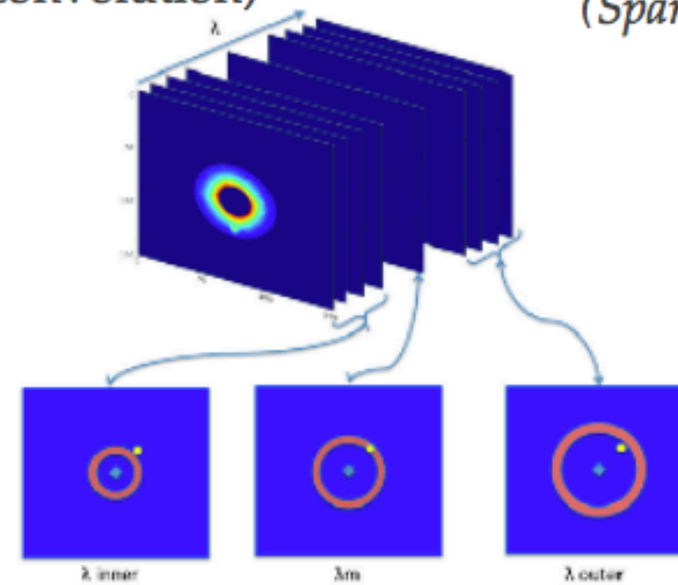
The companion rotates with the field,
while the PSF stays fixed



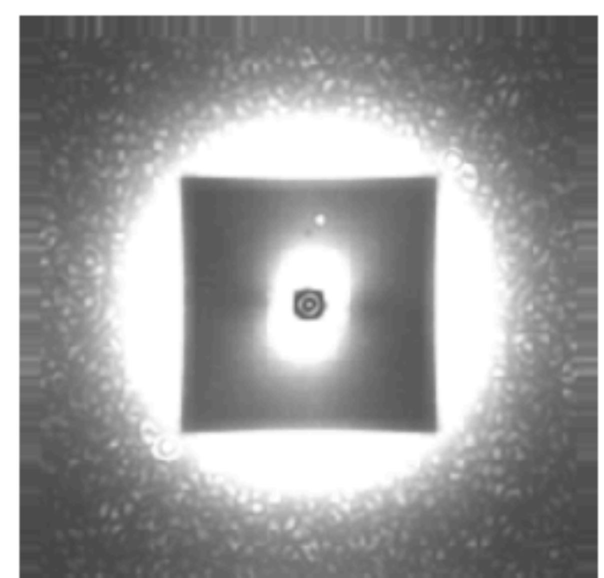
Spectral Differential Imaging (SDI)

(or spectral deconvolution)

(Sparks & Ford 2002)



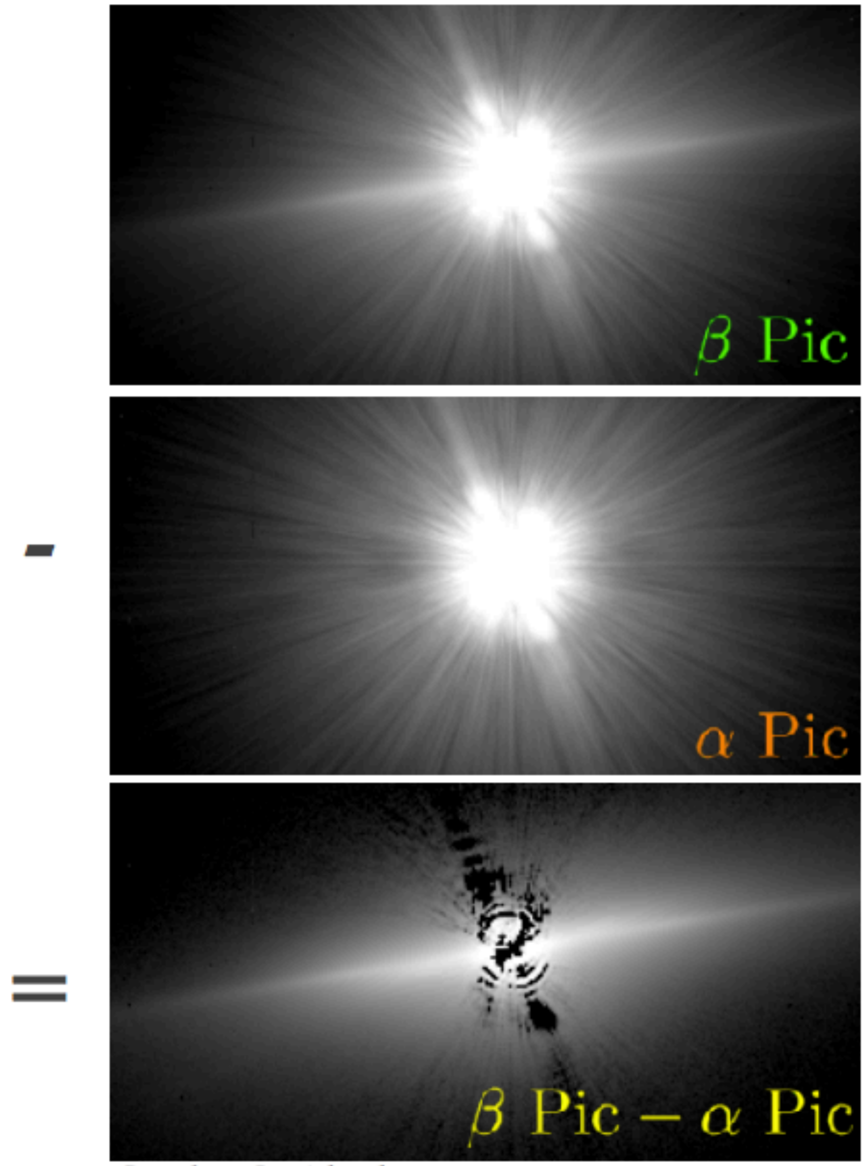
The companion stays fixed,
while the PSF expands with WL



Credit Valentin Christiaens

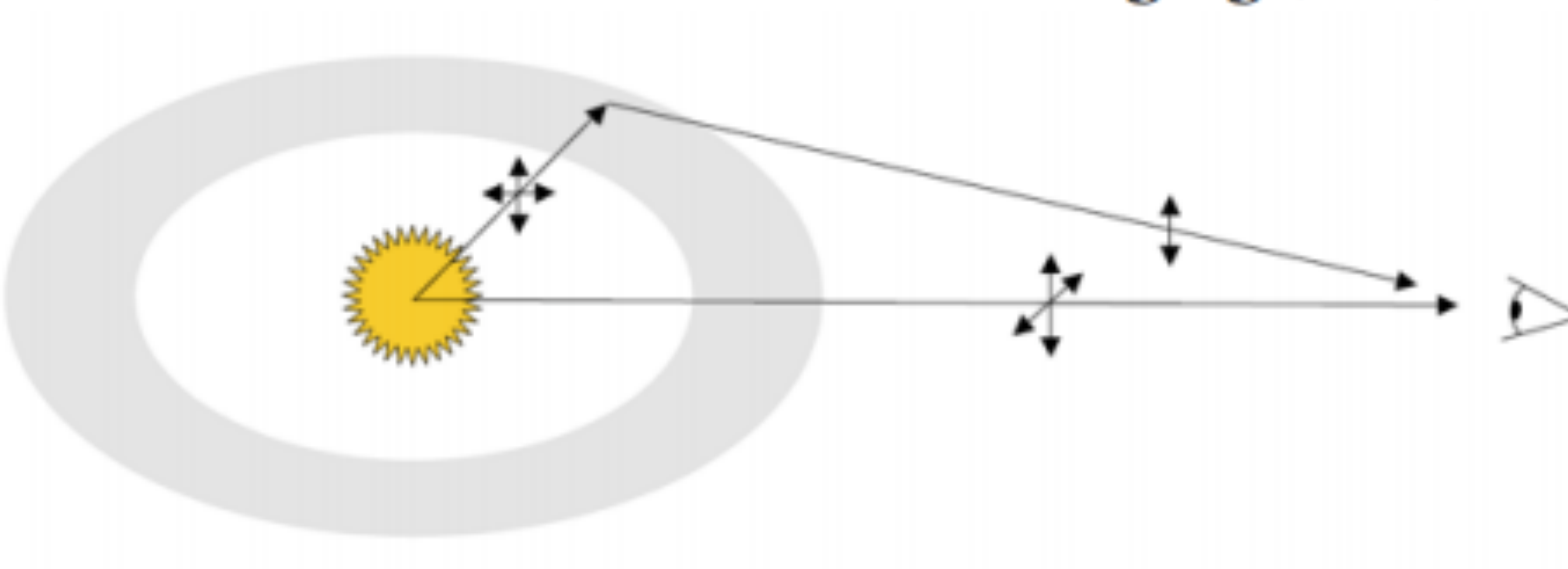
Detecting planets

Reference star Differential Imaging (RDI)



Credit: O. Absil

Polarimetric Differential Imaging (PDI)



