Regulation of star formation in low-metallicity galaxies by feedback and turbulence

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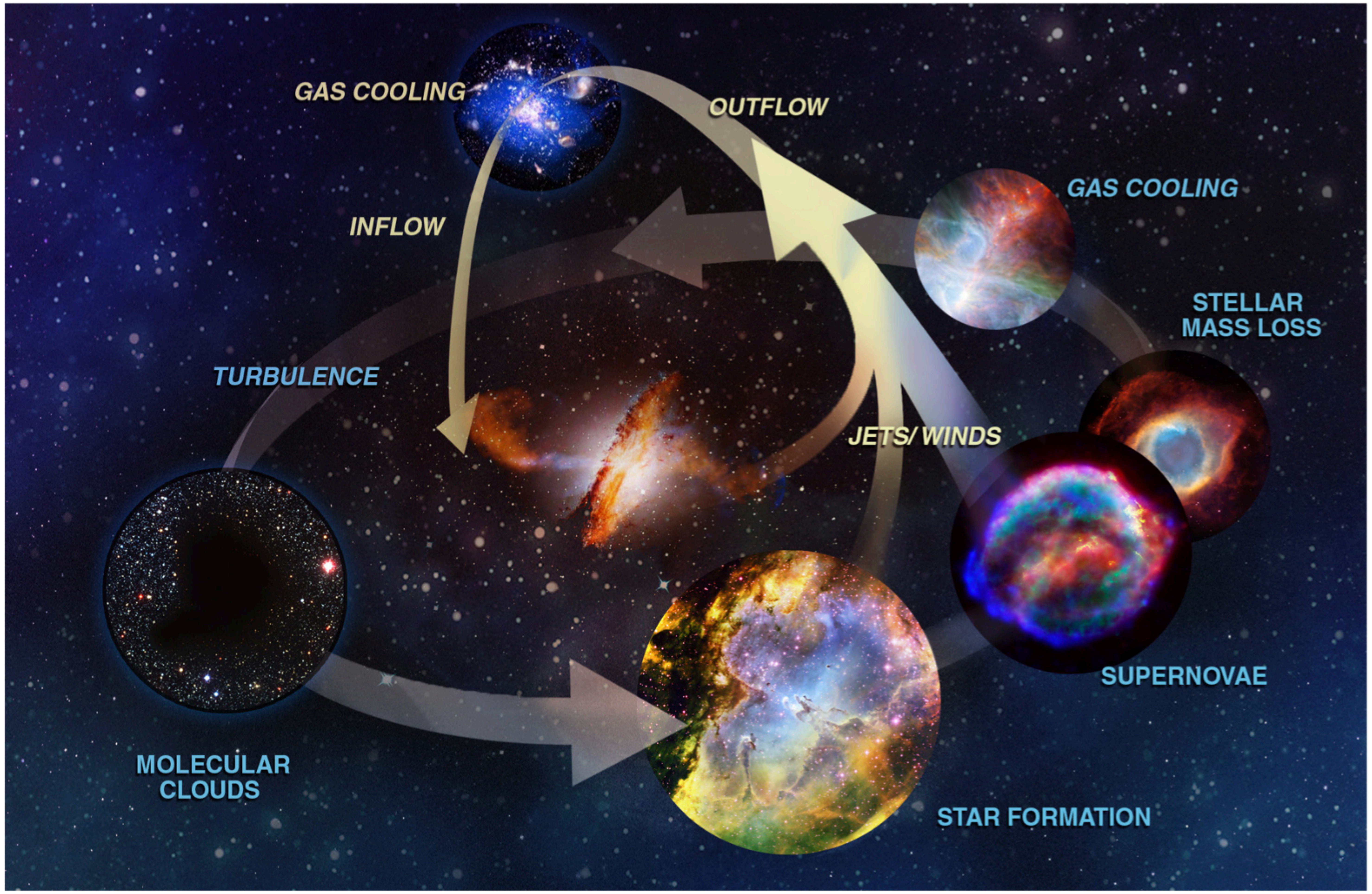
Classical picture of SF in galaxies

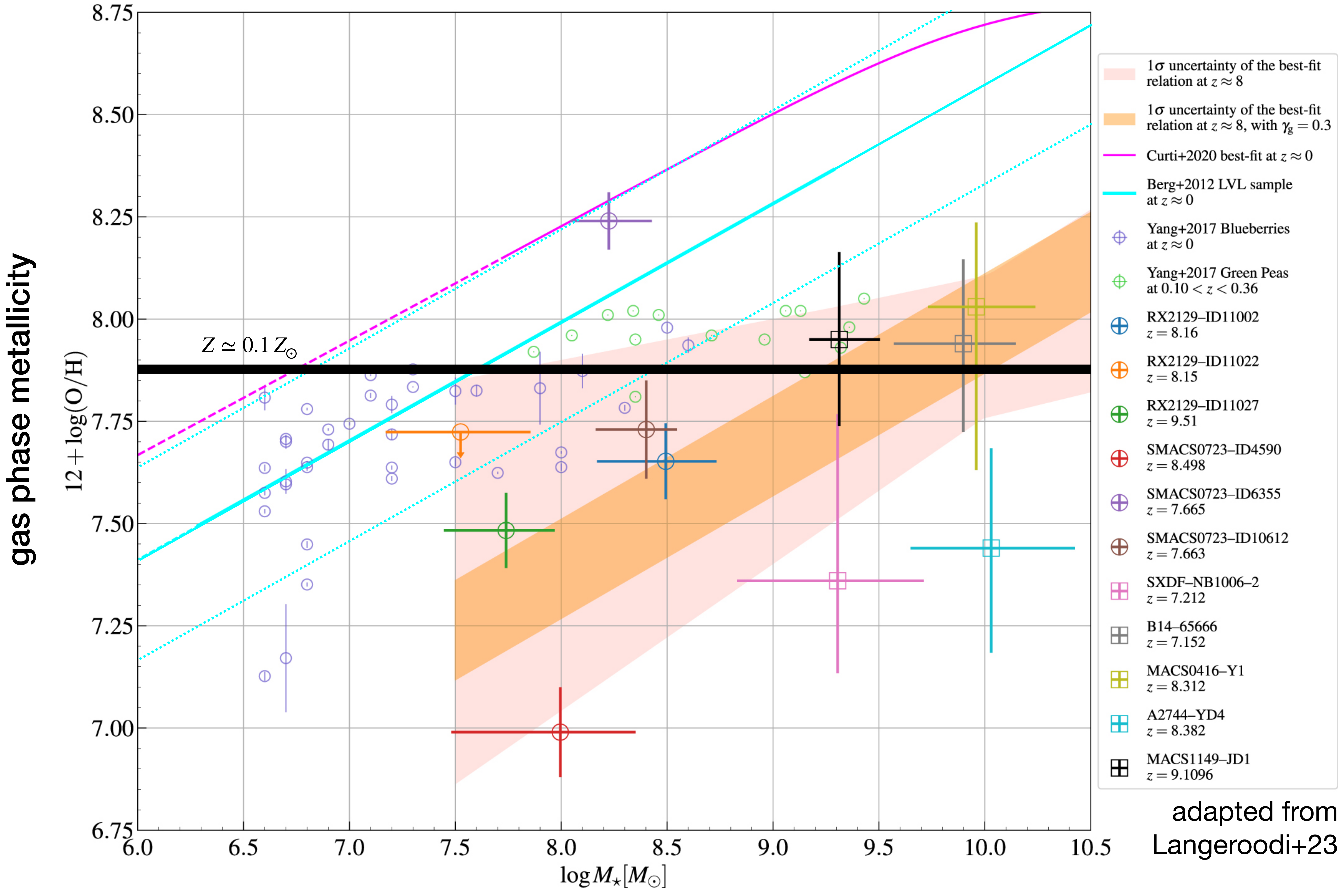
Feedback, turbulence encoded in ISM + regulates SF



