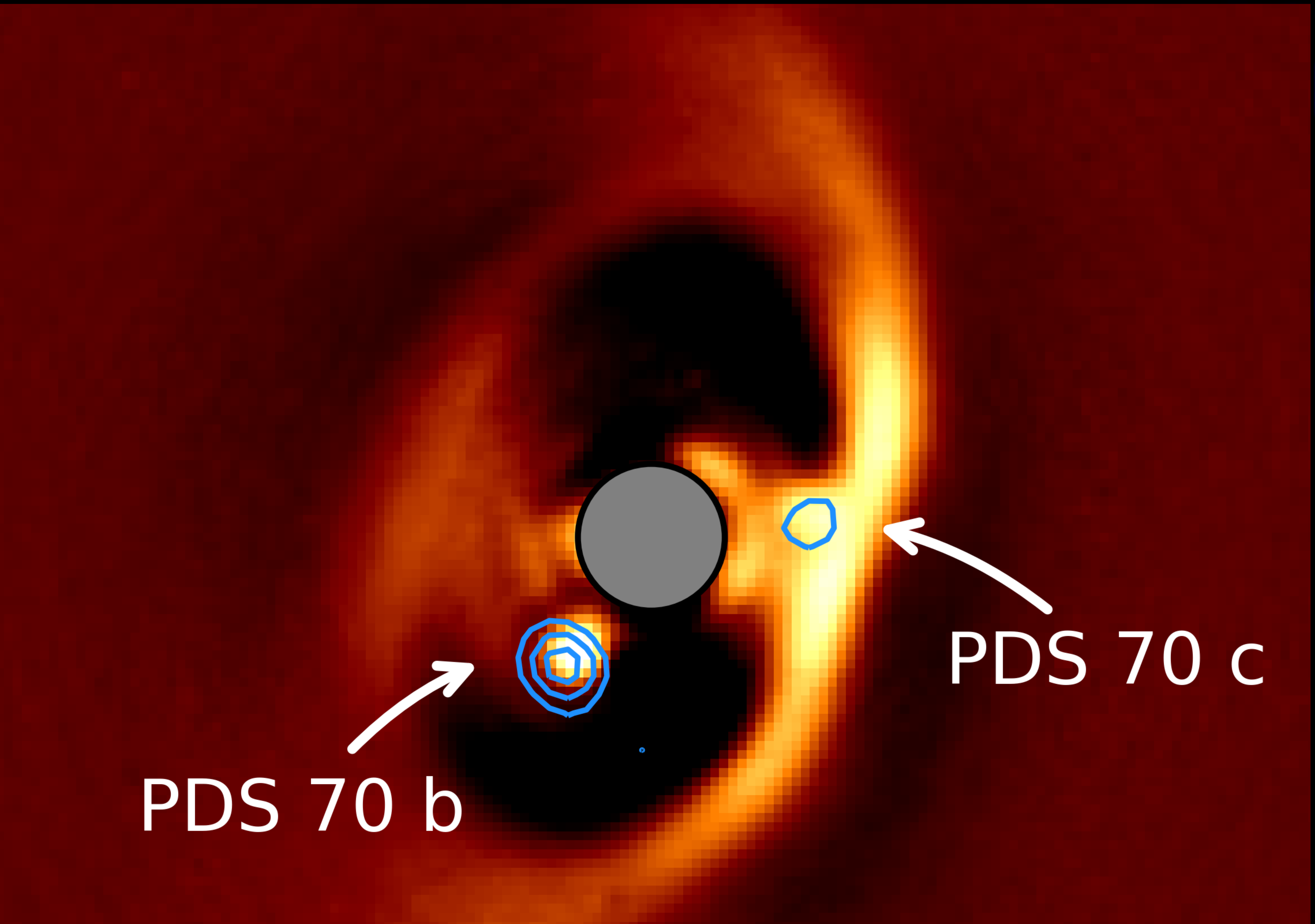
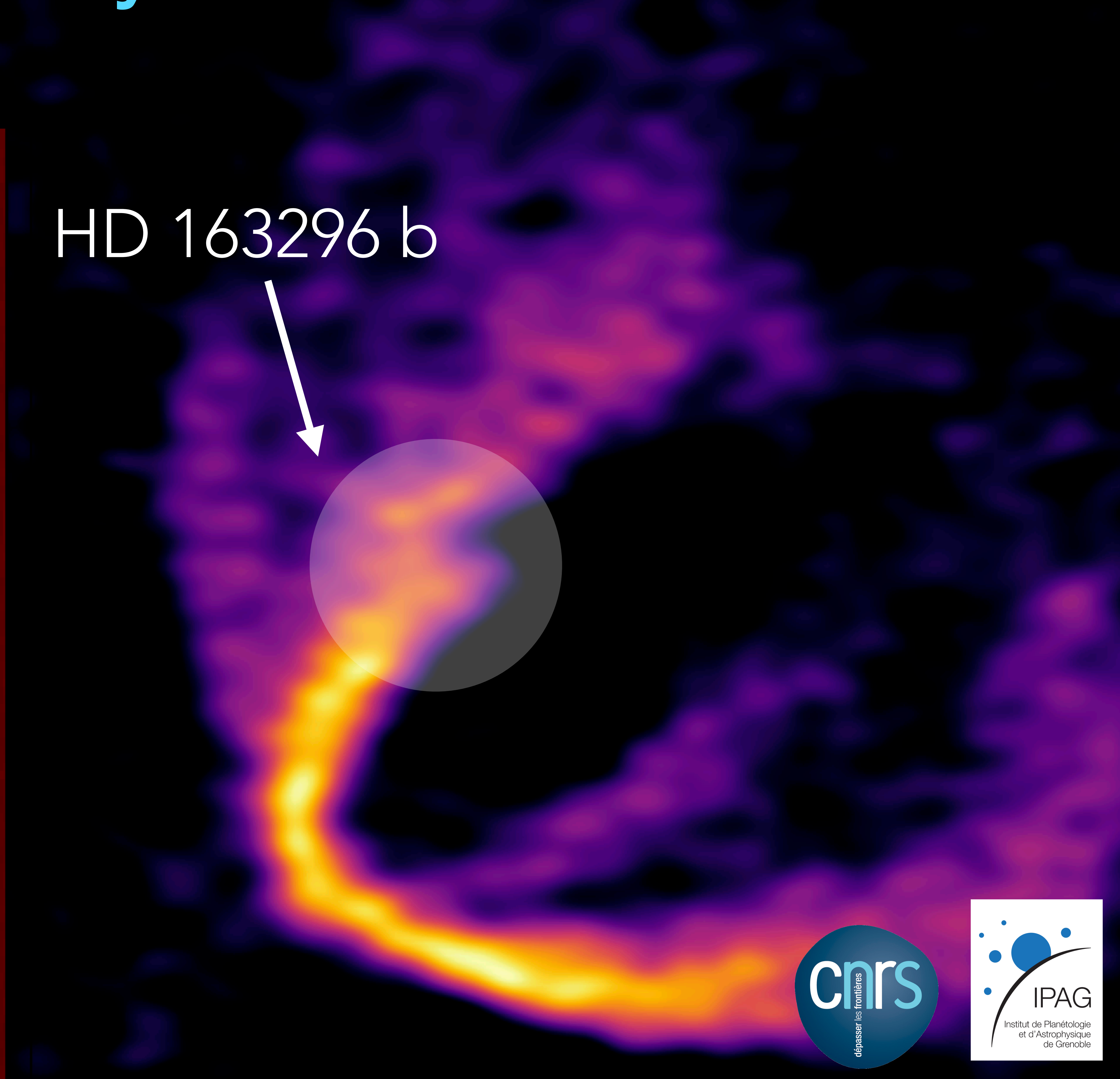
6 lessons in planet formation from observations and models of protoplanetary discs

Christophe Pinte





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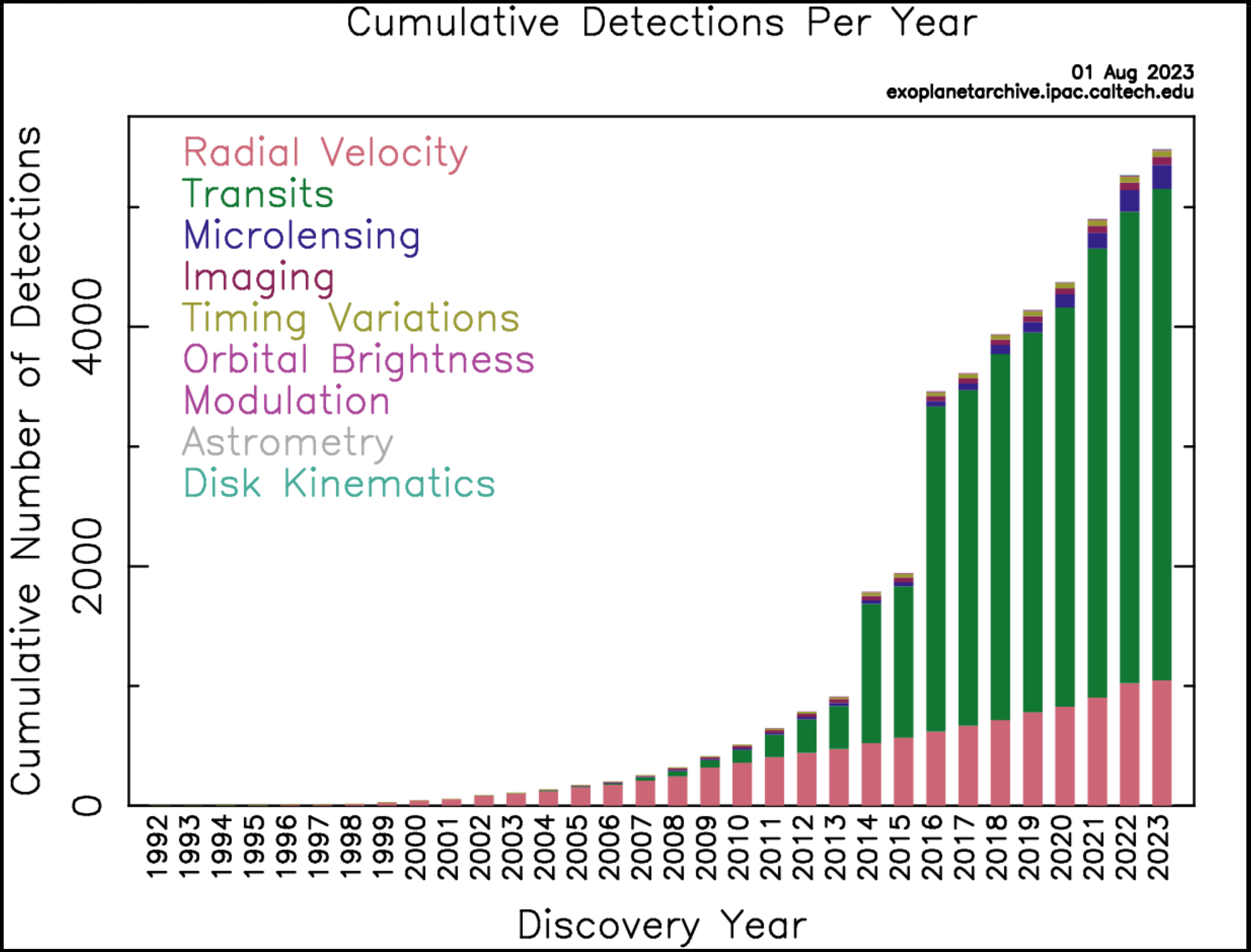
CONFIRMED DISCOVERIES	CANDIDATES	PLANETARY SYSTEMS
5,483	9,770	4,220

Last Update:August 10, 2023



Nearly every star has planets

Large diversity in the architectures of planetary systems

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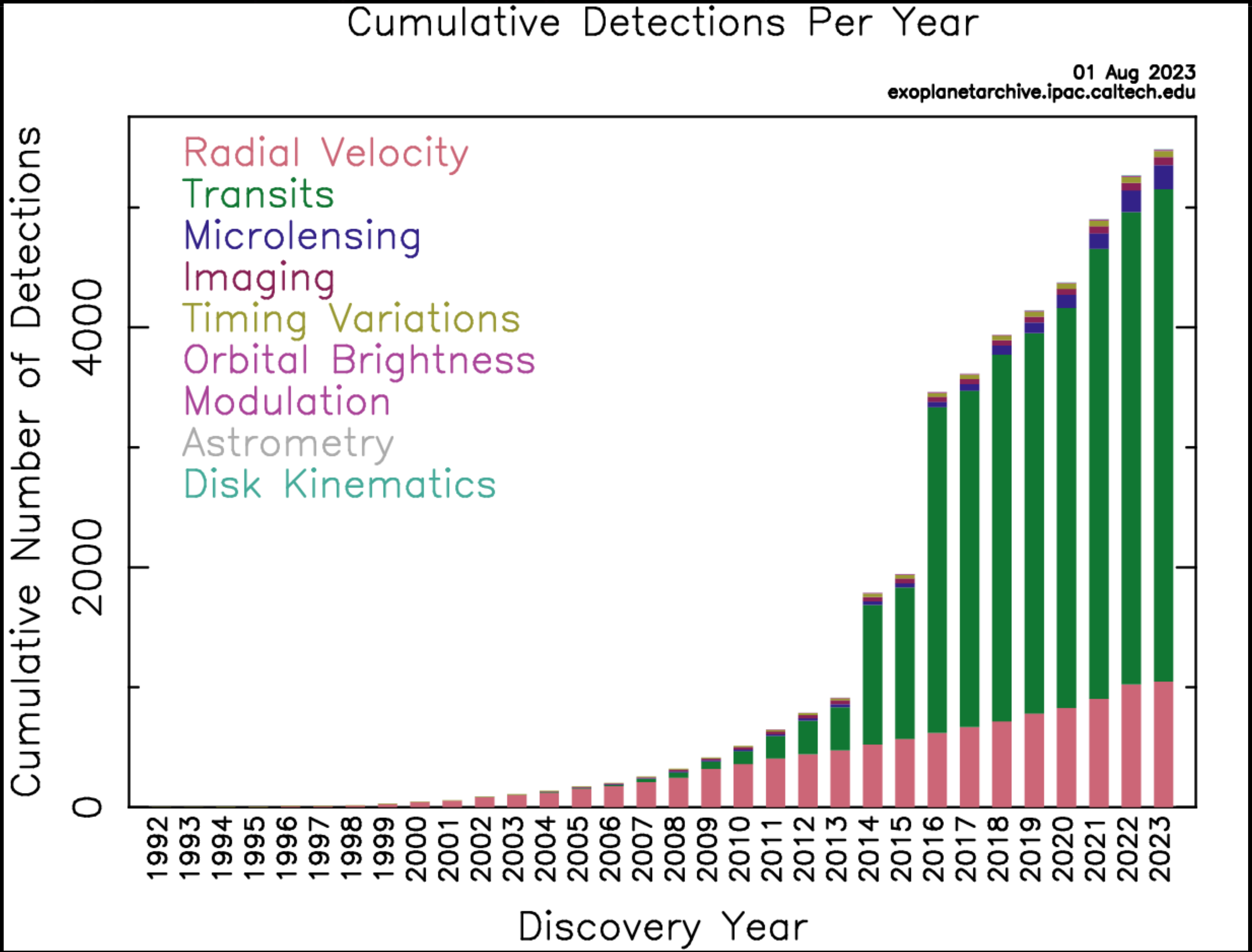

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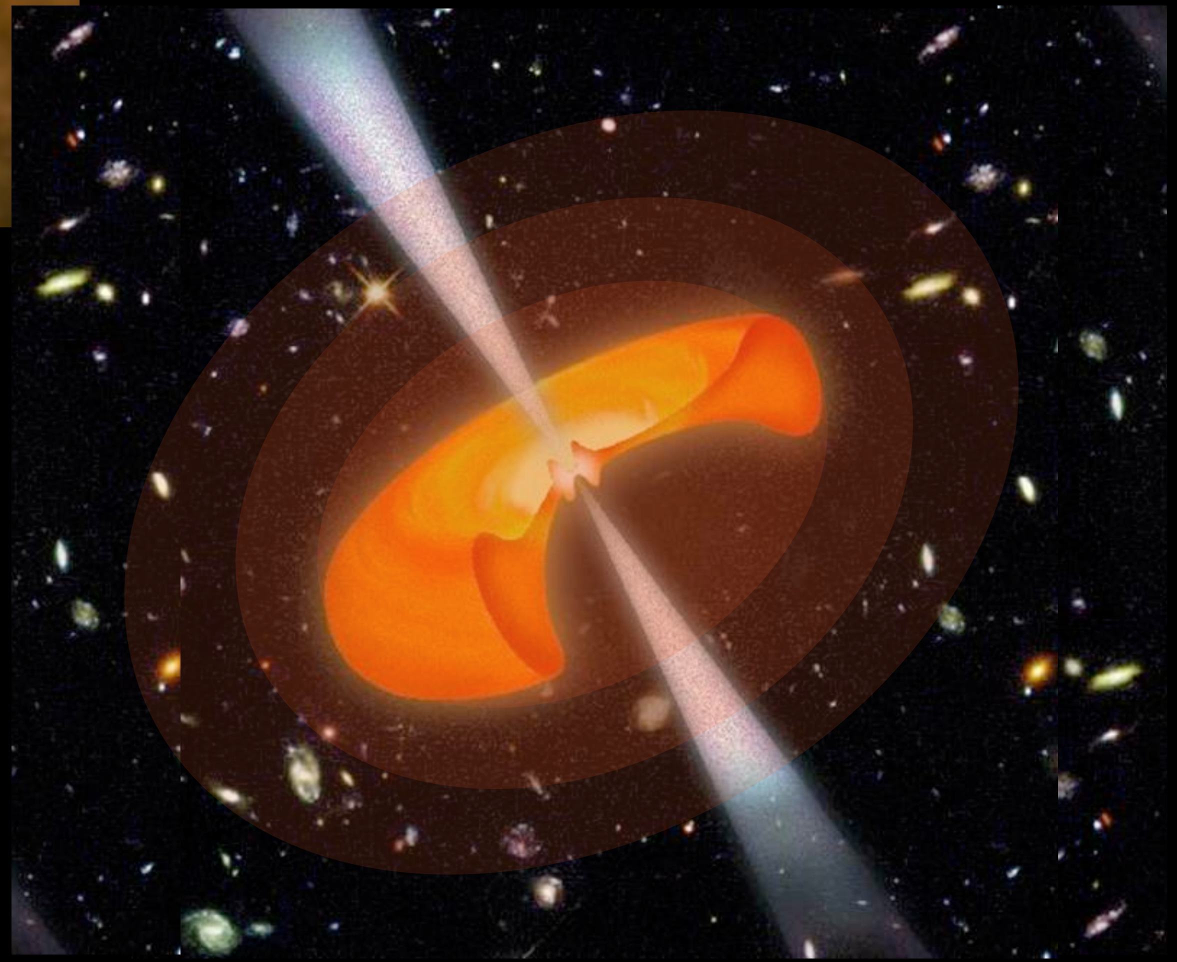
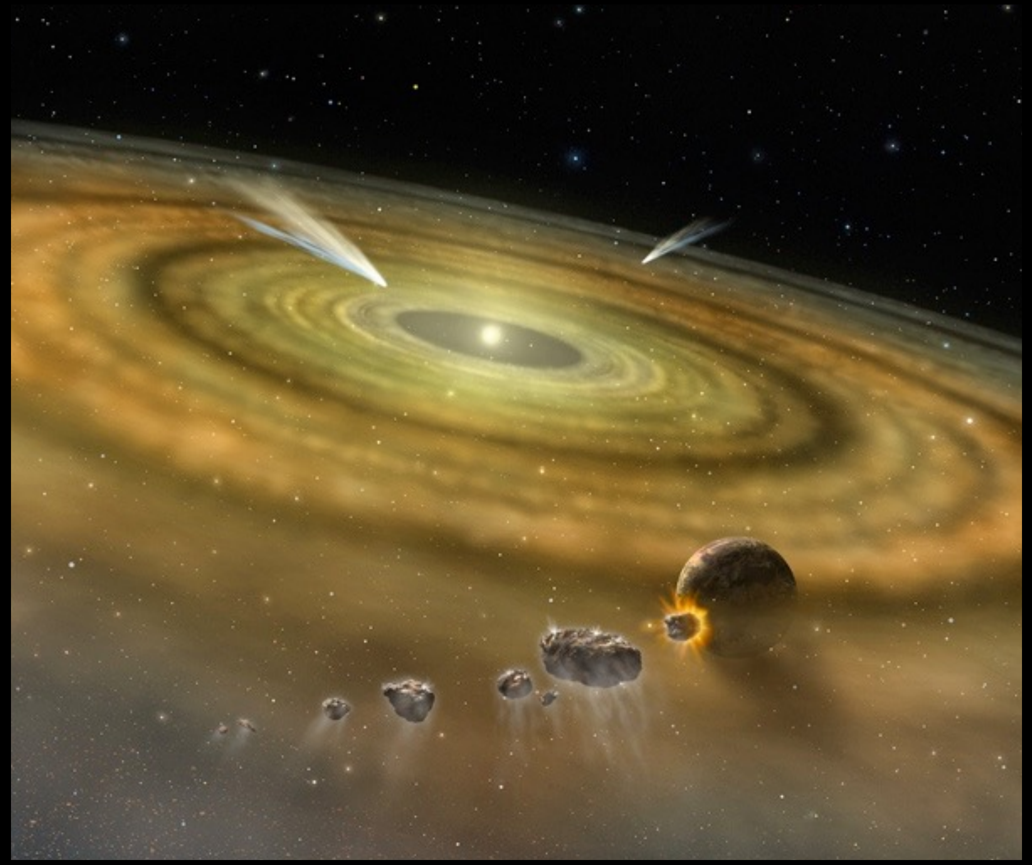
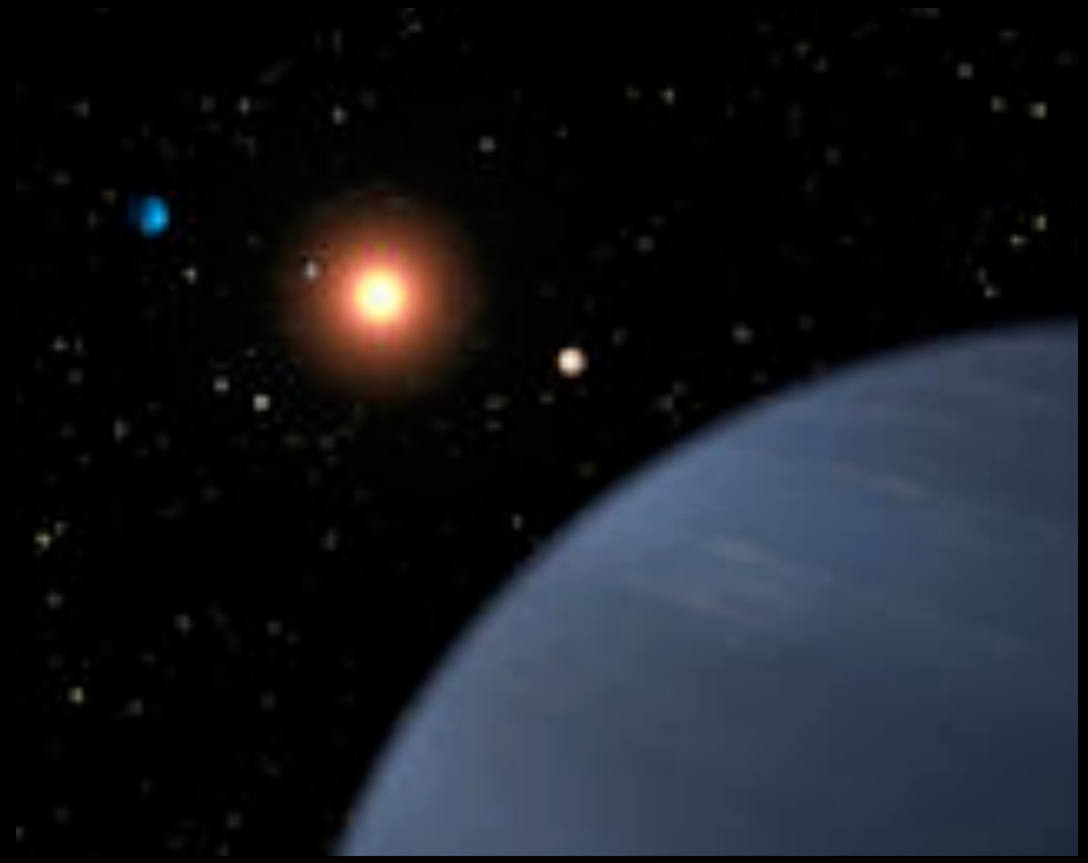
Large diversity in the architectures of planetary systems

How do they form?







From clouds
to envelopes,
to disks,
to planets

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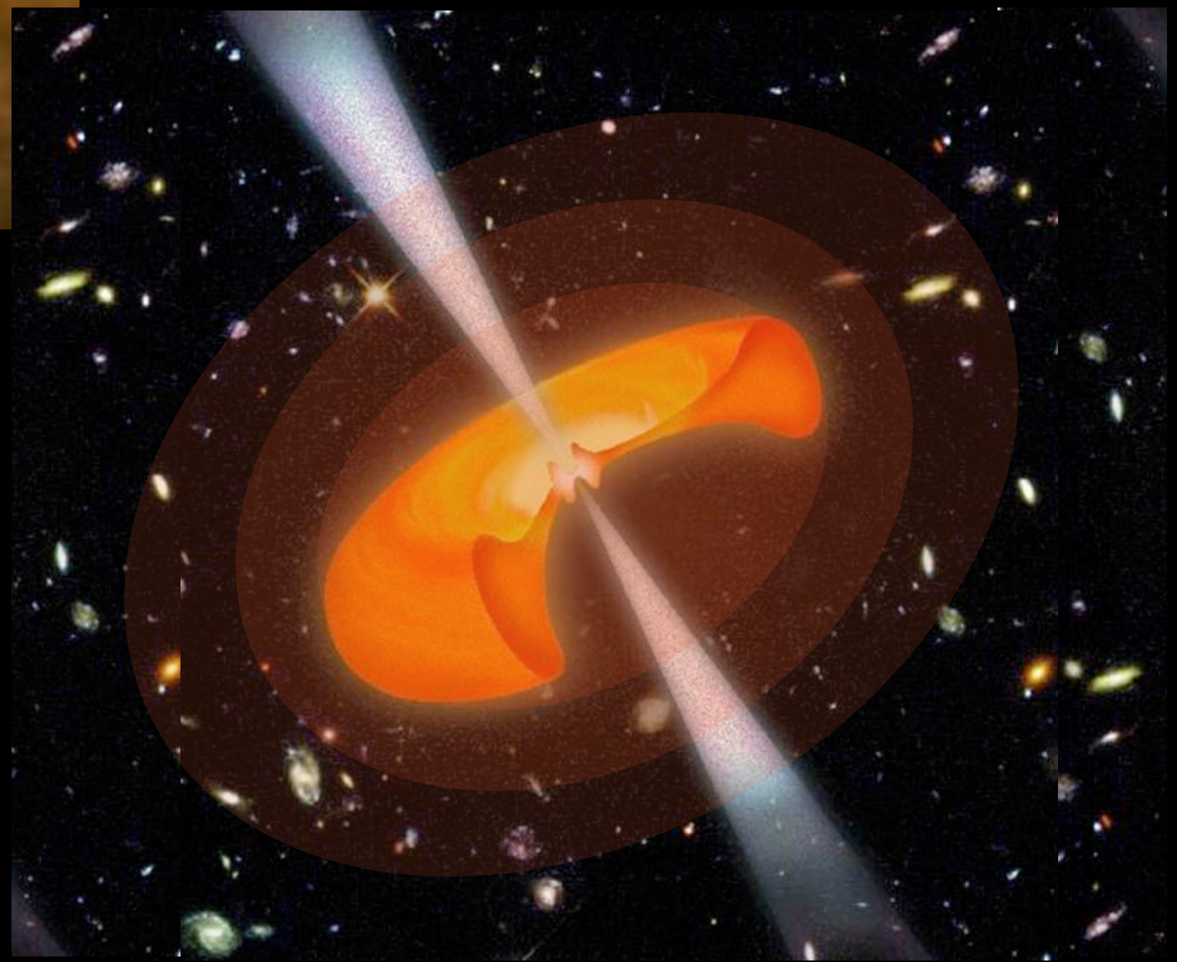
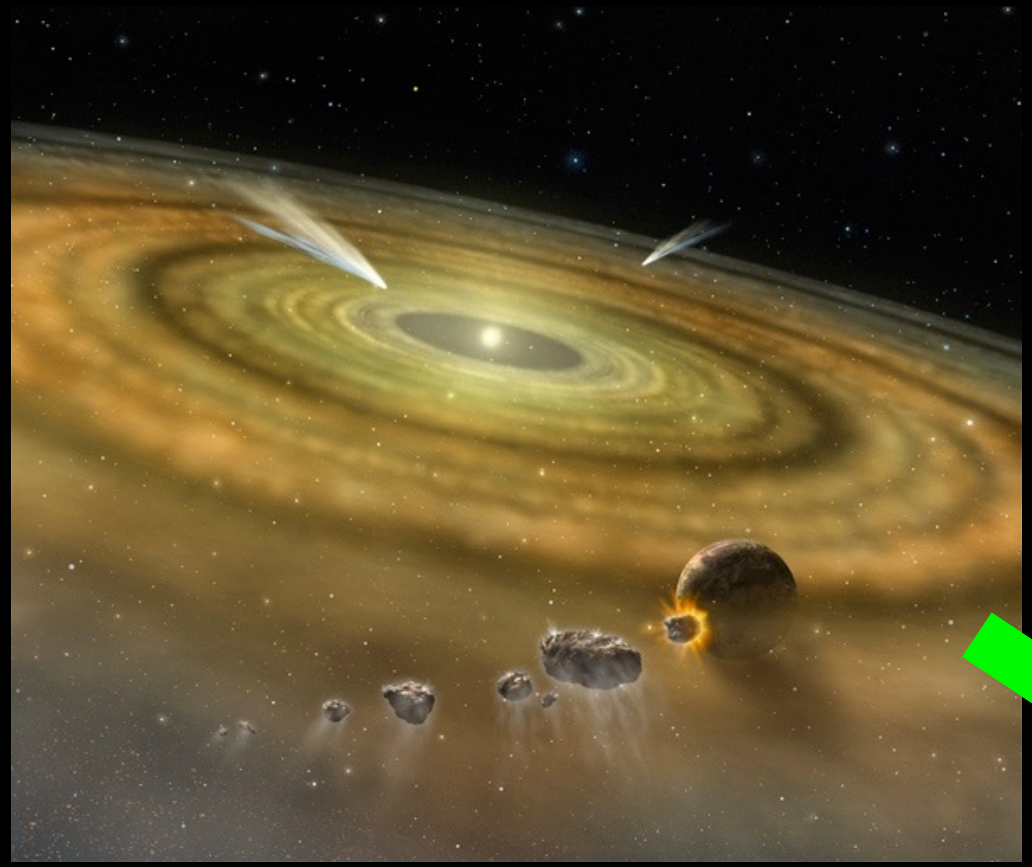
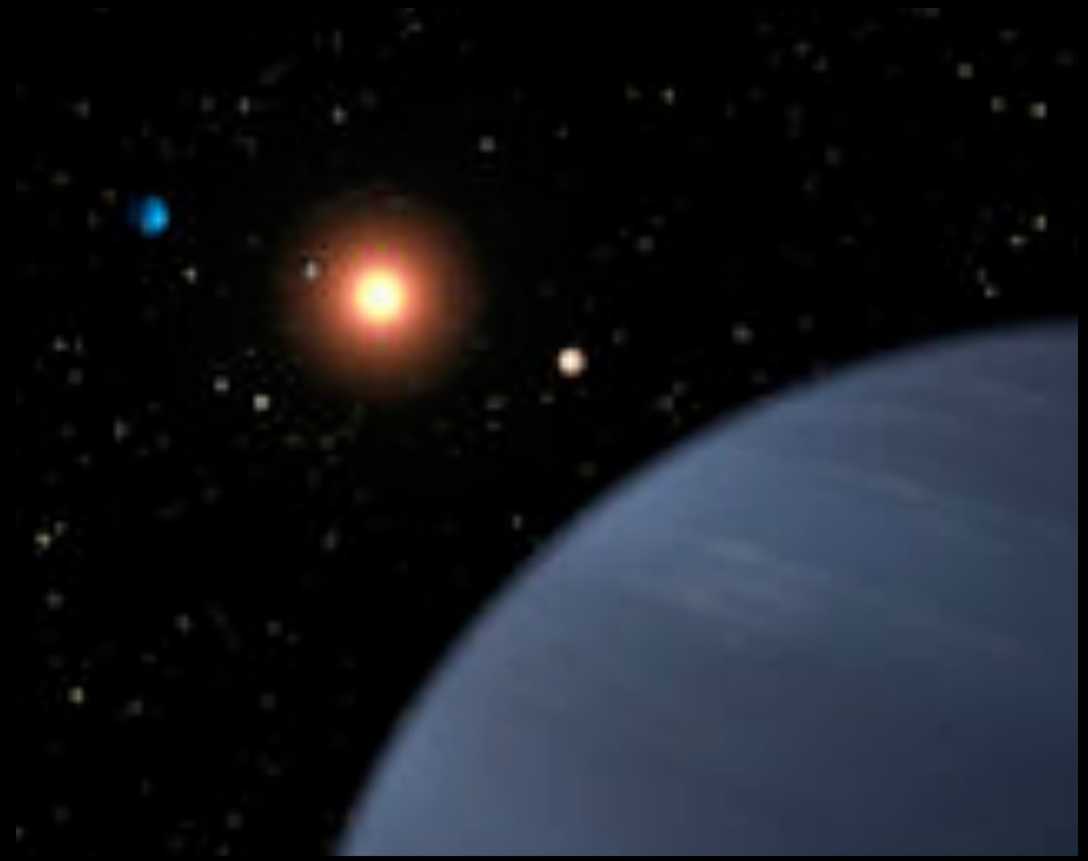




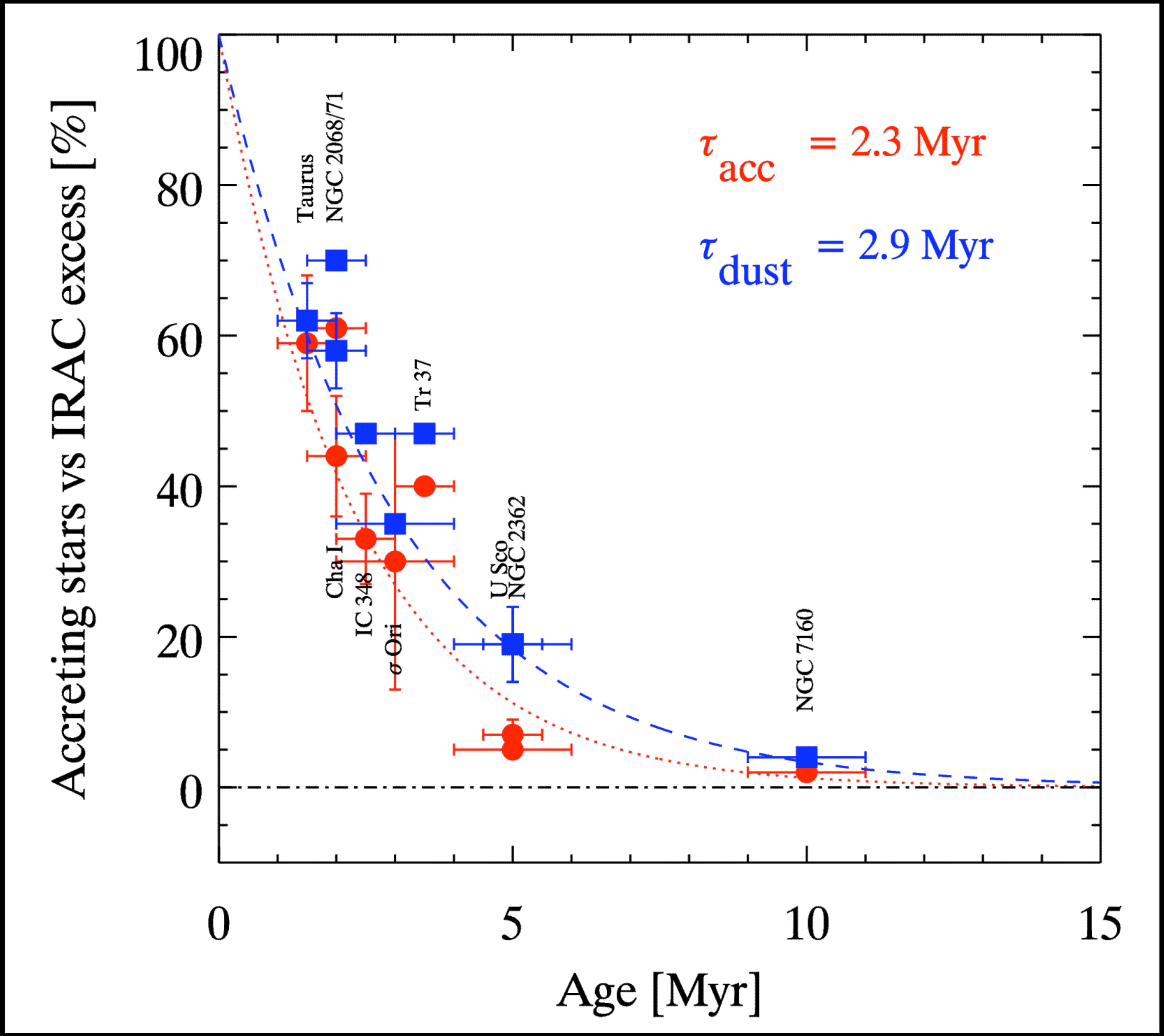
?



- *Timescale for gas dispersal and planet formation?*
- *Where are the planets forming ?*
- *Relative evolution of dust and gas ?*

Gas & Dust evolution

- Inner disk clearing
  ~ 2 Myr
- Gas & dust evolution strongly coupled



Fedele et al. 2009

What is new in the last 10 years?

the Atacama Large Millimetre/Submillimetre Array (ALMA)

What makes the rings ?

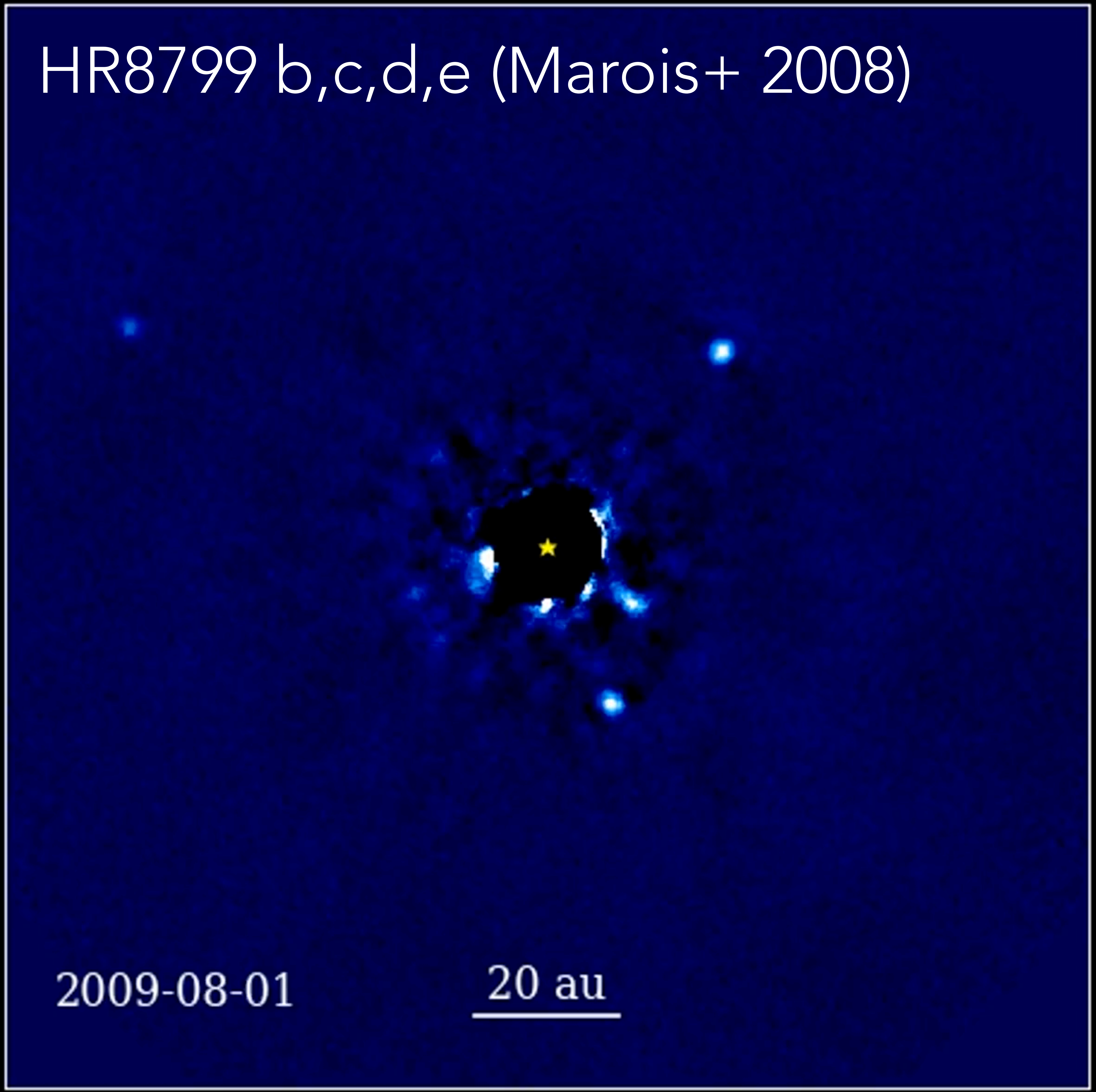
HL Tau (ALMA 2015)

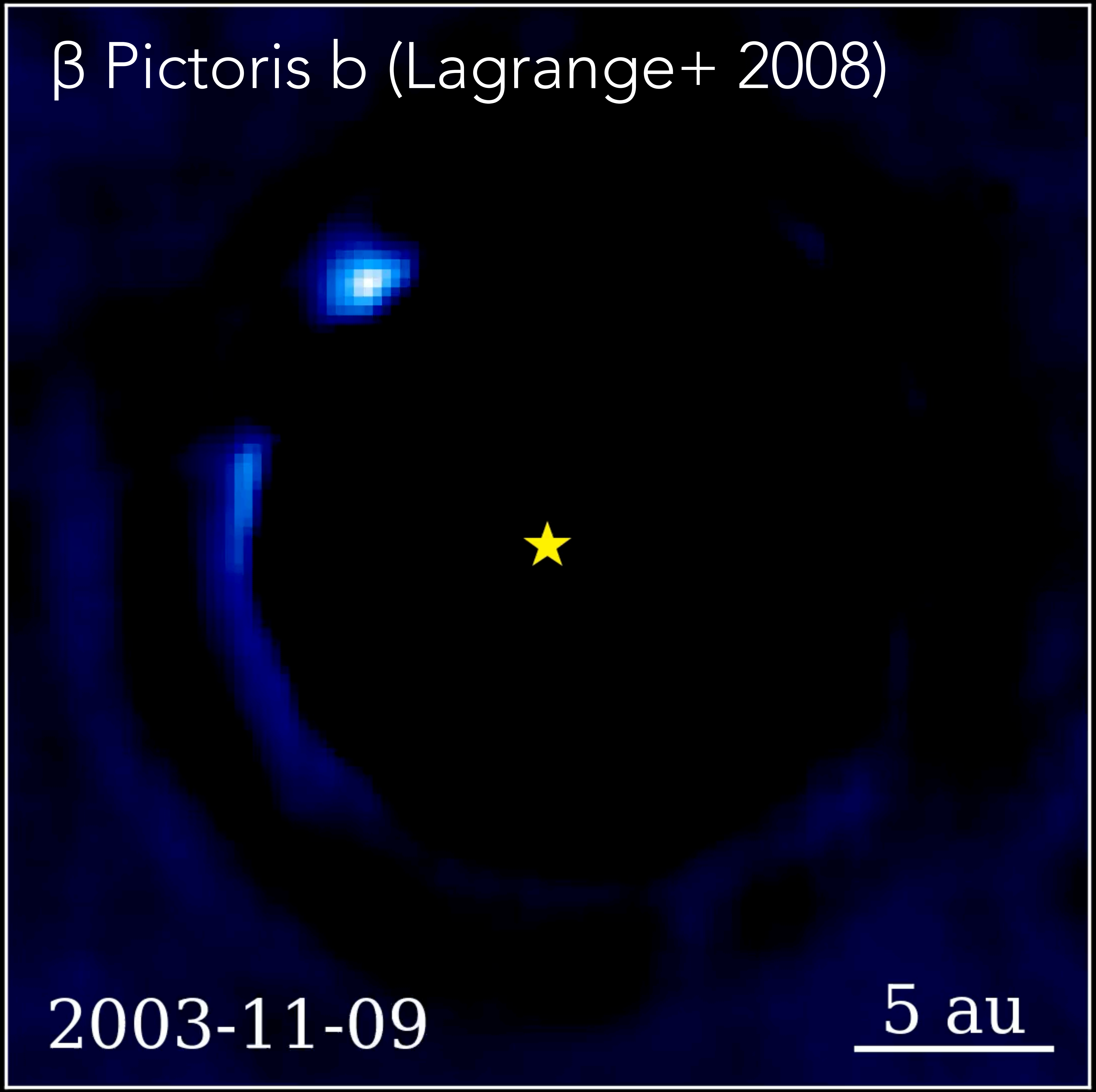
LOTS of speculation

- Magnetic fields?
- Snow/ice lines?
- Secular evolution ?
- dead-zone + thermal waves ?
- Planets?

