

# 惑星ができない！

- 理論観測両面から探る惑星形成 -

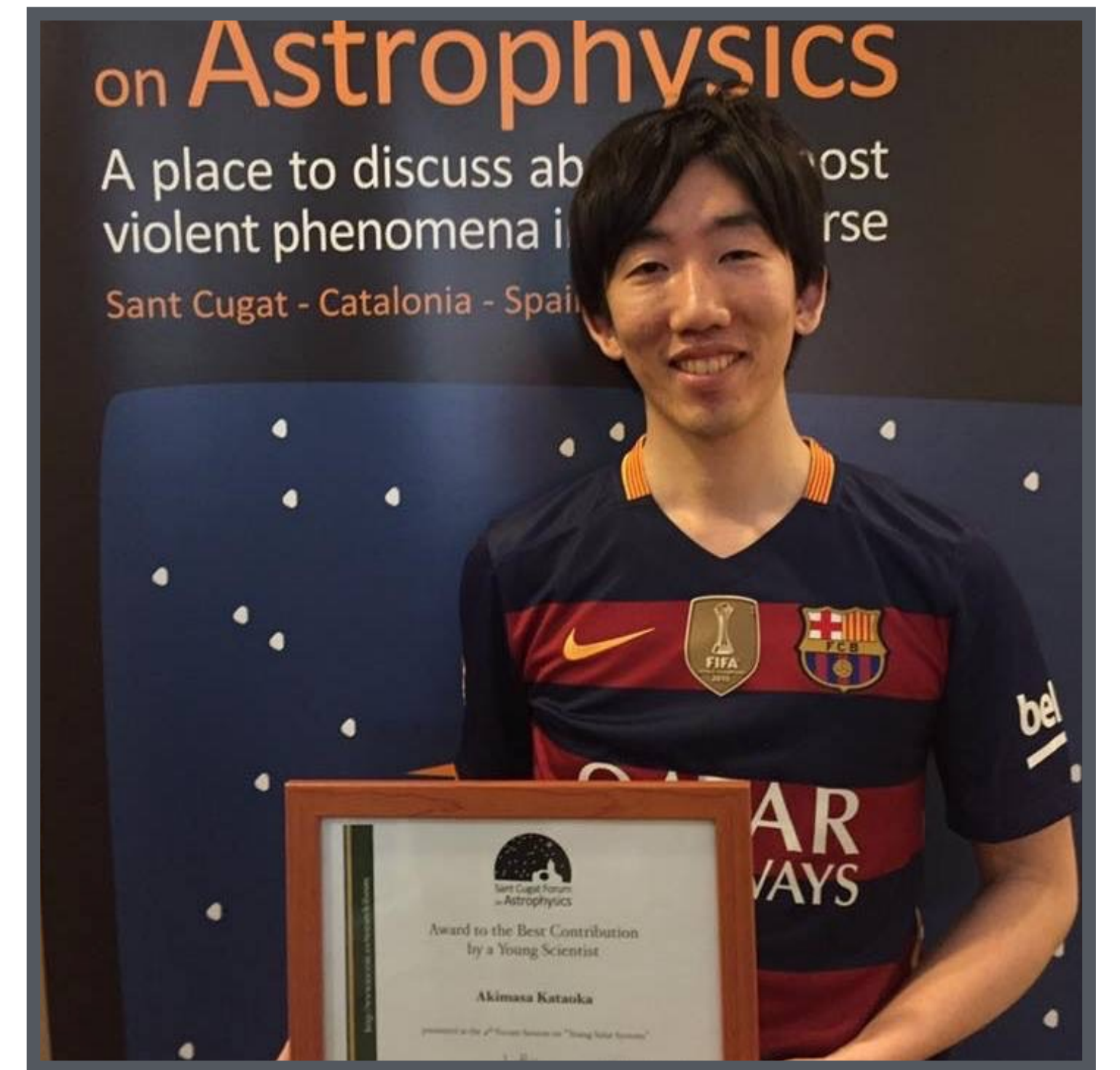
片岡章雅 (国立天文台)

# • 自己紹介

- 京大理学部・大学院修士 (2006-2012)
- 総研大博士課程/国立天文台 (2012-2014)
  - 2012年夏の学校会場係長
- 東工大研究員 (2014.9-2015.3)
- ハイデルベルク大学研究員 (2015.4-2017.3)
- 国立天文台 フェロー→助教 (2017.12-)

- 博士から他大に行きたい人
- 外国での研究生活について聞きたい人
- 夏の学校について議論したい人

⇒あとで捕まえて！



# 惑星ができない！

- 理論観測両面から探る惑星形成 -

## 概要

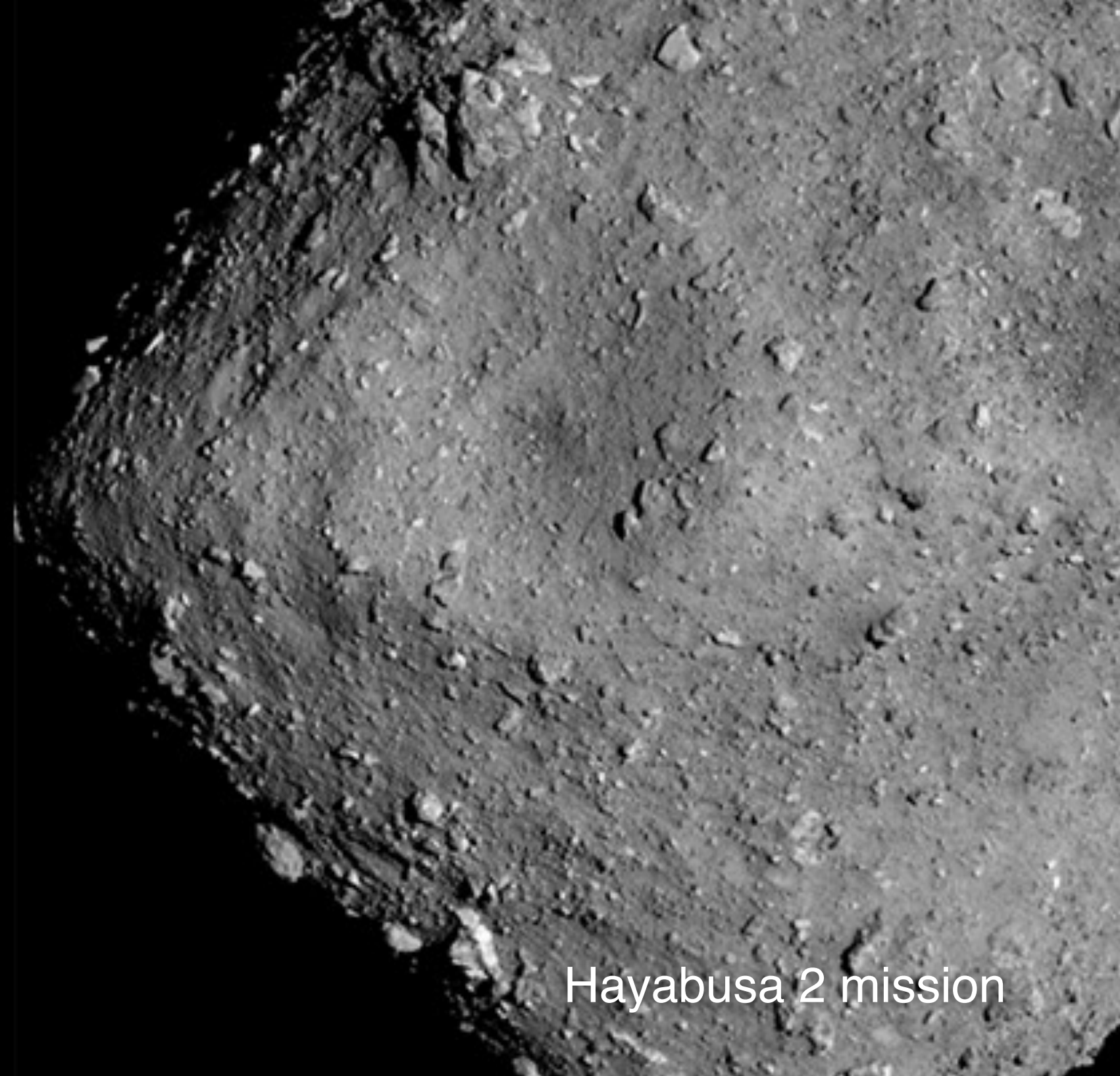
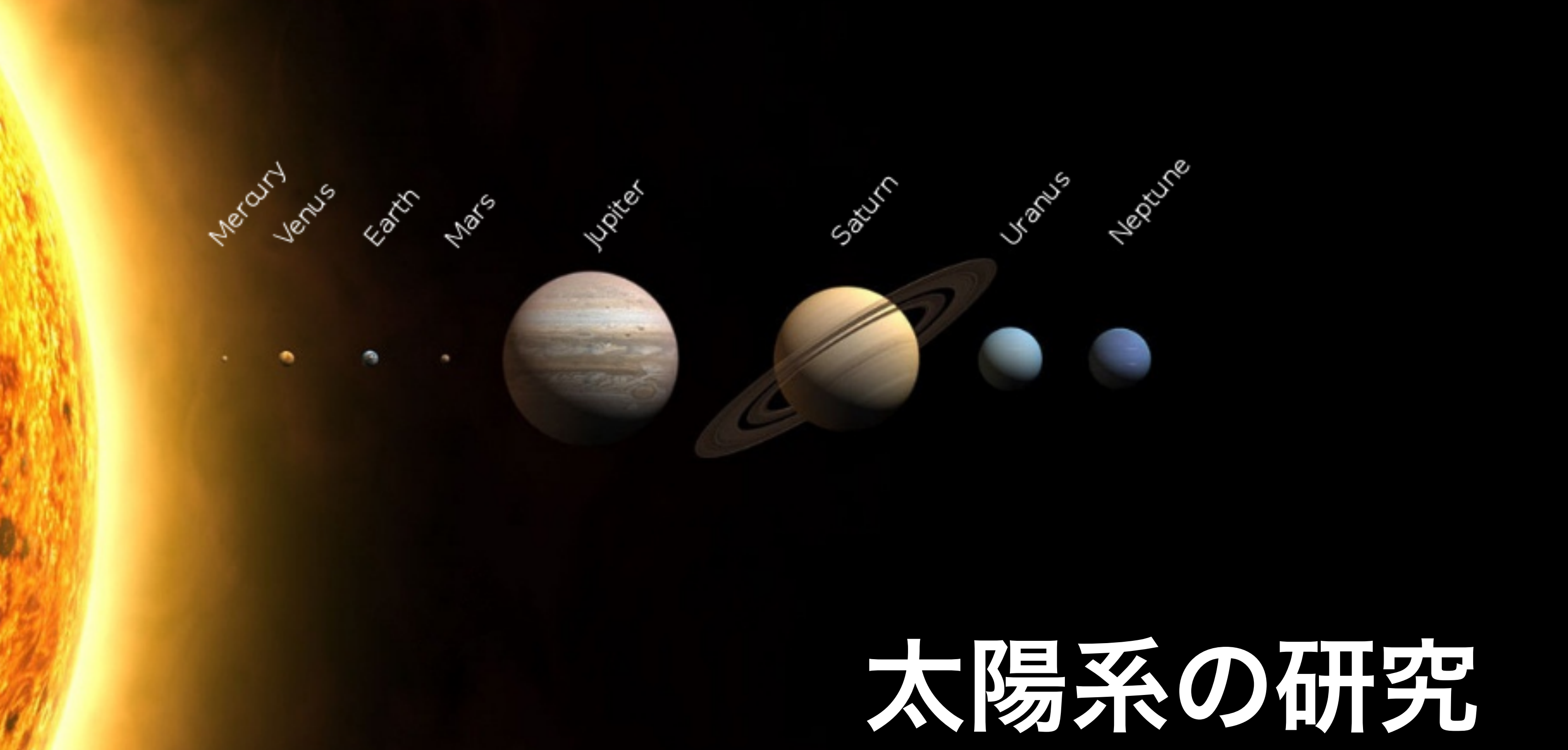
- 惑星形成と原始惑星系円盤
- ミリ波偏光観測によるダスト成長の制限

# 惑星の研究？

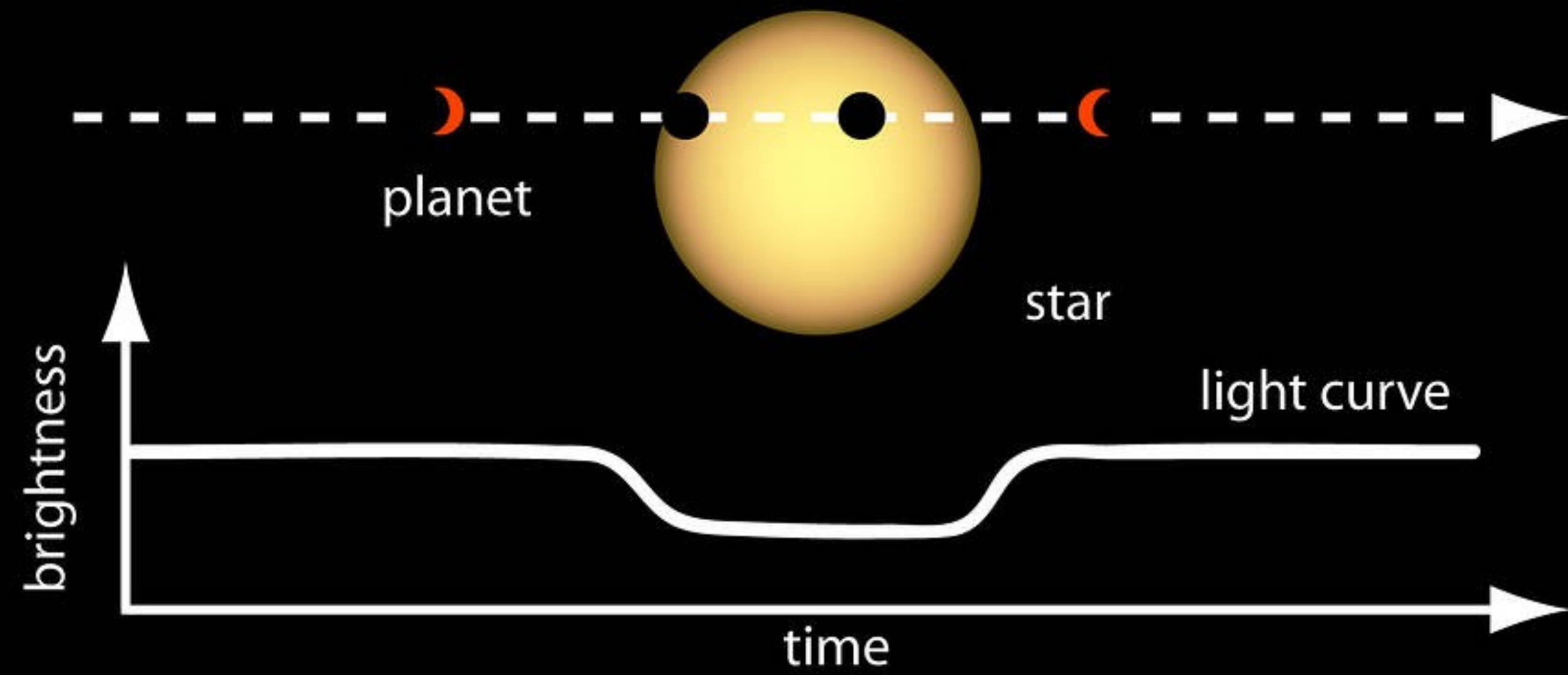
1. 太陽系の研究

2. 系外惑星の研究

3. 惑星形成の研究

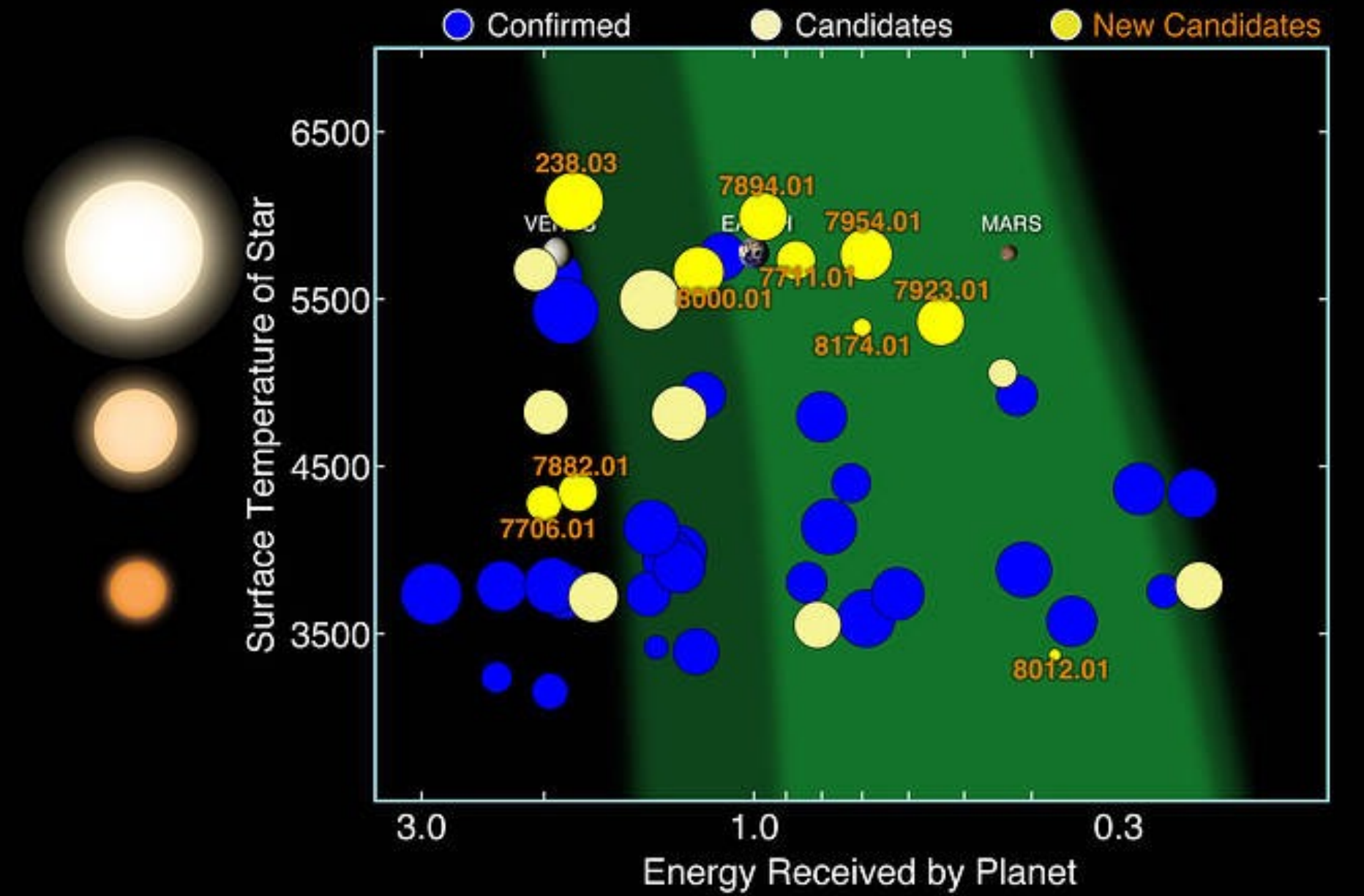


# 系外惑星の研究



## Kepler Habitable Zone Planets

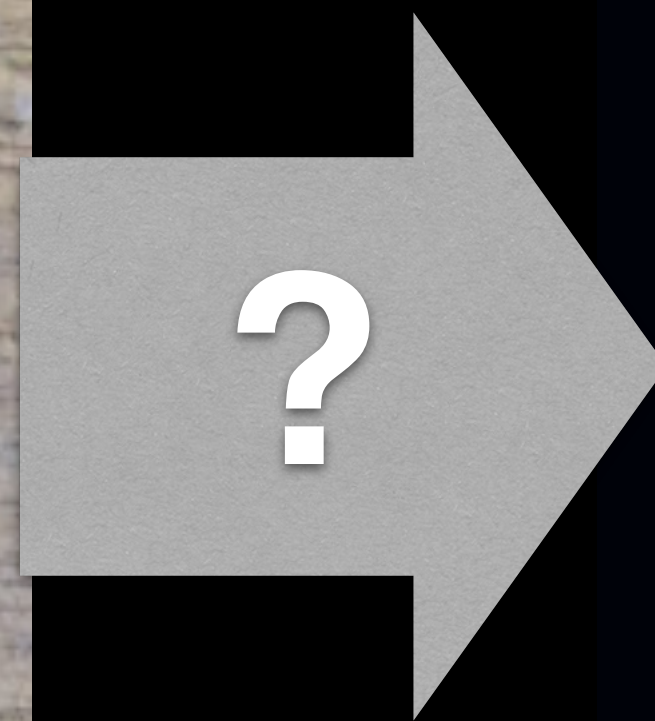
As of June 2017



# 惑星形成: 何を解き明かしたいか



~ 1  $\mu\text{m}$



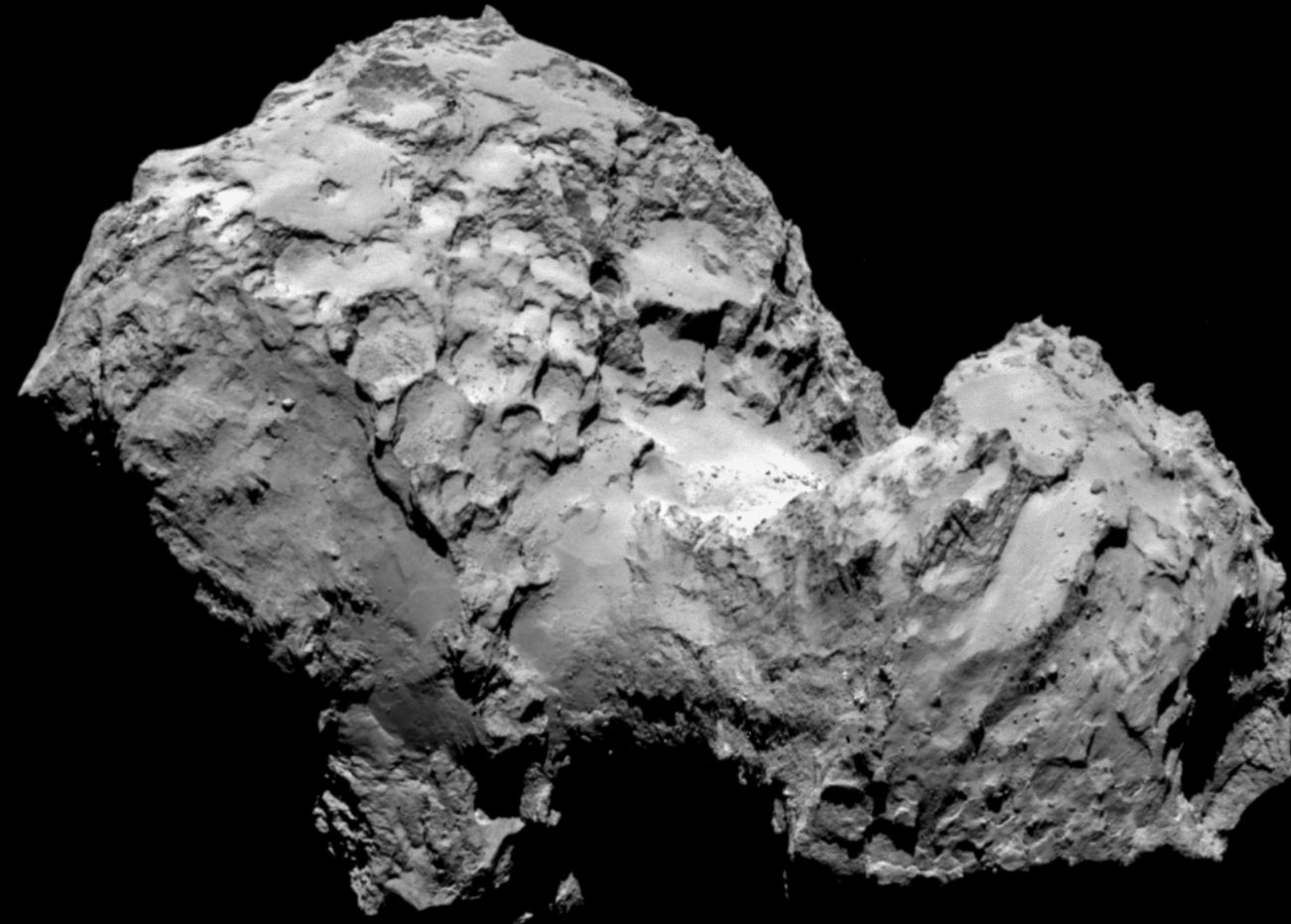
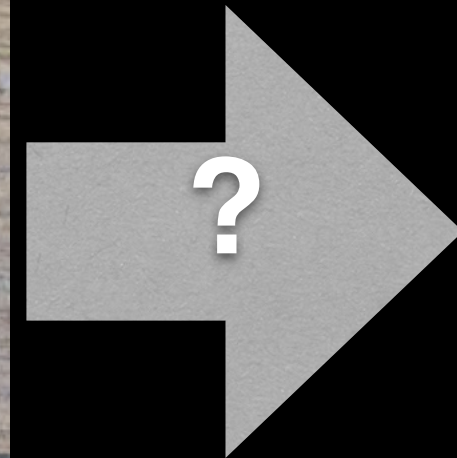
~ 1000 km

# 惑星形成: 何を解き明かしたいか

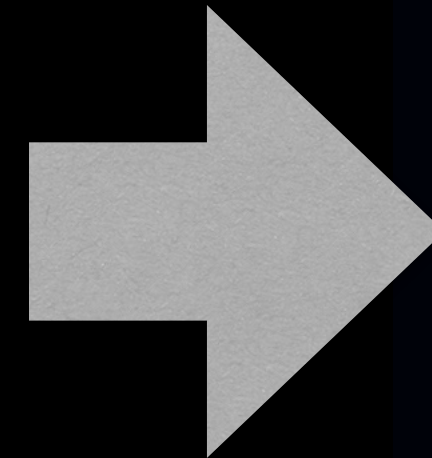
微惑星



~ 1  $\mu\text{m}$



~ 1 km

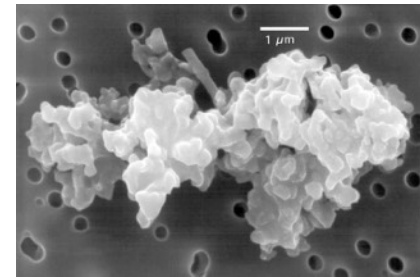


~ 1000 km



# ダストの合体成長

0.1 $\mu$ m



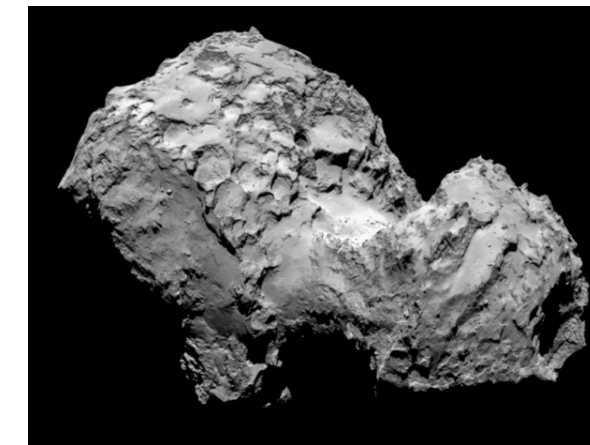
ダスト

衝突破壊/  
跳ね返り問題

1m

中心星  
落下問題

1km



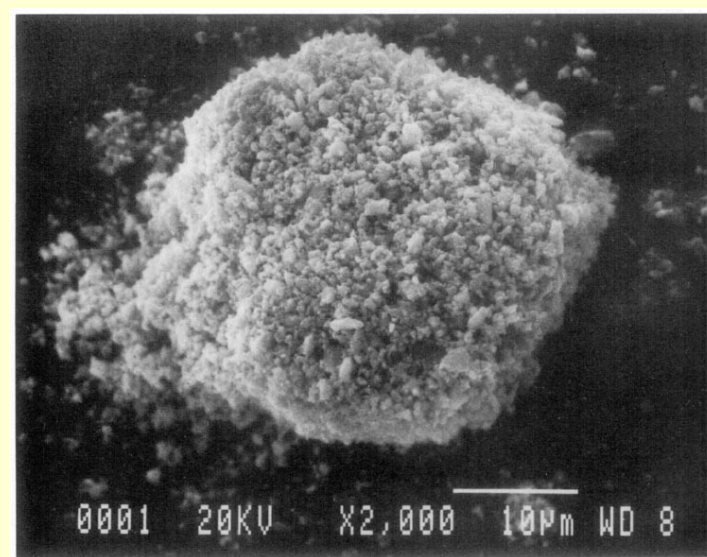
微惑星

10<sup>2-4</sup>km

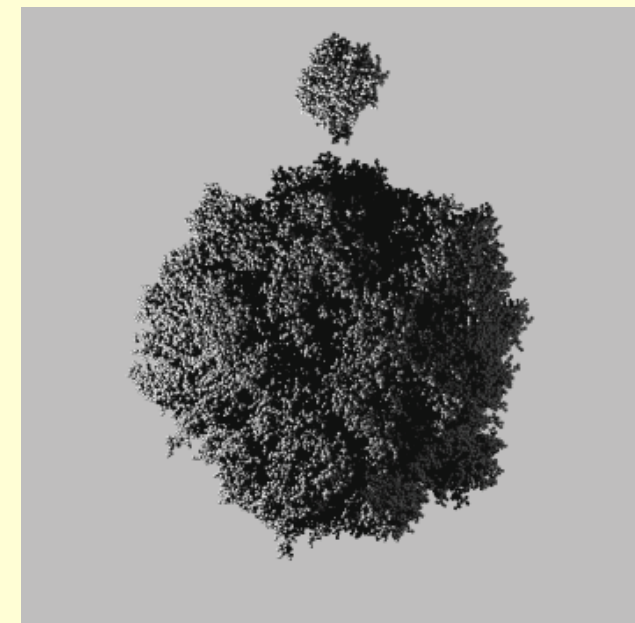


惑星

ダスト実験/数値計算

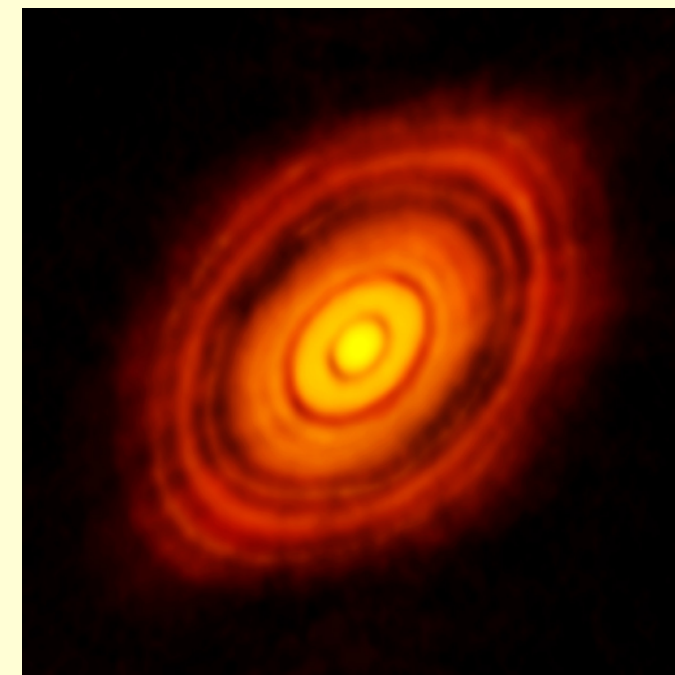


Blum & Münch 1993



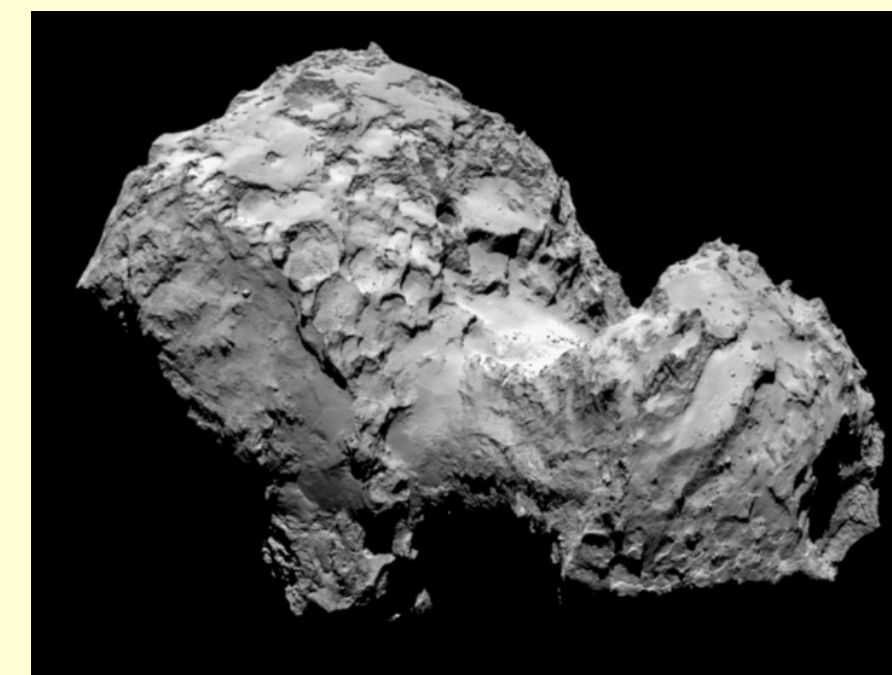
Wada et al. 2013

天文観測



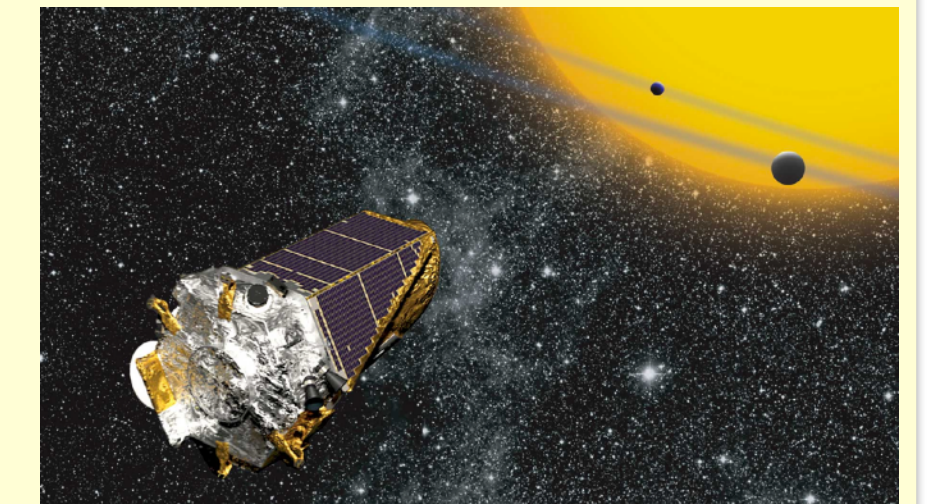
ALMA Partnership 2015

太陽系内



Rosetta mission

系外惑星



Kepler 宇宙望遠鏡  
→ TESS 望遠鏡

小石(≈1cm)同士をぶつけたら、くっつくのか？

小石くっつかない問題

跳ね返り障壁 (e.g., Zsom et al. 2010)



Blum et al. (Braunschweig)

jove

ダストは数 m/s の衝突で破壊される  
衝突破壊問題 (e.g., Blum and Münch 1993)

