

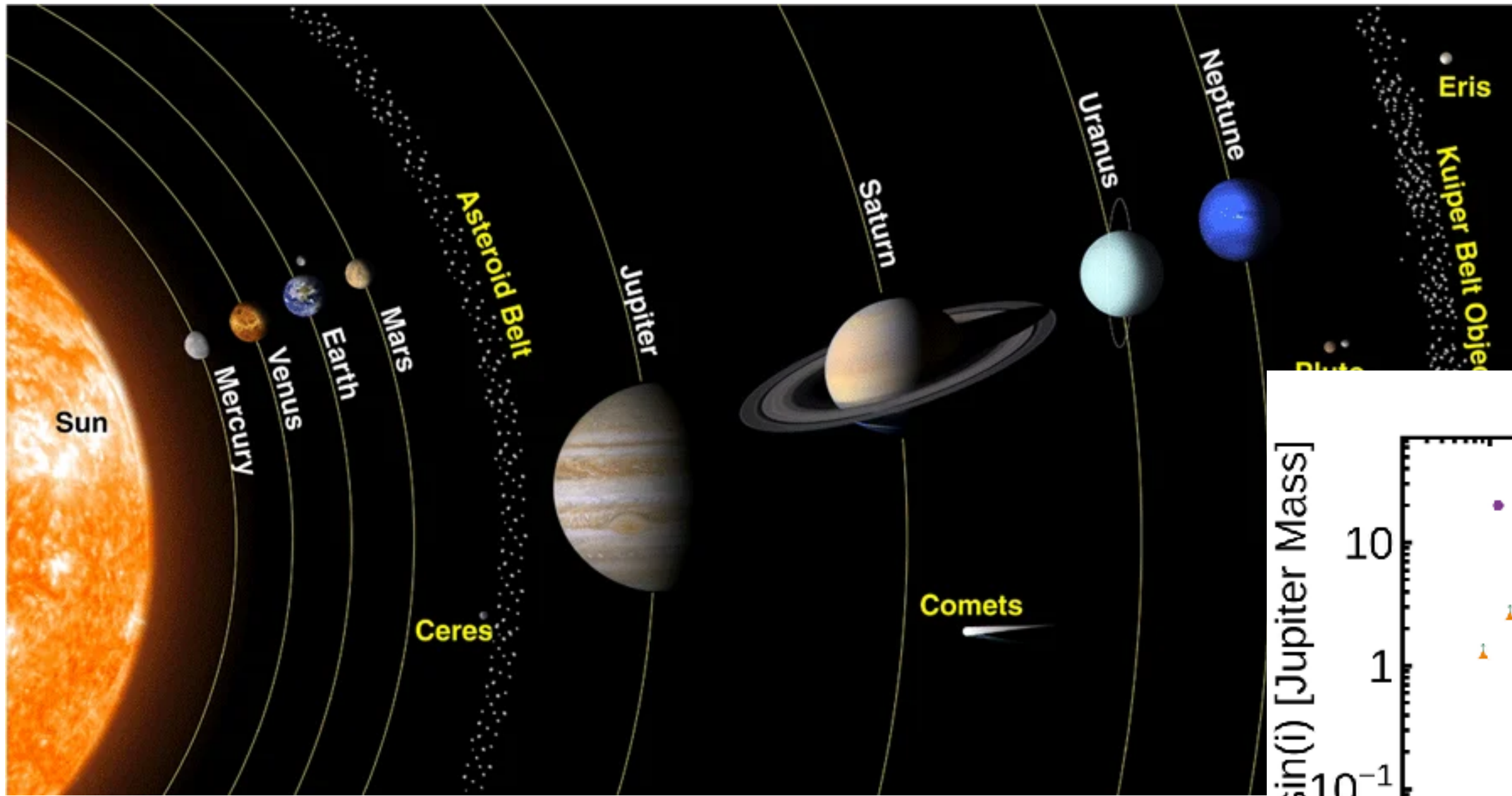
# JWSTでみる惑星形成円盤

ジェイムズ・ウェッブ宇宙望遠鏡

**田崎 亮**

東京大学大学院 総合文化研究科

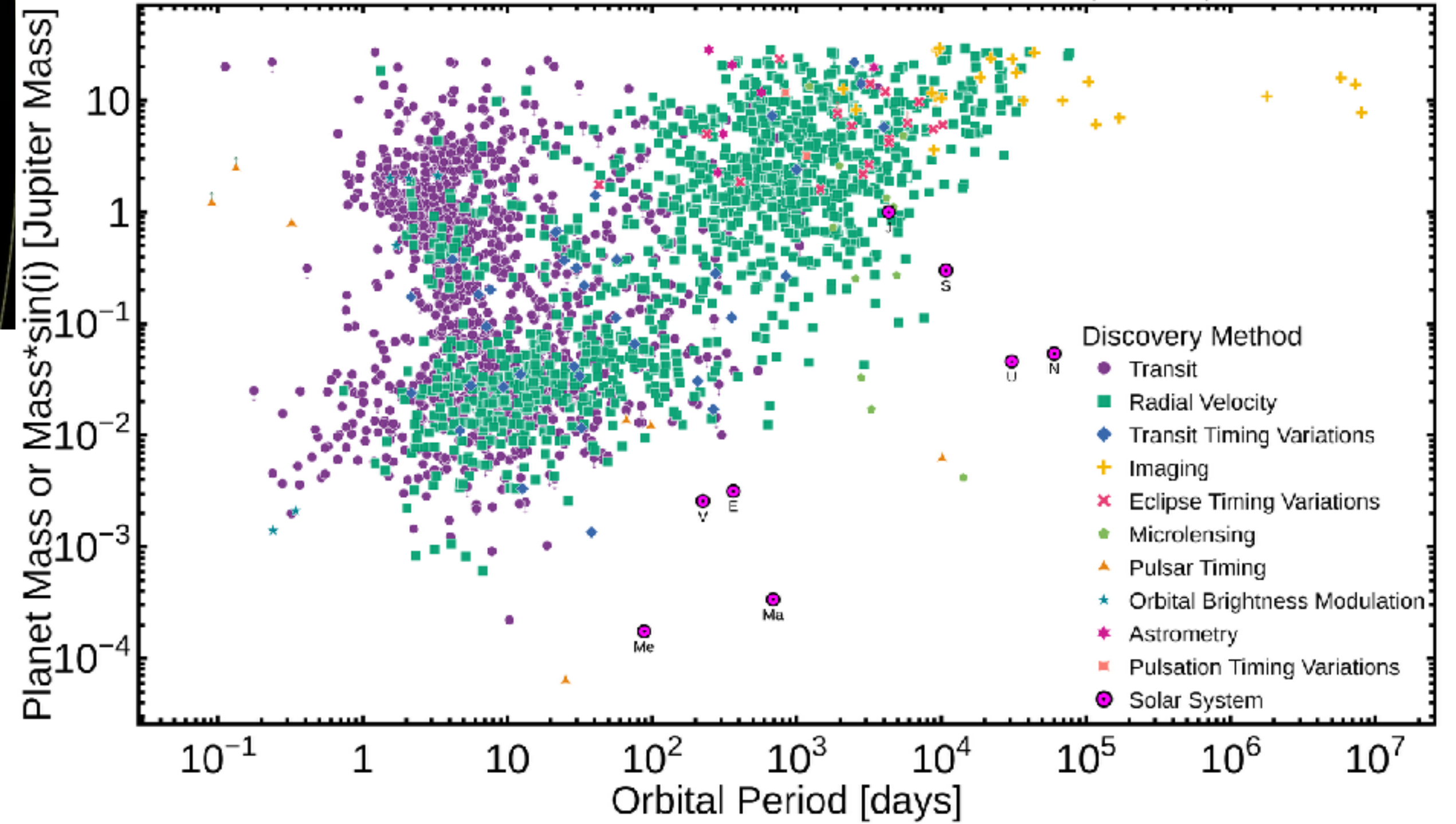




## 系外惑星の分布

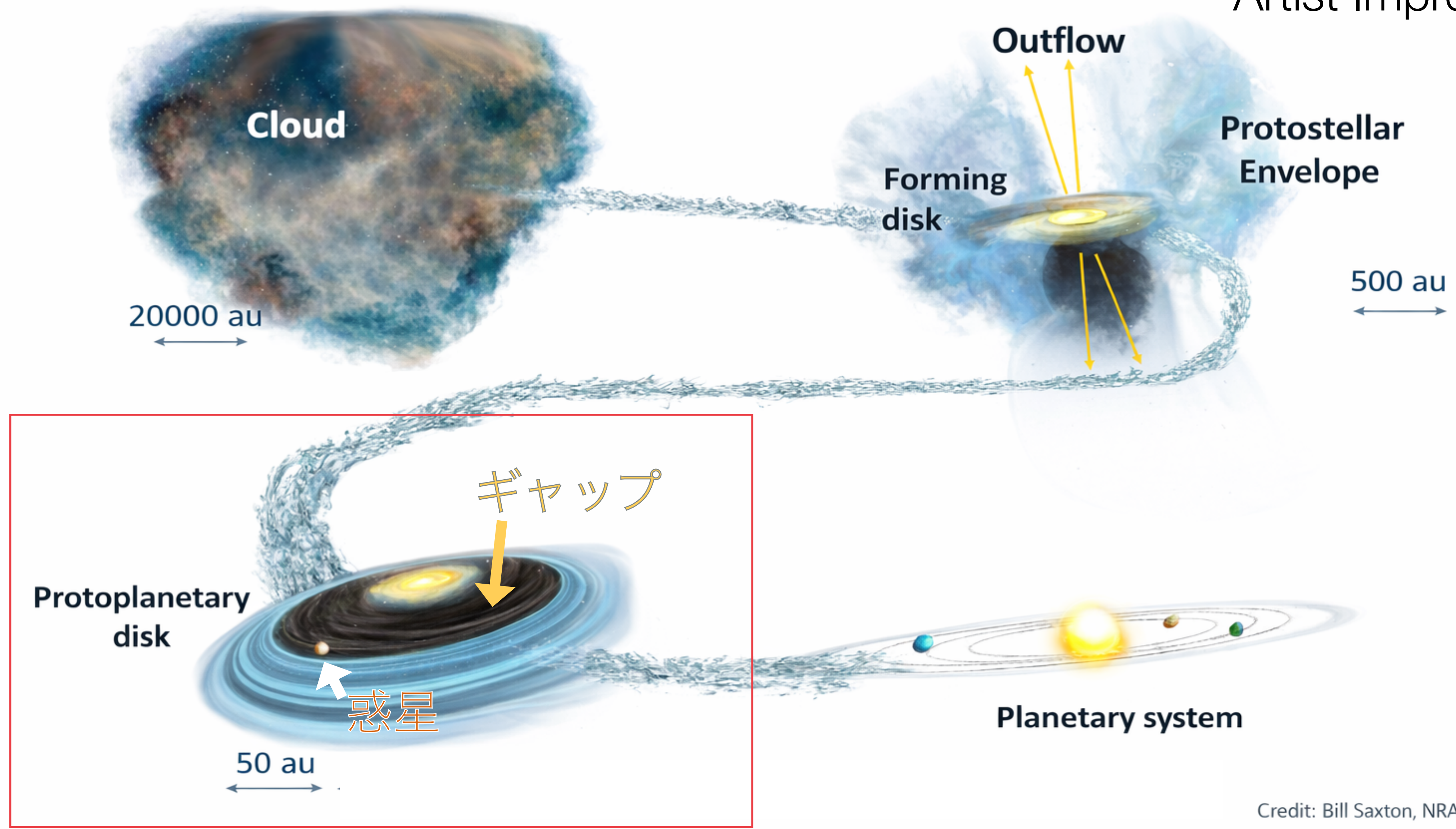
Planet Mass or Mass\* $\sin(i)$  vs Orbital Period

exoplanetarchive.ipac.caltech.edu, 2026-01-22



惑星系はどのように誕生したのか？

Artist Impression



Credit: Bill Saxton, NRAO/AUI/NSF

# 可視光で見た冬の星空

ふたご座

Gemini

Canis Minor

Monoceros

Orion

オリオン座

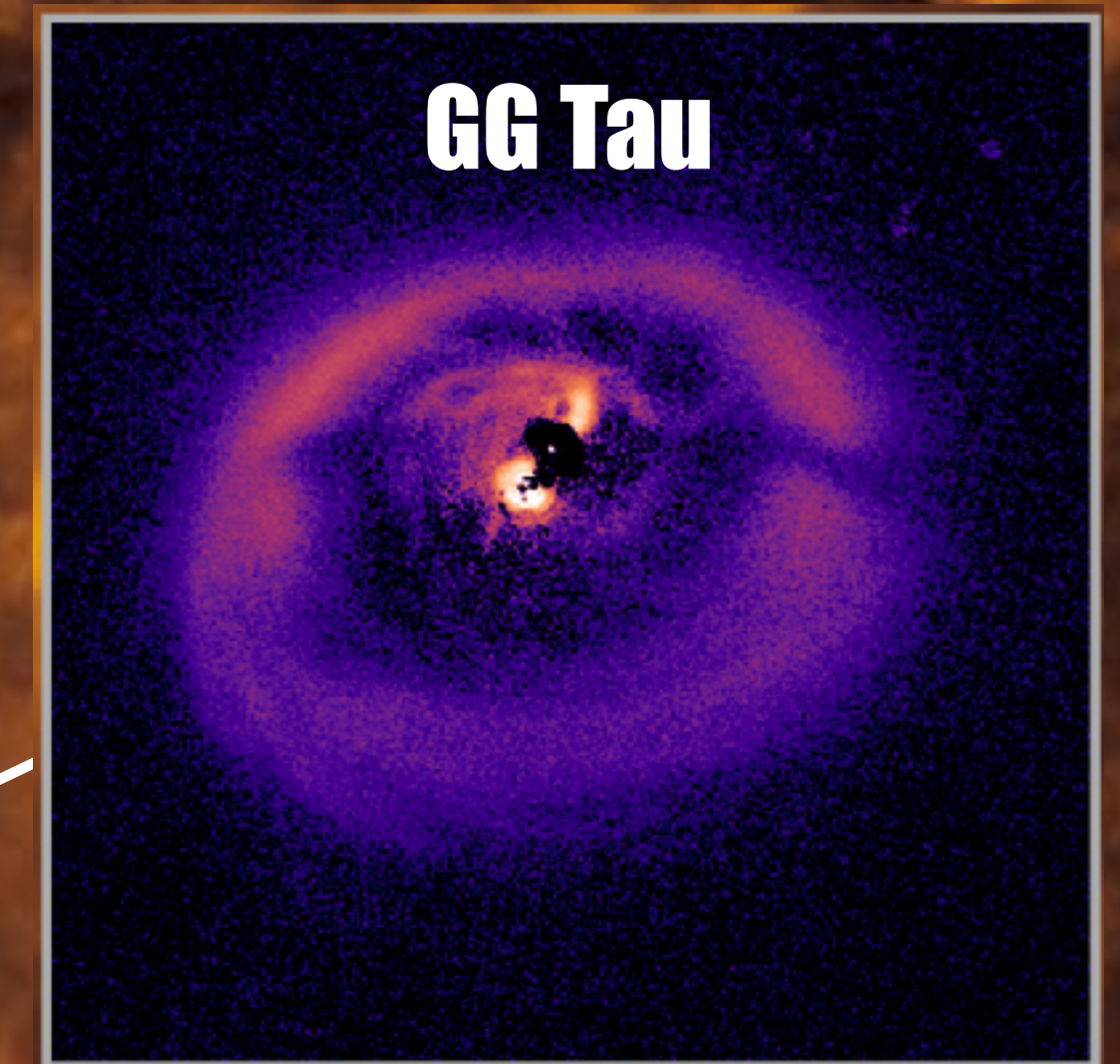
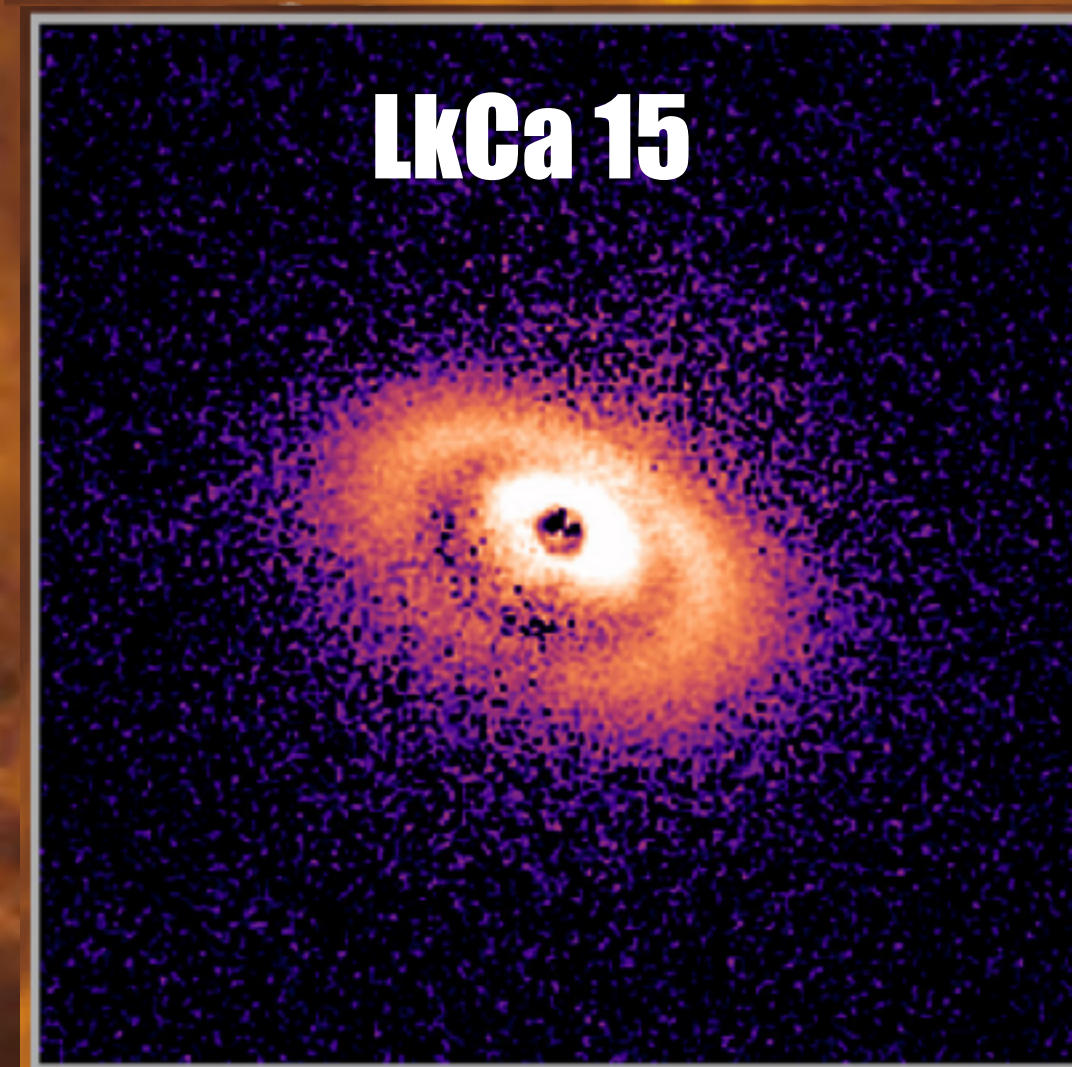
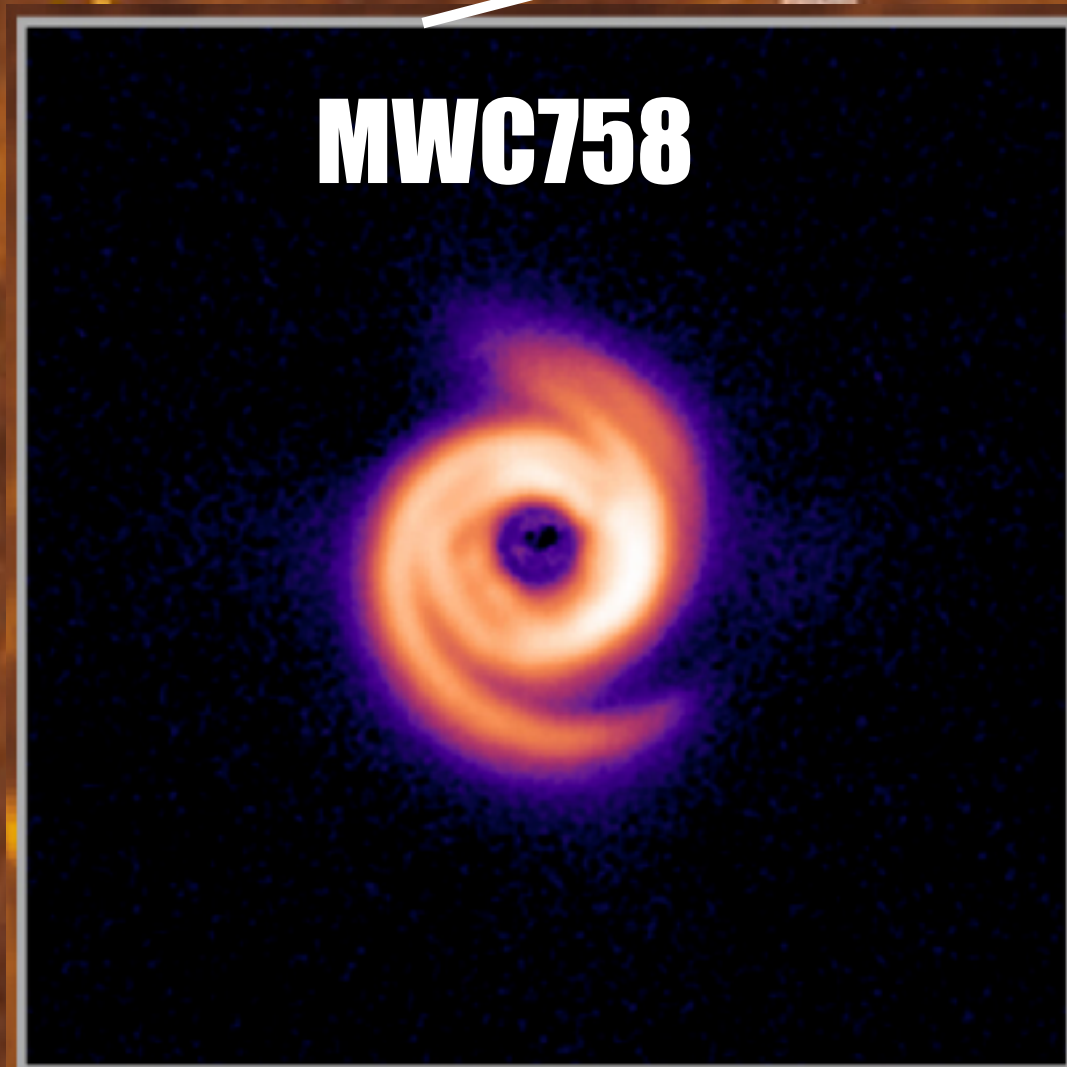
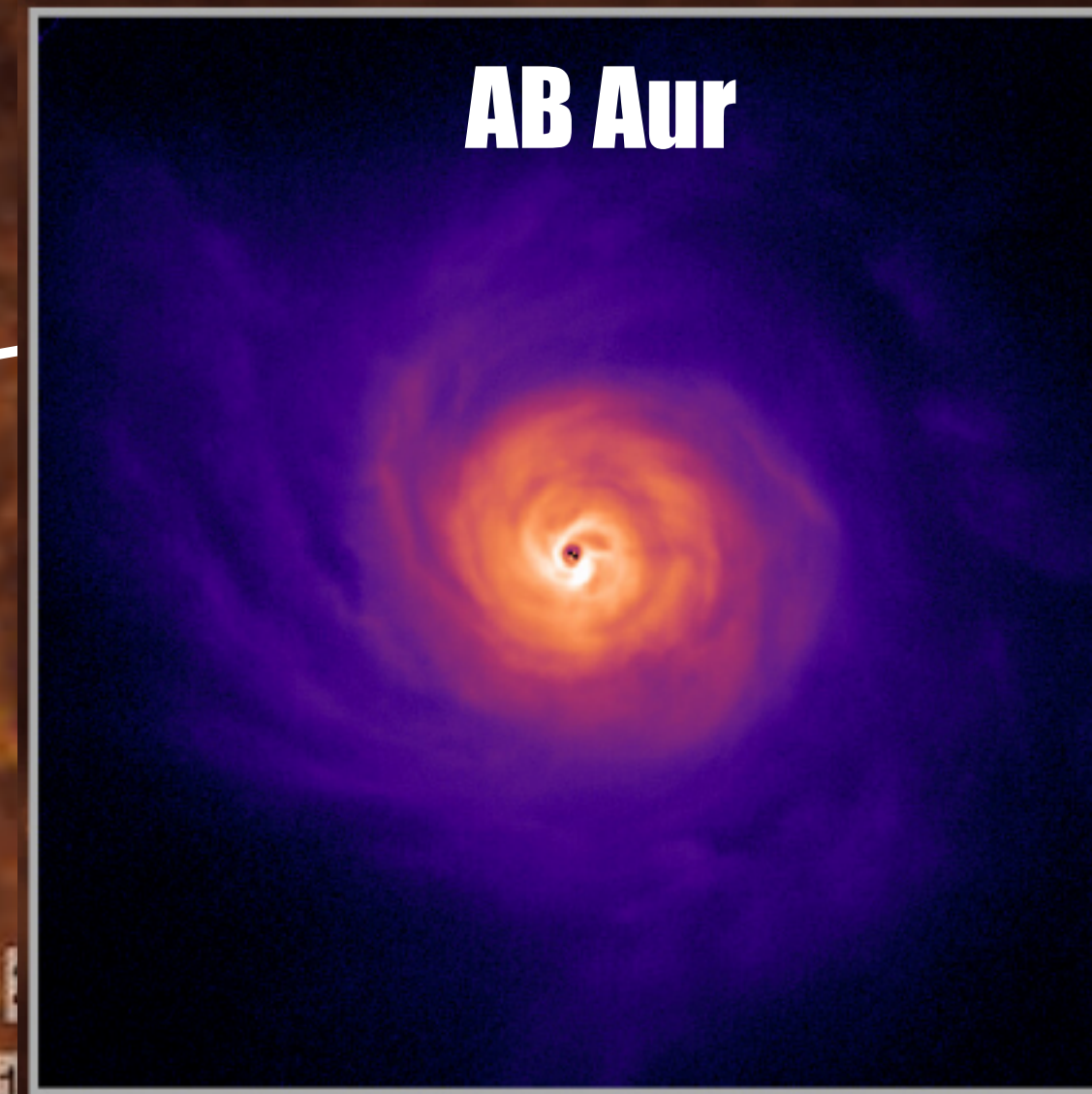
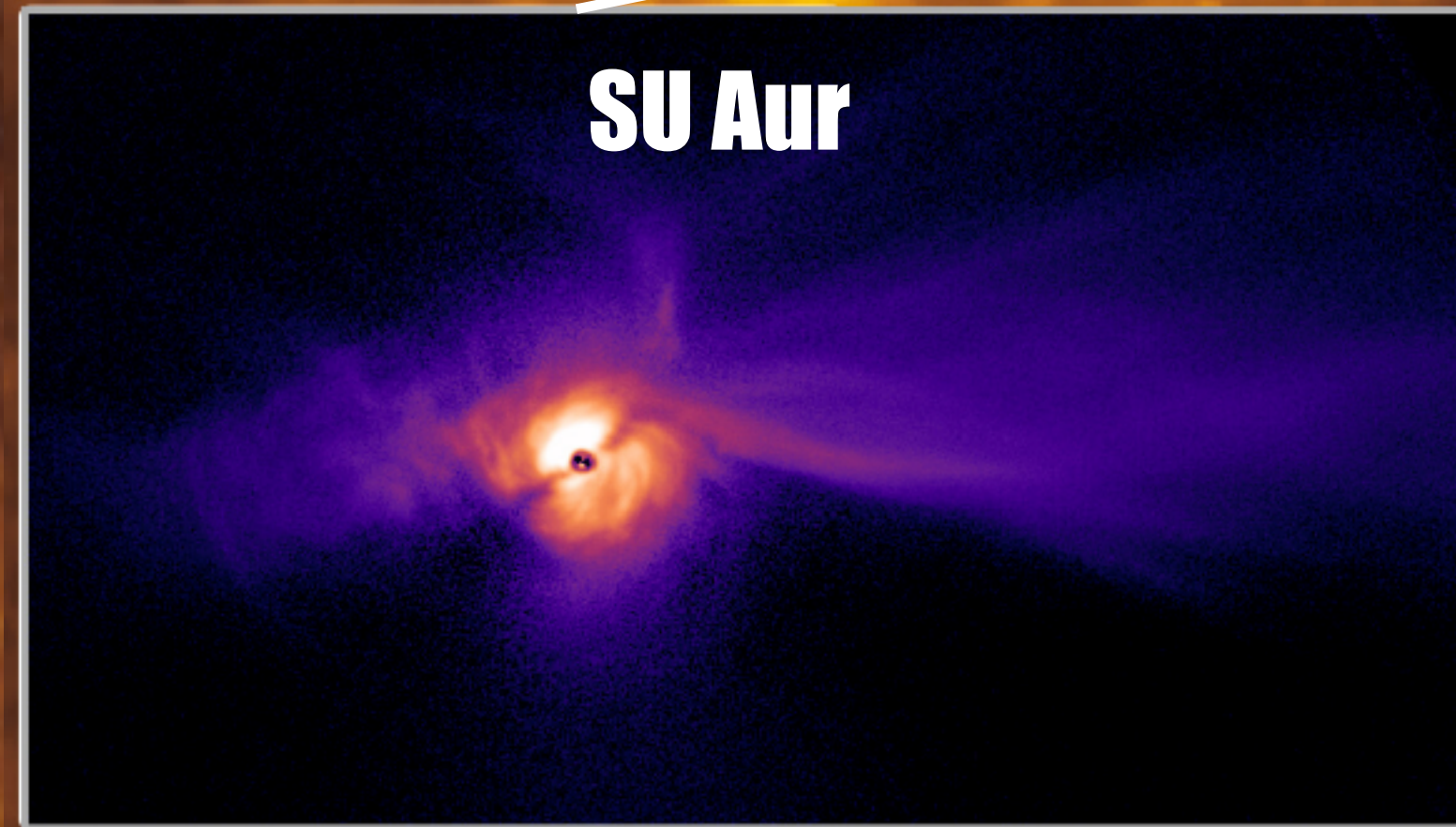
Taurus