What HL Tau reminds us of

What is new ?
Extreme adaptive optics systems (e.g. VLT/SPHERE, GPI)





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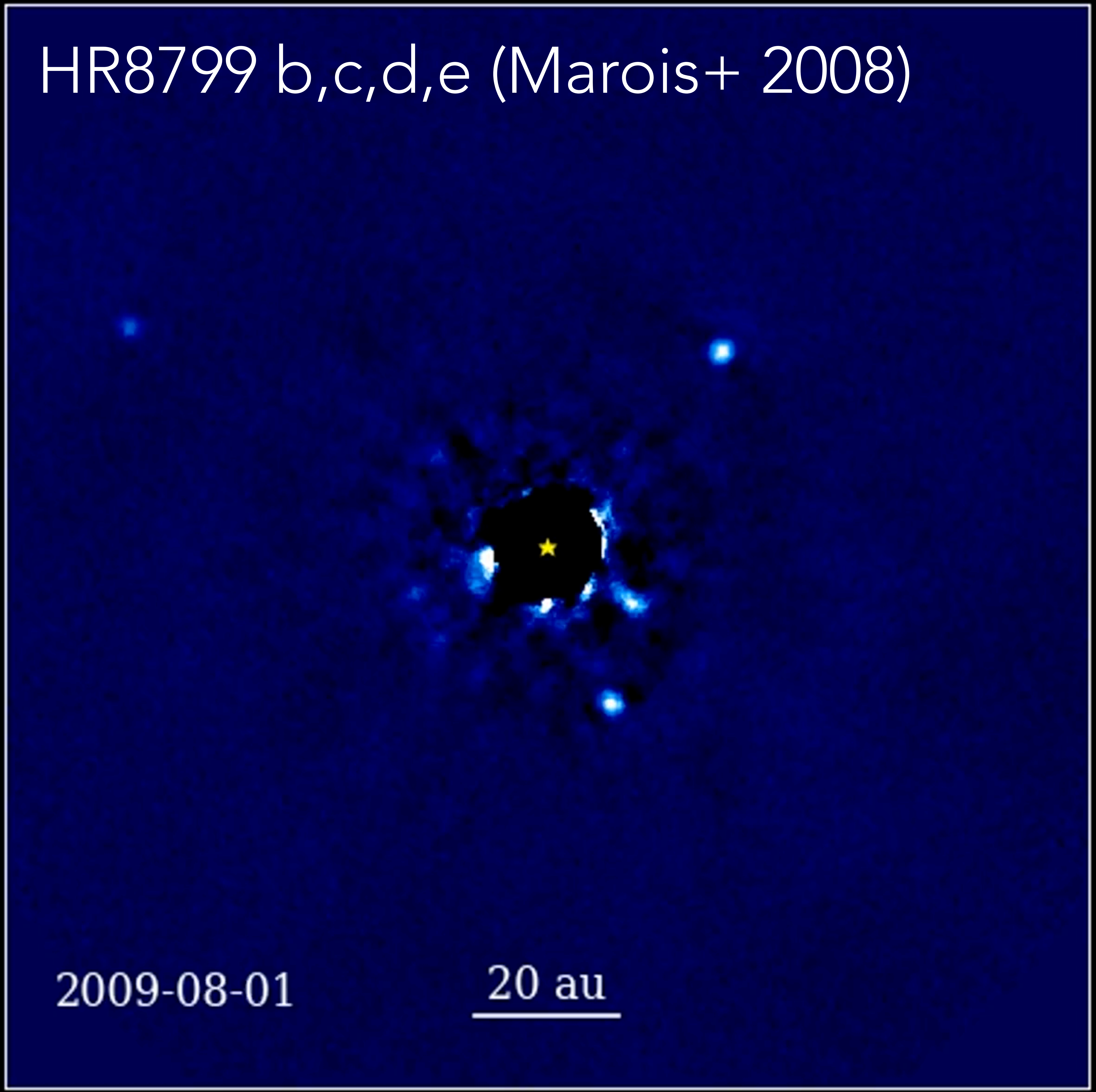
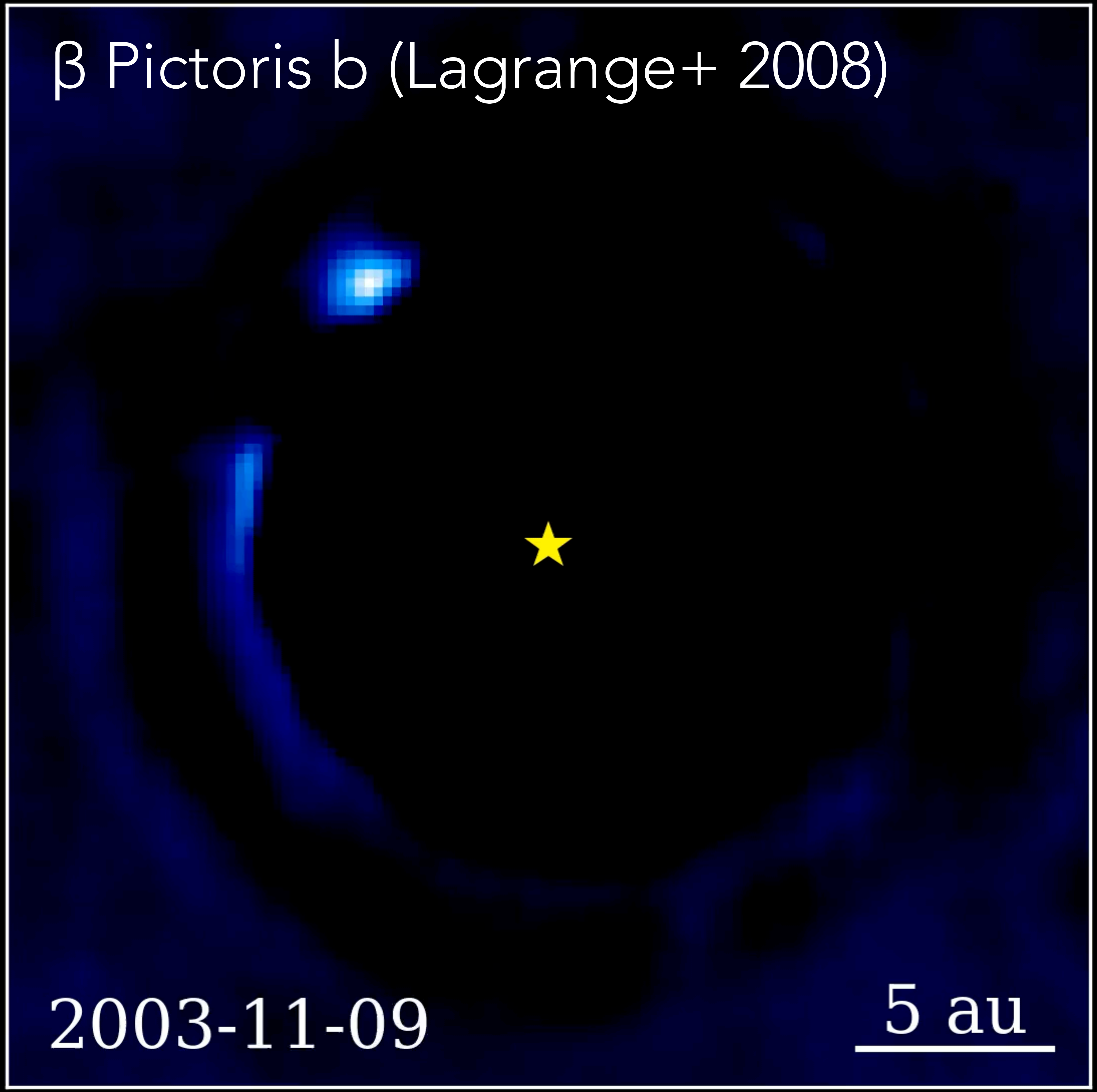
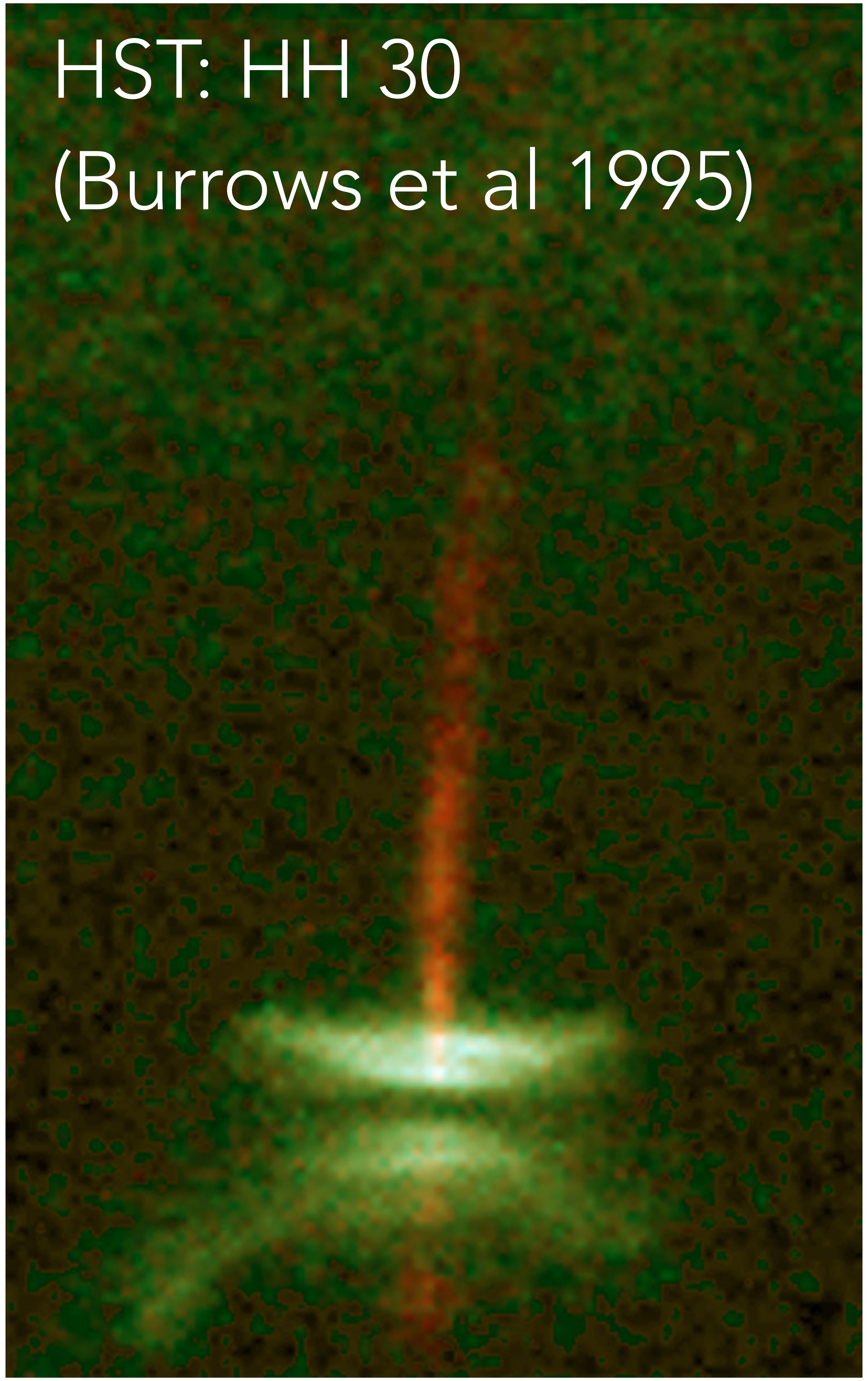




1. Imaging young planets is tricky

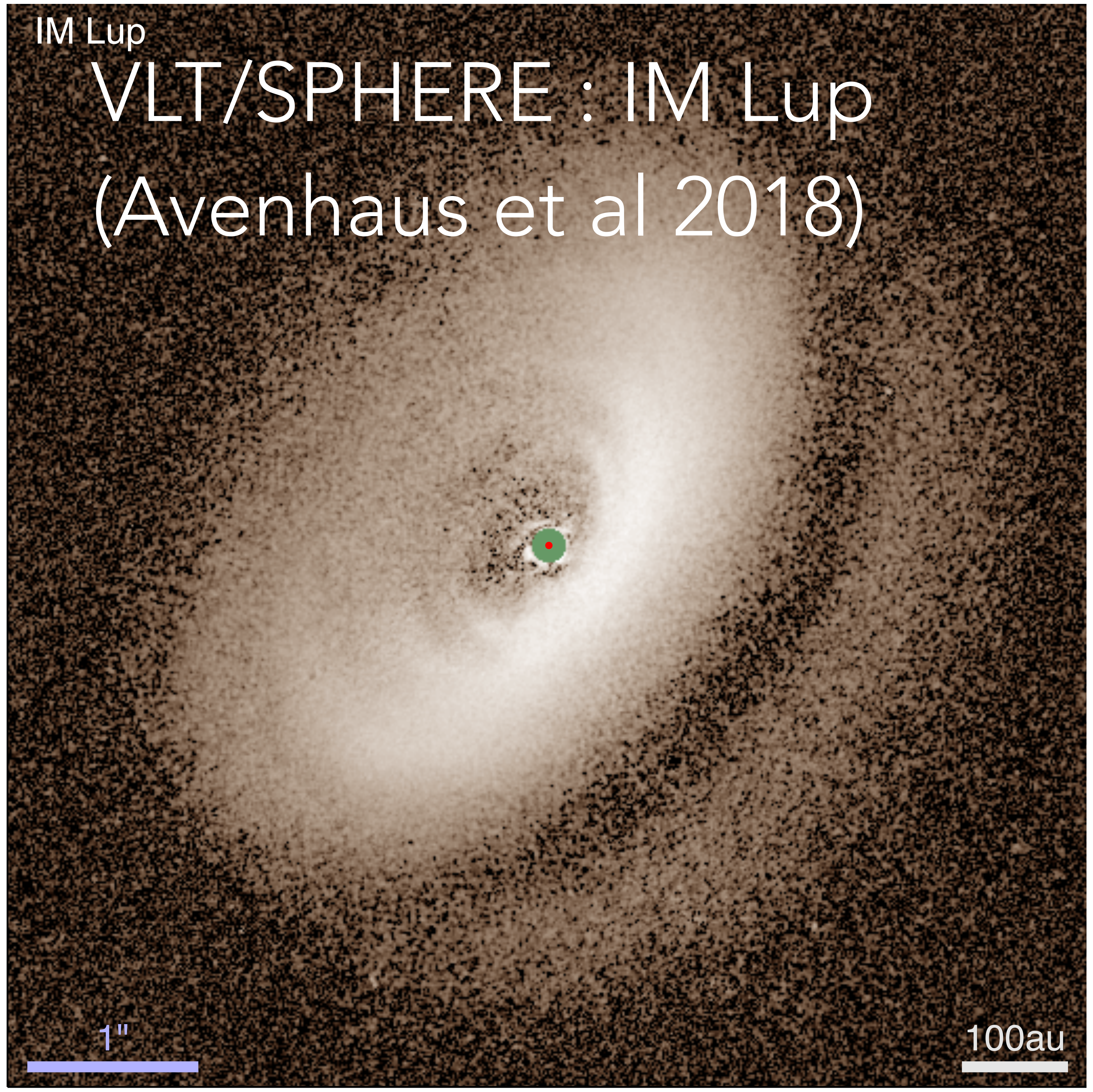
Detecting embedded planets is hard

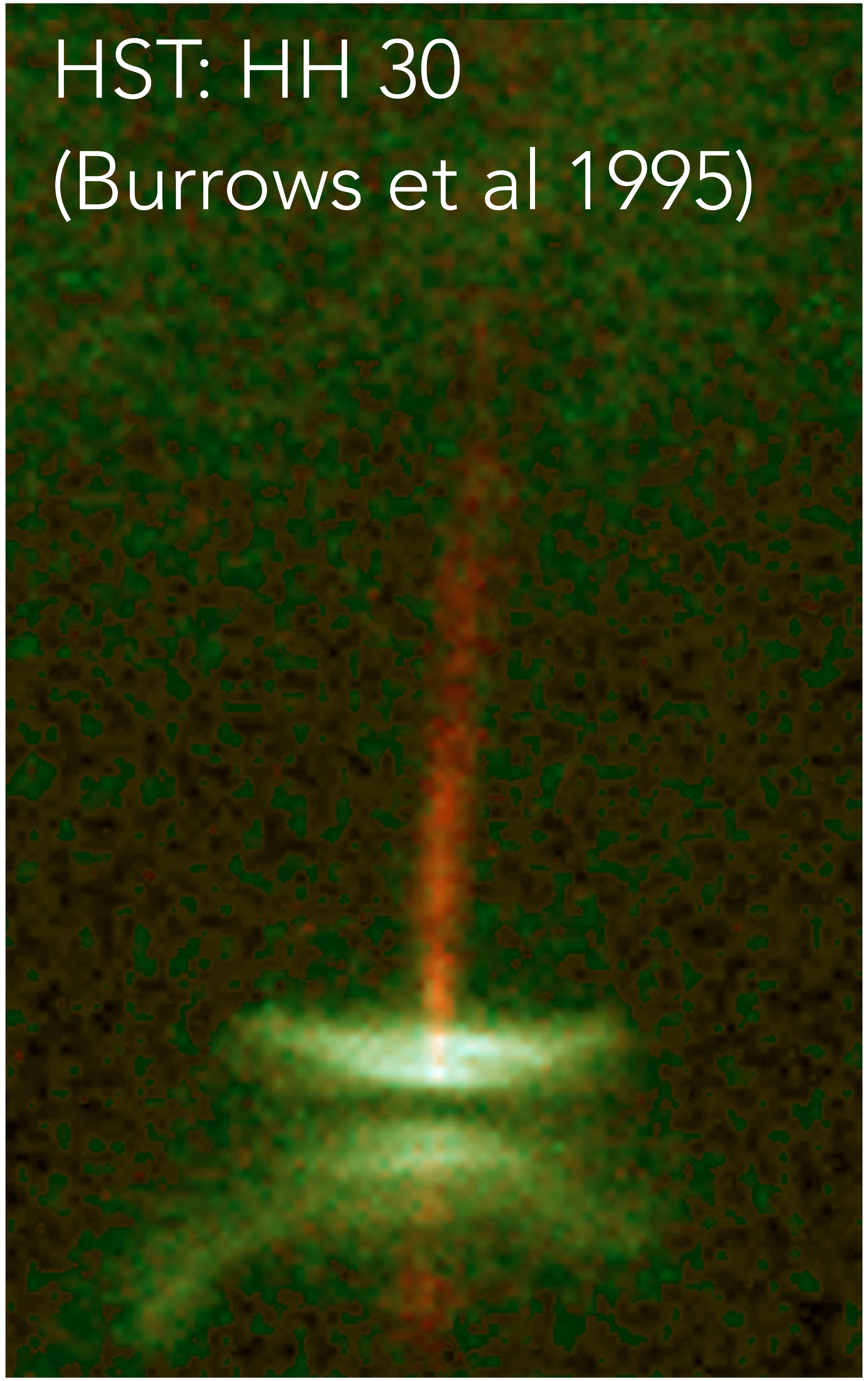
- Transit and radial velocities cannot be used to find planets around young stars



Detecting embedded planets is hard

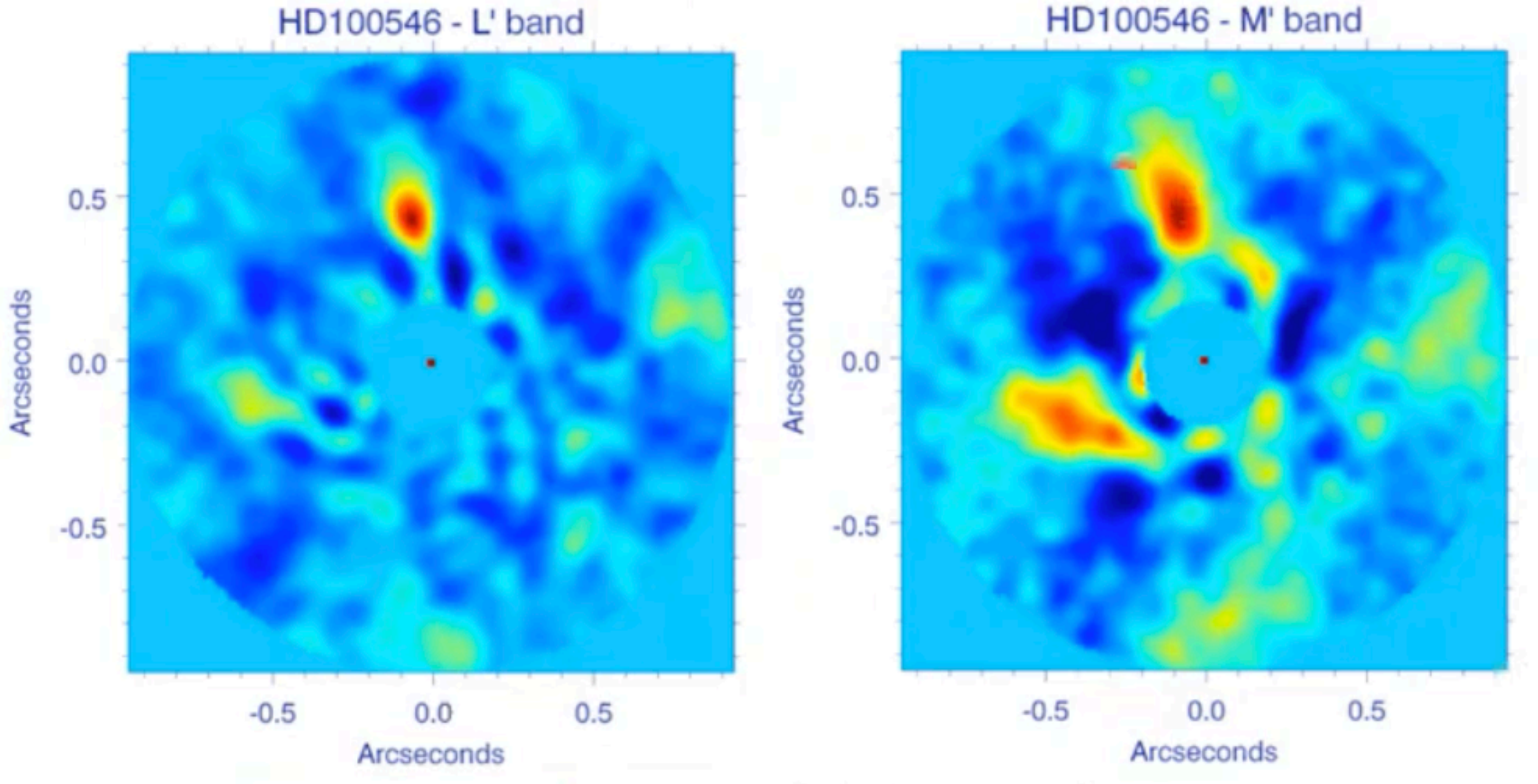
- Transit and radial velocities cannot be used to find planets around young stars
- Direct imaging limited by disc + distance





Protoplanet candidates have been hard to confirm

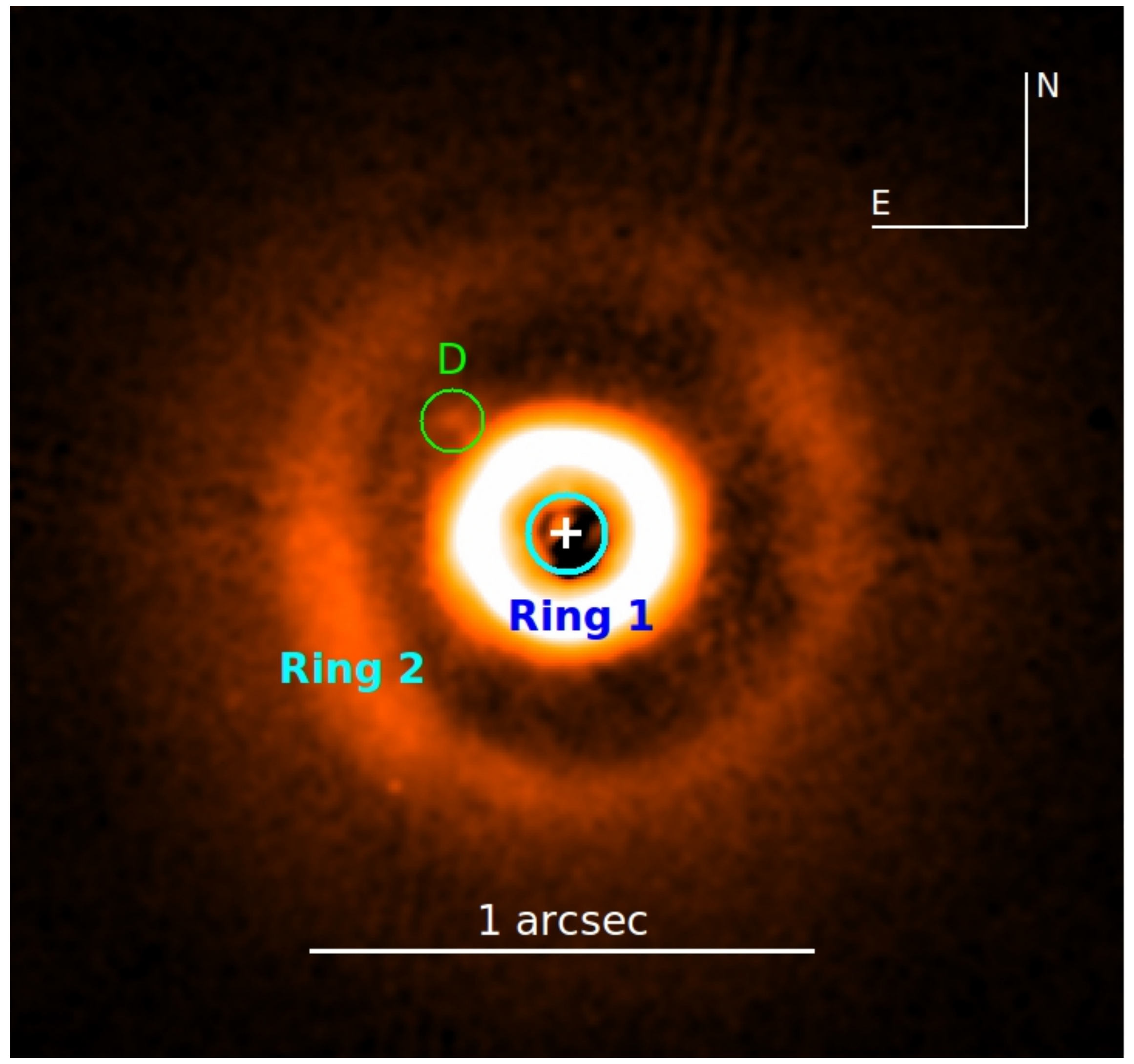
HD 100546 b



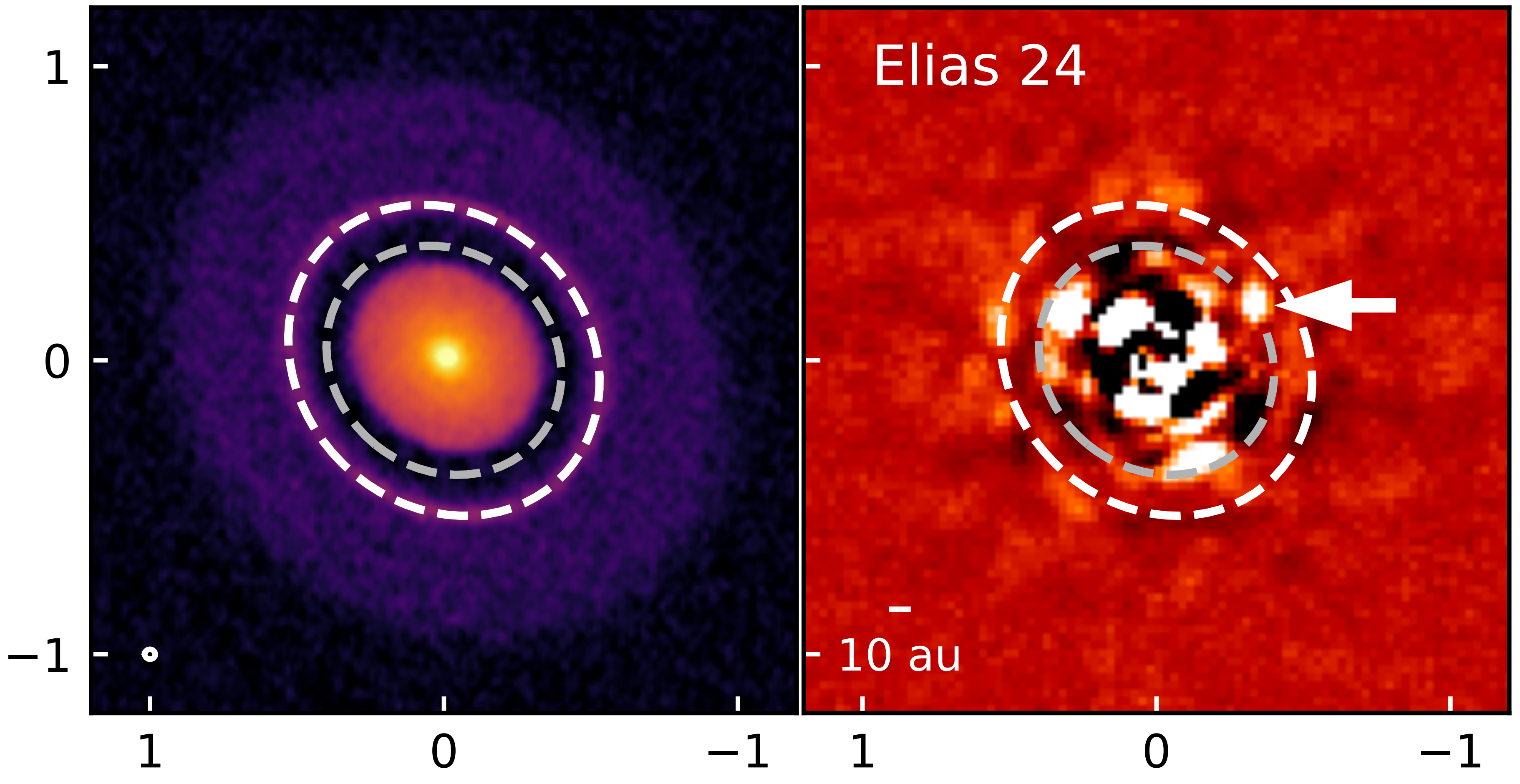
Quanz et al 2013, 2015, but see Rameau et al 2017, Folette 2017

HD169142

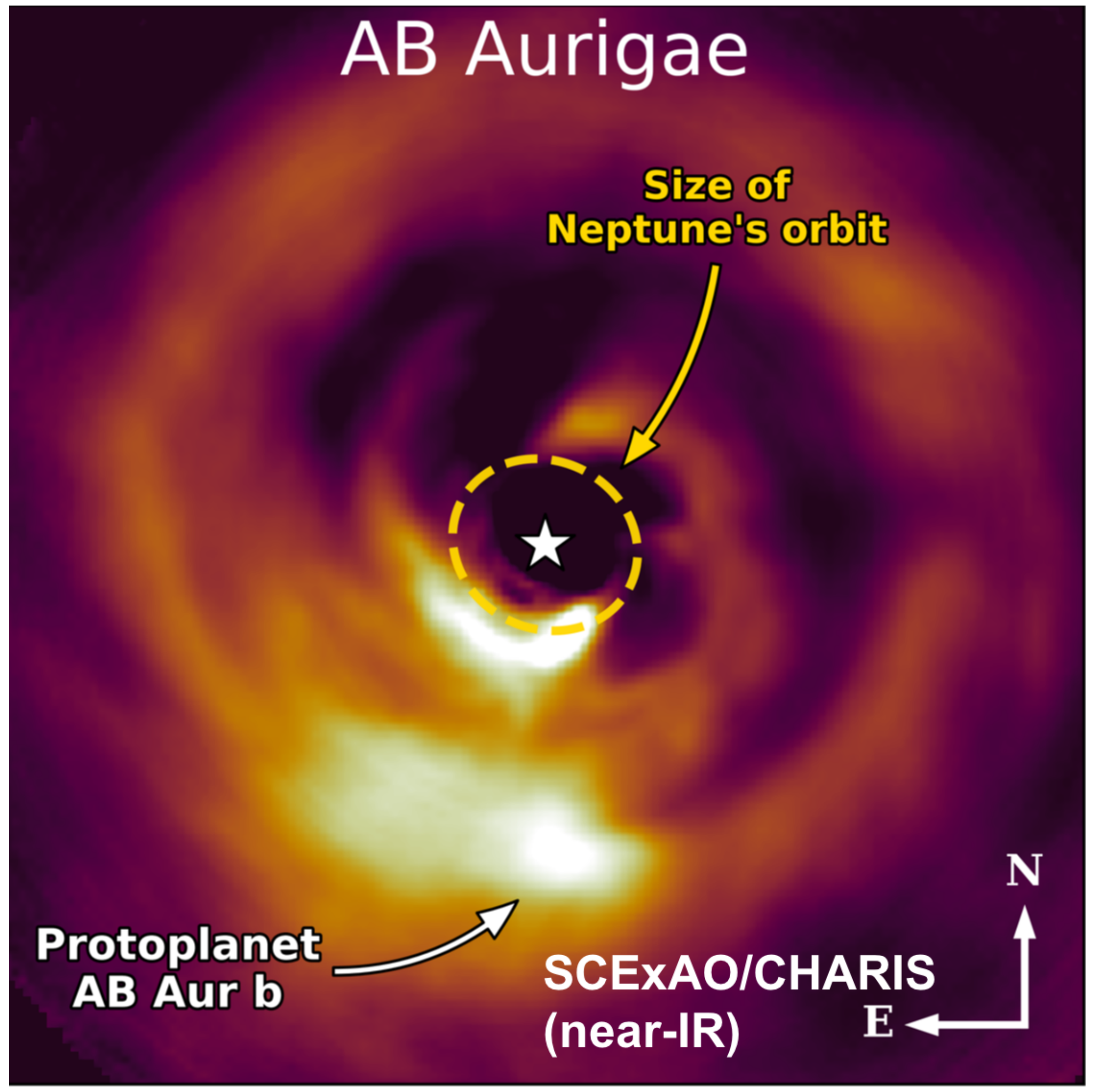
Reggiani et al 2014,
Biller et al 2014,
Phol et al 2017
Gratton et al 2019,
Hammond et al, 2023



Elias 2-24

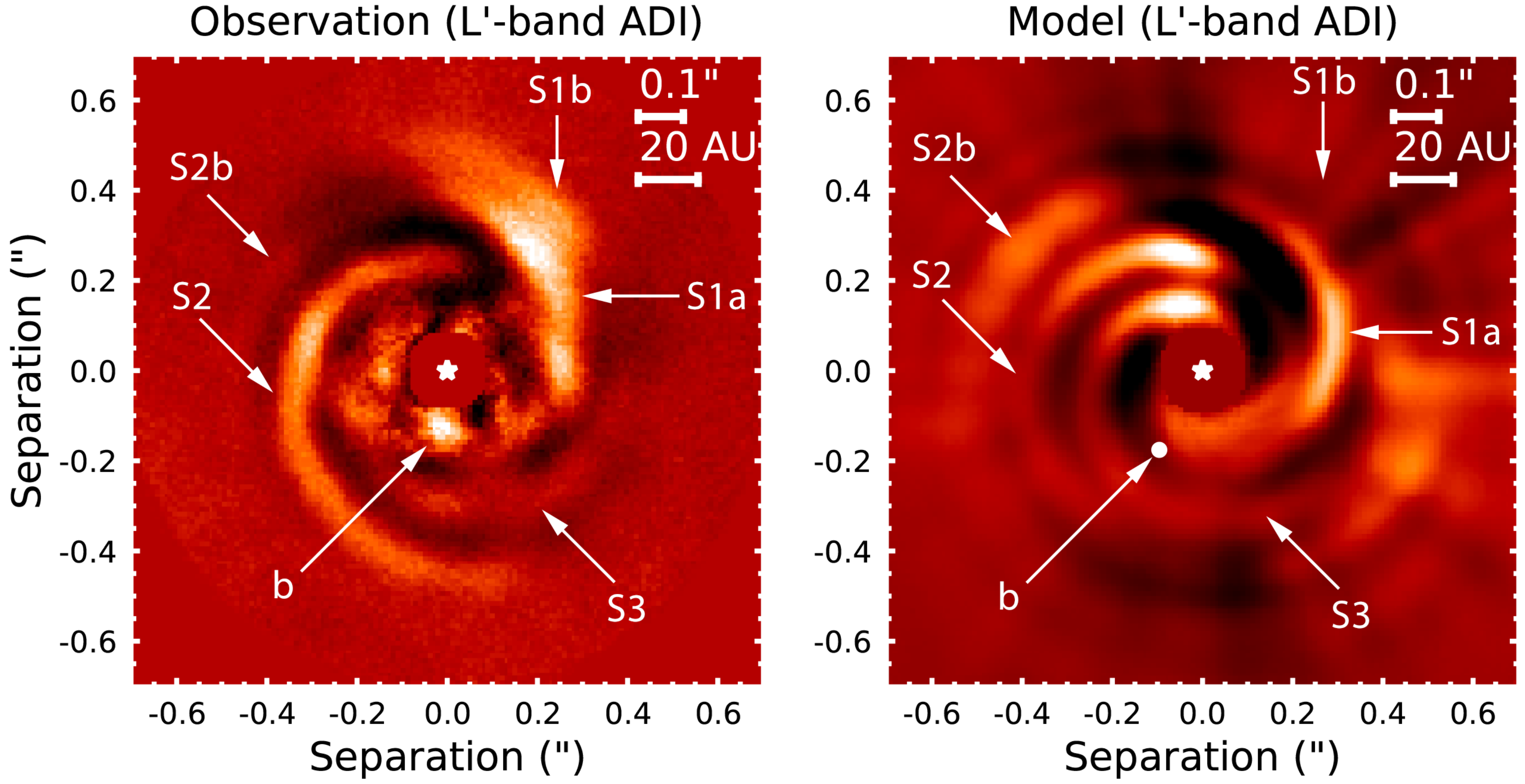


Jorquera et al, 2021



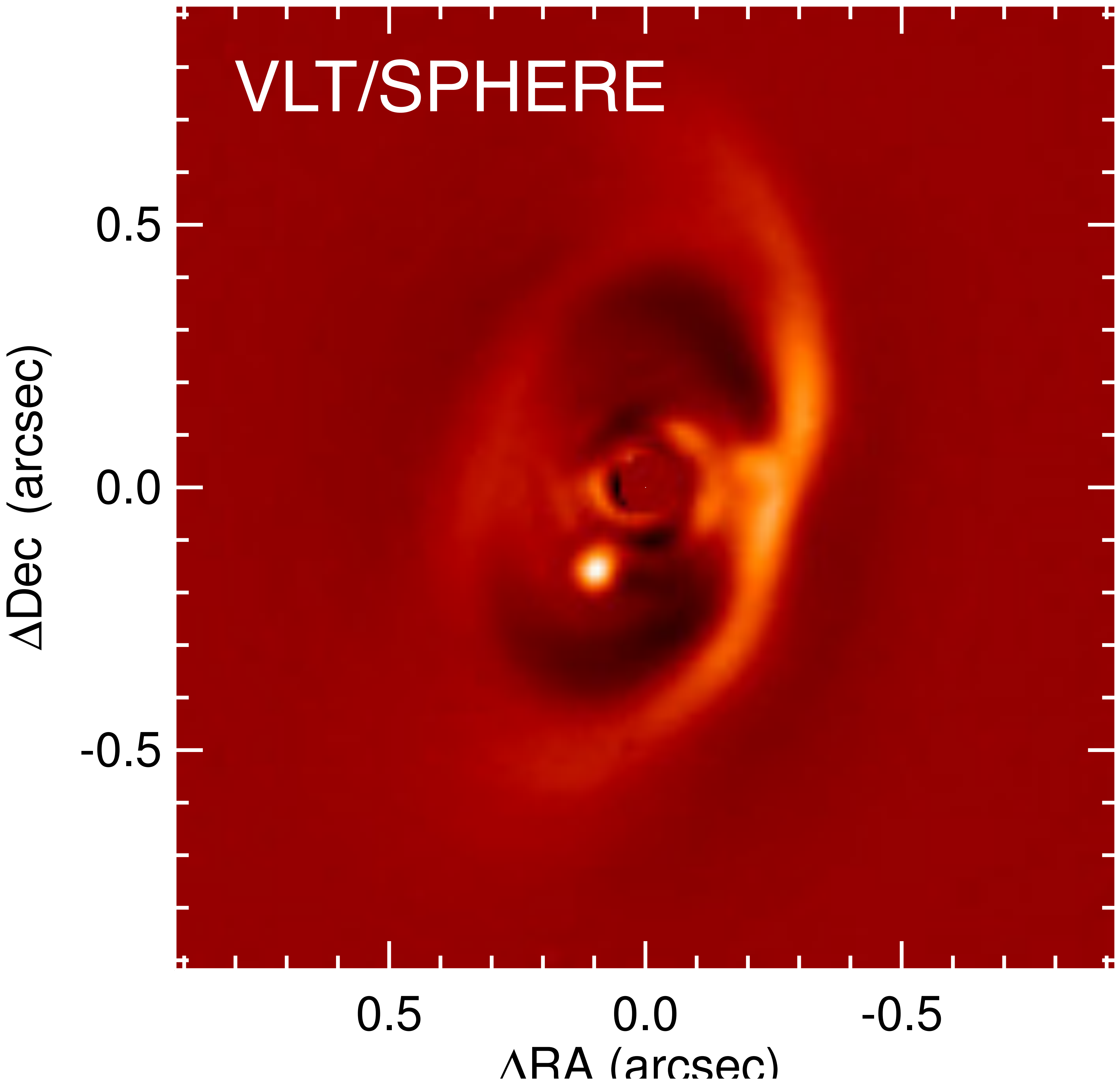
Currie et al 2022, Zhou et al 2022
But see also Jorquera et al 2022

