Models of FUV Illuminated Shocks:

Understanding the Water Abundances Observed With Herschel

Michael Kaufman
San Jose State University

in support of Herschel/WISH
and with collaboration of Gary Melnick & Volker Tolls (CfA) with support from NASA ADP program

See also: Lessafre et al. - FUV shock models for diffuse ISM; Gusdorf - this session

Models of FUV Illuminated Shocks:

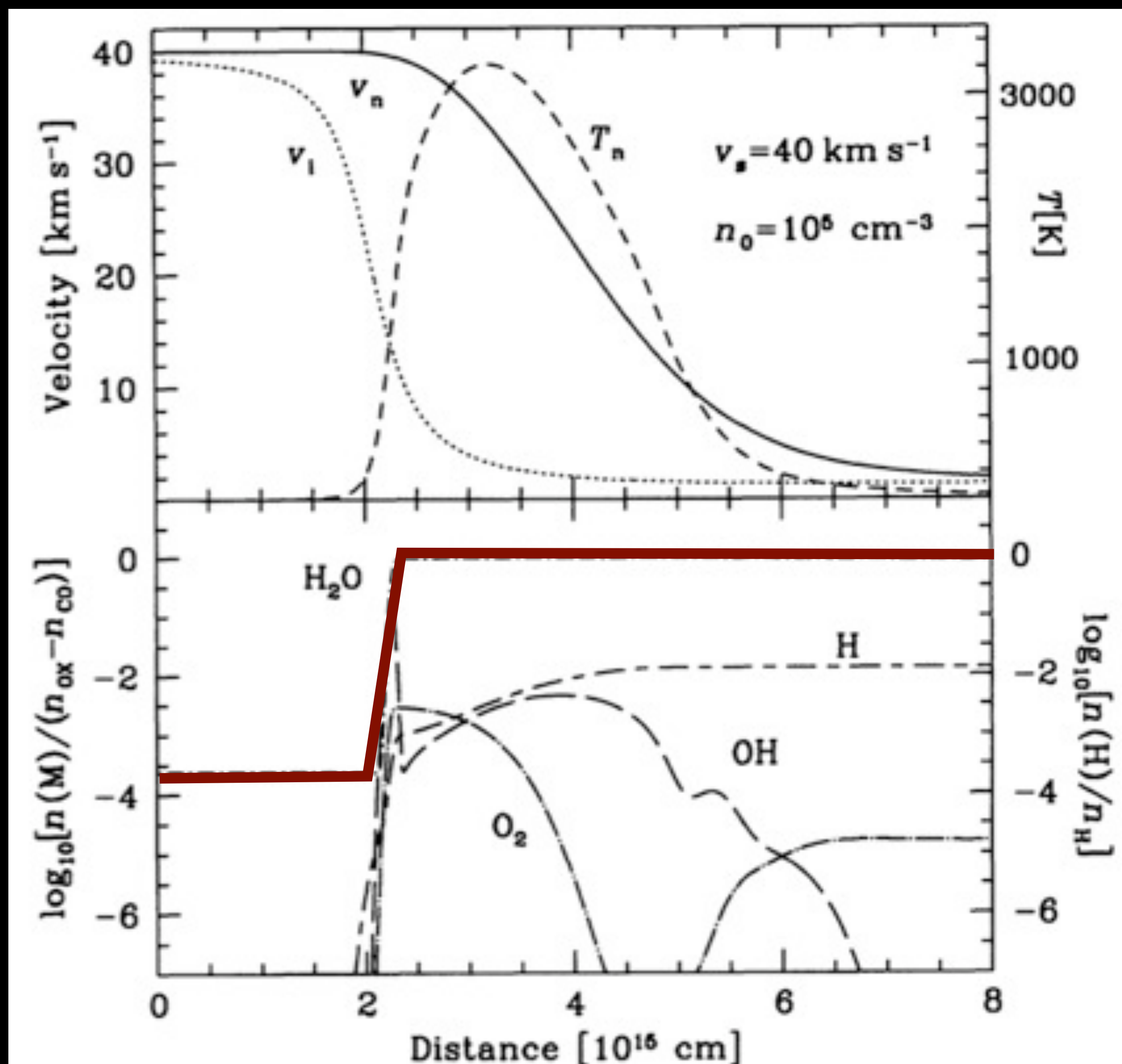
Can the water abundance in shocks be arbitrarily low?

- Review of shock basics and high T water chemistry
- Motivation for FUV
- FUV-influenced post-shock chemical abundances
- Effect of FUV on the coupling length
- Surface, shielded and "sequestered" shocks

C-Shock Profile

V

x/xo



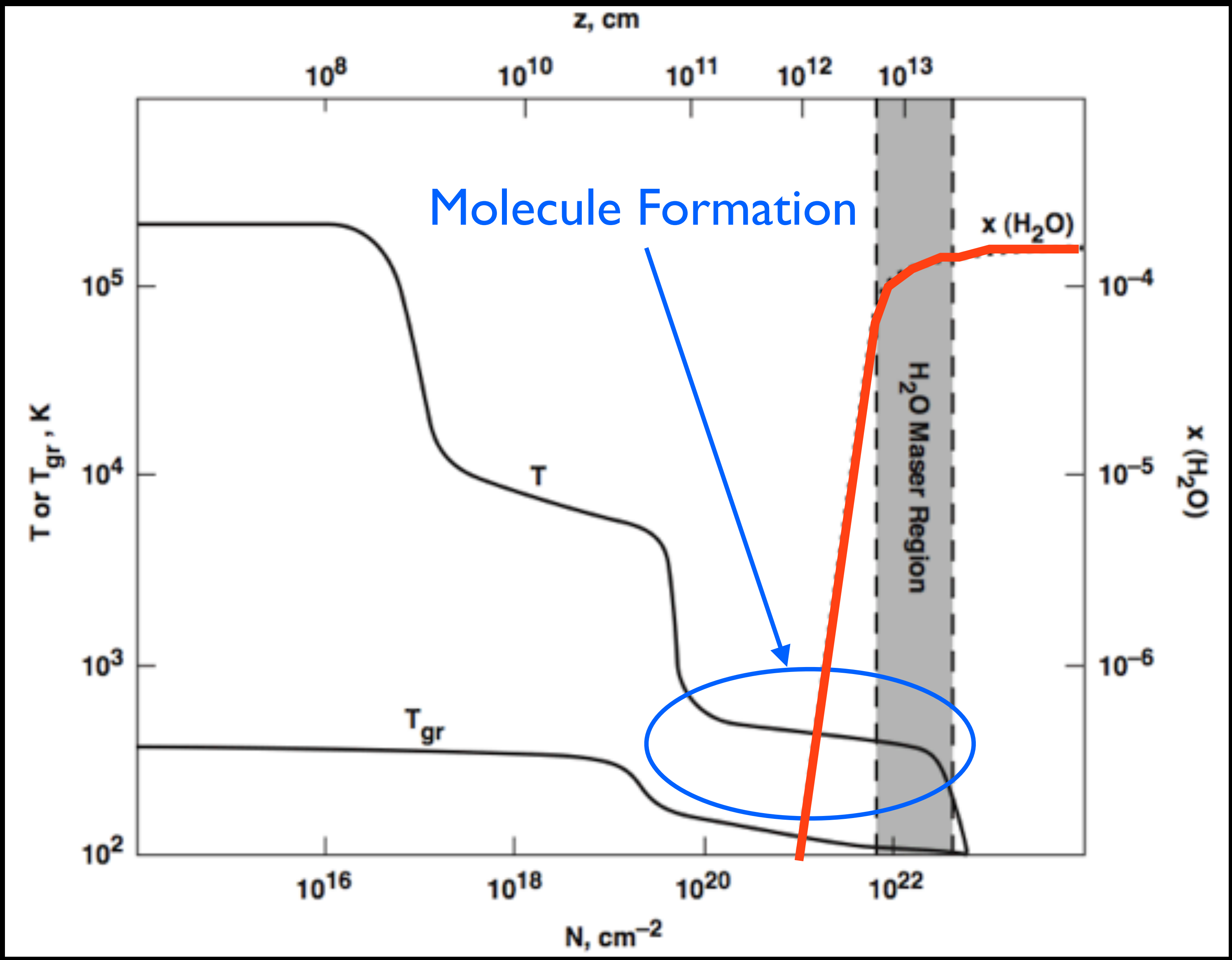
Kaufman & Neufeld 1996; Draine 1983

H_2 + O ==> OH + H

H_2 + OH ==> H_2O + H

- 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, lots of H_2O in the gas phase
  - If preshock gas is O-rich, neutral-neutral reactions dominate
  - If O is locked in ices, ion-neutral streaming sputters the ice off grains

