Thinking Broadly About Molecules in Astrophysics

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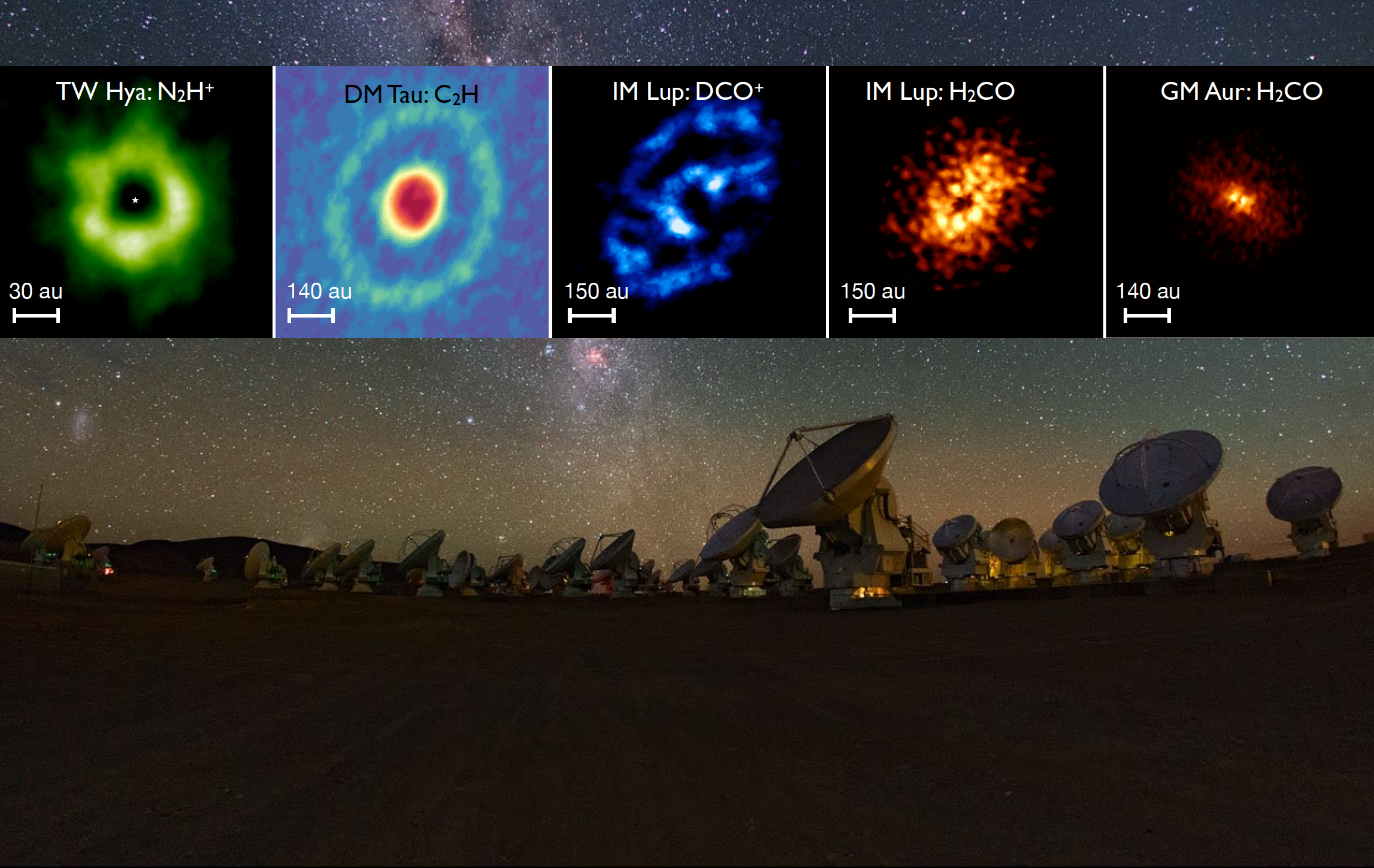
Thinking (less) Broadly About Molecules in Astrophysics

- How to link disk composition at formation to giant planet atmospheric composition.
  - ➡ K. Zhang, K. Schwarz, S. Krijt, F. Ciesla, K. Öberg, R. Murray-Clay
- Doppler detection of giant planets with ALMA. (Know thy disk, find thy planet)
  - ➡ R. Teague, J. Bae, T. Birnstiel, D. Forman-Mackey
- (very briefly) Molecules at high-z
  - ➡ E. Falgarone, N. Indriolo

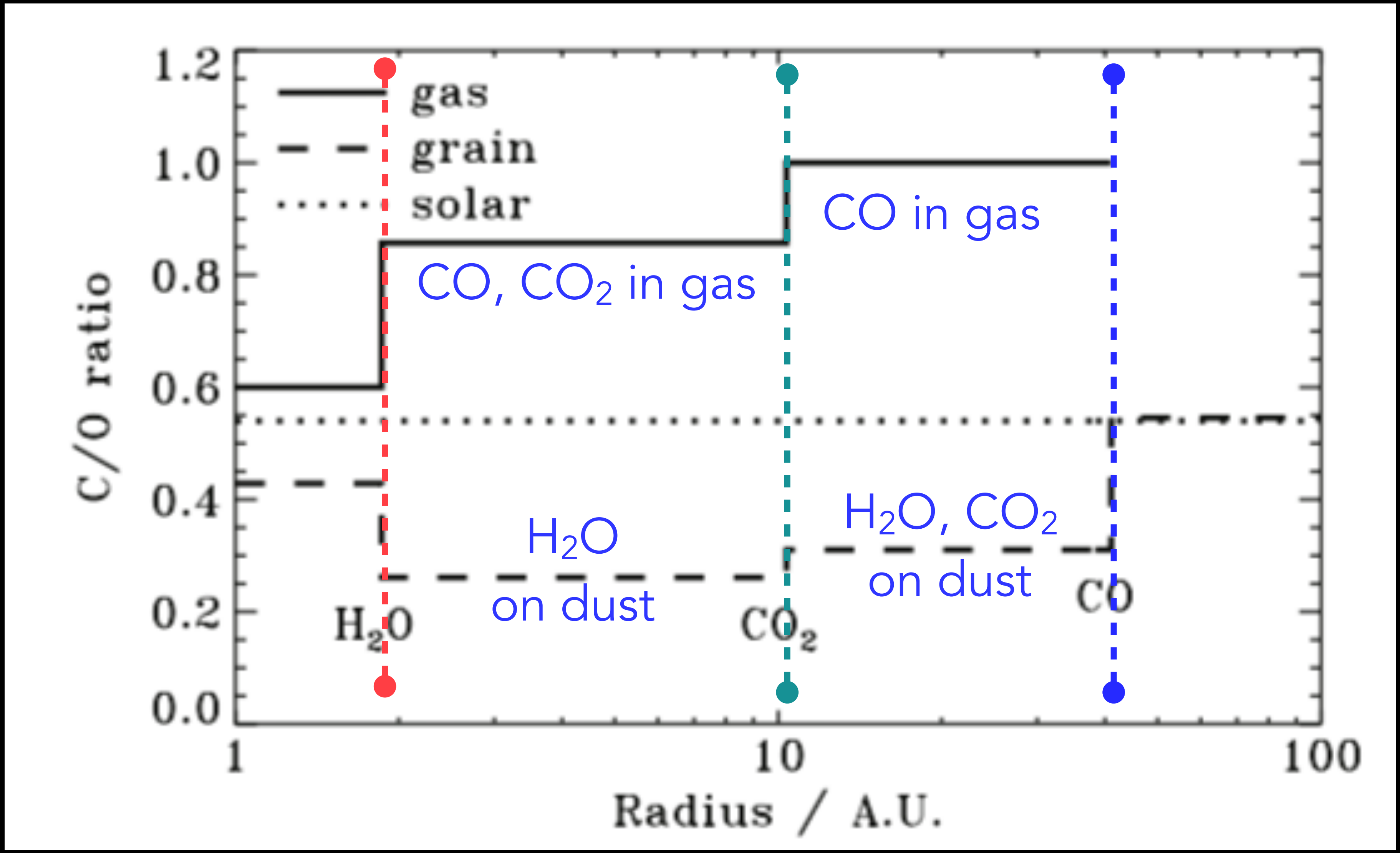

TW Hya: N_2H^+
30 au
DM Tau: C_2H
140 au
IM Lup: DCO^+
150 au
IM Lup: H_2CO
150 au
GM Aur: H_2CO
140 au

Bulk Composition in Giant Planets

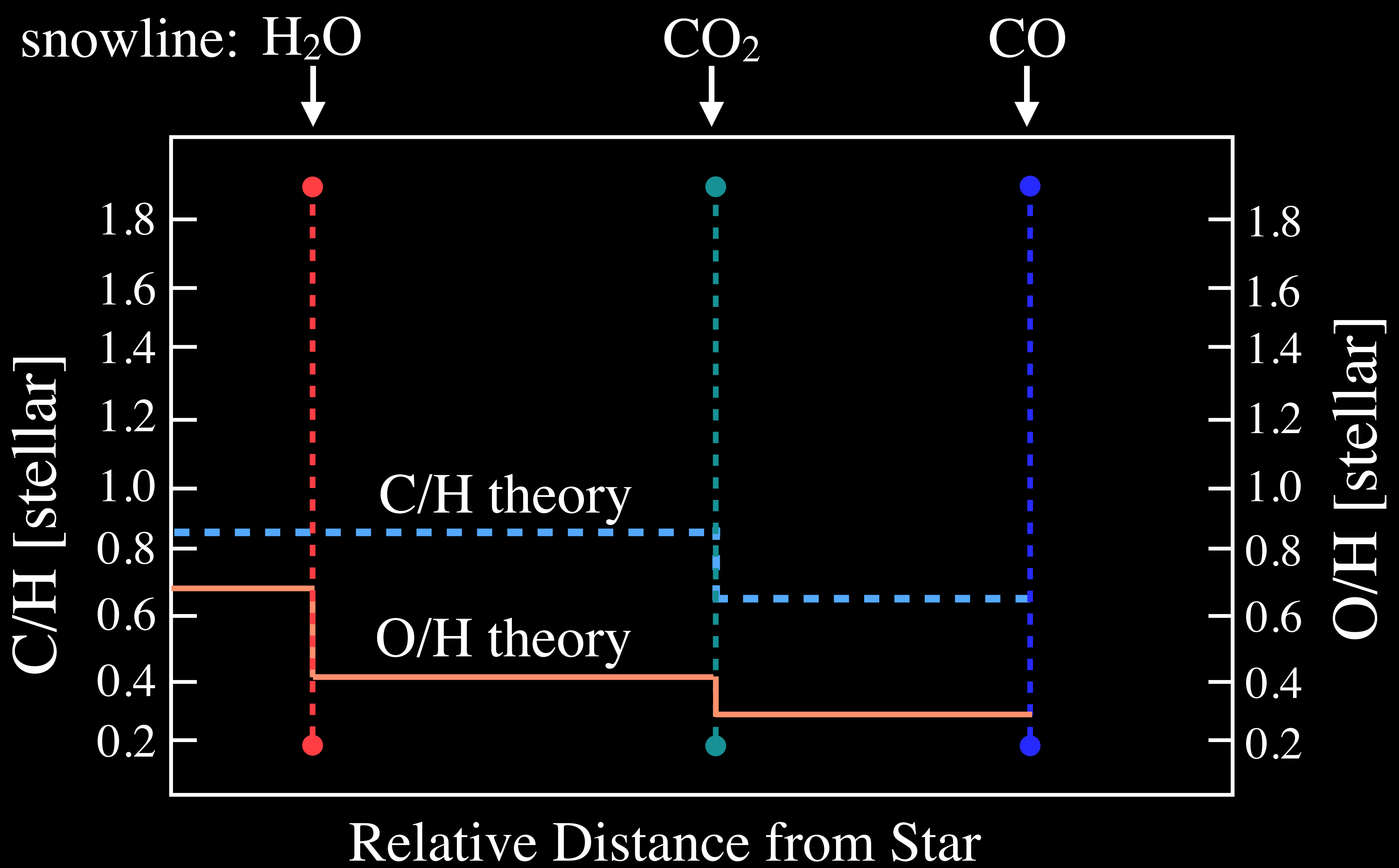
- *For planetary atmospheres - the chemistry dictates that the form in which something is supplied is lost.*
- *Focus on understanding bulk composition to look for signatures of origin.*
  - ➡ C/O ratio and C/H, O/H (N difficult to retrieve)
- *At BASE level relate to formation:*
  - ➡ Assume core-accretion
    - ❑ Core forms from solids
    - ❑ Envelope forms from gas - reflects gas composition

Disk Bulk Composition & Gas Giants

- To date clear focus on connective tissue has been the C/O ratio and snowlines (Öberg, Murray-Clay, & Bergin 2011).



Disk Bulk Composition & Gas Giants



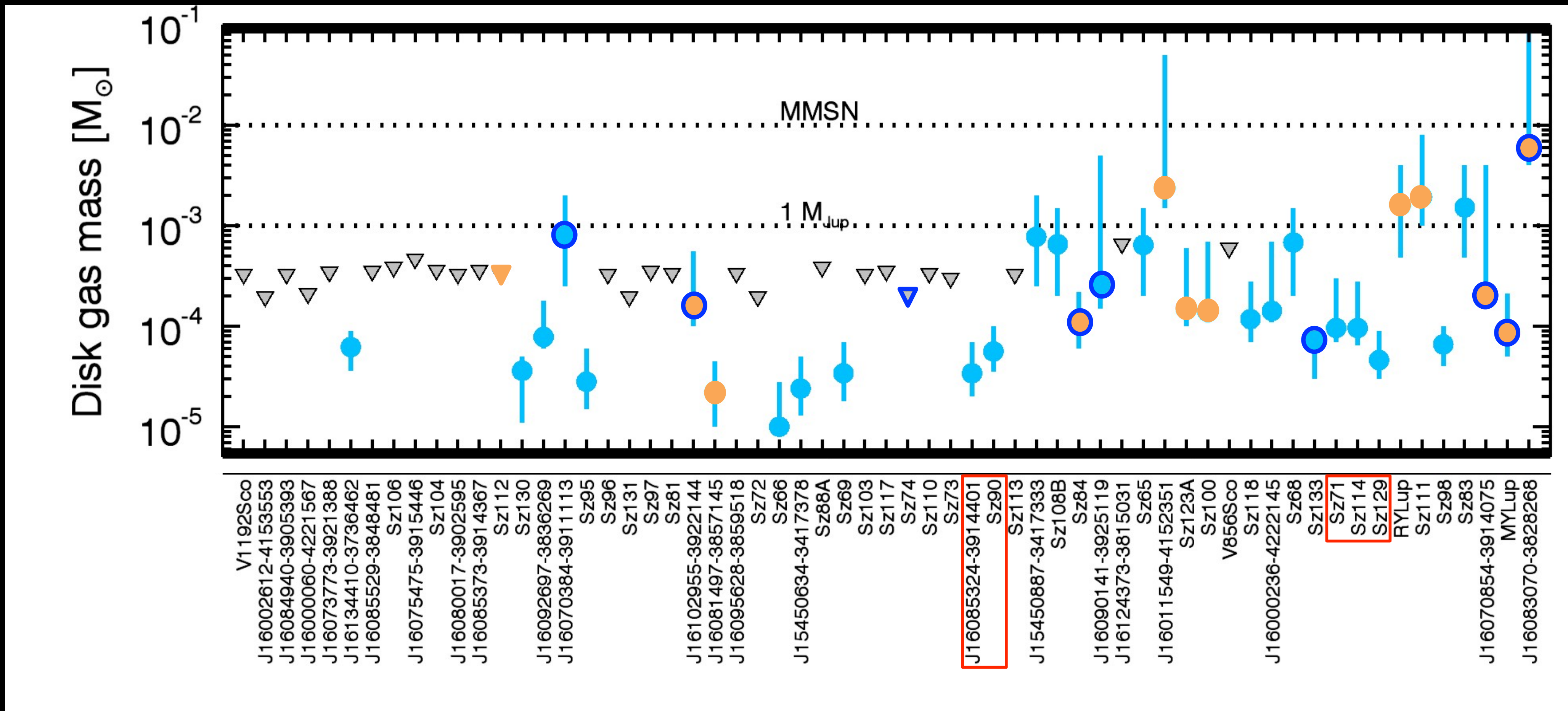
- Generic Expectations:
  - ➡ Molecules return to "normal" abundance inside their snowlines (for CO ~ 10^{-4} relative to H_2)
  - ➡ Beyond H_2O snowline: C/H close to stellar, O/H is substellar

Bulk Composition in Disks: X/H

- Need to infer H_2 mass to get C/H, O/H, etc.
- three methods:

1. thermal emission from dust grains at mm/sub-mm wavelengths (and a gas to dust ratio)
2. CO and isotopologue gas (and a CO abundance)
3. Detection of HD - to date only in 3 systems

CO Gas Mass Problem



if optically thin

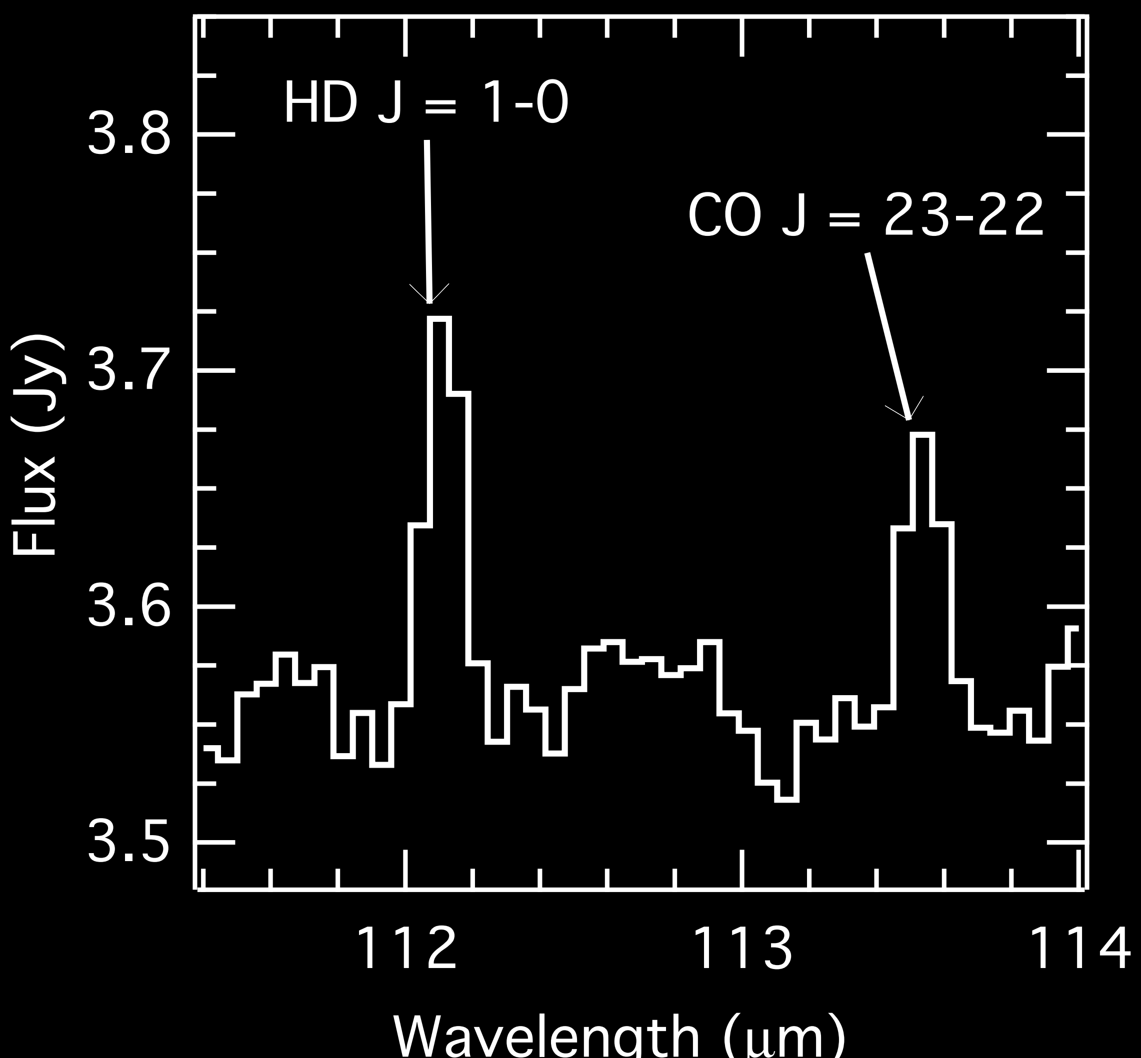
$$I_\nu(R) \propto \Sigma_{CO}(R) f(T)$$

