Being discrete - Star formation on (sub-)galactic scales

Robert Feldmann
Fermi National Accelerator Laboratory

in collaboration with: N. Gnedin, A. Kravtsov

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KICP Kavli Institute for Cosmological Physics at The University of Chicago

Fermilab

Outline

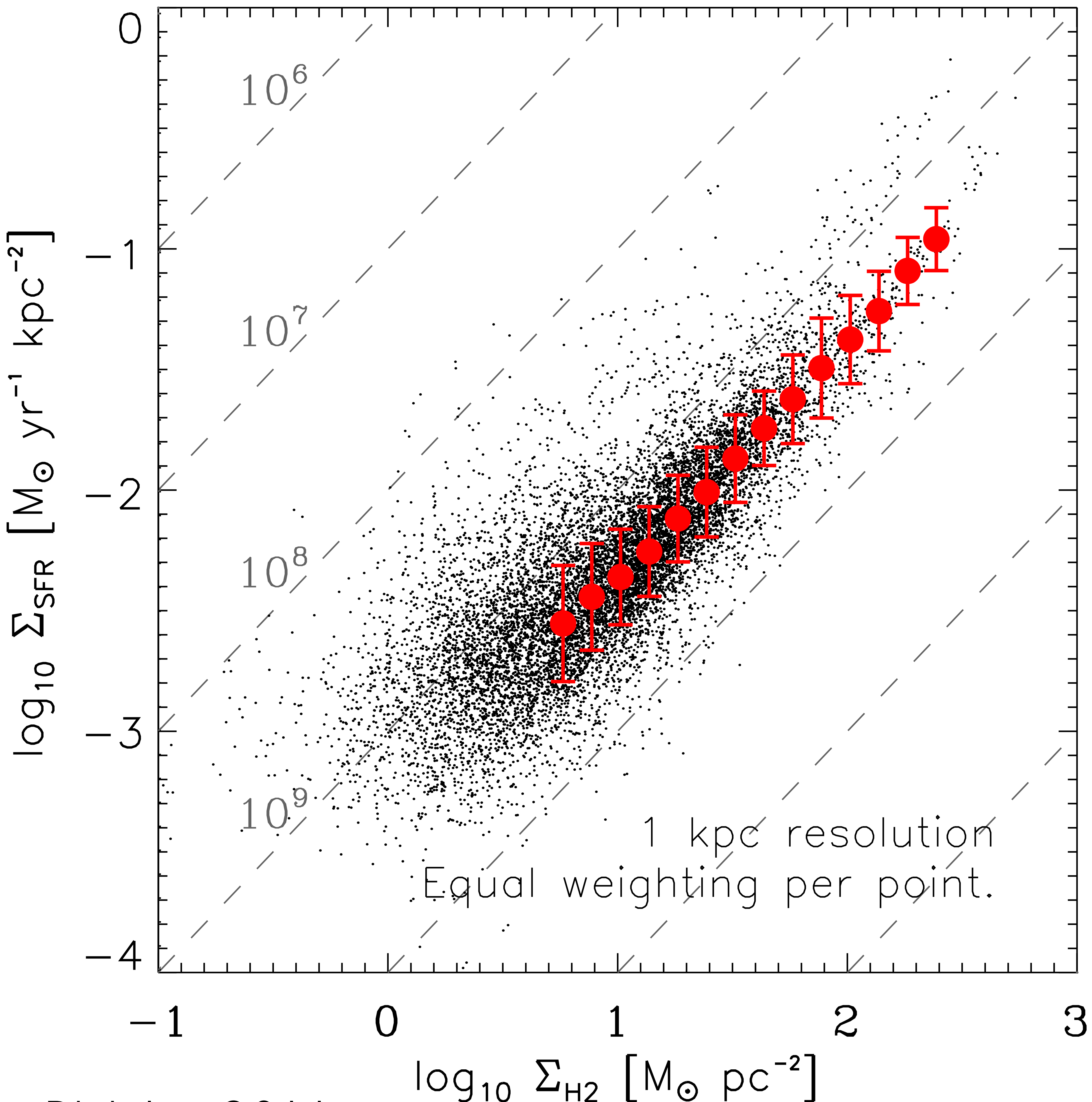
1. Running on gas: the Σ_{H2} - Σ_{SFR} relation

2. H_2, CO and SF in simulations

3. The H_2 - HI transition and mid-plane pressure

4. Slope and scatter of the Σ_{H2} - Σ_{SFR} relation

The Σ_{H2} - Σ_{SFR} relation

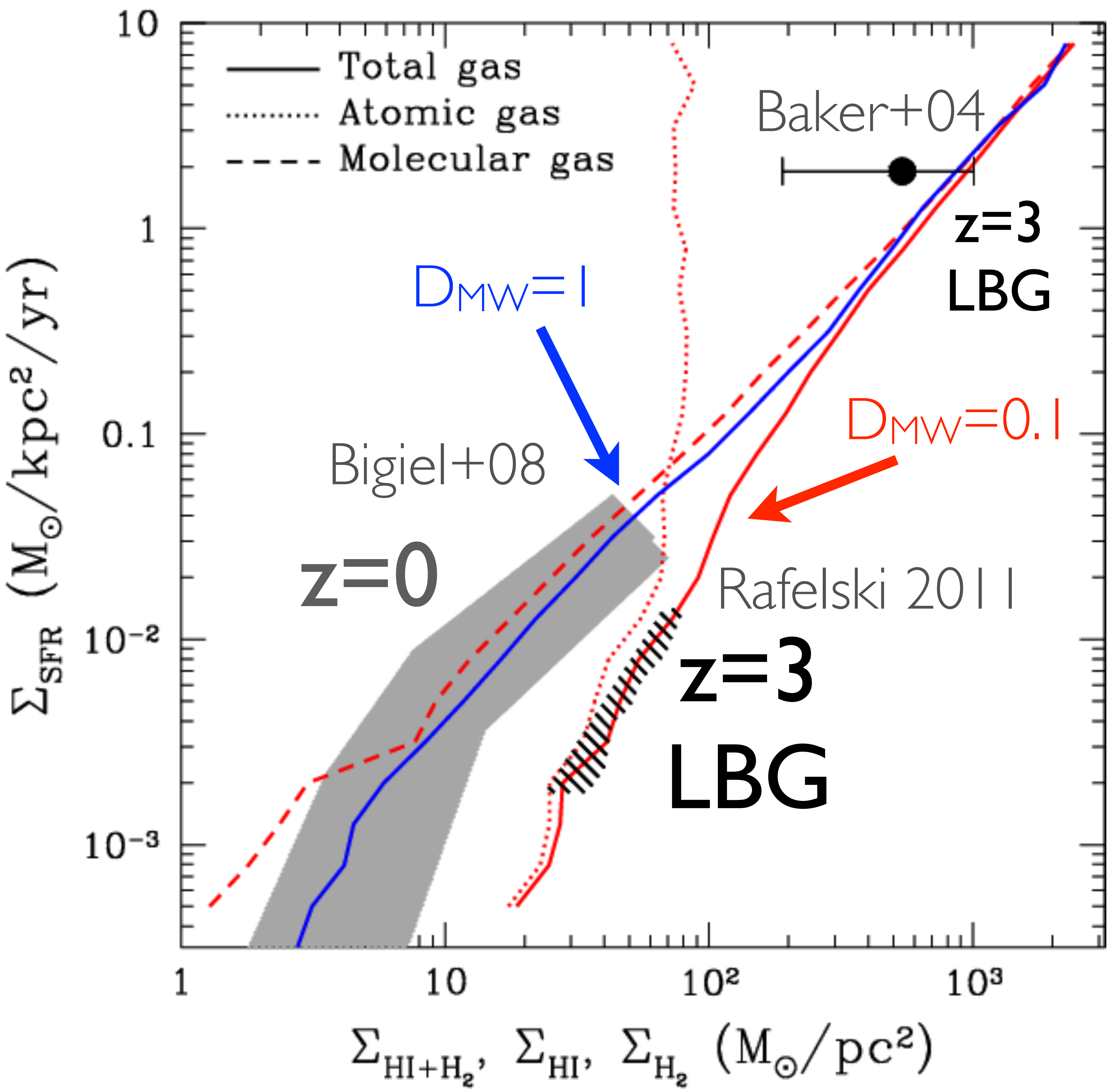


Bigiel + 2011

- observations: tight relation on kpc scales
- relation extends into HI dominated region
- relation ~ linear ➔ constant gas depletion time (τ_{dep})~ 1-2 Gyr
- slightly super-linear(1.1-1.2) when measured over 4 orders of magnitude (e.g. Genzel+10)