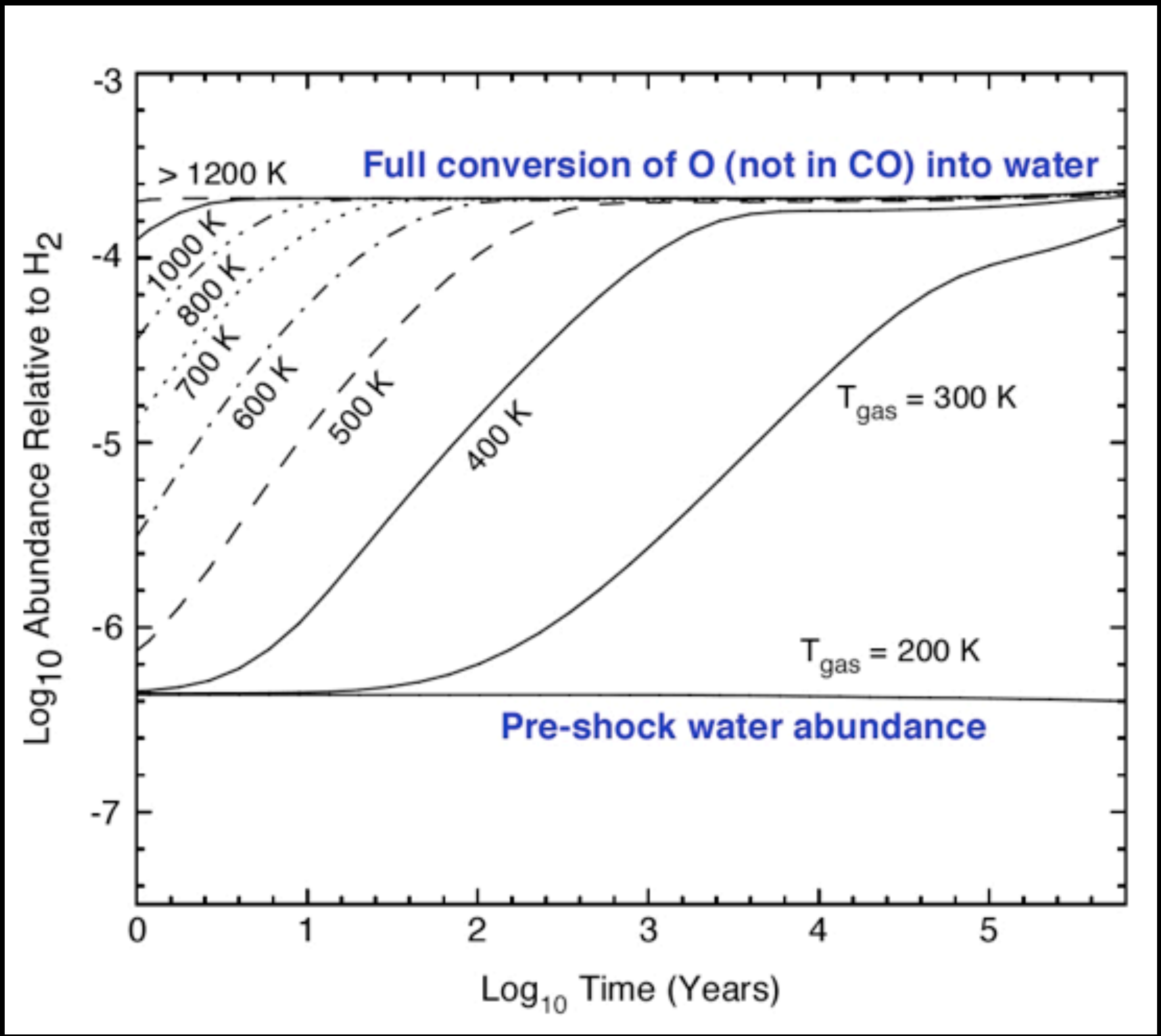
J-Shock Profile



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

Hollenbach, Elitzur & McKee 2013

Got Warm Gas?



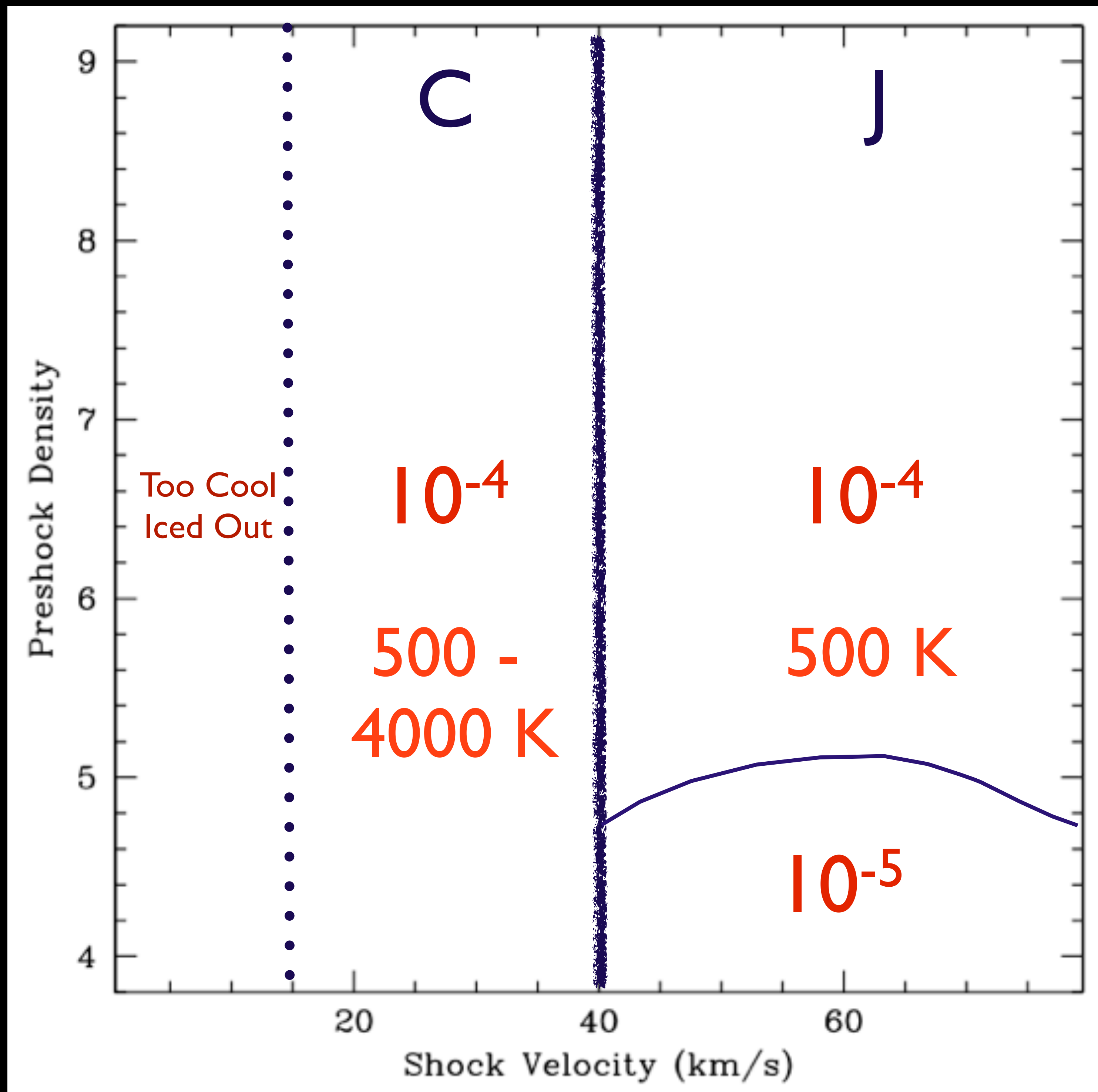
Bergin, Melnick & Neufeld 1998

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

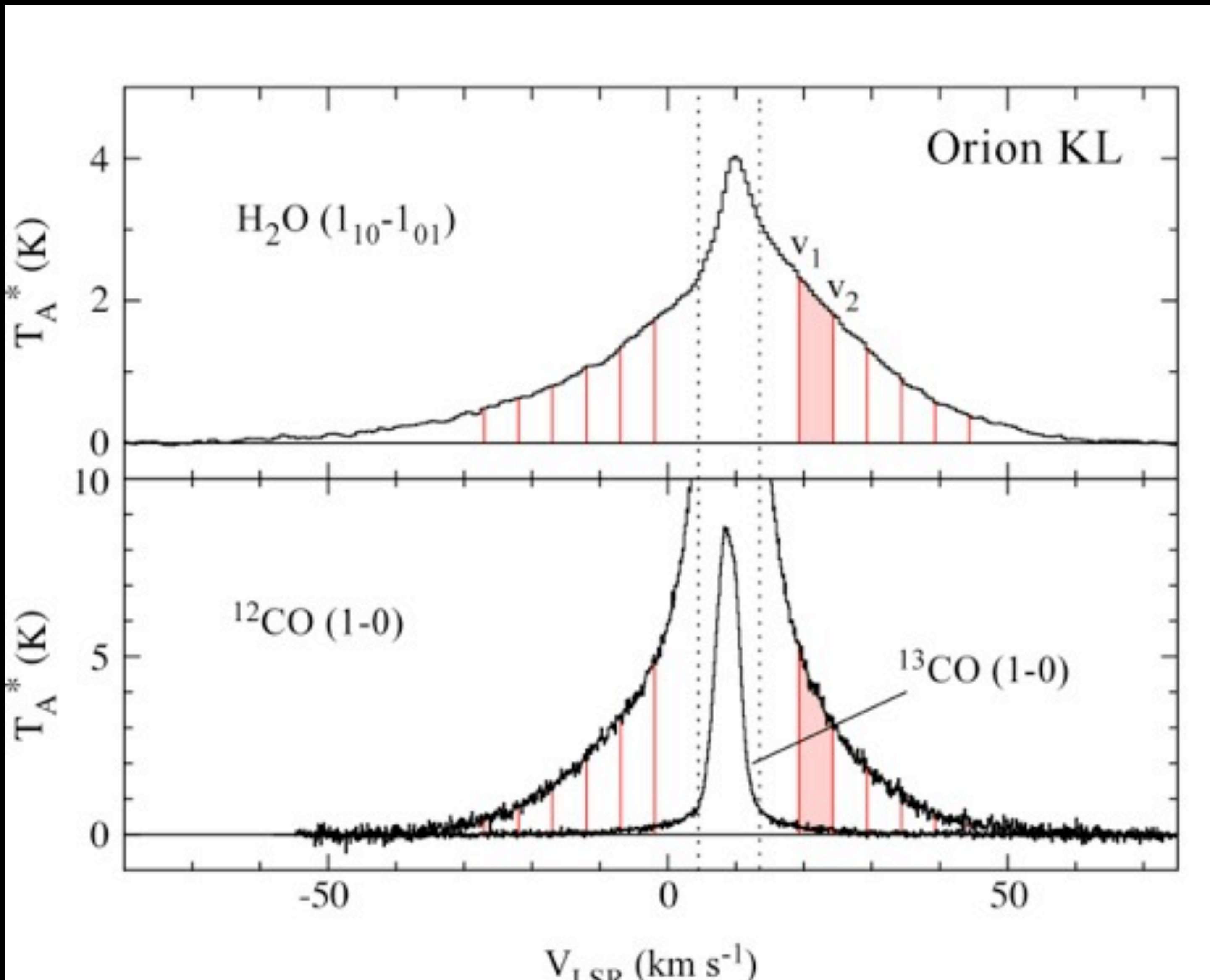
WISH expected to find high water abundances in shocked gas!

