

# PDS70

a young solar system in formation  
- pathway toward (exo)-planetology -

Gaël Chauvin

Miriam Keppler (MPIA), André Muller (MPIA), Jos de Boer (Leiden), Sebastian Haffert (Leiden), Dino Mesa (INAF), Myriam Benisty (FCLA), André Isella (Rice Univ.)...  
& SPHERE consortium



References: Keppler et al. (2018, A&A, 617, 44), Müller et al. (2018, A&A, 617, L2), Long et al. (2018, ApJ, 858, 112), Keppler et al. (2019, A&A, 625, 118), Haffert et al. (2019, Nat Astr., 3, 749), Isella et al. (2019, ApJ, 878, L25)

# The Star

---

Scorpius

Lupus

Centaurus

South Crux



PDS70 (V\* V1032 Cen)

Single star

K7 member of Upper Centaurus Lupus

distance:  $113.41 \pm 0.52$  pc (Gaia DR2)

age estimate:  $5.4 \pm 1.0$  Myr



# The Star

Scorpius



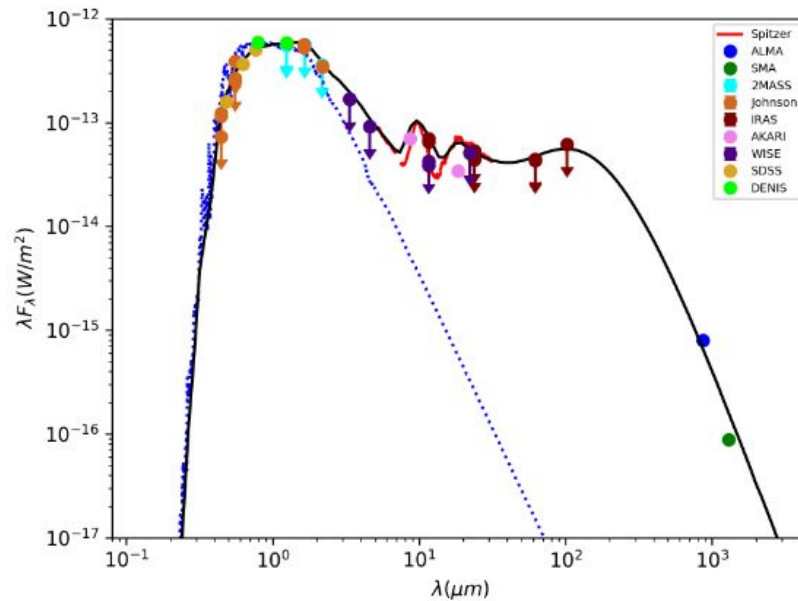
PDS70 (V\* V1032 Cen)

Single star

K7 member of Upper Centaurus Lupus

distance:  $113.41 \pm 0.52$  pc (Gaia DR2)

age estimate:  $5.4 \pm 1.0$  Myr



Transition disk

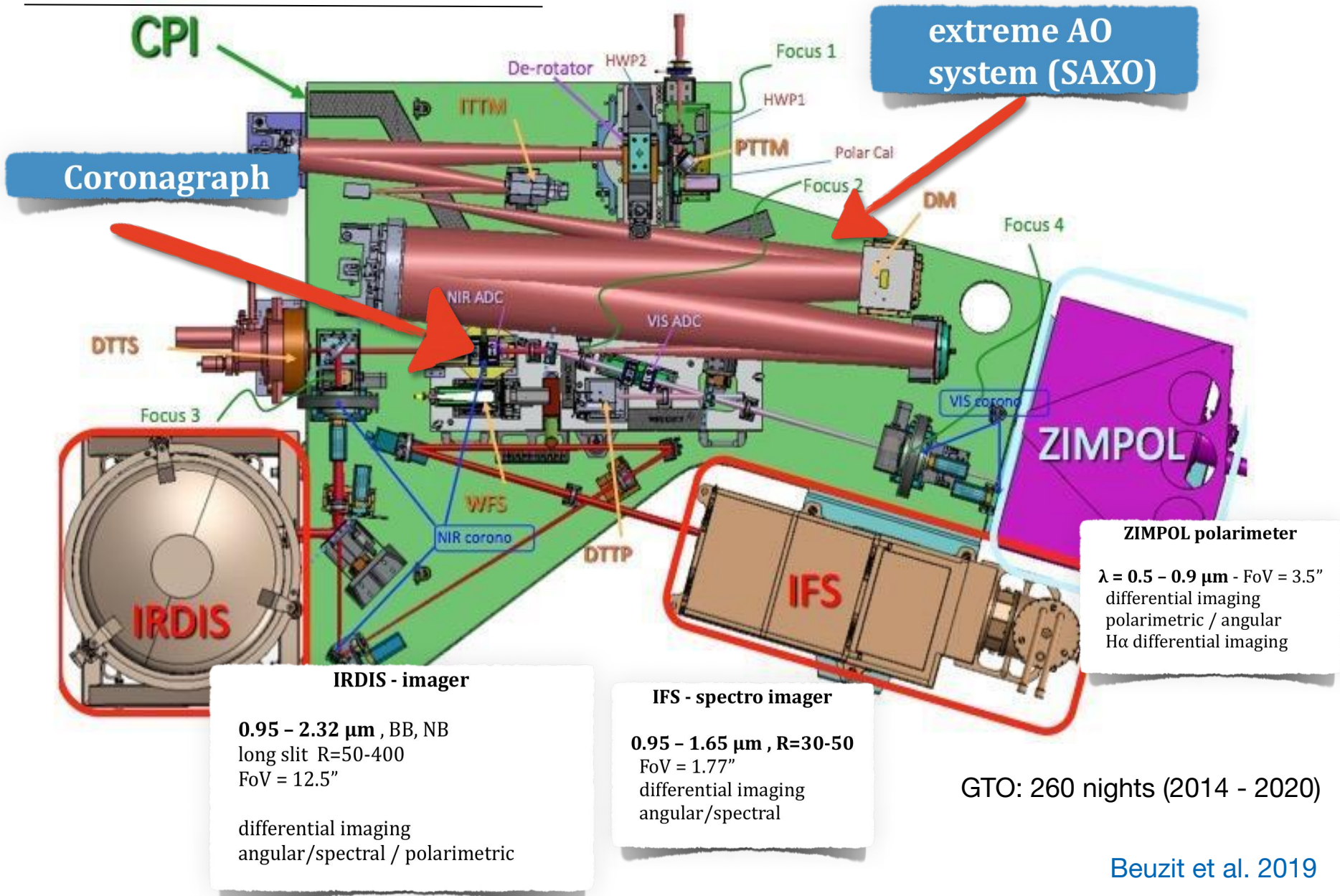
reduced nIR excess, indicating disk with  
inner region cleared of dust, although  
with a small optically thick inner disk

[Gregorio-Hetem & Hetem \(2002\)](#)

[Metchev et al. \(2004\)](#)

[Dong et al. \(2012\)](#), [Long et al. \(2018\)](#)