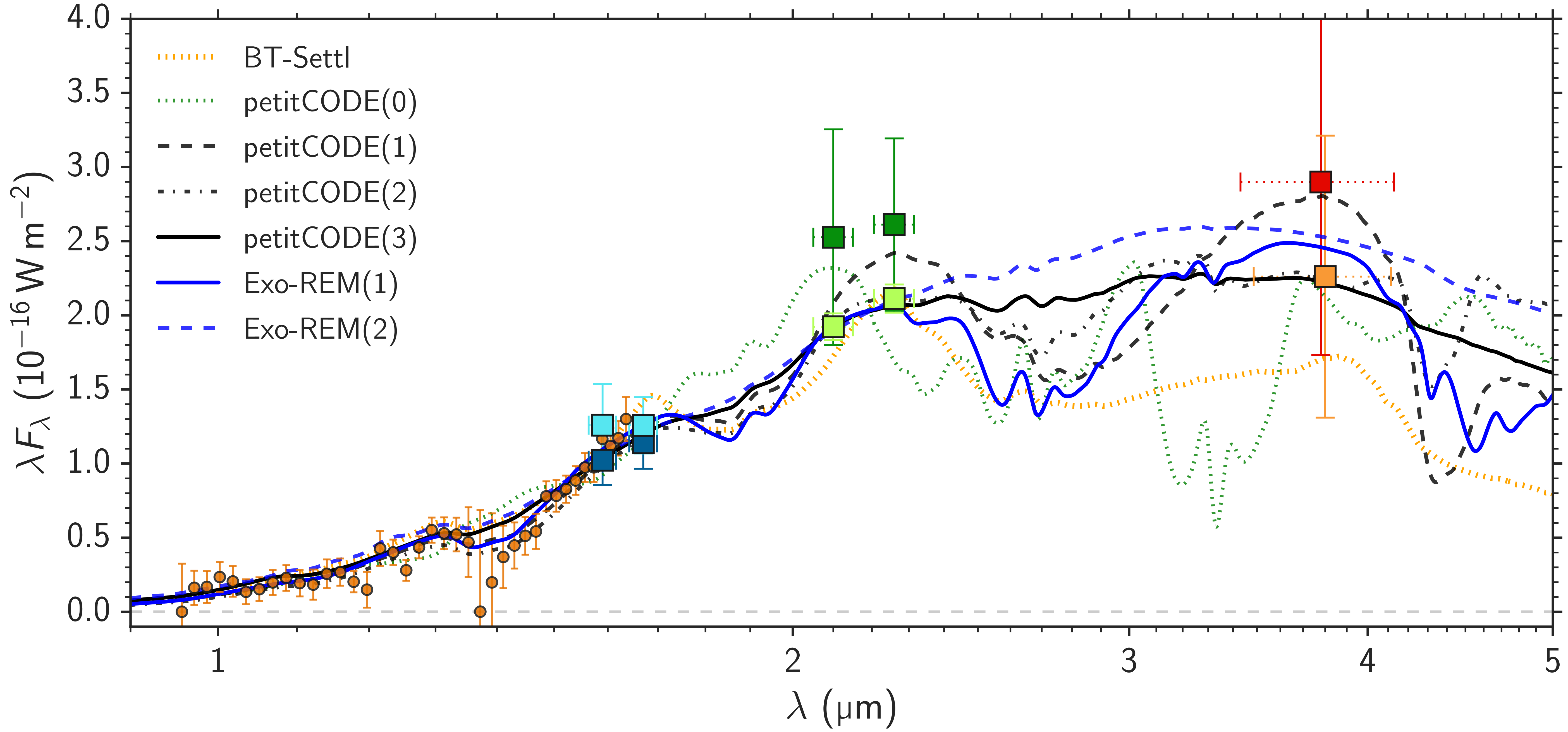
MWC758



Reggiani et al 2018, model by Calcino et al 2020

A remarkable exception : PDS 70 b and c

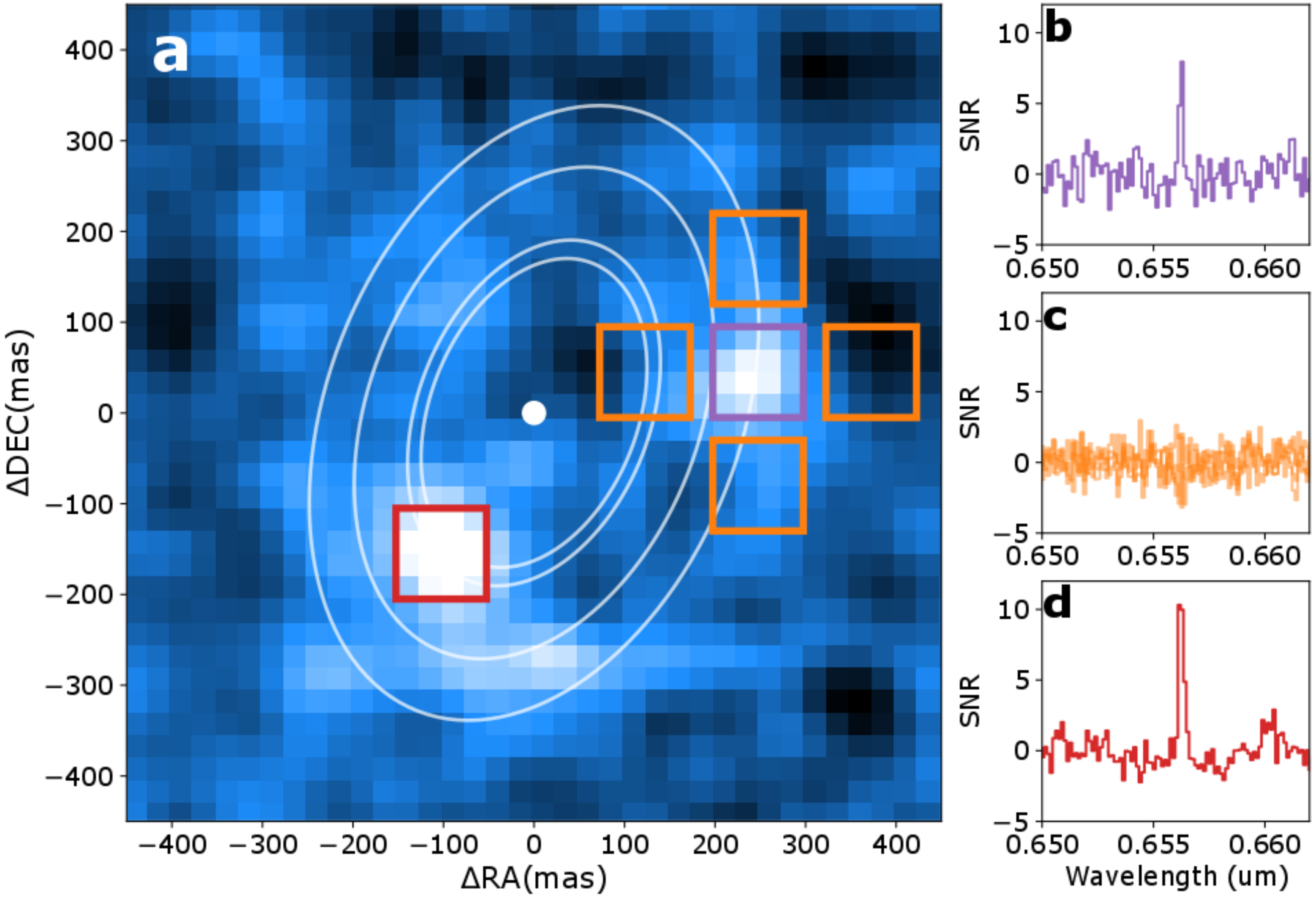




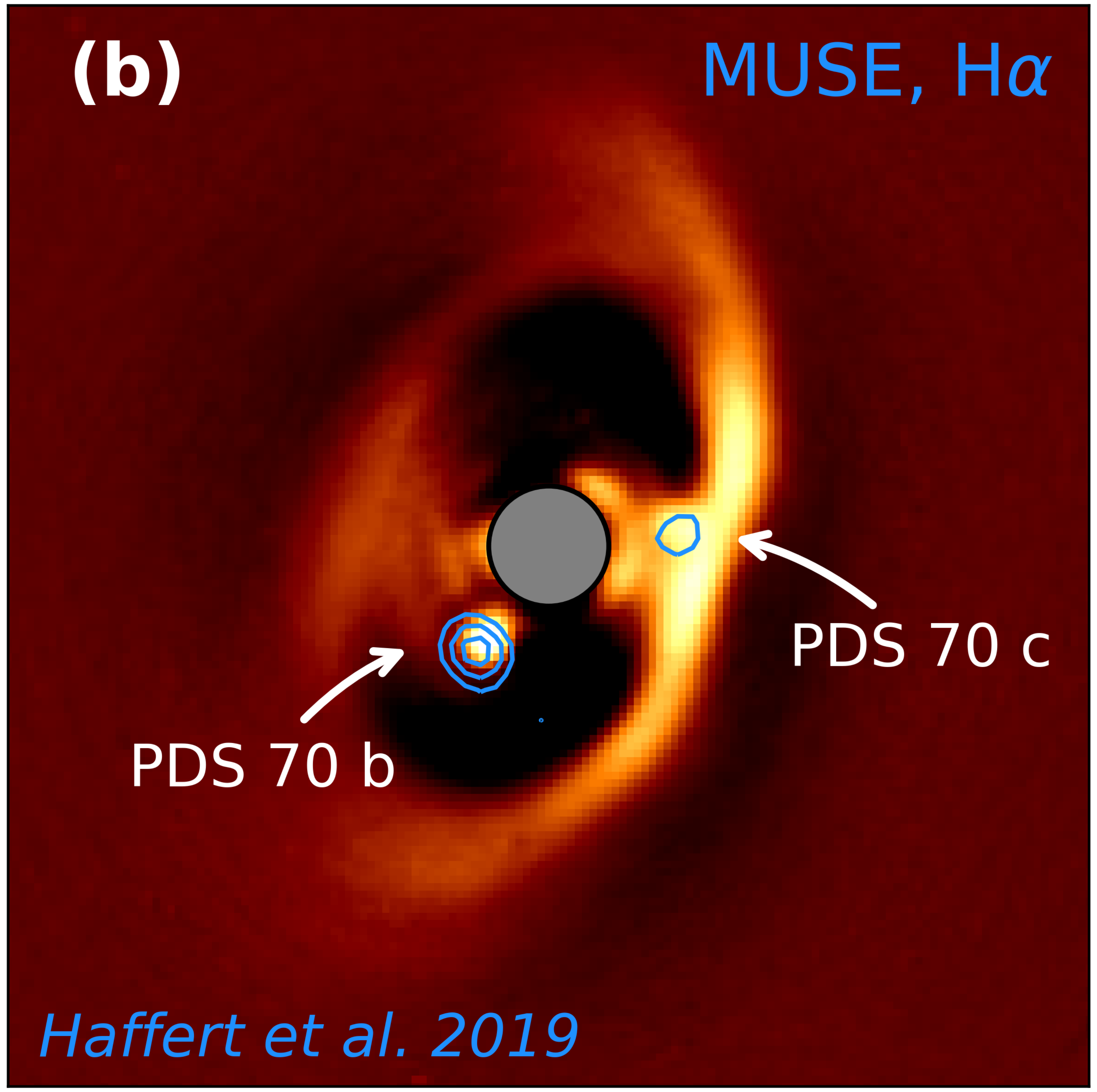
- ~ 22 au orbit
- 1000-1600K
- 1.4 to 3.7 R_{Jup}

Keppler et al. 2018
Muller et al 2018

MUSE : PDS 70 b, c in Hα

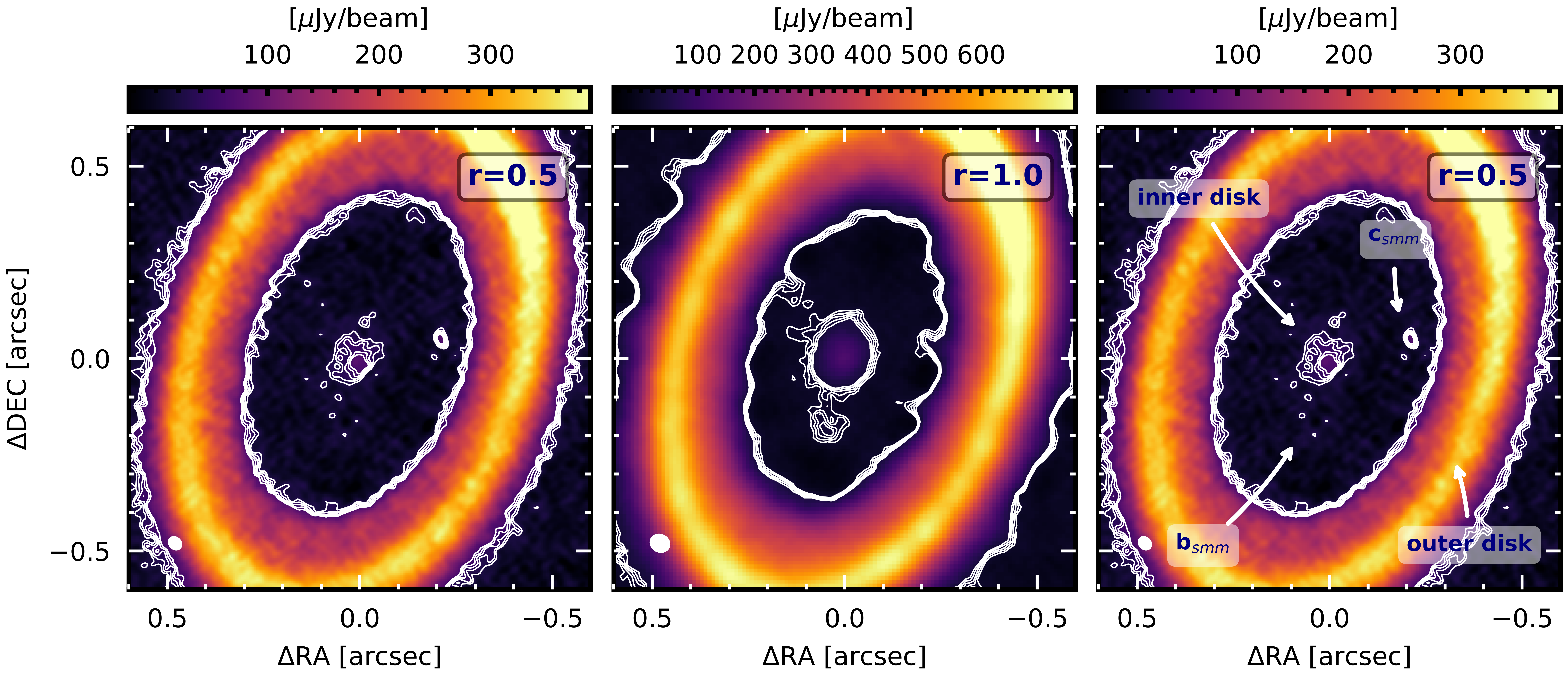


Haffert et al 2018
See also Wagner et al 2018



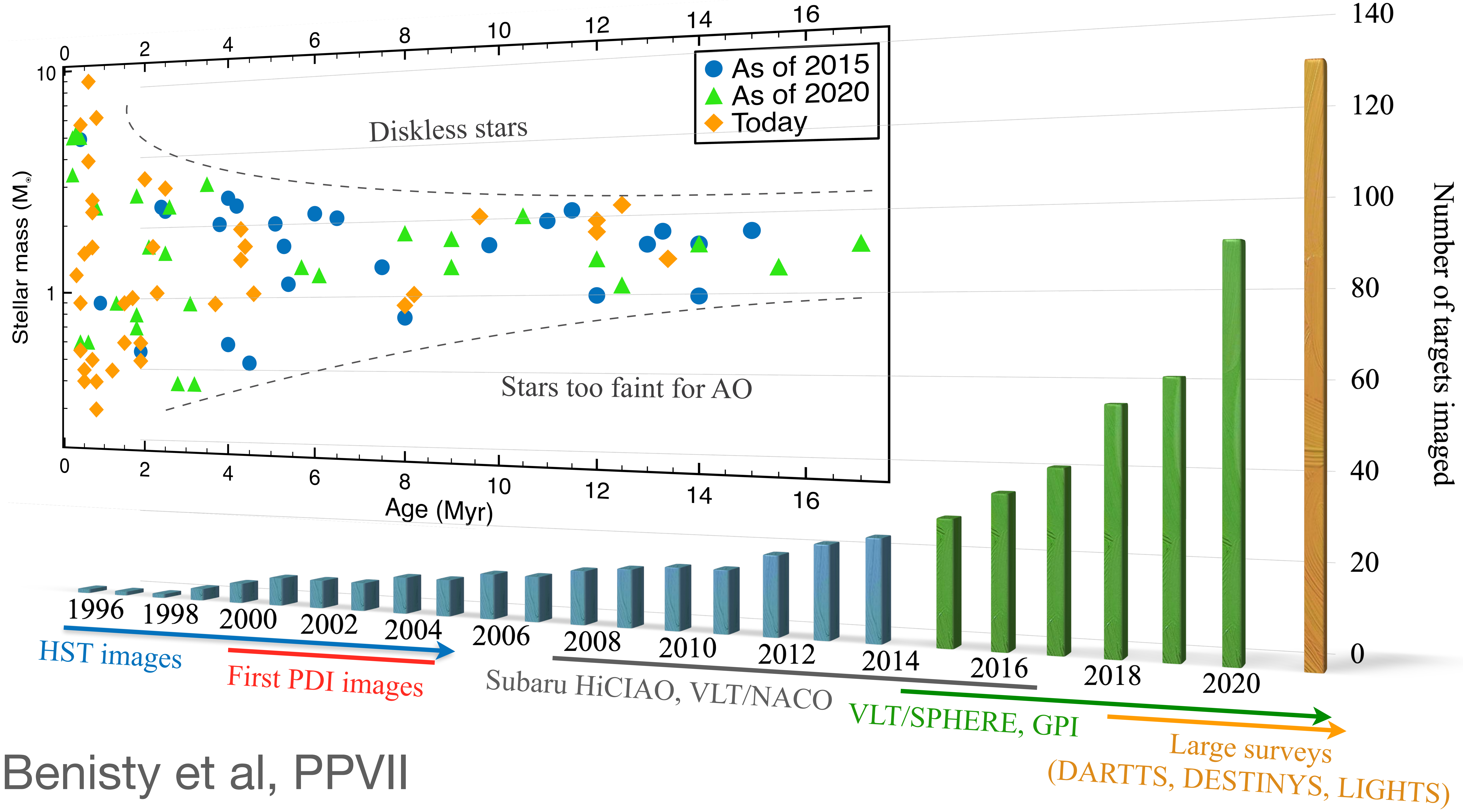
- Accretion rate ~ 10^{-8} Msun/yr
- comparable with stellar accretion rate

Circumplanetary discs in PDS 70

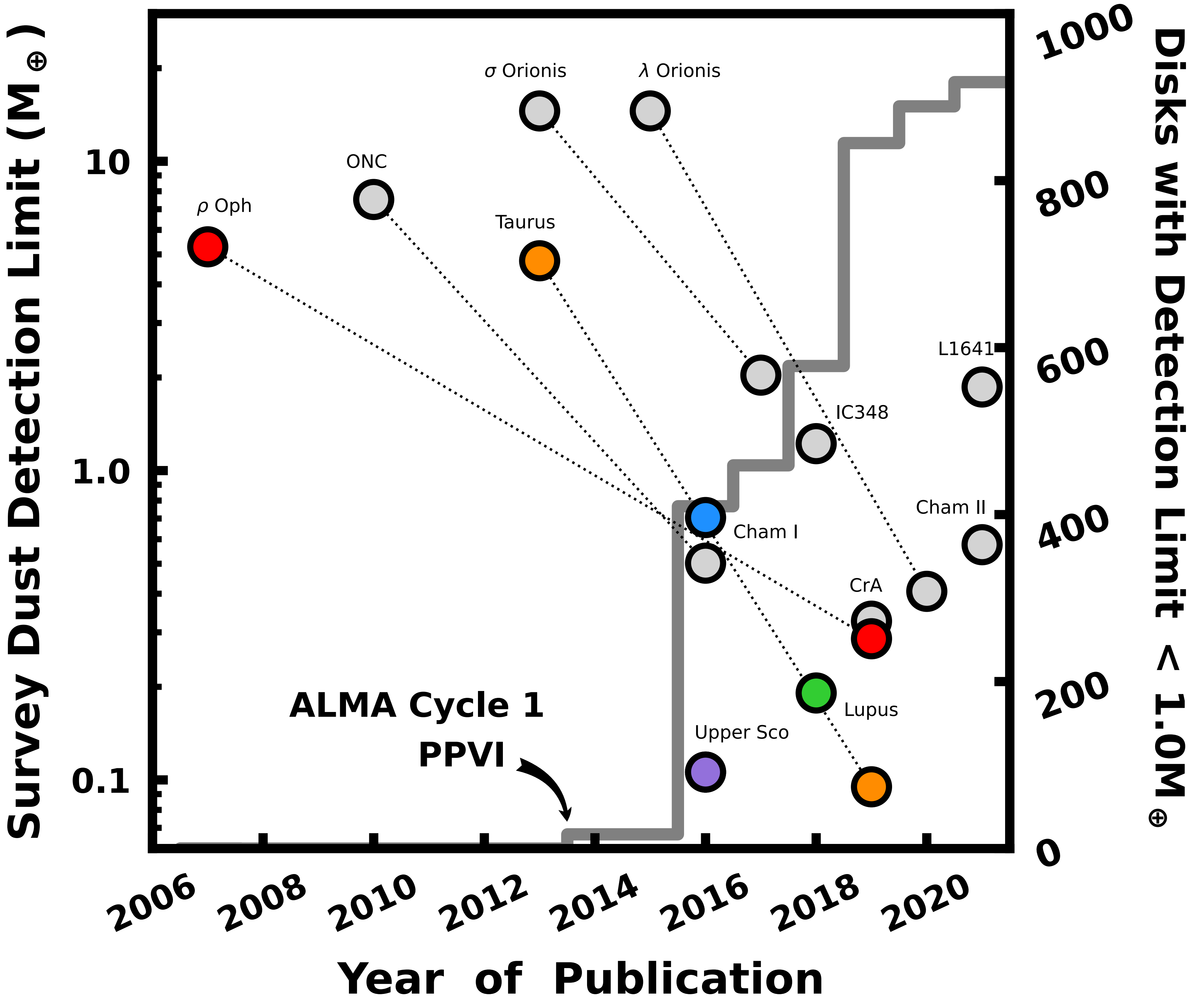


Isella et al 2019
Benisty et al 2021

About 100 disks have been imaged



Benisty et al, PPVII



Manara et al, PPVII

but we hardly found any protoplanets ...

2. Structures (and planets?) are everywhere

Extreme AO reveals stunning images of disks

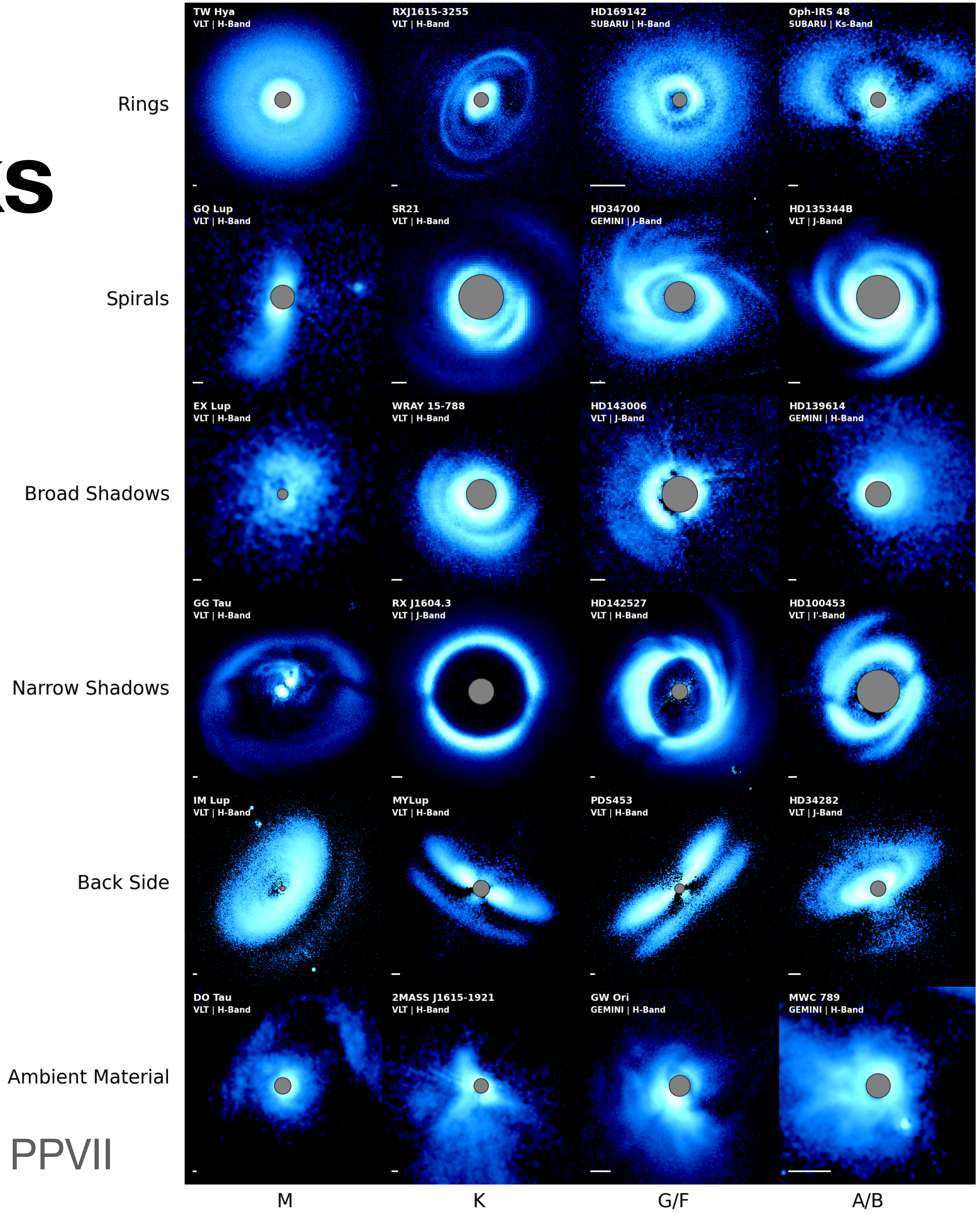
Evidence of embedded planets or companions ?

- gaps and rings
- inner cavities
- spirals
- shadows

Maybe …

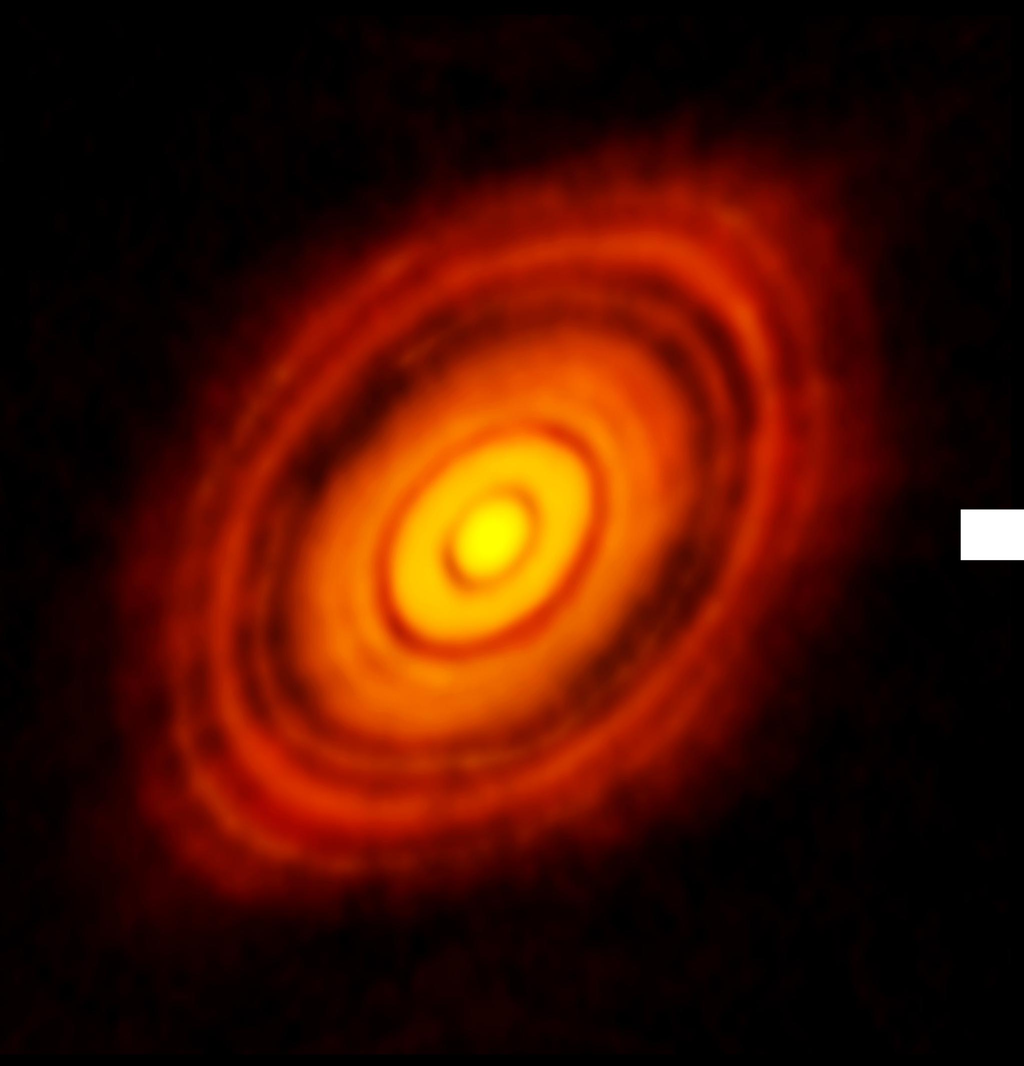
It also means planet formation is messy

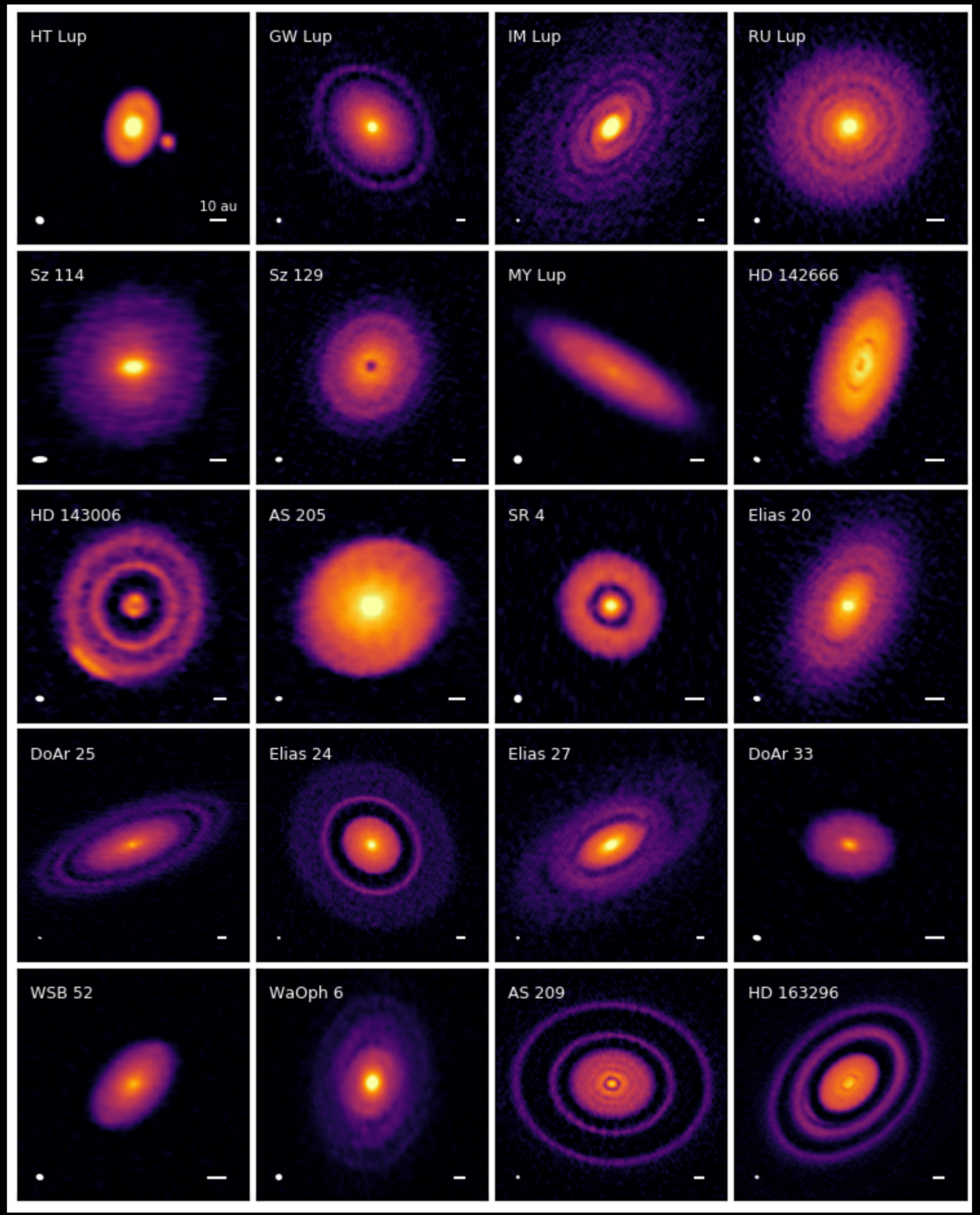
Benisty et al, PPVII



Are (some of) these structures caused by planets ?

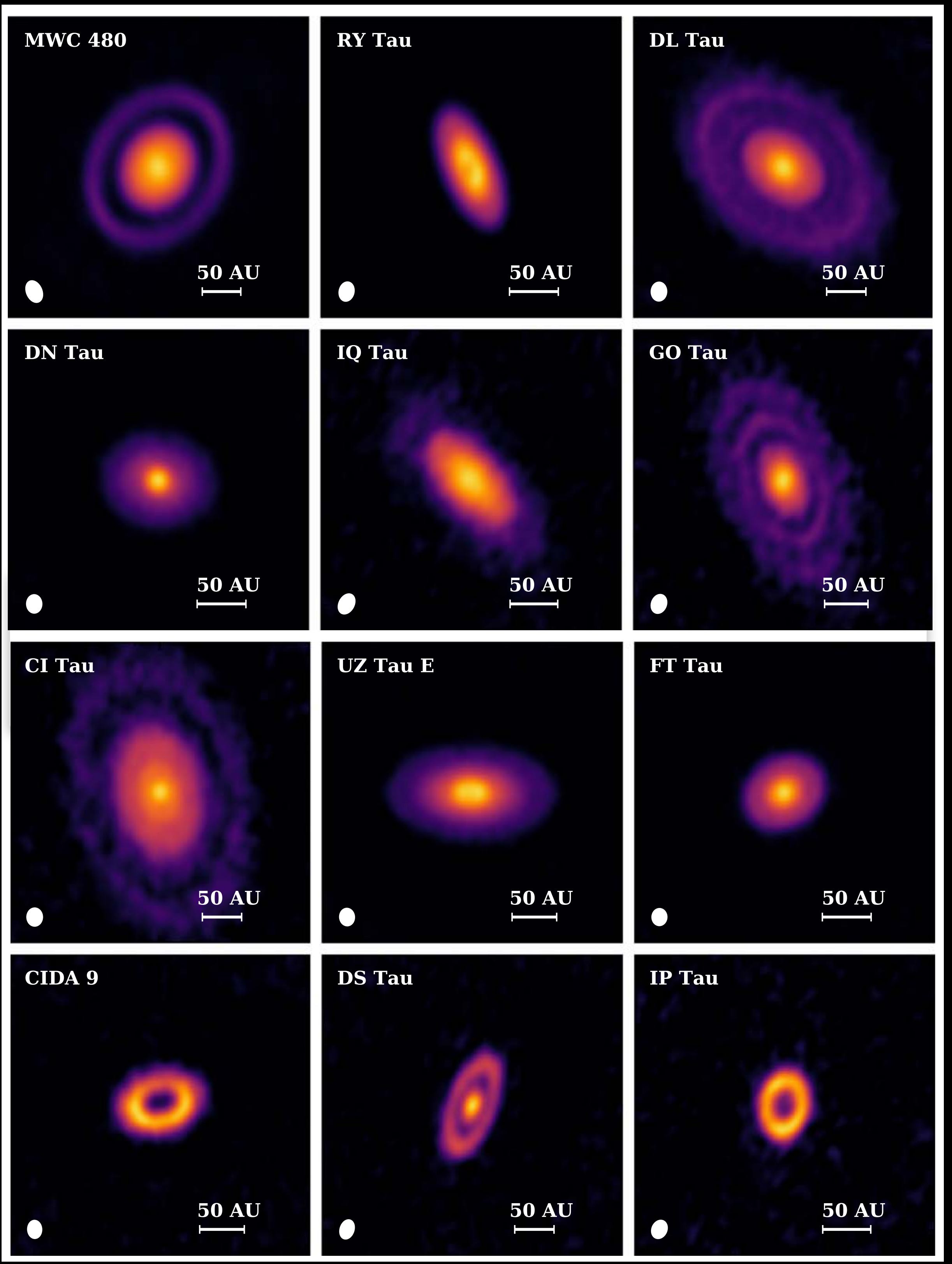
ALMA continuum surveys



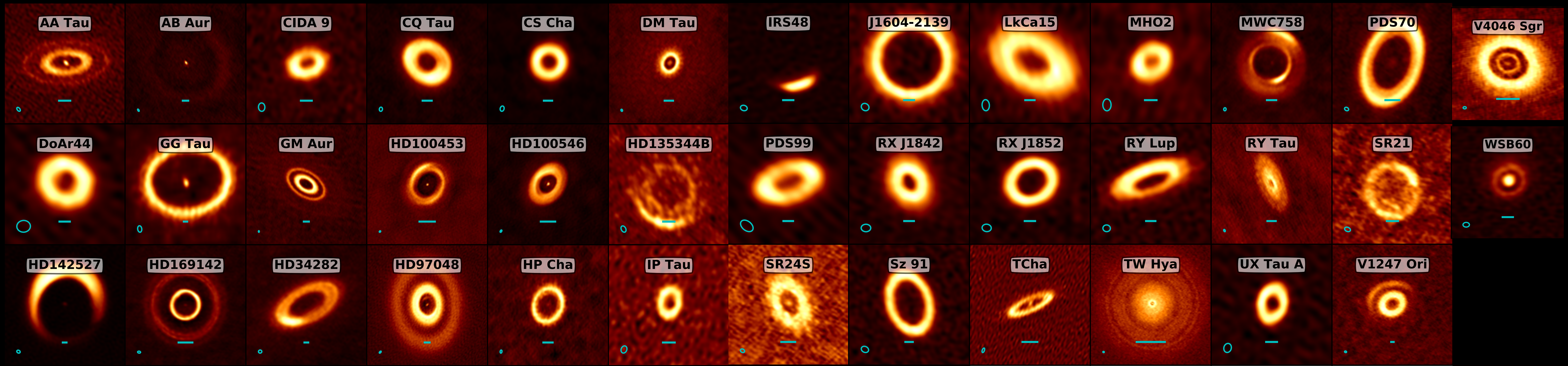


DSHARP
Andrews et al 2018

Taurus survey
Long et al 2018



Francis et al. 2020



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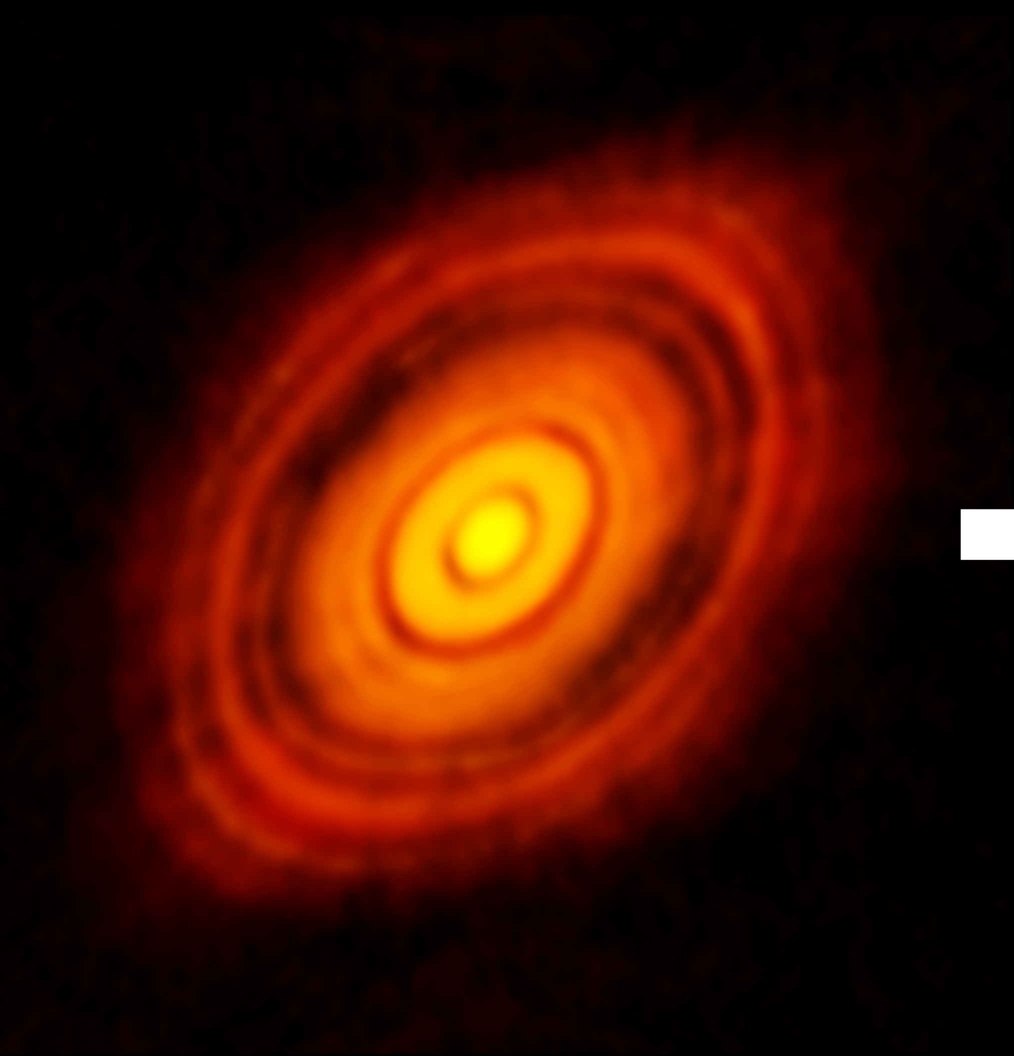

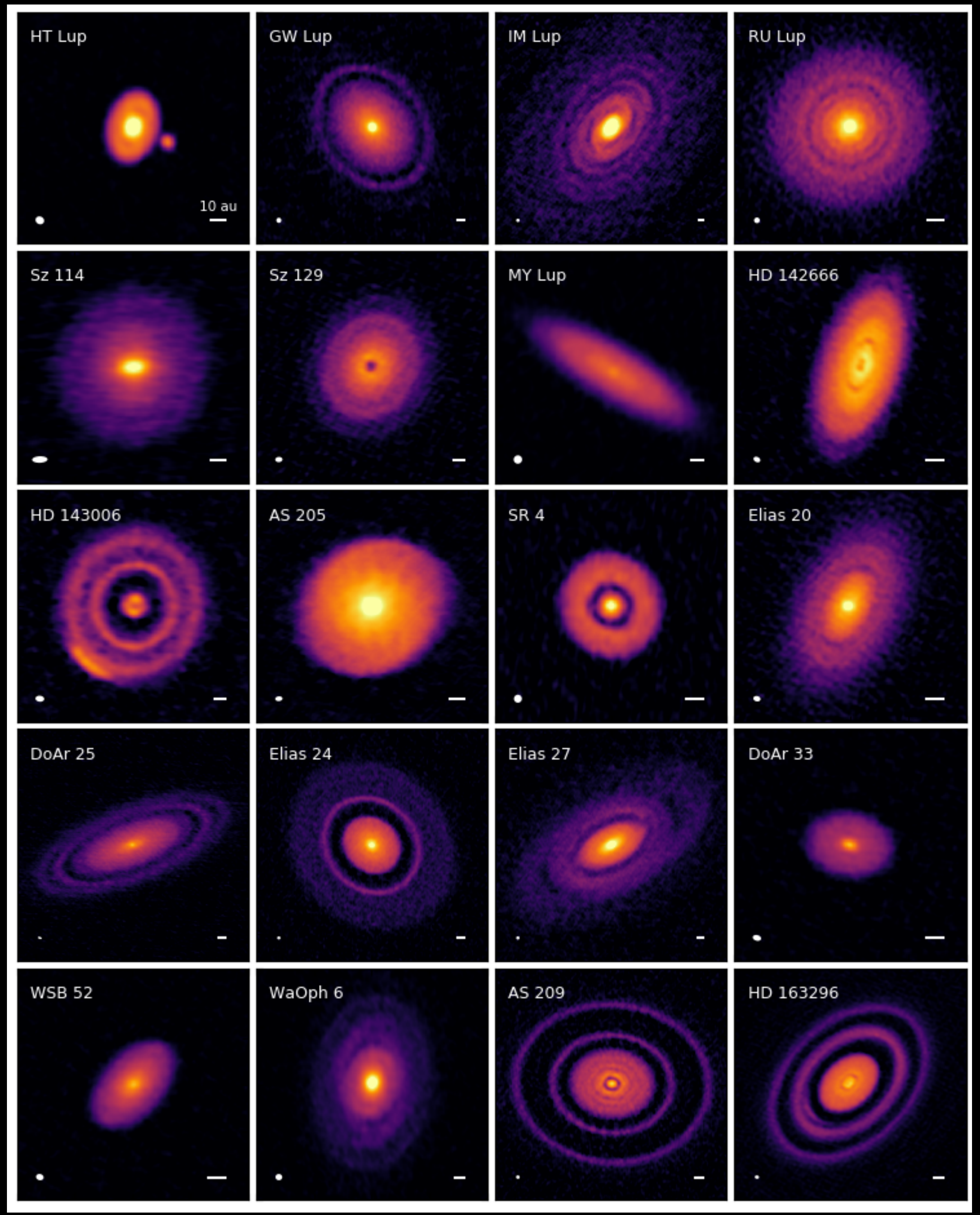

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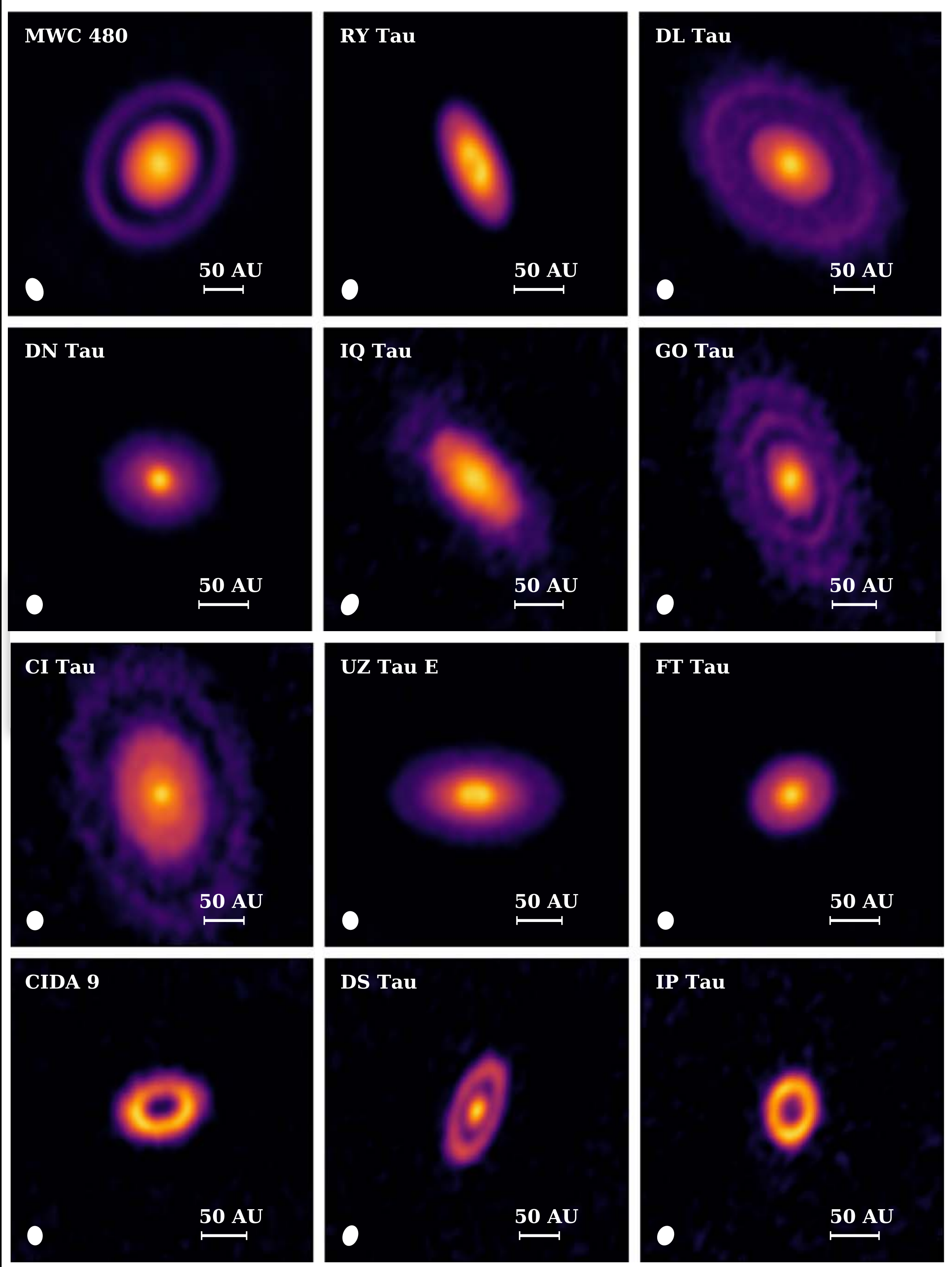

