宇宙生命計算科学連携拠点 第2回ワークショップ

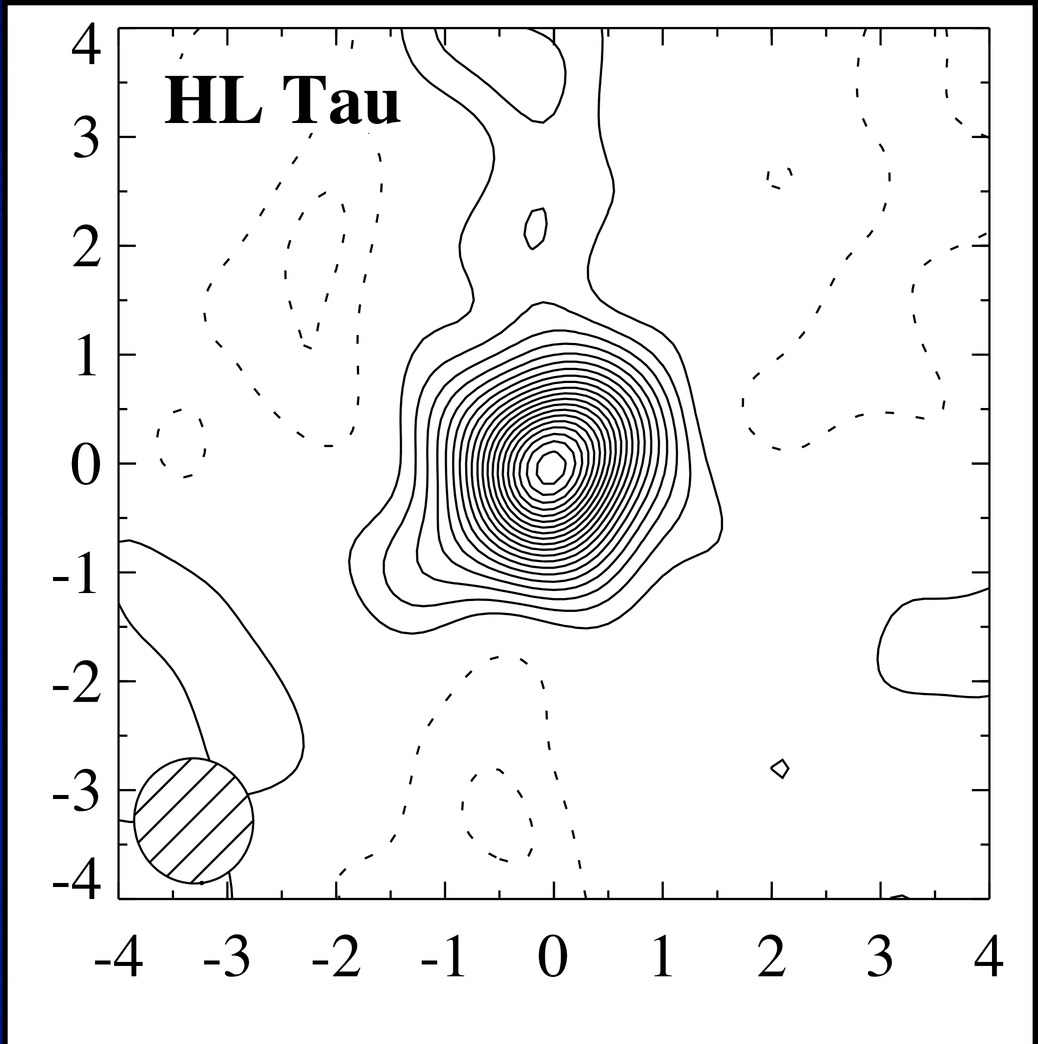
(April 27th, 2016 in Tsukuba)

惑星系形成に関する観測的制約

〜ALMA高解像度観測からの示唆〜

Munetake MOMOSE (Ibaraki University)

HL Tau in mm continuum after 2000



<u>**Nobeyama Millimeter Array**</u>

λ=2mm

1.2”× 1.1” (≈160au)

(Kitamura, Momose et al. 2002)

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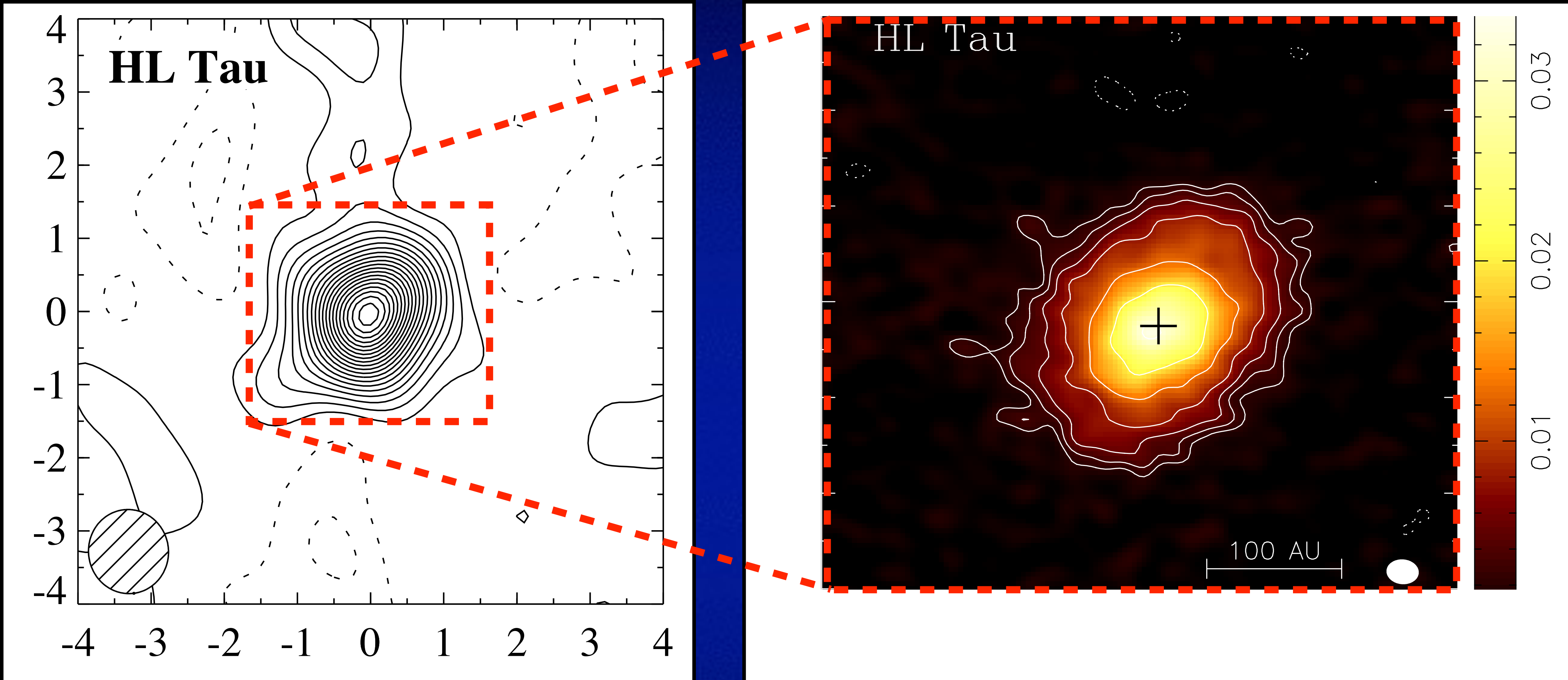

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λ=2mm
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<u>CARMA</u>
λ=1.3 mm,
0.13”× 0.17” (≈20au)

(Kwon, Looney & Mundy 2011)

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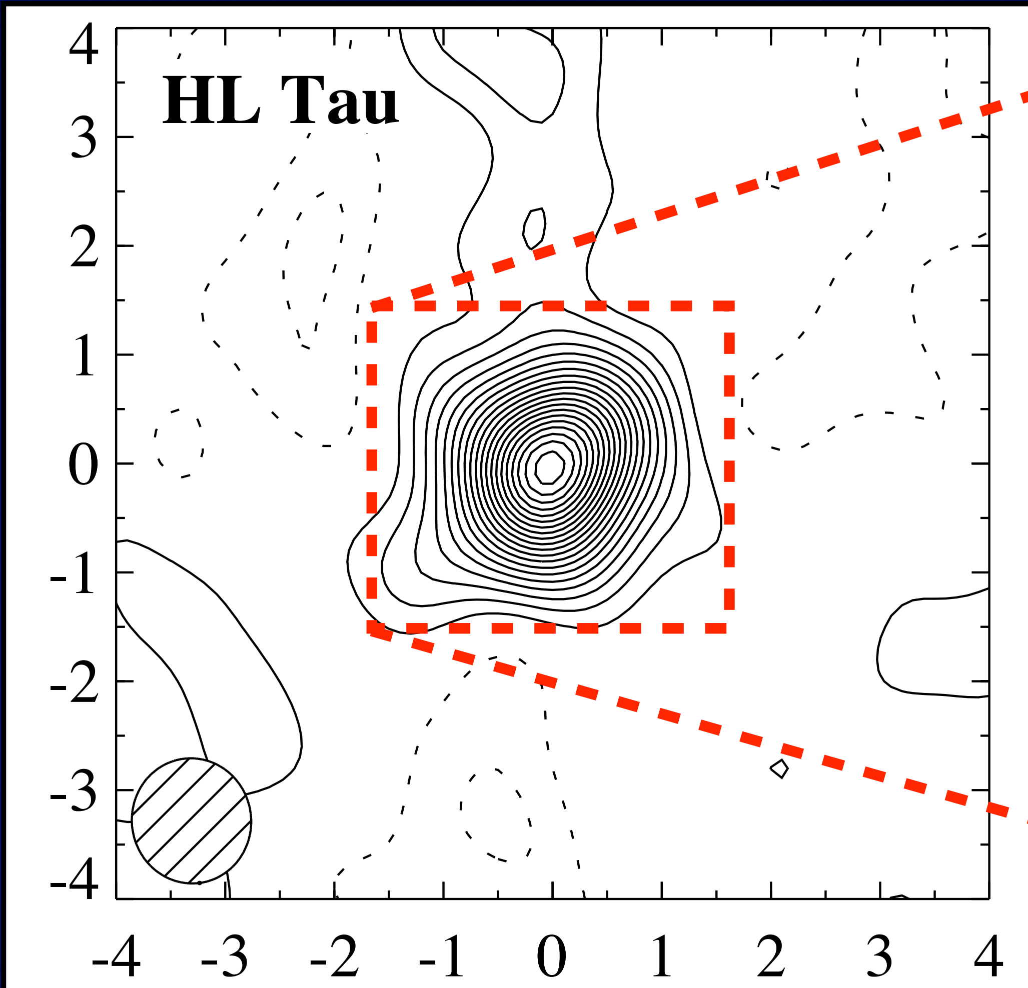

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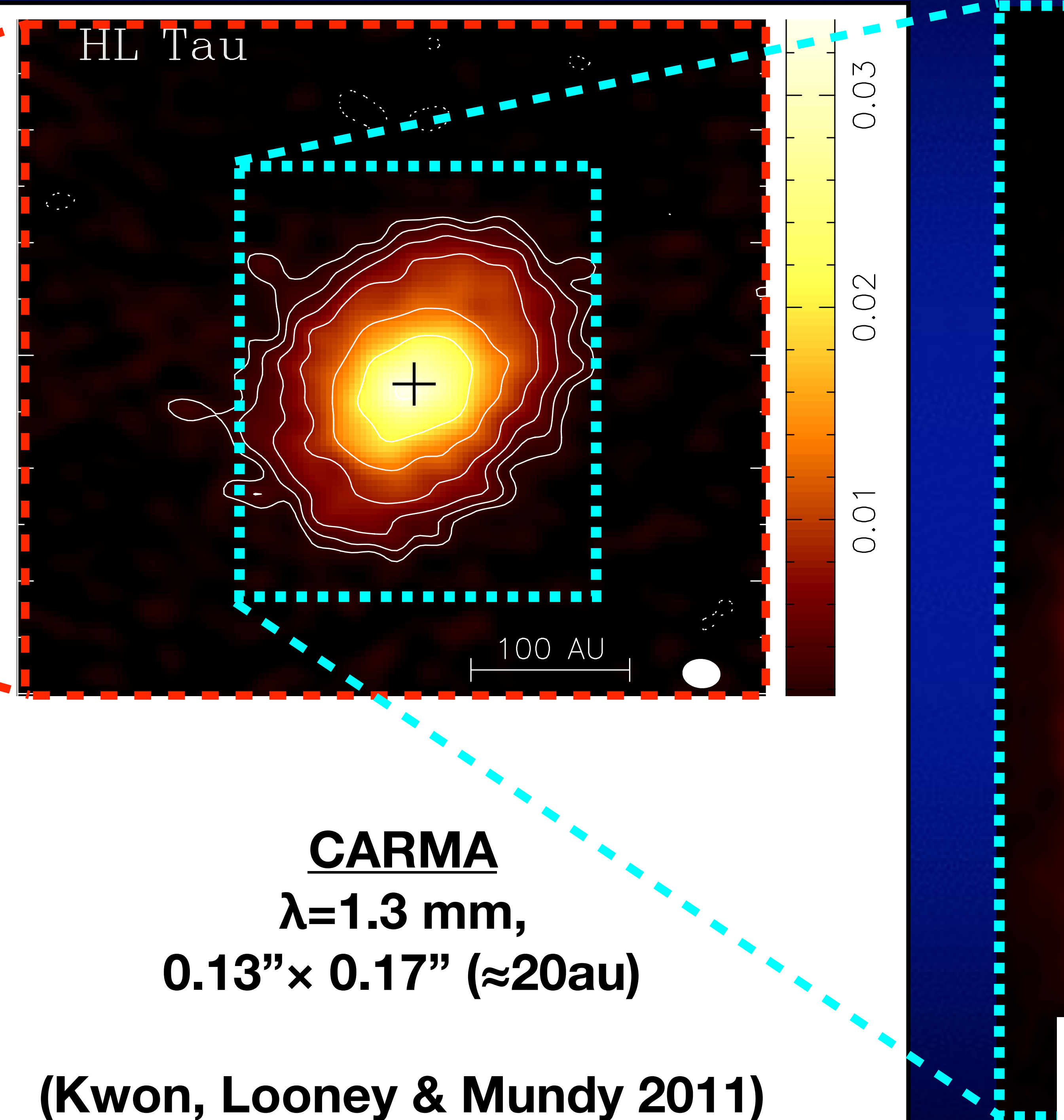

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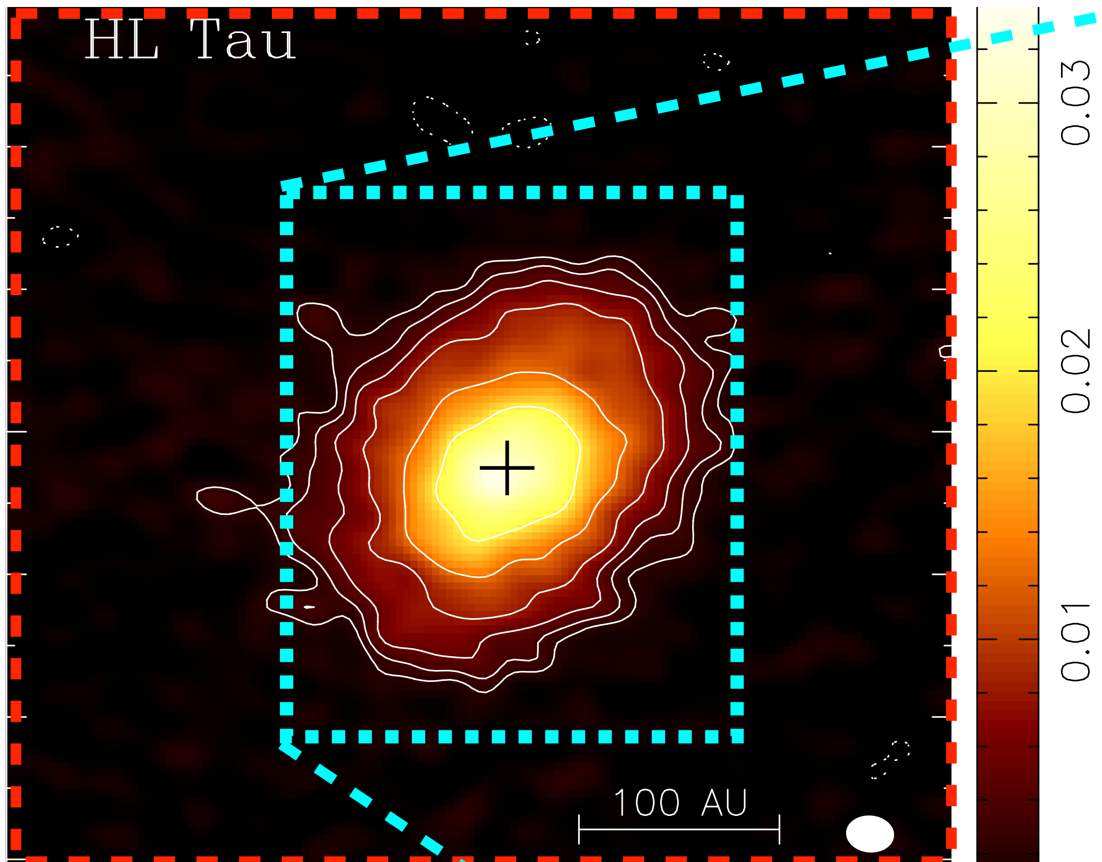

