Unlocking the Secrets of Planet Formation with Hydrogen Deuteride

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Collaborators

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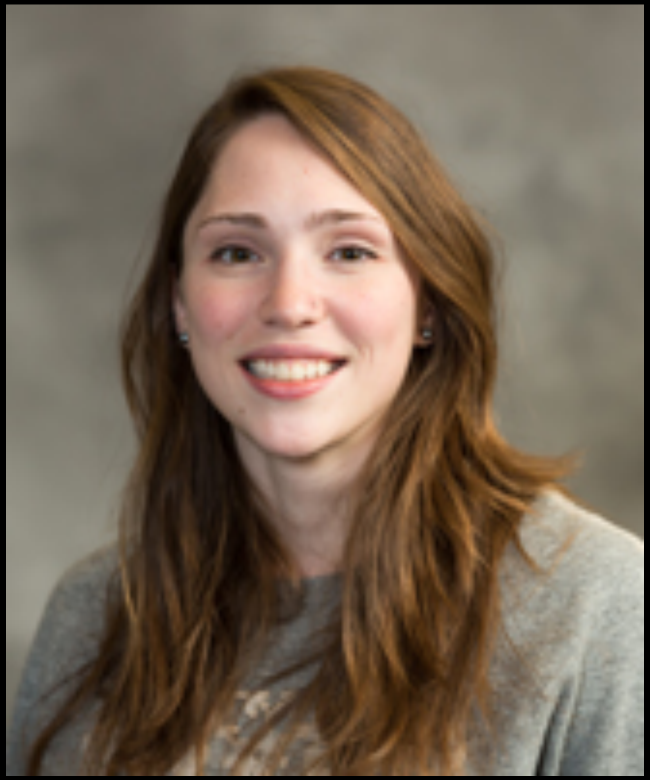
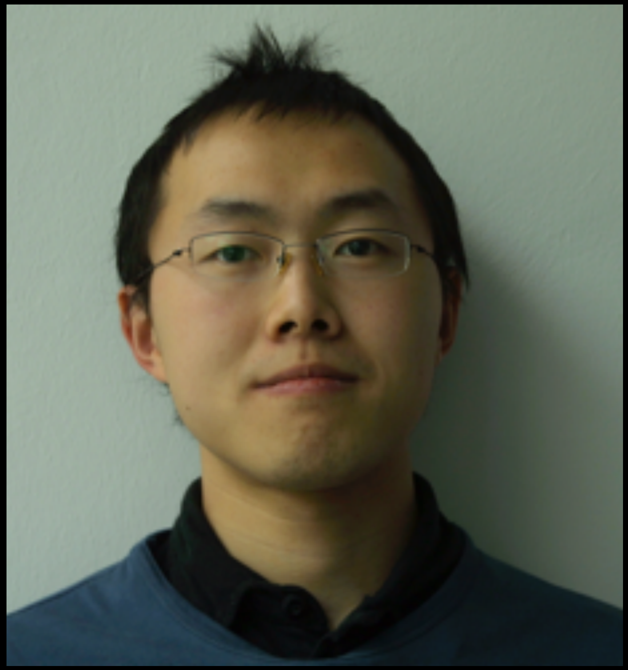


Kamber Schwarz

Fujun Du



Geoff Blake - Caltech

The Ingredients for a Habitable World

at right distance from star

liquid water

volatile elements (CHON)

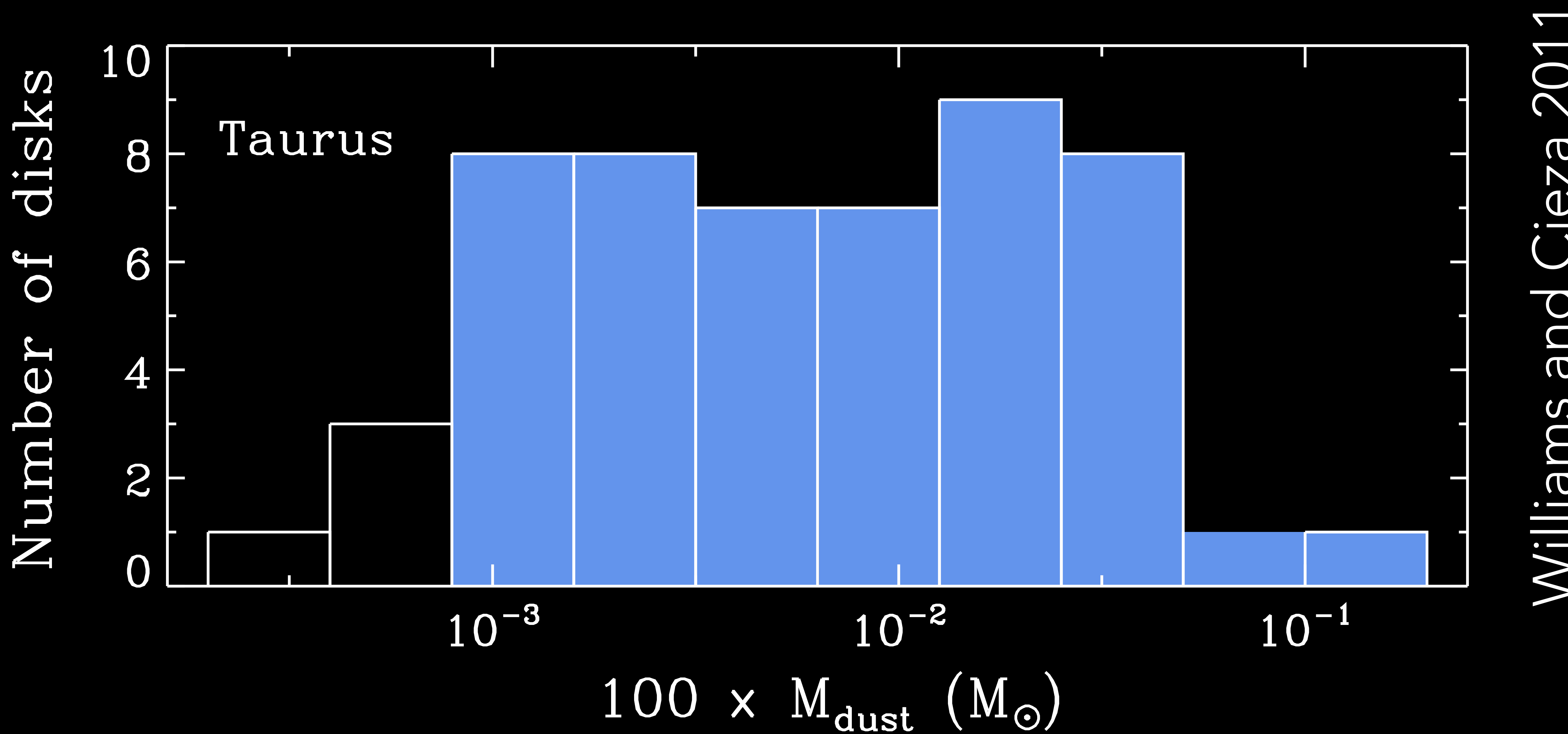
This Talk

- protoplanetary disk gas masses
  - ➡ detection of HD in TW Hya + 2 other sources
- depletion of oxygen and carbon in upper atmosphere of TW Hya
  - ➡ pointing to hidden volatile-rich pebbles or planetesimals
- Future surveys of HD with sensitive Far-IR telescope will provide grounding and unique information.
- Tremendous synergy with JWST results and ALMA

Protoplanetary Disk Gas Mass

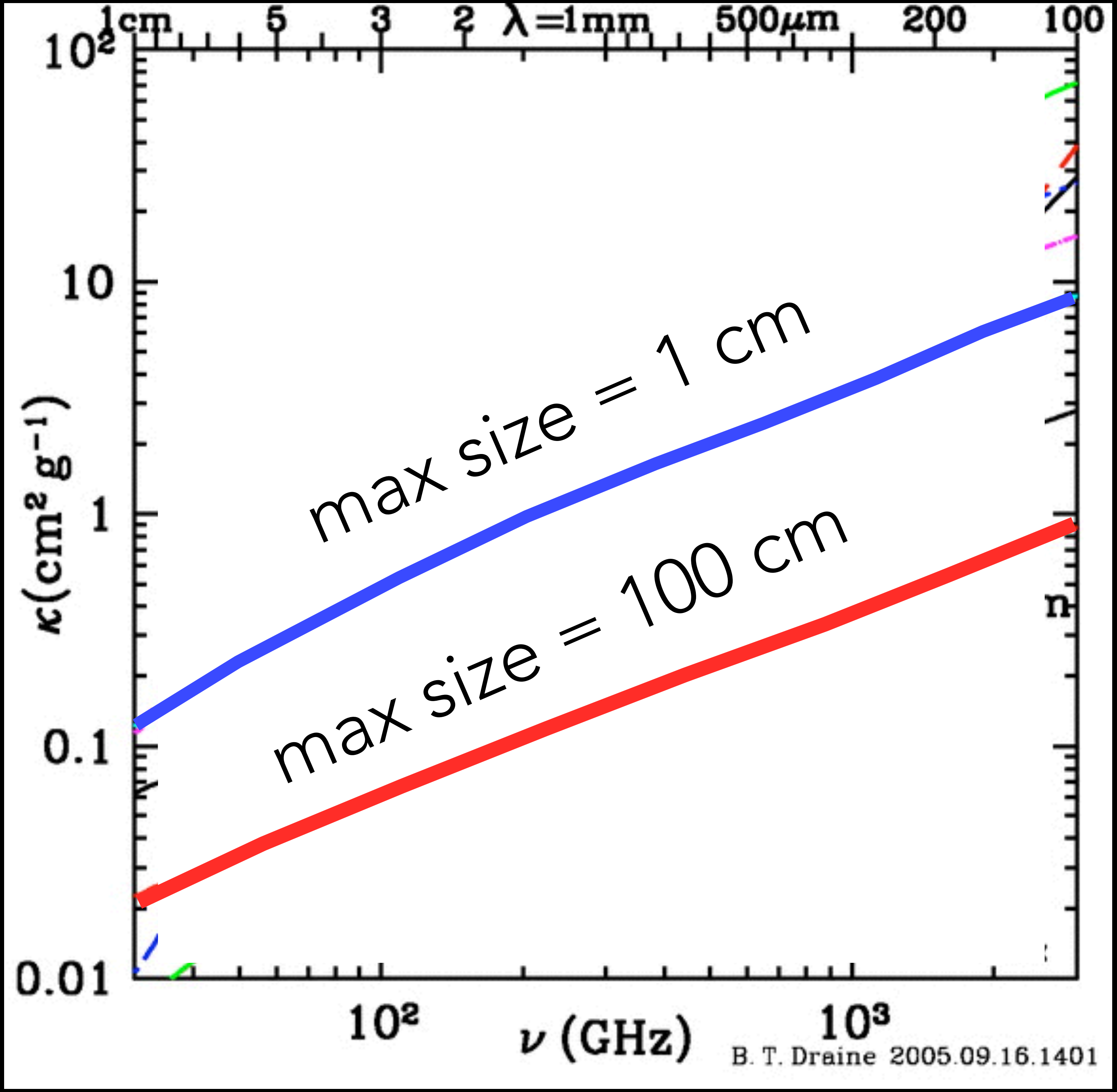
- Critical for timescales and physics of planet formation
- Linchpin for determination of chemical abundances
- Cannot trace H_2 directly - need to use proxies
  - ➡ thermal emission from dust grains at mm/sub-mm
  - ➡ thermo-chemical modeling of CO gas emission

Protoplanetary Disk Gas Mass



sub-mm wavelengths - Mass $\propto F_\nu/\kappa_\nu T$

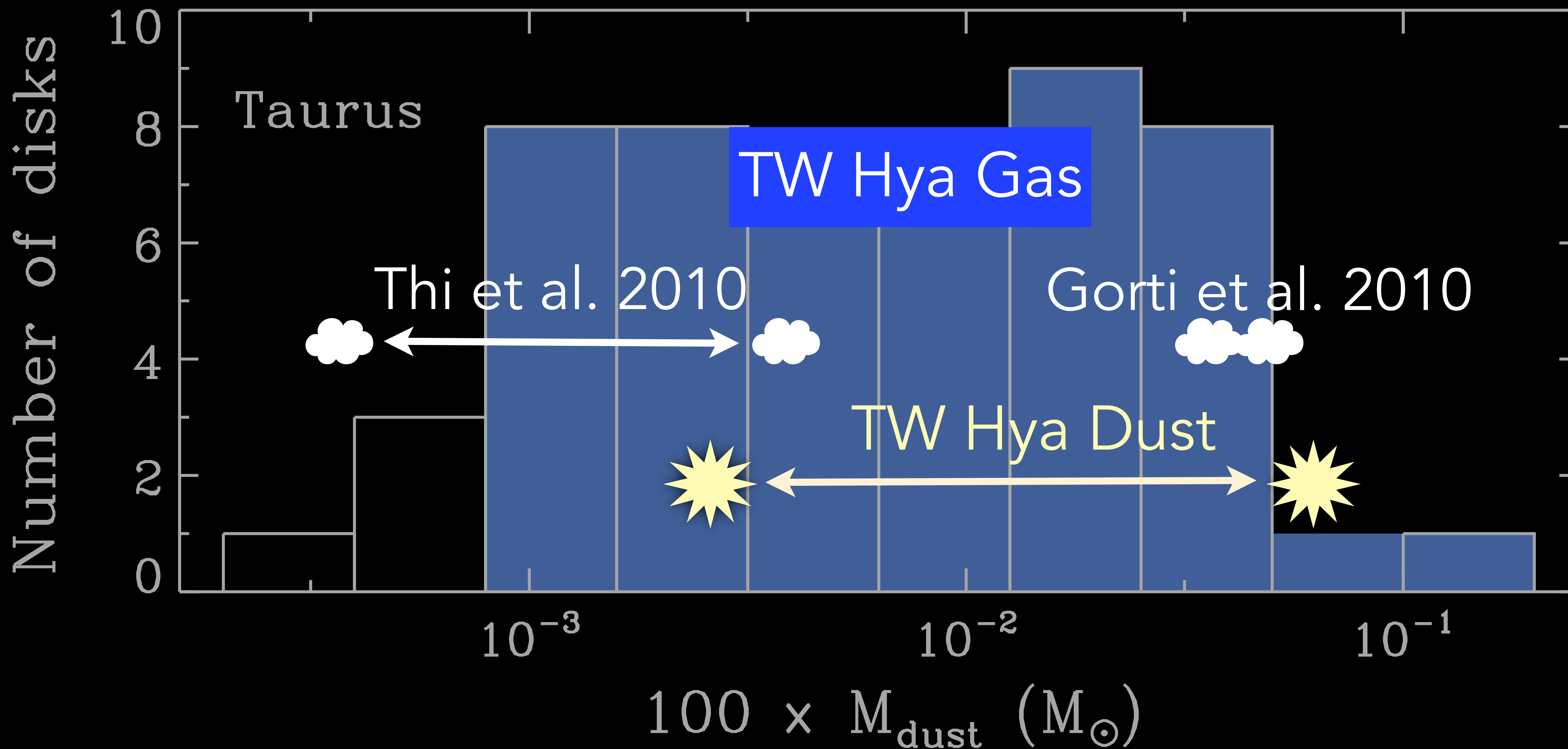
- $\tau = \kappa\sigma$
  - κ = dust mass opacity
  - σ = mass column density of grains
- the dust and GAS mass is uncertain - perhaps by a large factor



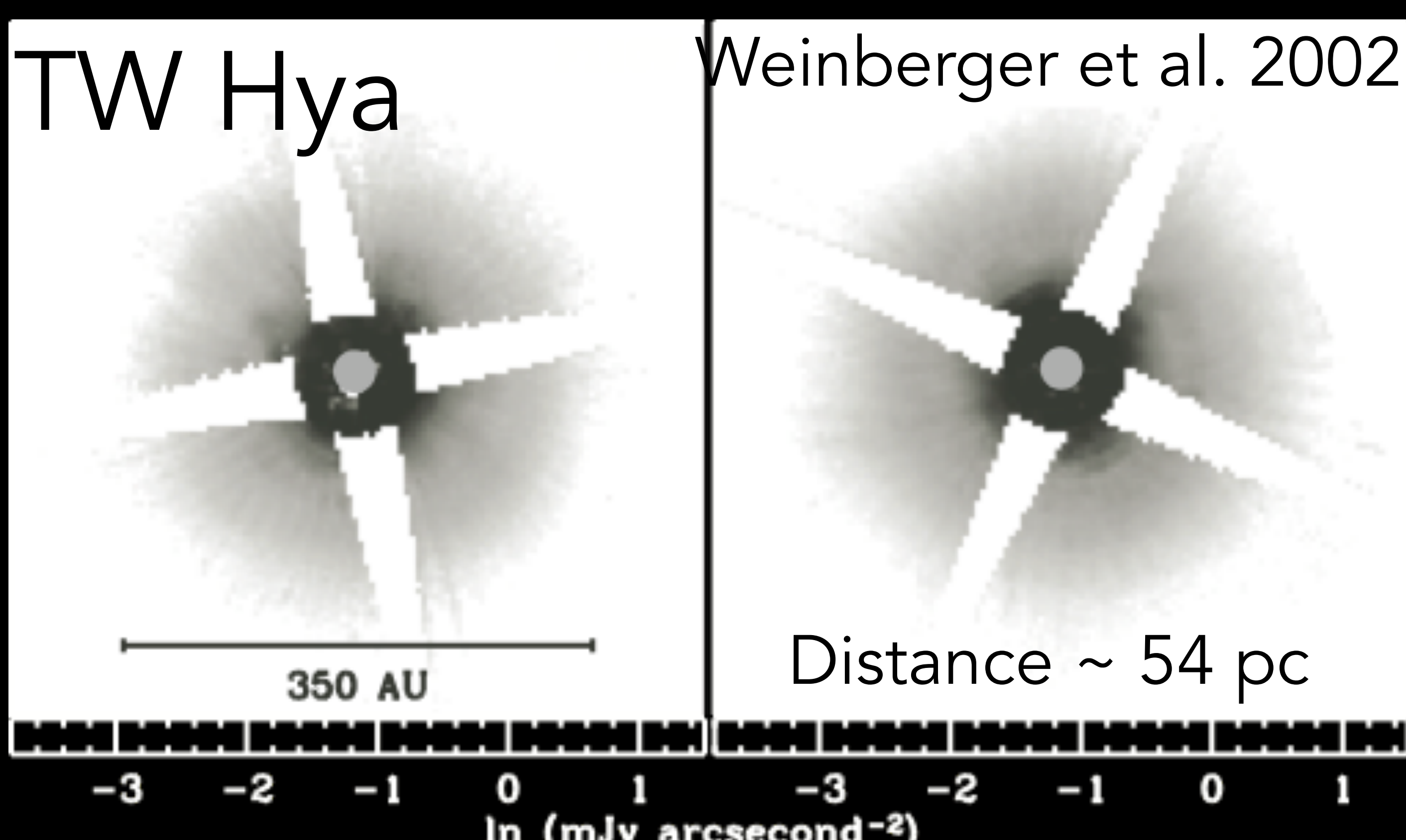
Draine 2006

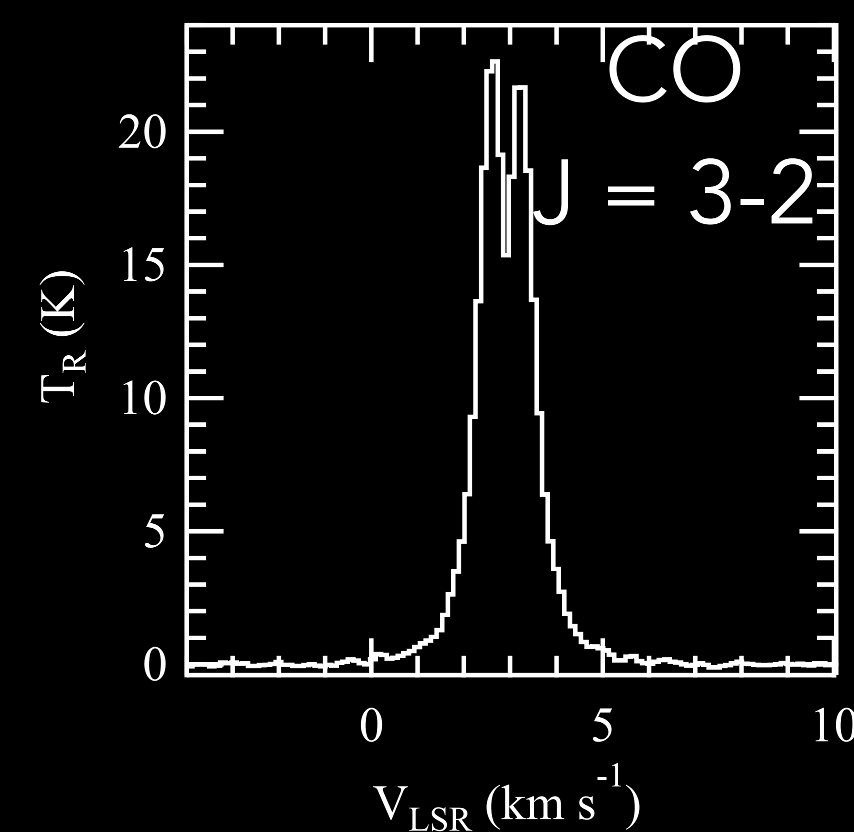
Thermo-chemical Models

- ➡ Models of the coupled disk thermal physics and chemistry
- ➡ predict and match observed line emission of a variety of species (CO, ^{13}CO, O I, …)
- ➡ Two models of the closest and best studied object - TW Hya - Gorti et al. 2010, Thi et al. 2010