Friday, October 18, 13

Post-shock H_2O Abundance



SWAS: spectral resolution adds nuance



Assume:

$n(H_2) = 10^5$ cm^{-3}

T_{gas} = 30 K (Low-lum. YSOs)
50 K (Lum. YSOs)
100 K (Orion KL)

$N(H_2)_{v_1,v_2} = 10^4 \times N(CO)_{v_1,v_2}$

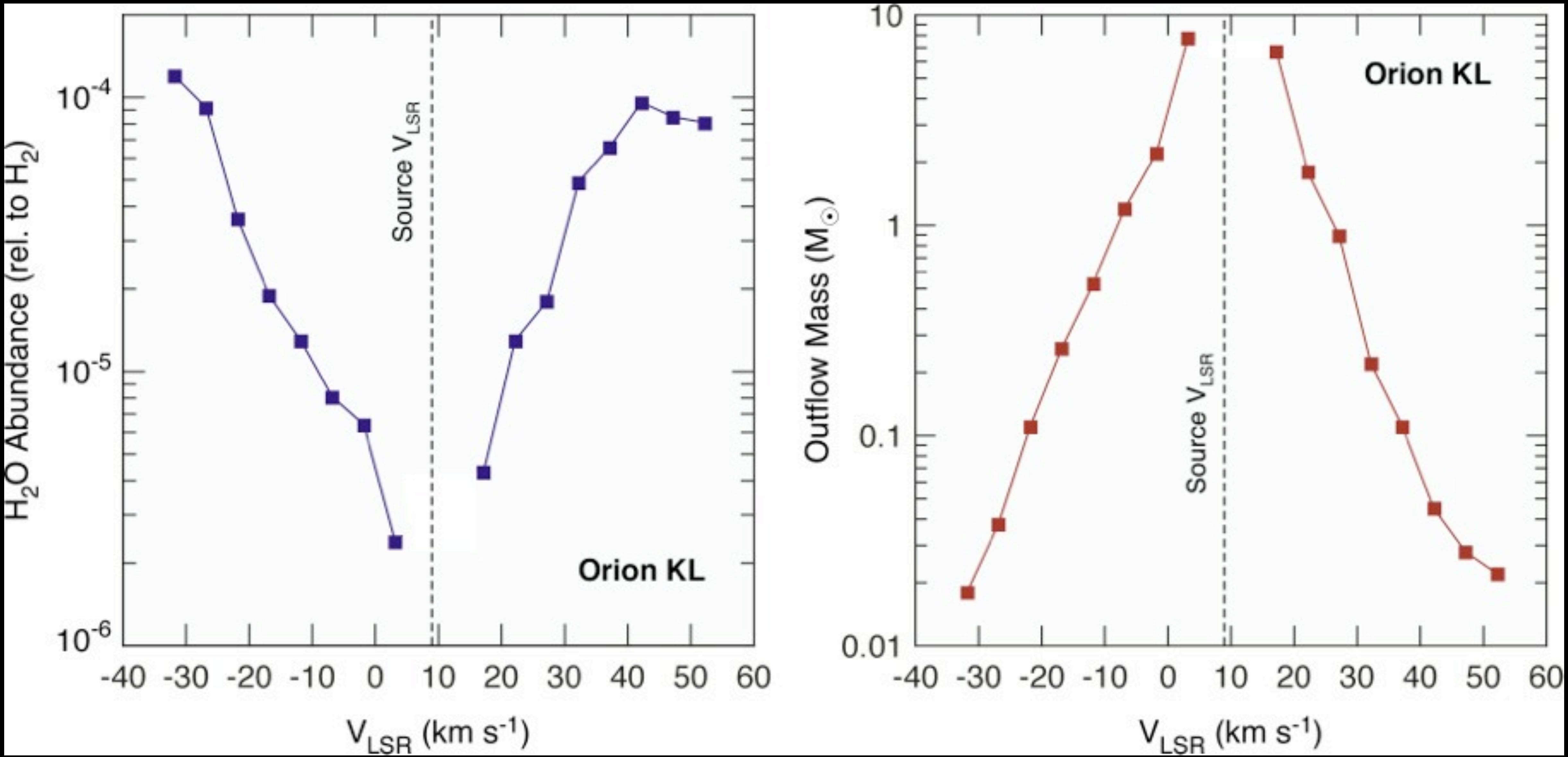
Check: SWAS ^{13}CO J = 5 - 4

Mass (v_1,v_2) = $m(H_2) \times N(H_2)_{v_1,v_2} \times$ emitting $area_{v_1,v_2}$

$x(o\text{-}H_2O)$ from LVG model that reproduces $\int T_A^*\, dv$ between v_1,v_2

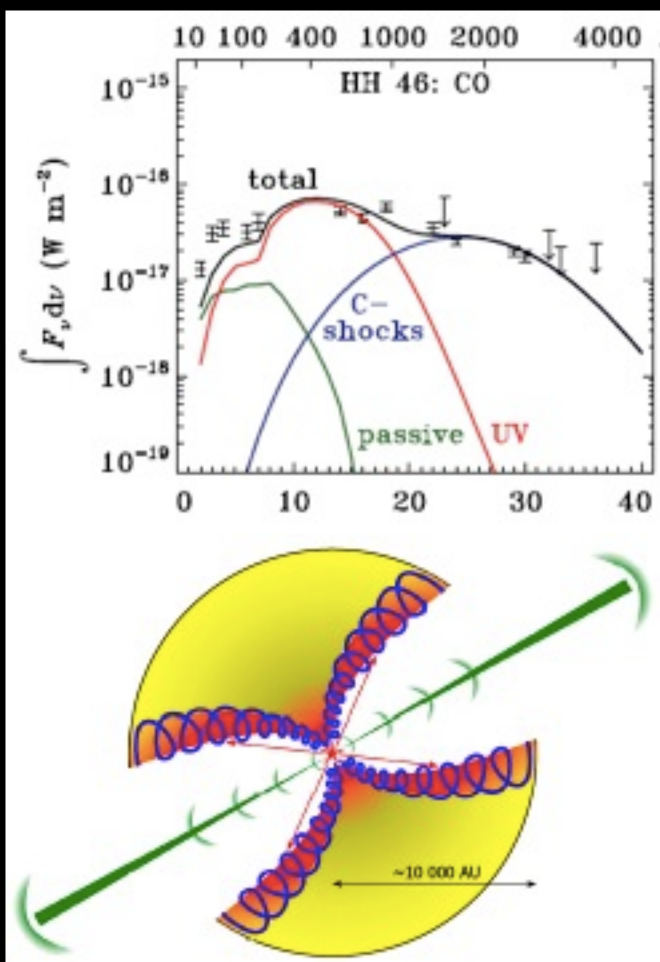
Franklin et al. 2008

Less than 1% of the outflow gas has passed through shocks strong enough to convert all O (not in CO) into H_2O