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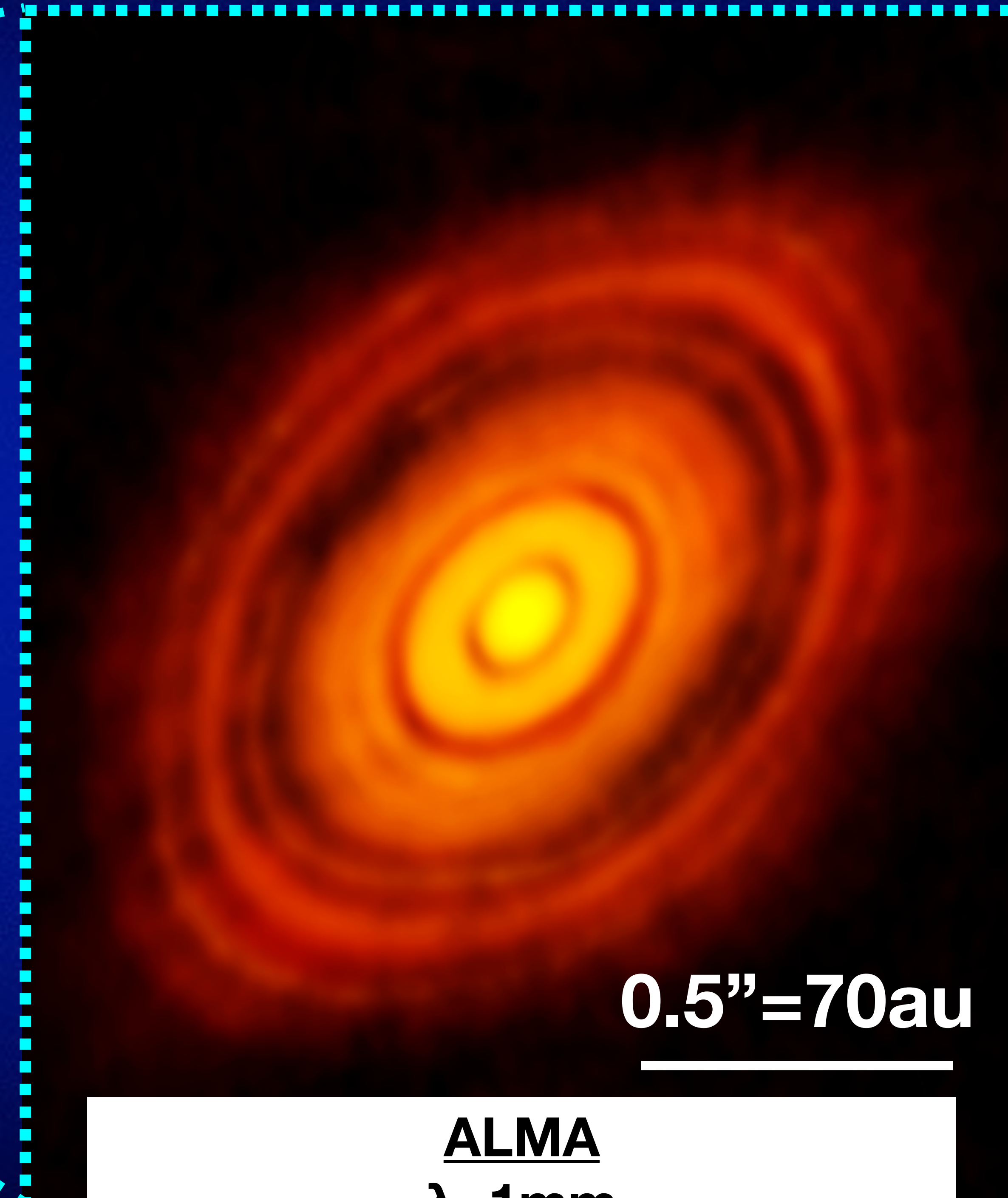


ALMA
λ=1mm
33.5mas × 21.1mas (≈3.5au)
(ALMA Partnership, 2015)

Contents

- **HL Tau**
  - a planetary system around very young star ?
  - planets vs. without planet
- **Other objects at highest resolution**
  - TW Hya etc.
  - shallower gaps in both old & young stars
- **Transitional disks**
  - spatial variation of g/d in a disk

Planet formation in a disk

— target of observations —

Dust in a disk (~ 0.1 μm)

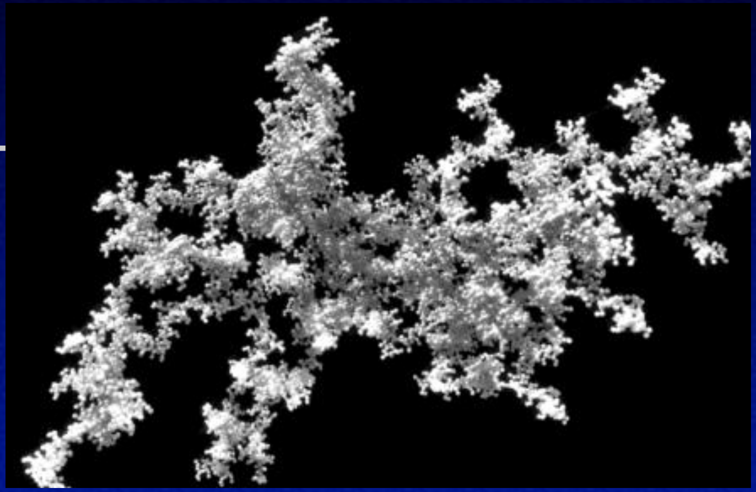
Planetesimals (~ 10 km)

Theories and simulations

(Proto)planets (> 1000 km)

Planet formation in a disk

—target of observations —



Dust in a disk (~ 0.1 μm)

(1)Dust Growth

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Theories and simulations

(Proto)planets (> 1000 km)

Planet formation in a disk

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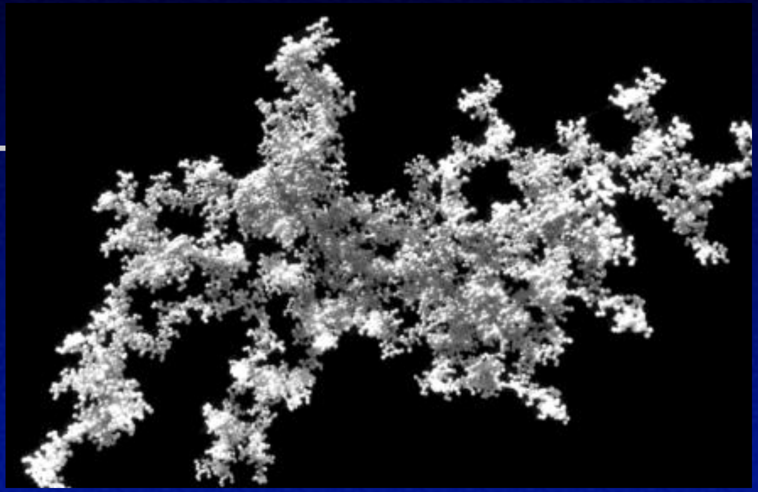


Dust in a disk (~ 0.1 μm)

(1)Dust Growth

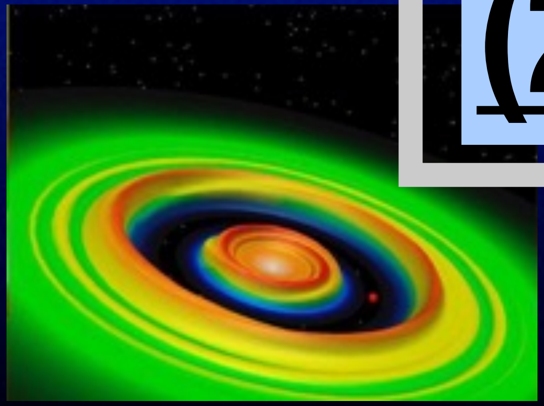
Planetesimals (~ 10 km)

Theories and simulations

(2) Feedback

(Proto)planets

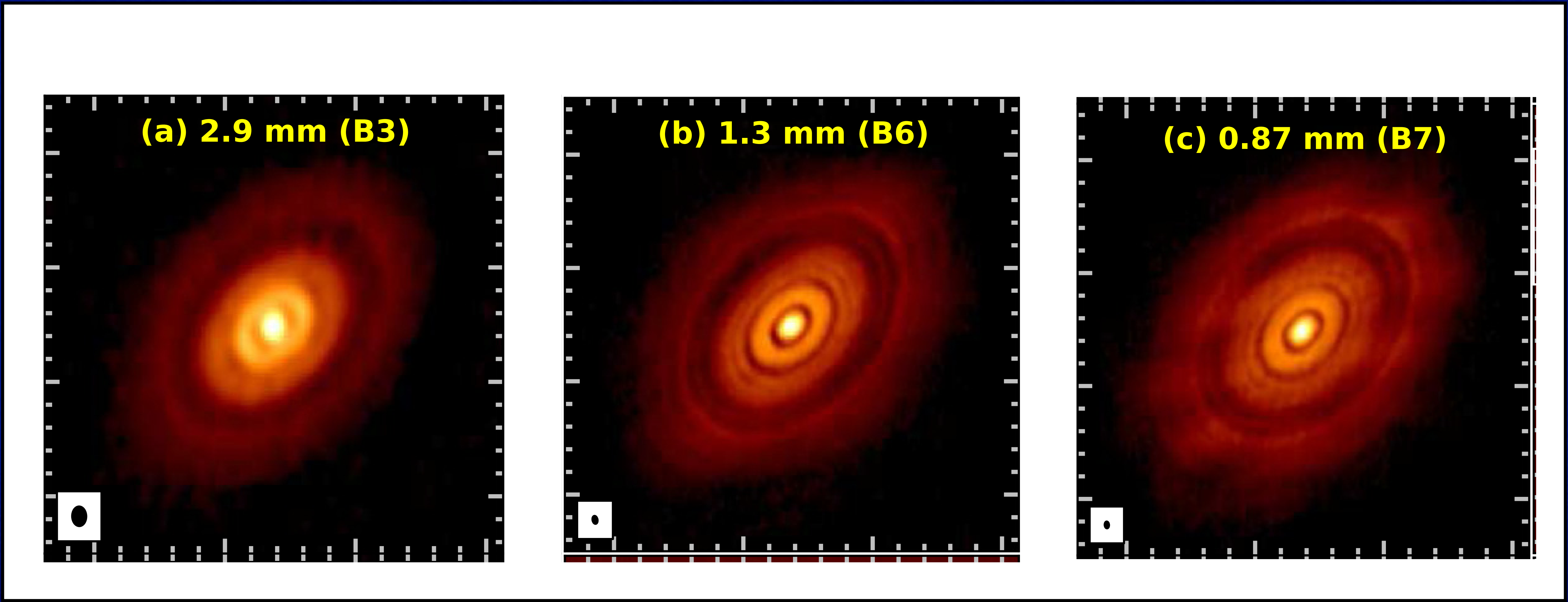
(> 1000 km)



Part 1
HL Tau image

Data released on Feb. 18, 2015

ALMA partnership, Brogan et al. (2015)

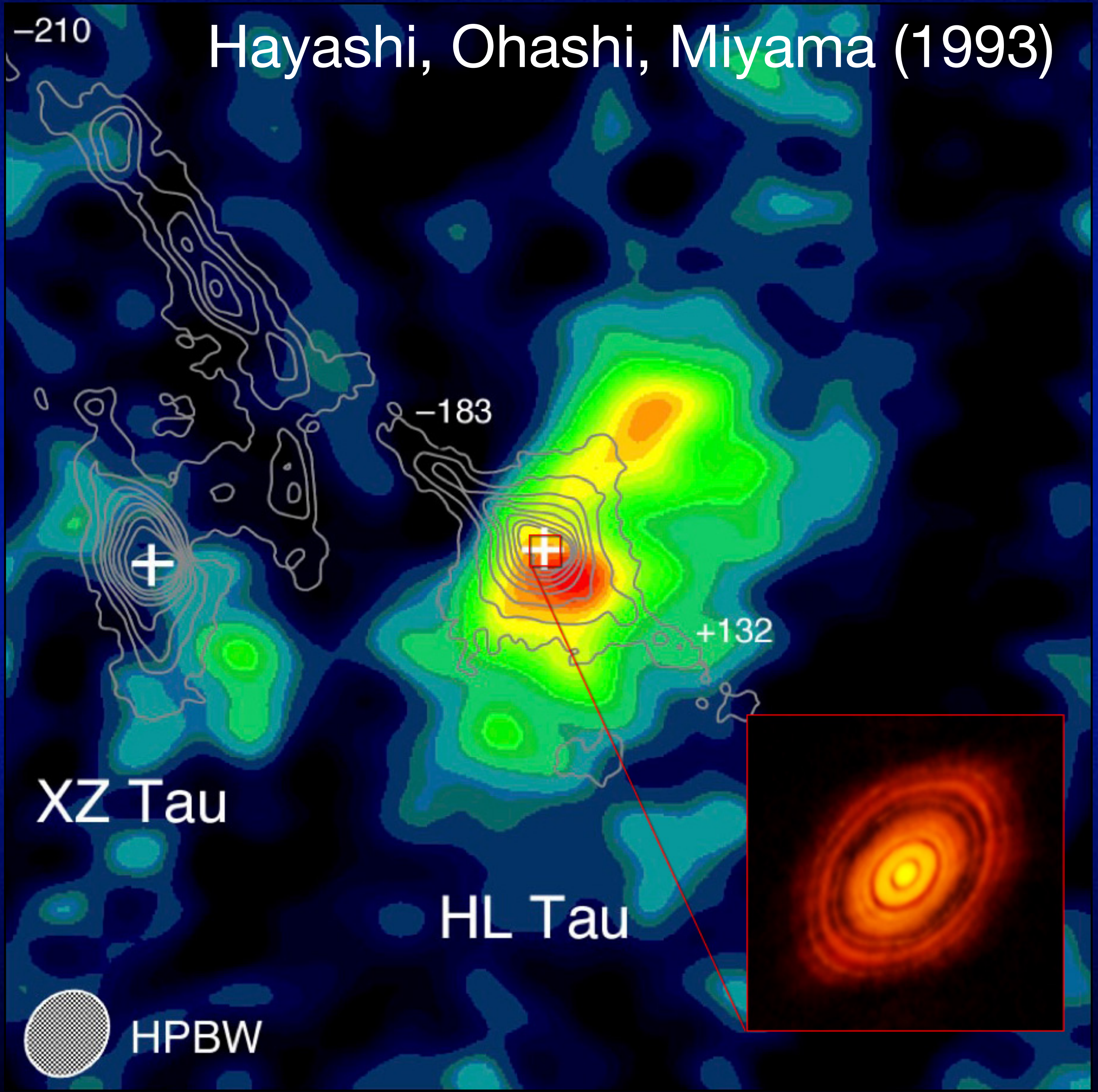


85mas * 61mas   35mas * 21mas   30mas * 19mas

※ 20mas = 2.8 AU

HL Tau:
— a “protostar-like” (age <10^6 yr) star

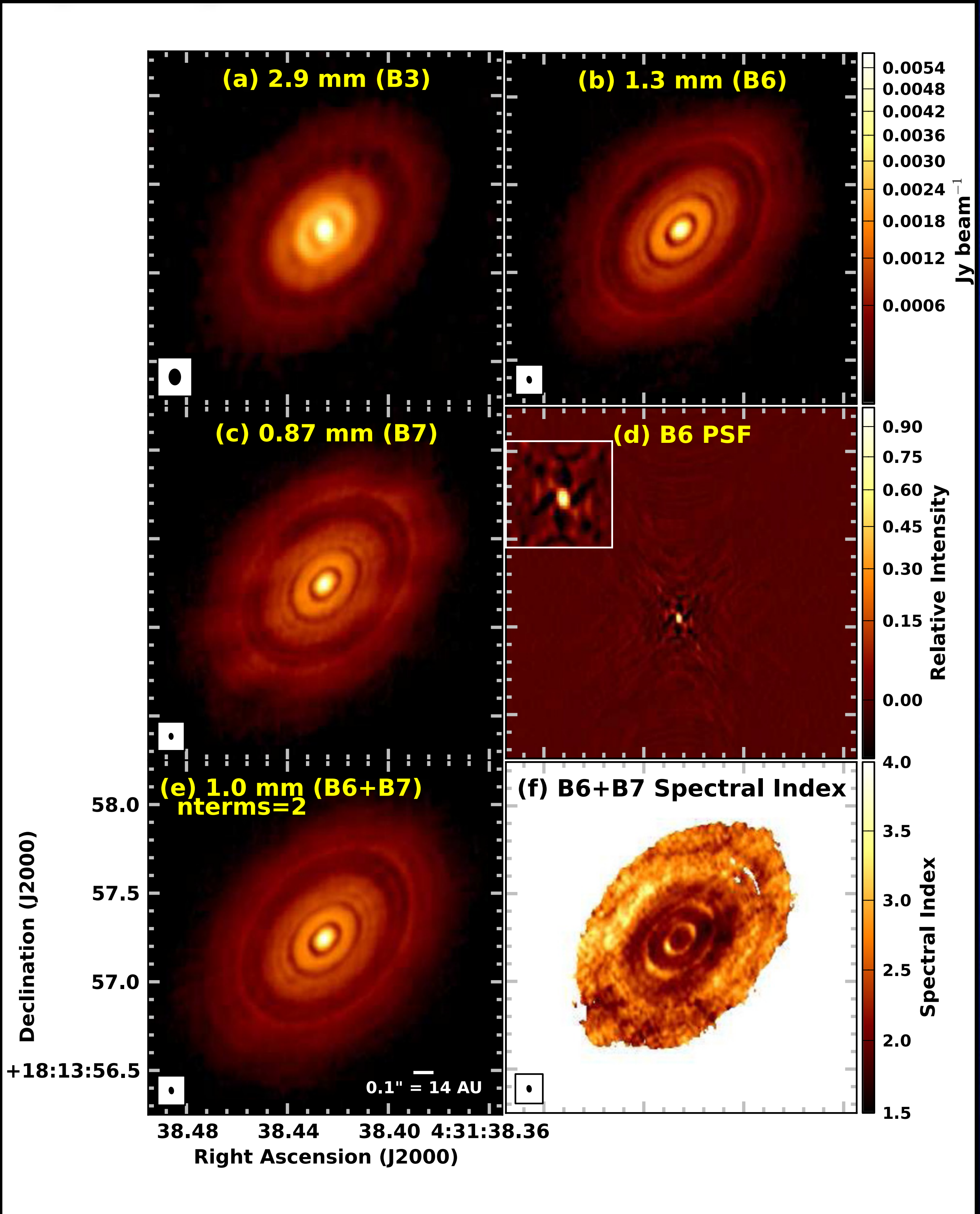
- “infalling envelope” in ^{13}CO(J=1-0)
- collimated jets in optical lines and outflows in CO
- nebulous at optical



Highlights of HL Tau images

ALMA Partnership+ (2015); Pinte+ (2016)

- Seven bright-dark rings
  - sharp edges near the minor axis
    👉 **dust sedimentation**
  - scale height ≈ 1au @ r =100au,
    👉 **α = 10^{-4} (small turbulence)**
- Spectral index
  - ≈2 (BR), ≈2.5 (DR) at r < 30 au
    👉 **τ in inner bright rings ≫ 1**
  - ≈3 in r > 70au; optically thin, smaller grains dominate ?
- Increase in central offsets with radius —planet formation ?