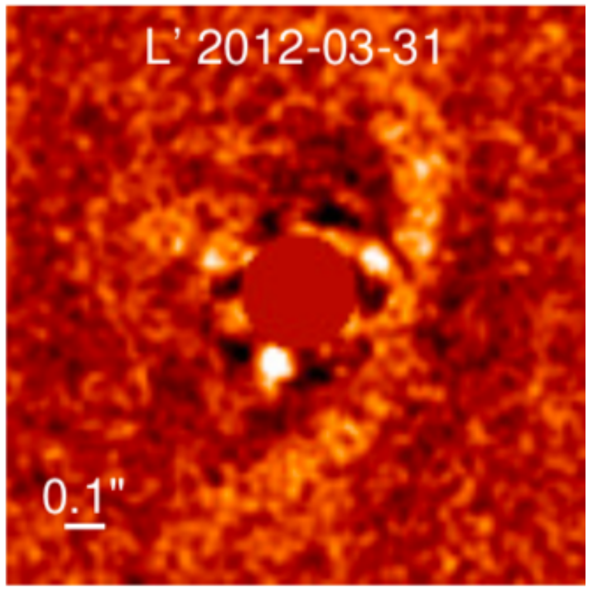
Not suitable for planets in disks:
dust scattering produces much more polarized light

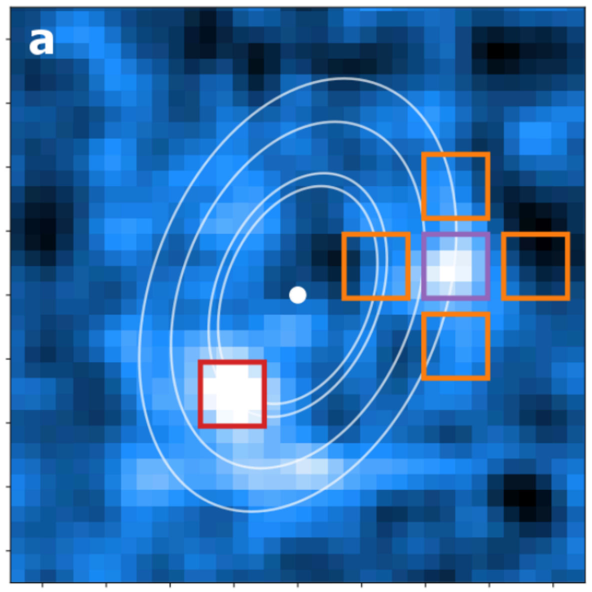
All 4 techniques may still result in non-real point sources in the image: multi-epoch (orbit) required to prove existence

Credit Valentin Christiaens

Detecting planets

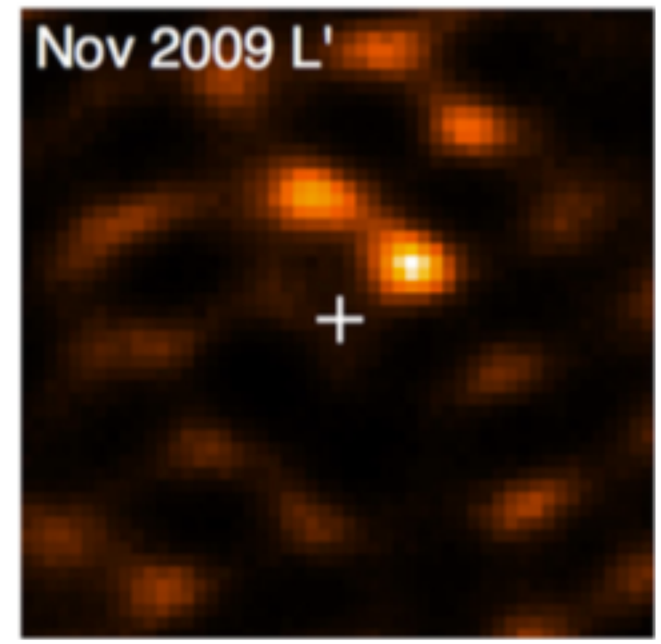
Success story: PDS70b (and c)

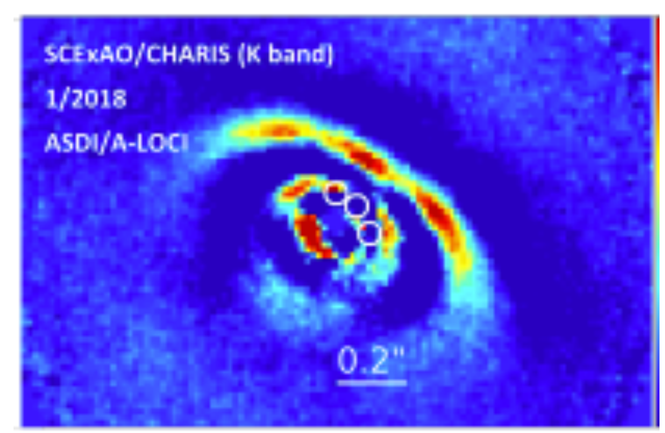




Keppler+2018, Wagner+2018, van Haffert+2019, etc.