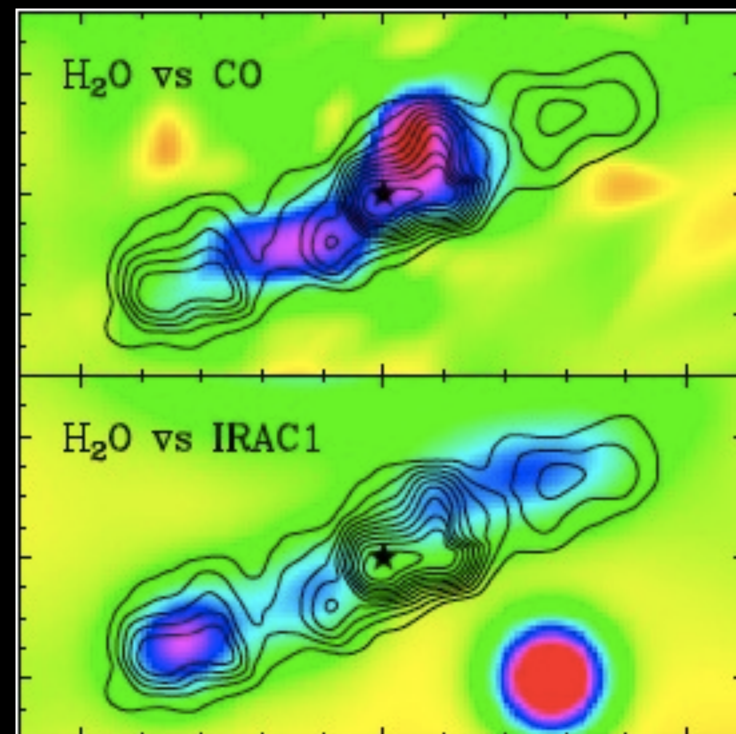
Franklin et al. 2008

..... and then came Herschel



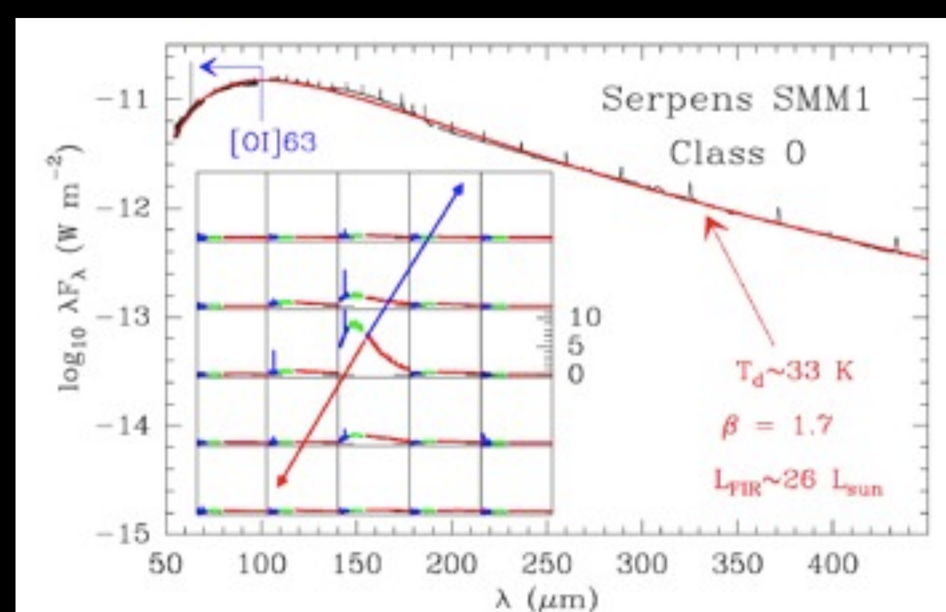
HH46 CO ladder

Visser et al. 2011



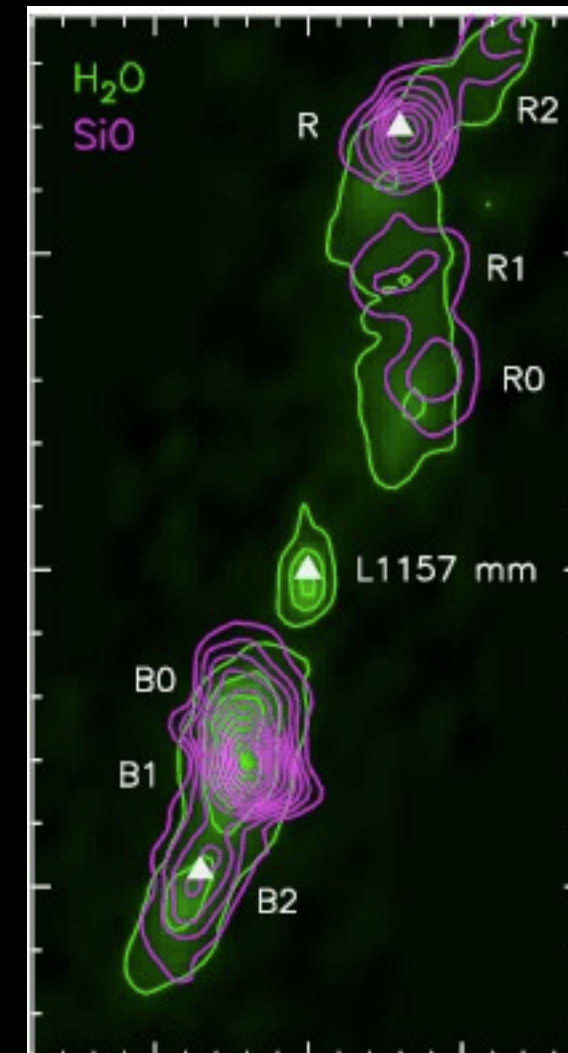
HH211 Tafalla et al. 2013

$x(H_2O) \sim 3 \times 10^{-7}$ at high nT



Ser SMM1 Goicoechea et al. 2013

$x(H_2O) < 2 \times 10^{-6}$, T ~ 800 K

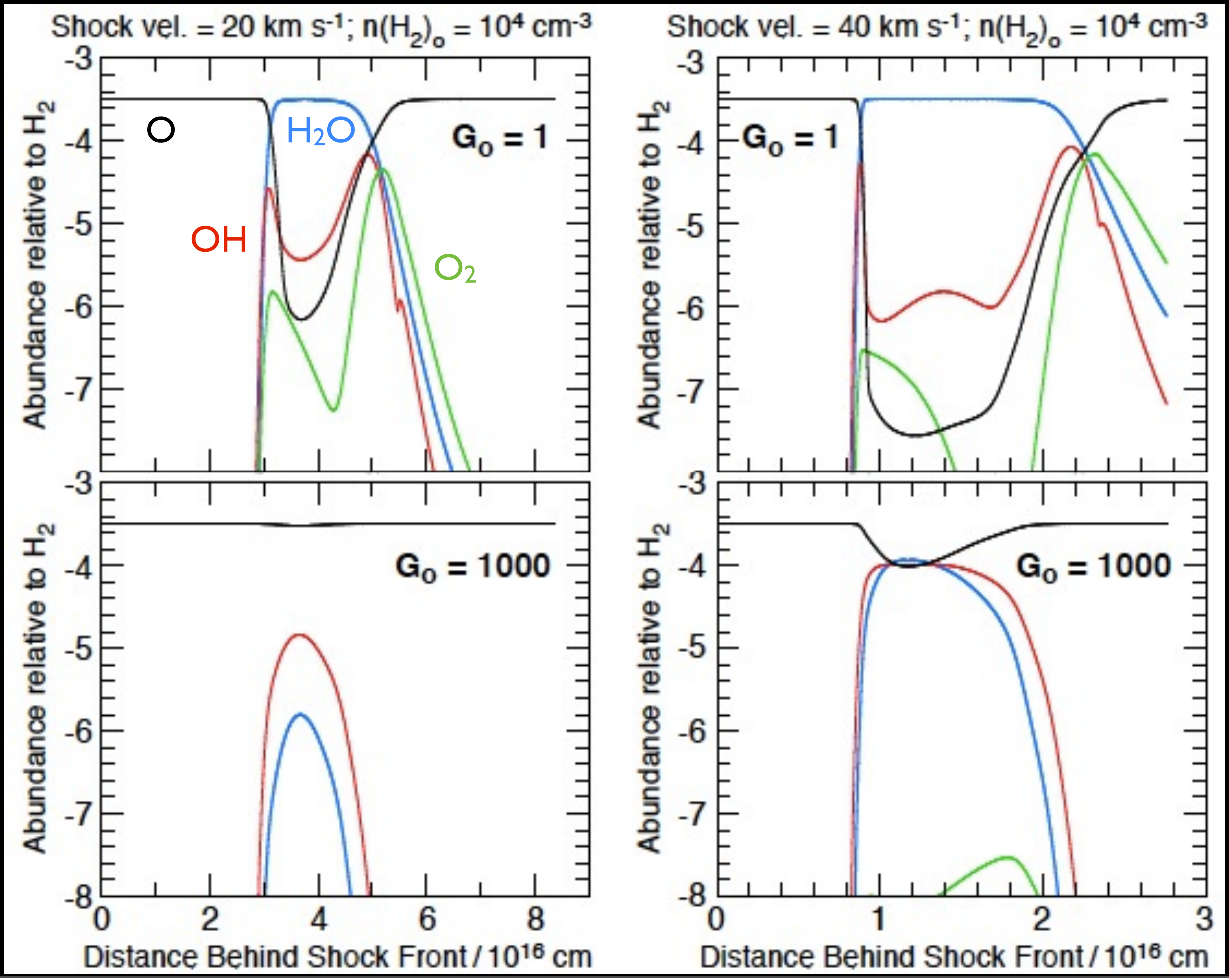


