Detailed modelling of star formation in a galactic context and its impact on the efficiency of stellar feedback

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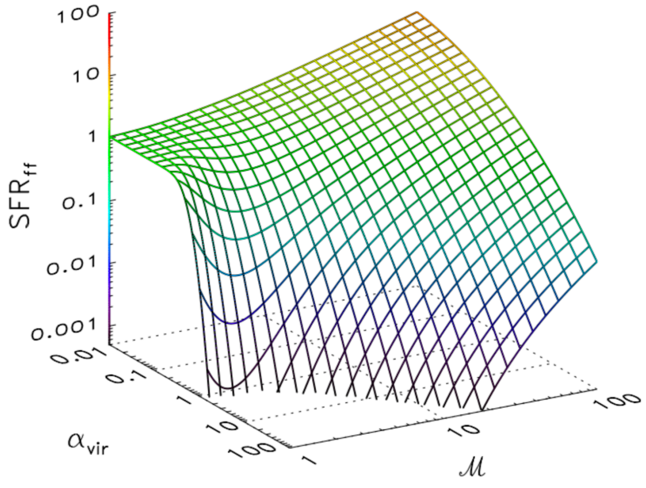
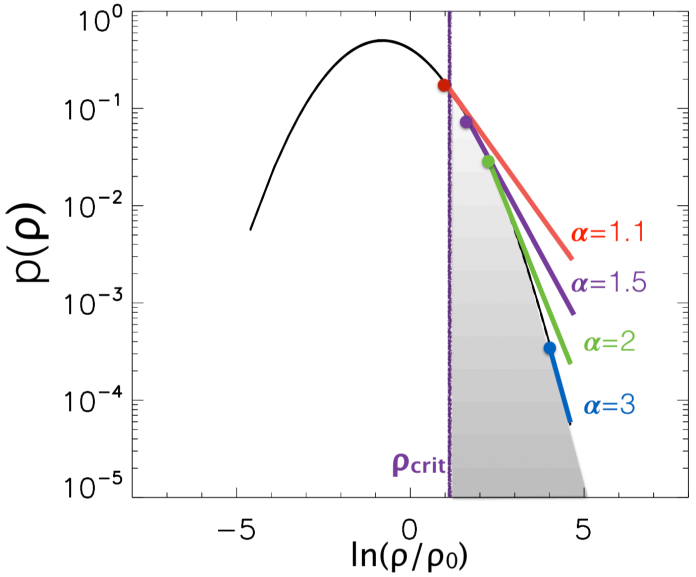
Motivation

- Canonical observed small scale star formation efficiency per freefall time, ϵ_{ff} = 1-2% has typically been adopted in SF prescriptions in simulations
- But what about unusual environments (e.g. MW CMZ, high redshift etc.)
- Meanwhile, star formation community provides various models to explain cloud scale efficiency e.g. gravity, turbulence, feedback regulation etc.
- Recently, upsurge in simulators adopting SF prescriptions based on local turbulent gas properties (see Hopkins+13,14,18, Semenov+16, Kimm+17, Trebitsch+17, Rosdahl+18, Lupi+18…)
- How do the various numerical methods compare with each other?
- **What is the impact on the regulation of galaxy properties by feedback with a varying SF efficiency?**



Krumholz & McKee 2005
(cf Federrath & Klessen 2012)



Burkhart 2018

Star formation

$$t_{\mathrm{ff}} = \sqrt{\frac{3\pi}{32G\rho}}$$

$$\dot{\rho}_* = \epsilon_{\mathrm{ff}} \frac{\rho_{\mathrm{gas}}}{t_{\mathrm{ff}}}$$

Restrict star formation to gas where we are about to lose ability to resolve collapse:

$$M_{\mathrm{Jeans}} < 8m_{\mathrm{cell}}$$

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Estimate level of subgrid turbulence using model inspired by Large Eddy Simulation (LES) approaches (e.g. Schmidt+2014)

$$\frac{\partial K}{\partial t} + \nabla_i \left(v_i K \right) = -P_K \nabla_i v_i + \tau_{ij} \nabla_i v_j - \epsilon$$

We don’t couple this back into the Euler equations as in true LES scheme, only use K in certain star formation prescriptions (see also Kretschmer & Teyssier 2019).

Virial parameter

$$\alpha = \frac{2E}{|W|} = \frac{5\left(\sigma_{\rm 1D}^2 + c_{\rm s}^2\right) R}{GM}$$

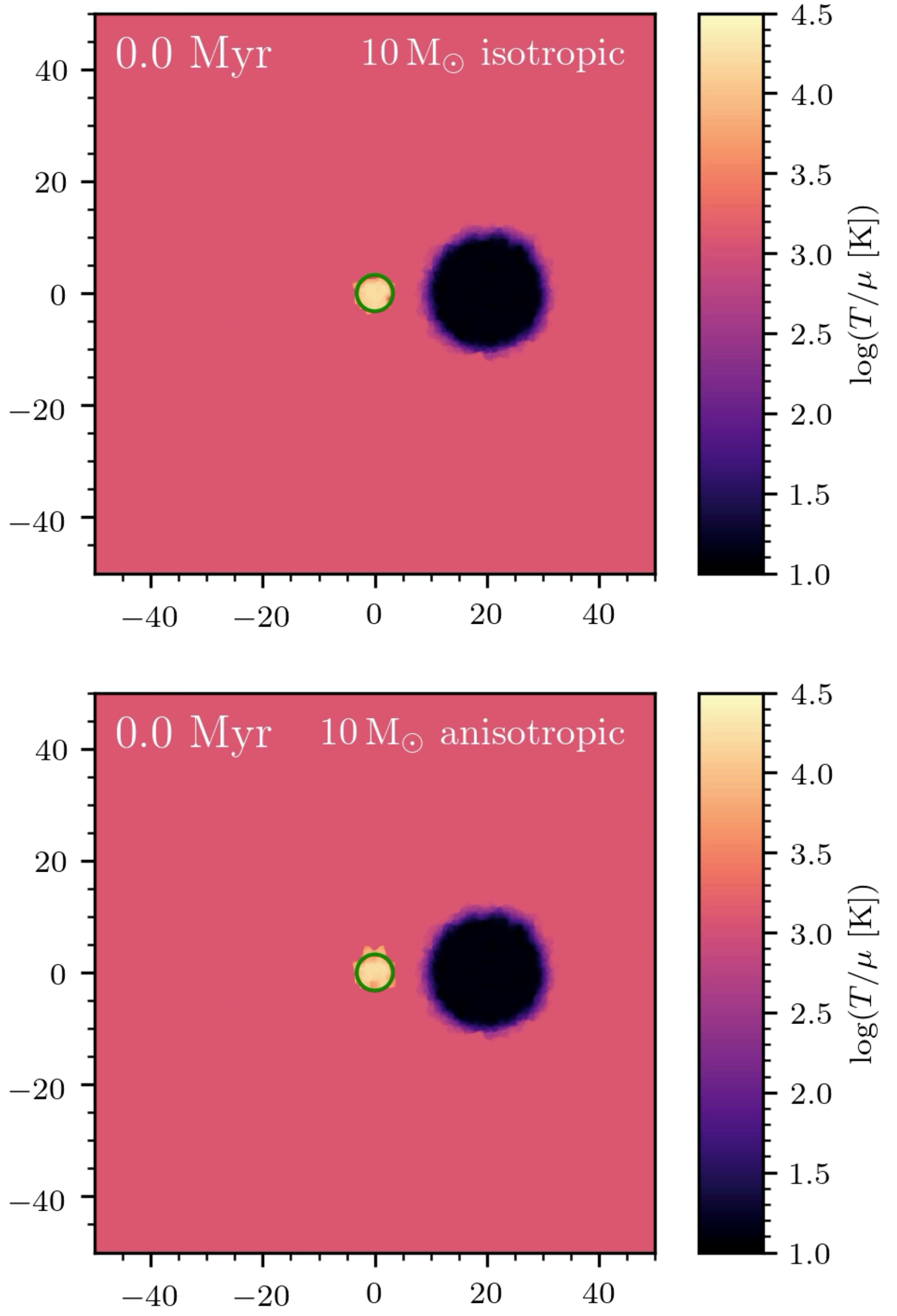
Explicit IMF sampling

- When star particle born, we sample from a Kroupa IMF to determine its content.
- We therefore know explicitly what mass stars make up the star particle
- Feedback from each star particle therefore tied directly to the individual stars that it hosts.
- Given the mass of the star, we have its lifetime, its luminosity and spectrum and SNe yields (Bressan+2012, Lanz & Hubeny 2003, Emerick+2019, Chieffi & Limongi 2004).
- If population averages are taken instead the interstellar radiation field is artificially smoothed out. This overestimates the ability of ionizing radiation to disrupt star forming regions.

