#### **Kiyoaki Doi1,2, Akimasa Kataoka2**  10 Doi and Kataoka From equation (10), the intensity along the major axis is independent of the dust scale height. Therefore, we z Akimaca Kataok herty et al. 2015, 2015, 2015, 2015, 2015, 2015, 2015, 2015, 2015, 2015, 2015, 2015, 2015, 2015, 2015, 2015, 20

**1. Graduate University for Advanced Studies (SOKENDAI) , 2. National Astronomical Observatory of Japan** toplanetary disk because the low ionization ratio in the other hand, from equation  $\mathbb{R}^d$  and  $\mathbb{R}^d$  and  $\mathbb{R}^d$ based on the dustrian terms in the dust scale  $\boldsymbol{b}$ OKENDAI), 2. National Astronomical Observatory of Japan **part of the part of t** JNLIYDAIJ , 4. IYAUVIIAI ASI (12), the intensity along the ridge except for the major  $\mathbf{C}^{\text{L}}$  for the major  $\mathbf{C}^{\text{L}}$ et al. 2016) to improve sensitivity and *uv*-coverage on iomical Obscrvatory of Ja dai kiyaaki setra@amail assume that the distribution that the distribution of the distribution  $\mathbf{S}$  per  $\mathbf{S}$  parameter is  $\mathbf{S}$ 

 $W_{\rm eff}$  discuss the conditions for constraining the dust of constraining the dust of constraining the dust of  $\alpha$ 

# **5.1 α/St**

· The relation of the dust scale height and α/St Figure 6. Azimuthal variation of the intensity along the intensity along the intensity along the intensity along the intensity and intensity along the intensity of the intensity of the internal contribution of the internal Figure 7. Reduced <sup>2</sup> of the intensity between observa- $\sinh t$  and  $\sinh t$ the grid distribution is consistent with the constant with t  $\frac{1}{2}$  and  $\frac{1}{5}$ ↵  $m$  of the dust scale bejoht and  $n/\mathbb{C}$ t when the duct sould

#### rection and cannot be explained by a simple disk model line of sight **on the only and Target** 4.1 Rough estimation aagn communicum major axis. On the other hand, from equation (11) and gn estimation is from our study. The dust scale height of the inner disk method as discussed as discussed in Section 2.3. The taken with Alma Band Gound

4.2. ↵*/St*

ring formation by dust traps at gas bumps and derived

the following relationship between dust ring width *w<sup>d</sup>*

*w<sup>d</sup>* =

4.3. *dust size*

In this section, we constrain the dust size based on the

↵*/St*. In the above section, we obtained ↵*/St* based on

where  $\mathcal{D}_{\text{max}}$  is the dust material density, and

*f*set. The Stokes number is expressed as

radius, and ⌃gas is the gas surface density. Therefore,

we can constrain the dust size from ↵*/St* obtained in the

above section and ↵, ⌃gas, and ⇢mat. We assume that

by Rab et al. (2020) based on the molecular emission

- **The intensity along the major axis does not depend on the dust scale height.** data used in this work. In section 3.2, we describe the on the dust and the radiust  $t \sim 3.3$  , we consider the azimuthal dependence of t intensity along the ridge as the first comparison method. In section 3.4, we compare the radial profile of the indust scale height 5 million of the scale h
- The intensity along the ring (except on the major axis) depends on the dust scale height.  $\sim$  component 3.1. *Observations* encity along the ring (even is independent of the dust sensors we have a large than the dustrial medicing the main of the sensors of the s  $ch$  computed  $\alpha$  and  $ch$   $\alpha$ herty et al. 2015) au pointes Uni
- **We can constrain the dust scale height from the azimuthal**  variation of the intensity.  $\blacksquare$ Imuthal use the  $\blacksquare$  4.2 the HD 163296 disk taken in the DSHARP campaign in the DSHARP campaign in the DSHARP campaign in the DSHARP ca  $\mathbb{R}^2$  (2016.1.00484.1.00 grams (Andrews et al. 2018). We select this target bedust scale height from the observed intensity along the can constrain the qust scale auvn or alo mitolijk, shorter baselines. The details of this image are shown ignt from the azimuthal

## 2. Data We discuss the conditions for constraining the constraining the dust of constraining the dust of

 : **fset**= the gas scale height/the dust scale height We run multiple simulation changing only f<sub>set</sub> and compare with the observation.