L1448 Santangelo et al. 2013

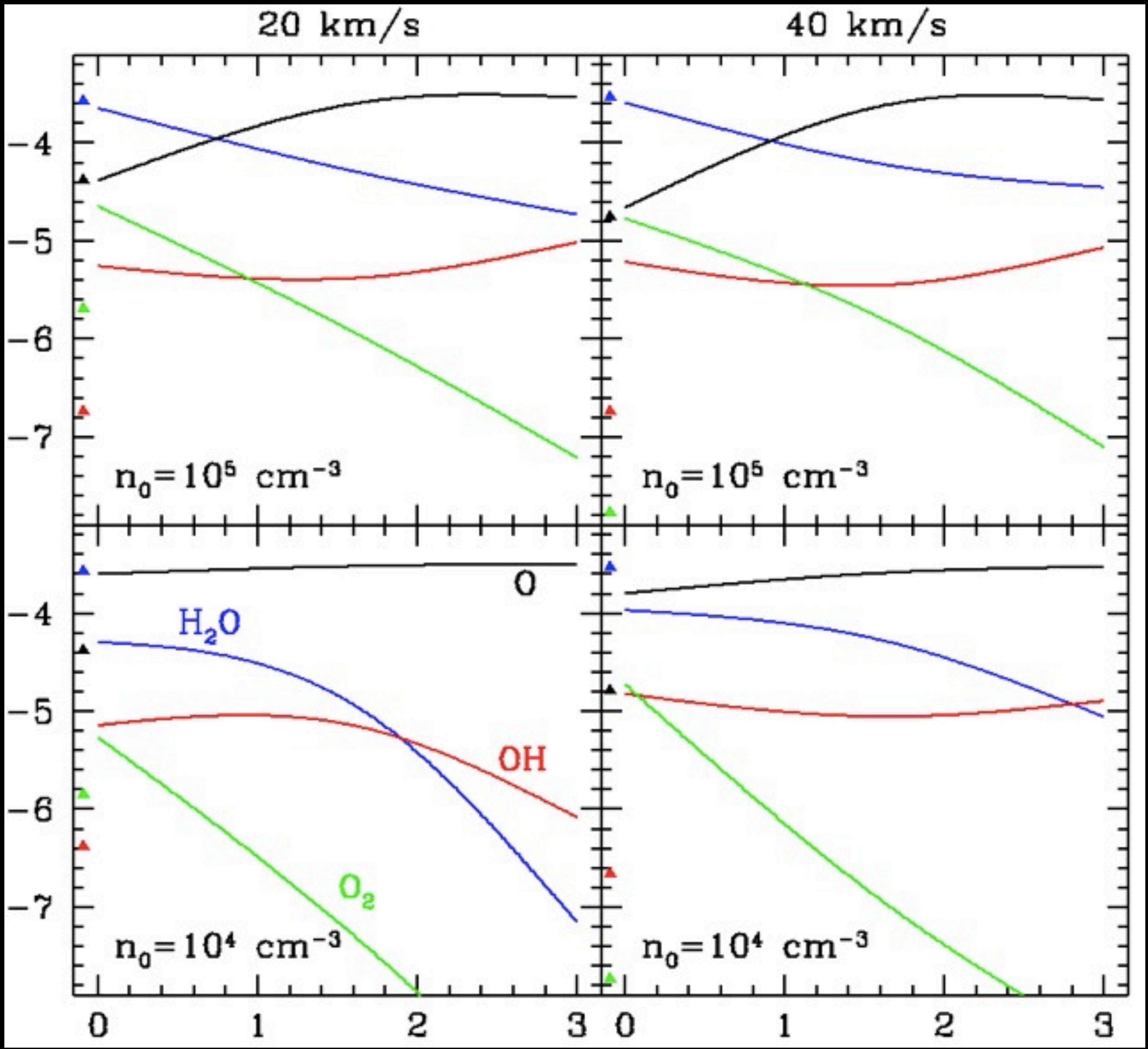
$x(H_2O) \sim 10^{-6} - 10^{-5}$

T ~ 1100 K

Simple Modification: Shock Chemical Profiles with External FUV



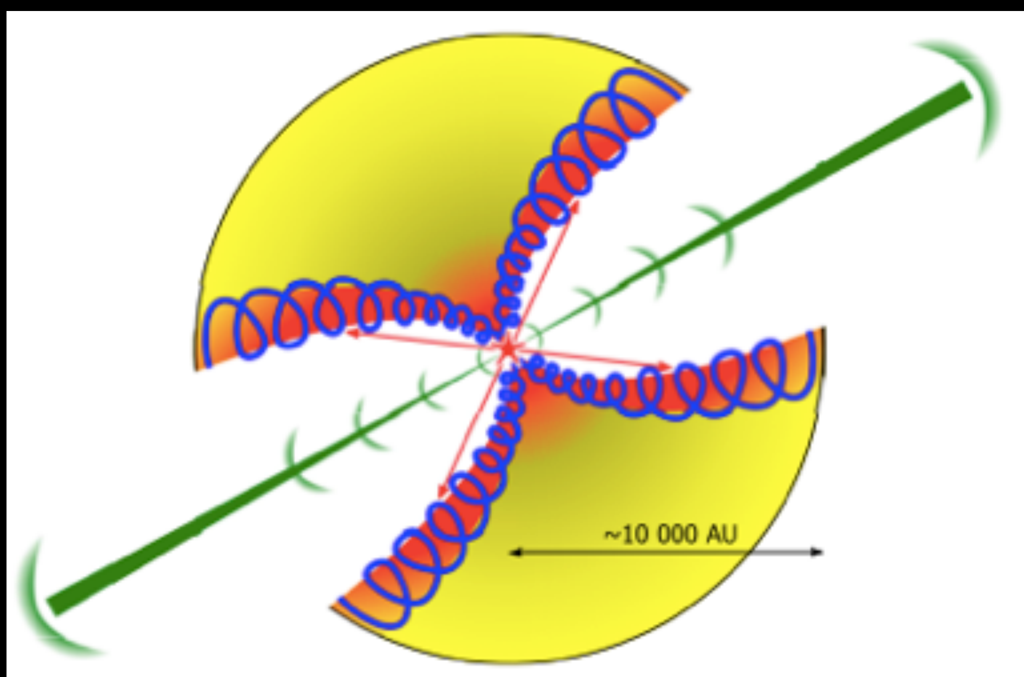
FUV influence on Postshock O-chemistry



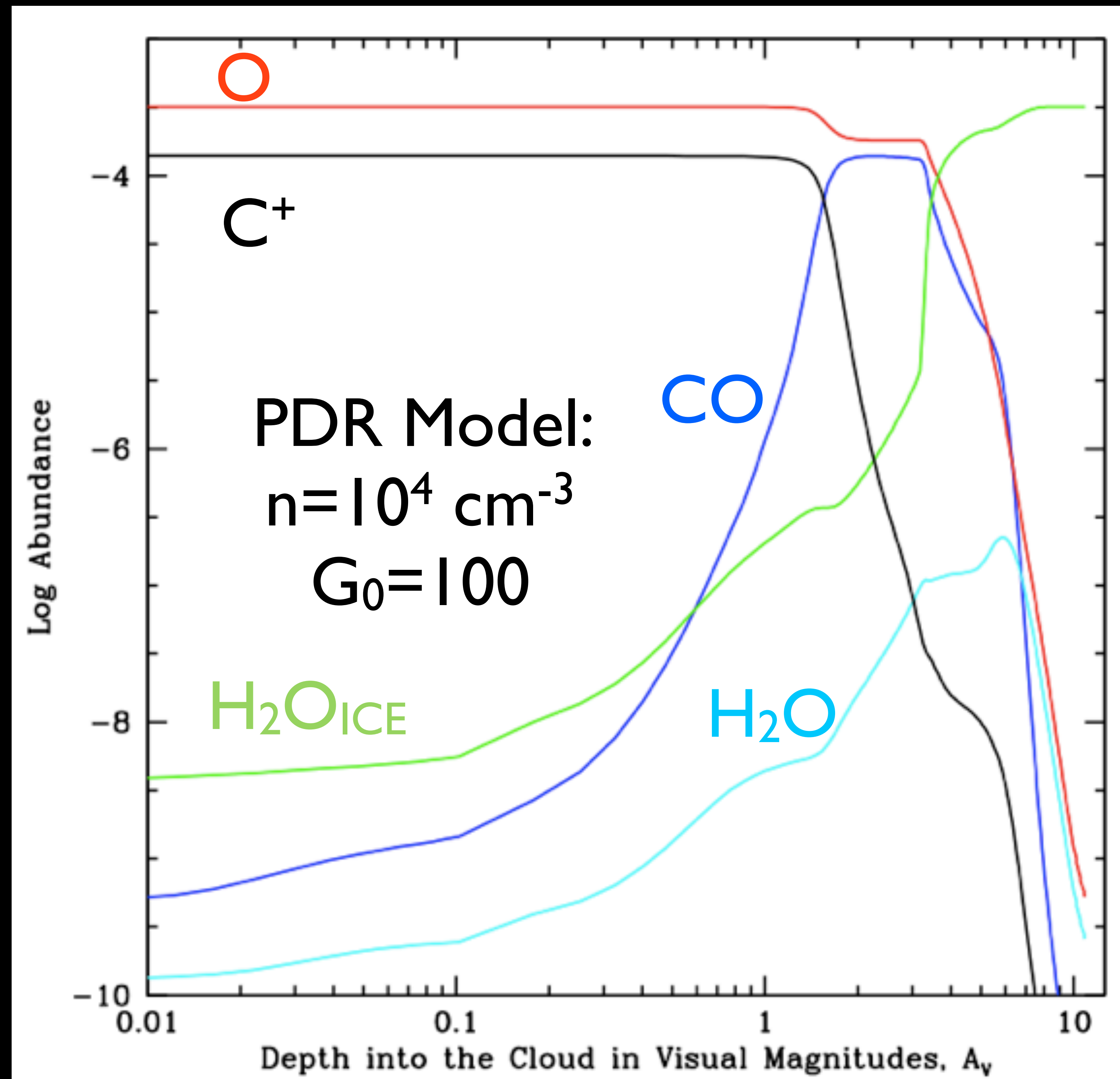
log[Column relative to H_2]

log[FUV Field Strength]

What are the preshock conditions in the protostellar environment?

