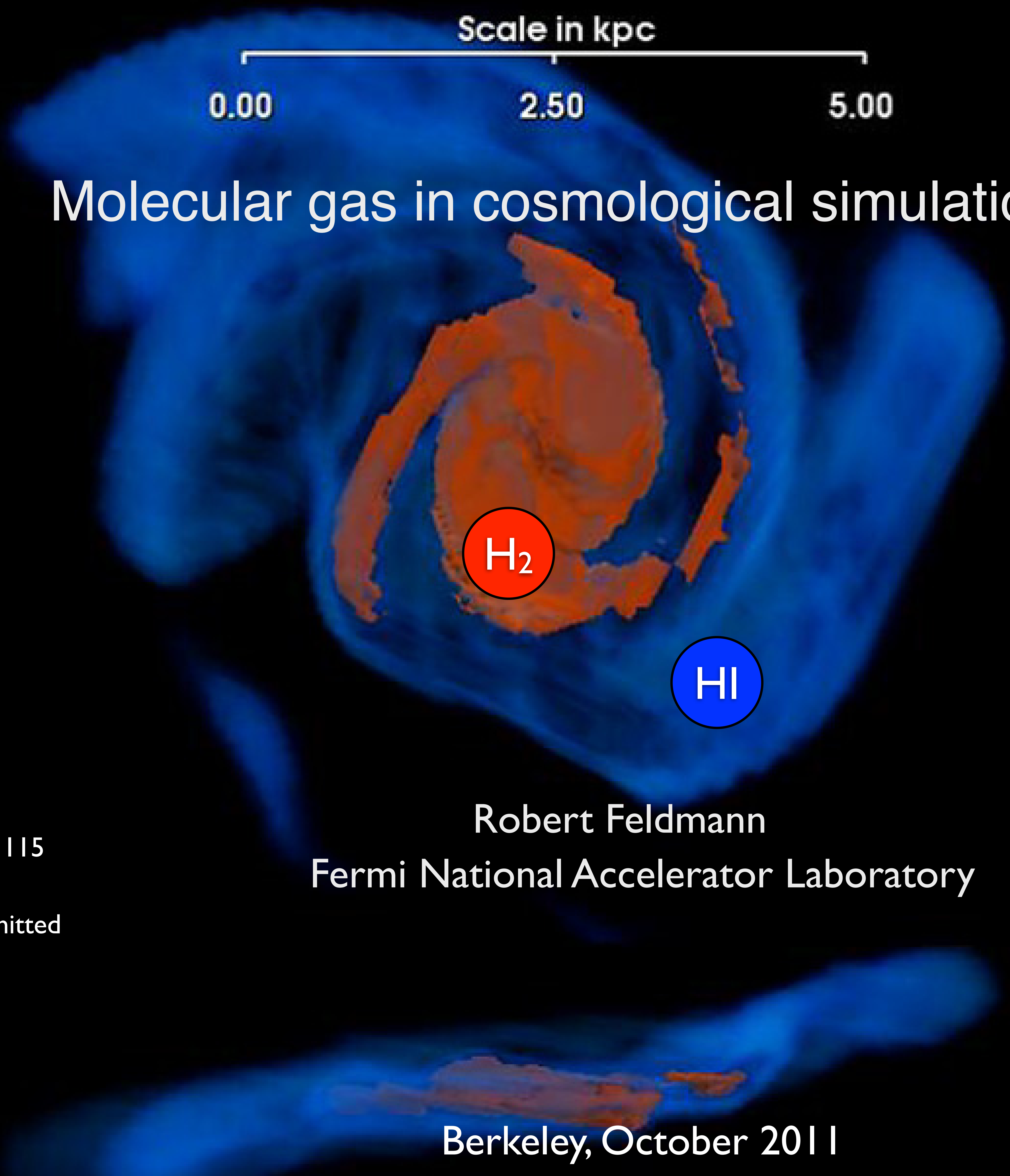
Molecular gas in cosmological simulations



Robert Feldmann
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Feldmann+11a, APJ 732, 115
arXiv:1010.1539
Feldmann+11b, APJ submitted
Feldmann+11c, in prep

KICP
Kavli Institute
for Cosmological Physics
at The University of Chicago

Fermilab

Berkeley, October 2011

Outline

- ★ Star formation in simulations and the role of H_2

- ★ Empirical star formation scaling relations

- ★ The role of the CO/H_2 conversion factor

  The surface densities of molecular clouds

  Implications for star formation relations

Outline

- ★ Star formation in simulations and the role of H_2

- ★ Empirical star formation scaling relations

- ★ The role of the CO/H_2 conversion factor
  - The surface densities of molecular clouds
  - Implications for star formation relations

How to make stars (in simulations)?

Ansatz:
"Schmidt law"

$$\dot{\rho}_* = \frac{\epsilon}{\tau}\rho_{\rm gas}$$

SF efficiency fuel

Motivation:

empirical "Kennicutt-Schmidt" relation

SFR surface density $\dot{\Sigma}_*$ & gas surface density $\Sigma_{\rm gas}$

$$\dot{\Sigma}_* \propto \Sigma^n_{\rm gas} \qquad n \sim 1.4$$

Different models - Different fuel efficiencies

CENSORED

e.g.,

① τ free-fall time ~ $\rho_{\mathrm{gas}}^{-0.5}$
ϵ constant

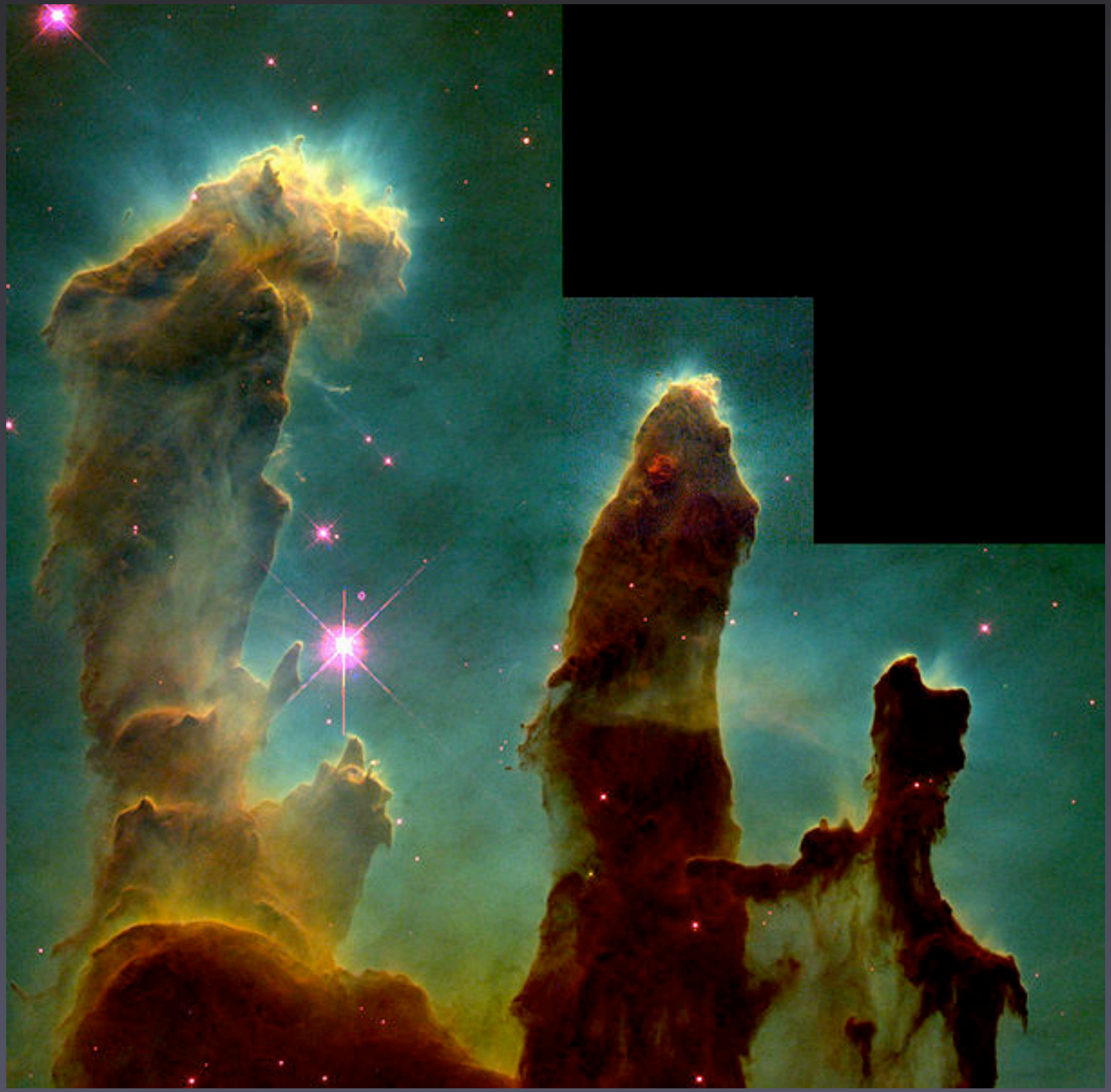
② ϵ/τ constant ~ 1 Gyr^{-1}

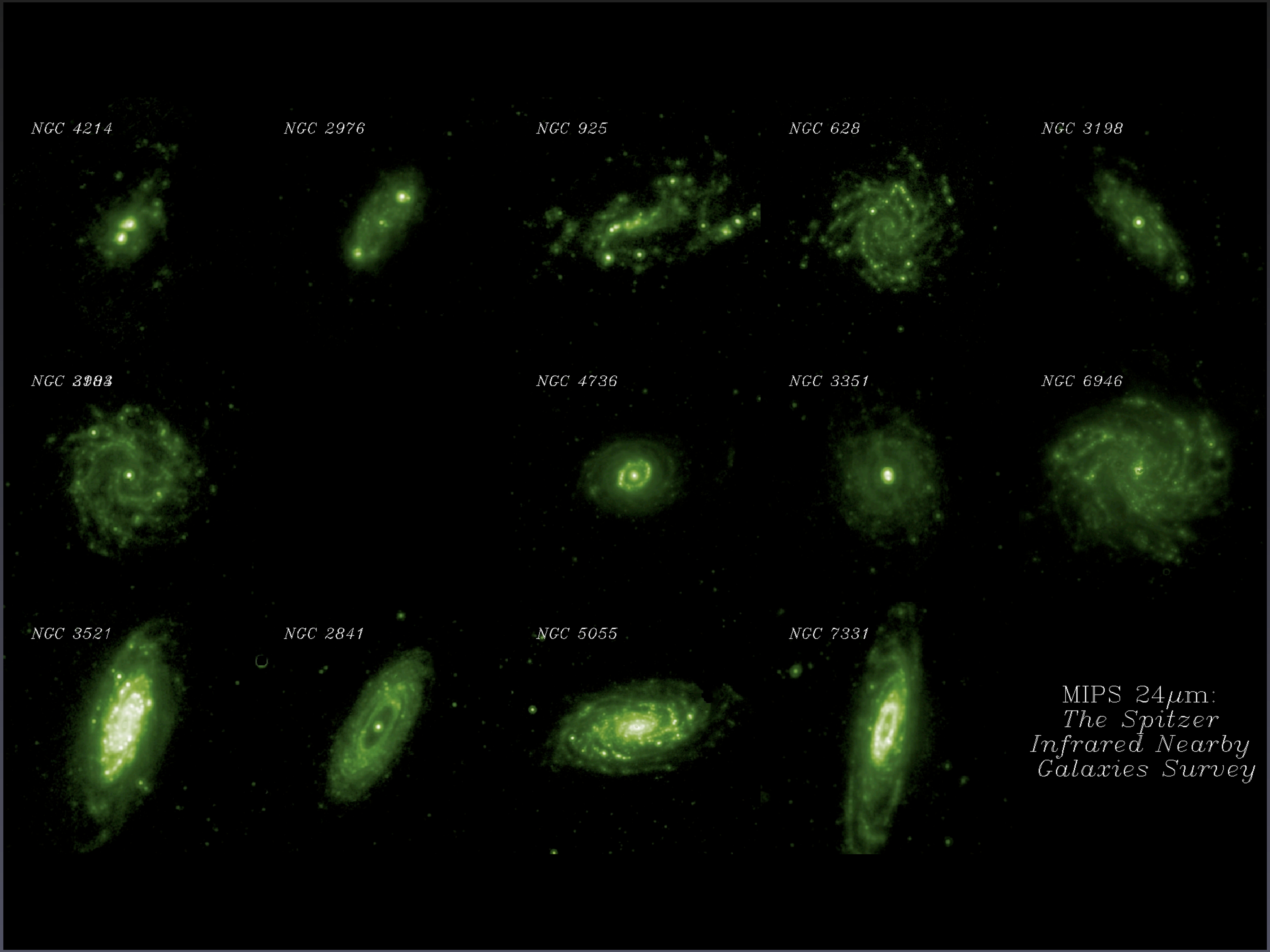
③ pressure based efficiency

$$A\left(1\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}\right)^{-n}\left(\frac{\gamma}{G}f_{\mathrm{g}}P_{\mathrm{tot}}\right)^{(n-1)/2}$$

plus additional star formation “criteria”

Stars form from molecular gas



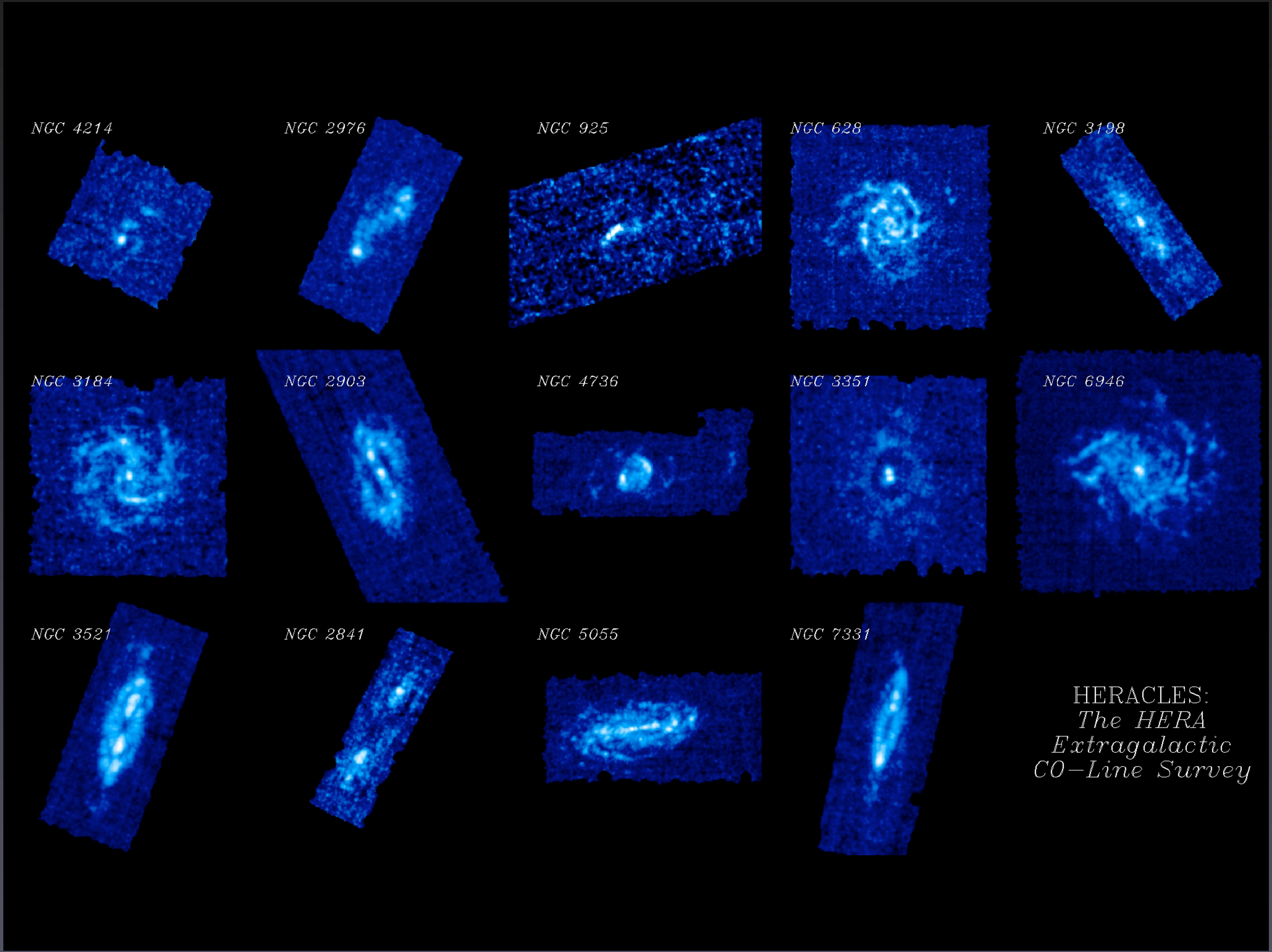


proxy of
(obscured) SF

SINGS
(Kennicutt+ 03)

from http://www.mpia.de/~leroy/Site/Talks.html

proxy of H_2

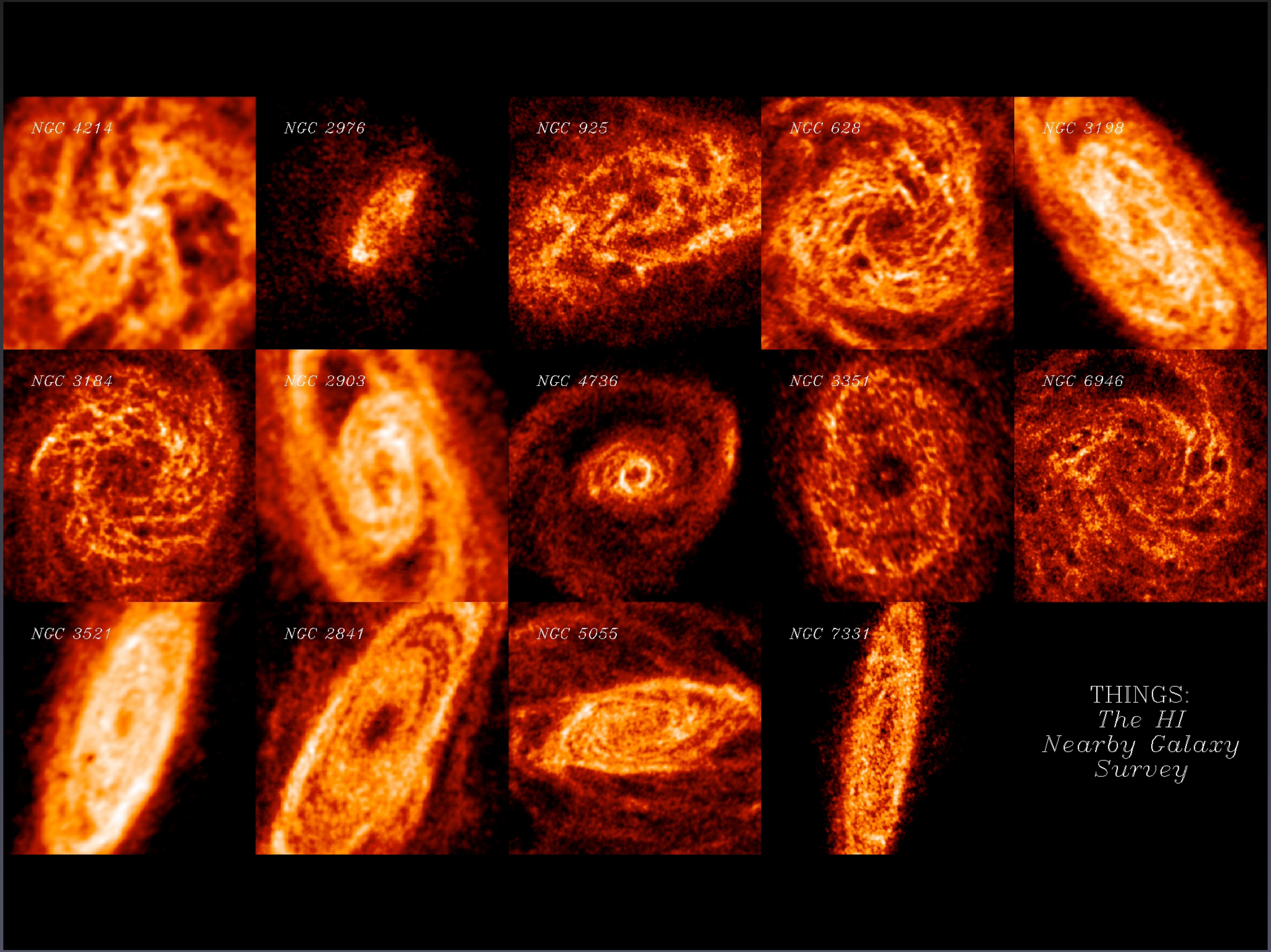


HERACLES

(Leroy+ 08)