#### **1. Principle** found a trend that the dust size decreases toward the outer region based on the spectrum at millimeter wavelength of the disk. Dullemond et al. (2018) constrained

Flaherty et al. (2015, 2017) put an upper limit of the

gas turbulence that  $\overline{\phantom{a}}$  3  $\overline{\phant$ 

# **Estimate on dust scale height from ALMA continuum image of the HD 163296 protoplanetary disk** ing the method to the method to the image of  $\mathcal{L}_{\mathcal{A}}$  is strong to the image of HD 163296. In Section

from observed radio continuum image. In this section,

⇢(*r, z*) = ⌃<sup>0</sup>

exp ✓

(*<sup>r</sup> <sup>r</sup>*0)<sup>2</sup>

*<sup>z</sup>*<sup>2</sup>

◆



### **& constrain this parameter!**

## **1.3 Summary**





**The growth of dust in protoplanetary disks** ally models with the ratio of planget formation. Thoroforo and the the innex ter of gas turbulence and supply the sungainty revealing the distribution and physical state of the dust in protoplanetary disks is a key to **density reveal the planet formation process.** sity (Epstein 1924; Adachi et al. 1976; Nakagawa et al. is the first step of planet formation. Therefore,

**1986: We constrain the dust scale height of 7 Katadraw Katadraw Ratadraw Rata HD 163296.** This object is known to have two distinct ring structures at distances of 68 and  $100$  ou from the control of HD 163296 from ALMA dust continuum observation. 2016), and in this study, we constrain the dust scale heights of these two rings. The  $\overline{\phantom{a}}$  required thought that h  $\overline{\phantom{a}}$  h  $\overline{\phantom{a}}$ 2018). The second contract evidence of a planet at 260 minutes at 260 mi **ring and**  $h_d/h_g < 0.44$  **in the outer ring, 140, where hg is the gas scale height and, hd is the** We consider the discussion of the disk hosting and axis when  $\mathcal{L}_1$ 100 au from the central star (Isella et al. results show that  $h_d/h_g$ > 0.55 in the inner

lanetary disks dust scale height. In other words, the dust is tion. Therefore, **flared in the inner ring, while it is settled in** In ysical state  $\qquad \qquad$  the outer ring. Wh sks is a key to buthe estimates of scale height at the dust gap at the peak positions in the major and major axes. In the major axes. In the major axes. In the major axes. In section 2.3, was died in polarization in the conditions that allow us that allow us that allow us that allow u<br>The conditions that allow us that allow us that allow us that allow us that allows the conditions of the condit 2.1. *Optical depth of an inclined disk*  $\frac{1}{2}$ **the outer ring**. When we take it together with based on polarization observations (Ohashi & Kataoka 2019), the picture of the dust scale height over the whole disk is represented as shown in Figure 2. 2 *<sup>z</sup>* tan<sup>2</sup> *i* is not too small compared to the other terms in the observed intensity. Then, we can constrain the WE LANE IL LUYELITET WILLT ricignit at the dust gap dusti validi is (Oriasiii a  $\mu$ luit $\sigma$  of the constraint scale is and is represented as

### We focus on the dust scale height at the dust ring to construct the physical state of protoplanet Pinte et al. (2016) estimate the dust scale height of HL **Abstract**