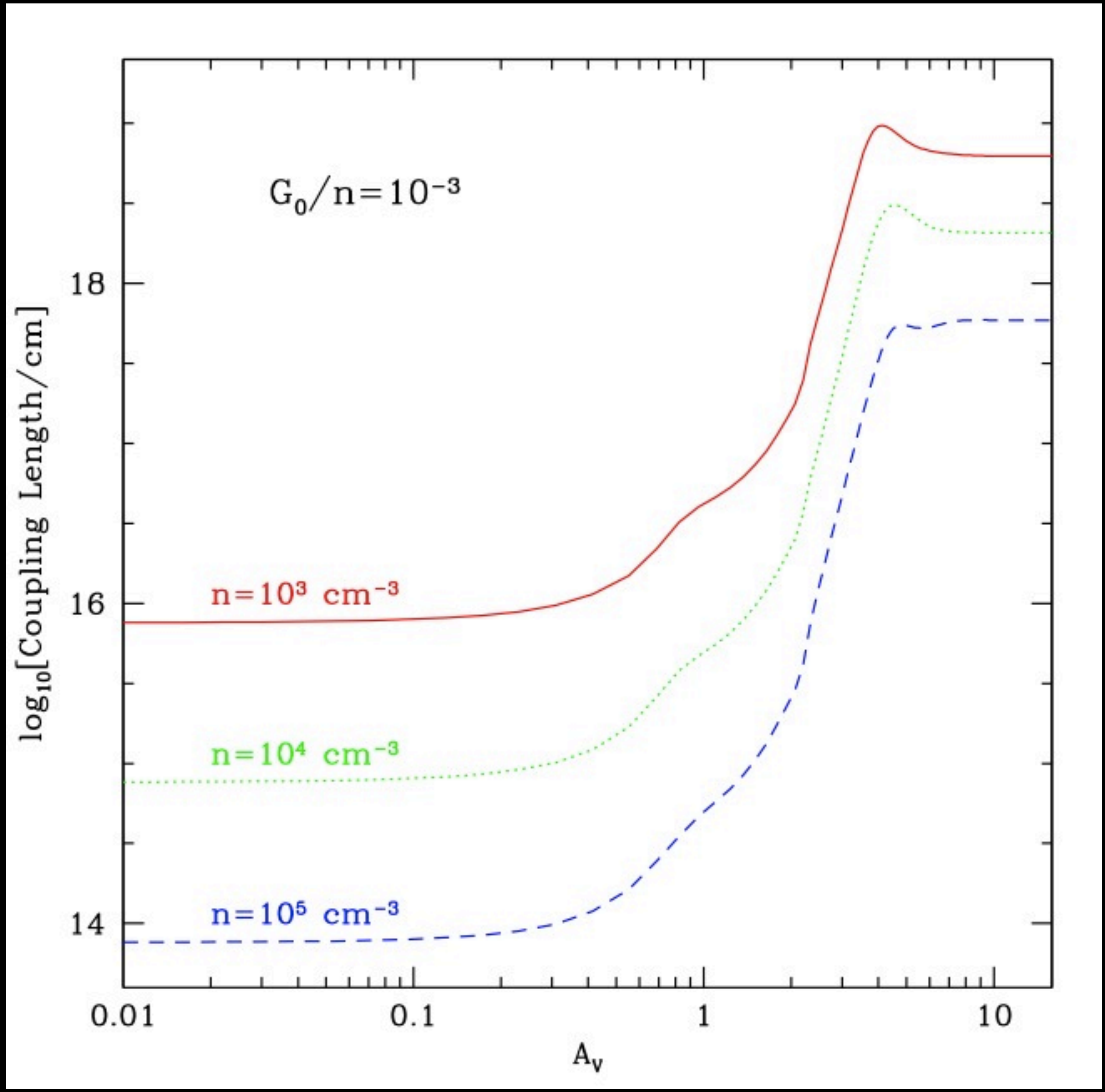


Visser et al. 2011



Hollenbach et al. 2009

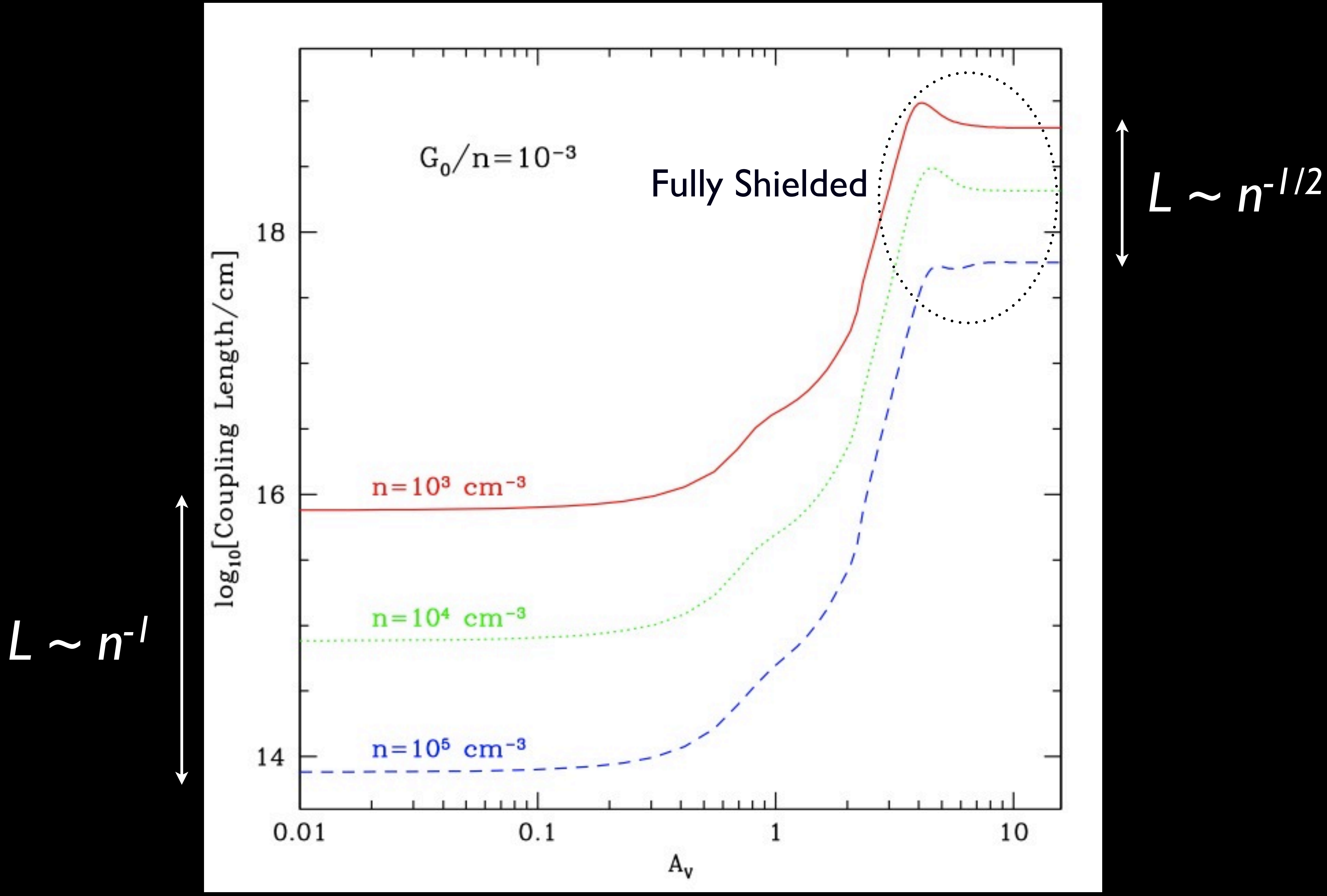
Coupling Length Varies With Extinction



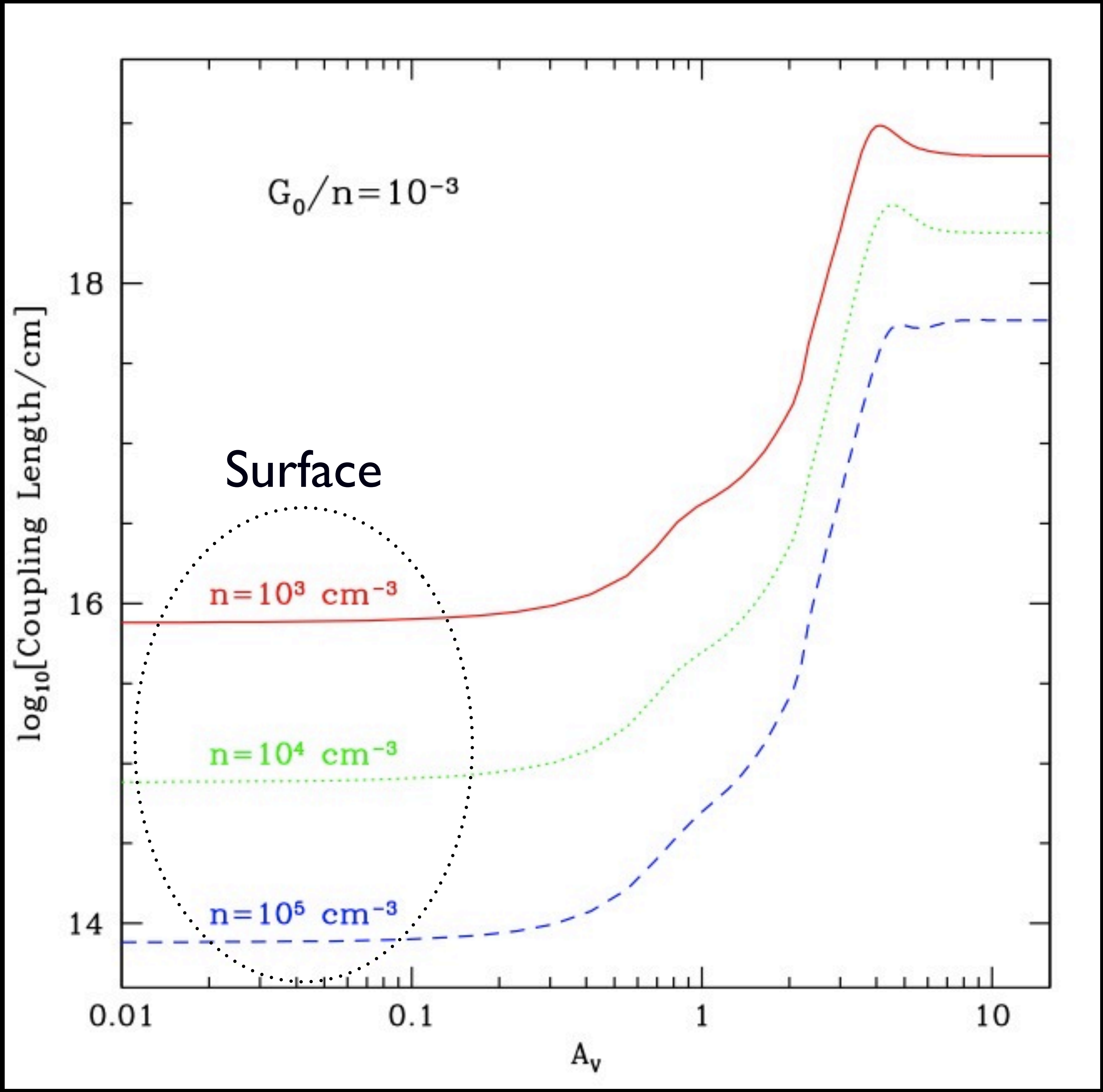
$L \sim n^{-1/2}$

$L \sim n^{-1}$

Coupling Length Varies With Extinction



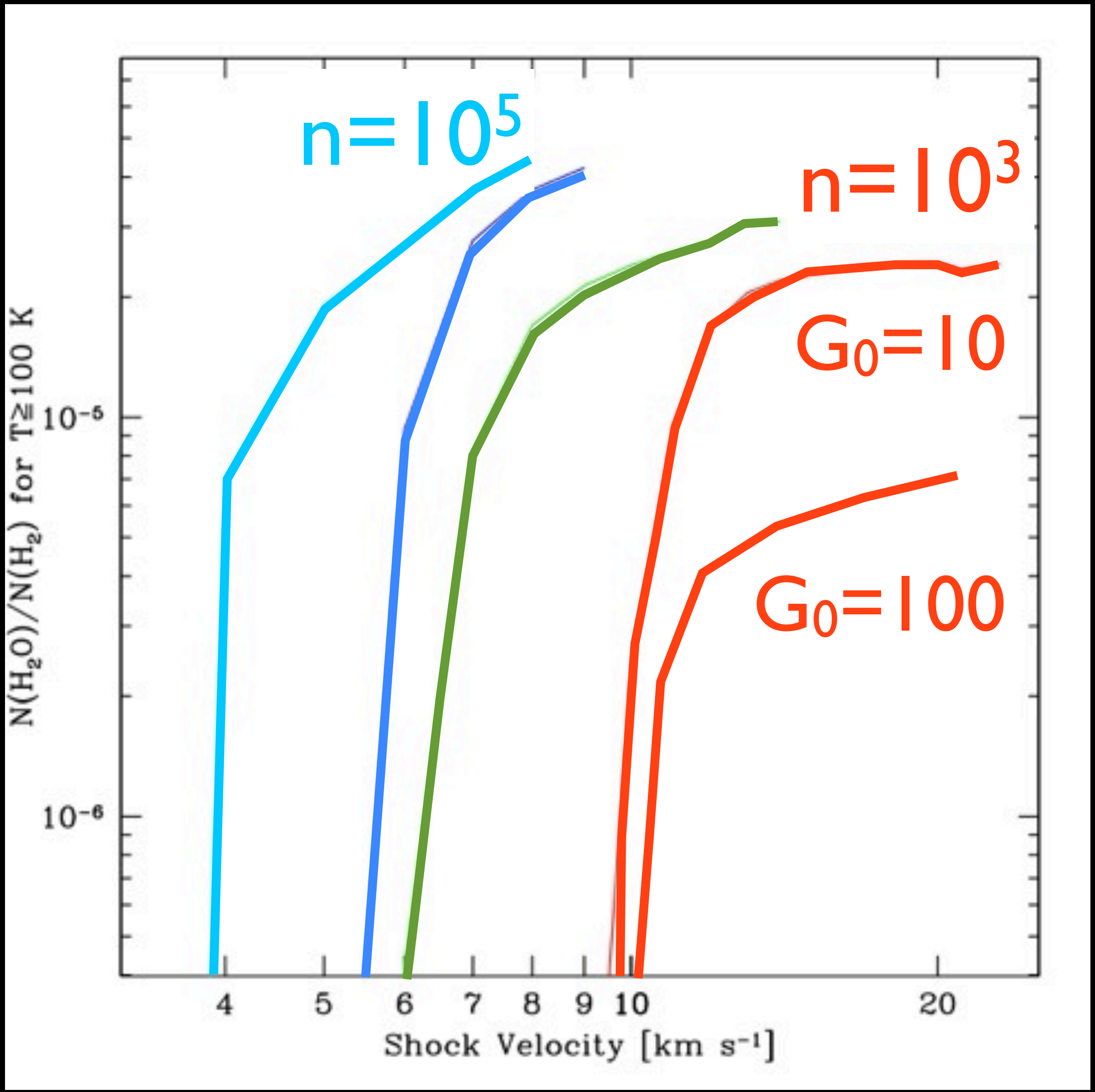
Coupling Length Varies With Extinction



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