$$\Sigma_{gas} = \Sigma_{CO} / x(CO)$$

Most disks *appear* to have < 1 $M_{Jupiter}$ of Gas Mass

Miotello+ 2017; Ansdell+ 2016 & Long+ 2017

Herschel Detection of HD towards TW Hya



Bergin et al. 2013

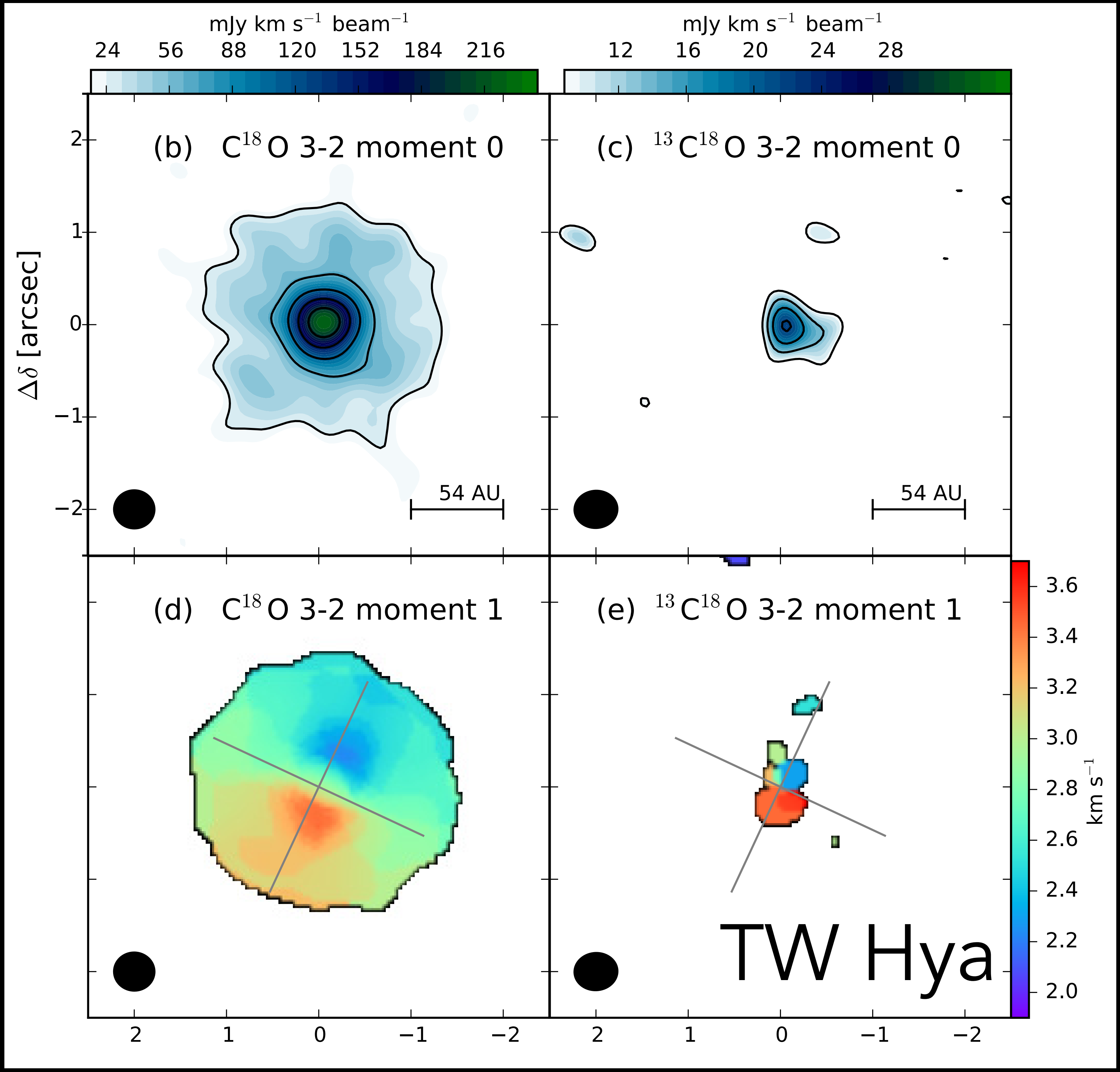
- ➡ HD has a dipole & D/H ratio is known (~1.5 x 10^{-5})
- ➡ More direct measurement of disk gas mass (~0.01-0.05 $M_\odot$)

$$I_\nu \propto M_{HD} f(T)$$

$$M_{gas} = M_{HD}/x(HD)$$

$$f(T) \propto \exp(-128/T)$$

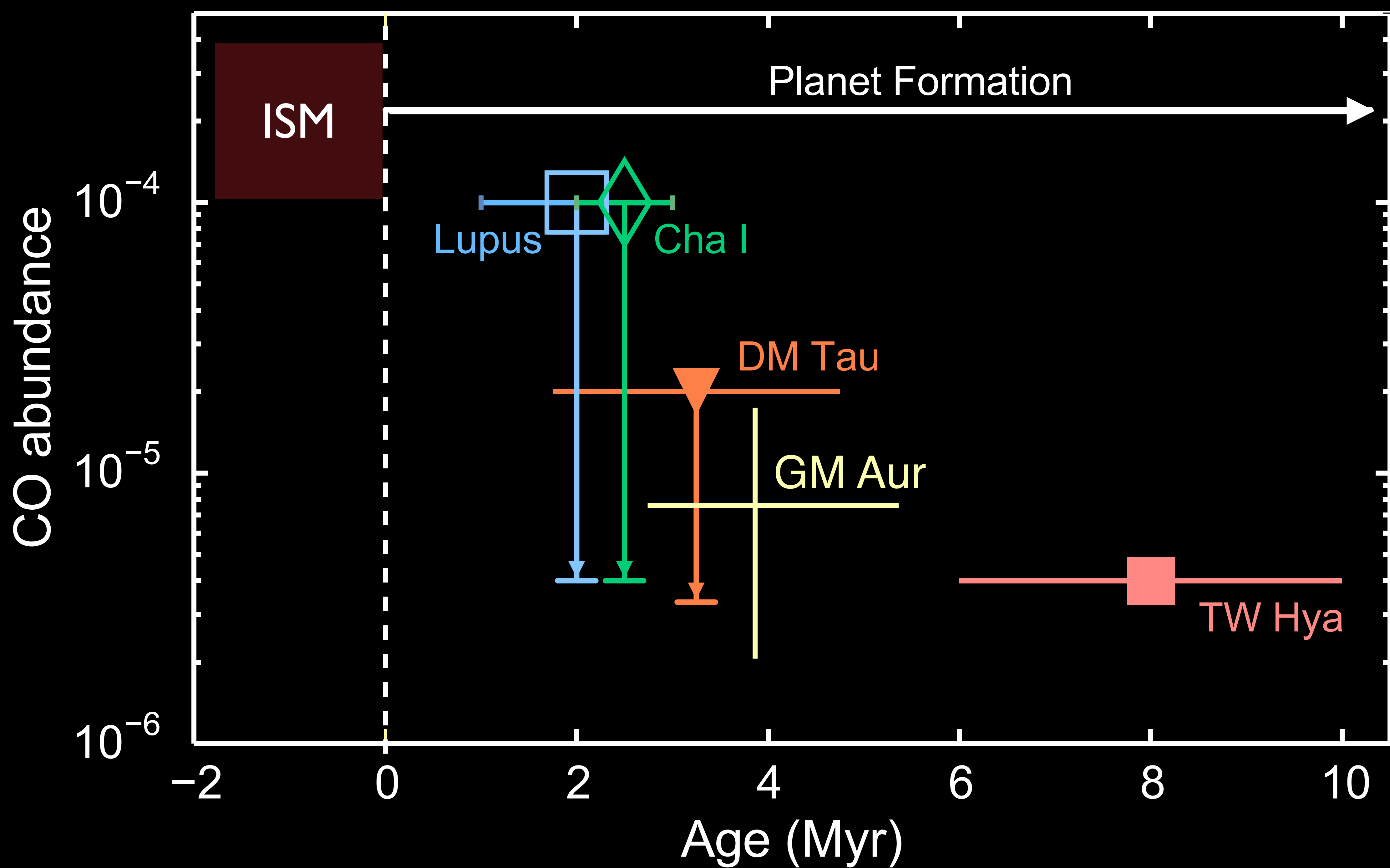
Peering into the midplane



$^{12}C^{16}O$
⇓ 77
$^{13}C^{16}O$
⇓ 560
$^{12}C^{18}O$
⇓ 1792
$^{12}C^{17}O$
⇓ 43120
$^{13}C^{18}O$

Zhang et al. 2017; Spatial Resolution: 0.5″ - 27.5 AU

CO Abundance in Disks



Zhang+ 2018, in prep.

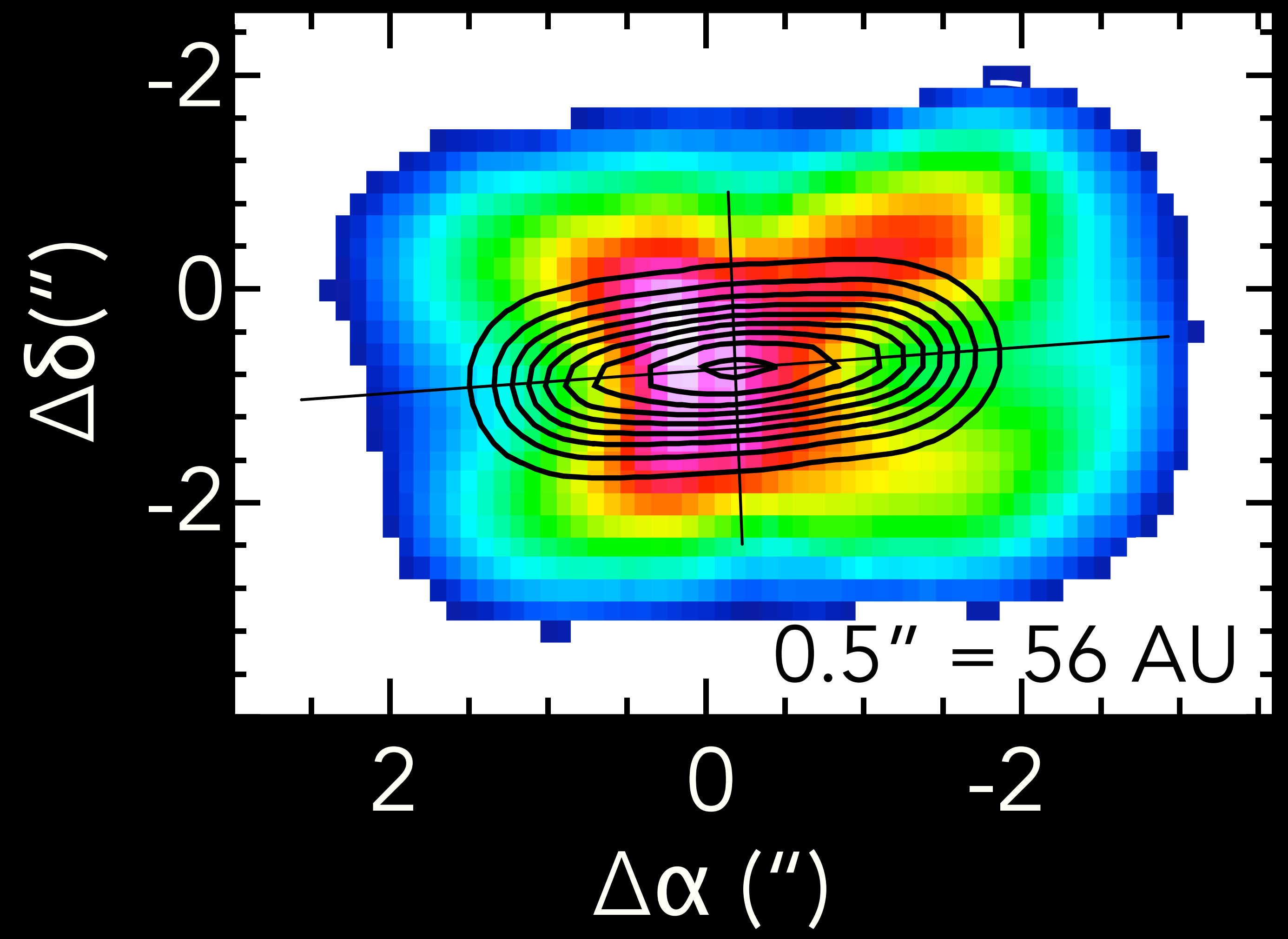
Inside CO snowline - 3 sources - CO abundance is not “normal” but % ~ 1

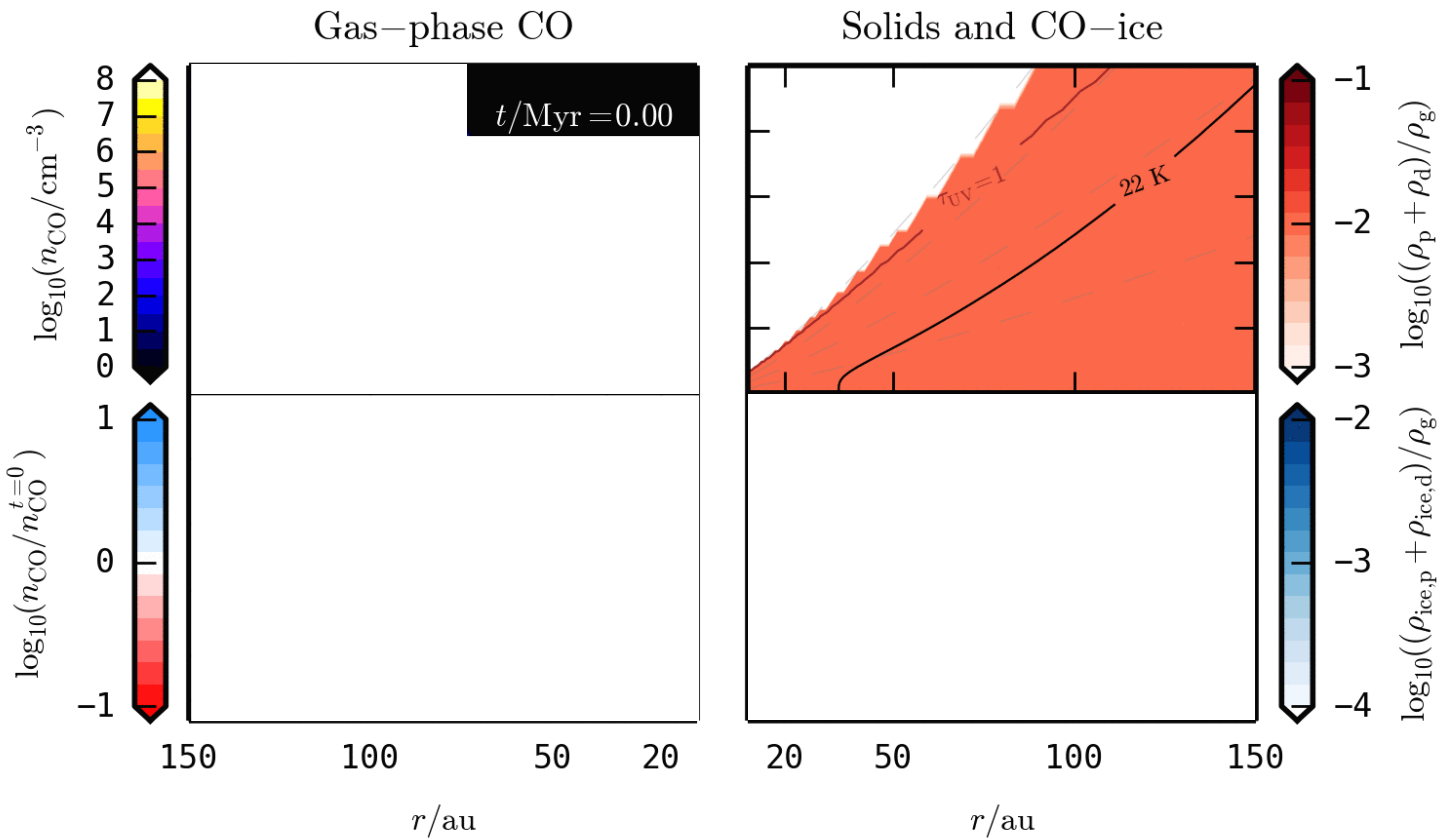
Where are the volatiles?

- Simplest solution: ice mass follows dust mass.
- Ice-coated dust has grown, settled to the midplane, and drifted closer to the star.

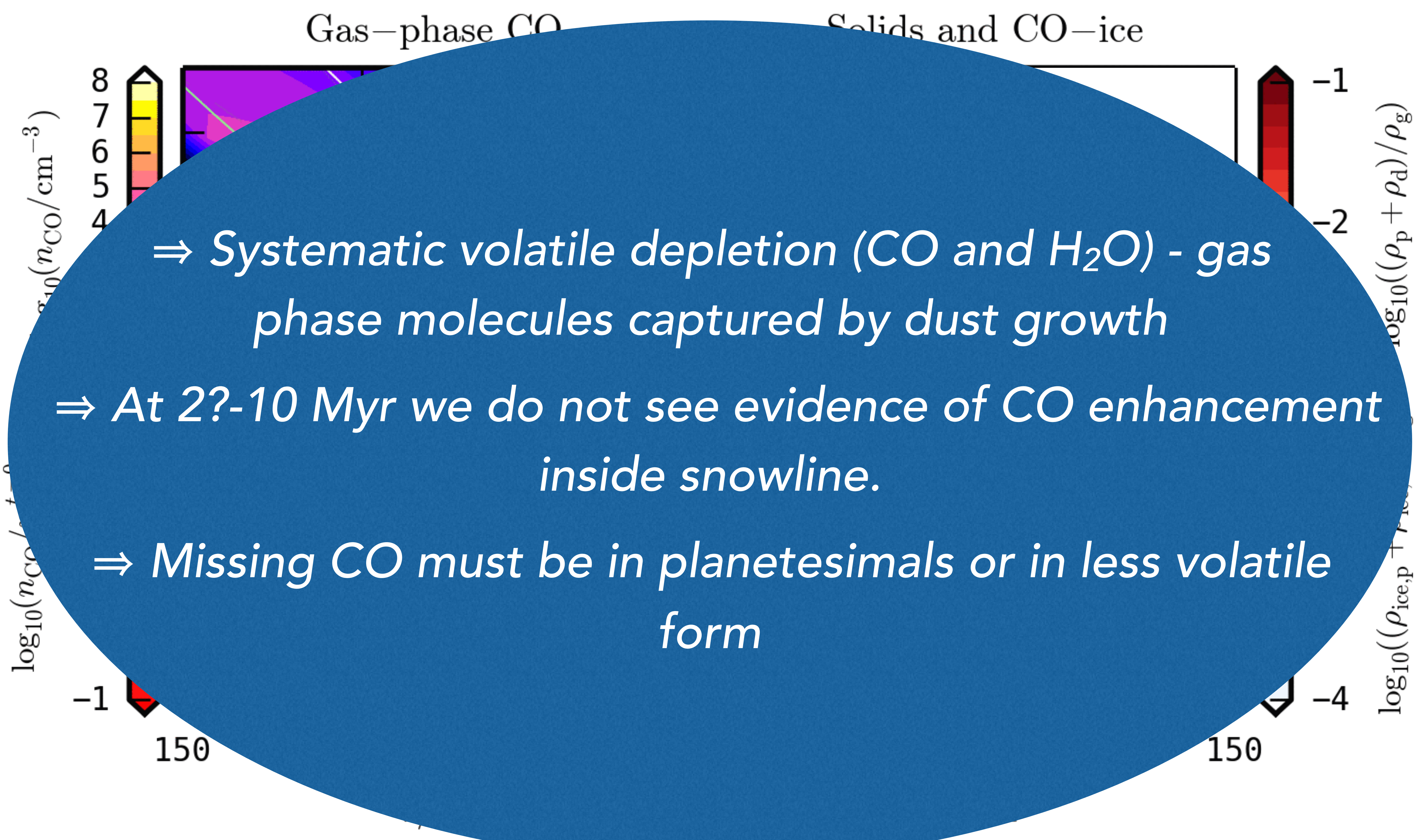
Grosso+ 2003

Dutrey+ 2016





Krijt, Schwarz, Bergin, & Ciesla 2017, ApJ, submitted



⇒ *Systematic volatile depletion (CO and H_2O) - gas phase molecules captured by dust growth*

