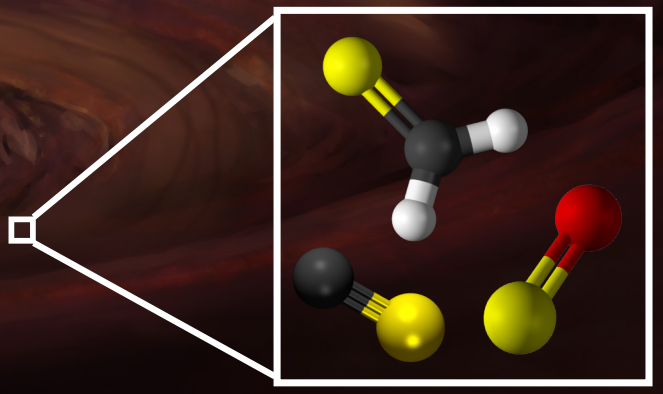
Sulfur Chemistry in Protoplanetary Disks as a Window into Planet Formation



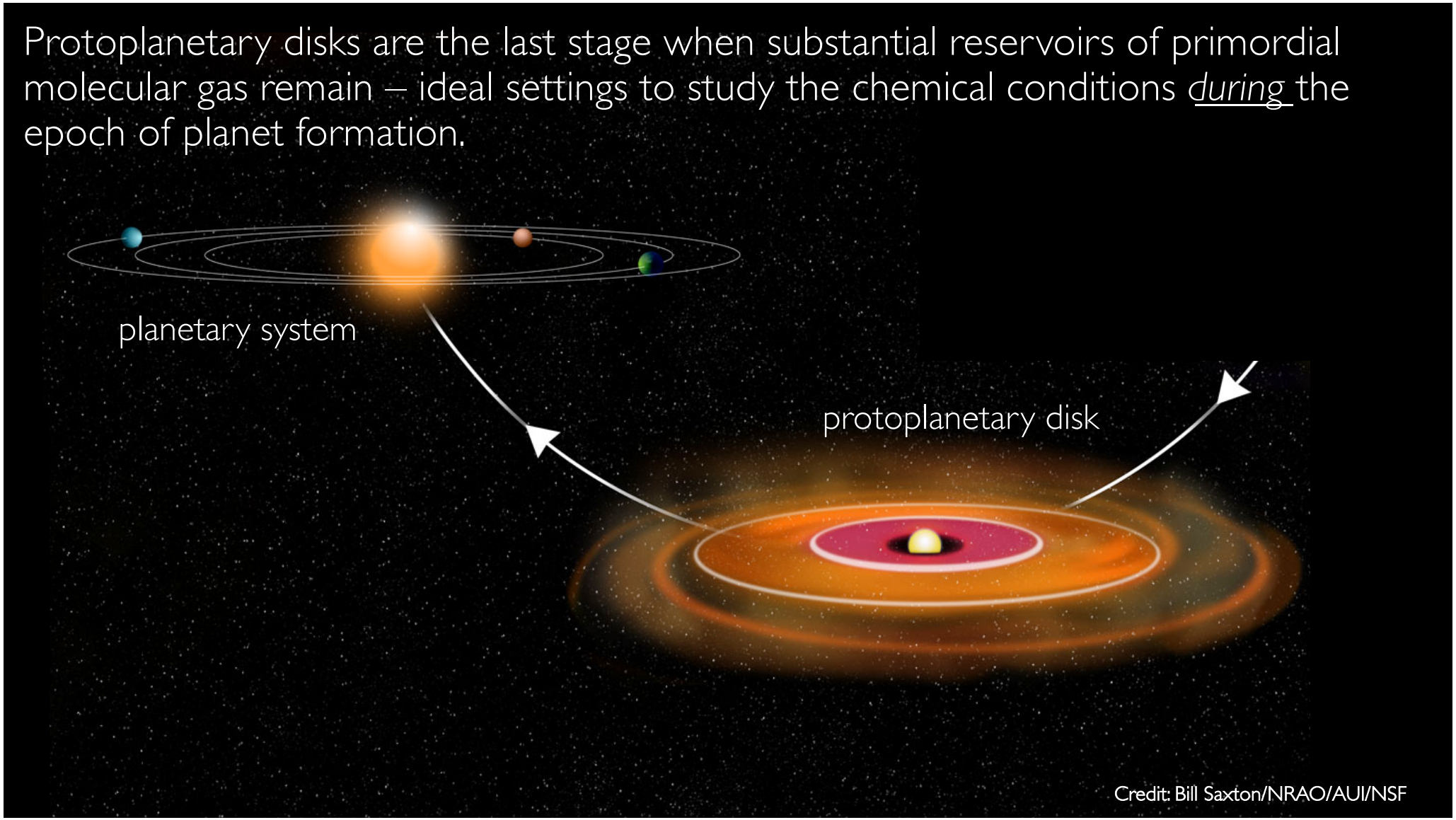
Charles J. Law

(Sagan Fellow, University of Virginia)

Collaborators: Romane Le Gal, Tomohiro Yoshida, Yoshihide Yamato, Viviana Guzmán, Ke Zhang, Alice Booth, Greta Guidi, Ilse Cleeves, Claudio Hernández-Vera, Hideko Nomura, Richard Teague, Yuhito Shibaike, Kenji Furuya, Takashi Tsukagoshi

NHFP Symposium, Pasadena, CA – September 19, 2024

Protoplanetary disks are the last stage when substantial reservoirs of primordial molecular gas remain – ideal settings to study the chemical conditions *during* the epoch of planet formation.



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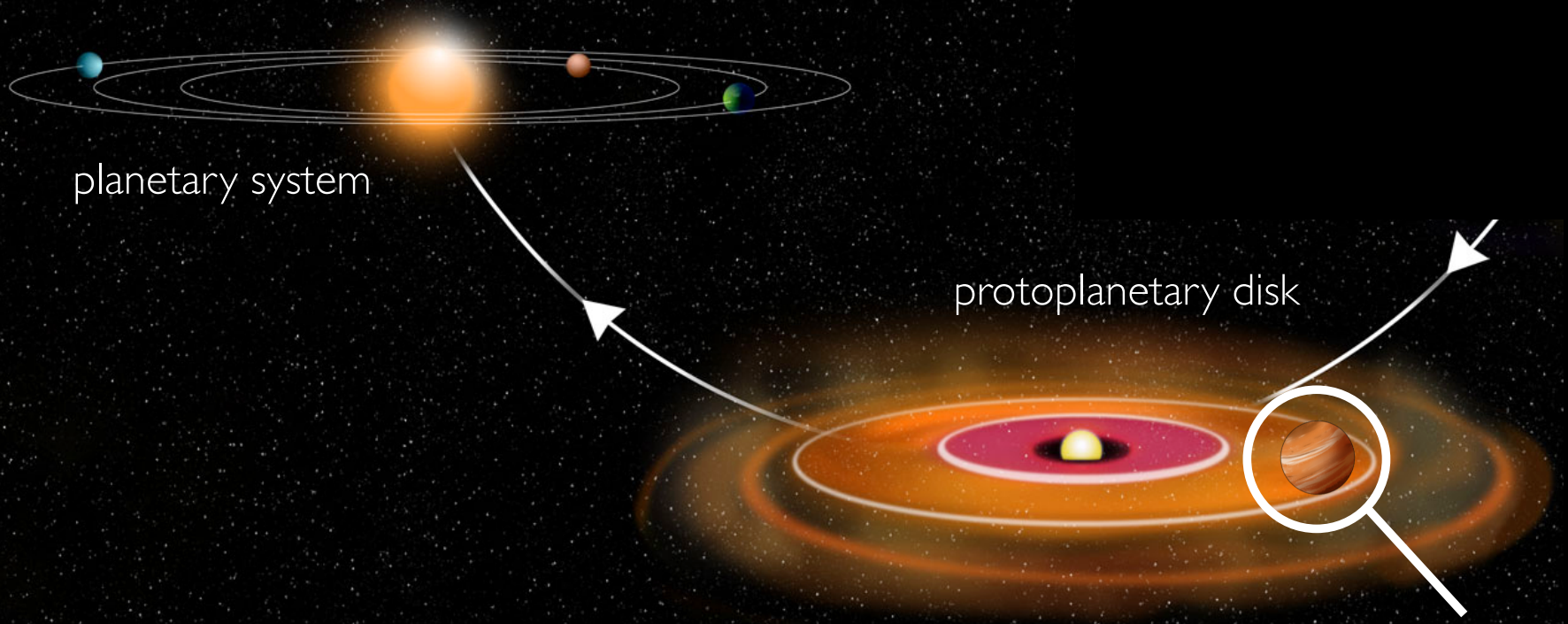
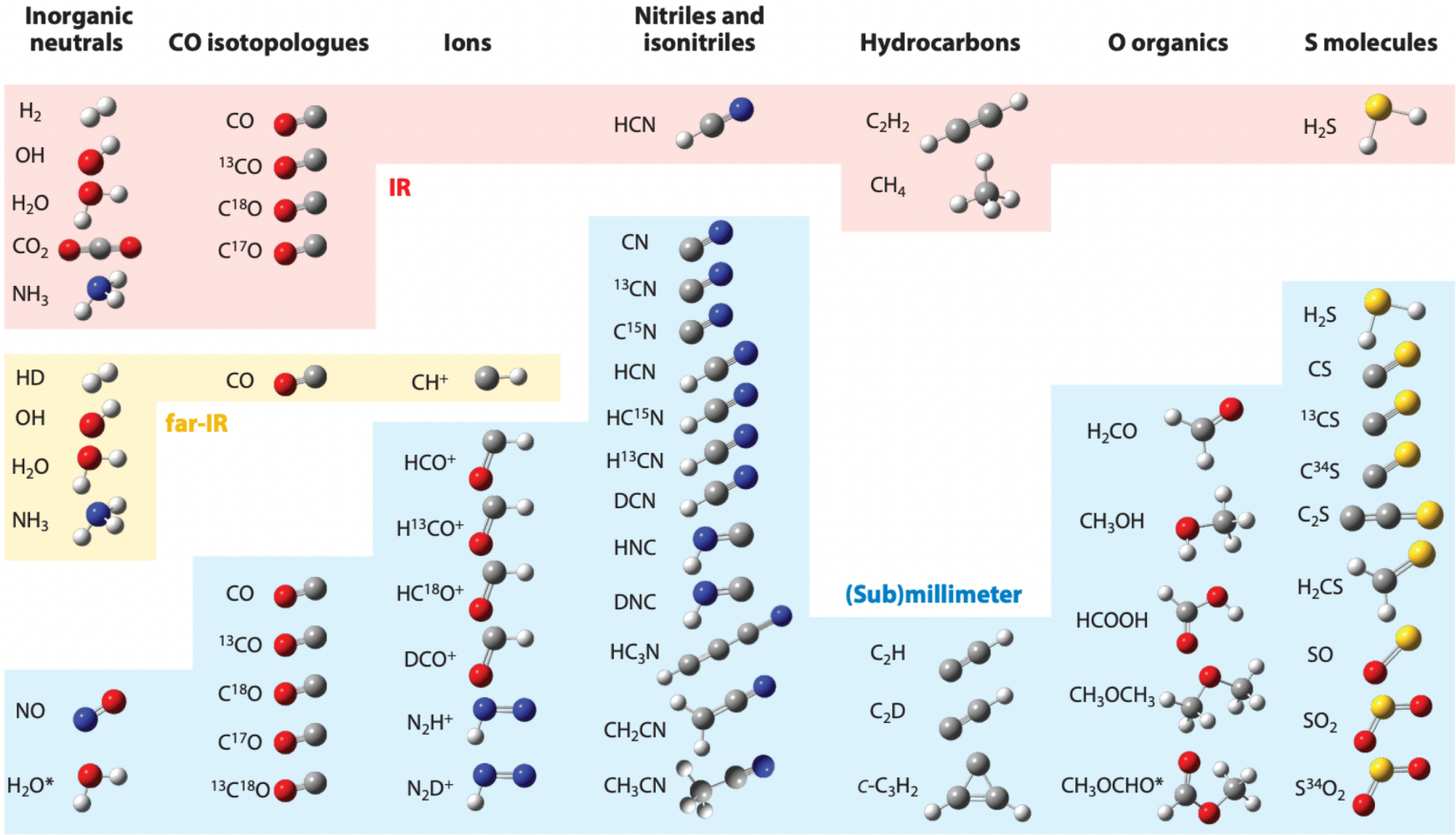


Planet formation is well underway and thus we can directly observe the environments from which planets are actively assembling.

Few sulfur-bearing molecules detected in disks



Öberg+23

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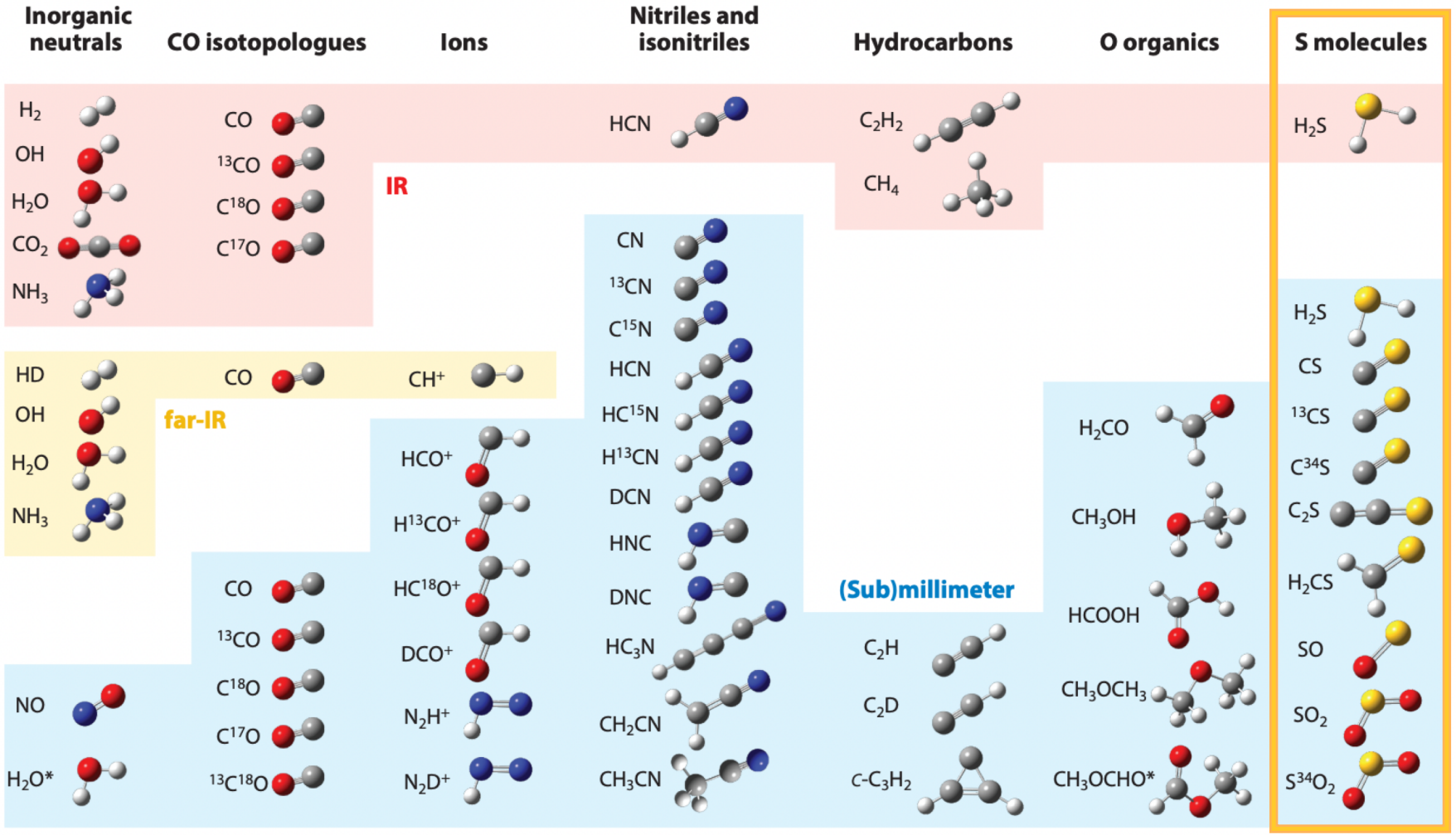

Öberg+23

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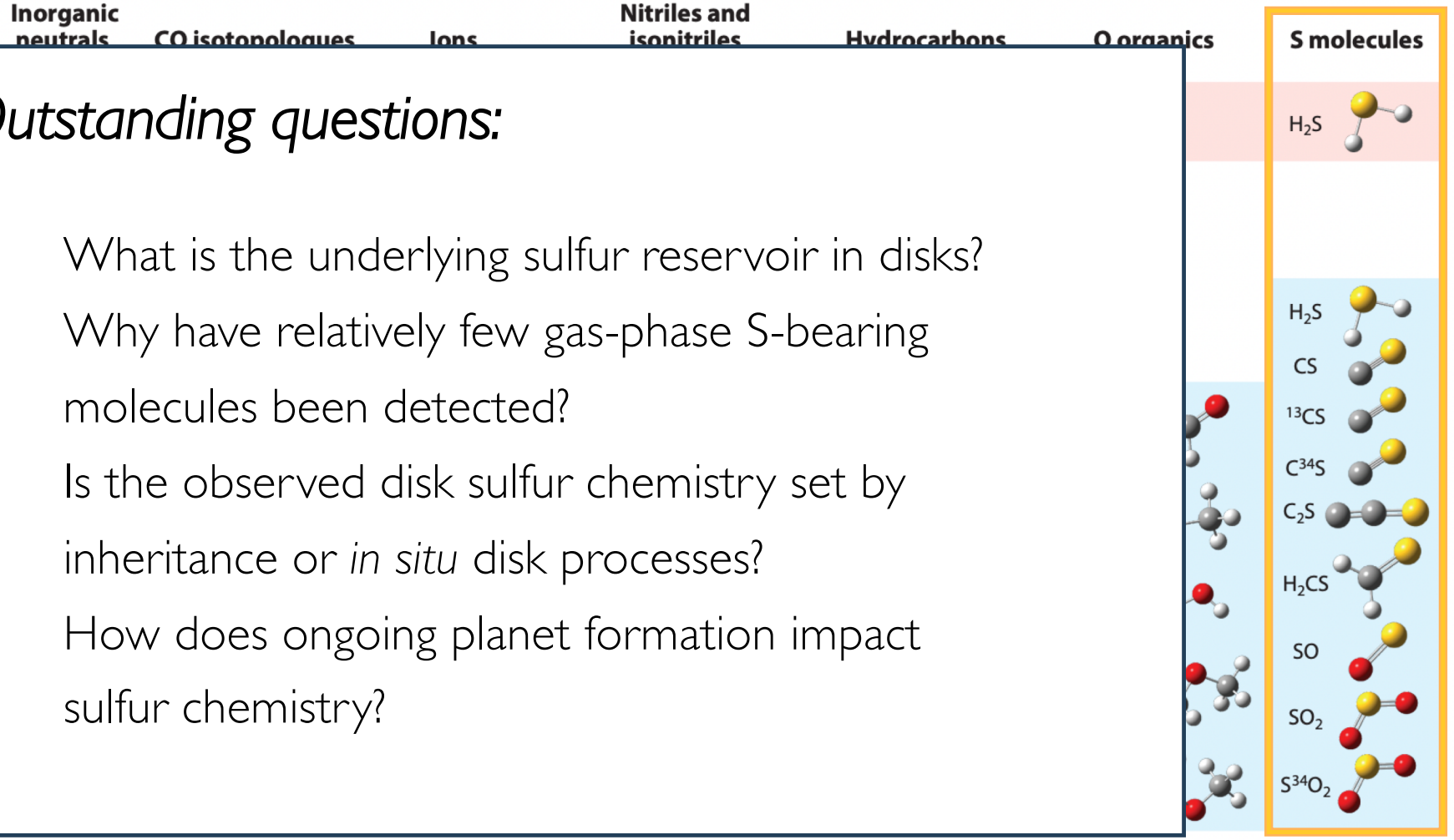
Outstanding questions:

- What is the underlying sulfur reservoir in disks?
- Why have relatively few gas-phase S-bearing molecules been detected?
- Is the observed disk sulfur chemistry set by inheritance or *in situ* disk processes?
- How does ongoing planet formation impact sulfur chemistry?