# SPHERE@VLT

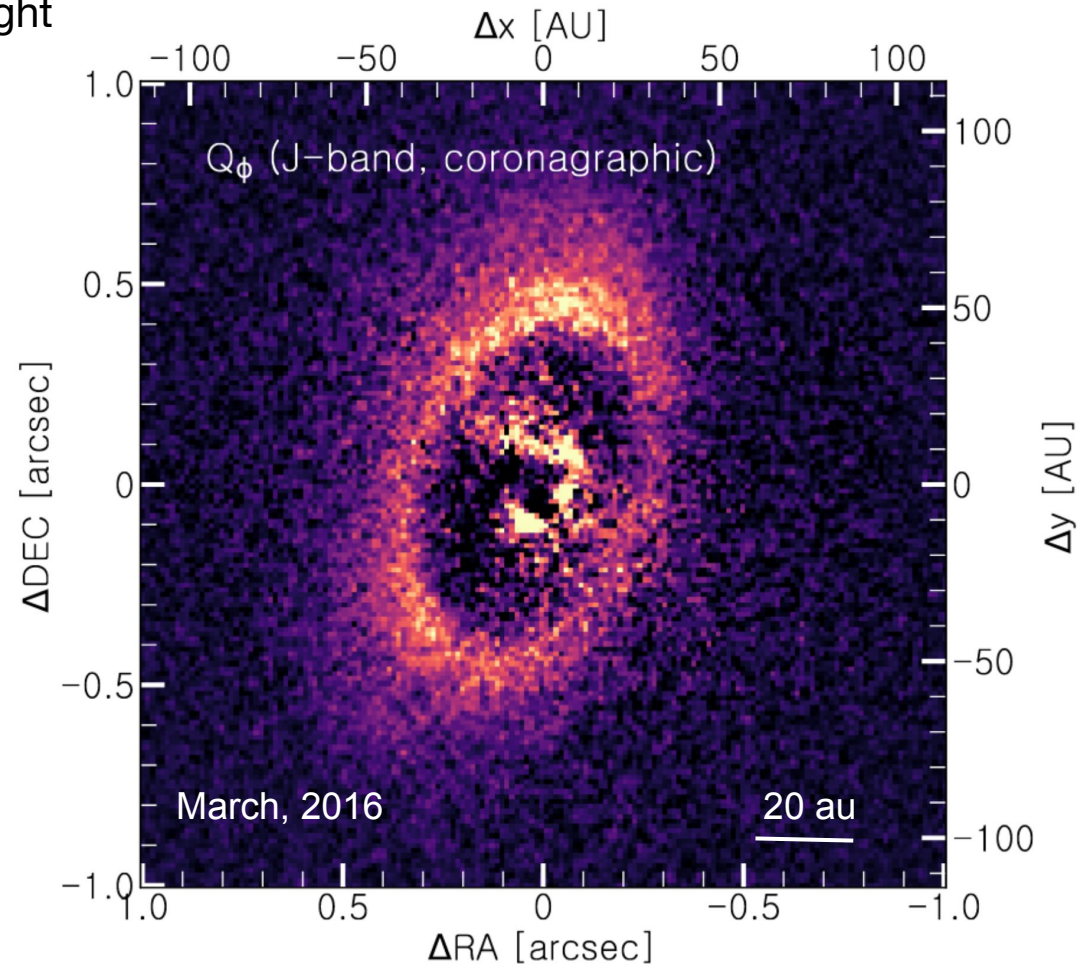




# Outer ring - Kuiper belt analog

## Polarimetric Differential imaging with SPHERE

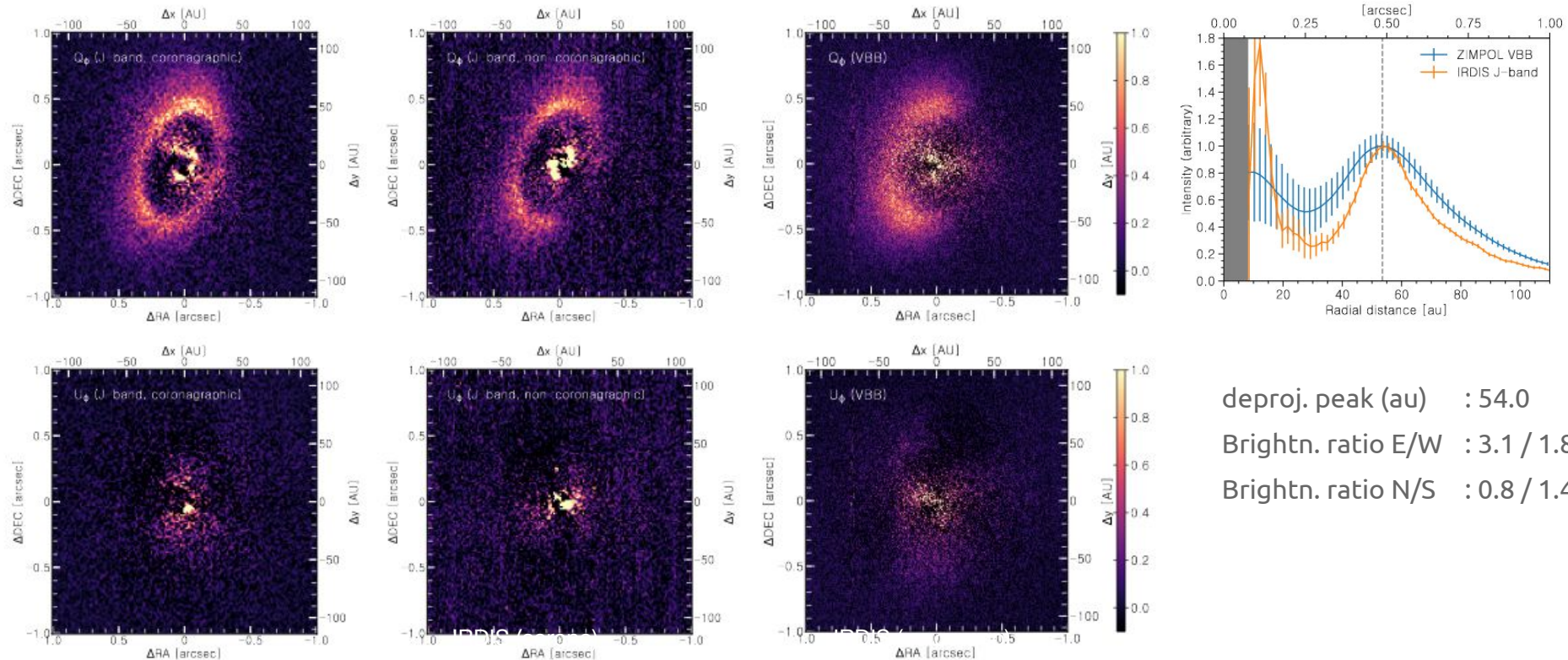
- IRDIS PDI, J-band
- Small dust seen in scattered light



# Outer ring - Kuiper belt analog

## Polarimetric Differential imaging with SPHERE

- IRDIS PDI, J-band + ZIMPOL PDI, VBB band
- Small dust seen in scattered light

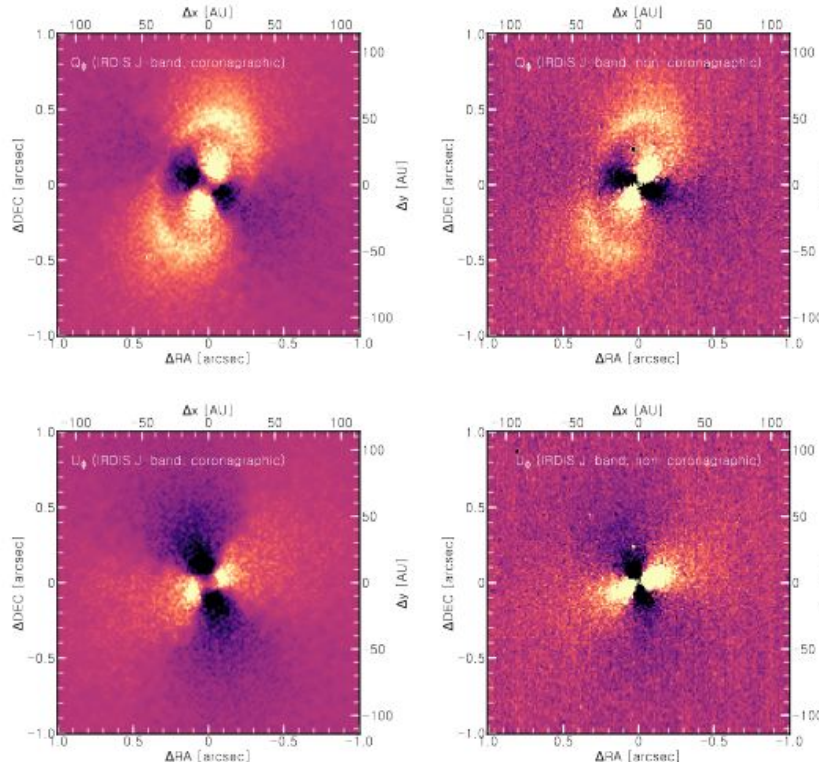


# Inner ring - Asteroids belt analog?

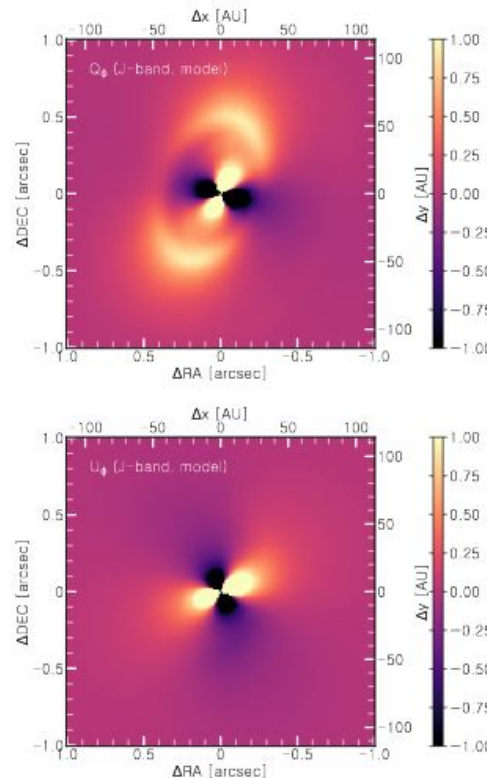
## Polarimetric Differential imaging with SPHERE

