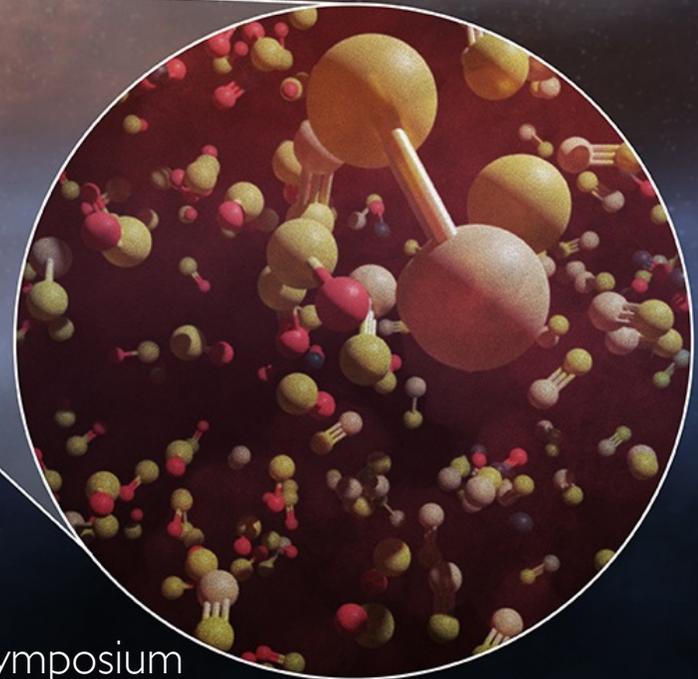


# Chemical Signatures of Ongoing Planet Formation in Protoplanetary Disks

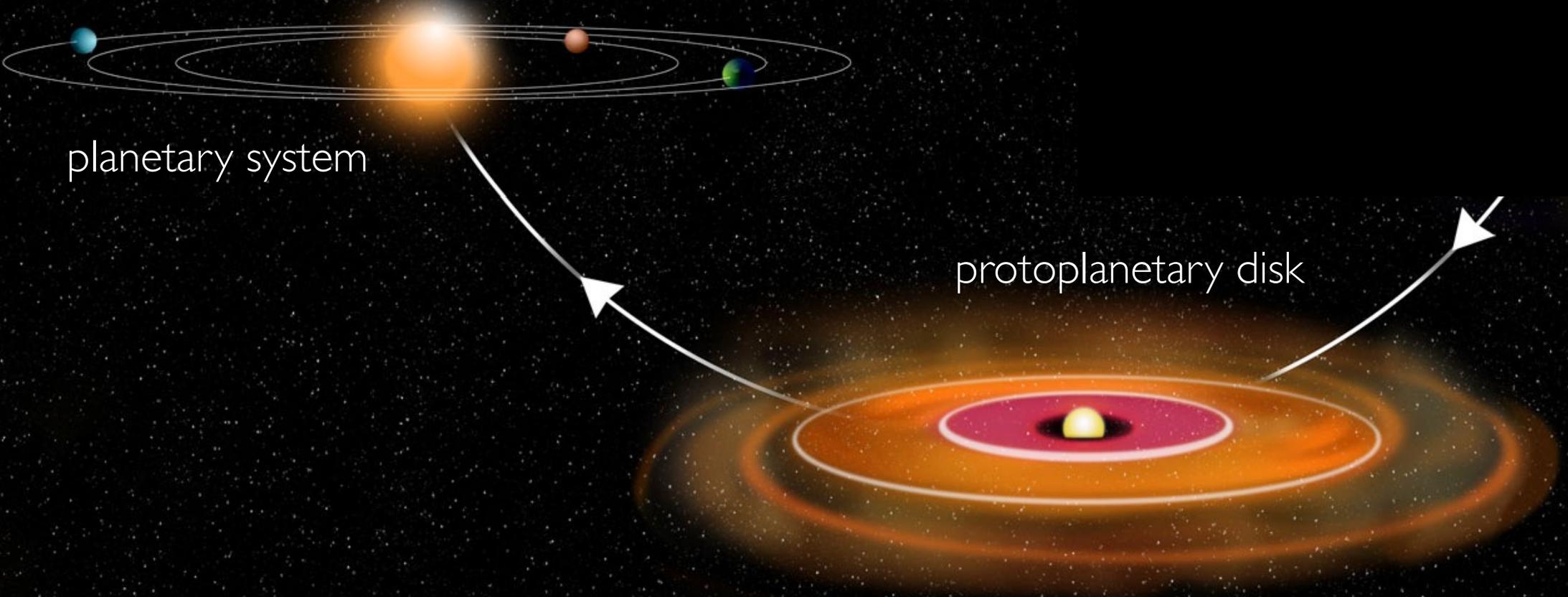
Charles J. Law  
*(University of Virginia)*

*Coauthors: Alice Booth & Karin Öberg*

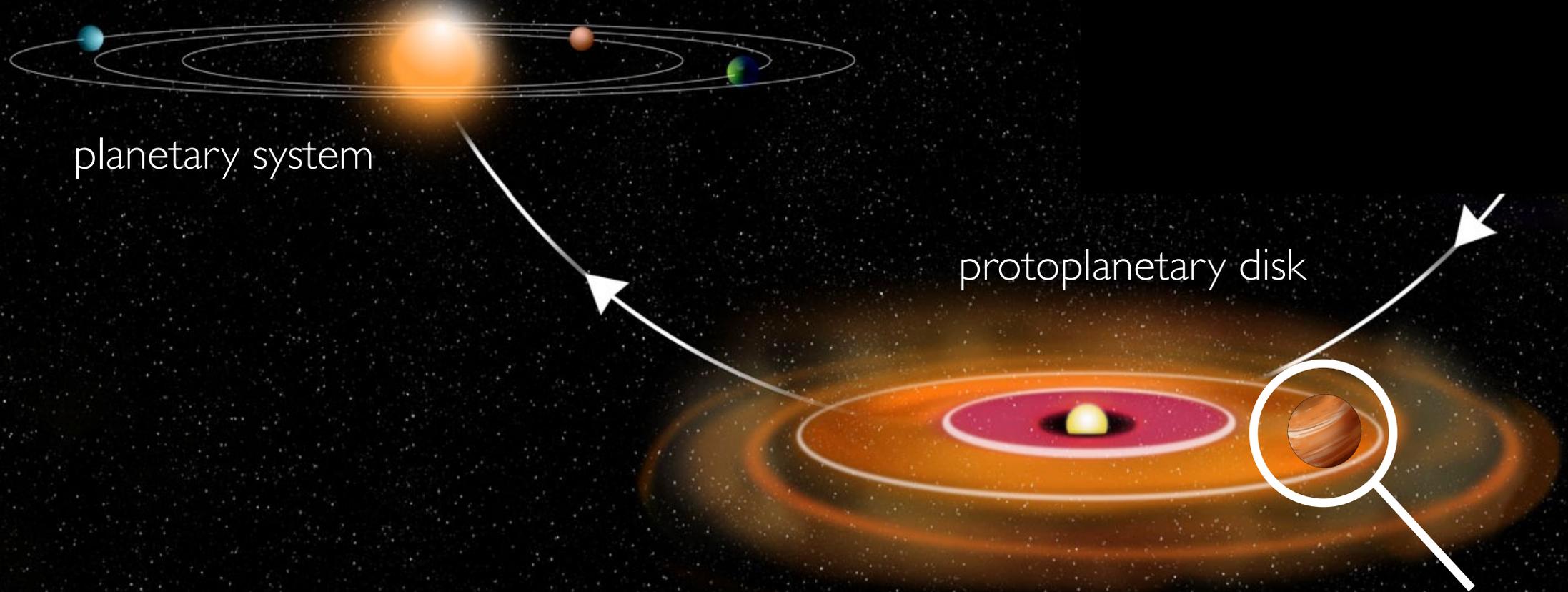
'23 NASA Hubble Fellowship Program (NHFP) Symposium



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.

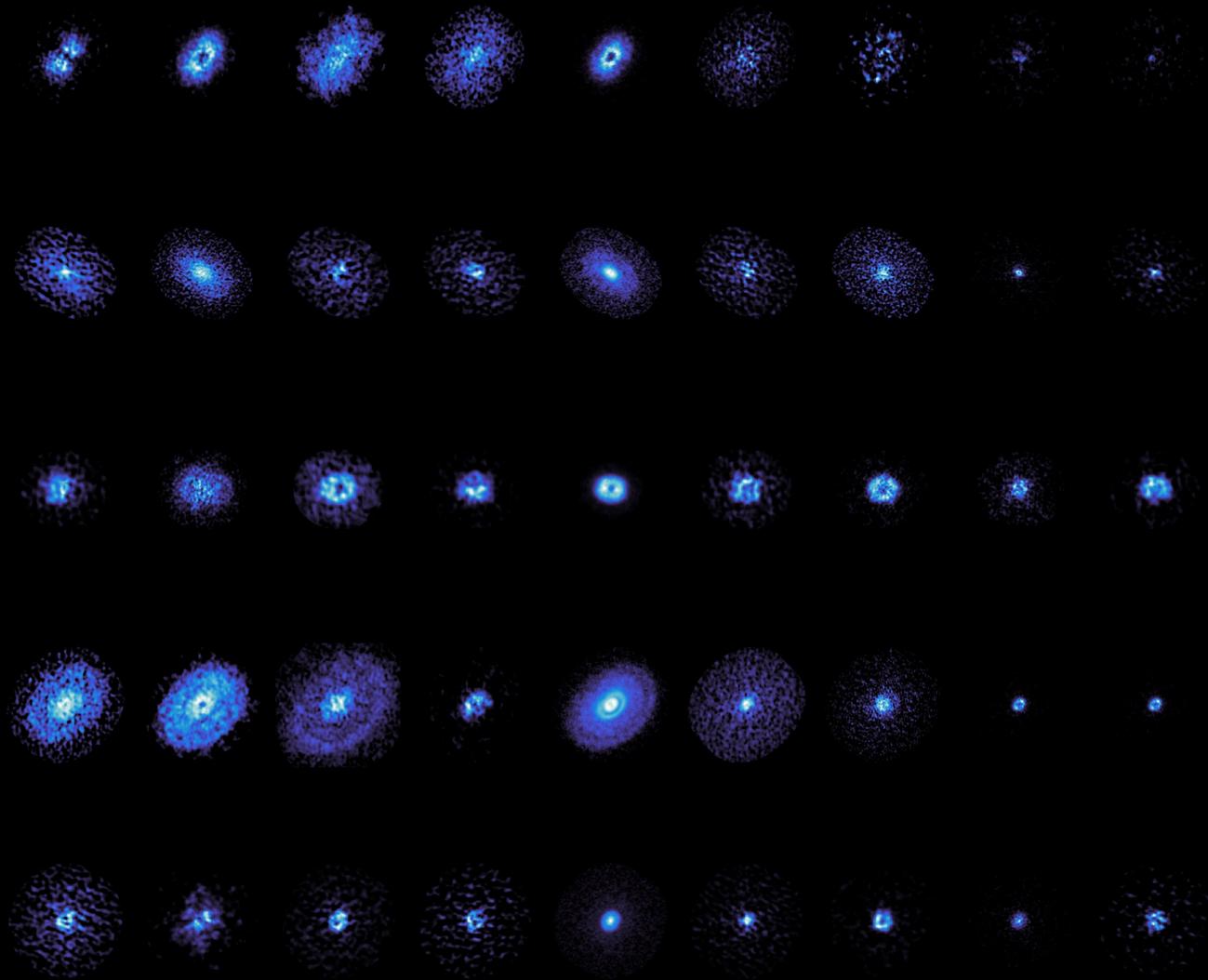


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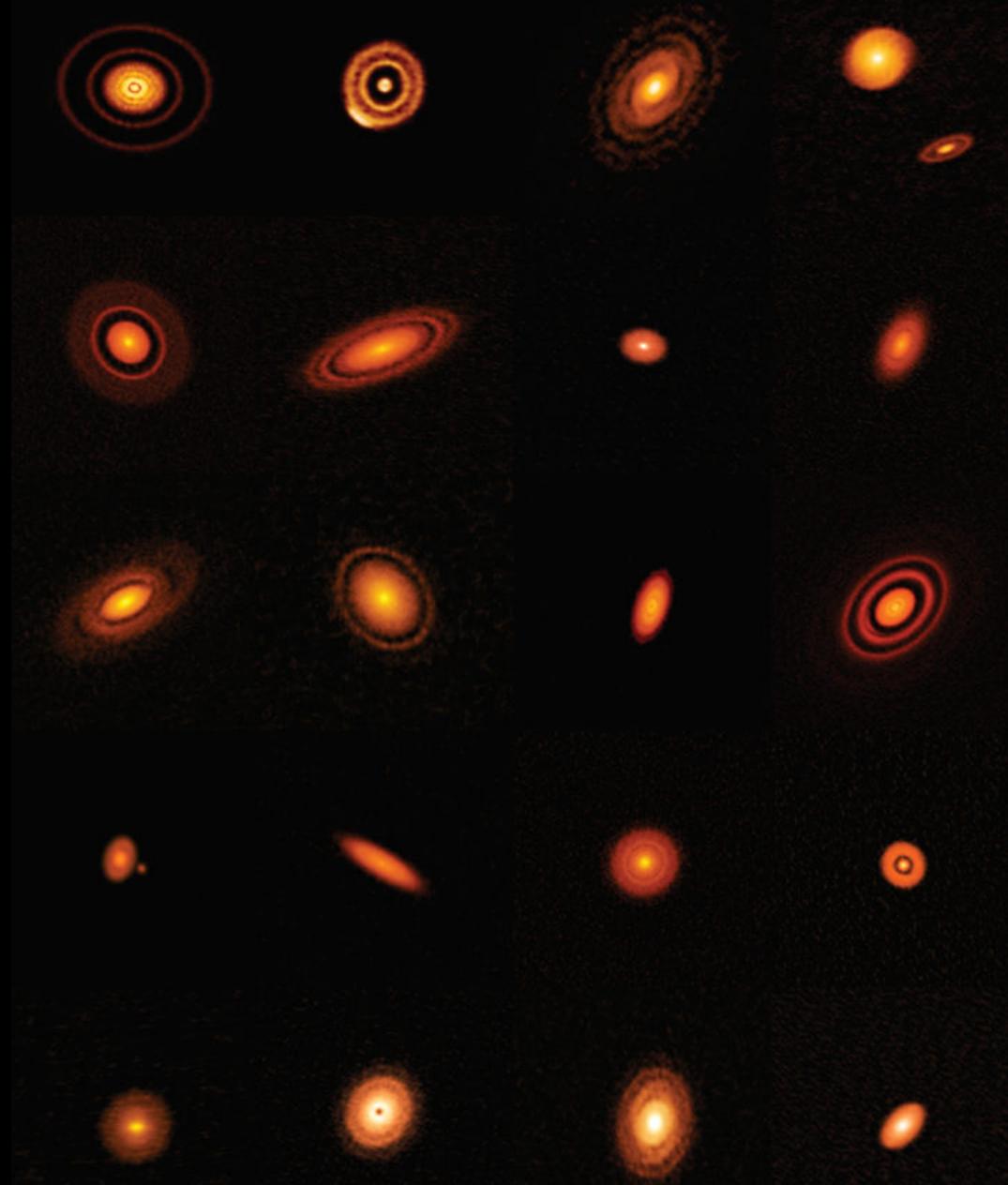


Planet formation is well underway and thus we can directly observe the environments from which planets are actively assembling.

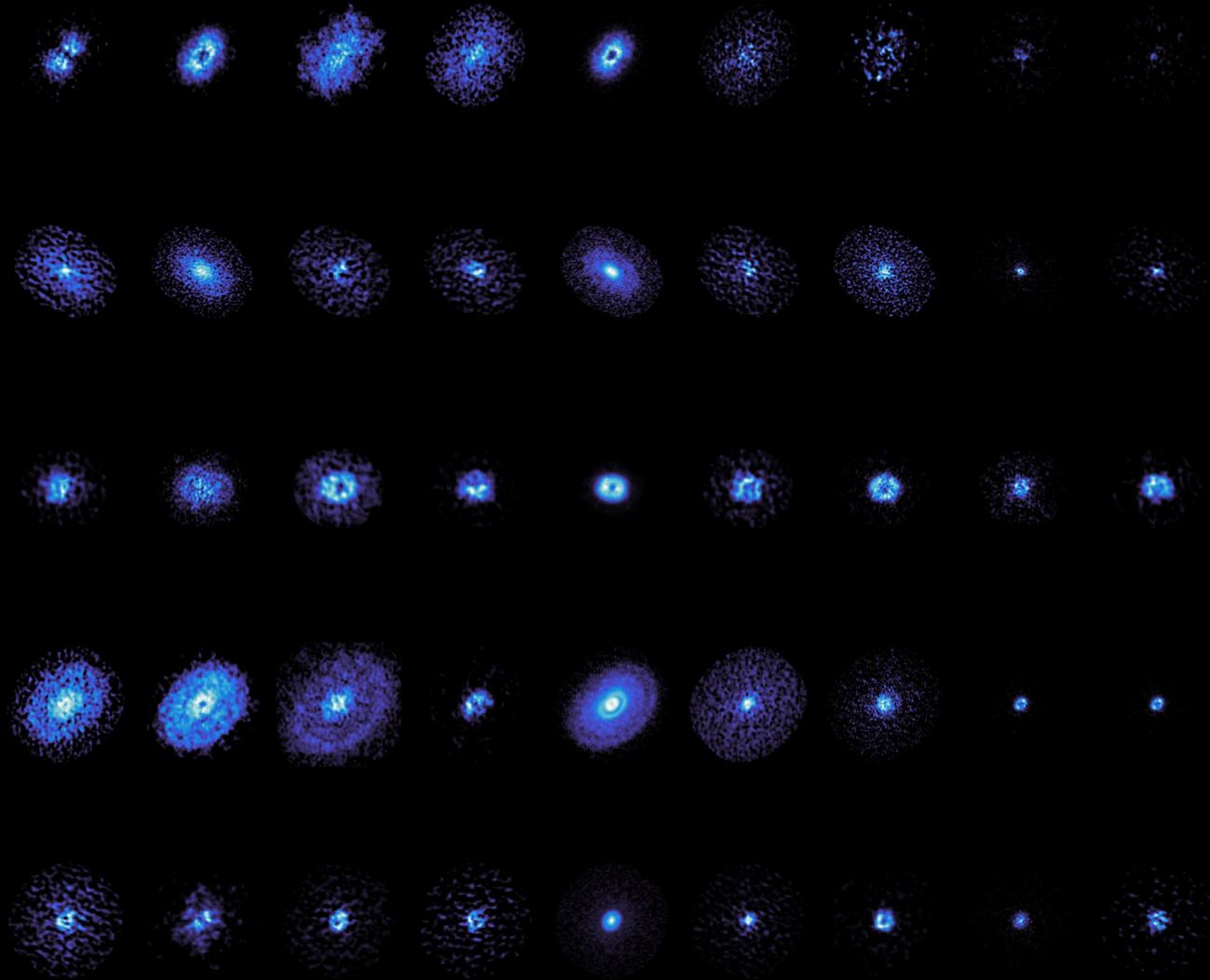
molecular line emission (MAPS / Öberg+21)