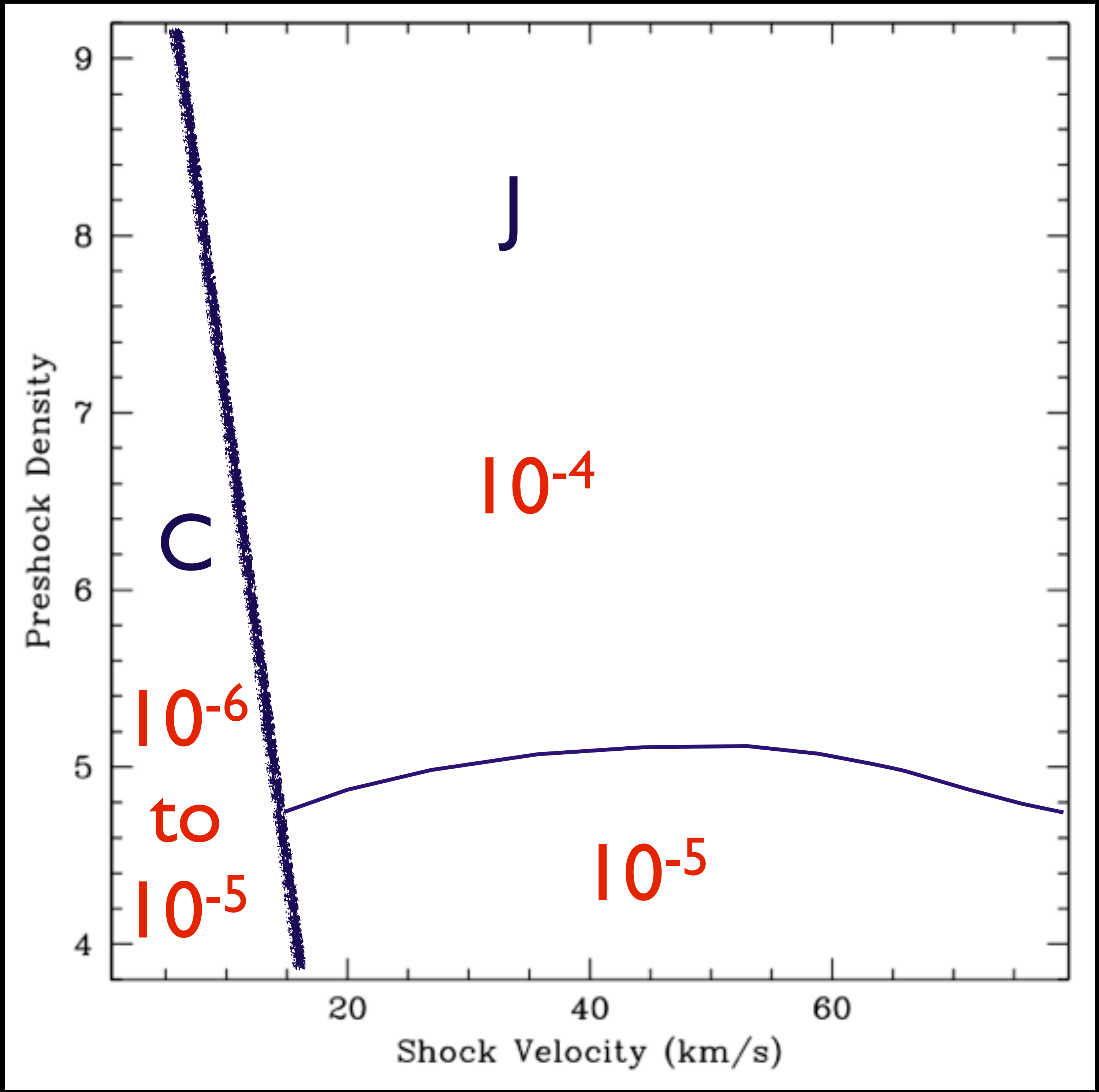
$L \sim n^{-1}$

H_2O Column Density in "Surface" Shocks

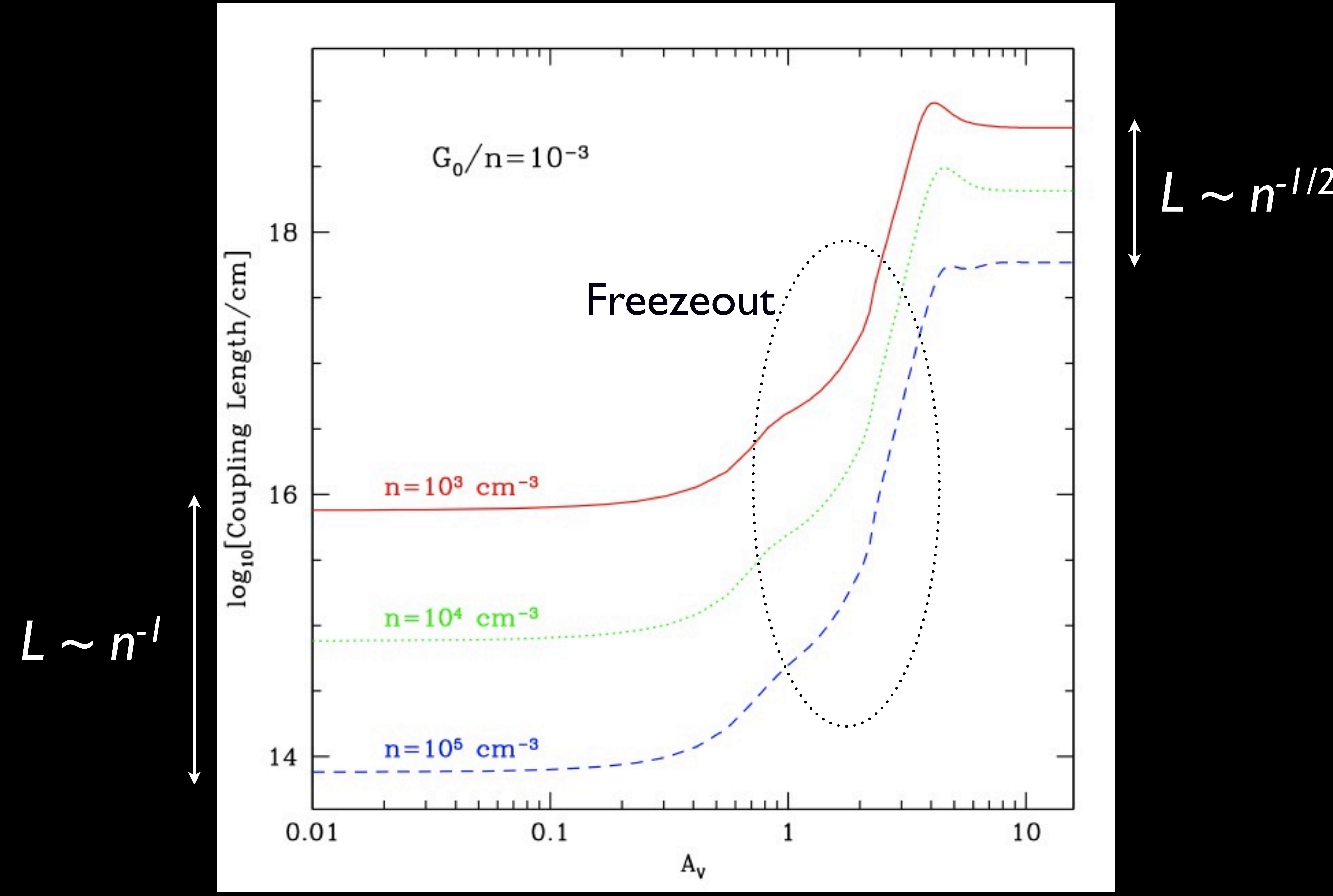


- Unlike shocks in well-shielded interiors, velocity of water formation is density dependent
- Cut-off velocity when shocks go through sonic-point (also density dependent)

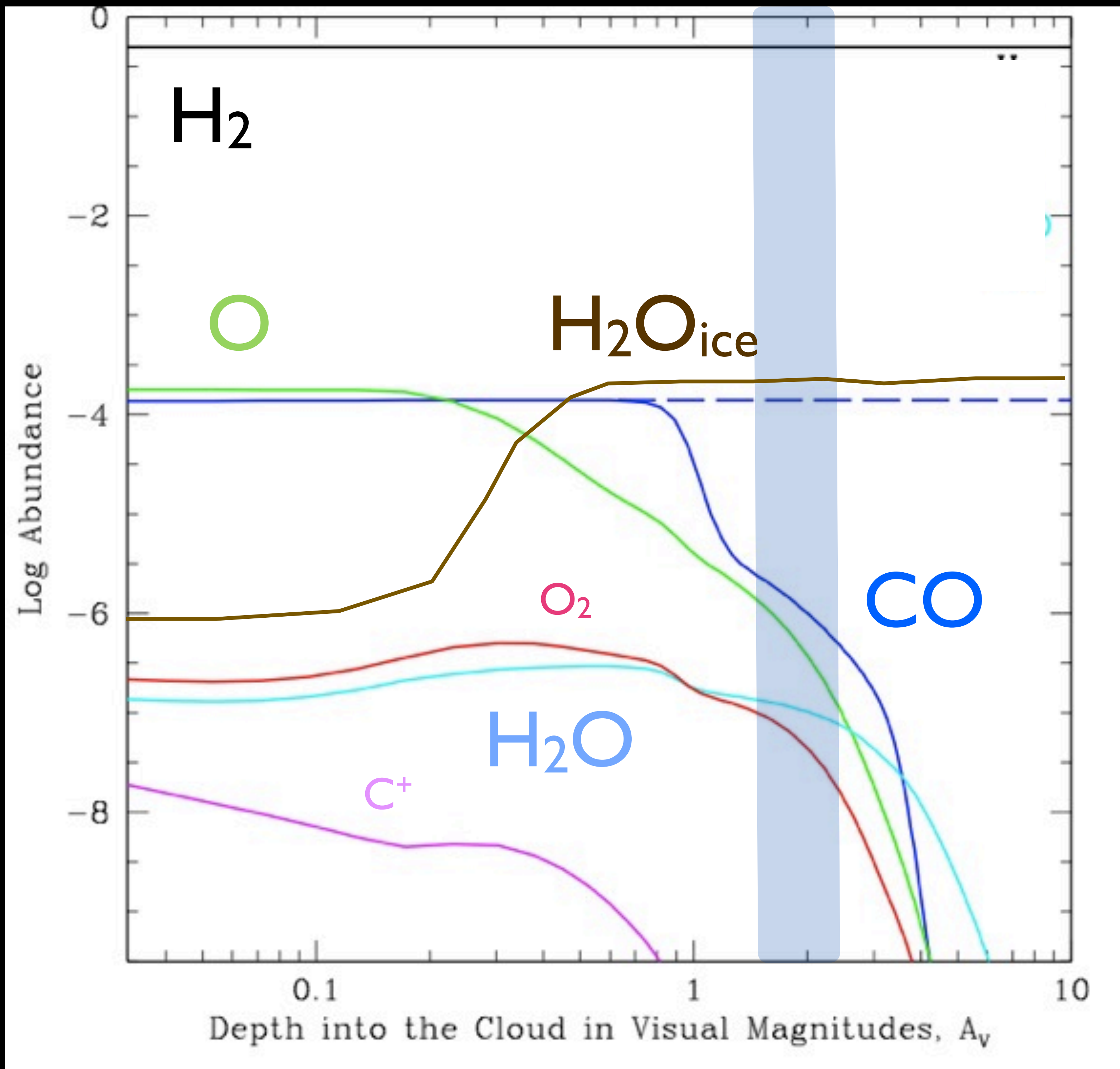
Post-shock H_2O Abundance: Surface Shocks