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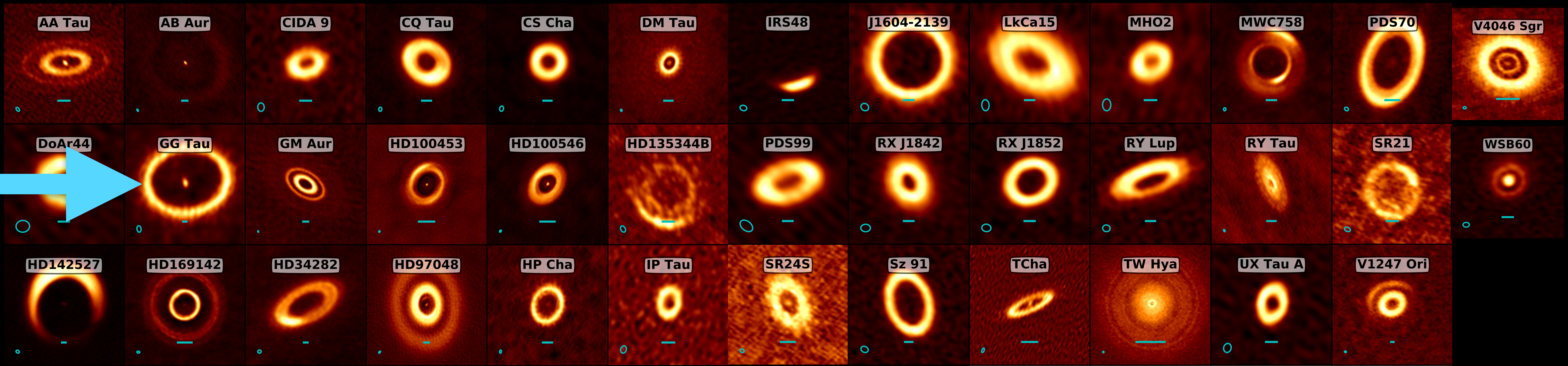


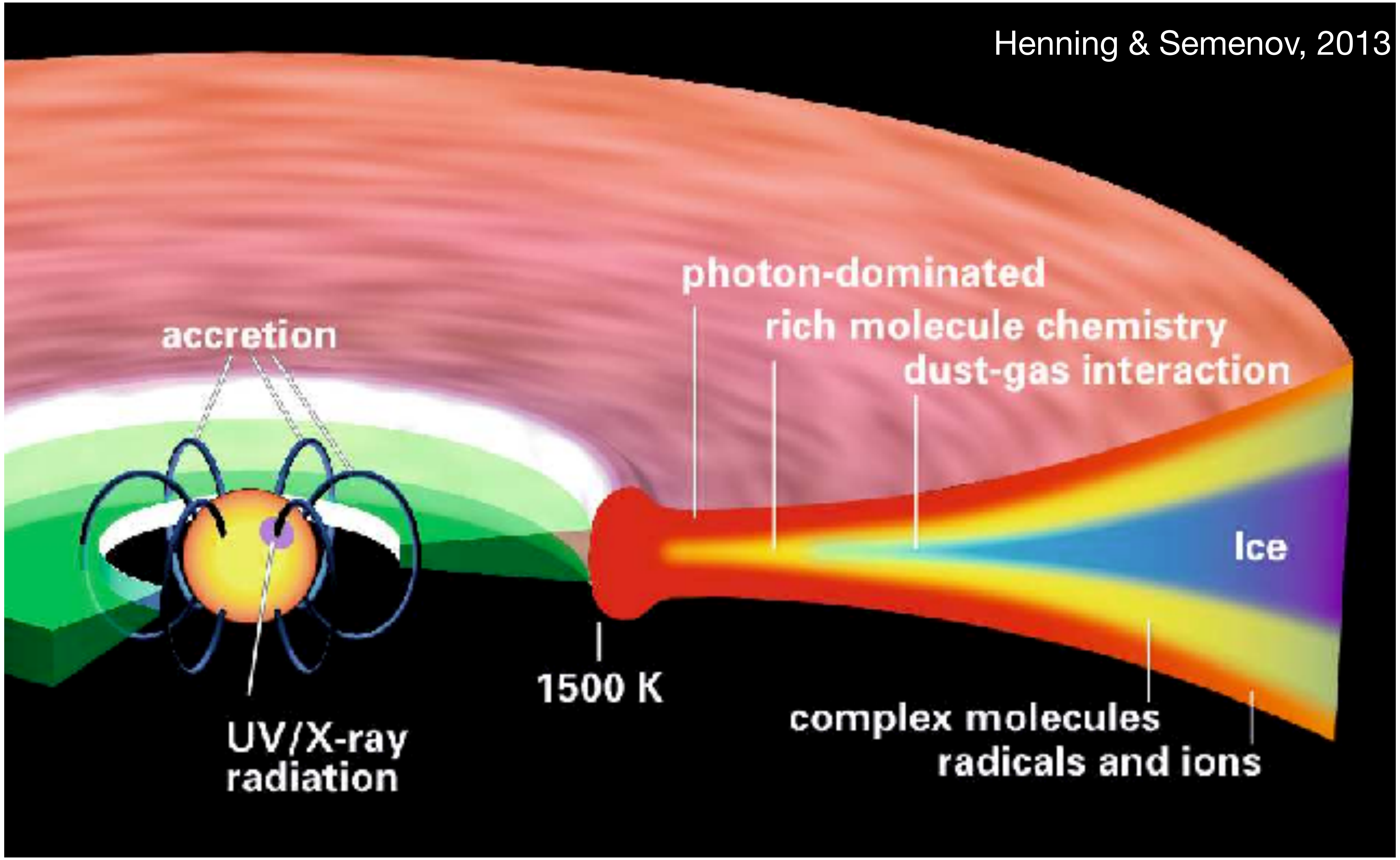
Talk by
N.T. Phuong

3. Disc kinematics:
some structures are caused by planets

Discs have a layered structure

Three layers:

- Hot atomic layer (PDR)
- **Warm molecular layer** → probed by ALMA in lines
- Cold icy mid plane → dust pebbles probed by ALMA in continuum



ALMA has phenomenal sensitivity and spectral resolution

- max resolution spectral of ~ 25m/s
  $\lambda/\Delta\lambda \approx 10^7$
- full spectral resolution + full spatial resolution remains impossible
- can reach rms of 5K at 0.1”, 50m/s in ~ 10h

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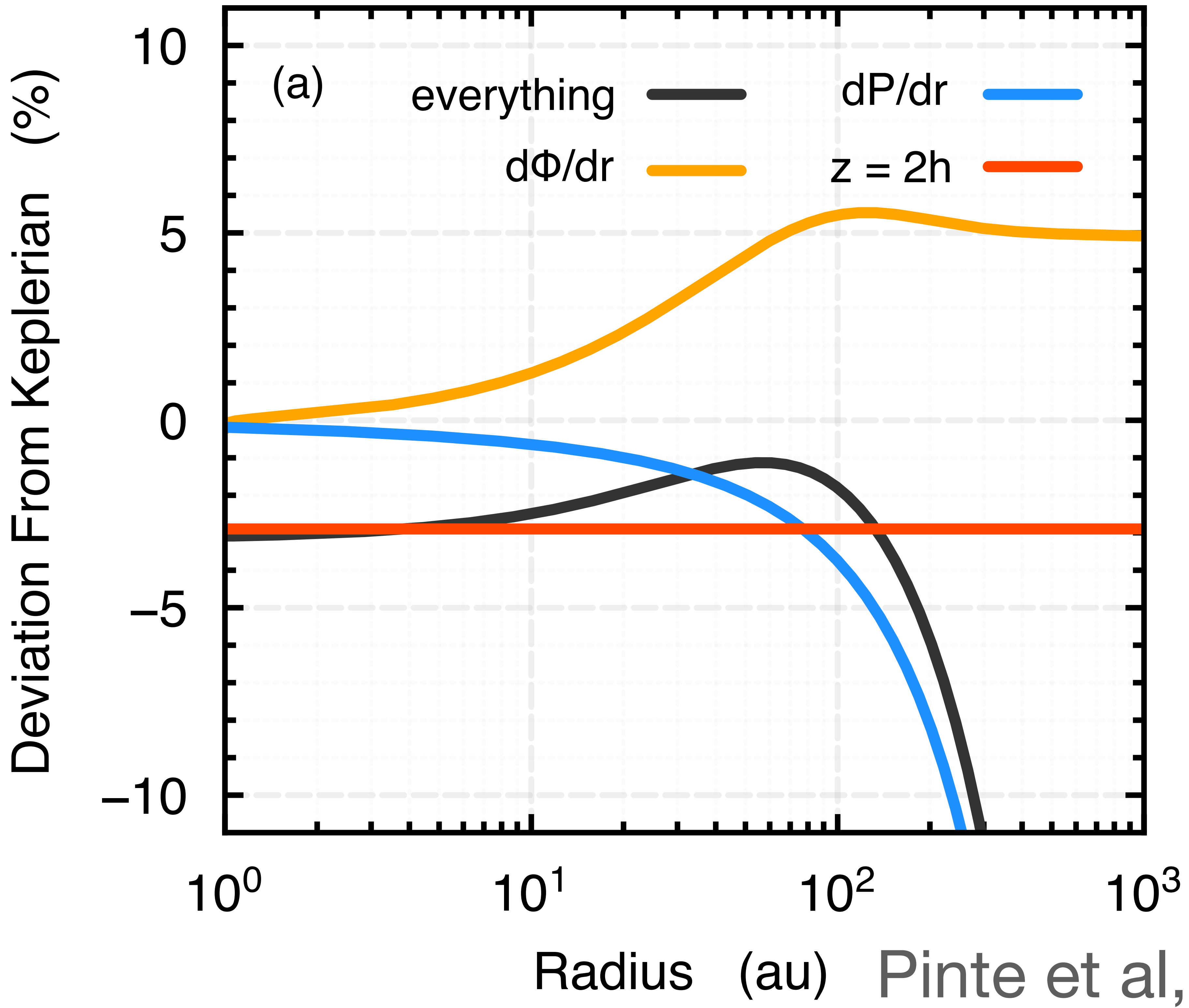

Pinte et al, PPVII

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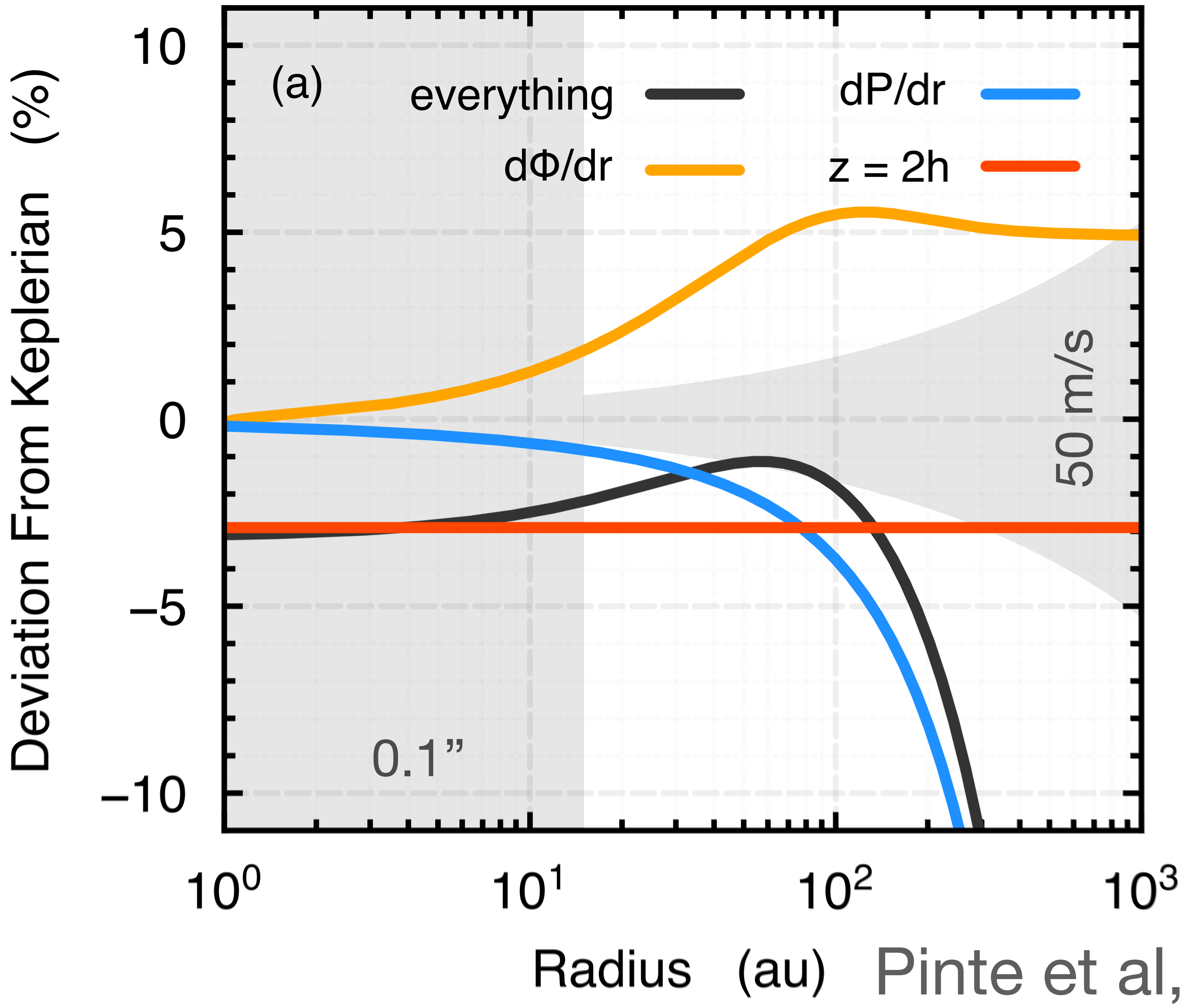
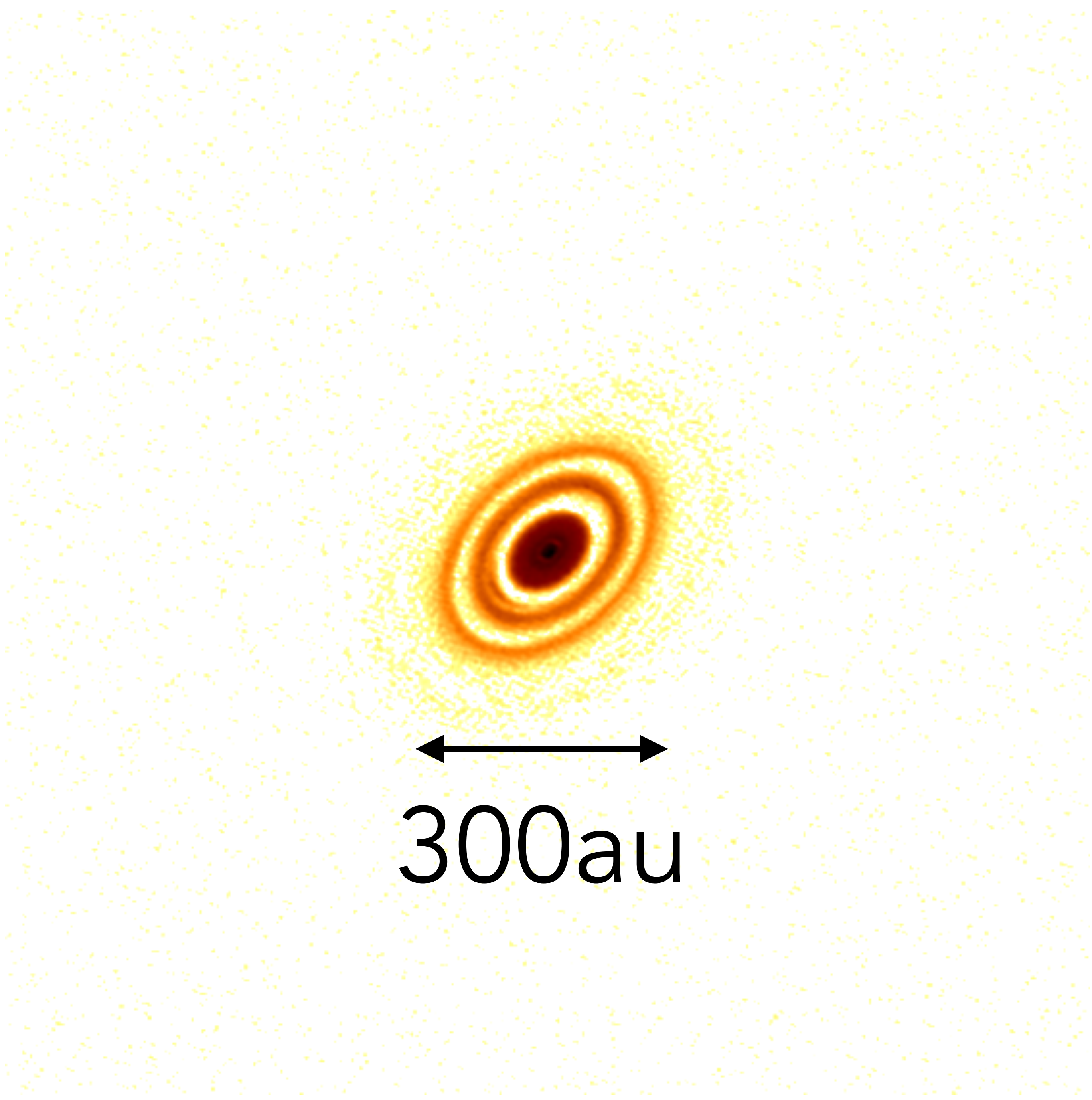


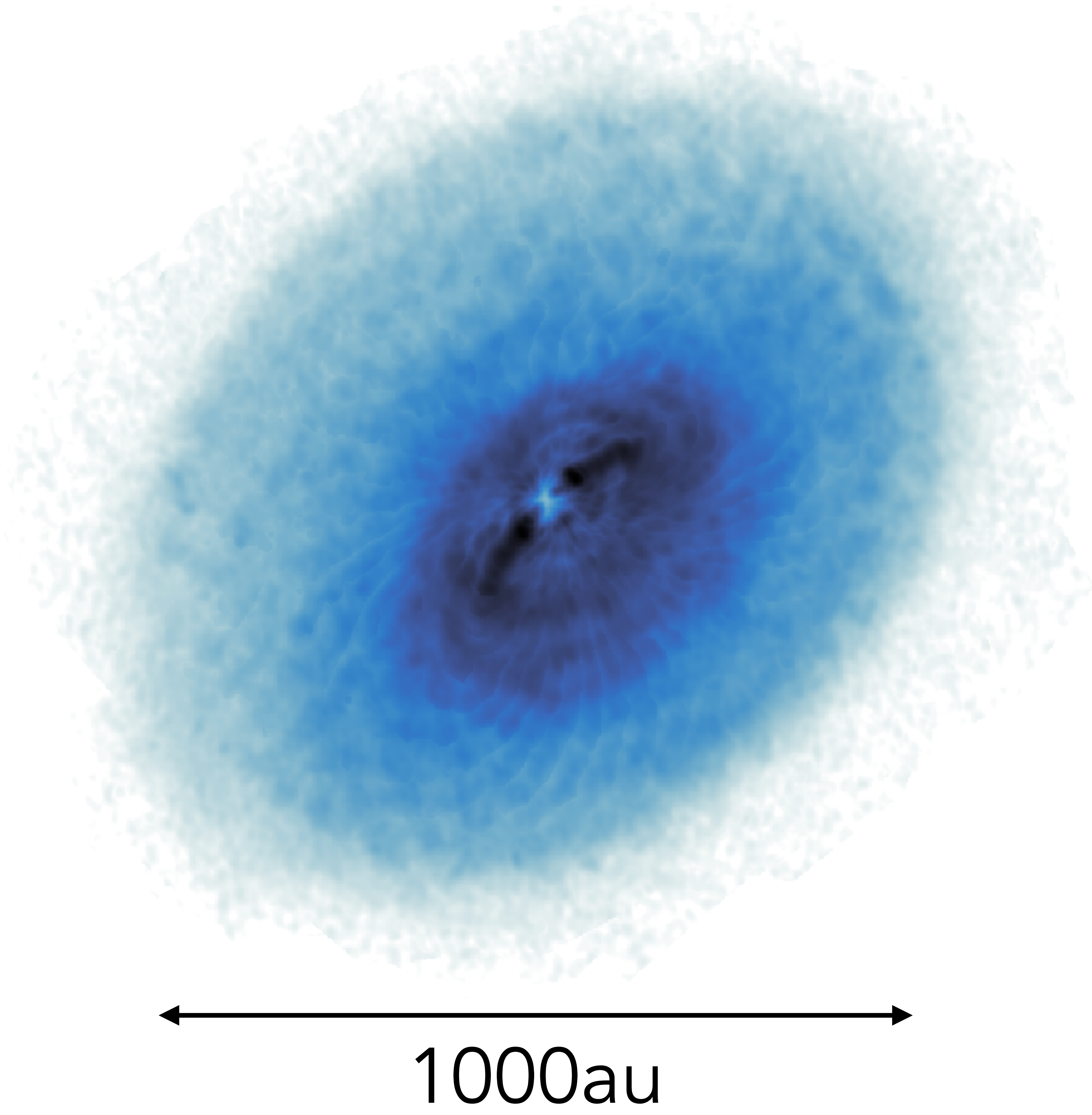
Pinte et al, PPVII

Typical maps of protoplanetary disks



Data from Andrews+2018, Huang+2018, Isella+2018

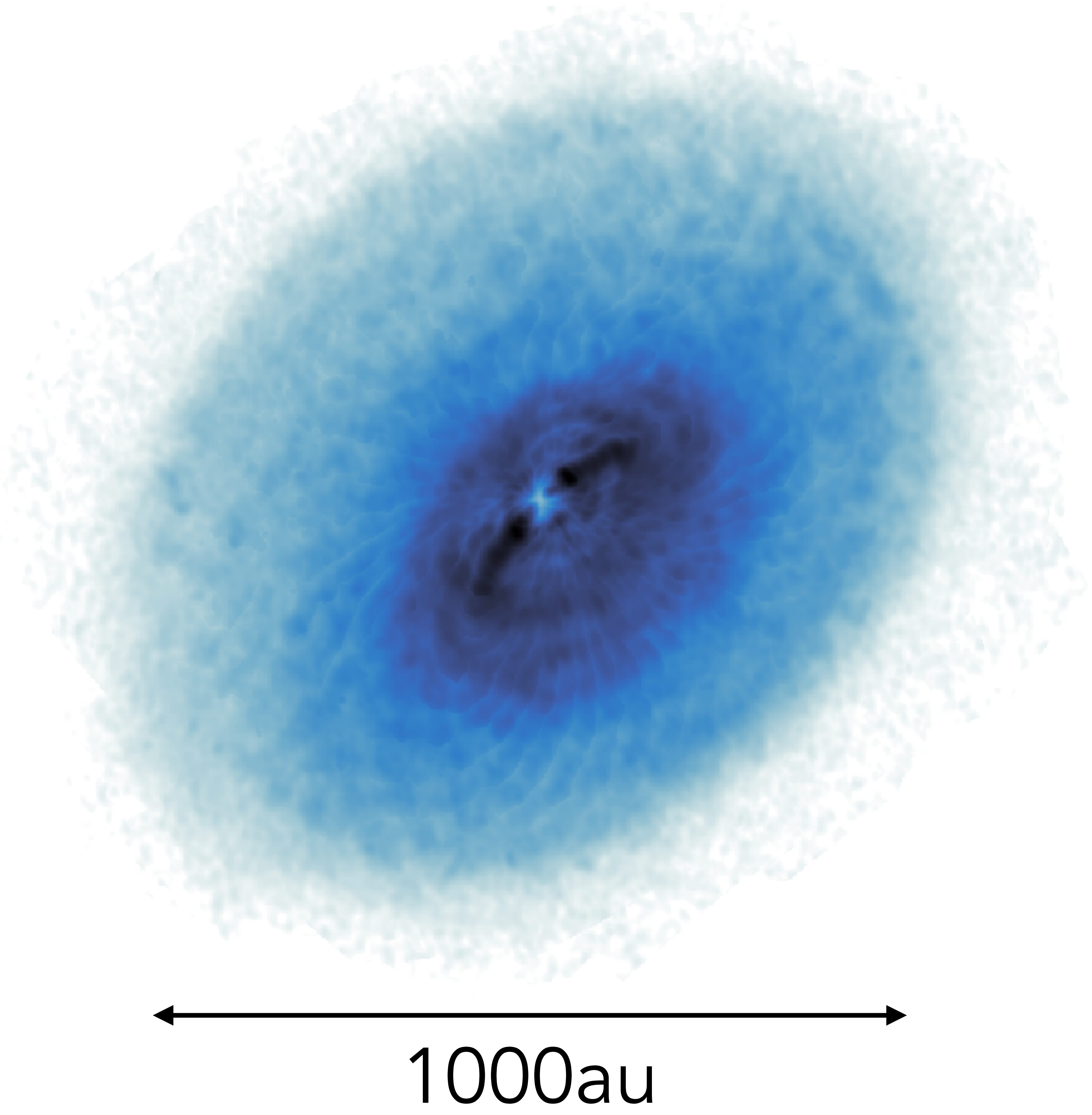
Typical maps of protoplanetary disks

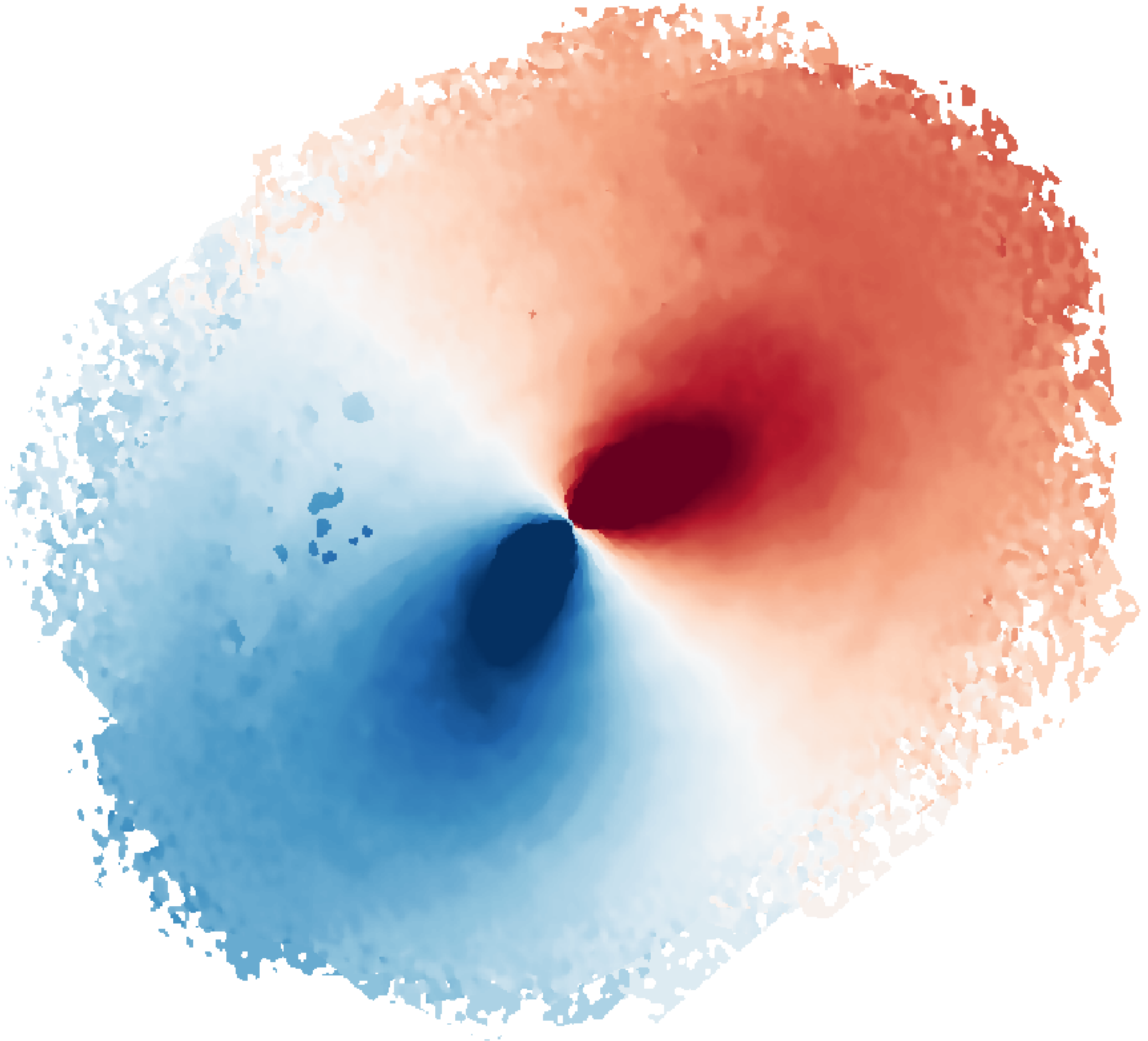


Gaseous disks significantly larger than mm continuum disks

Data from Öberg+2021, Czekala+2021, Law+2021, Teague+2021

Typical maps of protoplanetary disks





It is possible to extract a velocity field for the whole disk

Data from Öberg+2021, Czekala+2021, Law+2021, Teague+2021

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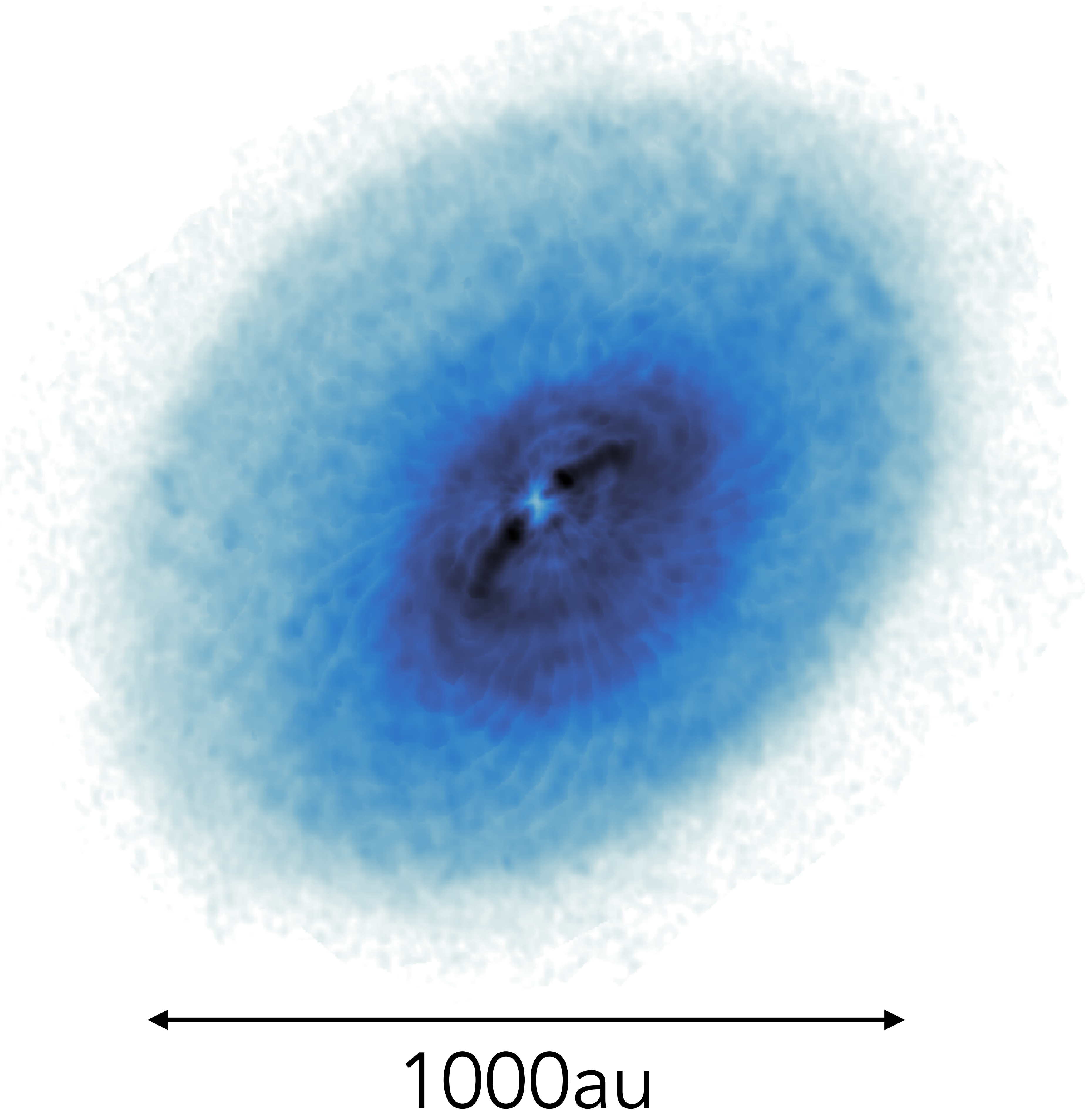

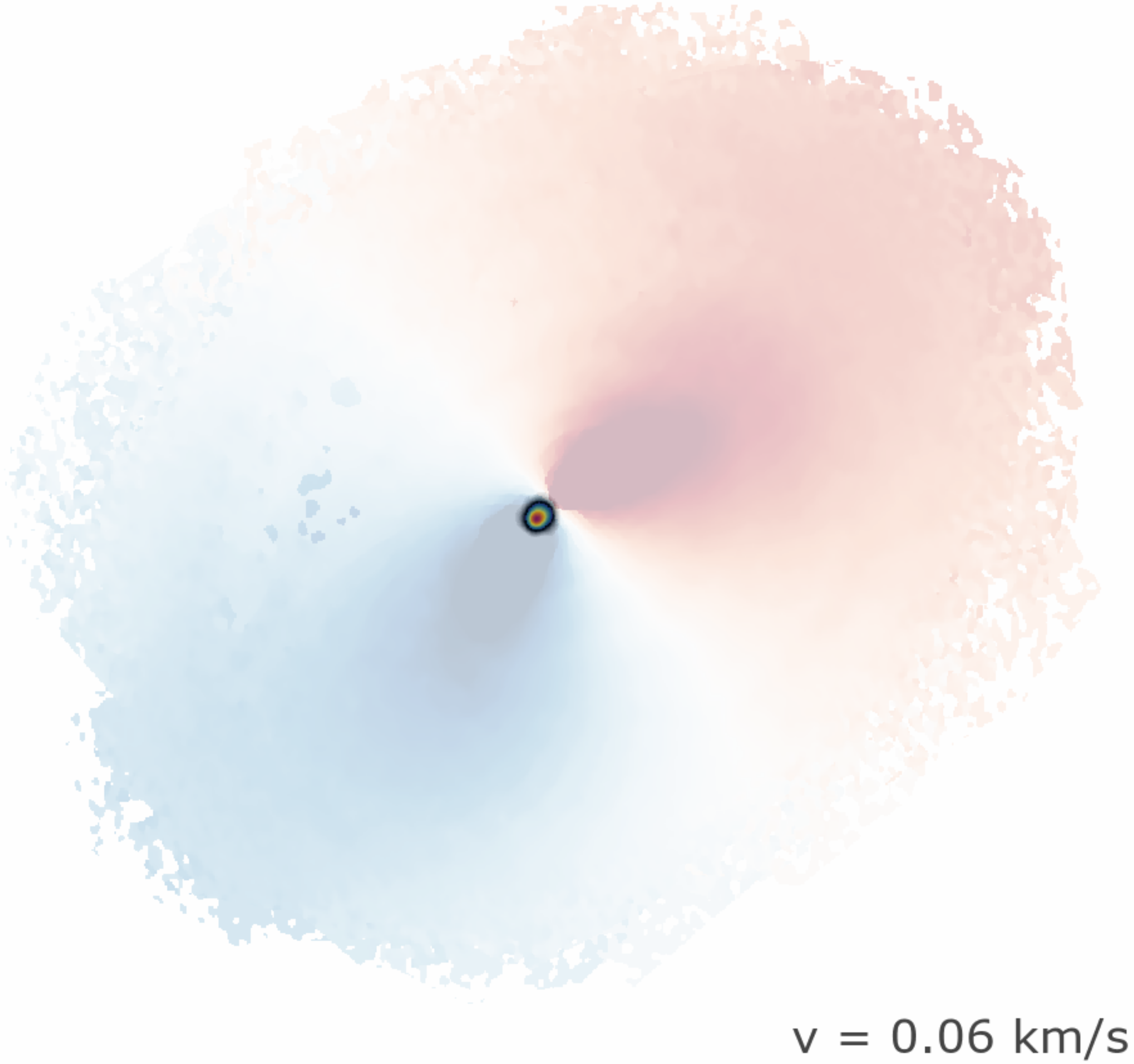

Channel maps trace isovelocity contours

Data from Öberg+2021, Czekala+2021, Law+2021, Teague+2021

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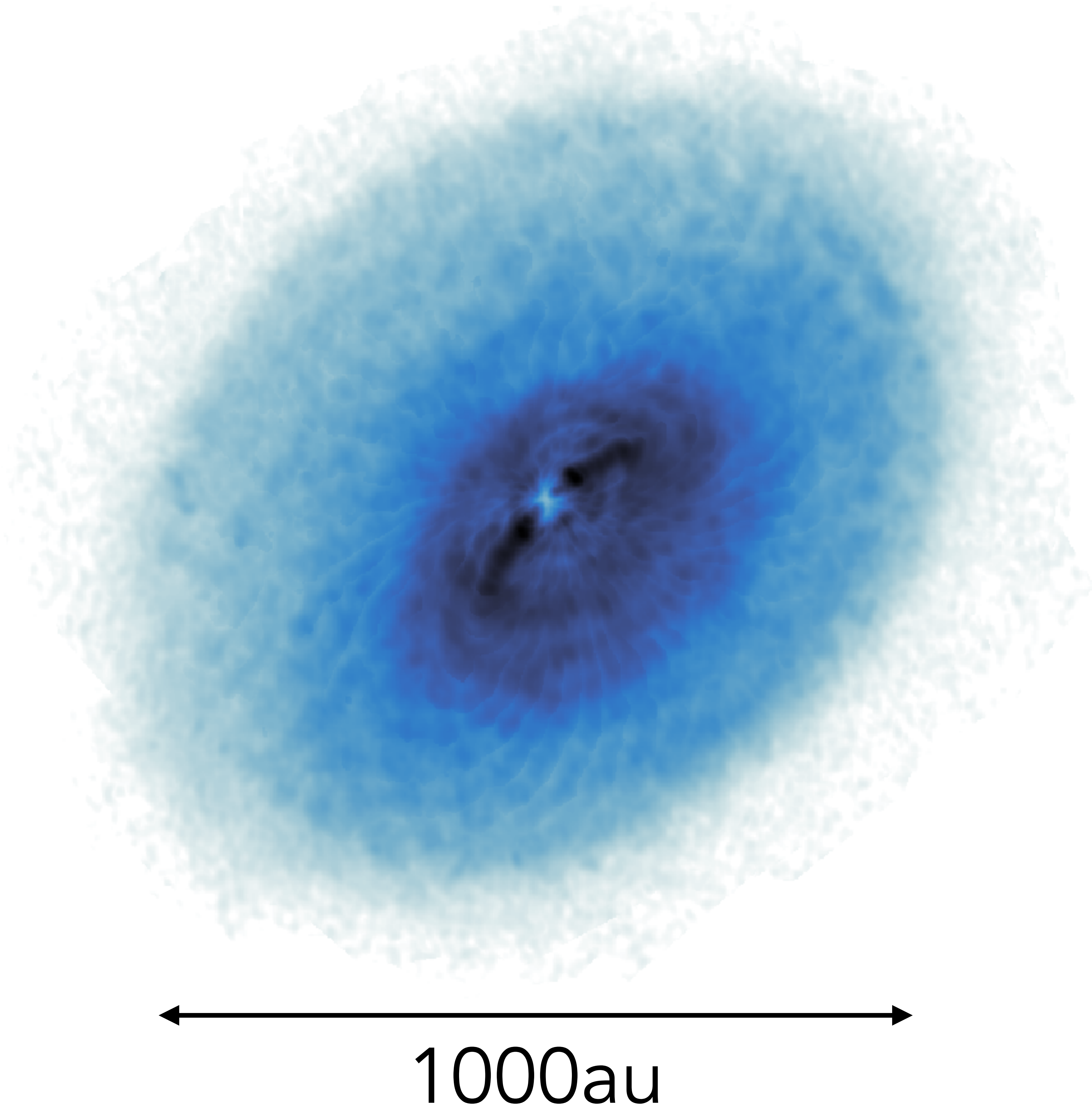