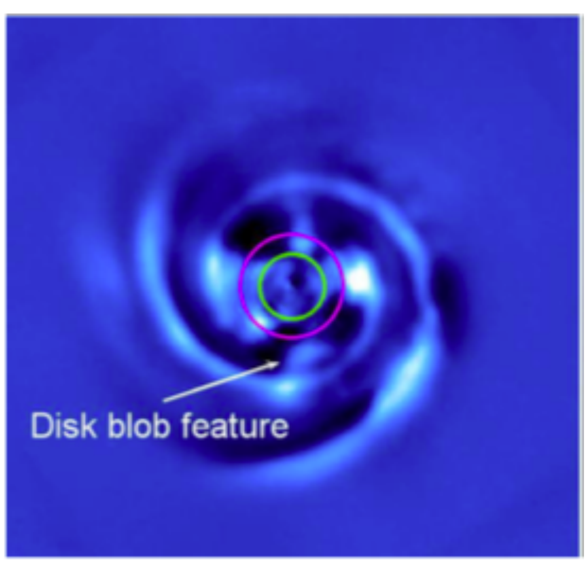
Not so successful: LkCa15b

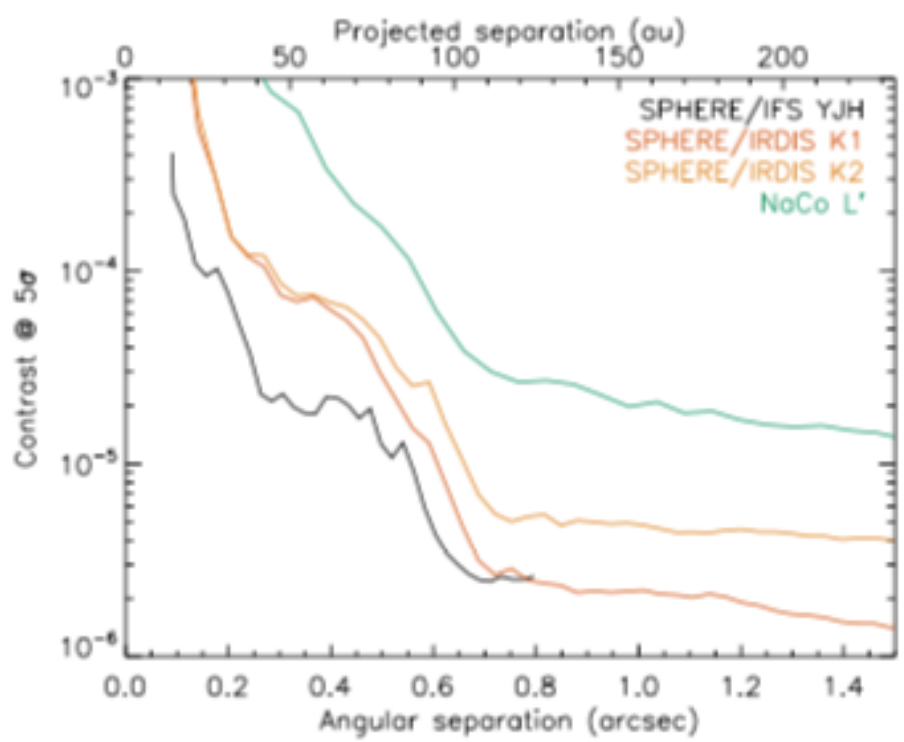




Kraus & Ireland 2012,
Sallum+2015
Currie+2019

And non-detections, like in HD135344B

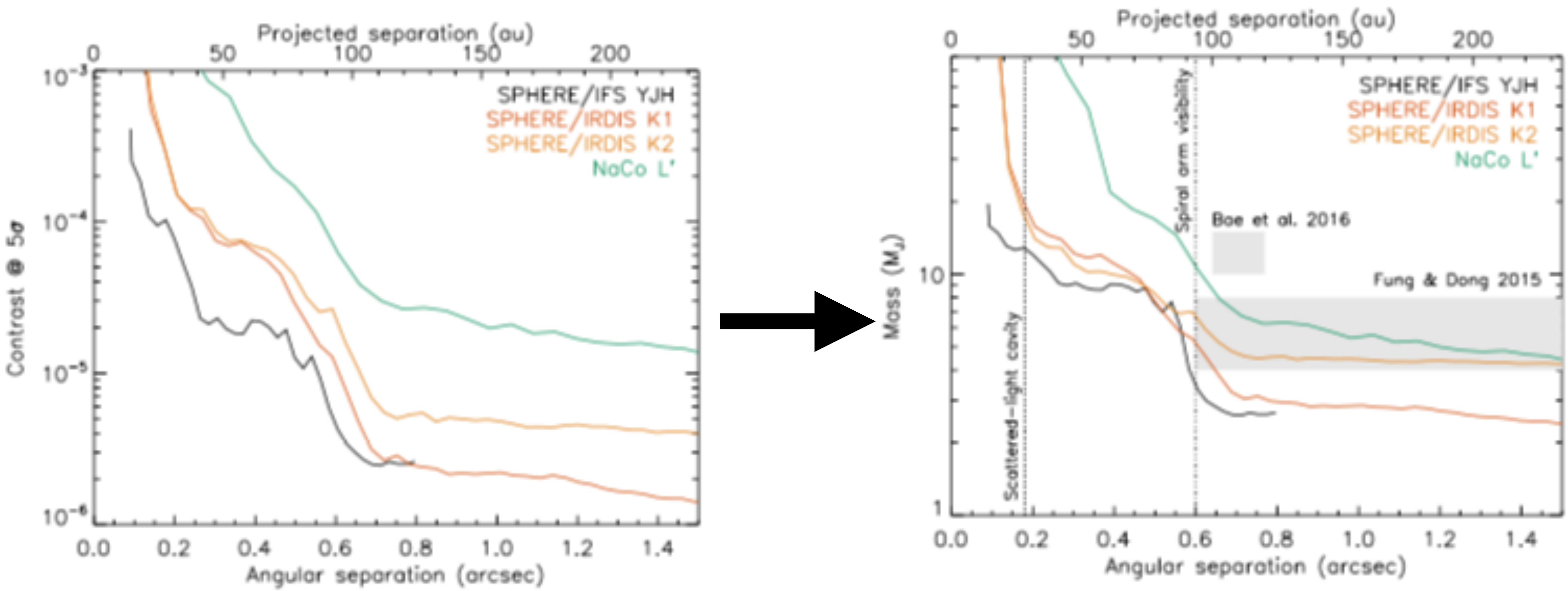




Maire+2017

Detecting planets

Contrast curve:
convert from contrast to planet mass

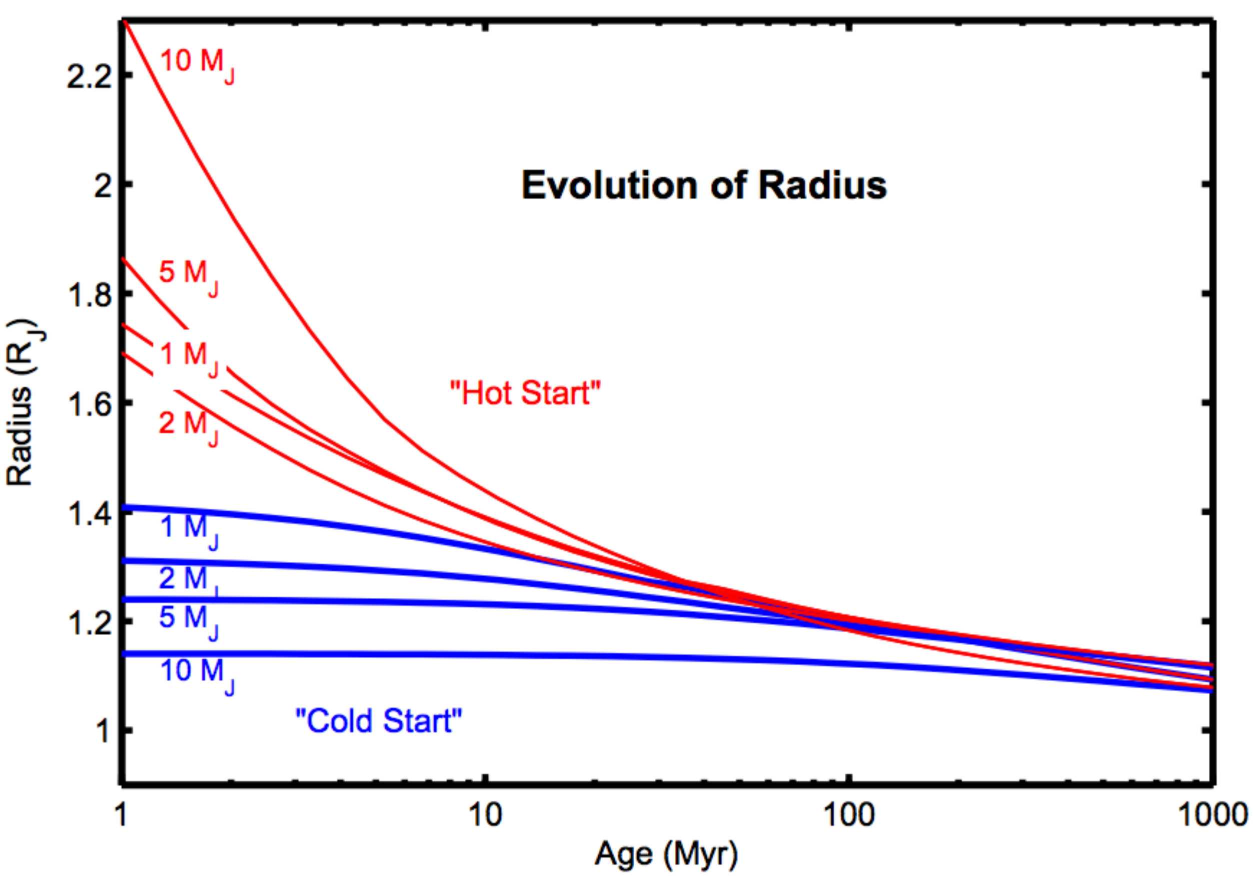


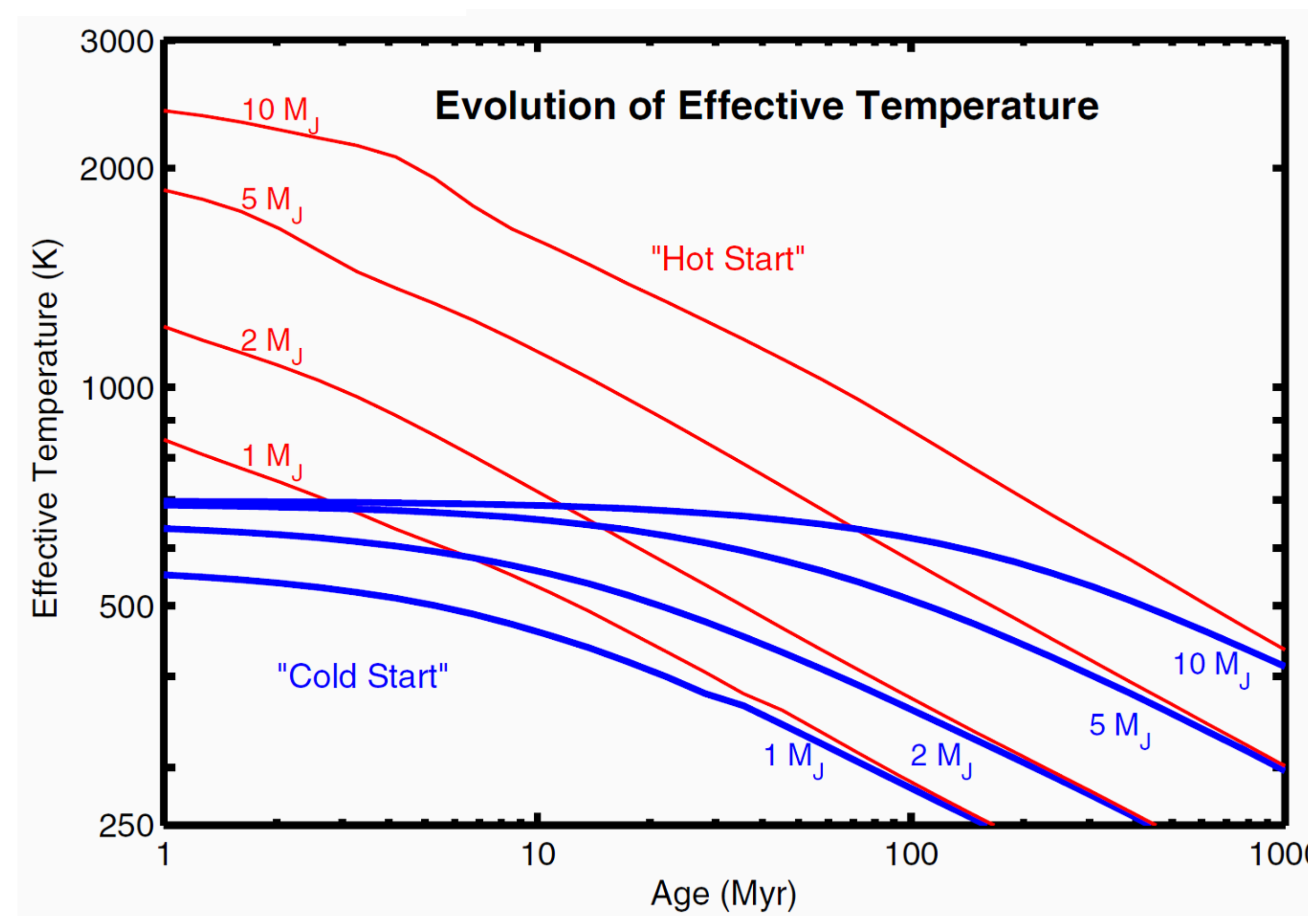
Convert contrast (with stellar luminosity) to a brightness,
which can then be converted to a mass using an evolutionary model

