Photochemical Heating by Water
in the Terrestrial Planet-Forming Regions of Disks

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Water in the Universe
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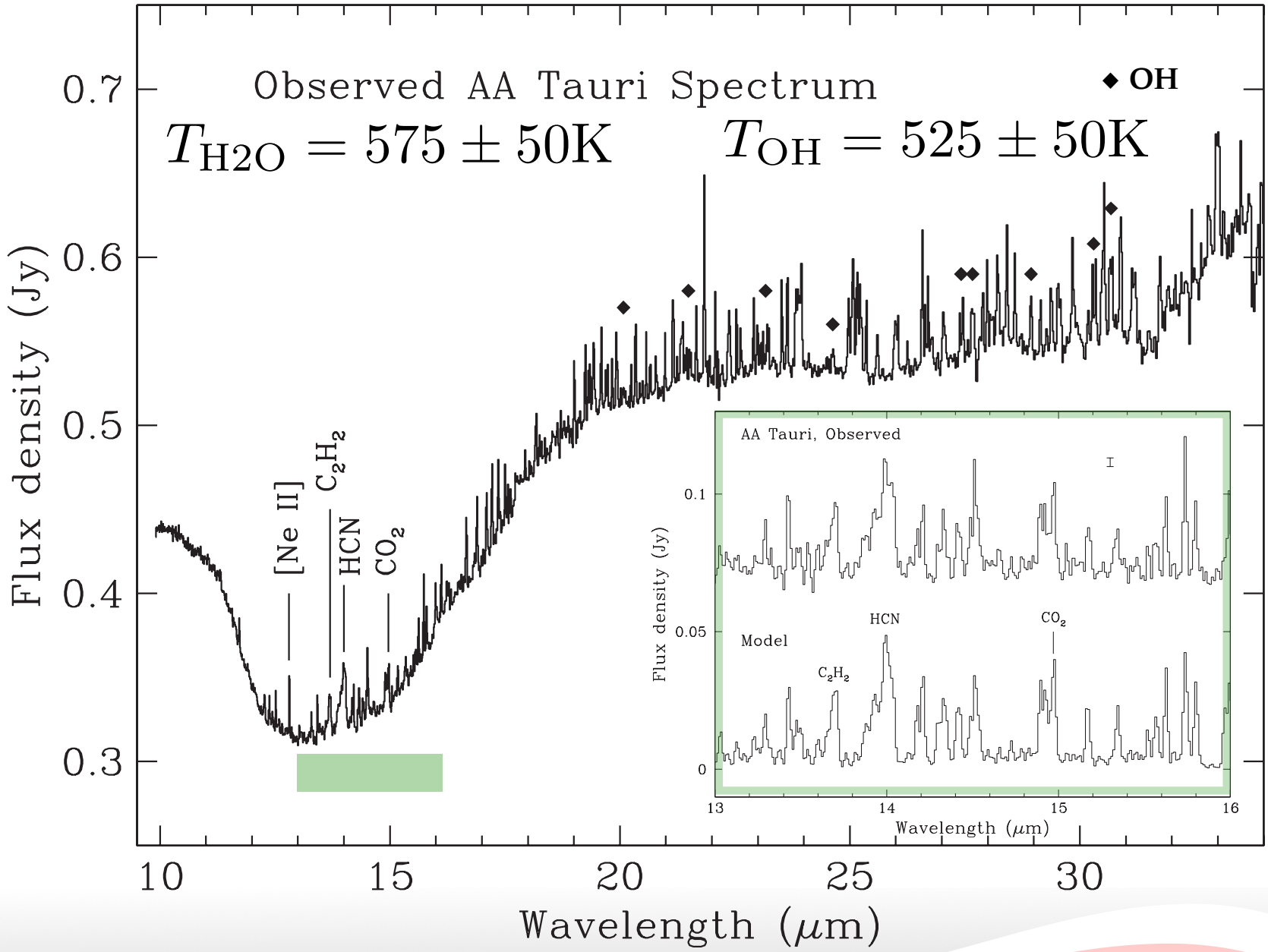
Warm molecular emission

Carr & Najita, 2008

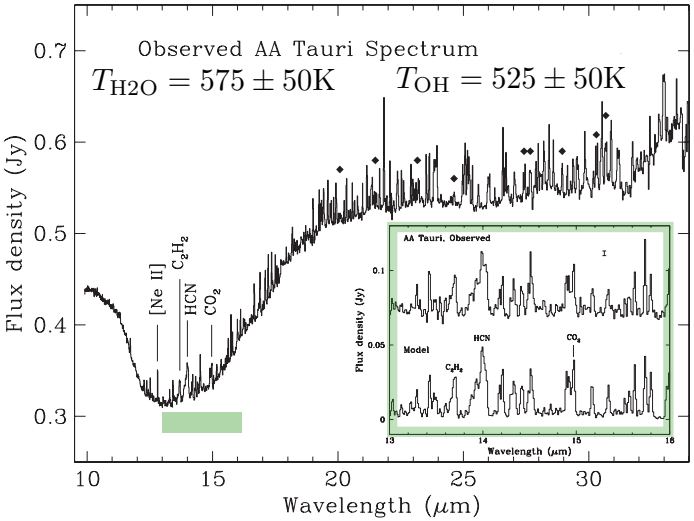


Warm molecular emission

Carr & Najita, 2008

Molecule	T (K)	N (10^{16} cm^{-2})	R* (AU)	Abundance to CO
H_2O	575 ± 50	65 ± 24	2.1 ± 0.1	1.3
OH	525 ± 50	8.1 ± 5.2	2.2 ± 0.1	0.18
HCN	650 ± 100	6.5 ± 3.3	0.60 ± 0.05	0.13
C_2H_2	650 ± 150	0.81 ± 0.32	0.60†	0.016
CO_2	350 ± 100	0.2 –13	1.2 ± 0.2	0.004 – 0.26
CO	900 ± 100	49 ± 16	0.7 ± 0.1	1.0

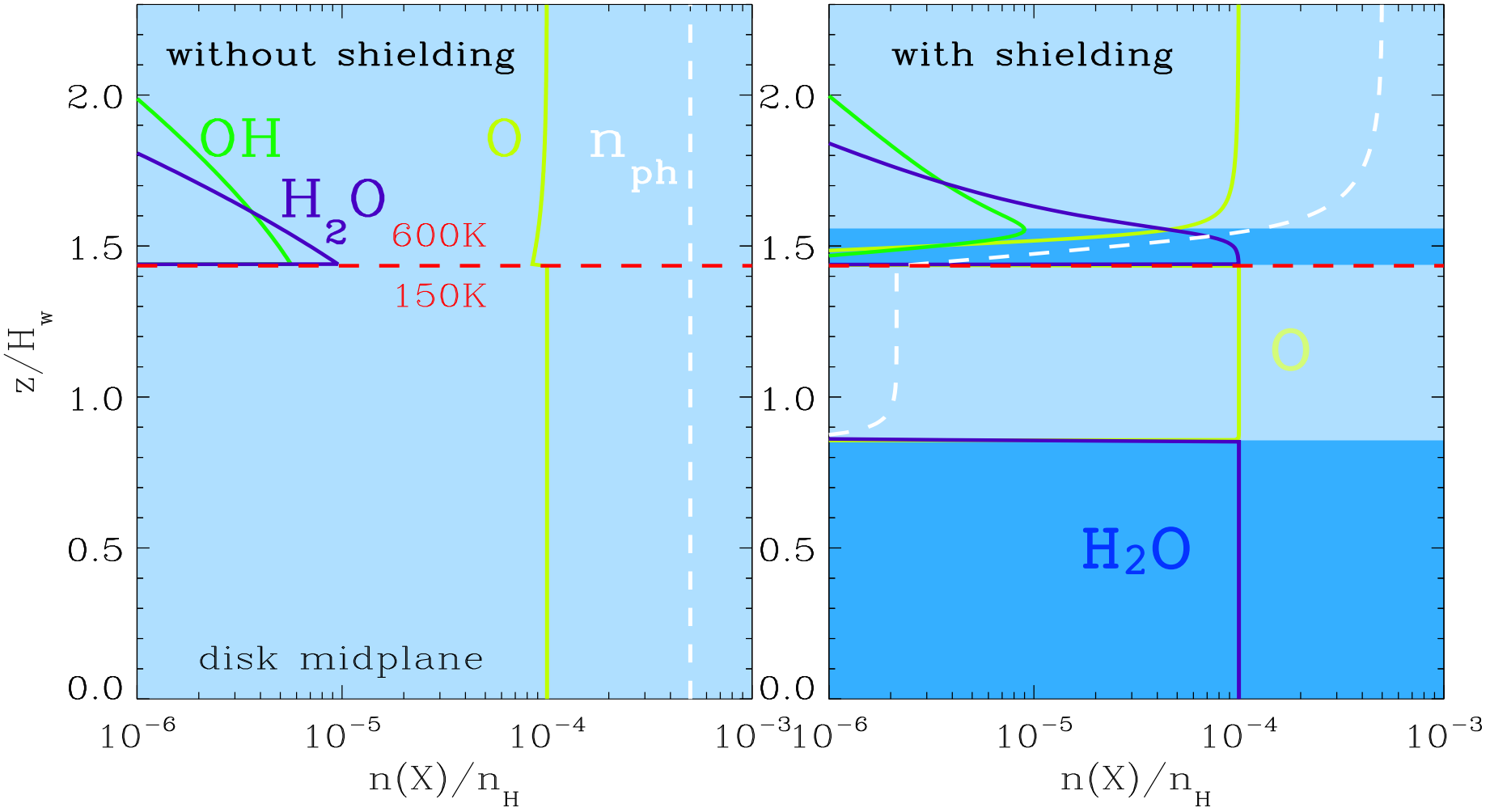
*The equivalent radius for the emitting area A ($R = [A/\pi]^{1/2}$). †Area was set to that derived for HCN.



