Effect of feedback on the normalization and slope of the molecular Kennicutt-Schmidt relation

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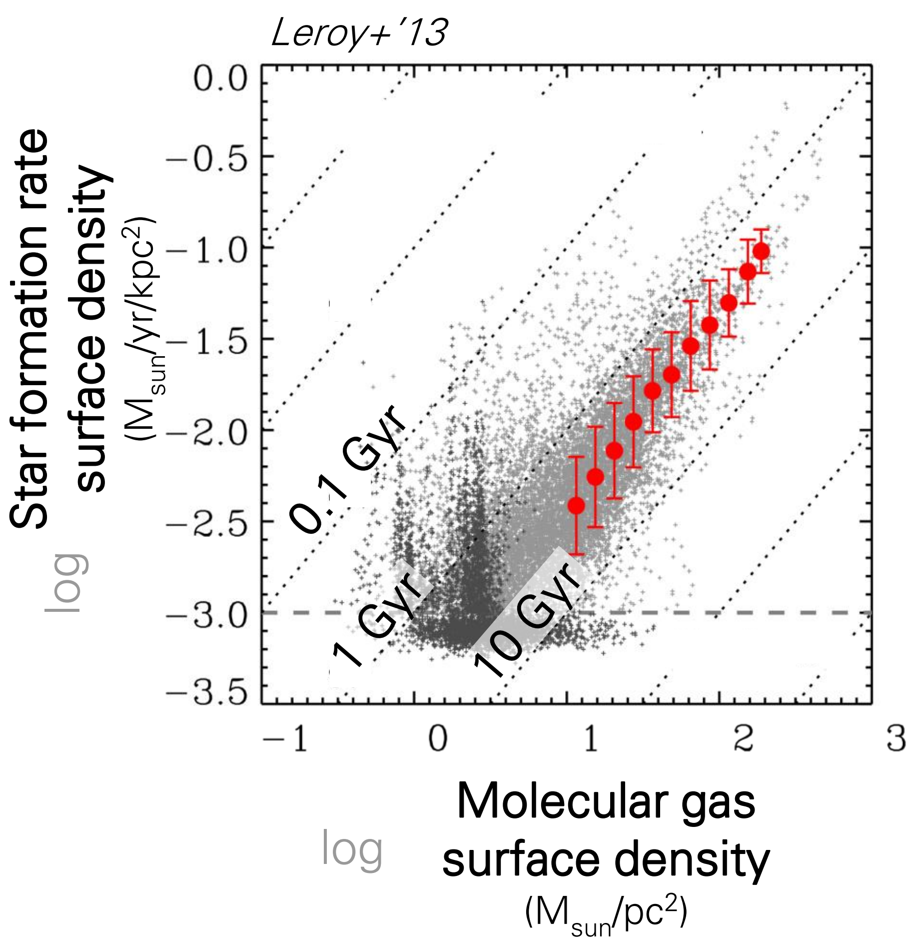
Molecular Kennicutt-Schmidt relation on ~kpc scale



Depletion time of molecular gas on ~kpc scale:

$$\tau_{\mathrm{H}_2} \equiv \frac{\Sigma_{\mathrm{H}_2}}{\dot{\Sigma}_\star} \approx 2 \pm 1 \text{ Gyr}$$

