AMANDEEP SINGH

A SUB-GRID MODEL FOR MOLECULAR GAS IN A COSMOLOGICAL GALAXY FORMATION SIMULATION

ABSTRACT

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- **Studying the CO line luminosity (L_{CO}) and the shape of the CO spectral line energy distribution (SLED) in galaxies in the Epoch of Reionization (EoR)**

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- RESULTS: post-process and resolve a cosmological simulation of a sample galaxy
- **FINALLY: compared to observations taken of similar galaxies**

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  - **different excitation requirements of the various CO lines - constrain gas properties (e.g. density, temperature) & gas heating mechanisms (e.g. FUV photons, etc.)**

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  - small physical scales (≈0.1 − 1 pc) of clumps in GMCs + complex network of chemical and physical reactions in the fully molecular parts of GMCs

  - **the high-resolution hydrodynamical simulations (down to scales of ≈30 pc) of the interstellar medium (ISM) density, turbulence level, metal enrichment & radiation field into which GMCs are embedded**

SUB-GRID MODEL OUTLINE

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MACH_NO ; METALLICITY ; G_O ; n_H_MEAN ; TEMPERATURE

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- **pdf = pdf(mach_no, n_H_mean)**

$$P_V(\rho) = \frac{1}{(2\pi\sigma^2)^{1/2}} \exp\left[-\frac{1}{2}\left(\frac{\ln(\rho/\rho_0) - \langle\ln(\rho/\rho_0)\rangle}{\sigma}\right)^2\right]$$

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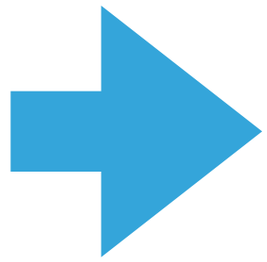

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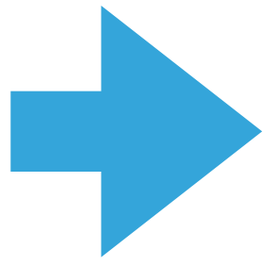

A gas cloud and it’s size

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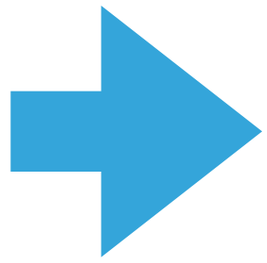

A gas cloud and it's size

- Solve the rate equation to get optical_depth, Lyman-Werner photons, molecular fractions of H2 and CO

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- **`tau = tau(jeans_length)`**

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- `c_s = c_s(T)`
- `jeans_length = jeans_length(c_s)`
- `tau = tau(jeans_length)`
- **`n_LW = G_o * exp(-tau)`**

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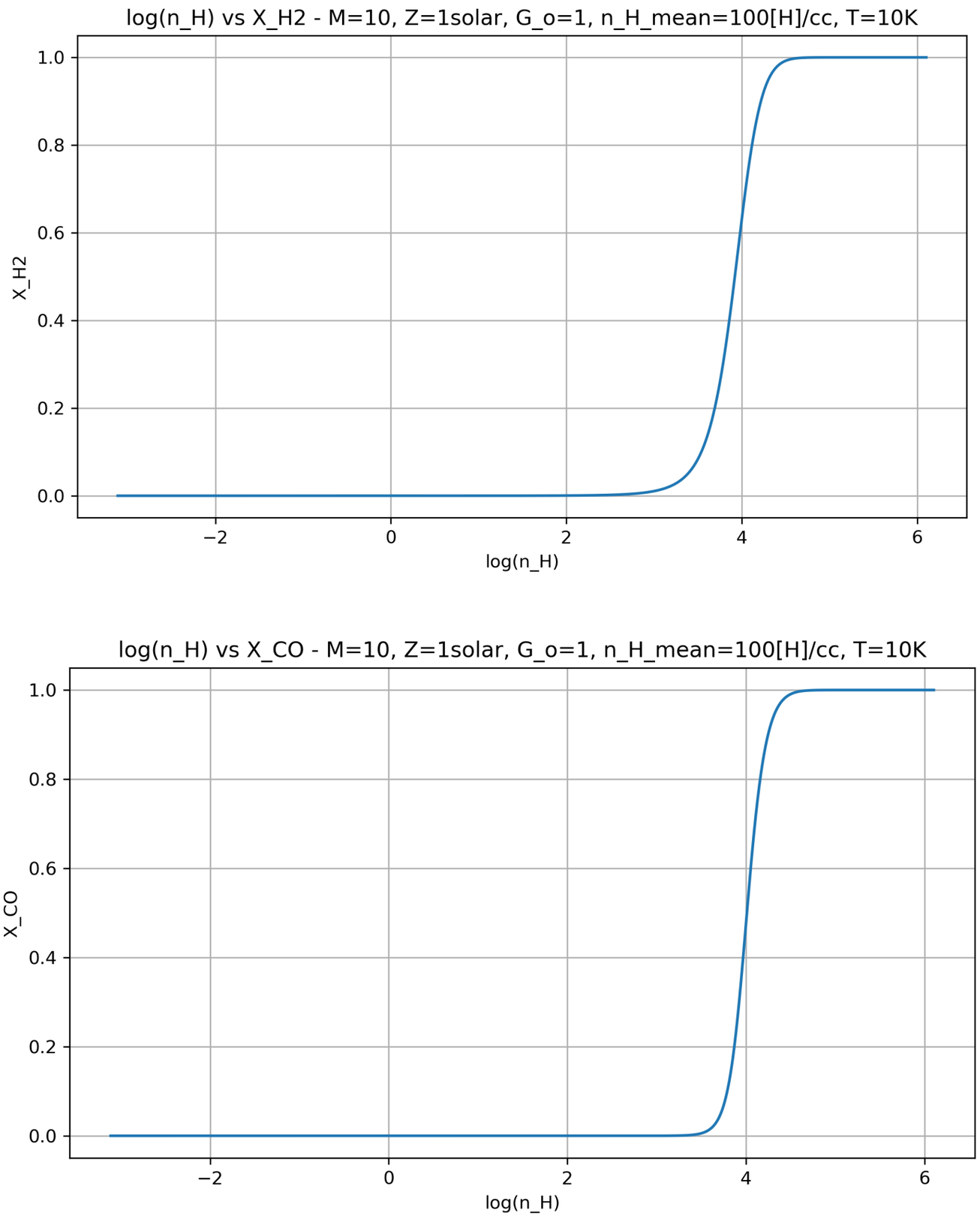
- `n_LW = G_o * exp(-tau)`
- **`X_H2 = X_H2(Z, n_LW)`**
- **`n_H2 = n_H * X_H2`**
- **`X_CO = X_CO(n_H2, n_LW)`**

SUB-GRID MODEL OUTLINE



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- **`n_H2 = n_H * X_H2`**
- **`X_CO = X_CO(n_H2, n_LW)`**

SELF-SHIELDING OF H2 !

(Draine & Bertoldi 1996)

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- **`n_H2 = n_H * X_H2`**

- **`n_LW_ss = G_o * exp(-tau) * S_H2(n_H2,j_len)`**
- **`X_H2_ss = X_H2(Z, n_LW_ss)`**
- **`n_H2_ss = n_H * X_H2_ss`**

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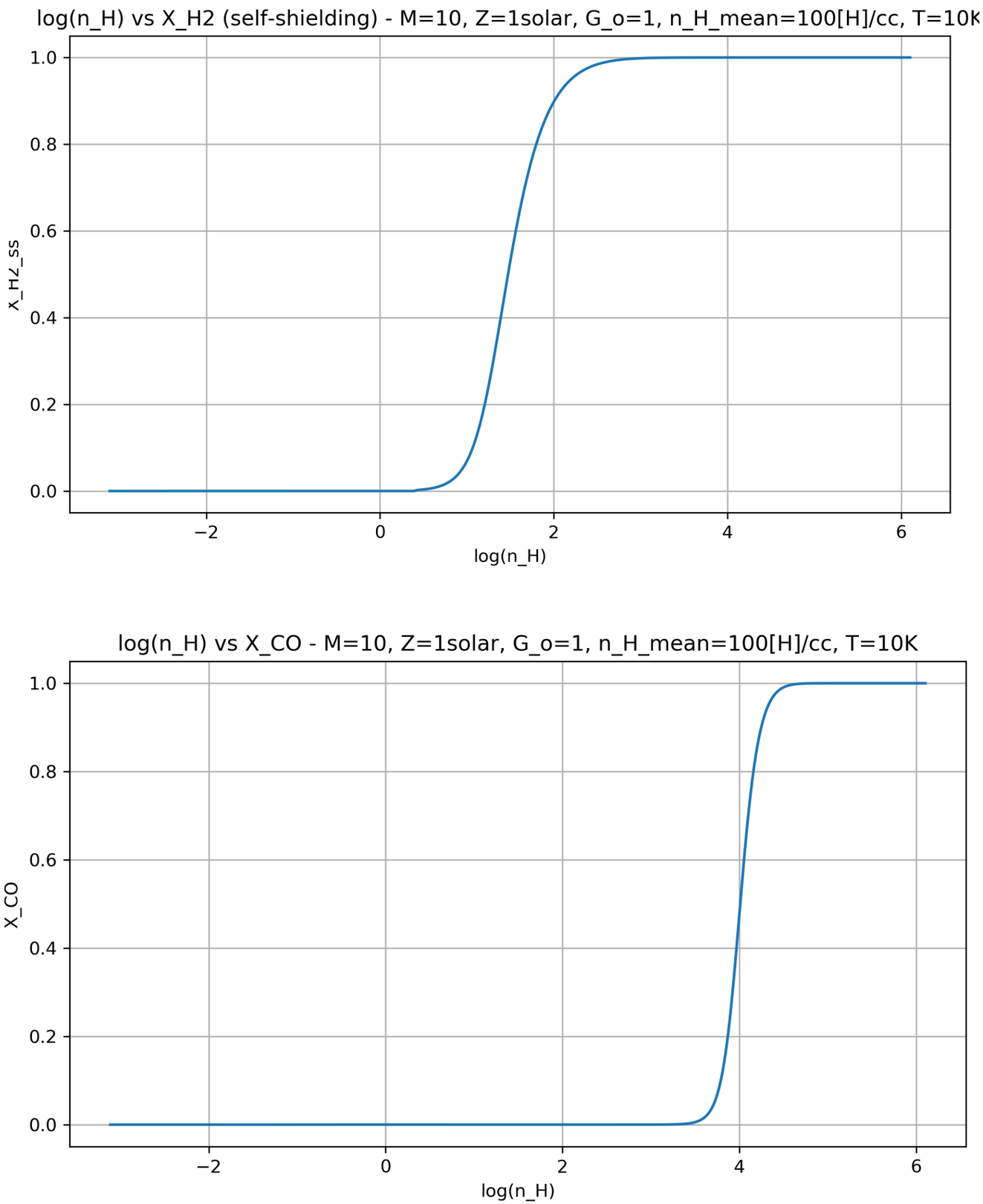

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- n_H2 = n_H * X_H2
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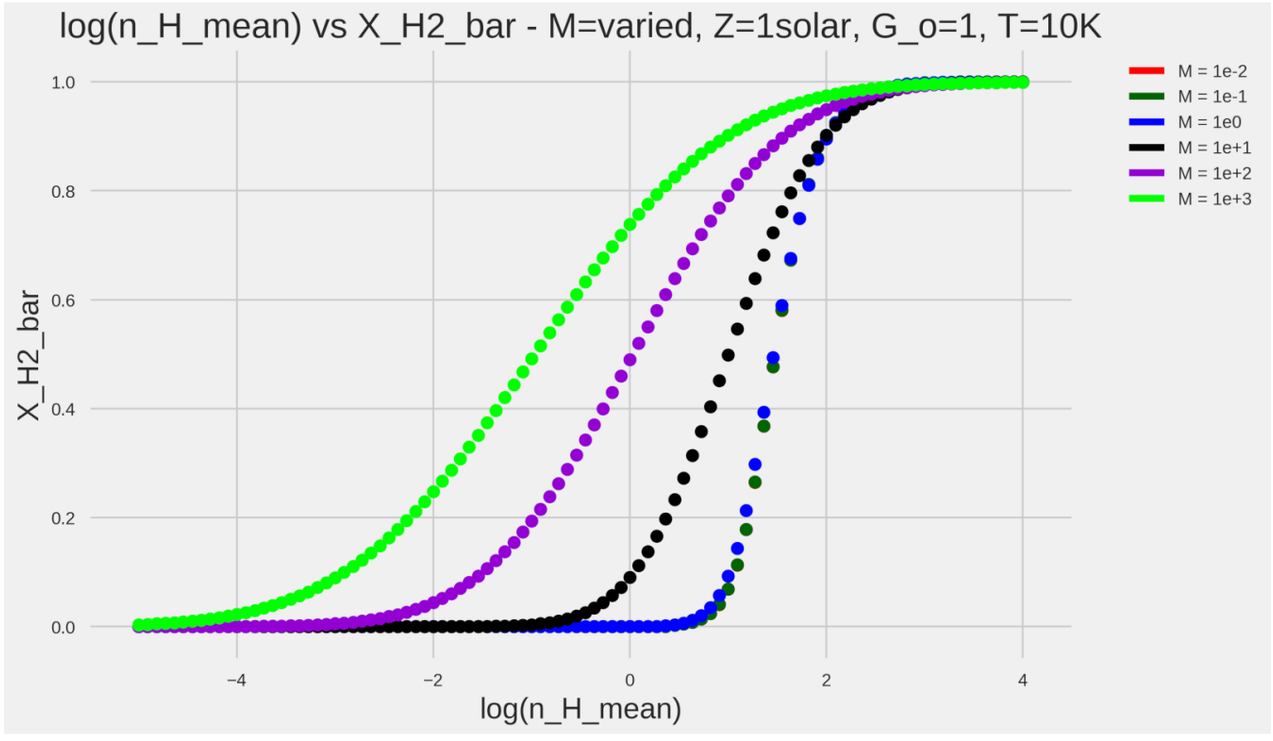
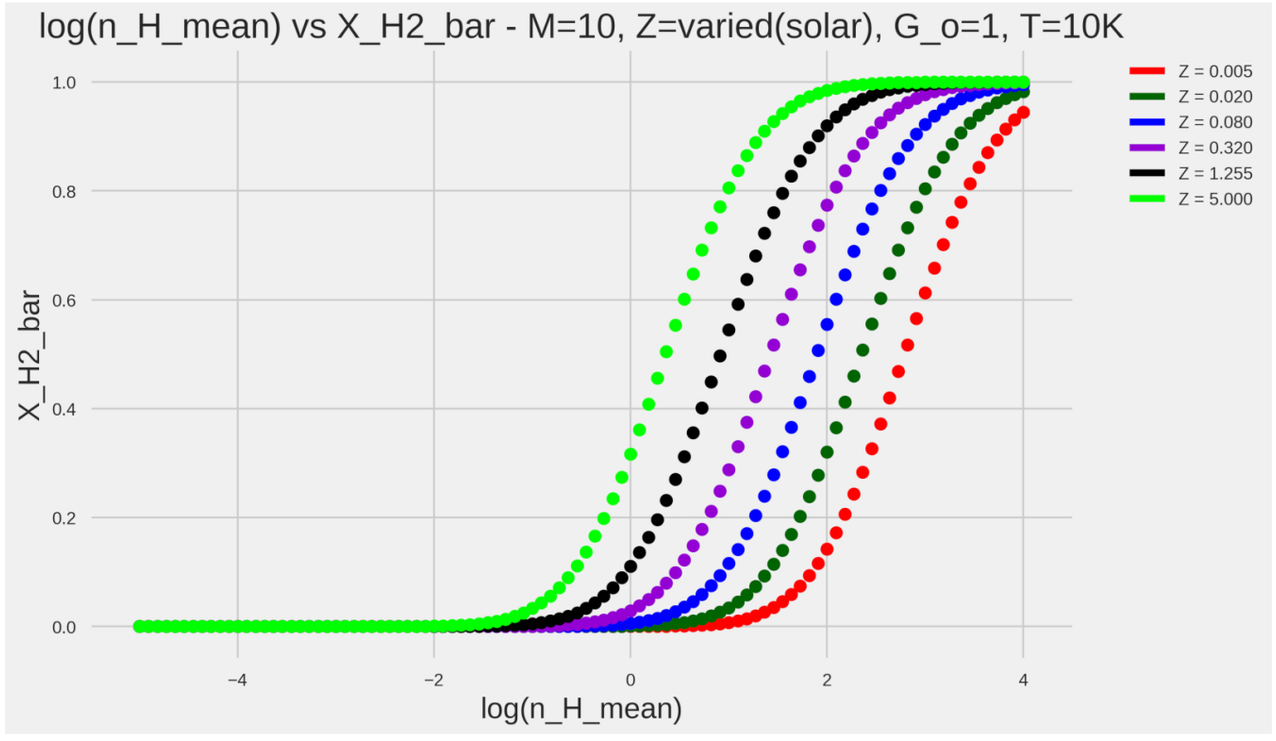
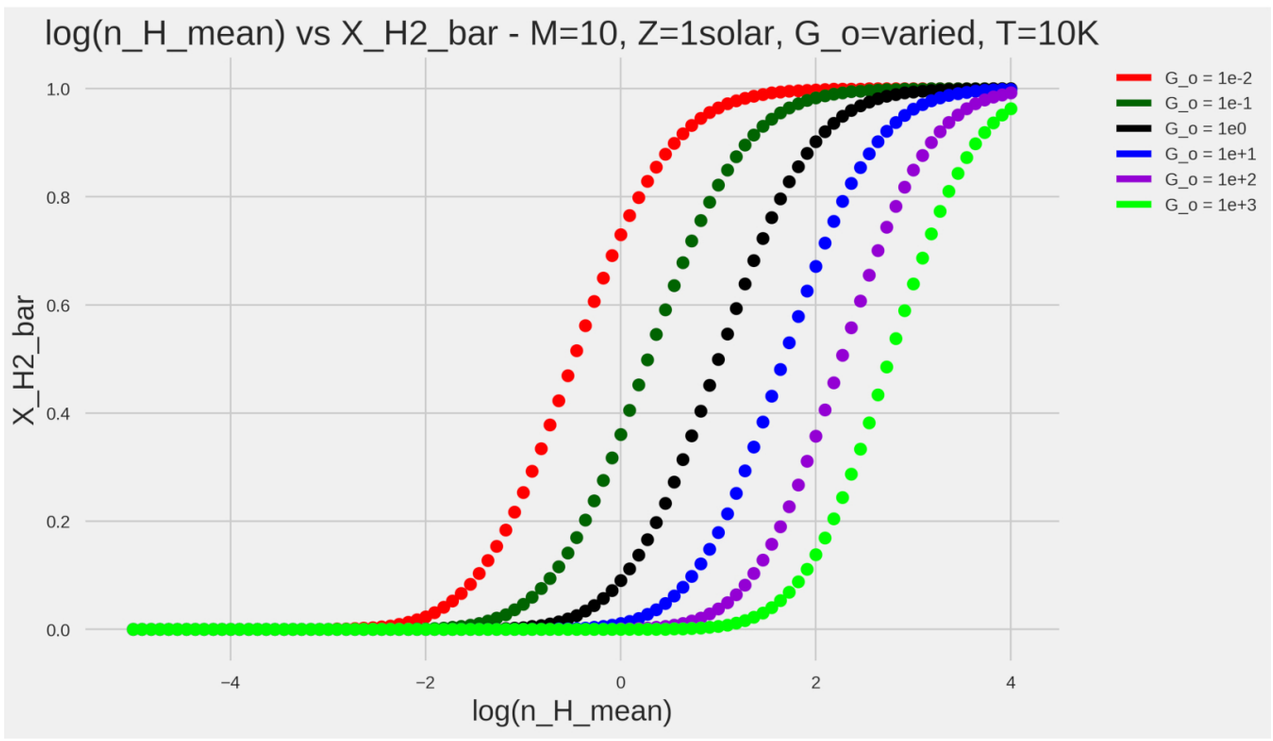
- X_H2_ss = X_H2(Z, n_LW_ss)
- n_H2_ss = n_H * X_H2_ss
- X_CO = X_CO(n_H2, n_LW)
- **X_H2_bar = integ (exp(s)* pdf * X_H2_ss * ds)**
- **X_CO_bar = integ (exp(s)* pdf * X_CO * ds)**

