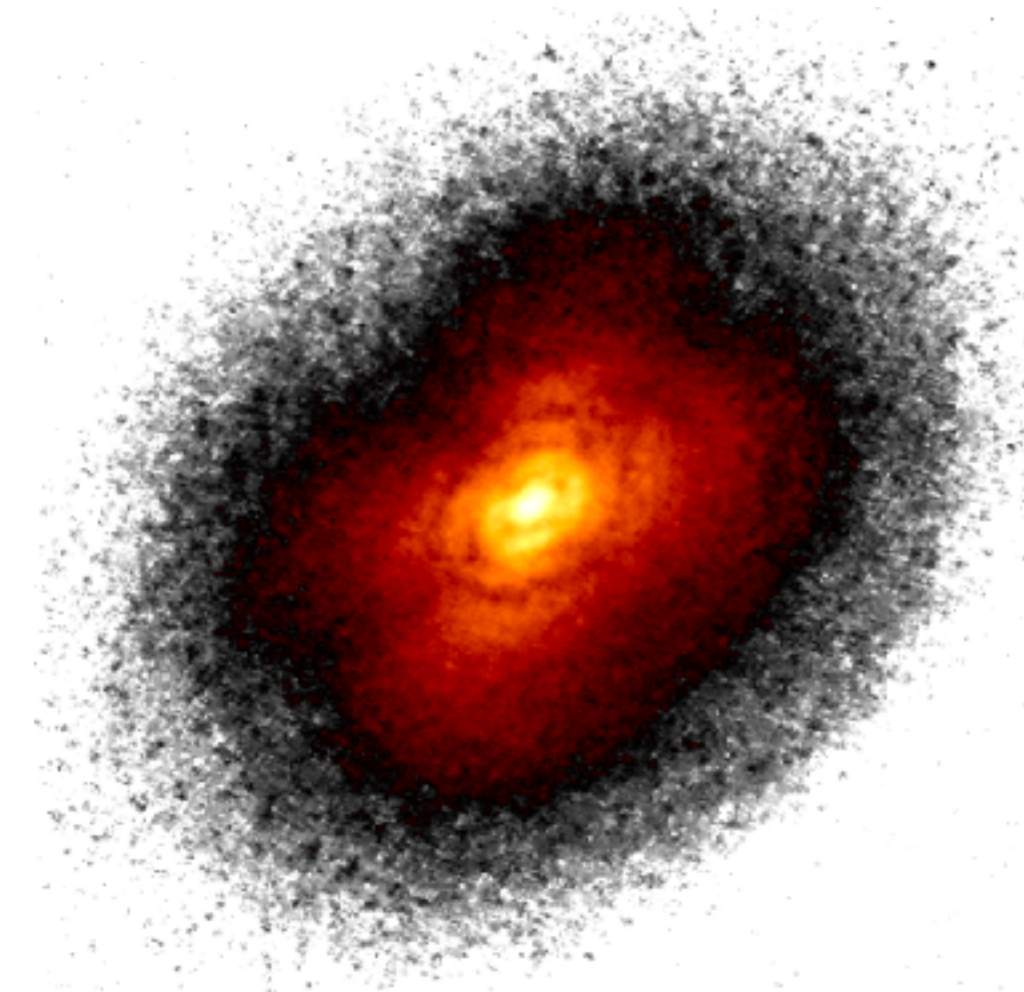
# The physico-chemical connection between nascent planets and their birth environment

## An observational perspective in PDS 70

**Stefano Facchini**

Collaborators: *Jaehan Bae, Myriam Benisty, Andrea Isella, Miriam Keppler, Richard Teague and many others*

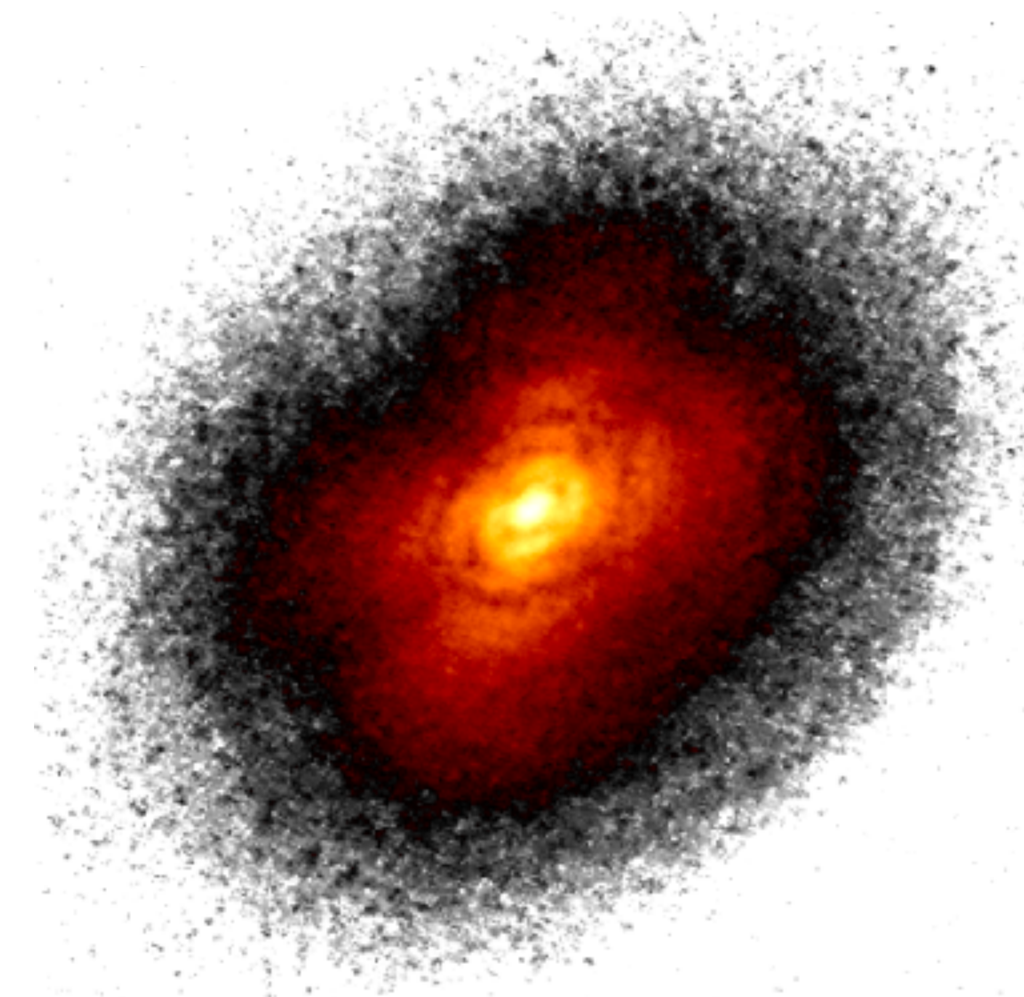
# Disks and protoplanets co-evolve



**Disk Dynamics Collaboration+2020**
Data from Isella+2018

# Disks and protoplanets co-evolve

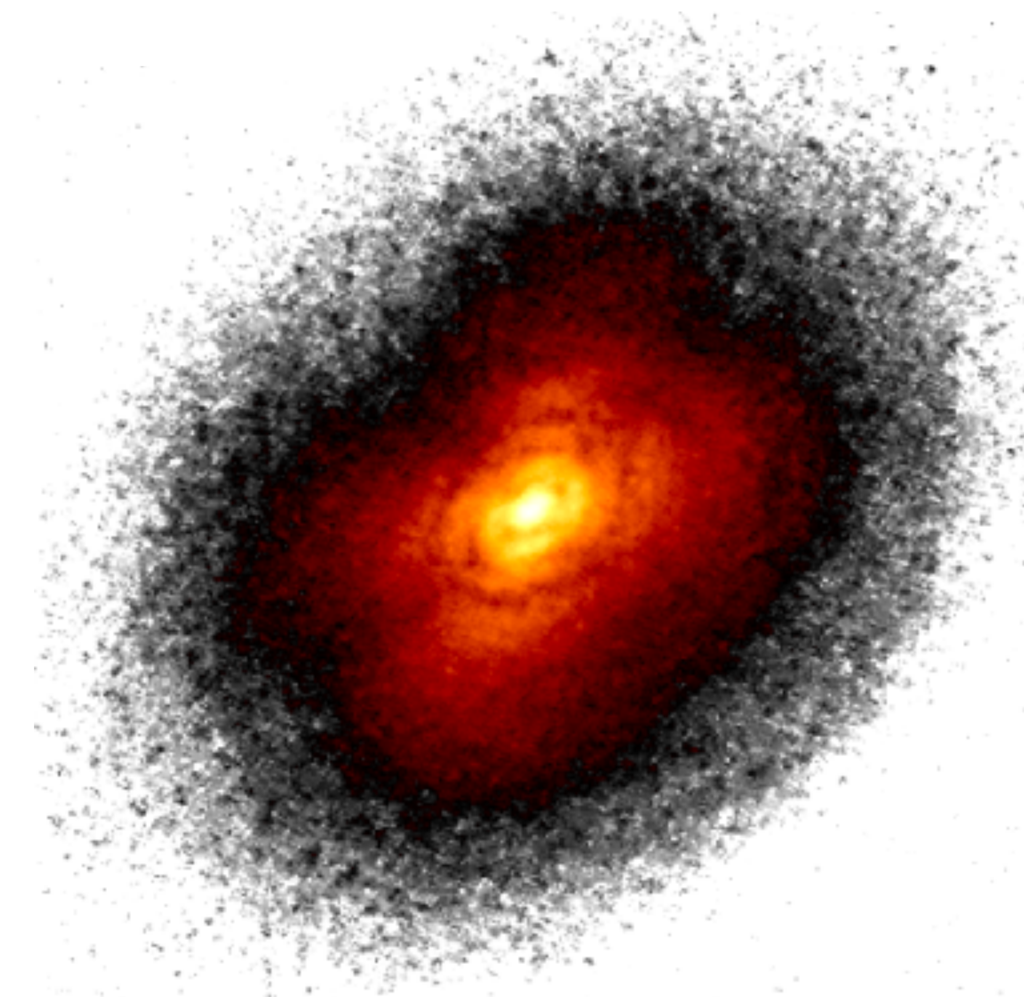
Structure
Ionisation
Dynamics
Accretion



**Disk Dynamics Collaboration+2020**
Data from Isella+2018

# Disks and protoplanets co-evolve

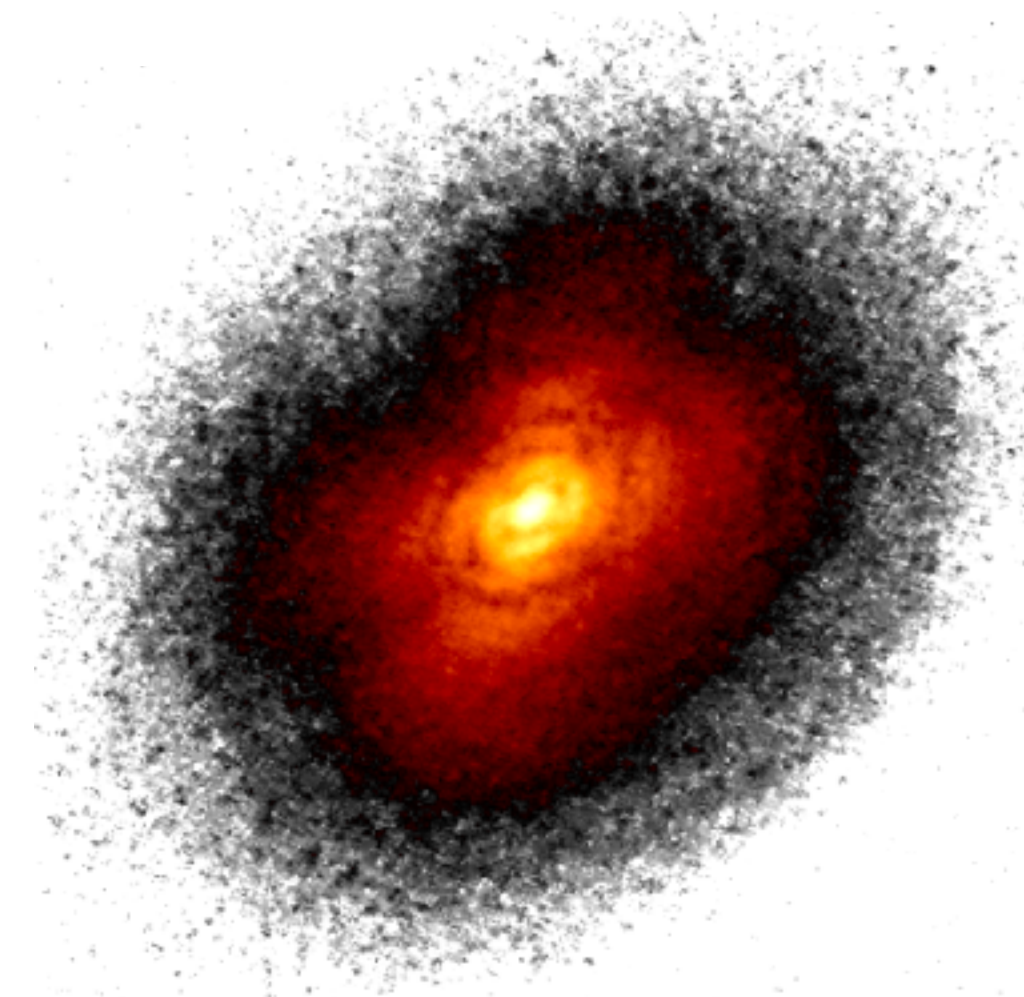
**Structure**
Ionisation
**Dynamics**
Accretion



**Disk Dynamics Collaboration+2020**
Data from Isella+2018

# Disks and protoplanets co-evolve

Structure
Ionisation
Dynamics
Accretion

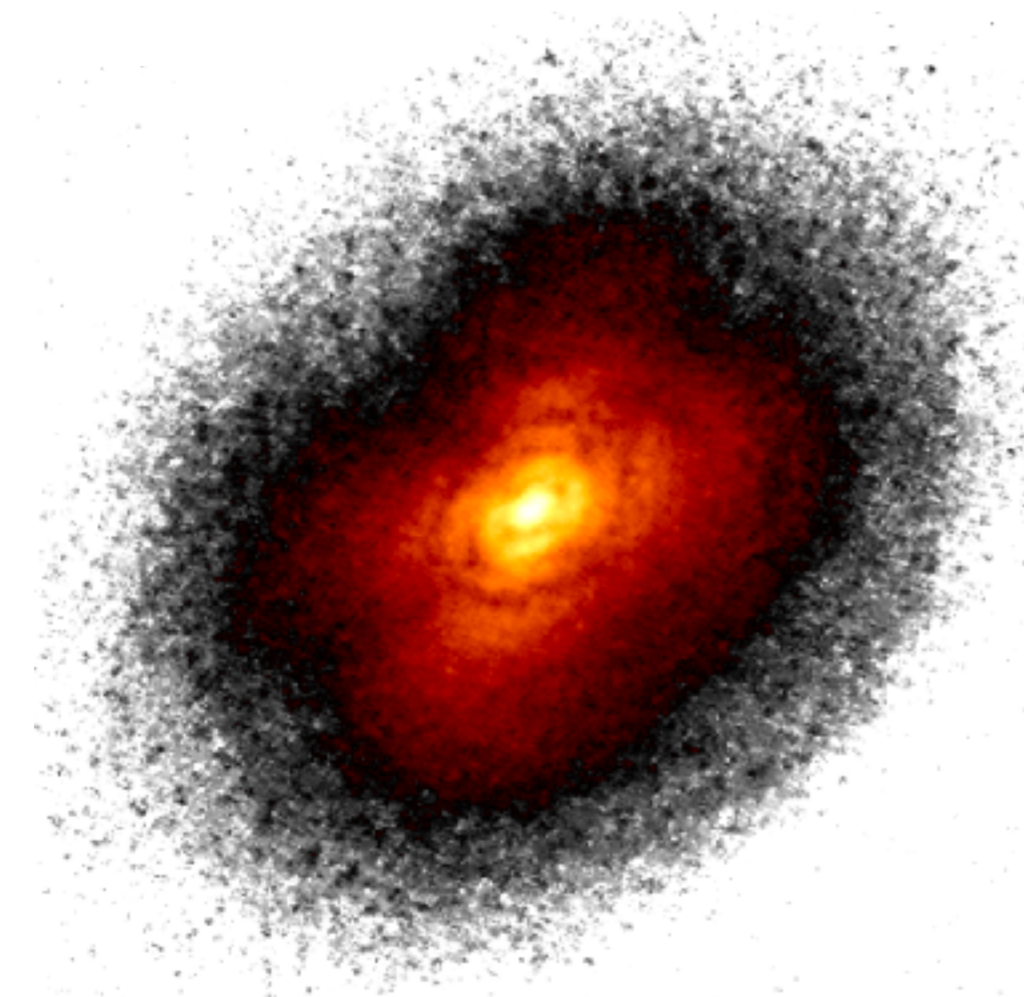


**Disk Dynamics Collaboration+2020**
Data from Isella+2018

Mass
Orbital radius
Chemical composition
Multiplicity

# Disks and protoplanets co-evolve

Structure
Ionisation
Dynamics
Accretion

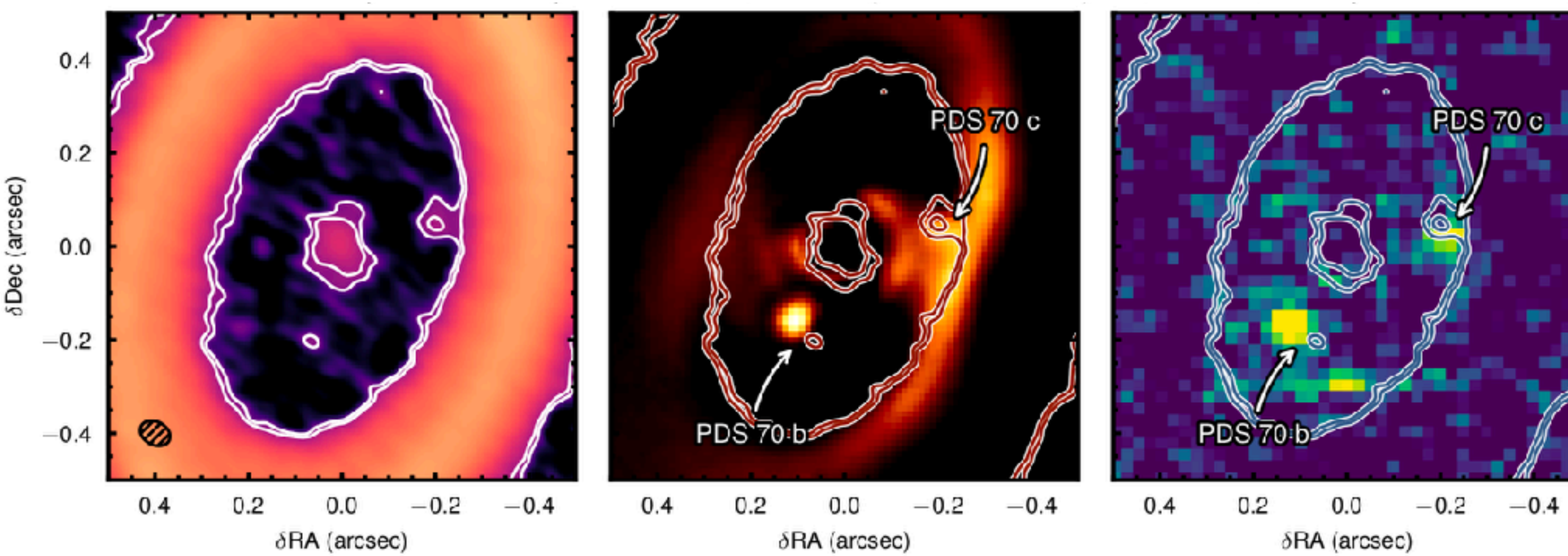


**Disk Dynamics Collaboration+2020**
Data from Isella+2018

Mass
Orbital radius
**Chemical composition**
Multiplicity

# PDS 70

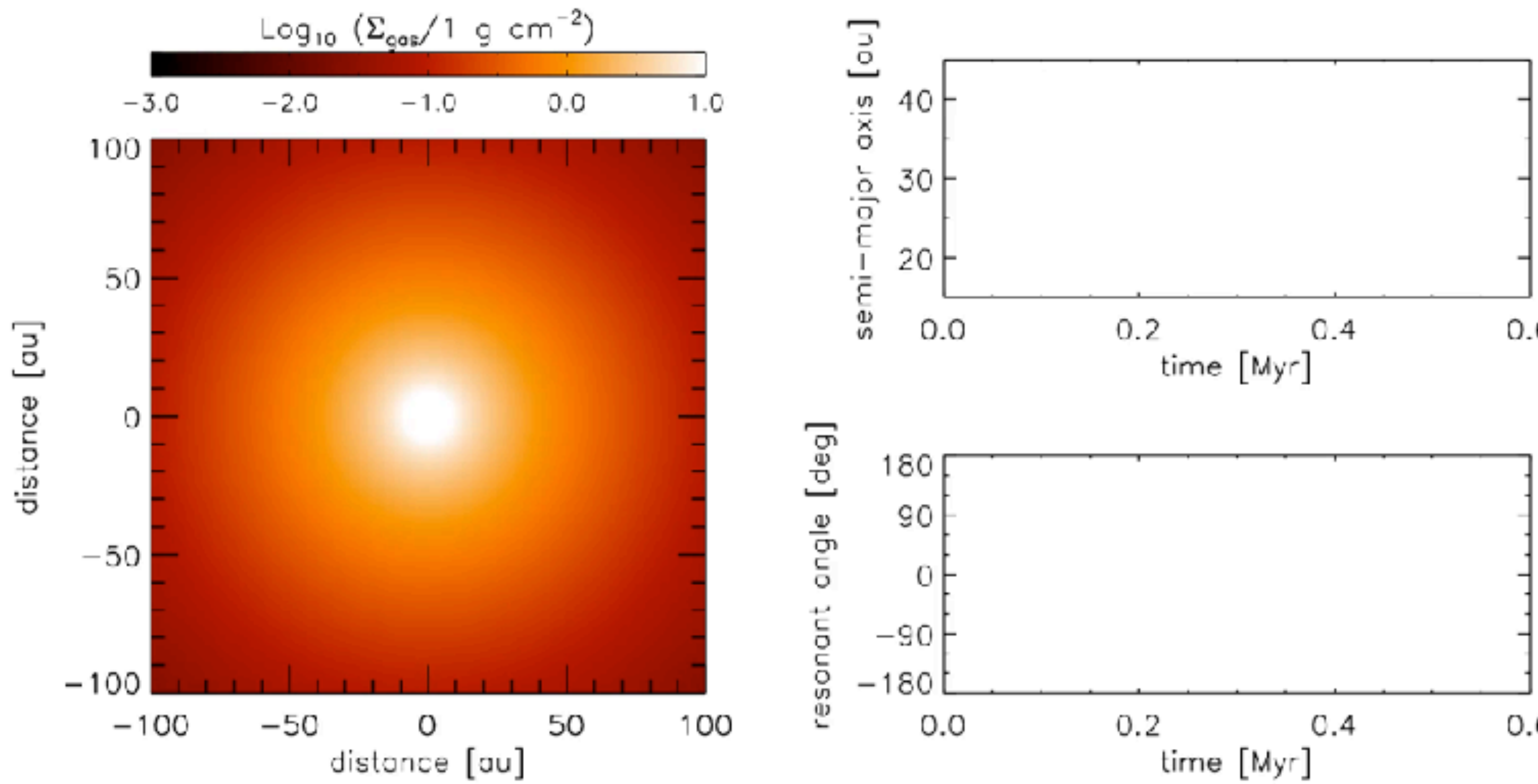
344 GHz continuum (Isella,…,**SF**+2019) NIR with VLT/SPHERE (Müller+2019) Hα with VLT/MUSE (Haffert+2019)




| **PDS 70b** | **PDS 70c** |
|---|---|
| $M_p$ ~ 5-9 $M_{Jup}$ | $M_p$ ~ 4 $M_{Jup}$ |
| a ~ 20.6 au | a ~ 34.5 au |
| $M_{acc}$ ~ 1-5x$10^{-8}$ $M_{Jup}$ $yr^{-1}$ | $M_{acc}$ ~ 1-5x$10^{-8}$ $M_{Jup}$ $yr^{-1}$ |

References: Keppler+2018, Haffert+2019, Christiaens+2019, Mesa+2019, Aoyama+2019, Thanathibodee+2019, Hashimoto+2020, Stolker+2020, Toci+2020

# Hydrodynamical simulations of PDS 70




**Bae,…,Facchini+2019**

2D simulations (FARGO) with 0.1 µm -1 mm dust included (Baruteau+2019).

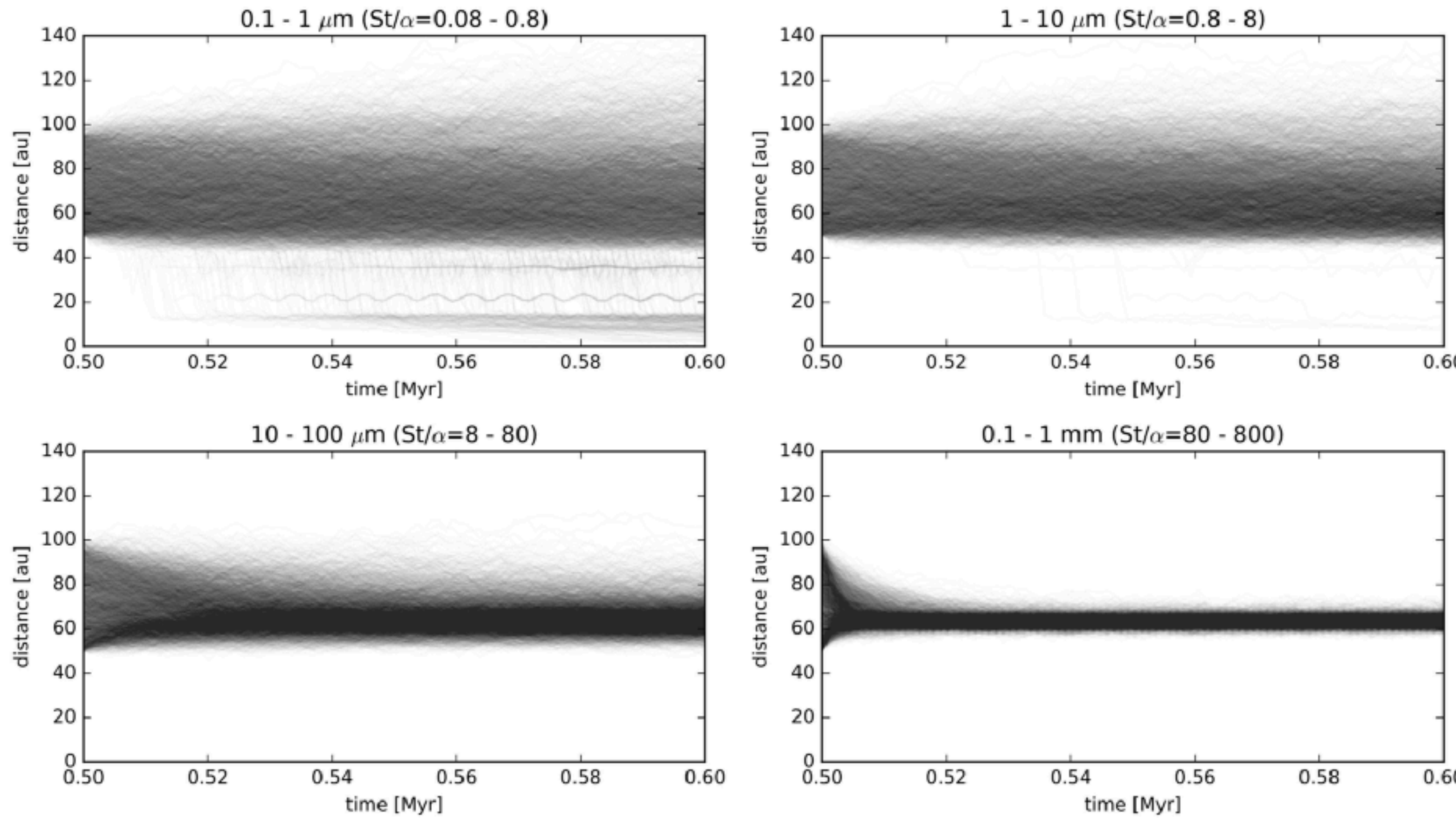
Mass of b: **5** $M_{Jup}$; Mass of c: **2.5** $M_{Jup}$

Simulations show that planet c is less massive than b, otherwise disk would be too eccentric.