Carr et al., 2004
Carr & Najita, 2011
Pascucci et al., 2009
Pontoppidan et al., 2010a, 2010b
Salyk et al., 2011
Najita et al., 2013

Water chemistry & self-shielding

Bethell & Bergin, 2009



$$O \underset{UV}{\overset{H_2}{\rightleftharpoons}} OH \underset{UV}{\overset{H_2}{\rightleftharpoons}} H_2O$$

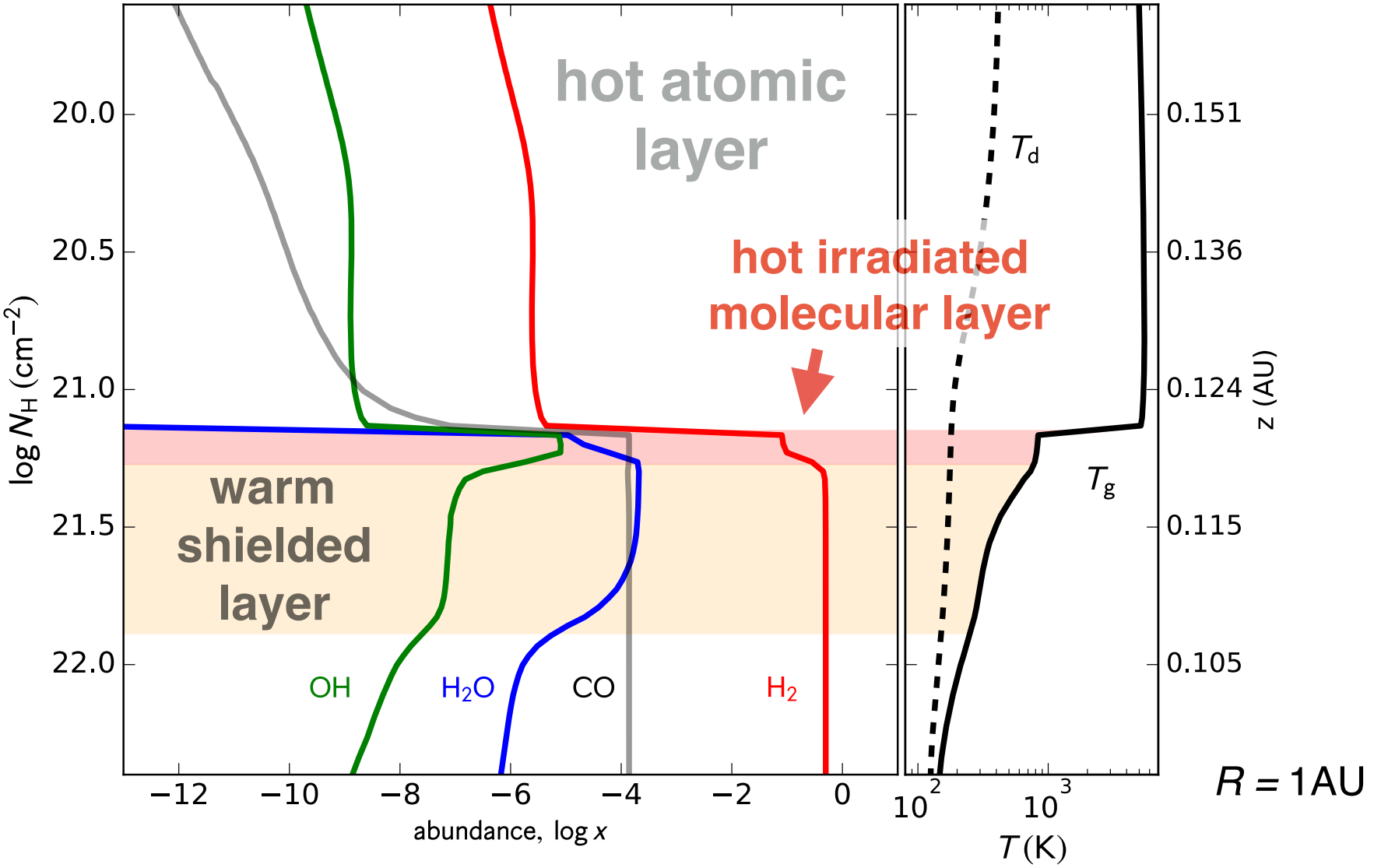
Our thermal-chemical disk model

Glassgold, Najita, & Igea, 1997
Glassgold, Najita, & Igea, 2004
Glassgold, Meijerink, & Najita, 2009
Adamkovics, Glassgold, & Meijerink, 2011

- **X-ray and FUV irradiated gas in a T Tauri disk**
- **Dust: H_2 formation, FUV opacity, and thermal accommodation**
- **~120 species, ~1200 reactions**
- **Photo-rates: use local FUV field, molecular cross sections, shielding**
- **Python codebase:**
  - Kinetics "pre-processor" of chemical rate equations
  - Modules for disk `structure`, `heating`, `cooling` & `FUV`
  - Wrapper to C-library for `LSODE` in `ODEPACK`