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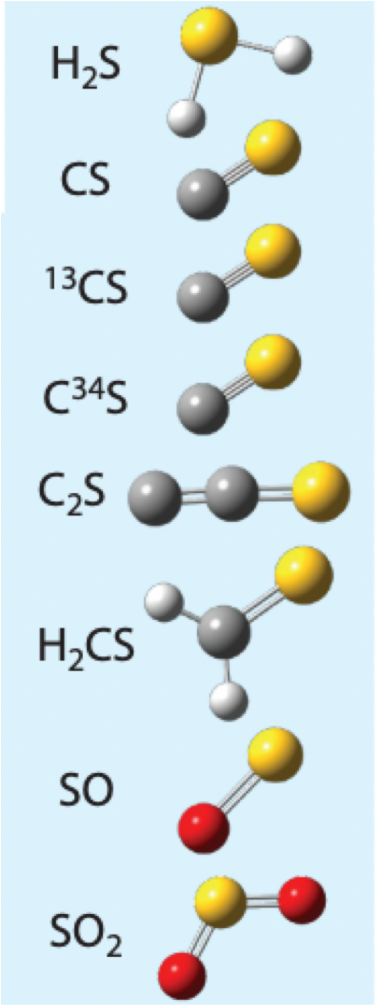

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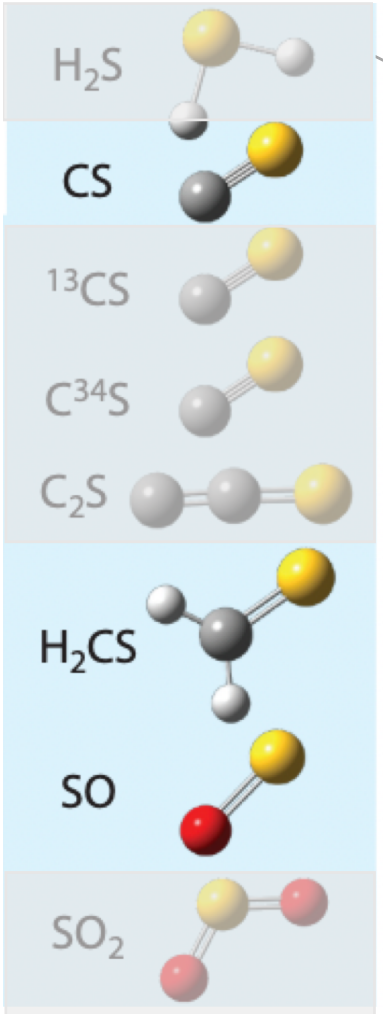
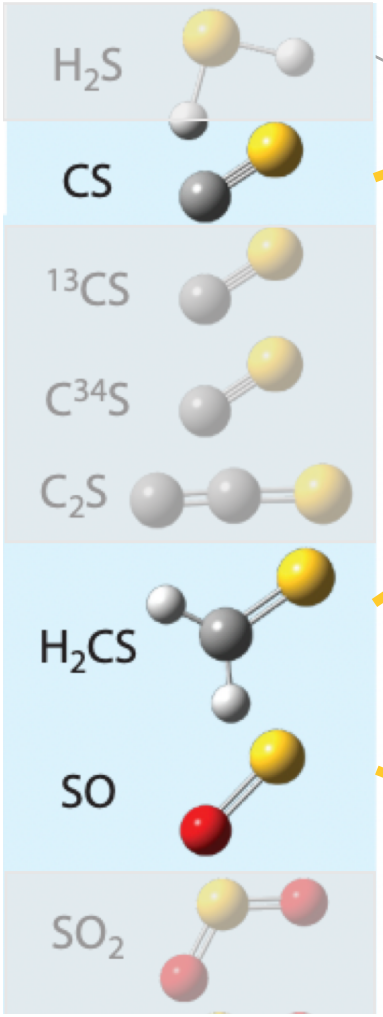


only in two or fewer disks

Few sulfur-bearing molecules detected in disks



Simplest S-bearing species and commonly detected

Detected in a handful of disks and show unexpectedly high abundances

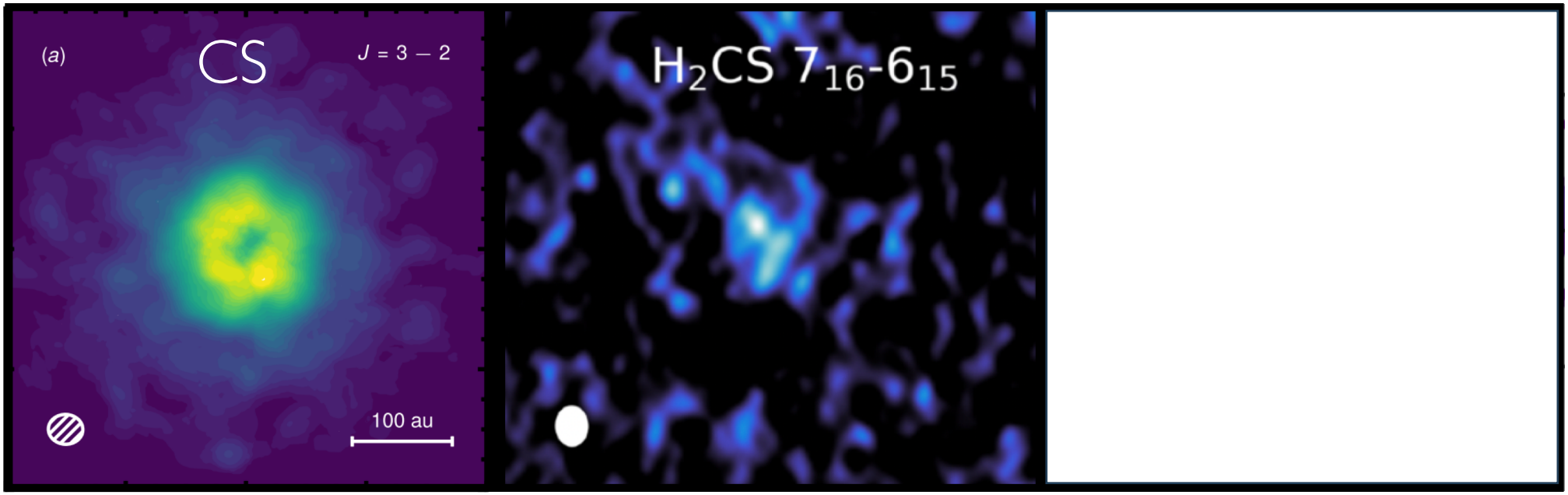
Oxygenated species in young disks with accretion, large-scale structures, or shocks

Teague+18

Bright but few multi-line observations to study excitation

Teague+18

Le Gal+21



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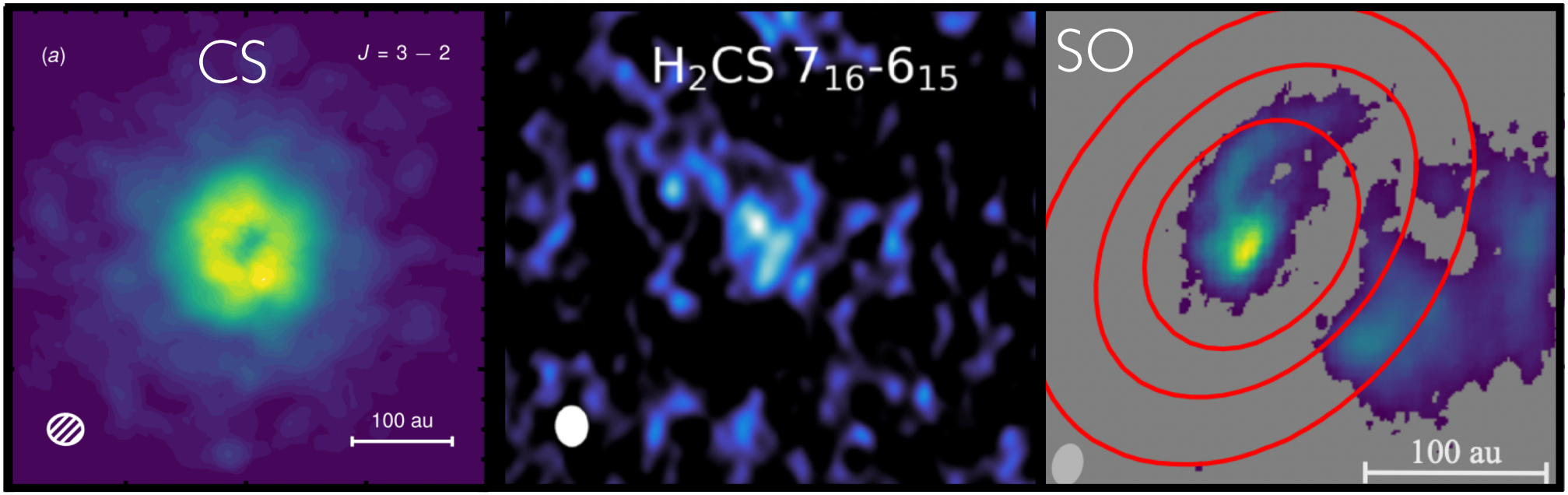
Weaker lines, fewer detections, and not well-spatially resolved

Teague+18 | Le Gal+21 | Garufi+22



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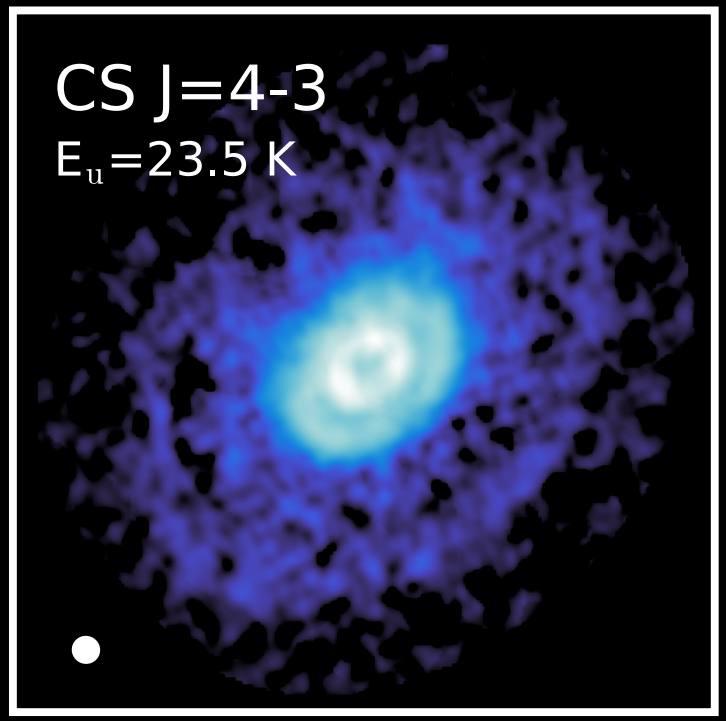
What is SO tracing (hot gas, shocks, outflows)?

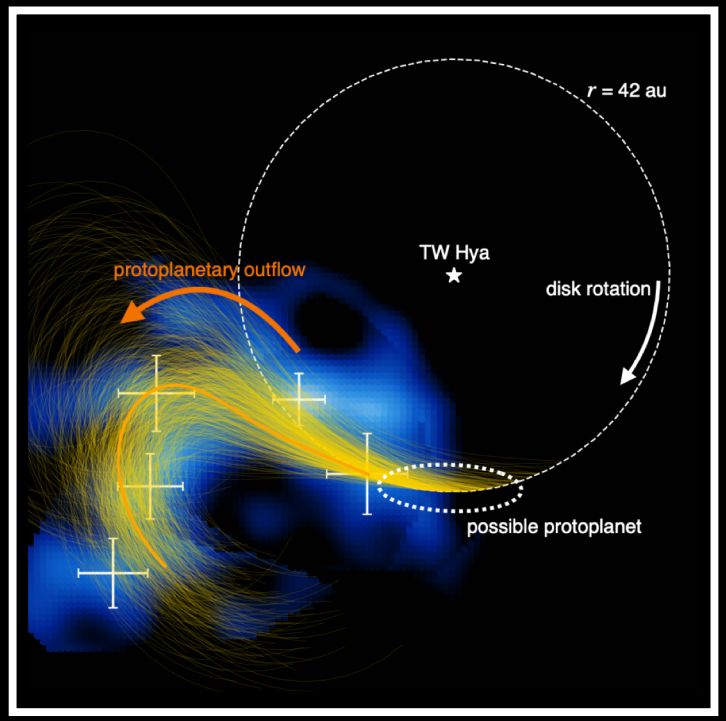
sulfur-bearing molecules provide uniquely powerful window into planet formation

Law+24, in prep.



mapping gas conditions in a planet-hosting disk

Yoshida, Nomura, CJL+24



identifying and characterizing embedded protoplanets

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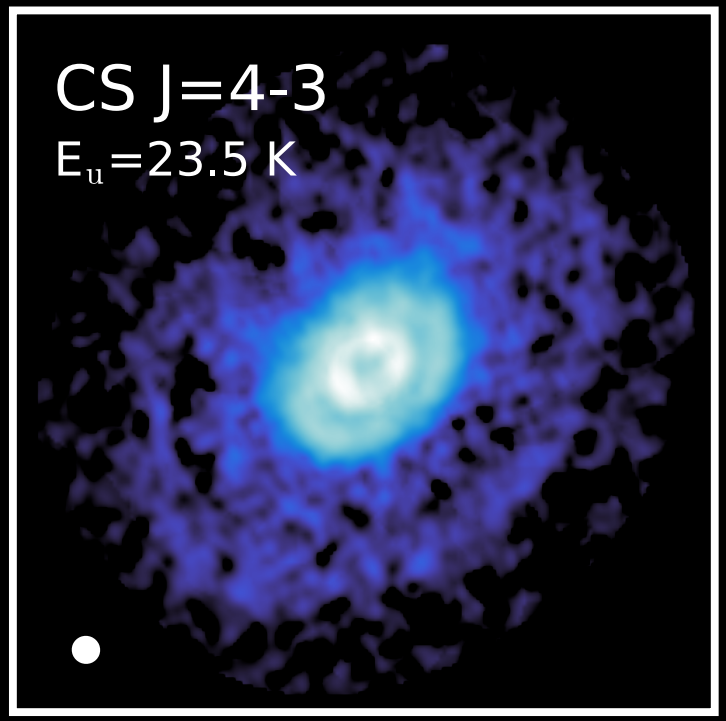

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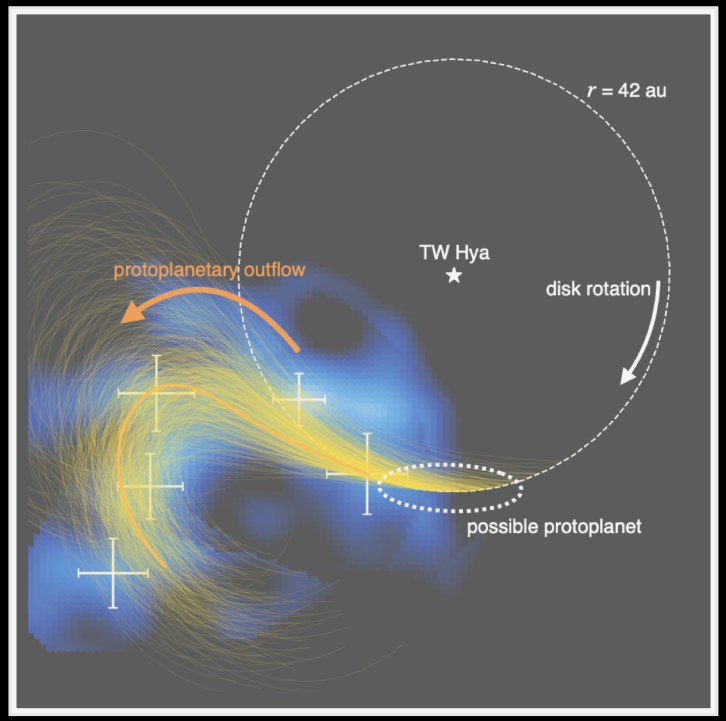
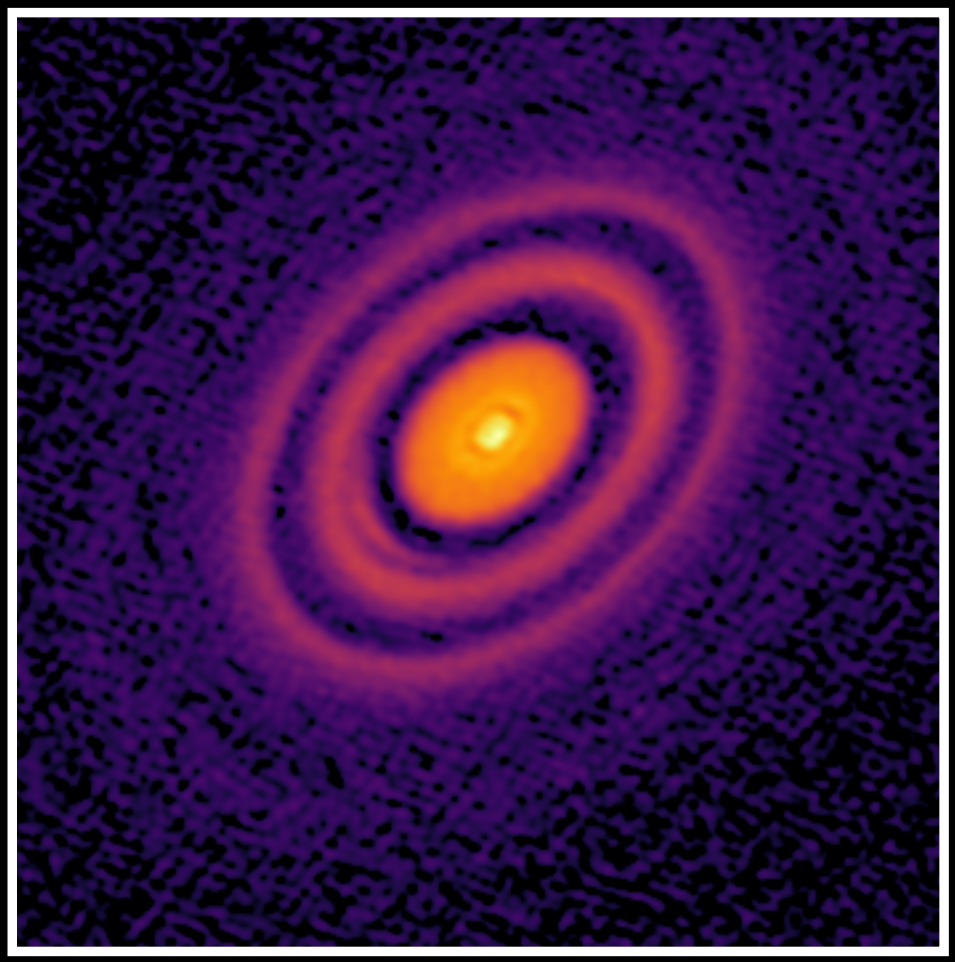


identifying and characterizing embedded protoplanets

The planet-hosting HD 163296 disk

- Nearby *(d = 101 pc)* Herbig star with an inclined disk
  Fairlamb+15, Isella+16
- Bright, gas-rich disk that likely hosts at least one Jupiter-mass planet
  e.g., Teague+18, Pinte+18, Law+21
- Extensively studied, but to date, very little data on sulfur emission
  Le Gal+21
- However, there is a large amount of ALMA and SMA archival data:
  2015.1.00847.S (PI: F. Du), 2015.1.01137.S (PI: T. Tsukagoshi), 2016.1.01086.S (PI: A. Isella), 2016.1.00884.S (PI: V. Guzmán), 2017.1.01682. S (PI: G. Guidi), 2021.1.00535.S (PI: Y. Yamato), 2021.1.00899.S (PI: K. Zhang), 2020A-S018 (PI: R. Le Gal)

mm dust



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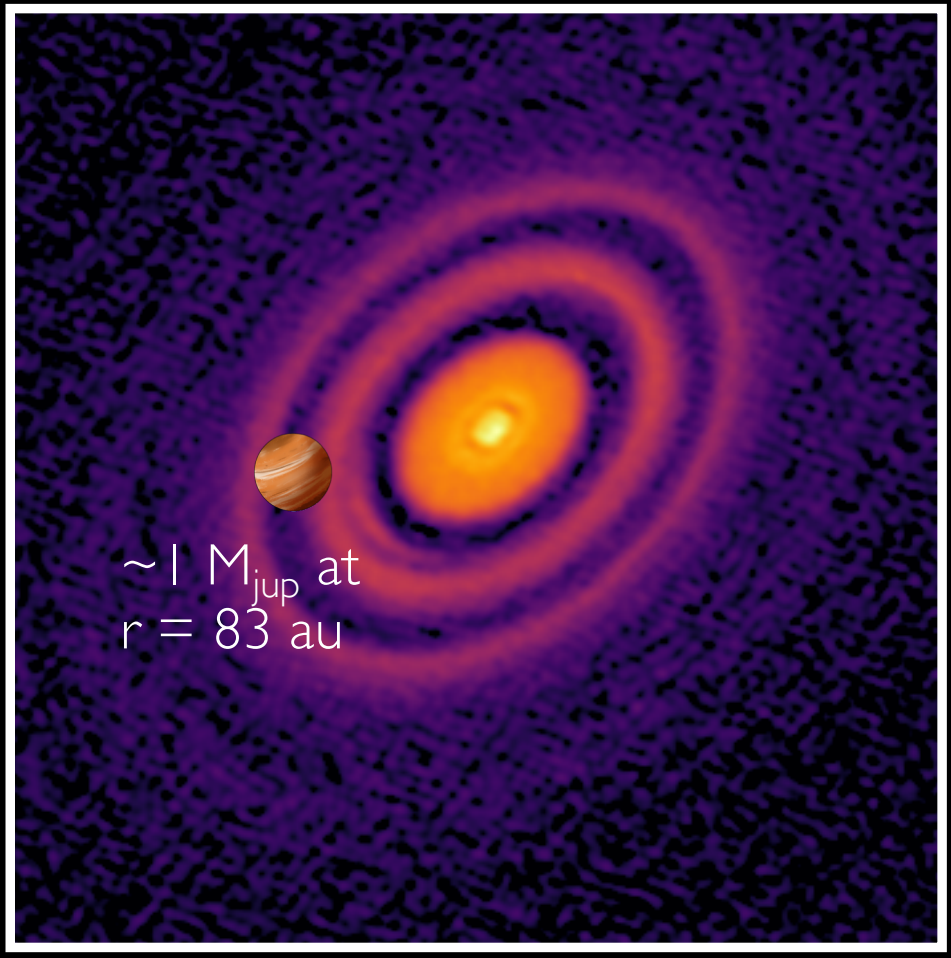