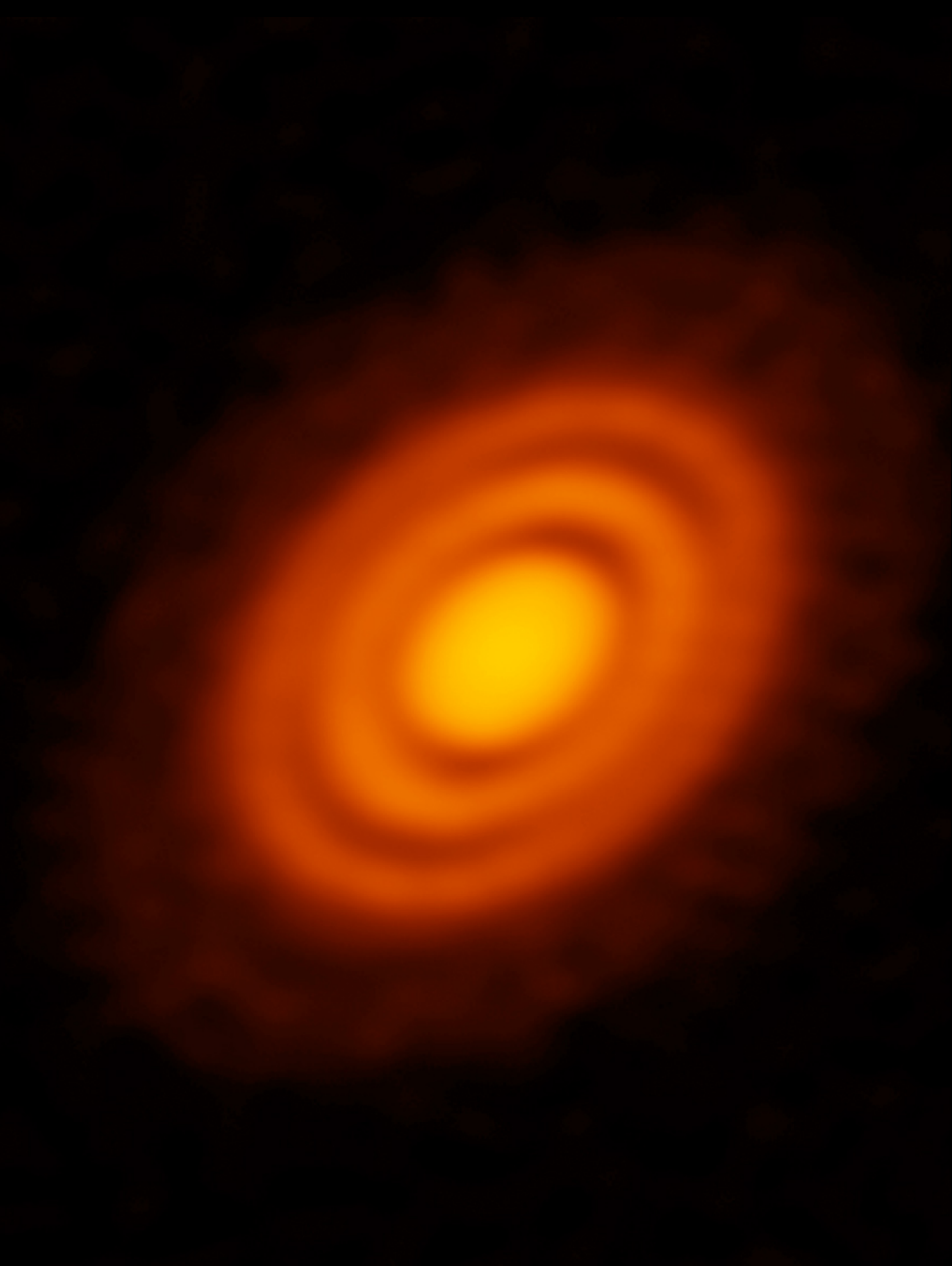
⇒ *At 2?-10 Myr we do not see evidence of CO enhancement inside snowline.*

⇒ *Missing CO must be in planetesimals or in less volatile form*

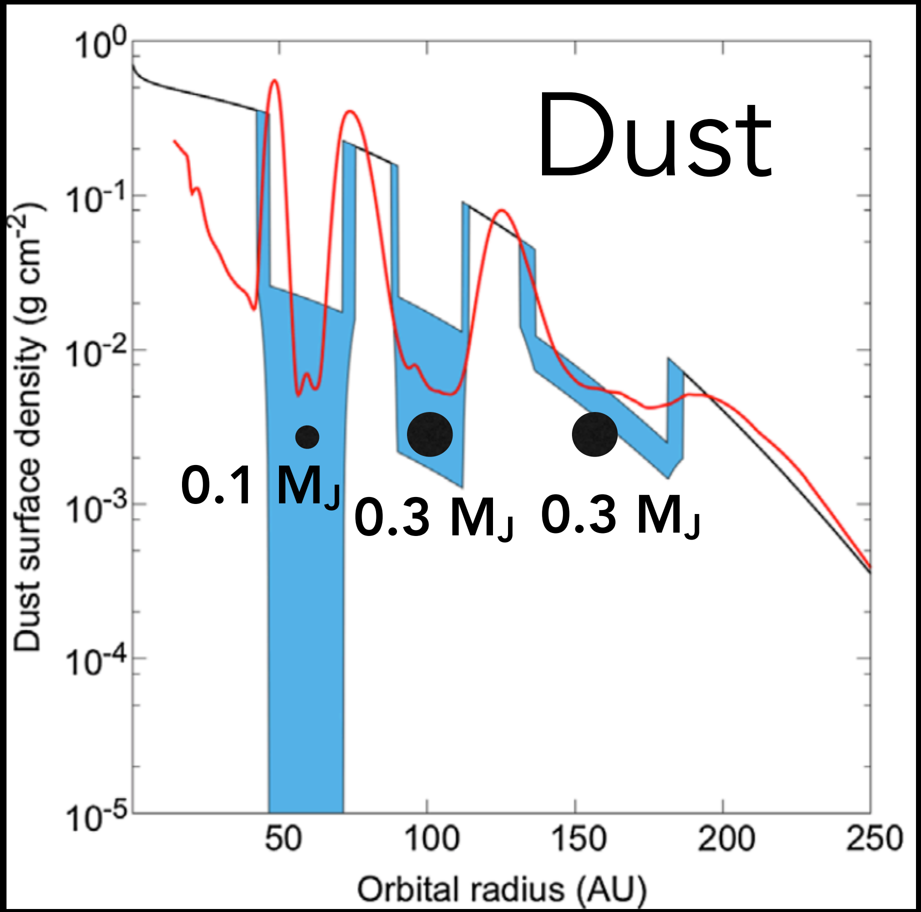
Krijt, Schwarz, Bergin, & Ciesla 2017, ApJ, submitted

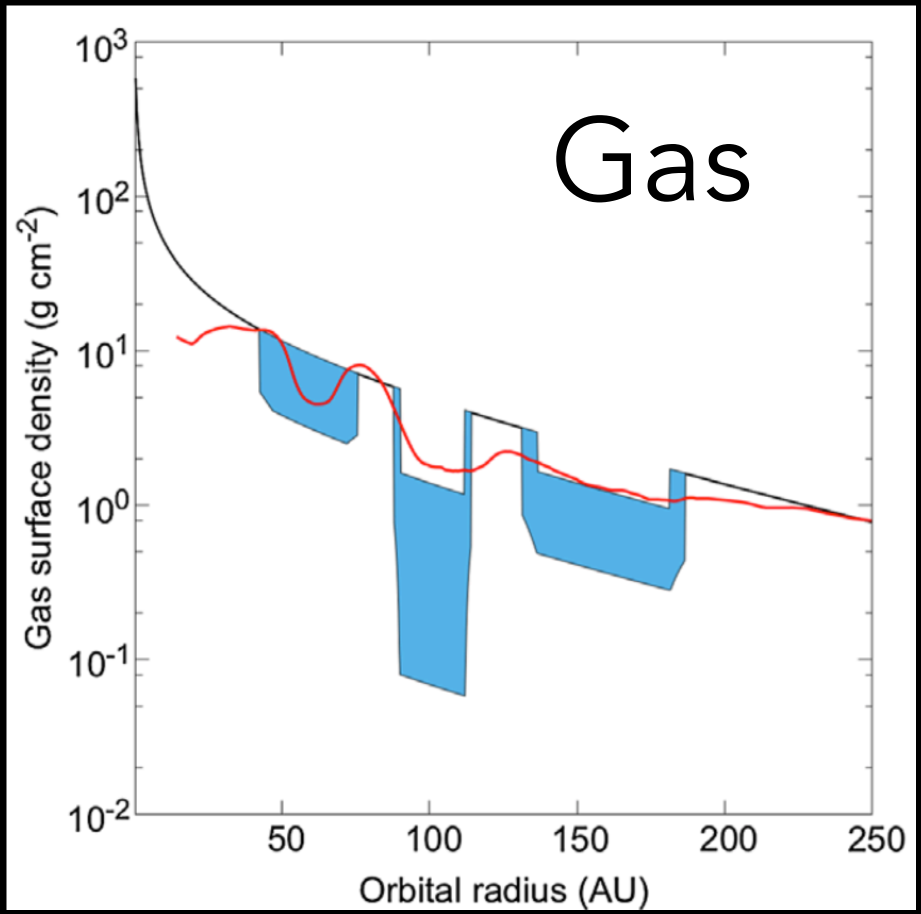
ALMA and Planets

Inferring planets with ALMA

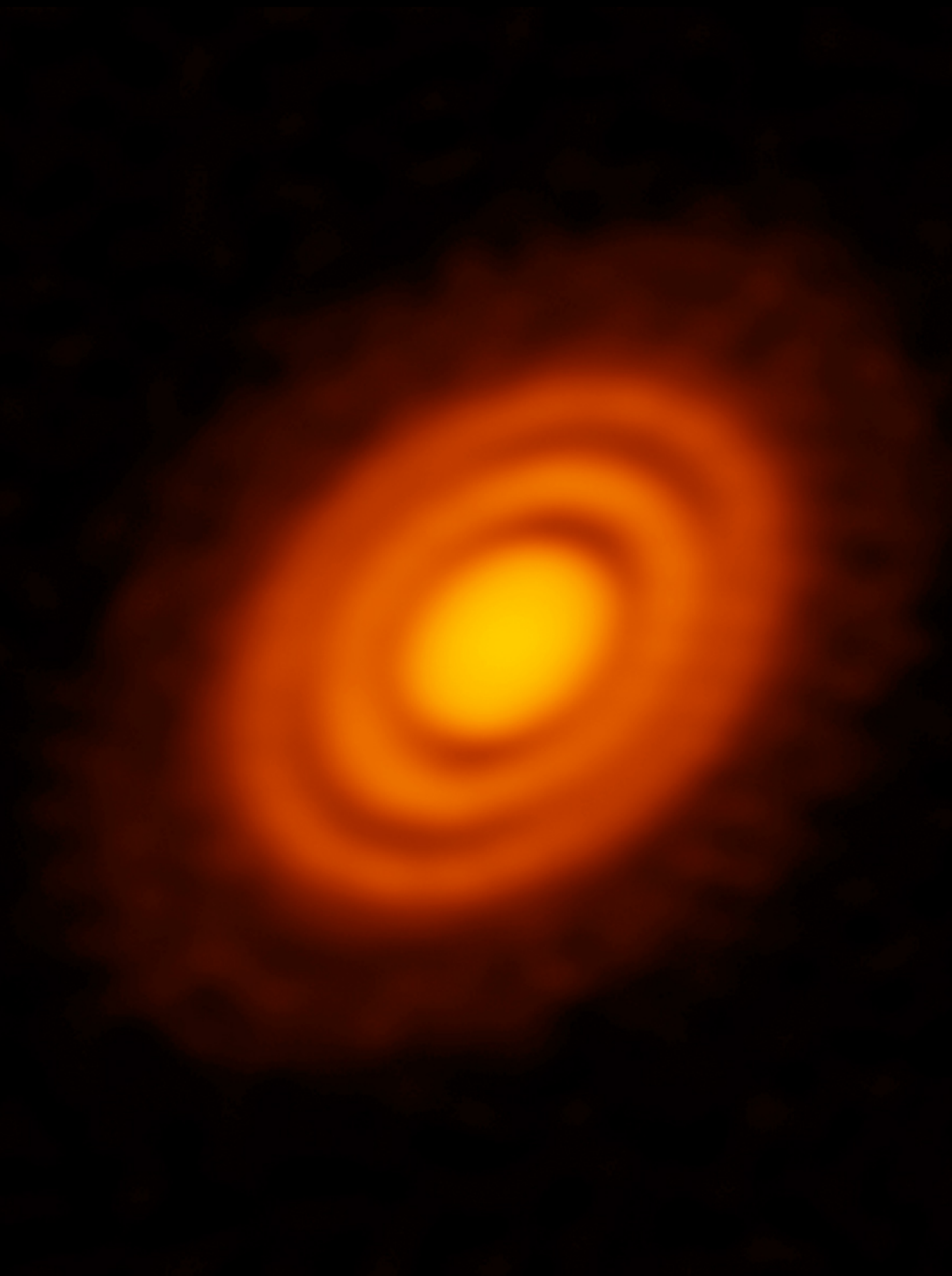


Isella+ 2016





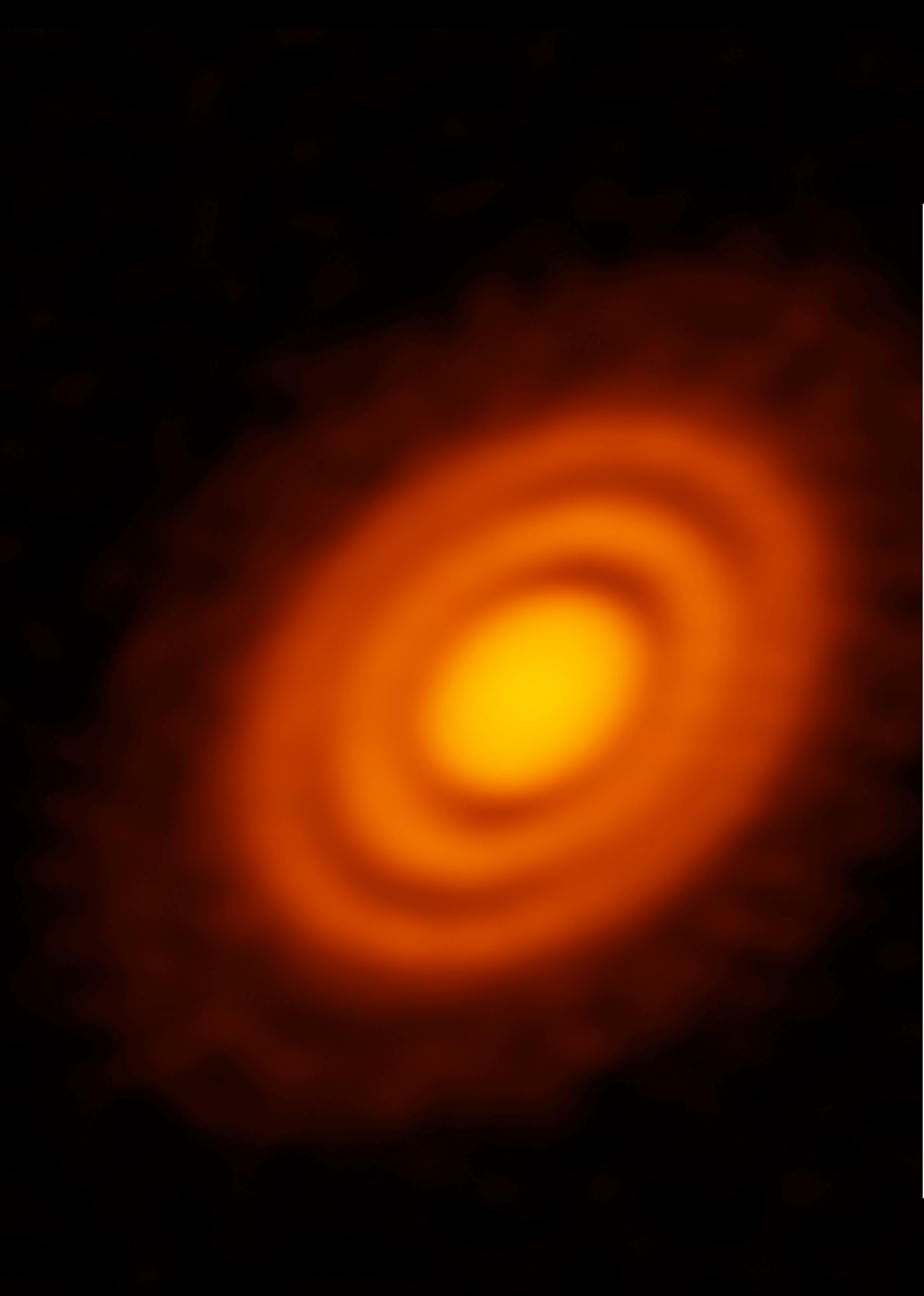
Inferring planets with ALMA

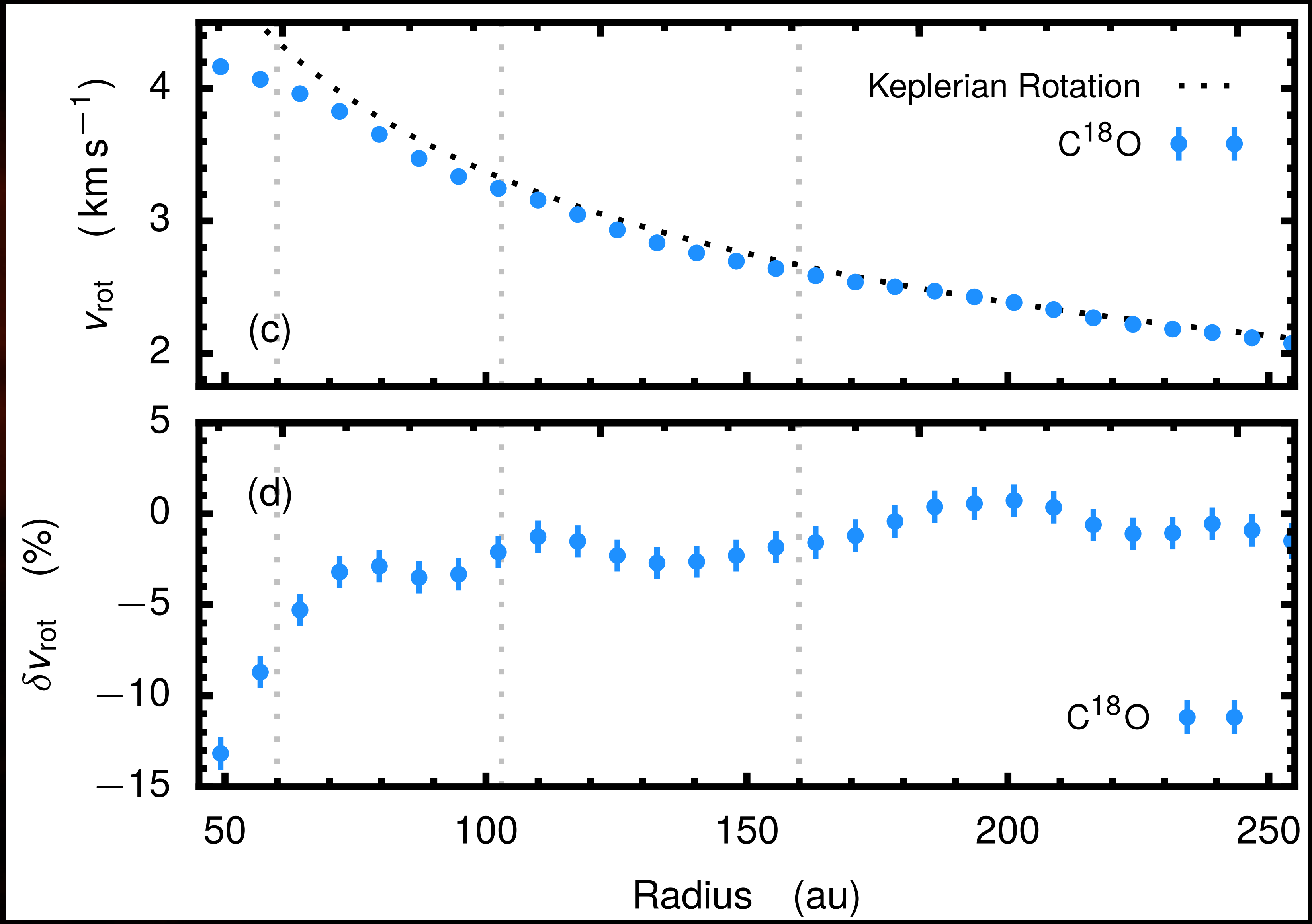


- Problems with interpreting dust emission profiles:
  - ➡ opacities are uncertain and may vary with position
  - ➡ additional interpretation for dips in emission
    - e.g. snowlines -> grain growth
- Using CO
  - ➡ uncertain gas-phase abundance (e.g. Favre +2013; Schwarz +2016; Kama +2016; Miotello +2017)
- lack independent tracers to get planet masses