一定密度合体成長の仮定は正しいのか？

ダスト(シリケートや氷)は星間空間で  
固体なので、この仮定は正しくない。



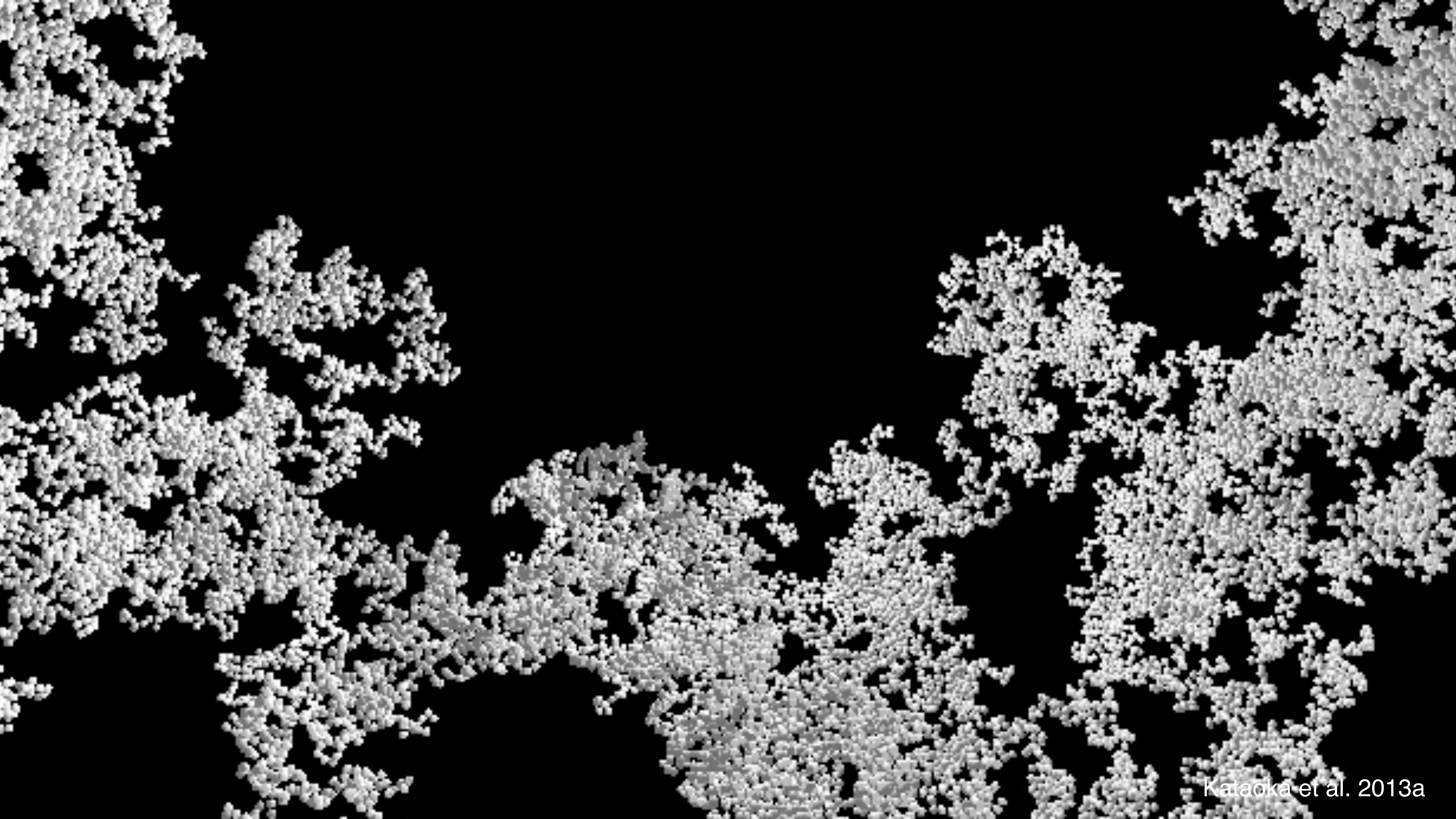
ダストは付着時に  
すき間を持つ



## 弾性体の力学 (Herz理論, 1896)

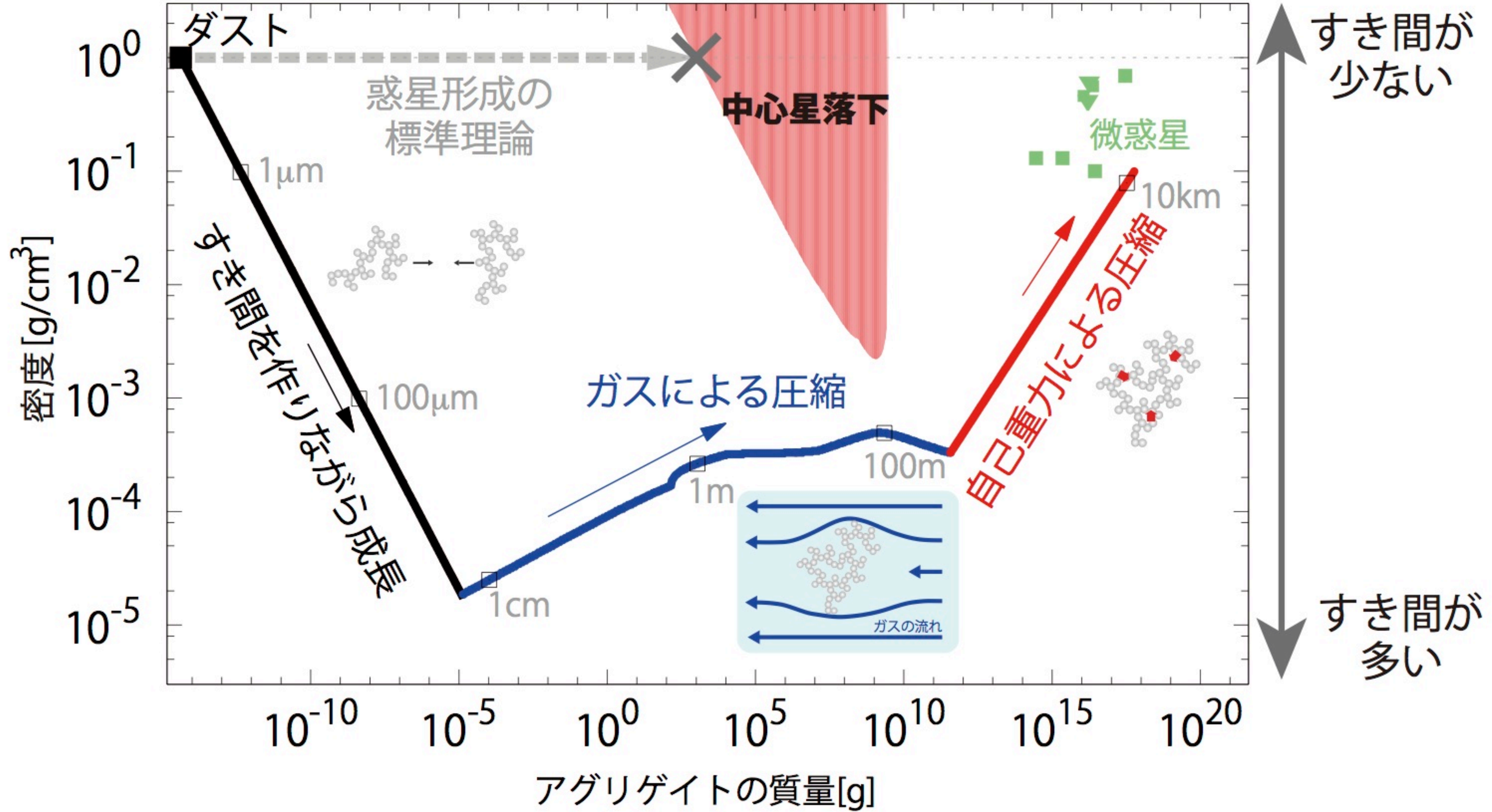
- 表面付着力を追加 (JKR理論, 1971)
- 接線応力/摩擦を追加 (Dominik and Tielens 1997)
- ポテンシャルエネルギーで記述 (Wada et al. 2007)







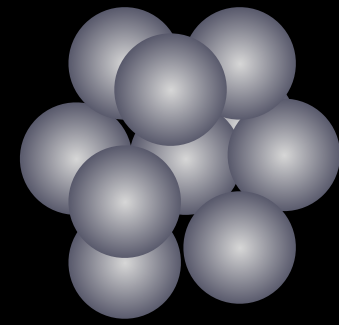
# 5天文単位でのアグリゲイトの密度進化



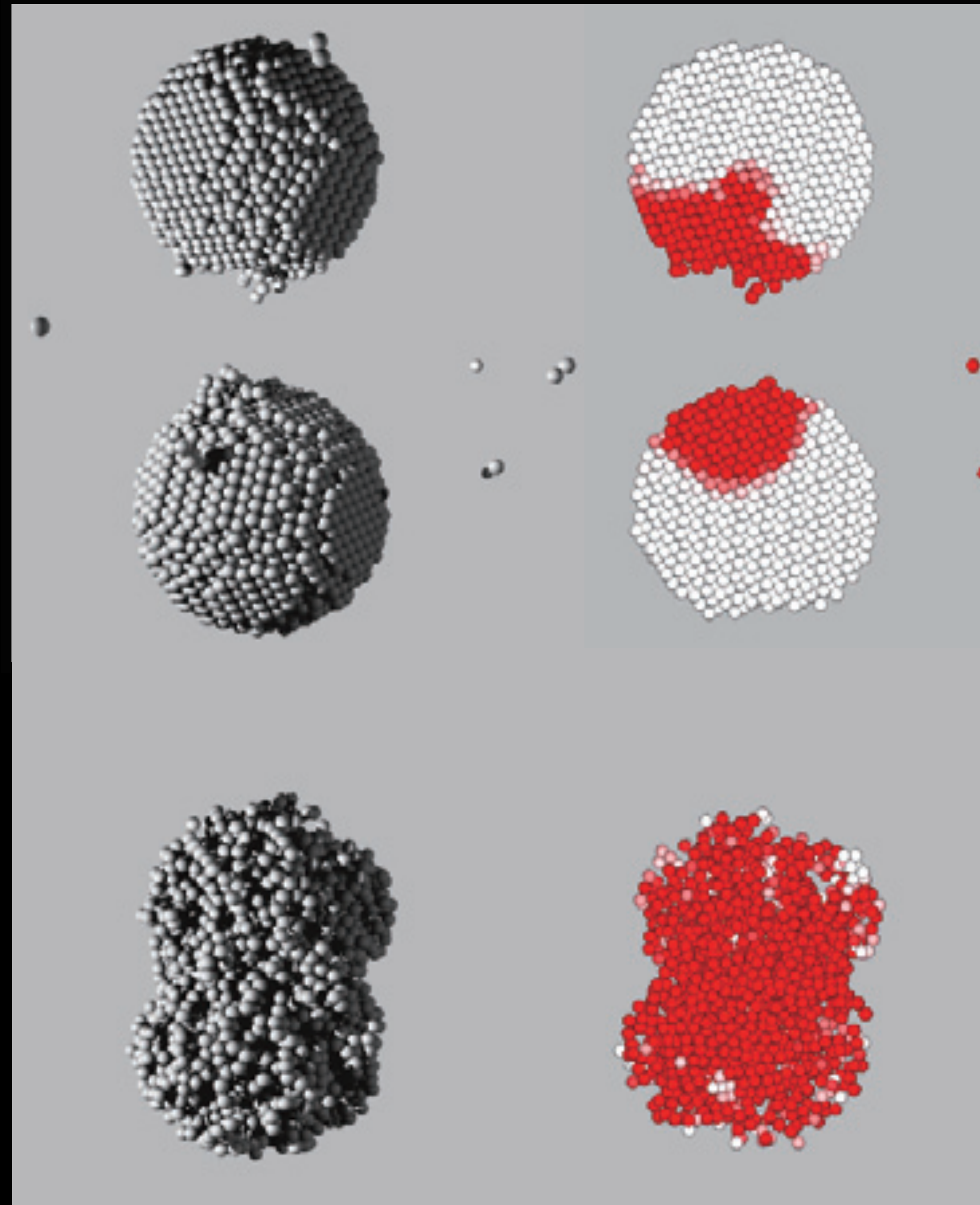
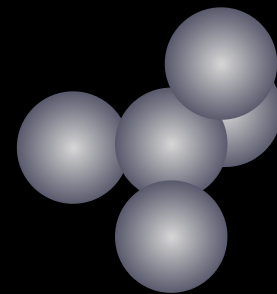
Kataoka et al. 2013b, 国立天文台 理論研究部プレスリリース

# 跳ね返り問題の解決

配位数 $\approx 11$

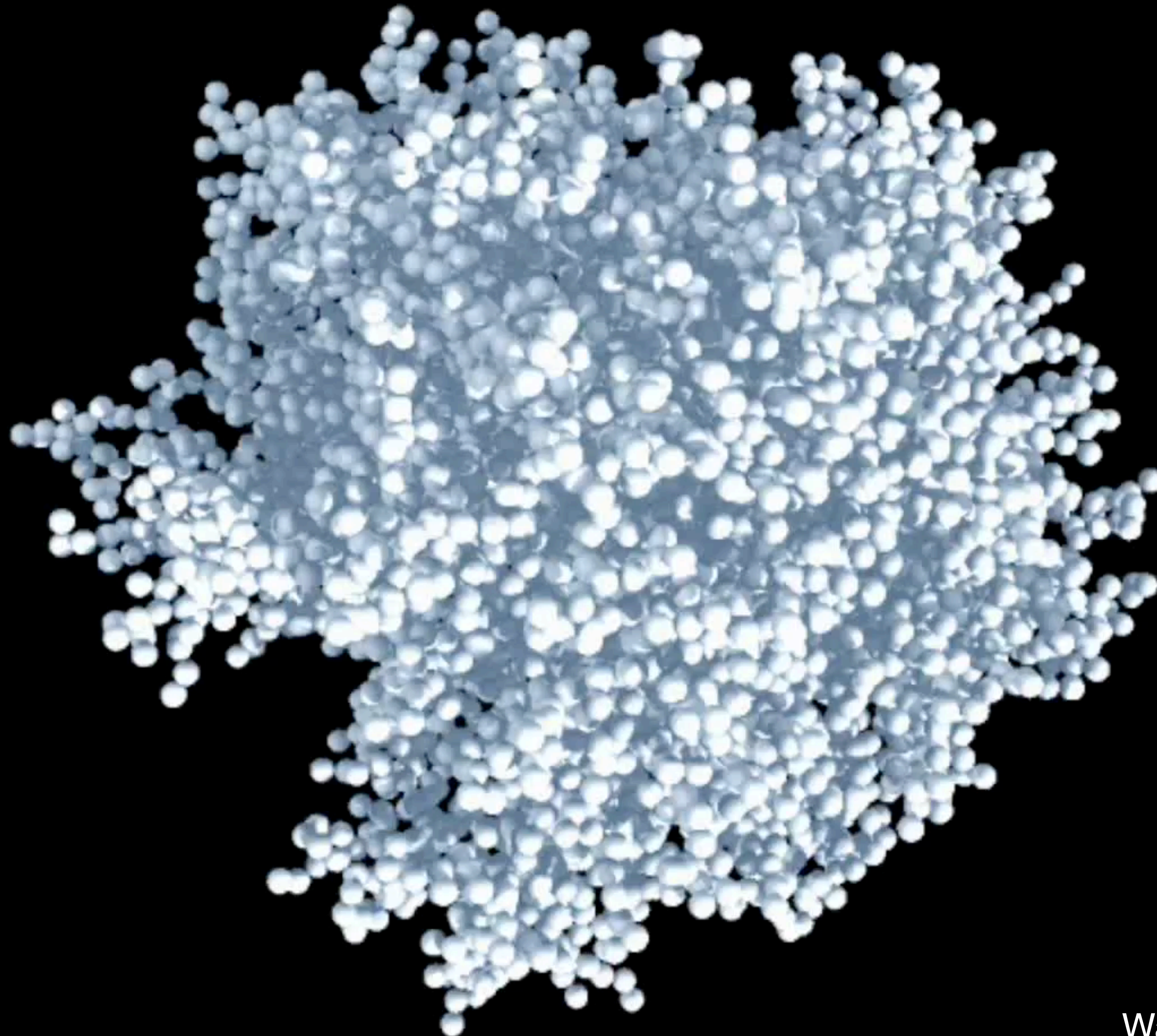


配位数 $\approx 4$



Wada et al. 2011

スカスカのダスト集合体 $\rightarrow$ 配位数小 $\rightarrow$ 跳ね返らない



ダスト集合体を破壊するのに必要な速度

$$(1/2) Nm_0 v^2 = (\text{結合の数}) \times (\text{結合の強さ})$$

$$\sim N \times E_{\text{break}}$$

$$\Rightarrow v \sim 1 \text{ m/s} \times (r_0/0.1 \mu\text{m})^{-5/6} \text{ for silicate,}$$

$$10 \text{ m/s} \times (r_0/0.1 \mu\text{m})^{-5/6} \text{ for ice}$$

Dominik and Tielens 1997

数値計算の結果

$$v = 8 \text{ m/s} \times (r_0/0.1 \mu\text{m})^{-5/6} \text{ for silicate,}$$

$$80 \text{ m/s} \times (r_0/0.1 \mu\text{m})^{-5/6} \text{ for ice}$$



Bastian Gundlach

2016年6月, ブラウンシュバイク工科大学にて



吸入器





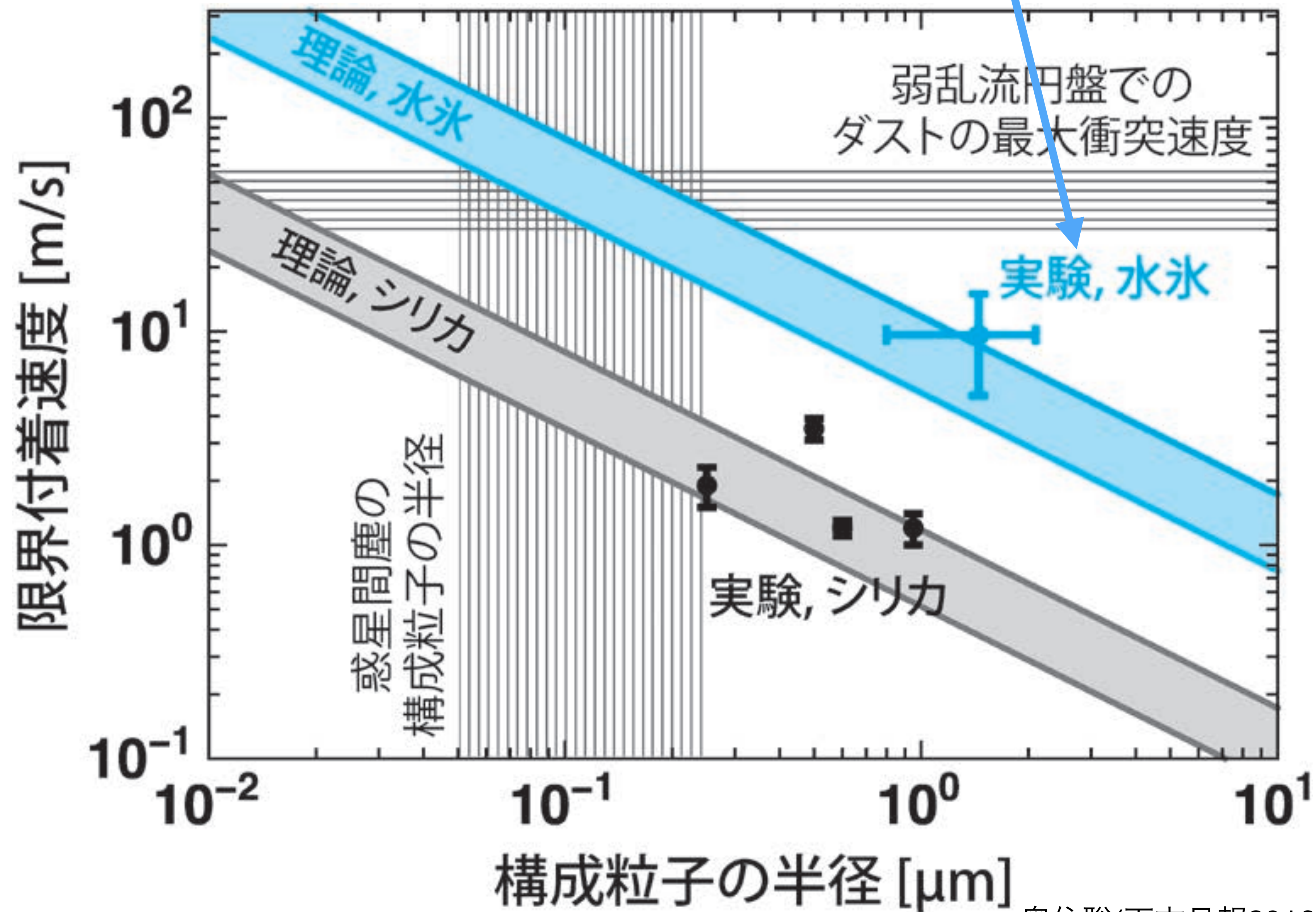




氷の粒

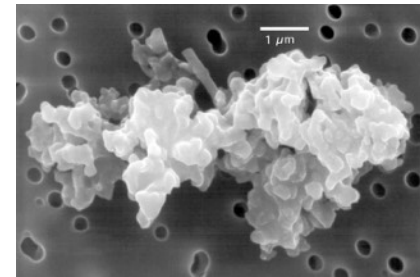
# 馬用吸入器 (粒径 $\approx 1.5 \mu\text{m}$ )





# ダストの合体成長

0.1 $\mu$ m



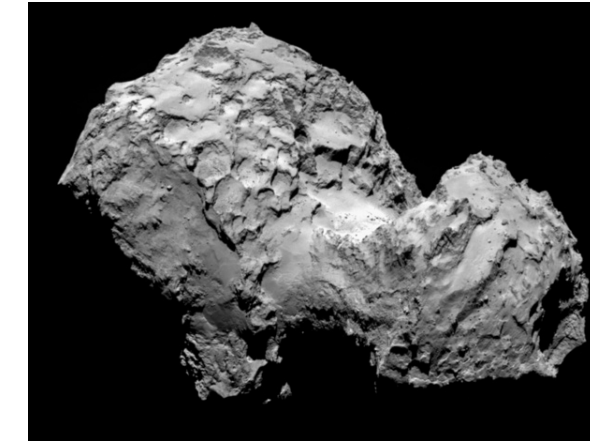
ダスト

衝突破壊/  
跳ね返り問題

1m

中心星  
落下問題

1km



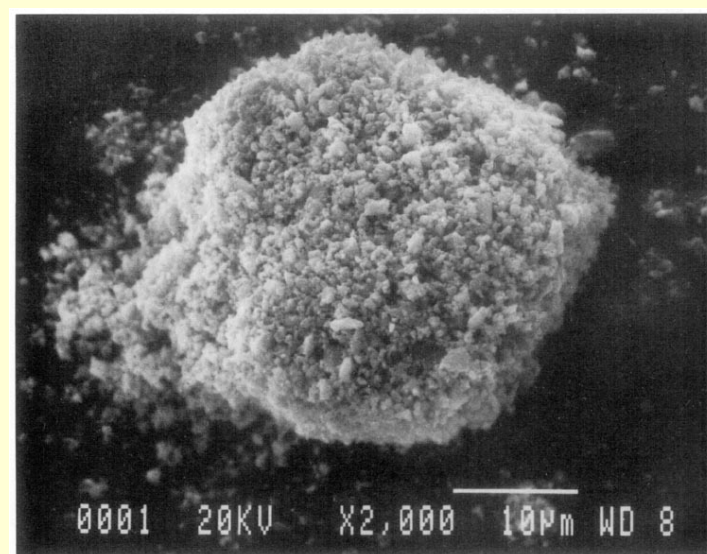
微惑星

10<sup>2-4</sup>km

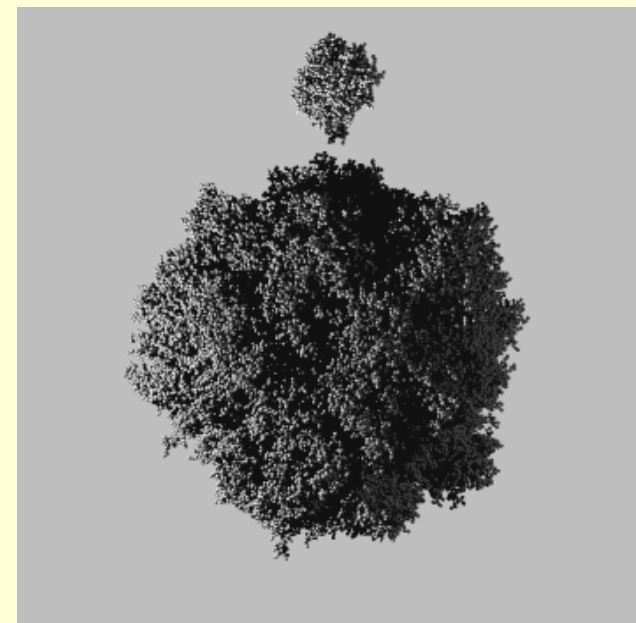


惑星

ダスト実験/数値計算

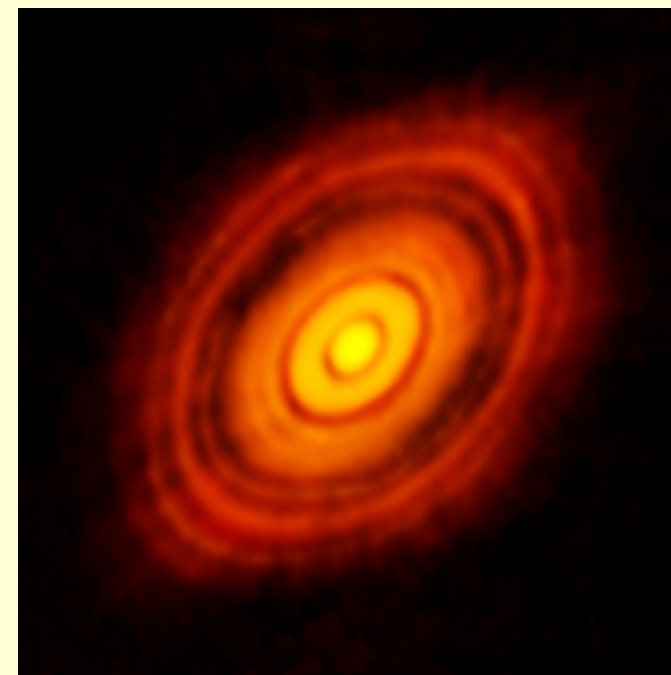


Blum & Münch 1993



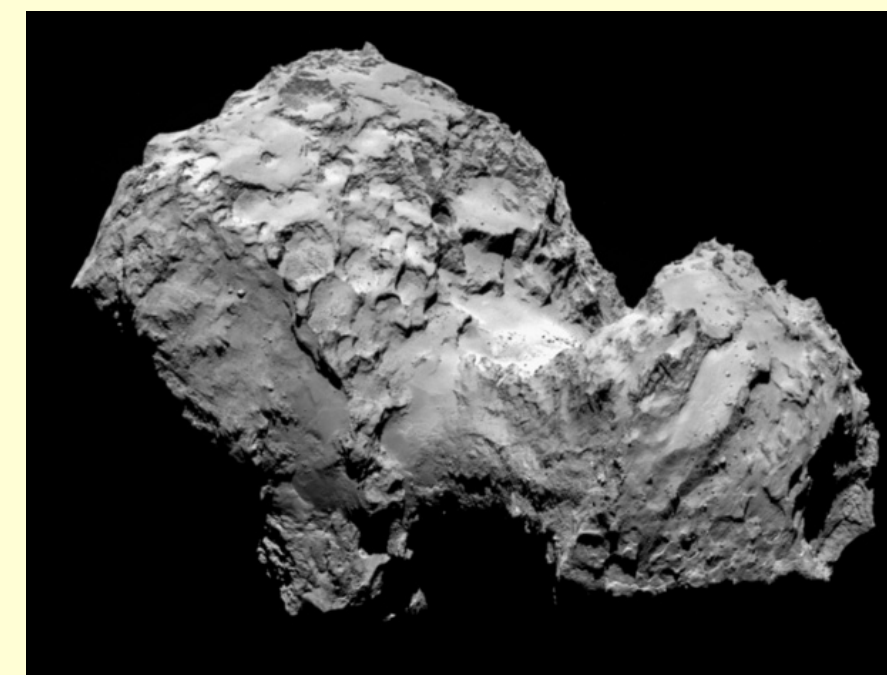
Wada et al. 2013

天文観測



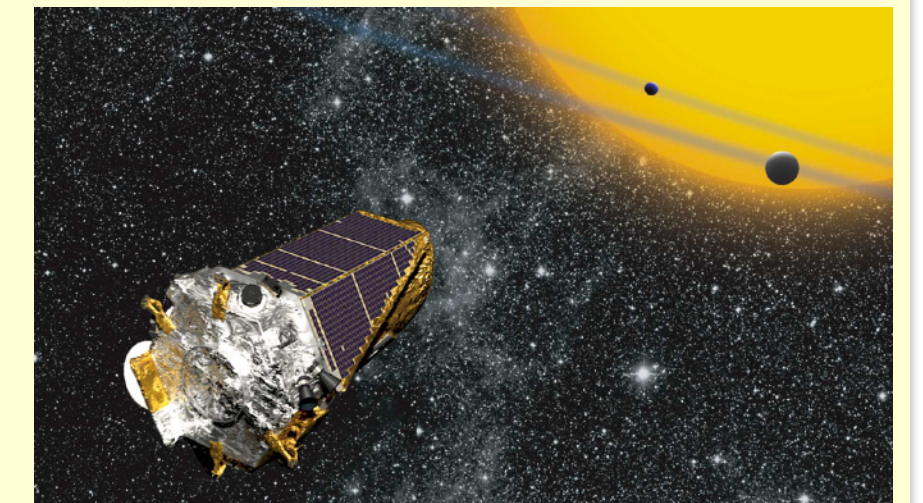
ALMA Partnership 2015

太陽系内



Rosetta mission

系外惑星



Kepler 宇宙望遠鏡  
→ TESS 望遠鏡

# 惑星形成の現場：原始惑星系円盤



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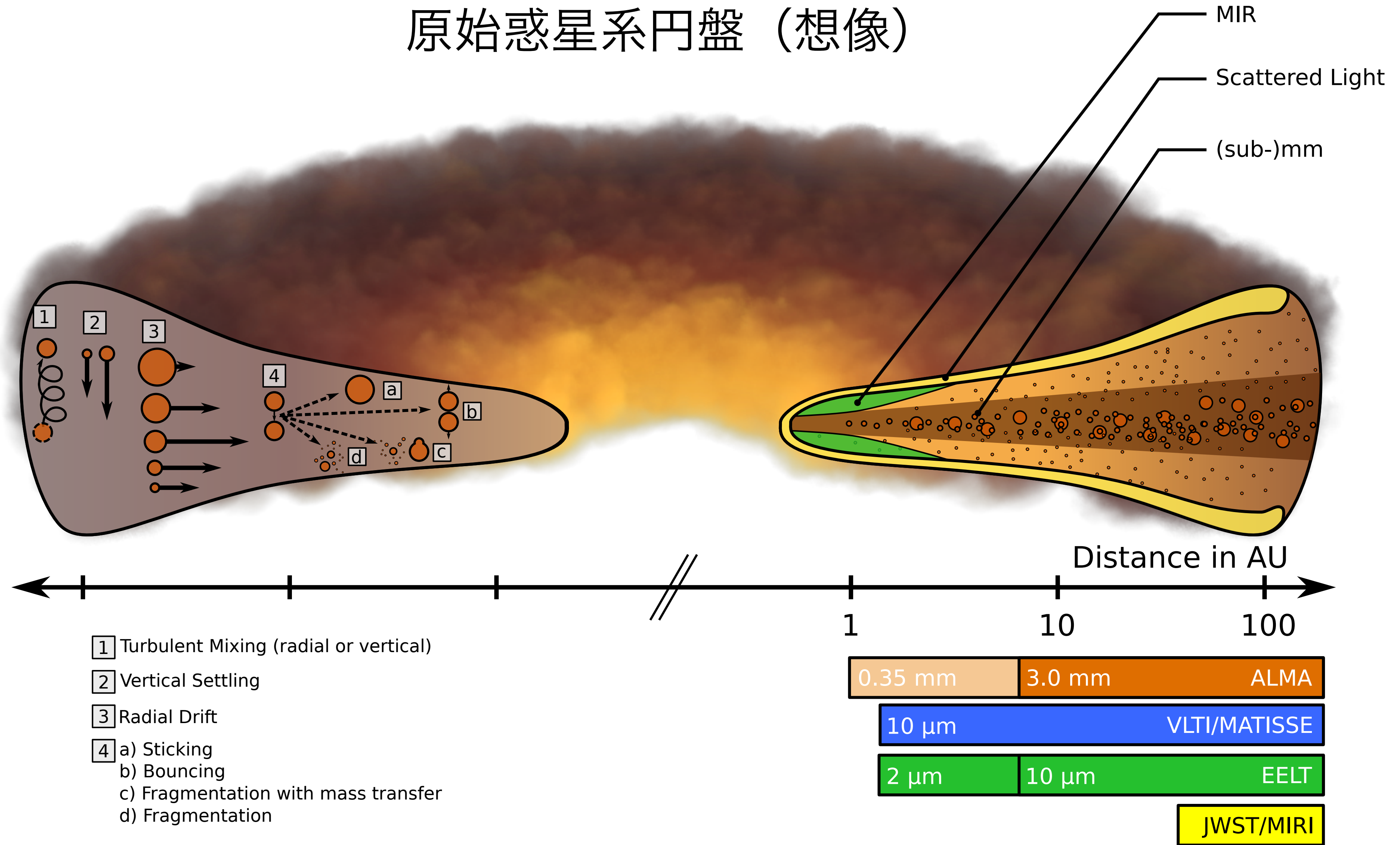
# 惑星形成の現場：原始惑星系円盤

