The Effect of FUV Radiation and Grain Surface Chemistry on Hydride Emission from Dense Shocks

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Michael Turner (SJSU) with support from NASA/ADAP program

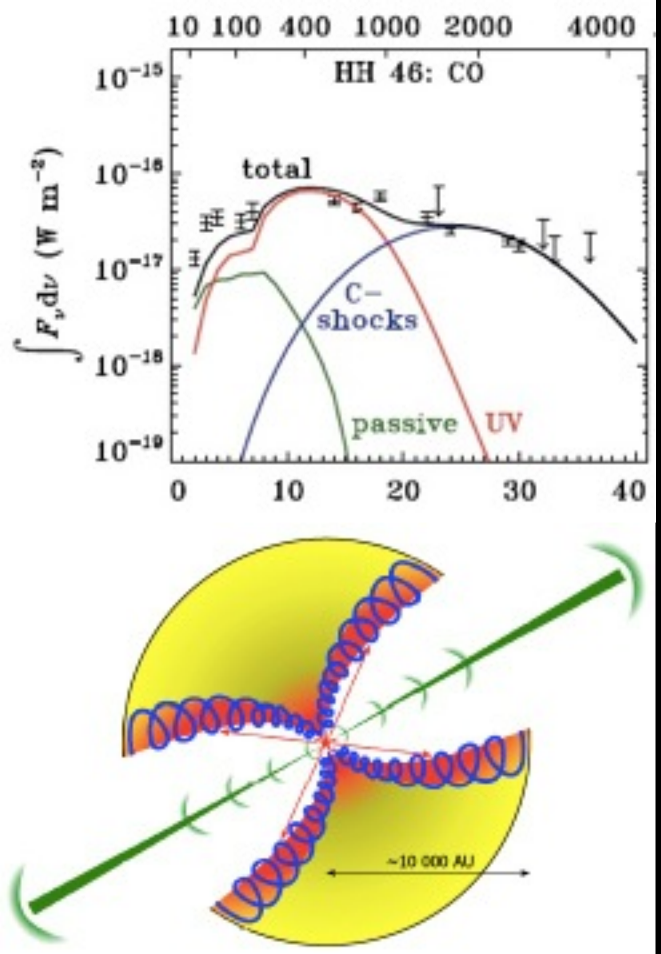
The Hydride Toolbox

Paris, 12-15 Dec 2016

Outline

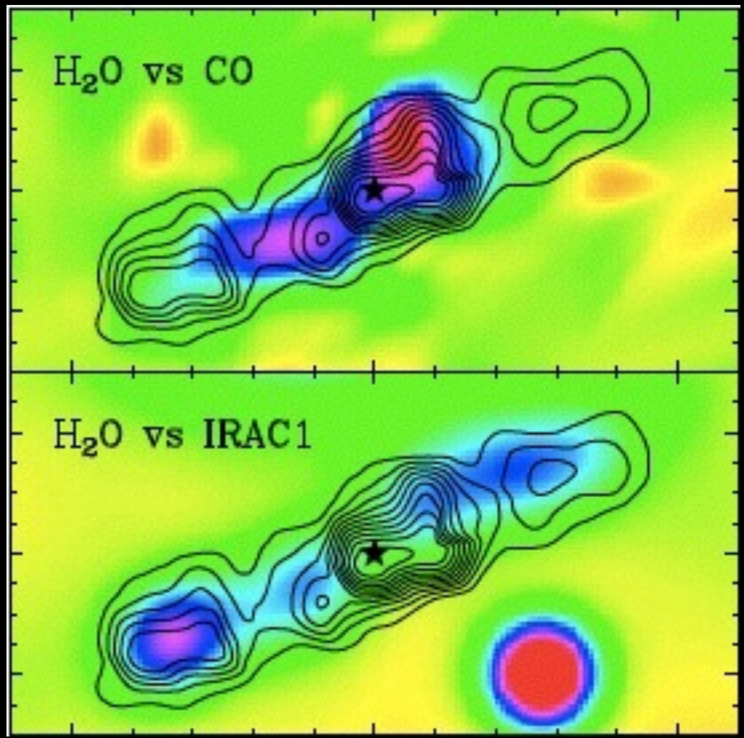
- Shock motivation
- Characteristics of main types
- The role of FUV - self-consistent modeling
  - Can we explain low H_2O abundances?
  - Can we explain low H_2O/OH?
- Model spectra and potential observations

Shocks are ubiquitous in protostars

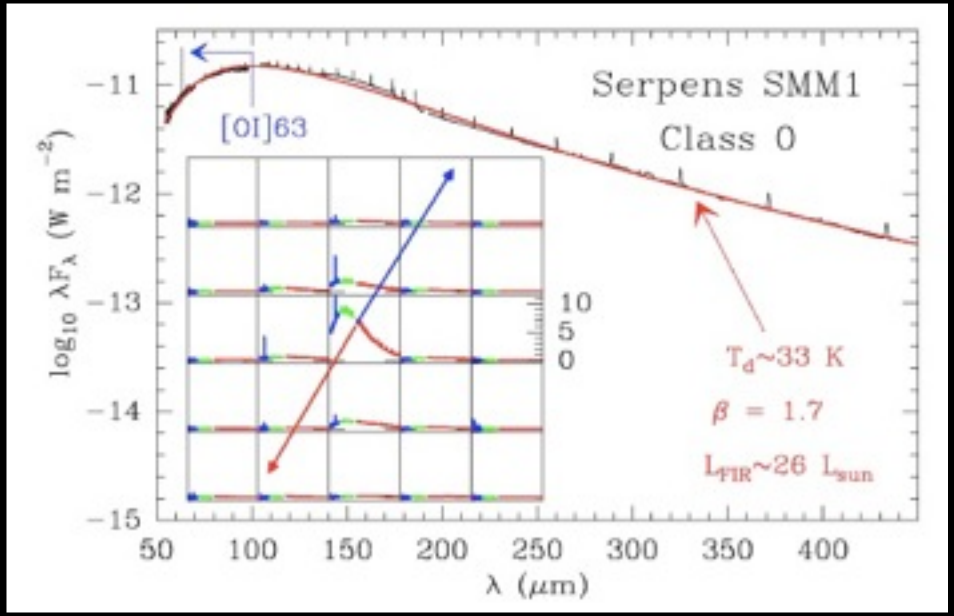


HH46 CO ladder

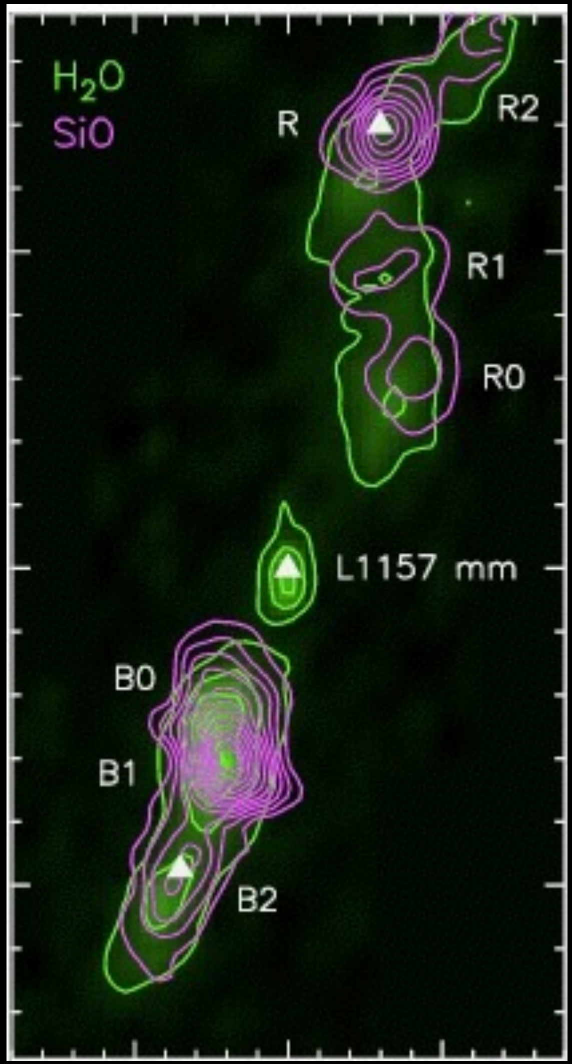
Visser et al. 2011



HH211 Tafalla et al. 2013
x(H_2O) ~ 3×10^{-7} at high nT~10^9

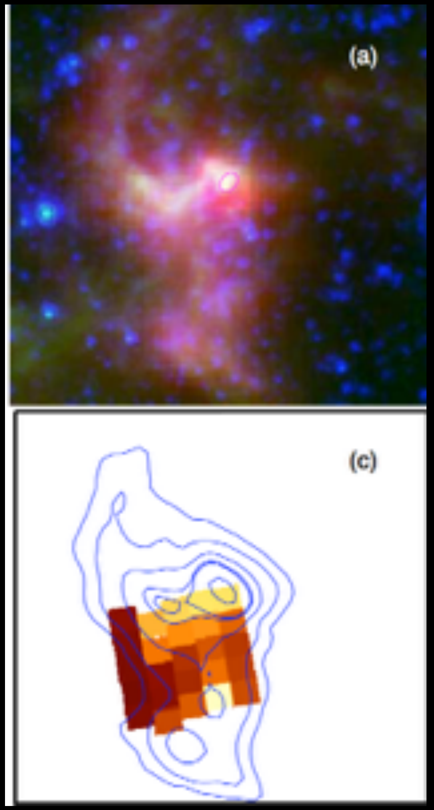


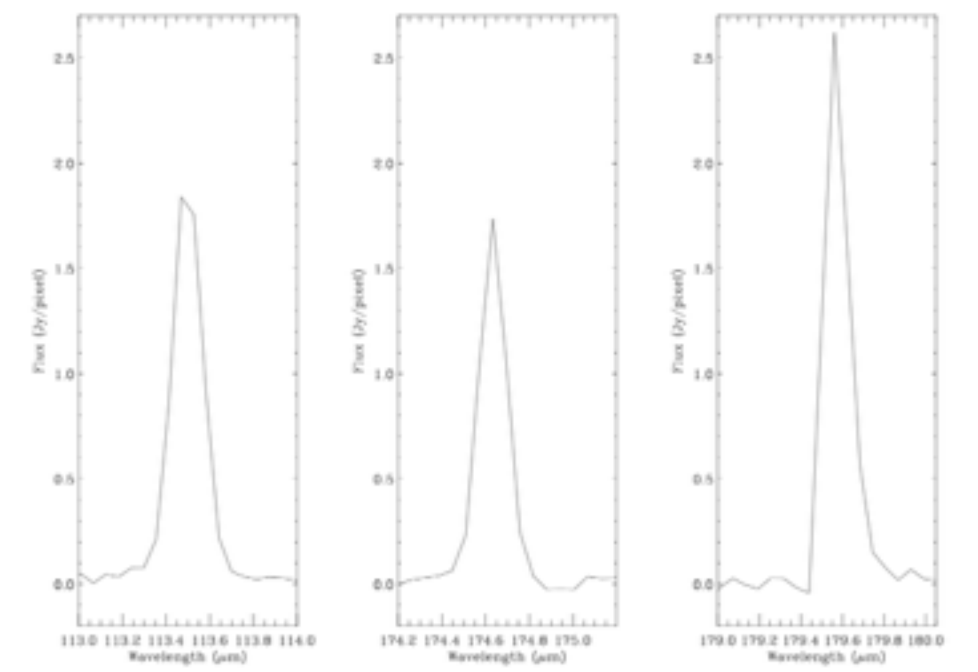
Ser SMM1 Goicoechea et al. 2013
x(H_2O) < 2×10^{-6}, T ~ 800 K



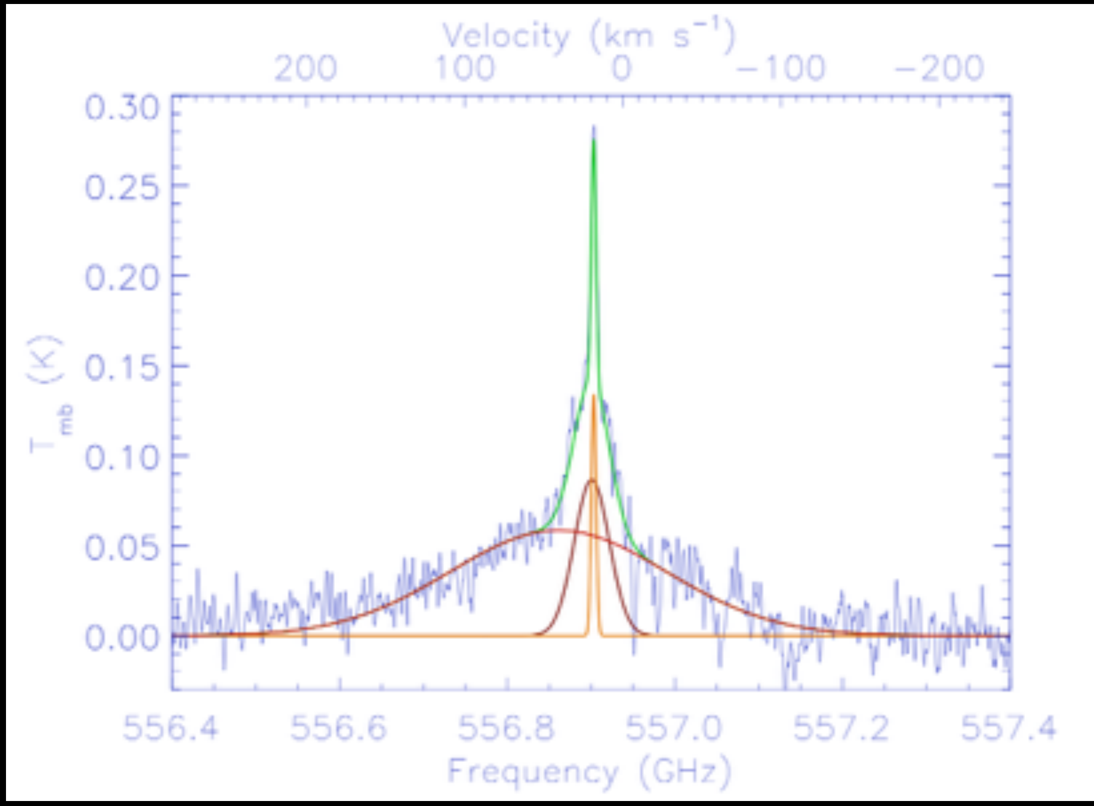
L1448 Santangelo et al. 2013
x(H_2O) ~ 10^{-6} - 10^{-5}
T ~ 1100 K