Doppler Detection of planets with ALMA

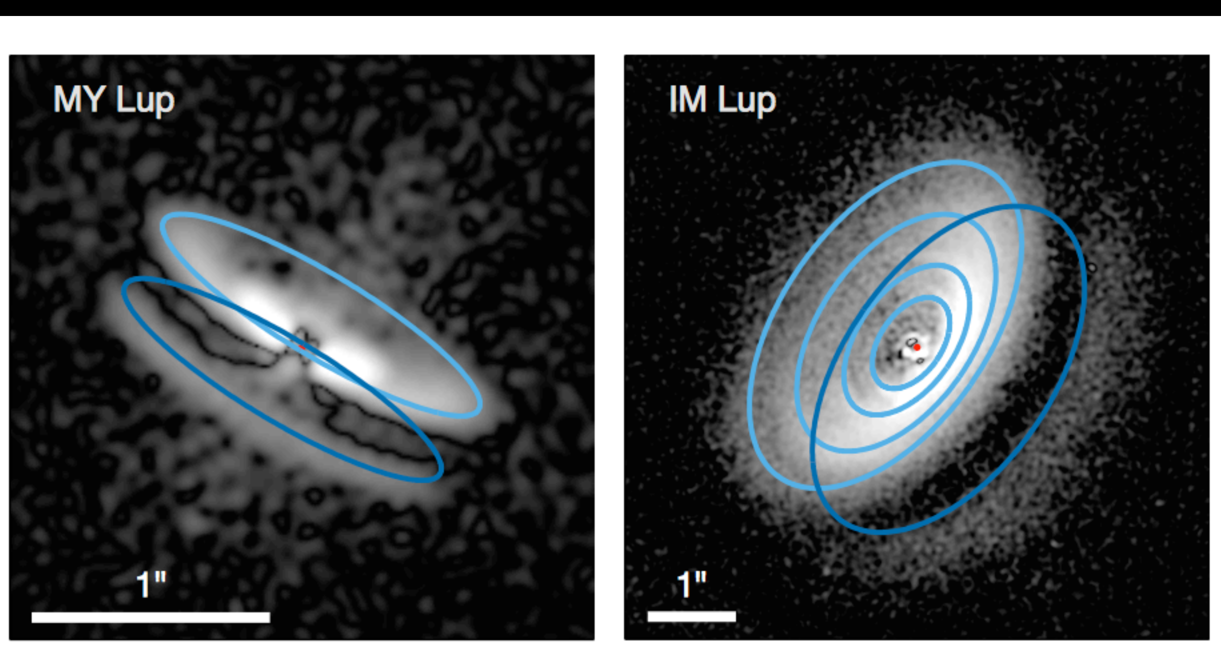
$$\frac{v_{rot}^2}{r} = \frac{GM_* r}{(r^2 + z^2)^{3/2}} + \frac{1}{\rho}\frac{\partial P}{\partial r}$$





Teague + 2018, subm.

Doppler Detection of planets with ALMA



Avenhaus+ 2018

Doppler Detection of planets with ALMA

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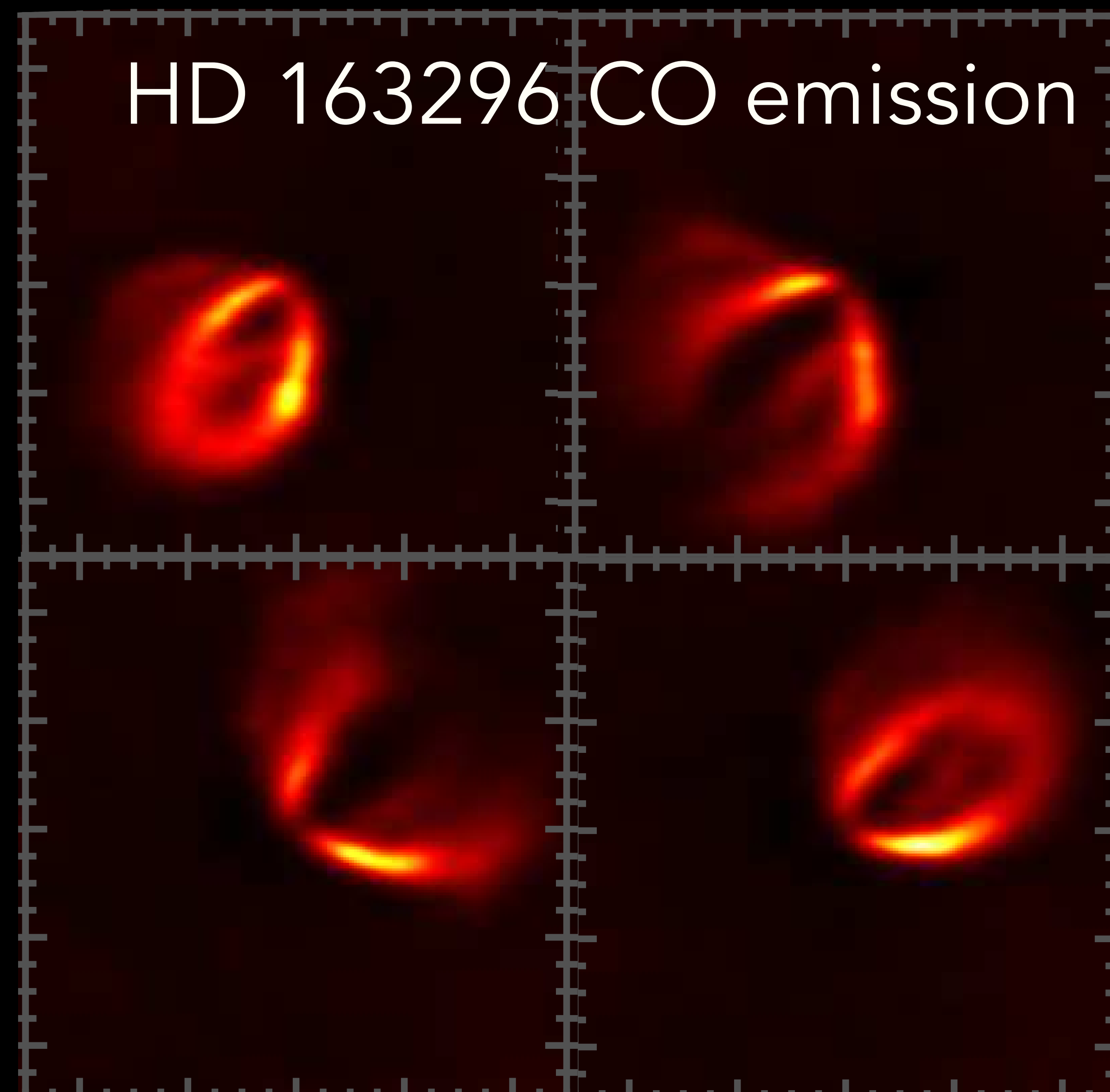
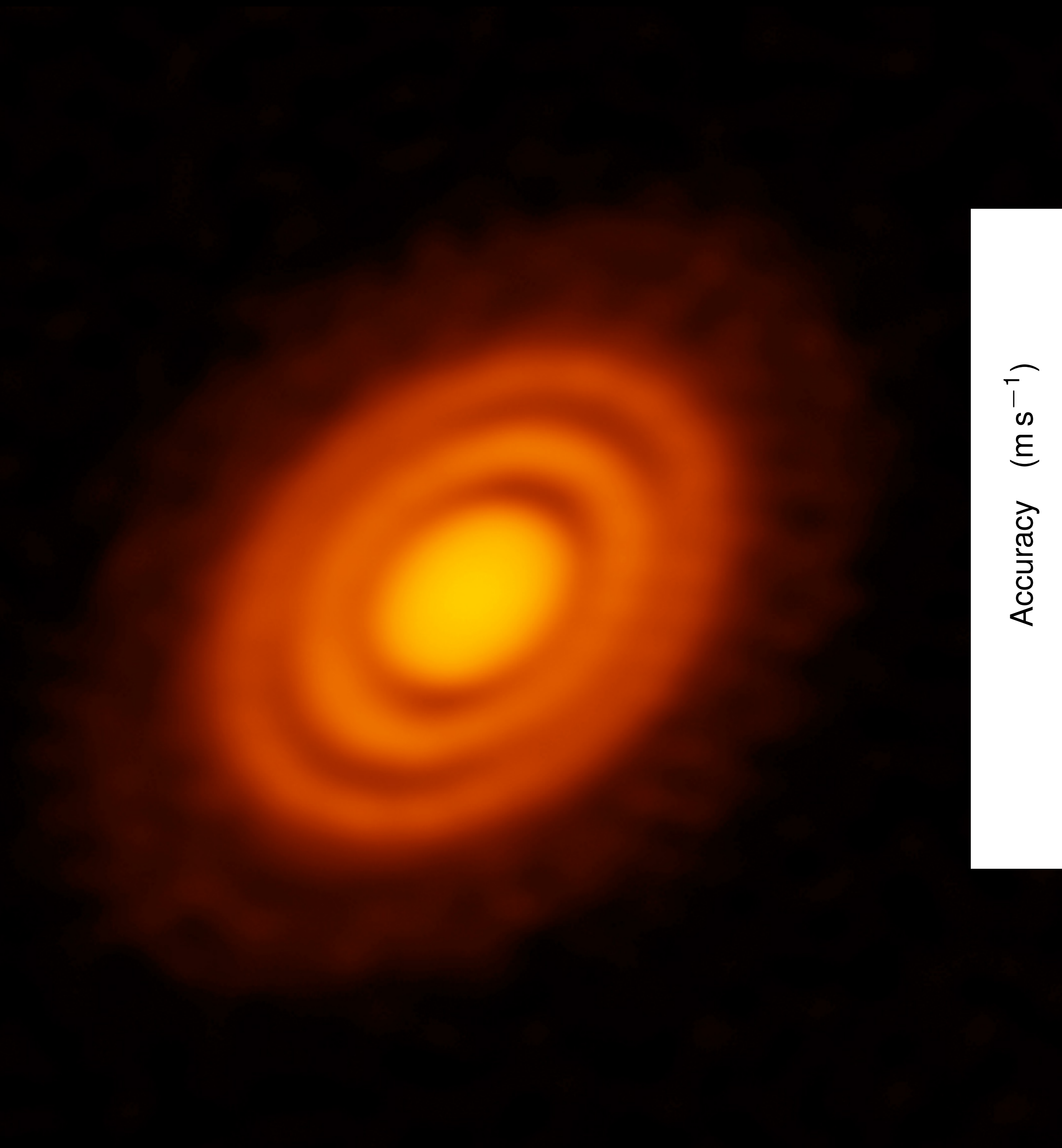
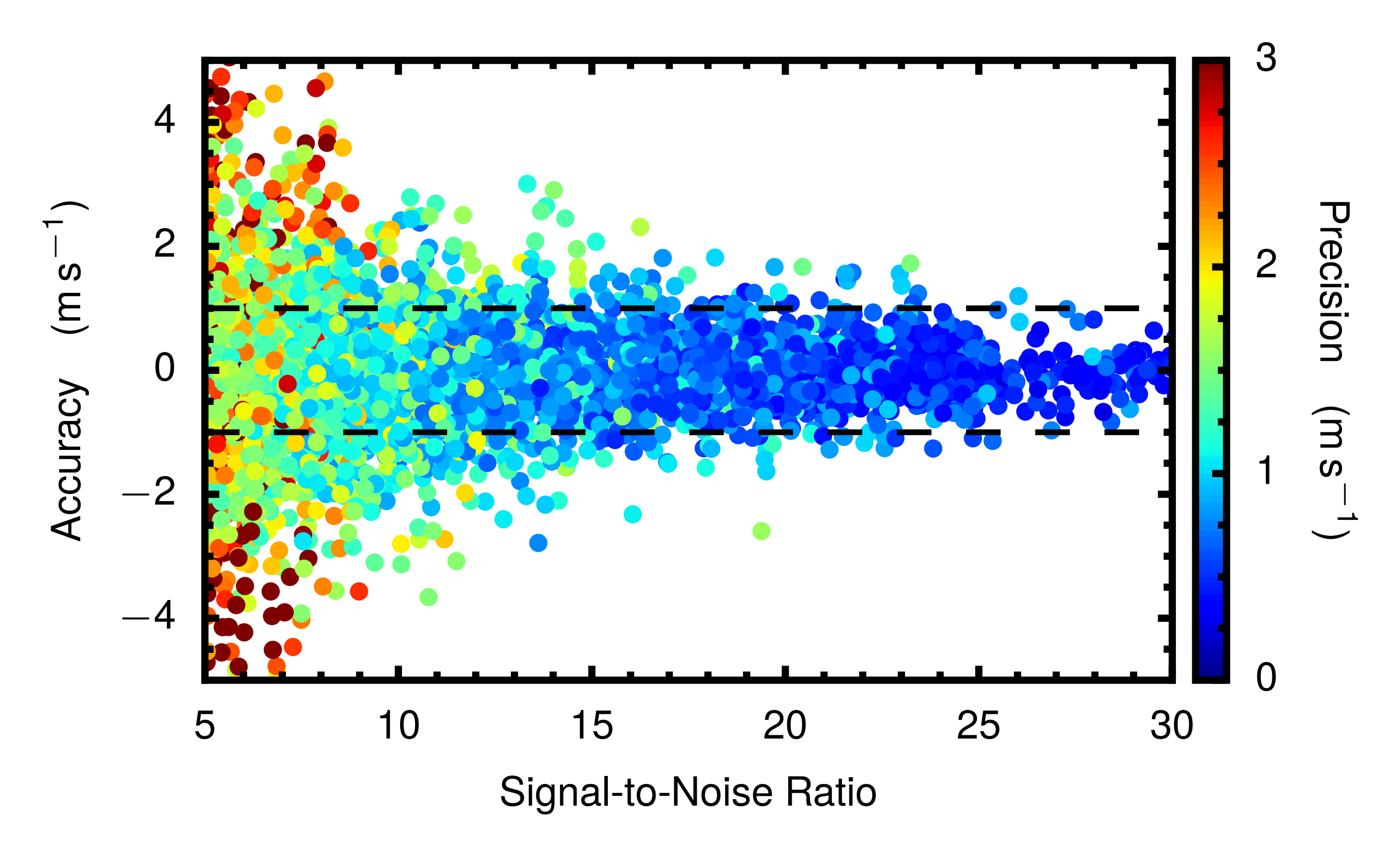


Rosenfeld+ 2013

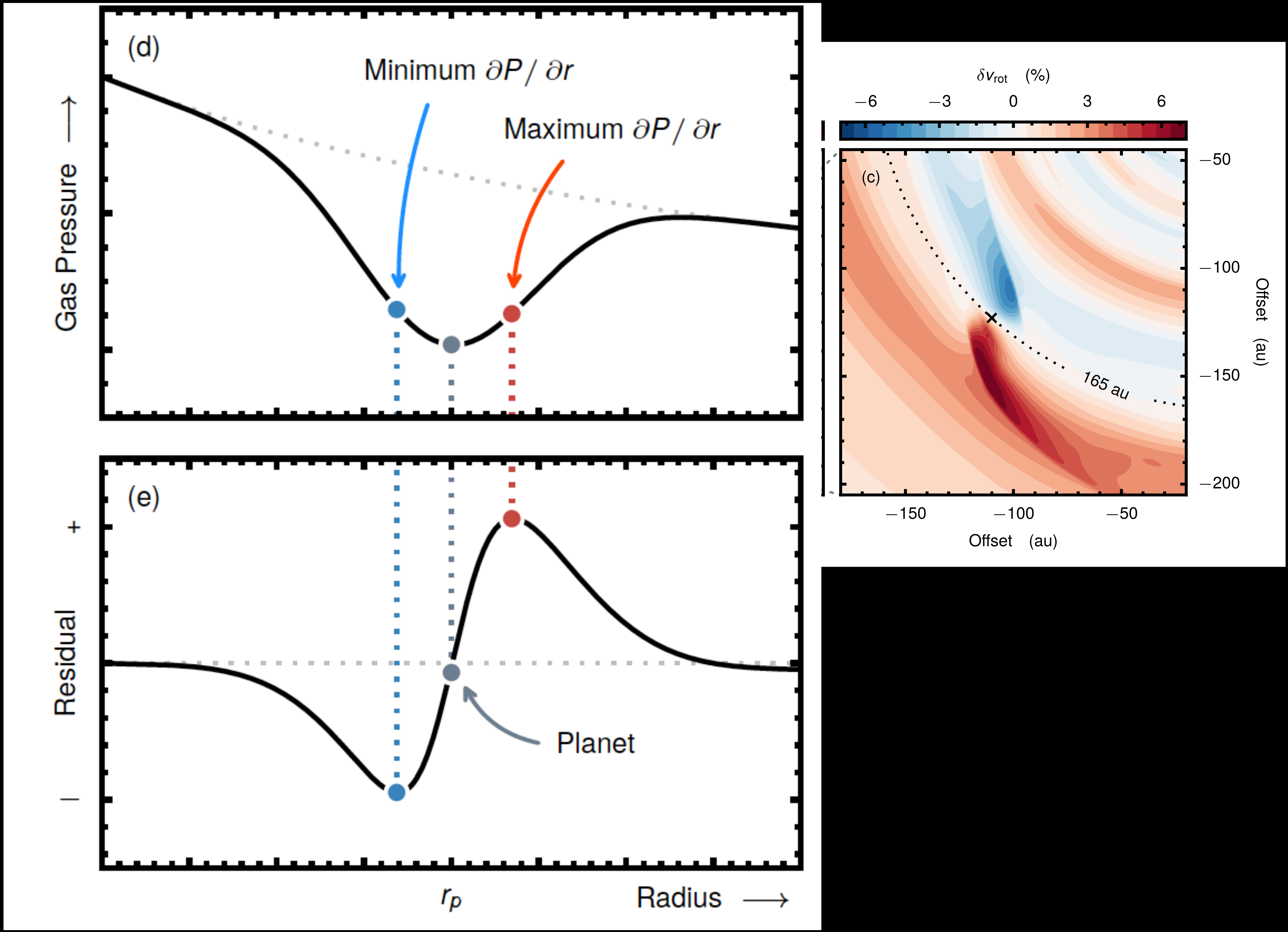
Doppler Detection of planets with ALMA





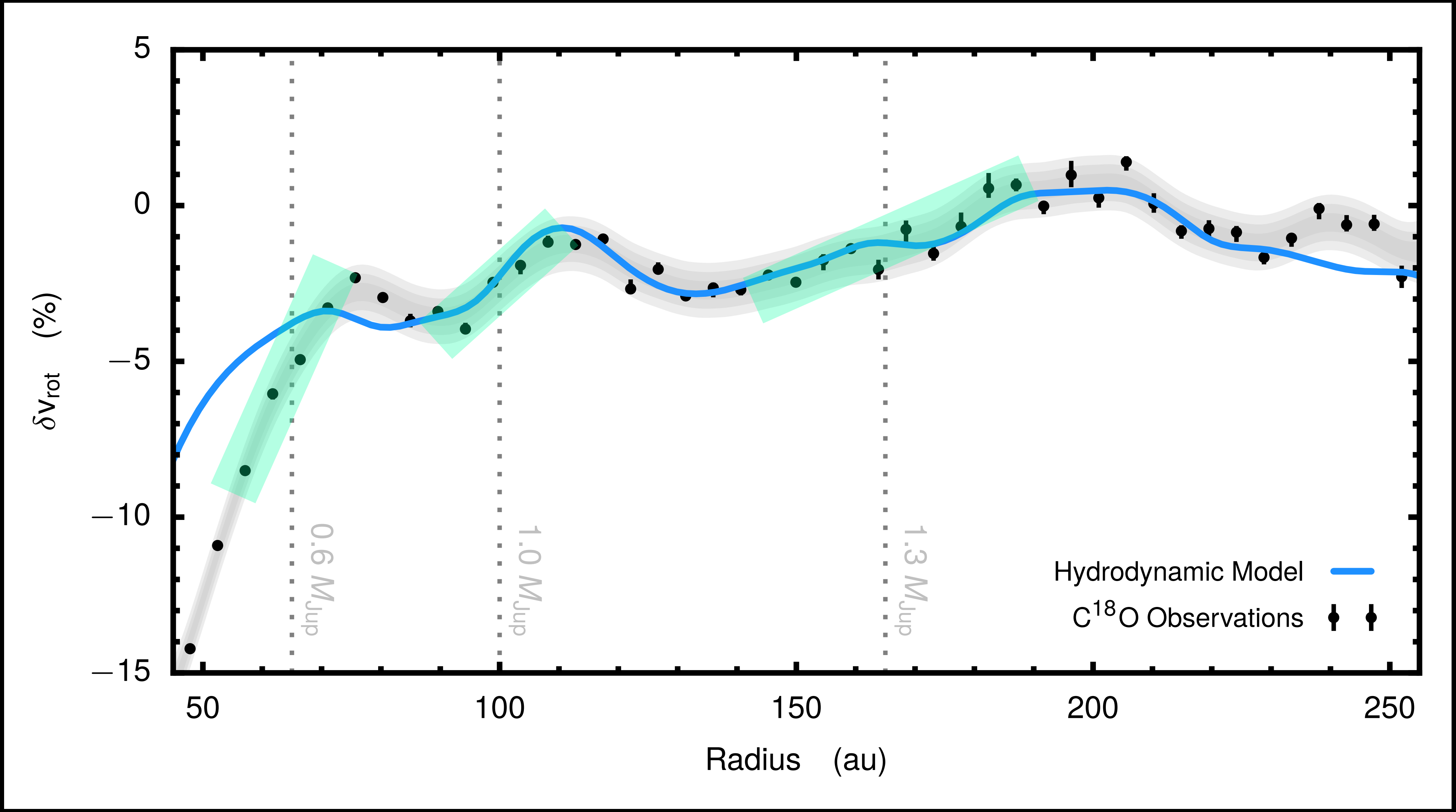
Teague + 2018, subm.