おうし座

Aries



# おうし座分子雲



DESTINYs survey papers:  
Ginski et al. (incl RT) 2024, Garufi et al. 2024, Vægård et al. 2024

# WISPIT 2

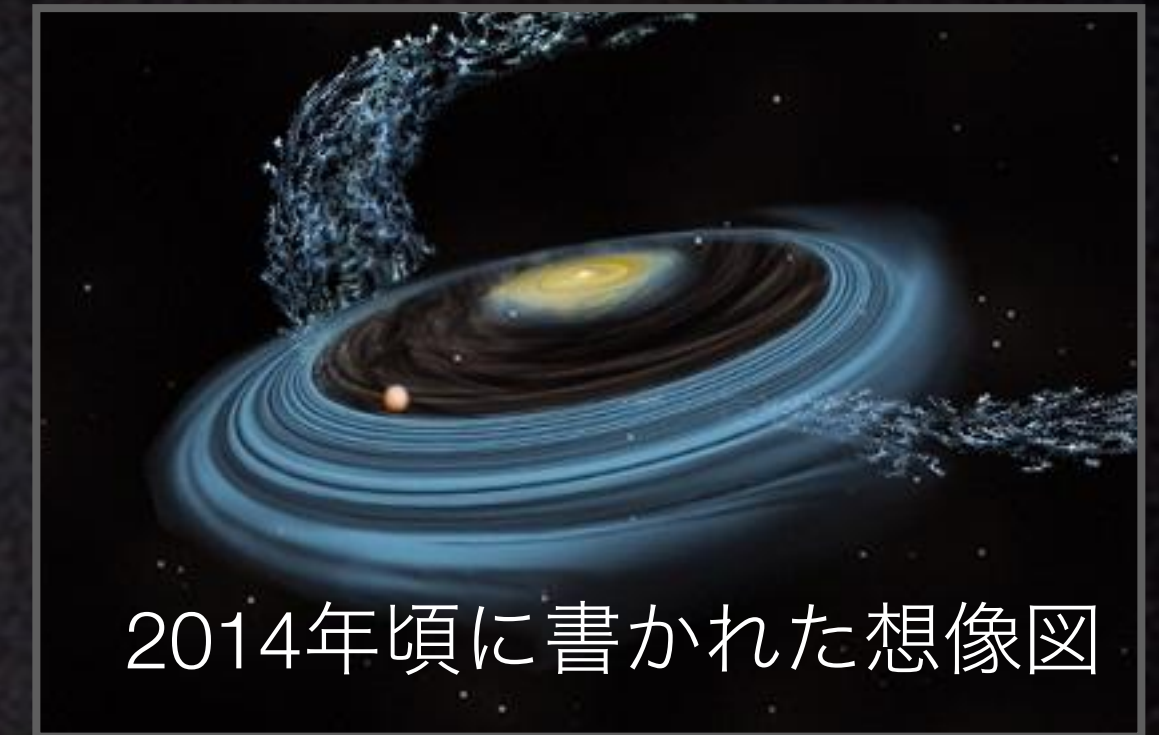
原始惑星系円盤

~ 160 au ~ 1.2"

中心星  
(masked)

惑星

~ 5  $M_{\text{Jupiter}}$   
@ 57.5 au



**惑星は原始惑星系円盤でできる！**

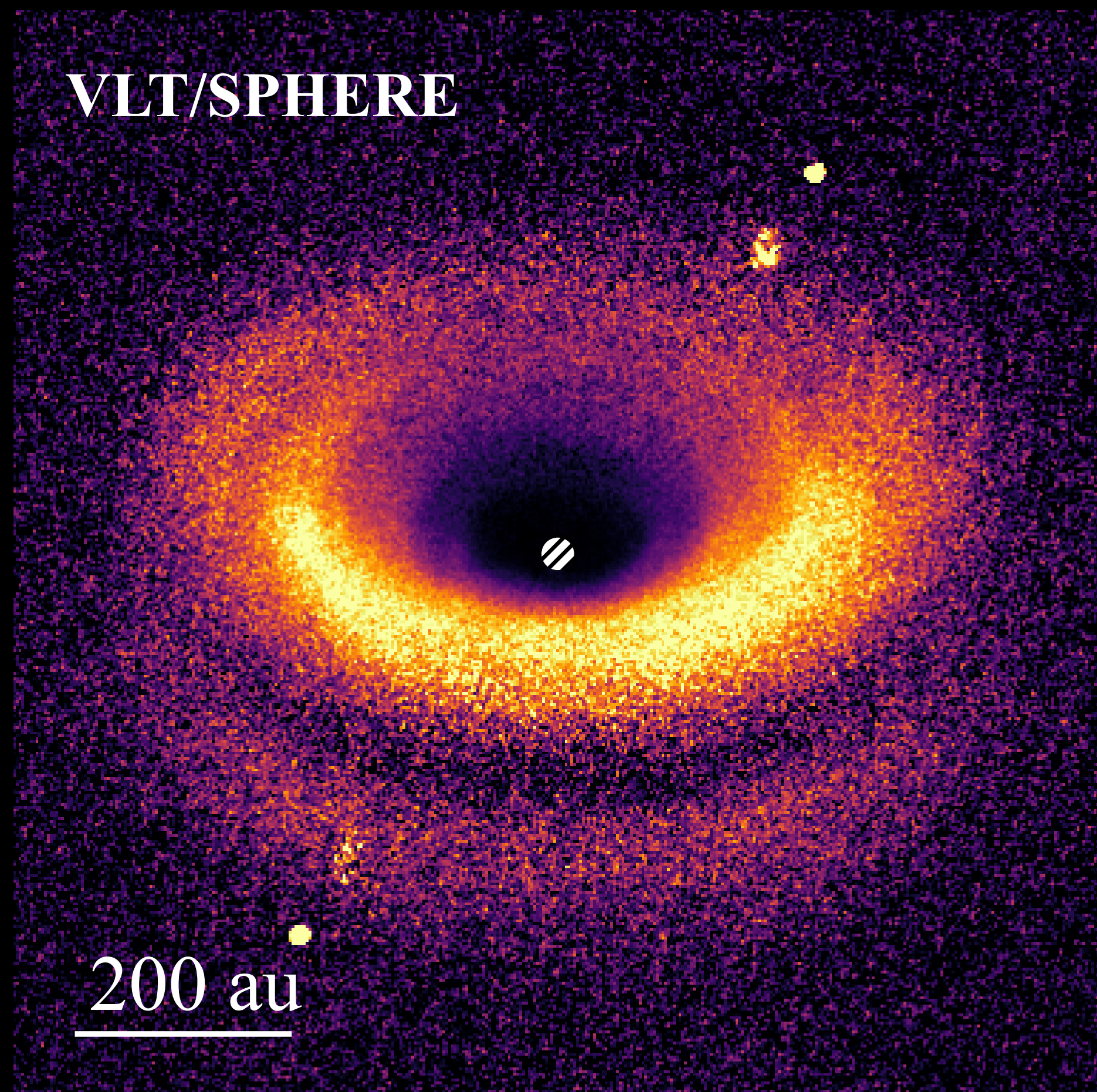
## 原始惑星系円盤について問い

- **ガスやダストの総量** (惑星の材料の総量)
- **ガスやダストの進化** (惑星形成時期・場所・環境)
- **ガスやダストの組成** (惑星の組成)

# 原始惑星系円盤の多波長観測の重要性

Near-IR

Millimeter wavelength

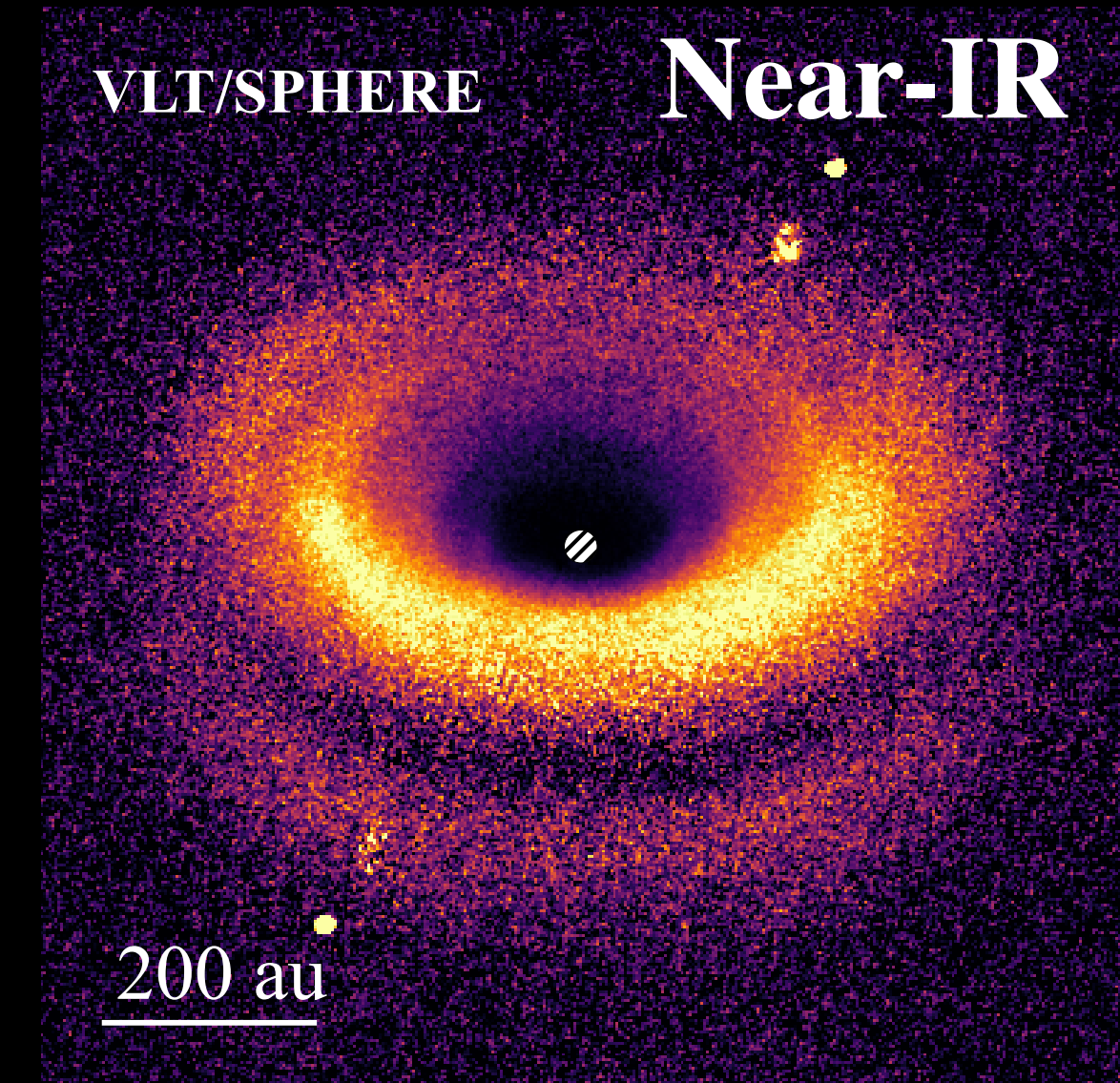
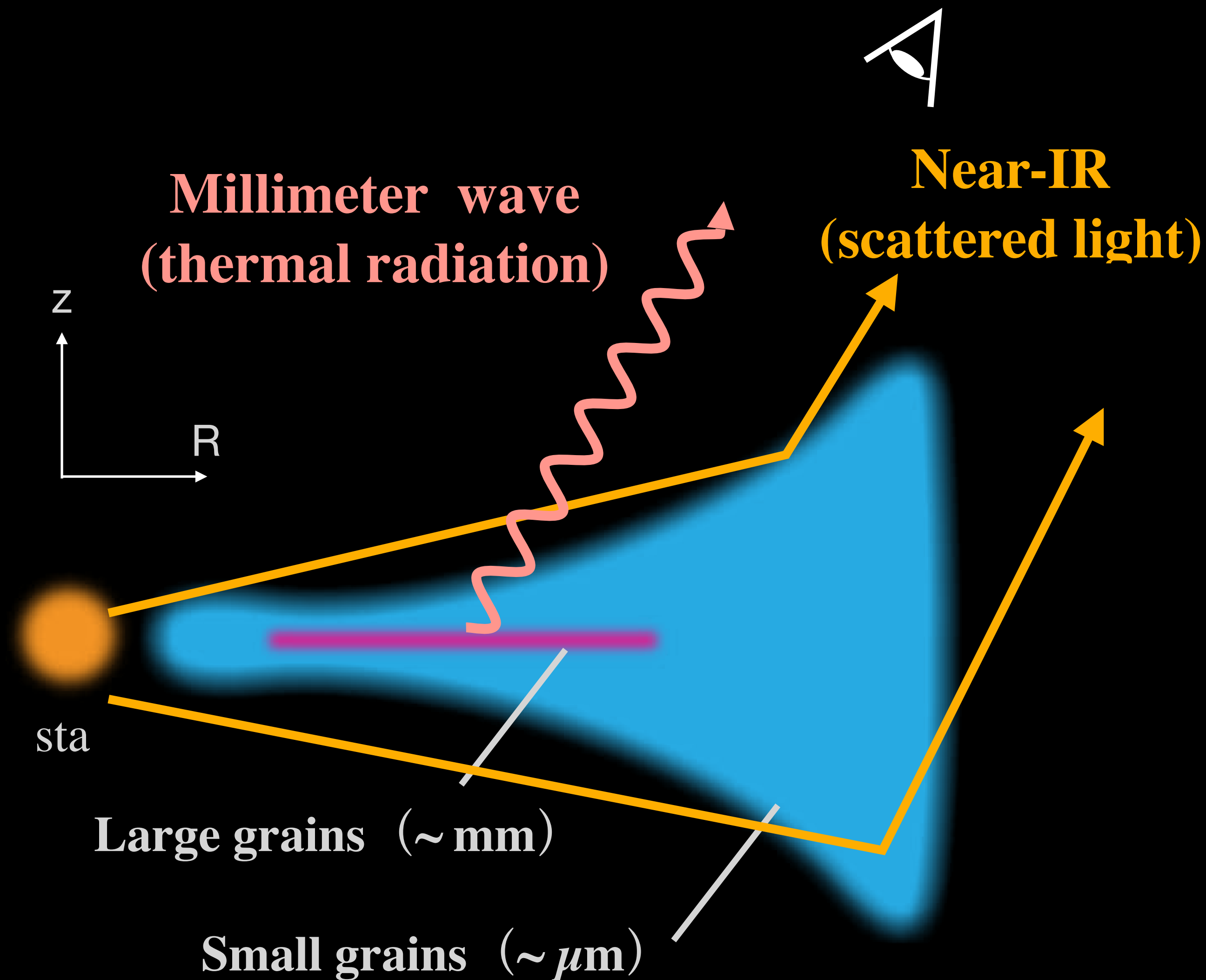


ALMA

200 au

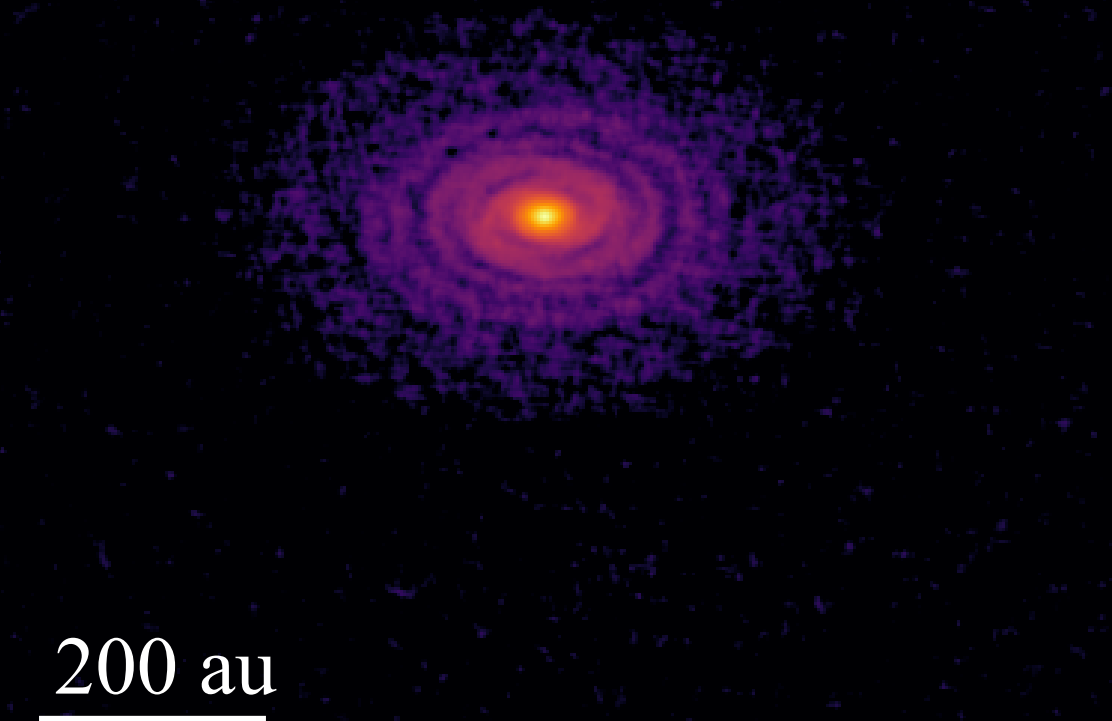
This image shows the same protoplanetary disk at millimeter wavelengths. The central star is a bright point source, and the disk appears as a diffuse, glowing ring. A scale bar at the bottom left indicates 200 astronomical units (au).

# 原始惑星系円盤の多波長観測の重要性



ALMA

Millimeter wave



# 原始惑星系円盤におけるダストの沈殿

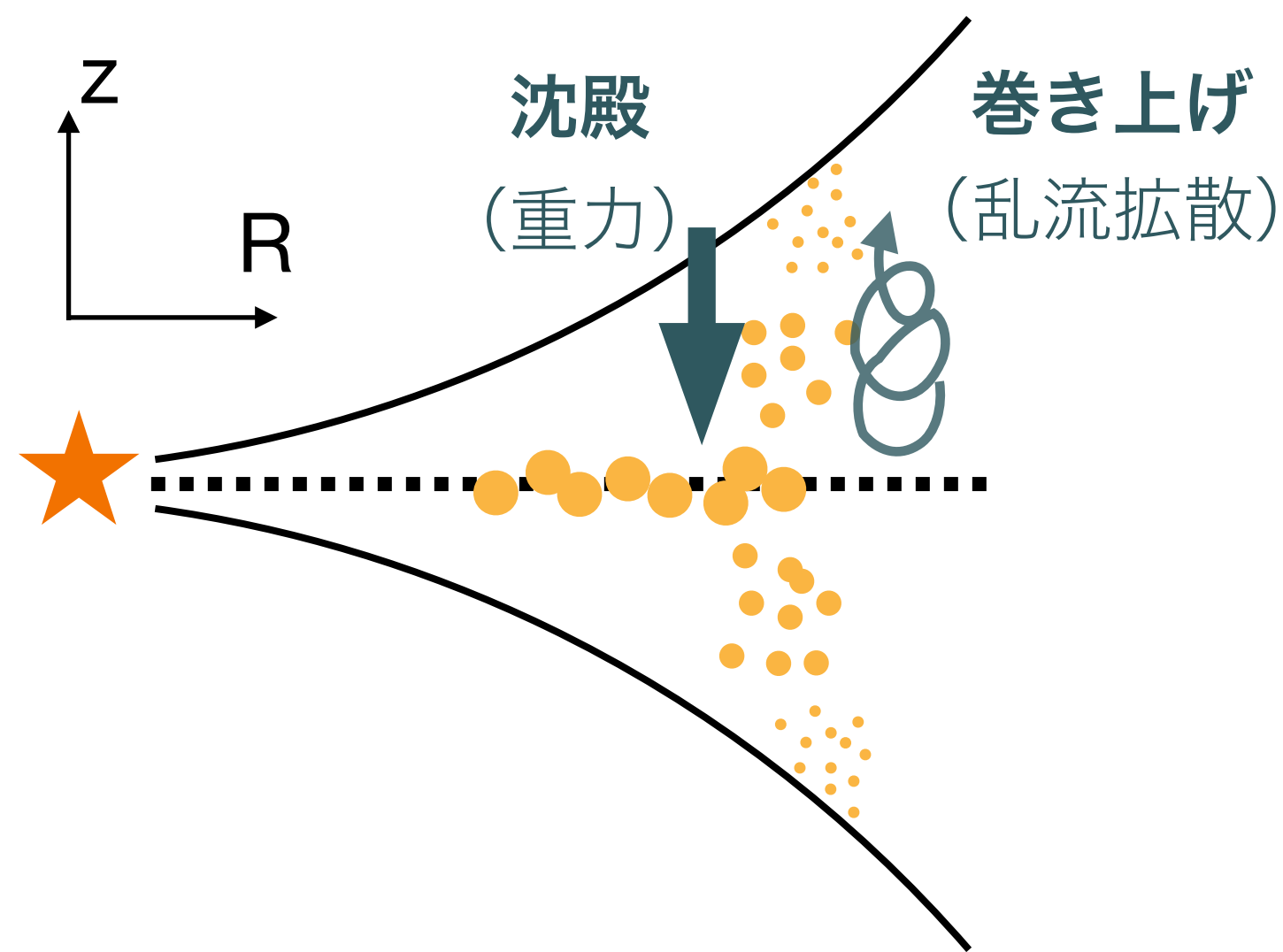
ダストの乱流拡散係数

e.g., Dubrulle et al. 1995, Dullemond & Dominik (2004)

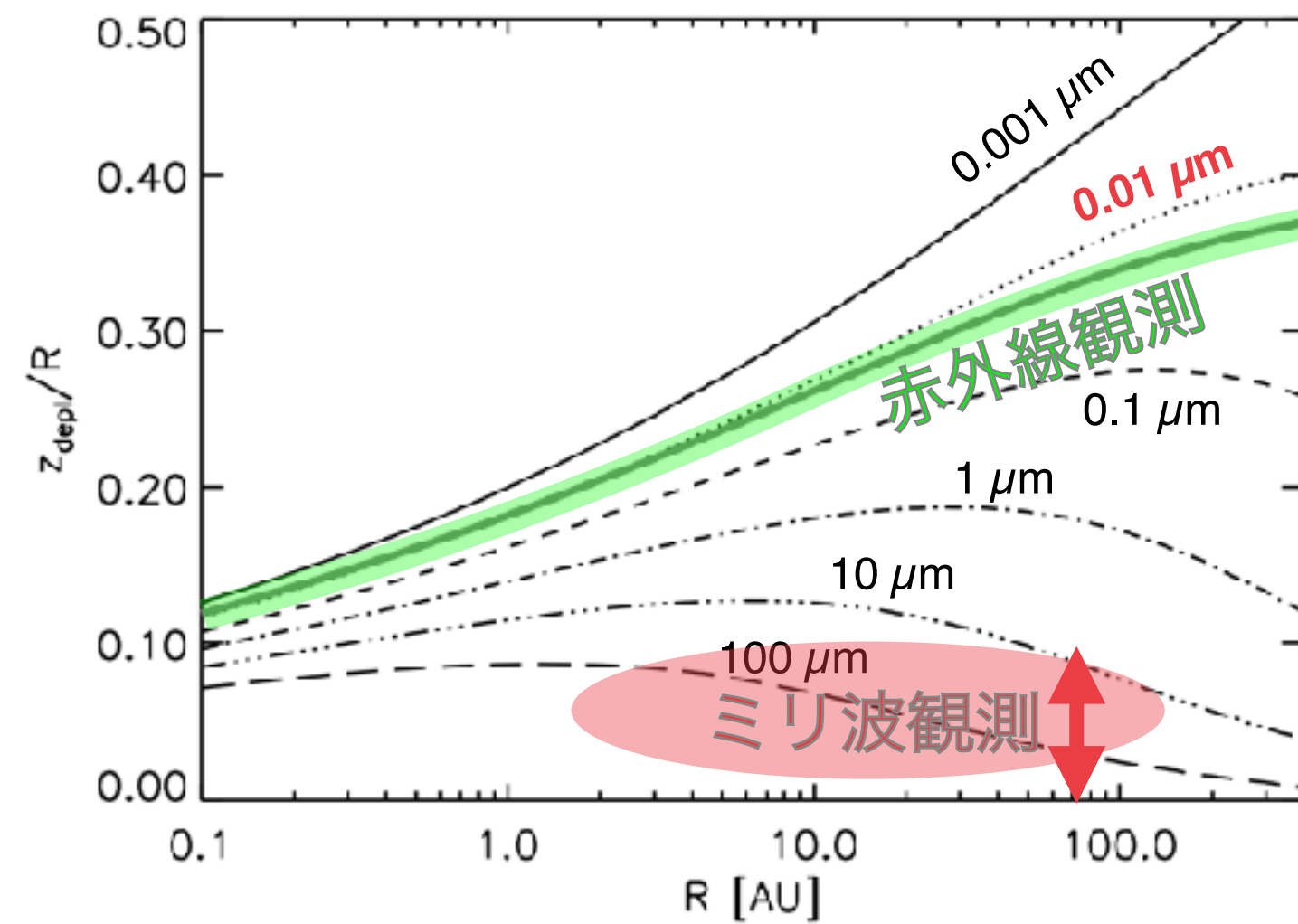
$$D = \alpha c_s H_g$$

ダスト層の厚み：重力による沈殿 ~ 沈殿を妨げる効果 (e.g., 乱流拡散)

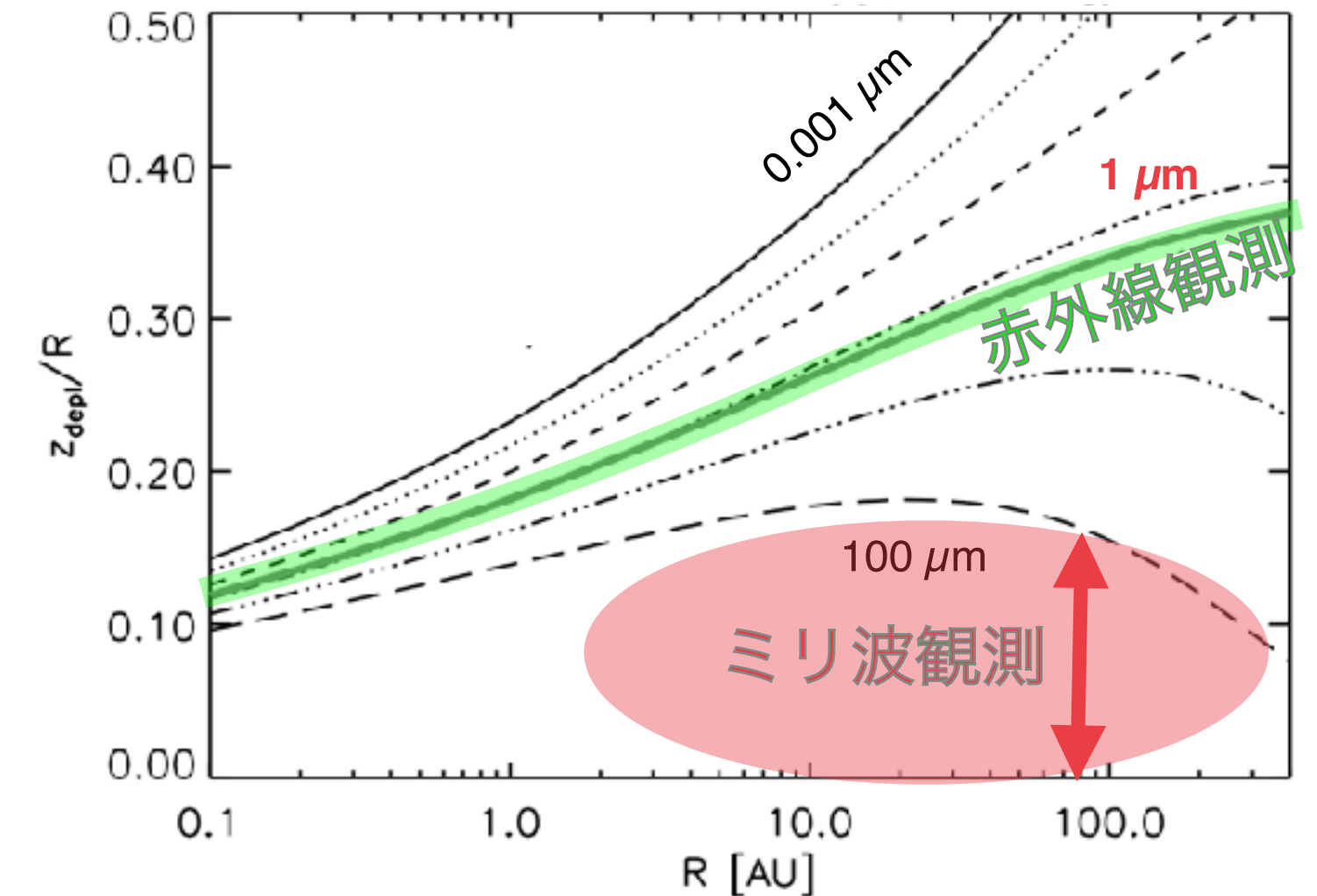
## 沈殿と乱流拡散の平衡状態



弱乱流 ( $\alpha = 10^{-4}$ )



強乱流 ( $\alpha = 10^{-2}$ )