円盤を“横から”見ている  
中心星は隠されている



= 500 AU

# 原始惑星系円盤 (想像)



# 可視光・赤外線望遠鏡



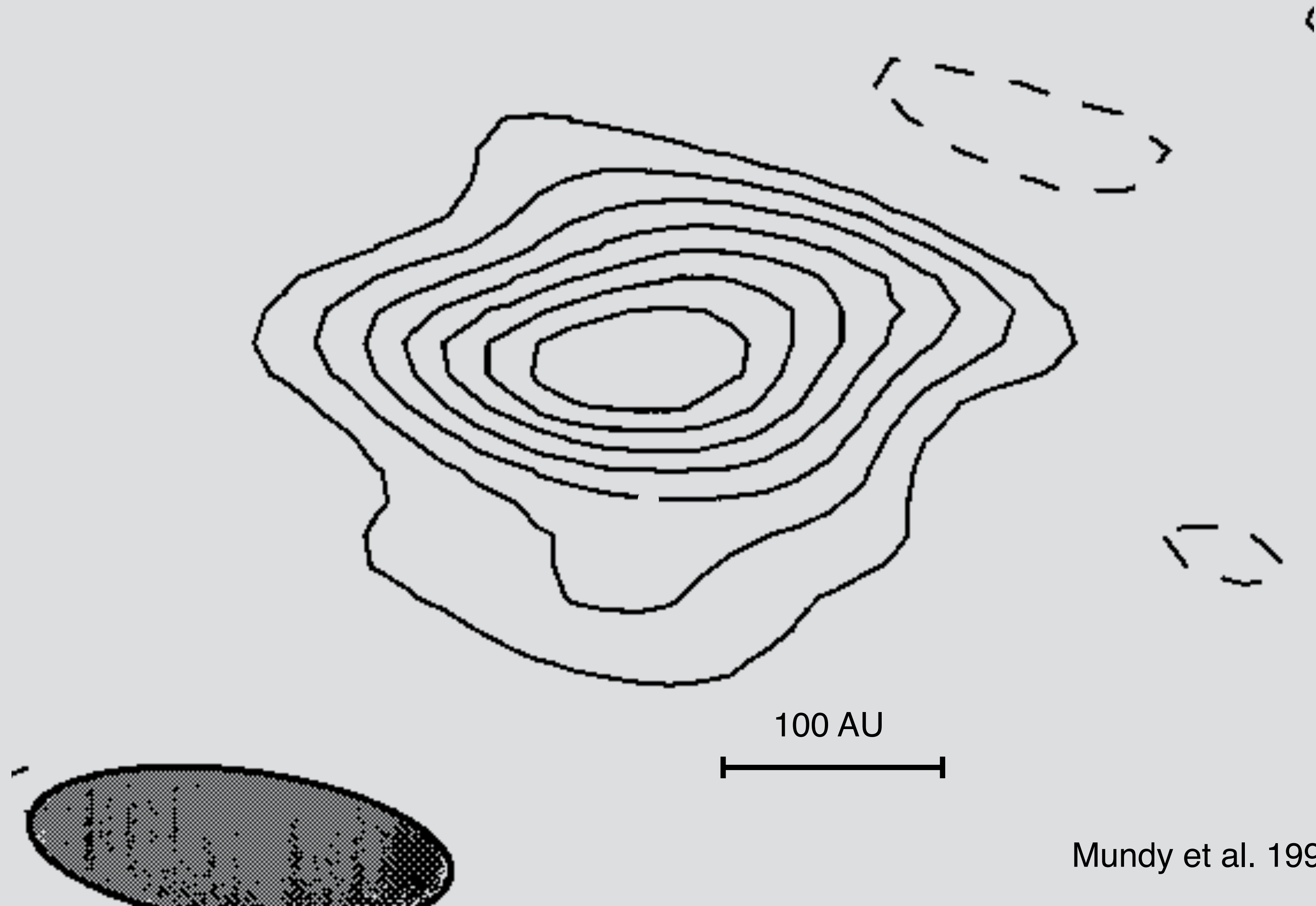
$\lambda \sim 0.1 - 1 \mu\text{m}$

# 電波干渉計

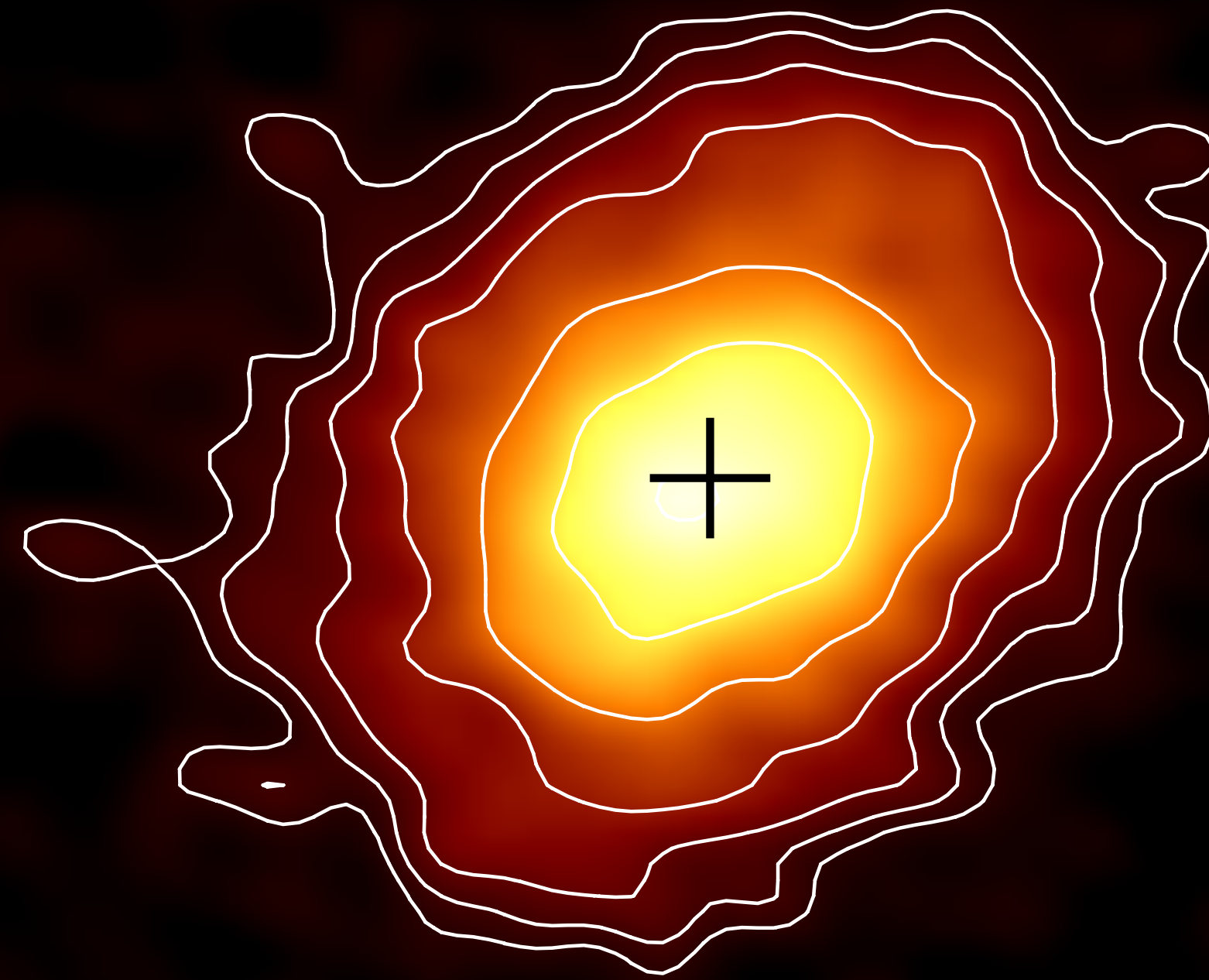


$\lambda \sim 1 \text{ mm}$

# HL Tau (BIMA 2.7 mm)



# HL Tau (CARMA 1.3 mm)

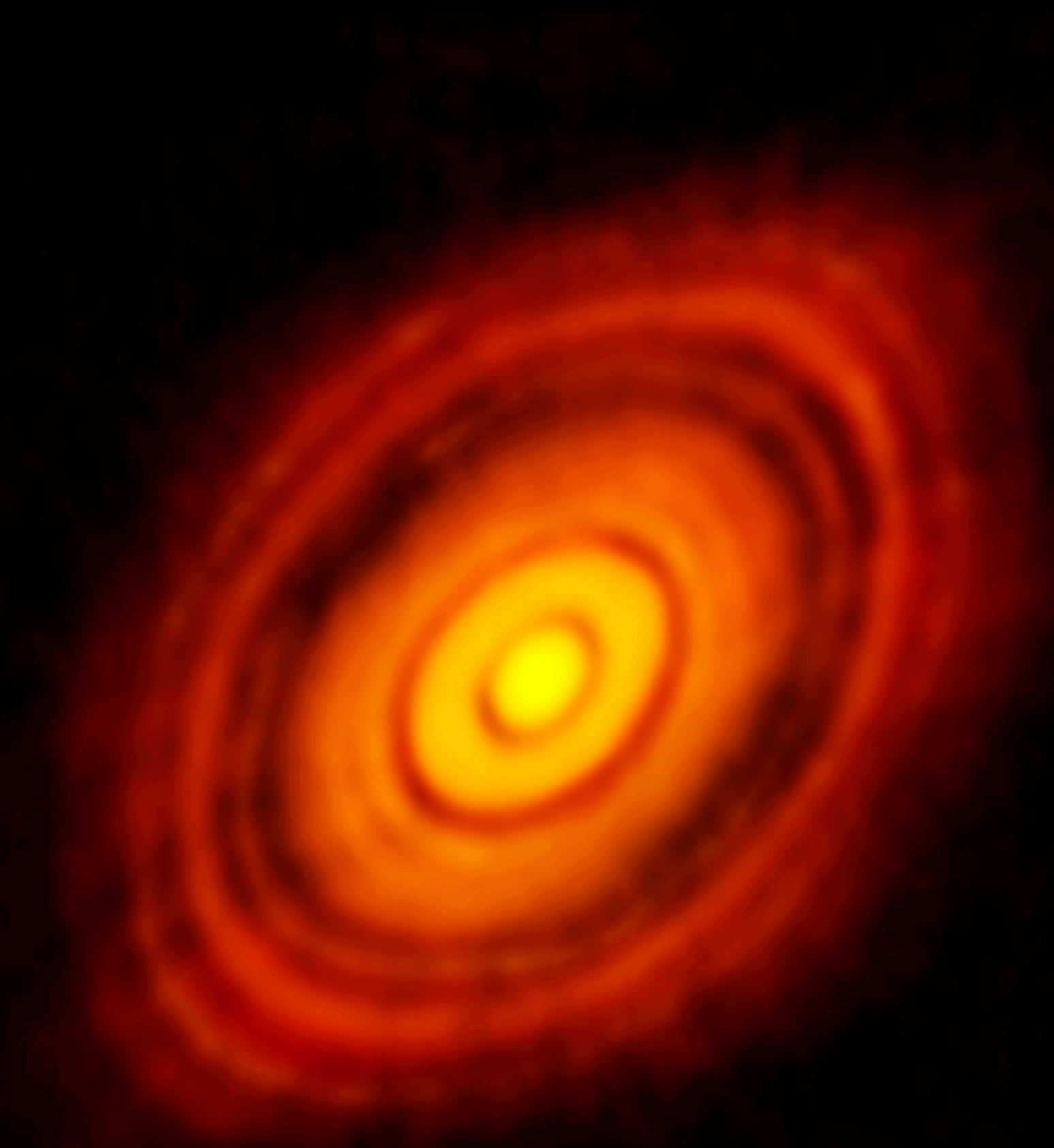


100 AU




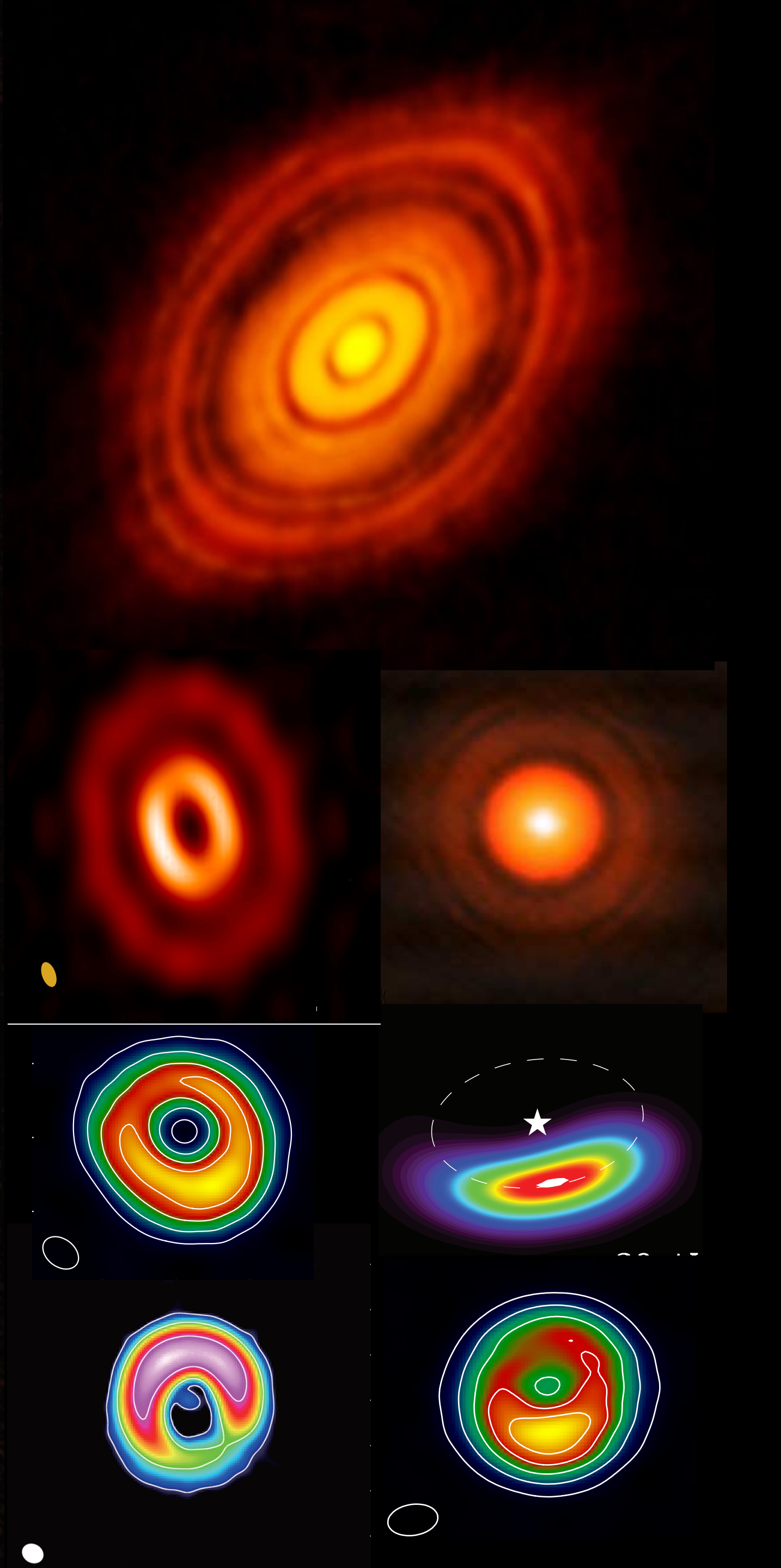
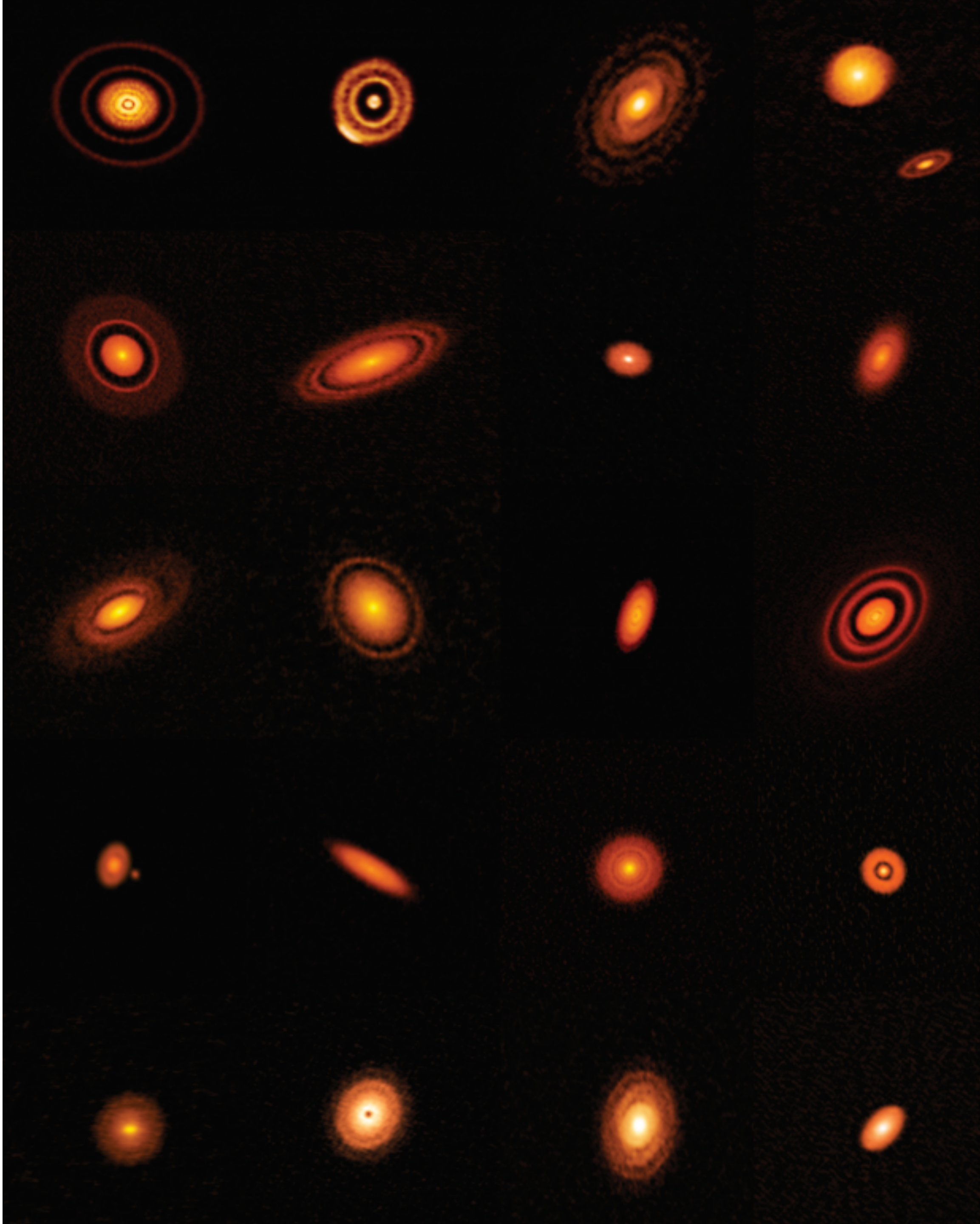
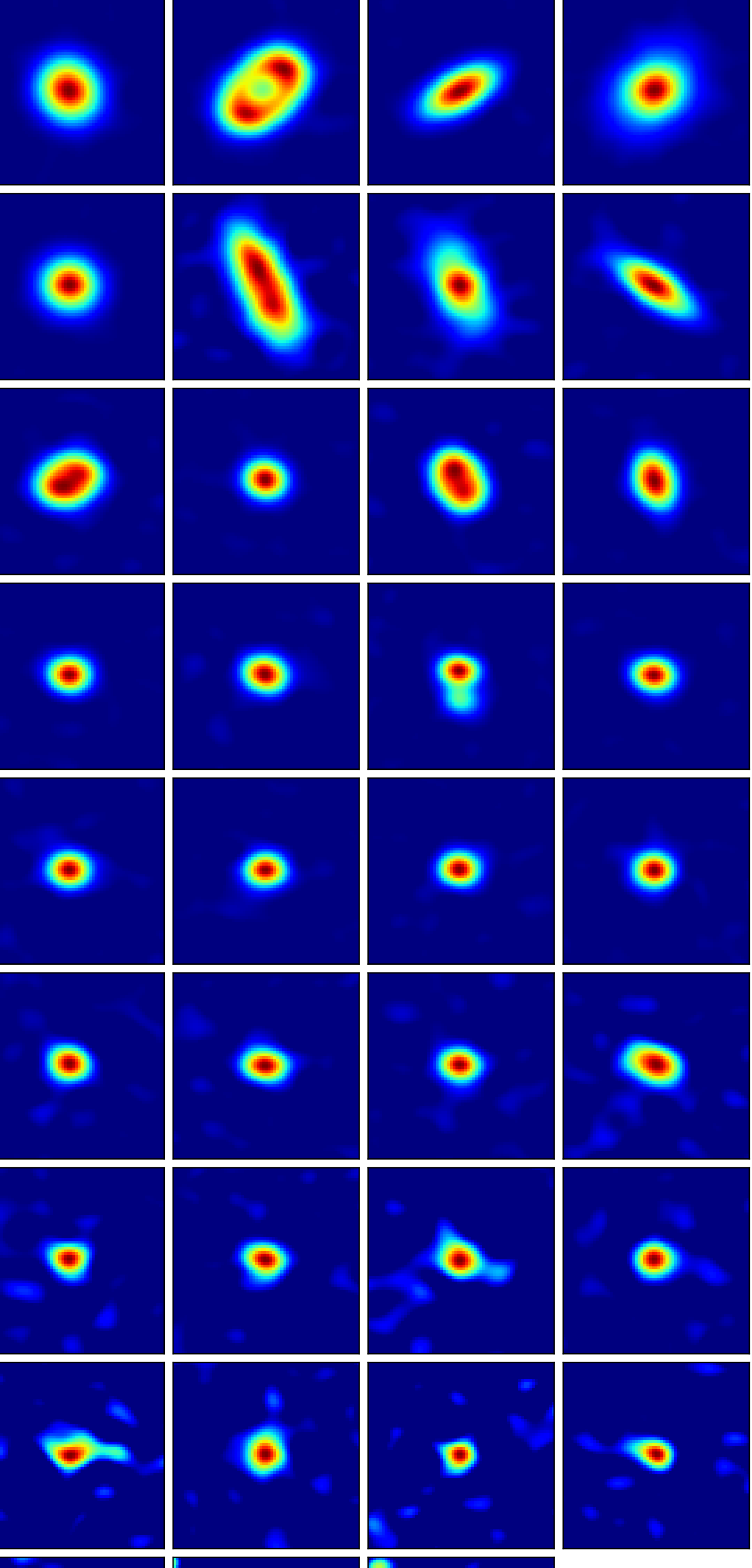
Kwon et al. 2011