- Surprisingly long

> dynamical timescales in ISM ~10-30 Myr

> depletion times in SF regions ~50-300 Myr

- Independent of molecular gas surface density

e.g., $\tau \sim \Sigma^{-0.5}$ is expected
if self-gravity alone regulates SF

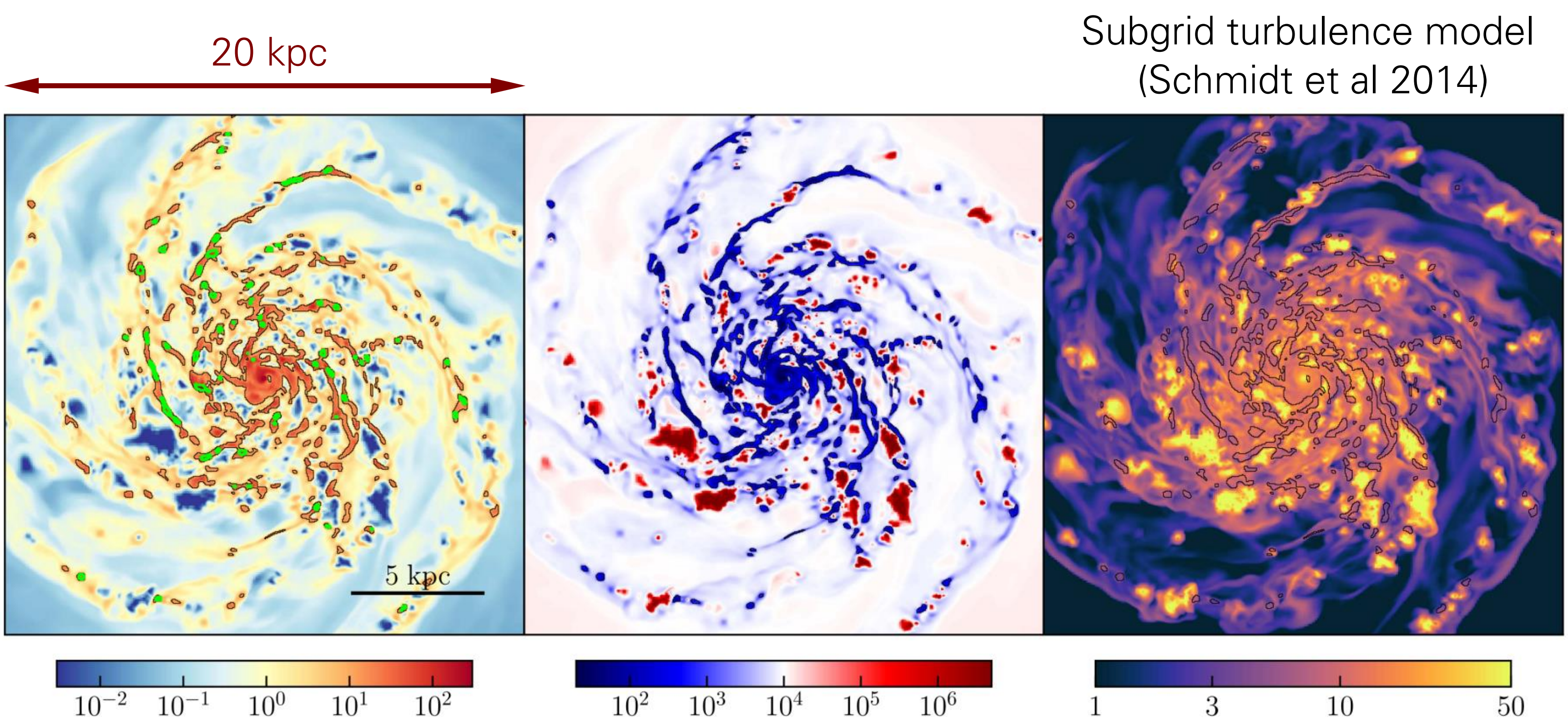
Wong & Blitz '02; Bigiel+'08,'11; Leroy+'08,'13; Genzel+'10,'15; Bolatto+'17; Utomo+'17; Colombo+'18

Simulations of ~L_* isolated disk galaxy

AGORA ICs | 40 pc resolution | ART code

Star formation prescription motivated by models of SF in supersonic turbulence

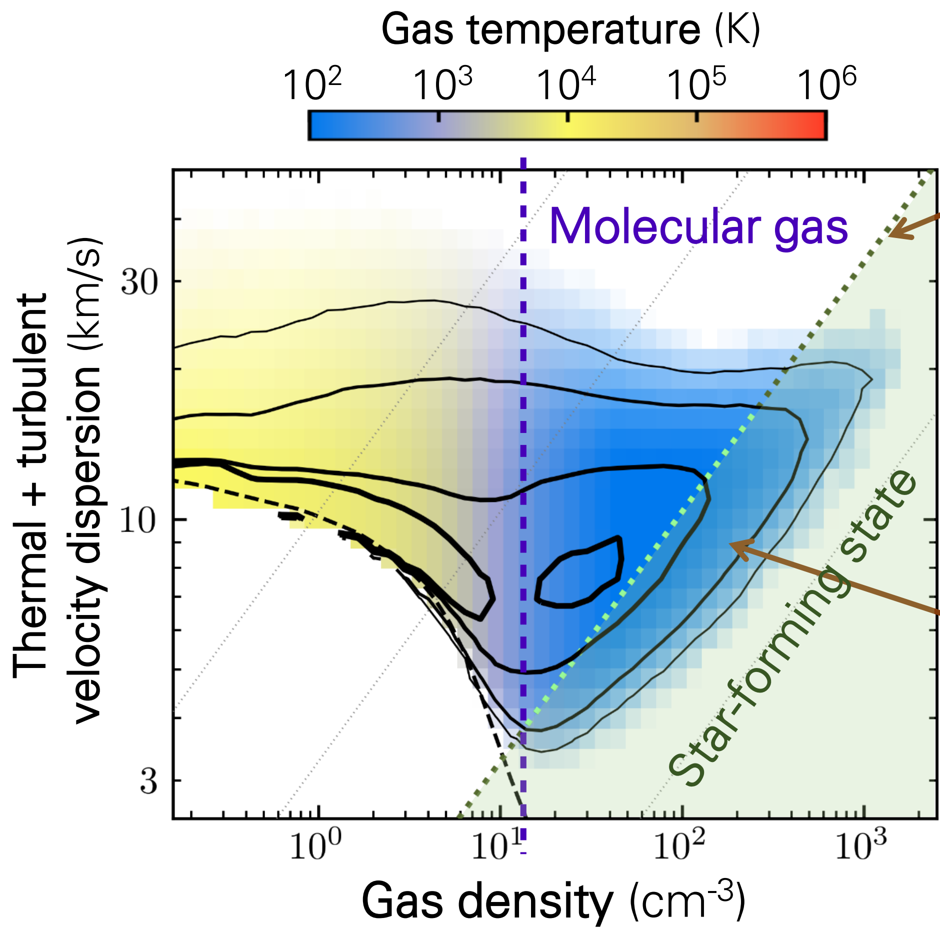
Feedback calibrated against supernova remnant simulations (Martizzi et al 2015)