- Inner disk detected, but not resolved (sequence below wo central source subtraction)

observations



RT model



### RT modeling (RADMC-3D)

Outer disk	: 60 - 120 au
Inner disk	: 0.04 - 2/20 au
$\delta_{\text{inner disk}}$	: 0.05/1.0
$\delta_{\text{outer disk}}$	: 1.0
$H_{100}$	: 13 au
$\beta$	: 1.25
PA (deg)	: $158.6 \pm 0.7$
Incl. (deg)	: $49.7 \pm 0.3$
Total mass	: $3.0 \times 10^{-5} M_{\text{sun}}$

Degeneracy btw solutions with different inner disk size and density

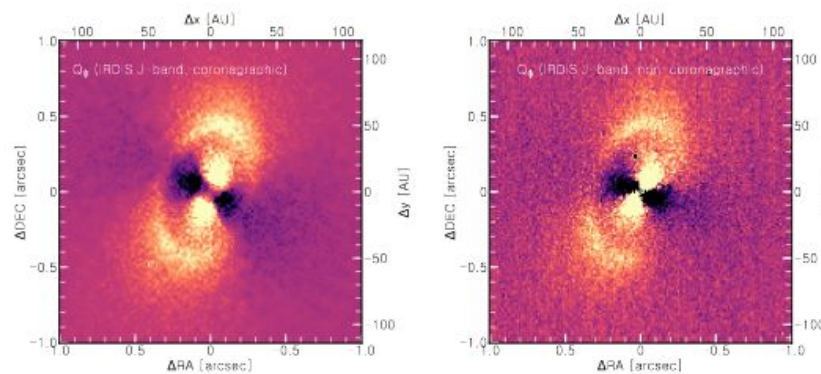


# Inner ring - Asteroids belt analog?

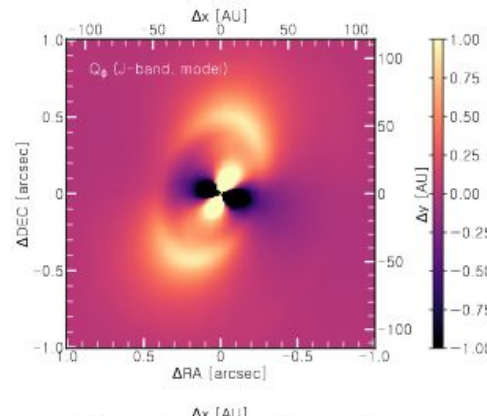
## Polarimetric Differential imaging with SPHERE

- Inner disk detected, but not resolved (sequence below wo central source subtraction)

observations

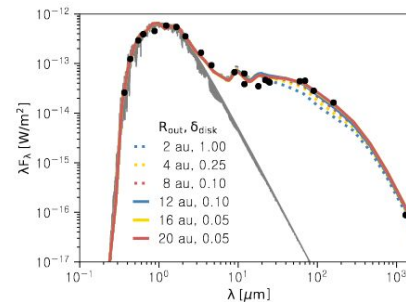
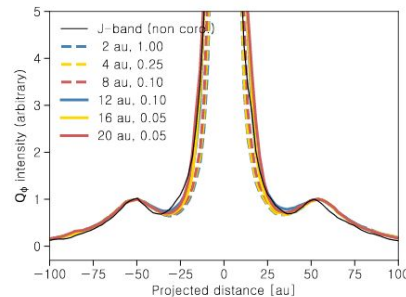
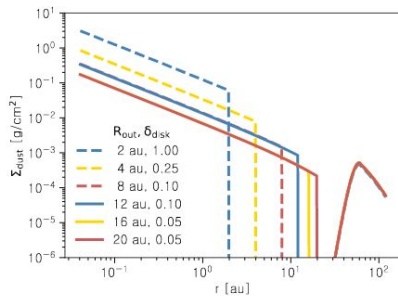


RT model



### RT modeling (RADMC-3D)

Outer disk	: 60 - 120 au
Inner disk	: 0.04 - 2/20 au
$\delta_{\text{inner disk}}$	: 0.05/1.0
$\delta_{\text{outer disk}}$	: 1.0
$H_{100}$	: 13 au
$\beta$	: 1.25
PA (deg)	: $158.6 \pm 0.7$
Incl. (deg)	: $49.7 \pm 0.3$
Total mass	: $3.0 \times 10^{-5} M_{\text{sun}}$



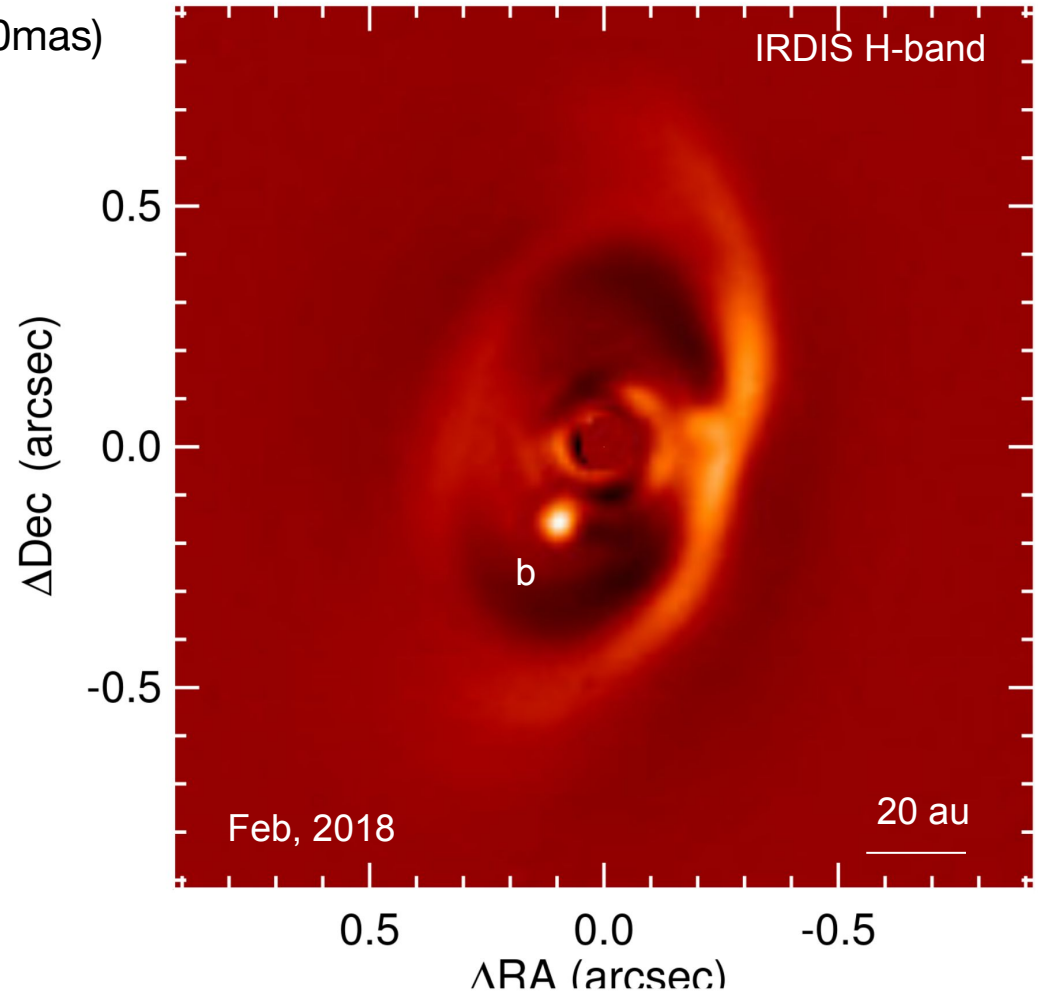
Degeneracy btw  
solutions with  
different inner disk  
size and density



# Giant planet, PDS70 b

## Angular Differential Imaging with SPHERE

- IRDIS “cADI” processing, H-band
- Planet candidate at 22 au (200mas) and  $\Delta H2 = 9.2$  mag



# Giant planet, PDS70 b

## NICI/NaCo/SPHERE confirmation

Verification using various algorithms, archival data, multi-epoch observations:

- Point source detection in ADI processing (TLOCI, PCA, cADI...)
- Different instruments at different wavelengths (H, K, L bands)
- 4-yr proper motion test rules out bkg contaminant,

NICI

SPHERE

NaCo

L' 2012-03-31

H2H3 2015-05-03

H2H3 2015-05-31

K1K2 2016-05-14

L' 2016-06-01

0.1"