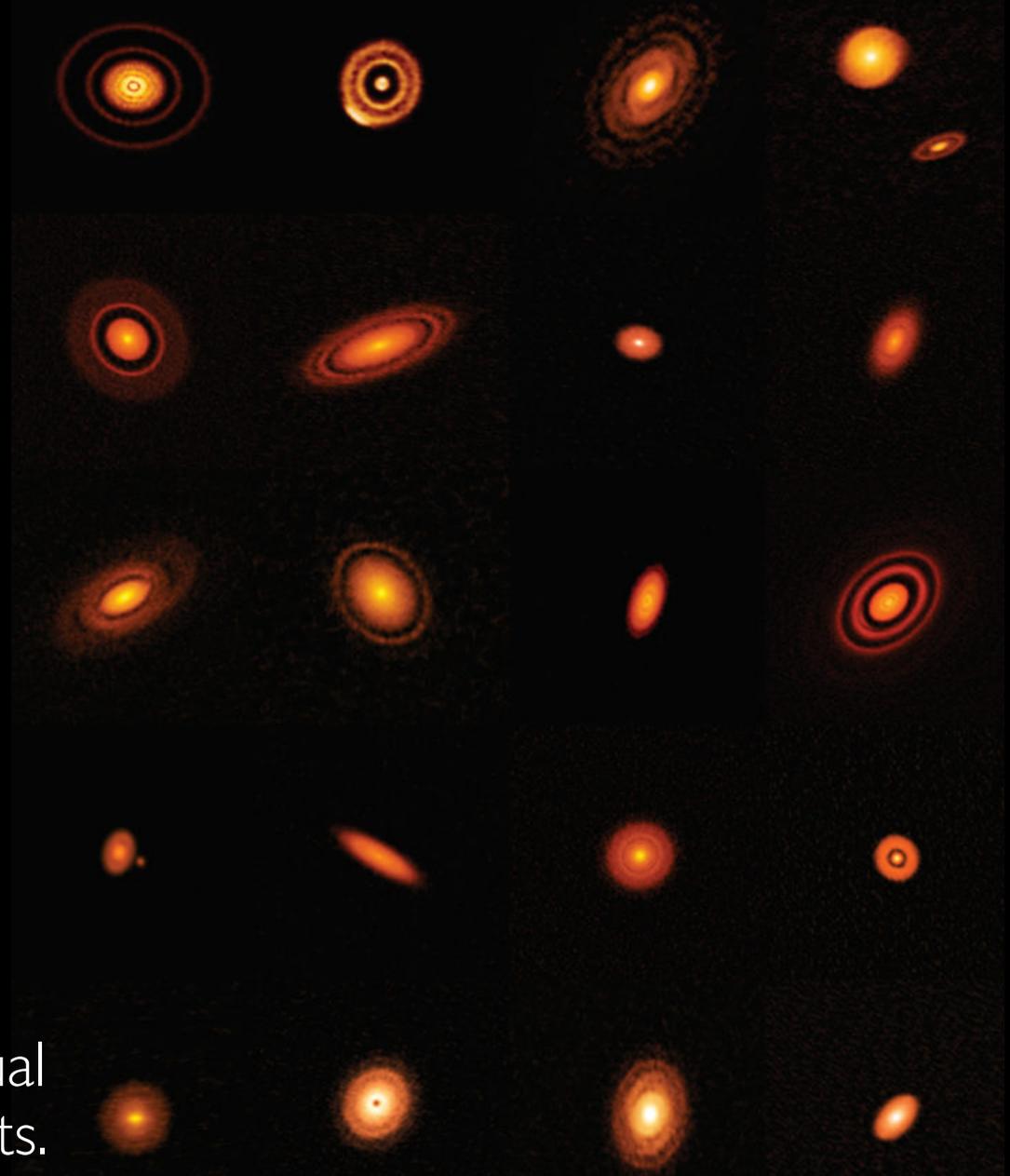
mm dust (DSHARP / Andrews+18)



molecular line emission (MAPS / Öberg+21)



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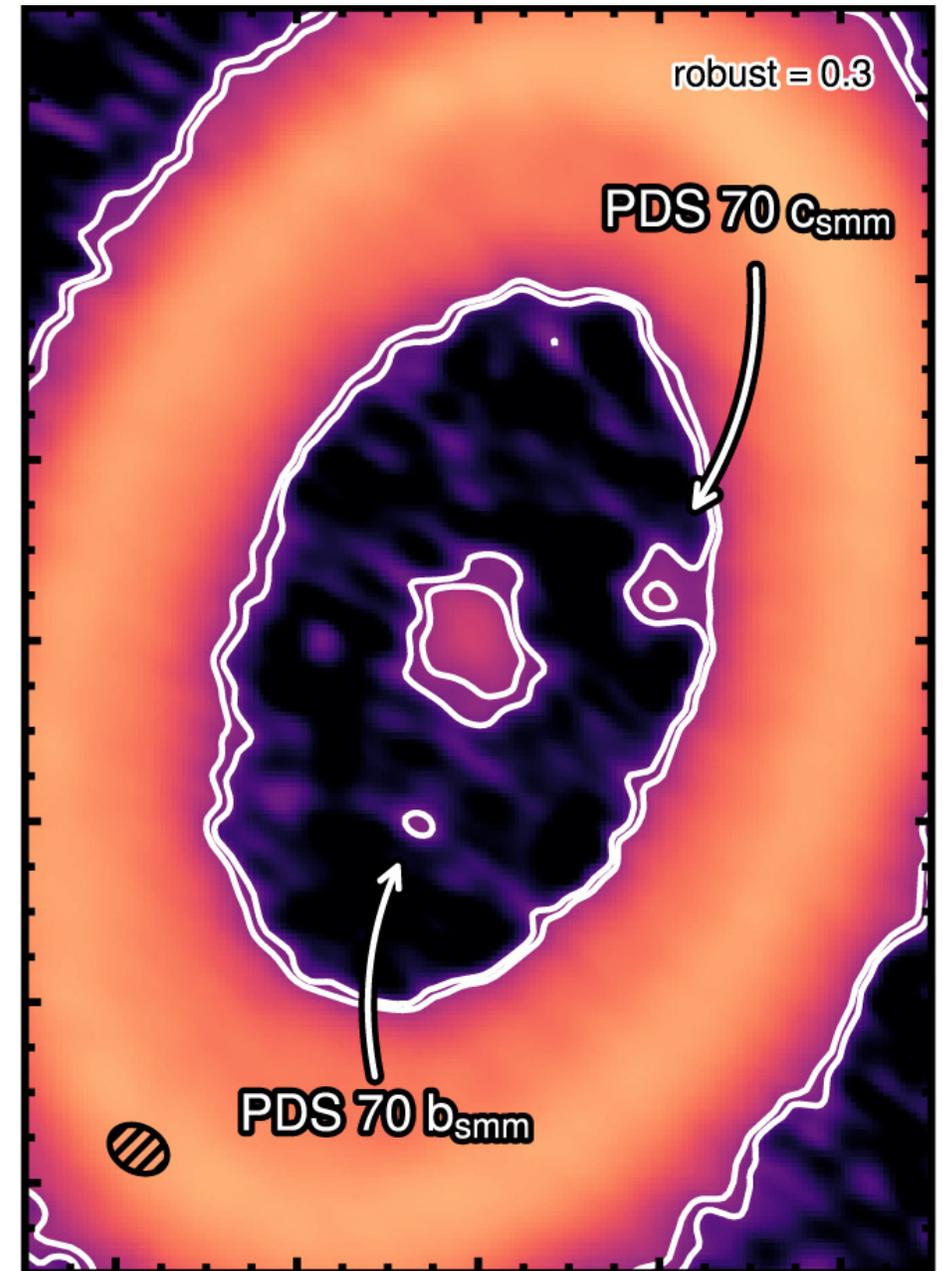
Remains difficult to unambiguously connect individual substructures with the location/properties of planets.

# Circumplanetary disks

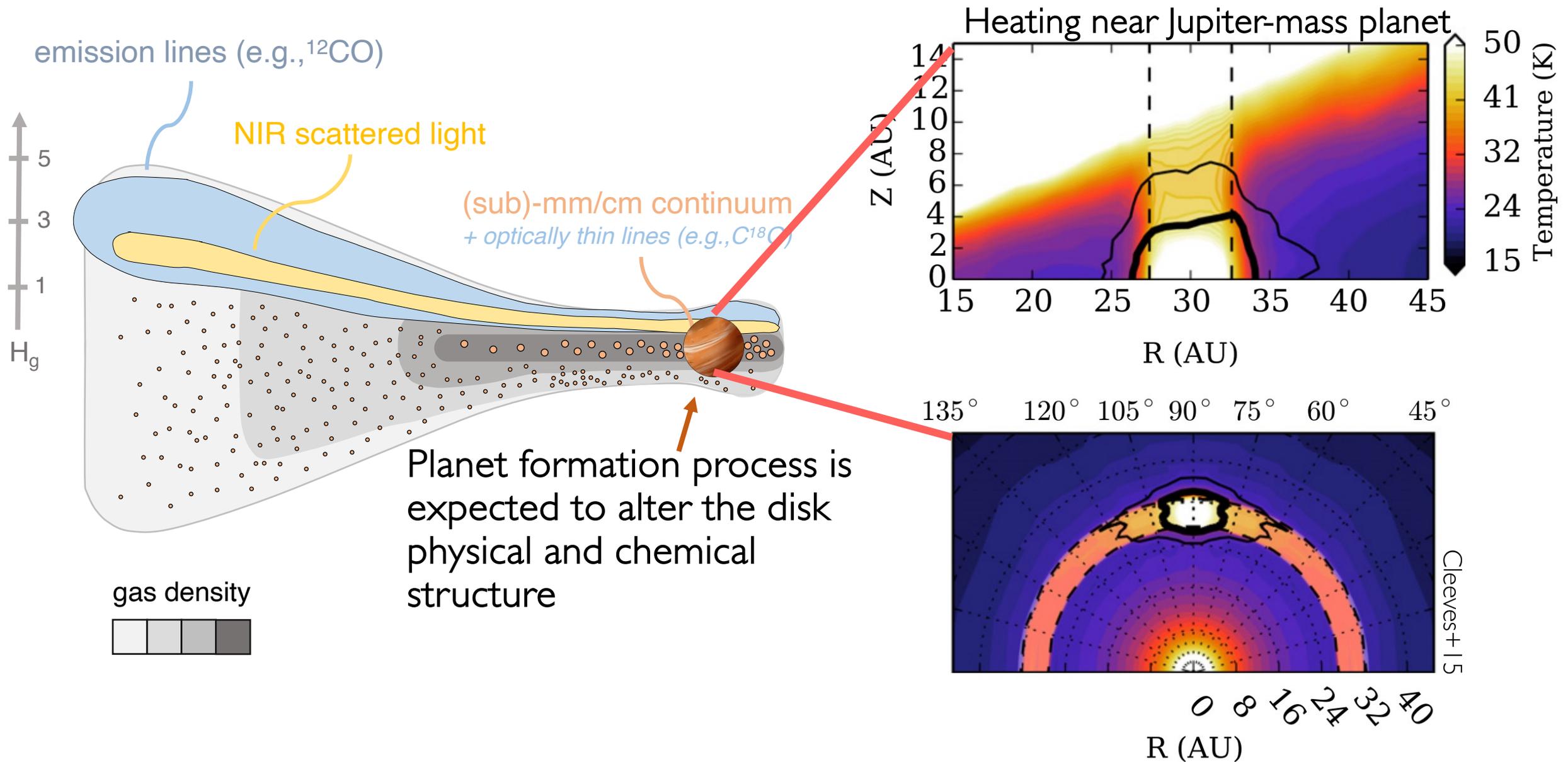
In a few systems, circumplanetary disks have been detected in their mm dust (PDS 70).

Such detections remain relatively scarce (e.g., Andrews et al. 2021), which may be due to mm dust depletion and high gas-to-dust ratios ( $> 1000$ ) in CPDs (Karlin et al. 2023).

But what about the prospects of using chemistry as a planet tracer?

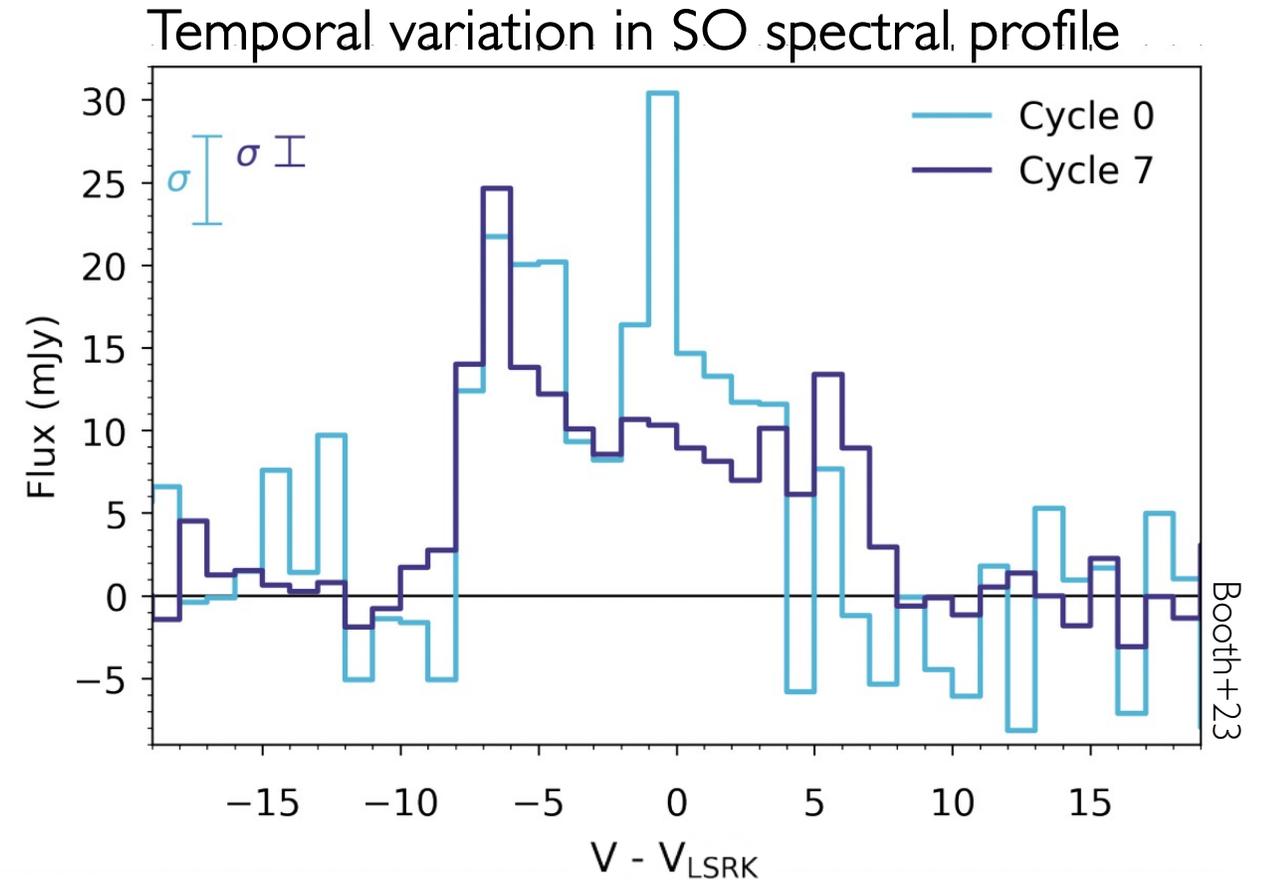
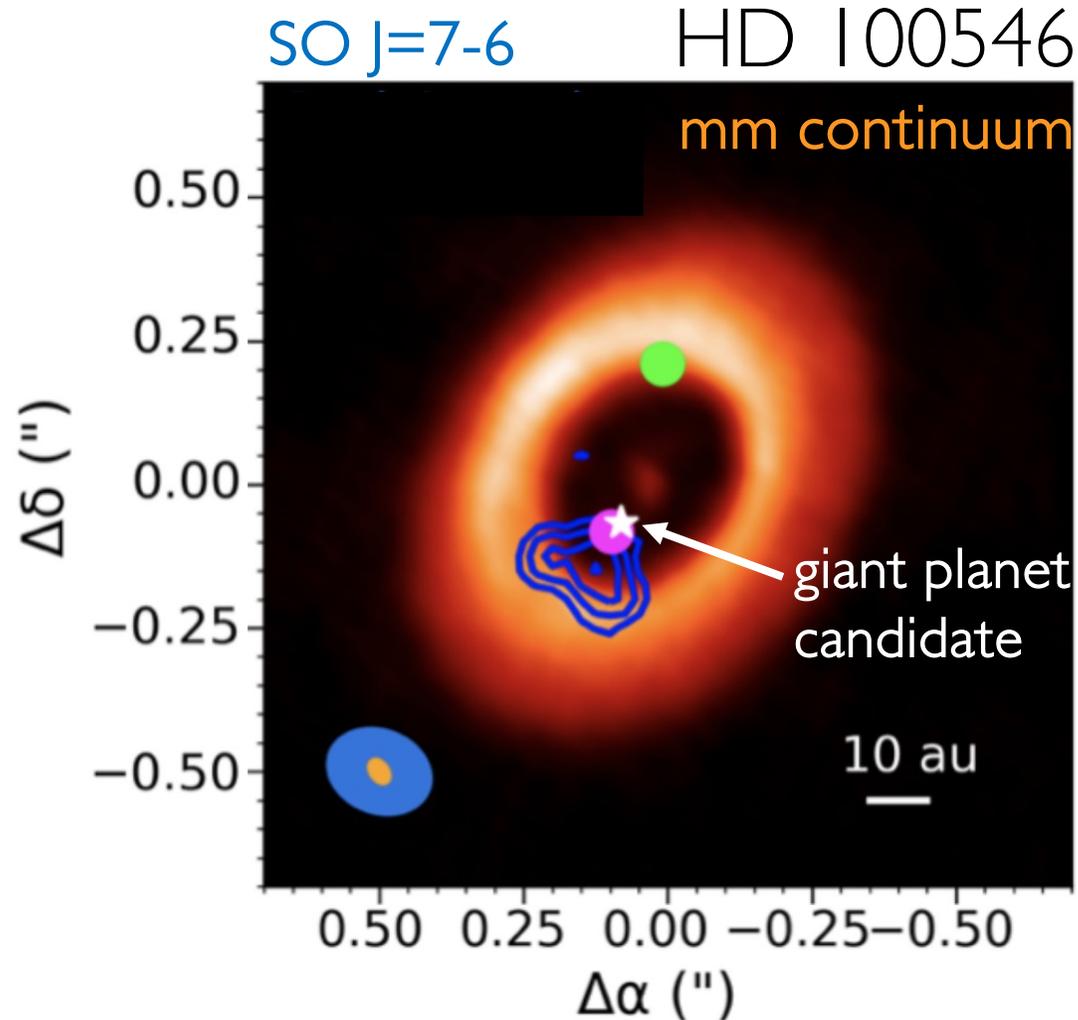


# Chemical signatures of embedded planets in disks



# Chemical signatures of embedded planets in disks

- Localized SO emission traces planet candidate in the HD 100546 disk and shows temporal variability over  $\sim 8.5$  years, or  $1/5^{\text{th}}$  of an orbit of a planet at 10 au



