Planet formation in action

The role of dust trapping in transitional disks

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Leiden Observatory

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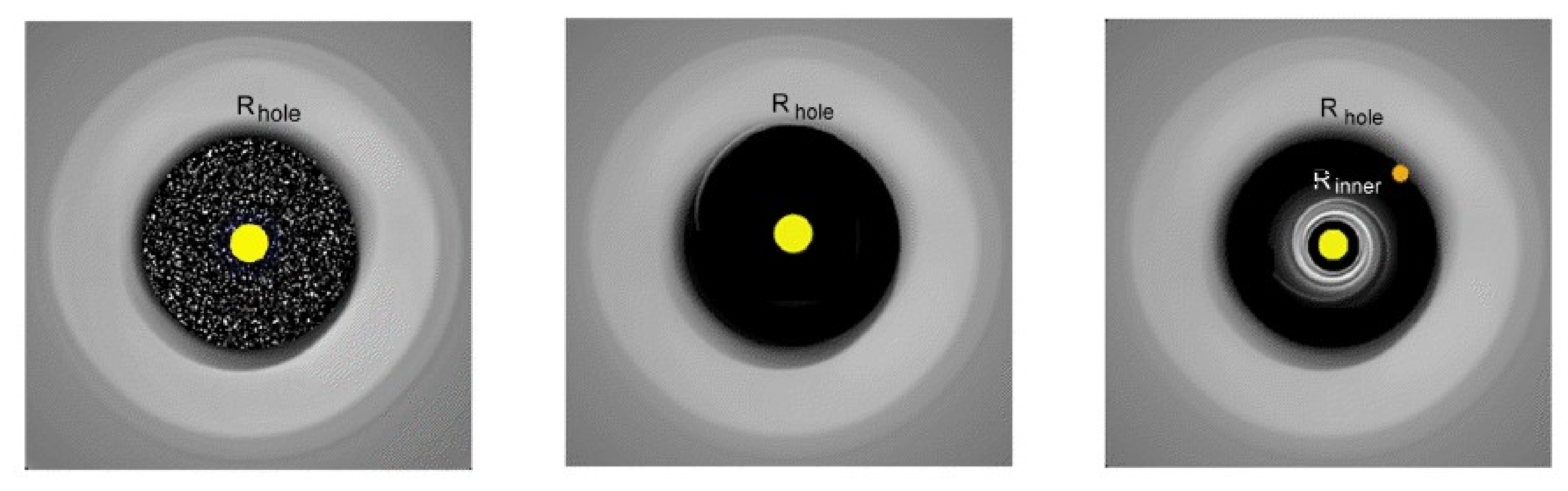
Sterrewacht Leiden

Transitional disks

- Dust hole: mechanisms

Grain growth | Photoevaporation | Stellar companion / Forming planet?



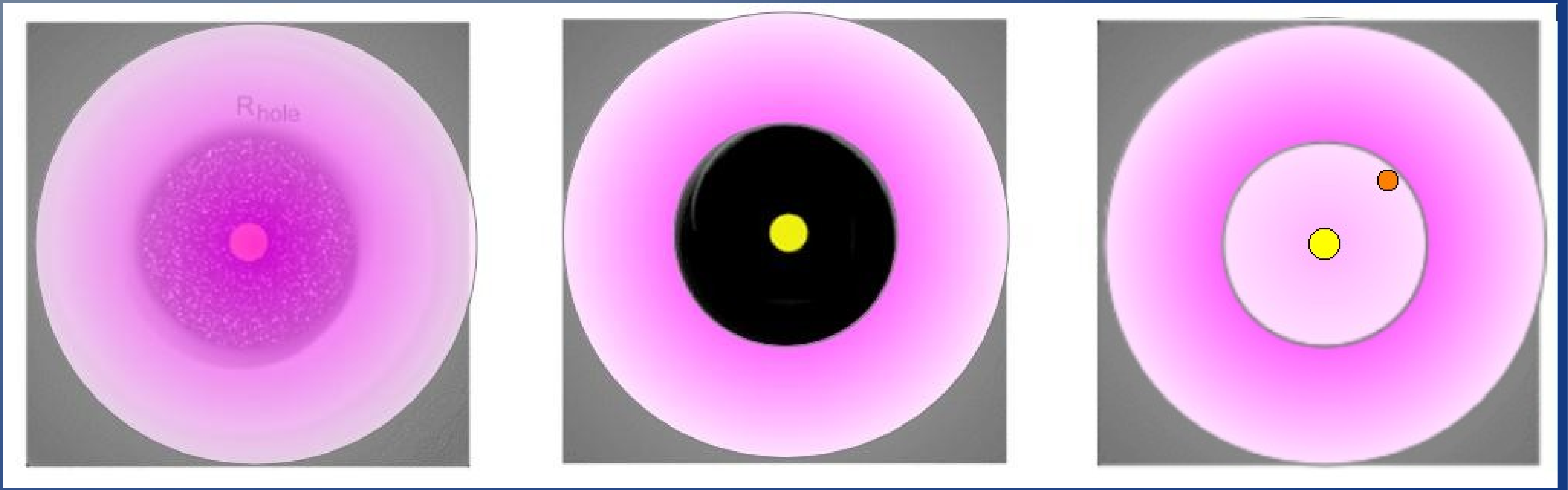
⇒ **What about the gas?**

Strom & Najita

Transitional disks

- Dust hole: mechanisms

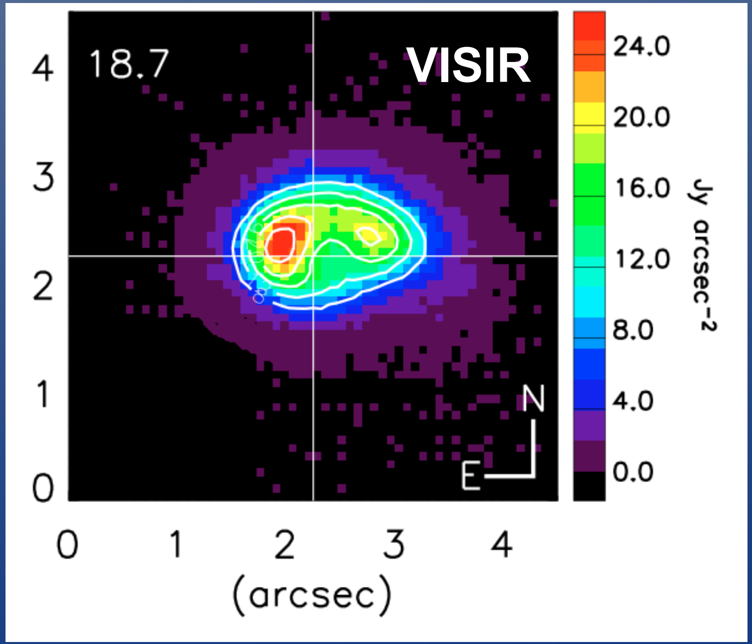
Grain growth　　Photoevaporation　　Stellar companion / Forming planet?

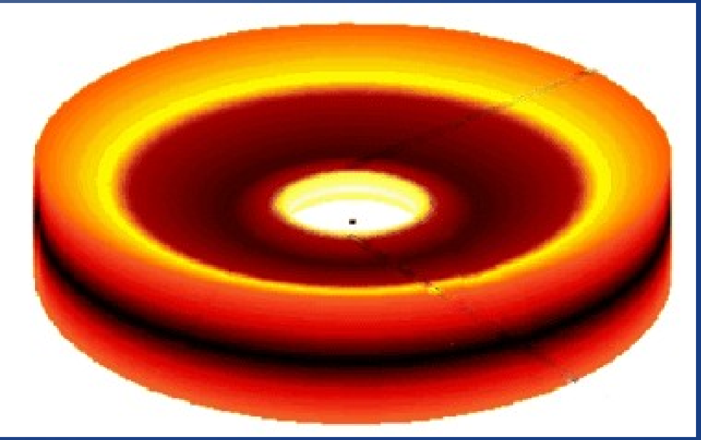


⇒ **Need to know the gas distribution and mass < 50 AU ⇒ ALMA**

Oph IRS 48

- Target Cycle 0: Oph IRS 48
- Dust ring (VISIR imaging) R_h=55 AU
- CO (v=1-0) gas hole (CRIRES) R_h=30 AU
- Ophiuchus (d~120 pc): 0.23" ⇔ R_b=14 AU