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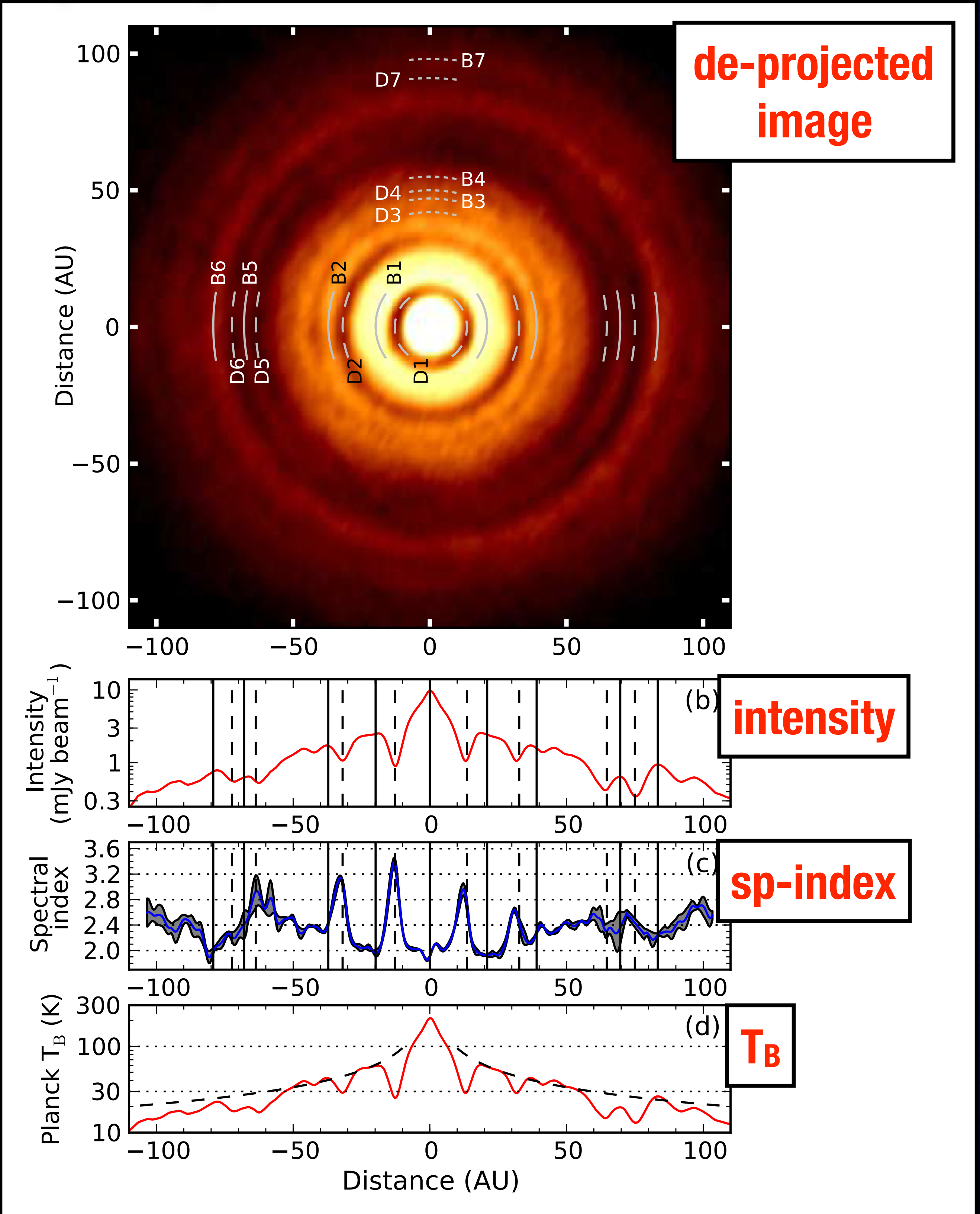


What is the origin(s) of rings/gaps ?

A. Planets

- **Kanagawa et al. (2015 in ApJL; 2016 in PASJ)**
- Tamayo et al. (2015), Dipierro et al. (2015), Akiyama et al. (2016), Jin et al. (2016) …

B. Mechanisms without planets

- Takahashi & Inutsuka (2014; 2016): Secular GI (a slow process due to friction btw gas and dust)
- Zhang+ (2015): Pebble growth near condensation fronts
- **Okuzumi+ (2016): Ring/gap formation by sintering** (based on the idea by Sirono 2011)

(1)Planets? : Mass vs. gap structure

Kanagawa, Muto, Tanaka, MM et al. (2015; 2016)

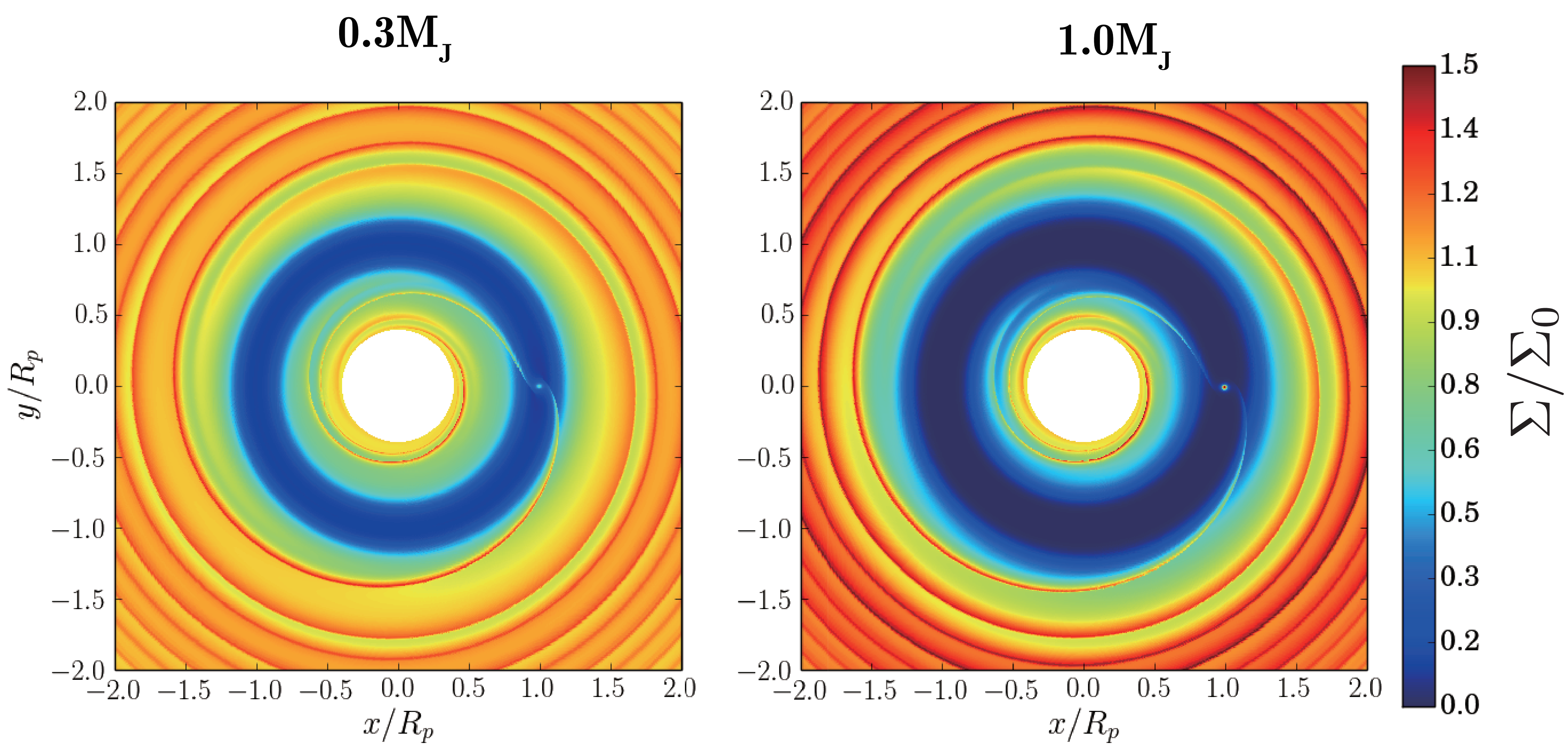
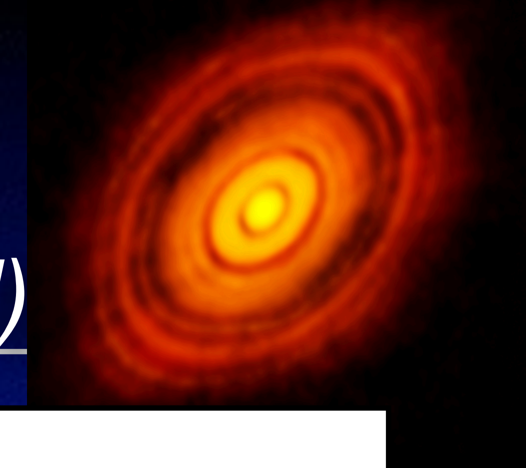


Fig. 1.— The surface density distributions at 10^4 planetary orbits obtained by two–dimensional hydrodynamic simulations for $M_p = 0.3M_J$ (*left*) and $M_p = 1.0M_J$ (*right*). Other parameters are set to be $h_p/R_p = 1/20$, $\alpha = 10^{-3}$ and $M_* = 1M_\odot$.

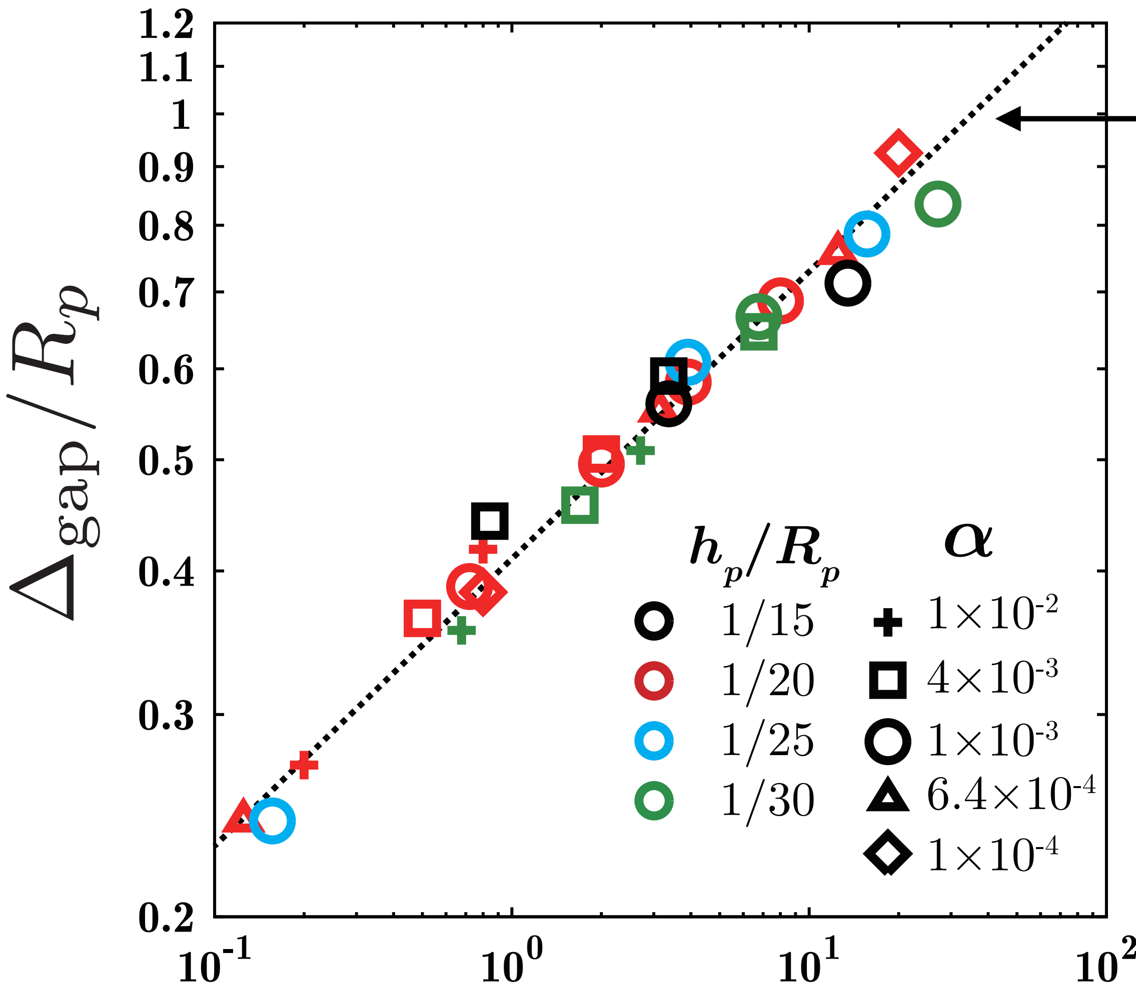
Mass estimates from gap width

Kanagawa, Muto, Tanaka, MM et al. (2016; PASJ)



Gap width vs.

K' (function of M_p, T, α)



$$K' = \left(\frac{M_p}{M_*}\right)^2 \left(\frac{h_p}{R_p}\right)^3 \alpha^{-1}$$

plot: simulation

line: empirical relation from simulations

If $M_\star = 1M_\odot$, α=10^{-3} and β=1.5

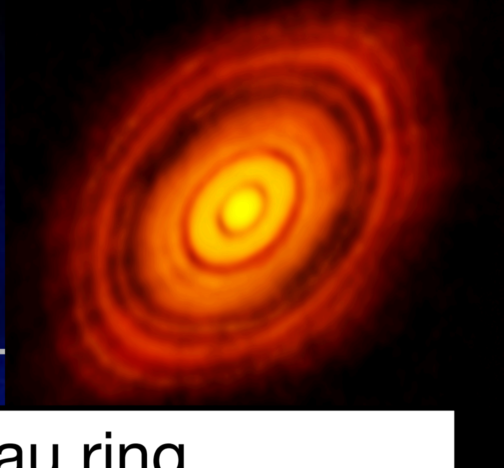
	10au	30au	80au
Δ_{gap}/R_p	0.81	0.23	0.29
M_p/M_J	1.4	0.2	0.5

Δ_{gap} = width of 0.5 $\Sigma_{unperturbed}$

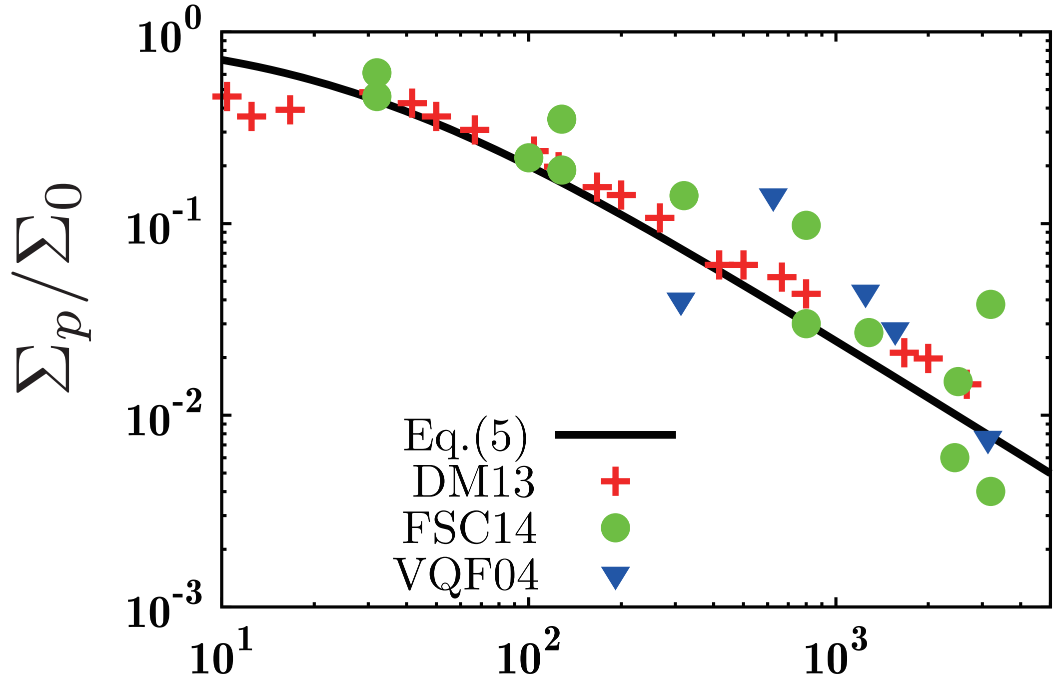
roughly consistent with "depleted mass" in each gap (Pinte+ 2016)