In this talk: I will assume n=1 throughout

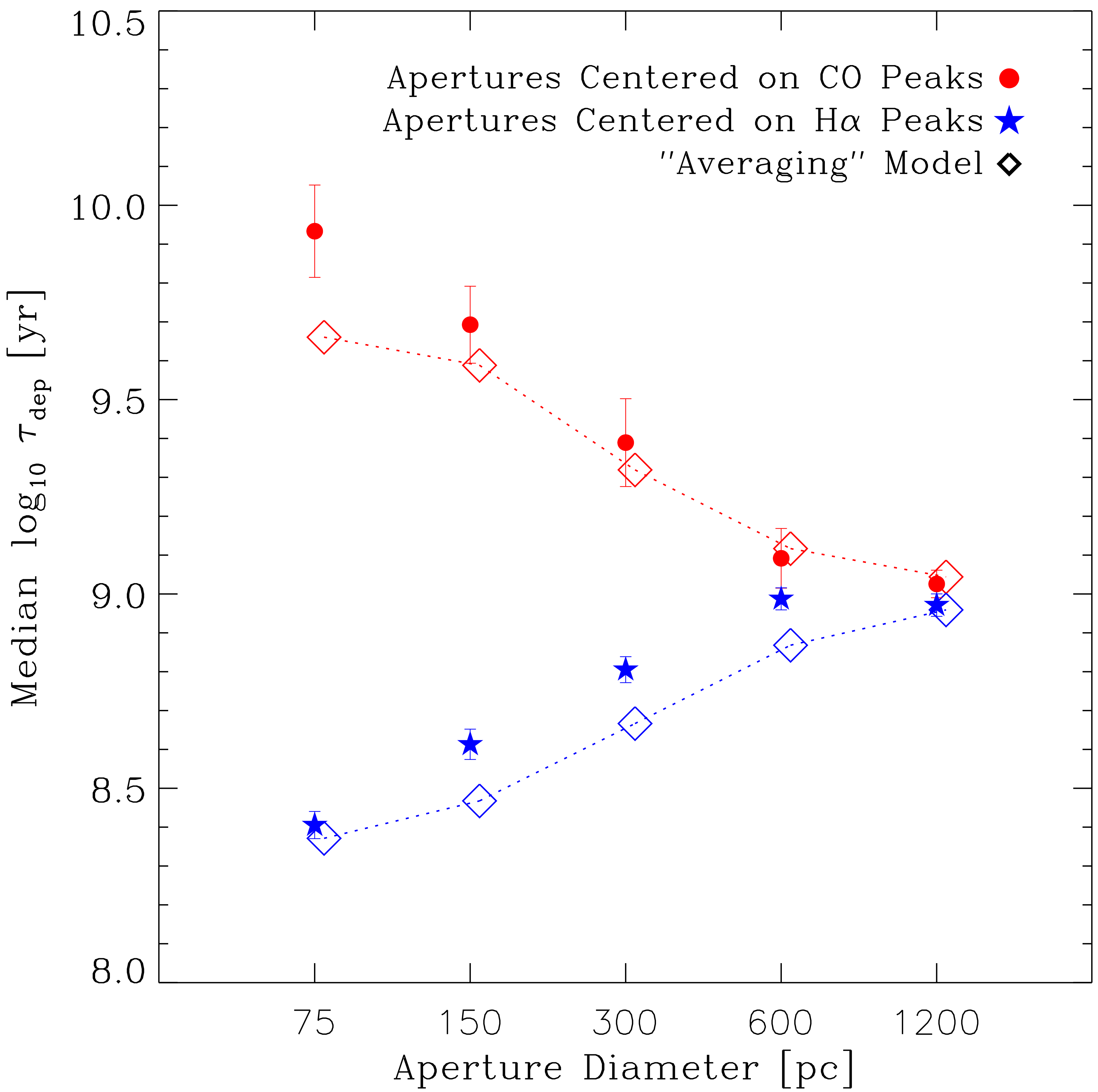
The Kennicutt-Schmidt (Σ_{tot} - Σ_{SFR}) relation



Gnedin & Kravtsov 2010

- Traditional K-S relation arises naturally from the HI ↔ H_2 transition (around Σ_c) for given Σ_{tot}
  - $\Sigma_{tot} \ll \Sigma_c$ → gas predominantly HI → little SF indep. of Σ_{tot}
  - $\Sigma_{tot} \sim \Sigma_c$ → H_2 fraction increases → steep increase of SF with Σ_{tot}
  - $\Sigma_{tot} \gg \Sigma_c$ → gas predominantly H_2 → SF ~ Σ_{tot}
- HI ↔ H_2 transition
  - larger Σ_{tot} → increased shielding
  - larger Σ_{tot} → higher formation rates
  - Σ_c changes with dust-to-gas ratio

The Scatter of the Σ_{H2} - Σ_{SFR} relation



Schruba + 2010

- scatter relatively small (~0.1-0.2 dex) on kpc scales
- but increases rapidly with resolution ➔ "break down of SF laws"
- On < few 100 pc scales: clear separation between CO and Hα emission
- Different interpretations:
  - Evolution model: CO regions (high τ_{dep}) evolve into Hα regions (low τ_{dep})
  - regional variations of τ_{dep}
  - Discreteness of SF (see later)

Questions

Why does the Σ_{H2} - Σ_{SFR} relation have a slope ~1.1-1.2 when measured over 4 orders of magnitude ?

What is the origin of the scatter of the Σ_{H2} - Σ_{SFR} relation & can we understand its change with scale?

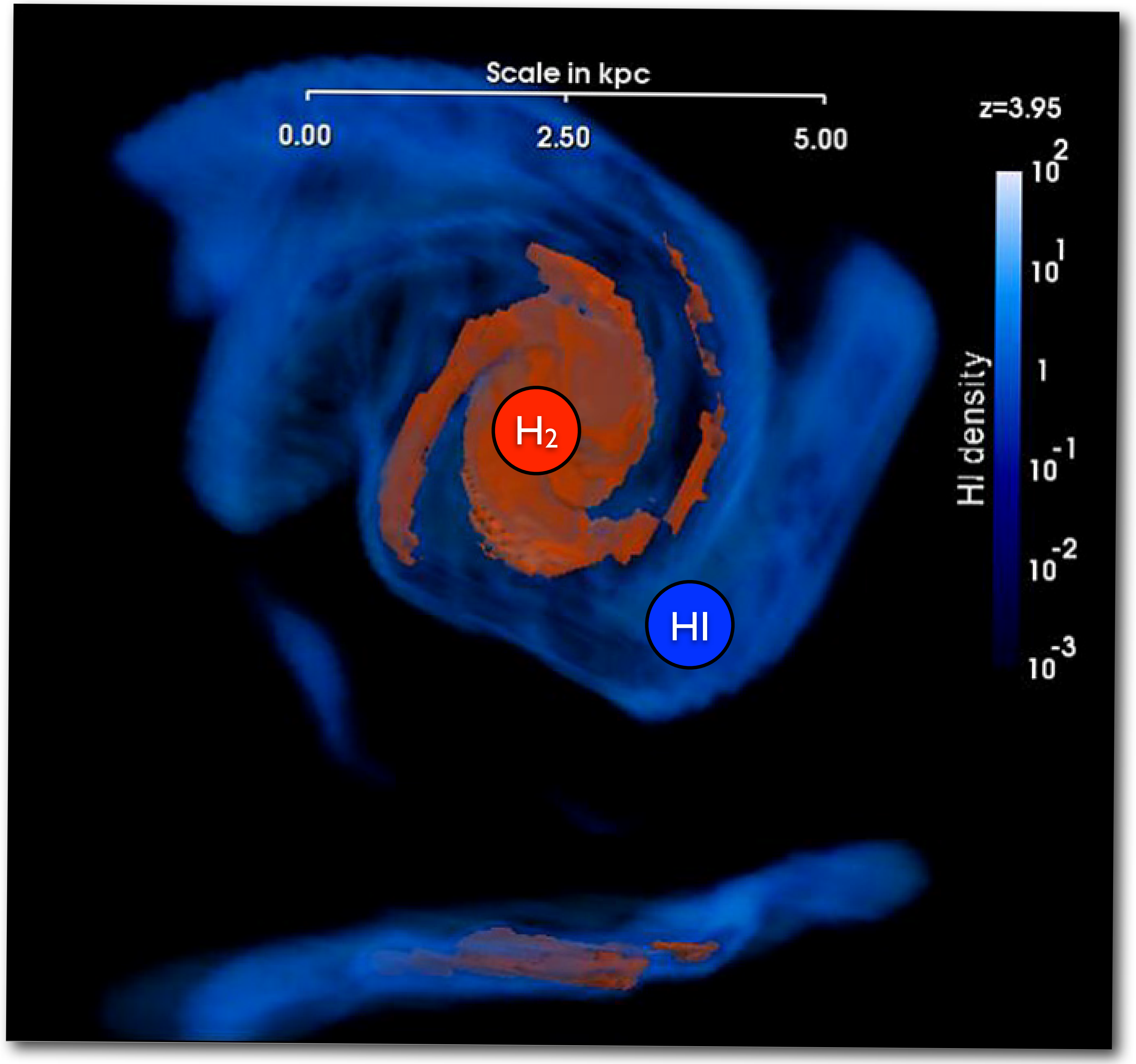
What is driving the H_2 - HI transition in galaxies?