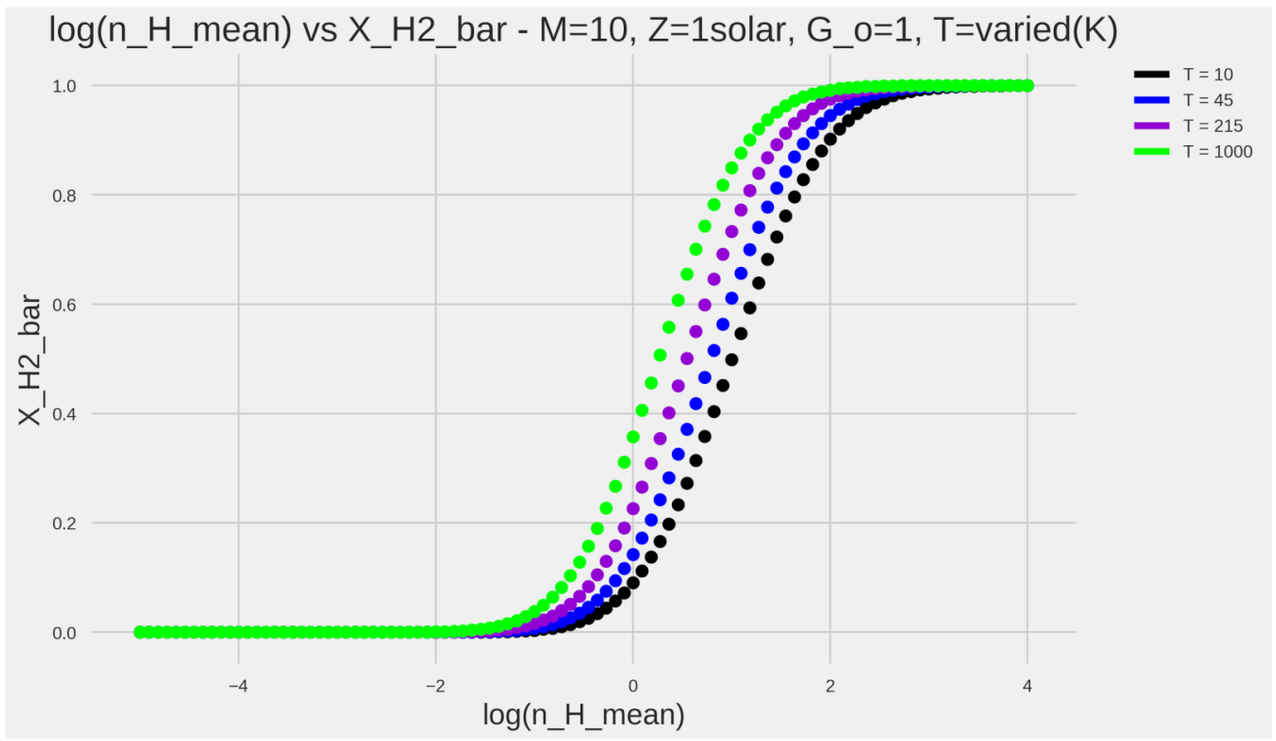
SUB-GRID MODEL – RESULTS

X_H2_BAR: (REFERENCE PLOTS)