HabEx Final Report

A key part of the parameter space

Local dwarfs + high redshift galaxies are low Z

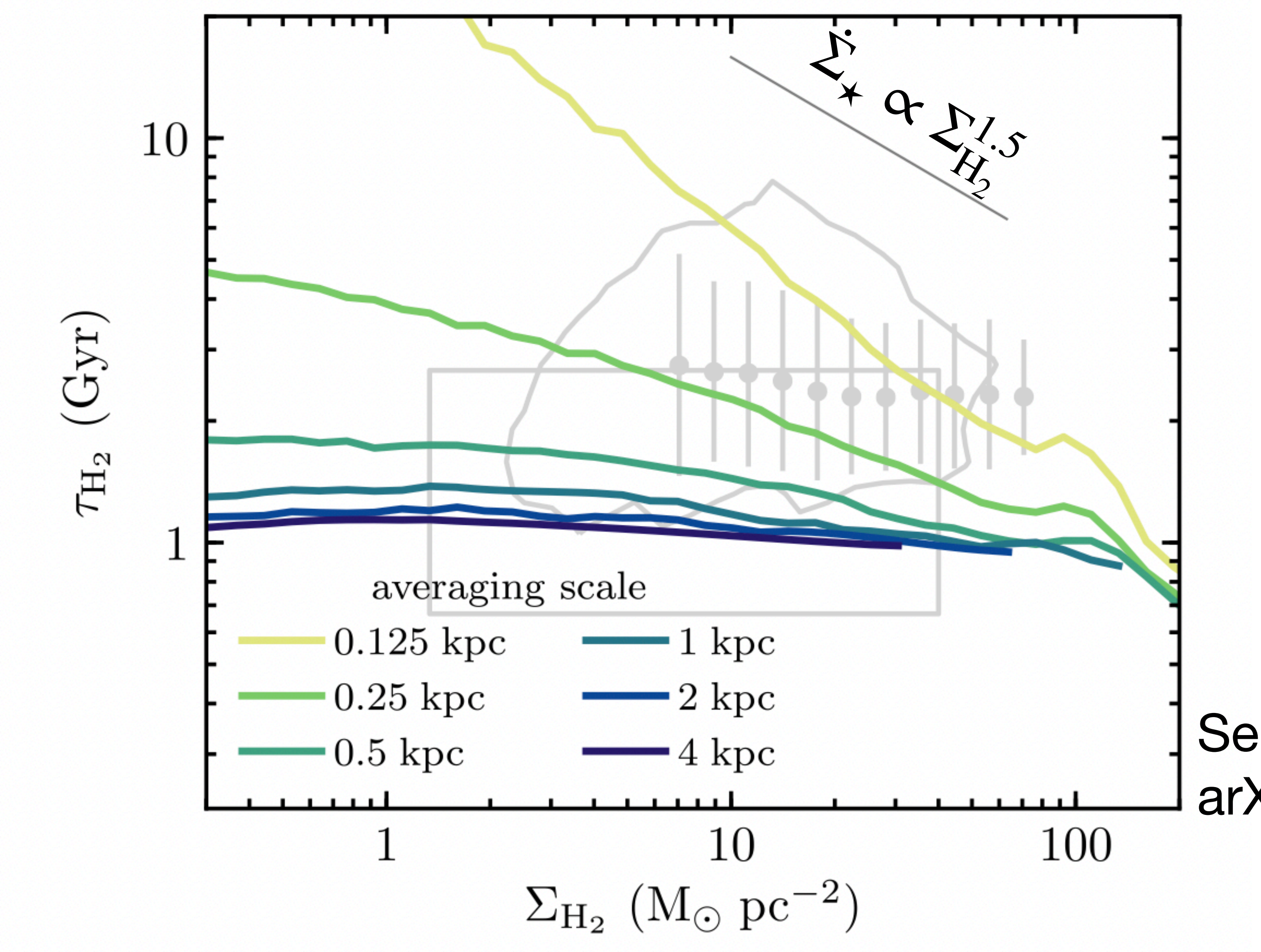


adapted from
Langeroodi+23

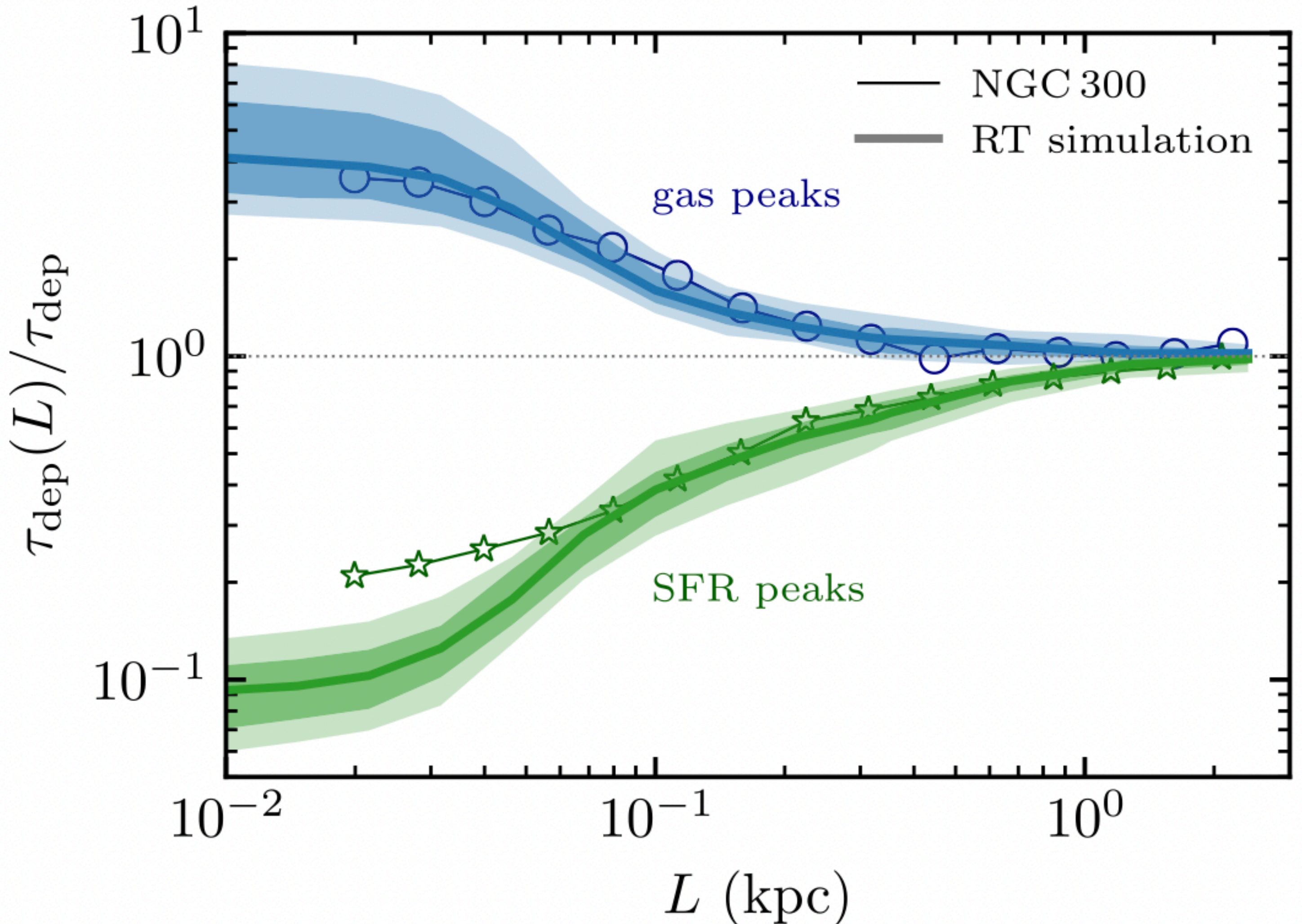
State-of-the-art simulations

Reproducing H_2 distribution and SF in nearby low Z dwarfs

- High resolution (~10 pc), realistic simulation (Semenov+21)
- SF (and so feedback) not based on H_2 — self-consistent modeling of hydrodynamics, UV radiative transfer
- Recover detailed SF properties observed in local dwarf galaxies



Semenov+19, arXiv:1809.07328



Semenov+21, arXiv:2103.13406

Virial parameter-based SF

Flexible, varies with gas properties, + not tuned

- Stochastic star formation set by star formation efficiency per free-fall time
- Fraction of gas forming stars set by gas motions, gas density, cell size
- Feedback + turbulence encoded in ISM behavior