Mass estimates from gap depth

Kanagawa, Muto, Tanaka, MM et al. (2015; ApJL)



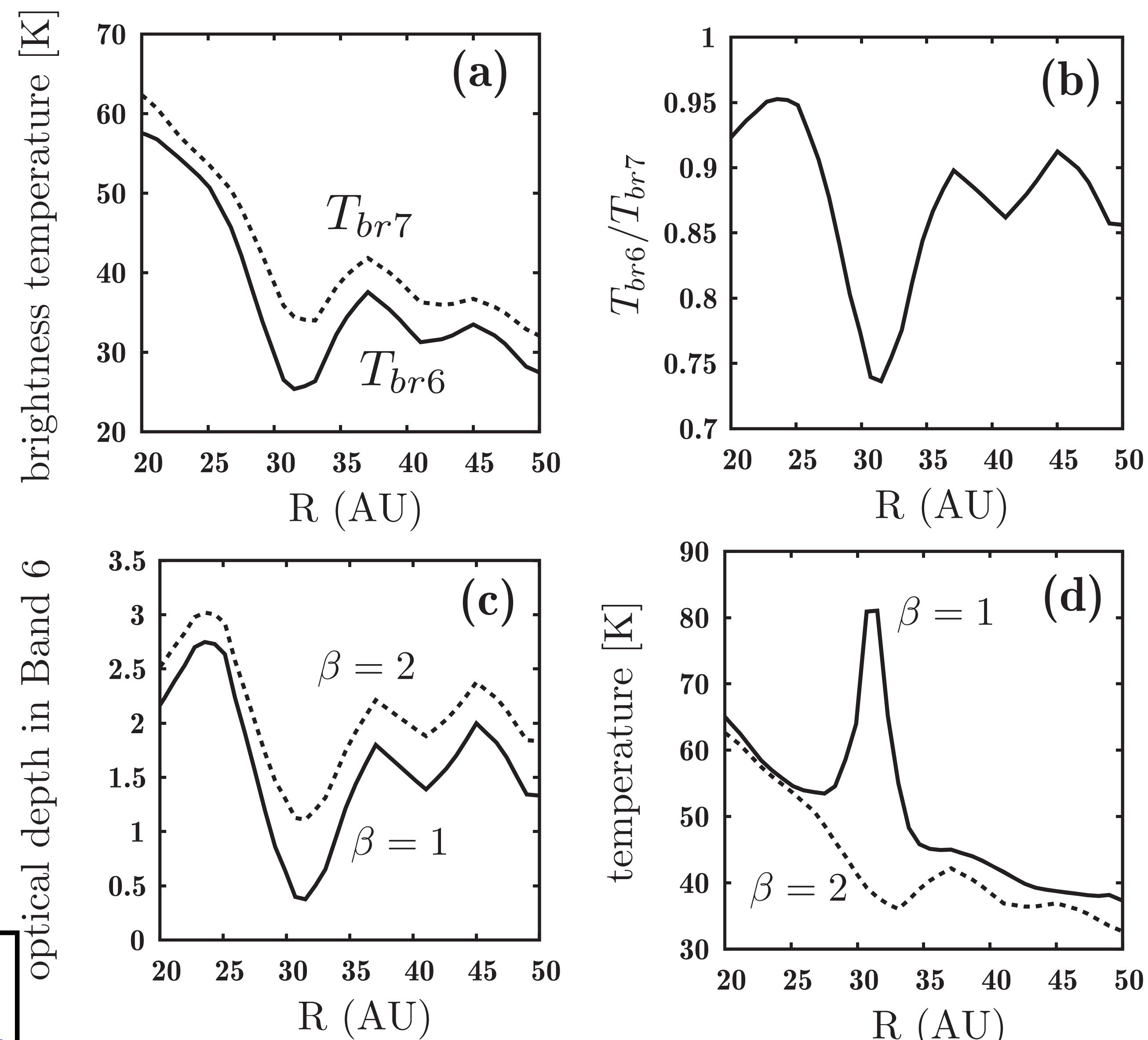
Gap depth vs. **K** (function of M_p, T, α)



$$K = \left(\frac{M_p}{M_*}\right)^2 h_p^{-5}\alpha^{-1}.$$

(Line) analytic formula from angular momentum flux and torque exerted by a planet on disk ***vs.*** *(dots) simulations*

Observations at ~30au ring

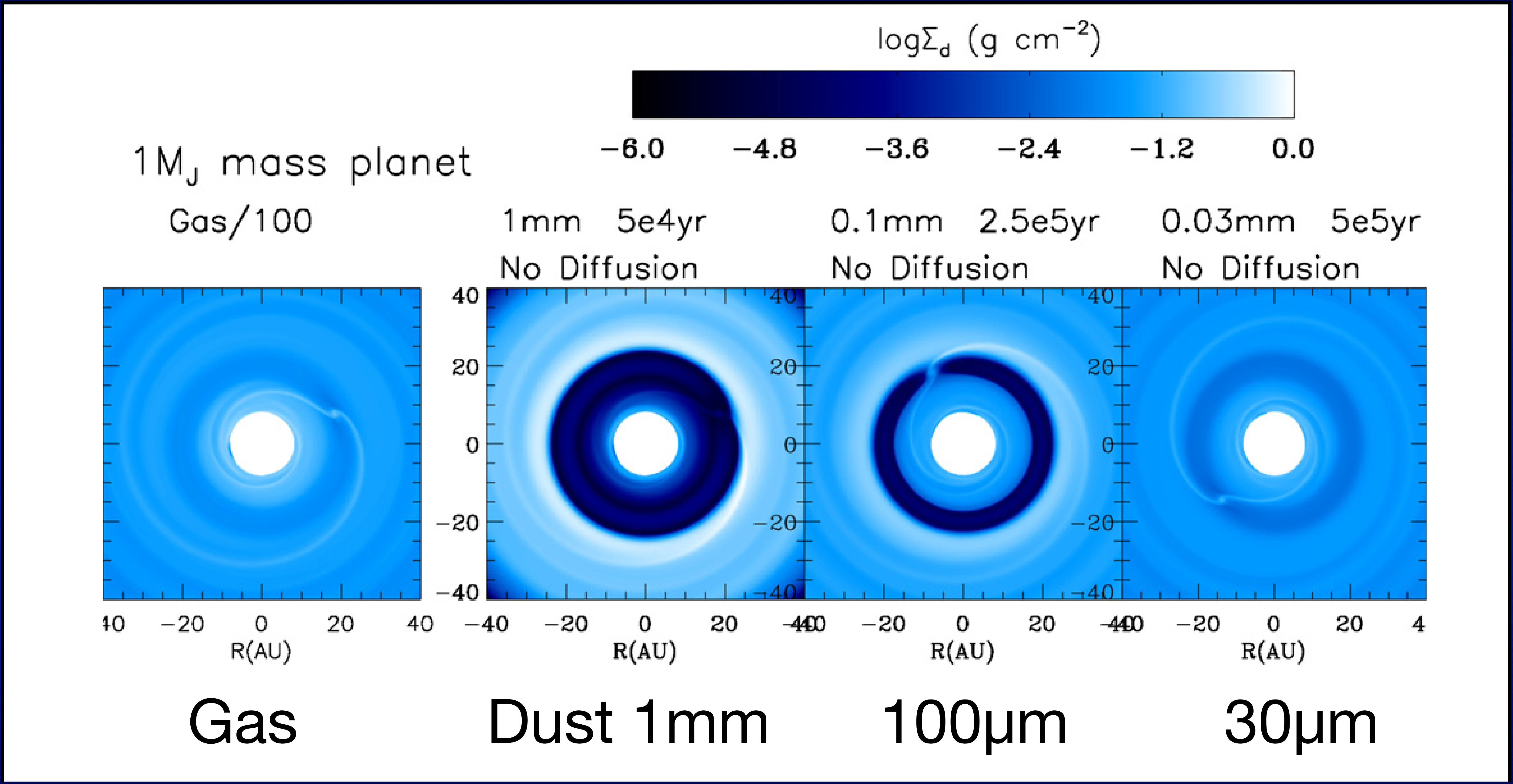


$M_p \approx$ (3-5) × 10^{-4} $M_\star$

for 30au gap if α=10^{-3}

Simulation on dust filtration

Zhu et al. (2012)



Smaller dust better couples with gas.

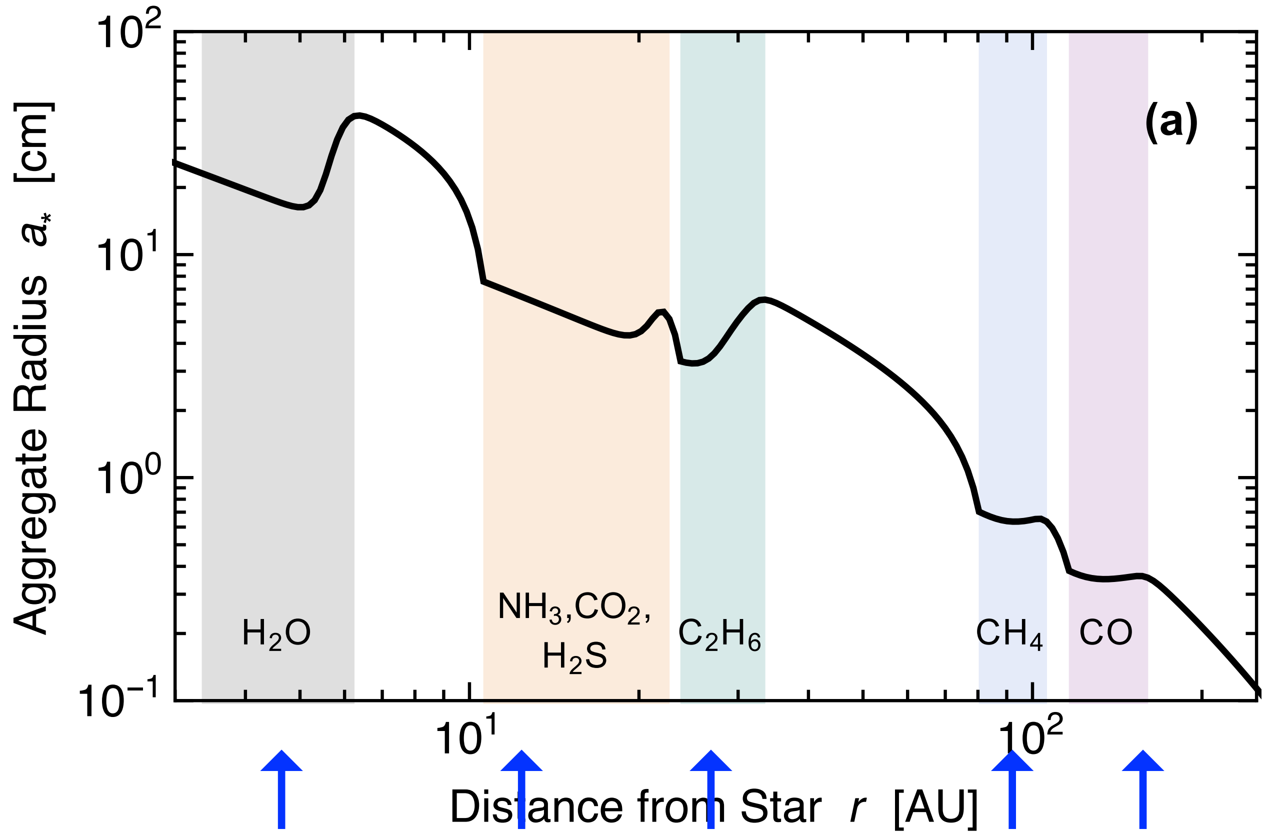
<u>**Larger dust tends to concentrate in a pressure bump.**</u>

(2) Sintering-induced multiple dust rings

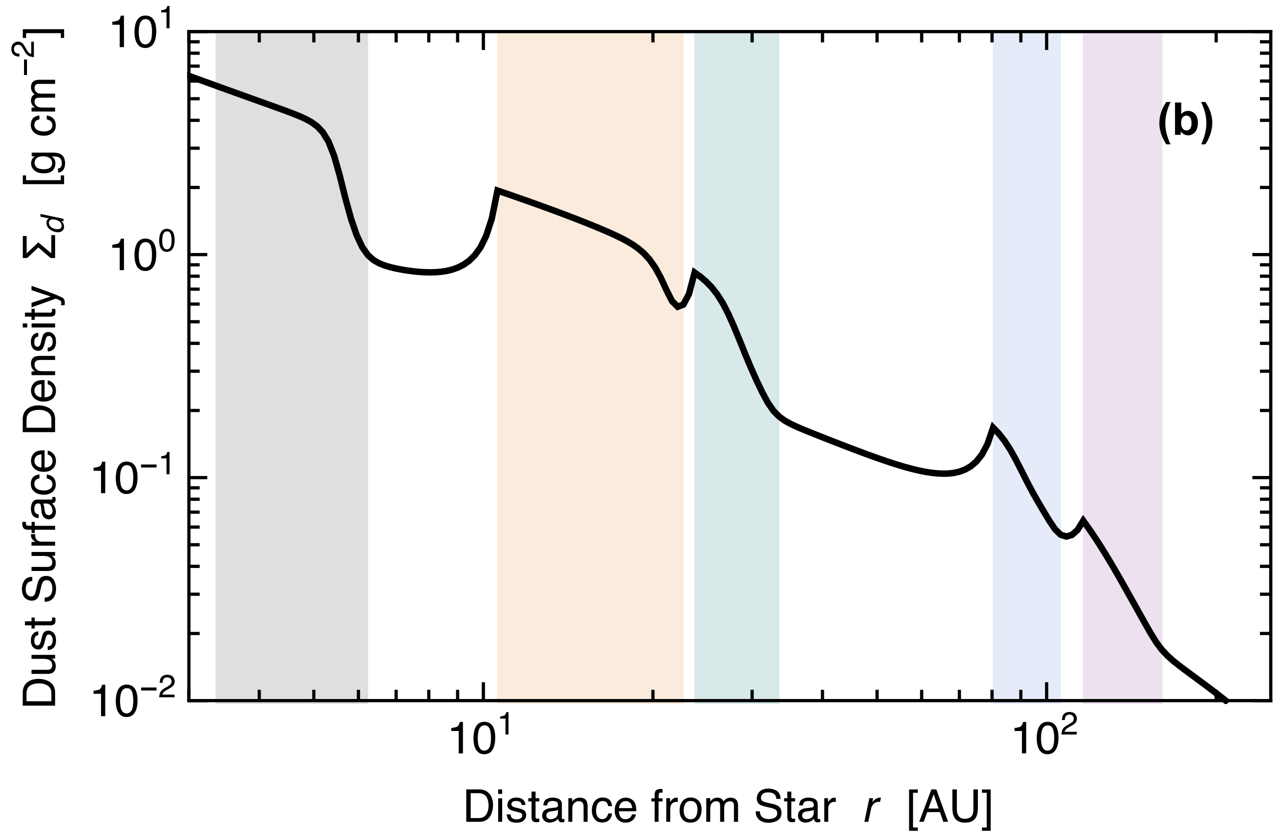
Okuzumi, Momose, Sirono, Kobayashi & Tanaka (2016)

Dust moves inward, through several "congestions"

Aggregate Size



Σ_{dust}



↑ H_2O

↑ NH_3 CO_2 H_2S

↑ C_2H_6

↑ CH_4

↑ CO

Sintering zones

(assume $T_d = T_b$ in the inner regions)

<u>**destruction of aggregates**</u>

→ smaller aggregates produced

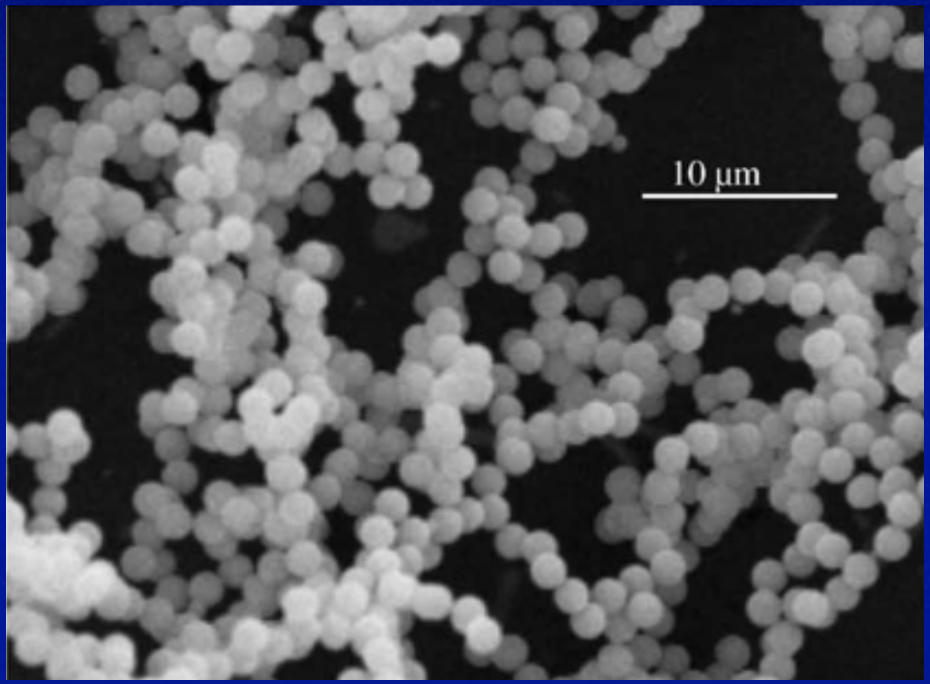
→ lower drift velocity

→ Σ_{dust} increased !