Maire+2017

Detecting planets

$$L = Area\ x\ flux = 4\pi R^2 \sigma_{SB} T^4$$





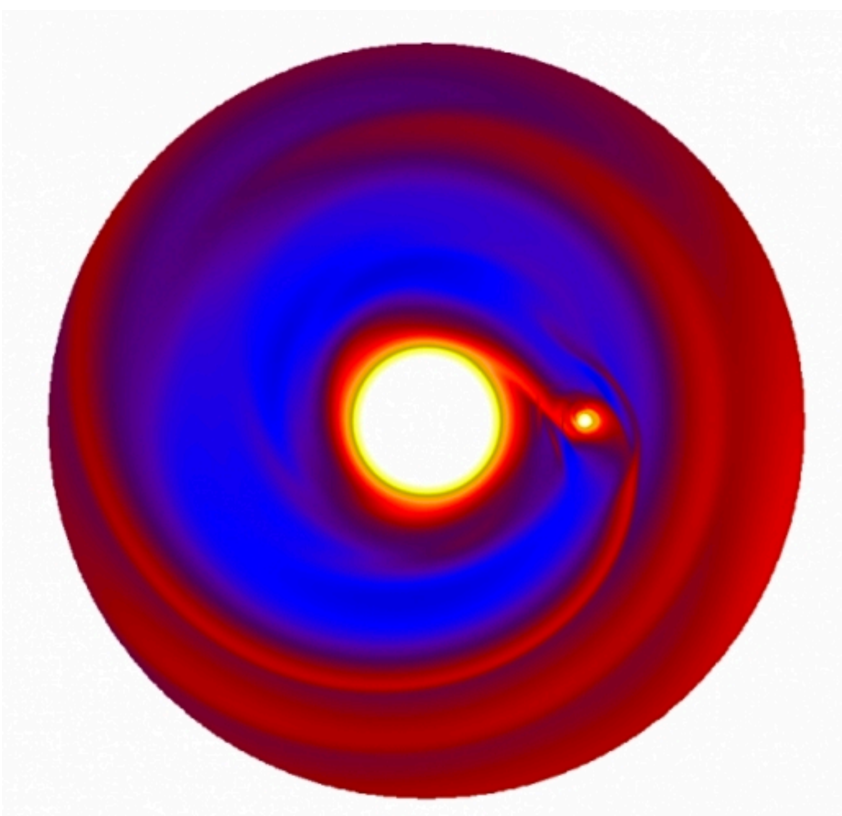
Problem 1: young planets are bright, but we don’t know exactly how bright (hot-start vs cold-start models)

Marley et al. 2007
Spiegel & Burrows 2012

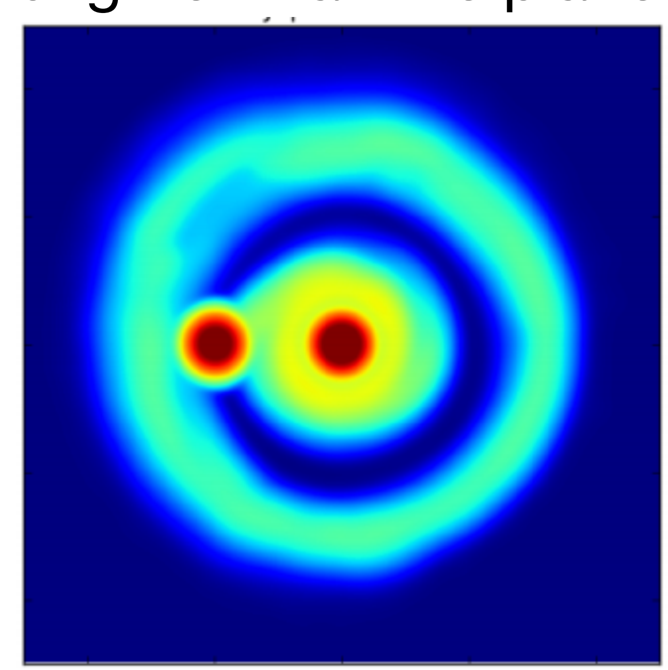
Detecting planets

Problem 2: for thermal emission, majority of emission originates from dust in the circumplanetary disk (CPD)

If a planet forms in a disk, accreting material naturally forms a circumplanetary disk



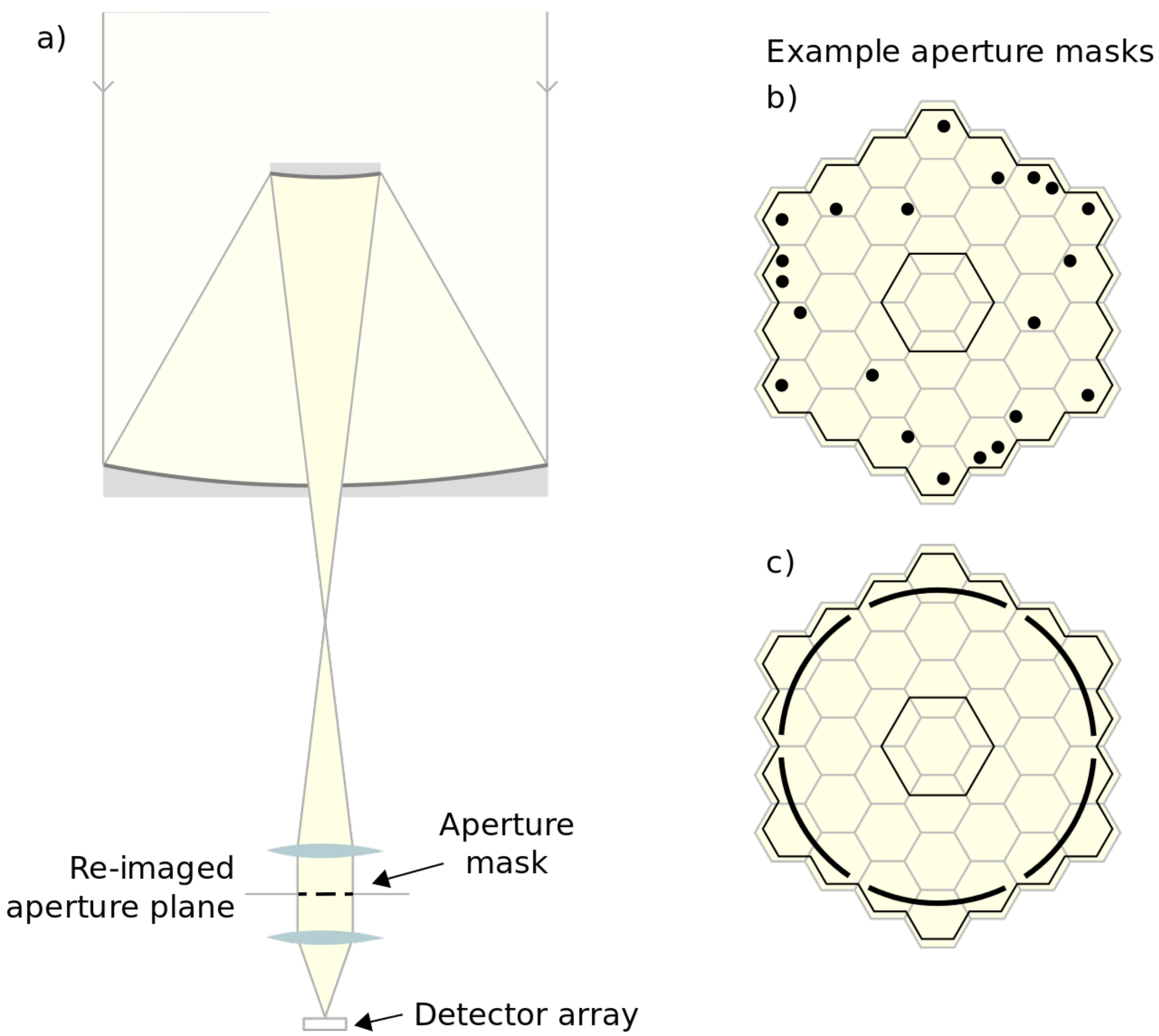
For typical conditions, the circumplanetary disk is 20-100x brighter than the planet in NIR