from http://www.mpia.de/~leroy/Site/Talks.html

H_I



THINGS

(Walter+ 08)

from http://www.mpia.de/~leroy/Site/Talks.html

In simulations we should form stars based on H_2

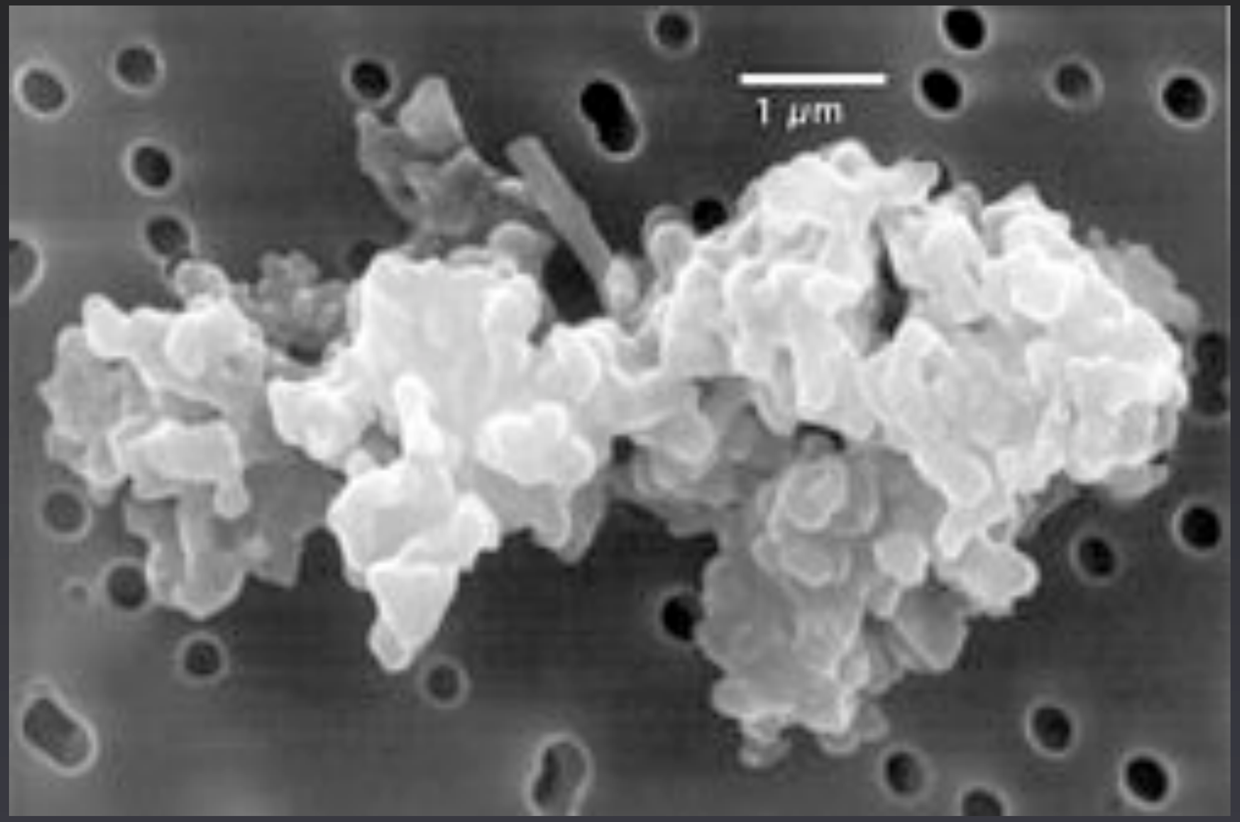
$$\rho_{\rm H_2} = f_{\rm H_2} \rho_{\rm gas}$$

Schmidt law

$$\dot{\rho}_* = \frac{\epsilon}{\tau} f_{\rm H_2} \rho_{\rm gas}$$

→ Need to estimate $f_{\rm H_2}$

Primer - H_2 chemistry



H_2 formation

- catalyzed by dust grains
- gas phase channel exists, but unimportant except in metal/dust free gas (Pop III)
- is slow: e.g., ~ Myr (at solar Z, depends on n_H)

H_2 destruction

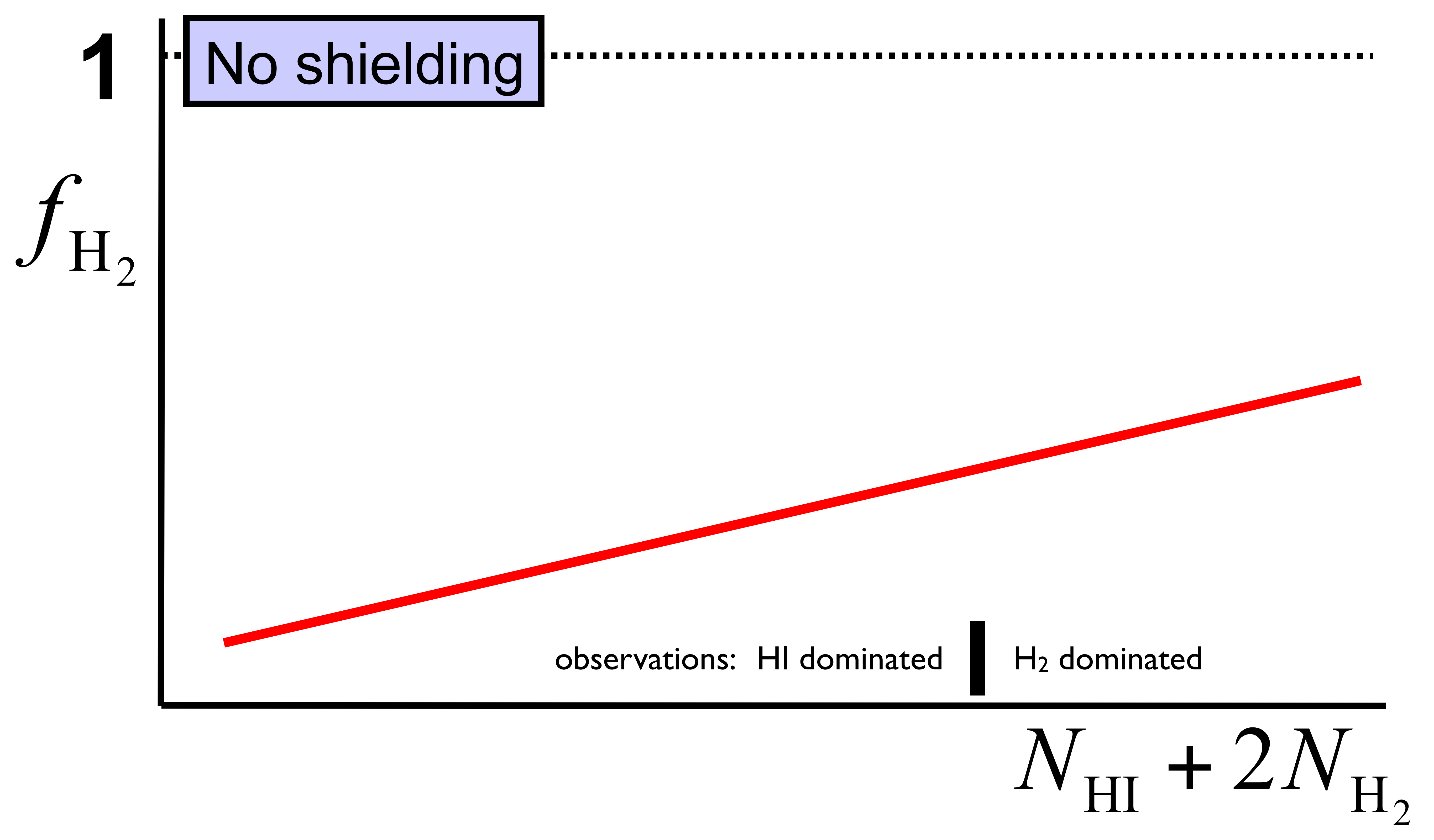
- photo-dissociated by UV radiation in the Lyman-Werner bands ~ 912 - 1100 Angstrom
- is fast ~ 1000 yr (at MW UV field)

in steady state: $\Gamma_{\mathrm{LW}} n_{\mathrm{H}_2} = R_{\mathrm{D}} n_{\mathrm{HI}} n$

$$f_{\mathrm{H}_2} = 1.8 \times 10^{-5} \left(\frac{n}{30\,\mathrm{cm}^{-3}} \right) \left(\frac{R_{\mathrm{D}}}{3 \times 10^{-17} \mathrm{cm}^3\,\mathrm{s}^{-1}} \right) \left(\frac{5 \times 10^{-11} s^{-1}}{\Gamma_{\mathrm{LW}}} \right)$$

Primer - H_2 chemistry

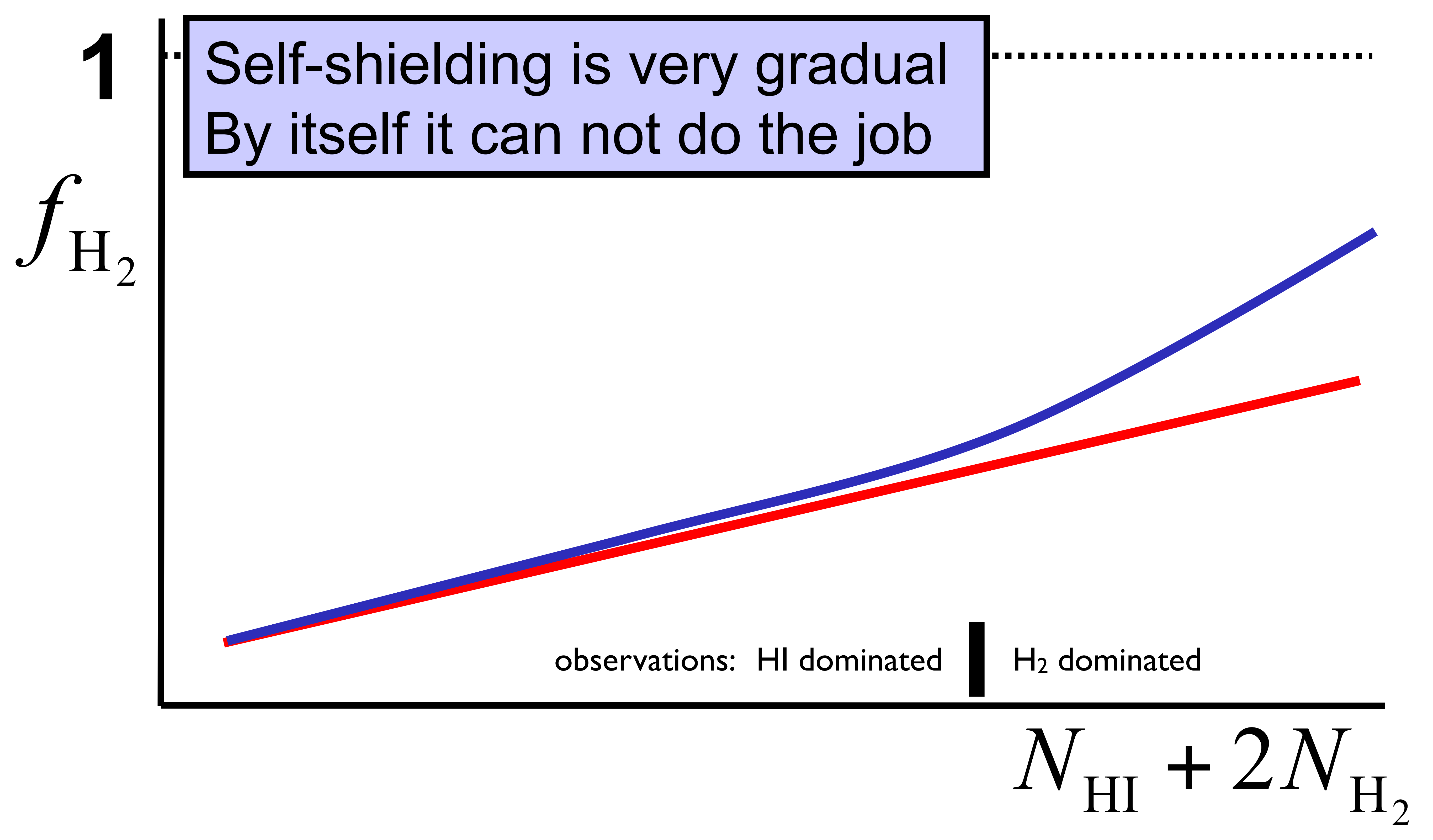
without shielding of UV radiation only trace amounts of H_2 in the ISM