$$\dot{\rho}_\star = \epsilon_{\rm ff}\frac{\rho_{\rm gas}}{t_{\rm ff}}$$

$$\epsilon_{\rm ff} \approx e^{-\sqrt{\alpha_{\rm vir}/0.53}}$$

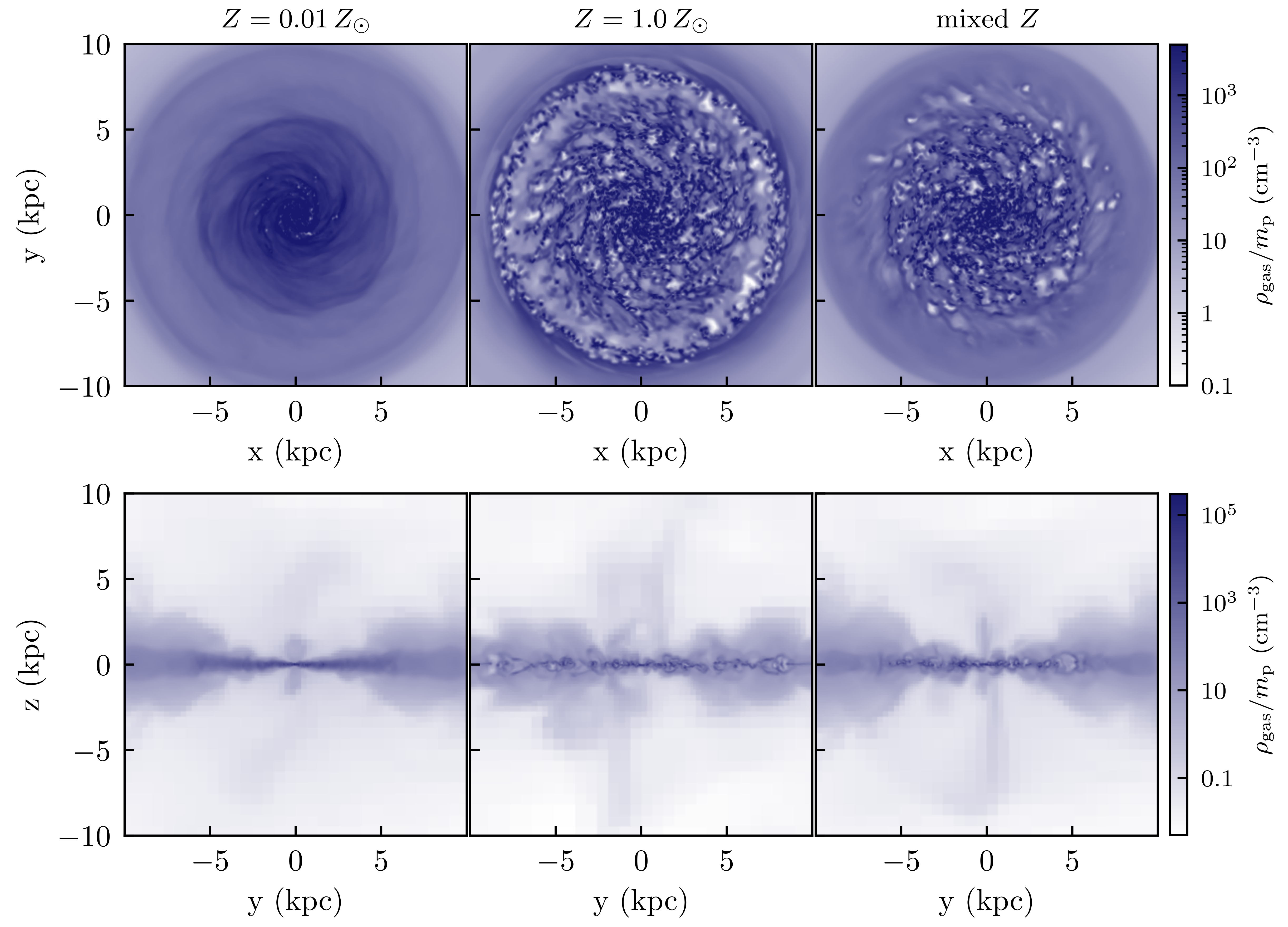
Padoan+12

$$\alpha_{\rm vir} = \frac{9.35\,(\sigma_{\rm tot}/100\,{\rm km\,s^{-1}})}{(n/100\,{\rm cm^{-3}})\times(\Delta x/40\,{\rm pc})}$$

Bertoldi & McKee 92

Calibrating on an isolated disk

Simulating galaxies at low metallicity



- Run at fixed Z, evenly log-spaced 0.01 - 1 $Z_\odot$, leaving all other physics the same
- Changes in ISM structure with metal abundance
- Changes in atomic/molecular fraction with metal abundance

Polzin+24a, arXiv:2310.10712

H_2 should be less abundant at low Z

Metal-rich models won’t apply properly to this regime

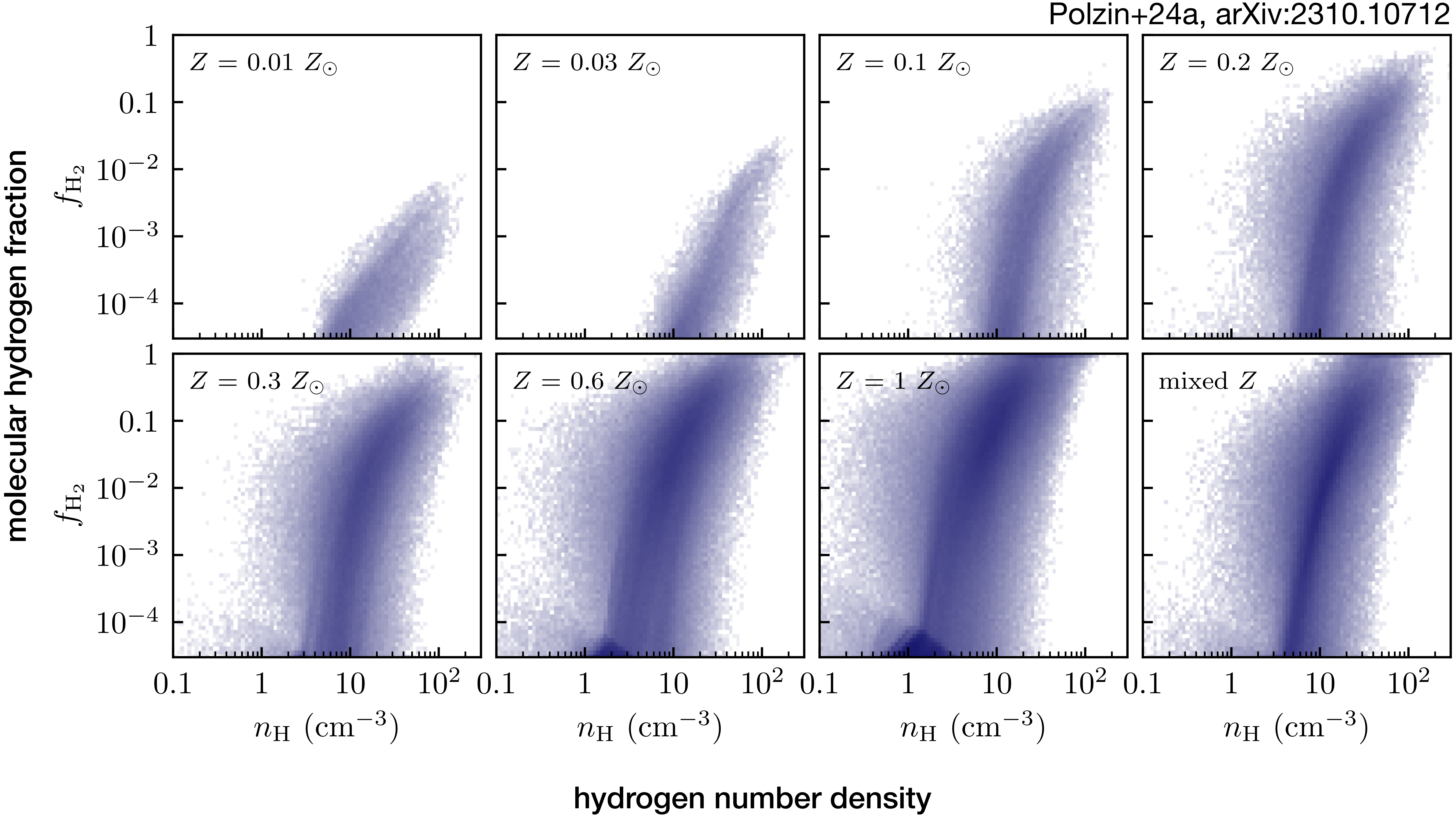
- At typical GMC densities (n_H ~ 50 cm^{-3}), H_2 formation time is comparable to lifetime of star forming regions at ~0.1 $Z_\odot$
- At lower Z, H_2 abundances drop dramatically
- HI-H_2 models for metal-rich gas will overpredict H_2 at low Z

$$t_{\mathrm{chem}} = 105 \overset{\substack{\textbf{gas metallicity}\\ \downarrow}}{\left(\frac{Z}{Z_\odot}\right)^{-1}} \overset{\substack{\textbf{gas density}\\ \downarrow}}{\left(\frac{n_{\mathrm{H}}}{\mathrm{cm}^{-3}}\right)^{-1}} \overset{\substack{\textbf{clumping factor}\\ \downarrow}}{\left(\frac{10}{f_c}\right)} \mathrm{Myr}$$