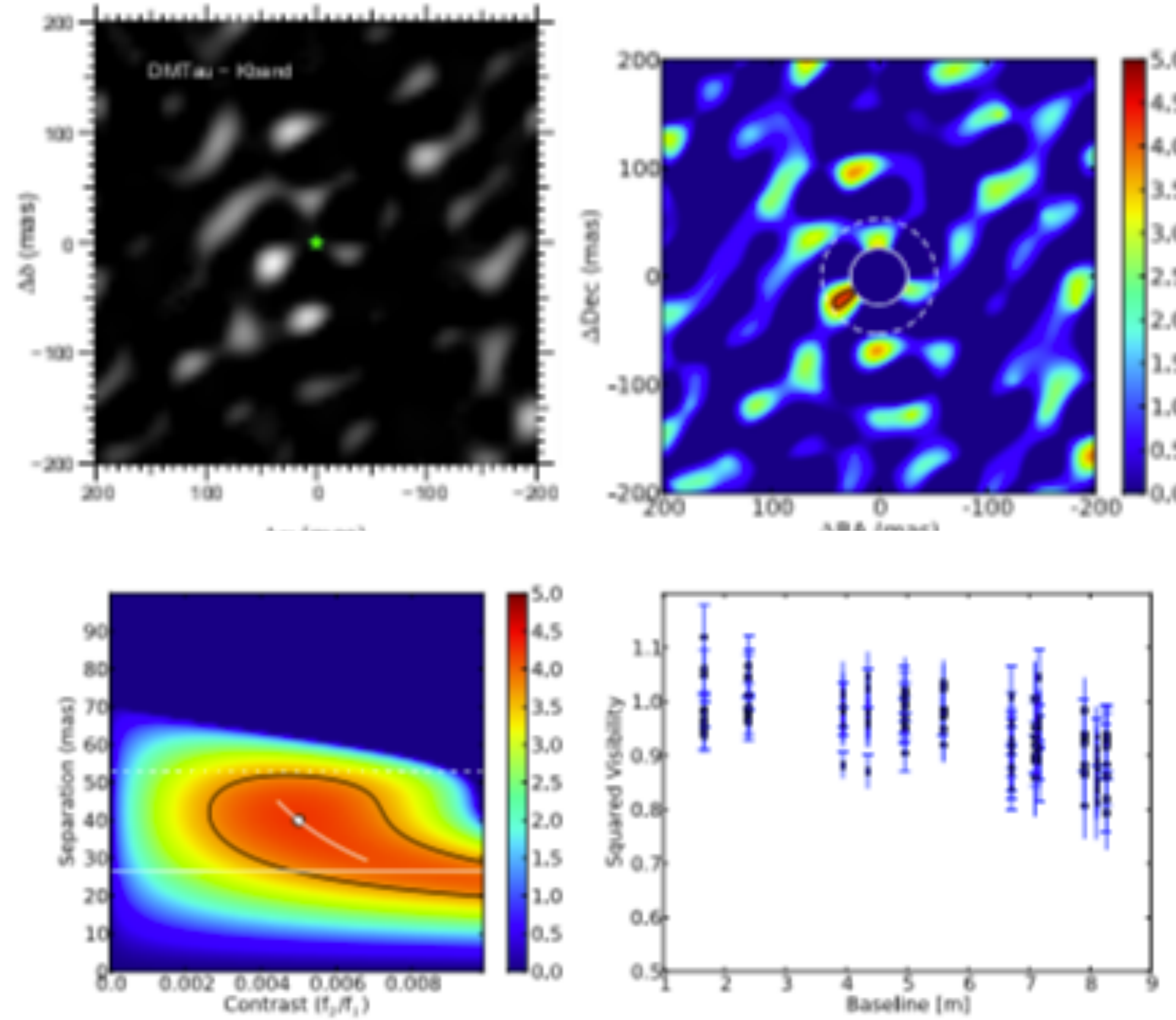


Hydrodynamical simulations by Szulagyi et al. 2018, 2019 of observability planets and CPDs

Detecting planets

Sparse Aperture/Non-redundant Masking (SAM/NRM):
creating an interferometer for a single dish telescope for small separation companions (<40 mas)





Problem: no proper uv-sampling so imaging is hard: interpretation from incomplete visibility curve, where any asymmetry can look like a planet
Other problems: brightness limited and small FOV

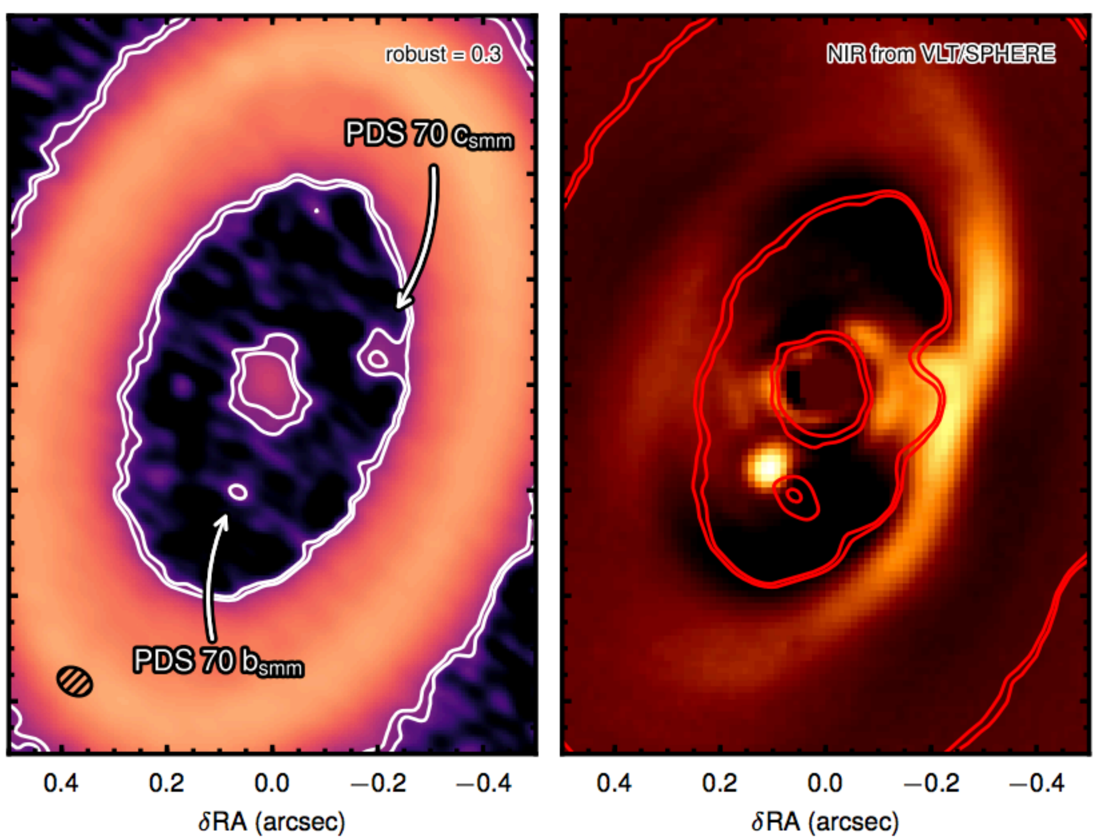
Tuthill et al . 2006
Willson et al. 2016

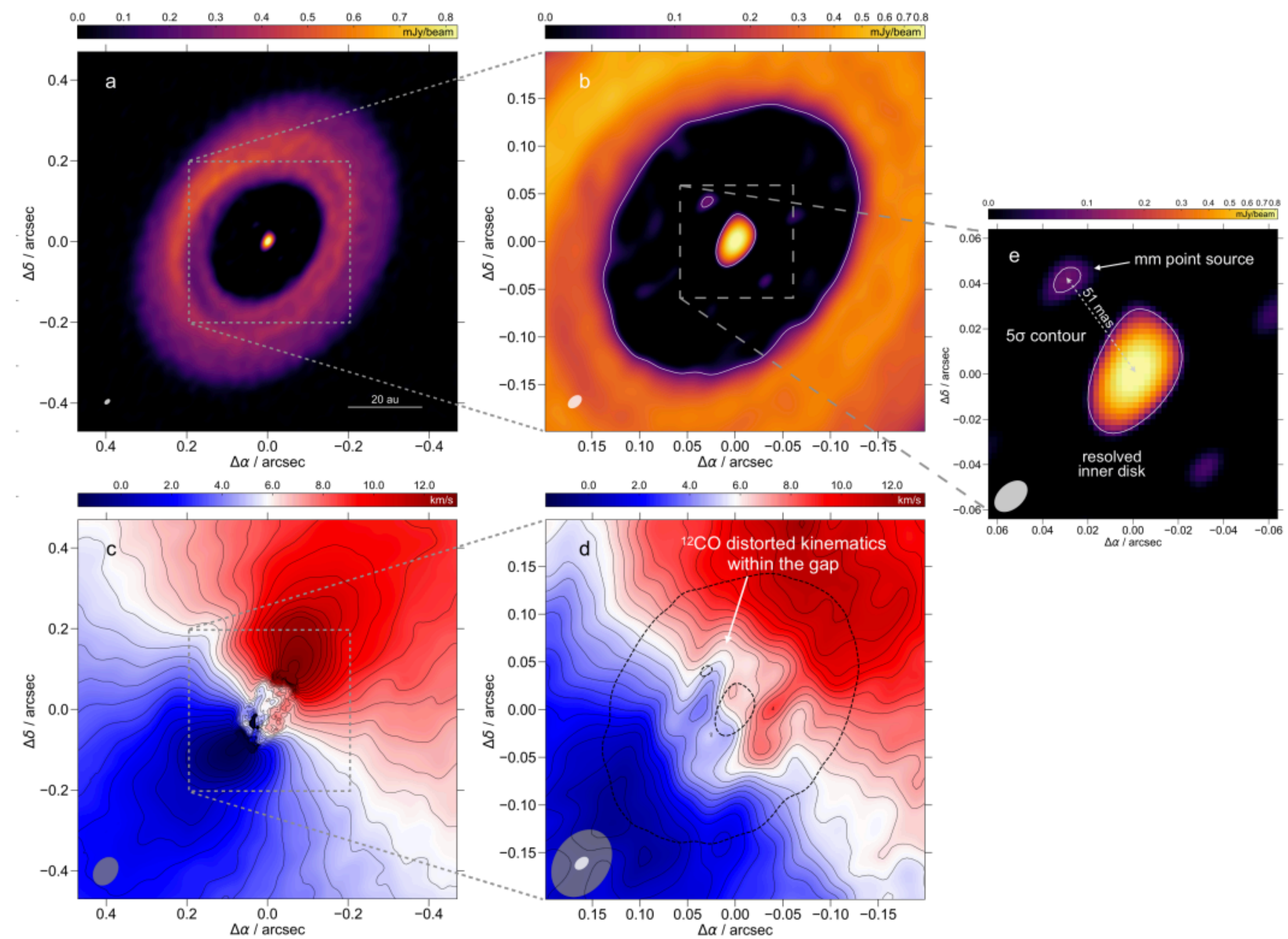
Detecting planets indirectly

Circumplanetary disks with ALMA continuum (and kinematics?)