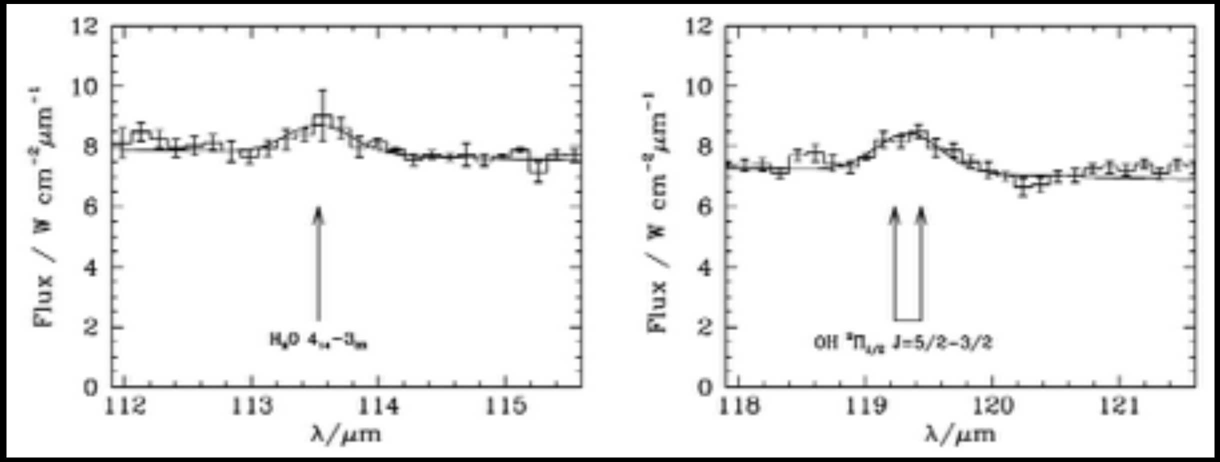
......supernovae



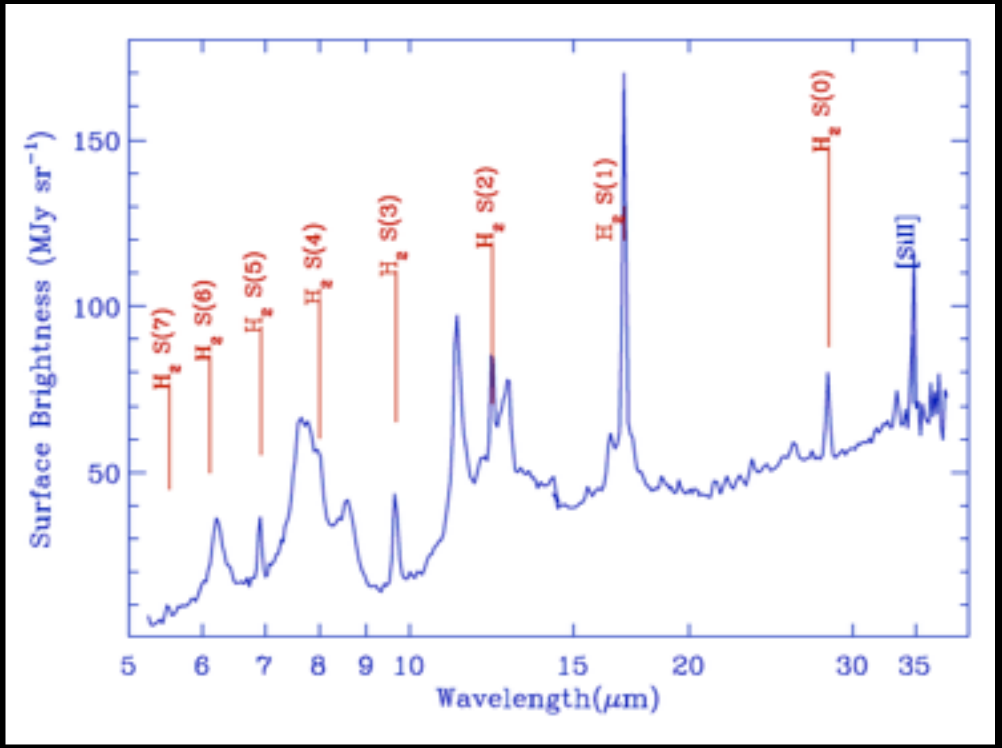


G347.9+0.2 Rho et al. 15

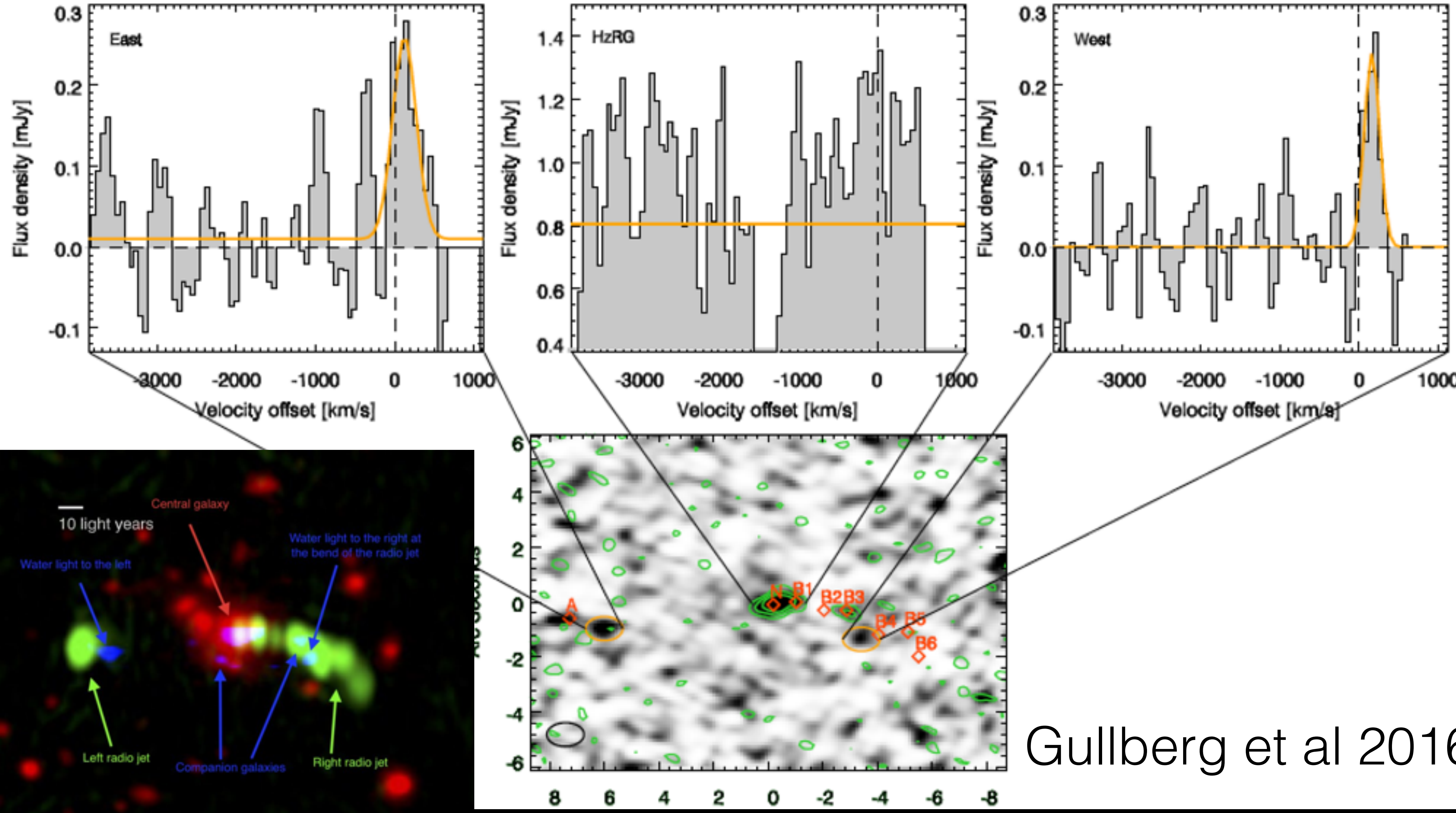




IC443, Snell et al. 05



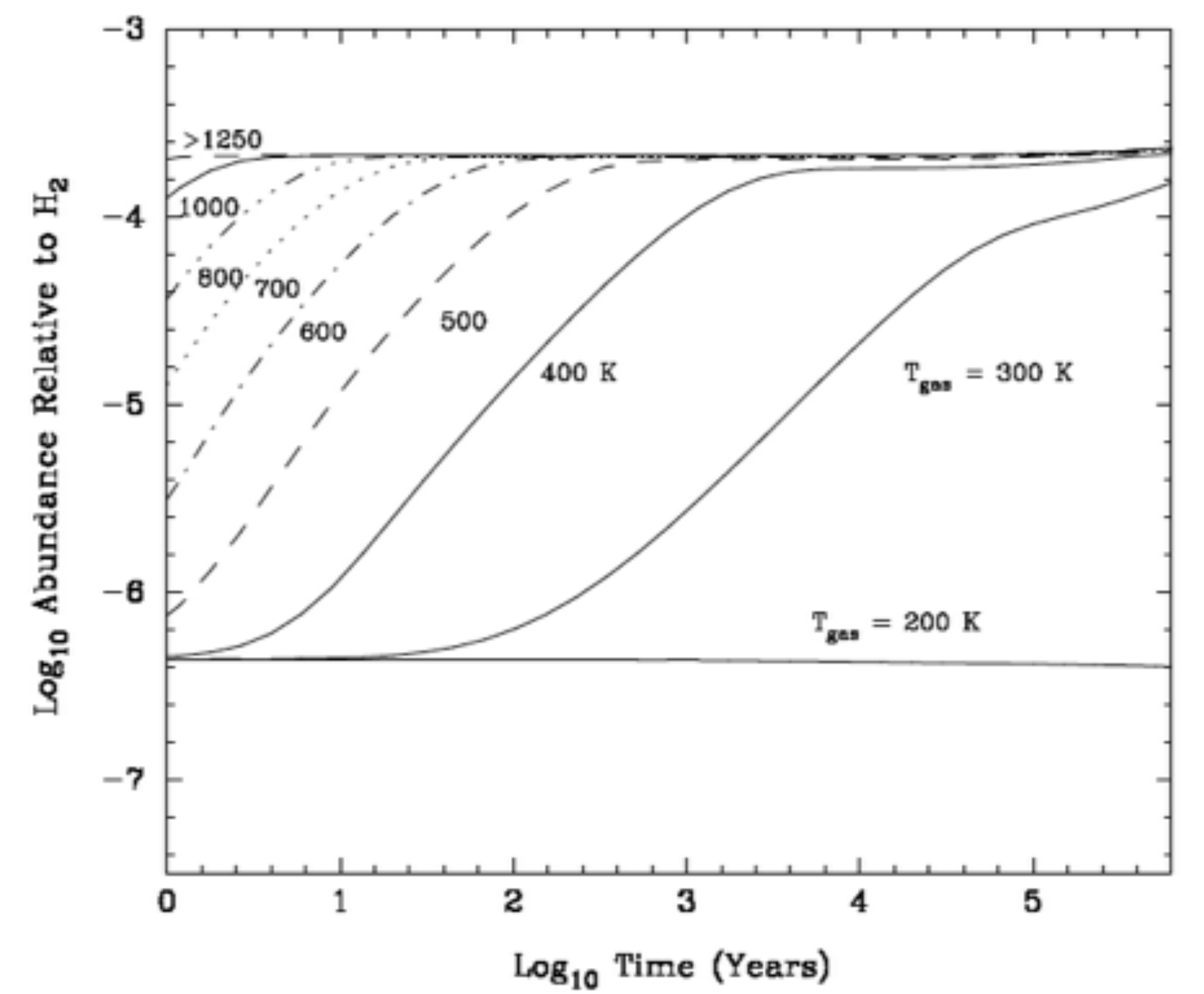
…. and even distant galaxies H_2O Emission at z=2.2



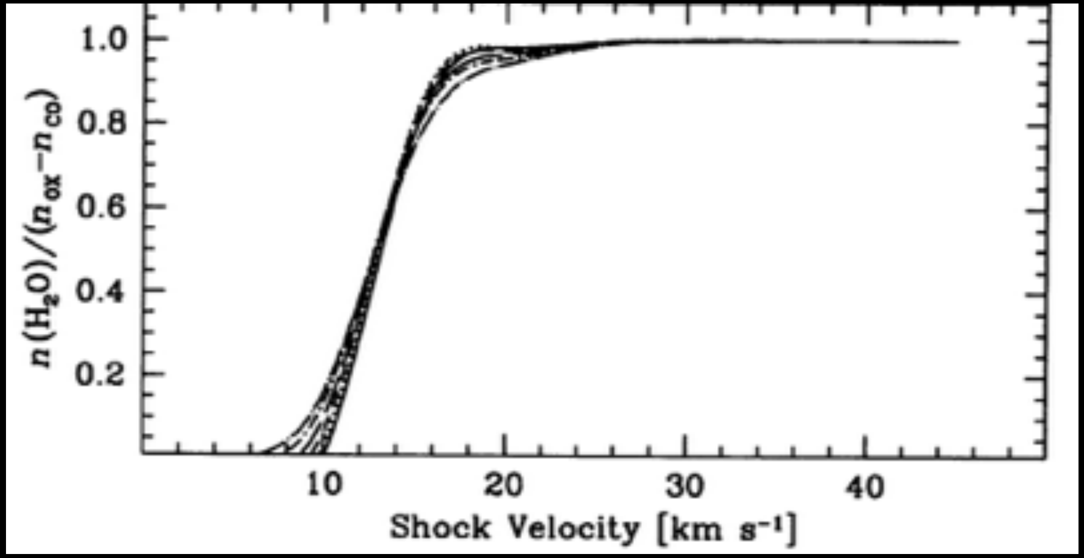
Gullberg et al 2016

Got Warm Gas?