i = 48°

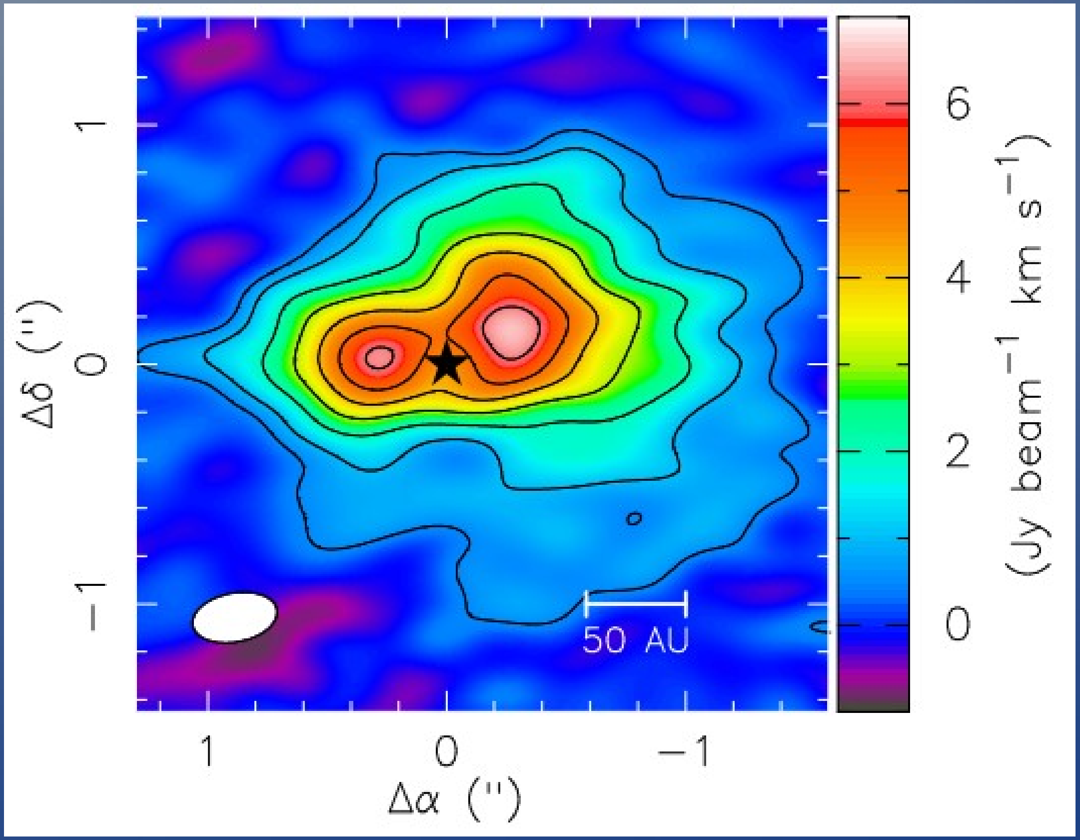
Geers et al. 2007
Brown et al. 2012

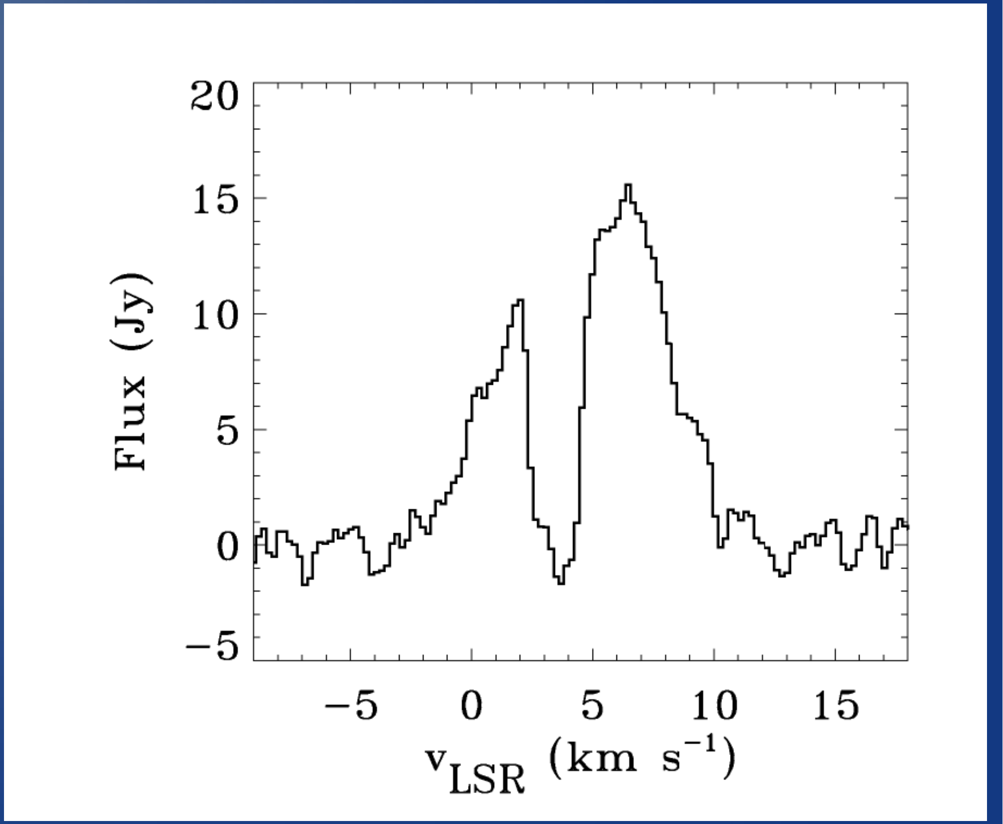
ALMA observations

- Band 9: ~690 GHz/0.44 mm
- Spatial resolution ~0.23” (Extended)
- Targets:
  - ^{12}CO 6-5
  - $C^{17}O$ 6-5
  - 685 GHz continuum
- Observations taken June-July 2012

ALMA observations

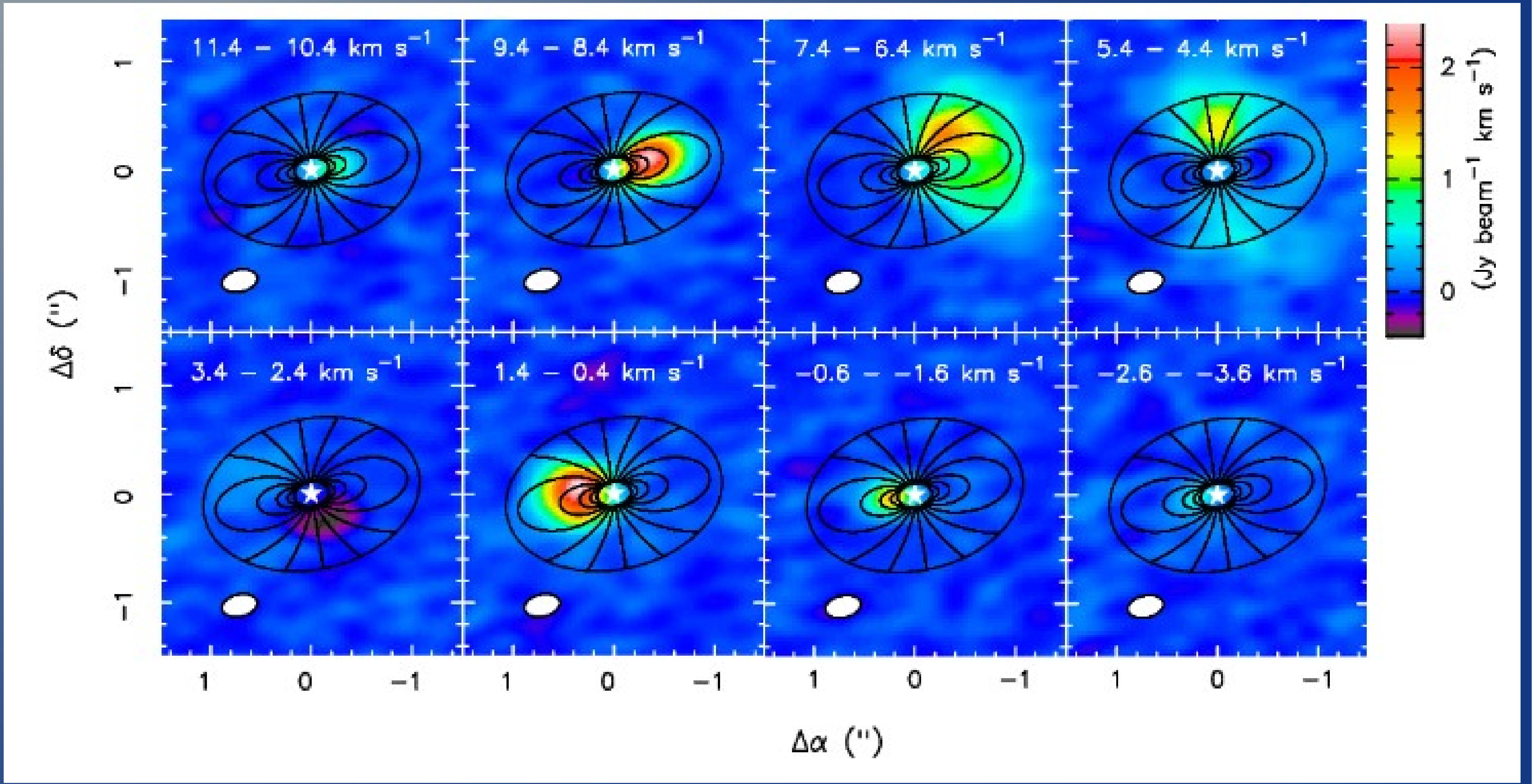
- Integrated ^{12}CO





Bruderer et al. 2014
Van der Marel et al. 2013

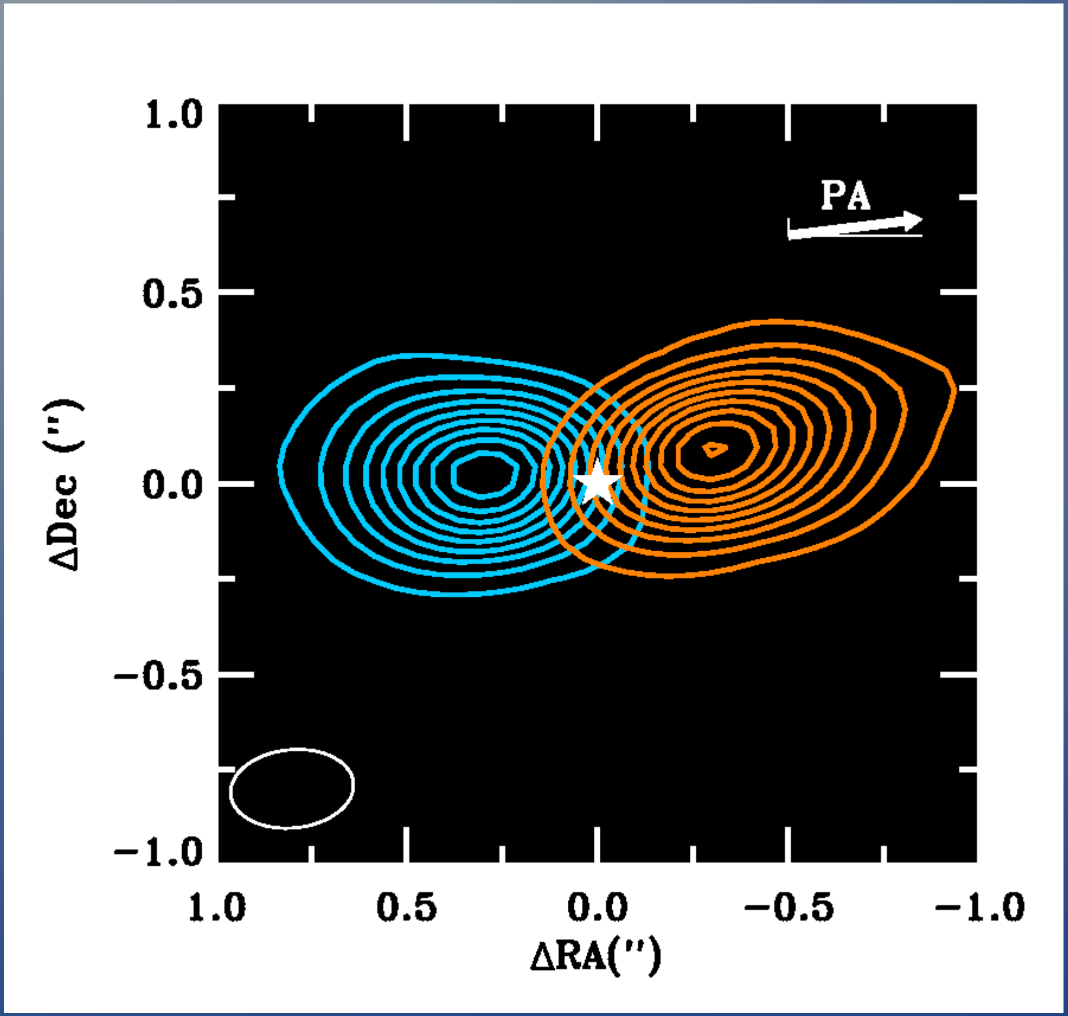
ALMA observations



^{12}CO 6-5 channels follow Keplerian motion (black)

