つくば宇宙フォーラム@筑波大学・計算科学研究センター

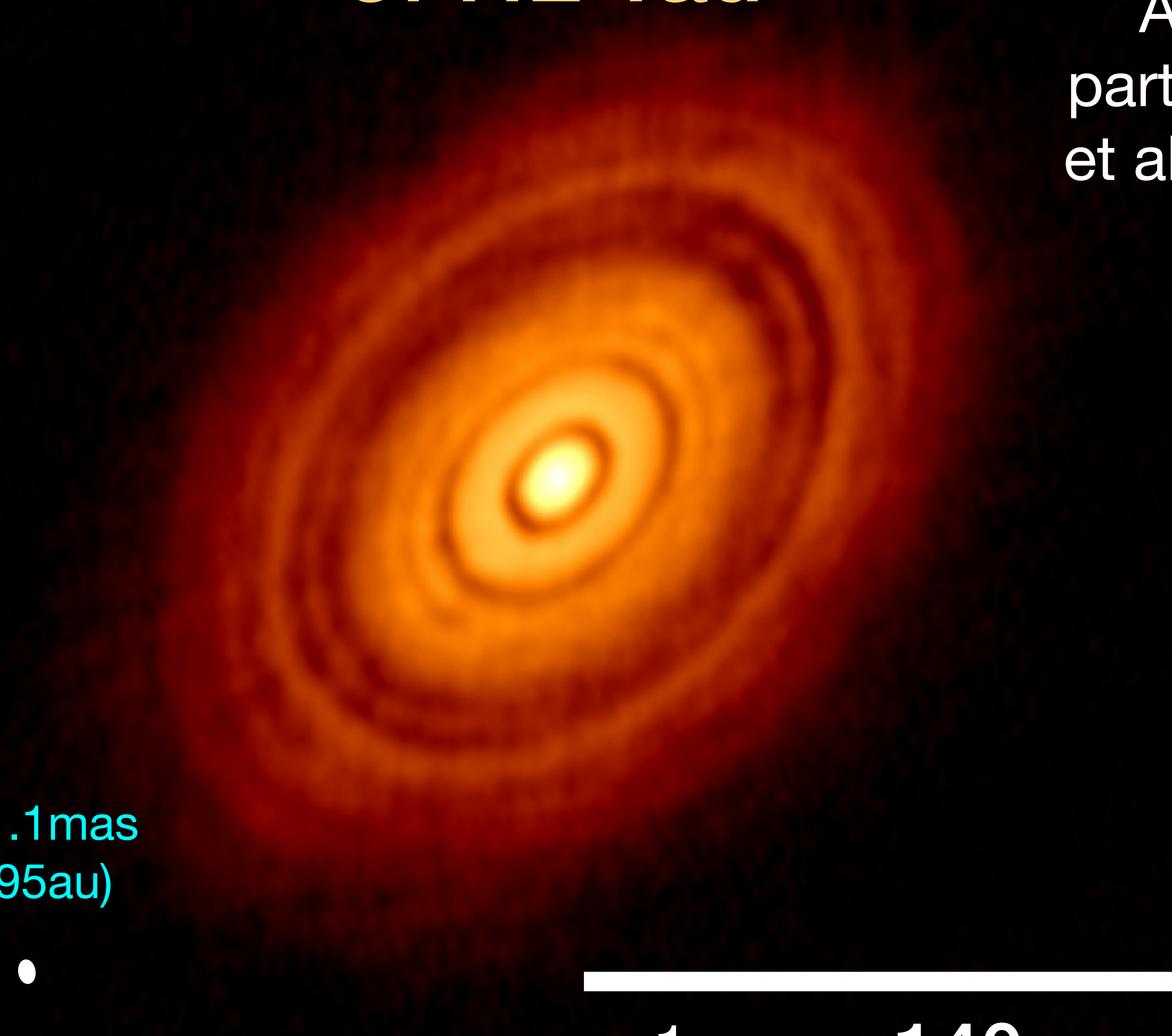
(November 11st, 2016)

High resolution observations of protoplanetary disks with ALMA ~ Signs of protoplanets in a disk ?~

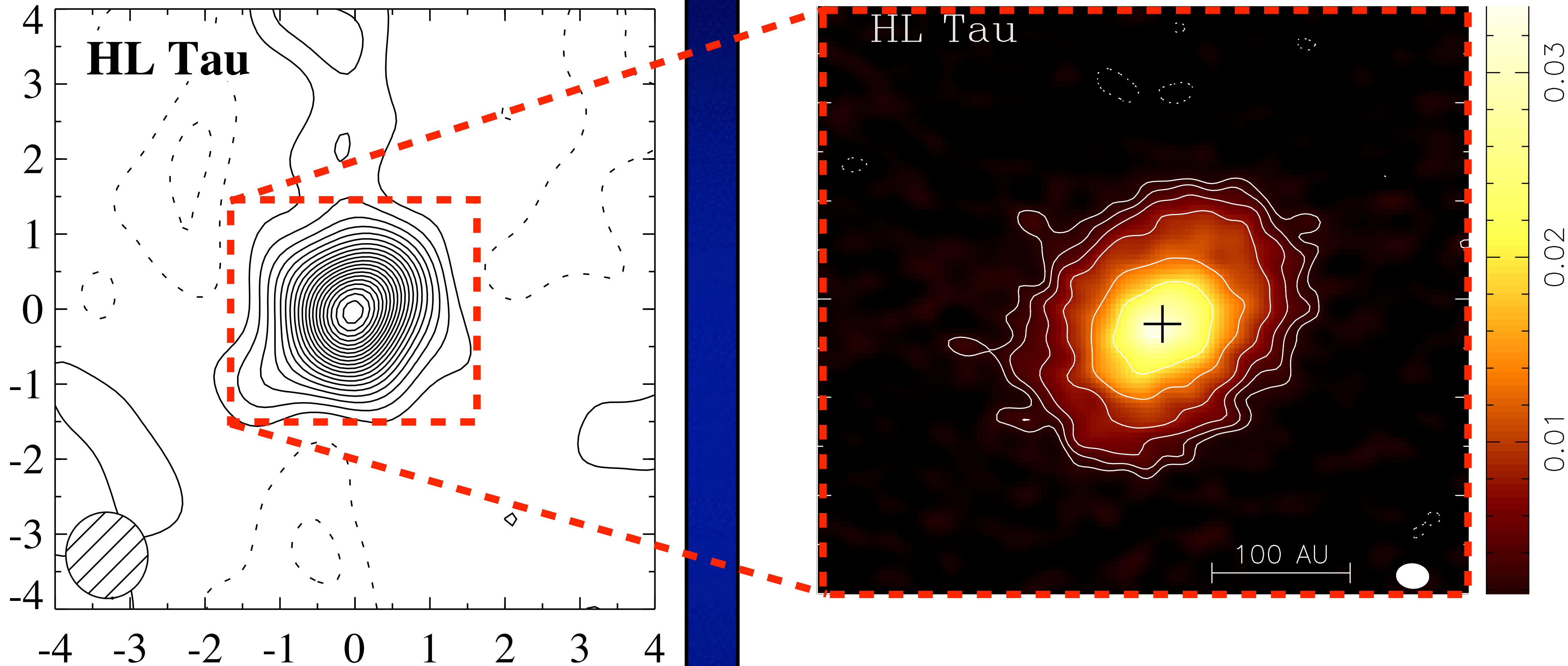
Munetake MOMOSE (Ibaraki Univ.)

Dust continuum at λ=1mm of HL Tau

ALMA partnership et al. (2015)



HL Tau in mm continuum after 2000



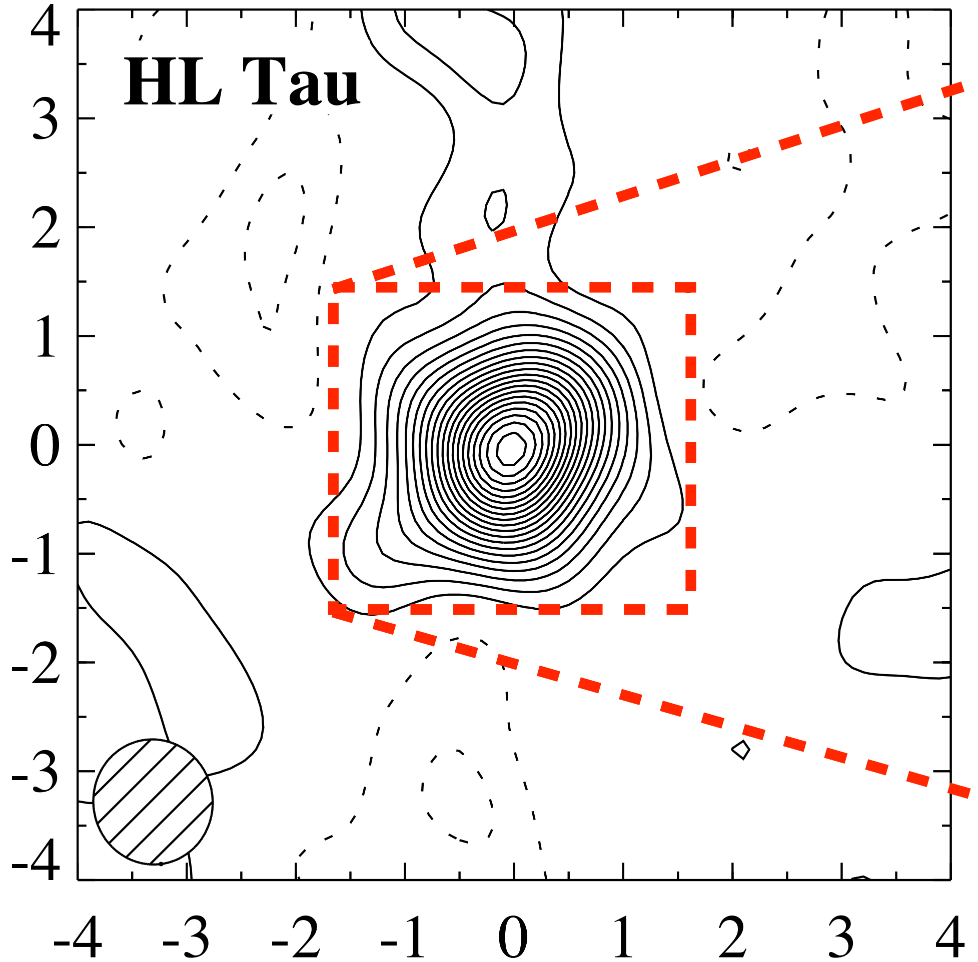
<u>Nobeyama Millimeter Array</u>
λ=2mm
1.2”× 1.1” (≈160au)

(Kitamura, Momose et al. 2002)

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

(Kwon, Looney & Mundy 2011)

HL Tau in mm continuum after 2000



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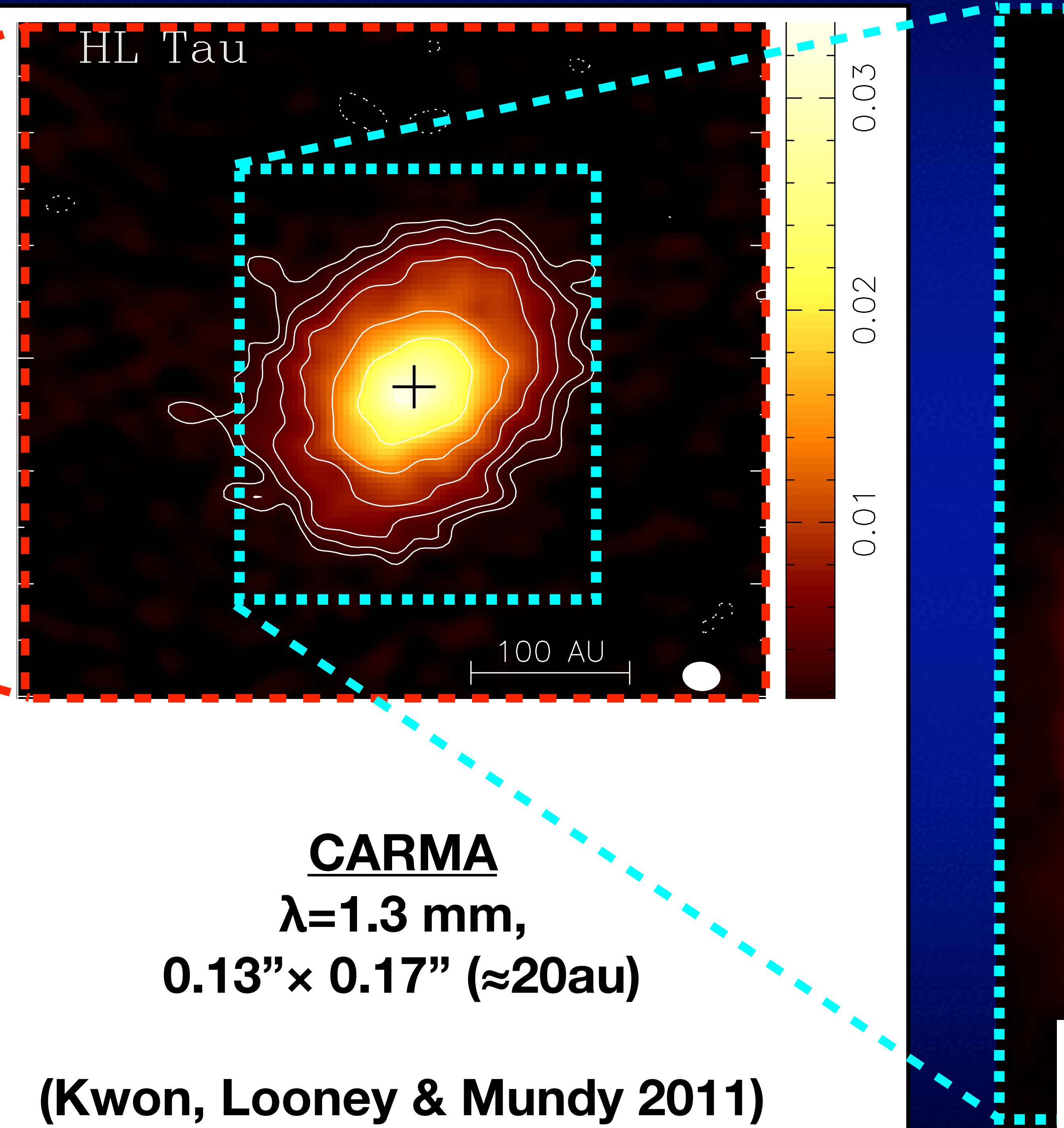

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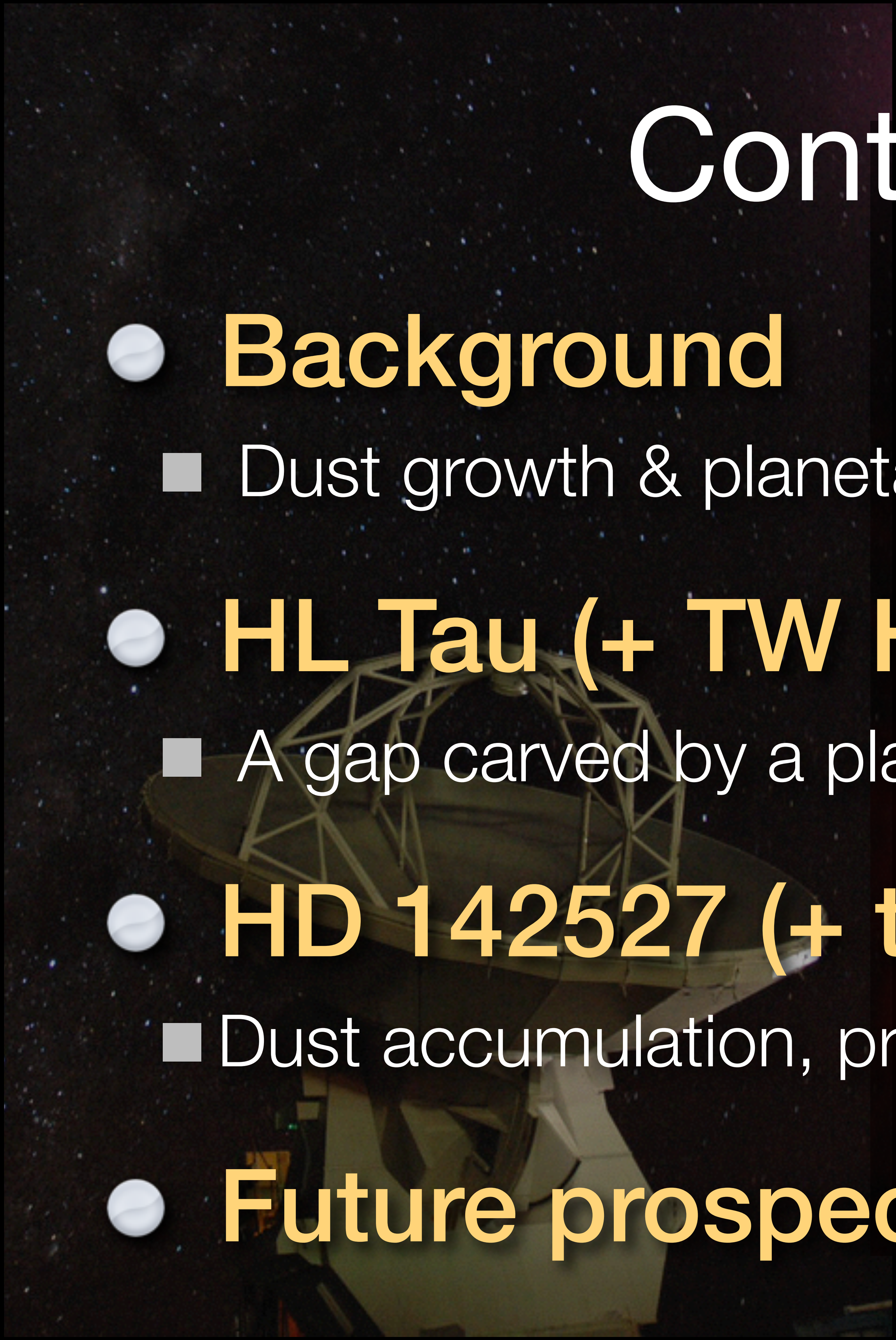


Contents

- **Background**
  - Dust growth & planetary gap in a disk
- **HL Tau (+ TW Hya)**
  - A gap carved by a planet ?
- **HD 142527 (+ transitional disks)**
  - Dust accumulation, properties & polarization
- **Future prospects**

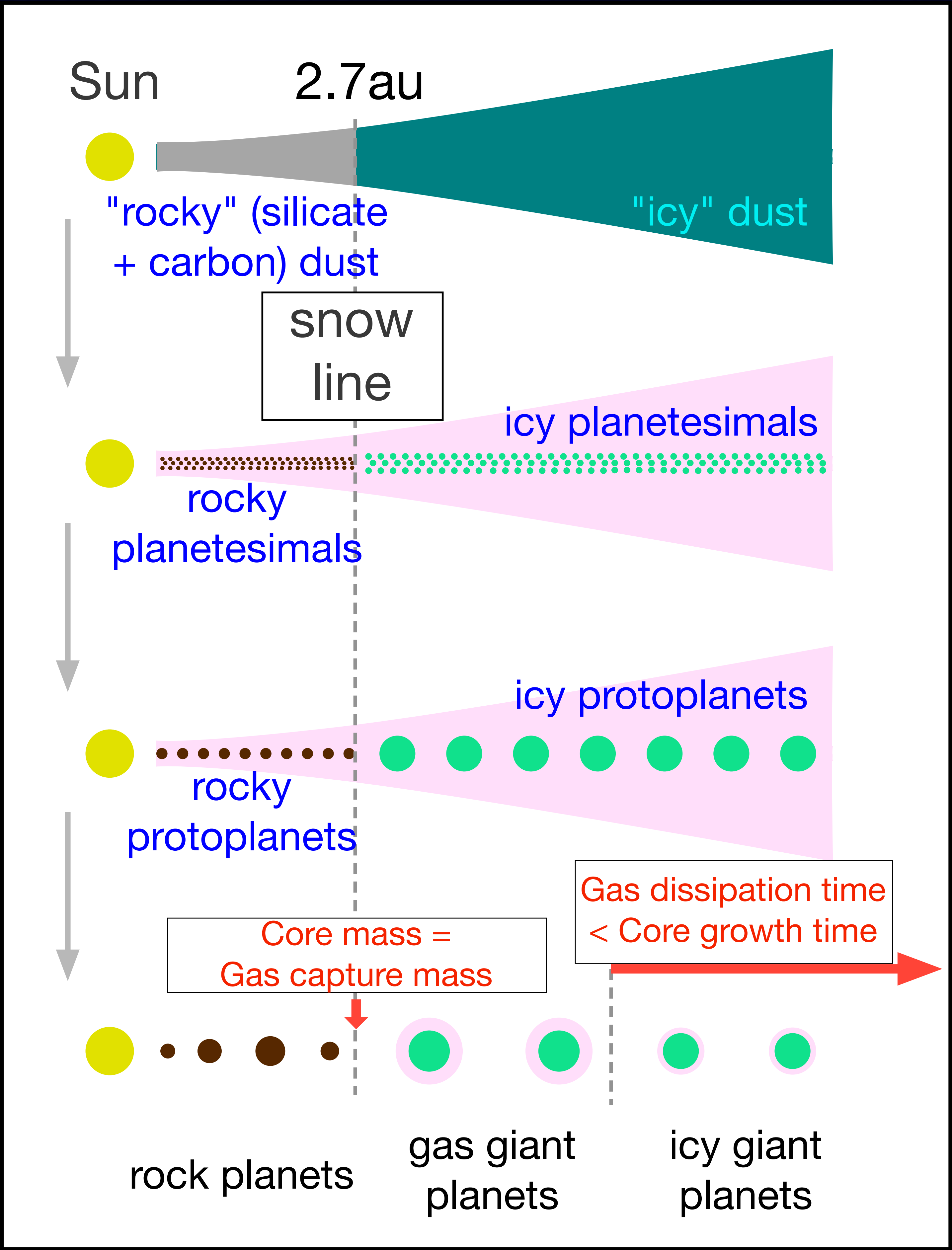
Part 1

Background

"Classical" Theory for Solar System Formation
(Hayashi, C. 1981)

- ***"Restored" disk model***
- ***"Planetesimal" hypothesis***

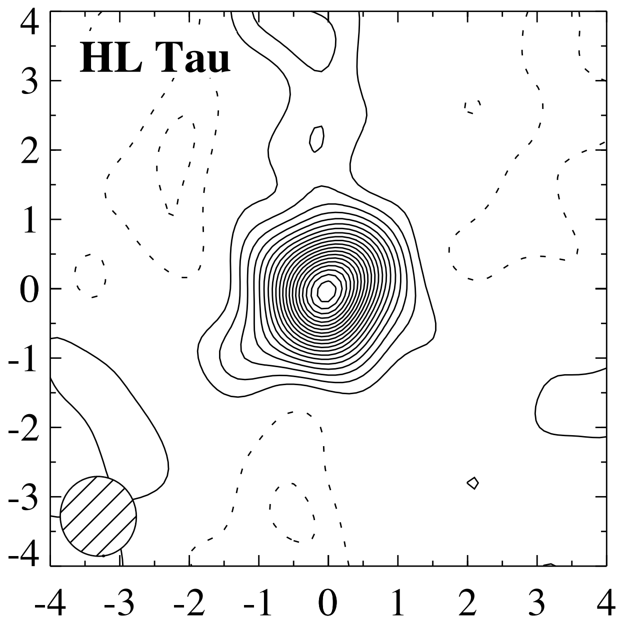
Protoplanetary disks = analogues of primordial solar nebula established in late 1980s

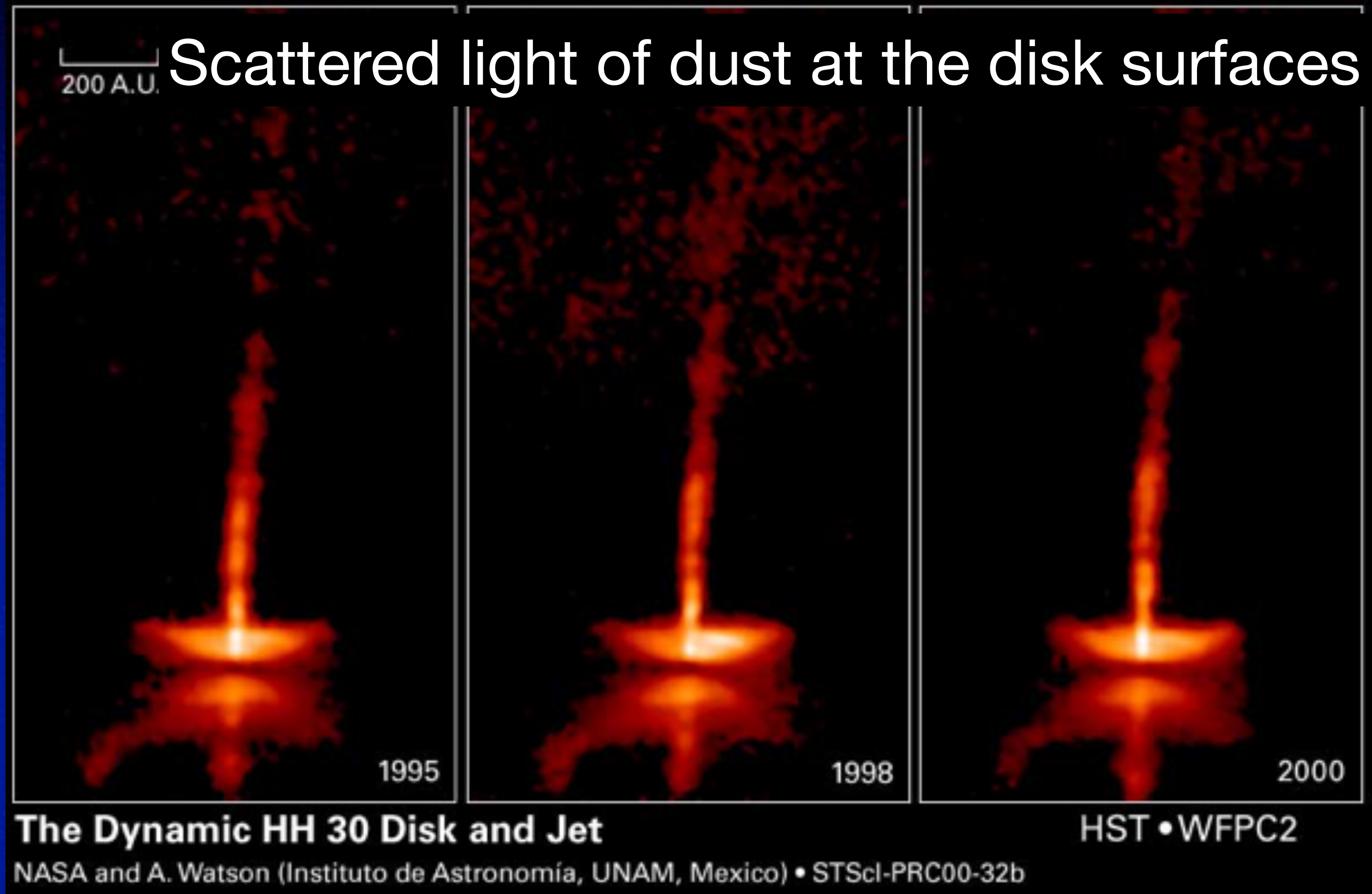


Radio

Optical, near-IR

Thermal radiation of dust particles (Kitamura, MM et al. 2002)

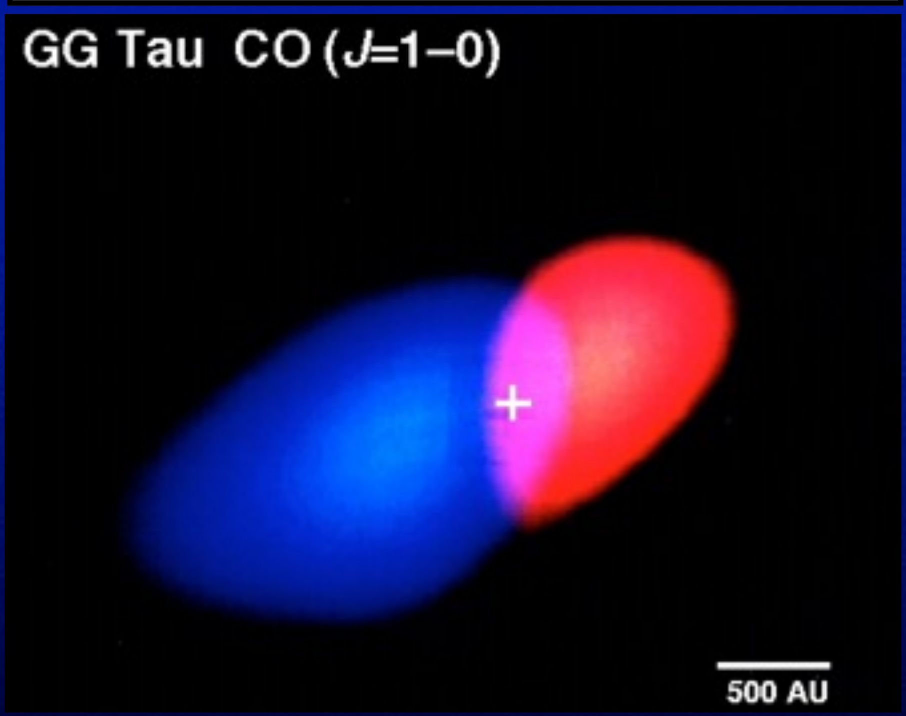




Scattered light of dust at the disk surfaces

(Stapelfeldt et al. 1999)

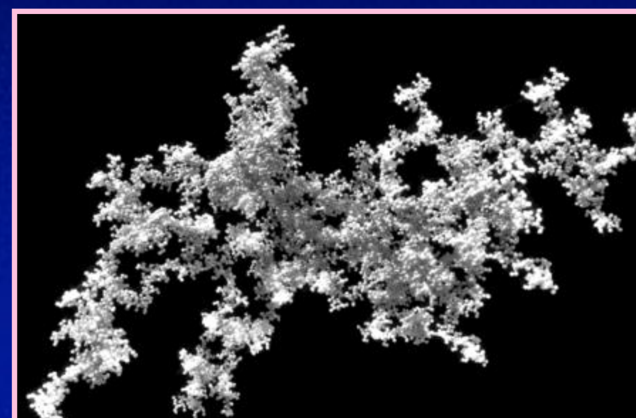
in R-band (λ=675nm)