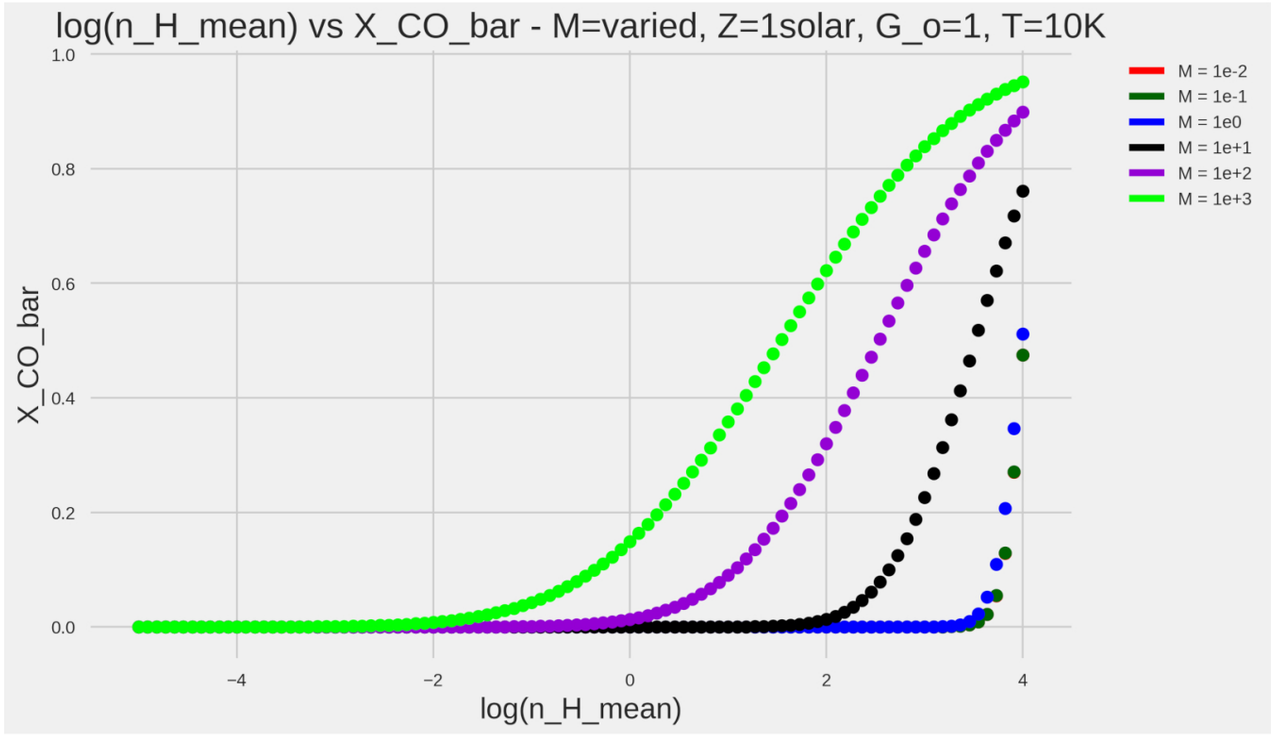


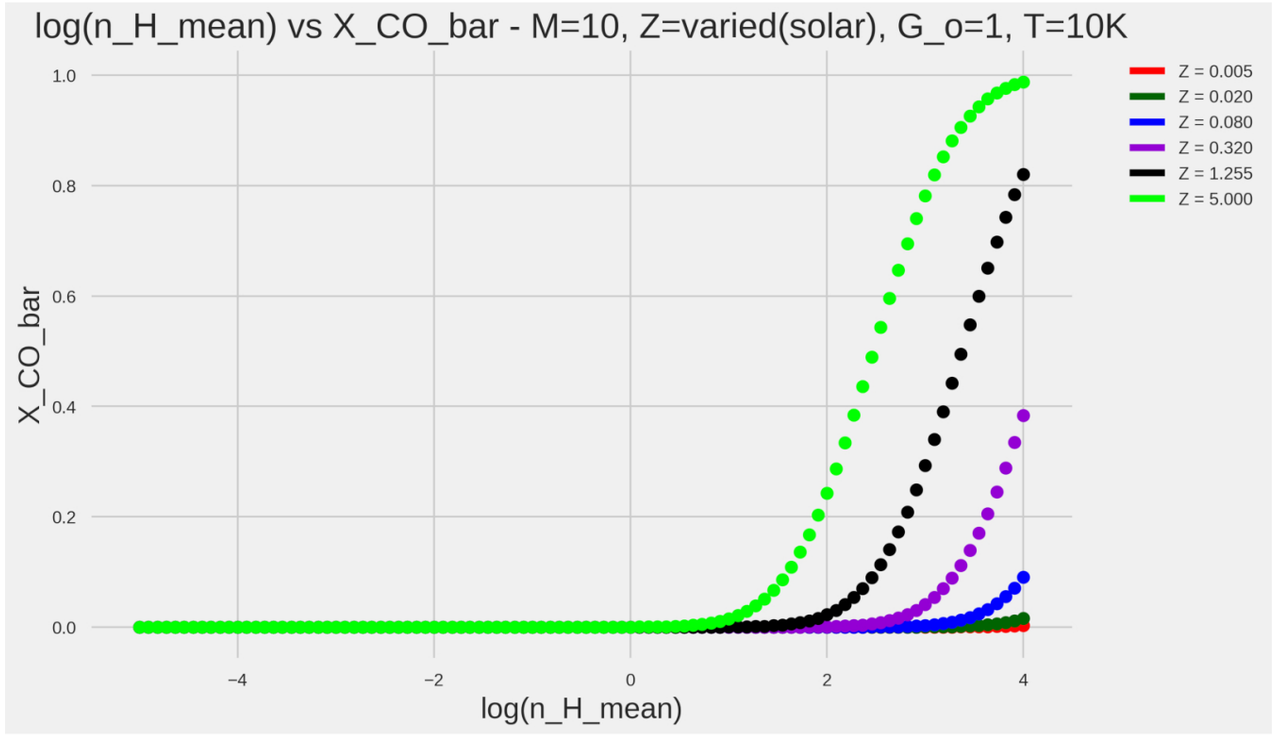


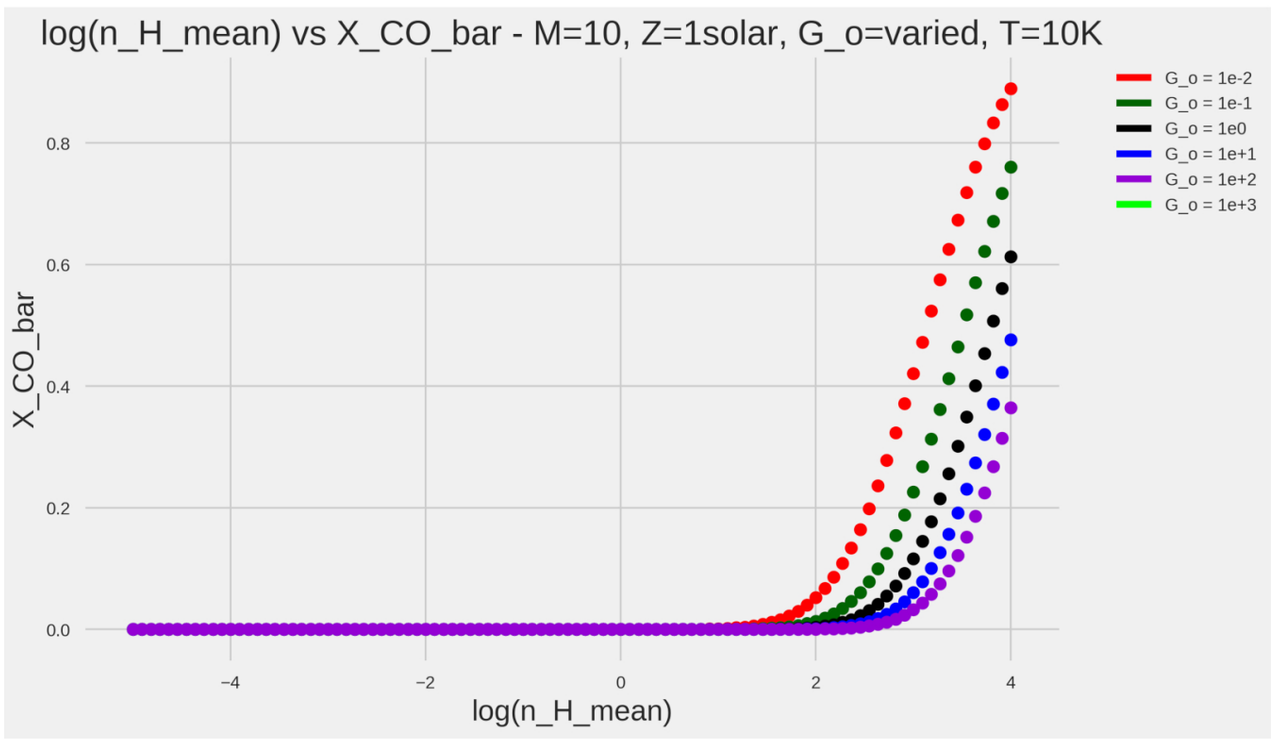


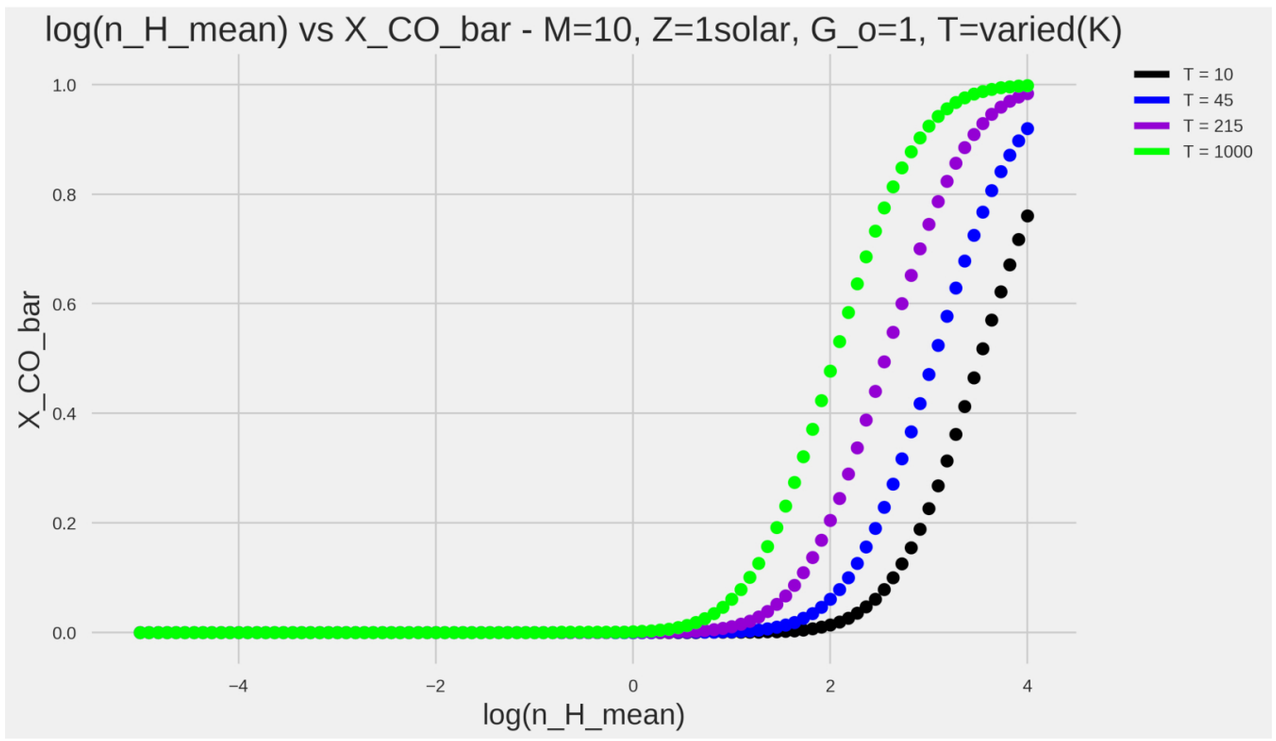


X_CO_BAR: (REFERENCE PLOTS)

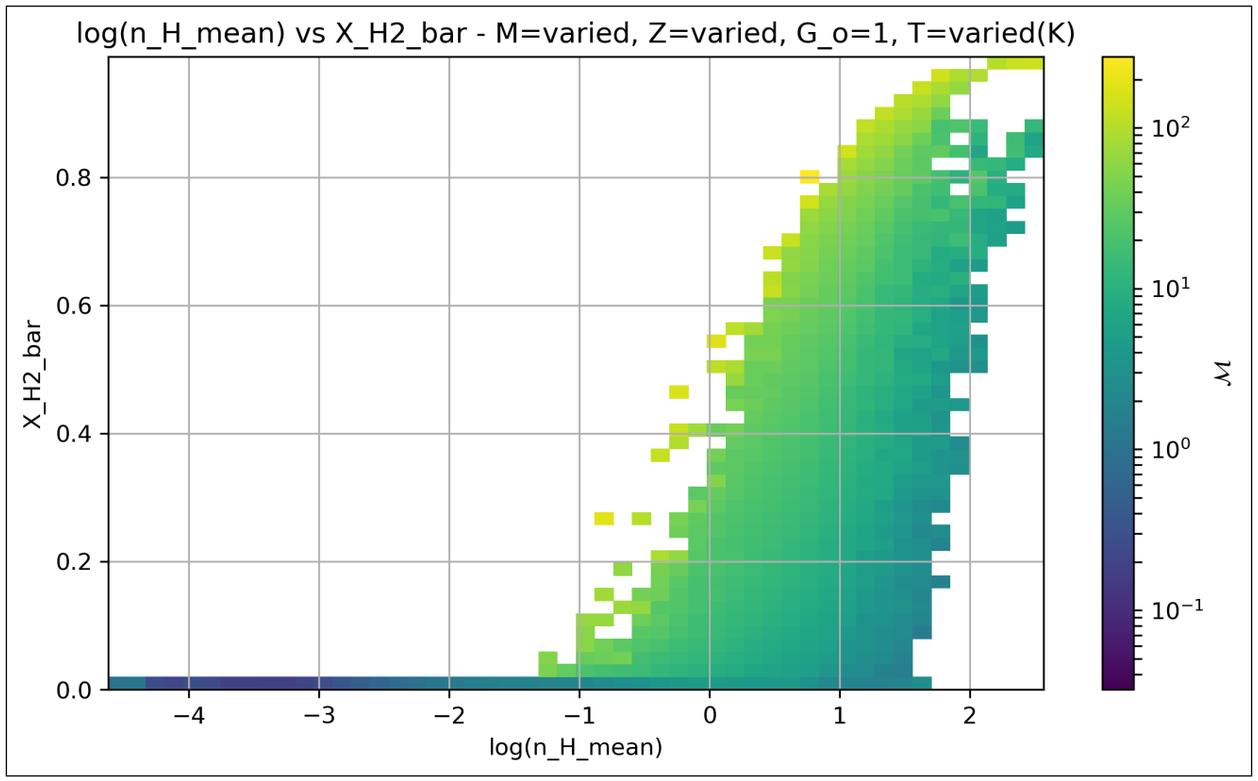


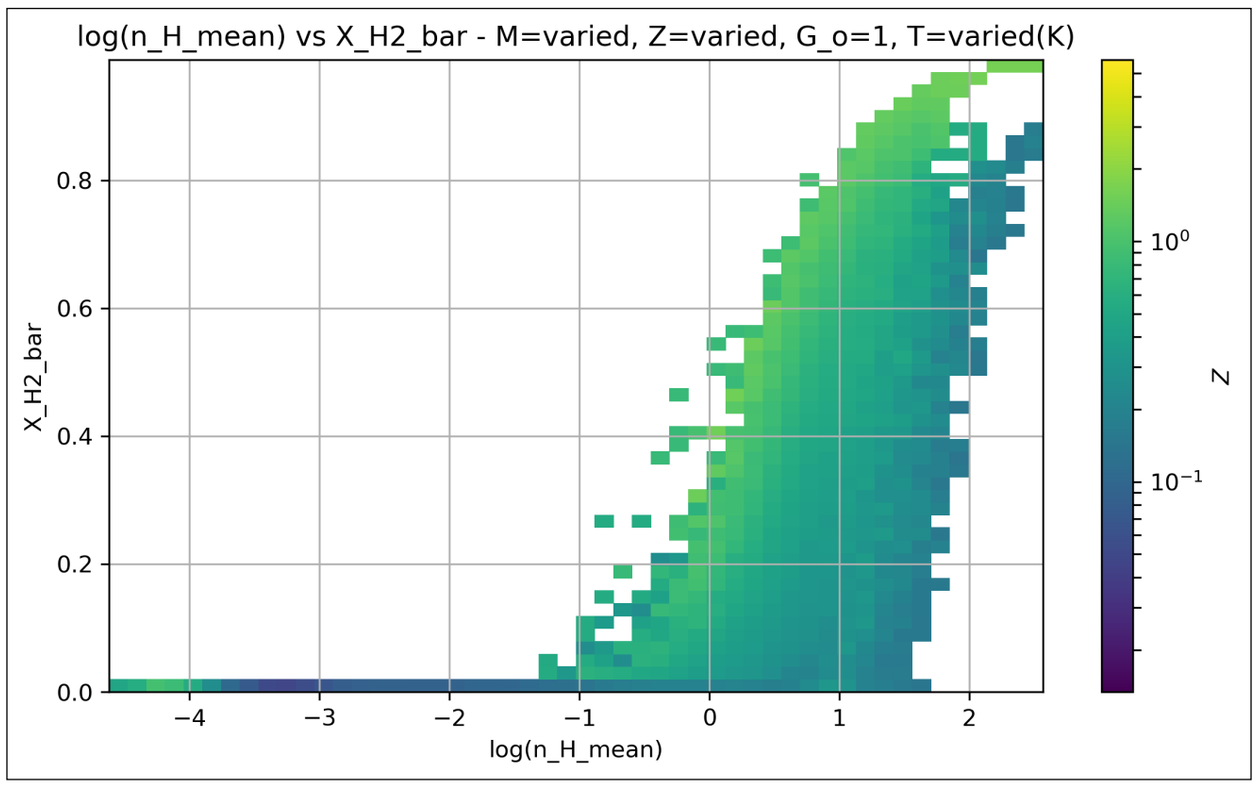






X_H2_BAR: (GALAXY SIMULATION)





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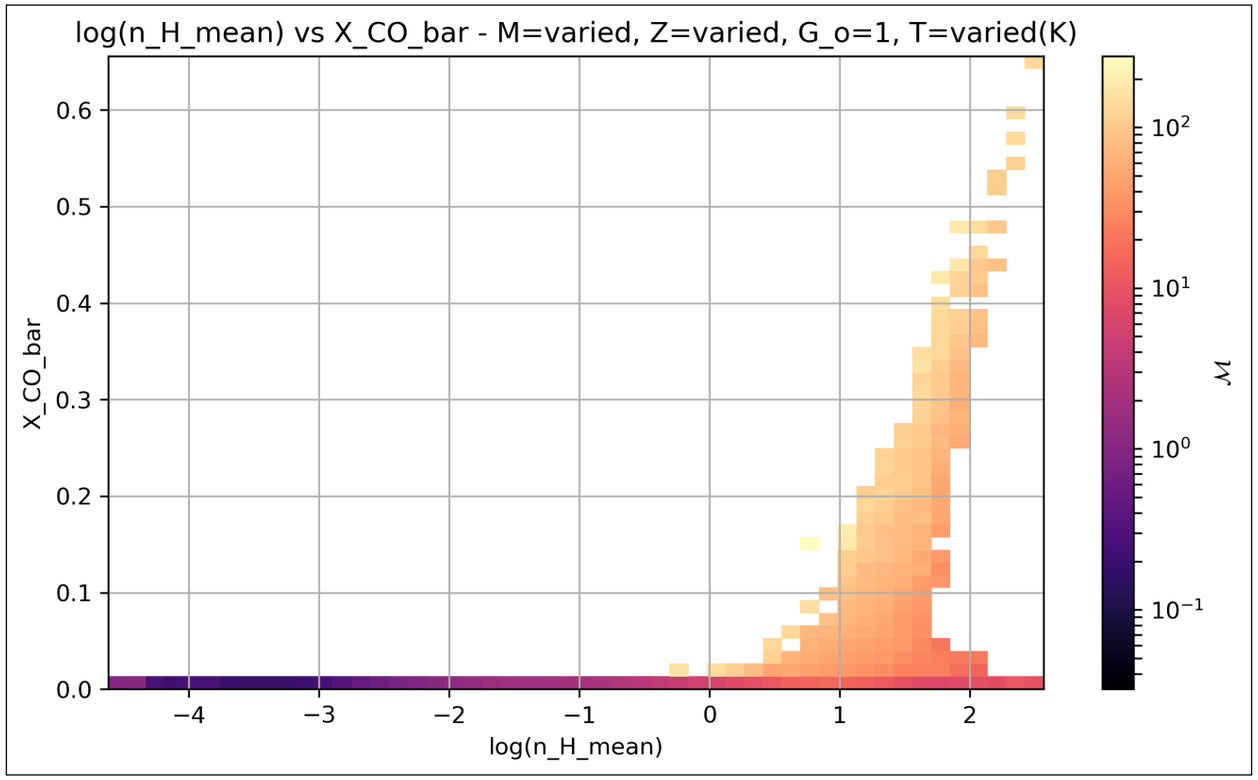
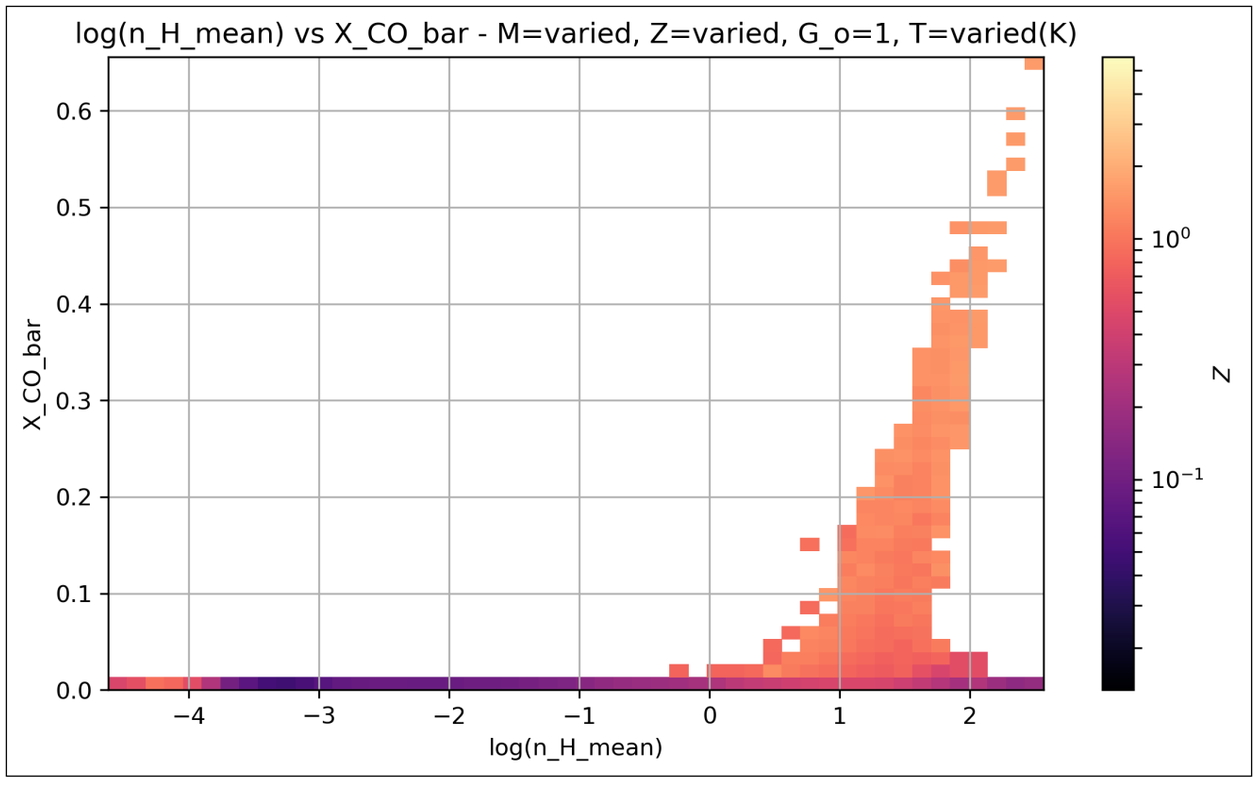
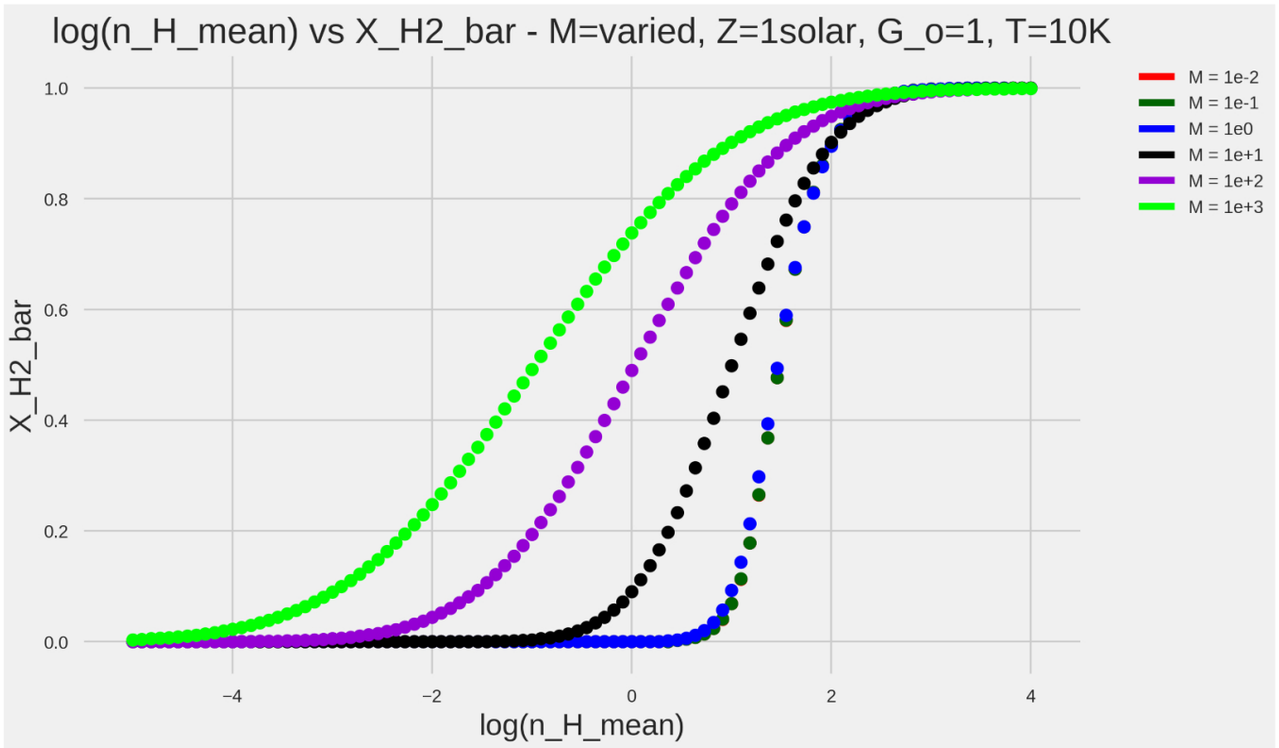
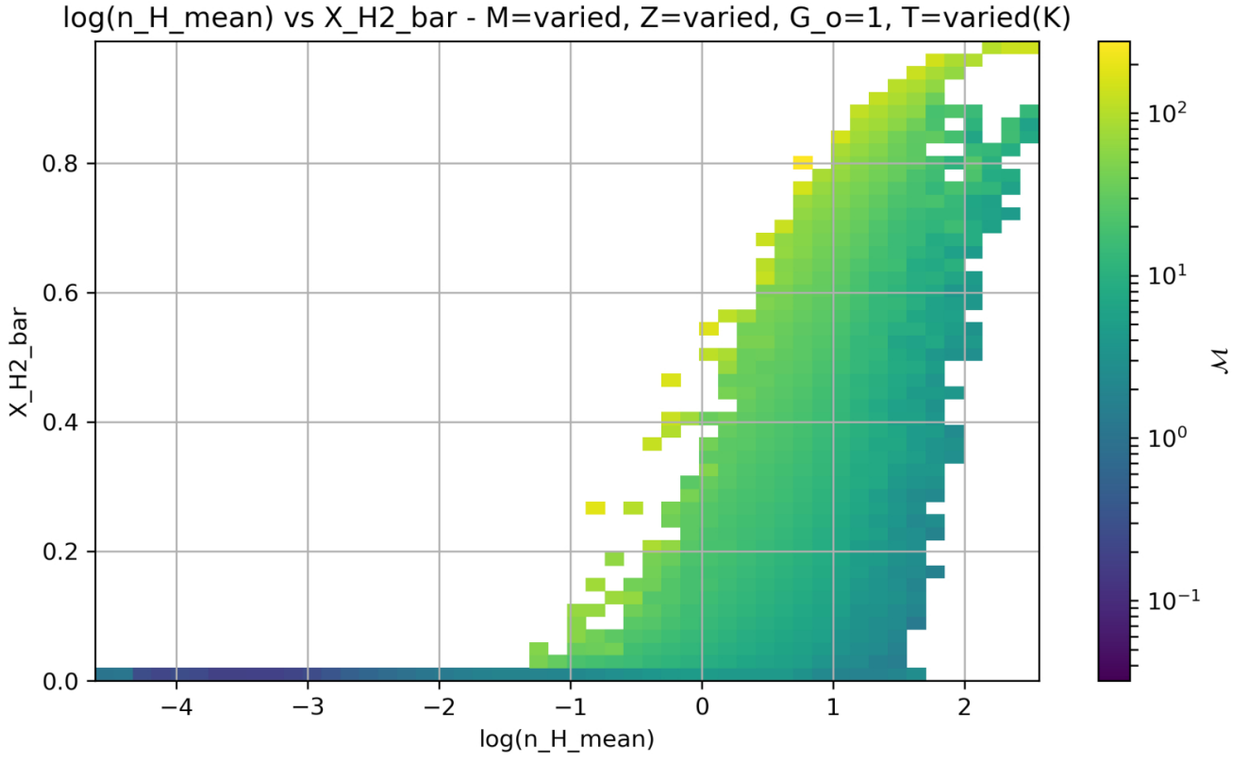