Time scale to make water is very short in warm gas ..... regardless of why it's warm



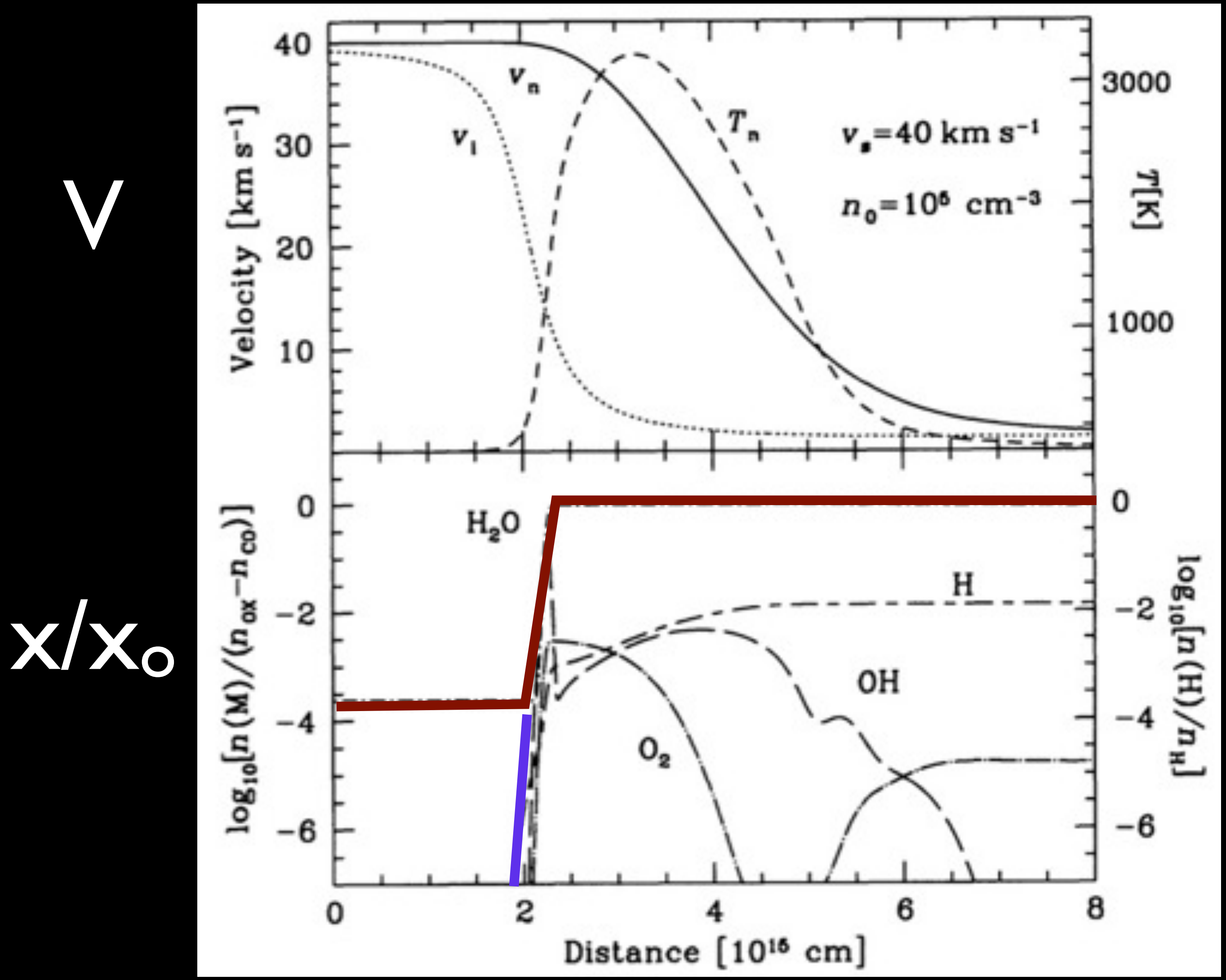
Bergin, Melnick & Neufeld 1998



Kaufman & Neufeld 1996

ISO, SWAS, WISH expected to find high water abundances in shocked gas!

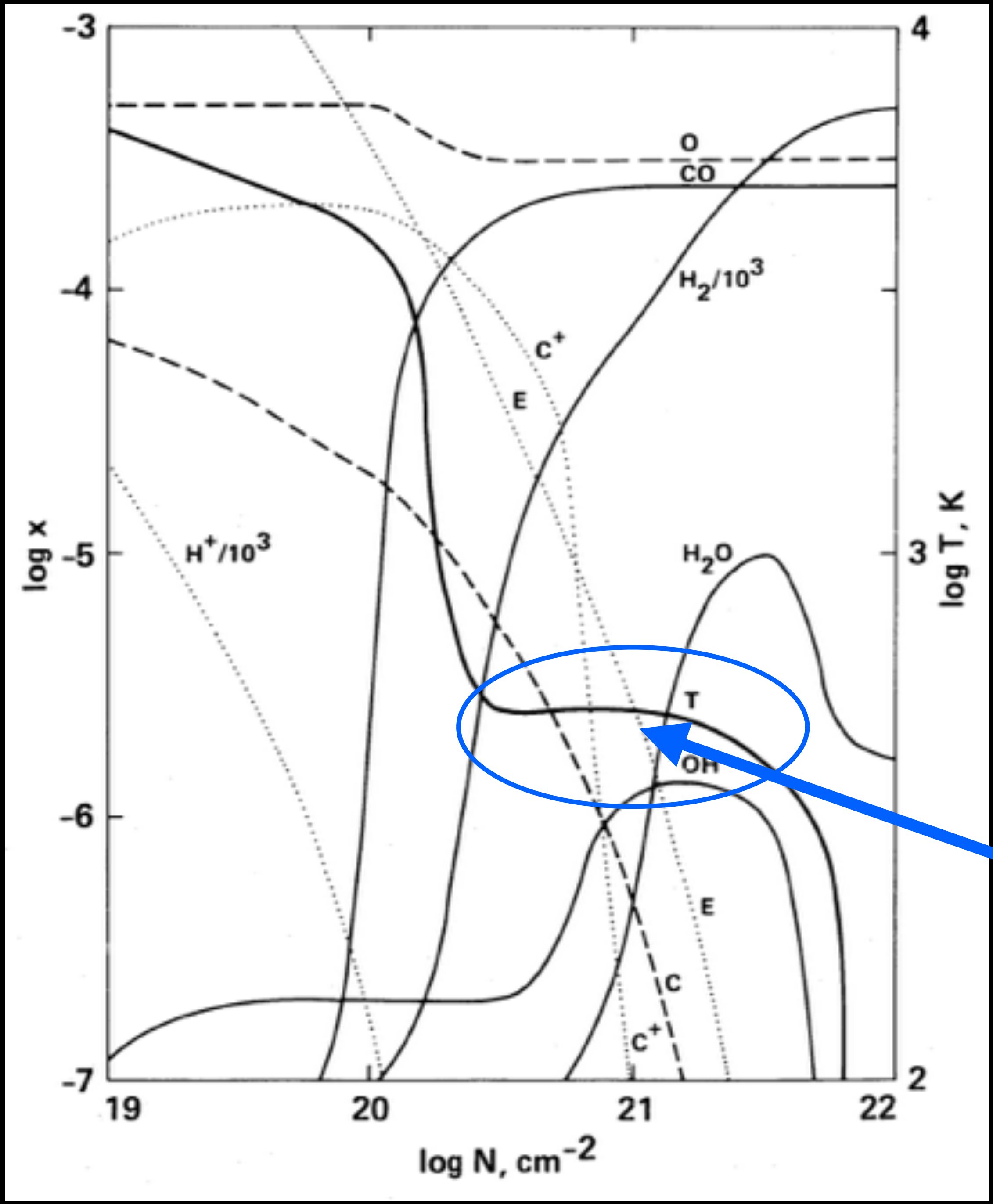
C-Shock Profile



- Continuous T, v
  - Low ionization fraction, carried by ions or grains bound to magnetic field
  - Efficient coolants so that shock doesn't "break down" (below 40 km/s)
- For v ~ 15 km/s, T high enough that gas-phase O ends up converted to water

- Emission from gas at a range of temperatures up to ~4000K
- Emission over a range of velocities (~10s of km/s)
- Hydrides (OH and H_2O) along with O, CO and H_2 are important coolants

J-Shock Profile

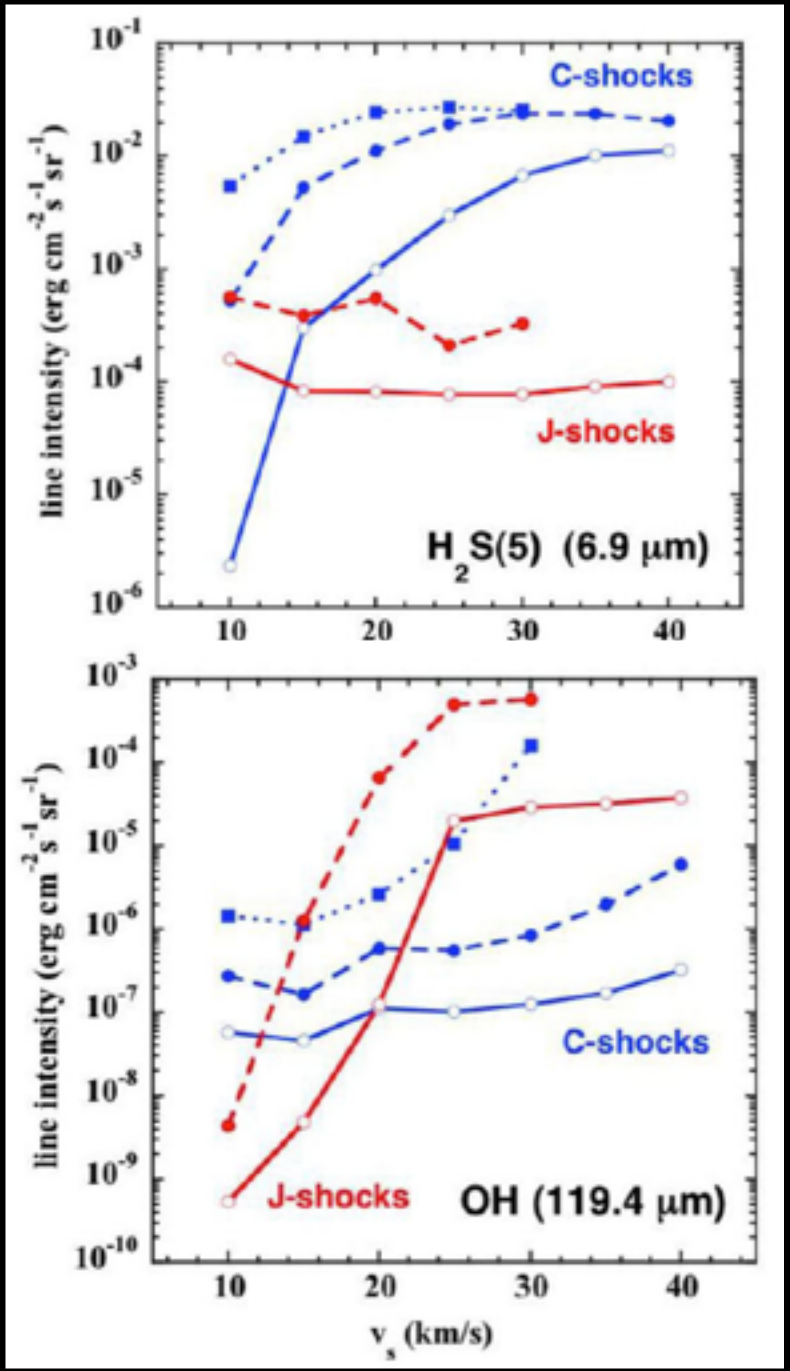


- Collisional and UV dissociation in the hot (T~10^4 K) post-shock gas
- H_2 reformation begins downstream at A_V ~ 0.1
- Water forms efficiently in the warm (T~500 K) molecular reformation plateau

- Molecular emission comes from ~500K plateau region
- Gas has fully decelerated once molecules form
- Limited column of H_2O and OH; CO, OI dominate cooling