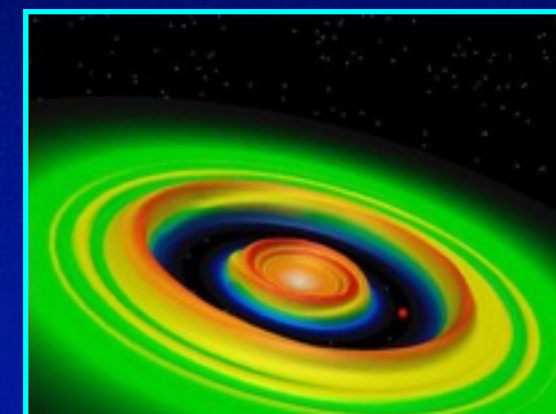
CO line emission, showing Keplerian rotation (Kawabe et al. 1993)

Protoplanetary disks around young stars

Targets of Observations



(1) Dust Growth in the Disk



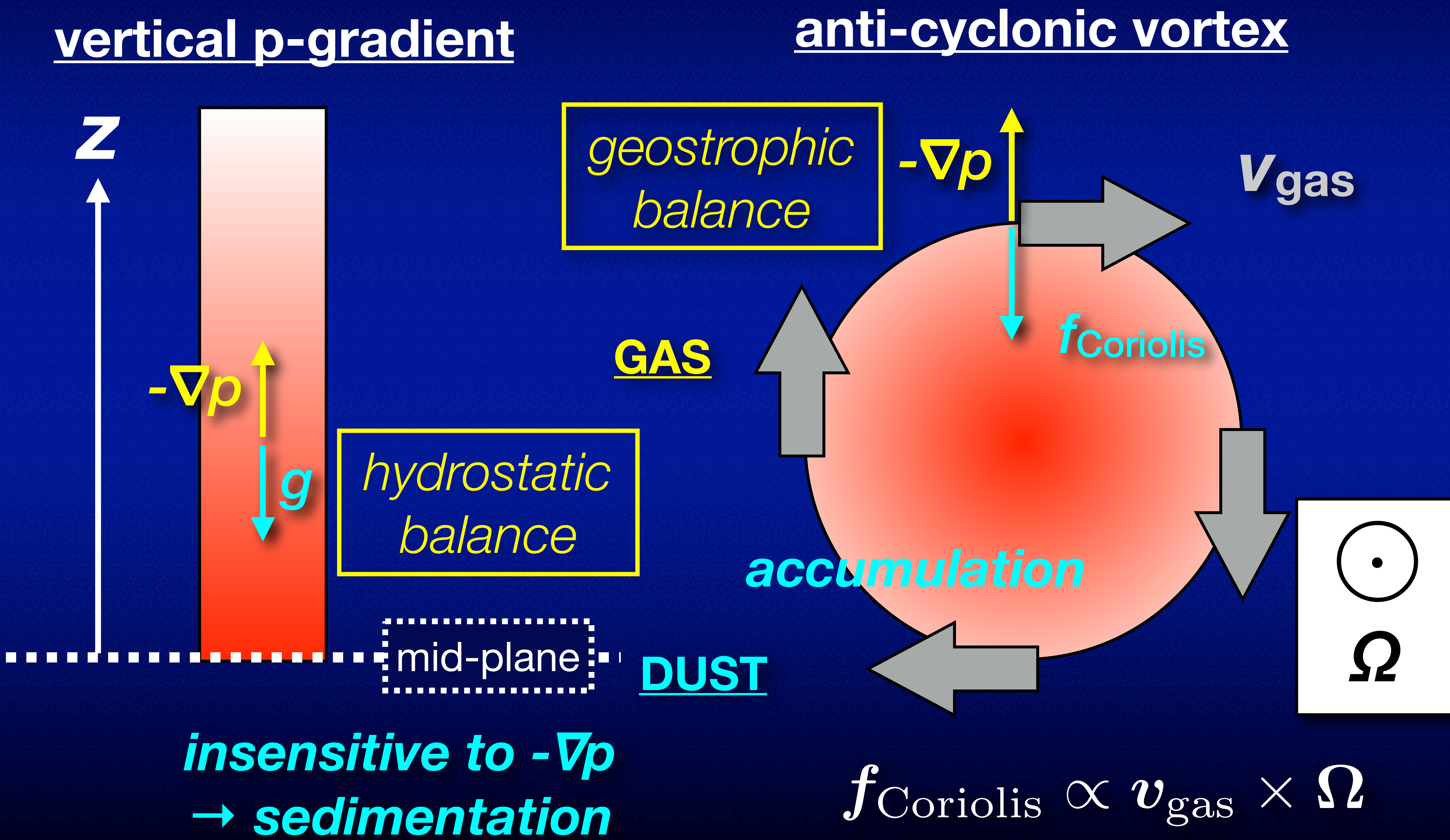
(2) Feedback by a Planet

dust | pebble | planetesimal/ protoplanet | planet

-8 -6 -4 -2 0 2 4 6 8

log (size [m])

Dust behavior in a gas disk (1): Accumulation in "high-pressure" regions

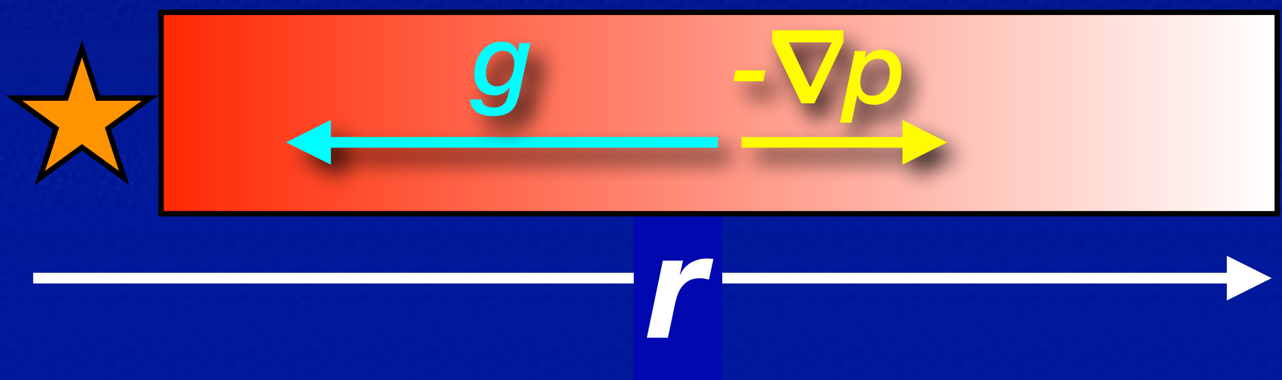


$$f_{\mathrm{Coriolis}} \propto \boldsymbol{v}_{\mathrm{gas}} \times \boldsymbol{\Omega}$$

Dust behavior (2): Radial drift by gas drag

Adachi et al. (1976); Weidenschilling (1977)

if $p(r)$ is higher at smaller r …

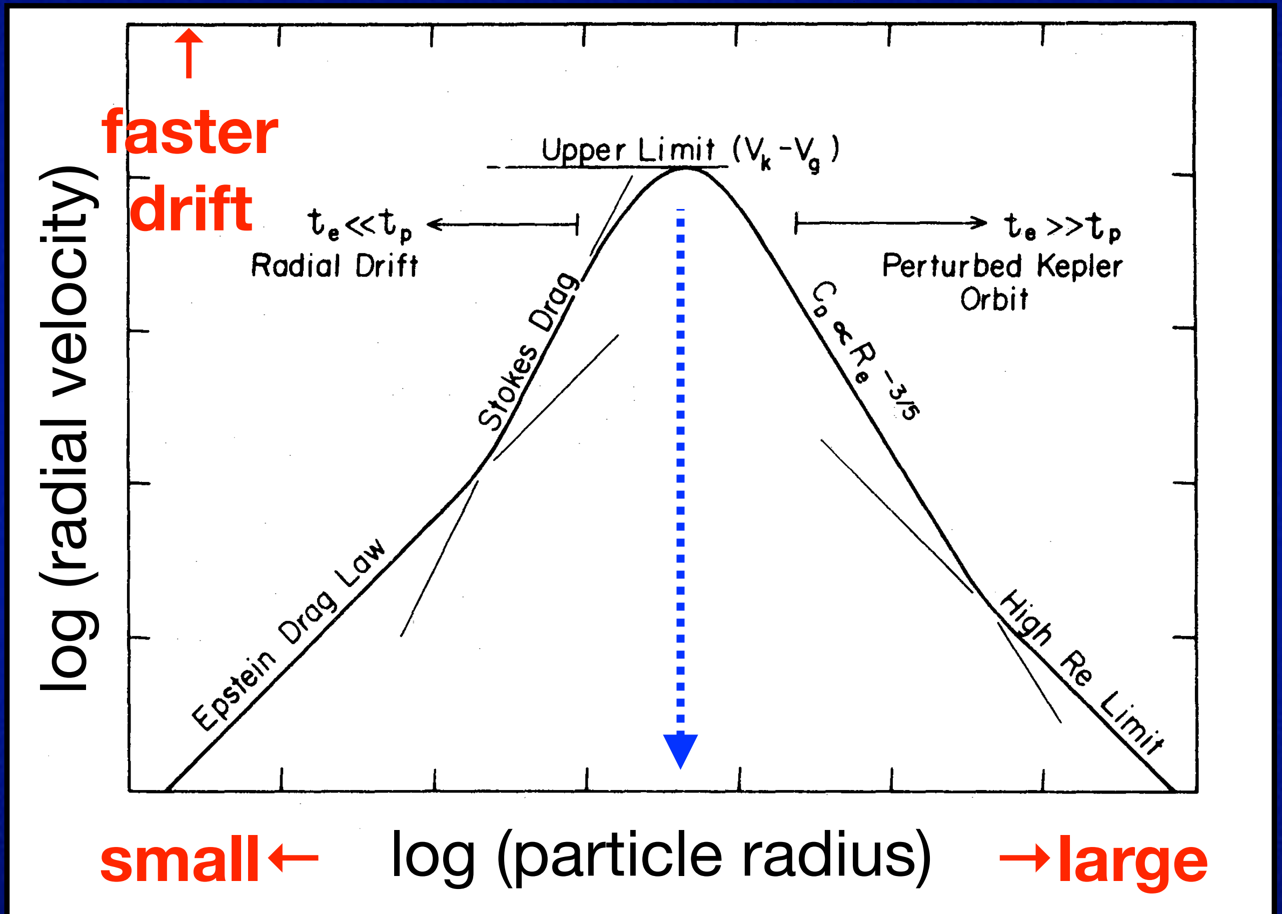


$v_{gas} < v_{dust}$

→ loss of angular momentum due to "head wind"

radial drift

Radial velocity vs. Particle size (schematic)



a barrier against growth at "cm-m" sizescale, where gas drag is most efficient

Fluffy aggregation of “icy” particles

Suyama, Tanaka & Wada (2008); Okuzumi+ (2012); Kataoka+ (2013)

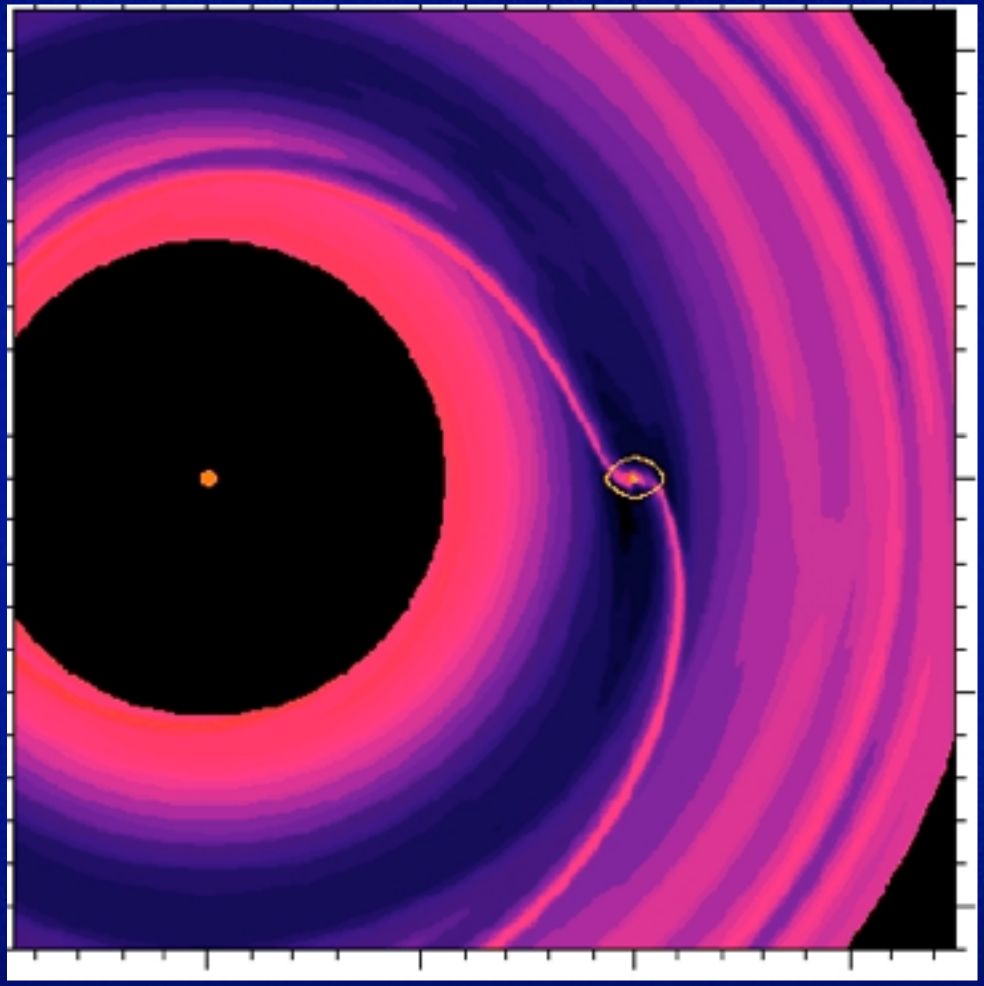
Overcome the growth/drift barriers

- **water ice: sticky ($v_{break\text{-}up} \approx 50$ m/s)**
- **efficient energy dissipation by rolling, vibration …**
- **fluffy structure: large (area/mass) ratio → rapid growth**

Disk-planet interaction

- Formation of <u>Spiral Density Wave</u> and <u>Gap</u>

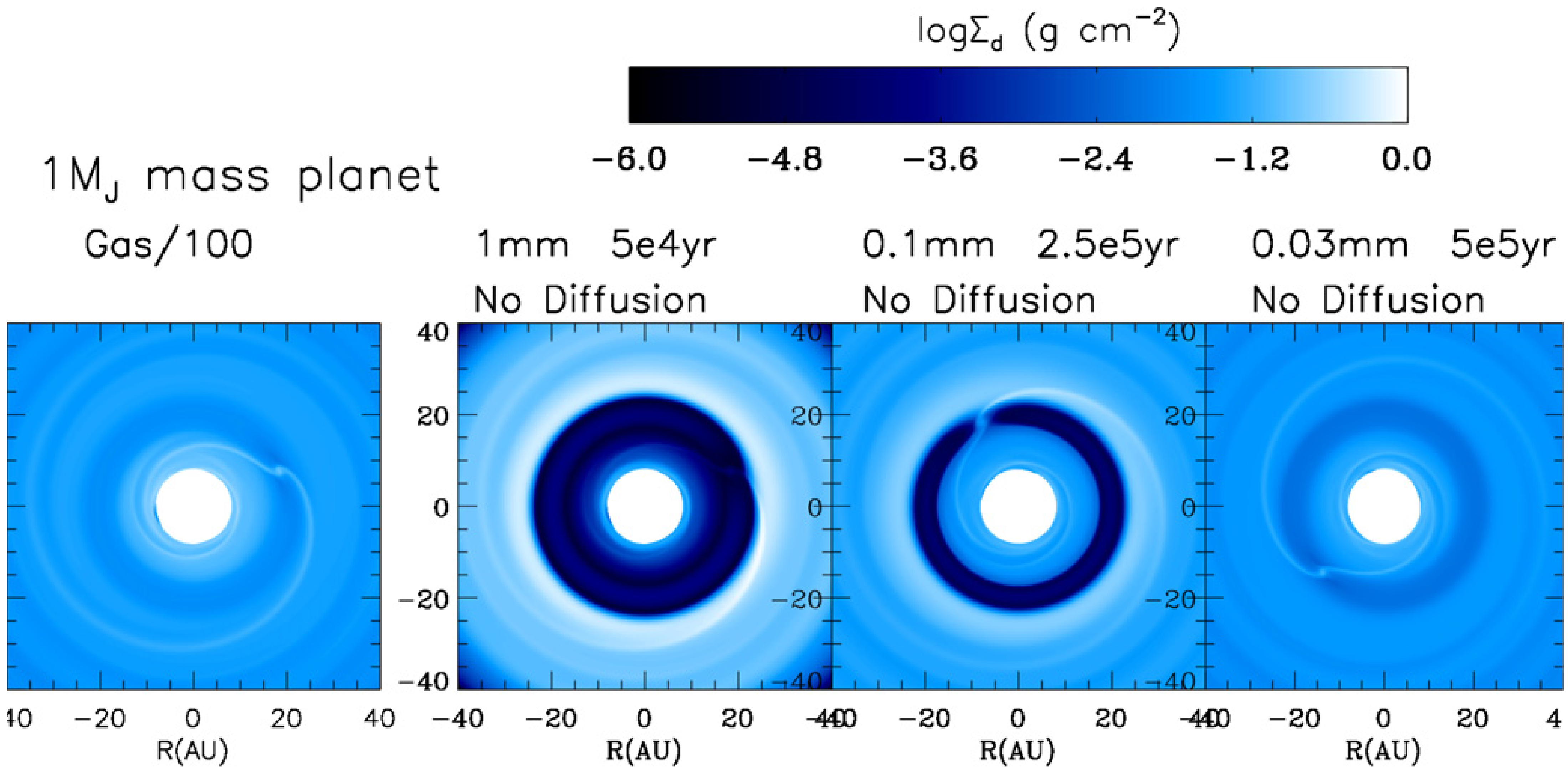
<u>A Low-mass Planet</u>
Spiral waves
(Muto et al. 2012)



<u>A High-mass Planet</u>
Spiral waves and a gap
(Artymovicz et al. 1998)

Simulation on dust filtration

Zhu et al. (2012)



Gas Dust 1mm 100μm 30μm

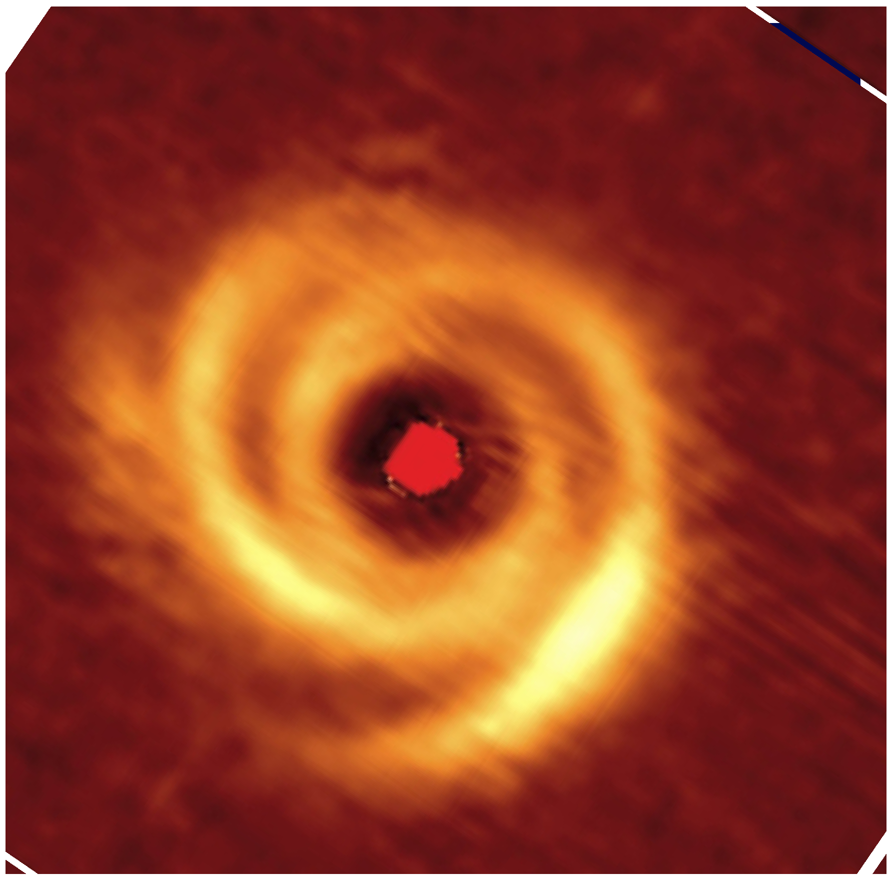
Smaller dust better couples with gas.

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

Evidence for dust filtration?: SAO206462 case

Muto+ (2012); Graufi+ (2013); Perez+ (2014)

PI at 2.2μm
with VLT/NACO



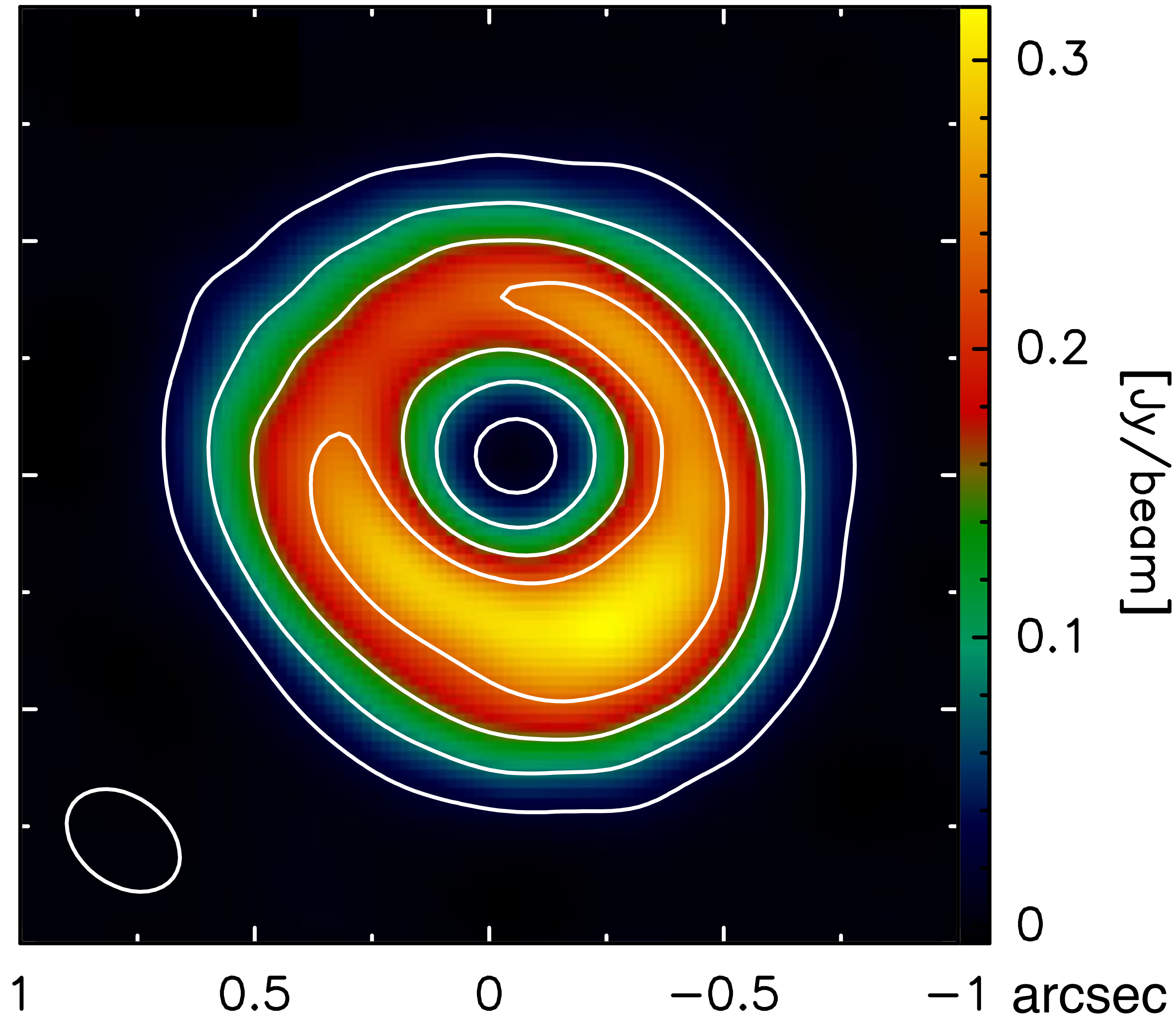
<u>Cavity size</u>

nIR < Submm

29 vs. 39 au

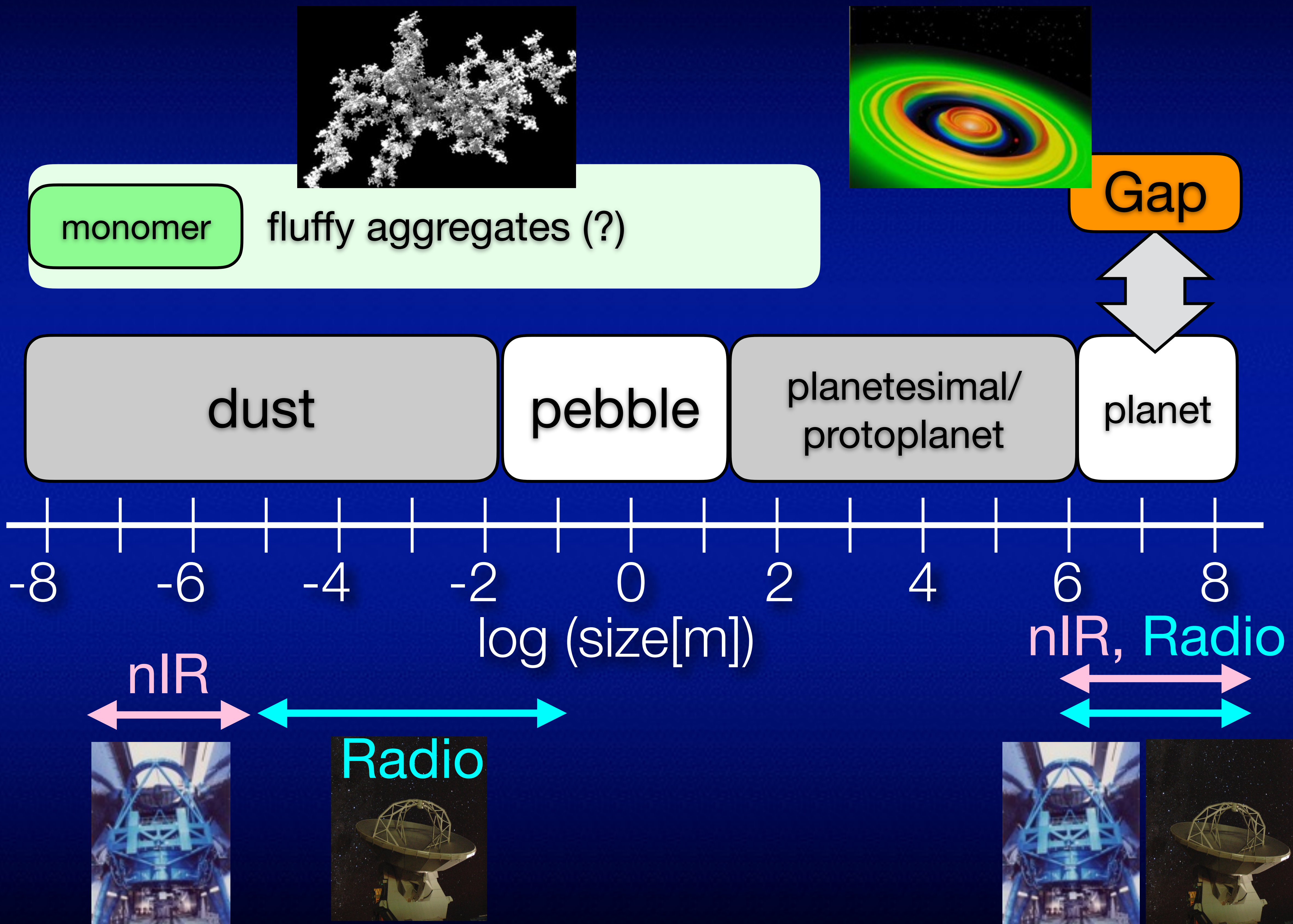
(a ~10M_J Planet at $r \approx$ 20au?)