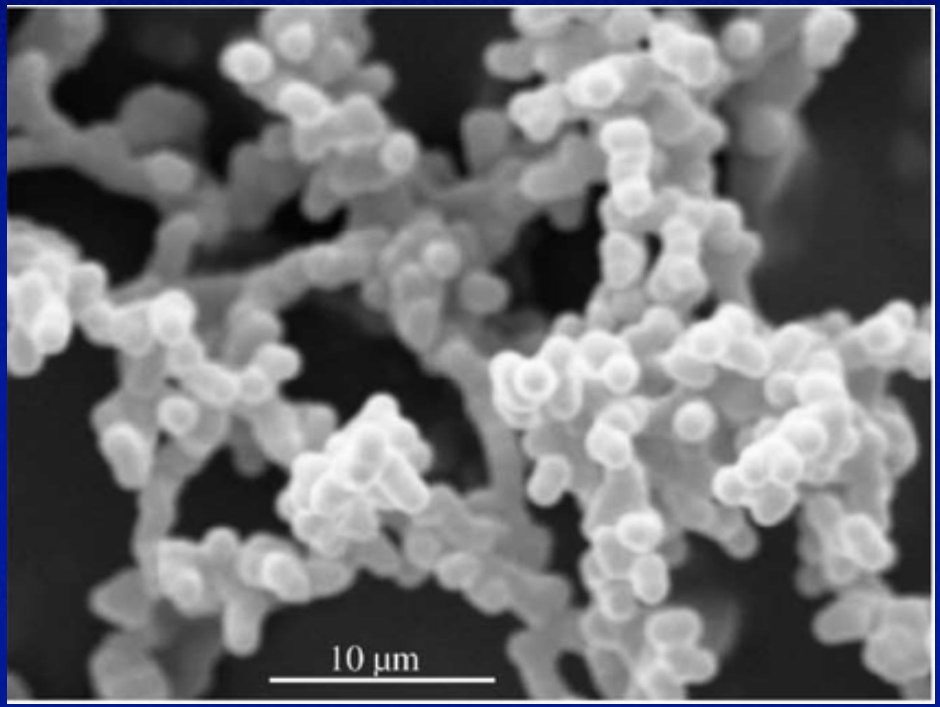
Sintered SiO_2 (T_{melt} =1920K) aggregate

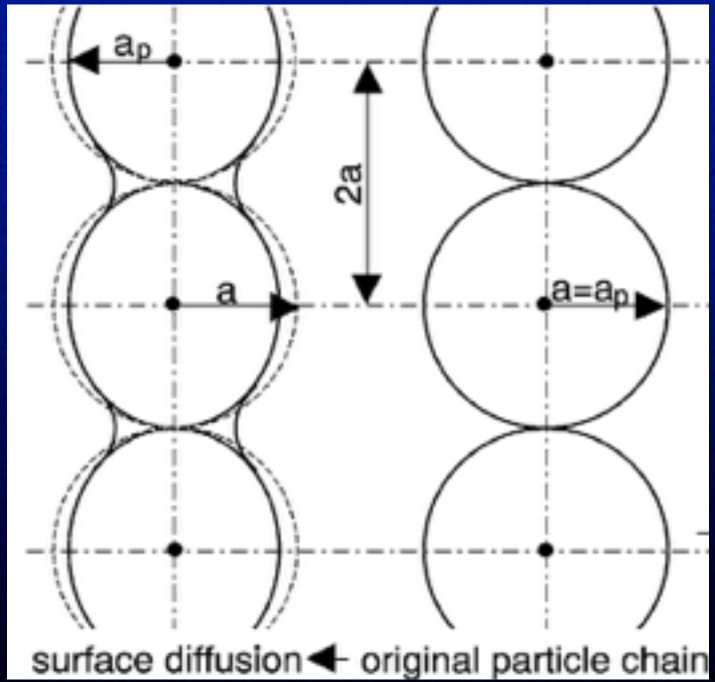
Poppe+ (2003)

SiO_2 aggregate



sintering at T=1470K





surface diffusion → "neck"

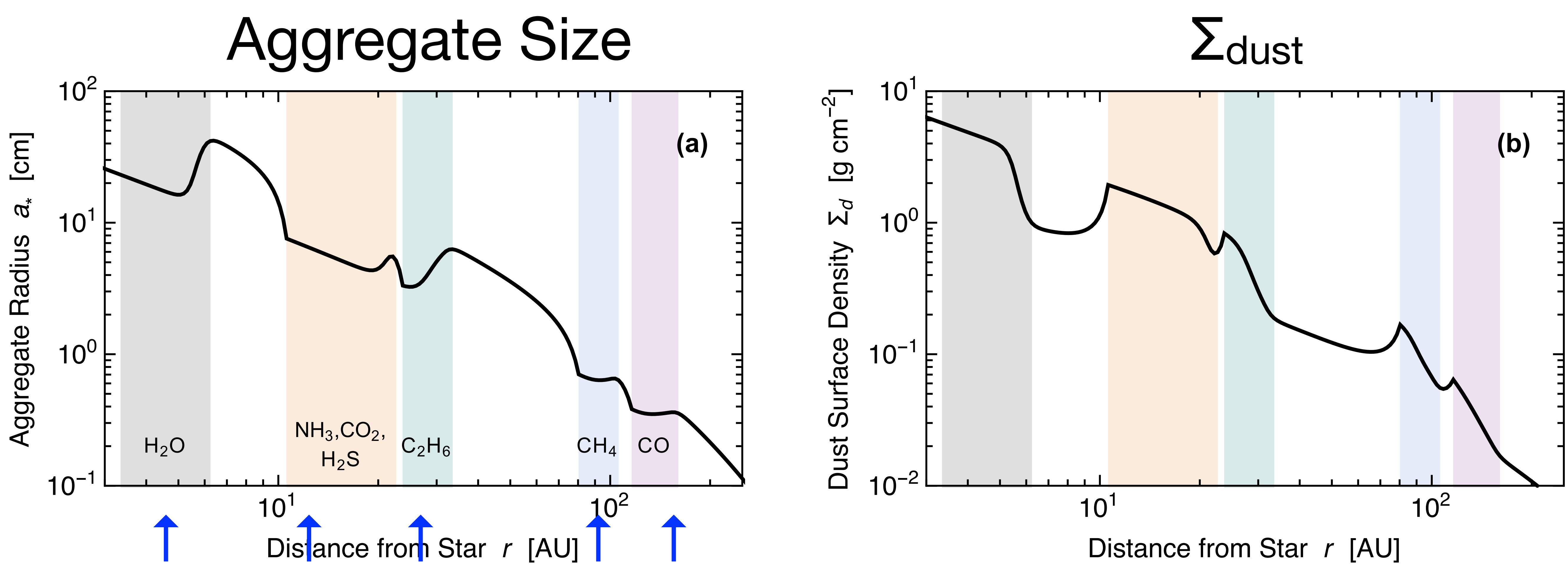
a small volume fraction,

only small amount of volatiles required

"multiple sintering zone with high Σ_{dust}"

1D Model Calculation (drift + growth/destruction)

Okuzumi, Momose, Sirono, Kobayashi & Tanaka (2016)



H_2O NH_3 CO_2 H_2S C_2H_6 CH_4 CO

Sintering zones
(assume $T_d = T_b$ in the inner regions)

destruction of aggregates

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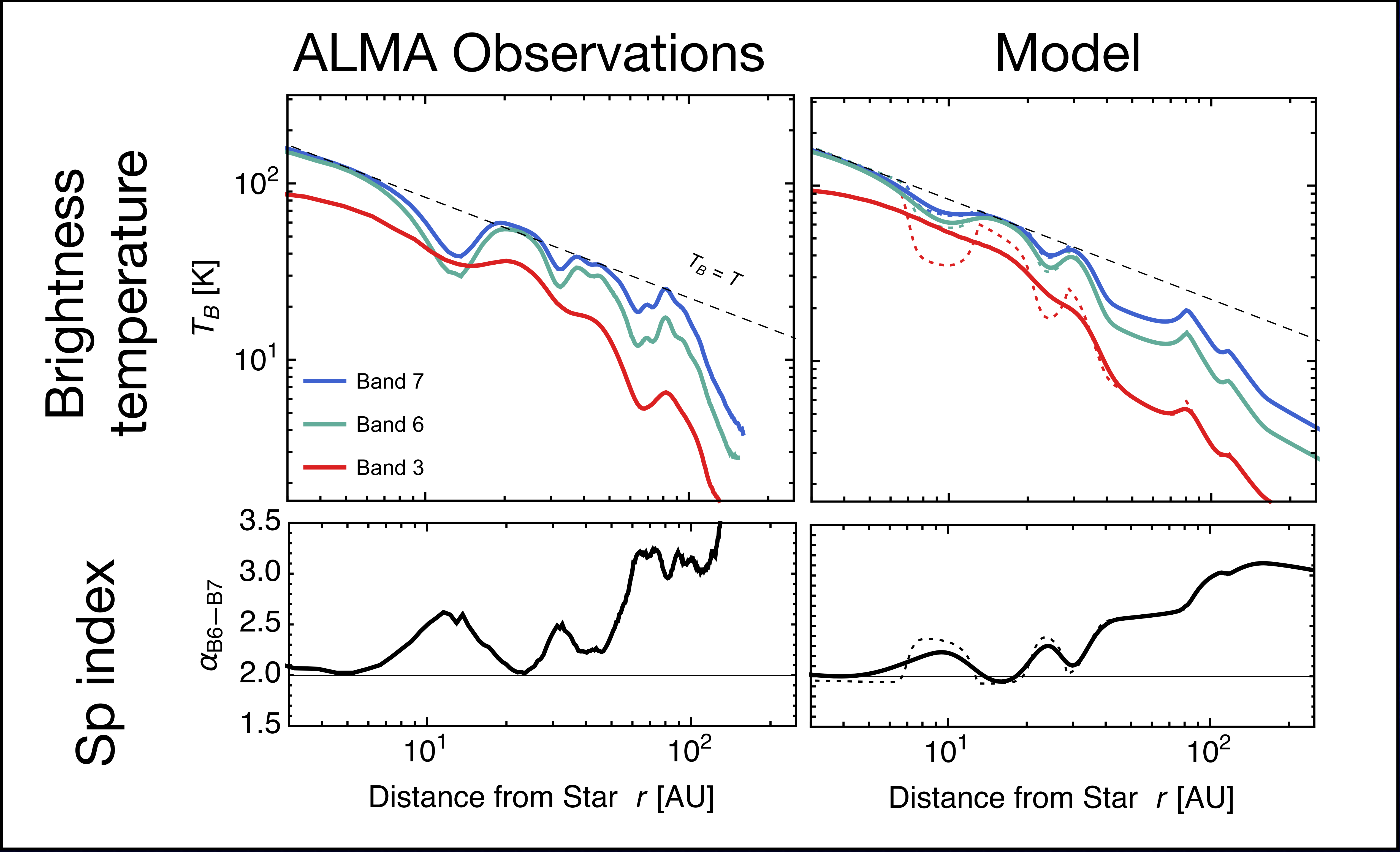
Comparisons in T_B with observations

Okuzumi, Momose, Sirono, Kobayashi & Tanaka (2016)



Part 2

Other objects at highest angular resolution

TW Hya

Andrews+ (2016); Tsukagoshi+ (will be submitted soon)

- d=54±6pc; age ~10Myr
- 24 x 18mas = 1.3 x1.0 au beam

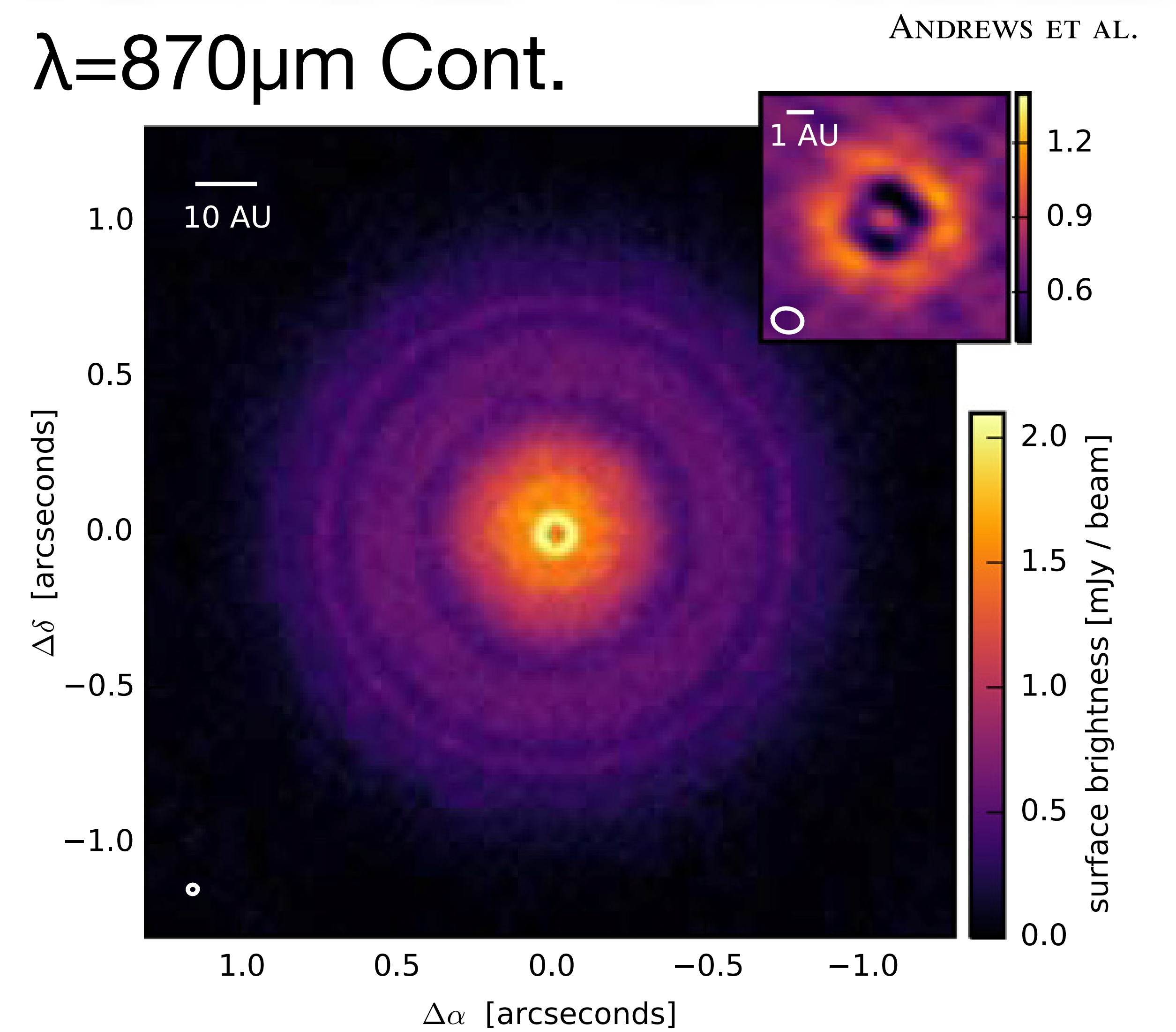


Figure 1. Synthesized image of the 870 μm continuum emission from the TW Hya disk with a 30 mas FWHM (1.6 au) circular beam. The rms noise level is ~35 μJy beam^{-1}. The inset shows a 0$''$.2 wide (10.8 au) zoom using an image with finer resolution (24 × 18 mas, or 1.3 × 1.0 au, FWHM beam).