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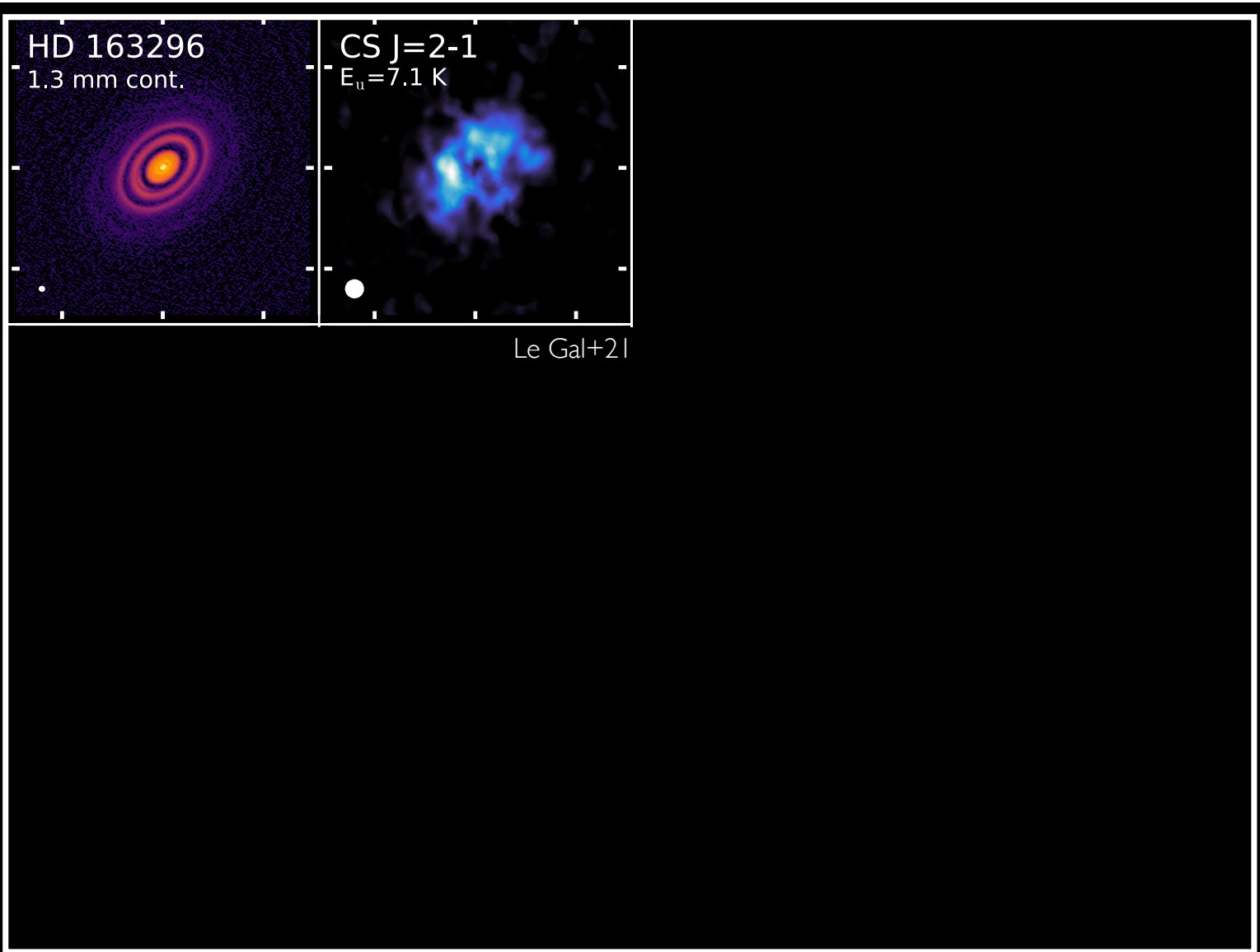
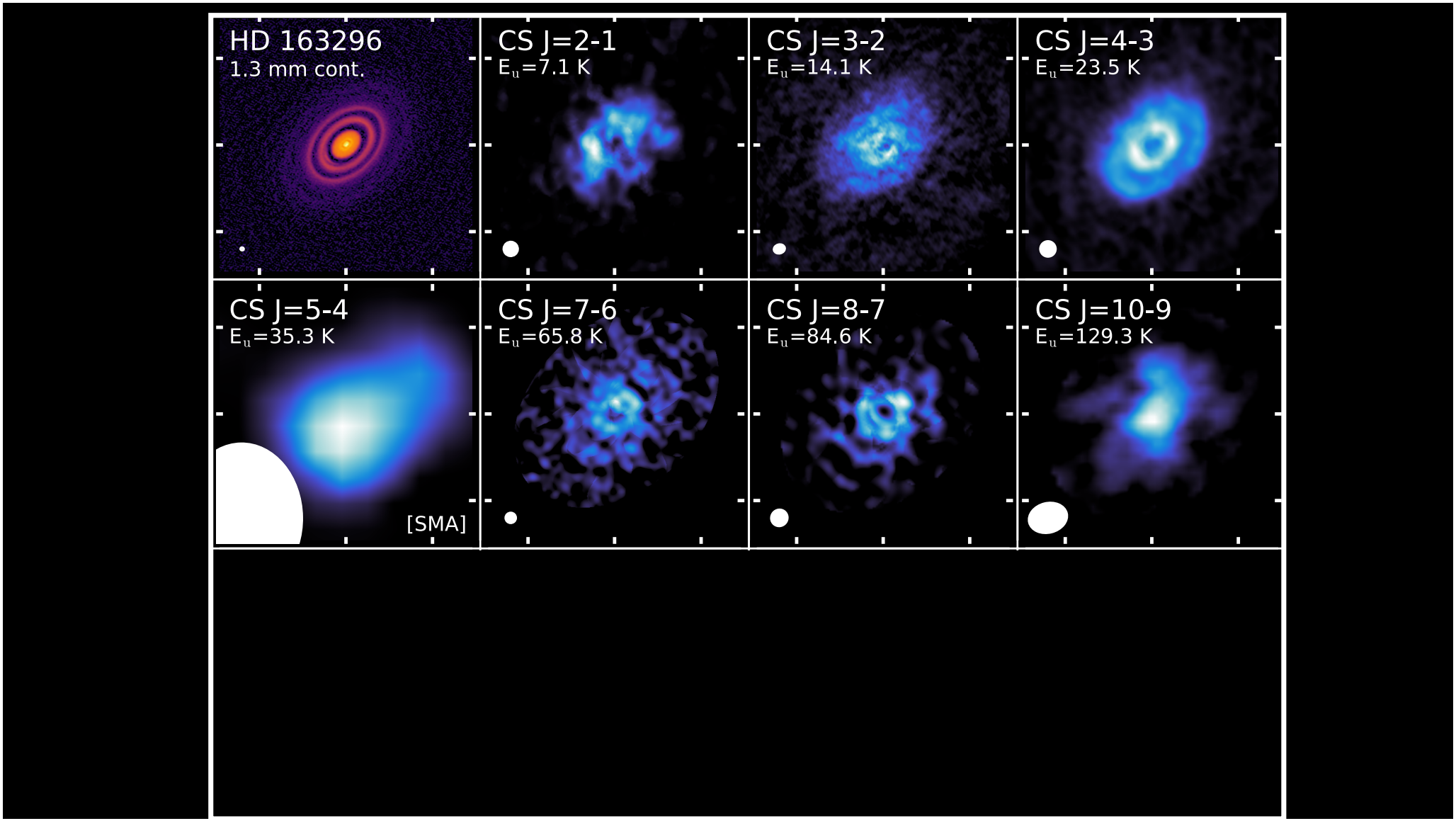

HD 163296
1.3 mm cont.
CS J=2-1
E_u=7.1 K
Le Gal+21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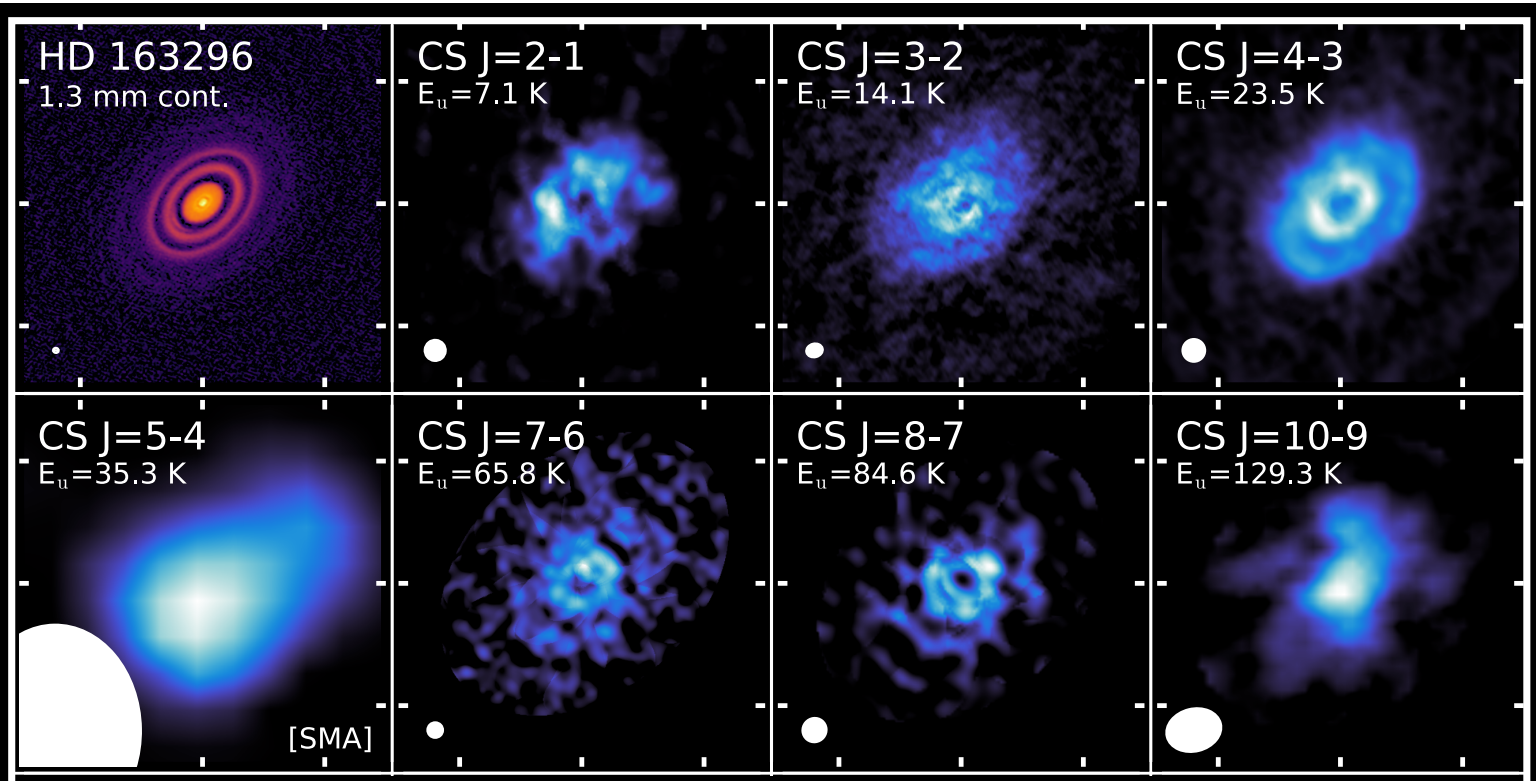
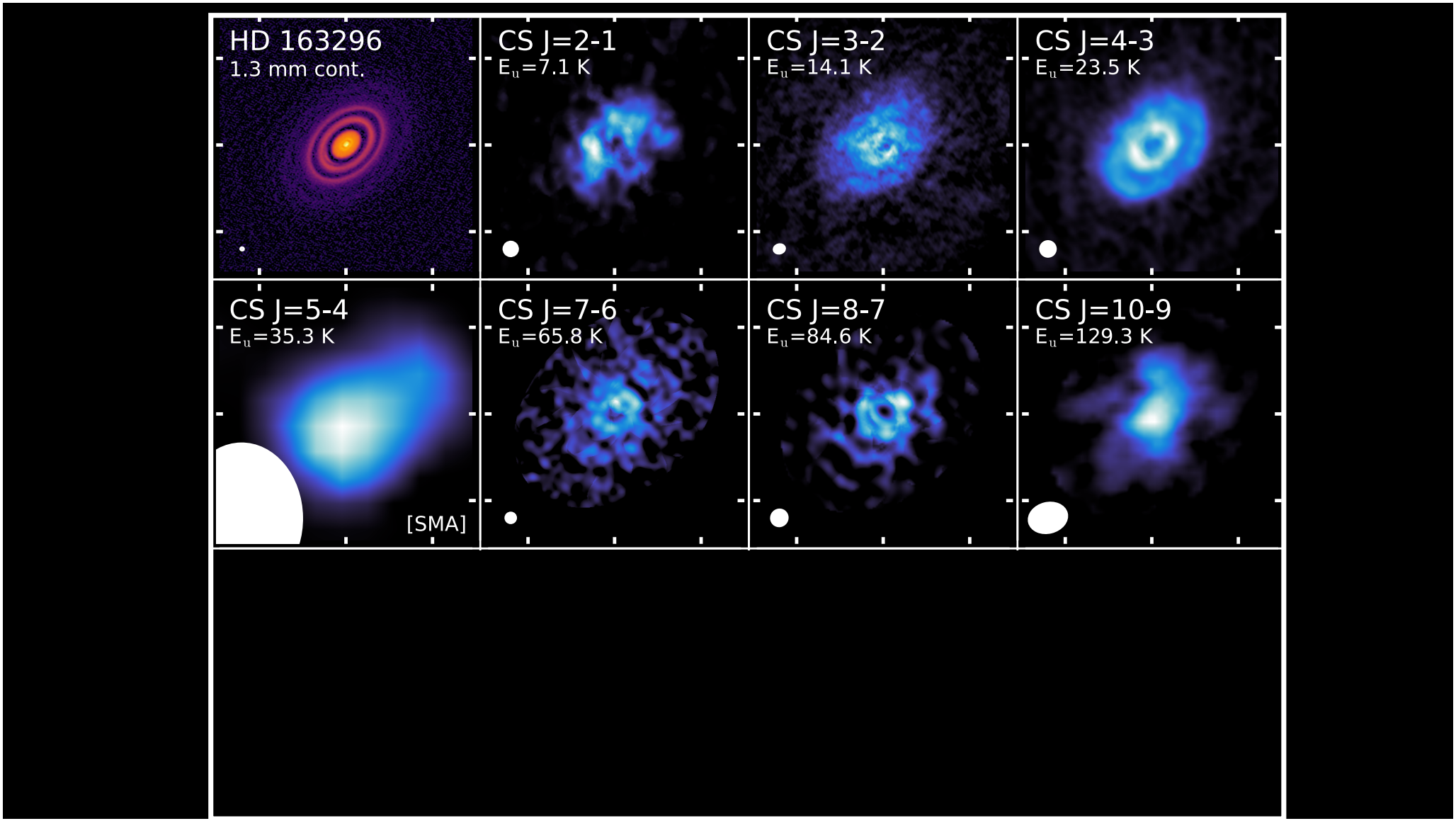
[SMA]
CS J=7-6
E_u=65.8 K
CS J=8-7
E_u=84.6 K
CS J=10-9
E_u=129.3 K



most lines have an angular resolution of
~0.2-0.4 arcsec, or 20-40 au!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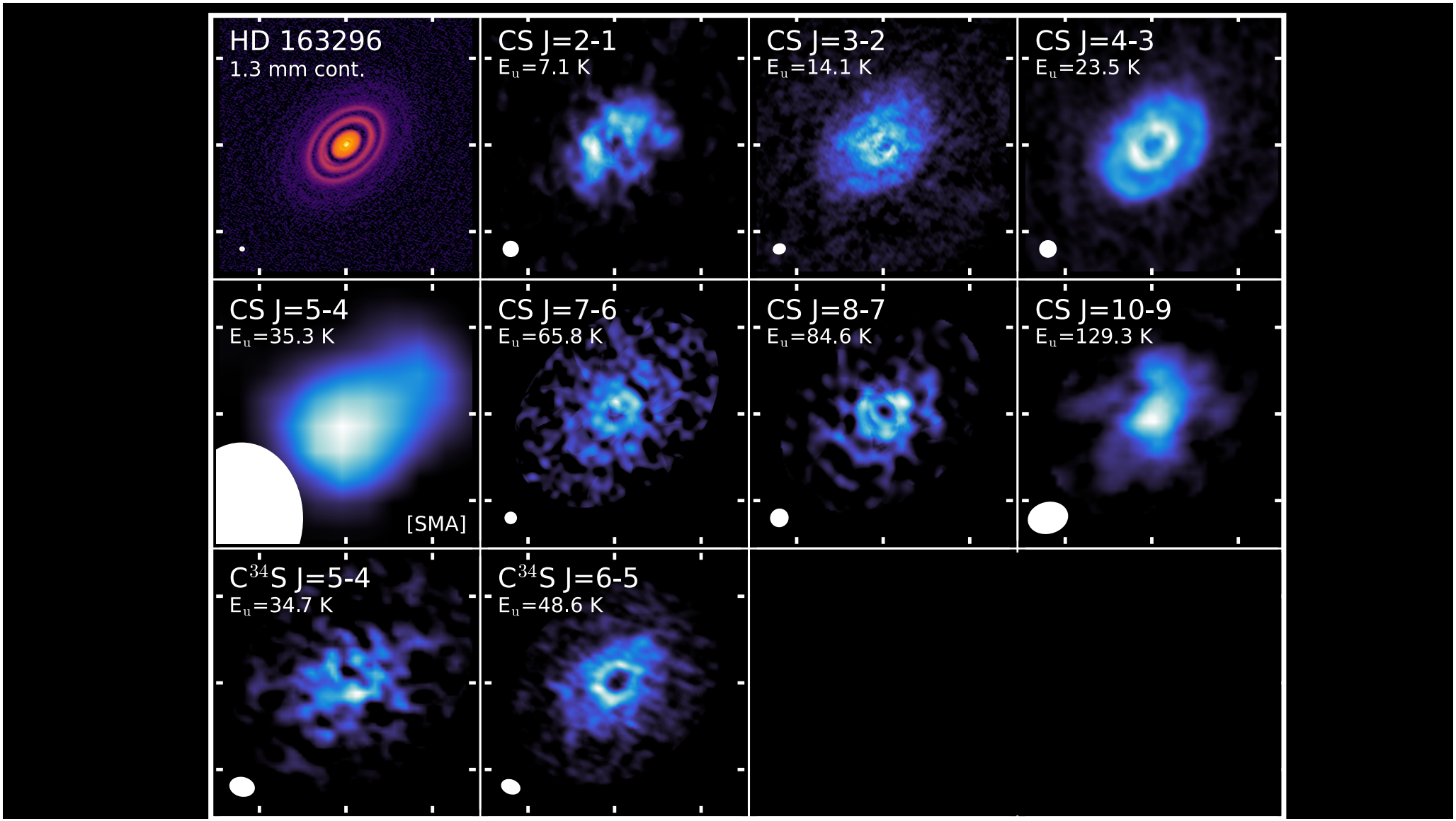
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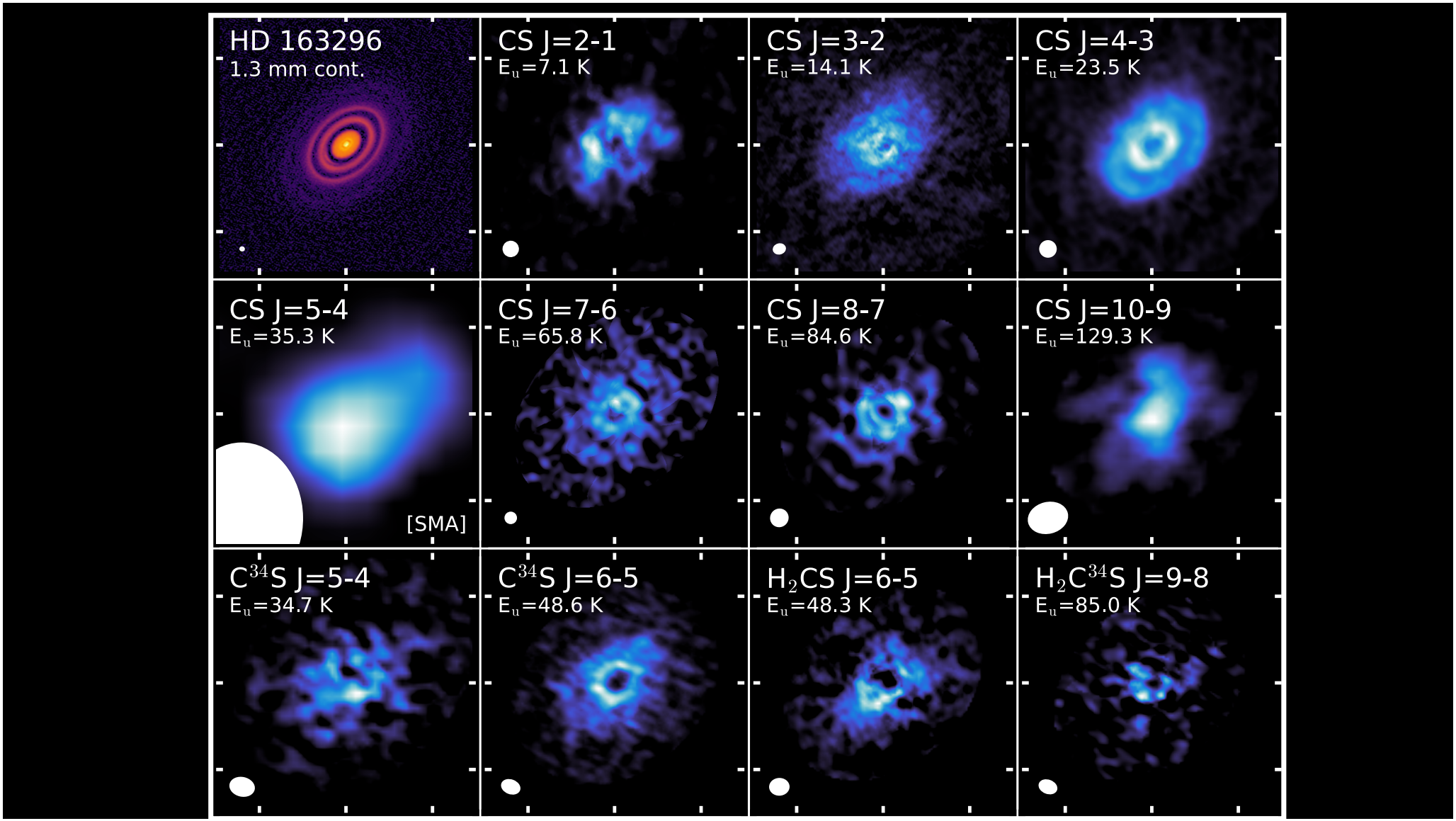
E_u=34.7 K
$C^{34}S$ J=6-5
E_u=48.6 K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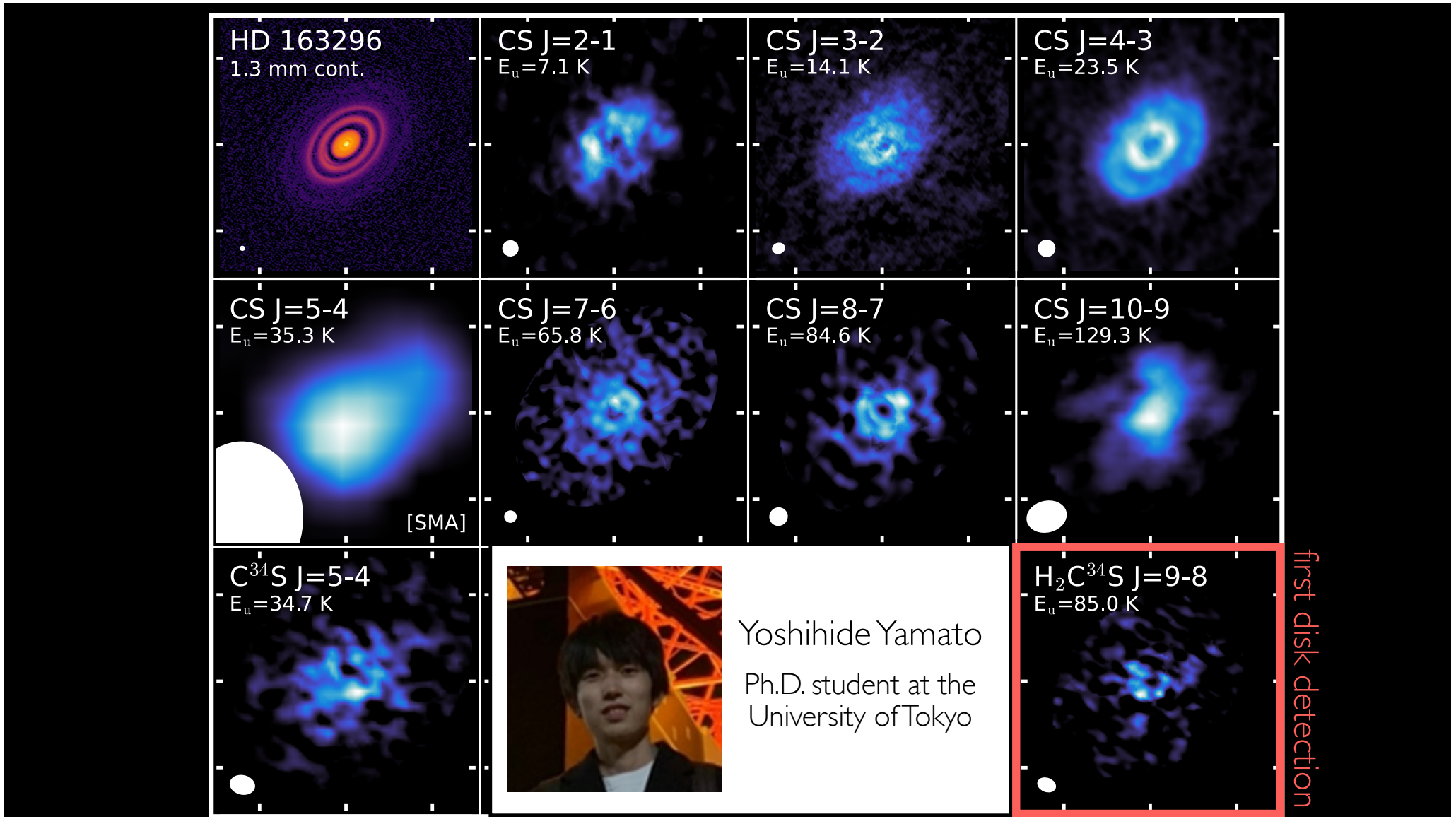
H_2CS J=6-5
E_u=48.3 K
$H_2C^{34}S$ J=9-8
E_u=85.0 K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Yoshihide Yamato
Ph.D. student at the
University of Tokyo
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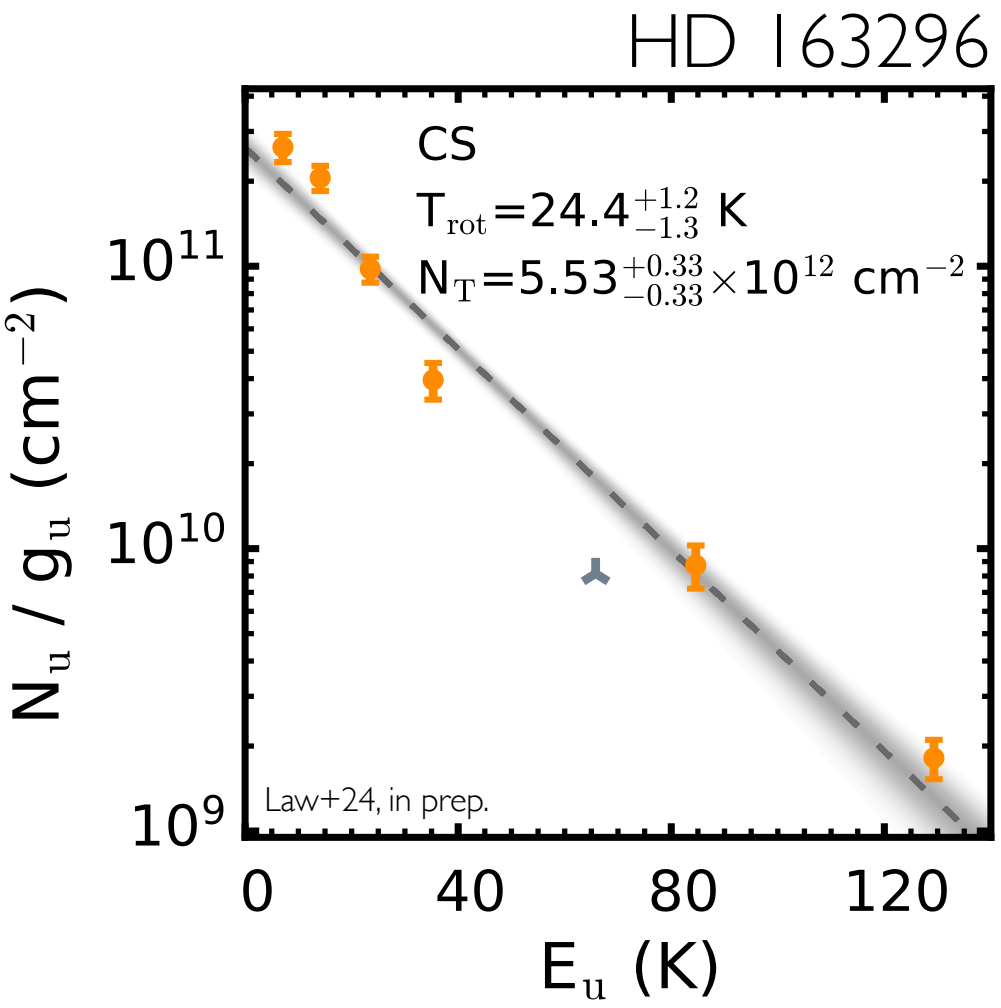
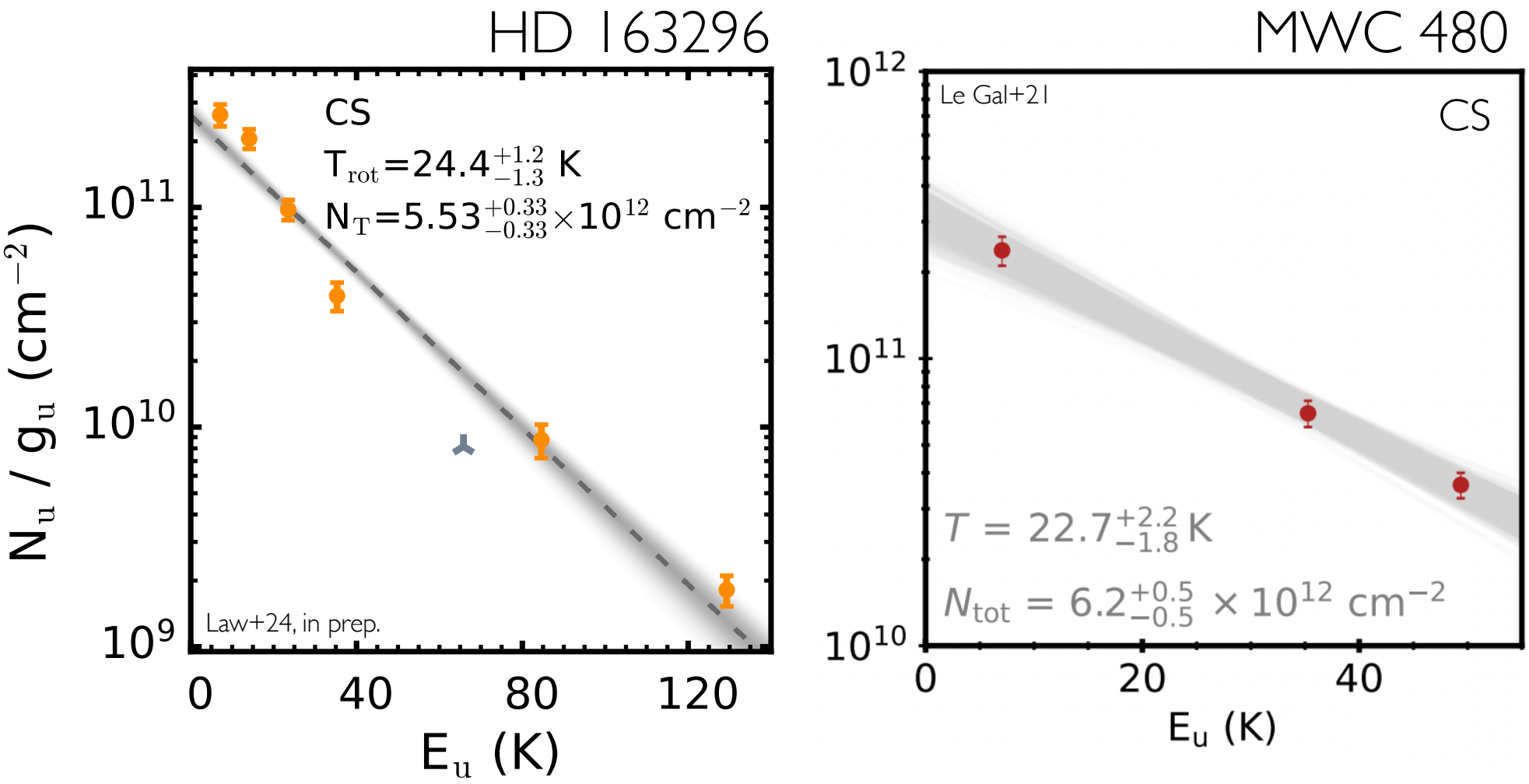
first disk detection



