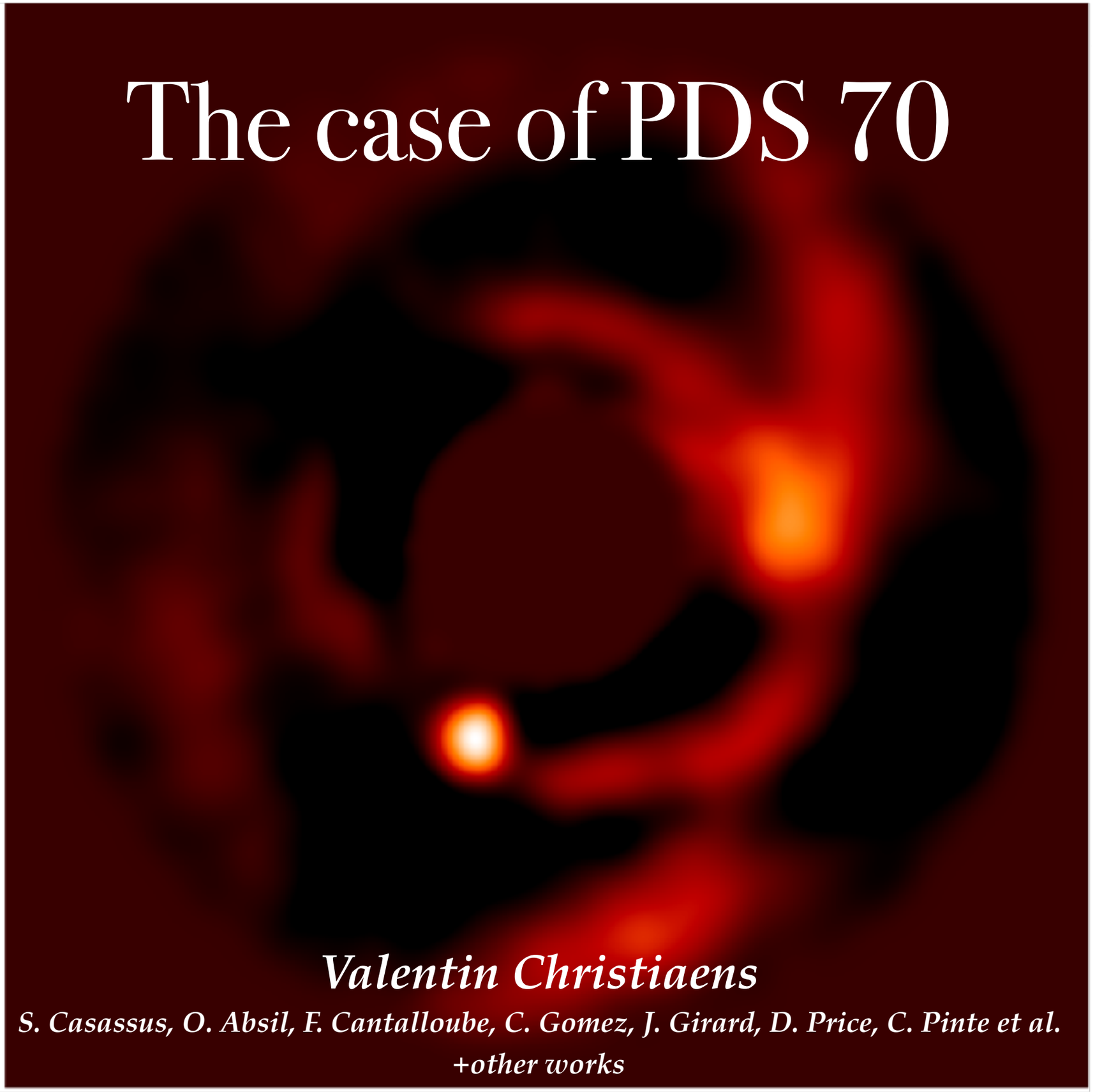
The case of PDS 70



Valentin Christiaens

S. Casassus, O. Absil, F. Cantalloube, C. Gomez, J. Girard, D. Price, C. Pinte et al.

+other works

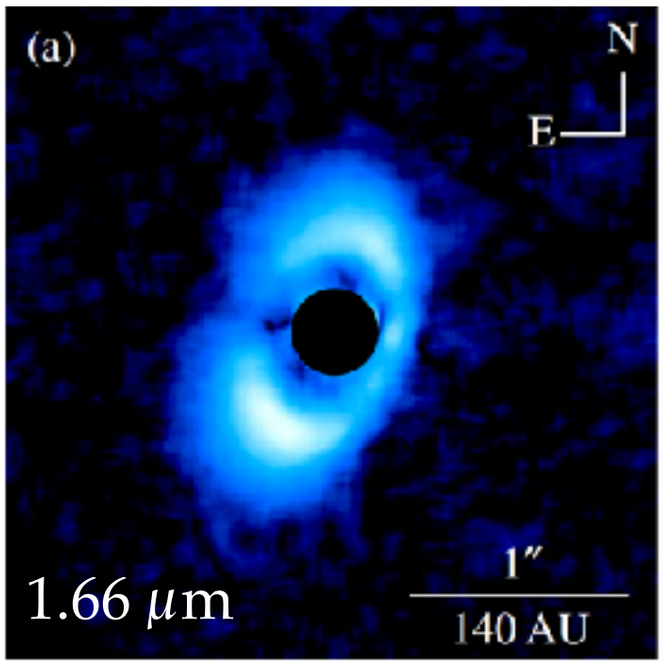
Disc-ussion workshop (15-19/07/2019)

Outline

- I. Circumstellar disc
- II. Protoplanet(s) vs extended disc structures
- III. Circumplanetary disc(s)
- IV. Future plans