# HL Tau (ALMA 1.0 mm)



100 AU

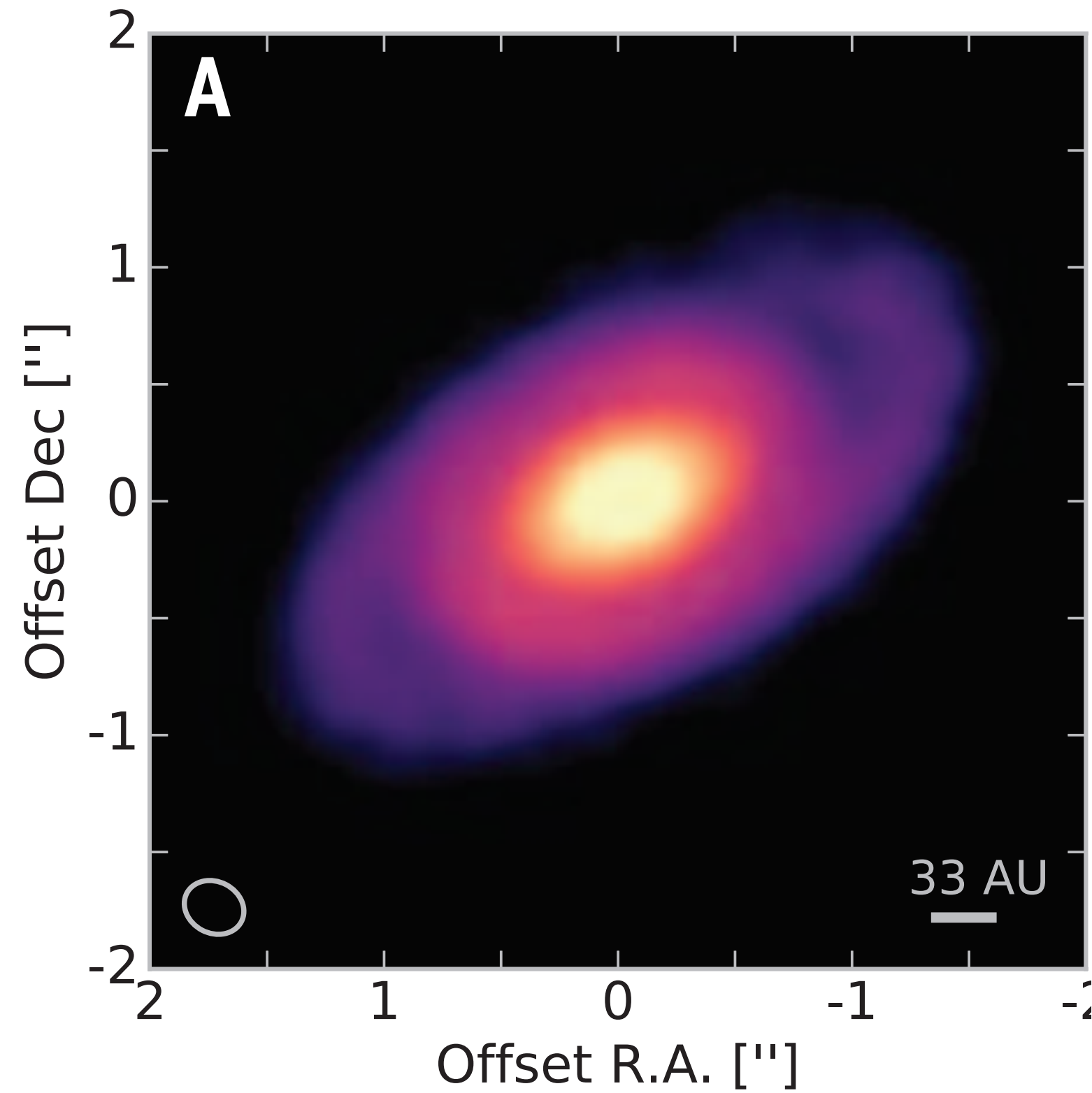






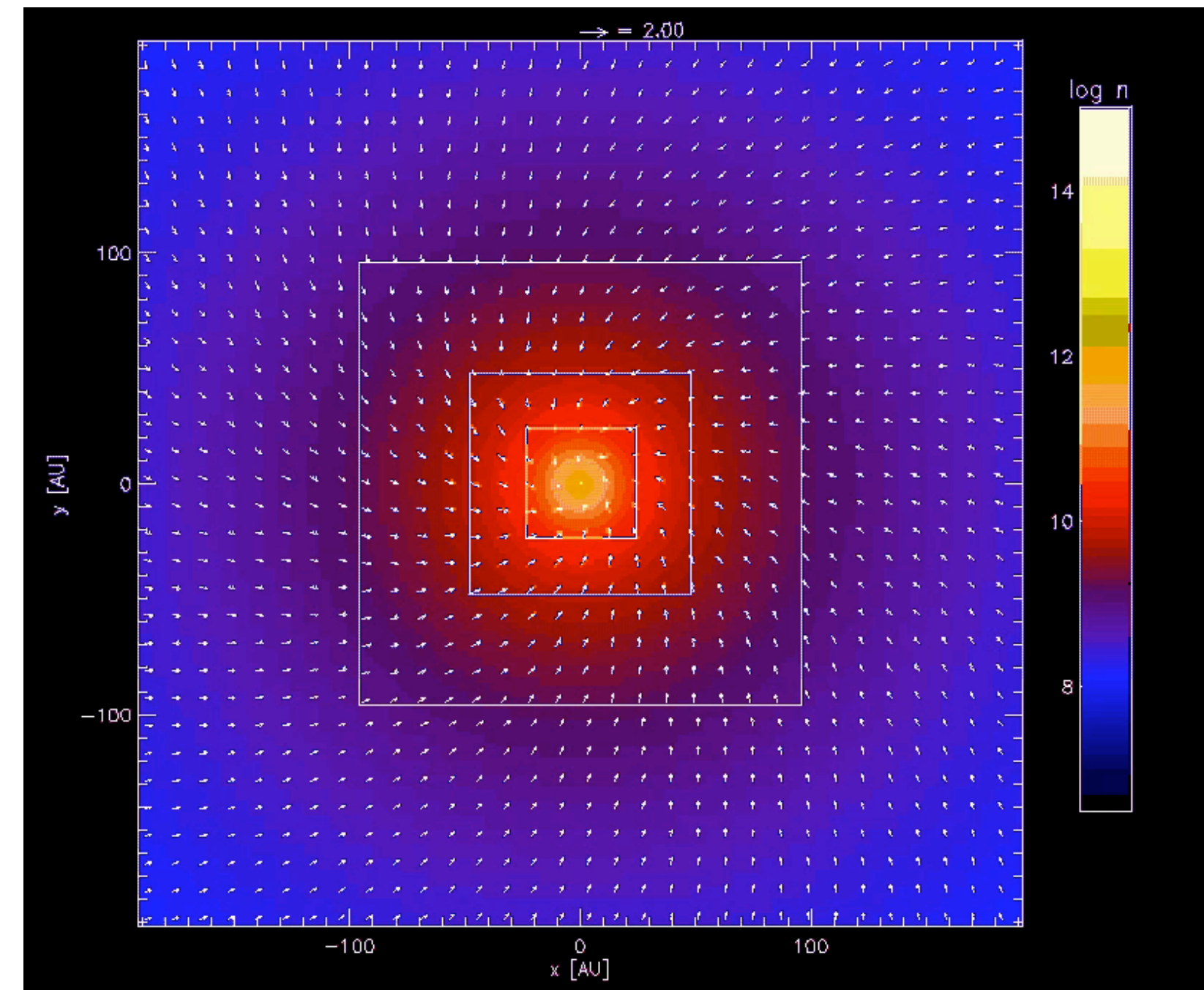
# ALMAで見えた2本の「うで」

観測された原始惑星系円盤 Elias 2-24



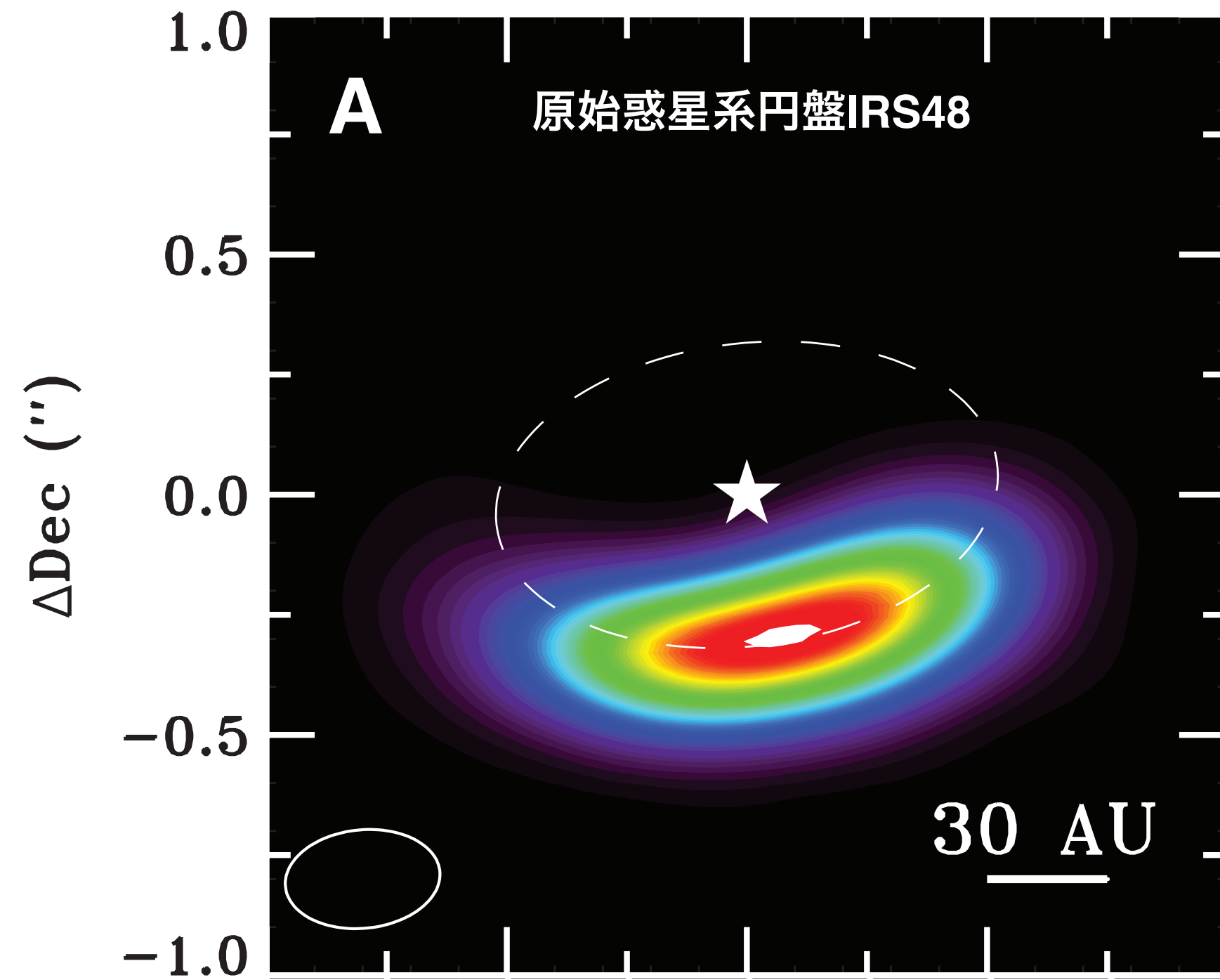
Perez et al. 2016

磁気流体シミュレーション

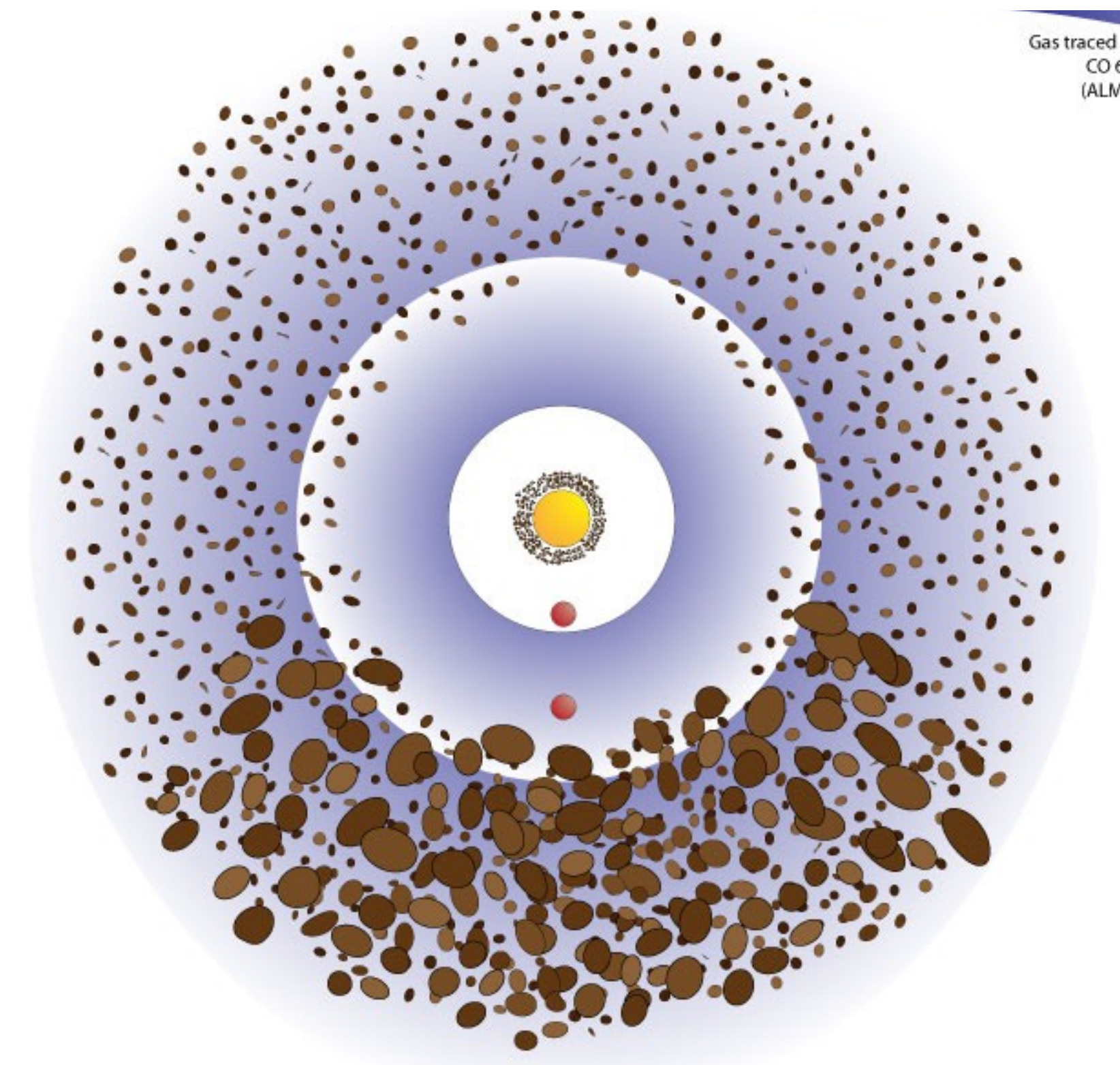


Tomida et al. 2017

# ALMAで見えた「偏った円盤」



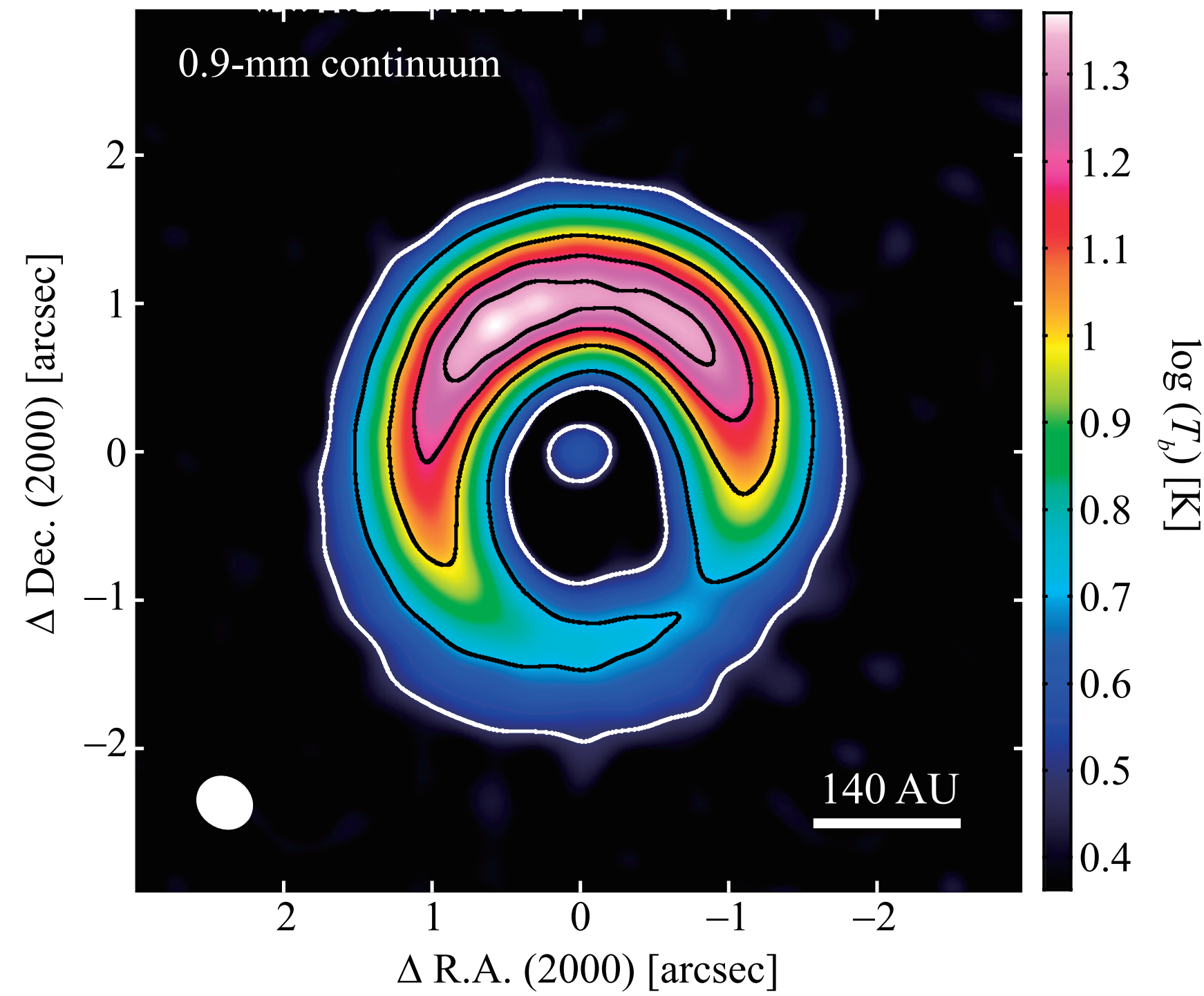
van der Marel et al. 2013



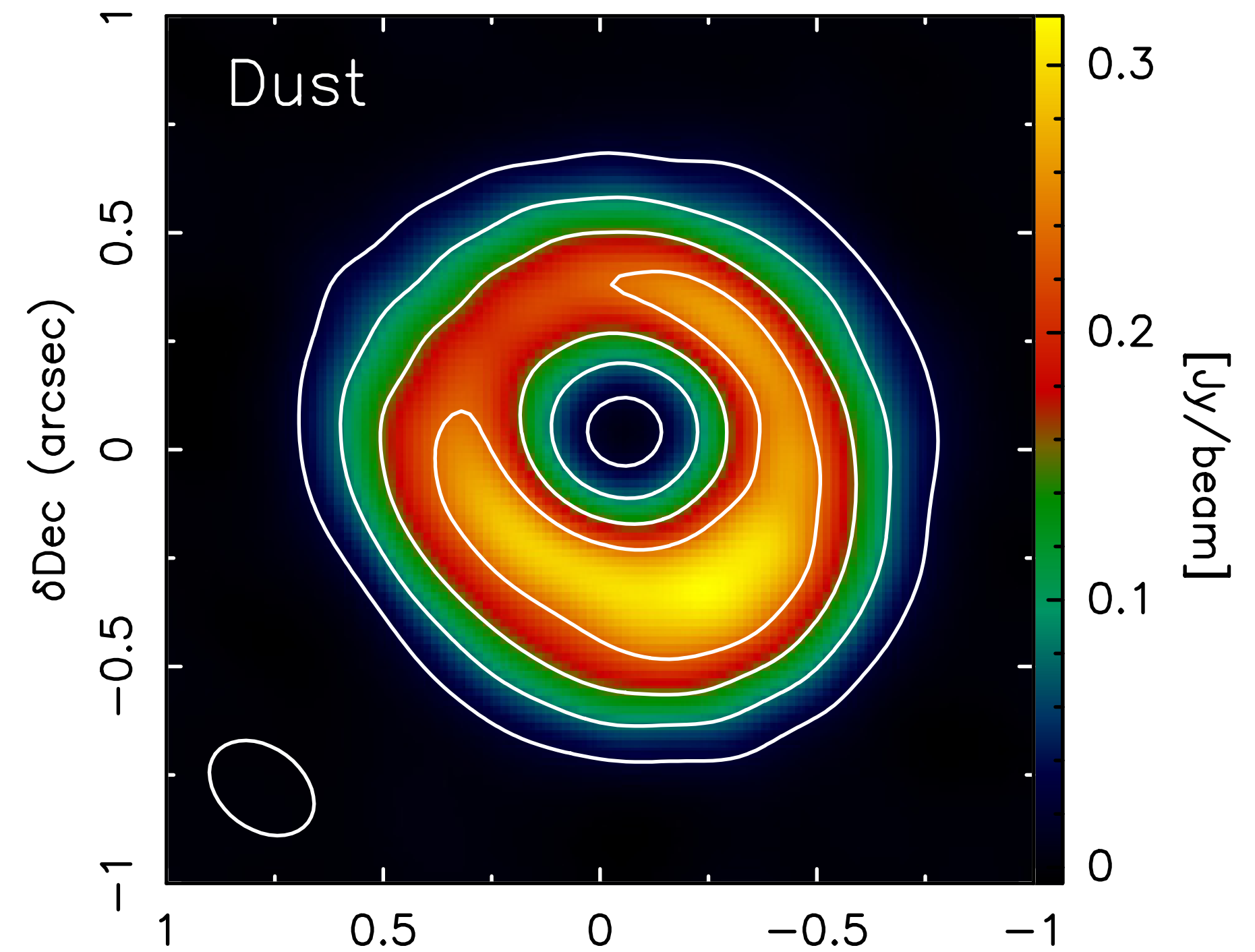
想像図 (van der Marel et al. 2013)

# ALMAで見えた「偏った円盤」

SAO 206462

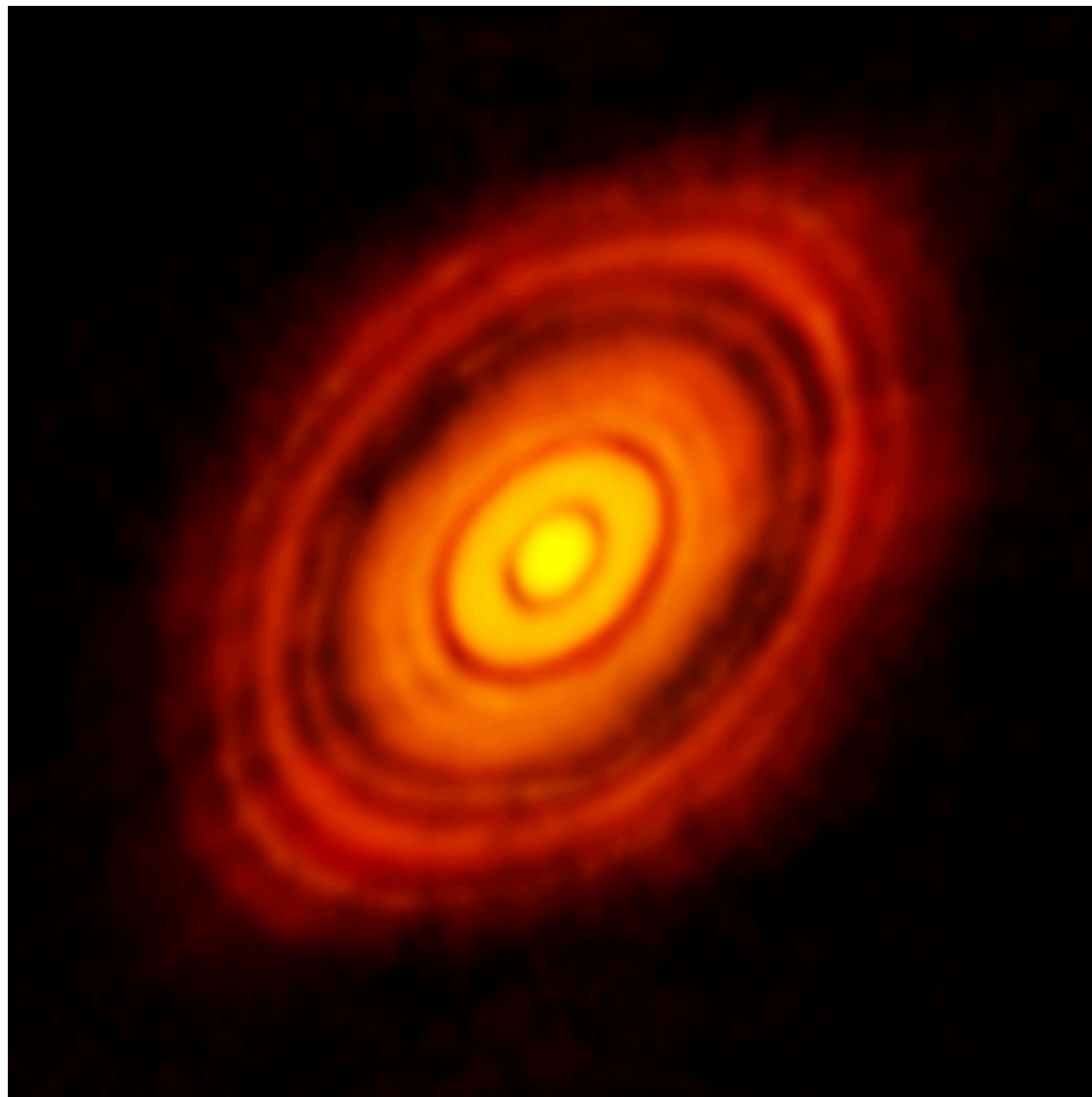


Fukagawa et al. 2013

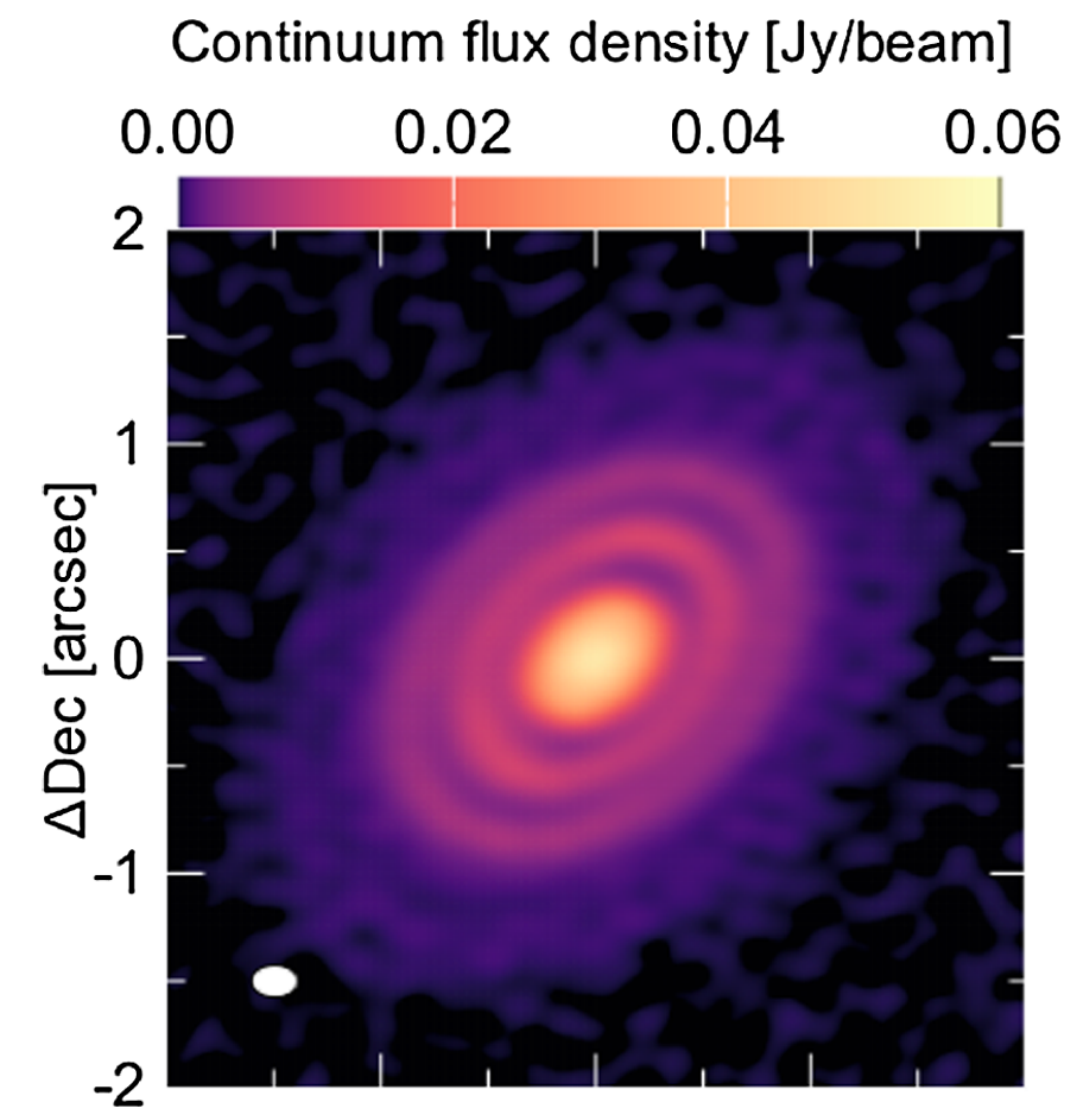


Perez et al. 2014

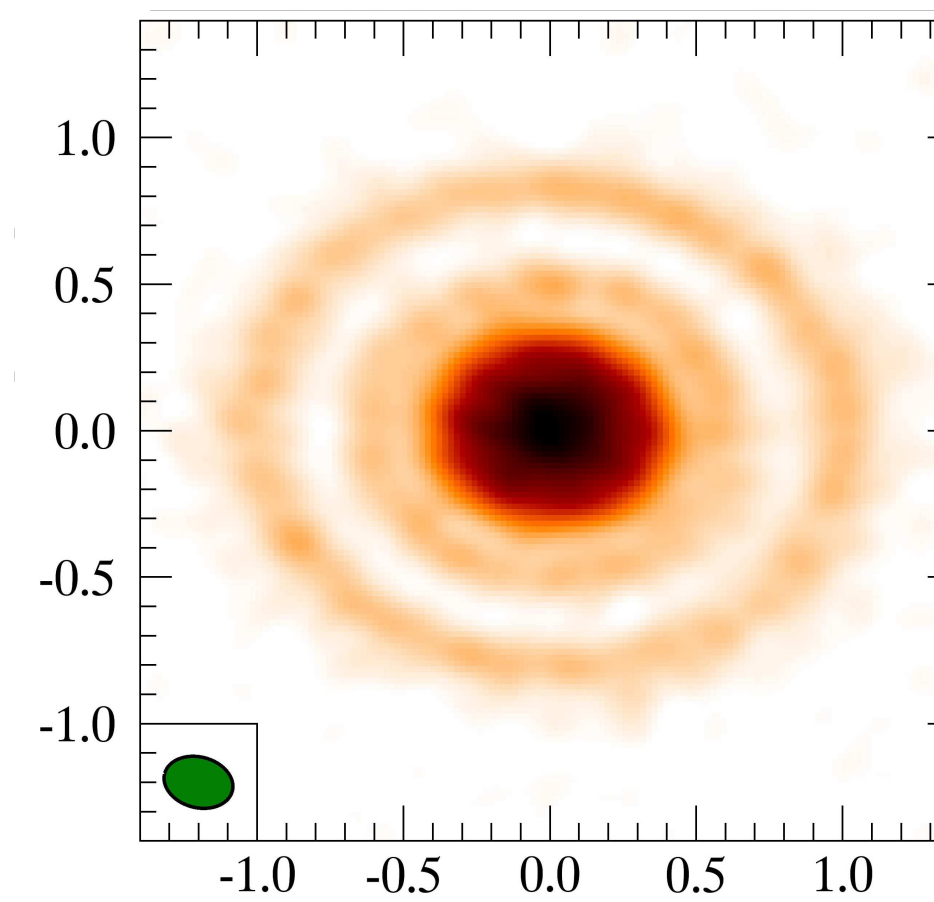
# ALMAで見えた「リング円盤」



ALMA Partnership 2015



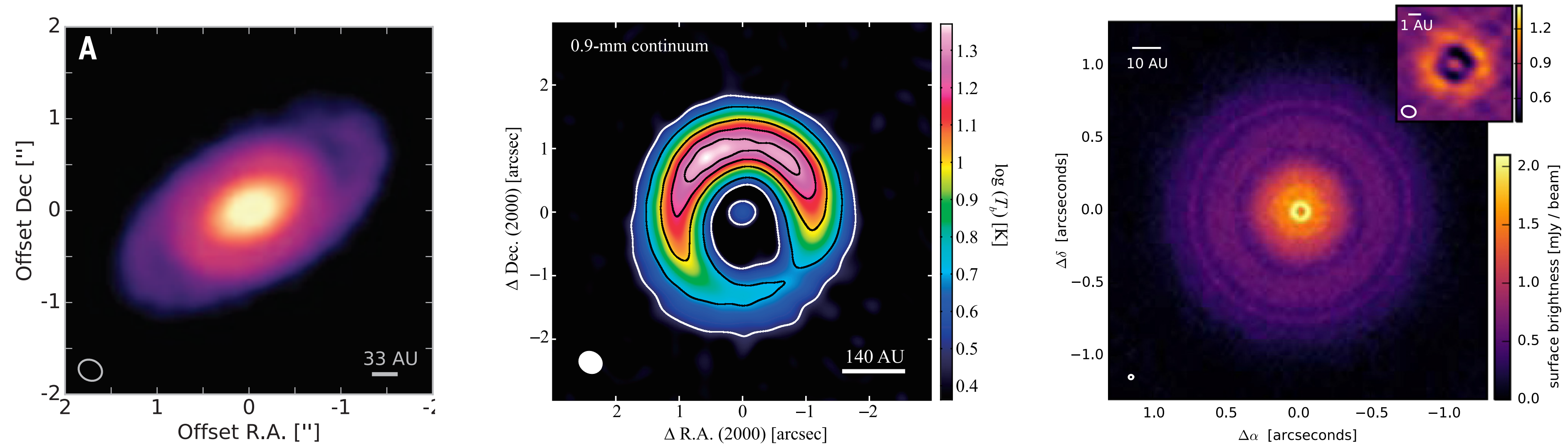
Isella et al. 2016



Fedele et al. 2018

# アルマで見た原始惑星系円盤

- アルマ以前は「円盤状のものがありそう」と思われていただけだったが...

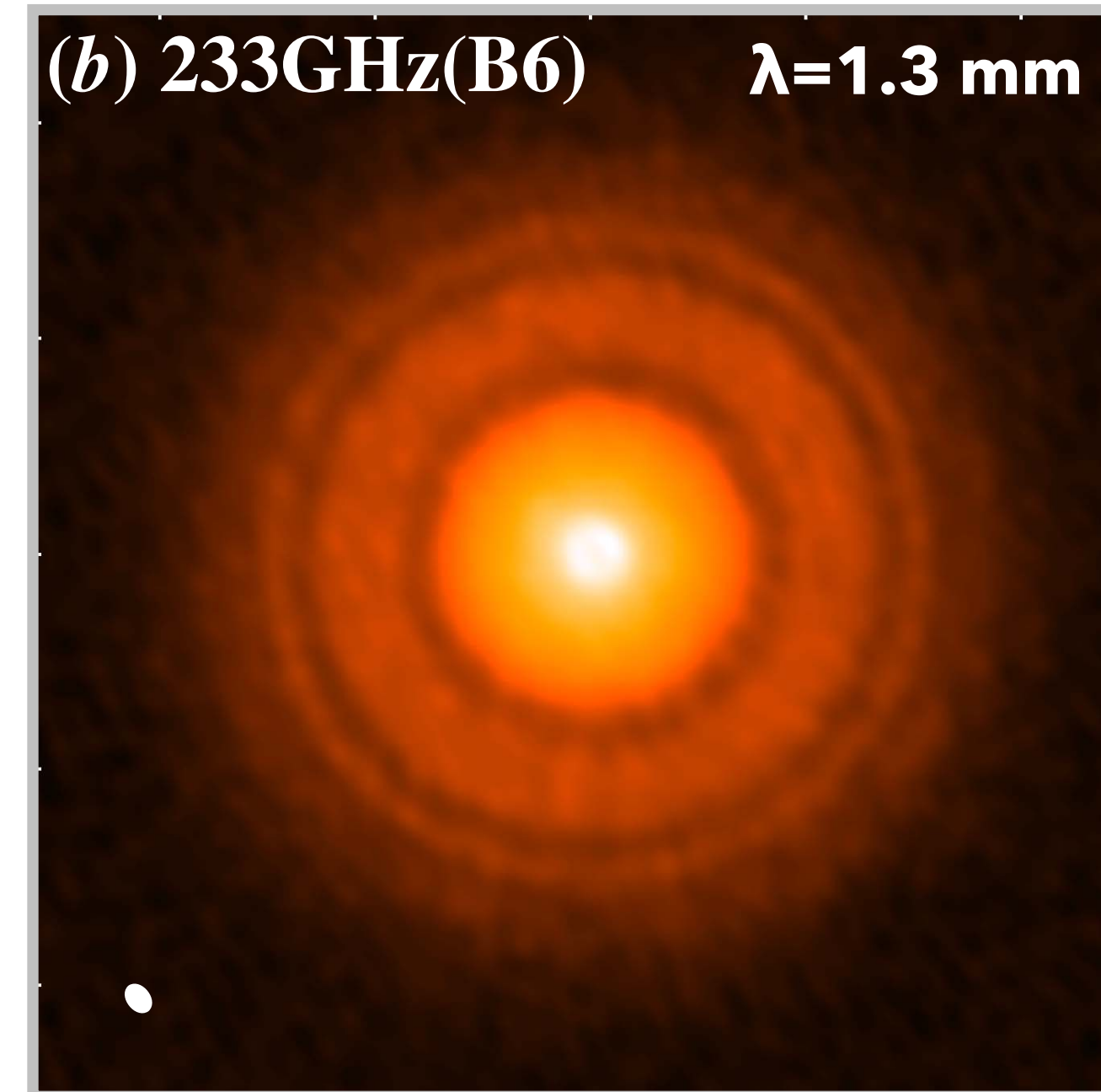
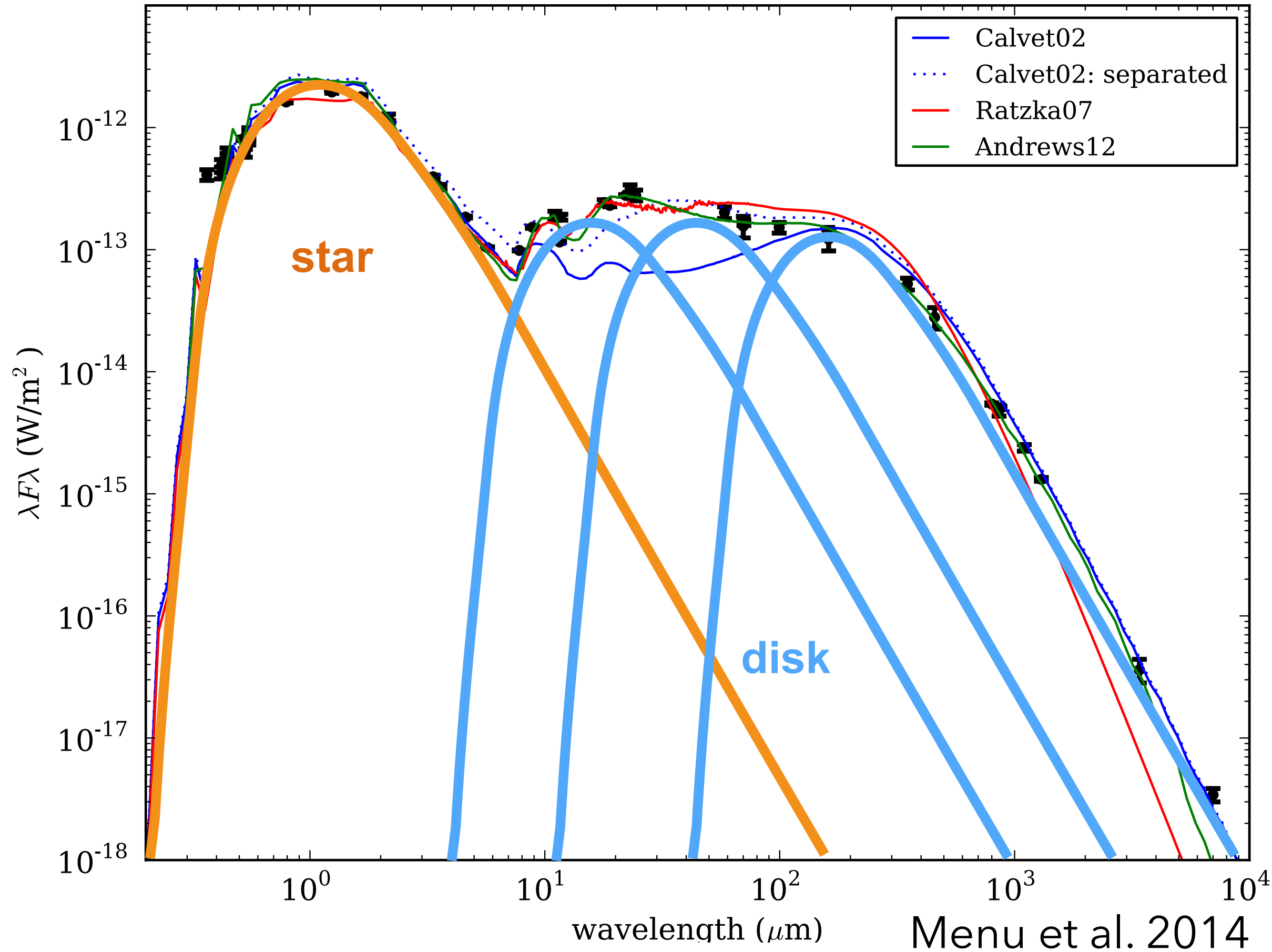


- 若い円盤→2本の腕が示すダイナミックな動き
- 偏った円盤→惑星誕生中か？
- リング・ギャップ構造→惑星がギャップの中にいる？

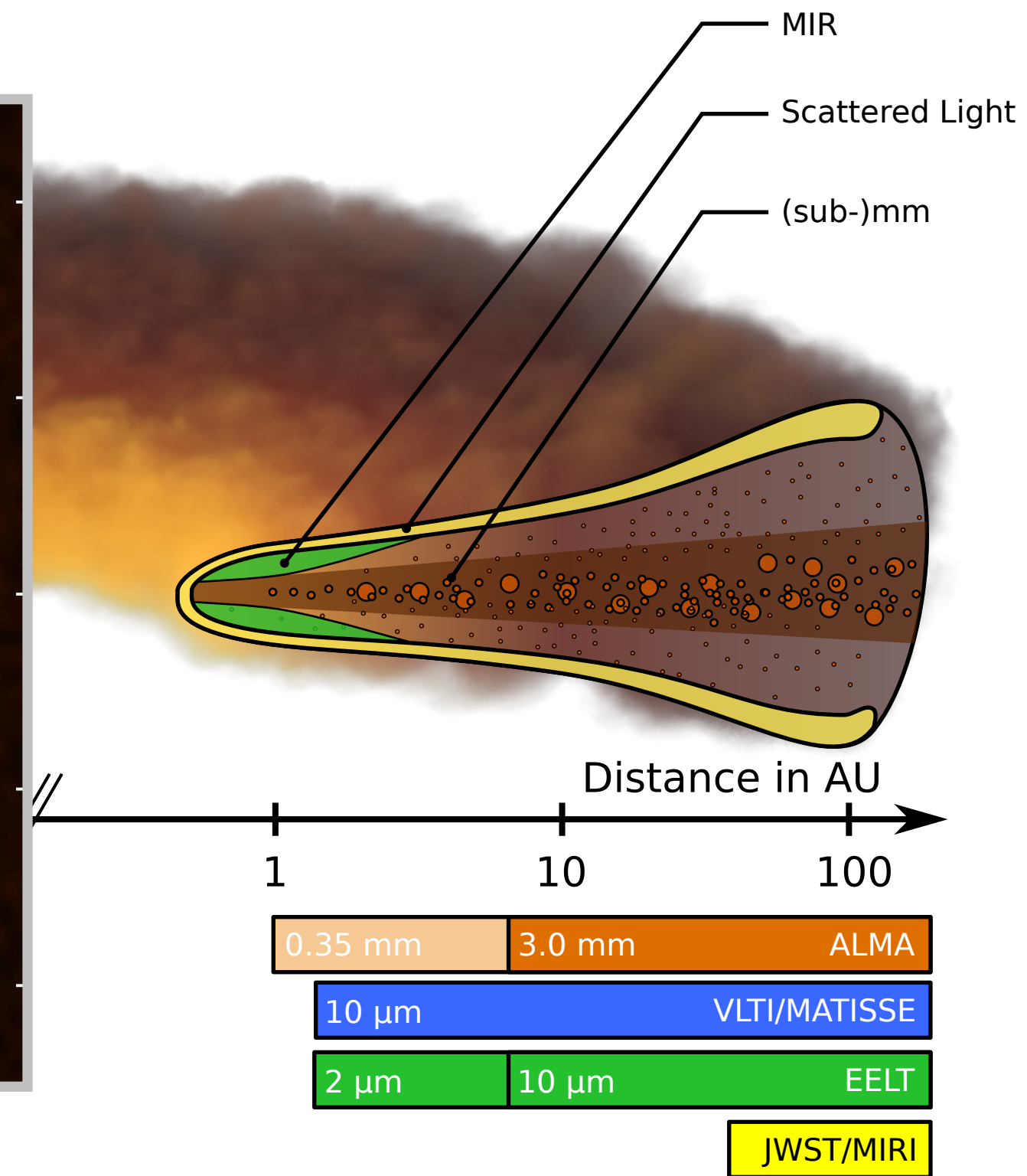
アルマで惑星形成の現場の姿がわかってきた。

# Protoplanetary disks - birthplace of planets

- TW Hya ( $M_{\text{star}} = 0.6 M_{\odot}$ ,  $T_{\text{eff}} = 4000 \text{ K}$ )  
SED