COMPARISON:


log(n_H_mean) vs X_H2_bar - M=varied, Z=1solar, G_o=1, T=10K
M = 1e-2
M = 1e-1
M = 1e0
M = 1e+1
M = 1e+2
M = 1e+3
X_H2_bar
log(n_H_mean)
1.0
0.8
0.6
0.4
0.2
0.0
−4
−2
0
2
4


log(n_H_mean) vs X_H2_bar - M=varied, Z=varied, G_o=1, T=varied(K)
X_H2_bar
log(n_H_mean)
$\mathcal{M}$
0.8
0.6
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0.2
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−4
−3
−2
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0
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2
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10^0
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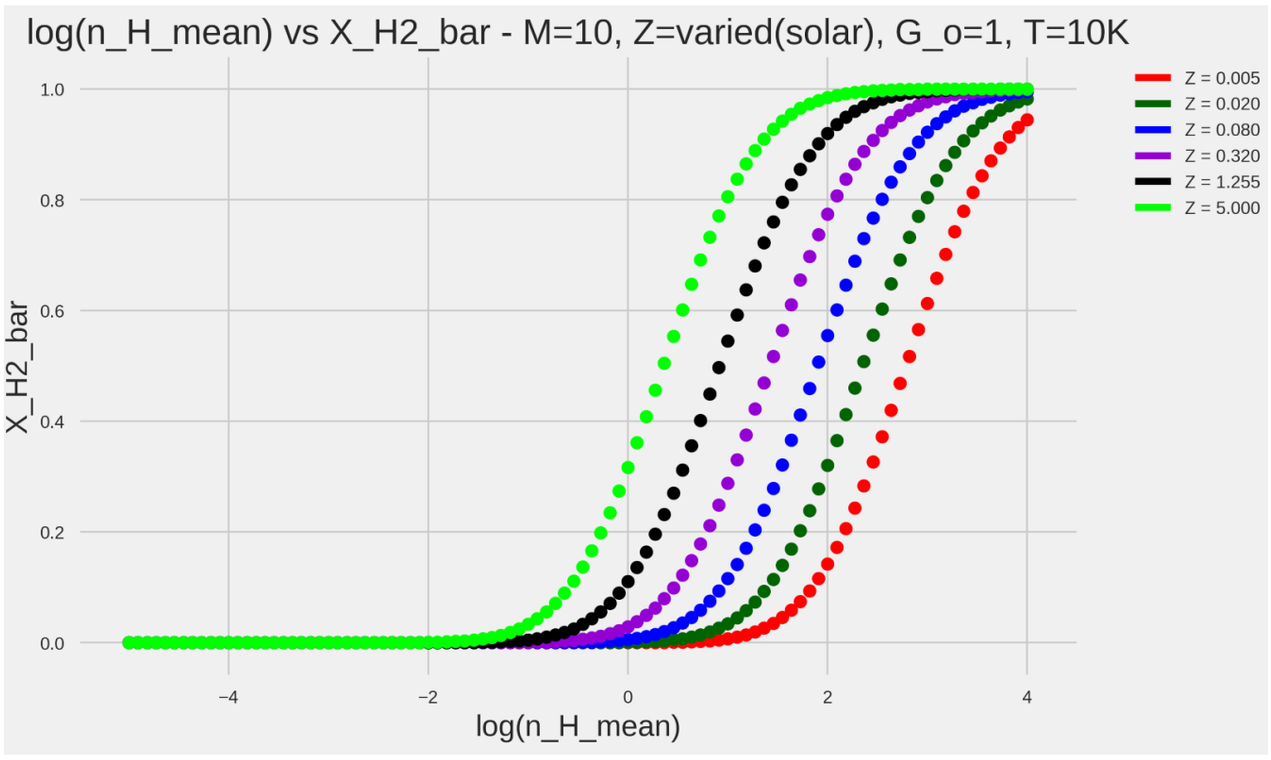
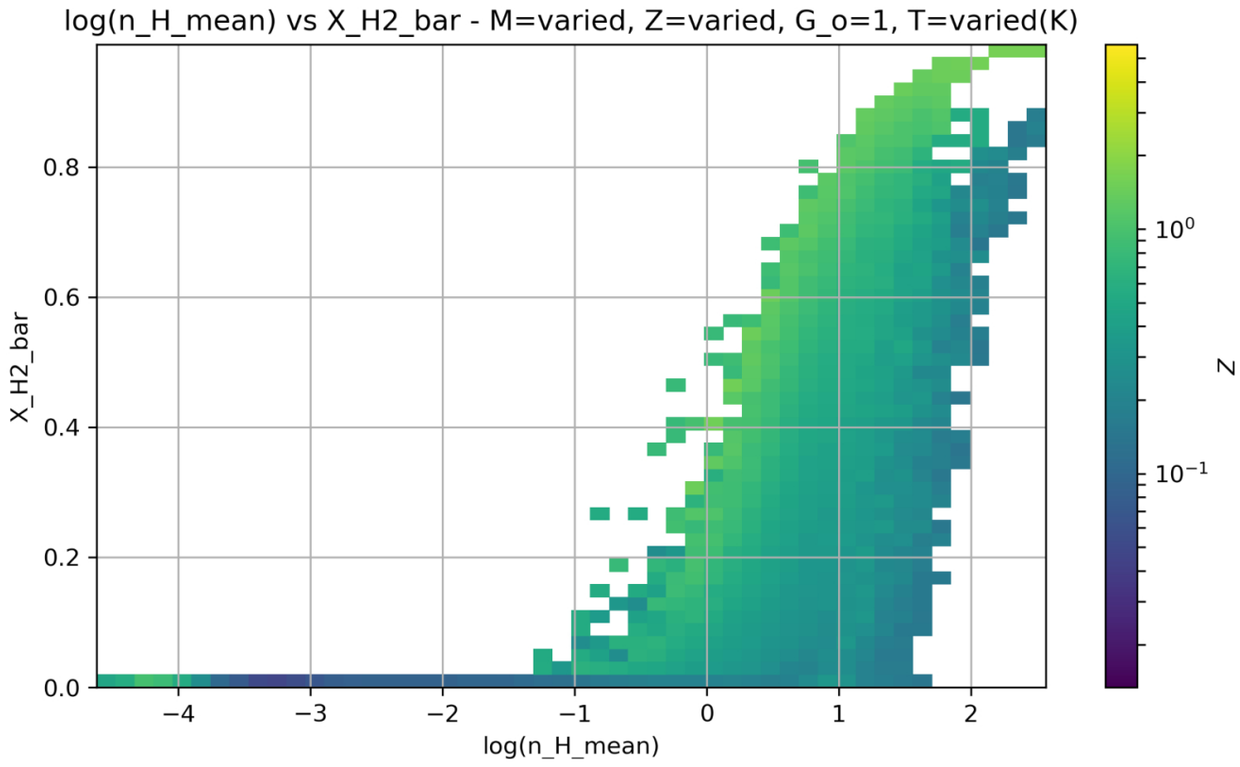

log(n_H_mean) vs X_H2_bar - M=10, Z=varied(solar), G_o=1, T=10K
Z = 0.005
Z = 0.020
Z = 0.080
Z = 0.320
Z = 1.255
Z = 5.000
X_H2_bar
log(n_H_mean)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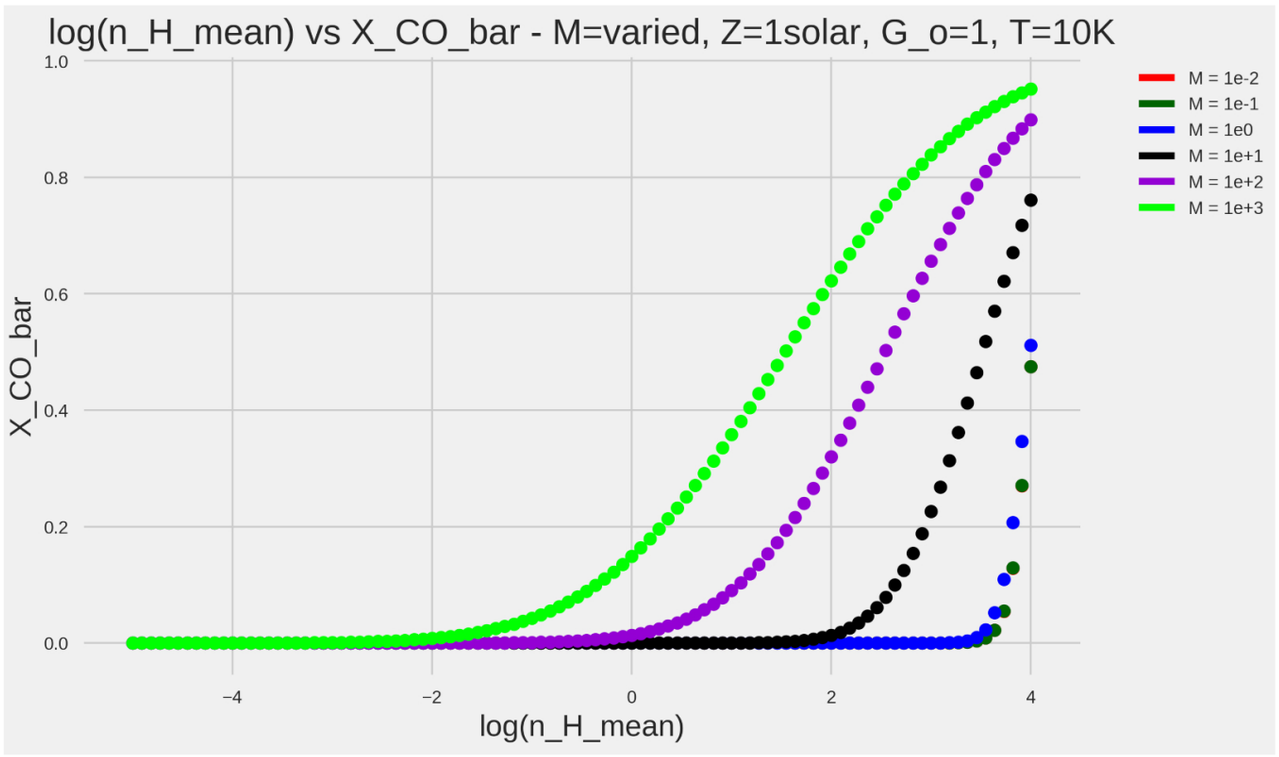
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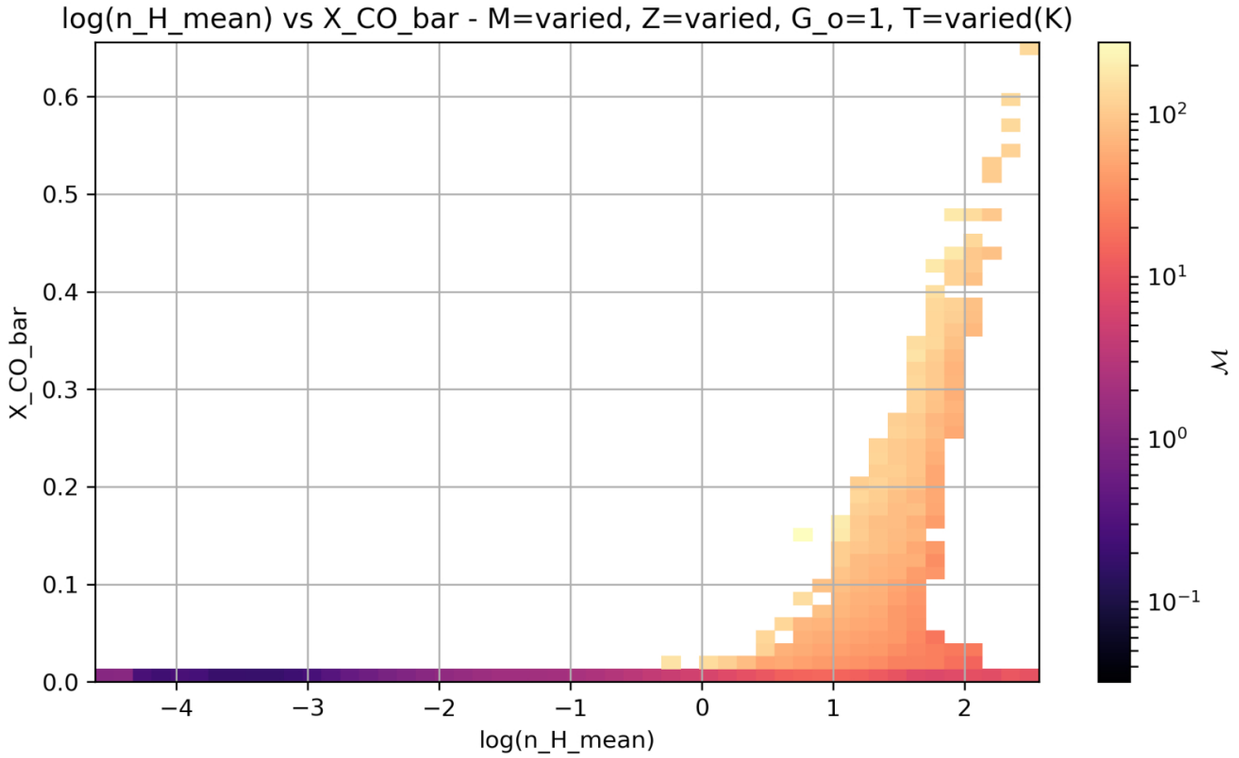
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X_CO_bar
log(n_H_mean)
$\mathcal{M}$