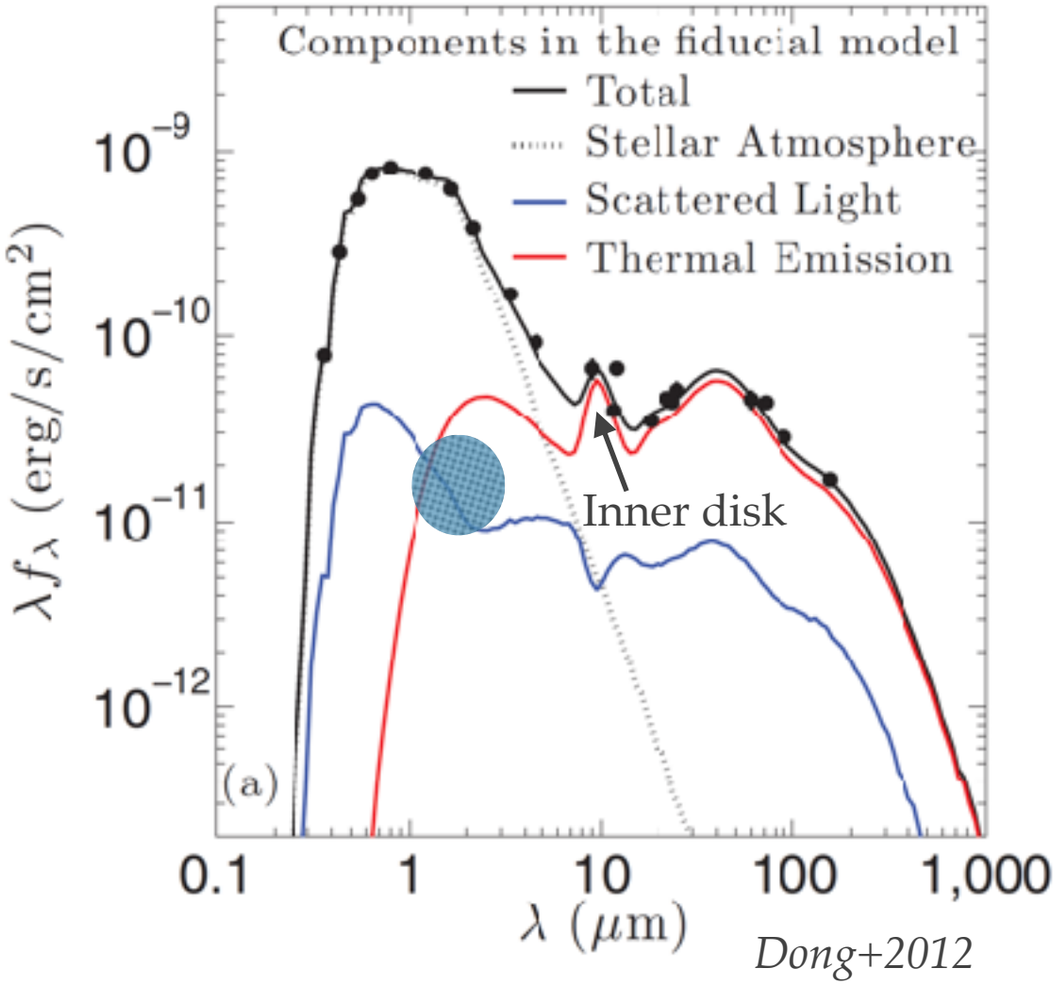
(Pre-)transition disc

NIR polarised light



Hashimoto+2012

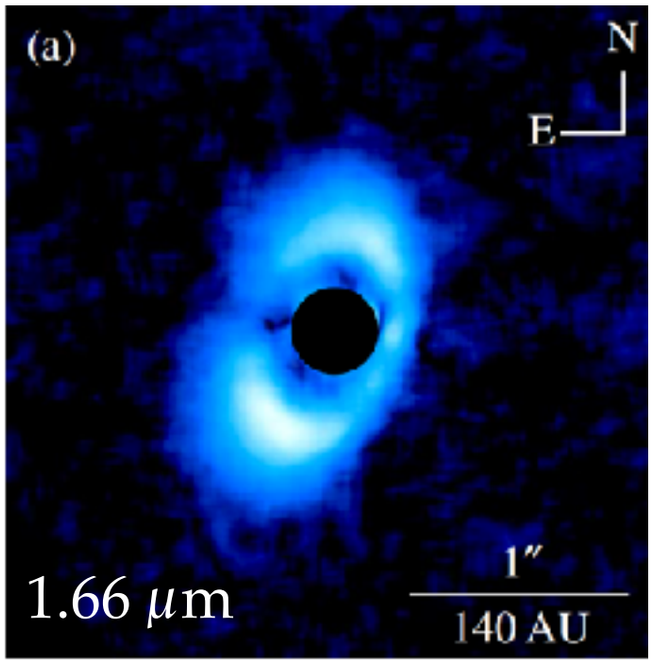
SED

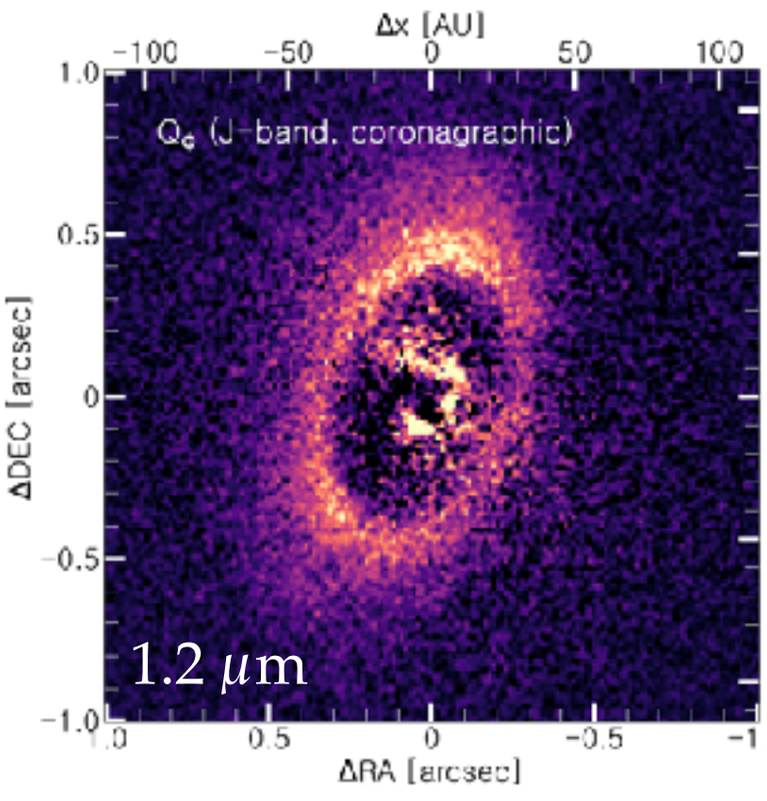


Dong+2012

(Pre-)transition disc

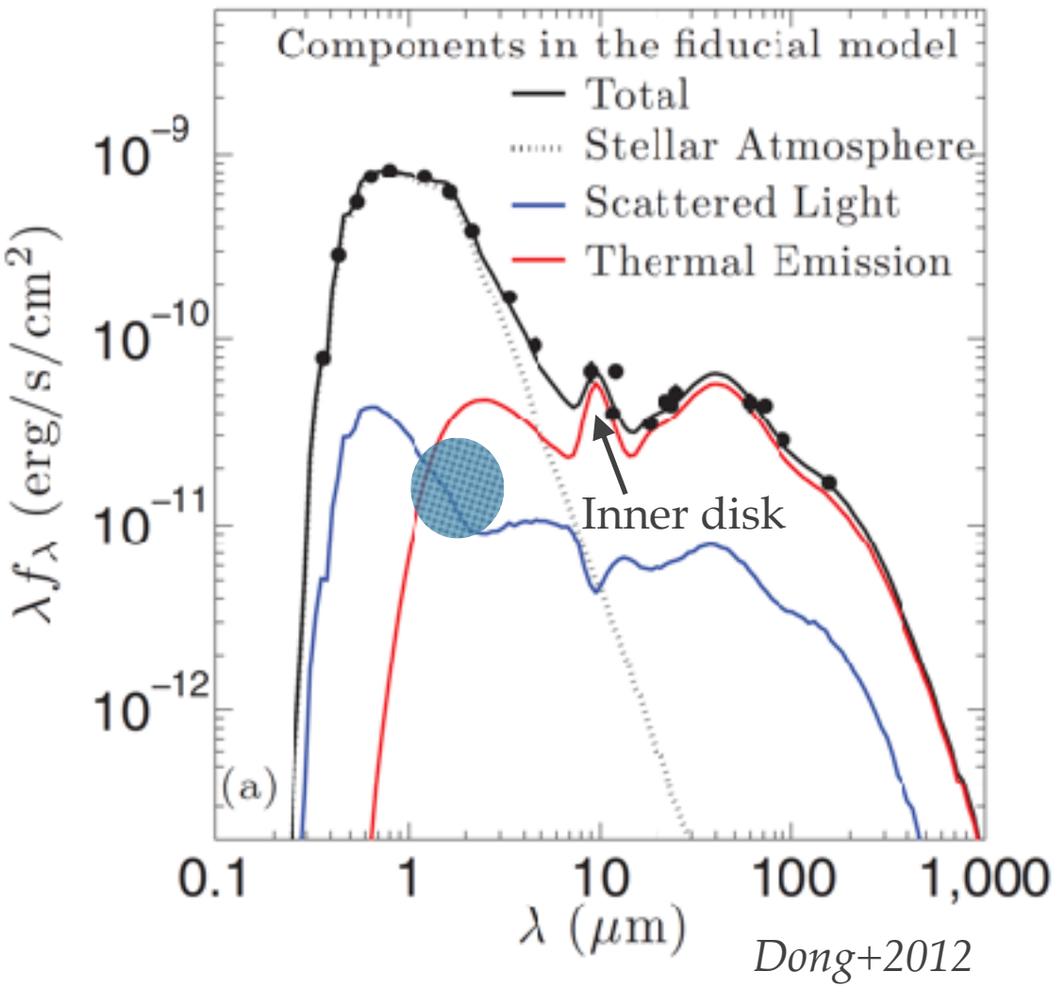
NIR polarised light





Hashimoto+2012

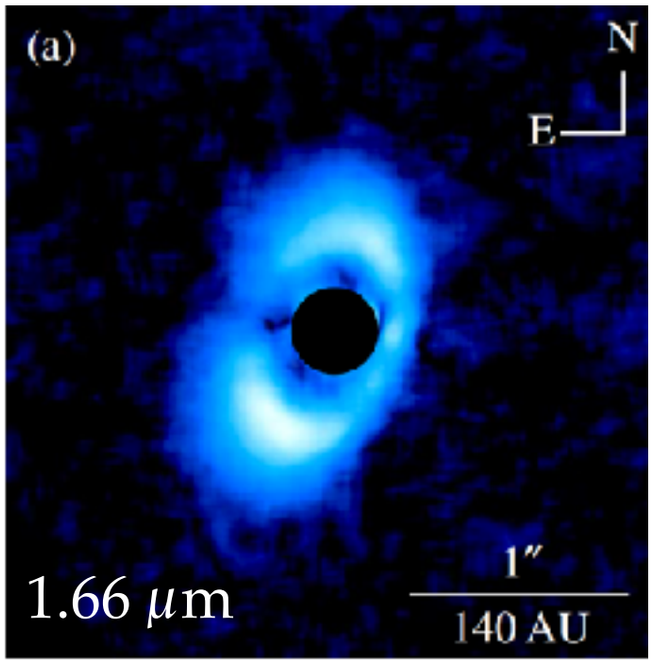
SED



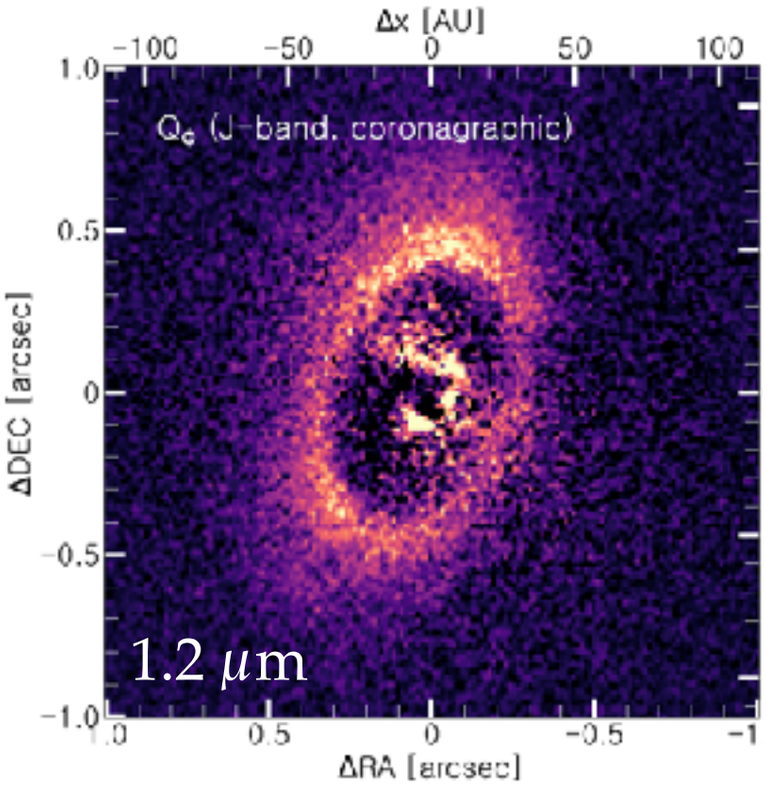
Dong+2012

(Pre-)transition disc

NIR polarised light

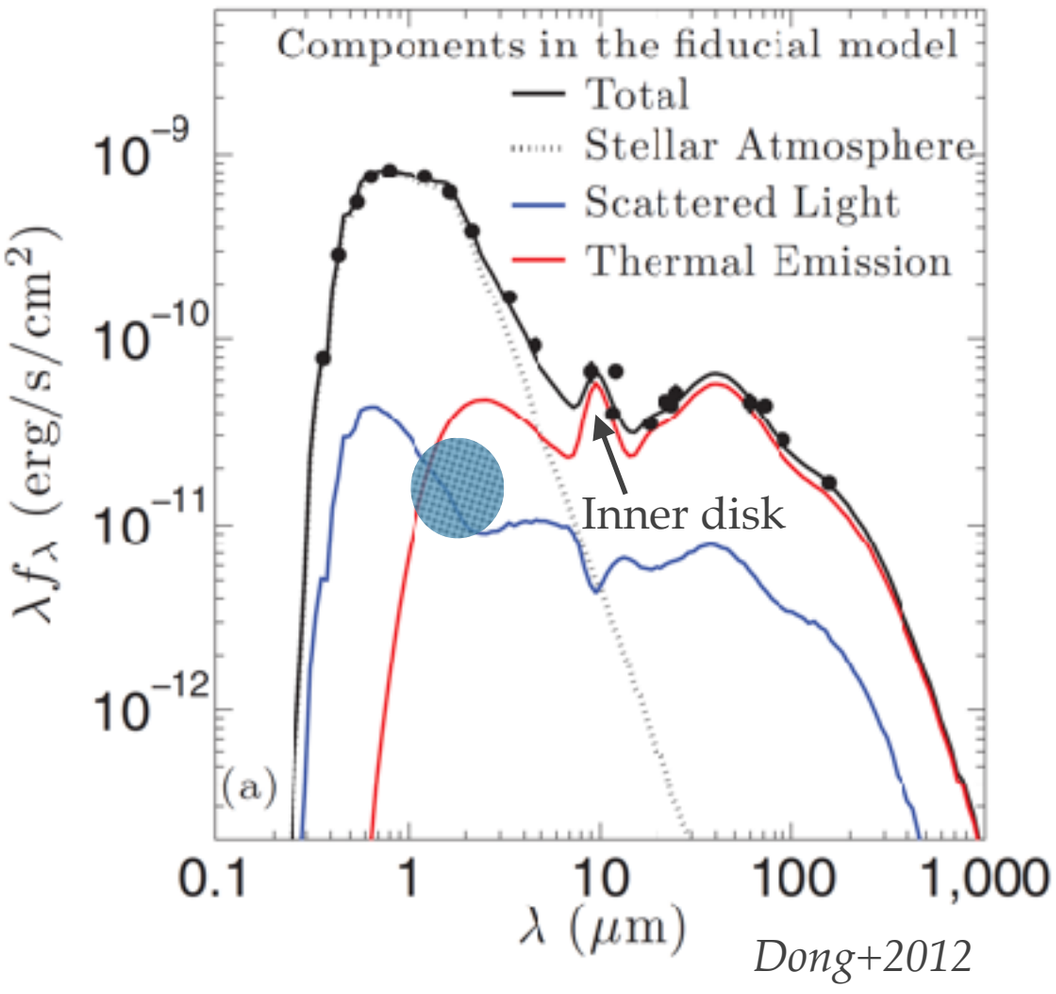


Hashimoto+2012



Keppler+2018

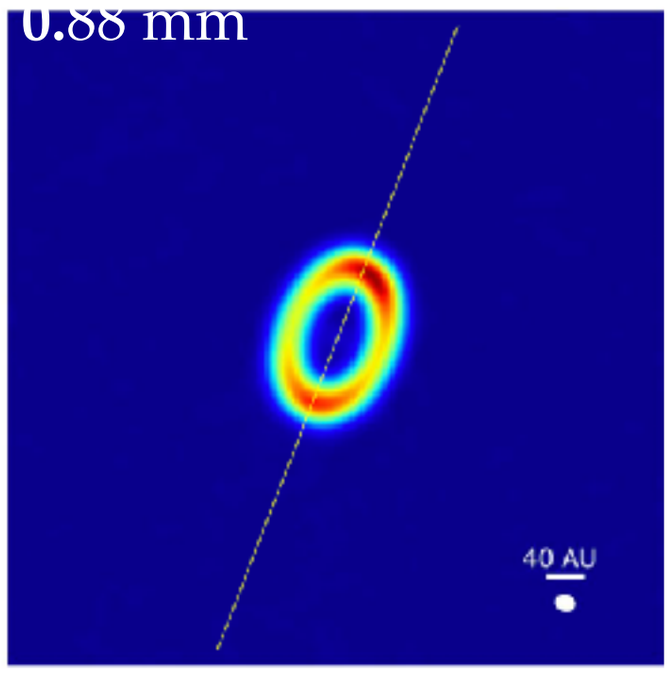
SED



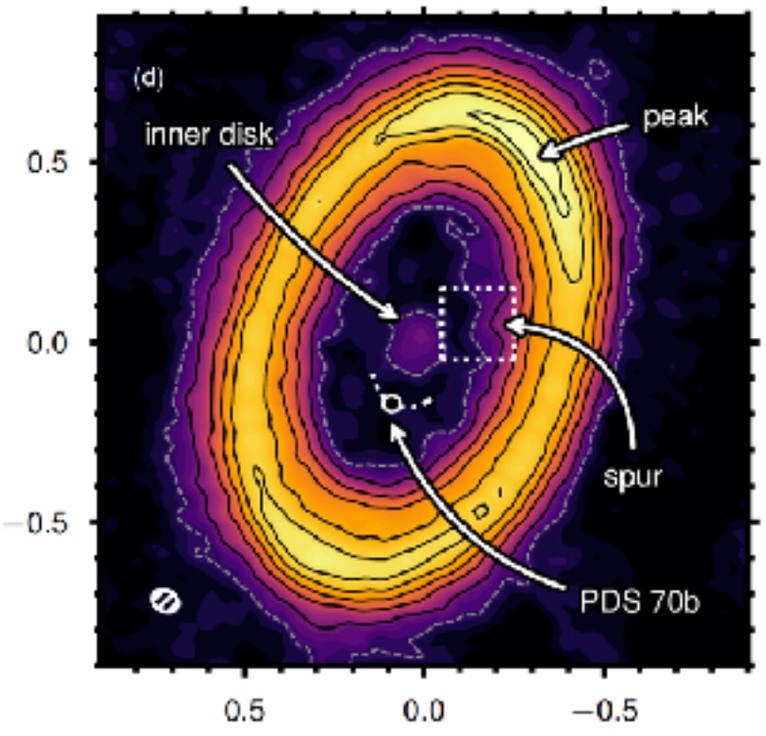
Dong+2012

(Pre-)transition disc

sub-mm continuum



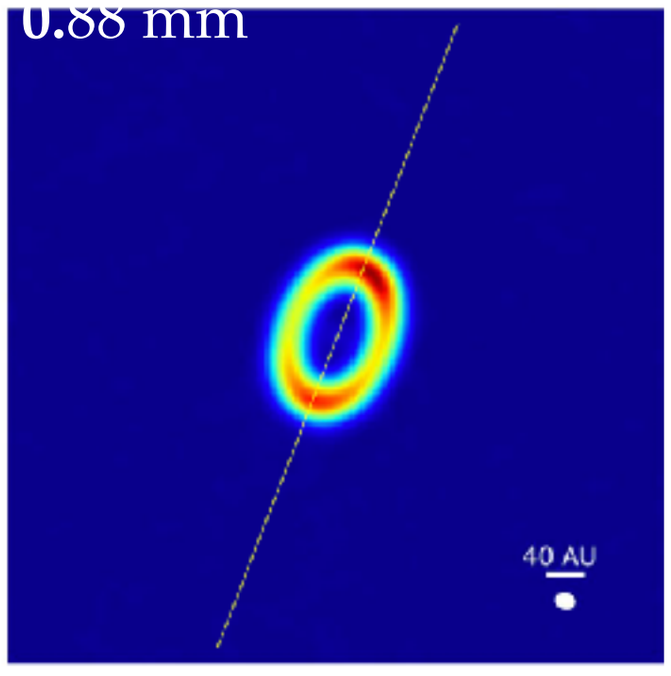
Long+2018



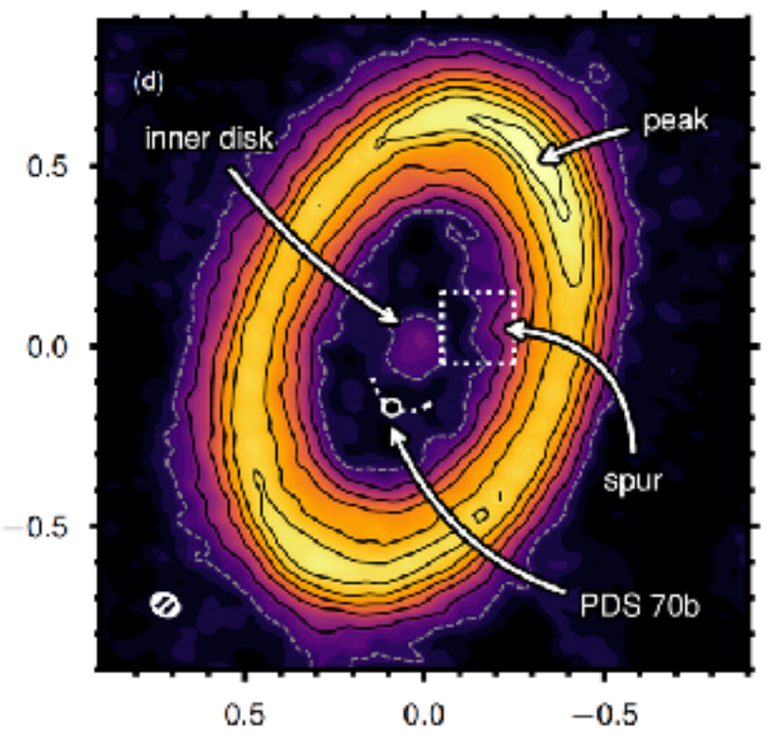
Keppler+2019

(Pre-)transition disc

sub-mm continuum

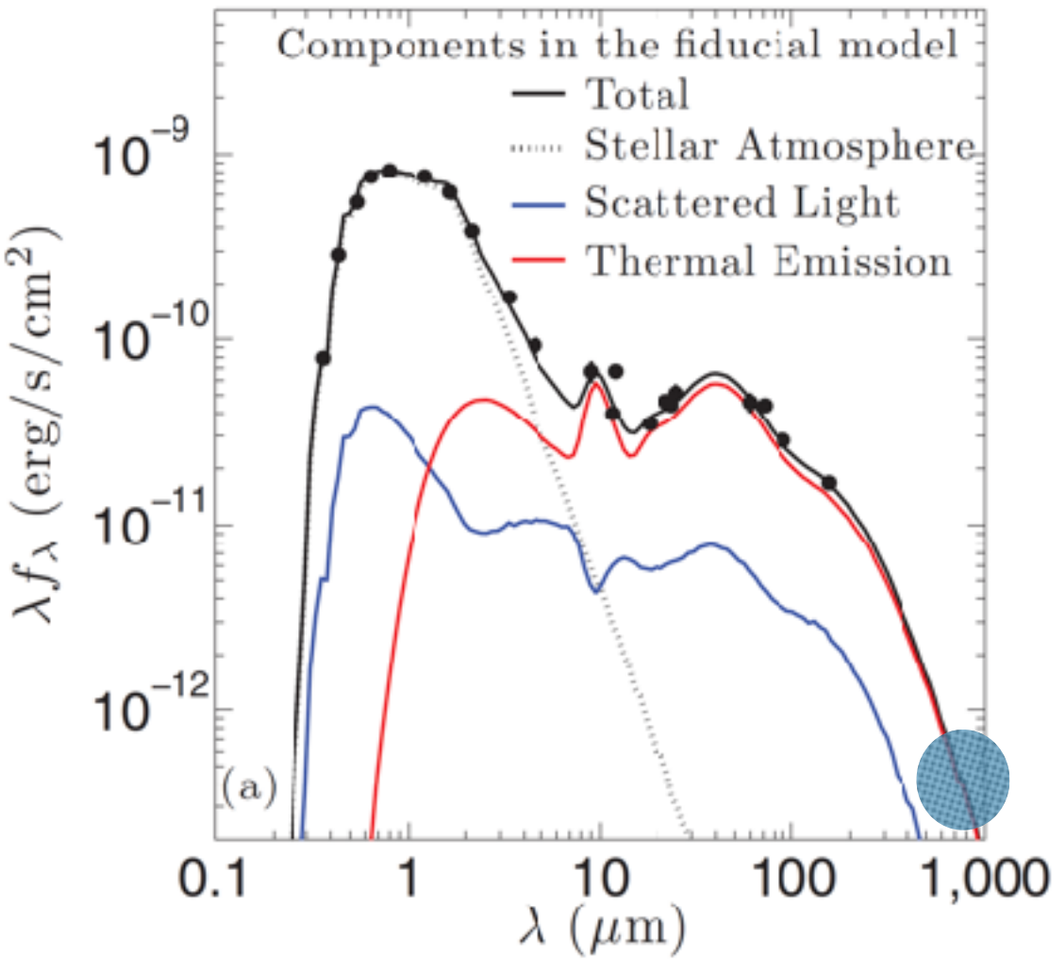


Long+2018



Keppler+2019

SED

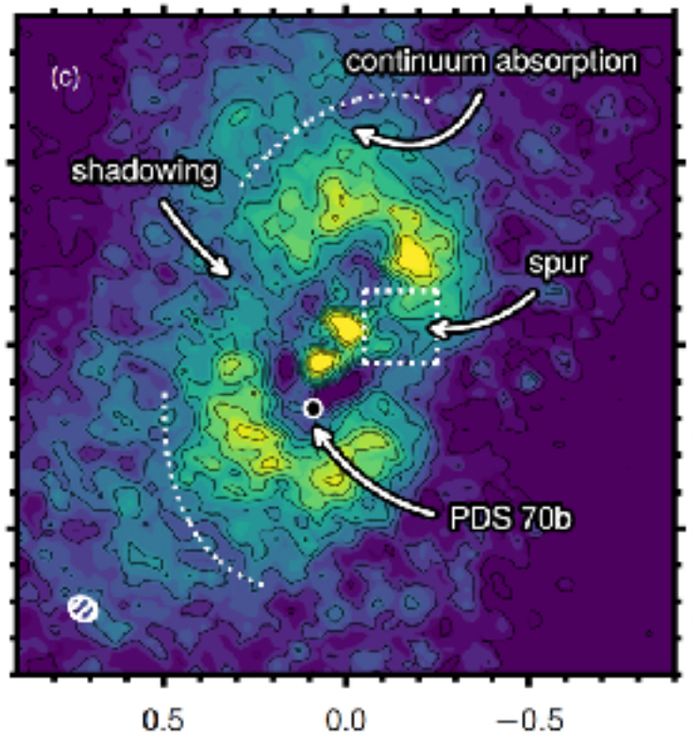


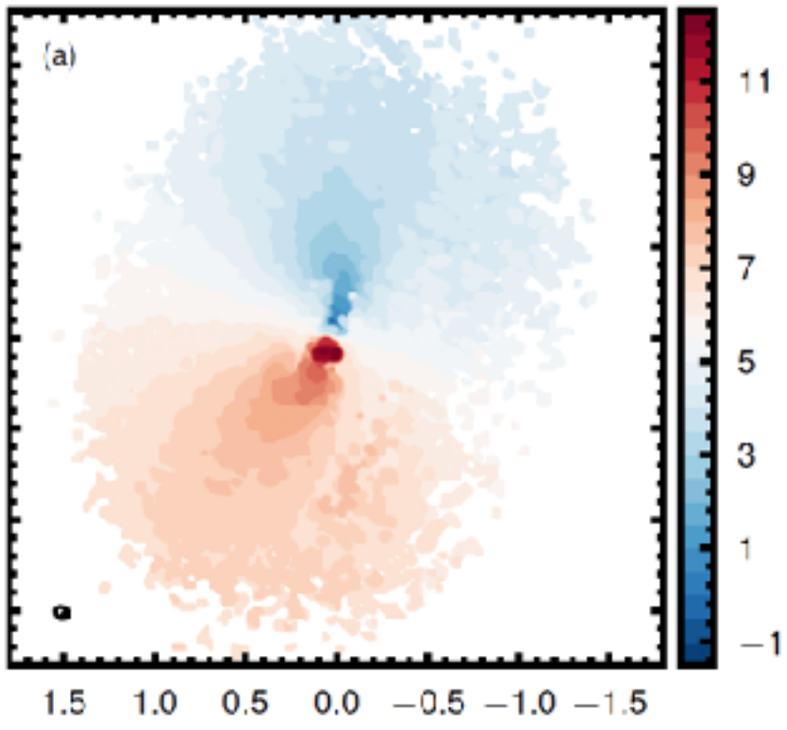
Dong+2012

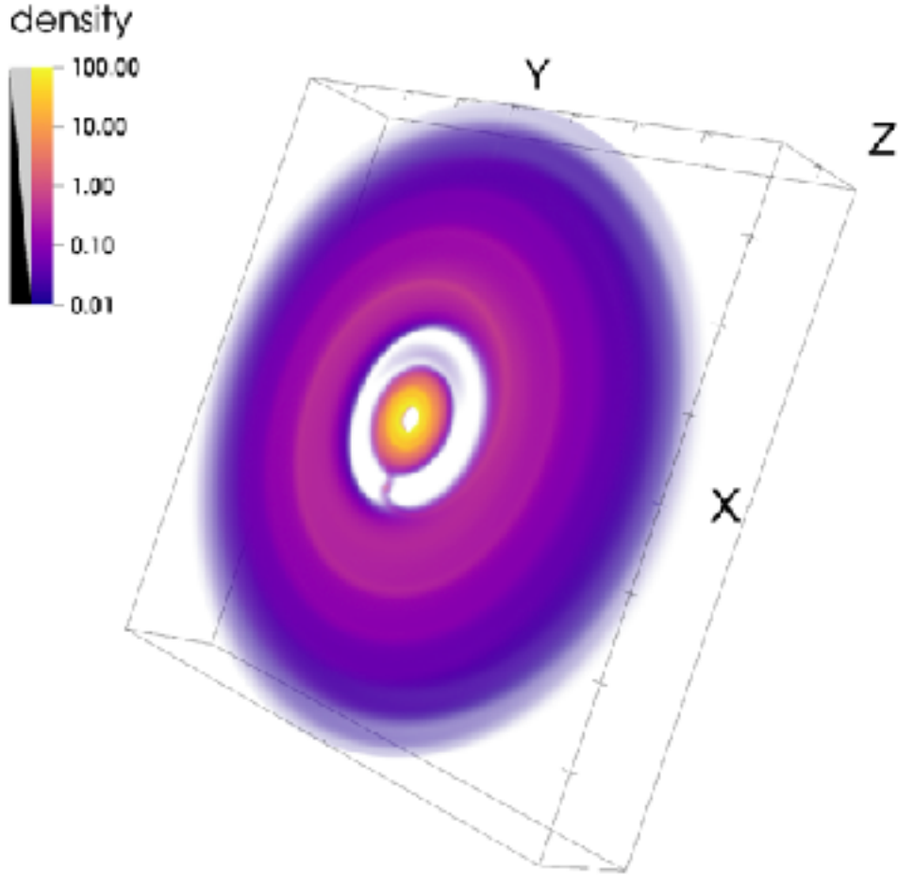
(Pre-)transition disc

Keppler+2019

^{12}CO J=3-2



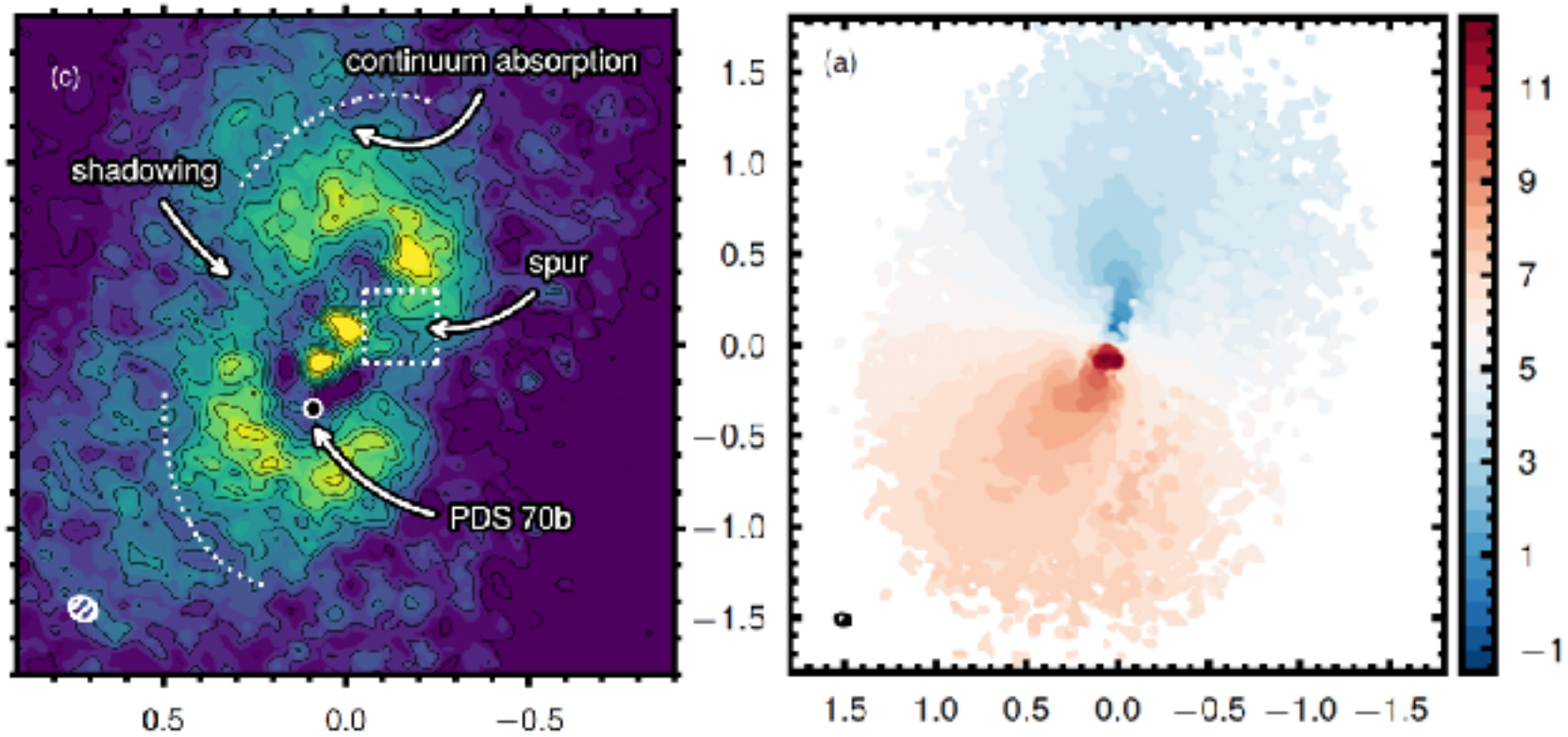


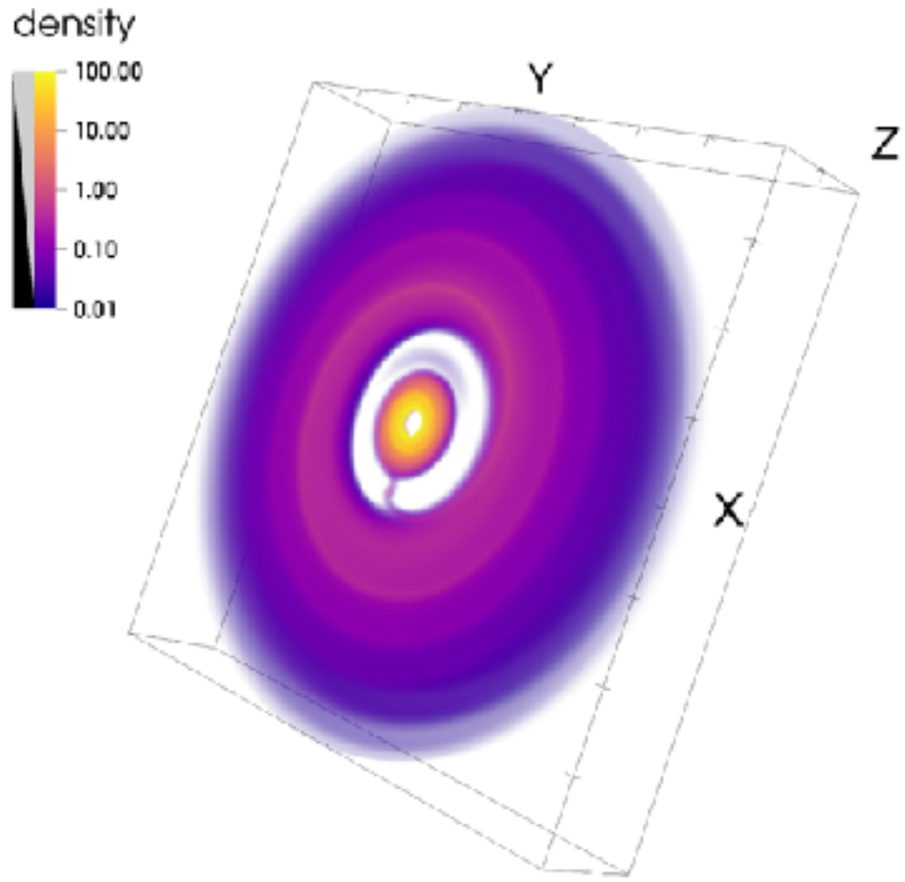


(Pre-)transition disc

Keppler+2019

^{12}CO J=3-2



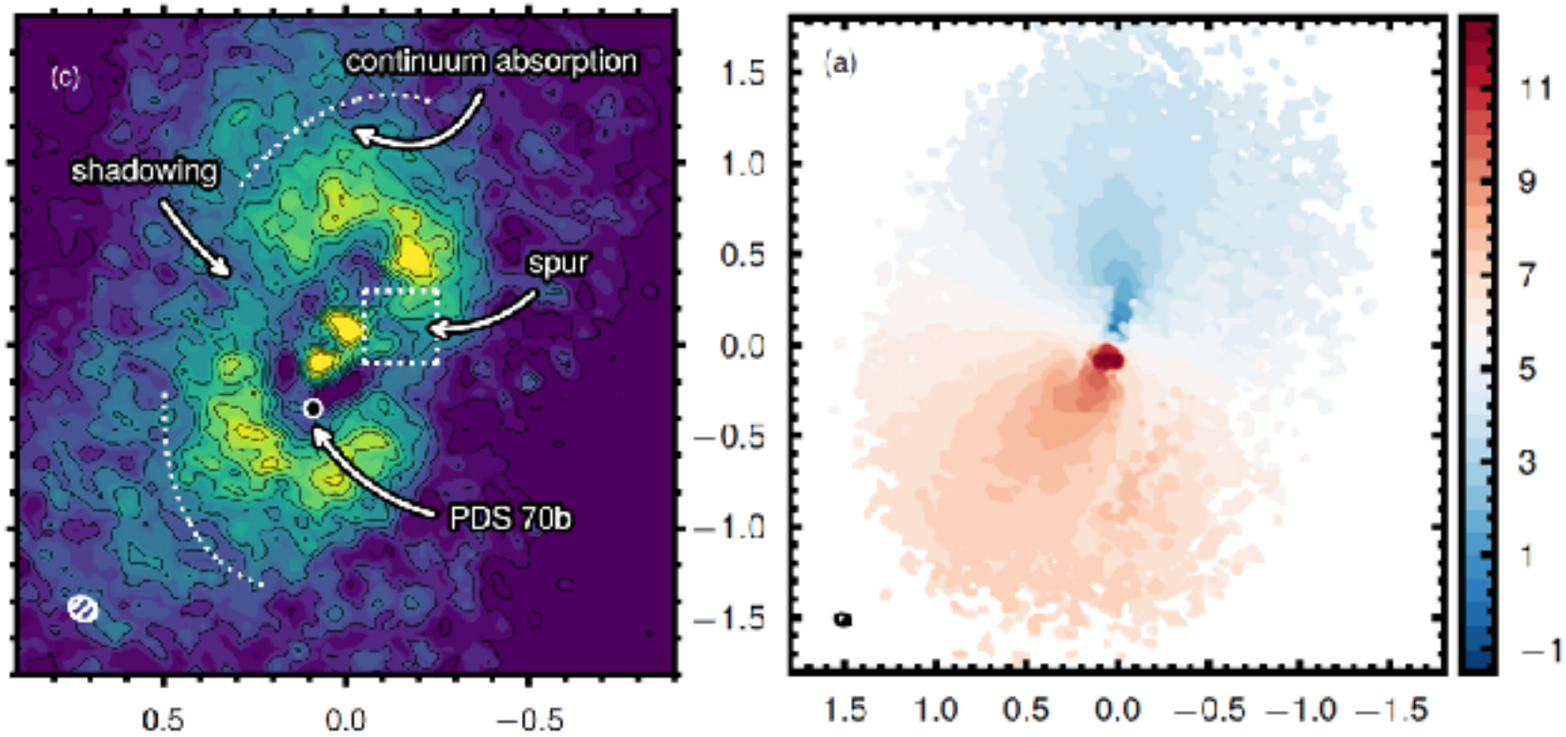


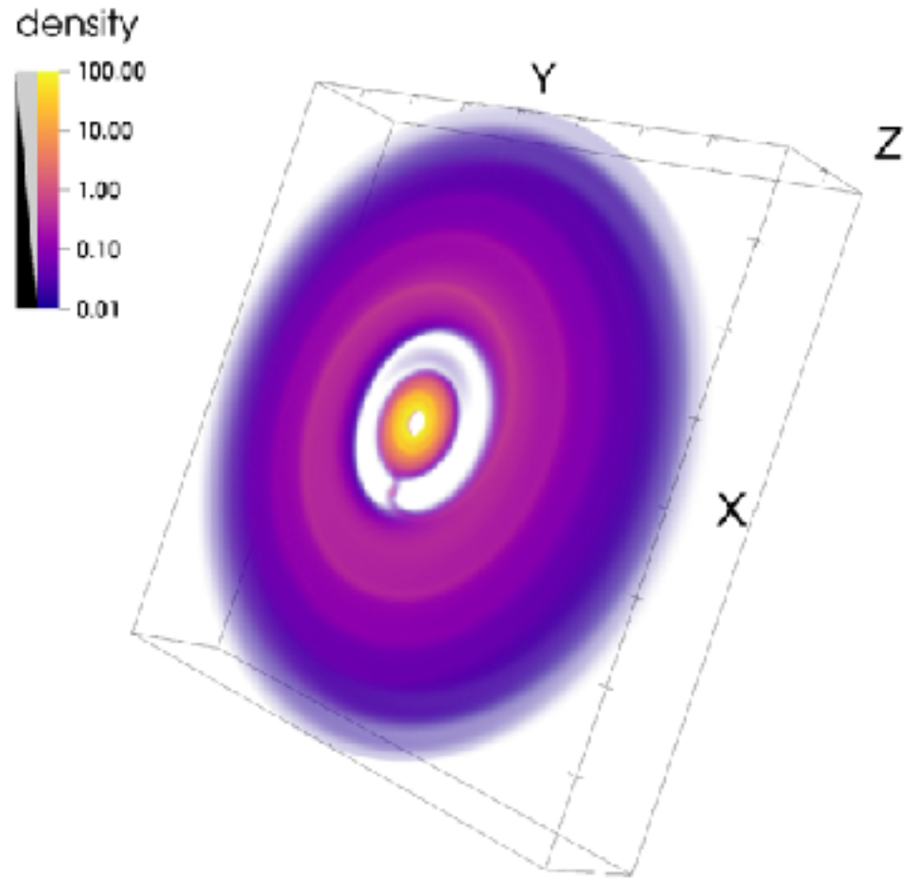
- No reported kink => Not enough gas in large gap?