# HD 169142 disk

- Nearby ( $d = 115$  pc) Herbig star with a face-on protoplanetary disk

*Raman+06, Panić+08*

- Hosts multiple rings and gaps in NIR/scattered light, cm, and mm

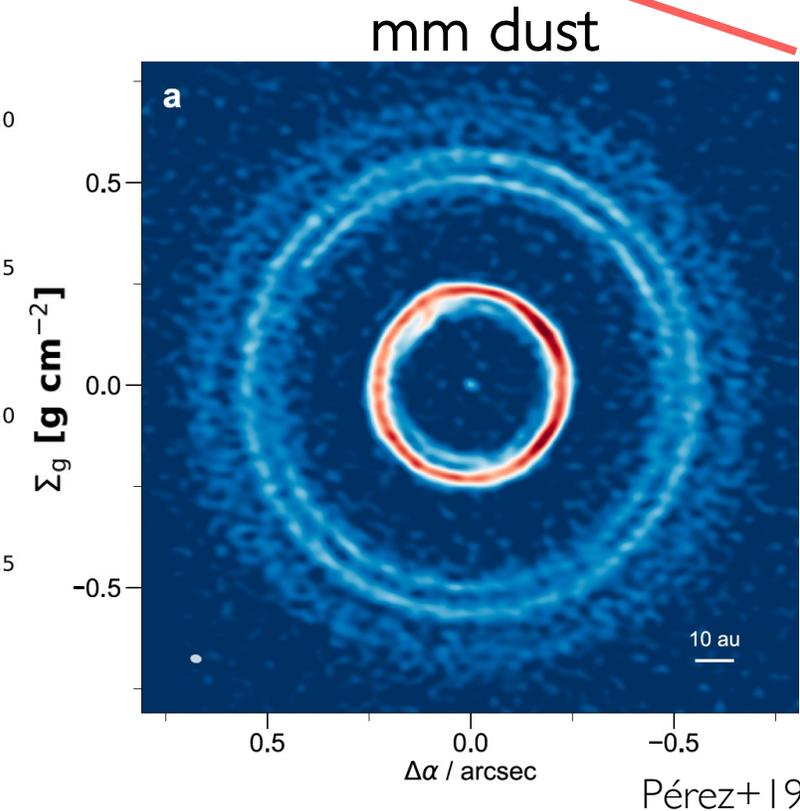
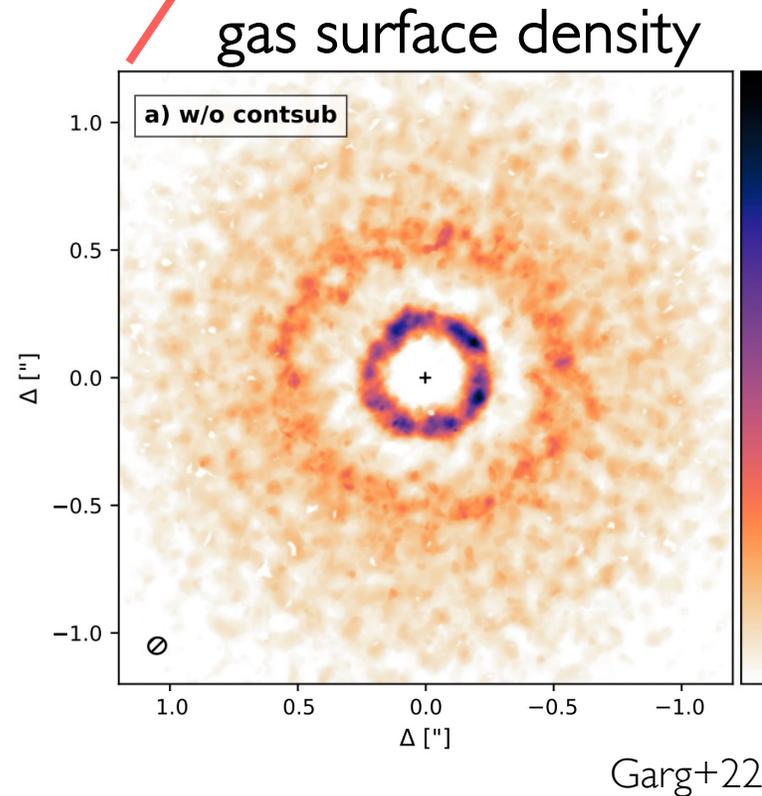
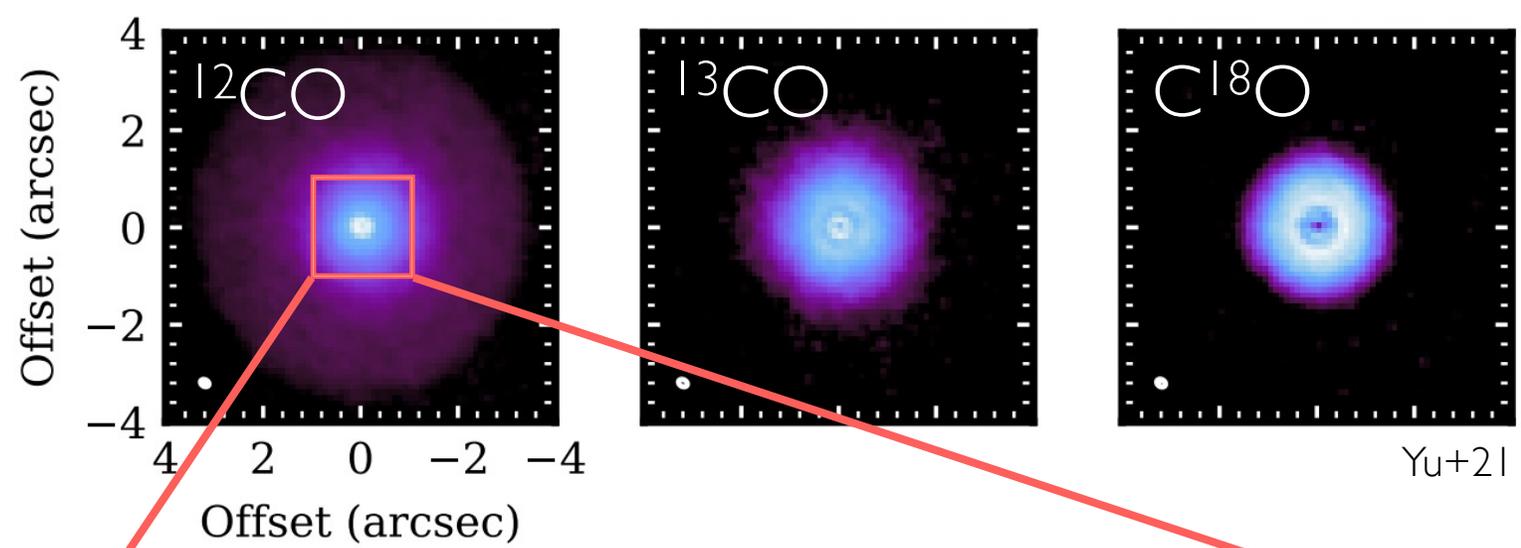
*e.g., Honda+12, Ligi+18, Gratton+19, Pérez+19*

- Gas-rich disk with existing CO and DCO<sup>+</sup> observations

*Fedele+17, Yu+21, Garg+22*

- Evidence for a giant protoplanet ( $\sim$ few  $M_{\text{Jup}}$ ) at 38 au, including gas-/dust-depleted gap and kinematic excess

*Bertrang+18, Pérez+19, Toci+20, Leemker+22*



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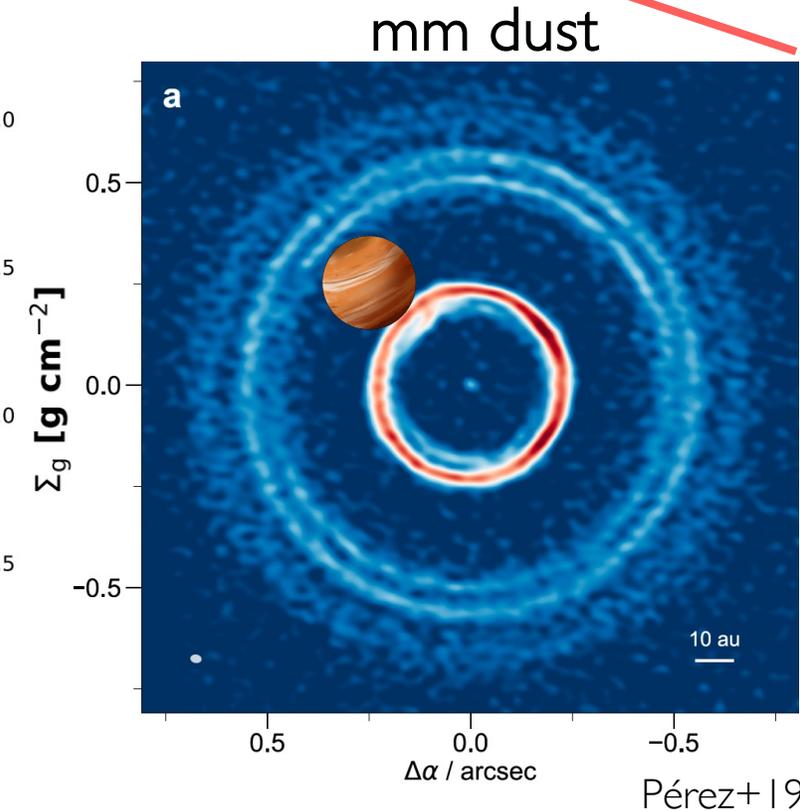
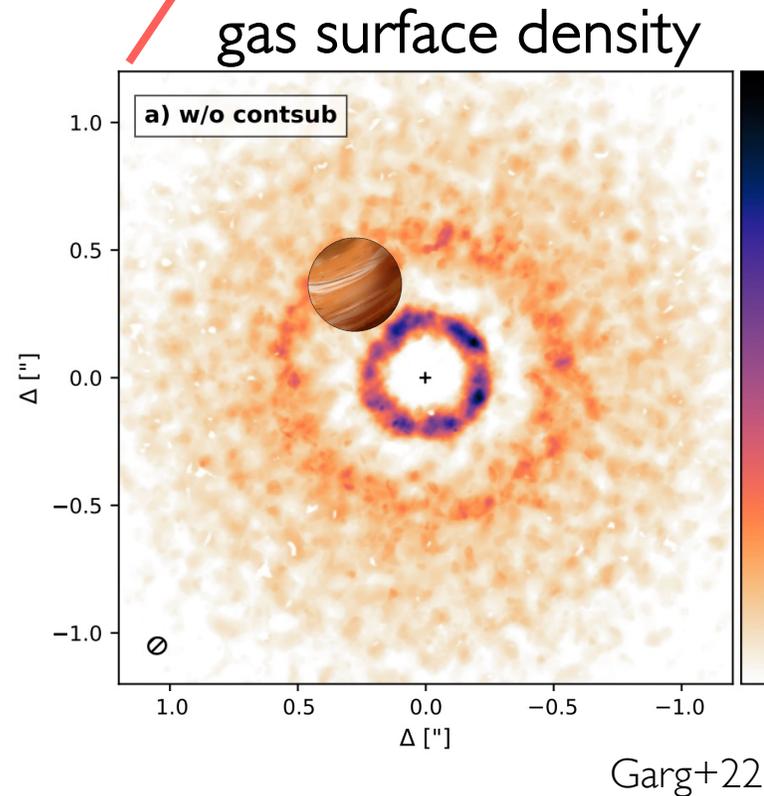
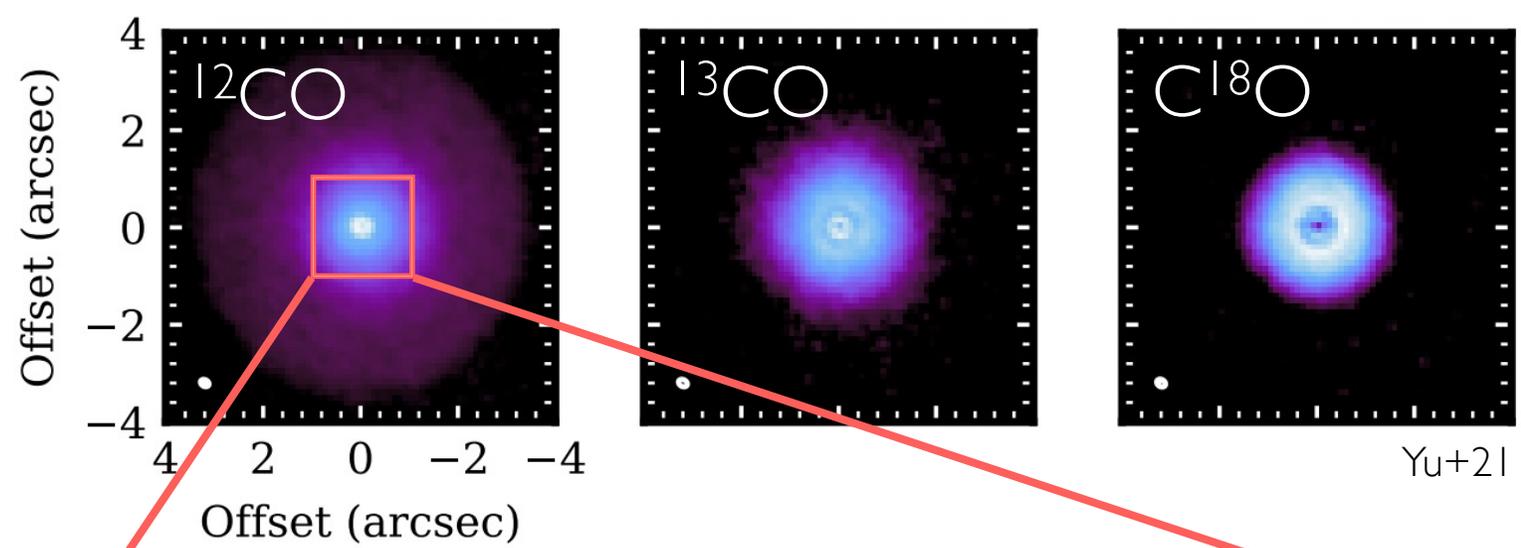
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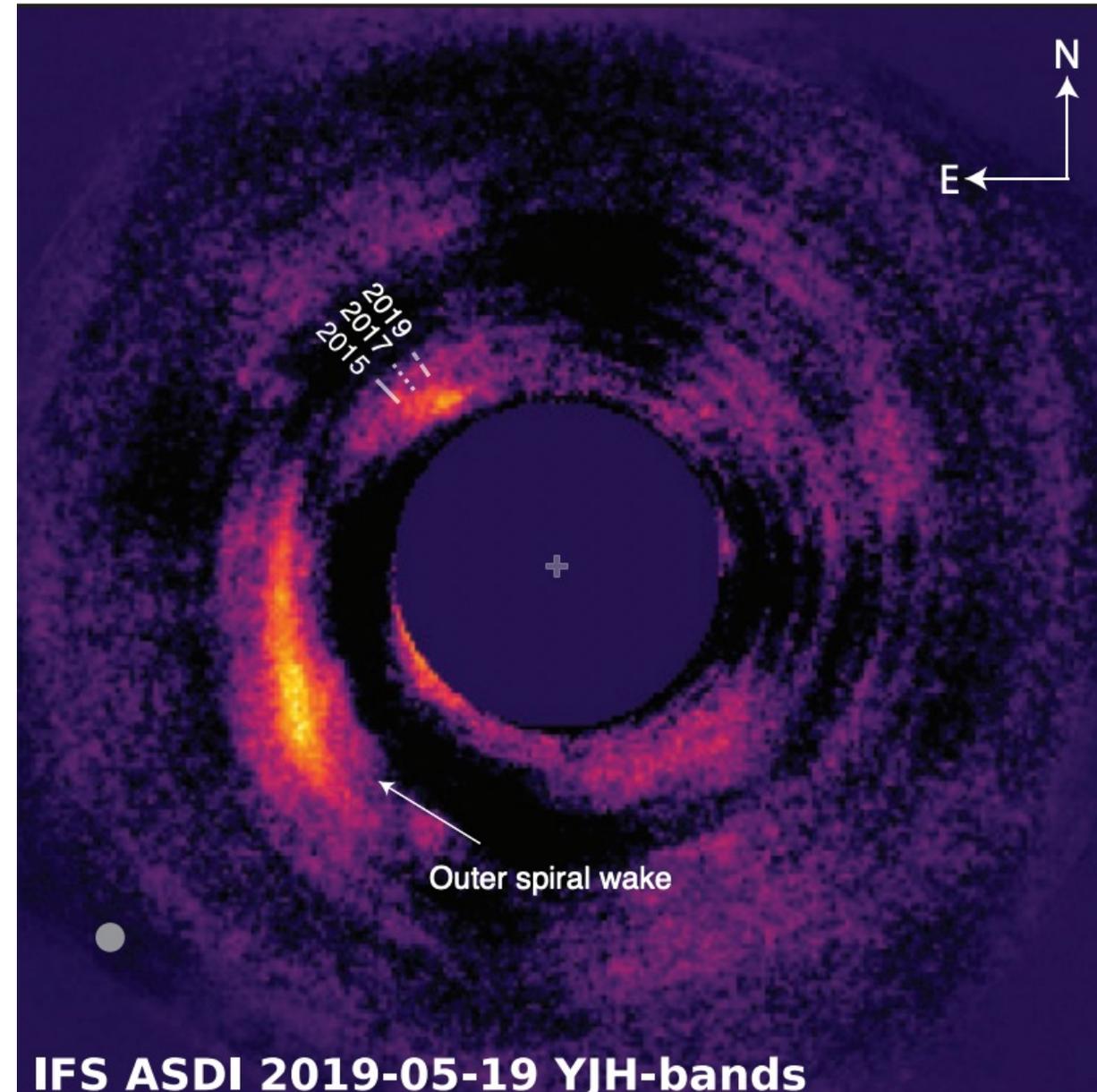
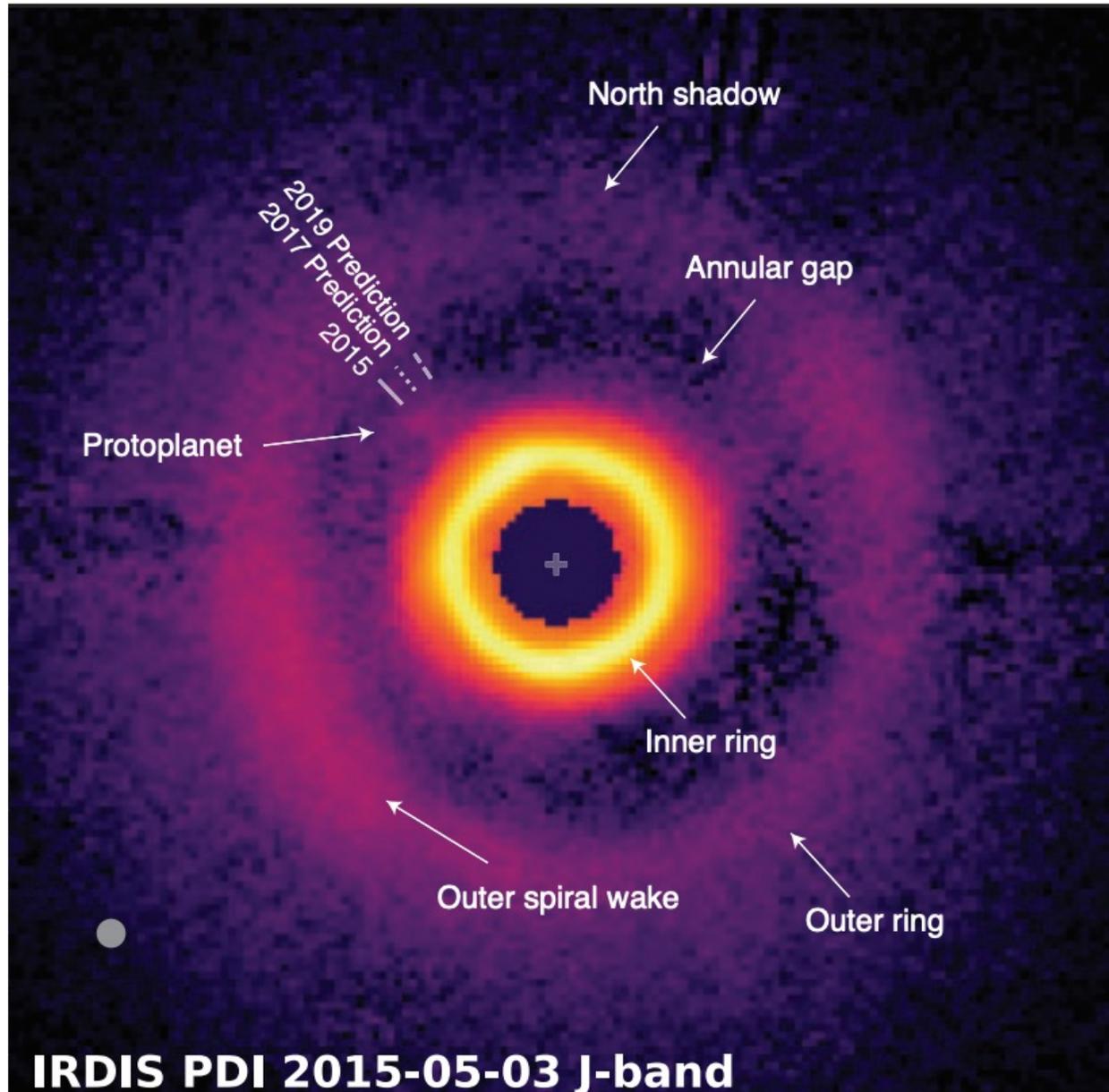
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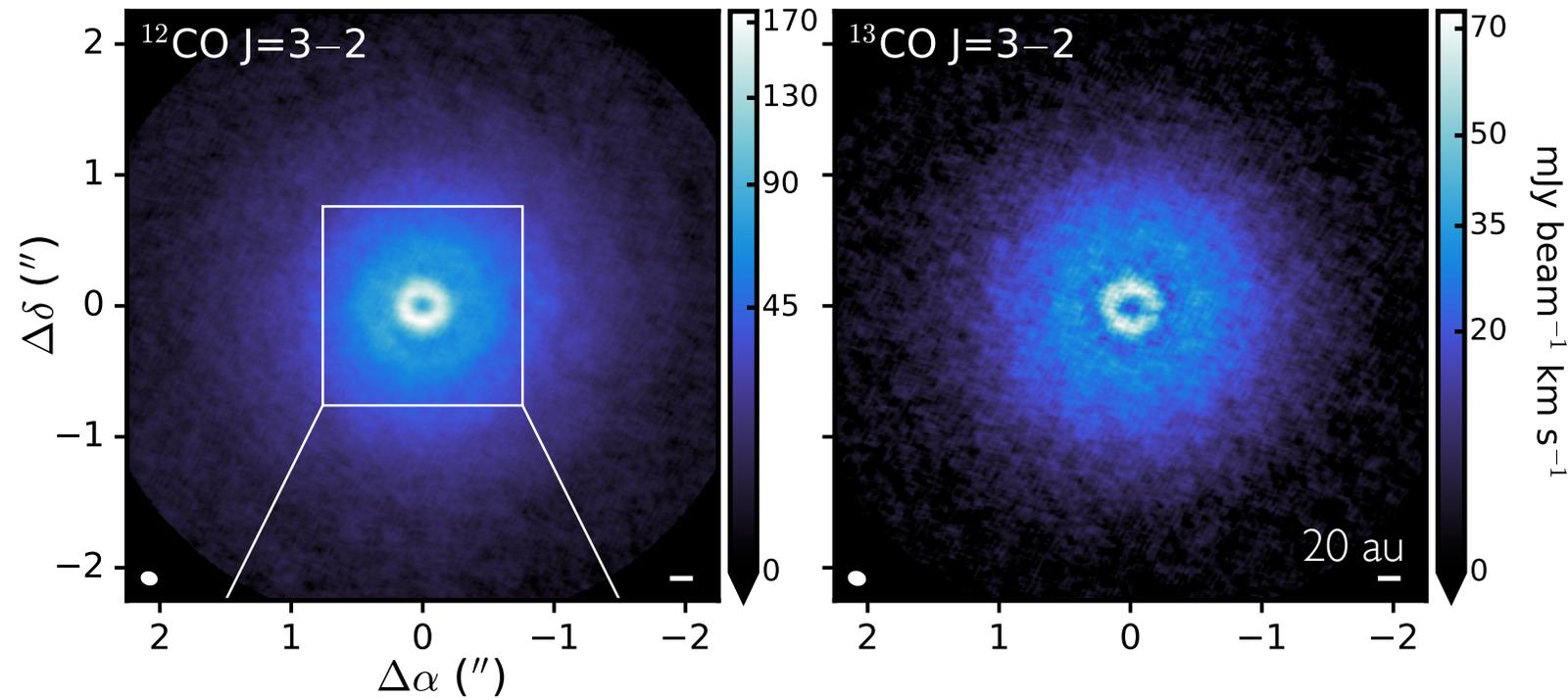
# Recently-confirmed protoplanet HD 169142 b