Most comprehensive, multi-line CS data in a planet-forming disk to date!



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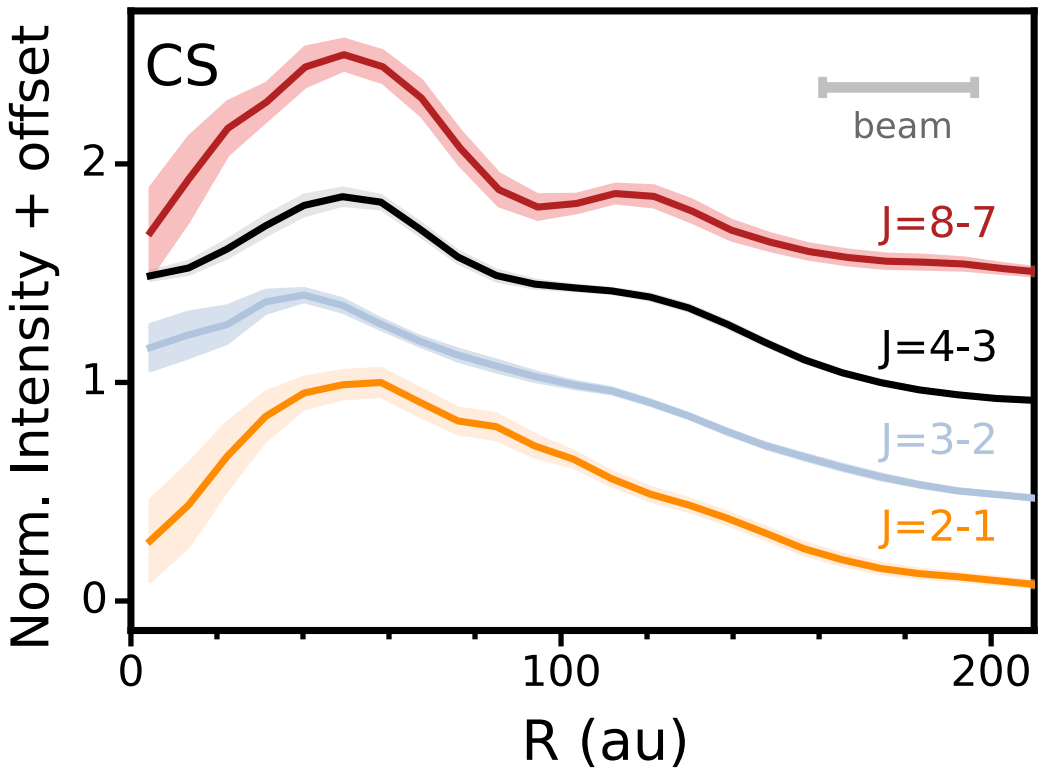
Spatially-resolved sulfur chemistry

- Four CS lines at 35 au-resolution allow spatially-resolved excitation



Law+24, in prep.

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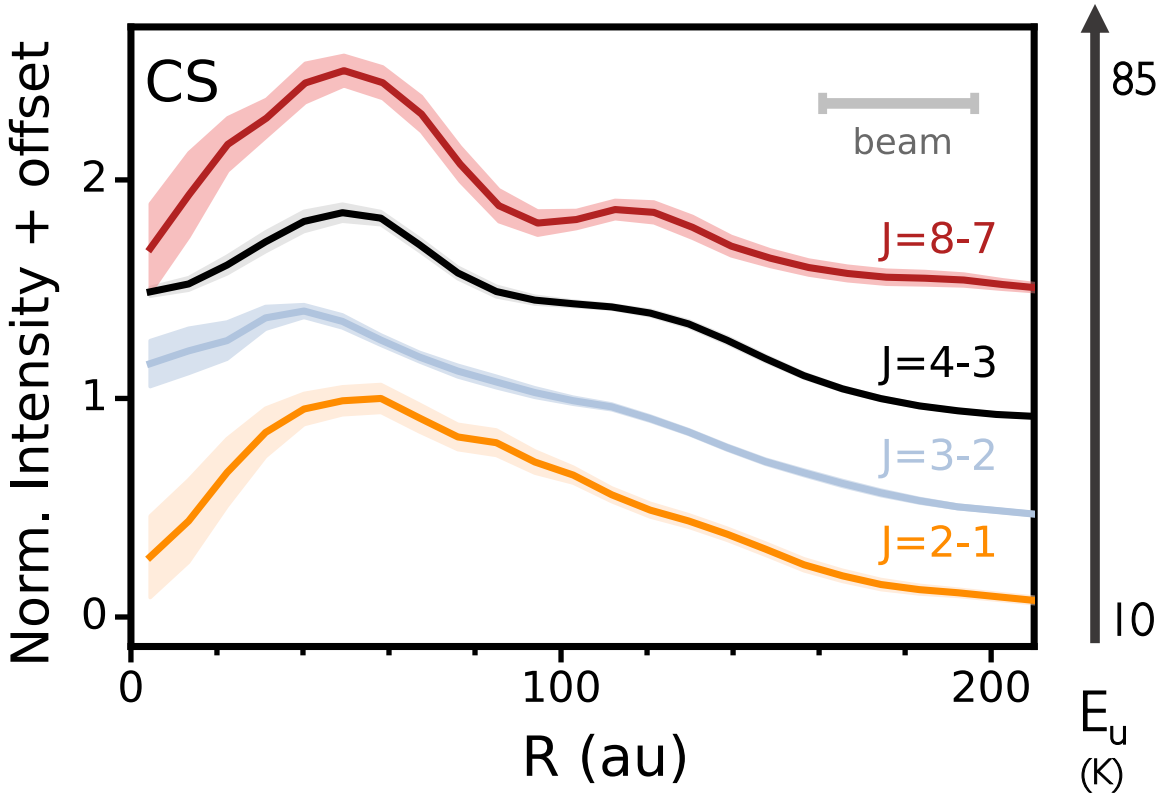

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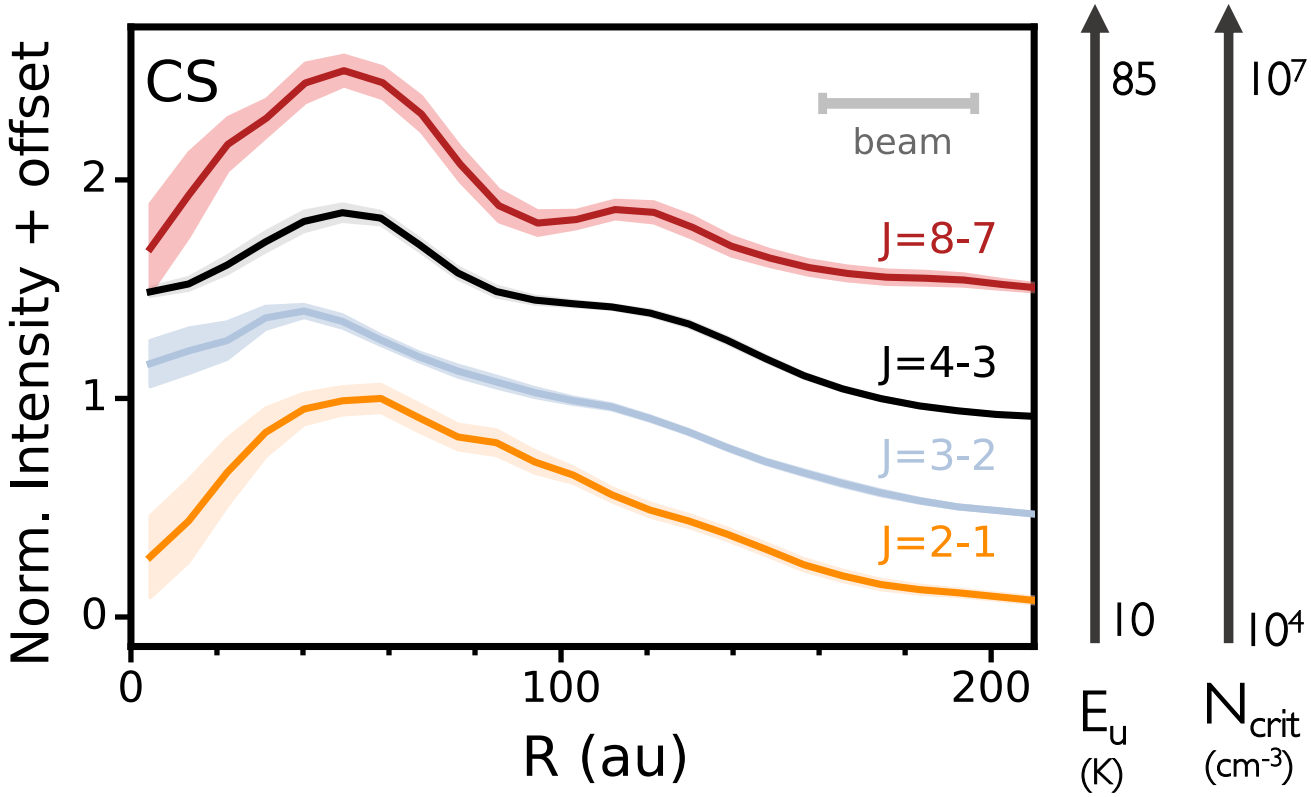

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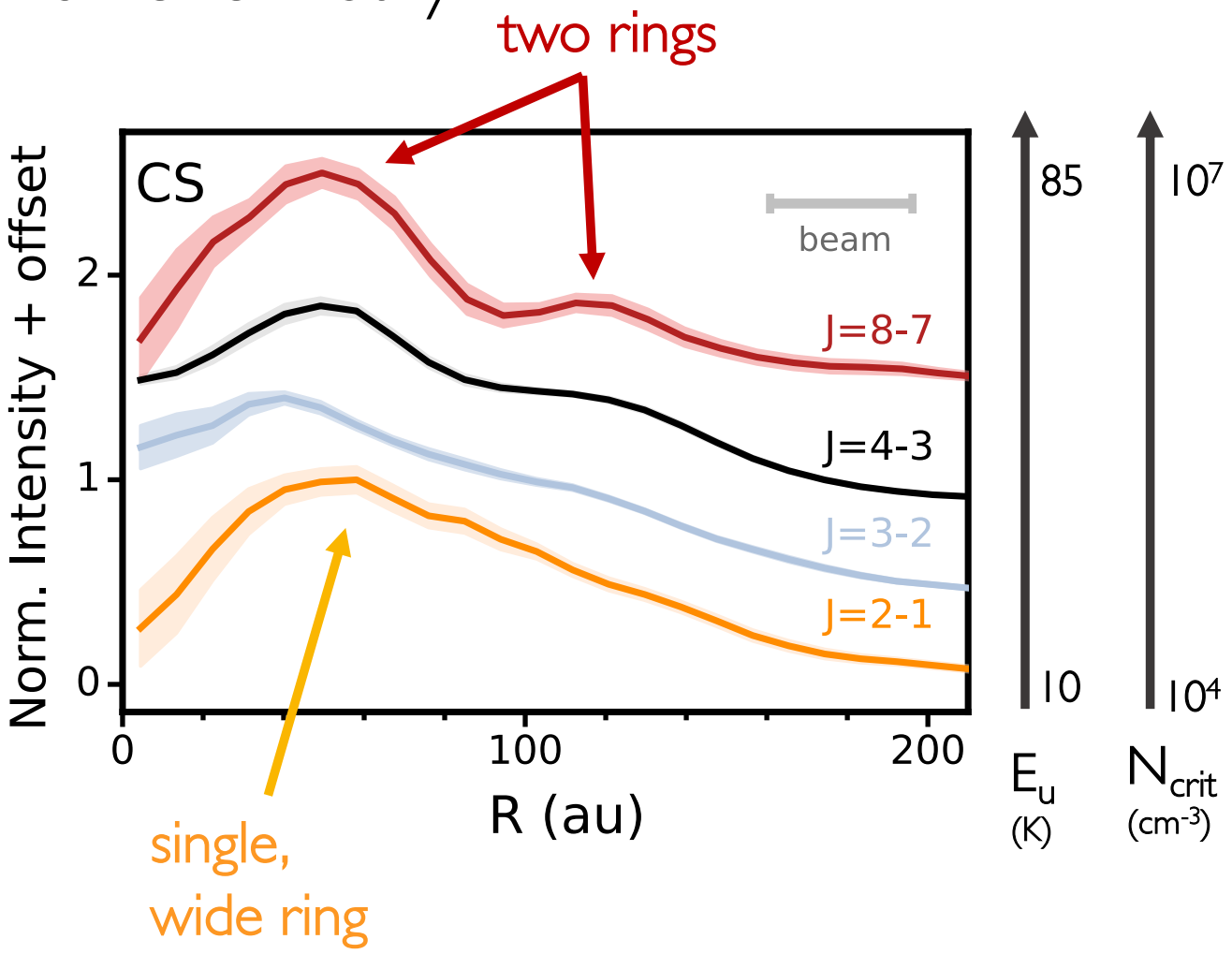