Photoionization feedback

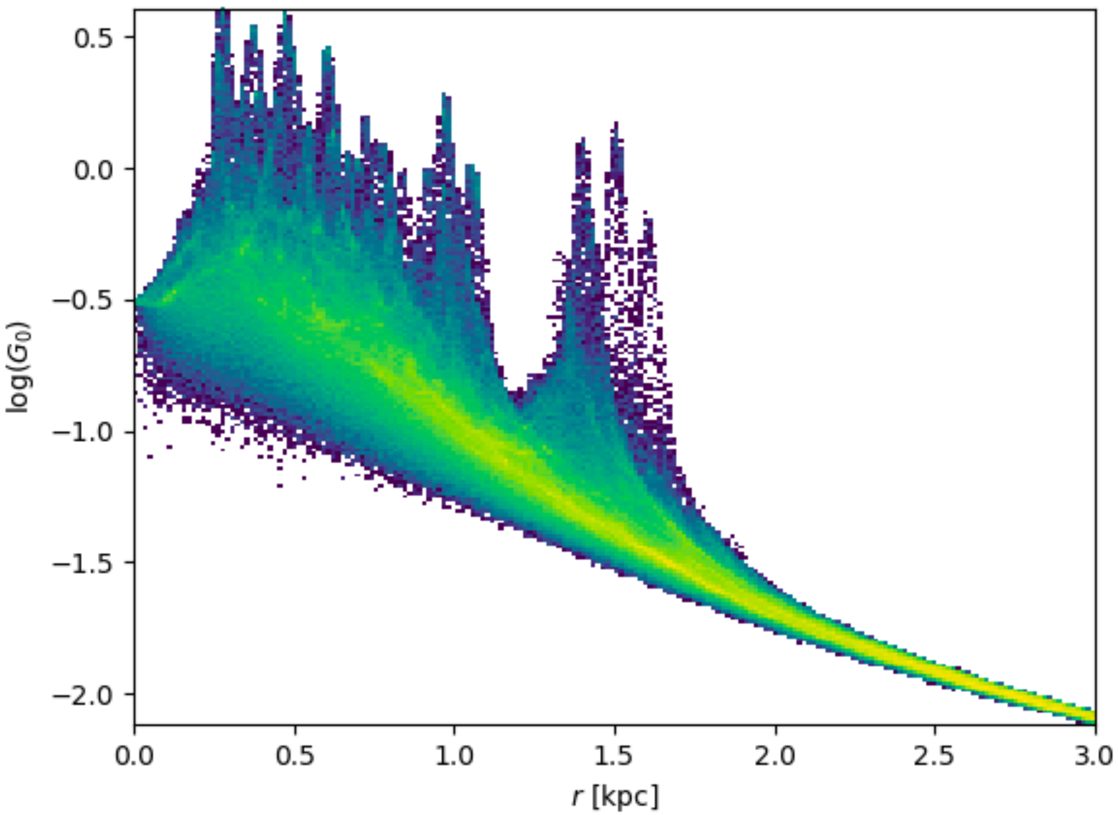
New overlapping Strömgren approximation scheme including angular information

- Tag gas cells around star particle as ionized, searching until recombination rate equals ionizing rate
- Search carried out independently in multiple angular pixels (HEALPix)
  - This avoids the well-known mass biasing effect which leads to anisotropic distribution of photons and unphysical overestimation of the ionization of distant dense clumps
  - Negligible extra computational expense if done right
- Scheme copes with overlapping HII regions
- Temperature floor of 10^4 K imposed on tagged cells



Spatially varying photoelectric heating

- Total flux incident on gas cell by using tree method (same pass as the gravity calculation)
- Local extinction approximation, attenuation by dust at source and receiving location using Jeans length approximation
  - Dust to gas ratio modelled as broken power law with metallicity
- Photoelectric heating efficiency varies as a function of density using a fit to Wolfire+2003 equilibrium curves
  - Efficiency actually a function of temperature and free electron abundance but this cannot be adopted unless sources of free electrons (C^+, cosmic rays, soft X-ray etc.) modelled accurately, otherwise impact efficiency is severely underestimated

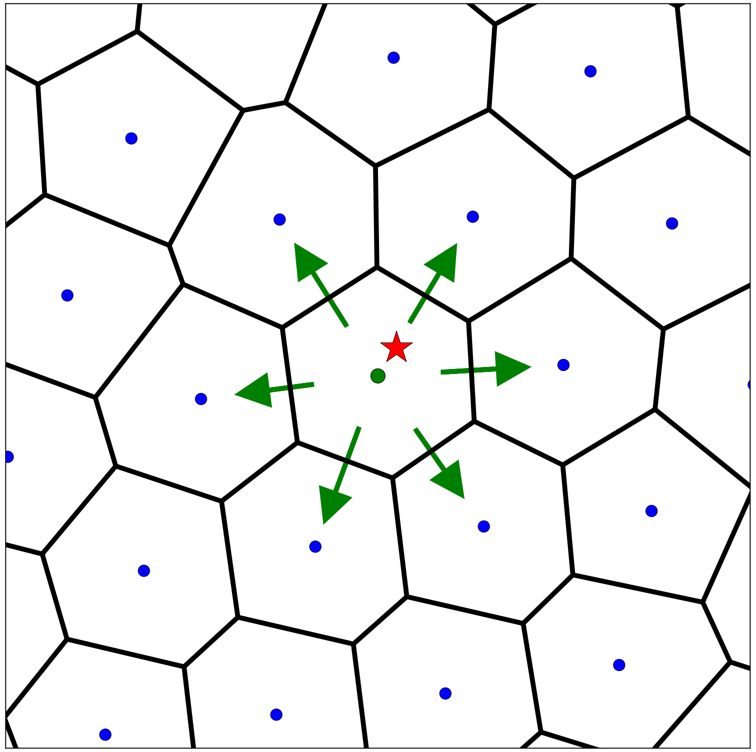


$$n\Gamma_{\rm PE} = 1.3 \times 10^{-24} n\epsilon D G_{\rm eff}\ {\rm erg\,cm^{-3}\,s^{-1}}$$

Supernova feedback

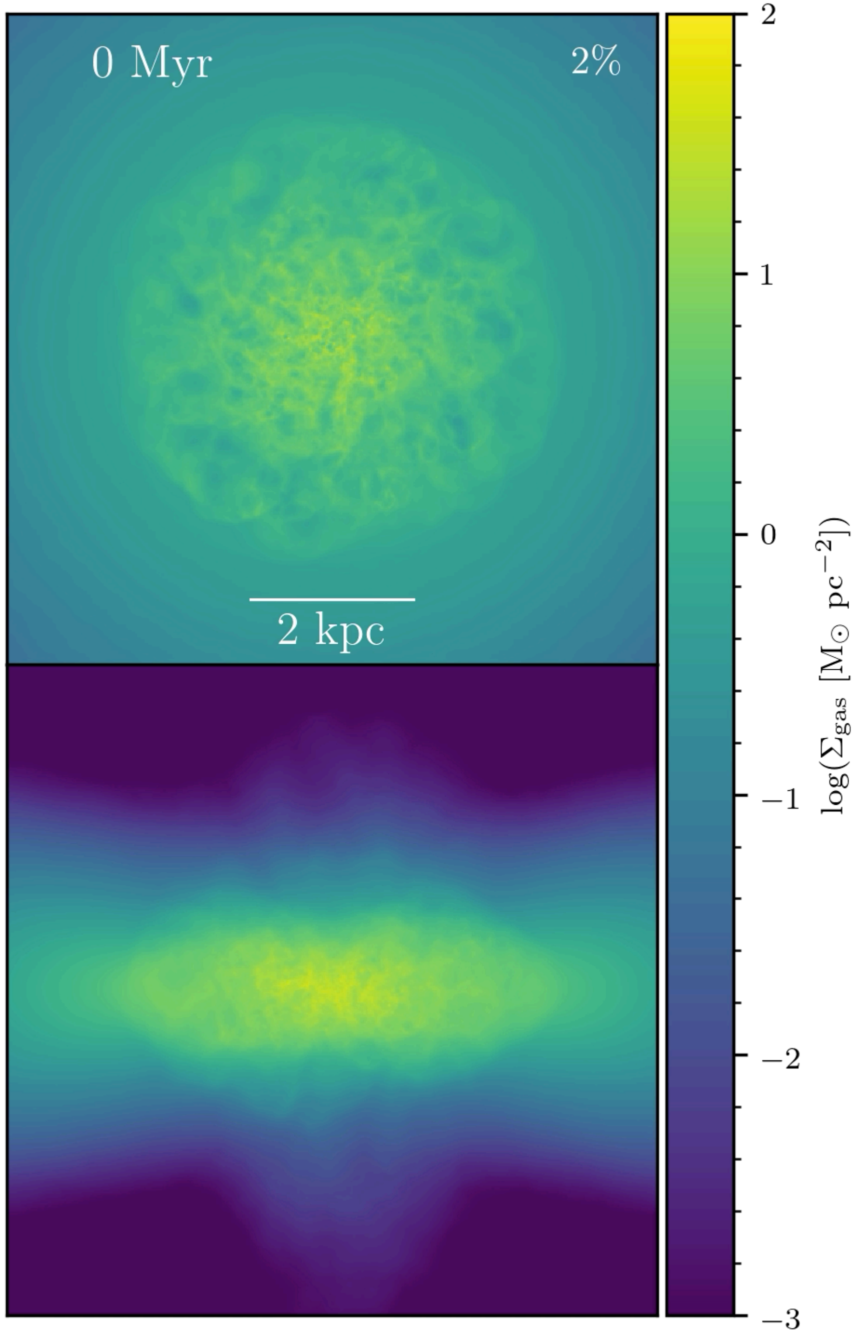
Smith, Sijacki & Shen 2018 MNRAS 478 302
(arXiv:1709.03515)

- “Mechanical” feedback scheme
  - Injects correct momentum appropriate to stage of SNR resolved
  - Novel scheme to guarantee isotropic deposition of mass, metals, energy and momentum
  - No tunable parameters BUT implicit assumptions (e.g. uniform background medium)