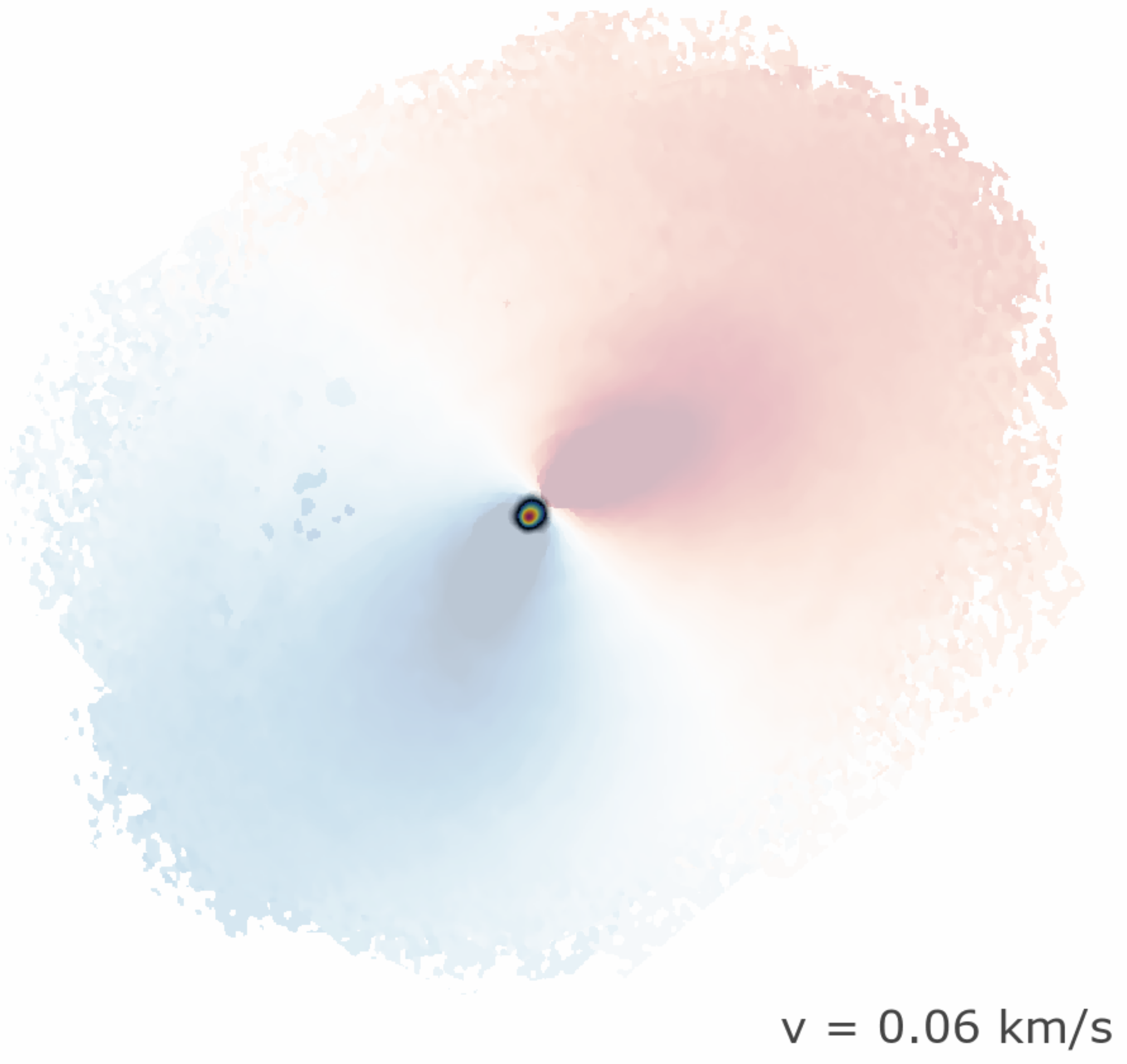

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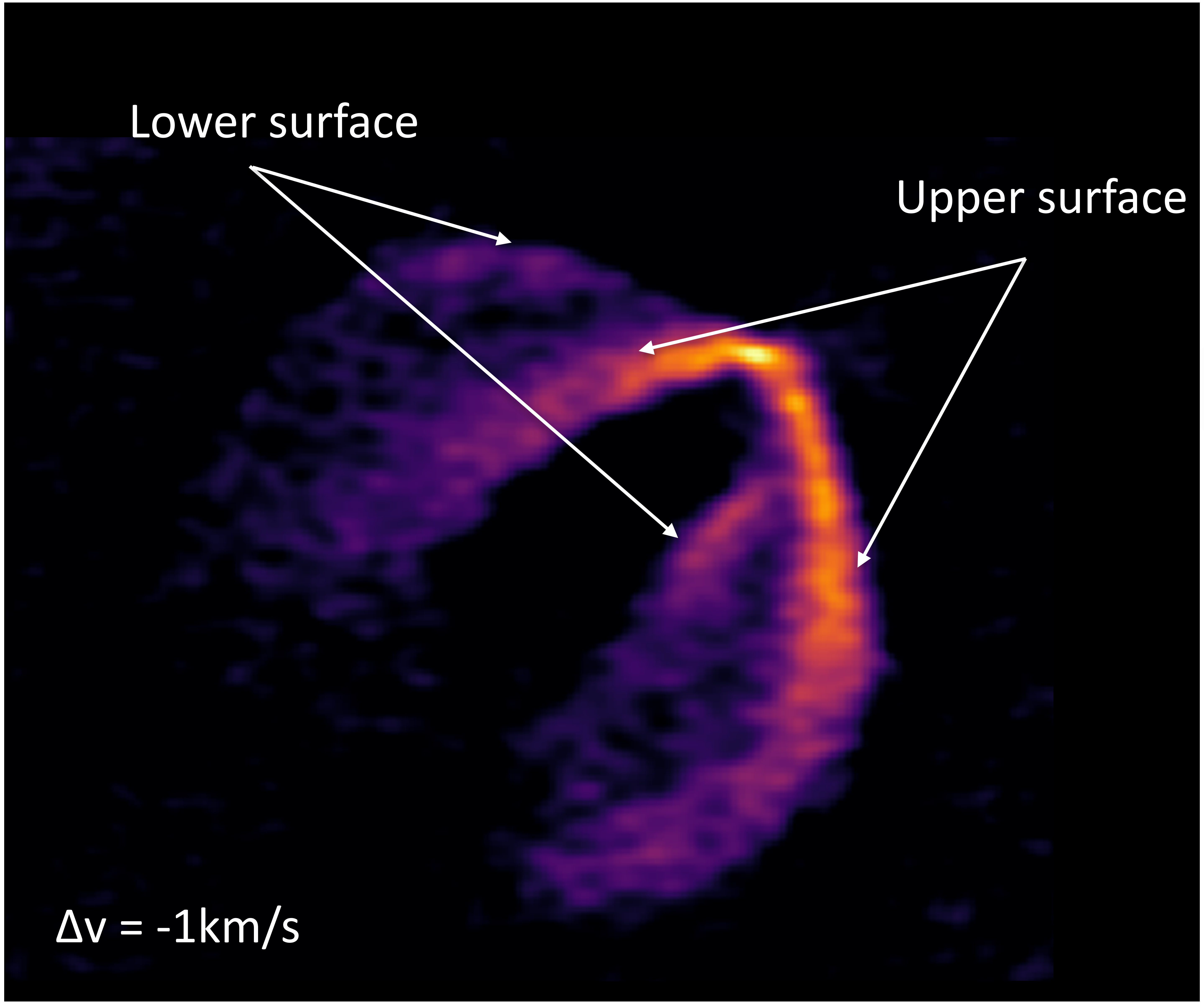
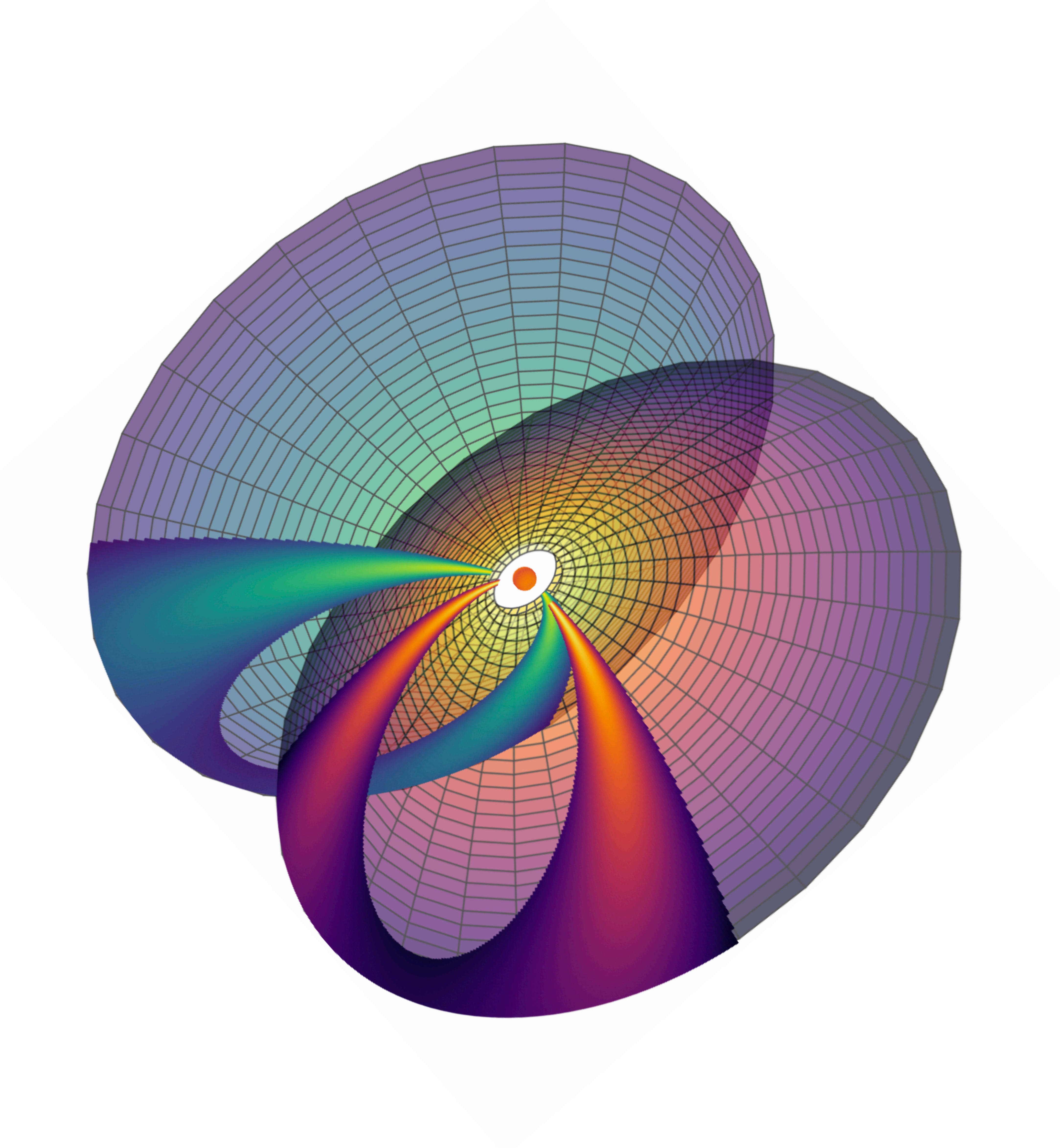
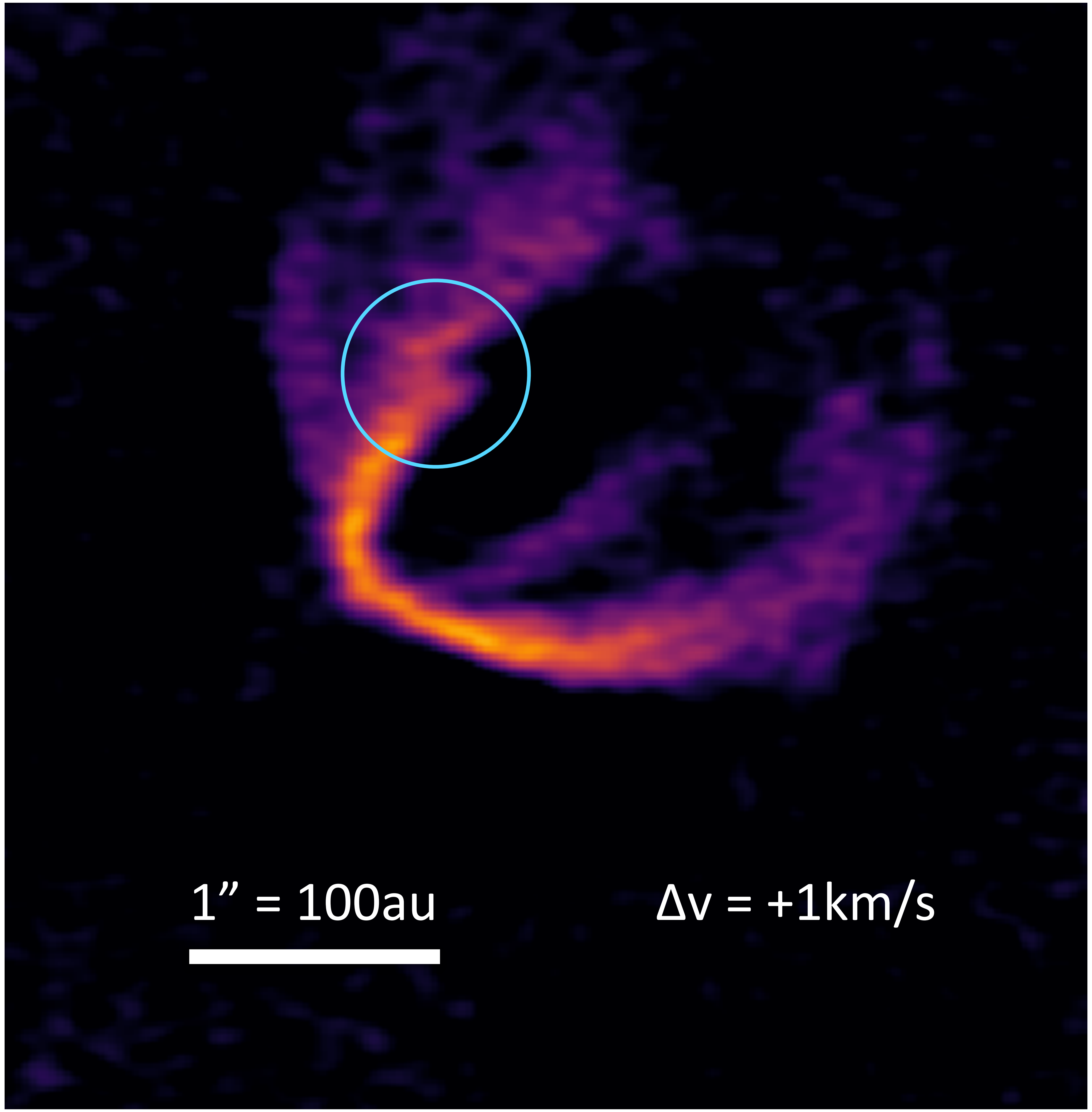
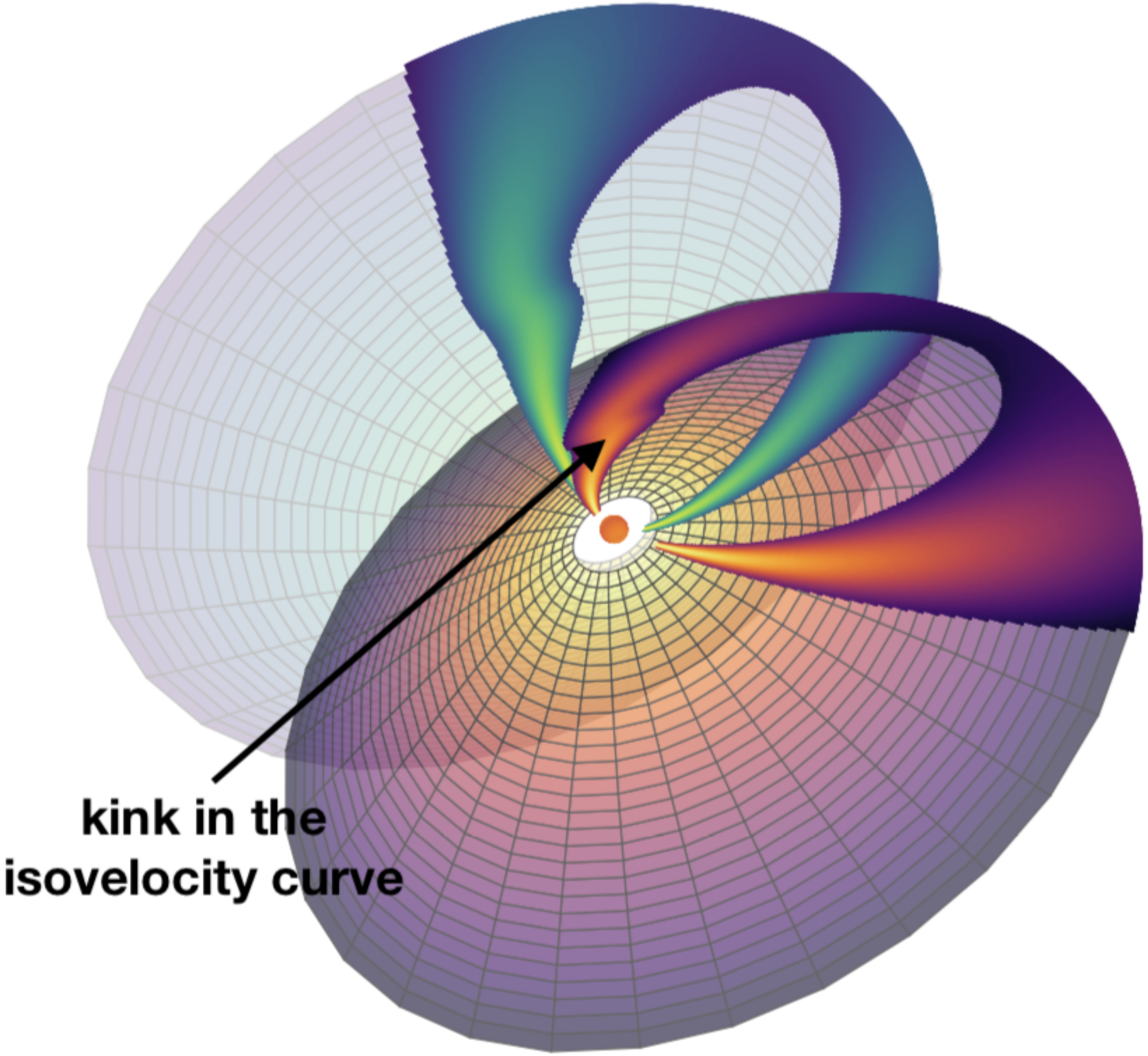
Separating the CO layers at high spectral resolution



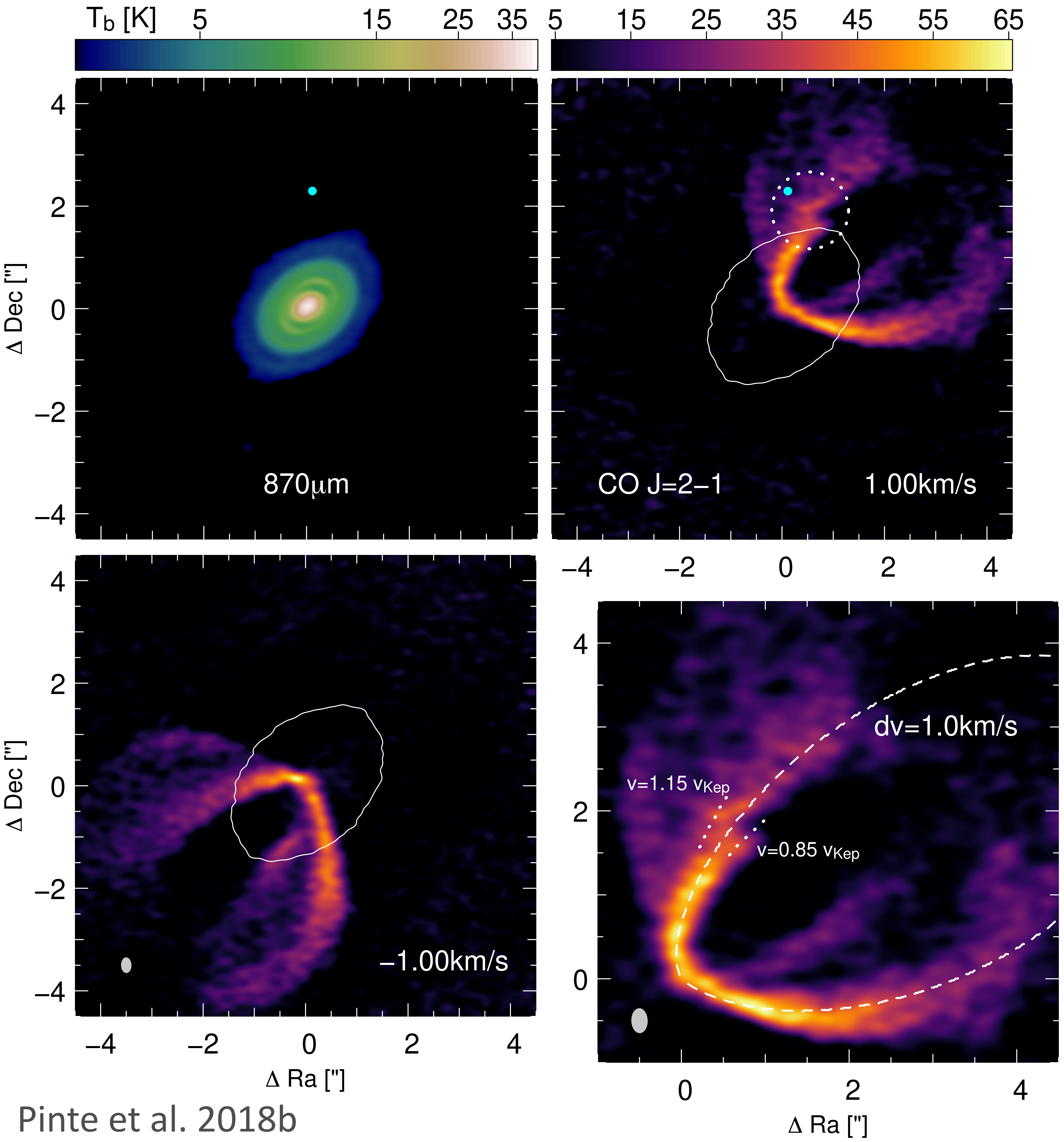


Mapping the CO layers : velocity “kink”





Evidence for embedded planet

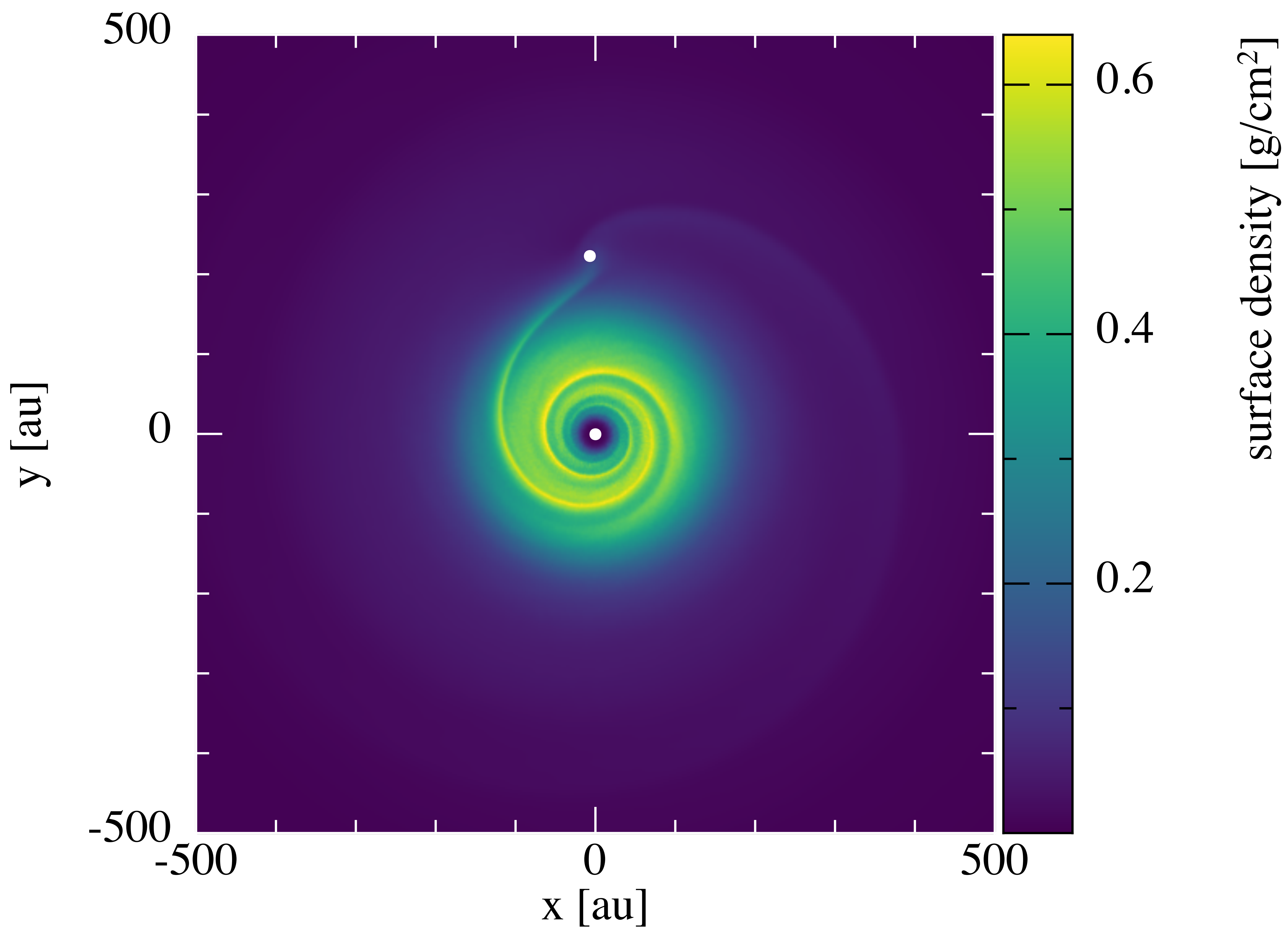


Pinte et al. 2018b

Localised velocity “kink” deviation ≈ 15% from Keplerian rotation

Distance 230au (assuming planet is in the midplane)

What happen when you put a planet in a disc ?



Gas density

Phantom model

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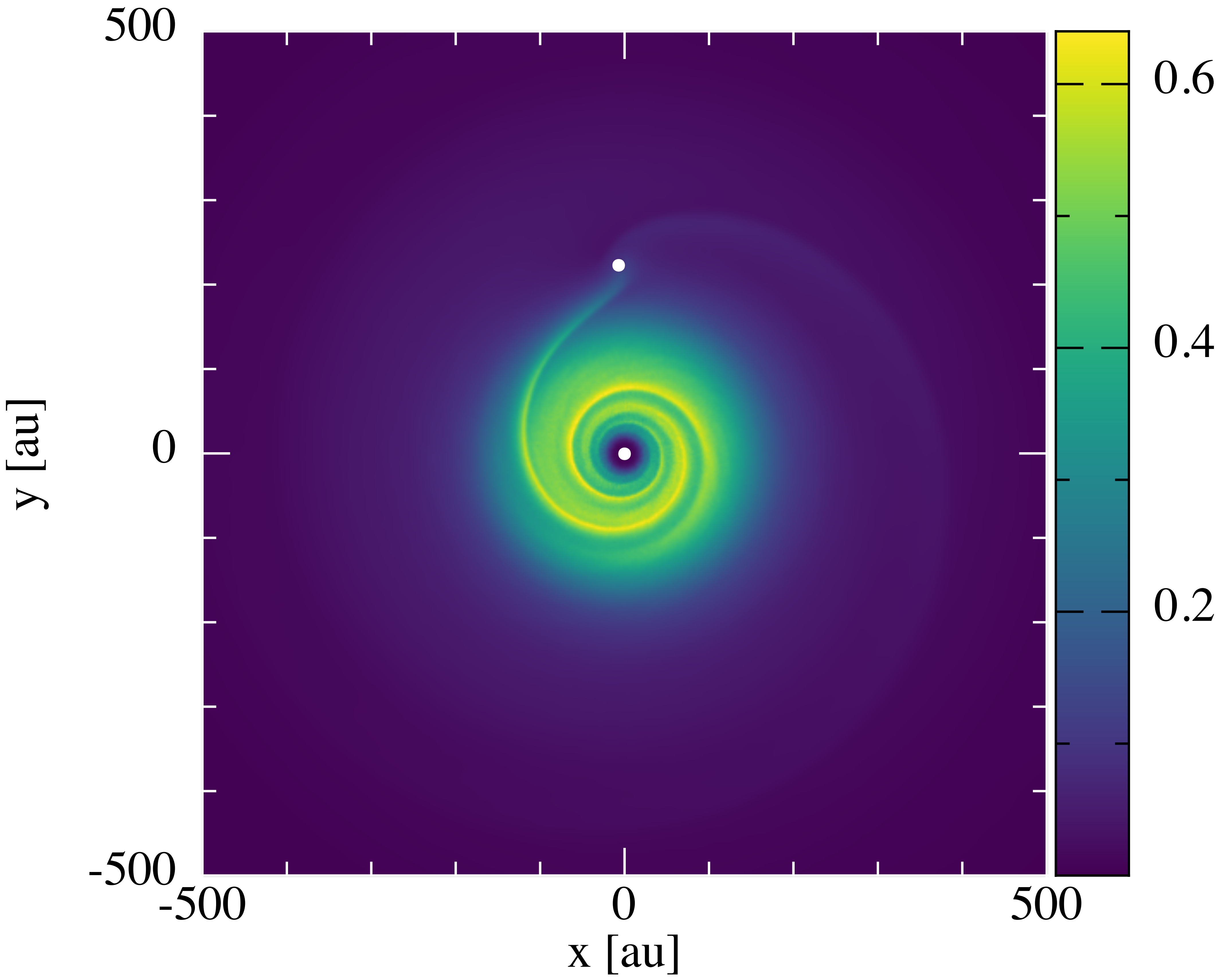

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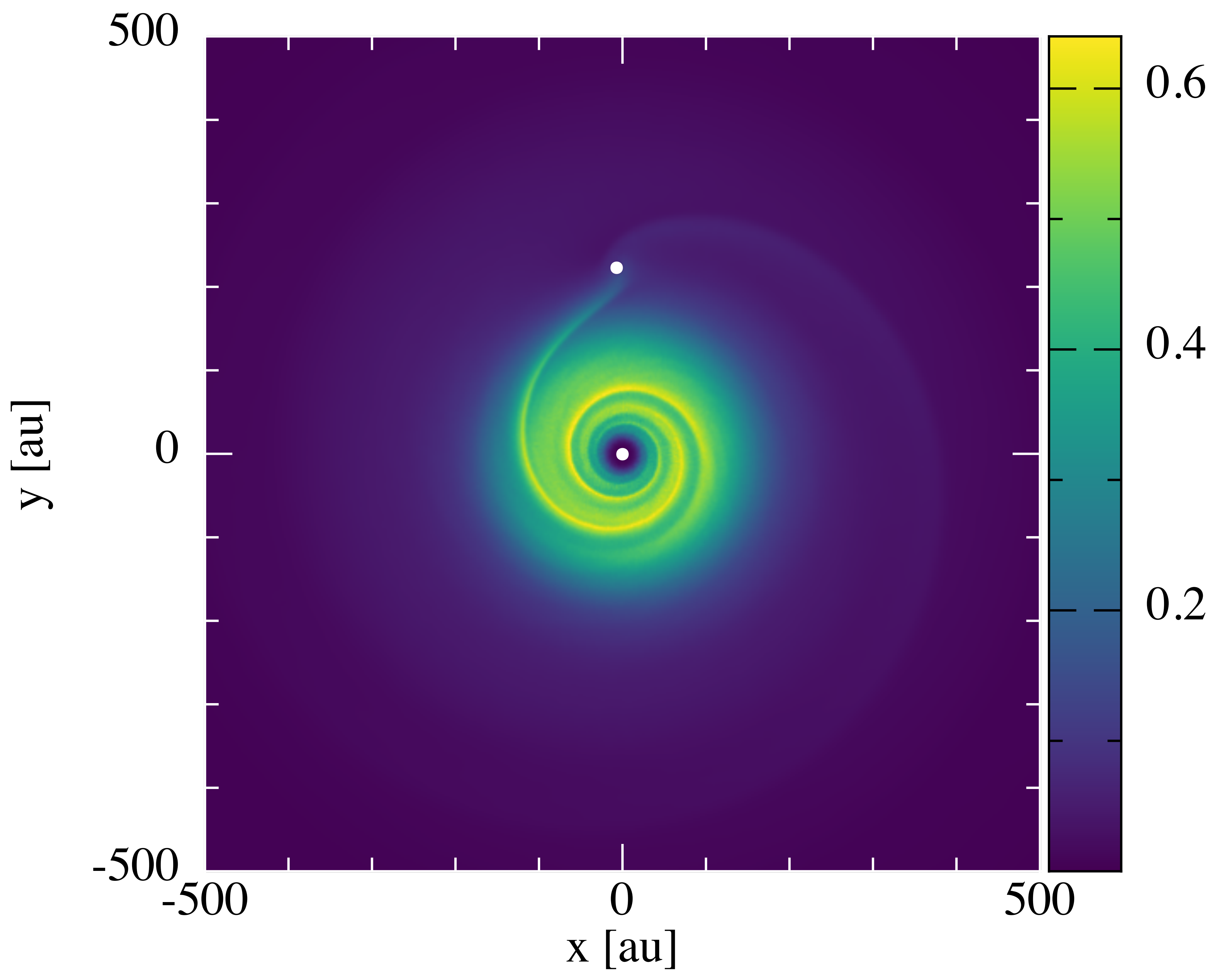
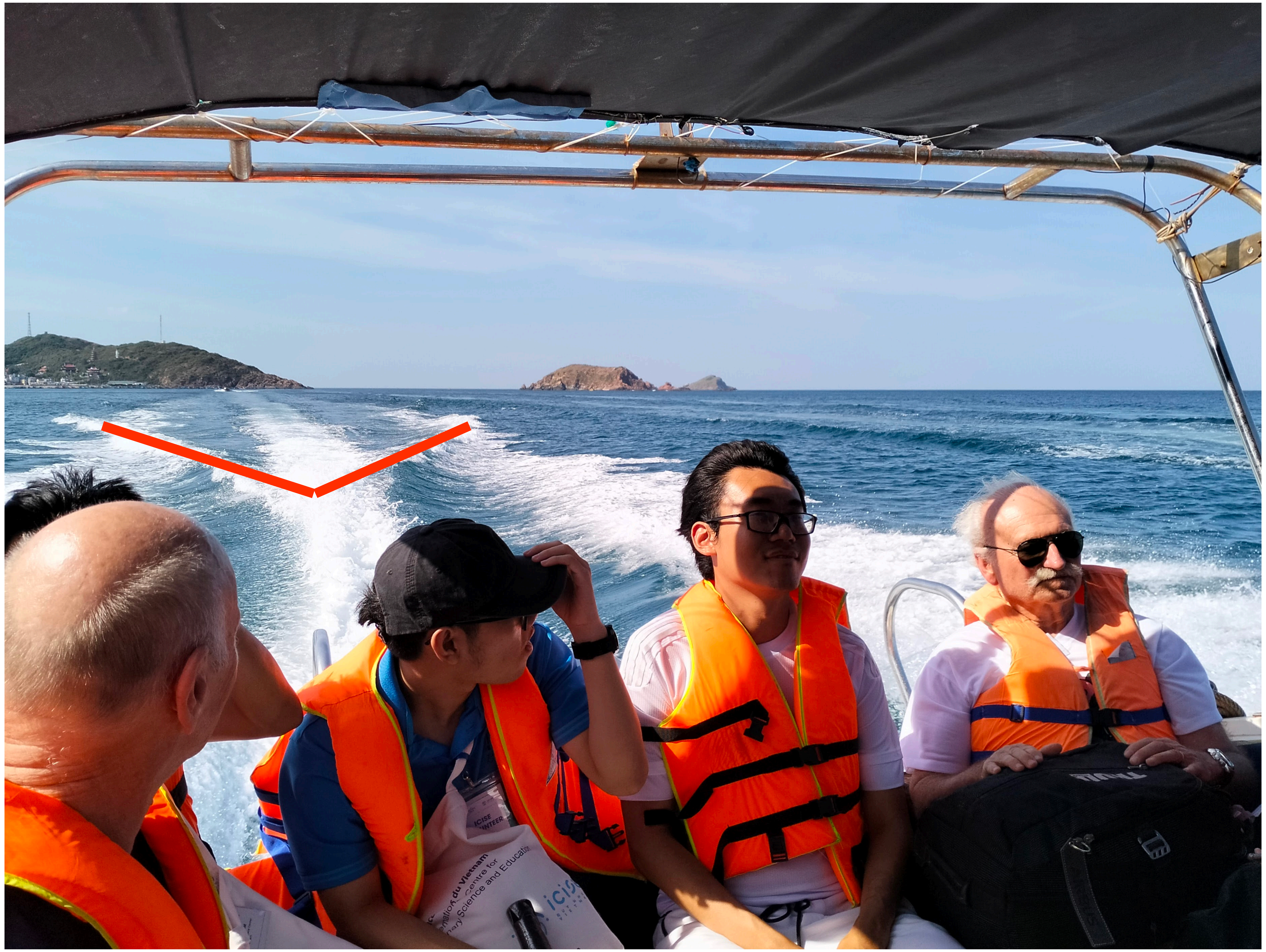


Gas density



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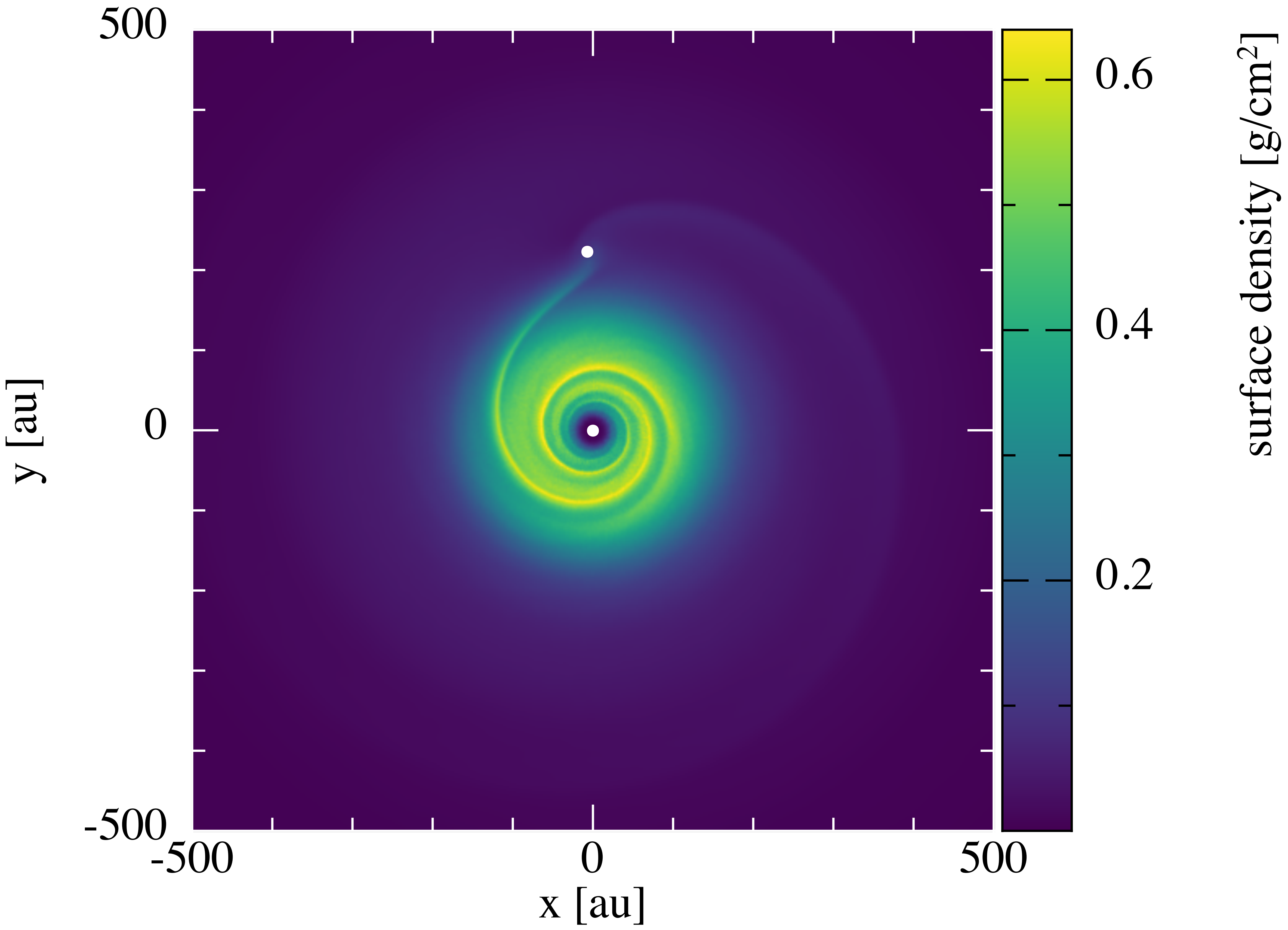

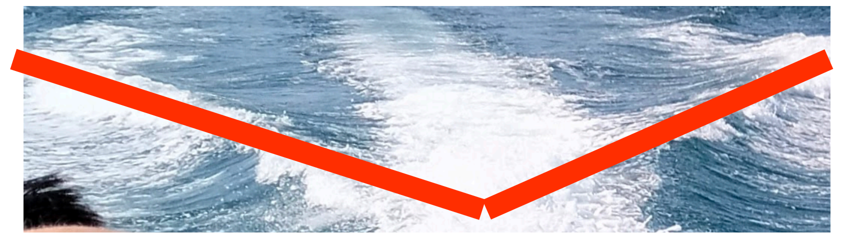

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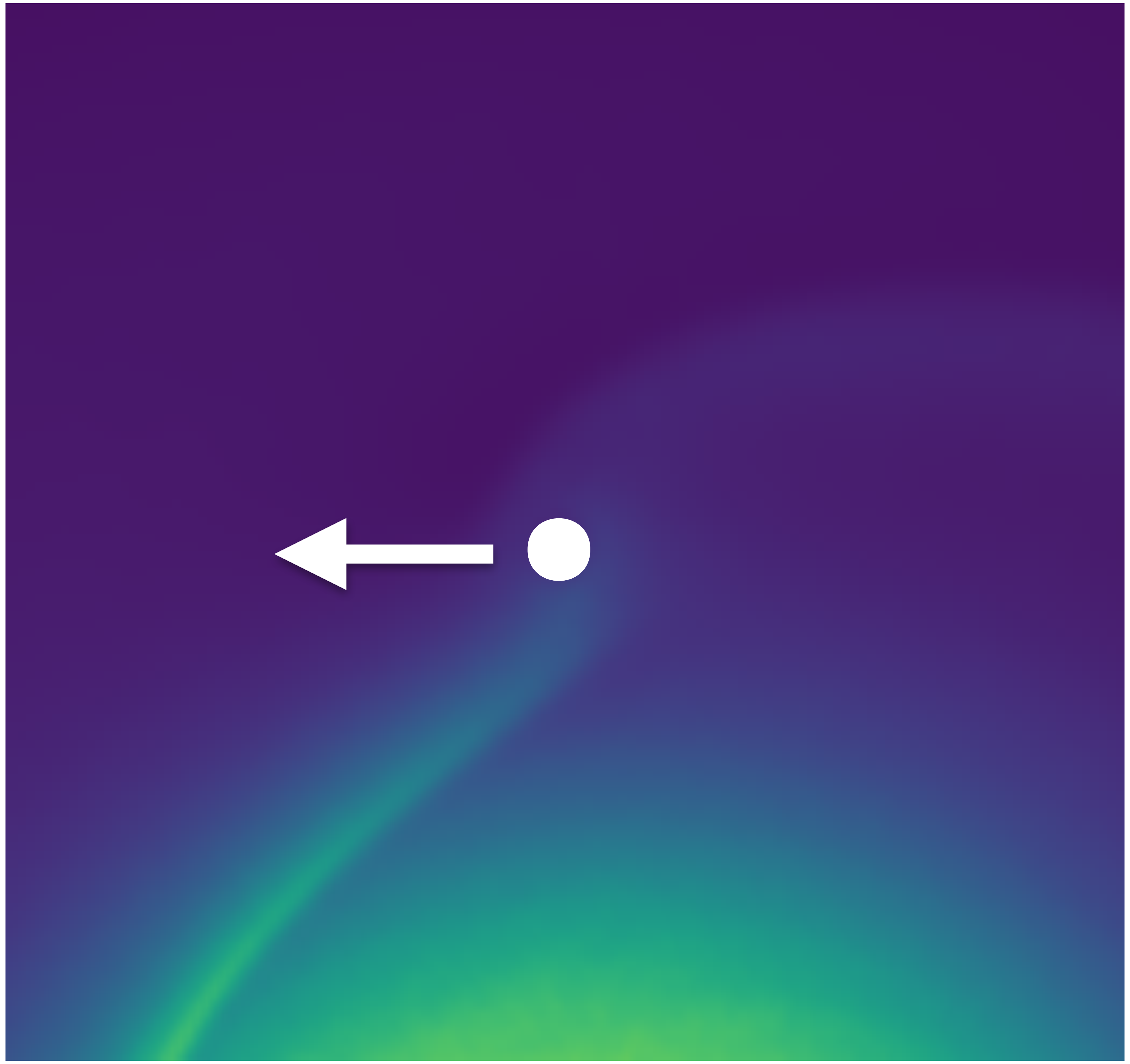