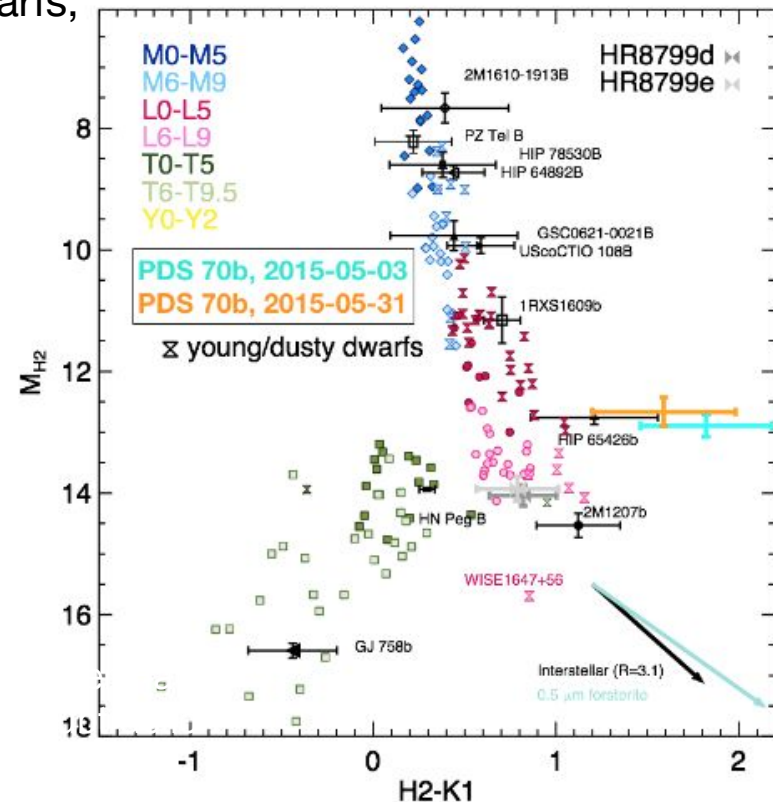


# Giant planet, PDS70 b

## NICI/NaCo/SPHERE confirmation

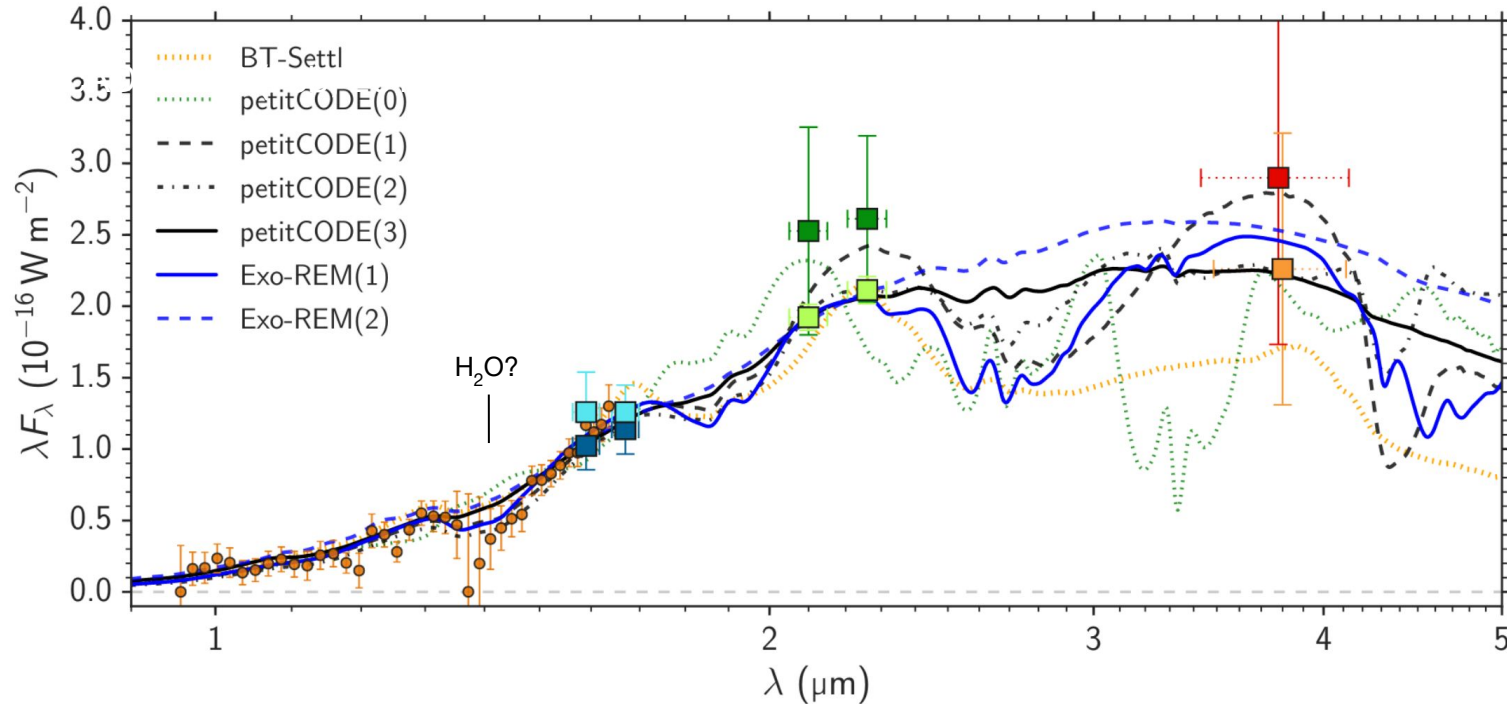
Verification using various algorithms, archival data, multi-epoch observations:

- Point source detection in ADI processing (TLOCI, PCA, cADI...)
- Different instruments at different wavelengths (H, K, L bands)
- 4-yrs proper motion test rules out bkg contaminant,
- Very red colors similar to dusty mid-L type dwarfs,
  - ( $\Delta K1 = 7.81 \pm 0.31$  mag ;  $\Delta L' = 6.8 \pm 0.6$  mag)
- Evol. Model predictions (DUSTY, Hot-start):
  - $7 \pm 2 M_{\text{Jup}}$  planet,  $T_{\text{eff}} = 1200 \pm 200$  K,
  - $\log(g) = 3.9 \pm 0.9$  dex



# Giant planet, PDS70 b

## Spectral characterization



### Atmospheric model fitting:

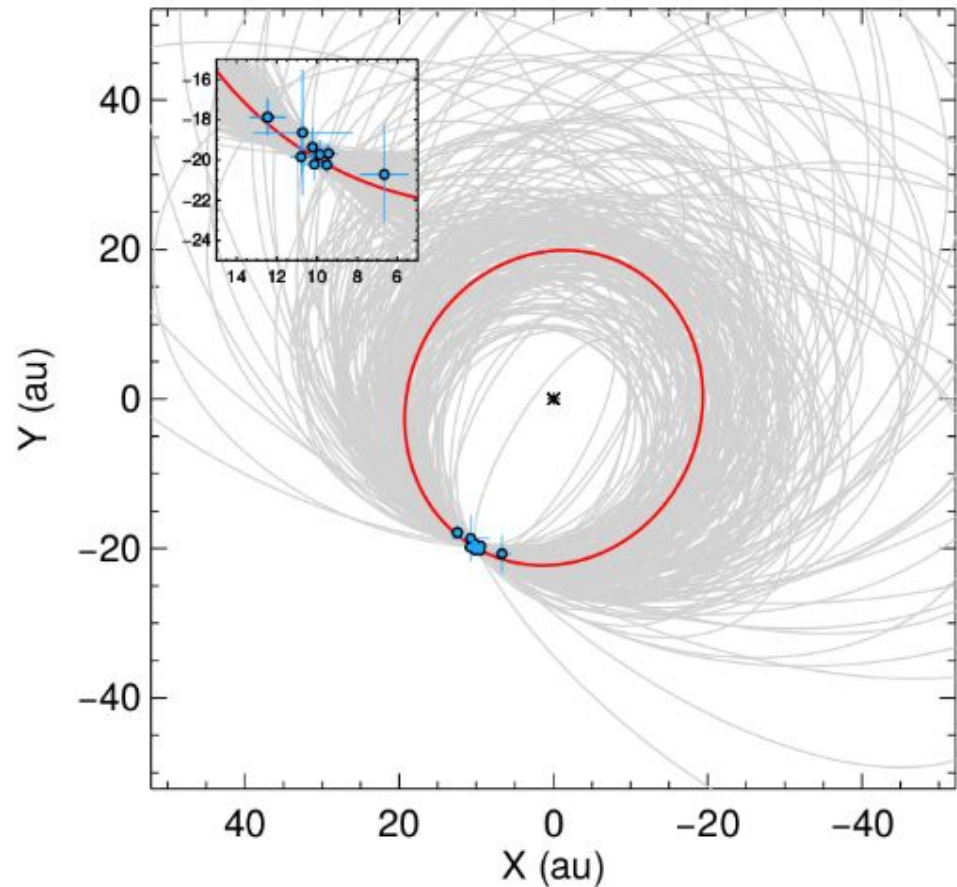
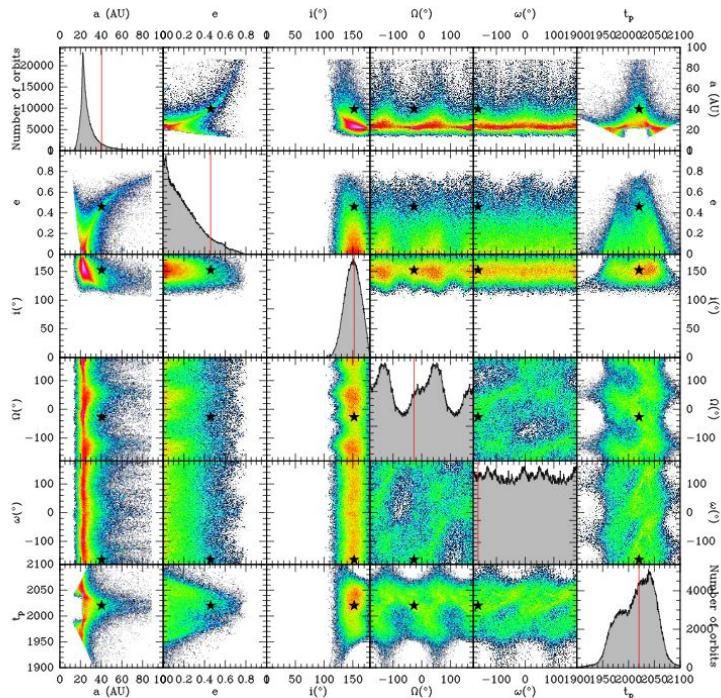
- Very red spectrum (with H<sub>2</sub>O absorption?),
- No obvious solution using different models,
- Cloudy models: better fit with low Teff (1100K) and surface gravity of log(g) < 4.1