HD100546

PDS70

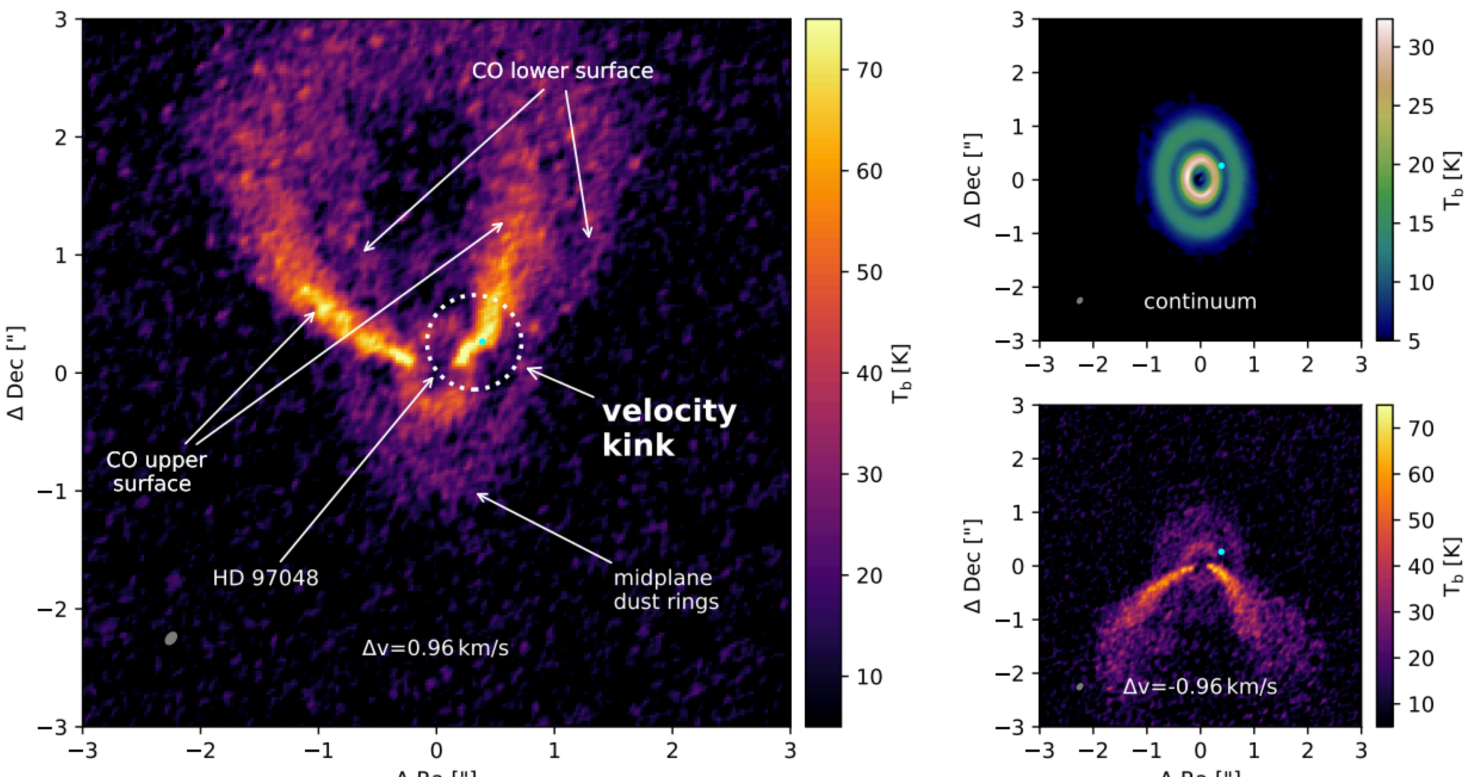




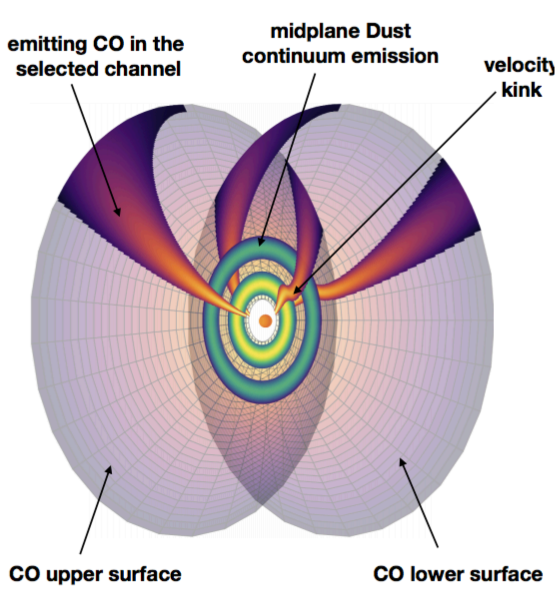
Isella et al. 2019
Perez et al. 2019

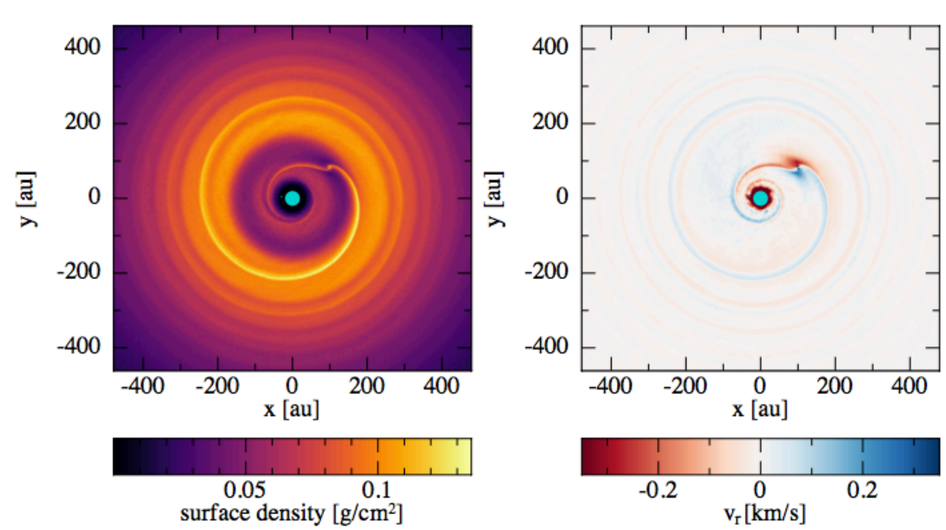
Detecting planets indirectly

Spiral waves launched at Lindblad resonances by planet cause ‘kink' in ^{12}CO velocity pattern