need shielding of UV

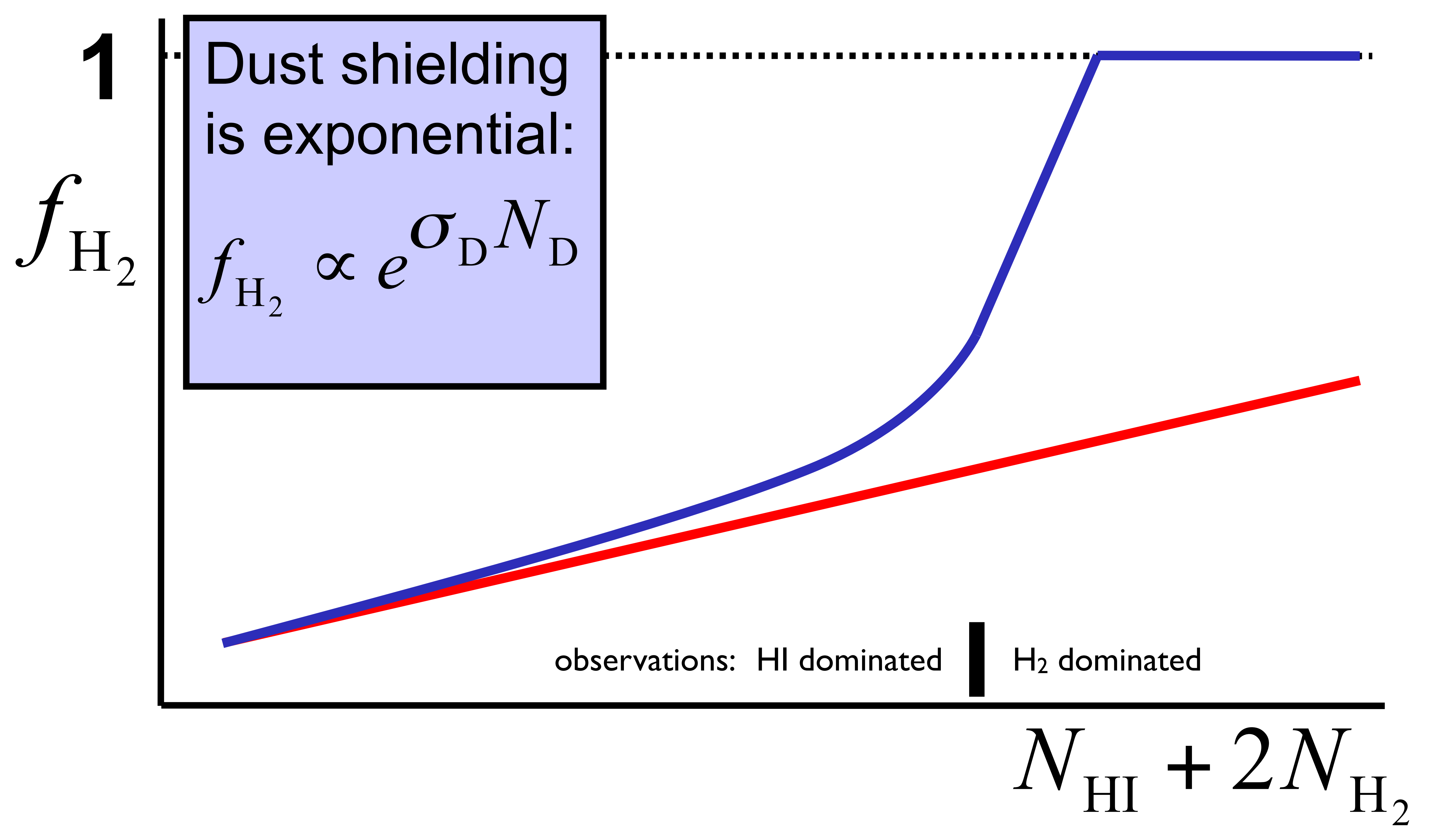
- H_2 self-shielding
- dust shielding

Primer - H_2 chemistry

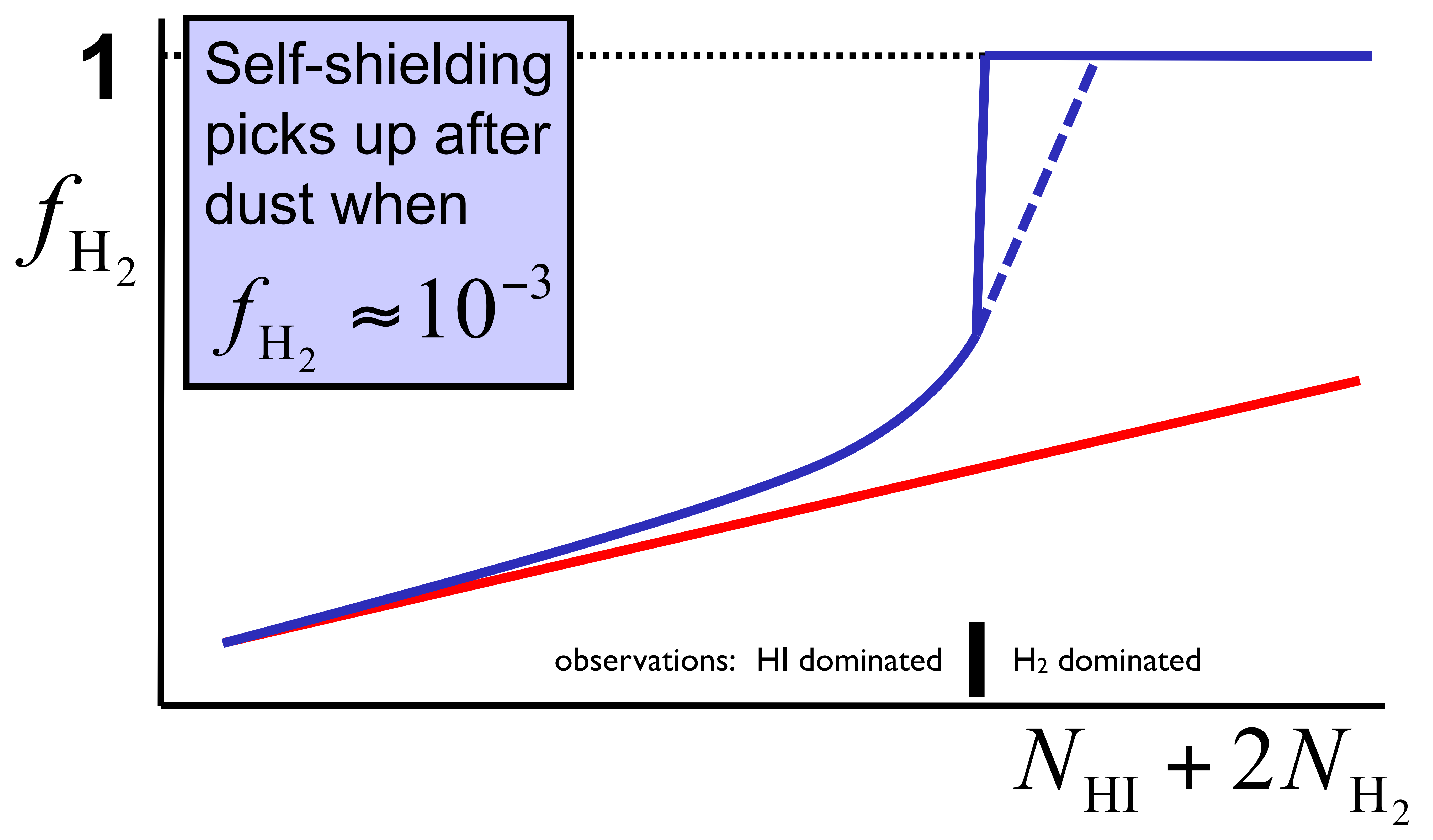


Self-shielding is very gradual
By itself it can not do the job

Primer - H_2 chemistry



Primer - H_2 chemistry



Self-shielding picks up after dust when

$f_{H_2} \approx 10^{-3}$

ART*

- N-body + AMR hydro code

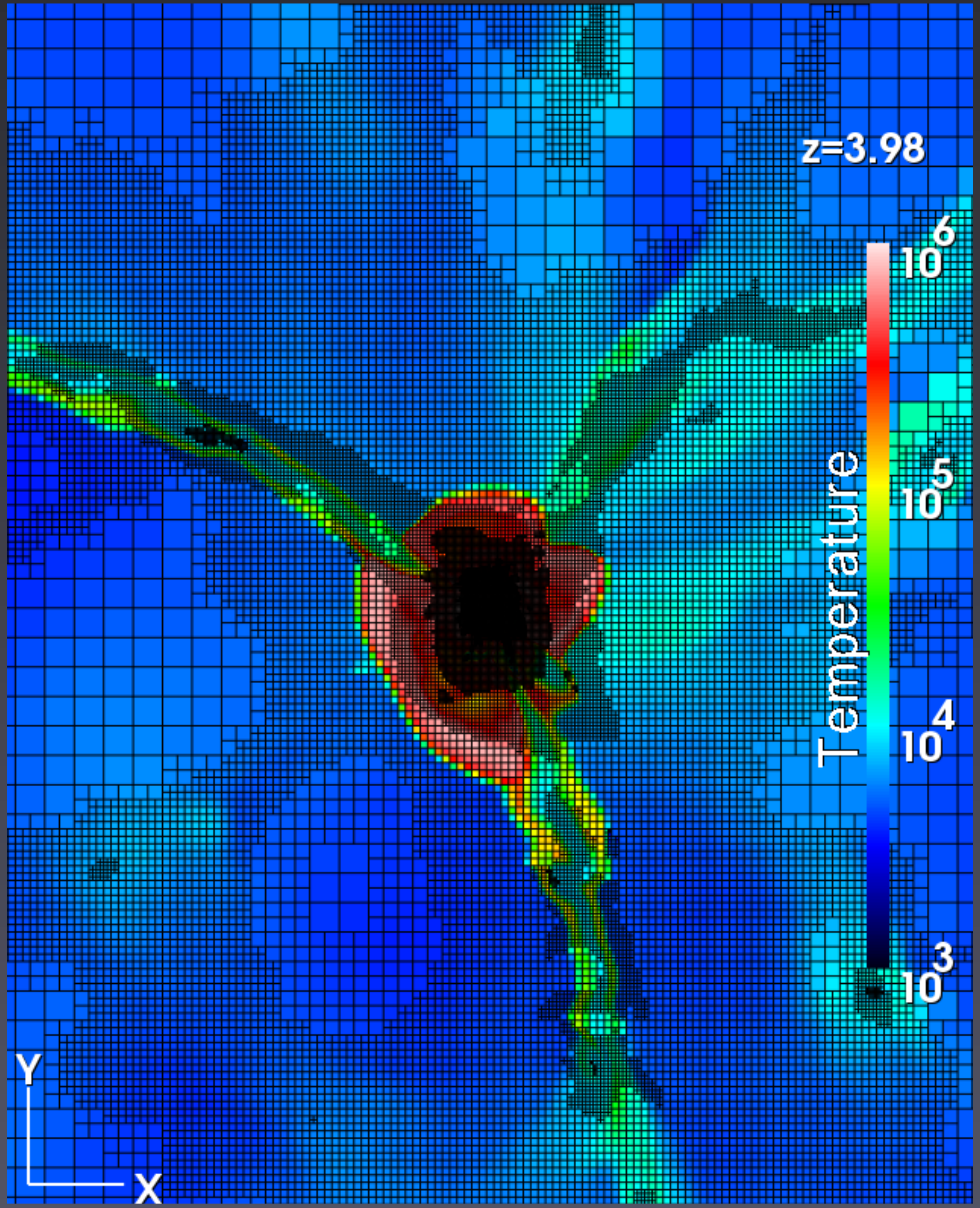
*Adaptive Refinement Tree (Kravtsov+ 97,02)

AMR:

- whole space part of a mesh
- selective refinement of the mesh in regions of "interest", e.g., regions of high density

- non-equilibrium cooling & ionization
- non LTE chemical network
- radiative transfer in the LW bands (OTVET)
- subgrid modeling of SF based on H_2

$$\dot{\rho}_* = \frac{\epsilon}{\tau} f_{\mathrm{H_2}} \rho_{\mathrm{gas}}$$



The chemistry in ART

- non-equilibrium network of various H and He species
- incl. H_2 formation on dust grains

- two adjustable parameters that account for limited spatial resolution (~50 pc):
  - clumping factor
  - coherence length (for shielding)

$$\left\{\begin{aligned}
\dot{\mathcal{I}}_{\mathrm{H\,I}} &= -n_{\mathrm{H\,I}}\Gamma_{\mathrm{H\,I}} - C_{\mathrm{H\,I}}n_e n_{\mathrm{H\,I}} + R_{\mathrm{H\,II}}n_e n_{\mathrm{H\,II}},\\
\dot{\mathcal{I}}_{\mathrm{H\,II}} &= -\dot{\mathcal{I}}_{\mathrm{H\,I}} = -R_{\mathrm{H\,II}}n_e n_{\mathrm{H\,II}} + n_{\mathrm{H\,I}}\Gamma_{\mathrm{H\,I}} + C_{\mathrm{H\,I}}n_e n_{\mathrm{H\,I}},\\
\dot{\mathcal{I}}_{\mathrm{He\,I}} &= -n_{\mathrm{He\,I}}\Gamma_{\mathrm{He\,I}} - C_{\mathrm{He\,I}}n_e n_{\mathrm{He\,I}} + (D_{\mathrm{He\,II}} + R_{\mathrm{He\,II}})n_e n_{\mathrm{He\,II}},\\
\dot{\mathcal{I}}_{\mathrm{He\,II}} &= -n_{\mathrm{He\,II}}\Gamma_{\mathrm{He\,II}} - (D_{\mathrm{He\,II}} + R_{\mathrm{He\,II}})n_e n_{\mathrm{He\,II}} - C_{\mathrm{He\,II}}n_e n_{\mathrm{He\,II}} + n_{\mathrm{He\,I}}\Gamma_{\mathrm{He\,I}} + C_{\mathrm{He\,I}}n_e n_{\mathrm{He\,I}} + R_{\mathrm{He\,III}}n_e n_{\mathrm{He\,III}},\\
\dot{\mathcal{I}}_{\mathrm{He\,III}} &= -R_{\mathrm{He\,III}}n_e n_{\mathrm{He\,III}} + n_{\mathrm{He\,II}}\Gamma_{\mathrm{He\,II}} + C_{\mathrm{He\,II}}n_e n_{\mathrm{He\,II}},\\
\dot{\mathcal{I}}_{\mathrm{H}_2} &= \dot{\mathcal{I}}_{\mathrm{H}^-} = \dot{\mathcal{I}}_{\mathrm{H}_2^+} = 0.
\end{aligned}\right.$$

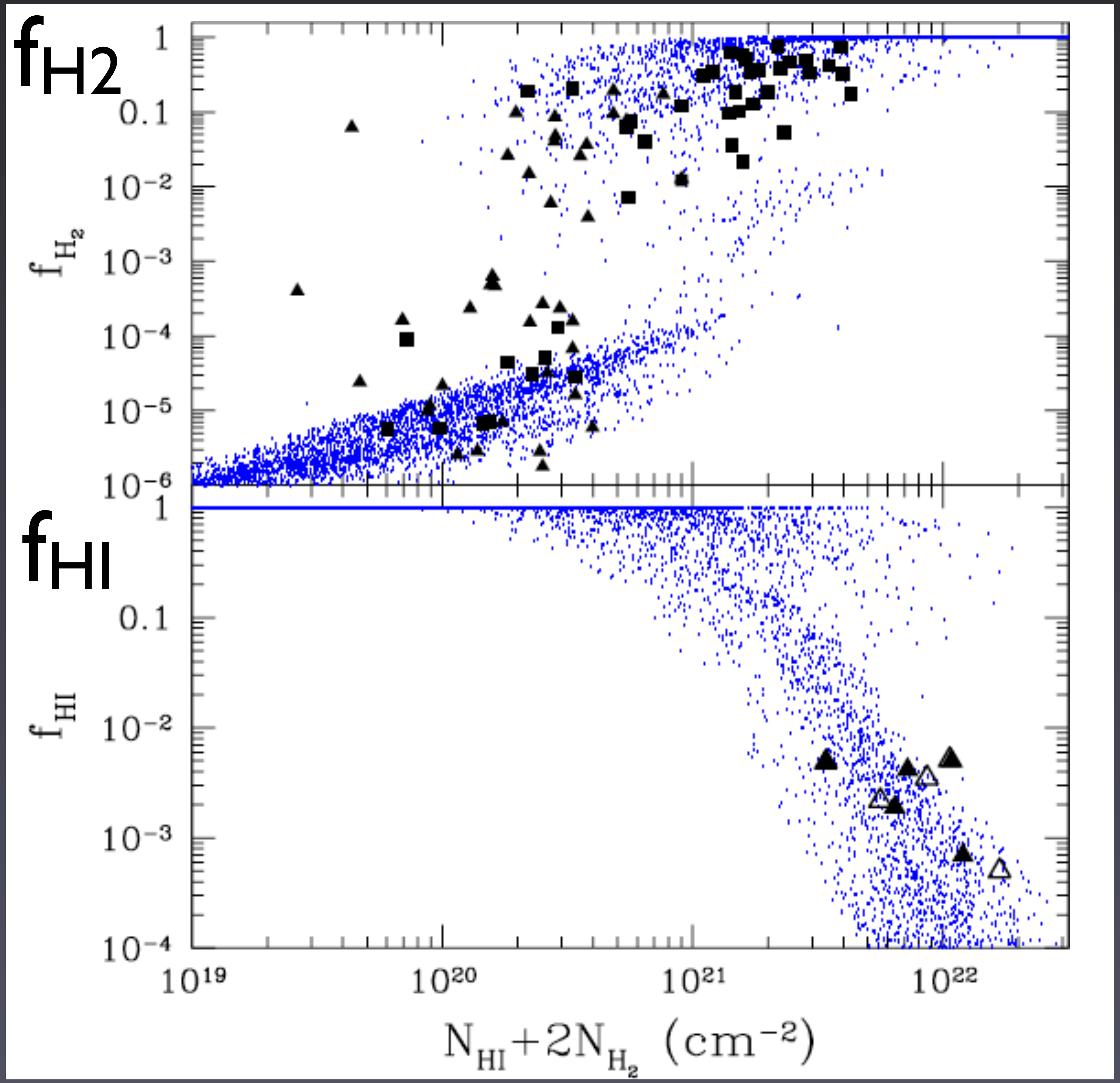
$$\left\{\begin{aligned}
\dot{\mathcal{M}}_{\mathrm{H\,I}} &= \Gamma_{\mathrm{A}}n_{\mathrm{H}^-} + \Gamma_{\mathrm{B}}n_{\mathrm{H}_2^+} + 2\Gamma_{\mathrm{E}}n_{\mathrm{H}_2} + 2\Gamma_{\mathrm{LW}}n_{\mathrm{H}_2} - k_1 n_e n_{\mathrm{H\,I}} - k_2 n_{\mathrm{H}^-}n_{\mathrm{H\,I}} - k_3 n_{\mathrm{H\,II}}n_{\mathrm{H\,I}} - k_4 n_{\mathrm{H}_2^+}n_{\mathrm{H\,I}}\\
&\quad - k_{26}n_{\mathrm{He\,II}}n_{\mathrm{H\,I}} - 2k_{30}n_{\mathrm{H\,I}}^3 - 2k_{31}n_{\mathrm{H\,I}}^2 n_{\mathrm{H}_2} - 2k_{32}n_{\mathrm{H\,I}}^2 n_{\mathrm{He\,I}} + 2k_5 n_{\mathrm{H\,II}}n_{\mathrm{H}^-} + 2k_6 n_e n_{\mathrm{H}_2^+} + k_7 n_{\mathrm{H}_2}n_{\mathrm{H\,II}}\\
&\quad + 2k_8 n_e n_{\mathrm{H}_2} + 2k_9 n_{\mathrm{H\,I}}n_{\mathrm{H}_2} + 2k_{10}n_{\mathrm{H}_2}n_{\mathrm{H}_2} + 2k_{11}n_{\mathrm{He\,I}}n_{\mathrm{H}_2} + k_{14}n_e n_{\mathrm{H}^-} + k_{15}n_{\mathrm{H\,I}}n_{\mathrm{H}^-} + k_{21}n_{\mathrm{H}_2^+}n_{\mathrm{H}^-}\\
&\quad + 3k_{22}n_{\mathrm{H}^-}n_{\mathrm{H}_2^+} + k_{23}n_e n_{\mathrm{H}_2} + k_{24}n_{\mathrm{He\,II}}n_{\mathrm{H}_2} + k_{27}n_{\mathrm{He\,I}}n_{\mathrm{H\,II}} + k_{28}n_{\mathrm{He\,II}}n_{\mathrm{H}^-} + k_{29}n_{\mathrm{He\,I}}n_{\mathrm{H}^-},\\
\dot{\mathcal{M}}_{\mathrm{H\,II}} &= \Gamma_{\mathrm{B}}n_{\mathrm{H}_2^+} + 2\Gamma_{\mathrm{C}}n_{\mathrm{H}_2^+} - k_3 n_{\mathrm{H\,I}}n_{\mathrm{H\,II}} - k_5 n_{\mathrm{H}^-}n_{\mathrm{H\,II}} - k_7 n_{\mathrm{H}_2}n_{\mathrm{H\,II}} - k_{16}n_{\mathrm{H}^-}n_{\mathrm{H\,II}} - k_{27}n_{\mathrm{He\,I}}n_{\mathrm{H\,II}} + k_4 n_{\mathrm{H}_2^+}n_{\mathrm{H\,I}}\\
&\quad + k_{24}n_{\mathrm{He\,II}}n_{\mathrm{H}_2} + k_{26}n_{\mathrm{H\,I}}n_{\mathrm{He\,II}},\\
\dot{\mathcal{M}}_{\mathrm{He\,I}} &= -k_{27}n_{\mathrm{H\,II}}n_{\mathrm{He\,I}} - k_{29}n_{\mathrm{H}^-}n_{\mathrm{He\,I}} + k_{24}n_{\mathrm{He\,II}}n_{\mathrm{H}_2} + k_{25}n_{\mathrm{He\,II}}n_{\mathrm{H}_2} + k_{26}n_{\mathrm{He\,II}}n_{\mathrm{H\,I}} + k_{28}n_{\mathrm{He\,II}}n_{\mathrm{H}^-},\\
\dot{\mathcal{M}}_{\mathrm{He\,II}} &= -k_{24}n_{\mathrm{H}_2}n_{\mathrm{He\,II}} - k_{25}n_{\mathrm{H}_2}n_{\mathrm{He\,II}} - k_{26}n_{\mathrm{H\,I}}n_{\mathrm{He\,II}} - k_{28}n_{\mathrm{H}^-}n_{\mathrm{He\,II}} + k_{27}n_{\mathrm{H\,II}}n_{\mathrm{He\,I}} + k_{29}n_{\mathrm{H}^-}n_{\mathrm{He\,I}},\\
\dot{\mathcal{M}}_{\mathrm{He\,III}} &= 0,\\
&\boxed{\dot{\mathcal{M}}_{\mathrm{H}_2} = -\Gamma_{\mathrm{D}}n_{\mathrm{H}_2} - \Gamma_{\mathrm{E}}n_{\mathrm{H}_2} - \Gamma_{\mathrm{LW}}n_{\mathrm{H}_2}} - k_7 n_{\mathrm{H}_2}n_{\mathrm{H\,II}} - k_8 n_e n_{\mathrm{H}_2} - k_9 n_{\mathrm{H\,I}}n_{\mathrm{H}_2} - k_{10}n_{\mathrm{H}_2}n_{\mathrm{H}_2} - k_{11}n_{\mathrm{He\,I}}n_{\mathrm{H}_2}\\
&\quad - k_{23}n_e n_{\mathrm{H}_2} - k_{24}n_{\mathrm{He\,II}}n_{\mathrm{H}_2} - k_{25}n_{\mathrm{He\,II}}n_{\mathrm{H}_2} + k_2 n_{\mathrm{H}^-}n_{\mathrm{H\,I}} + k_4 n_{\mathrm{H}_2^+}n_{\mathrm{H\,I}} + k_{21}n_{\mathrm{H}_2^+}n_{\mathrm{H}^-} + k_{30}n_{\mathrm{H\,I}}^3\\
&\quad + k_{31}n_{\mathrm{H\,I}}^2 n_{\mathrm{H}_2} + k_{32}n_{\mathrm{H\,I}}^2 n_{\mathrm{He\,I}},\\
\dot{\mathcal{M}}_{\mathrm{H}_2^+} &= -\Gamma_{\mathrm{B}}n_{\mathrm{H}_2^+} - \Gamma_{\mathrm{C}}n_{\mathrm{H}_2^+} + \Gamma_{\mathrm{D}}n_{\mathrm{H}_2} - k_4 n_{\mathrm{H\,I}}n_{\mathrm{H}_2^+} - k_6 n_e n_{\mathrm{H}_2^+} - k_{21}n_{\mathrm{H}^-}n_{\mathrm{H}_2^+} - k_{22}n_{\mathrm{H}^-}n_{\mathrm{H}_2^+} + k_3 n_{\mathrm{H\,I}}n_{\mathrm{H\,II}}\\
&\quad + k_7 n_{\mathrm{H}_2}n_{\mathrm{H\,II}} + k_{16}n_{\mathrm{H\,II}}n_{\mathrm{H}^-} + k_{25}n_{\mathrm{H}_2}n_{\mathrm{He\,II}},\\
\dot{\mathcal{M}}_{\mathrm{H}^-} &= -\Gamma_{\mathrm{A}}n_{\mathrm{H}^-} - k_2 n_{\mathrm{H\,I}}n_{\mathrm{H}^-} - k_5 n_{\mathrm{H\,II}}n_{\mathrm{H}^-} - k_{14}n_e n_{\mathrm{H}^-} - k_{15}n_{\mathrm{H\,I}}n_{\mathrm{H}^-} - k_{16}n_{\mathrm{H\,II}}n_{\mathrm{H}^-} - k_{21}n_{\mathrm{H}_2^+}n_{\mathrm{H}^-} -\\
&\quad - k_{22}n_{\mathrm{H}_2^+}n_{\mathrm{H}^-} - k_{28}n_{\mathrm{He\,II}}n_{\mathrm{H}^-} - k_{29}n_{\mathrm{He\,I}}n_{\mathrm{H}^-} + k_1 n_e n_{\mathrm{H\,I}} + k_{23}n_e n_{\mathrm{H}_2},
\end{aligned}\right.$$