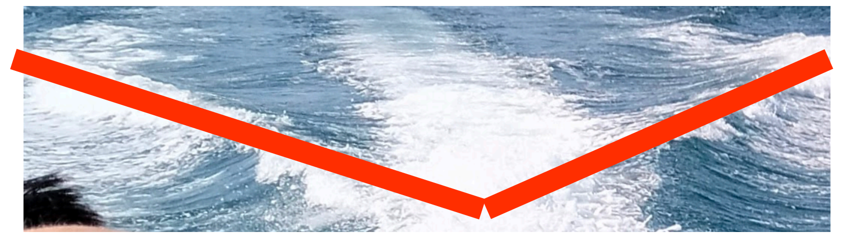

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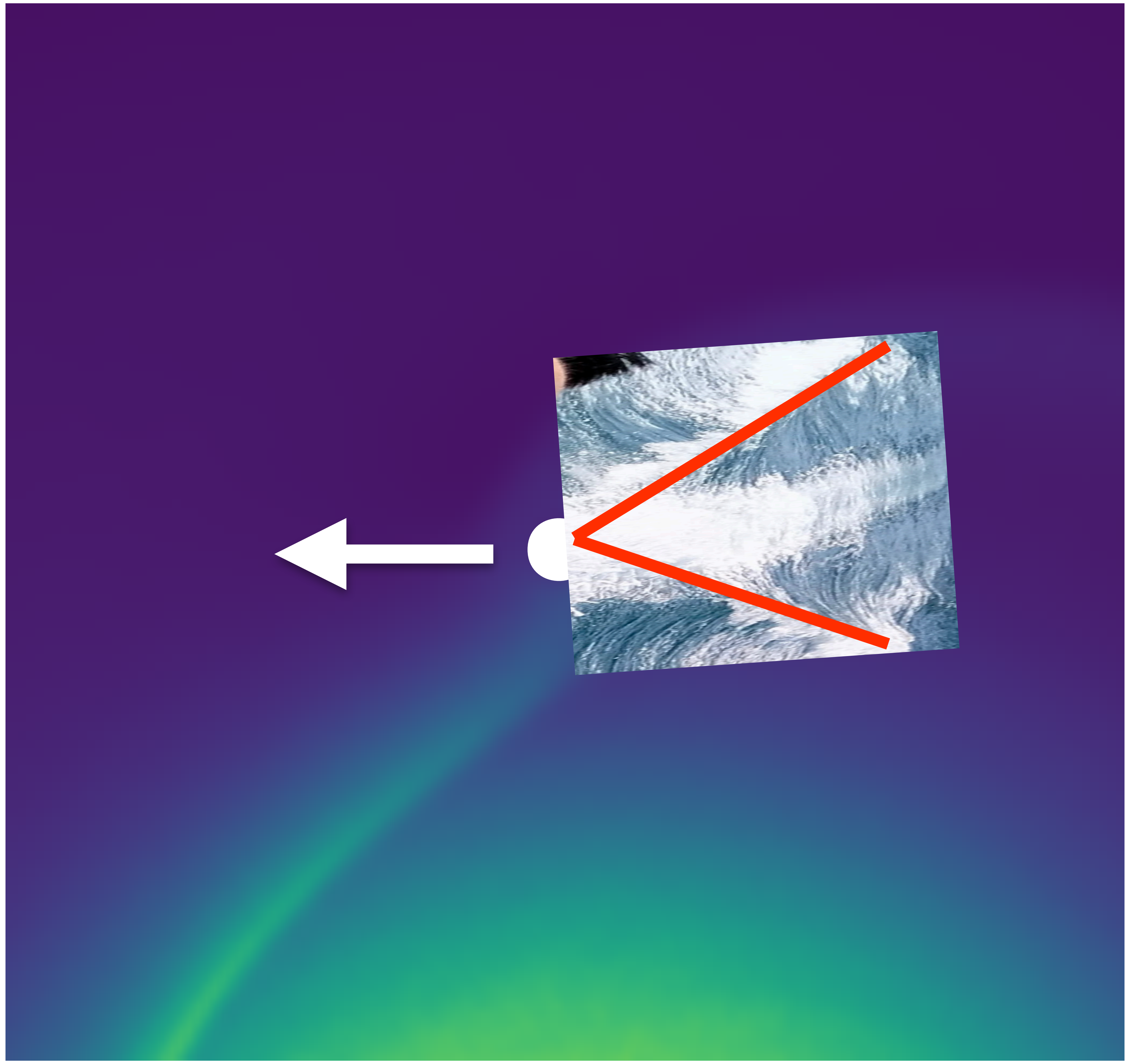

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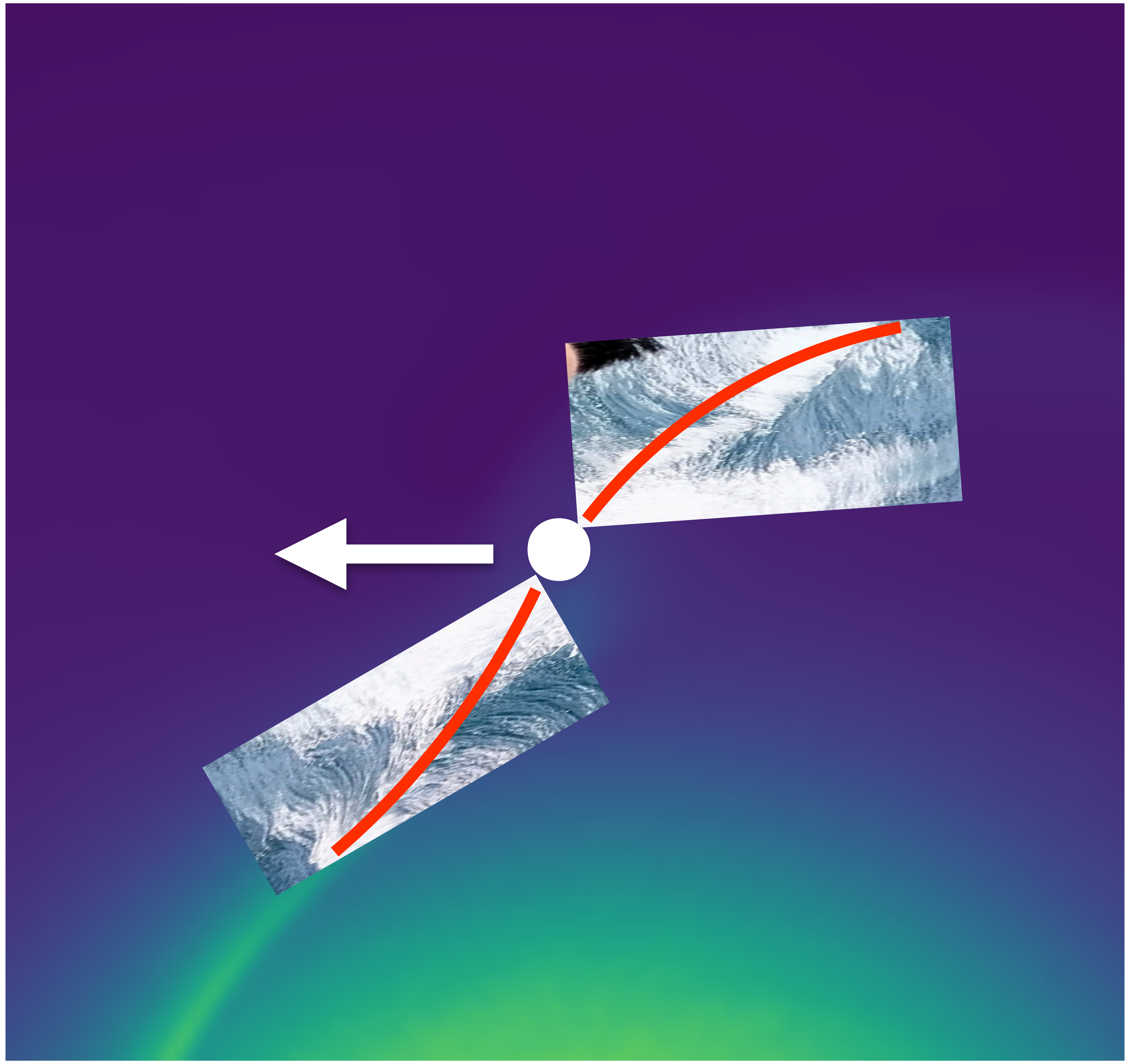

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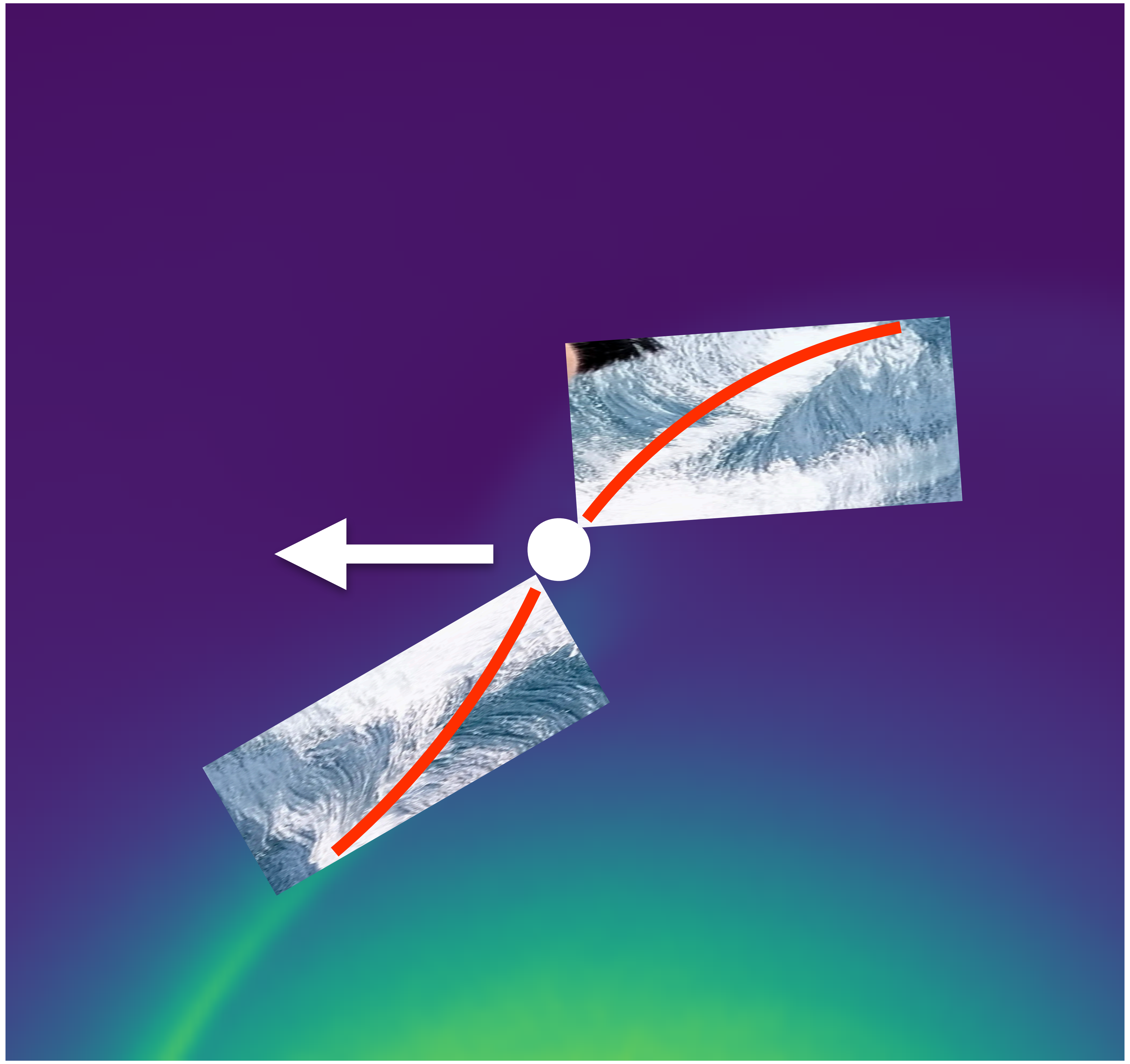
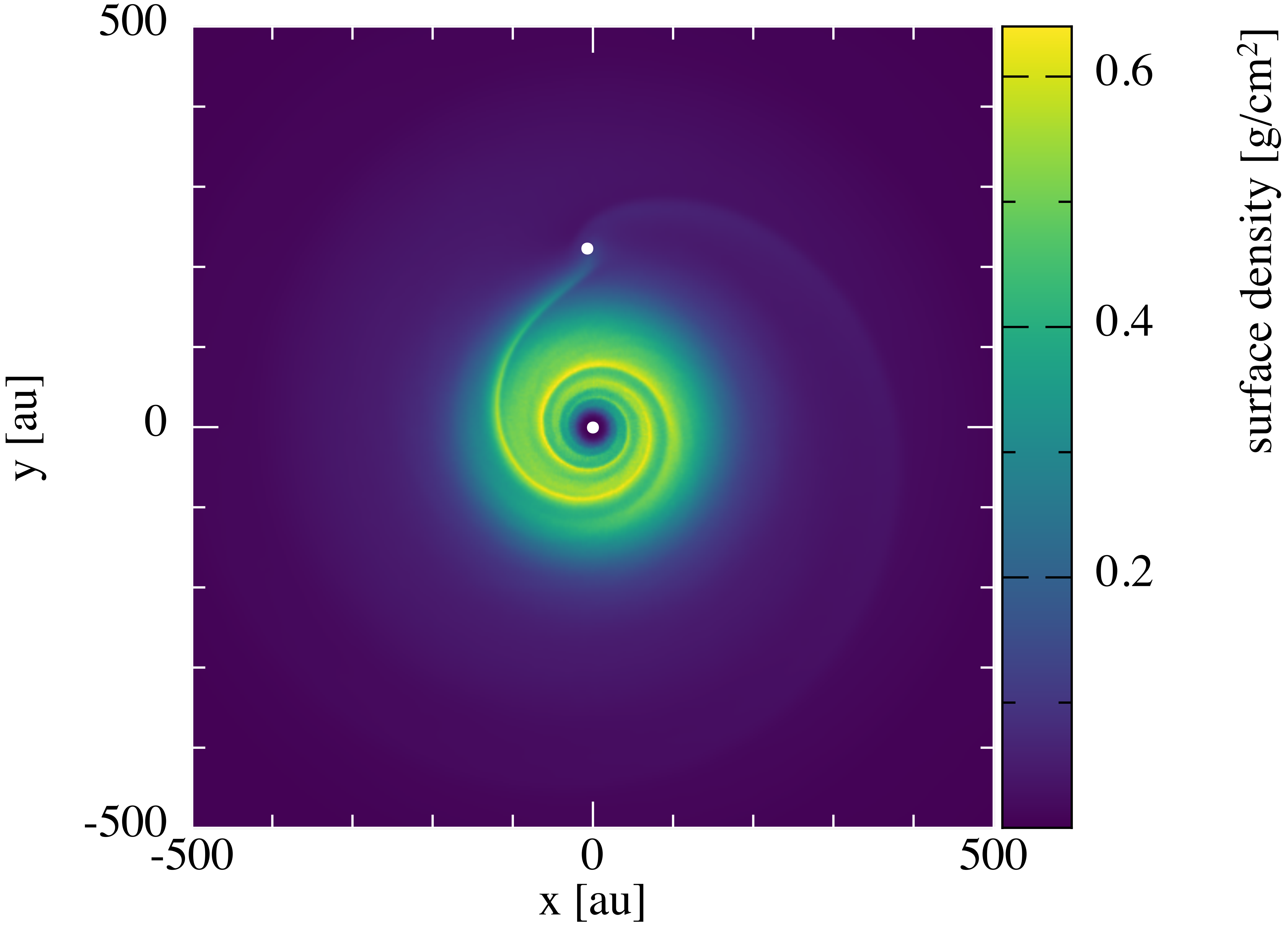


Amplitude of the wake depends on size and speed of the boat

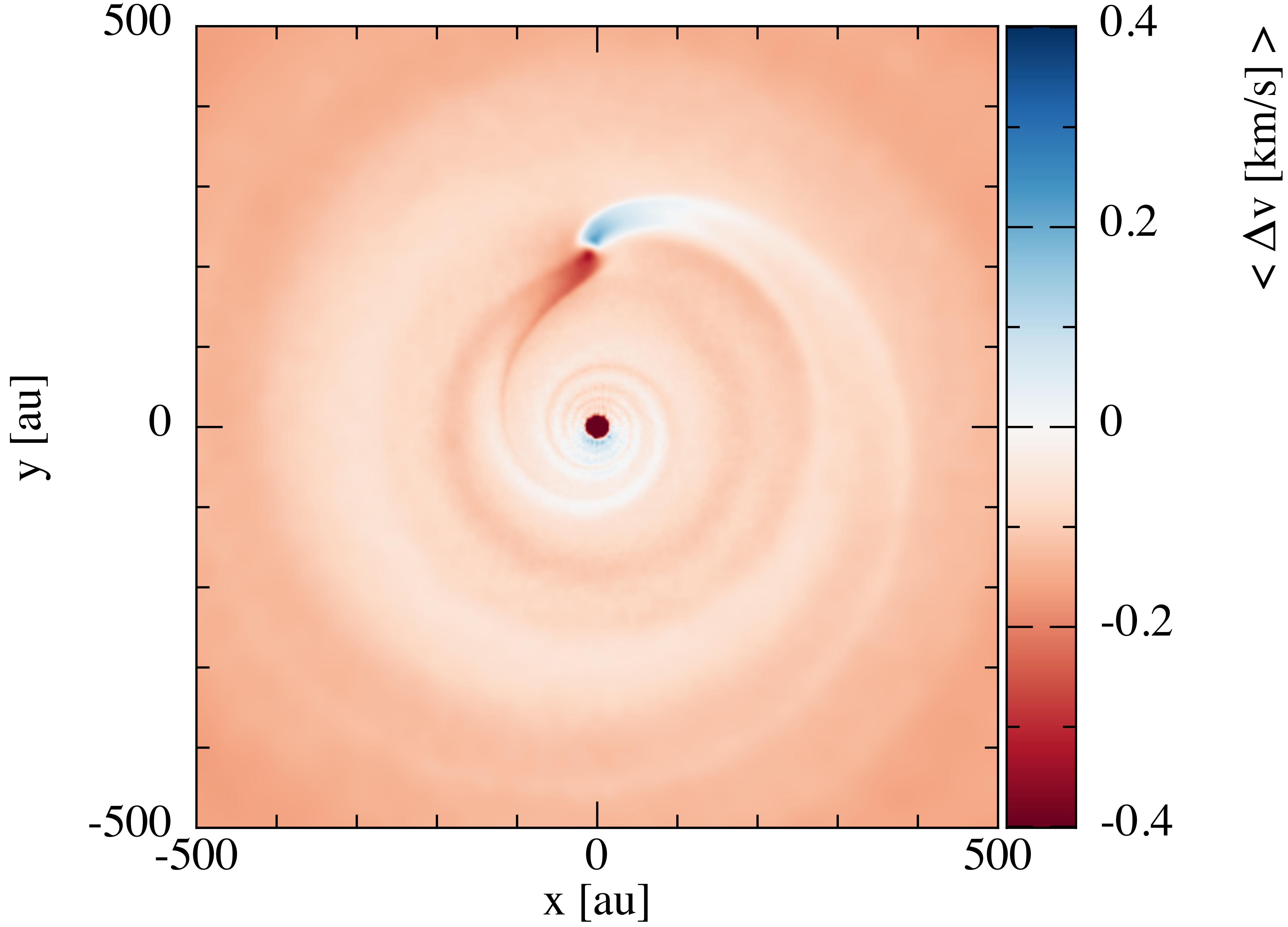
or

planet mass and orbital separation

What happen when you put a planet in a disc ?



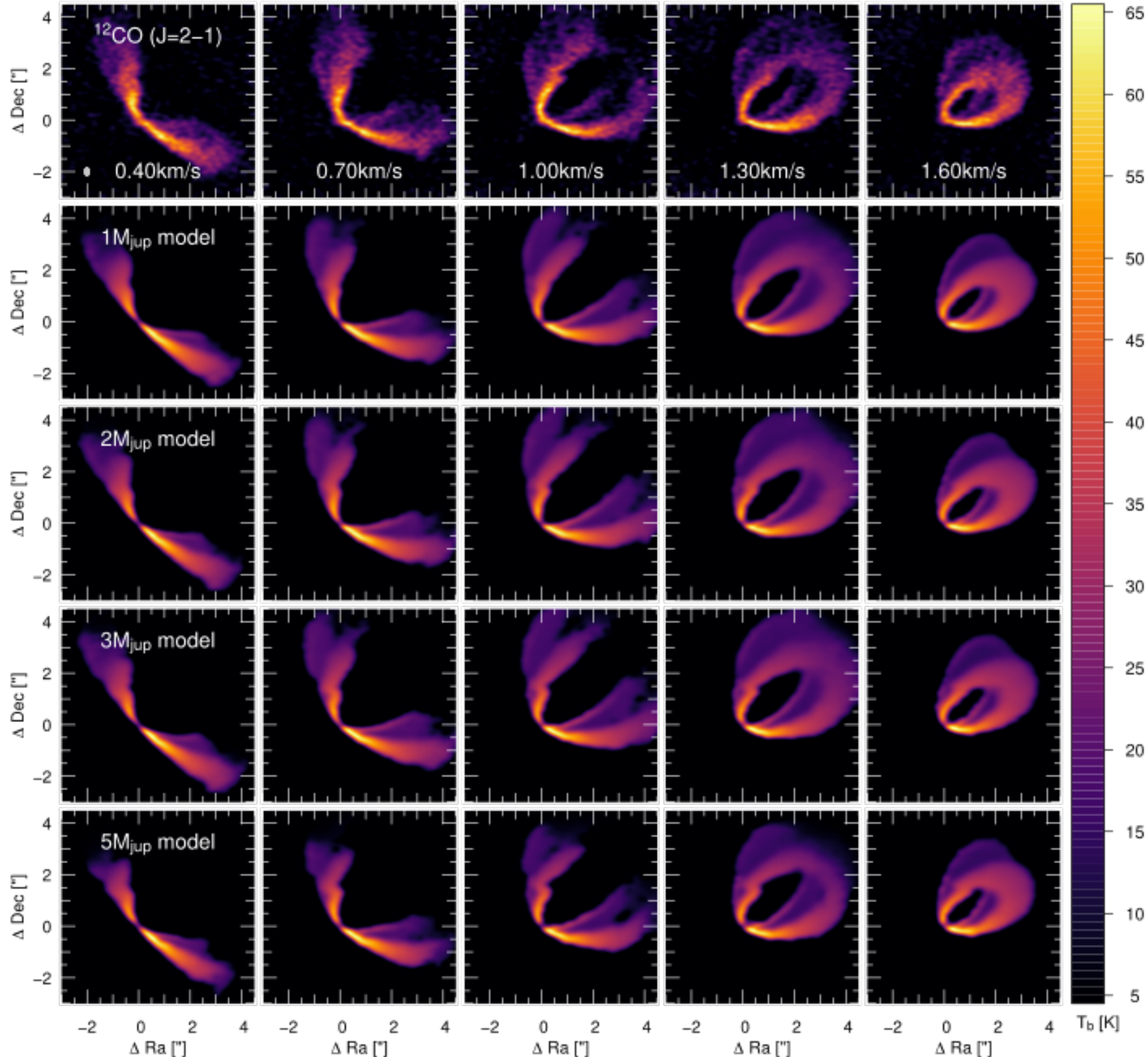
Gas density



Deviation from Keplerian velocity

Phantom model

Observations vs models

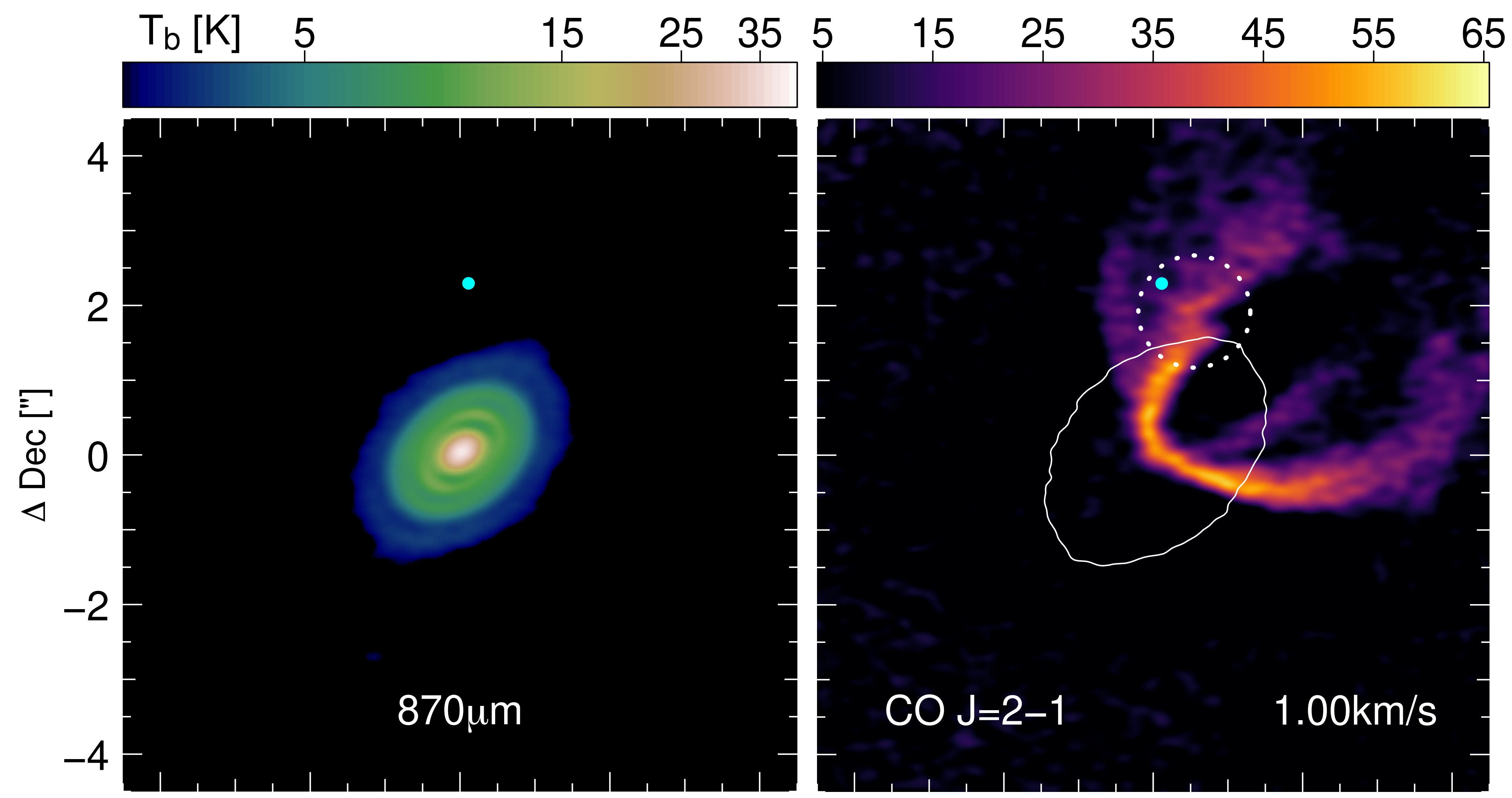


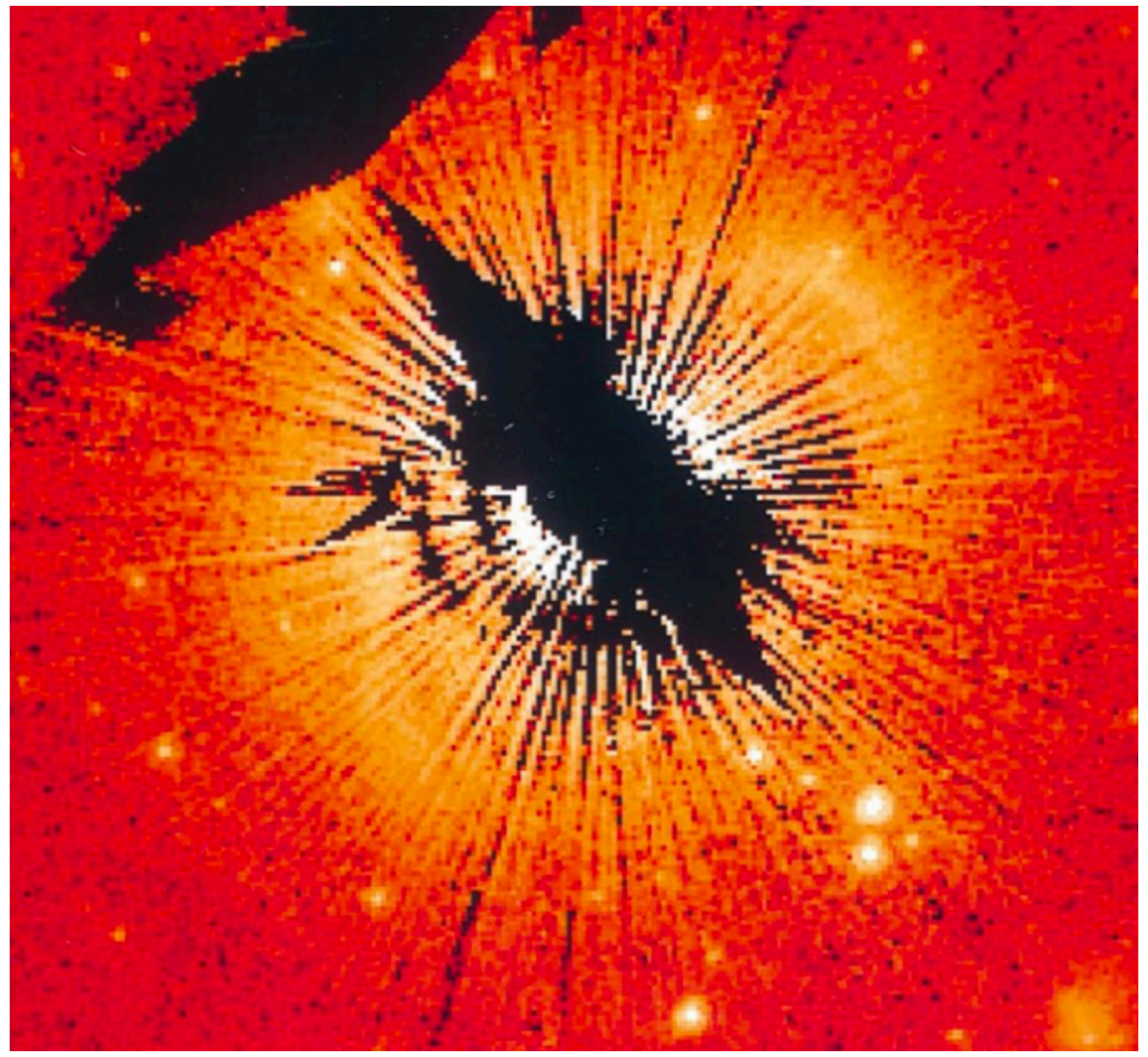
Post-processing of Phantom simulation with RT code MCFOST

Planet mass ≈ $2M_{Jup}$

Good agreement with semi-analytical precription. Bollati et al., 2021

$$\Delta v_p \propto \frac{m_p}{m_{\rm th}} = \frac{m_p}{M_*}\left(\frac{h_p}{r_p}\right)^{-3}$$





THE ASTROPHYSICAL JOURNAL, 544:895–902, 2000 December 1

STIS CORONAGRAPHIC IMAGING OF THE HERBIG Ae STAR: HD 163296

C. A. GRADY AND DAVID DEVINE
NOAO/STIS, Goddard Space Flight Center, Code 681, Greenbelt, MD 20771
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Received 1999 November 11; accepted 2000 June 9

ABSTRACT

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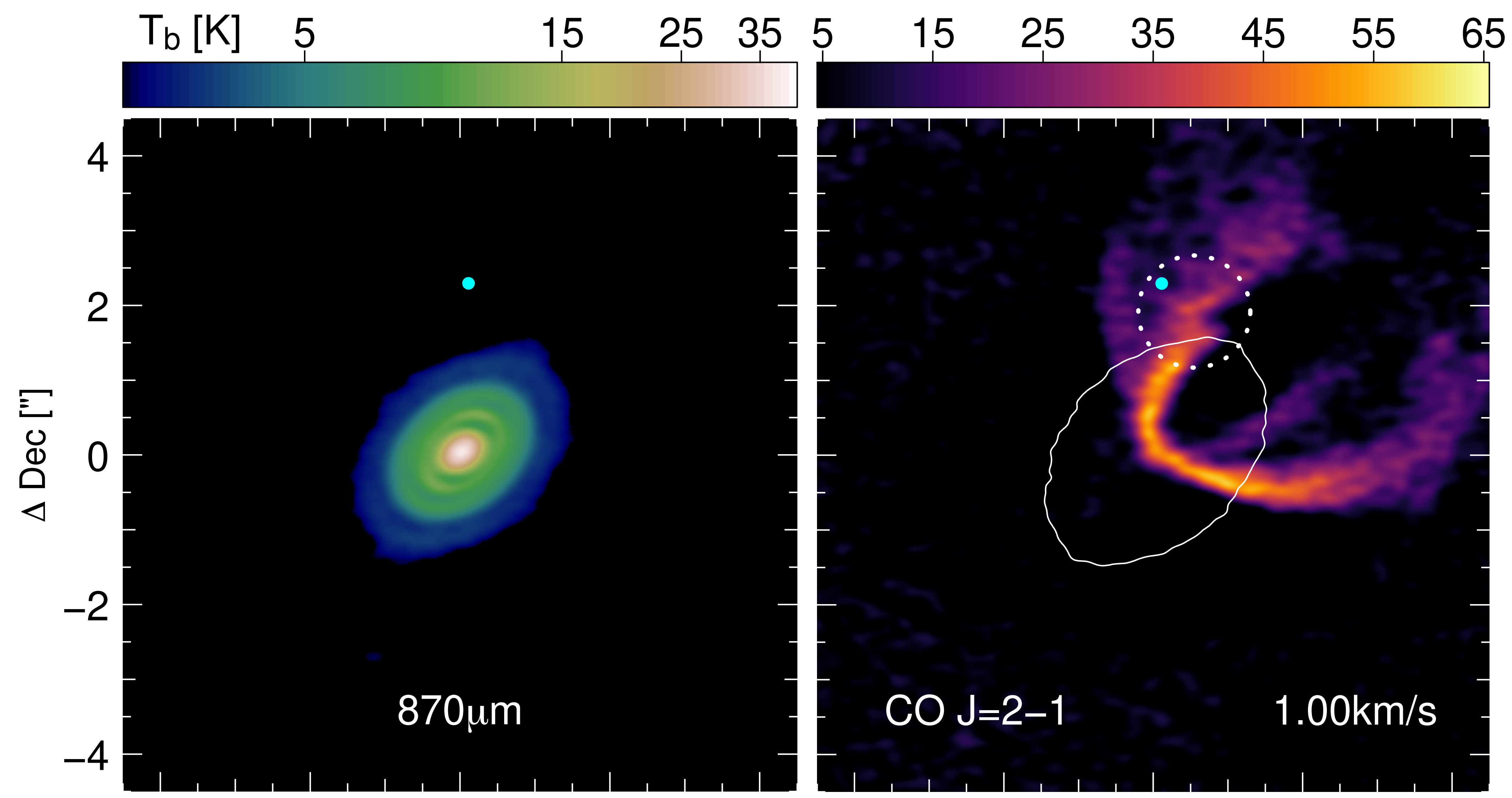

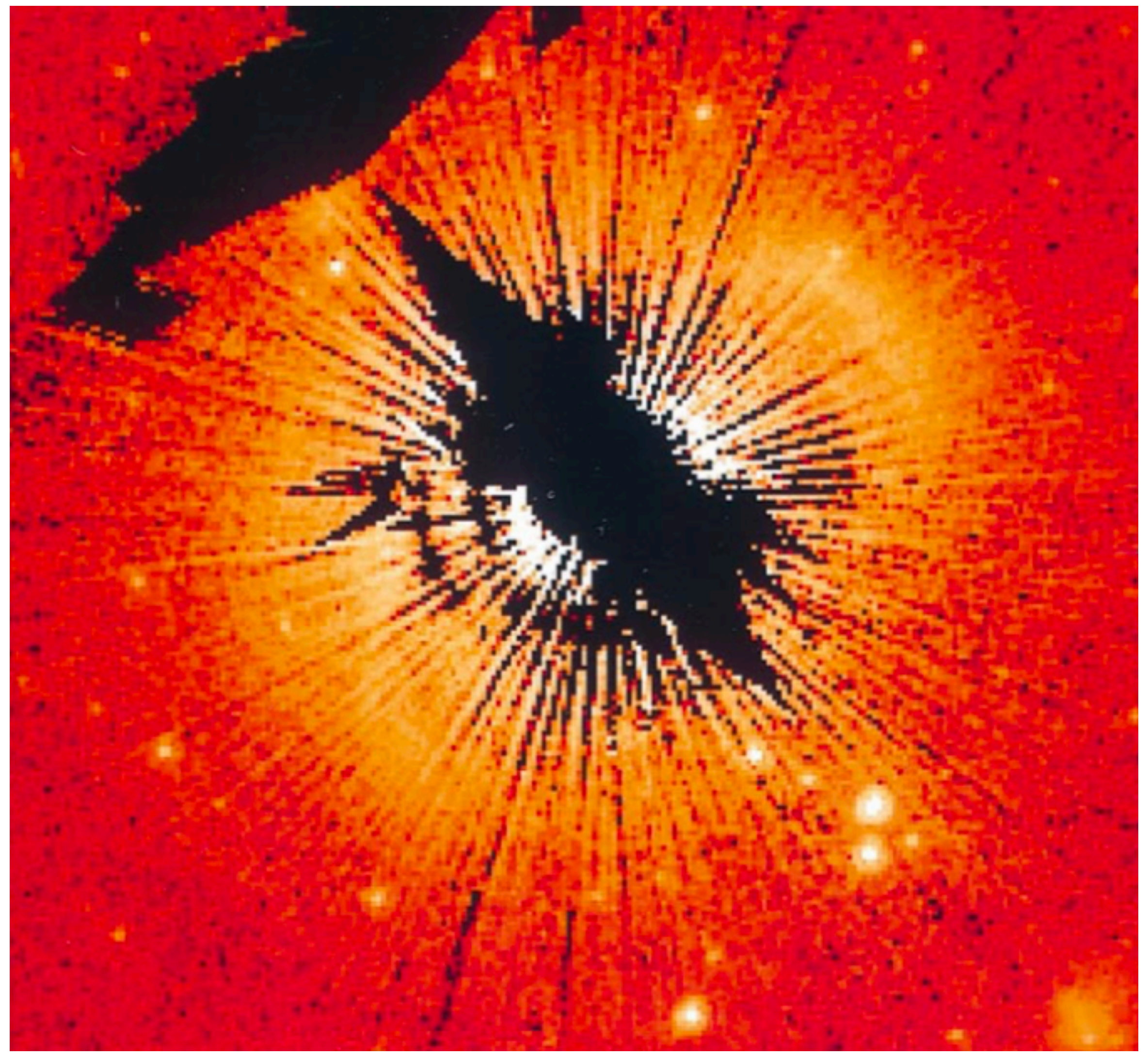

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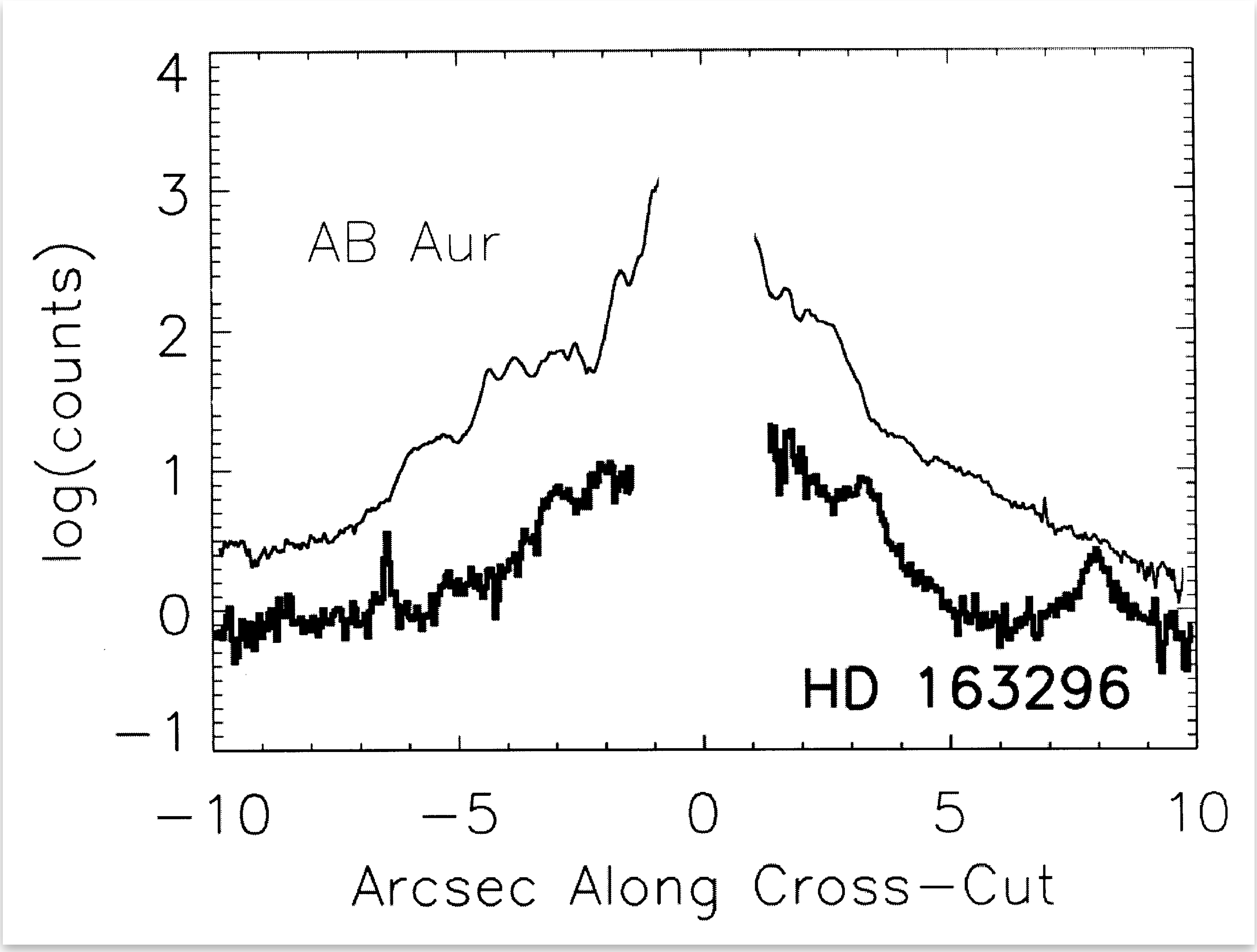