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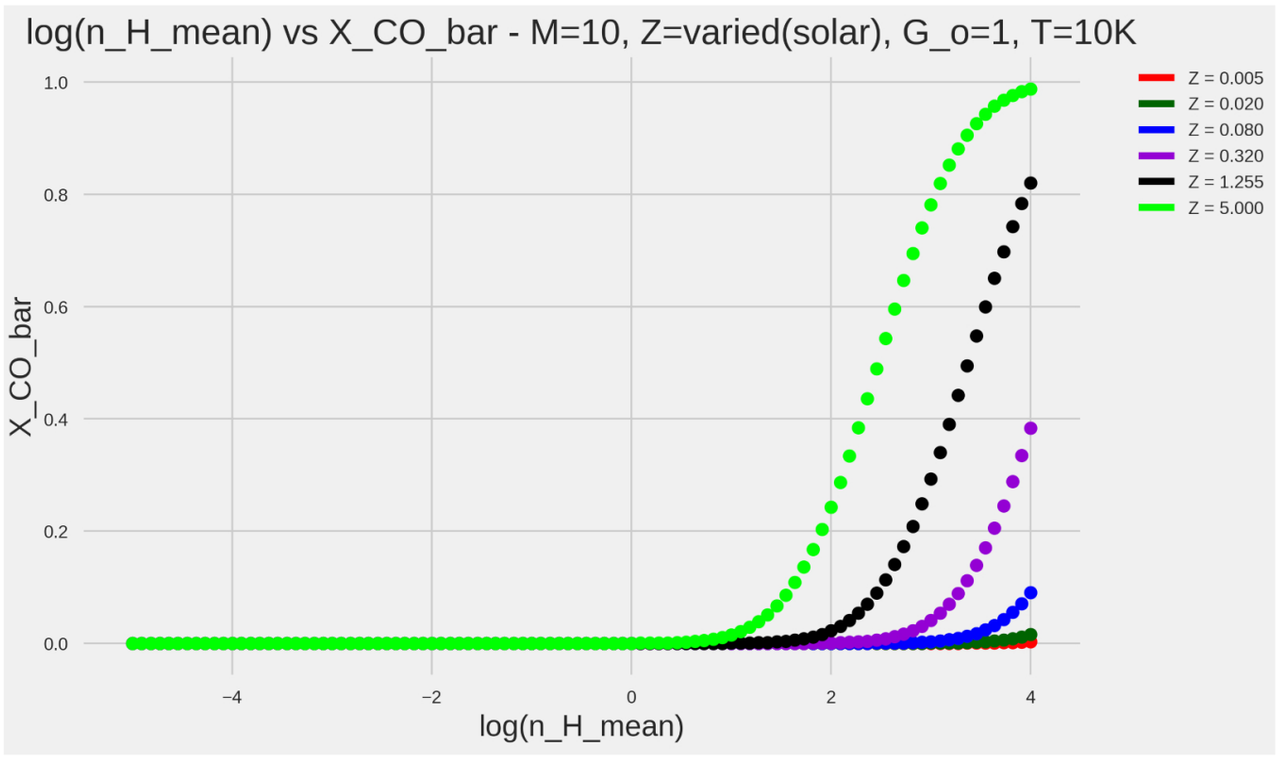
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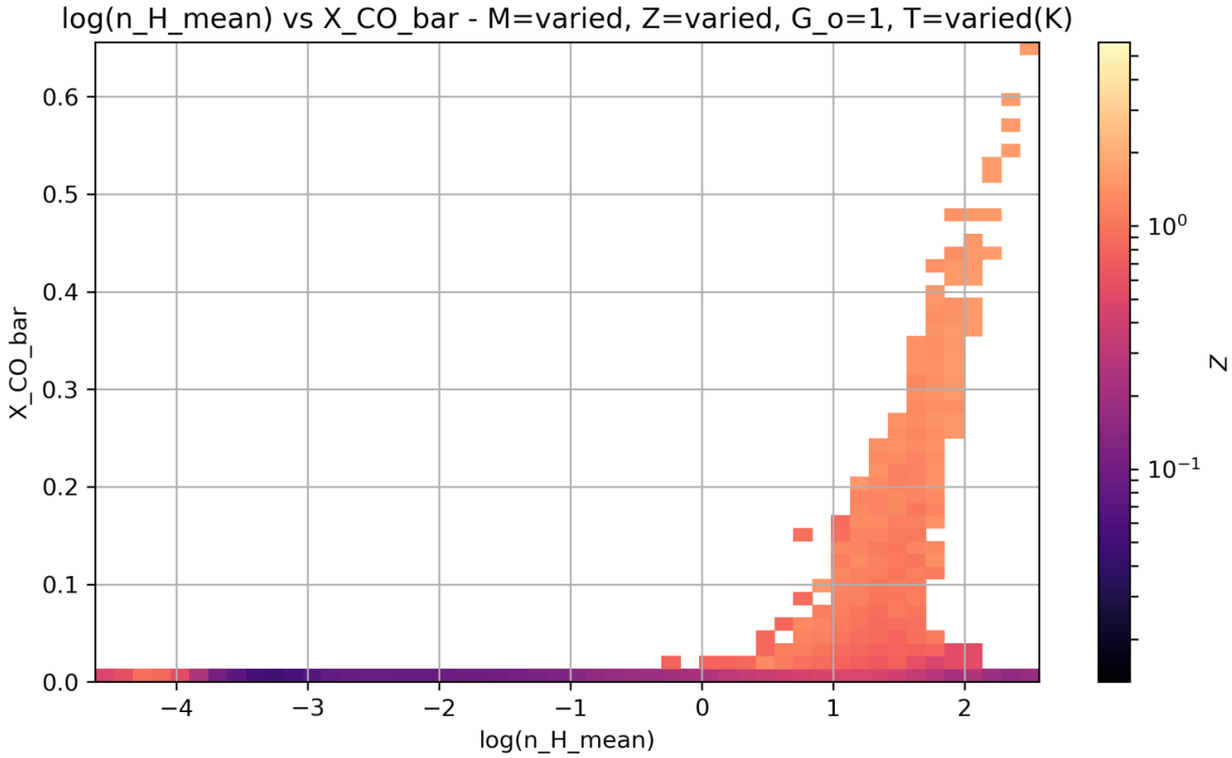
log(n_H_mean) vs X_CO_bar - M=varied, Z=varied, G_o=1, T=varied(K)
X_CO_bar
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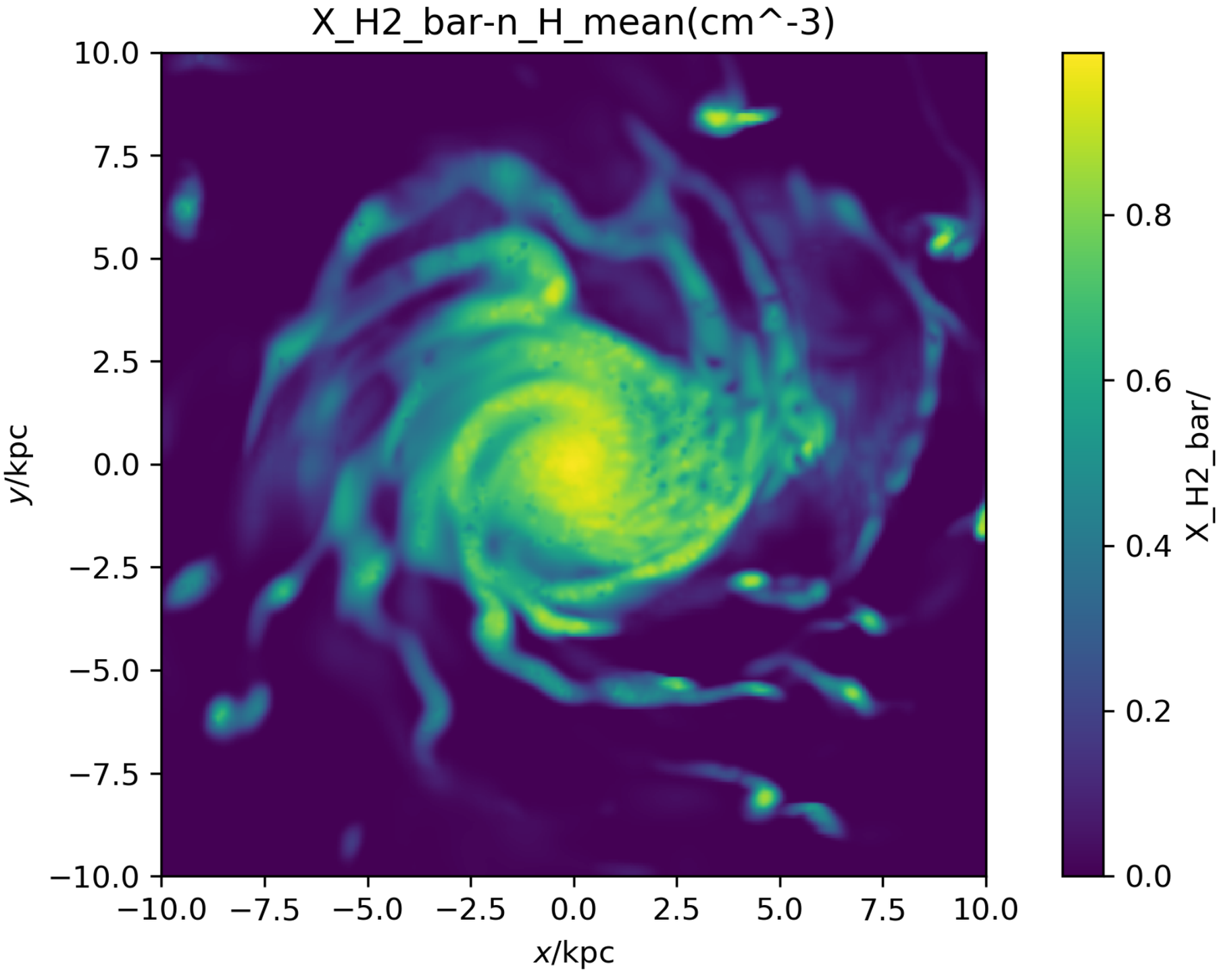
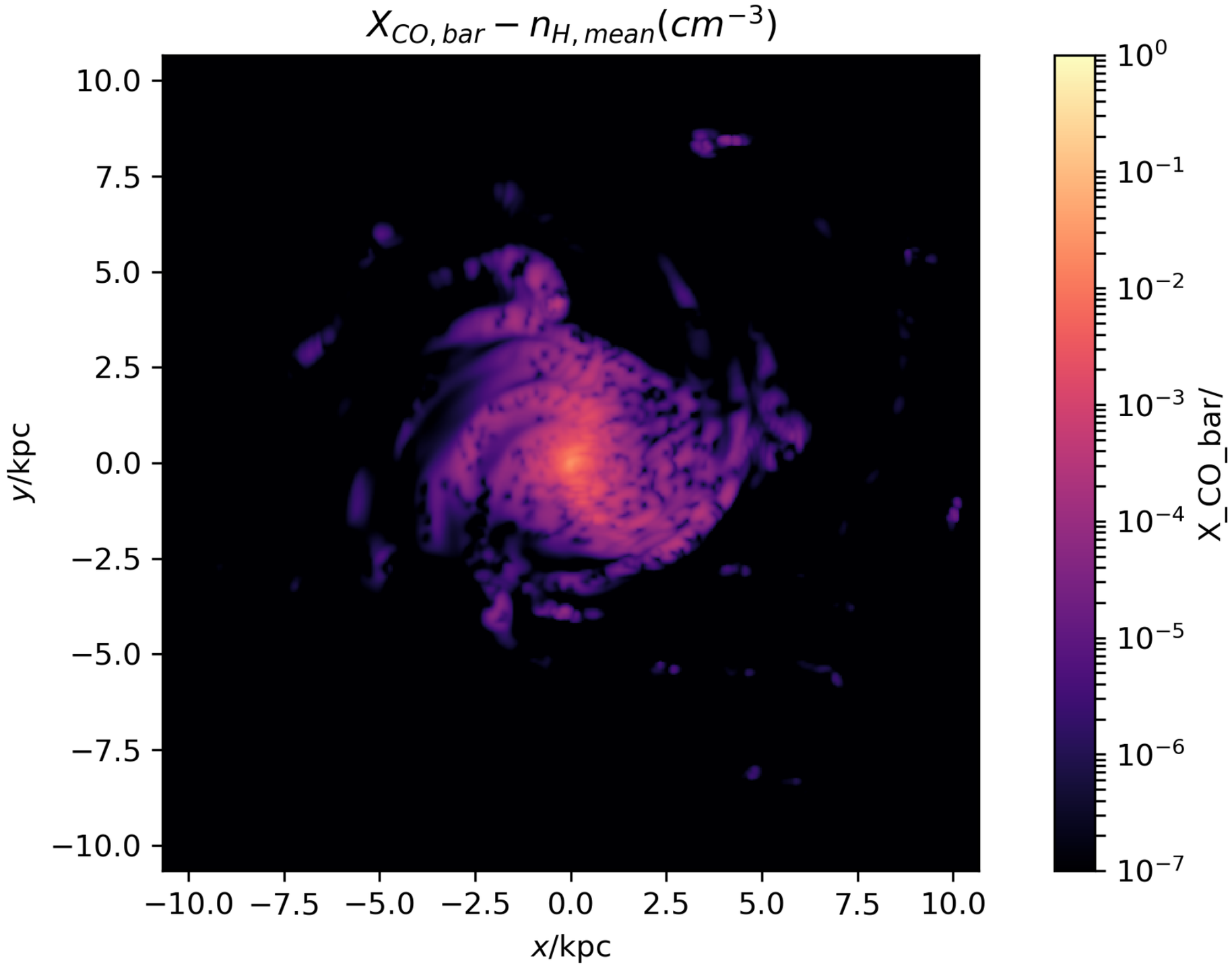
Z

GALAXY MAPS:

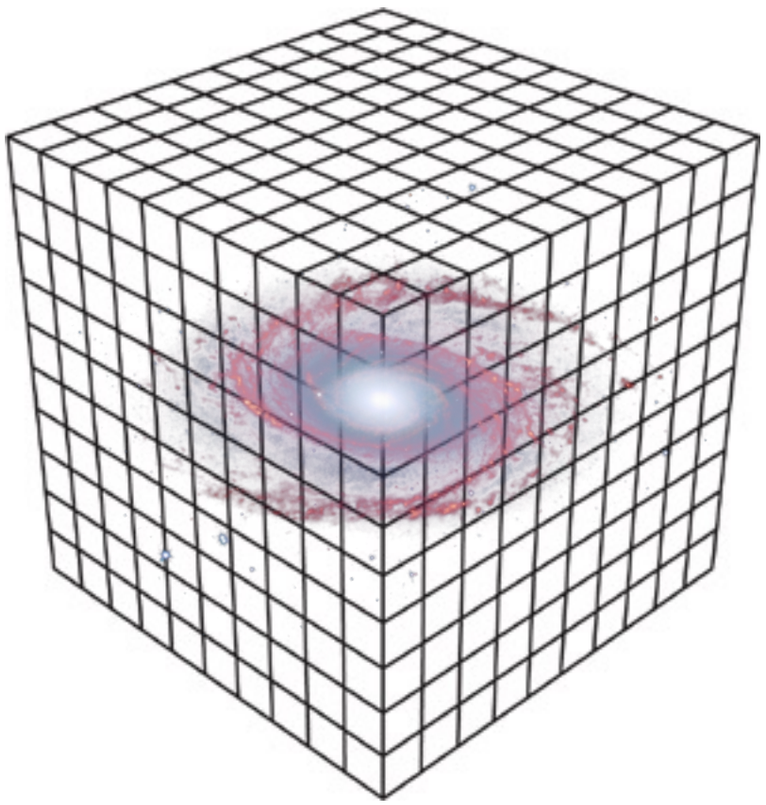

X_H2_bar-n_H_mean(cm^-3)
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
y/kpc
−10.0
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0
x/kpc
0.8
0.6
0.4
0.2
0.0
X_H2_bar/

GALAXY MAPS:


$X_{CO,bar} - n_{H,mean}(cm^{-3})$
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
y/kpc
−10.0 −7.5 −5.0 −2.5 0.0 2.5 5.0 7.5 10.0
x/kpc
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
X_CO_bar/

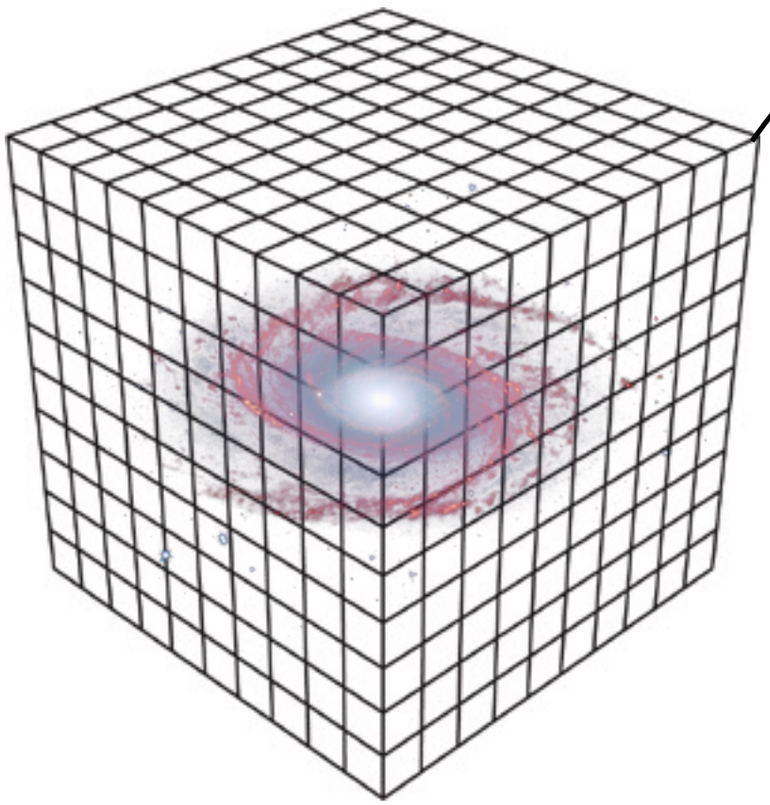
RT MODEL OUTLINE

RT MODEL OUTLINE



Galaxy Simulation

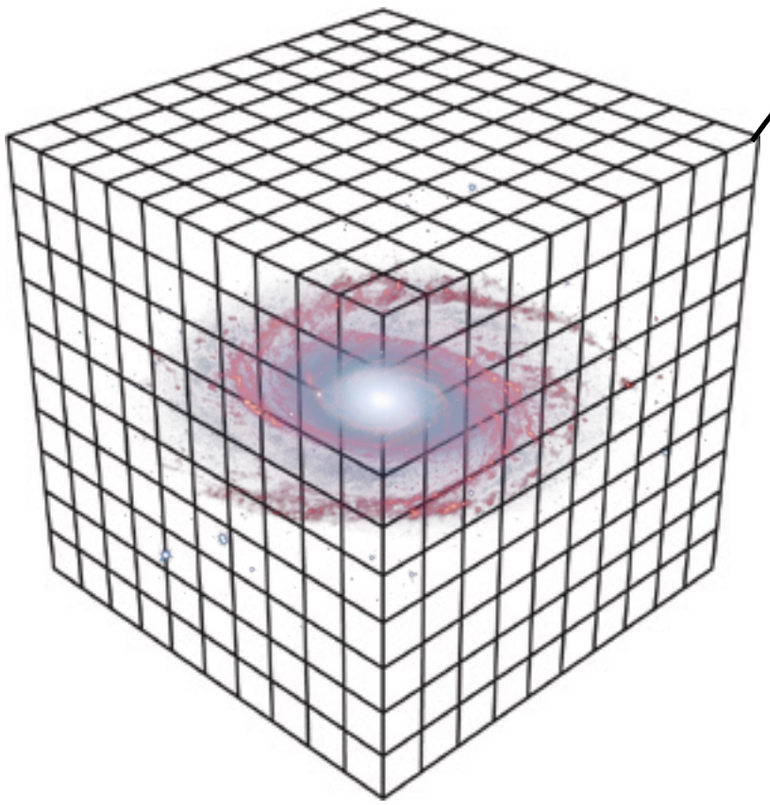
RT MODEL OUTLINE



Galaxy Simulation

For each cell in this simulation
—> SUB-GRID MODEL

RT MODEL OUTLINE

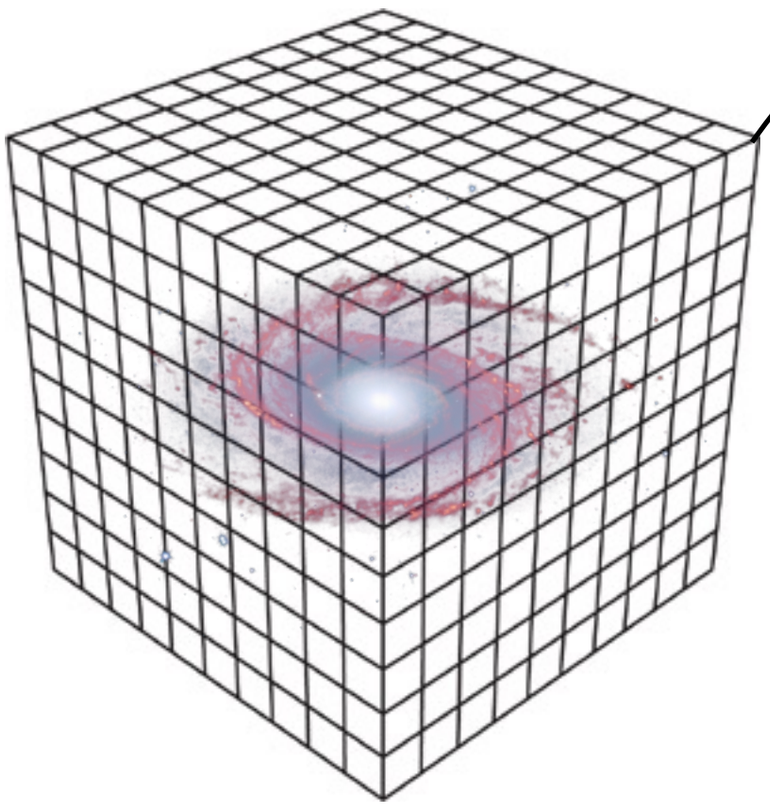


Galaxy Simulation

For each cell in this simulation
—> SUB-GRID MODEL

For each cell —> one emissivity
(for one emission line)

RT MODEL OUTLINE



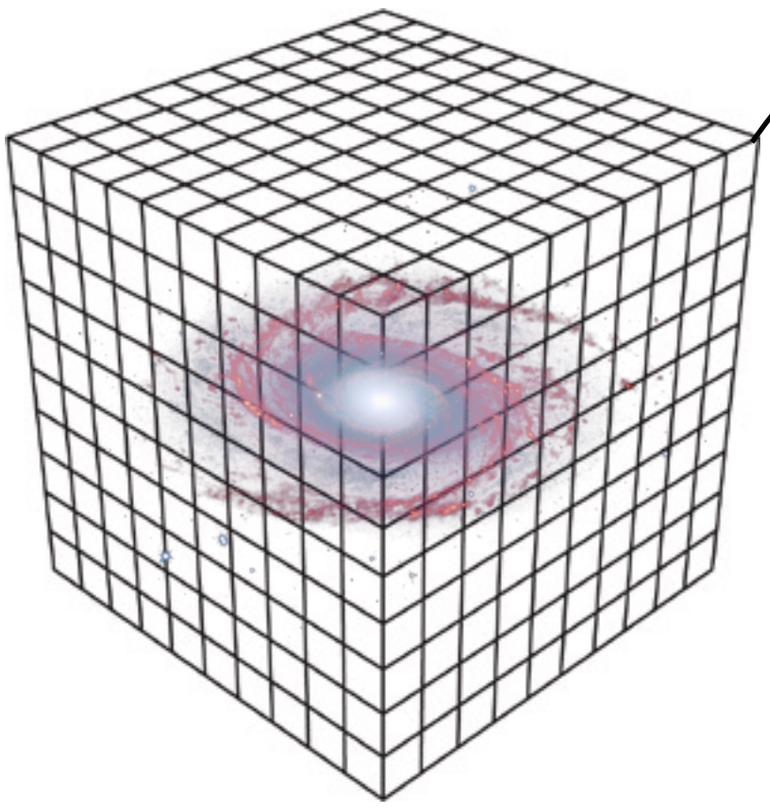
Galaxy Simulation

For each cell in this simulation
–> SUB-GRID MODEL

For each cell –> one emissivity
(for one emission line)

From emissivity –> Luminosity of
each cell

RT MODEL OUTLINE



Galaxy Simulation

For each cell in this simulation
—> SUB-GRID MODEL

For each cell —> one emissivity
(for one emission line)

From emissivity —> Luminosity of
each cell

Summing over all cell-luminosities
to get L_CO (Total Luminosity of
the galaxy)

RT MODEL OUTLINE

- **nu, E, A, B –> from Leiden Atomic and Molecular Database (LAMDA) file**

RT MODEL OUTLINE

- nu, E, A, B –> from Leiden Atomic and Molecular Database (LAMDA) file
- **Only taking one emission, Level 2 to Level 1**

RT MODEL OUTLINE

- nu, E, A, B –> from Leiden Atomic and Molecular Database (LAMDA) file
- Only taking one emission, Level 2 to Level 1
- **Level population, n_i –> LTE**

RT MODEL OUTLINE

- nu, E, A, B –> from Leiden Atomic and Molecular Database (LAMDA) file
- Only taking one emission, Level 2 to Level 1
- Level population, n_i –> LTE
- **pdf, lambda_jeans, n_CO –> from sub-grid model**

RT MODEL OUTLINE

- nu, E, A, B –> from Leiden Atomic and Molecular Database (LAMDA) file
- Only taking one emission, Level 2 to Level 1
- Level population, n_i –> LTE
- pdf, lambda_jeans, n_CO –> from sub-grid model
- **Optical depth (tau) and escape probability (beta)**

RT MODEL OUTLINE

- nu, E, A, B –> Leiden Atomic and Molecular Database (LAMDA) from file
- Only taking one emission, Level 2 to Level 1
- Level population, n_i –> LTE
- pdf, lambda_jeans, n_CO –> from sub-grid model
- Optical depth (tau) and escape probability (beta)
- **Emissivity, j_10 = j_10(beta, pdf, n_CO, nu, A)**

RT MODEL OUTLINE

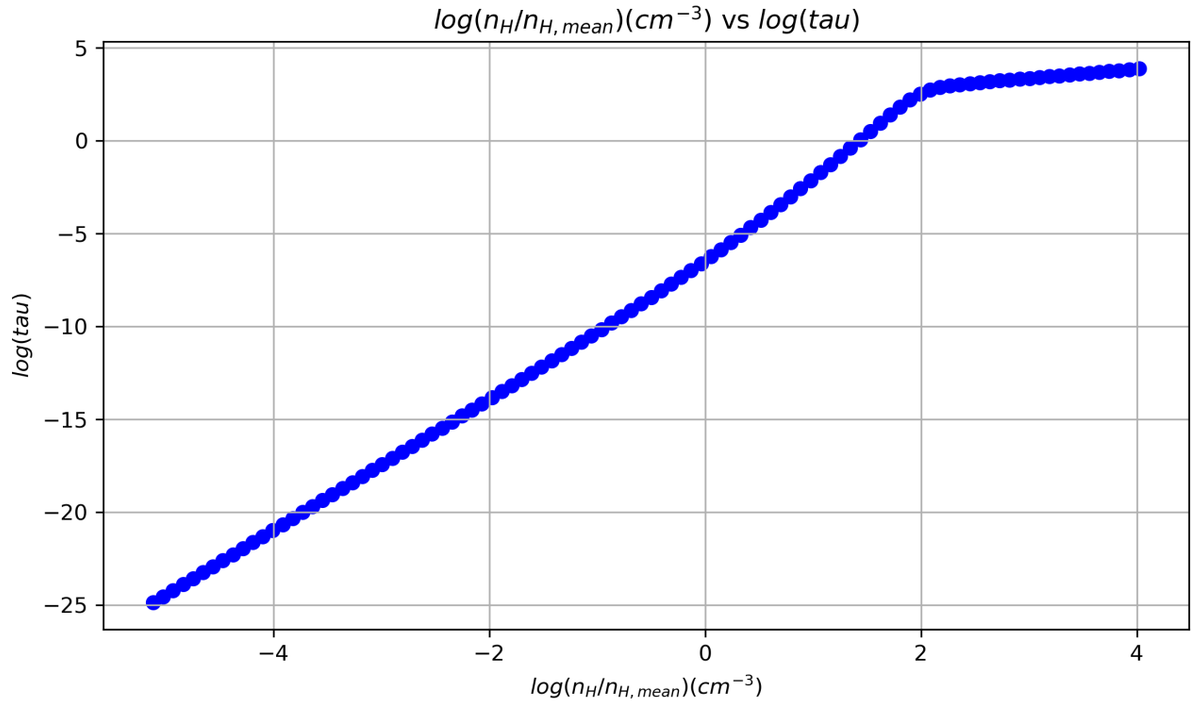
- nu, E, A, B –> from Leiden Atomic and Molecular Database (LAMDA) file
- Only taking one emission, Level 2 to Level 1
- Level population, n_i –> LTE
- pdf, lambda_jeans, n_CO –> from sub-grid model
- Optical depth (tau) and escape probability (beta)
- Emissivity, j_10 = j_10(beta, pdf, n_CO, nu, A)
- **l_CO = j_10 * (dx^3)**