Cont. at 450μm with ALMA



<u>SAME SCALE !</u>

Solids in protoplanetary disks

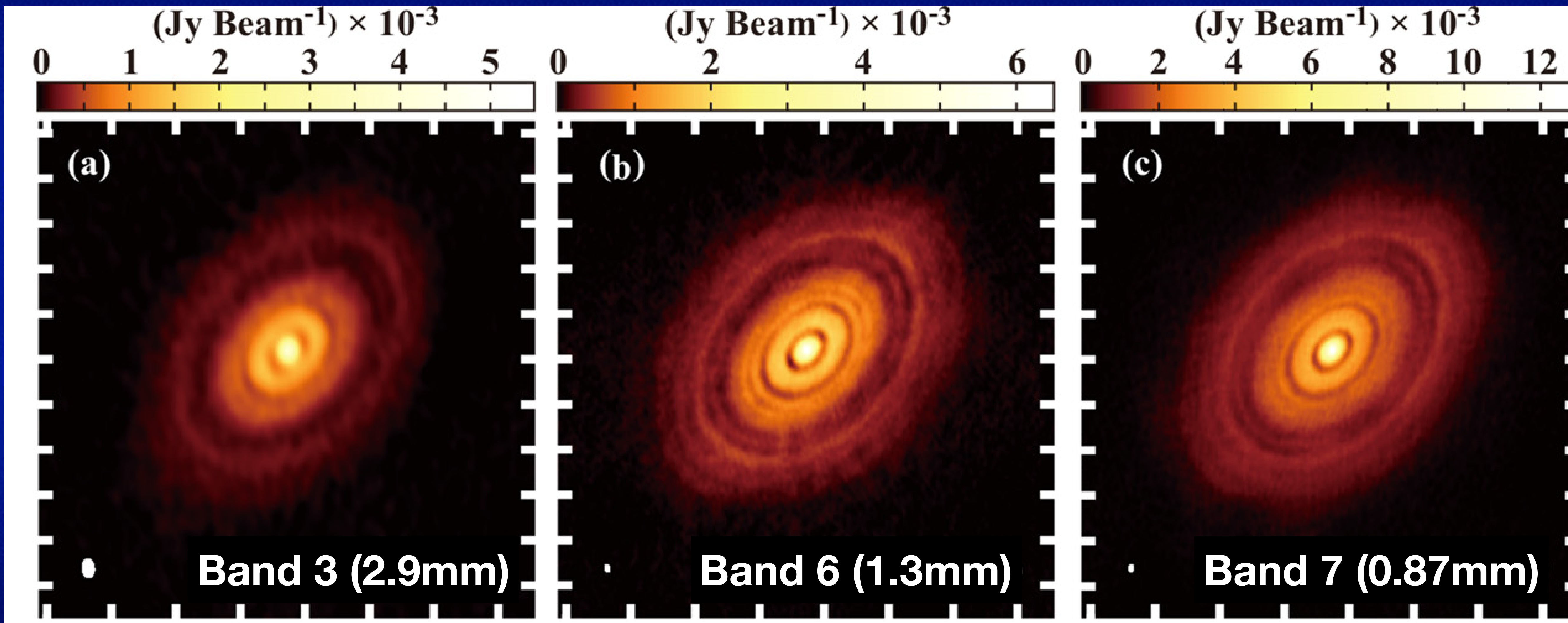


Part 2

HL Tau (+ TW Hya)

Data released on Feb. 18, 2015

Imaging by Akiyama, Hasegawa, Hayashi & Iguchi (2016)

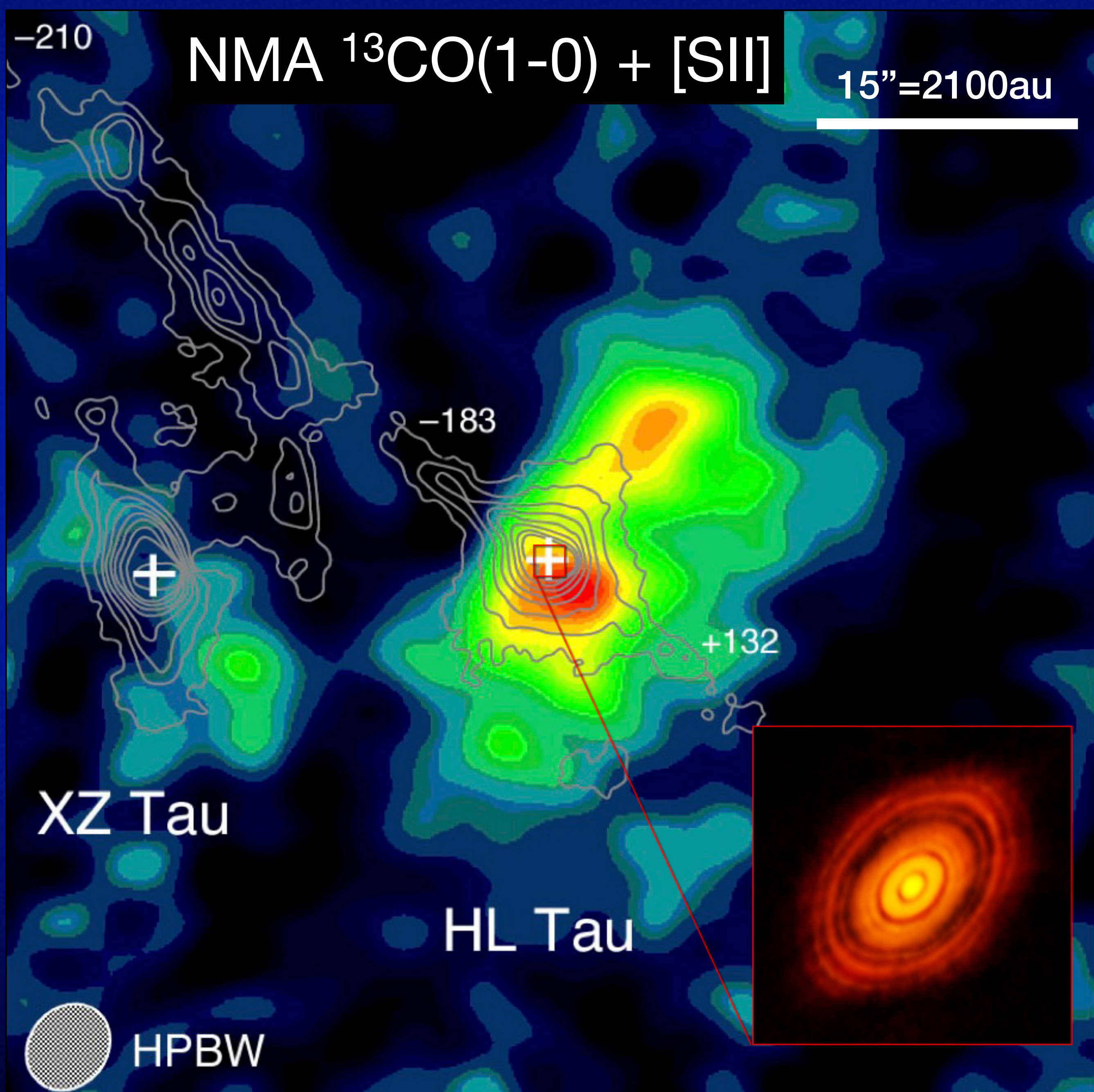


82mas * 54mas **35mas * 23mas** **29mas * 19mas**

※ 20mas = 2.8 AU

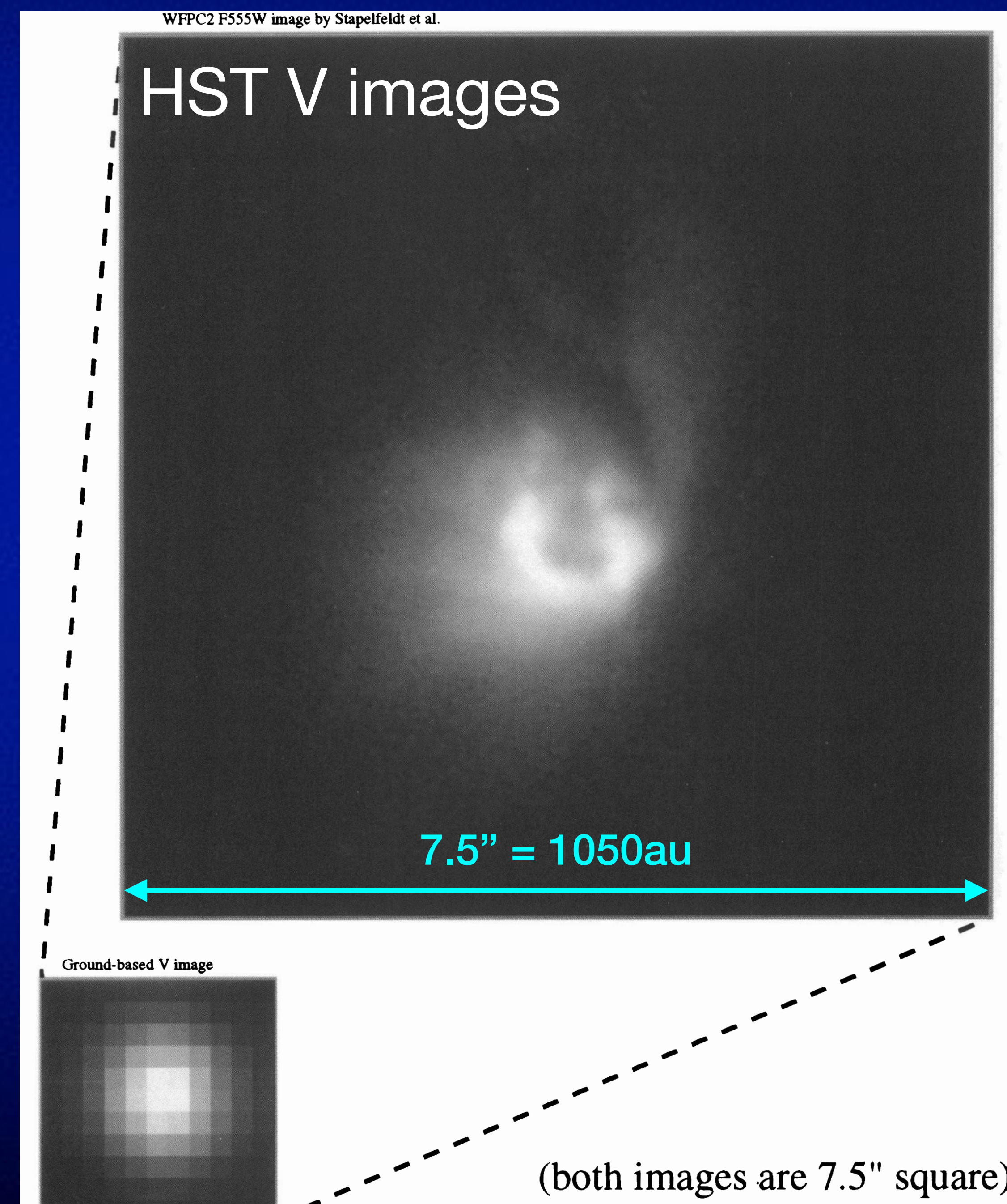
HL Tau:
— a "protostar-like" (age $<10^6$ yr) star

"infalling" envelope (~10^3au) + optical jets



Hayashi, Ohashi, Miyama (1993)

nebulous at optical

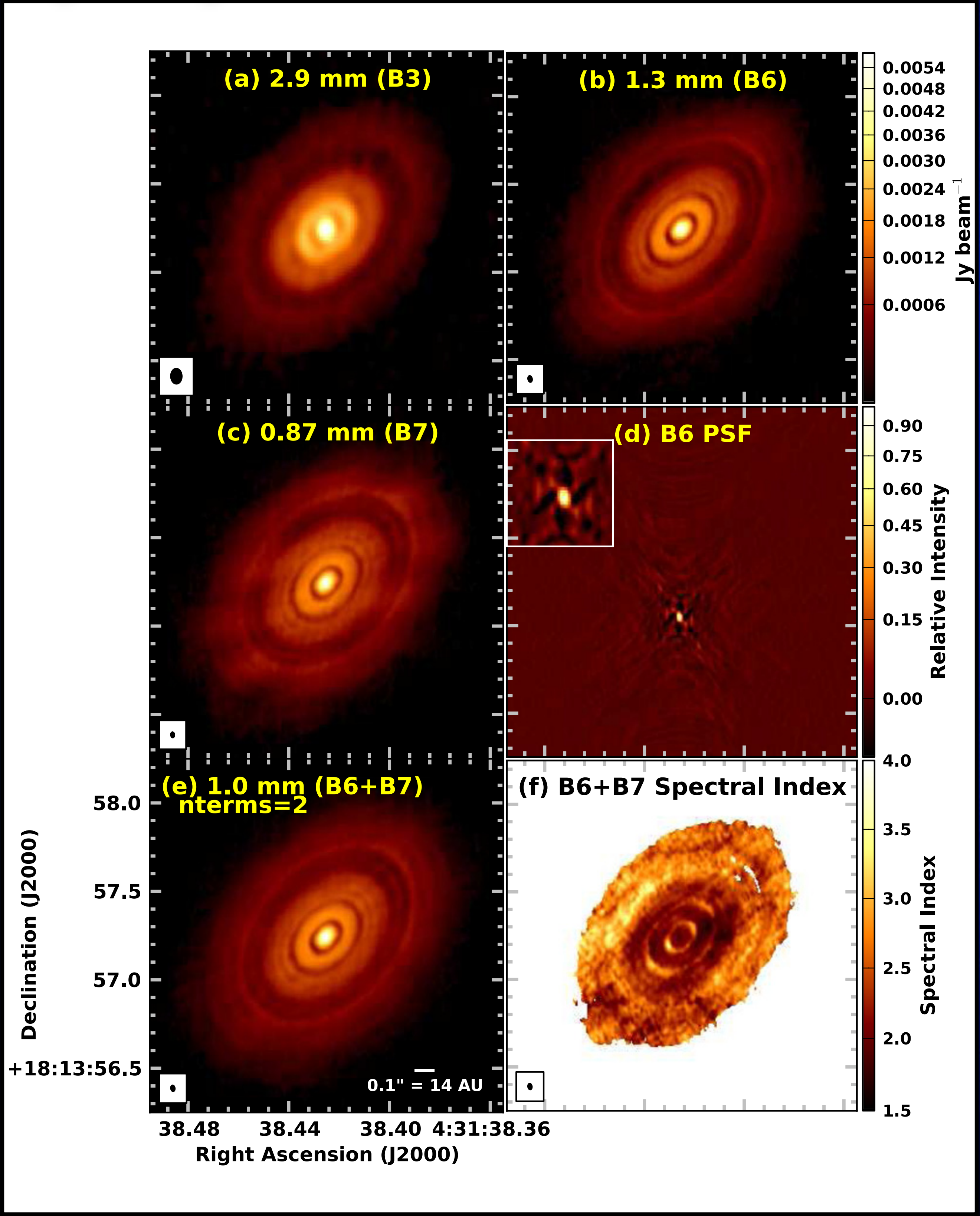


Stapelfeldt+ (1995)

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,
    👈 **$\alpha = 10^{-4}$ (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 ?



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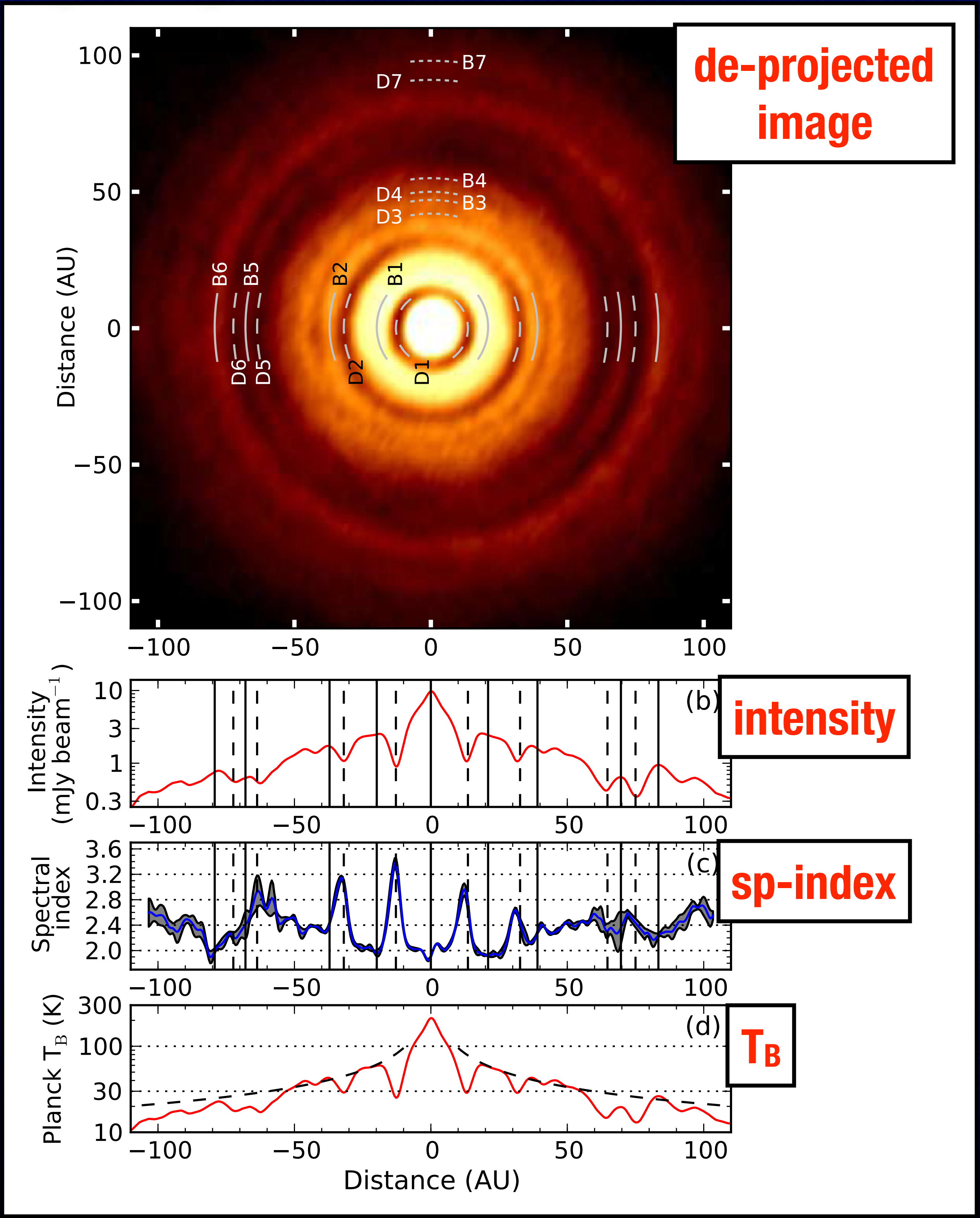


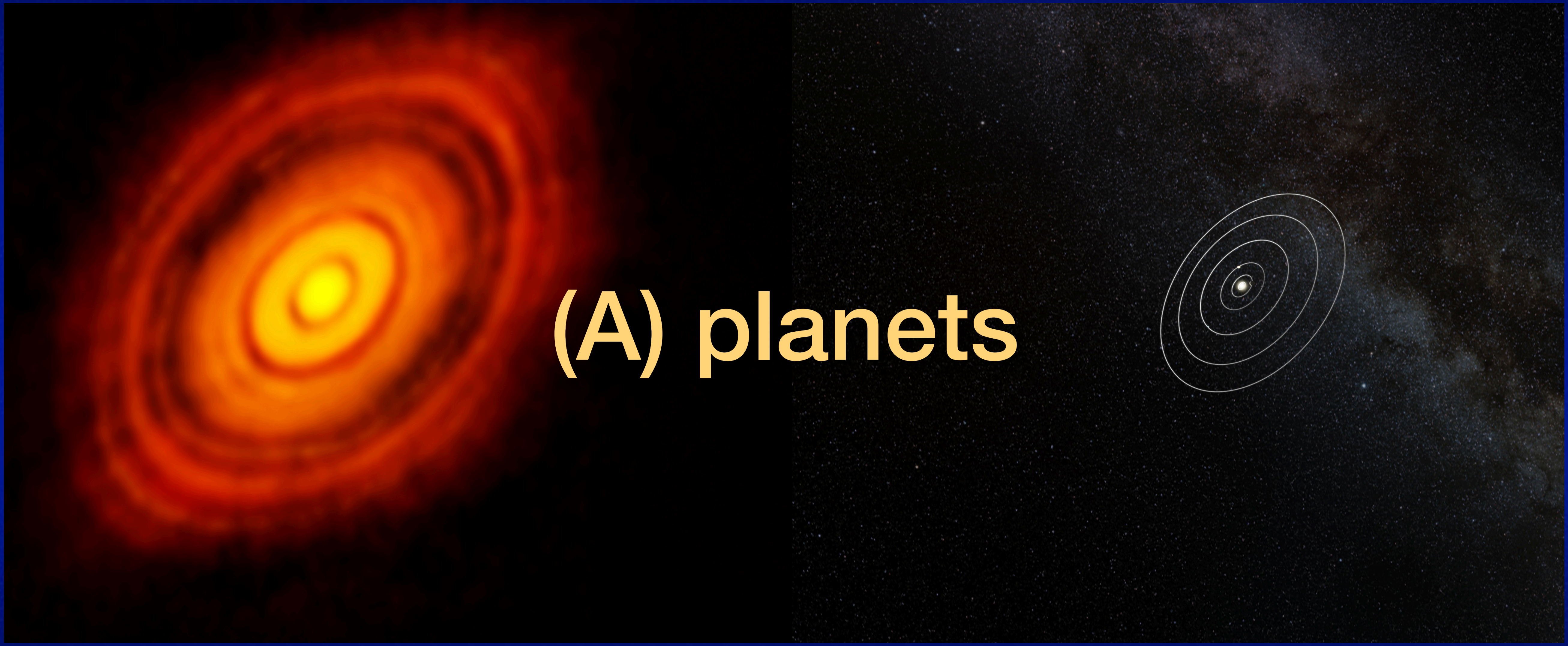
What is the origin(s) of rings/gaps ?

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)


(A) planets

Planet Mass vs. gap structure

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

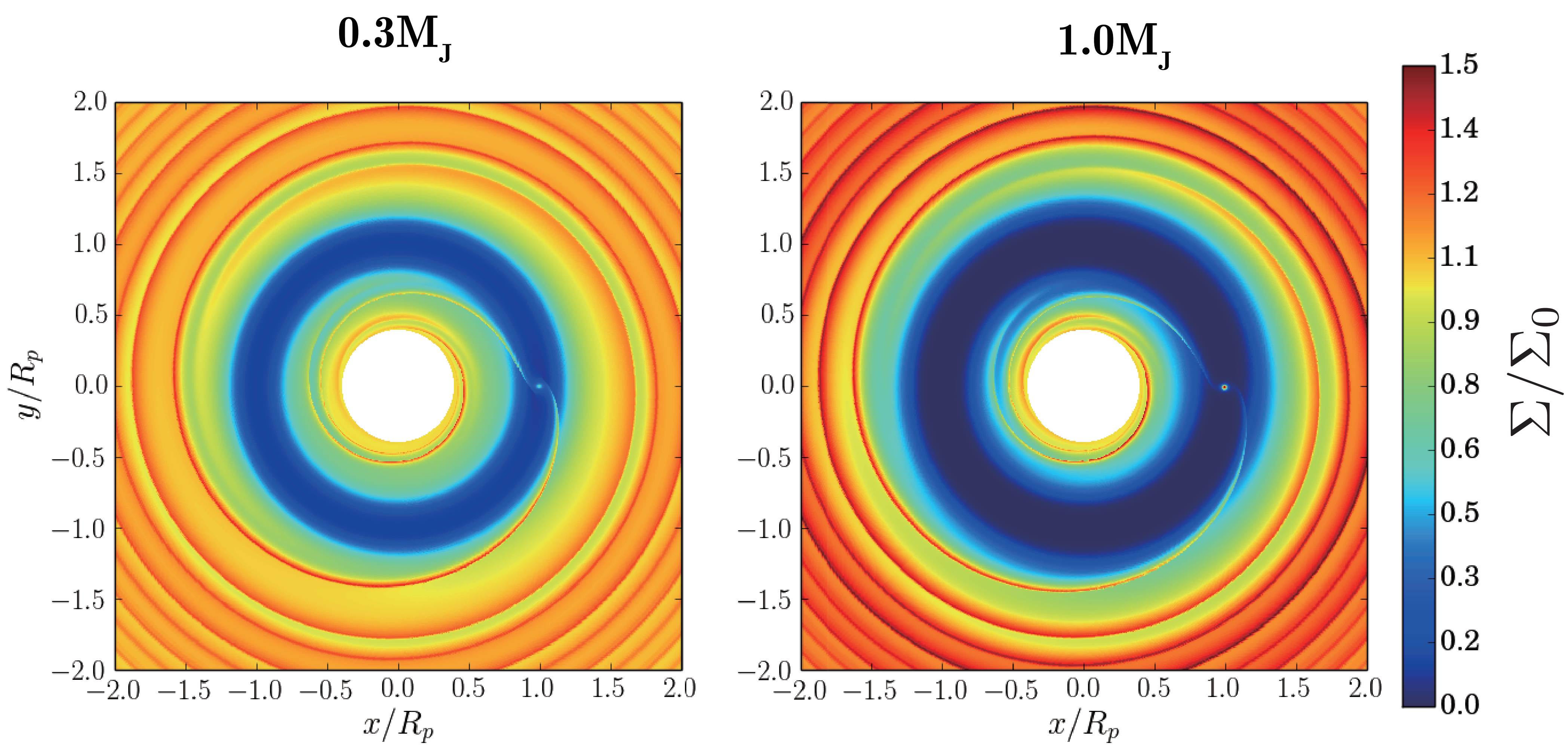
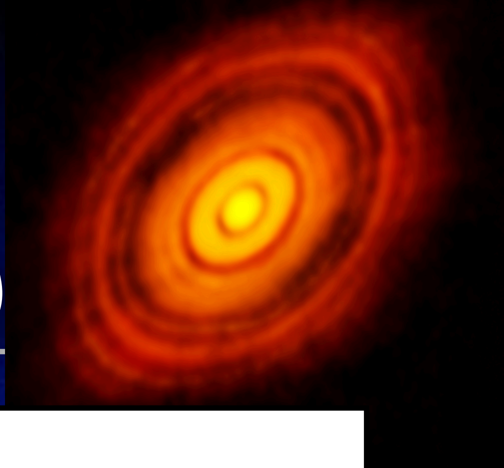
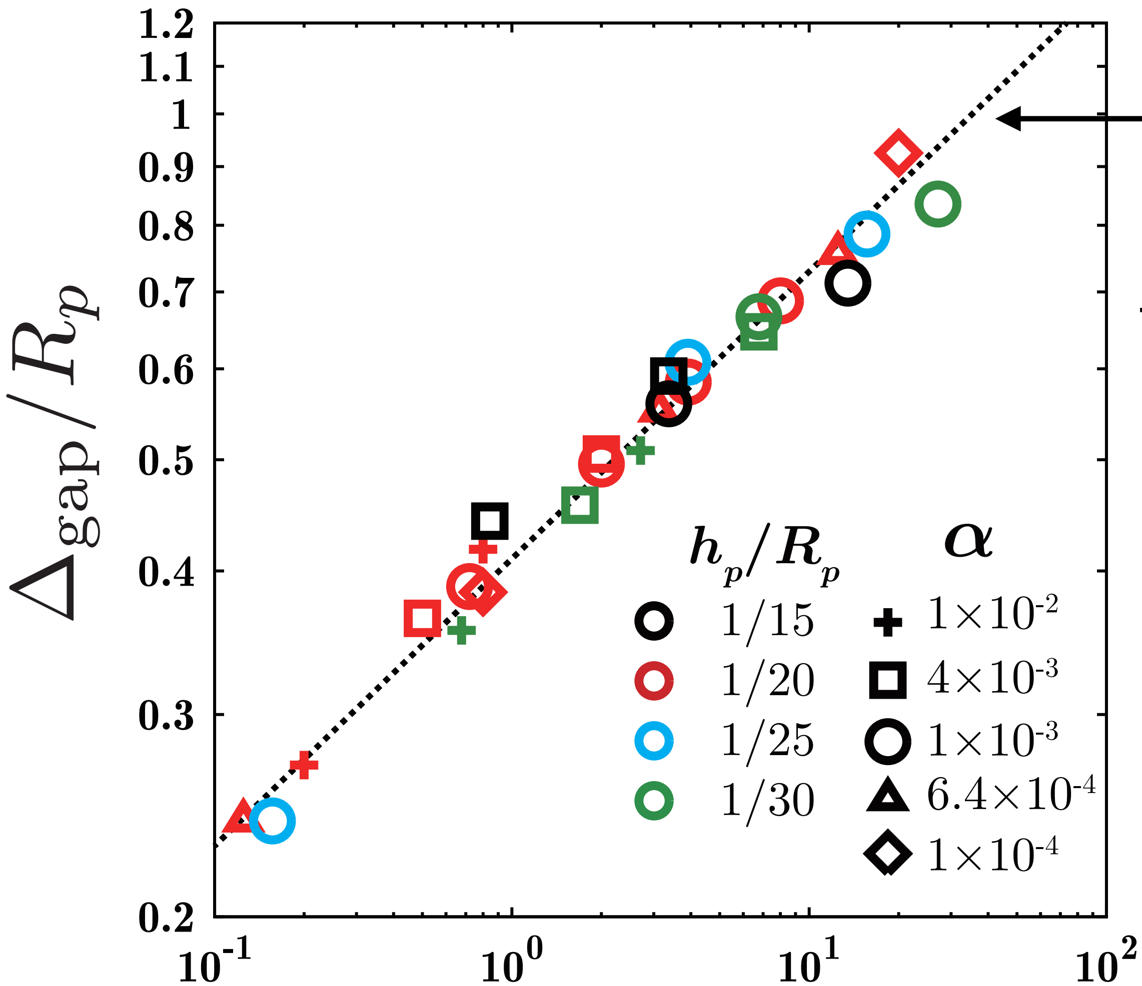


Fig. 1.— The surface density distributions at 10^4 planetary orbits obtained by two–dimensional hydrodynamic simulations for $M_p = 0.3M_J$ (*left*) and $M_p = 1.0M_J$ (*right*). Other parameters are set to be $h_p/R_p = 1/20$, $\alpha = 10^{-3}$ and $M_* = 1M_\odot$.