Gas density (cm^{-3}) | **Temperature** (K) | **Turbulent velocity** (km/s)

Semenov, Kravtsov, Gnedin 2016 ApJ 826, 200; 2017 ApJ 845, 133; 2018 ApJ 861, 4

Star formation and feedback on resolution scale



Star formation criterion:

$$\alpha_{\rm vir} < 10$$

$$\alpha_{\rm vir} \approx 9.35 \frac{(\sigma_{\rm tot}/10\,{\rm km\,s^{-1}})^2}{(n/100\,{\rm cm^{-3}})(\Delta/40\,{\rm pc})^2}$$

Local star formation rate:

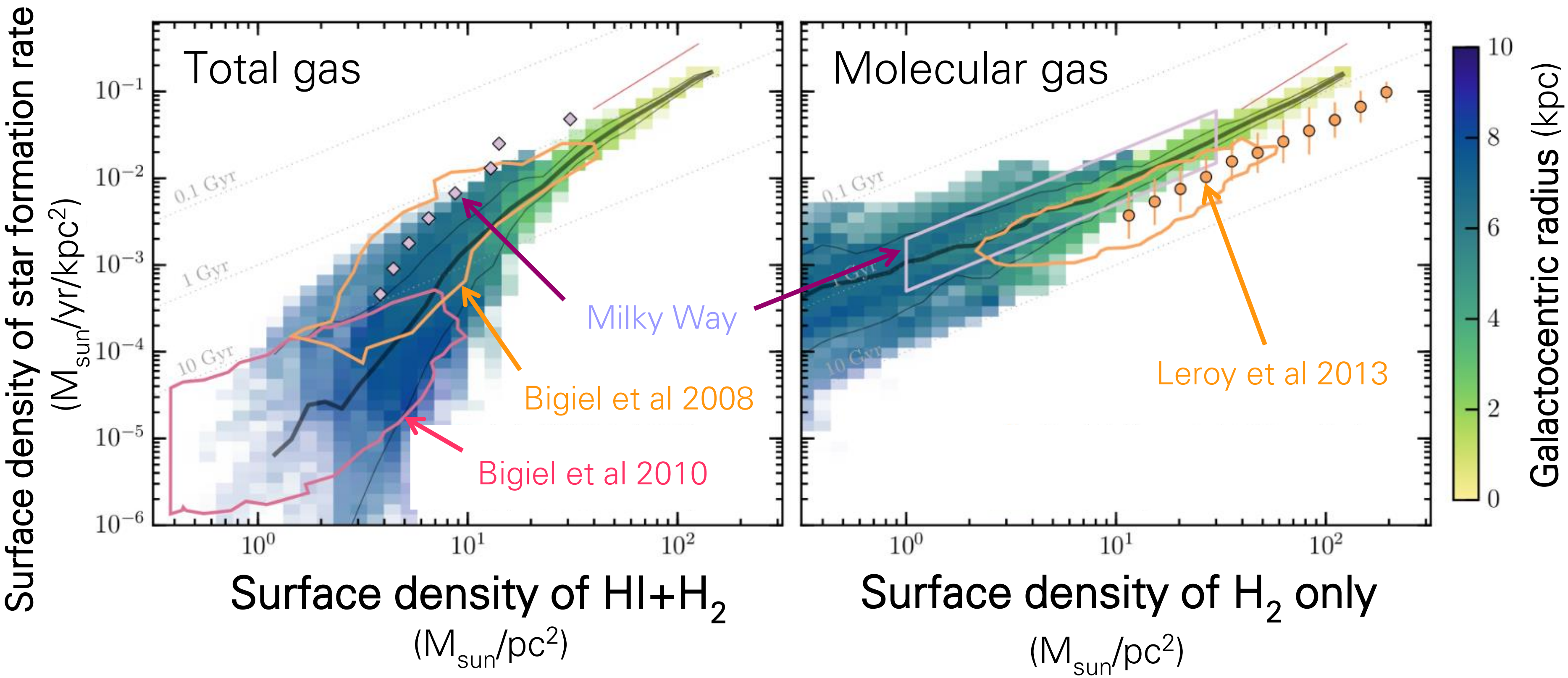
$$\dot{\rho}_\star = \epsilon_{\rm ff} \frac{\rho}{t_{\rm ff}} \propto \rho^{1.5}$$

$$\epsilon_{\rm ff} = 1\%$$

Fiducial simulation reproduces Kennicutt-Schmidt relation

- Correct normalization (i.e. long global depletion time)
- For molecular gas the slope is close to linear (despite steeper local relation)