Dullemond & Dominik (2004)

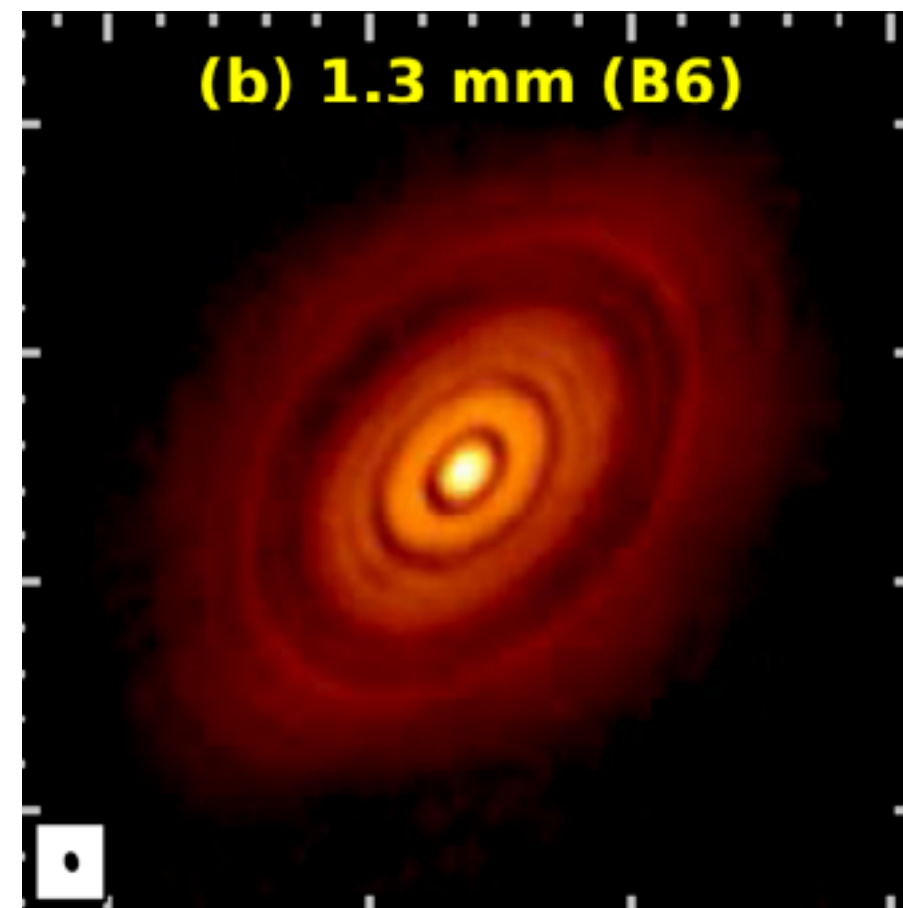
乱流強度の観測的指標

- 表層部のダストサイズ (赤外線観測)
- ミリ波放射の幾何学的厚み

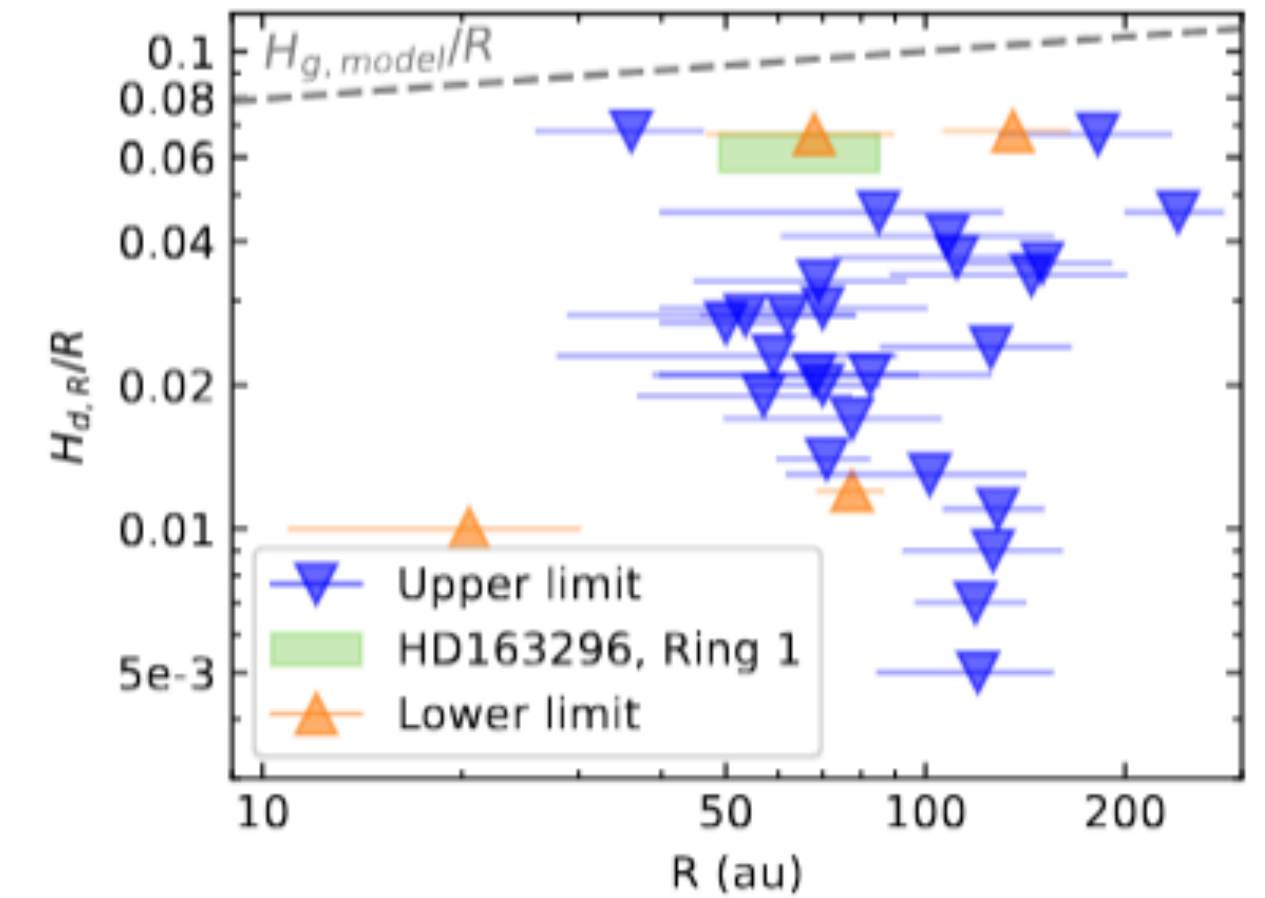
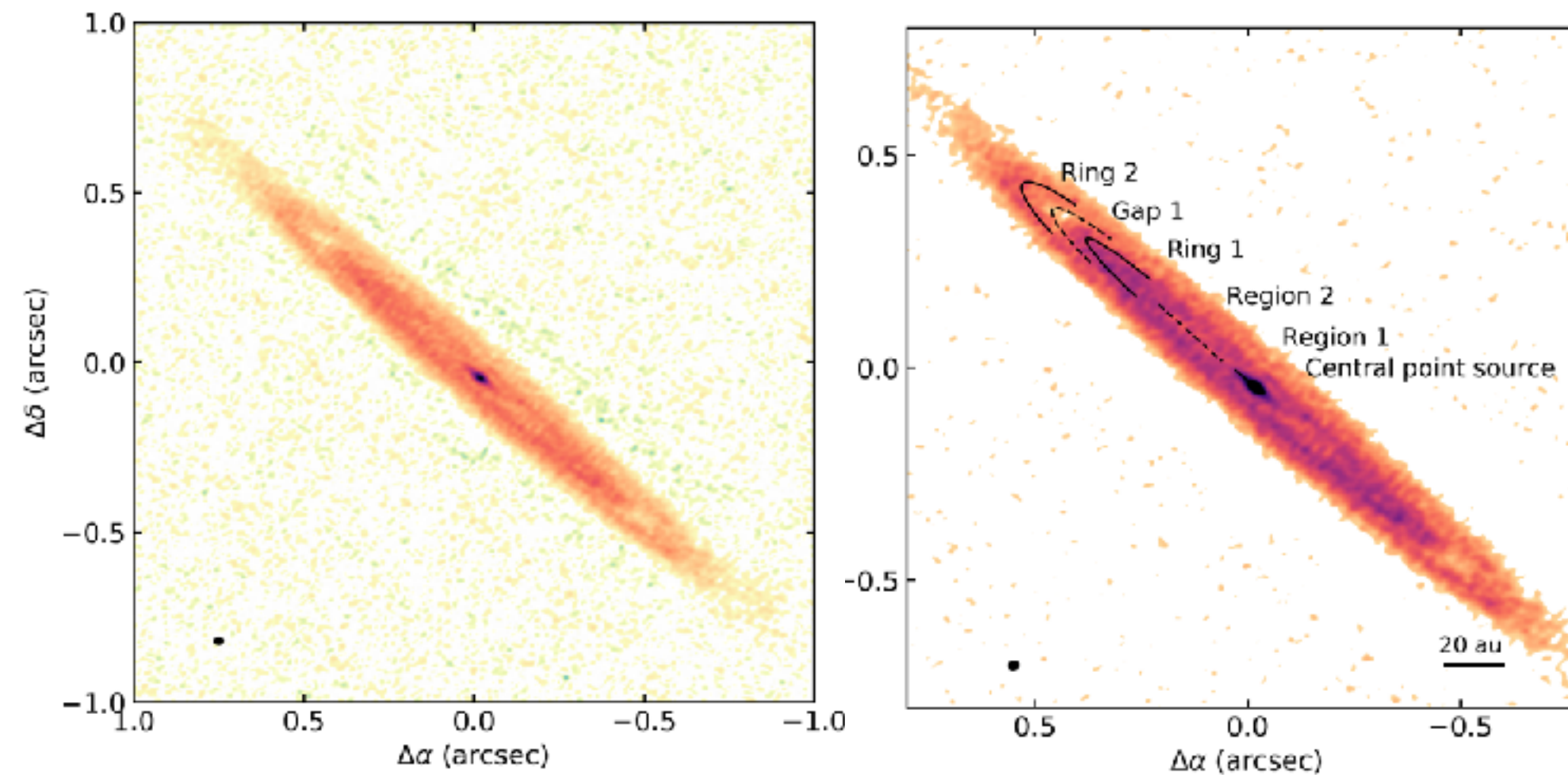
# ダストの沈殿：ミリ波放射層（ペブル層）の厚み

本講演ではALMAでみえるダスト放射を担うダストをペブル（ $\sim 100 \mu\text{m} - 1 \text{ cm}$ ）と呼ぶ

HL Tau



Oph 163131

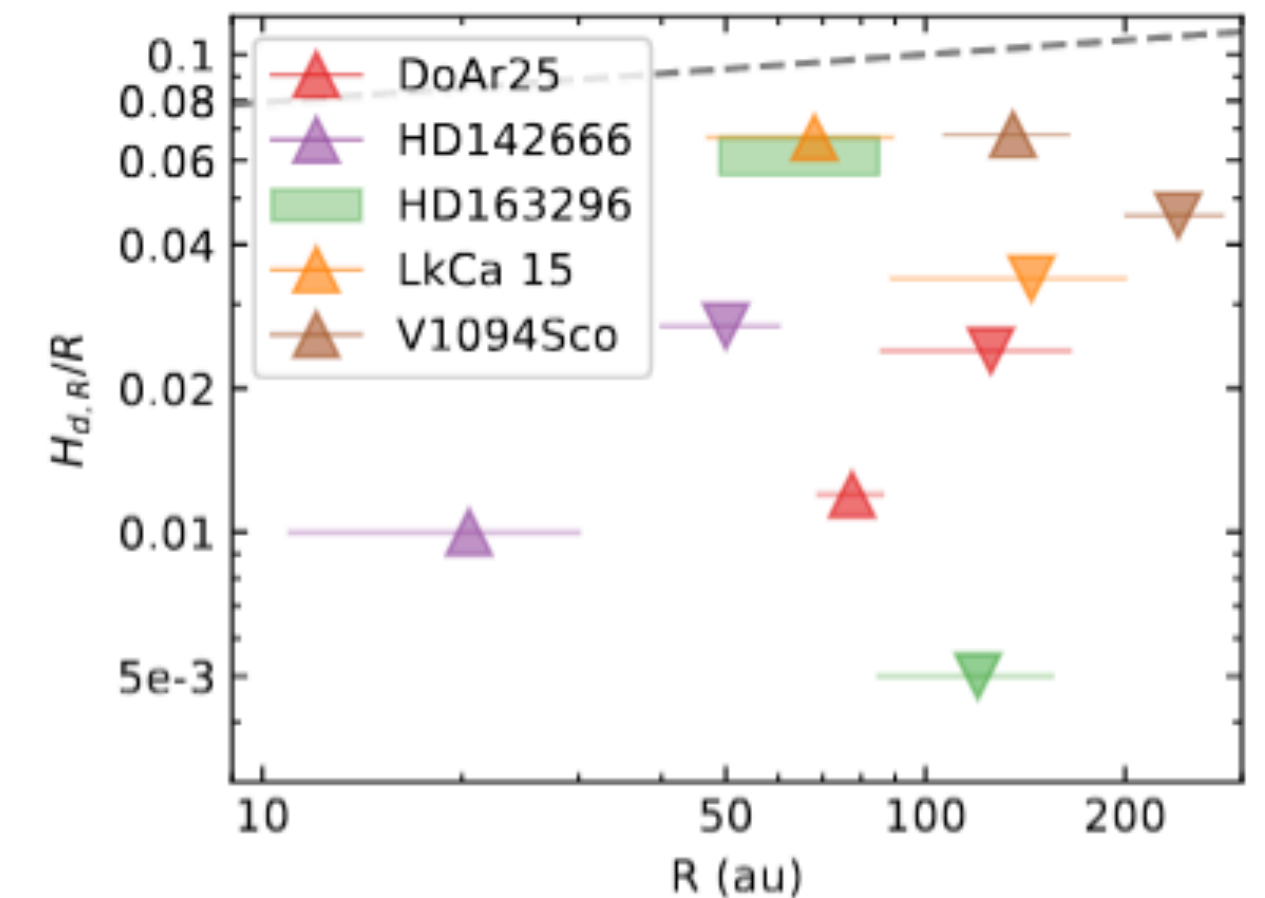


ALMA Partnership et al. 2015,  
Pinte et al. 2016

$h_{\text{pebble}}/r \sim 0.01$  at 100 au

Villenave et al. 2022

$h_{\text{pebble}}/r < 0.005$  at 100 au



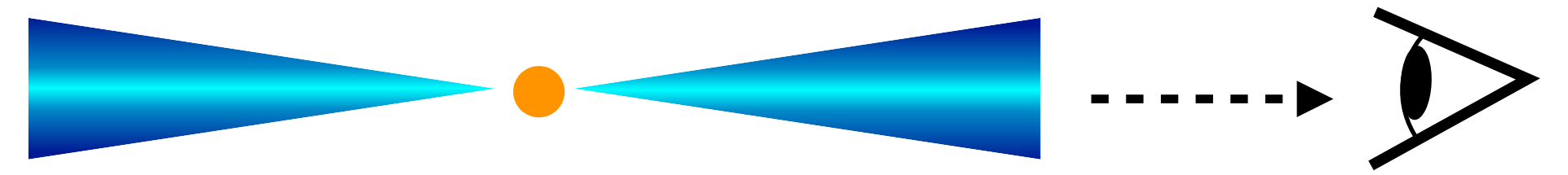
- ペブル層の厚み（観測）： $h/r \sim 0.5\% - 10\%$  (at  $r=100 \text{ au}$ )
- 降着率や円盤ペブル質量とは相関がない (Villenave et al. 2025)

Villenave et al. 2025

# エッジオン原始惑星系円盤

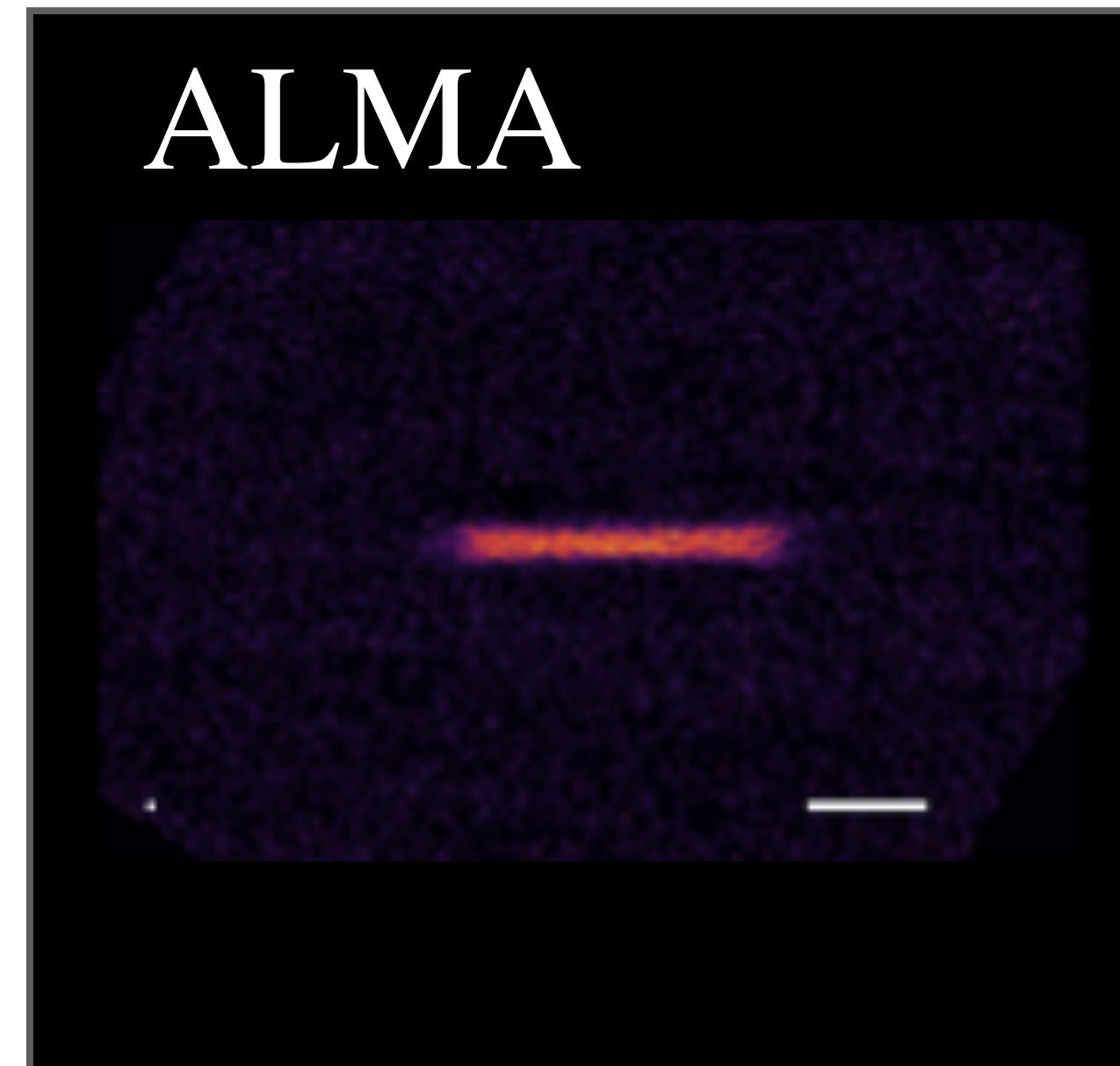
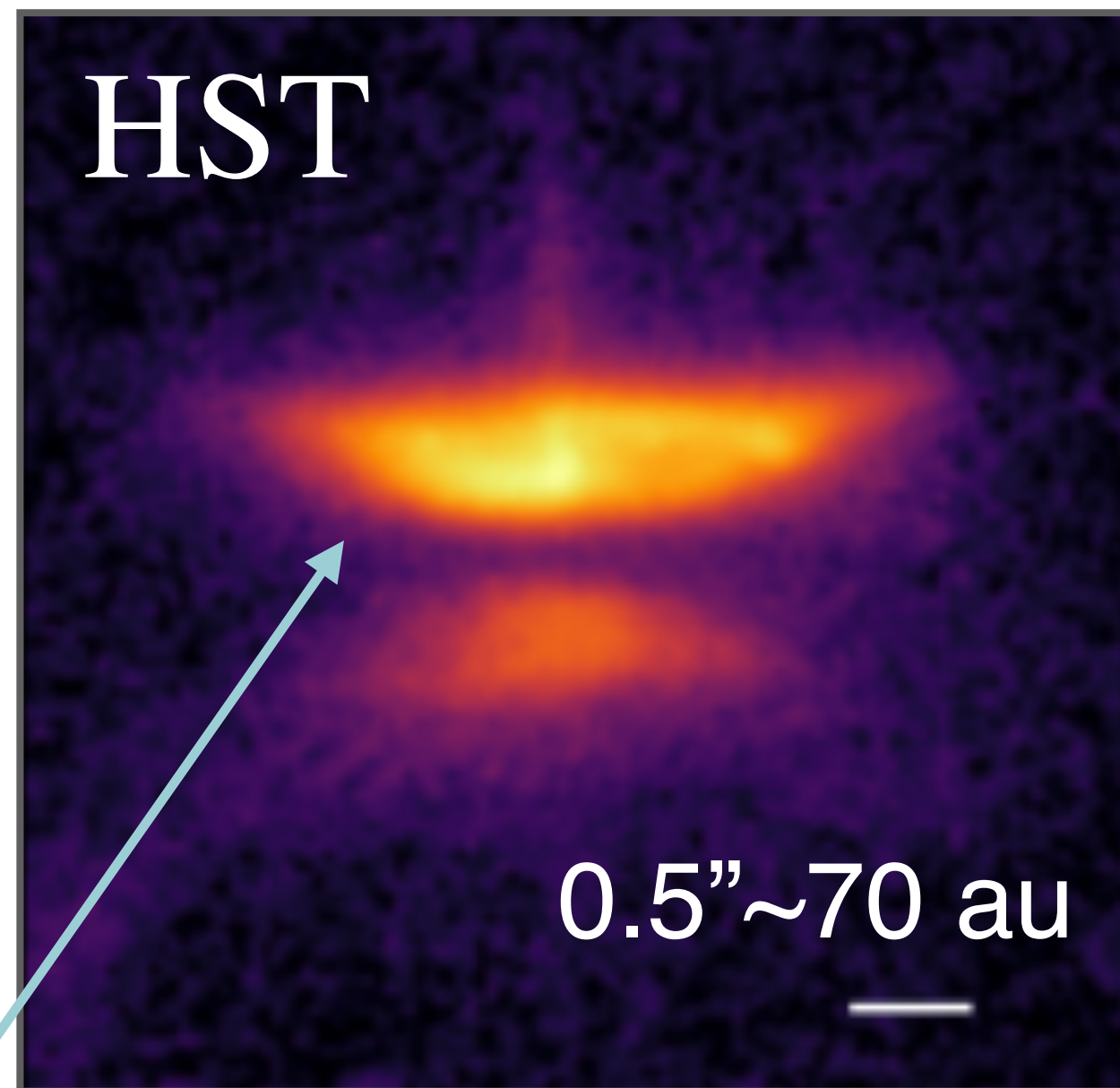
...原始惑星系円盤をほぼ真横から見込む天体

円盤内の鉛直構造 (e.g., ダストの沈殿) を多波長で調べる上で最適の天体



近赤外線 ( $\lambda=0.8 \mu\text{m}$ )