Mass estimates from gap width
Kanagawa, Muto, Tanaka, MM et al. (2016; PASJ)



Gap width vs.
K' (function of M_p, T, α)



$$K' = \left(\frac{M_{\rm p}}{M_*}\right)^2 \left(\frac{h_{\rm p}}{R_{\rm p}}\right)^3 \alpha^{-1}$$

plot: simulation

line: empirical relation from simulations

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

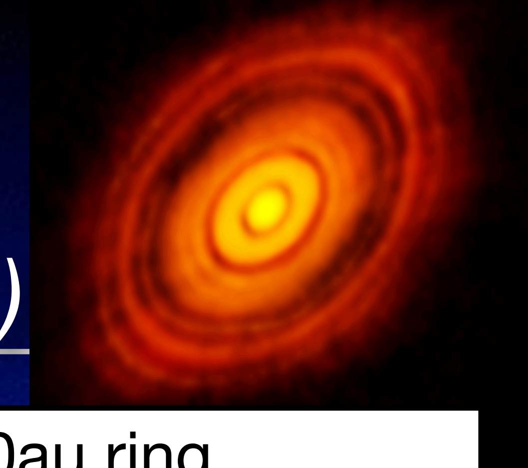
	10au	30au	80au
Δ_{gap}/R_p	0.81	0.23	0.29
M_p/M_J	1.4	0.2	0.5

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

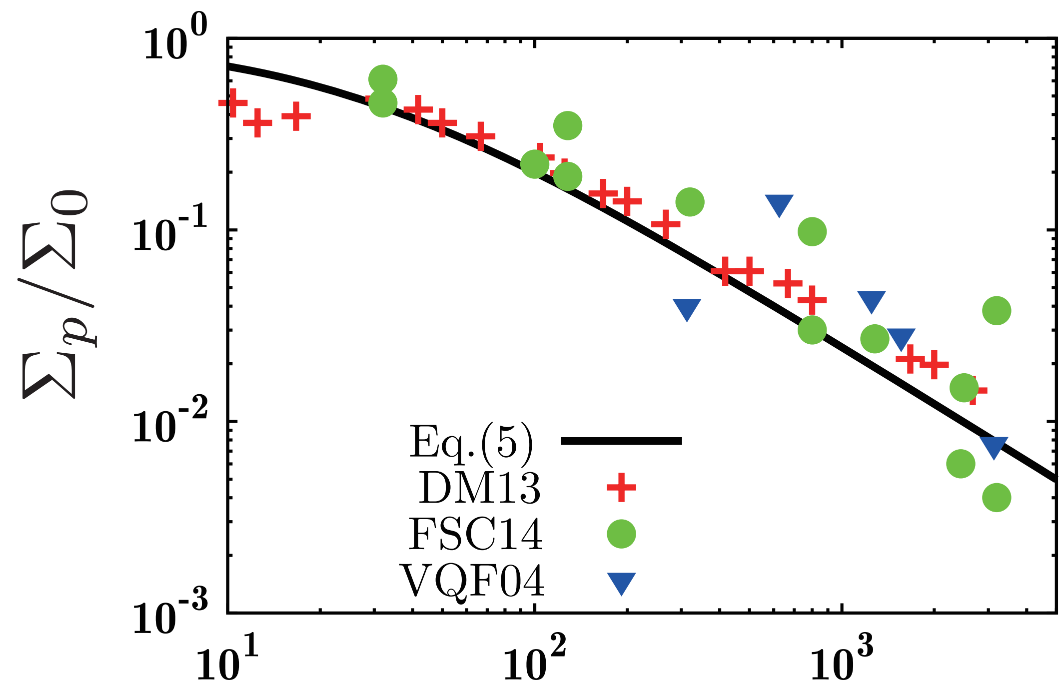
roughly consistent with "depleted mass" in each gap (Pinte+ 2016)

Mass estimates from gap depth

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



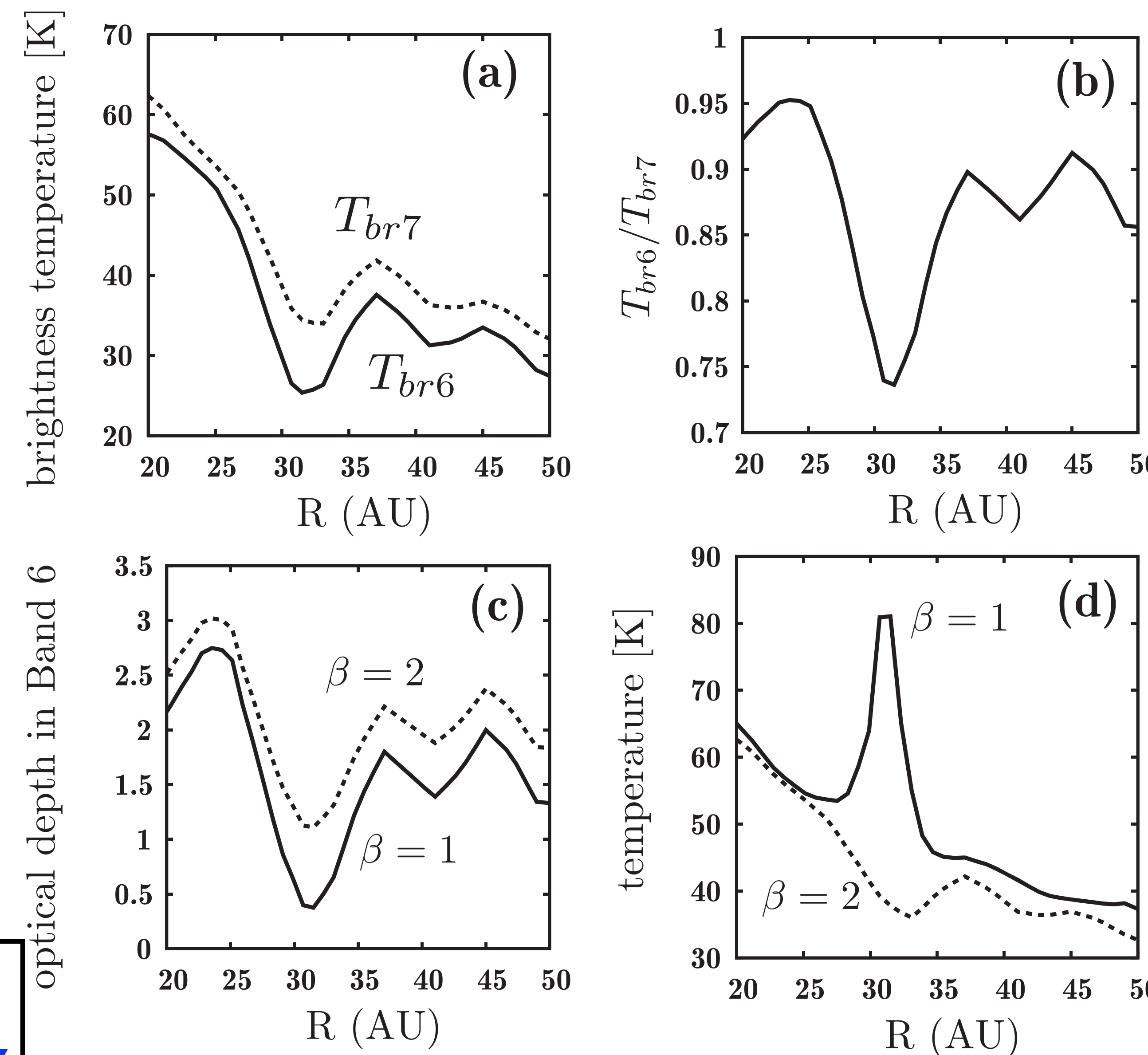
Gap depth vs. ***K*** (function of M_p, T, α)



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

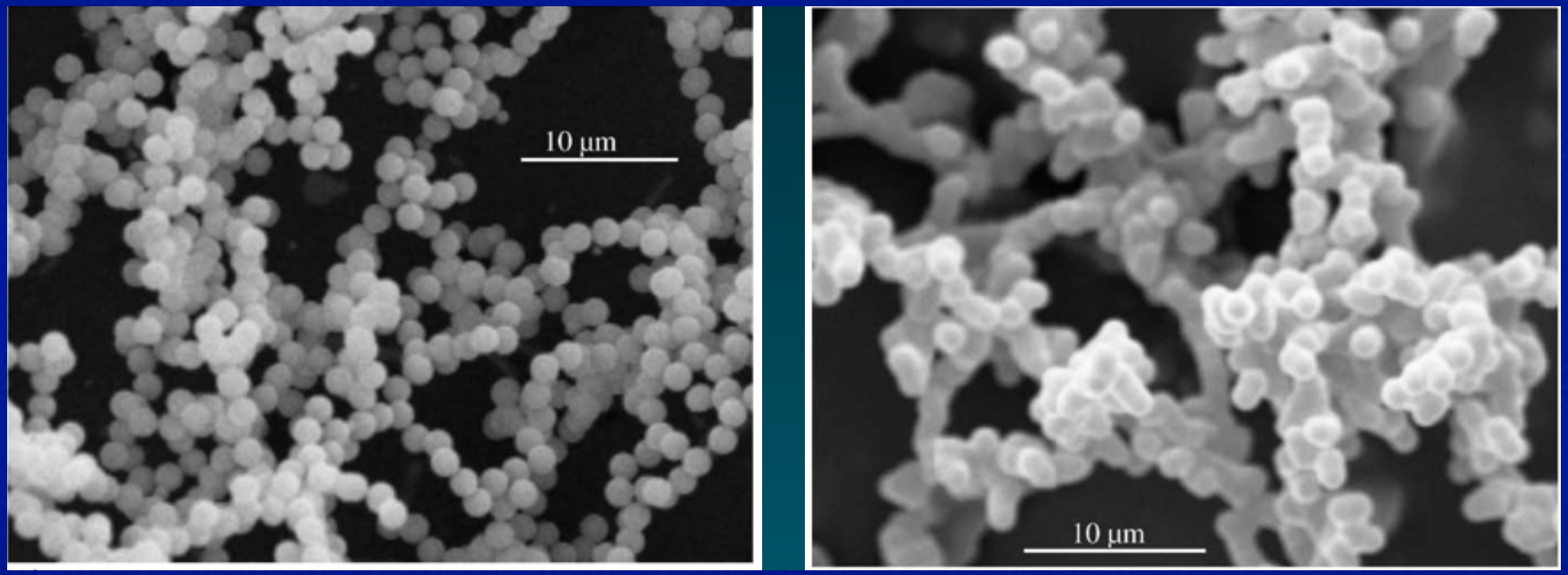
(Line) analytic formula from angular momentum flux and torque exerted by a planet on disk vs. (dots) simulations

Observations at ~30au ring



$M_p \approx$ (3-5) × 10^{-4} $M_\star$ for 30au gap if α=10^{-3}

(B) without planets



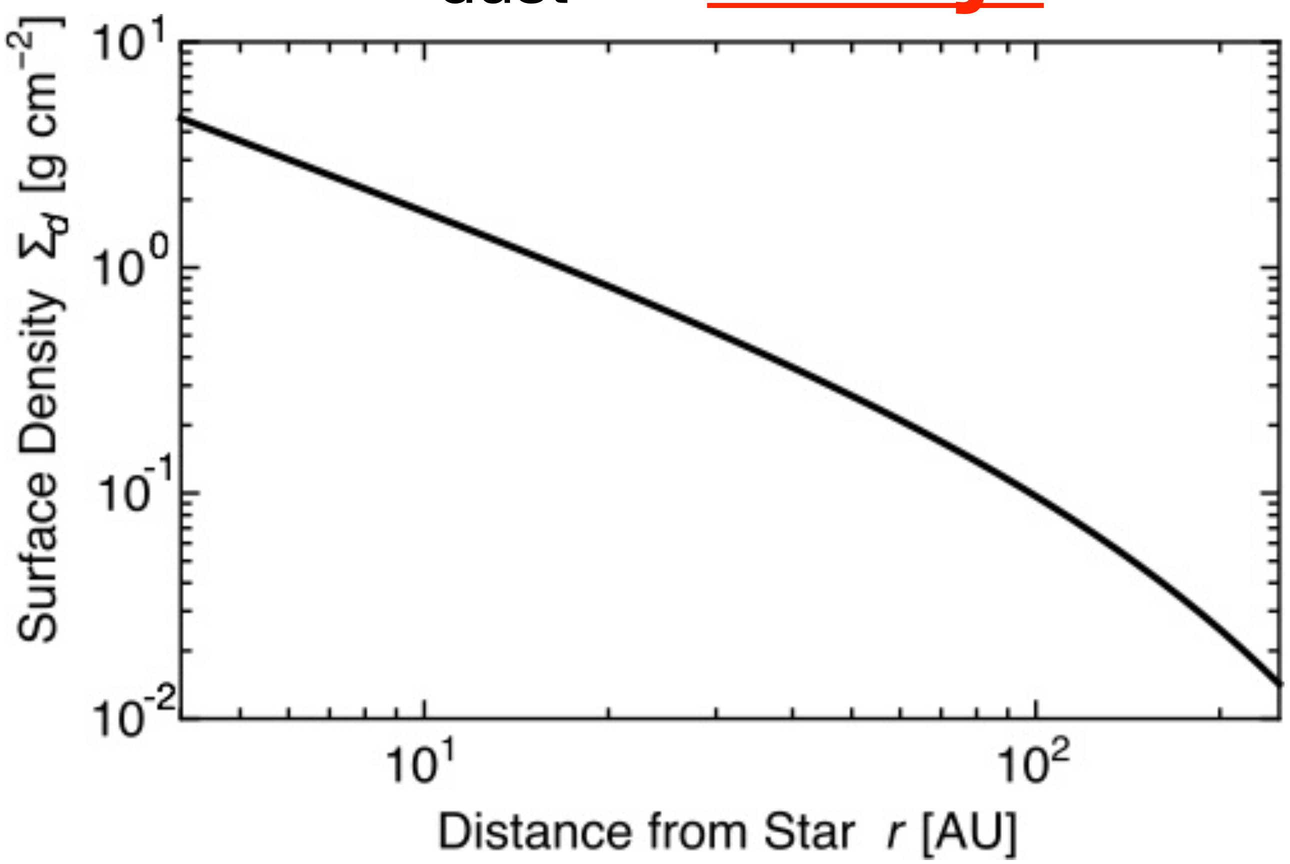
[sintering (焼結) induced ring formation]

Simulation based on 1D model

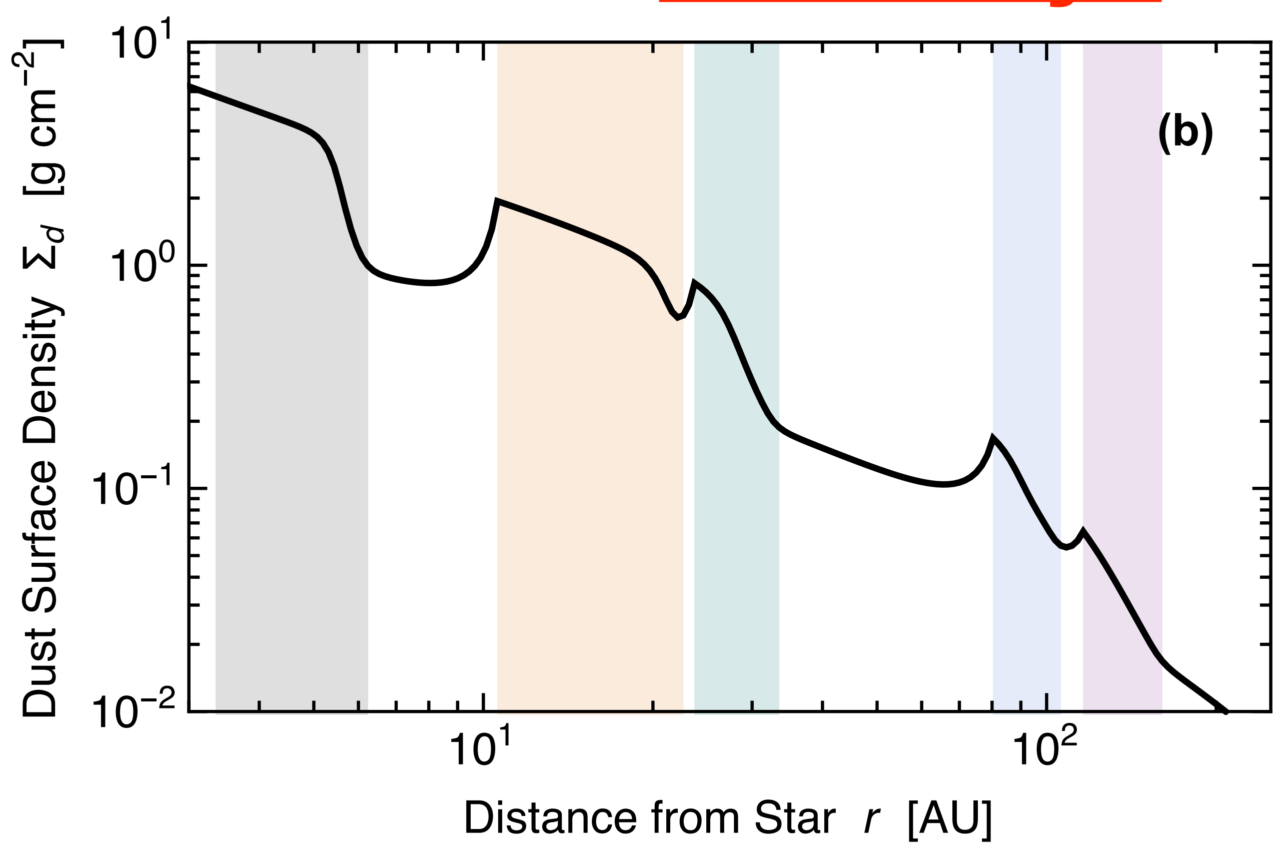
including radial drift + coagulation/fragmentation of dust

Dust moves inward, through several “traffic jams”

Σ_{dust} @ **t=0Myr**



Σ_{dust} @ **t=0.26Myr**



initial condition

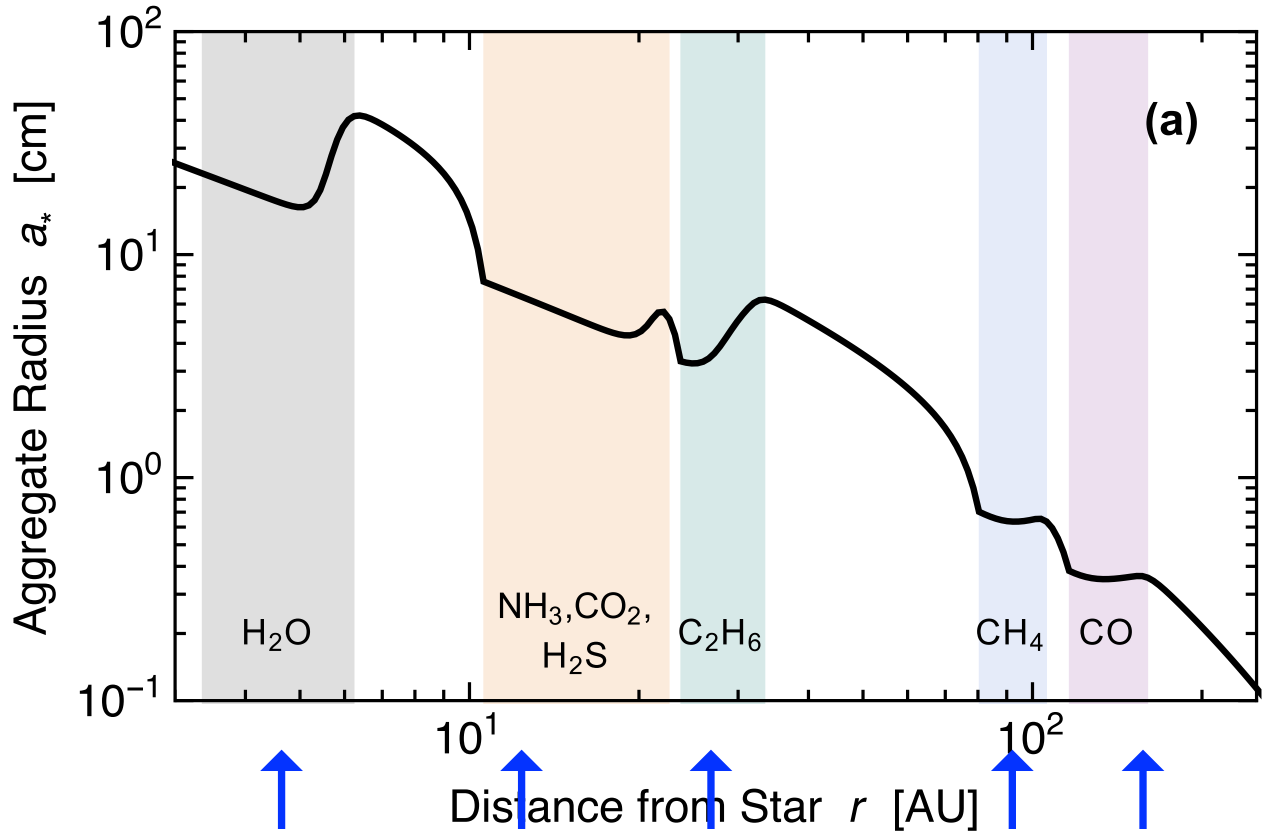
- *Σ*: power-law + exponential cutoff
- *T*: power-law (from T_b in B7)
- g/d = 100 (gets higher at t>0)

Sintering-induced multiple dust rings

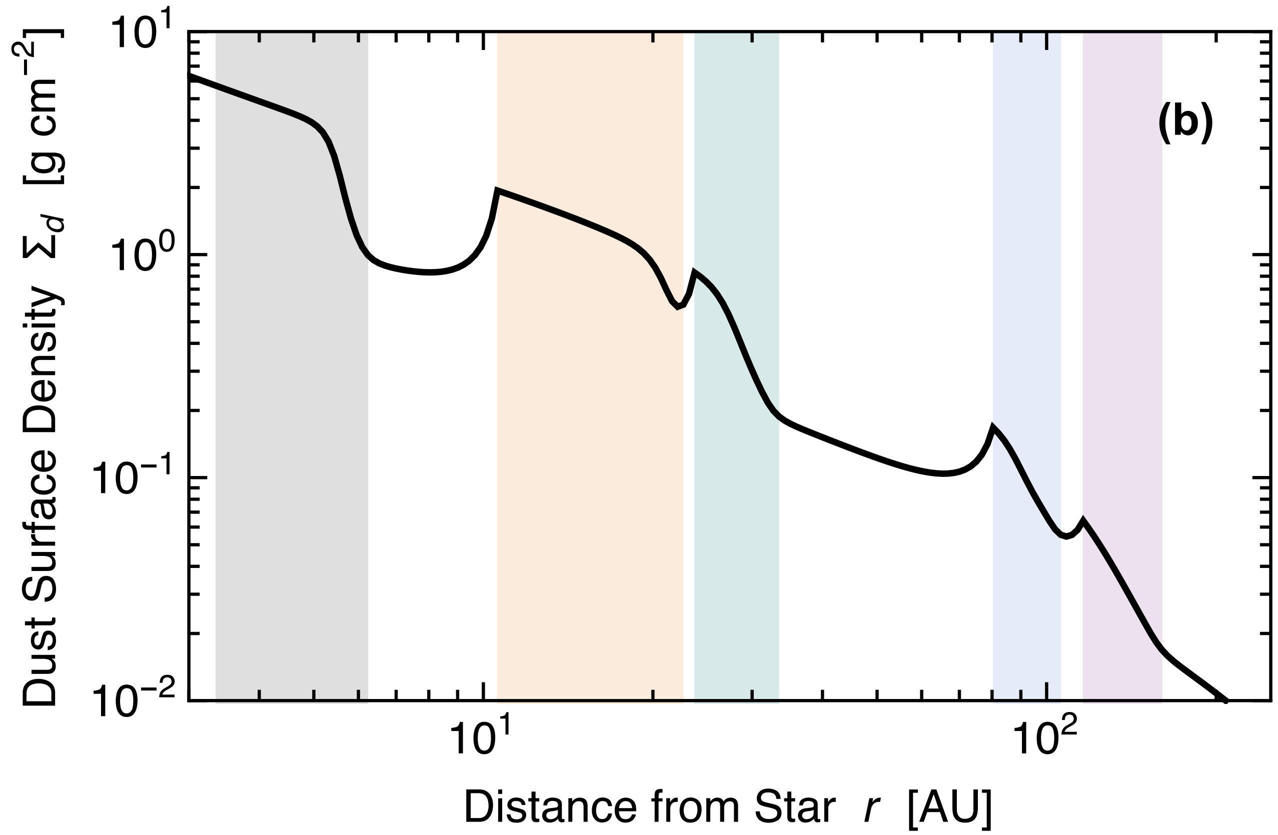
Okuzumi, Momose, Sirono, Kobayashi & Tanaka (2016)

Dust moves inward, through several "traffic jams"

Aggregate Size @ **t=0.26Myr**



Σ_{dust} @ **t=0.26Myr**



H_2O NH_3 C_2H_6 CH_4 CO

CO_2

H_2S

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

destruction of aggregates

→ smaller aggregates produced

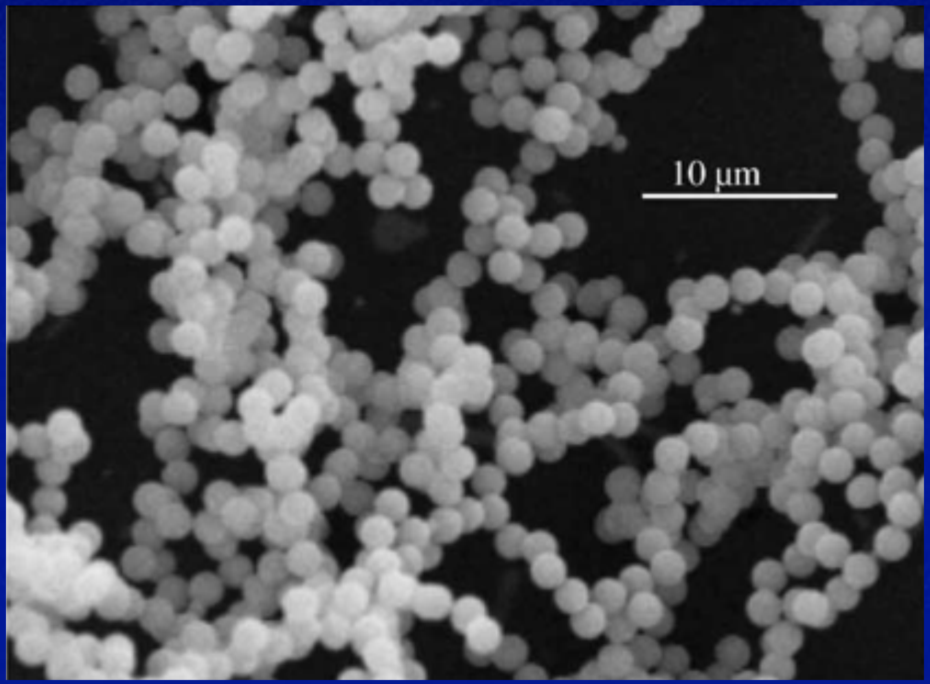
→ lower drift velocity

→ Σ_{dust} increased !

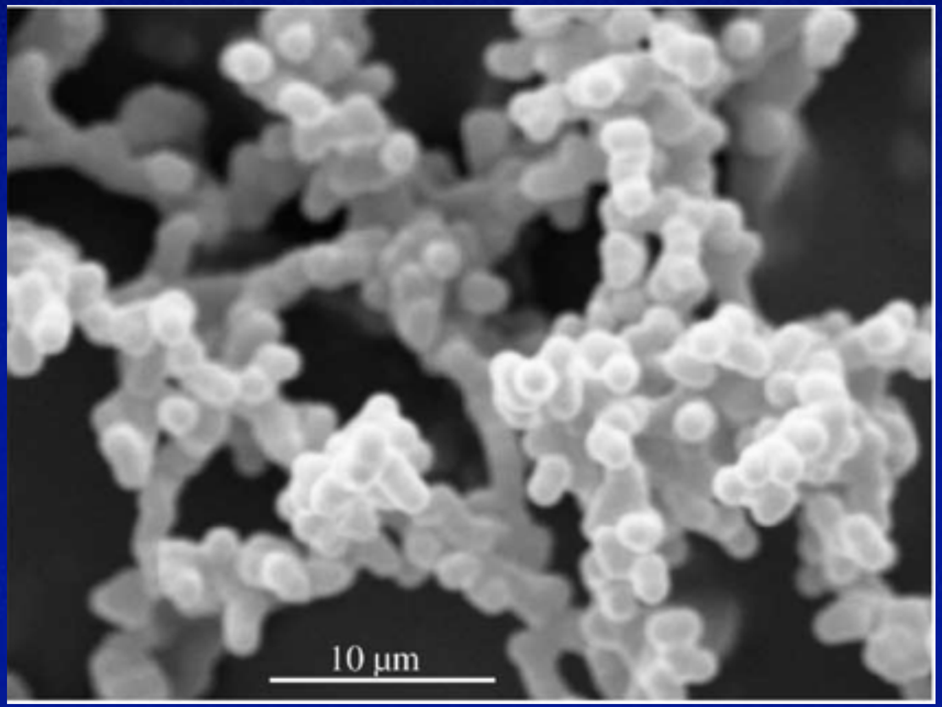
Sintered aggregate in laboratory

Poppe+ (2003)

SiO_2 aggregate



sintering at slightly below T_{melt}

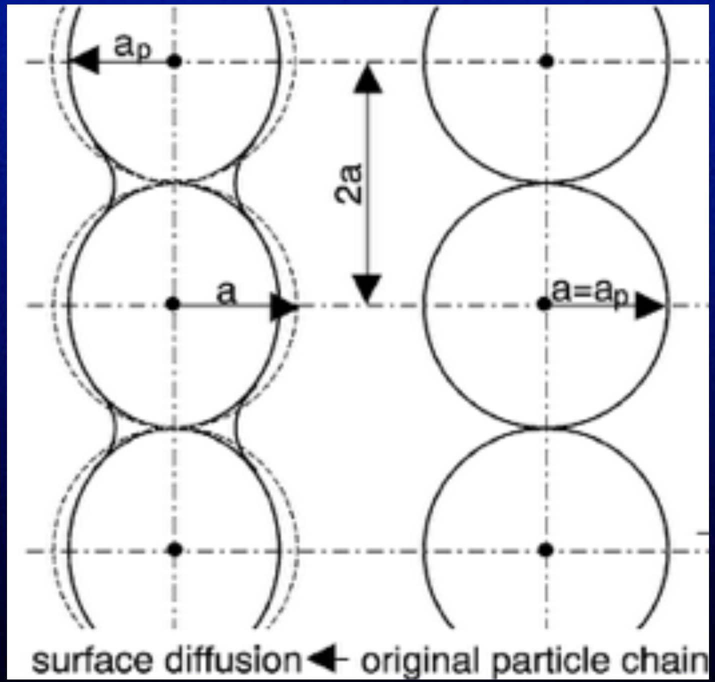


surface diffusion → "neck"

a small volume fraction,

only small amount of volatiles required

"multiple sintering zones with high Σ_{dust}"



Conditions for sintering (neck formation) by species *j*

1. outside *j*'s snowlike , i.e., $\boxed{r > r_{\mathrm{snow},j}}$

2. (the growth rate of neck radius)$^{-1}$ < (collision frequency)$^{-1}$, or

$$\boxed{t_{\mathrm{sint},j} < t_{\mathrm{coll}}}$$

$$t_{\mathrm{sint},j} = 4.7 \times 10^{-3} \frac{(2\pi m_j)^{1/2}}{V_j^2 \gamma_j} \frac{a_0 (k_{\mathrm{B}} T)^{3/2}}{P_{\mathrm{ev},j}(T)}$$

$$t_{\mathrm{coll}} = f(a_*, n_*, \Delta v)$$

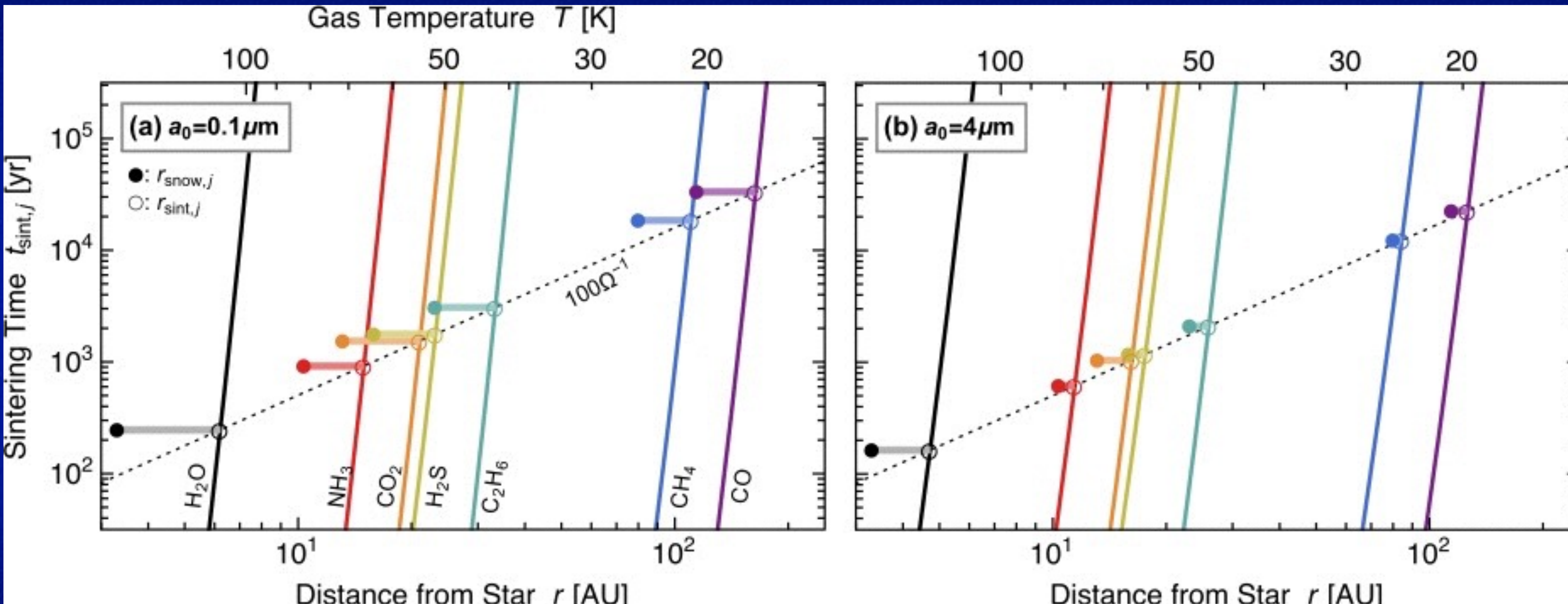
steep function of *T*, but also on a_0, the "monomer" size of the aggregate