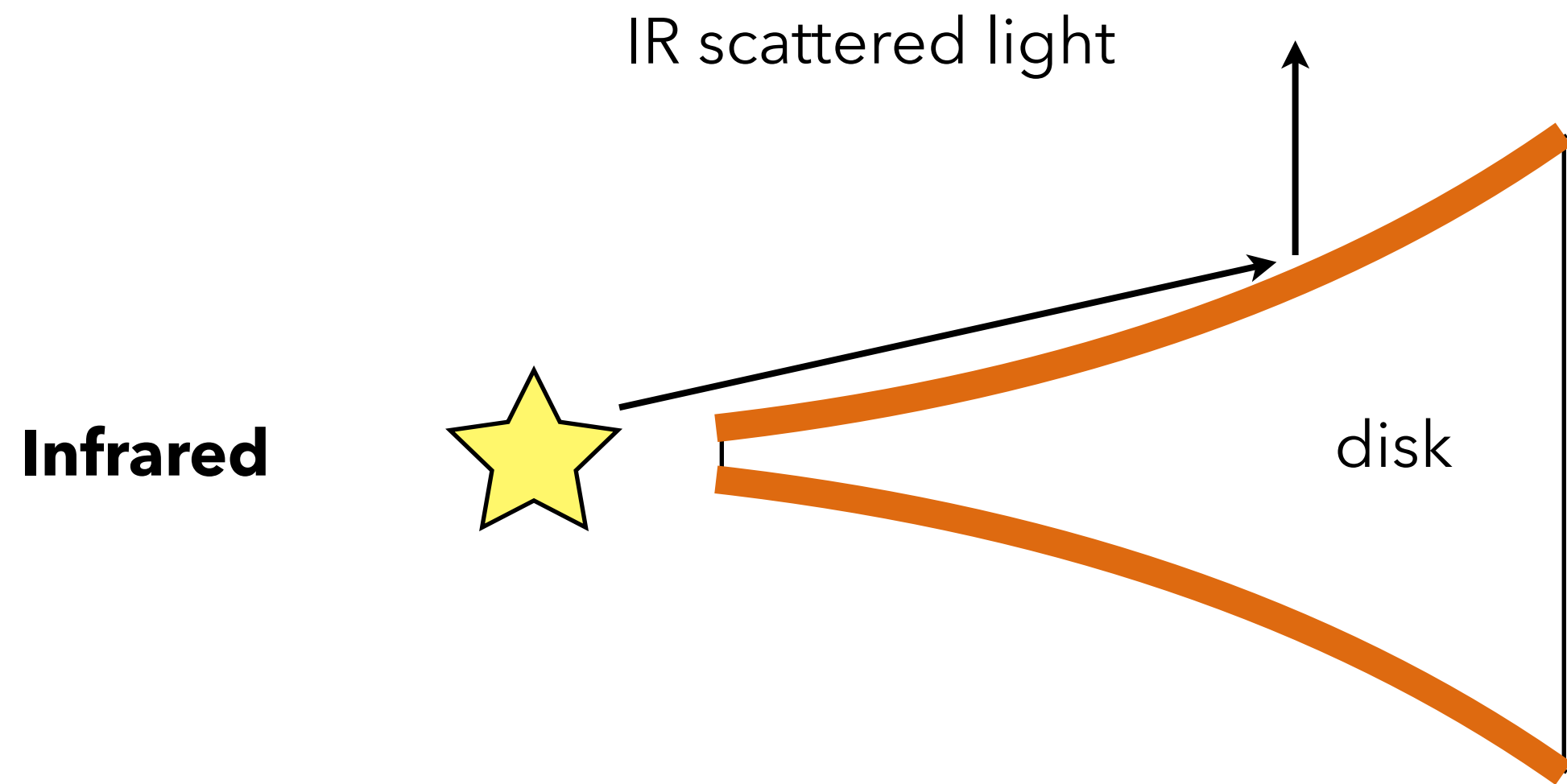
Tsukagoshi et al. 2016



Testi et al. 2014

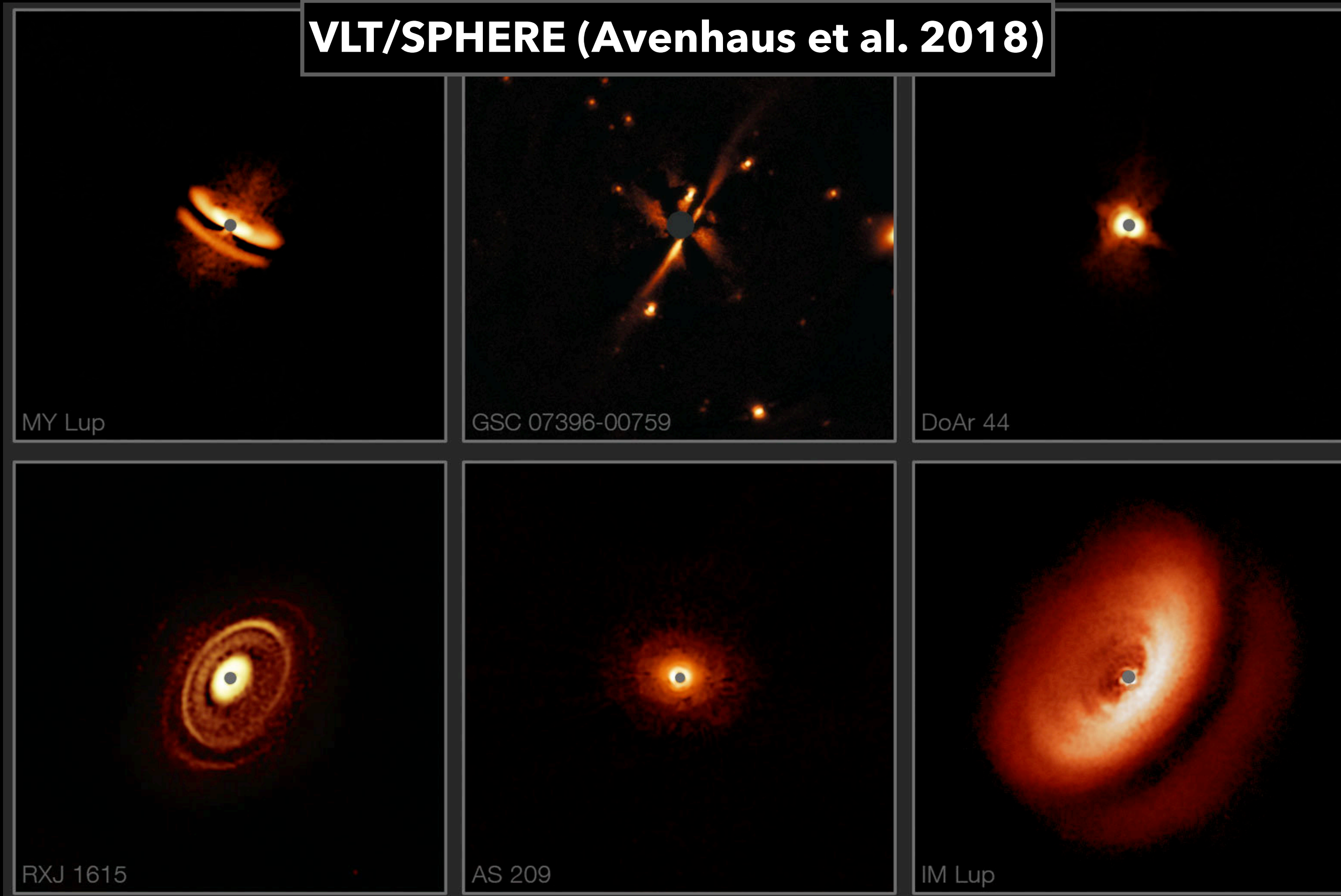
- We observe midplane at millimeter wavelengths
- Disks have sub-structures at ~10 au scales
  - Physical origin is under discussion

# Infrared polarization

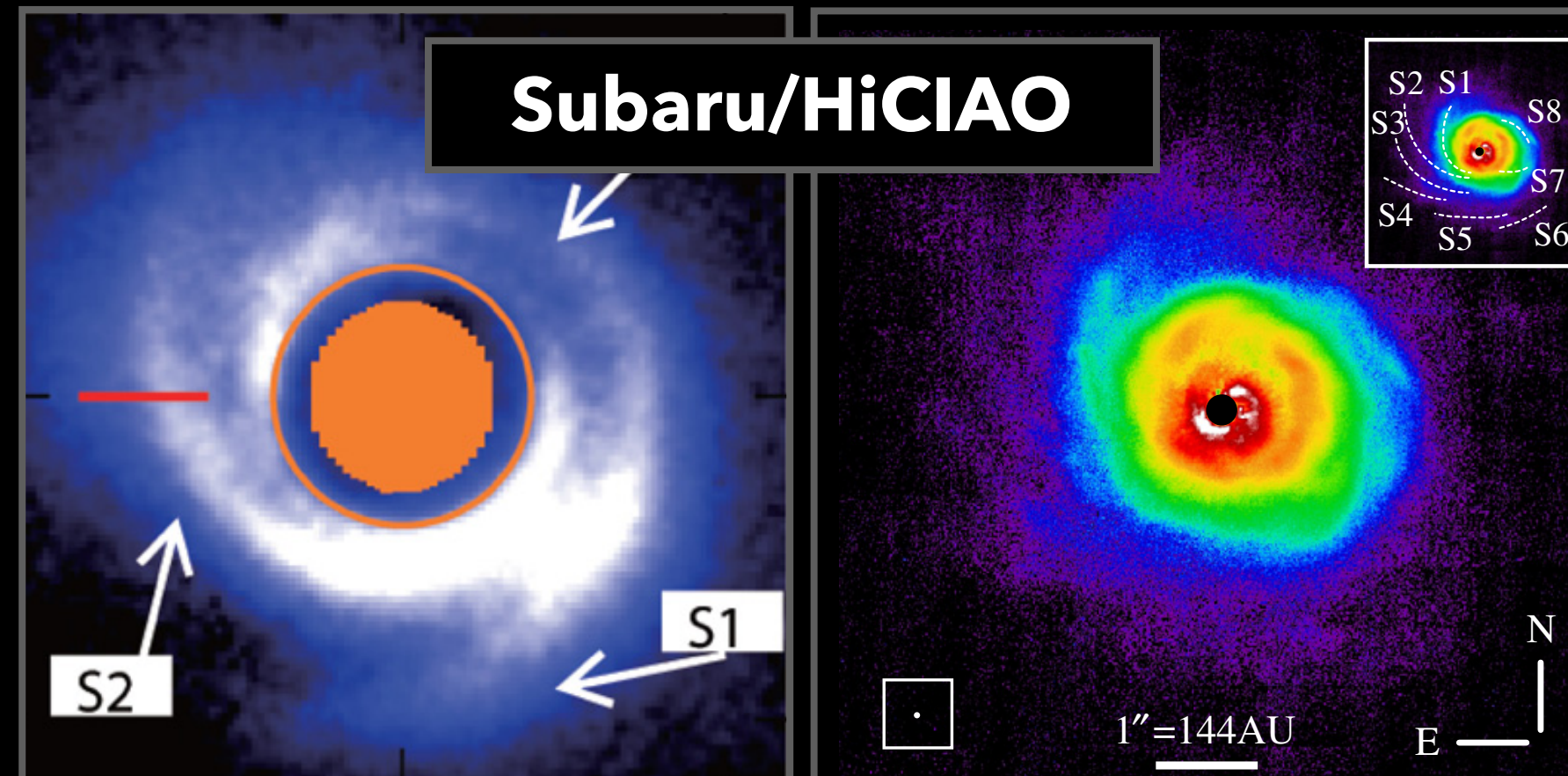


- We observe scattered light with infrared polarization
- Infrared polarization traces the surface layer
  - Full of structures (such as spiral arms)

VLT/SPHERE (Avenhaus et al. 2018)

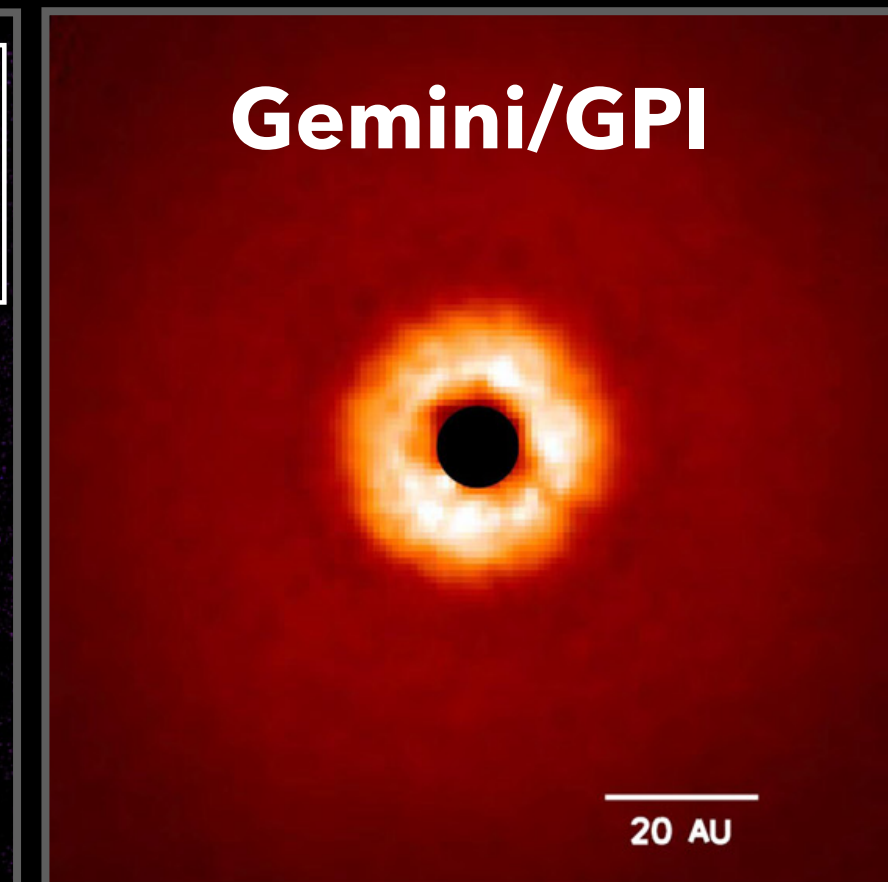


Subaru/HiCIAO



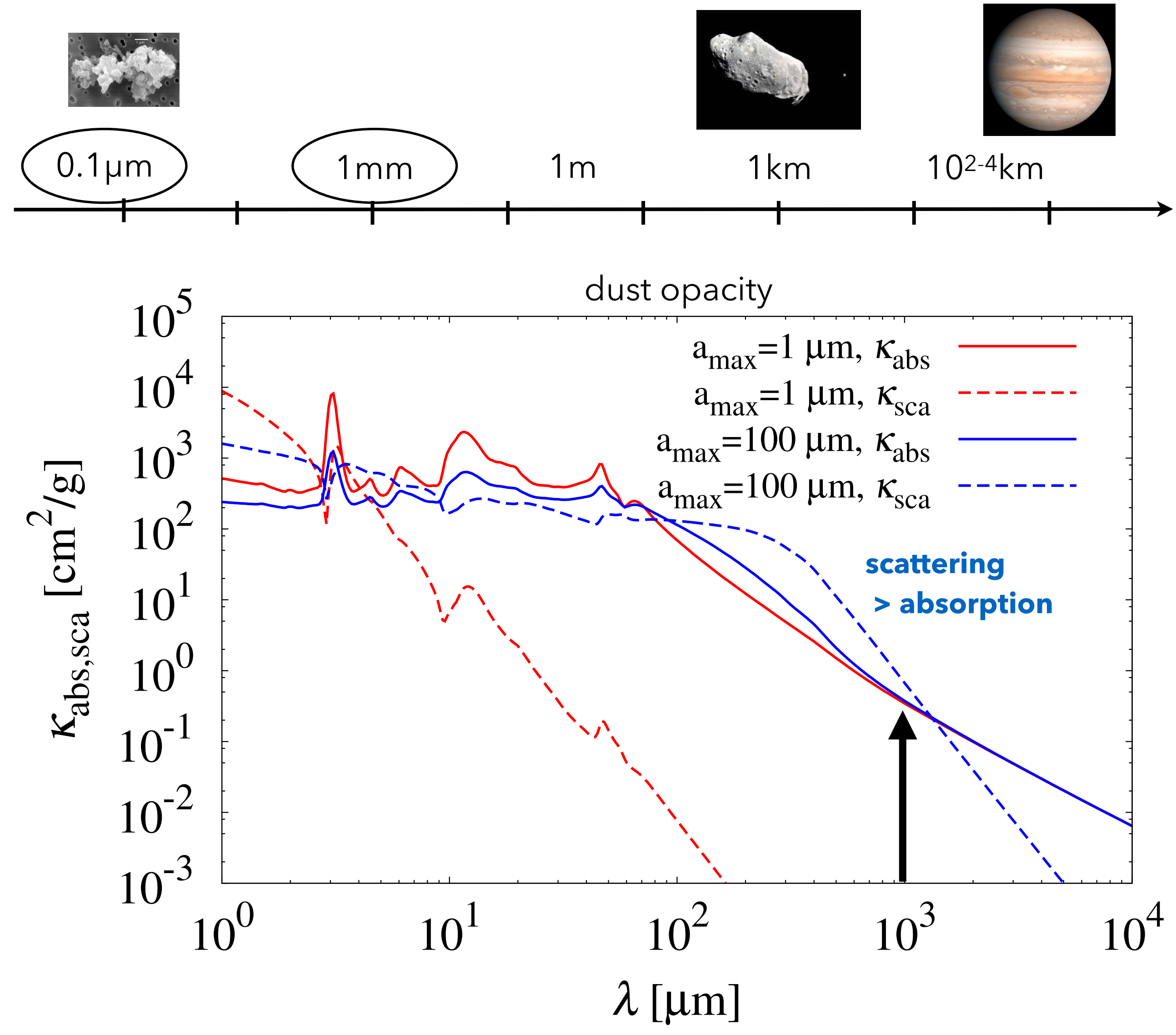
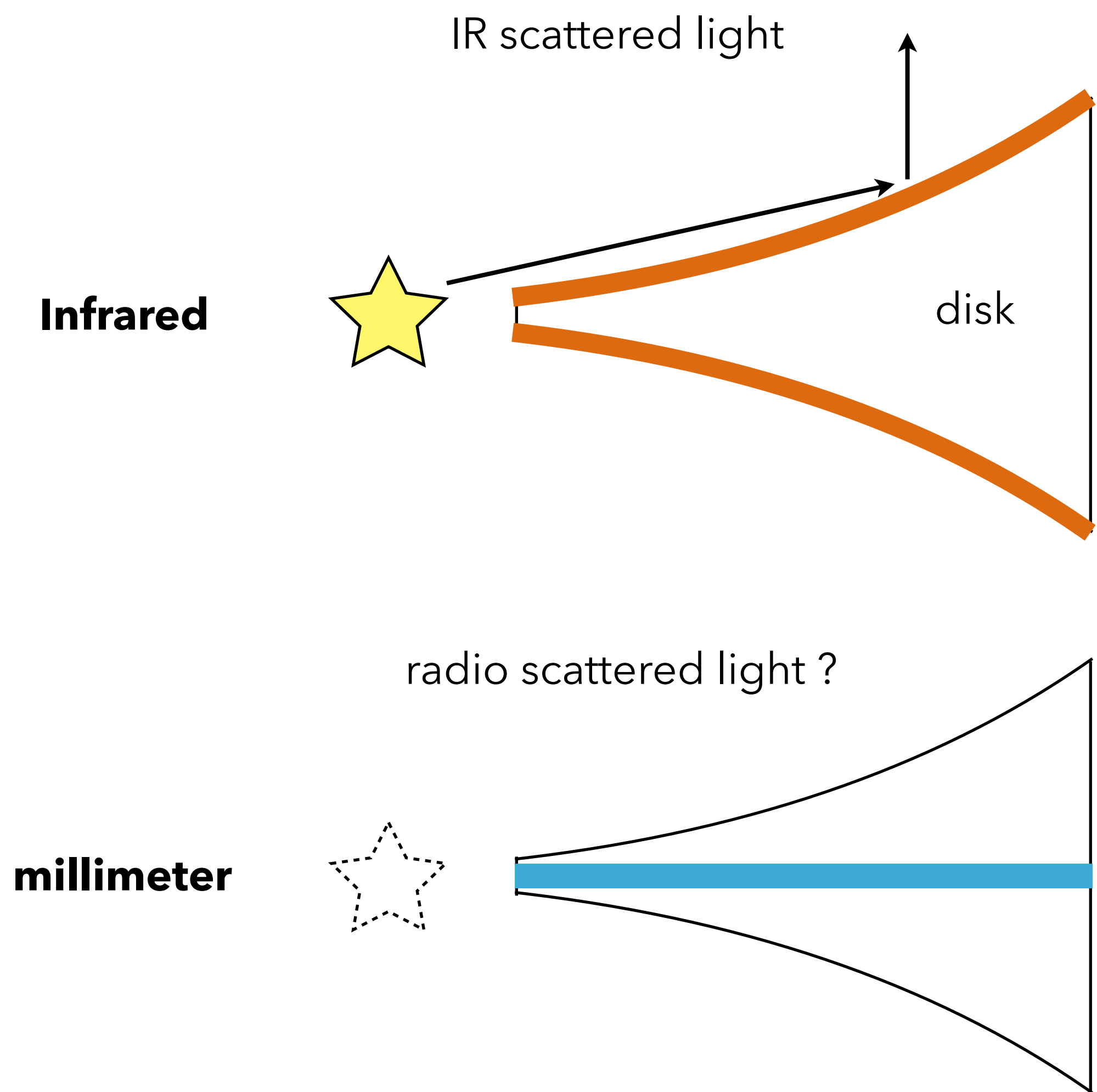
(Muto et al. 2012, Hashimoto et al. 2011)

Gemini/GPI



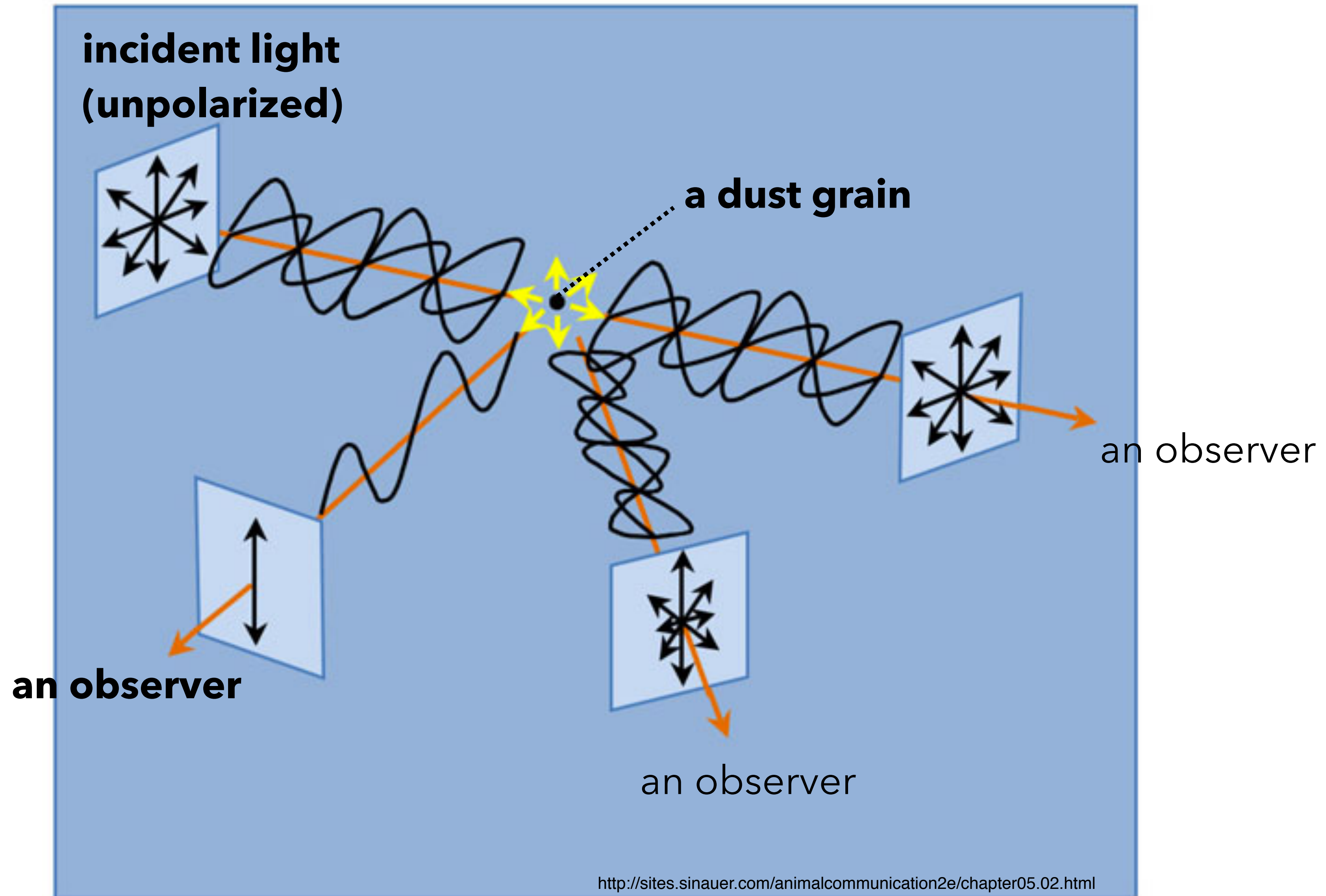
(Rapson et al. 2015)