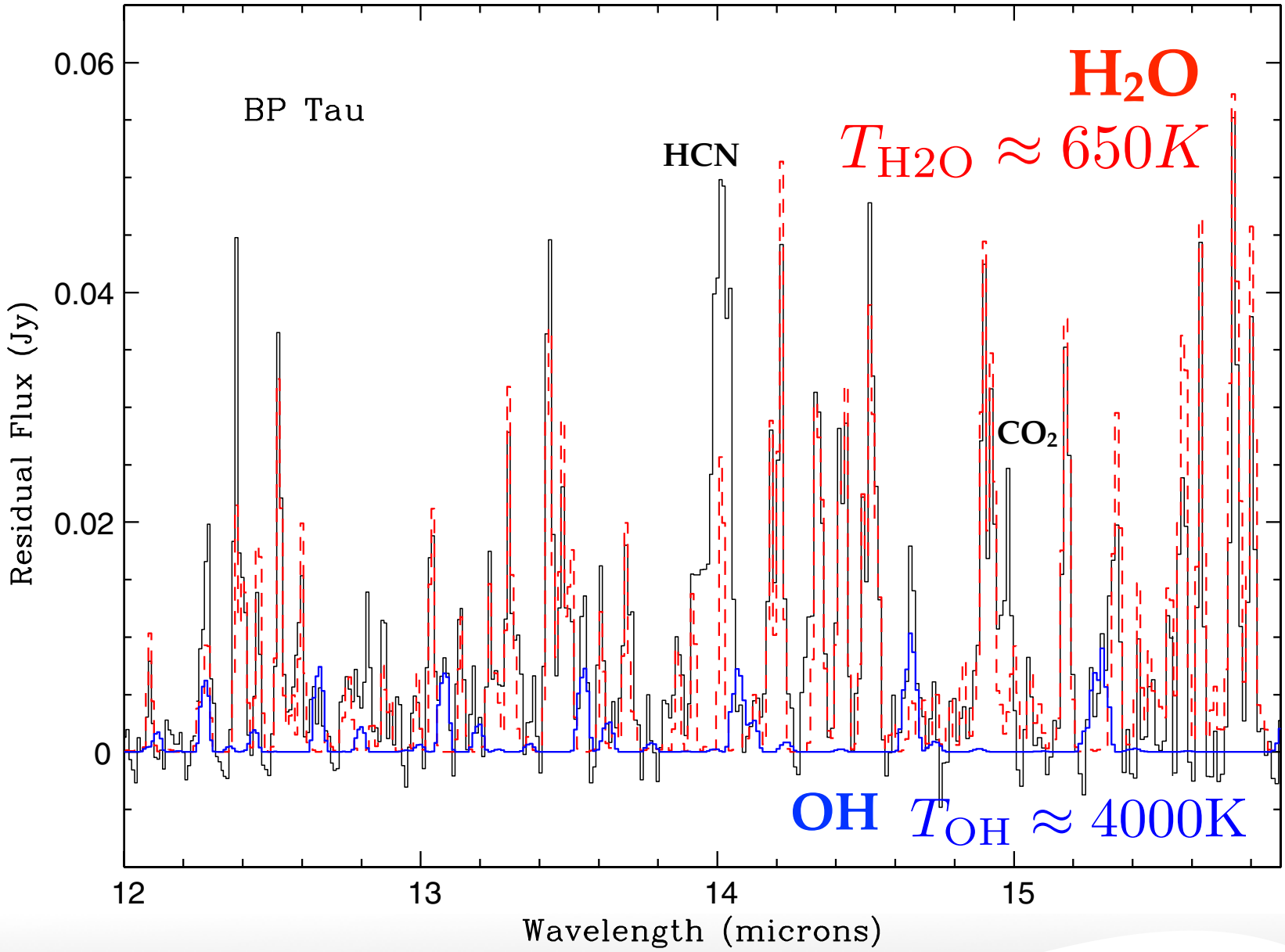
Layered disk gas

Ádámkovics, Glassgold, & Najita, 2014



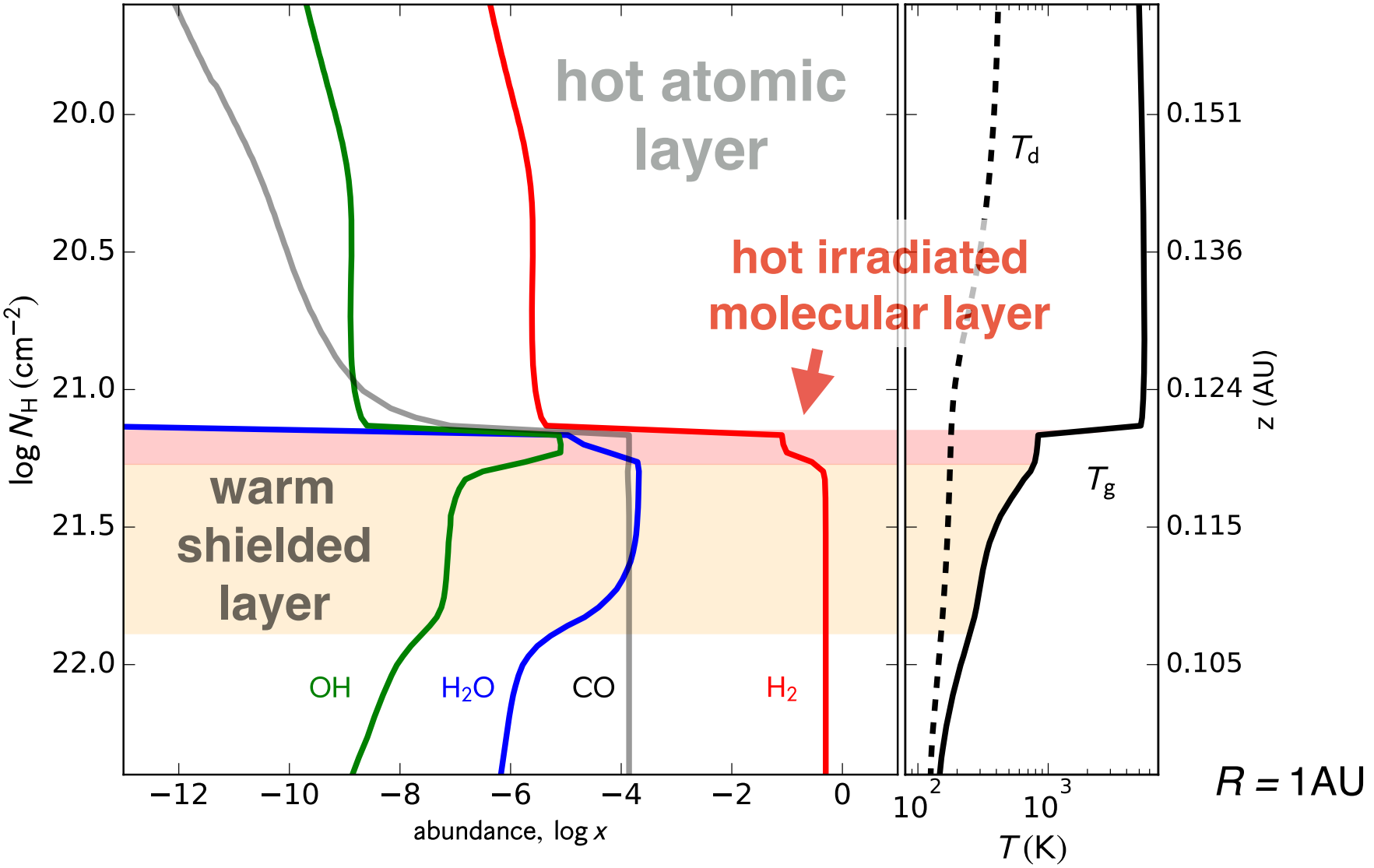
Observations

Carr & Najita, 2011; 2014



Layered disk gas

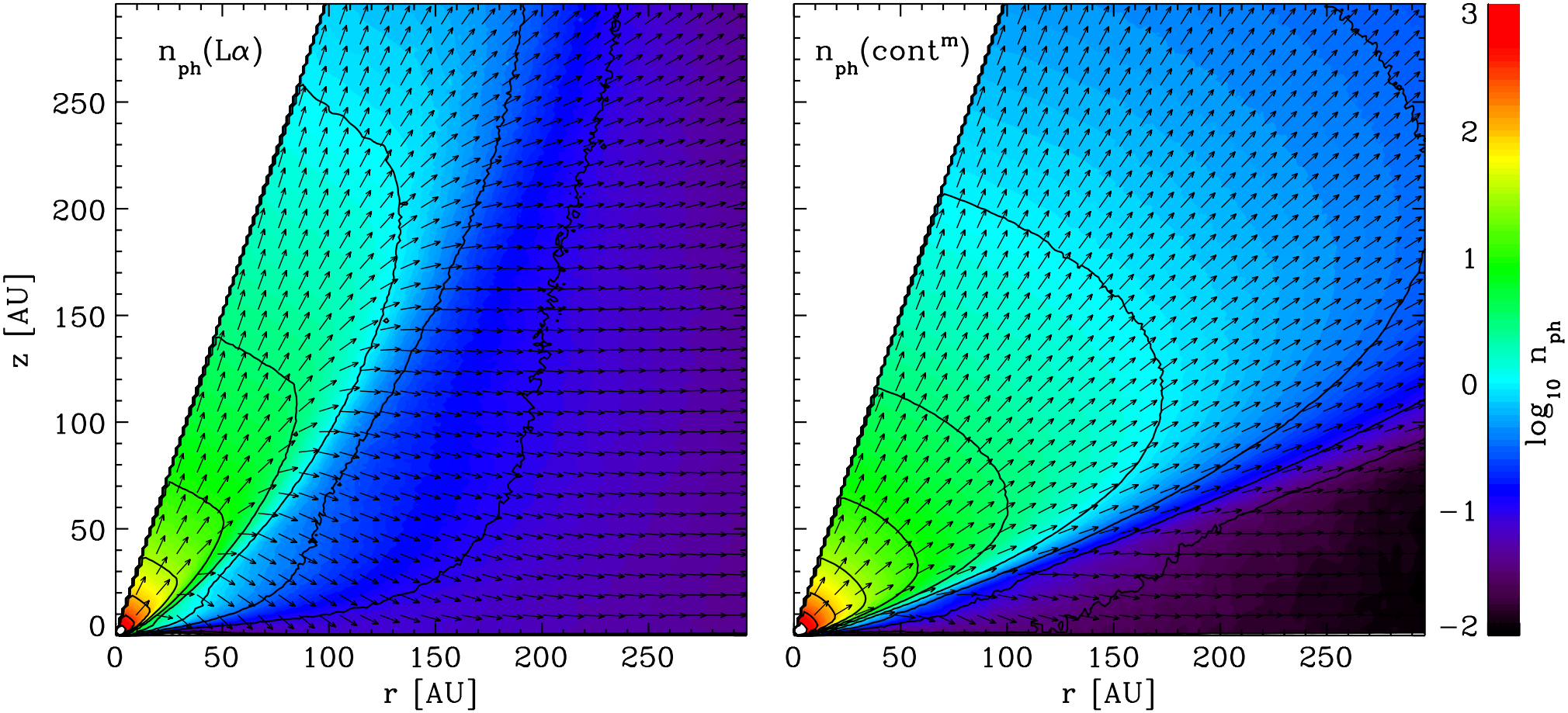
Ádámkovics, Glassgold, & Najita, 2014



FUV is important

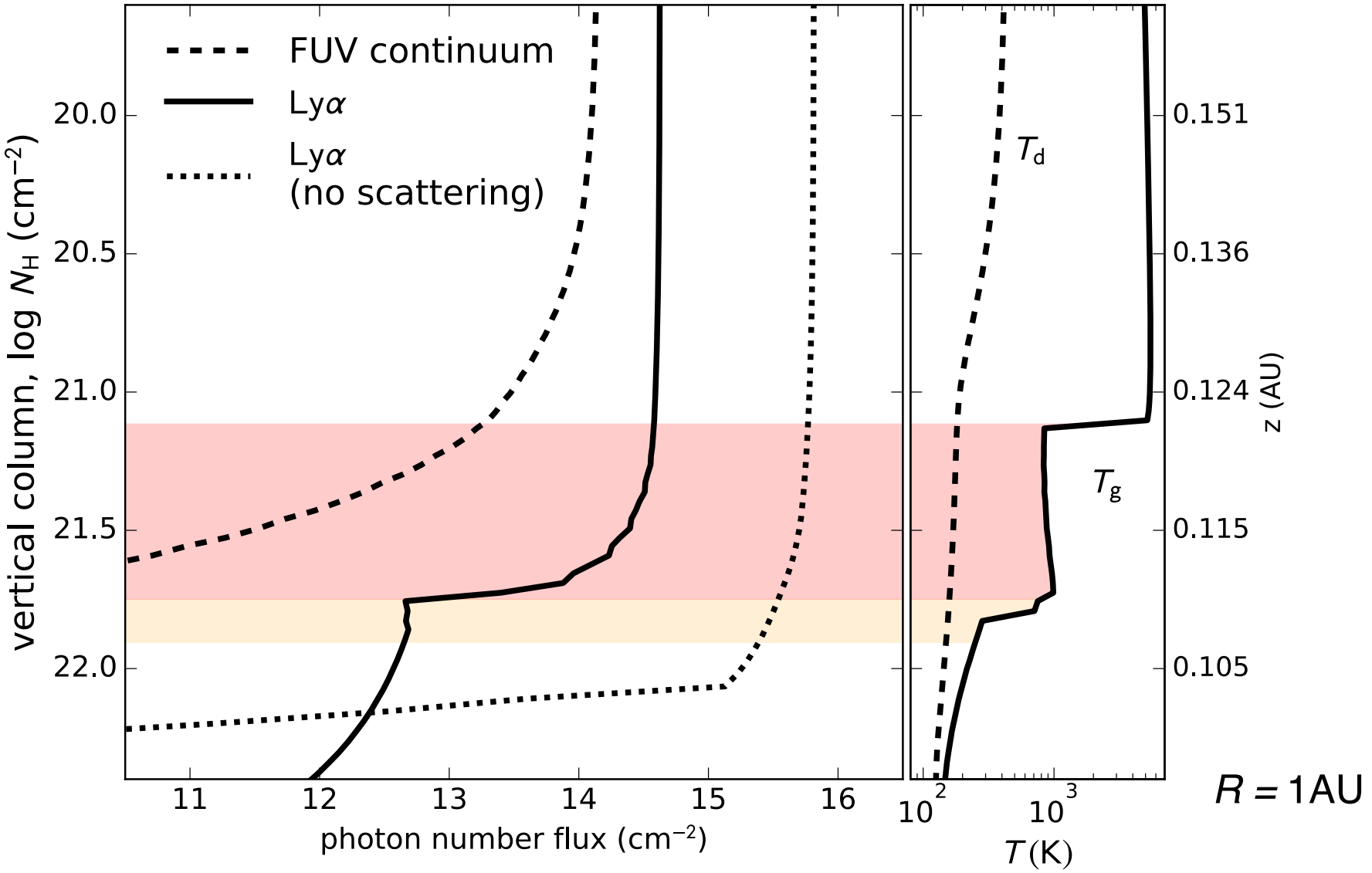
FUV radiative transfer: scattered Lya

Bethell & Bergin, 2011



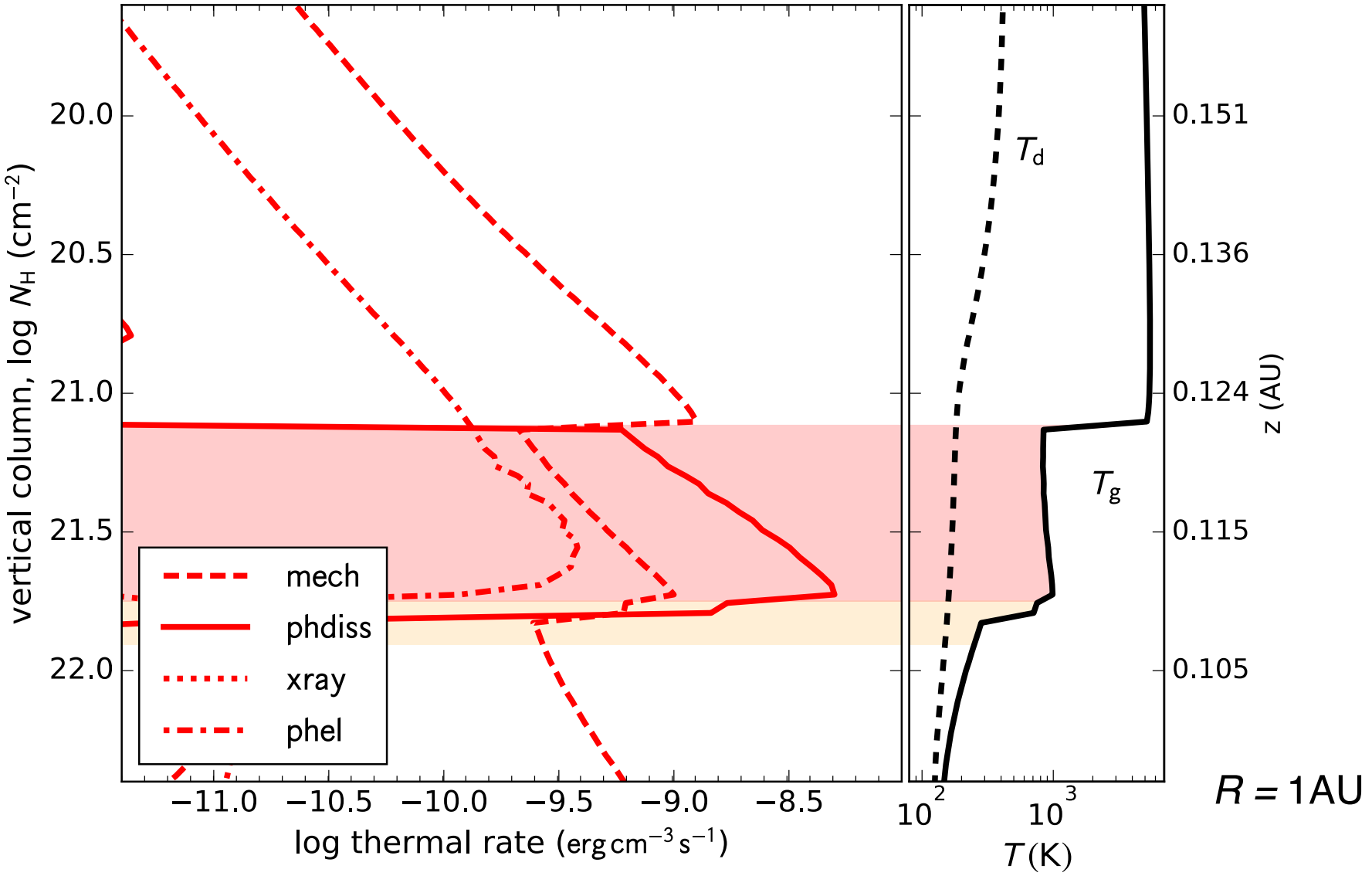
FUV continuum and Lyα

Ádámkovics, Najita, & Glassgold, 2016



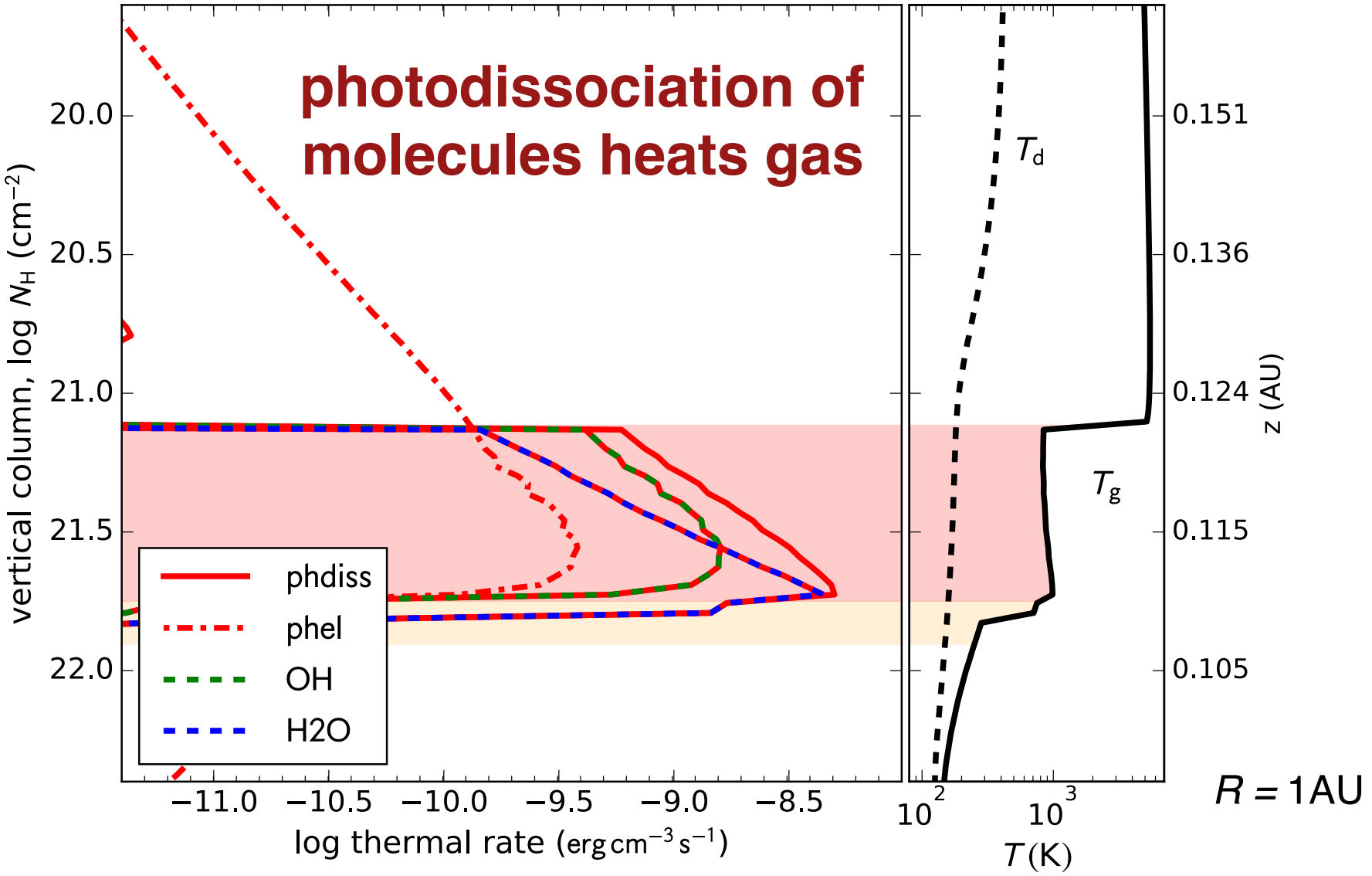
Thermal processes: heating