Hammond+23



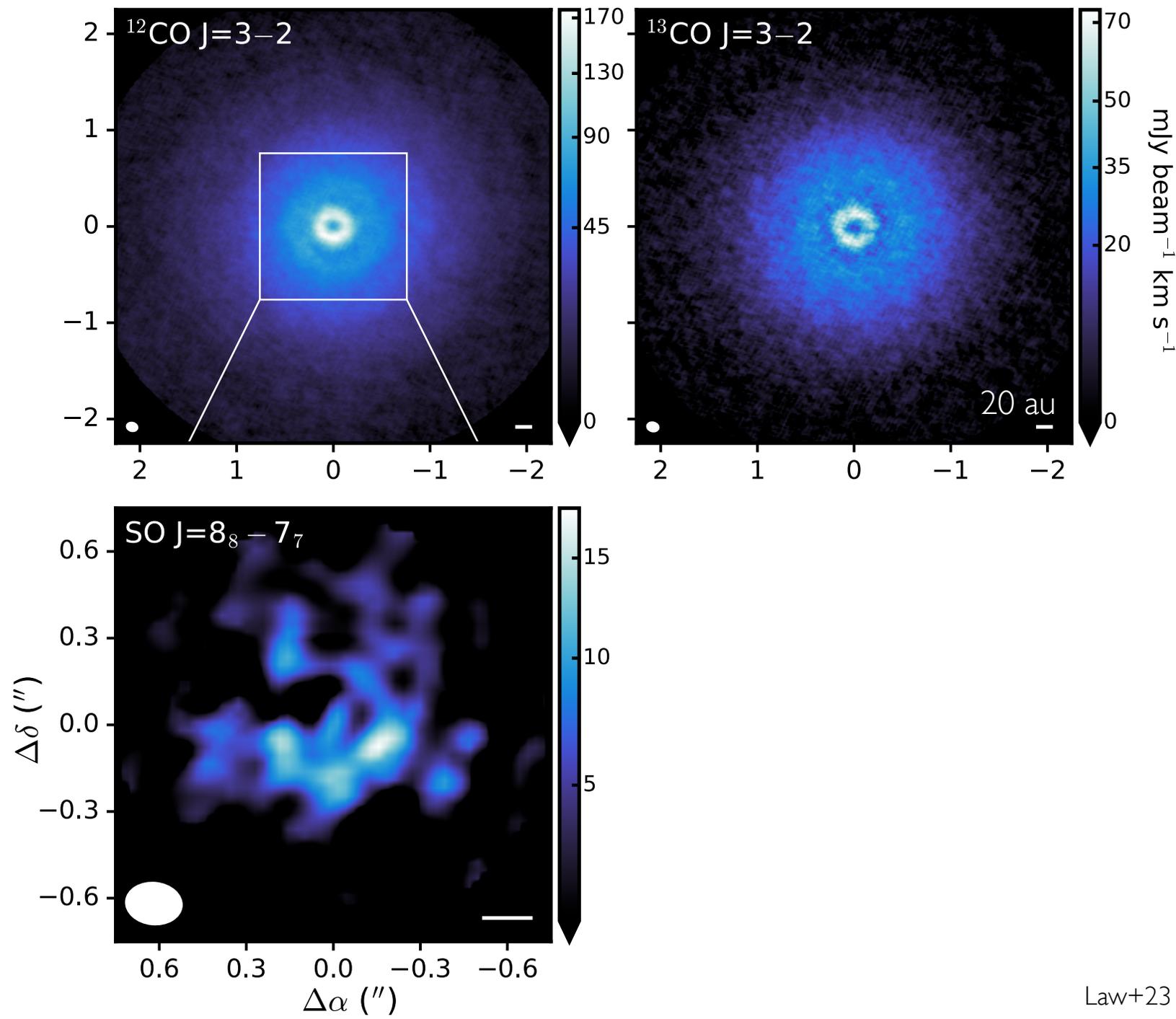
# ALMA archival data

- High-resolution ( $\sim 0.''2$  / 20 au) observations in ALMA archive
- Covered  $^{12}\text{CO}$  &  $^{13}\text{CO}$   $J=3-2$  but also several other lines of interest in a “continuum” window ( $\sim 0.45$  km/s)



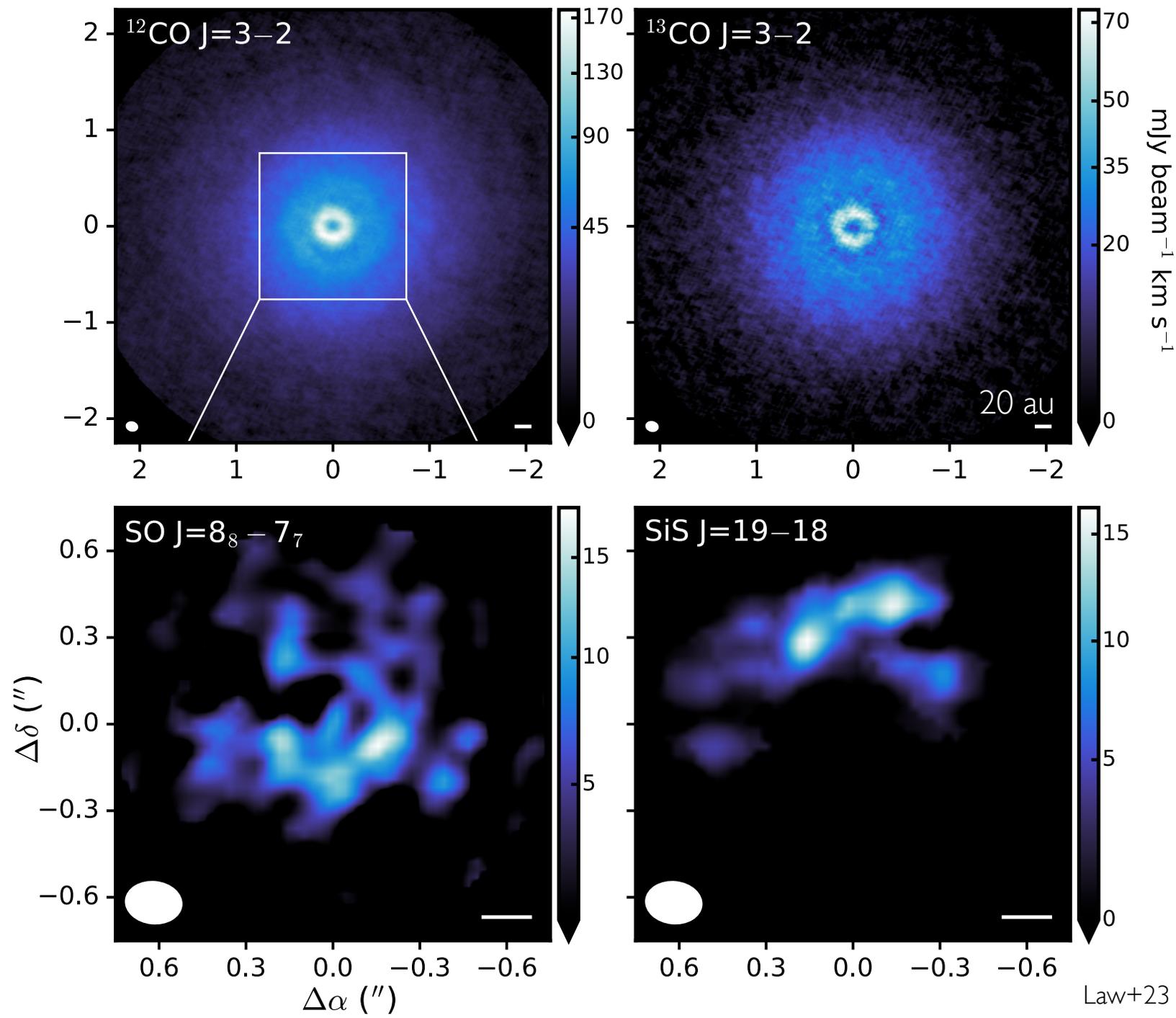
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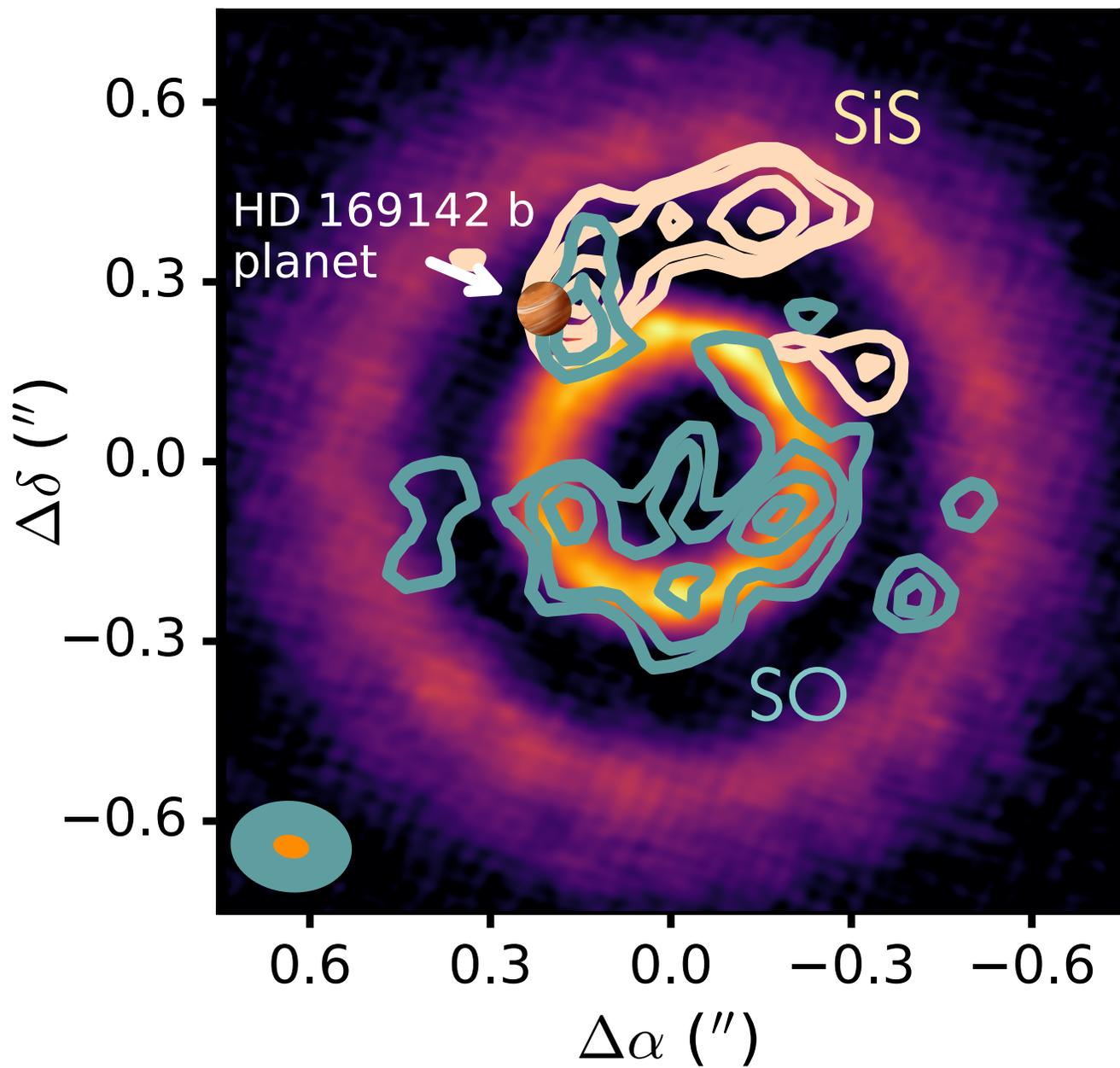
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  - Thermal desorption of S-rich ices



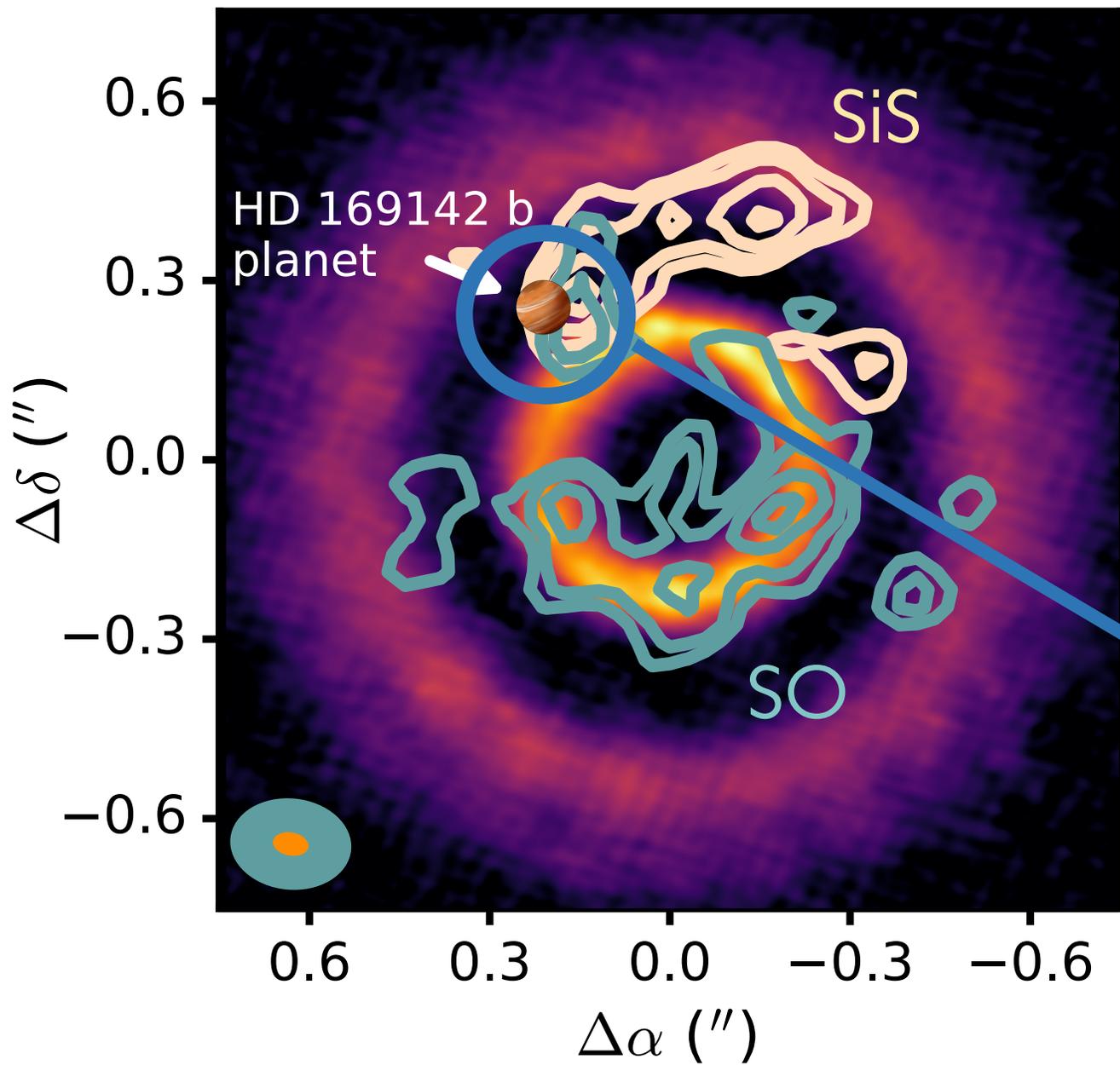
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- Bright, ring-like SO emission and 5<sup>th</sup> detection in a disk
  - Thermal desorption of S-rich ices
- First detection of SiS in a disk!