Planets enter 2:1 resonance, with outward migration: **Jupiter-Saturn analogue**

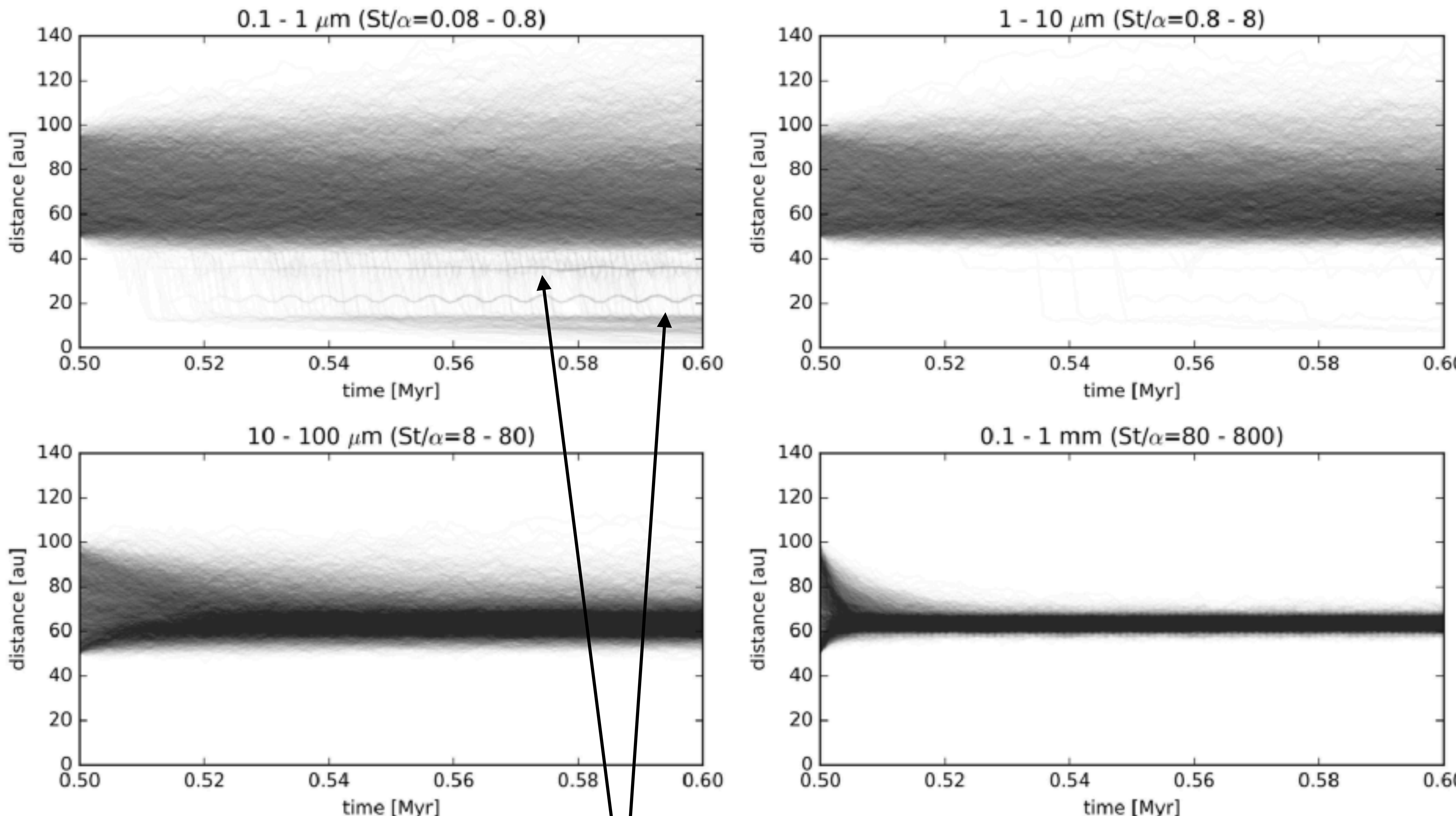
# Dust segregation and filtration

**Trajectories of dust particles**



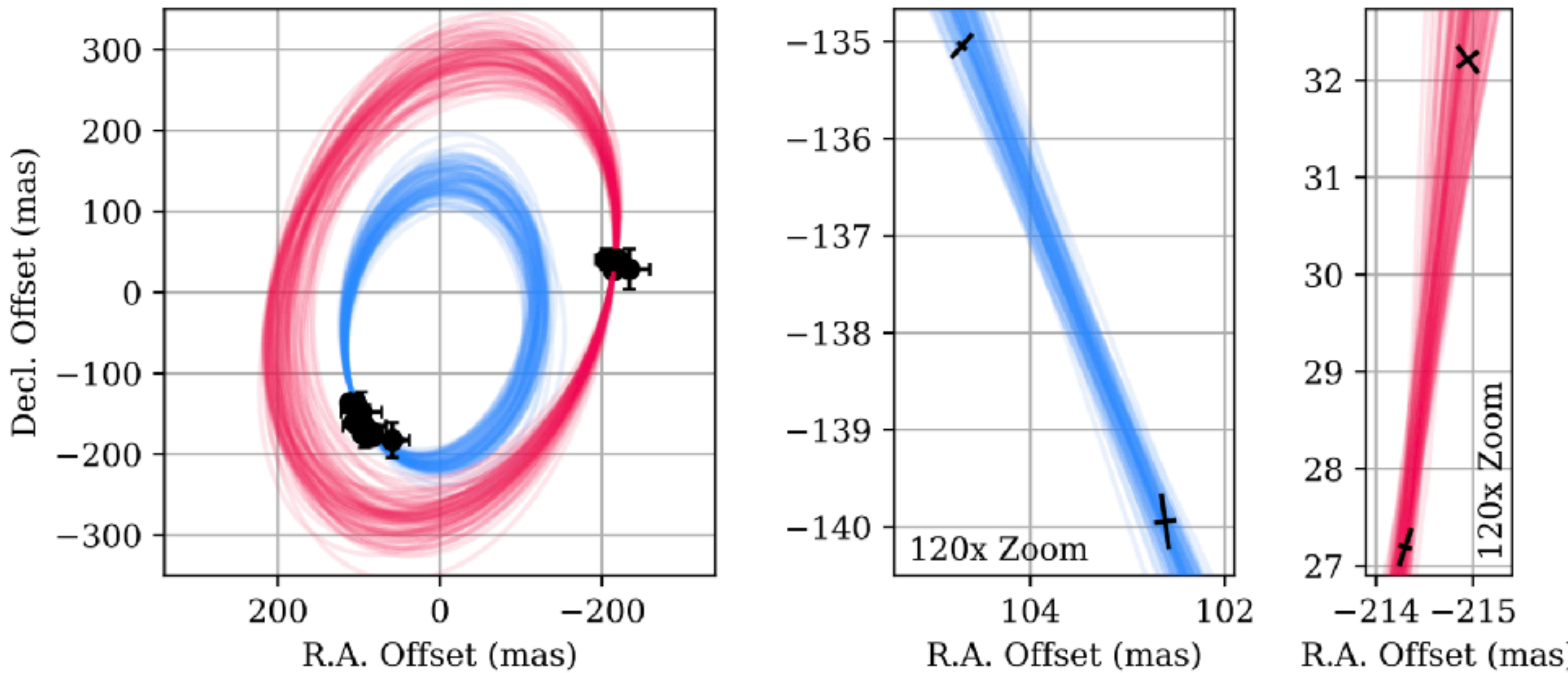
# Dust segregation and filtration

**Trajectories of dust particles**




Small grains only are able to leak through the cavity and reach the inner disk and the proximity of the two planets

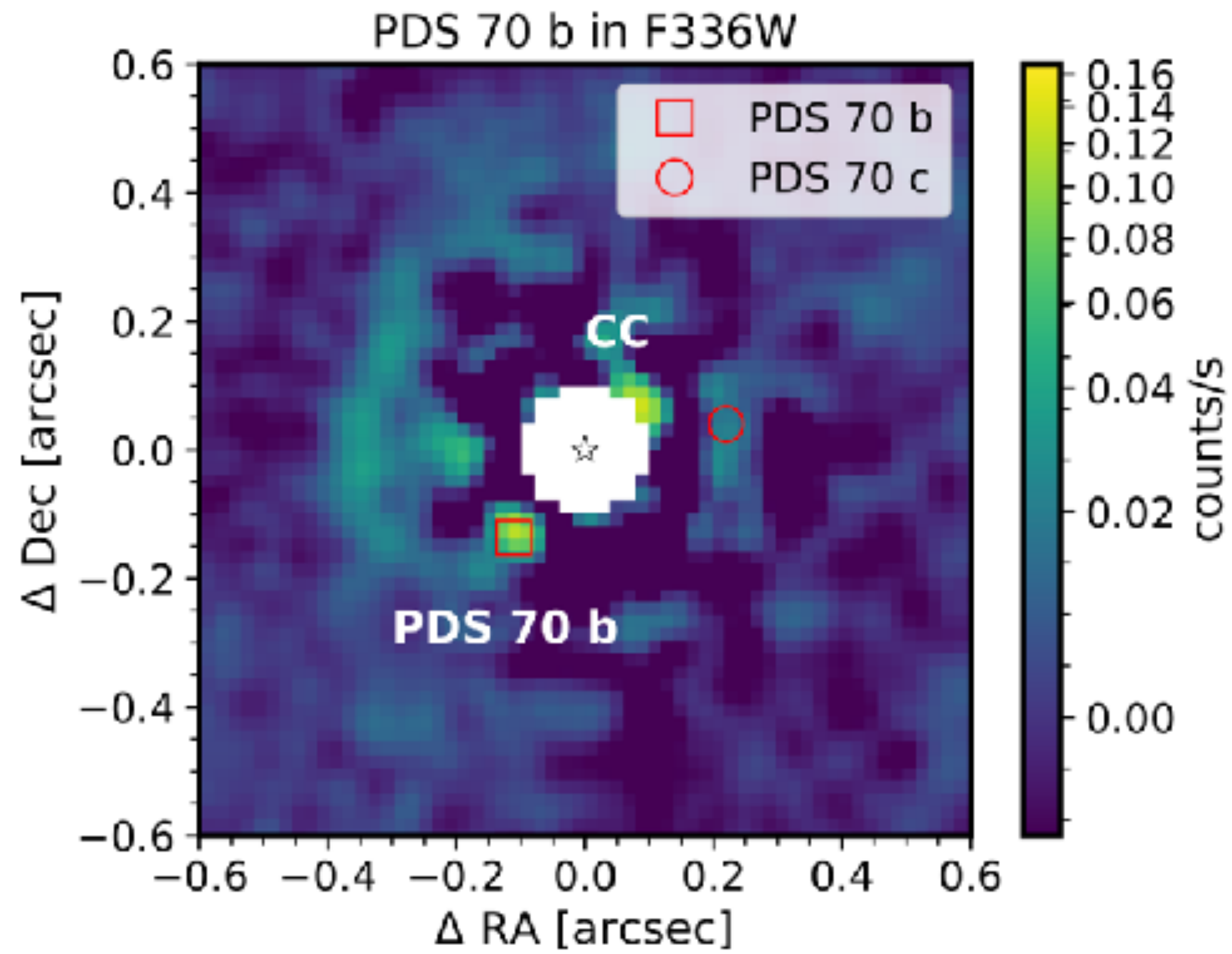
# Orbits constrained by VLTI/GRAVITY

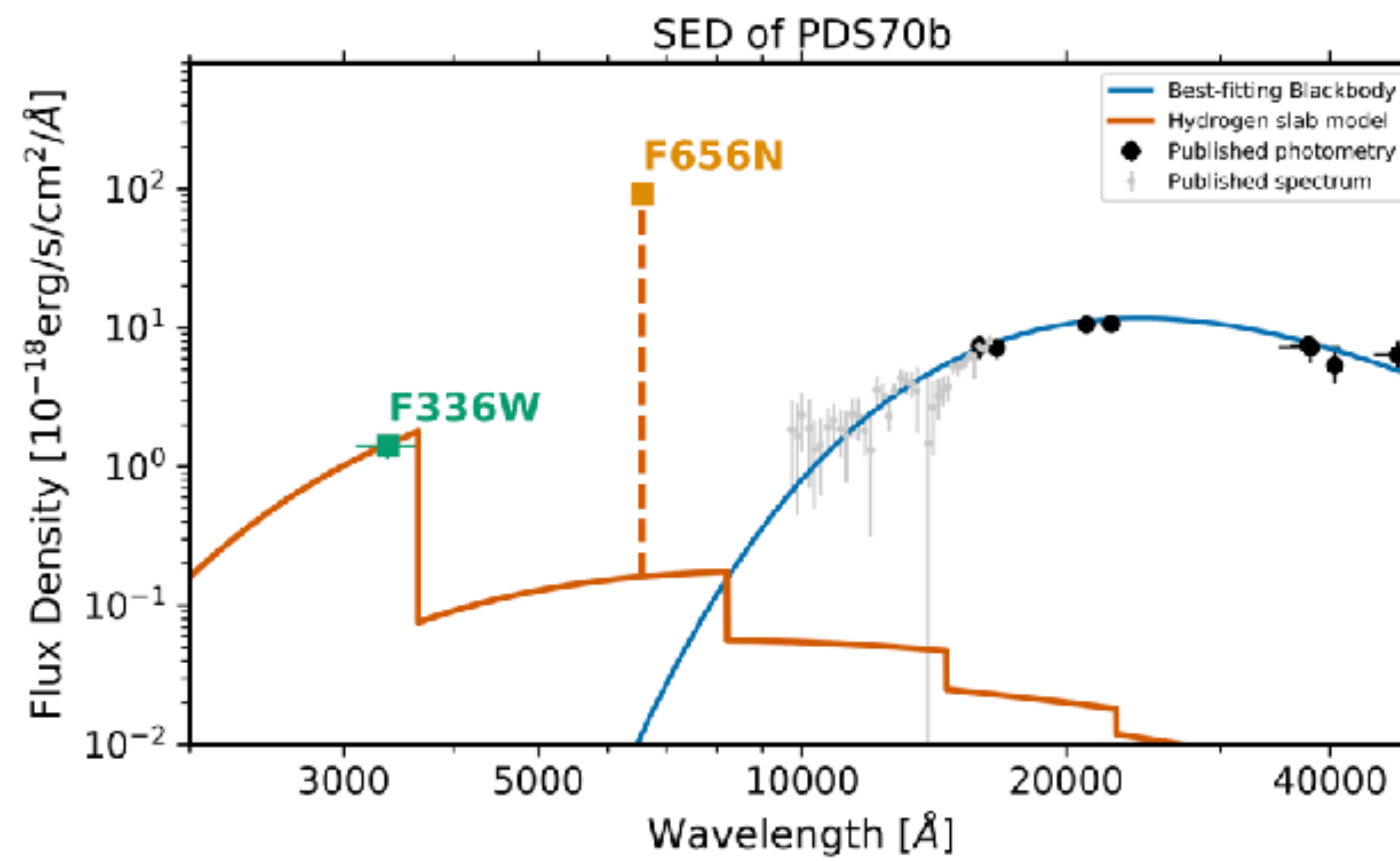



**Wang,...,Facchini+2021**

Planet b has eccentricity of 0.17, c is nearly circular, and they are close to 2:1 MMR, as predicted by Bae,...,Facchini+2019 (see also Toci+2020)

# Accretion signatures



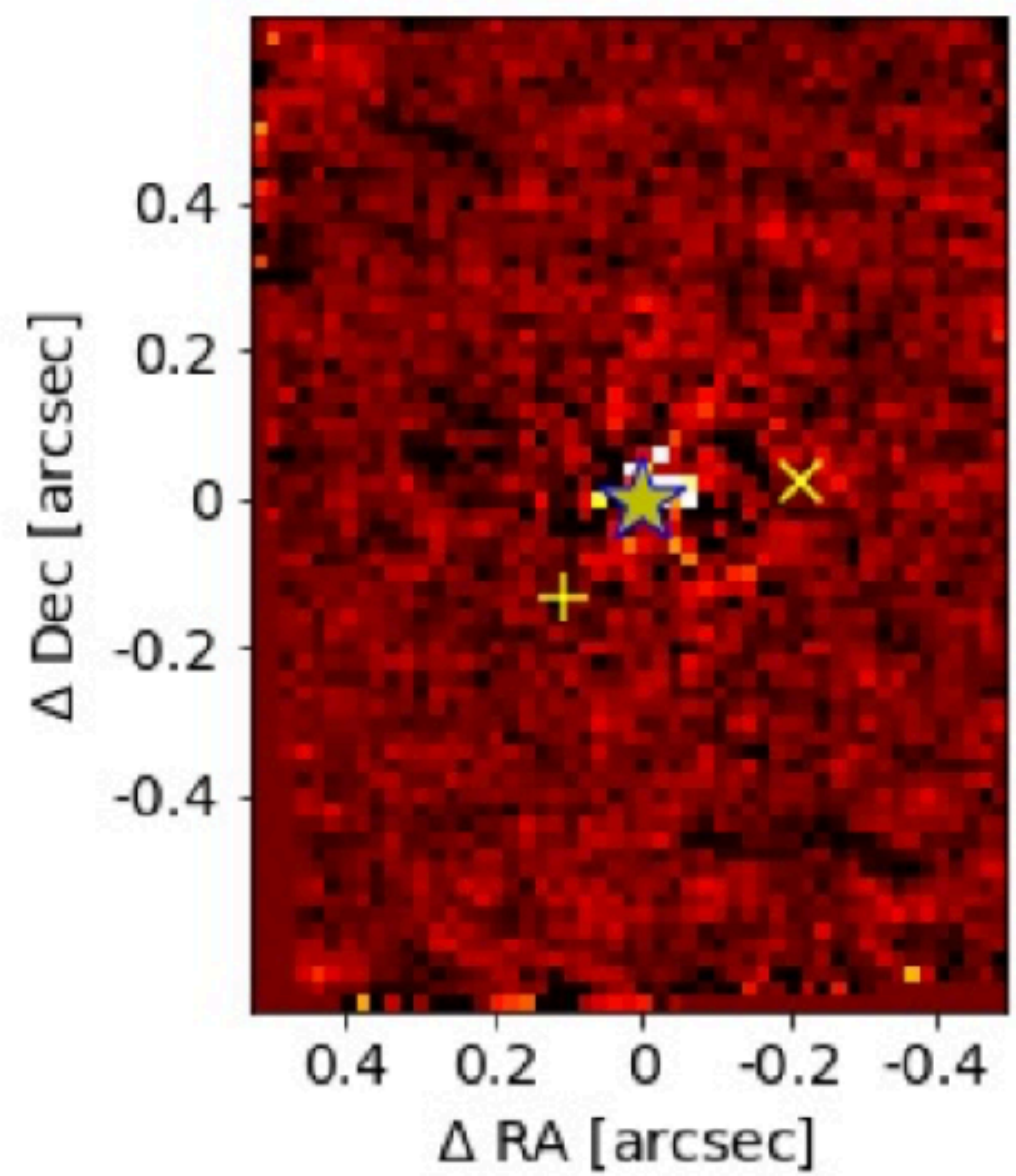




Zhou+2021

Accretion detected in both planets from Hα (Haffert+2019)
PDS 70b detected in UV (Zhou+2021)

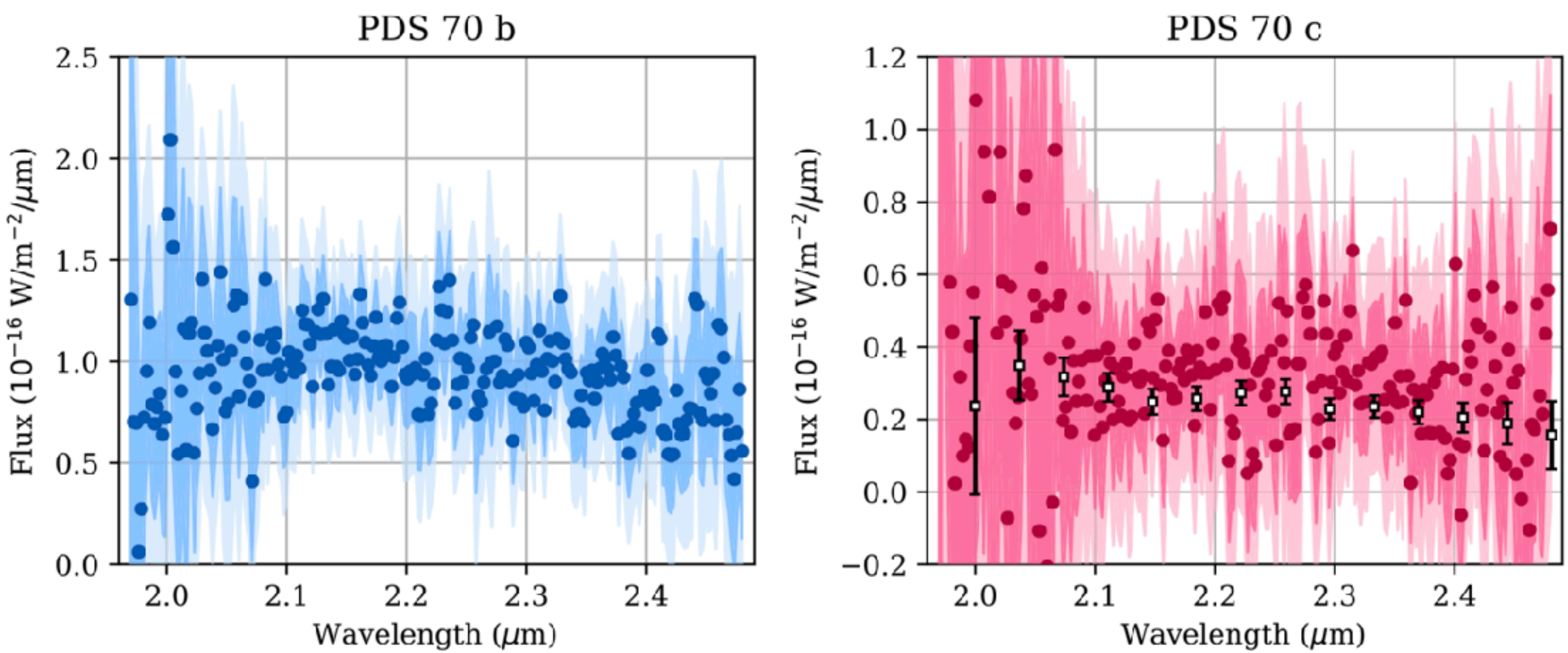
# Spectroscopic constraints

Hydrogen series: Hα only one detected, stringent upper limits on:
- Hβ (Hashimoto+2020)
- Br α (Stolker+2020)
- Br γ (Wang,…,Facchini+2021)
- Pa β (Uyama+2021)




Uyama+2021

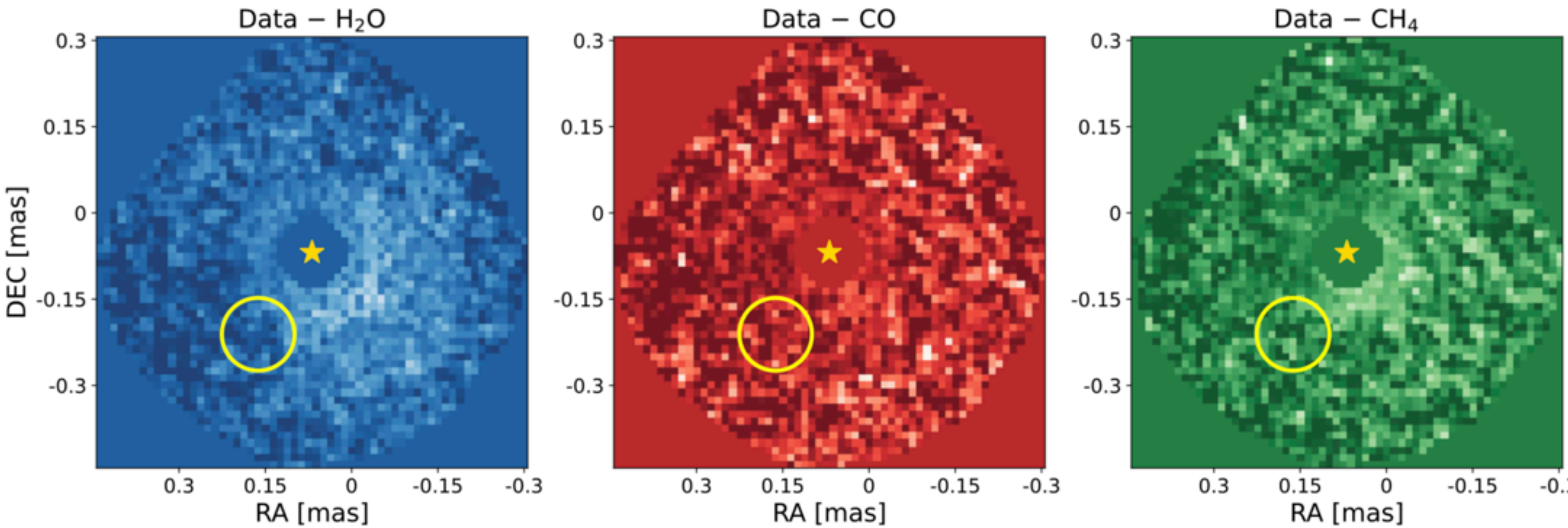
# Emission spectrum not constraining on C/O ratio




Wang,…,Facchini+2021

*K*-band emission spectrum lacks atmospheric features.
The elemental abundances are unconstrained

# Absorption spectrum not constraining on C/O ratio




Cugno+2021

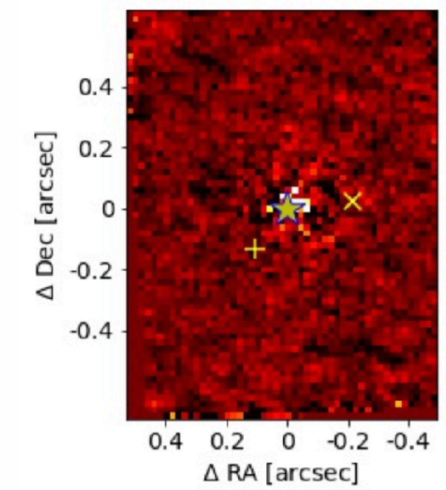
No molecular features detected in SINFONI spectrum

# Vertical structure of dust close to the planet

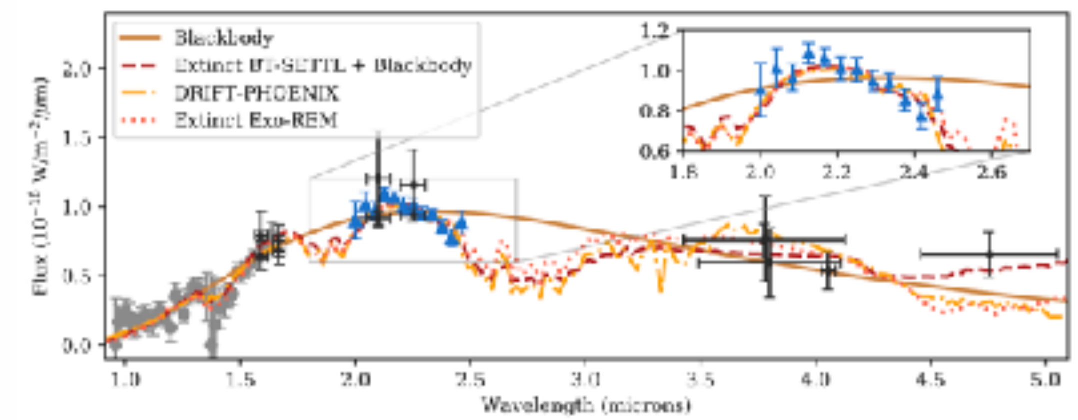
*Hydrogen series:*
$A_V$ ~ 0.9 - 2 magnitudes

*SED modelling*
$A_V$ ~ 4 magnitudes

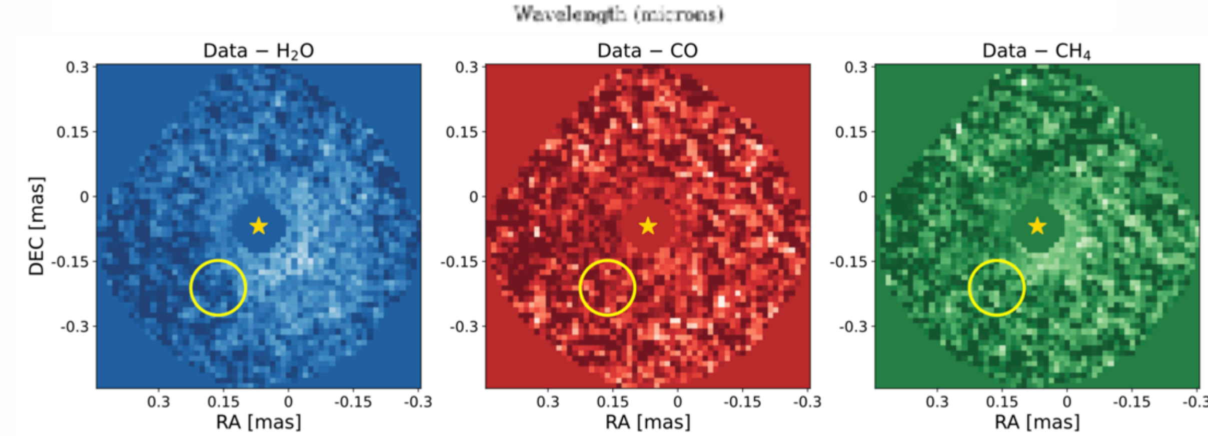
*Lack of molecular features*
$A_V$ ~ 16-17 magnitudes