Shock types: gross characteristics

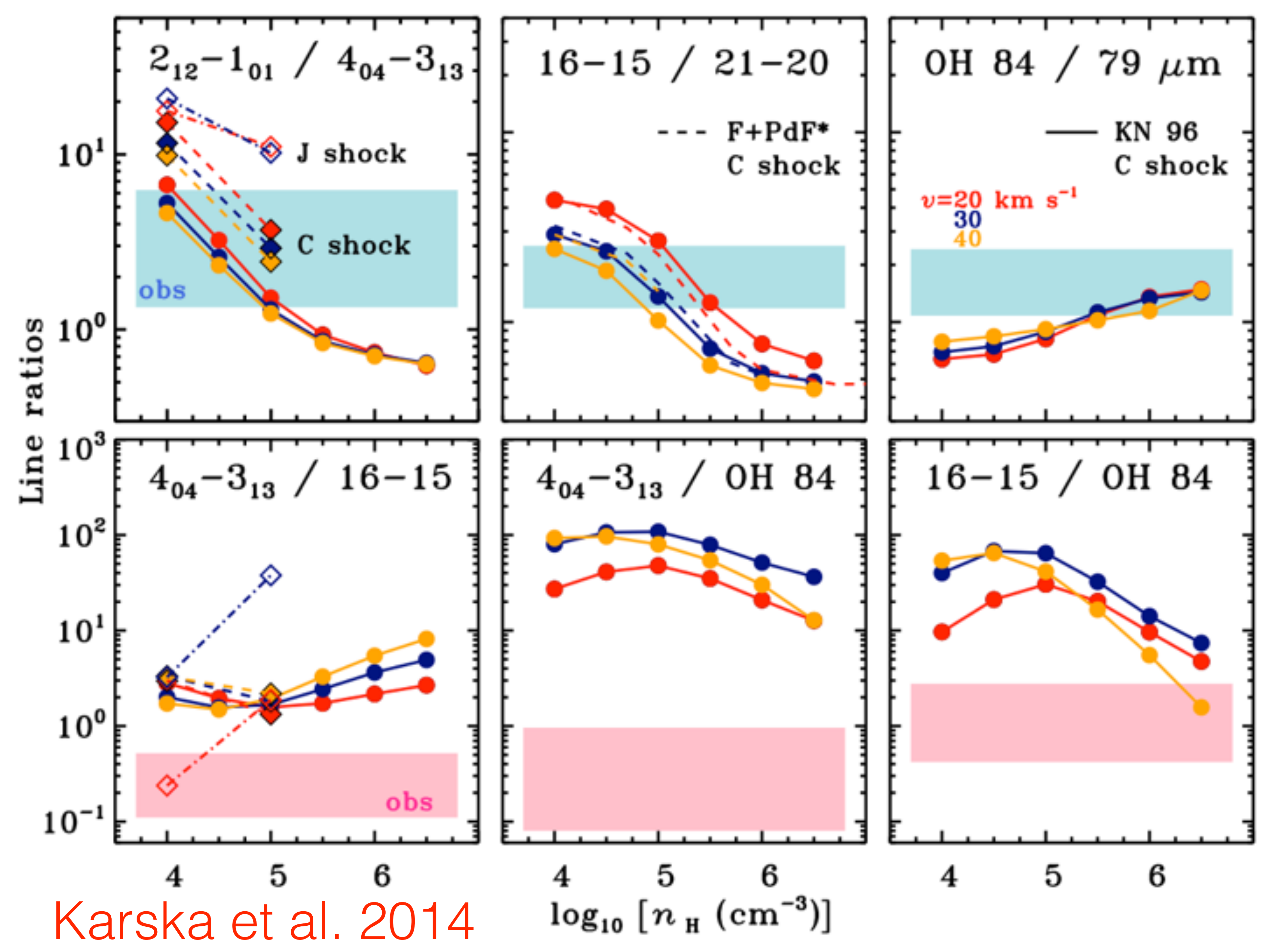
- C-shock allows molecules to survive to T~4000 K. All free O driven into H_2O, high ratio of H_2O/OH.
- J-shocks reach far higher temperatures, but molecules are dissociated ==> reformation plateau at ~500 K, significant atomic H drives H_2O back to OH, low ratio of H_2O/OH.



Flower and PdF 13

But something is missing…

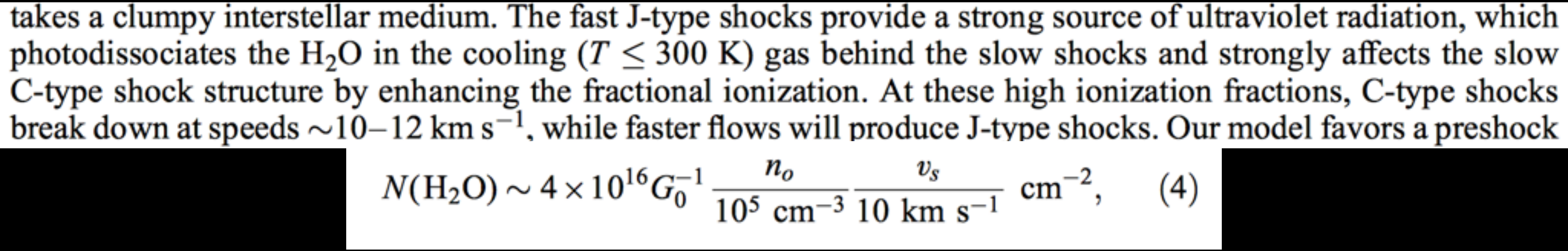
WISH low-mass sources have “wrong” abundances (Karska14)



Karska et al. 2014

But something is missing…

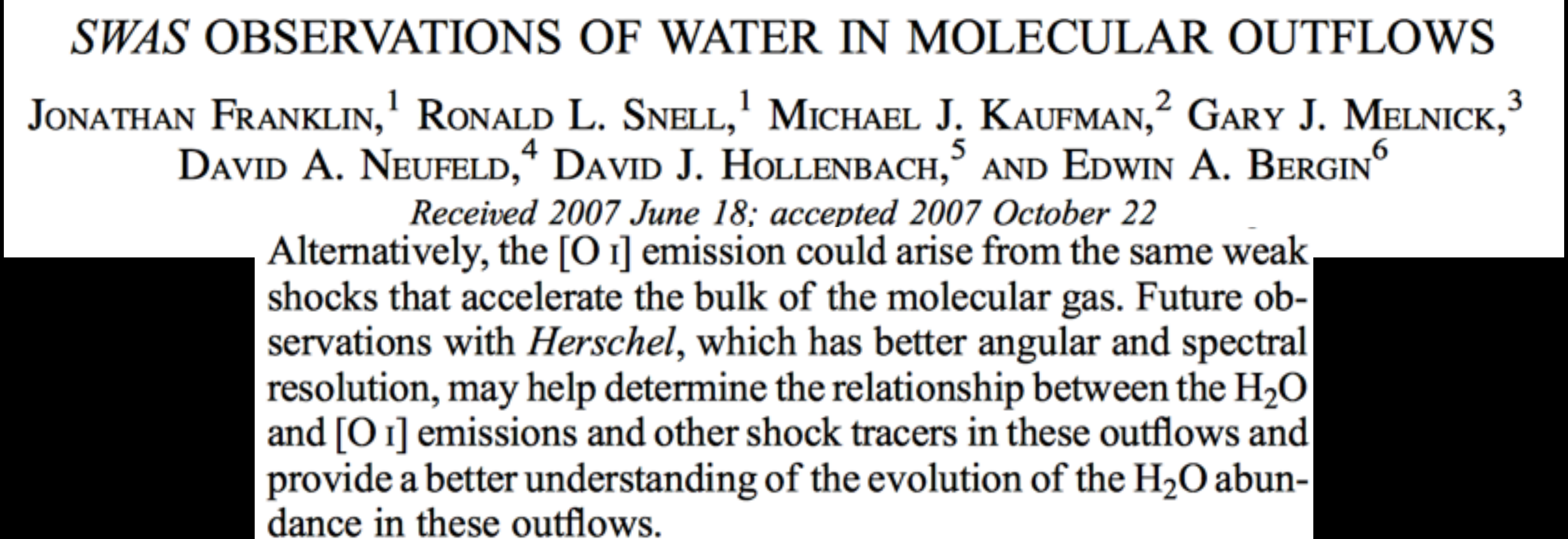
C-shocks influenced by the environment near SNRs
(Snell et al. 2005)



takes a clumpy interstellar medium. The fast J-type shocks provide a strong source of ultraviolet radiation, which photodissociates the H_2O in the cooling ($T \leq 300$ K) gas behind the slow shocks and strongly affects the slow C-type shock structure by enhancing the fractional ionization. At these high ionization fractions, C-type shocks break down at speeds ~10–12 km s^{-1}, while faster flows will produce J-type shocks. Our model favors a preshock

$$N(H_2O) \sim 4 \times 10^{16} G_0^{-1} \frac{n_o}{10^5 \text{ cm}^{-3}} \frac{v_s}{10 \text{ km s}^{-1}} \text{ cm}^{-2}, \qquad (4)$$

Most shocked H_2O is not at an abundance of 10^{-4} in outflows
(Franklin et al. 2007)



SWAS OBSERVATIONS OF WATER IN MOLECULAR OUTFLOWS

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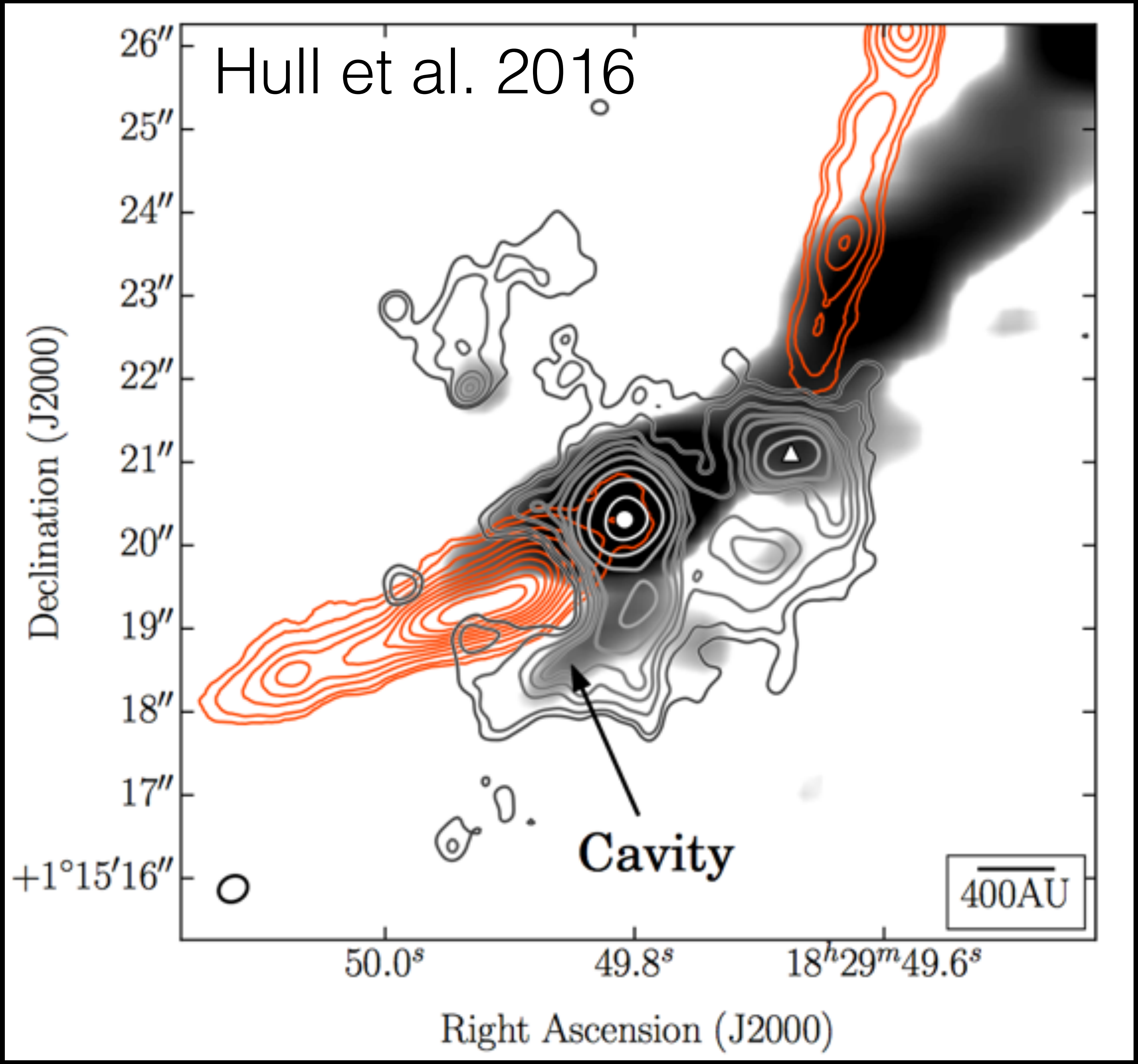
David A. Neufeld,[4] David J. Hollenbach,[5] and Edwin A. Bergin[6]