SO and SiS emission  
at planet location!

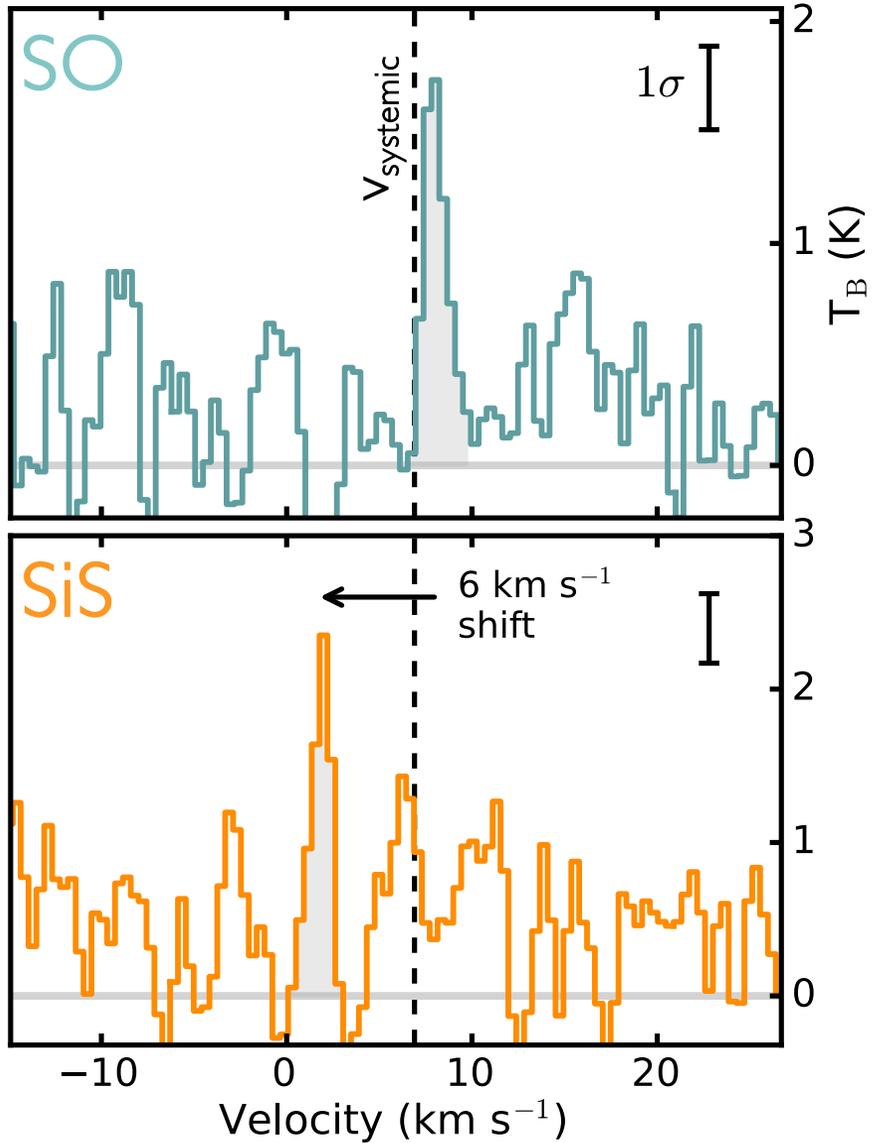


SO and SiS emission  
at planet location!

Extract spectrum here

# SiS is non-Keplerian and blue-shifted

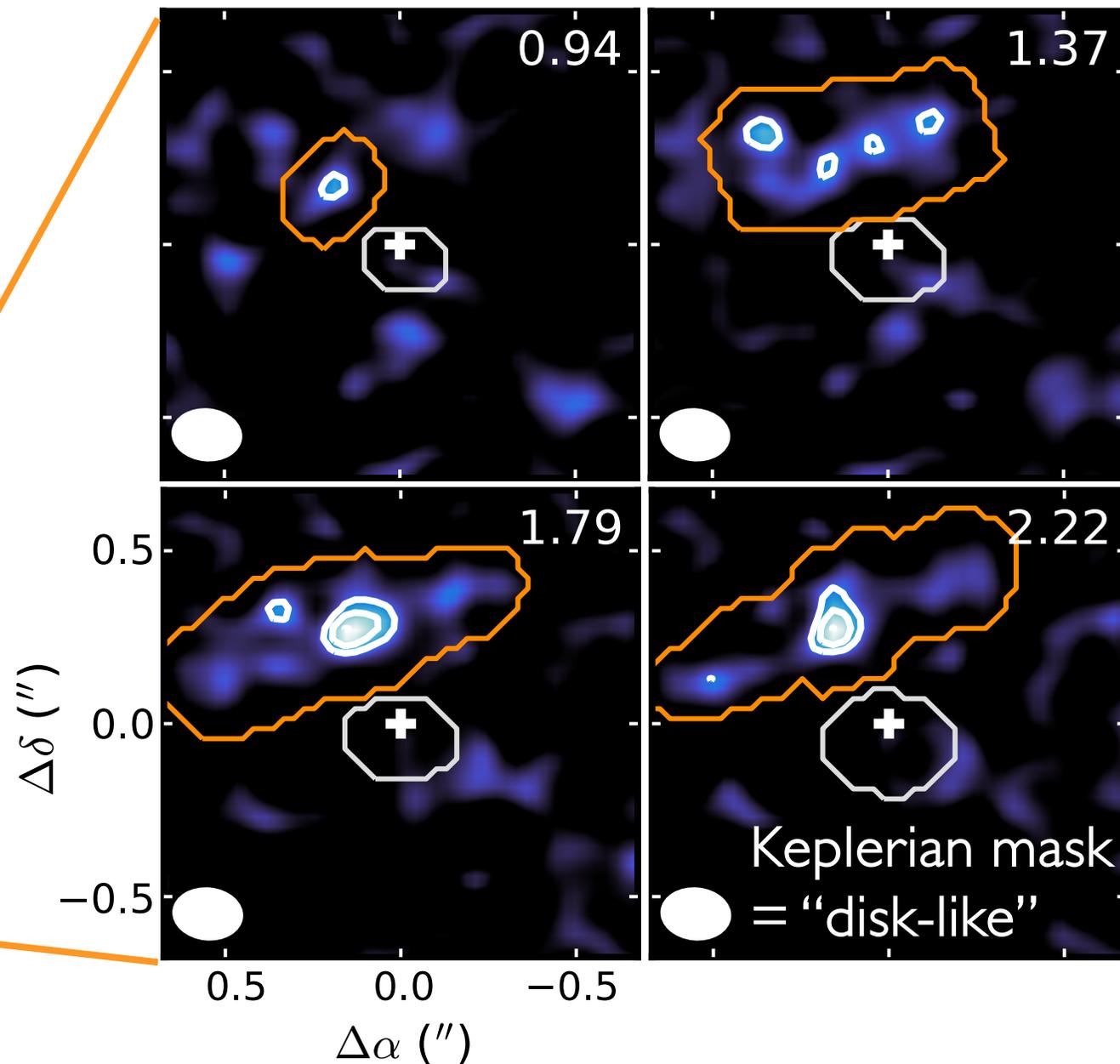
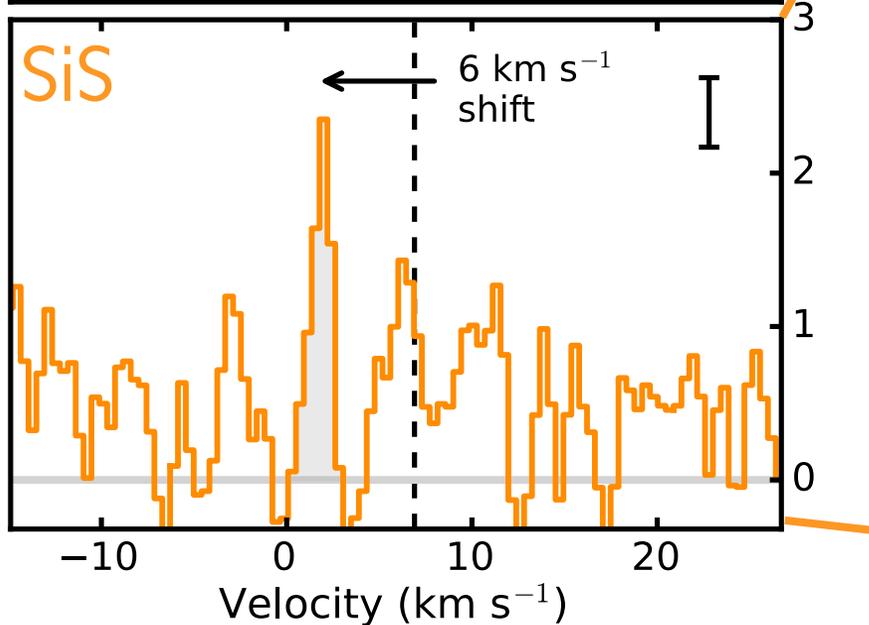
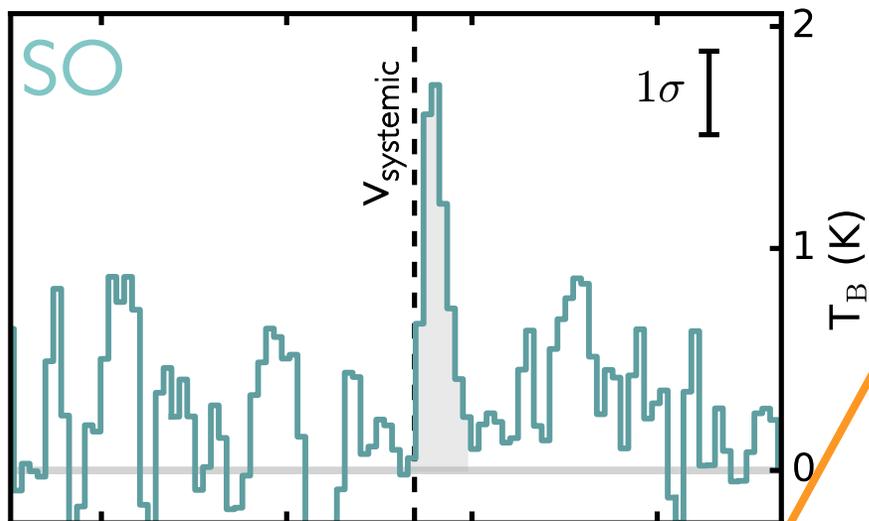
Planet location



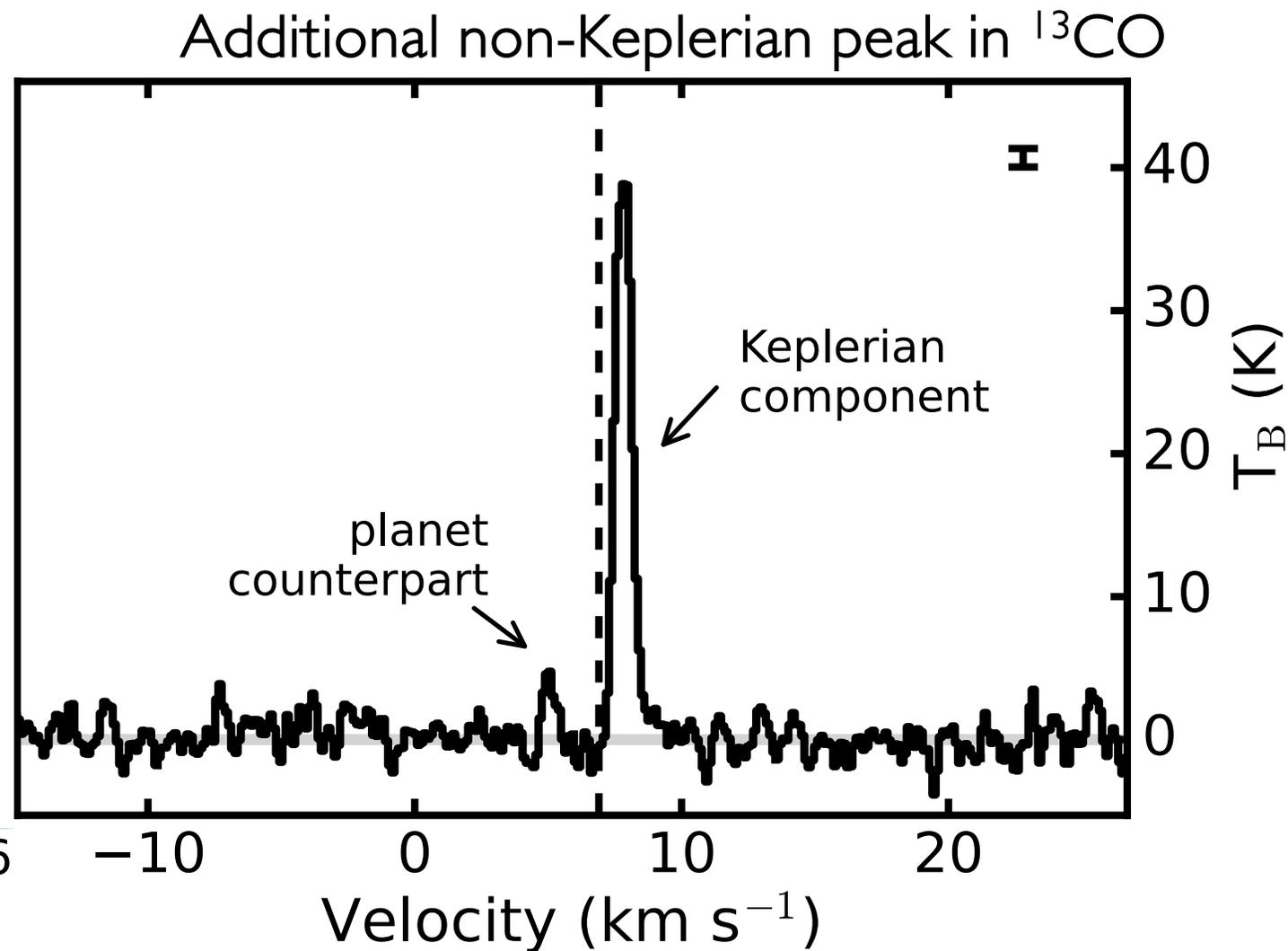
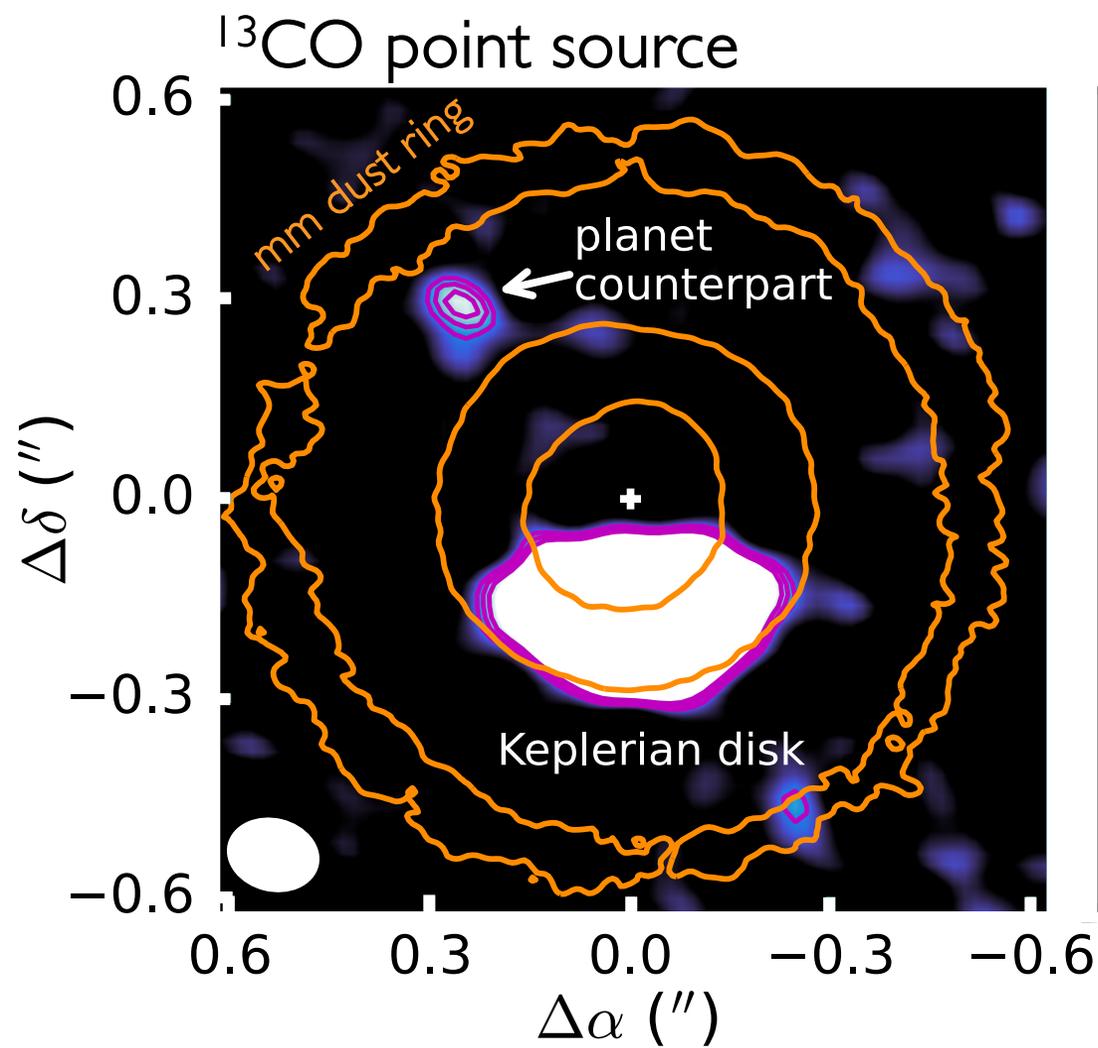
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## SiS channel maps