Doppler Detection of planets with ALMA



Teague + 2018, subm.

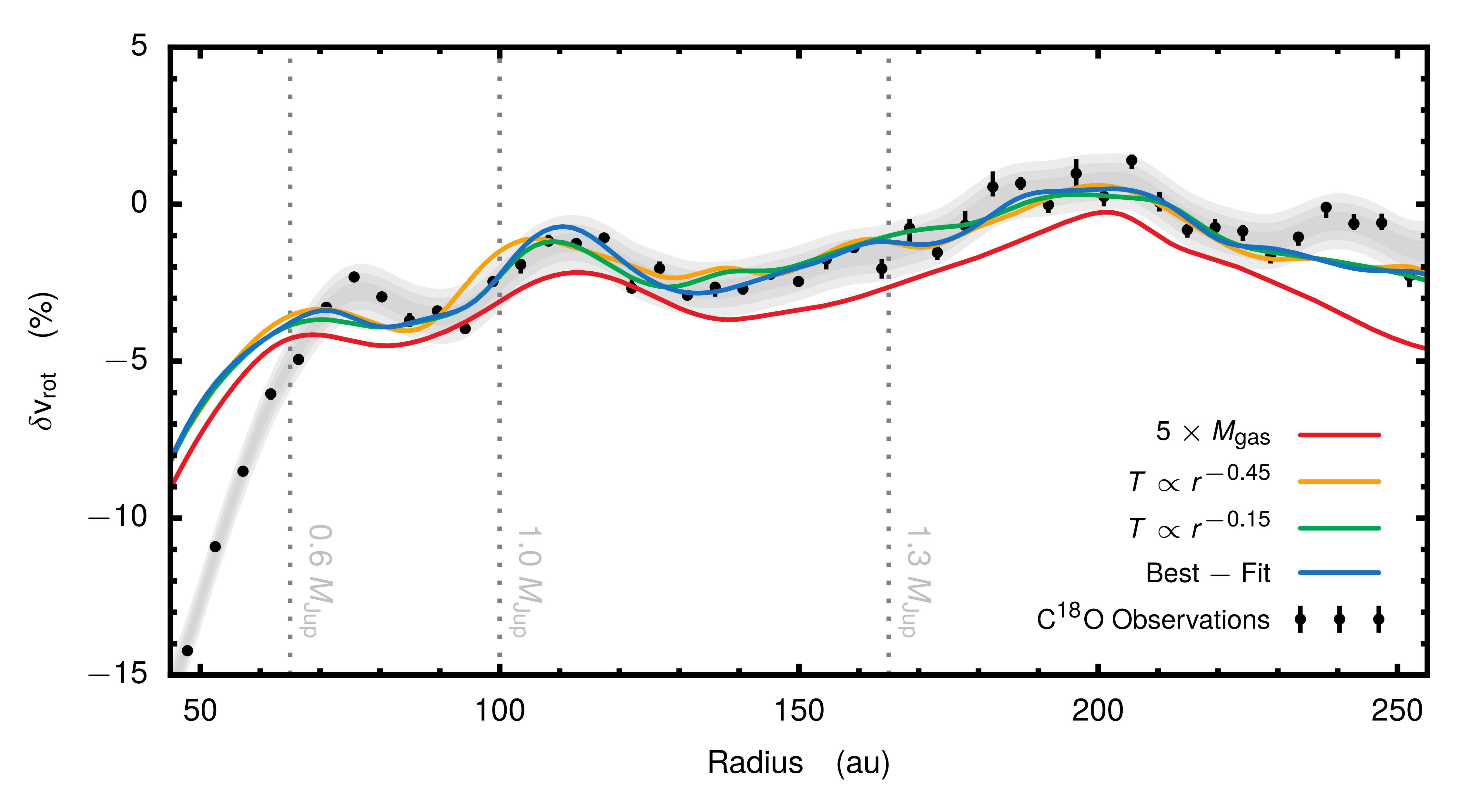
Doppler Detection of planets with ALMA



2D and 3D Hydrodynamical Models by J. Bae

Teague + 2018, subm.

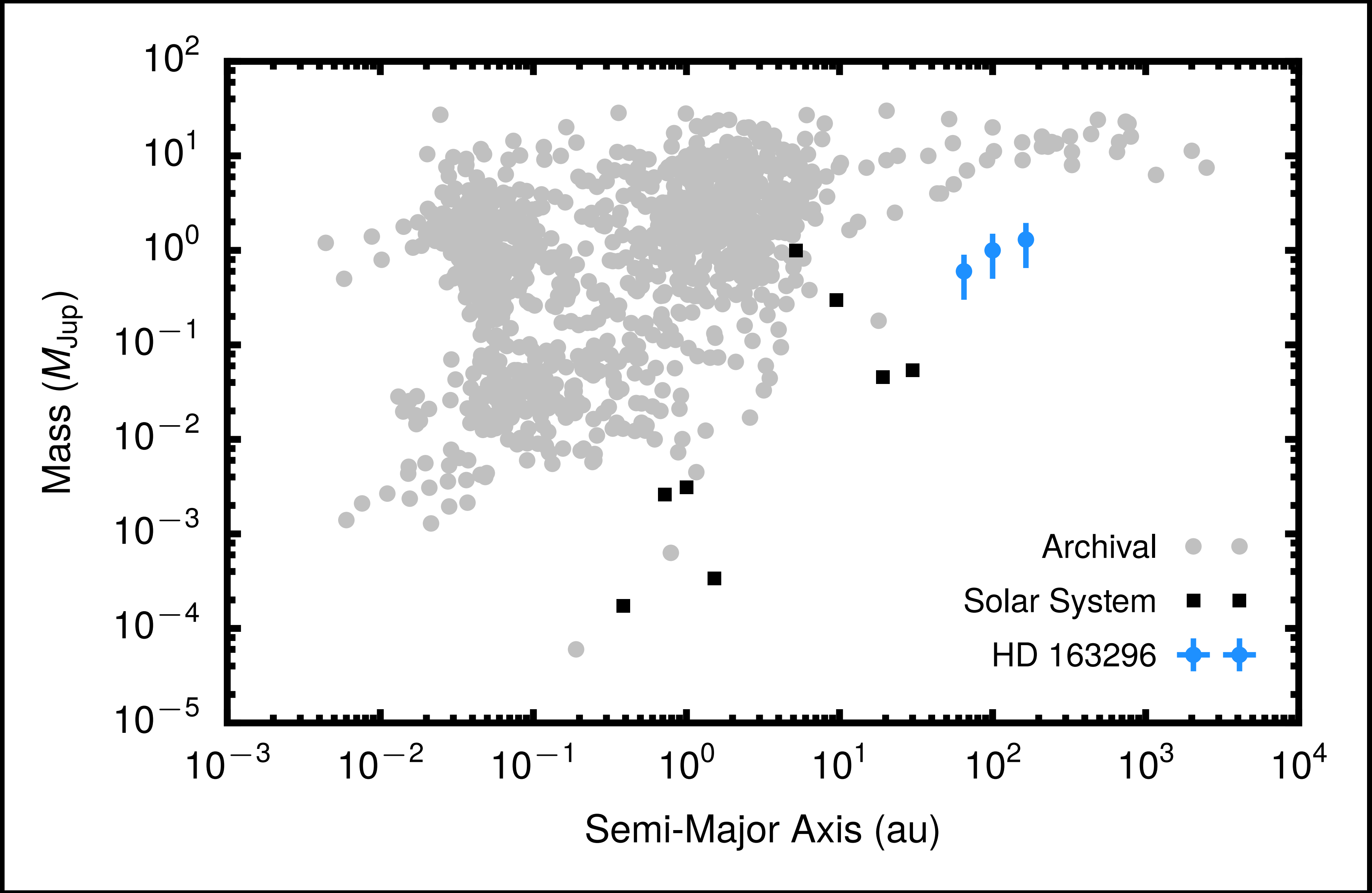
Doppler Detection of planets with ALMA



Not sensitive to absolute calibration - can set stronger constraints on planet mass

Teague + 2018, subm.

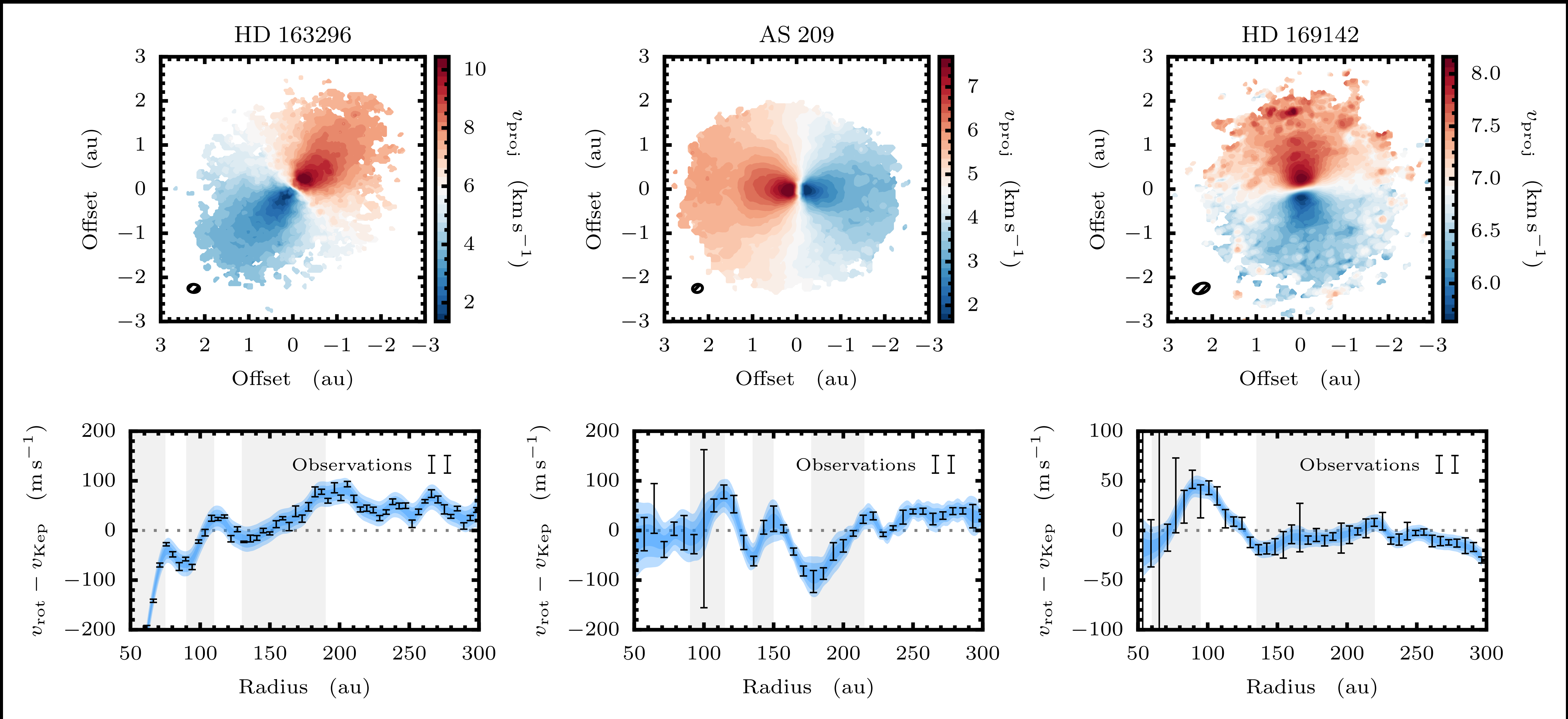
Doppler Detection of planets with ALMA



dynamical timescales at these distances
are > disk lifetime

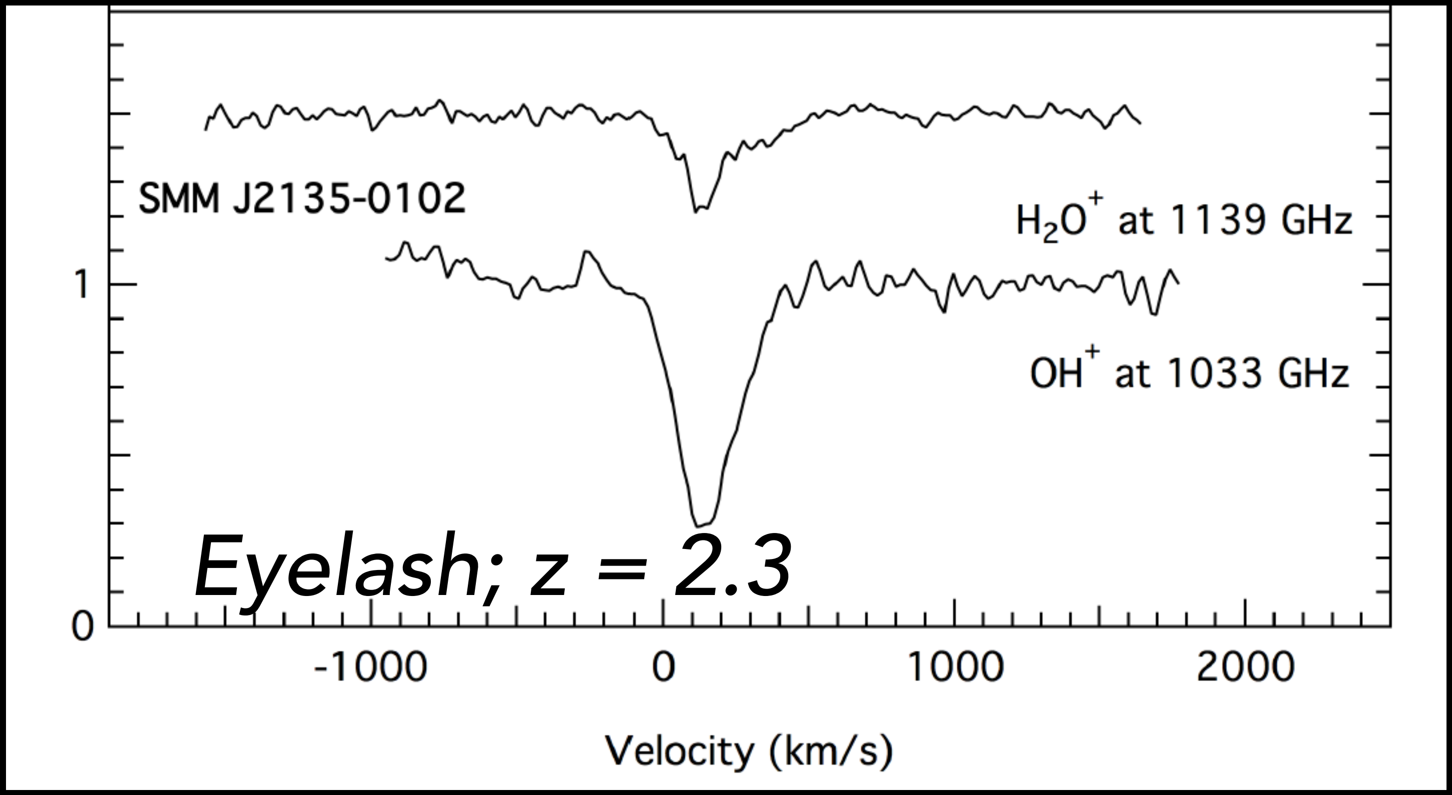
Teague + 2018, subm.

Tip of the Iceberg



Summary+

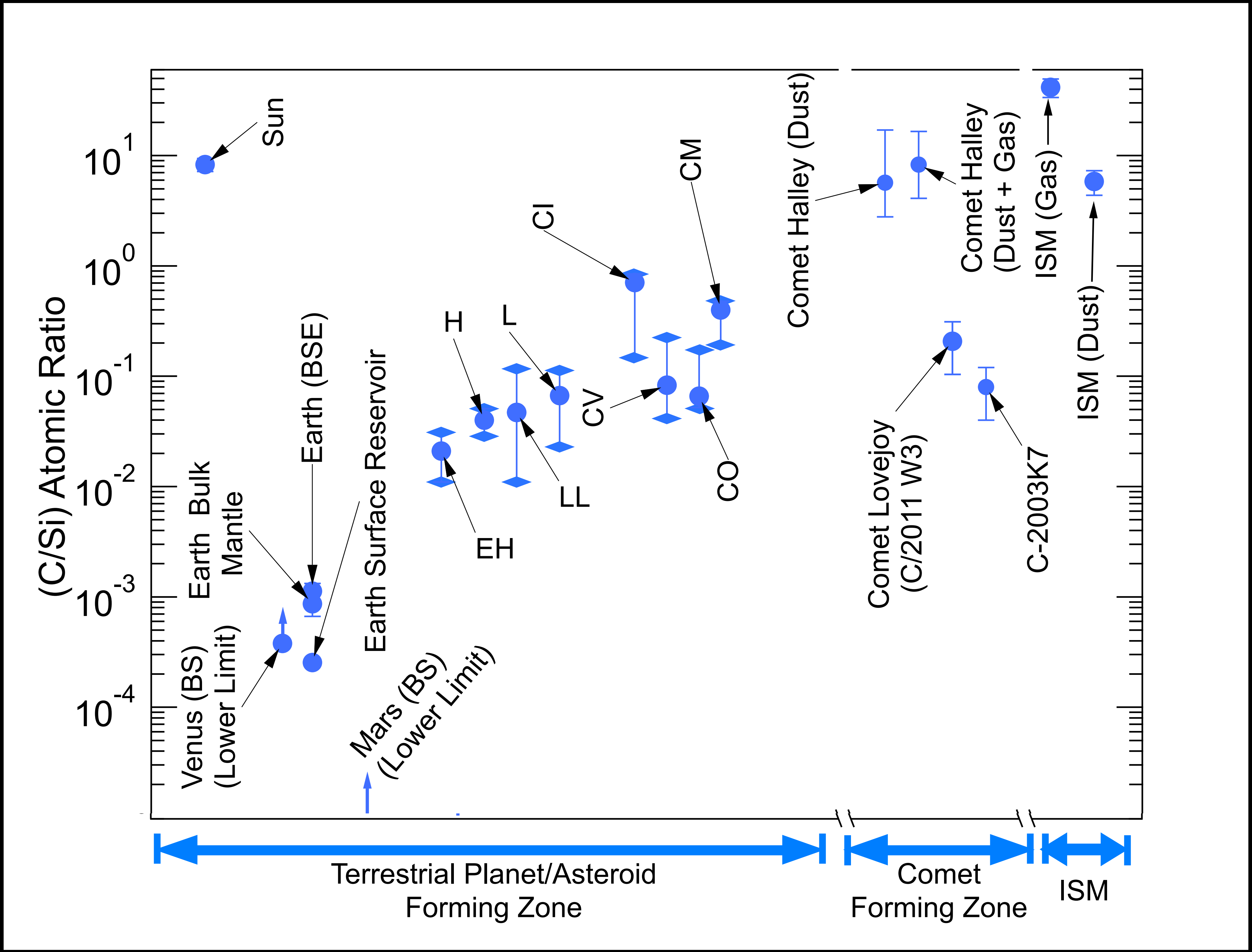
- There is a carbon problem in the formation of Earth-like worlds
- We are capturing key aspects of planet formation chemistry with ALMA.
- We are inferring the presence of forming planets with ALMA via the doppler effect.
- Molecules @ high-z are opening new avenues to explore star formation physics (energy input and CR ionization in galaxy halos)



Indriolo+ 2018, submitted

- ➡ go to scales and add in $H2O^+$/OH^+/ CH^+

What about Terrestrial Worlds?