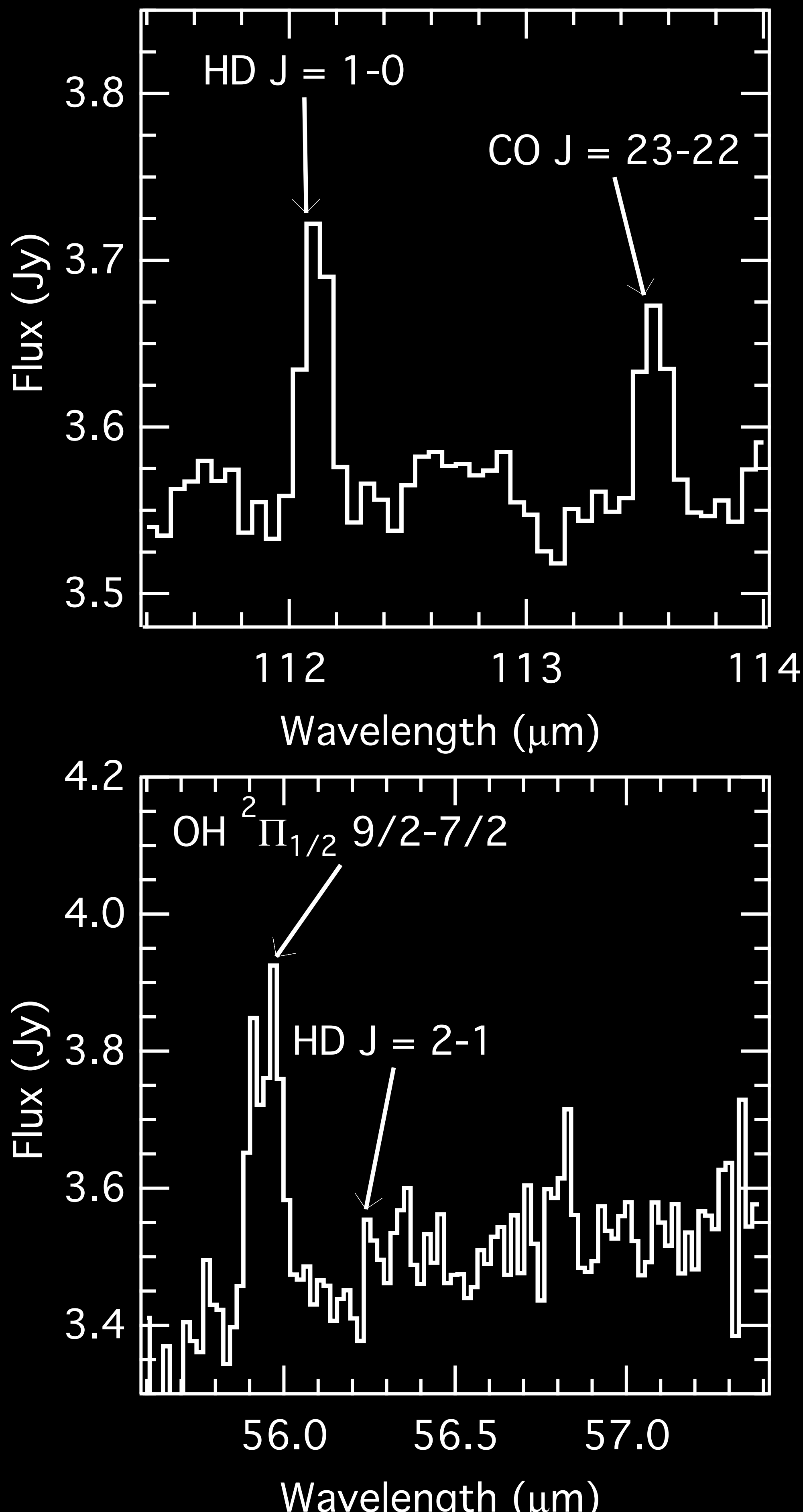


Williams and Cieza 2011





Herschel Detection of HD towards TW Hya



- ➡ HD is a million times more emissive than H_2 at T ~ 20 K.
- ➡ Atomic D/H ratio inside the local bubble is well characterized (~1.5×10^{-5})
- ➡ HD will follow H_2 in the gas

Bergin et al. 2013

HD and Disk Gas Mass

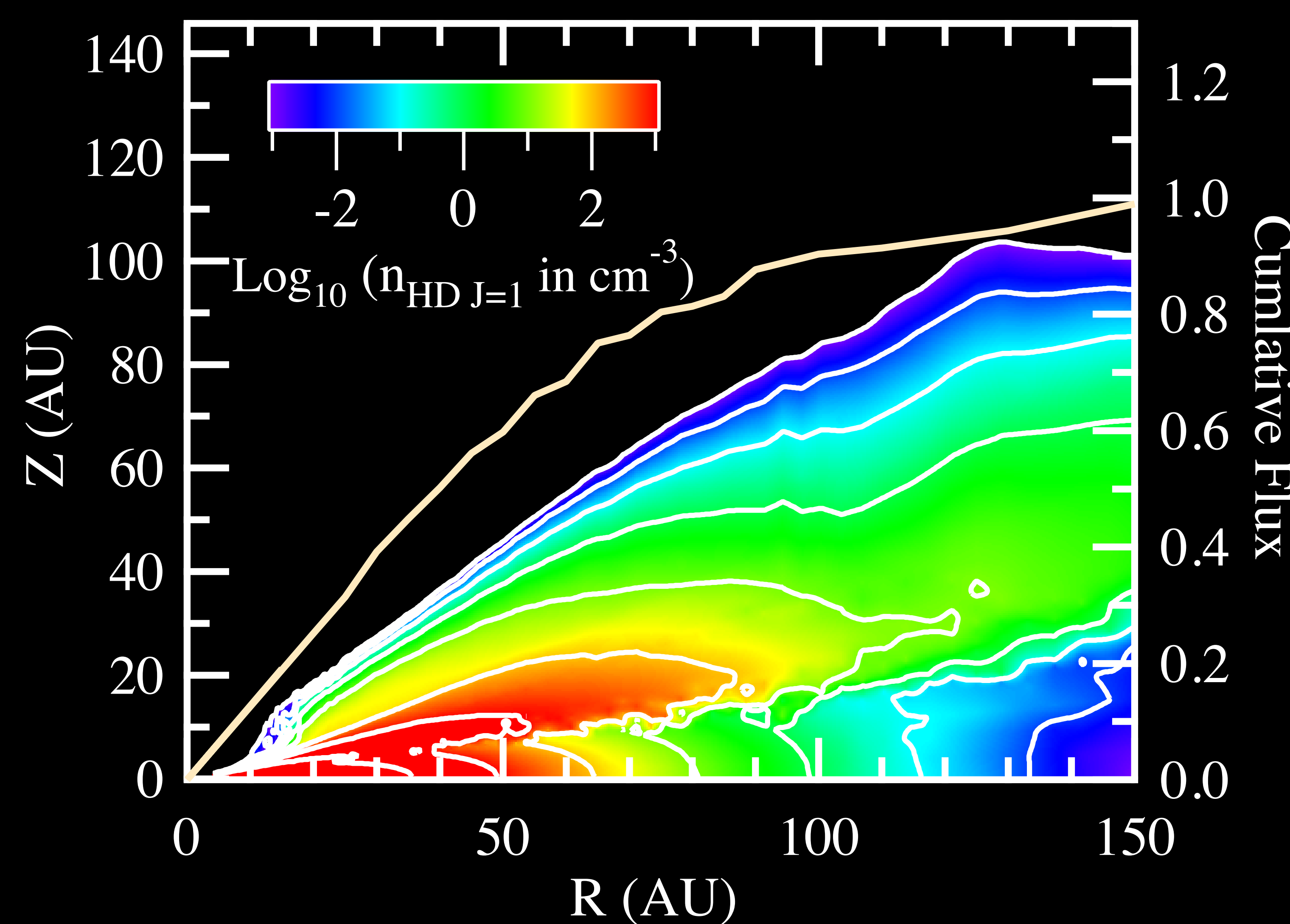
➡ Emission is strongly sensitive to gas temperature:

$$M_{gas} \propto \frac{F_l}{x(\mathrm{HD})} D^2 \exp\left(\frac{128.5\mathrm{K}}{T_{gas}}\right)$$

➡ Does not trace $T_{gas} < 20$ K because J = 1 state is not populated

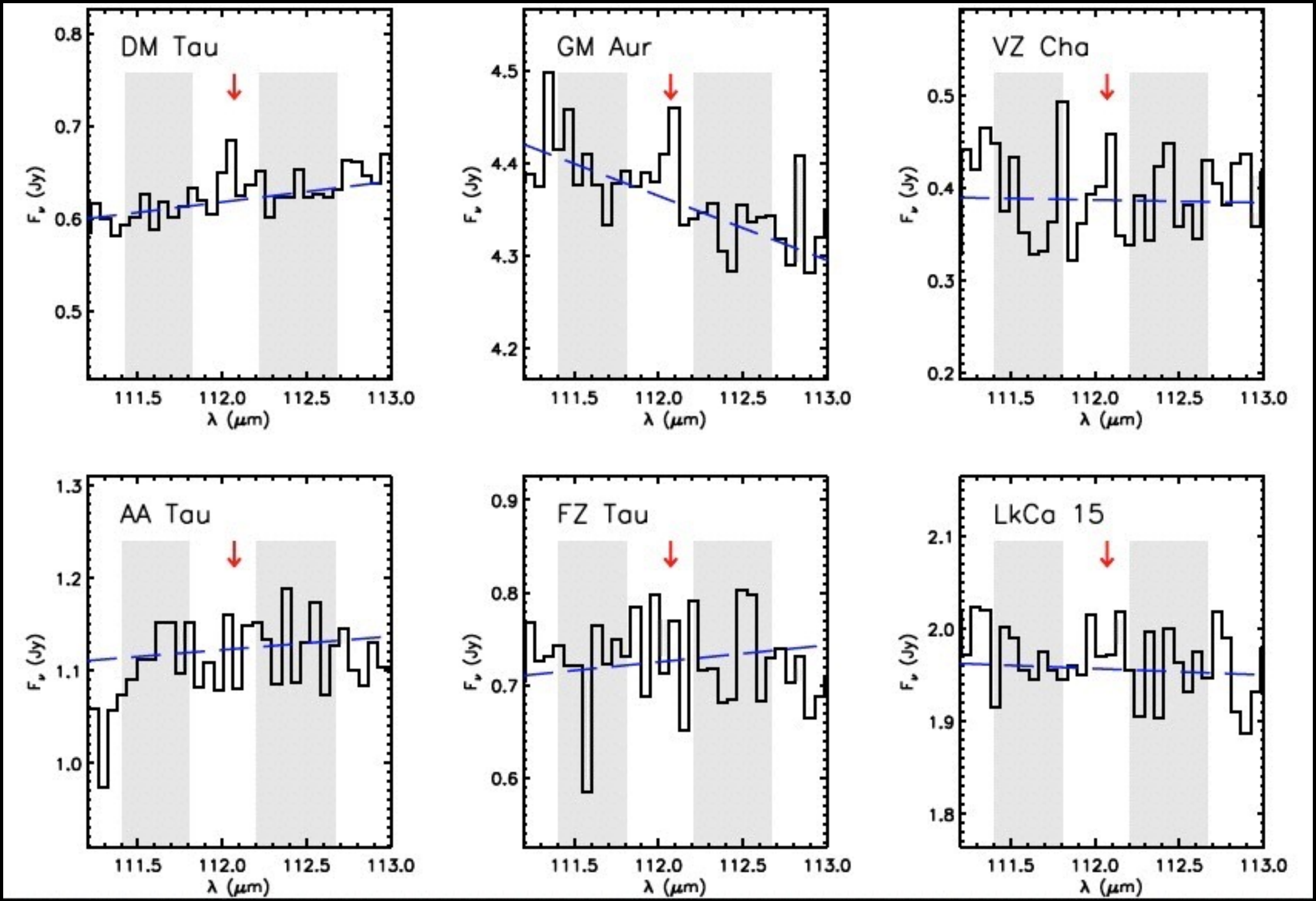
TW Hya Disk Mass

- ➡ $M_{gas} = 0.003\ M_\odot$ - HD line flux a factor of 20 too low
- ➡ $M_{gas} = 0.060\ M_\odot$ - HD line flux a factor of 2 below observed
- ➡ TW Hya disk mass $M_{disk} \sim 0.05\ M_\odot$



Bergin et al. 2013

Limited HD Survey

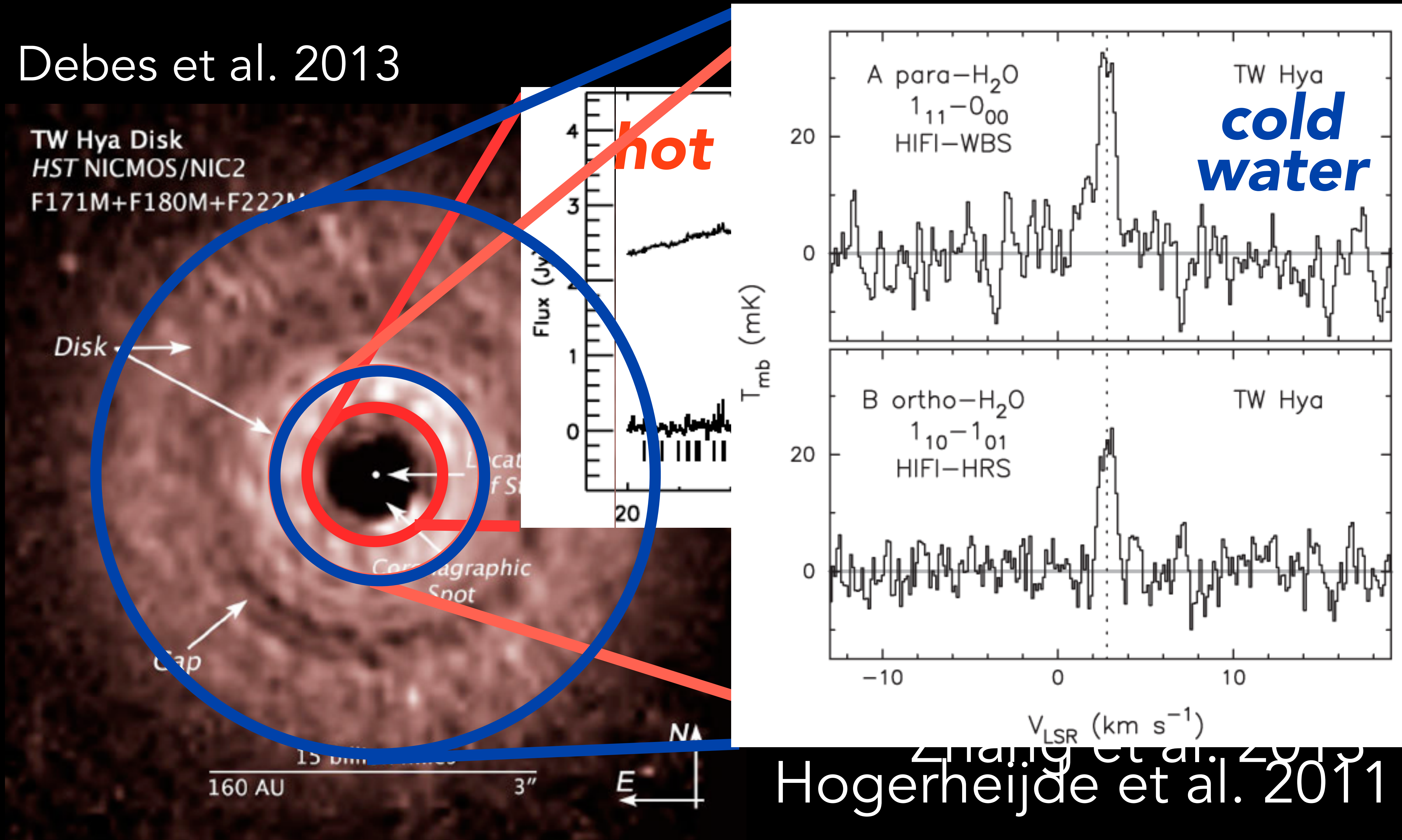


McClure et al. 2015, in prep.


B
C
N
O
Si
P
S
Cl
Fe
Ni
Cu
Zn
As
Se
Br
I
Mo
Pd
Ag
Cd
Sn
Sb
Te
W
Ir
Pt
Au
Hg
Pb
Bi
Po

Oxygen in TW Hya

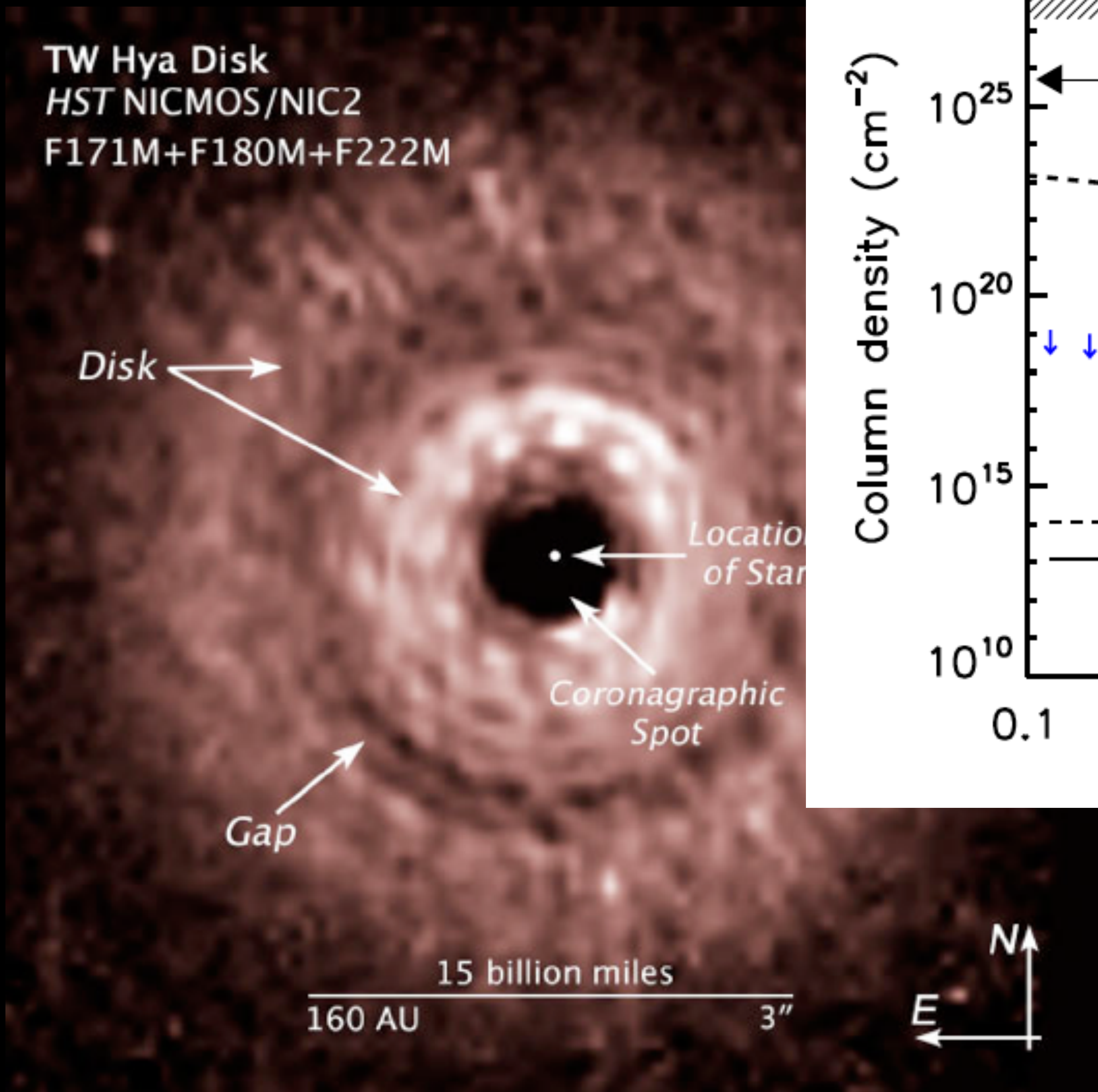
Debes et al. 2013

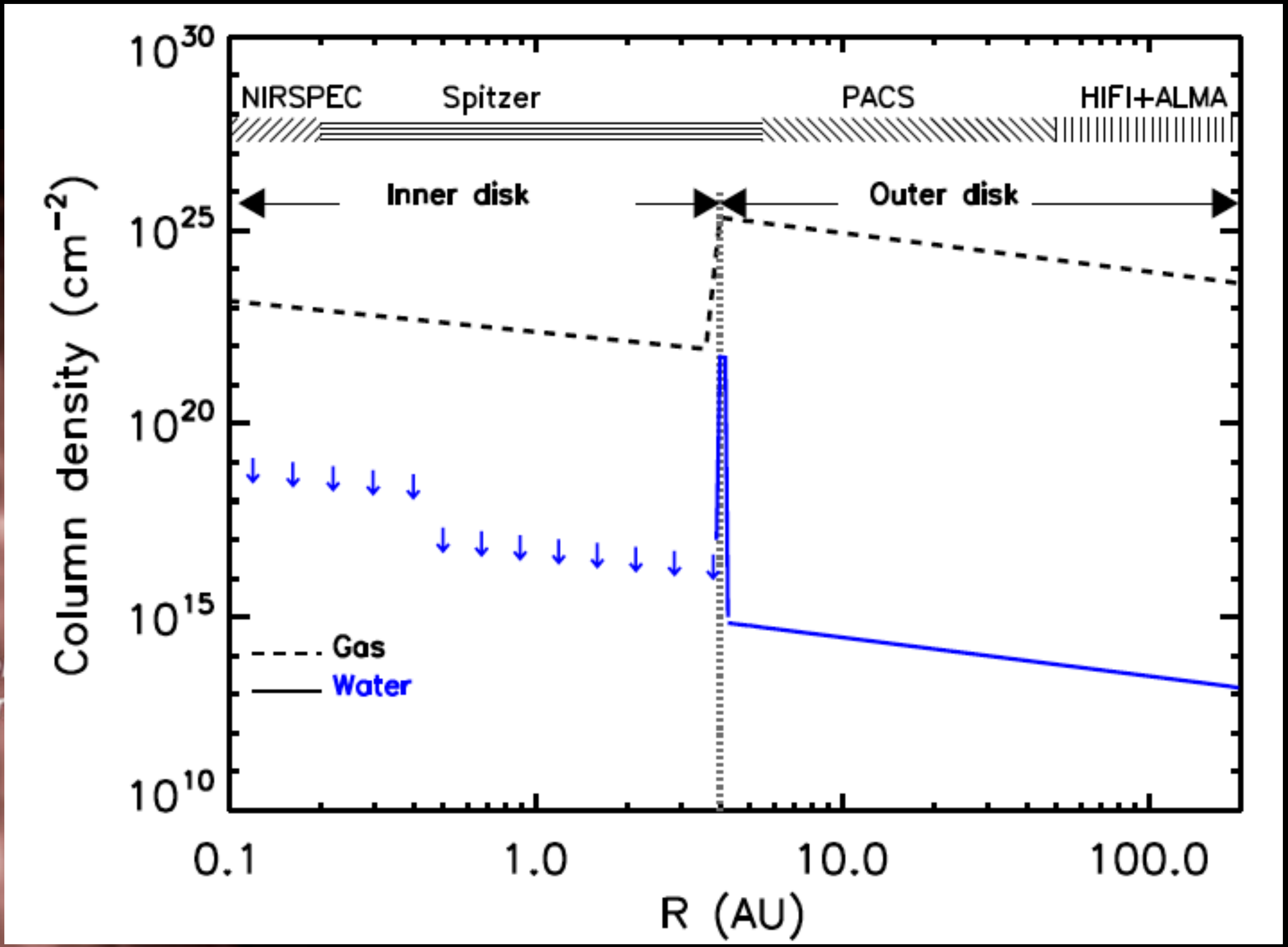


Hogerheijde et al. 2011

Oxygen in TW Hya

Debes et al. 2013





Zhang et al. 2013

Thermo-Chemical Model
Du & Bergin 2014

- adopt physical model of gas and dust distribution - fit the dust SED
- solve (2D) dust radiation transfer
- propagate UV (continuum/Ly α) and X-ray photon - solve in concert with H_2 & H_2O (Bethell & Bergin 2011)
- solve coupled chemistry (> 500 species and > 5000 reactions) and thermal physics
- predict emission lines (non-LTE approx)
- *include HD to constrain mass*

Constrained Disk Chemistry

- ➡ Re-examine all TW Hya Data with knowledge of HD
- ➡ use new thermochemical model (Du and Bergin 2014)