$$\left\{\begin{aligned}
&\boxed{\dot{\mathcal{D}}_{\mathrm{H}_2} = D_{\mathrm{MW}}R_0 C_\rho n_{\mathrm{H\,I}}(n_{\mathrm{H\,I}} + 2n_{\mathrm{H}_2})},\\
\dot{\mathcal{D}}_{\mathrm{H\,I}} &= -2\dot{\mathcal{D}}_{\mathrm{H}_2},\\
\dot{\mathcal{D}}_{\mathrm{H\,II}} &= \dot{\mathcal{D}}_{\mathrm{He\,I}} = \dot{\mathcal{D}}_{\mathrm{He\,II}} = \dot{\mathcal{D}}_{\mathrm{He\,III}} = \dot{\mathcal{D}}_{\mathrm{H}^-} = \dot{\mathcal{D}}_{\mathrm{H}_2^+} = 0,
\end{aligned}\right.$$

If you can read this, you have good eyes!

The best - it actually works!

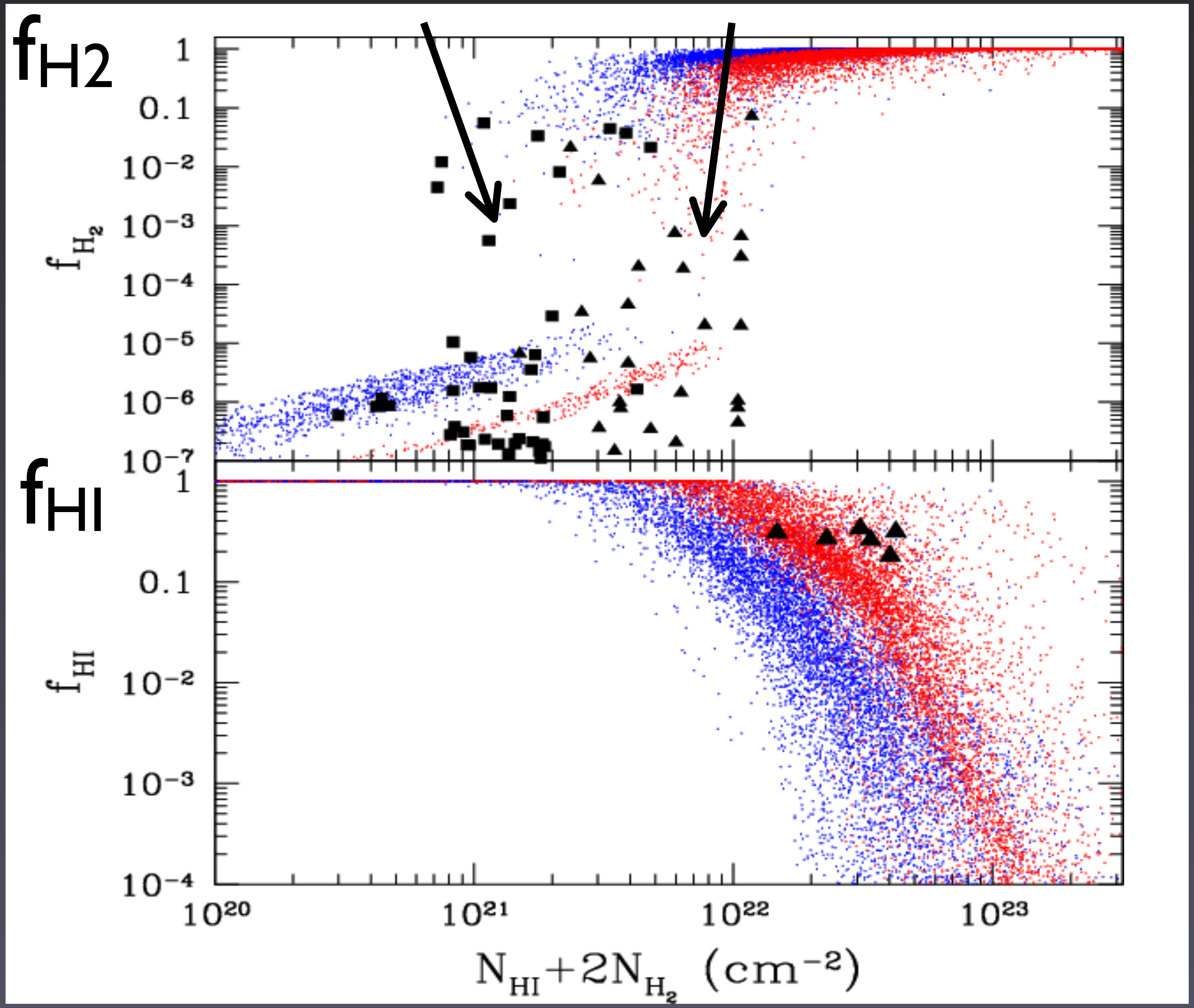
MW



Training

LMC

SMC



Testing

Gnedin&Kravtsov 11

Outline

- ★ Star formation in simulations and the role of H_2

- ★ Empirical star formation scaling relations

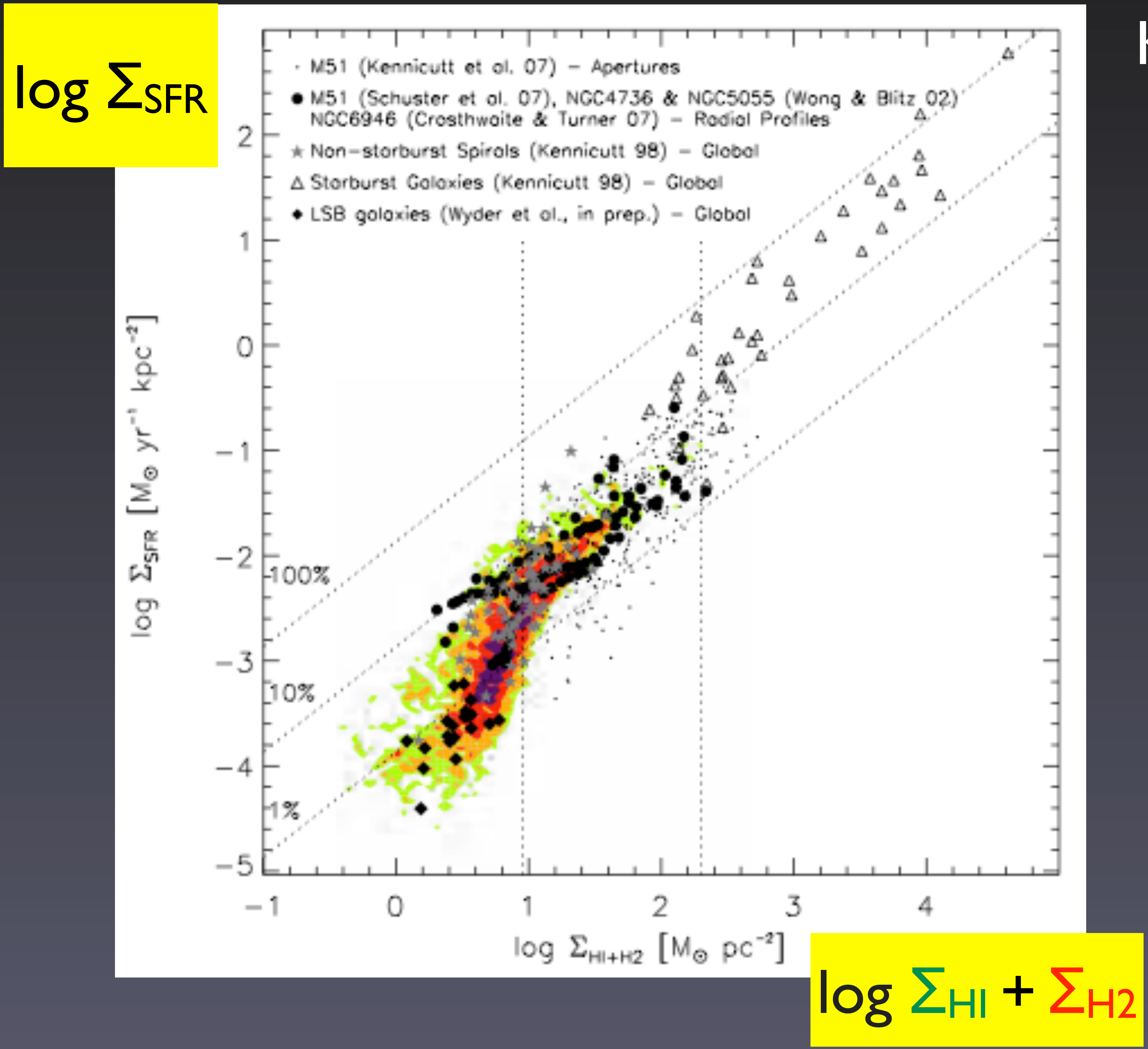
- ★ The role of the CO/H_2 conversion factor

  The surface densities of molecular clouds

  Implications for star formation relations

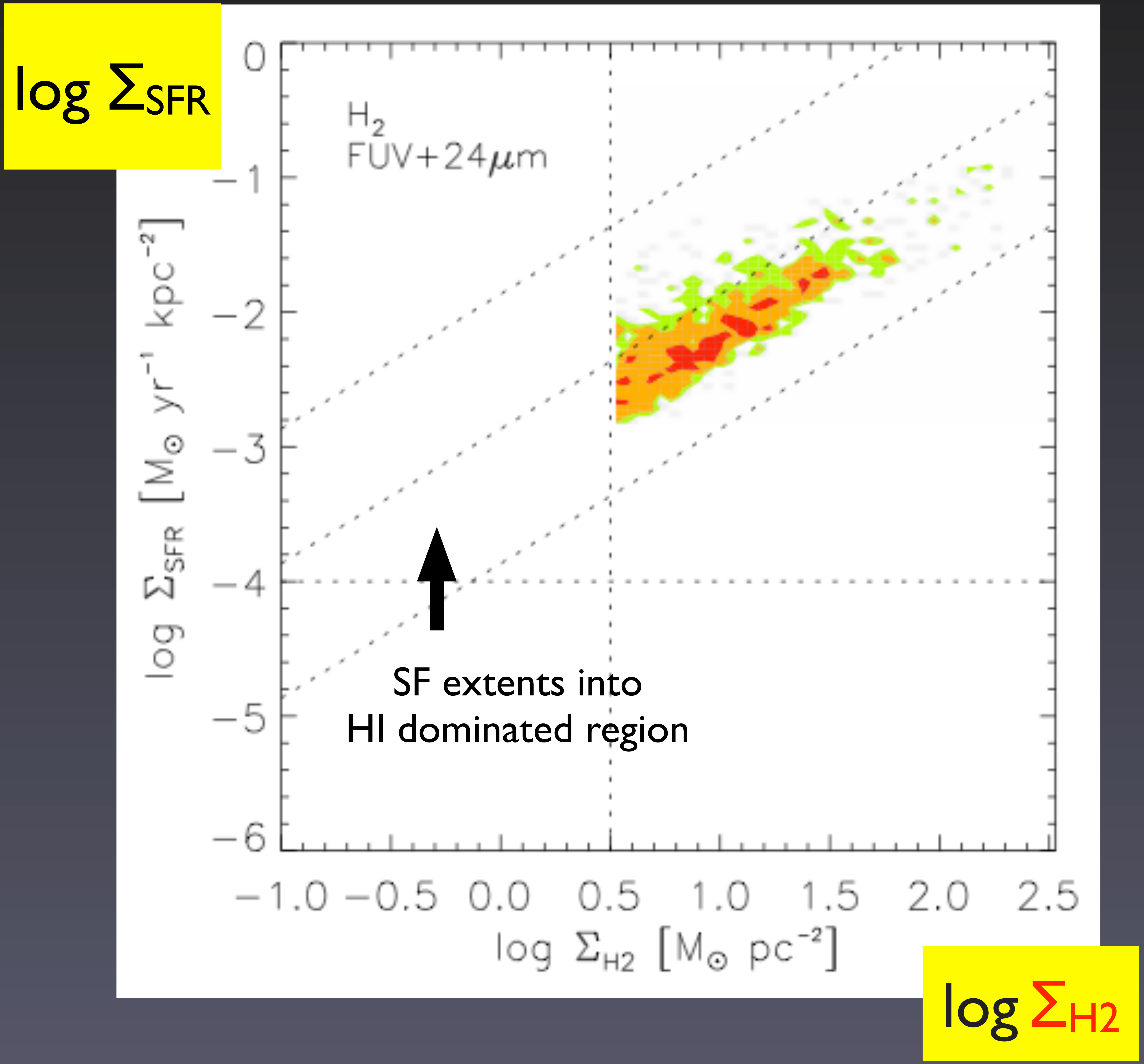
Kennicutt-Schmidt relation

- “threshold” ~ 10 M_{sun} pc^{-2}
- slope n~1.4



log Σ_{SFR}

log Σ_{HI} + Σ_{H2}



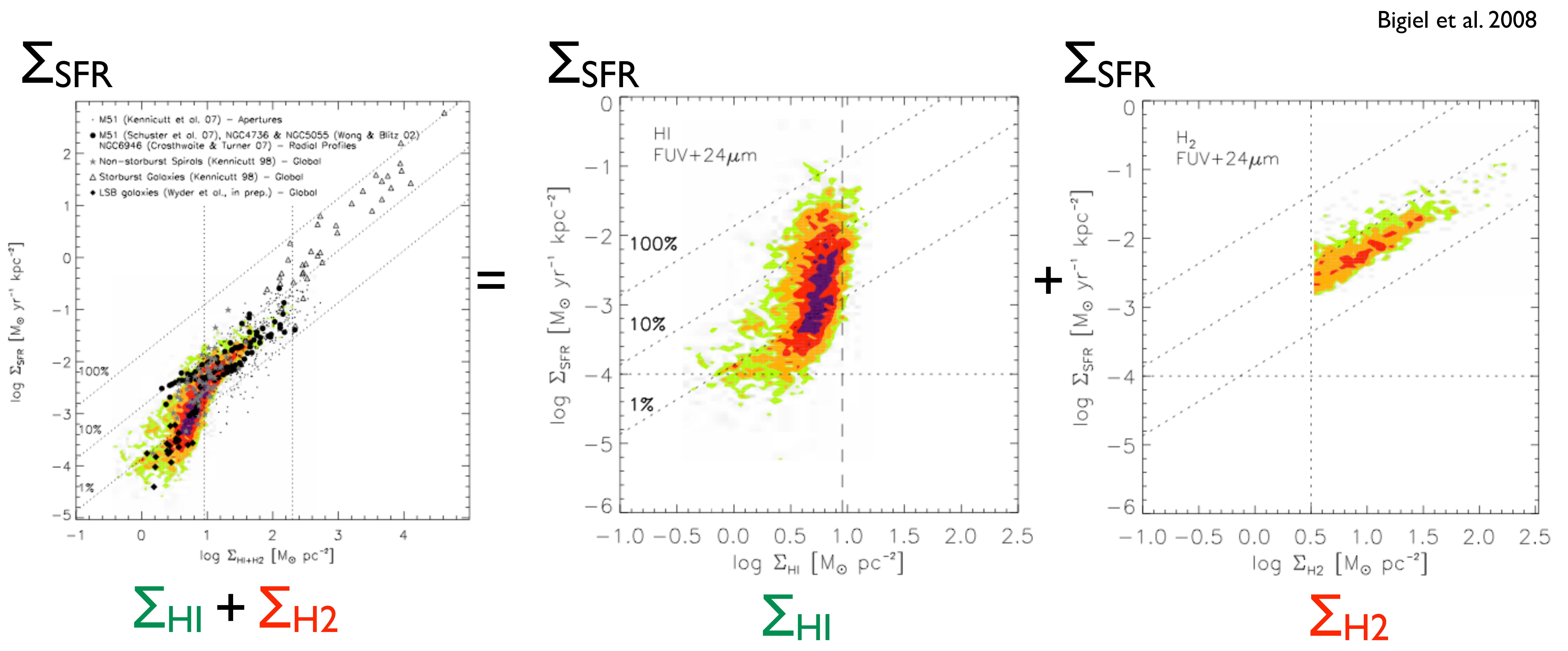
SF extents into
HI dominated region

Kennicutt-Schmidt relation

- “threshold” ~ 10 M_{sun} pc^{-2}
- slope n~1.4

- there exists a molecular version:
  - slope n~1
  - ~const depletion time 1-2 Gyr