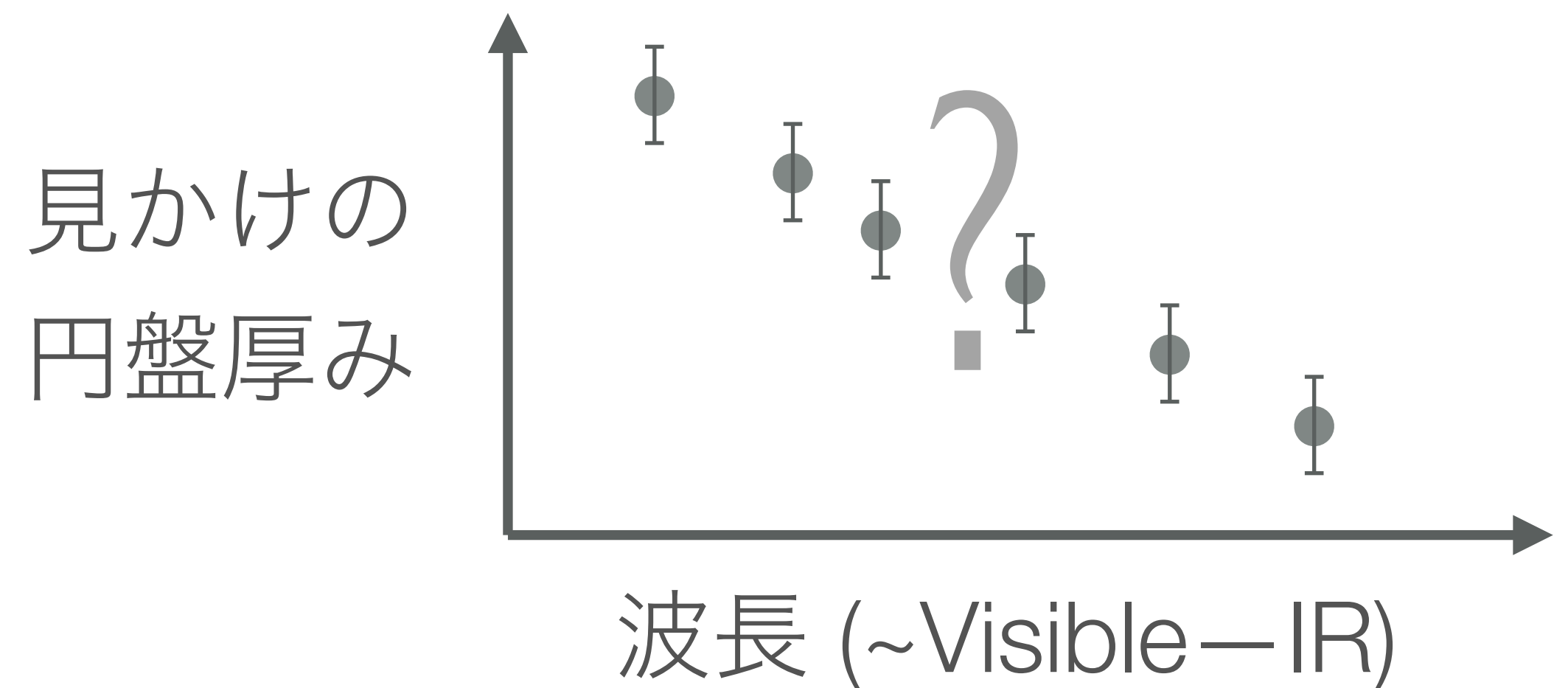
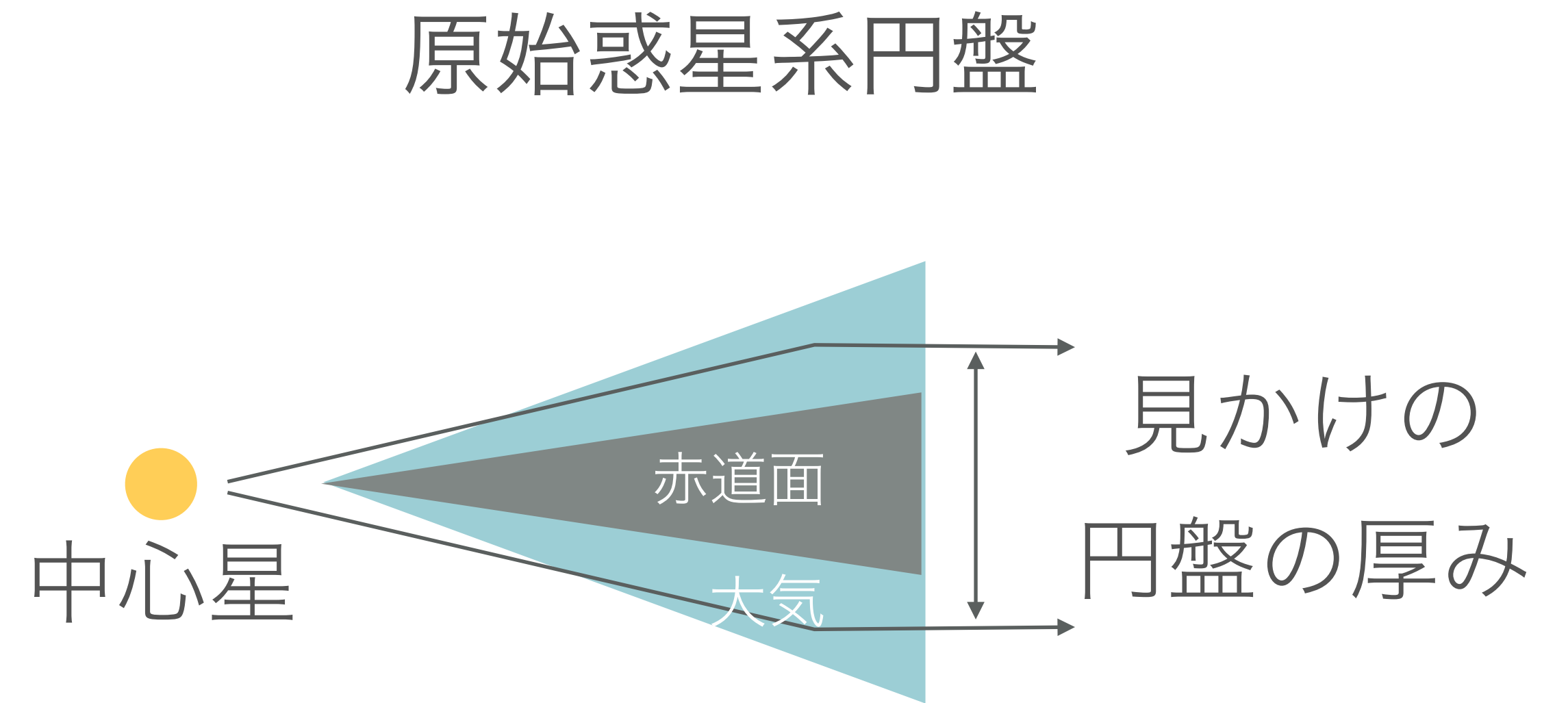
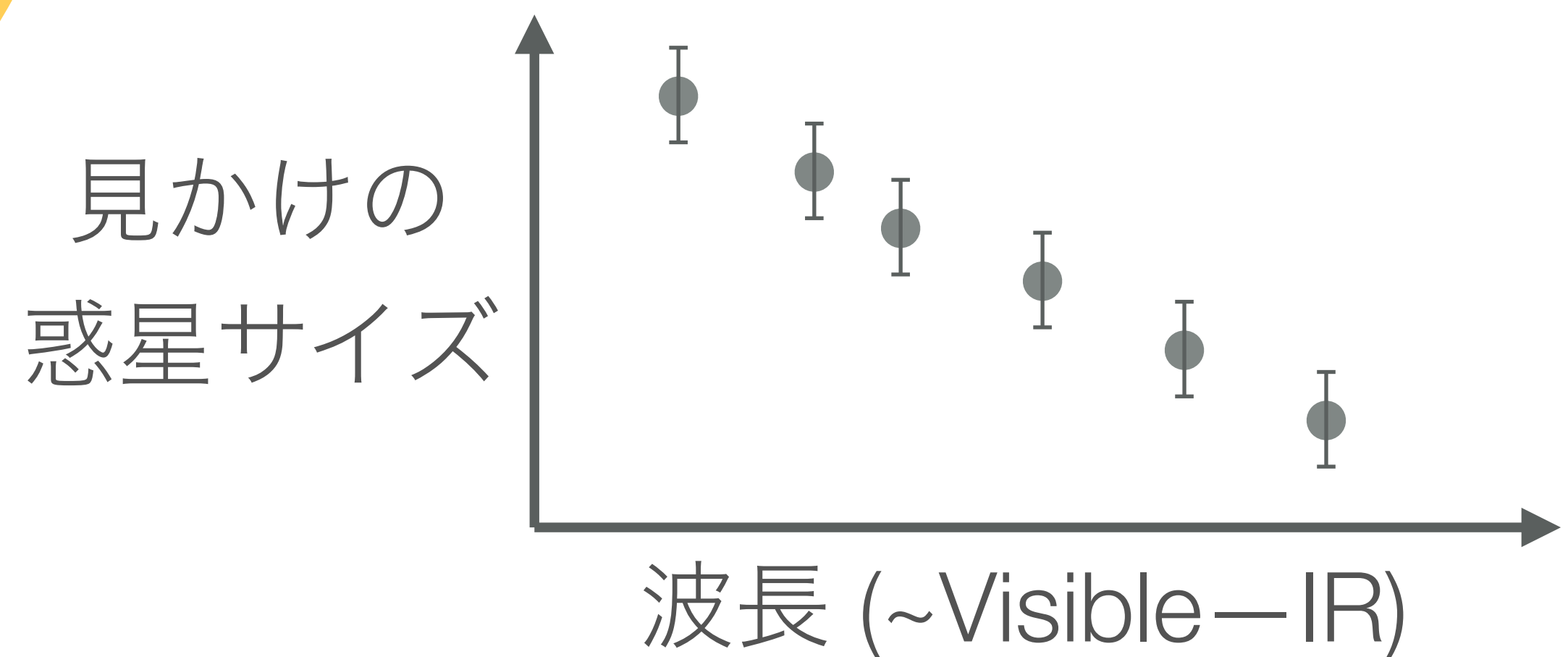
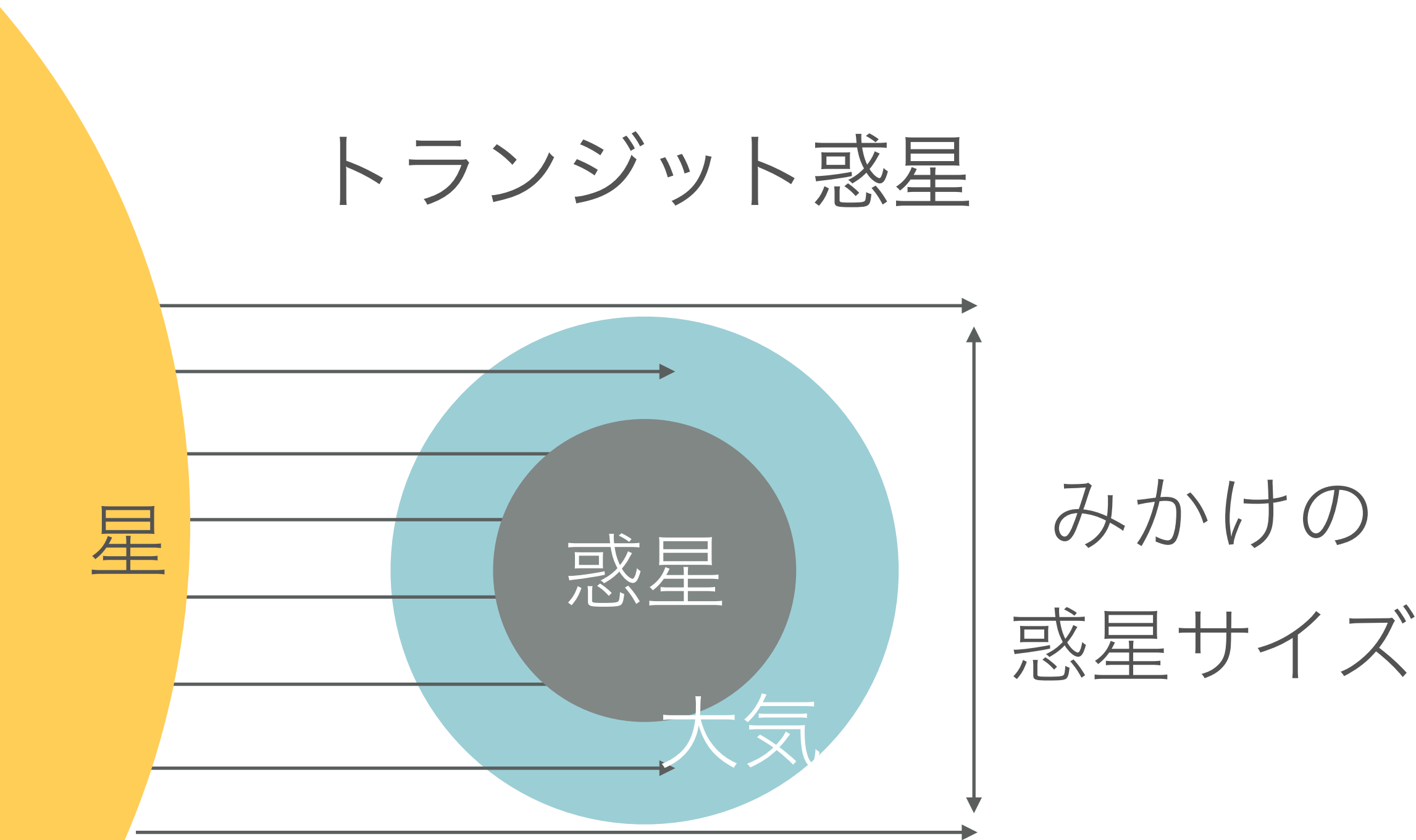
ミリ波 ( $\lambda=1.3 \text{ mm}$ )



HH 30  
Tazaki et al. 2025

表層に巻き上がっているダストの大きさ?

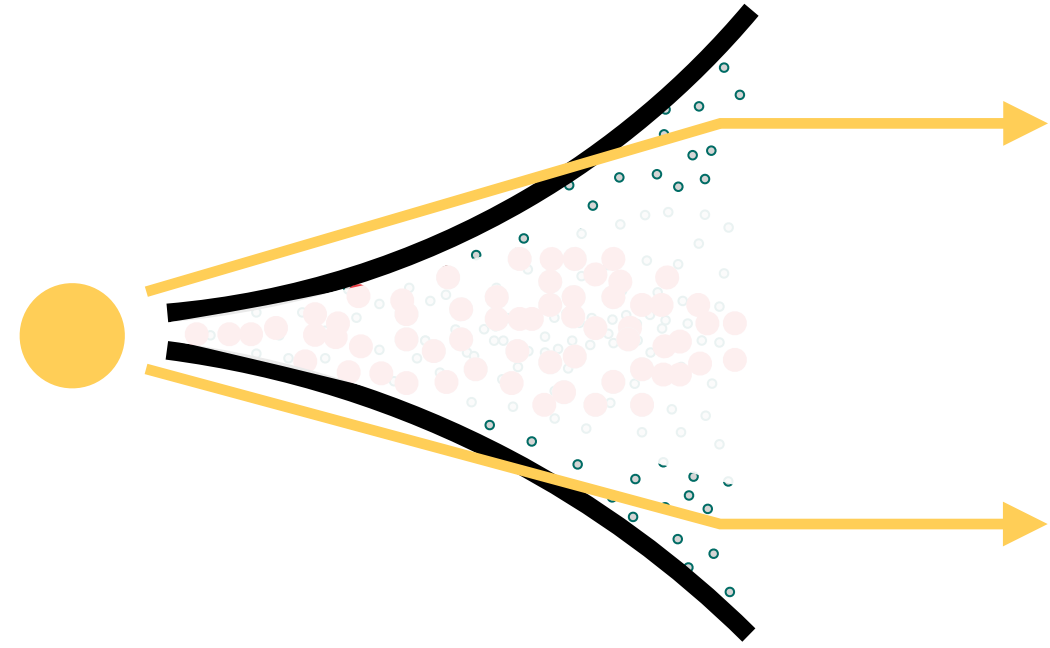
# 円盤表層のダストのサイズをどう測るか？



# Proof of concept: 輻射輸送計算

小さなダストが支配的 (Rayleigh散乱的)

(dominated by sub- $\mu\text{m}$  grains)



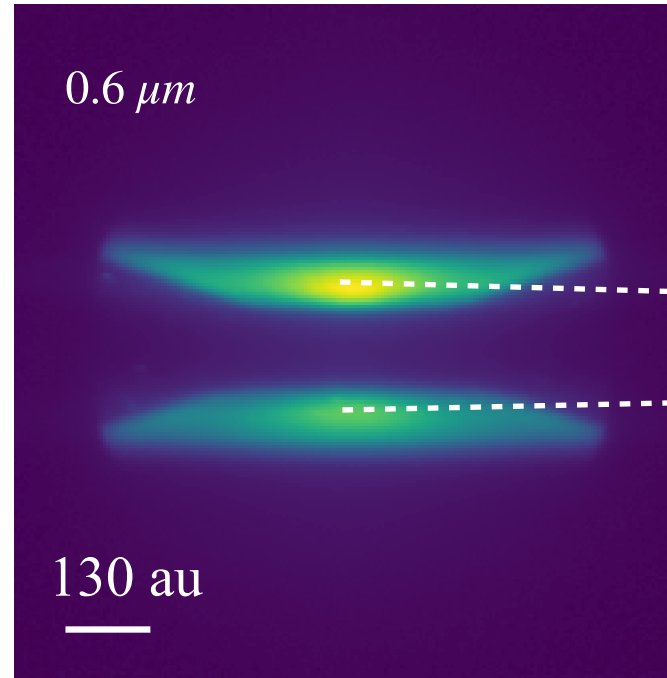
大きなダストが支配的 (幾何光学的)

(dominated by micron-sized grains)

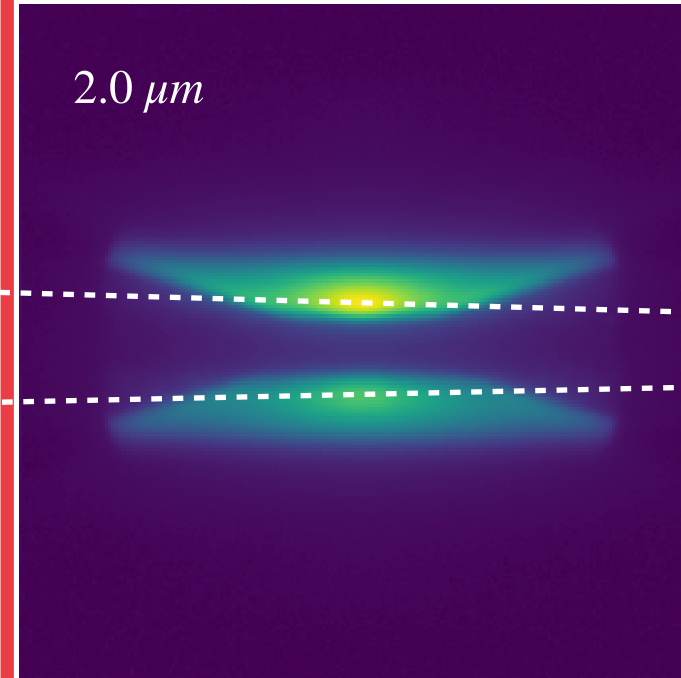


モデル予測

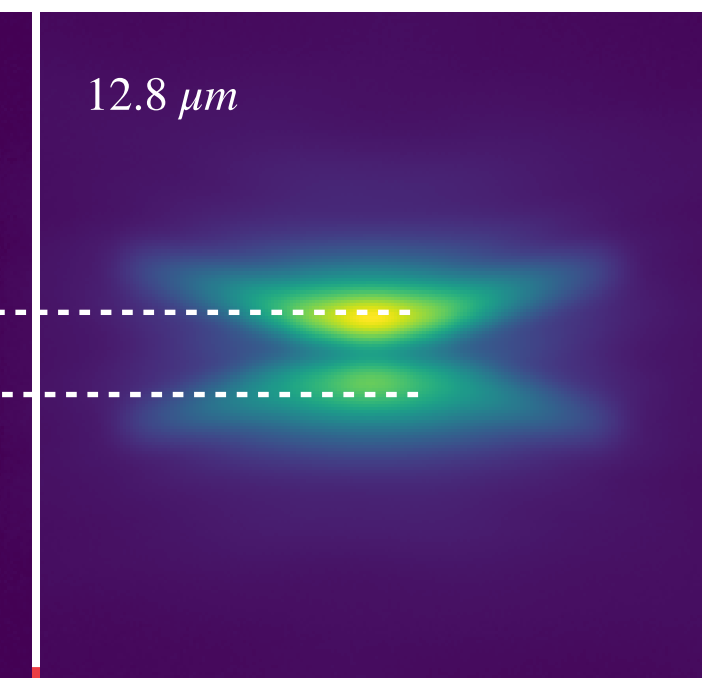
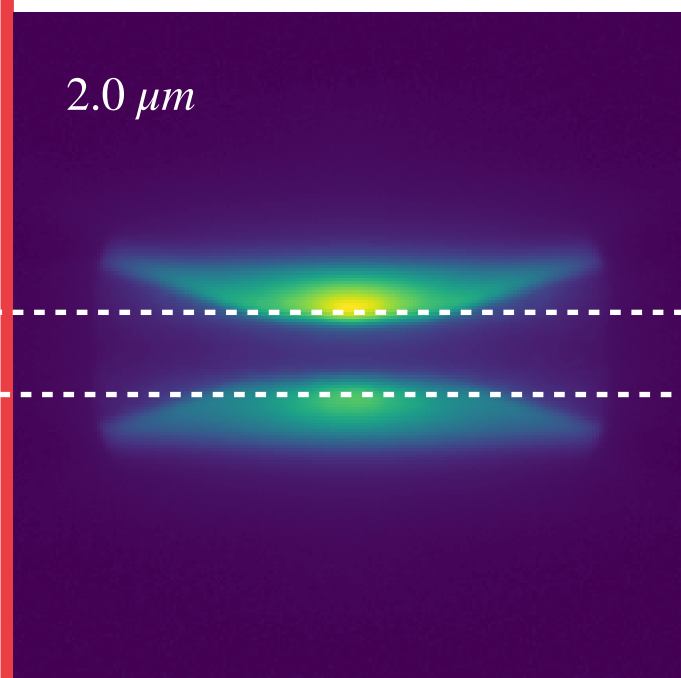
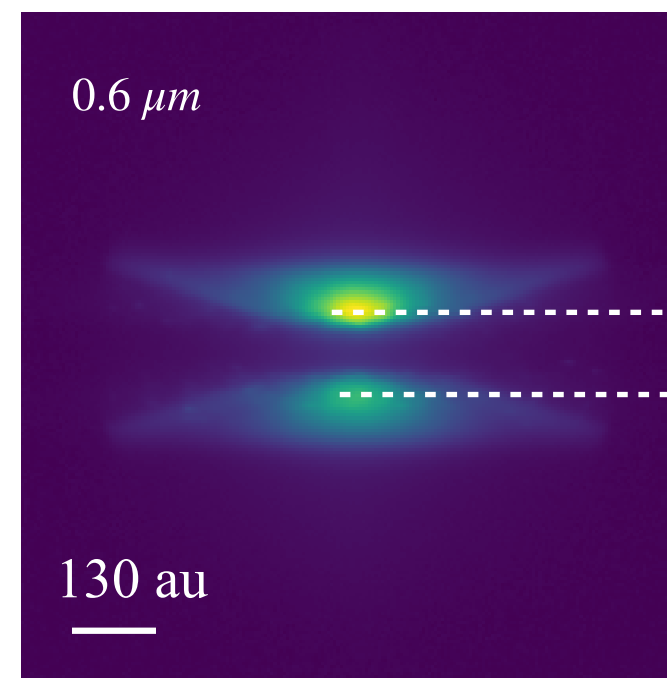
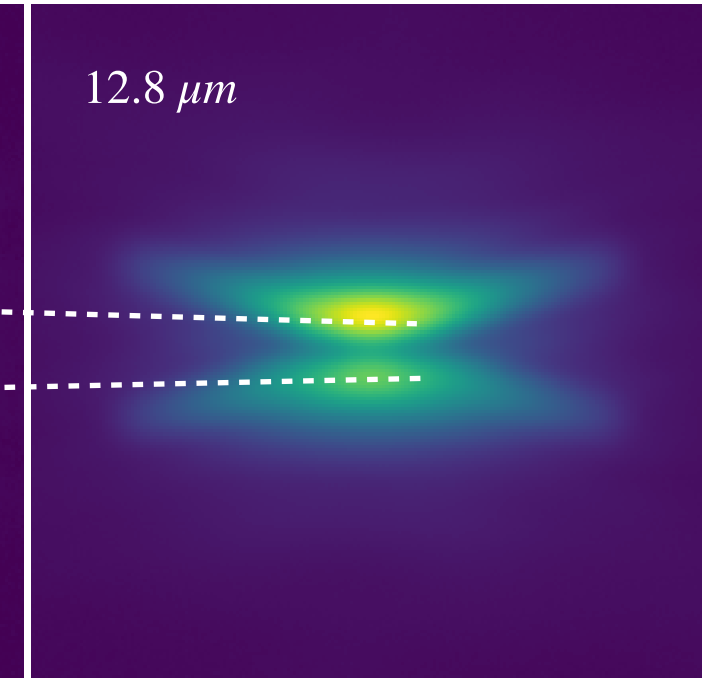
Visible (HST)



Near-IR



Mid-IR



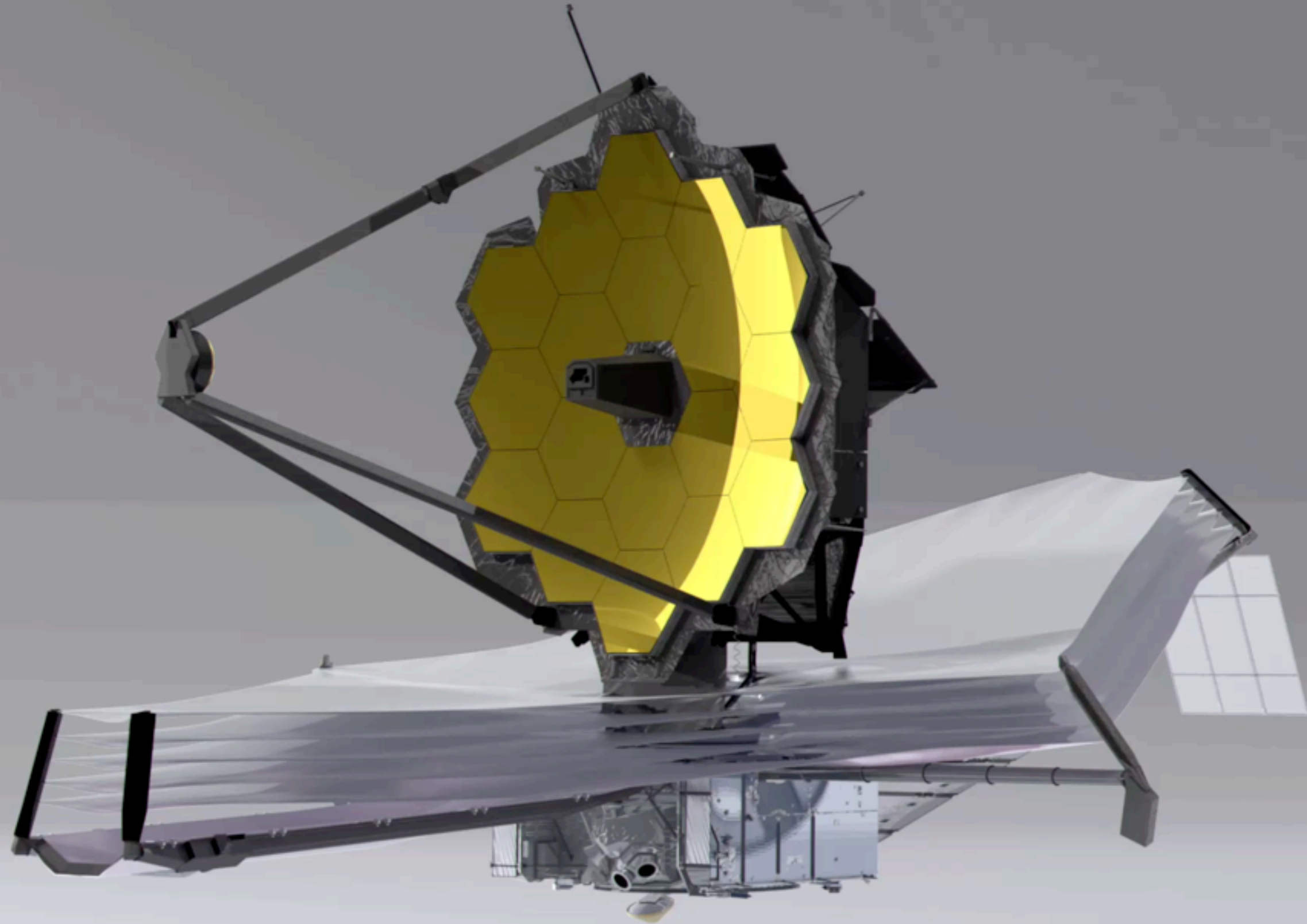
エッジオン円盤を可視光から近・中間赤外線にかけて

空間分解した観測ができれば、円盤表層のダストサイズが求まりそう！

# James Webb Space Telescope (JWST)

Launched in 2021

Wavelength: Near-IR to Mid-IR



# Hubble Space Telescope (HST)

Launched in 1990

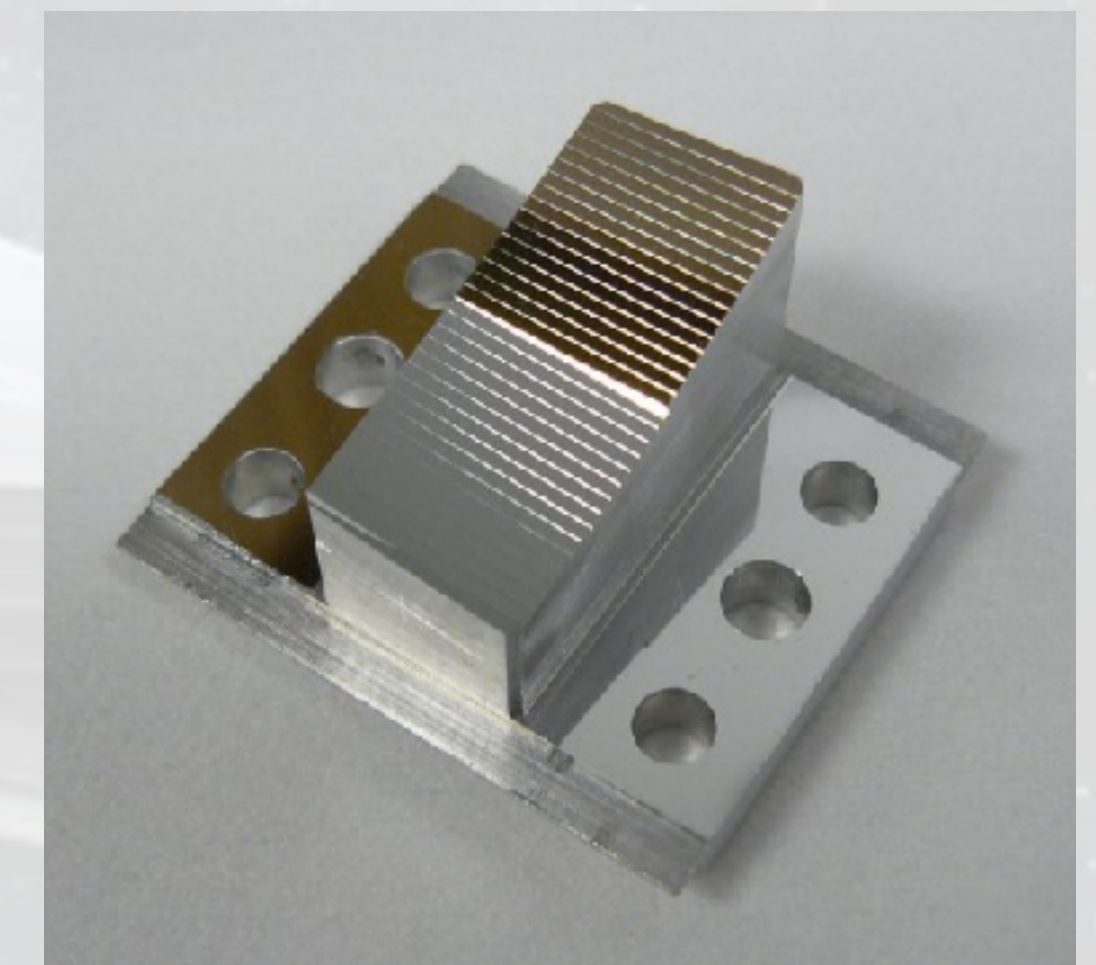
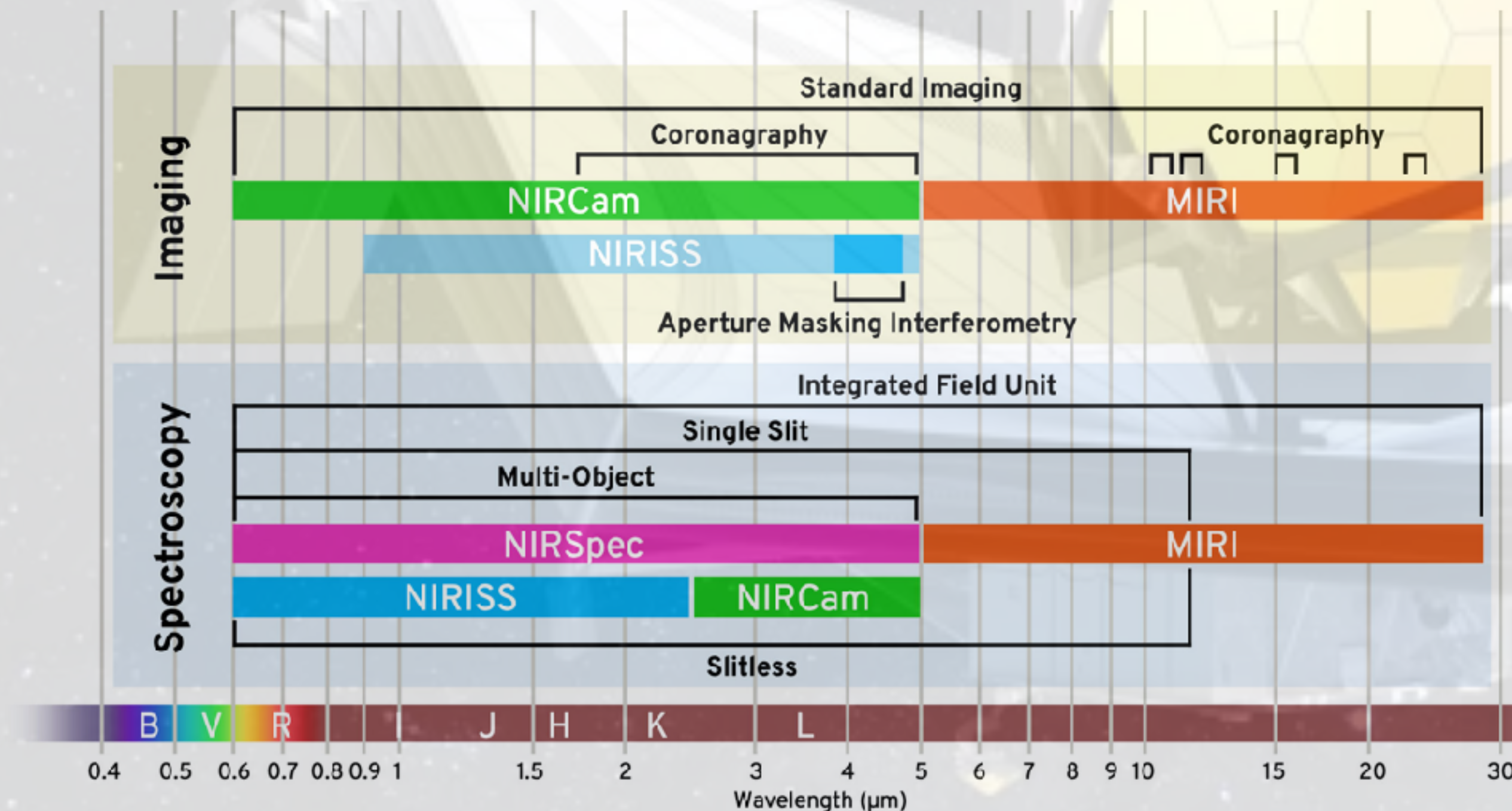
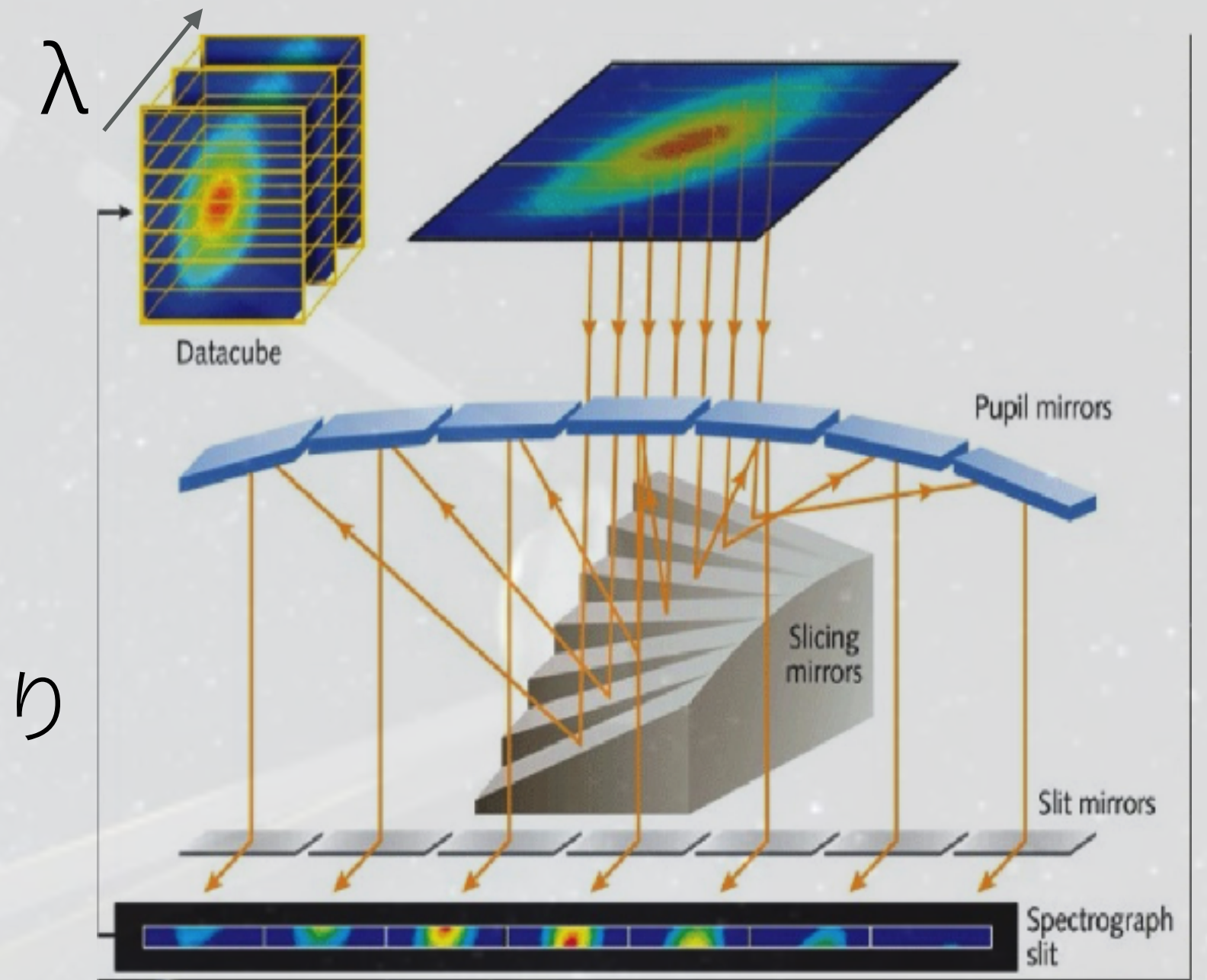
Wavelength: UV, Optical, Near-IR