Tau from the emission division division division division division division division division division divisio<br>Tau from rings inside gaps inside gaps inside gaps in side gaps in side gaps in the emission division division

uter ring, We find  $\alpha$ /St > 0.48 for the inner ring and  $\alpha$ / ella et al. The dust scale height is modeled with the ight is modeled with the nstrain the stratio of the gas turbulence  $\alpha$  and the Stokes o rings. The comparing a comparing the comparison in the dust scale coordinate system as **r**  $\frac{1}{2}$  at the central star,  $\frac{1}{2}$  and  $\frac{1}{2}$  at the central star,  $\frac{1}{2}$  and  $\frac{1}{2}$ n the inner beight we constrain, we constrain the α/St. and, h<sub>d</sub> is the **St < 0.19** for the outer ring with 2σ error range. density of this object is expressed as  $\mathcal{O}(\mathcal{O})$  $\overline{\text{HUC}}$  and the divides ulations. In the dust search  $\sigma$  constraint the distribution. i the liller ring and di ting with zo enor range. comparison method.

#### zone. As shown in Figure 11, however, the dust scale height of HD 163296 varies complex like the radial distribution of HD 163296 varies complex like the radial di<br>Di-daou and the radial di-daou and the radial di-daou and the radial di-daou and the radial di-daou and the ra **4. Result** From equation (10), the intensity along the major axis is independent of the dust scale height. Therefore, we combining the data of project 2013.1.00366.S13 (Flaherty et al. 2015) and project 2015. et al. 2016) to improve sensitivity and *uv*-coverage on From equation (10), the intensity along the major axis is independent of the dust scale height. Therefore, we can construct a disk model that is independent of the  $\sim$  2016.1.00484.L), which is one of the ALMA large programs (Andrews et al. 2018). We select this target because the spatial resolution is high enough to apply our

with a dead zone. This suggests that the suggests that the suggests that the suggests that the suggests that the<br>This suggests that the suggests that the suggests that the suggests of the suggests of the suggests of the su iparison with the intensity along the peak observation and the simulation (f<sub>set</sub> =1, 2, 8) and gas ring width *wg*.  $\begin{array}{c} \overbrace{\phantom{a}\qquad \qquad}$   $\qquad \qquad$  The comparison with the intensity along the peak of the ring of the gampariaan with the inte **CONDANSON WILL LIIG ING** si valiuli aliu lii panoricon with the intens height of the ring. Therefore, we can constrain the dust stien ond the cinquiction alion and the  $\mathcal S$ glang the needs of the ring et al. 2019). We are the central star we are the central star mass and the central star mass  $-4$   $2$   $0$ et  $-$  I,  $\angle$ , O/ wavelengths of = 1*.*25 mm. This image was made by *T*(*r*) = 18*.*7 [K] اد /۱ *.* (13)

In 2σ error range r ring is  $f = 14107$ is consistent with our results about the scale height.  $•$  inner ring:  $f_{\text{set}} = 1.1^{+0.7}$ -0.1 • outer ring: f<sub>set</sub> < 2.4 cause the spatial resolution is high enough to apply our method as discussed in Section 2.3. This image was taken with  $\Delta E$  alma  $\Delta E$  and  $\Delta E$  and  $\Delta E$  and  $\Delta E$  and  $\Delta E$ wavelengths of  $\mathcal{L}_{\mathcal{A}}$  and the 1*.25 mm. This image was made by the 1.25 mm.* midplane, and ✓ = ⇡*/*2 is the north pole. error range with a large profile with is one of the ALMA large pro-<u>miler</u> er ring: f<sub>set</sub> < 2.4 400 [au] *.* (13)  $\mathbf{L}$  163296 disk taken in the DSHARP campaign in the DSH  $\overline{\phantom{a}}$  . We select this target beer ring:  $t_{\rm est}$  = 1.1<sup>+0.7</sup> .0.4 method as discussed in Section 2.3. This image was Ring ↵*/St* ↵frag ↵1 mm er ring:  $t_{\text{set}} < 2.4$ (1) (2) (3) (4)