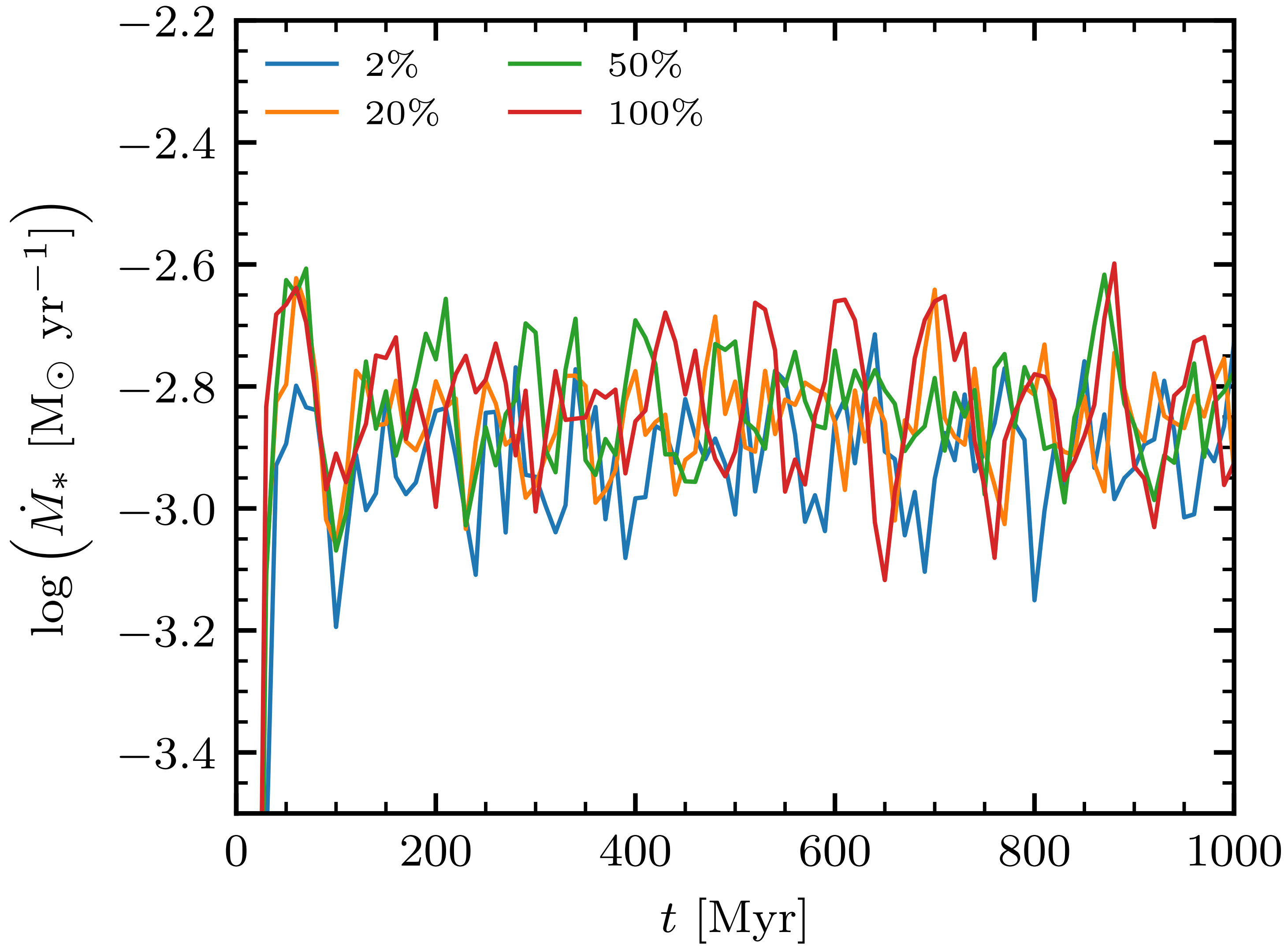


Simulation details

- Isolated dwarf galaxy
- $M_{vir} = 10^{10}\ M_{\odot}$
- $M_{disk,gas} = 7x10^{7}\ M_{\odot}$
- $M_{disk,star} = 10^{7}\ M_{\odot}$
- $r_s = 1$ kpc
- $Z_{Initial} = 0.1\ Z_{\odot}$
- Resolution of 20 $M_{\odot}$ per gas cell
- Cooling from GRACKLE library (B. Smith+2017), primordial and metal



Global Star Formation Rate



- "Steady-state" SFR established
- Very slight trend for higher SFR with higher fixed ϵ_{ff} (more on this later)

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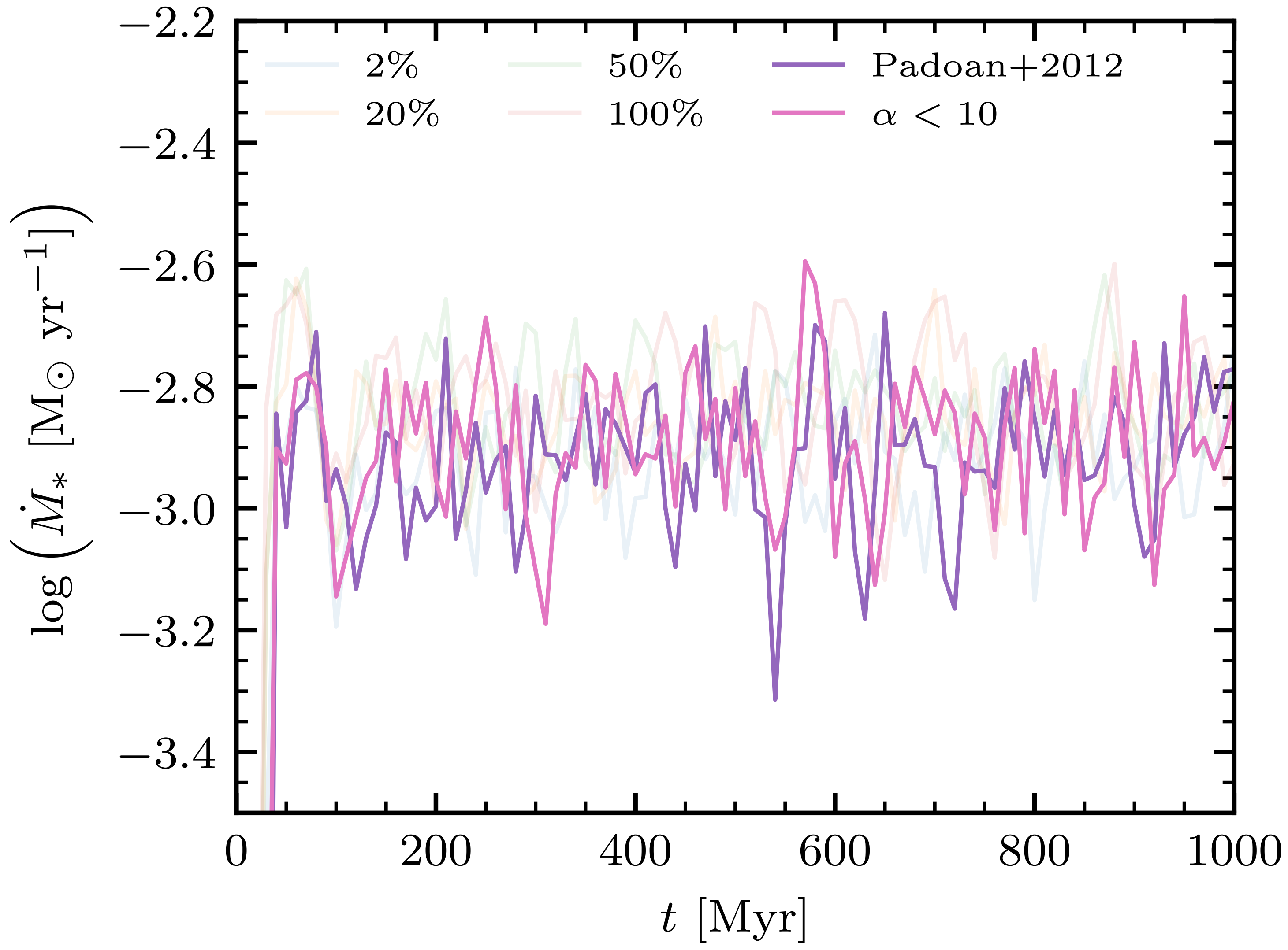
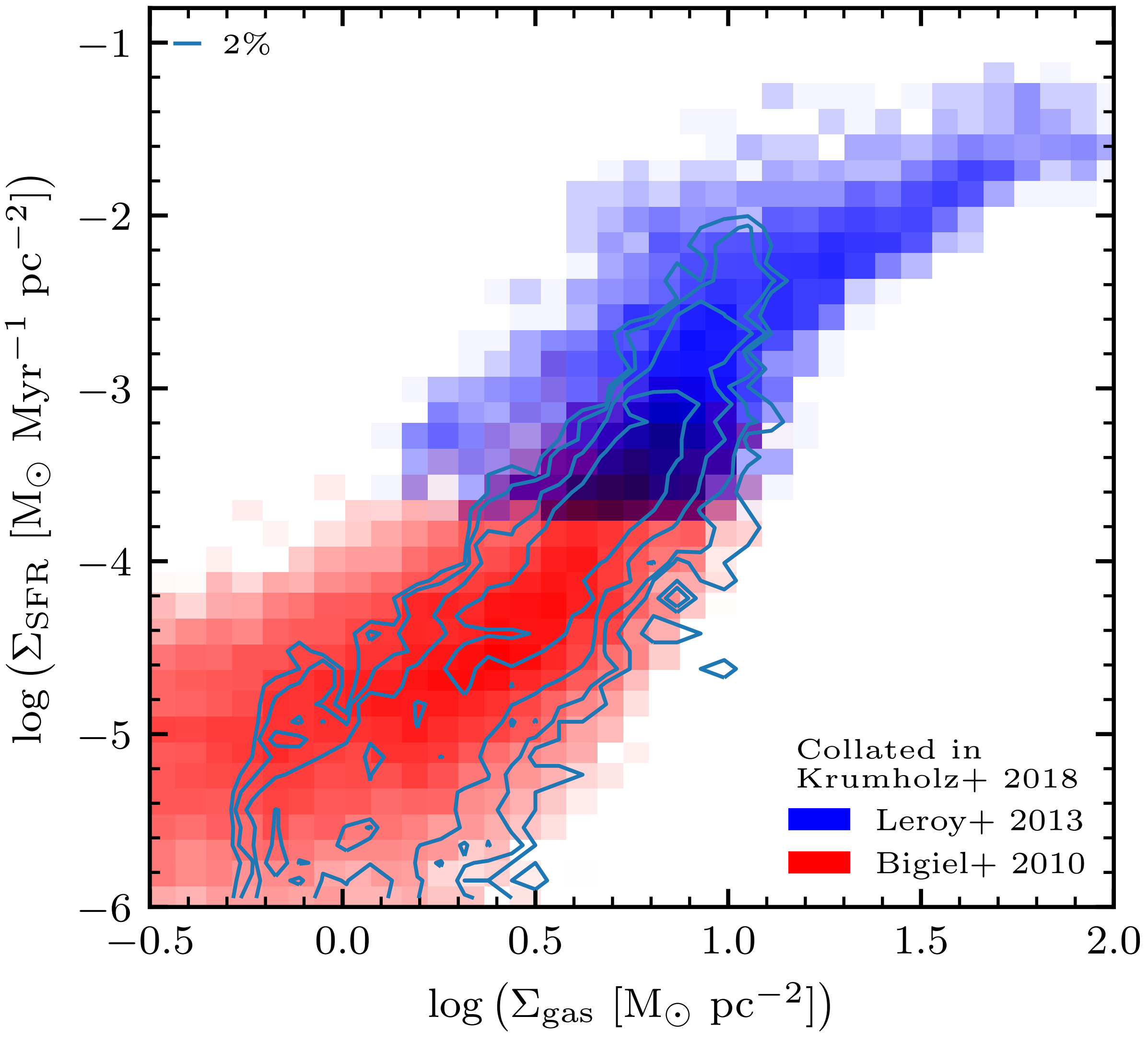