(m_j, V_j, γ_j)
mass, volume, surface energy of species j

Δv: collision velocity (← turbulent & drift velocities) ;
(a_*, n_*): the size and number density of aggregates

Sintering zones when $t_{col} = 100\Omega_{kep}^{-1}$ and $\Sigma_d = 0.01\Sigma_g$

vertical lines = $t_{sint, j}$



a_0 = 0.1 μm case

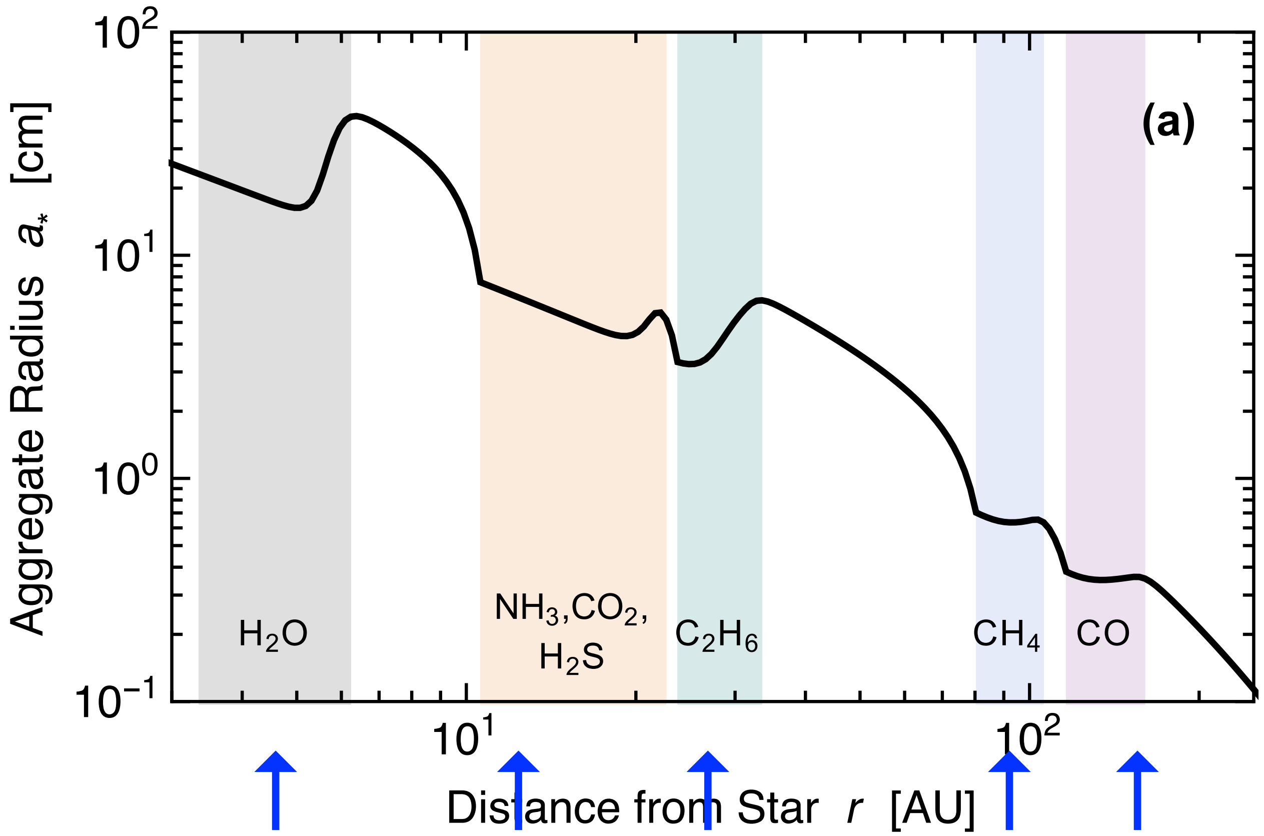
a_0 = 4 μm case

narrower sintering zones because of longer $t_{sint, j}$

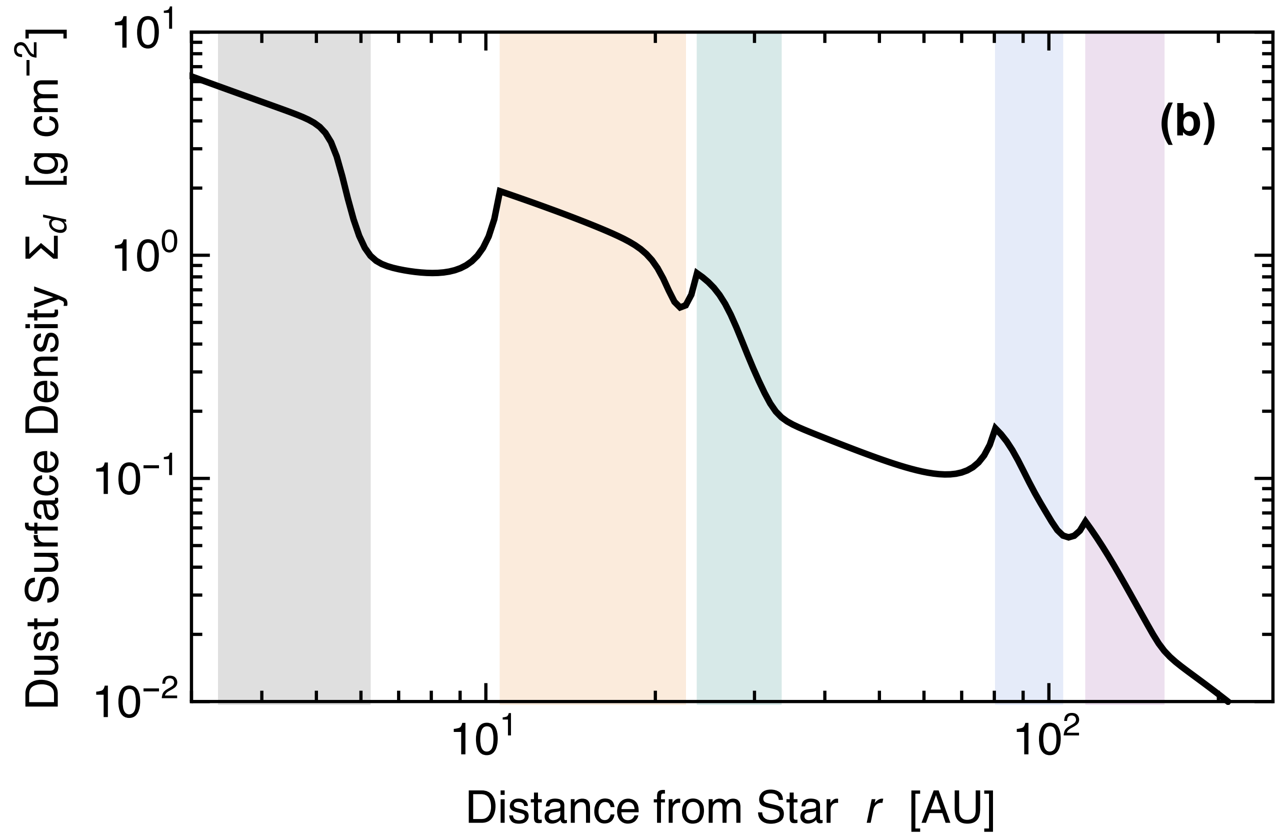
1D Model Calculation (drift + growth/destruction)

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

Aggregate Size



Σ_{dust}



↑ ↑ ↑ ↑ ↑

H_2O NH_3 C_2H_6 CH_4 CO

CO_2

H_2S

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

<u>destruction of aggregates</u>

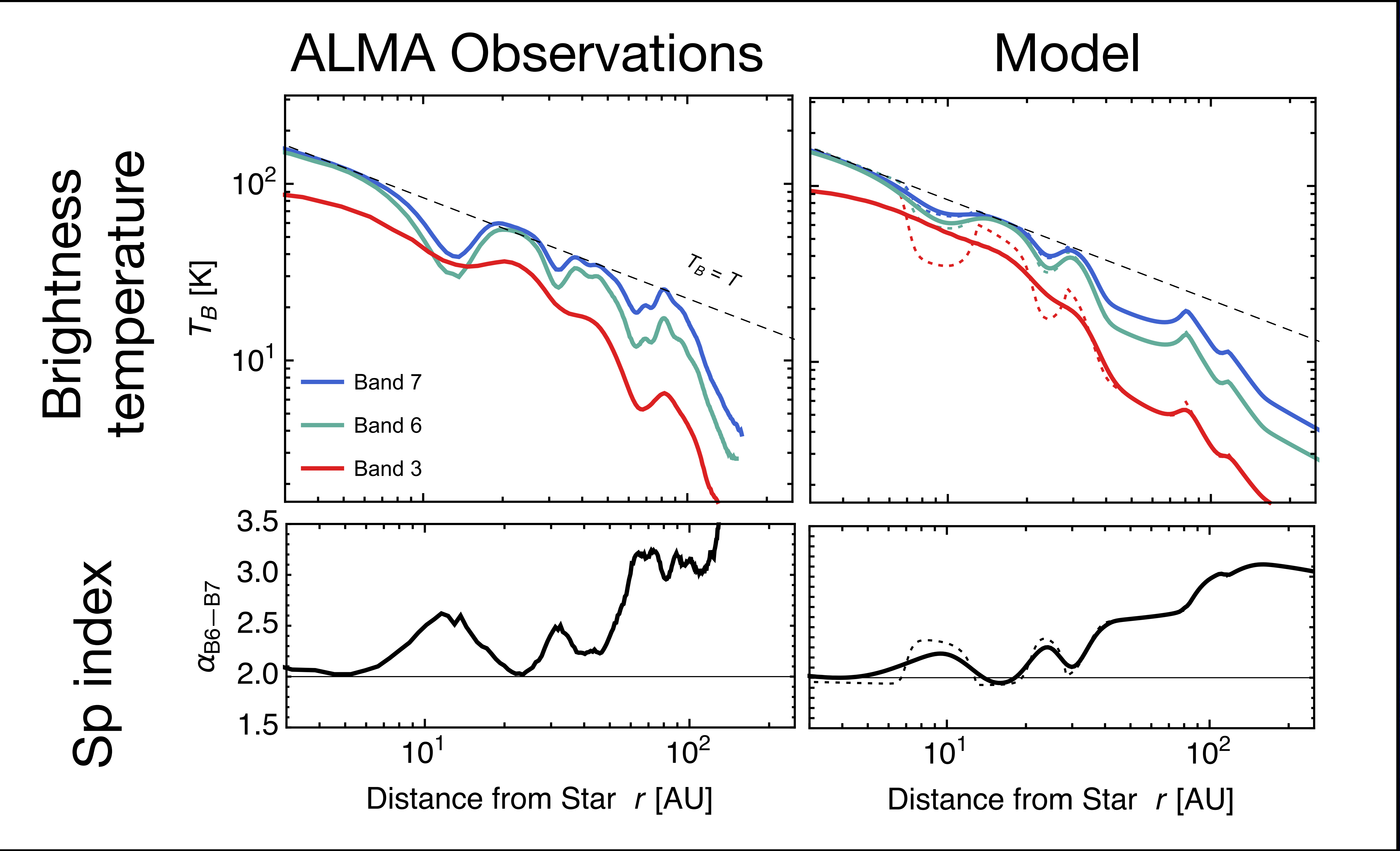
→ smaller aggregates produced

→lower drift velocity

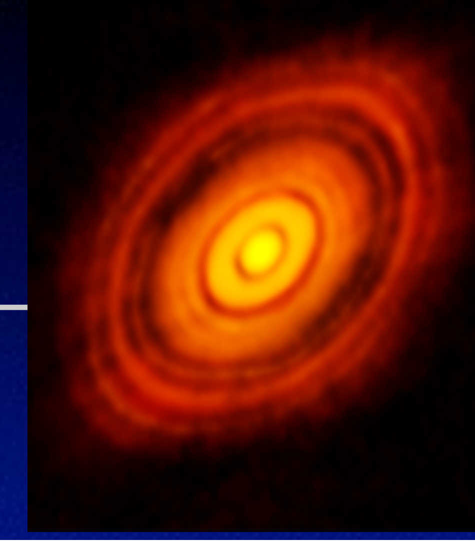
→ Σ_{dust} increased !

Comparisons in T_B with observations

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

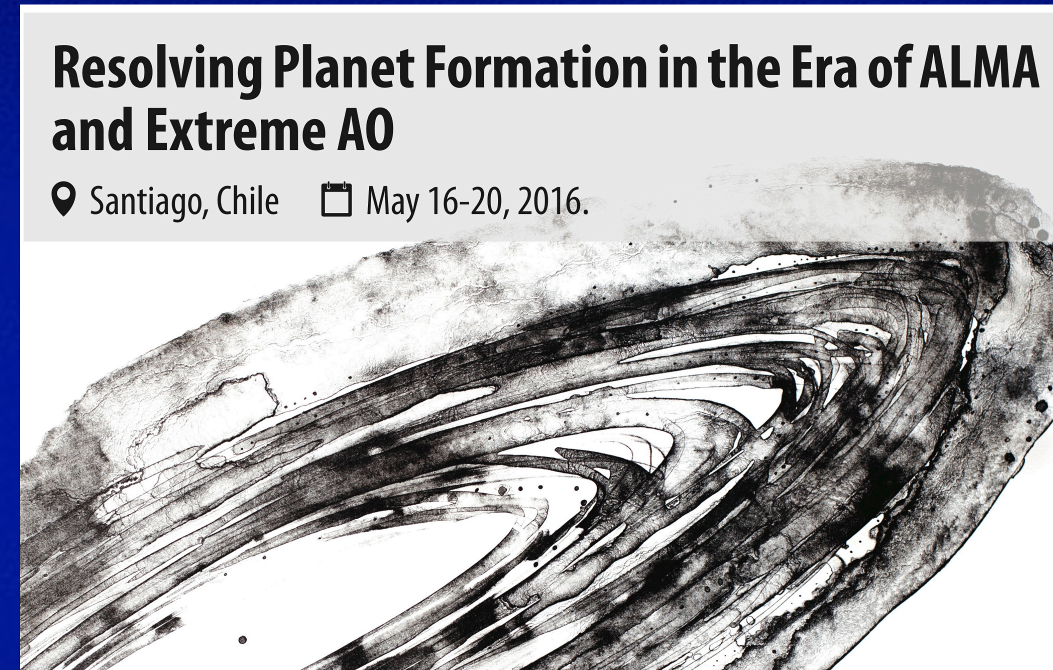


Summary talk of the conference held in May 16-20, 2016 (by D. Wilner)



- What causes the gaps in the HL Tau disk?
  - *(a) Planets*
  - *(b) MHD zonal flows*
  - *(c) Chemistry*
  - *(d) Other*
  - *(e) More than one of the above*

- Votes: *(a) 17 (b) 1 (c) 1 (d) 4 (e) 84*



TW Hya

Andrews+ (2016)

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

ANDREWS ET AL.

λ=870μm Cont.

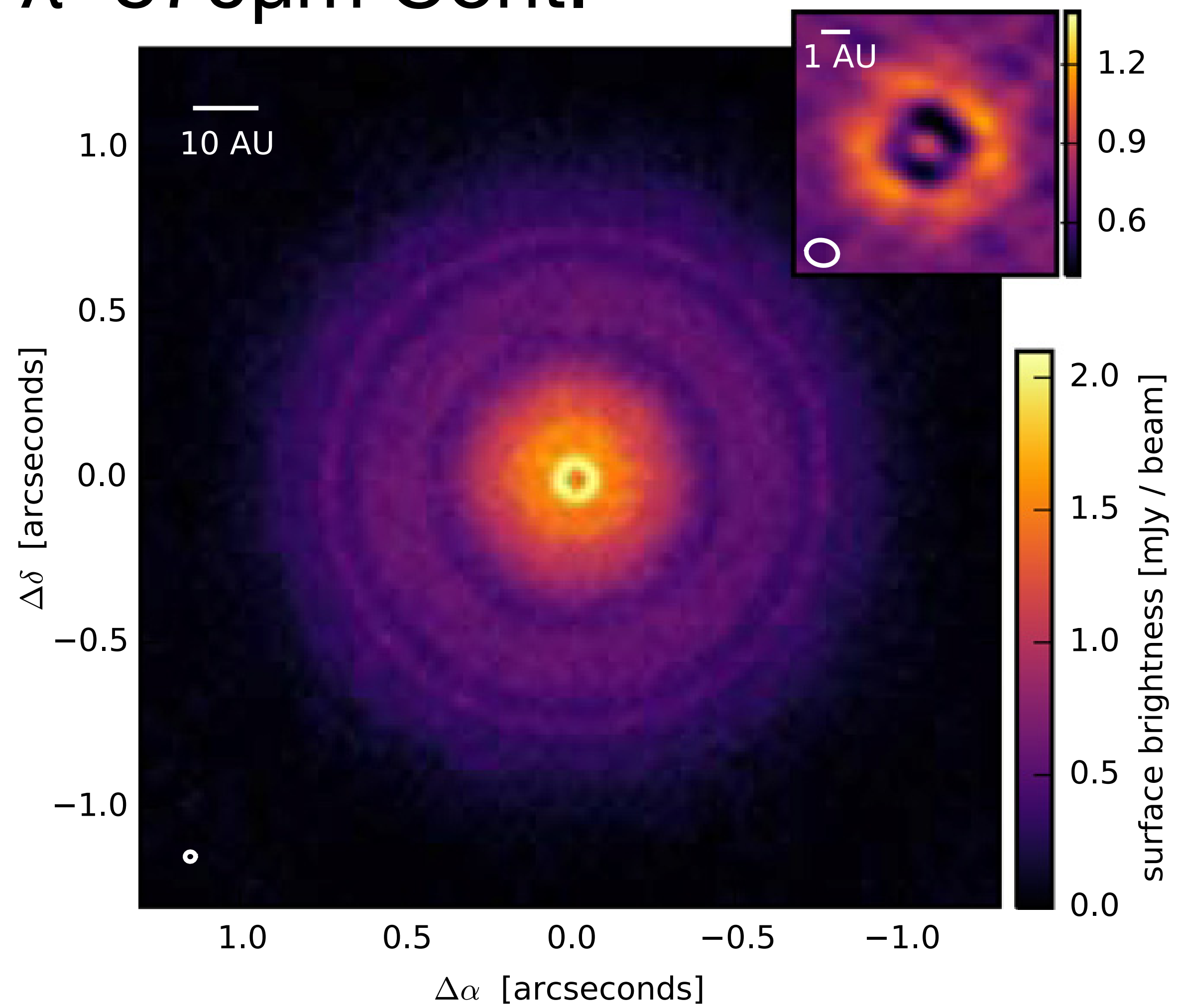


Figure 1. Synthesized image of the 870 μm continuum emission from the TW Hya disk with a 30 mas FWHM (1.6 au) circular beam. The rms noise level is ~35 μJy beam^{-1}. The inset shows a 0.″2 wide (10.8 au) zoom using an image with finer resolution (24 × 18 mas, or 1.3 × 1.0 au, FWHM beam).

(r,θ) coordinate

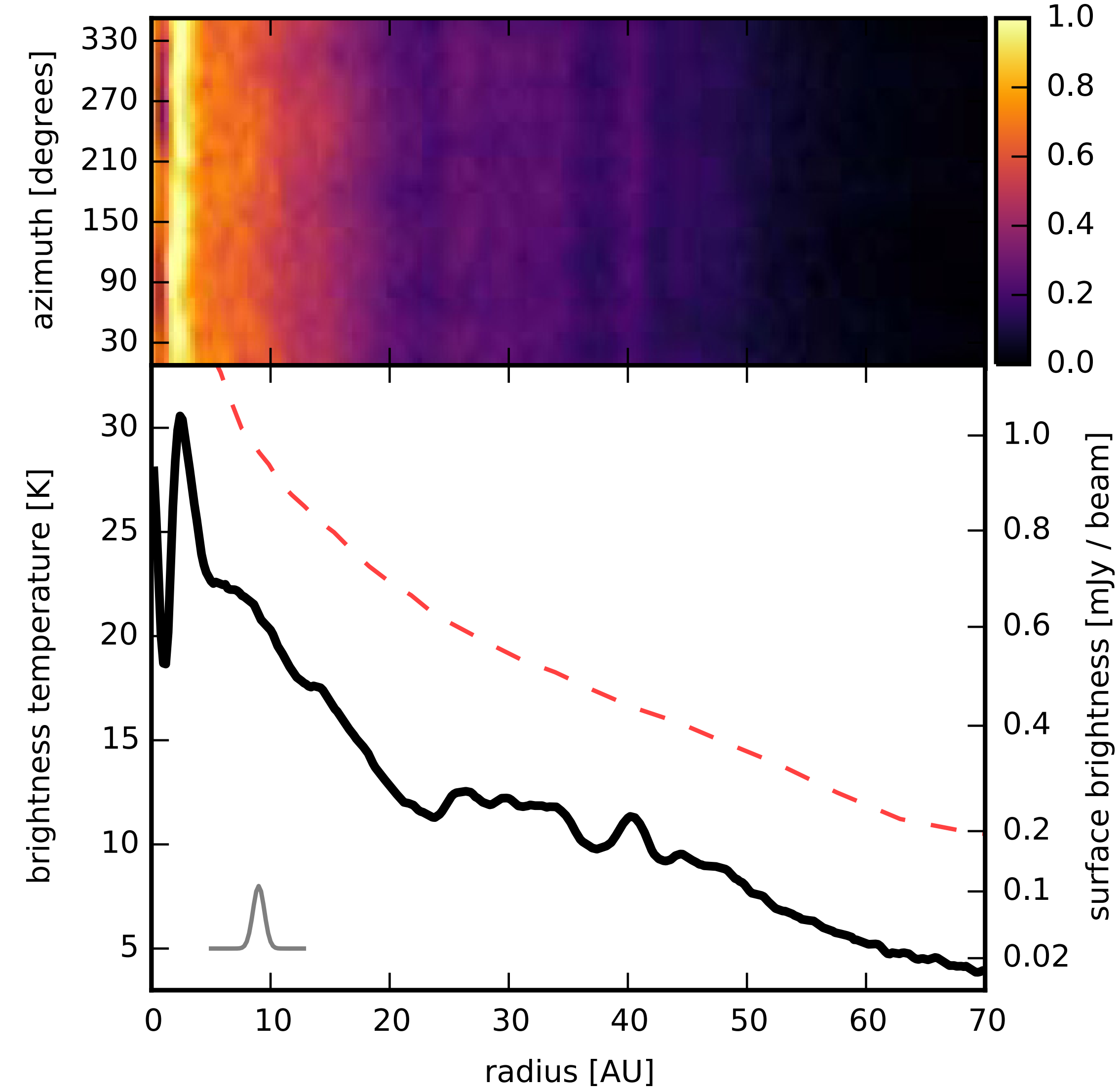


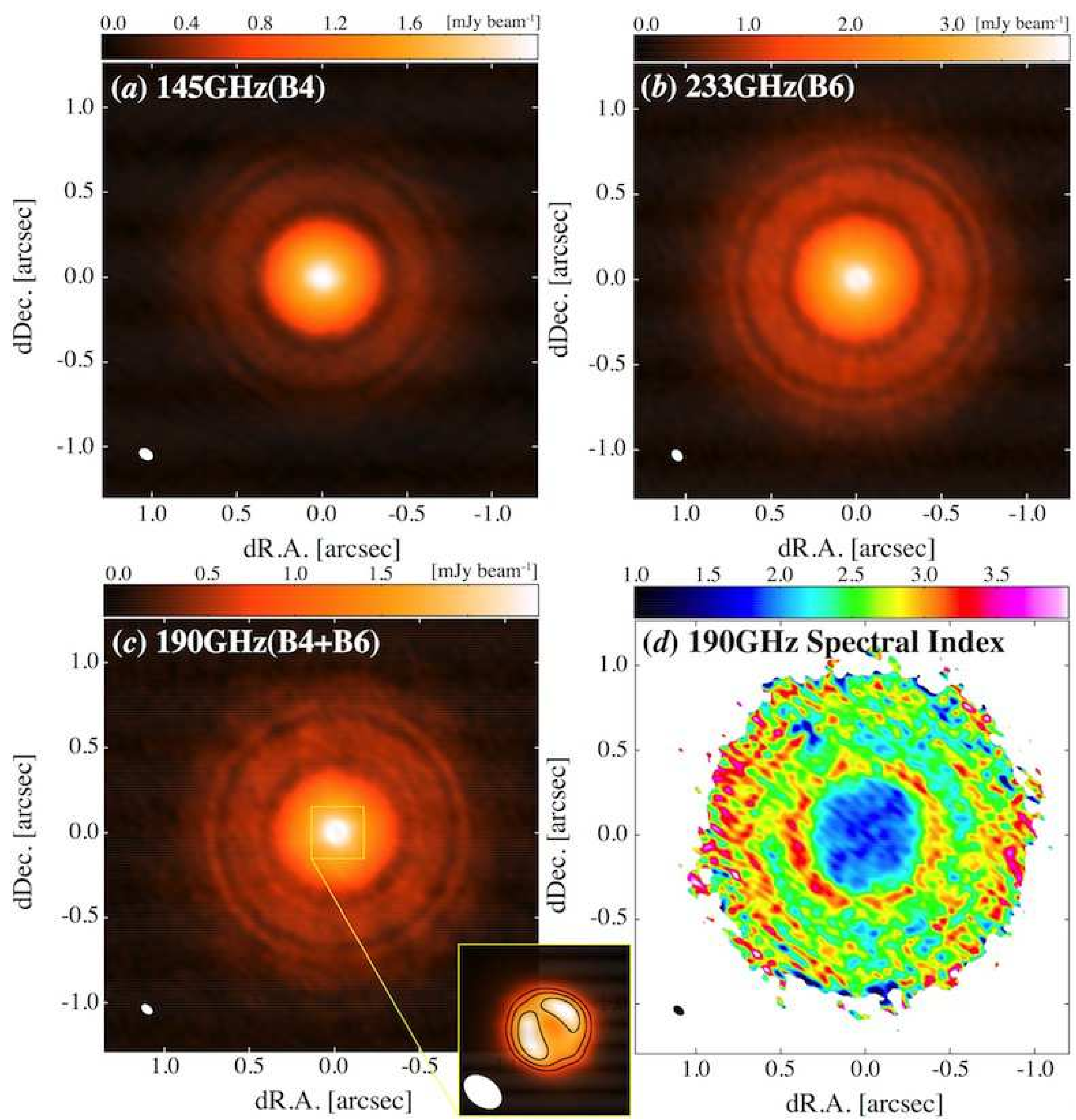
Figure 2. (top) High-resolution (24 × 18 mas beam) synthesized image described in Section 2, deprojected into a map in polar coordinates to more easily view the disk substructure. (bottom) The azimuthally averaged radial surface brightness profile. For reference, the dashed red curve shows the midplane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

TW Hya

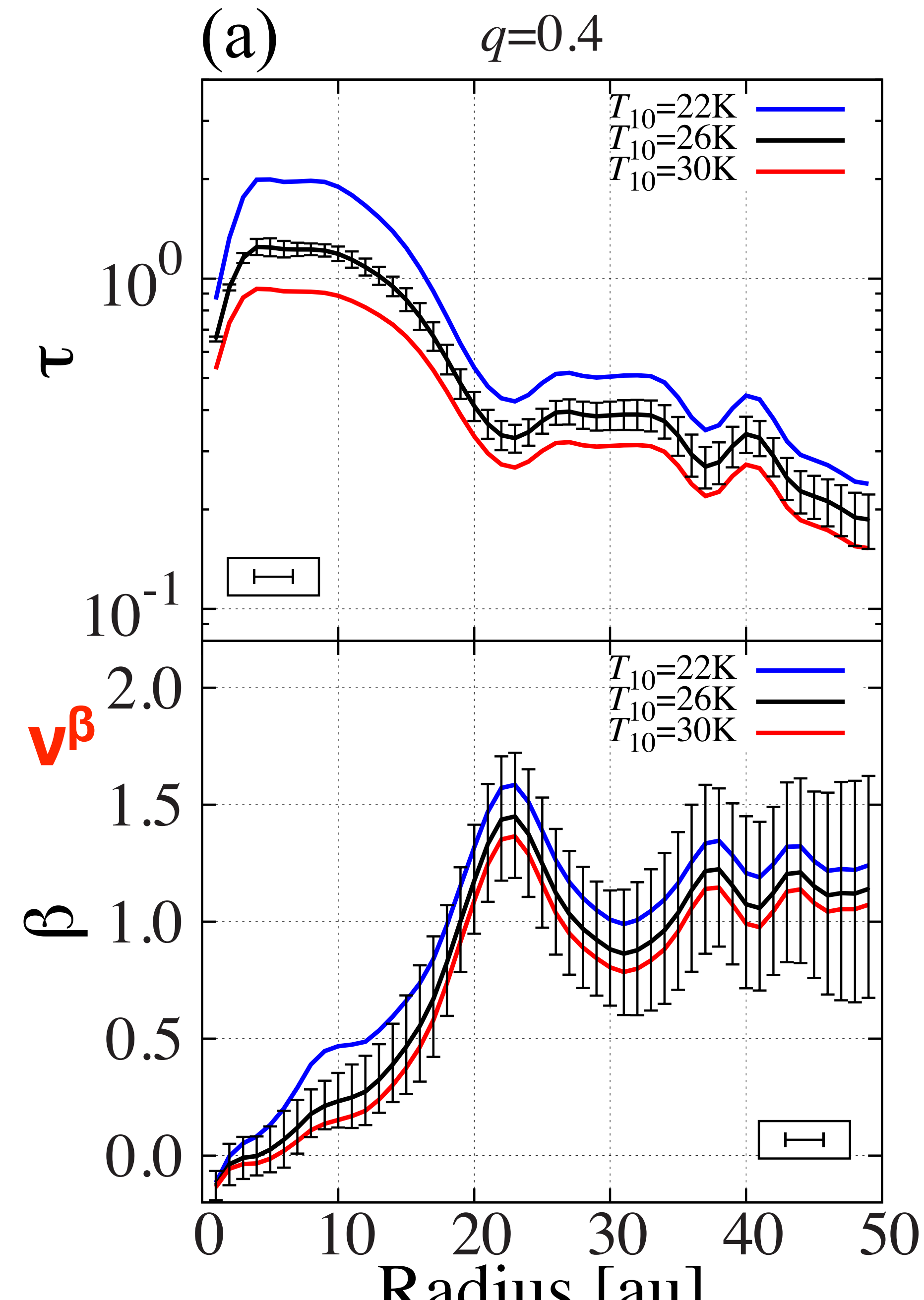
Tsukagoshi+ (2016); see also Nomura+ (2016)