### 5. Discussion dicate gas and dust, respectively. This equation can be expected as an expectively. This equation can be expected inner ring *<sup>&</sup>gt;* <sup>0</sup>*.*<sup>48</sup> *<sup>&</sup>gt;* <sup>1</sup>*.*<sup>4</sup> ⇥ <sup>10</sup><sup>2</sup> *<sup>&</sup>gt;* <sup>3</sup>*.*<sup>6</sup> ⇥ <sup>10</sup><sup>3</sup> outer ring *<sup>&</sup>lt;* <sup>0</sup>*.*<sup>19</sup> *<sup>&</sup>lt;* <sup>8</sup>*.*<sup>9</sup> ⇥ <sup>10</sup><sup>3</sup> *<sup>&</sup>lt;* <sup>3</sup>*.*<sup>0</sup> ⇥ <sup>10</sup><sup>3</sup>



inner part of the disk suppresses the disk suppresses the magneto-rotation of the magneto-rotation of the magneto-

#### $\epsilon$ rg. are dust to har bully lourer ring. are **4.2 Estimation using**  $**χ**<sup>2</sup>$ **inner ring:** the dust is flared up outer ring: the dust is settled is linearly spaced between *r*in = 10 au and *r*out = 200 au **gundanon using**  $\boldsymbol{\lambda}^$ comparison method. 3.1. *Observations* nathon using youter ring the dust is e. is linearly spaced between *r*in = 10 au and *r*out = 200 au Dubrulle et al. 1995; Youdin & Lithwick 2007) need other mechanisms to keep the dust remain small for the construction of our result and Flaher et al. (2017).  $\mathbf{r}$  $\mathcal{L}$  is graduated by planets,  $\mathcal{L}$ fragmentation of dust grains by sintering at snowlines,

- **•** inner ring:  $a/St > 0.48$ **• outer ring: a/St < 0.19** regions represent the area which have non-axisymmetric fea- $\cdot$  lnner ring: a/5t  $>$  0.48  $\hskip.1in$ the beam (Huang et al. 2018).
- **5.2 The gas turbulence a, and the Stokes number (St**∝**the dust size)** 3.4. *Consistency with the radial profiles h<sup>d</sup>* = *hg,* (16) line observations. Flaherty et al. (2017) put an upper **limit that △ 103, so we can calculate the dust radius of the dust radius of the dust radius of the dust radius** for the typical three turbulence that ↵ = 3 ⇥ <sup>10</sup><sup>3</sup> *,* <sup>1</sup> ⇥ <sup>10</sup><sup>4</sup>. We show the results in Table 2. If we along the minor axes to check the constant of Figure 8 shows the radial profiles of the observations the Chaire the peak is. the signes intimediation midplane. Compared to the results of our study, the  $\blacksquare$ dust is settled, while the inner ring is inconsistent with this process because the dust is flared.

et al. 2016) to improve sensitivity and *uv*-coverage on

**Fig 4.** The possible range of turbulence (a) and Stokes number (St). The **interpative metabolism**  $\blacksquare$ blue and orange areas represent the possible range of a and St for the **canalization** inner and outer rings, respectively. The red dashed line represents the **dead in the post-up tensor of the postfragmentation limit**, and the **blue** and **orange** lines represent the limit of **a/ St**. The brown dashed line represents the upper limit of α from the observation of line broadening (Flaherty et al. 2017). The green dashed line represents the St when the dust size is 1 mm. own deched line represents the upper limit of a out dad not inno roprodonto the apportunities a  $\eta$ representation in the framentation  $\eta$  is the  $\eta$ settled, the turbulence is not weak, and the dead zone The last possible mechanism we consider is secular to  $\mathbb{R}^n$ dochod lino  $\alpha$  and  $\alpha$  also in the Indian shift  $\alpha$ inaga et al. 2019). The SGI is stabilized by the turbu-



### **3. Method** around HD 163296 to constrain the dust scale height by comparing the observation and radiative transfer sim-



400 [au]