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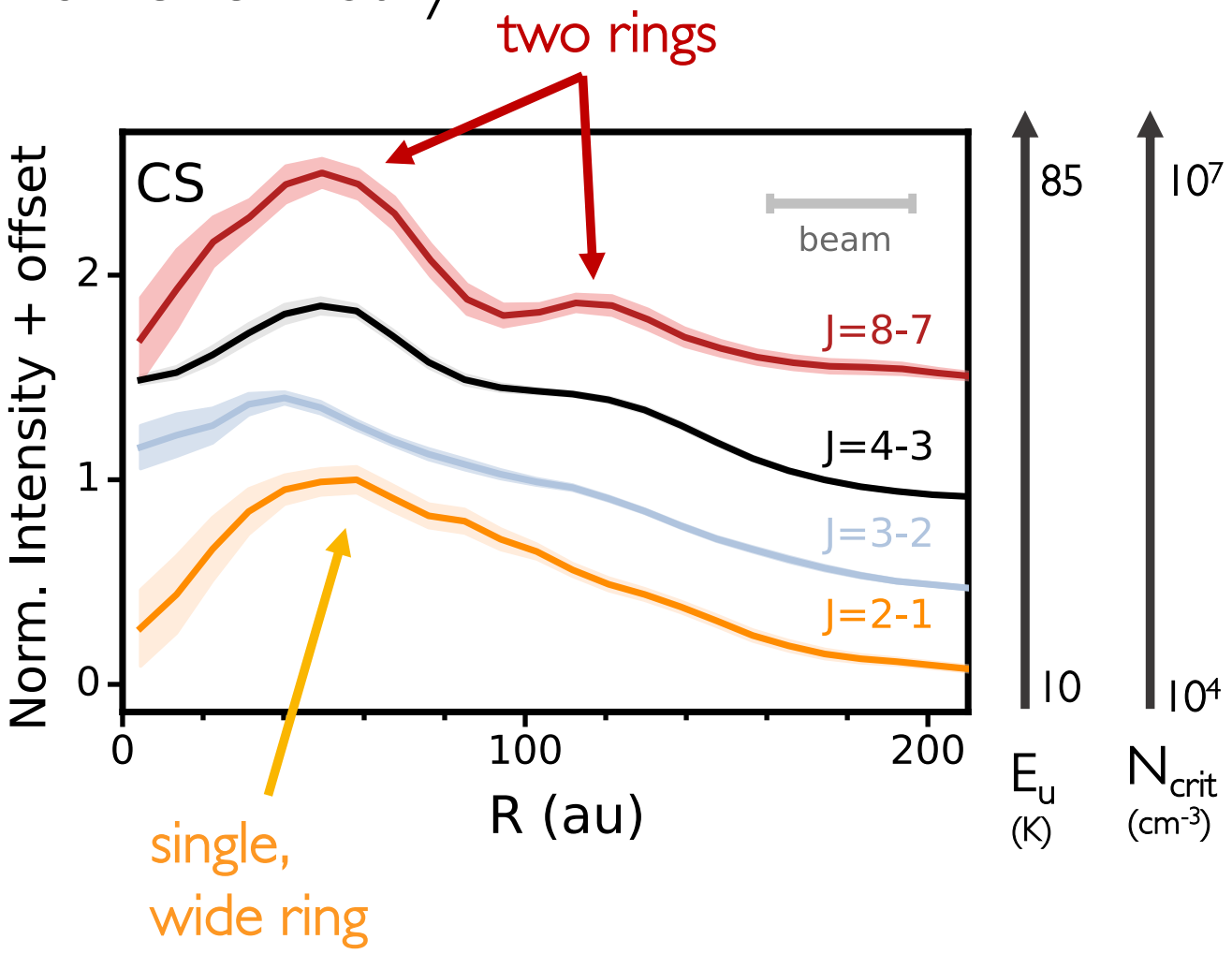

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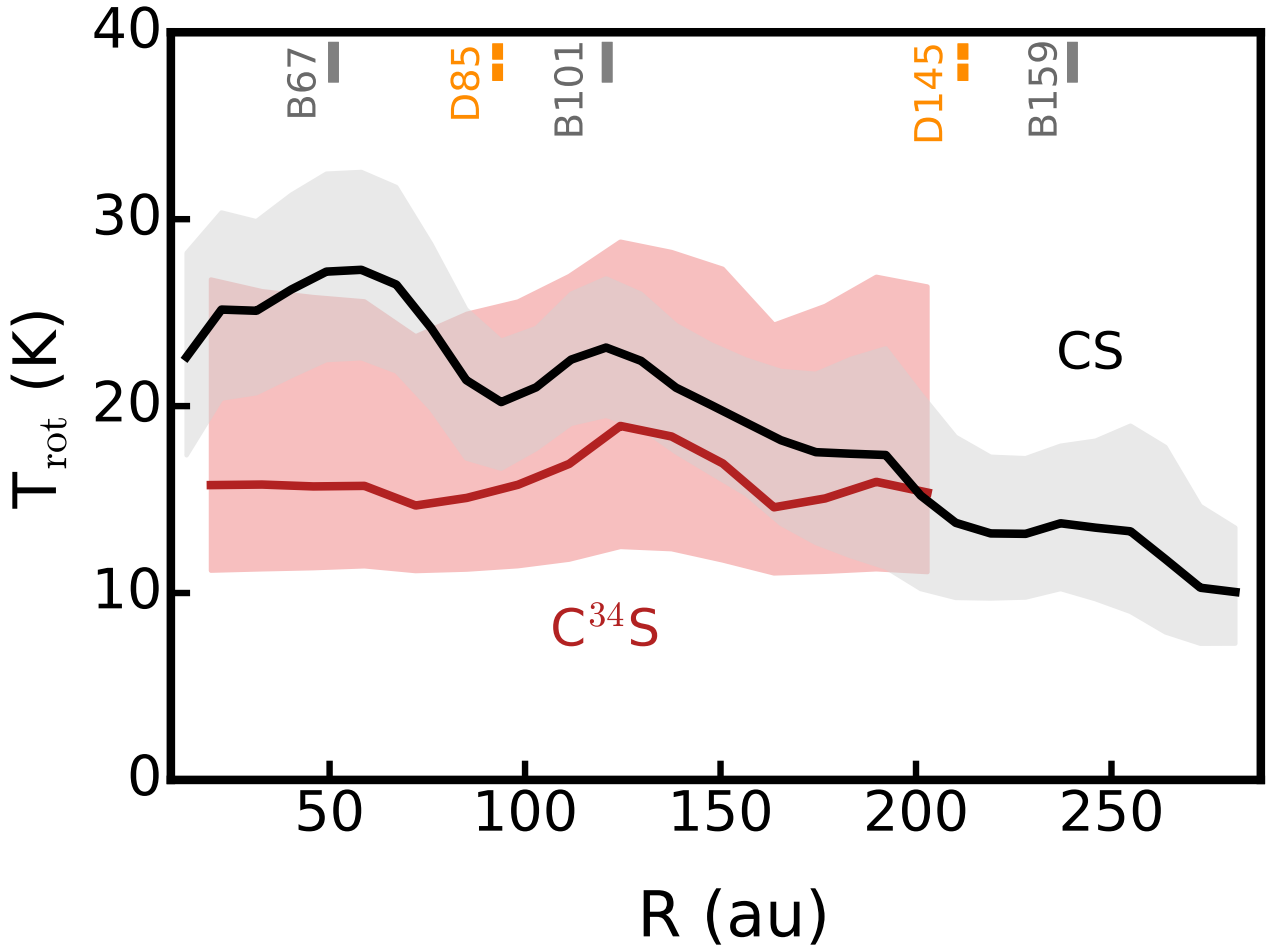

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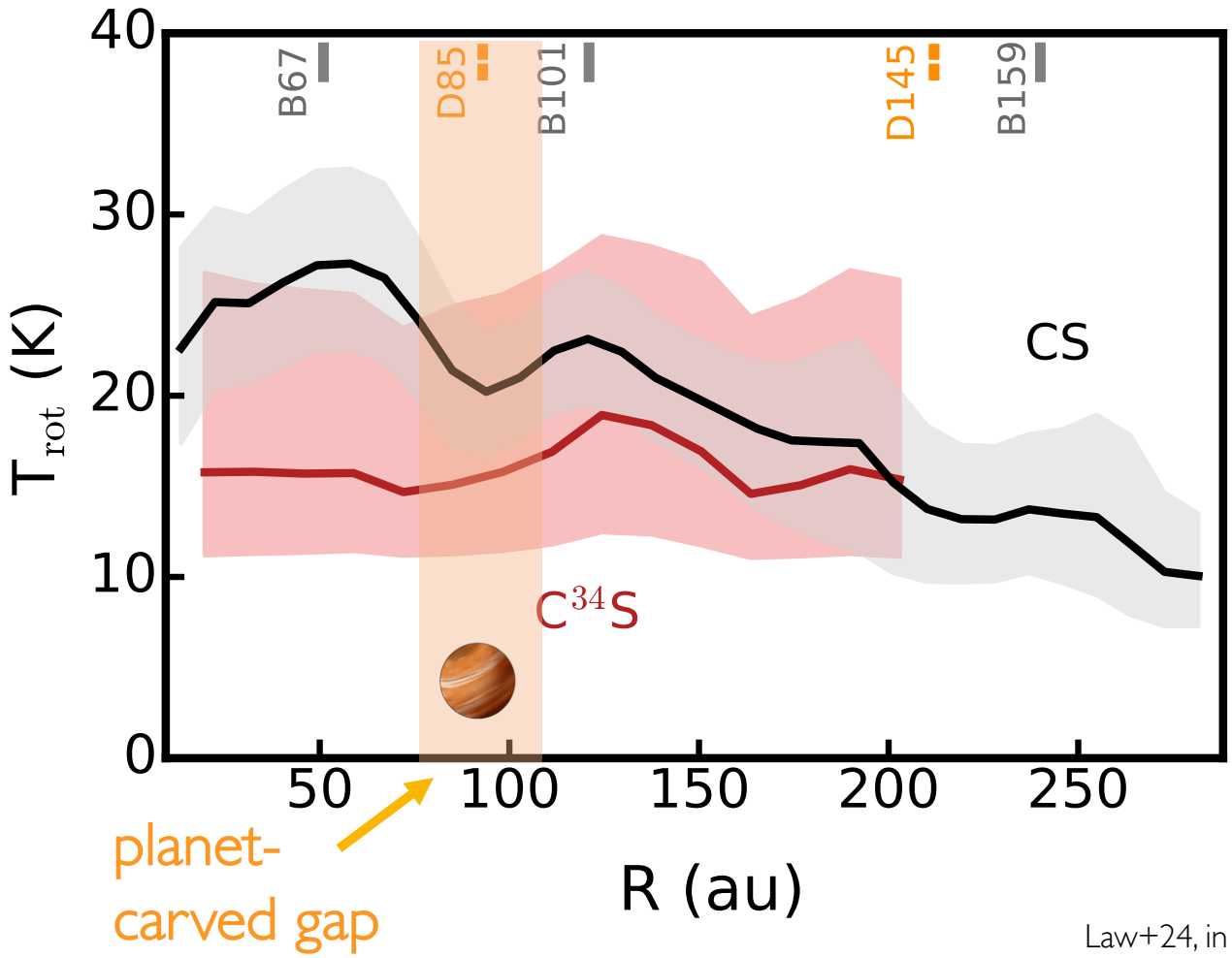

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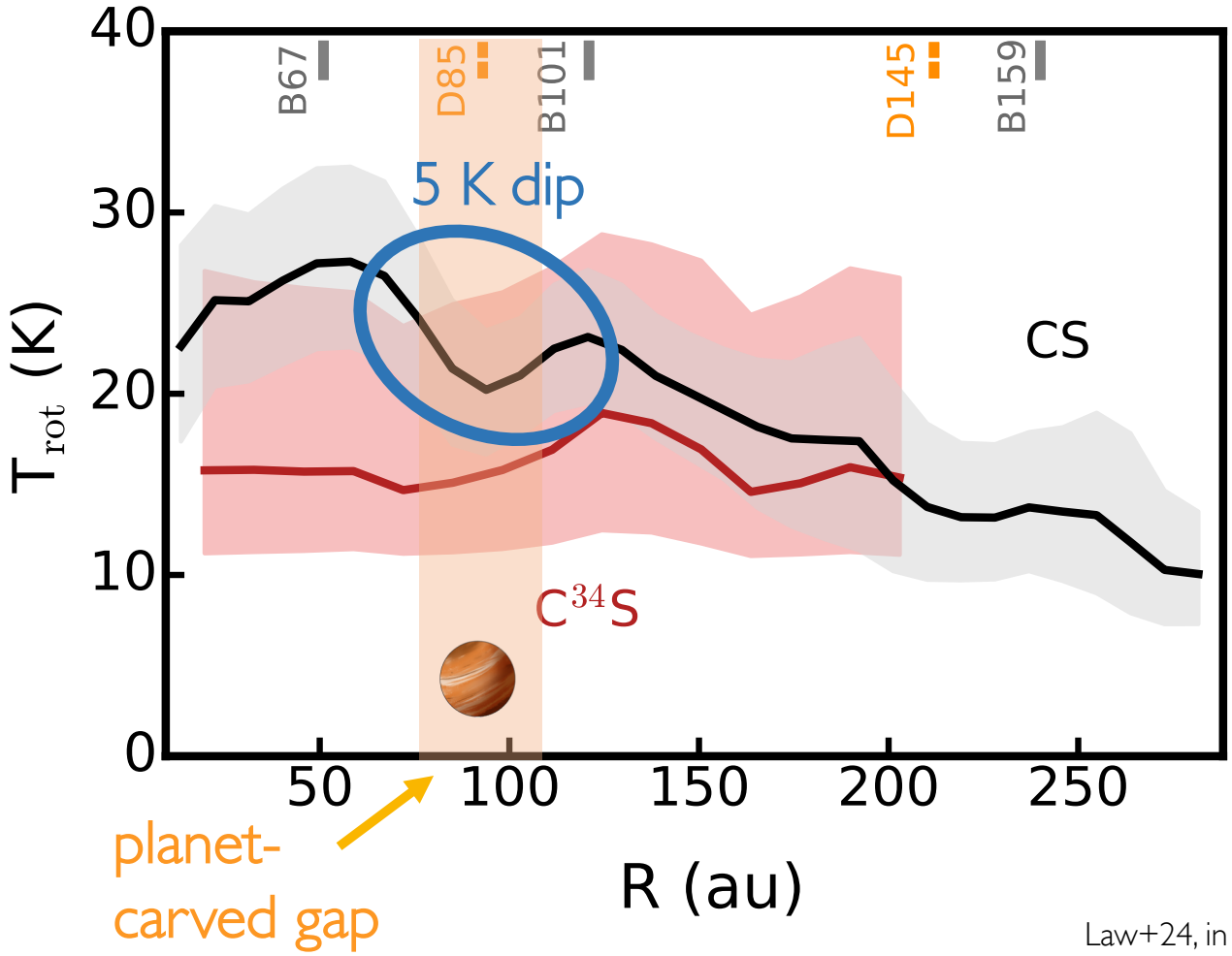
- Independent inference on gas density n_H is consistent with a ~1 M_{Jup} planet!



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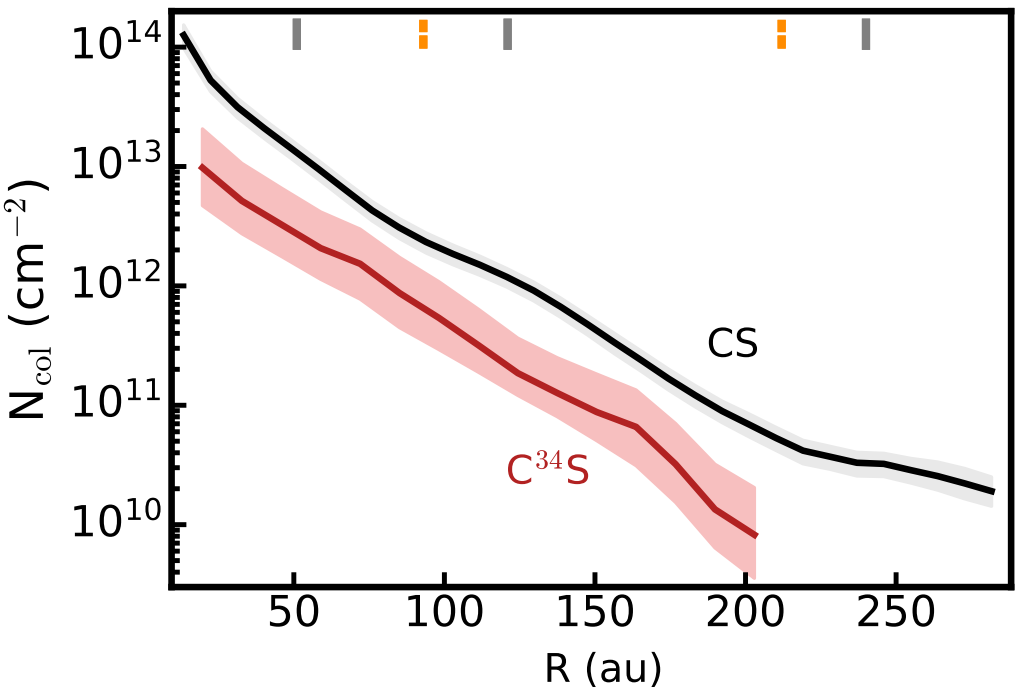
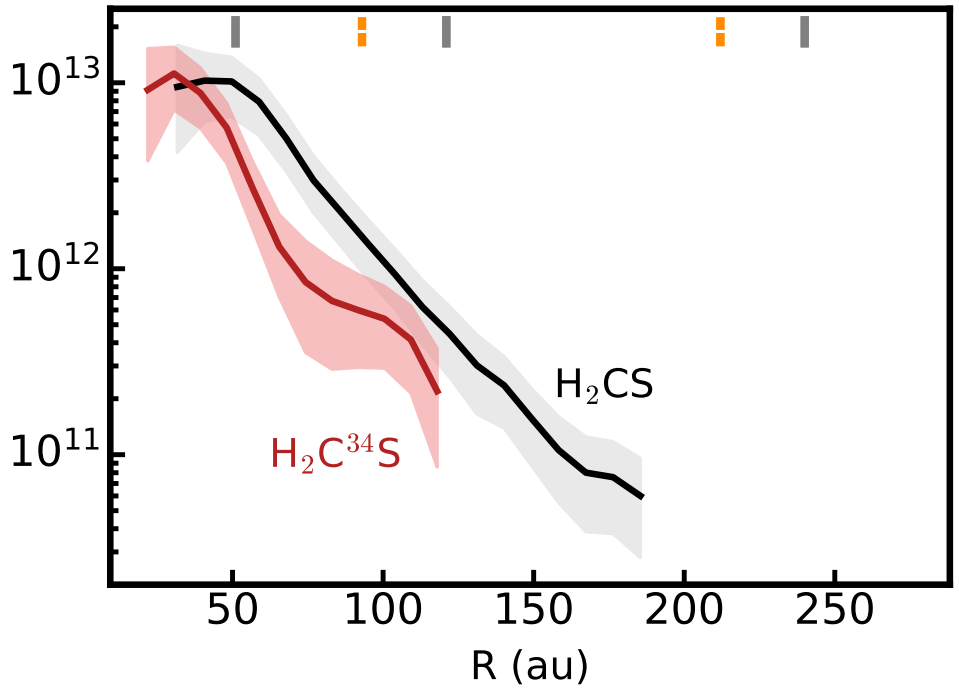
Sulfur isotopic ratios

- Can map out column density profiles for all molecules and measure isotopic ratios





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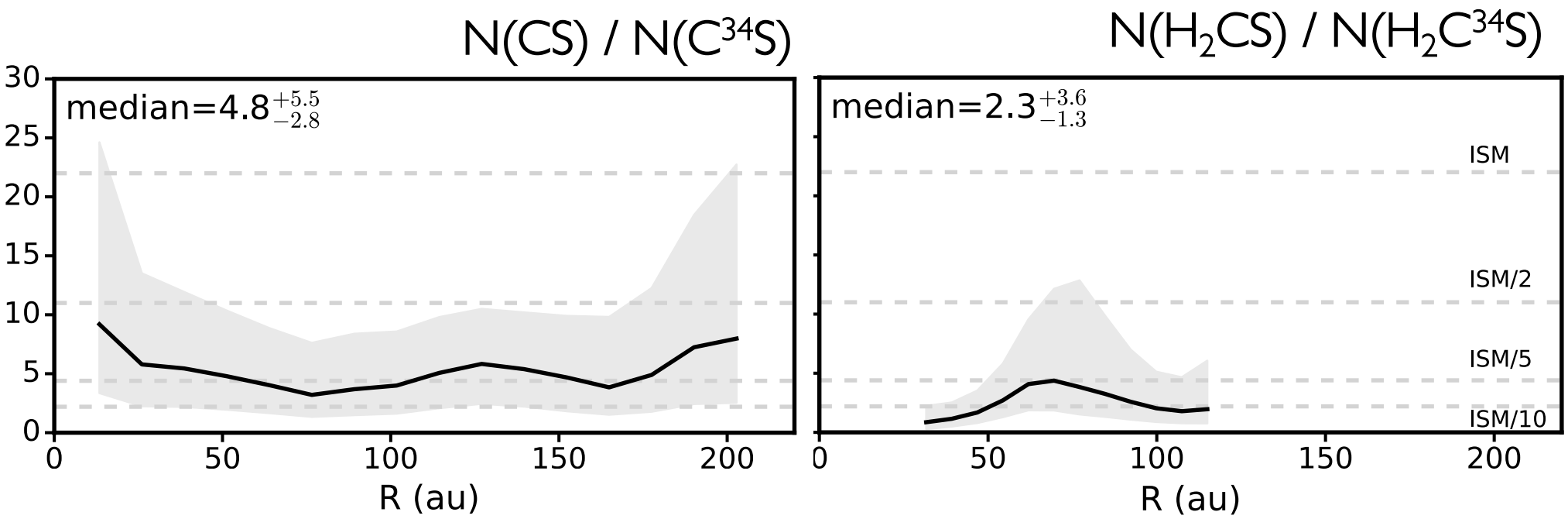

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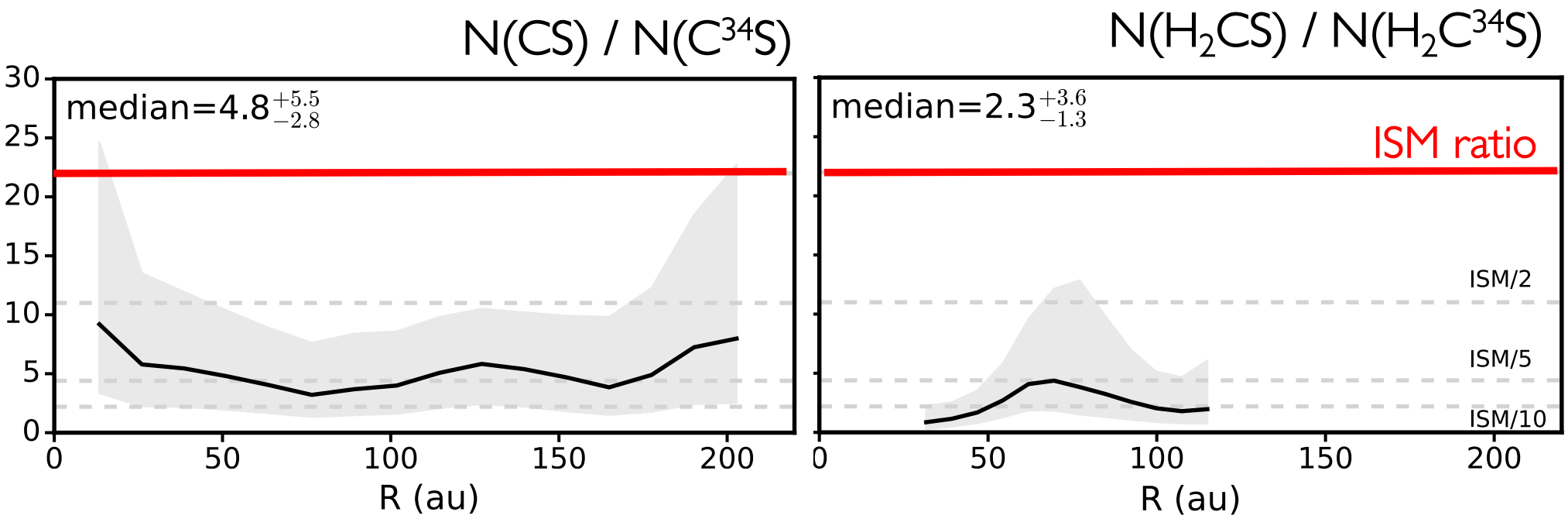