Coupling Length Varies With Extinction



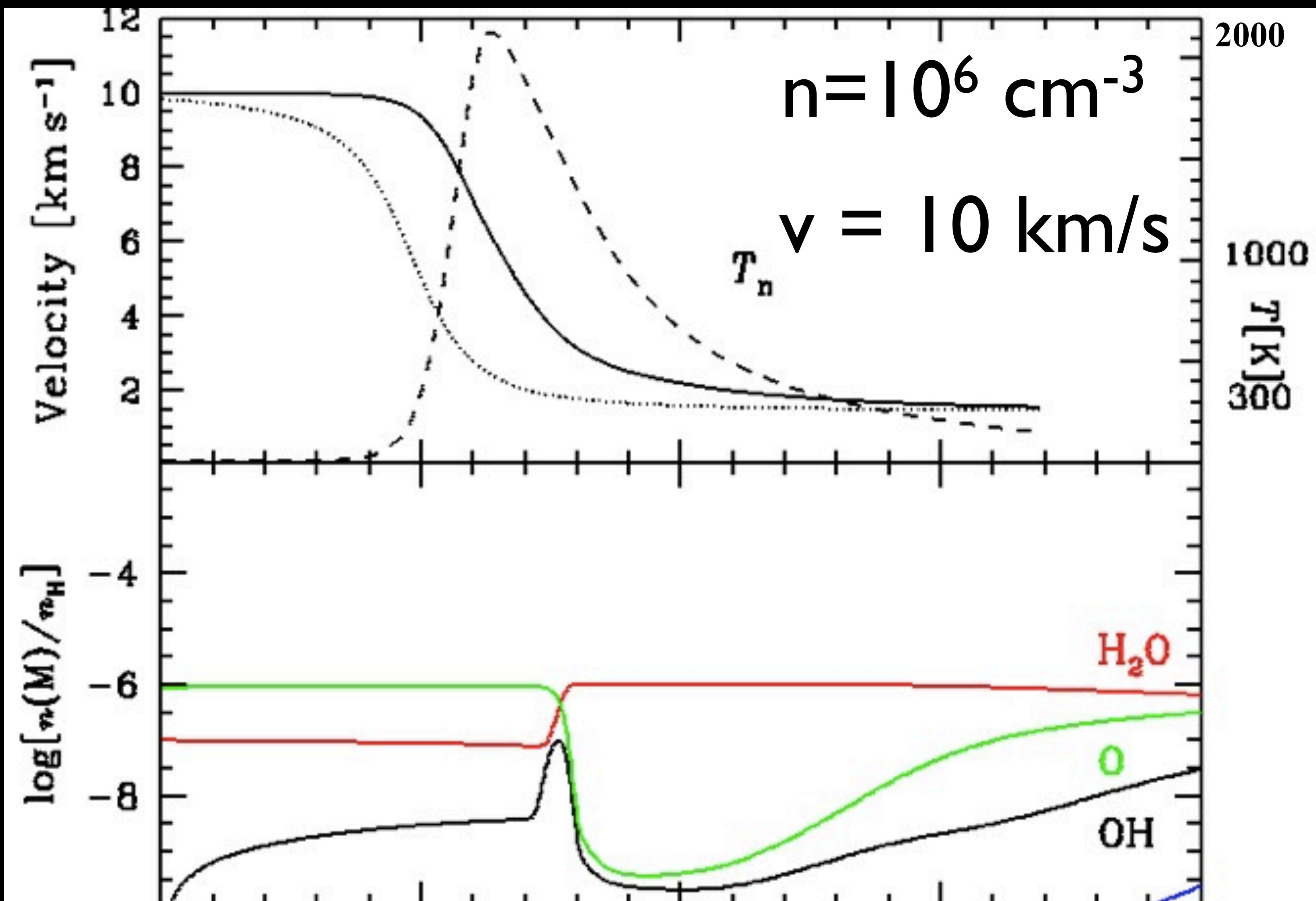
Preshock PDR: $n=10^6$ cm^{-3}, $G_0=10^2$
SEQUESTERED OXYGEN!



Gas at $A_V \sim 2$ has the conditions needed for suppression of water abundance

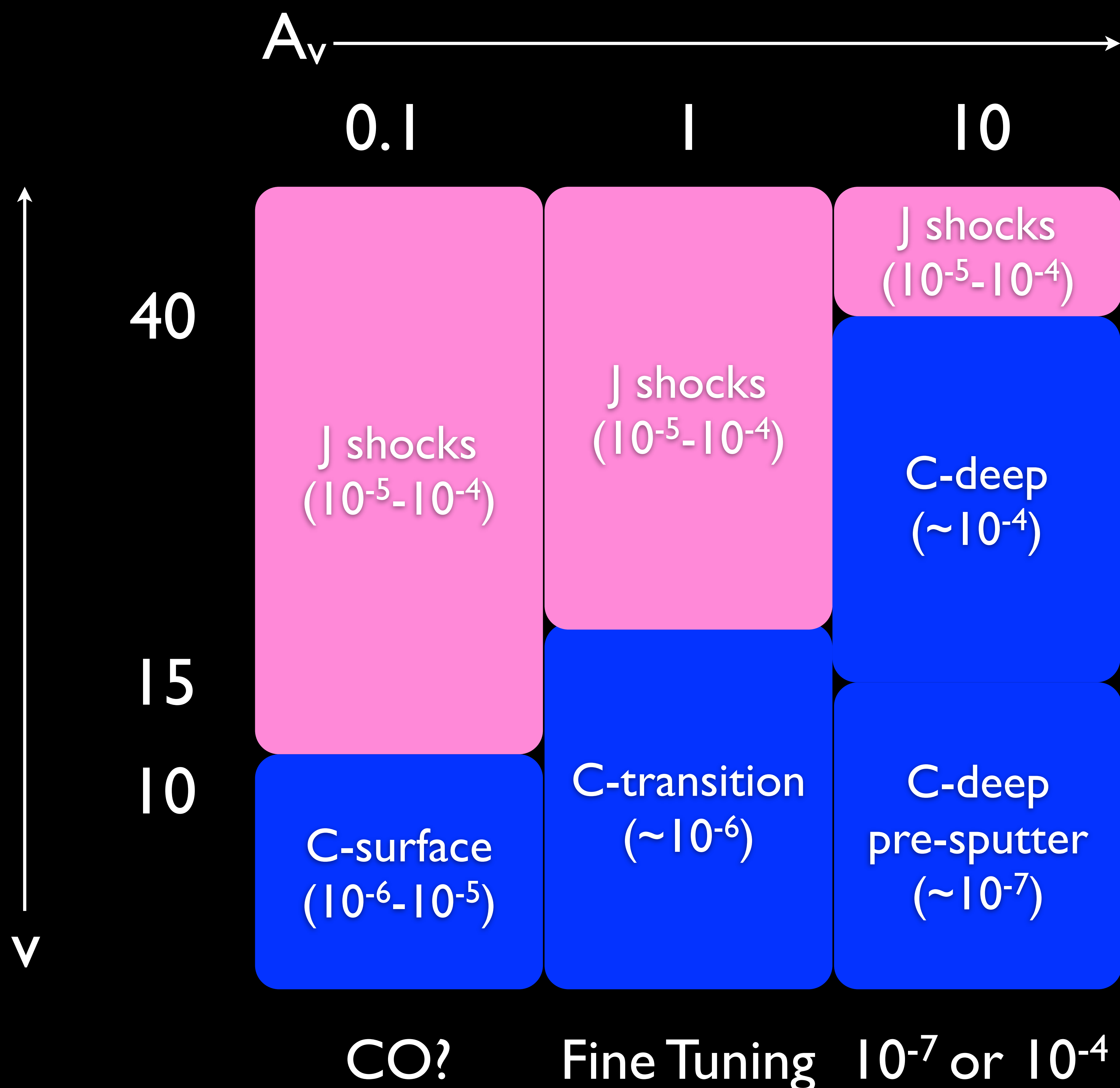
- O frozen out
- CO abundance down
- Coupling length such that shocks over ~15 km/s break down

Transition Region: Freeze-out *and* Shortened L_{in}



- Preshock gas has higher ionization fraction and almost all O frozen out on grains
- Dissociation breakdown occurs at v < 15 km/s ==> very little water in the gas phase

Gas can be STRONGLY shocked and still not make much H_2O



A_V
0.1
1
10
40
15
10
v
J shocks
(10^{-5}-10^{-4})
J shocks
(10^{-5}-10^{-4})
J shocks
(10^{-5}-10^{-4})
C-deep
(~10^{-4})
C-surface
(10^{-6}-10^{-5})
C-transition
(~10^{-6})
C-deep
pre-sputter
(~10^{-7})
CO?
Fine Tuning
10^{-7} or 10^{-4}

So.... where can you get (really) low H_2O abundances from C-shocks?

- Not in fully shielded gas, unless speed is low ($v < 15$ km/s).....but maybe none!
- Maybe in surface gas: C-shocks make water efficiently even at low velocity, but sufficiently high FUV can suppress it. PROBLEM: little CO emission!
- Perhaps in "freezeout" gas, where ion-neutral coupling heats gas in slow-ish shocks BUT leaves volatiles frozen on grains.