Uyama+2021



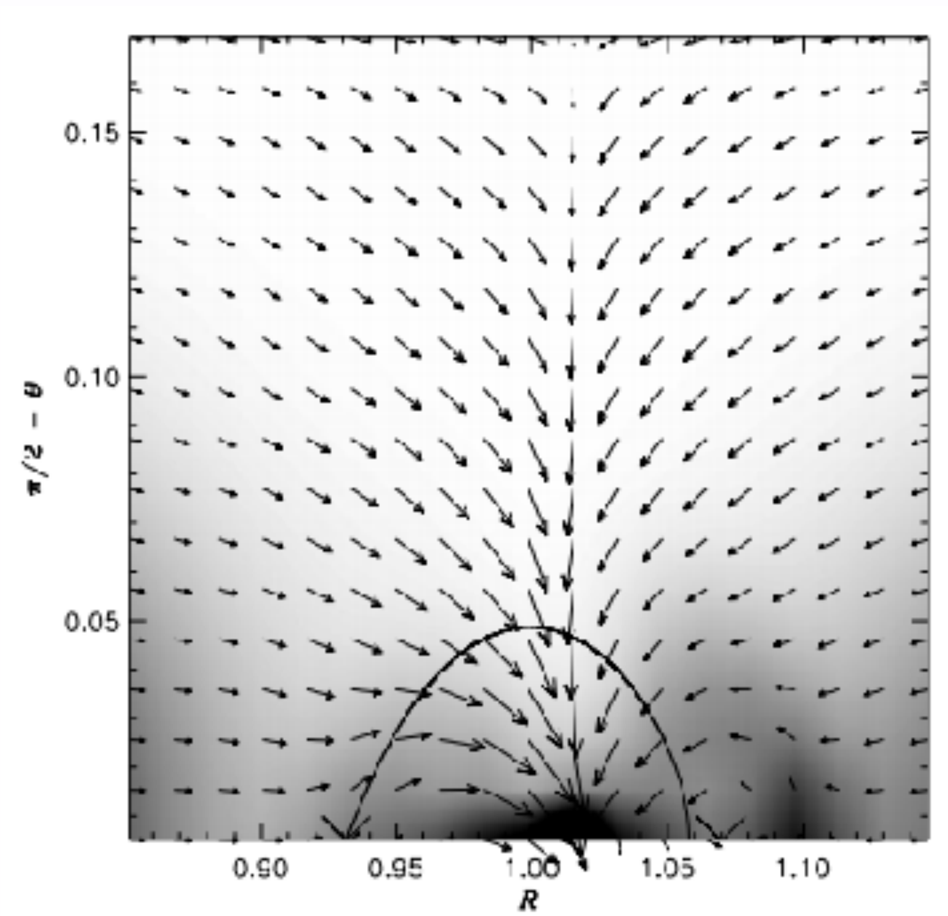

Wang+2021

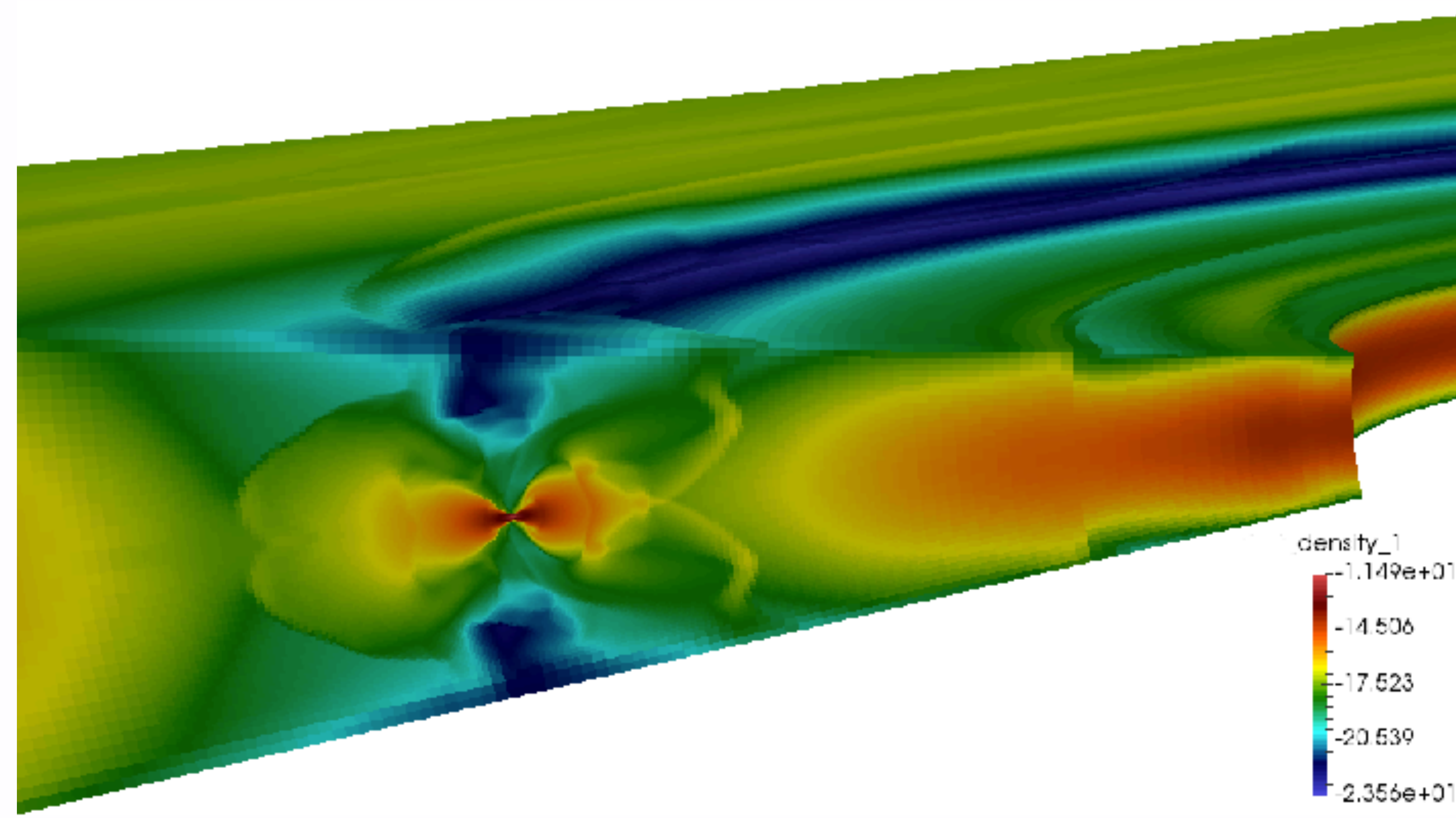



Cugno+2021

Different tracers probe different heights in the accretion - planetary atmosphere column

# Accretion mediated by circumplanetary disks



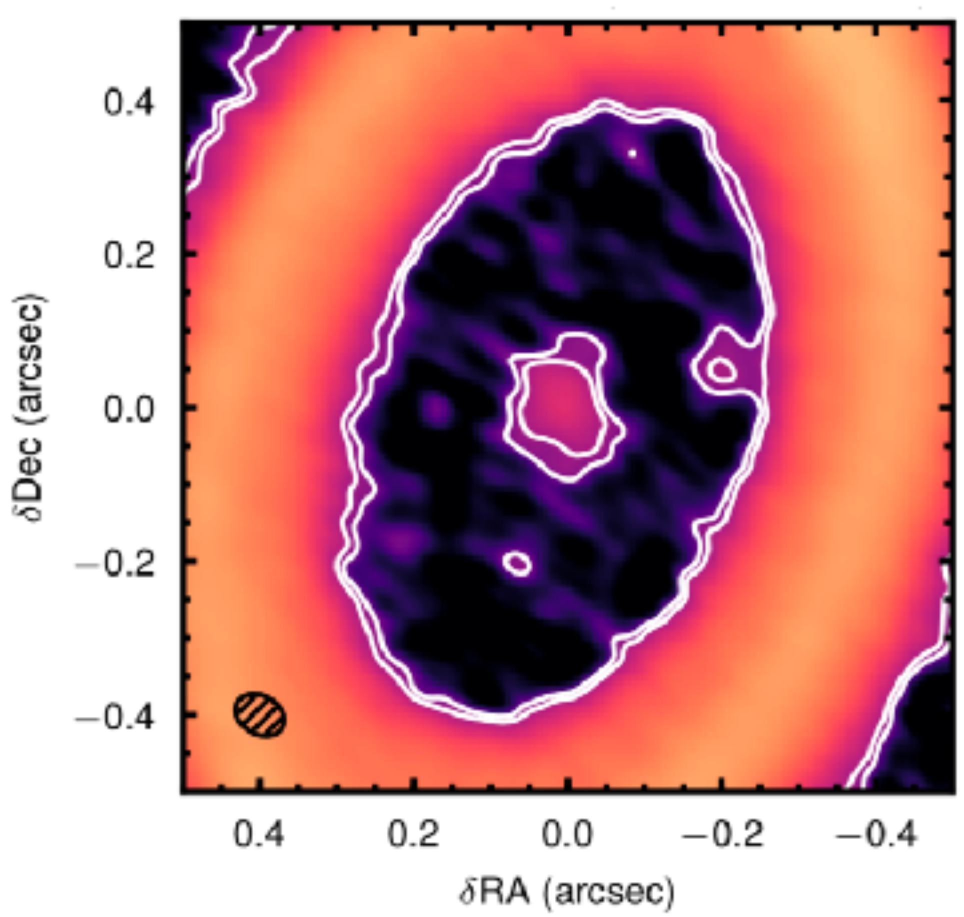




Most of the infalling material is radially expelled
e.g. Szulagyi+2017

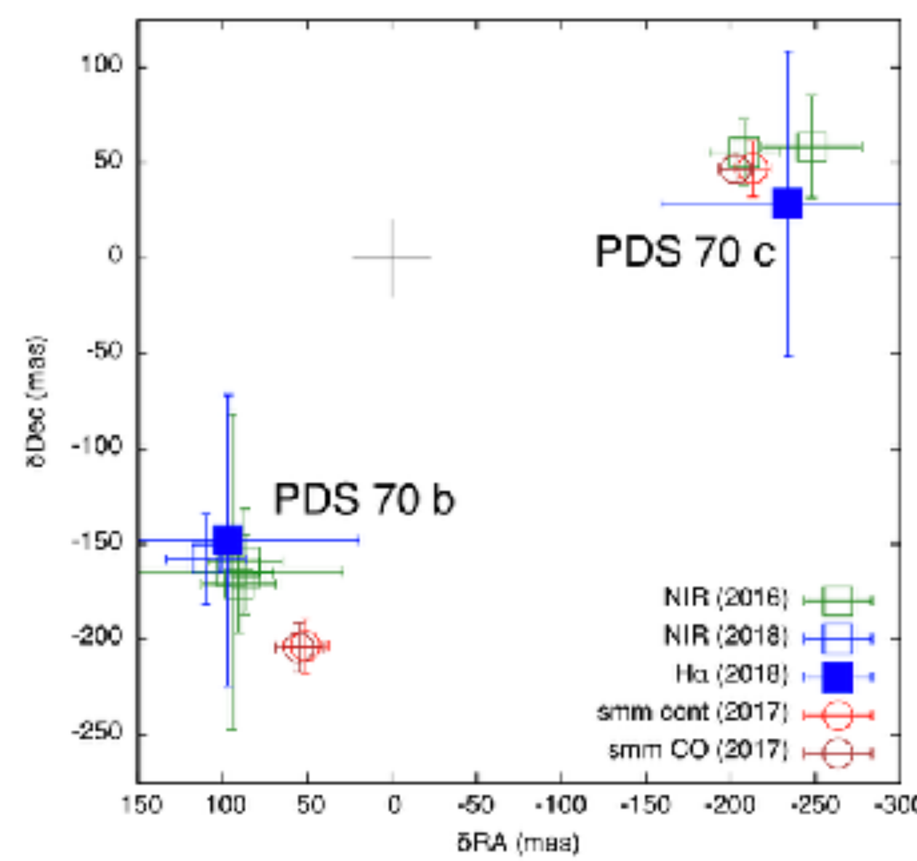
Accretion occurs from the poles
e.g. Kley+2001

# First evidence of circumplanetary disk from ALMA

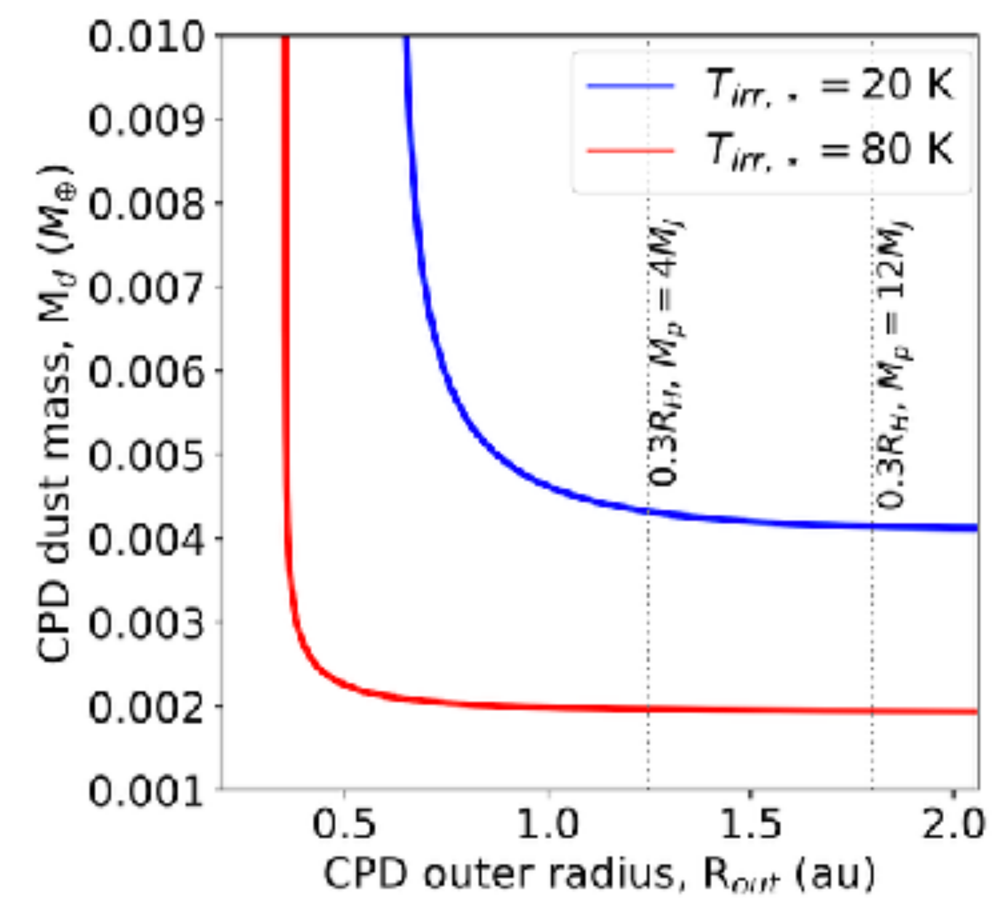
**ALMA 870 μm continuum**




**Astrometry**



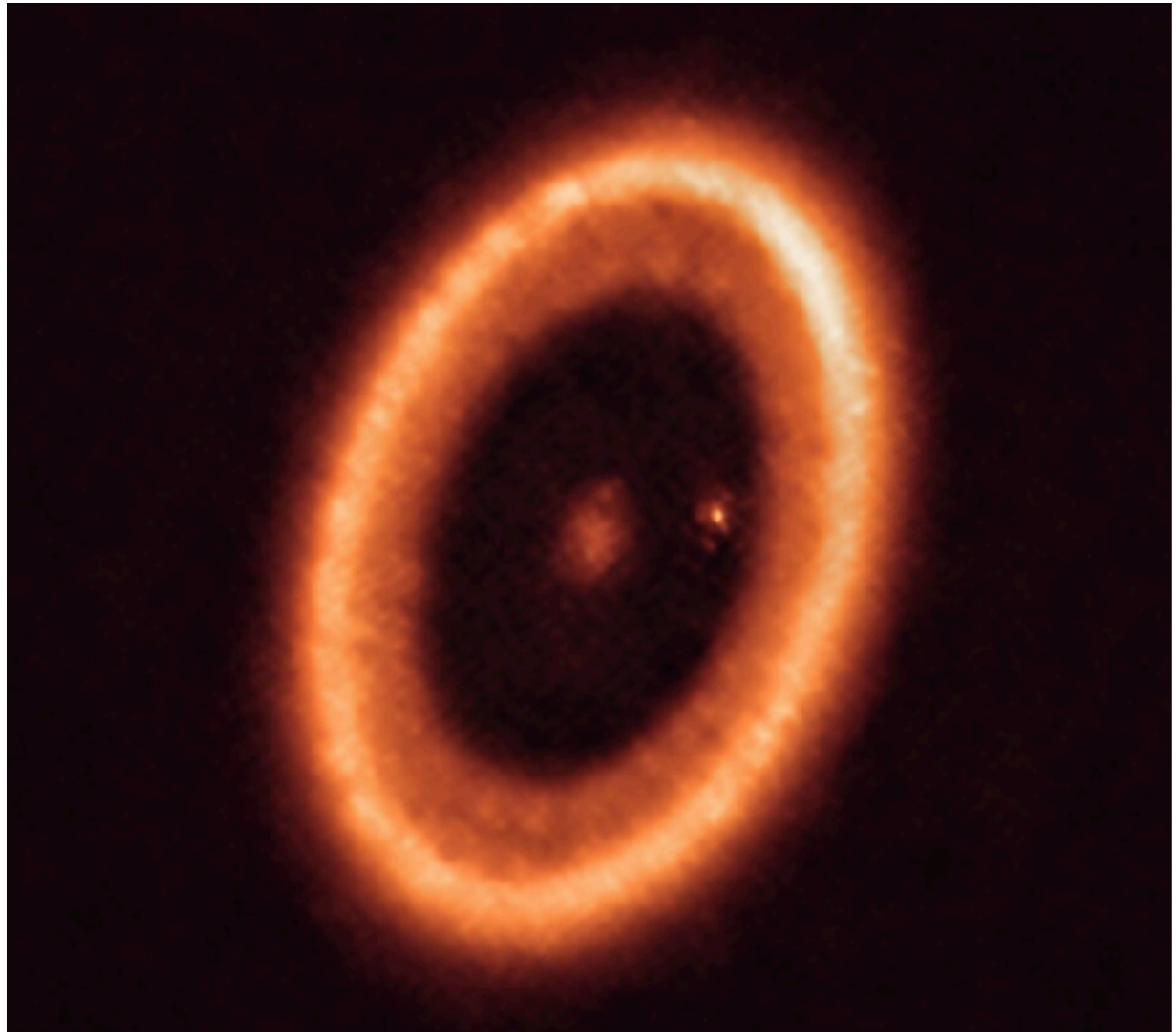

**CPD-c mass/radius**



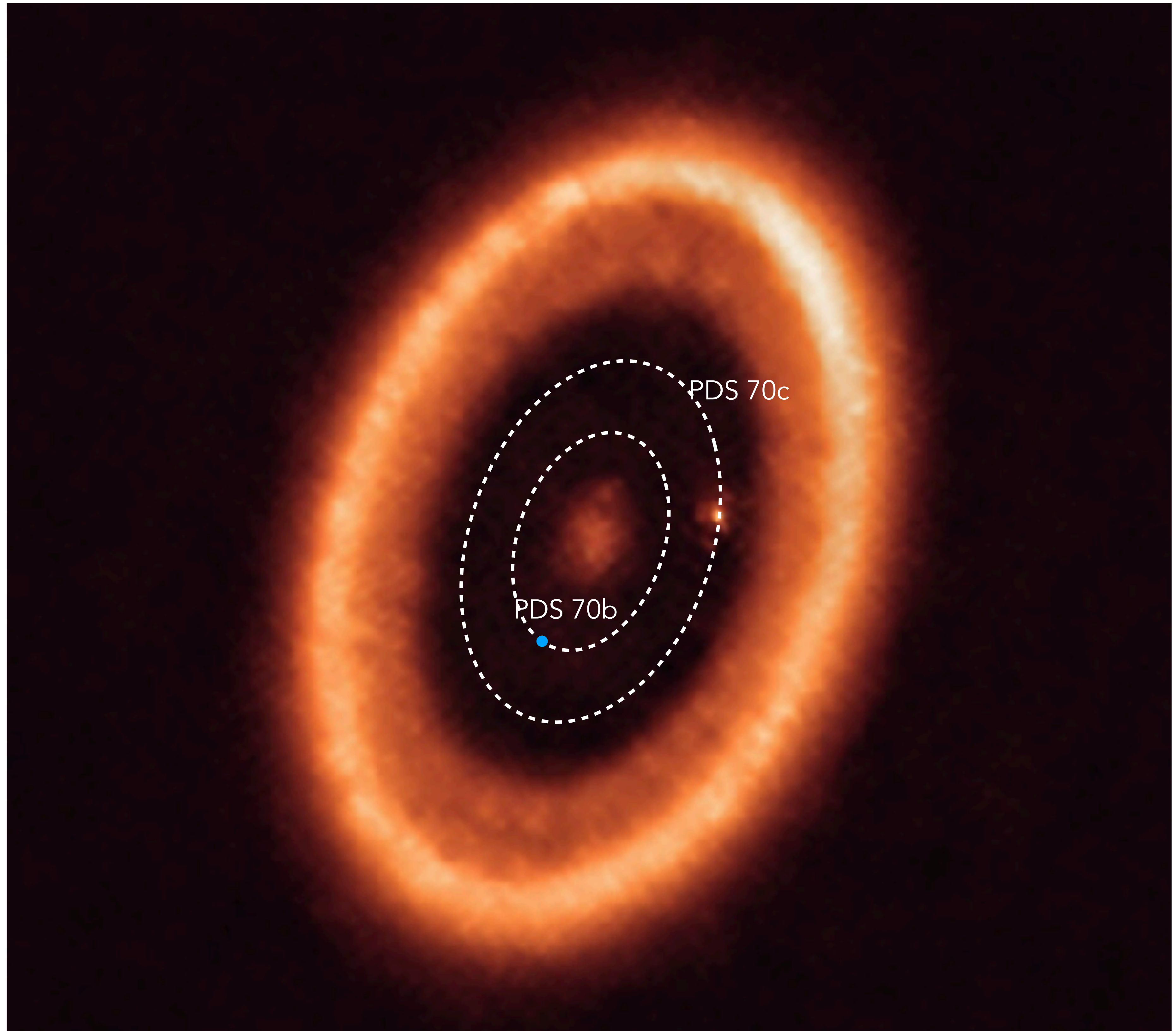

mm close to b shows astrometry not consistent with IR data

Isella,…,Facchini+2019

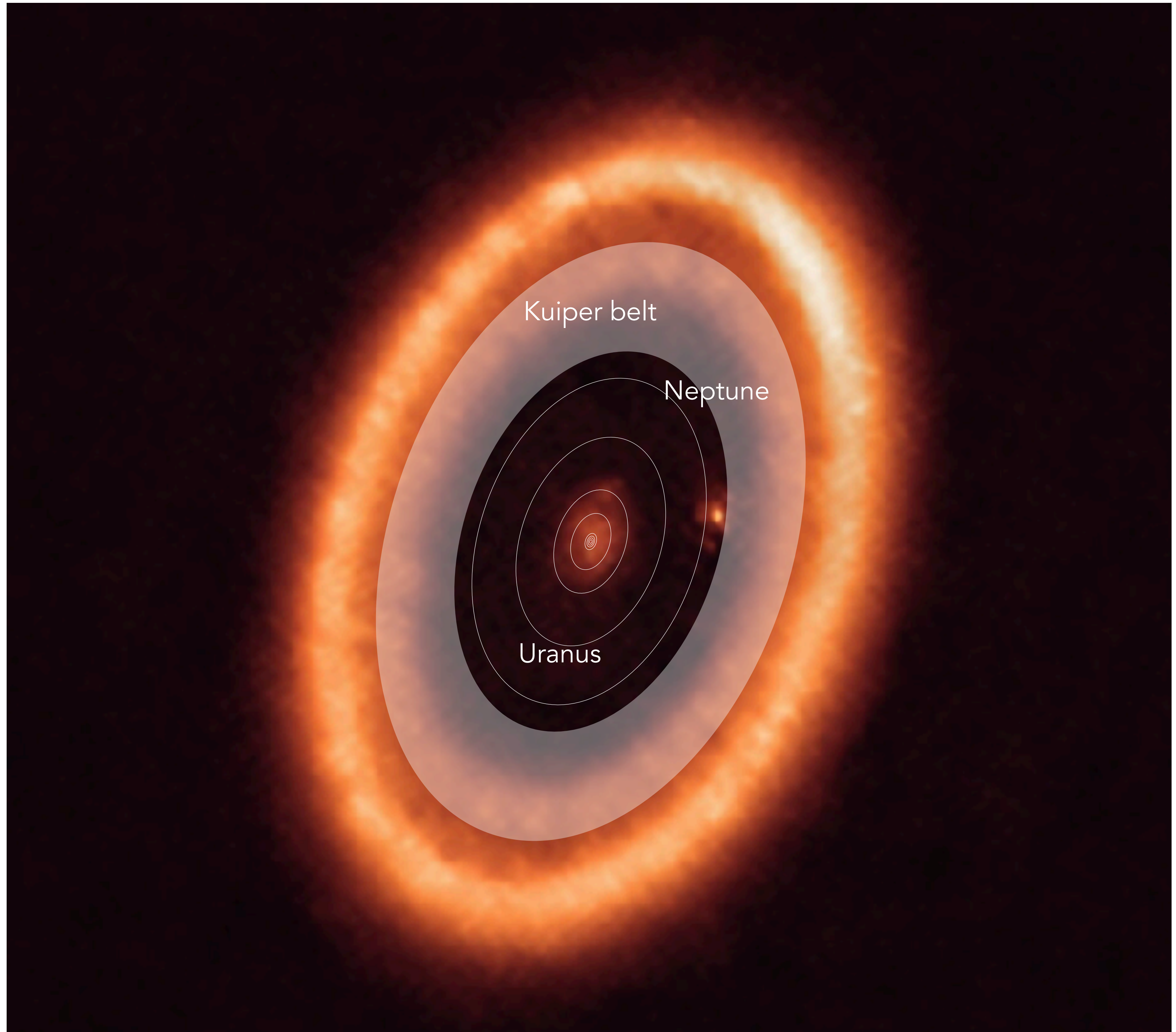
See also Christiaens+2019 for IR detection in PDS 70b