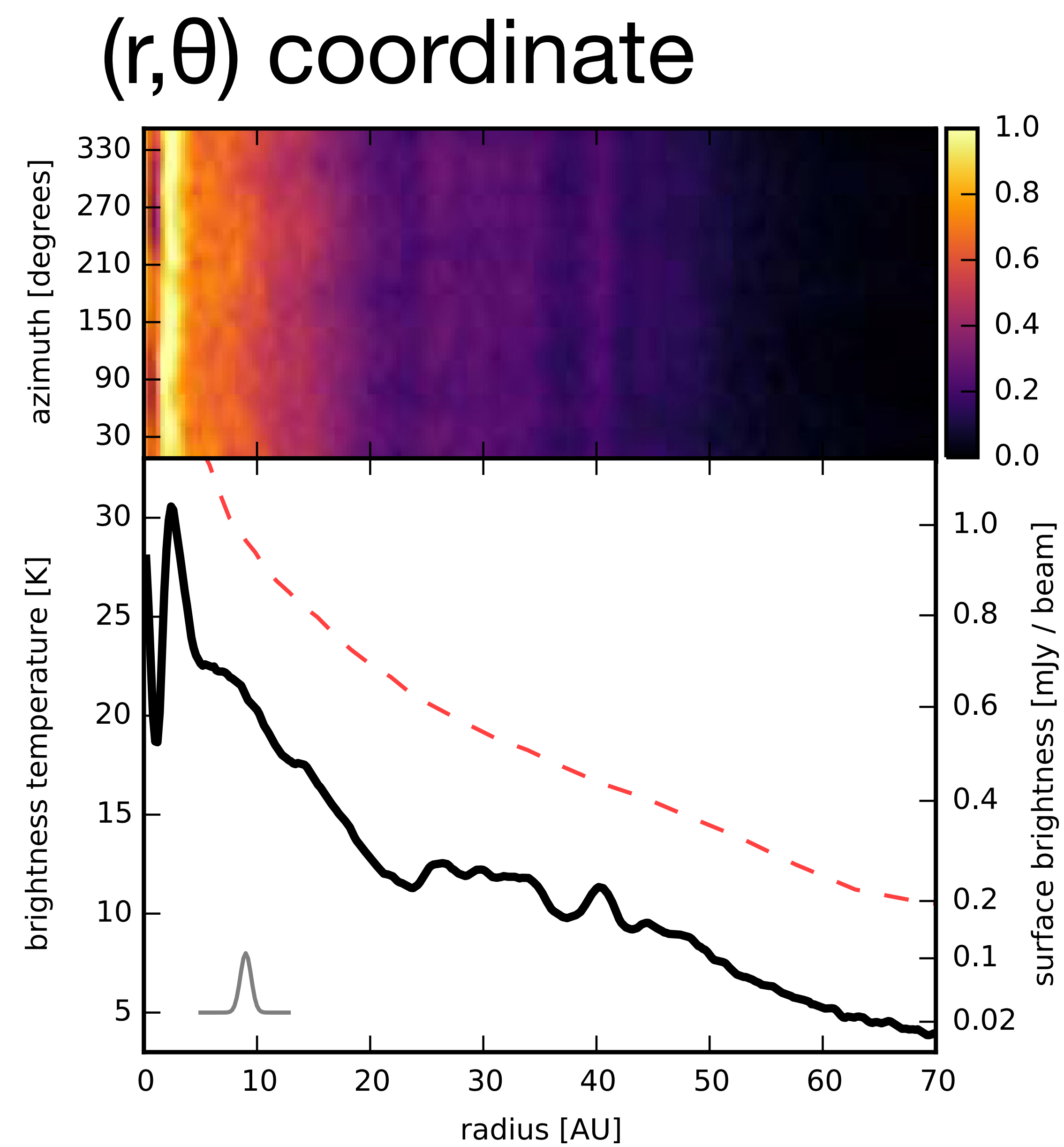
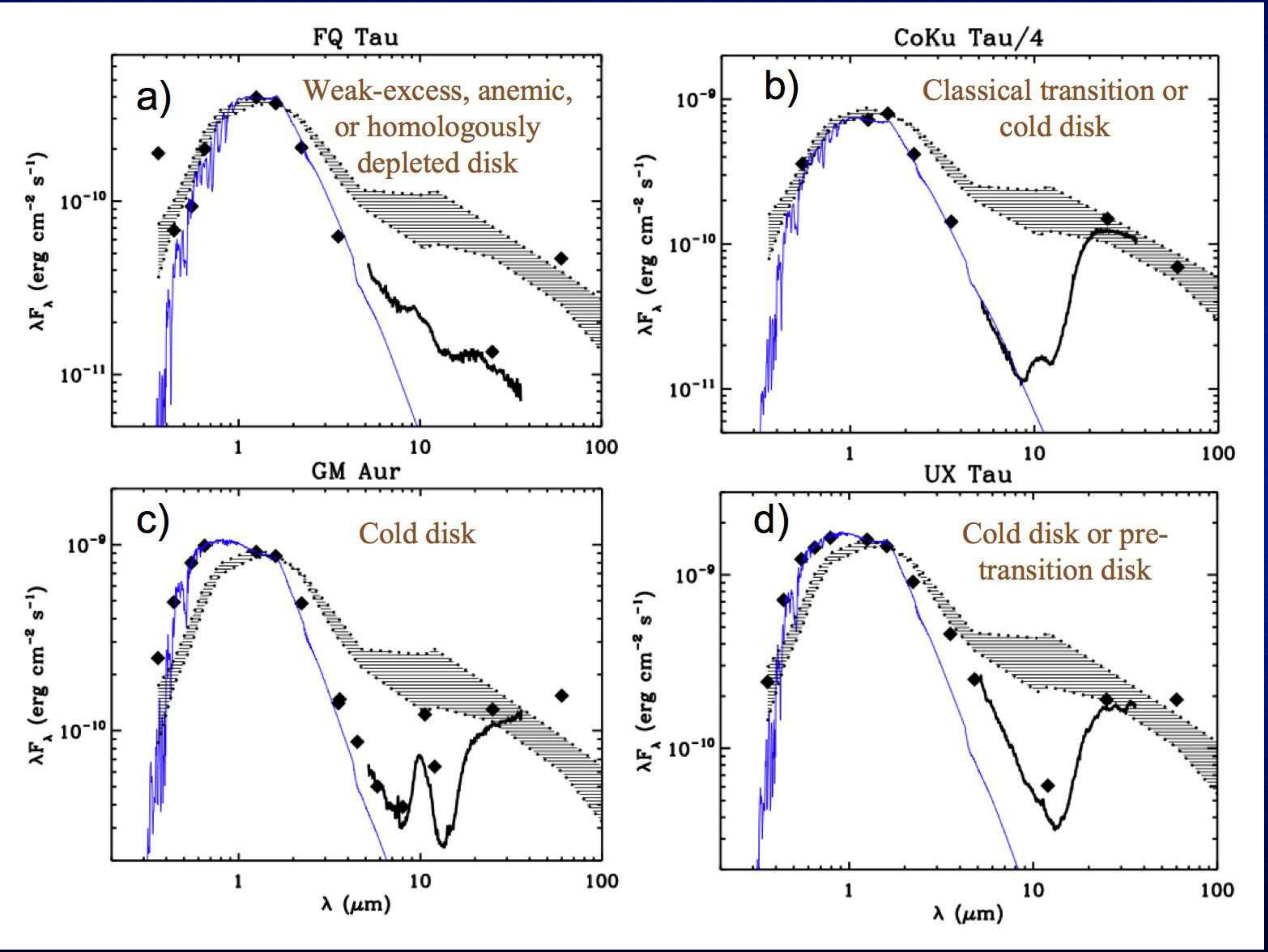


Figure 2. (top) High-resolution (24 × 18 mas beam) synthesized image described in Section 2, deprojected into a map in polar coordinates to more easily view the disk substructure. (bottom) The azimuthally averaged radial surface brightness profile. For reference, the dashed red curve shows the midplane temperature profile derived from a representative model disk. The gray curve in the bottom left reflects the profile of the synthesized beam.

Part 3
Transitional Disks

Transitional Disks

(Williams & Cuzzi 2011)

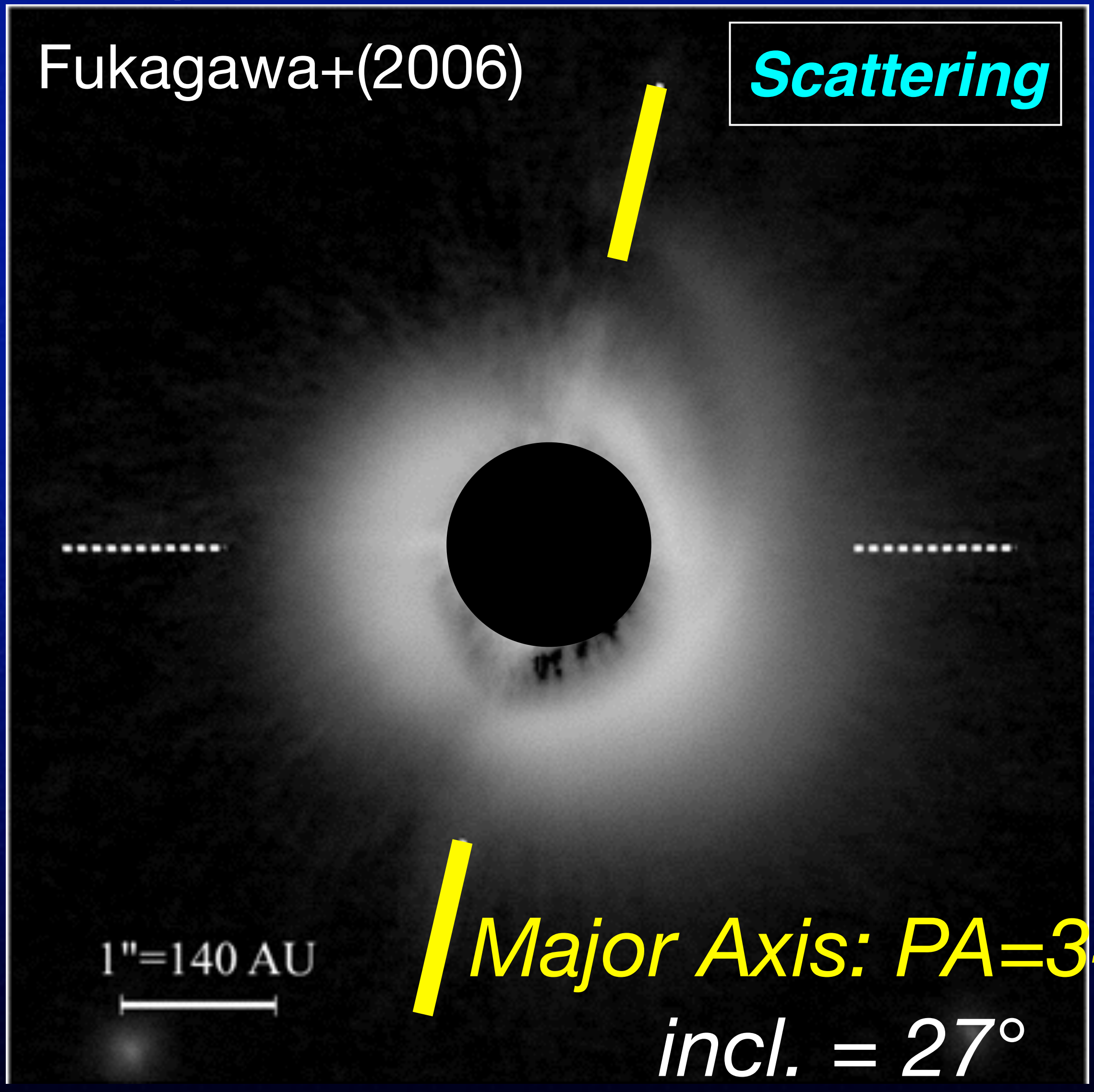


“非軸対称リング”のガス定量

~HD 142527~

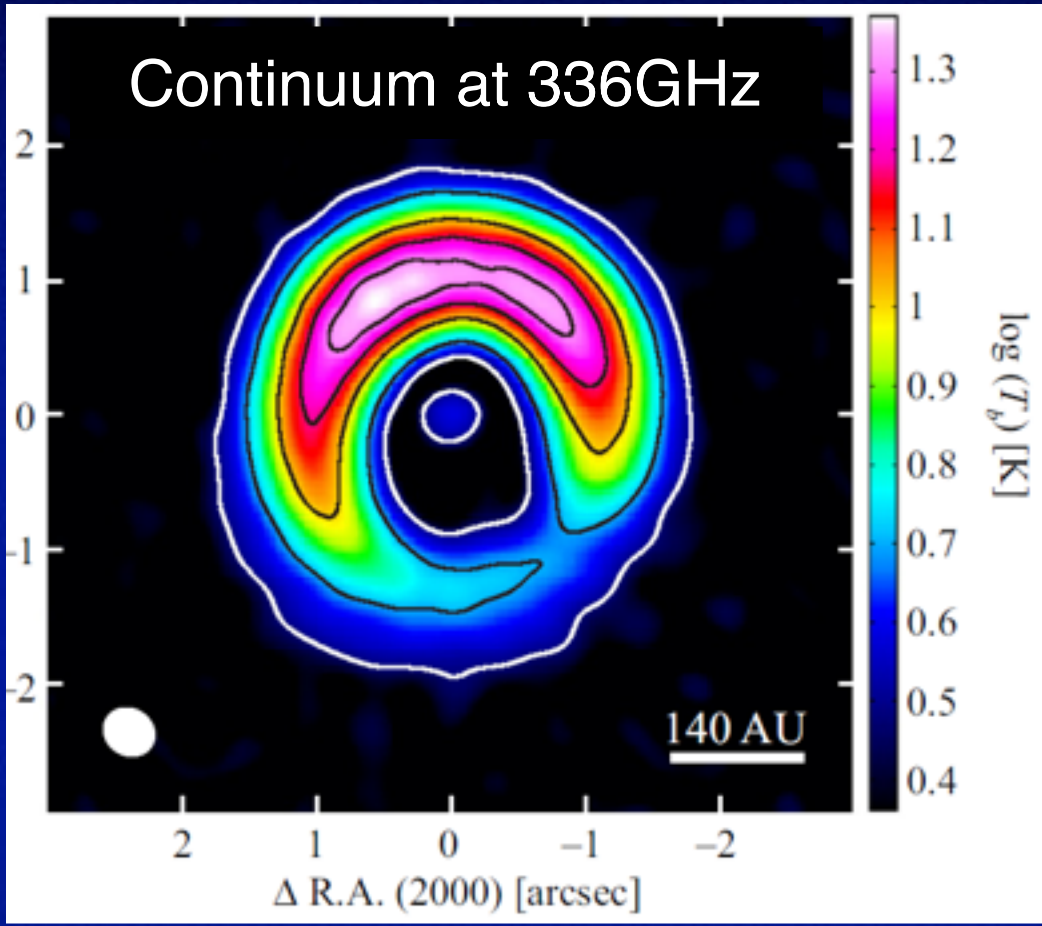
- $M_\star = 2.2 M_\odot$
- d=140 pc
- Sp.Type = F6

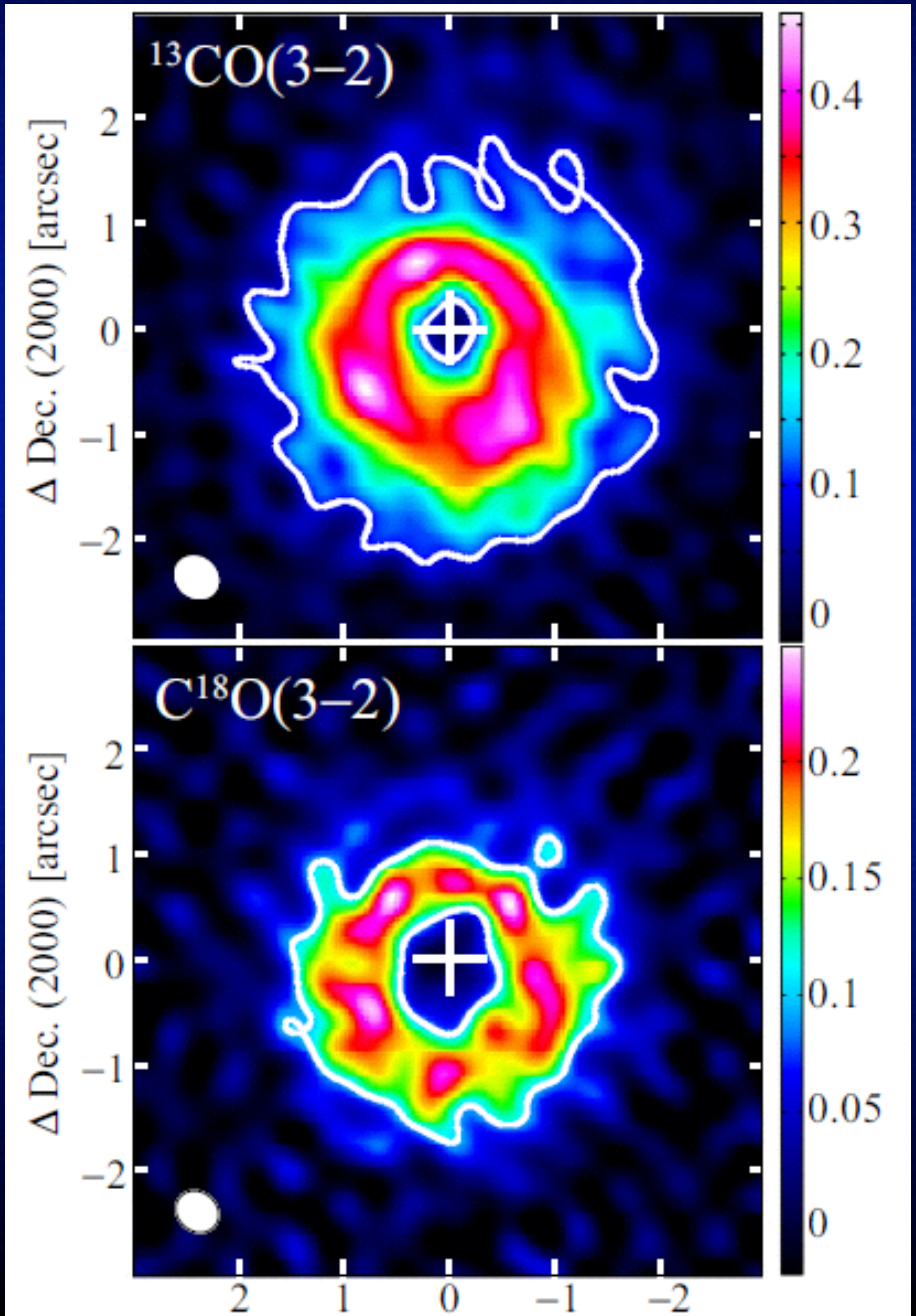
1.6μm with Subaru/CIAO



HD142527: Dust vs. Gas

Fukagawa et al. (2013); Muto et al. (2015)



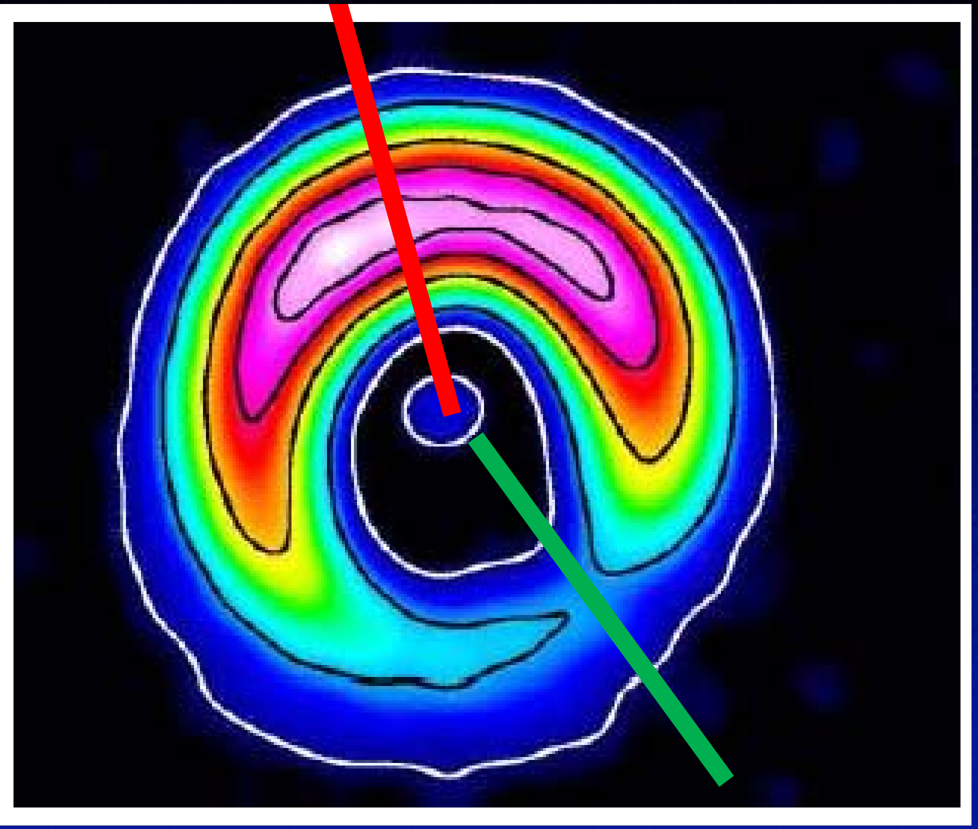


Dust: 著しい非対称

Gas: それほどでもない

Outline of Modeling

Muto et al. (2015)