Model	$T_{\text{eff}}$ (K)	$\log g$ $\log_{10}$ (cgs)	$(M/H)$ (dex)	$f_{\text{sed}}$	Radius $R_J$	Mass <sup>b</sup> $M_J$
BT-Settl	1590	3.5	—	—	1.4	2.4
<i>petitCODE</i> (0)	1155	5.5	−1.0	—	2.7	890.0
<i>petitCODE</i> (1)	1050	≤2.0	≥1.0	1.5 <sup>a</sup>	2.0	0.2
<i>petitCODE</i> (2)	1100	2.65	1.0	1.24	3.3	1.9
<i>petitCODE</i> (3)	1190	≤3.5	0.0	≤1.5	2.7	8.9
Exo-REM(1)	1000	3.5	1.0	—	3.7	17
Exo-REM(2)	1100	4.1	1.0	1	3.3	55



# Giant planet, PDS70 b

## Orbital characterization



### MCMC orbital fitting:

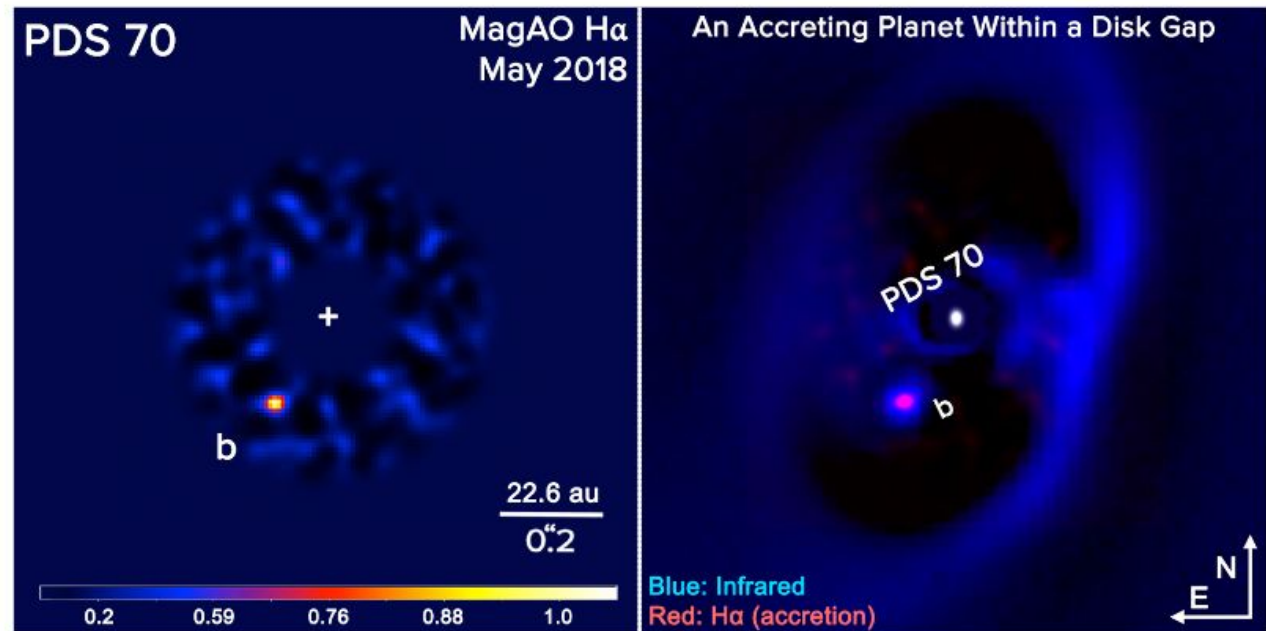
- $a = 22.2 [-9.7, +6.7]$  au,
- Low-eccentricity solutions favored,
- $\text{incl.} = 151.1 [-13.6, +14.4]$  deg (retrograde), compatible with coplanar configuration

Müller et al. (2018)

# Giant planet, PDS70 b

## Signs of accretion?

- MagAO H $\alpha$  observations, Feb 10<sup>th</sup>, 2017 and May 3<sup>rd</sup>, 2018 and [May 4<sup>th</sup>, 2018](#)
- PCA ADI processing, PDS70 b detected at 2-3 sigma (independent confirmation)
- mass accretion rate:  $M_{\text{acc}} = 10^{-8 \pm 1} M_{\text{Jup}}/\text{yr}$ ,





# Two Giant Planets?

## PDS70 c: A second accreting planet in the system!

Integral Field spectrograph **MUSE-NF**,  $R_\lambda = 4000$ , Comm. observations, [June 2018](#)  
H $\alpha$  Line Mapping, PDS70 b and c detected at more than 3 sigma

PDS 70 c, compatible with detection  
seen with NaCo and SPHERE

Predicted Properties:

- .  $4 M_{\text{Jup}}$  at 305 mas (35 au)
  - . b and c in mean motion resonance?
  - . nIR Spectra obtained by SPHERE
- [Mesa et al. \(2019\)](#)

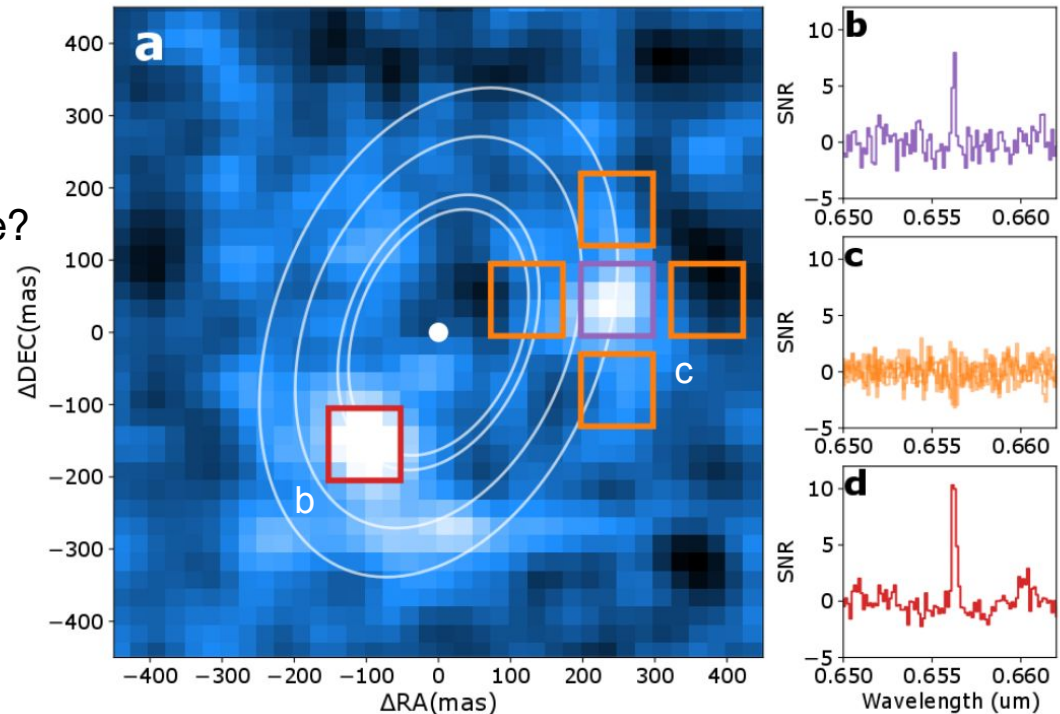
Accretion rates:

$$\text{b: } \dot{M}_{\text{acc}} = 2.10^{-8.0 \pm 0.4} M_{\text{Jup}}/\text{yr},$$

$$\text{c: } \dot{M}_{\text{acc}} = 10^{-8.0 \pm 0.4} M_{\text{Jup}}/\text{yr},$$