=> Can use simulations to understand the origin of KS normalization and slope

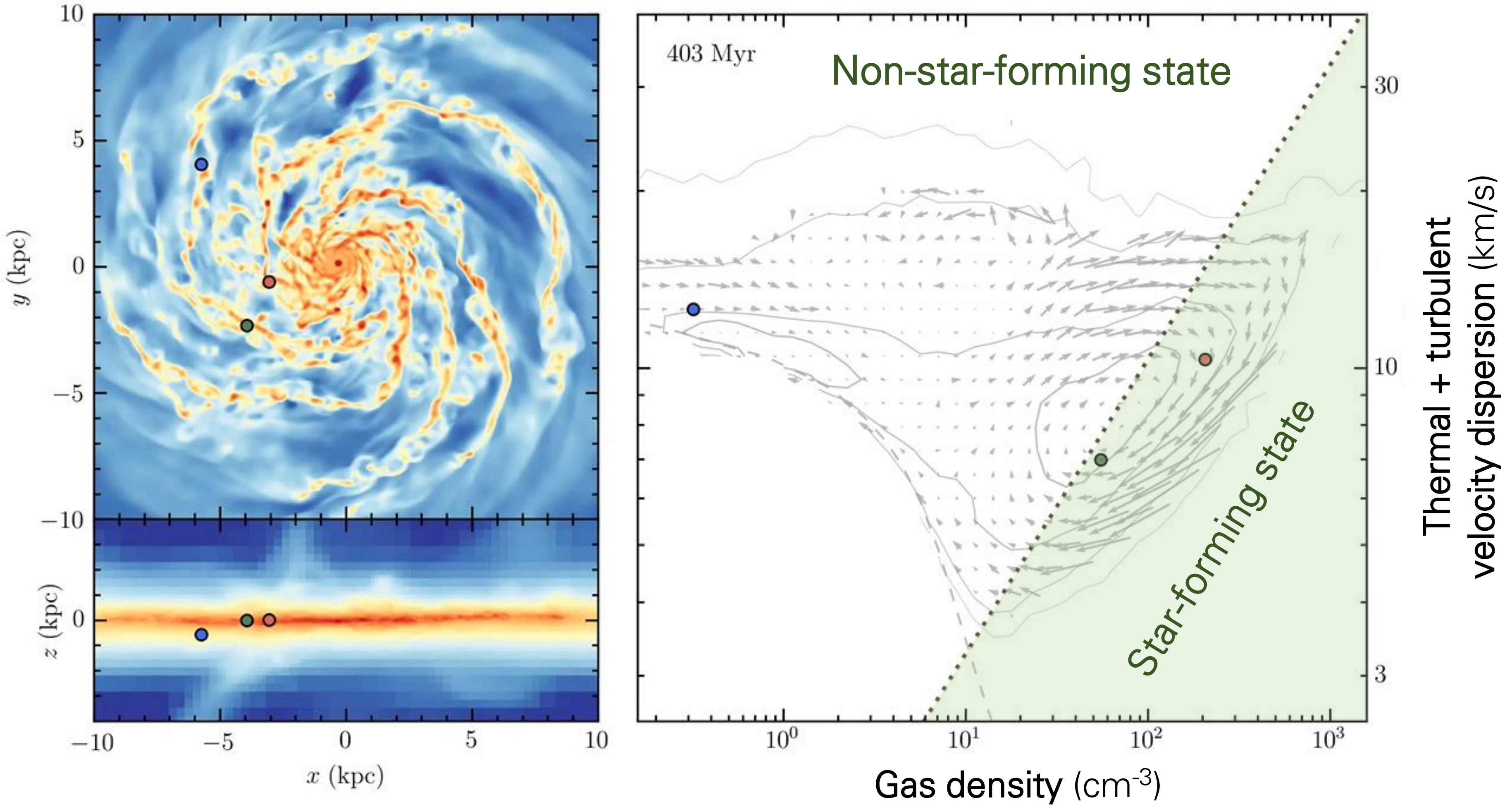


Fiducial SF prescription: $\epsilon_{ff} = 1\%$ and $\dot{\rho}_\star \propto \rho^{1.5}$ in gas with $\alpha_{vir} < 10$

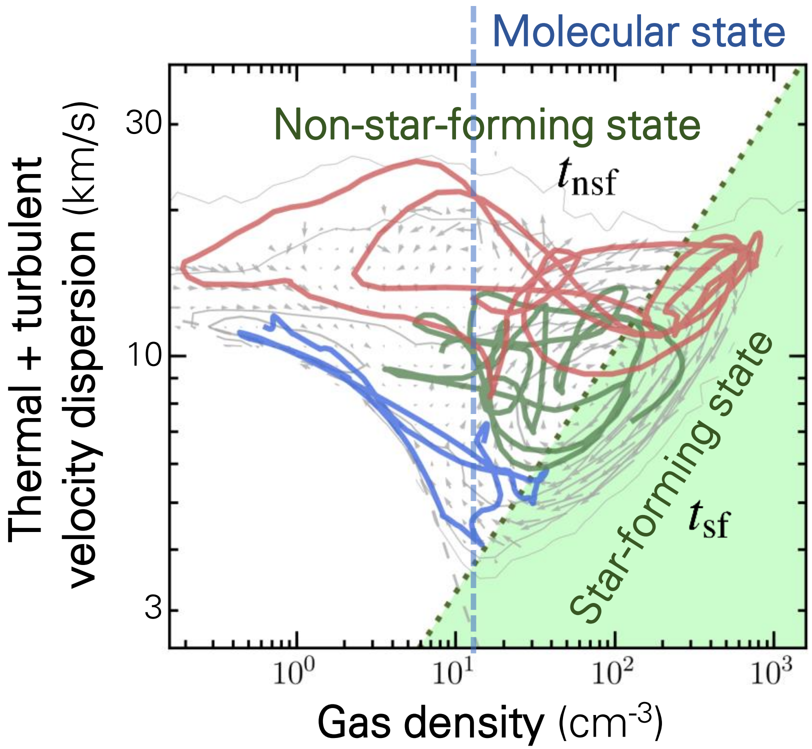
Semenov, Kravtsov & Gnedin 2017, ApJ 845, 133 (arXiv:1704.04239)

