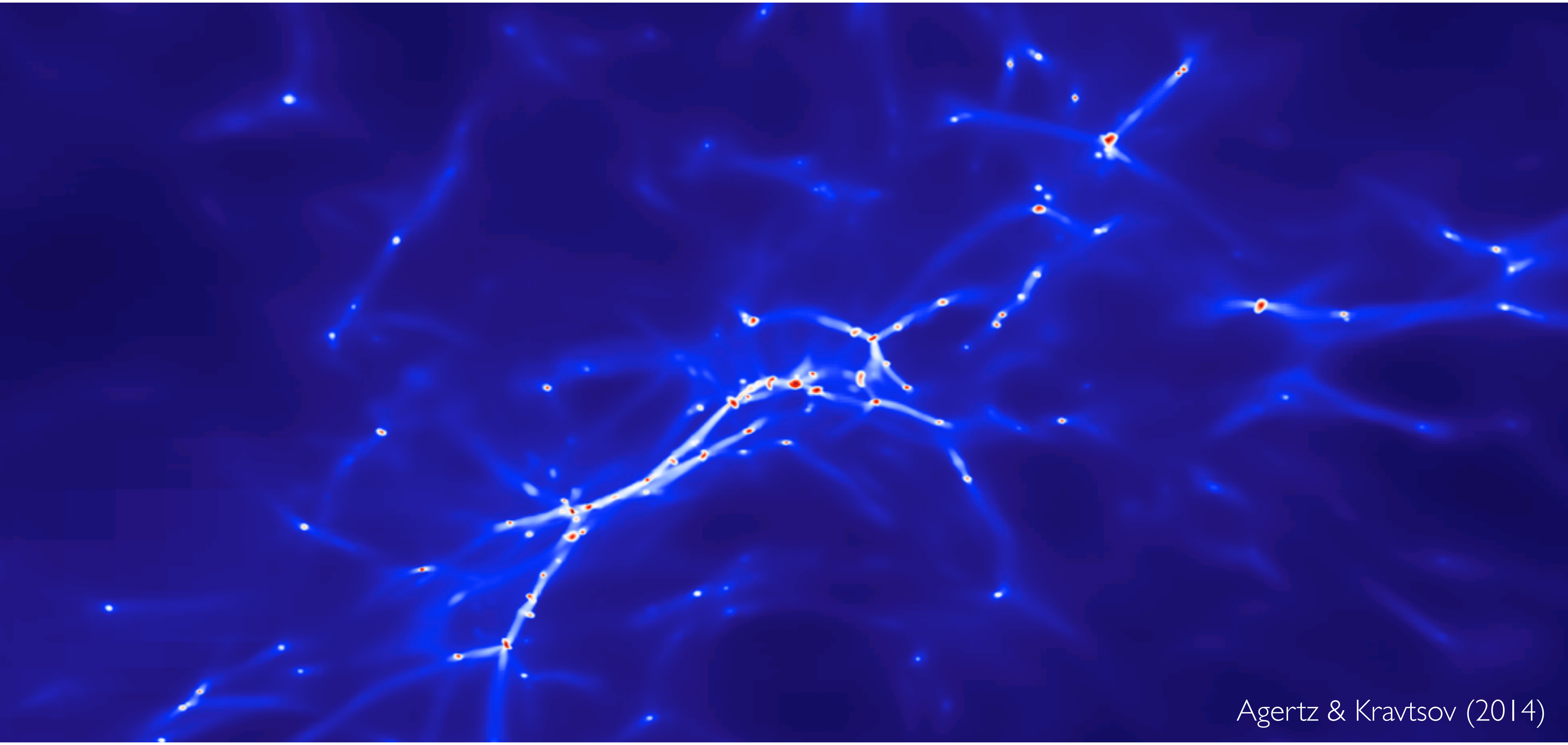
On the interplay between star formation and stellar feedback in galaxy formation simulations



Agertz & Kravtsov (2014)