- 2D Disk model (Kanno+ 2013)
  - Σ_{dust}: Gaussian-like
  - $\Sigma_{gas} = \Sigma_{dust} \times (g/d)$: ***NG***

    → power-law with boundaries

    + inner/outer floors

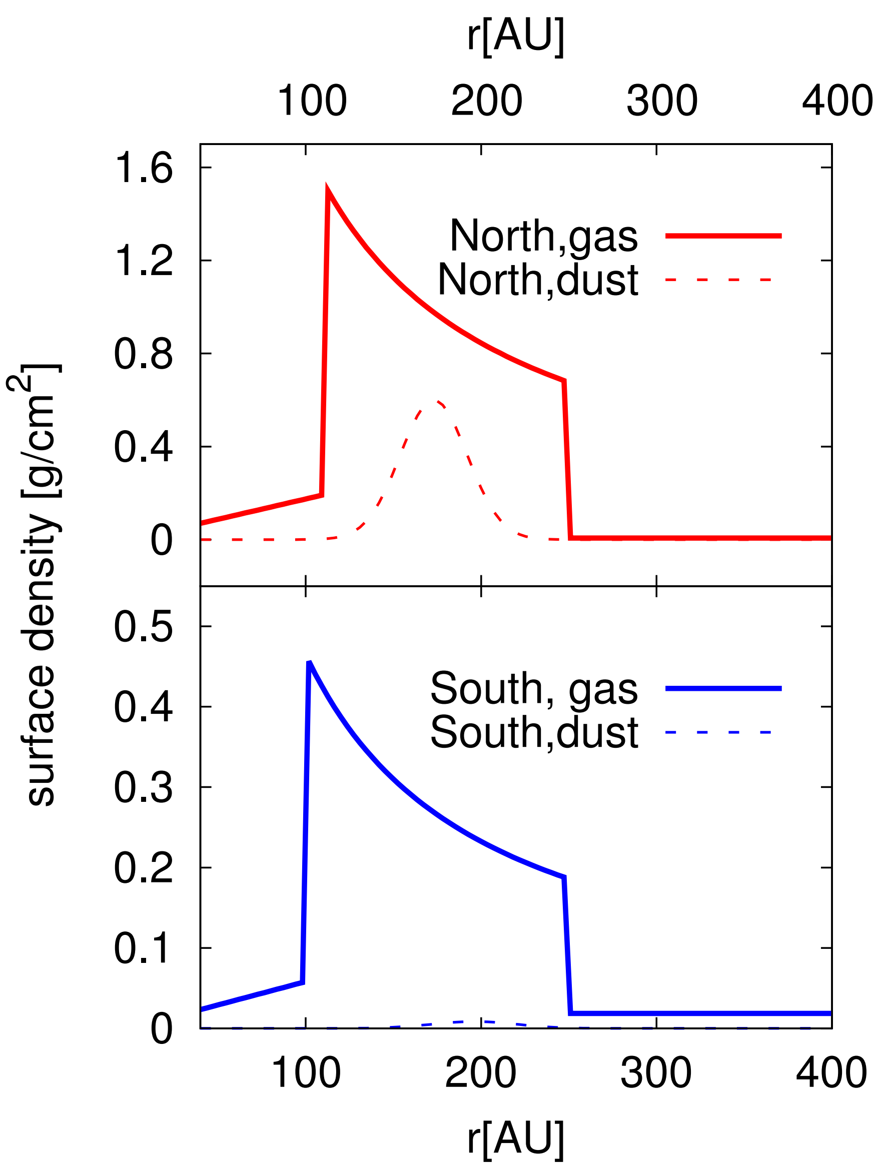
$\Sigma_{dust}(r)$ with hydrostatic equilibrium → $\rho_{dust}\ (r,\theta)$	M1-methodで温度場を計算。ダスト観測を再現する$\rho_{dust}(r,\theta)$固定	$^{13}CO/C^{18}O$動径分布を満たす$\Sigma_{gas}(r)$, or 静水圧平衡下の$\rho_{gas}(r,\theta)$を探す

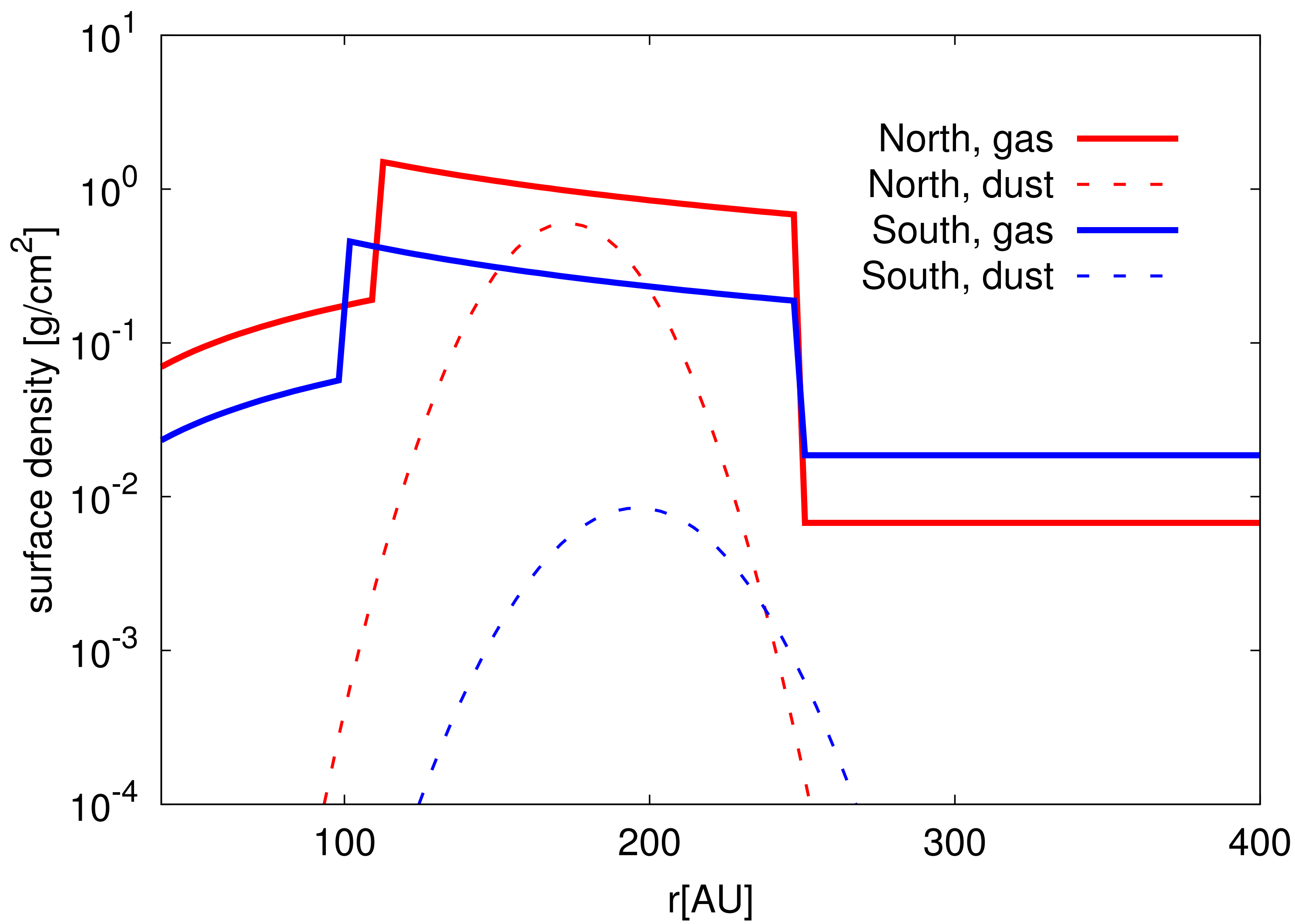
仮定

局所熱平衡, δV = Thermal velocity

Gas distribution and g/d variation

Red: North, Blue: South

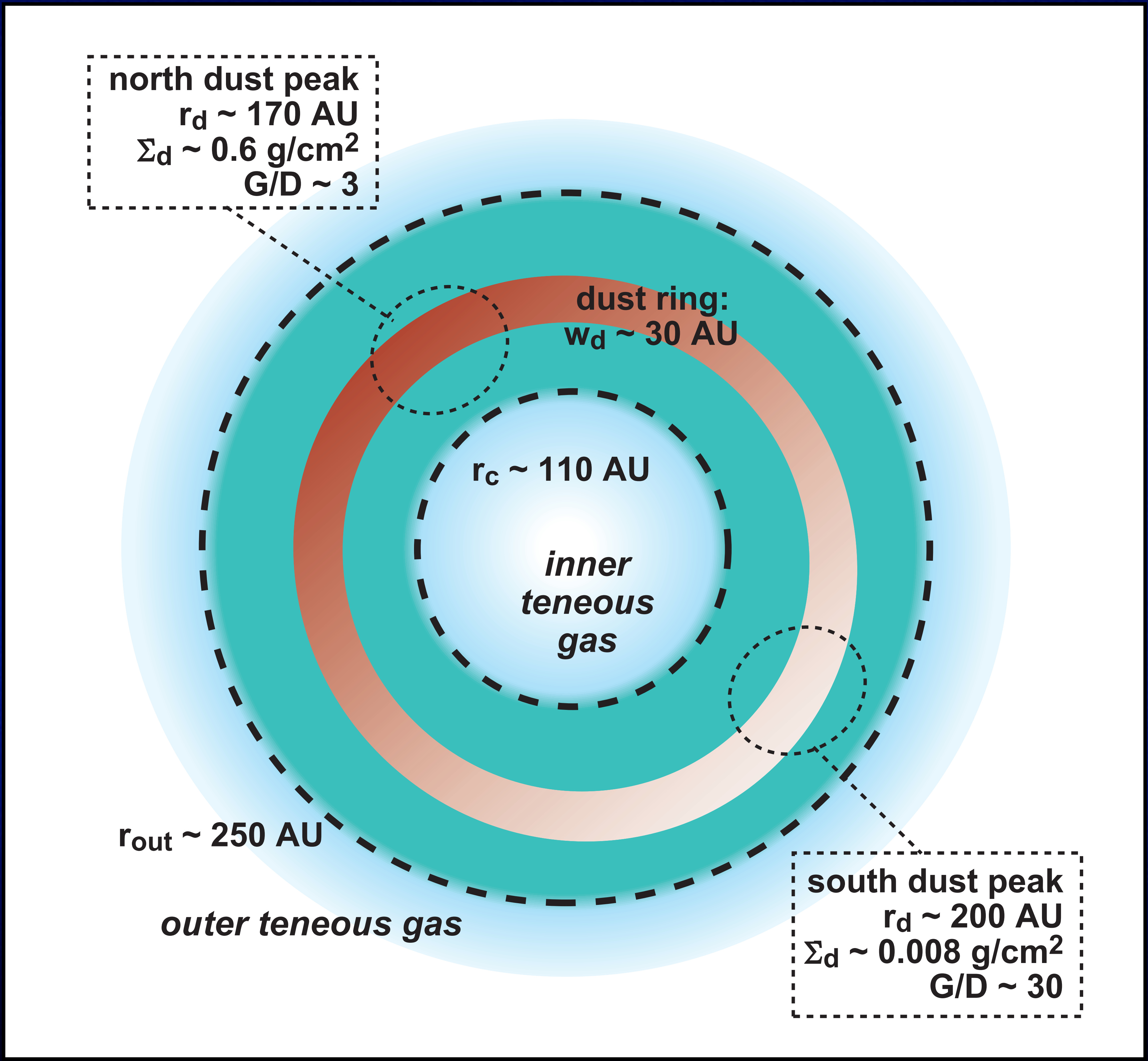




- spatial variation of g/d
- overall g/d ≈ 10-30, smaller than the ISM

HD142527: Summary

Muto et al. (2015)