Ádámkovics, Najita, & Glassgold, 2016



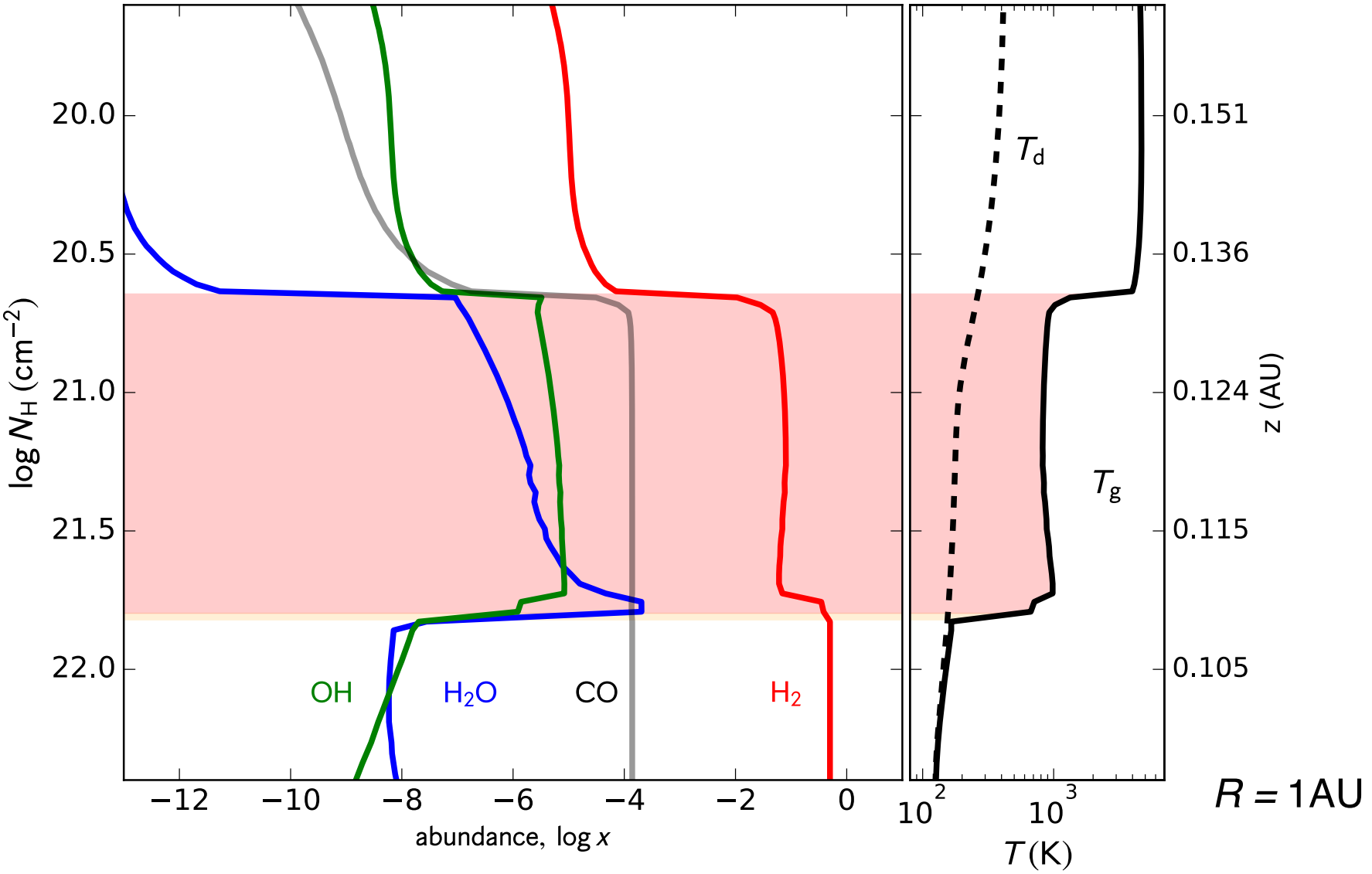
Photochemical heating

Glassgold & Najita, 2015



Hot molecular gas

Ádámkovics, Najita, & Glassgold, 2016

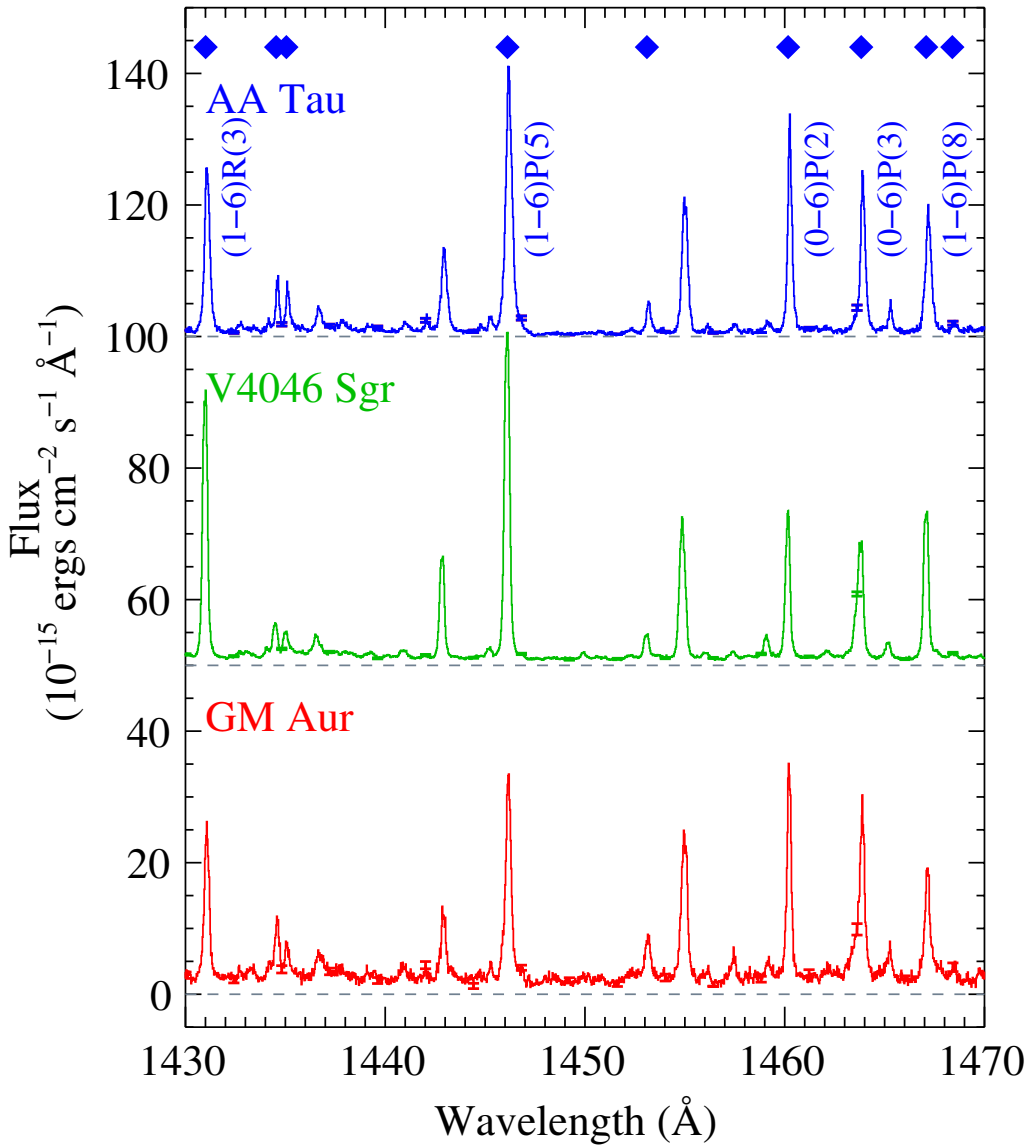


Fluorescent H_2 Emisssion

Ardila et al., 2002; Herczeg et al., 2002

France et al., 2012

- **H_2 excitation ~ 2500 K**
- **Hot H_2 pumped by Lyα**
- **emitting region < 0.5 AU**



H2 Fluorescent Emission

France et al., 2012

Target	FWHM$_{[1,7]}$[a] (km s^{-1})	$\langle R_{H_2}\rangle_{[1,7]}$[a] (AU)
AA Tau	62 ± 4	0.69 ± 0.08