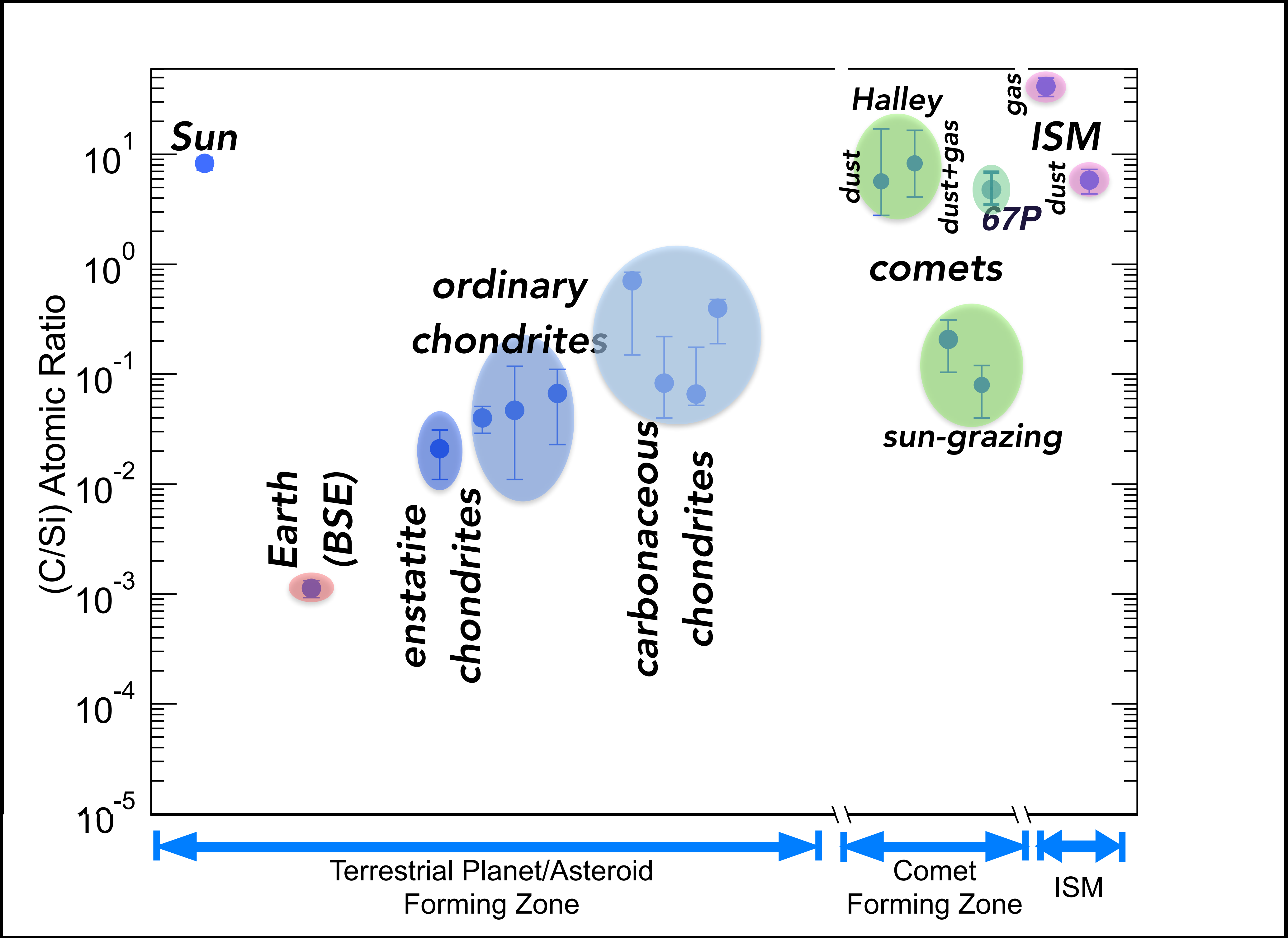


Bergin +2015

How Can We Connect to Terrestrial Planet Formation?

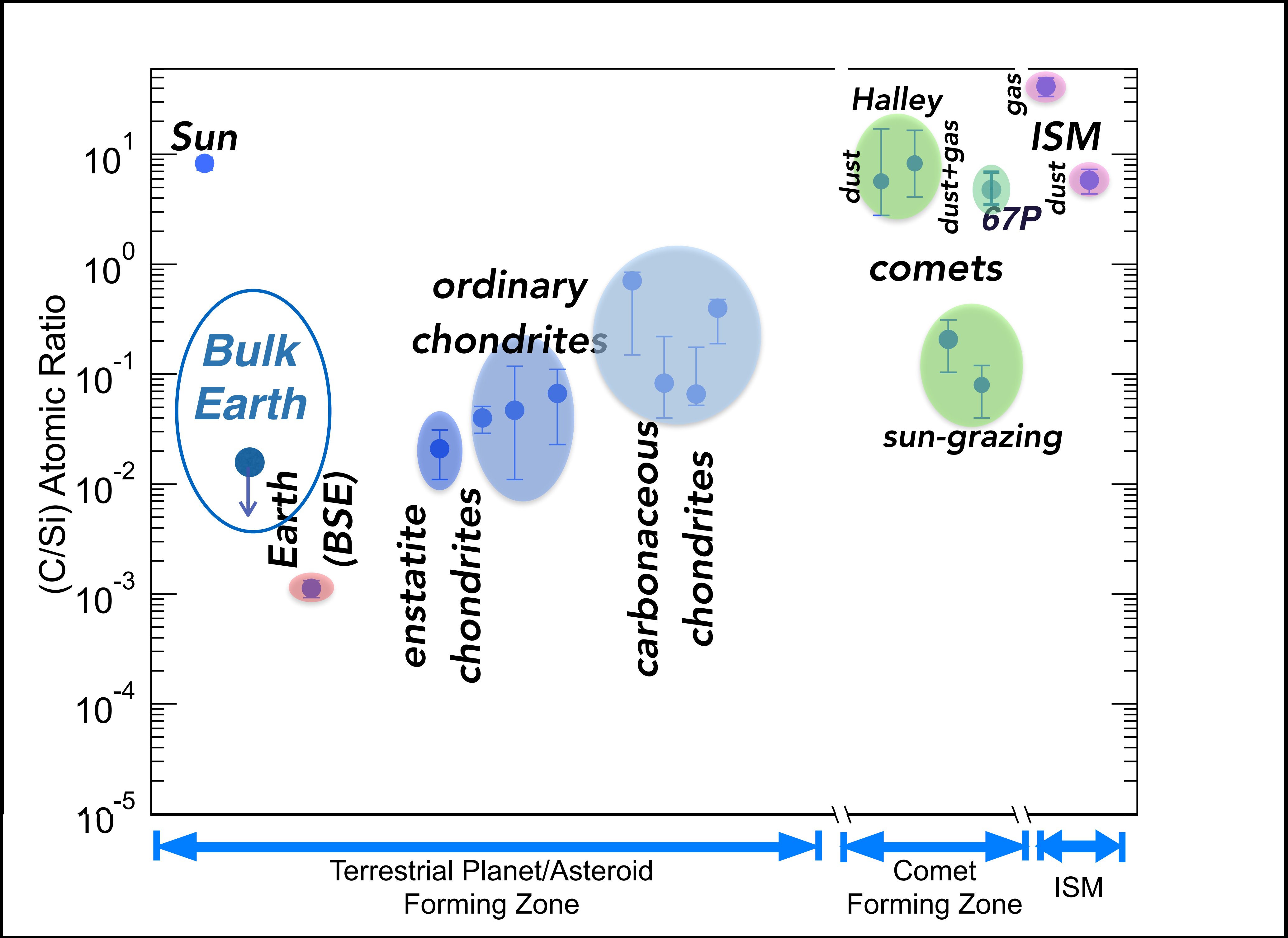
- Difficult.....
- Lot of focus on water vapor/ice
- What about other needed elements such as carbon?
- Where is bulk carbon?

What about Terrestrial Worlds?



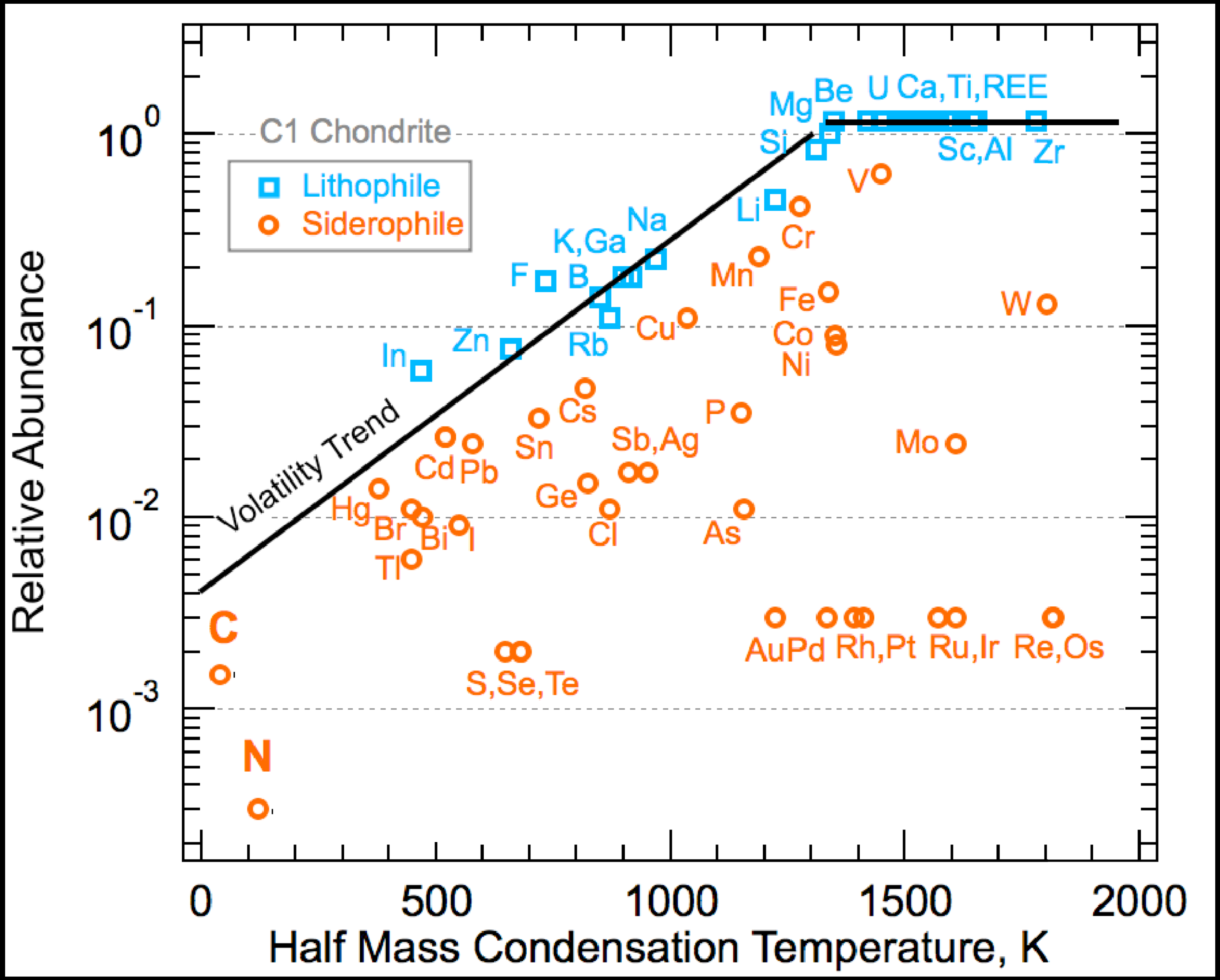
Bergin +2015

What about Terrestrial Worlds?



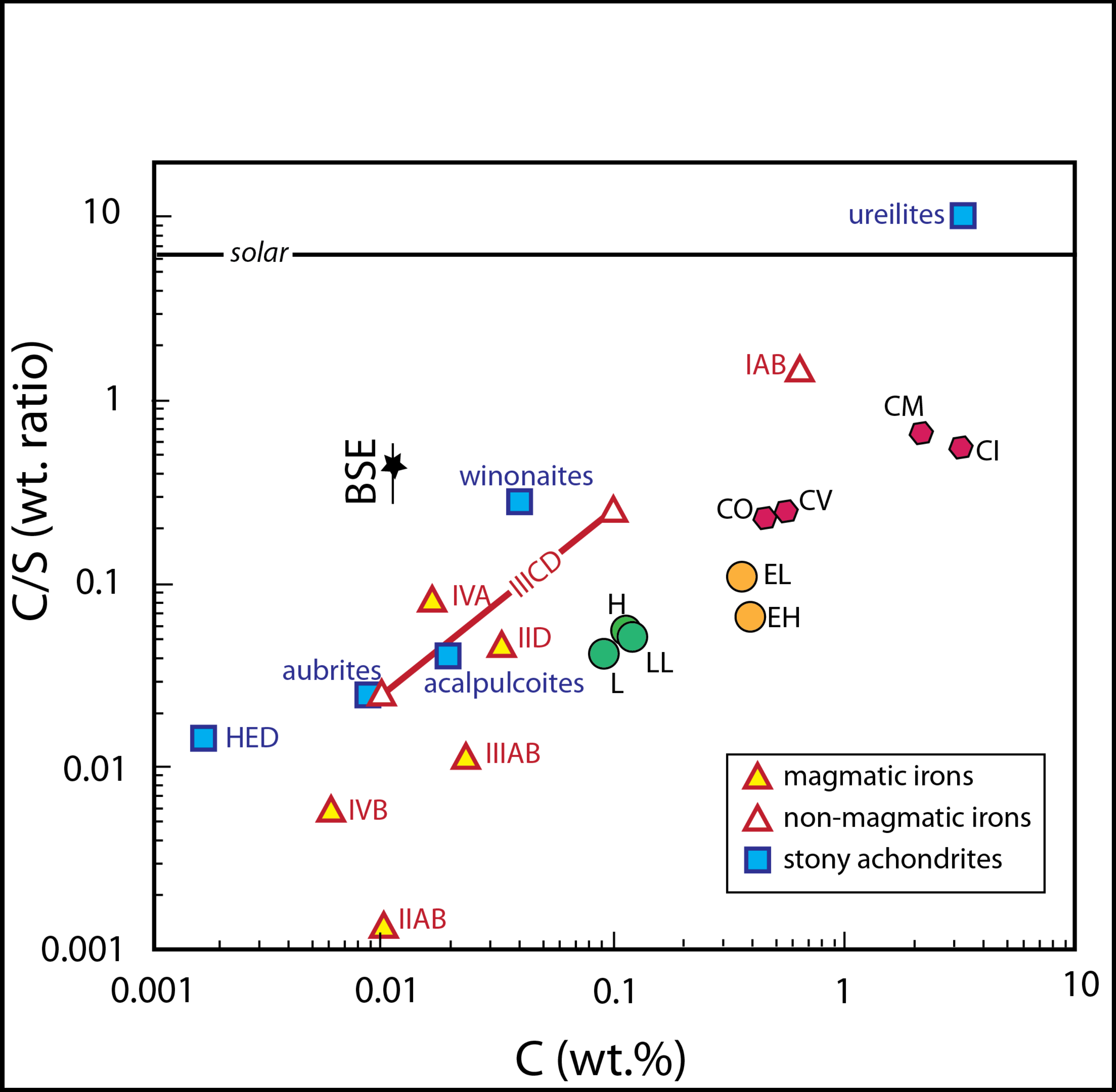
Bergin +2015, Li + 2018, in prep.

What about Terrestrial Worlds?



Li + 2018, in prep.

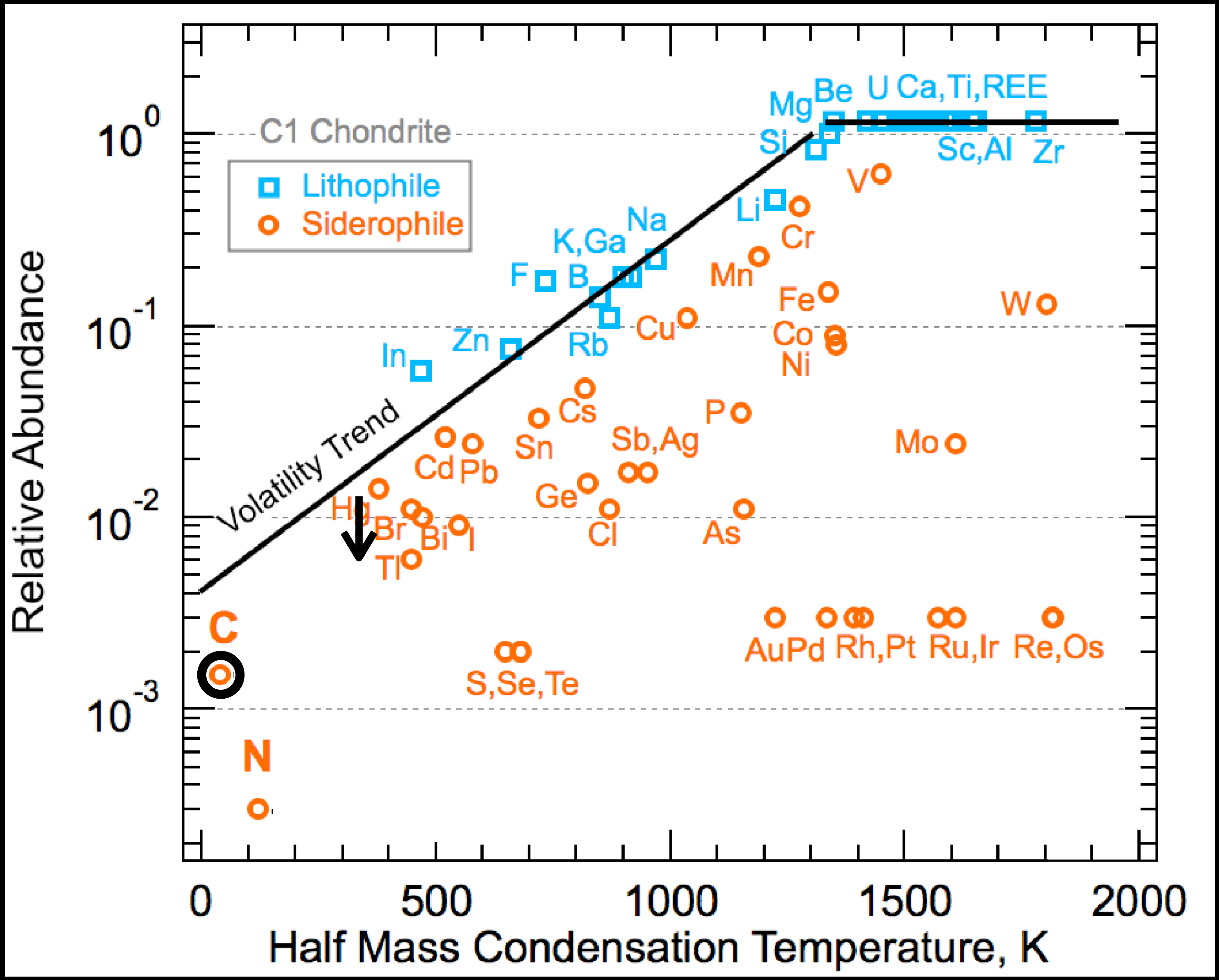
Sublimation Temperature of Carbon Grains



Li + 2018, in prep.