Oscar Agertz, University of Surrey

with Andrey Kravtsov, Sam Leitner, Nick Gnedin and Craig Booth

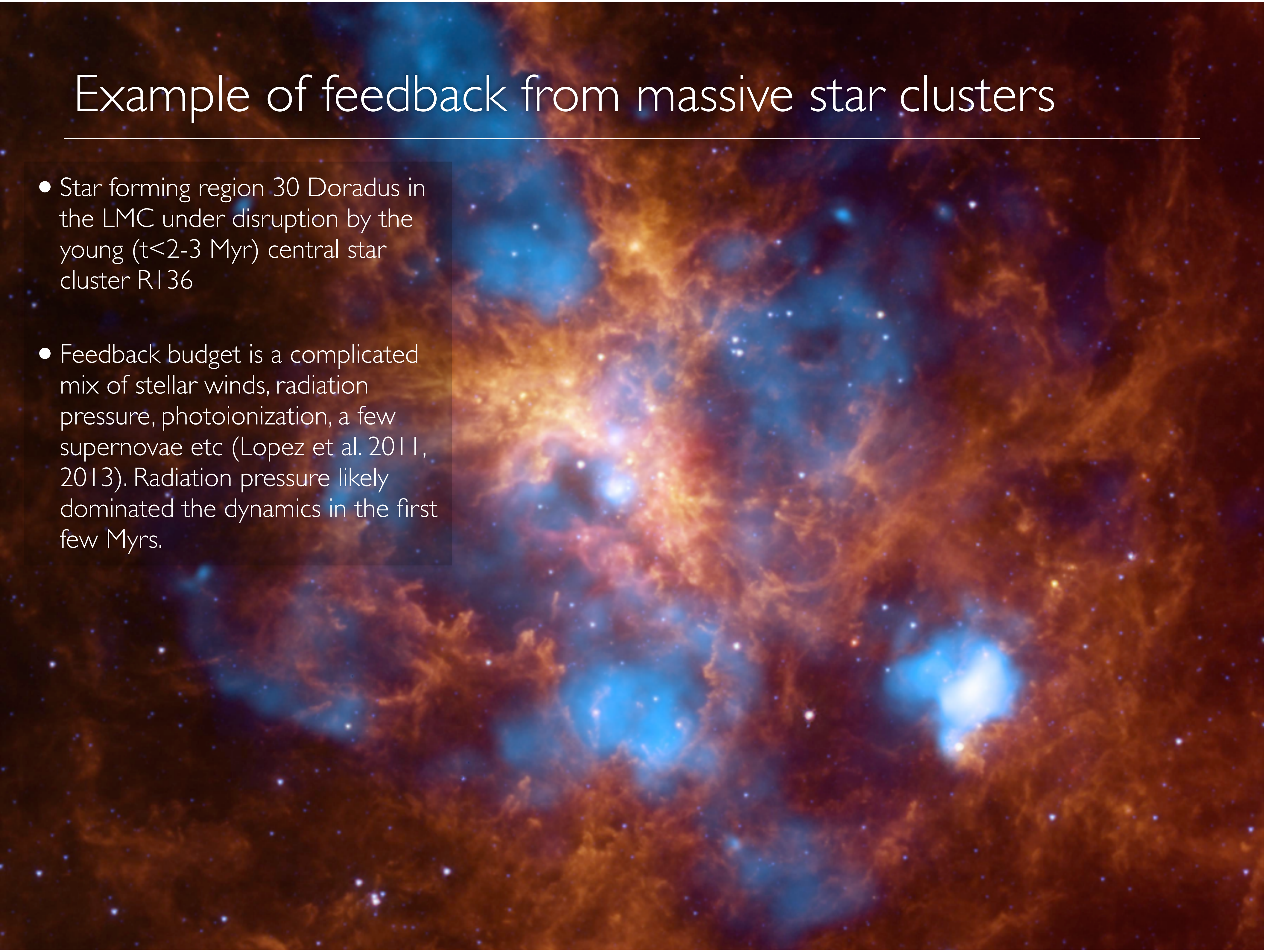
On the interplay between star formation and stellar feedback in galaxy formation simulations

- How does the local star formation efficiency affect the efficiency of feedback?

- For which models do we achieve self-regulation and reasonable galactic characteristics?

- Are galaxy formation models degenerate, and if so, how can we break those degeneracies?

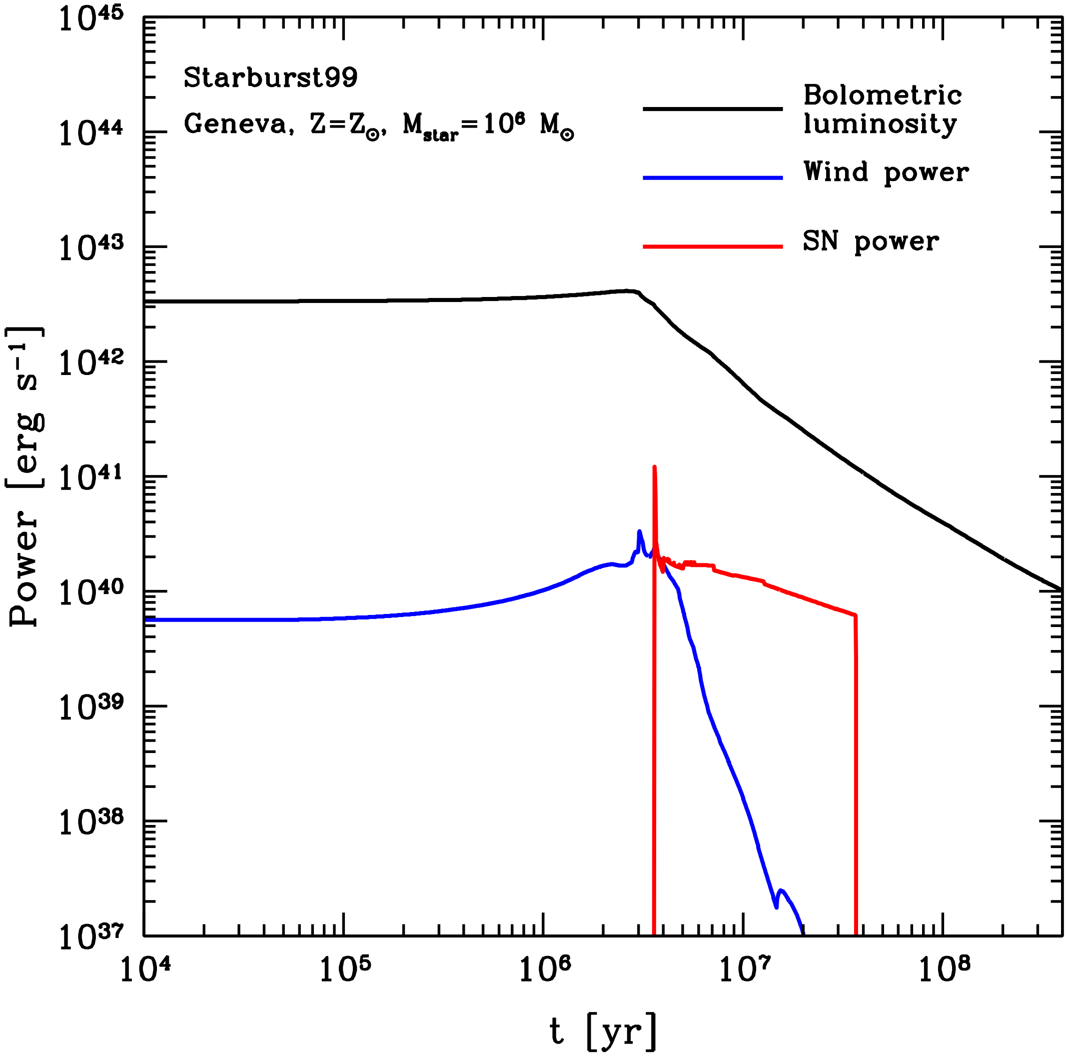
Example of feedback from massive star clusters