$C^{+}\ ^{2}P_{3/2} - {}^{2}P_{1/2}$

$O\ I\ ^{3}P_{1} - {}^{3}P_{2} + {}^{3}P_{0} - {}^{3}P_{1}$

CO 2-1, 3-2, 6-5, 10-9, 23-22

^{13}CO 2-1, $C^{18}O$ 2-1

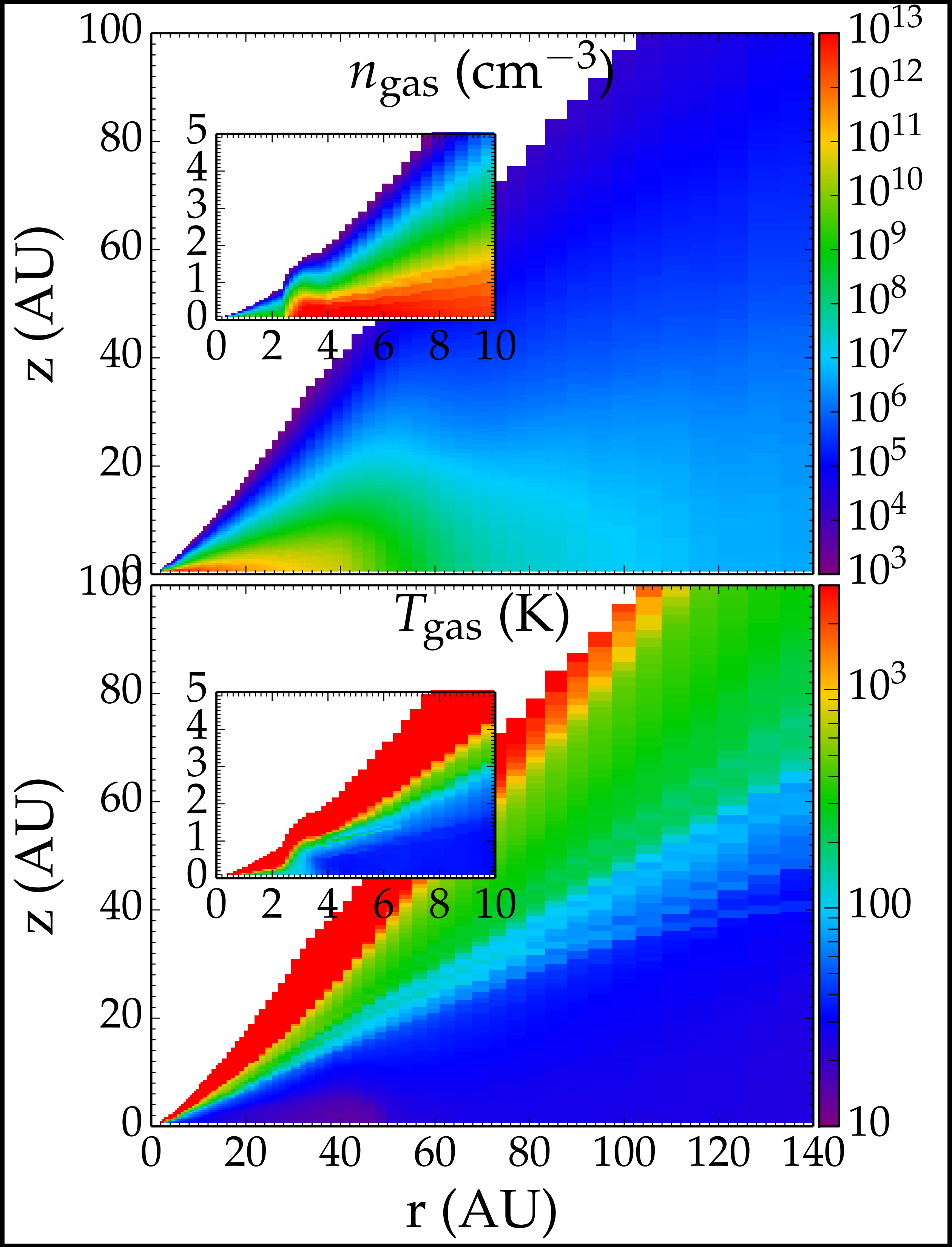
HD 1-0 (detection) + HD 2-1 (limit)

H2O (Spitzer/IRS, Herschel/PACS, Herschel/HIFI)

OH (Spitzer/IRS)

Du, Bergin, & Hogerheijde 2015, in prep.

Physical Structure



<u>Two models</u>

1. O + C depleted beyond snow lines
2. O +C undepleted

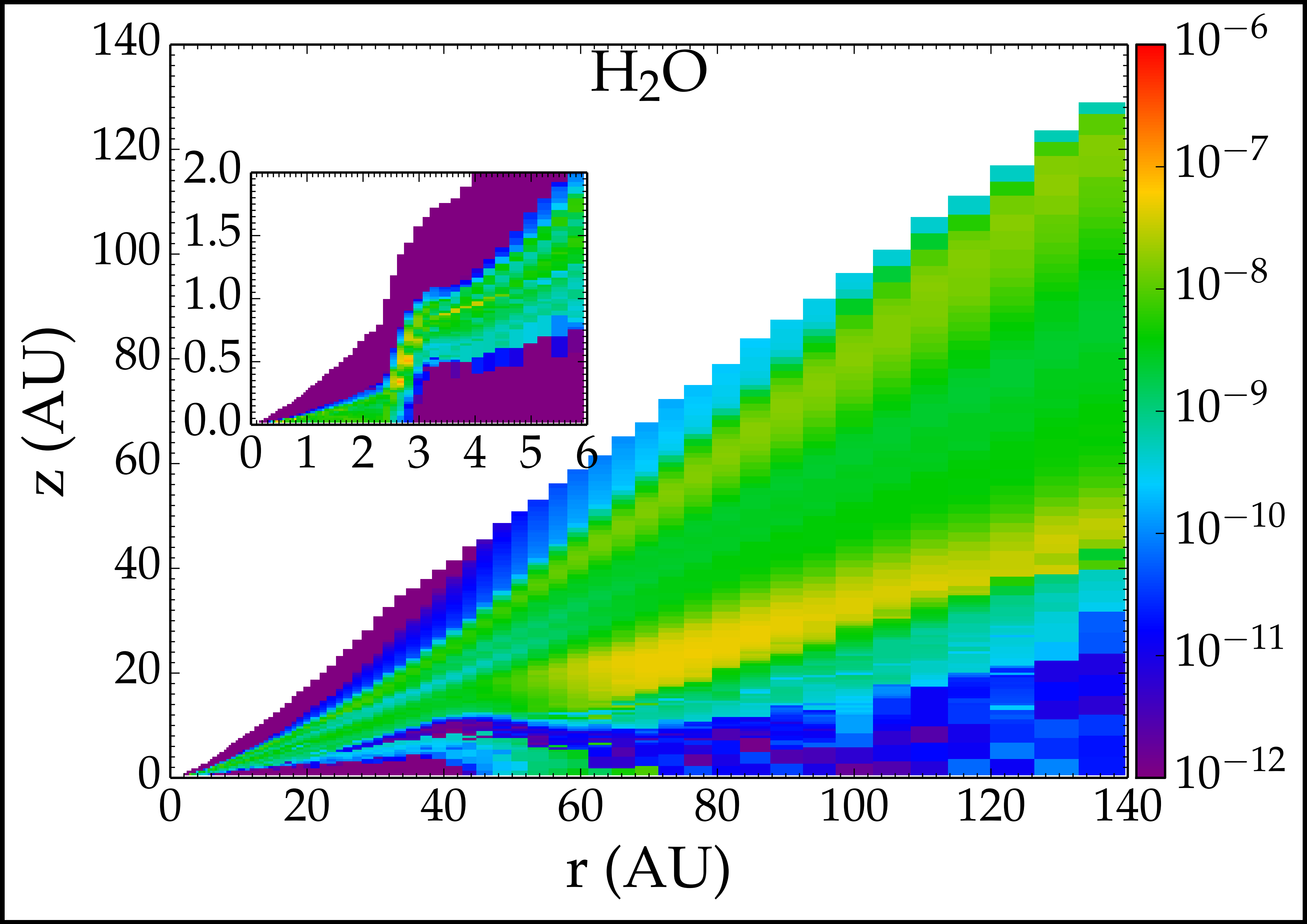
Main elemental carriers -

O: H_2O (ice and gas), CO, O I

C: CO (ice + gas), organics

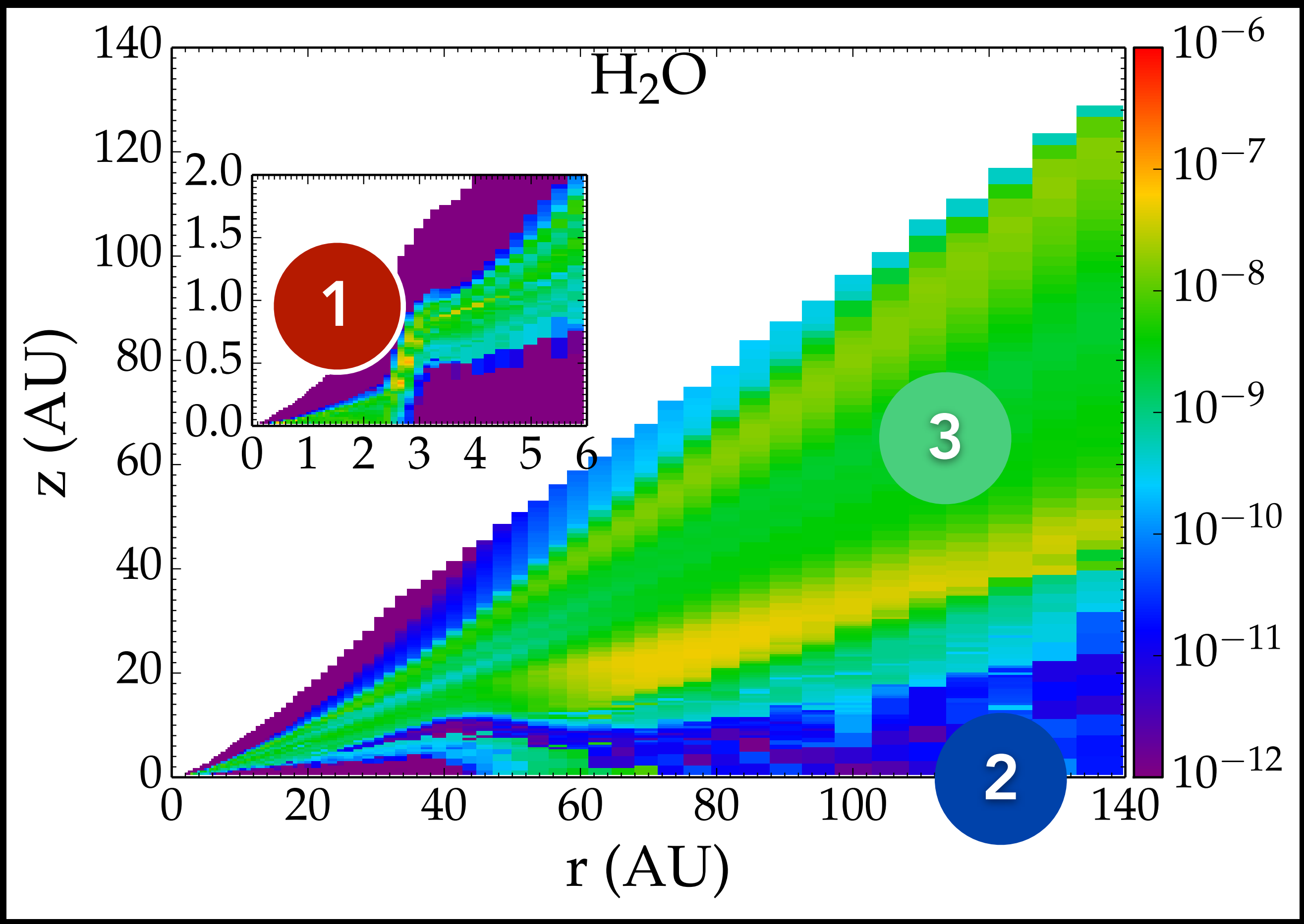
Du, Bergin, & Hogerheijde 2015, in prep.

Water Abundance undepleted O



Du, Bergin, & Hogerheijde 2015, in prep.

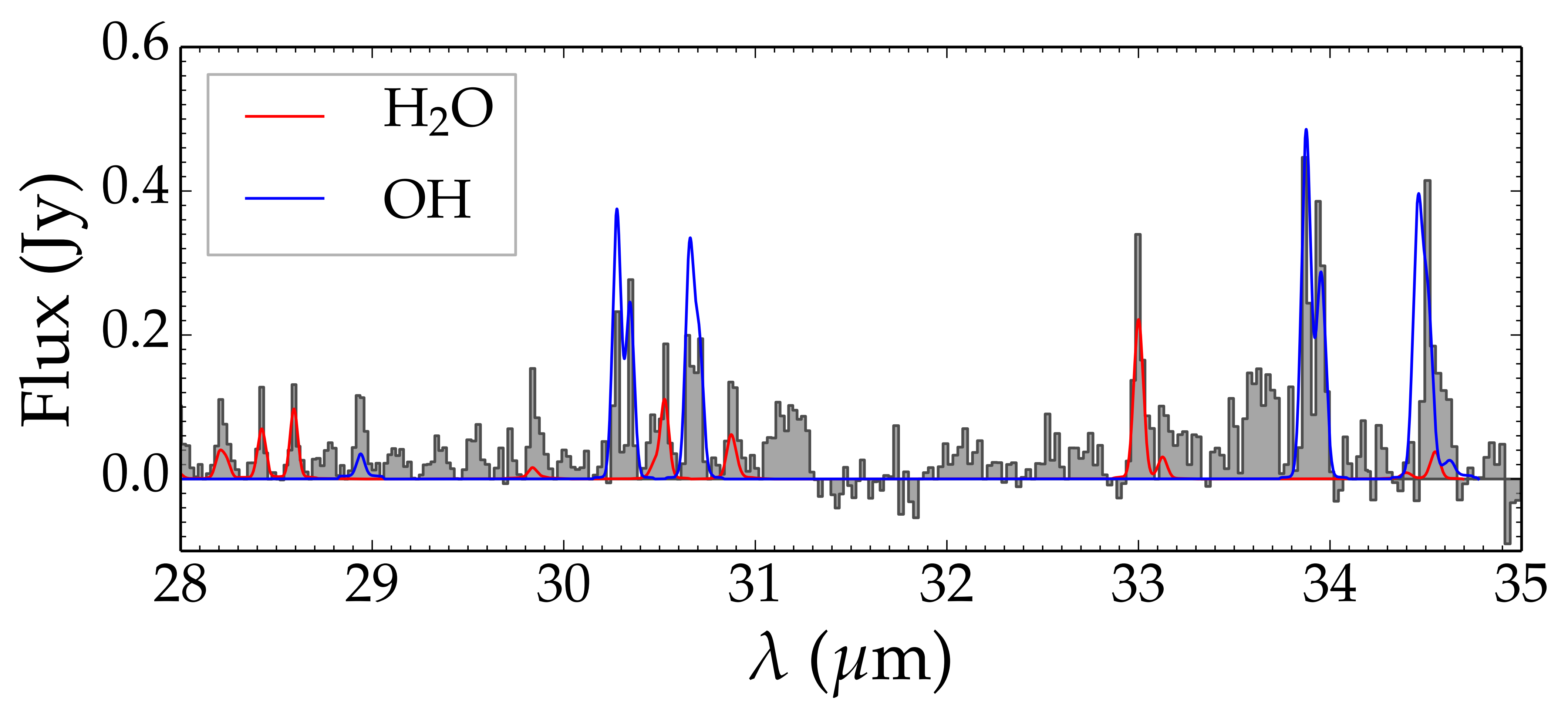
Water Abundance undepleted O

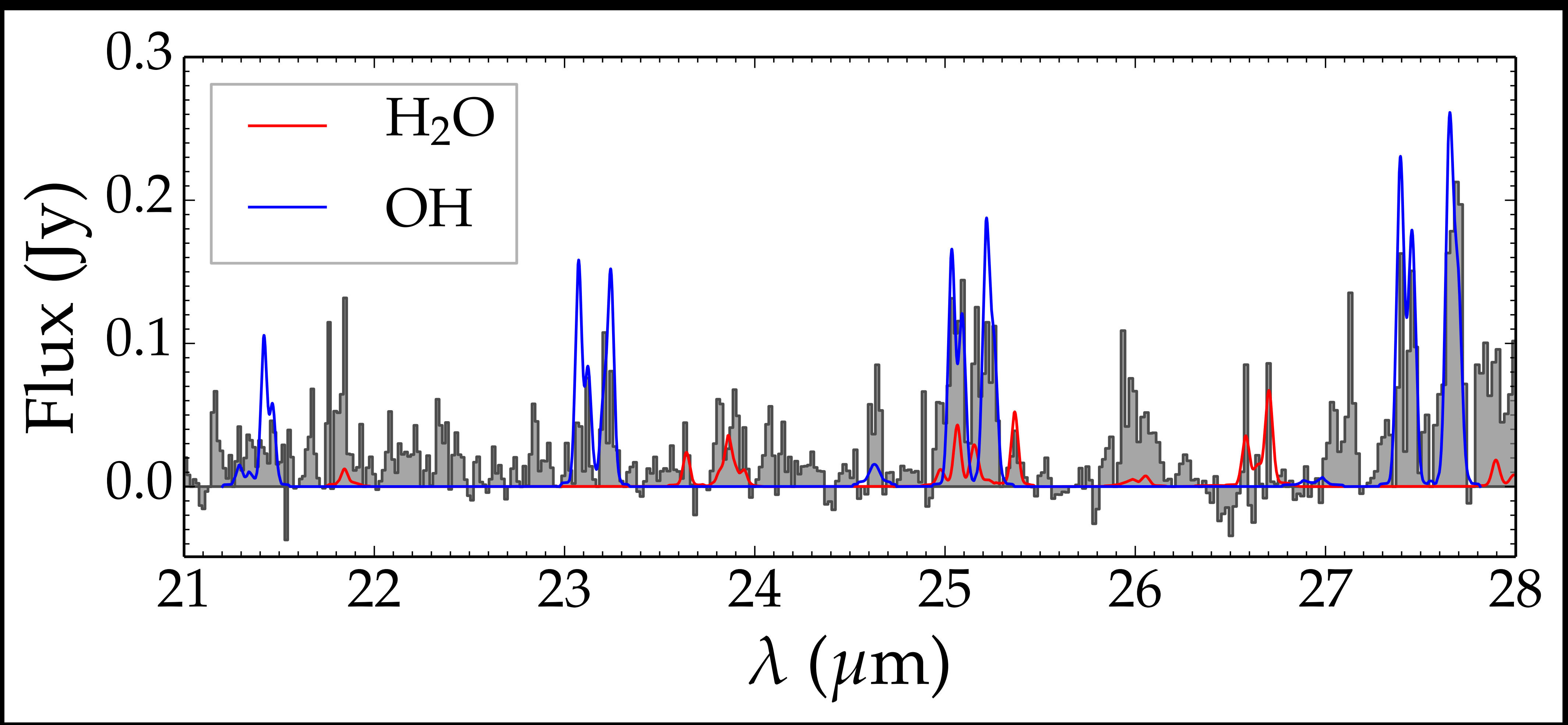


1. Hot water chemistry and ice evaporation - balanced by exposure to stellar irradiation

2. Water ice dominated - beyond snow line (4 AU for TW Hya) no ice evaporation in midplane

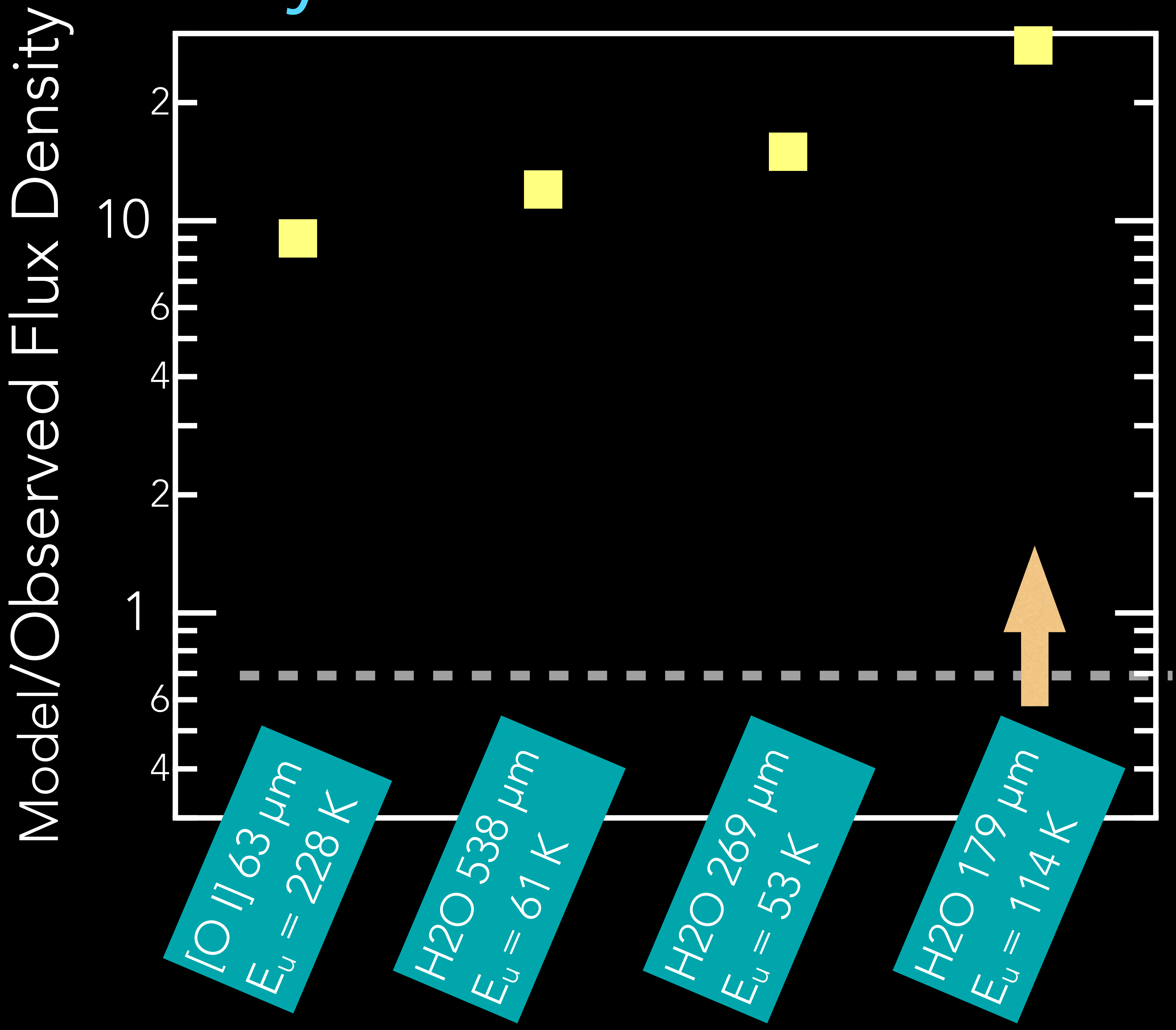
3. Photodesorption layer - UV radiation must be present