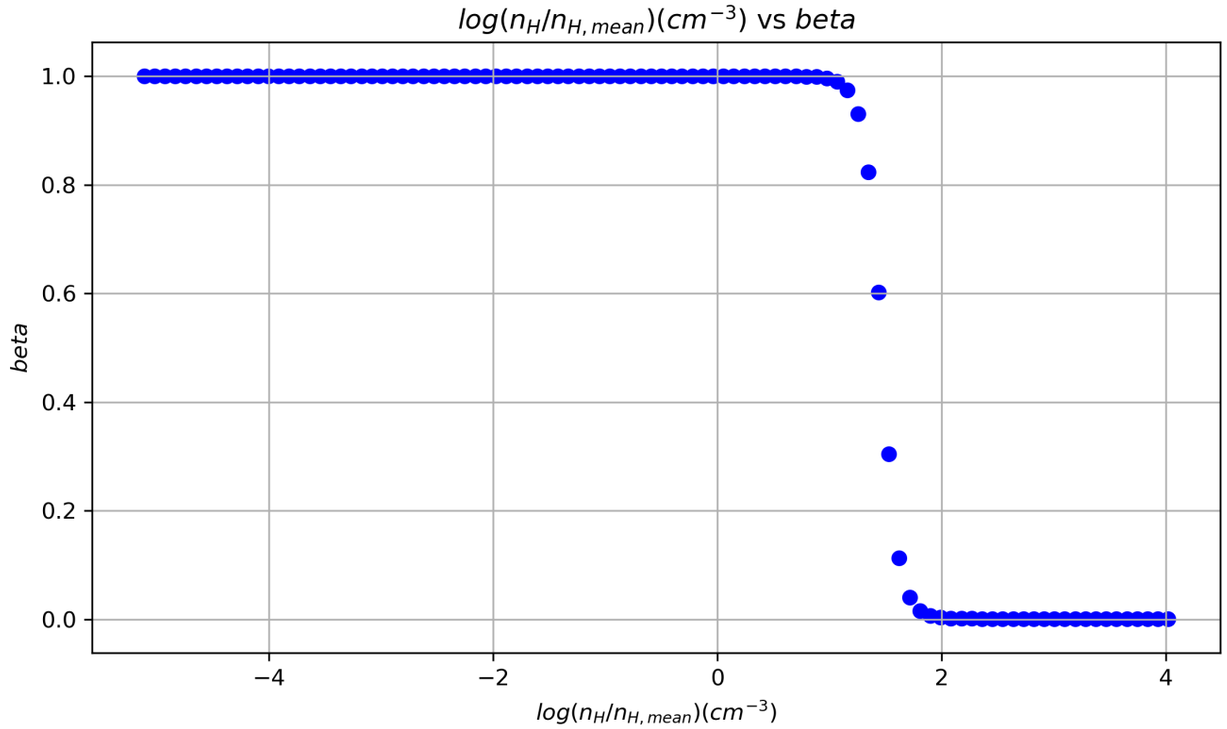
RT MODEL OUTLINE

- nu, E, A, B –> from Leiden Atomic and Molecular Database (LAMDA) file
- Only taking one emission, Level 2 to Level 1
- Level population, n_i –> LTE
- pdf, lambda_jeans, n_CO –> from sub-grid model
- Optical depth (tau) and escape probability (beta)
- Emissivity, j_10 = j_10(beta, pdf, n_CO, nu, A)
- l_CO = j_10 * (dx^3)
- **L_CO = sum(l_CO)**

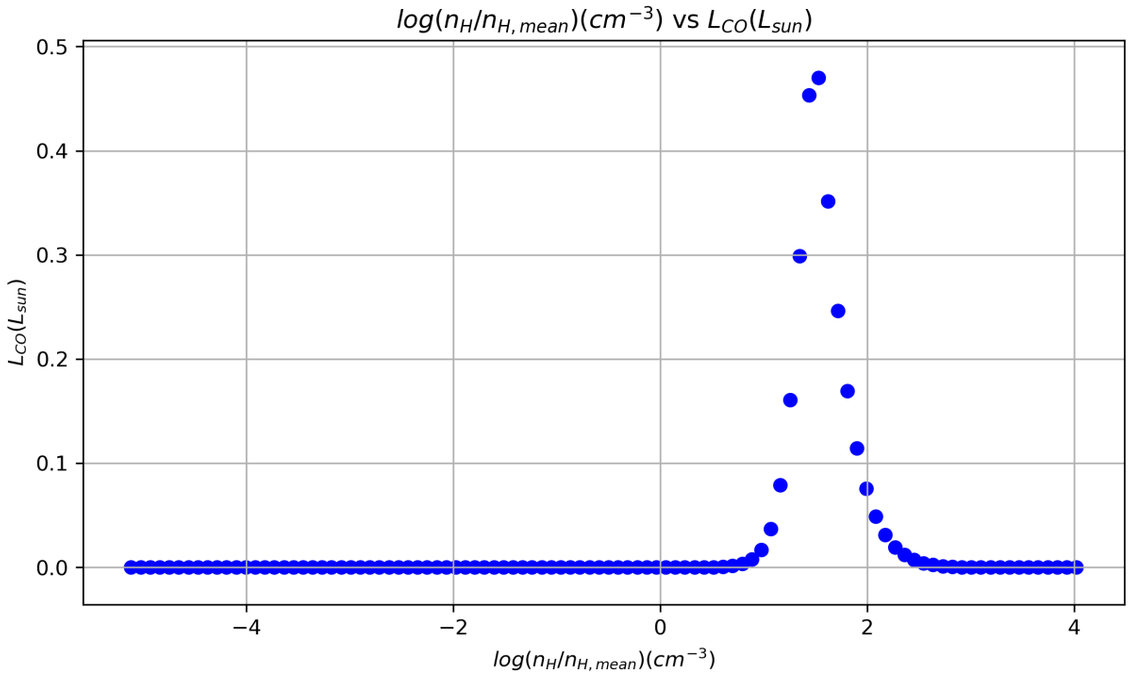
RT MODEL – RESULTS

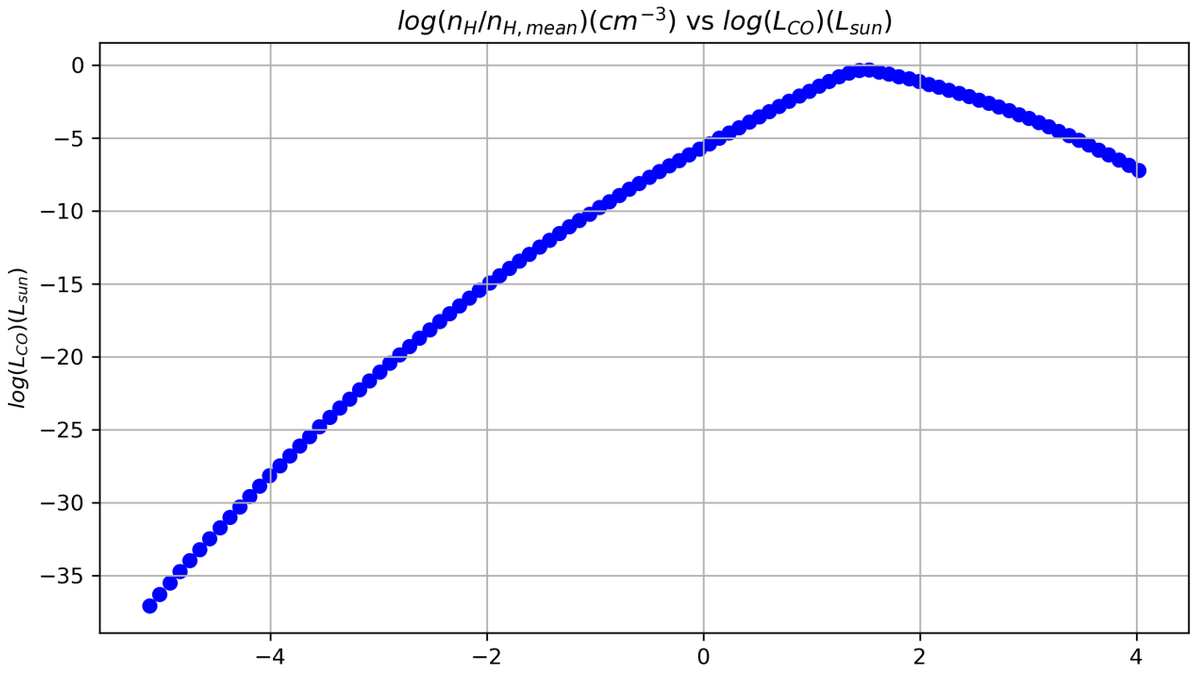
RT MODEL RESULTS:

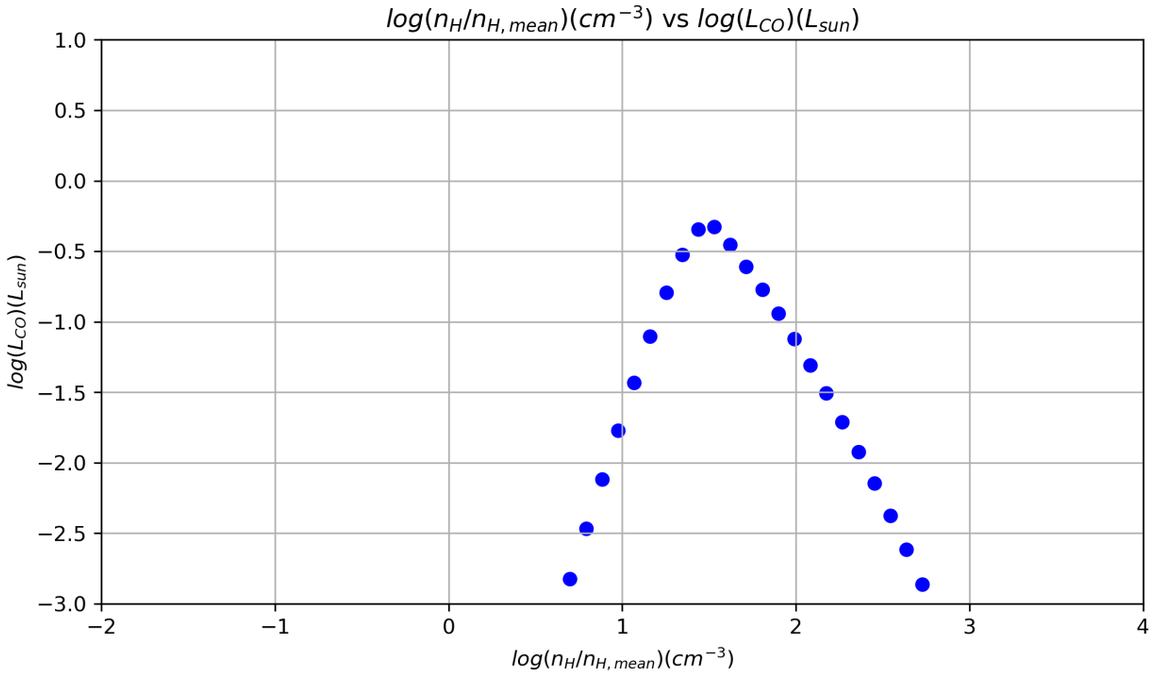




RT MODEL RESULTS:

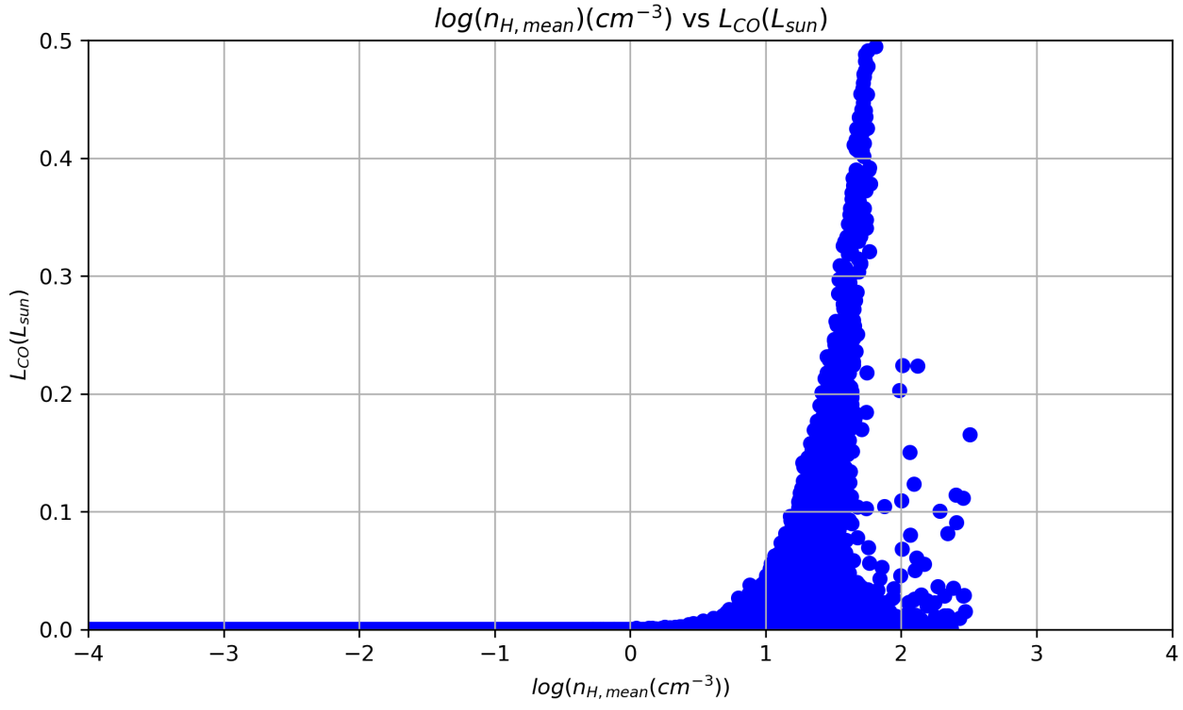






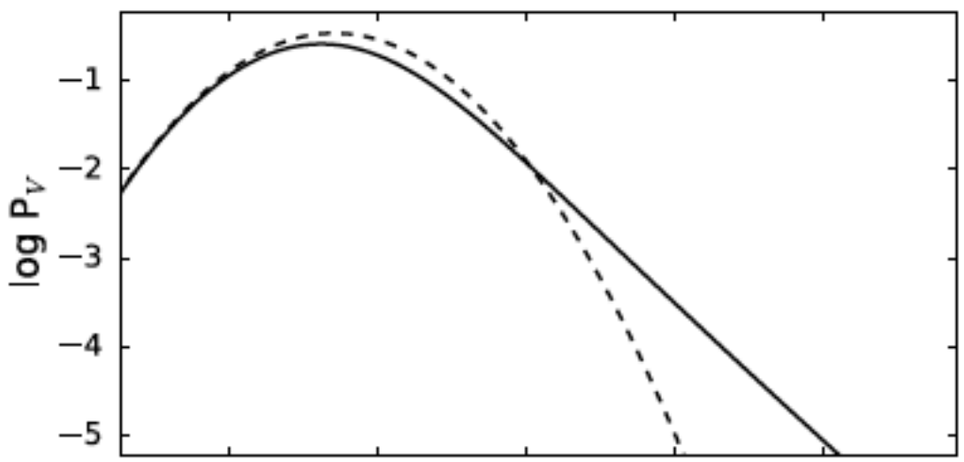
RT MODEL RESULTS:

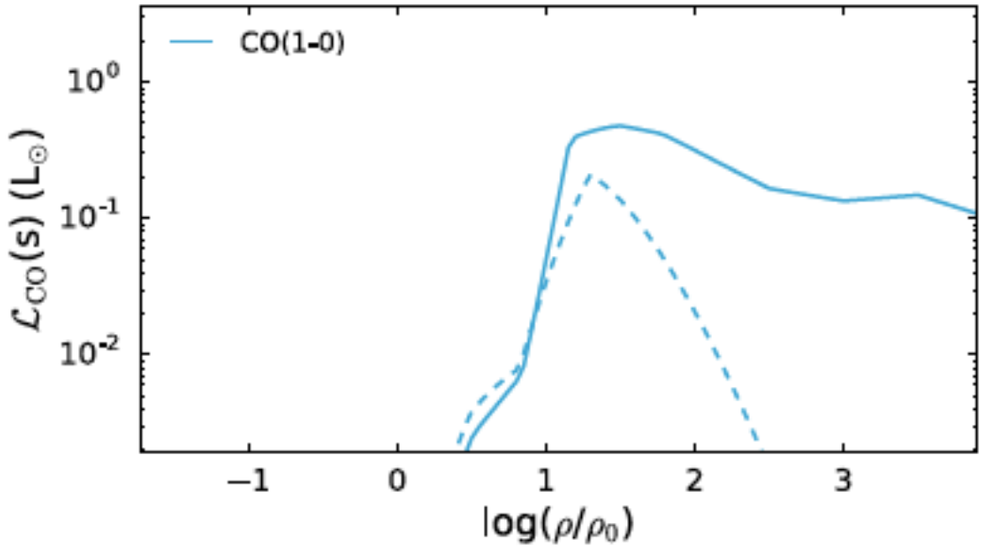
From the model



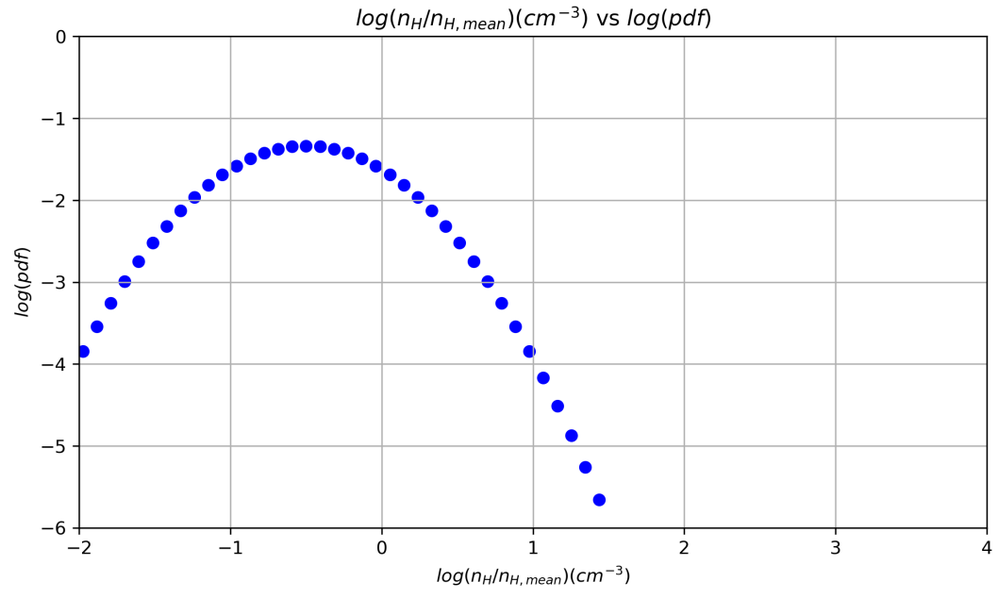
From post processing the simulation

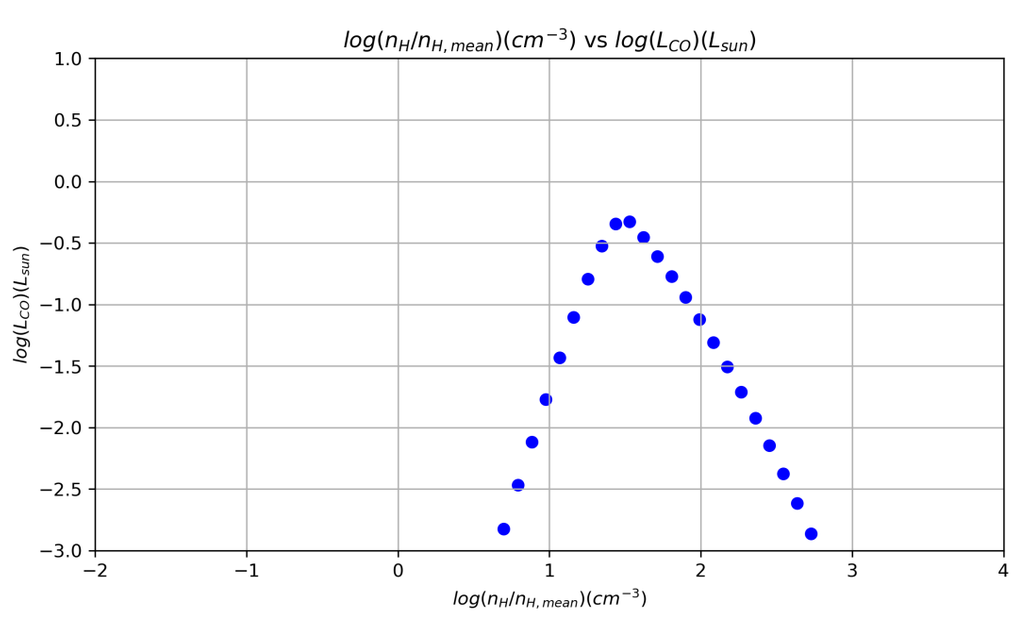
RT MODEL RESULTS:





Vallini, et al.





RT MODEL RESULTS:

From the simulation we get:

L_CO/L_sun = 2.52

Vallini, et al. get (after pdf-evolution):

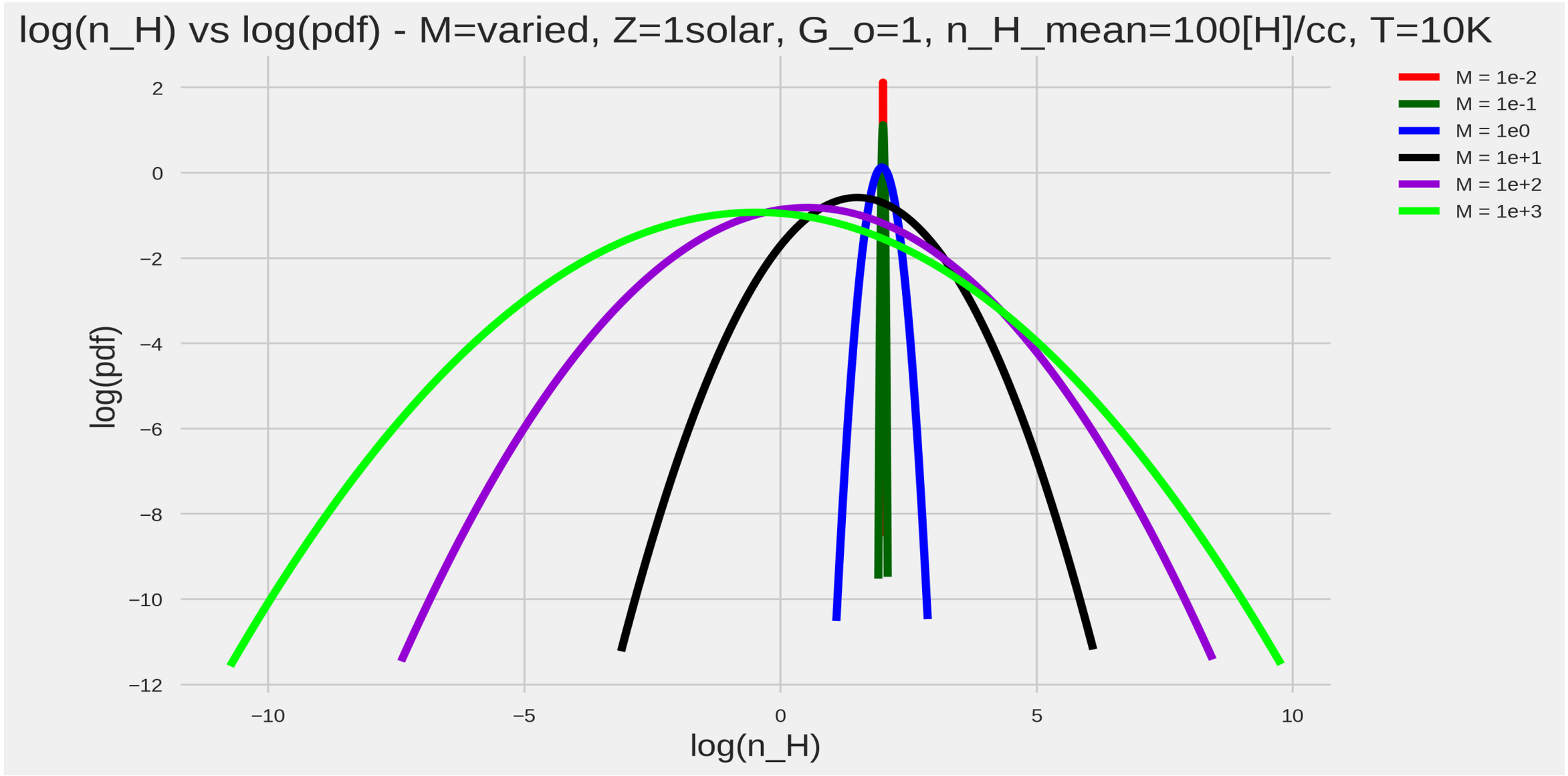
L_CO/L_sun = 4.85

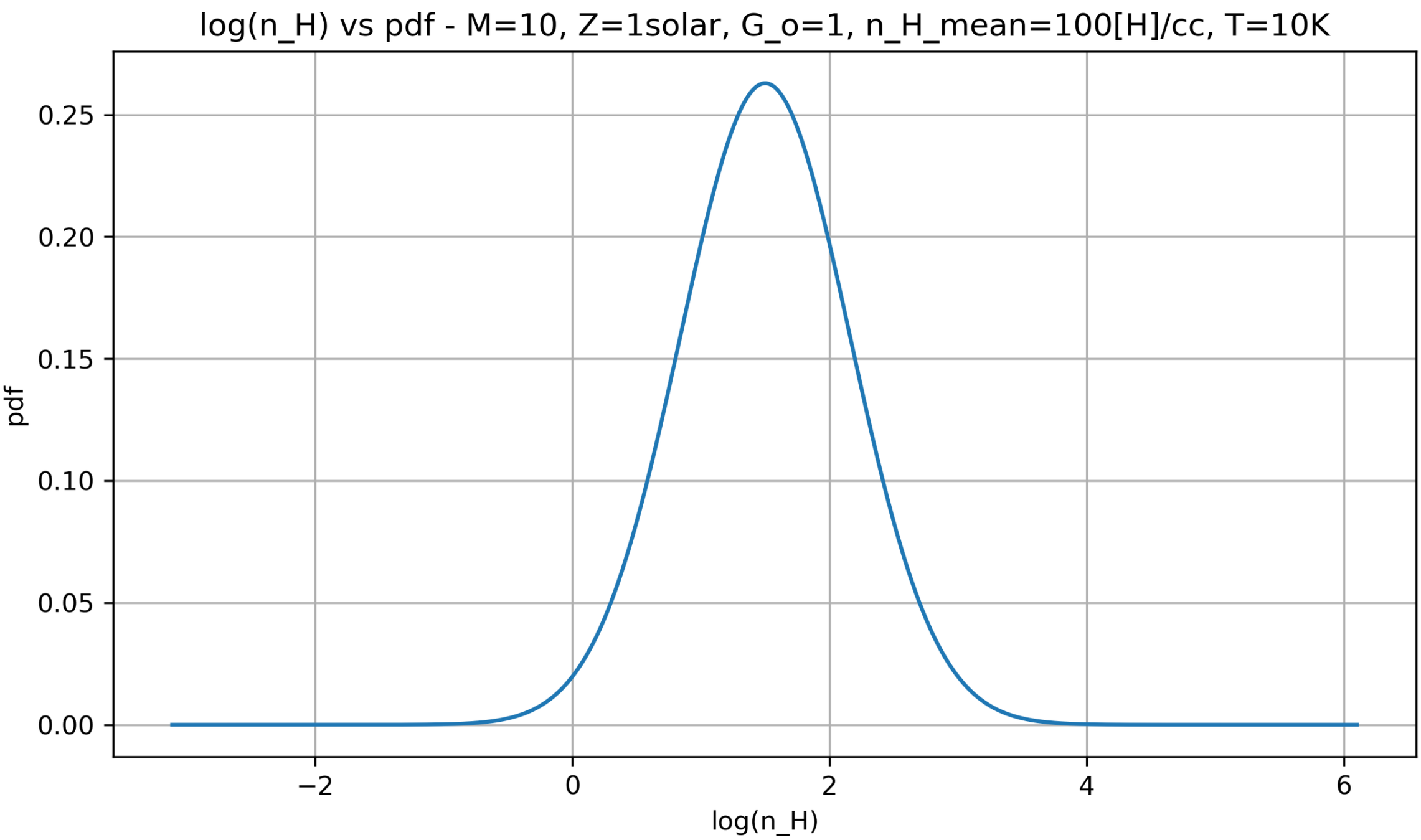
DOWN THE LINE…

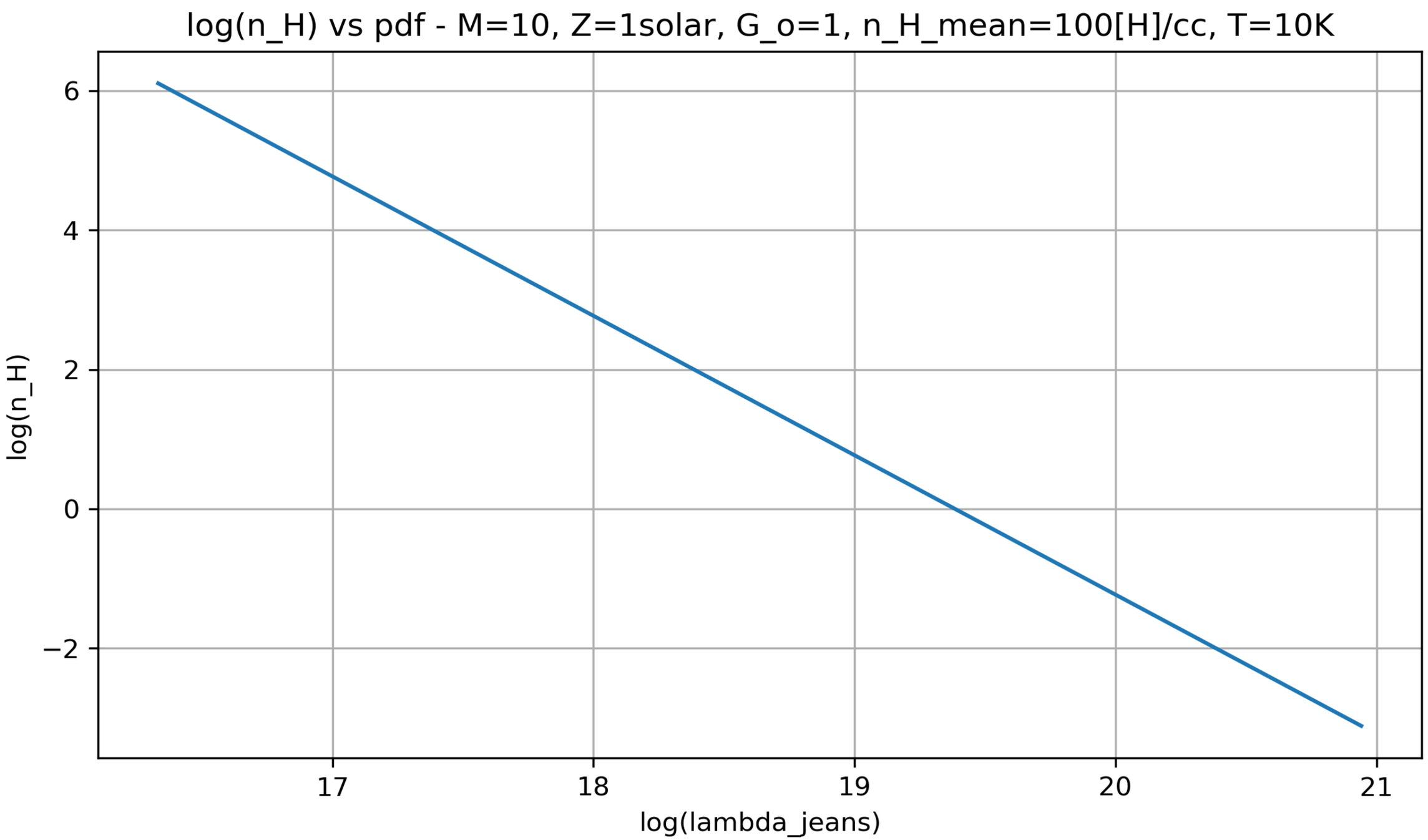
- ✓ PDF Evolution
- ✓ Comparing with observations from ALMA

FIN.

AFTER-LIFE


log(n_H) vs log(pdf) - M=varied, Z=1solar, G_o=1, n_H_mean=100[H]/cc, T=10K
M = 1e-2
M = 1e-1
M = 1e0
M = 1e+1
M = 1e+2
M = 1e+3
log(pdf)
2
0
−2
−4
−6
−8
−10
−12
−10
−5
0
5
10
log(n_H)


log(n_H) vs pdf - M=10, Z=1solar, G_o=1, n_H_mean=100[H]/cc, T=10K
pdf
0.25
0.20
0.15
0.10
0.05
0.00
−2
0
2
4
6
log(n_H)


log(n_H) vs pdf - M=10, Z=1solar, G_o=1, n_H_mean=100[H]/cc, T=10K
log(n_H)
6
4
2
0
−2
17
18
19
20
21
log(lambda_jeans)