# Scattering-induced polarization

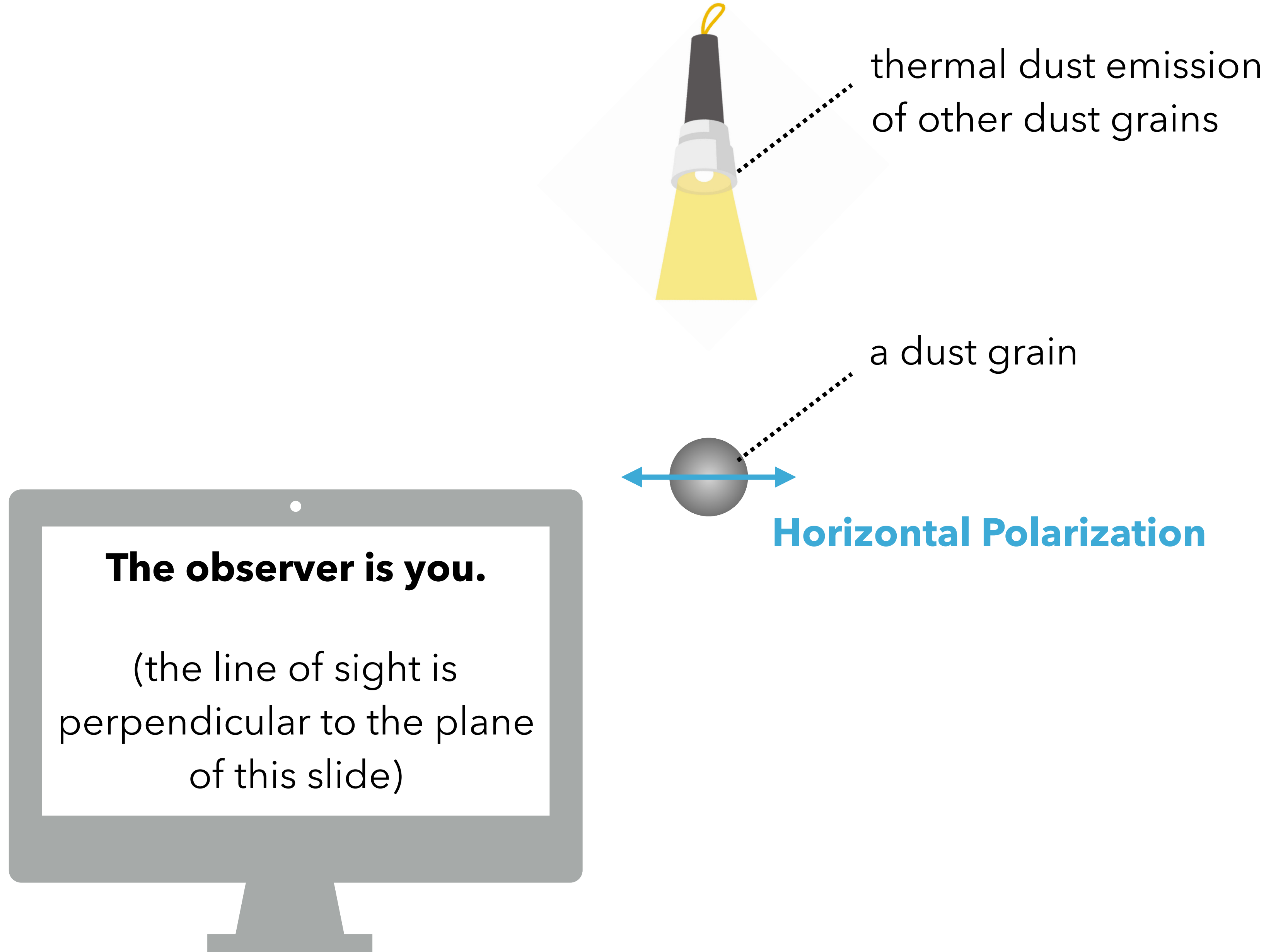




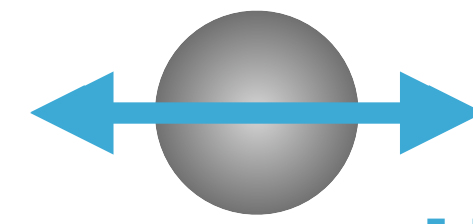
# Polarization due to scattering



# Polarization due to scattering



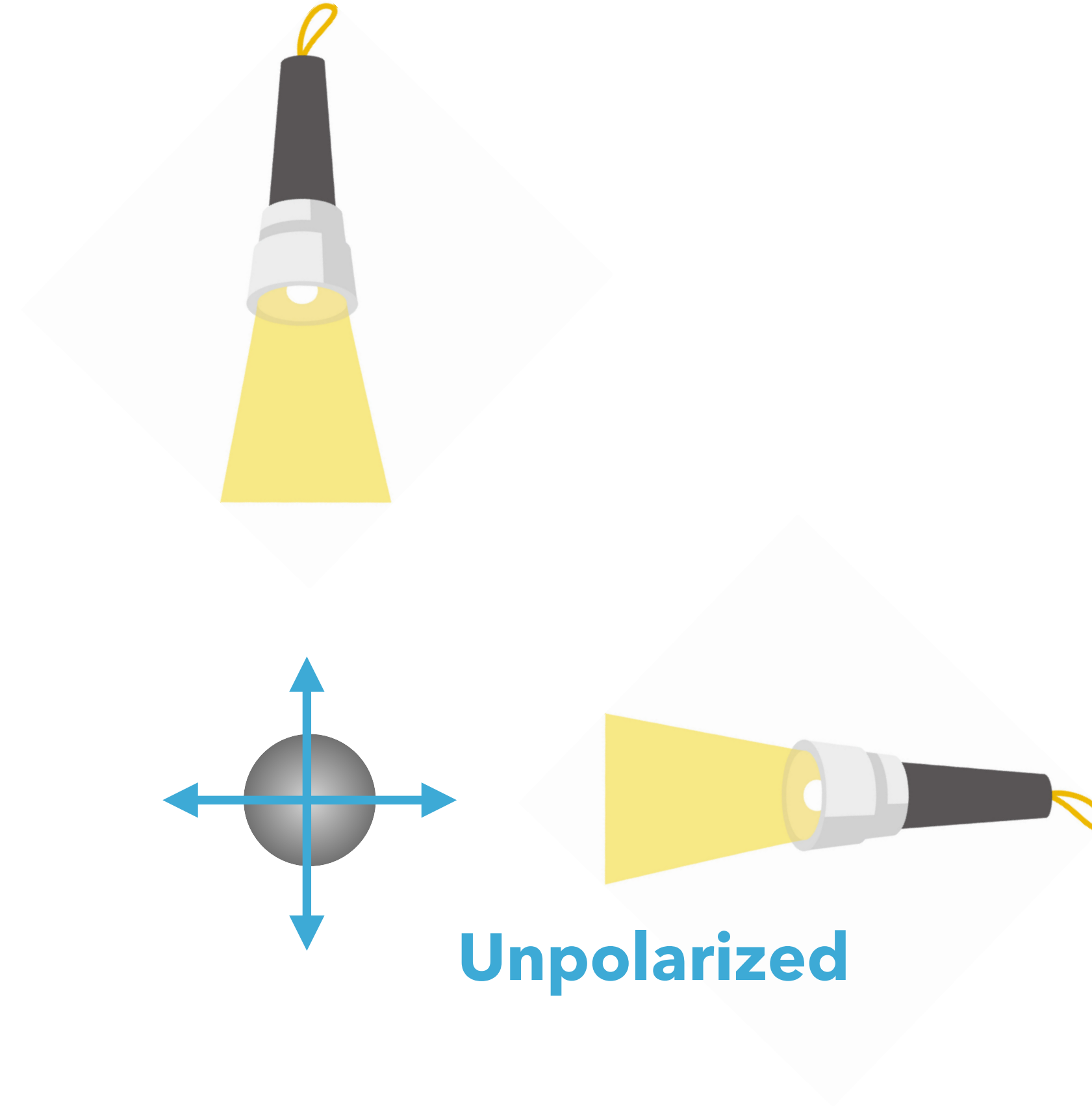
# Polarization due to scattering



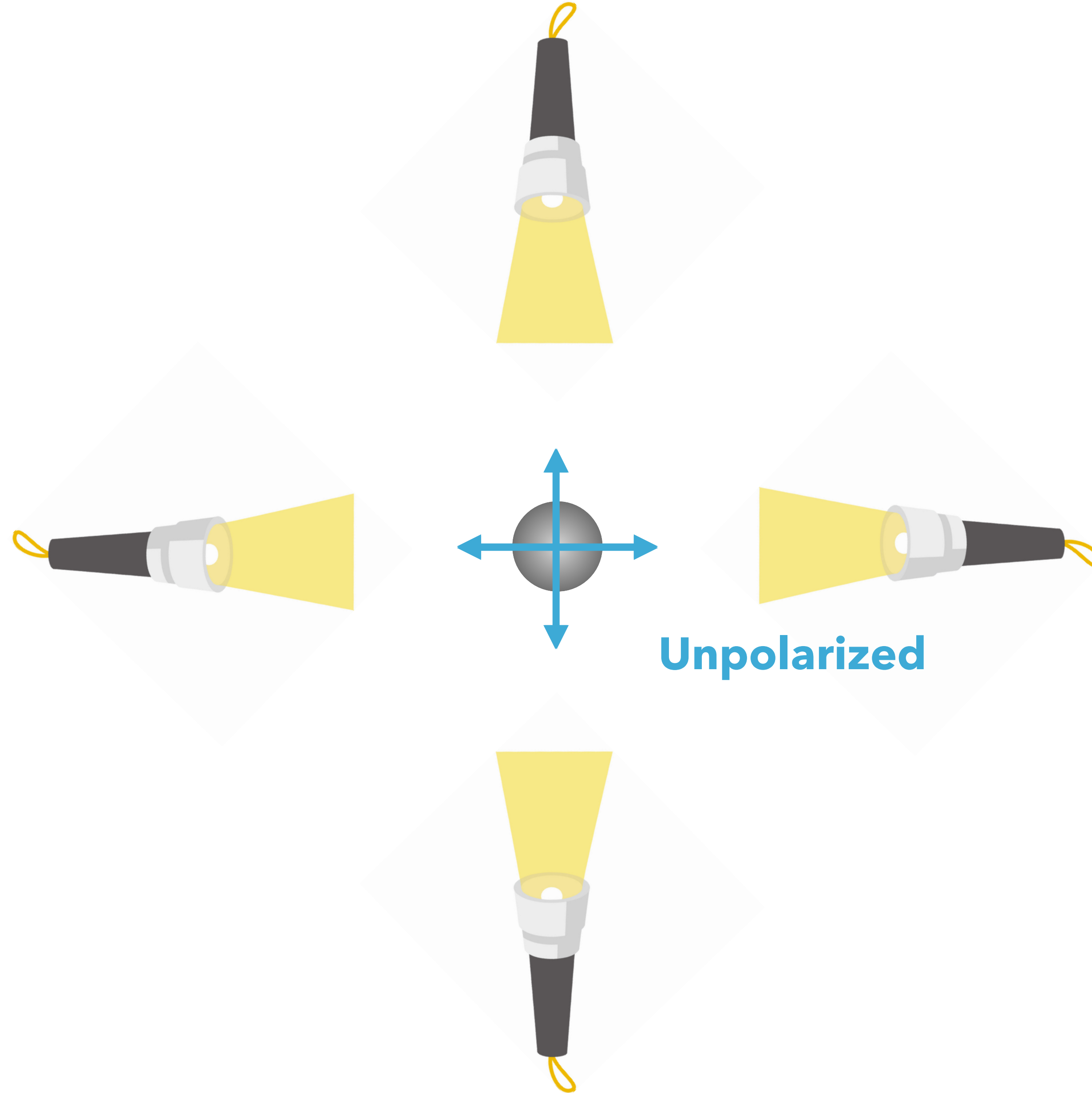
**Horizontal Polarization**



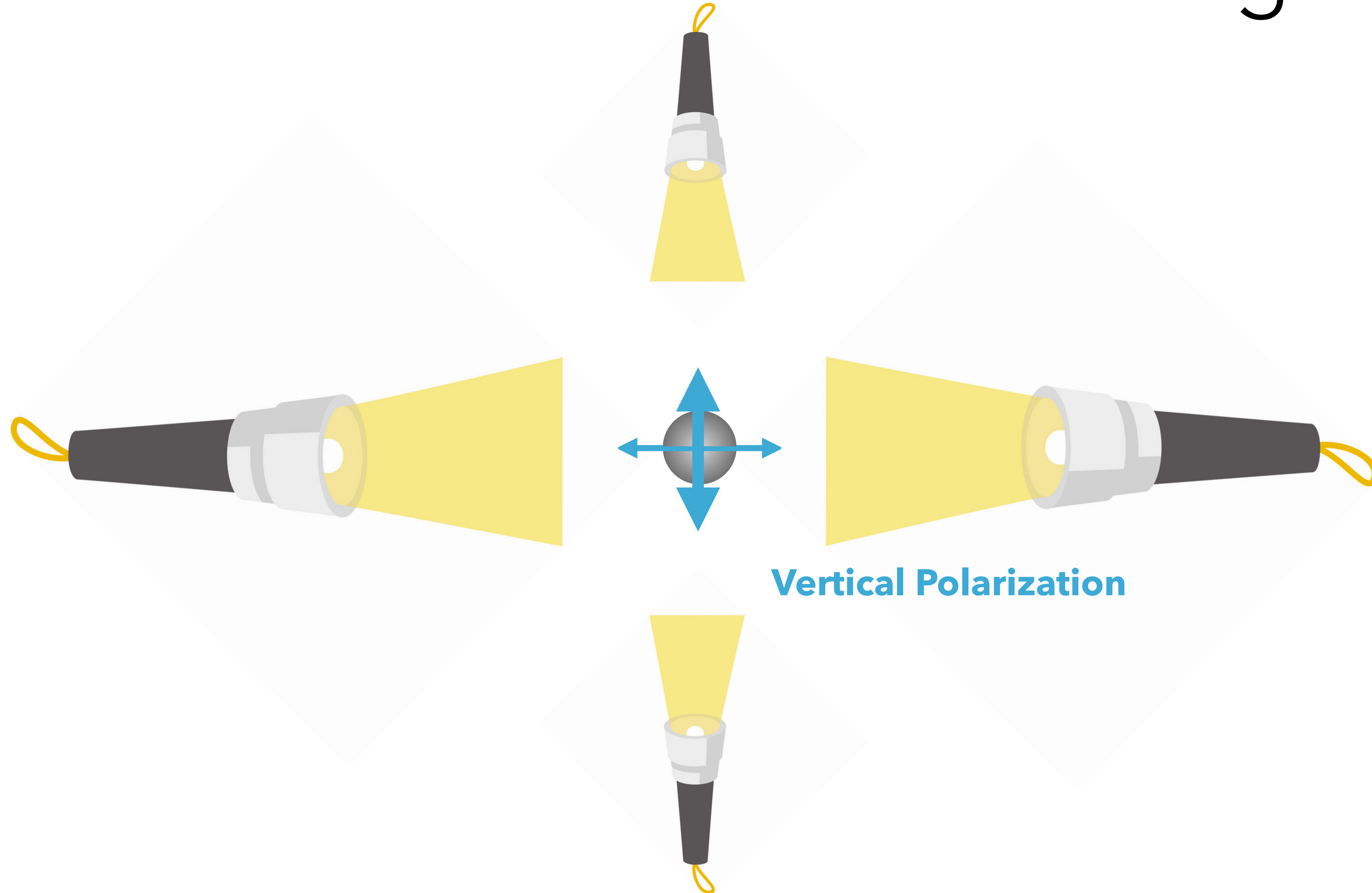
# Polarization due to scattering

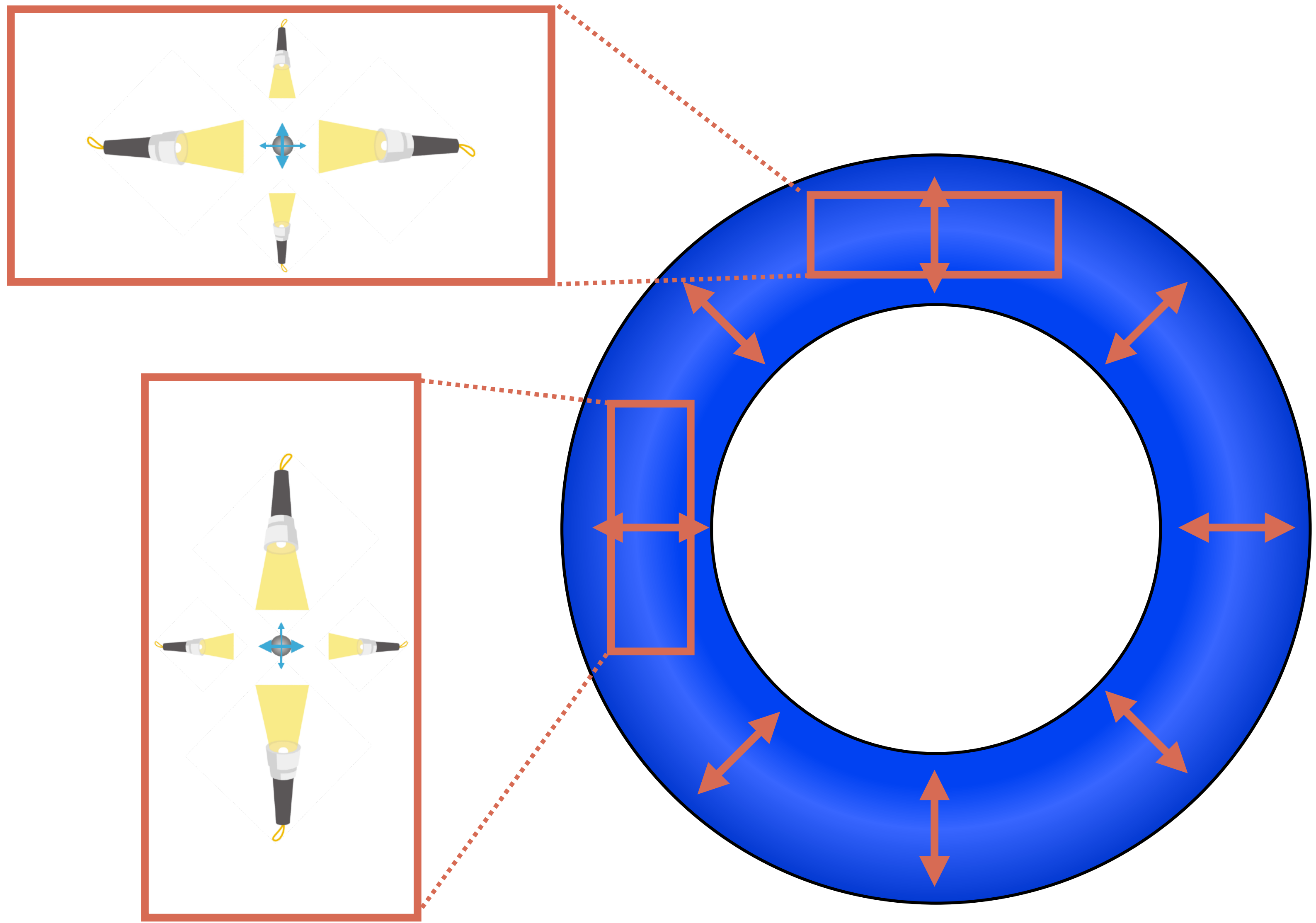


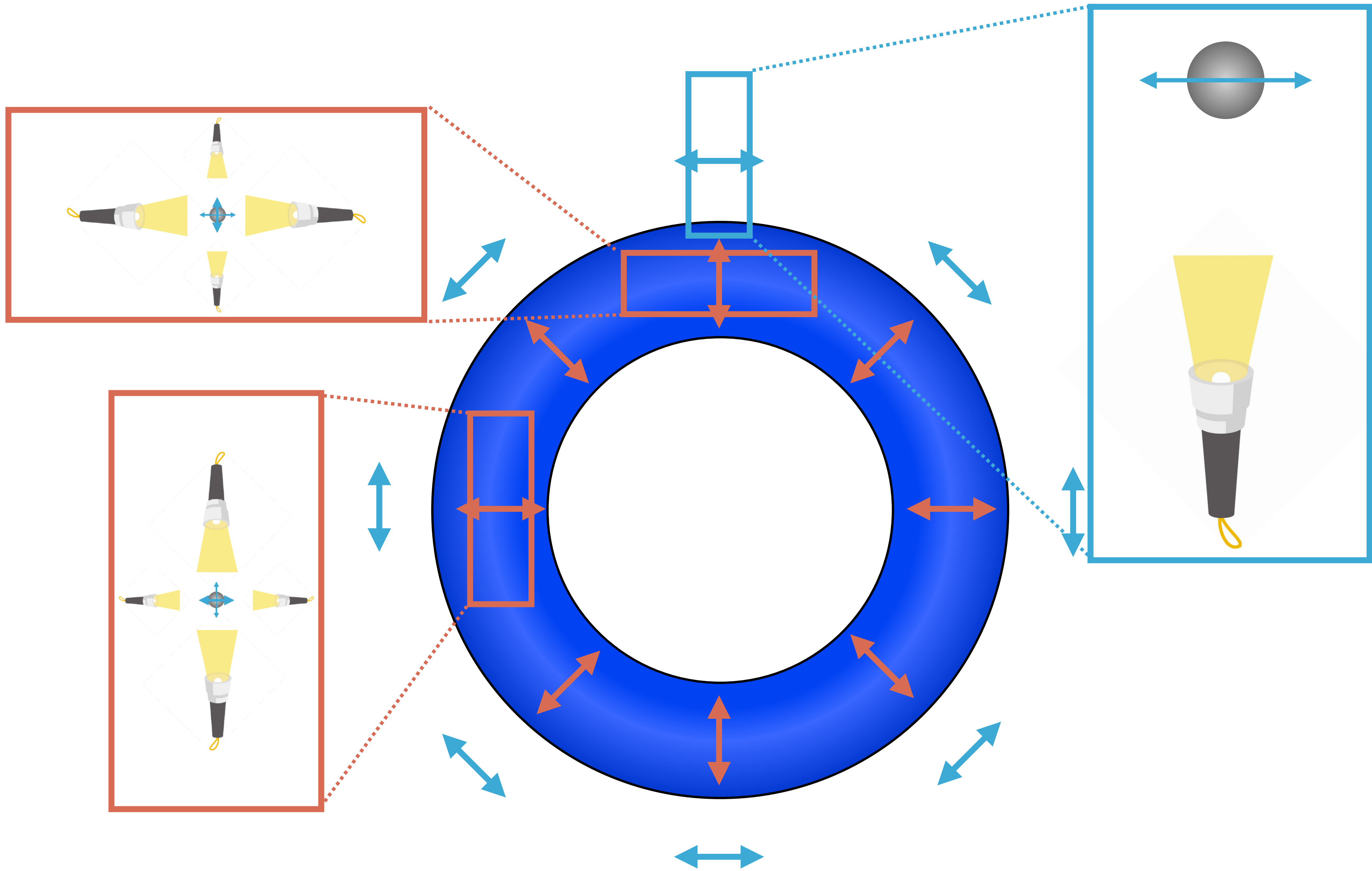
# Polarization due to scattering



# Polarization due to scattering

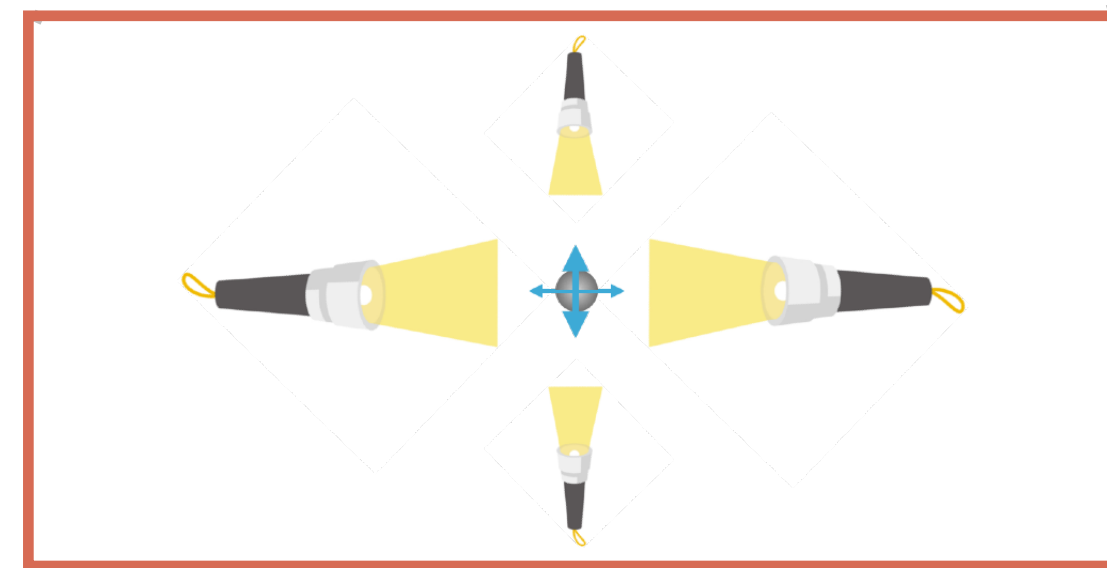
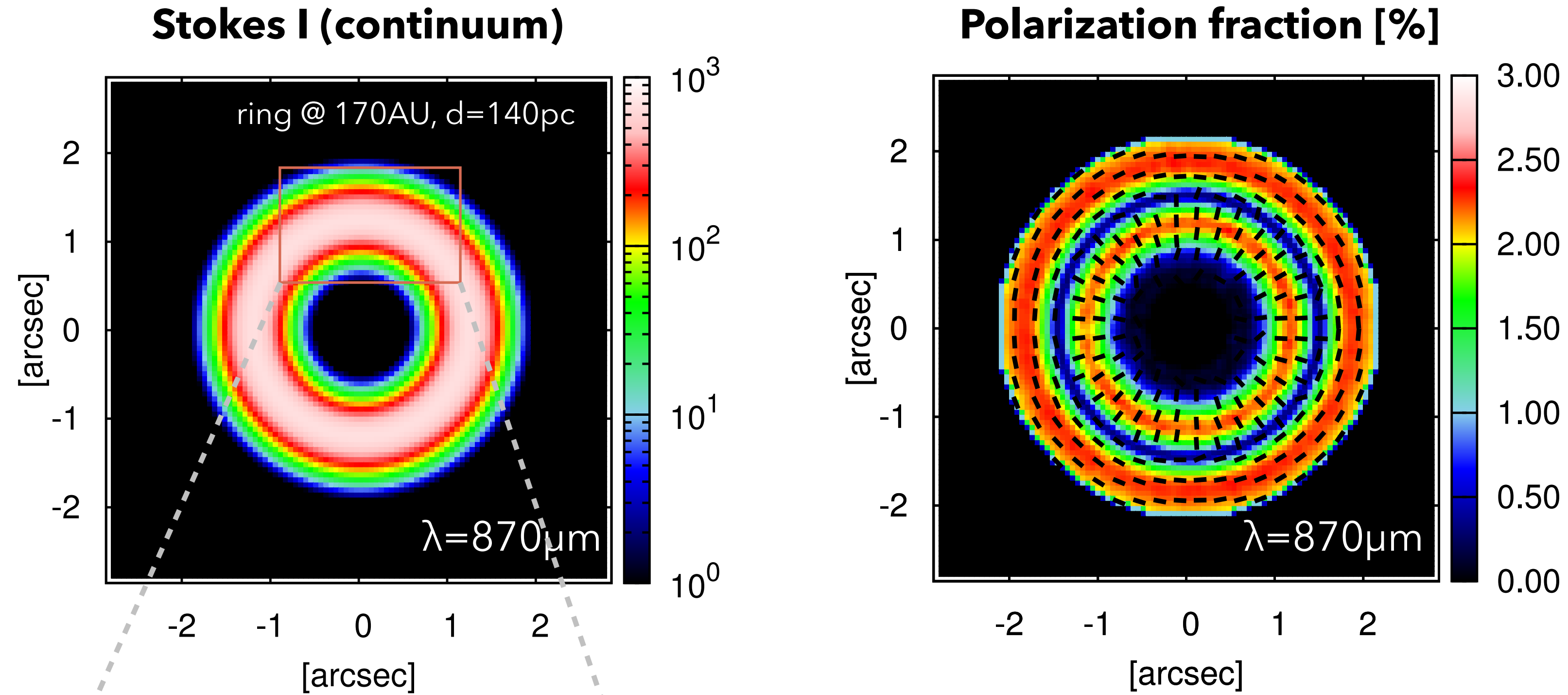








# Theoretical prediction

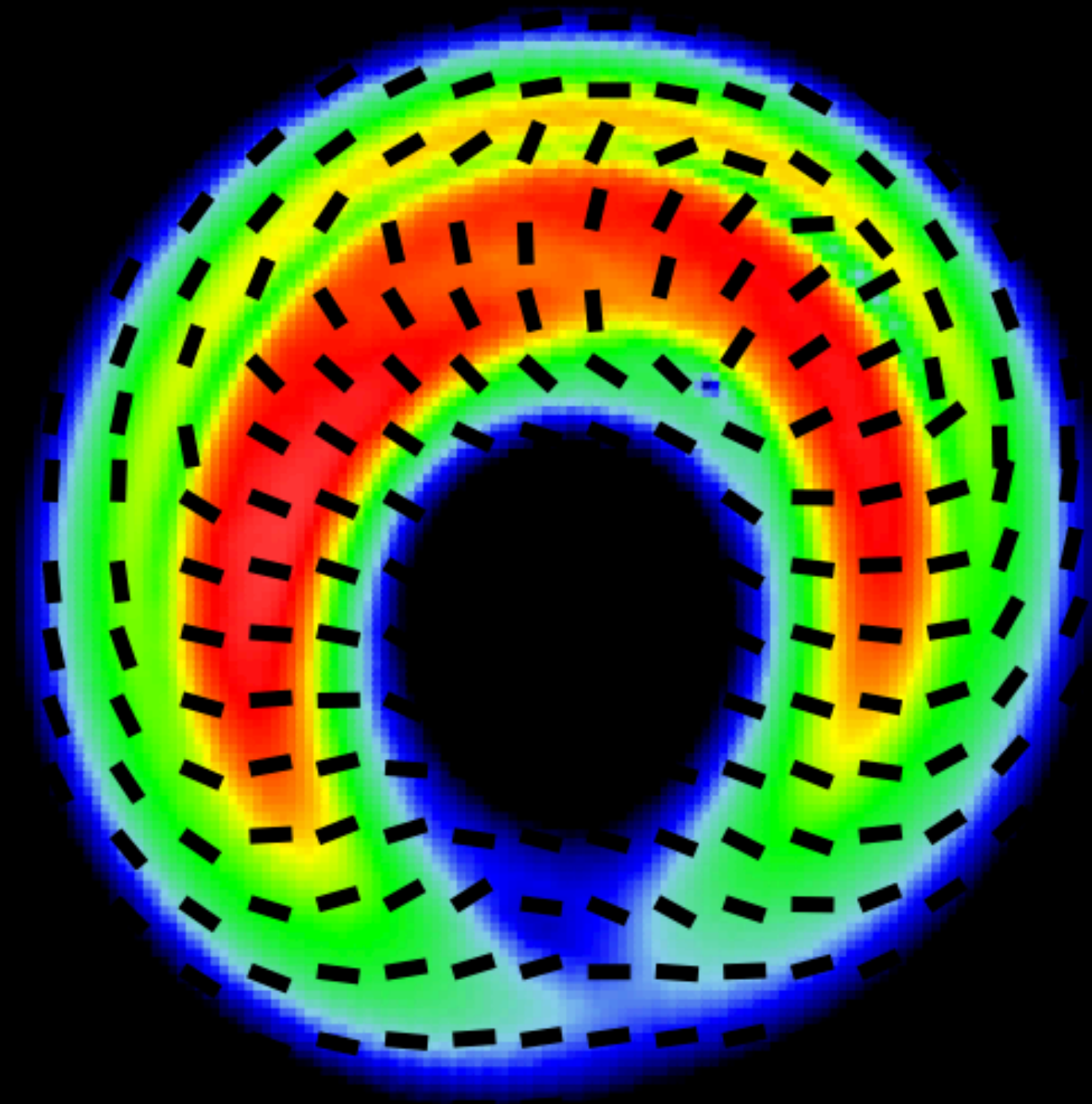


Anisotropy  $\rightarrow$  net polarization

The polarization degree is as high as 2.5%  
 $\rightarrow$  detectable with ALMA

Kataoka, et al., 2015

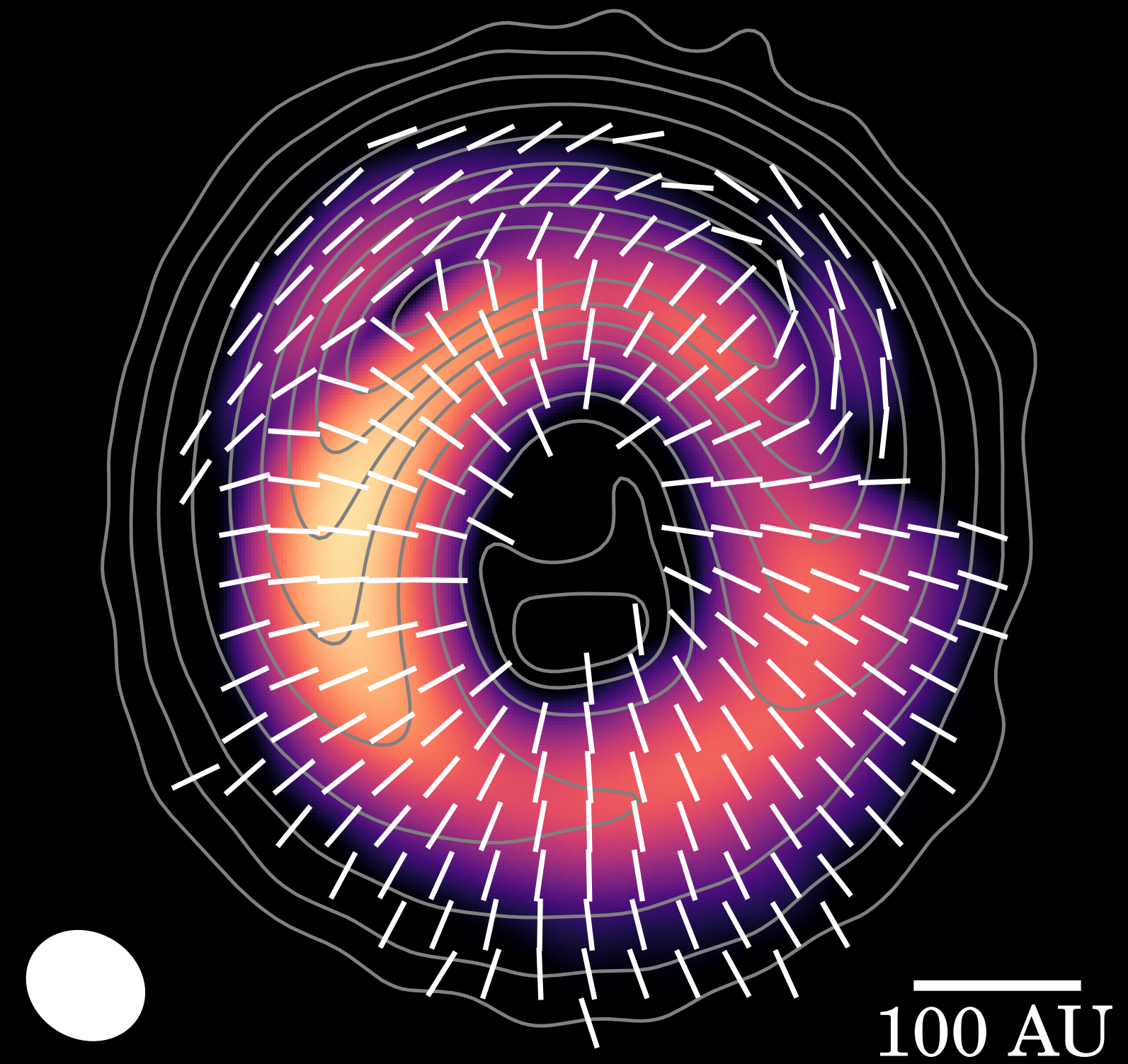
## 散乱偏光の理論予測



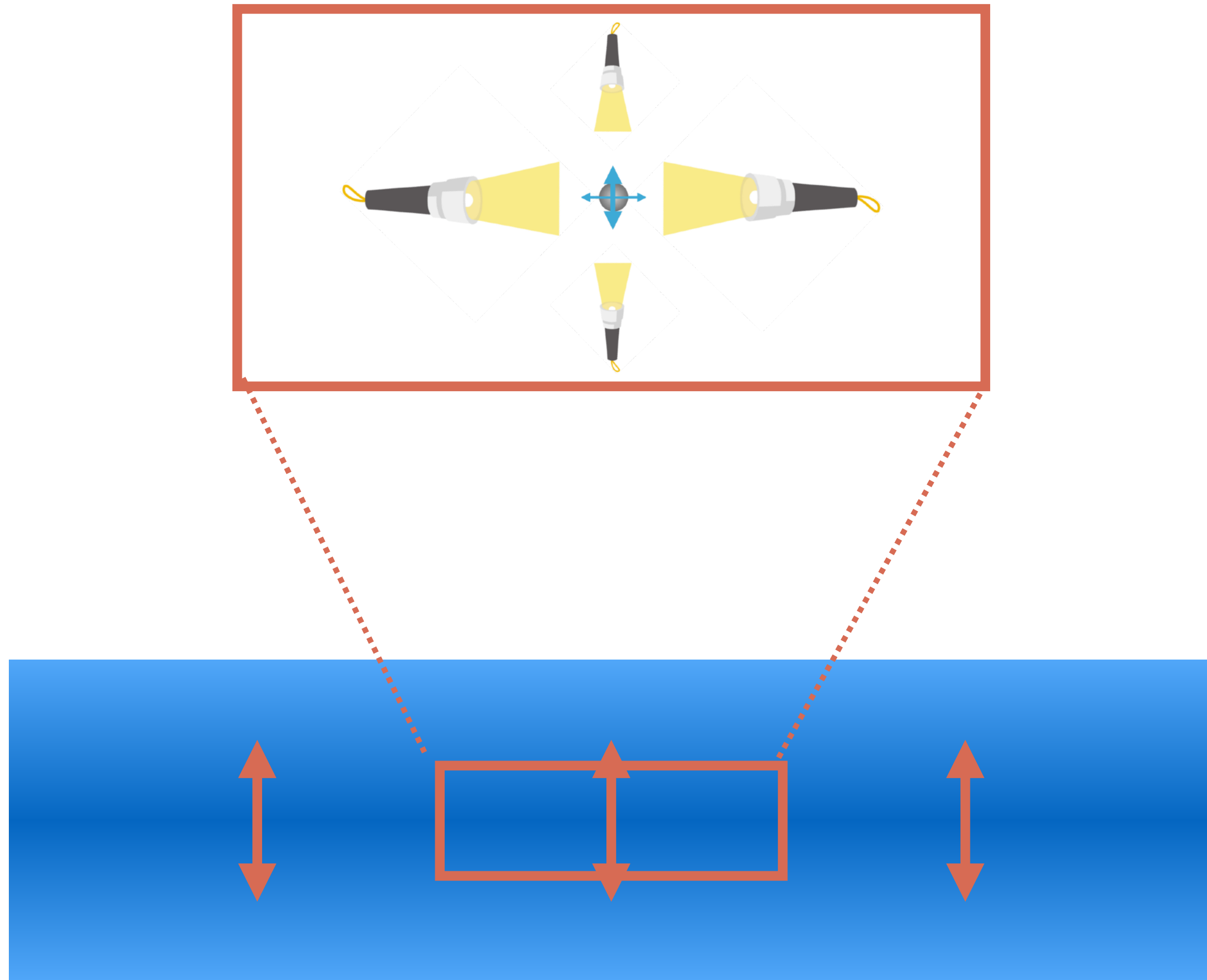
Cycle 3 観測提案書 (PI:Kataoka)

cf.) Kataoka et al. 2015

## ALMA 観測

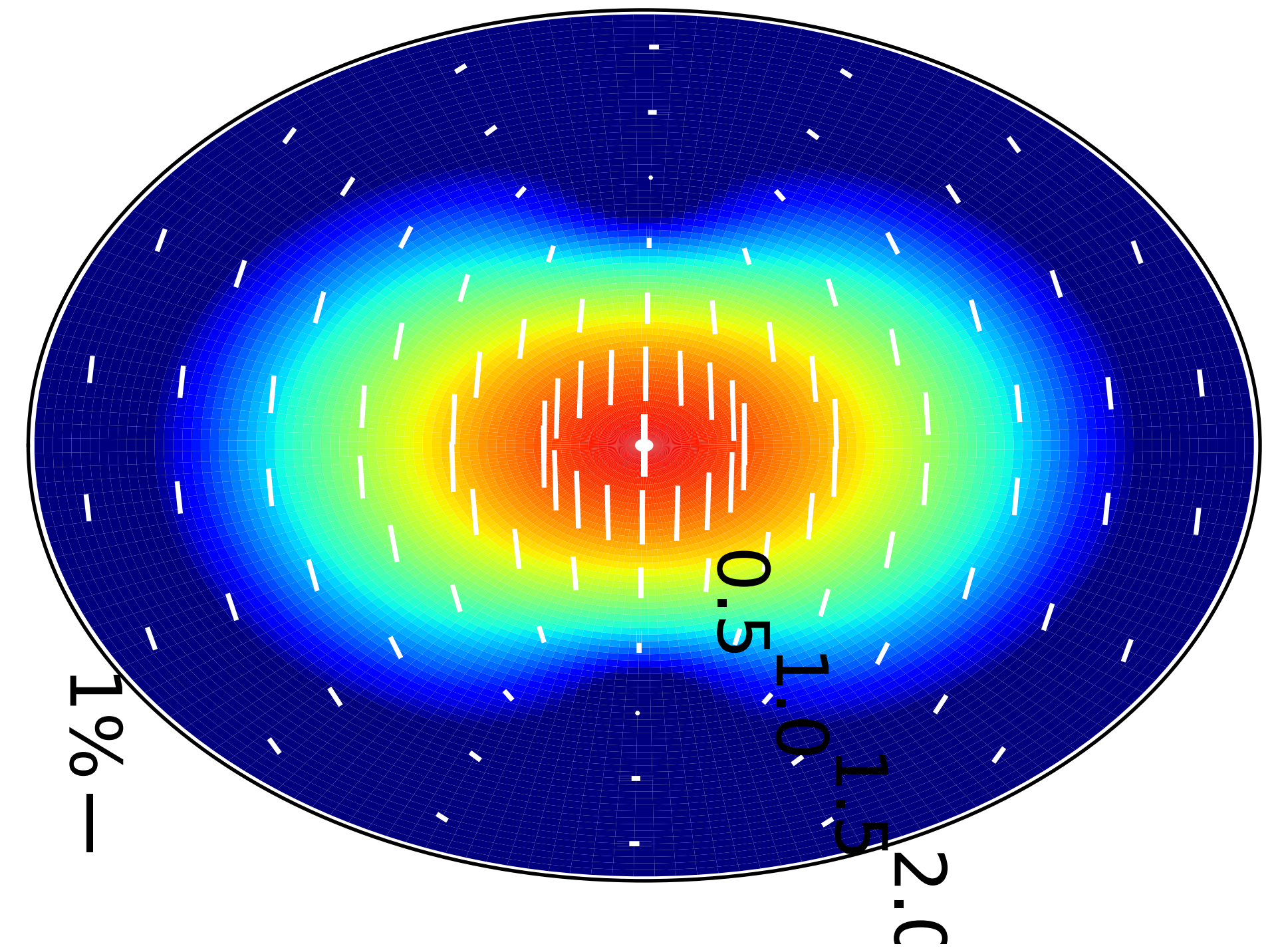


Kataoka, et al. 2016b



(disk, edge-on view)

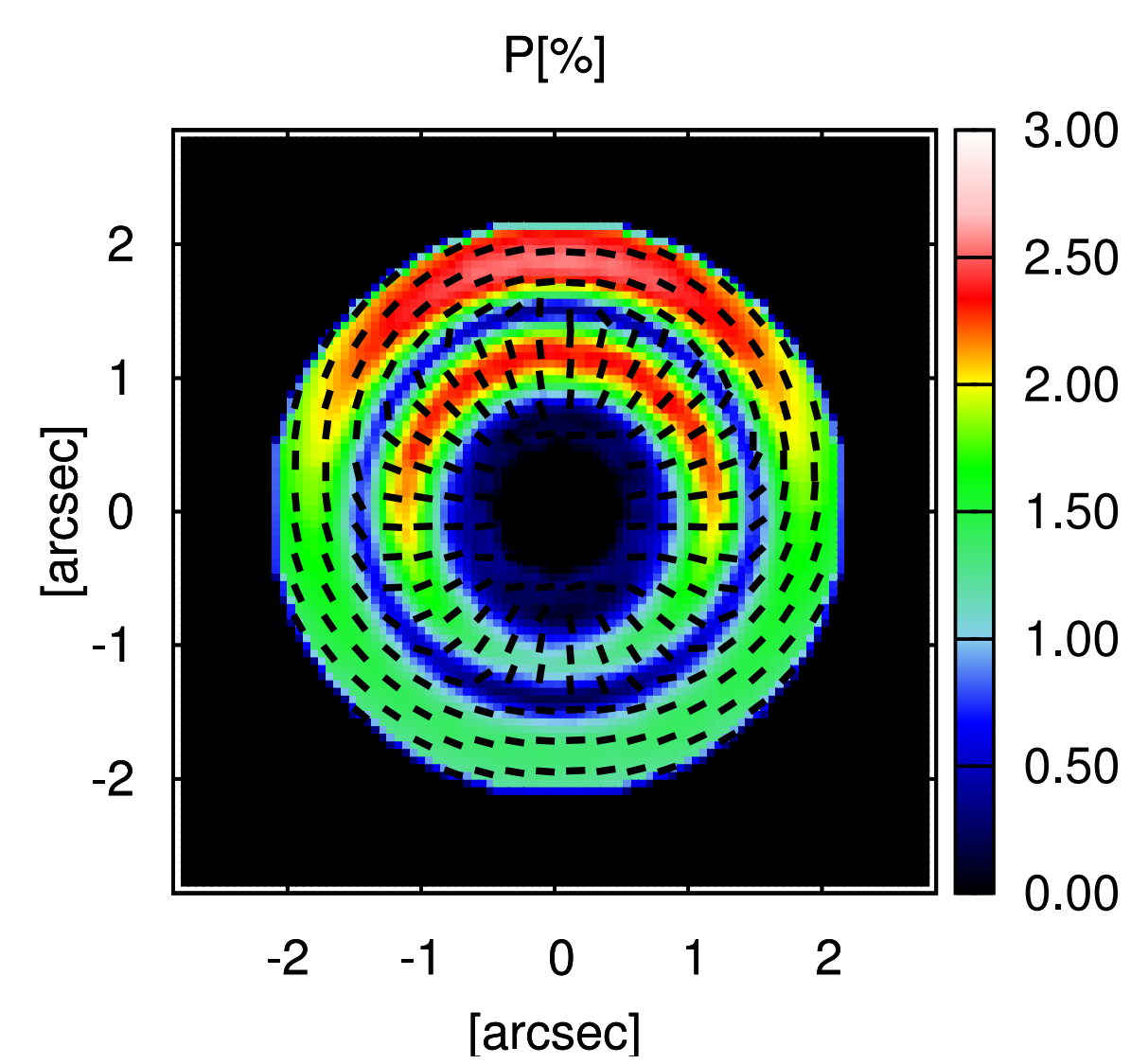
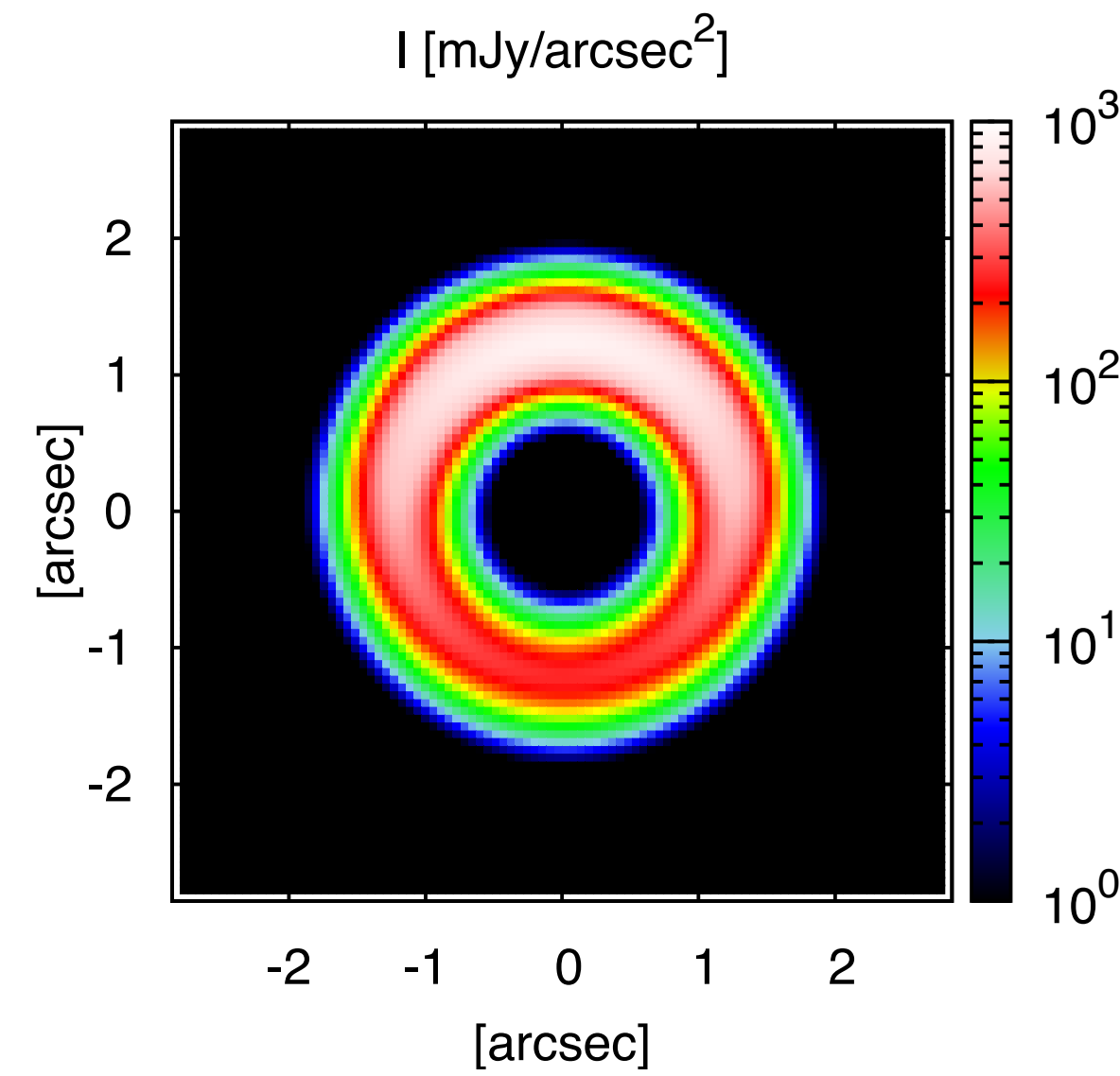
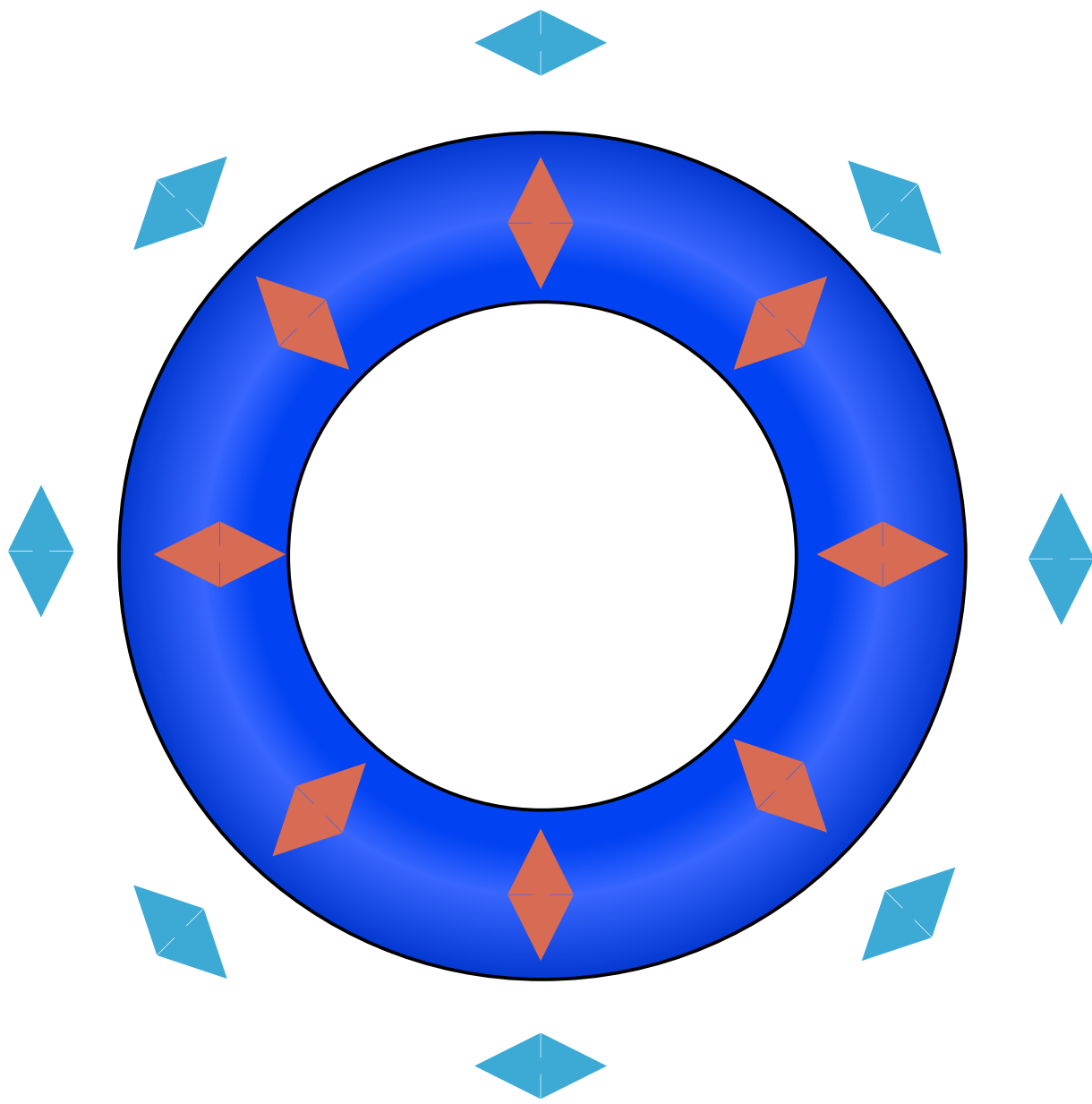
$i=45^\circ$