- Star forming region 30 Doradus in the LMC under disruption by the young ($t<2$-3 Myr) central star cluster R136
- Feedback budget is a complicated mix of stellar winds, radiation pressure, photoionization, a few supernovae etc (Lopez et al. 2011, 2013). Radiation pressure likely dominated the dynamics in the first few Myrs.

The stellar feedback budget in cosmological simulations

Agertz et al. (2013)



Via STARBURST99
(Leitherer et al. 1999)

The momentum injection rates are roughly equal!

$$\dot{p}_{\rm SNII} \sim \dot{p}_{\rm winds} \sim \frac{L_{\rm mech}}{v} \sim \frac{L_{\rm bol}}{c} \sim \dot{p}_{\rm rad}$$

The stellar feedback budget in cosmological simulations

Agertz et al. (2013)

A star particle of mass m*, plus an IMF, gives us a time-resolved release of:

Energy: $\dot{E}_{\rm tot} = \dot{E}_{\rm SN}(m_*, t, Z_*) + \dot{E}_{\rm wind}(m_*, t, Z_*)$

Momentum: $\dot{p}_{\rm tot} = \dot{p}_{\rm SN}(m_*, t, Z_*) + \dot{p}_{\rm wind}(m_*, t, Z_*) + \dot{p}_{\rm rad}(m_*, t, Z_{\rm gas})$

Mass loss: $\dot{m}_{\rm tot} = \dot{m}_{\rm SN}(m_*, t, Z_*) + \dot{m}_{\rm winds}(m_*, t, Z_*)$

Metals: $\dot{m}_{Z,\rm tot} = \dot{m}_{Z,\rm SN}(m_*, t, Z_*) + \dot{m}_{Z,\rm winds}(m_*, t, Z_*)$

All rates are calibrated on the stellar evolution code STARBURST99 (*Leitherer et al. 1999*). See also *Hopkins et al. (2012)*.

- All simulations performed using the Adaptive-Mesh-Refinement (AMR) code RAMSES (*Teyssier 2002*)

- Cosmic ray feedback (Booth et al. 2013) $+\dot{E}_{\rm CR}$

Uncertainties in momentum generation

The **initial** momentum injection rate from SNe, stellar winds and radiation pressure are roughly equal

$$\dot{p}_{\rm SNII} \sim \dot{p}_{\rm winds} \sim \frac{L_{\rm mech}}{v} \sim \frac{L_{\rm bol}}{c} \sim \dot{p}_{\rm rad}$$

- If photons scatter off dust particles multiple times, essentially diffusing through an optically thick medium, the total momentum deposition can be boosted by the (IR) optical depth of the medium (e.g. *Gayley et al. 1995*)

$$\dot{p}_{\rm rad} = \tau \frac{L}{c}$$

- Supernovae explosions undergoing a successful adiabatic **Sedov-Taylor** phase, will also boost momentum (e.g. *Mckee & Ostriker 1988, Blondin et al. 1998*)

$$p_{\rm ST} = M_{\rm ST} v_{\rm ST} \approx 2.6 \times 10^5 \, E_{51}^{16/17} n_0^{-2/17} M_\odot \, {\rm km\, s^{-1}} \longrightarrow \quad p_{\rm ST} \sim 10 \, p_{\rm SNII}$$

- **The success of momentum generation depends on environment**, e.g. cooling in unresolved shocks. *Thornton et al. (1998), Cho & Kang (2008)* and *Krausse et al. (2013)* found that only 10-20% of thermal energy is converted into kinetic energy. The stability of feedback accelerated shells also limits the amount of injected momentum (*Krumholz & Thompson 2013*).

Uncertainties in momentum generation

- Thermal feedback is inefficient in galaxy formation simulations; **the gas cooling time in dense gas is short** (e.g. *Katz 1992*).

$$t_{\rm cool} \approx 10^3 \left(\frac{100\,{\rm cm}^{-3}}{n_H} \right) \,{\rm years}$$

- Successful implementations of thermal feedback usually assume an extended period of **adiabatic evolution** (*Gerritsen 1997, Stinson et al. 2006, Governato et al. 2010, Agertz et al. 2011, Guedes et al. 2011*). Alternatively, one may find ways of depositing the energy outside of star forming regions (runaway stars, *Ceverino & Klypin 2010*) or by enforcing large temperature jumps via selective energy deposition (*Dalla Vecchia & Schaye 2013*).