**3.1 The setup of radiative transfer simulation** We estimate the dust scale height by comparing the observation with radiative transfer simulation using RADMC-3D(Dullemond et al. 2012).  $\frac{1}{2}$ te setup of faulative trail 3.2. *Setup of the simulation* iparing the opservation with  $MC$ -3 $D/D$ ullemond et al. 2012) simulations with RADMC-3D (Dullemond et al. 2012). In our simulation, we use spherical coordinates (*r,* ✓*,* ),

• The fixed parameters

- The dust surface density: estimated from the intensity along the major axis extensive the fits data of the fits data of the image of the image of the internal control of the i julianus mon and muchany along are
- The dust opacity: from the DSHARP dust model(Birnstiel et al. 2018)  $\overline{a}$  and  $\overline{a}$  and  $\overline{a}$  and  $\overline{a}$  this target bemidplane, and ∴ is the north pole. The north pole of the north pole. The north pole of the north pole. The north pole. The north pole of the north pole. The north pole of the north pole. The north pole of the north pole. IUSL MIOGEI(BIrnstiel et al. 2018)
- The dust temperature: from CO line observation(Dullemond et al. 2020) **• The parameter we aim to estimate** e dust temperature: from CO if taken with a community continued band for the corresponding of the corresponding  $\alpha$ shoorugtion (Dullemond at al. 2020) UNUUL VC

**• The dust scale height** 

settled in the outer ring.

is smaller in the dead zone and larger outside the dead zone and larger outside the dead zone and larger outsi<br>In the dead zone and larger outside the dead zone and larger outside the dead zone and larger outside the dead

Figure 7. Reduced <sup>2</sup> of the intensity between observa-

tions and simulations along the ridge for each *f*set. We use

data at every FWHM. We exclude data for the area which

has a crescent structure (shaded area in Figure 6). The hor-

izontal lines represent locations where the minimum reduced

along the major and minor axes. Around the inner ring

at 68 au, the intensity along the major axis is larger than

that along the minor axis. On the other hand, around

the outer ring at 100 au, the intensity along the major

and minor axes is almost the same.

major (top) and minor (bottom) axes of the observation

and simulations in case of *f*set = 1 and 8. From the top

of Figure 9, we can see that the simulations reproduces

the observations well on the major axis. The bottom of

4, we discuss physical quantities such as the turbulence **Submitted to AAS journals**

3.1. *Observations*

the HD 26316 disk taken in the HD 263296 disk taken in the DSHARP campaign in the DSHARP campaign in the DSHARP campaign in the US

smooth power-law distribution derived by Dullemond

represents the upper limit of ↵ from the observation of line

3. dust accumulation of the outeredge of the dead zone,

and 4. secular gravitational instability (SGI). This study

shows that the settling conditions of the two rings are

di↵erent. Therefore, we consider ring formation mecha-

pressure gaps induced by planets (Lin & Papaloizou

1979; Goldreich & Tremaine 1980; Du↵ell & MacFadyen

2013; Fung et al. 2014; Kanagawa et al. 2015). Zhu et al.

(2012) show that large dust accumulates on the outside

process consist of large dust, the dust is settled to the

Another possible mechanism is the sintering of the

dust (Okuzumi et al. 2016; Zhang et al. 2015). The

sintering theory predicts the rings are consist of small

dust fragments. The inner ring may be explained by the

dust sintering because the dust is flared, but the outer

ring cannot be explained because the dust is settled,

which suggests large dust grains.

Another possible mechanism is the dust accumulation

at the outer edge of the dead zone (Flock et al. 2015;

Pinilla et al. 2016; Mori & Okuzumi 2016; Ueda et al.

2019). The dead zone is the inner region of the disk

where the MRI is stabilized, and turbulence is stabilized, and turbulence is stabilized, and turbulence is stabilized, and

weak. However, since the inner ring is not

lence, so the turbulence must be weak for instability to



et al. 2018). We assume that the central star mass