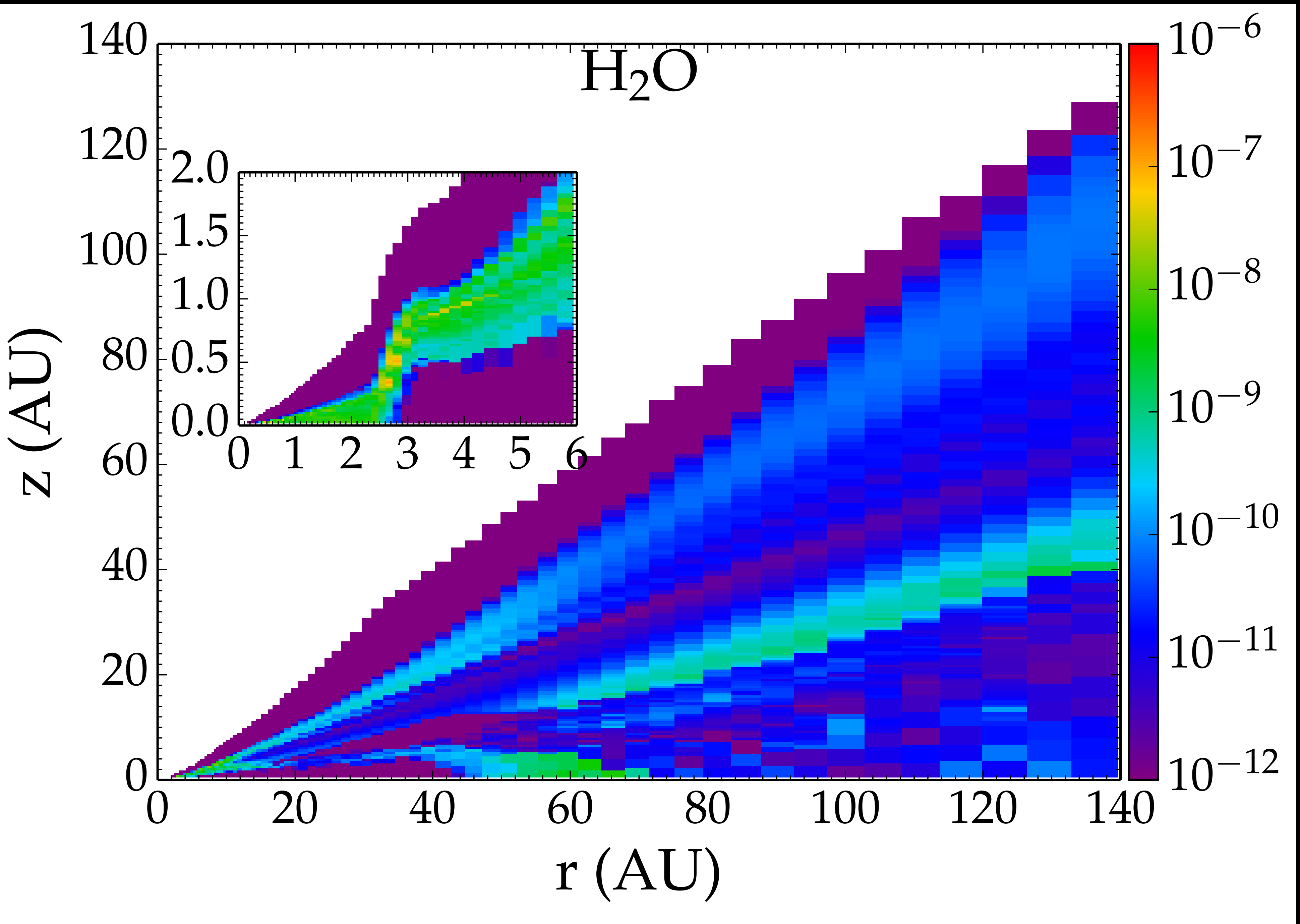
Du, Bergin, & Hogerheijde 2015, in prep.

Water beyond the snow line..



Du, Bergin, & Hogerheijde 2015, in prep.

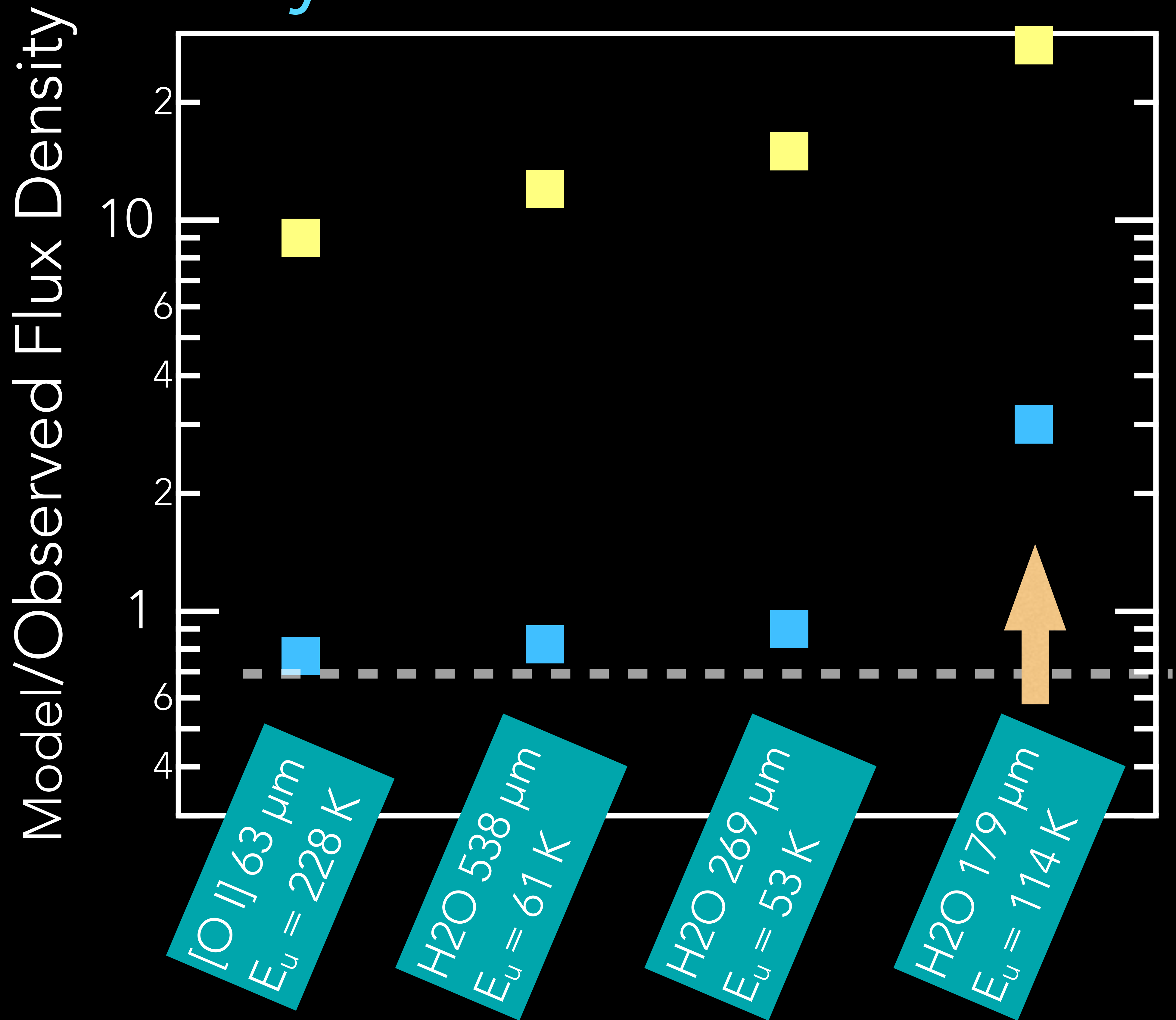
Water Abundance depleted O



- Need to remove water ice from layers with UV (i.e. reduce photodes. efficiency)
- Also in 5-20 AU need to reduce available O to form water via gas phase reactions

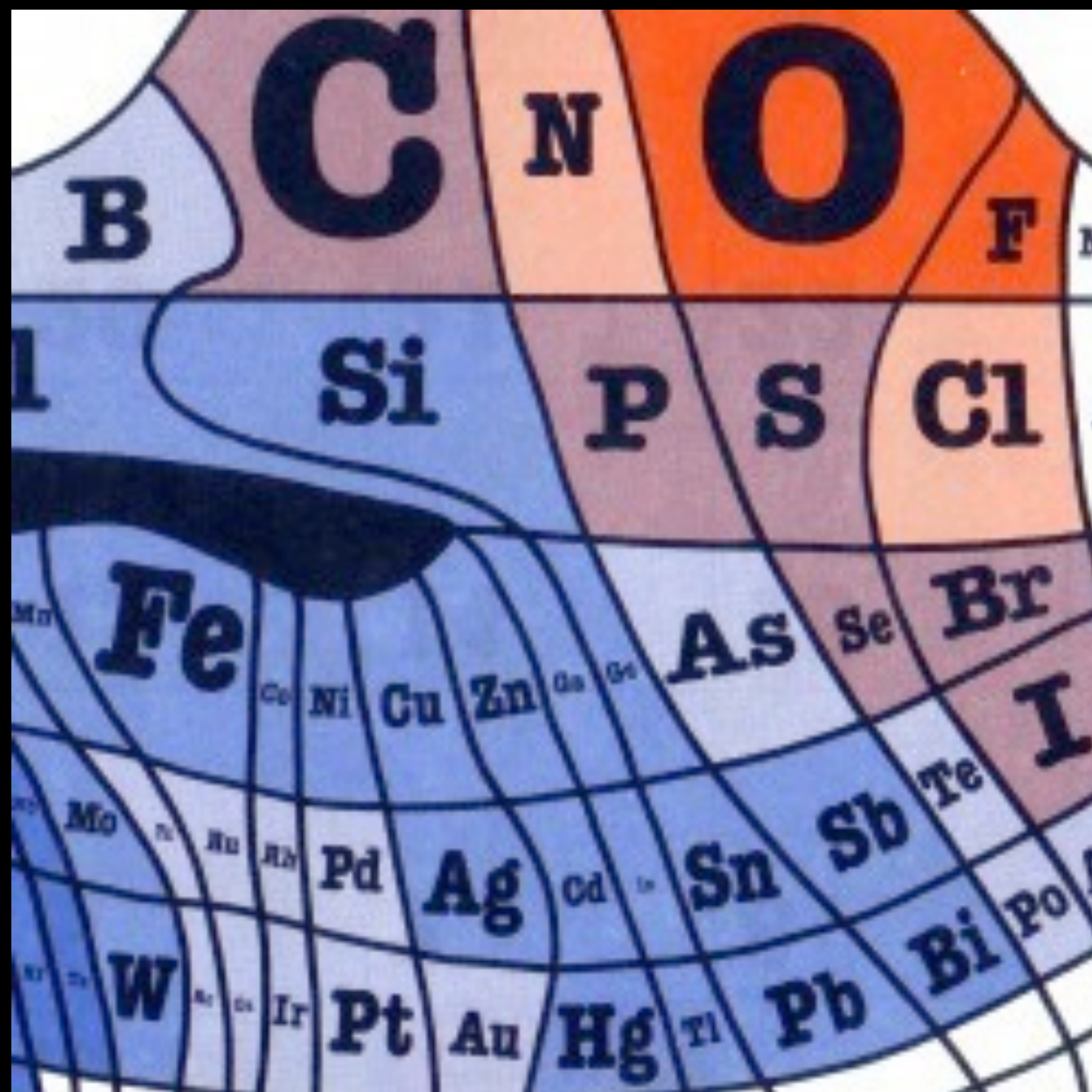
Du, Bergin, & Hogerheijde 2015, in prep.

Water beyond the snow line..



Du, Bergin, & Hogerheijde 2015, in prep.

What about Carbon?

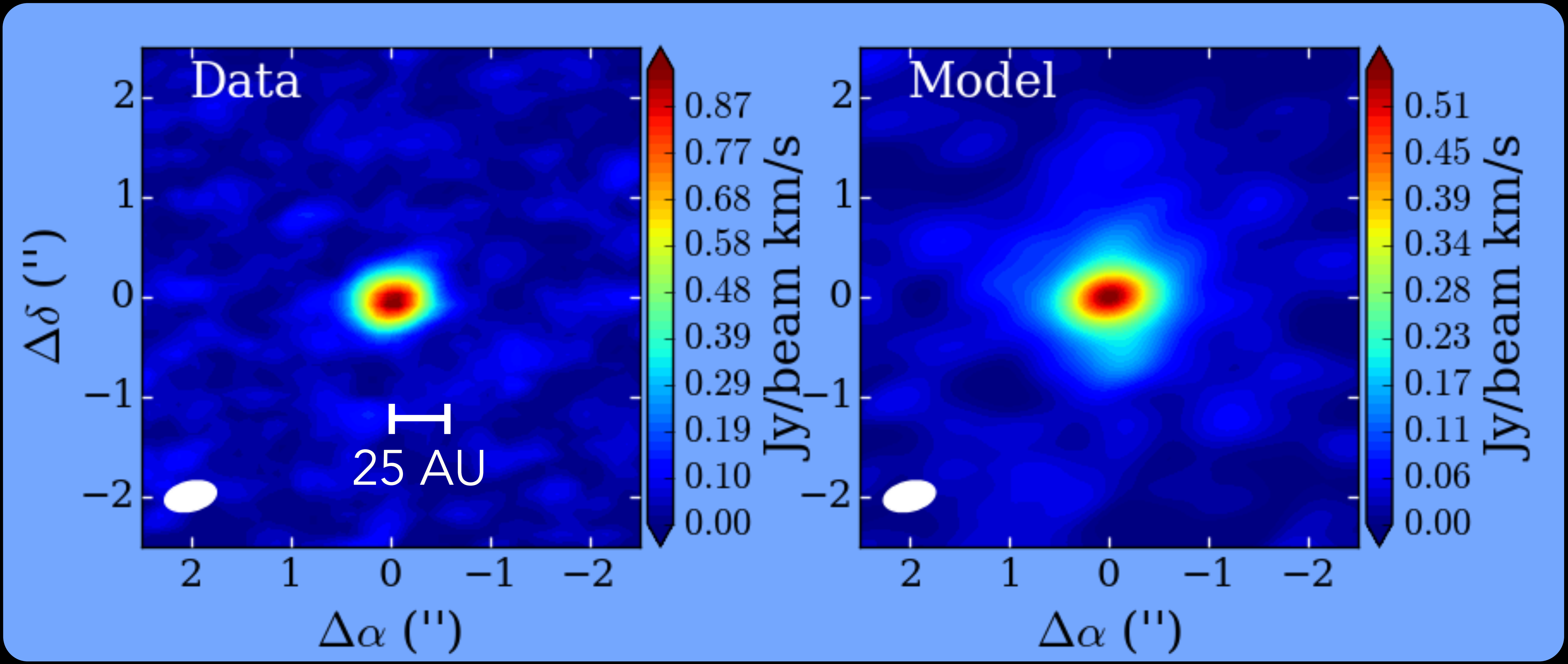


HD and $C^{18}O$ in TW Hya

- Favre et al. 2013
  - ➡ Emission ratio $F_{J=2\text{-}1}(C^{18}O)/F_{J=1\text{-}0}(HD)$ is proportional to the CO abundance
    - — assuming optically thin, D/H ratio, $^{16}O/^{18}O$ ratio, and gas temperature
  - ➡ Excitation
    - — HD will not emit if $T_{gas} < 20$ K
    - — CO freezes onto grains if $T_{gr} < 20$ K
  - ➡ CO Abundance $< 10^{-5}$ (+ same result from 2 additional independent models)

CO Snowline

ALMA $C^{18}O$ J = 6-5



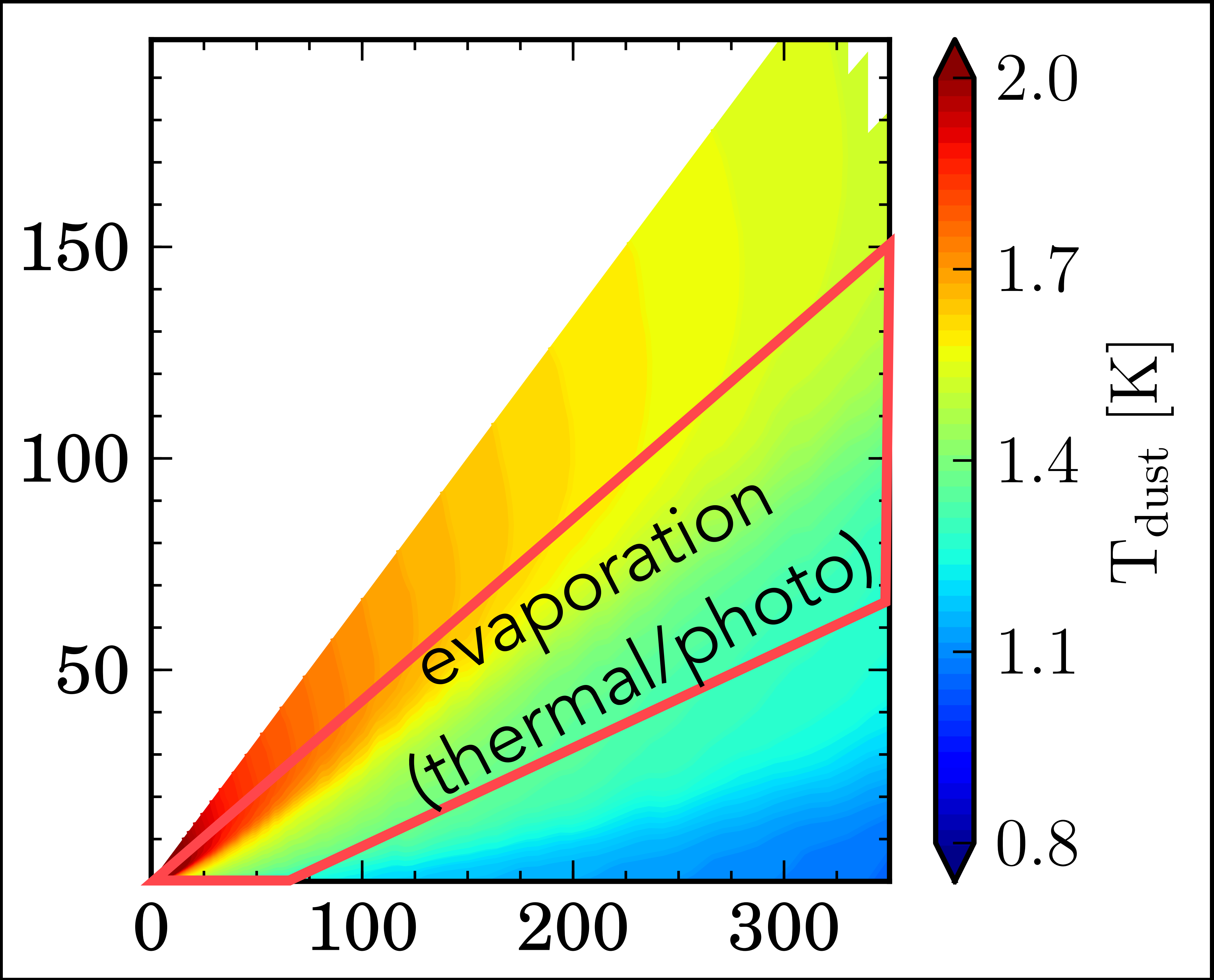
- ➡ Direct detection of CO snow line
- ➡ Needs reduced CO abundance in inner disk

Schwarz et al., in prep.

Systematic Effect

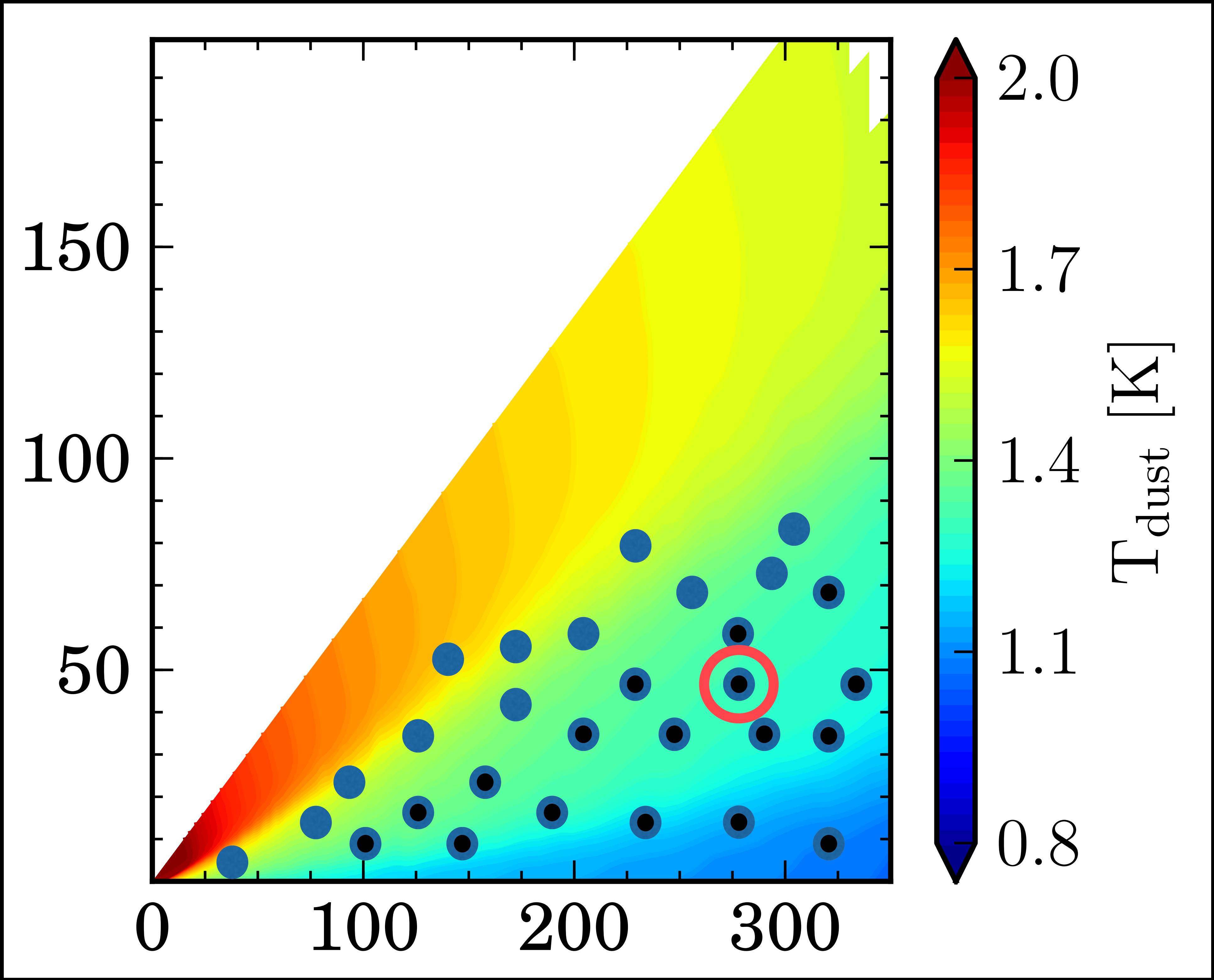
- Cold water emission survey
  - ➡ 7+ systems surveyed - no detections beyond TW Hya and HD100546 (Du et al., in prep.)
- C^+ detected in 27% out of 47 T Tauri stars surveyed by Herschel -- all have UV excess (Dent et al. 2013)
- O I less emissive compared to continuum in sample of 21 transition disks (Keane et al. 2014)
- ALMA observations of C I find evidence for missing carbon (Tsukagoshi et al. 2015)