Bruderer et al. 2014

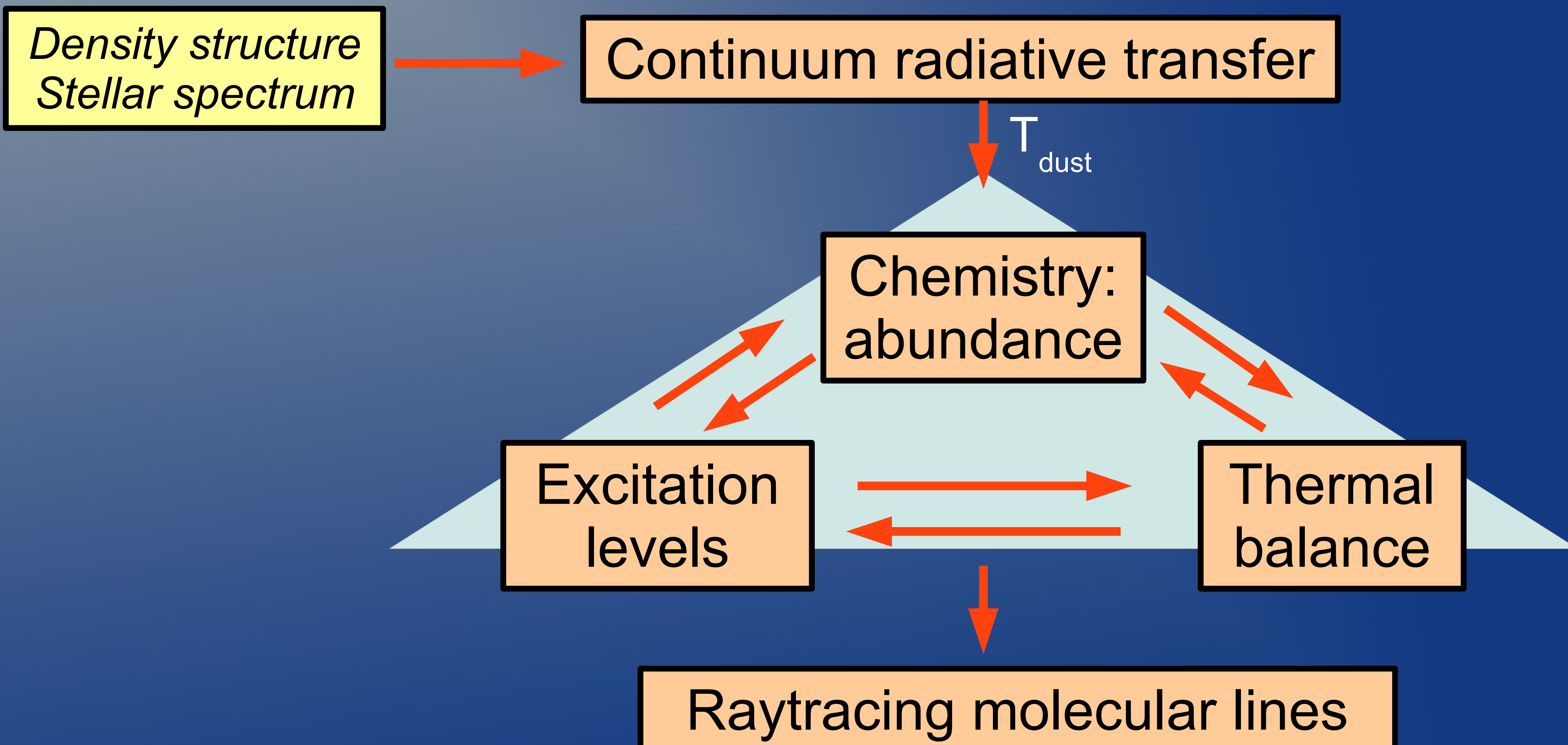
ALMA observations



- Initial conclusions:
  - Full gas disk
  - Keplerian motion
  - 20 AU gas hole

Gas modeling

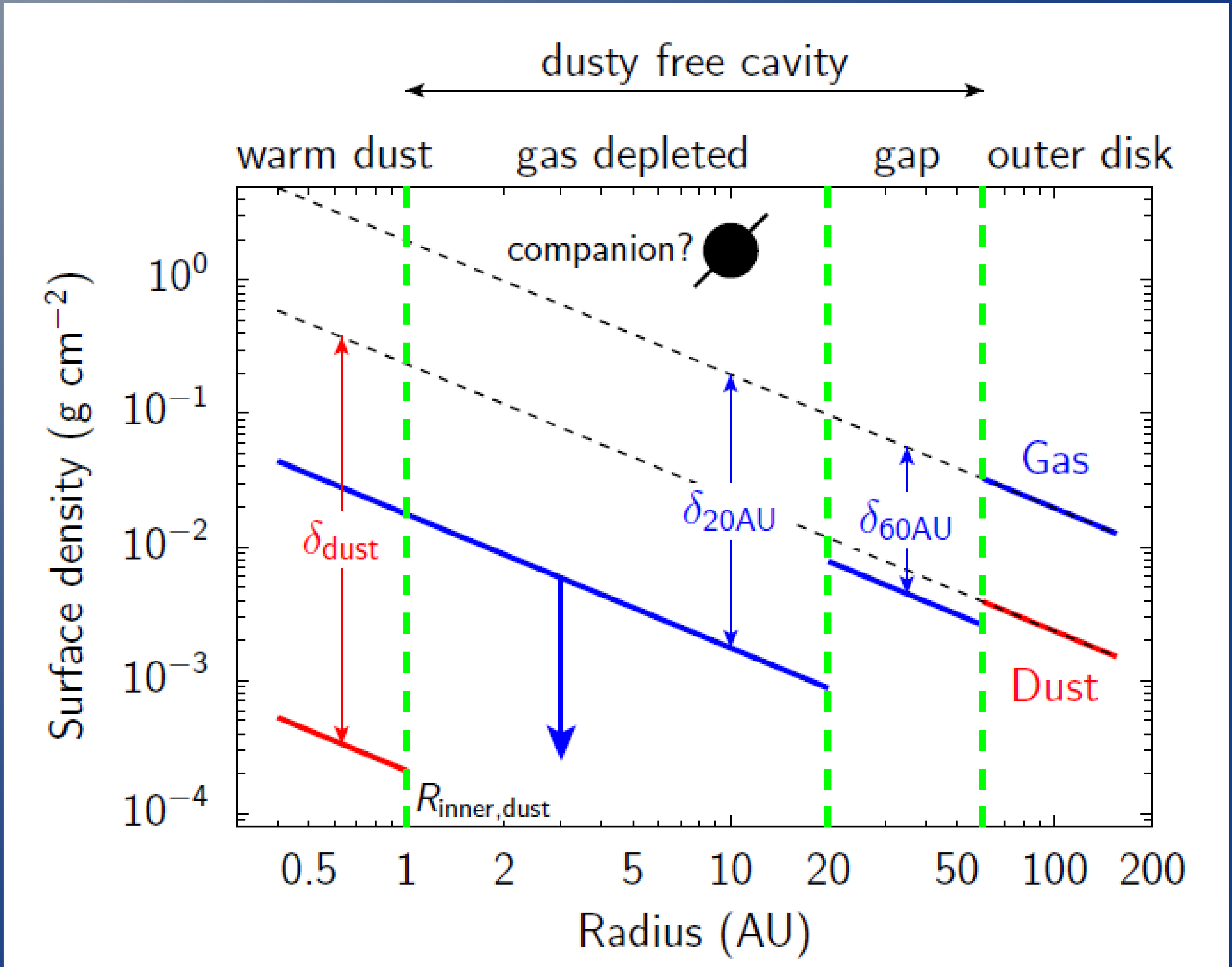
- Analysis gas distribution: **DALI** (Bruderer 2013)