- "Steady-state" SFR established
- Very slight trend for higher SFR with higher fixed ϵ_{ff} (more on this later)
- Models with dependence on turbulence are also consistent w.r.t. global properties but induce differences on small scale properties/relations

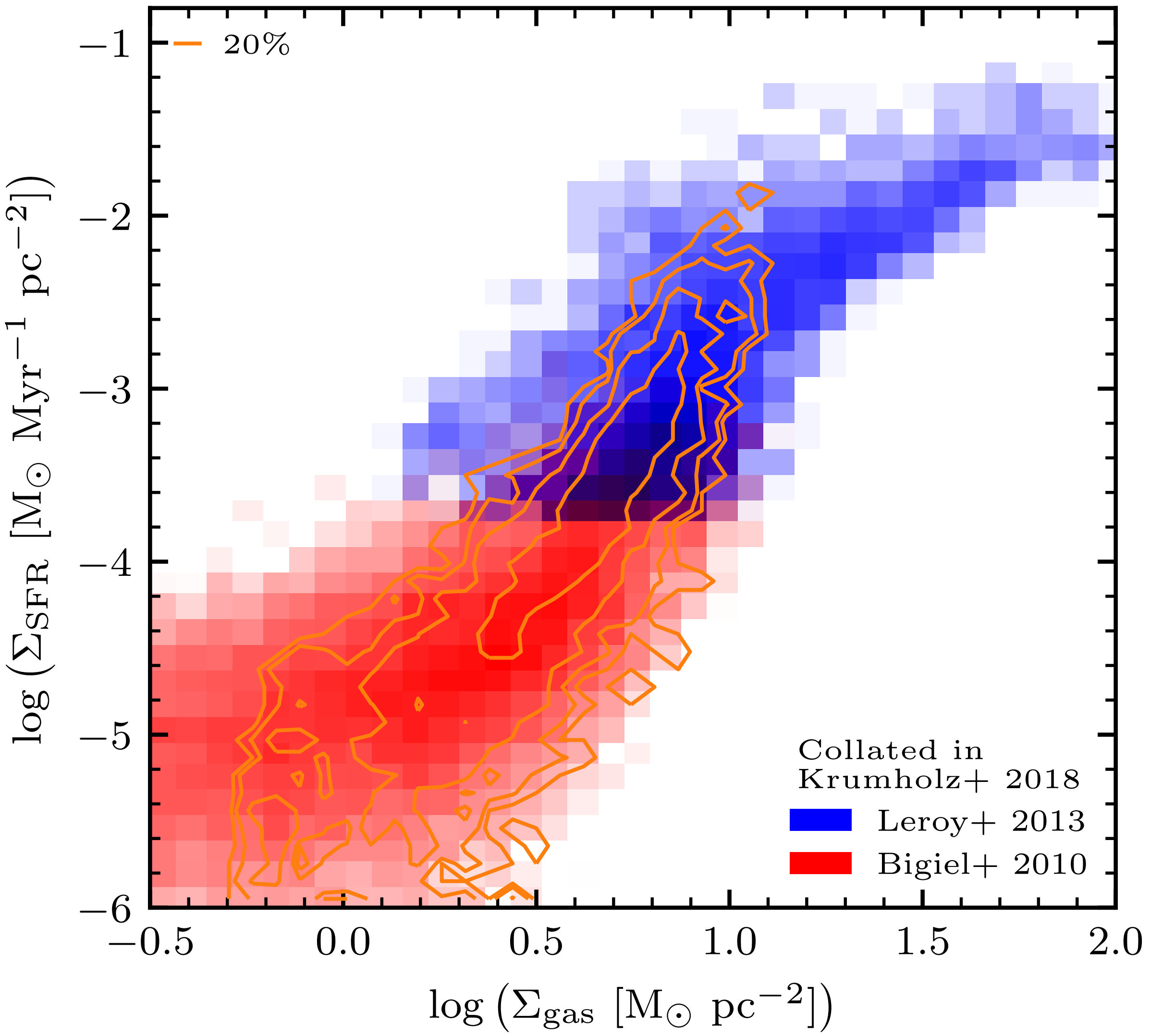
Kennicutt-Schmidt



- All simulations consistent with observations
- Simulations broadly consistent with each other, tendency for slightly higher SFR surface densities with increasing fixed ϵ_{ff}

Contours show 100 pc annuli, measured every 5 Myr from 100 Myr onwards

Kennicutt-Schmidt



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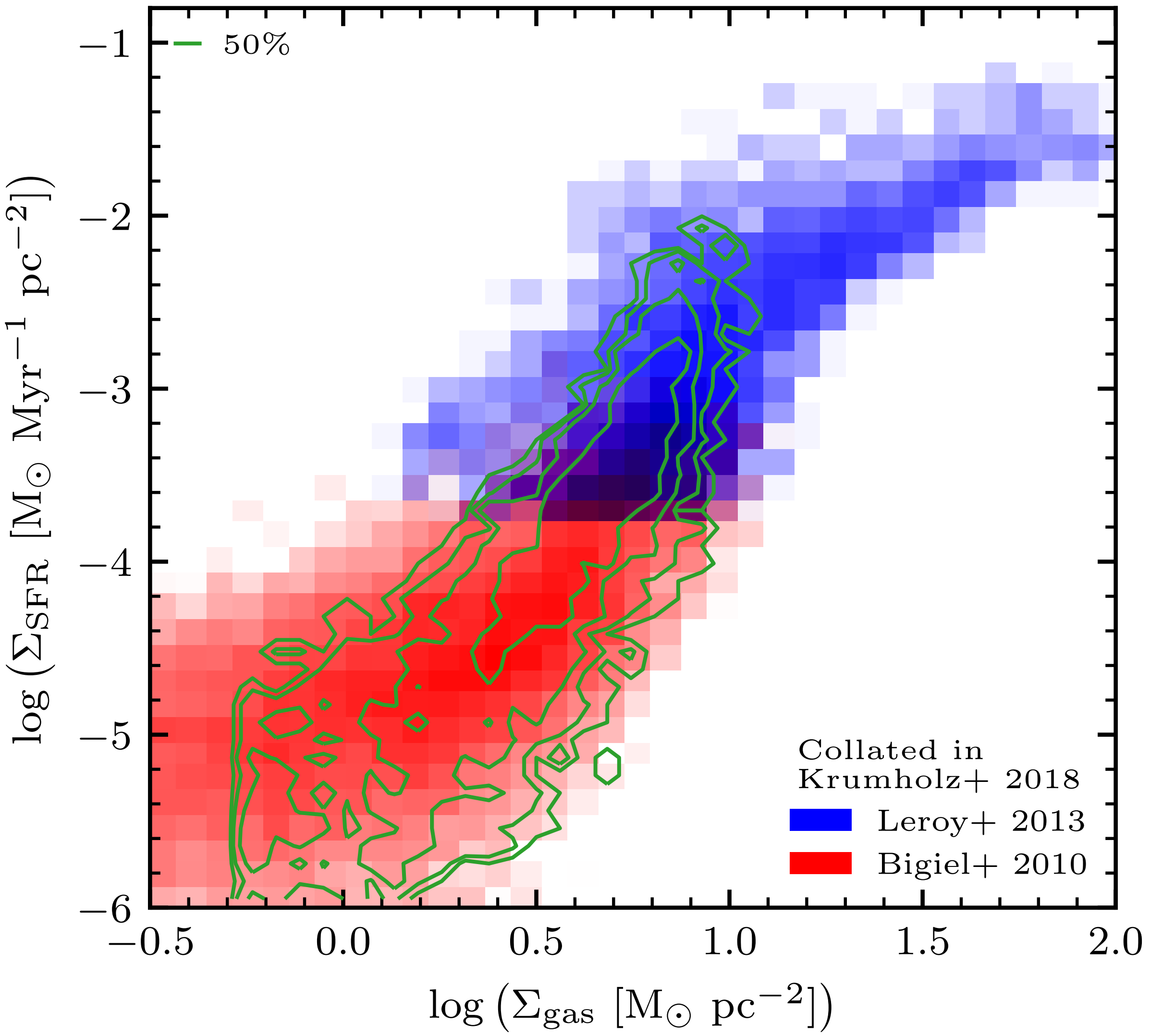