- λ=2mm & 1.3mm
- 4 x 3 au beam

β is larger in the 22au gap; deficient in large grains
($\kappa(\nu) \propto \nu^{\beta}$) ← consistent with a planetary gap



$\kappa(\nu) \propto \nu^{\beta}$



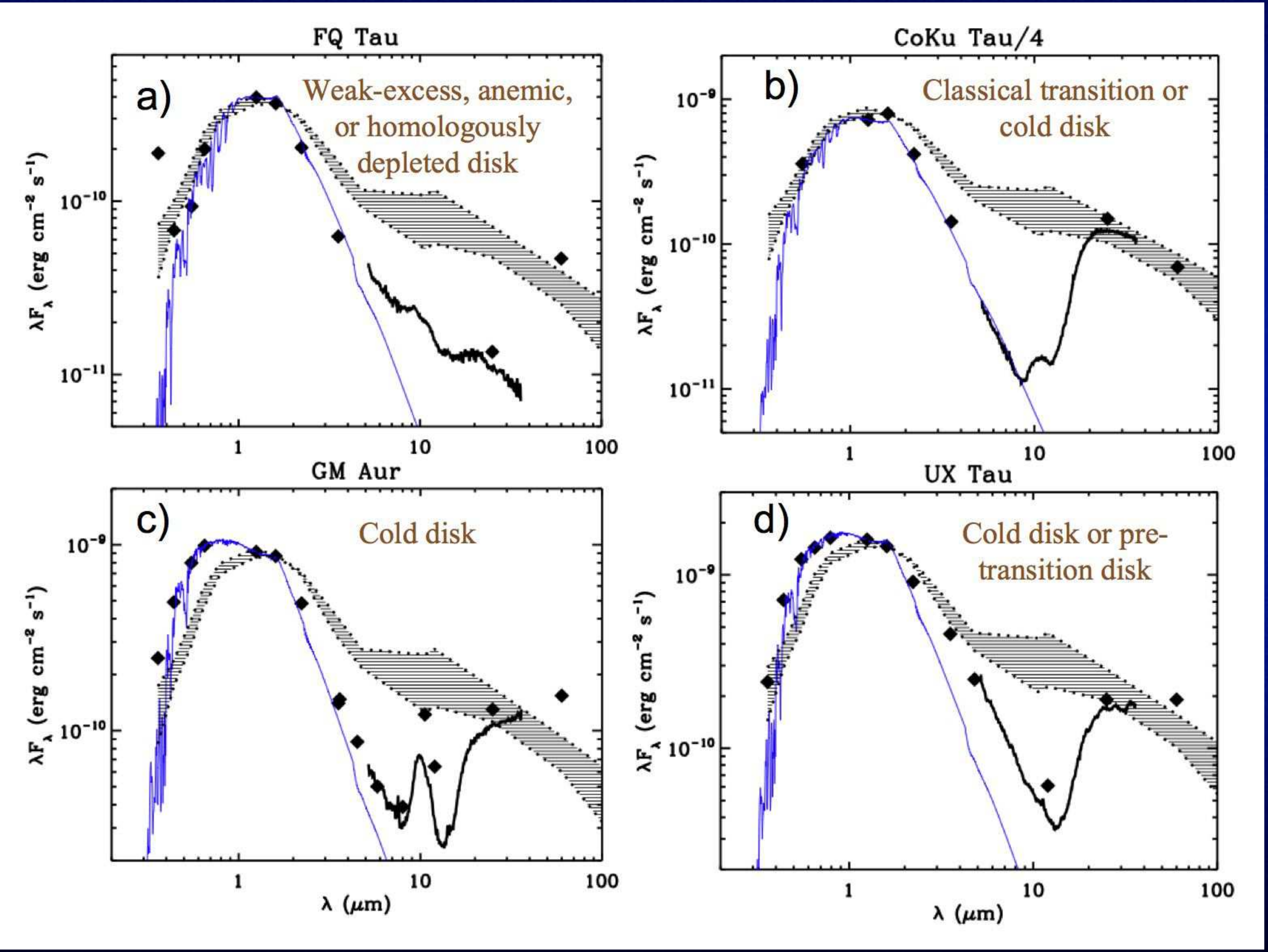
- **HL Tau (age < 10^6 yr)**
  - gaps at r≈12au, 32au, 82au
  - depths, consistent with (0.2-1.4)M_J planets, formed by Gravitational Instability ?
  - mechanisms without planet are also proposed
- **TW Hya (age ~ 10^7 yr)**
  - gaps at r≈22au, possibly carved by a Neptune-mass planet formed via planetesimals ?

Part 3

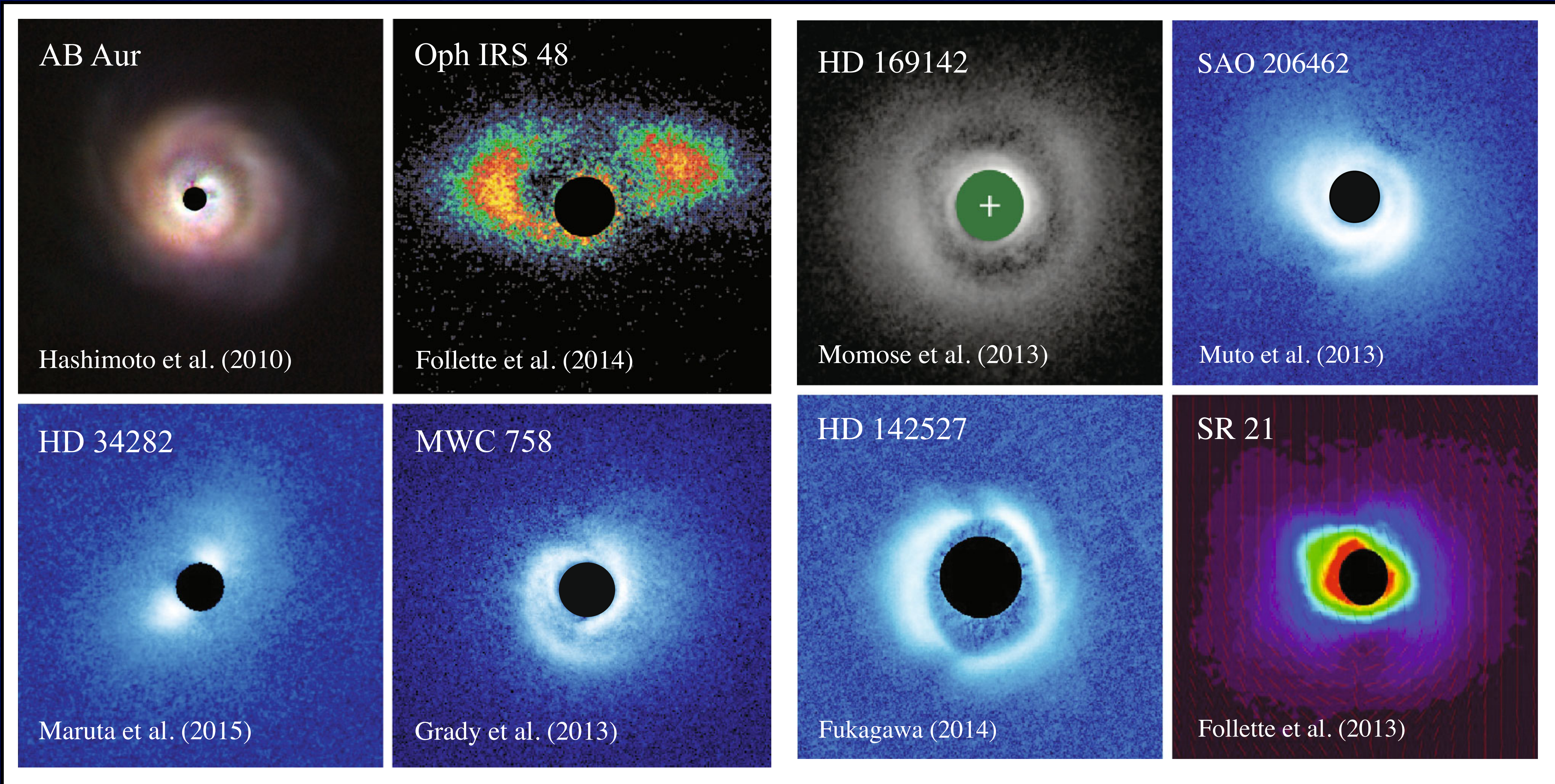
Transitional Disks & HD 142527

Transitional Disks

(Williams & Cuzzi 2011)



Transitional Disks by SEEDS



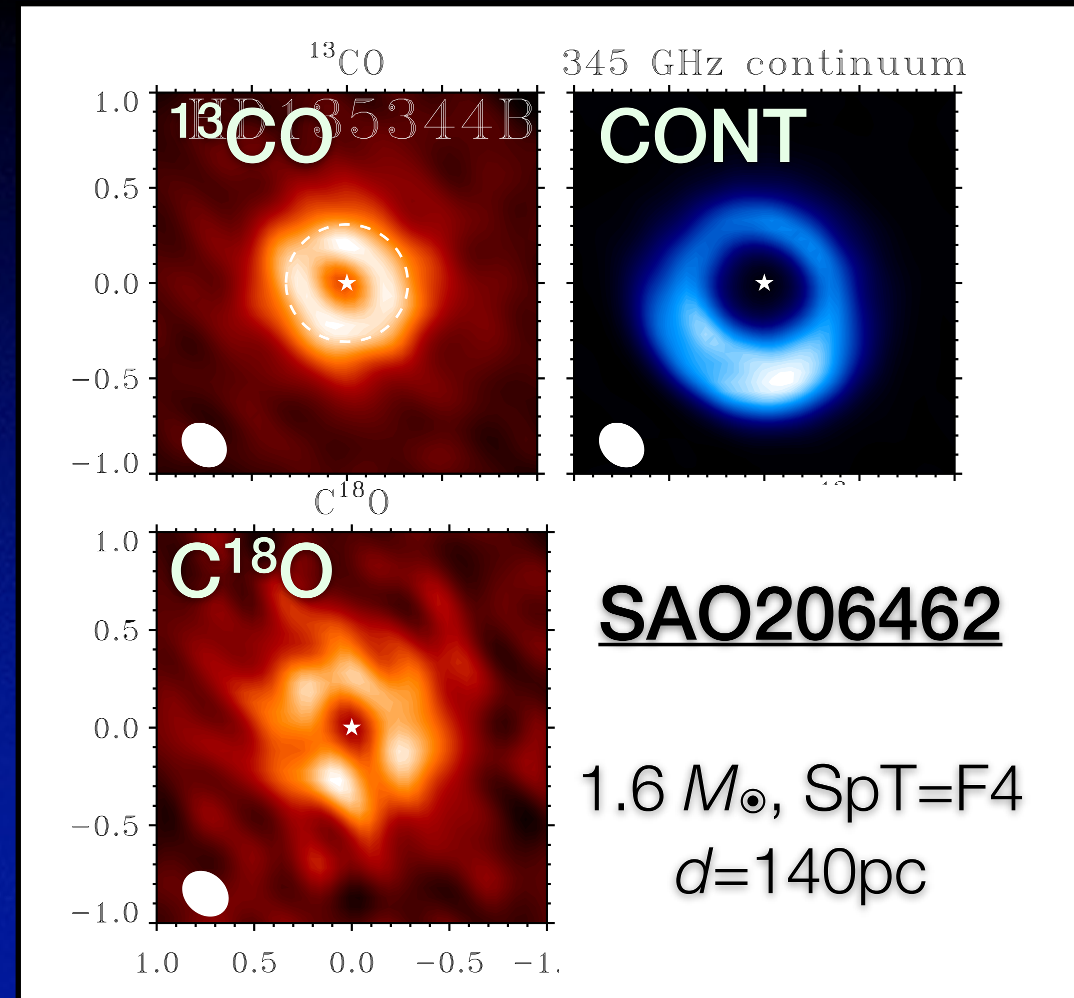
spirals, ring-gap structure

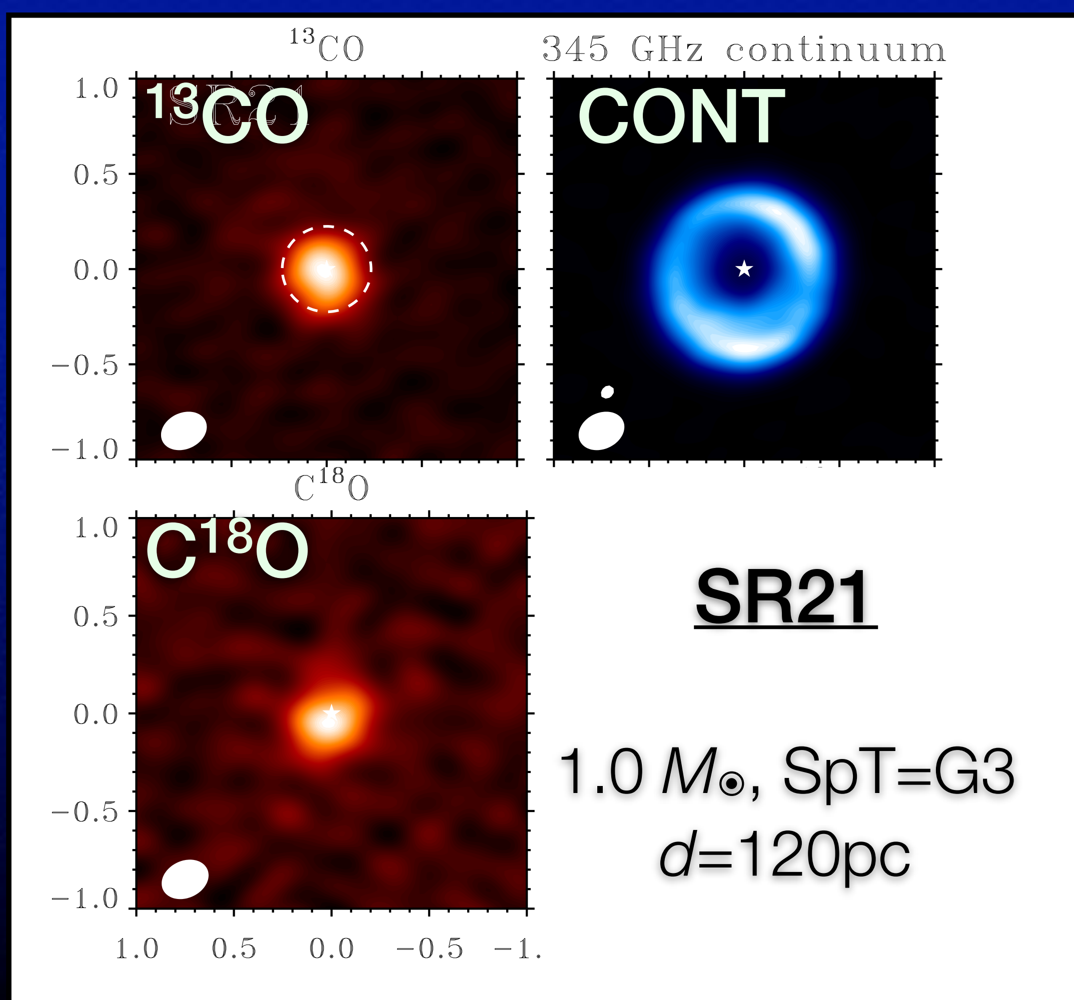
Grady+ (2015)

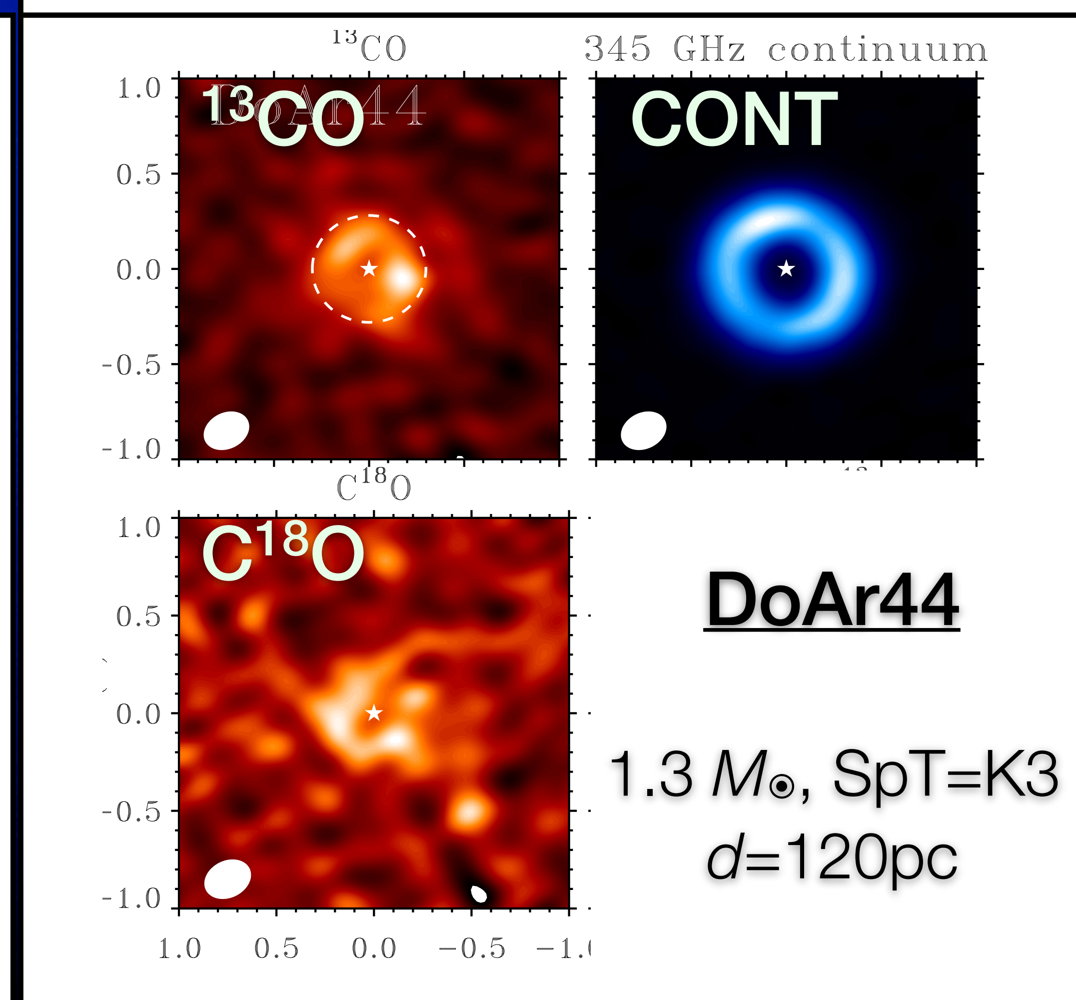
Mini-survey of 4 transitional disks

(van der Marel+ 2015)

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







Mini-survey of 4 transitional disks

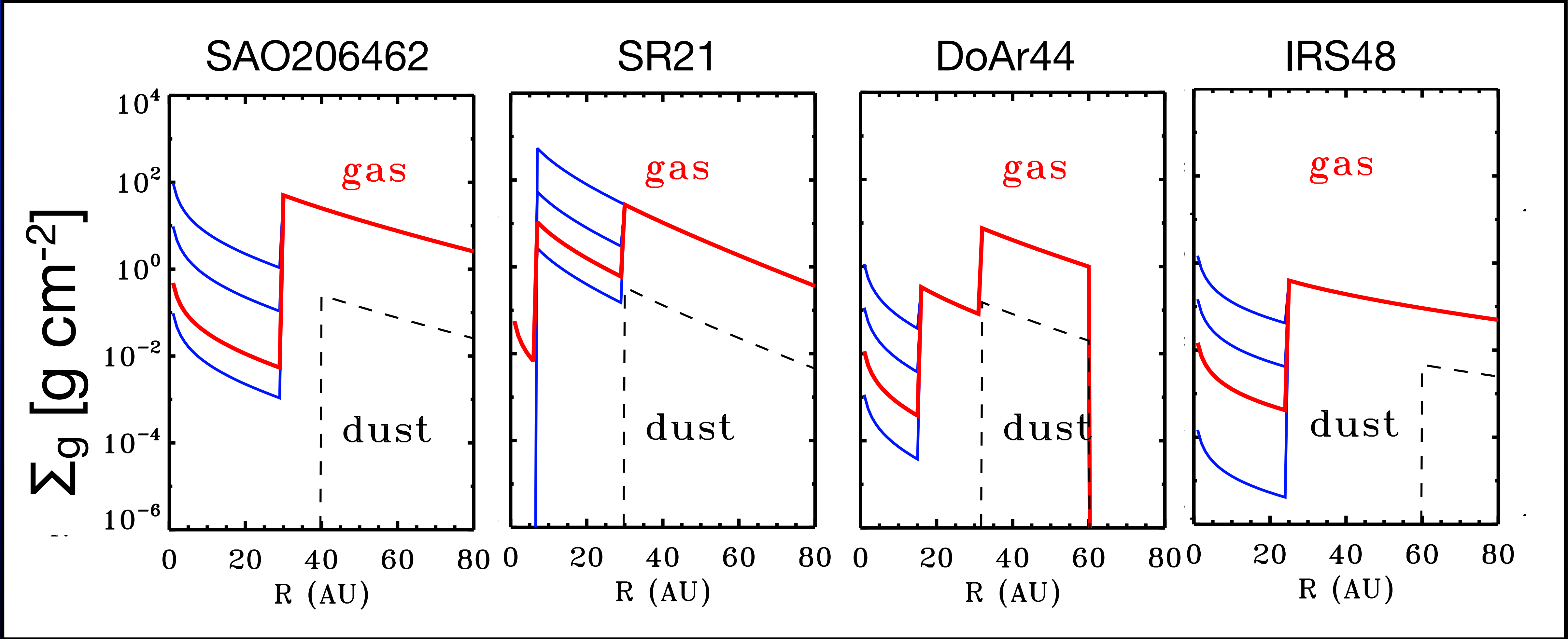
(van der Marel+ 2015)

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

overall g/d

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

c.f. HD1425257: ~30



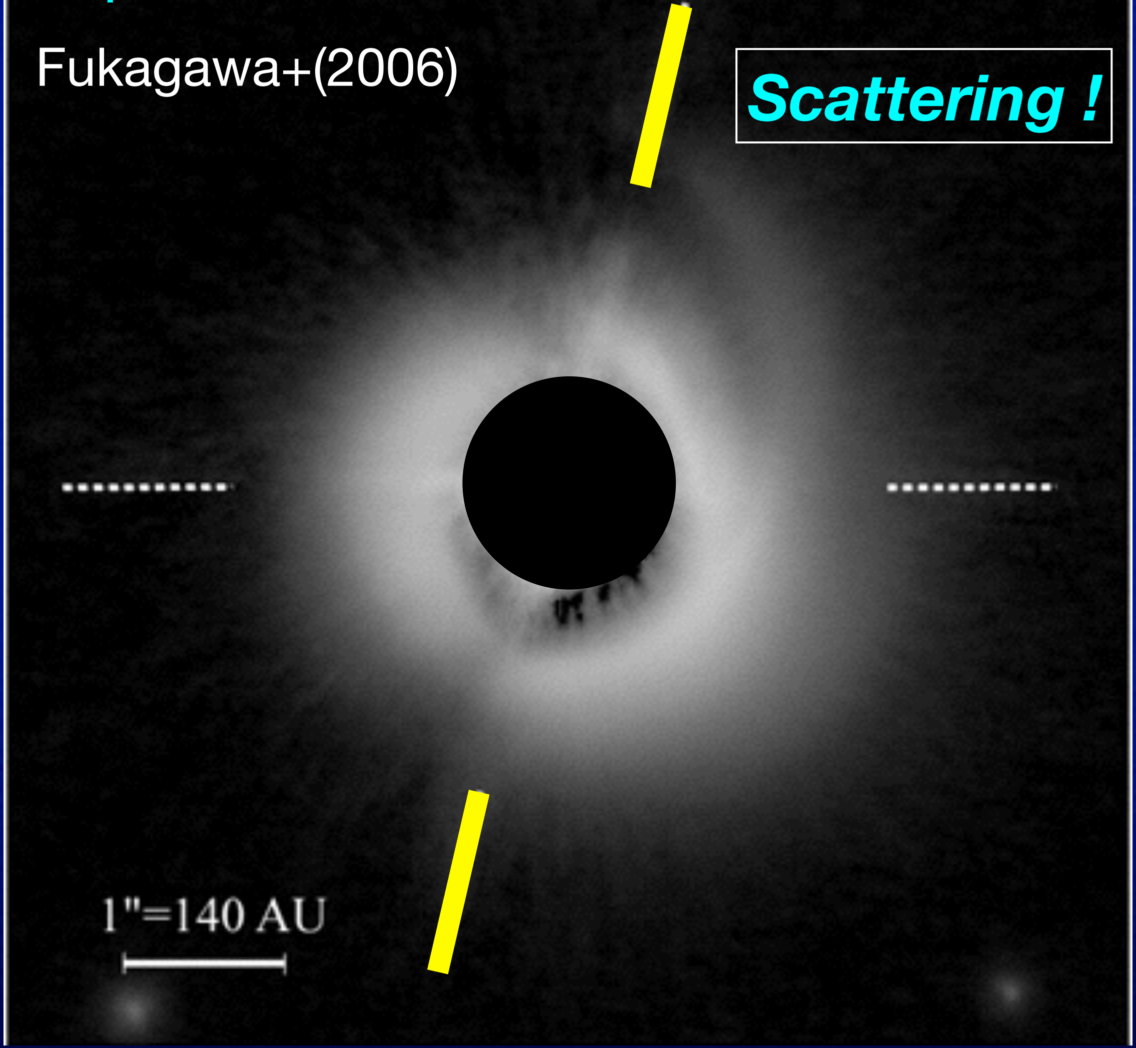
A transitional disk around HD 142527

- Herbig Fe star

  (d=140pc, $M_\star = 2.2M_\odot$)

1.6µm with Subaru/CIAO

Fukagawa+(2006)

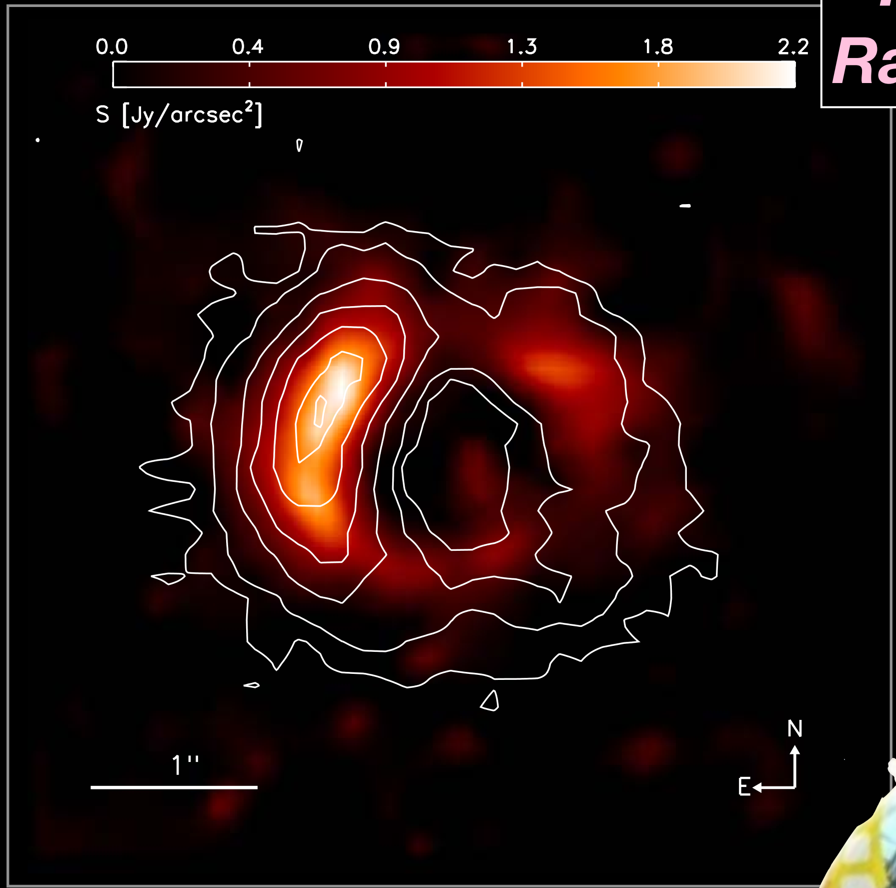


Major Axis: PA=341°

incl. = 27°, NE(Far) - SW(Near)