# James Webb Space Telescope (JWST)

- 口径6.5 mの赤外線宇宙望遠鏡（史上最大！）
  - 六角形セグメント鏡18枚で構成
  - 高空間分解能・高感度を実現
- 0.6  $\mu\text{m}$  – 28.5  $\mu\text{m}$ をカバーする撮像・分光装置を搭載
  - （～近）中間赤外線は大気の吸収が強く，地上観測は限界あり

Integral Field Unit (IFU)の仕組み

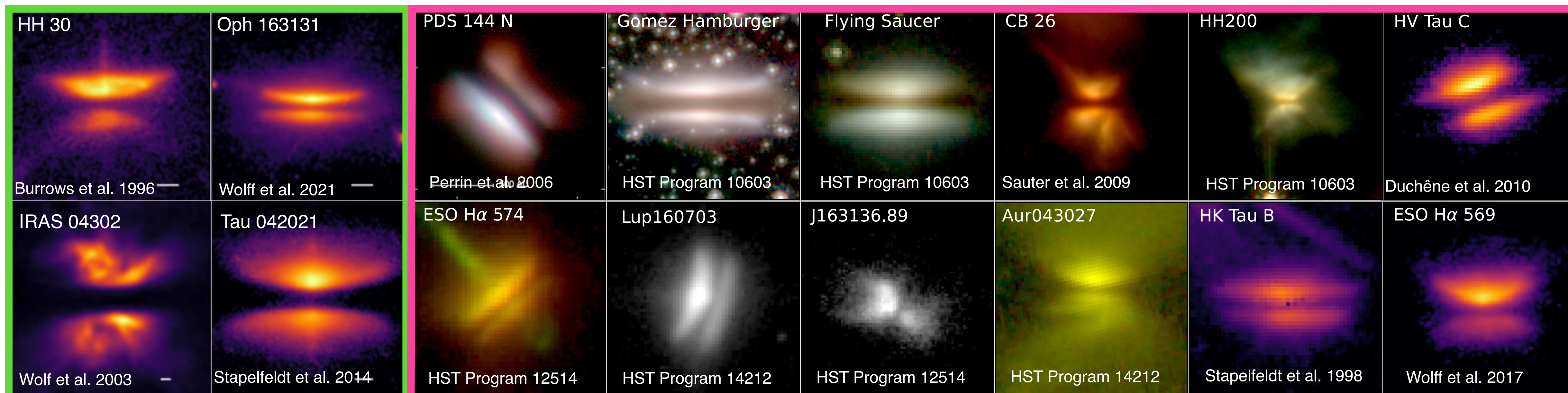


# JWST Cycle 1 & 2: Broadband imaging survey

PIs: F. Ménard & K. Stapelfeldt (incl RT as Co-I)

## Cycle 1 (4 targets)

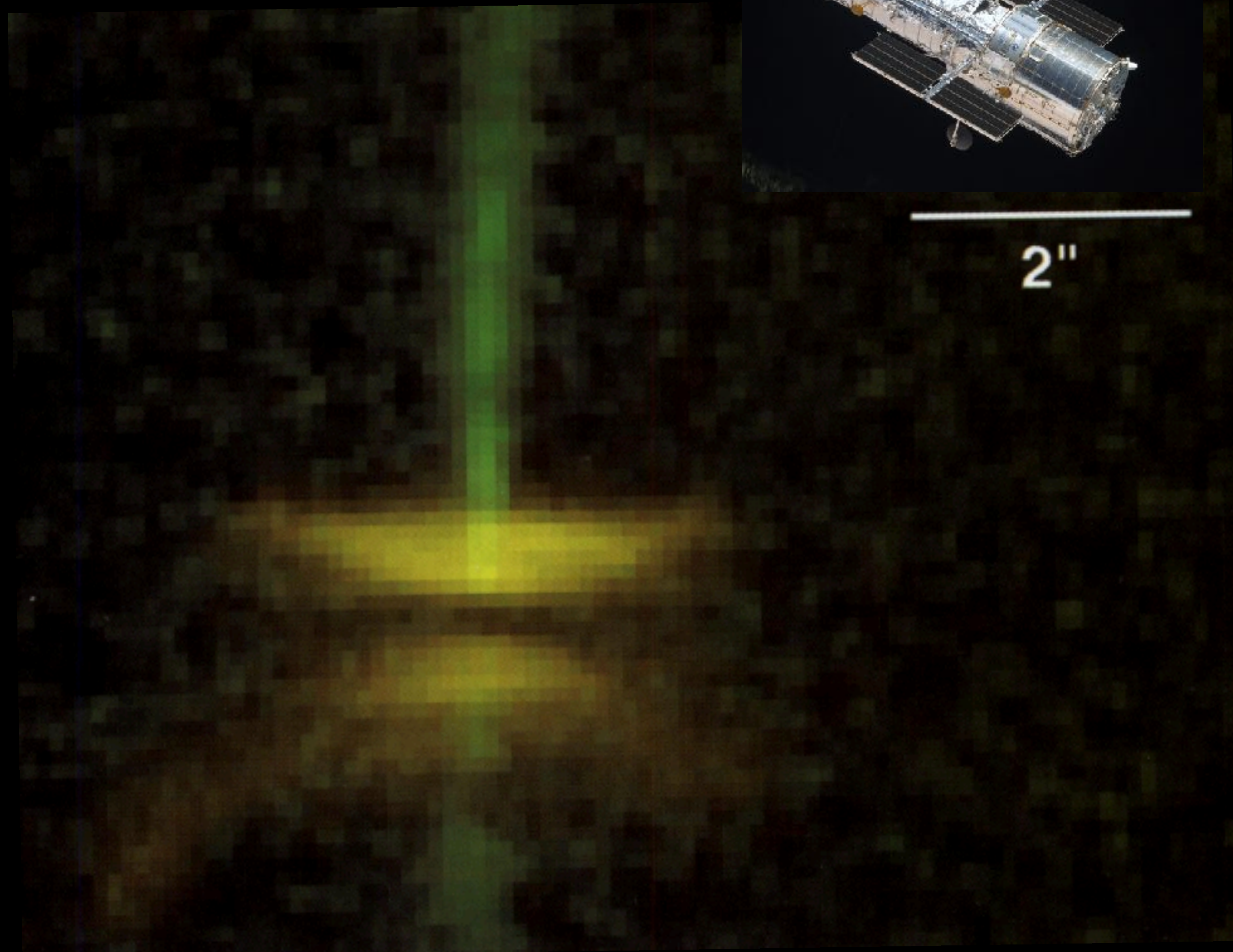
## Cycle 2 (13 targets)



- 5—7 broadband filters from NIRCcam and MIRI imager for each target
  - $\lambda=1 \mu\text{m}$  (or  $2 \mu\text{m}$ ) —  $7.7 \mu\text{m}$  (or  $21 \mu\text{m}$ ).
- Cover 17 EoDs in total, which is more than a half of the full sample of confirmed EoDs to date ( $\sim 30$ ; Stapelfeldt 2014).



2''



300 au ~ 2''



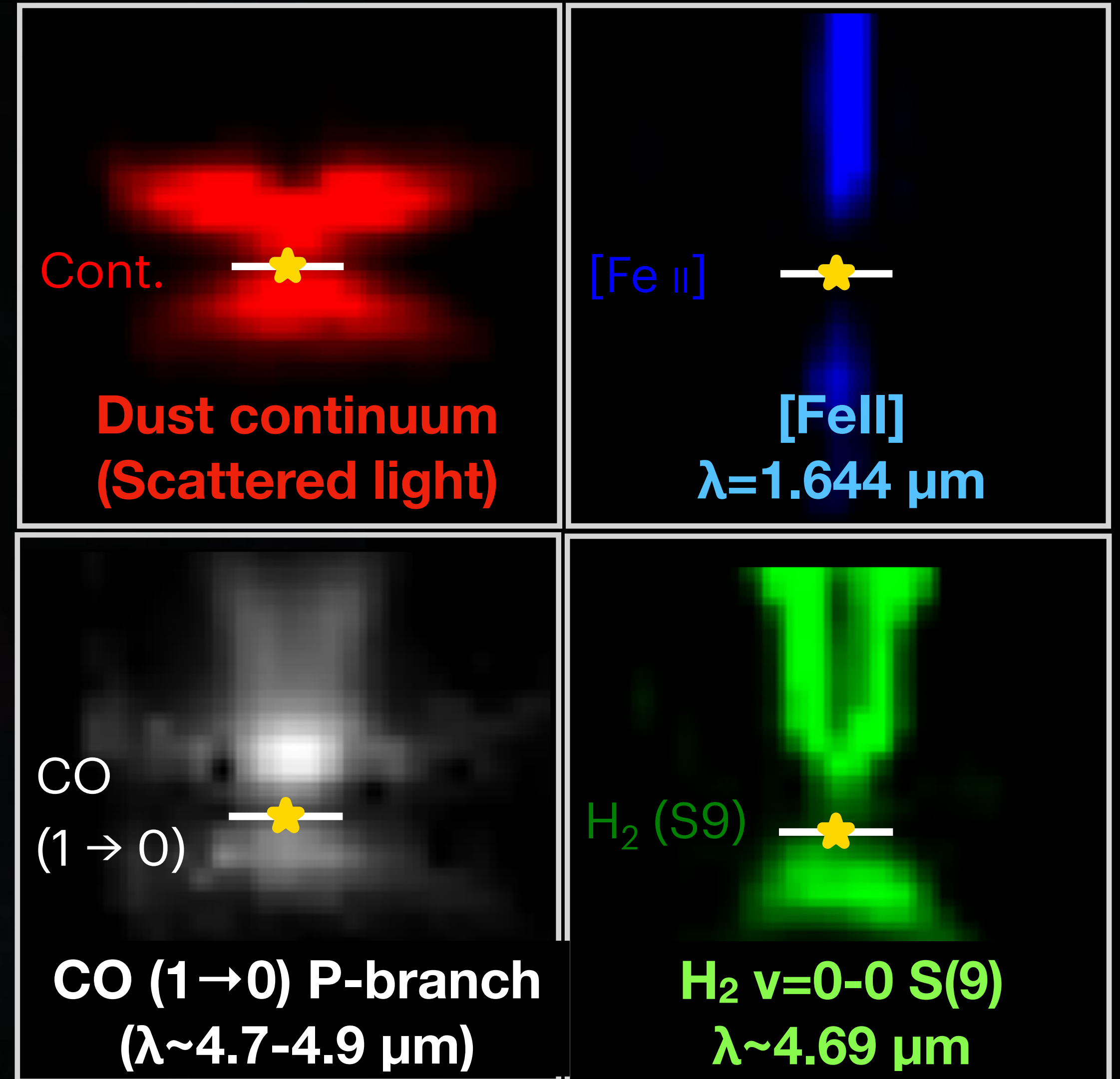
# NIRCam MIRI/Imager (Tazaki et al. 2025)

NIRCam/F200W 2.0  $\mu\text{m}$   
NIRCam/F444W 4.4  $\mu\text{m}$   
MIRI/F770W 7.7  $\mu\text{m}$   
MIRI/F1280W 12.8  $\mu\text{m}$

300 au  $\sim 2''$   
└──────────┘

Image credit: ESA/Webb, NASA & CSA, Tazaki et al.

# NIRSpec/IFU (Pascucci et al. 2025)



# Dust scattered light of the HH 30 disk

Tazaki et al. 2025

HST

$\lambda=0.6 \mu\text{m}$

$0.8 \mu\text{m}$

$2 \mu\text{m}$

$4 \mu\text{m}$

JWST

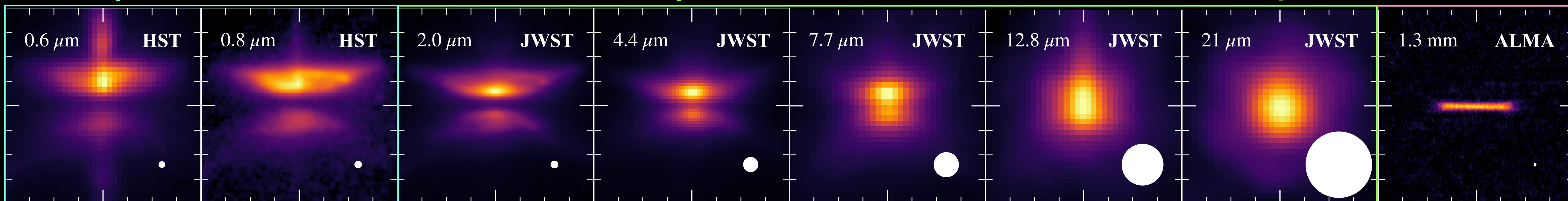
$7.7 \mu\text{m}$

$12.8 \mu\text{m}$

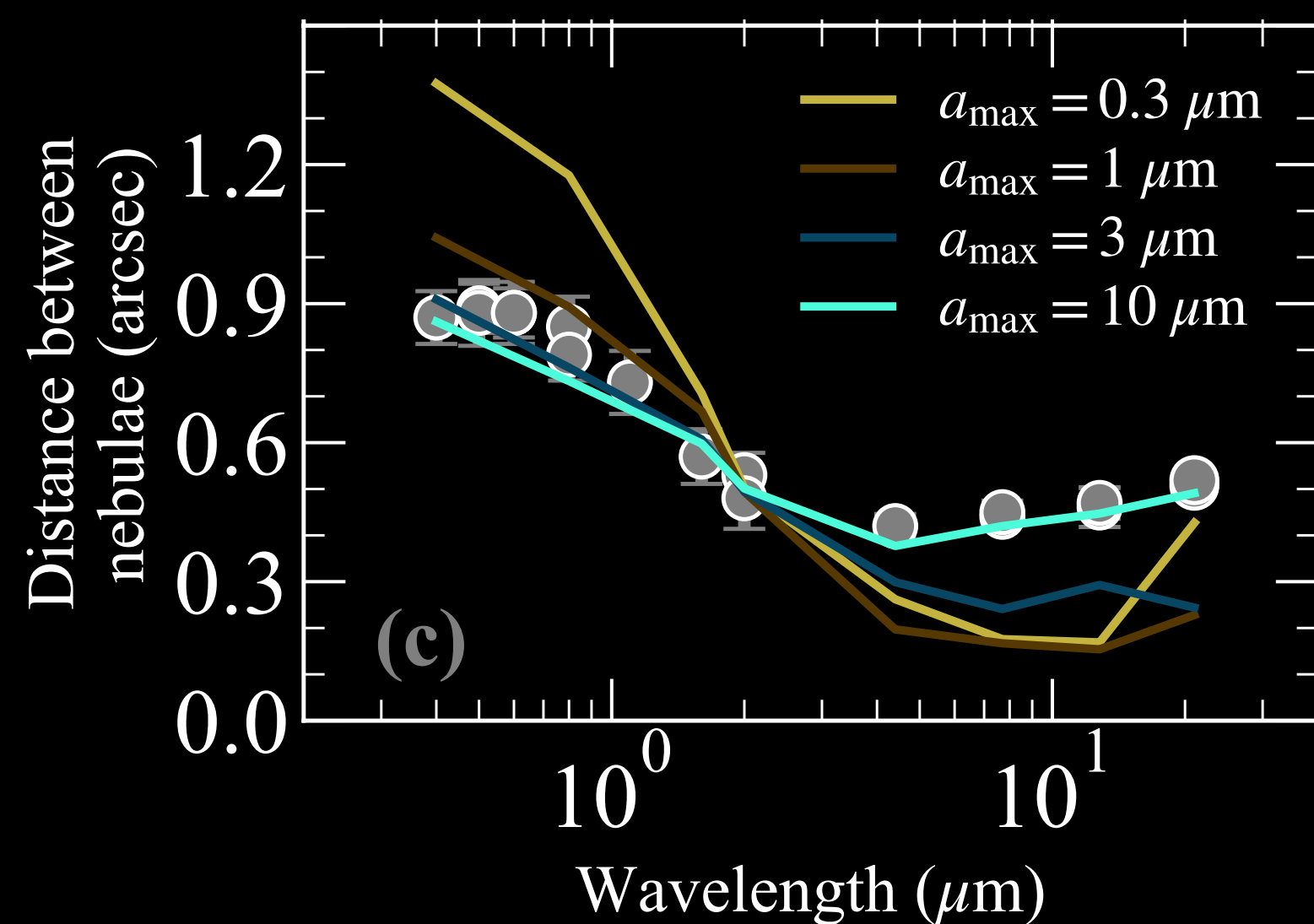
$21 \mu\text{m}$

ALMA

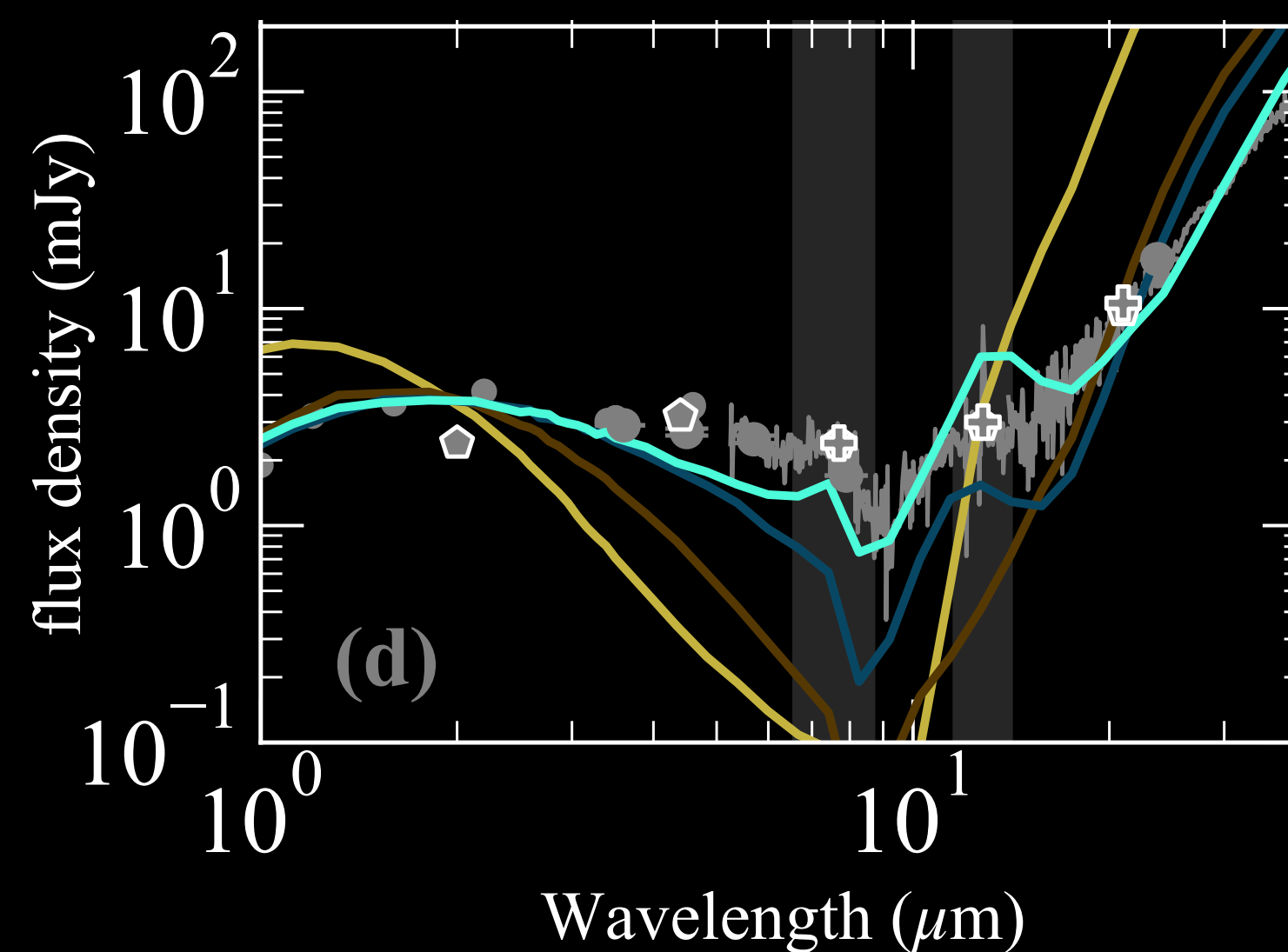
$1.3 \text{ mm}$



Disk thickness



SED



~10  $\mu\text{m}$ サイズのダスト (@表層)  
が円盤の厚みやSEDをよく再現

# the case of Tau 042021

Duchêne et al. (incl RT) 2024

HST

$\lambda=0.6 \mu\text{m}$

$0.8 \mu\text{m}$

$2 \mu\text{m}$

$4 \mu\text{m}$

JWST

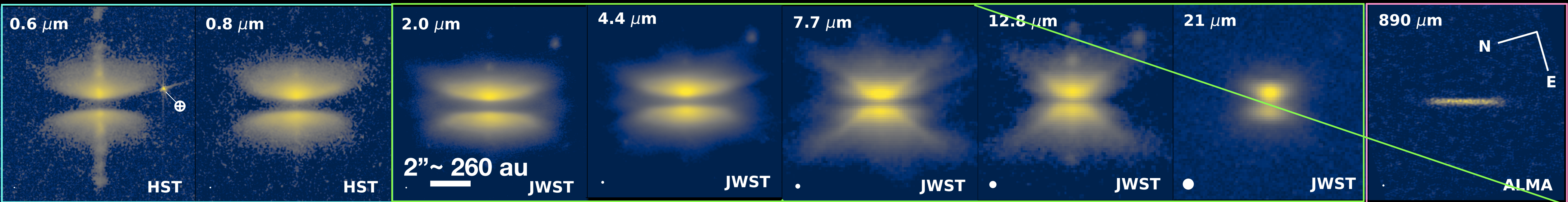
$7.7 \mu\text{m}$

$12.8 \mu\text{m}$

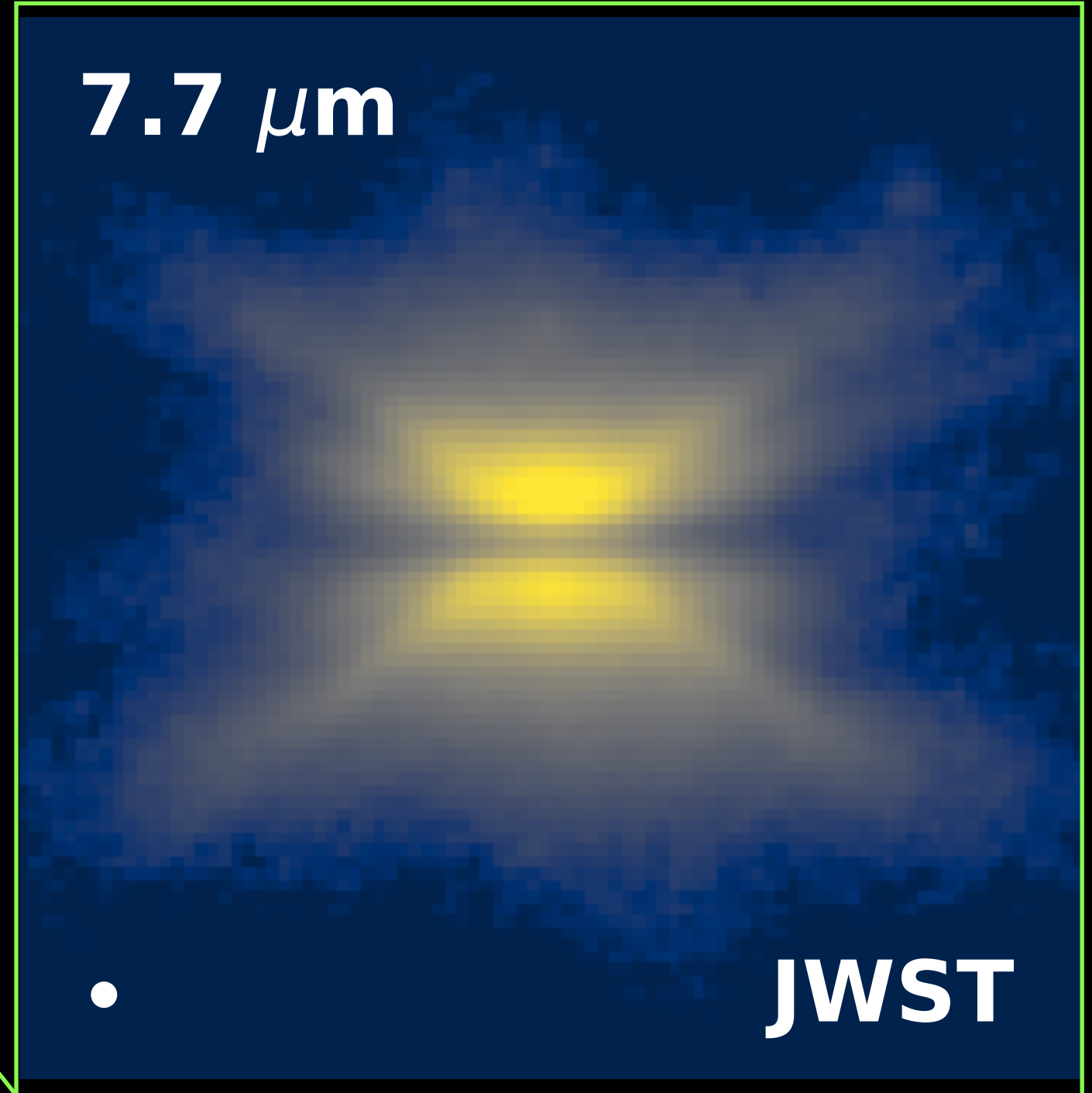
$21 \mu\text{m}$

ALMA

$1.3 \text{ mm}$

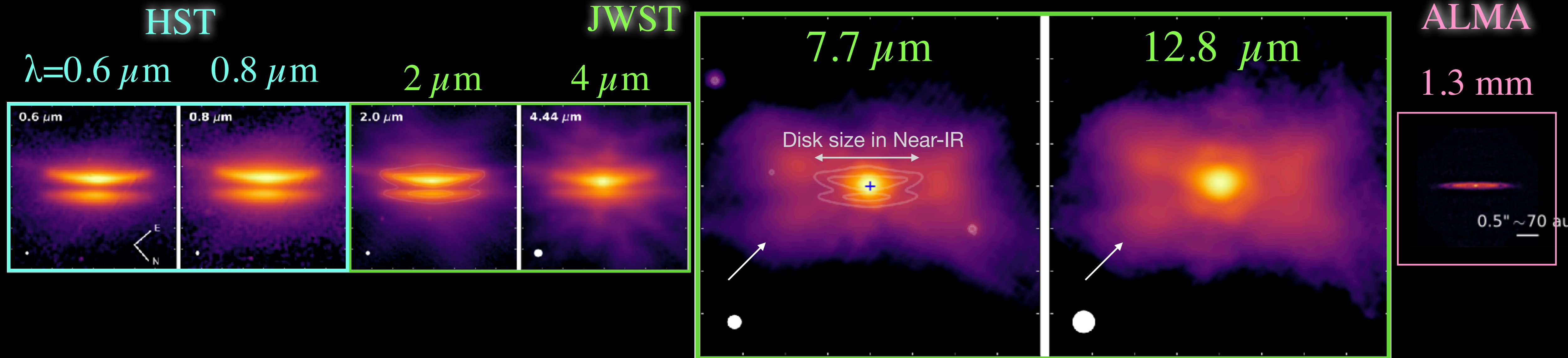


- $\sim 10 \mu\text{m}$ サイズのダスト (@表層) と整合的
- 中間赤外線でX字状の構造を発見
- $\text{H}_2$  and PAH emission  
(Arulanantham et al. 2024, Pascucci et al. 2024, Dartois et al. 2025)