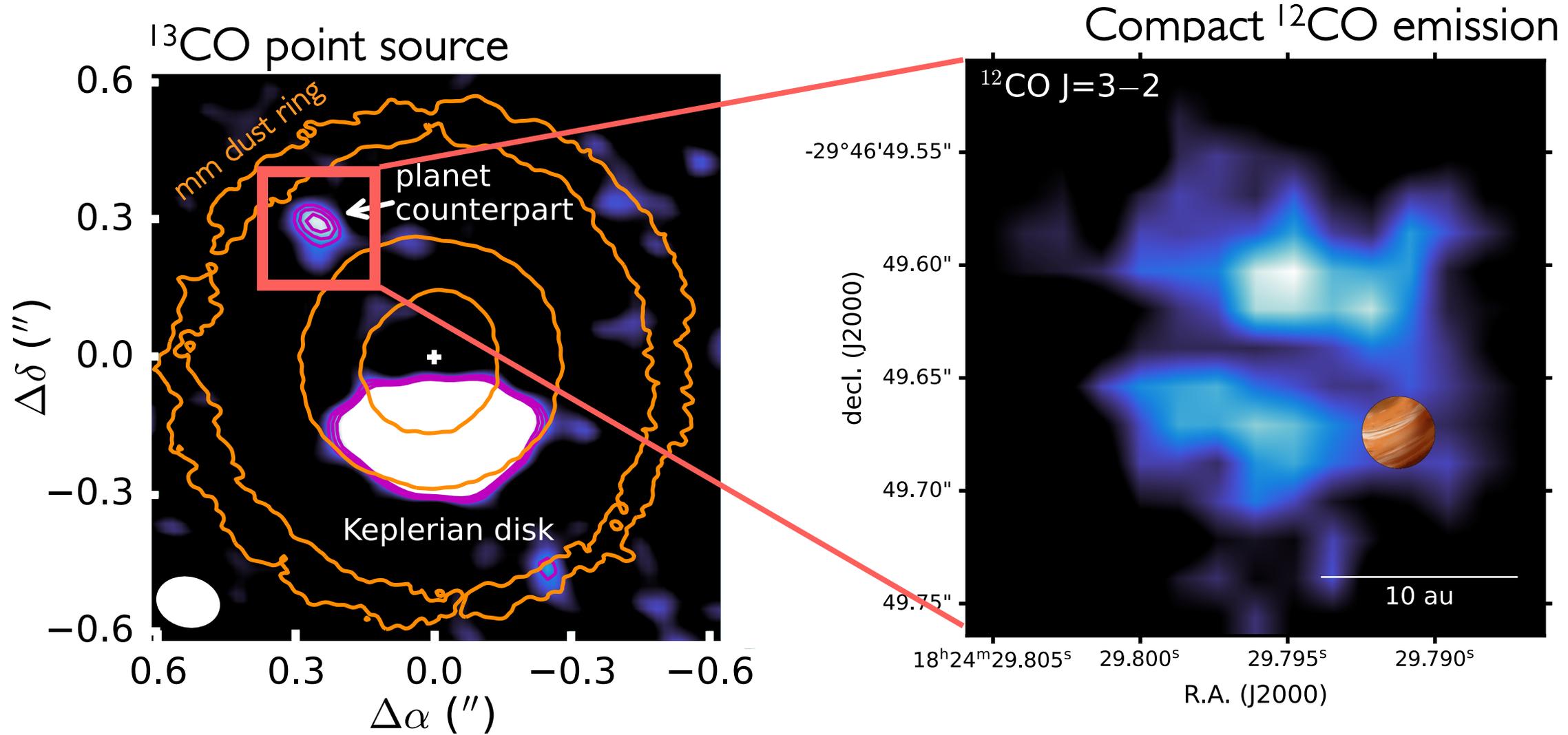
Planet location



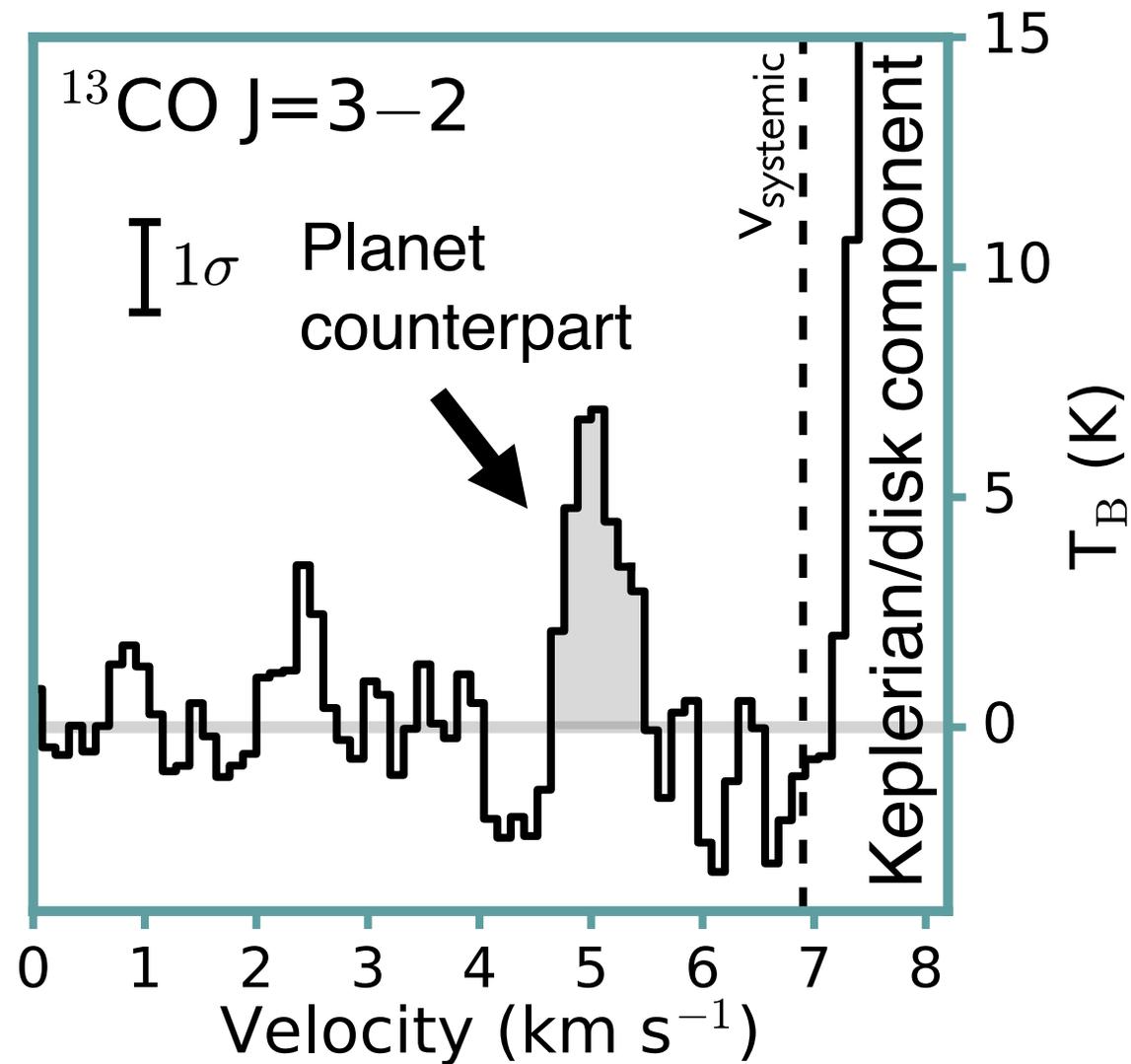
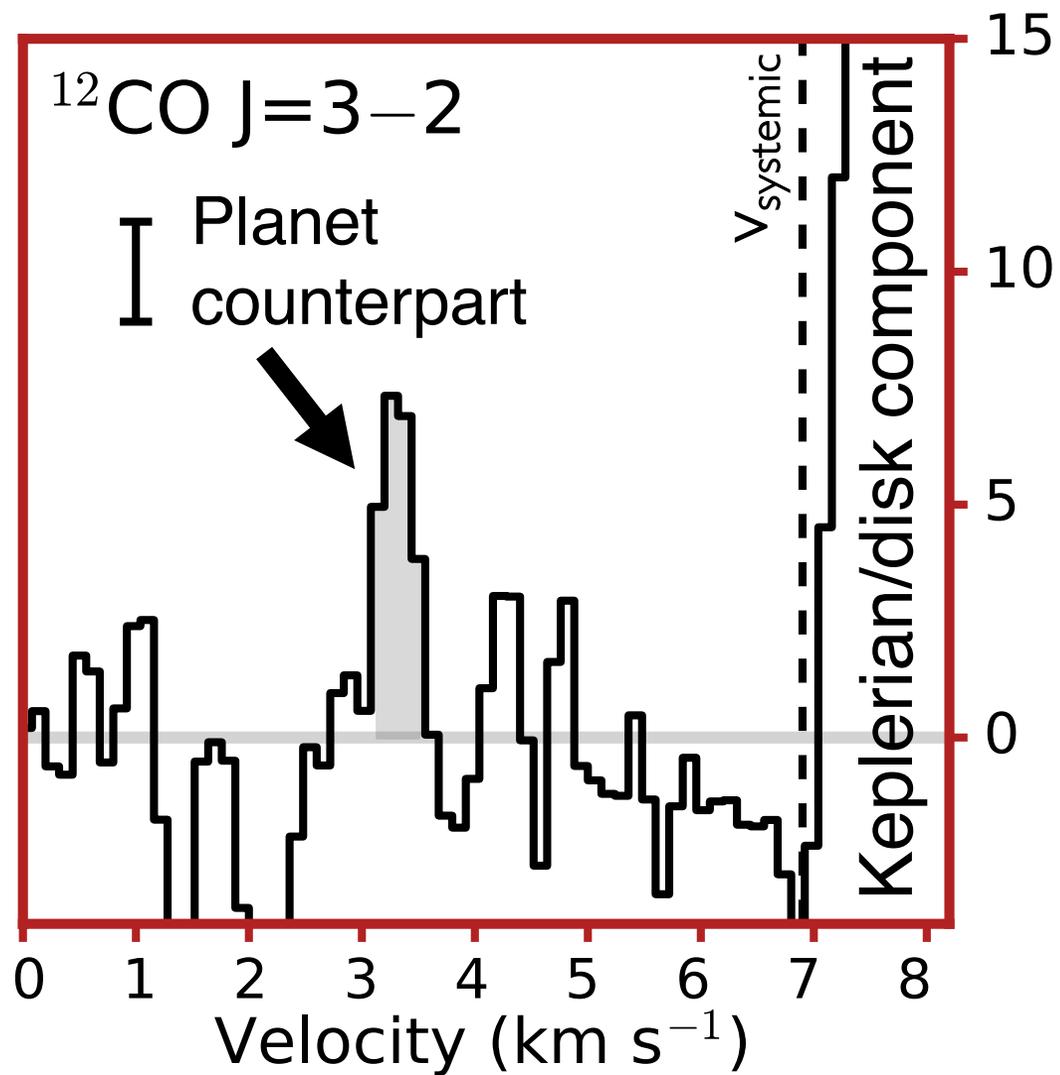
# Compact $^{13}\text{CO}$ emission at the planet position



We also see a planetary counterpart in  $^{12}\text{CO}$  emission!

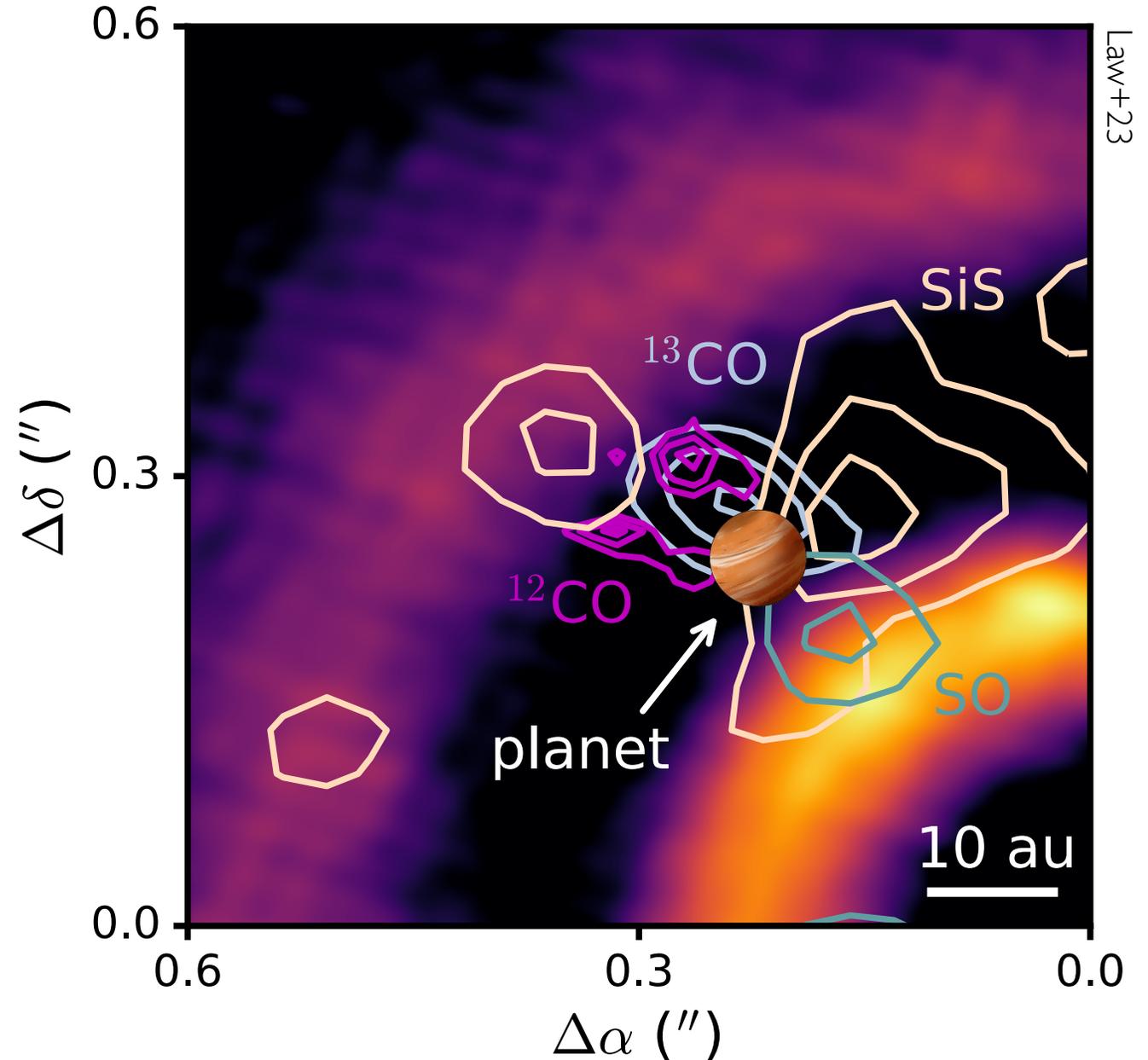


Both  $^{12}\text{CO}$  and  $^{13}\text{CO}$  are blue-shifted



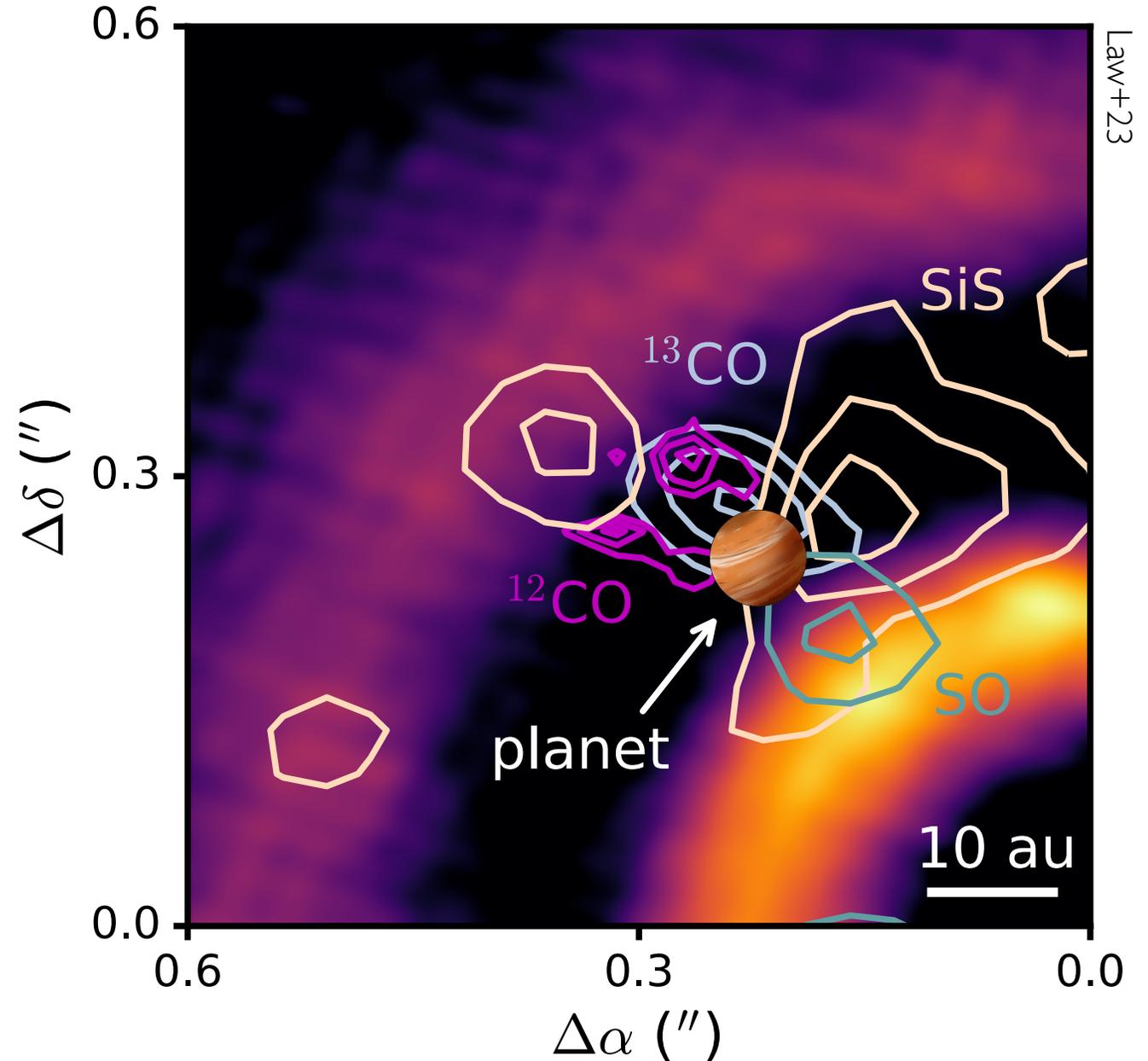
# What is causing these chemical asymmetries?