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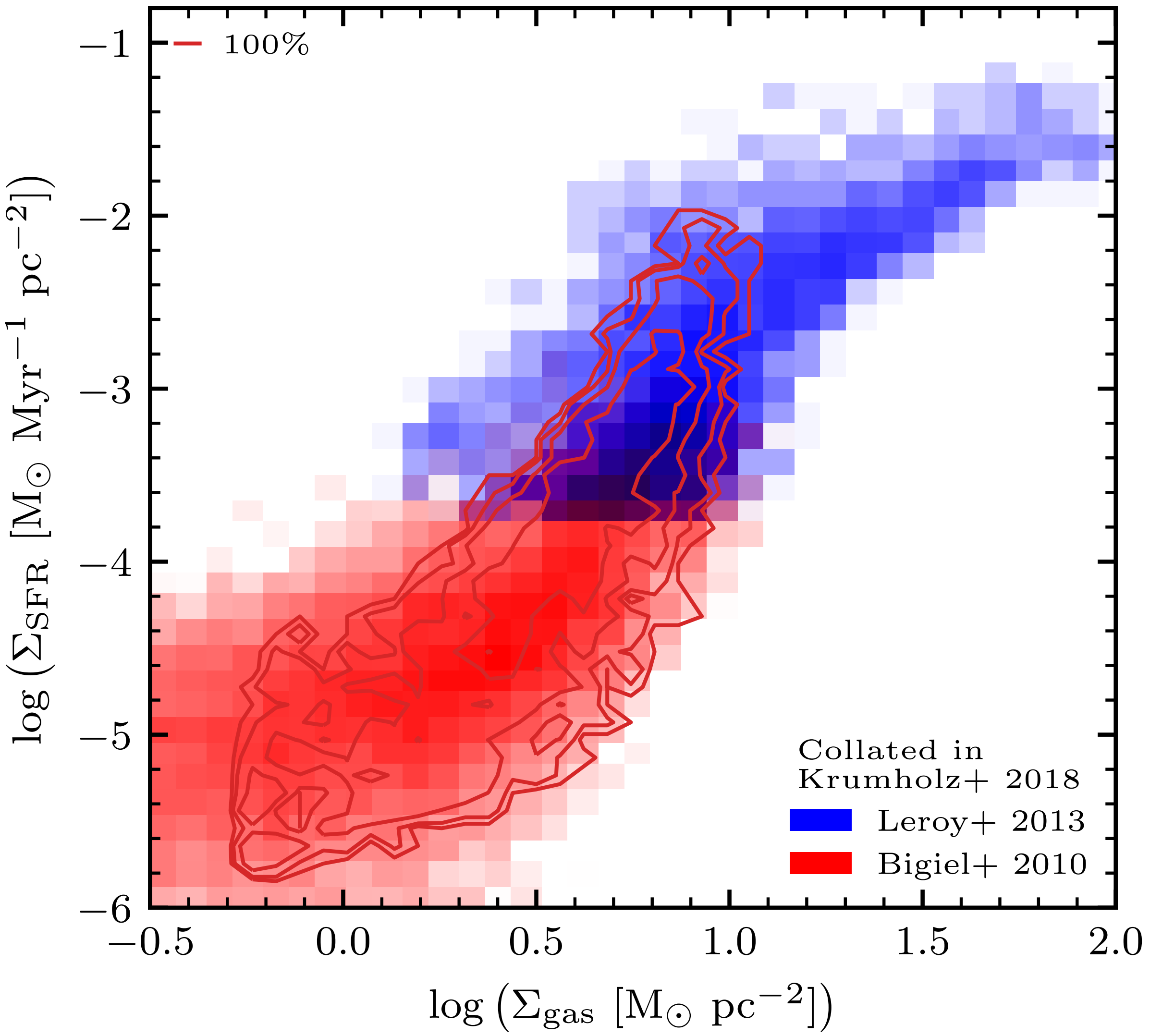

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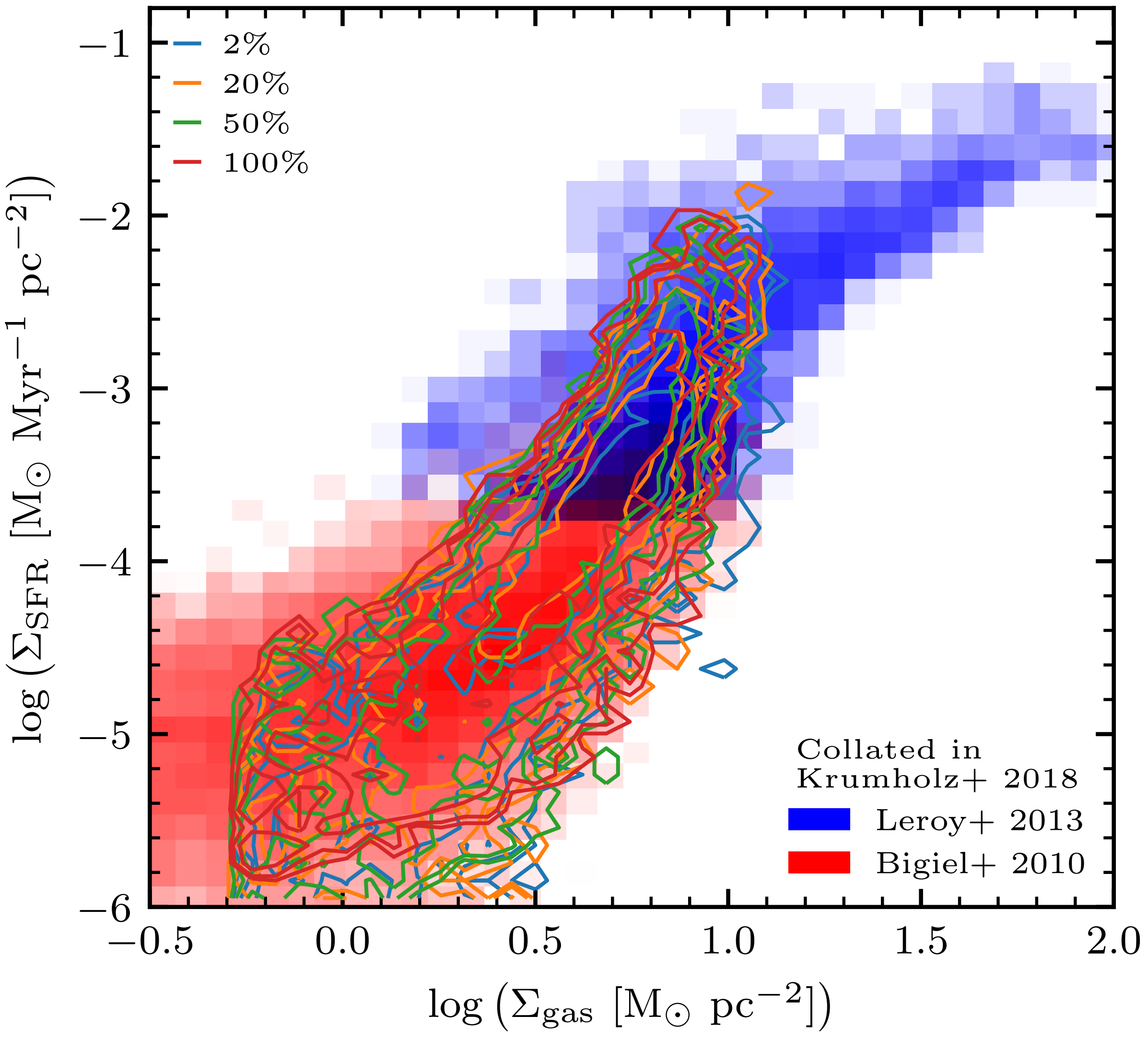