- Must be below S
  ➡ $T_{sub}(FeS)$ ~ 800 K
- Must be above H_2O
  ➡ $T_{sub}(H_2O)$ ~ 200 K
- Nakano et al. 2003 - solar system organics
  ➡ T_{sub} ~ 400 K

What about Terrestrial Worlds?



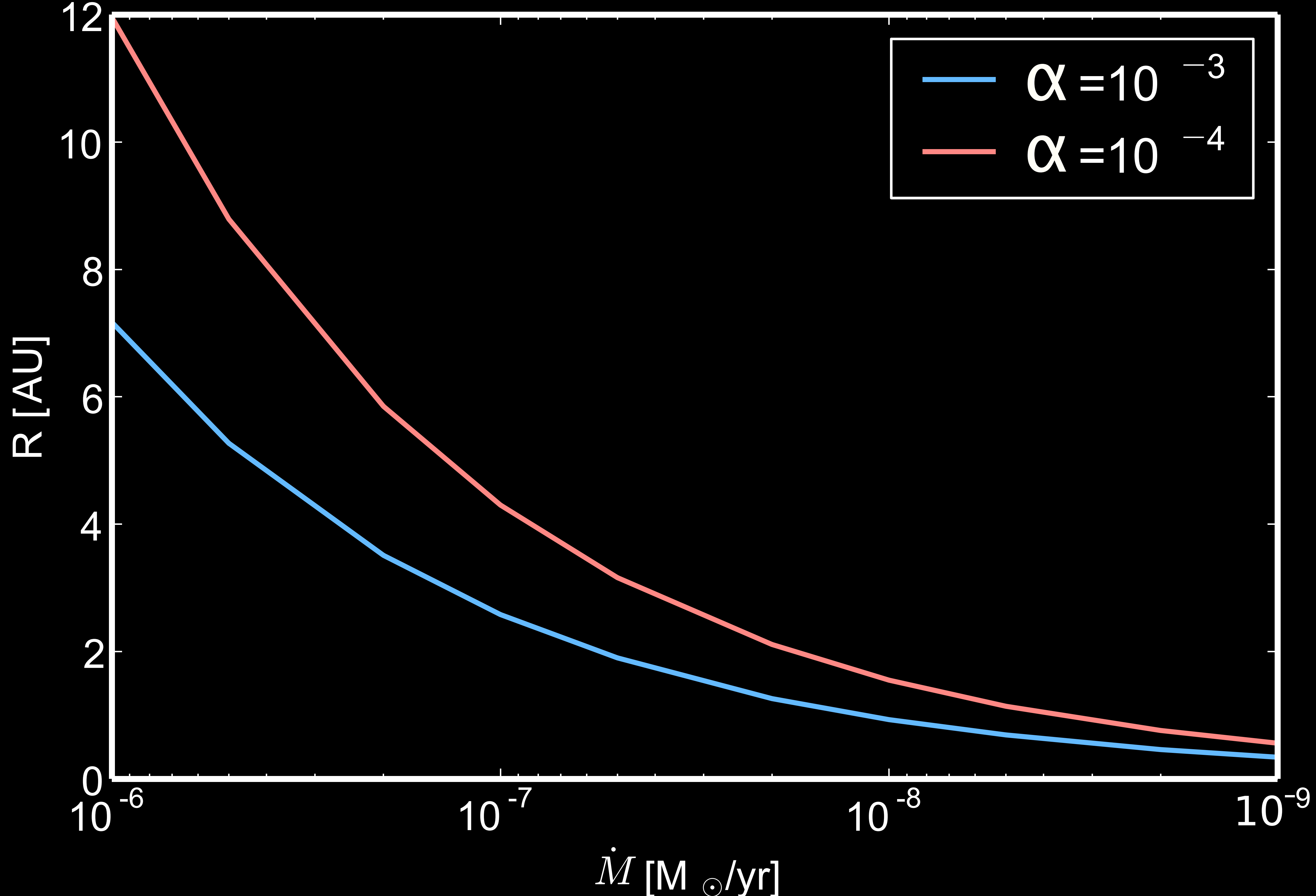
Li + 2018, in prep.

What about Terrestrial Worlds?

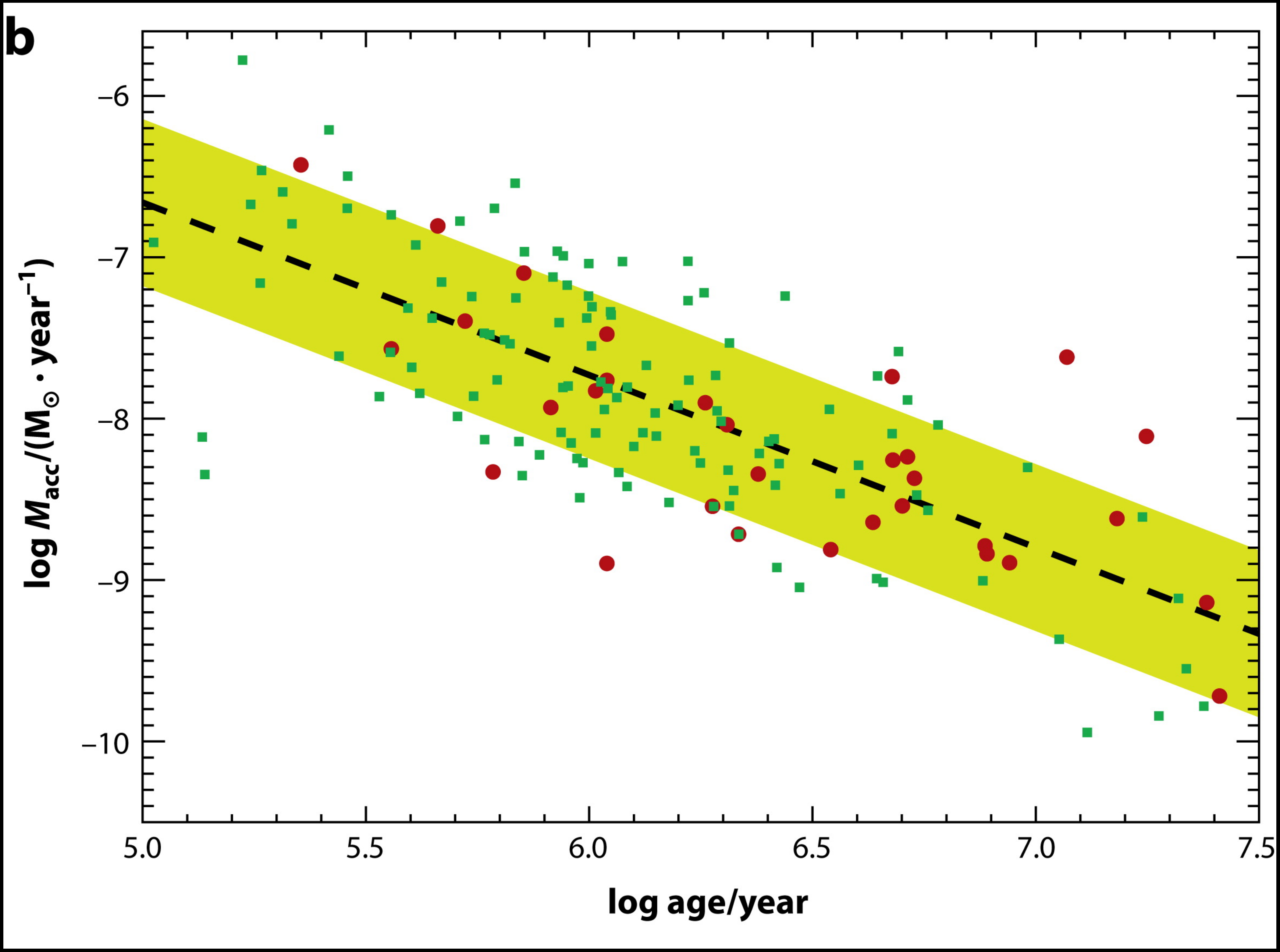
- 2 possible scenarios

1. Earth's carbon is consistent with trend
   - ➡ Carbon is in the core.
2. Earth is truly carbon poor
   - ➡ Large fraction of Earth's materials had to form inside of sublimation point of refractory carbon

"Soot-line"

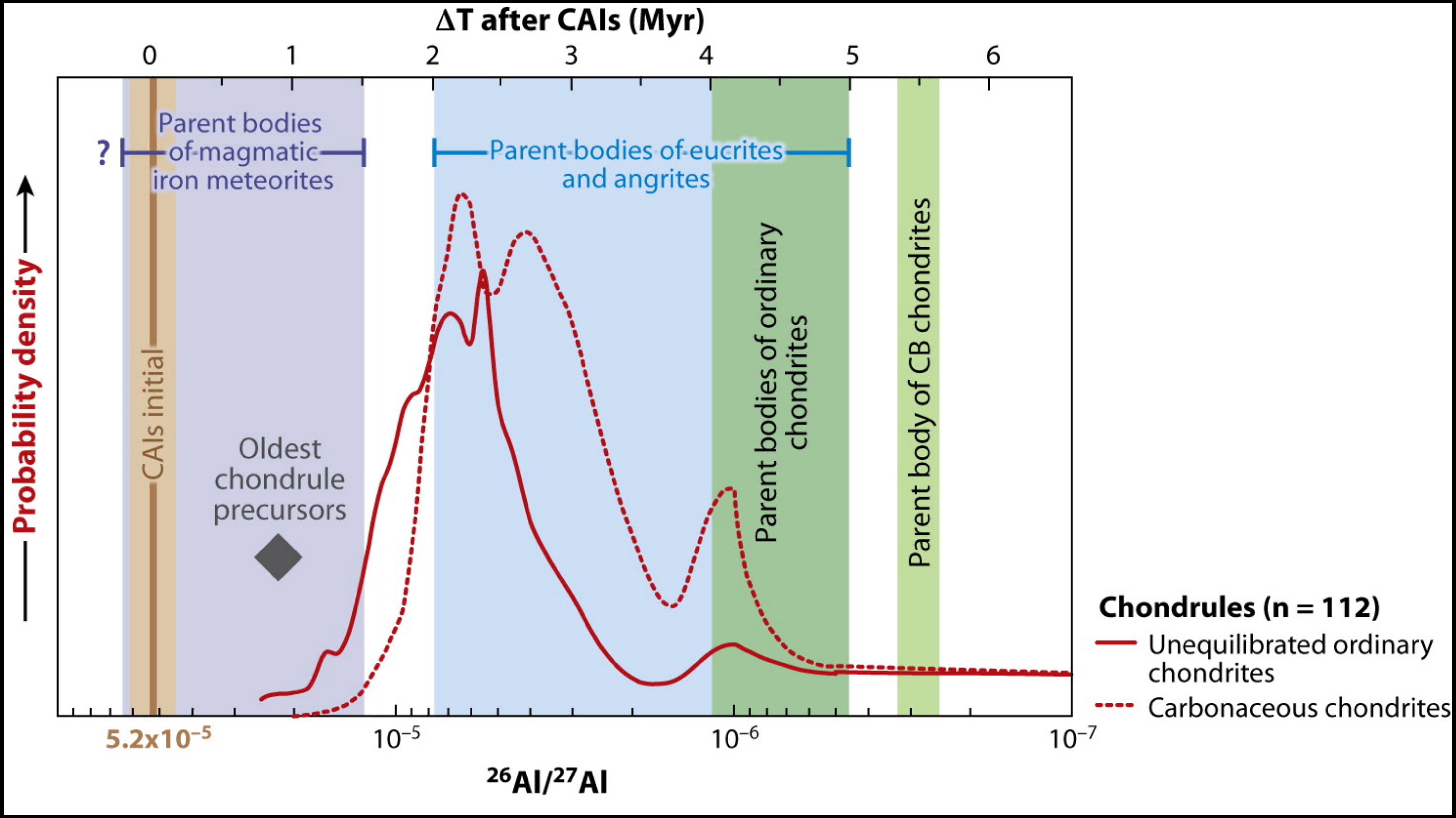


Astronomical Constraints on Accretion



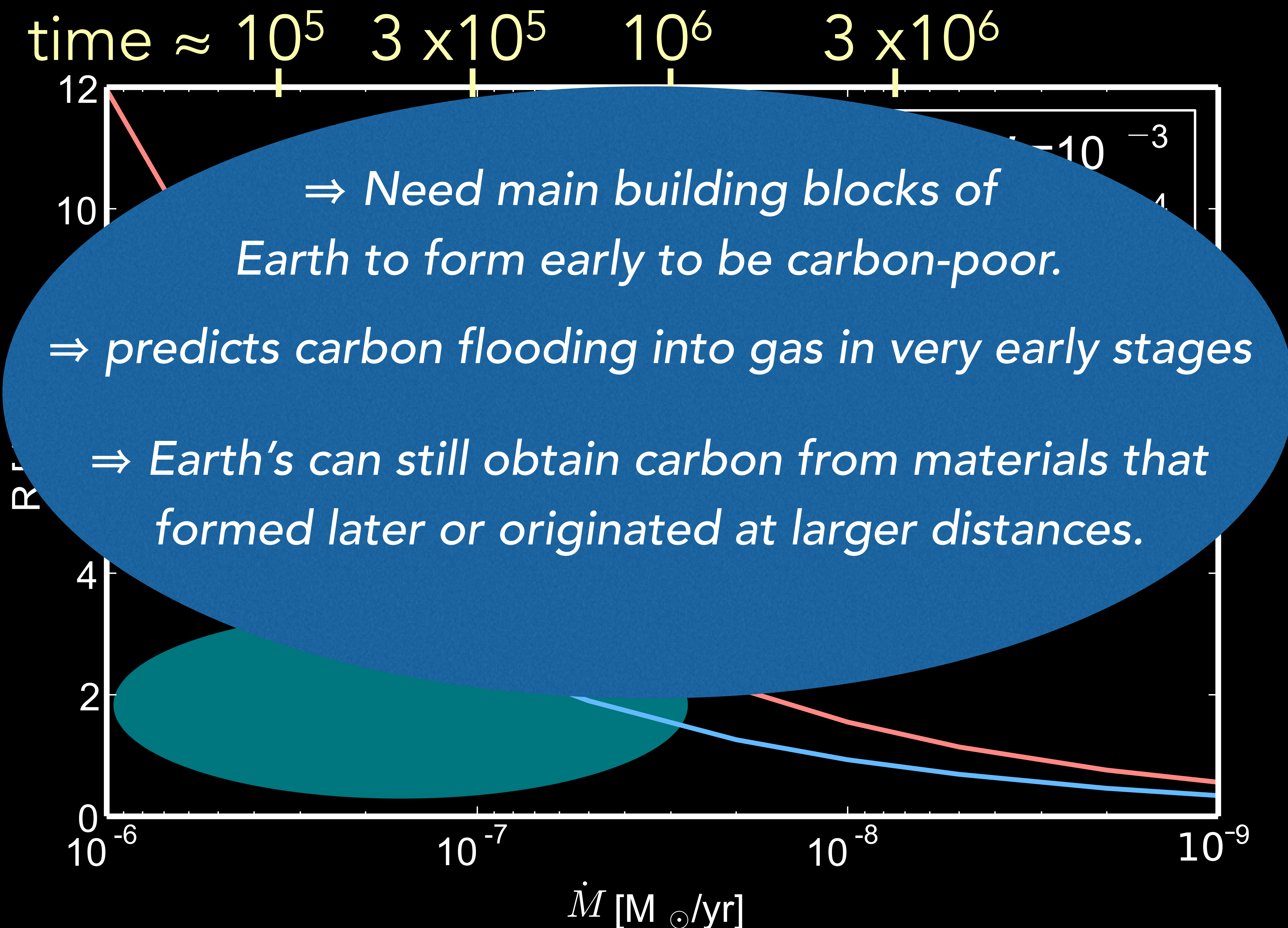
Hartmann+ 2016

Timescales in Solar System



Dauphas & Chaussidon 2011

"Soot-line"



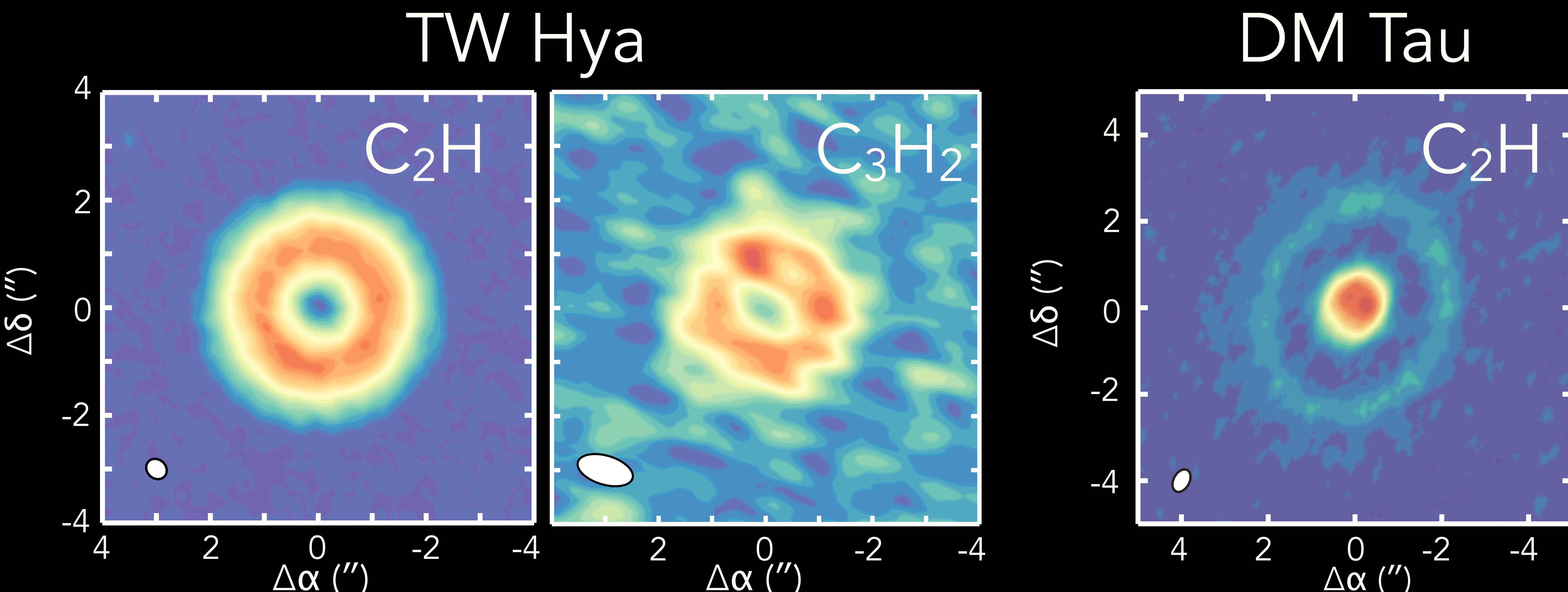
⇒ Need main building blocks of Earth to form early to be carbon-poor.

⇒ predicts carbon flooding into gas in very early stages

⇒ Earth's can still obtain carbon from materials that formed later or originated at larger distances.