Benisty, Bae, Facchini+2021



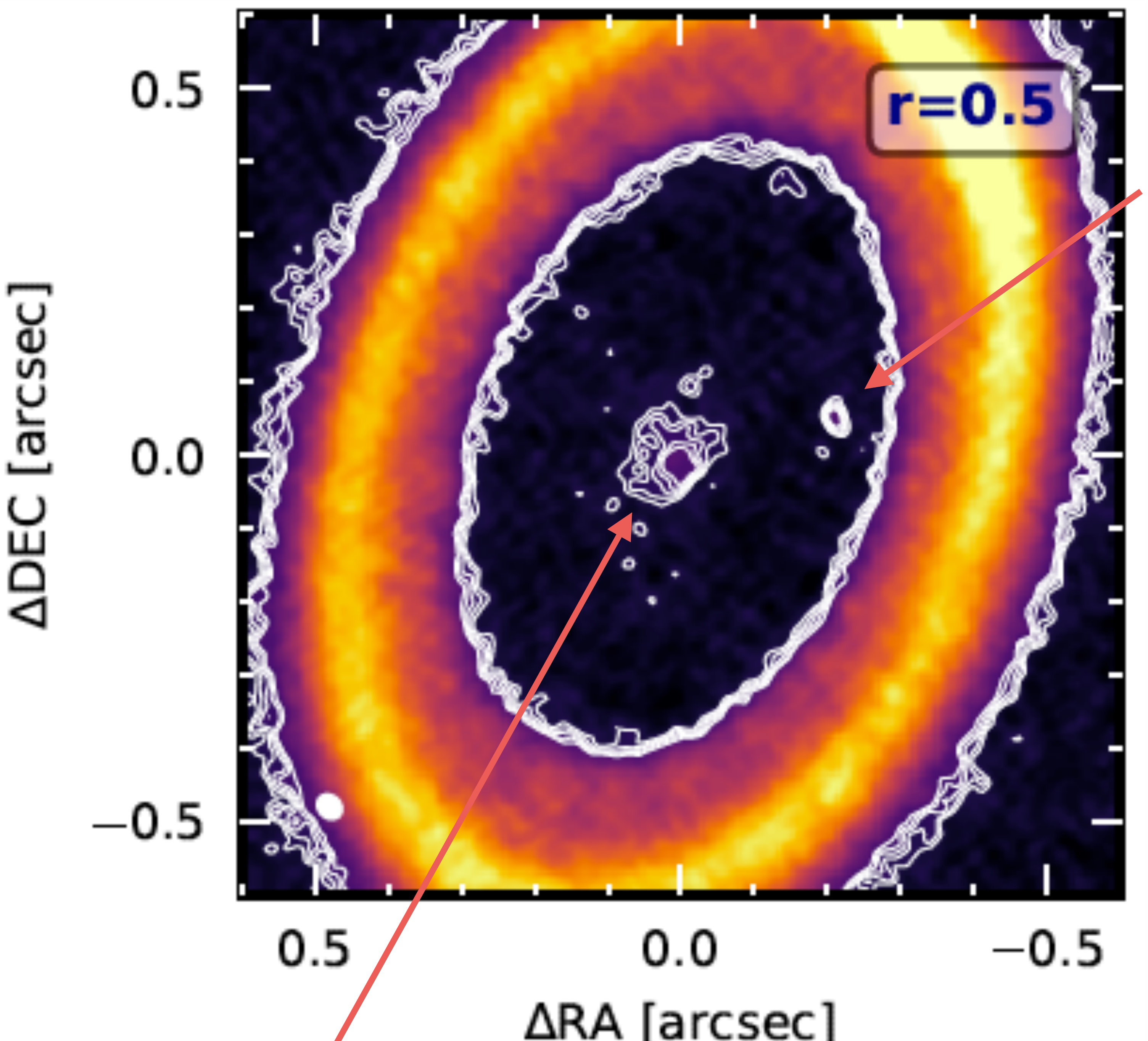

Benisty, Bae, Facchini+2021



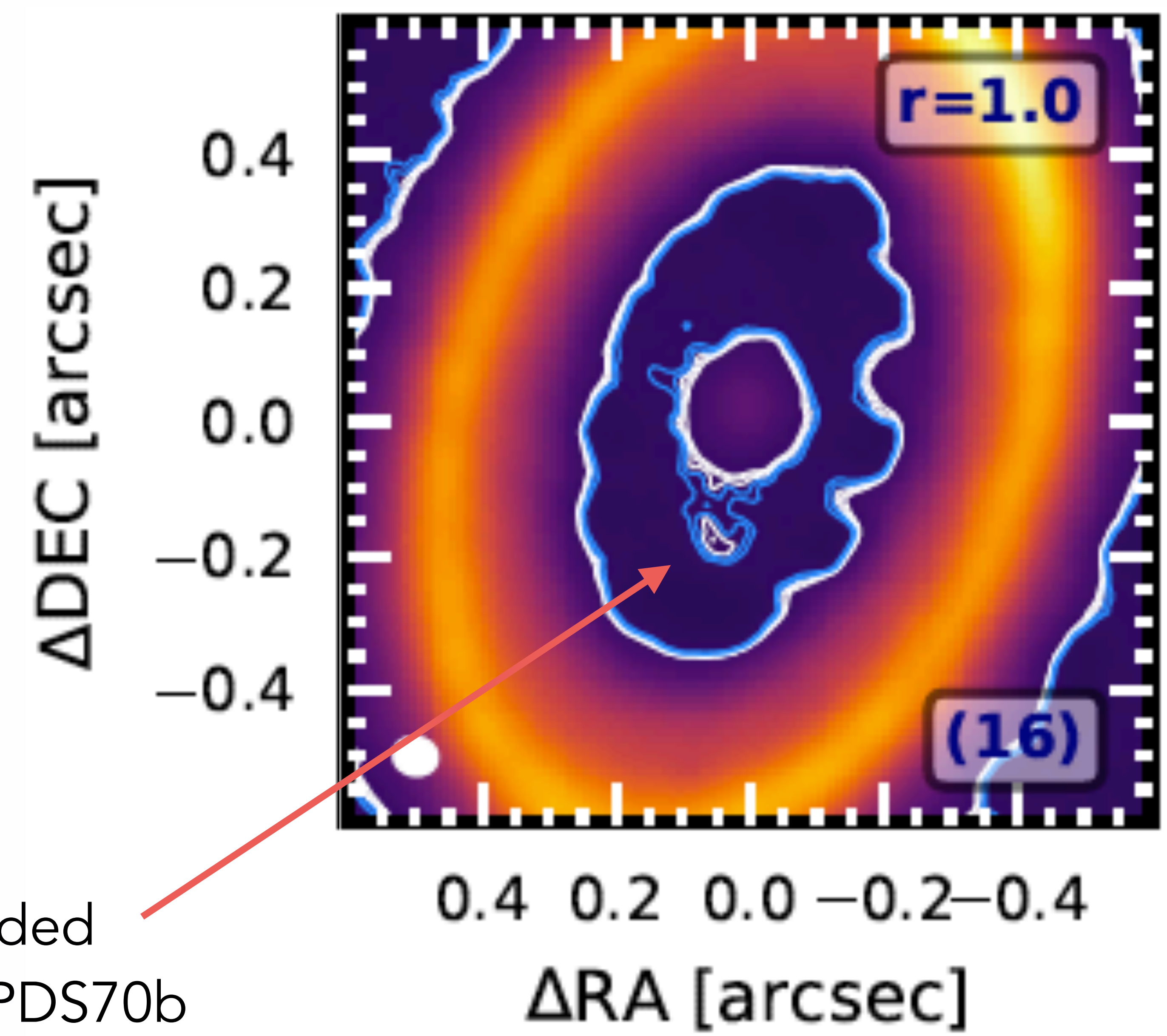

Benisty, Bae, Facchini+2021

# Circumplanetary material

New ~20 mas (2.3 au) resolution observations at 855 μm




Compact emission co-located with PDS70c

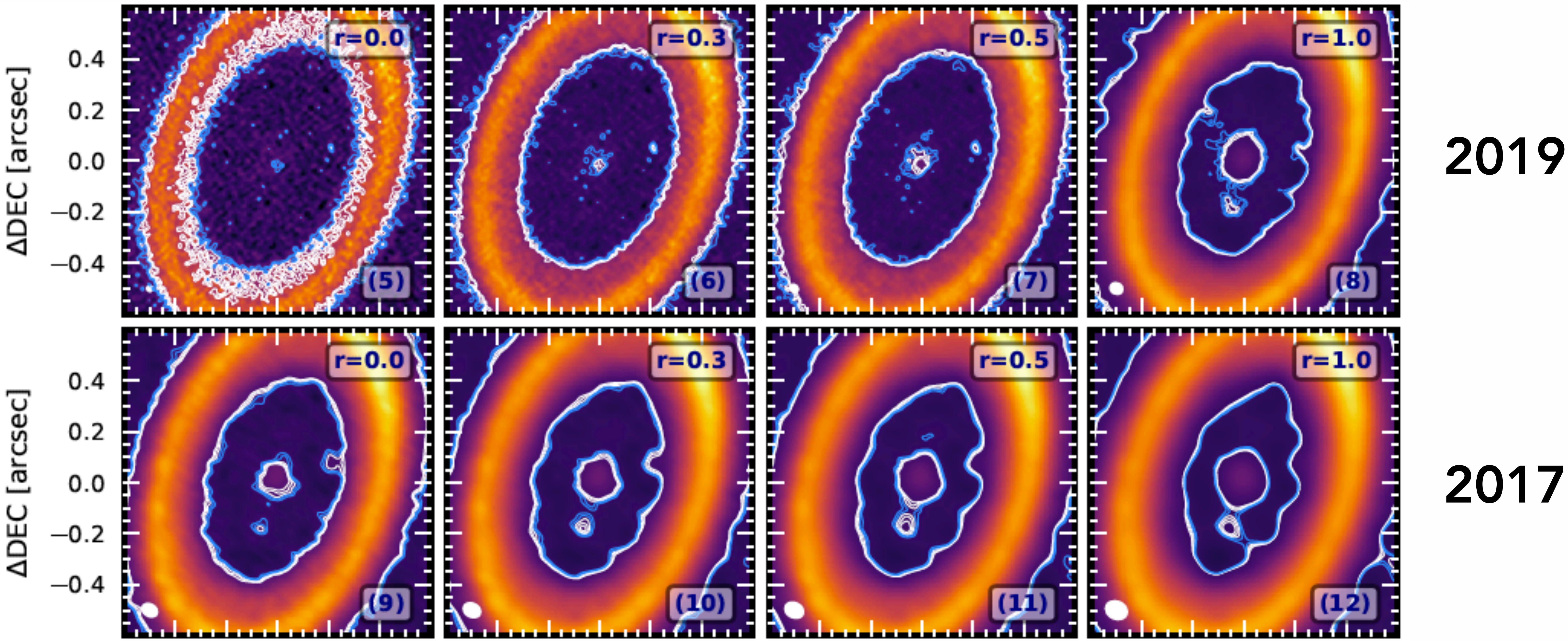



Faint optically thin inner disk

Faint extended emission *near* PDS70b

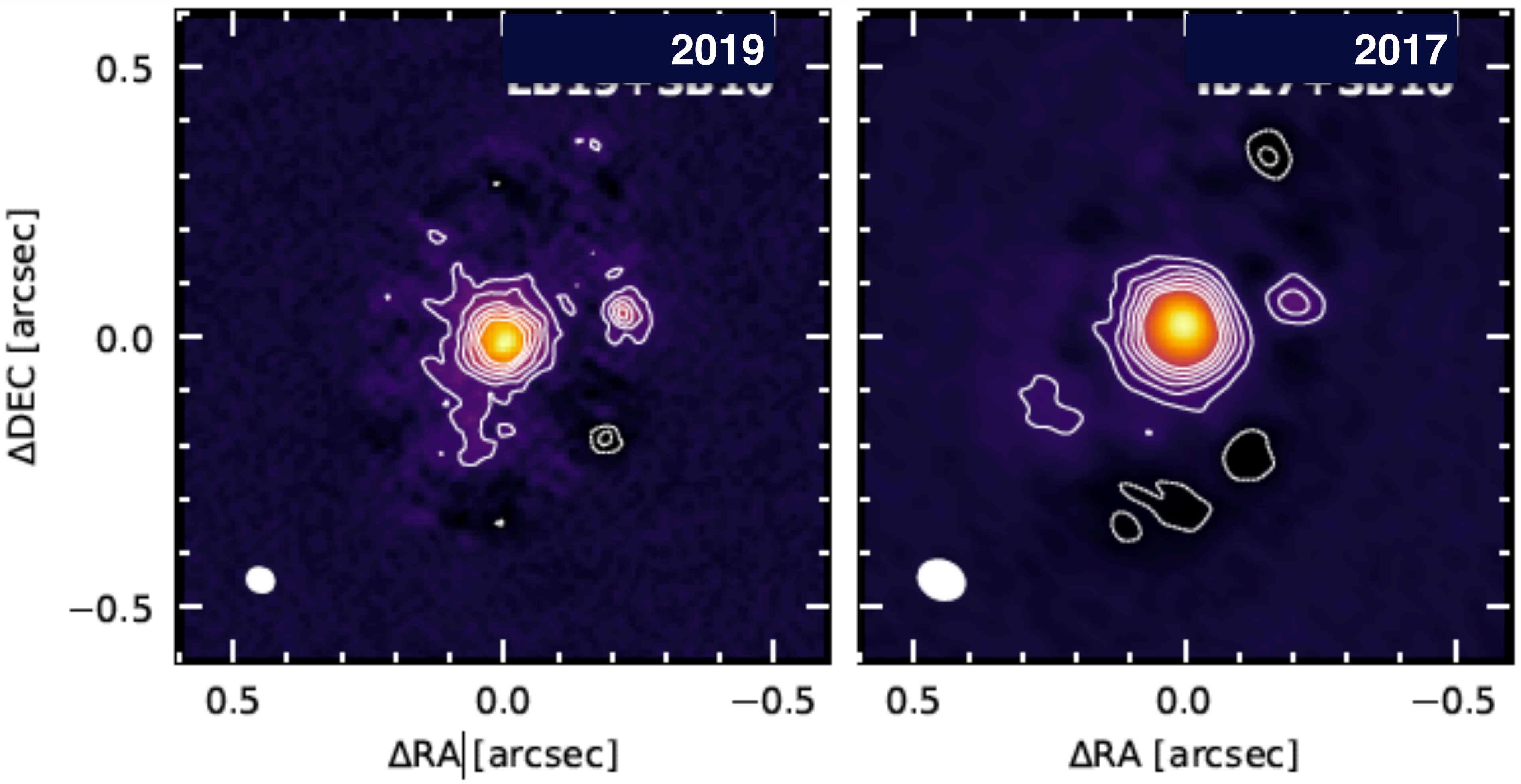
Benisty, Bae, Facchini+2021

# Circumplanetary material



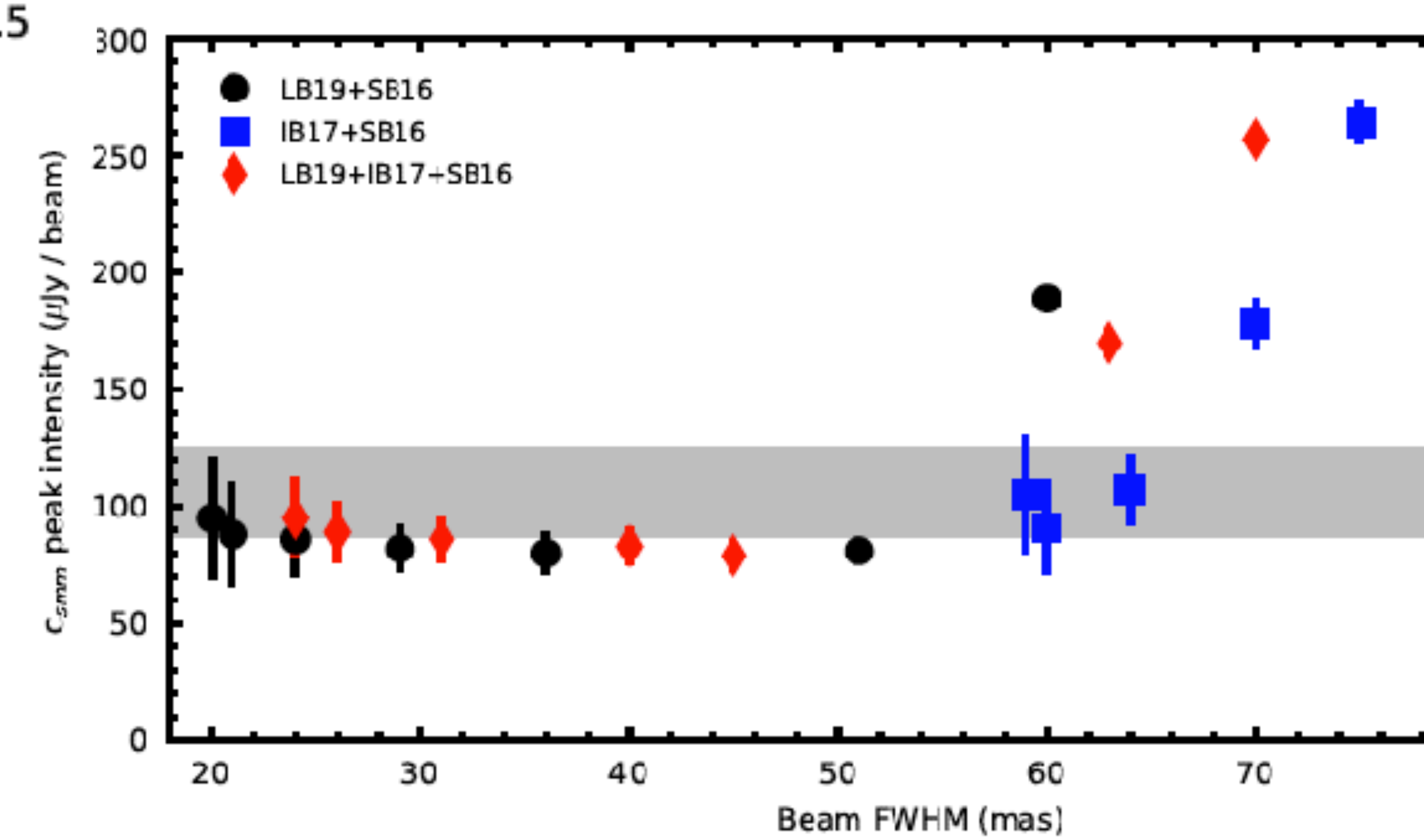

Emission around PDS70c recovered independently in all images from 2017 and 2019
Emission around PDS70b only recovered with beam > 50 mas; morphology unclear

# A circumplanetary disk around PDS70c

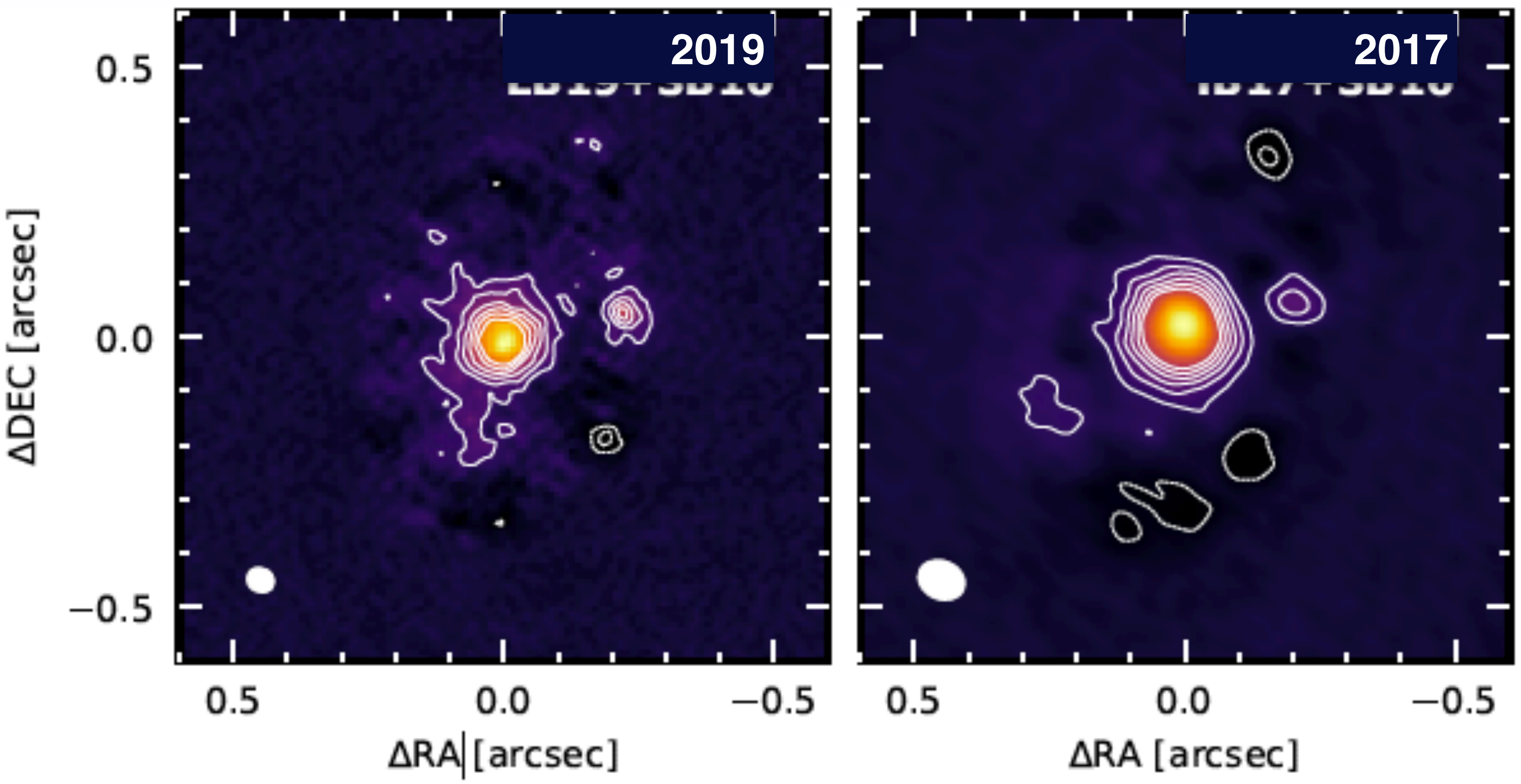



“Cavity images” after subtraction of the FT of the CLEAN model of the outer disk
16 “sigma” detection of $c_{smm}$

Peak I similar in all images as long as it is spatially resolved from the ring.
CPD is unresolved, with extent < 1.2 au



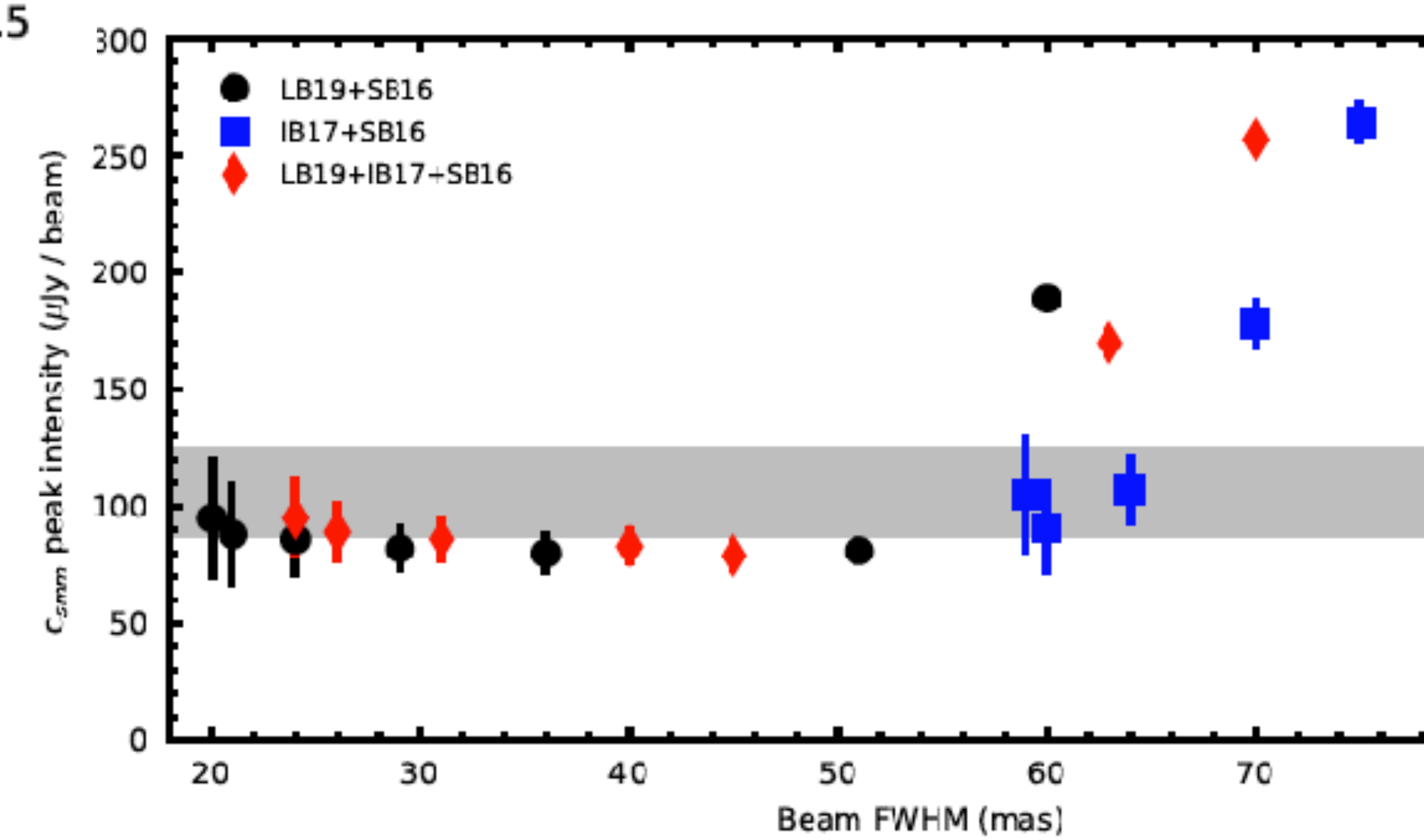
# A circumplanetary disk around PDS70c



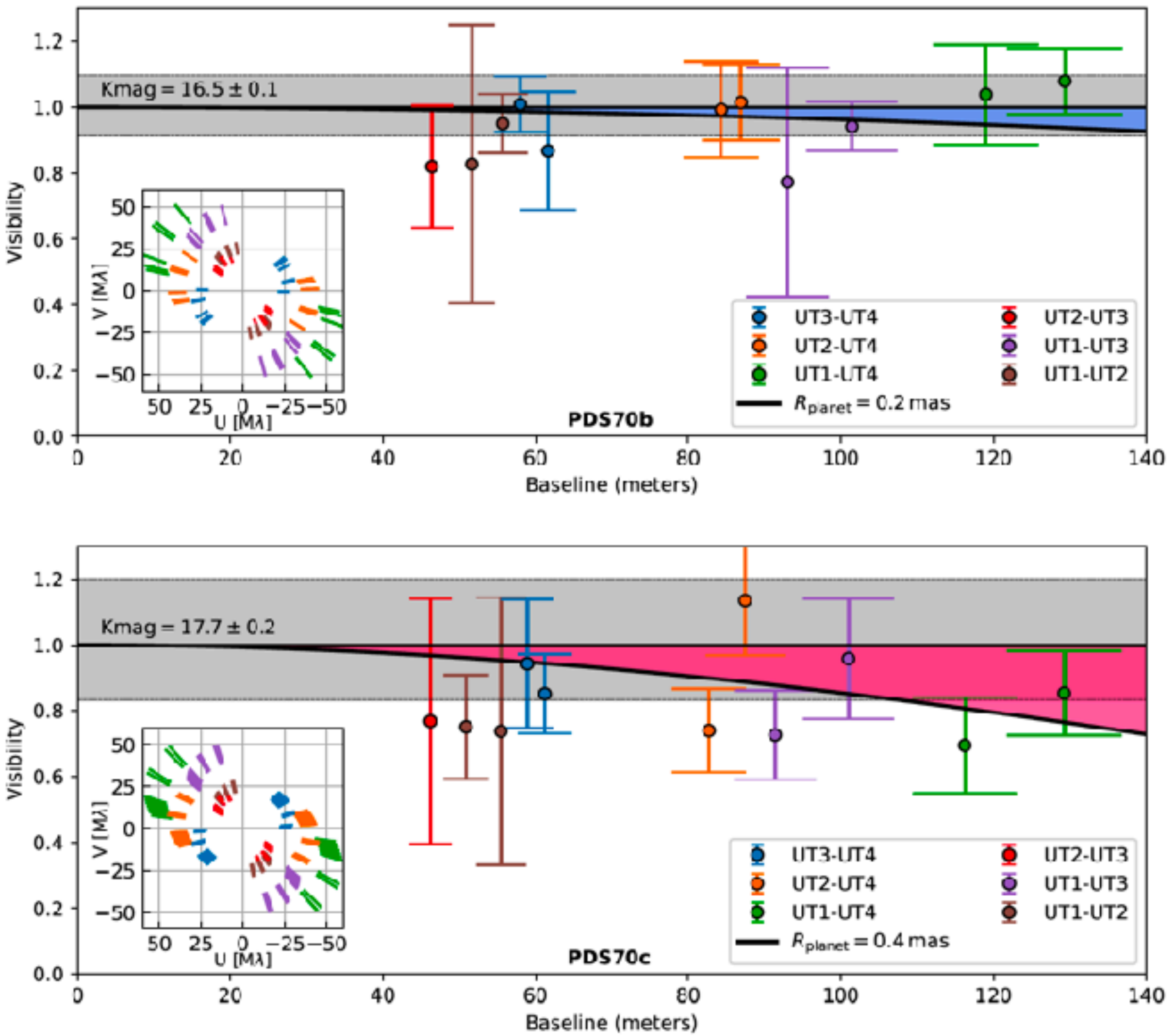

"Cavity images" after subtraction of the FT of the CLEAN model of the outer disk
16 "sigma" detection of $c_{smm}$

See Sean's talk on robustness of CPD detections

Peak I similar in all images as long as it is spatially resolved from the ring.
CPD is unresolved, with extent < 1.2 au



# CPD extent

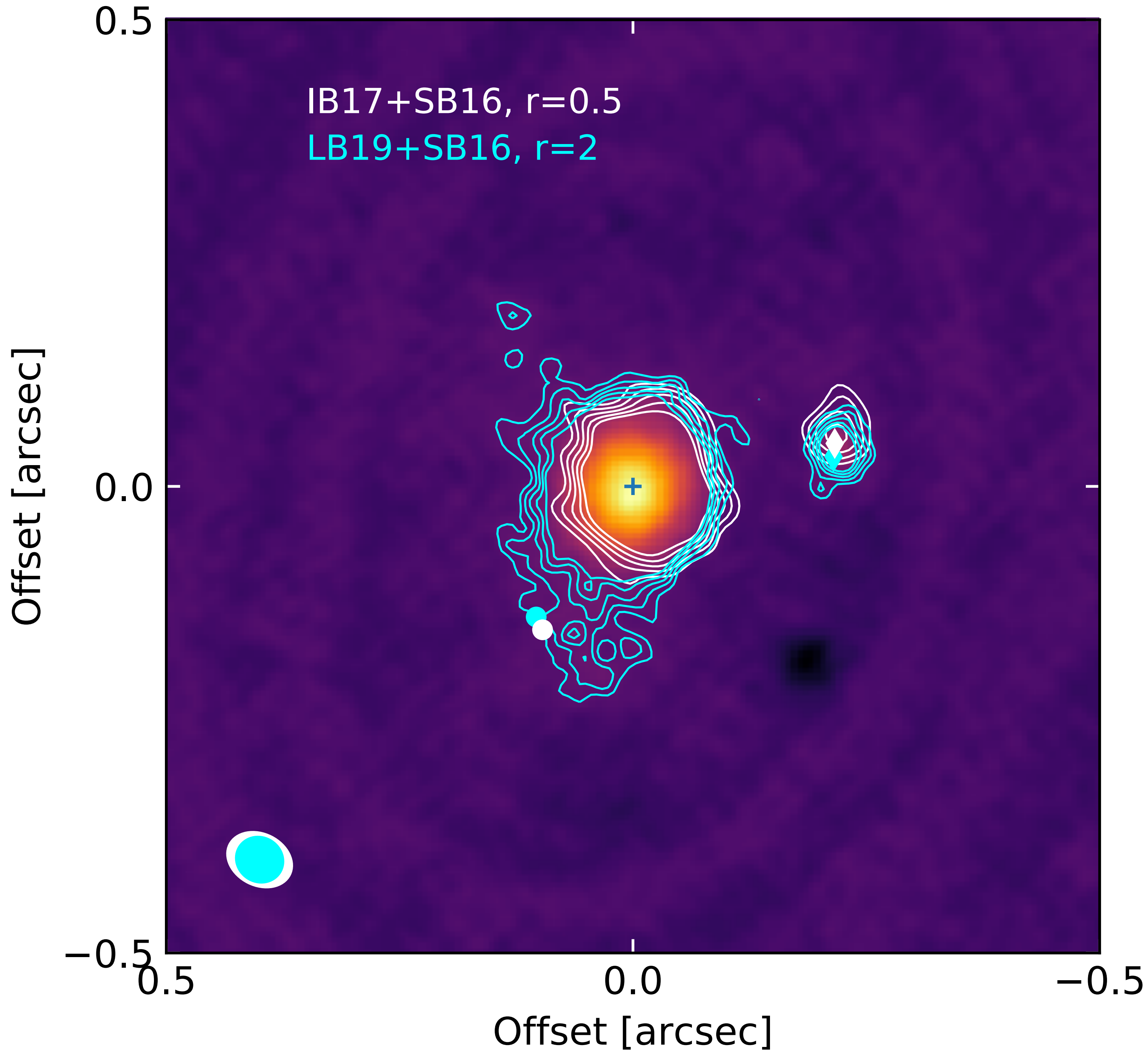


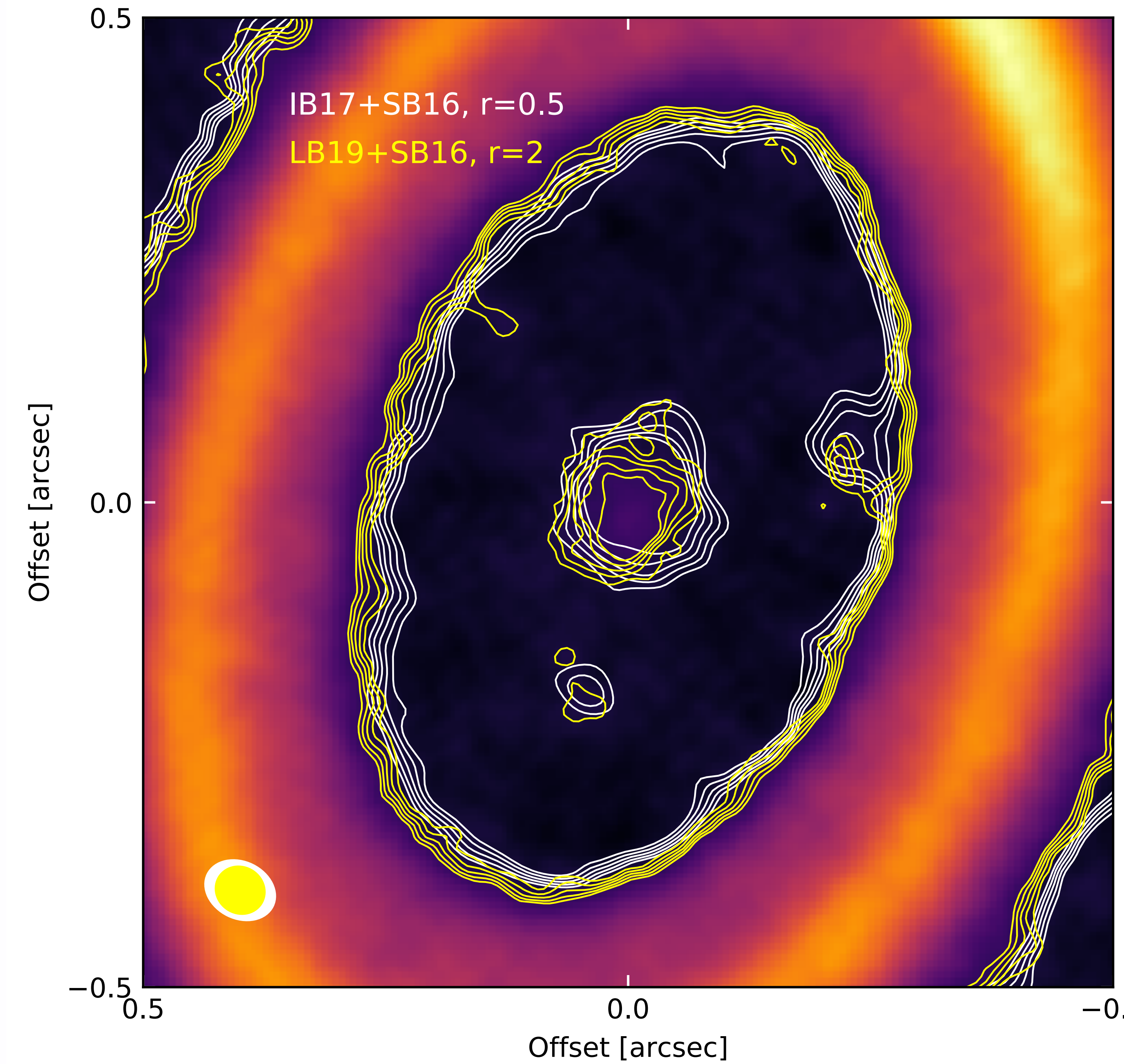

- Hill radius of PDS70c ~ 3.1 au
- Truncation expected at 1/3 RH~ 1 au consistent with CPD extent in the submm < 1.2 au
- CPD in the IR < 0.1 au from GRAVITY