- Particularly useful for transition disks: complex heating

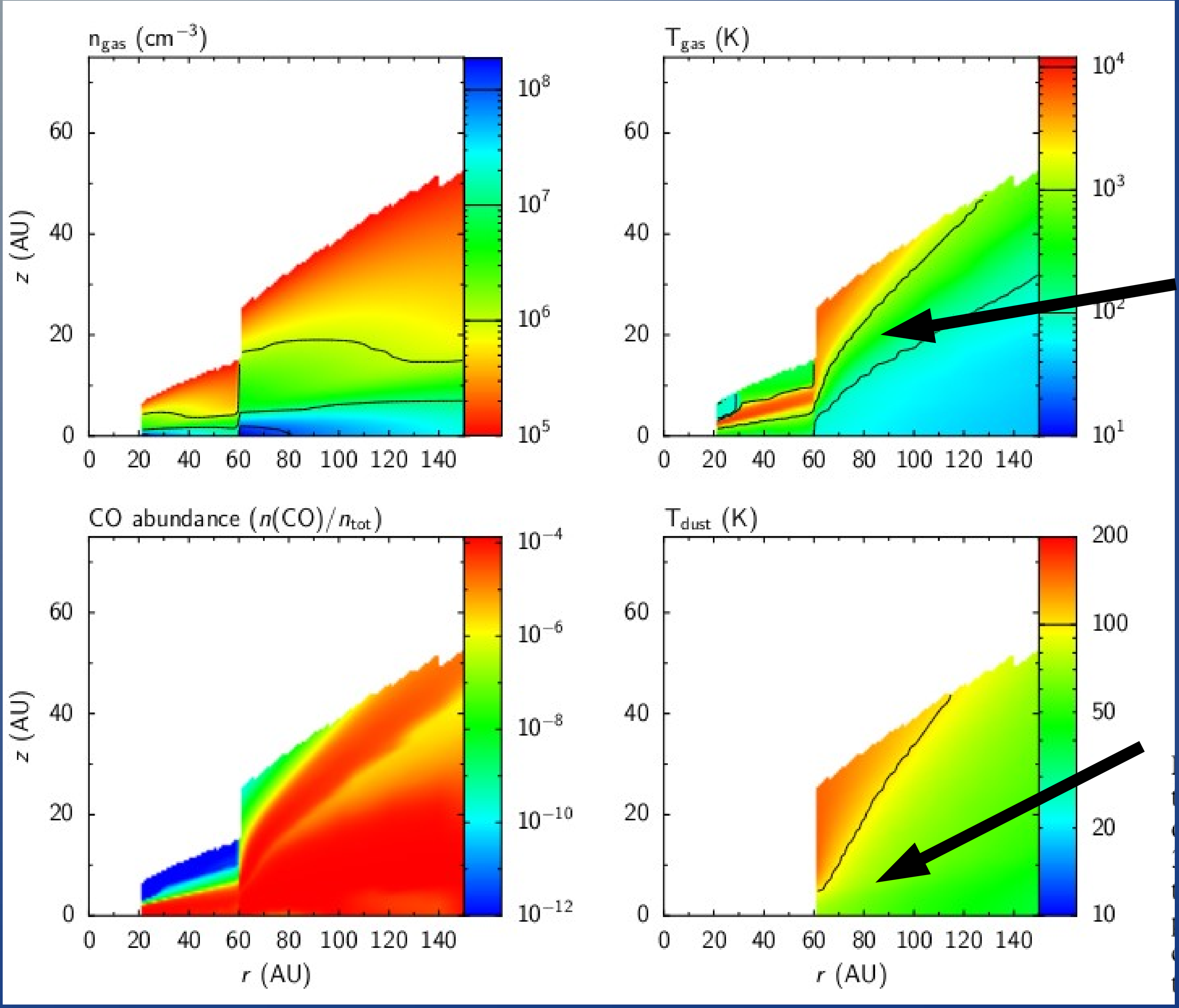
Gas modeling

Input: axisymmetric density model with density drops



Bruderer et al. 2014

Gas modeling

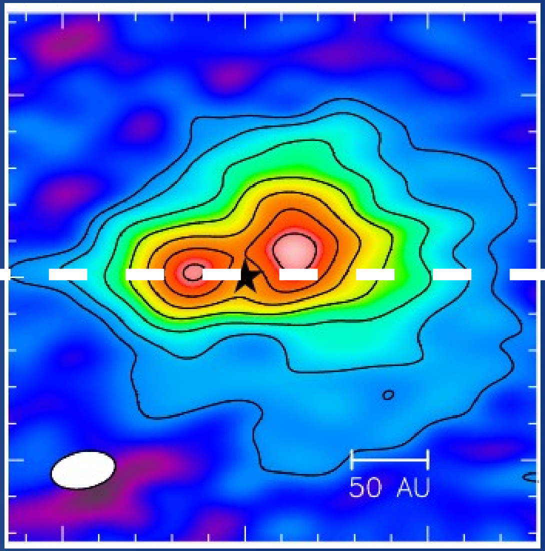


Tgas ~ 10 000 K
UV heating

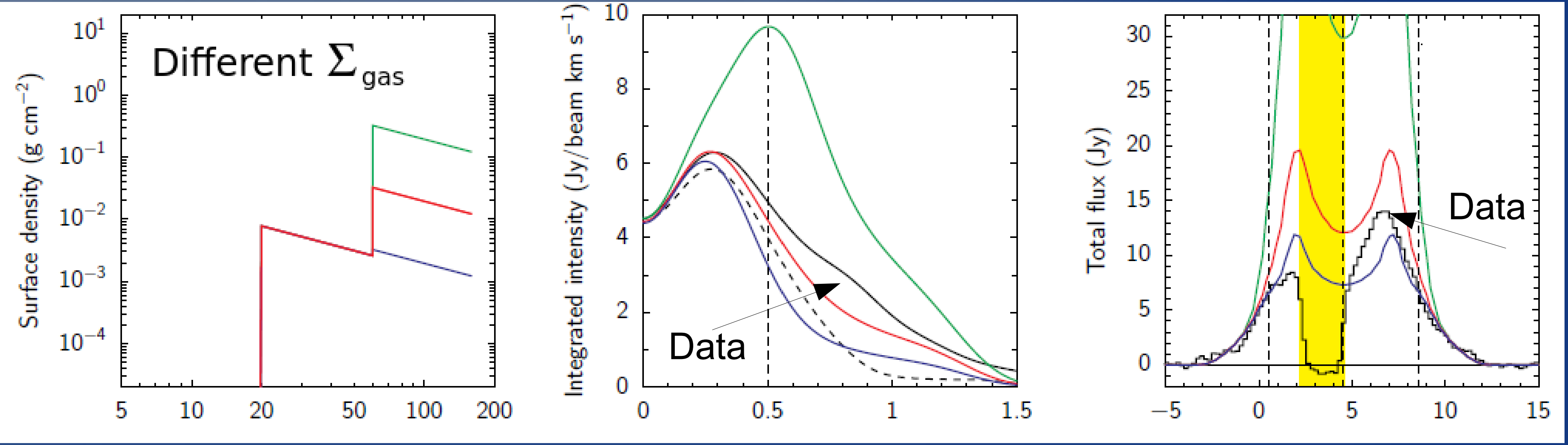
Tdust > 20 K
No CO freeze out!

Gas modeling

- Comparison with data



Profile Major axis cut Spectrum



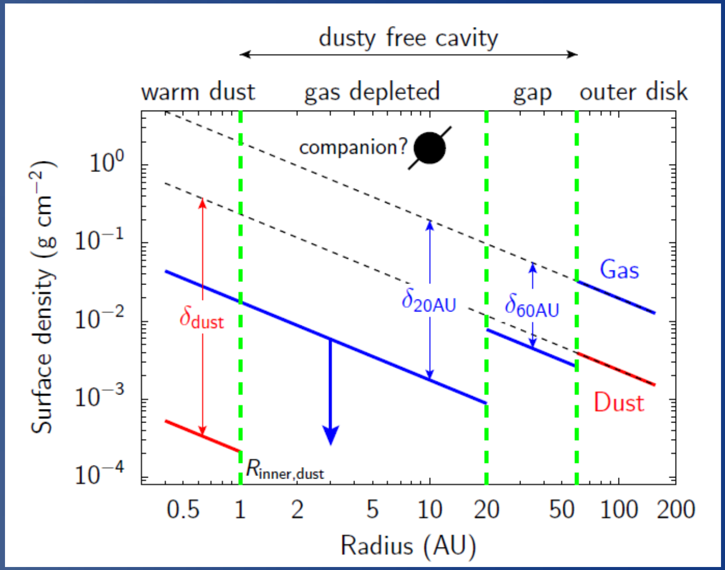
Gas modeling

- ^{12}CO optically thick, **but...**
  - Marginal $C^{17}O$ 6-5 detection
  - Spatially resolved: optical thickness varies
    - Large scale height
    - Low disk mass

- Analysis of gas density structure down to factor of a few!

Gas modeling

- Instead of one gas hole, **two** density drops at 20 & 60 AU
  - Outer drop factor 12
  - Inner drop factor >10



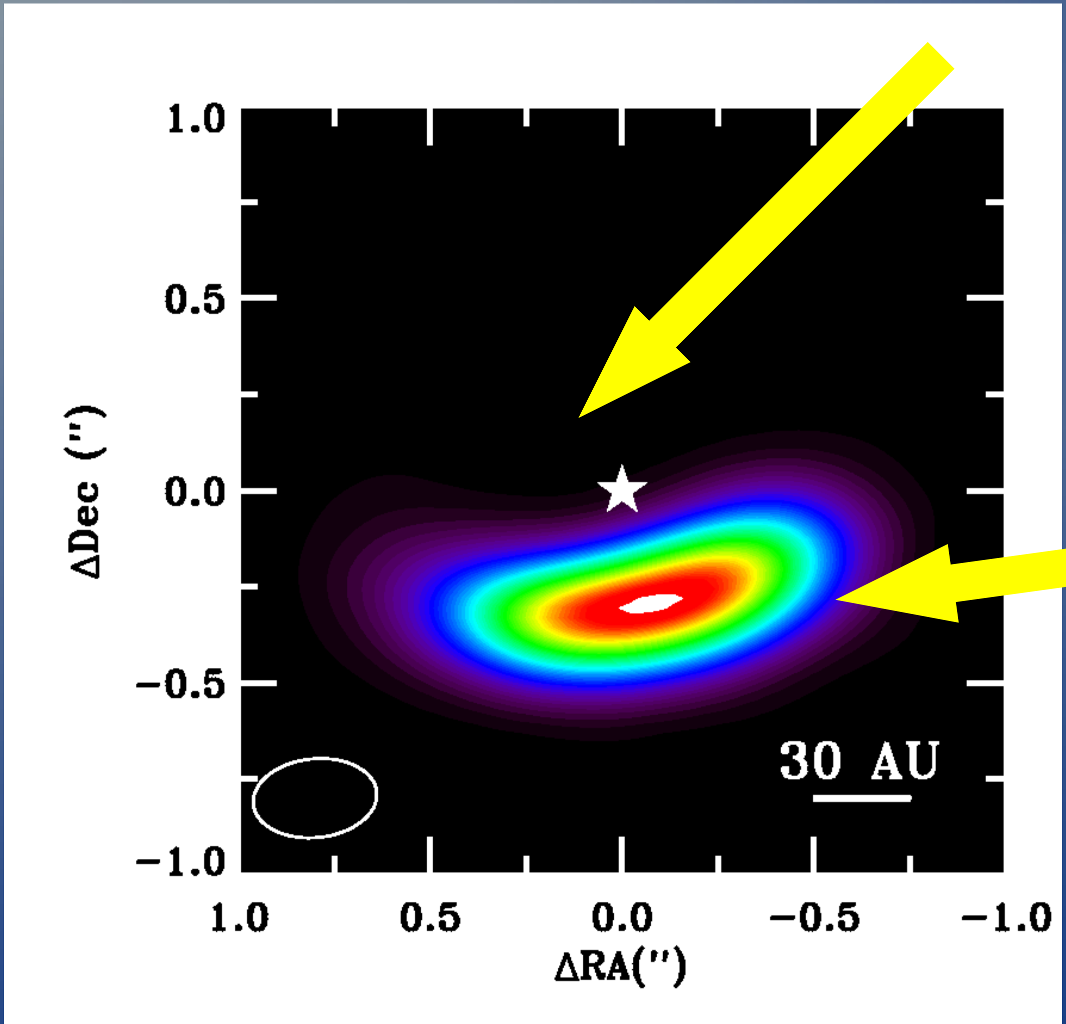
- Density drop points directly to planet clearing
  - Indirect evidence for planets in disk

- Total gas mass ~0.15 M_{Jup}

- **And what about the dust?**

A gigantic dust trap!

Missing dust

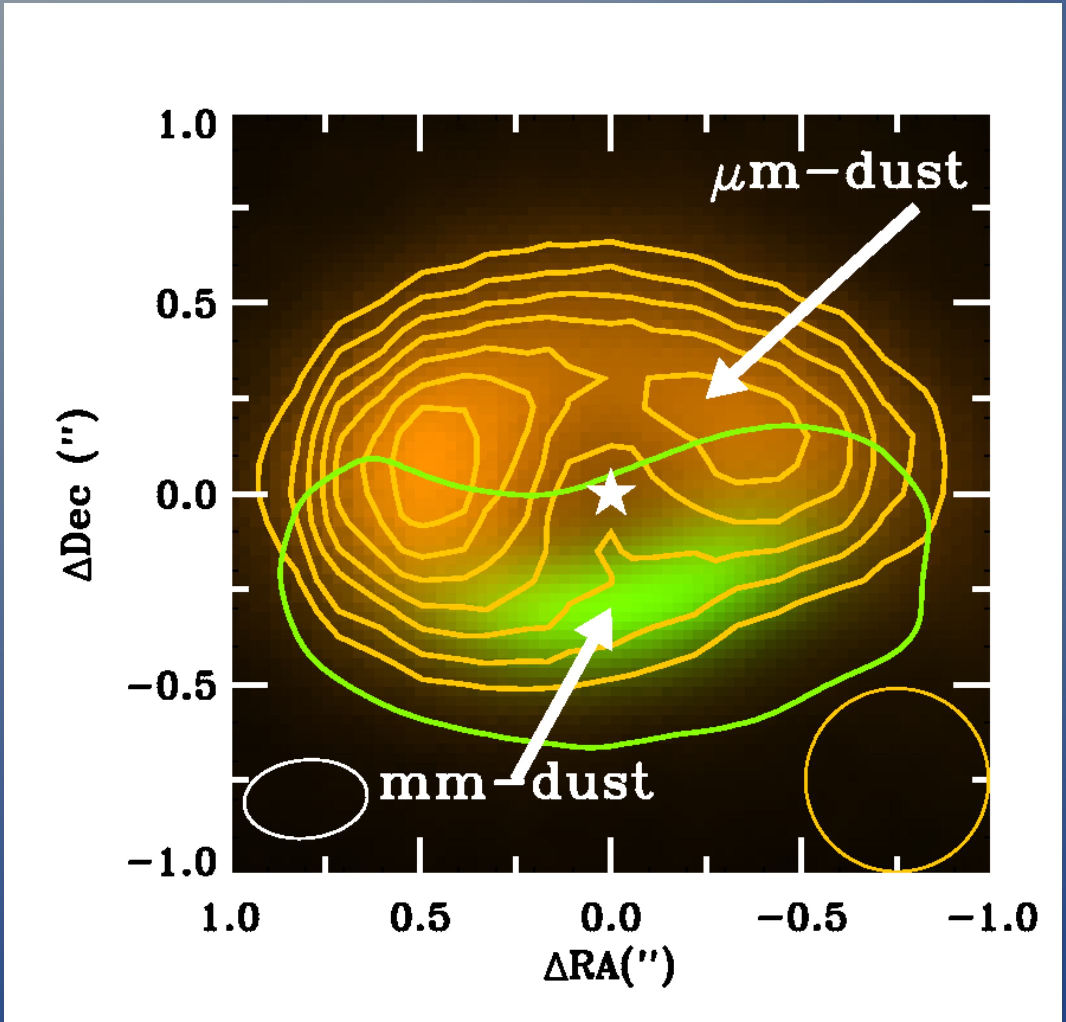


Continuum peak ~390σ!