Krumholz 12

Isolating the role of metallicity

Predictions from a suite of realistic simulations



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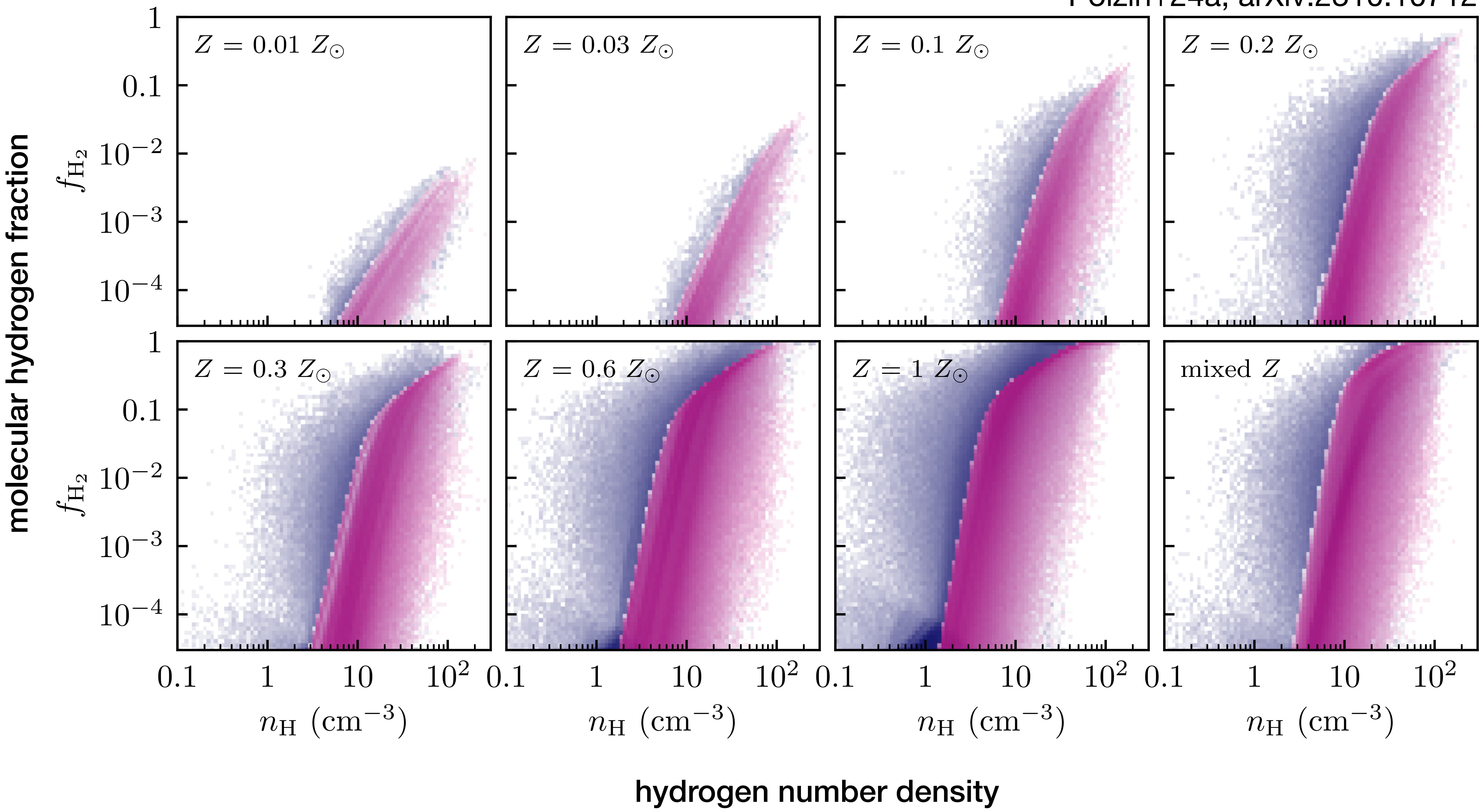
Capturing the Z, U-dependences

Accurate HI-H_2 transition location and max f_{H2}

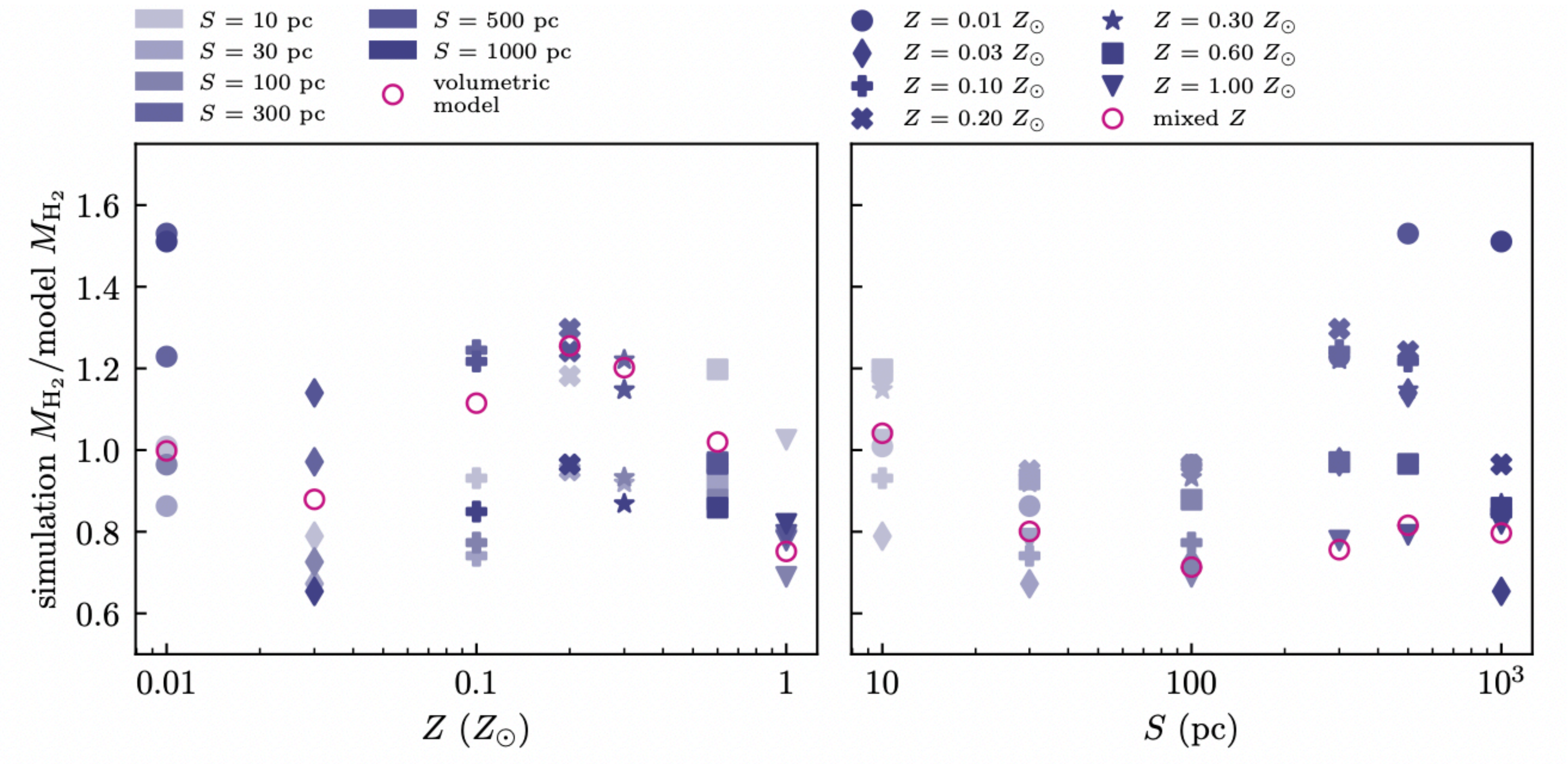
Polzin+24a, arXiv:2310.10712



Accurately model H_2 in low Z regime

Good for recovering HI + H_2 masses!

- Simple functional form, dependent on n_H, radiation field strength, and gas metallicity
- Recovers H_2 mass to within factor of 1.25 (1.5) across metallicitie (and scales)
- No assumptions of chemical equilibrium etc.