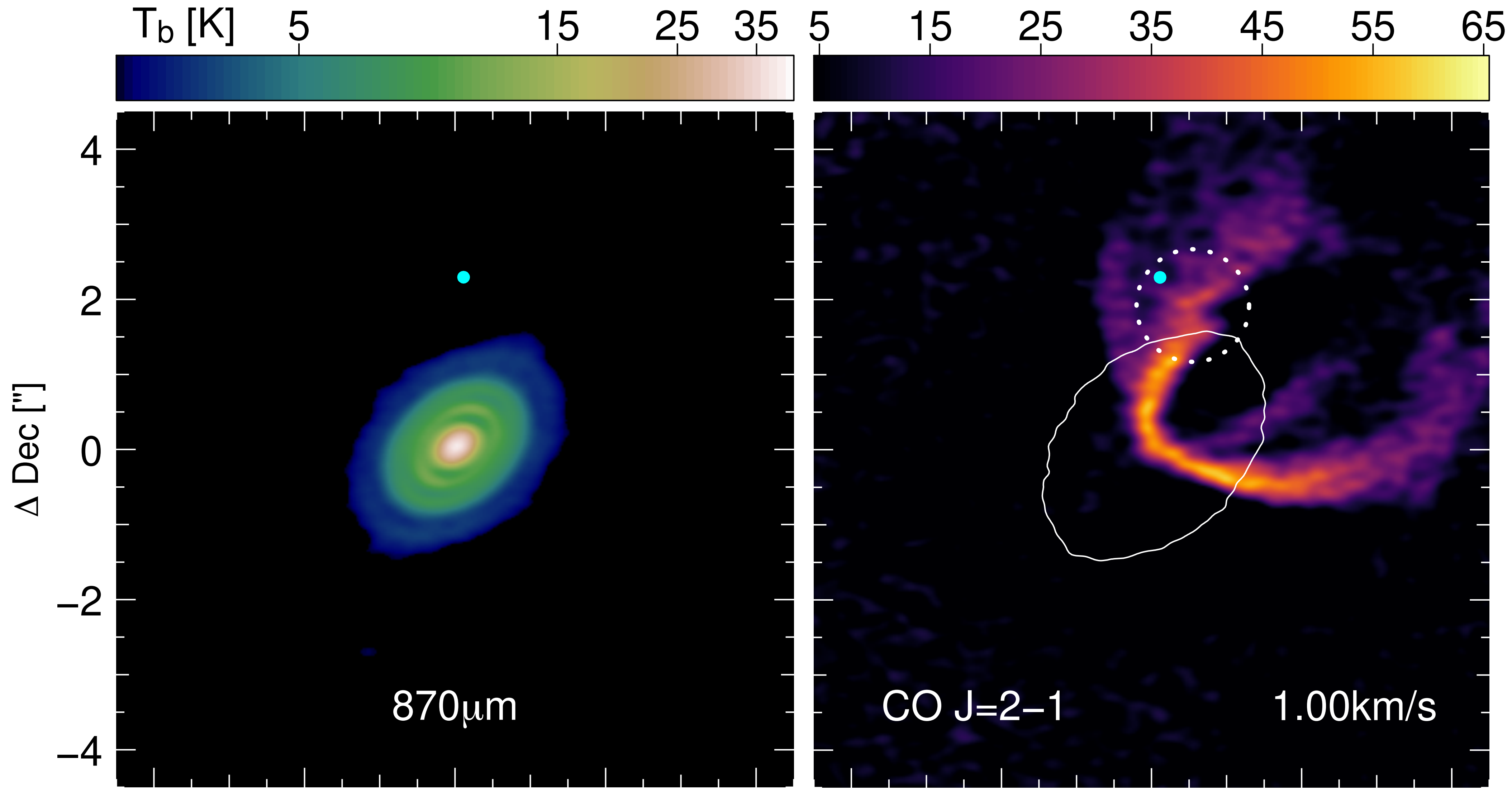

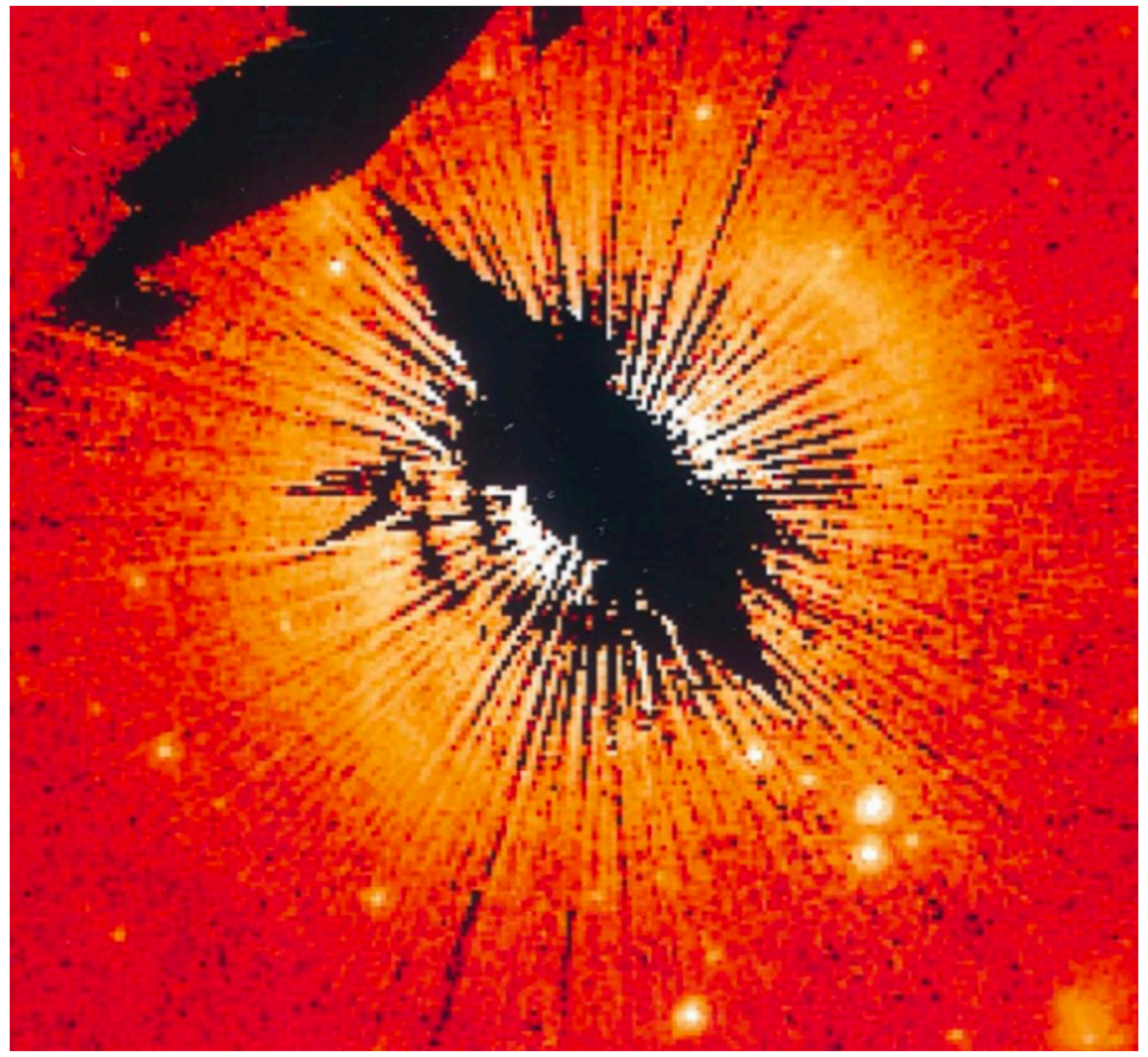

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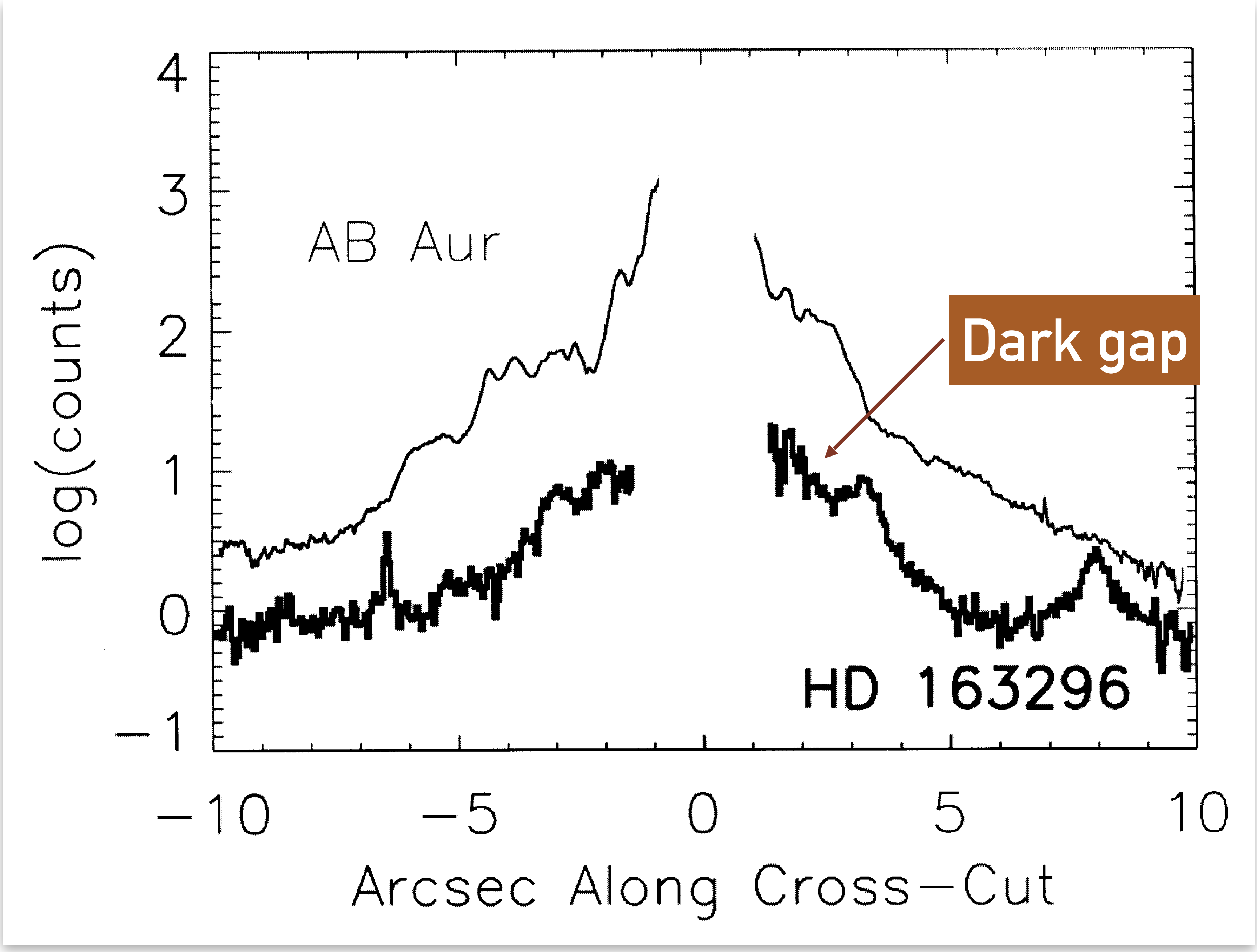

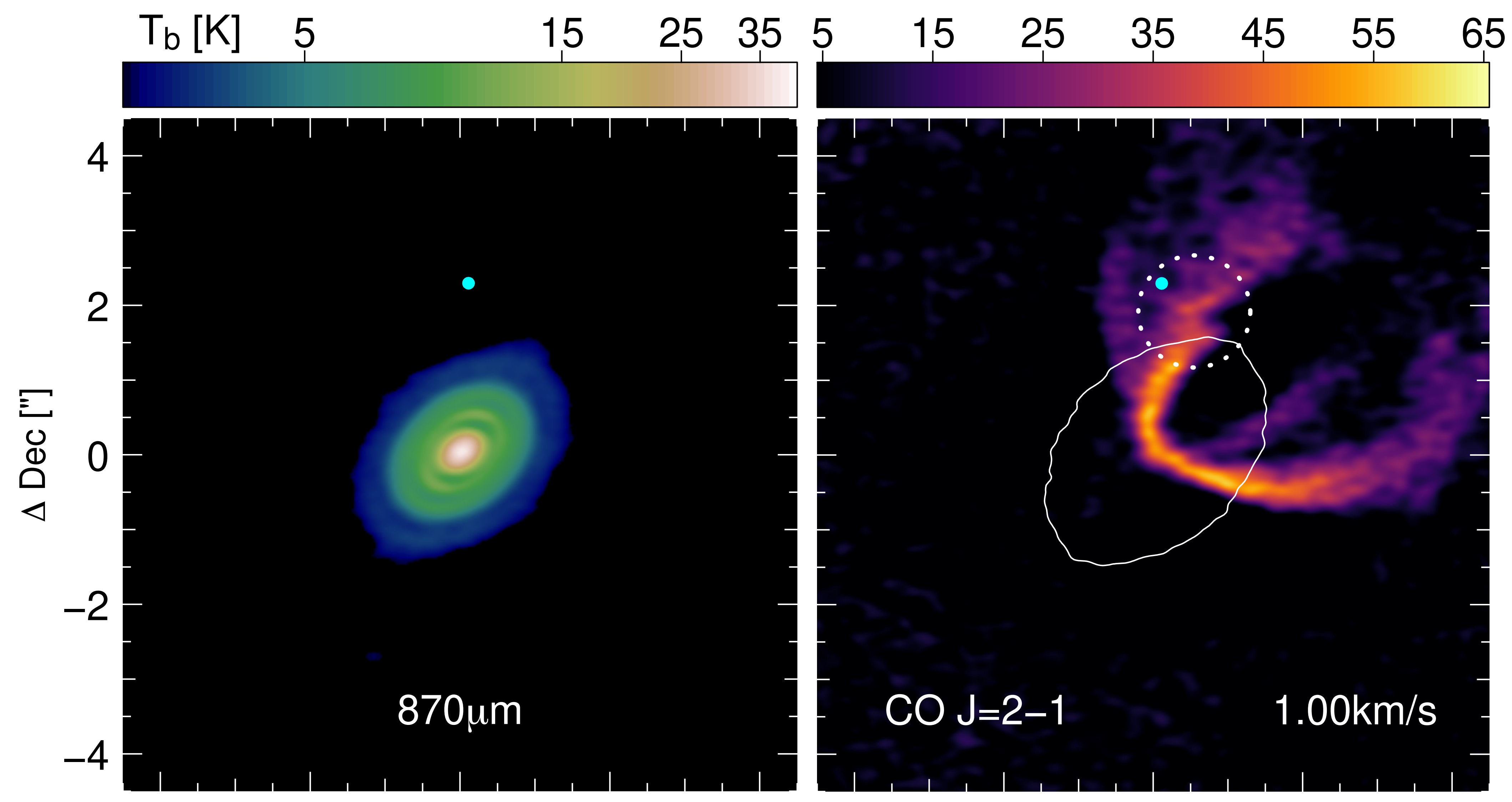

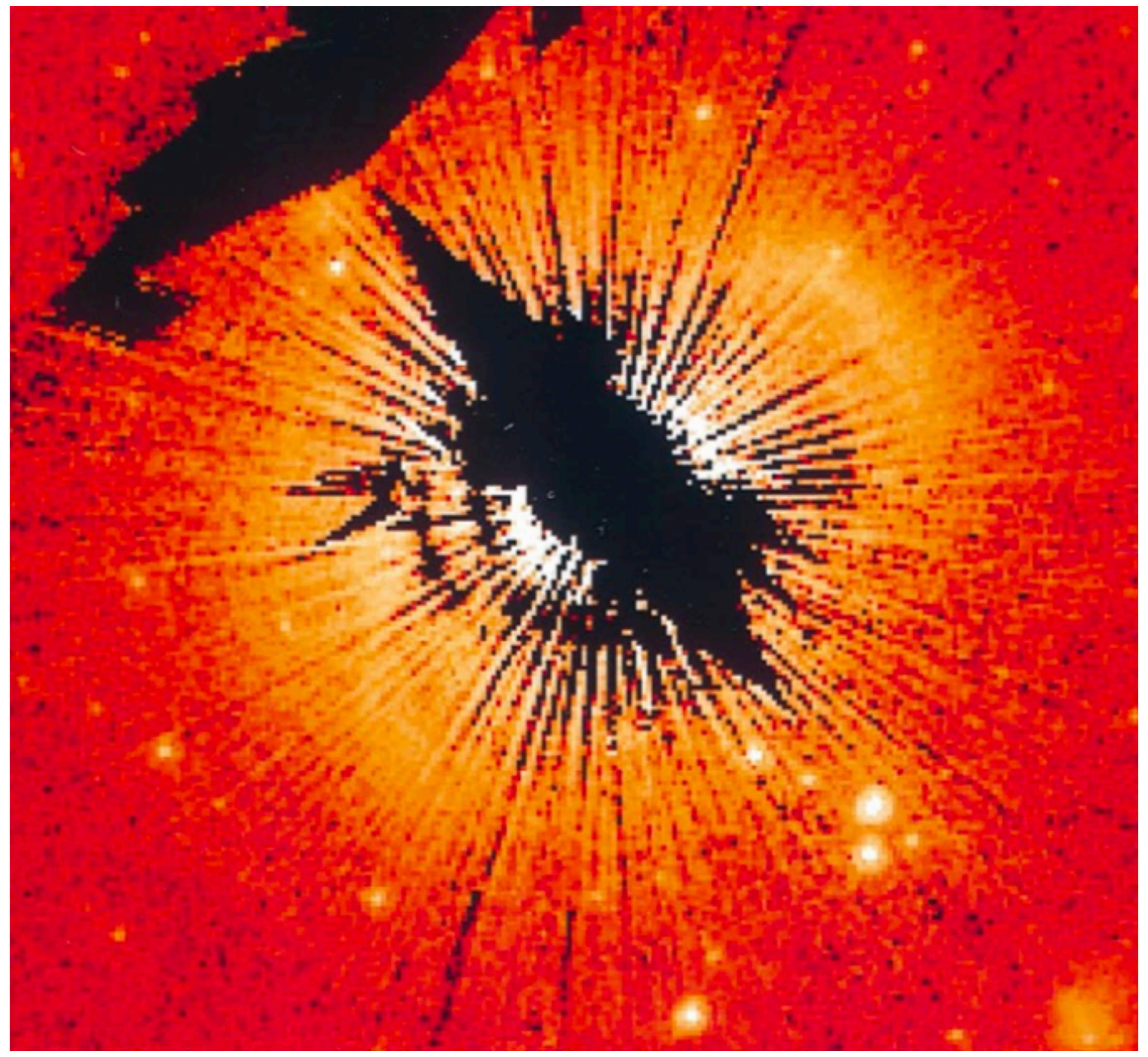

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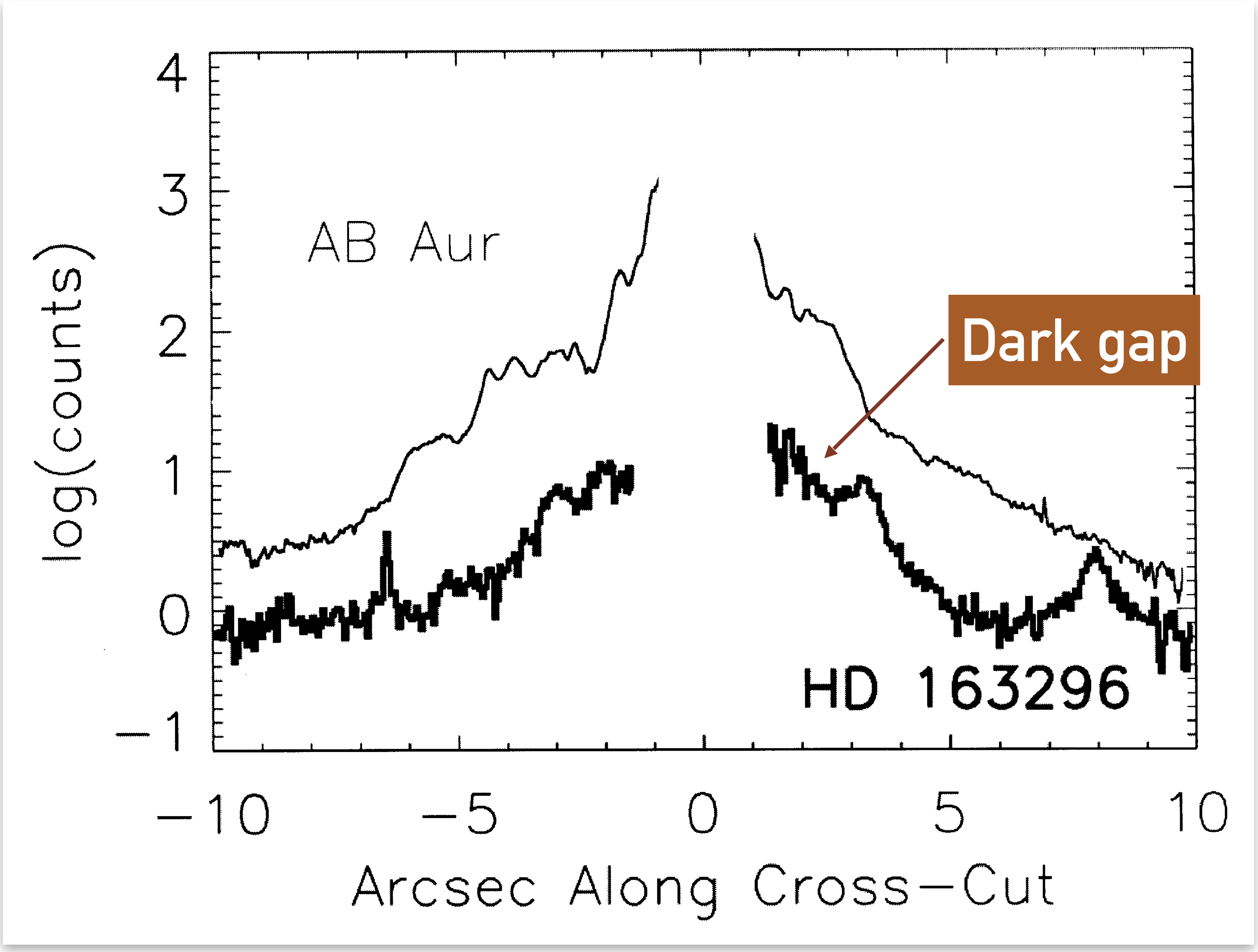
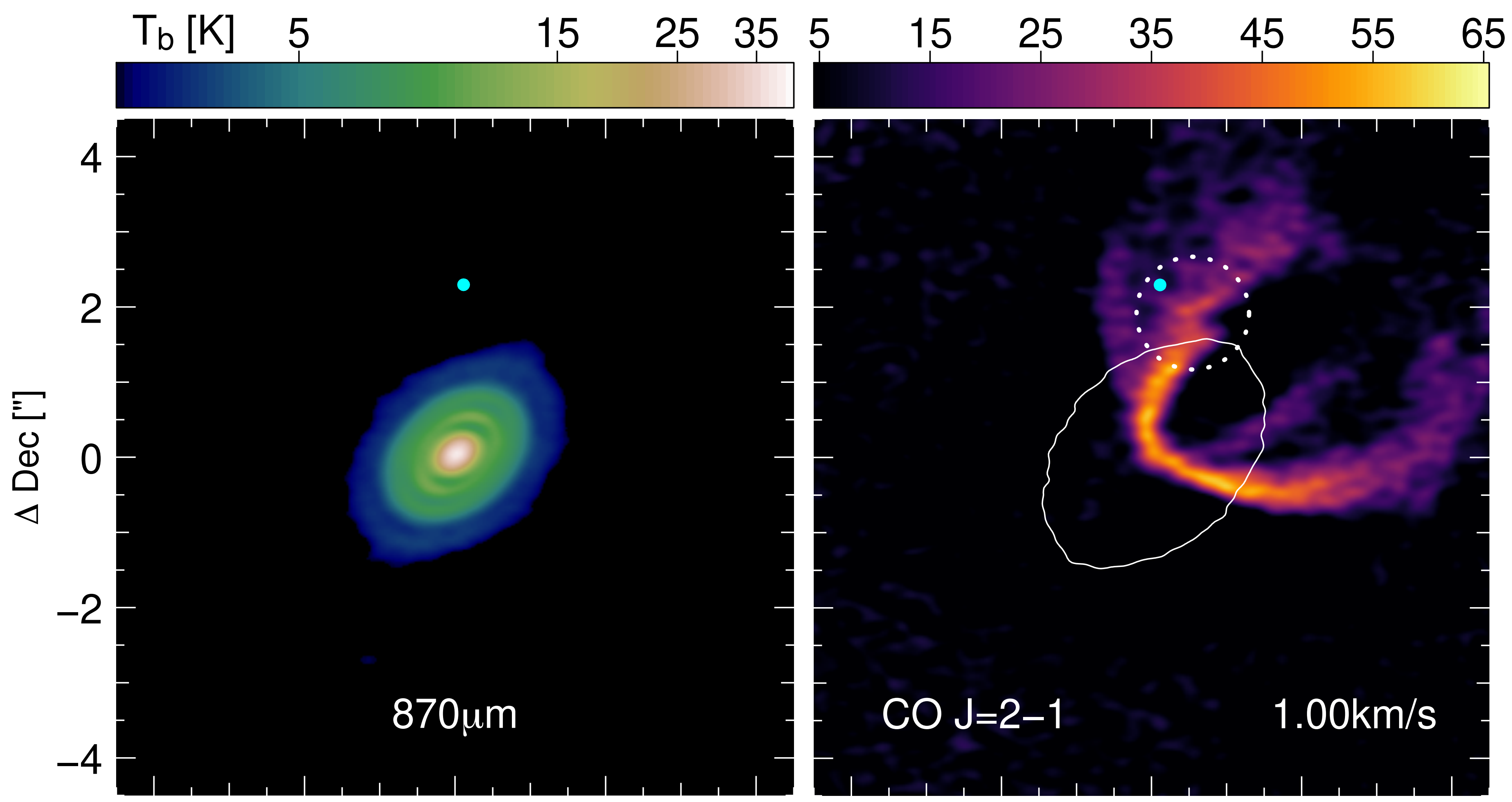


INFERRED ~ 20 YEARS AGO!



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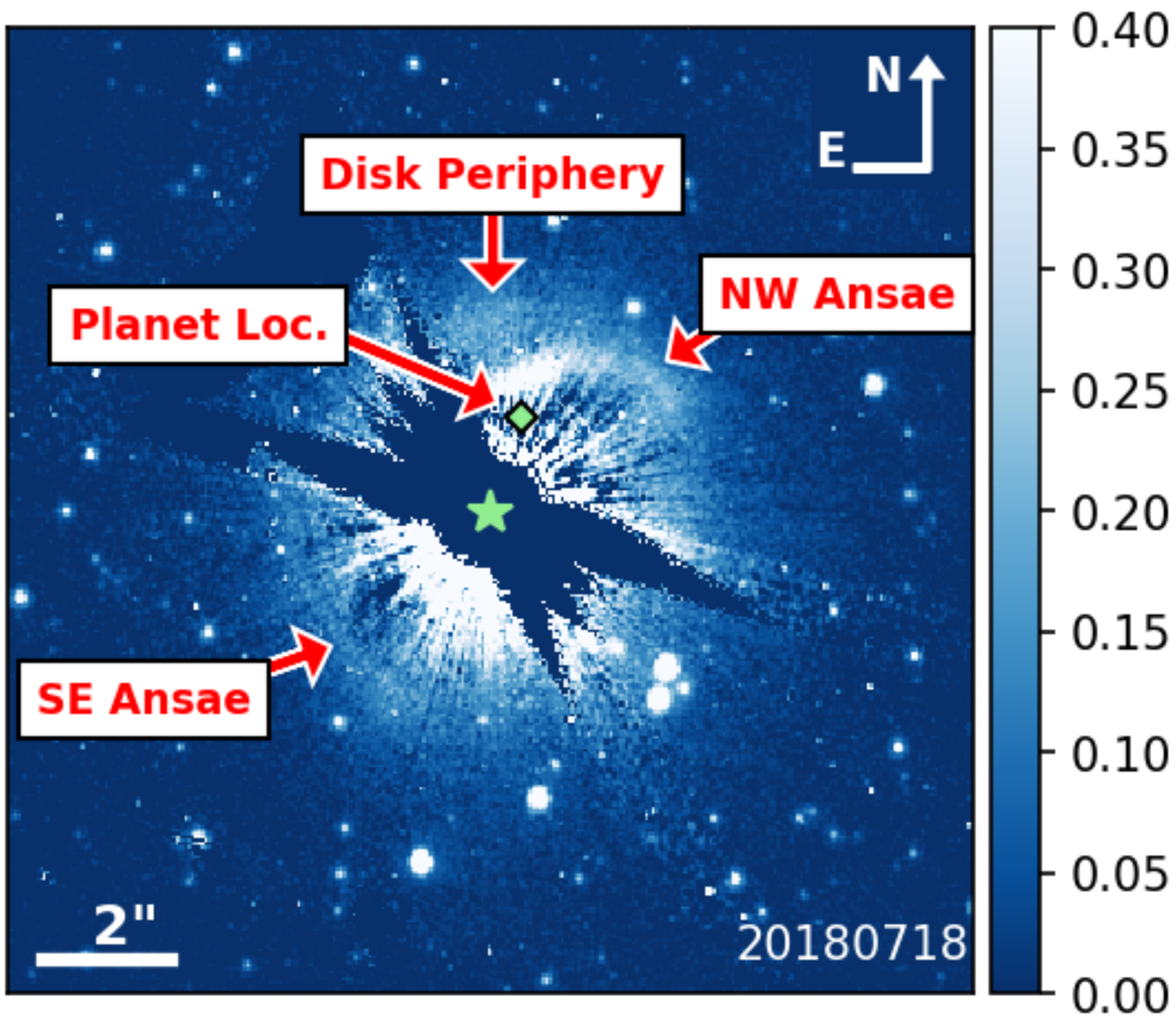
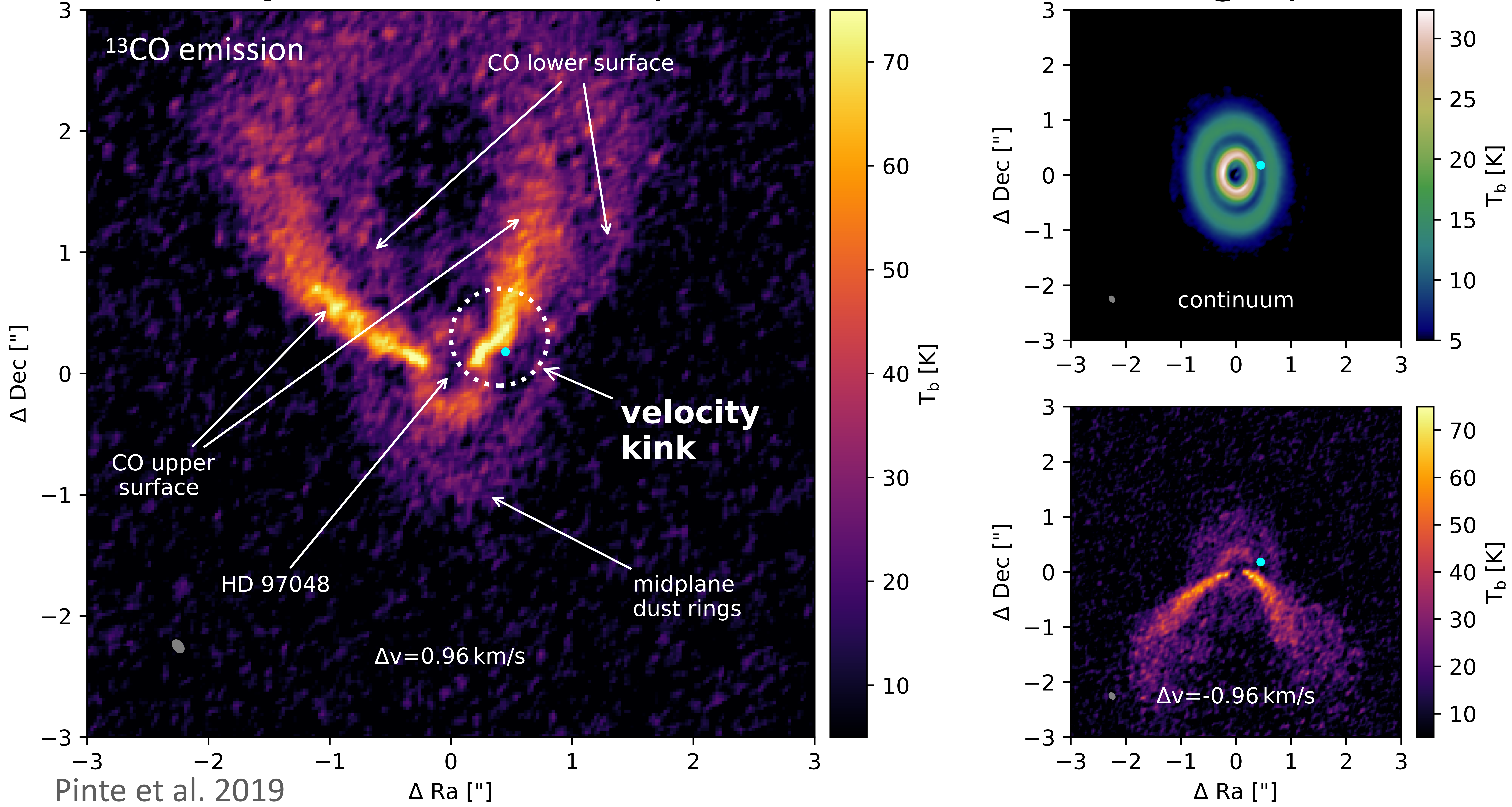


Rich et al 2020

Velocity "kink" co-spatial with a dust gap



Pinte et al. 2019

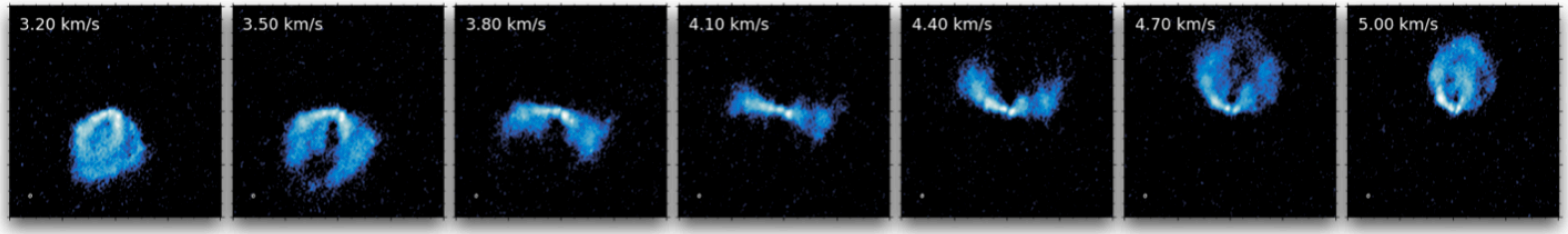
Velocity deviations might be common

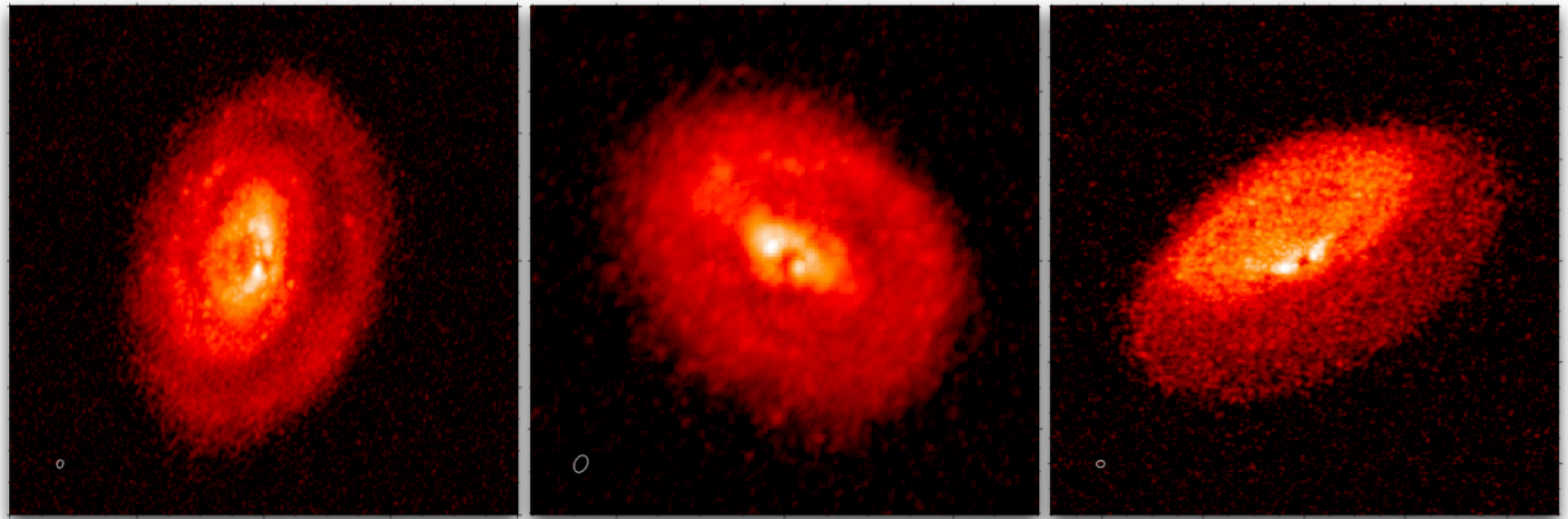
Pinte et al., 2020

exoALMA — A 180h ALMA Large Program to search for embedded planets

co-PIs: Myriam Benisty, Stefano Facchini, Misato Fukagawa, Christophe Pinte, *Richard Teague*

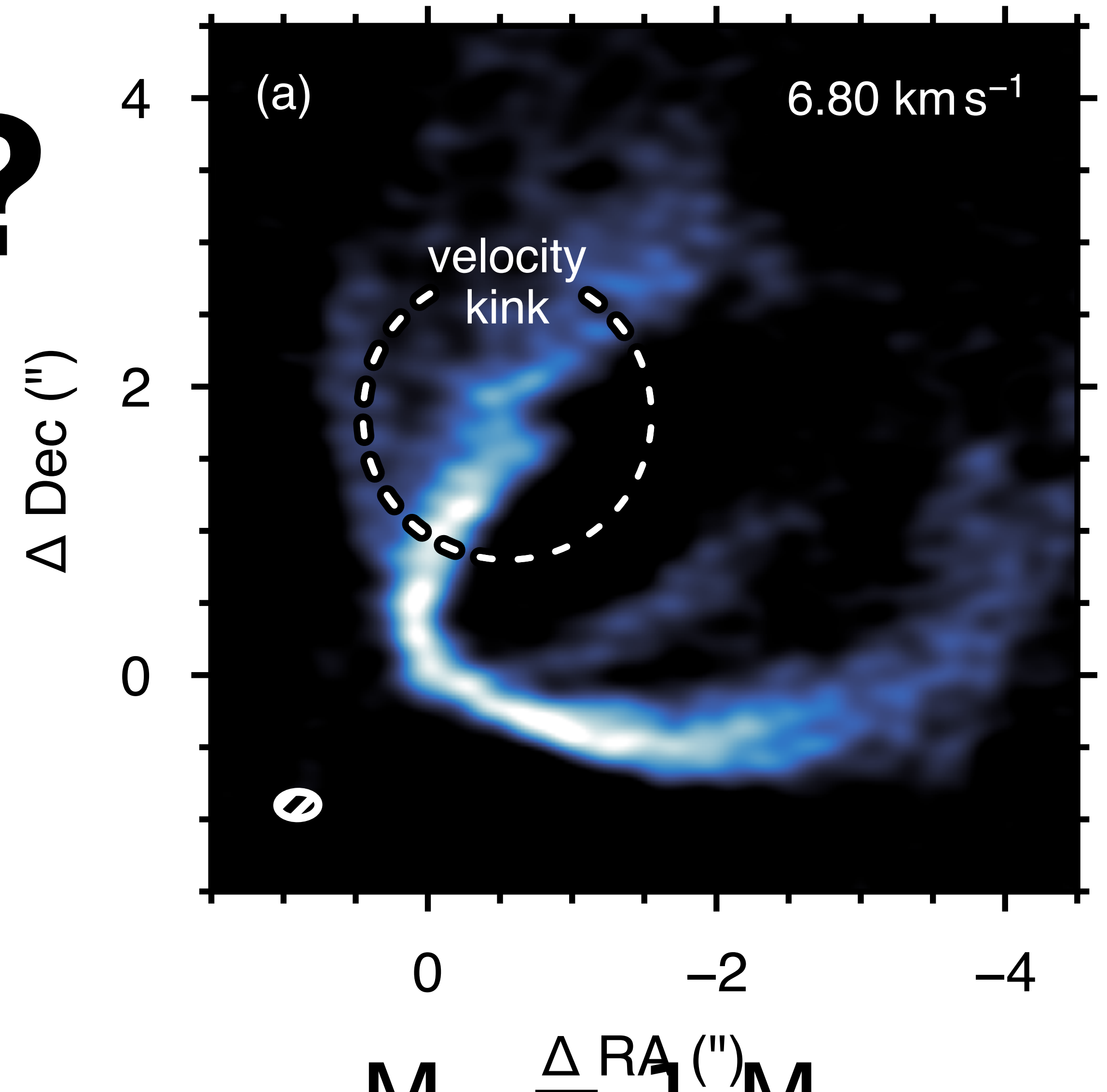
New level of data quality (28 m/s, 0.1”, >10h per source)

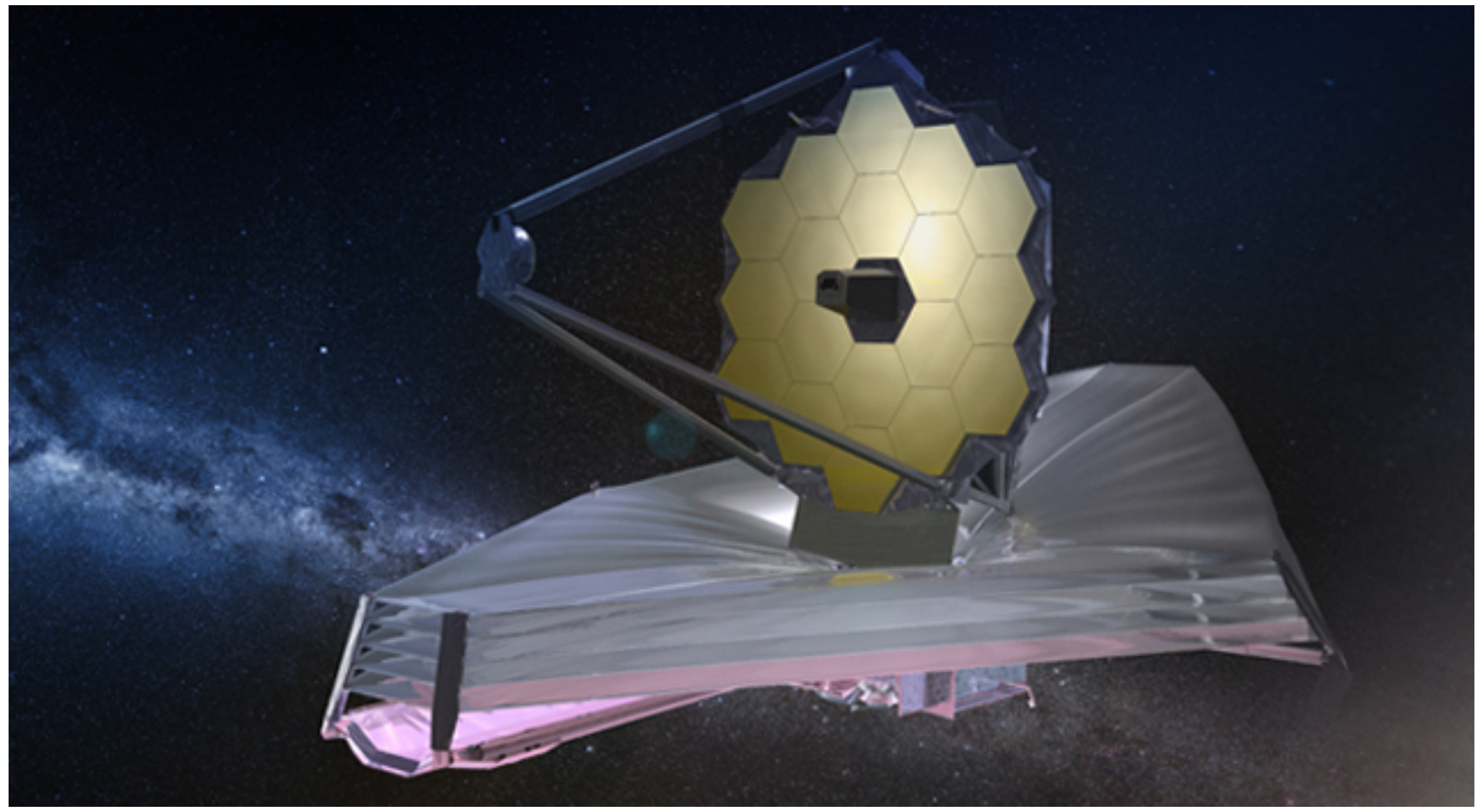


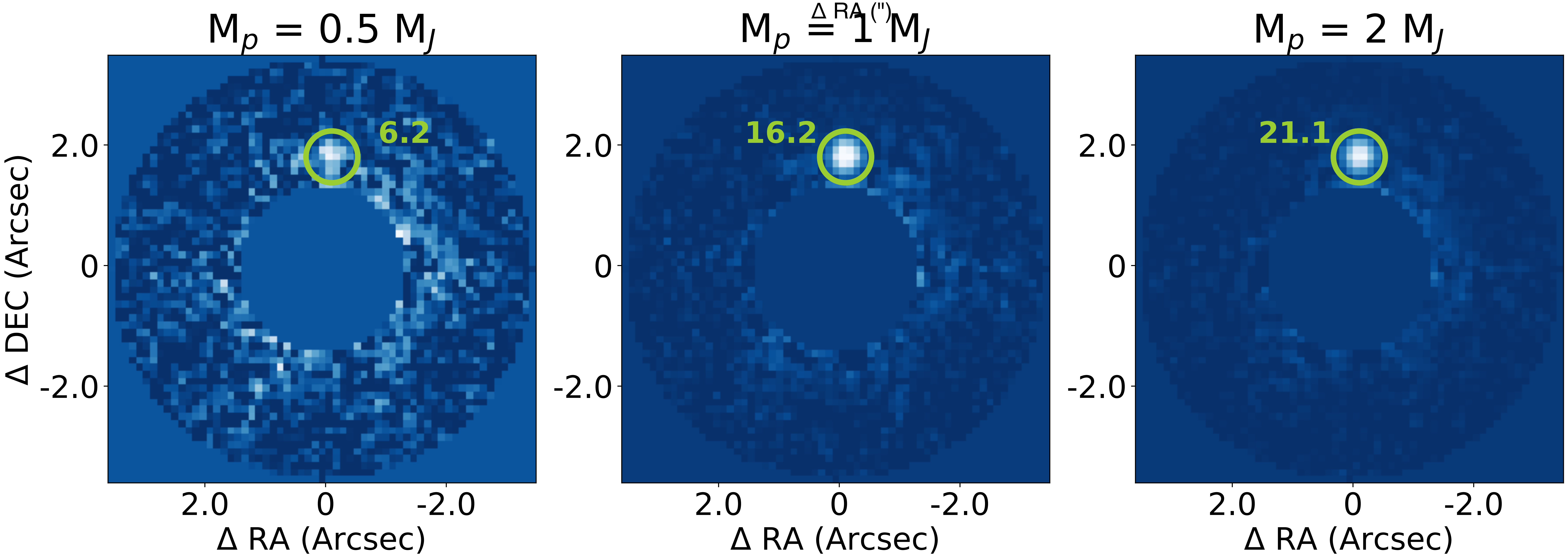


JWST direct image ?

Observing HD163296 next week !!