Yang, Li, et al. 2016

See also [Kataoka et al. 2016a](#)

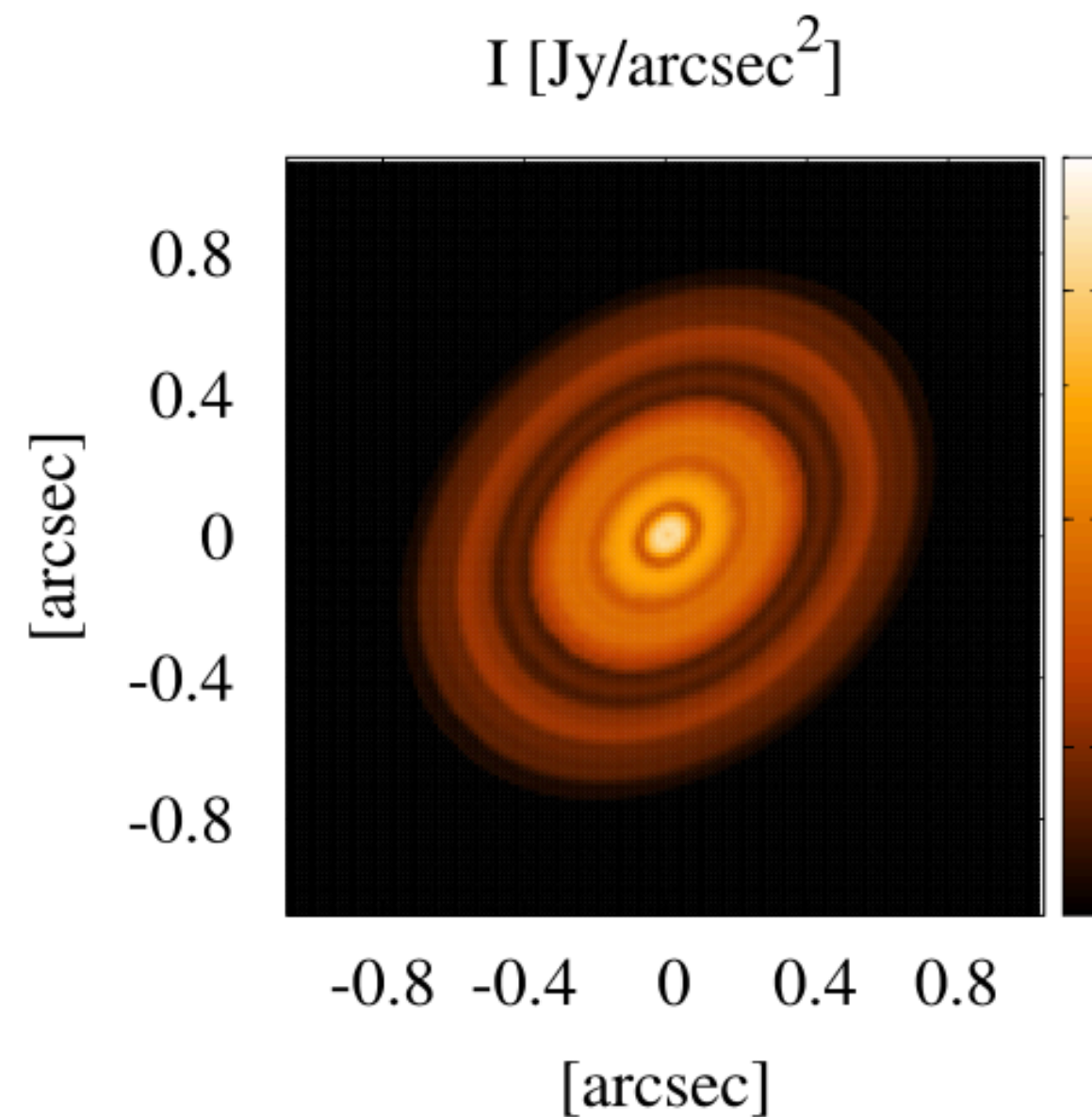
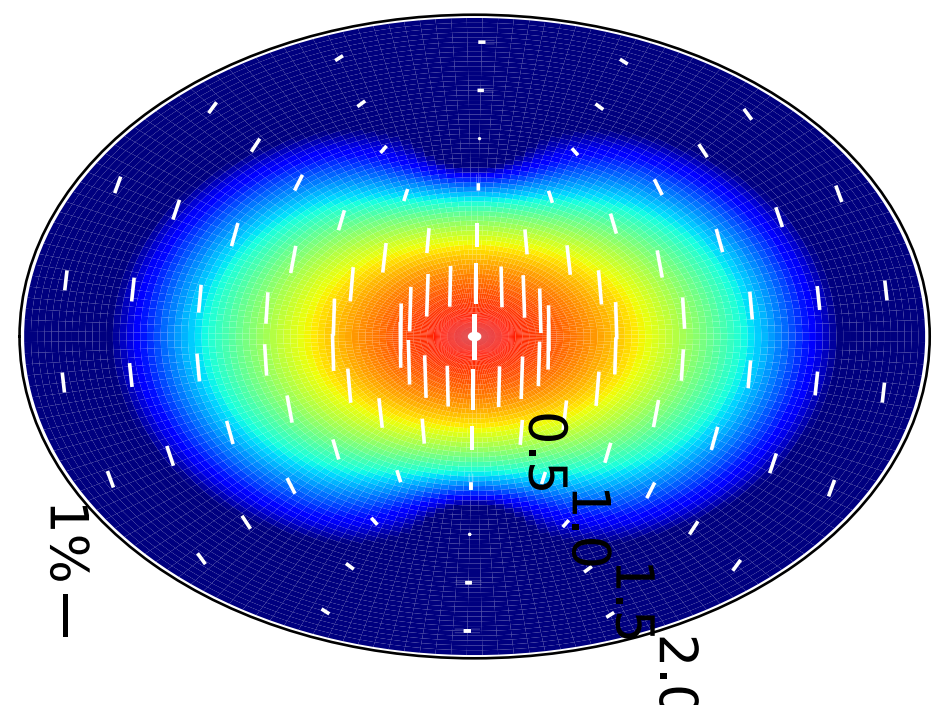
# Radiative transfer calculations



## Pol. vectors

Radial inside,  
azimuthal outside

[Kataoka, et al., 2015](#)



Parallel to the  
disk minor axis

[Kataoka, et al., 2016a](#)

see also [Yang et al. 2016](#)

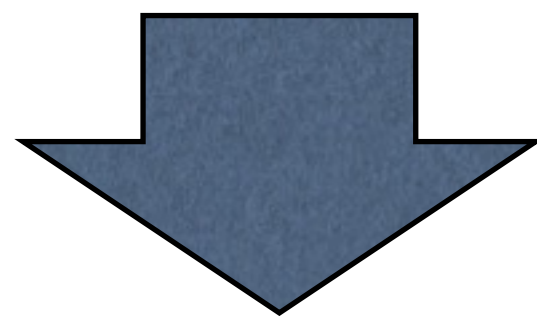
# Conditions of dust grains for polarization

- For efficient scattering

**(grain size)  $> \sim \lambda$**

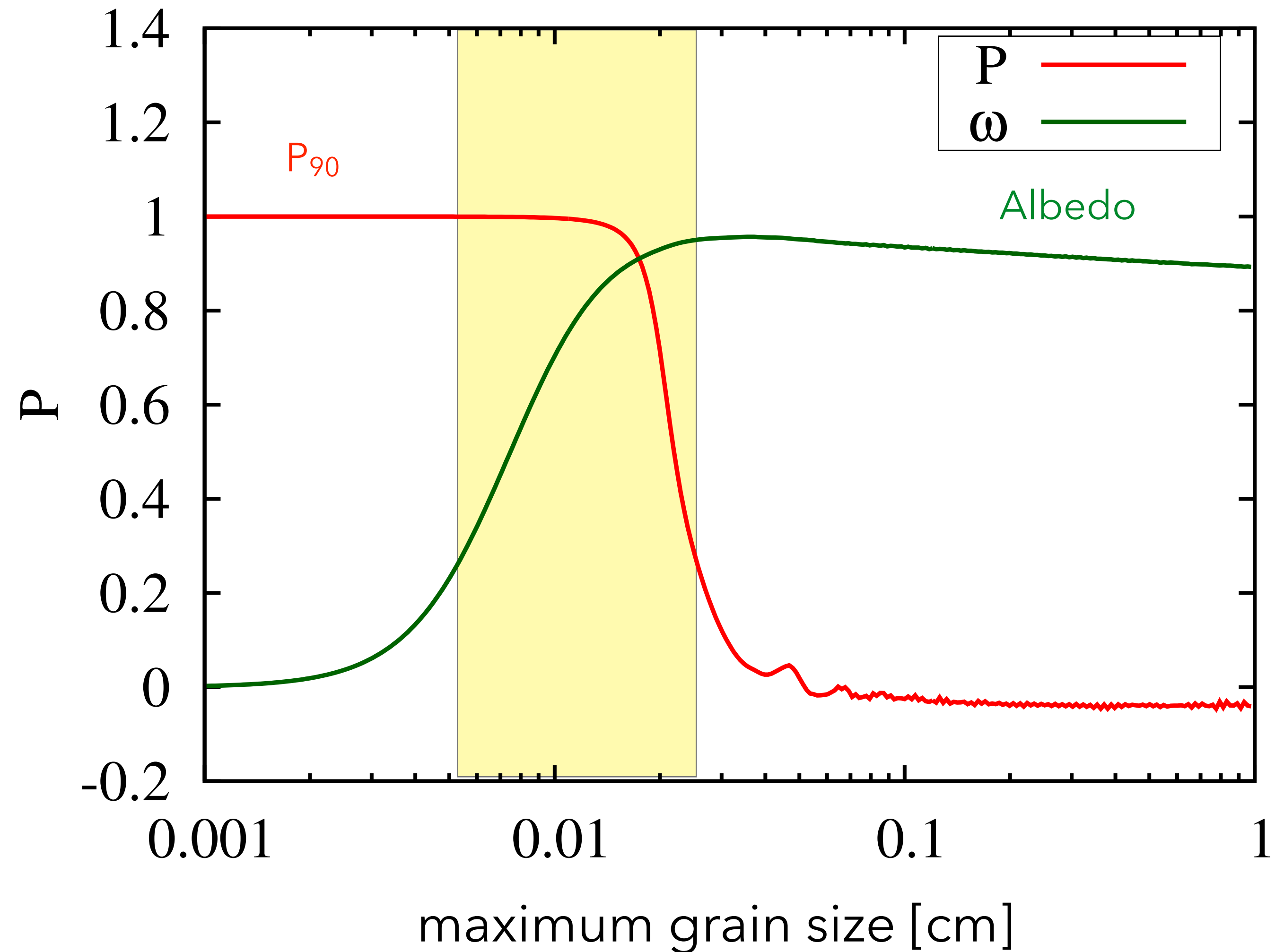
- For efficient polarization

**(grain size)  $< \sim \lambda$**

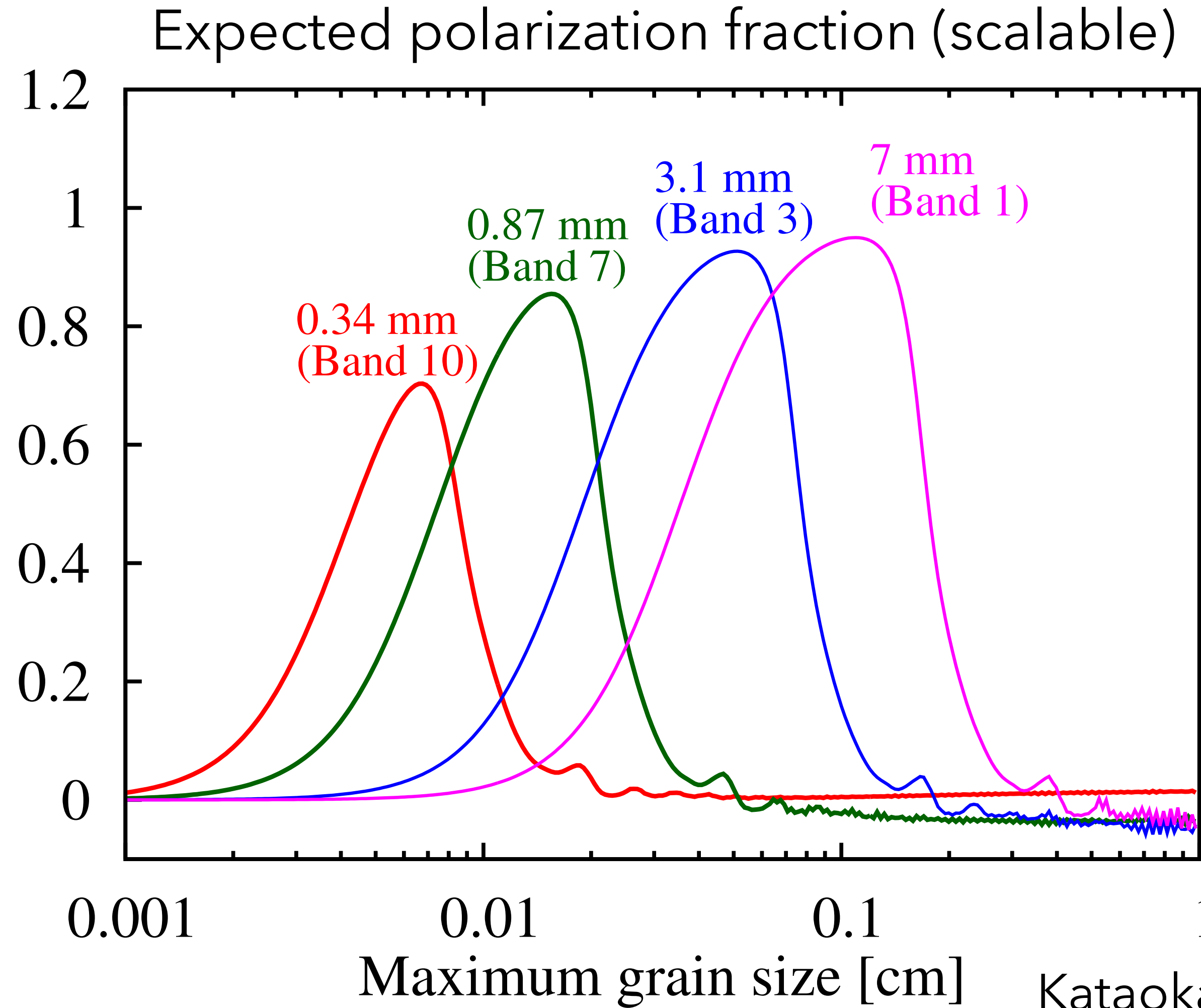


**Polarization requires  
(grain size)  $\sim \lambda/2\pi$**

$\lambda=870 \mu\text{m}$  (ALMA Band 7)

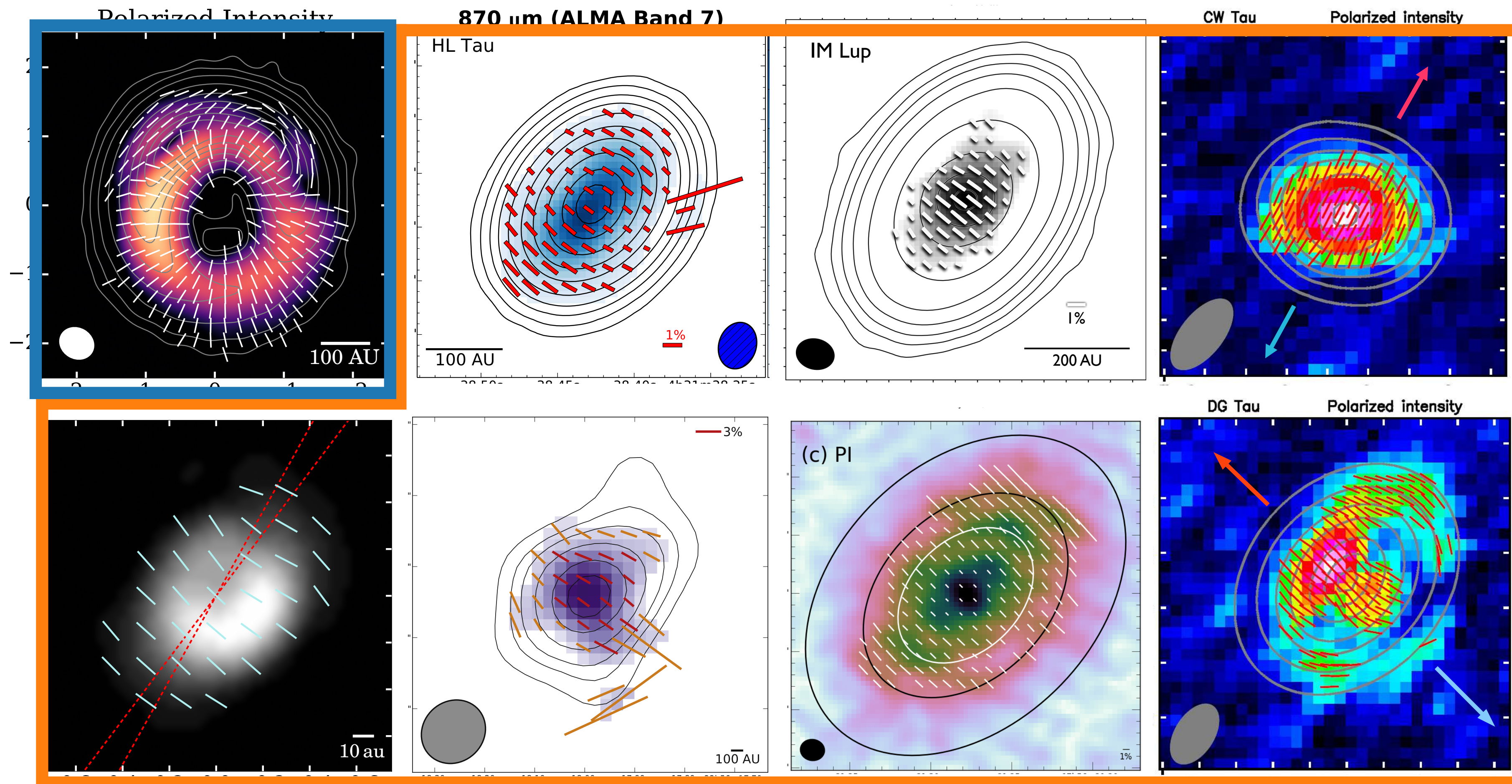


# Grain size constraints by polarization



**Multi-wave polarization → constraints on the grain size**

# Millimeter-wave polarization of disks



HD 142527; Kataoka et al. 2016, HL Tau; Stephens et al. 2017, IM Lup; Hull et al. 2018, CW Tau and DG Tau; Bacciotti et al. 2018, Cepheus A HW2 ; Fernández-Lopez et al. 2016, HD 163296; Dent et al. 2019, HD100546; Pohl et al. in prep.

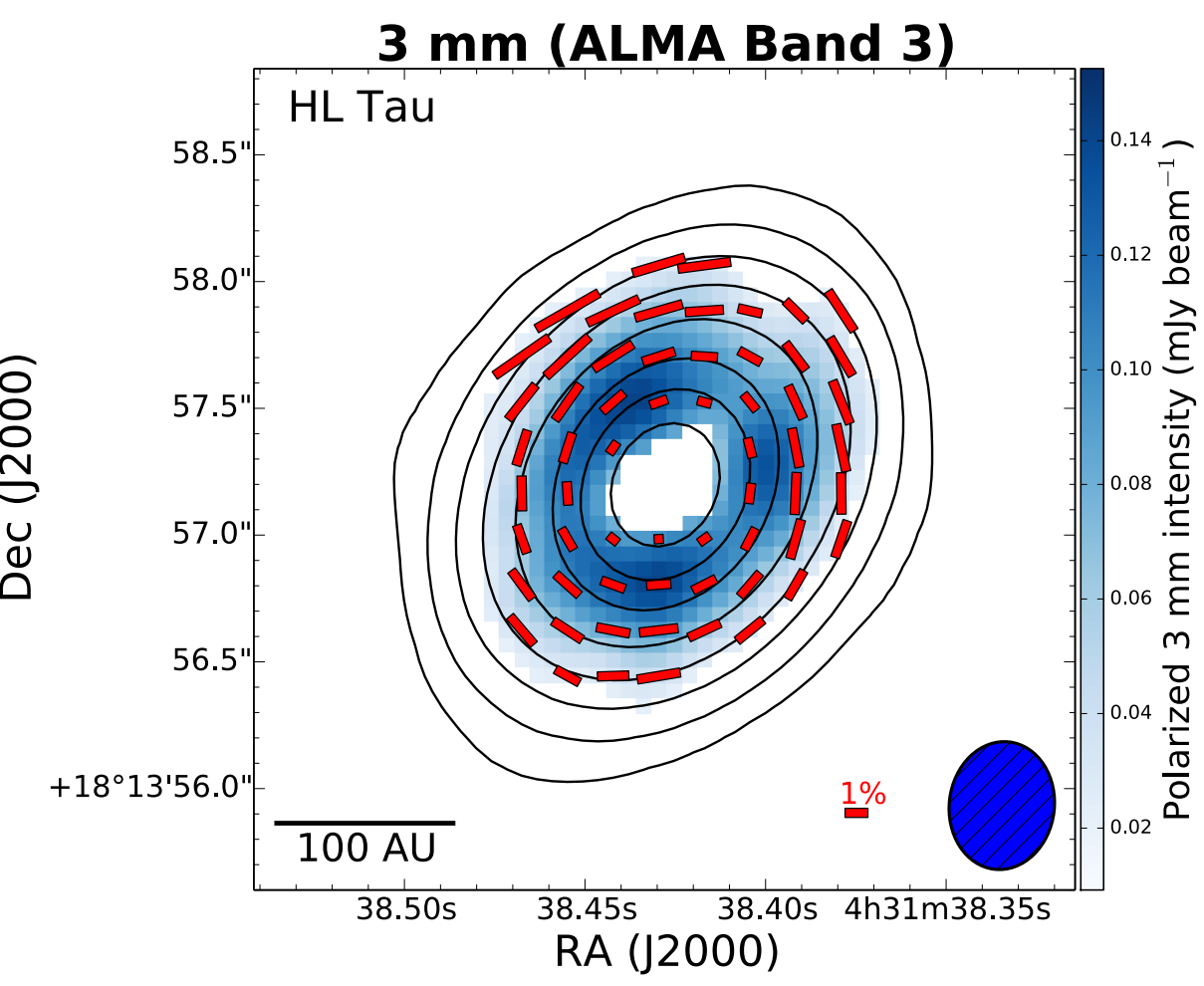
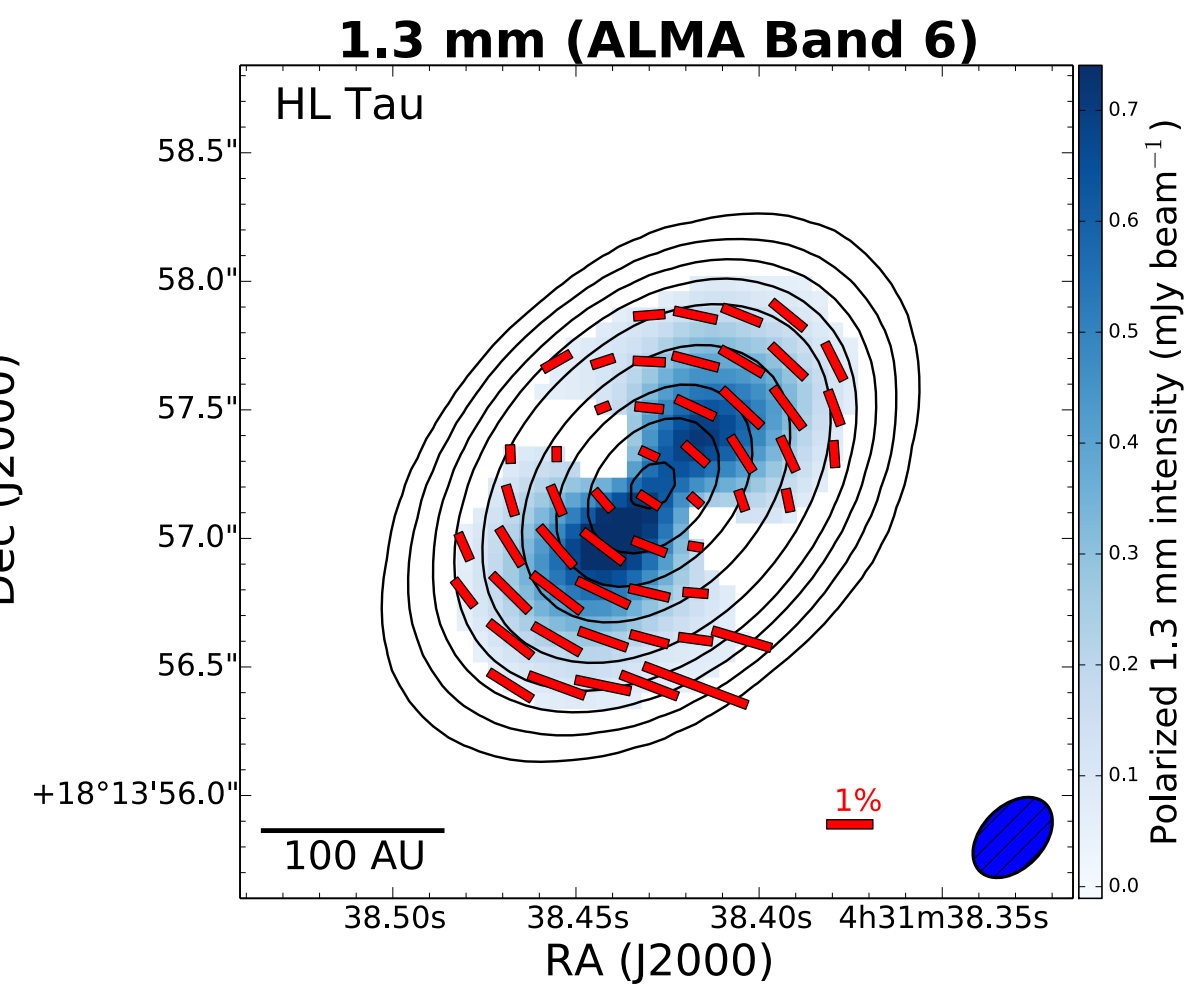
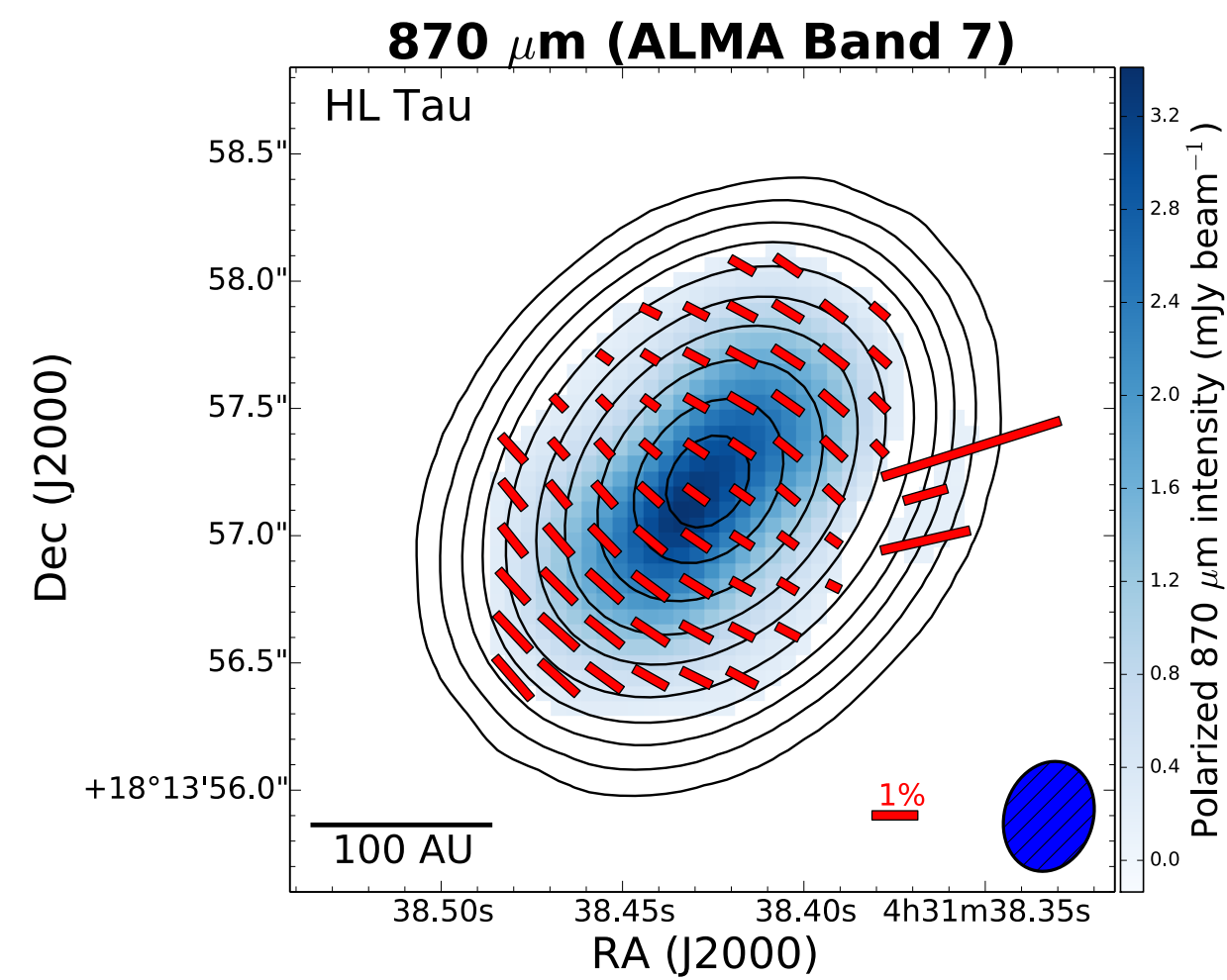
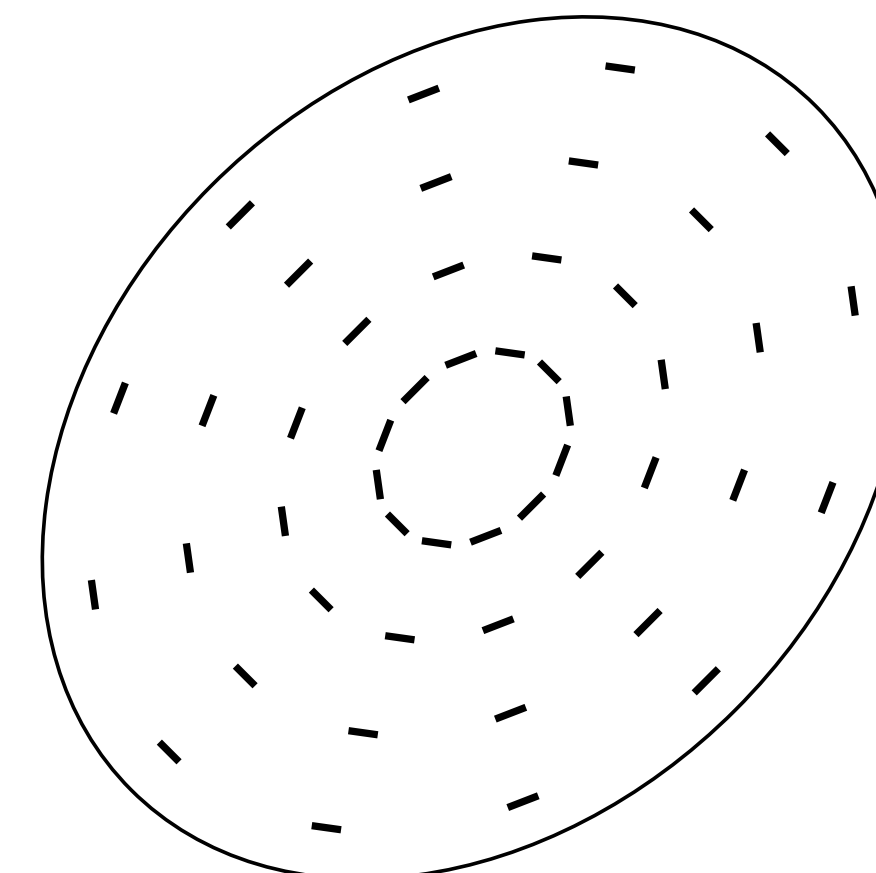
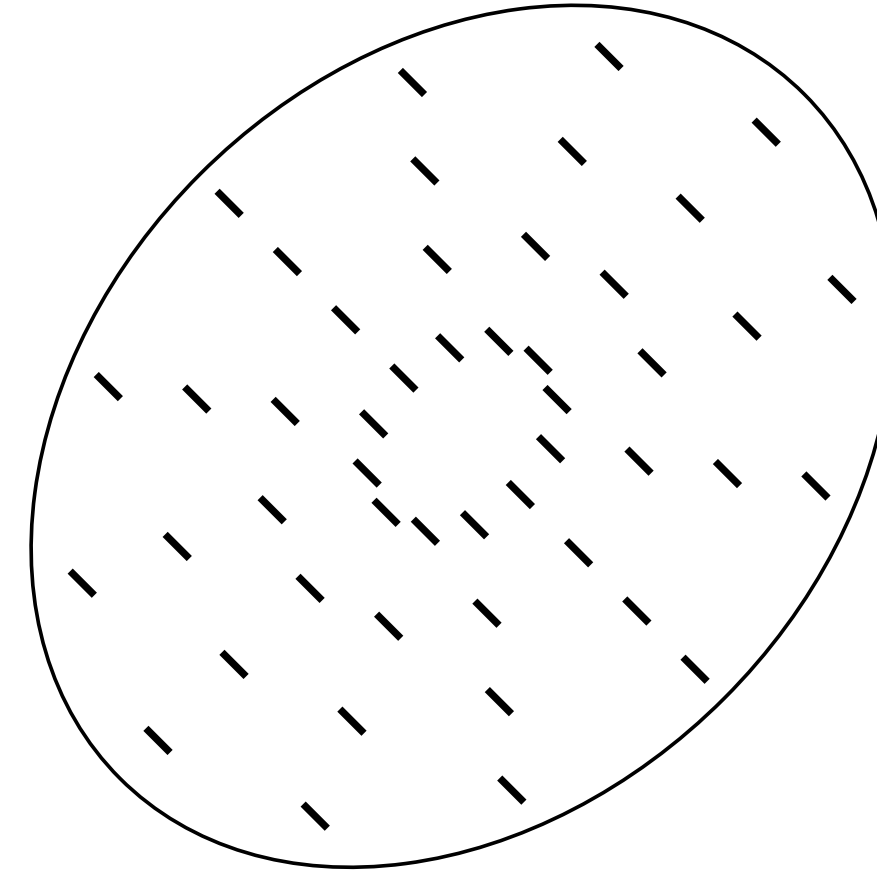
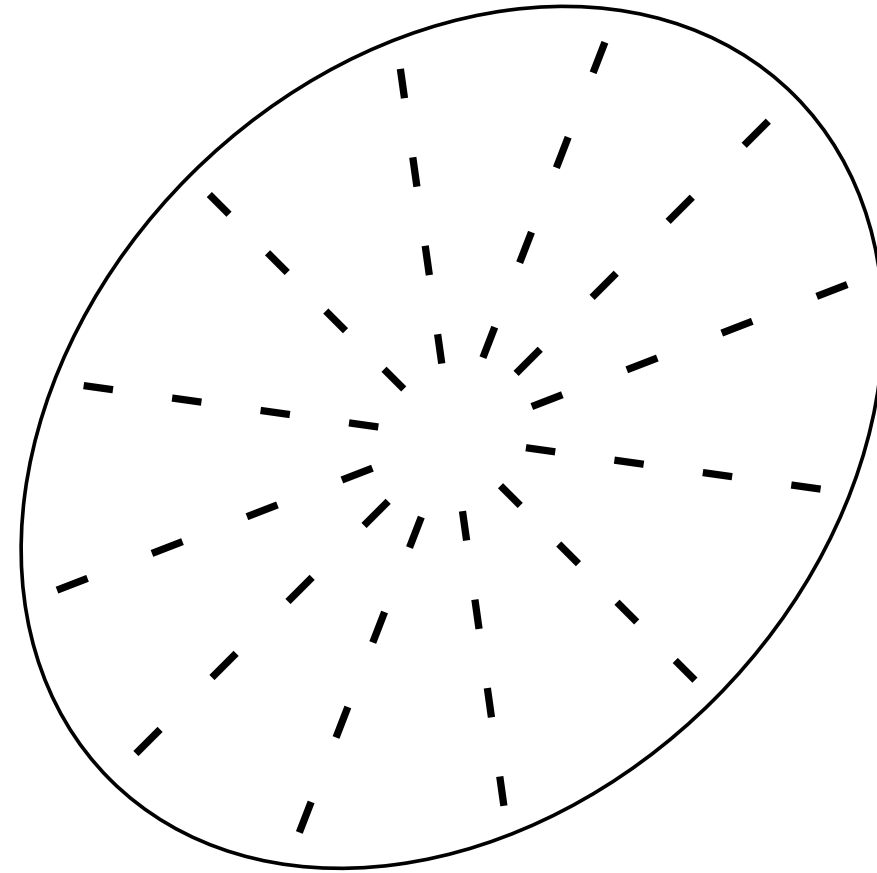
**Inclined disks: self-scattering at 870  $\mu\text{m}$**   
**a lopsided disk: self-scattering at north and alignment at south**