σ = 0.8 mJy/beam

van der Marel et al. 2013

Large vs small dust

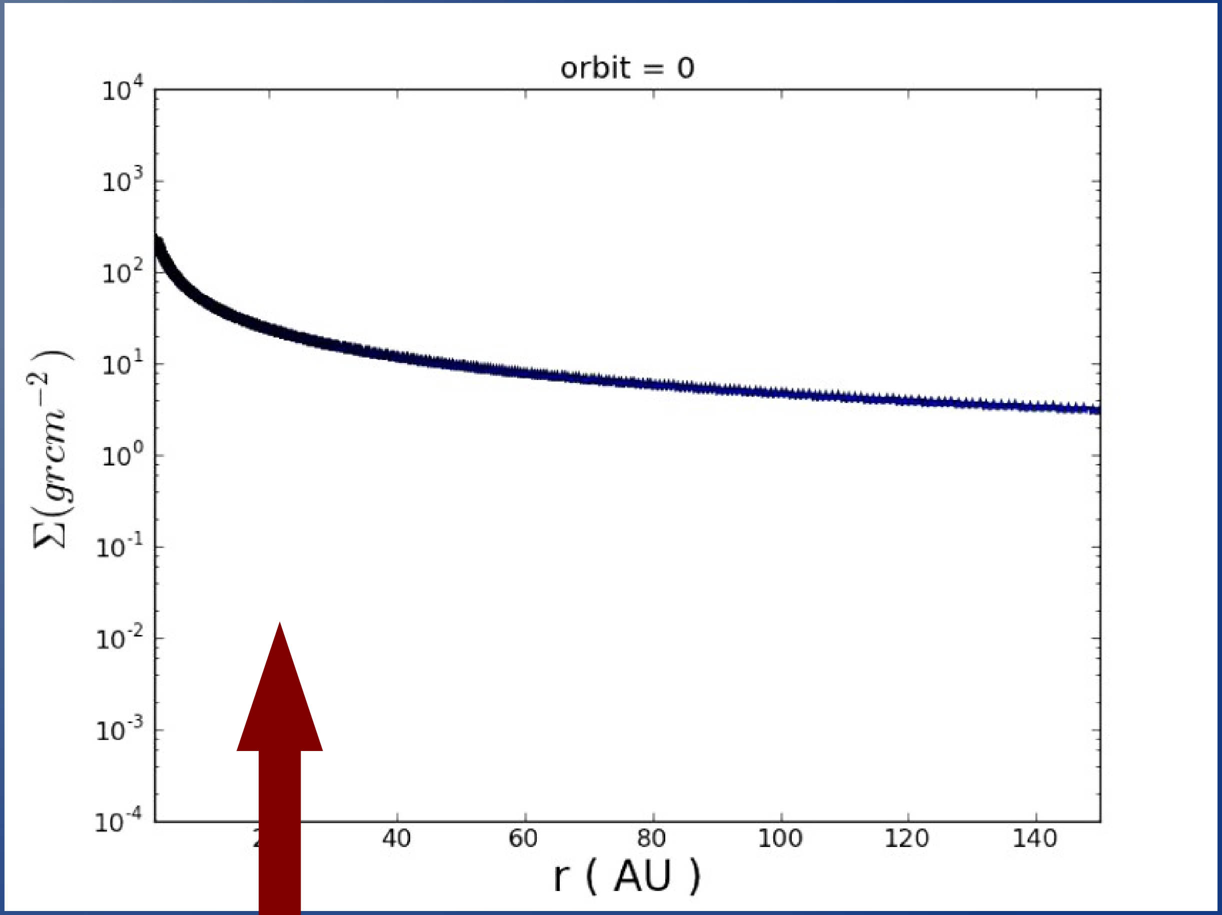


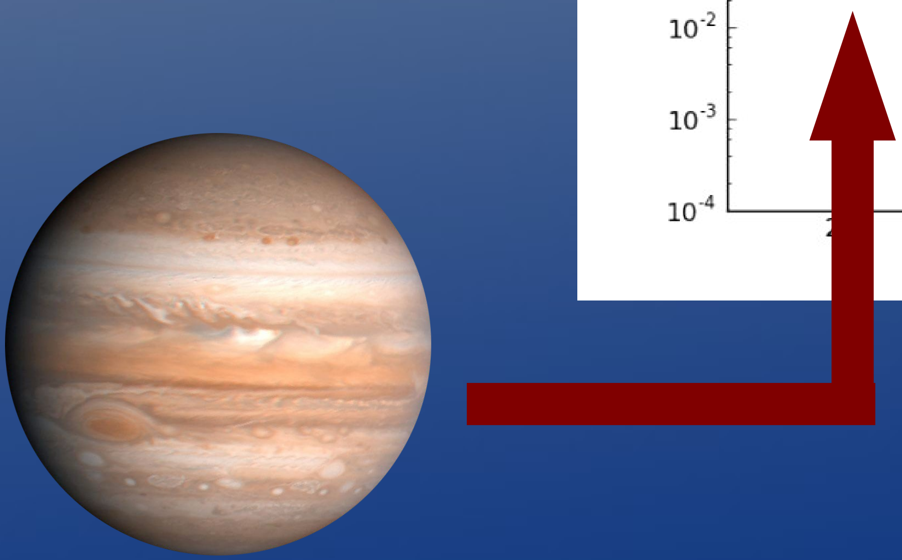
- Not only gas, but also small dust emission indicates a full ring
- Separation mm-dust and μm-dust

What can cause this structure?

Dust trapping

- FARGO model
- Gas density: planet clearing





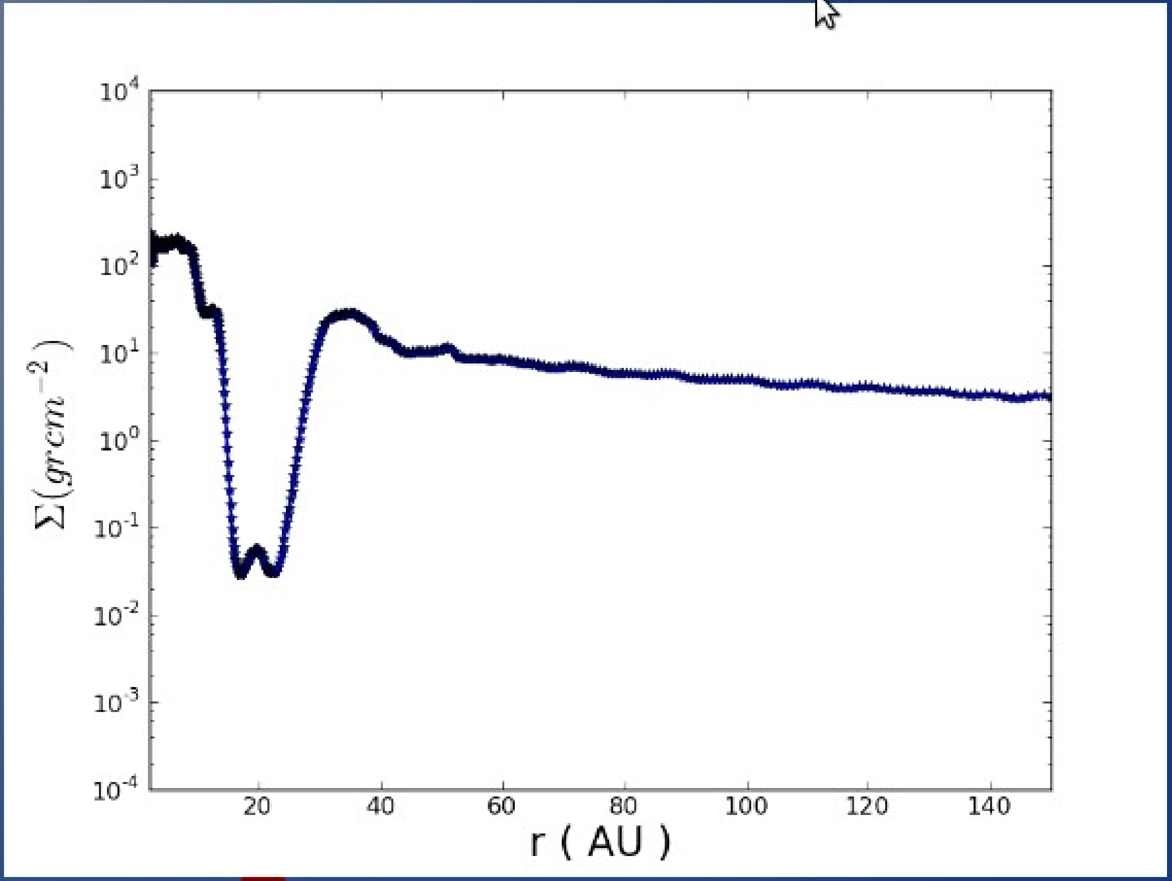
Pinilla et al. 2012

Dust trapping

Pinilla et al. 2012

Dust trapping

- Depth and shape of the gap depend on the planet mass
- Planet generates a radial pressure bump in gas



What happens to the dust?

Pinilla et al. 2012

Dust evolution

- Micron-sized dust grains in protoplanetary disks

Growth >12 orders of magnitude

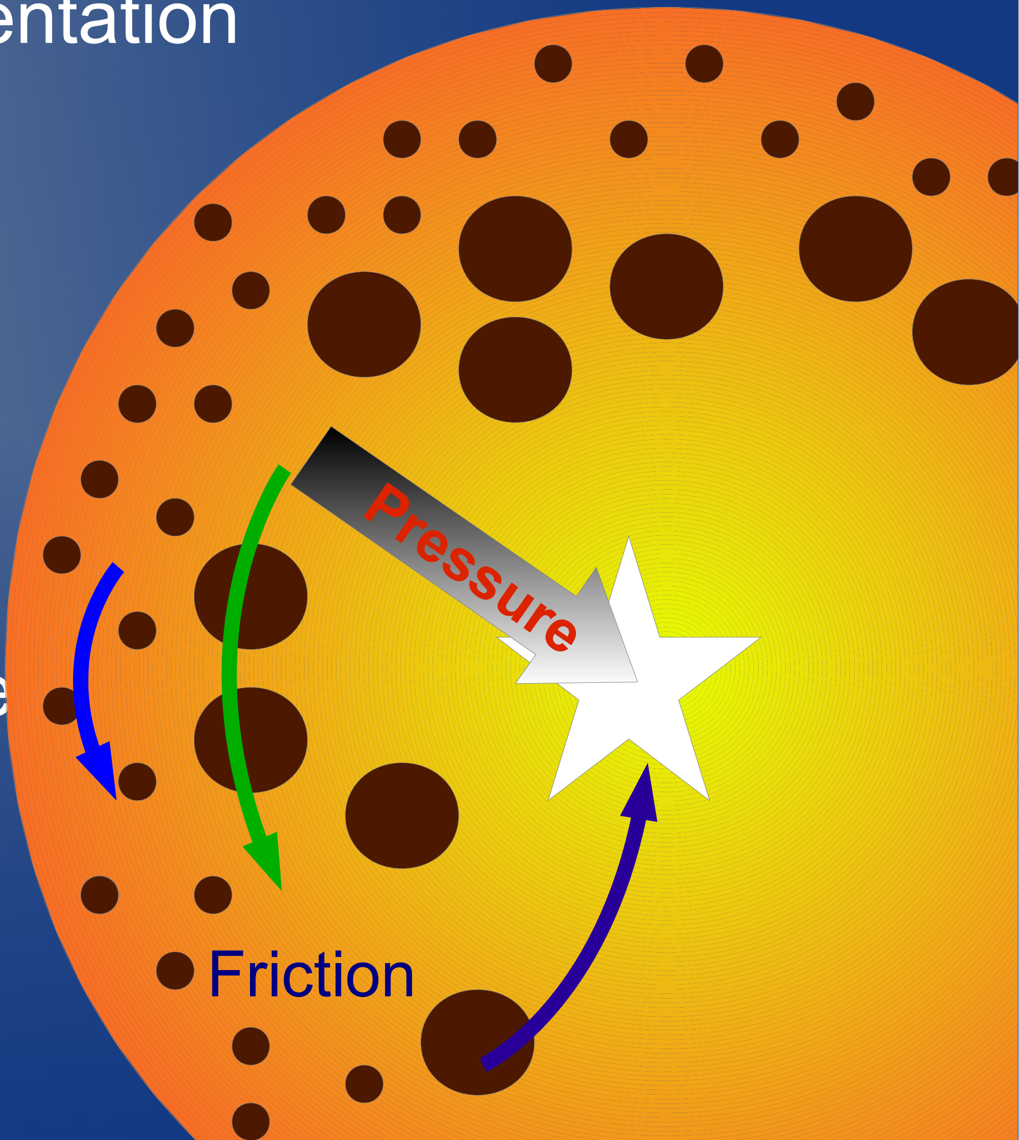
- Rocky planets (>1000 km)