ExoGravity program

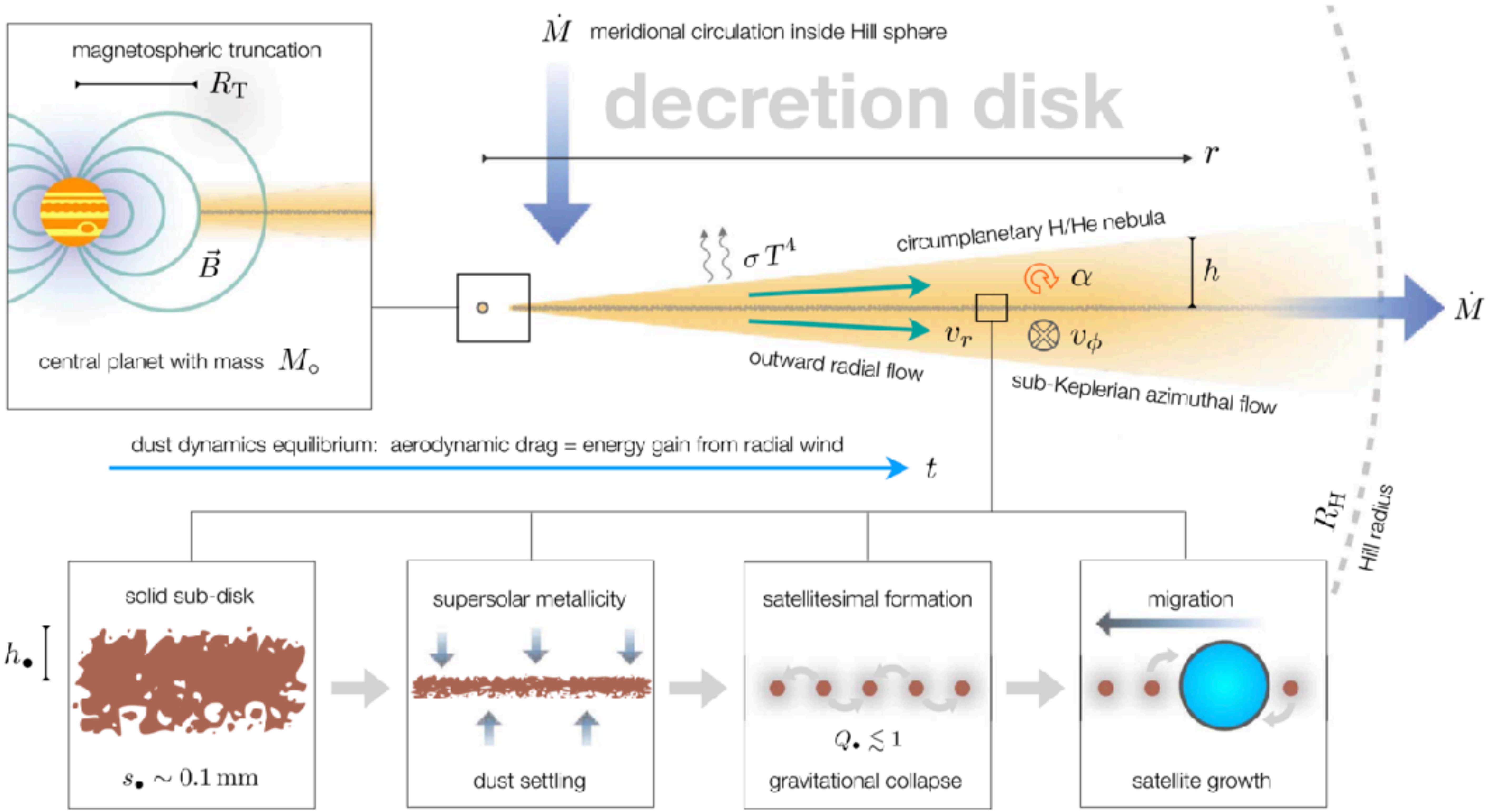
**Wang,…,Facchini+2021**

# Displacemement of photo-center of CPD-c in agreement with expected astrometry (work in progress)



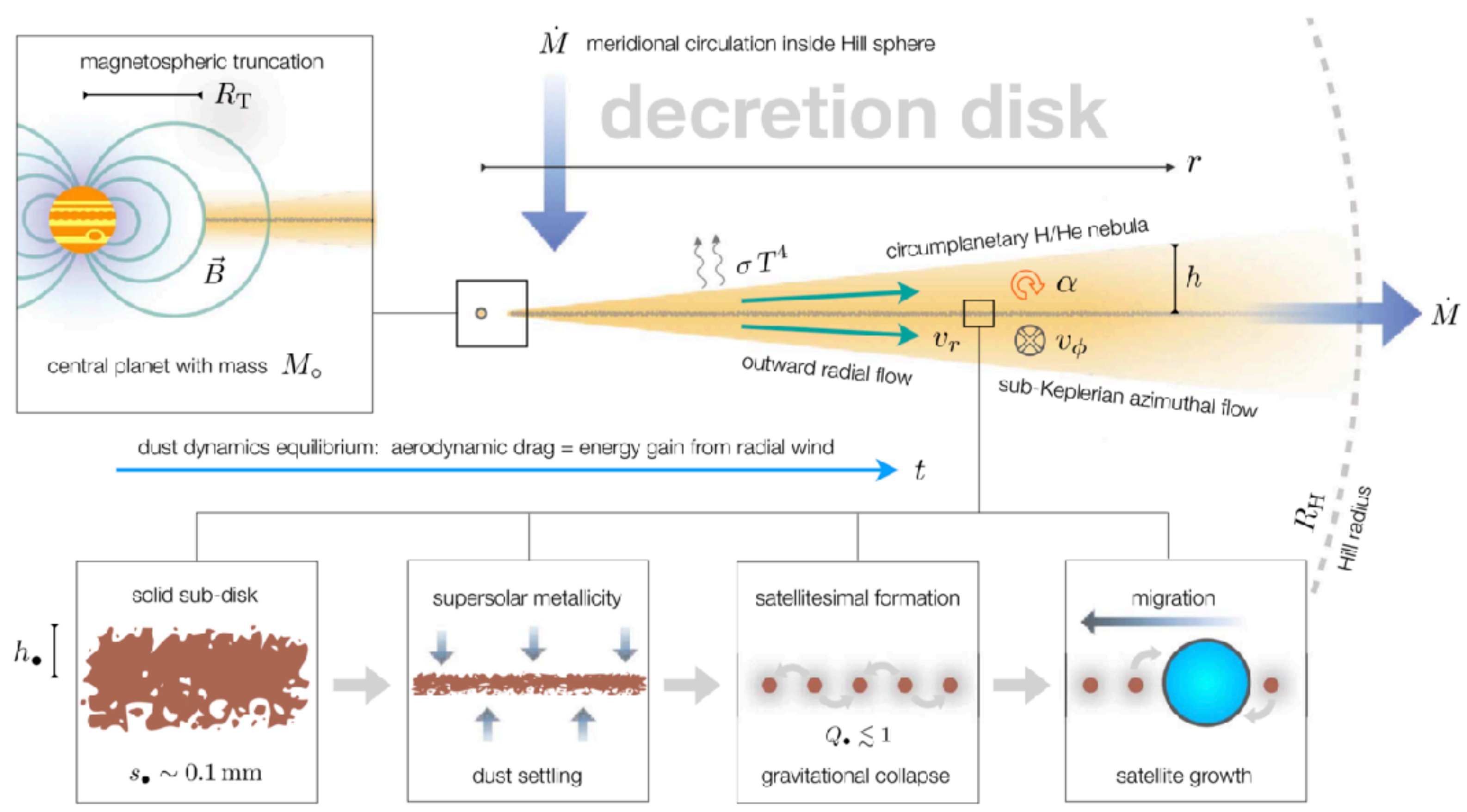



# Dust entrainment in CPDs

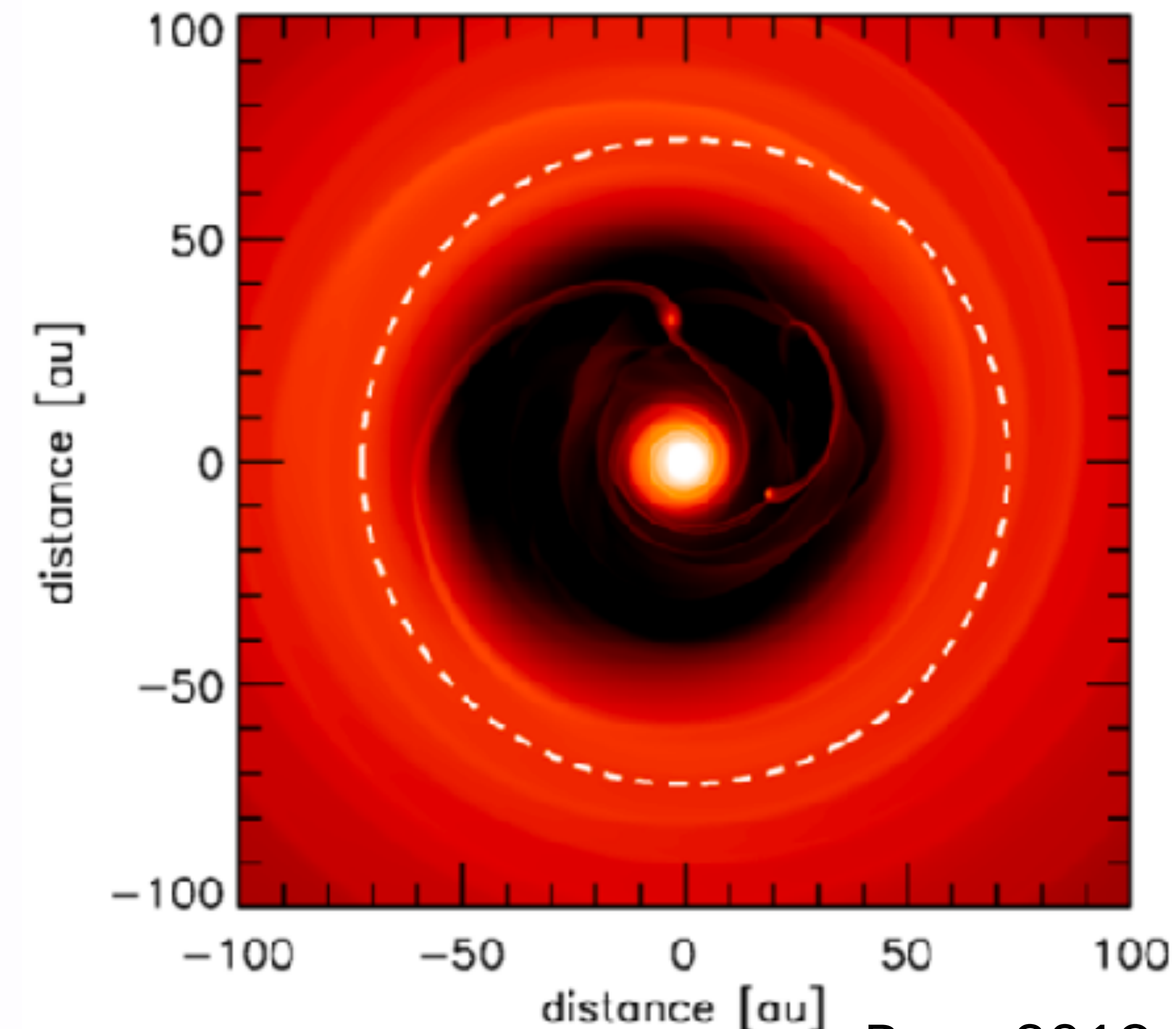



Batygin & Morbidelli 2020

# Dust entrainment in CPDs



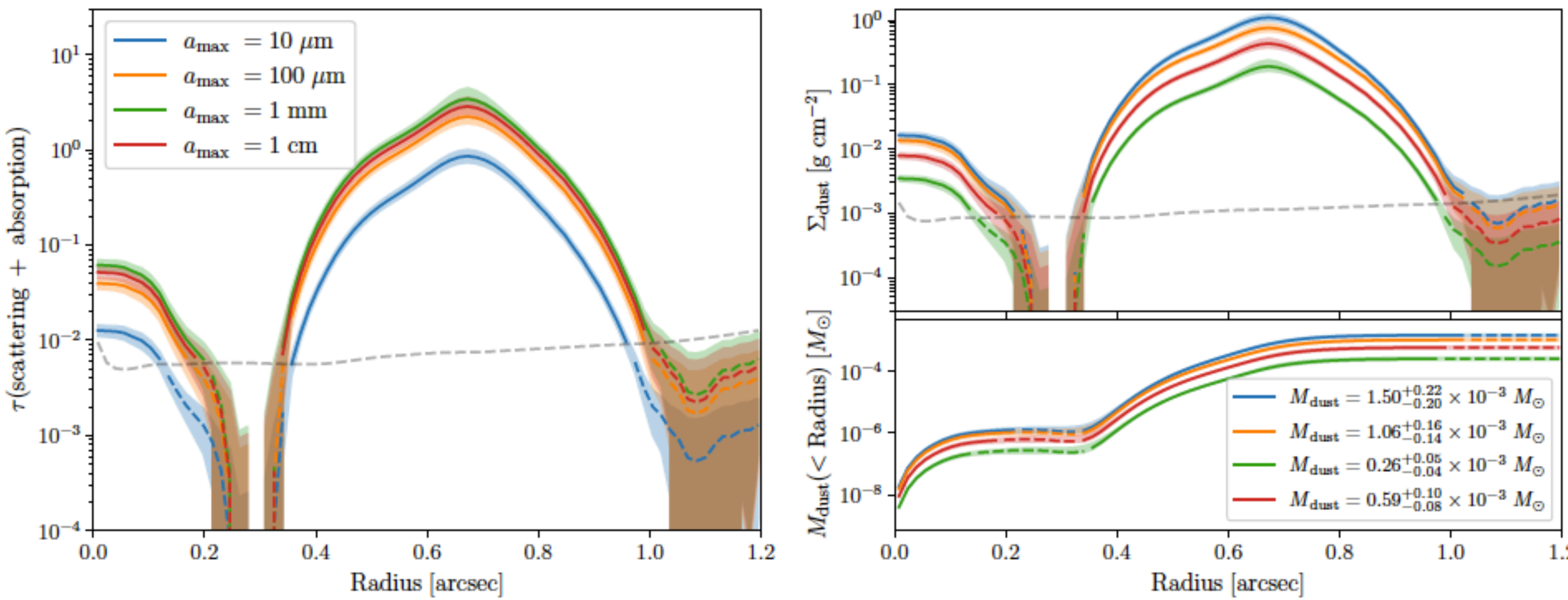

Batygin & Morbidelli 2020




Bae+2019

Planet b is not in proximity of outer pressure maximum: accretion disk, rather than decretion disk?

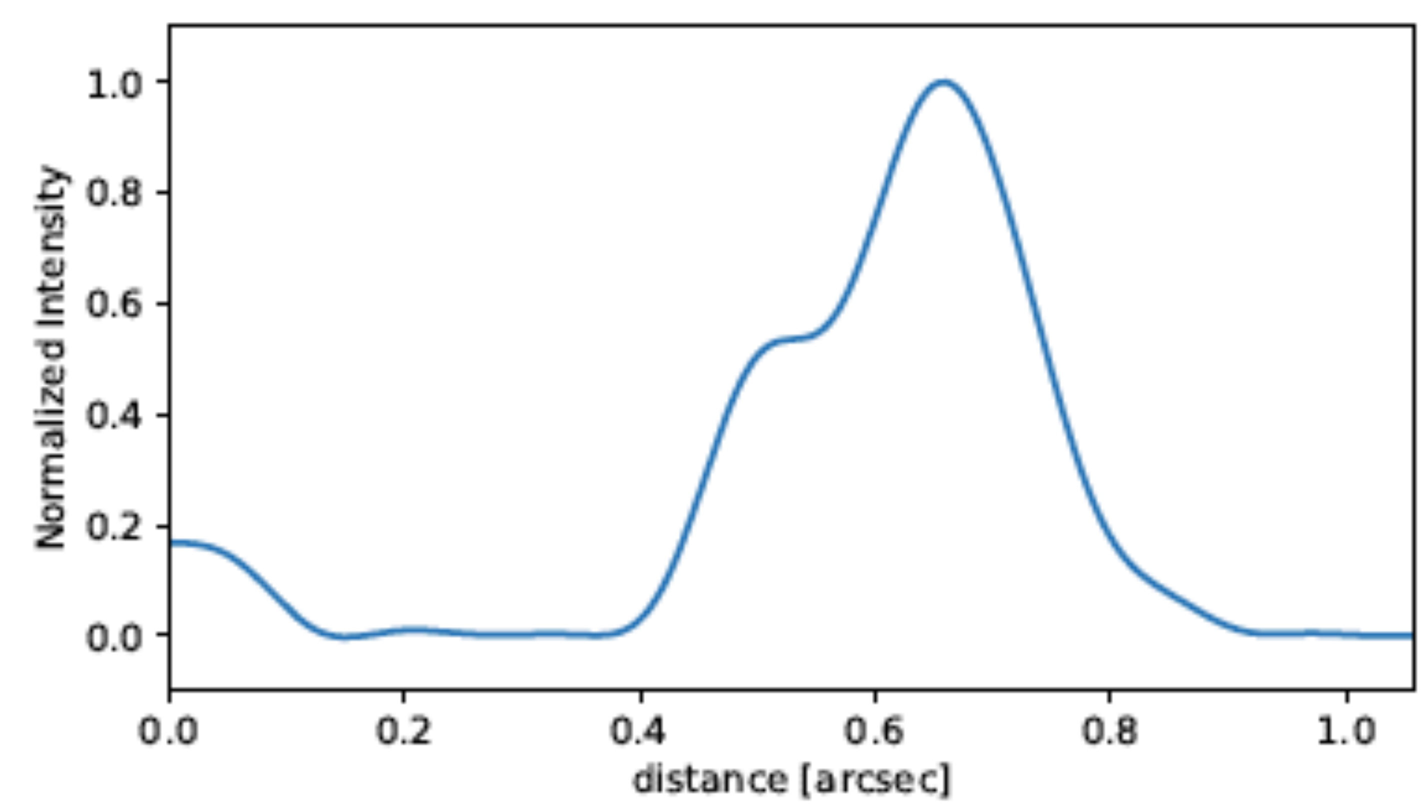
# Inner disk

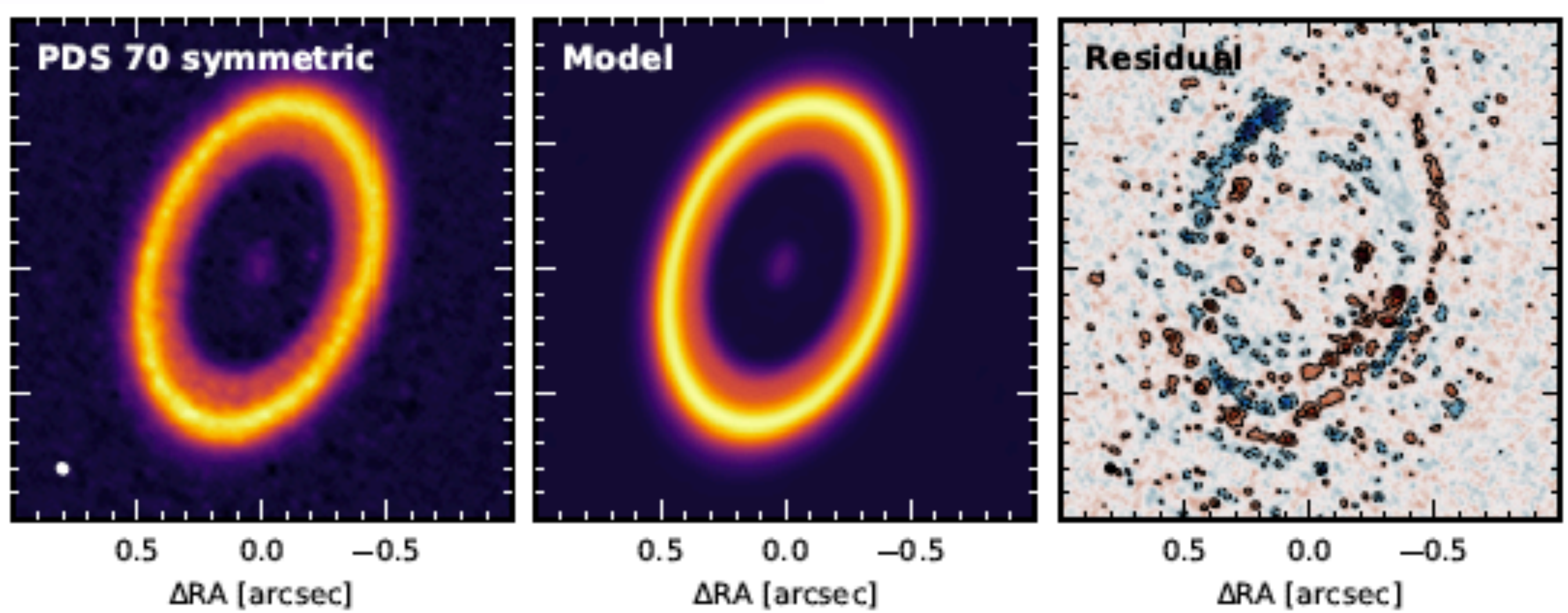



- Inner disk models have dust size distribution with $a_{min}$ =0.05 μm and $a_{max}$ given in plot
- Inner disk is optically thin with $M_d$~$10^{-7}$ $M_{sun}$
- PDS70b and the inner disk are starved due to the filtering of material by PDS70c

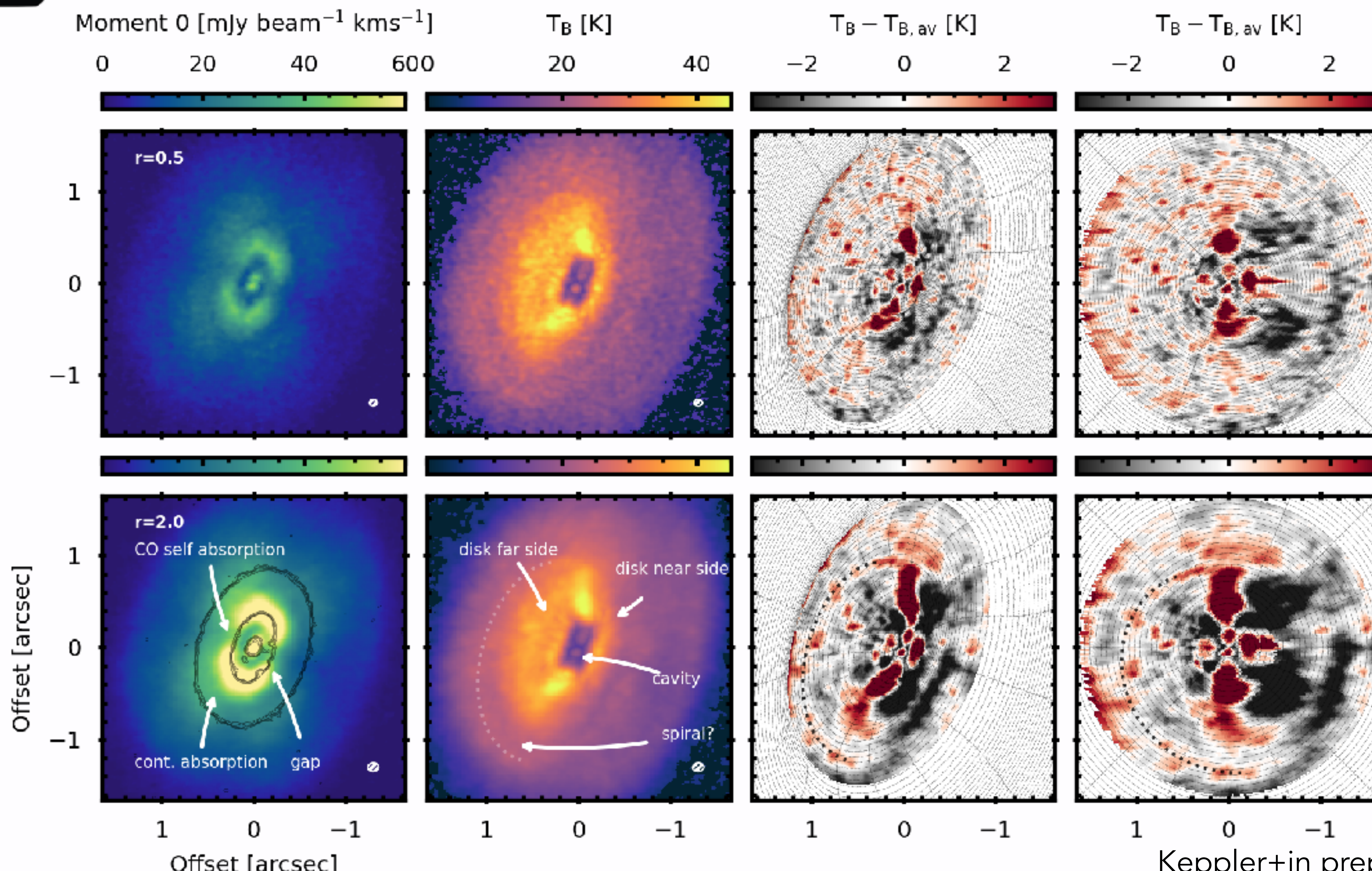
# A yet-undetected third planet?

- Outer ring resolves in a ring + inner shoulder
- Could trace an undetected low mass planet embedded in the outer disk (e.g. Perez+2019,Facchini+2020)



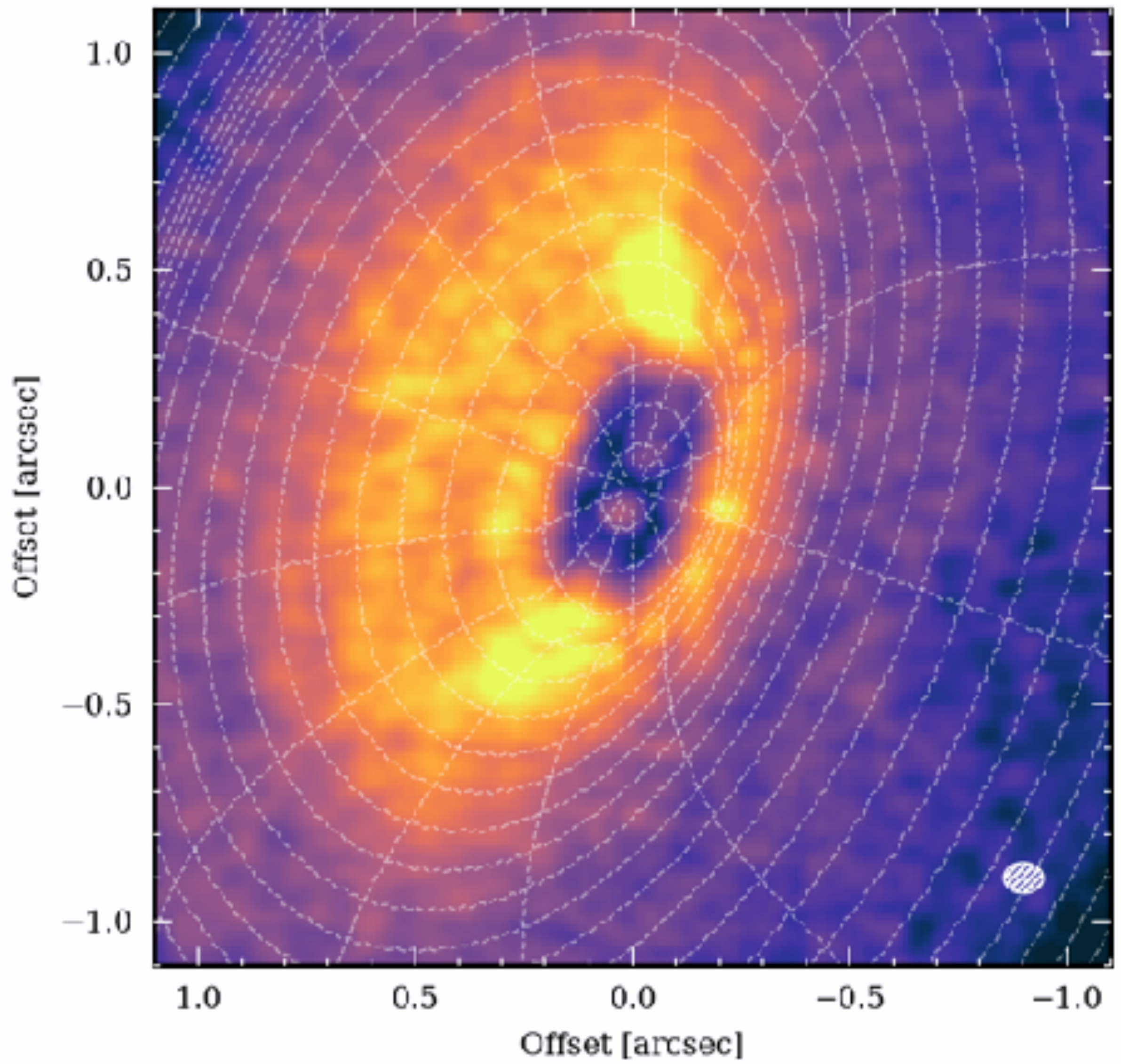



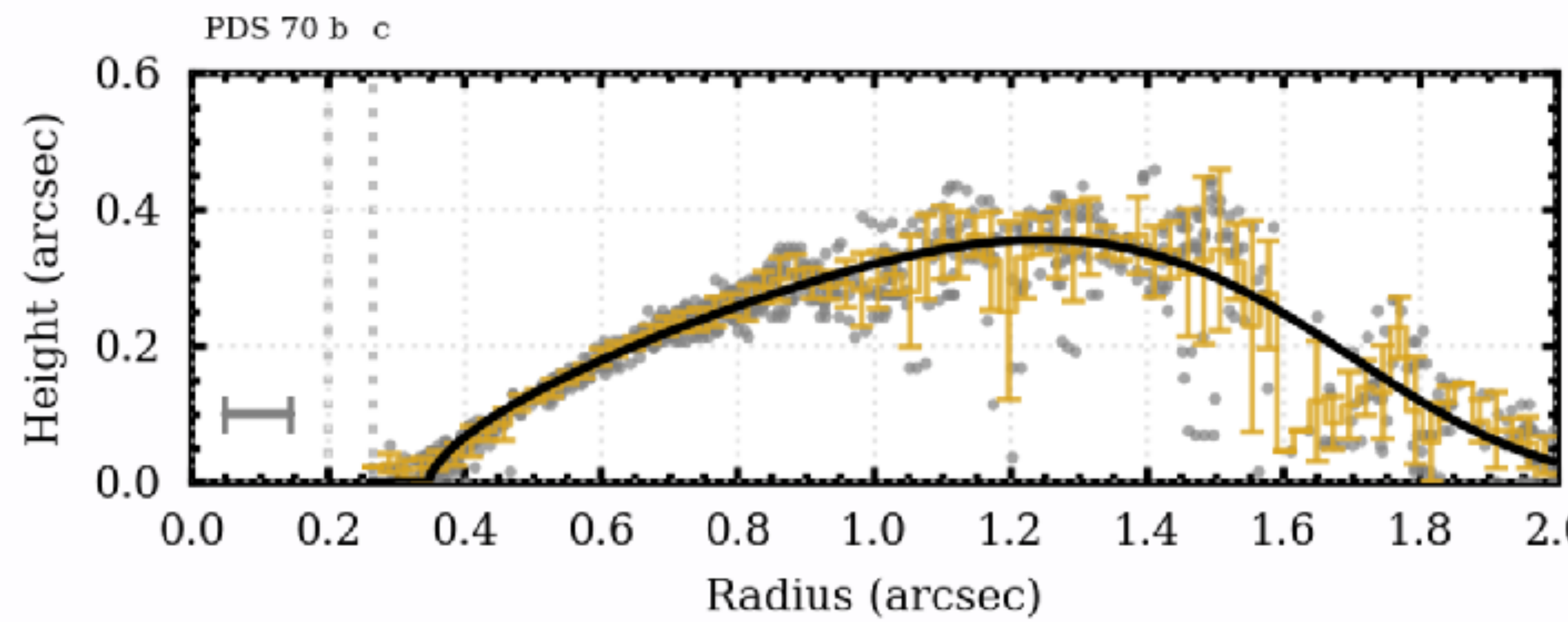
# CO and kinematics




Keppler+in prep.