What role does the CO-H_2 conversion factor play?

N-body + AMR hydro code ART*

*Adaptive Refinement Tree (Kravtsov+97,02)

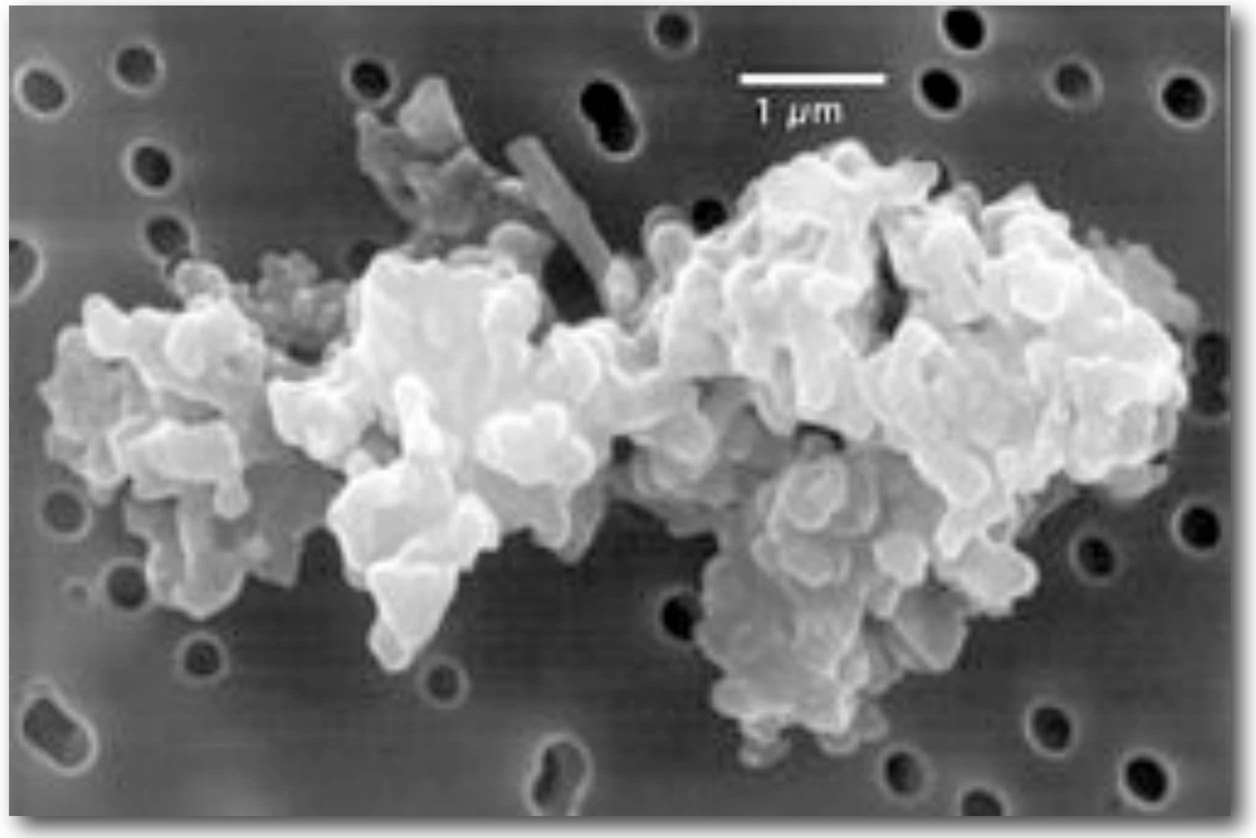
- non-equilibrium cooling & ionization
- non LTE chemical network
- radiative transfer in the LW bands (OTVET)
- metal enrichment, SN feedback
- H_2 formation & destruction, including dust-shielding and self-shielding
- subgrid modeling of stochastic SF based on H_2
- CO, FUV, Hα emission in post-processing



- cosmological, zoom-in simulations
- $\Delta x \sim 60$ pc, $m_{DM} \sim 1.3 \times 10^6$ $M_\odot$

Modeling: H_2

- H_2 density is an advected field with source terms
  - formation catalyzed on dust grains
  - dissociation by UV radiation in the LW bands
- Shielding is important: $\Gamma_{\rm LW} \Rightarrow \Gamma_{\rm LW} S_{\rm H_2} S_{\rm D}$
    - Dust shielding
    - H_2 self-shielding



$$S_{\rm D} = e^{-D_{\rm MW}\,\sigma_0\,n_{\rm H}\,L_{\rm Sob}}$$

$$S_{\rm H_2} = \begin{cases} 1, & \text{for } N_{\rm H_2} < 10^{14}\,{\rm cm}^{-2}, \\ (N_{\rm H_2}/10^{14}\,{\rm cm}^{-2})^{-3/4}, & \text{for } N_{\rm H_2} > 10^{14}\,{\rm cm}^{-2}, \end{cases}$$

$$N_{\rm H_2} \approx n_{\rm H_2} L_c$$

CO

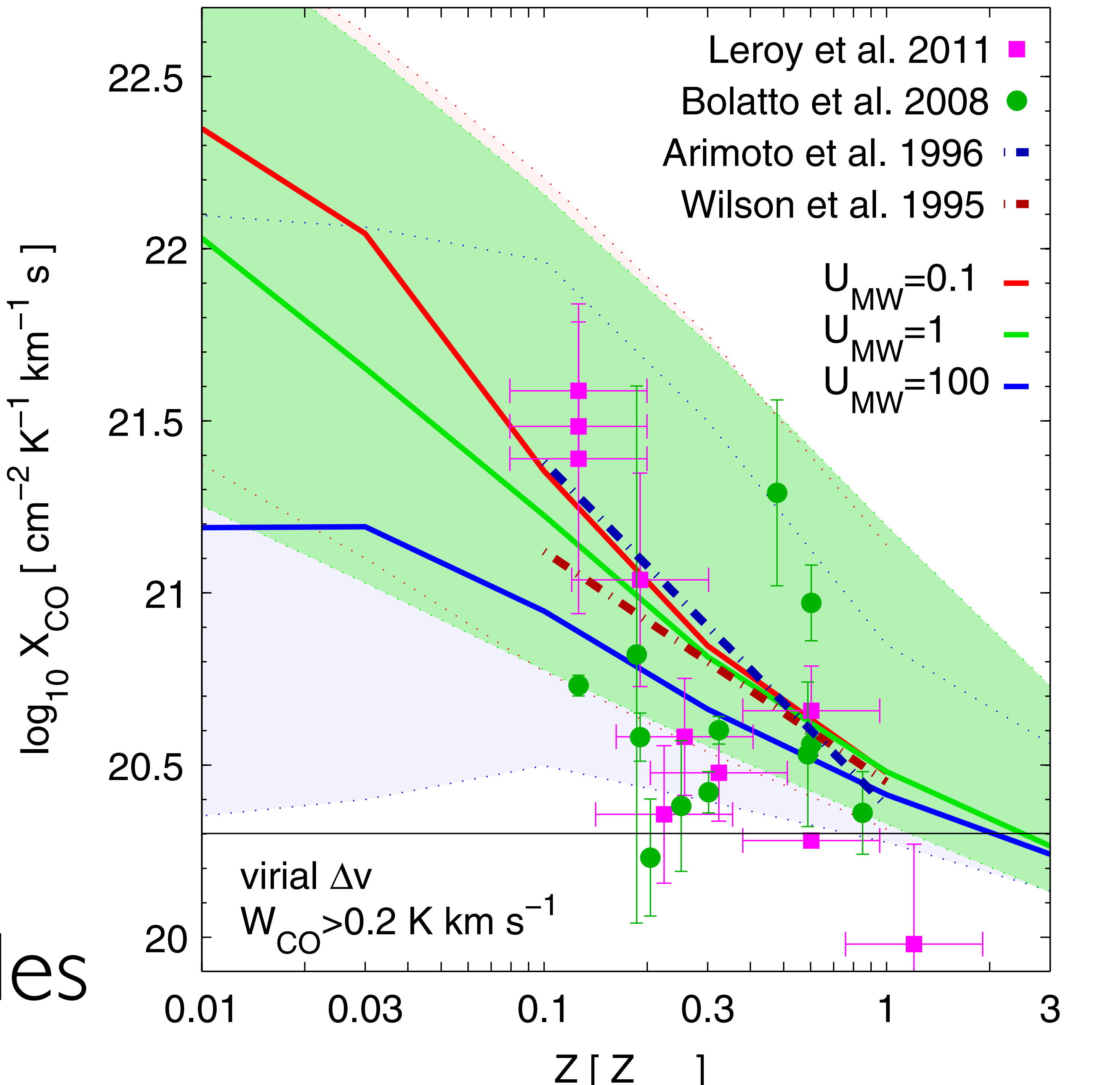
starting point:

- MHD, driven turbulence ISM simulations (Glover, Mac Low, 2010)
- CO abundance as function of Z & N

added:

- modeled of dependence on UV (photodiss. eq.)
- virial scaling of CO line width with gas surface density
- compute CO emission from each cell in the escape probability formalism

see Feldmann et al. 2012, APJ, 747, 2 *arxiv:1112.1732*



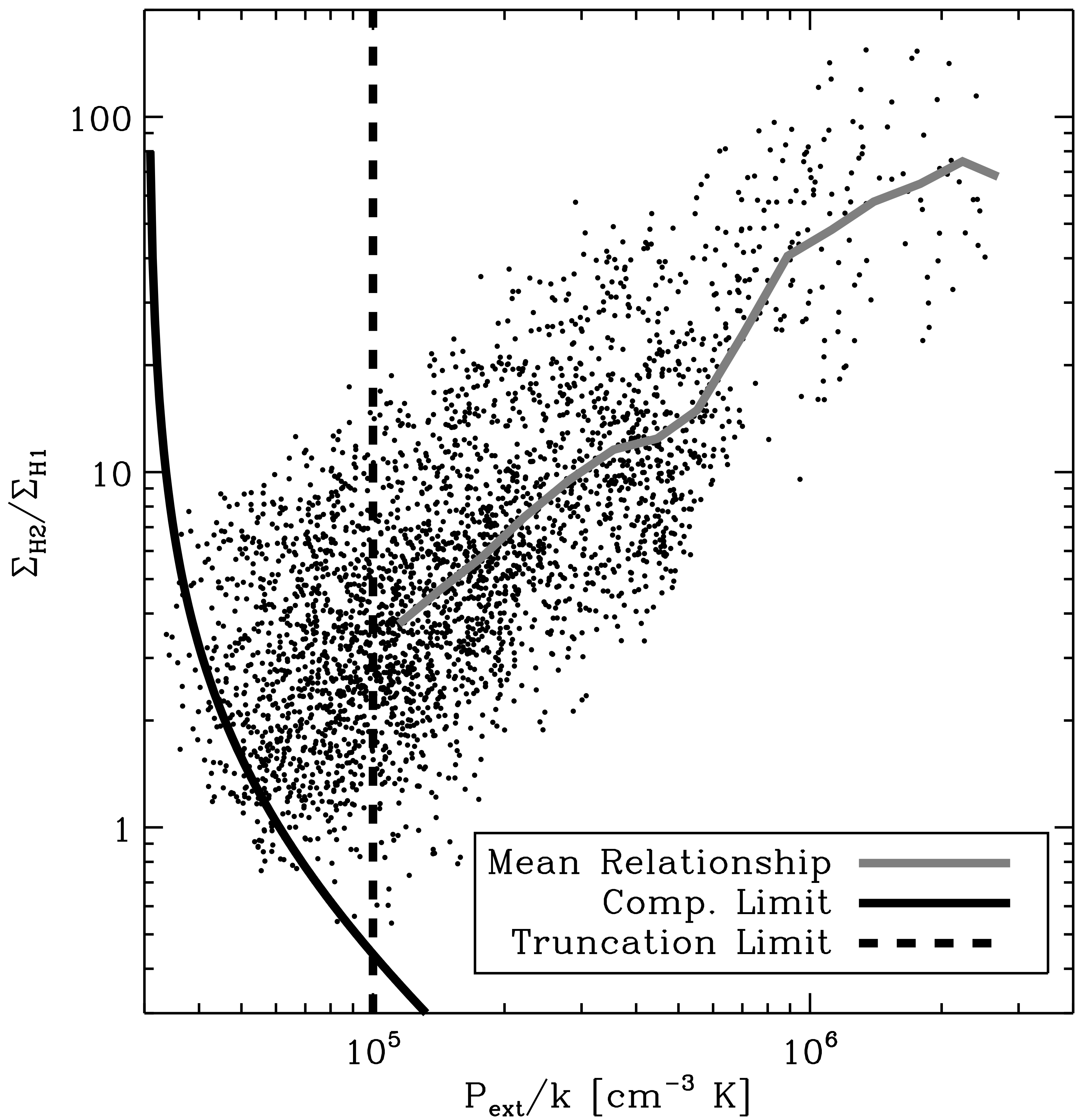
SFR tracers (Hα, FUV)

- use Starburst-99 + ages and metallicities of star particles

The H_2 to HI transition

The H_2 to HI ratio scales with midplane pressure

$$P_{\rm ext} = (2G)^{0.5}\Sigma_g v_g \left[\left(\frac{\Sigma_*}{h_*}\right)^{0.5} + \left(\frac{\pi}{4}\frac{\Sigma_g}{h_g}\right)^{0.5}\right]$$



Blitz & Rosolowski 2006

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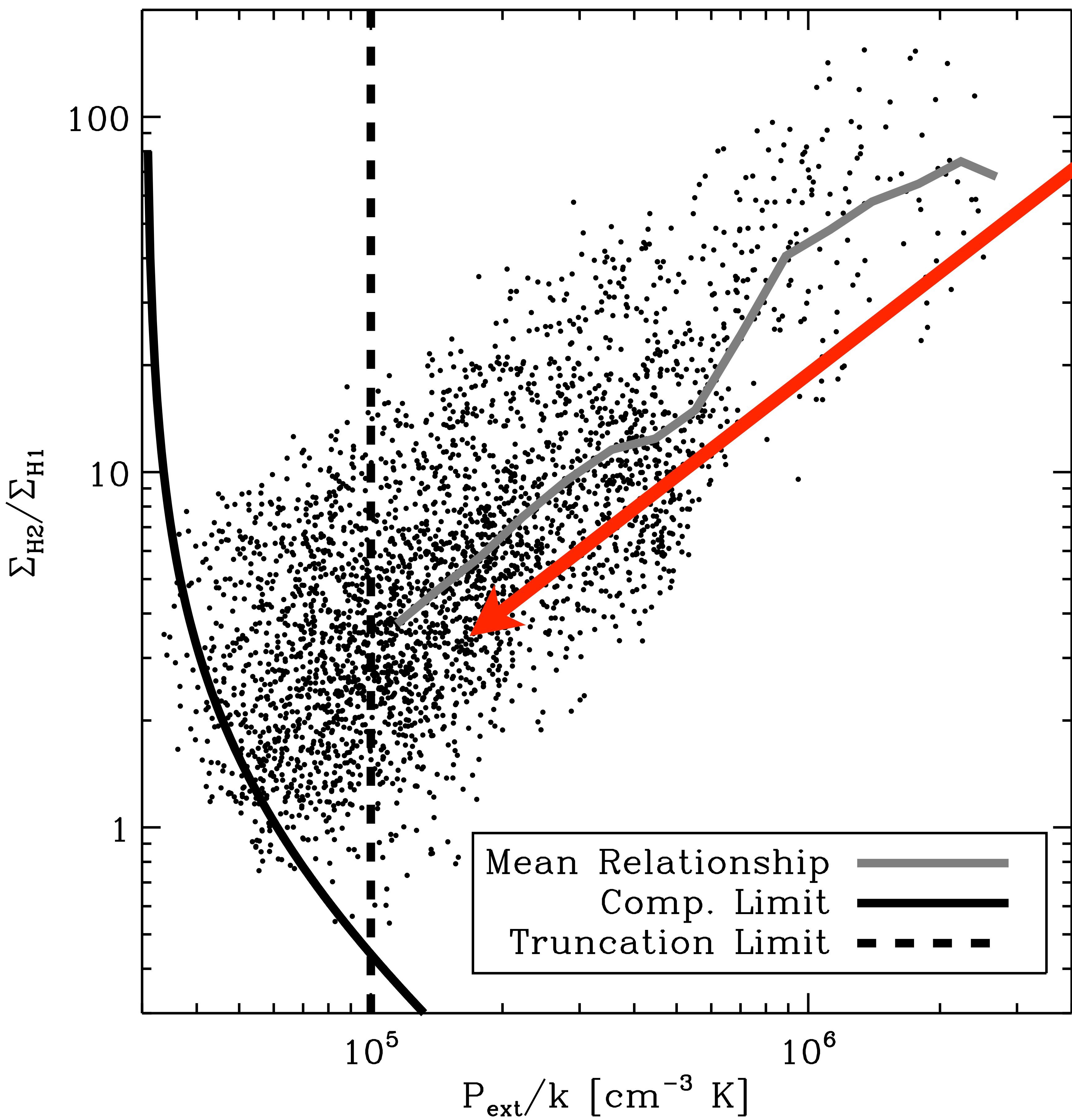


Blitz & Rosolowski 2006

often $R_{mol} > 1$ ⇒ H_2 dominated regime

Elmegreen '93 formula: $R_{mol} \sim P^{2.2}/j$ derived for $f_{H2} \lesssim 0.1$!

no reason to expect it to describe the asymptotic ($f_{H2} \sim 1$) slope

simpler:

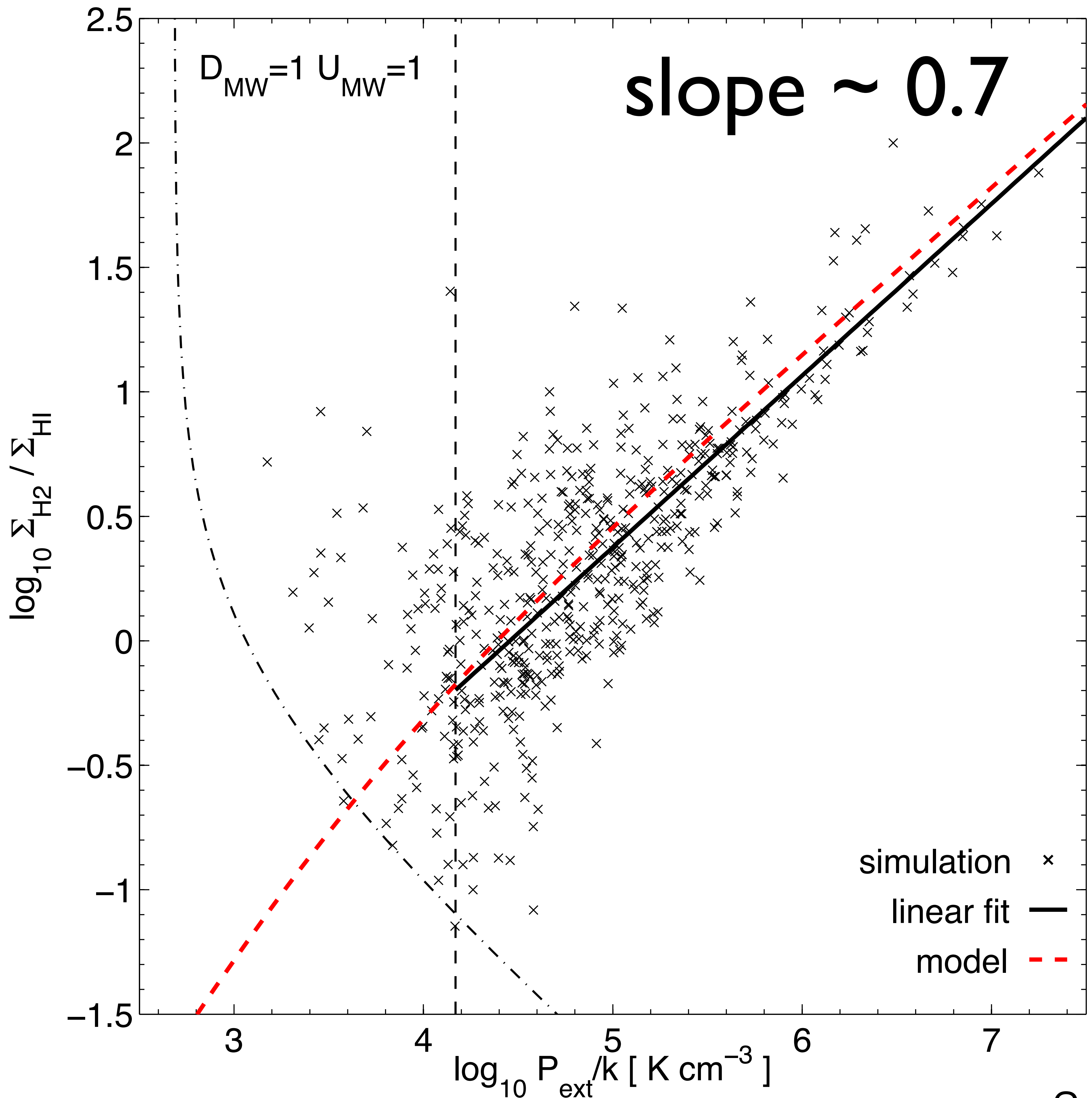
for $f_{H2} \sim 1$

$\Sigma_* \propto \Sigma_g^{1+\alpha}$ or $\Sigma_* \ll \Sigma_g$

$$P_{\rm ext} \propto \Sigma_g^{1.5+0.5\alpha}$$

$R_{\rm mol} \propto \Sigma_g$ ⇒ $R_{\rm mol} \propto P_{\rm ext}^{\frac{2}{3+\alpha}}$

The H_2 to HI transition



Feldmann et al. in prep

built simple model based on fitting formula by Gnedin & Kratsov 2011

Model: $\Sigma_{\mathrm{HI+H_2}}$ given

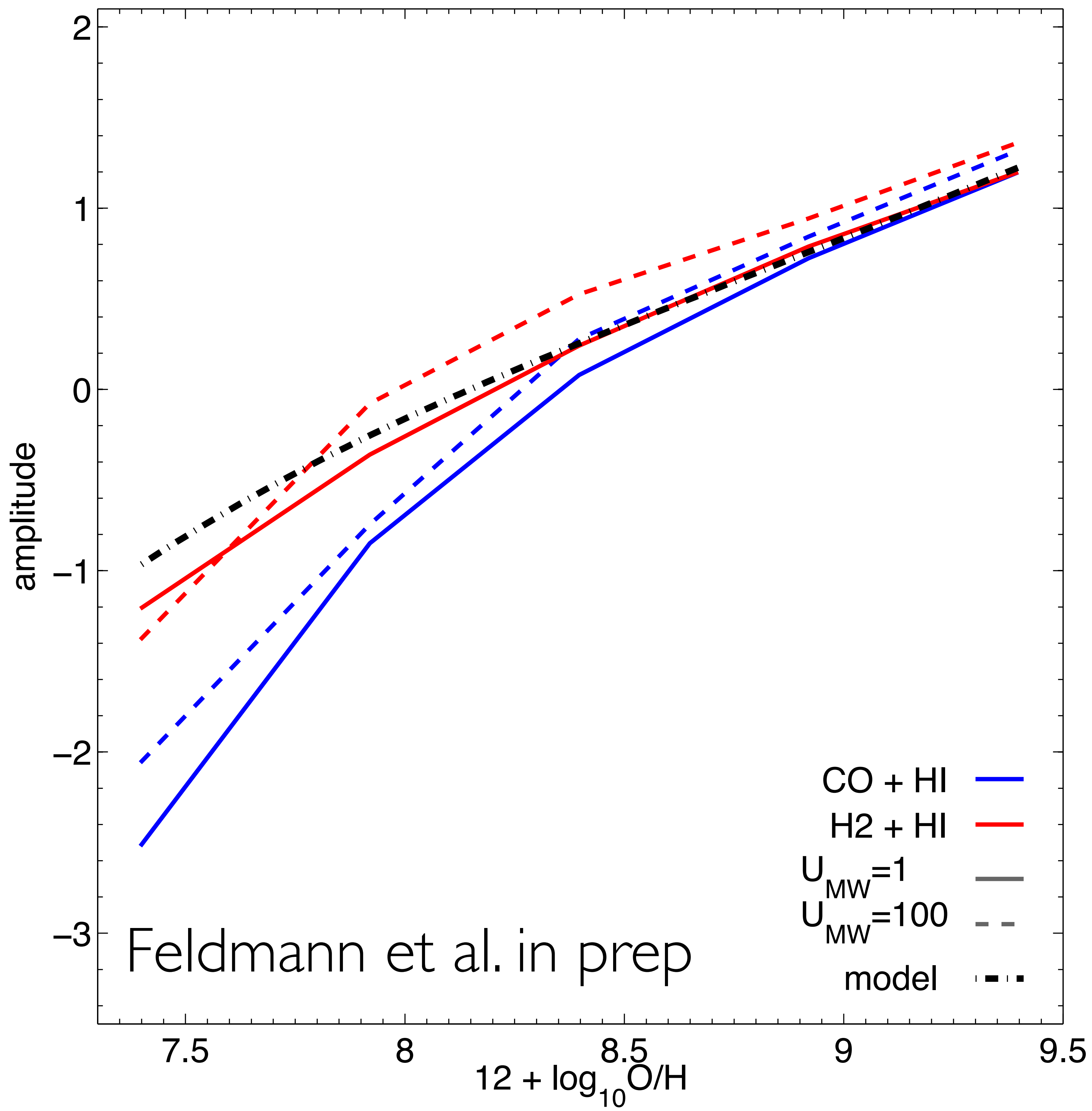
$$\Sigma_{\mathrm{H_2}} = \frac{\Sigma_{\mathrm{HI+H_2}}}{(1 + \Sigma_{\mathrm{c}}/\Sigma_{\mathrm{HI+H_2}})^2}$$