ISM gas evolution is rapid and cyclic

- Gas cycles between SF and non-SF states on <100 Myr timescale
- Feedback disperses SF regions making SF stages short
- Most of the time gas spends in the non-SF state



Physical origin of long gas depletion times



Gas depletion time:

$$\tau_{dep} = \frac{M_g}{\dot{M}_\star} = \frac{1}{f_{sf}} \frac{M_{sf}}{\dot{M}_\star} = \frac{\tau_{dep,sf}}{f_{sf}}$$

Depletion time *of star-forming gas* (explicitly depends on the SF recipe)

Mass fraction of star-forming gas:

$$f_{sf} = \frac{M_{sf}}{M_g} \sim \frac{t_{sf}}{t_{sf}+t_{nsf}} = \left(1 + \frac{t_{nsf}}{t_{sf}}\right)^{-1}$$

$$\tau_{dep} \sim \tau_{dep,sf} + \frac{\tau_{dep,sf}}{t_{sf}} t_{nsf}$$

$$N_{dep} \sim \frac{\tau_{dep,sf}}{t_{sf}}$$

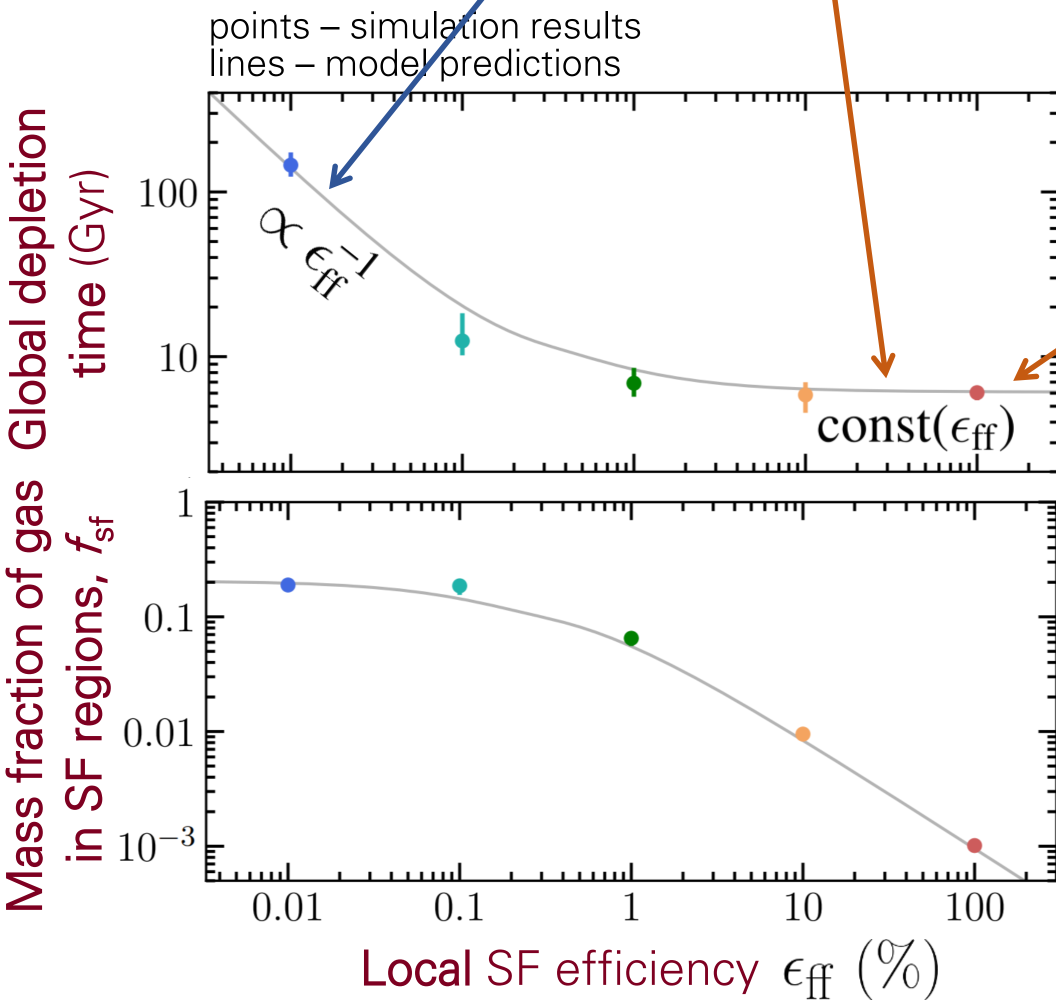
(depletion time) = (depletion time in SF state) + (total time in non-SF state over N_{dep} cycles)