# CO and kinematics



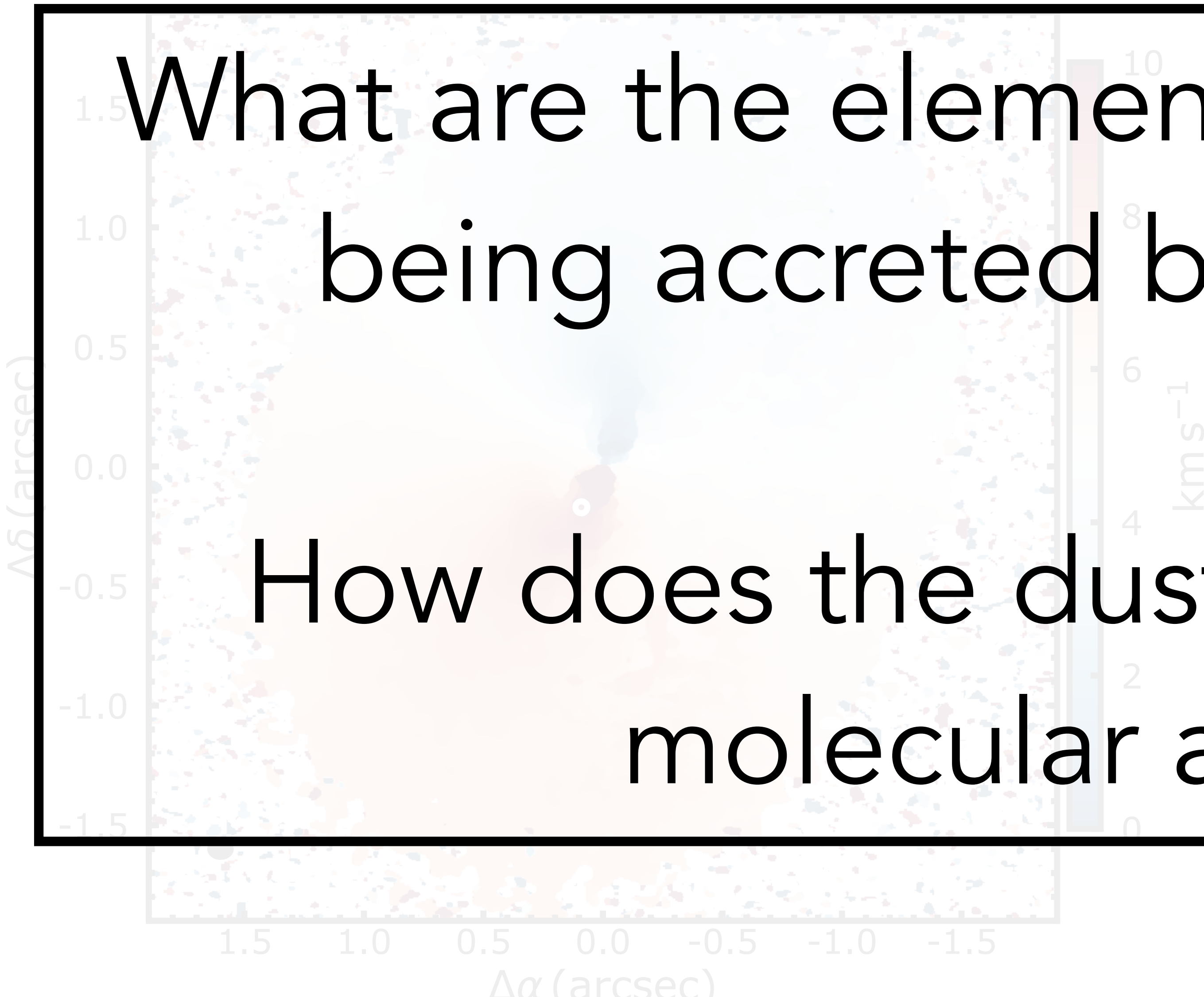



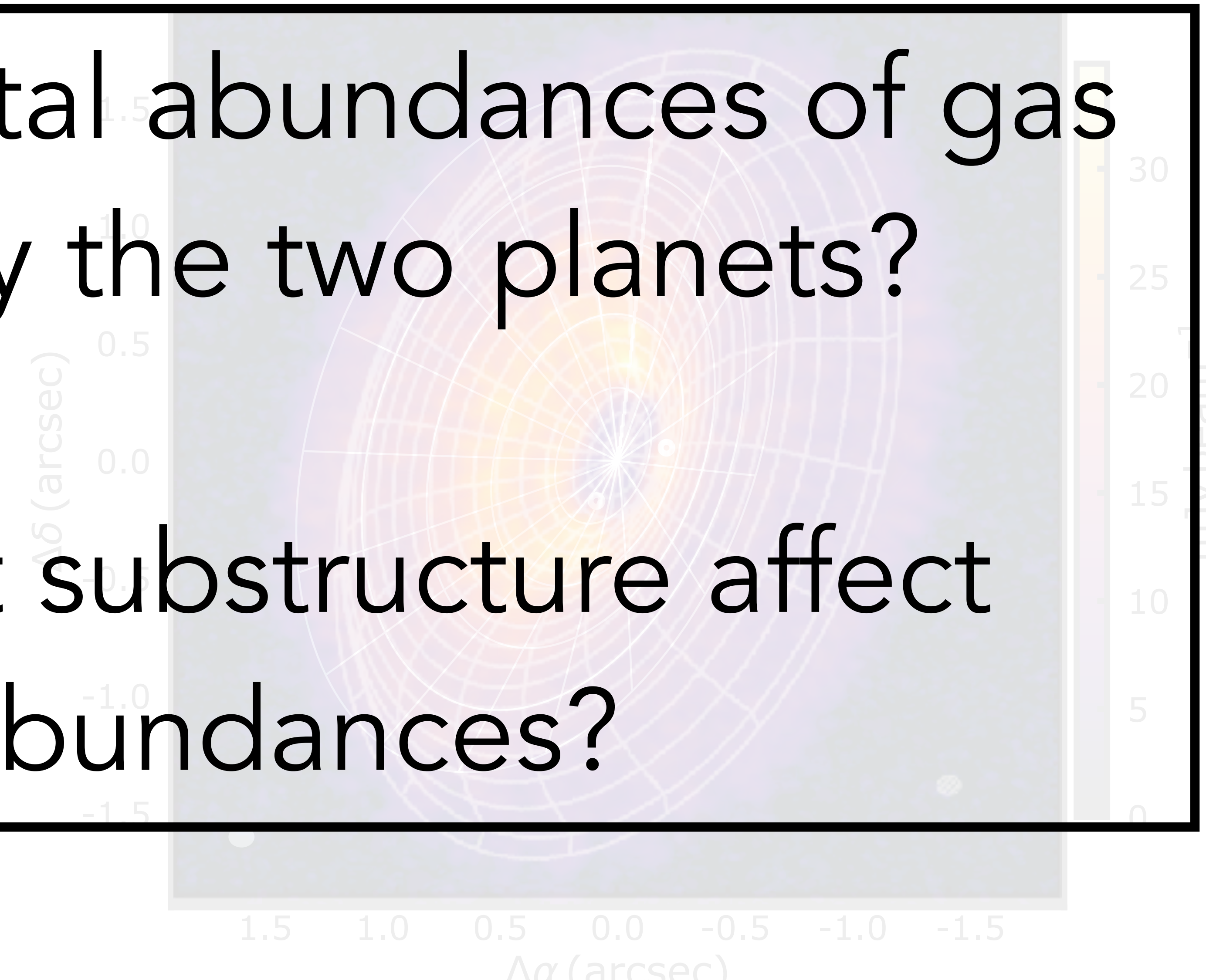

Vertical structure well determined,
cavity wall particularly pronounced

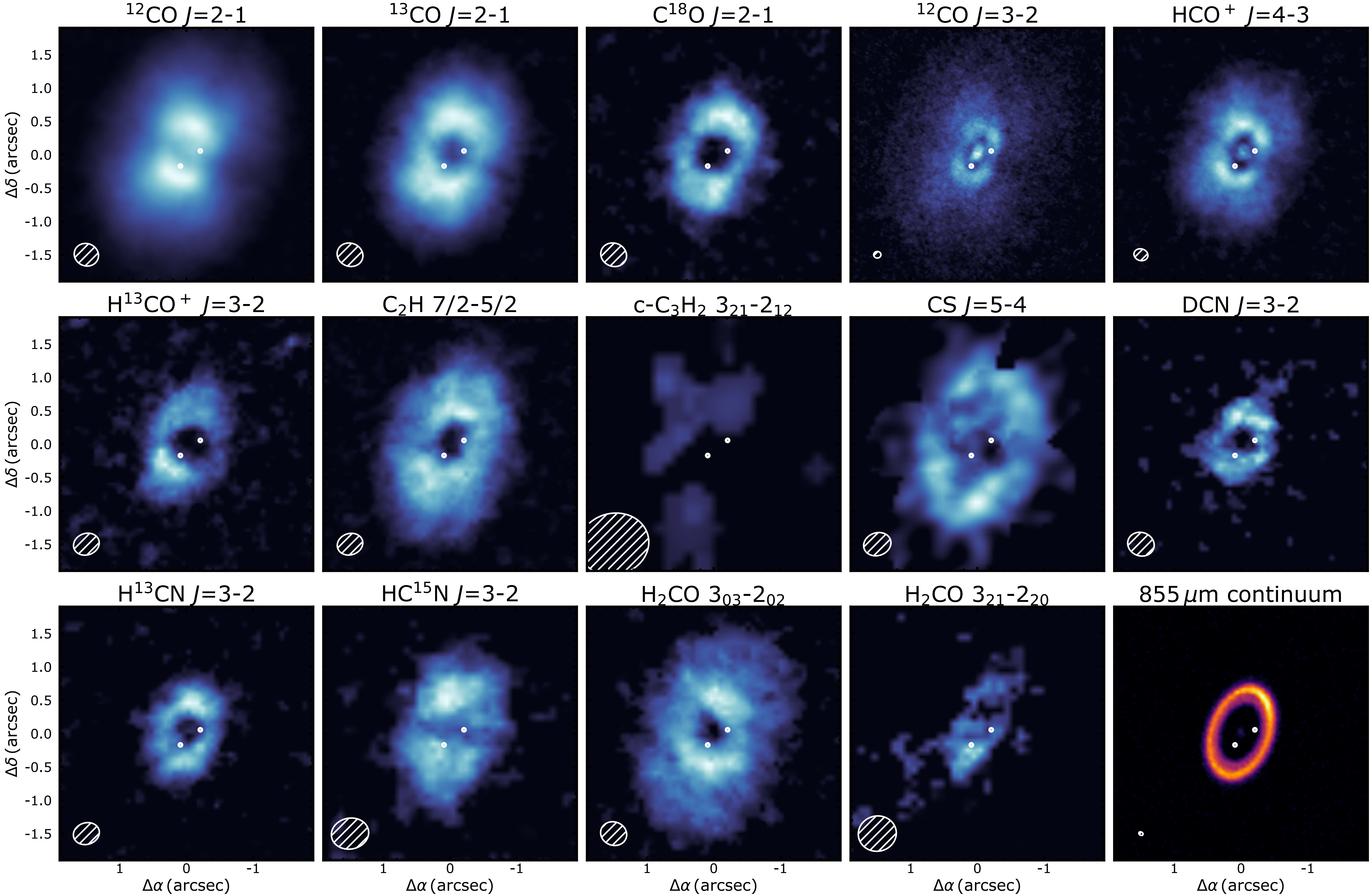
# Chemistry of PDS 70

What are the elemental abundances of gas being accreted by the two planets?

How does the dust substructure affect molecular abundances?

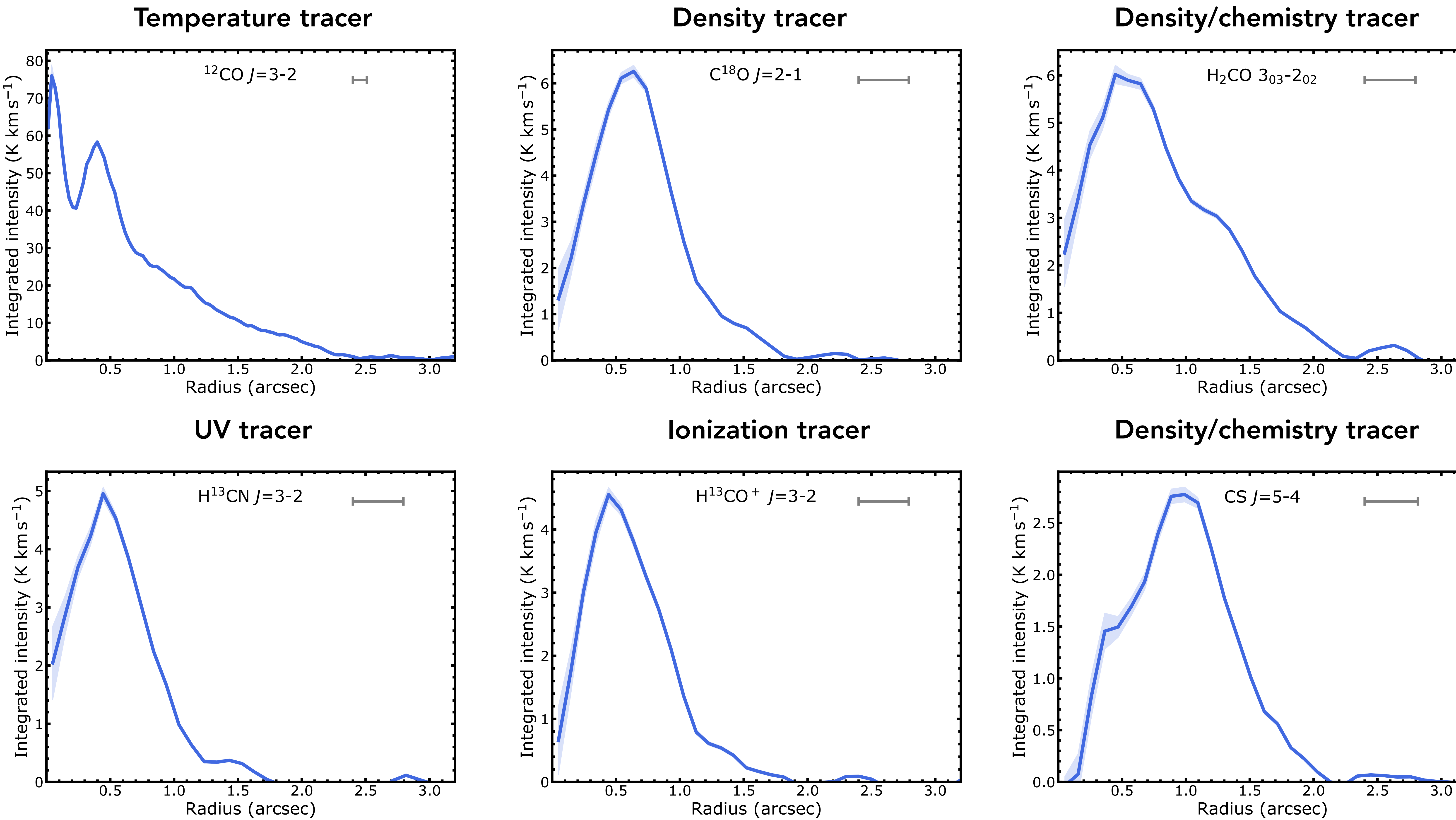


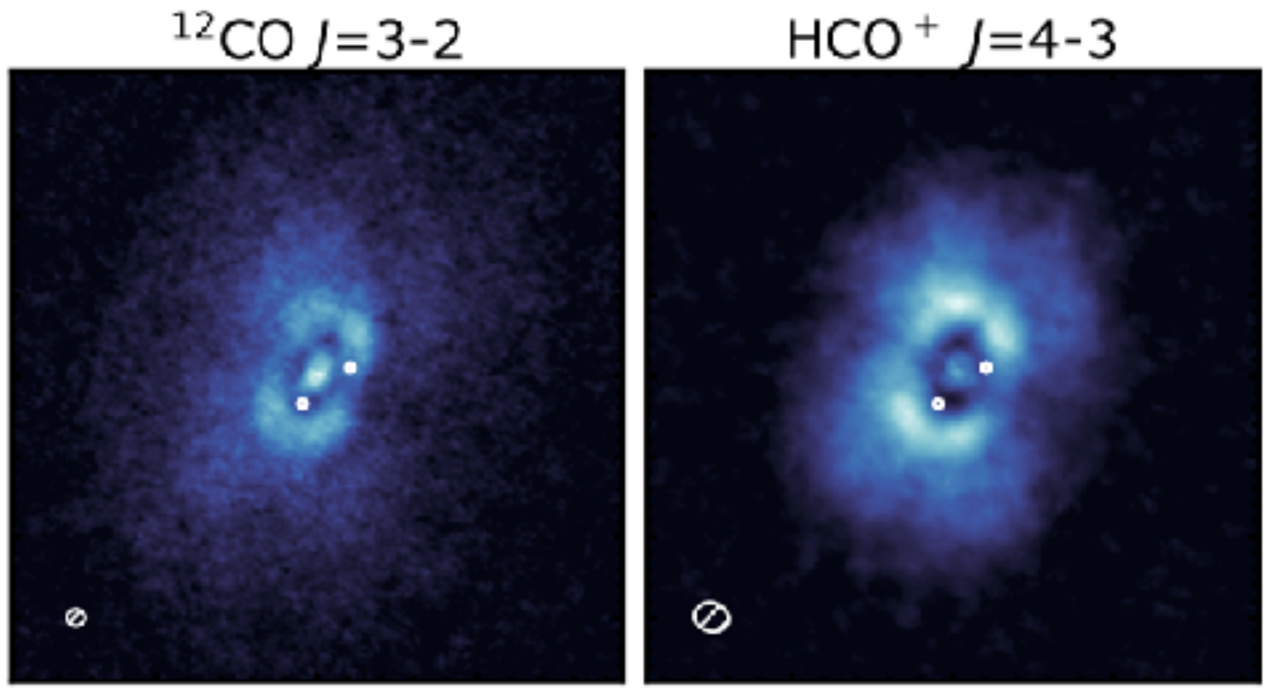



Facchini+2021

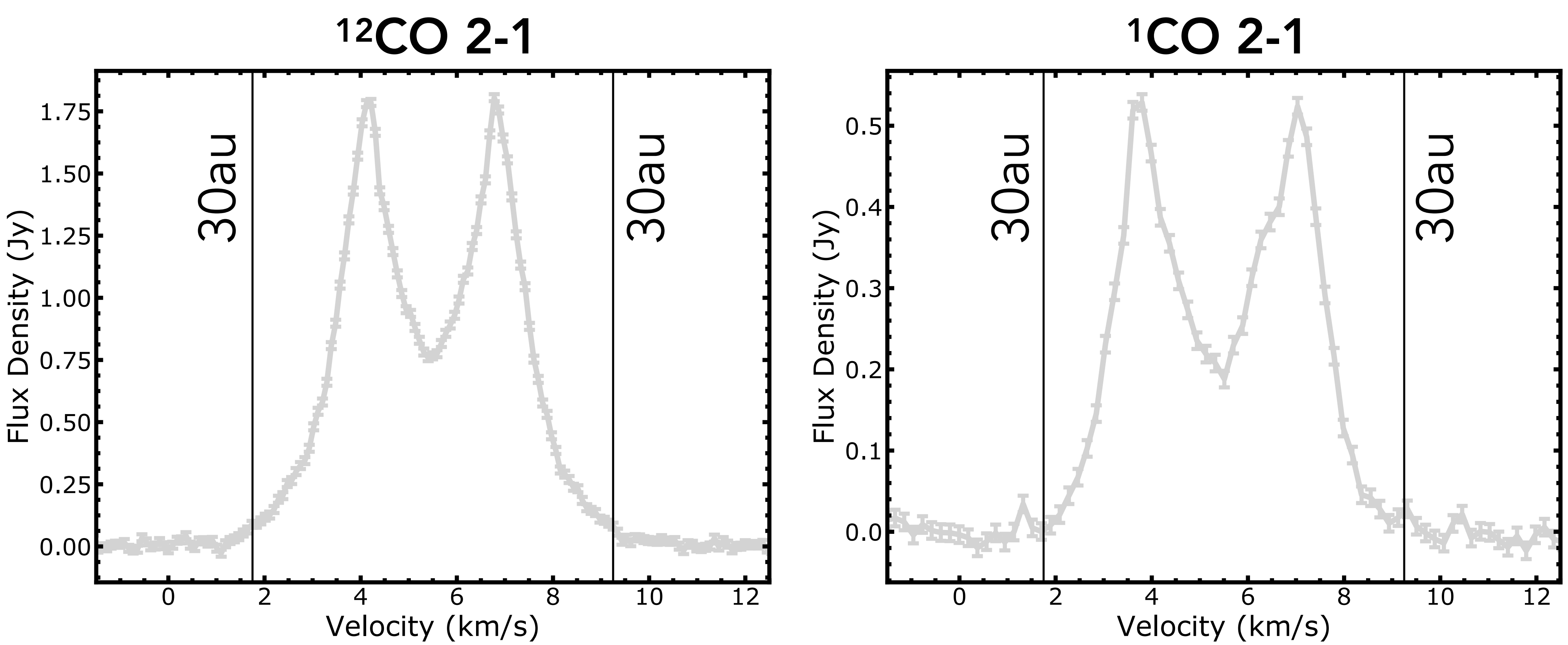
# Radial profiles



# Inner disk detected only in $^{12}CO$ and $HCO^+$



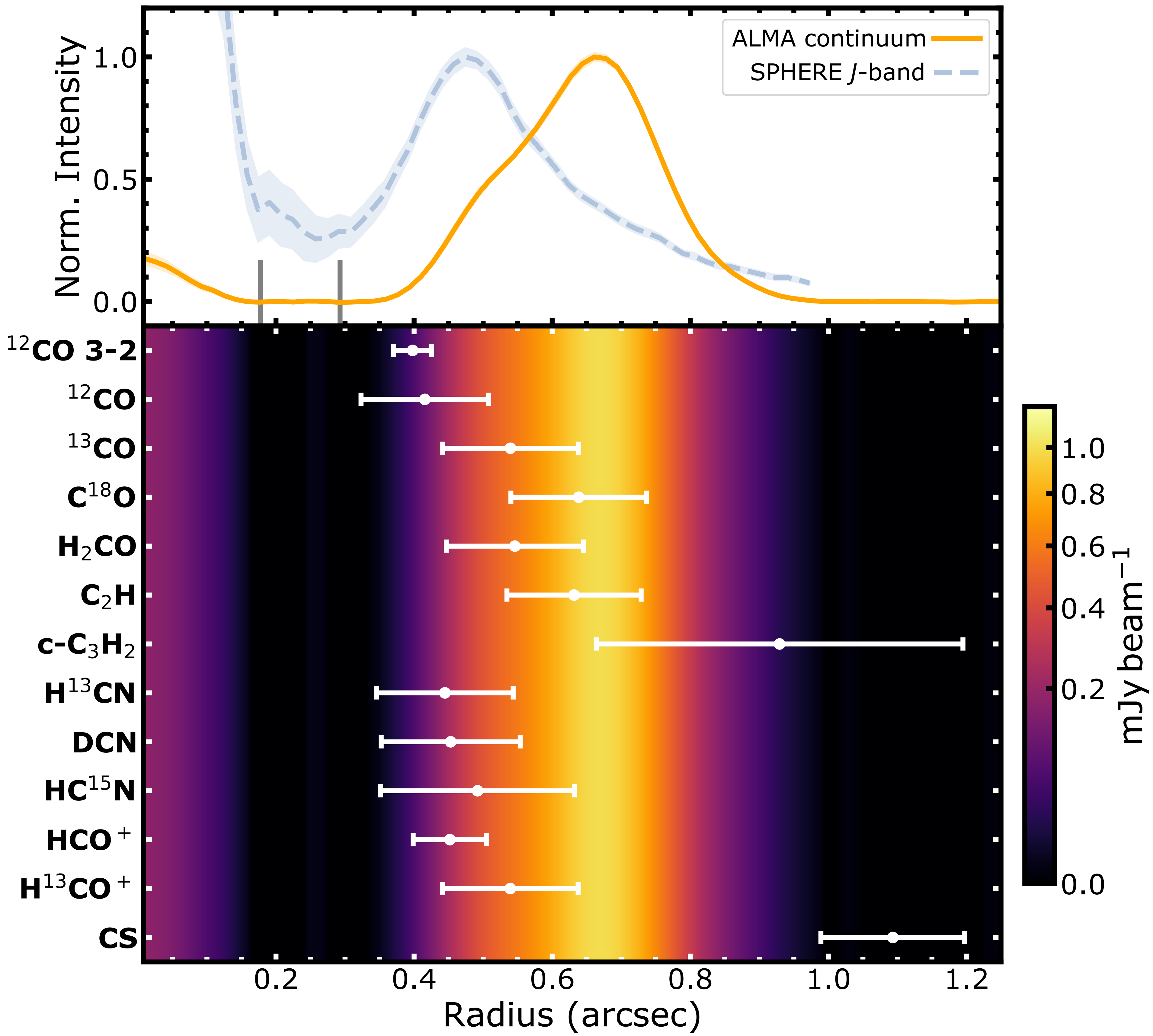

Observed in high angular resolution images



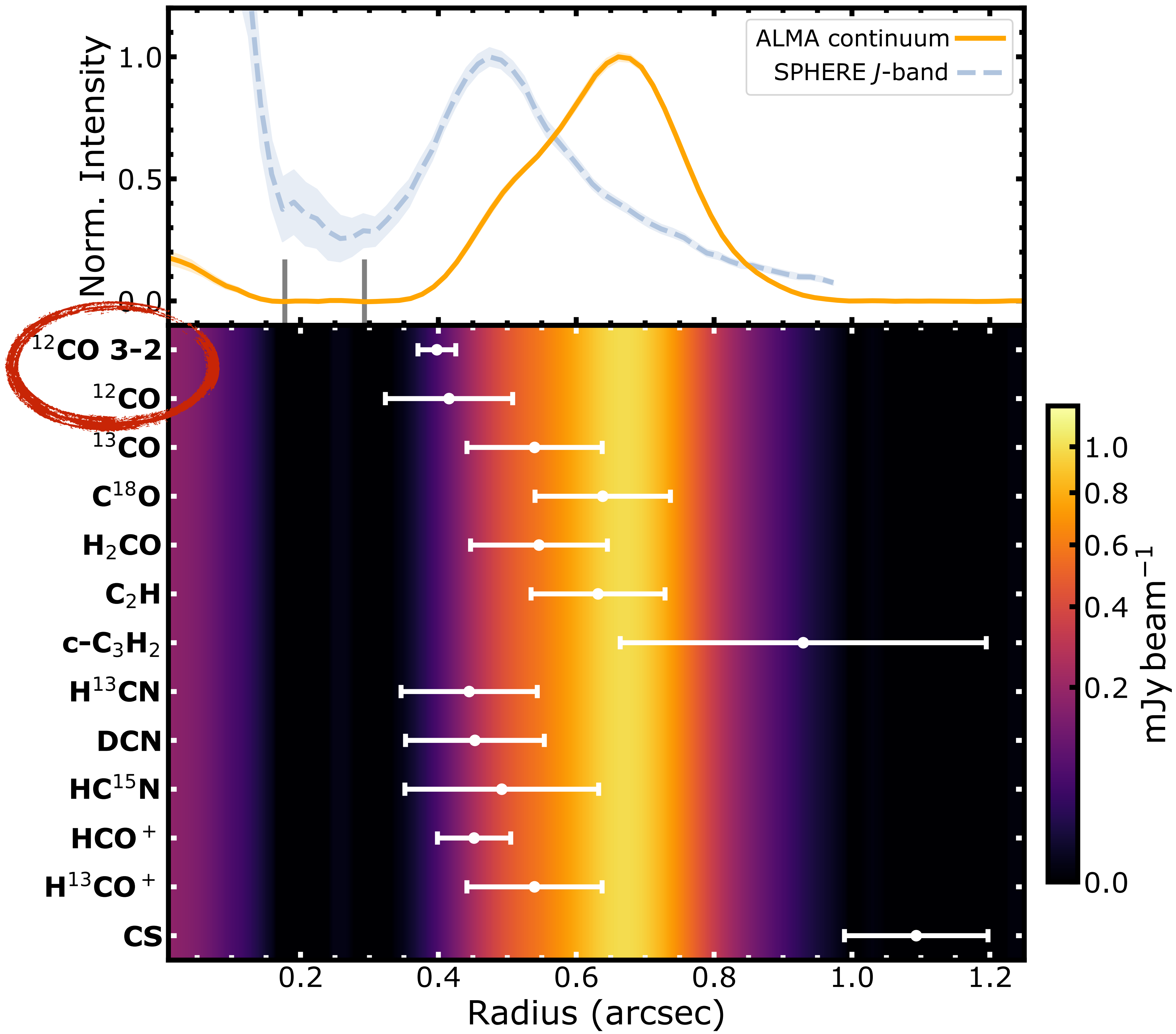

$^{13}CO$ not showing velocities associated to inner disk in low resolution images