# the case of Oph 163131

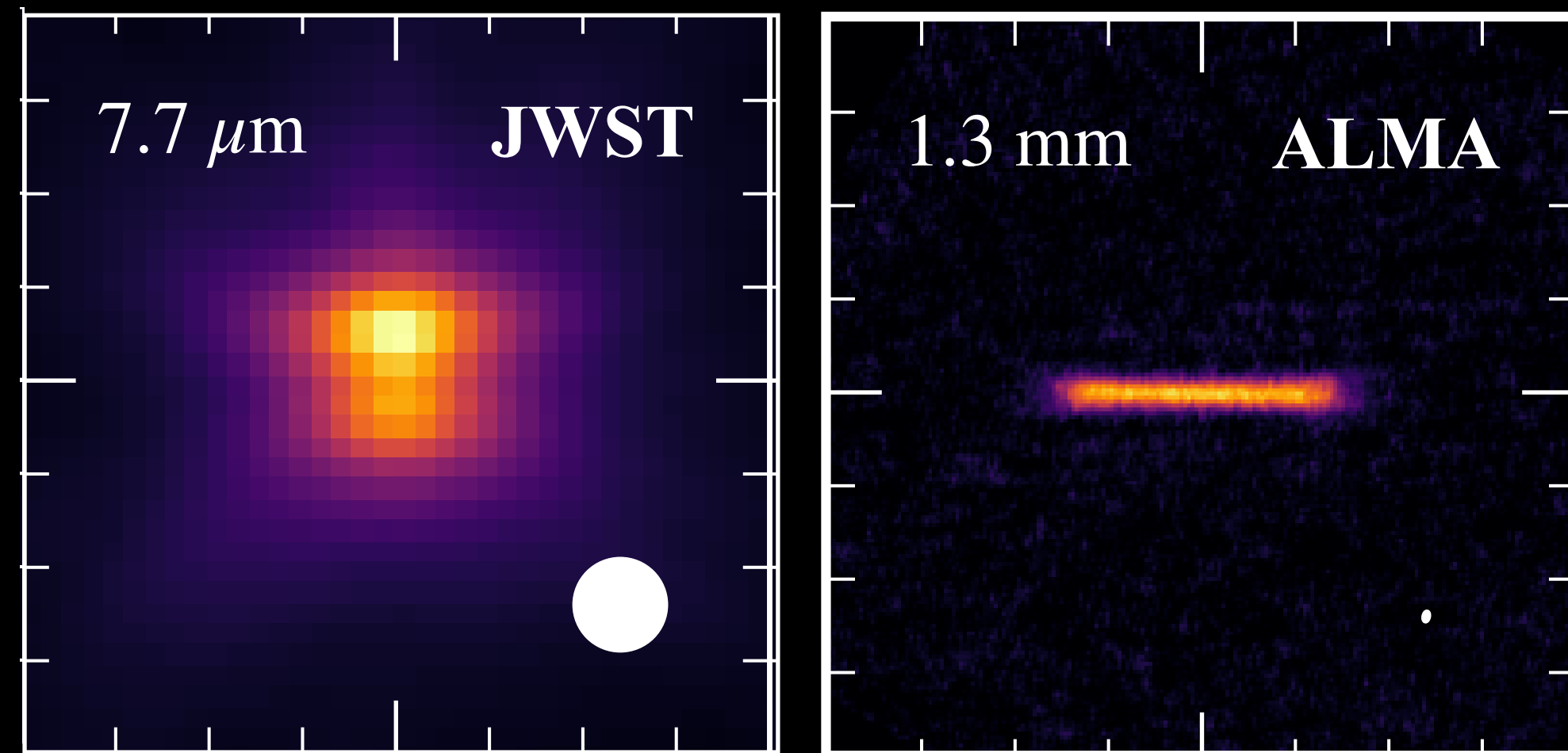
Villenave et al. (incl RT) 2024



- Oph 163131は強く沈殿したペブル円盤をもつ (Villenave et al. 2022)
- 赤外線観測は表層ダストサイズ $<0.5 \mu\text{m}$ を示唆
- 中間赤外線で空間的に広がった構造を発見

# Dust settling: IR vs millimeter

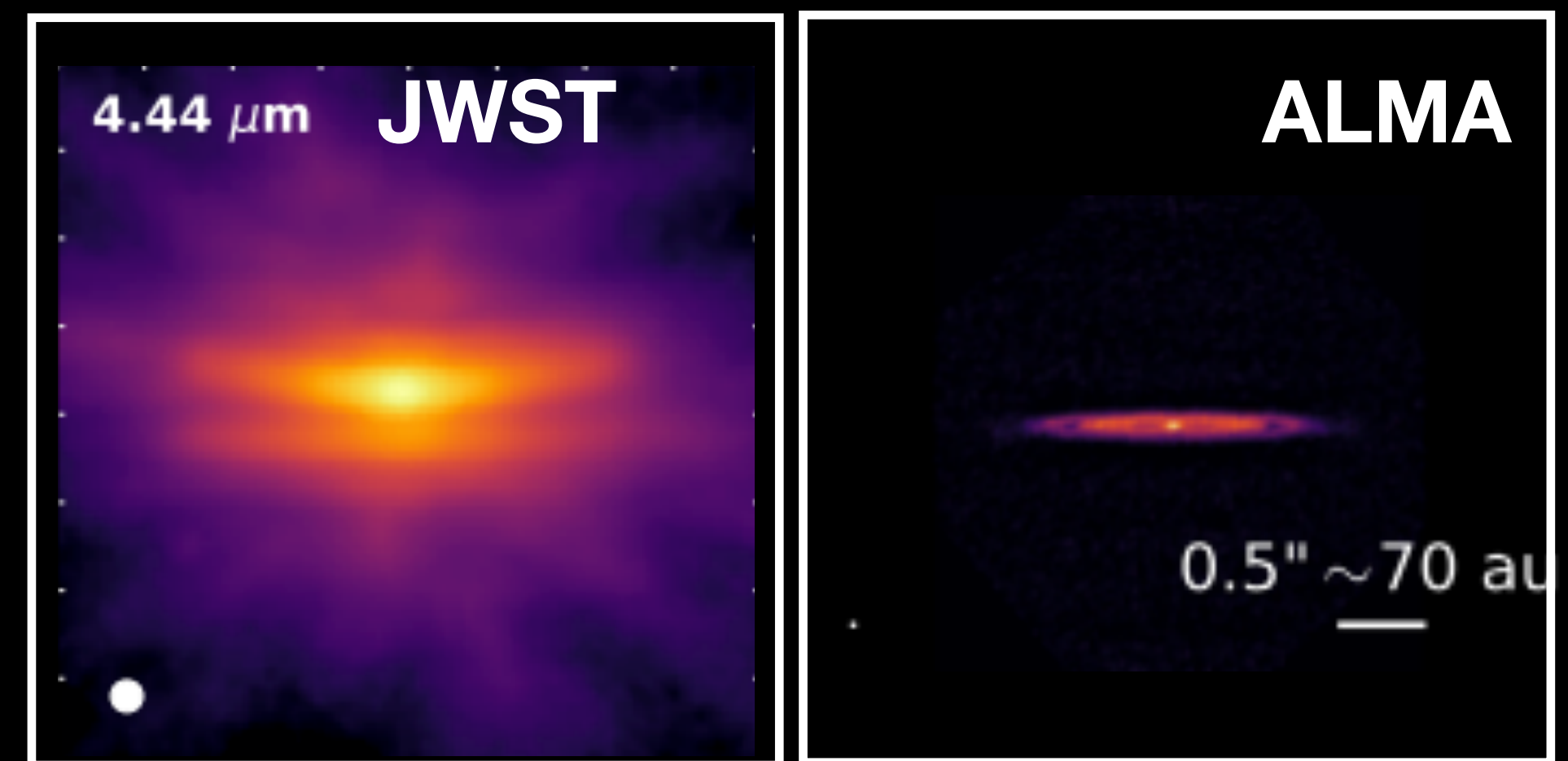
HH 30 (moderately settled)



$$a_{\text{max,surf}} \gtrsim 3 \mu\text{m}$$

$$h_{\text{pebble}}/r \sim 0.05$$

Oph 163131 (highly settled)



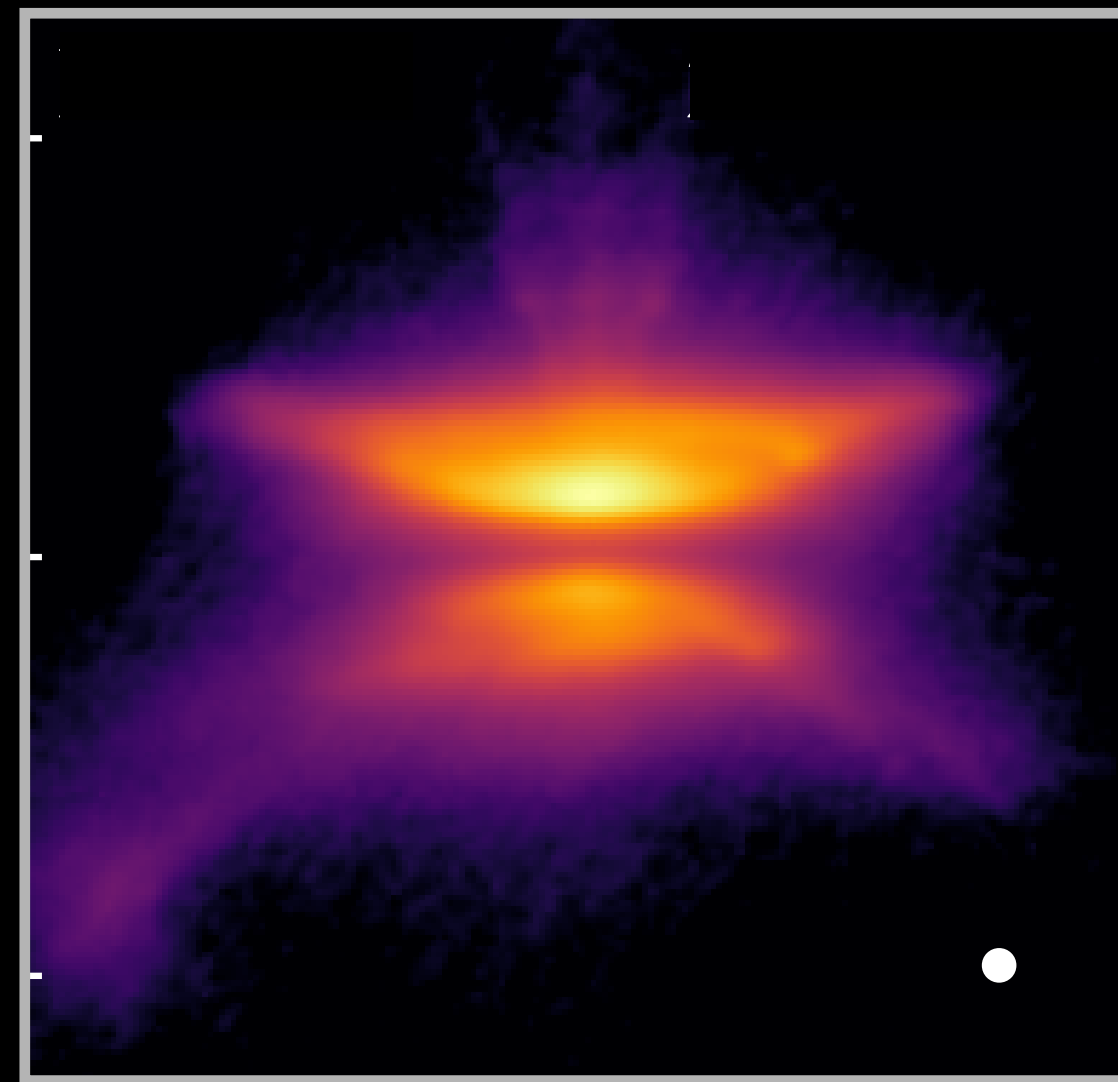
$$a_{\text{max,surf}} \lesssim 0.5 \mu\text{m}$$

$$h_{\text{pebble}}/r \lesssim 0.005$$

Possible correlation between IR and millimeter dust settling?

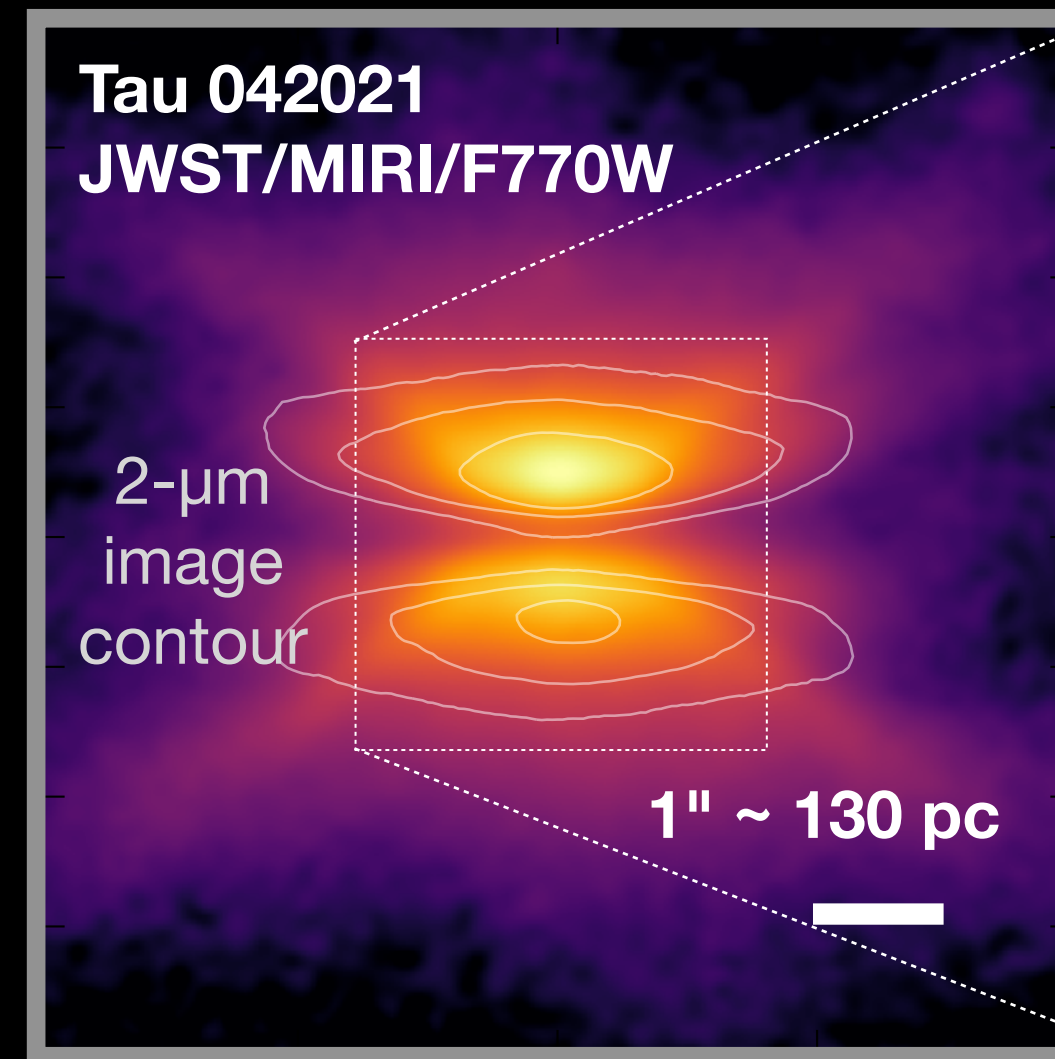
# Diverse morphology of edge-on disks at IR

HH 30

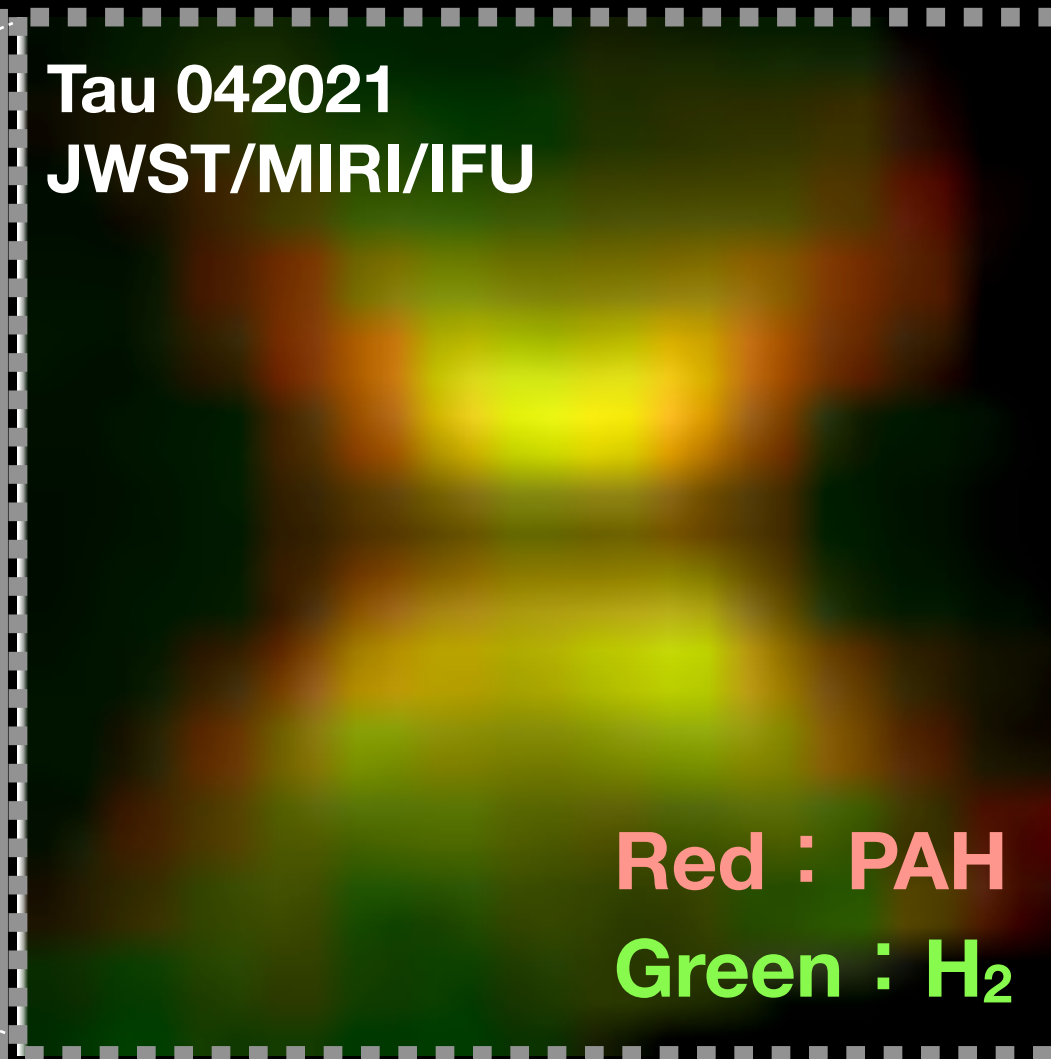


Tazaki et al. 2025

Tau 042021

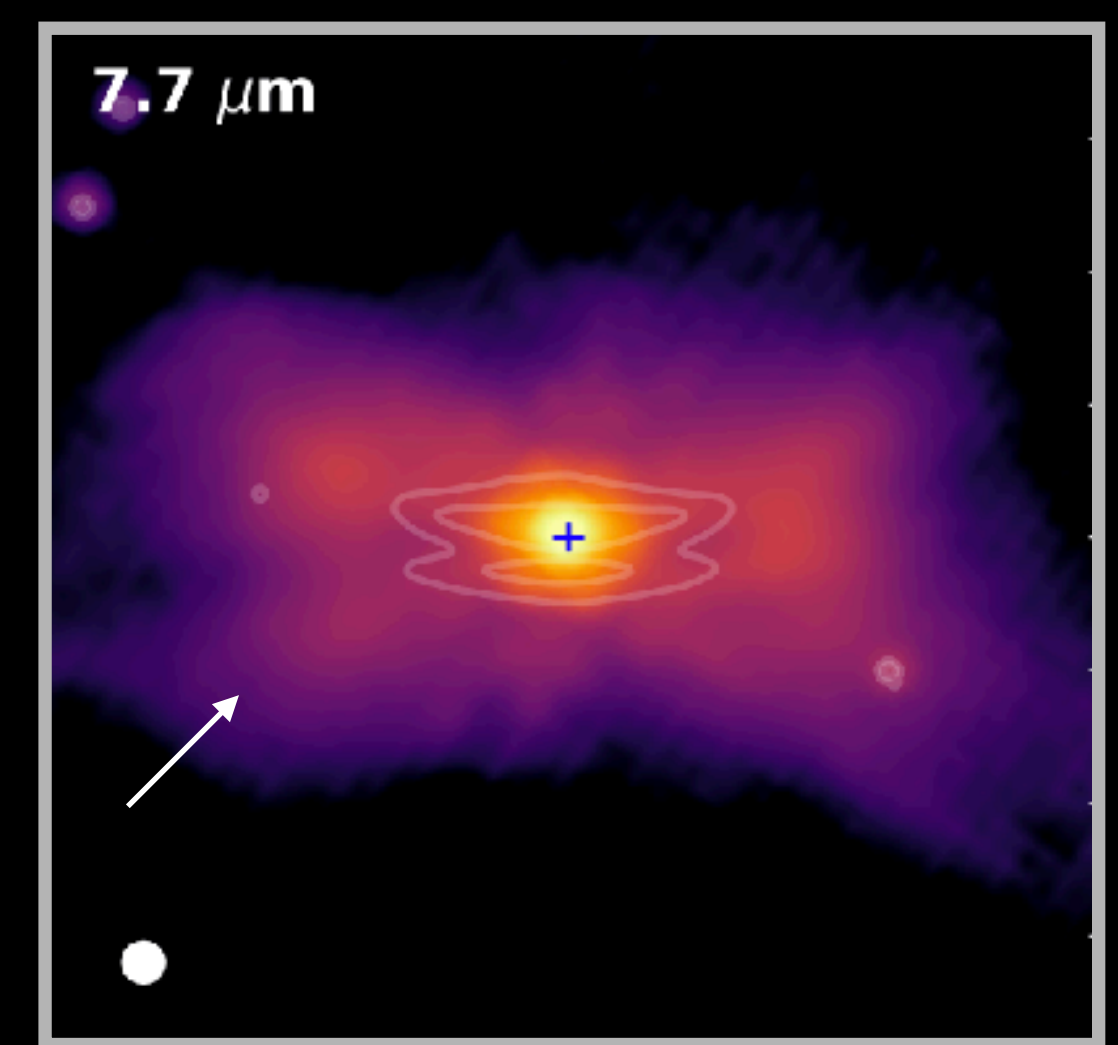


Duchêne et al. 2024



Dartois et al. 2025

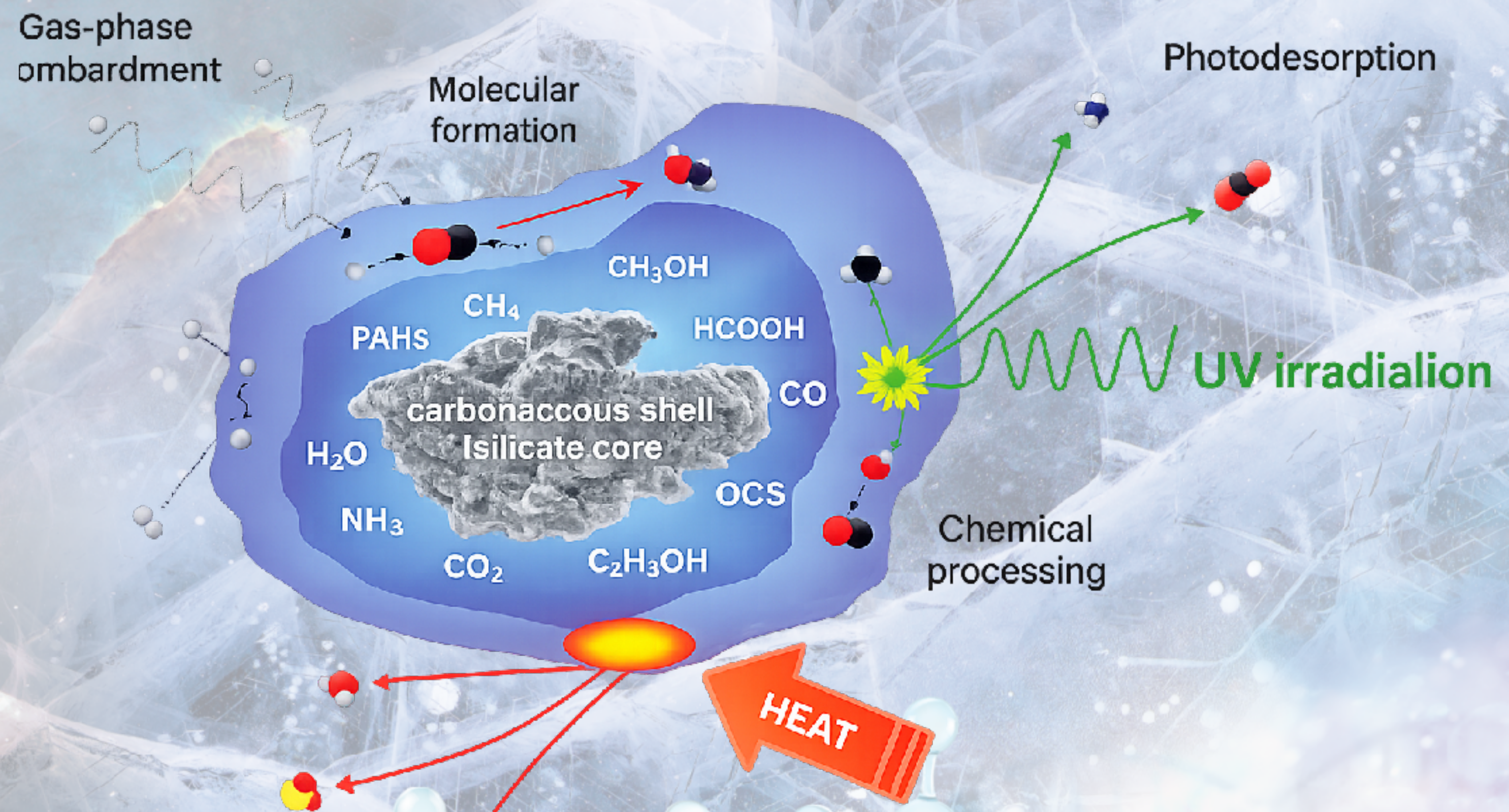
Oph 163131



Villenave et al. 2025

- MHD wind (Pascucci et al. 2025)? Photoevaporation (Nakatani et al. 2025)?
- Constraint on dust and PAH entrainment ?