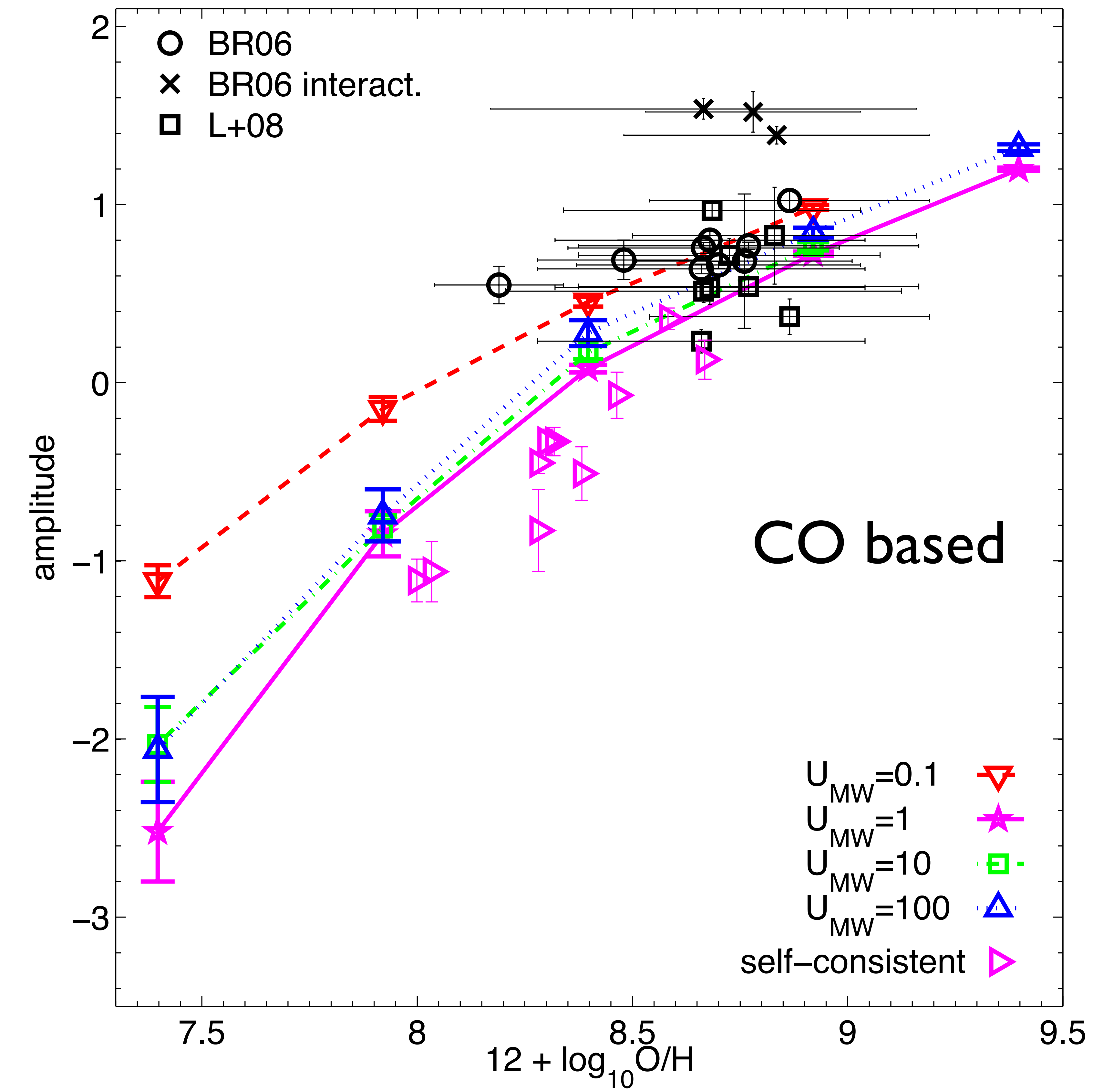
$$\Sigma_{\mathrm{HI}} = \Sigma_{\mathrm{HI+H_2}} - \Sigma_{\mathrm{H_2}}$$

$$\Sigma_{\mathrm{c}} = \Sigma_{\mathrm{c}}(D_{\mathrm{MW}}, U_{\mathrm{MW}})$$

find slope ~0.7 (vs. B&R'06 ~0.9, W&B'02 ~0.8), consistent amplitude

The H_2 to HI transition





- steep decline of amplitude with Z
- well explained by model => i.e. by $\Sigma_c(Z)$
- more severe if H2 based on CO (X_{CO} effect)

- no strong trend with UV field
- not in conflict with observations

(but not confirmed yet either)

Extremely crude model!

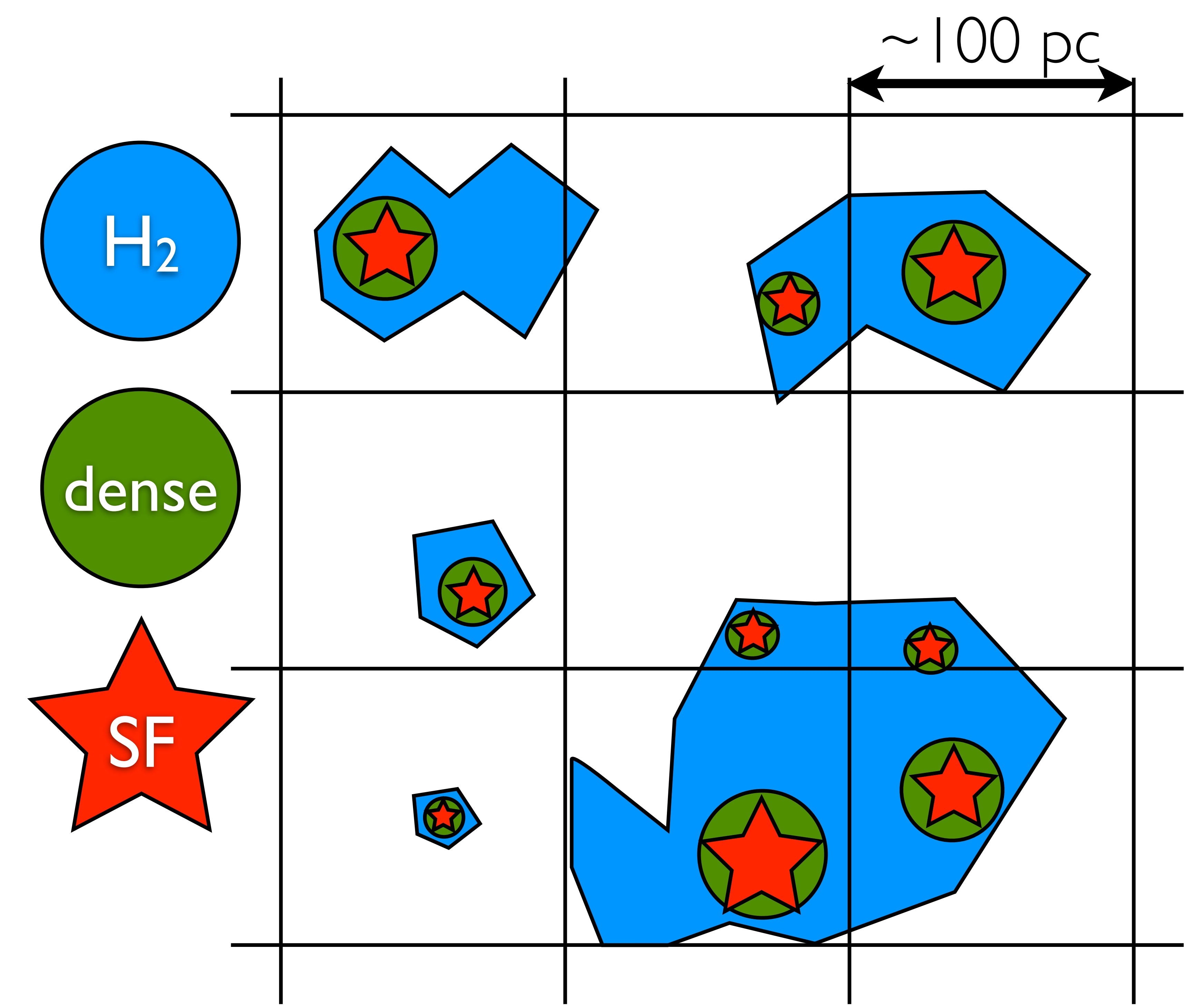
Ansatz: SF = Poisson Process with rate $\Delta t_{\mathrm{SF}}^{-1}$

on avg. 1 SF event per Δt_{SF} per volume element!
Δt_{SF}~10-20 Myr

$$\langle \mathrm{SFR} \rangle = \frac{M_{\mathrm{H}_2}}{\tau_{\mathrm{dep}}}$$ (ensemble avg. SFR)

$N_{\Delta t}$
- draw Poisson distr. random variable with mean and variance $\Delta t / \Delta t_{\mathrm{SF}}$
- number of "SF events" in time Δt

$$\mathrm{SFR}_{\Delta t} = \frac{N_{\Delta t}}{\langle N_{\Delta t} \rangle} \langle \mathrm{SFR} \rangle$$ (observed SFR)



Feldmann + 2012 (arXiv:1204.3910)