(Pre-)transition disc

Keppler+2019

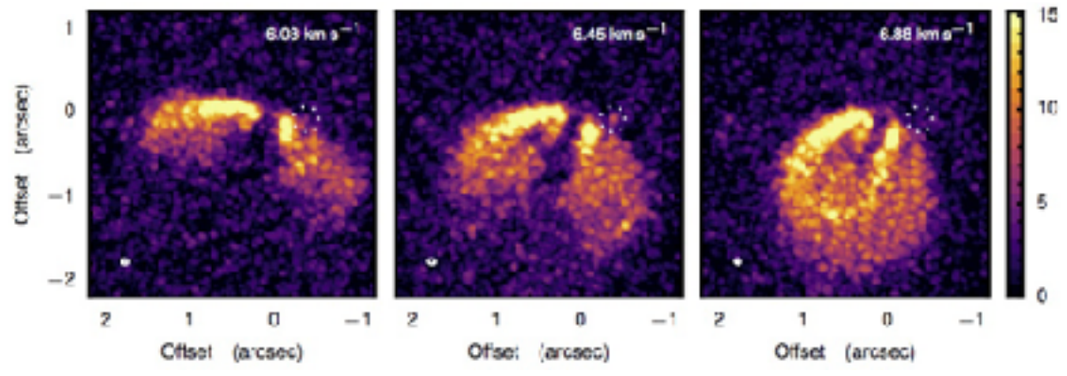
^{12}CO J=3-2





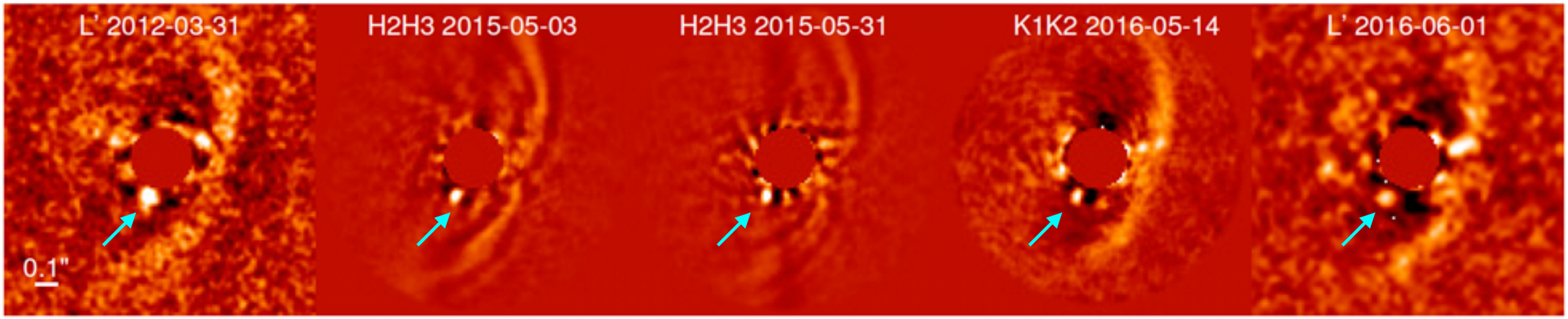
- No reported kink => Not enough gas in large gap?

- Tentative localized ^{12}CO emission



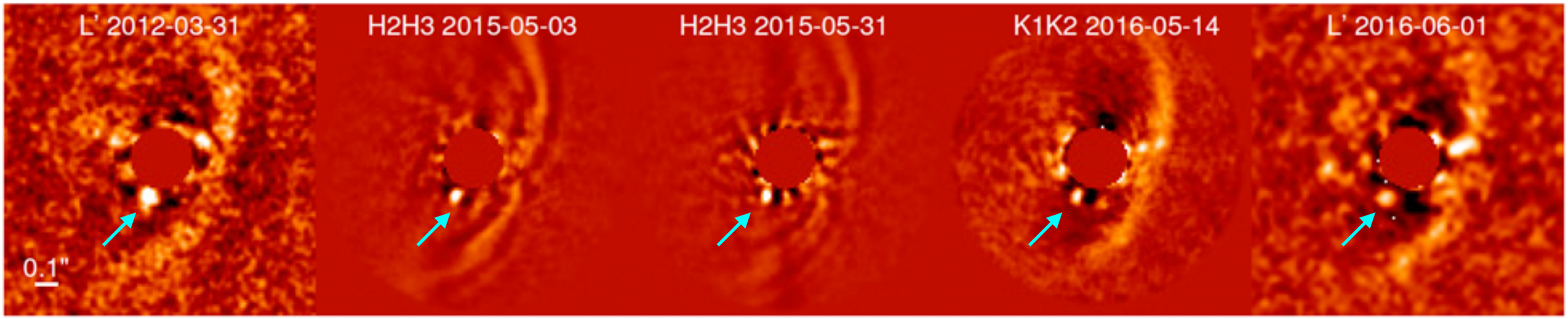
PDS 70 b

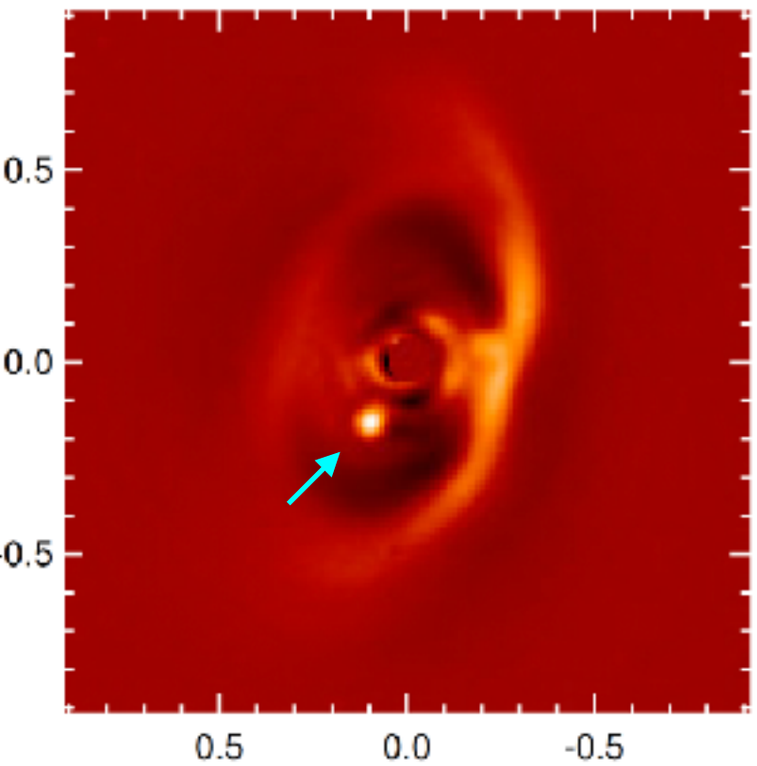
Keppler+2018



PDS 70 b

Keppler+2018

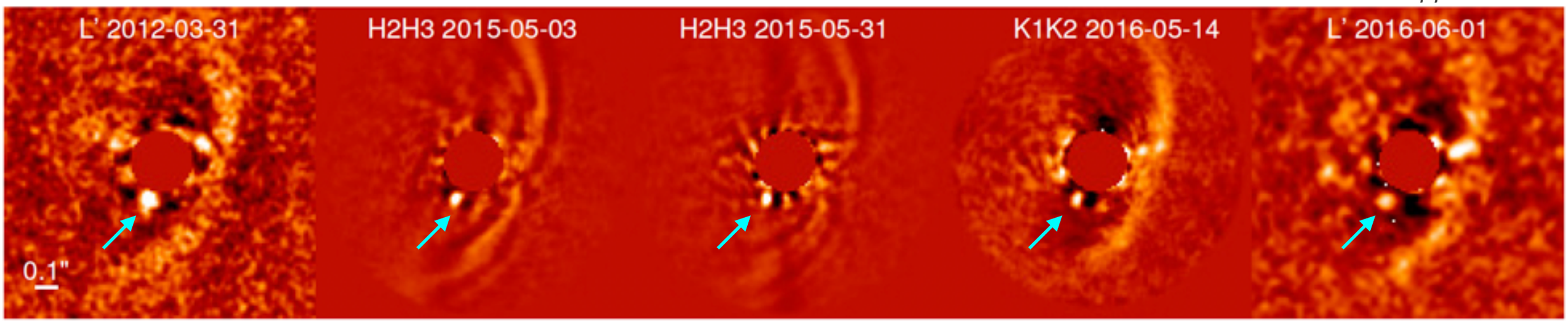


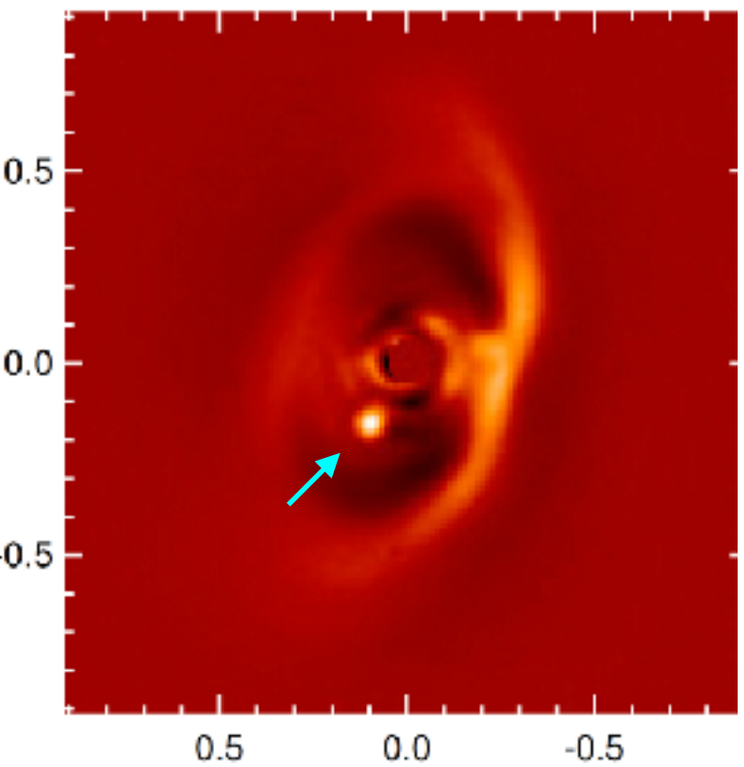


Müller+2018

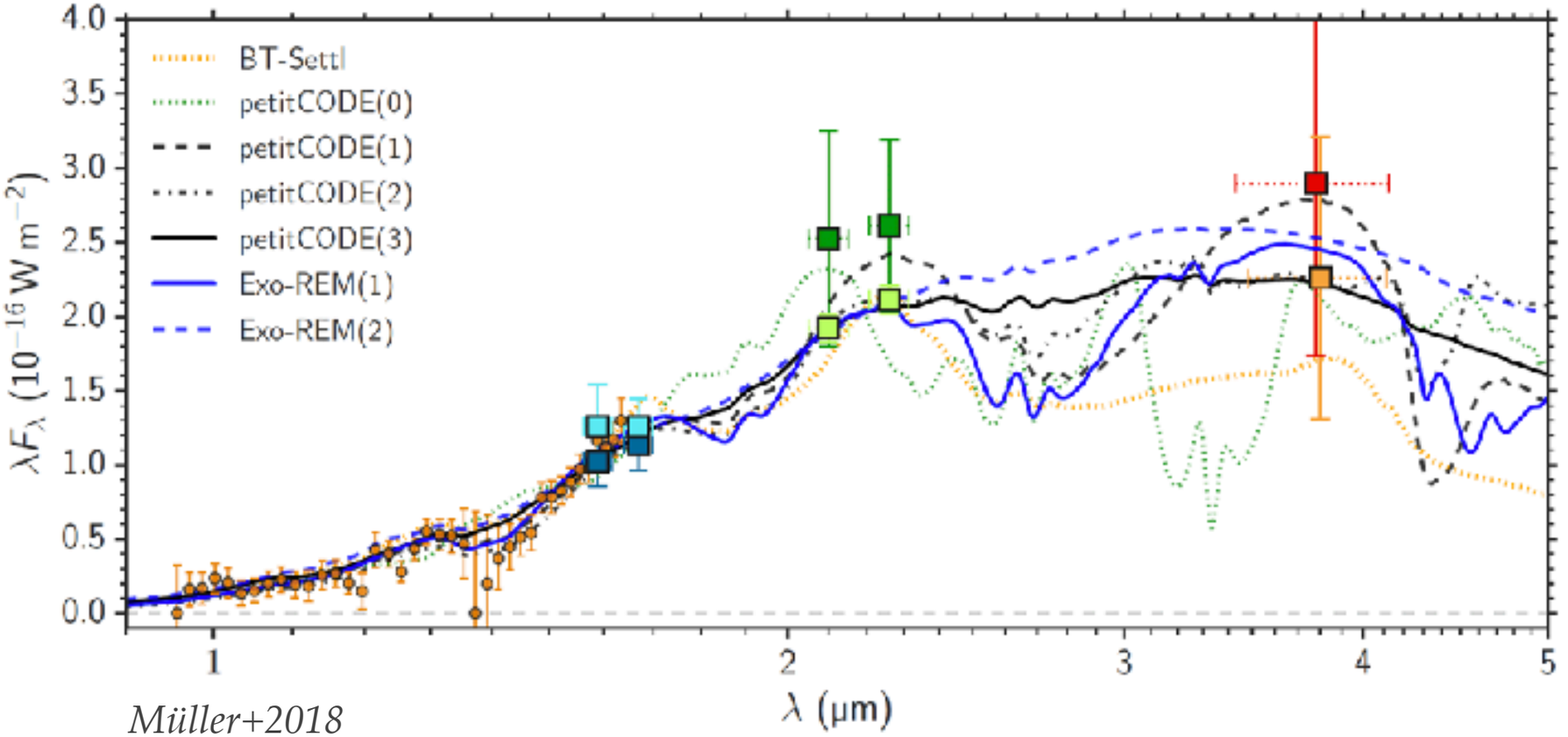
PDS 70 b

Keppler+2018





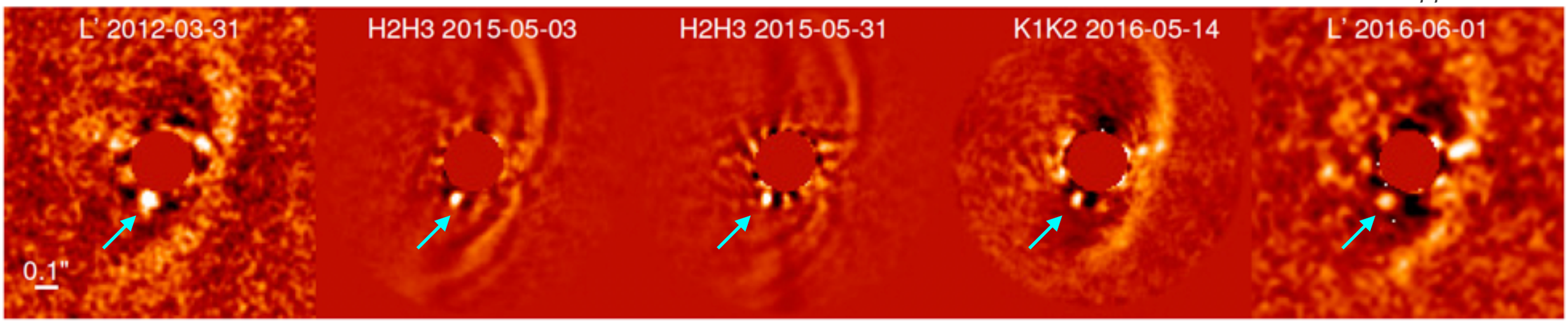
Müller+2018

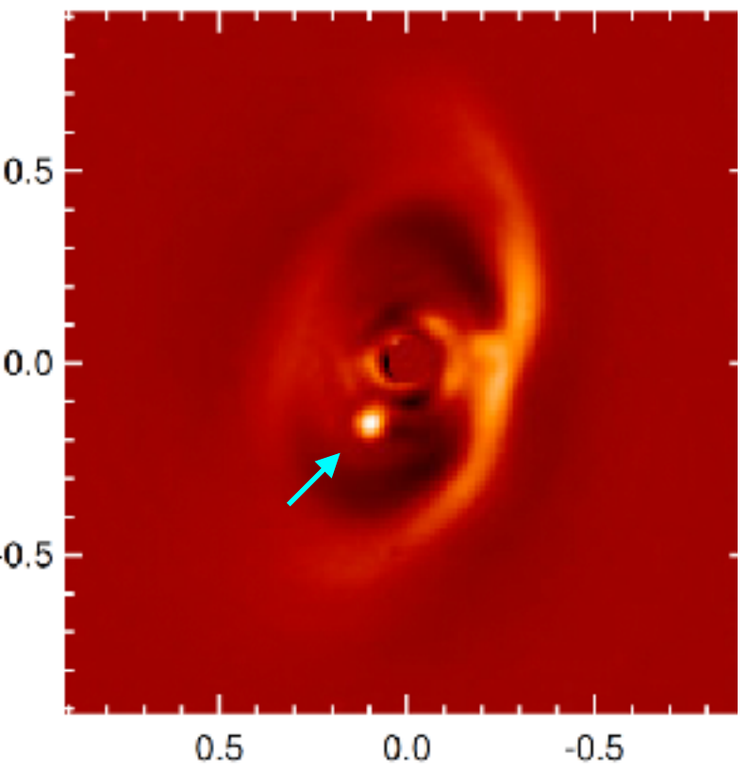


Müller+2018

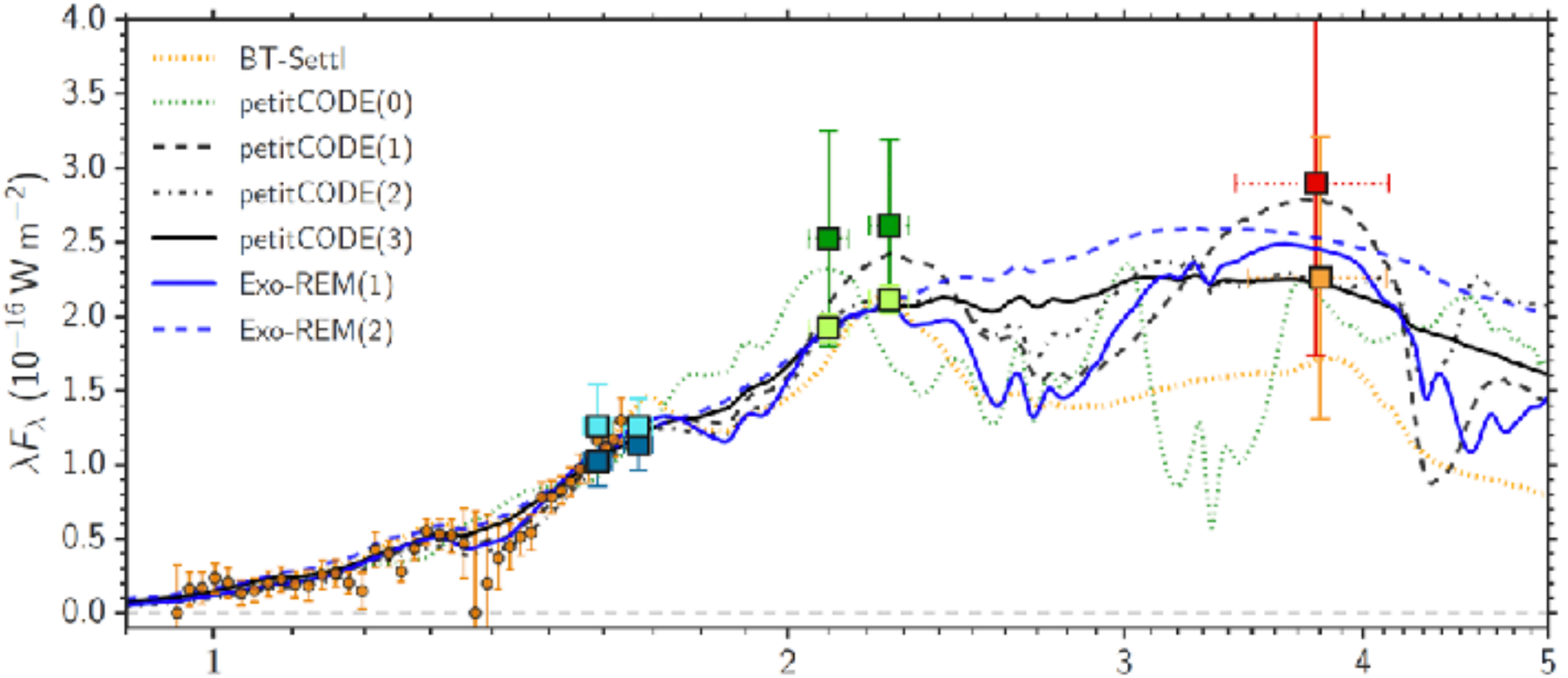
PDS 70 b

Keppler+2018





Müller+2018



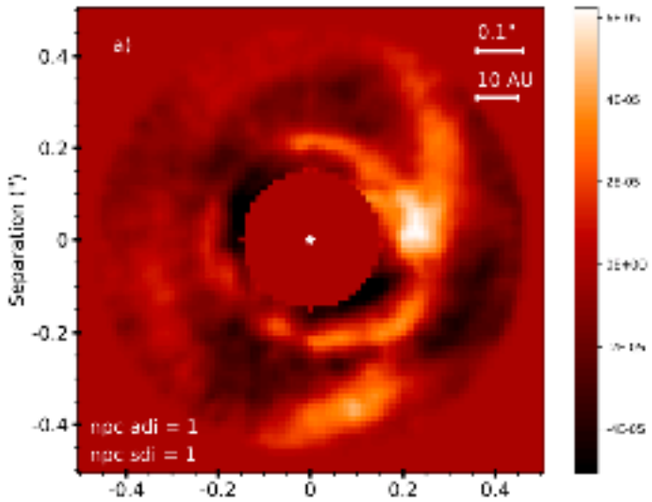
Müller+2018

=> ~4–17 M_{Jup}?

PDS 70 b

Point source or filtered extended signal?

PCA-SADI



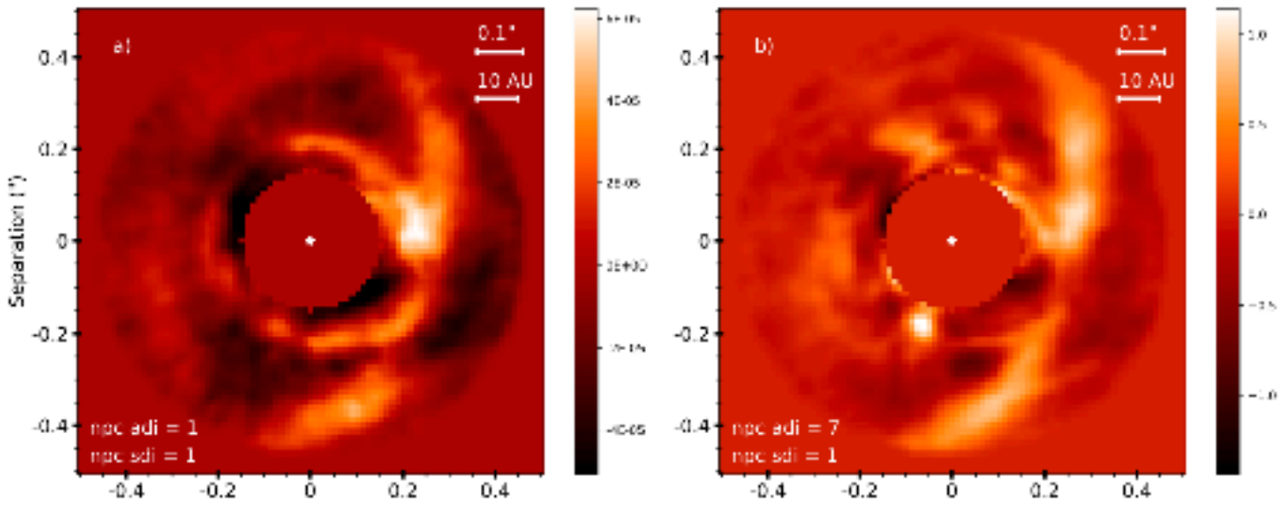
PCA-ASDI

Christiaens+2019a

PDS 70 b

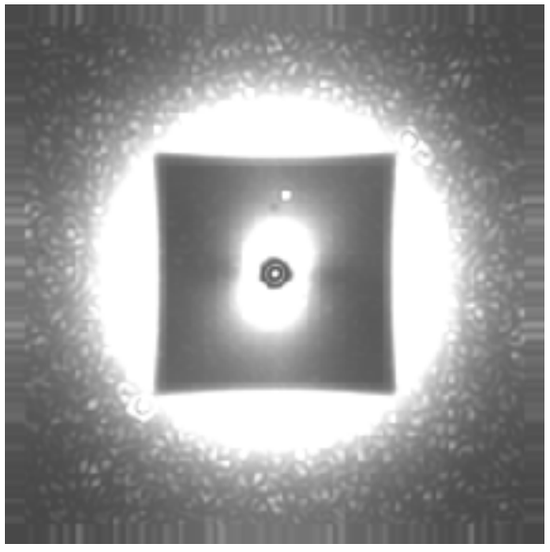
Point source or filtered extended signal?