- For most of our models, we consider a fraction of the thermal energy to evolve as a second energy variable, dissipating over some timescale. See also *Teyssier et al. (2013)*.

$$\frac{\partial}{\partial t}(E_{\rm fb}) + \nabla \cdot (E_{\rm fb} v_{\rm gas}) = -P_{\rm fb} \nabla \cdot v_{\rm gas} - \frac{E_{\rm fb}}{t_{\rm dis}}$$

$$t_{\rm dis} = 10\,{\rm Myr}$$

Radiation pressure model

$$\dot{p}_{\rm rad} = (1+\tau_{\rm IR})\frac{L}{c}$$

$$\tau_{\rm IR} \approx \kappa_{\rm IR}\Sigma_{\rm cl}$$

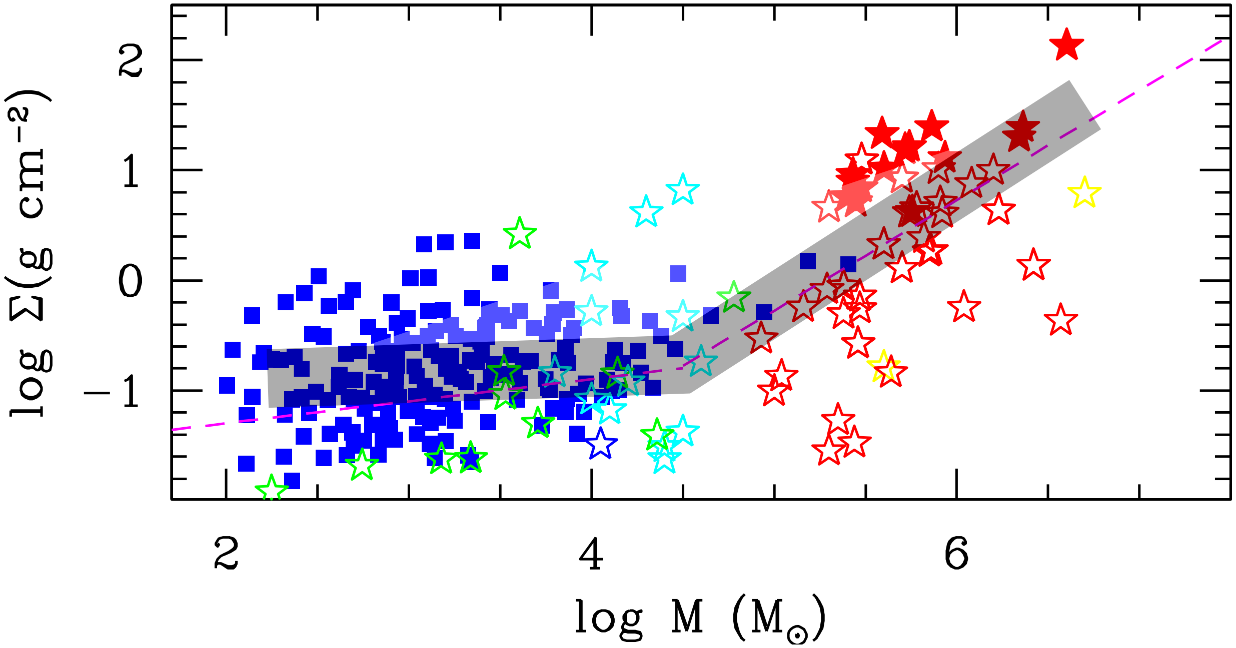
$$\kappa_{\rm IR,0} = 5\,{\rm cm}^2\,{\rm g}^{-1}$$

$$\kappa_{\rm IR} = \kappa_{\rm IR,0}\left(\frac{Z}{Z_\odot}\right)$$

Li & Draine (2001) and
Semenov et al. (2003)

Size-mass relation of molecular clumps/young star clusters

Portegies Zwart et al. (2010), Krumholz & Matzner (2009), Fall et al. (2010), Mackey & Gilmore (2003)