Received 2007 June 18; accepted 2007 October 22

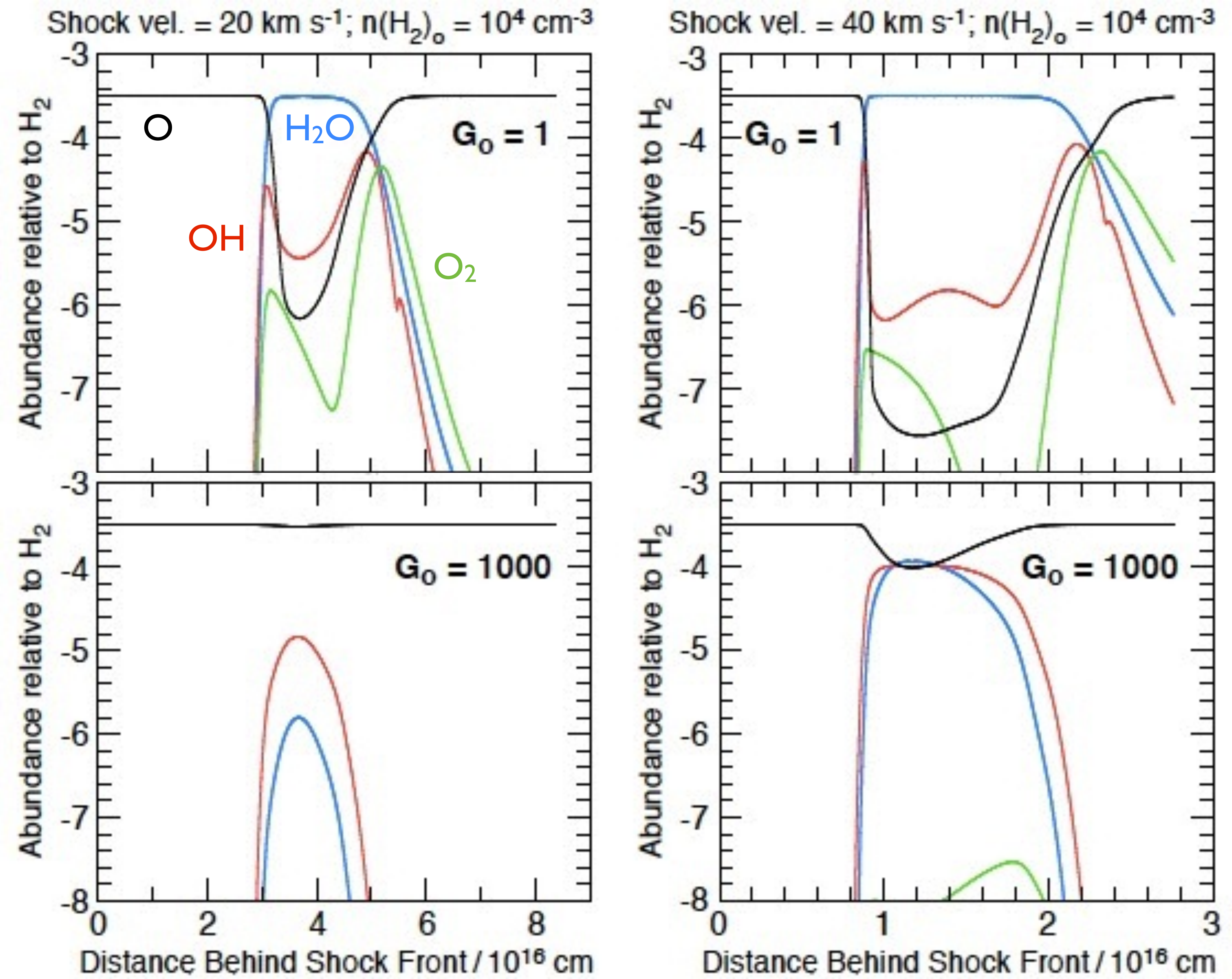
Alternatively, the [O i] emission could arise from the same weak shocks that accelerate the bulk of the molecular gas. Future observations with *Herschel*, which has better angular and spectral resolution, may help determine the relationship between the H_2O and [O i] emissions and other shock tracers in these outflows and provide a better understanding of the evolution of the H_2O abundance in these outflows.

Evidence for ionized outflow cavity - FUV from protostar?

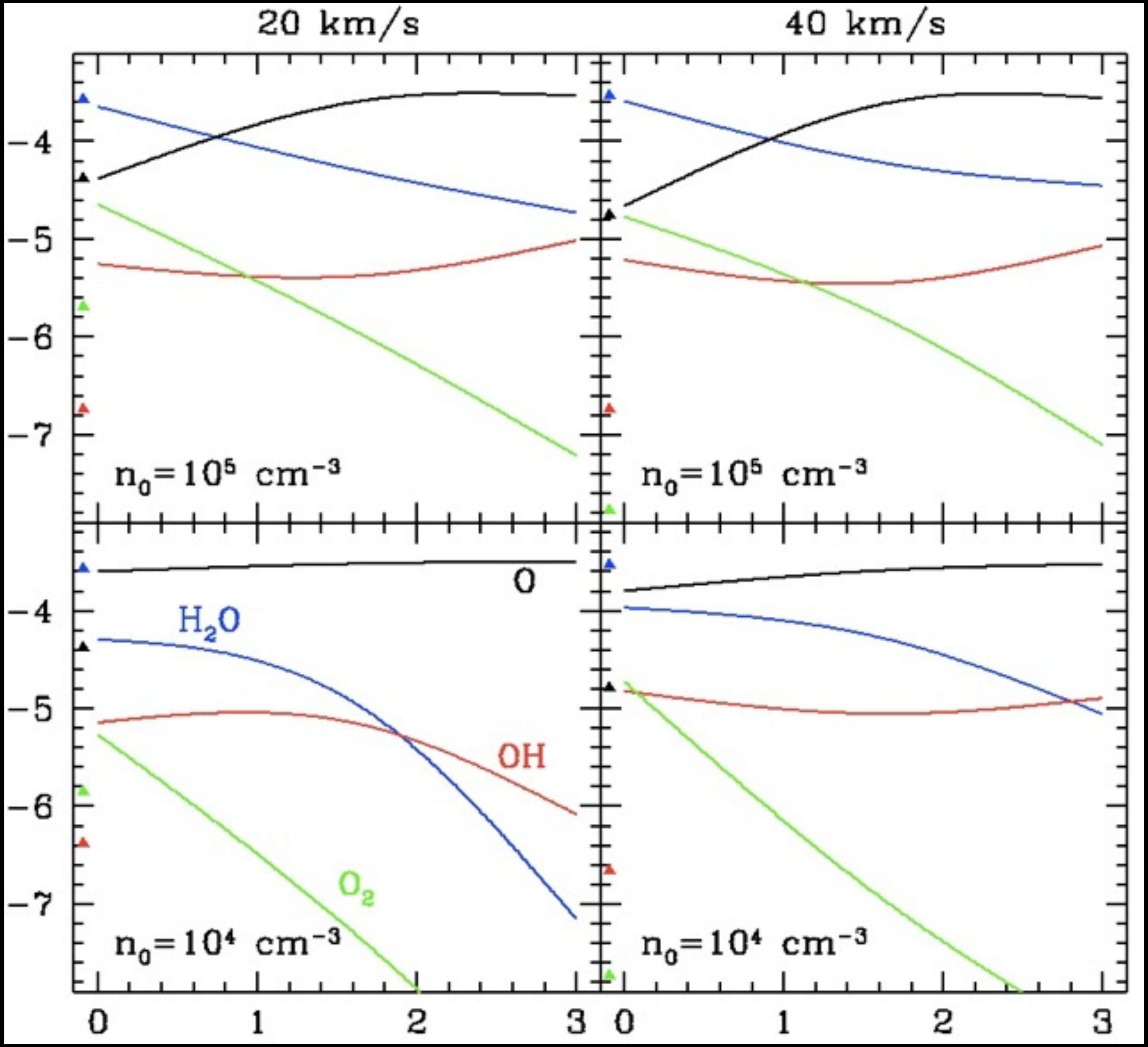


Serpens SMM1

Simple Modification:
Shock Chemical Profiles with External FUV



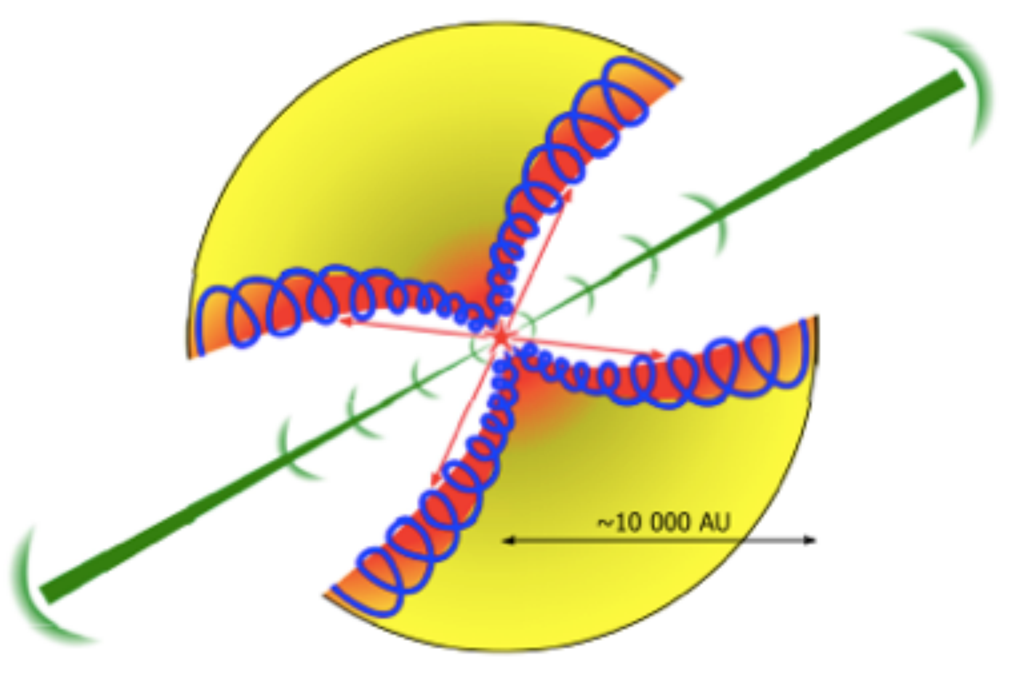
FUV influence on Postshock O-chemistry



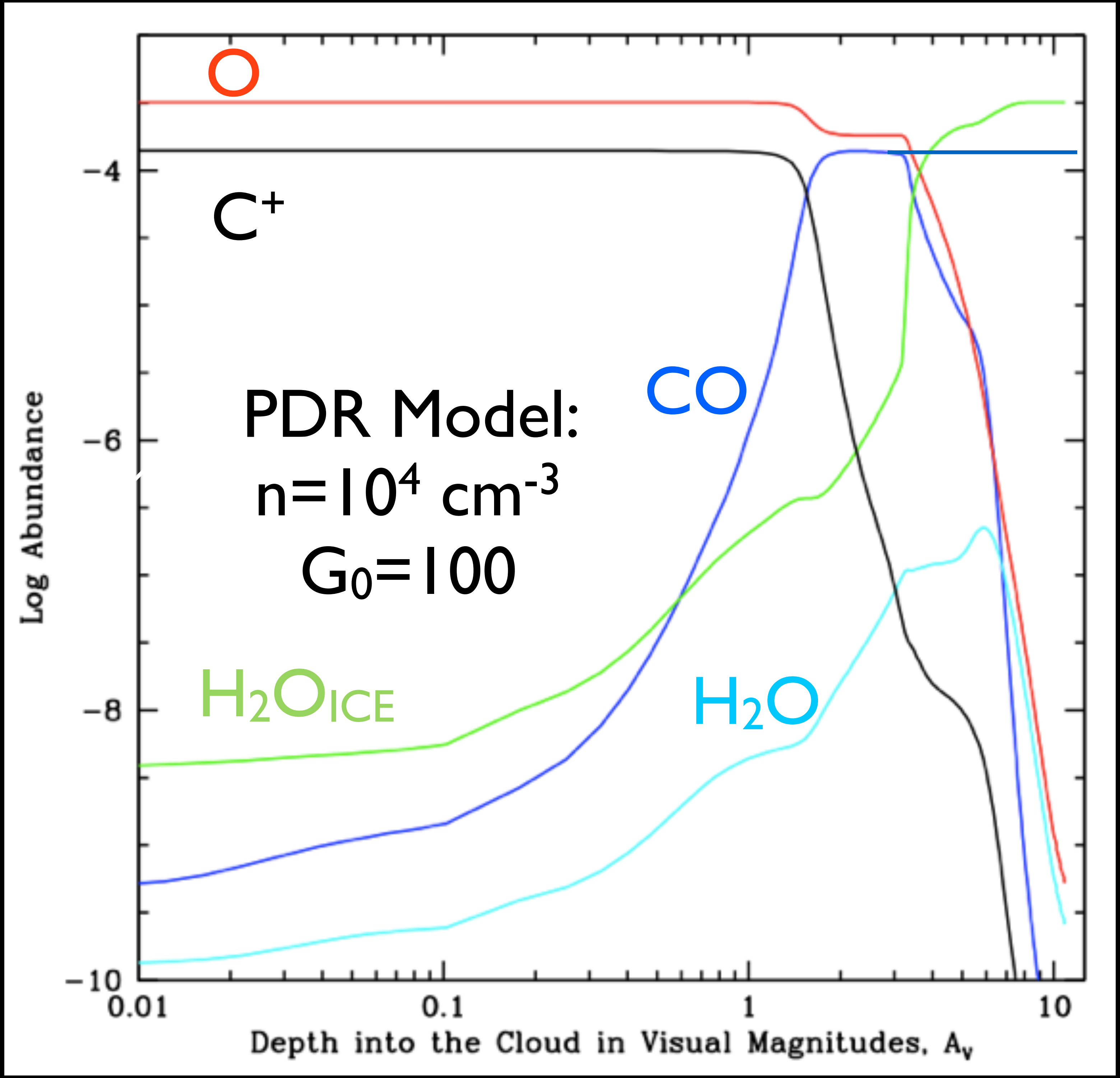
log[Column relative to H_2]

log[FUV Field Strength]

What are the preshock conditions in the protostellar environment?