# Disk ice

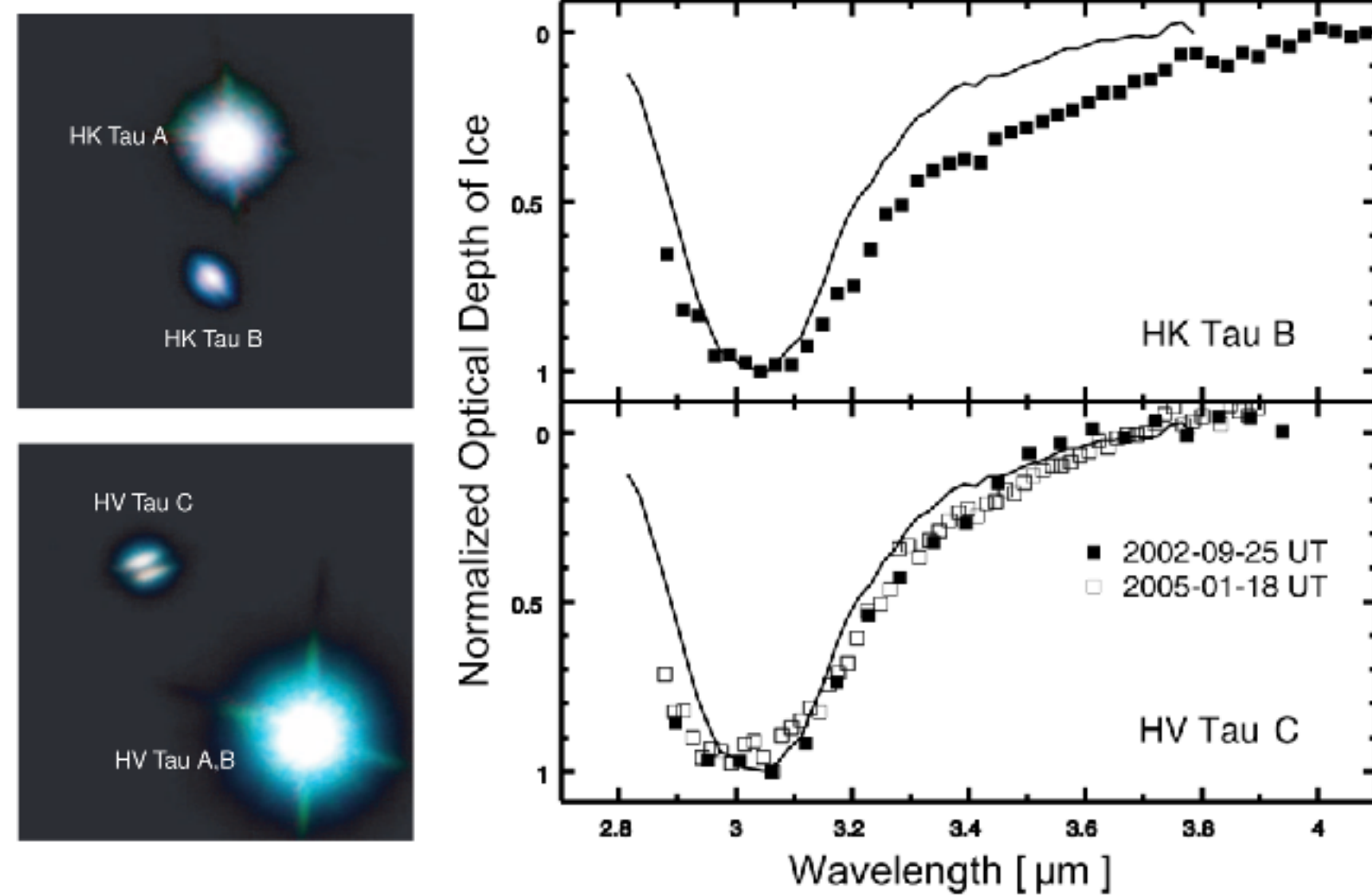


(Burke and Brown 2009)

# 原始惑星系円盤の氷観測

## Edge-on disks (スリット分光/スリットレス分光)

Pontoppidan et al. 2005, Terada et al. 2007, Terada et al. 2012, Terada & Tokunaga 2012, 2017, Aikawa et al. 2012



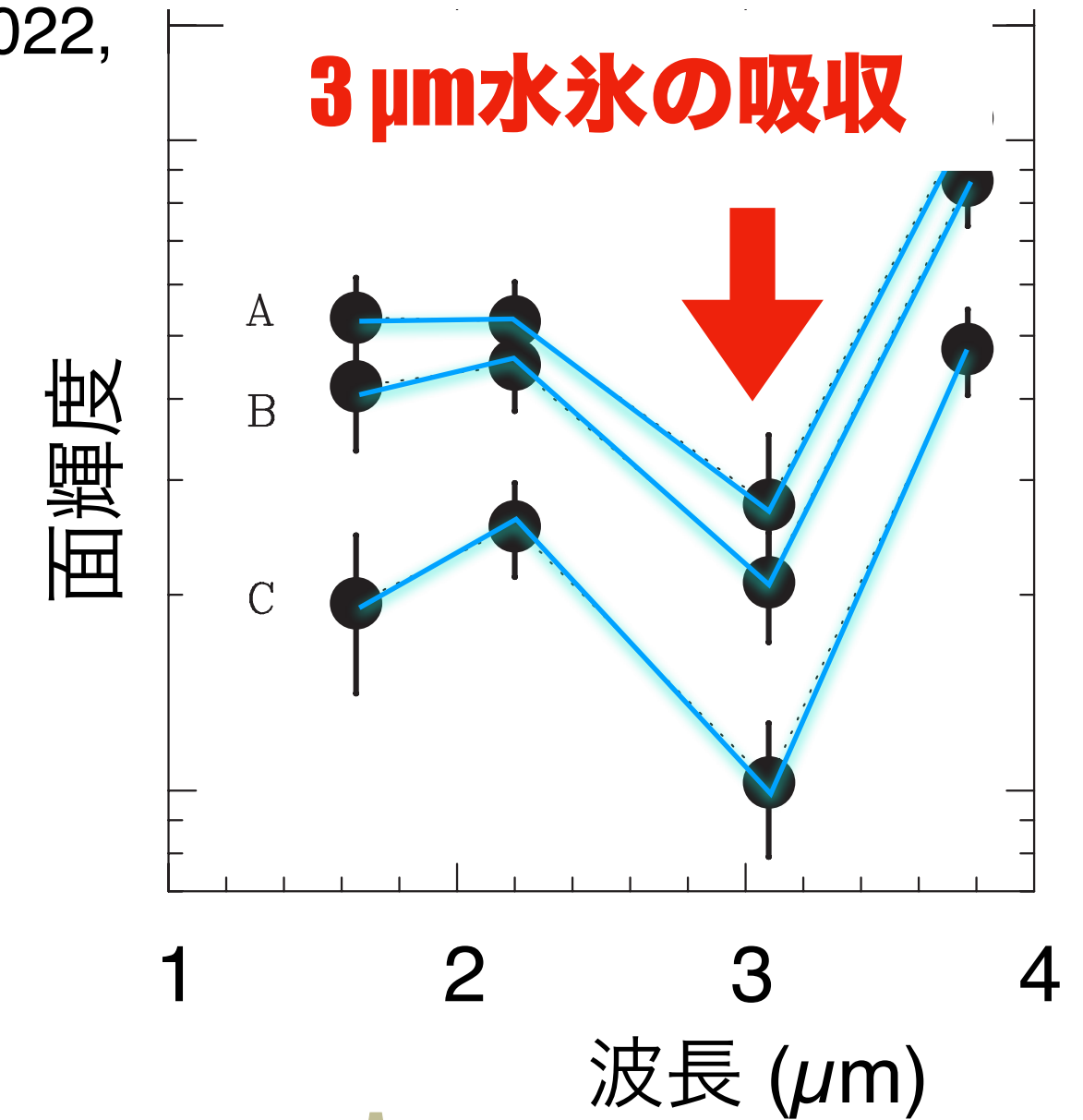
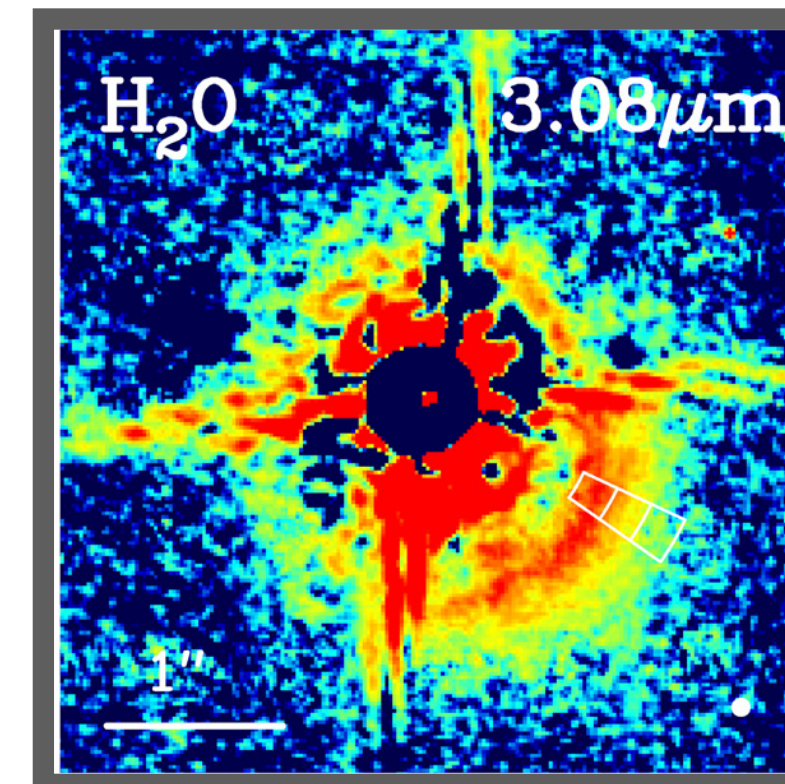
Terada et al. 2007

スペクトル  氷の空間分布の情報

## Face-on disks (多色撮像観測・偏光スリット分光)

Honda et al. 2009, Honda et al. 2016, Honda et al. 2022, Betti et al. 2022, Honda, RT et al 2022

### HD 142527



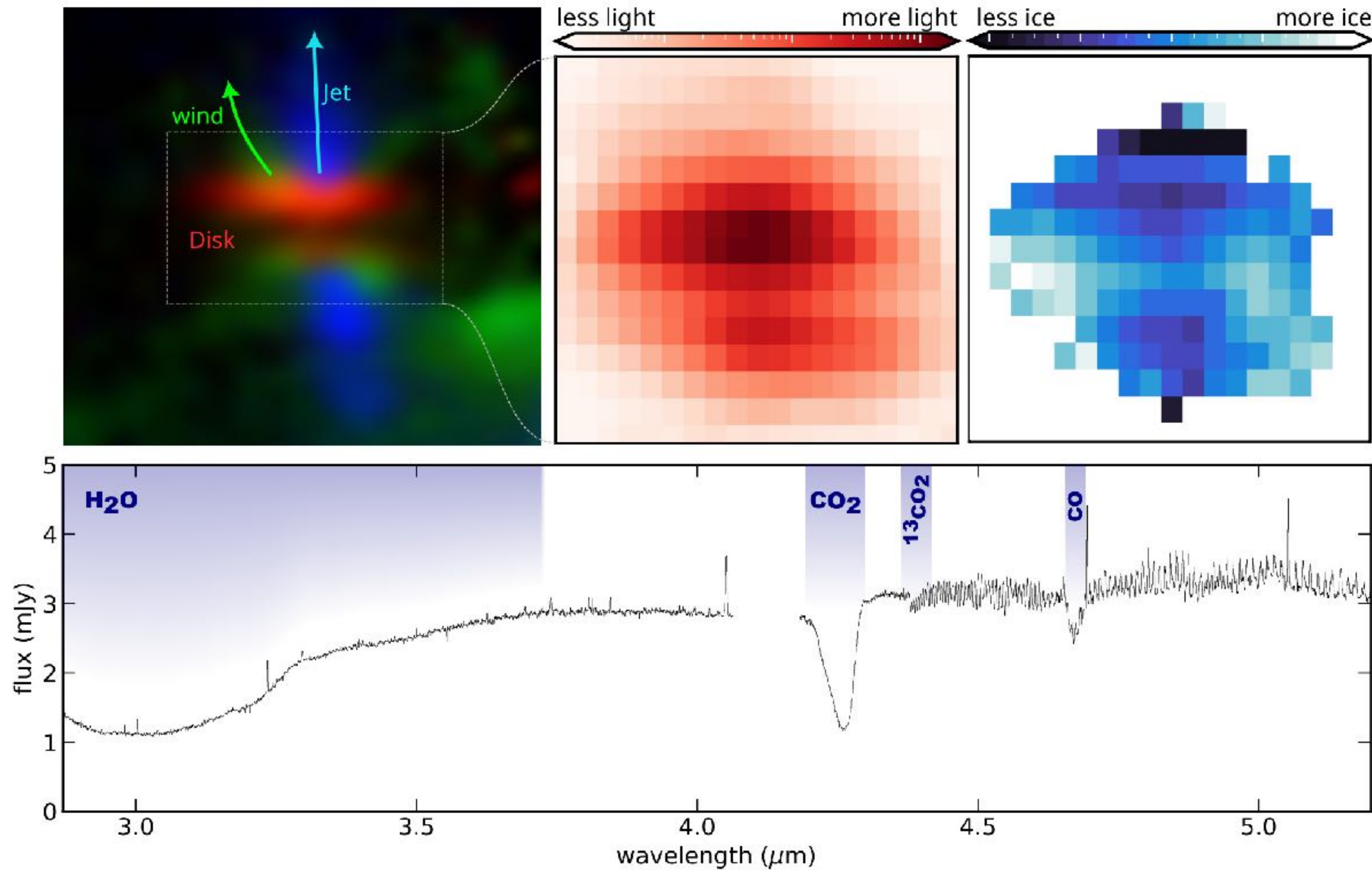
Honda et al. 2009

スペクトル  氷の空間分布の情報

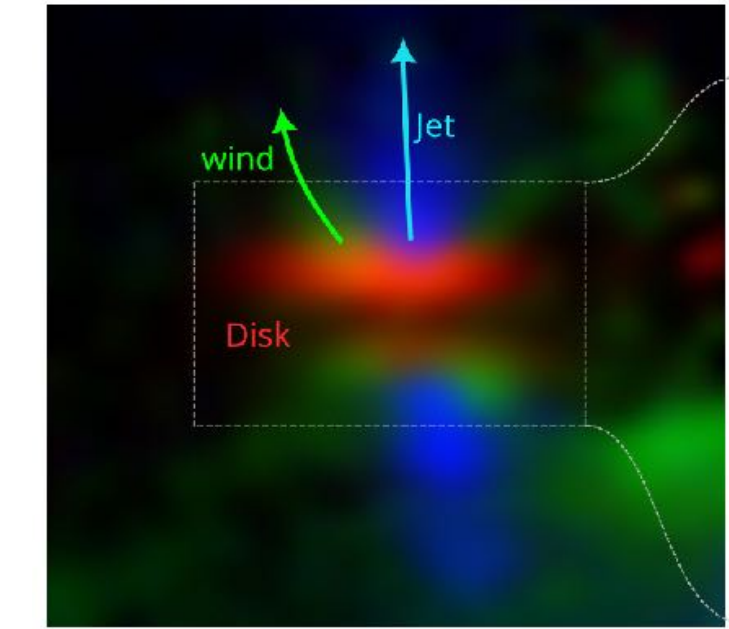
JWSTの面分光観測によって初めて円盤内の氷の性質・空間分布が解明されることが期待

(スペクトル  氷の空間分布の情報 )

# JWST/NIRSpec/IFUによるエッジオン円盤の面分光観測



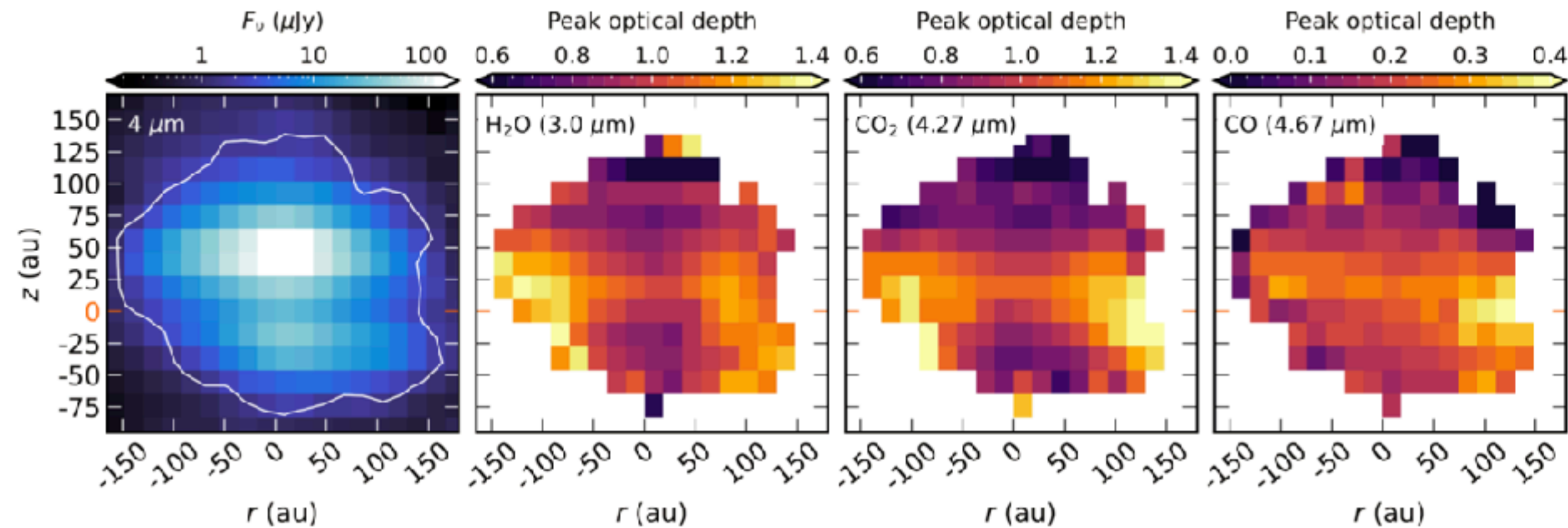
# Ice in disk surface



- In disks, H<sub>2</sub>O, CO, <sup>12</sup>CO<sub>2</sub>, <sup>13</sup>CO<sub>2</sub>, OCN- ices are detected (Sturm et al. 2023, 2024, Ballering et al. 2024, Potapov et al 2025)

- Vertical stratification of ice is less clear, and volatile ice also exists at high surfaces (Sturm et al. 2024, Dartois et al. 2025)

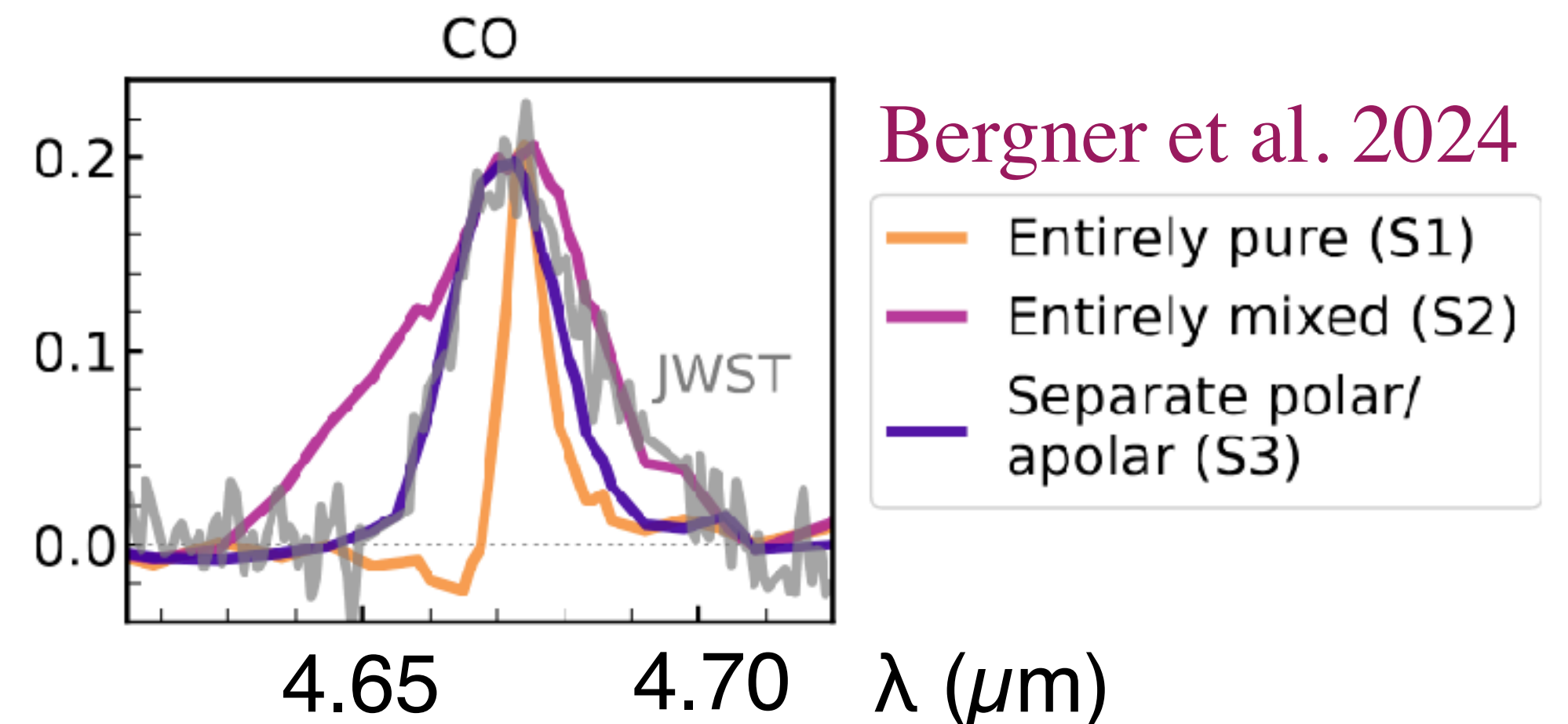
- 4.6 μm CO-ice feature is consistent with CO being trapped in ice (Bergner et al. 2024)



Sturm et al. 2023

- ⚠️ Optically thick and edge-on viewing geometry complicate the ice abundance + isotope ratio interpretation

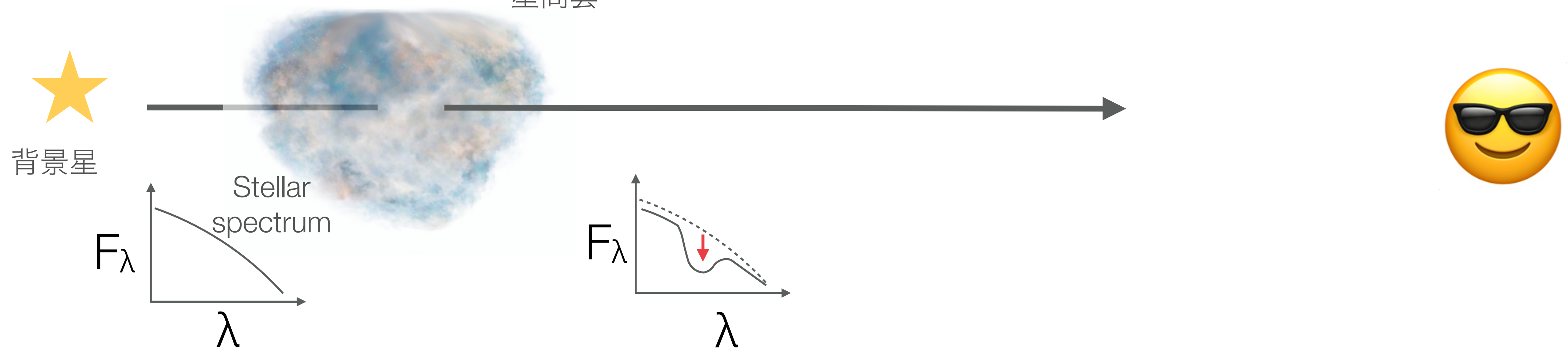
Sturm et al. 2023, Martinien et al. 2025



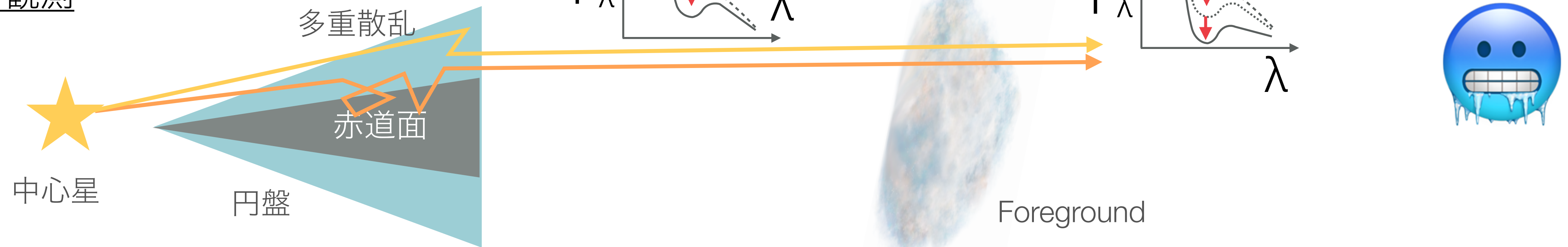
Bergner et al. 2024

# エッジオン円盤の氷吸収解釈の問題点

## 星間氷の観測



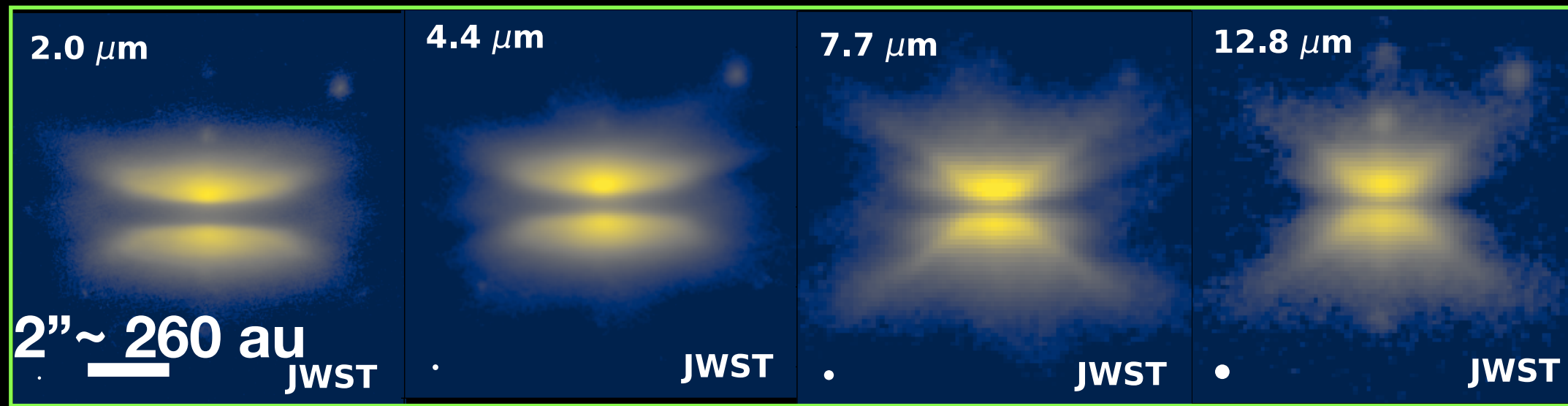
## 円盤氷の観測



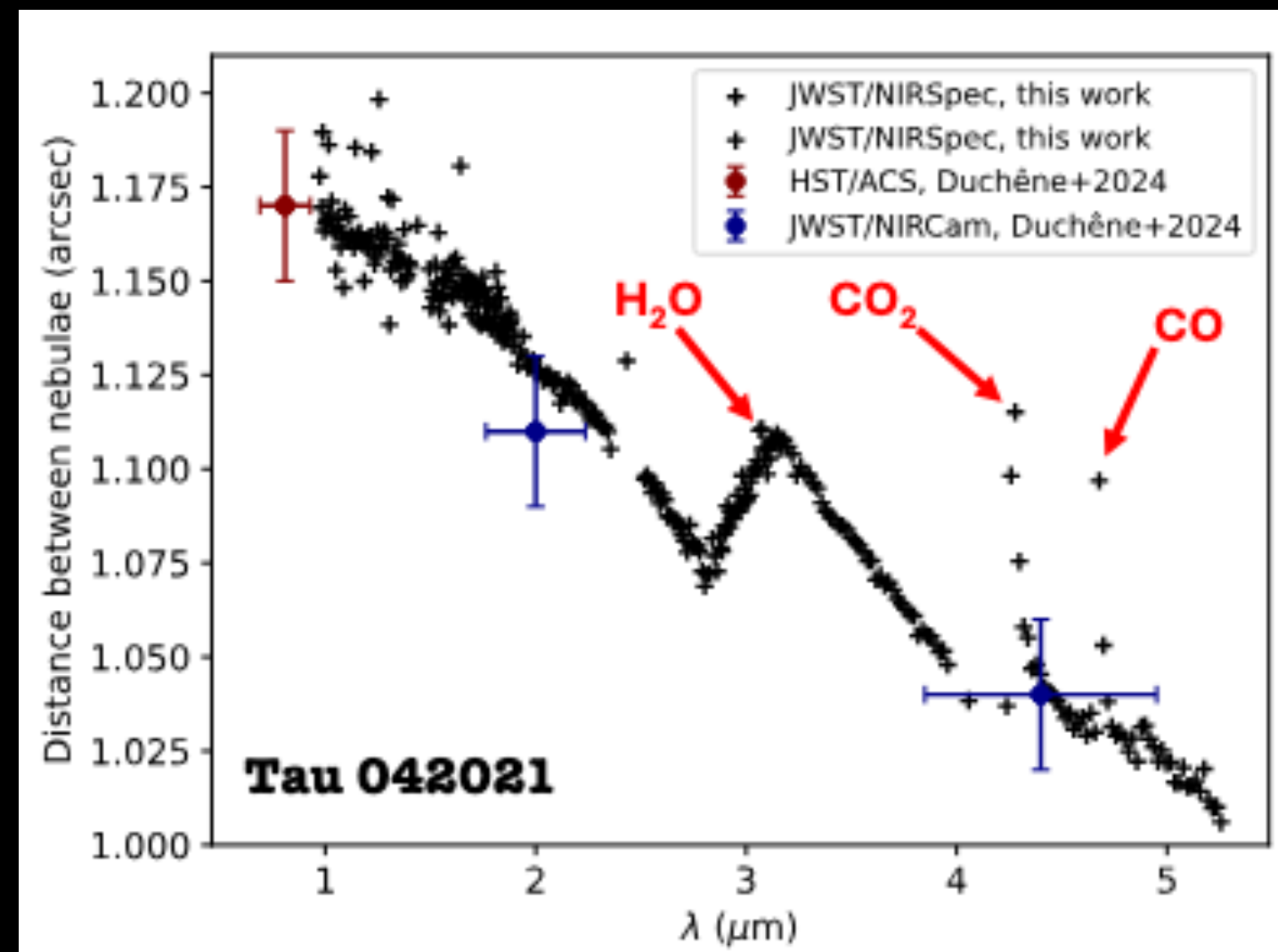
複雑な輻射輸送効果 (e.g., 多重散乱)  
(Sturm et al. 2023)