Possible Mechanism



Possible Mechanism

- radial + vertical pressure gradients
- dust settling + growth + radial drift
- sequesters volatiles in midplane
- particles must be large enough to frustrate feedback

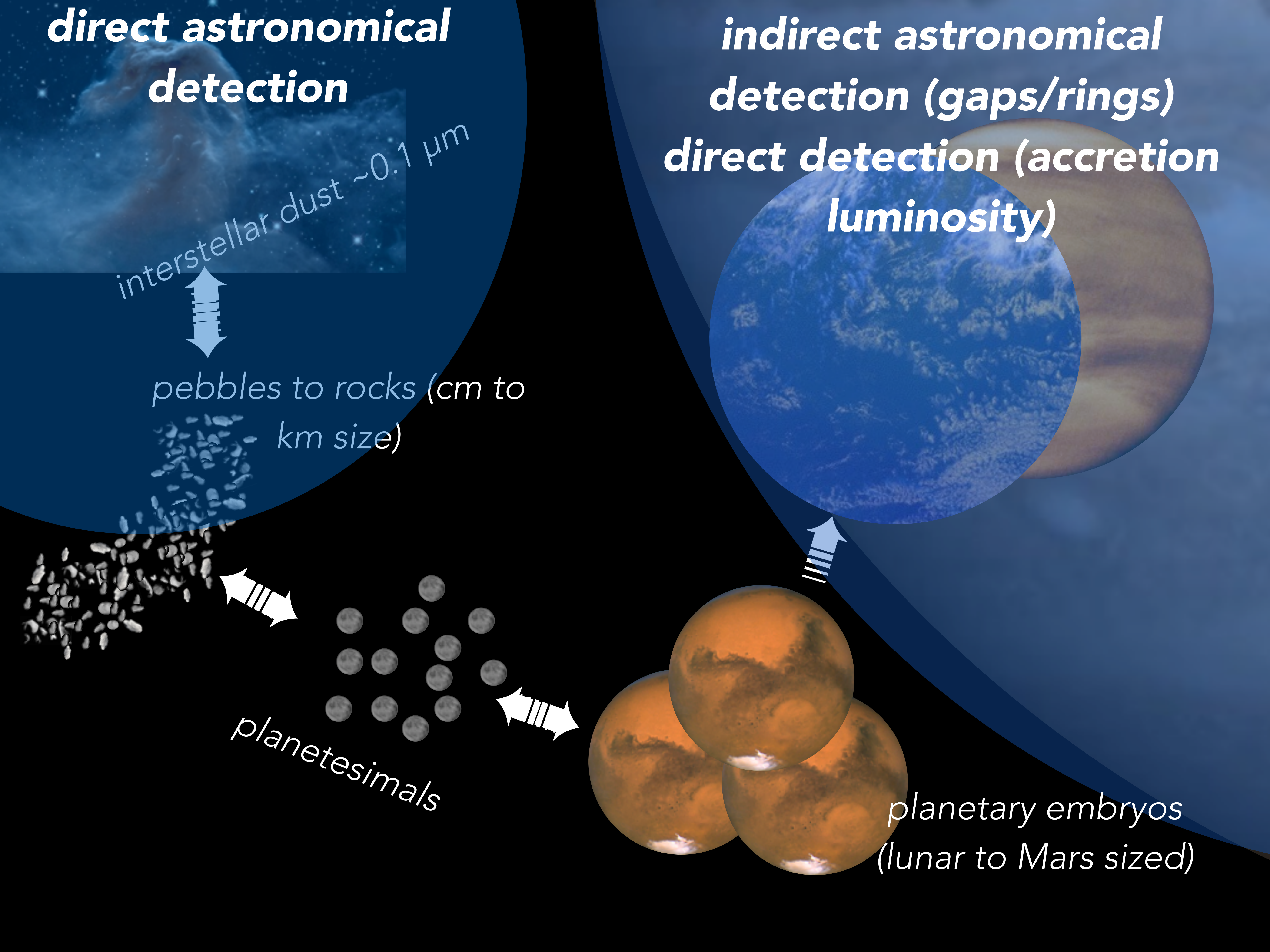


Summary

- Survey of HD emission in disks using a sensitive Far-IR telescope is central to science case for a future instrument
- Could survey hundreds of systems and obtain real statistics.
- Resolved data in closest systems could provide information on mass distribution.
- HD emission and its constraint on mass unlocks ability to explore chemical composition - can track implantation of volatiles, D/H ratios, etc.
- Inferring systematic effects in one system - with wide ranging implications.

Possible Mechanism

- ➡ Planet formation step #1 — settling of dust to midplane.
- ➡ Ice coatings facilitate coagulation - increases settling to a dust-rich midplane, followed by radial drift
- ➡ Beyond snow-lines icy pebbles and eventually planetesimals form - depleting volatiles from the emissive surface layers.
- ➡ Must happen at some level - but details have not been explored.

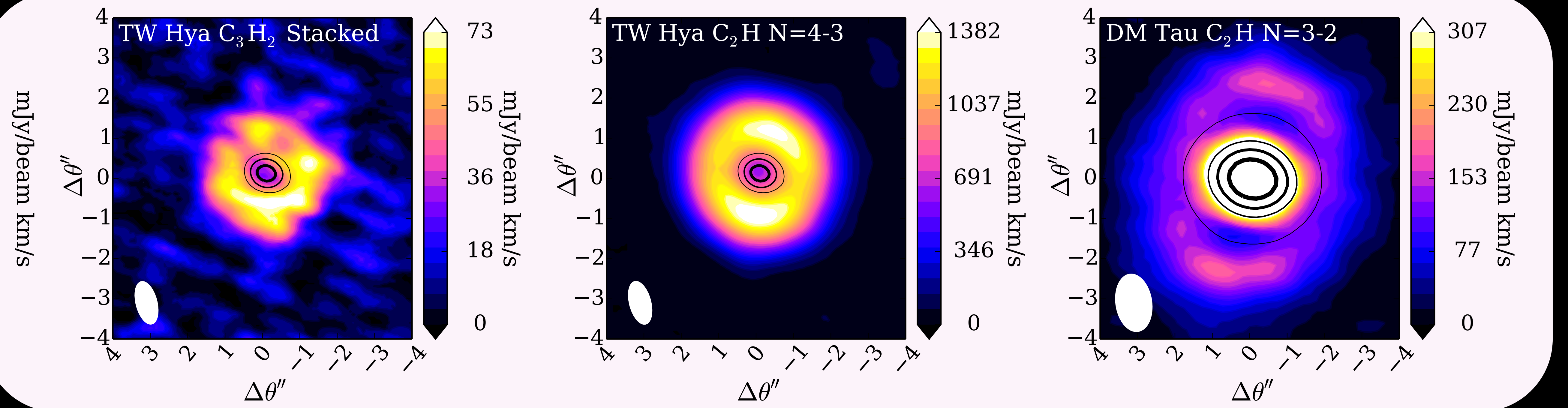

direct astronomical detection
indirect astronomical detection (gaps/rings)
direct detection (accretion luminosity)
interstellar dust ~0.1 µm
pebbles to rocks (cm to km size)
planetesimals
planetary embryos (lunar to Mars sized)

Implications

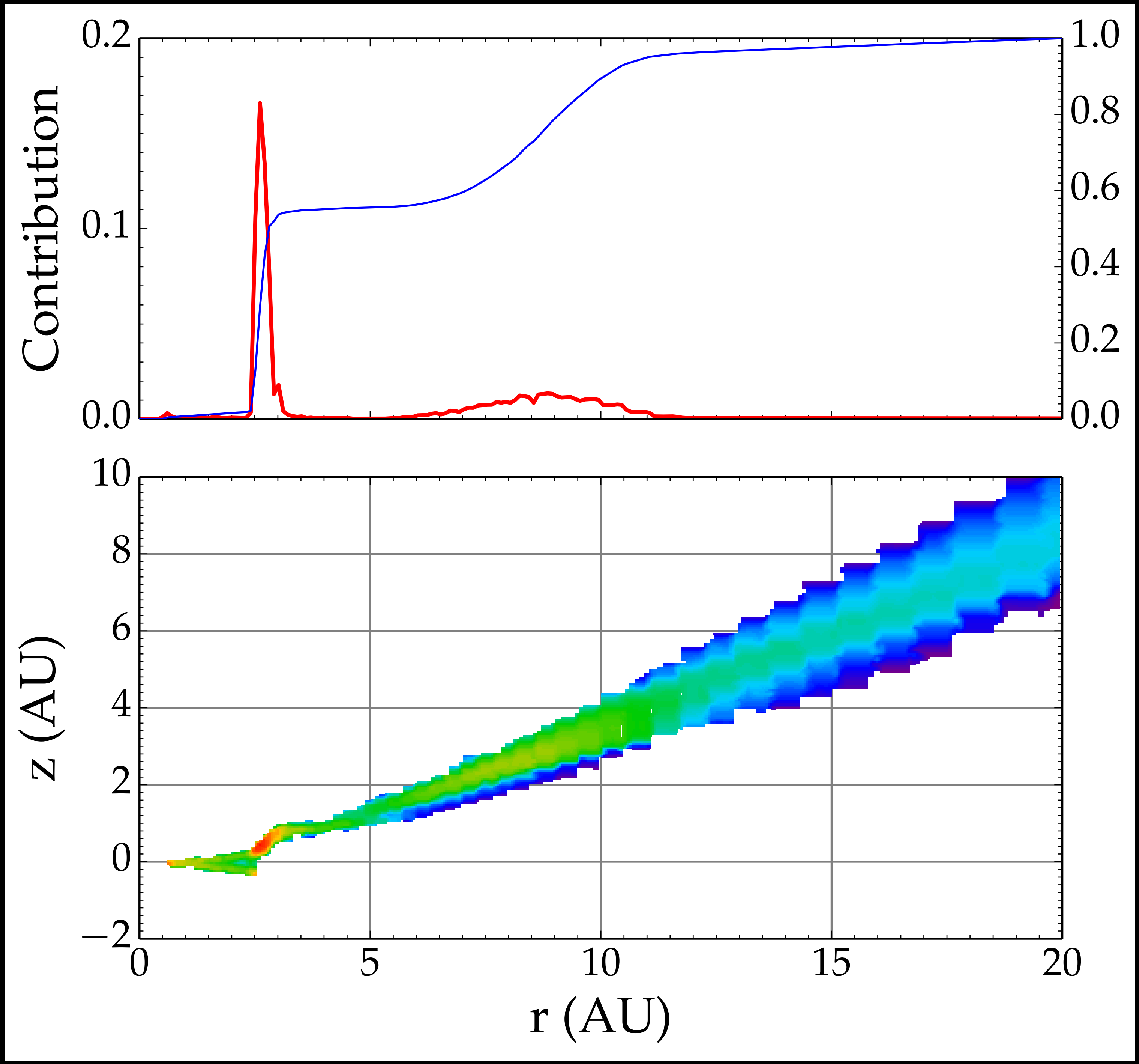
- Volatile depletion - signature of formation of ice-rich pebbles, perhaps planetesimals
- Can track ingredients of habitable worlds
- Measurements of gas-dissipation or mass from species such as CO trace are intertwined with planetesimal formation timescale
- Mass constraints from HD are central to breaking degeneracies

Du, Bergin, & Hogerheijde 2015, in prep.

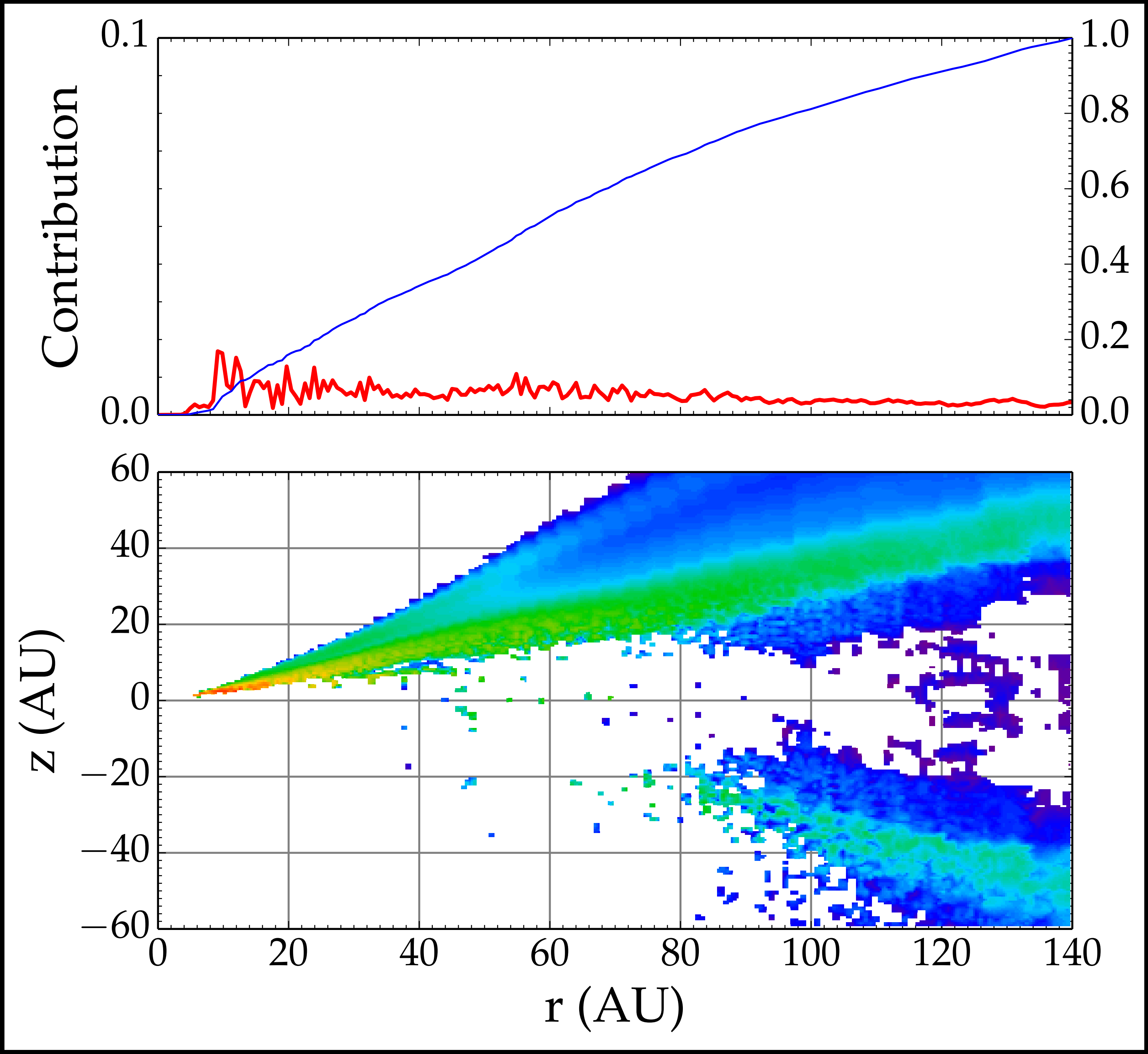
New ALMA Data



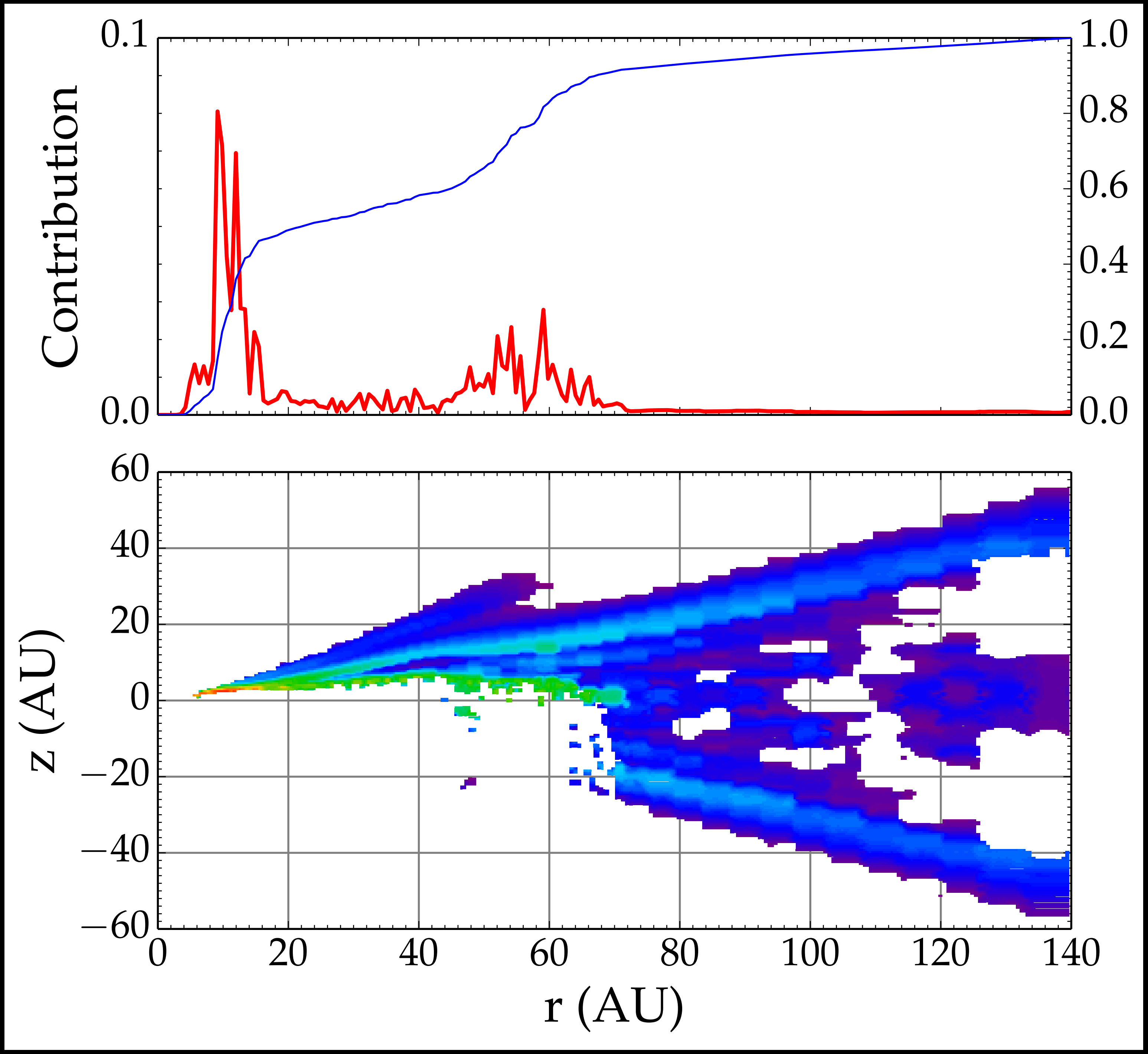
p-H_2O 33 µm (depl. O)