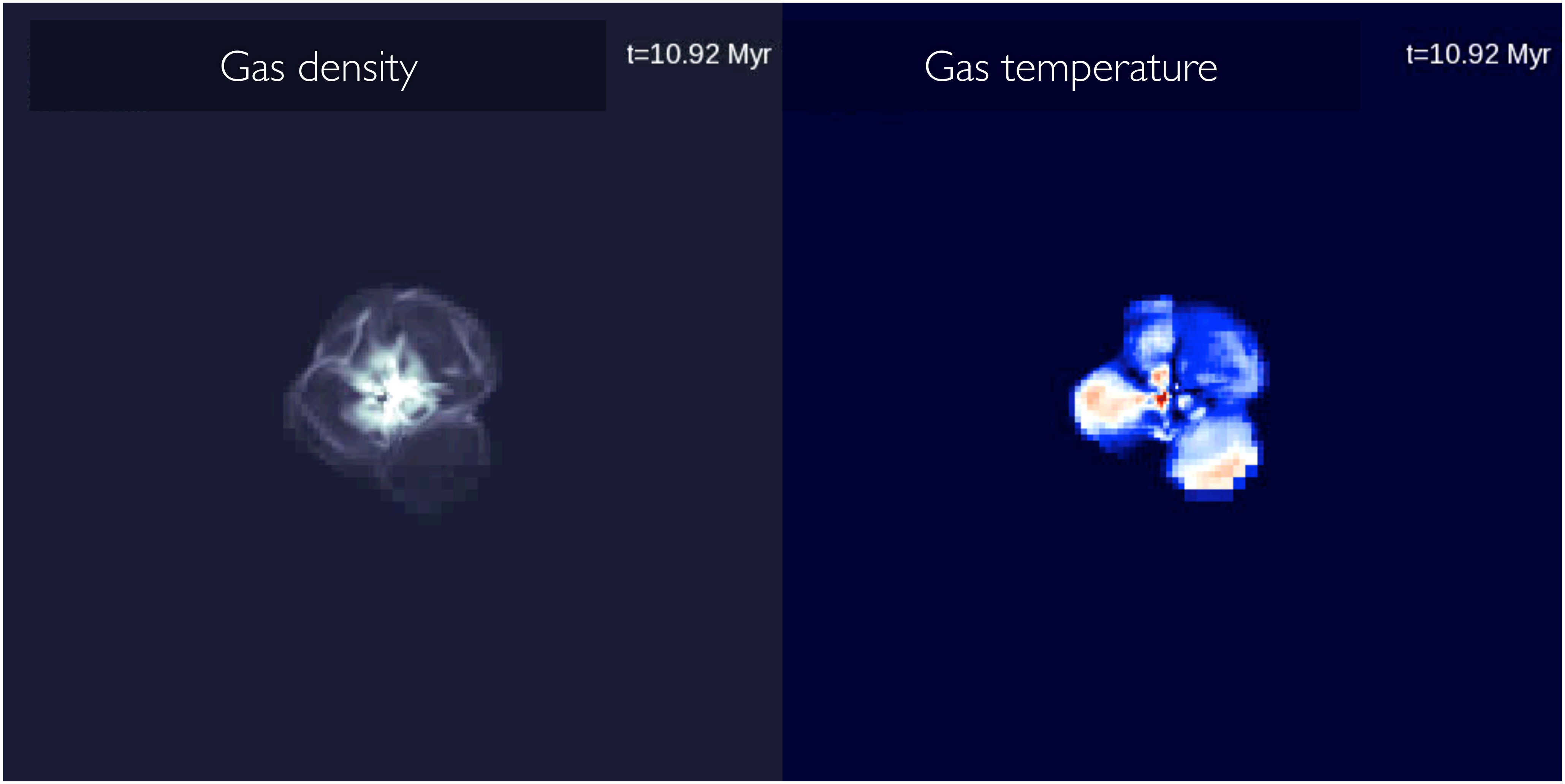


Galaxy formation simulations do not resolve the density structure of star forming clouds; we adopt an ***empirical model*** of the natal cloud densities (Agertz et al. 2013)

Idealized experiment at the resolution (almost) affordable in galaxy formation simulations:

The star formation efficiency in a Giant Molecular Cloud

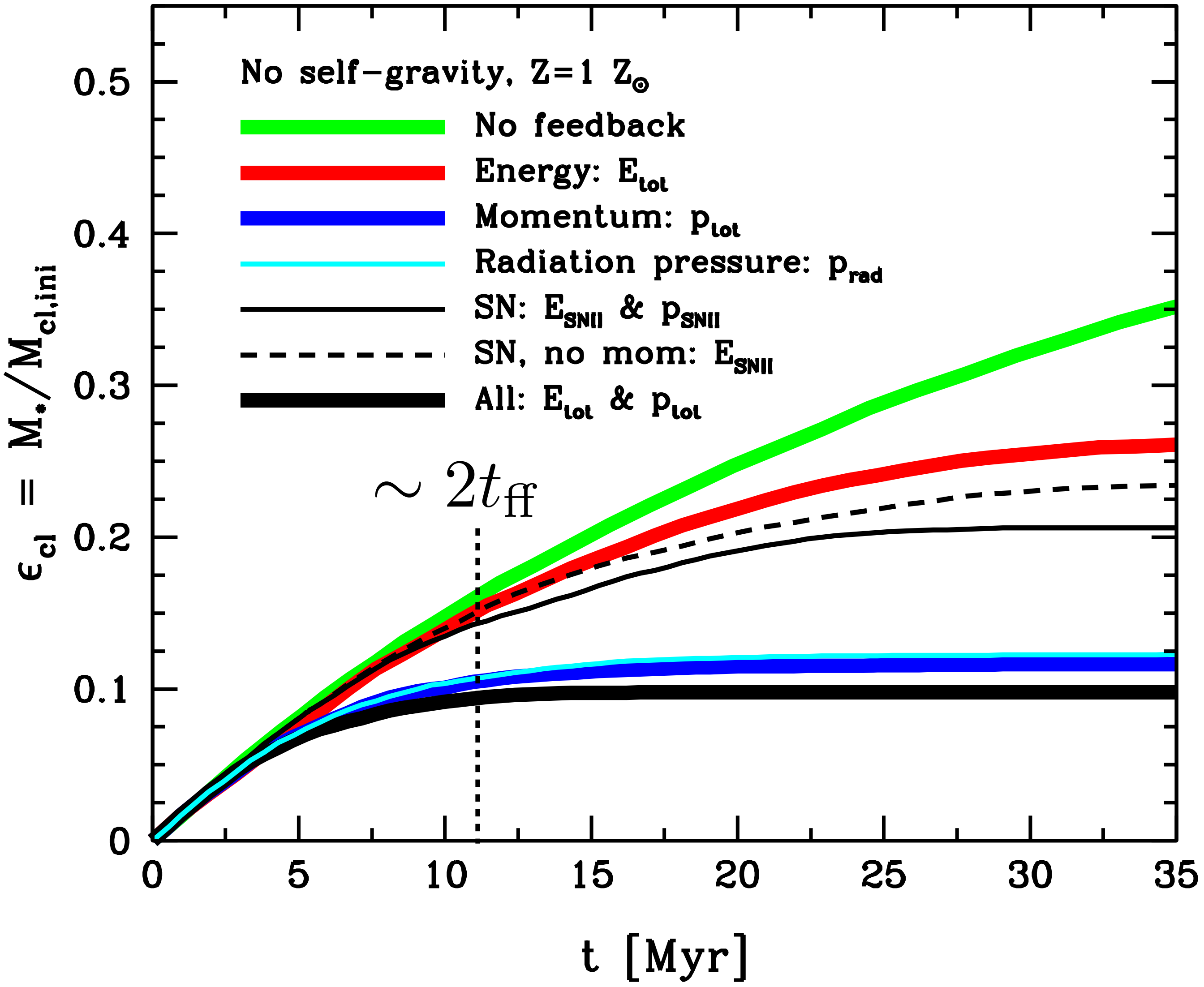
$n_{\rm cl} = 100\,{\rm cm}^{-3}$ $r_{\rm cl} = 50\,{\rm pc}$ $M_{\rm GMC} \approx 10^6\,M_\odot$