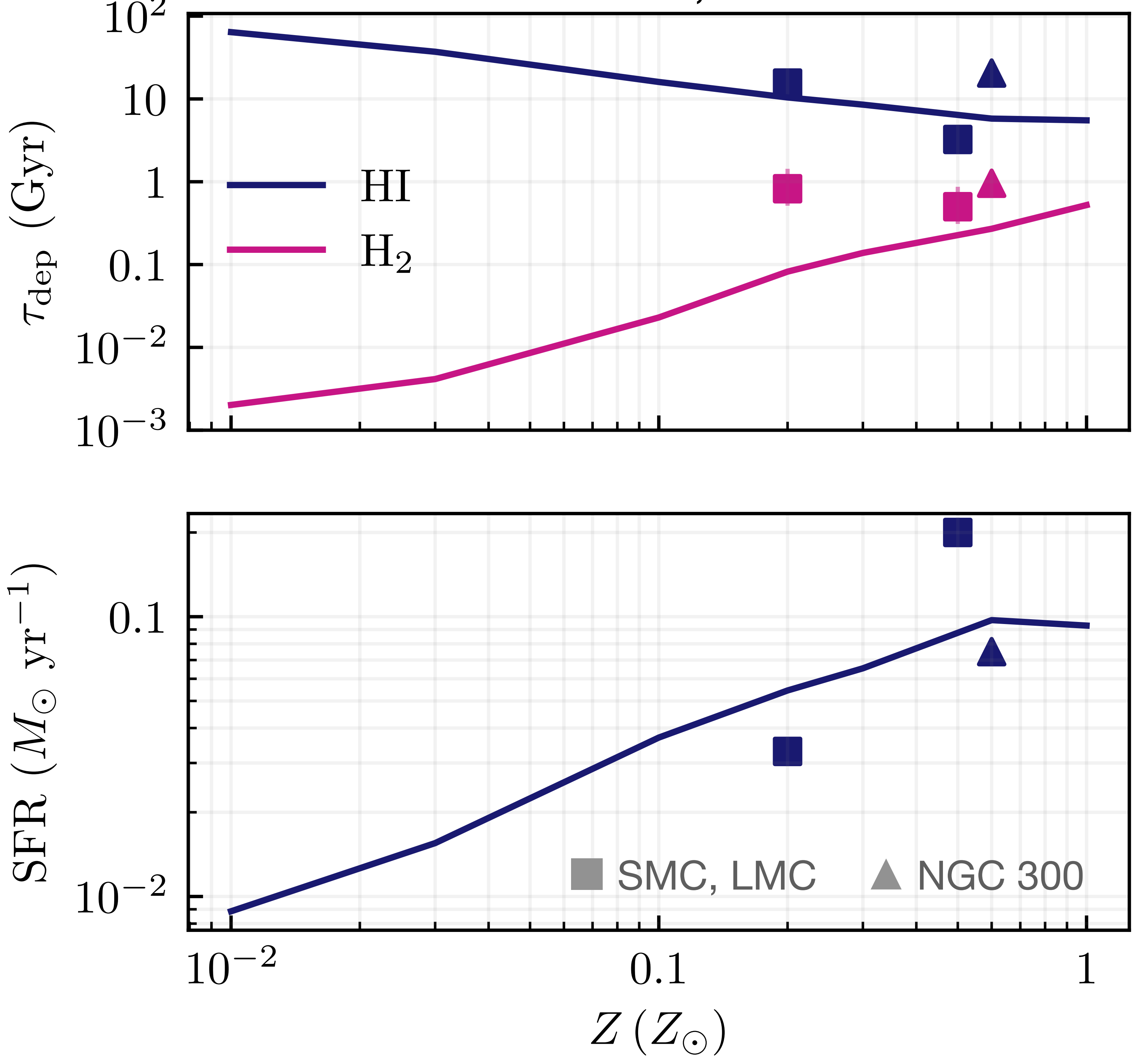


Polzin+24a, arXiv:2310.10712

H_2 abundance and SF decouple

… so H_2 should not be used in SF prescriptions

Polzin+24a, arXiv:2310.10712

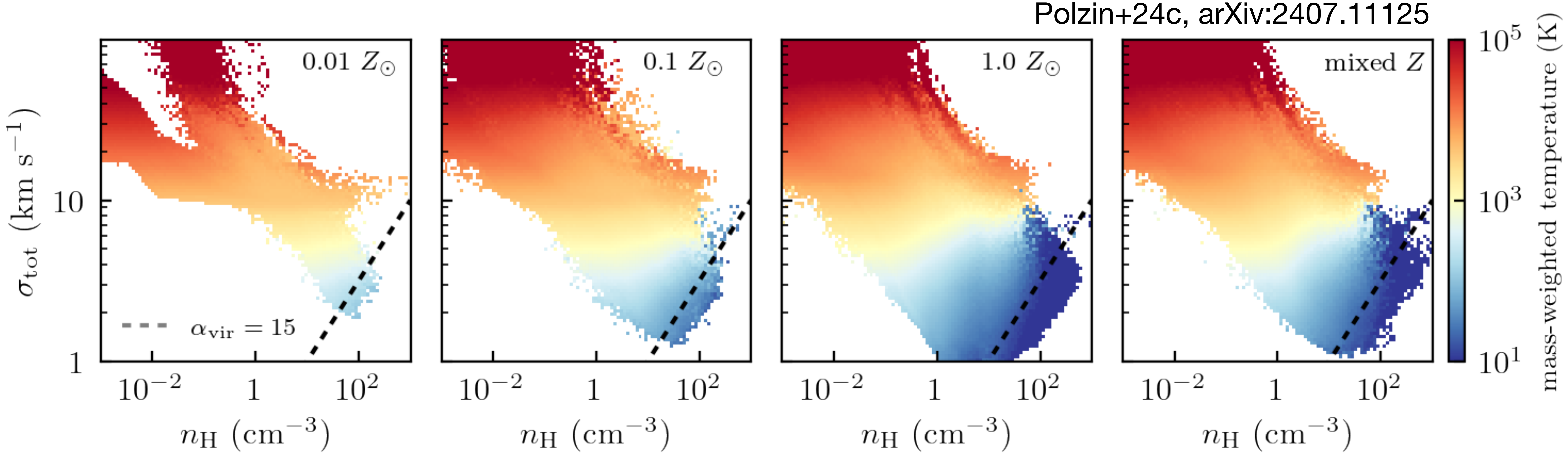


- SF and H_2 abundance decouple at low metallicity
- Stars form out of cold, dense gas generally in absence of molecular gas

SF in cold, dense gas

SFR lower in low Z runs due to less cold, dense gas

Polzin+24c, arXiv:2407.11125

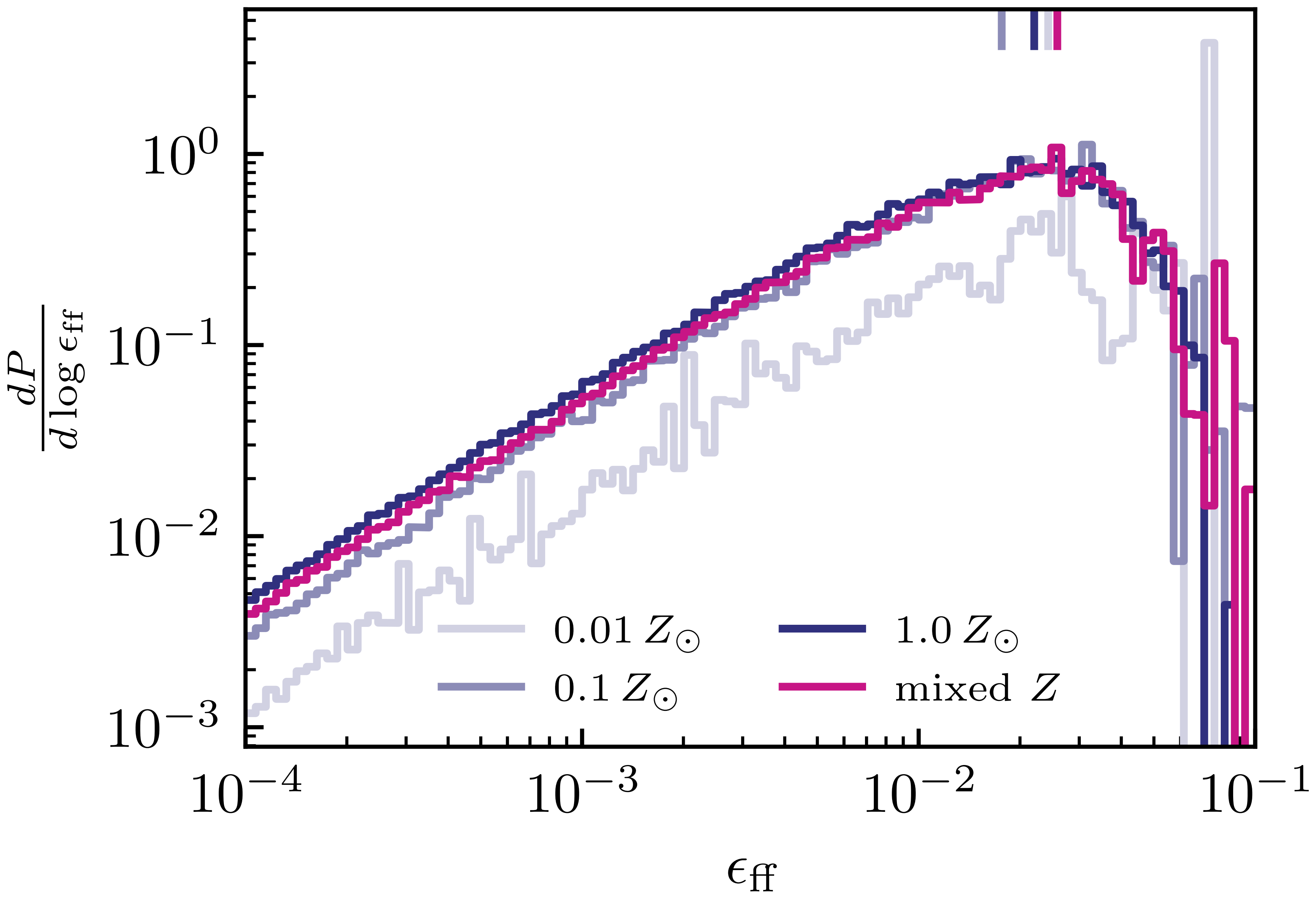


H_2 abundance and SF decouple

… so H_2 should not be used in SF prescriptions

- Star-forming gas is ~uniformly efficient, regardless of metallicity
- On small scales, SFE set by turbulence and feedback, not H_2 fraction