PCA-SADI

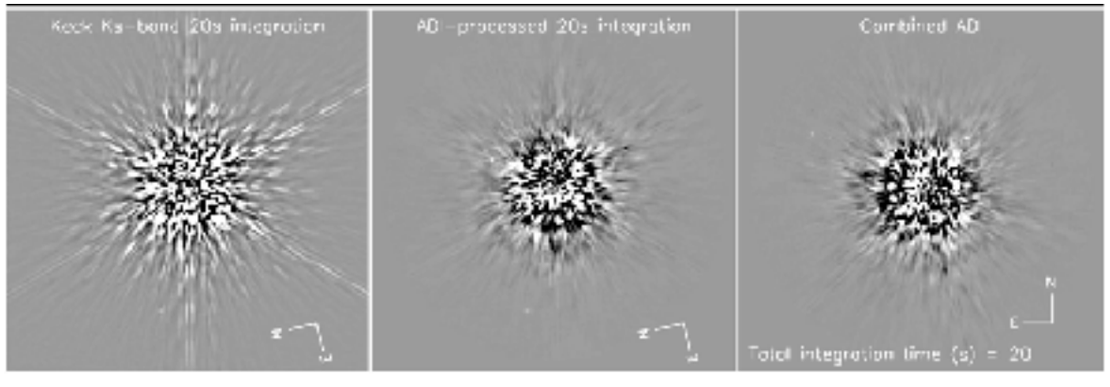


PCA-ASDI

SDI



ADI



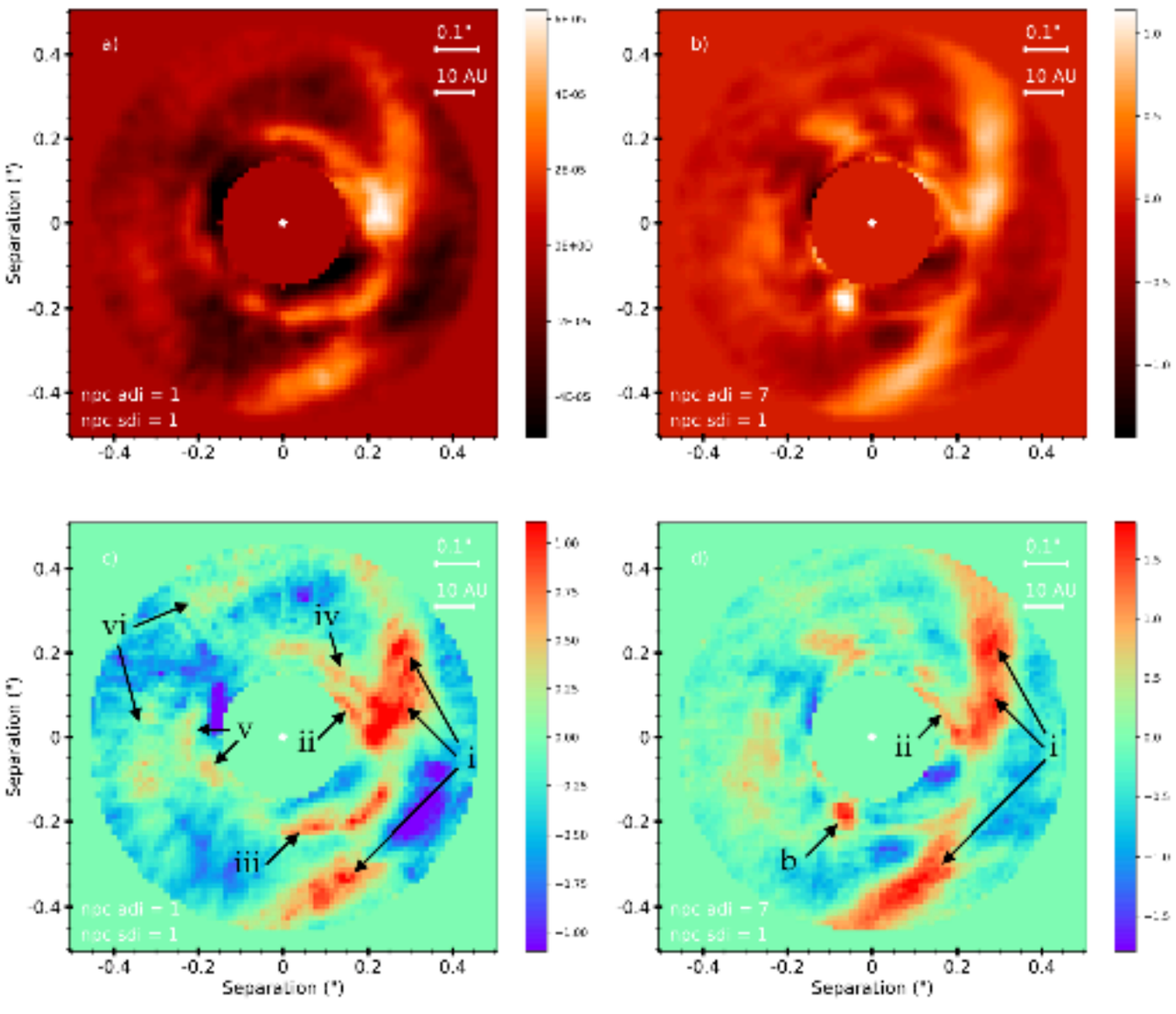
Christiaens+2019a

PDS 70 b

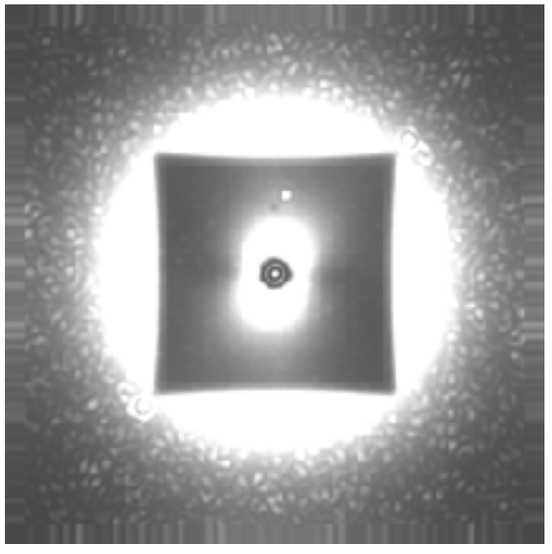
Point source or filtered extended signal?

PCA-SADI

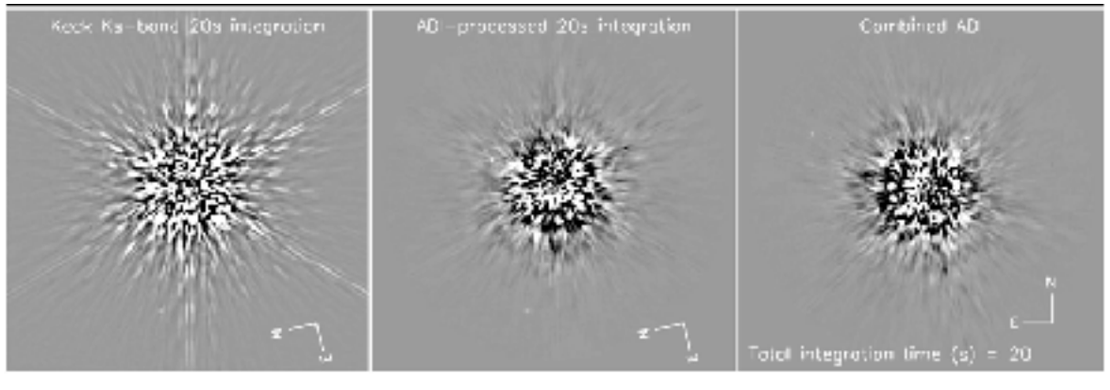
PCA-ASDI



SDI



ADI

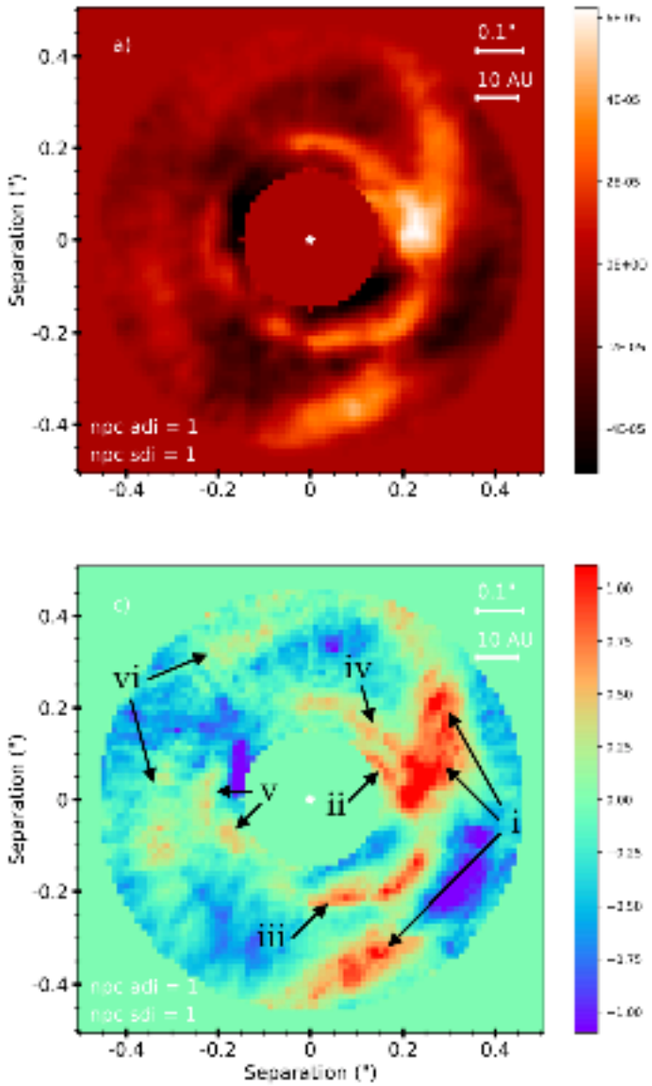


Christiaens+2019a

PDS 70 b

Point source or filtered extended signal?

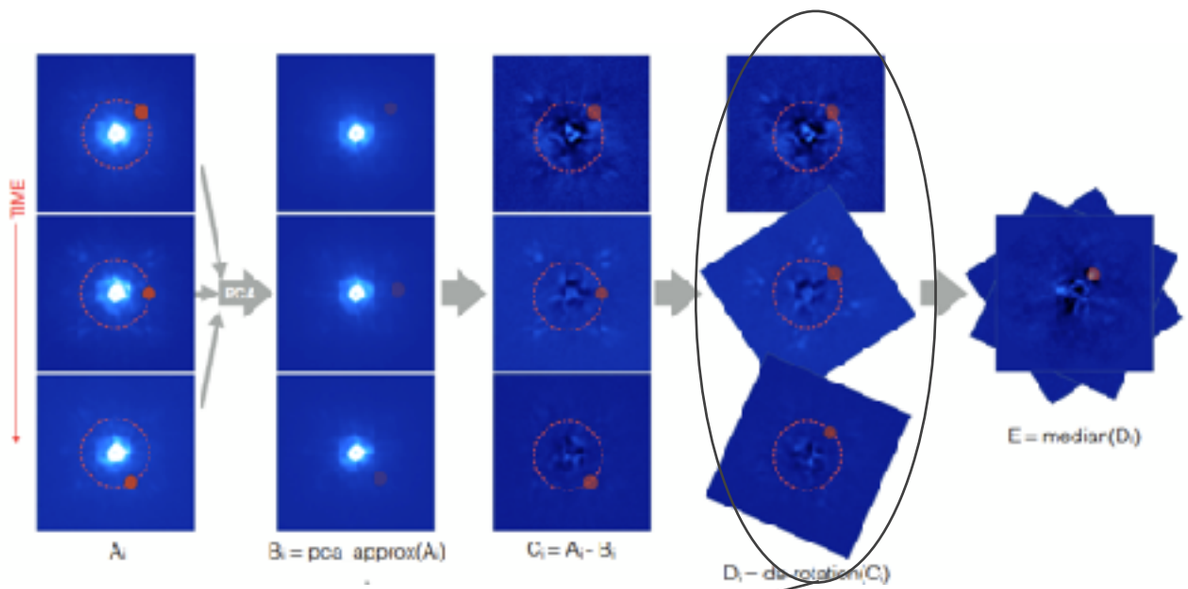
PCA-SADI



PCA-ASDI

Christiaens+2019a

$$\mathrm{STIM}(i,j) = \frac{\mu(x_{i,j})}{\sigma(x_{i,j})}$$

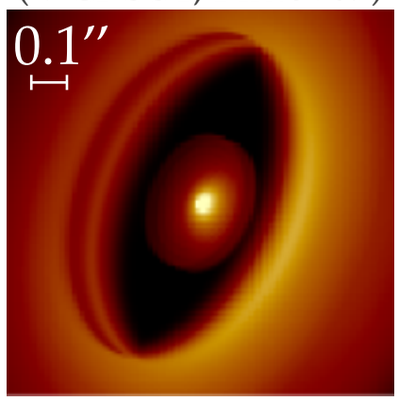


Pairet+2018

Processing of MCFOST model

RT model
(MCFOST; Pinte+09)

MODEL



(log scale)

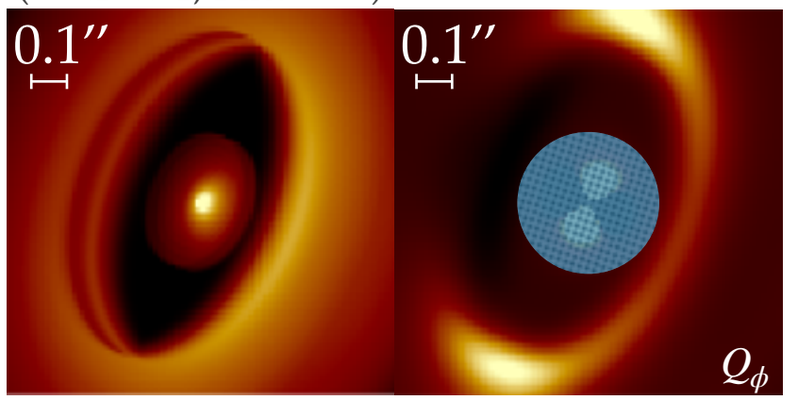
OBS

Processing of MCFOST model

RT model
(MCFOST; Pinte+09)

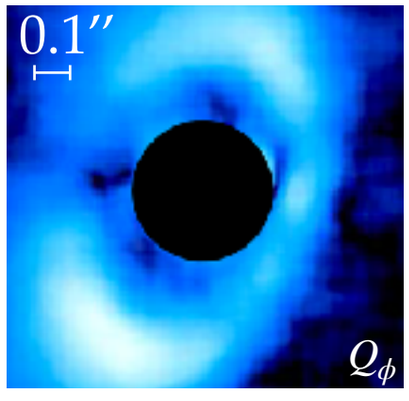
polarized light
1.66 μm

MODEL



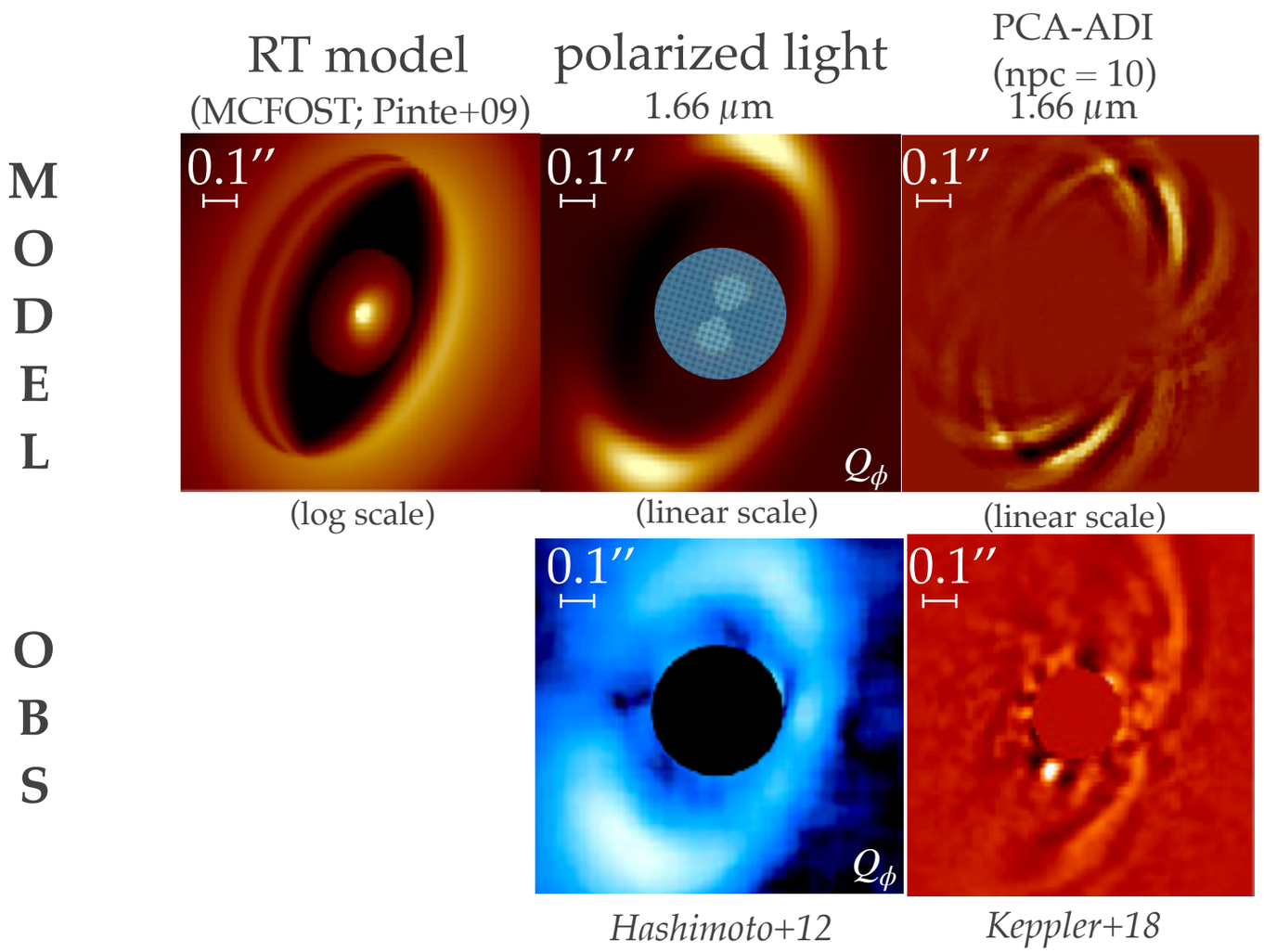
(log scale) (linear scale)