Hydrocarbon Rings

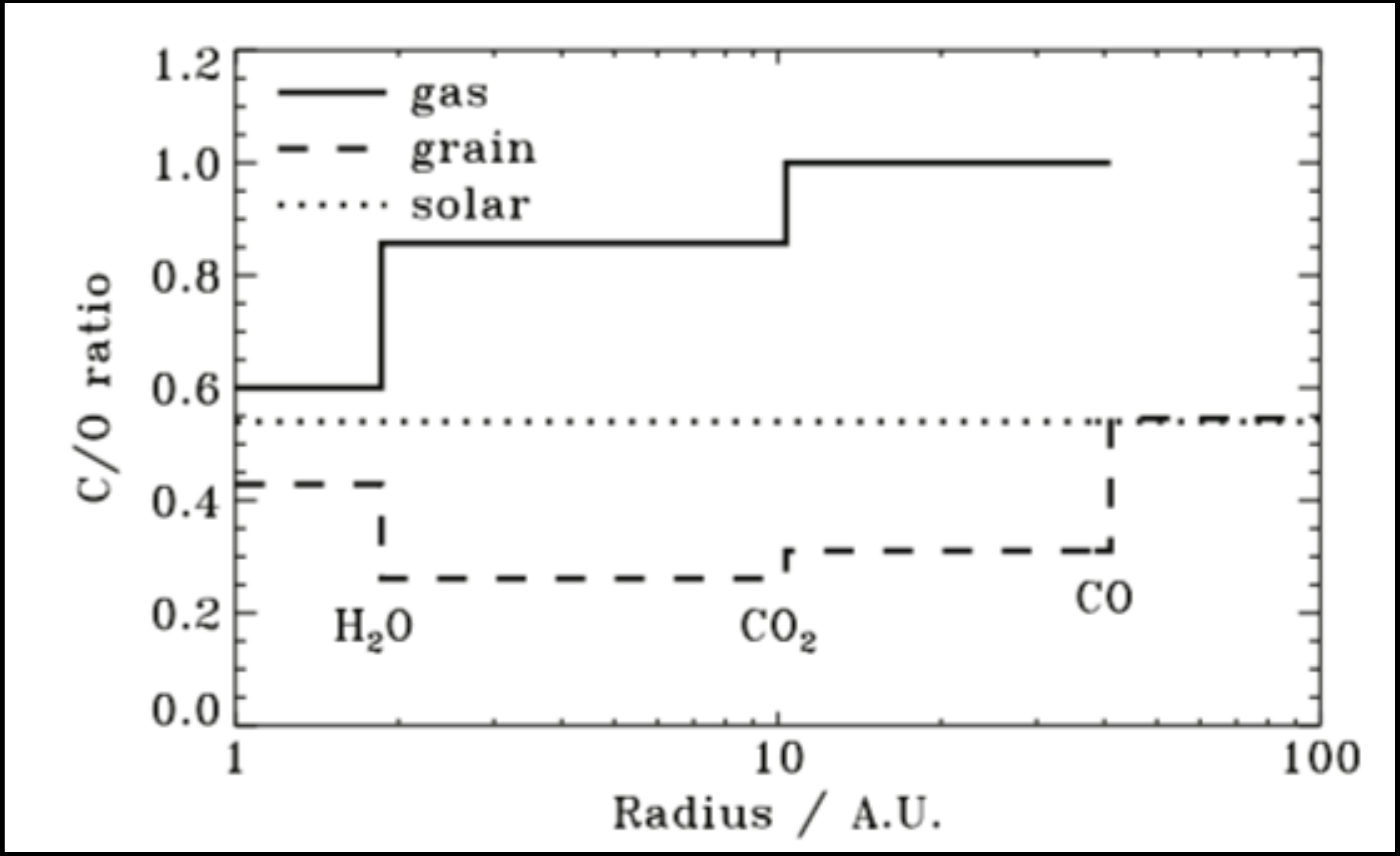
- Dust evolution - more UV
- Ingredients: UV photons, CO, H_2 gas, no oxygen



Bergin + 2016

Disk Bulk Composition & Gas Giants

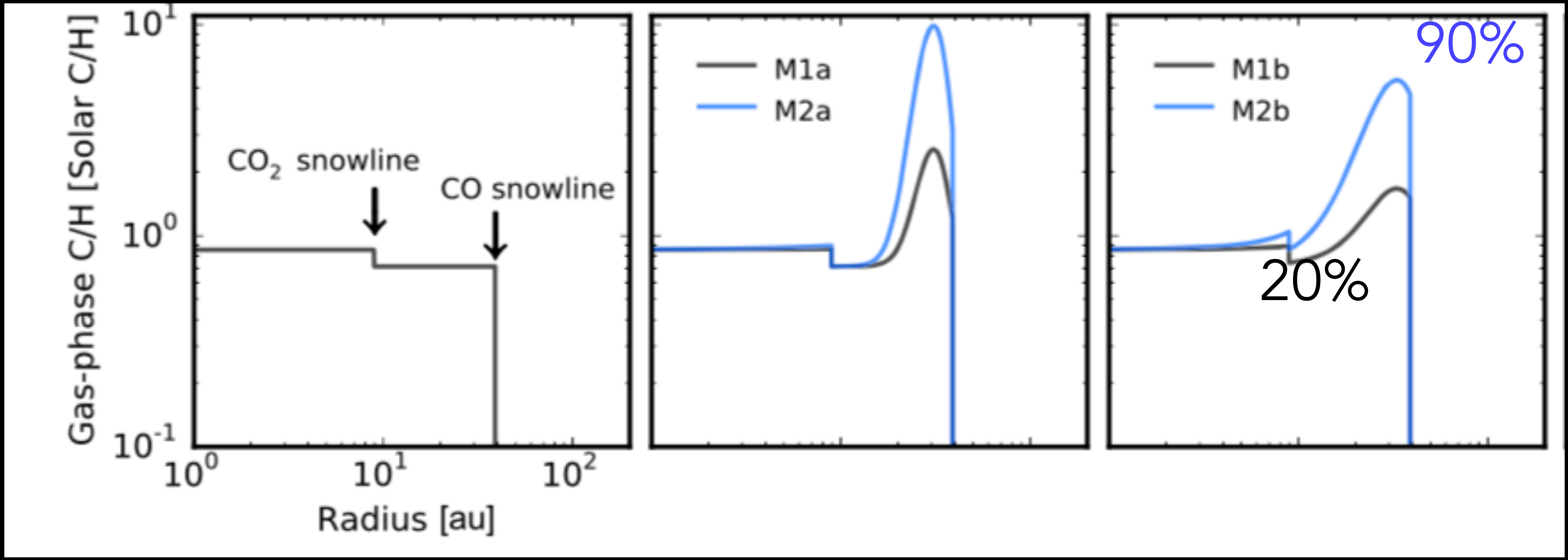
- To date clear focus on connective tissue has been the C/O ratio and snowlines (Öberg, Murray-Clay, & Bergin 2011).



complications:
migration
pollution
core dilution

Disk Bulk Composition & Gas Giants

- Another link can be due to pebble drift in disks and snowlines (Guillot & Hues 2006, Öberg & Bergin 2016; Booth +2017; Madhusudhan +2017).



Öberg & Bergin 2016

elevate C/H, N/H? in gas (O/H substellar beyond water snow line)

<u>Big question</u>: when does this happen? & where is this material deposited?

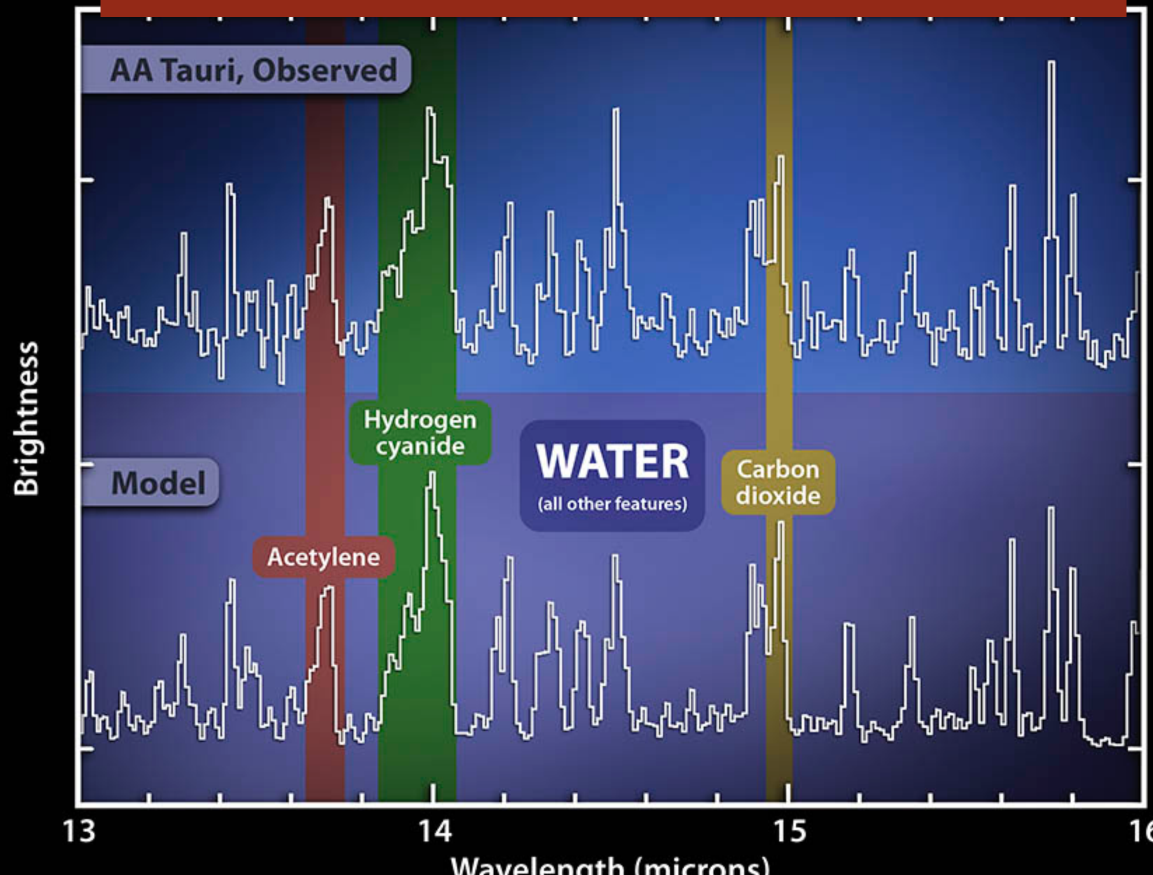
1) Measurements of Bulk Composition in Disks: C/O

- Beyond water snowline: water is missing from gas

  (Bergin +2010; Hogerheijde +2011; Du+ 2015; Blevins+2016; Du+ 2017)

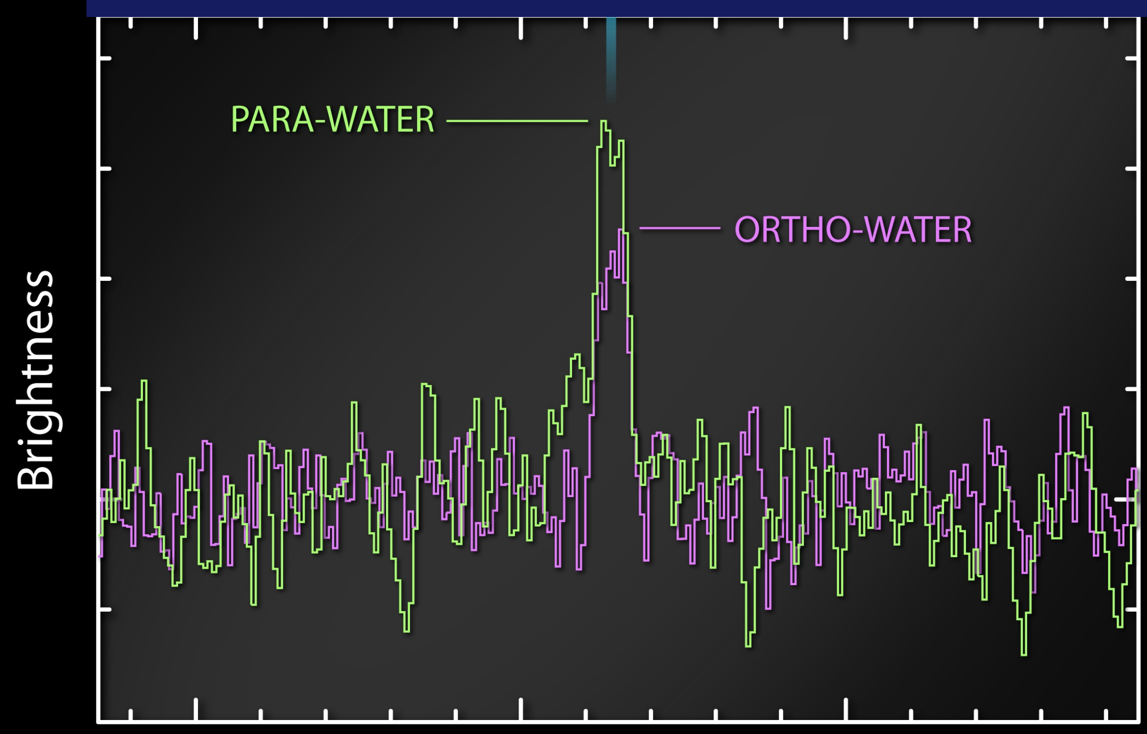
- C/O in gas is at least unity (until CO freezes)

Hot water: inside snowline



Organic Molecules and Water in a Protoplanetary Disk Spitzer Space Telescope • IRS
NASA / JPL-Caltech / J. Carr (Naval Research Laboratory) ssc2008-06a

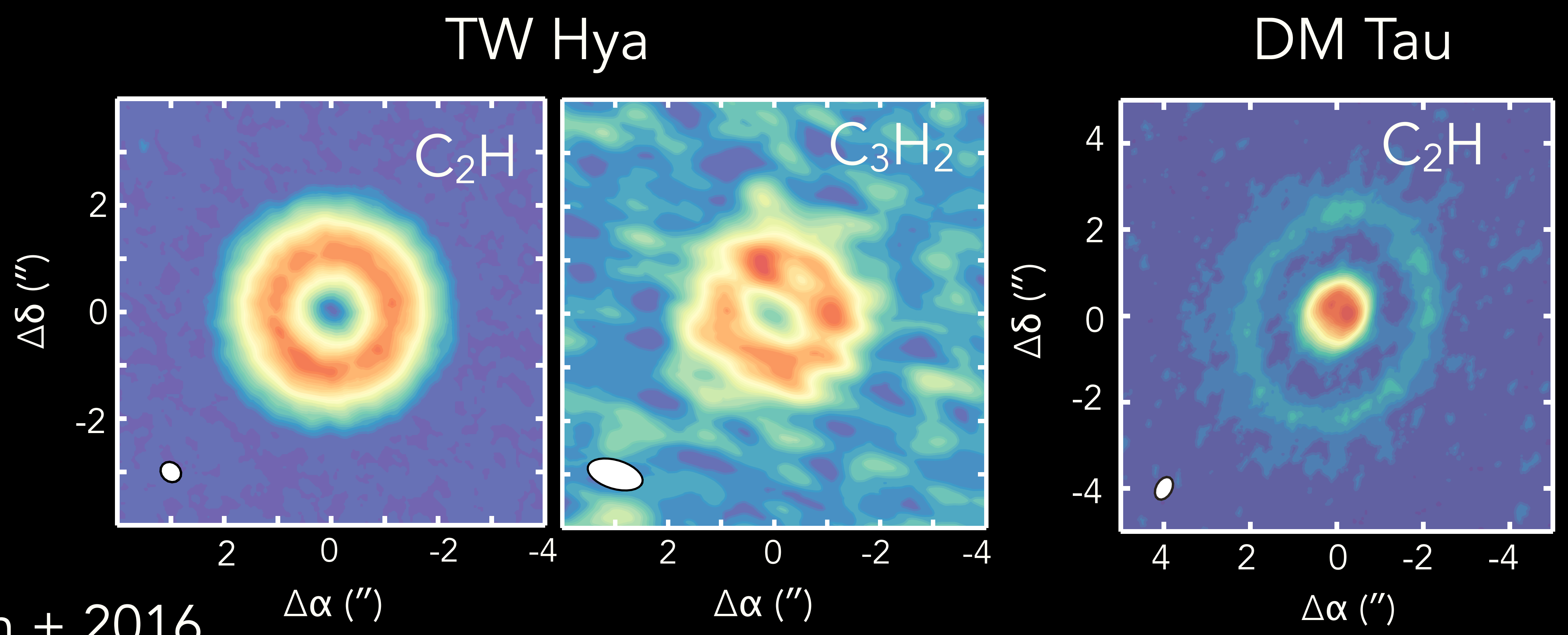
Cold water: beyond snowline



HIFI Spectroscopic Signatures of Water Vapor in TW Hydrae Disk
ESA/NASA/JPL-Caltech/M. Hogerheijde (Leiden Observatory)

1) Measurements of Bulk Composition in Disks: C/O

- Hydrocarbons: C/O ≥ 1 may exist in some layers (Kama+ 2016; Bergin+ 2016)
- Inside water snowline: C/O in accretion flow may be high (Najita +2013)



Bergin + 2016

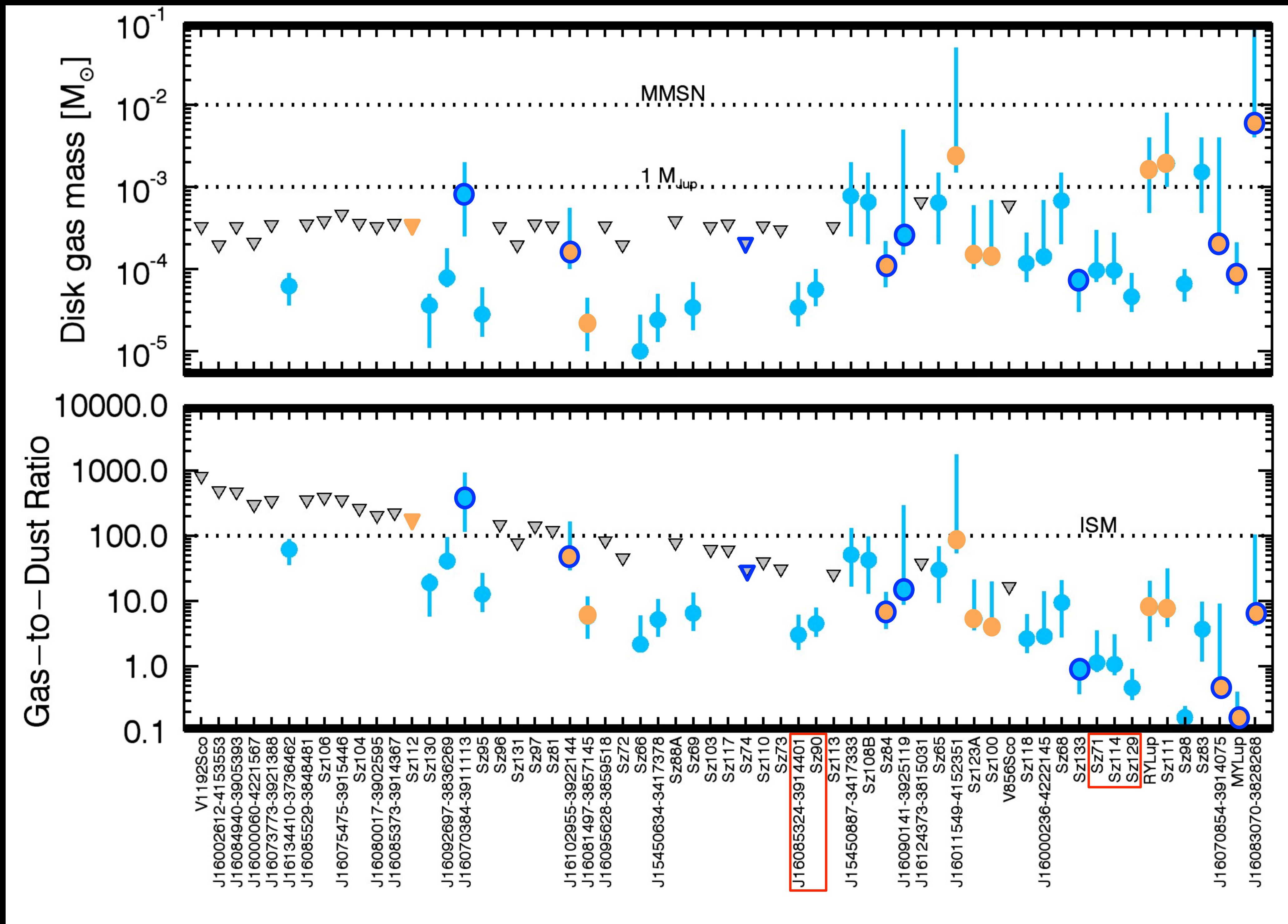
1) Measurements of Bulk Composition in Disks: X/H

- Need to infer H_2 mass to get C/H, O/H, etc.
- three methods:

1. thermal emission from dust grains at mm/sub-mm wavelengths (and a gas to dust ratio)
2. CO and isotopologue gas (and a CO abundance)
3. Detection of HD - to date only in 3 systems

➡ New methods: drift (D. Powell), mass accretion rates (G. Rosotti), scattered light (e.g van Boekel).

The Problem



Miotello et al. 2017; see also Ansdell et al. 2016

⇒ ***Volatiles appear to be depleted from gas.***

When? Early

⇒ ***What does this mean for giant planets?***

IF they form *late* - gas is depleted in C, O (N?)
IF they form early - gas may be enriched in C/H (substellar O/H)

⇒ ***Needed Astronomical Constraints***

More HD observations (SOFIA-HIRMES);
JWST observations of H_2O + organics
ALMA obs. of midplane (5 - 10 AU)