Although each cycle is short, depletion is long because the number of cycles is large

Semenov, Kravtsov, Gnedin 2017 ApJ 845, 133
2018 ApJ 861, 4

Dependence of depletion time on local SF efficiency

$$\tau_{\rm dep} \sim \tau_{\rm dep,sf} + \frac{\tau_{\rm dep,sf}}{t_{\rm sf}} t_{\rm nsf}$$



By definition:

$$\tau_{\rm dep,sf} \sim \frac{\tau_{\rm ff}}{\epsilon_{\rm ff}} \propto \epsilon_{\rm ff}^{-1}$$

Feedback limits SF stages:

$$t_{\rm sf} \propto \epsilon_{\rm ff}^{-1}$$

Model explains self-regulation!

(i.e., independence of global depletion time from local $\varepsilon_{\rm ff}$)

Dobbs+'11; Agertz+'13,'15; Hopkins+'13,'17

Star-forming gas mass fraction shows the opposite behavior:

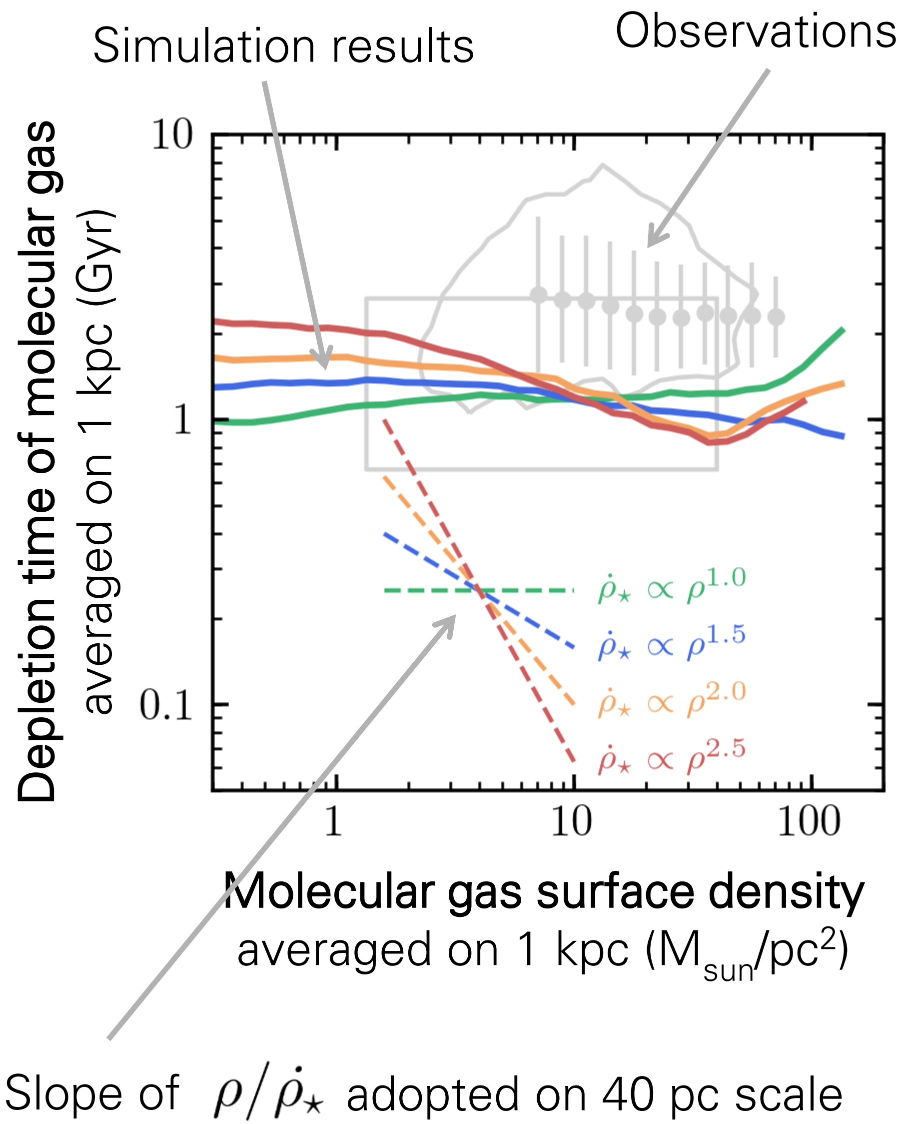
$$f_{\rm sf} \sim \left(1 + \frac{t_{\rm nsf}}{t_{\rm sf}}\right)^{-1}$$