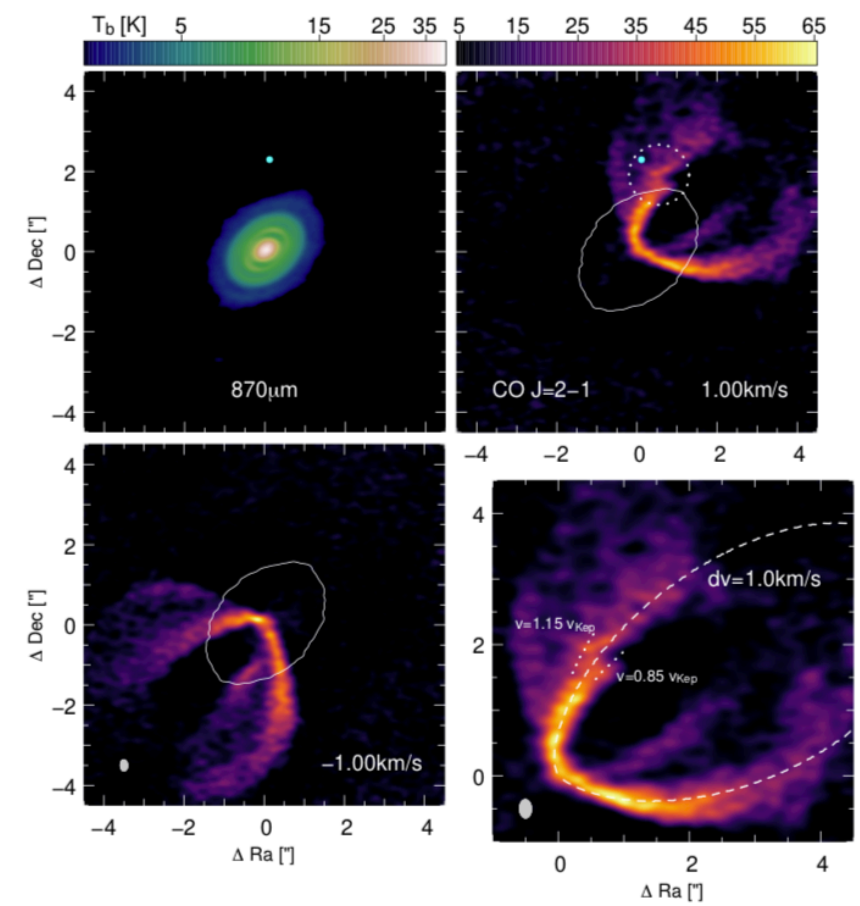


HD97048





HD163296

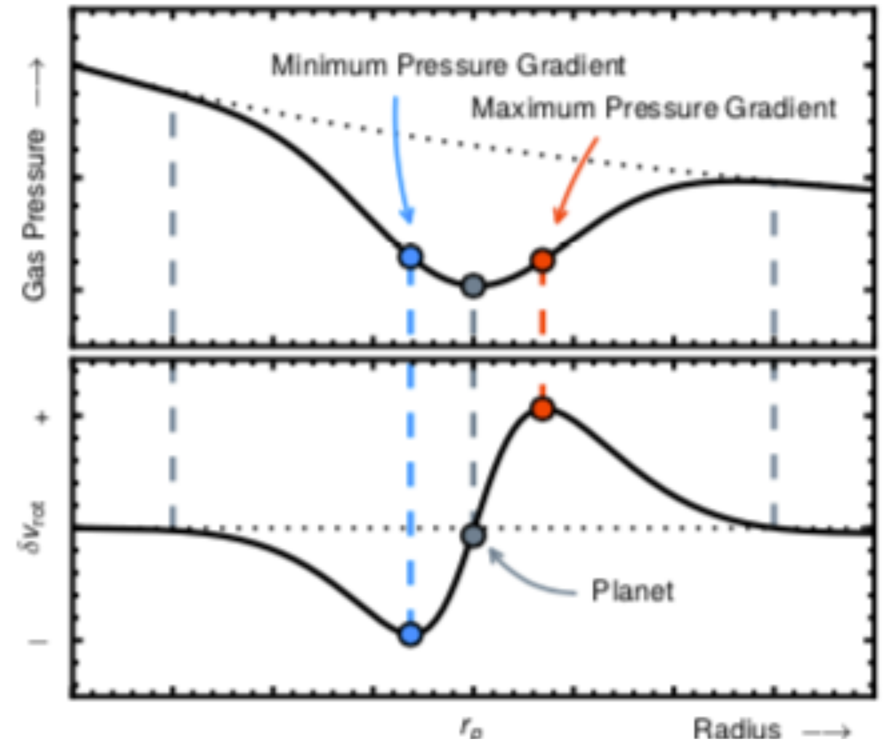


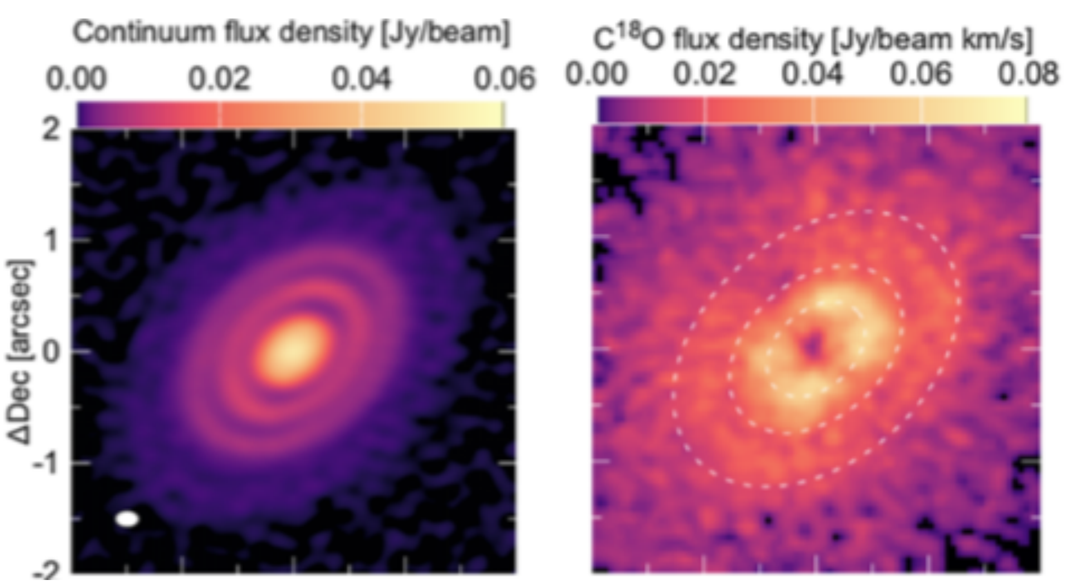
Pinte et al. 2018, 2019

Detecting planets indirectly

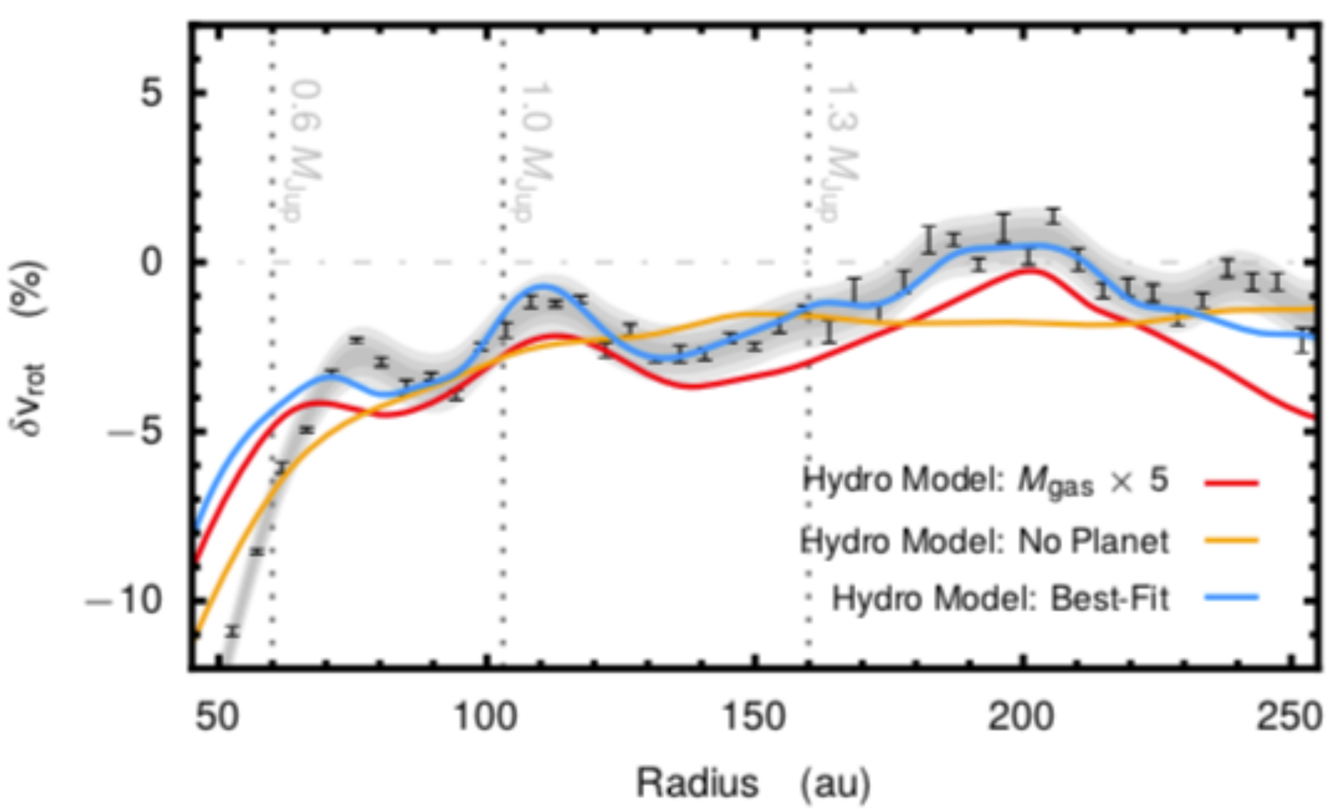
Pressure bumps at the edge of gas gaps create minor changes in the rotational velocity:

Use azimuthally averaged $C^{18}O$ velocity profile to derive gas gaps and planets masses