OBS

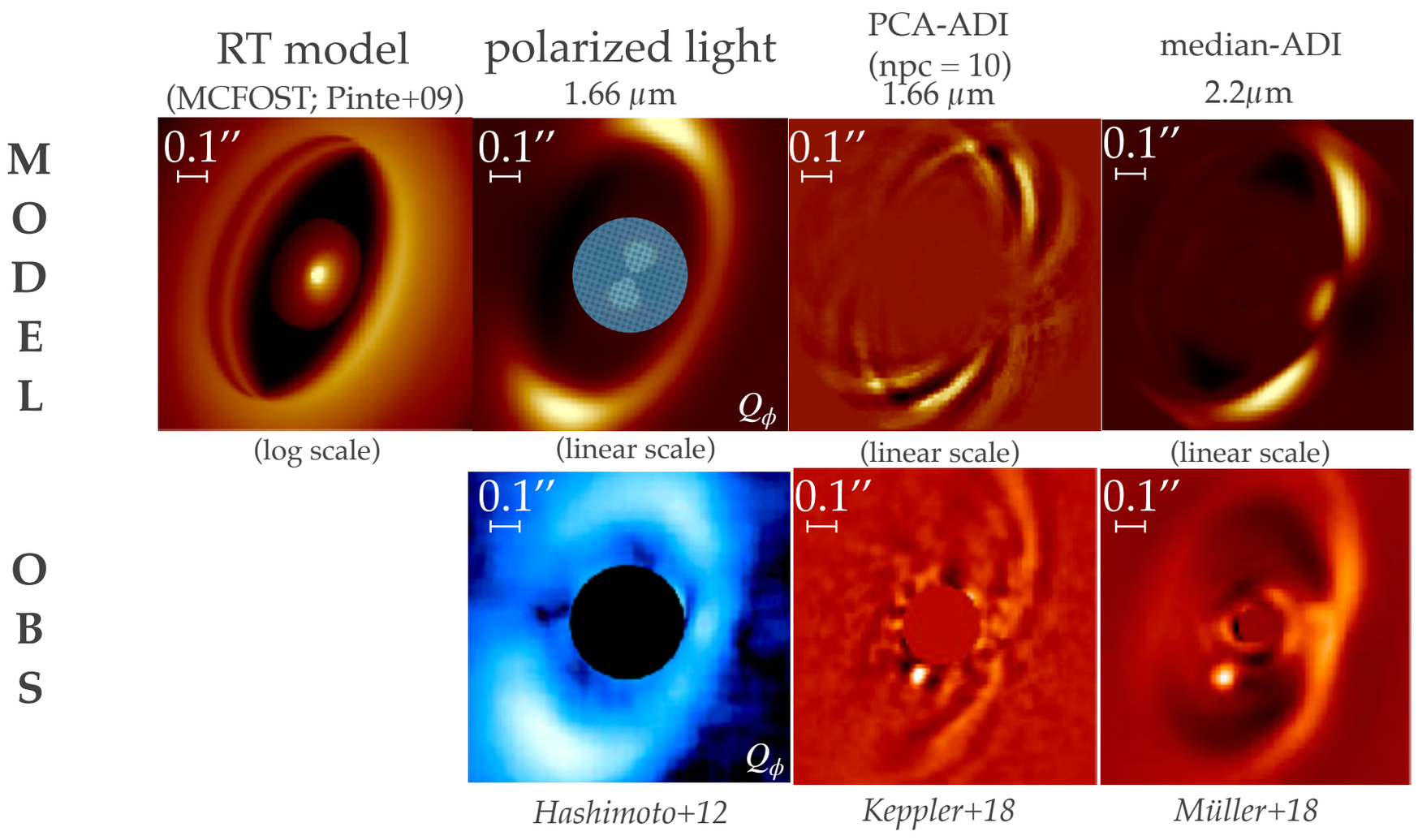


Hashimoto+12

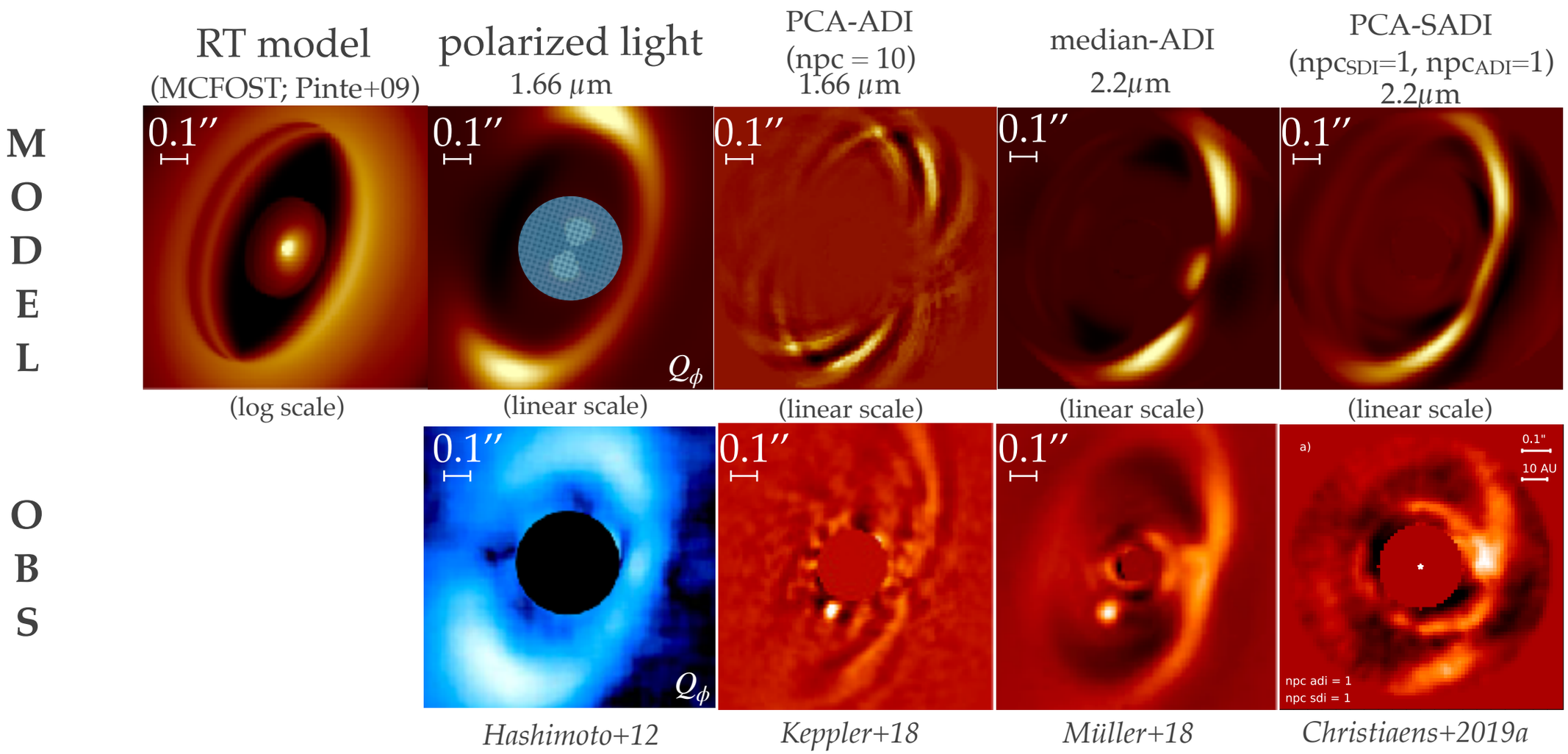
Processing of MCFOST model



Processing of MCFOST model



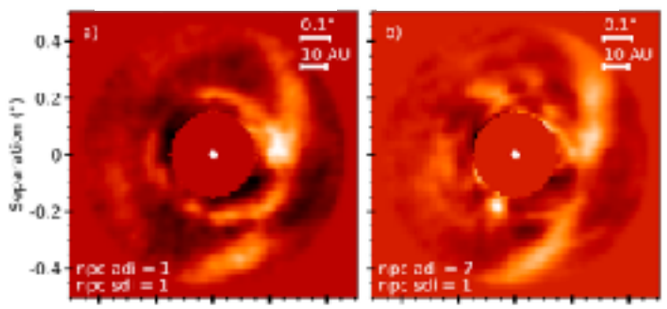
Processing of MCFOST model



Forward modeling

Christiaens+2019a

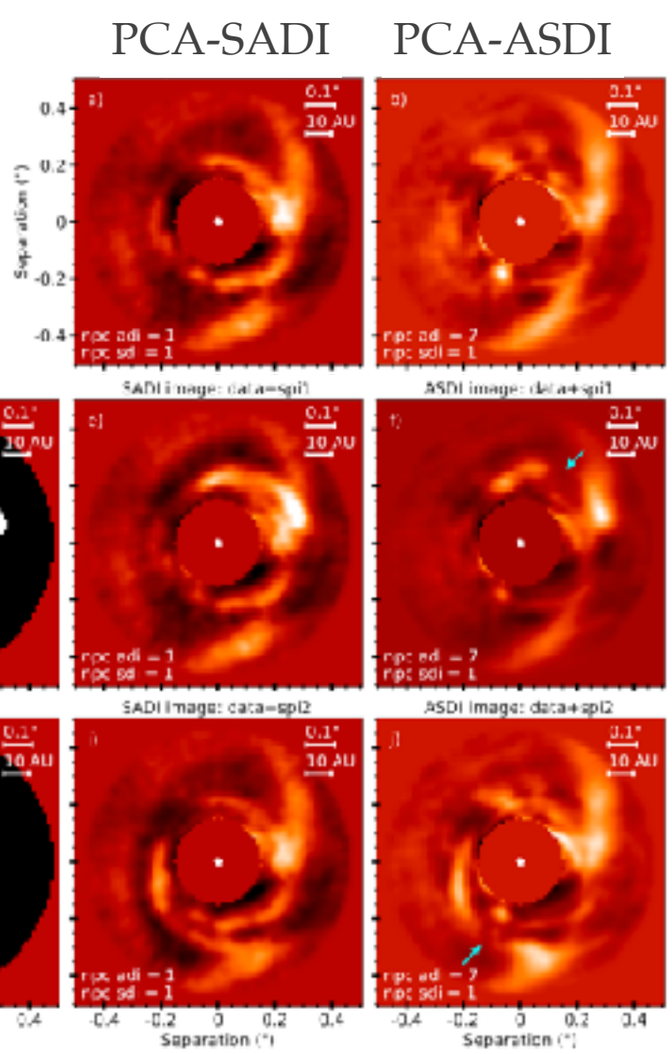
PCA-SADI PCA-ASDI



Forward modeling

Christiaens+2019a

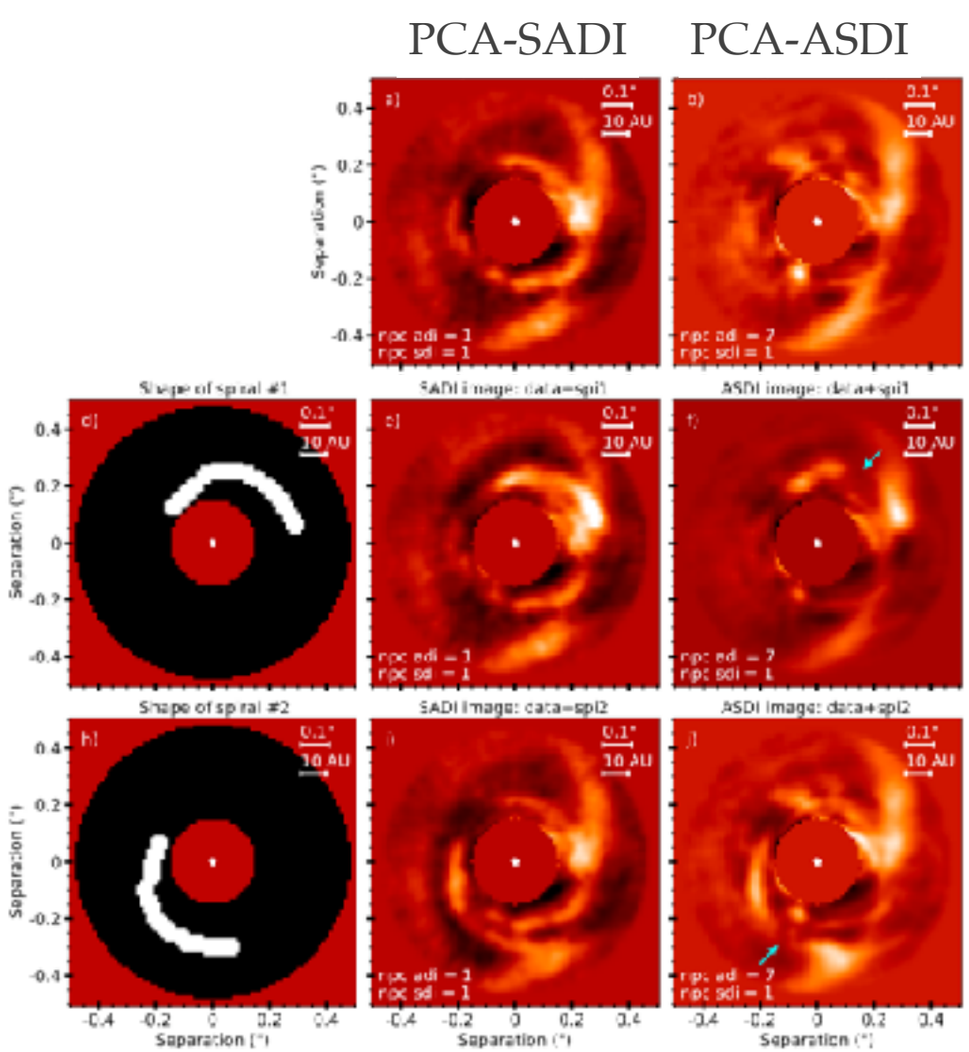
Synthetic spiral injections



Forward modeling

Christiaens+2019a

Synthetic spiral injections

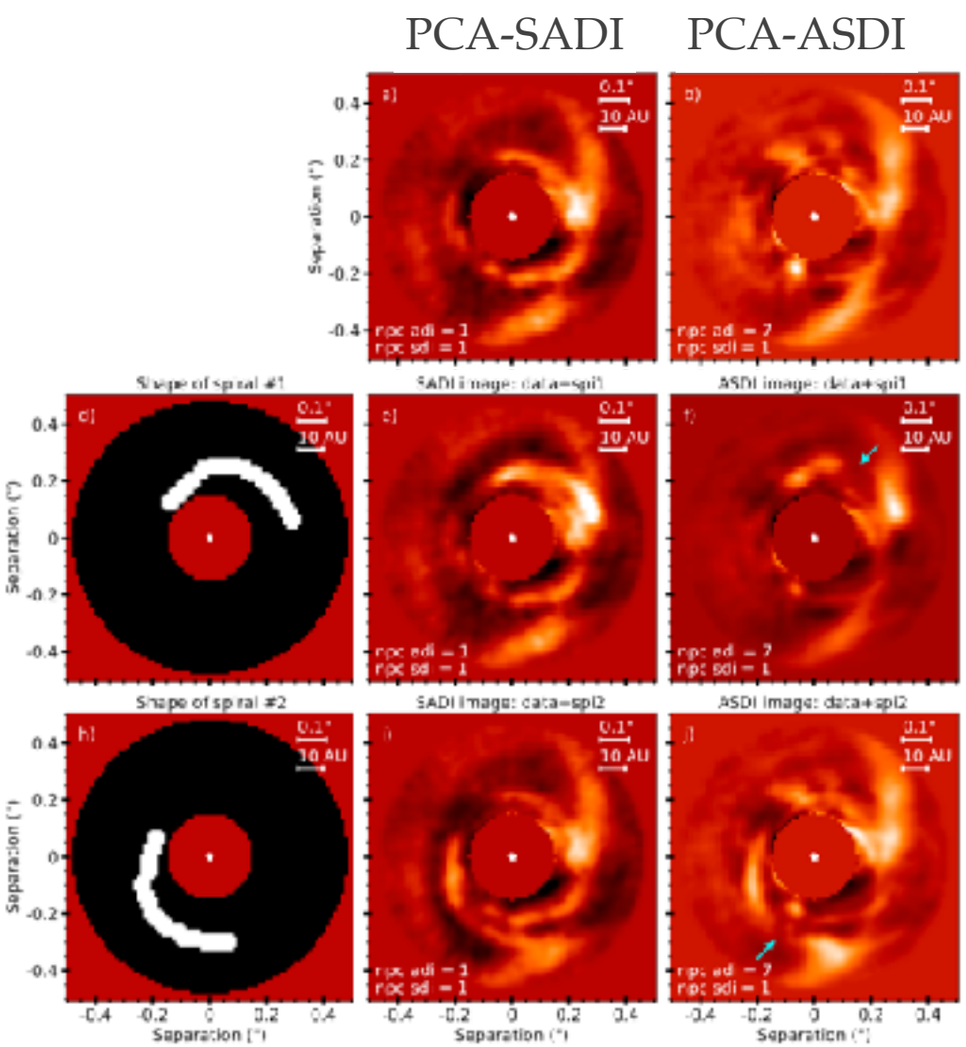


=> PCA-SADI recovers better azimuthally extended structures

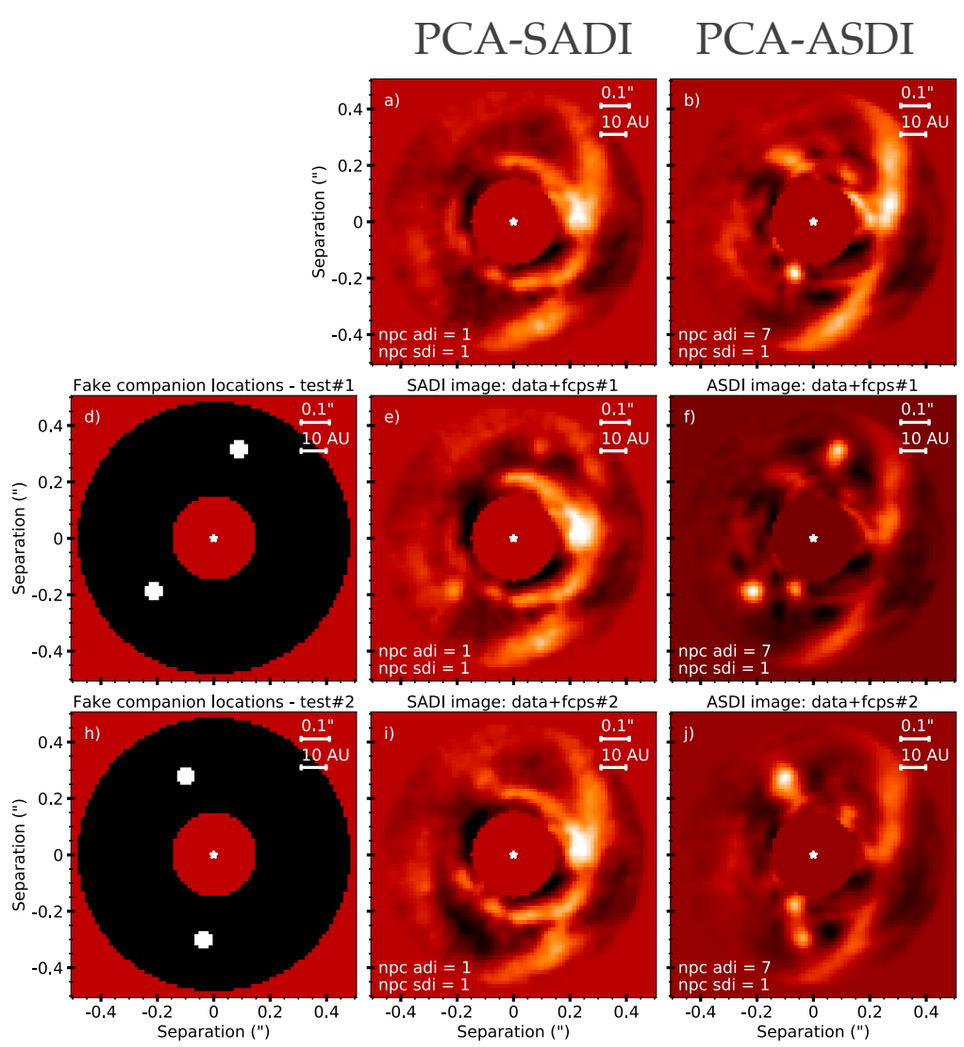
Forward modeling

Christiaens+2019a

Synthetic spiral injections



Fake companion injections

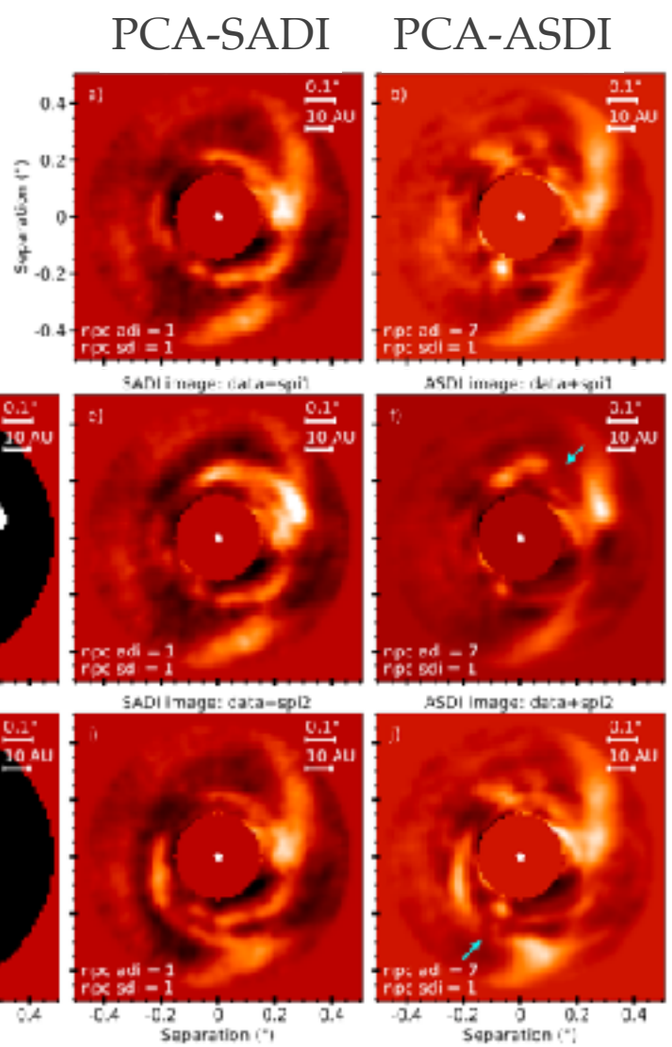


=> PCA-SADI recovers better azimuthally extended structures

Forward modeling

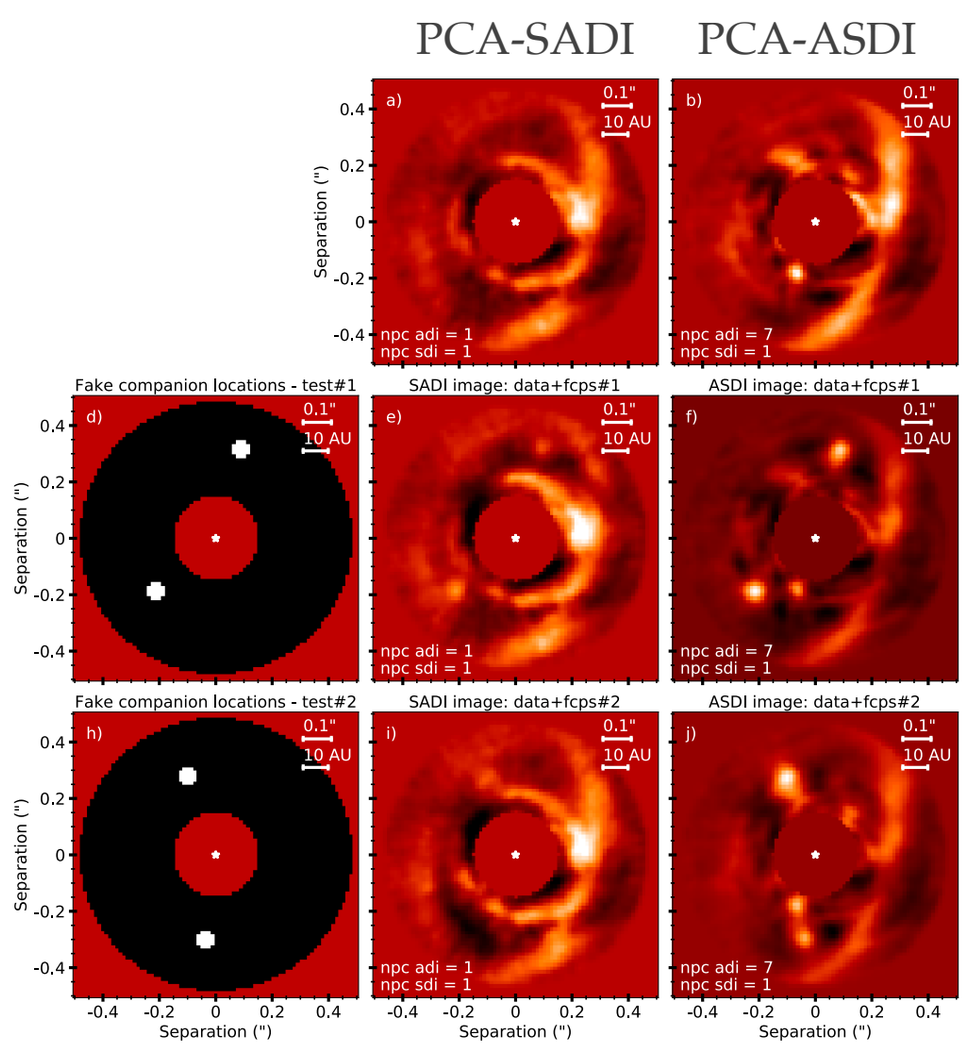
Christiaens+2019a

Synthetic spiral injections



=> PCA-SADI recovers better <u>azimuthally extended structures</u>

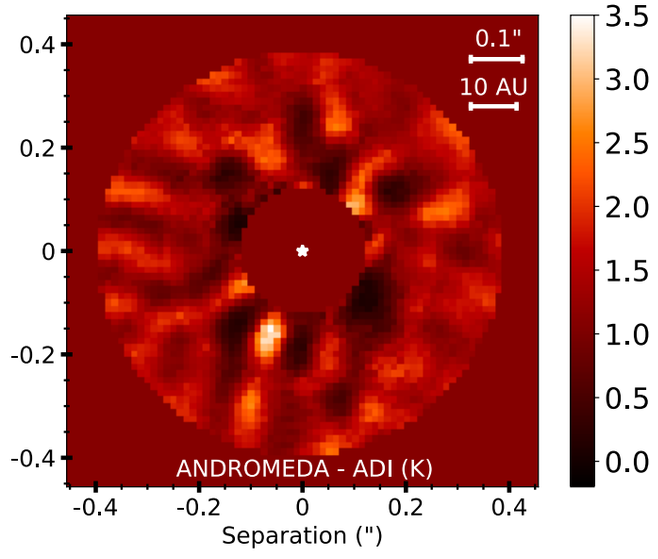
Fake companion injections



=> PCA-ASDI recovers better <u>point sources</u>

ANDROMEDA detection

(Mugnier+2009; Cantalloube+2015)

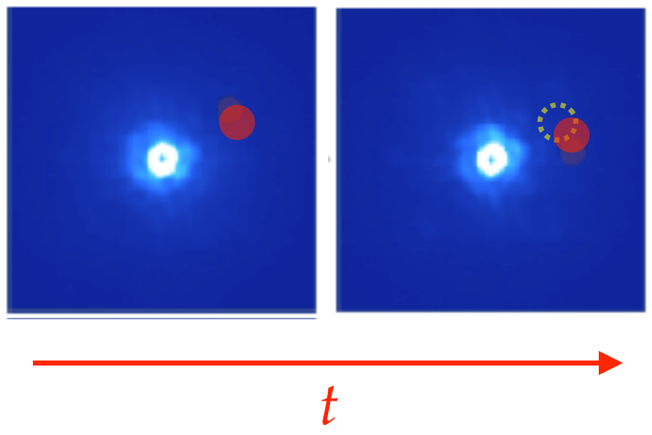


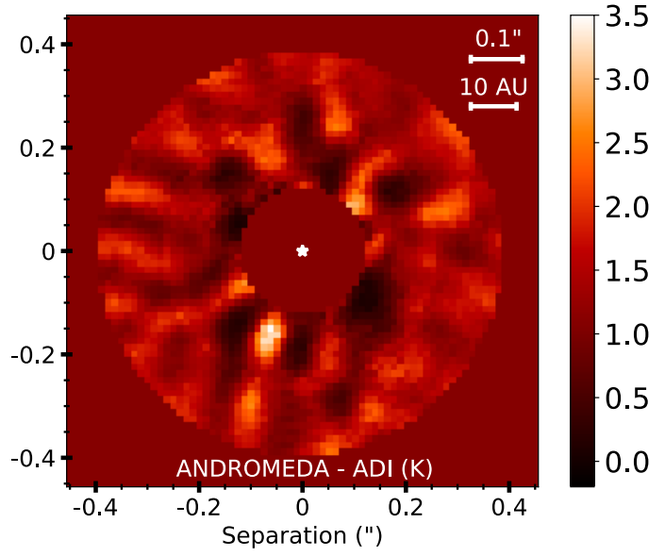
Christiaens+2019a

ANDROMEDA detection

(Mugnier+2009; Cantalloube+2015)

Pairwise subtraction
of frames with
~0.5 FWHM rotation



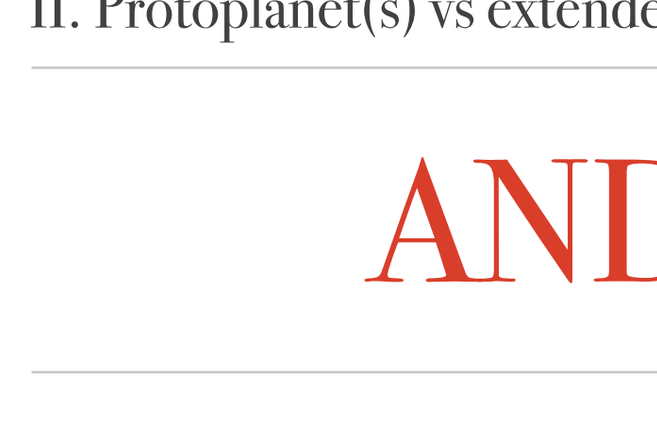


Christiaens+2019a

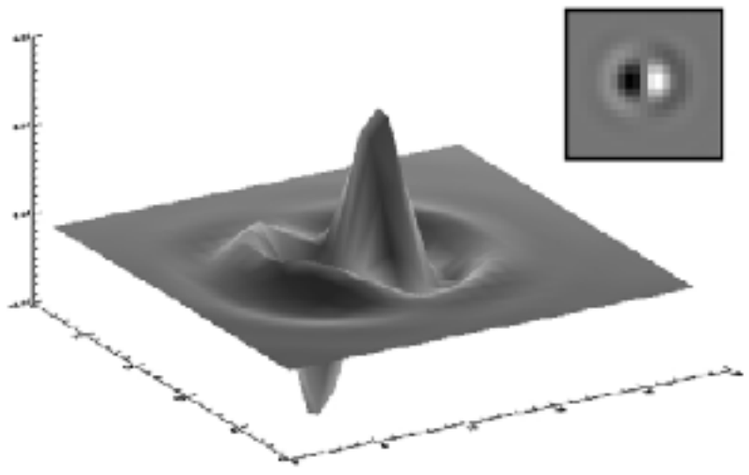
ANDROMEDA detection

(Mugnier+2009; Cantalloube+2015)

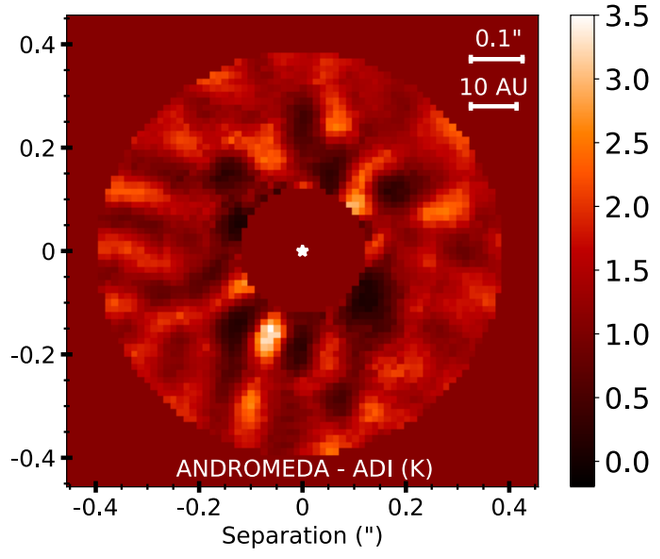
Pairwise subtraction of frames with ~0.5 FWHM rotation