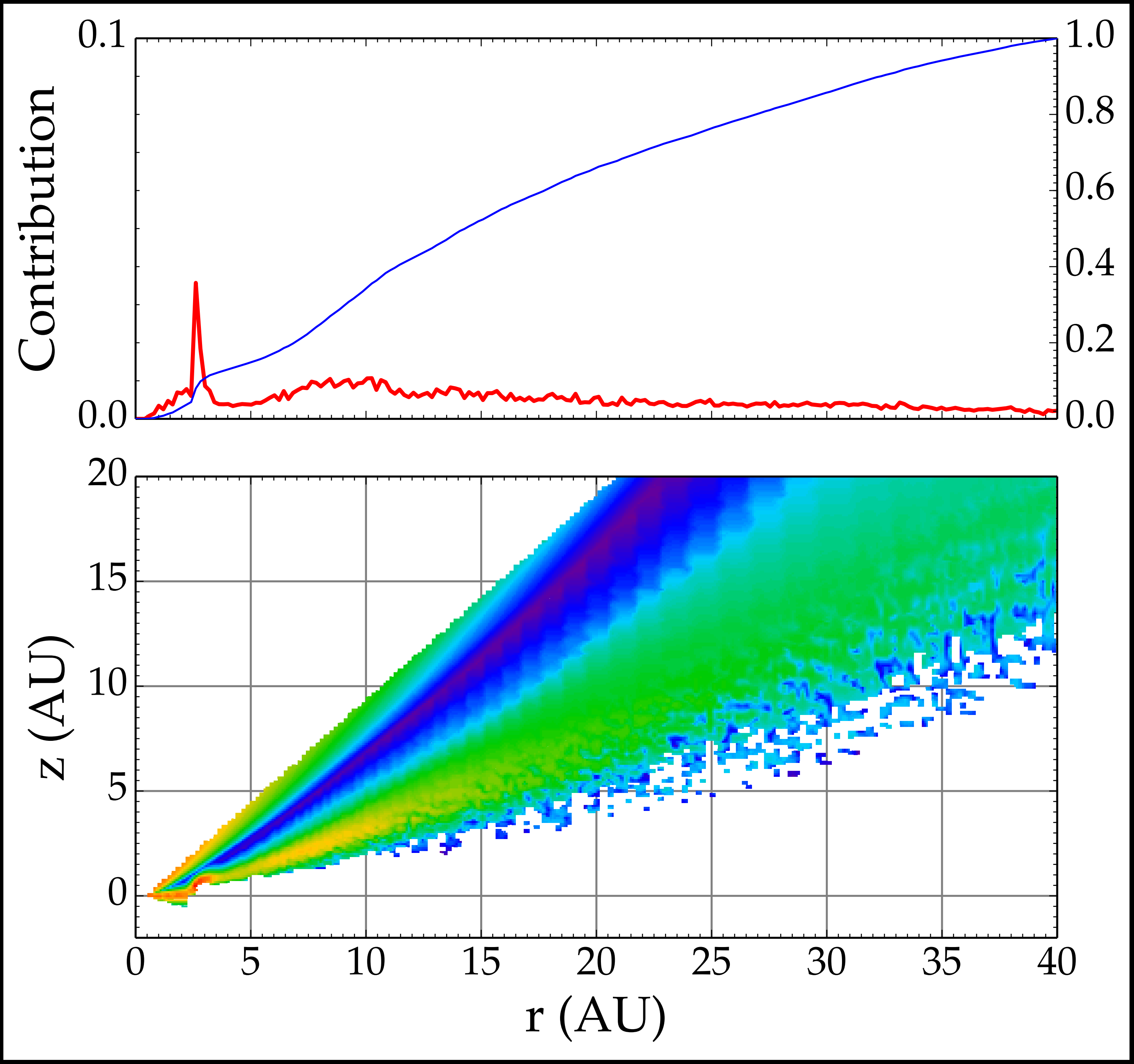
o-H2O 179 μm undepleted O



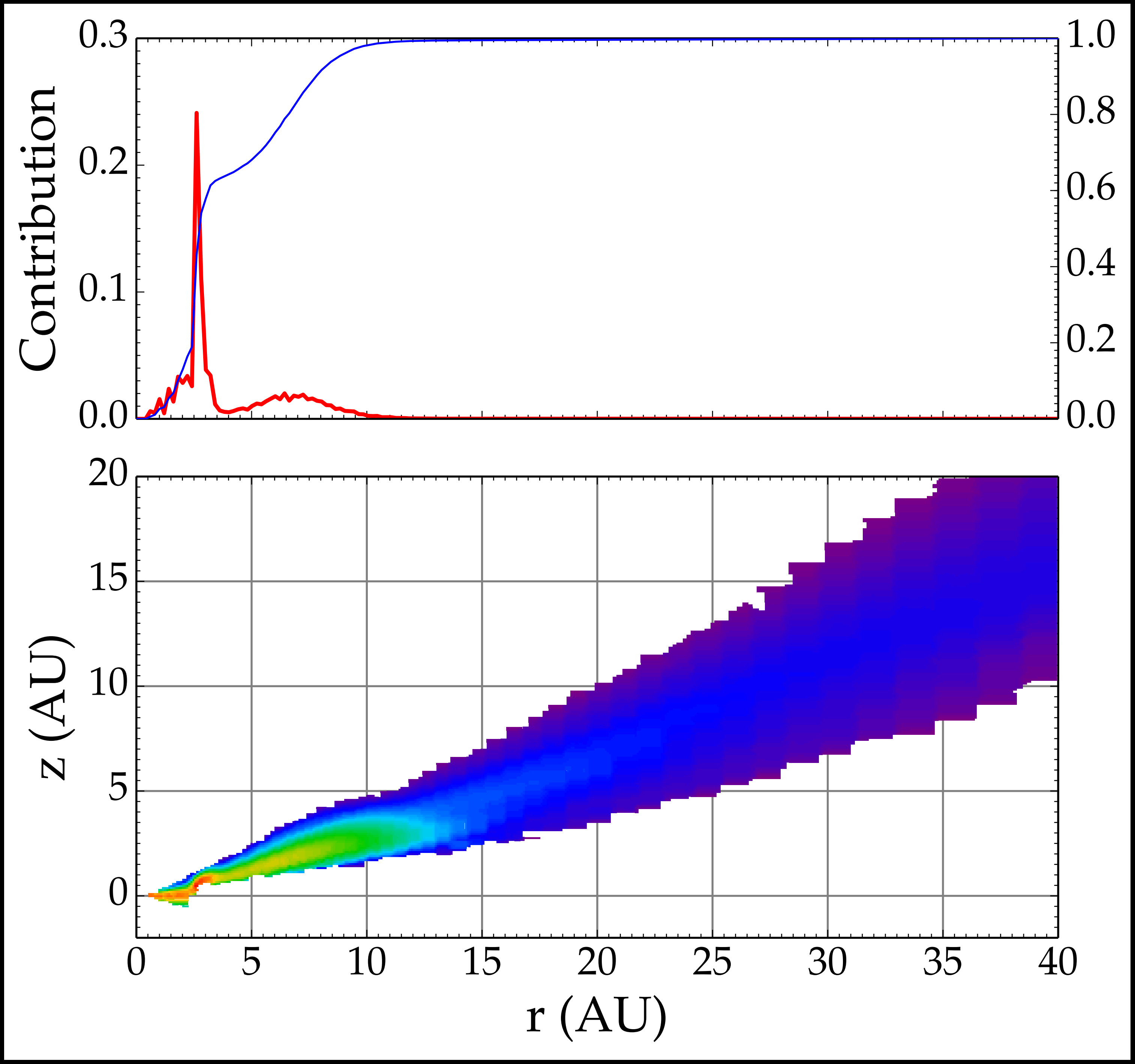
o-H2O 179 μm depleted O

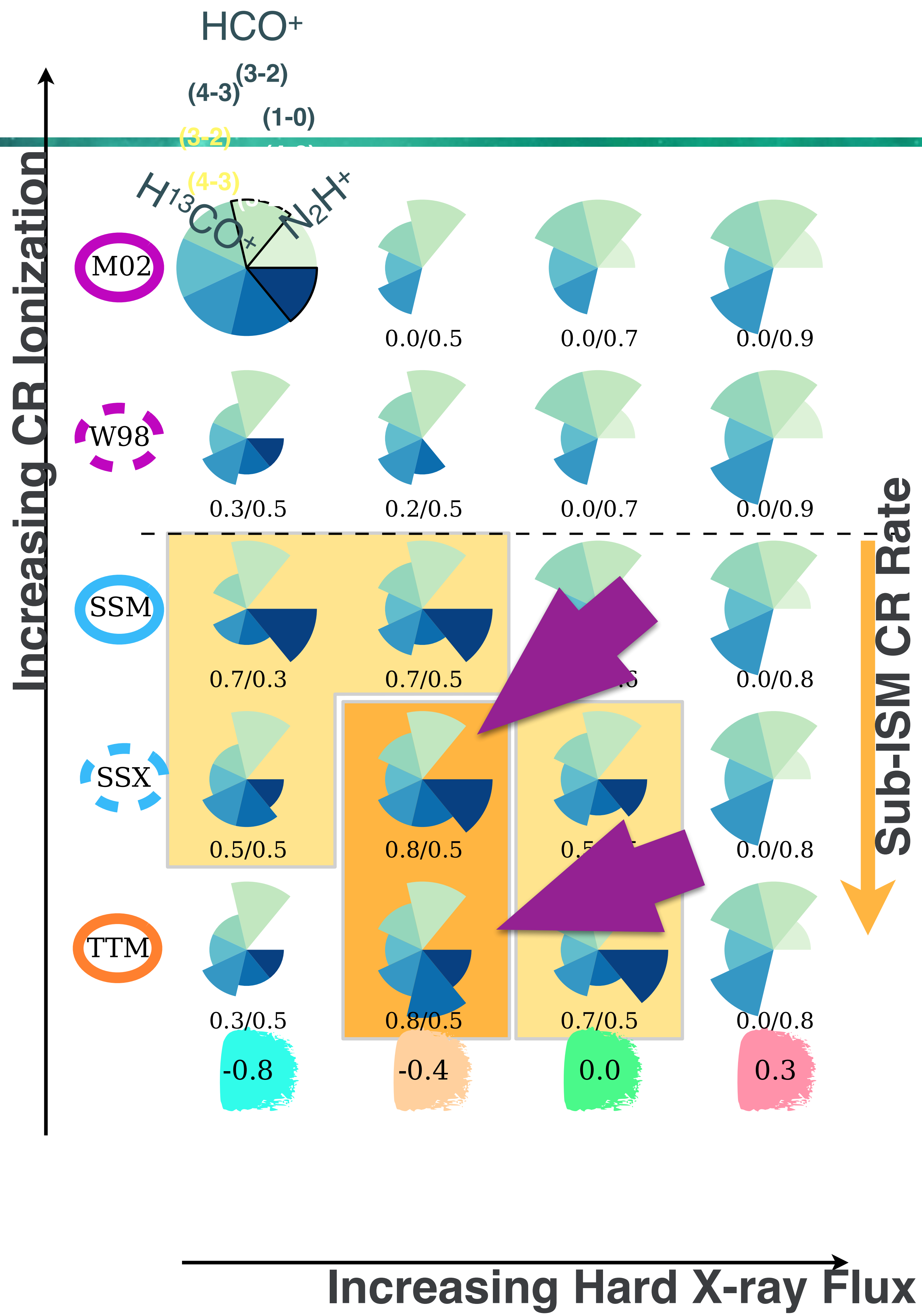


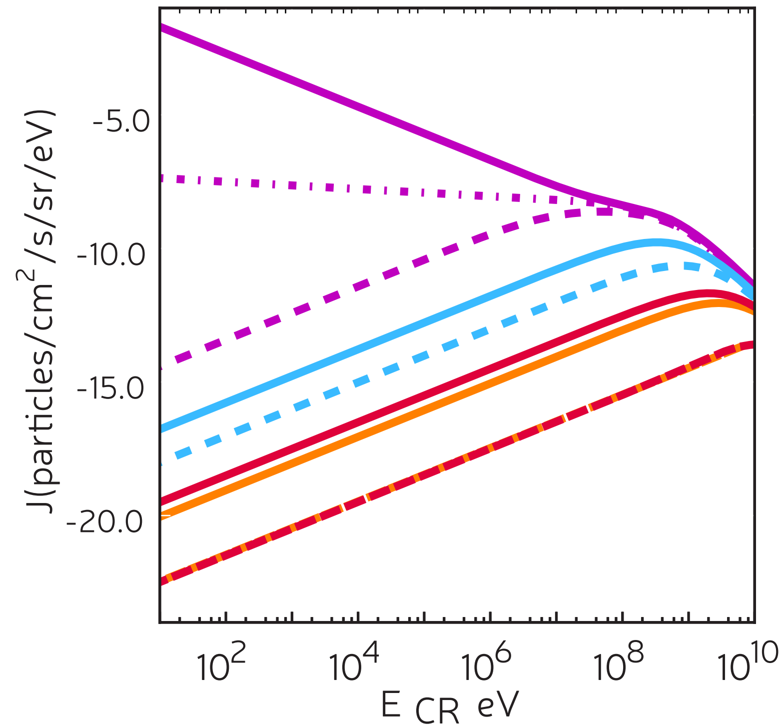
O I 63 μm undepleted O



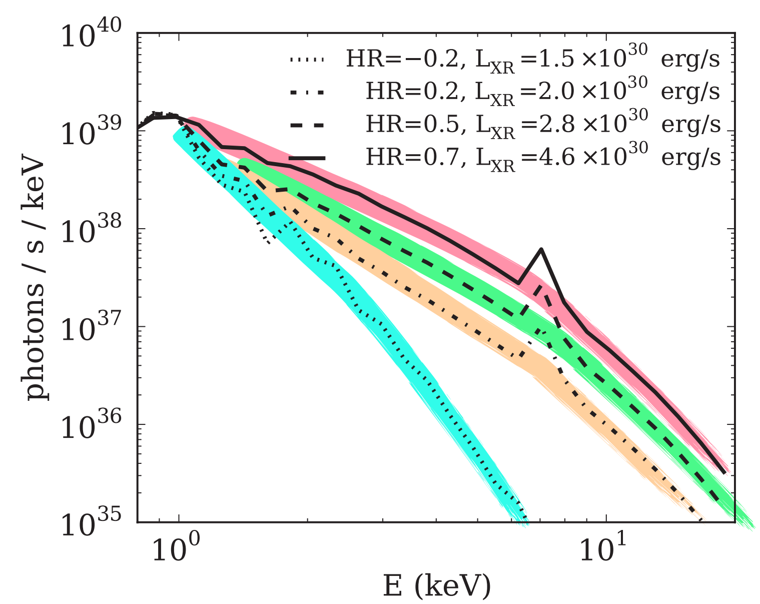
O I 63 µm undepleted O







CR Models from Cleeves +2013a.

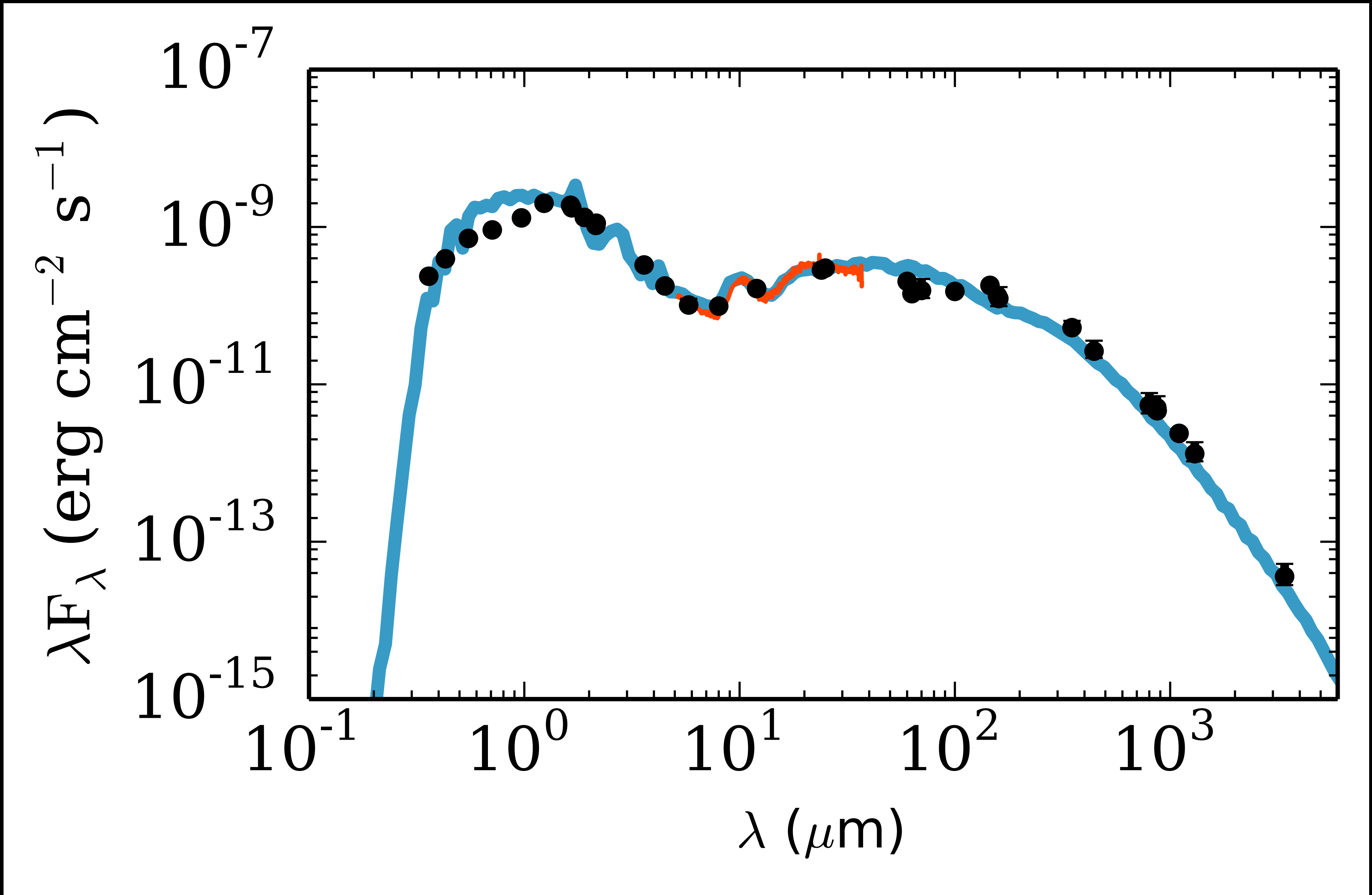


XSPEC Models Based on Kastner+ 1999, 2003. Cleeves (sub).

What does this mean?

- One disk -- has HD to underpin mass -- has depleted C and O in upper layers
- Infer missing C and O in rocks
- Solar system: "thermal modeling predicts that large (> 5–7-km-radius) fully undifferentiated bodies must accrete most of their masses after ~1.5 Myr after CAI formation, fully differentiated bodies must complete most of their accretion before ~1.5 Myr after CAIs" (Weiss & Elkins-Tanton 2013)
- Conclusion: locking of ices in large planetesimals must happen - and it happens early.

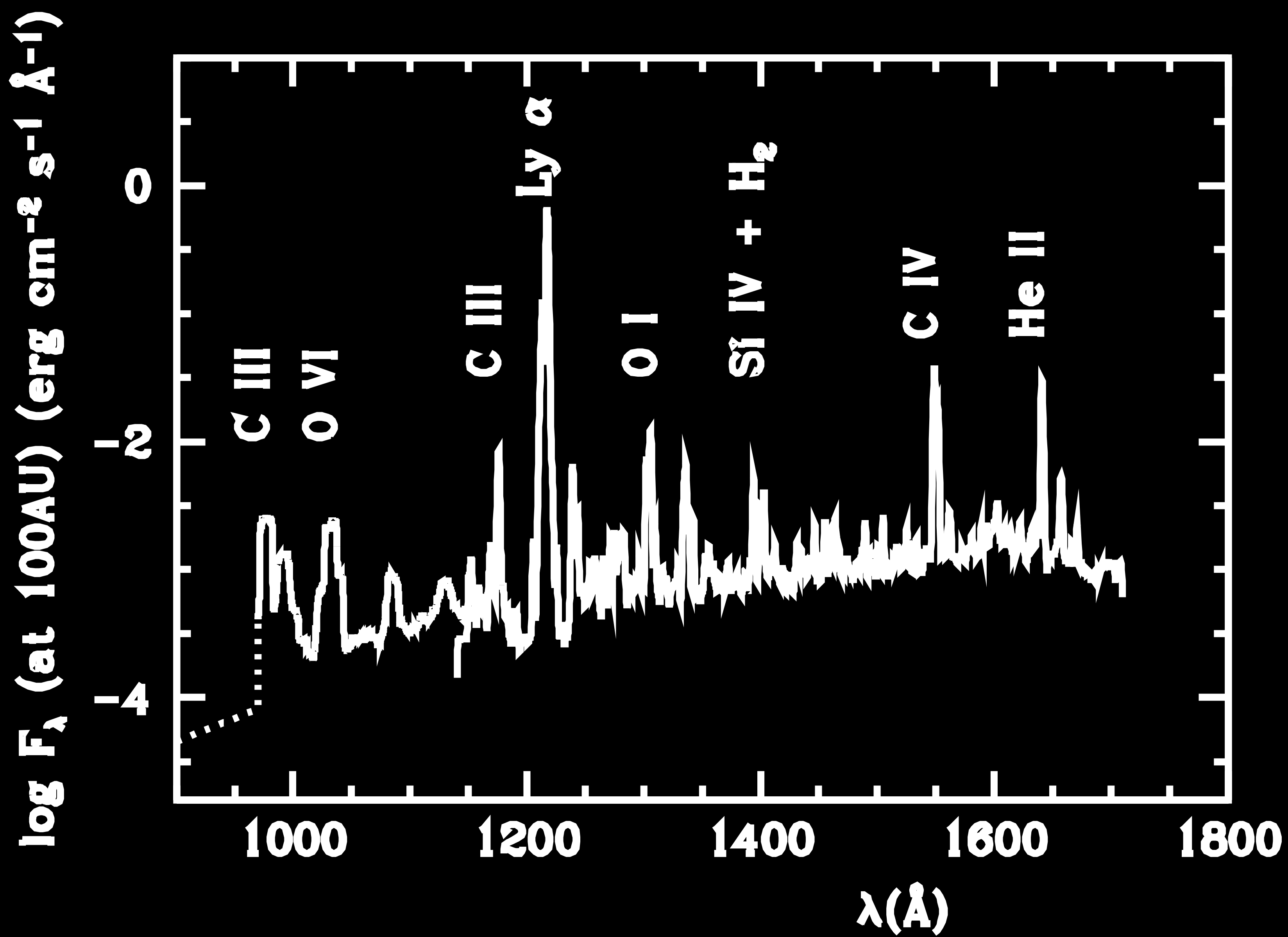
Dust Distribution



constrains dust physical structure

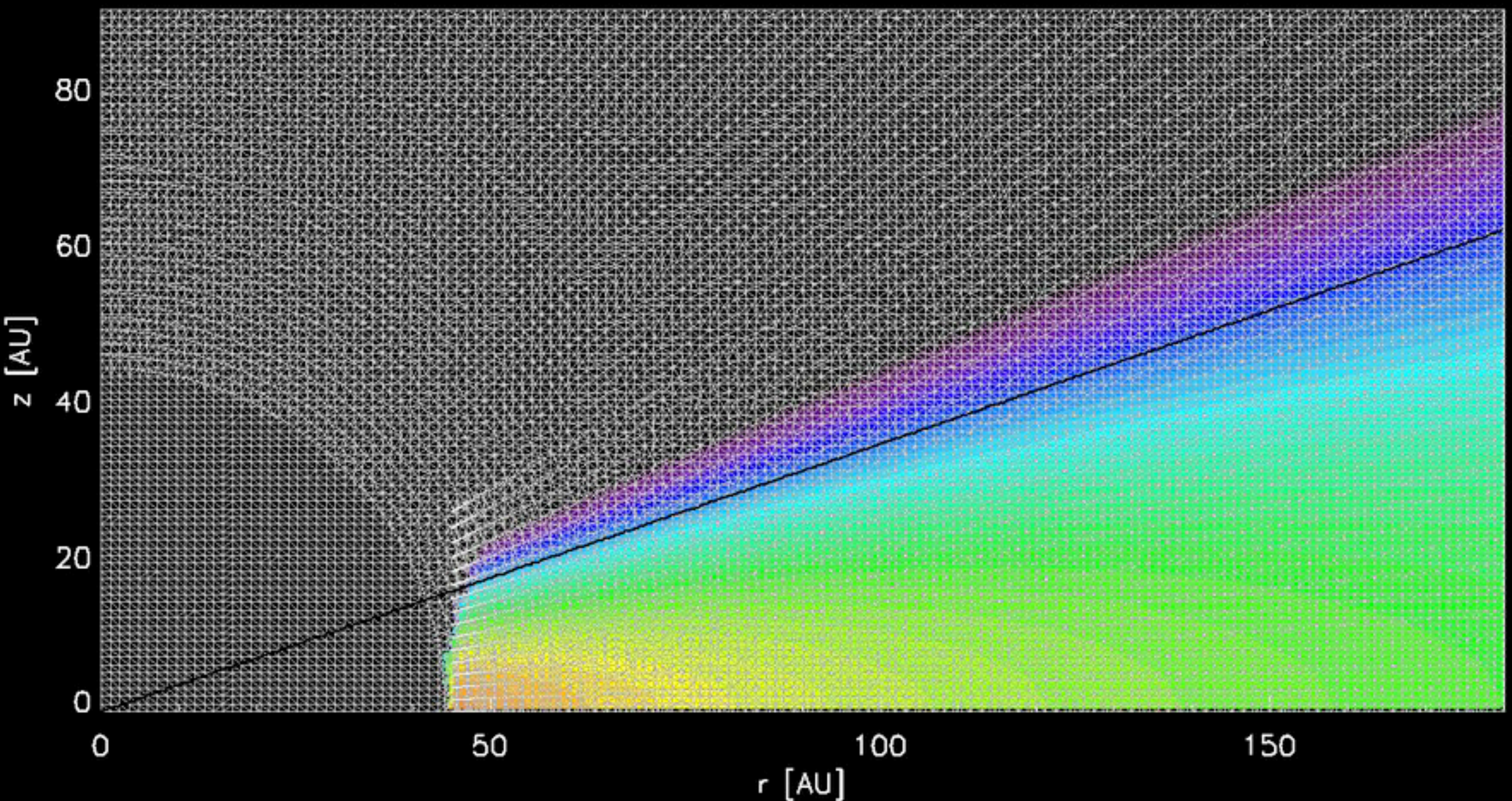
UV Radiation Field

- ➡ Accretion generates UV radiation
- ➡ water is dissociated by photons with 912 - 2000 Å
- ➡ Disks have strong Ly α radiation field
- ➡ X-rays are also important