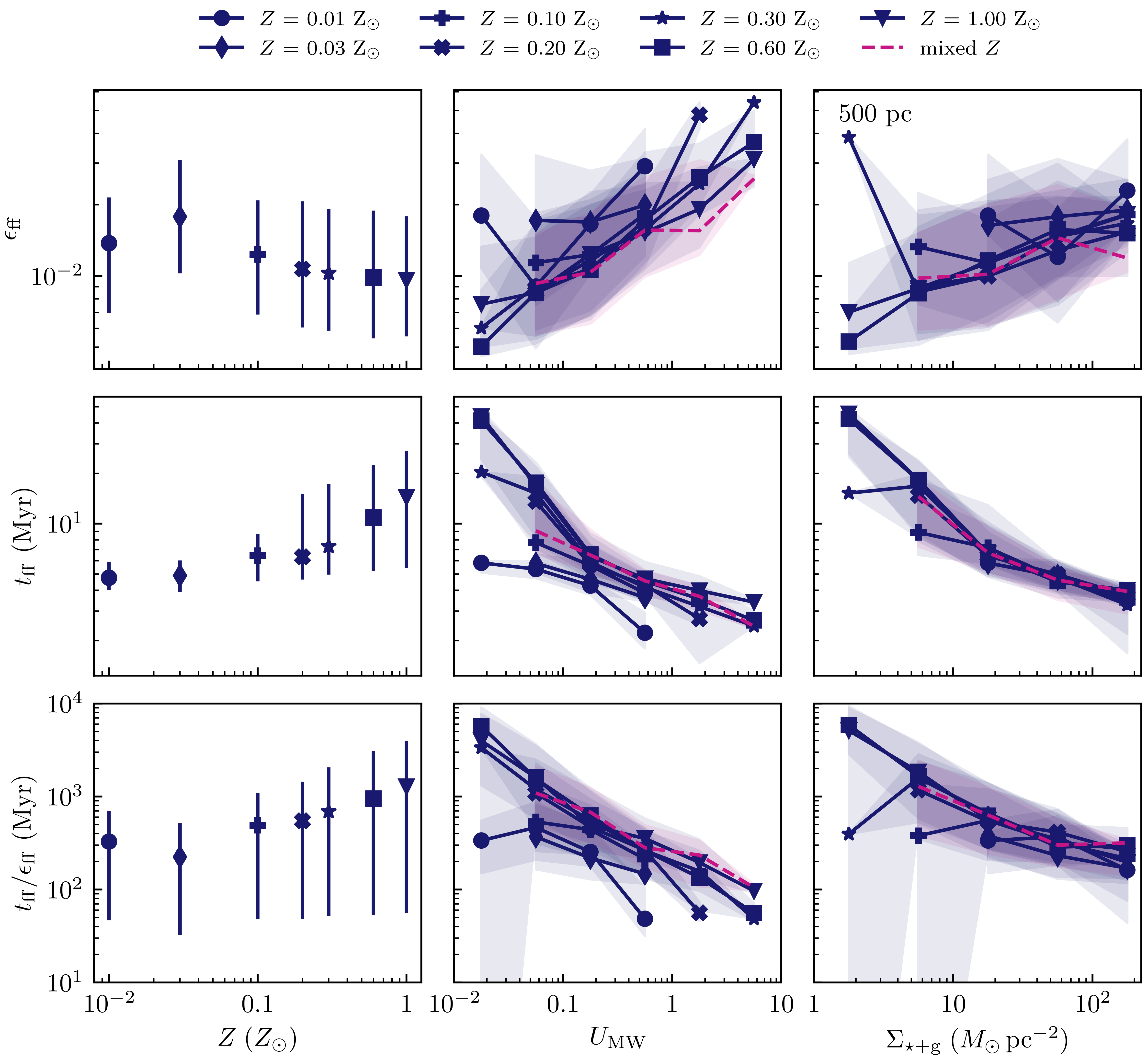
Polzin+24c, arXiv:2407.11125



Accurate SFEs across conditions

Modeling star formation directly for low Z galaxies

- Little dependence on Z , U, or Σ; universality of $\epsilon_{\rm ff}$ on galaxy scales (+ smaller) **with no tuning**
- Similarly, SFE not tied to H_2 abundance
- Preparing a cell-by-cell model of star forming gas fraction + timescale



Polzin+24c, arXiv:2407.11125

Non-turbulent re-simulation

Role of thermal vs. turbulent motions in the ISM

- Use Padoan+12 model for subgrid turbulence as default — based on virial parameter, where $\sigma_{\rm tot} = \sqrt{\sigma_{\rm t}^2 + c_{\rm s}^2}$
- Turn off turbulence which redefines $\sigma_{\rm tot} = c_{\rm s}$

$$\epsilon_{\rm ff} \approx e^{-\sqrt{\alpha_{\rm vir}/0.53}}$$

Padoan+12

$$\alpha_{\rm vir} = \frac{9.35\,(\sigma_{\rm tot}/100\,{\rm km\,s^{-1}})}{(n/100\,{\rm cm^{-3}}) \times (\Delta x/40\,{\rm pc})}$$

Bertoldi & McKee 92

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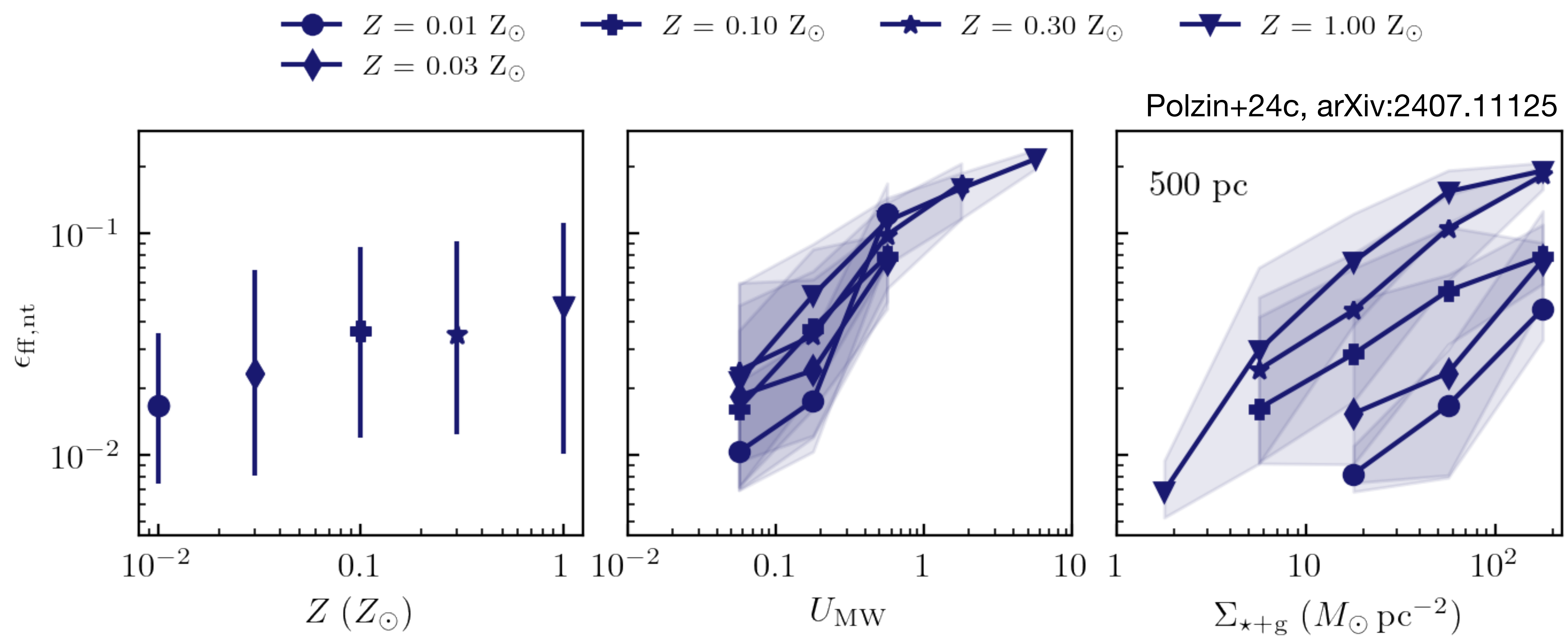

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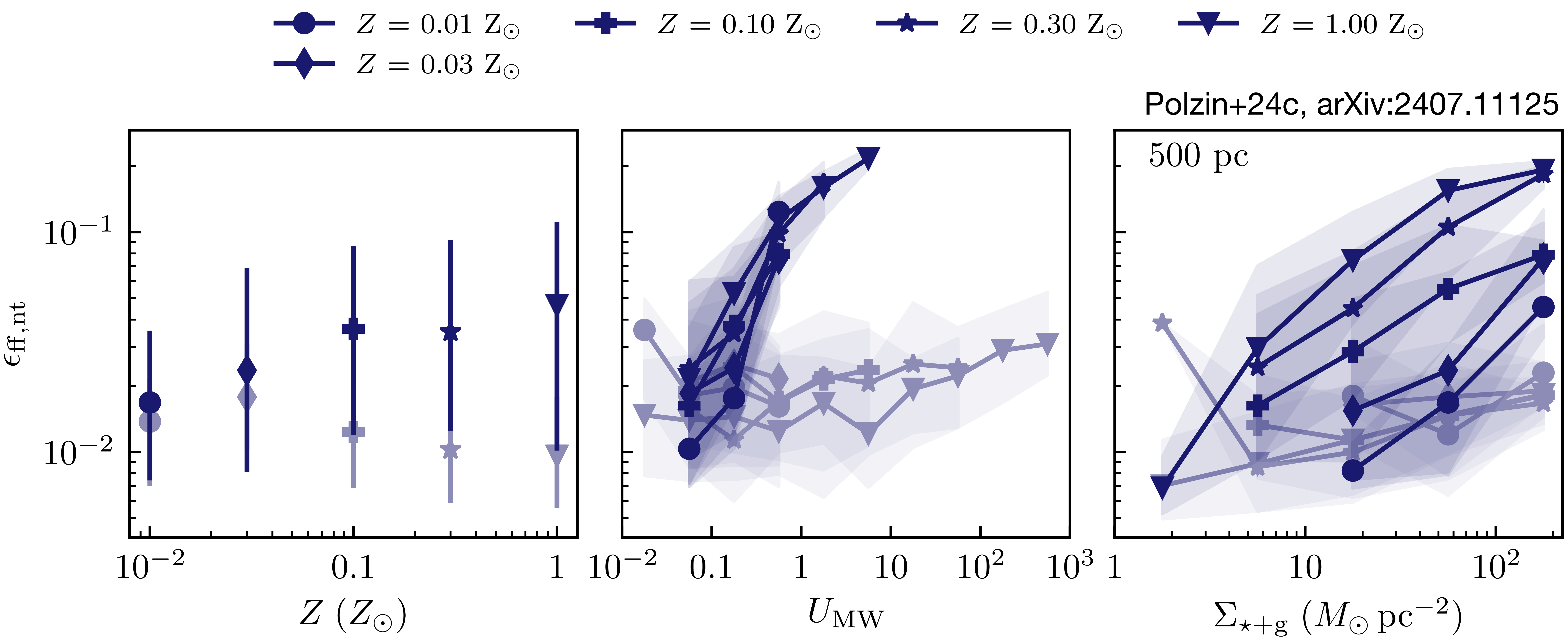