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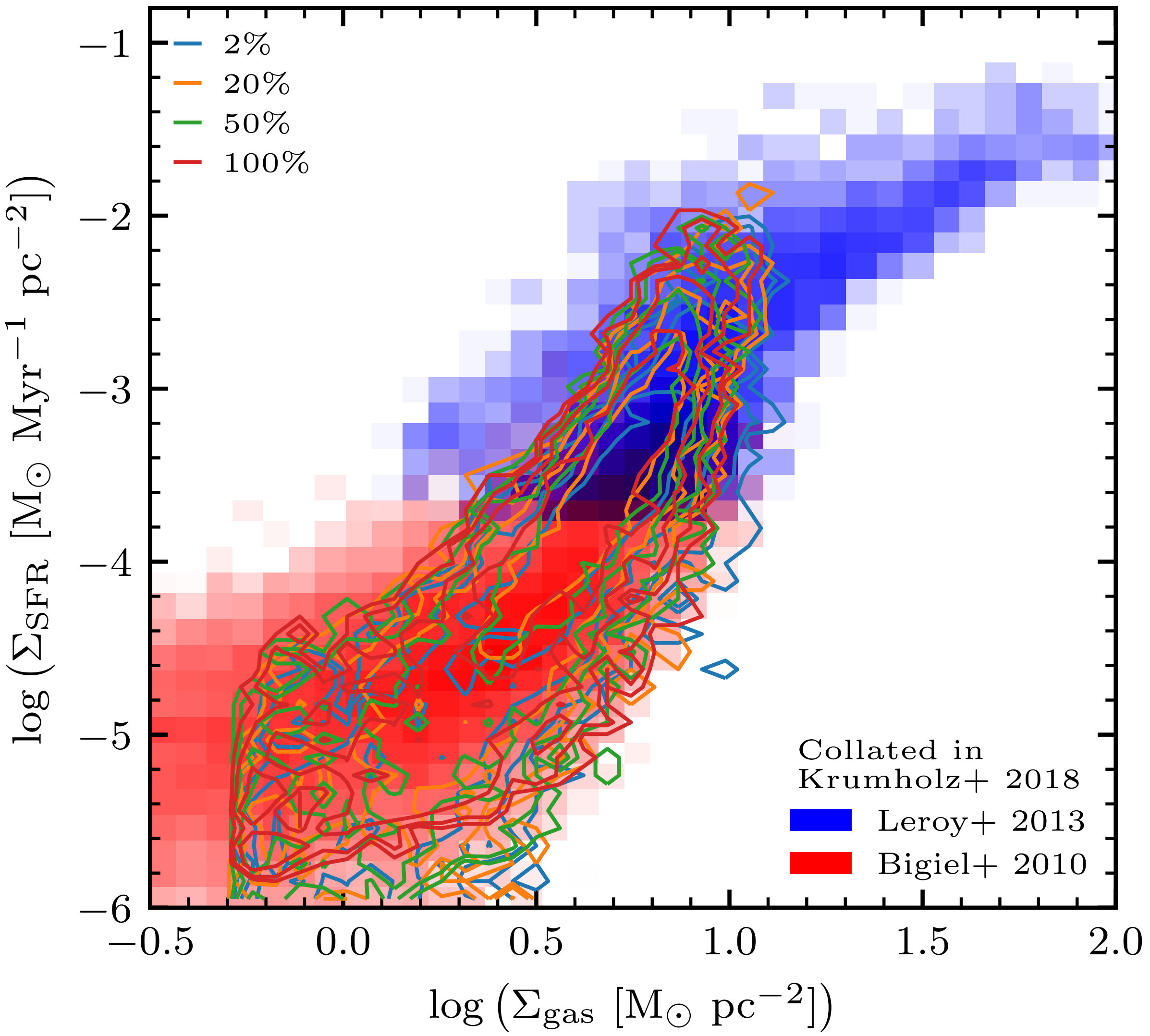


Σ_{SFR} is relatively insensitive to star formation criteria

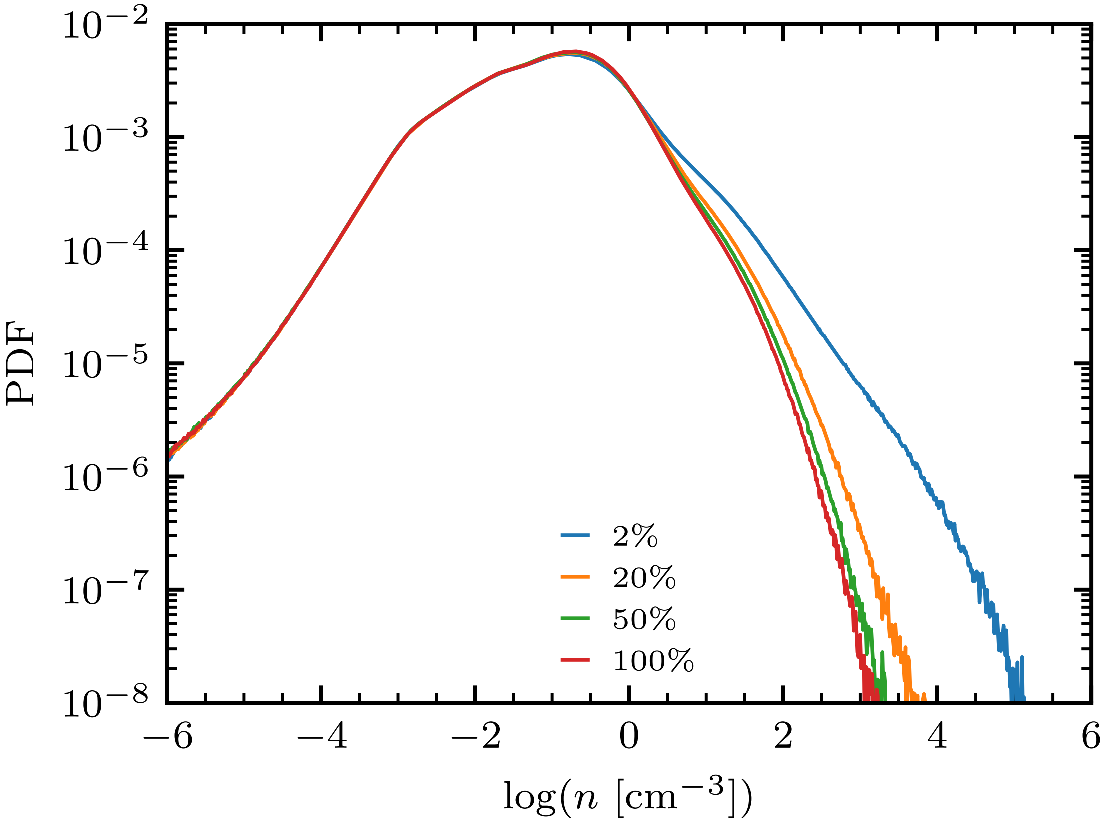
We can expect this for a disk in an equilibrium maintained (dominantly) by feedback

$$W \equiv P_{\mathrm{DE}} = \eta \Sigma_{\mathrm{SFR}}$$

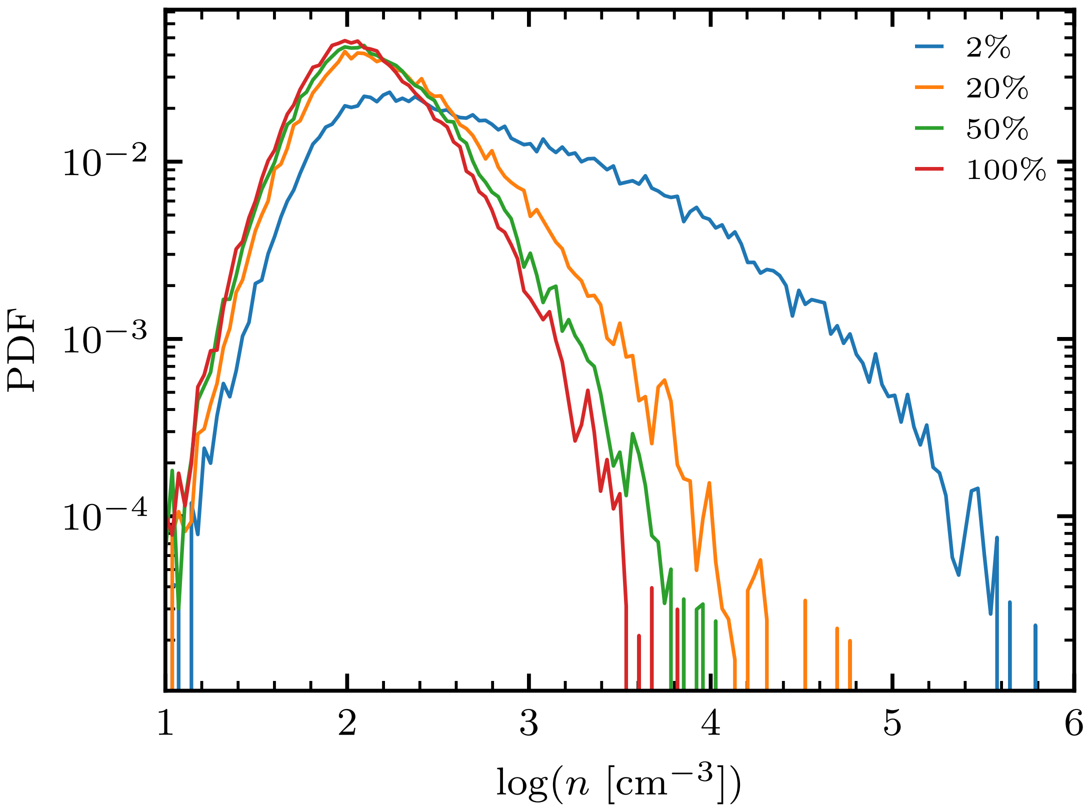
"Feedback yield"

See e.g. Ostriker+2010, Ostriker & Shetty 2011, Kim+2011,2015, Krumholz 2017,2018