Maximum match-filter in the residual images



$$L(\mathbf{r}_0, a) \propto \exp\{-\frac{1}{2}\sum_k \sum_{\mathbf{r}} \frac{|\Delta(\mathbf{r},k) - a\, p(\mathbf{r},k;\mathbf{r}_0)|^2}{\sigma_\Delta^2(\mathbf{r})}\}$$



Christiaens+2019a

ANDROMEDA detection

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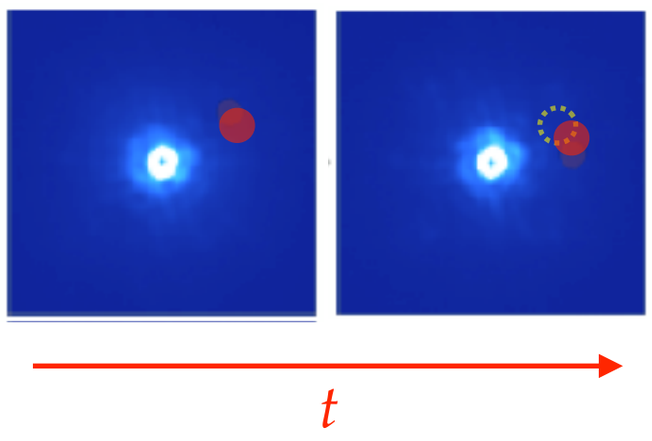
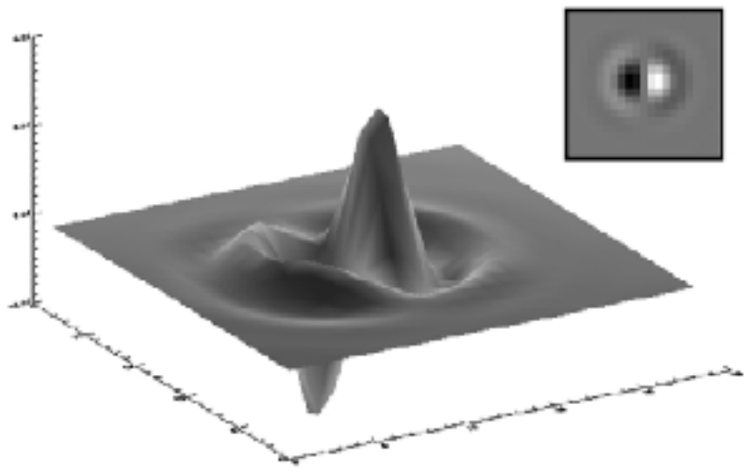
Pairwise subtraction of frames with ~0.5 FWHM rotation → Maximum match-filter in the residual images → Combination of all residual images → { Astrometry / Photometry, Detection SNR map





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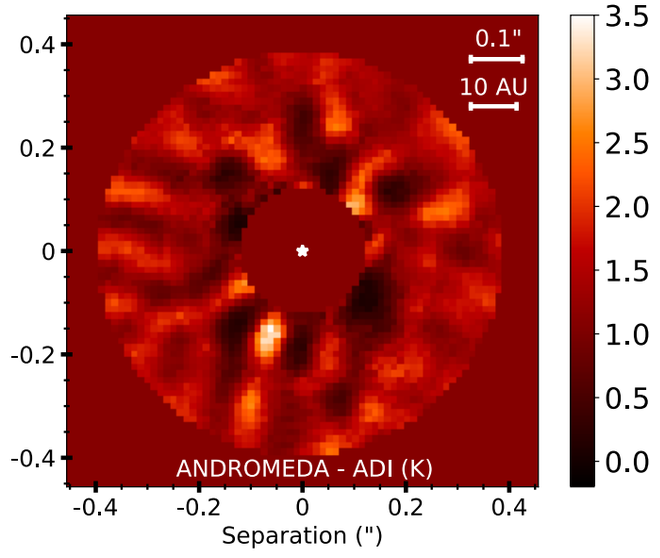
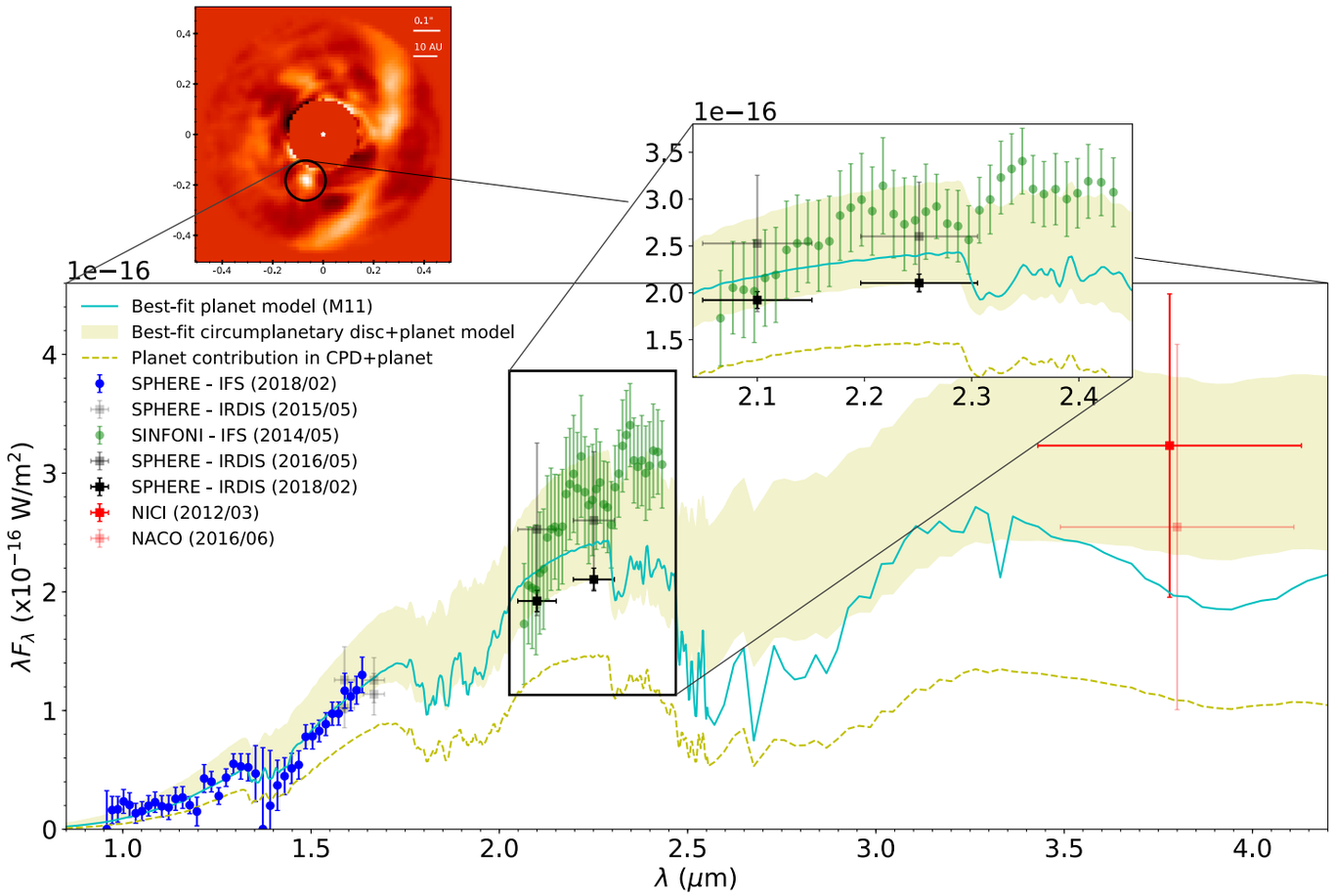


Christiaens+2019a

IR excess around PDS 70 b

Christiaens+2019b



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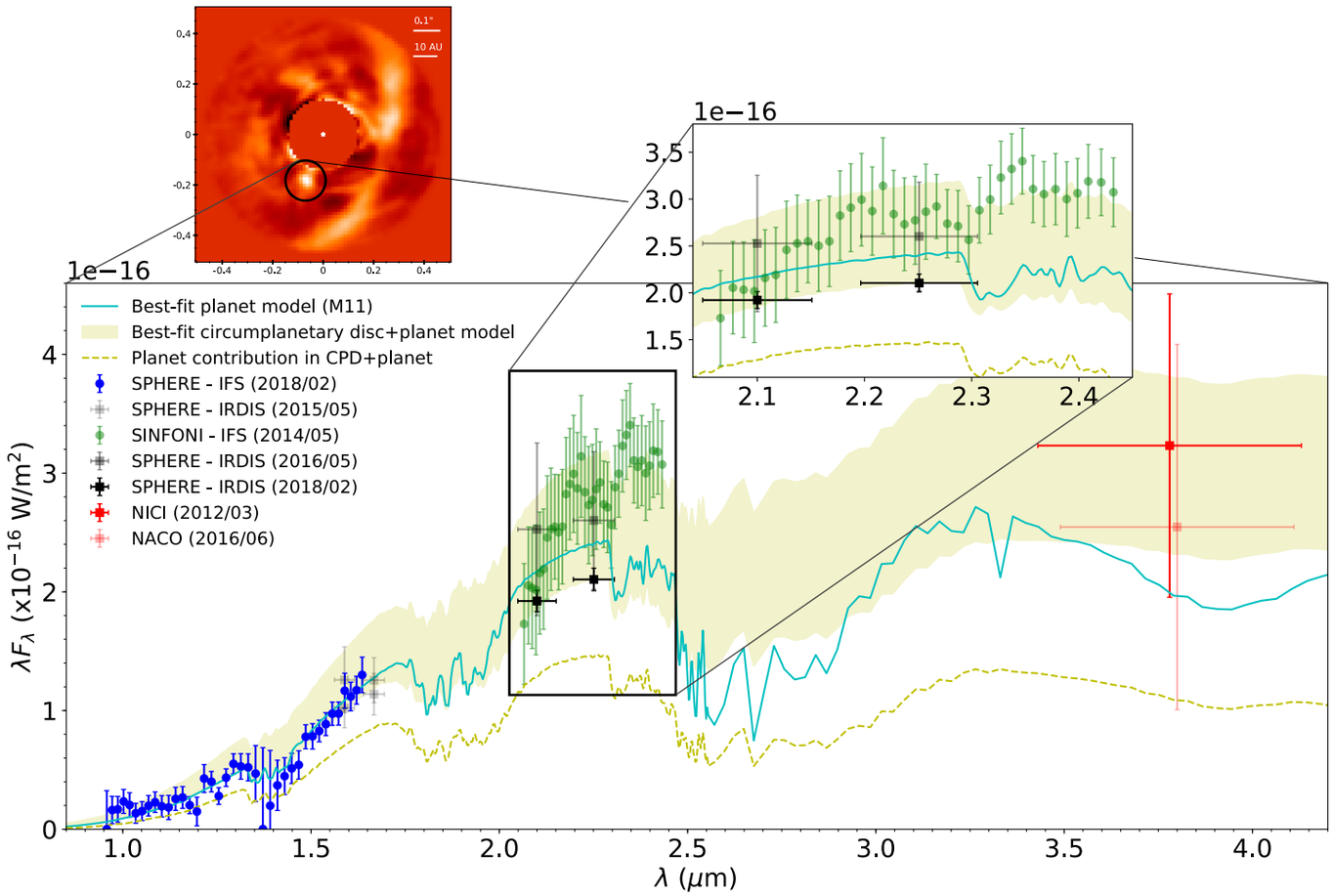

Planet only

- T_{eff}~**1100–1500 K**
- log(g)~**3.0–4.0**
- R_b~**2.2–3.3 R_J**
- A_V~**3–4 mag**
- M_b~**1.9–42 M_J**

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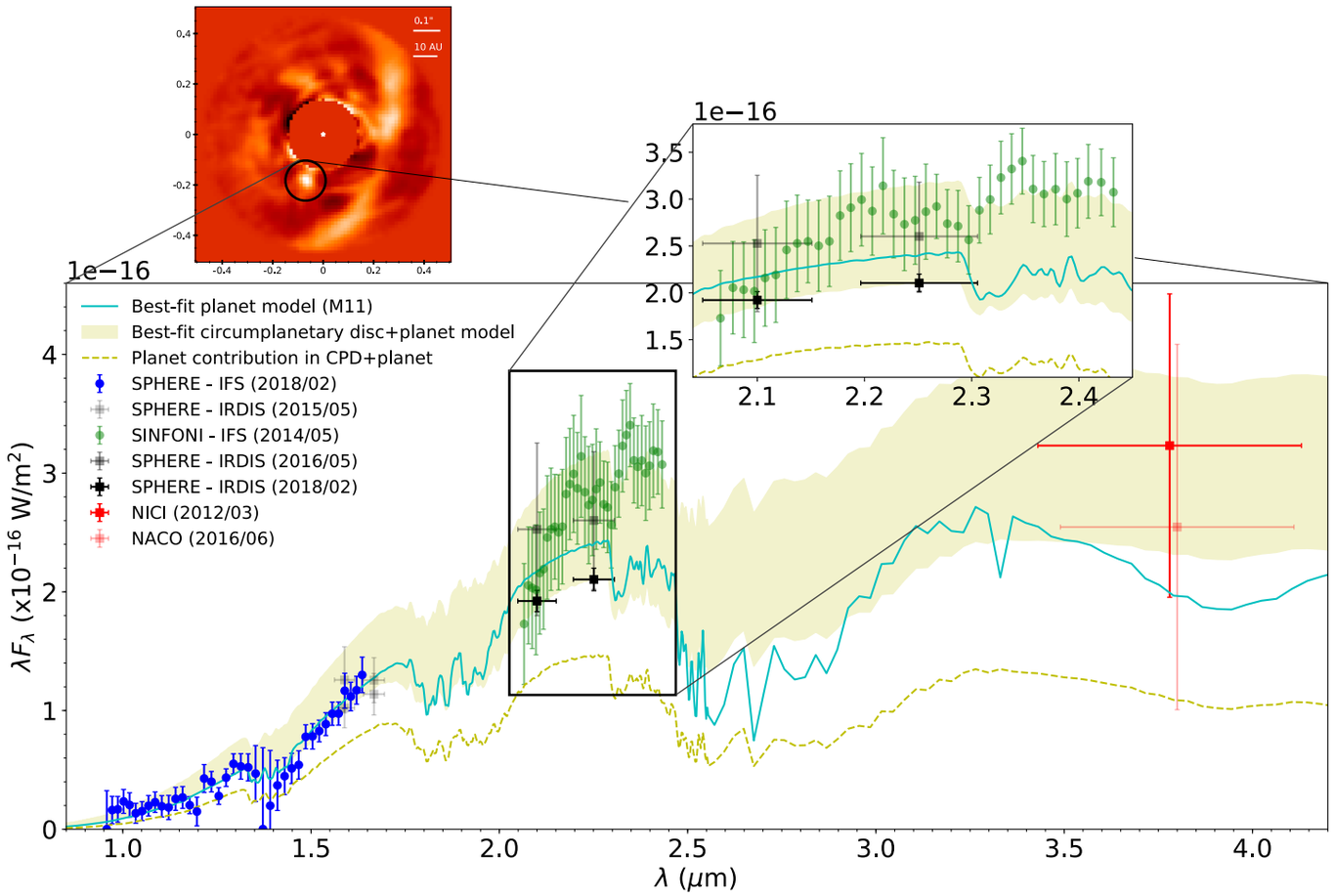
Christiaens+2019b



Planet only	Planet+CPD
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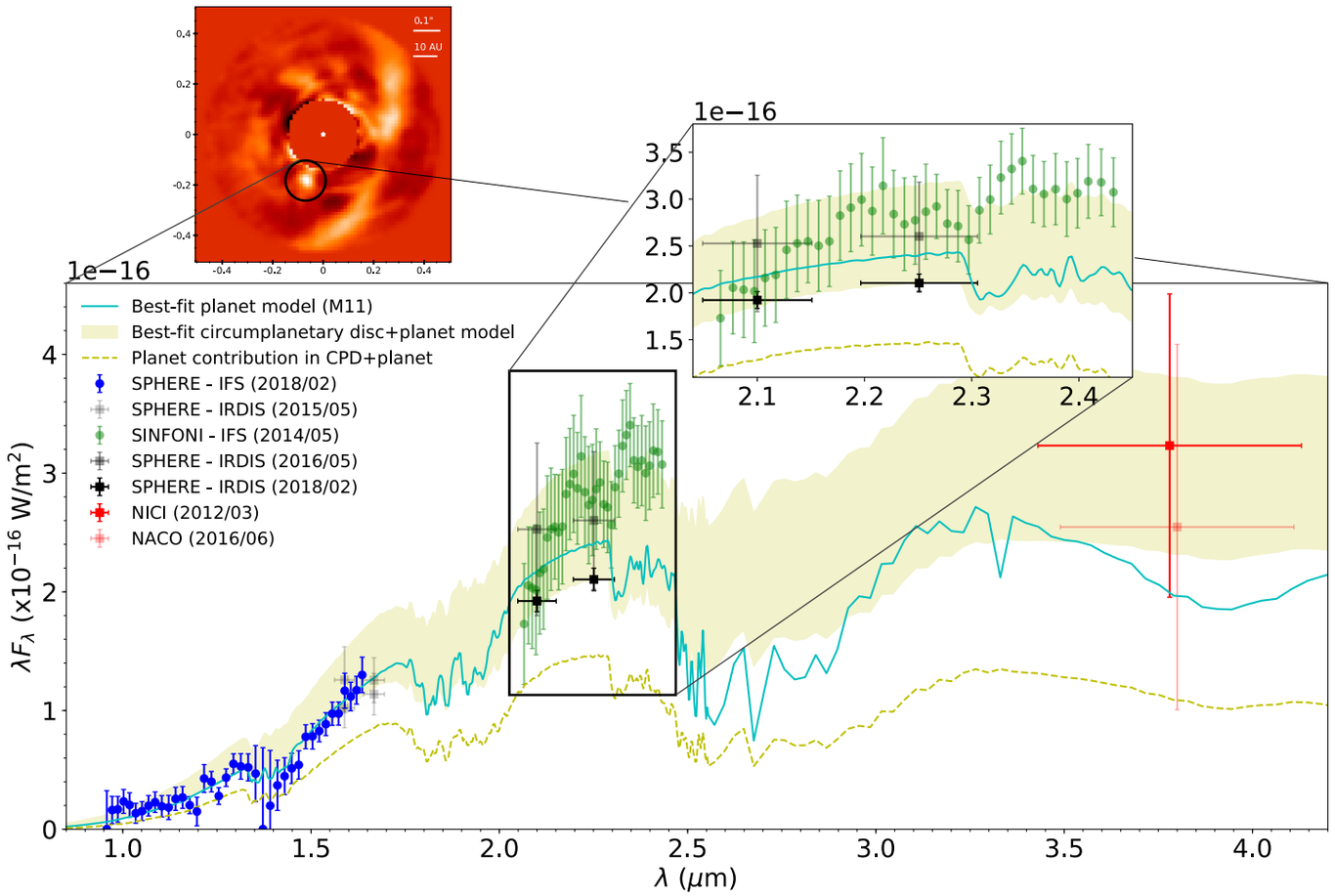
Christiaens+2019b



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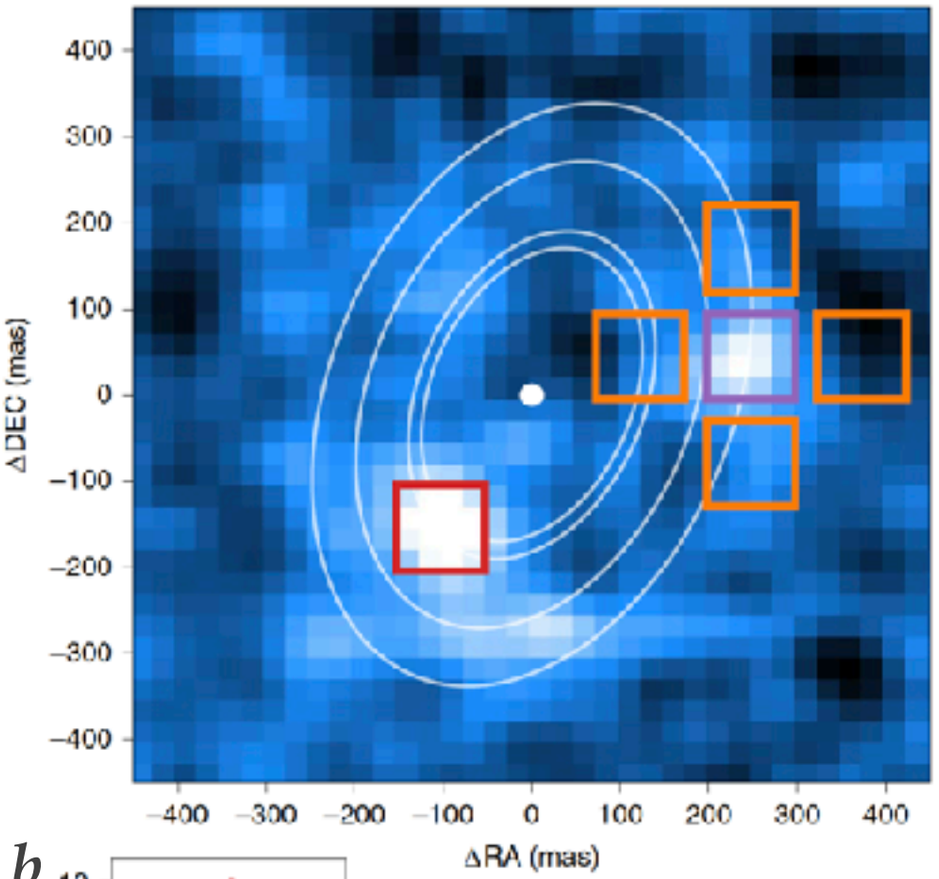
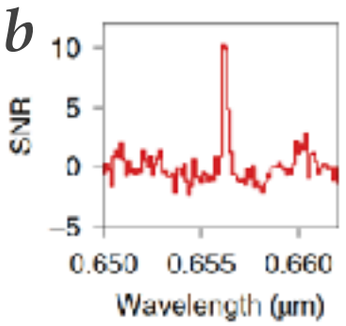
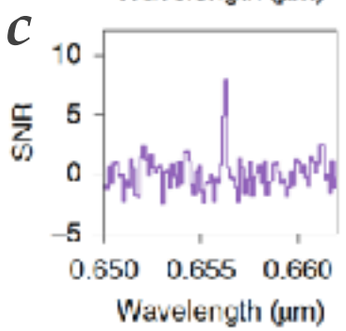
=> ~10 M_{Jup} with CPD?