Consequences of the stochastic SF model

- observed depletion time given a SF tracer with lifetime Δt

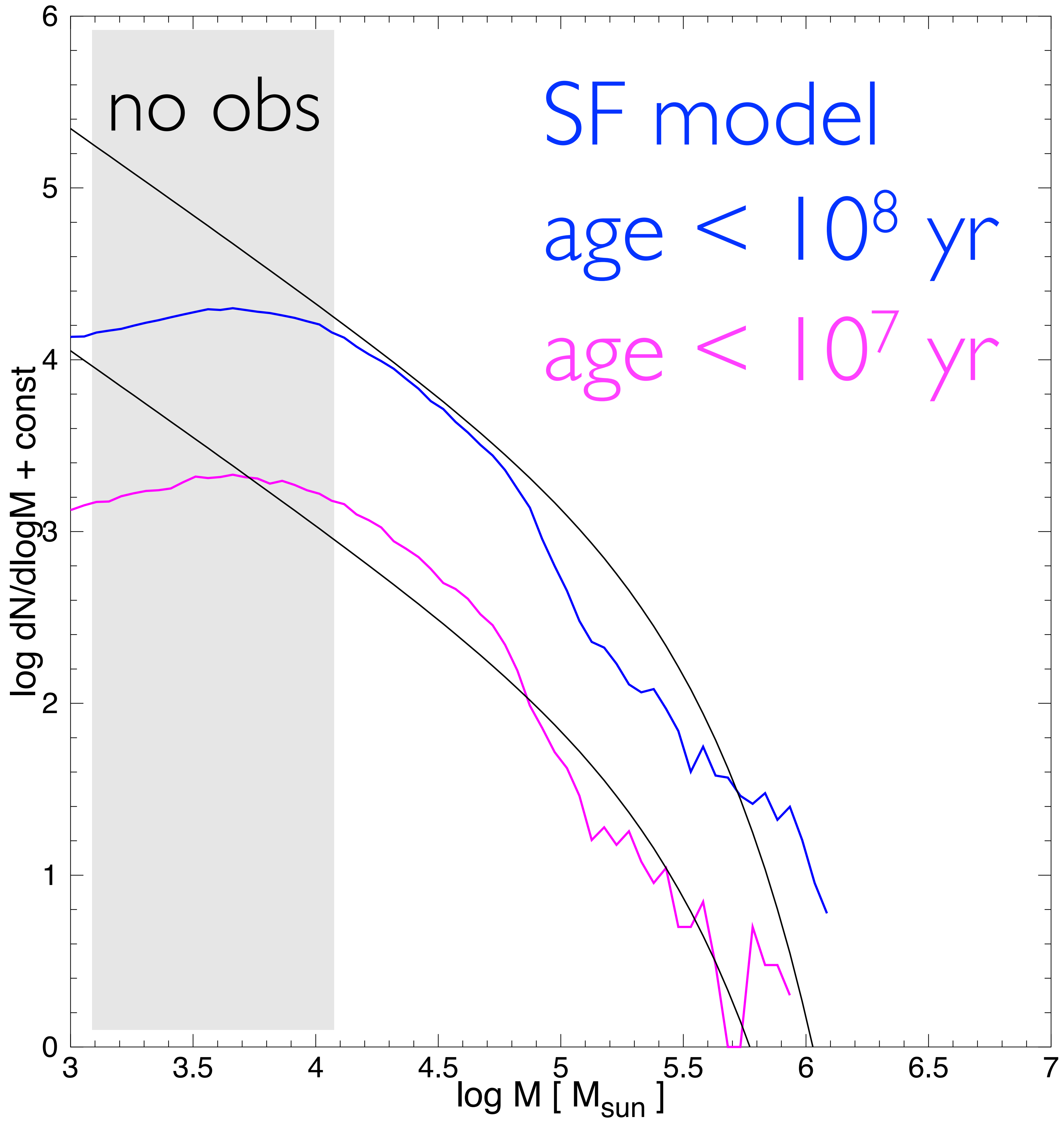
$$M_{\mathrm{H}_2}/\mathrm{SFR}_{\Delta t} = \tau_{\mathrm{dep}} \frac{\langle N_{\Delta t} \rangle}{N_{\Delta t}} = \tau_{\mathrm{dep}} \frac{\Delta t / \Delta t_{\mathrm{SF}}}{N_{\Delta t}}$$

⇨ observed depletion time can be much shorter than the global average & depends on tracer

- introduces scatter in the Σ_{H2} - Σ_{SFR} relation via
  - Poisson (discreteness) noise in the number of SF events
  - fluctuations in the avg. SFR due to H_2 variations
  - their covariance

MF of young massive clusters

(M* ~ 2.5×10⁵ M$_\odot$, see Portegies Zwart et al. 2010)



Arguments for Δt_{SF} ~ 10-20 Myr on ~100 pc scales

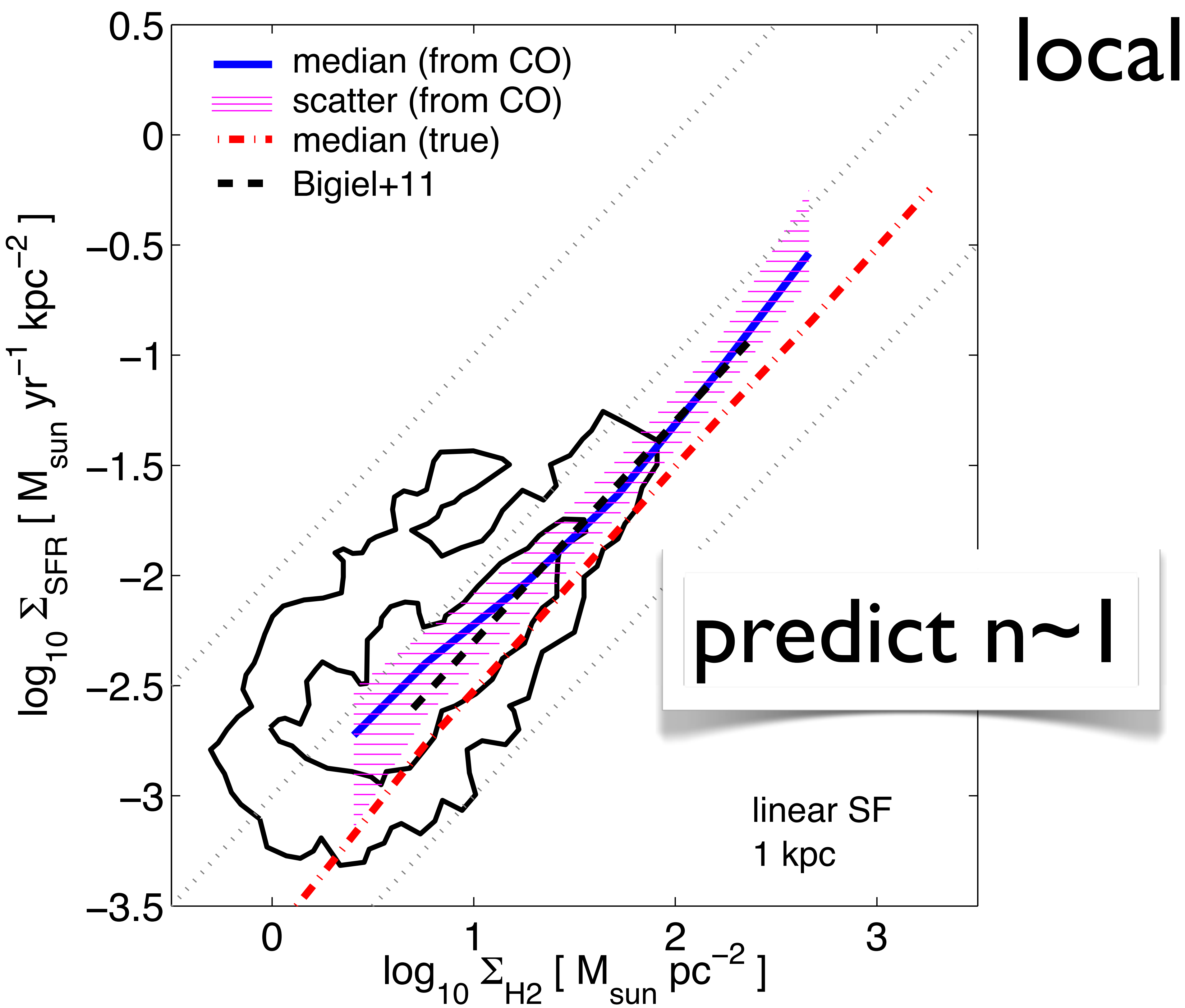
- lower limit: crossing time L/σ ~ 10 Myr (at l=100 pc)
- upper limit: scatter in the Σ_{H2} - Σ_{SFR} relation
- reproduces reasonable cluster mass function
- consistent with observed relation between SFR & maximum embedded star cluster mass (Weidner+04)