AK Sco	57 ± 35	1.25 ± 0.77
BP Tau	70 ± 6	0.13 ± 0.02
CS Cha	18 ± 7	9.00 ± 4.55
CV Cha	22 ± 30	4.75 ± 3.88
DE Tau	55 ± 6	0.23 ± 0.04
DF Tau A[f]	64 ± 7	0.16 ± 0.03
DK Tau A[f]	55 ± 2	0.24 ± 0.02
DM Tau	27 ± 5	0.80 ± 0.24
DN Tau	71 ± 19	0.09 ± 0.04
DR Tau	35 ± 7	2.09 ± 0.62
GM Aur	41 ± 11	1.68 ± 0.65
HD 104237	94 ± 77	0.10 ± 0.07
HD 135344B	26 ± 1	...
HN Tau A[f]	61 ± 17	0.47 ± 0.18
IP Tau[f]	102 ± 29	0.17 ± 0.07
LkCa 15	53 ± 3	0.62 ± 0.06
RECX 11	54 ± 3	0.85 ± 0.08
RECX 15[f]	41 ± 4	0.62 ± 0.10
RU Lupi	40 ± 2	0.30 ± 0.03
RW Aur A[g]	...	...
SU Aur	49 ± 6	2.67 ± 0.58
SZ 102	47 ± 7	...
TW Hya	18 ± 2	...
UX Tau A	29 ± 3	1.76 ± 0.33
V4046 Sgr	45 ± 1	0.95 ± 0.06
V836 Tau	47 ± 20	0.99 ± 0.50

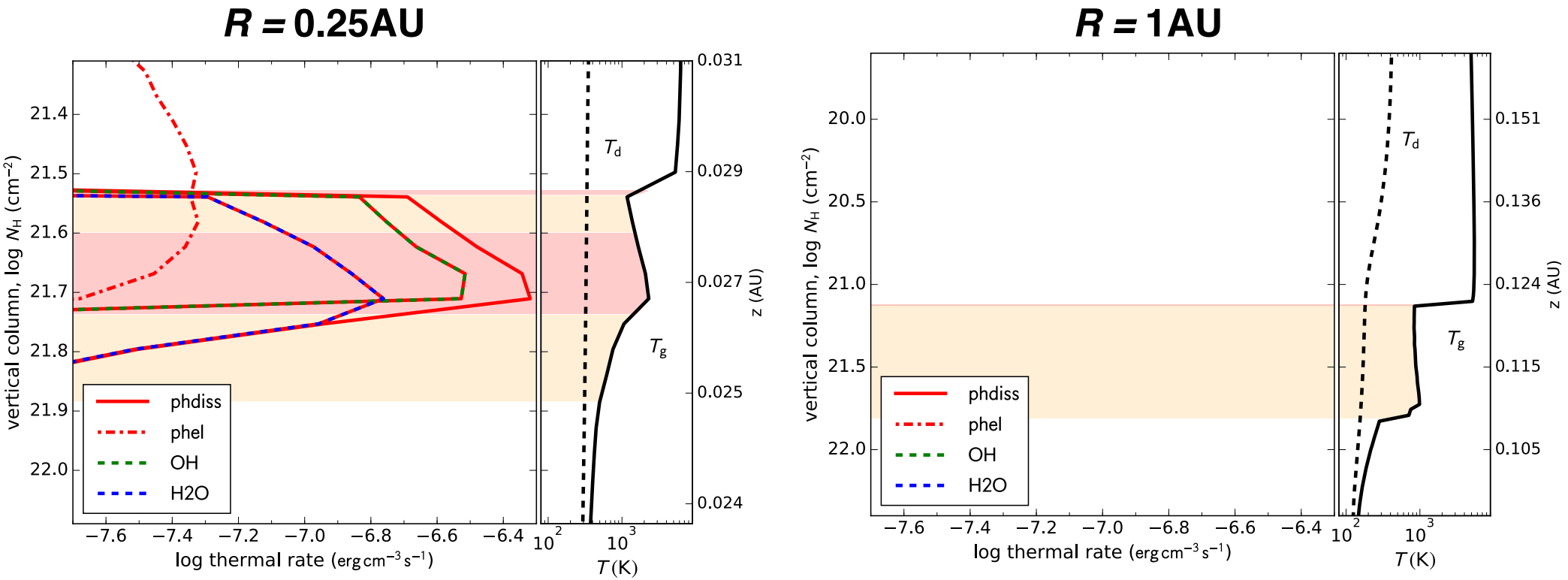
For the case of H_2 in a circumstellar disk, we define a simple metric to characterize the average H_2 radius, $\langle R_{H_2}\rangle$,

$$\langle R_{H_2}\rangle_m = GM_* \left(\frac{2\sin(i)}{\mathrm{FWHM}_m} \right)^2 , \qquad (2)$$

where M_* is the stellar mass, i is the inclination angle, and FWHM_m is the mean of the Gaussian FWHMs for a given progression m. This definition of the average molecular radius