Inner disk has low surface density in both gas and dust, maintains $M_{acc} \sim 10^{-10}\ M_{sun}/yr$ (Thanathibodee+2020)

# Peak of radial profiles reveal complex interplay between chemistry and dust substructure

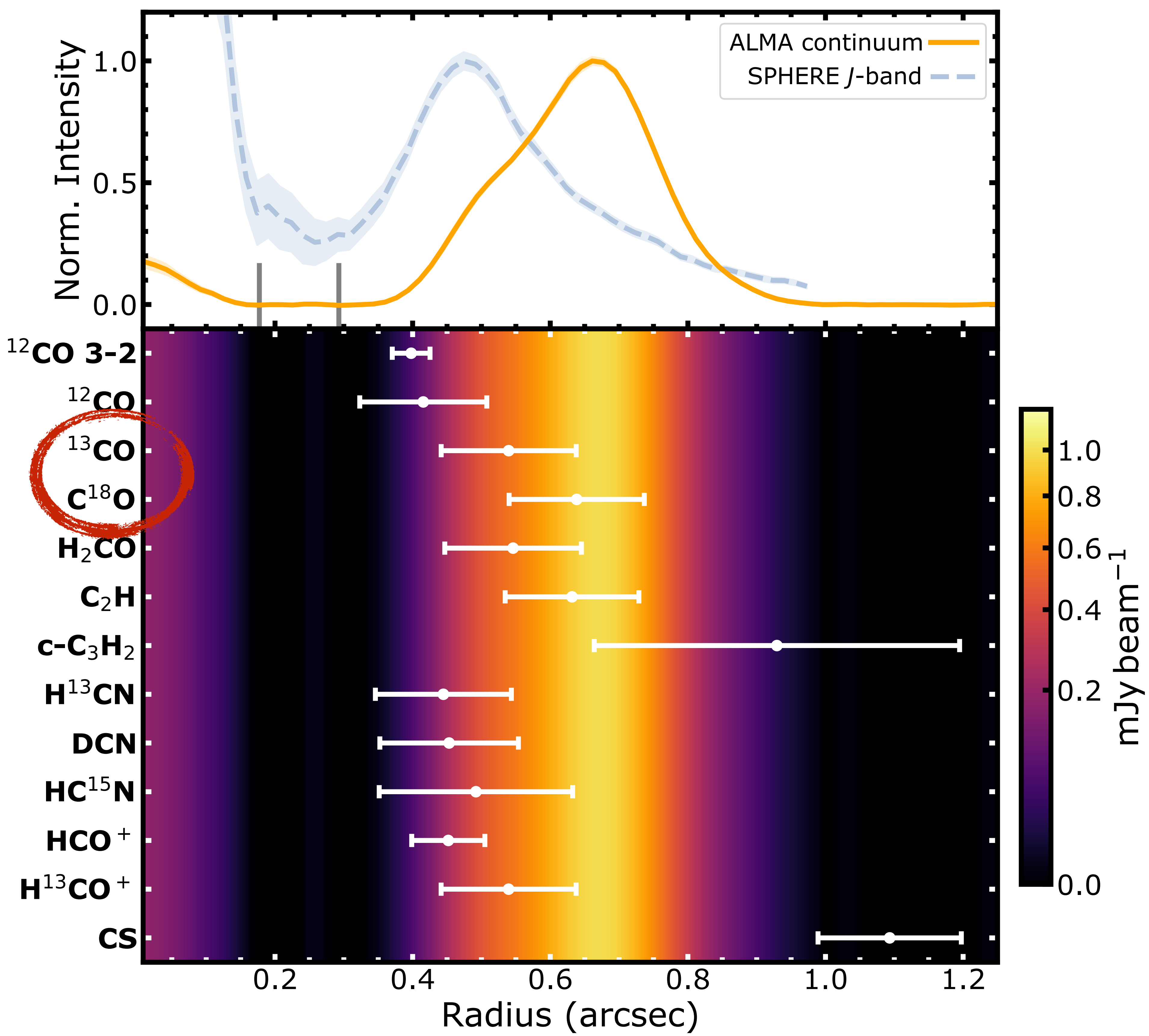


# Peak of radial profiles reveal complex interplay between chemistry and dust substructure




**$^{12}$CO**: density increase, at the edge of cavity wall (e.g. Facchini+2018a)

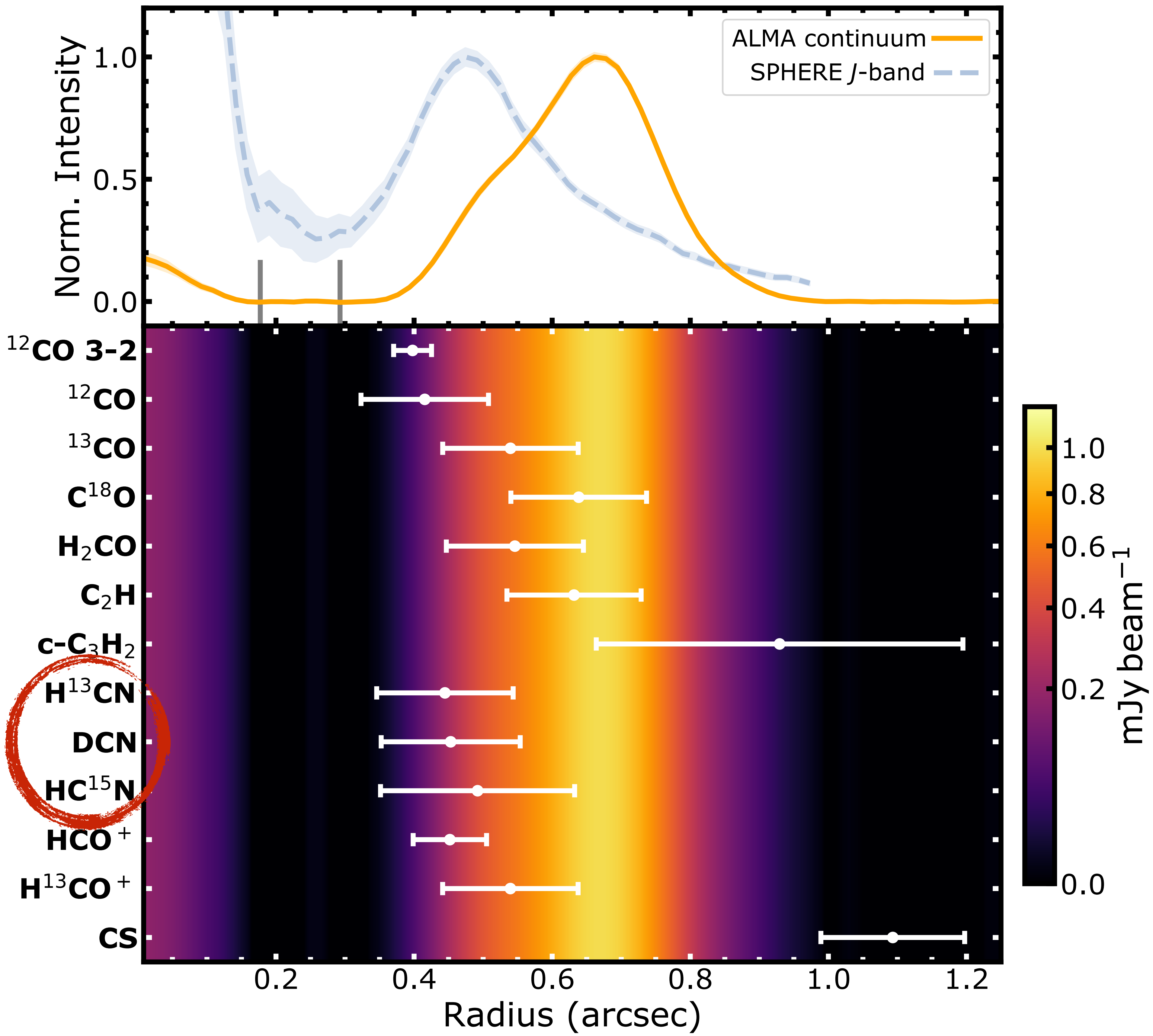
# Peak of radial profiles reveal complex interplay between chemistry and dust substructure




**$^{12}$CO**: density increase, at the edge of cavity wall (e.g. Facchini+2018a)

**$^{13}$CO, C$^{18}$O**: high column densities, pressure maximum outside orbits of planets (e.g. Facchini+2018a)

# Peak of radial profiles reveal complex interplay between chemistry and dust substructure

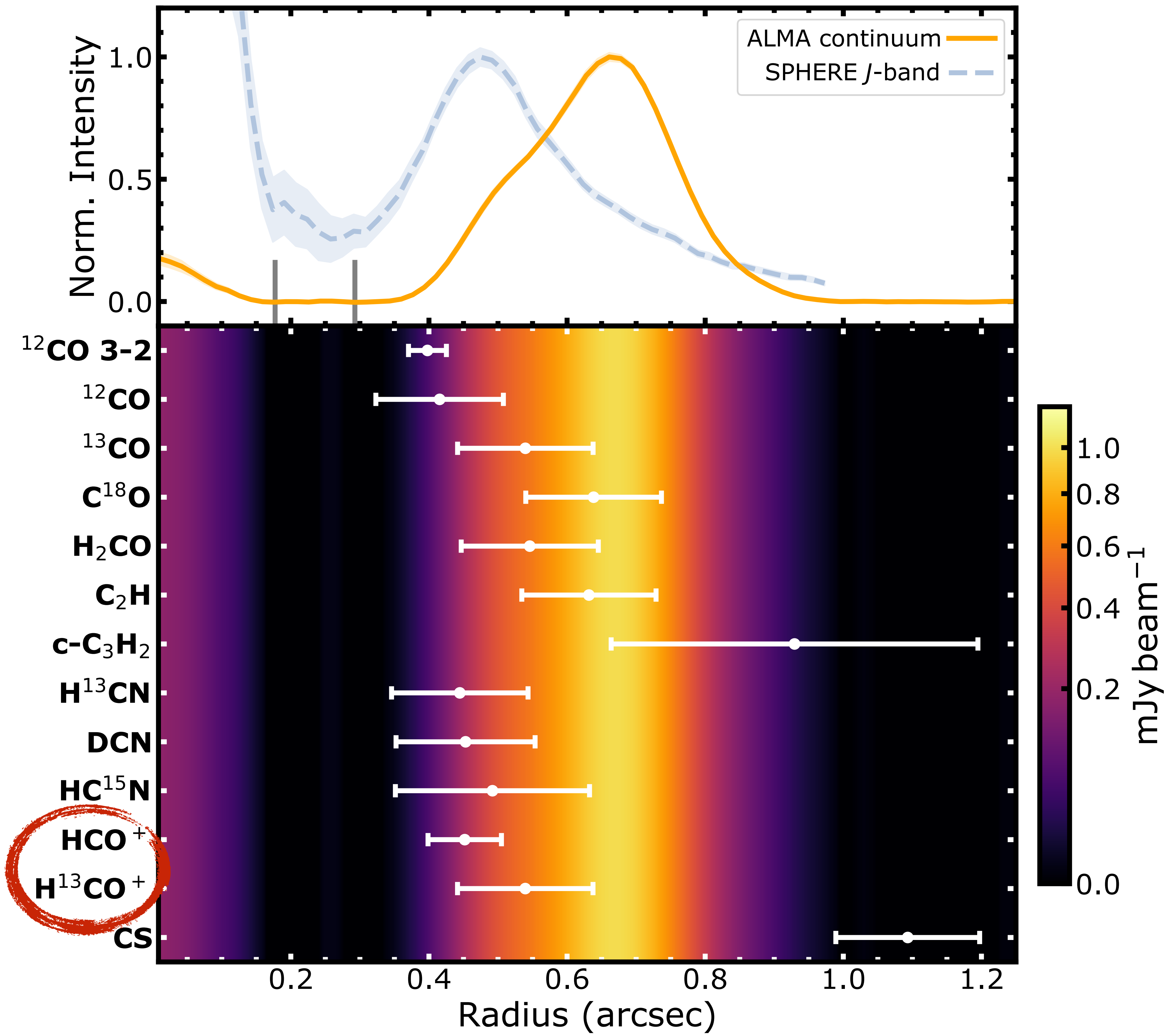



**$^{12}$CO**: density increase, at the edge of cavity wall (e.g. Facchini+2018a)

**$^{13}$CO, C$^{18}$O**: high column densities, pressure maximum outside orbits of planets (e.g. Facchini+2018a)

**HCN** isotopologues: high UV irradiation, formed via $H_2^*$ (e.g. Cazzoletti,…,Facchini+2018)

# Peak of radial profiles reveal complex interplay between chemistry and dust substructure




**$^{12}$CO**: density increase, at the edge of cavity wall (e.g. Facchini+2018a)

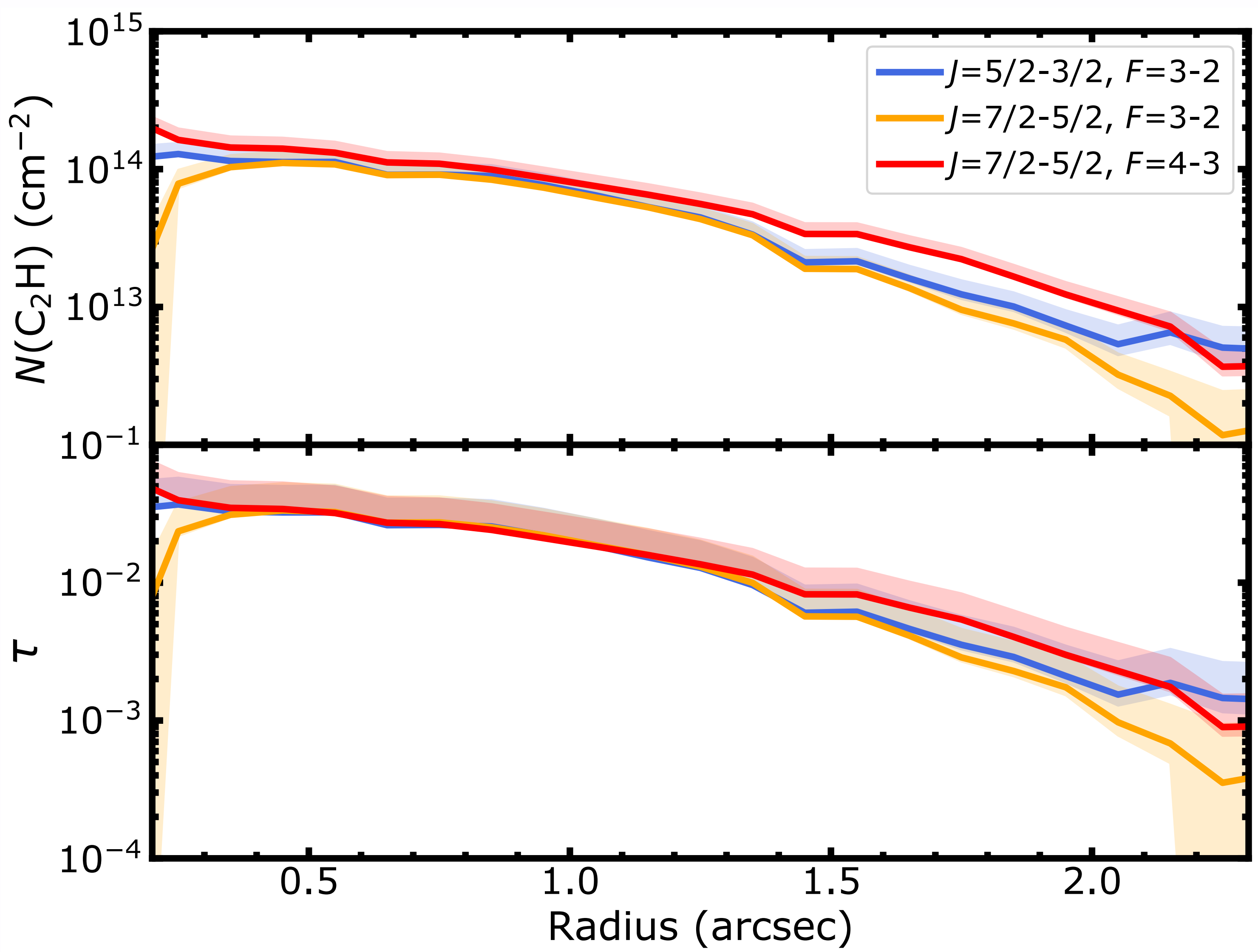
**$^{13}$CO, C$^{18}$O**: high column densities, pressure maximum outside orbits of planets (e.g. Facchini+2018a)