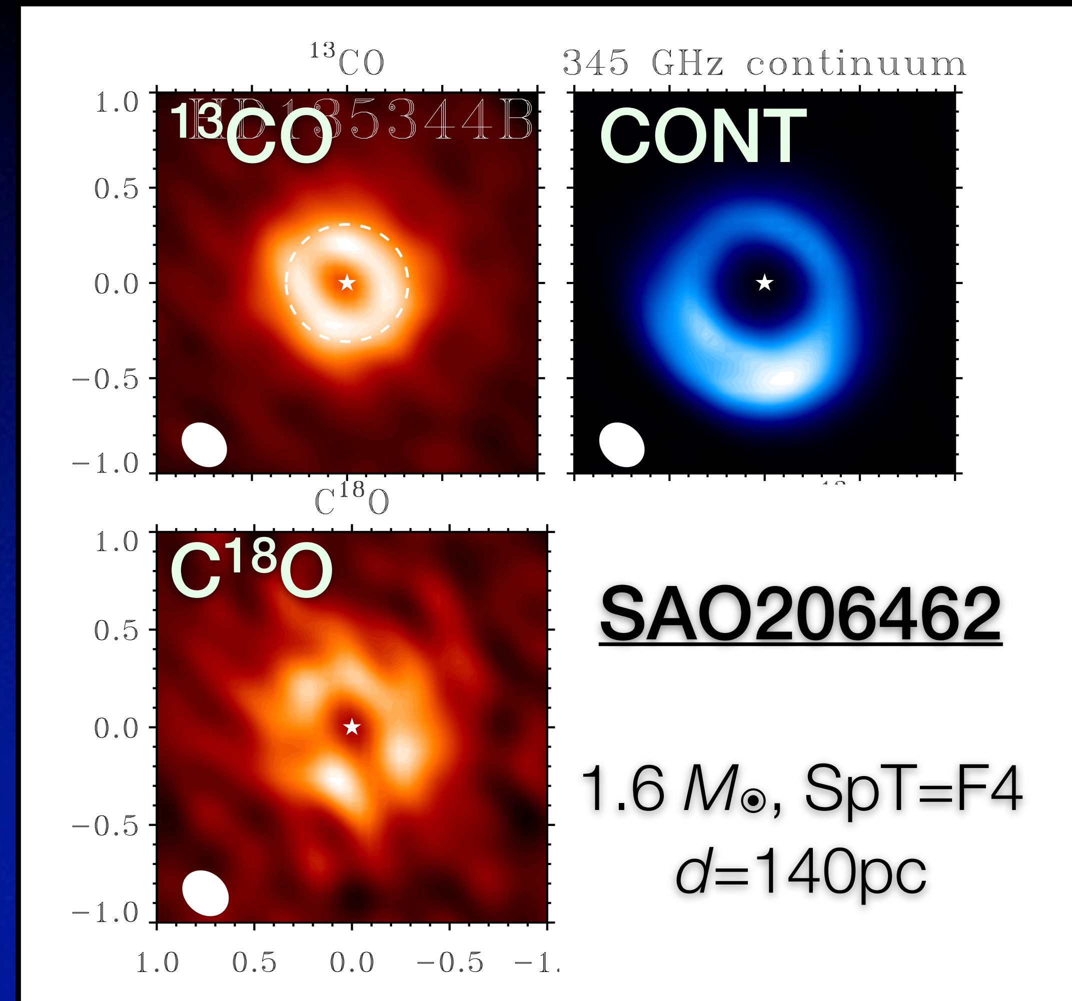


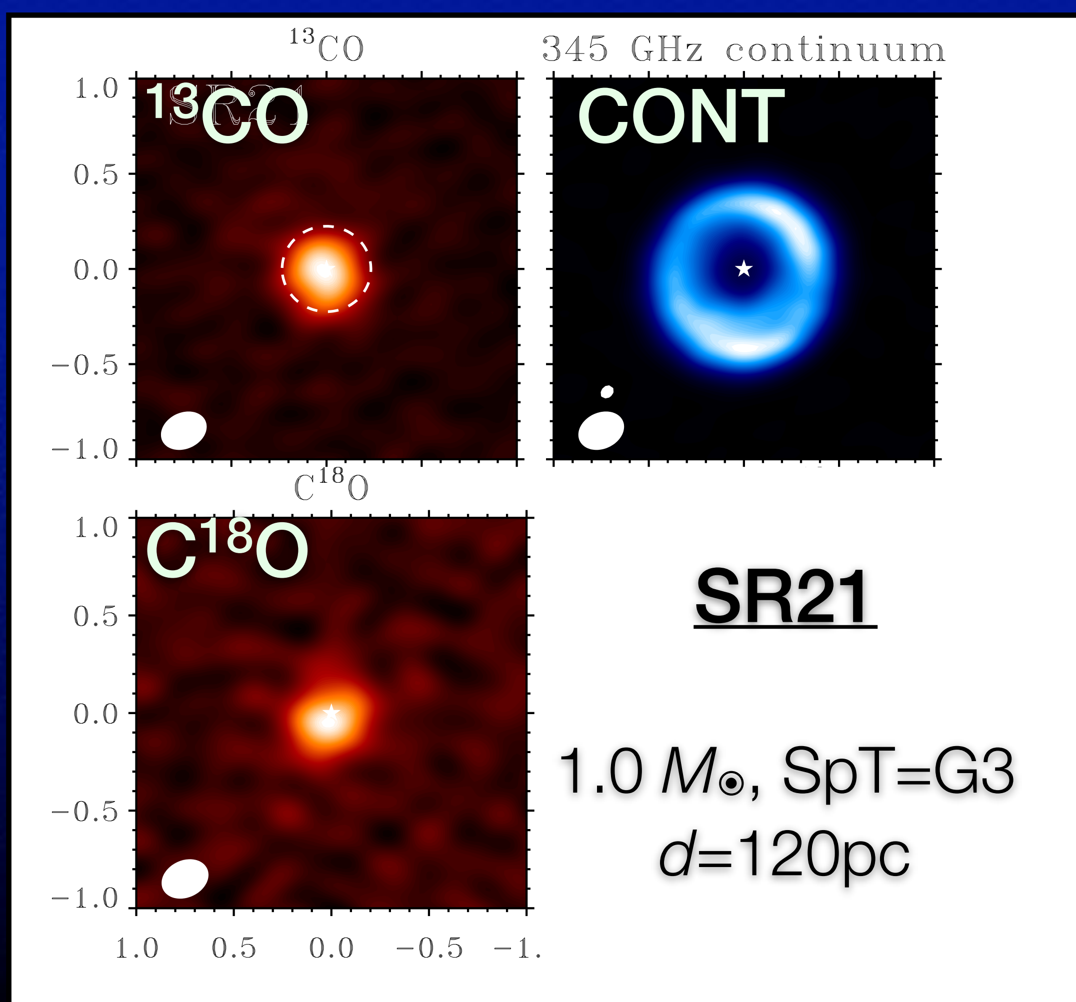
overall g/d ~ 30

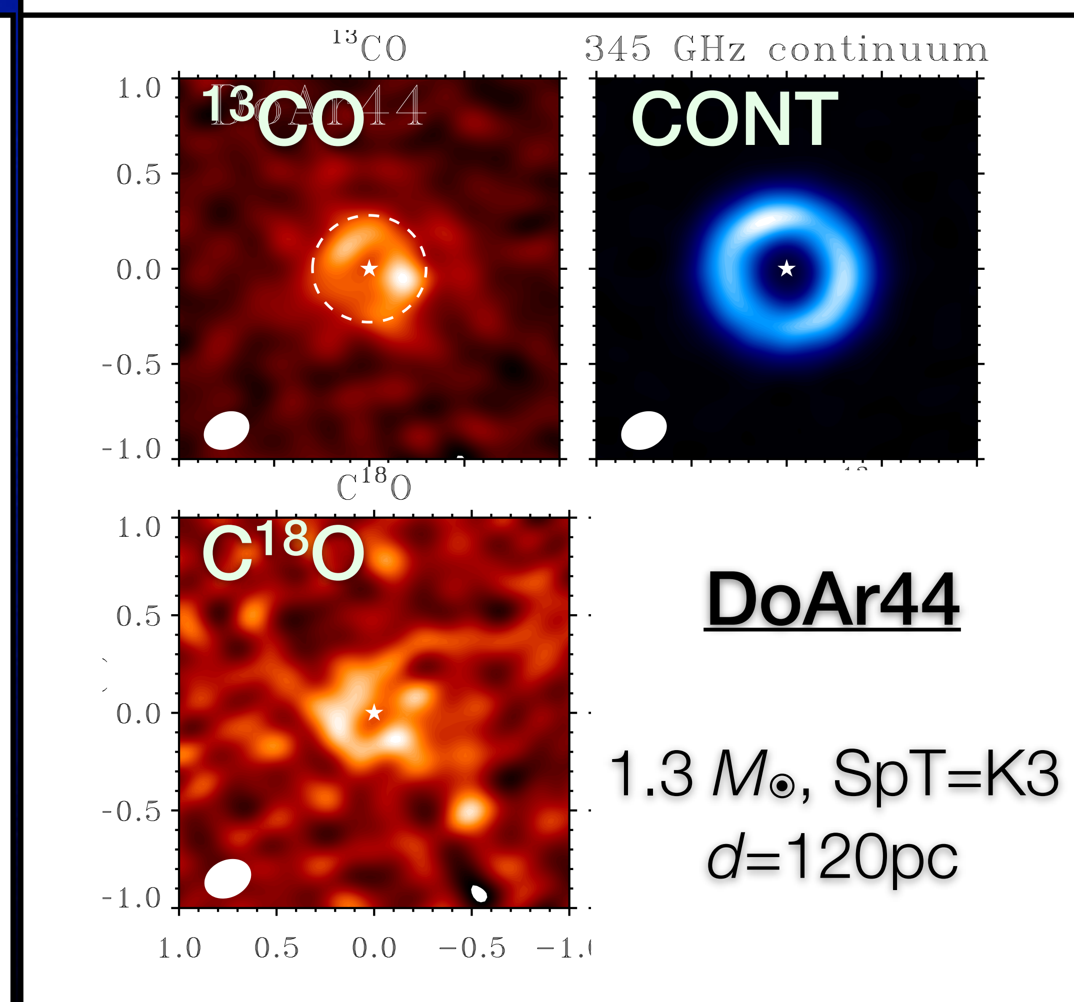
Mini-survey of 4 transitional disks

(van der Marel+ 2015)

- $\Delta\Sigma_{gas} = 10^{-2} - 10^{-4}$ in a cavity
- $\alpha = 10^{-3} - 10^{-4}$ if the cavity is caused by a planet with $< 10\, M_J$ (e.g., Kanagawa+ 2015)







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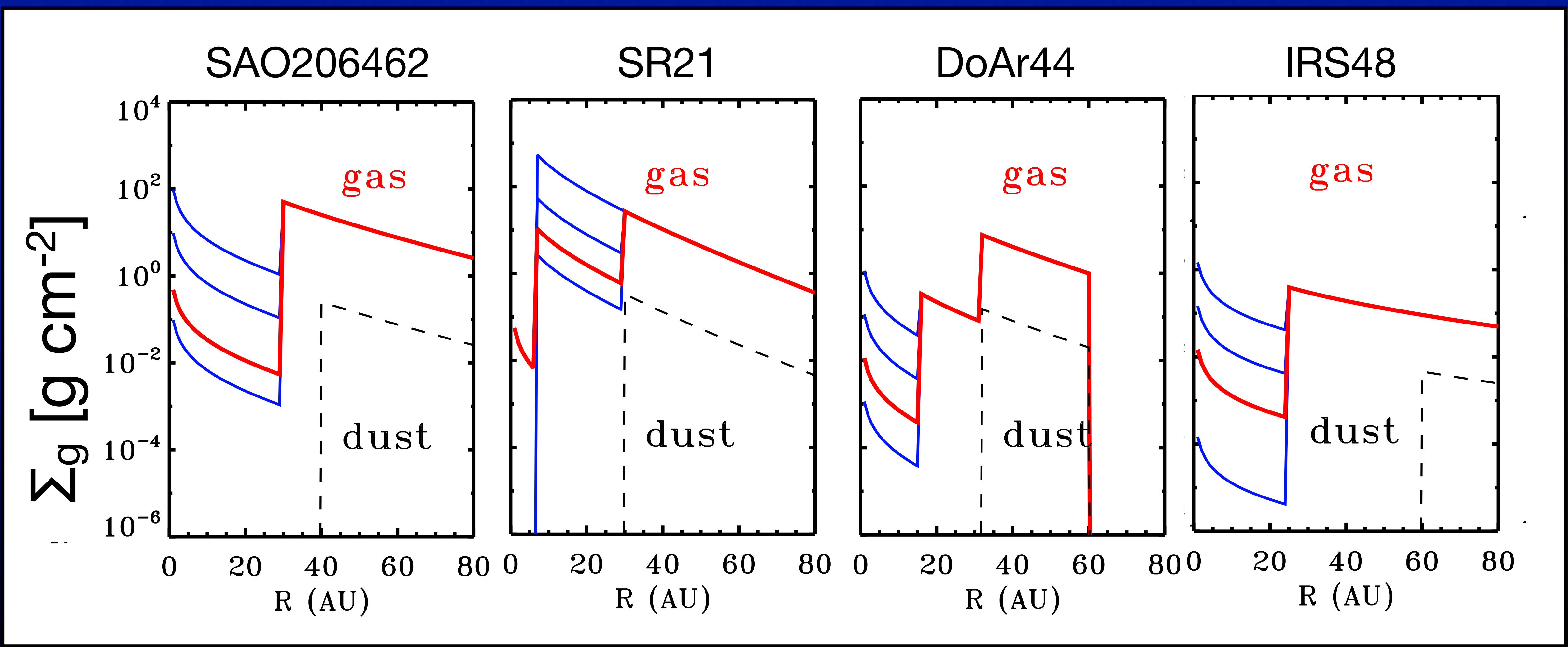
<u>overall g/d</u>

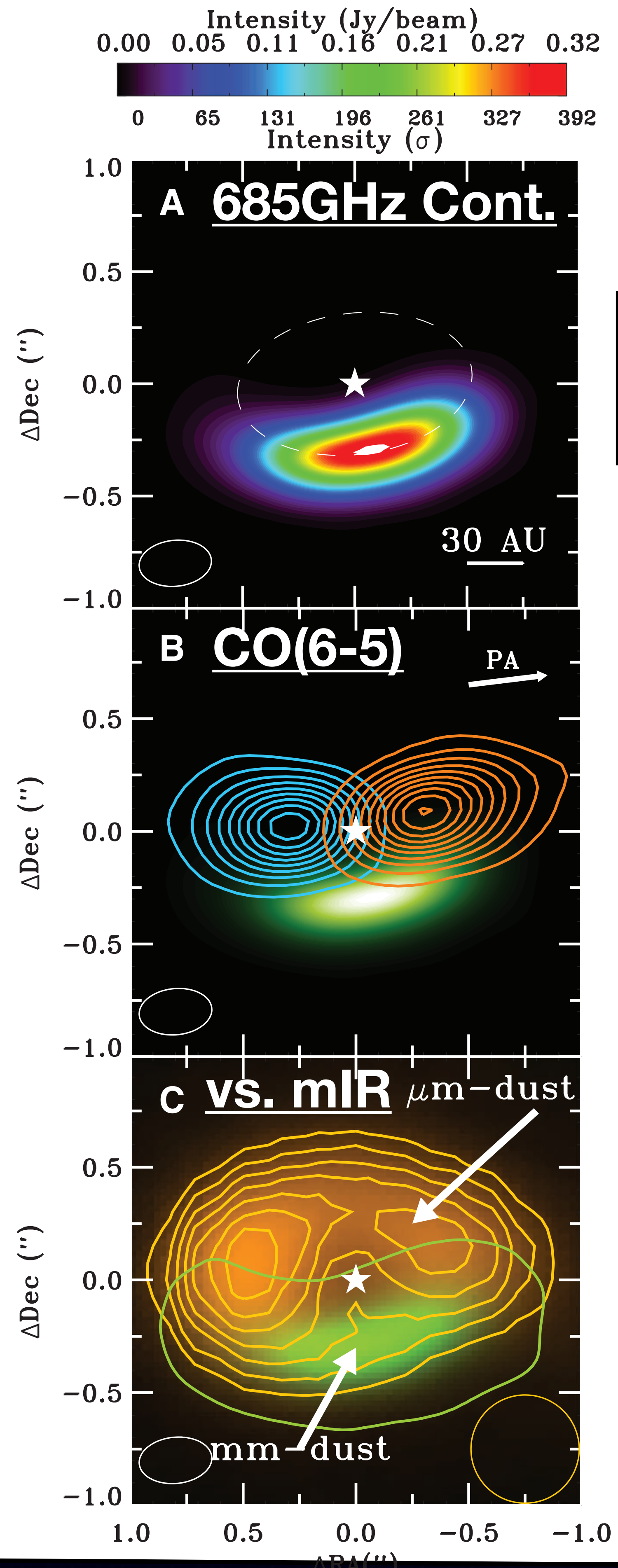
SAO206462: 80
SR21: 100
DoAr: 100
IRS 48: 12

c.f. HD1425257: ~30



Dust at submm & mIR vs. CO (6-5)

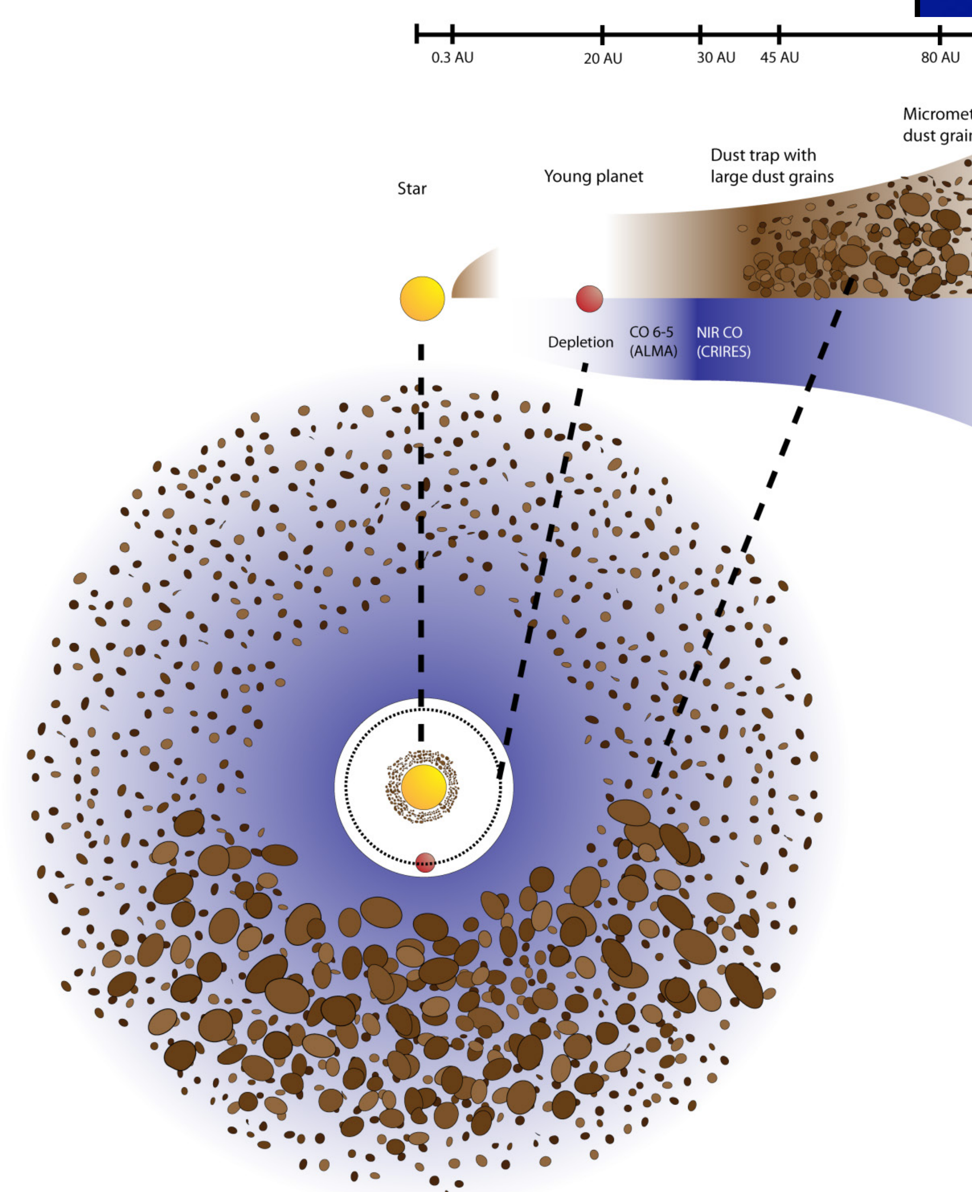
van der Marel et al. (2013); Birnstiel et al. (2013)



0.32”×0.21” beam
contrast along PA > 130

Larger dust is trapped in a vortex with pressure bump ?

Fig. 1. IRS 48 dust and gas observations. The inclined disk around IRS 48 as observed with ALMA Band 9 observations, centered on the star (white star symbol). The ALMA beam during the observations is 0.32″ × 0.21″ and is indicated with a white ellipse in the lower left corner. (**A**) The 0.44-mm (685 GHz) continuum emission expressed both in flux density and relative to the root mean square (rms) level (σ = 0.82 mJy per beam). The 63 AU radius is indicated by a dashed ellipse. (**B**) The integrated CO 6-5 emission over the highest velocities in contours (6,12,...,60σ_{CO} levels, σ_{CO} = 0.34 Jy km s^{-1}): integrated over –3 to 0.8 km s^{-1} (blue) and 8.3 to 12 km s^{-1} (red), showing a symmetric gas disk with Keplerian rotation at an inclination i = 50°. The green background shows the 0.44-mm continuum. The position angle is indicated in the upper right corner. (**C**) The Very Large Telescope Imager and Spectrometer for the mid-infrared (VISIR) 18.7-μm emission in orange contours (36 to 120σ_{VISIR} levels in steps of 12σ_{VISIR}, σ_{VISIR} = 0.2 Jy arc sec^{-2}) and orange colors, overlayed on the 0.44-mm continuum in green colors and the 5σ contour line in green. The VISIR beam size is 0.48″ in diameter and is indicated with an orange circle in the bottom right corner.



ALMAで浮かび上がった論点

- **<1Myrでの惑星形成？**
  - HL Tauは普遍的か？，そもそも惑星か？
- **<10auの円盤構造**
  - 複雑な動径分布，非軸対称
- **ダスト放射 ≠ ガス放射**
  - ダストの移動，濃集，g/dの大きな変化