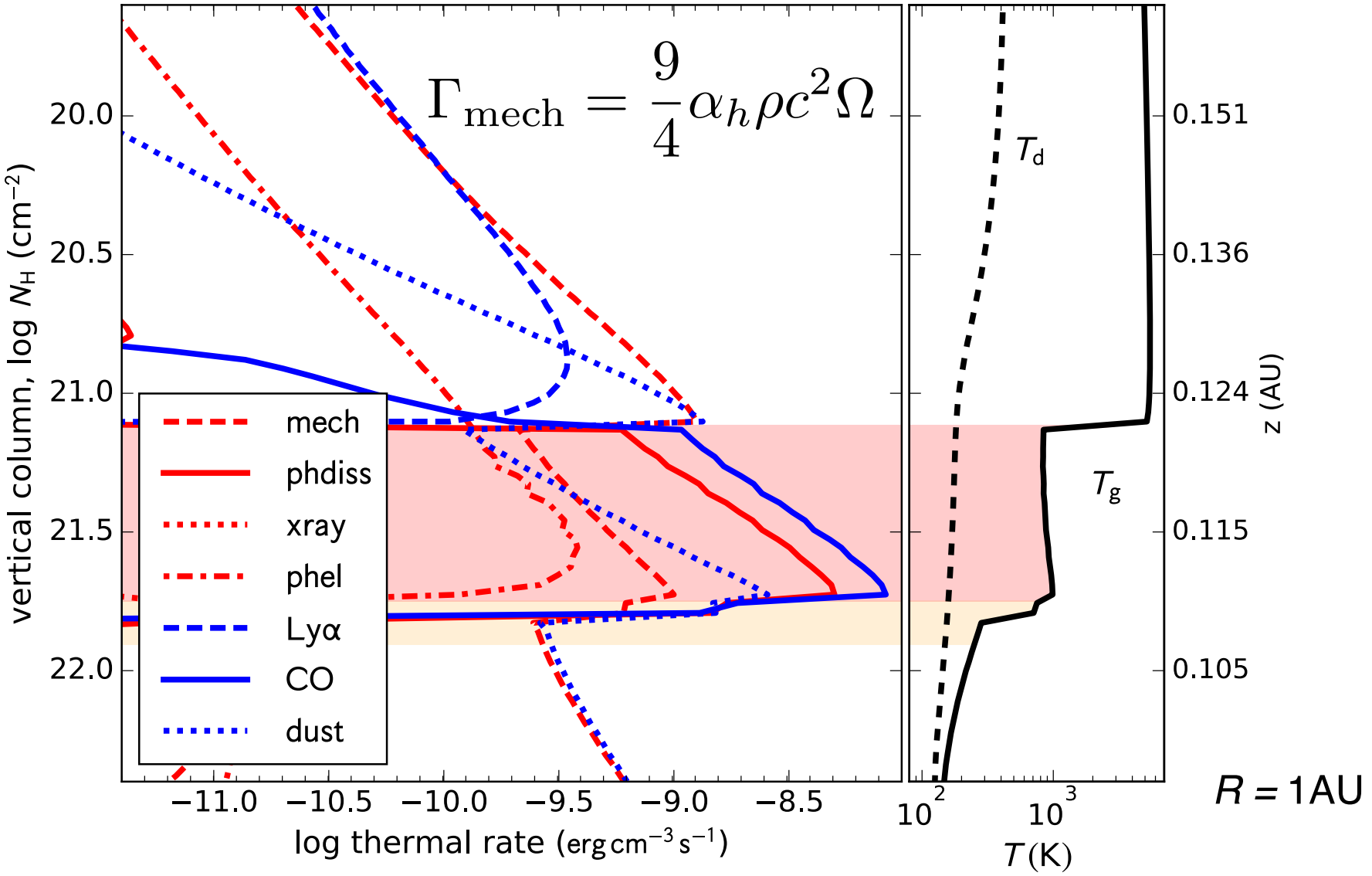
Fluorescent H_2 Emisssion

Ádámkovics, Najita, & Glassgold, 2016

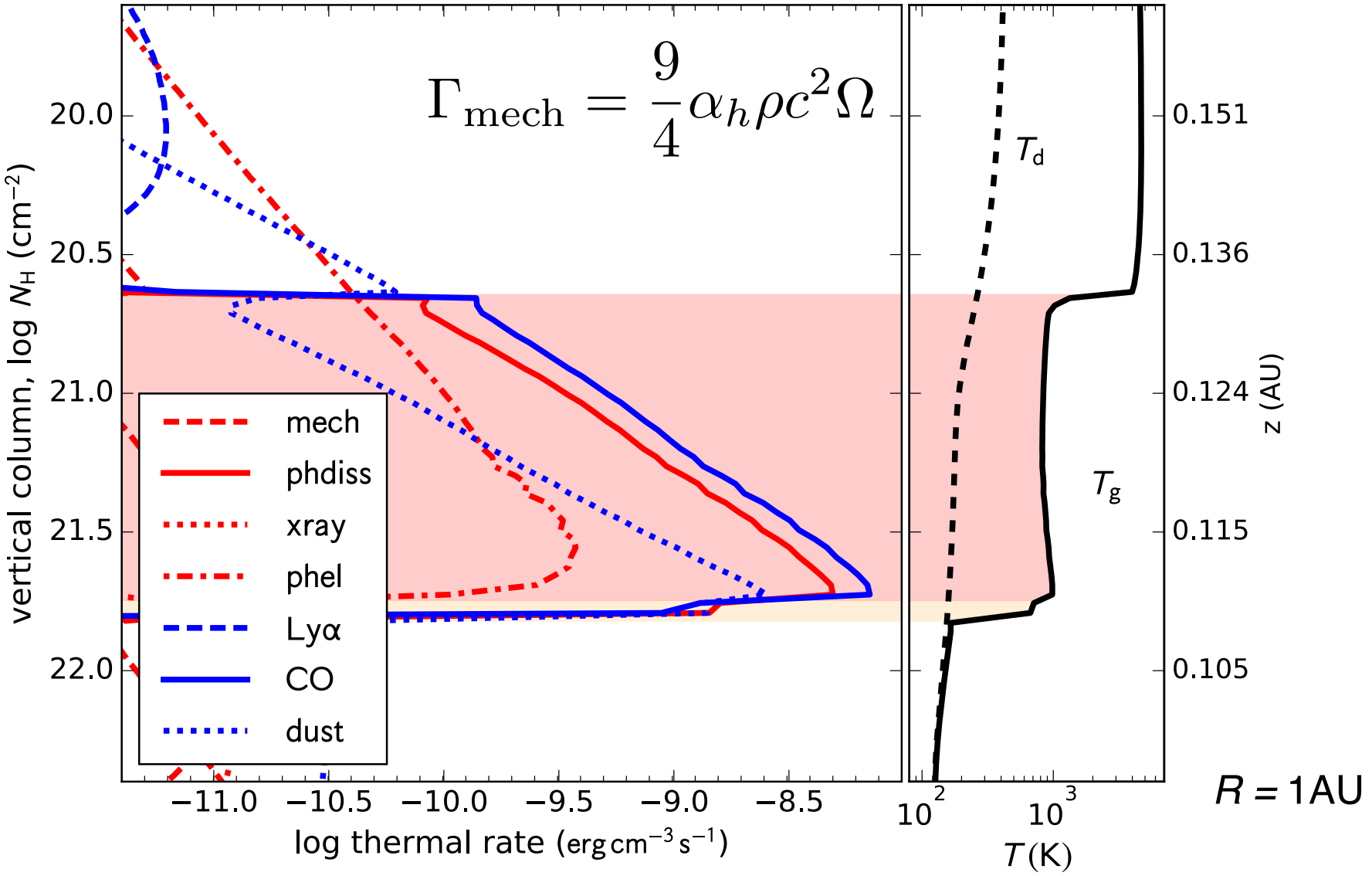


Dissociation of H_2O & OH by Lyα heats gas,
Hot H_2 for fluorescent emission can be thermally pumped

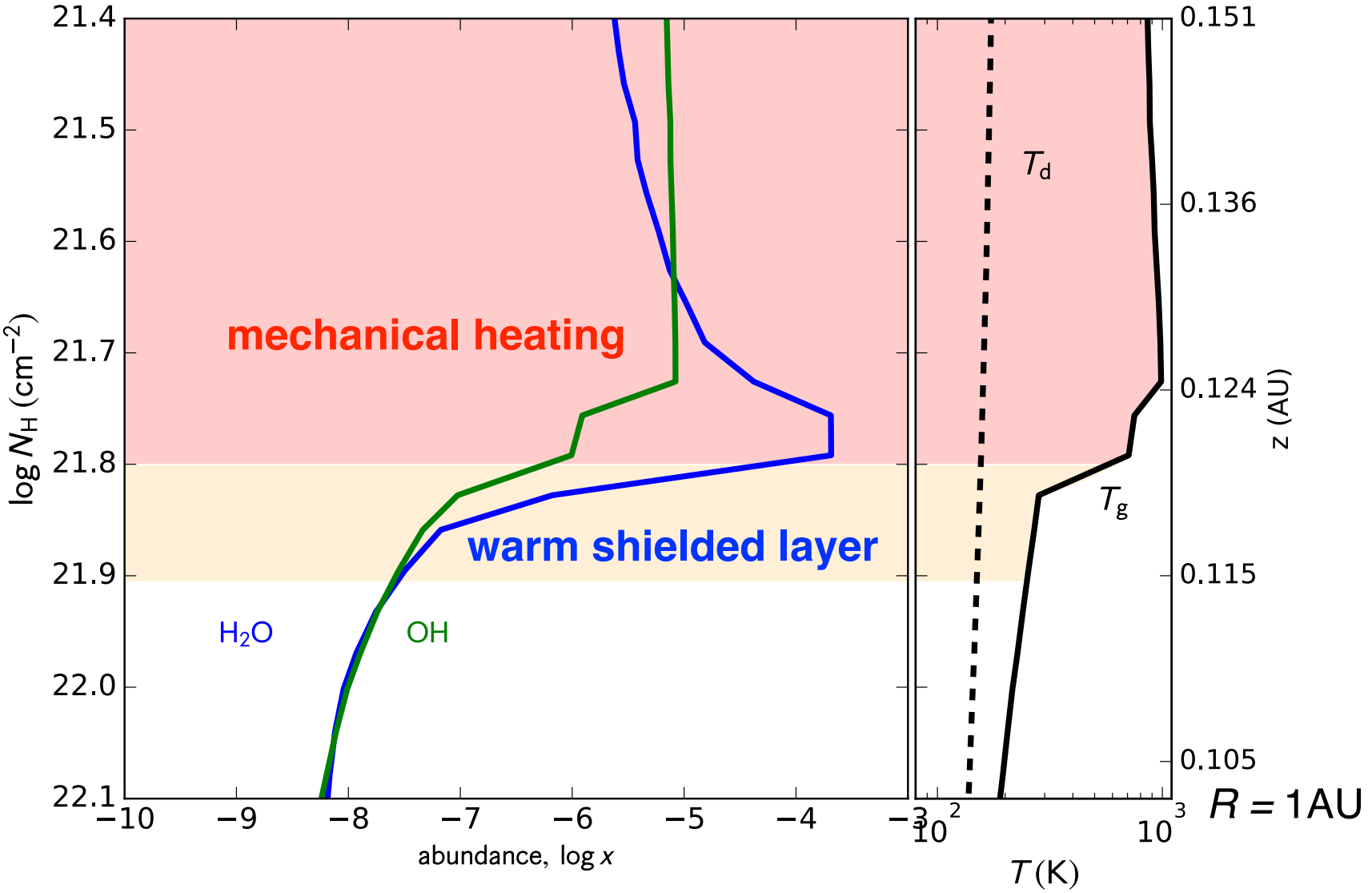
Role of mechanical heating: hot irradiated layer