PDS 70 b and c

Haffert+2019







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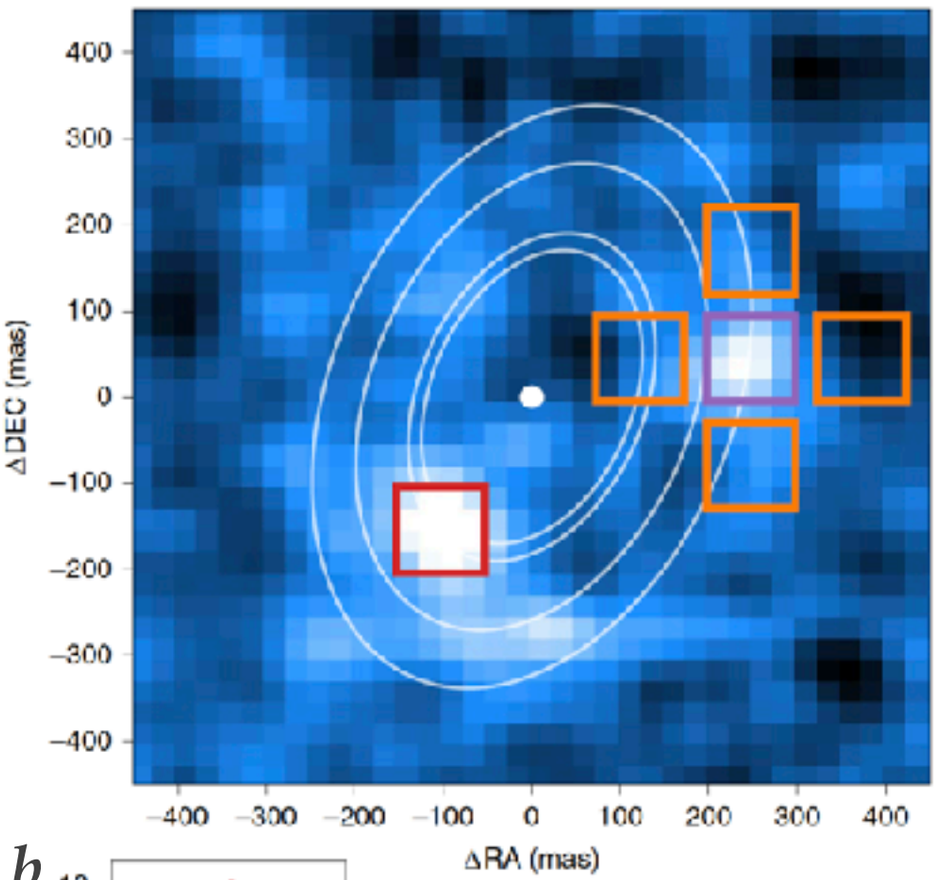

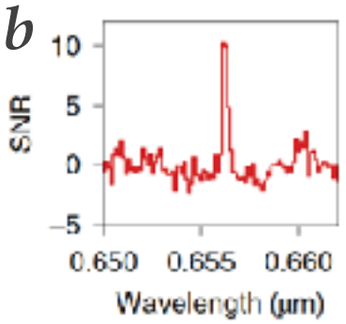

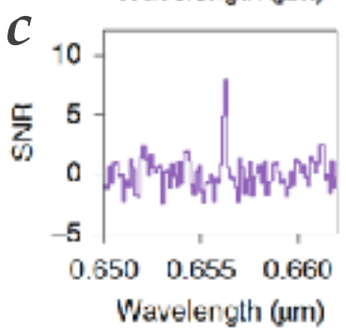

Observable	star		*b*	*c*
Redshift w.r.t star	/	≠	25 km s^{-1}	30 km s^{-1}
Line width	147 km s^{-1}	>	123 km s^{-1}	102 km s^{-1}
Line shape	inverted P-Cygni	≠	Gaussian	Gaussian

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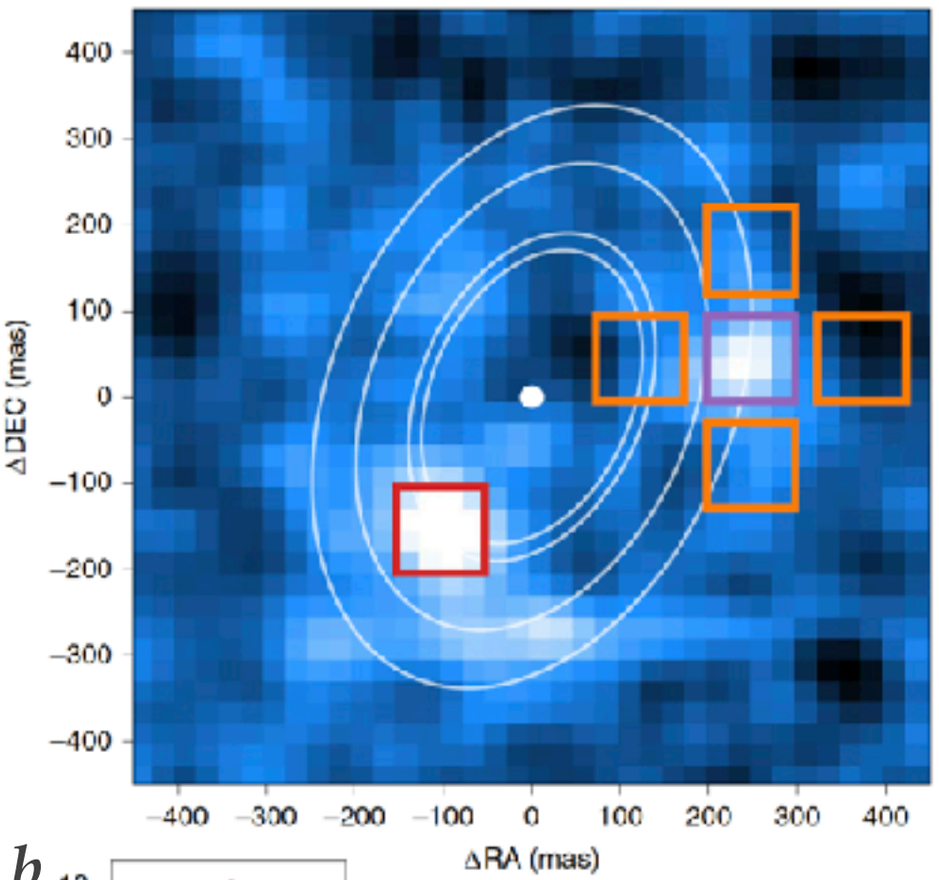
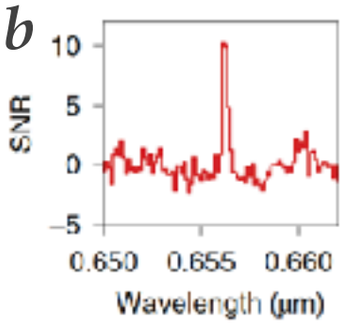
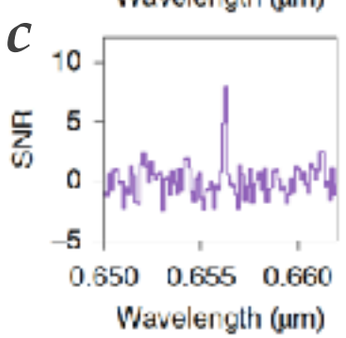
Haffert+2019







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PDS 70 b and c

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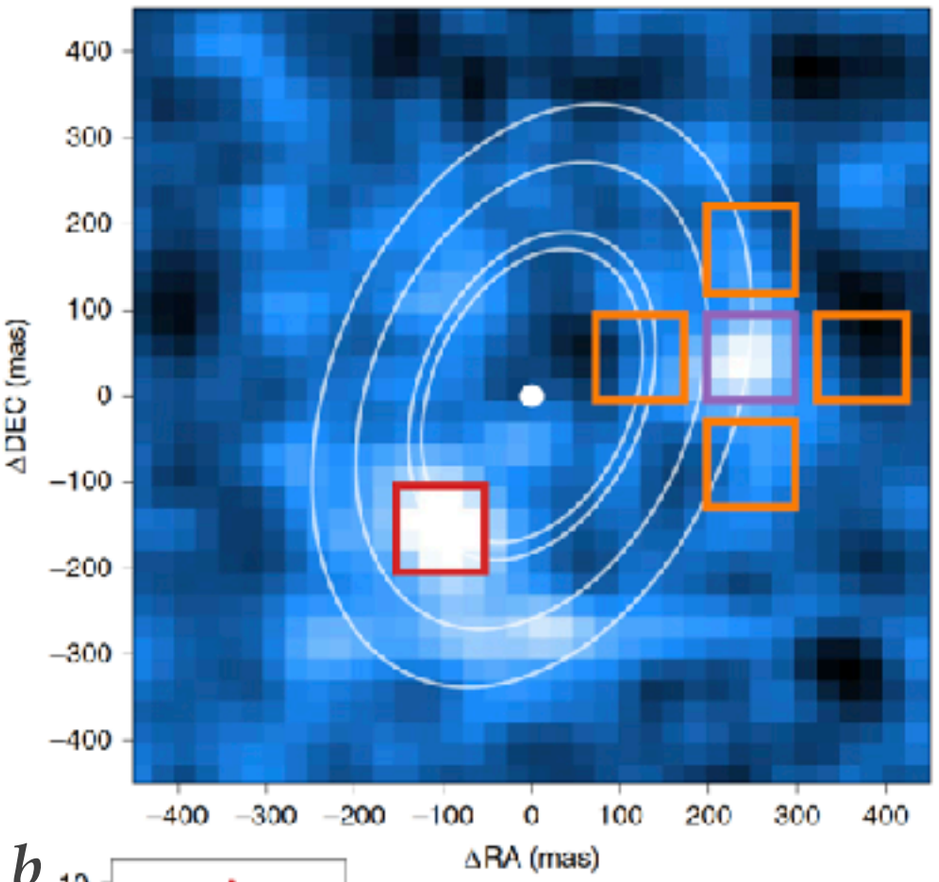

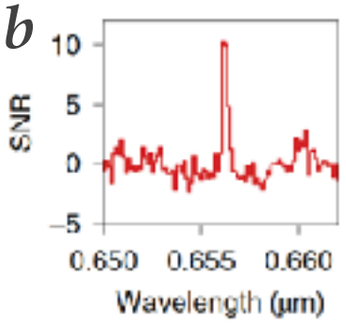

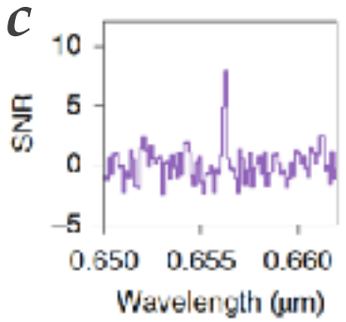

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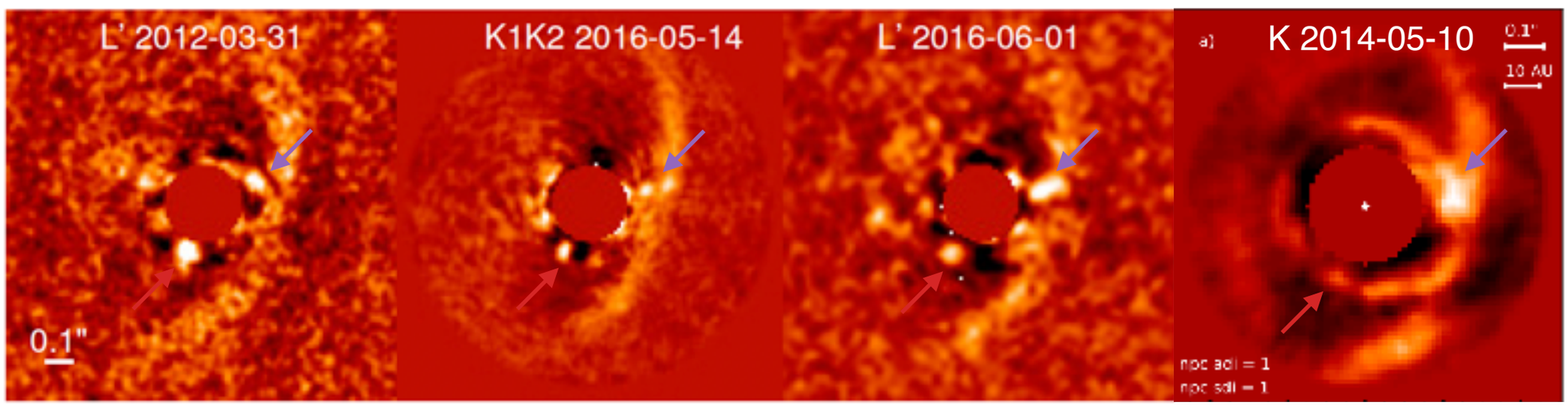

Keppler+2018

Christiaens+2019a

PDS 70 b and c

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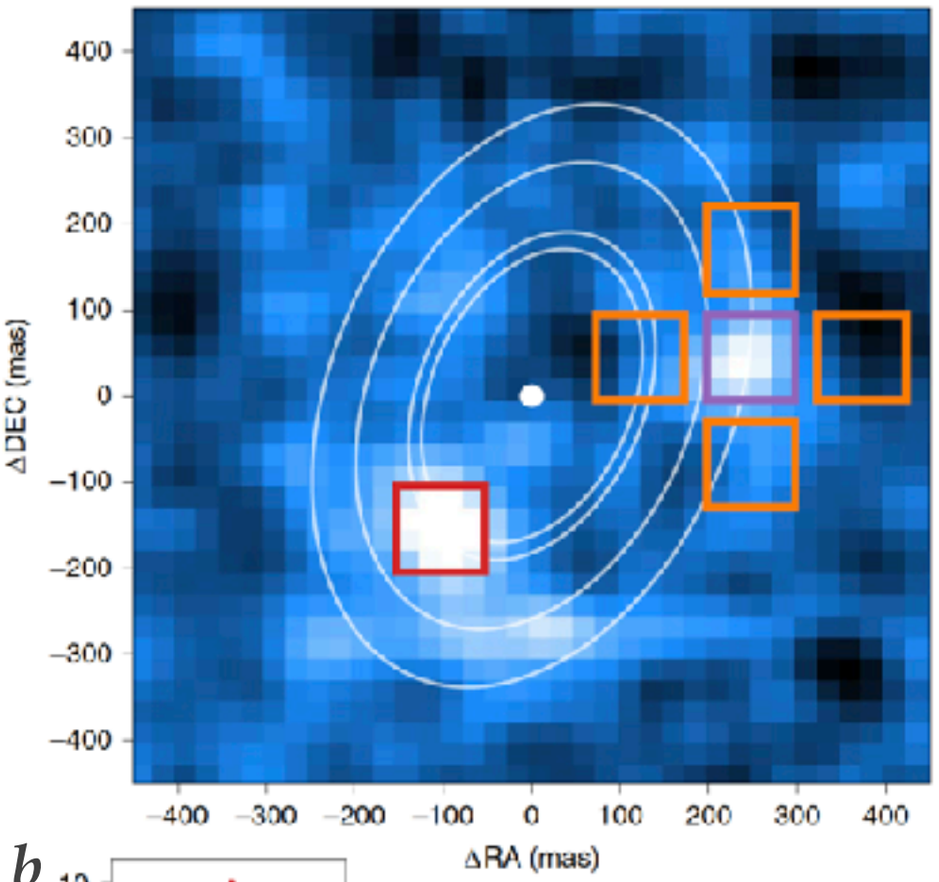

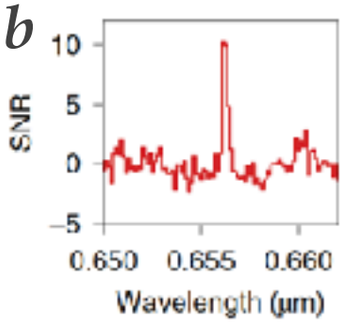

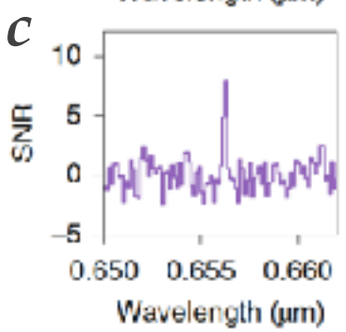

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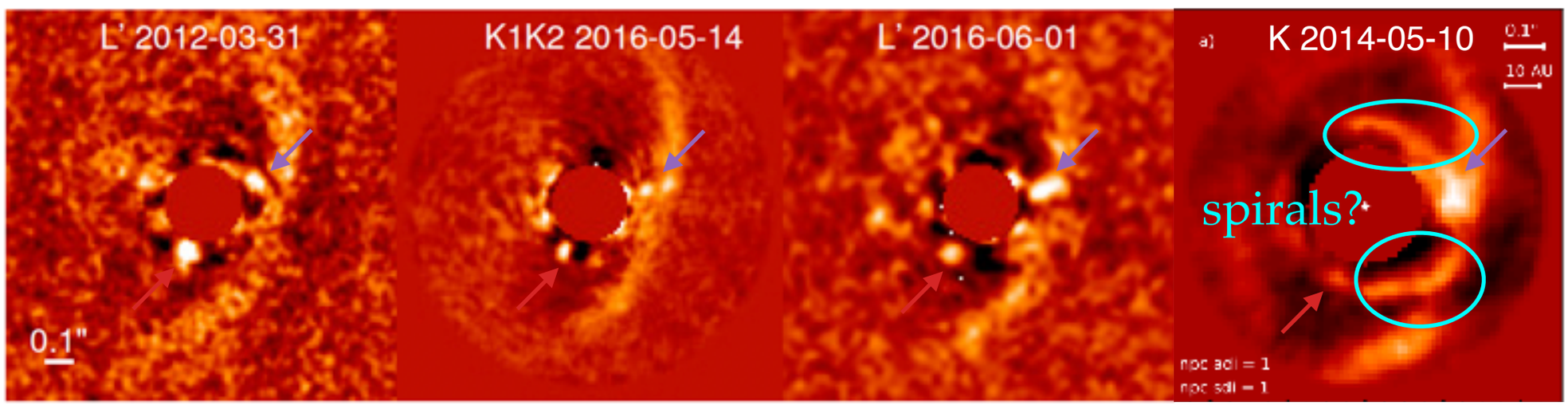
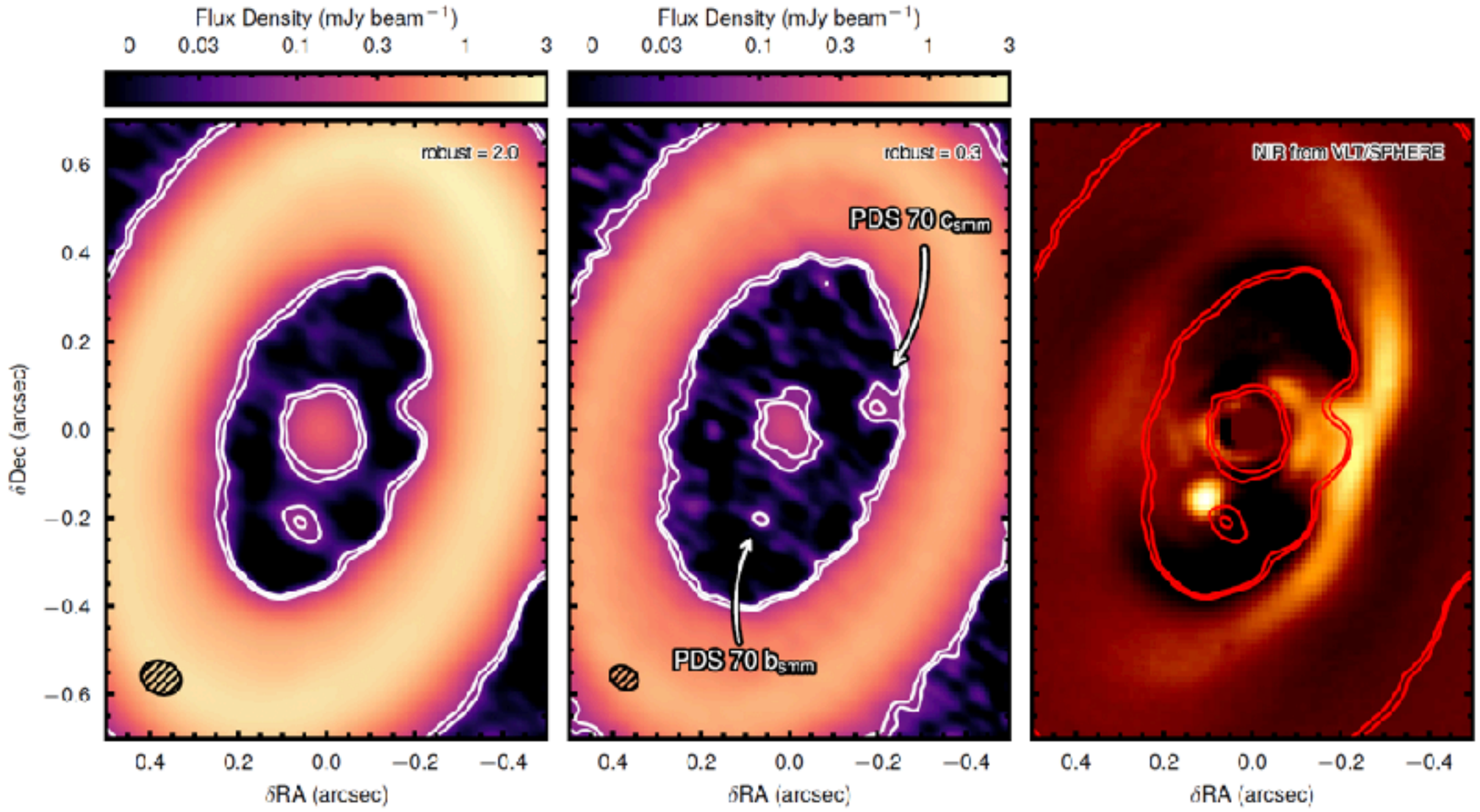


Keppler+2018

Christiaens+2019a

sub-mm CPD(s)?

Isella+2019



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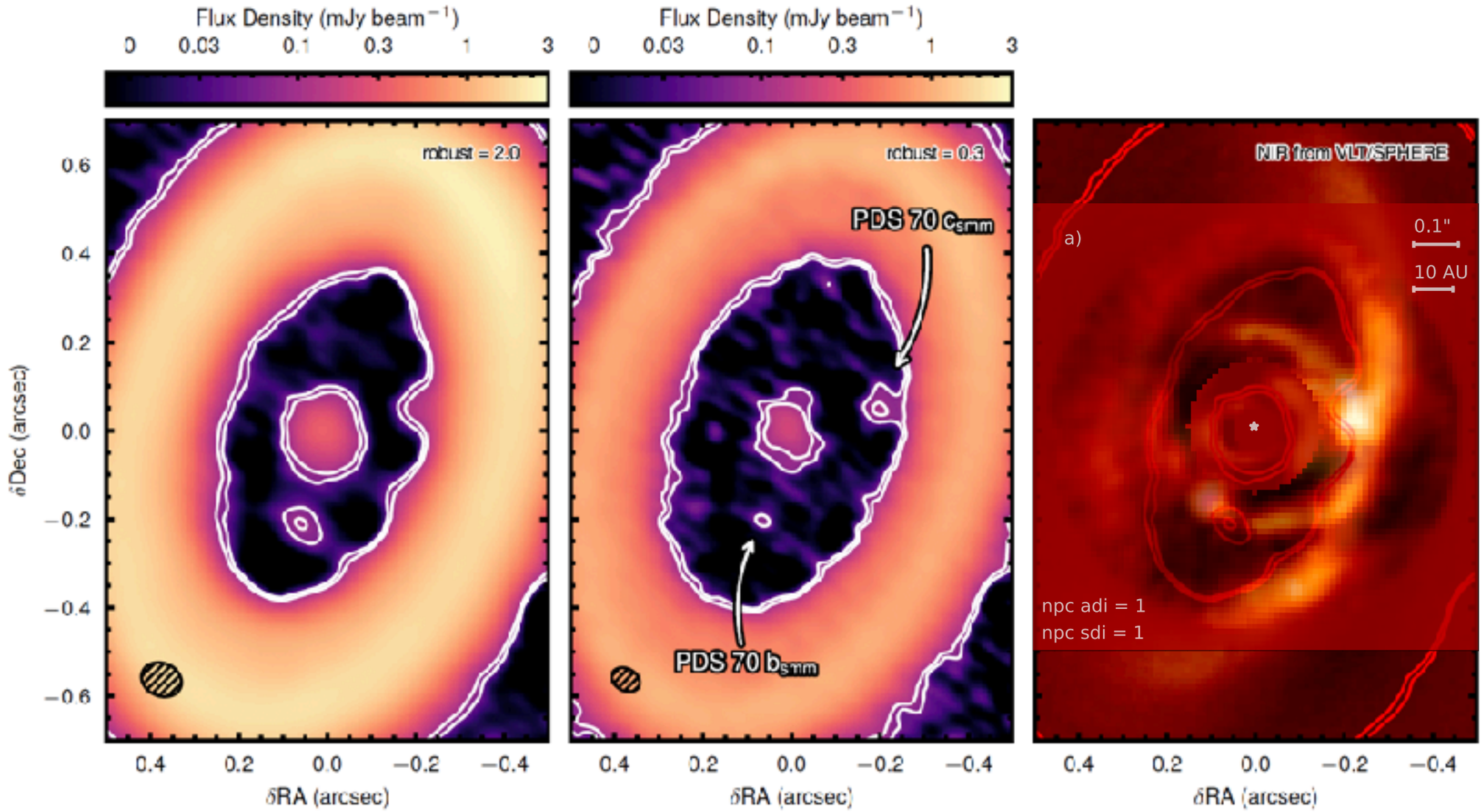

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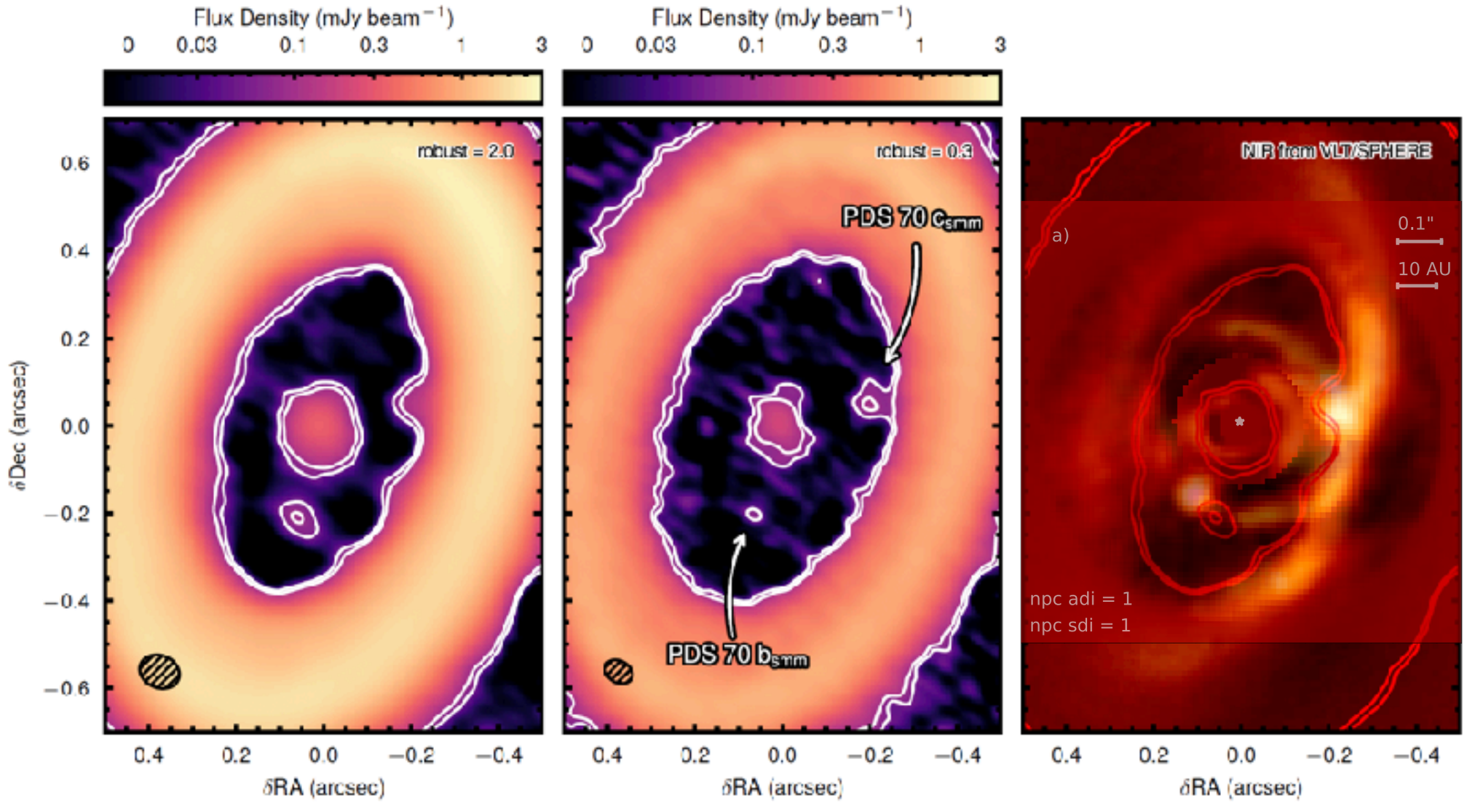