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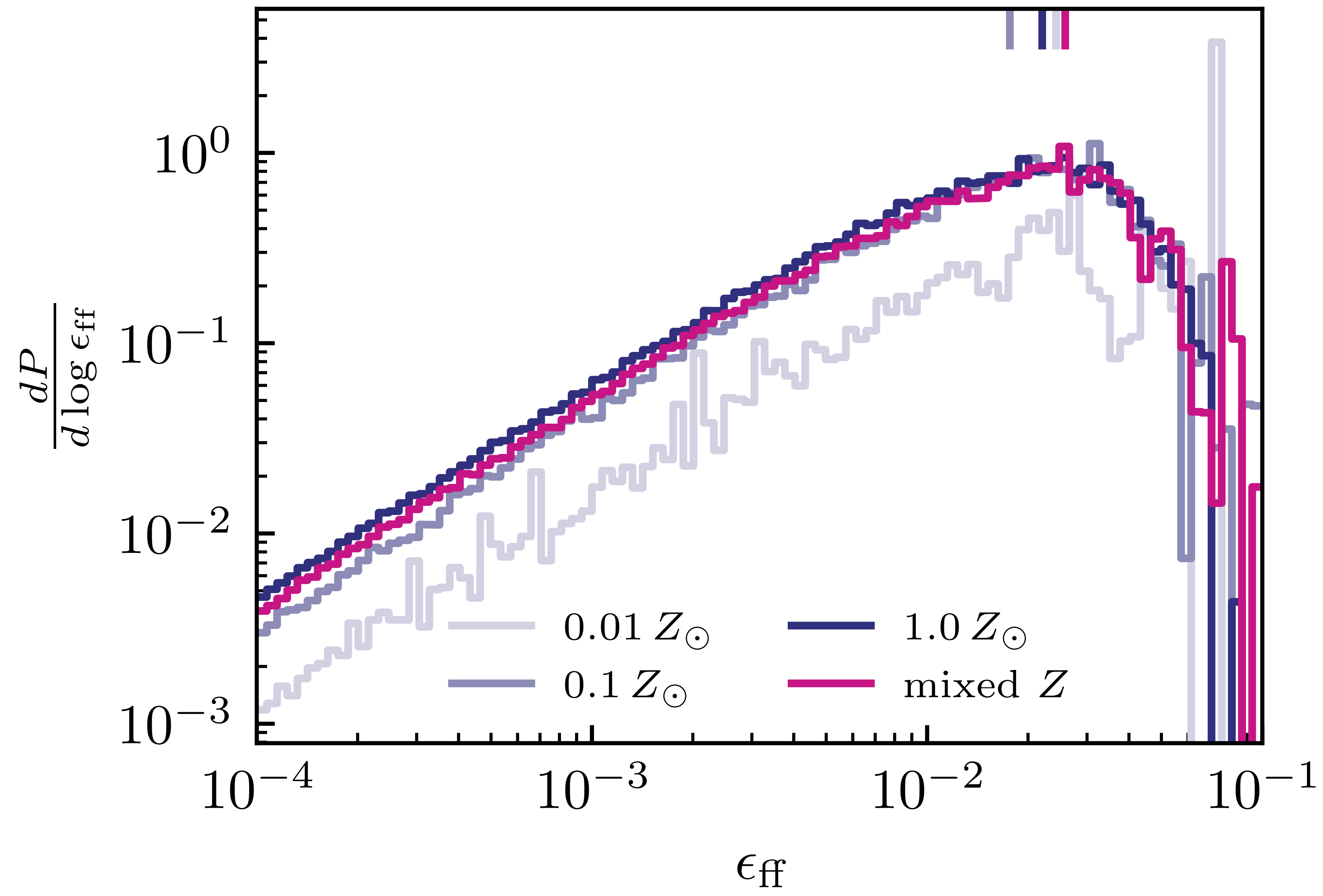
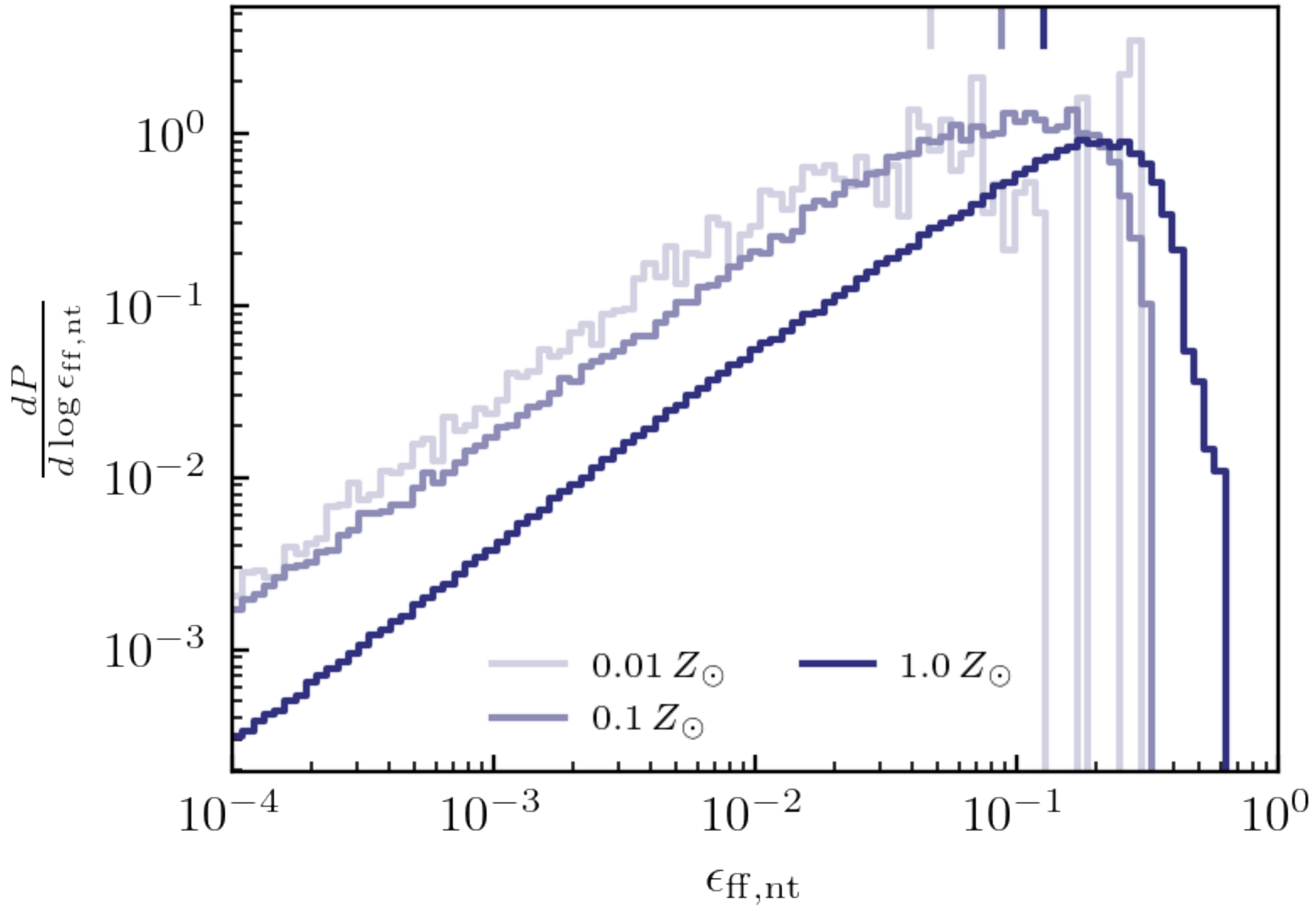
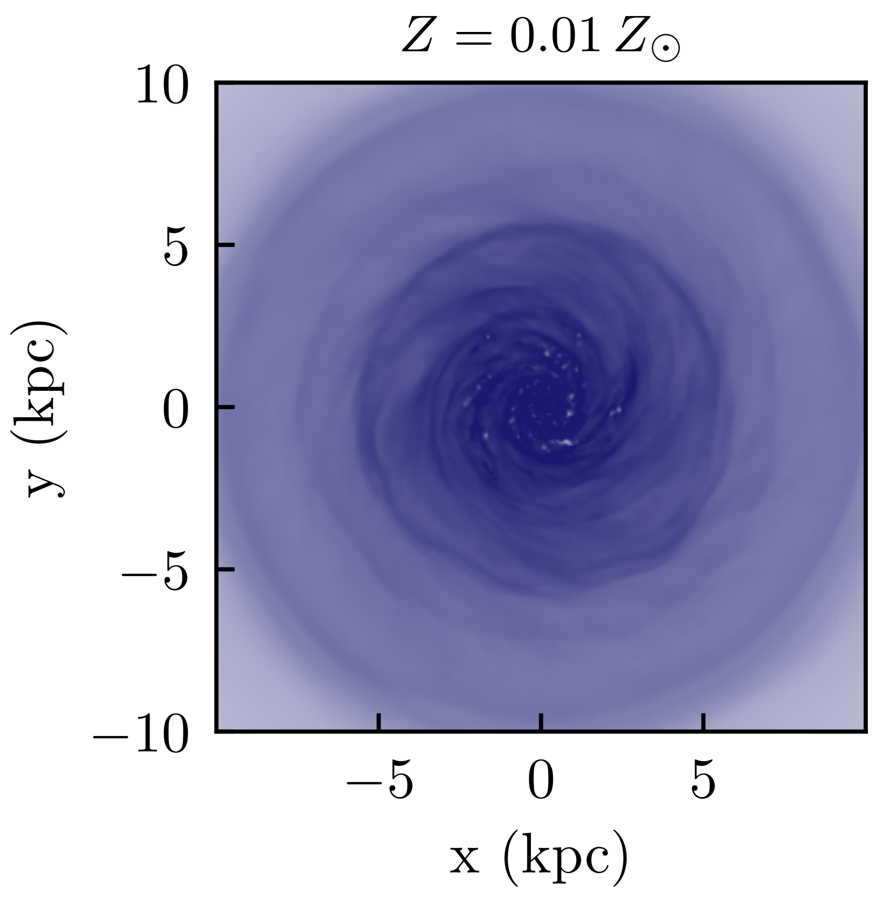