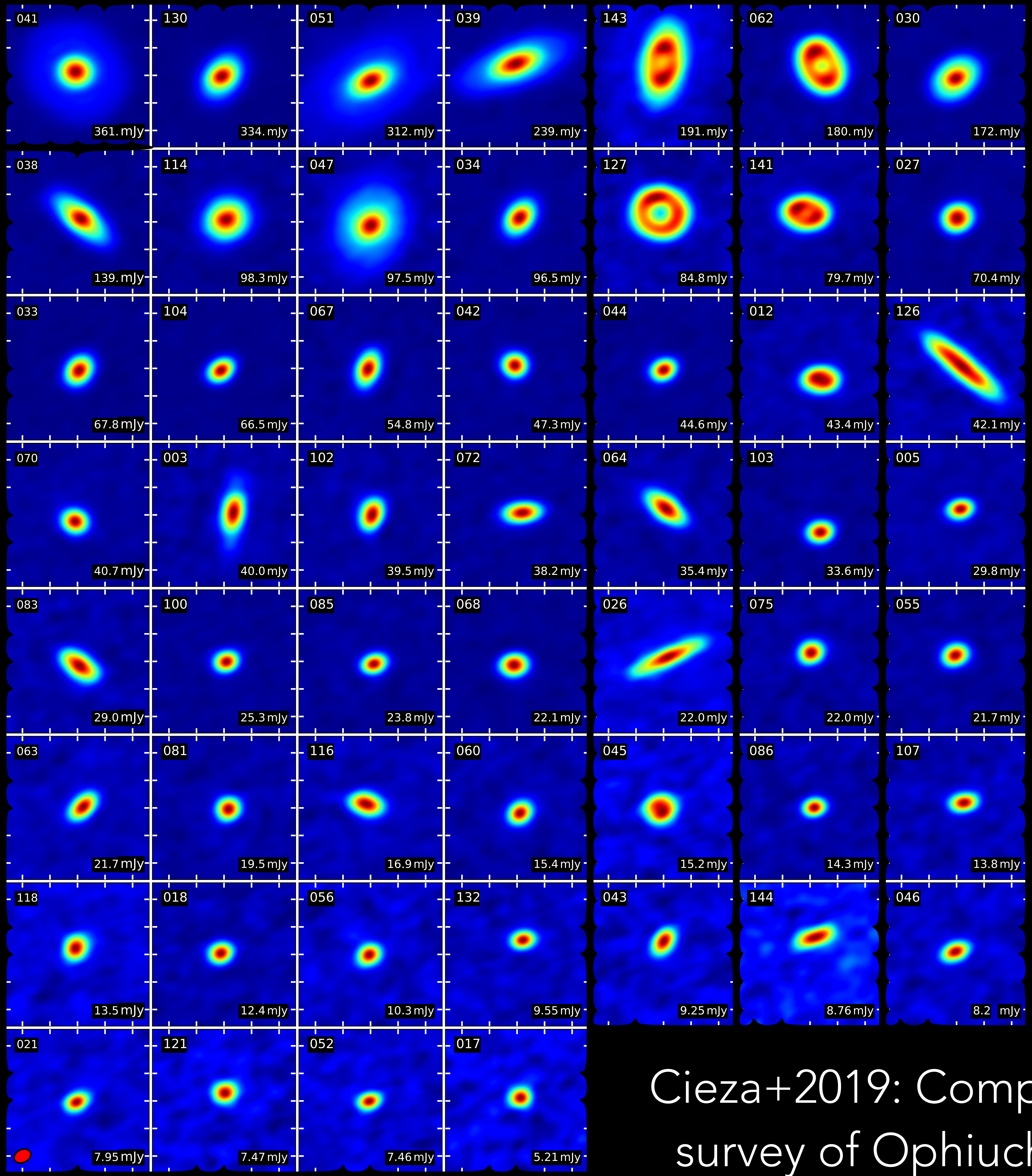


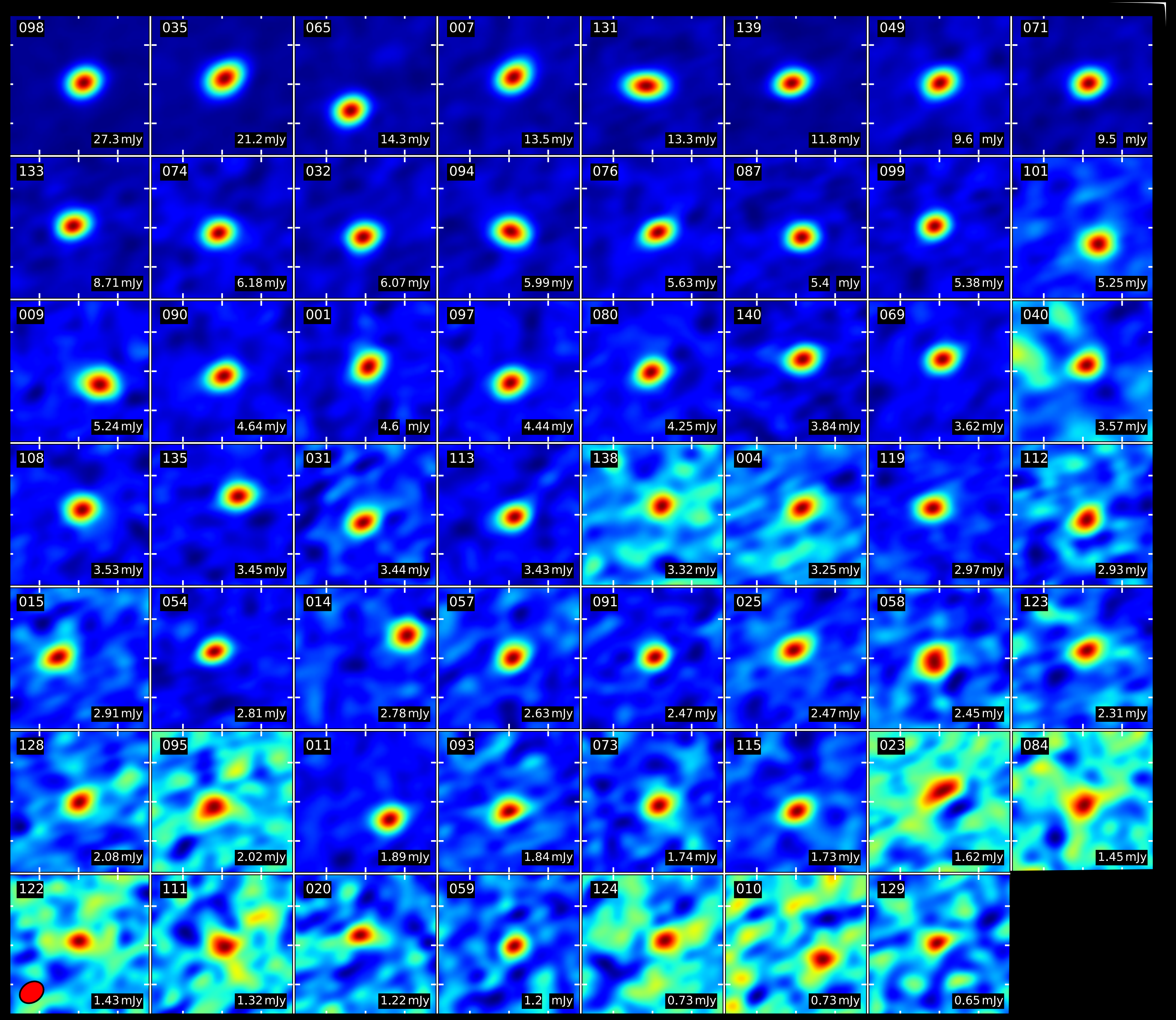


+ Roman Space Telescope (~ 2026) : coronographic contrast < 10^{-7}

4. Solar systems analogues are common, but we cannot resolve them yet

ARE GAPS AND RINGS TYPICAL?





Cieza+2019: Complete survey of Ophiuchus

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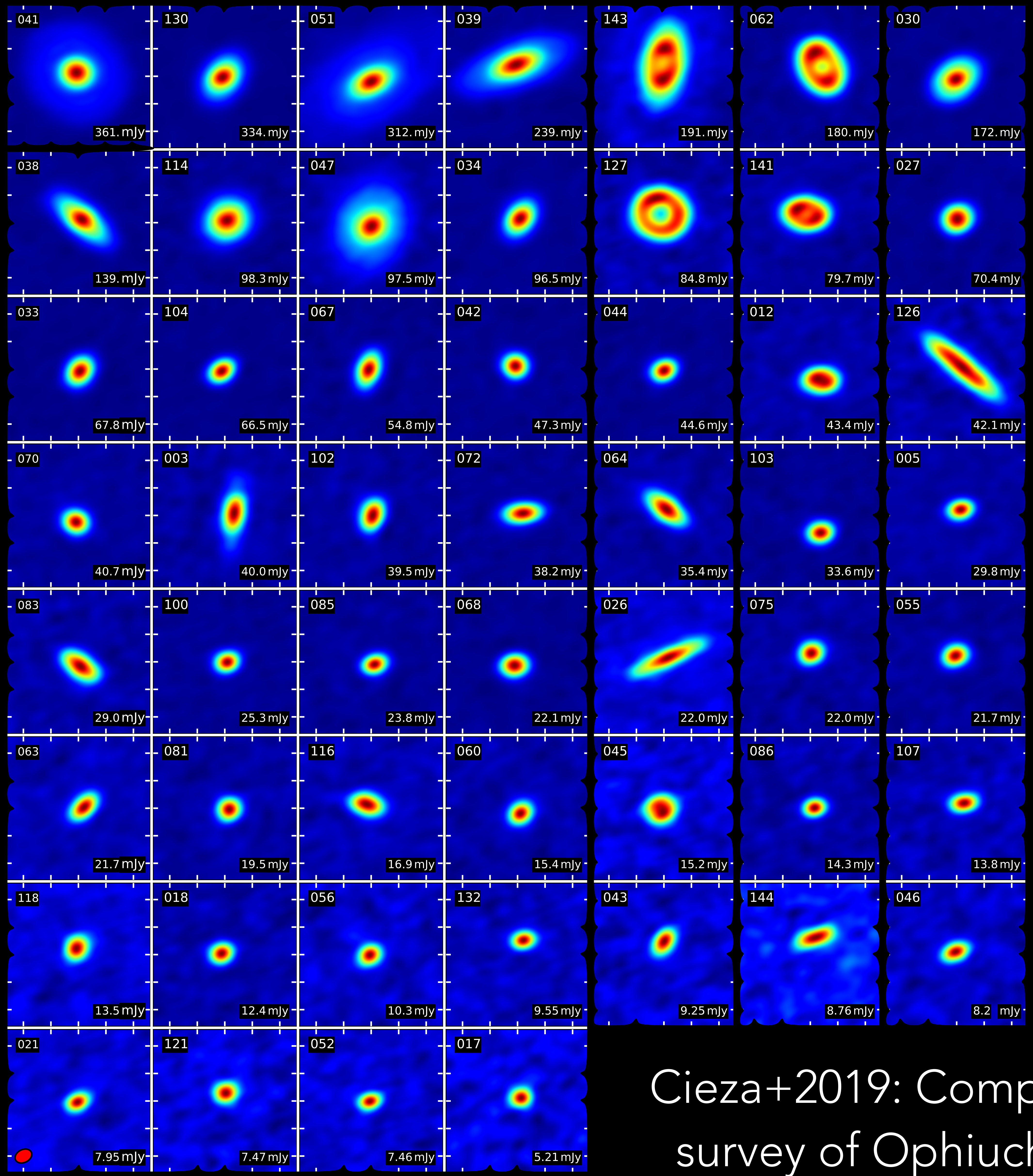
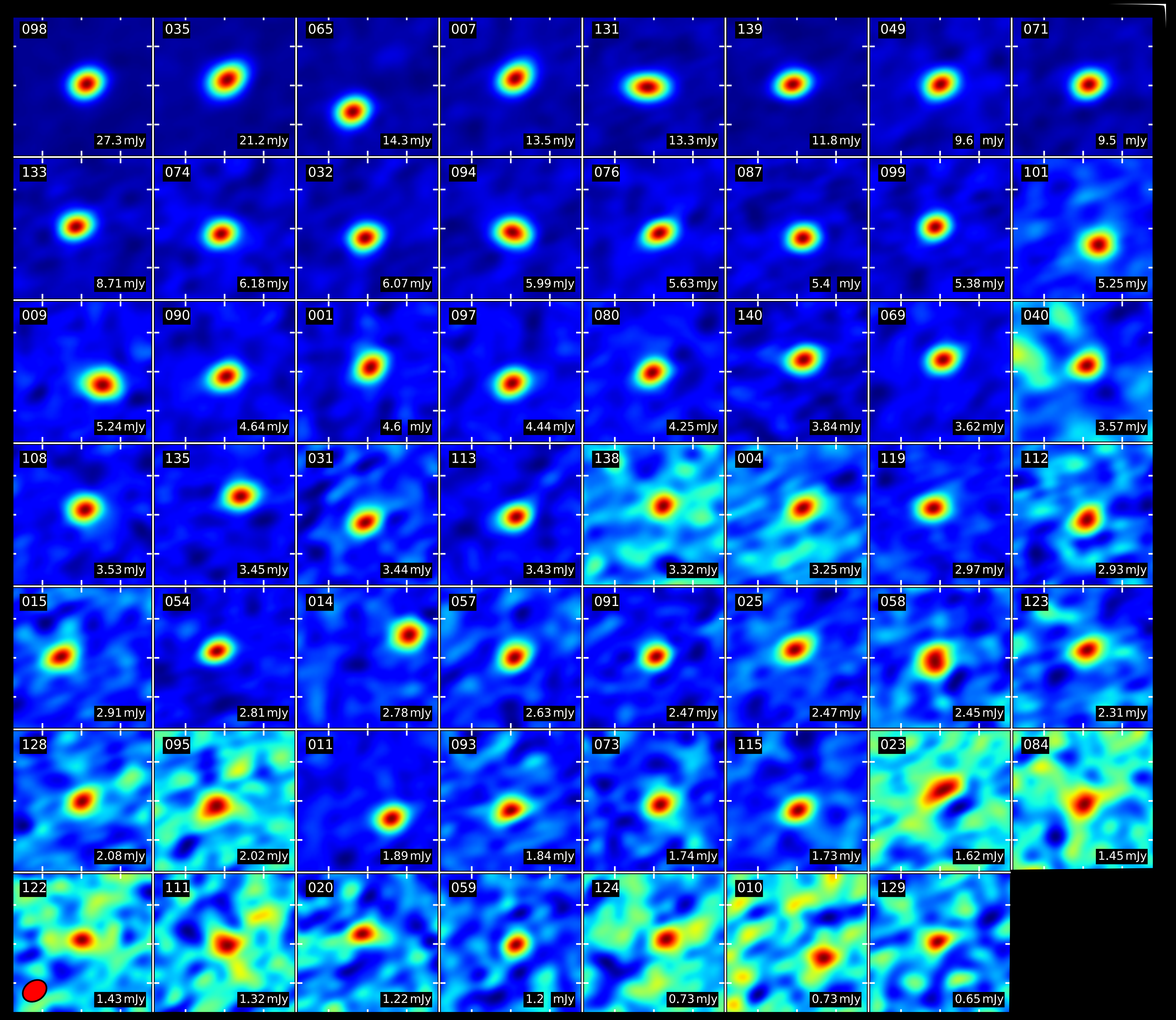


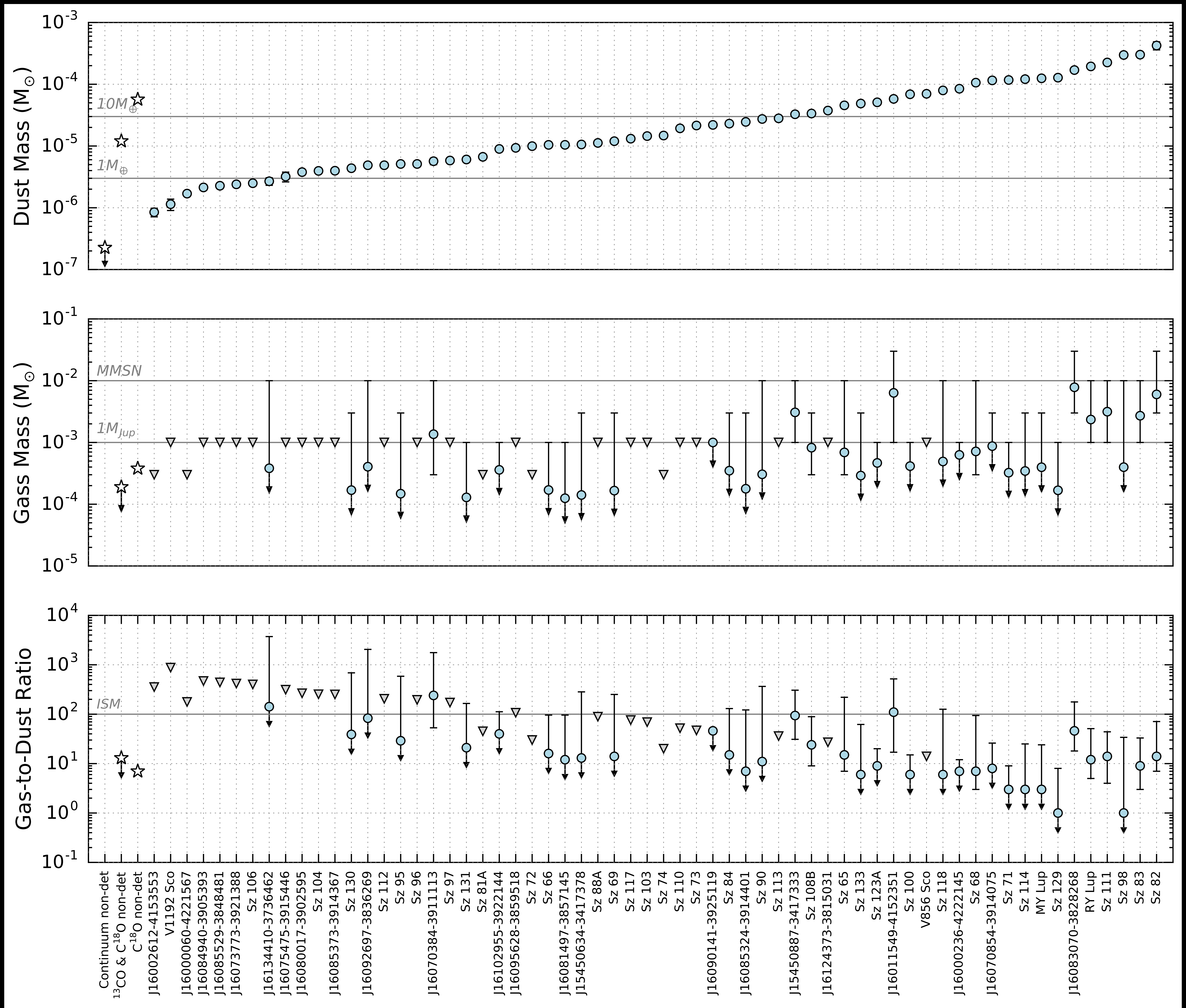
Yes, but lots of compact discs



Cieza+2019: Complete survey of Ophiuchus

5. Planet formation must be rapid (<1 Myr)

There is not enough mass in protoplanetary discs to form planets



Ansdell+2016: ALMA survey of protoplanetary discs in Lupus molecular cloud

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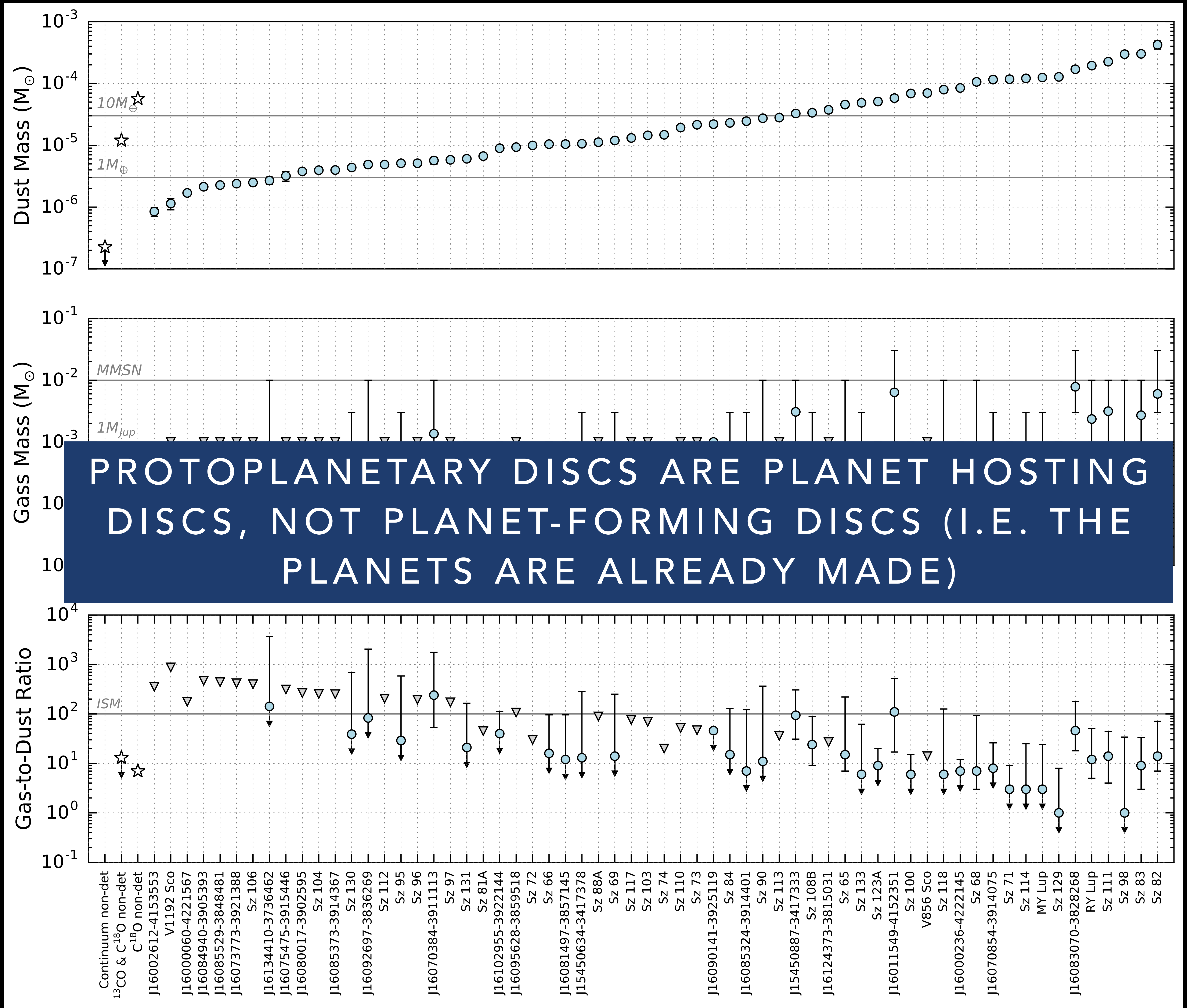
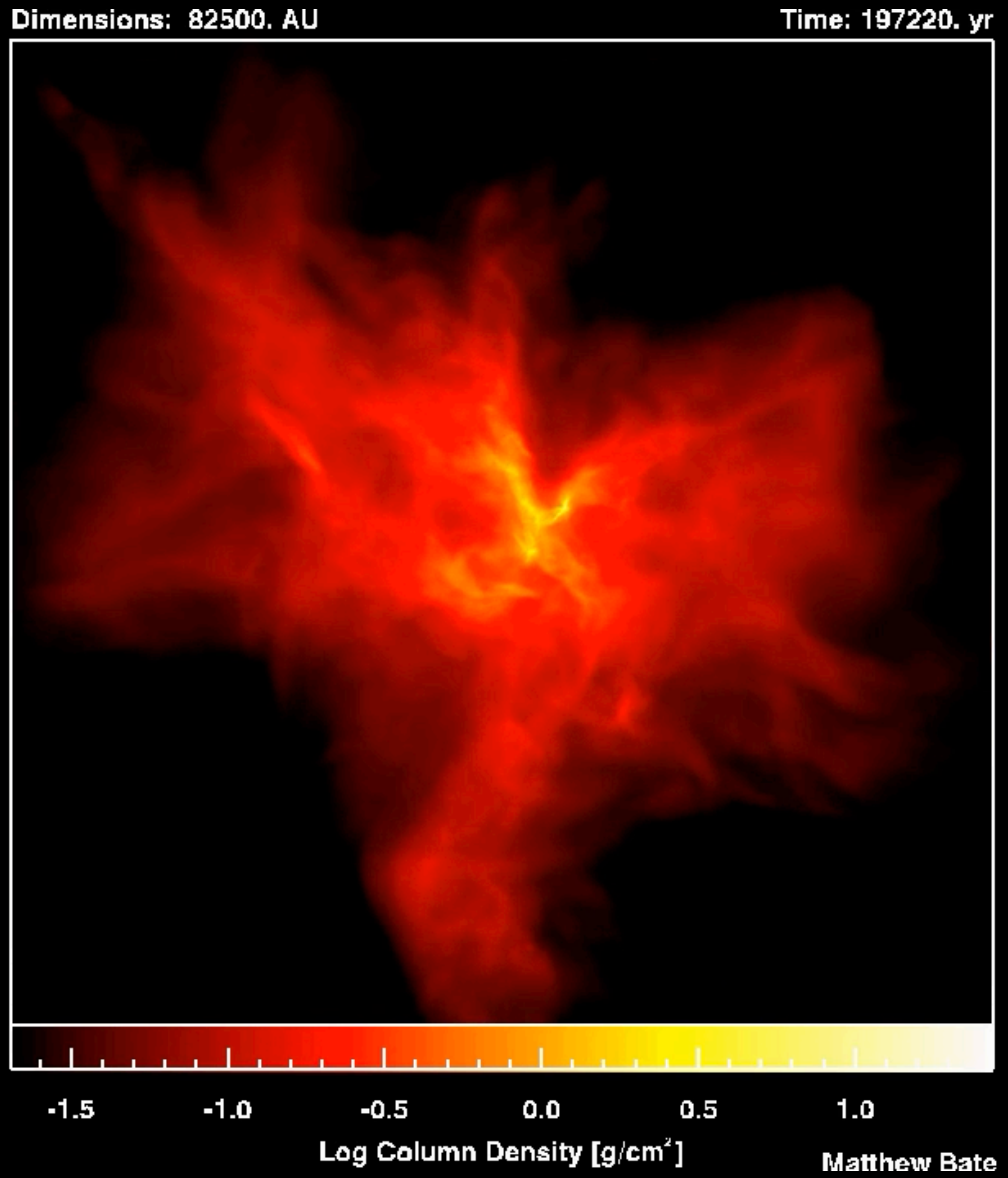


PROTOPLANETARY DISCS ARE PLANET HOSTING DISCS, NOT PLANET-FORMING DISCS (I.E. THE PLANETS ARE ALREADY MADE)

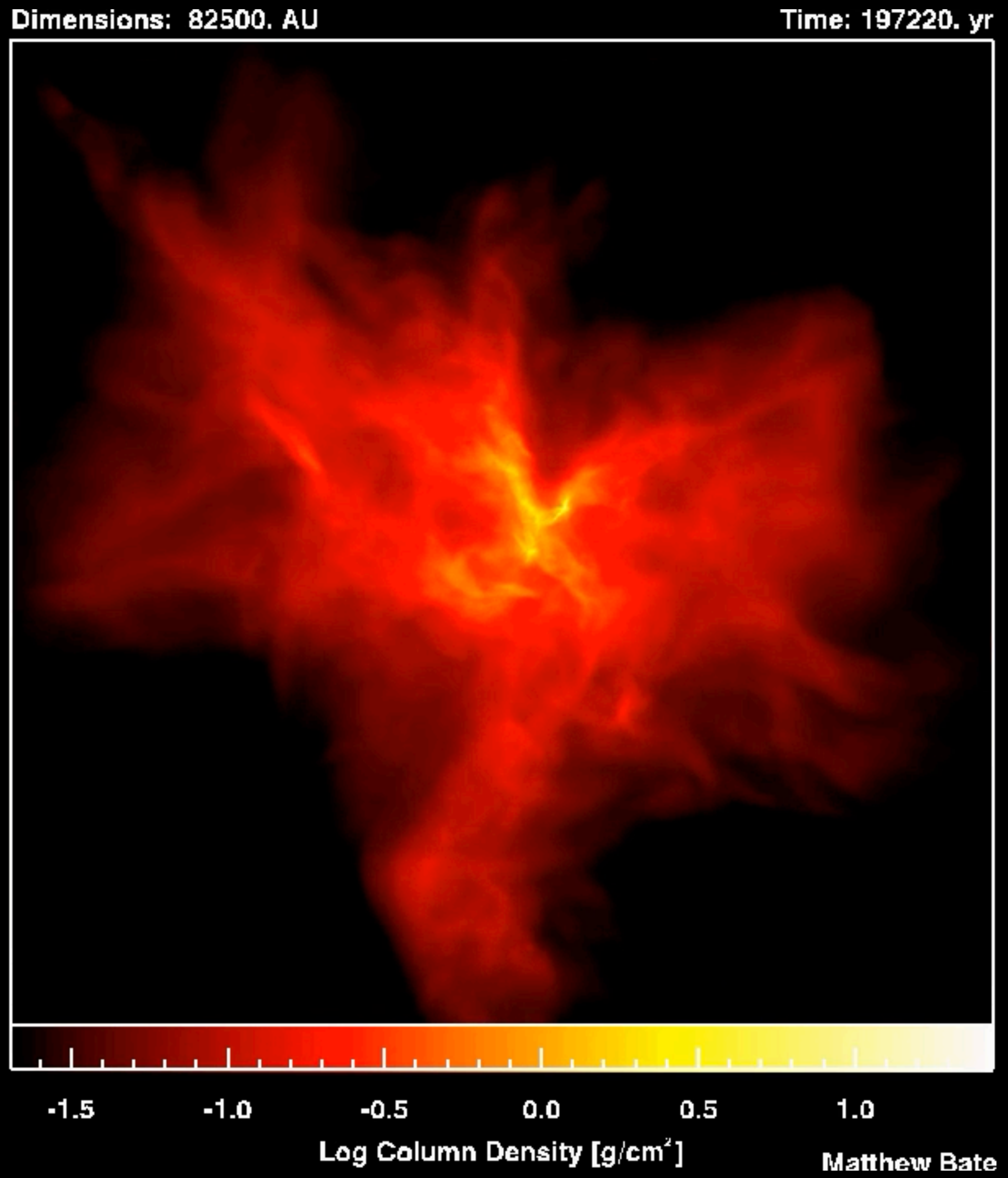
Ansdell+2016: ALMA survey of protoplanetary discs in Lupus molecular cloud

6. Planet formation occurs in a dynamic environment

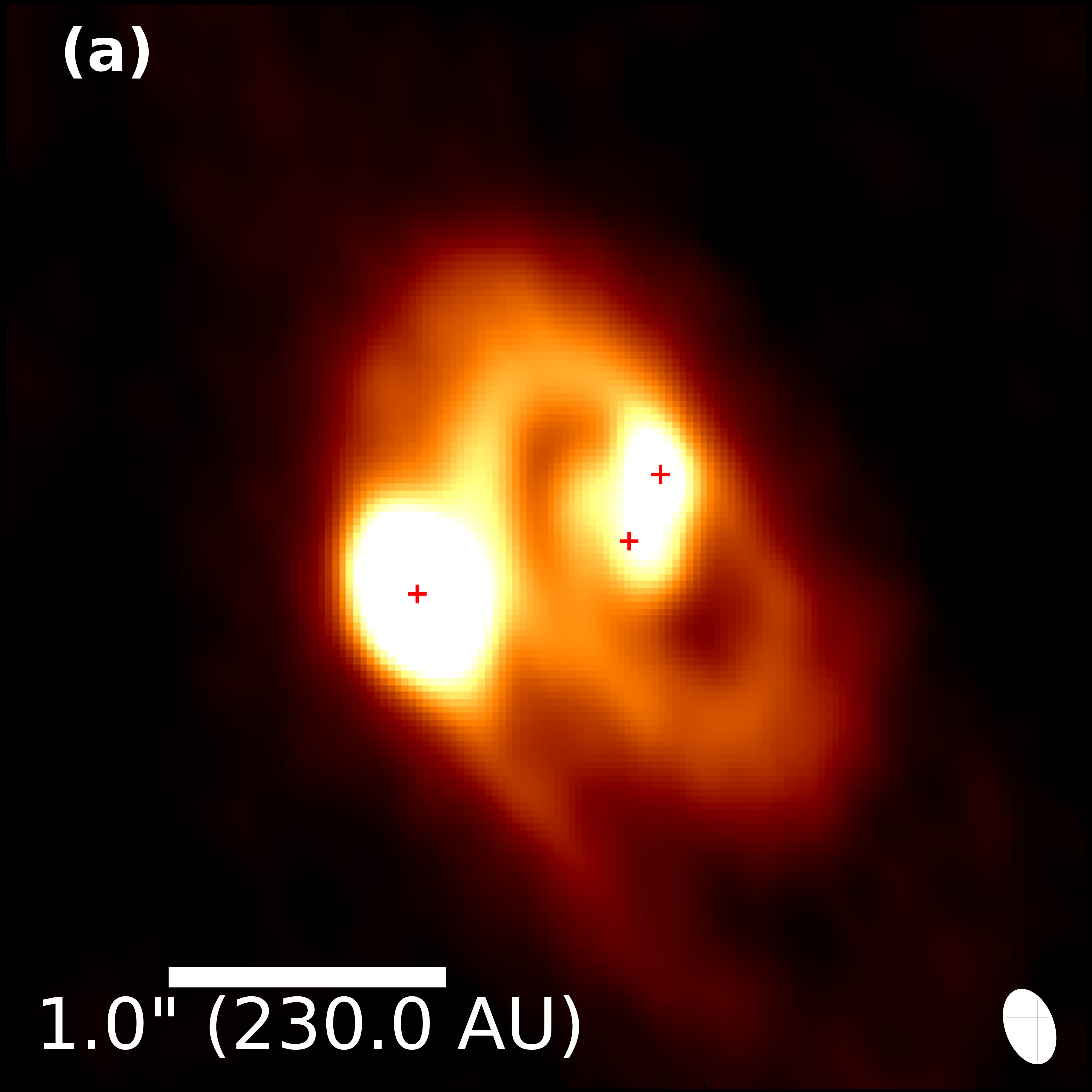
Our understanding of star formation



Our understanding of star formation

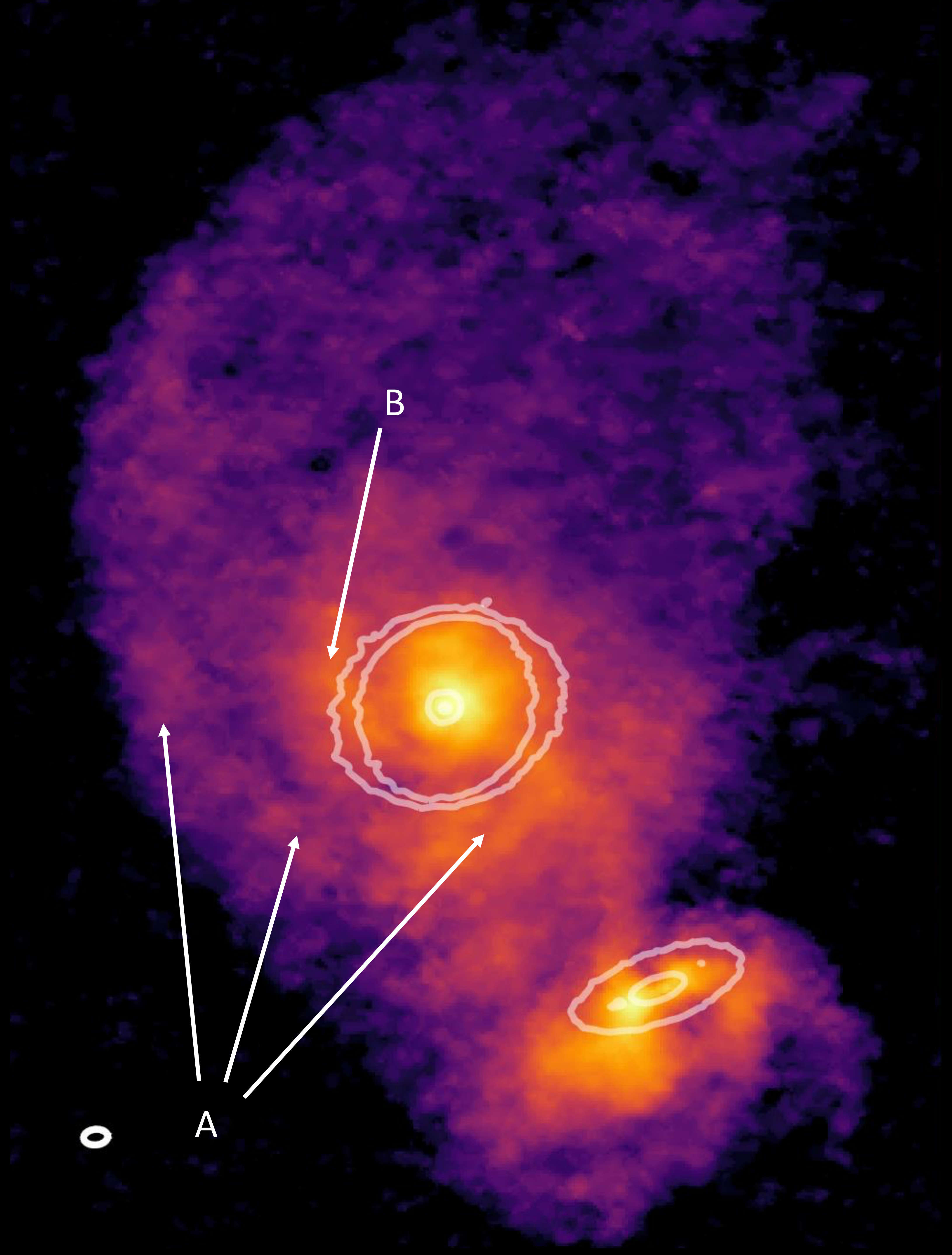


i.e. planet formation happens during this…



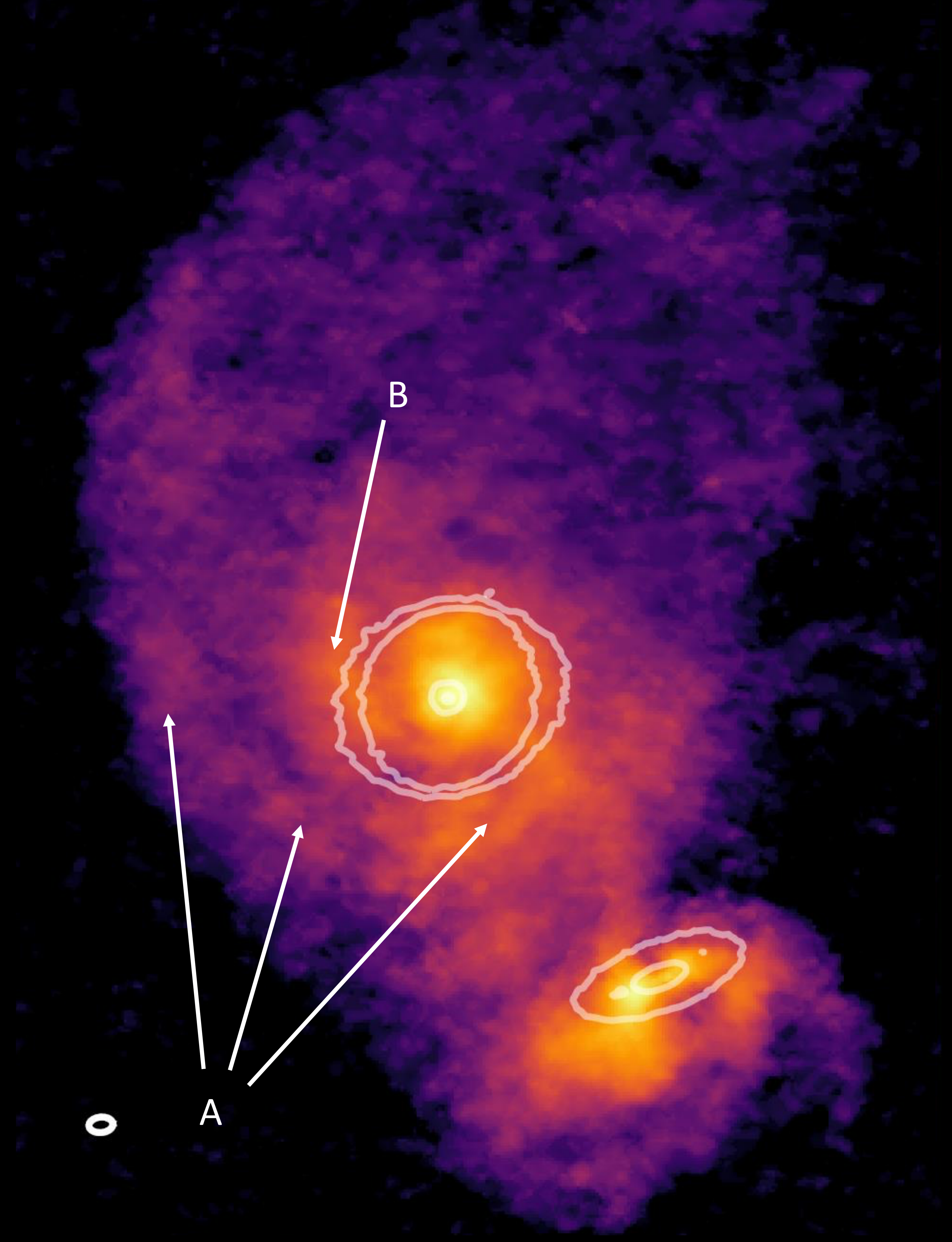
ALMA image of protostellar disc in L1448 IRS3B
(Tobin et al. 2016)

STELLAR FLYBYS



AS205 in CO with ALMA
Kurtovic et al. (2018)

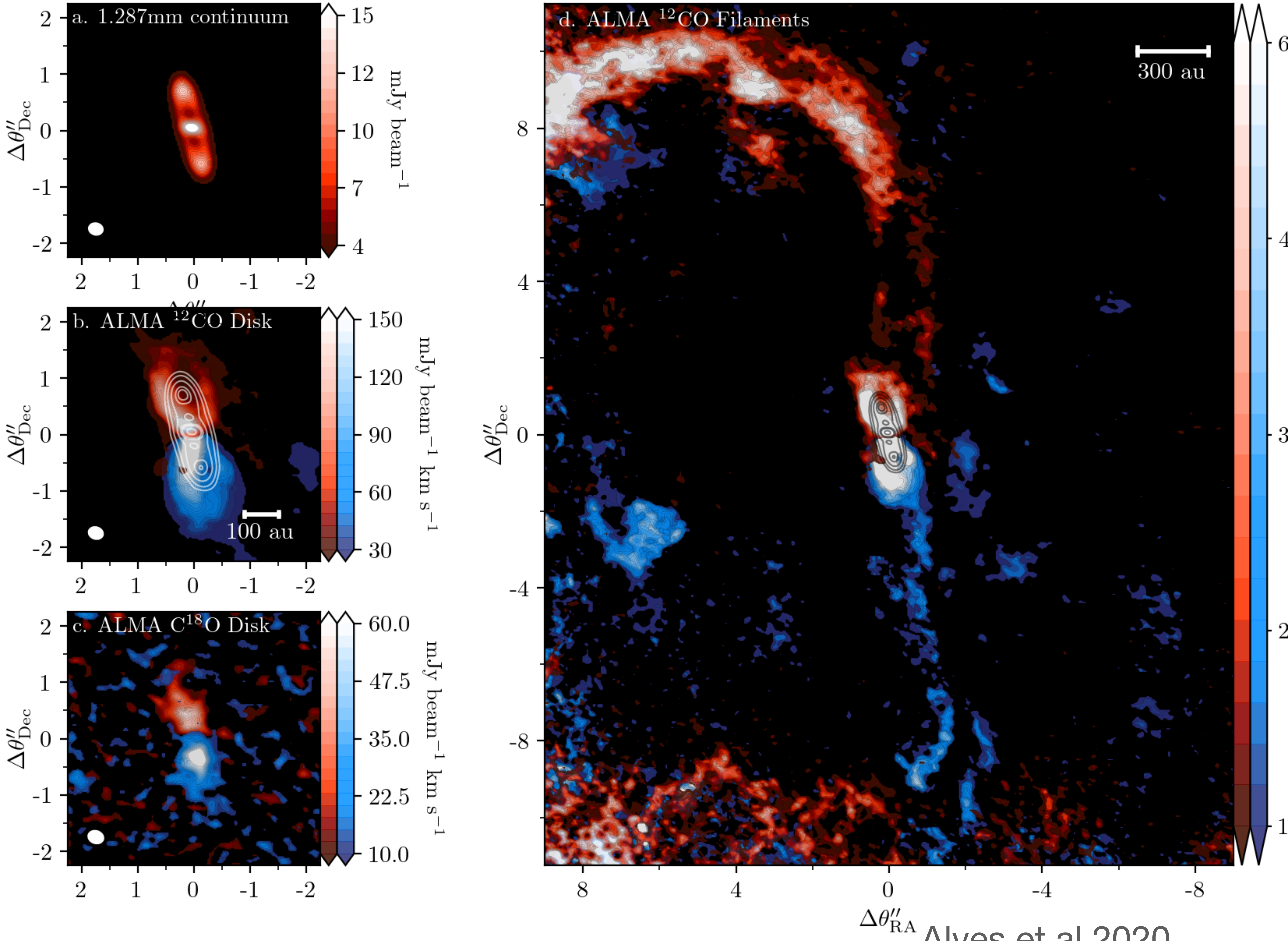
STELLAR FLYBYS



AS205 in CO with ALMA
Kurtovic et al. (2018)

Was the outer solar system shaped by a stellar flyby?
(Pfalzner et al. 2018)

Large scale infall



Alves et al 2020

Concluding remarks

- Direct imaging of protoplanets yield a few stunning detections, and candidates to follow-up.
So far probing tip of the iceberg. Exciting discovery space ahead of us.

- Planet formation is rapid and occurs in a dynamic environment, while the disc is massive

- ALMA can also detect the kinematic signatures of embedded planets.

- At least some of the cavities and gaps are carved by planets.

- Simultaneous detection in imaging + kinematics:
will provide luminosity + mass of planets, as pathway to constrain entropy and distinguish between planet formation scenarii