Density of all gas



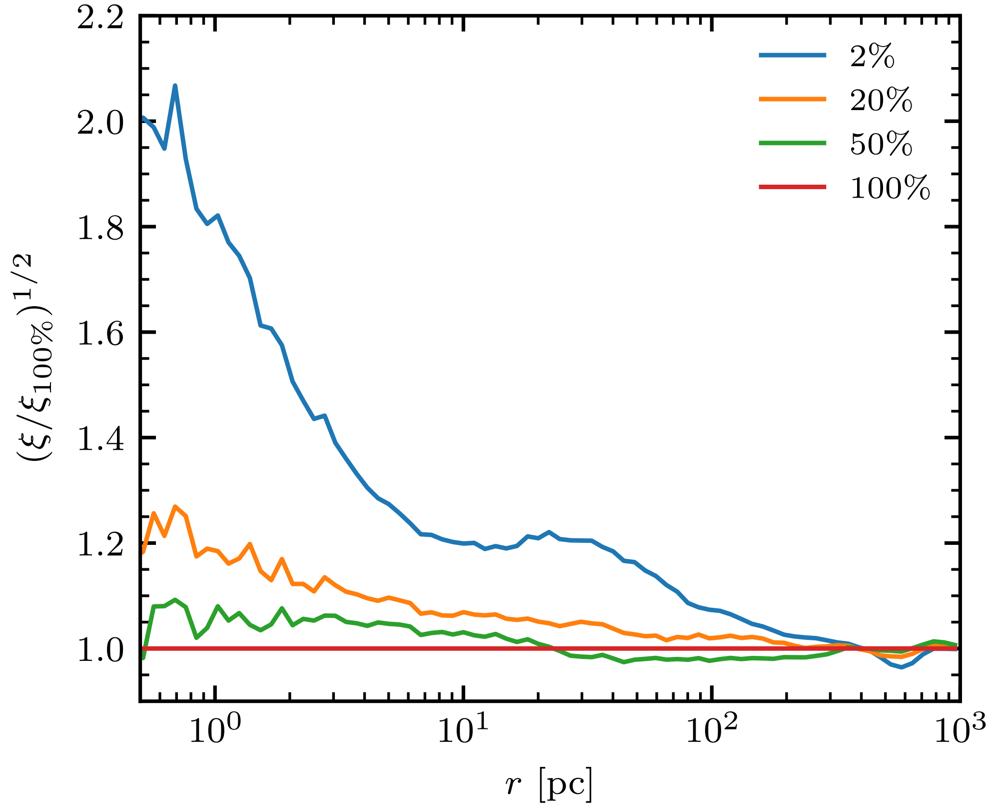
Density of gas where star particle created



Stacked from 100 Myr onwards

Lower local star formation efficiency means more dense gas

Relative clustering of stars < 40 Myr



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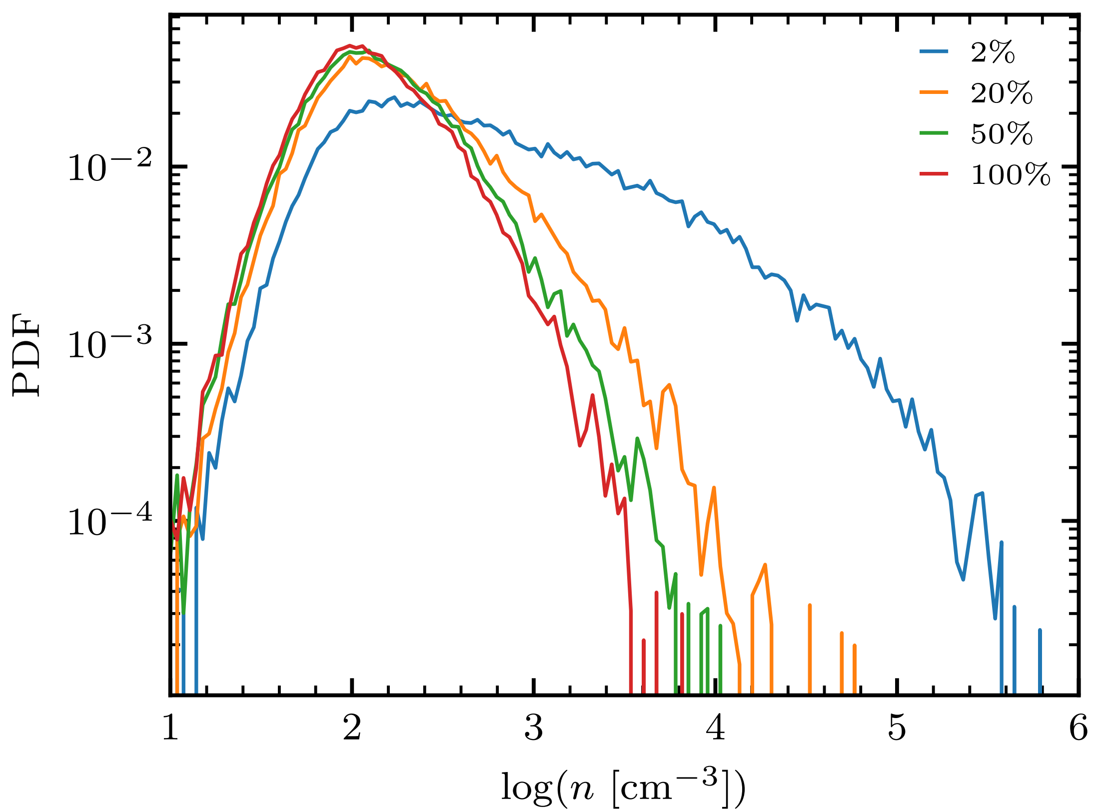
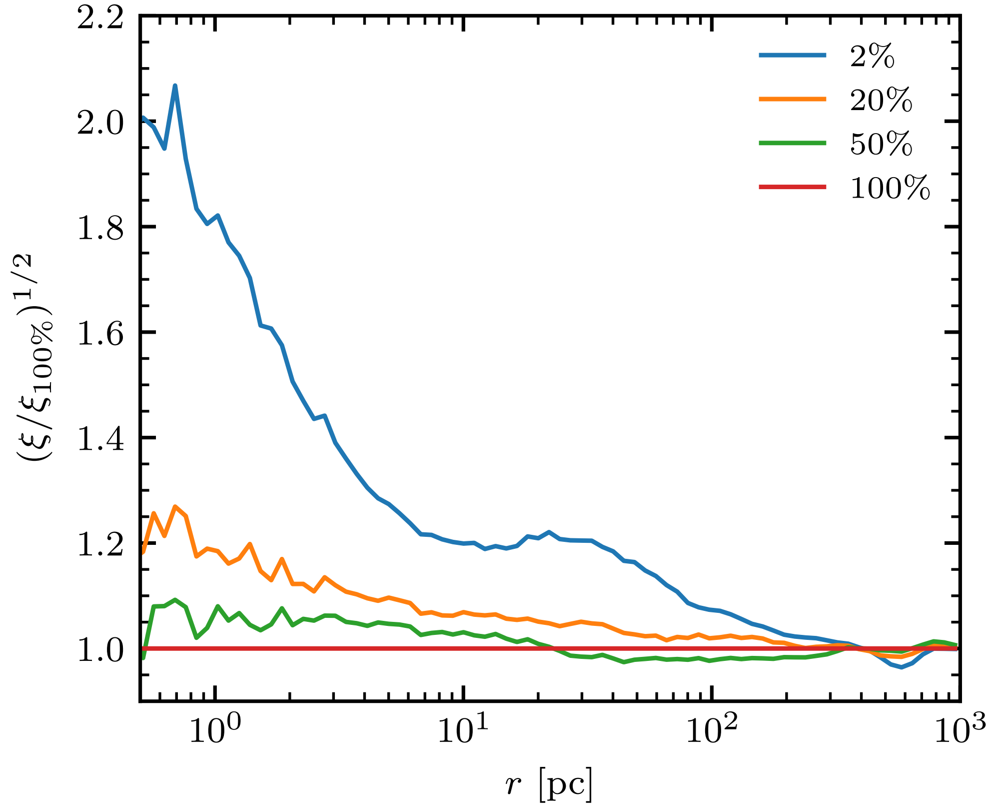


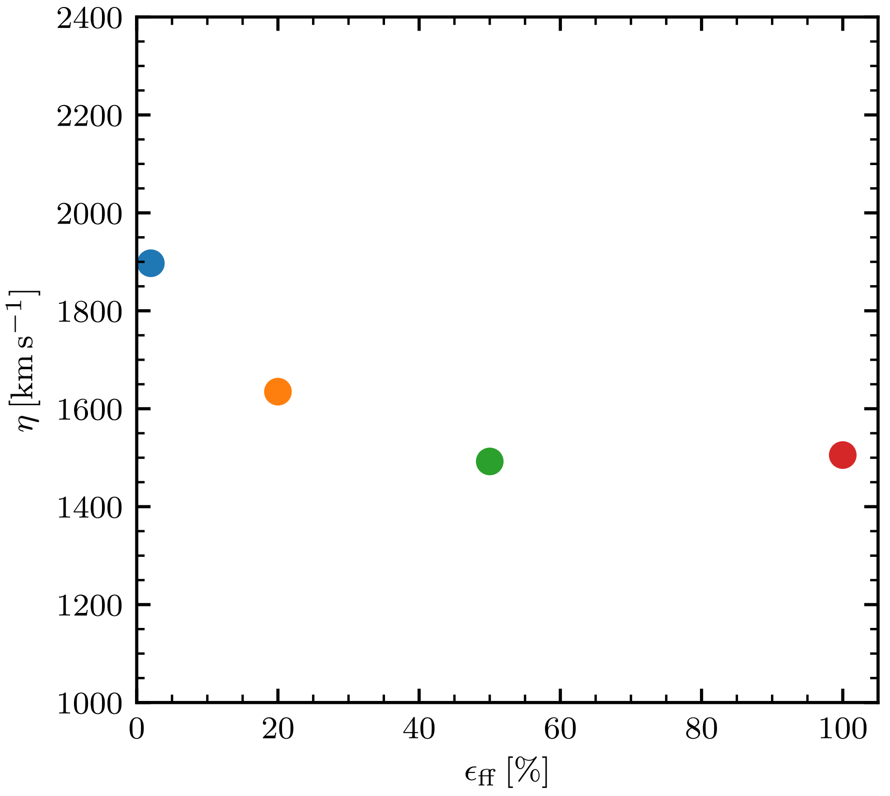
Lower local star formation efficiency increases clustering of stars