- SO / SiS are shocked gas tracers
  - SO: thermal desorption of S-rich ices
  - SiS: Si from dust grains, which implies strong shocks around planet
- Planet-driven outflow is most consistent with blue-shifted SiS and CO emission lines and small offsets from planet location
- Need deeper and higher-velocity-resolution observations!
  - Archival data had  $\sim 0.45$  km/s channels



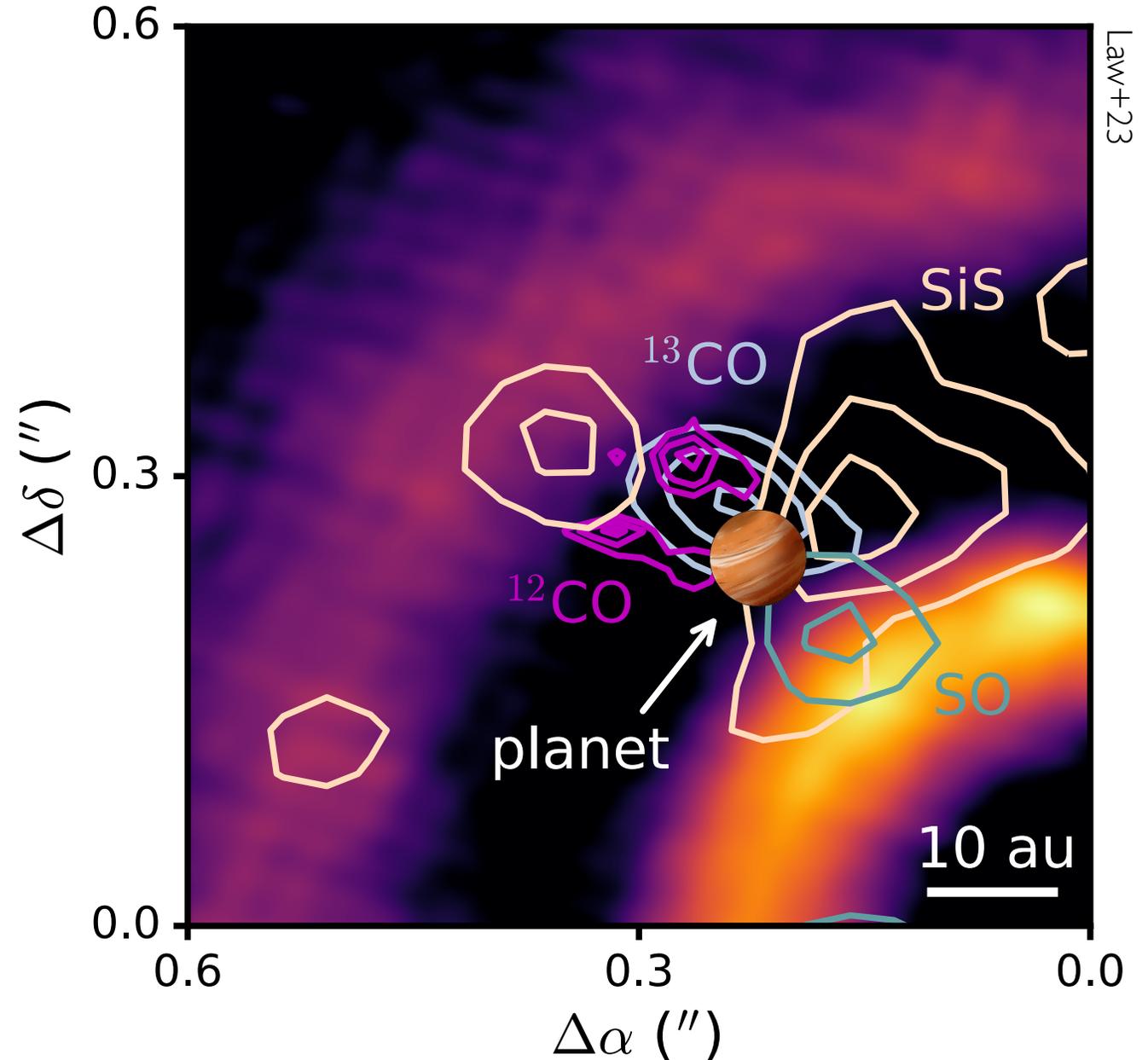
# HD 169142 is *ideal* for observational follow-up

- Gas-/dust-cleared gap and face-on disk allows *direct view of gas near planet*
  - Better velocity resolution to uncover origins of the SO and SiS emission
  - Search for hot gas-phase chemistry in shocked gas around HD 169142 b
  - Measure C/O ratio near planet



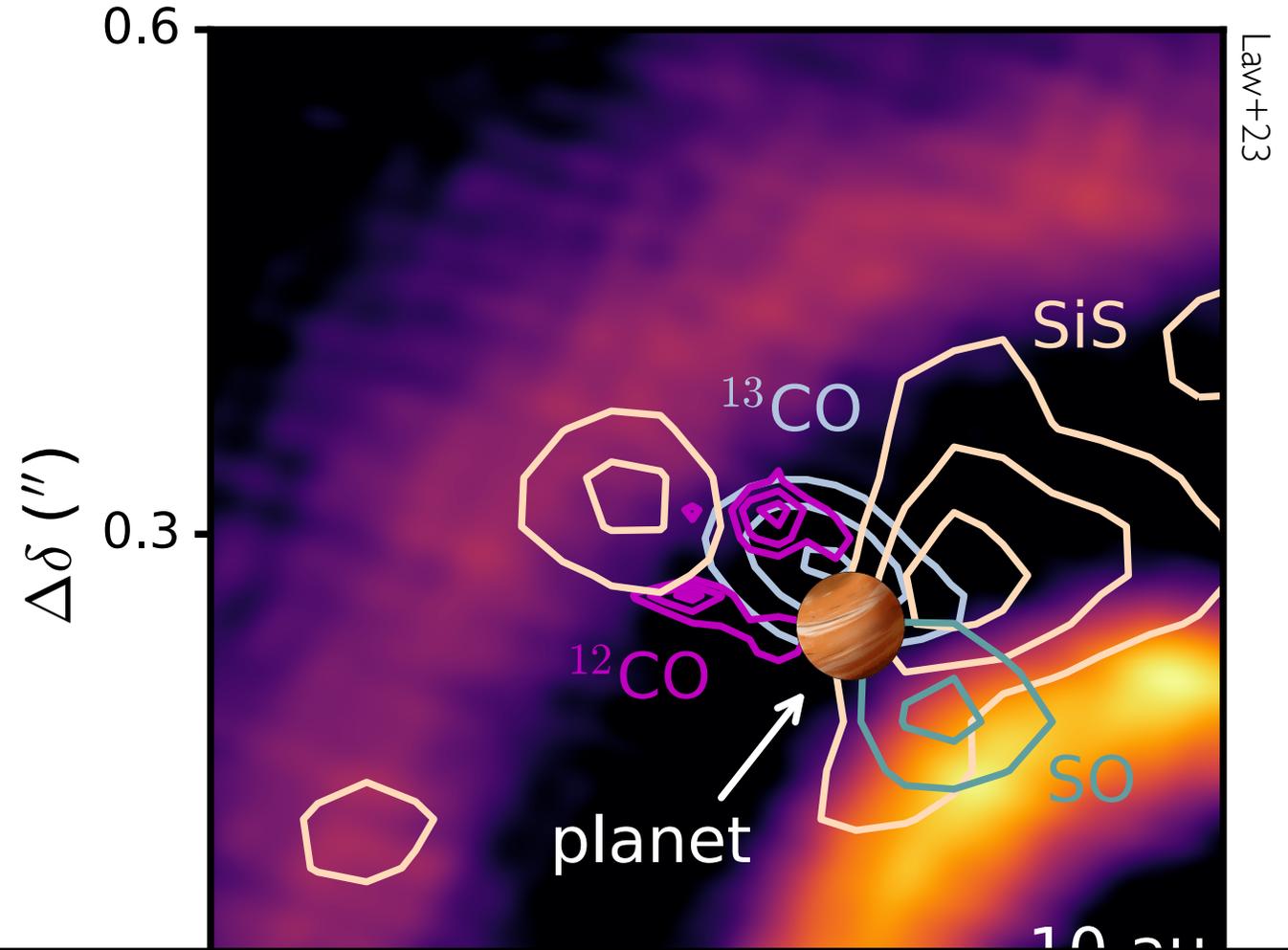
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- Powerful template for future searches of planet-related chemical asymmetries
  - S- and Si- bearing molecules as a new way to confirm embedded planets!



# HD 169142 is *ideal* for observational follow-up

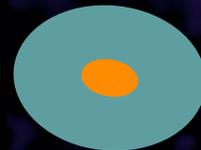
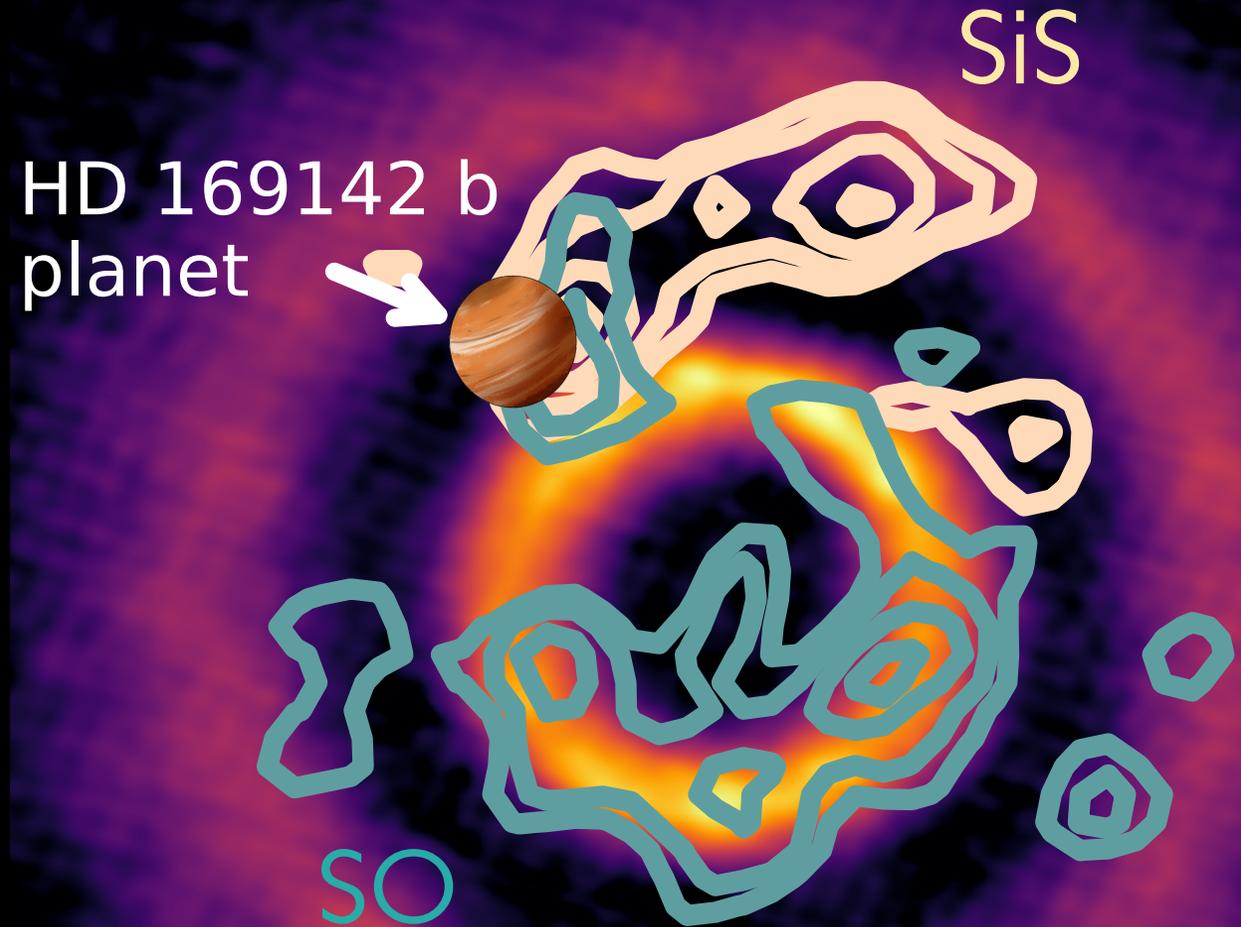
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Accepted ALMA proposal (PI: C. Law) for ~20 hrs to follow up this discovery!

# Summary

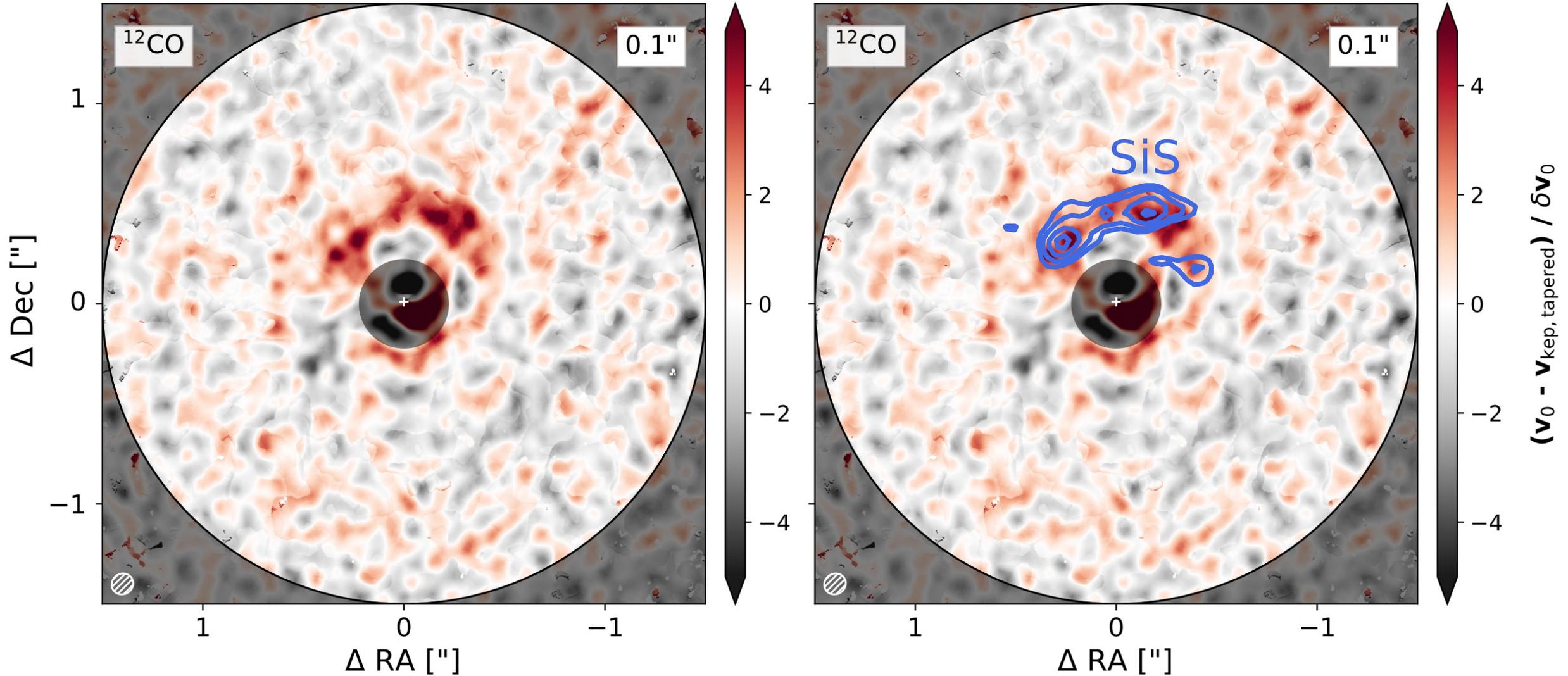
- Compelling chemical signatures associated with recently-confirmed HD 169142 b protoplanet
- SO and SiS represent novel tracers of embedded giant planets
  - Highlights utility of archival data in finding “surprise” detections
- HD 169142 demonstrates the power of chemistry to trace embedded planets and a new way to identify protoplanets



Law+23 ApJL, 952, 19  
cjl8rd@virginia.edu

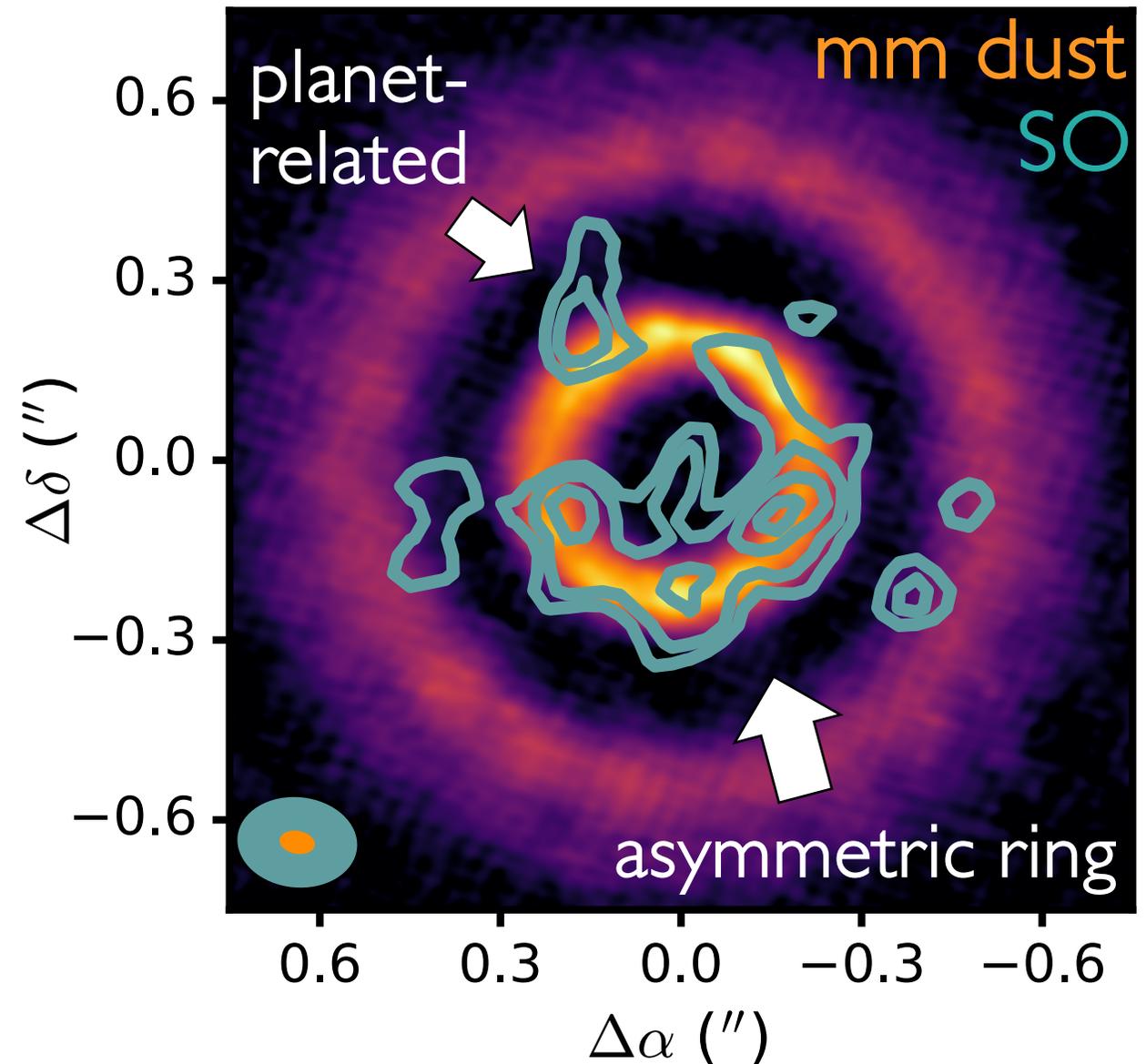
# SiS is co-spatial with $^{12}\text{CO}$ kinematic excess