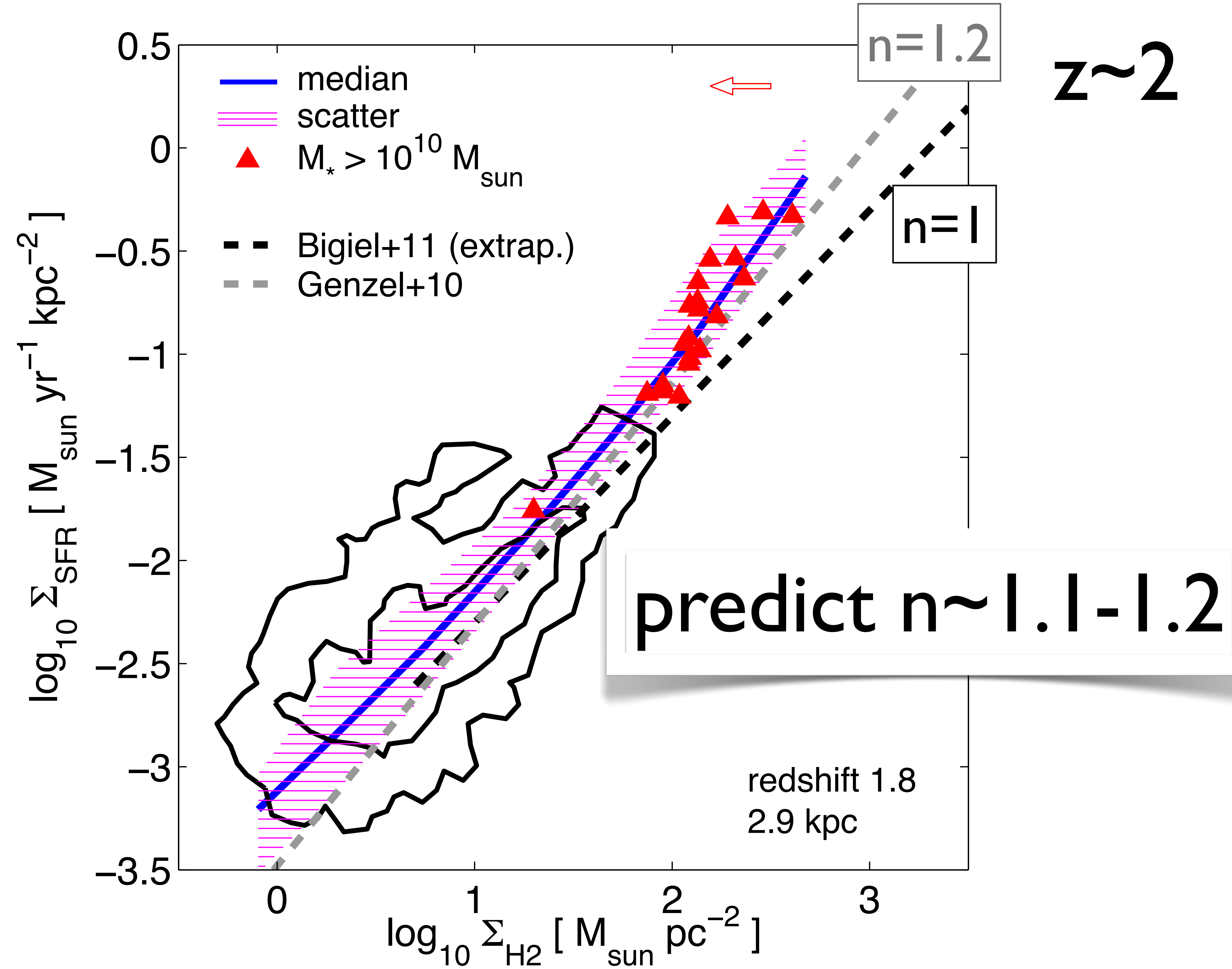
Δt_{SF} fundamentally different from t_{ff}

- time between SF events
- decreases with scale

- duration of SF event
- increases with scale

The Slope of the Σ_{H2} - Σ_{SFR} relation (reloaded)

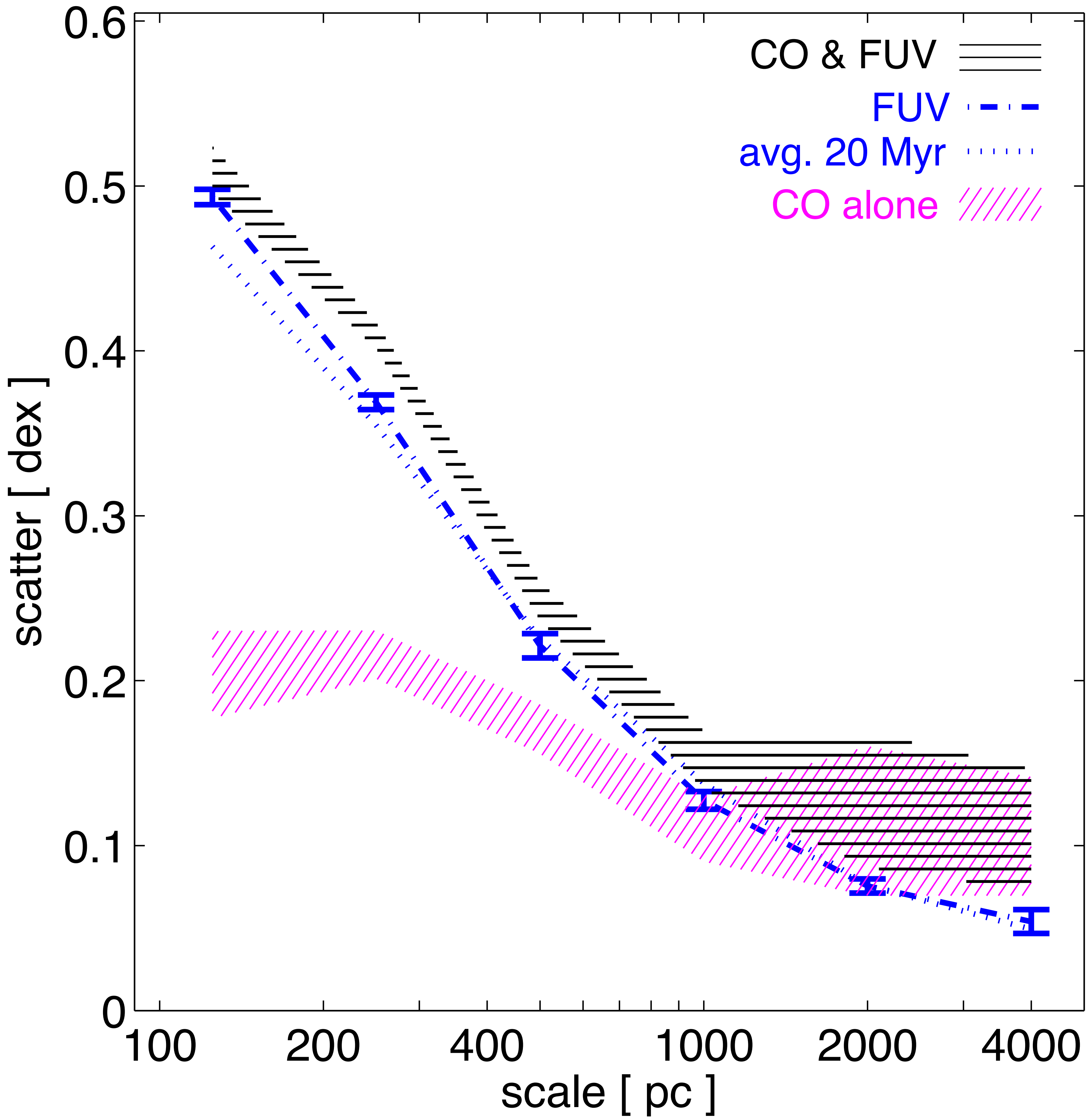




Slight super-linearity in observed molecular KS relation explained by:

- Increase of X_{CO} with column density (primarily)
- Increase of X_{CO} with decreasing metallicity of higher z galaxies

Feldmann + 2012
(arXiv:1204.3910)



Scatter

- strong increase with decreasing scale
- above ~ 1 kpc: X_{CO} variations dominate
- below ~ 1 kpc: discreteness noise of SF
- decreases with increasing tracer lifetime
- increases with increasing Δt_{SF}
- scaling ~$l^{-0.5}$: 2D configuration + finite width of density pdf

Feldmann + 2011 (arXiv:1010.1539)

Feldmann + 2012 (arXiv:1204.3910)

Conclusions

1. Σ_{H2} - Σ_{SFR} relation clearly important test-bed for SF modeling
2. CO-H2 conversion factor can lead to increase in slope of the Σ_{H2} - Σ_{SFR} relation at large surface densities
3. Scatter in the Σ_{H2} - Σ_{SFR} relation
    - potentially caused by discreteness of SF
    - testable predictions for the scatter and τ_{dep} as function of SF tracer lifetime
4. Scatter roughly ~scale$^{-0.5}$; explained by 2D set-up of the gas disk & width of the density pdf
5. Strong Z dependence of the amplitude of the pressure - H_2/HI relation in self-consistent H_2 models

Thank you!