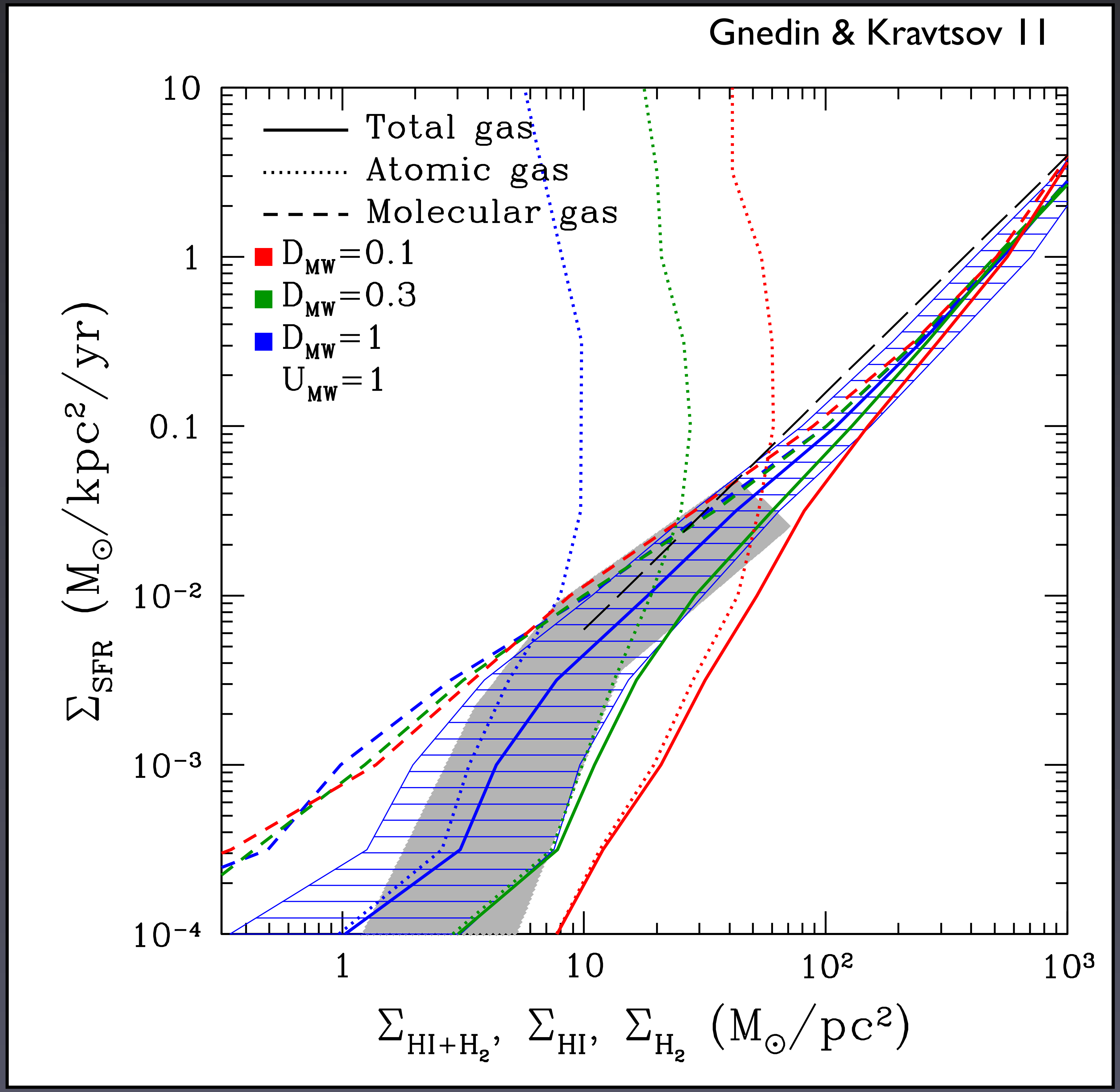
Threshold in KS relation consequence of HI - H_2 transition

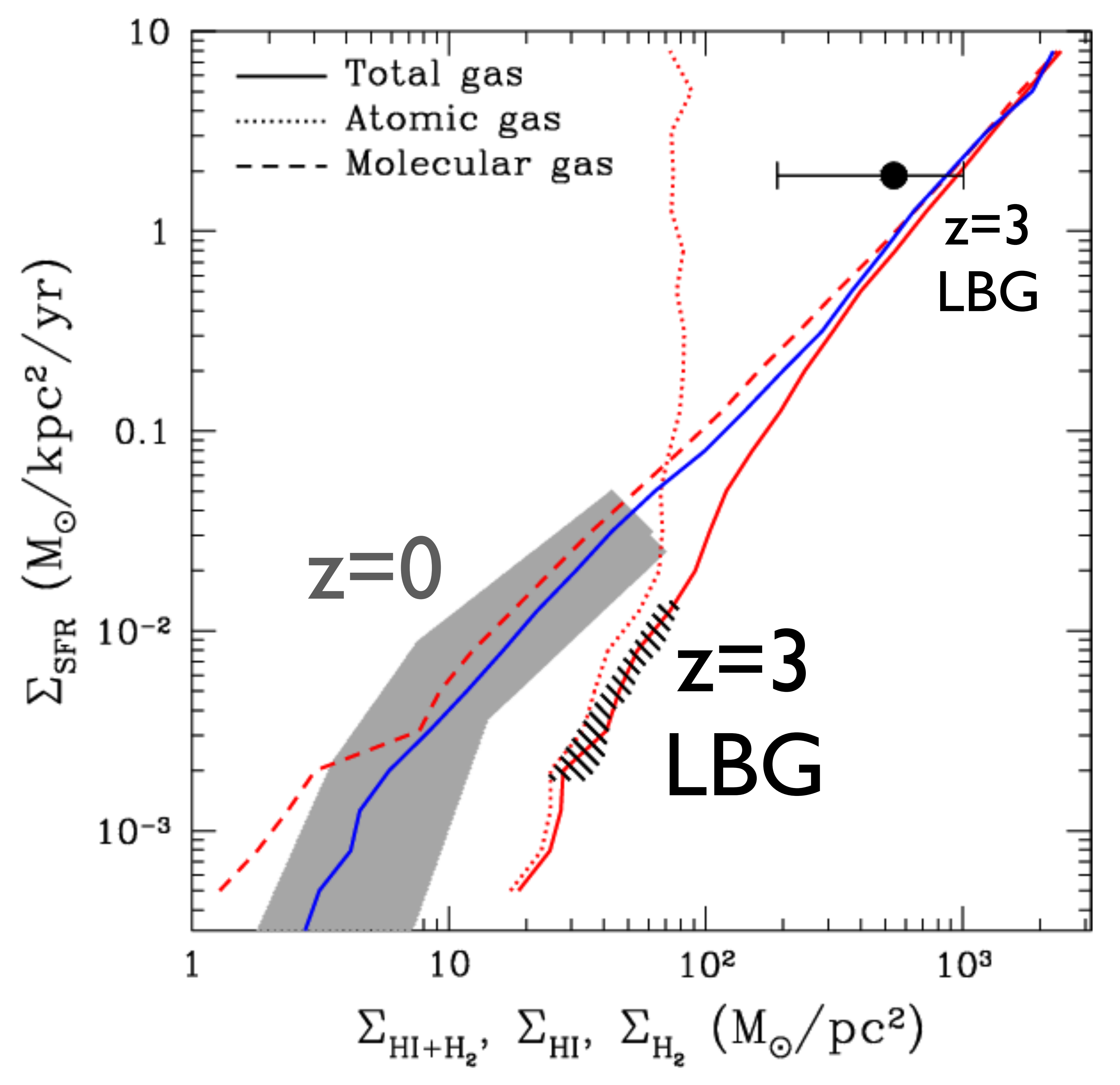


Bigiel et al. 2008

Threshold in KS relation consequence of HI - H_2 transition

KS relation not universal! Changes with Z & UV





What about the molecular version of the KS relation?

What about the molecular version of the KS relation?

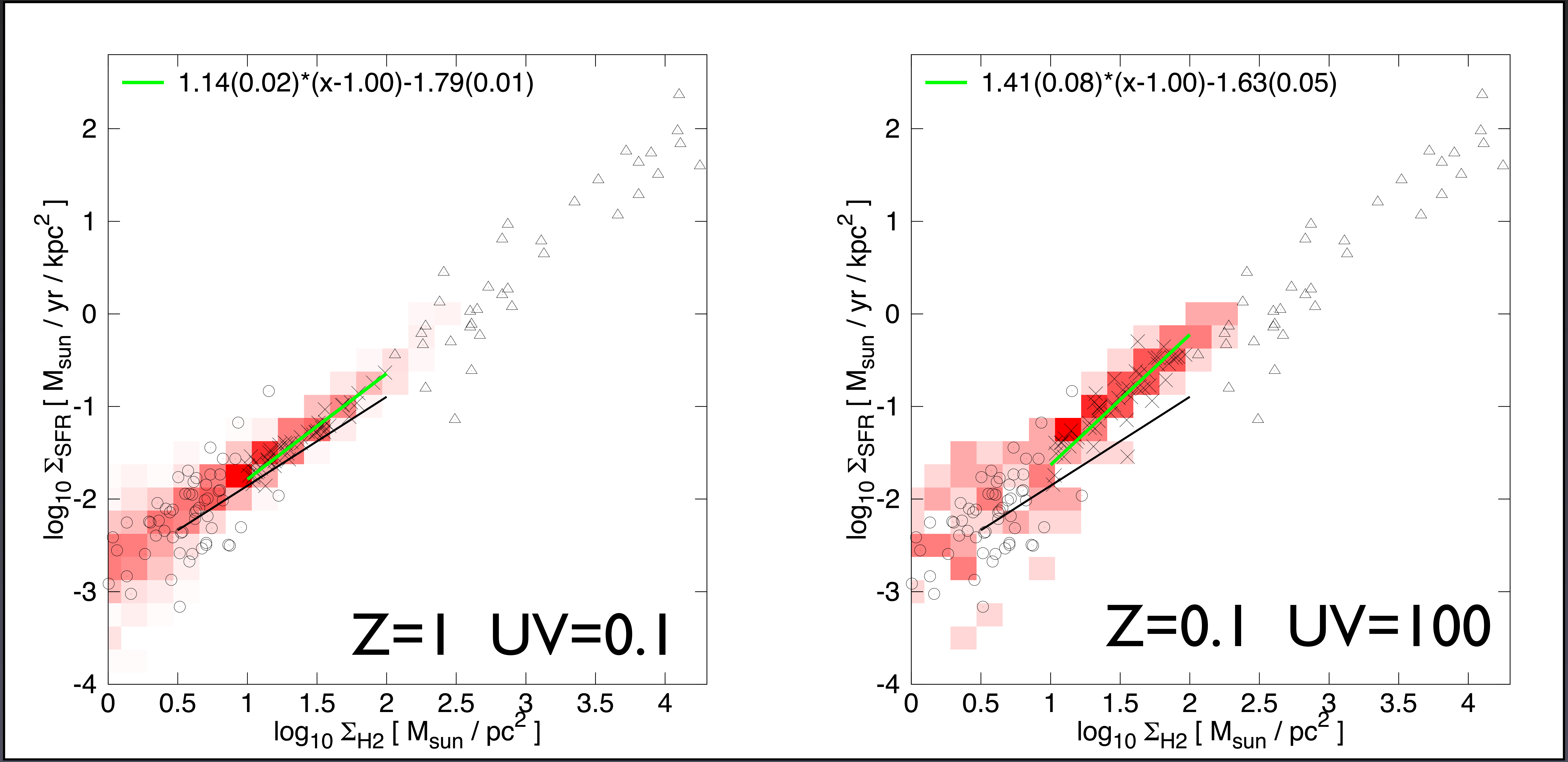
Is $\Sigma_{\rm SFR} - \Sigma_{\rm H_2}$ universal ?

What about the molecular version of the KS relation?

Is $\Sigma_{\mathrm{SFR}} - \Sigma_{\mathrm{H_2}}$ universal ?

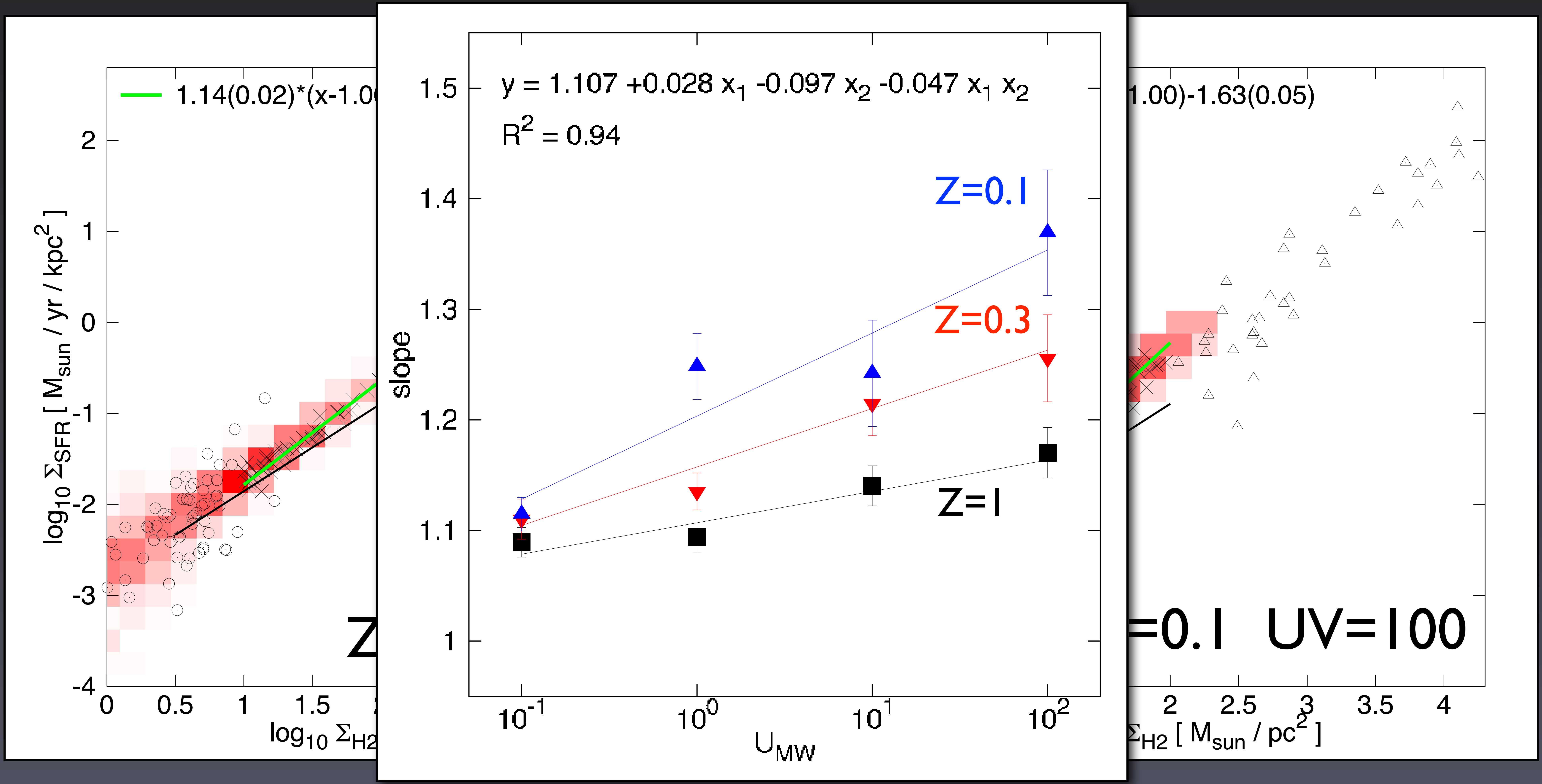
What is causing its scatter ?

Is $\Sigma_{\rm SFR} - \Sigma_{\rm H_2}$ universal?



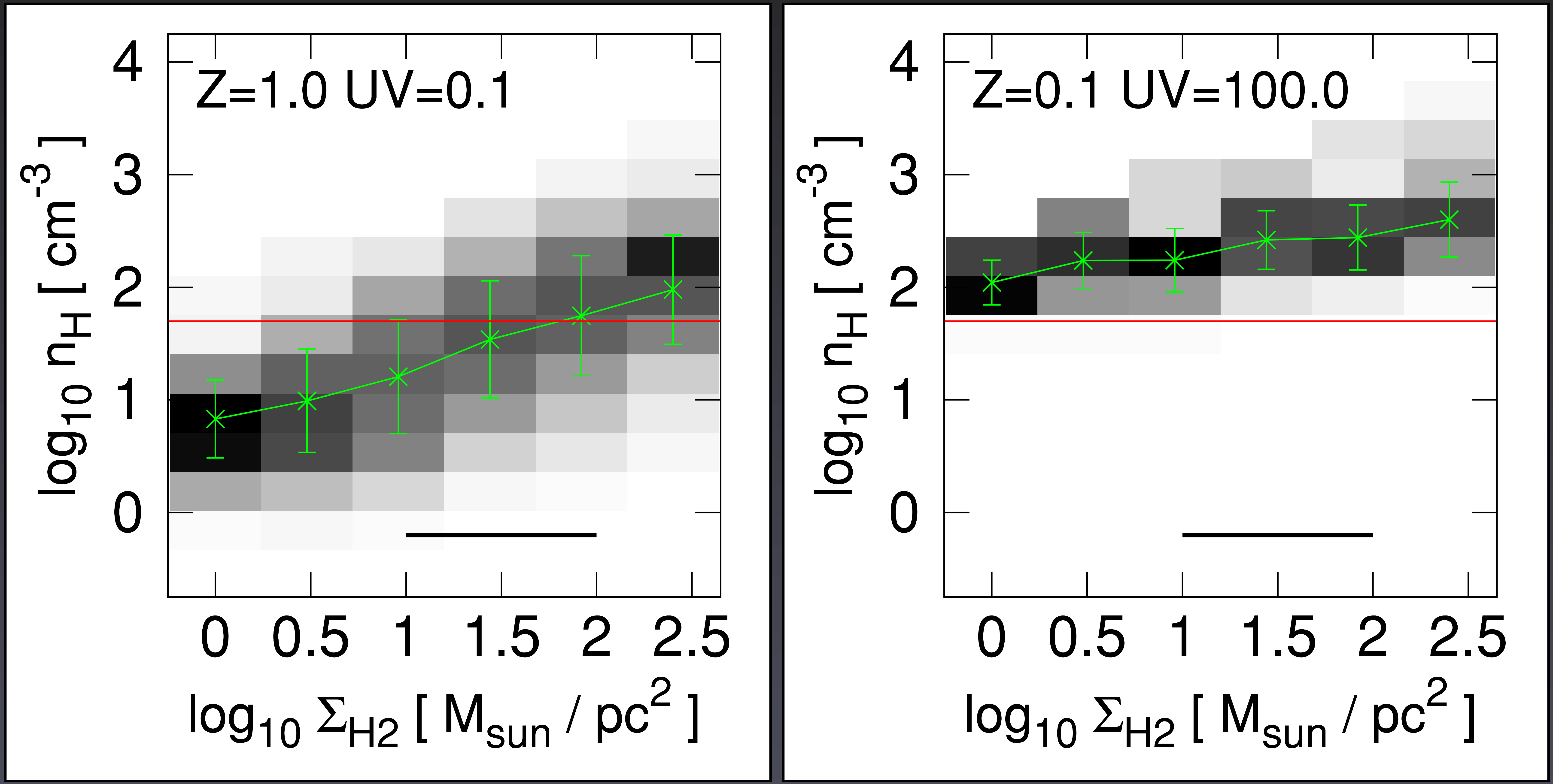
change in slope & intercept with Z, UV!