Role of mechanical heating: hot irradiated layer



Role of mechanical heating: warm shielded layer



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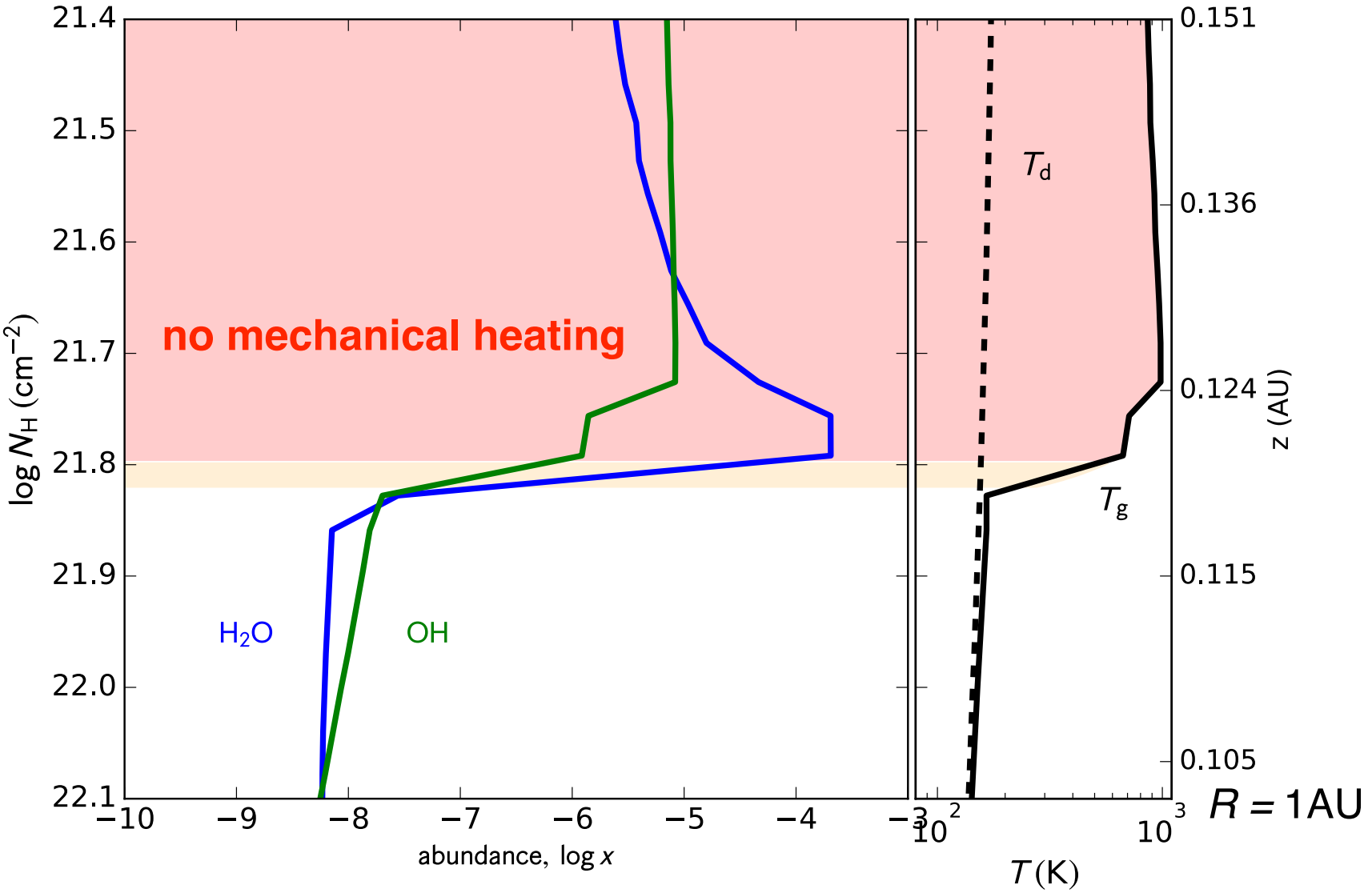
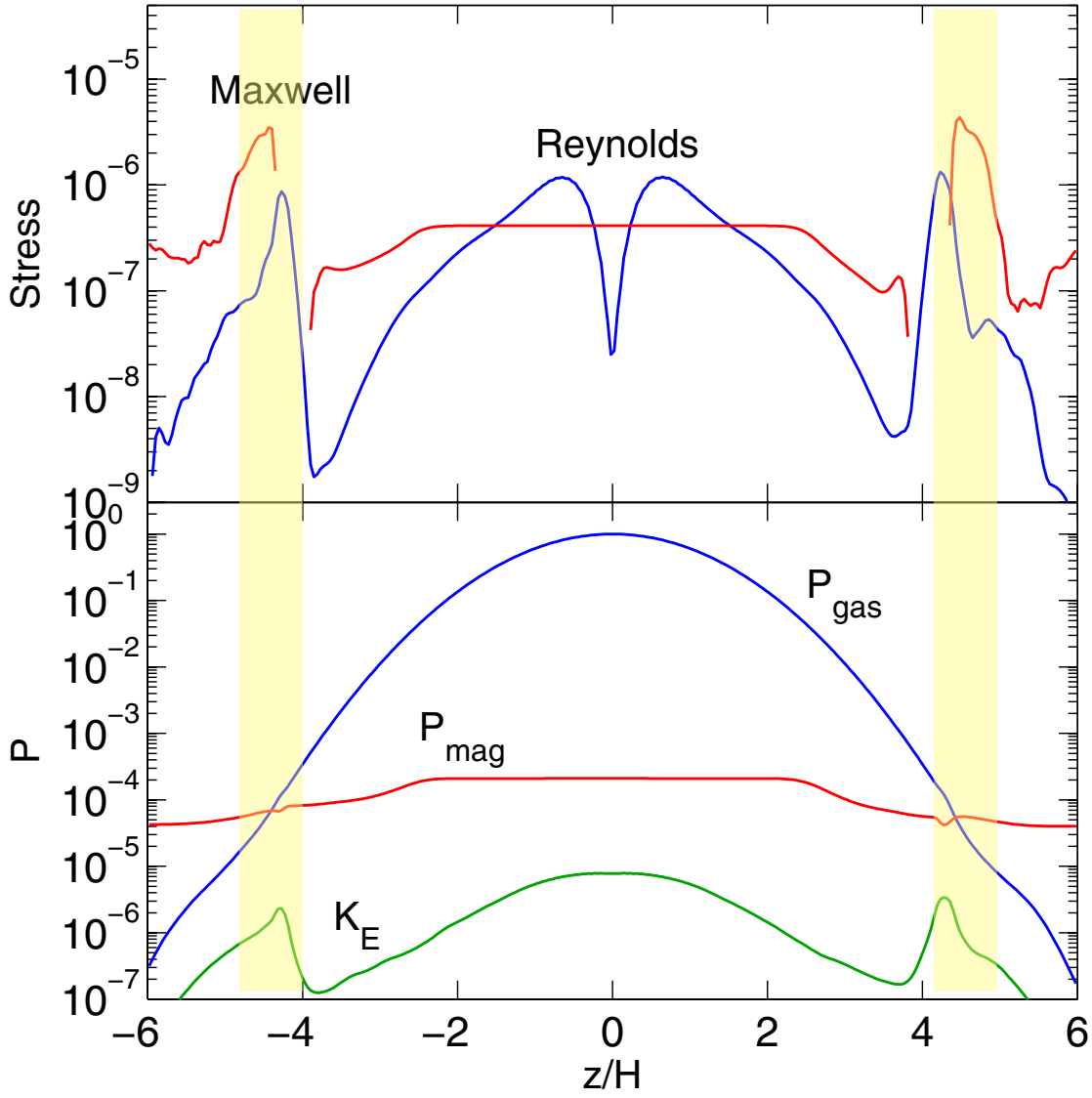


Turbulent (mechanical) heating

Bai & Stone, 2013



$R = 1\text{AU}$

Summary

Some roles of water in the inner region of disks:

1. **FUV photochemical (radiative) heating of hot irradiated layer**
2. **Diagnostic of mechanical heating of warm molecular layer**
3. **Shielding mid-plane from Lyα and FUV continuum radiation**

Thank you!

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