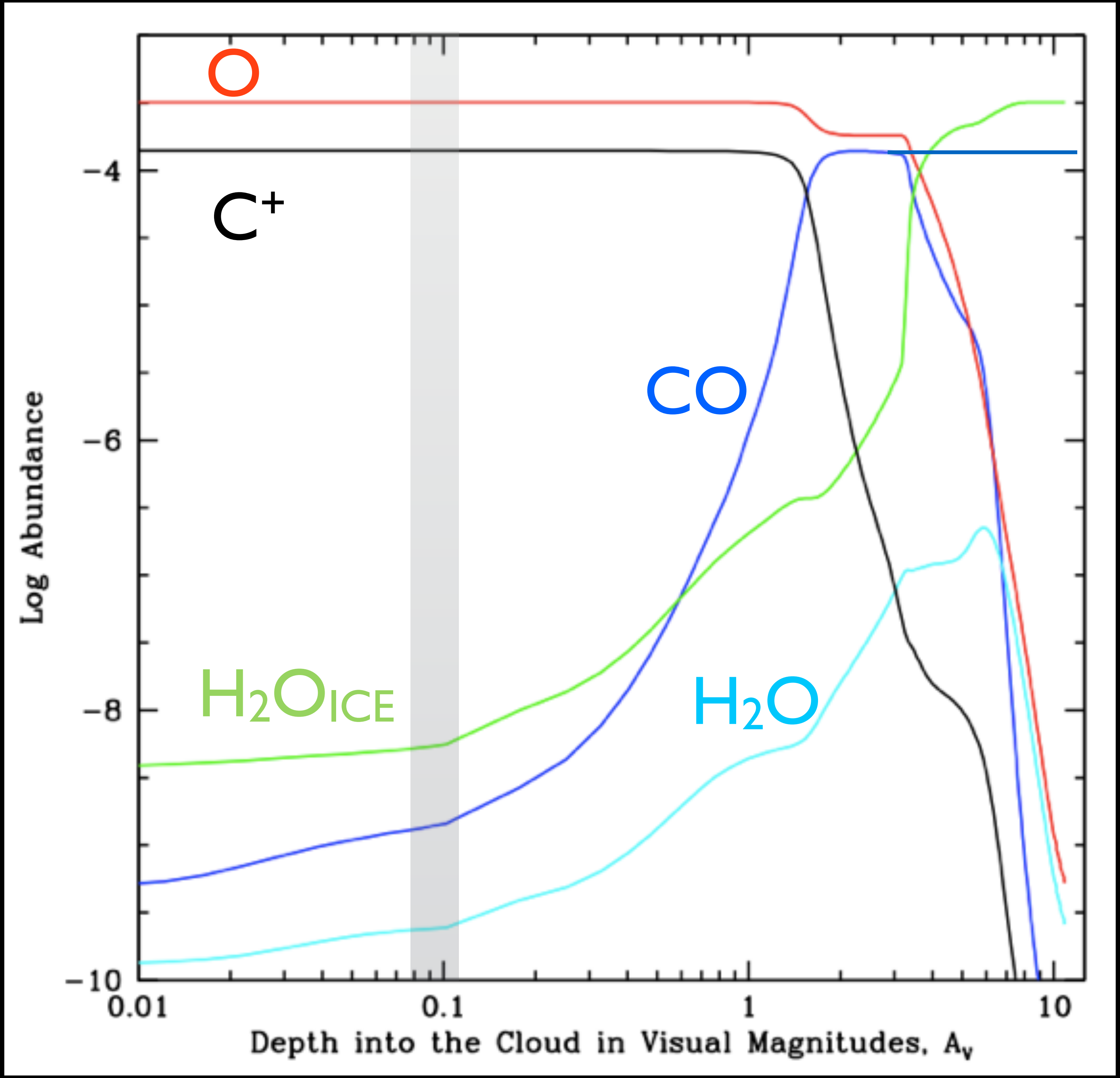
Visser et al. 2011



Hollenbach et al. 2009

What are the preshock conditions in the protostellar environment?

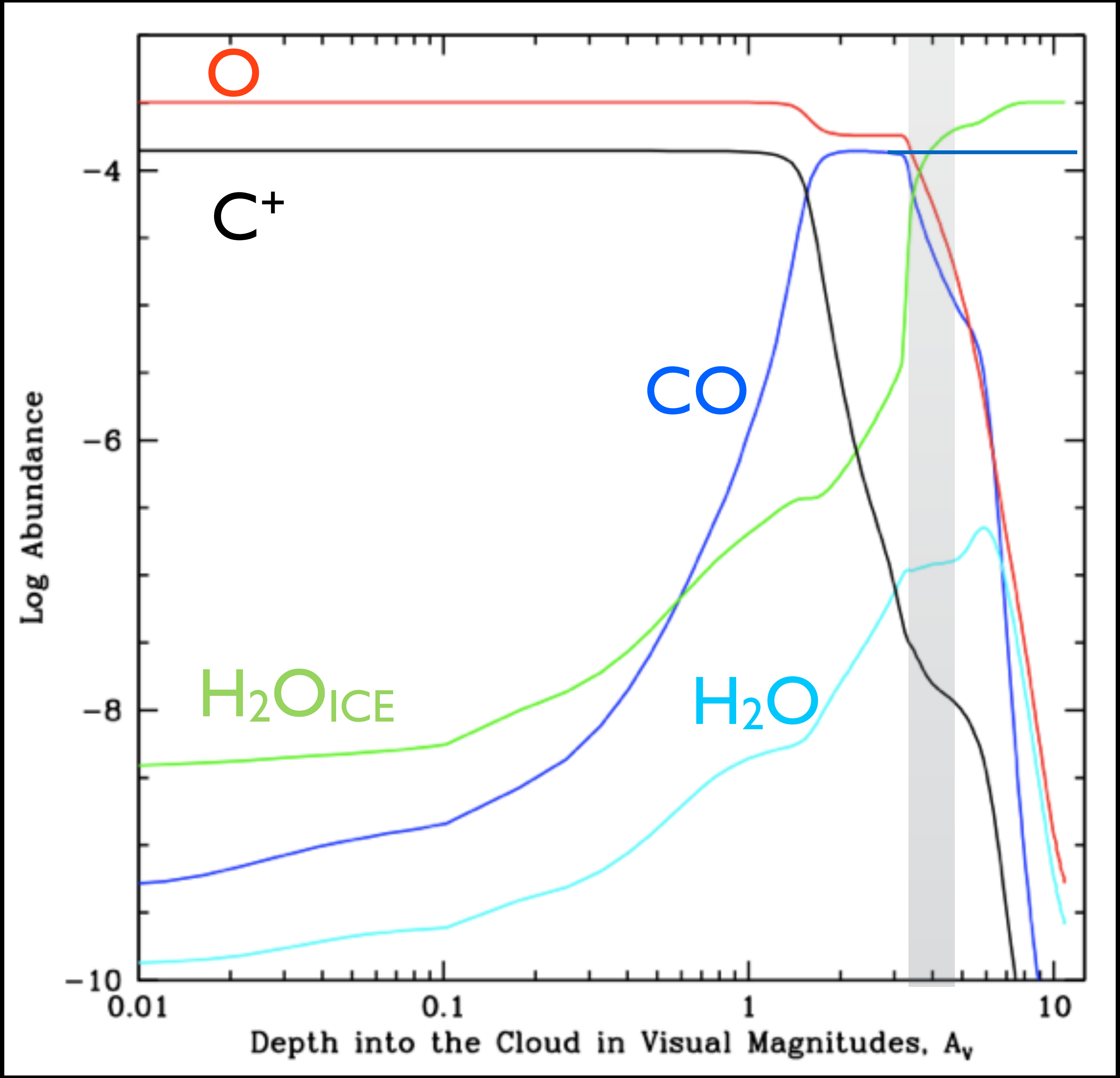
$A_V = 0.1$:
All oxygen available but high ionization fraction makes shocks breakdown at low speeds



Hollenbach et al. 2009

What are the preshock conditions in the protostellar environment?

A_V = few:
Oxygen frozen out by factor of 10. Ionization may not allow shocks above sputtering speed.

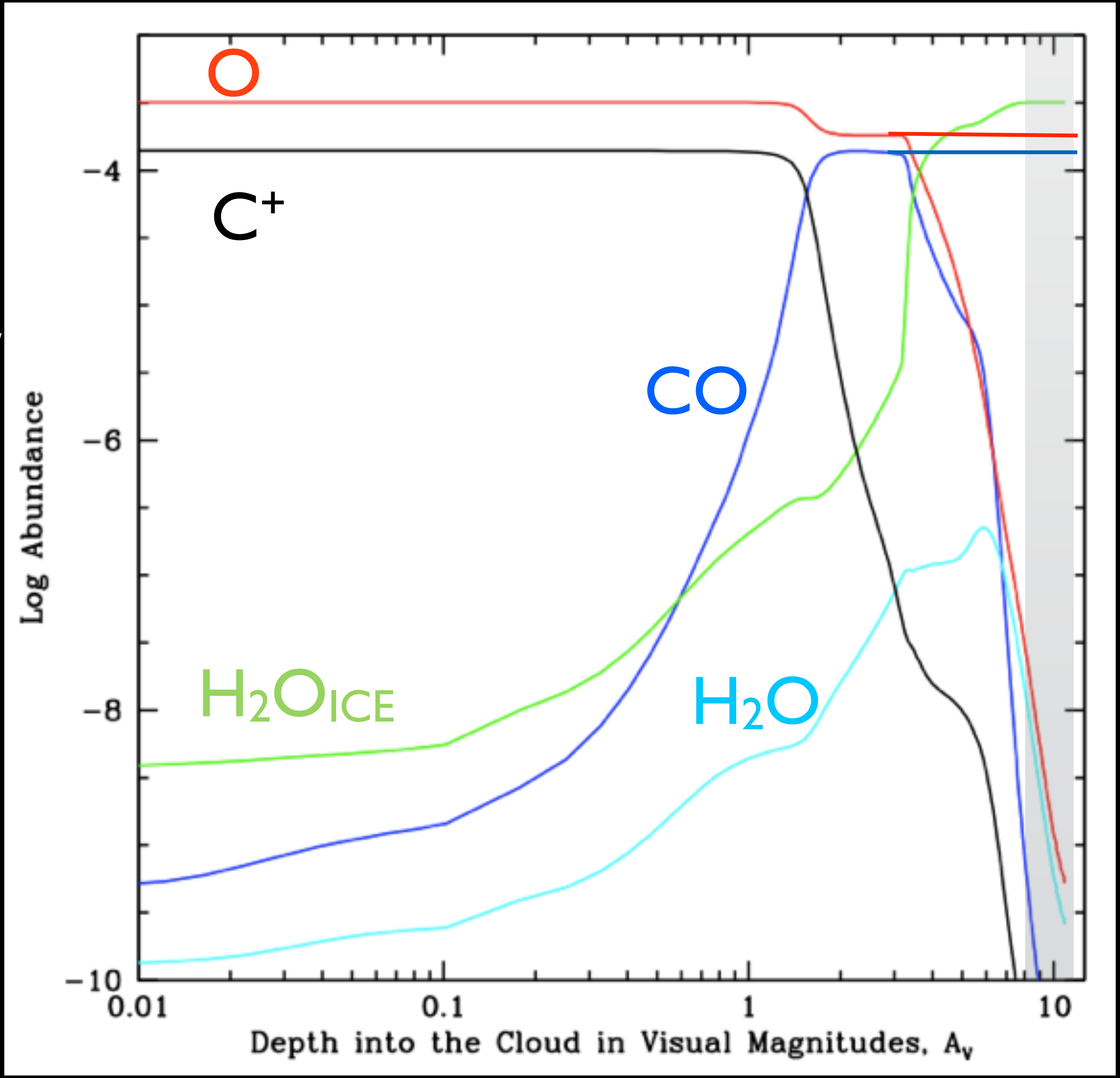


Hollenbach et al. 2009

What are the preshock conditions in the protostellar environment?

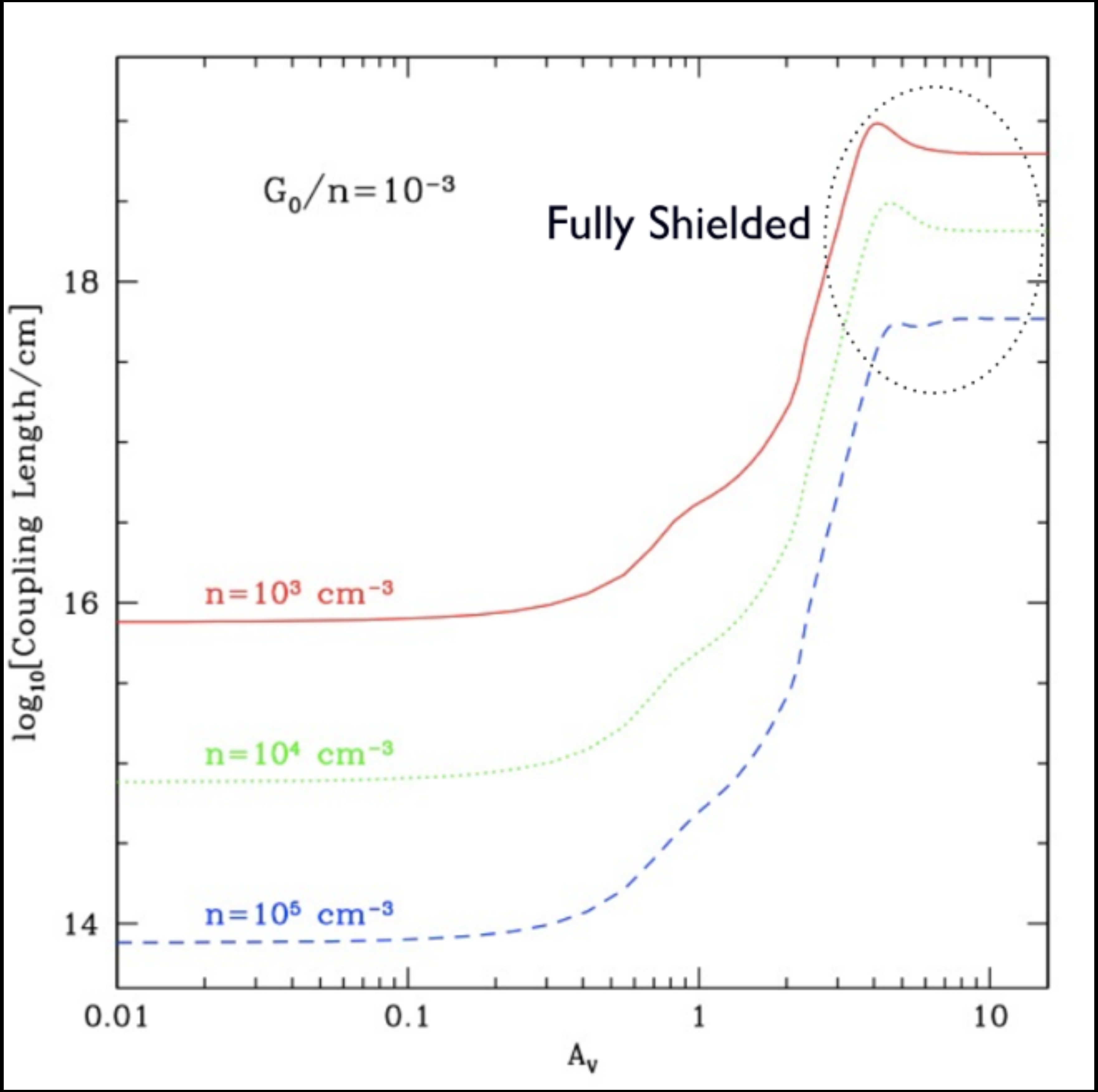
$A_V = 10$:

All oxygen frozen out; low water without sputtering since O is locked in the ice.