=> Growth by random motions, collisions, sticking

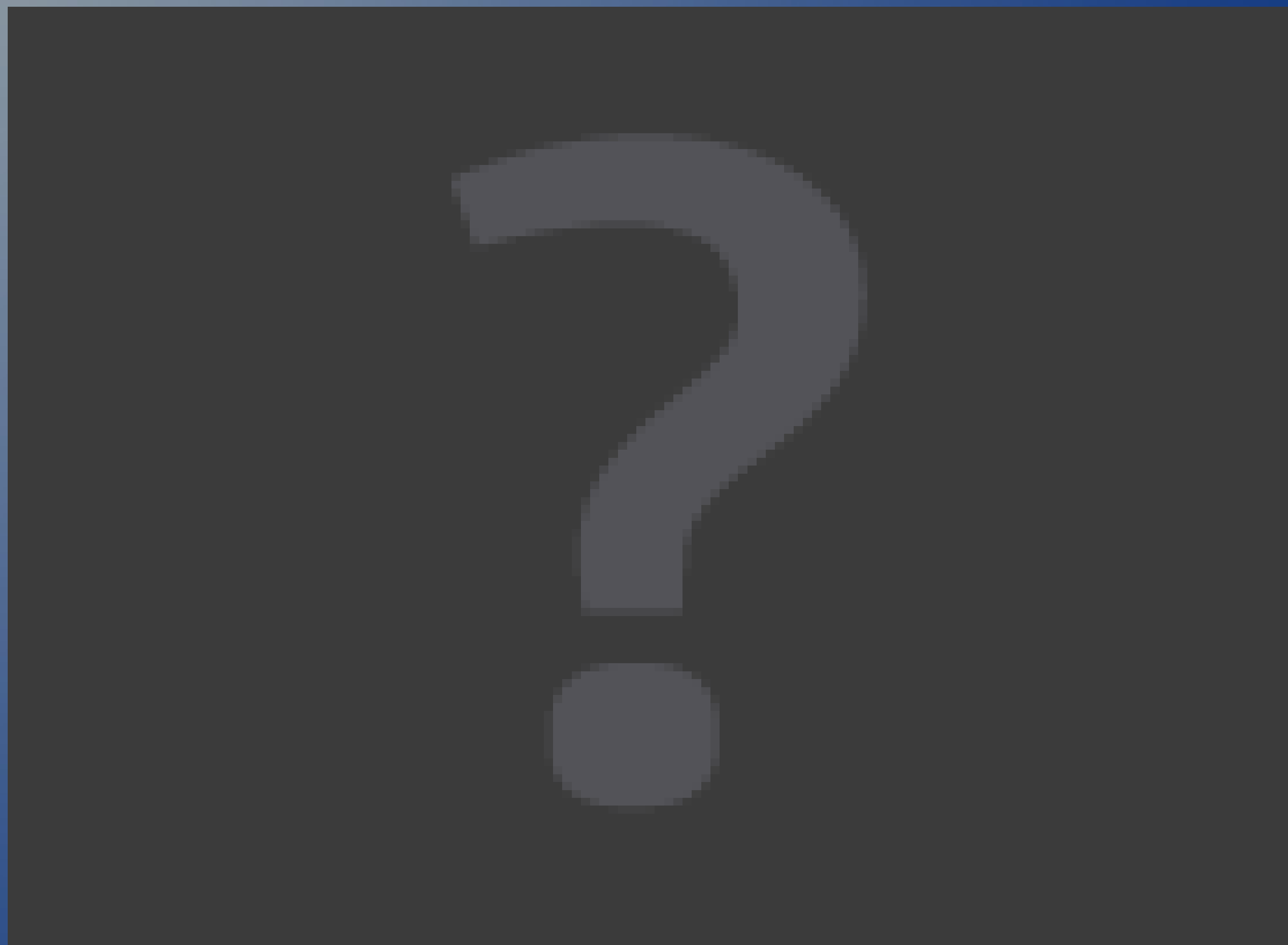
Dust evolution

- Dust growth in a normal disk
  - Coagulation and fragmentation
  - Radial inward drift
- Dust can not grow beyond millimeter sizes?
- Two dust properties:
  - Large particles move towards high pressure
  - Small particles move with the gas

=> Pressure bump?



Dust trapping



Combination dust dynamics and dust evolution

Pinilla et al. 2012

Dust trapping

- What is the origin of the azimuthal asymmetry?
- Steep drop
  $\Rightarrow$ pressure bump becomes Rossby unstable

Pinilla et al 2012
Birnstiel et al. 2013
Ataiee et al. 2013

Dust trapping

- What is the origin of the azimuthal asymmetry?
- Steep drop
  $\Rightarrow$ pressure bump becomes Rossby unstable:

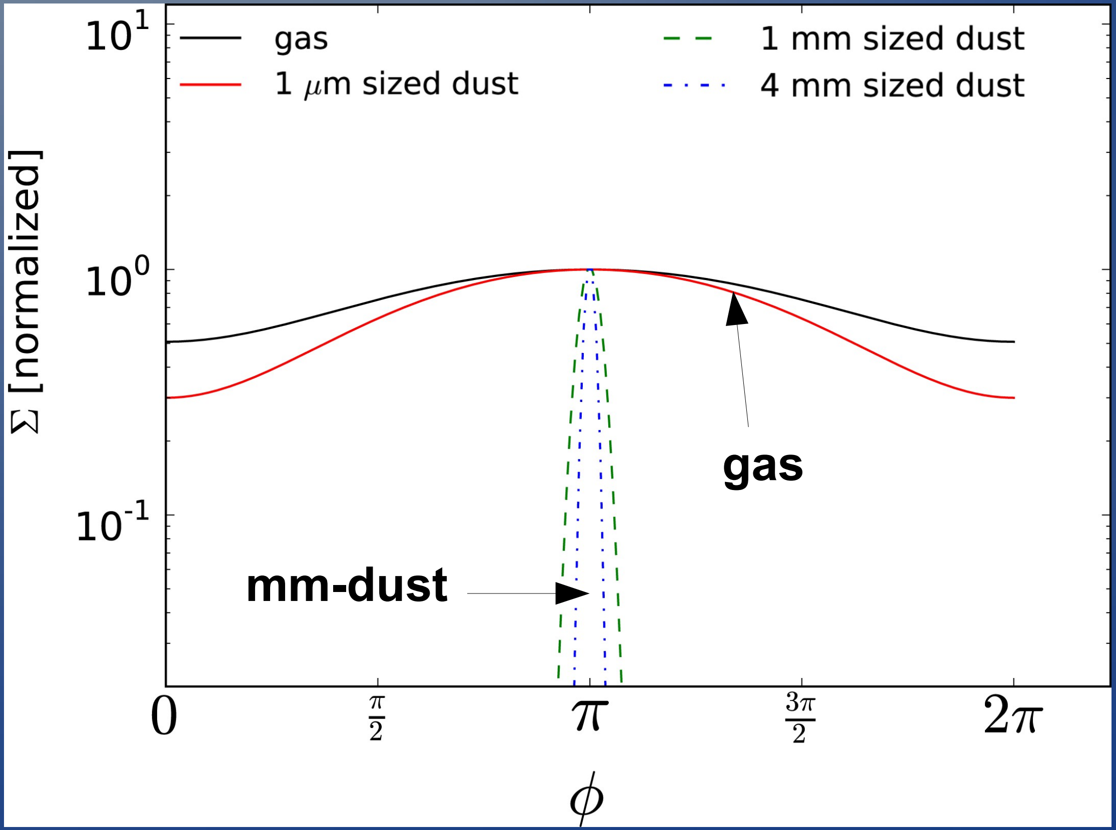
long-lived vortex

(moving on Keplerian orbit)

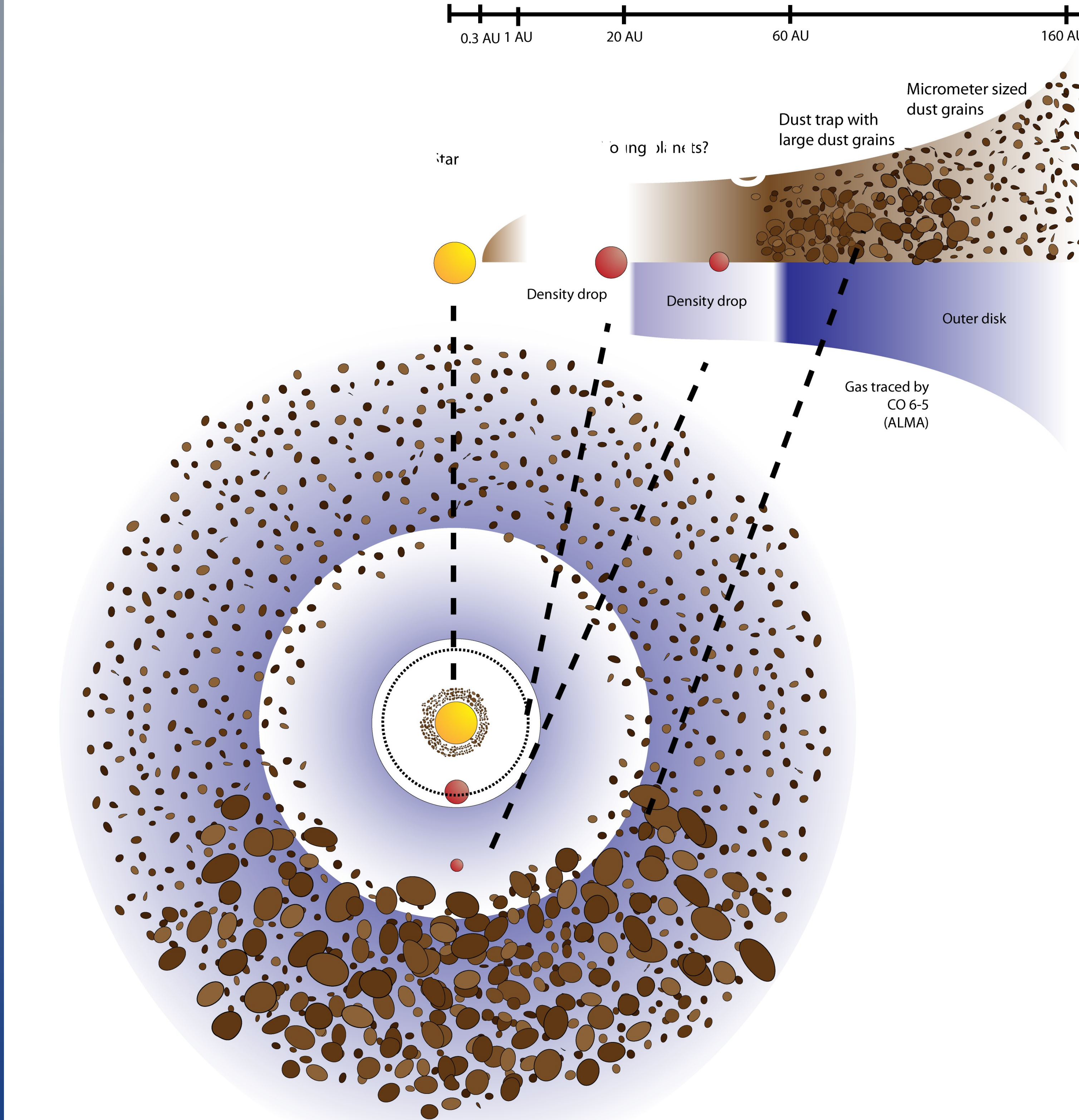
Pinilla et al 2012
Birnstiel et al. 2013
Ataiee et al. 2013