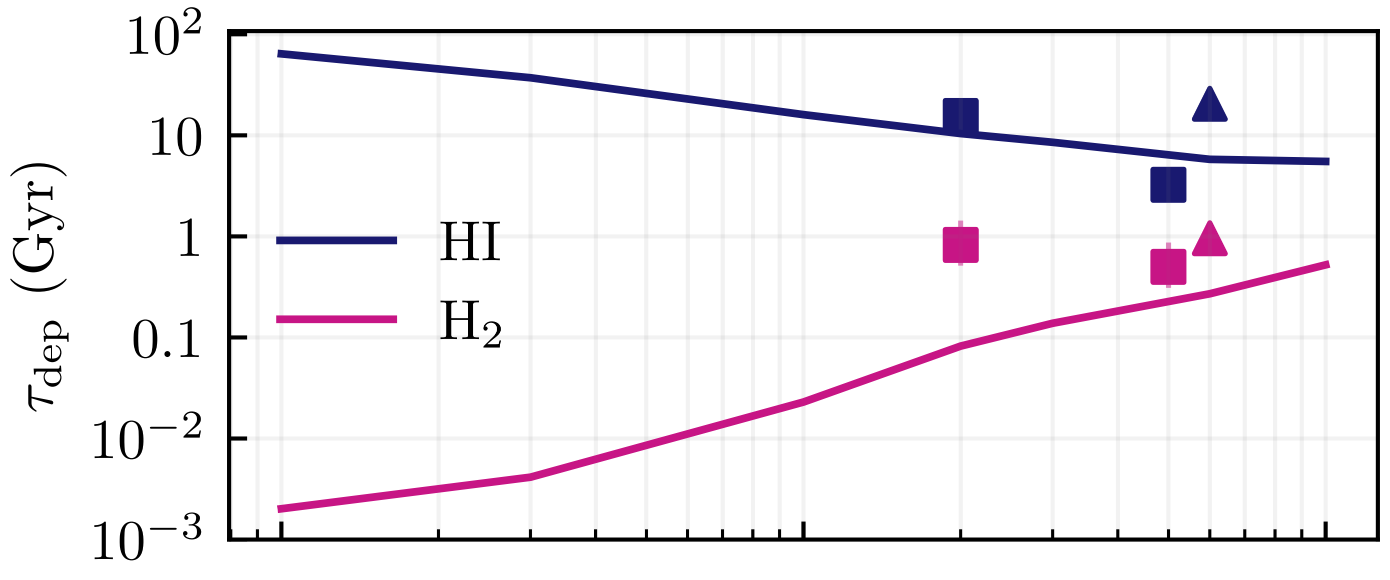
Note different axis scales!

Quick summary

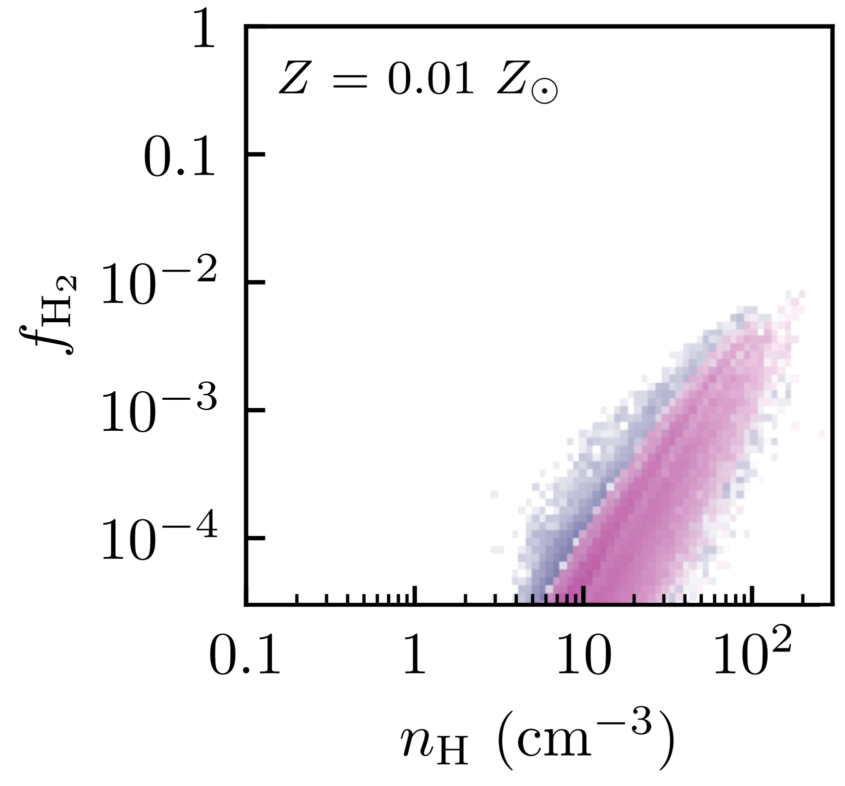
SF regulated by turbulent compression + dispersive feedback



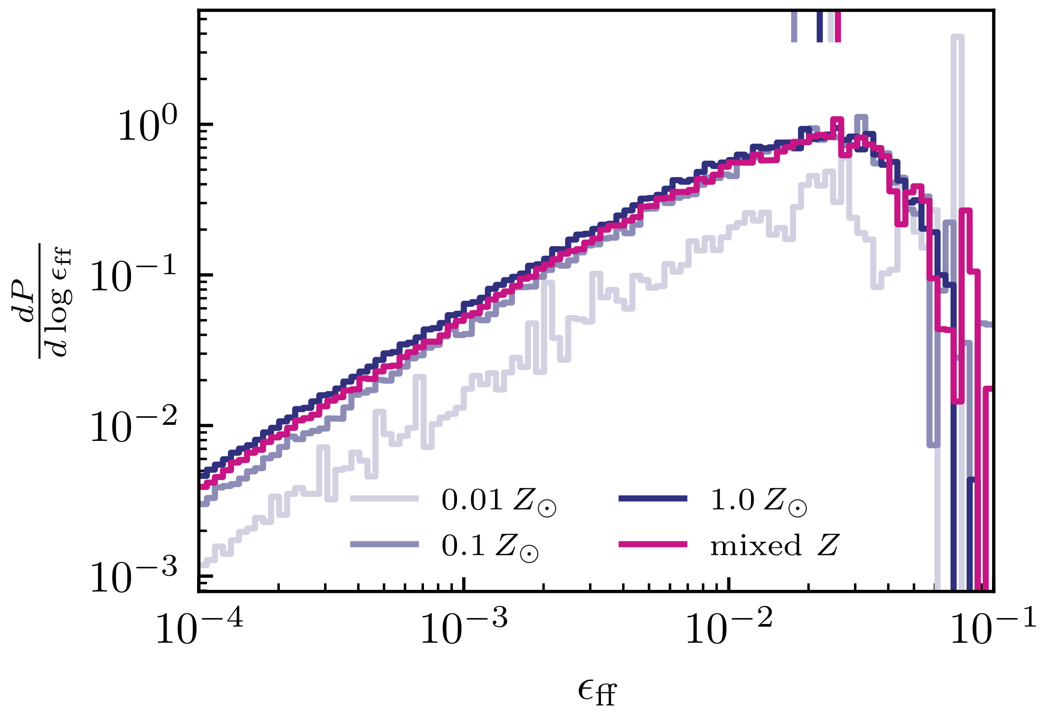
Run state-of-the-art sim at different fixed Z; find and model changes in ISM properties with metal abundance



SF driven by presence of cold, dense gas in low Z regime



Simple HI-H_2 model for low Z regime; captures location of transition and change in H2 abundance with metallicity



SFE ~uniform regardless of galaxy/ISM properties due to turbulence/ feedback