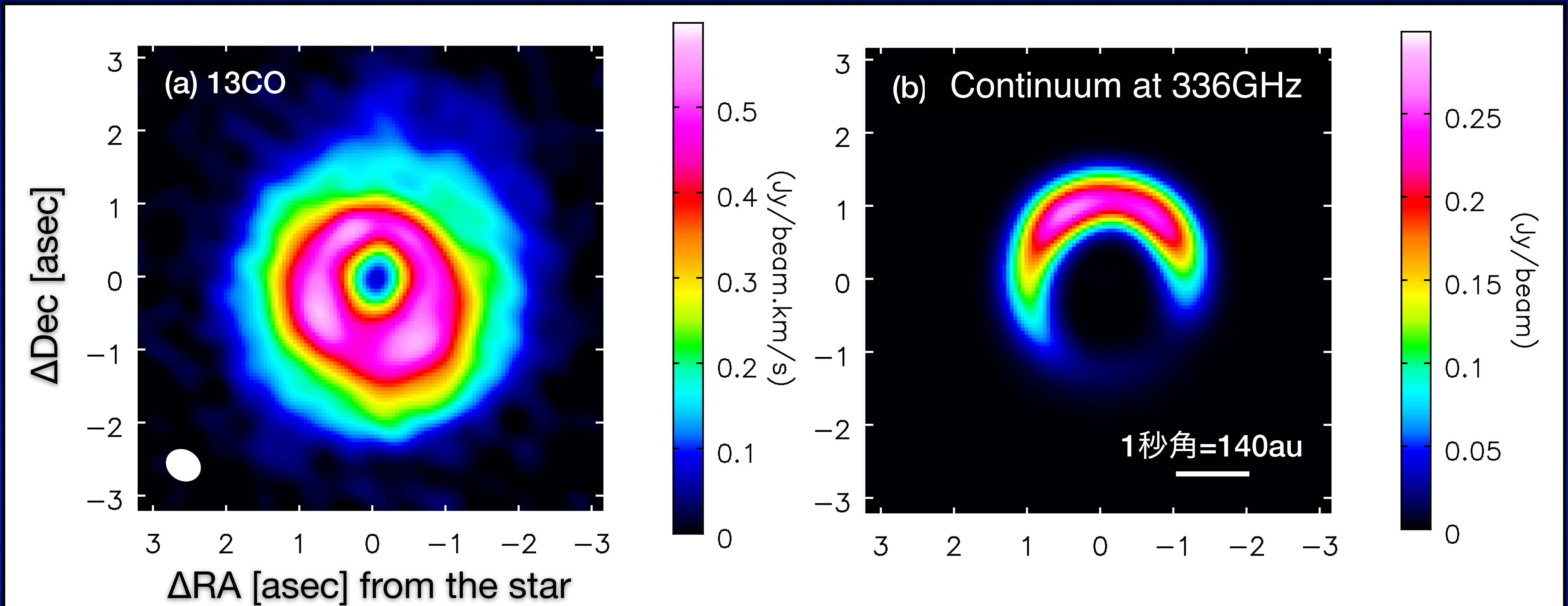
18.72µm with VISIR/VLT (color) and 24.5µm with Subaru/CIAO (contour)

Fujiwara+(2006); Verhoeff+(2011)



HD142527 with ALMA : Dust vs. Gas

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



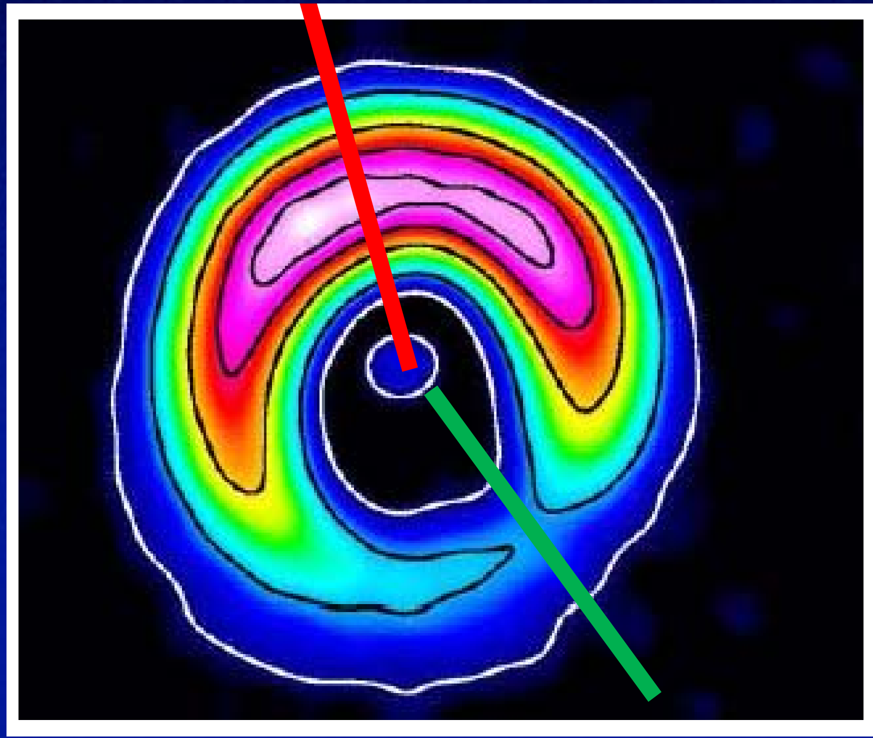
Gas: rather circular, smooth distribution in r=100-250au

Dust: very asymmetric, gaussian-like peaked at r=160au

Outline of Modeling

Muto et al. (2015); Kanno, Harada & Hanawa (2013)

- 2D Disk model
  - Σ_{dust}: Gaussian-like
  - Σ_{gas} : power-law with boundaries + inner/outer floors
- Dust opacity
  - spherical
  - $dn(a)/da \propto a^{-3.5}$ & a_{max} = 1mm



($\beta \approx 1$, κ_{abs} Max, Σ_{dust} Min … ?)

$\Sigma_{dust}(r)$ & hydrostatic equilibrium → $\rho_{dust}(r,\theta)$

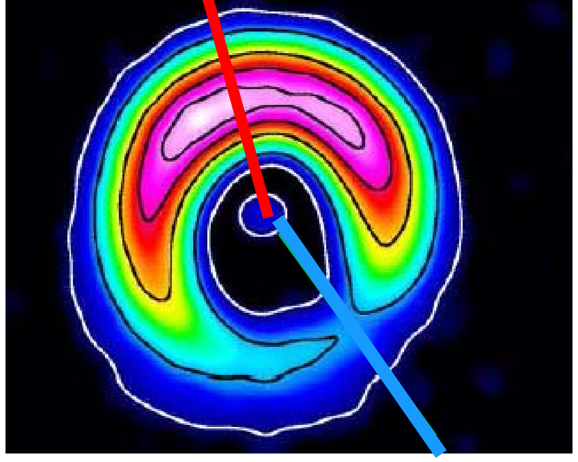
$T(r,\theta)$ by RT calculation (M1-method); $\rho_{dust}(r,\theta)$ is fixed so that $I_{dust}(r)$ is reproduced.

$\Sigma_{gas}(r)$ is searched so that radial profiles of $^{13}CO/C^{18}O$ (3-2) are reproduced.

other assumptions

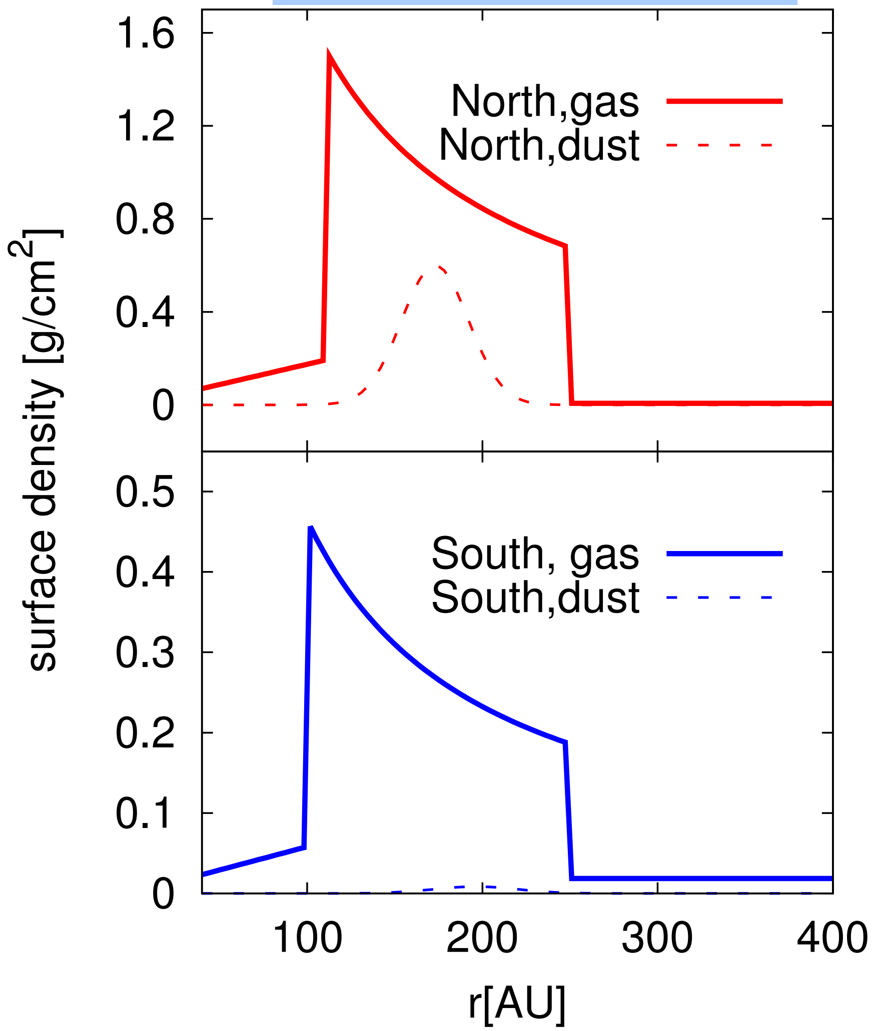
LTE, δV = Thermal velocity

Surface density distribution and g/d variation

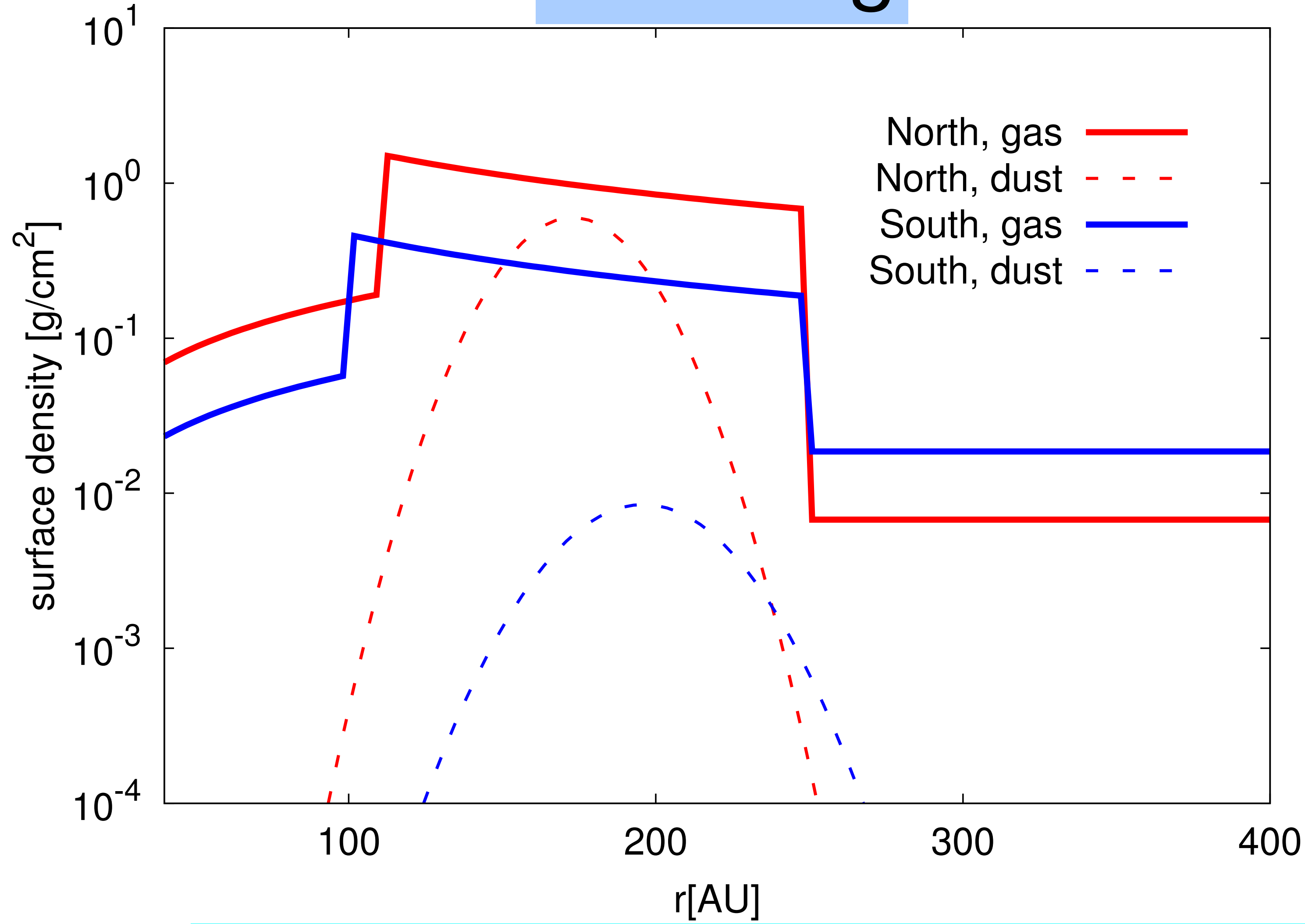


Red: North
Blue: South

linear-linear



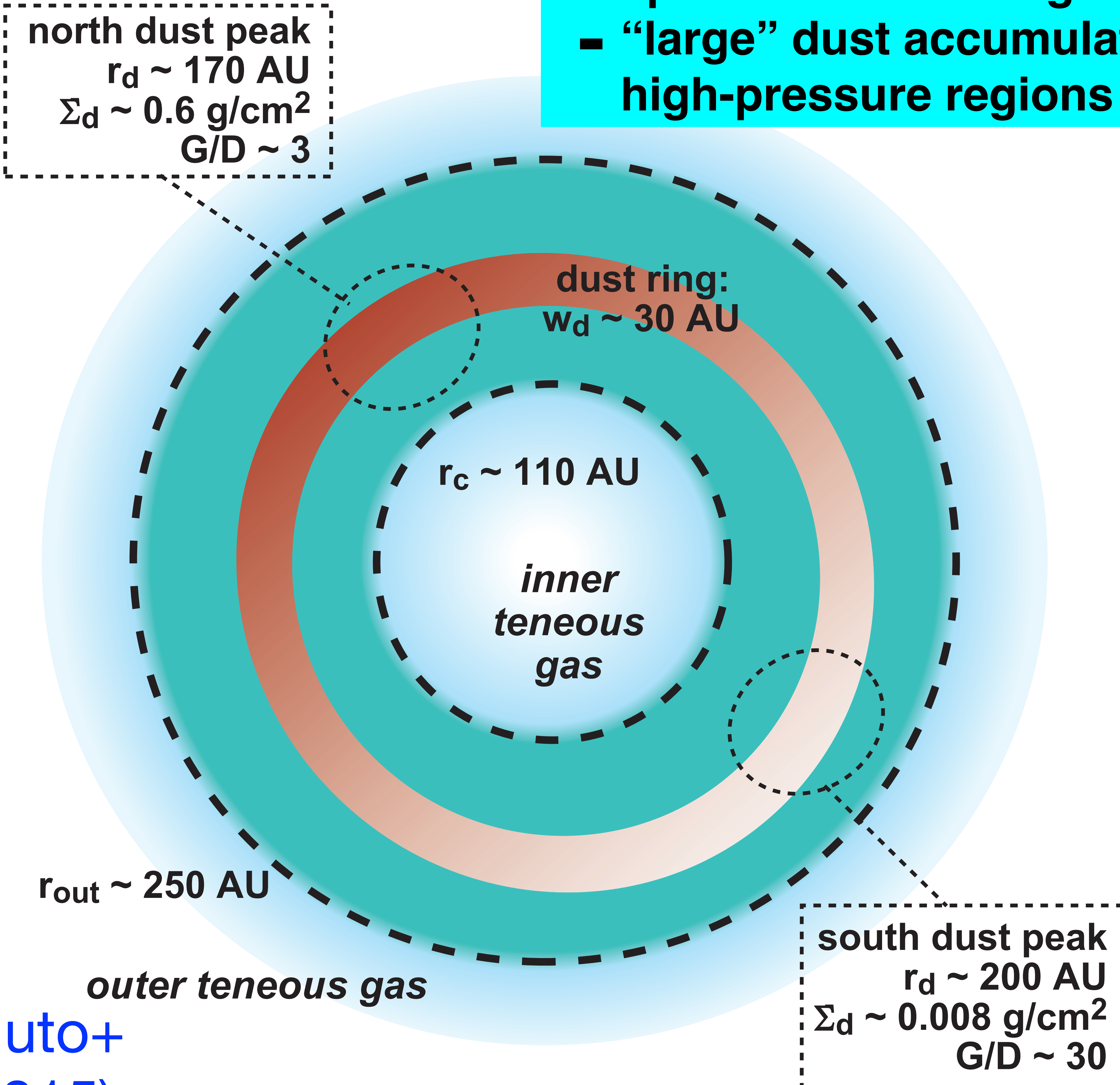
linear-log



Muto+ (2015)

- **spatial variation of g/d**
- **dust (mm-size) accumulation in high-pressure regions**

- **spatial variation of g/d**
- **“large” dust accumulation in high-pressure regions**



Muto+ (2015)

More recent works on dust properties in HD 142527

(1) Dust modeling for all position angles (Soon et al.)

(2) Polarization, due to self-scattering (Kataoka et al.)

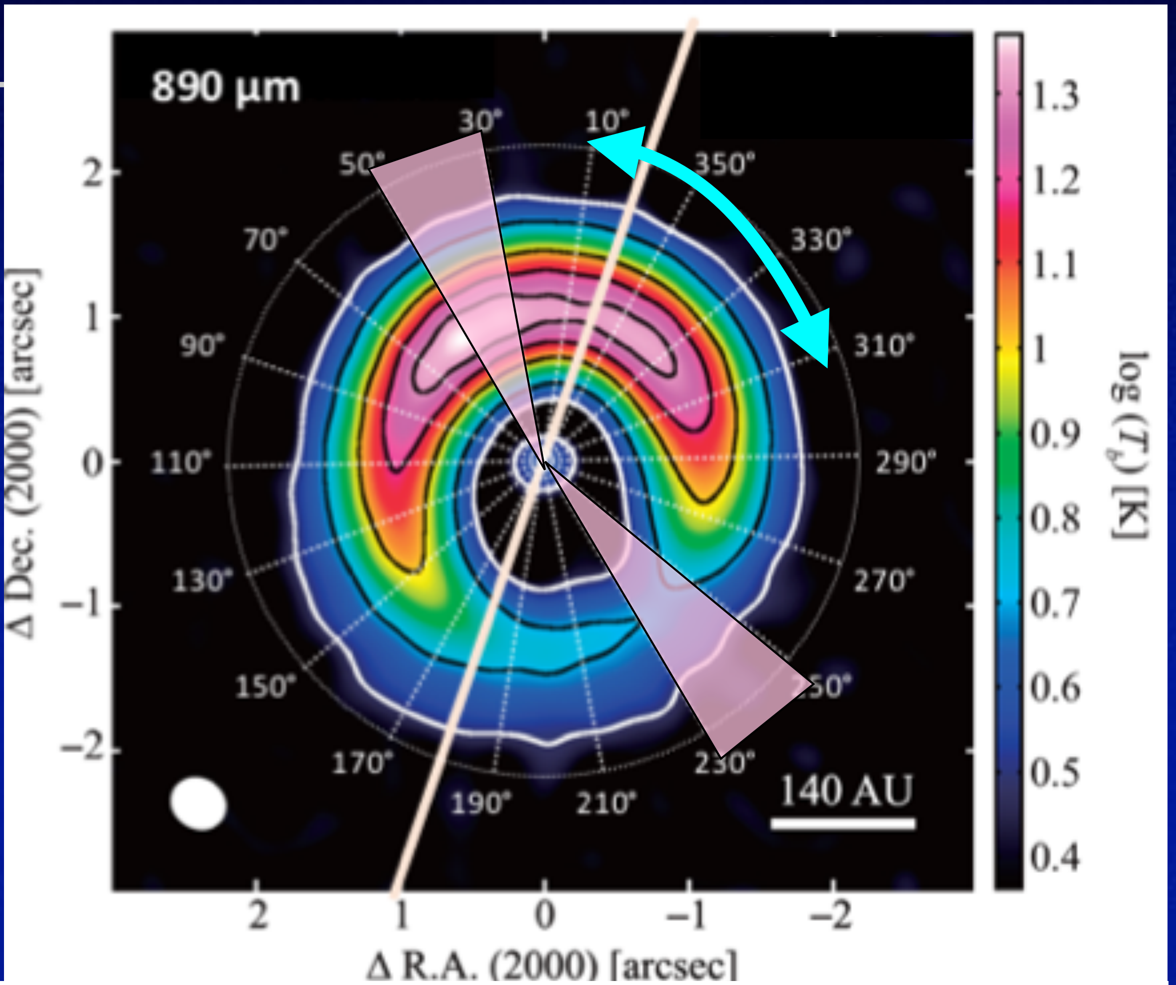
Dust models for all directions

Soon et al. (submitted to PASJ)

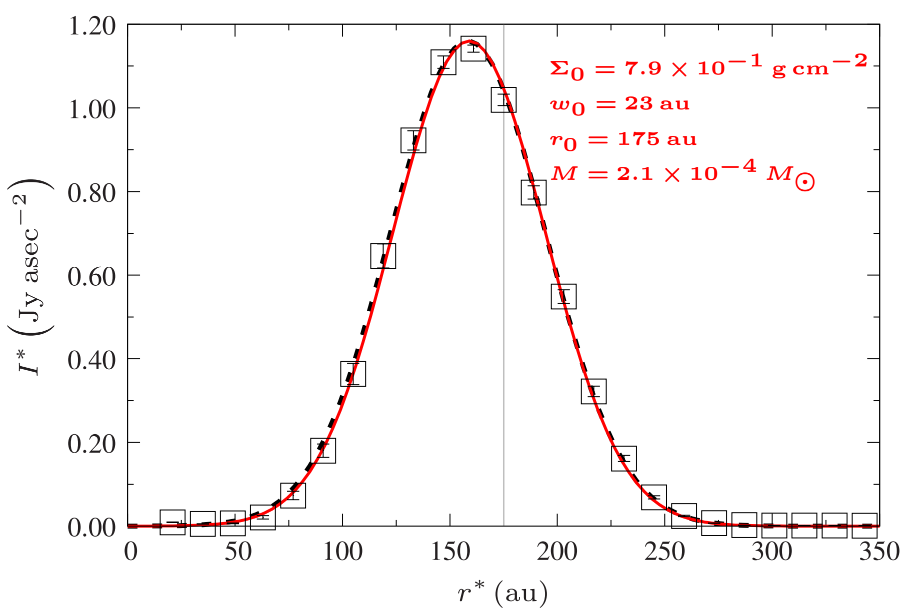
difficult to fit by dust with a high albedo

- Disk is divided into sectors with $\Delta PA = 20°$
- Same method as Muto+ (2015)
- Dust: a_{max} = 1mm is assumed

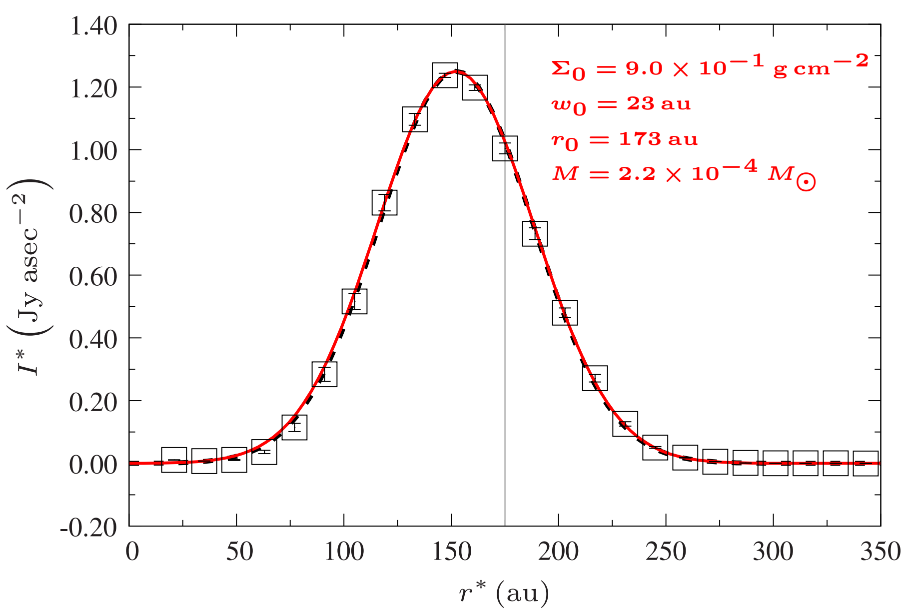
$$\Sigma(r) = \Sigma_0 \exp\left[\left(-\frac{r-r_0}{w_0}\right)^2\right]$$



PA'=10-30°



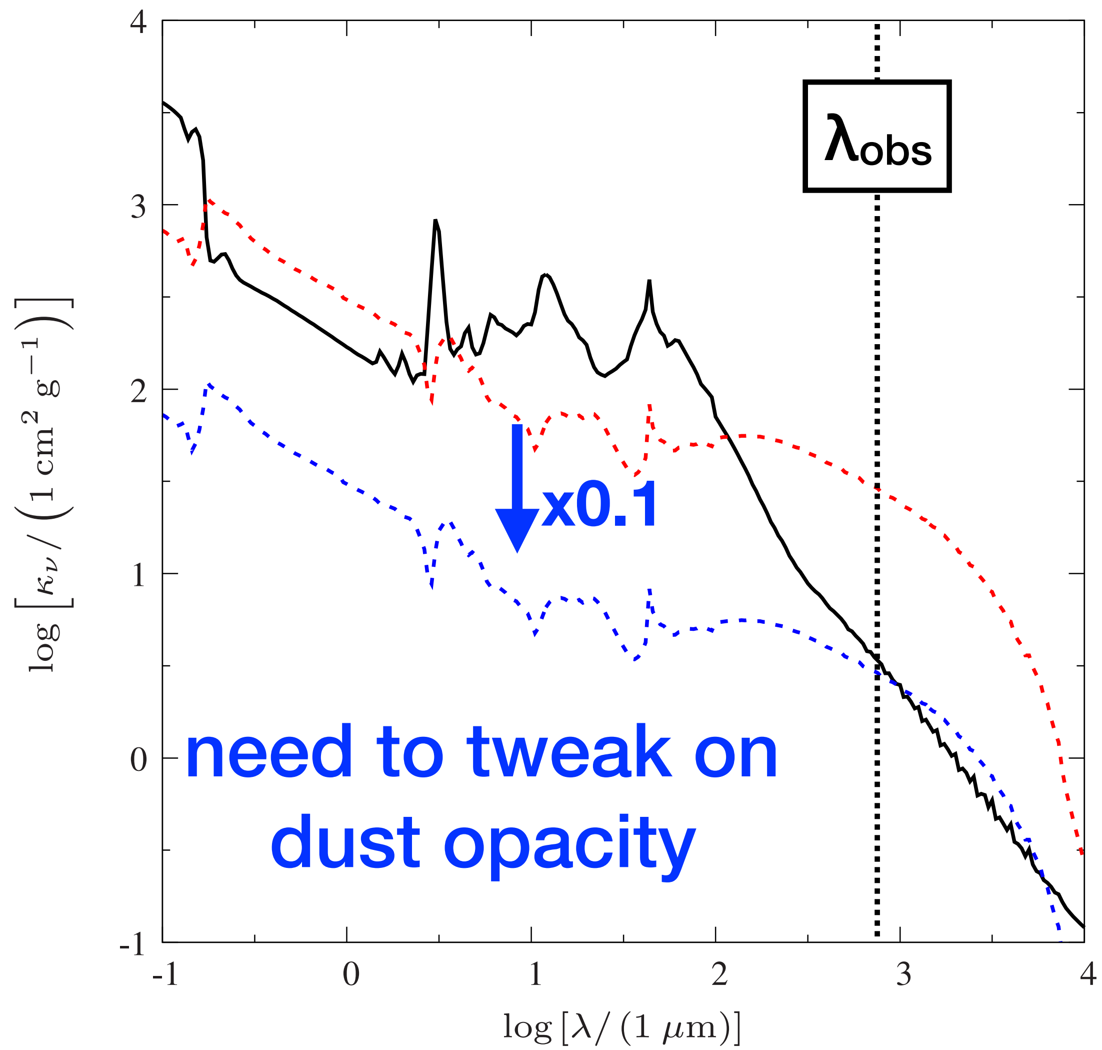
PA'=30-50°



……

……

Observed intensity cannot be reproduced unless $\kappa_{abs} \gtrsim \kappa_{scat}$



black: κ_{abs}
red: κ_{scat} (when a_{max}=1mm & $dn(a) \propto a^{-3.5}da$)
blue: $0.1\kappa_{scat}$

NW side: inner wall is hidden by outer parts

Effective optical depth ~ 1

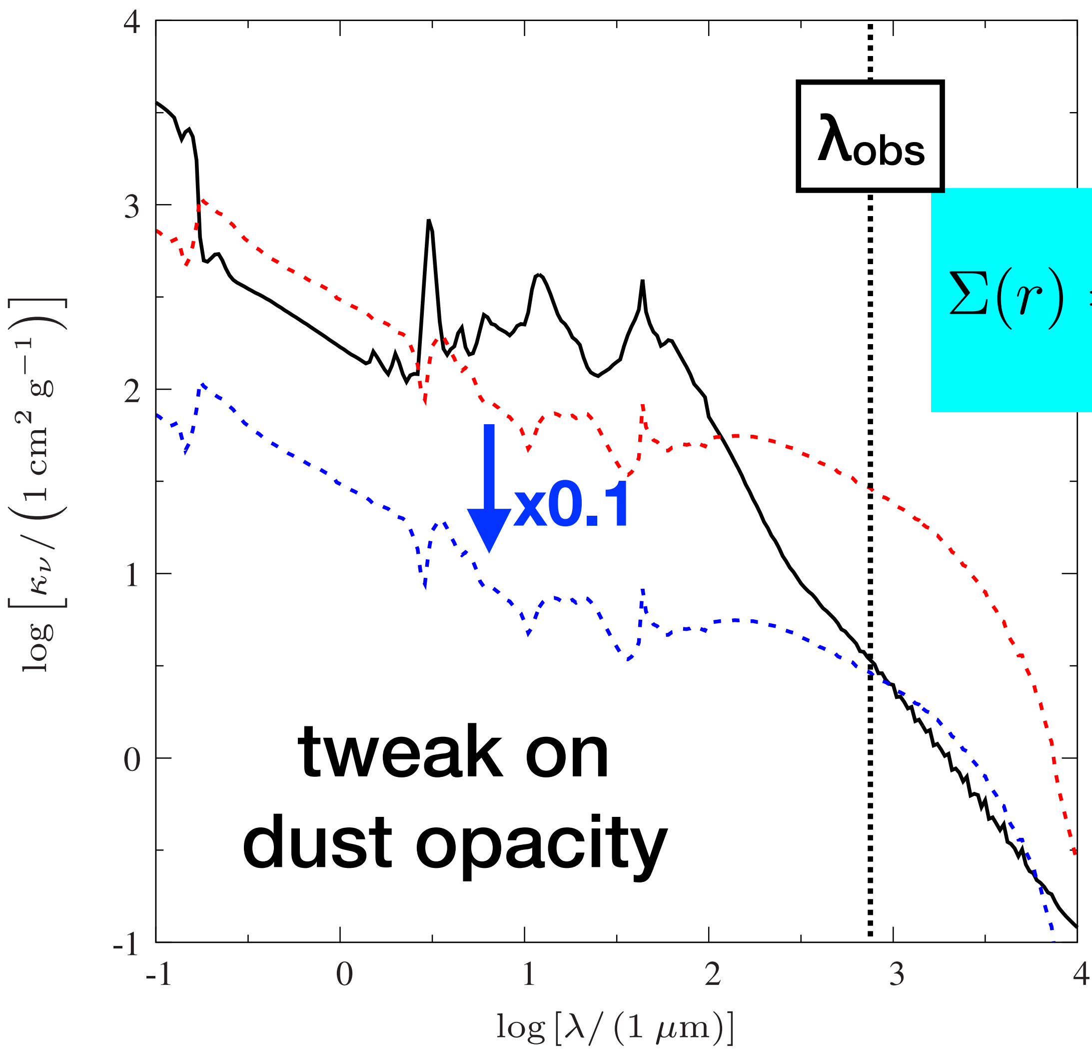
$$\tau_{\nu,\mathrm{eff}} \approx \frac{\Sigma_0 \sqrt{\kappa_{\nu,\mathrm{a}}(\kappa_{\nu,\mathrm{a}} + \kappa_{\nu,\mathrm{s}})}}{\cos i}$$