Low resolution (dx= 10 pc) calculation of GMC destruction
(Agertz et al. 2013)

Idealized experiment:
The star formation efficiency in a Giant Molecular Cloud

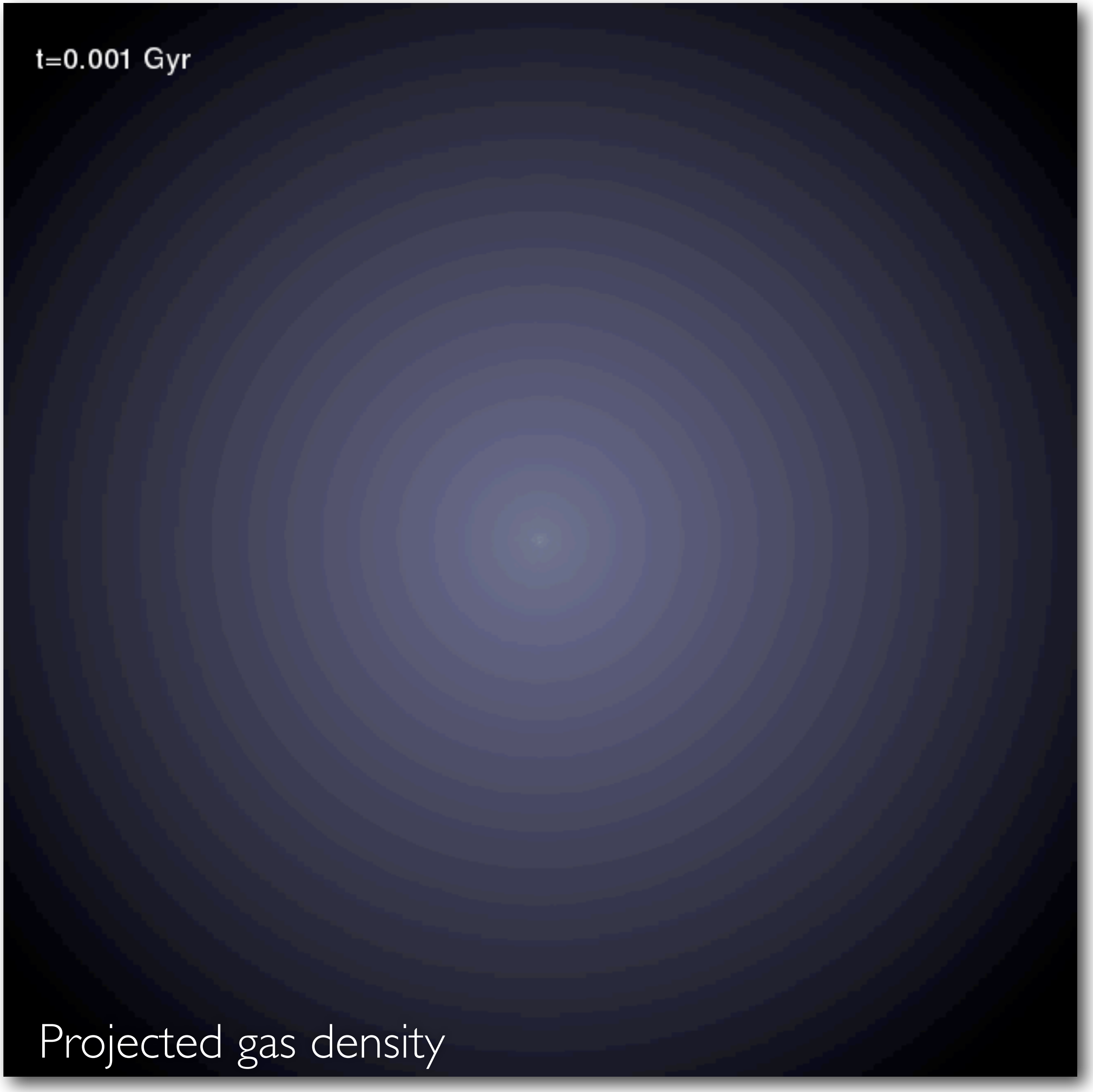
$n_{\rm cl} = 100\,{\rm cm}^{-3} \qquad r_{\rm cl} = 50\,{\rm pc}$