Hollenbach et al. 2009

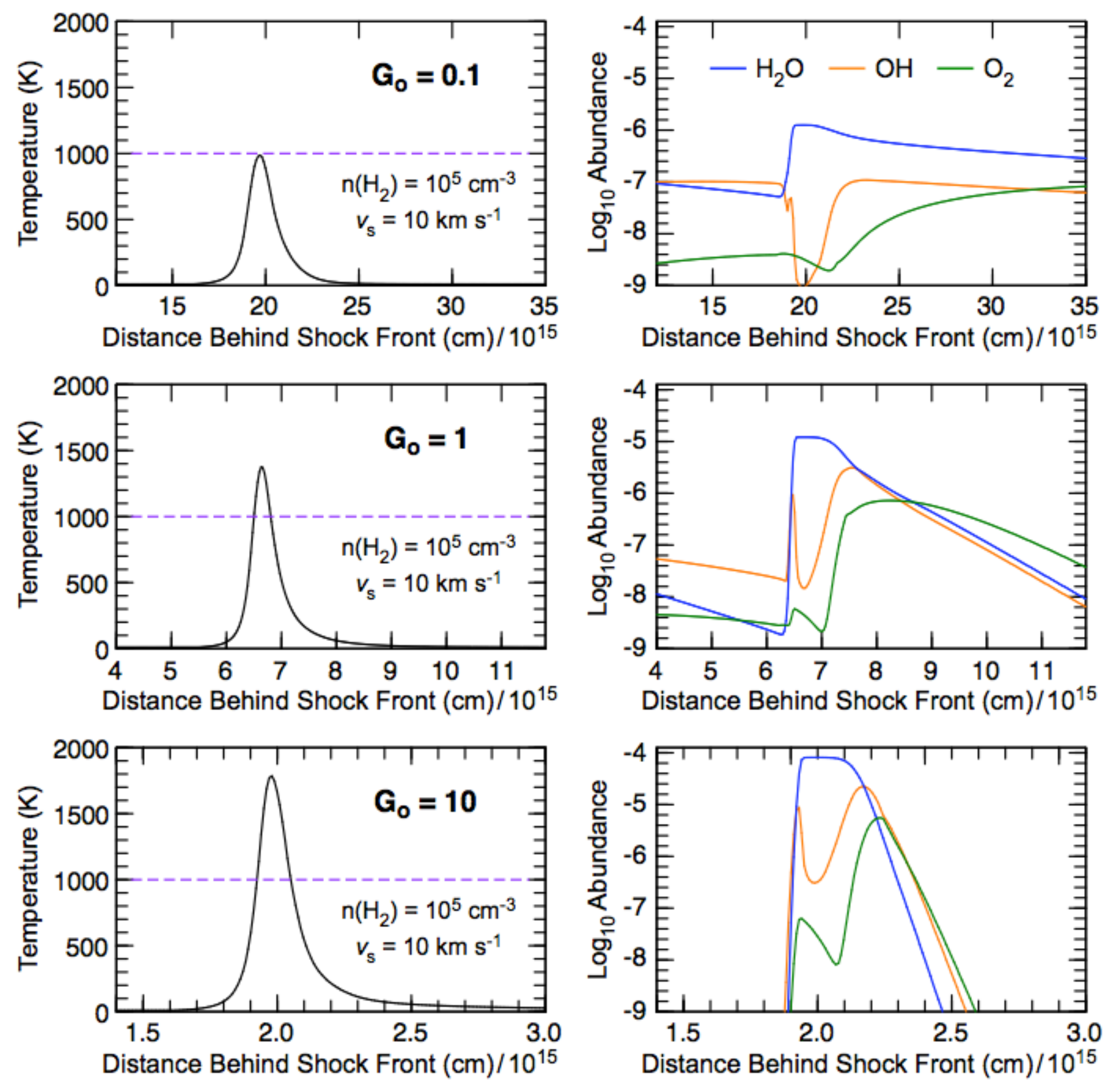
Coupling Length Varies With Extinction



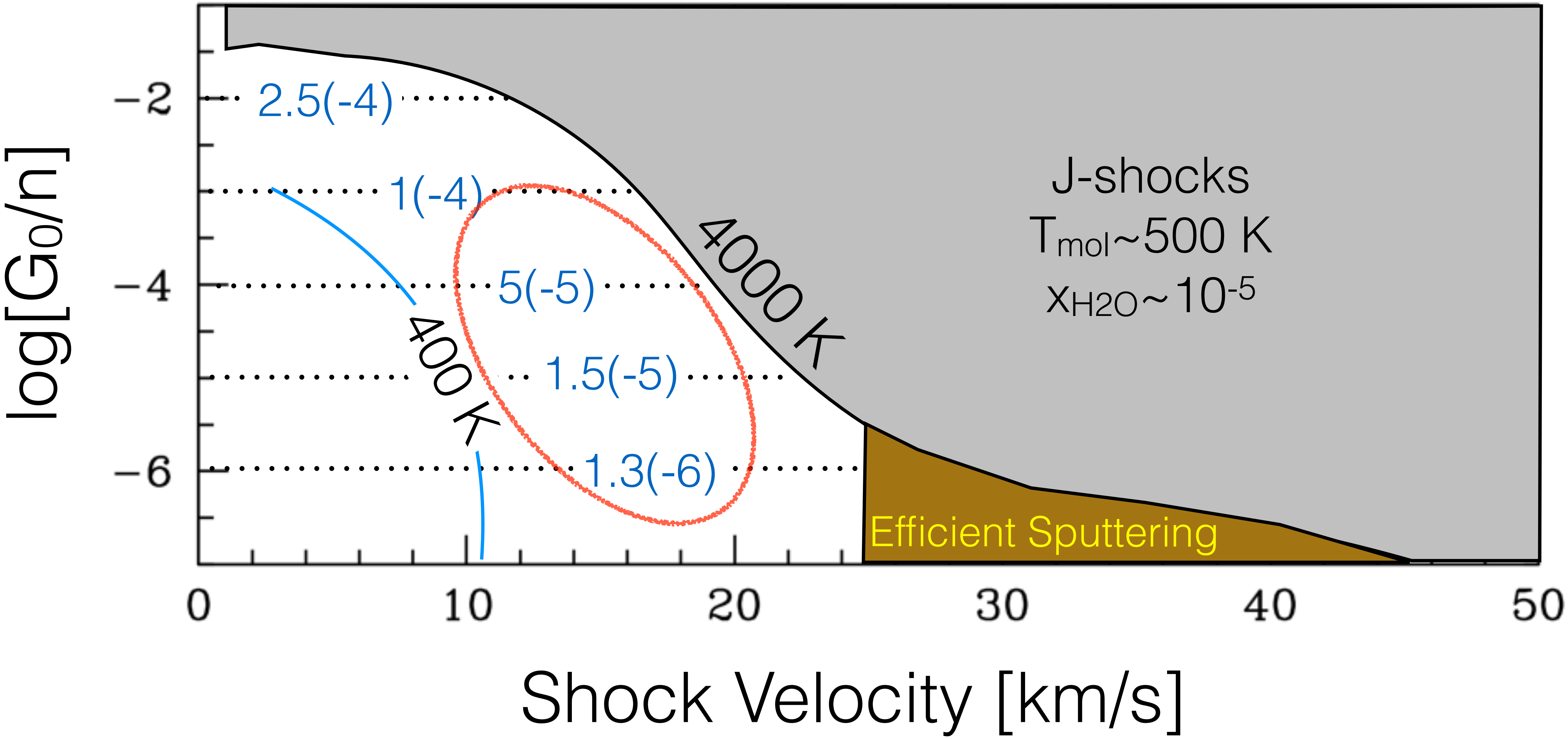
$L \sim n^{-1/2}$

$L \sim n^{-1}$

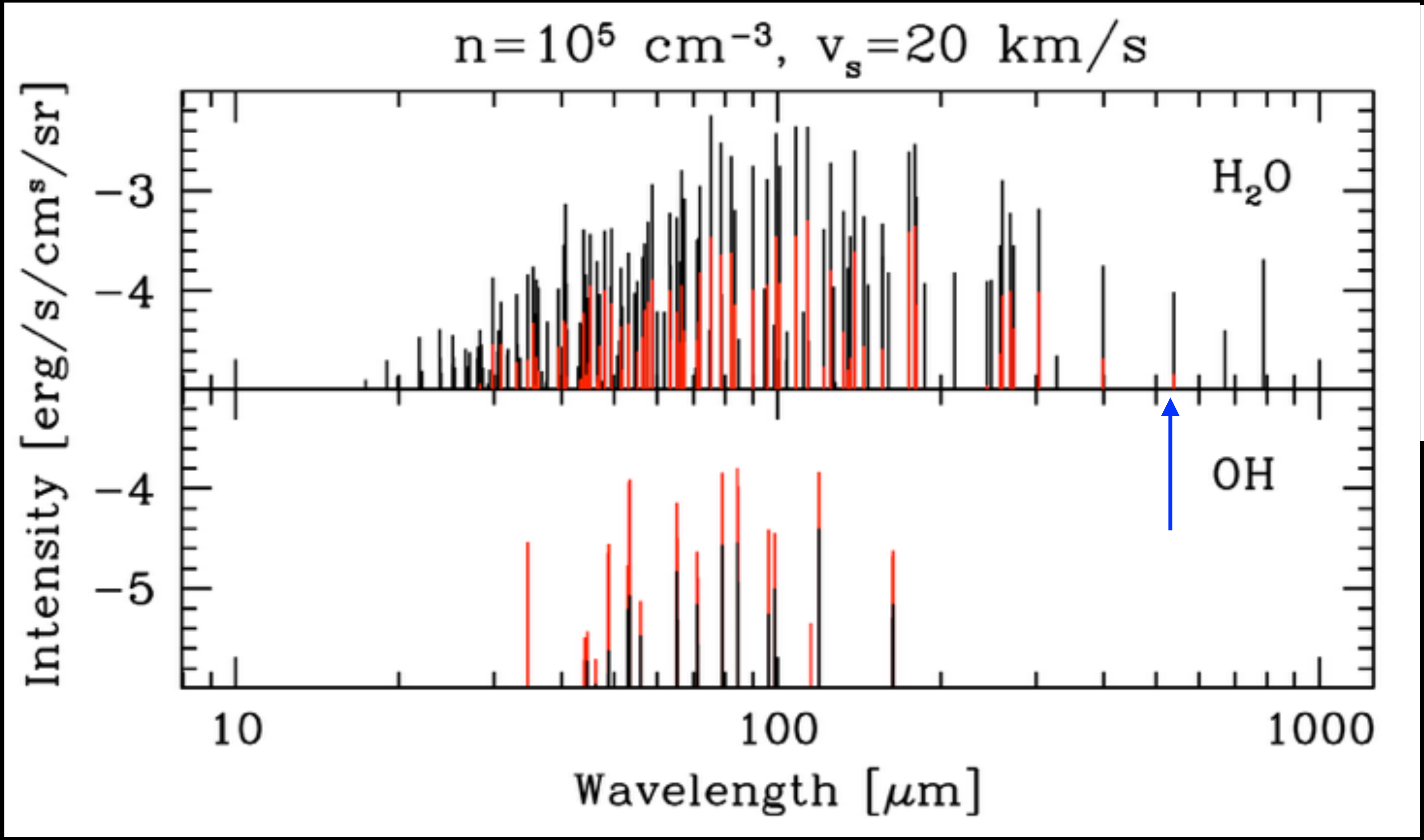
- As FUV field is increased, length scale goes down/ T_{max} goes up
- As FUV field is increased, available gas-phase oxygen goes up
- As FUV is increased, post-shock gas is more dissociated