Clustered SNe more efficient at driving turbulence and winds
(see e.g. Sharma+2014, Fielding+2017b,2018, Yadav+2017)

Relative clustering of stars < 40 Myr



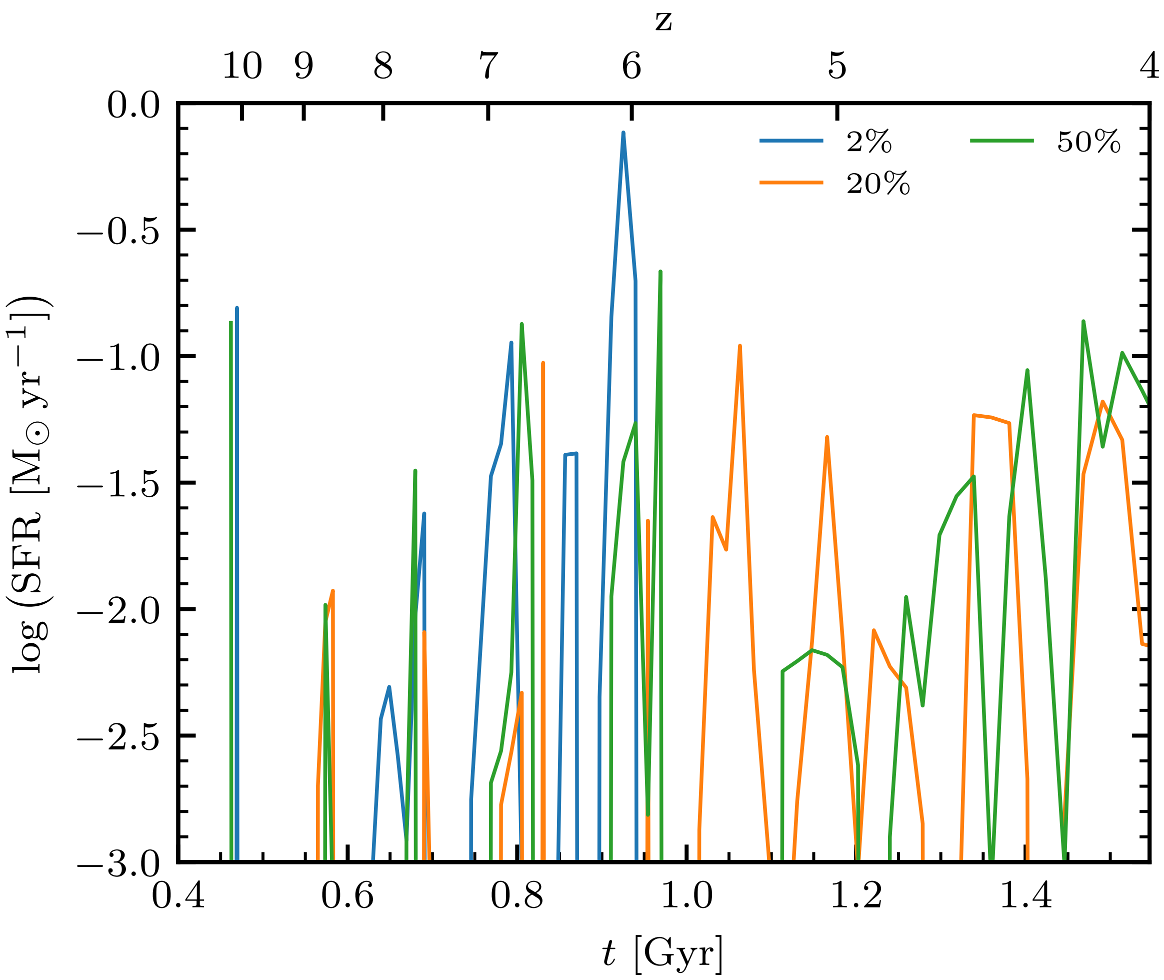
Feedback yield

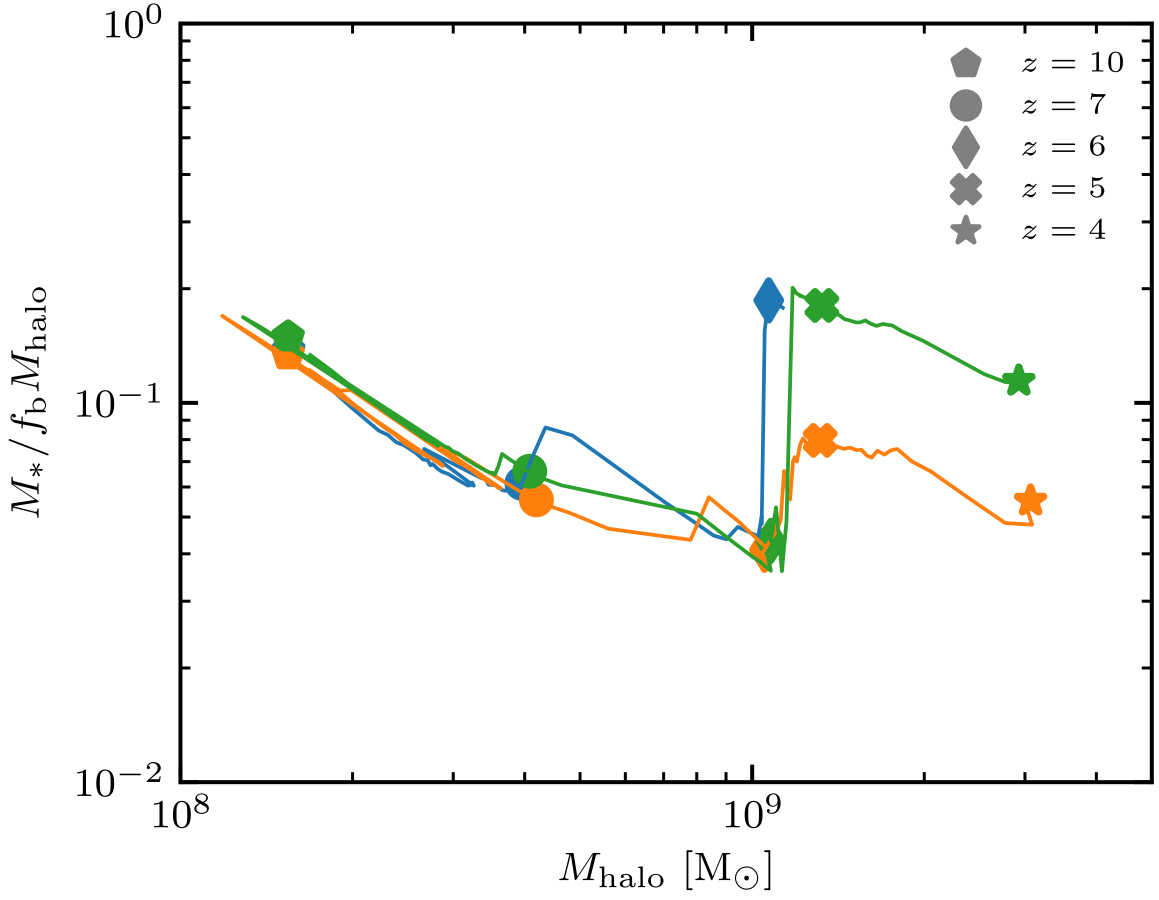


Feedback yield is higher for lower SF efficiency, around 25% effect

$$\eta = \frac{P_{\mathrm{DE}}}{\Sigma_{\mathrm{SFR}}}$$

Work in progress: cosmological zoom-ins of z = 0 10^{10} $M_\odot$ isolated dwarfs





- In cosmological environment, at early times the galaxy is not near equilibrium configuration.
- Star formation is dominated by bursts.
- Differences in star formation prescription are amplified because self-regulation is not possible in the same way as in the settled disk case. These are extremely chaotic systems.
- See also **Smith, Sijacki & Shen 2019 MNRAS 485 3317 (arXiv:1807.04288)**

Summary

- For an idealized disk galaxy that is regulated by feedback, global galaxy properties (SFR, Σ_{SFR}, morphologies etc.) depend only weakly on small scale star formation efficiency adopted.
- However, local SF efficiency impacts details of small scale ISM structure. SF regions collapse to higher densities, stars more clustered for lower SF efficiency.
- Increased clustering results in increased feedback yield, but marginal effect (~25%)
- When star formation is extremely bursty (i.e. far from equilibrium in low mass/high redshift) small scale star formation efficiencies can have large impact on global galaxy properties