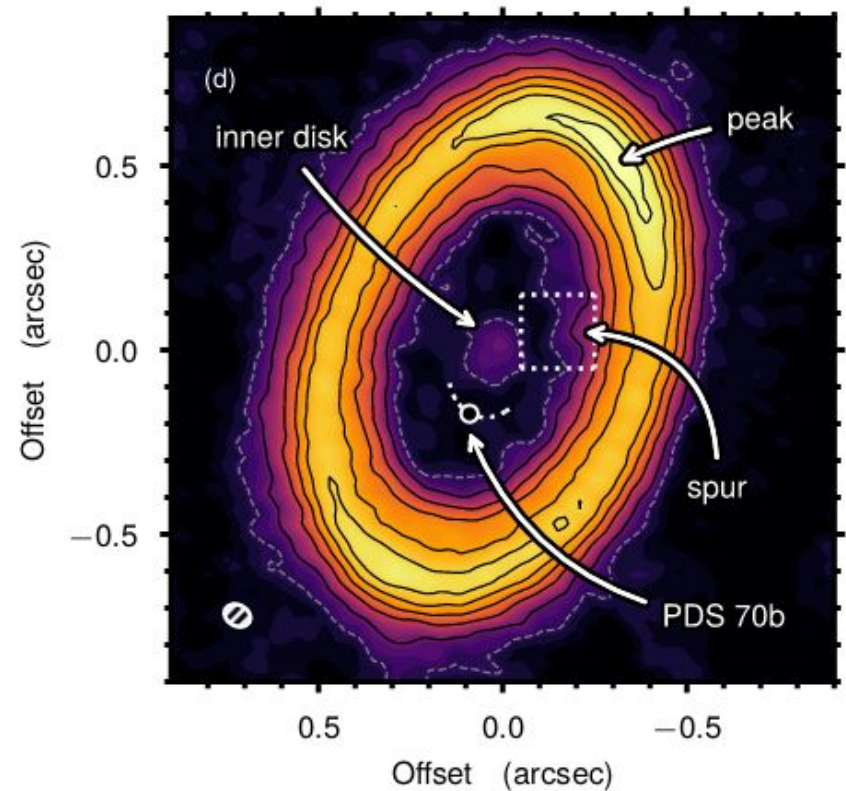
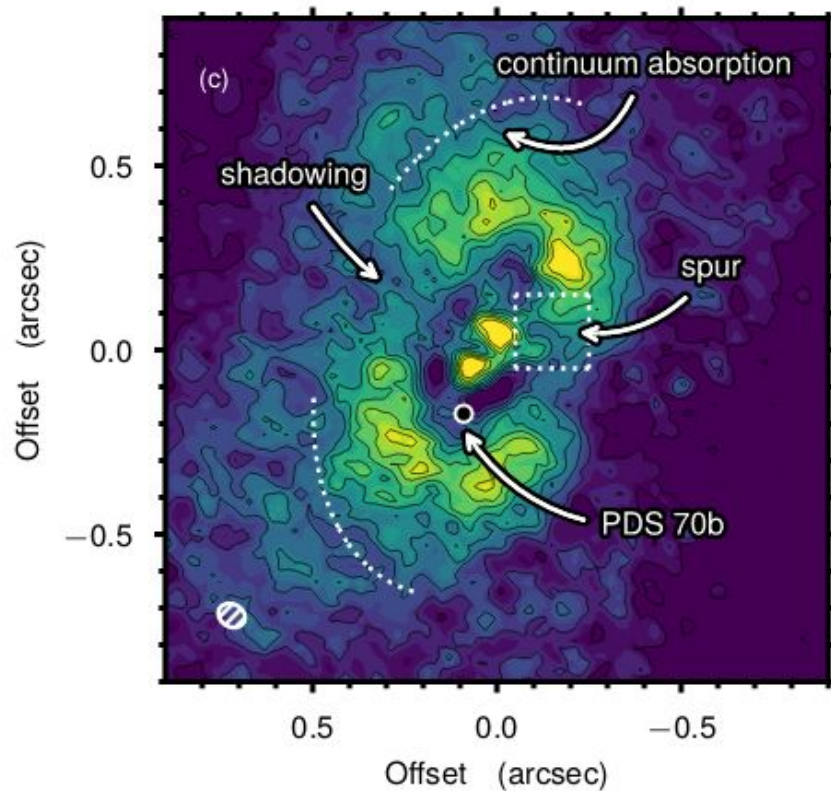
Magnetospheric Accretion origin

[Tanathidobee et al. \(2019\)](#)



# Highly Structured Architecture

ALMA Band-7 View in  $^{12}\text{CO}$  and in continuum



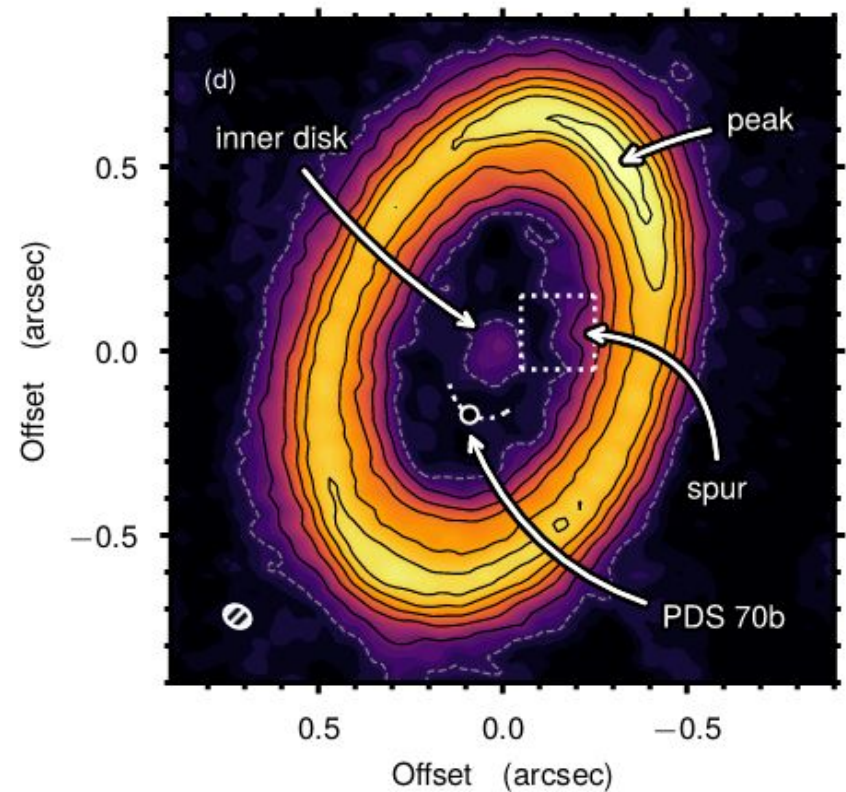
Long et al. (2018); Keppler et al. (2019)

# Highly Structured Architecture

## ALMA Band-7 View in $^{12}\text{CO}$ and in **continuum**

Emission from dust continuum show structured ring:

- inner disk detected (up to 15 au),
- peaked at 74au,
- asymmetry N/S,
- spur/bridge, location of PDS 70 c?