Dust trapping

- Small gas asymmetry ⇔ large dust asymmetry



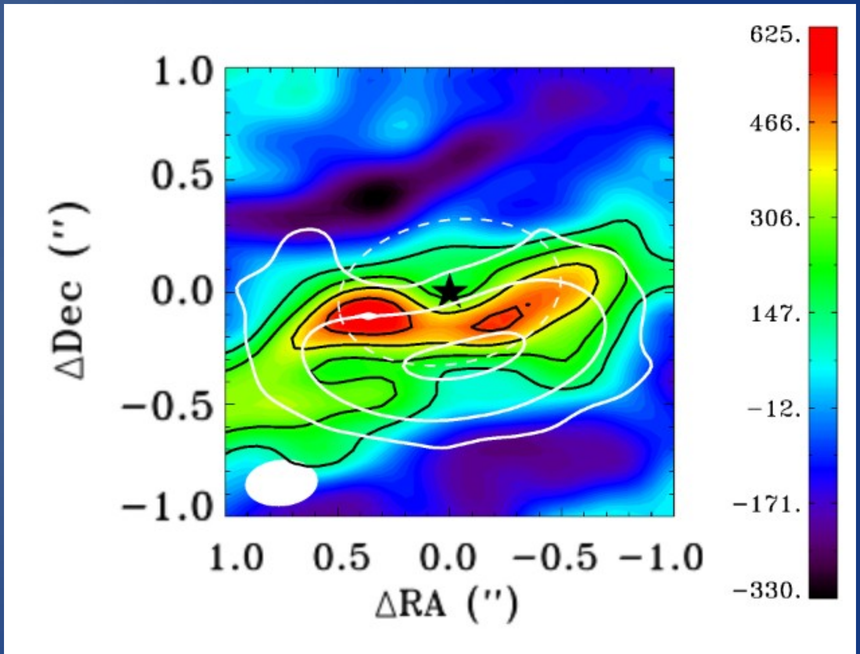
Birnstiel et al. 2013
Van der Marel et al. 2013



0.3 AU
1 AU
20 AU
60 AU
160 AU
Micrometer sized dust grains
Dust trap with large dust grains
Density drop
Density drop
Outer disk
Gas traced by CO 6-5 (ALMA)

Vortex?

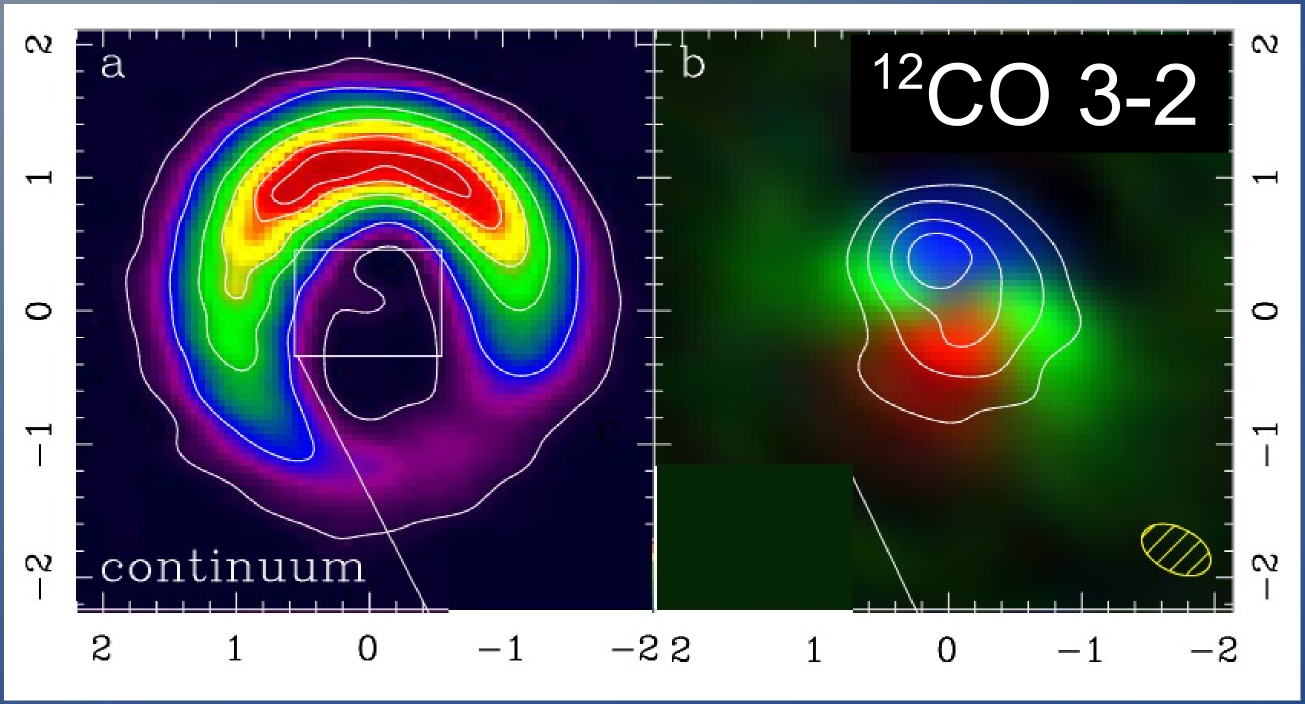
- Warm H_2CO (E_U ~ 174 K) detected
- Hints gas asymmetry?
  - H_2CO detected in south but **not cospatial** with dust
    - Dust absorption?
  - ^{12}CO: **less** emission in south
    - lower T (shielding)?
- Vortex dissipated?
- CO isotopologues in ALMA Cycle 2!

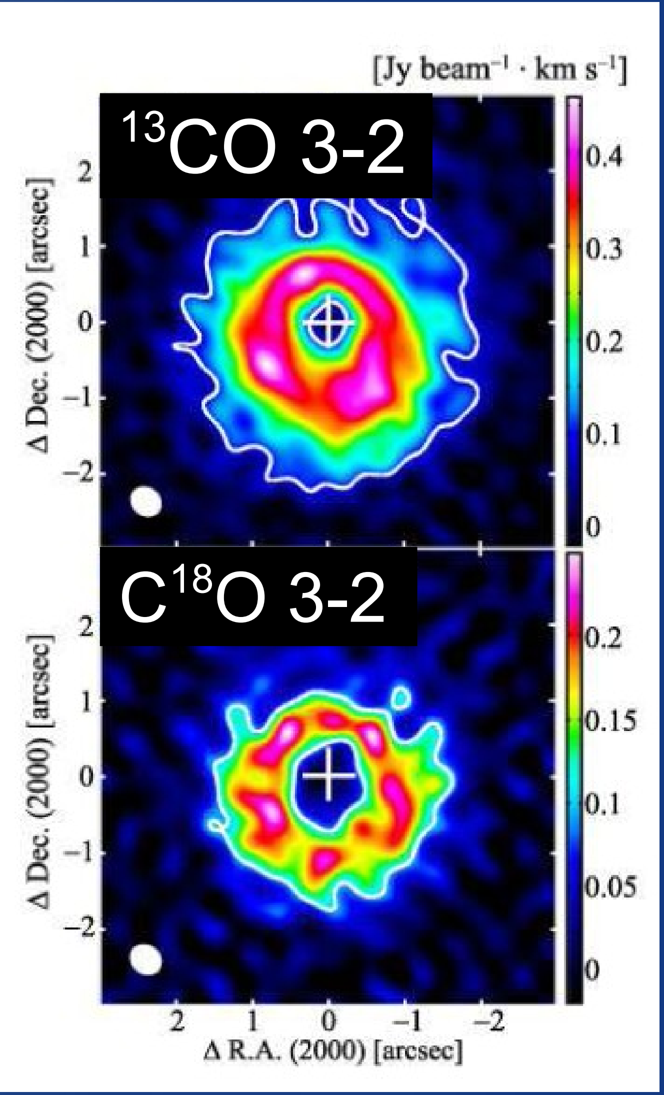


Van der Marel et al. 2014

Other ALMA dust traps?

- HD142527 (Band 7)

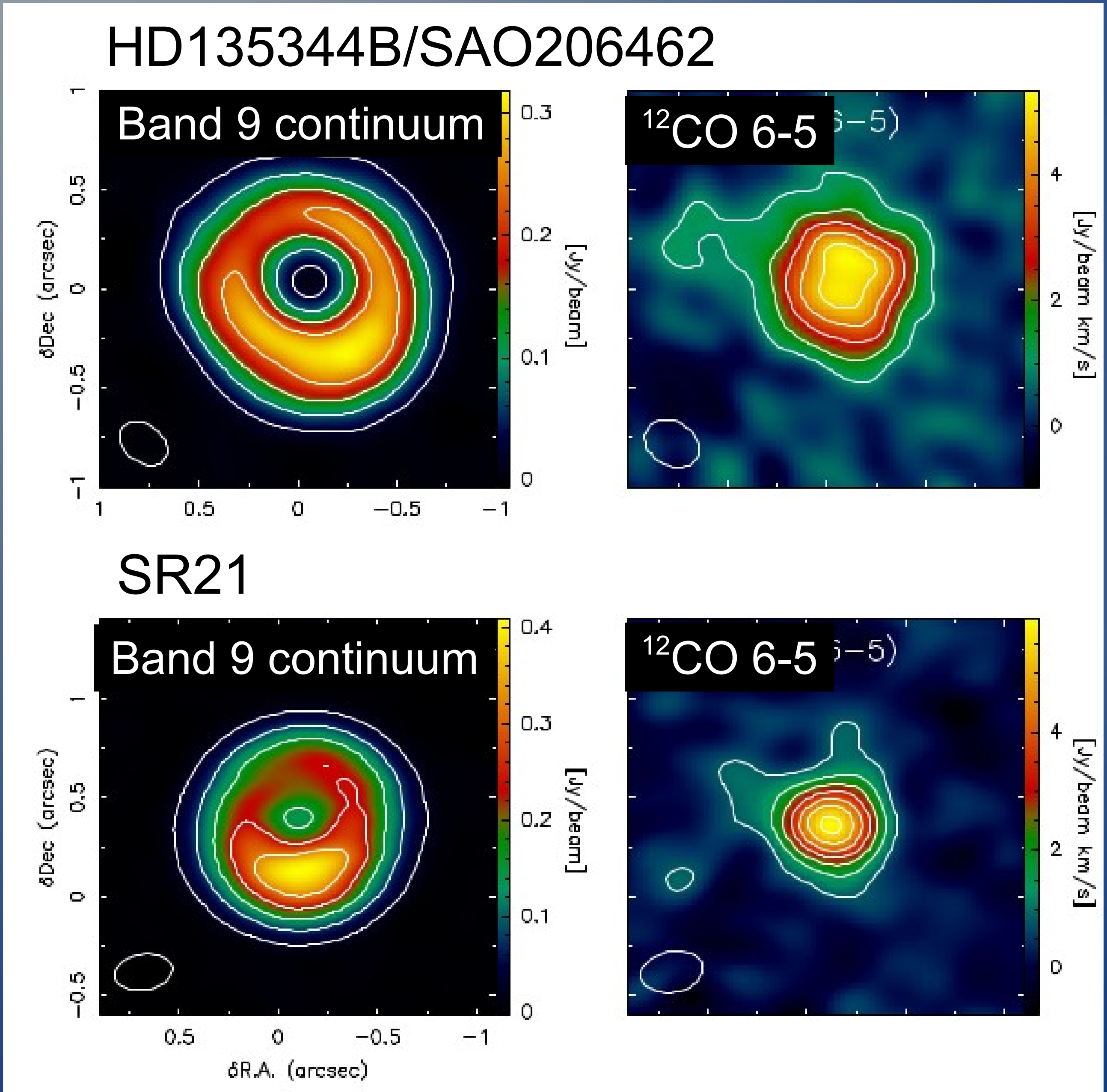




- Azimuthal asymmetry in dust
- CO present inside dust hole (^{12}CO), but density decreased (isotopologues)

Casassus et al. 2013
Fukagawa et al. 2013

Other ALMA dust traps?