Foregroundやenvelopeの影響  
(Pontoppidan et al 2005, Aikawa et al. 2012)

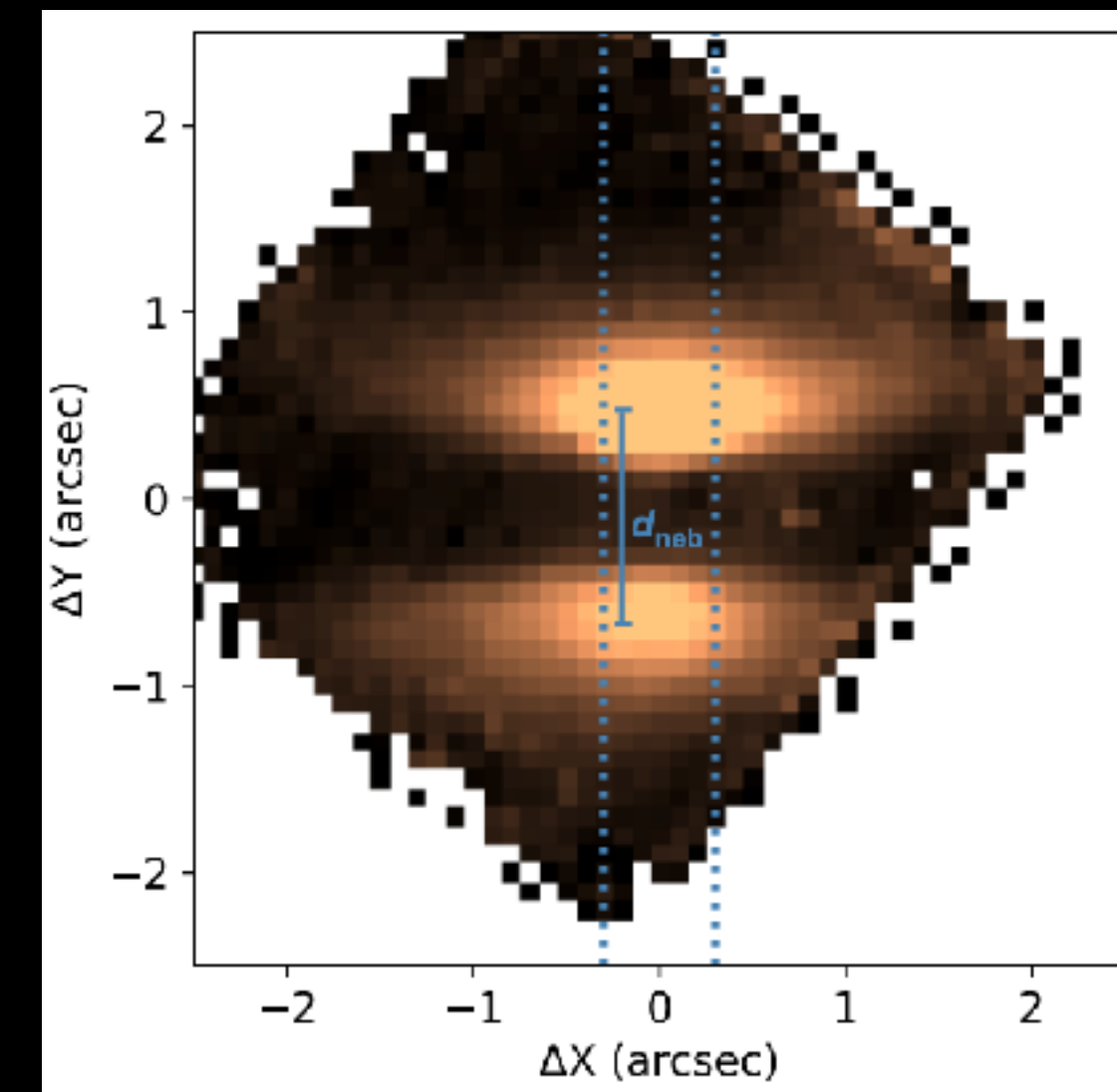
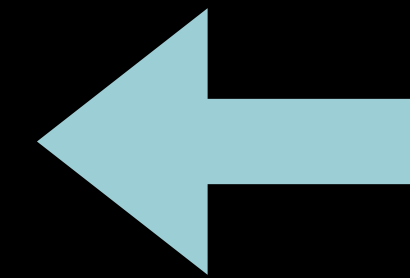
# Disk Thickness...Again



Disk  
thickness



面分光  
データ



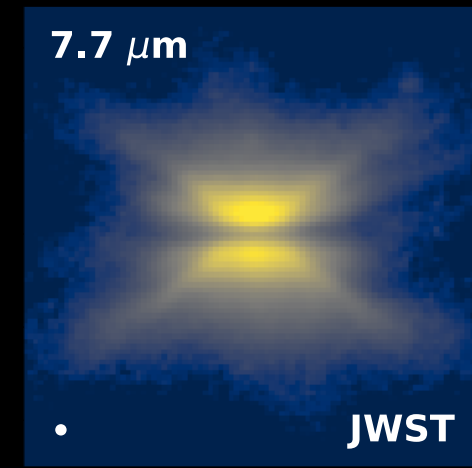
H<sub>2</sub>O, CO<sub>2</sub>, COの氷吸収フィーチャーに対応して,  
円盤の幾何学的厚み (平均的な光学的厚み) が変化

# Attenuation curves of protoplanetary icy dust

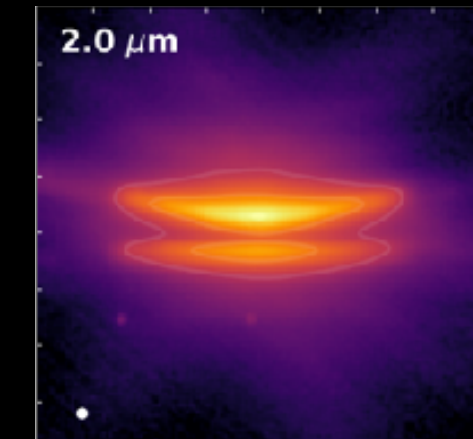
Martinien et al. (incl RT) 2025



HH 30

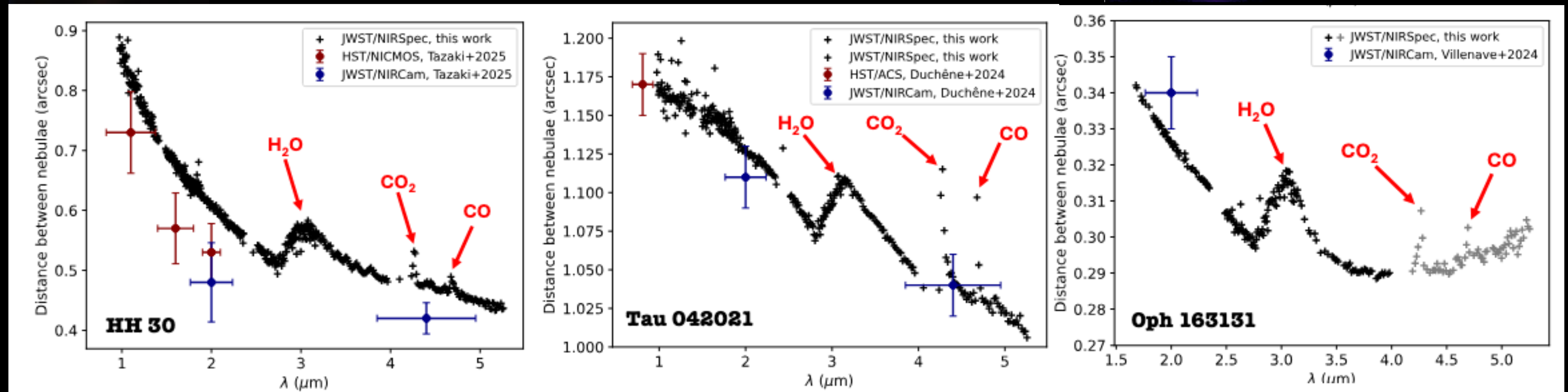


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Oph 163131

Disk  
thickness

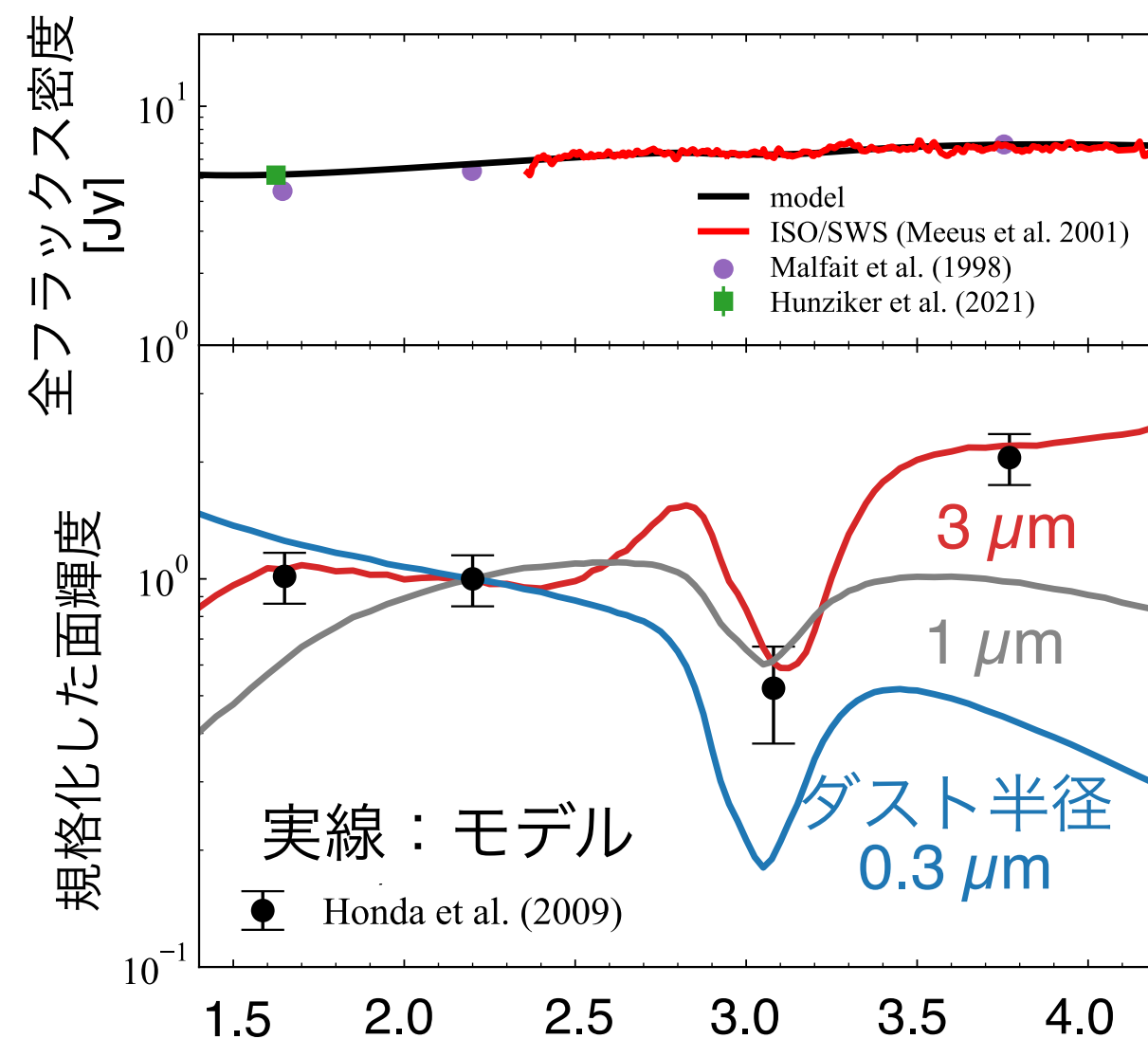
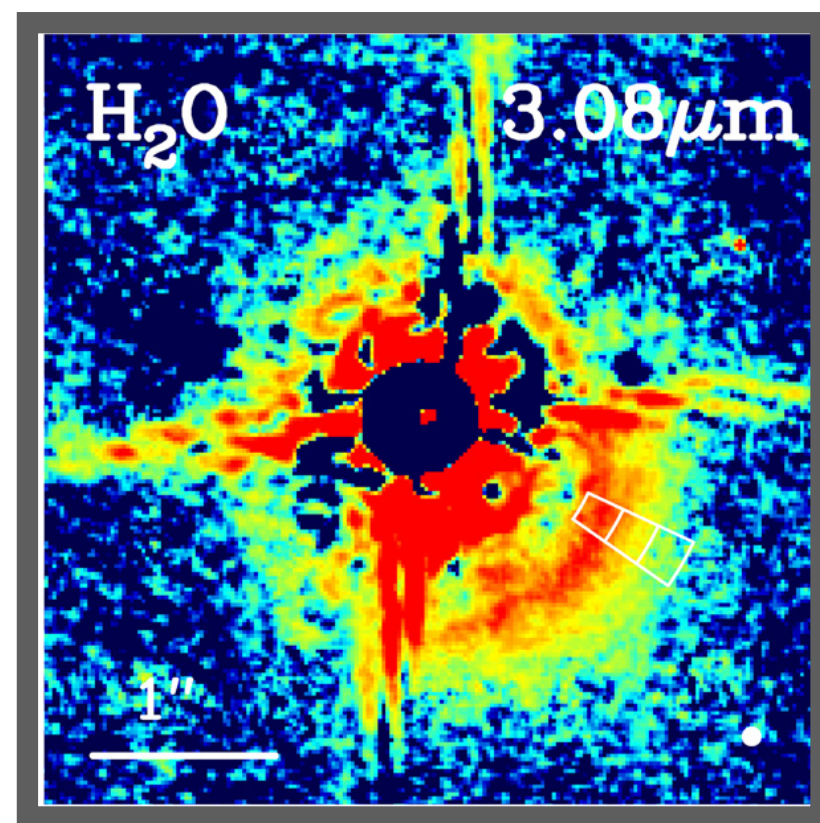


- (空間的にある程度平均した) 氷の存在量の制約で有効なアプローチ
- 前景雲は円盤の幾何学的厚みを変えないため、前景雲によらない氷量推定が可能

# Radial distribution of disk ice?

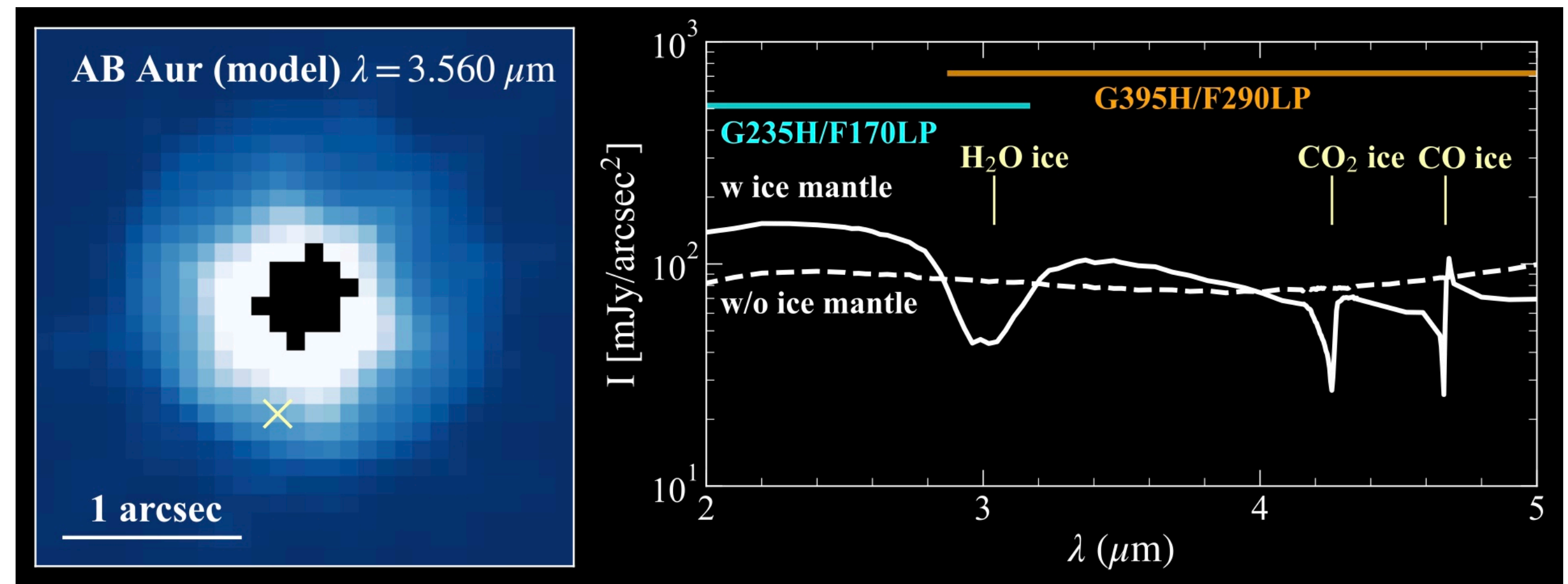
- 氷の空間分布を知るにはnon-edge-on円盤が最適
  - 散乱アルベドに起因する氷の散乱光フィーチャー (Inoue et al. 2008, Tazaki et al. 2021)
  - 地上望遠鏡による多色撮像観測で検出 (Honda et al. 2009, Honda et al. 2016, Betti et al. 2022)
- JWST/NISpecによる面分光観測に期待!

すばる望遠鏡による水氷の検出 (Honda et al. 2009)

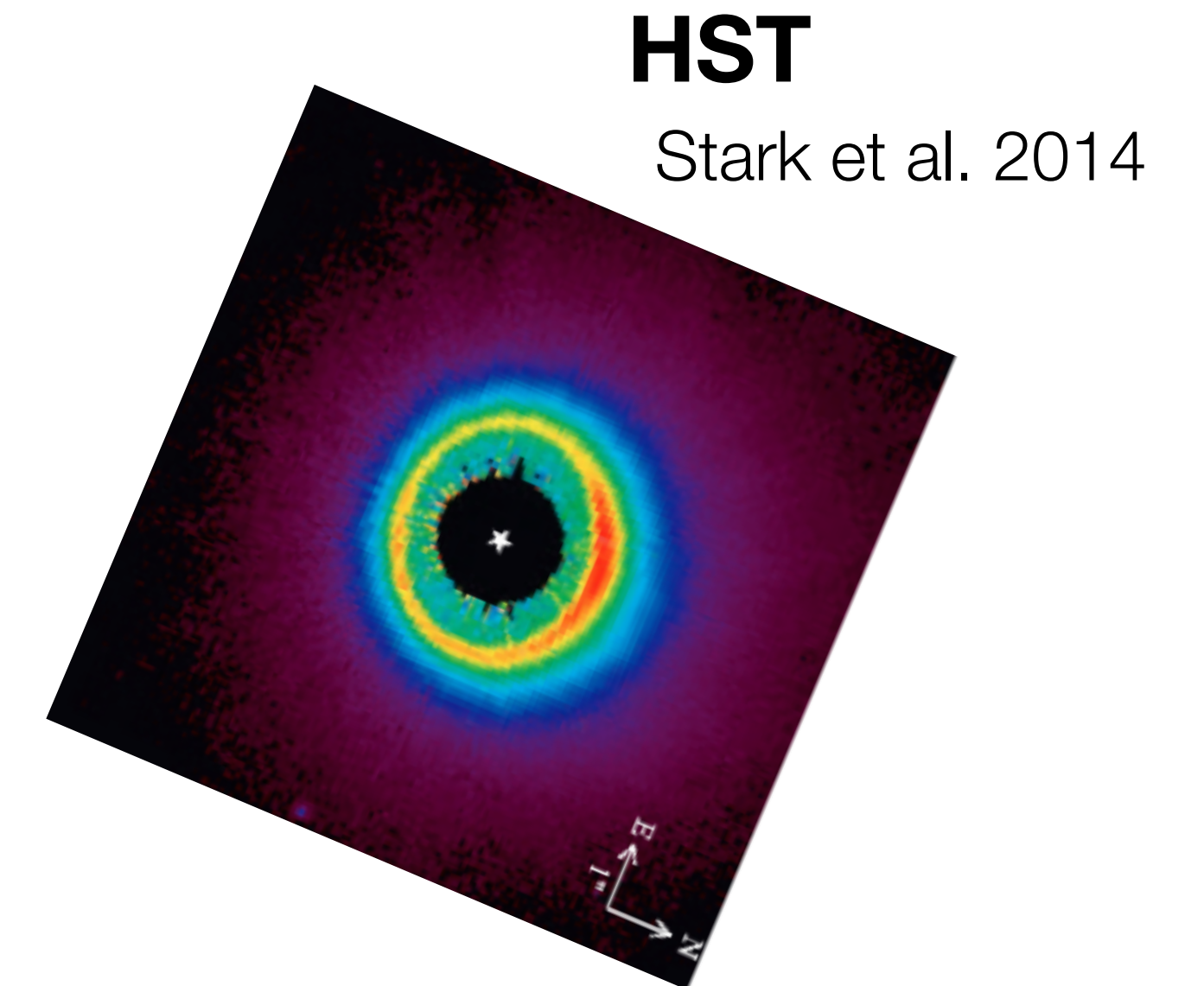
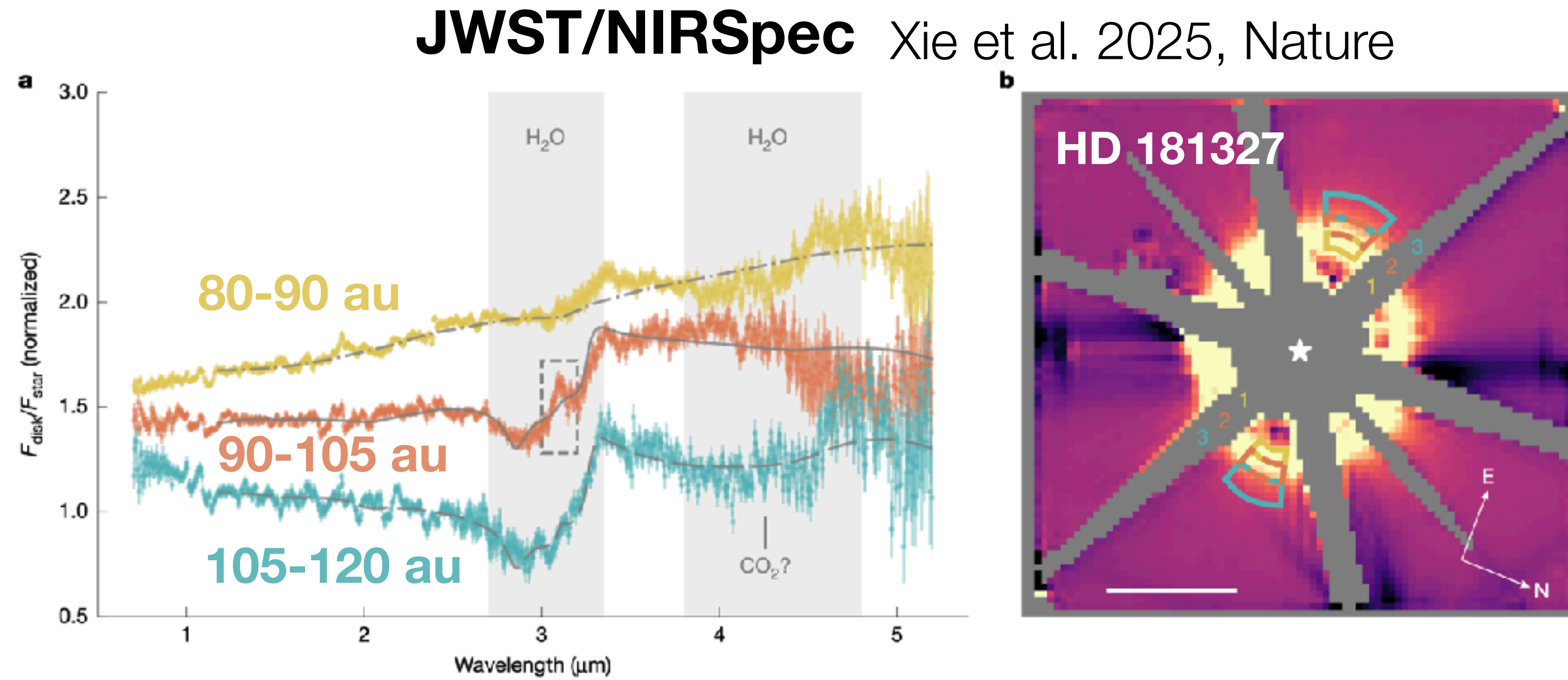


Tazaki et al. 2021 波長 ( $\mu\text{m}$ )

Our model prediction for JWST/NIRSpec observations

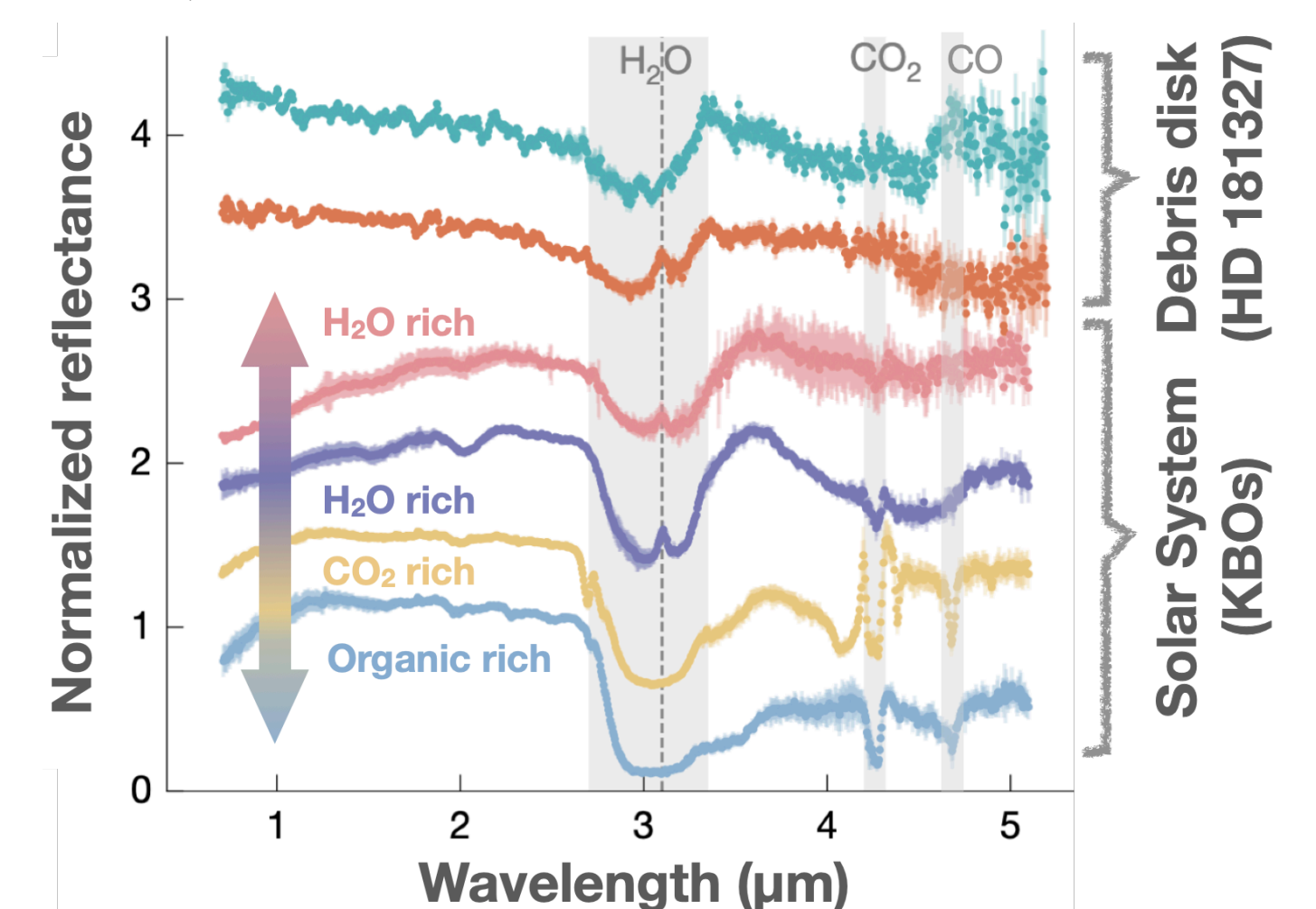


# Crystalline water ice in a debris disk



HD 181327周りのデブリ円盤から結晶化した水氷の吸収を検出

- 太陽系のカイパーベルト天体にも類似のスペクトルを示す天体が存在 (e.g., Pinilla-Alonso et al. 2025)
- 結晶質氷の起源？



# まとめ

**JWSTによって原始惑星系円盤のダストの観測的研究が進展している！**

- **エッジオン円盤表層部におけるダストサイズの推定が可能に**
  - 円盤表層部に大きなダスト ( $\sim 10 \mu\text{m}$ ) の兆候を示す天体の発見
    - なぜ沈殿していない？
  - ペブル円盤 (ALMA観測) の厚みと表層ダストサイズの対応
- **円盤風や空間的に広がった中間赤外線放射の発見**
  - 光蒸発やMHD円盤風との関連？
- **原始惑星系円盤やデブリ円盤での揮発性氷の検出**
  - 各種氷の存在量の評価やエッジオン天体以外での氷の検出が今後の課題