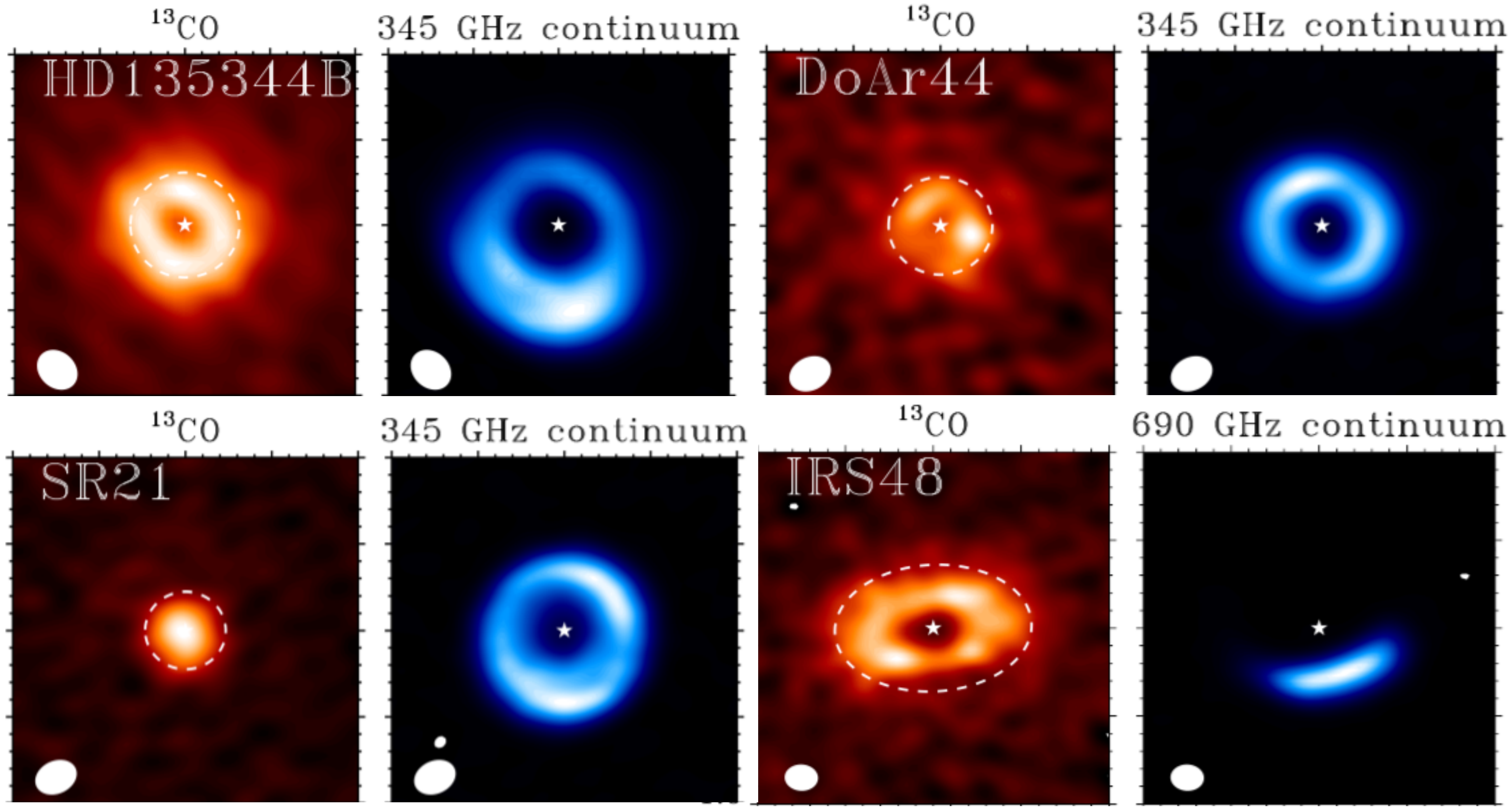
HD163296



Teague et al. 2018

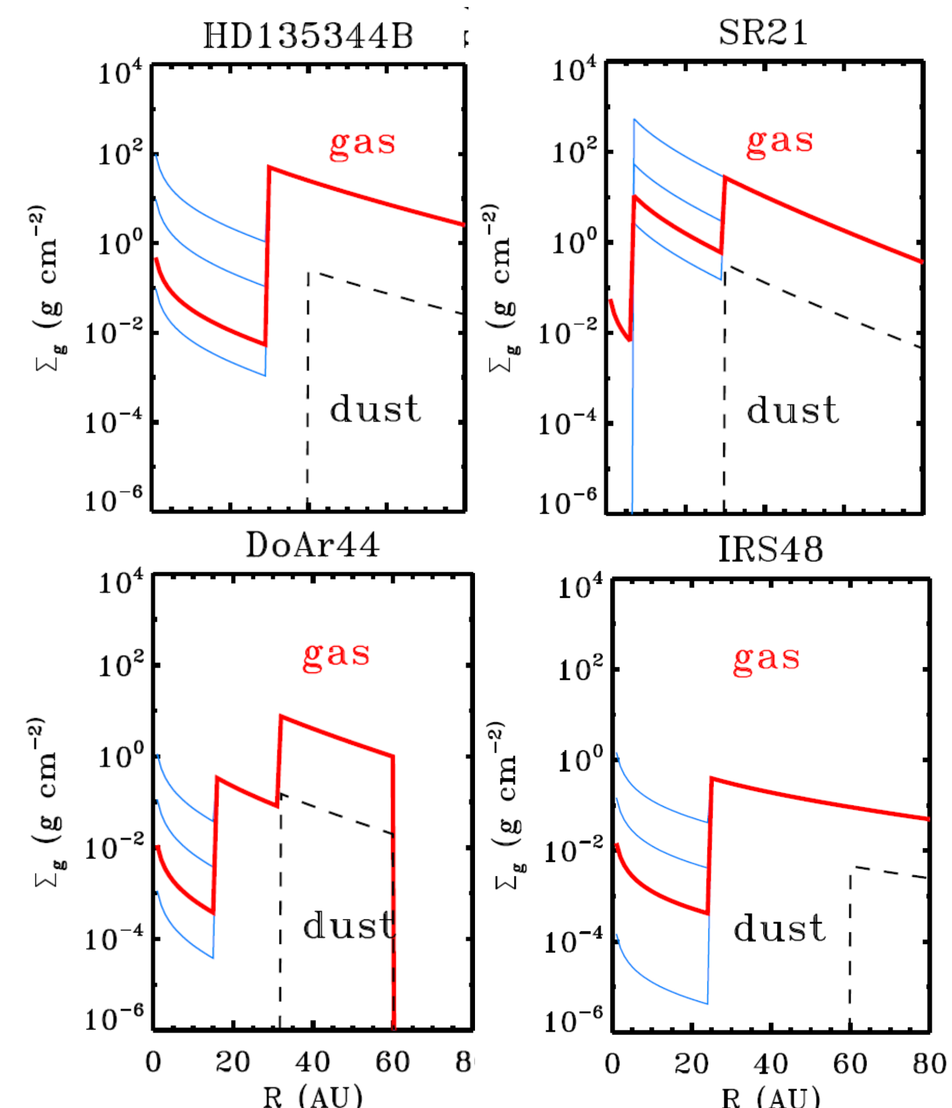
Detecting planets indirectly

Observations

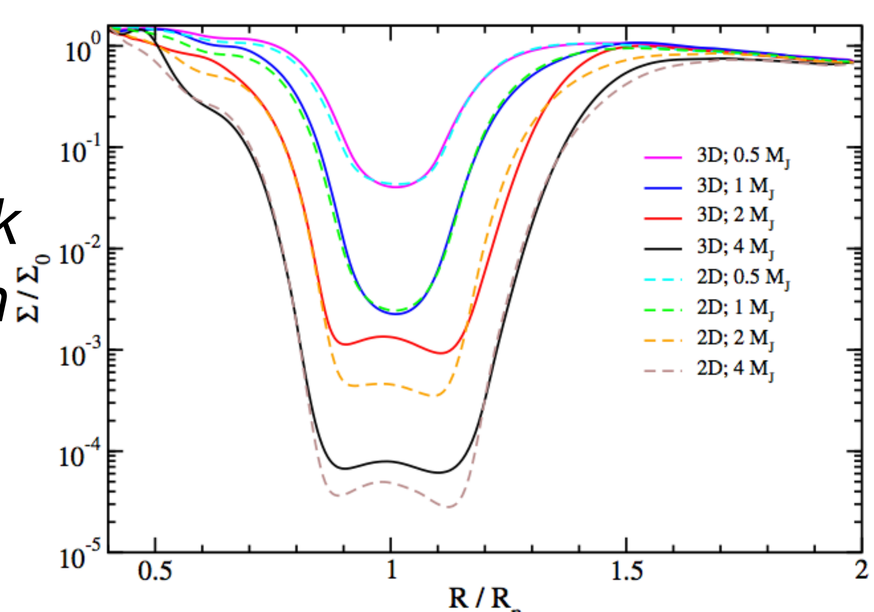


ALMA CO maps reveal deep gas gaps, consistent with clearing by Jupiter-mass planets

Derived surface density



Planet-disk interaction model



Derived depth depends on our understanding of CO chemistry/heating

Van der Marel et al. 2016
Fung & Chiang 2016

Open questions

- How reliable are indirect methods to derive planet masses?
- How well do we understand circumplanetary disk accretion?
- How well do we understand evolutionary models of planet atmospheres to convert brightnesses to planet masses?
- Are planets truly responsible for gaps and rings in ring disks?
- How do we test observationally for the proposed (magneto)hydrodynamic processes causing rings and gaps?
- How does planet migration affect the picture of planet locations in disks vs exoplanet demographics?
- How representative are the large ring disks in the bigger picture of exoplanet demographics and planet formation?

Open questions

- How do ring disks relate to transition disks? Both massive and bright compared to majority of disks (disk surveys), so same disk population or selection effect? And if related, how do they evolve into each other?

- Are transition disks caused by planets or stellar companions?

- Why are asymmetries only found in a fraction of transition (and ring) disks?

- How do we solve the chicken and egg problem if planets create dust traps? How are the first planets formed?

- When and how do planets form?

Questions?

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