- Radiation pressure alone destroys the GMC in ~2 free-fall times.
- When the full feedback model is accounted for, the results agree with luminosity weighted observed conversion efficiencies in massive Milky Way GMCs (*Evans et al. 2009, Murray 2011*)

$$\langle \epsilon_{\rm cl} \rangle \approx 0.08$$

Milky Way-like galactic disks (Agertz et al. 2013)



Projected gas density

- Global models of a Milky Way-like galactic disk.

$$M_{200} = 10^{12}\, M_{\odot}$$

$$M_{\rm disk} = 4.5 \times 10^{10}\, M_{\odot}$$

$$f_{\rm gas} = 20\%$$

- Initial conditions used in the AGORA project (Kim et al. 2014), where we will study how different codes and feedback implementations affect galactic evolution.

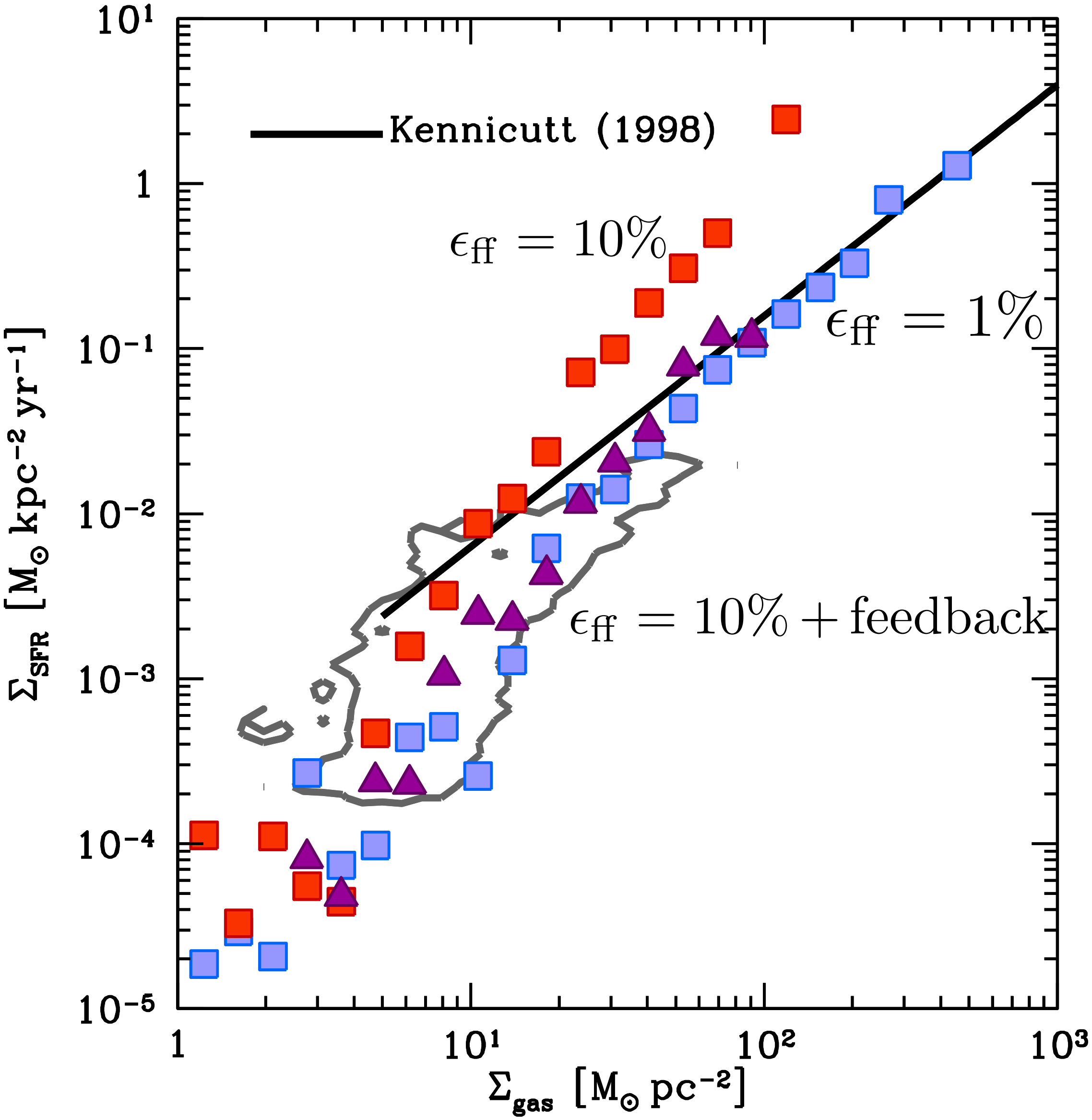
Milky Way-like galactic disks (Agertz et al. 2013)

Feedback strength and the Kennicutt-Schmidt relation

- Without feedback, the Kennicutt Schmidt relation scales roughly linearly with the small scale star formation efficiency per free-fall time.