When scattering gets dominant,

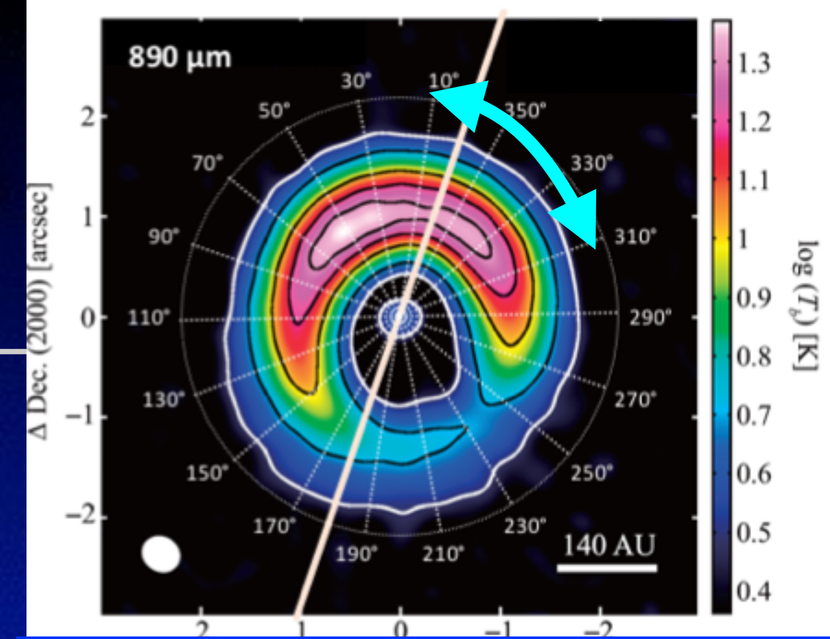
- optical surface (last scattering surface) gets located closer to us .
- regions from which observable photons escape gets smaller

Dust models for all directions

Soon et al. (submitted to PASJ)

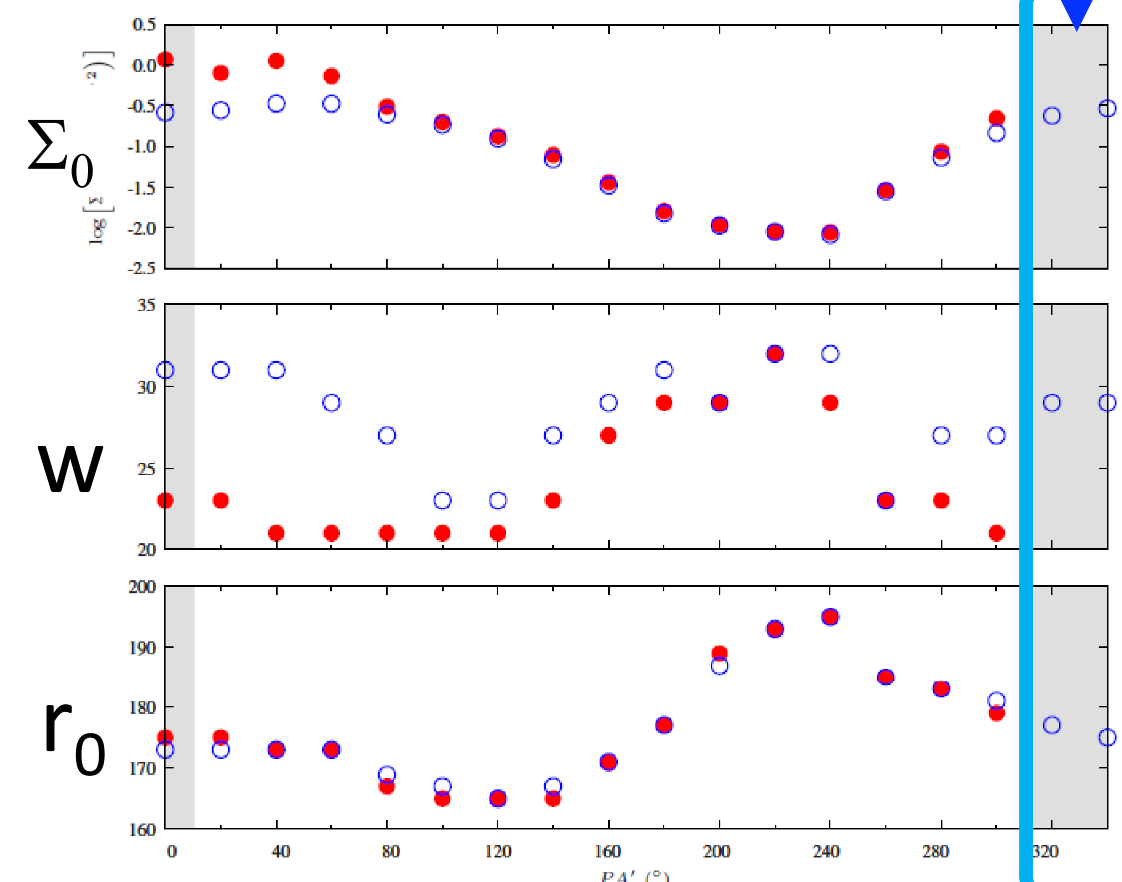


black: κ_{abs}
red: κ_{scat} (when a_{max}=1mm & $dn(a) \propto a^{-3.5}da$)
blue: $0.1\kappa_{scat}$



$$\Sigma(r) = \Sigma_0 \exp\left[\left(-\frac{r-r_0}{w_0}\right)^2\right]$$

a solution exists
in the case of reduced κ_{scat}



Major axis | Minor axis | Major axis

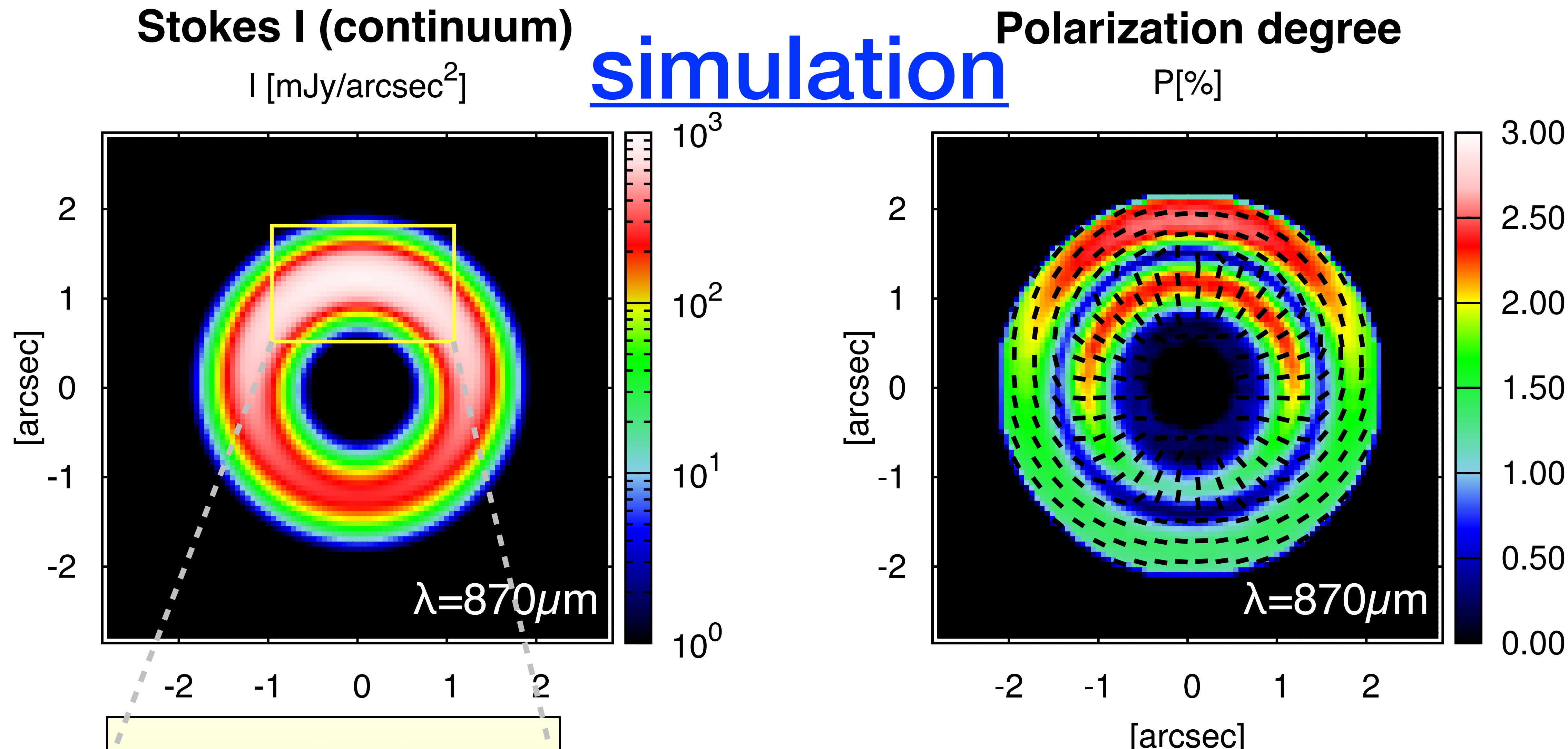
More recent works on dust properties in HD 142527

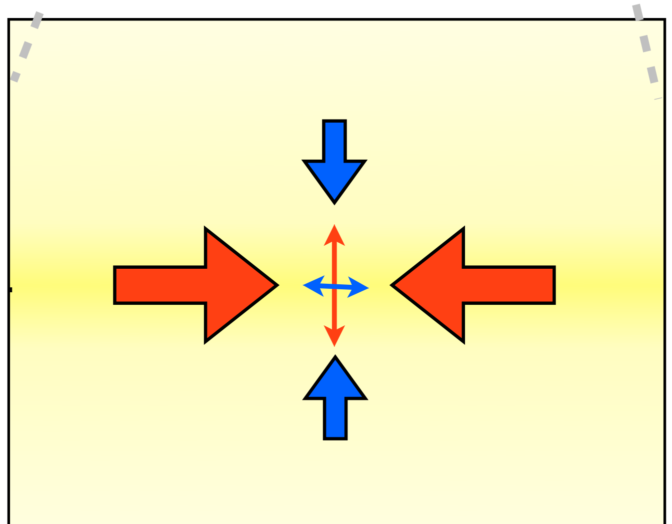
(1) Dust modeling for all position angles (Soon et al.)

(2) Polarization, due to self-scattering (Kataoka et al.)

Constraint on dust size by polarization ?

Kataoka, Muto, MM et al. (2015)





Anisotropy → net polarization

dust size ~ λ/2π: significant κ_{scat}

The polarization is also expected from rings

Condition for polarization due to scattering

Kataoka, Muto, MM et al. (2015)

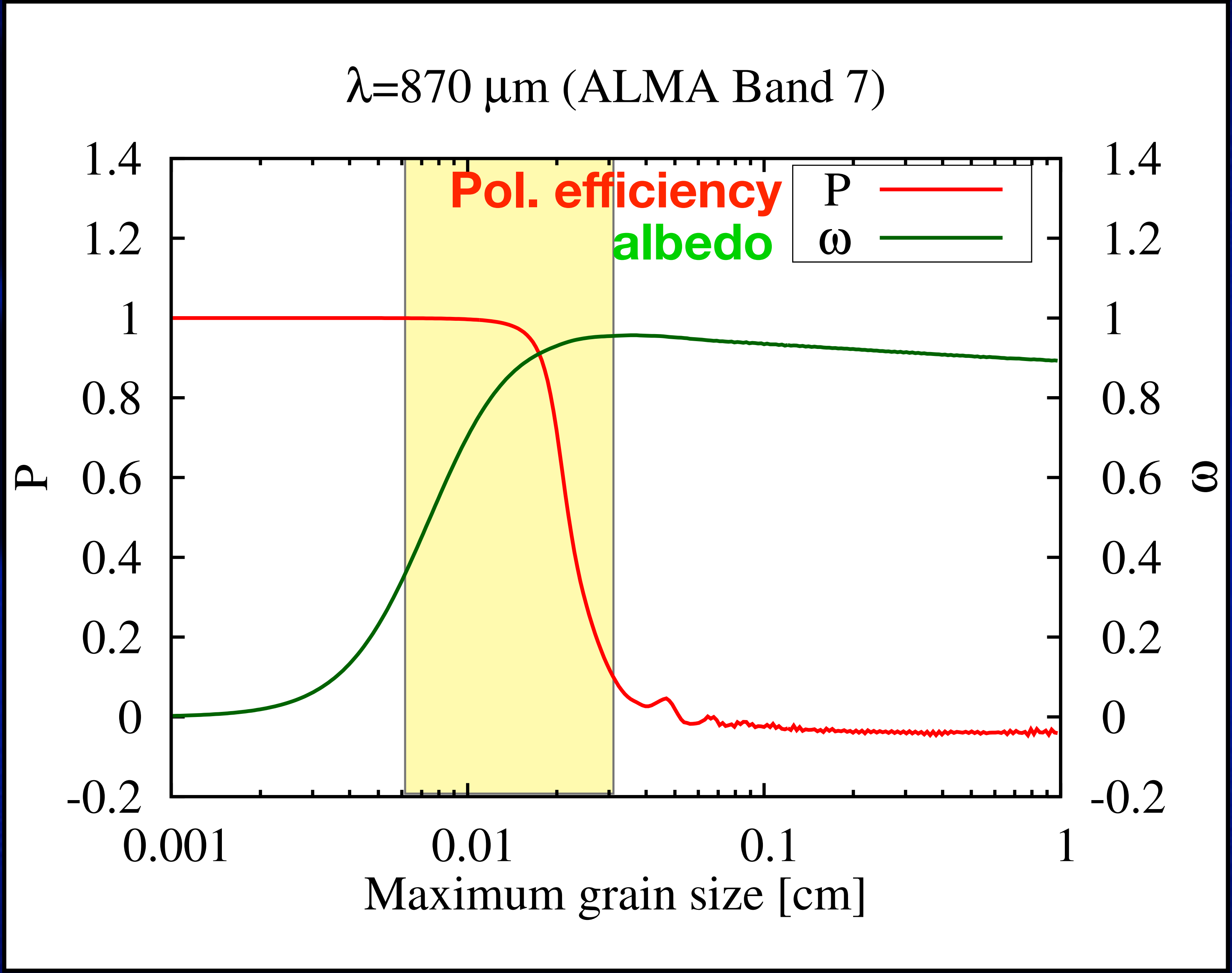
- For efficient scattering

  (grain size) ≳ $\lambda/2\pi$

- For efficient polarization

  (grain size) ≲ $\lambda/2\pi$

There is a grain size which contributes most to the polarized emission



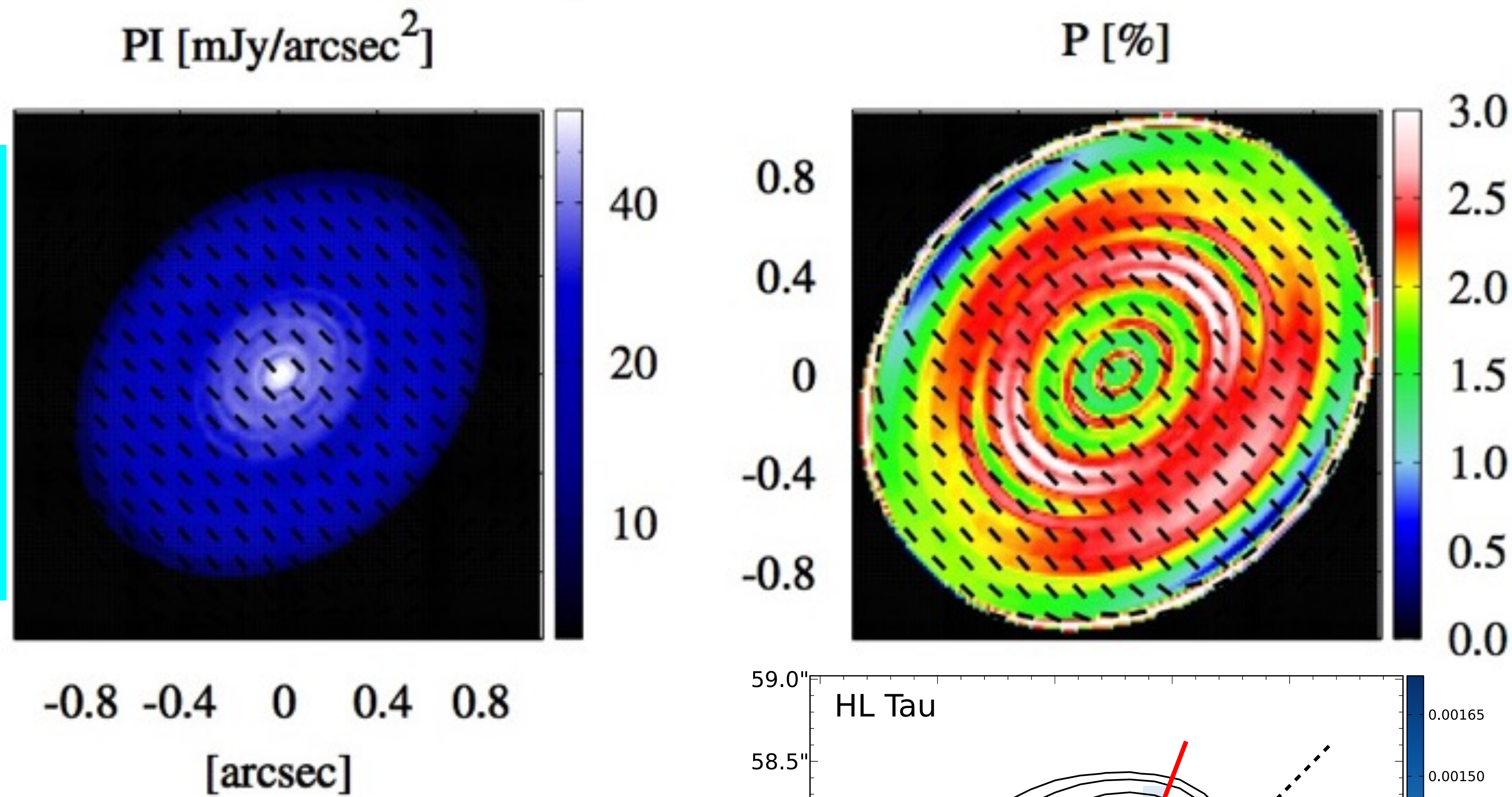
If (grain size) ~ $\lambda/2\pi$, the polarized emission due to dust scattering is strongest

CARMA Obs. of HL Tau: polarization by scattering ?

Kataoka, Muto, MM et al. (2016)

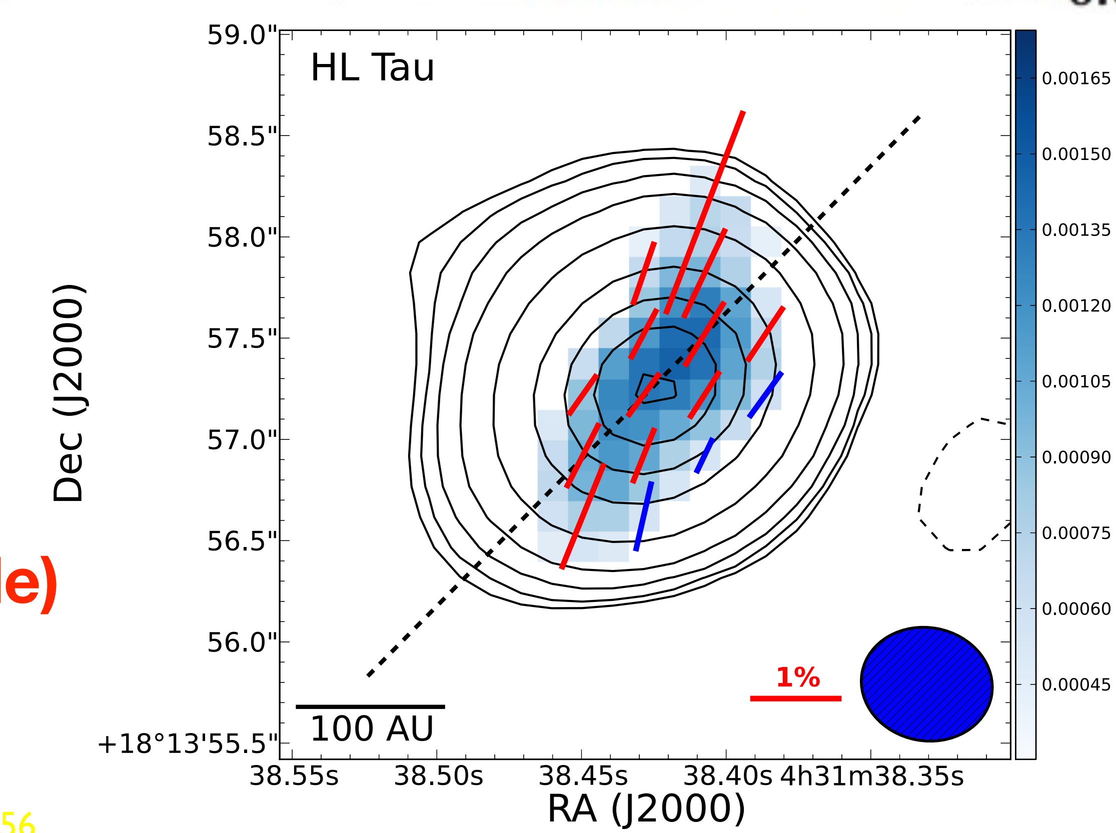
RT Calculation in a_{max}=150μm,

taking account of multiple rings revealed by ALMA



CARMA Pol. Image at λ=1.25mm

"B-field" direction
(perpendicular to pol. angle)
by Stephans+ (2014)

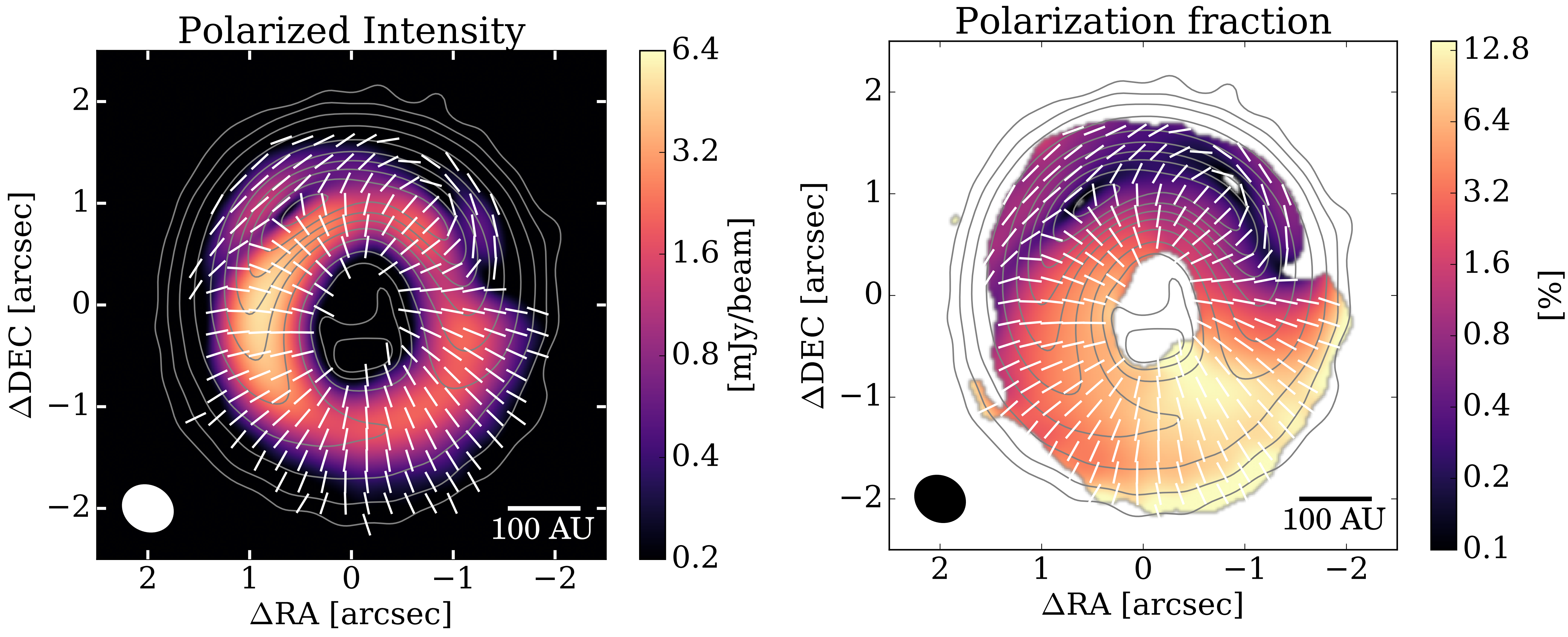


Dust Polarization at λ=0.9mm with ALMA

Kataoka, Tsukagoshi, MM et al. (2016)

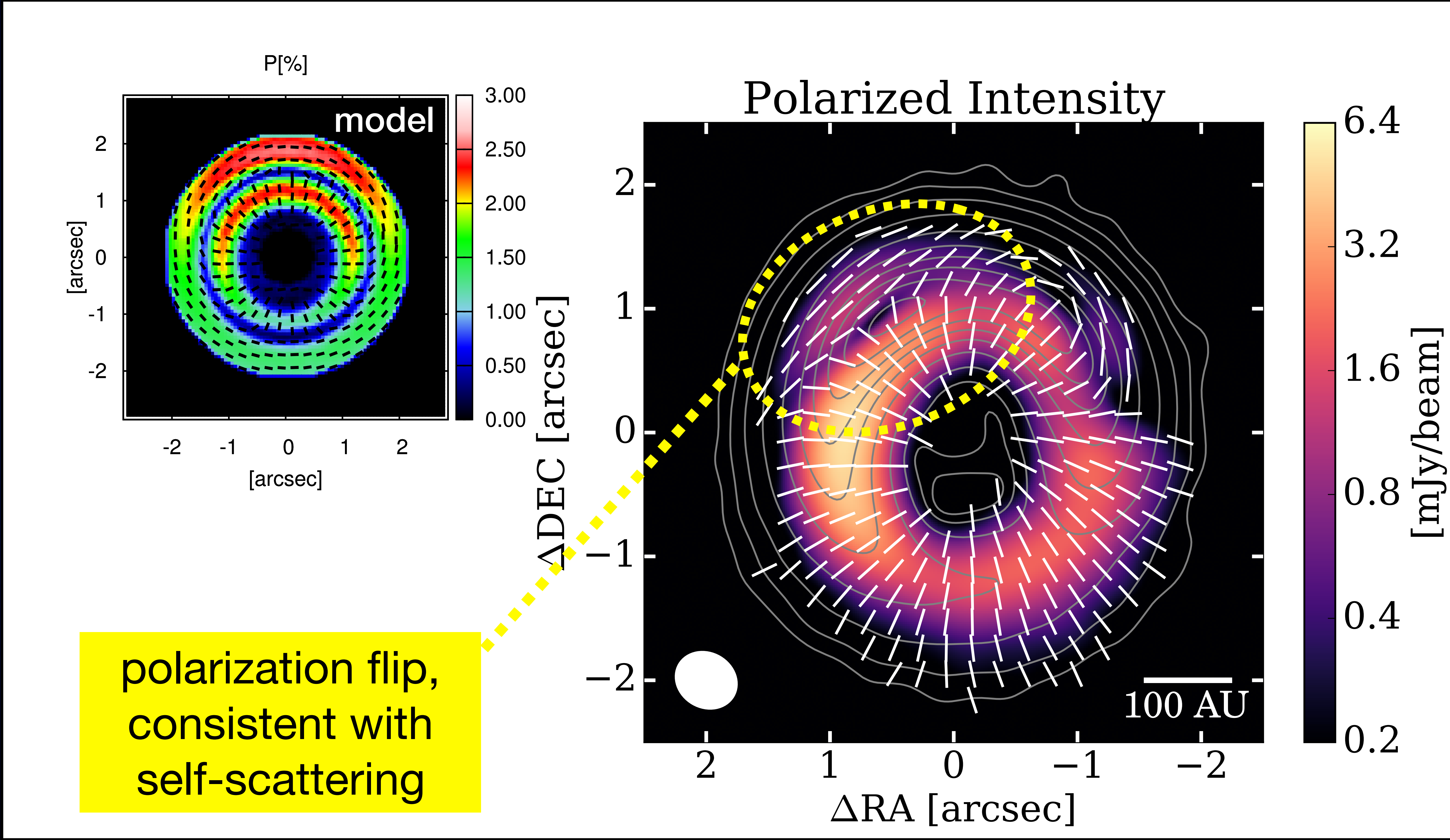
NEW !

ALMA Observations !



Dust Polarization at λ=0.9mm with ALMA

Kataoka, Tsukagoshi, MM et al. (2016)



Transitional disks

- a central hole; deficient in large dust grains but not in gas & smaller grains
- planetary origin ?

Our studies on HD 142527

- significant spatial variation of g/d, with dust-accumulated regions (planetesimal forming zone?)
- optical properties of dust particles;

(1) modeling -> dust growth (small β) but low albedo

(2) polarization due to self-scattering ? -> dust size