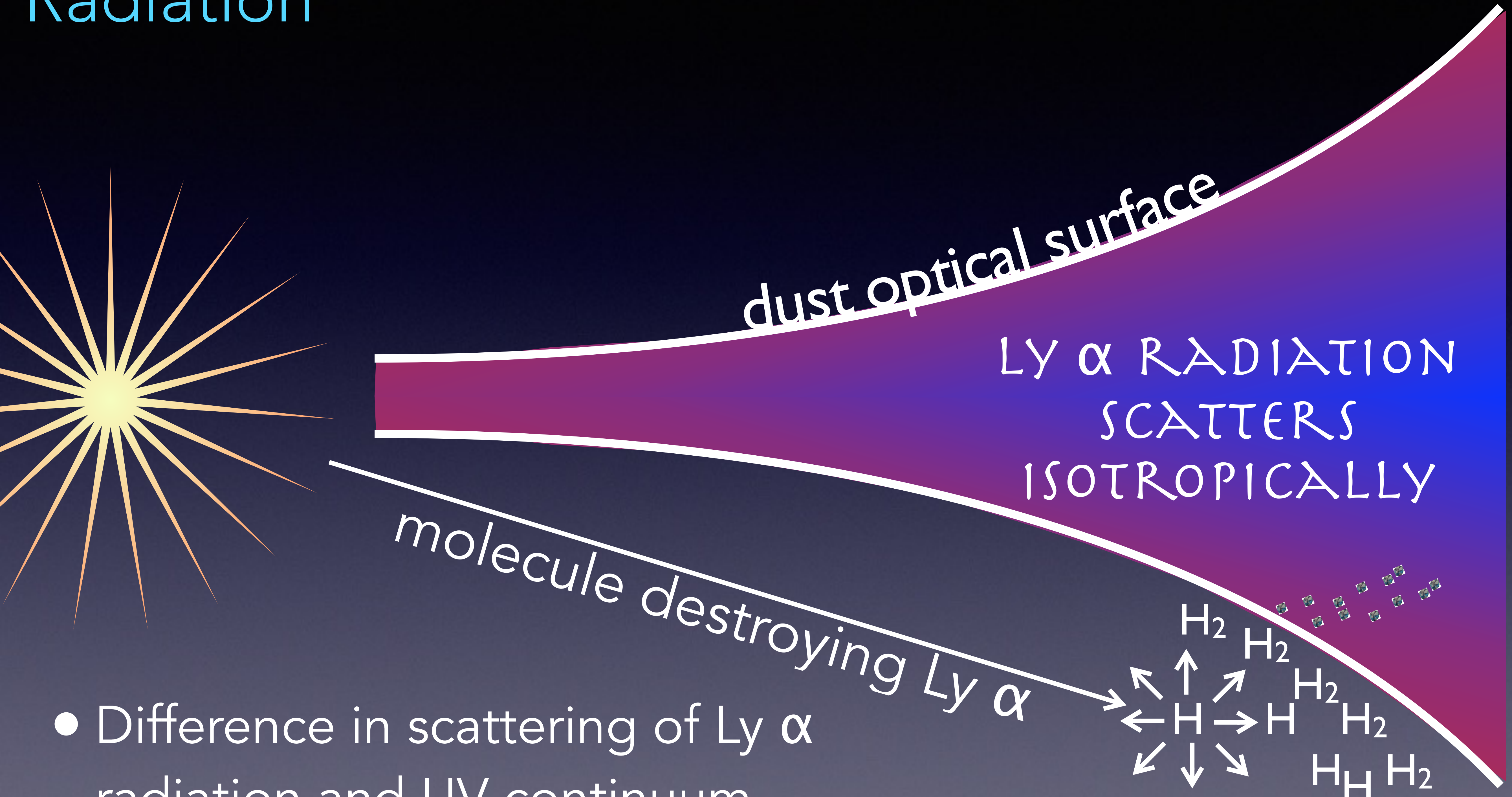
Bergin et al. 2003

UV Propagation



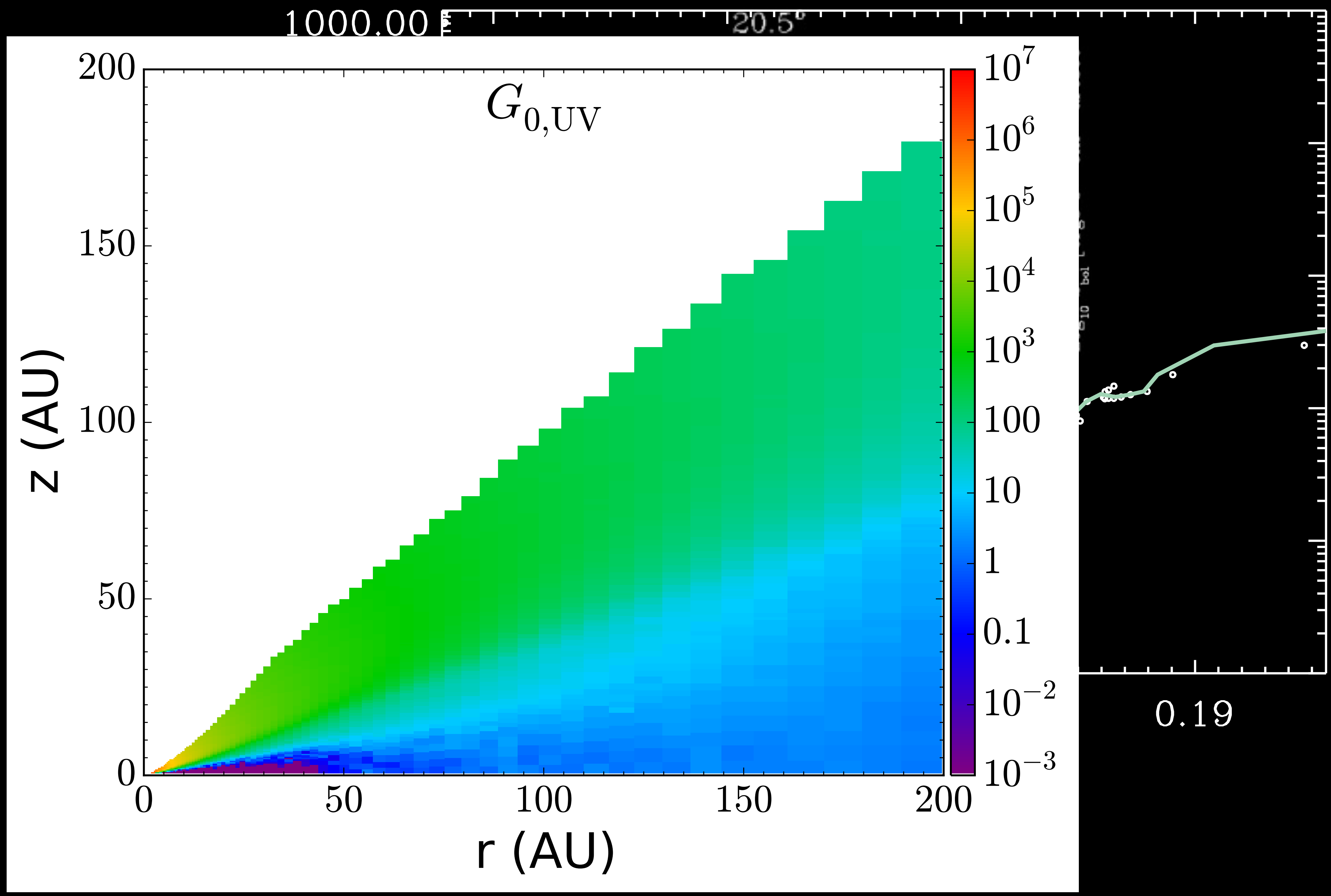
Bethell & Bergin 2011

Physical Picture: Propagation of Lyman α Radiation

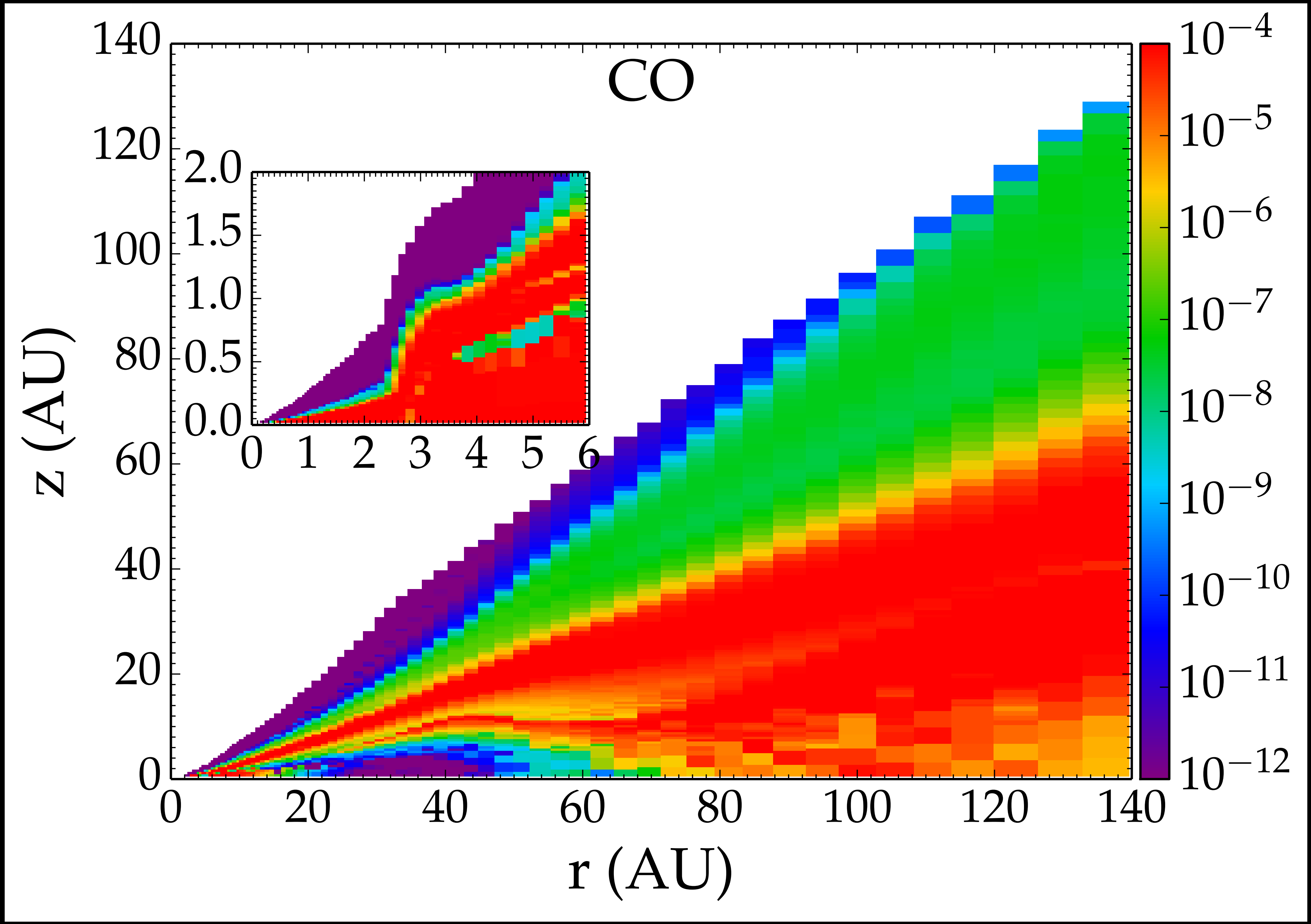


- Difference in scattering of Ly α radiation and UV continuum
- Ly α has greater penetration

Ly α Radiation Transfer



Bethell & Bergin 2011



CO
z (AU)
r (AU)
0
20
40
60
80
100
120
140
0.0
0.5
1.0
1.5
2.0
1
2
3
4
5
6
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10^{-6}
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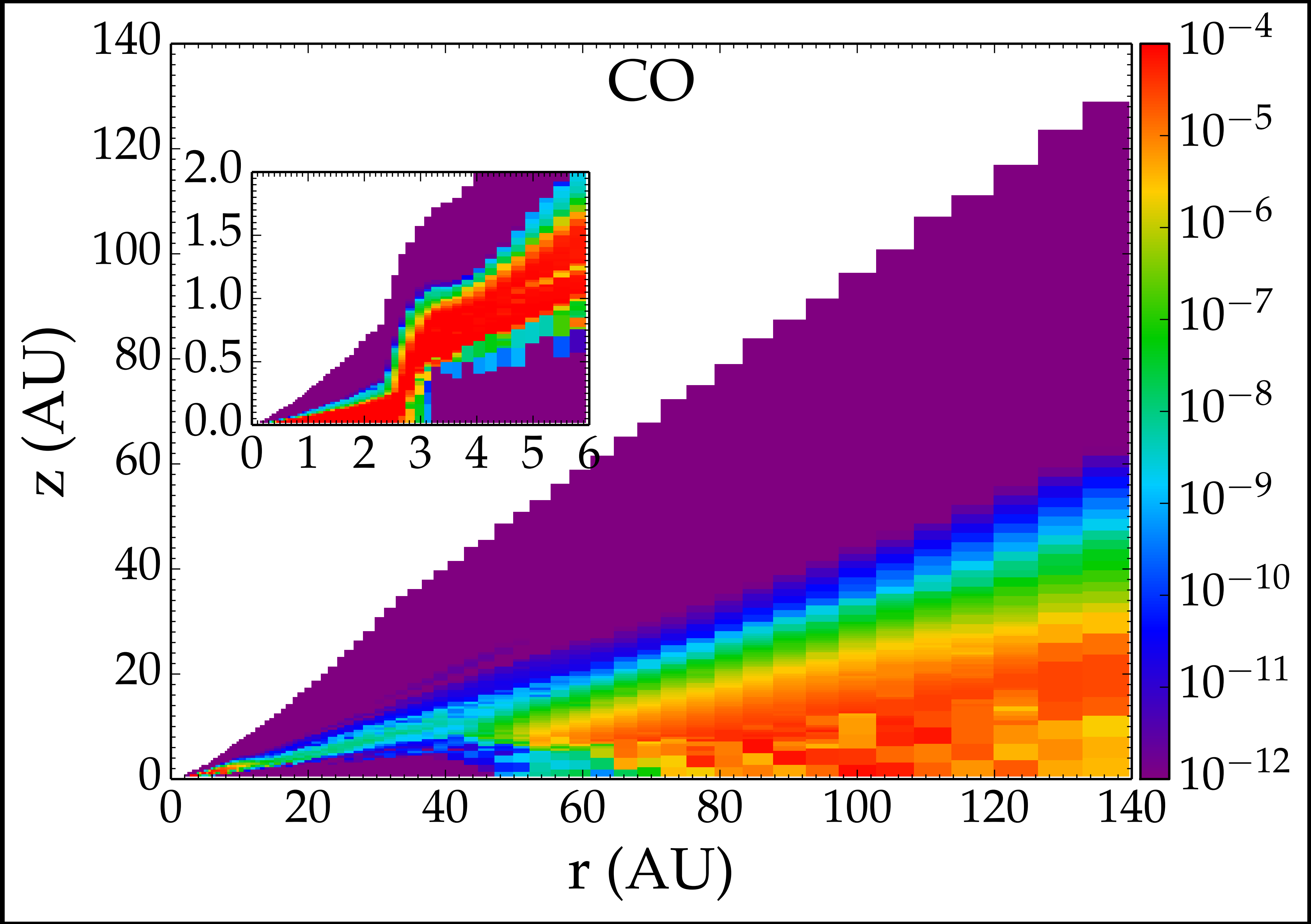
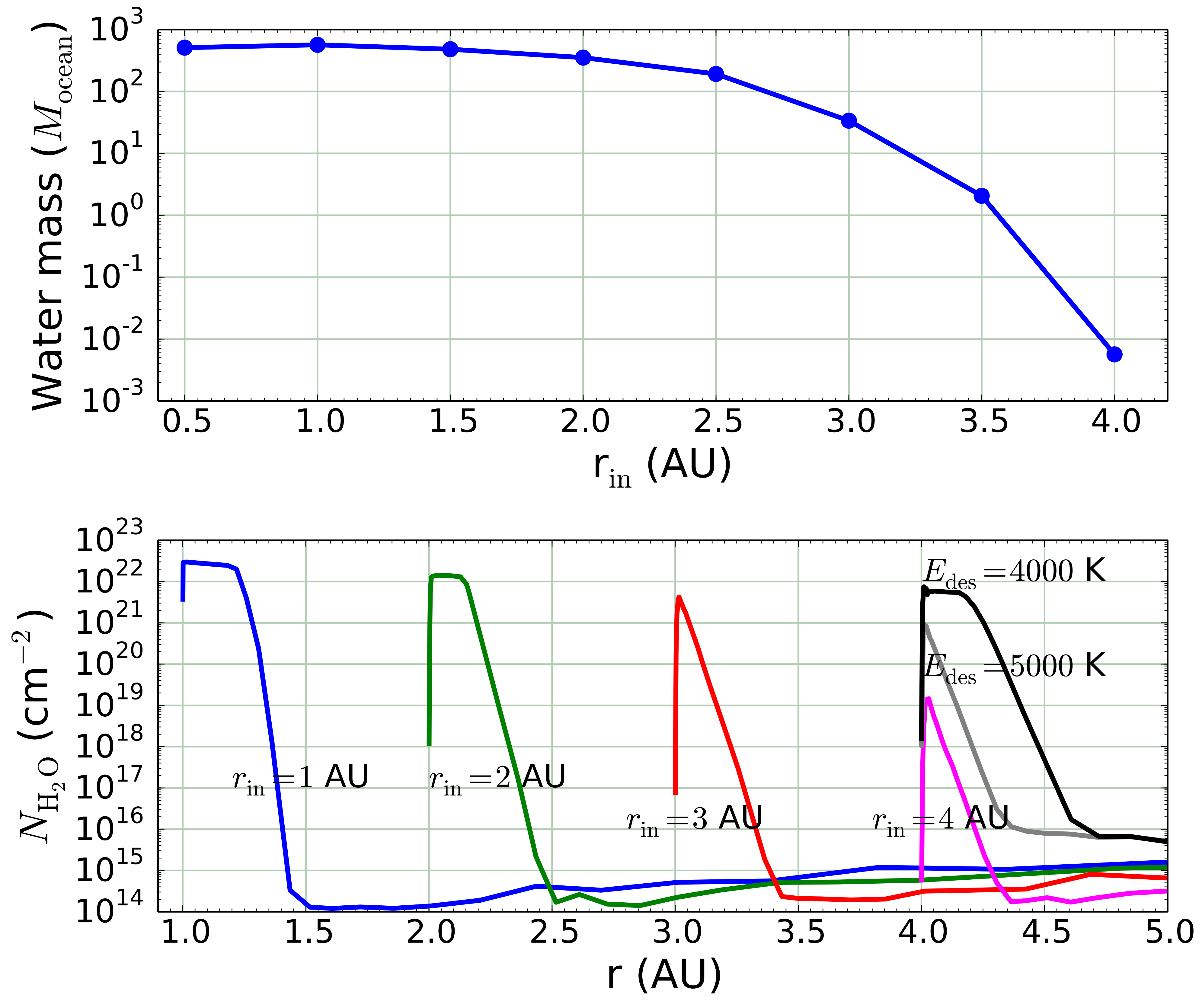
10^{-11}
10^{-12}

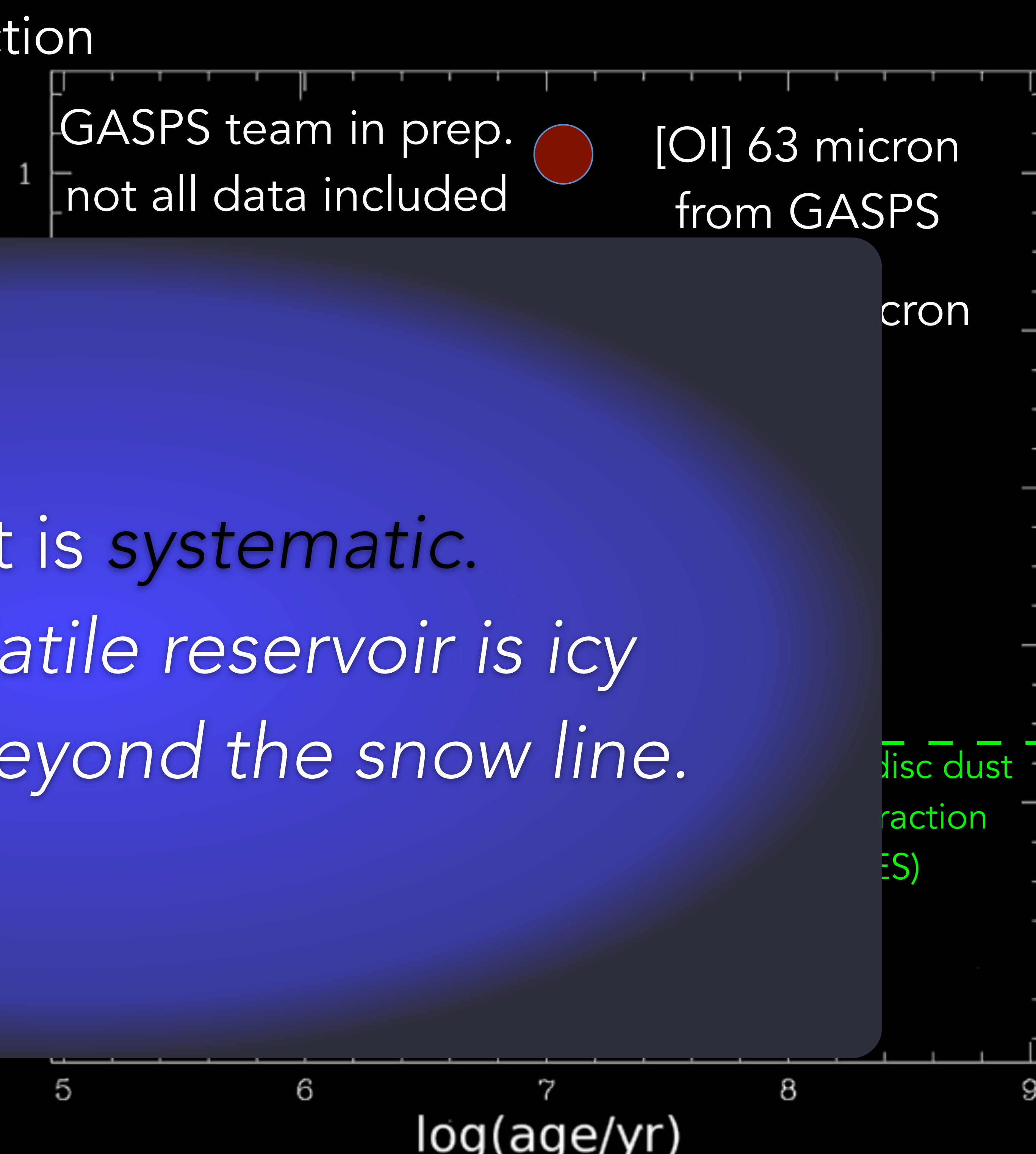


CO
z (AU)
r (AU)
0
20
40
60
80
100
120
140
2.0
1.5
1.0
0.5
0.0
1
2
3
4
5
6
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}

Dependence on Inner Cavity Radius



[OI]63 (warm gas) and continuum detection rate vs time



GASPS su
sensitivity

The gas
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Prelimin
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conversi
to H_2 ma

This effect is *systematic*.