$f_{\rm sf}$ can be used to constrain $\varepsilon_{\rm ff}$

Hopkins+'13

Semenov, Kravtsov, Gnedin 2018 ApJ 861, 4

Slope of molecular Kennicutt-Schmidt relation



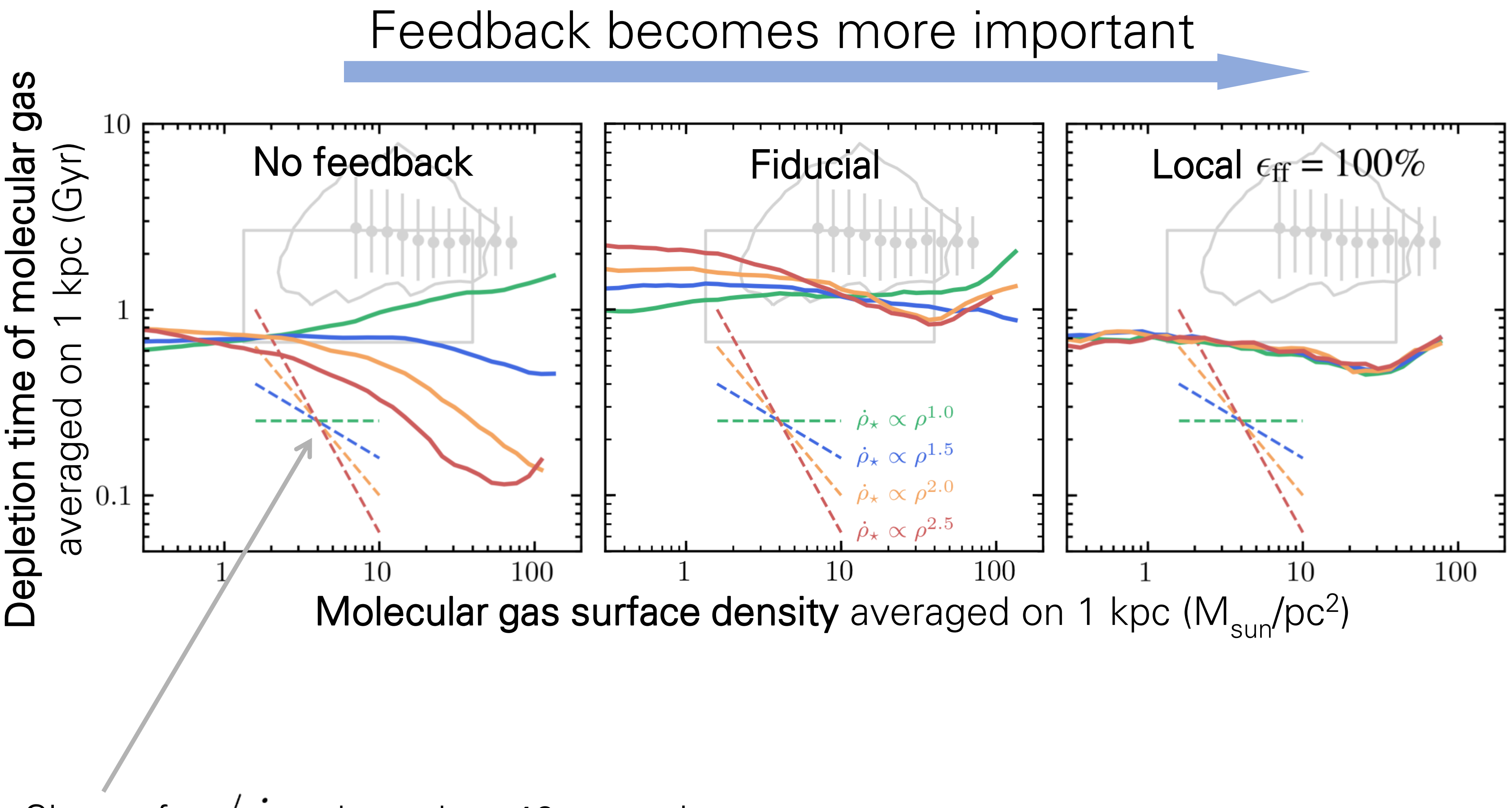
Apart from normalization, simulations also reproduce the linear slope

$\tau_{dep,H2}$ is constant on kpc scale

independent of the assumptions on resolution scale (40 pc)

Semenov, Kravtsov, Gnedin 2018b in prep.