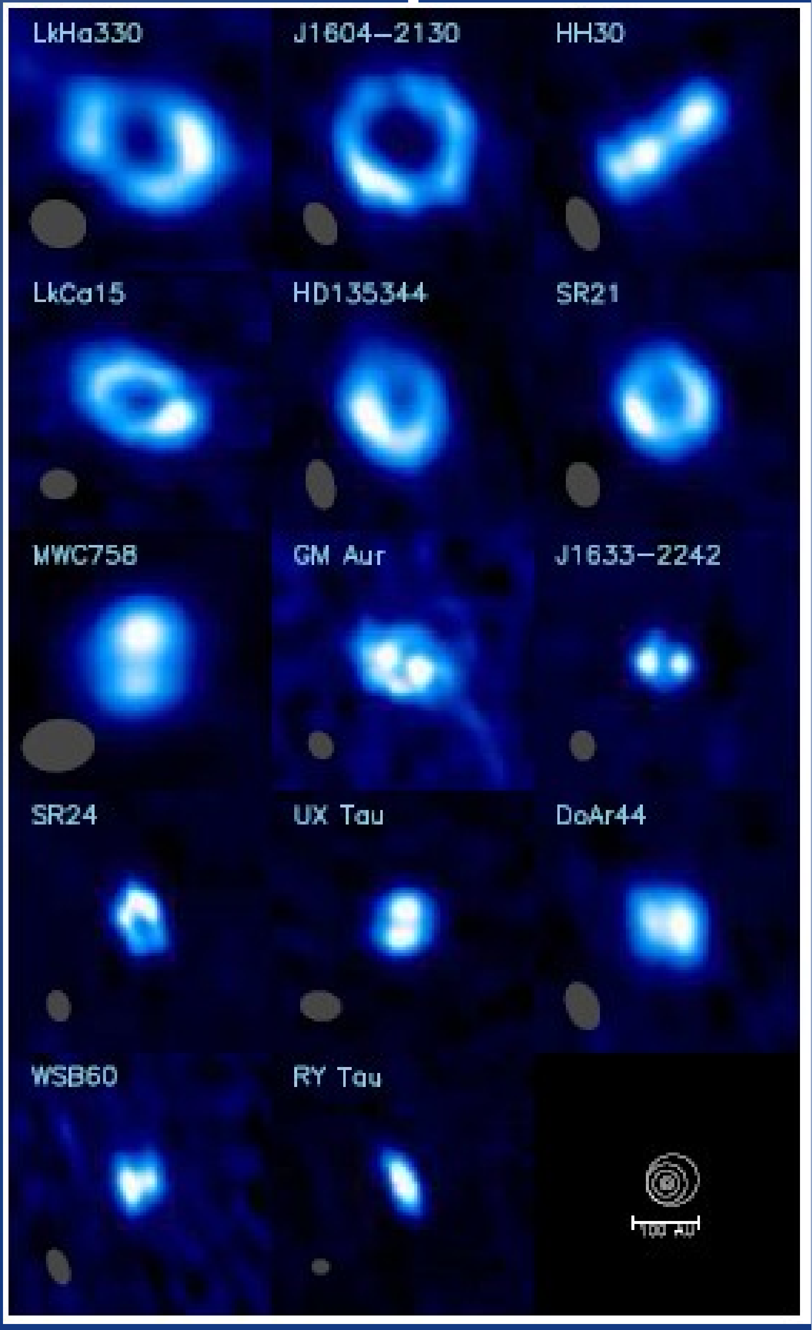


- Azimuthal asymmetry in dust
- ^{12}CO inside hole
- Density drop not constrained, but ALMA Cycle 1 program on ^{13}CO and $C^{18}O$ 3-2

Perez et al. 2014

Transitional disks as dust traps?

- Millimeter dust rings
  => Radial trapping
- Asymmetric dust rings
  => Radial & azimuthal trapping
  => Radial trapping & eccentricity
- Evidence trapping
  - Millimeter dust not enough
  - Gas **and** dust observations!
  - Multi-wavelength



Williams & Cieza 2011

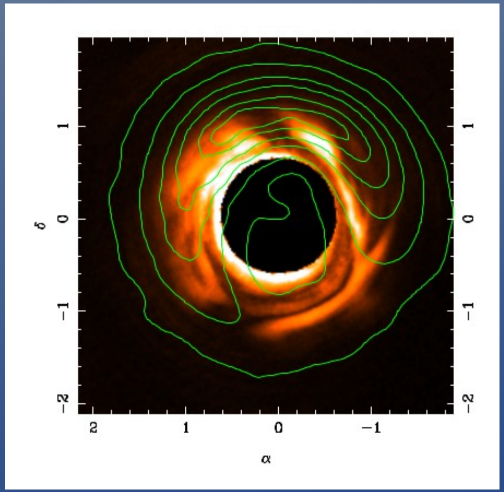
Transitional disks as dust traps?

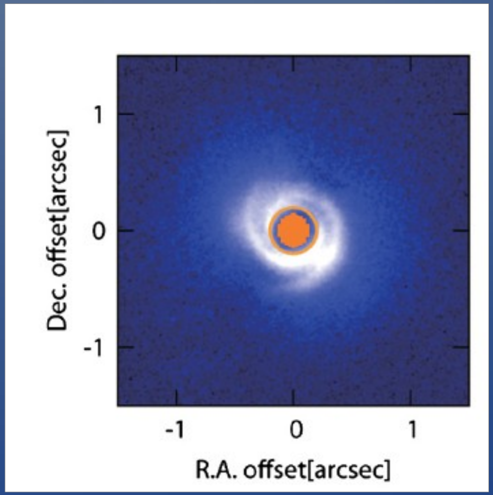
- Trapping efficiency ~ dust particle size

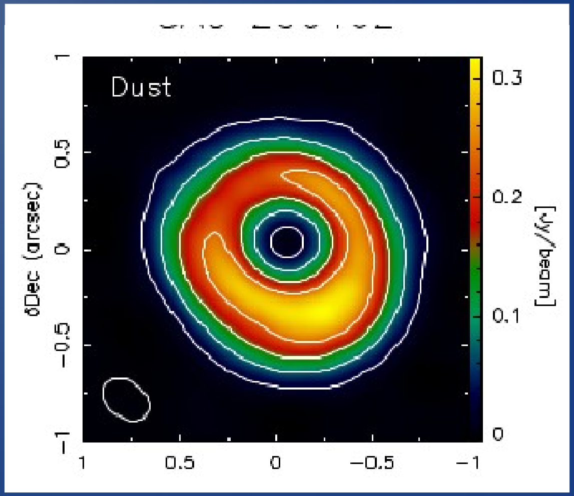
1) Compare large dust with small dust

HD142527

HD135344B/
SAO206462





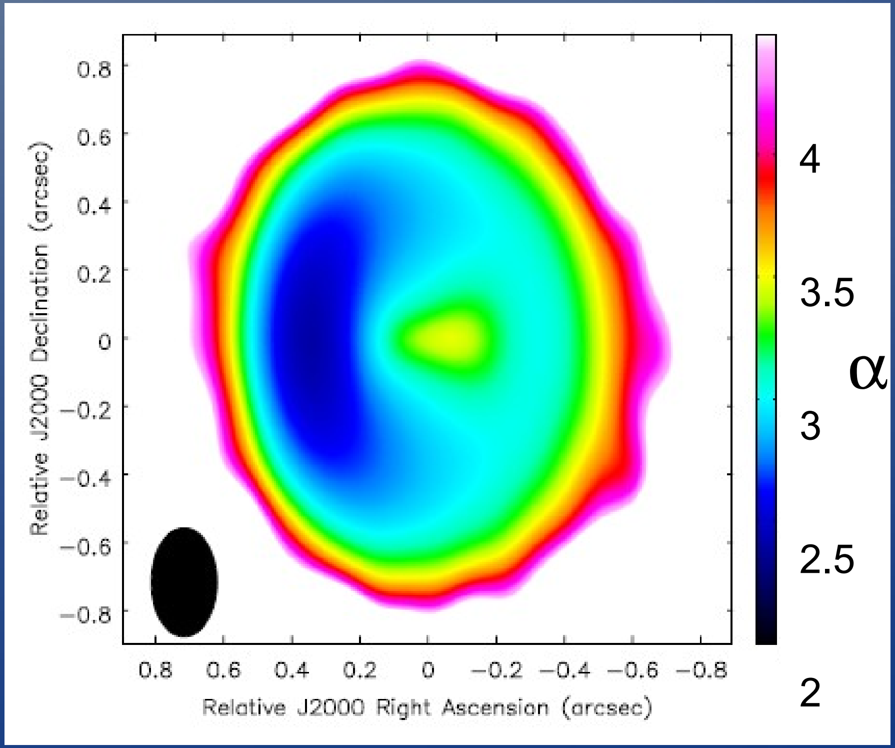


Casassus et al. 2013
Muto et al. 2012
Perez et al. 2014

Transitional disks as dust traps?

- Trapping efficiency ~ dust particle size

2) Compare mm-dust at different wavelengths =>emission at longer wavelengths more concentrated azimuthally and radially!



spectral index α: $F(\nu) \sim \nu^{-\alpha}$

Birnstiel et al. 2013

Transitional disks as dust traps?

- Gas pressure bump:
  not necessarily density gradient
- Alternatives:
  - Dead zones (viscosity gradient)
  - Zonal flows (viscosity gradient)
  - Baroclinic instability (entropy gradient)
- Difficult to observe... (except excluding density)
- Other alternative: gravitational instability?

Meheut et al. 2012

Conclusions

- Transitional disks with planets may all be dust traps
- Trapping in radial **and** azimuthal direction possible
- Evidence for dust trap in separation large & small dust
- **Evidence for embedded planets in resolved gas!**

- **ALMA is the key for further studies of dust trapping in transitional disks**
- ***Stay tuned for more results in Cycle 0, 1 and 2!***