Garg+22



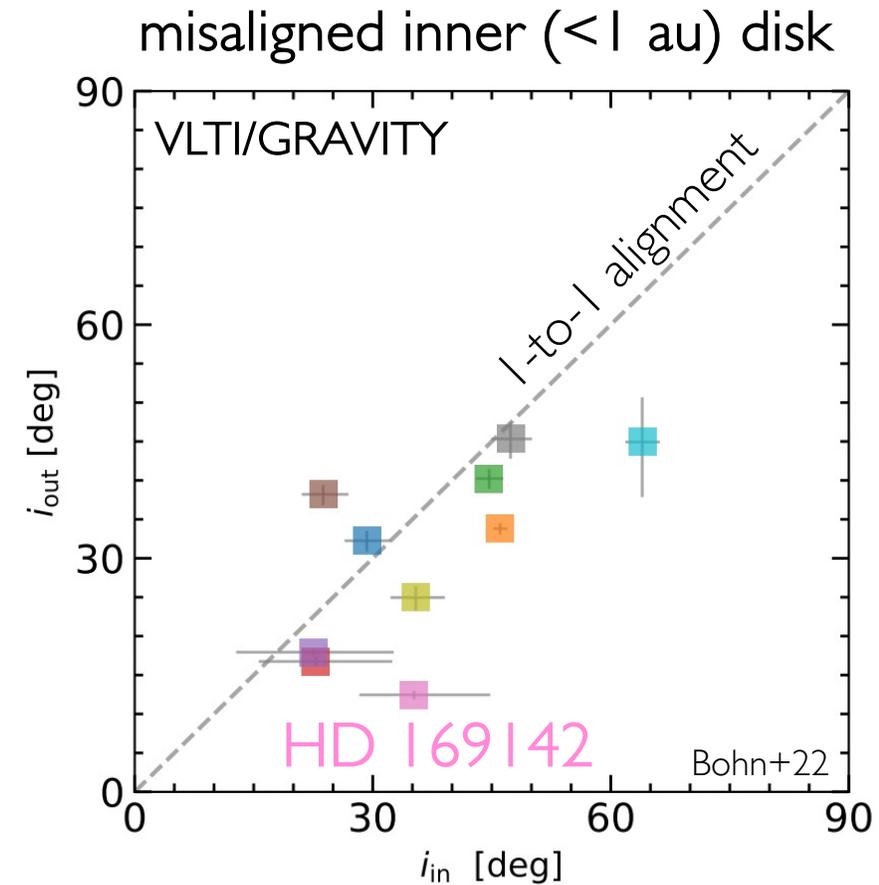
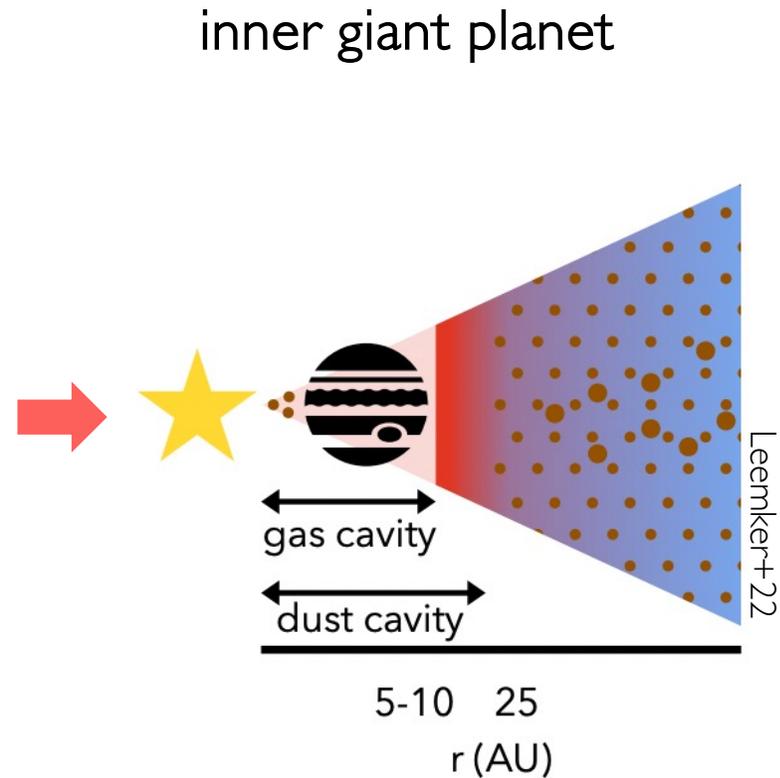
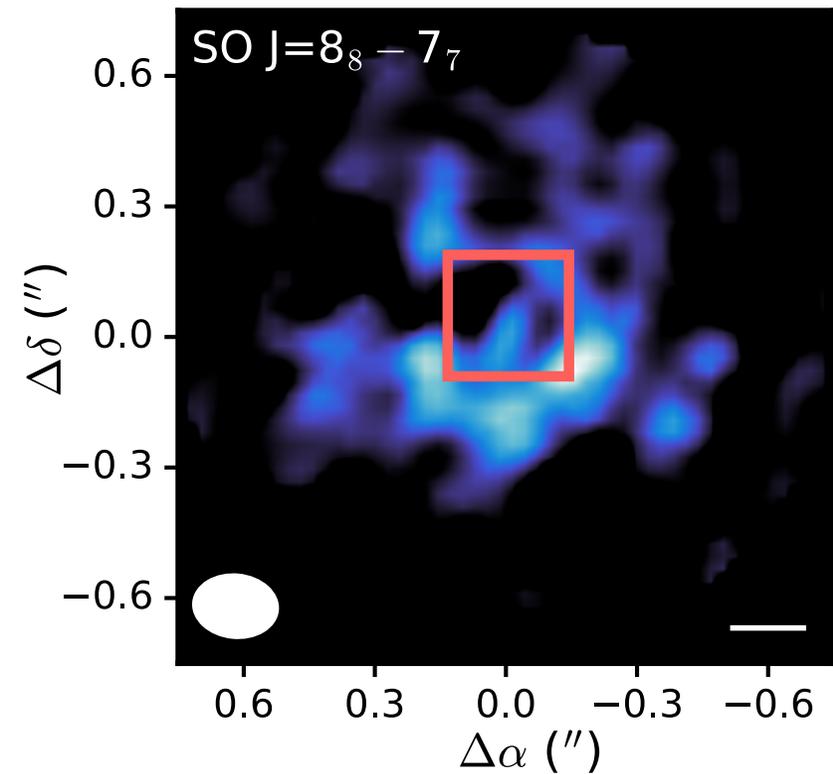
# Origins of SO asymmetry in HD 169142 disk

- Bright, double-ringed SO emission
- Thermal desorption of S-rich ices
  - Inner SO emission ring at edge of inner dust cavity
- Broad, north-south SO asymmetry is likely due to misaligned inner disk
  - VLT/GRAVITY showed substantial misalignment (Bohn+22)
- Changing azimuthal X-ray illumination and temperature structure results in SO asymmetries (Young+21)



# Origins of SO asymmetry

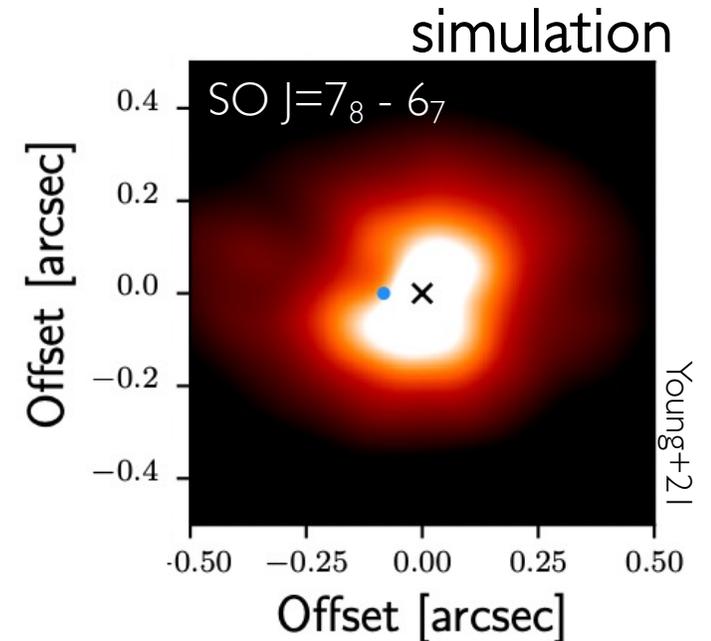
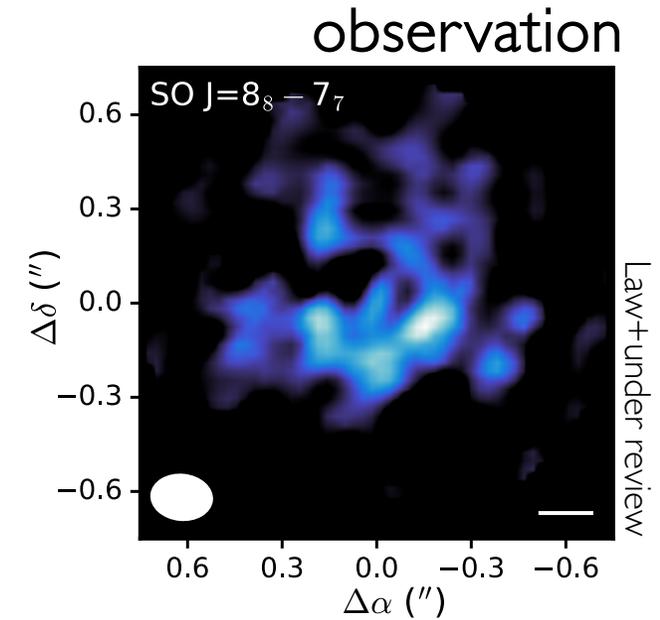
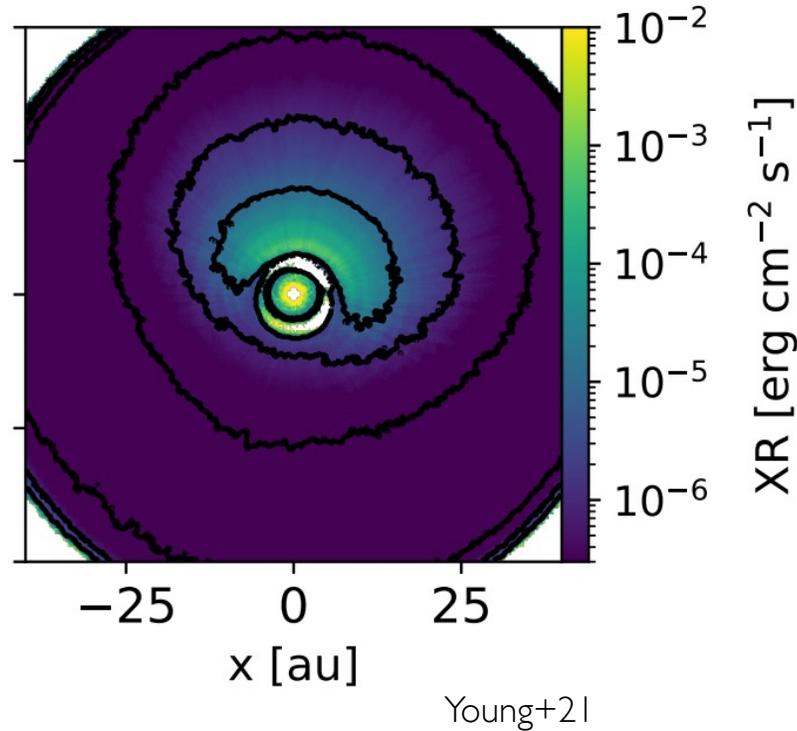
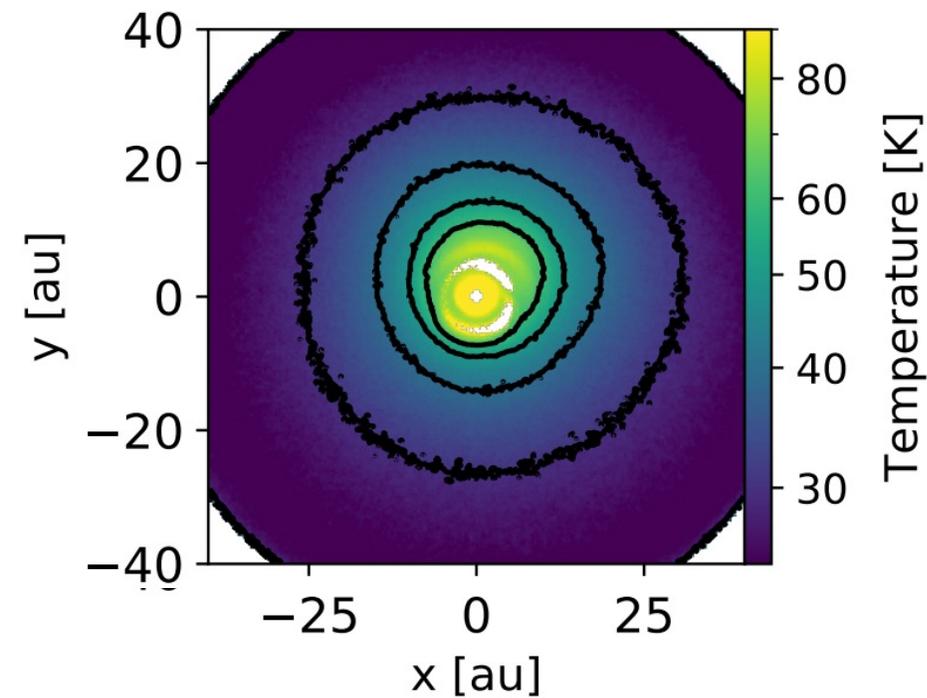
- *Misaligned inner disk from inner giant planet*
  - VLT/GRAVITY showed substantial inner disk misalignment
  - Changing azimuthal X-ray illumination / temperature structure



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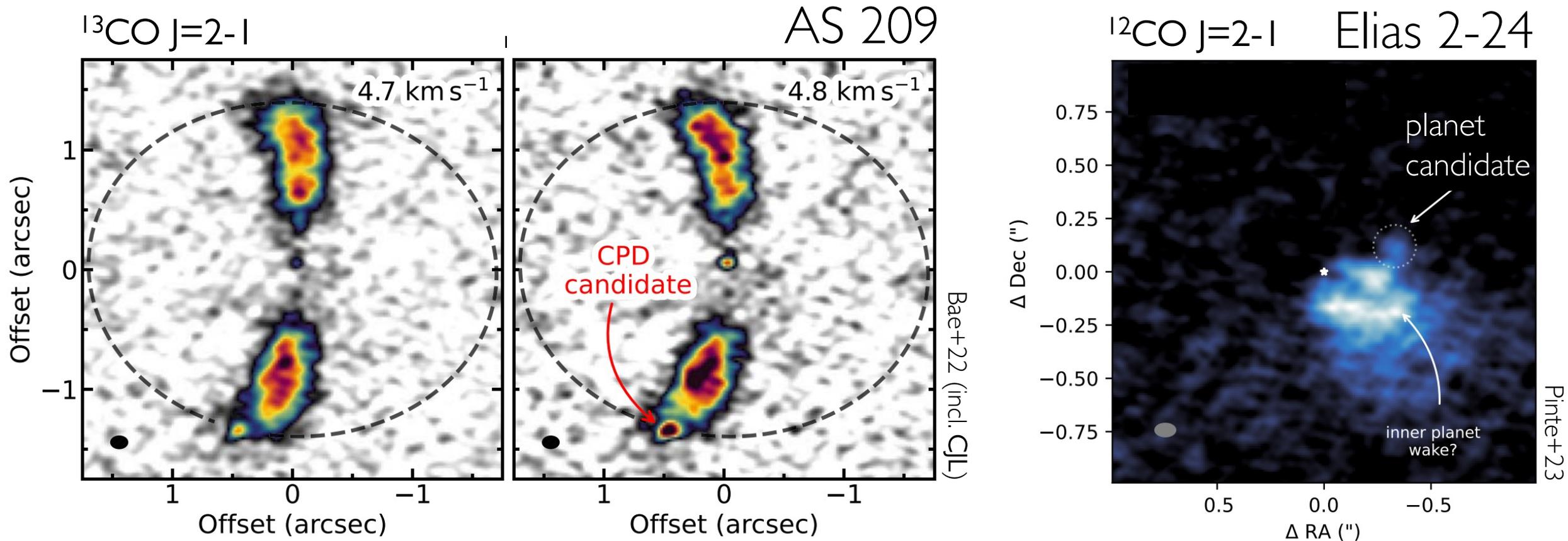
- *Misaligned inner disk from inner giant planet*
  - VLT/GRAVITY showed substantial inner disk misalignment
  - Changing azimuthal X-ray illumination / temperature structure

models of misaligned inner disks



# Chemical signatures of embedded planets in disks

- Detections of localized  $^{12}\text{CO}$  or  $^{13}\text{CO}$  emission around planet candidates in the AS 209 and Elias 2-24 disks
- May just be local gas over-densities rather than chemical changes



# HD 169142 is chemically-rich!

- HD 169142 disk itself is strikingly chemically-rich.
- Detected  $>10$  molecules in ALMA archival data.
  - Including several  $\text{CH}_3\text{OH}$  lines, indicating inheritance of complex ices from earlier stages
- Booth, CJL+in press, A&A