Long et al. (2018); Keppler et al. (2019)

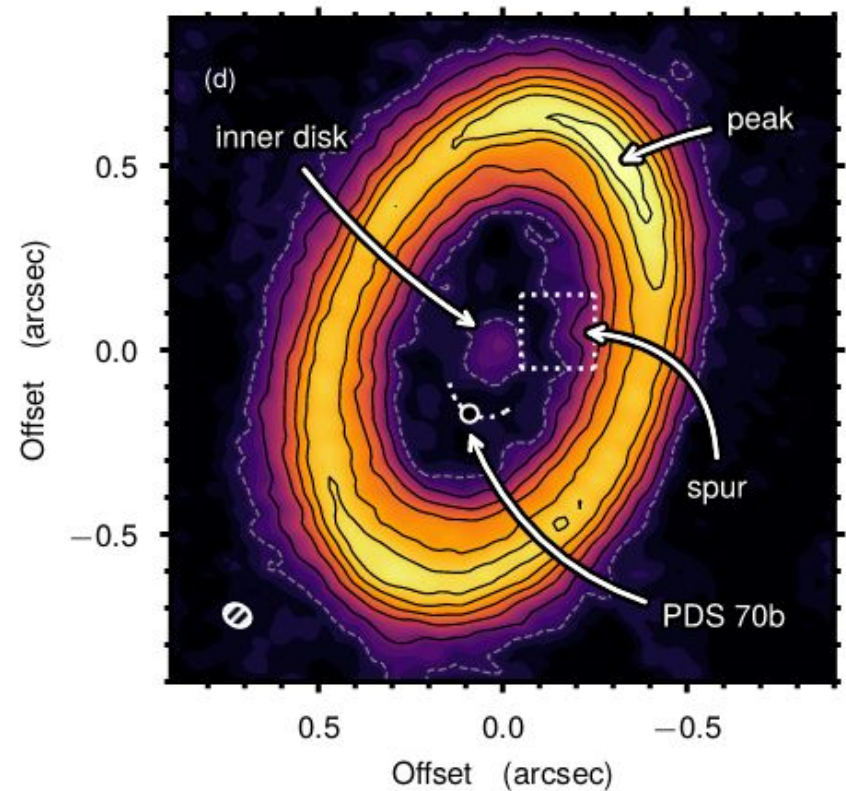
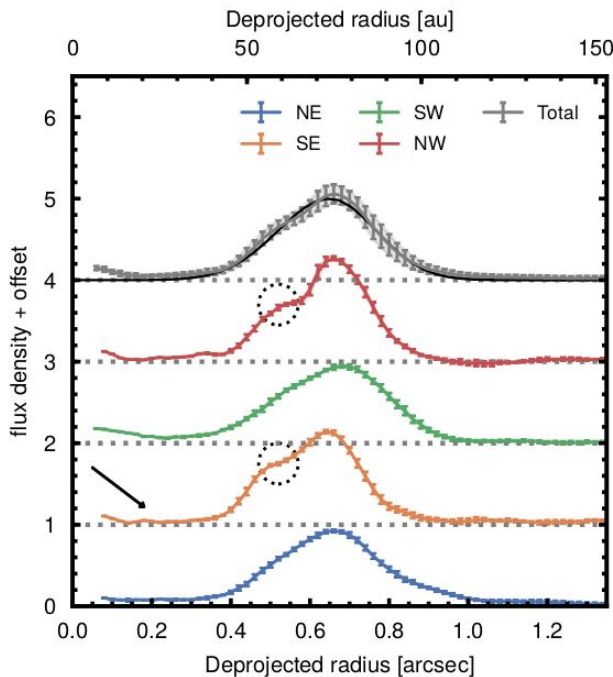


# Highly Structured Architecture

## ALMA Band-7 View in $^{12}\text{CO}$ and in **continuum**

Emission from dust continuum show structured ring:

- inner disk detected (up to 15 au),
- peaked at 74au,
- asymmetry N/S,
- spur/bridge, location of PDS 70 c?
- outer ring substructures?



Long et al. (2018); Keppler et al. (2019)

# Highly Structured Architecture

## ALMA Band-7 View in $^{12}\text{CO}$ and in **continuum**

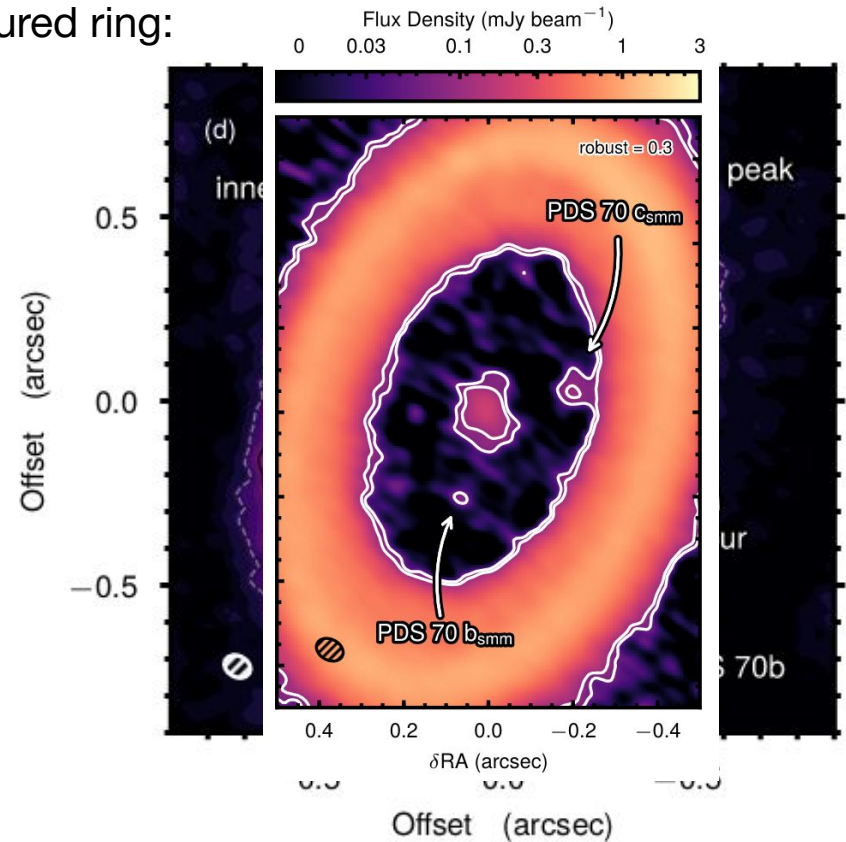
Emission from dust continuum show structured ring:

- inner disk detected (up to 15 au),
- peaked at 74au,
- asymmetry N/S,
- spur/bridge, location of PDS 70 c?
- outer ring substructures?

CPD detection around c!

- CPD mass =  $3 \cdot 10^{-3} M_{\text{Earth}}$
- $M_{\text{dust}}/M_{\text{b}} = 10^{-5} - 10^{-4}$ ,

(Isella et al. 2019)



Long et al. (2018); Keppler et al. (2019)

# Highly Structured Architecture

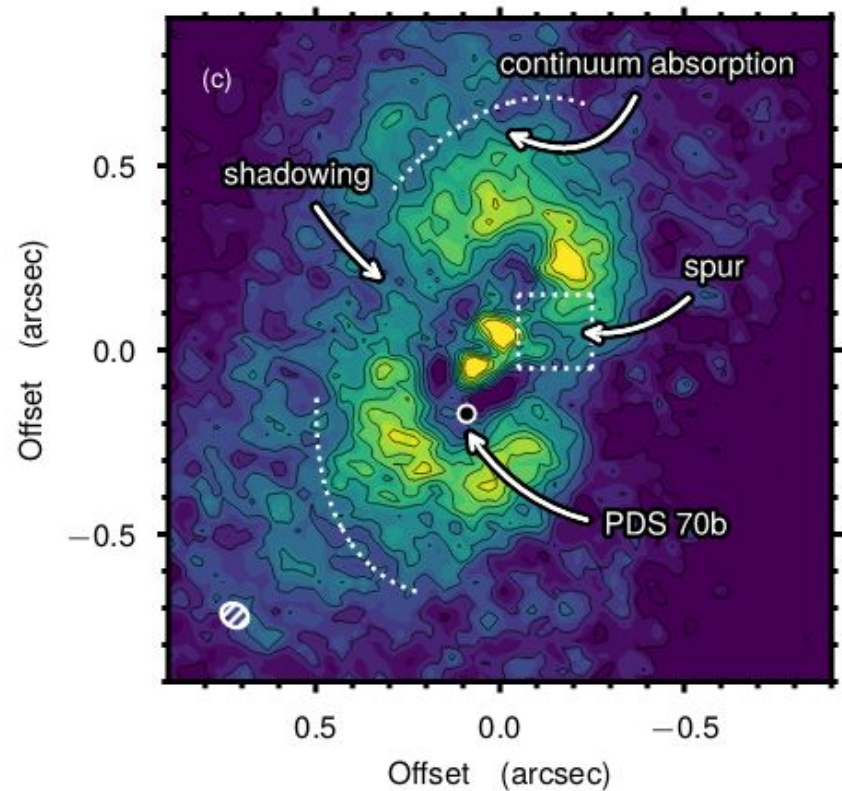
## ALMA Band-7 View in $^{12}\text{CO}$ and in continuum

CO-integrated intensity shows two radial intensity depressions at

- 0.2'', location of PDS 70 b,
- 0.6'', optically thick dust effect,

Azimuthal modulation (CO self absorption)

Bridge feature at location of PDS 70 c?