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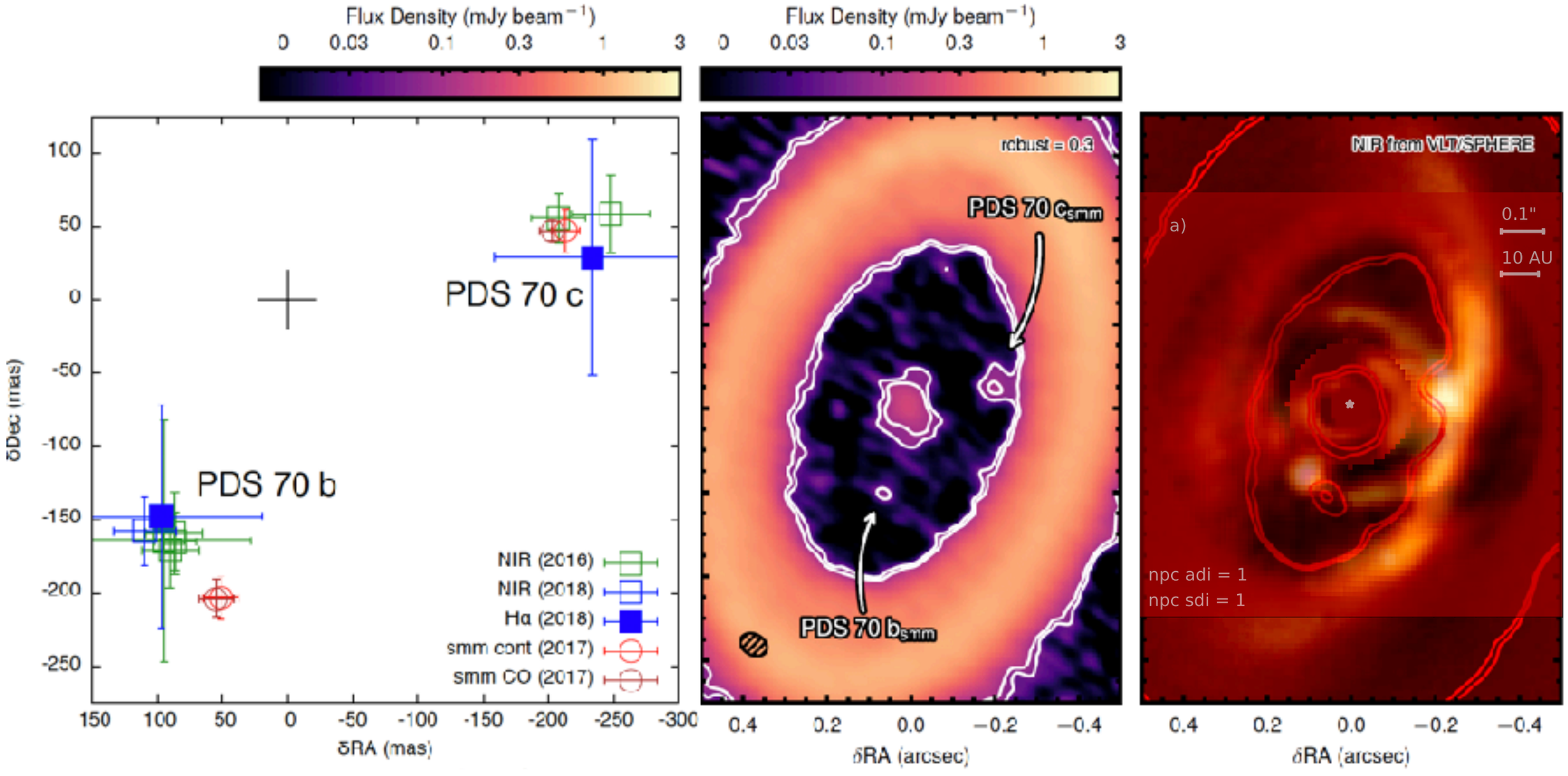

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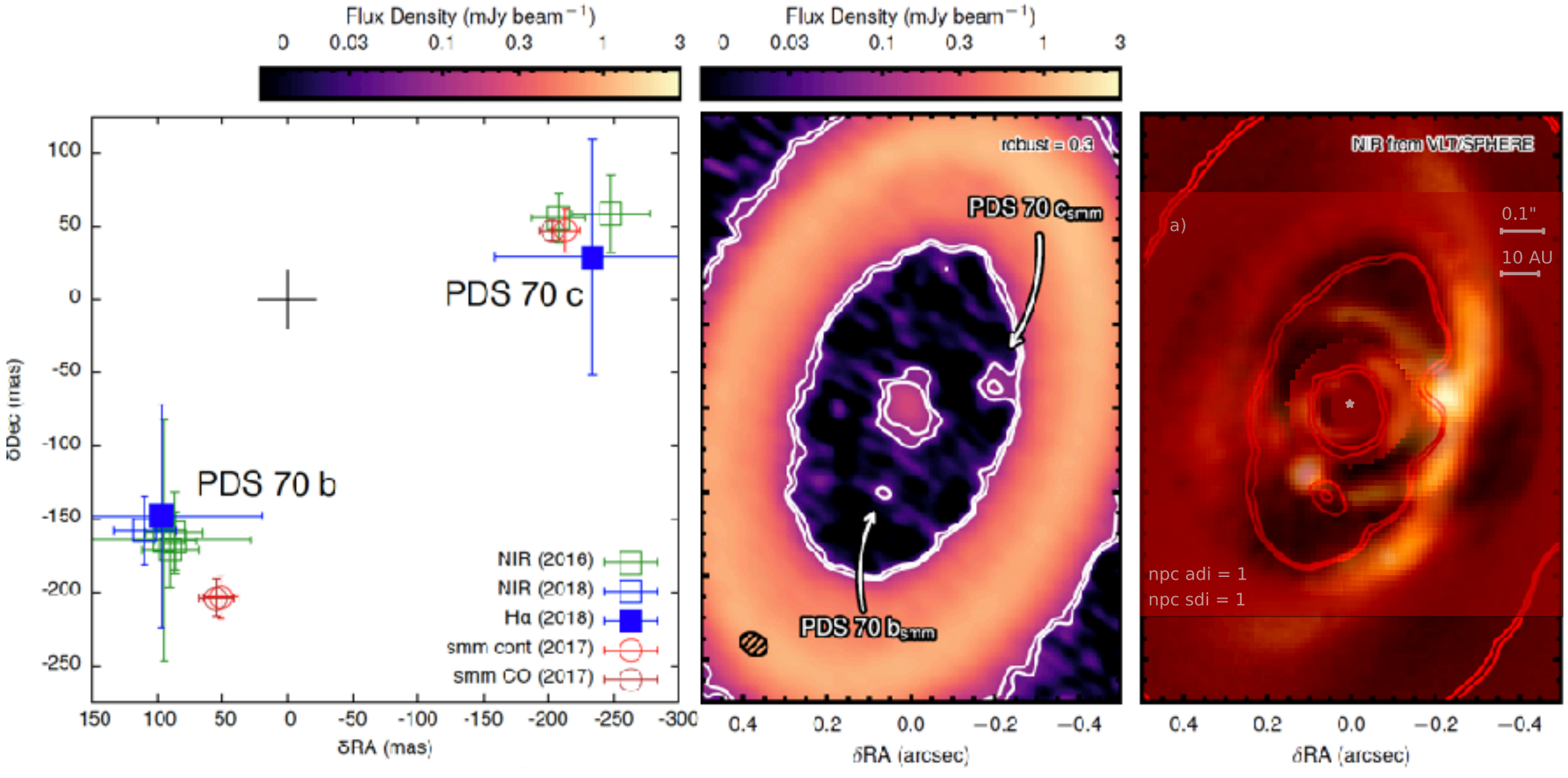
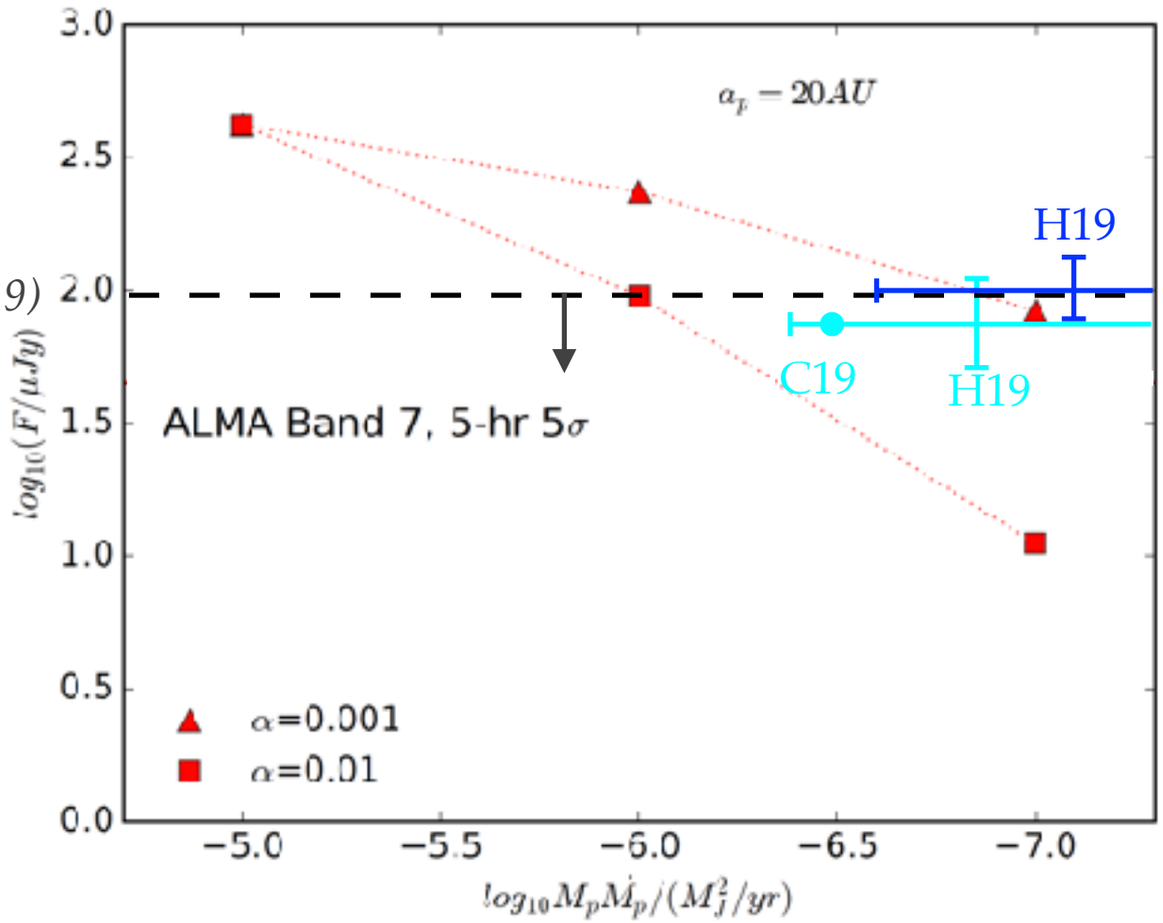


- Why is b shifted in sub-mm and IR?!
  - Star not at centre of the disc?
  - IR/Hα signals trace a jet from the protoplanet? (as protostars; Hartigan+11)
  - Sub-mm clump traces tip of the spiral?

Constraints on the CPD

- α?



5σ (Isella+2019)

Zhu+2018

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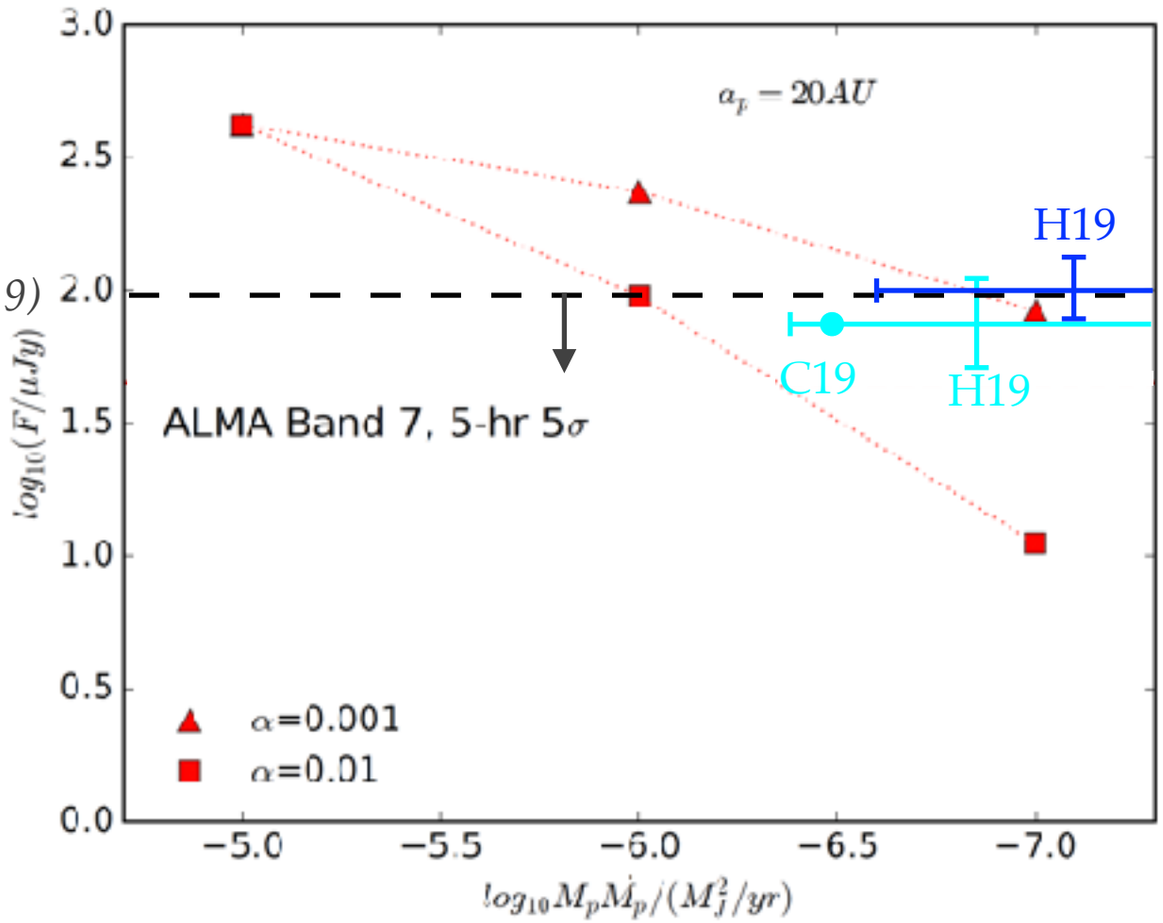

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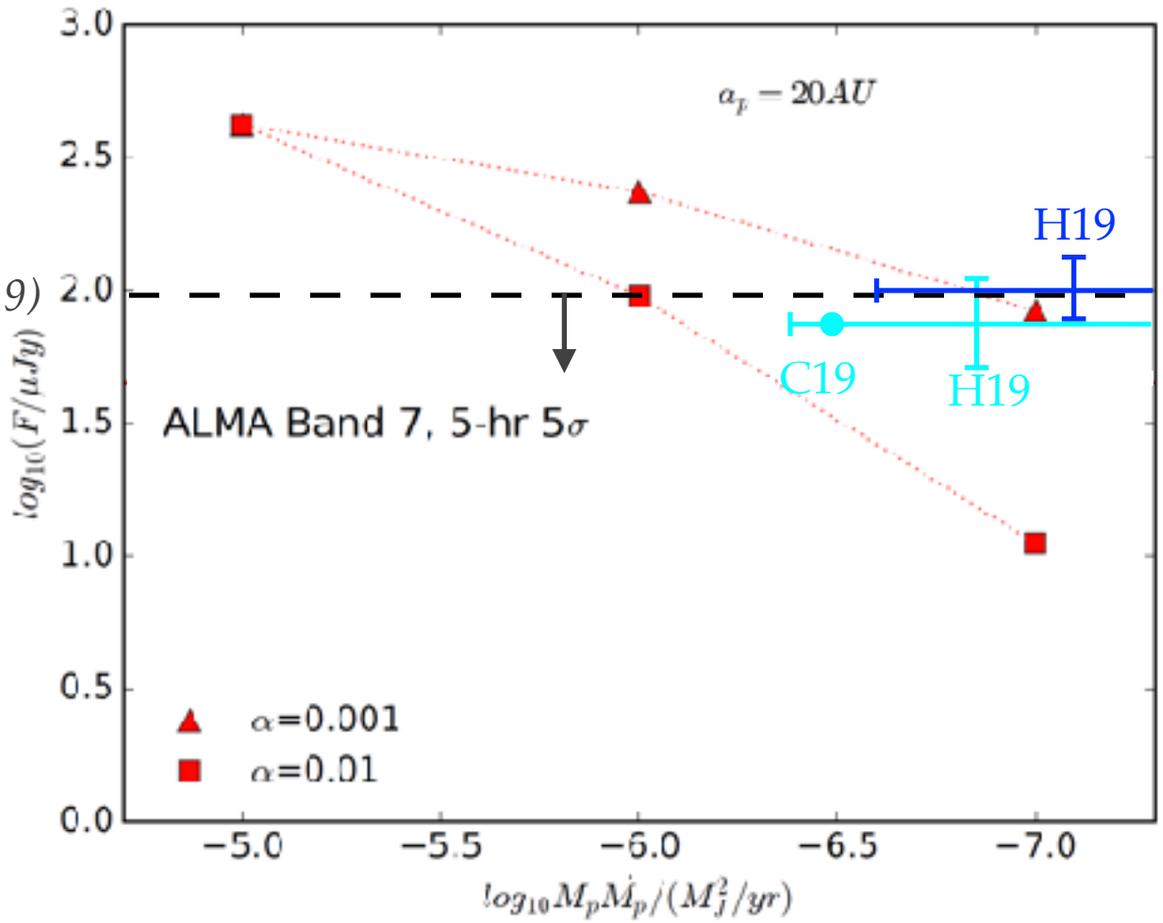

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- Mass?
  - Mass of $CPD_b \sim 1.8 - 3.2 \times 10^{-3} M_\oplus$ *(Isella+2019)*
  - Mass of $CPD_c \sim 2.0 - 4.2 \times 10^{-3} M_\oplus$ *(Isella+2019)*
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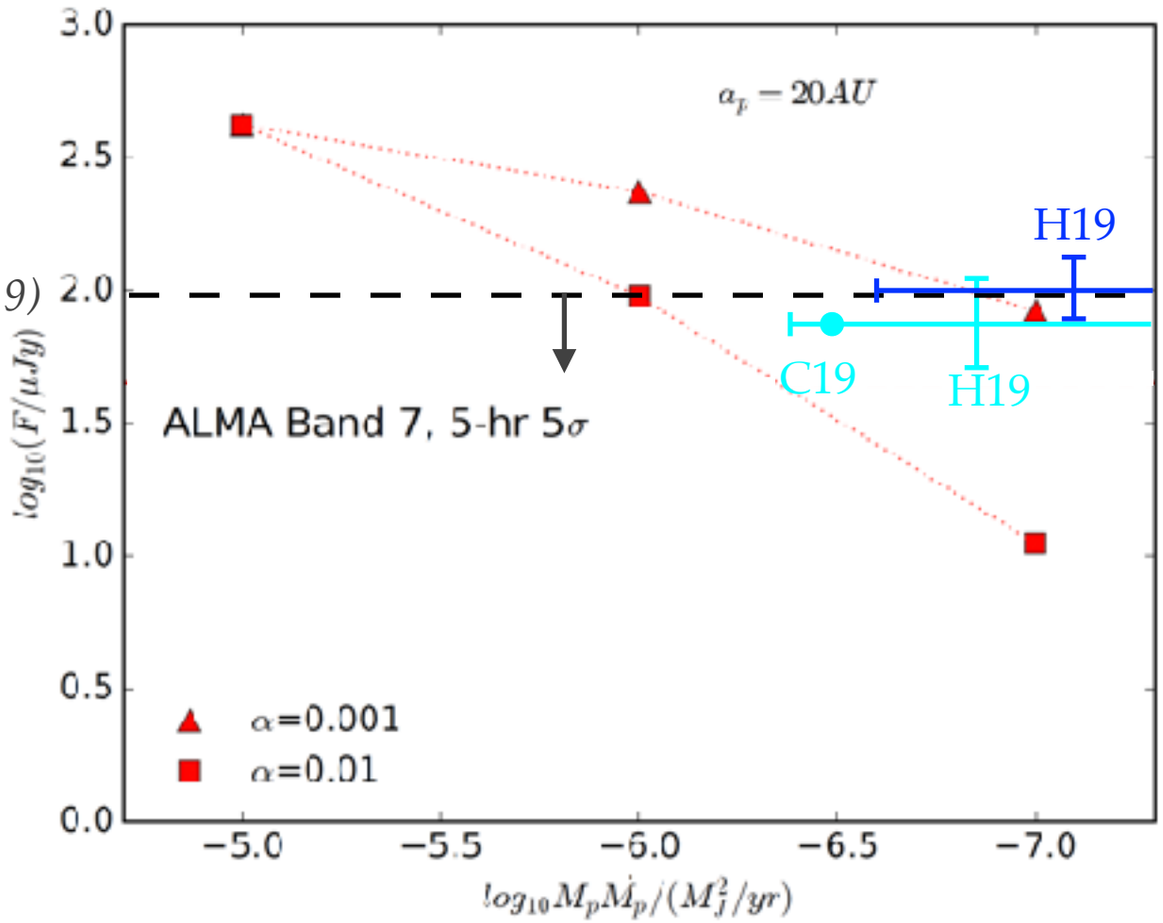

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=> Most of the CPD mass has been accreted already (almost formed planets)?
or CPD dust made mostly of small grains?

What's next?

- Search for Brγ in SINFONI data the same way as Hα in MUSE data (on-going)
  - Confirm mass accretion rate inferred with Hα (less extinction for Brγ)?
  - Study variability (at different timescales)!

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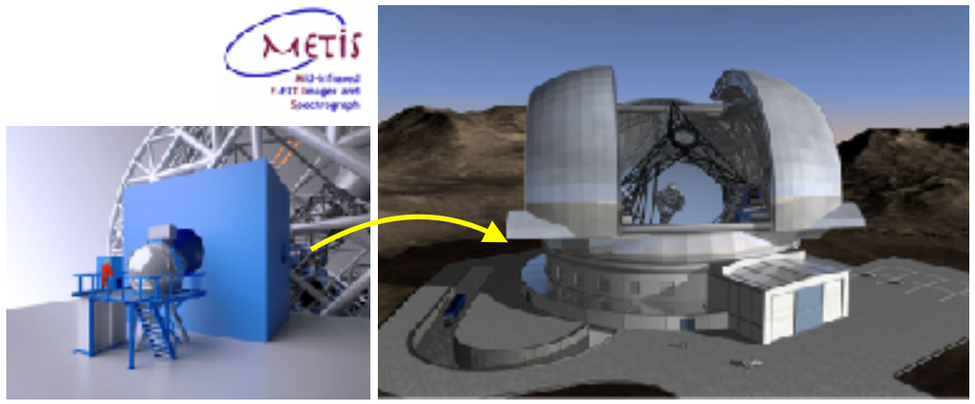
- ELT / METIS (2025)
  => mid-IR spectrum (3–20μm)!



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- a~**20.9 AU**
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Müller+2018

- a~**22.2 AU**
- e~**0–0.2**
- T_{eff}~**1000–1600 K**
- log(g)~**2.7–4.0**
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CPD_b

Christiaens+2019b

- $\dot{M}_b$~**$10^{-7.3}$–$10^{-7.8}$ M_J yr^{-1}**

Haffert+2019

- $\dot{M}_b$~**$10^{-7.3}$–$10^{-8.1}$ M_J yr^{-1}**

Isella+2019

- $M_{\mathrm{CPD}_b} \sim 1.8 - 3.2 \times 10^{-3} M_\oplus$?

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- $\dot{M}_b$~**$10^{-7.3}$–$10^{-7.8}$ M_J yr^{-1}**

Haffert+2019

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Isella+2019

- $M_{\mathrm{CPD}_b} \sim 1.8 - 3.2 \times 10^{-3} M_\oplus$?

PDS 70 c

Haffert+2019

- a~**34.5 AU**

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CPD_c

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- $\dot{M}_c$~**$10^{-7.6}$–$10^{-8.4}$ M_J yr^{-1}**

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Summary

- All clues suggest PDS 70 b and c are authentic accreting protoplanets

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- T_{eff}~**1500–1600 K**
- log(g)~**4.0**
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Müller+2018

- a~**22.2 AU**
- e~**0–0.2**
- T_{eff}~**1000–1600 K**
- log(g)~**2.7–4.0**
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Close to 2:1 resonance
=> Grand-Tack like scenario?

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- Direct imaging (easier in large gaps) complementary to gas kinematics detections