Sulfur fractionation in HD 163296

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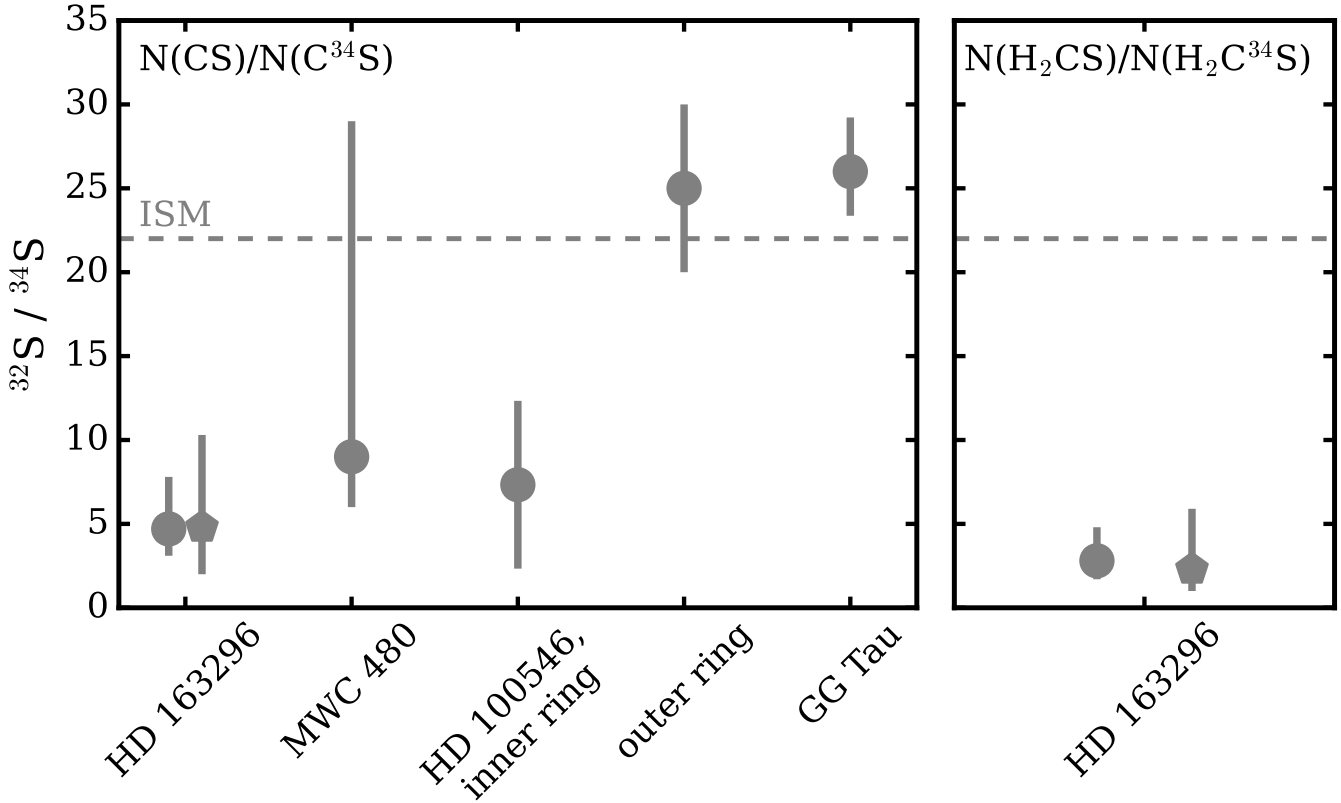
- Perhaps, disks around Herbig stars show enhanced ^{34}S?
- Small sample size, so we need additional multi-line observations of ^{34}S isotopologues



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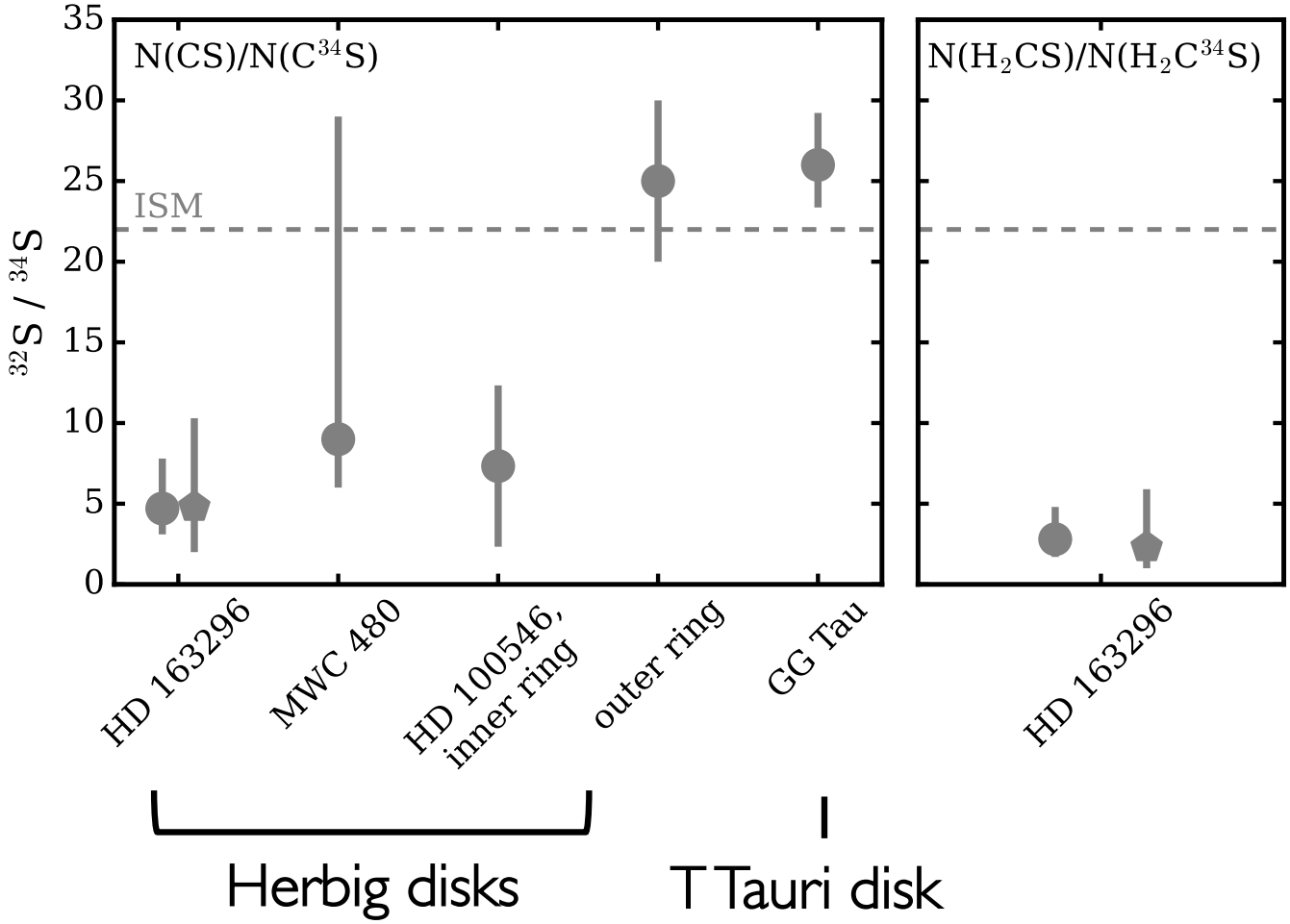

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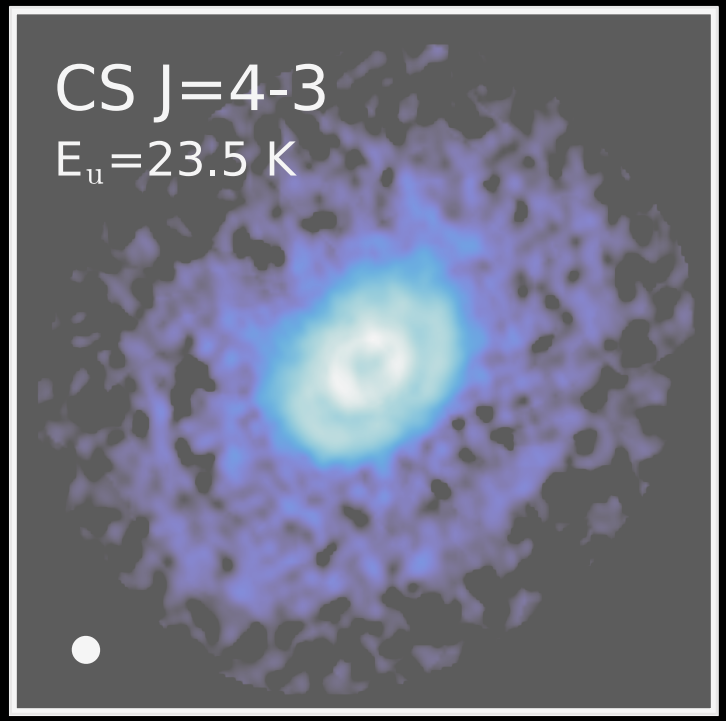
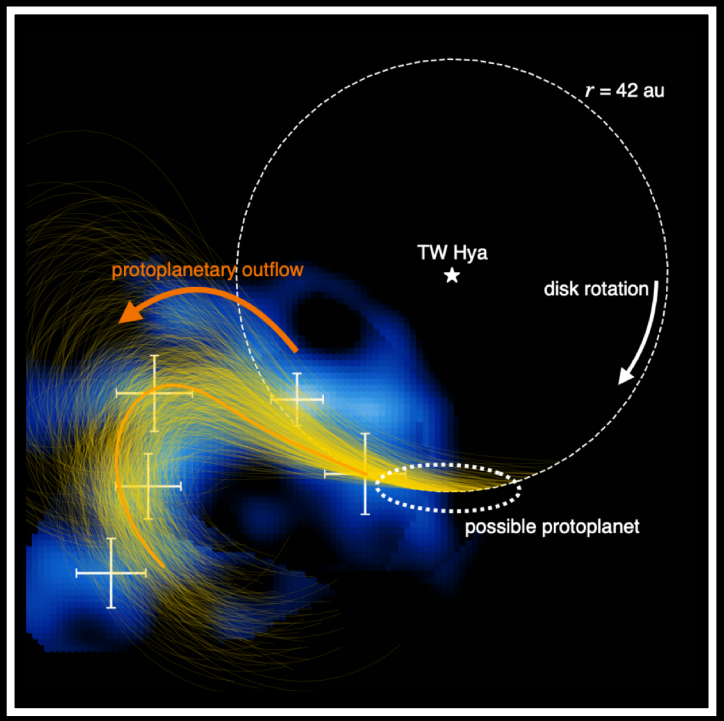


mapping gas conditions in a planet-hosting disk

Yoshida, Nomura, CJL+24



identifying and characterizing embedded protoplanets

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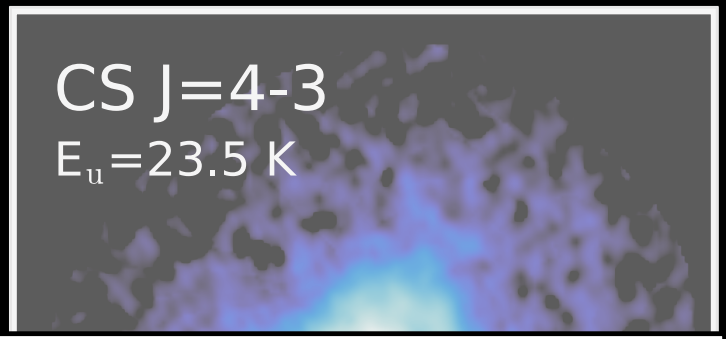
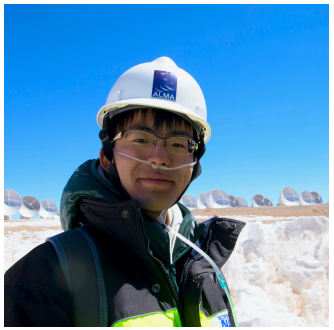


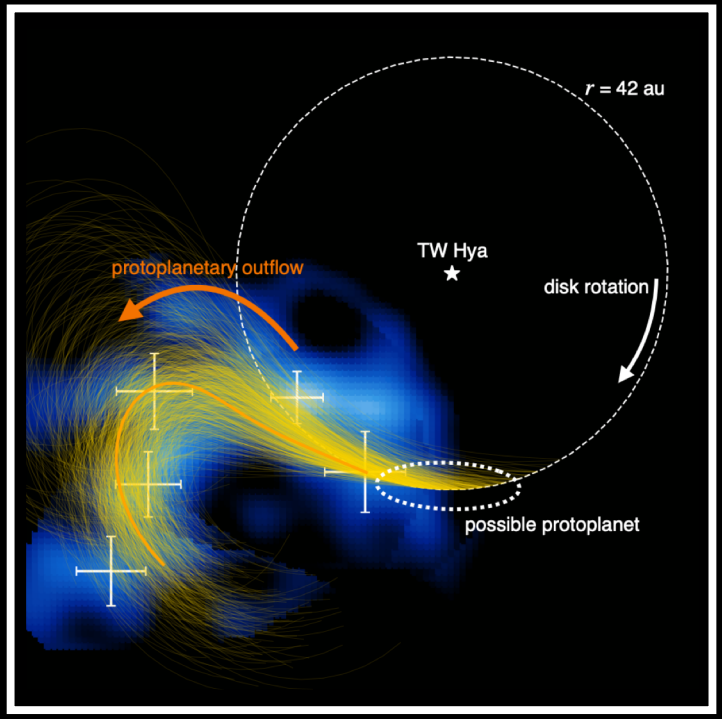


Tomohiro Yoshida

Ph.D. student at the National Astronomical Observatory of Japan

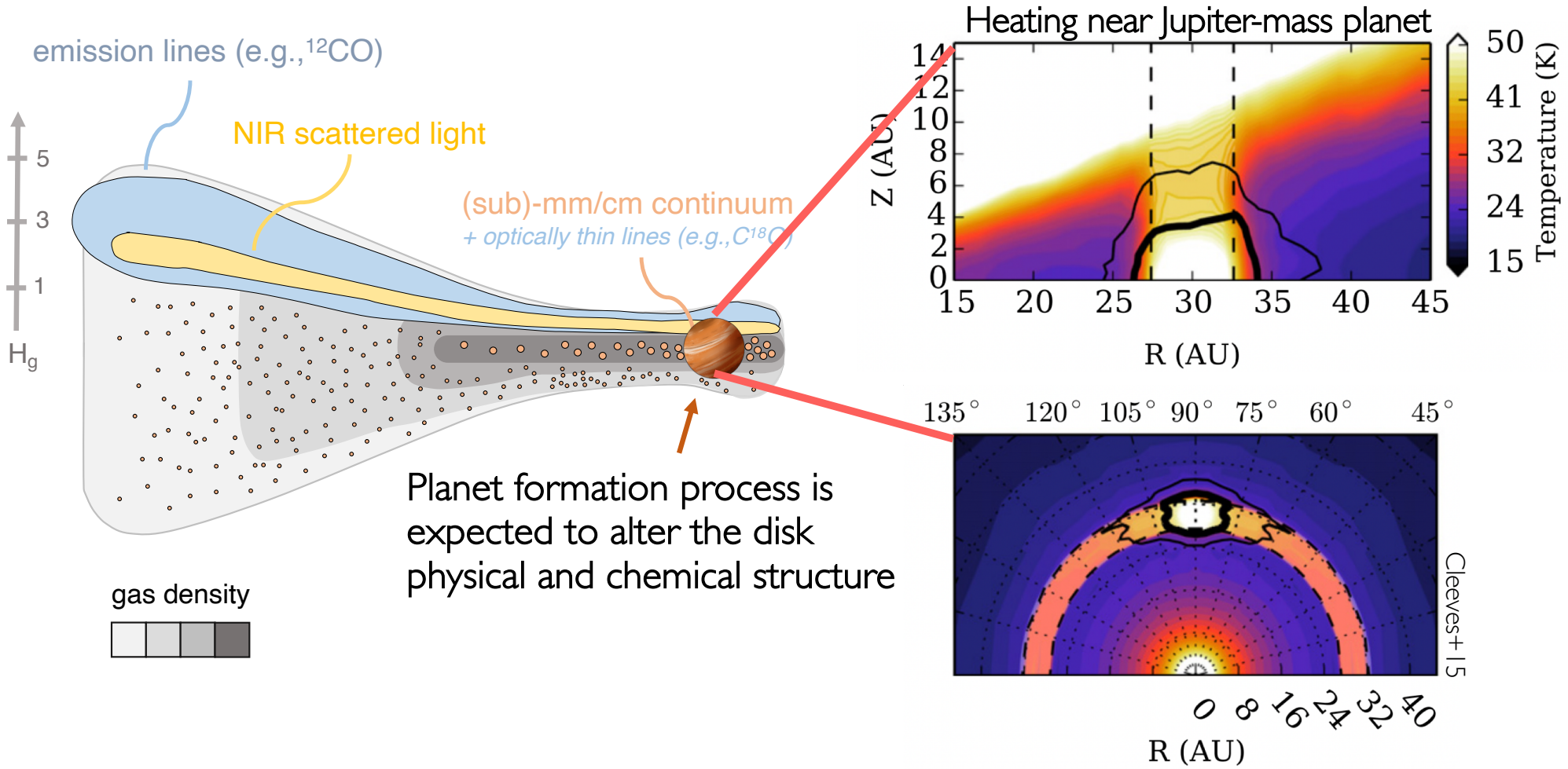
mapping gas conditions in a planet-hosting disk

Yoshida, Nomura, CJL+24



identifying and characterizing embedded protoplanets

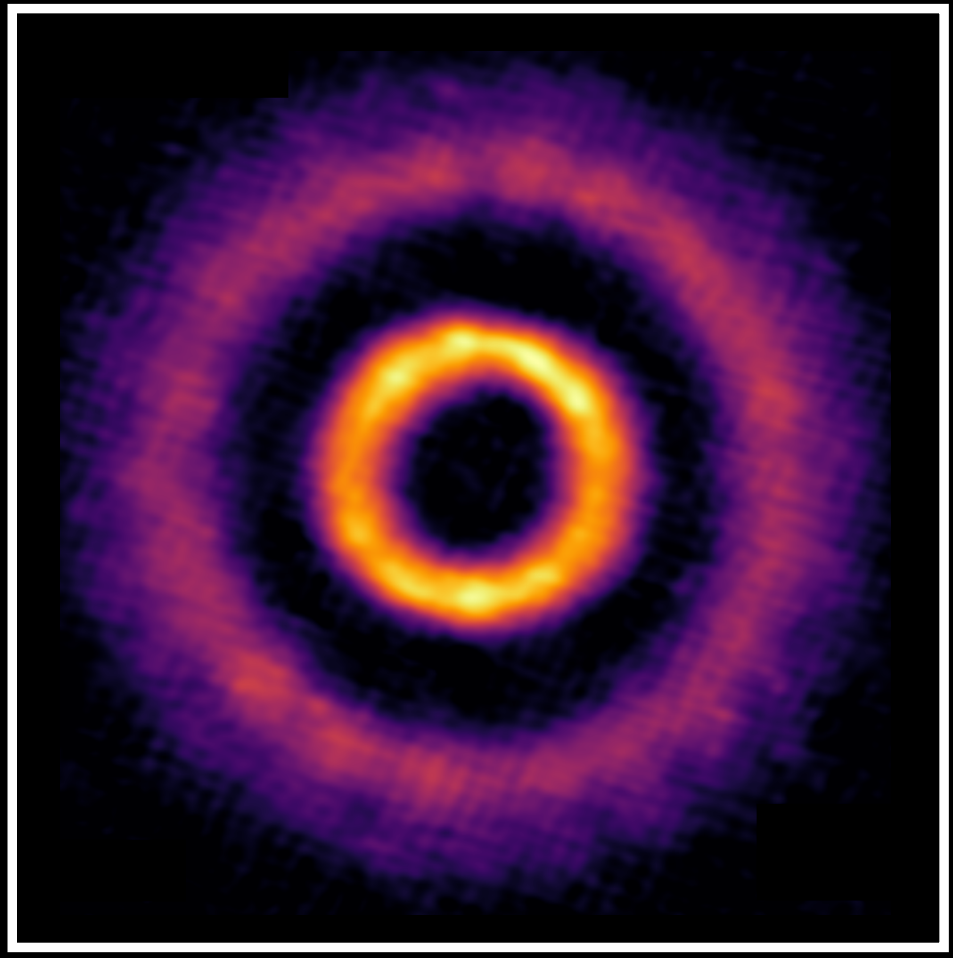
Chemical signatures of embedded planets in disks