**HCN** isotopologues: high UV irradiation, formed via $H_2^*$ (e.g. Cazzoletti,…,Facchini+2018)

**HCO$^+$** isotopologues: high X-rays irradiation (e.g. Cleeves+2015)

# Column densities

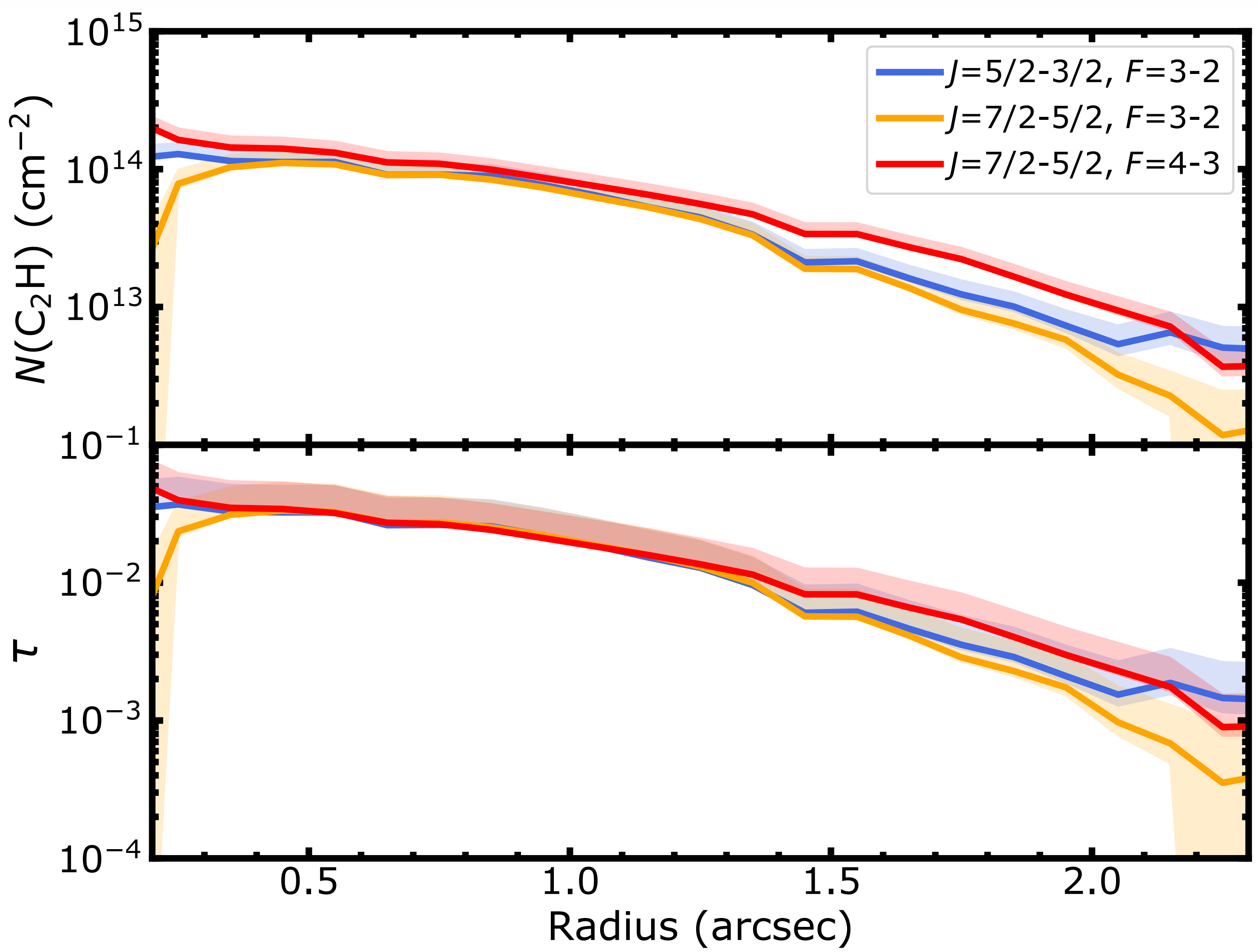
## $C_2H$




Three hyperfine transitions agree well, showing that the method is robust

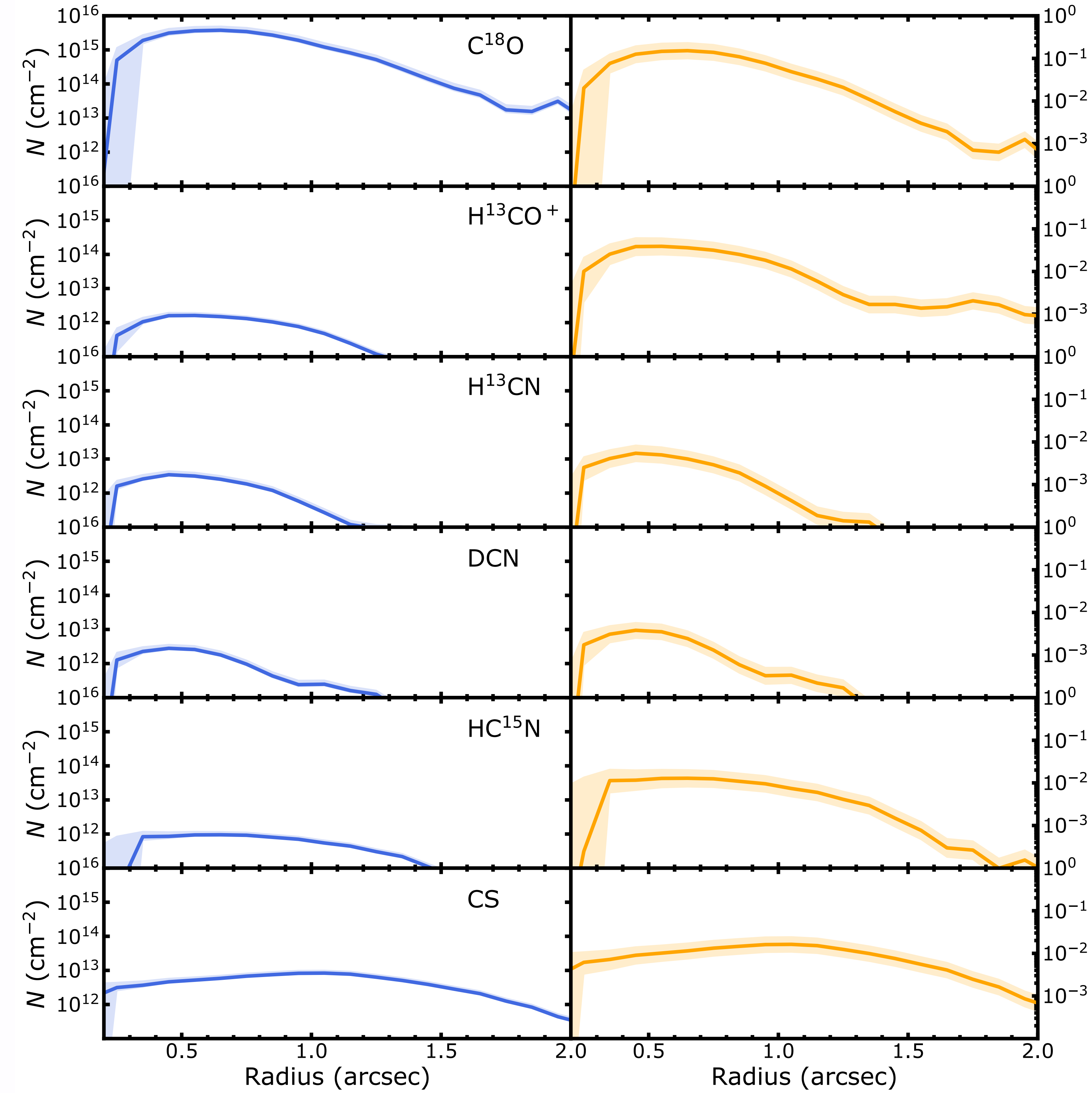
# Column densities

## $C_2H$

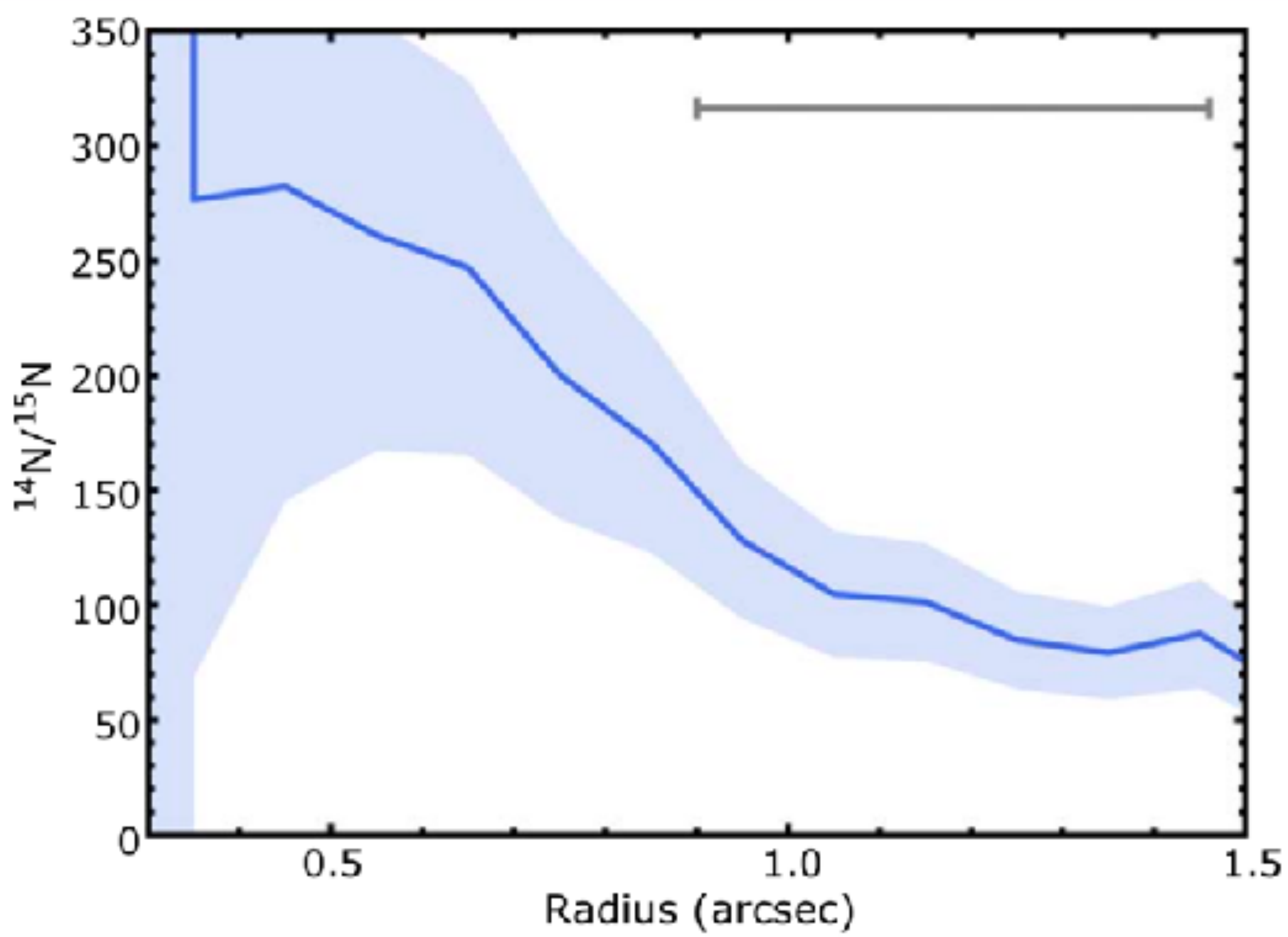


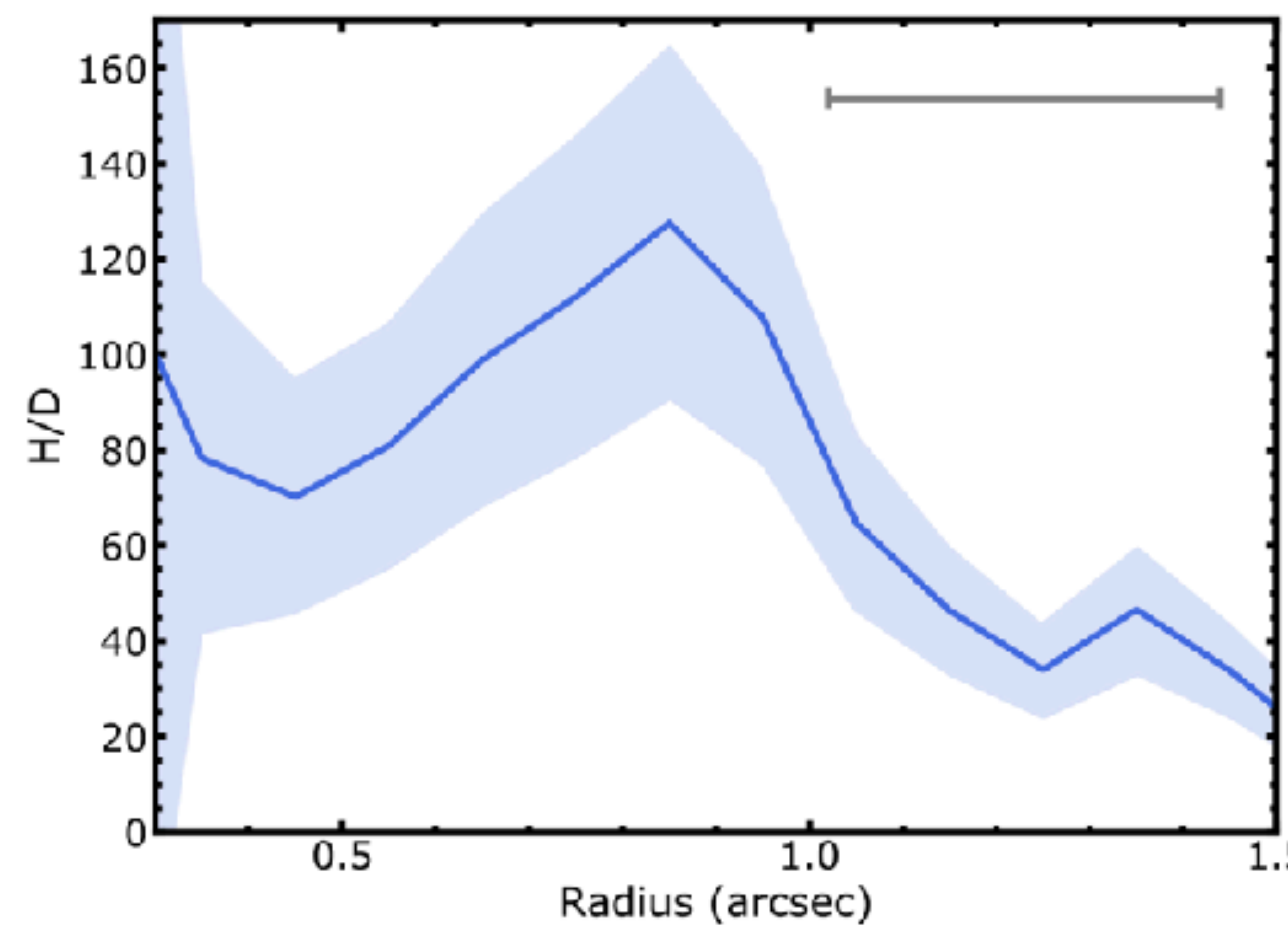

Three hyperfine transitions agree well, showing that the method is robust

## Other molecules



# Deuteration: chemistry and temperature

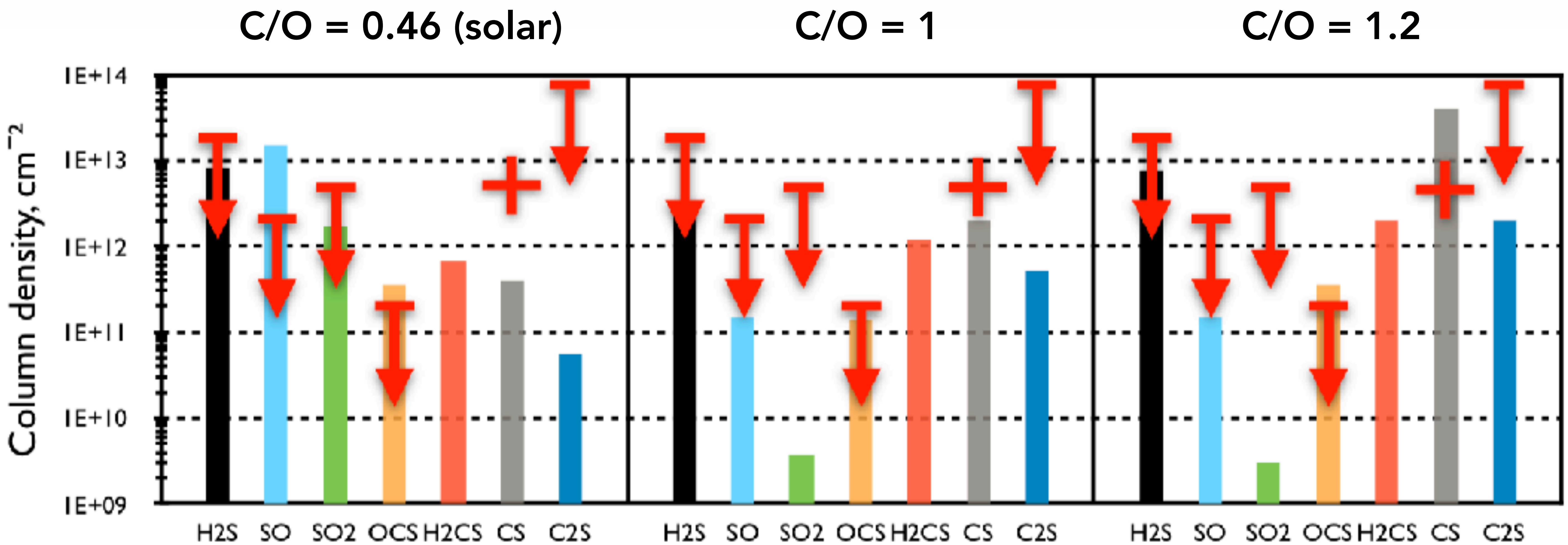



Nitrogen fractionation from $H^{13}CN/HC^{15}N$ also shows reprocessed material (solar $^{14}N/^{15}N$ ~ 440), trend is anti-correlated with temperature

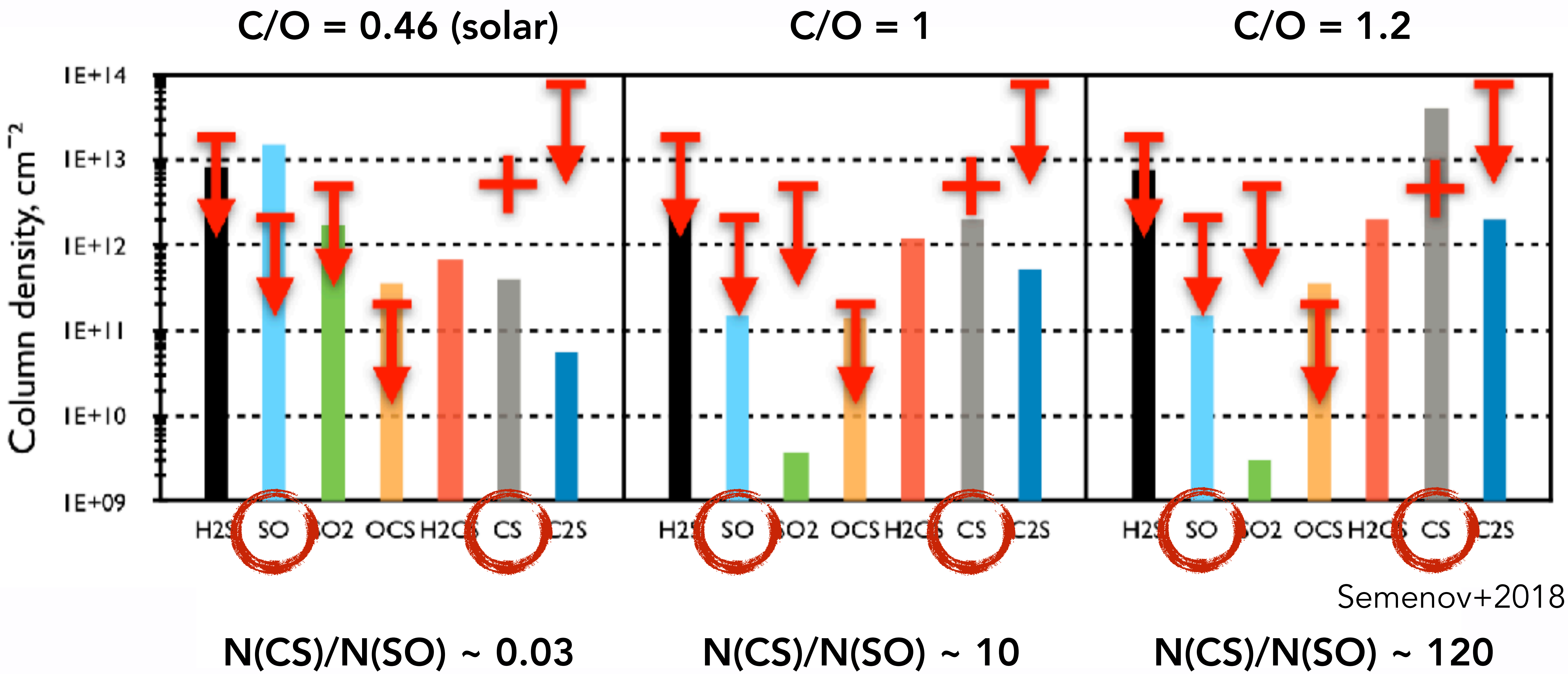
Deuteration from $H^{13}CN/DCN$ shows significantly reprocessed material (solar H/D ~ 5 x $10^4$), with maximum at mm peak

# Column density ratio of CS/SO indicates C/O>1




Semenov+2018

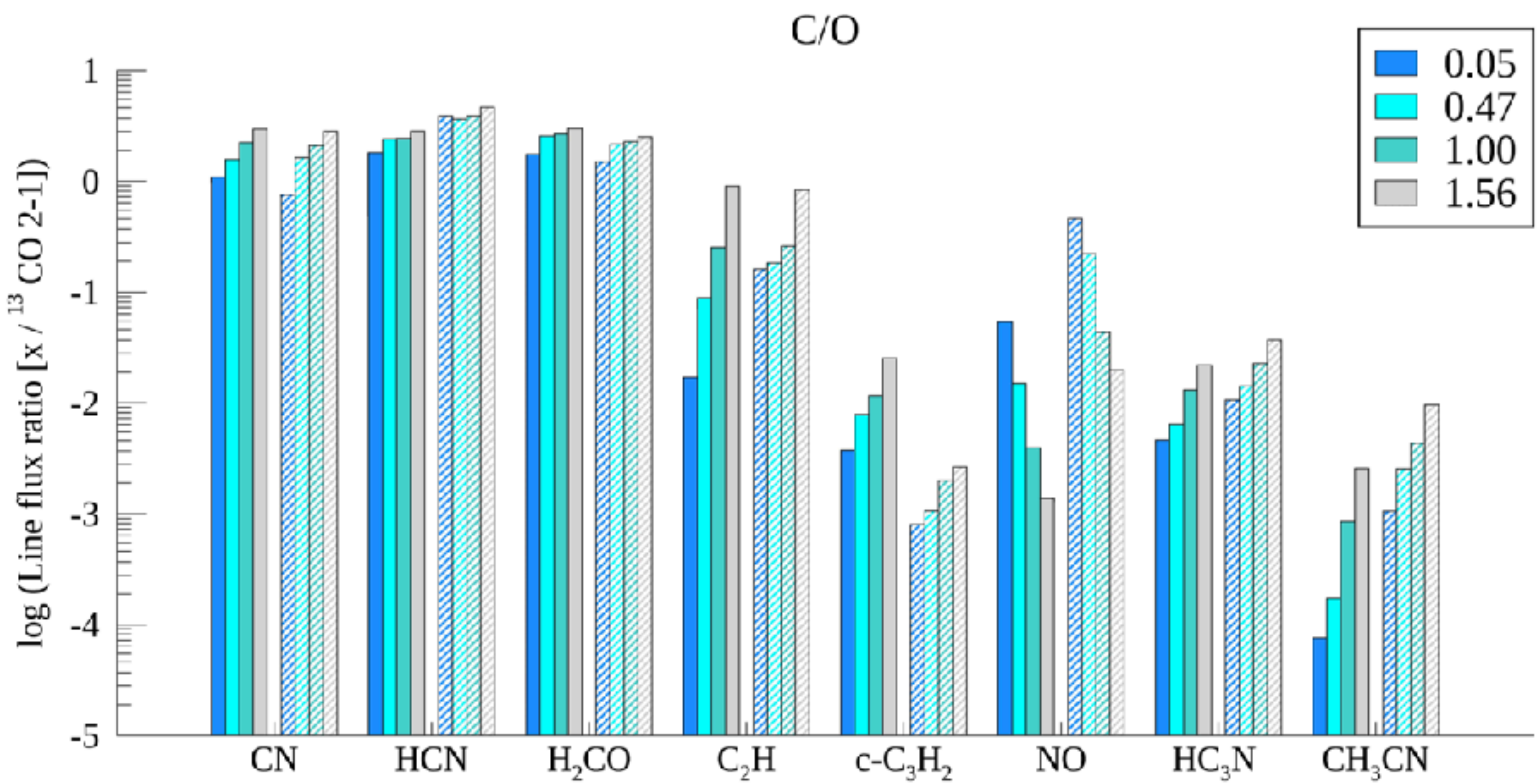
# Column density ratio of CS/SO indicates C/O>1




In PDS 70, N(CS)/N(SO) > 100

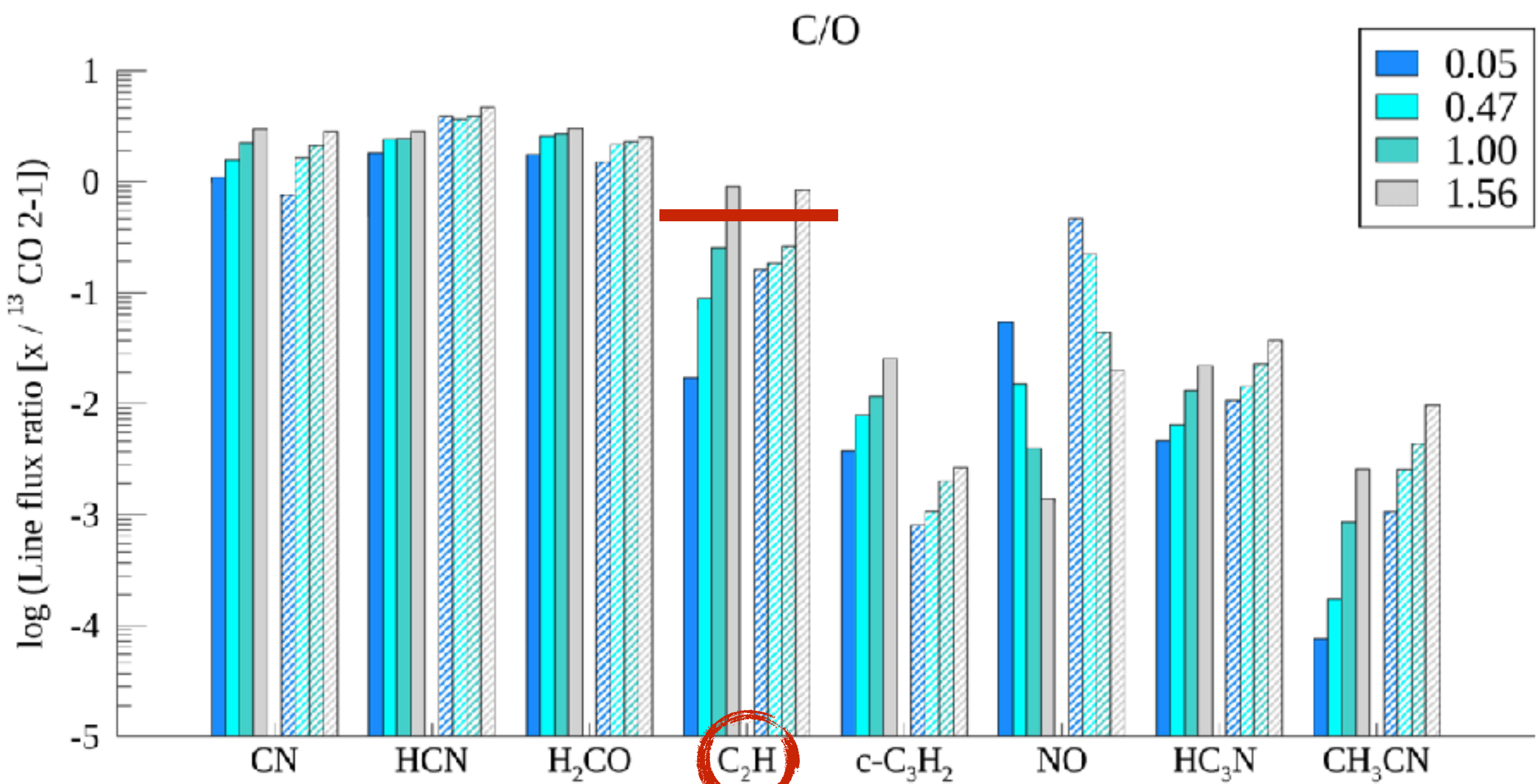
First evidence of planet hosting disk harbouring high C/O molecular gas

# High $C_2H/^{13}CO$ flux ratio indicates same result



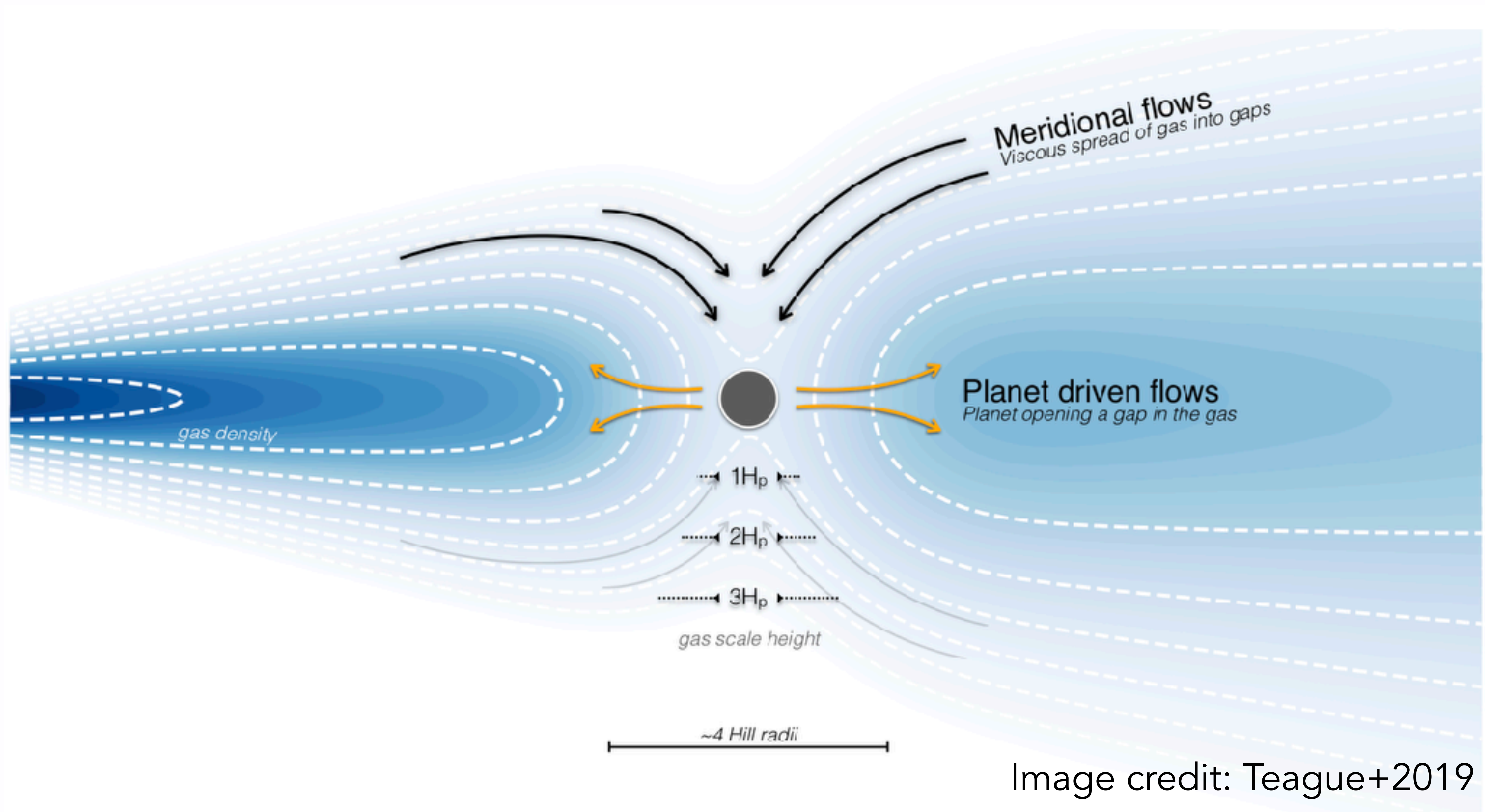

**Miotello, Facchini+2019;** Fedele & Favre 2020

# High $C_2H/^{13}CO$ flux ratio indicates same result




**Miotello, Facchini+2019;** Fedele & Favre 2020

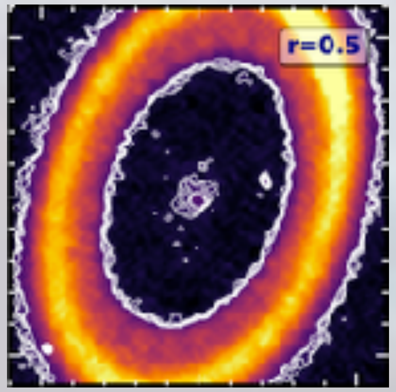
In PDS 70, $C_2H/^{13}CO$ ~ 0.8, indicating C/O > 1.
First evidence of planet hosting disk harbouring high C/O molecular gas




Gas is accreted from surface layers: with giant planet formation, are we tracing the atmosphere building material?

# Conclusions

**CPD detected** around PDS 70c
**Diffuse material detected** in proximity of PDS 70b, origin not clear



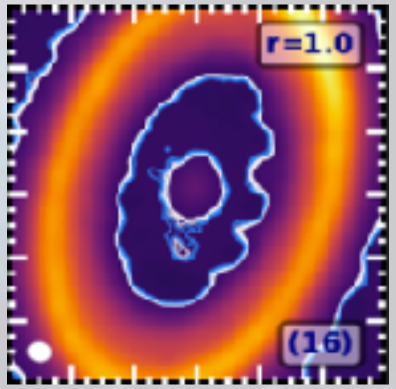
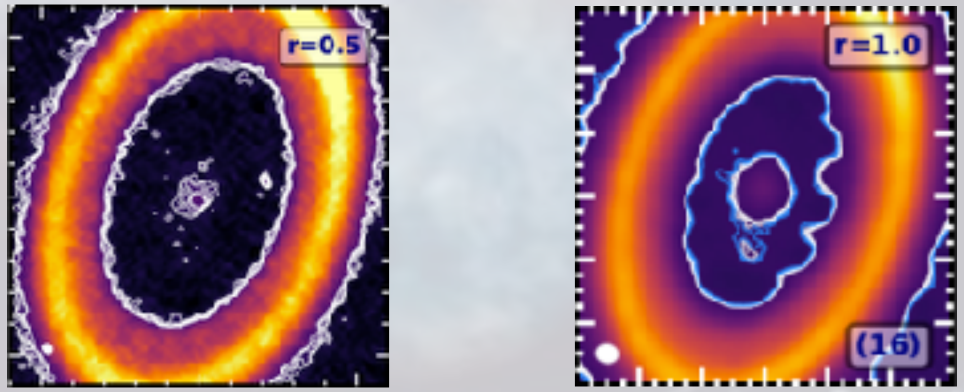




Image credit: Saxton, NASA/JPL

# Conclusions

**CPD detected** around PDS 70c

**Diffuse material detected** in proximity of PDS 70b, origin not clear




**Inner disk** presents low surface brightness emission in both ALMA continuum and gas tracers

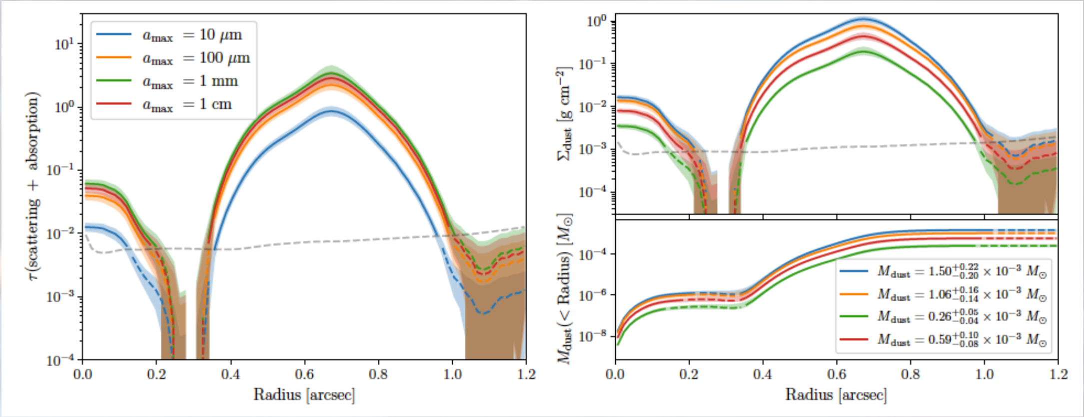
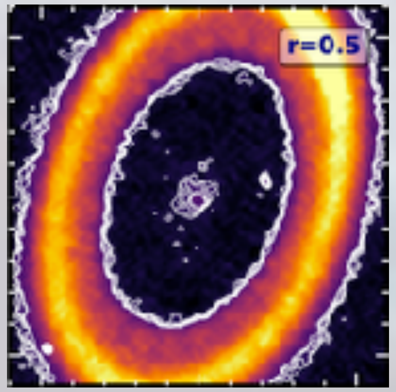


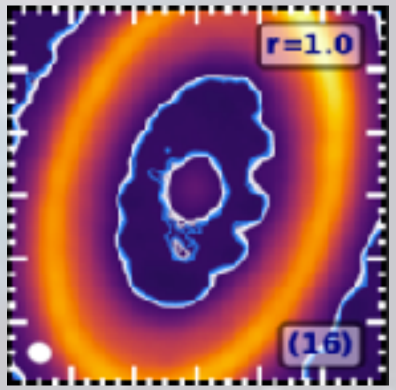

Image credit: Saxton, NASA/JPL

# Conclusions

**CPD detected** around PDS 70c

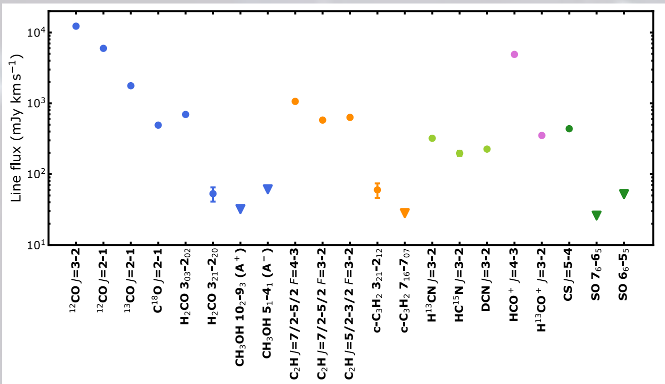
**Diffuse material detected** in proximity of PDS 70b, origin not clear

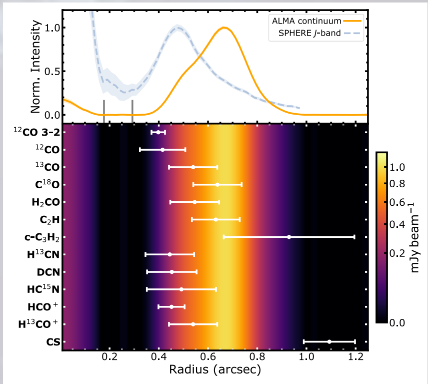



**Surface layer** gas possesses **C/O > 1**

Chemical abundances and dust substructure present **complex interplay**





**Inner disk** presents low surface brightness emission in both ALMA continuum and gas tracers

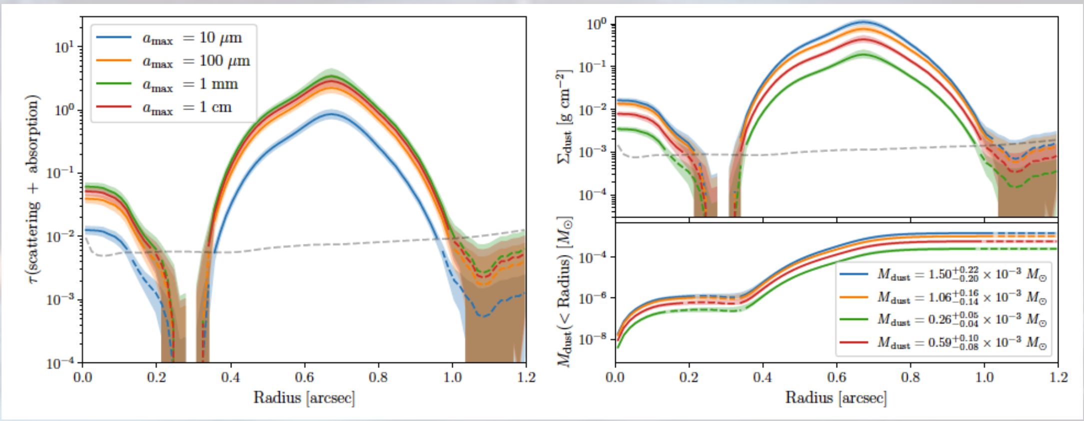


Image credit: Saxton, NASA/JPL