FUV Illuminated Shocks - Parameter Space



Effect of FUV on H_2O and OH Emission

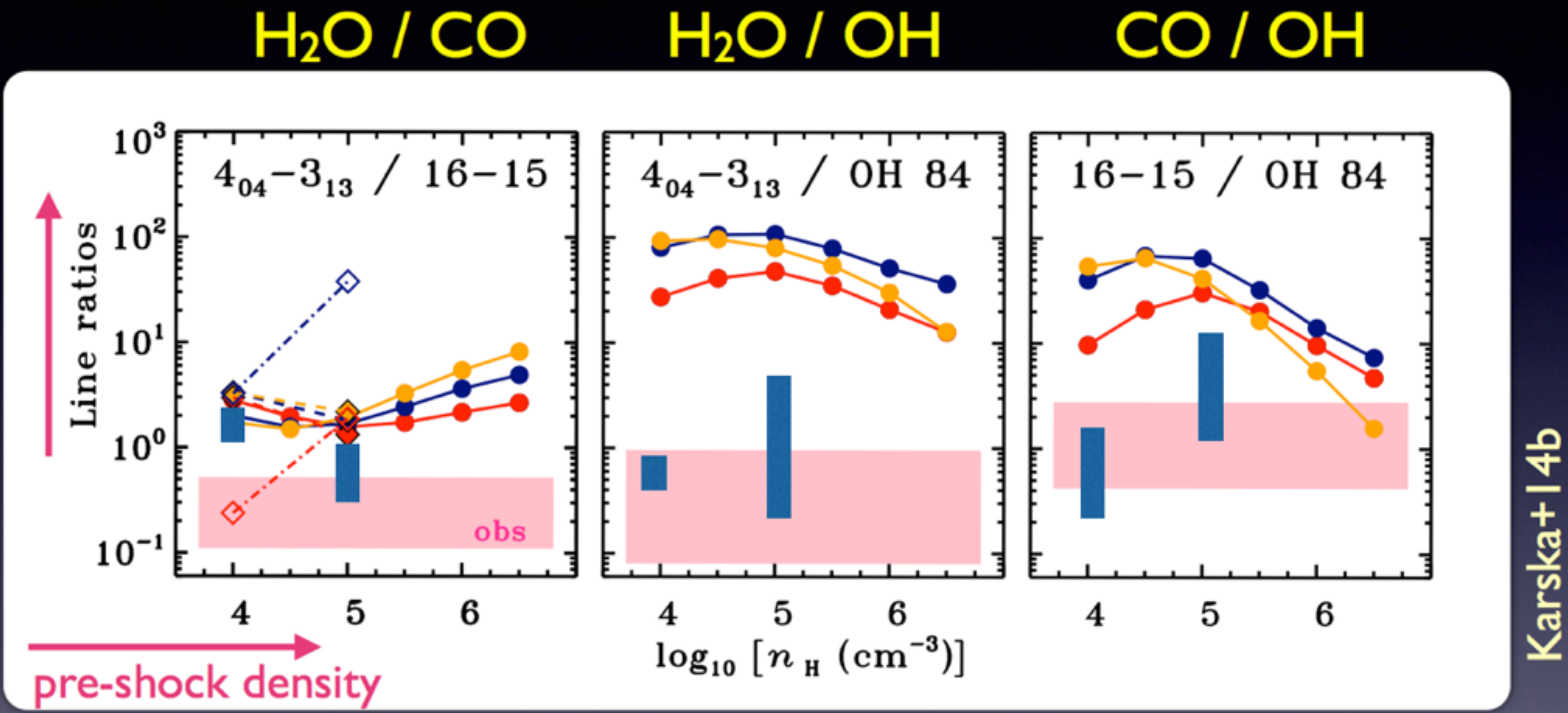


Black no FUV, all gas phase

Red G_0=10

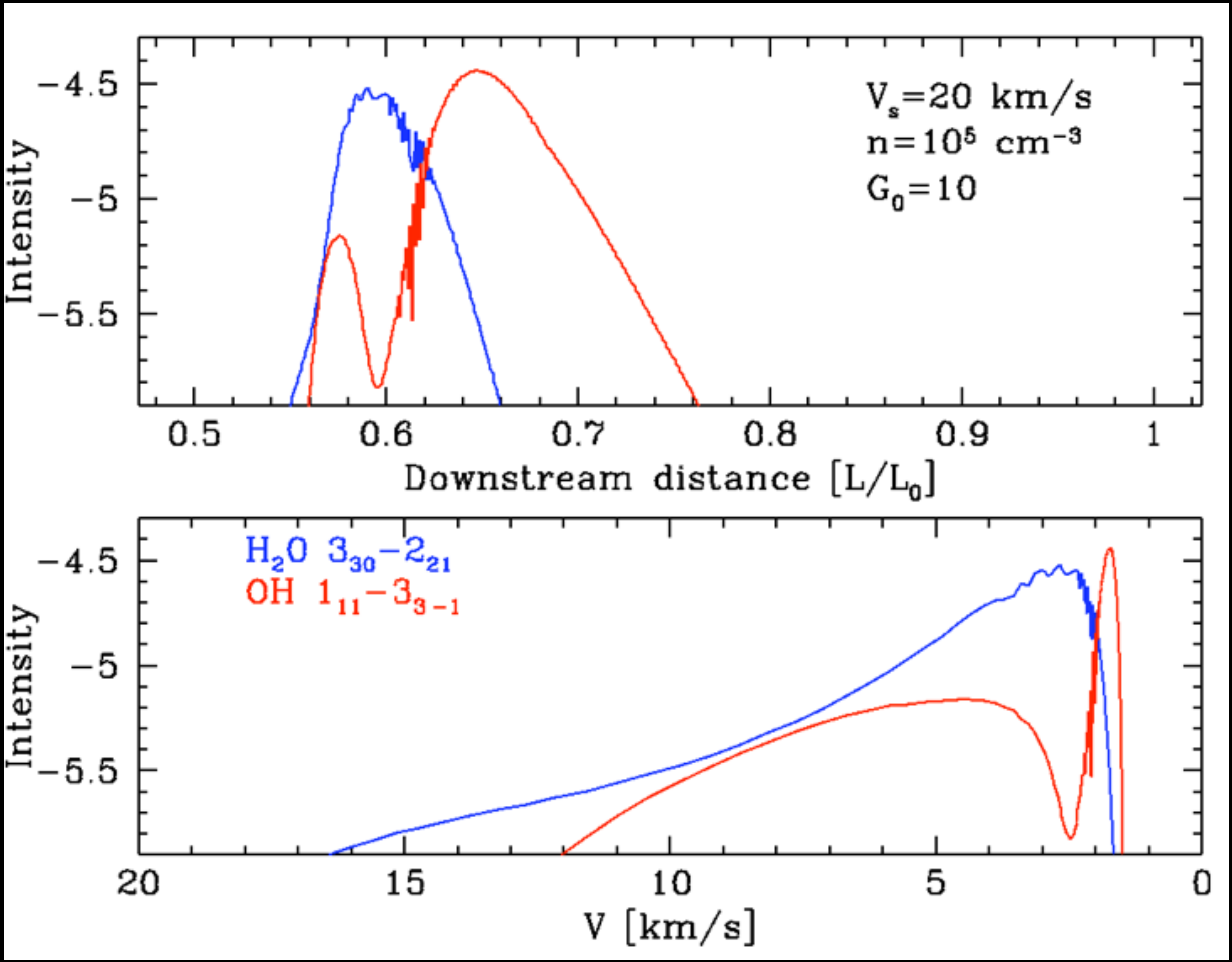
Note:
F_{FUV}/F_{shock} ~ 0.01

FUV moves ratios in the correct direction



Karska+14b

Line profiles

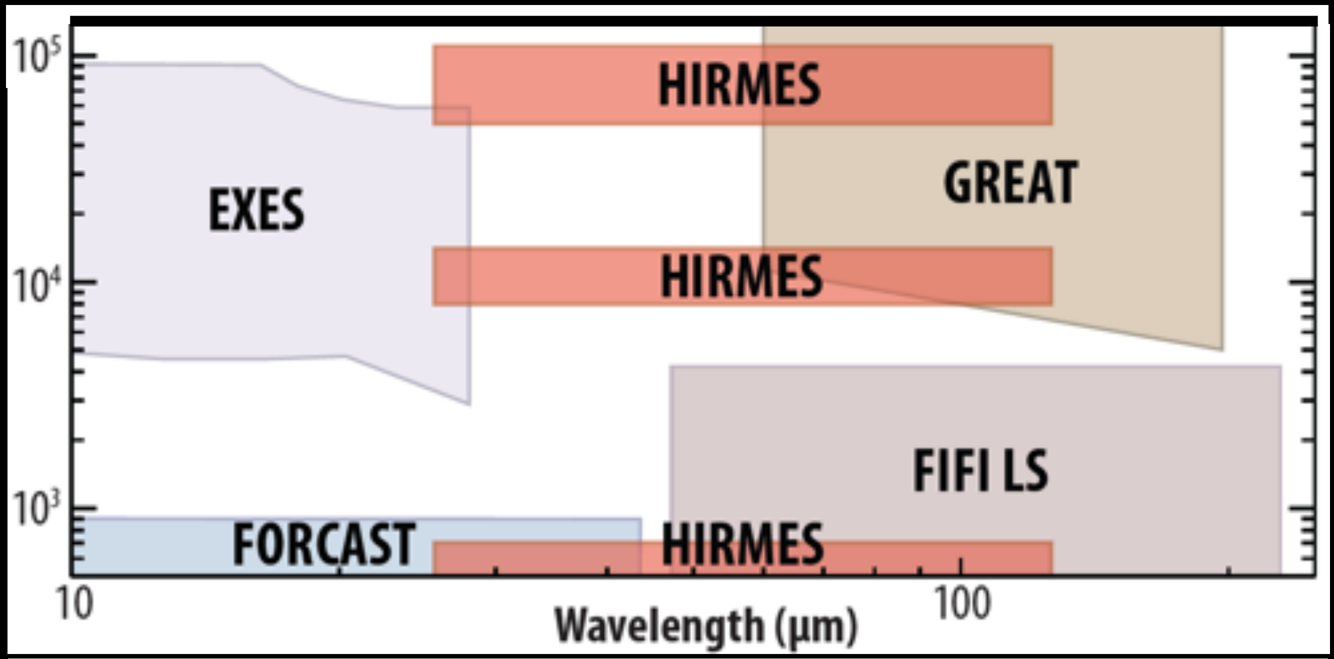


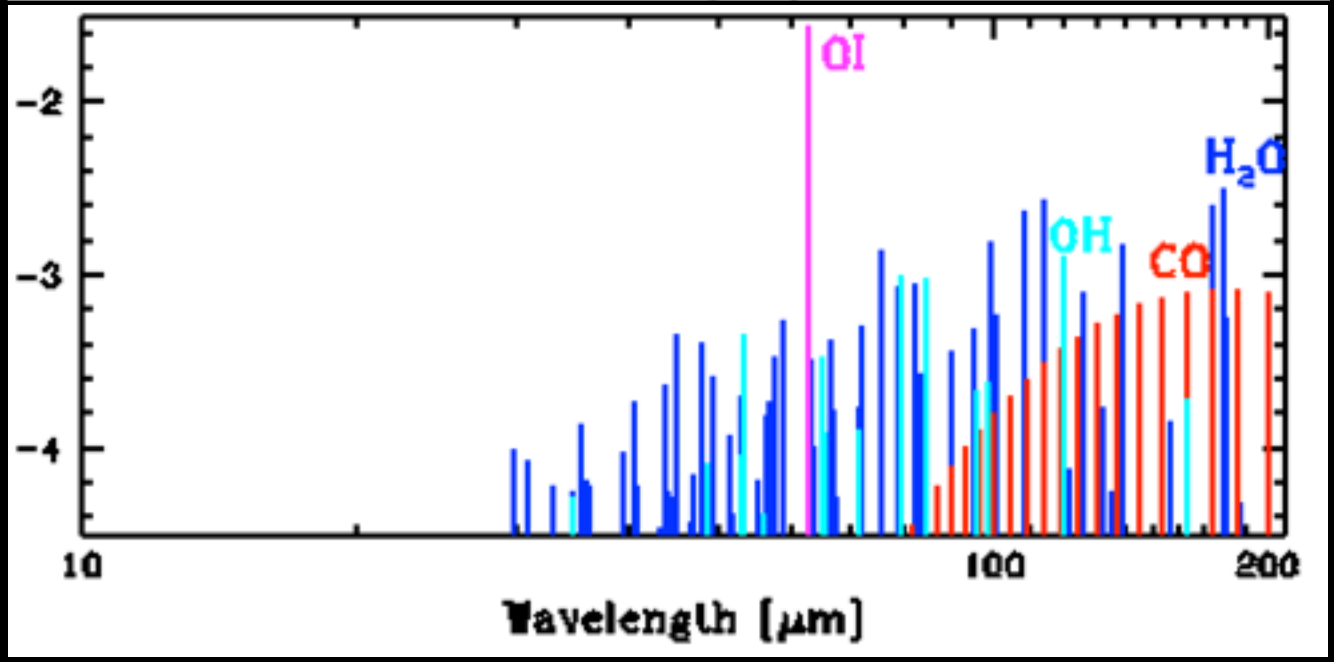
HIRMES: Next-generation spectrograph for SOFIA

- Coverage from 22-120 micron

- Full scan mode complements bygone Herschel capabilities

- High-res mode gives up to 3 km/s resolution; shock profiles: OH/H_2O





Summary

- Higher G_0/n: More O and H_2O in pre-shock gas
- Higher G_0/n: Smaller velocity at which H_2O formation turns on and lower velocity of C-shock breakdown, perhaps excluding sputtering
- Higher G_0/n: Greater relative O and OH emission from downstream gas
- Promising comparisons with observations ranging from massive outflows, through O_2, and low-mass stars.