The planet-hosting HD 169142 disk

- Nearby *(d = 115 pc)* Herbig star with a face-on disk
  Blondel & Djie 2006, Fedele+17
- Bright, gas-rich disk that hosts at a confirmed ~1-5 Jupiter-mass planet
  e.g., Raman+06, Panić+08, Booth, CJL+23
- Planet seen via moving NIR point source, disk gas kinematics, and carves dust & gas gap
  e.g., Gratton+19, Garg+22, Hammond+23
- Chemical signatures of planet seen in SO and SiS (also ^{12}CO, ^{13}CO)
  Law+23

mm dust



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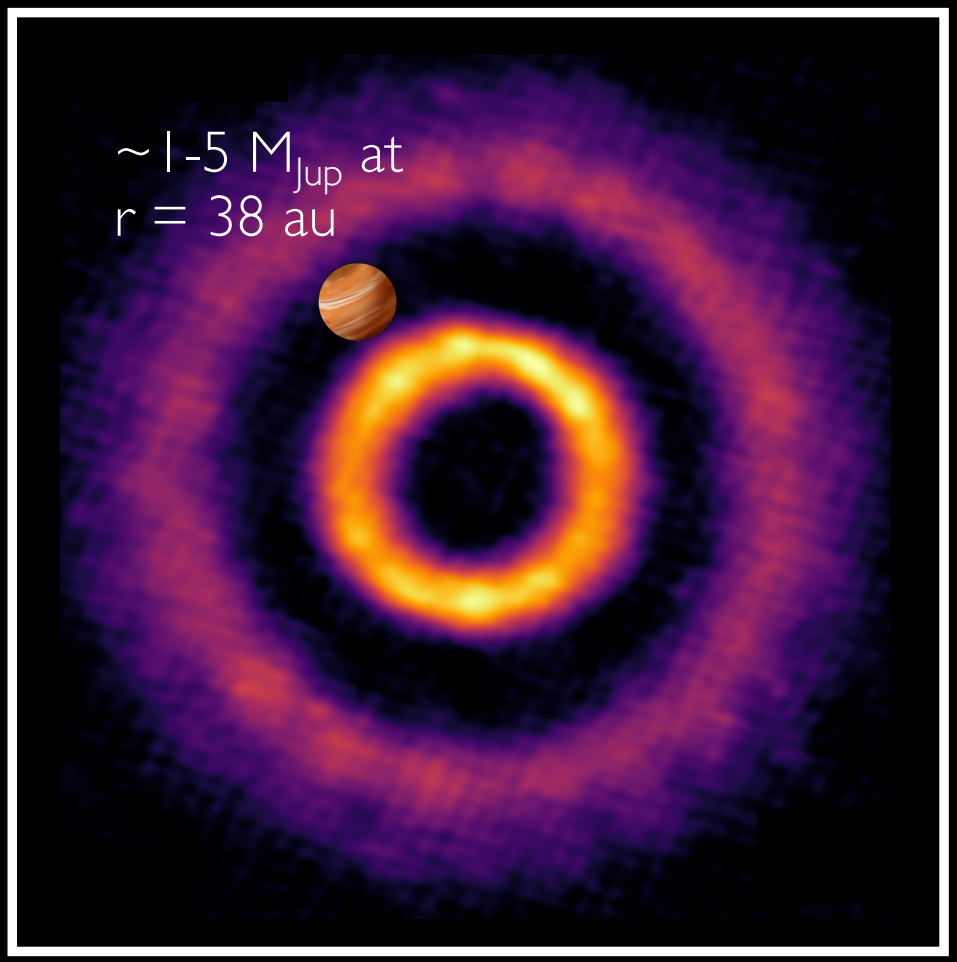

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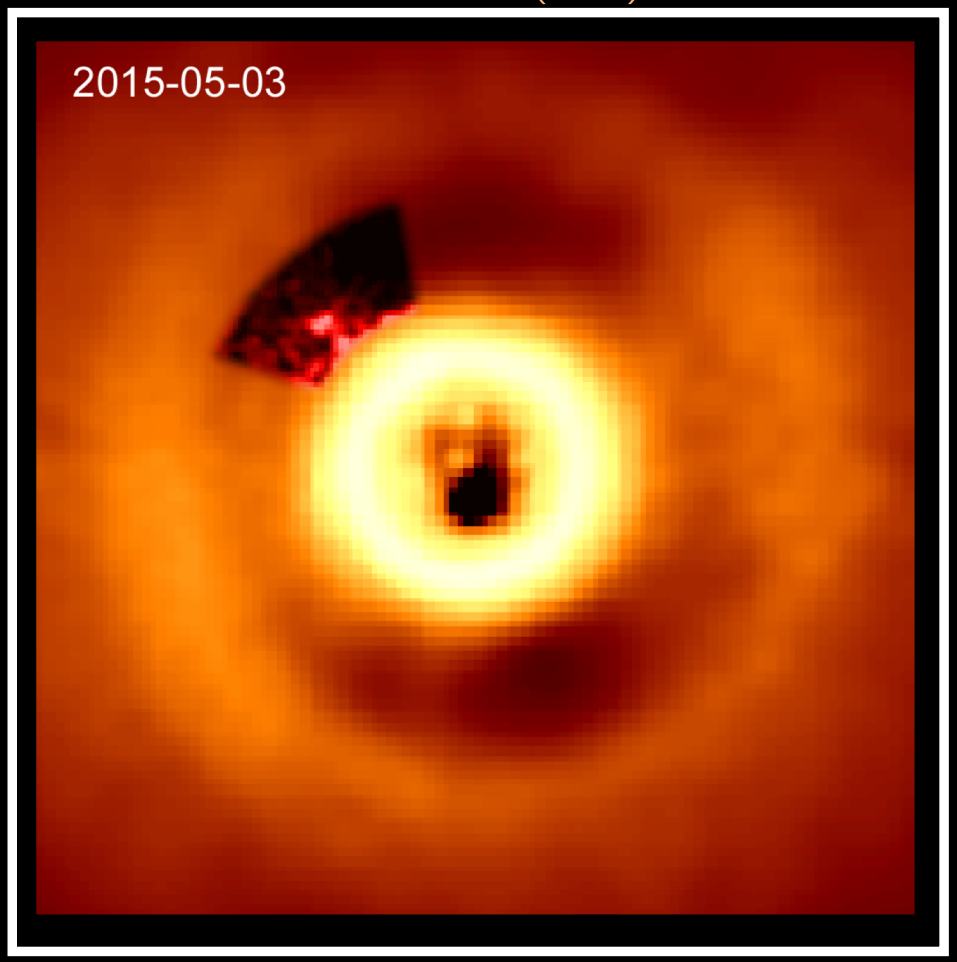
(sub)-micron dust



Hammond+23

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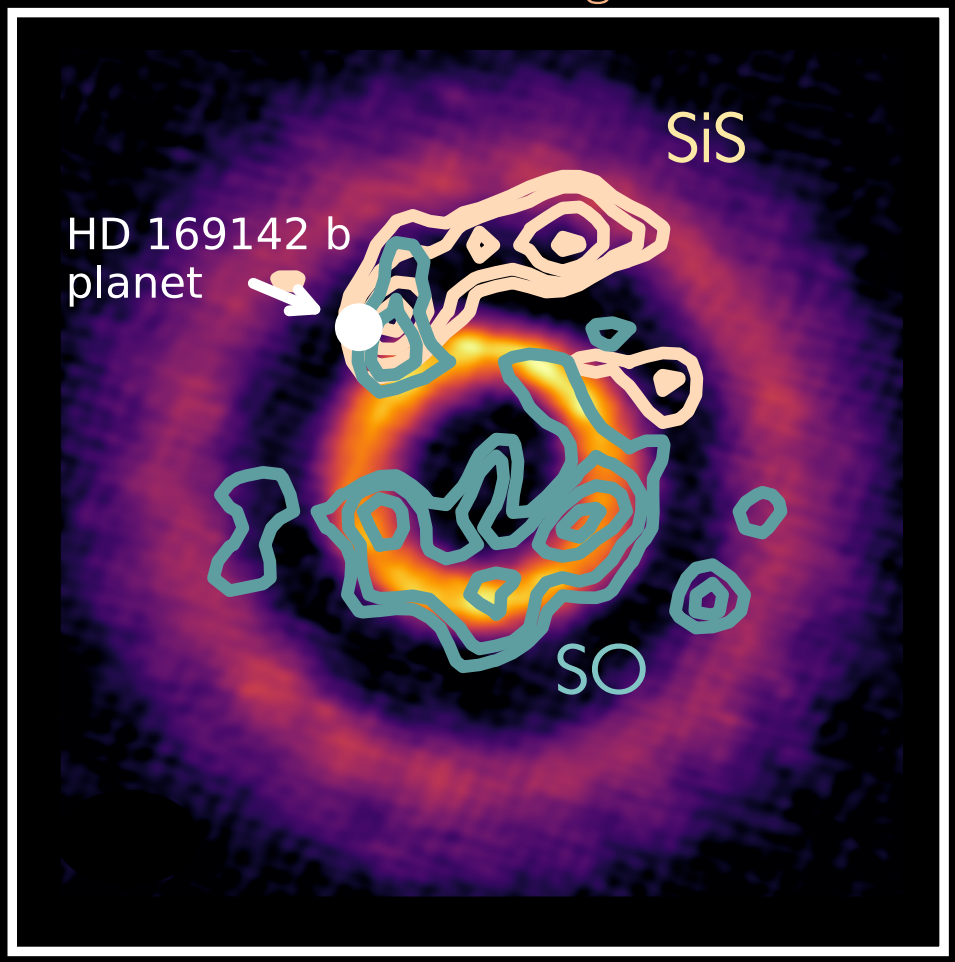
gas + mm dust



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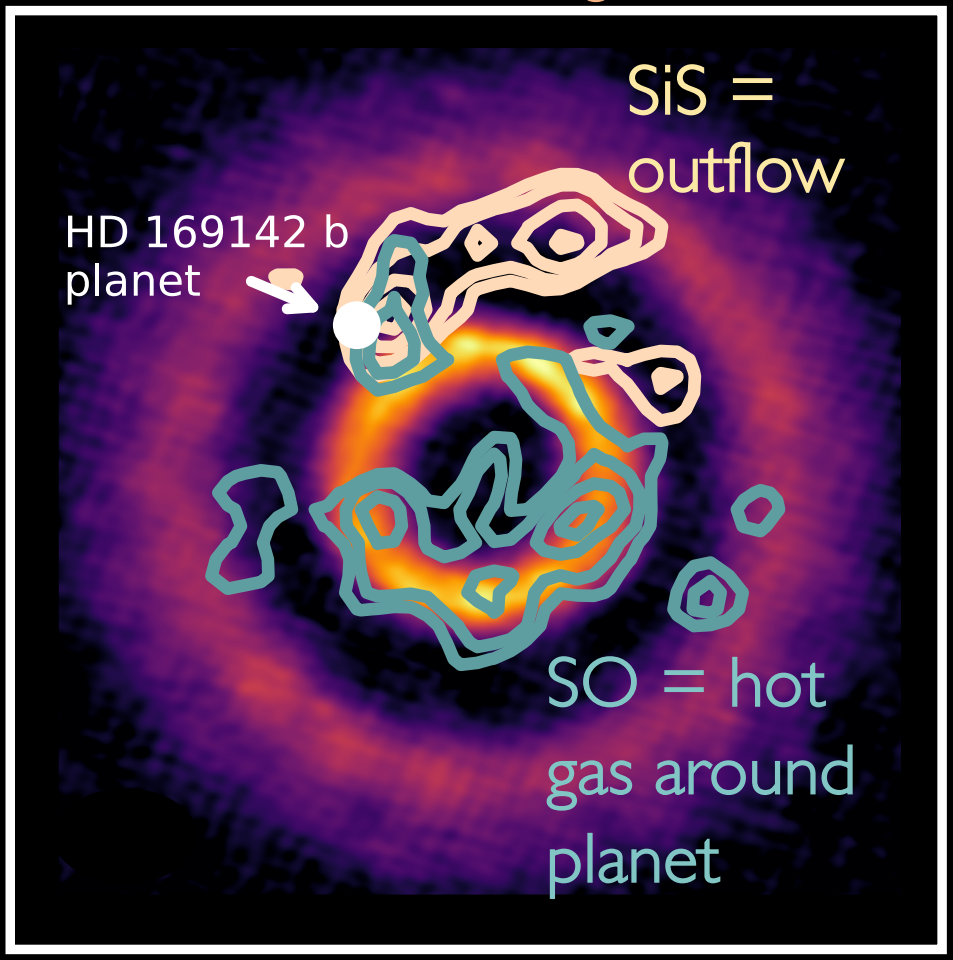

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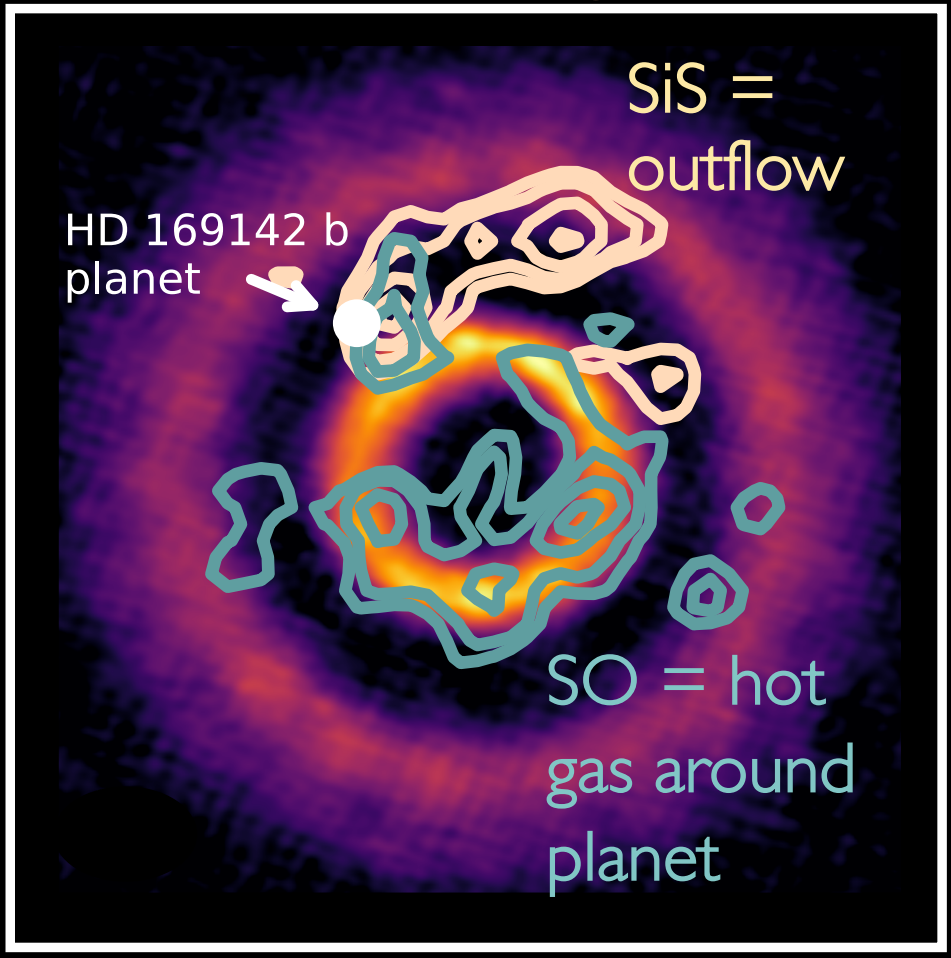
Questions:

- Is this a unique system, or we can find more?
- Can we use SO to detect additional planets?

gas + mm dust



Law+23

Super-Earth formation in the TW Hya disk

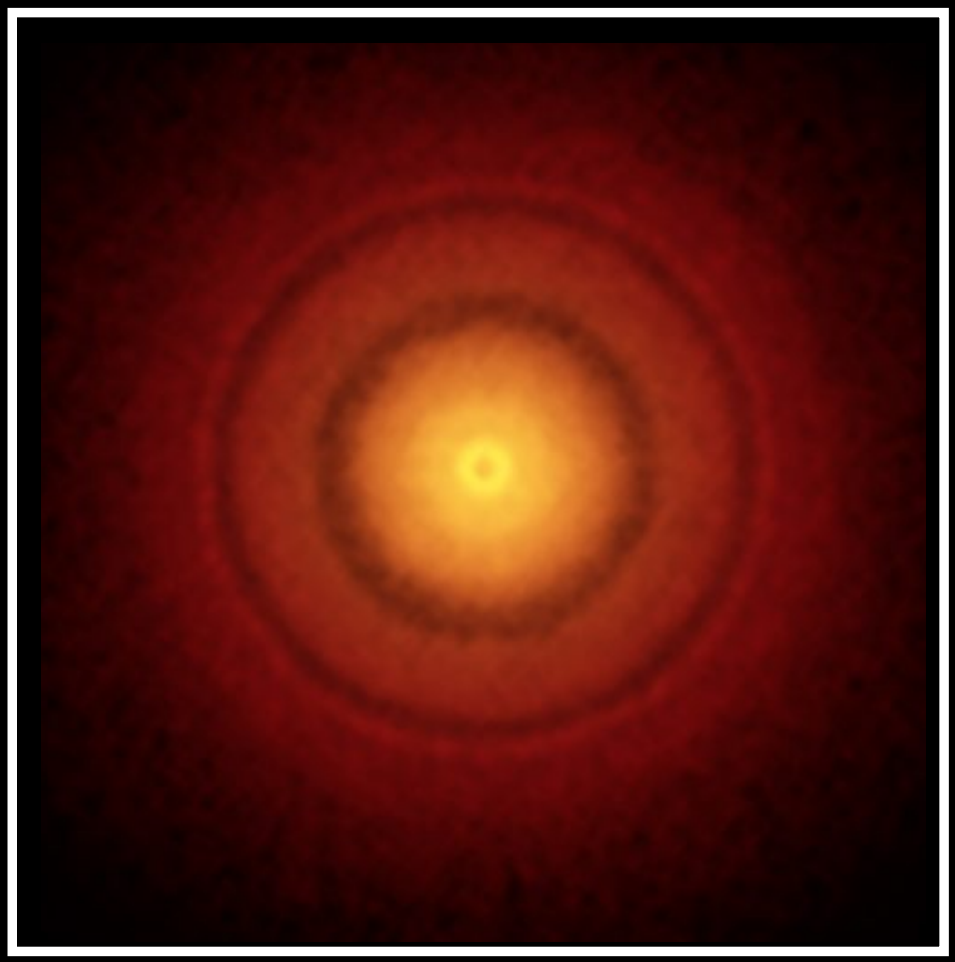
- Nearest *(d = 60 pc)* gas-rich protoplanetary disk

  e.g., Andrews+16, Teague+16, Huang+18

- Two super-Earths can explain the inner dust gaps at 24 au and 41 au

  Mentiplay+18

mm dust



Andrews+16

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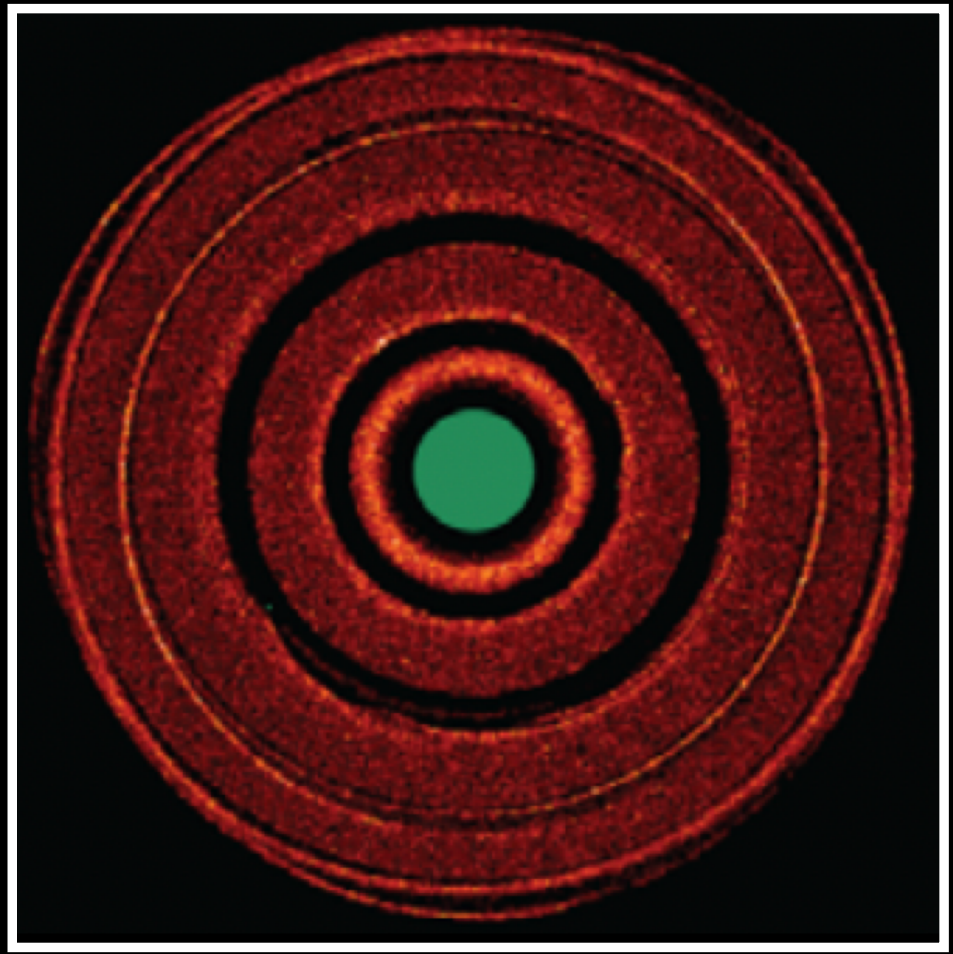
modeled mm dust



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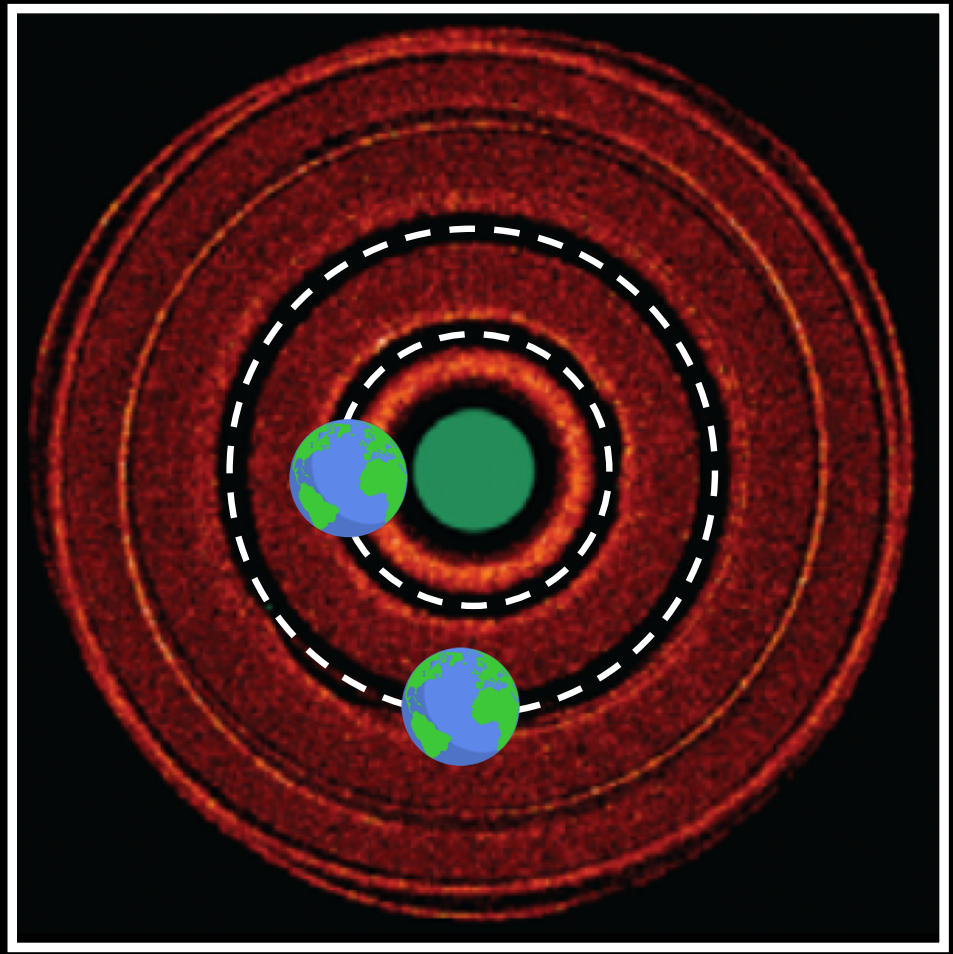