Is $\Sigma_{\mathrm{SFR}} - \Sigma_{\mathrm{H_2}}$ universal?



change in slope & intercept with Z, UV!

Is $\Sigma_{\rm SFR} - \Sigma_{\rm H_2}$ universal?



due to

- changing density pdf with Z, UV (intercept)
- changing density pdf with large scale surface density (slope)
- non-linear Schmidt law

What is causing its scatter ?

Due to width of density pdf & non-linear Schmidt law?

No

- subdominant
- does not increase with decreasing scale as observed

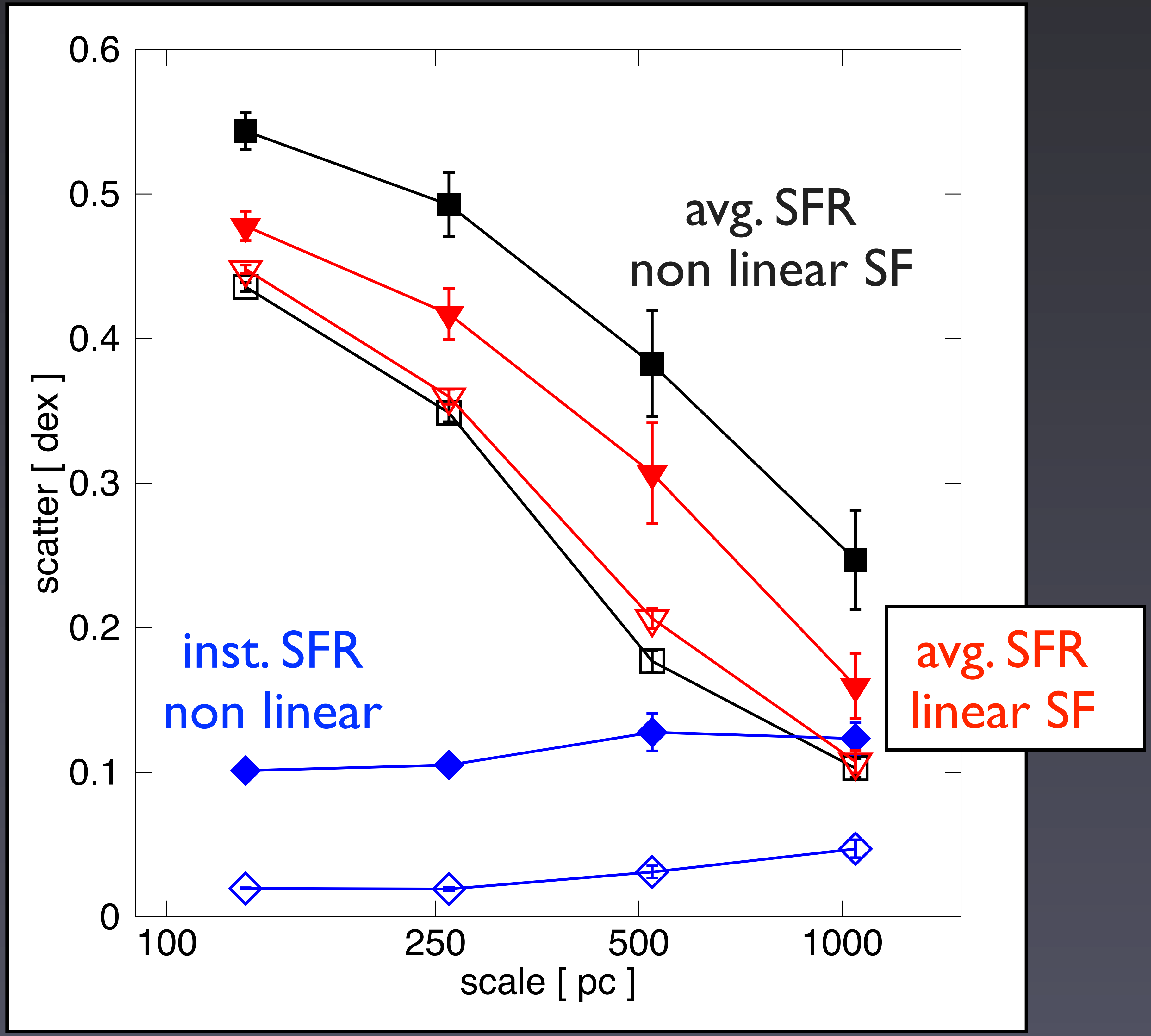
Instead

- Due to the way SFR are measured!

  => time averaging

- Due to the way H_2 masses are measured!

  => conversion factor



Outline

- ★ Star formation in simulations and the role of H_2

- ★ Empirical star formation scaling relations

- ★ **The role of the CO/H_2 conversion factor**
  - The surface densities of molecular clouds
  - Implications for star formation relations

The CO/H_2 conversion ("X") factor

H_2

- lowest excited levels in the rotational ladder ~ few 100 K
- in the electronic ground state no electric dipole moment

  => impossible to detect in emission at conditions typical of molecular cloud (~10 K)

- measure emission from tracer molecules instead
- CO - 2nd most abundant molecule (after H_2)
- I will discuss only J=1-0 transition of $^{12}C^{16}O$

$$\boxed{X_{\mathrm{CO}} = \frac{N_{\mathrm{H_2}}}{W_{\mathrm{CO}}}}$$

X-factor

- CO integrated intensity => H2 column density
- CO luminosity => H2 mass

introduces major observational uncertainty

Modeling the X-factor

complicated problem:

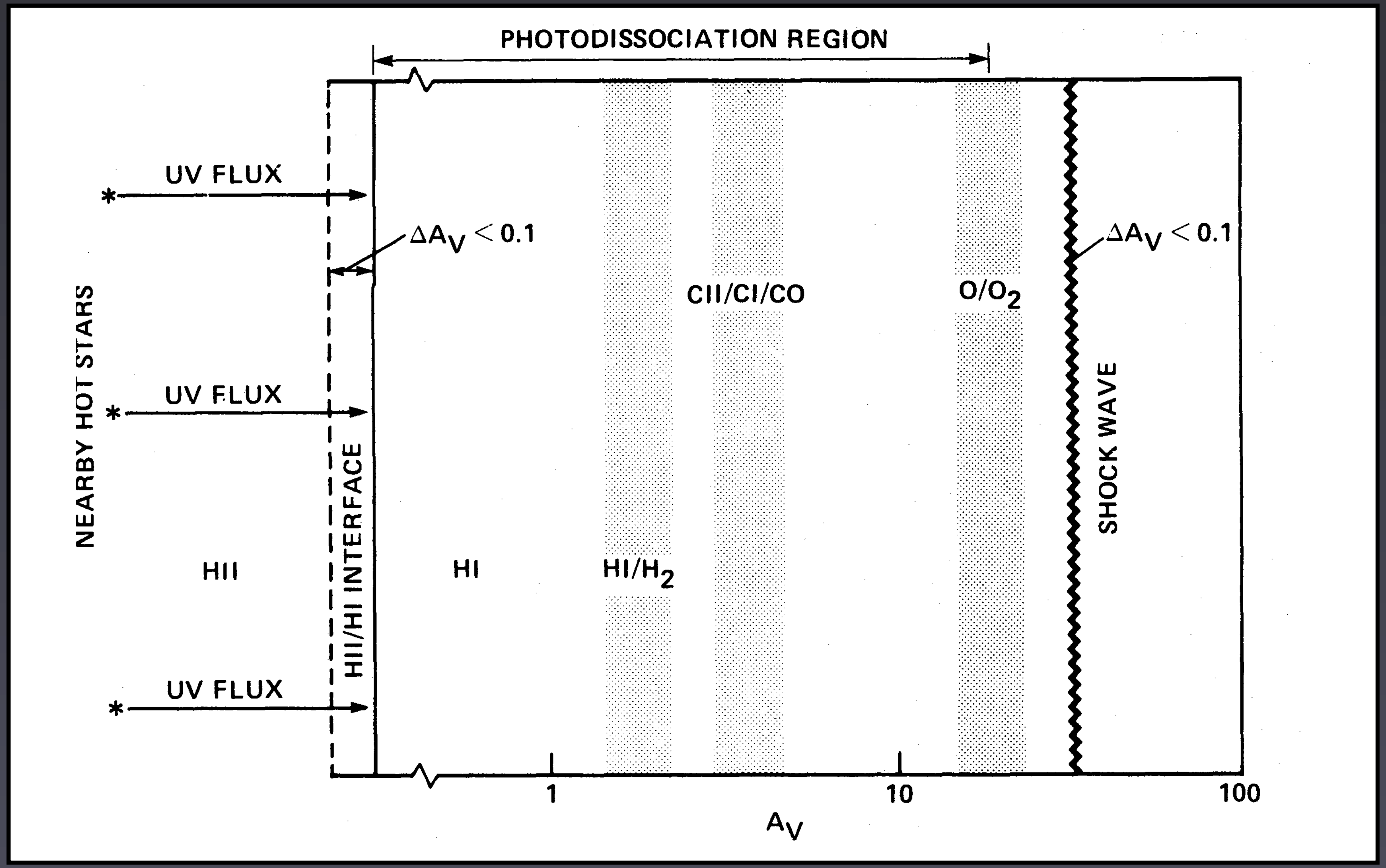
- need to know CO & H_2 abundance
  => chemical network required
- CO line is rarely optically thin
  => optical depth effects need to be considered
- CO emission depends on gas temperature & velocity dispersion
  => need some estimates for them
- the ISM is highly turbulent, complicated density structure and is not in steady state
- cannot resolve relevant scales (sub-pc) in a cosmological simulation
- ...

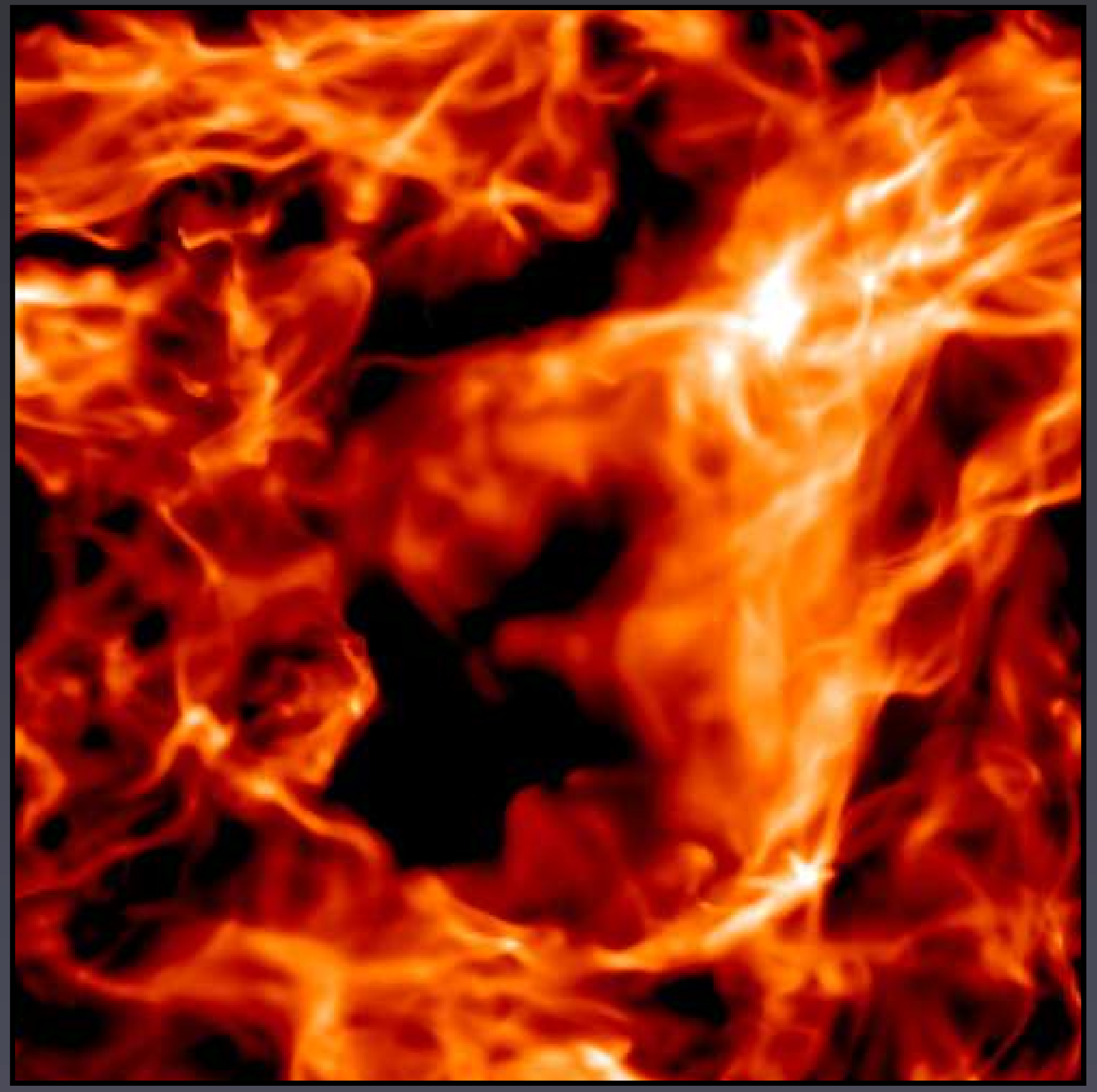
⇨ all approaches rely on approximations

Approaches for modeling the X-factor

simplified geometry / steady state

small scale ISM simulations





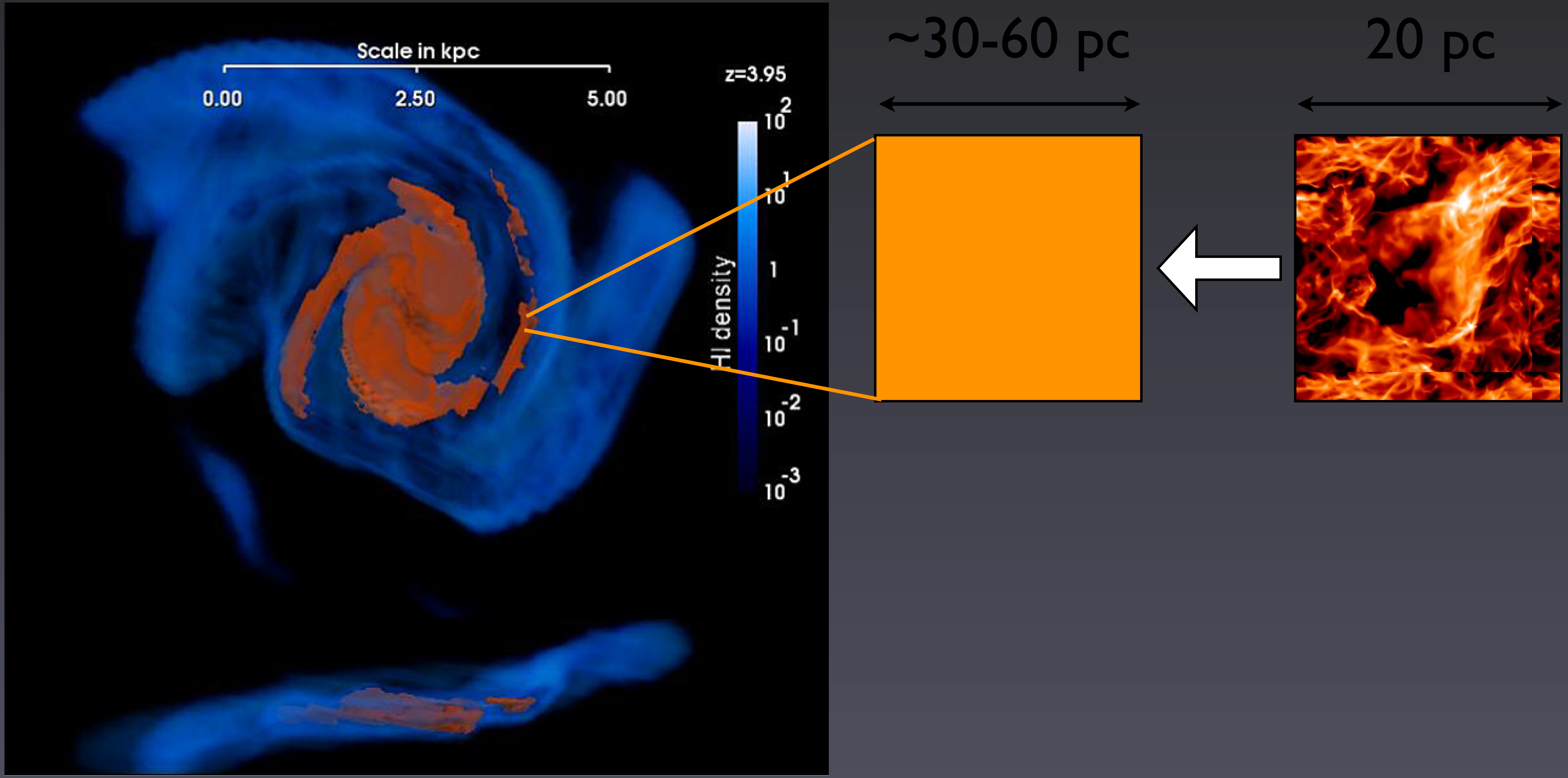
main drawback:

simplistic treatment of the ISM

main drawback:

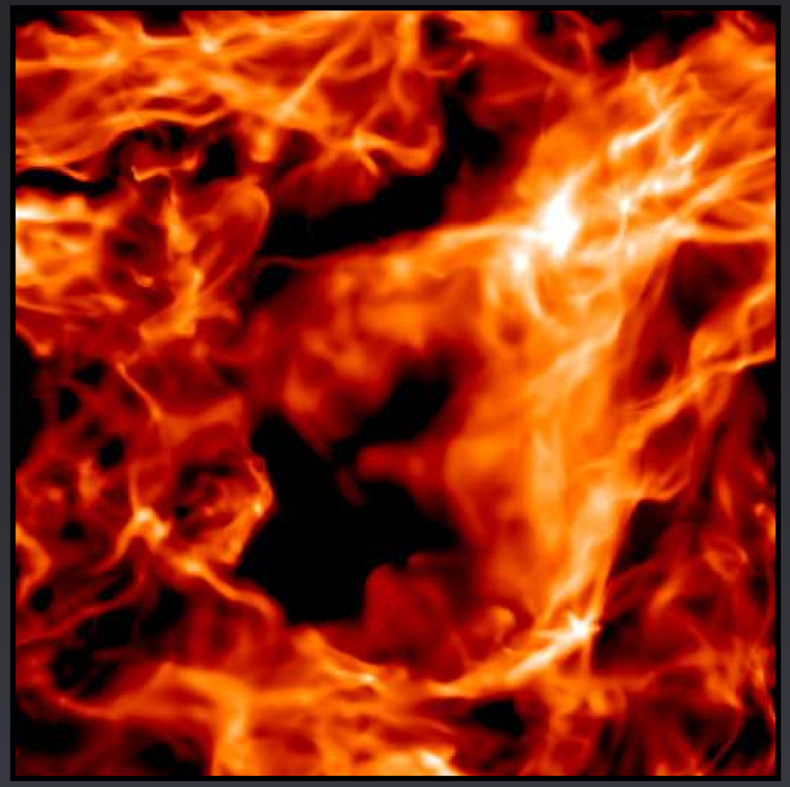
rather expensive

Our approach for modeling the X-factor



cosmological simulation   simulation cell   ISM simulation

ISM Simulations



magneto-hydrodynamical, driven turbulence simulations (ZEUS) of a 20 pc box

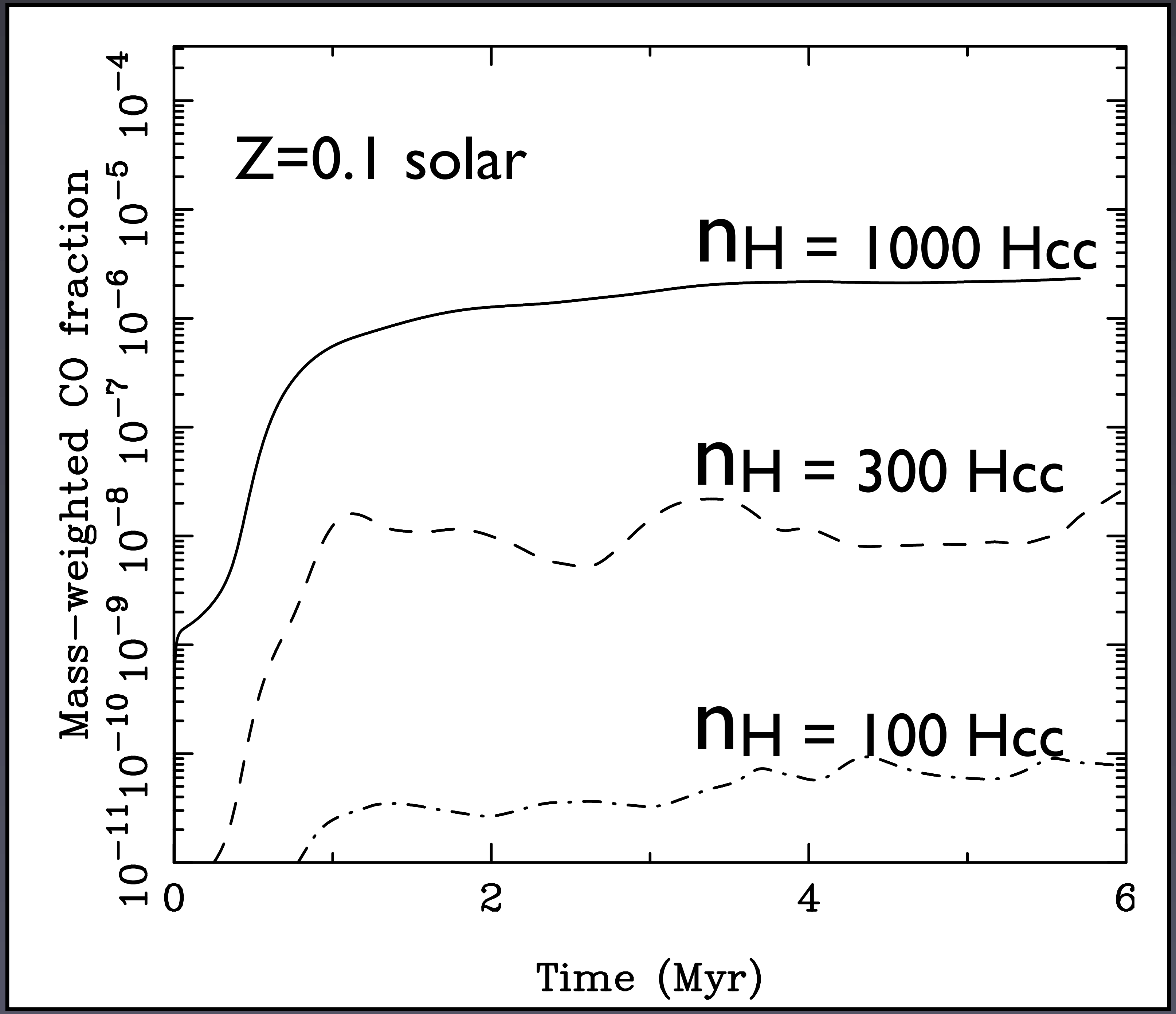
Glover, Federrath, Mac Low, Klessen 2009

Glover, Mac Low, 2010

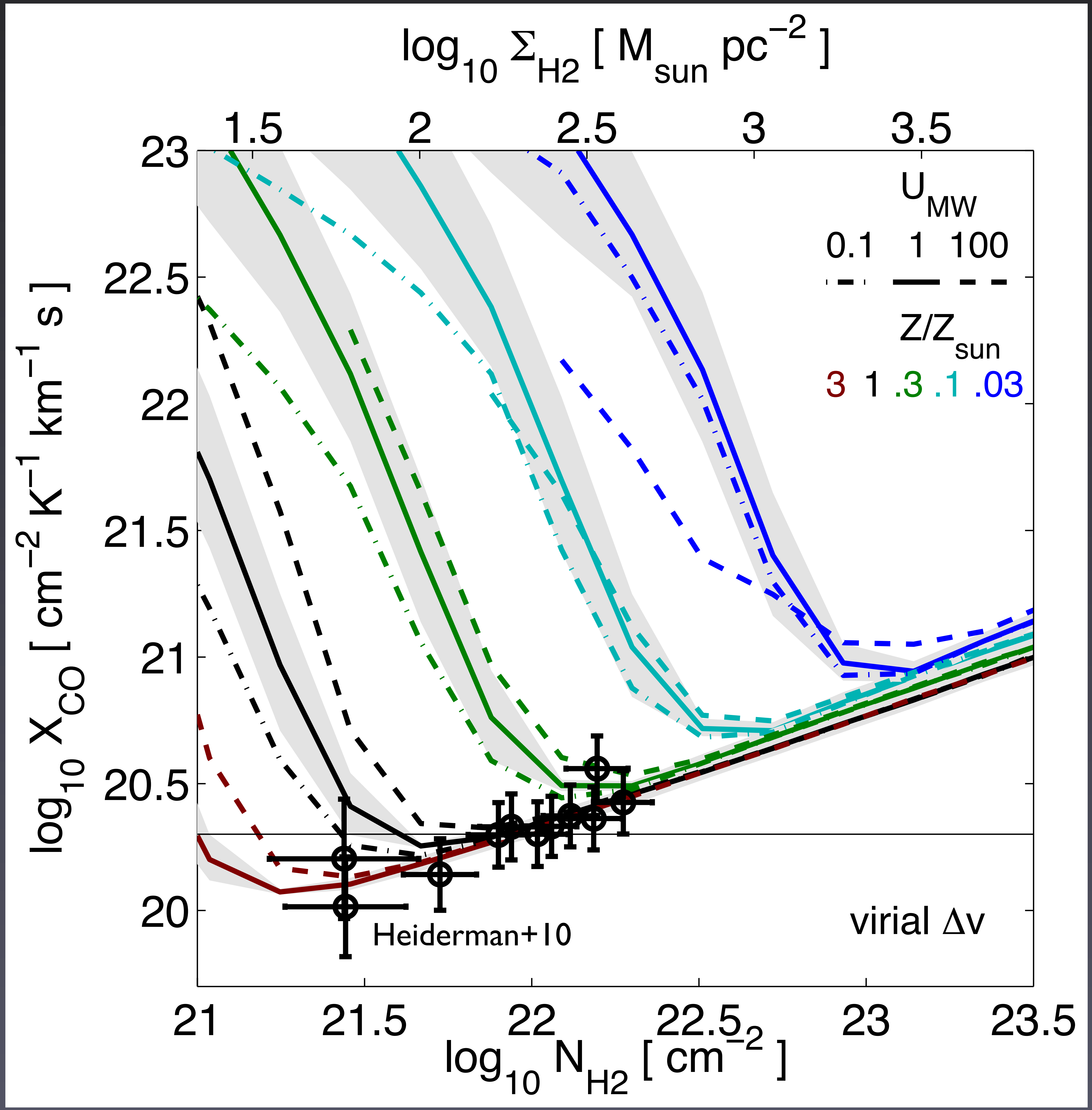
provide
- CO abundance as function of Z & N & only them!!
- only for UV=1

follow
- thermal,
- chemical and,
- dynamical evolution

but
- no self-gravity
- no star formation or feedback



Model predictions



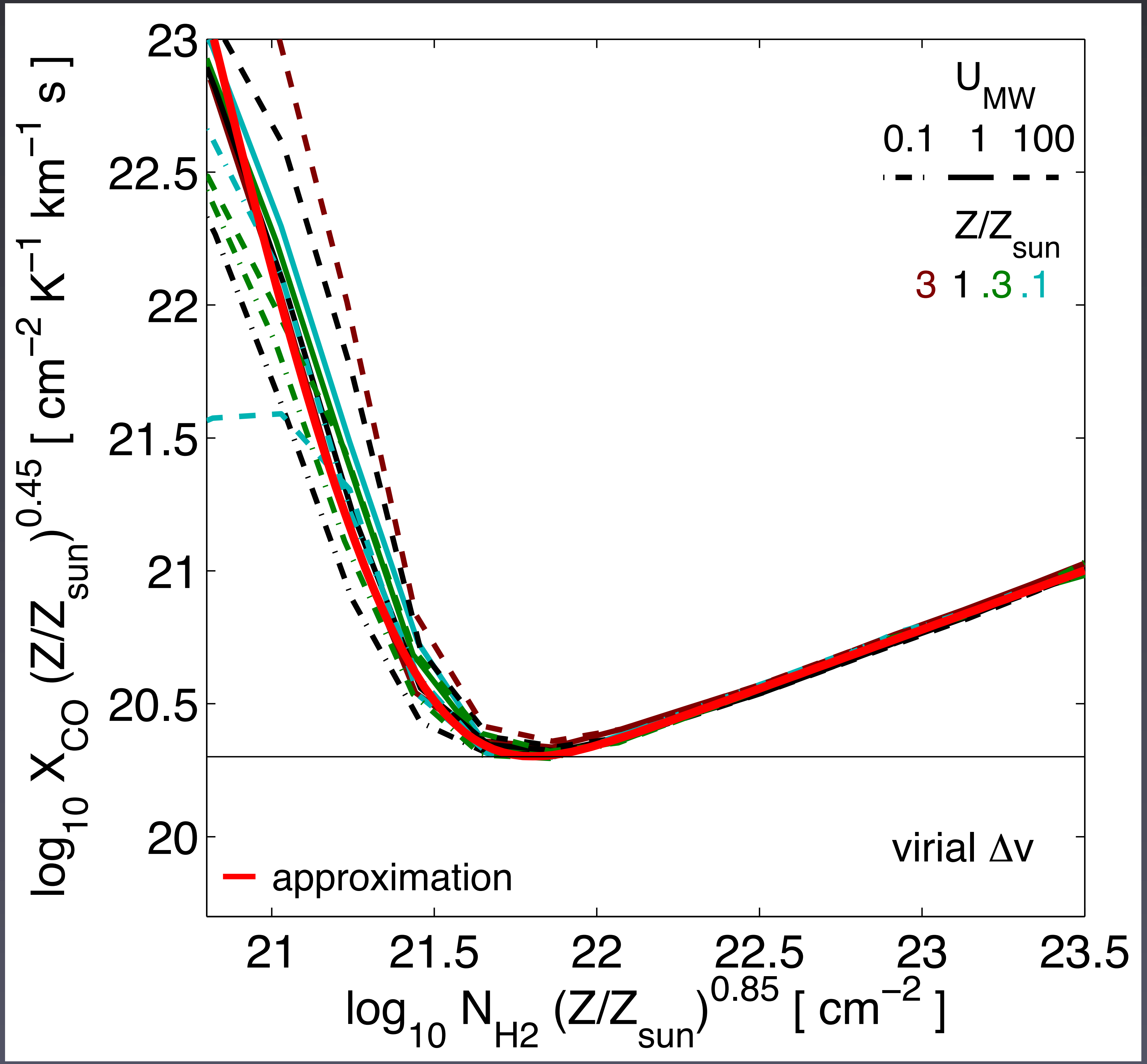
- metallicity dependence strong
- UV dependence only secondary role
- increase of X_{CO} for low and high N_{H2}

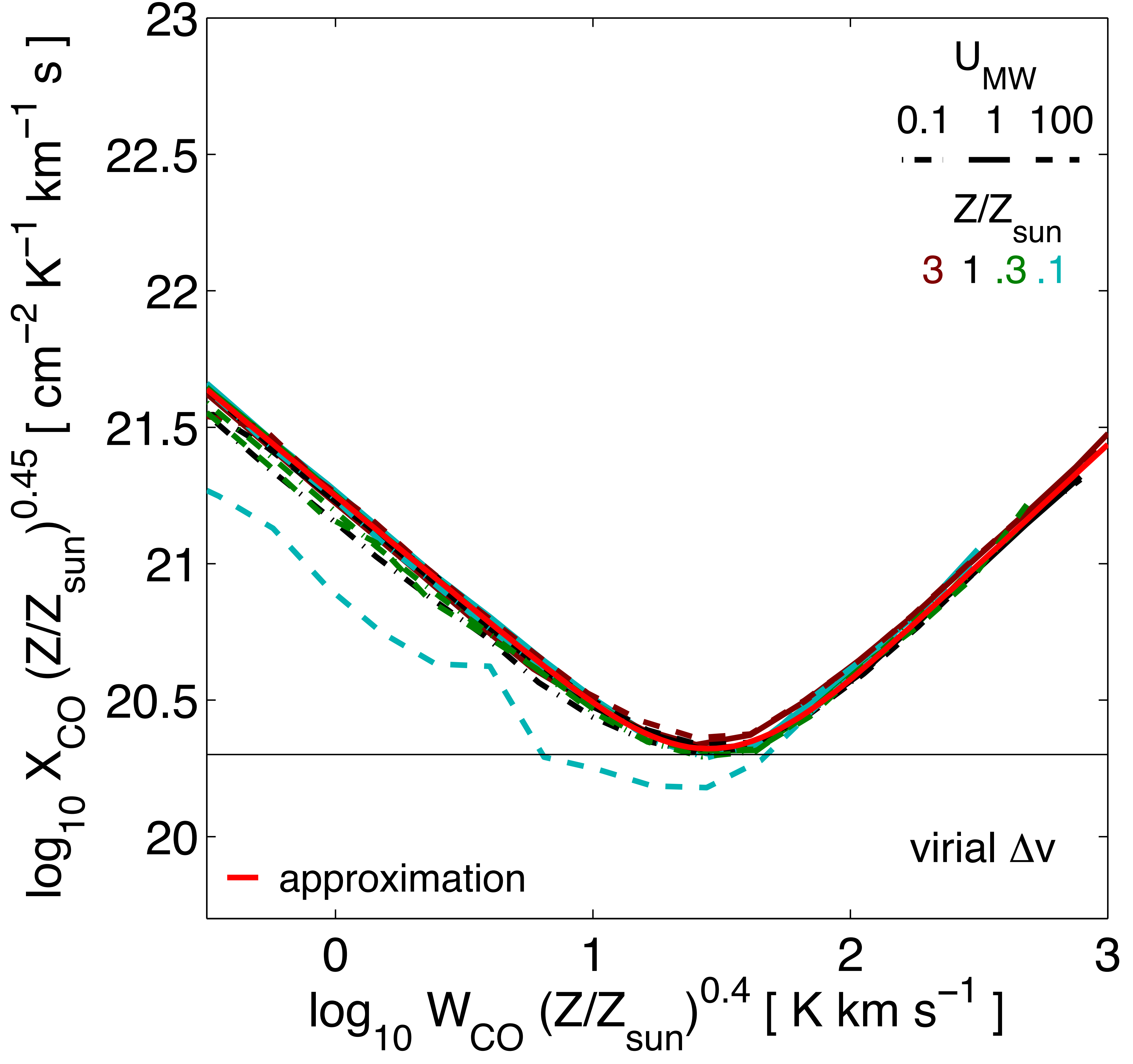
- for cells of ~60 pc (~GMC size) consistent with observations of MW GMCs
- under MW conditions: $X_{CO} \sim 2\times10^{20}$ K^{-1} cm^{-2} km^{-1} s for wide range of H_2 column densities

A fitting formula

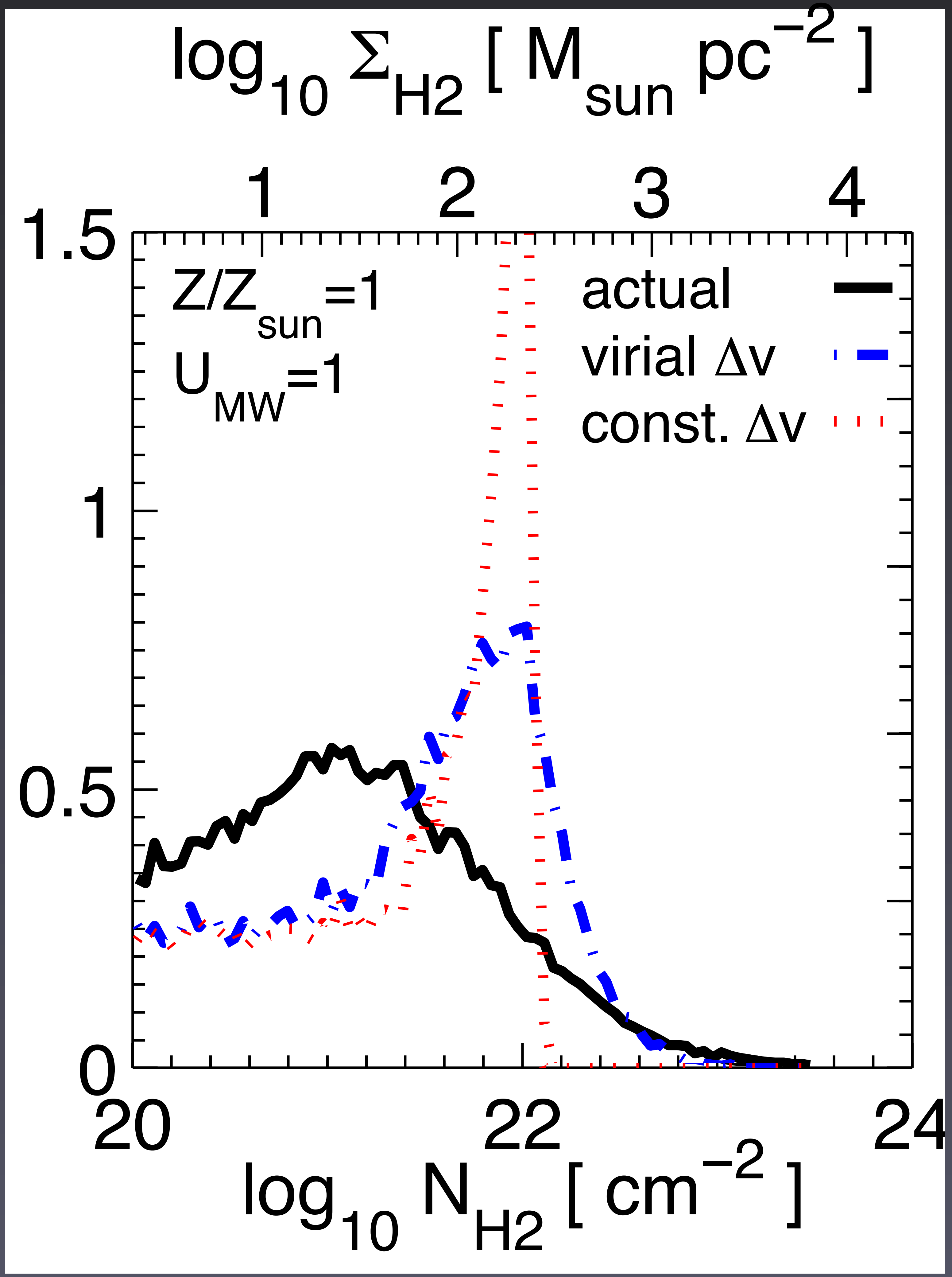
$$X'_{\rm CO} = (1+e^{-N'_{\rm H_2}}/N'_{\rm H_2})^{5.5}(1+e^{-1/N'_{\rm H_2}}N'_{\rm H_2})^{0.445},$$

$$X'_{\rm CO} = (1+e^{-W'_{\rm CO}}/W'_{\rm CO})^{0.78}(1+e^{-1/W'_{\rm CO}}W'_{\rm CO})^{0.88}$$