Effect of feedback on the molecular KS slope



Slope of $\rho/\dot{\rho}_\star$ adopted on 40 pc scale

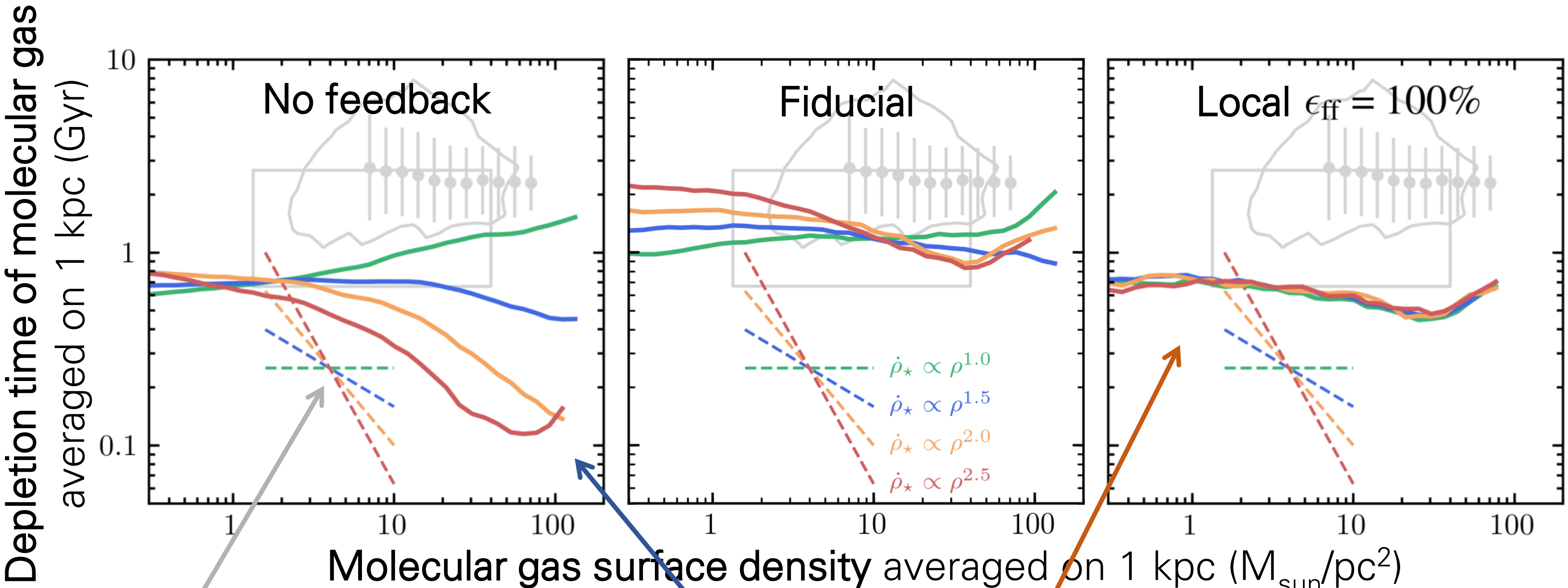
Semenov, Kravtsov, Gnedin 2018b in prep.

Effect of feedback on the molecular KS slope

$$\dot{\rho}_\star = \epsilon_{\rm ff} \frac{\rho}{t_{\rm ff}} \propto \epsilon_{\rm ff}\, \rho^{1.5}$$

Local slope different from 1.5 ⇔ ε_{ff} dependent on ρ

Therefore, when depletion time is insensitive to ε_{ff}
it is also insensitive to the local slope!



$$\tau_{\rm dep} \sim \tau_{\rm dep,sf} + \frac{\tau_{\rm dep,sf}}{t_{\rm sf}} t_{\rm nsf}$$

Slope of $\rho/\dot{\rho}_\star$ adopted on 40 pc scale

Semenov, Kravtsov, Gnedin 2018b in prep.

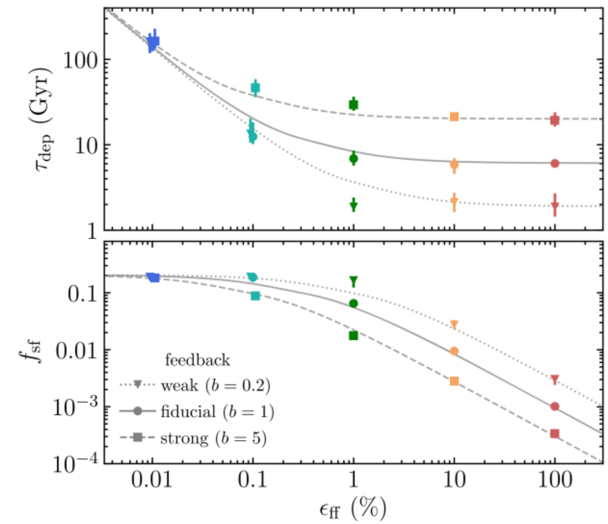
Summary

The origin of the Kennicutt-Schmidt relation:

$$\tau_{\rm dep} \sim \tau_{\rm dep,sf} + \frac{\tau_{\rm dep,sf}}{t_{\rm sf}} t_{\rm nsf}$$

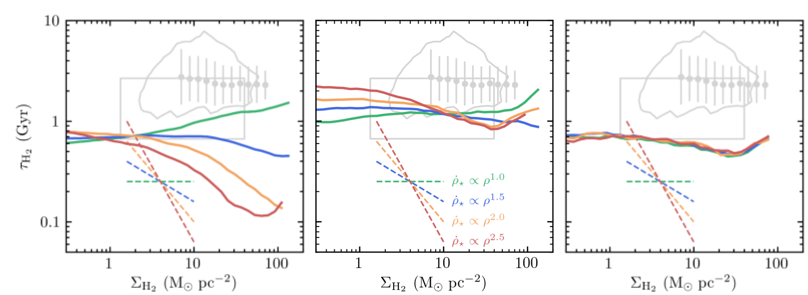
Normalization (global depletion time)

- $\tau_{\rm dep}$ is long because gas has to go through a large number of cycles spending only a small fraction of time in SF state
- Shows two limiting regimes with qualitatively different dependence on star formation and feedback parameters



Slope (dependence of $\tau_{\rm dep}$ on Σ_{H2})

- Also shows two limiting regimes with different dependence on the local slope
- Efficient feedback leads to a linear molecular KSR independent of the local SF recipe (another manifestation of self-regulation)



Semenov, Kravtsov, Gnedin 2017 ApJ 845, 133
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