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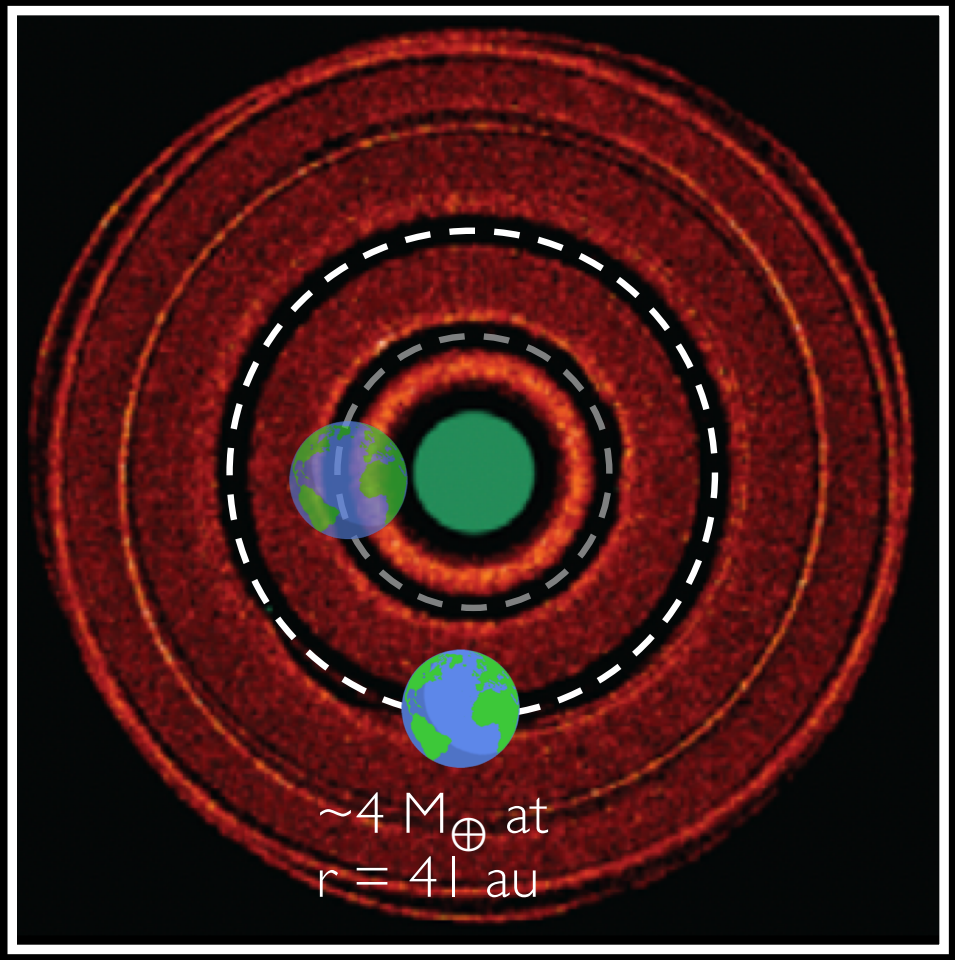
- Also, very well studied with a large amount of ALMA archival data:

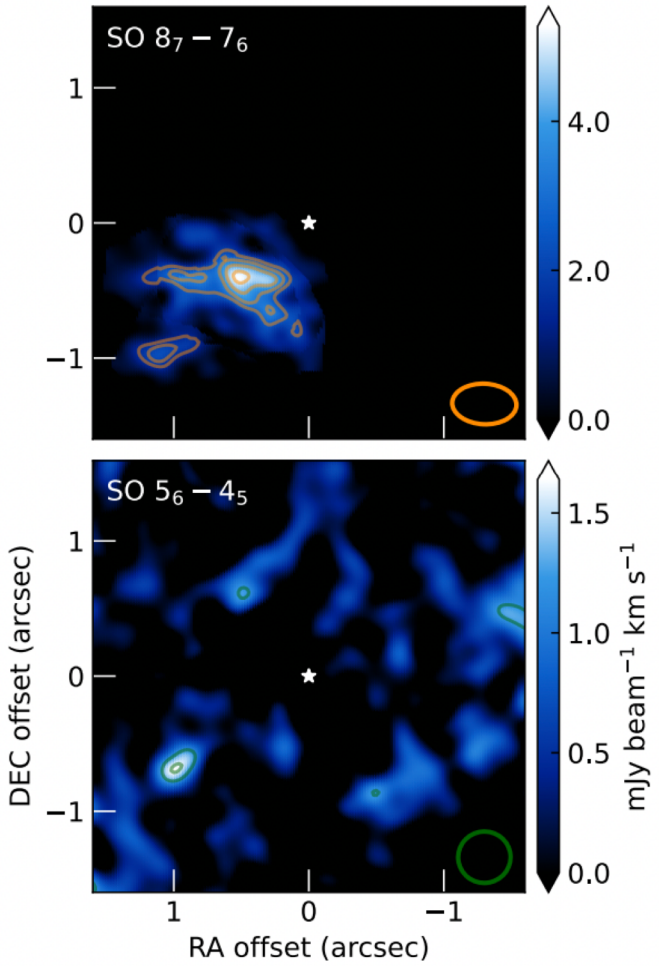
  2016.1.00311.S (PI: I. Cleeves), 2019.1.01177.S (C. Eistrup)

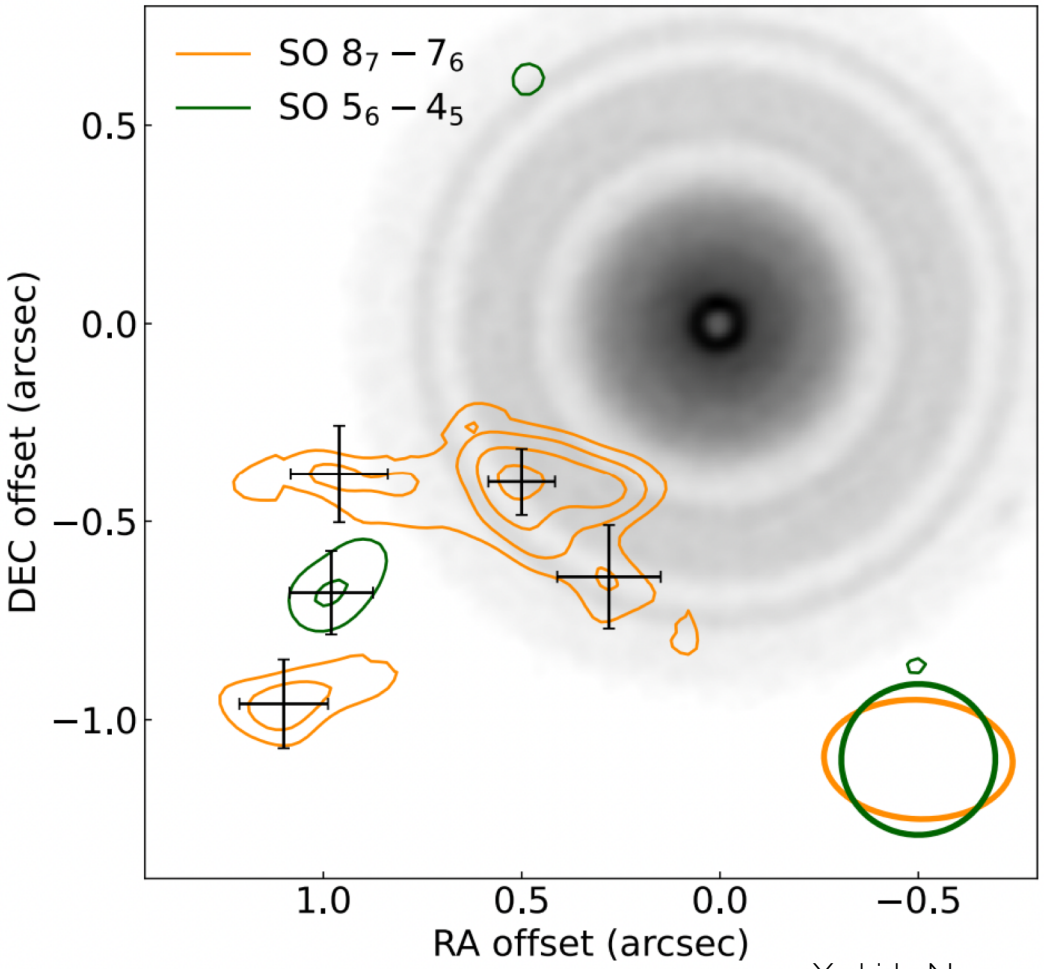
modeled mm dust



Mentiplay+18

Asymmetric SO detected in the TW Hya disk





Yoshida, Nomura, CJL+24

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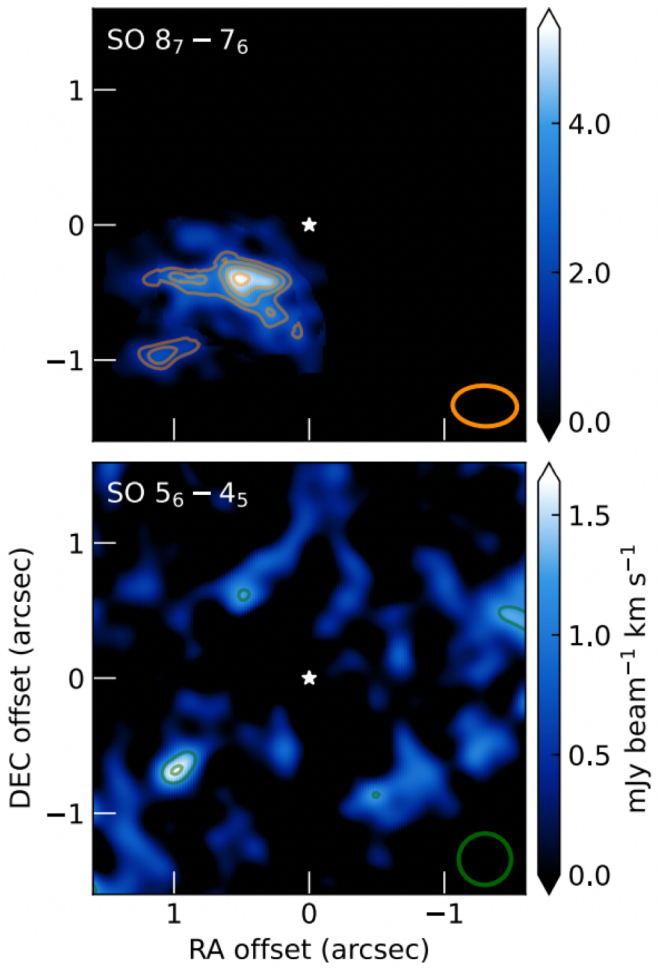
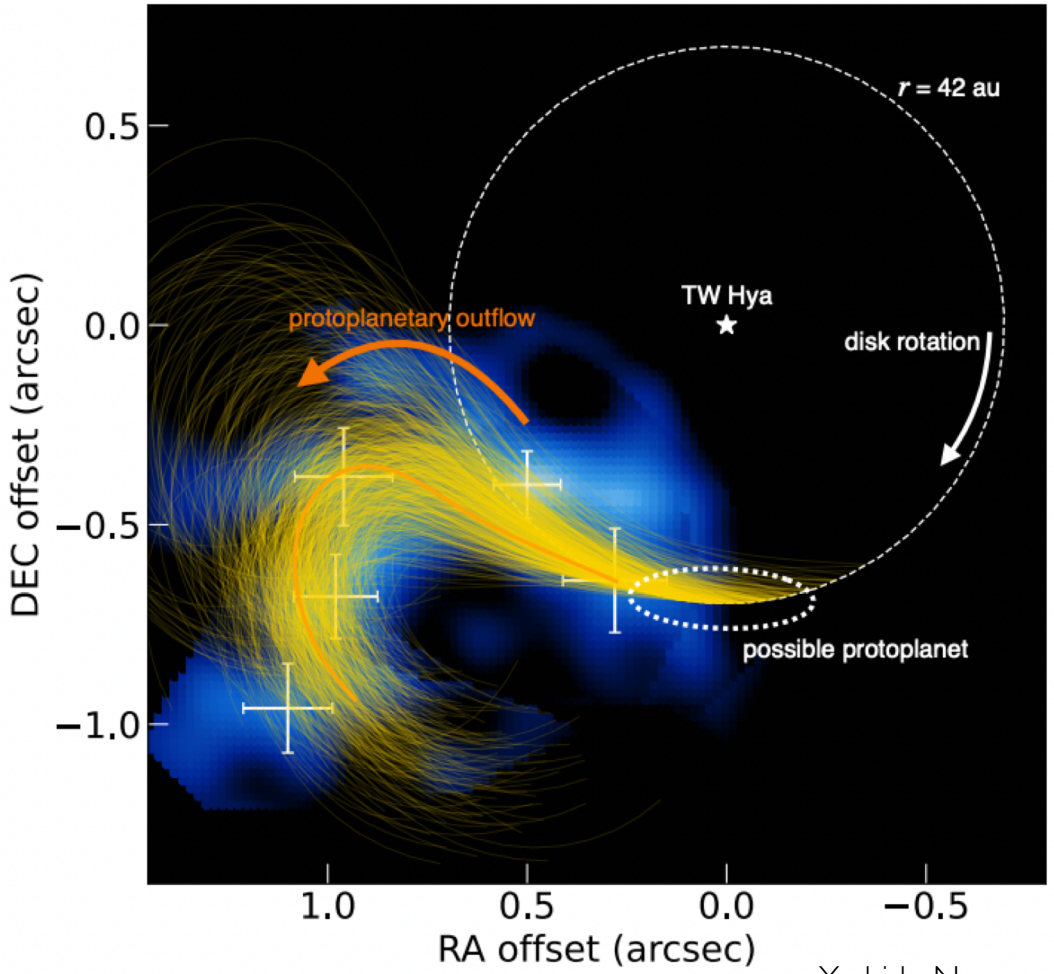
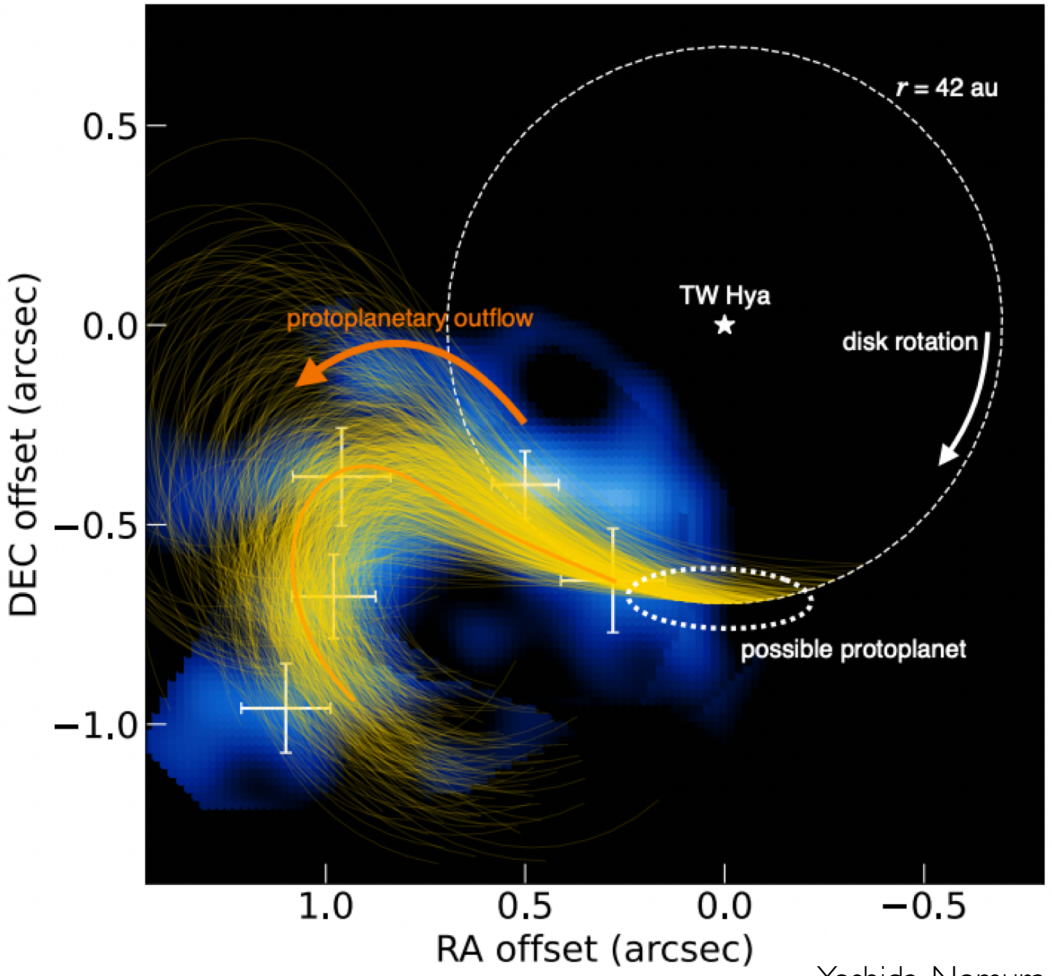




Yoshida, Nomura, CJL+24

Asymmetric SO detected in the TW Hya disk

- SO morphology and kinematics are consistent with a ballistic outflow
- Best-fit planet mass is ~4 $M_{\oplus}$ planet
- Mass-loss rate of ~10^{-6} to 10^{-8} M_{Jup} yr^{-1}
- Unique opportunity to probe the earliest phase of planet formation



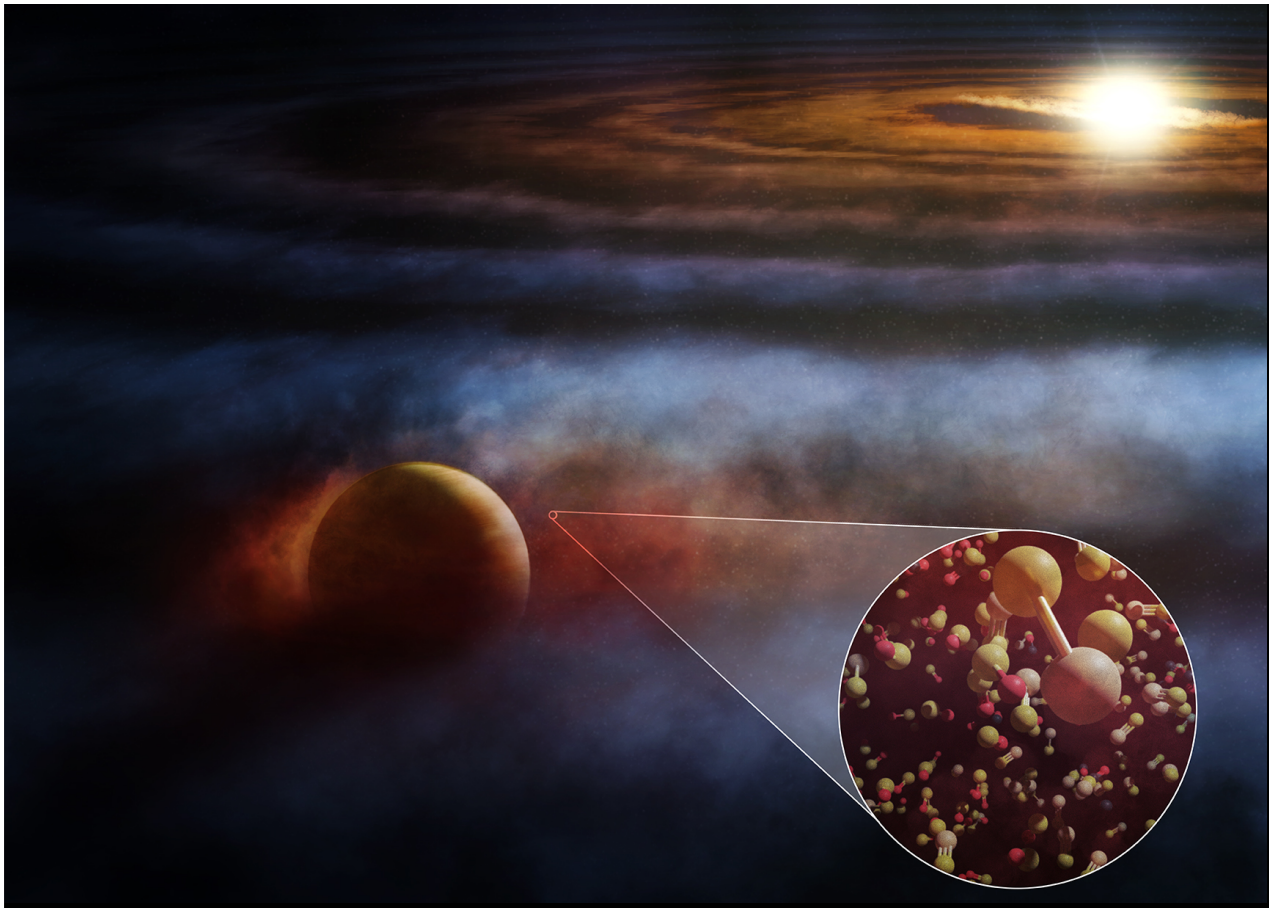
Yoshida, Nomura, CJL+24

The future is bright

- **Several** ongoing or recently-accepted Large Programs focused on gas content of protoplanetary disks
  - DECO *(PI: I. Cleeves)* targets 80 disks in many lines, including CS and SO
  - CHEER *(PI: J. Pegues)* will target 20 Herbig disks in many S-bearing molecules (H_2CS, SO, SO_2, SiS)
  - SMA-SPEC *(PI: K. Öberg)* is observing 40 disks in a total ~110 GHz of bandwidth
  - WSU ALMA will vastly improve bandwidth of ALMA

Summary

- Multi-line observations of sulfur species in the HD 163296 disk provide:
  - Spatially-resolved gas conditions
  - Gas density in planet-carved gap
  - Robust measurement of ^{34}S fractionation
- Planet-driven outflow in SO in TW Hya reveals ~4 $M_\oplus$ planet
- Sulfur-bearing molecules provide a powerful window into planet formation!



Thank you!