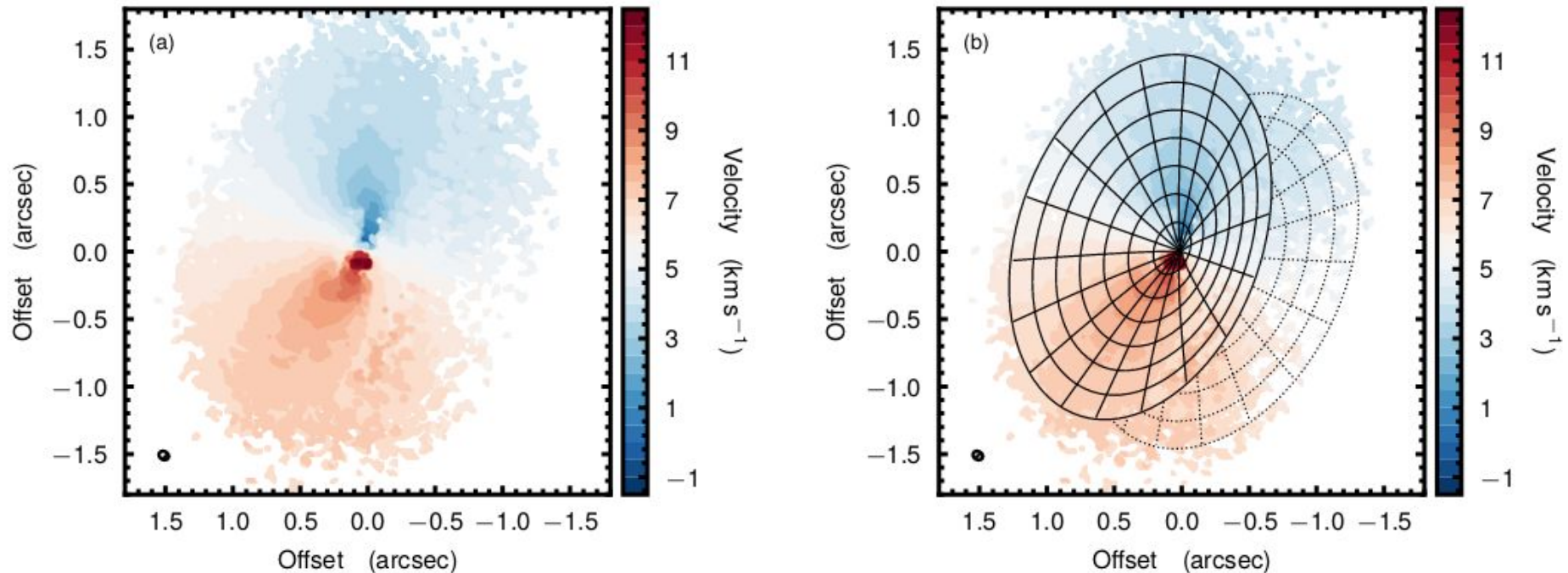




# Highly Structured Architecture

ALMA Band-7 View in  $^{12}\text{CO}$  and in continuum

Rotation profile of  $^{12}\text{CO}$  (best fit surface on the right)



Long et al. (2018); Keppler et al. (2019)

# Highly Structured Architecture

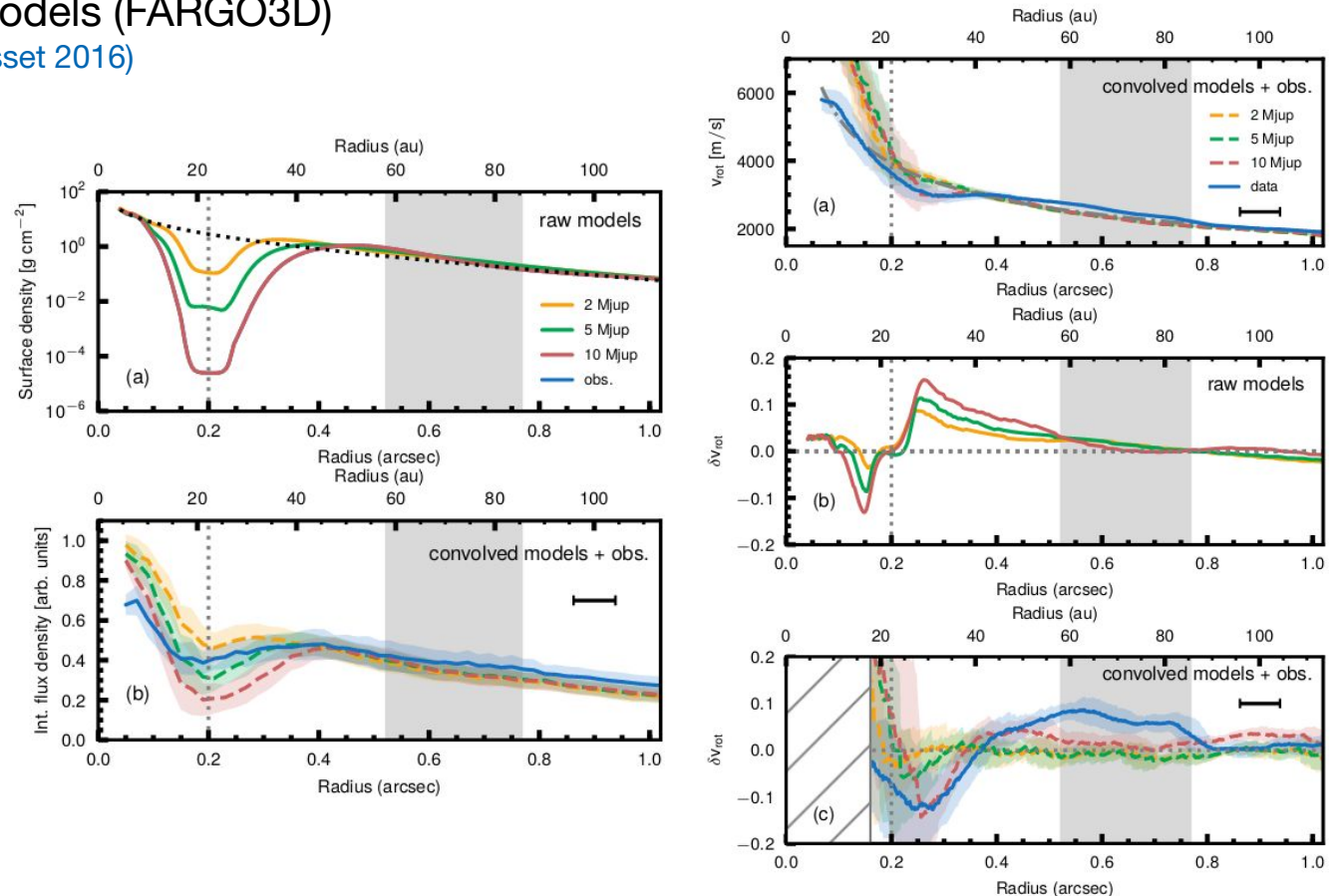
## ALMA Band-7 View in $^{12}\text{CO}$ and in continuum

$^{12}\text{CO}$  intensity profile & rotation curve (with deviation from Keplerian motion)  
+ hydro and RT models (FARGO3D)  
(Benitez-Llambay & Masset 2016)

sub/super Keplerian Motion  
observed below  $0.8''$ .

One  $5\text{--}10\text{ M}_{\text{Jup}}$  planet not  
sufficient to explain both CO  
flux density & rotation profile.

Add planet like PDS70 c  
responsible for the deviation!



# Take away message

---

PDS70: Ideal Lab to study the Solar System origin

- multi-belt architecture (Kuiper/asteroids analogues)
- 2 Giant Planets detected in thermal & H $\alpha$  emission
- Red spectra indicative of CPDs? Direct detection of the CPD around c,
- Mean motion resonance 2:1 (b & c), add. “d” (outer ring sub structures)?
- Amazingly illustrative of the SPHERE/MUSE/ALMA synergy



# Take away message

PDS70: Ideal Lab to study the Solar System origin

- multi-belt architecture (Kuiper/asteroids analogues)
- 2 Giant Planets detected in thermal & H $\alpha$  emission
- Red spectra indicative of CPDs? Direct detection of the CPD around c,
- Mean motion resonance 2:1 (b & c), add. “d” (outer ring sub structures)?
- Amazingly illustrative of the SPHERE/MUSE/ALMA synergy

Finding more?

- Getting deeper, closer & **fainter**
- SPHERE+ (VLT-2030 roadmap)
- white book soon available on arXiv!

<https://zenodo.org/record/3356290>