Most likely volatile reservoir is icy planetesimals beyond the snow line.

W. Thi - Universe Explored by Herschel

Protoplanetary Disk Gas Mass

Complications

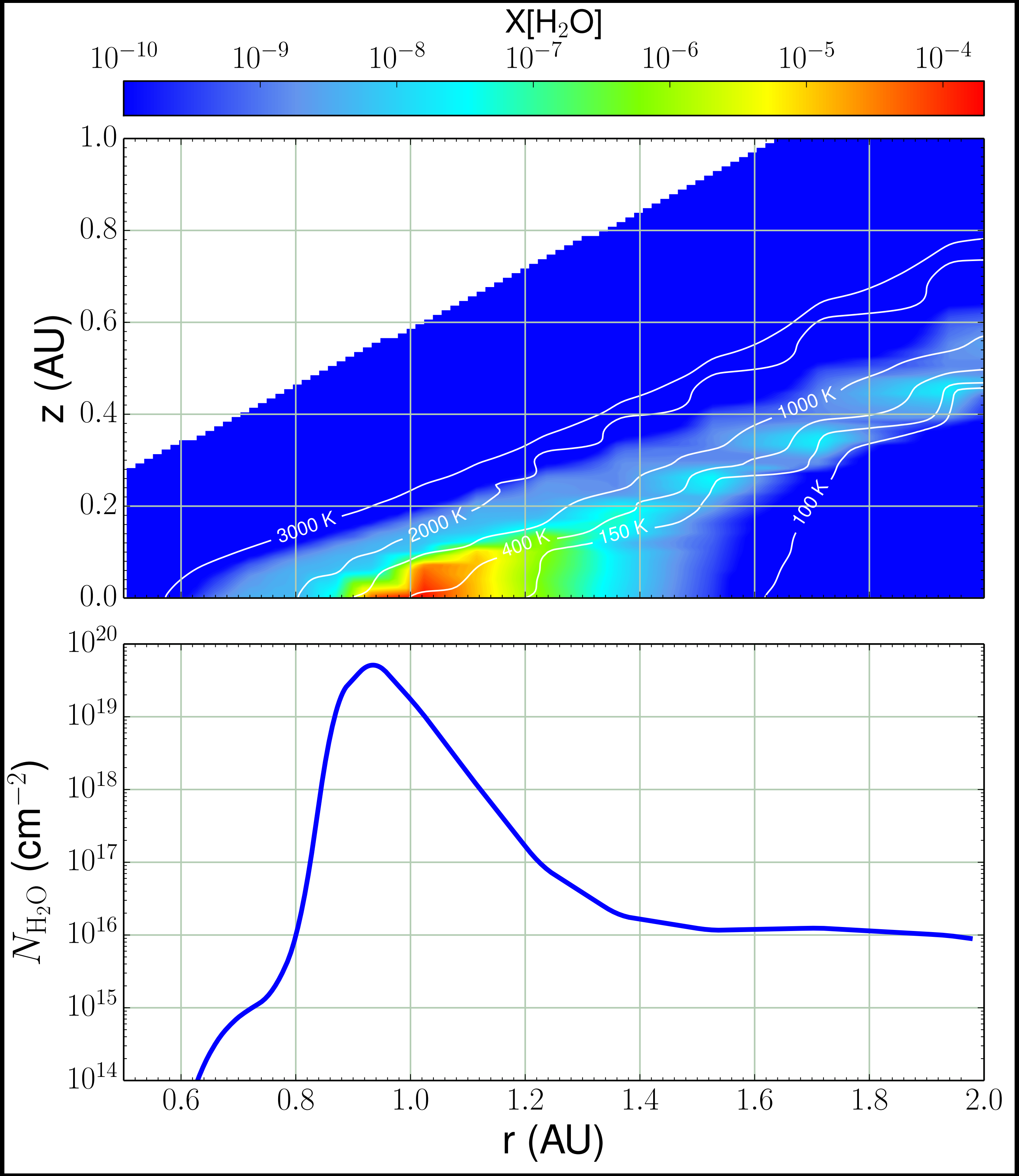
➡ H_2 is does not emit for typical temperatures (20 K) that characterize the disk mass reservoir

Proxies

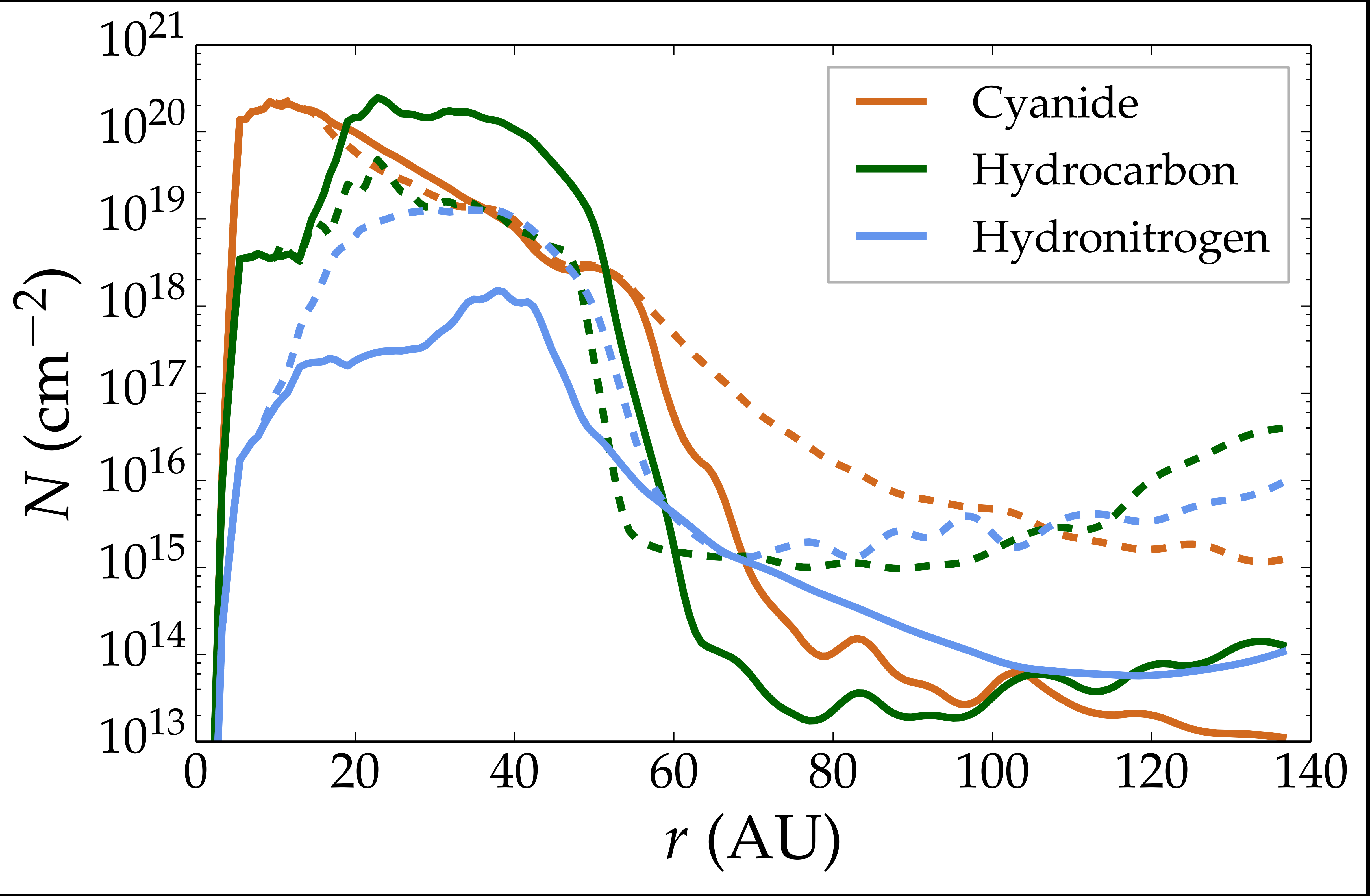
➡ thermal emission from dust grains at mm/sub-mm wavelengths

➡ thermo-chemical modeling of gas emission, primarily CO and isotopologues

Water Distribution



Implications

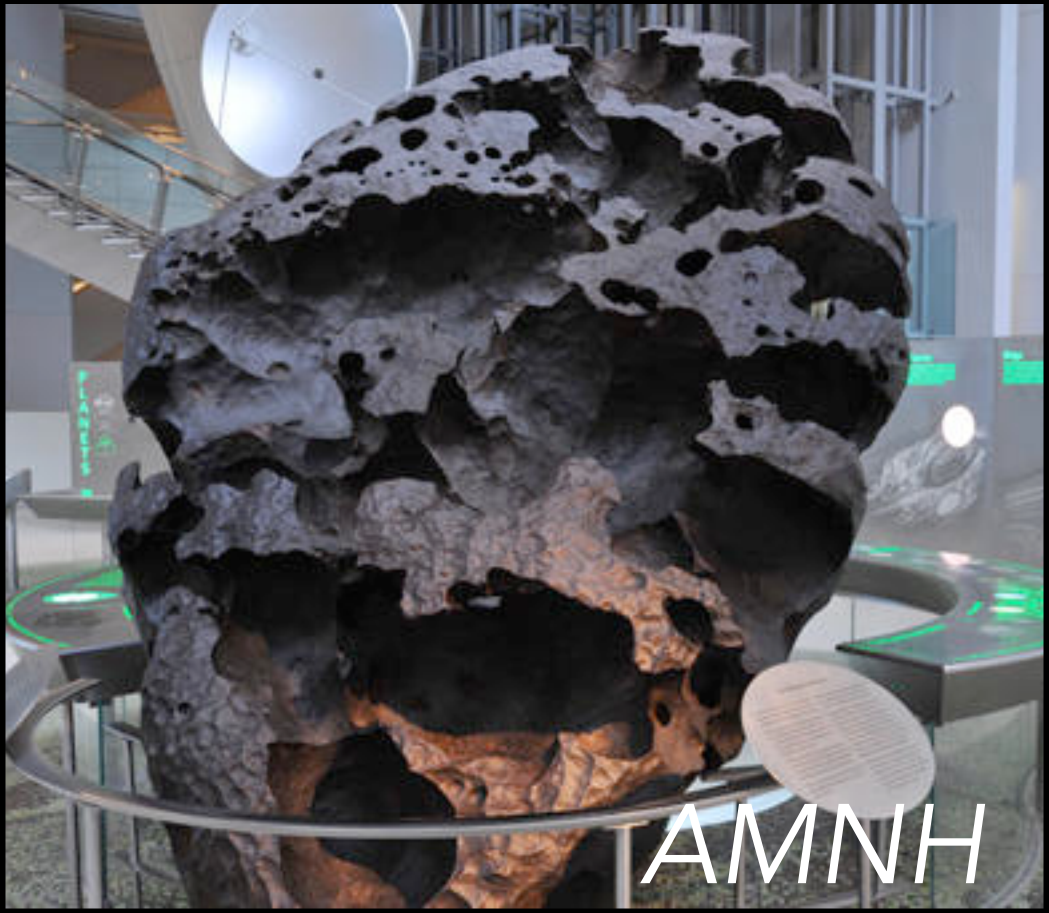


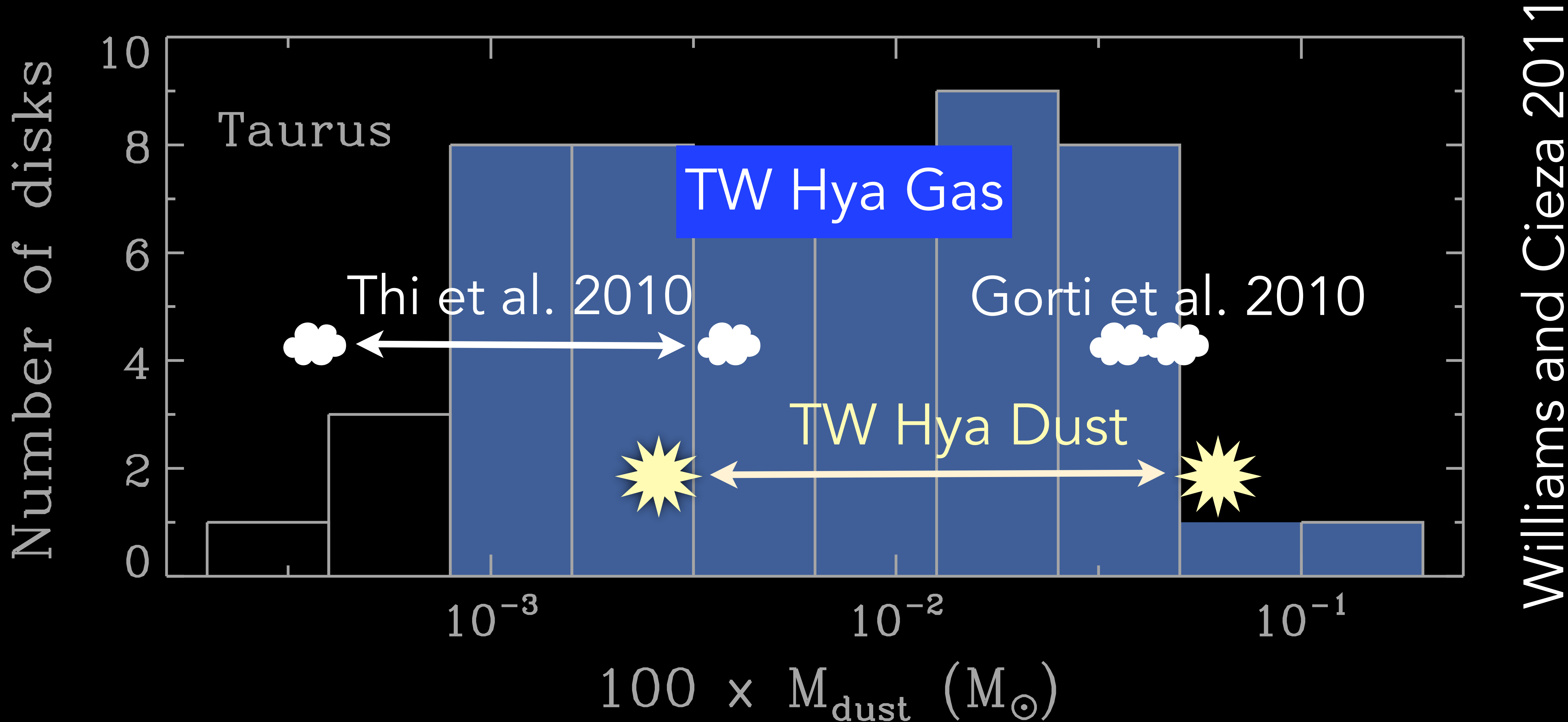
Du, Bergin, & Hogerheijde 2015, in prep.

Cosmochemical Record

- Hf-W dating of iron meteorites
  - ➡ differentiation occurred < 1.5 Myr after CAI formation (Kleine+ 2005, Qin+ 2008, Kruijer+2014
- Requires many-km sized bodies heated by ^{26}Al
  - ➡ differentiation is not instantaneous
  - ➡ accretion age estimates of parent body are ~0.1 - 0.5 Myr

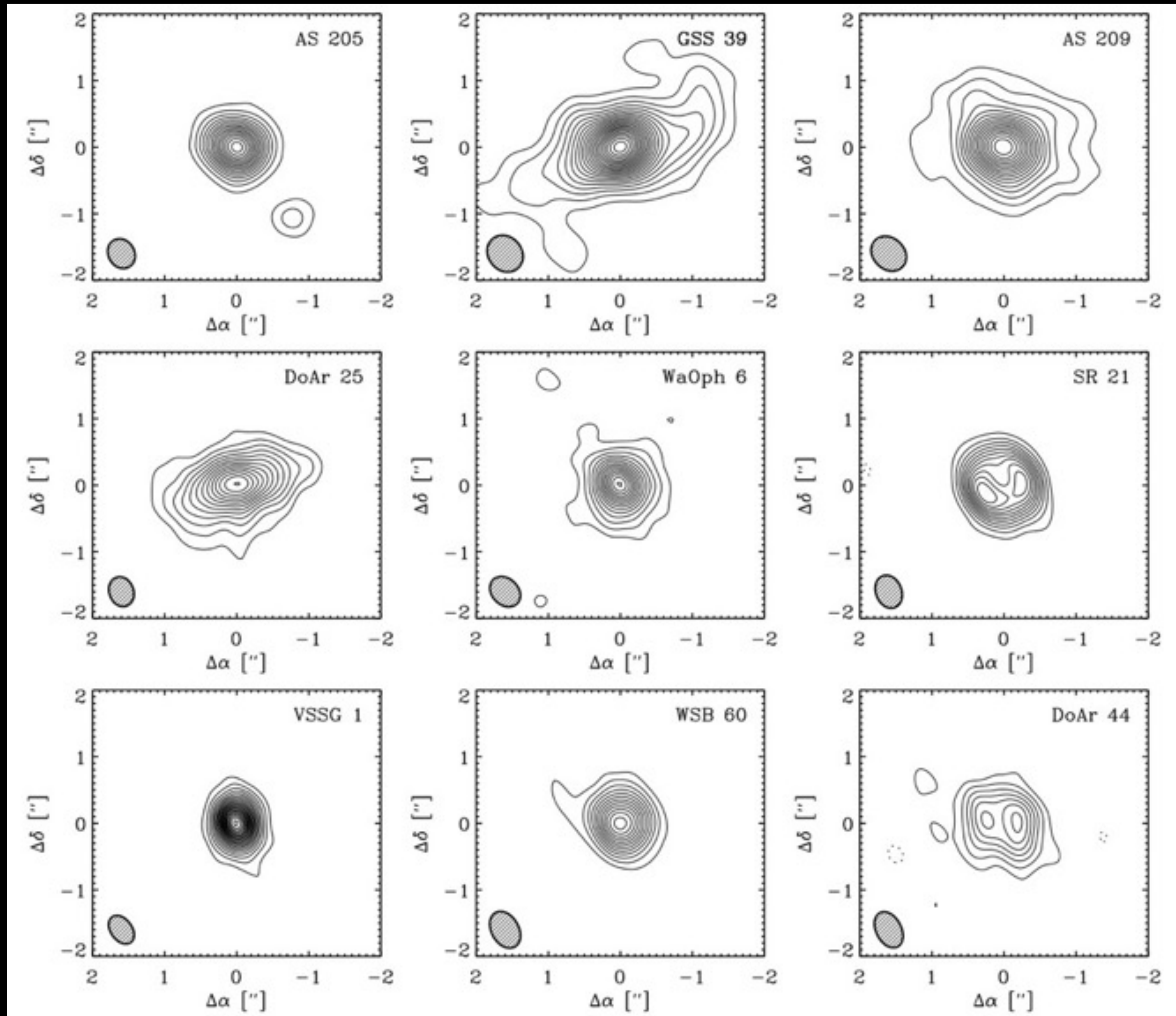
Williamette Meteorite (Iron)





- TW Hya has a massive gas disk
- many times MMSN
- other systems are underestimated?

Bergin et al. 2013

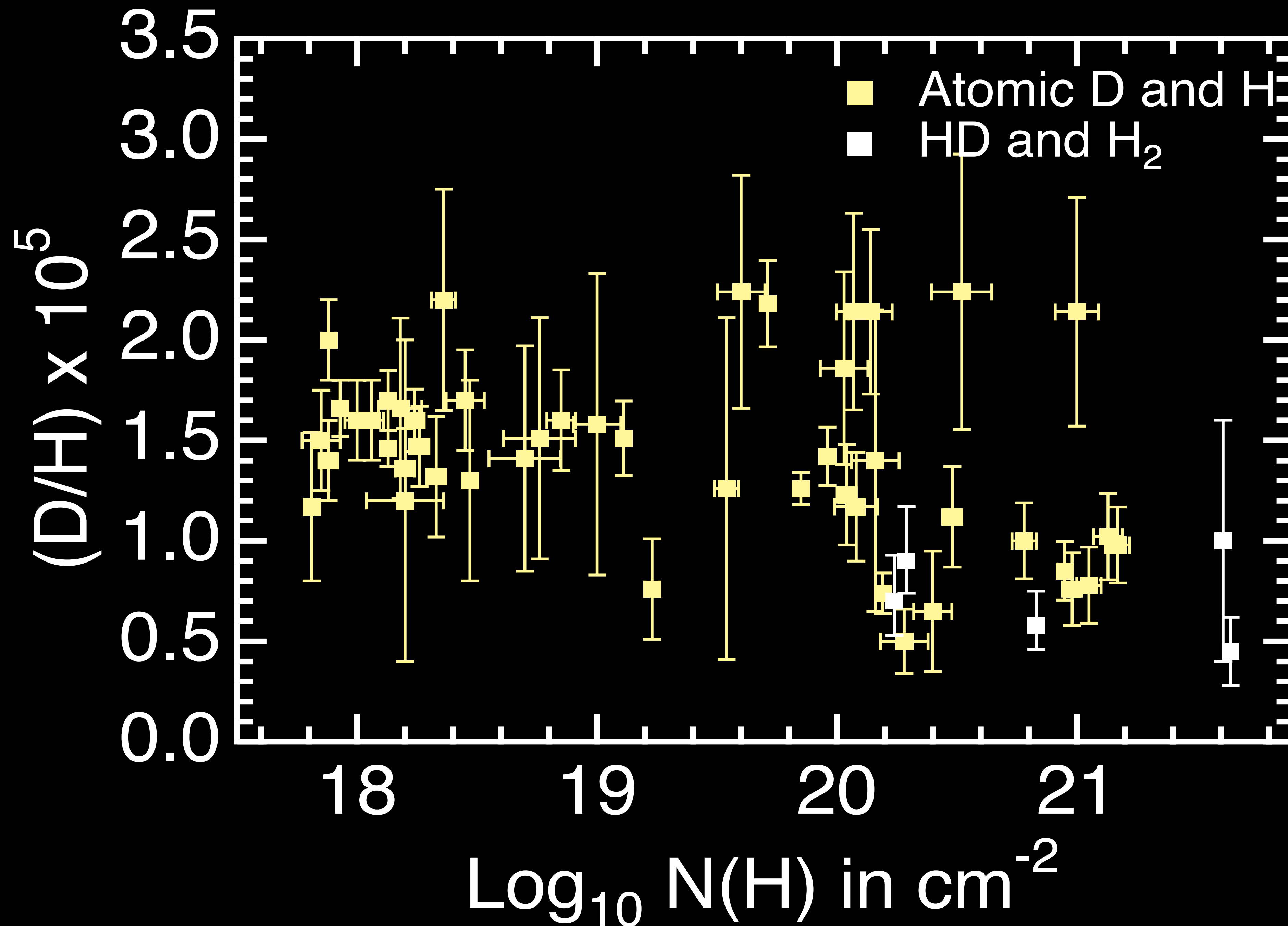


Andrews et al. 2009

➡ Mass (gas + dust) = $F_\nu D^2/\kappa_\nu B_\nu[T(r)]$

➡ at sub-mm wavelengths - Mass $\propto F_\nu/\kappa_\nu T$

Deuterium Abundance



from atomic D & H (Friedman et al. 2006)

from HD & H_2 (Neufeld et al. 2006)