# Polarization mechanisms

(alignment with B-fields)

self-scattering

alignment with radiation



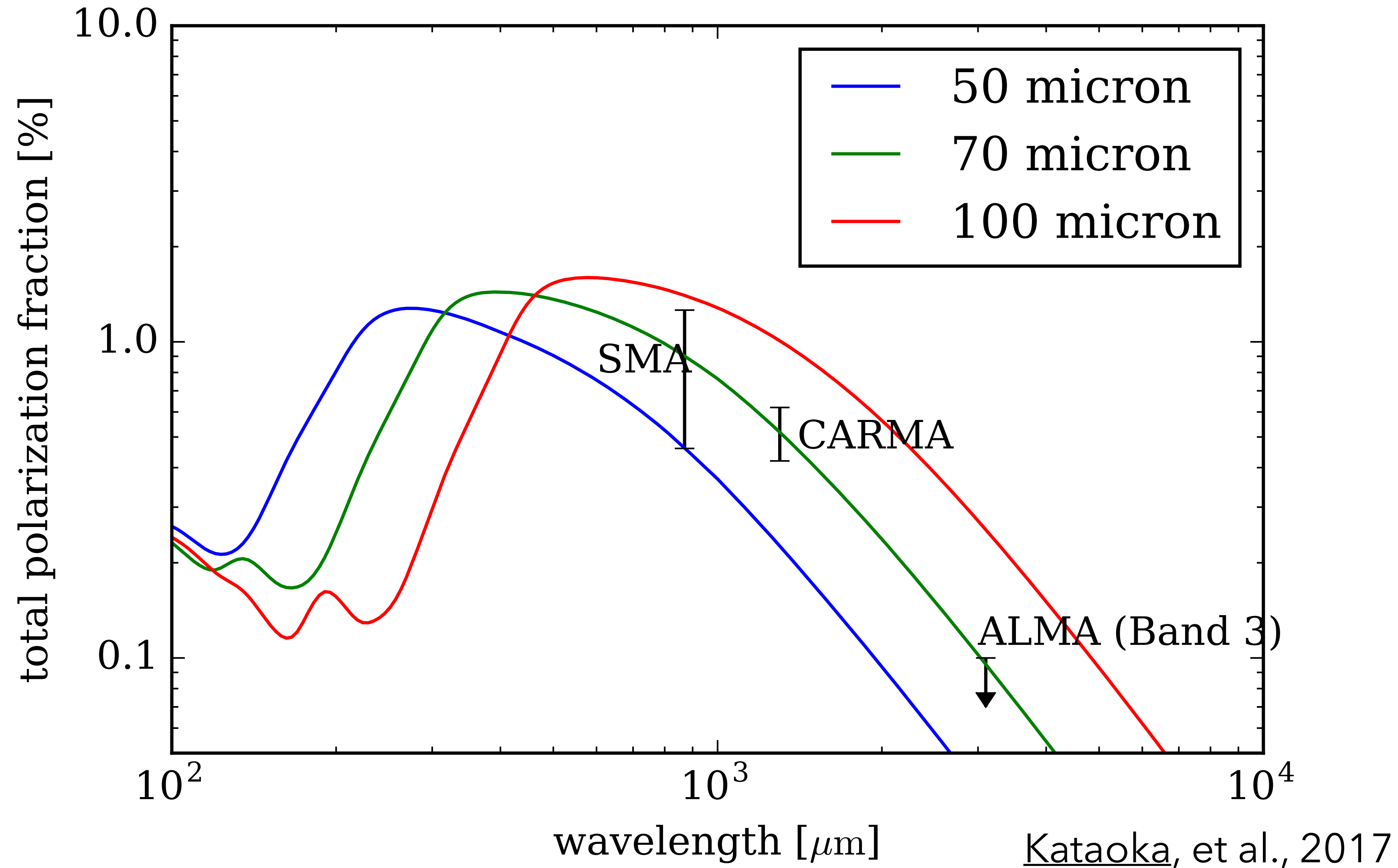
Stephens et al. 2017 (see also Kataoka et al. 2017)

self-scattering

alignment with radiation



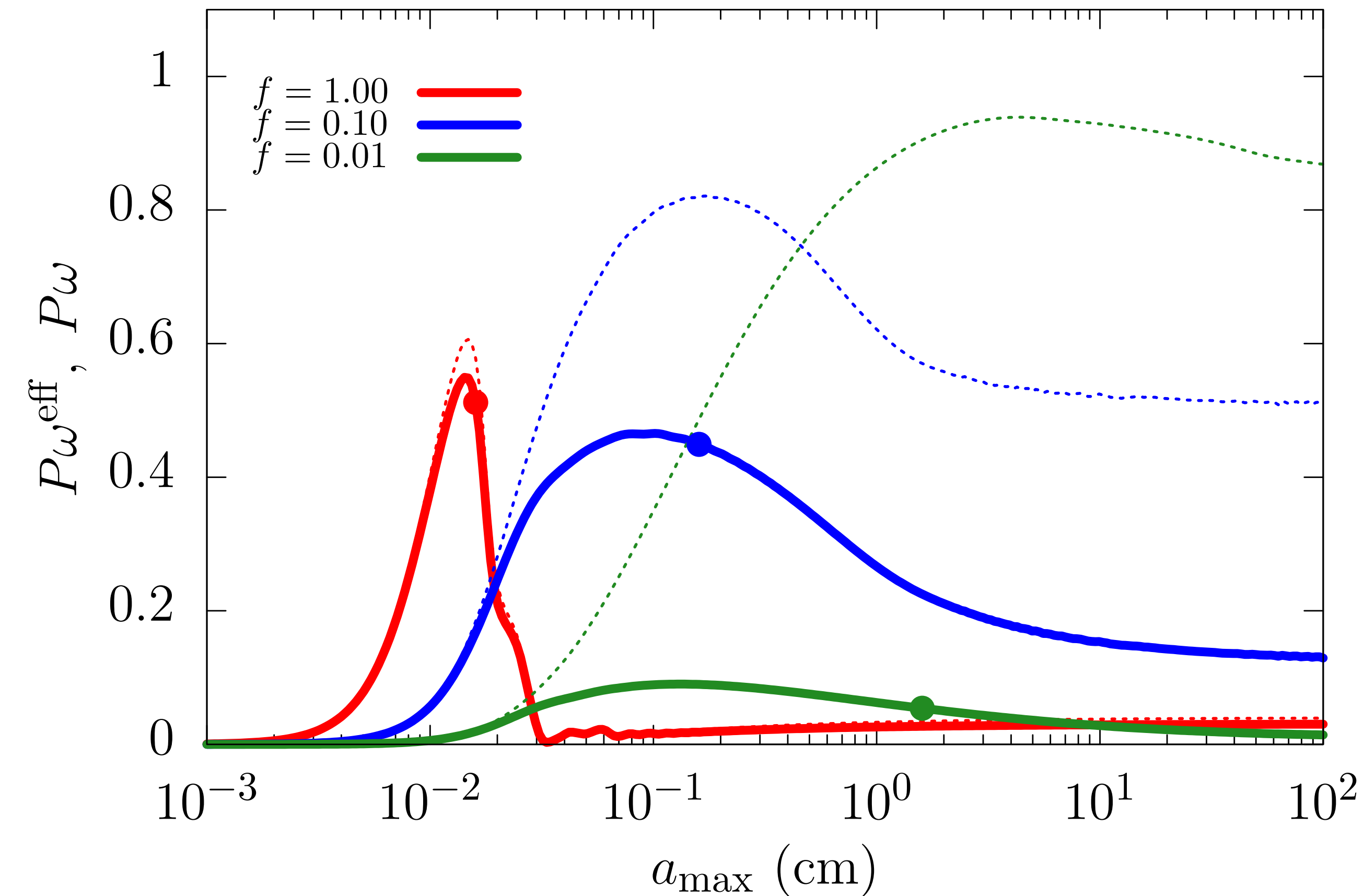
# What can we learn? - grain size



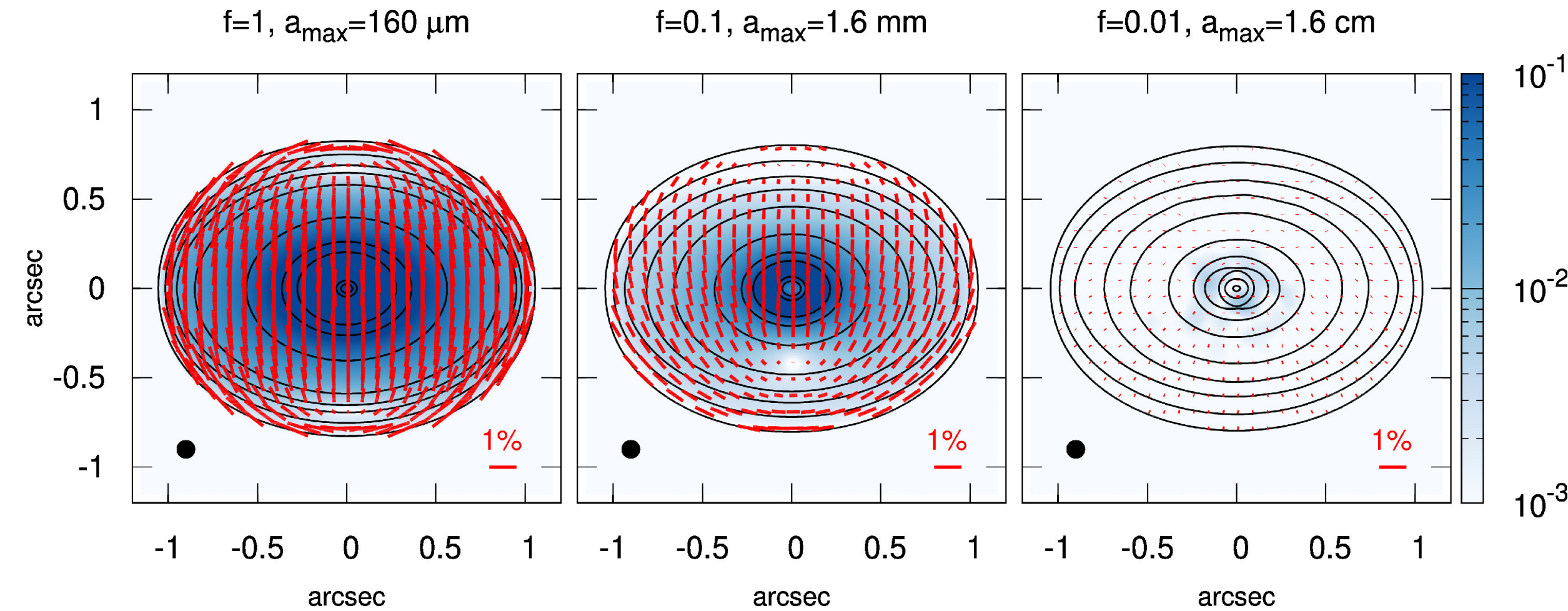
**The maximum grain size is ~ 70  $\mu\text{m}$**

# Effects of porosity on self-scattering

Prediction on polarization fraction



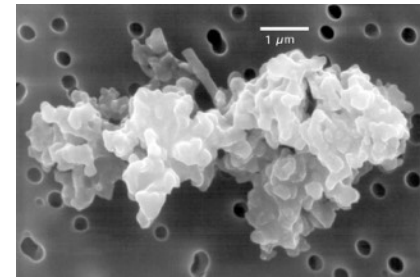
Modeling of HL Tau



- Porosity widen the window for polarization to be detected
- Extremely fluffy aggregates ( $f < 0.01$ ) is not likely

# ダストの合体成長

0.1 $\mu$ m



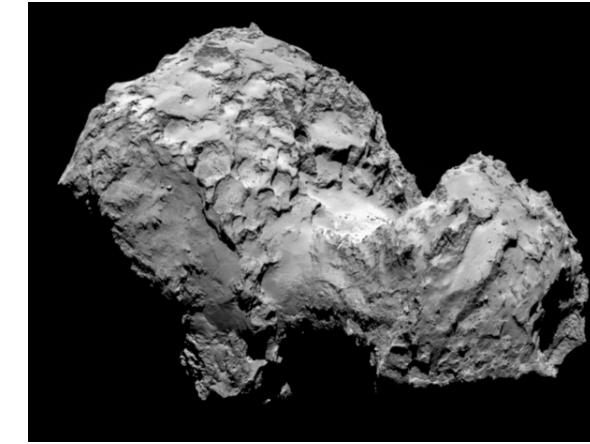
ダスト

衝突破壊/  
跳ね返り問題

1m

中心星  
落下問題

1km



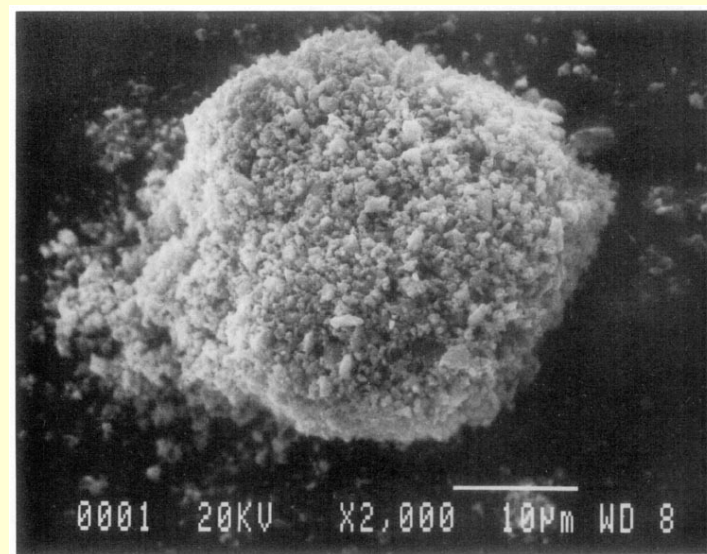
微惑星

10<sup>2-4</sup>km

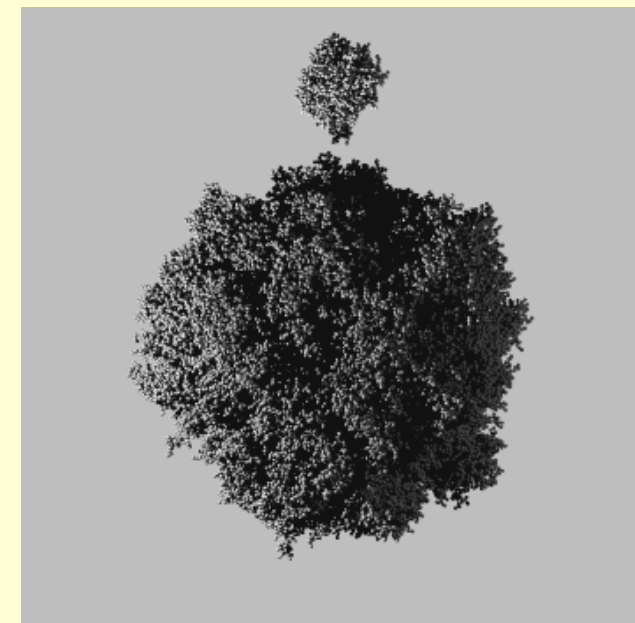


惑星

ダスト実験/数値計算

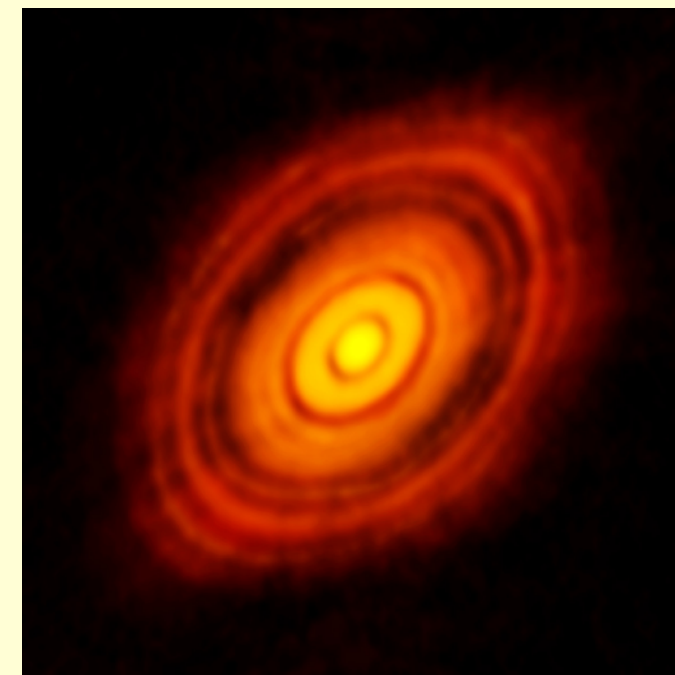


Blum & Münch 1993



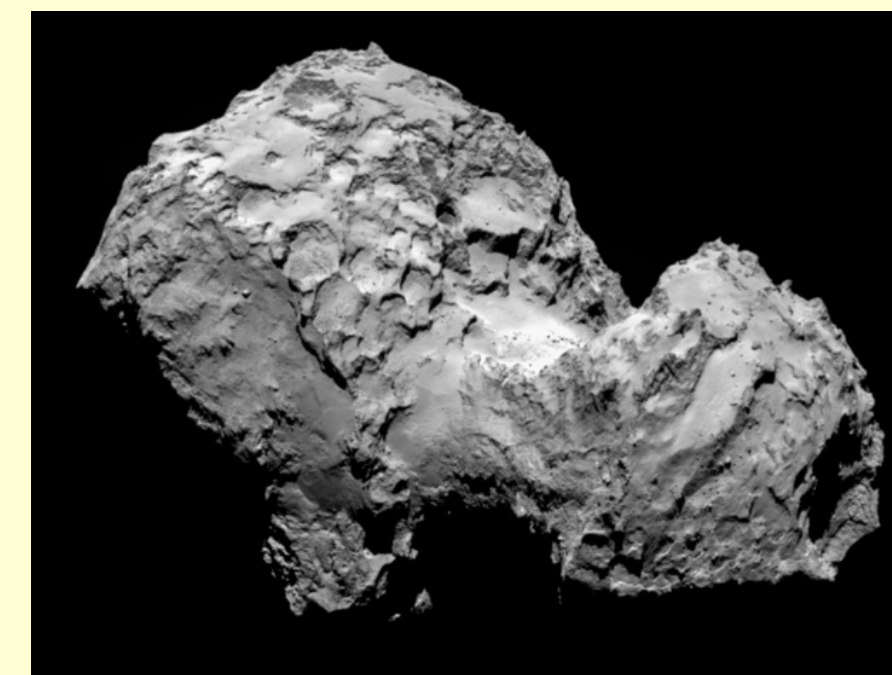
Wada et al. 2013

天文観測



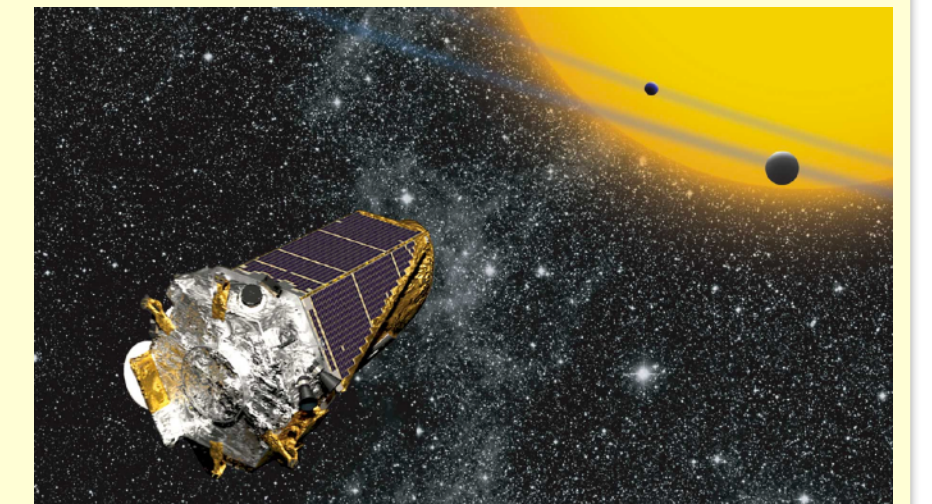
ALMA Partnership 2015

太陽系内



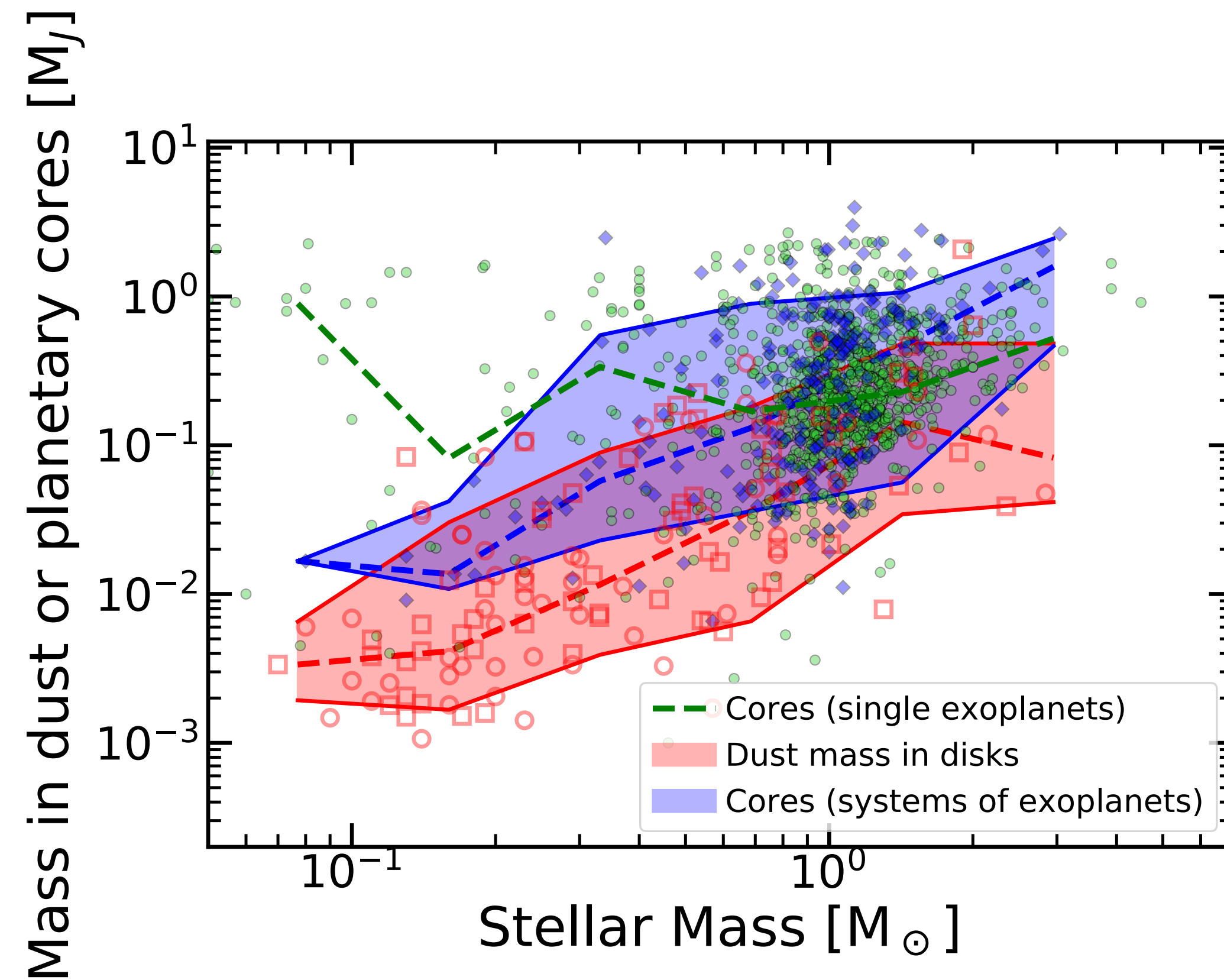
Rosetta mission

系外惑星



Kepler 宇宙望遠鏡  
→ TESS 望遠鏡

# Mass budget problem



**Fig. 3.** Masses of the cores of single exoplanets and the sum of the cores in exoplanetary systems, as well as disk masses, as a function of the mass of their host star. The colored regions encompass the 10th and 90th percentile of the distributions, while the dashed lines represent the median of the distributions, as labeled.

# • おわりに

## • これまでの研究

- 修士時代に星形成磁場における偏光観測予測。博士時代は完全に理論。PDで初めて観測論文を書く。

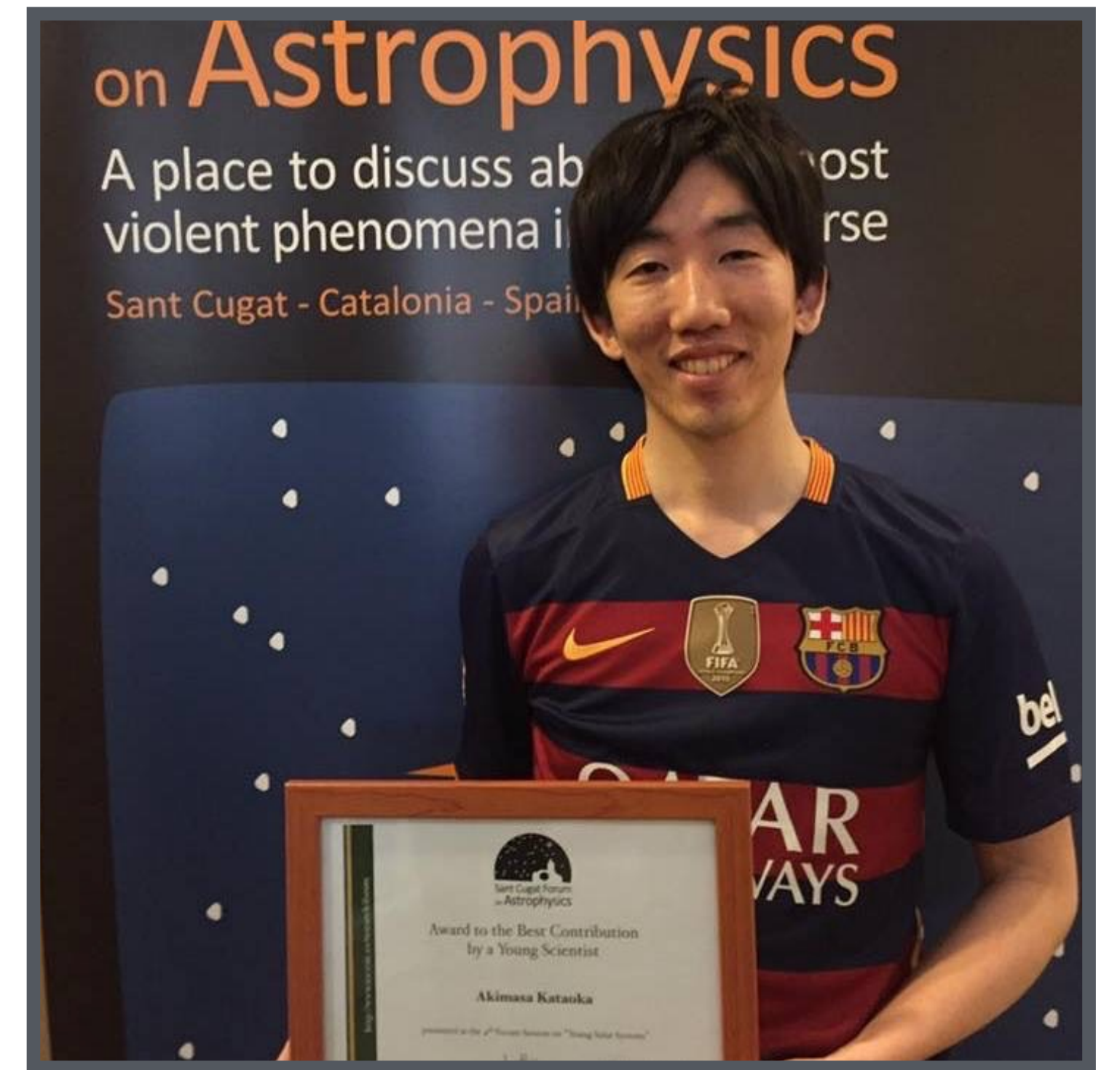
## • 理論屋が観測にも手を出せる時代

- ALMAはキャリブレーション済みのデータをくれる。
- プロポーザルは理論的背景があると強い

## • 研究する上では、良い問題を見つけることが大事

- 博士から他大に行きたい人
- 外国での研究生活について聞きたい人
- 夏の学校について議論したい人

⇒あとで捕まえて！



# まとめ

- 弾性体の力学を応用し、ダストは惑星形成の初期段階で隙間の多い構造を取ることを理論的に証明
- すき間の多いダスト集合体は跳ね返り障壁を回避
- 氷粒子の場合、衝突破壊問題を回避可能
- (中心星落下問題を回避)
- 散乱に起因するミリ波偏光理論の確立
- ALMA観測によりミリ波偏光を実証