Inferred H_2 column densities from CO observations



$$2 \times 10^{20} \mathrm{cm}^{-2} \mathrm{K}^{-1} \mathrm{km}^{-1} \mathrm{s}$$

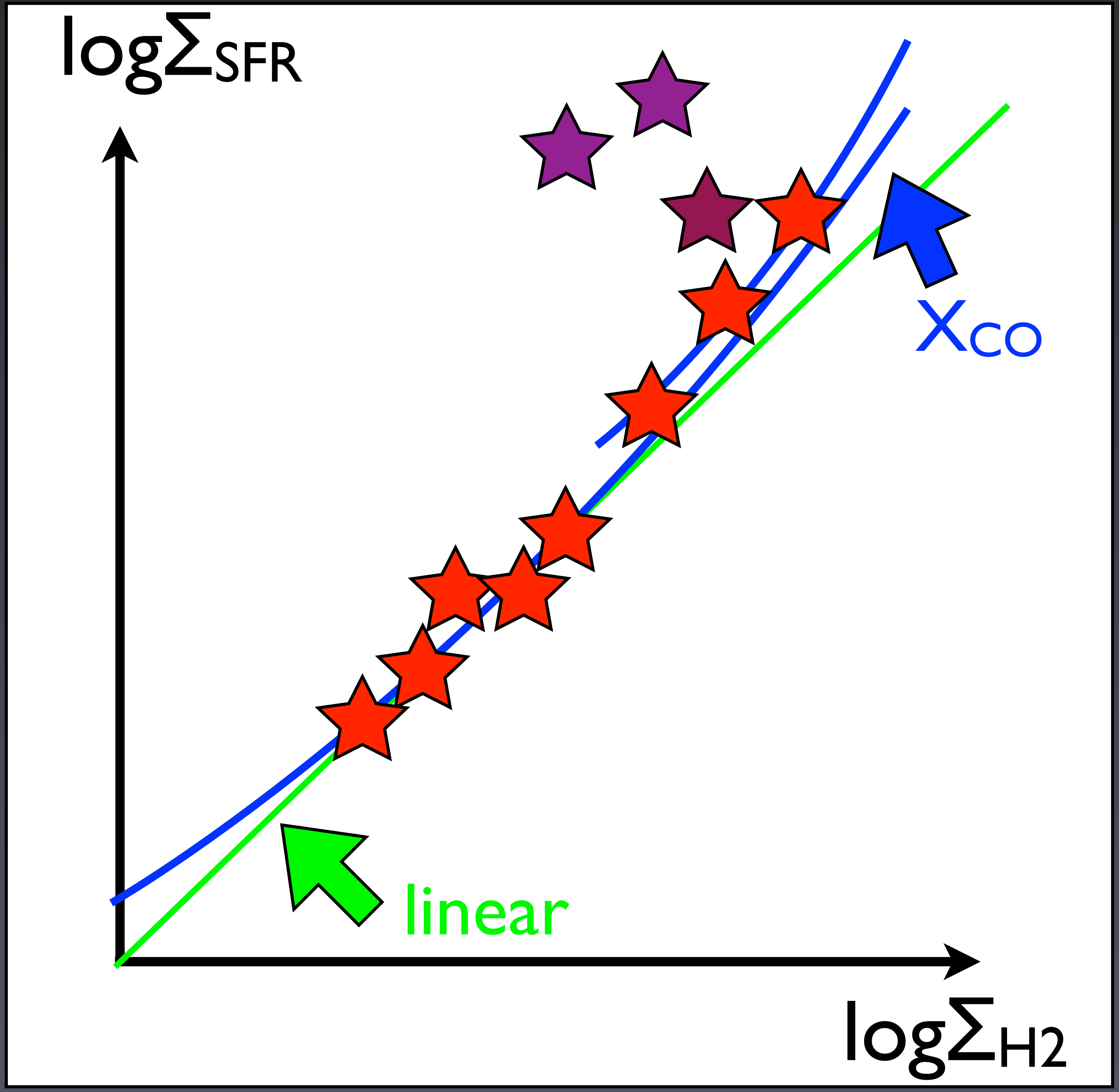
$$N_{\mathrm{H}_2}^{\mathrm{obs}} = N_{\mathrm{H}_2} X_{\mathrm{CO,MW}} / X_{\mathrm{CO}}$$

$$X_{\mathrm{CO}} = X_{\mathrm{CO,MW}} \left(\frac{N_{\mathrm{H}_2}}{10^{22} \mathrm{cm}^{-2}} \right)^{1/2}$$

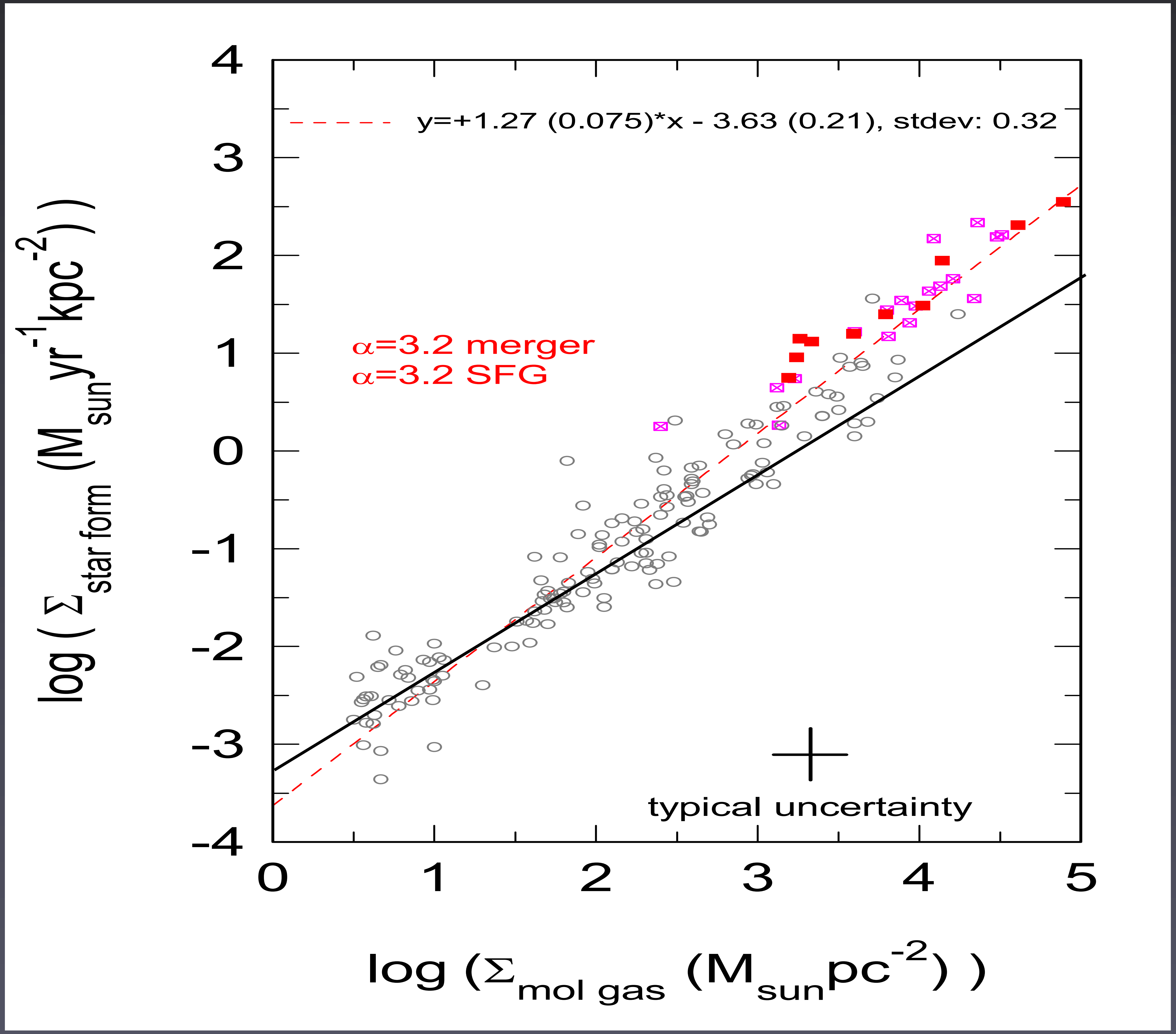
$$N_{\mathrm{H}_2}^{\mathrm{obs}} = \left(10^{22} \mathrm{cm}^{-2} N_{\mathrm{H}_2}\right)^{1/2}$$

biased!

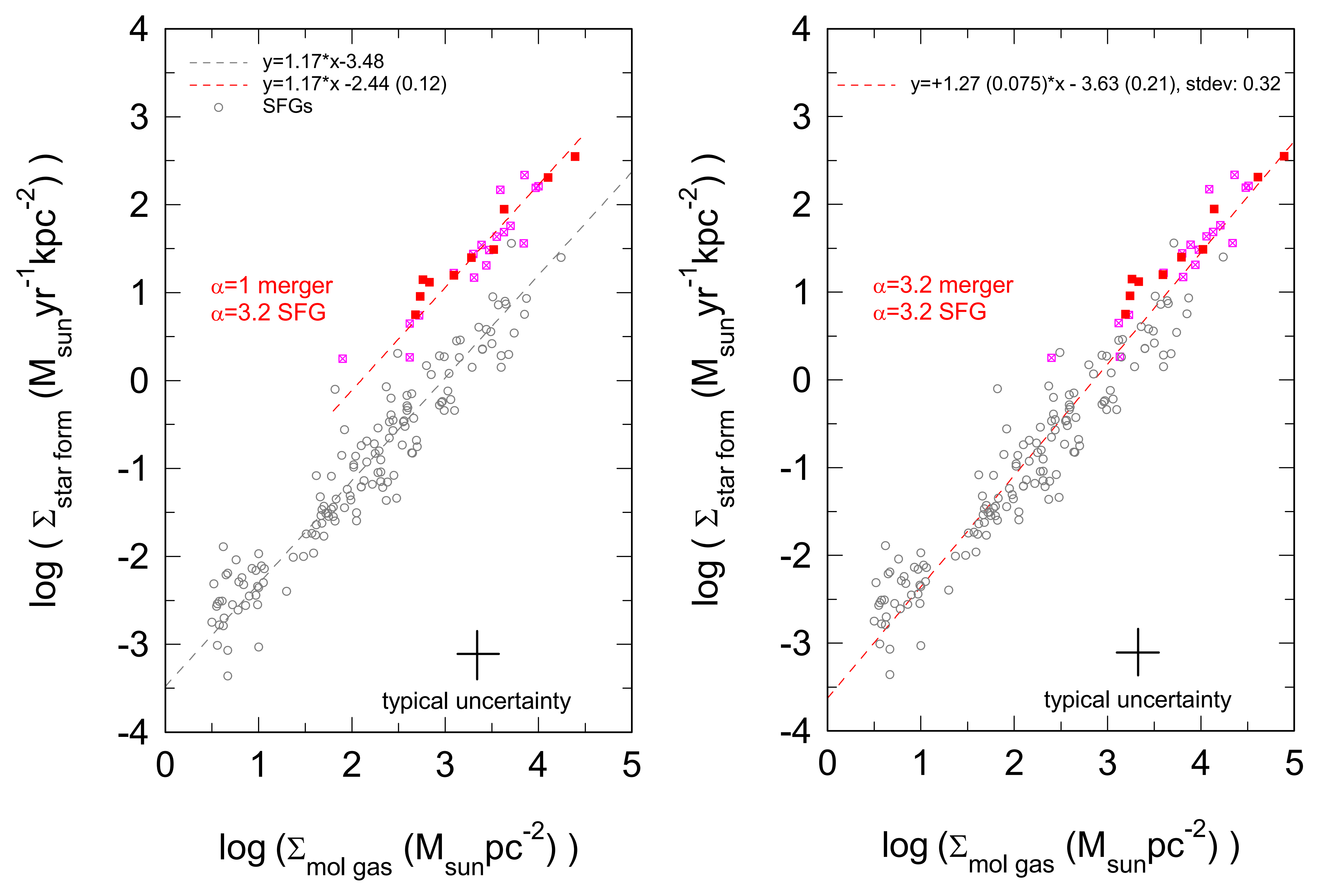
“Forbidden” region in the molecular KS relation?



Genzel et al. 2010



Closing Remark: Bimodality in SF ?


Genzel et al. 2010

- two distinct relations? (Genzel, Tacconi)
- just a short phase during mergers (Teyssier, Bournaud)
- excitation effect of 3-2 CO, while in truth a 1.5 slope (Narayanan)

Note:

any $X_{CO}(N_{H2})$ will collapse the bi-modality

Another possibility:

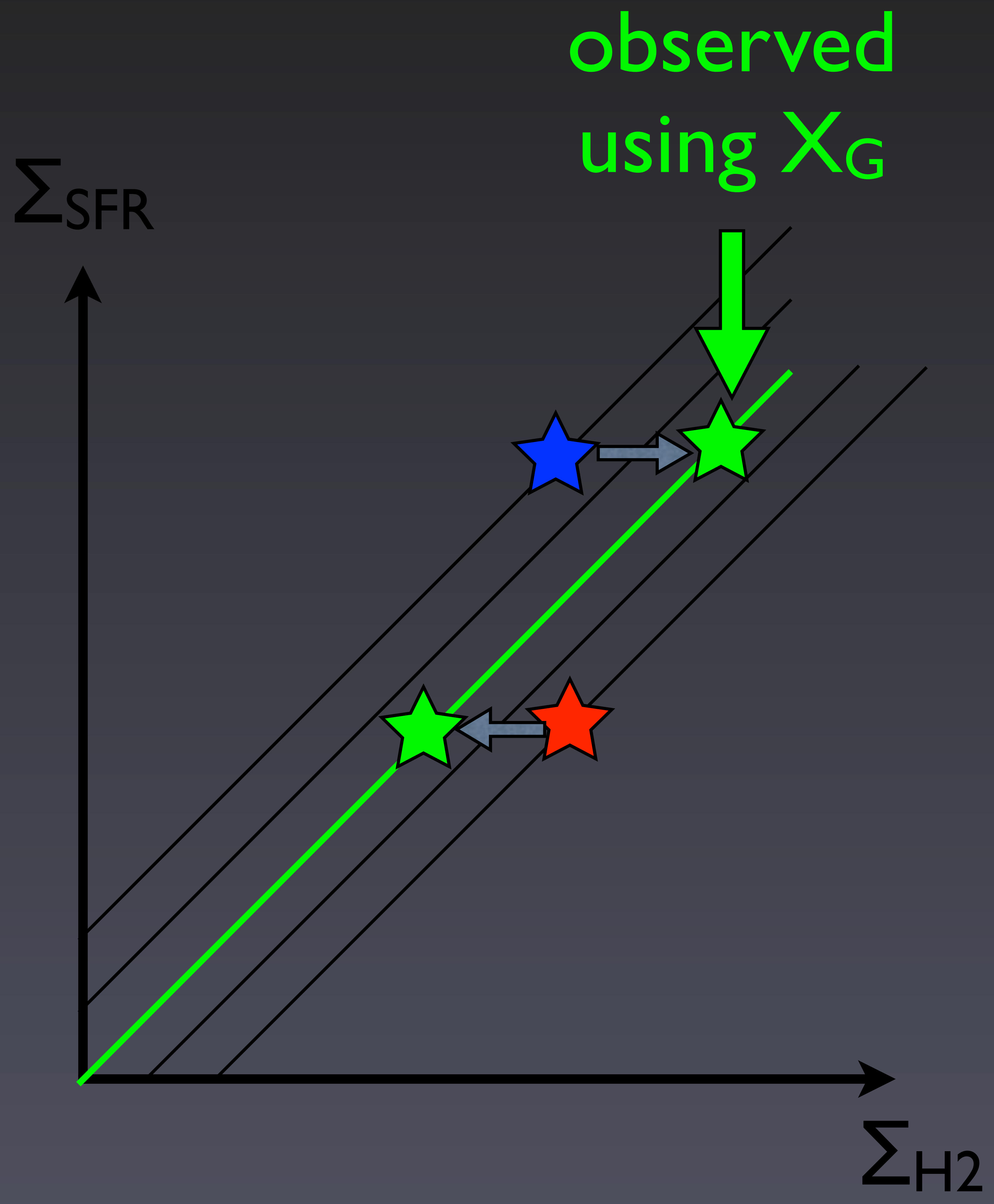
linear SF relation & CO emission driven by SFR *at fixed H_2 surface density*

Closing Remark: Bimodality in SF ?

$$W_{\mathrm{CO}} = \alpha \Sigma_{\mathrm{SFR}}|_{\Sigma_{\mathrm{H}_2}}$$

$$\Sigma_{\mathrm{SFR}} = \alpha^{-1}\Sigma_{\mathrm{H}_2}/X_{\mathrm{CO}}$$

$$\Sigma_{\mathrm{H}_2}^{\mathrm{obs}} = \Sigma_{\mathrm{H}_2}X_{\mathrm{G}}/X_{\mathrm{CO}} = \Sigma_{\mathrm{SFR}}\alpha X_{\mathrm{G}}$$



★ SFR > $SFR_{expected}$, W_{CO} > $W_{CO,expected}$, thus X < X_G, Σ_{H2}^{obs} > Σ_{H2}

Maybe we know less about the KS relation than we think!

Summary

1. non-linear H_2-based Schmidt law
   => slope & intercept of molecular KS relation depend on Z, UV

2. large scatter in molecular KS relation due to time averaging property of SF tracer
   (& X_{CO} effects)

3. X_{CO} effects can narrow the observed surface density range of molecular clouds

4. X_{CO} dependence on Z & surface density may explain slight super-linearity of molecular KS relation