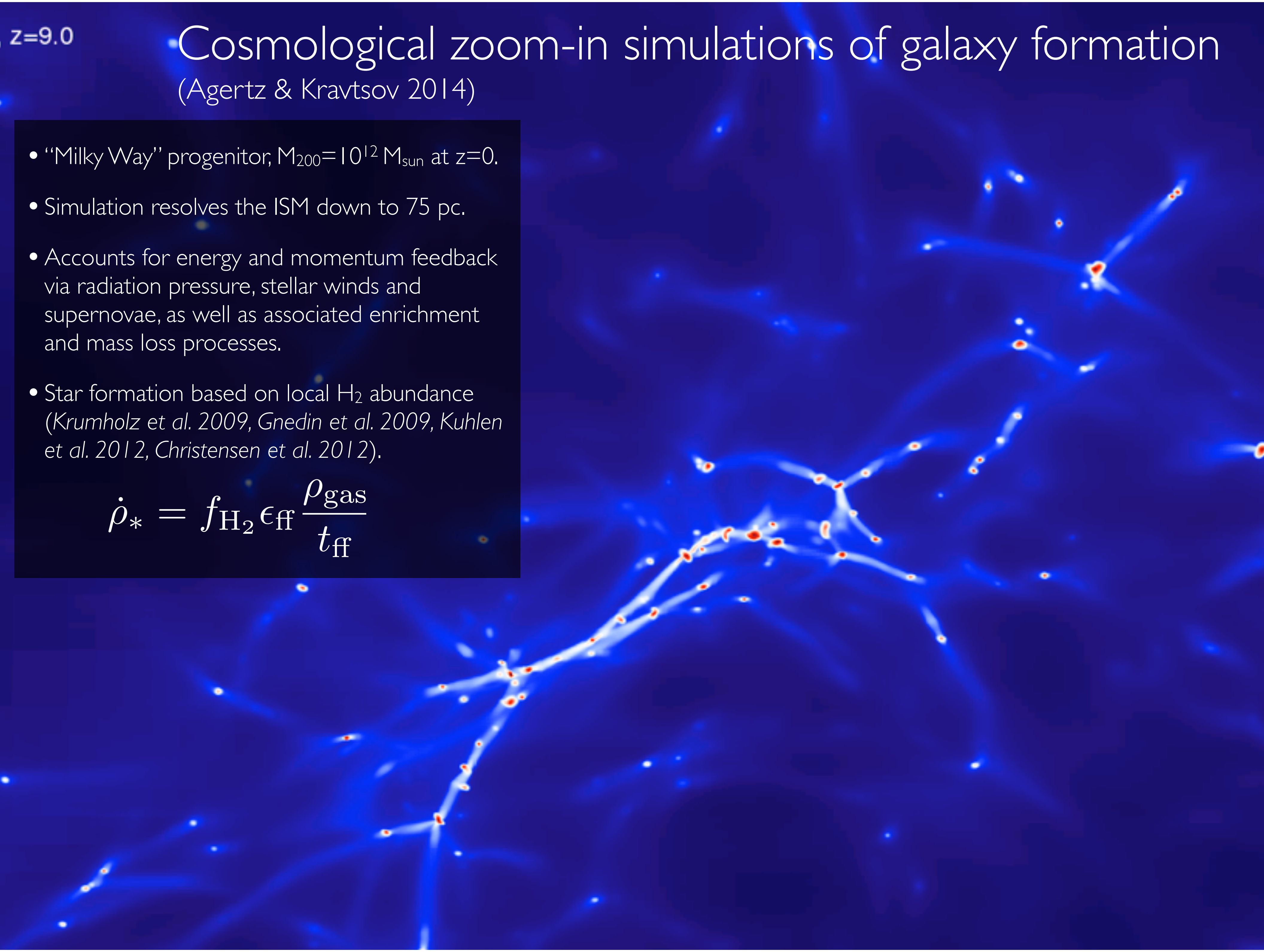
- Adopting our full feedback budget makes the simulated Kennicutt-Schmidt relation less sensitive to the underlying ϵ_{ff}, and in closer agreement to observations.

- However, this tells us nothing about the cosmological baryon cycle in galaxies!



Cosmological zoom-in simulations of galaxy formation

(Agertz & Kravtsov 2014)



- “Milky Way” progenitor, $M_{200}=10^{12}\ M_{sun}$ at z=0.
- Simulation resolves the ISM down to 75 pc.
- Accounts for energy and momentum feedback via radiation pressure, stellar winds and supernovae, as well as associated enrichment and mass loss processes.
- Star formation based on local H_2 abundance (*Krumholz et al. 2009, Gnedin et al. 2009, Kuhlen et al. 2012, Christensen et al. 2012*).

$$\dot{\rho}_* = f_{\mathrm{H_2}} \epsilon_{\mathrm{ff}} \frac{\rho_{\mathrm{gas}}}{t_{\mathrm{ff}}}$$

Cosmological zoom-in simulations of galaxy formation

(Agertz & Kravtsov 2014)

- **How does the local star formation efficiency affect the efficiency of feedback?**
- For which models do we achieve self-regulation?
- Are galaxy formation models degenerate, and if so how can we break those degeneracies?

- We parametrize the location star formation rate as:

$$\dot{\rho}_* = f_{\mathrm{H}_2} \frac{\rho_{\mathrm{g}}}{t_{\mathrm{SF}}}$$

$$t_{\mathrm{SF}} = t_{\mathrm{ff}}/\epsilon_{\mathrm{ff}}$$

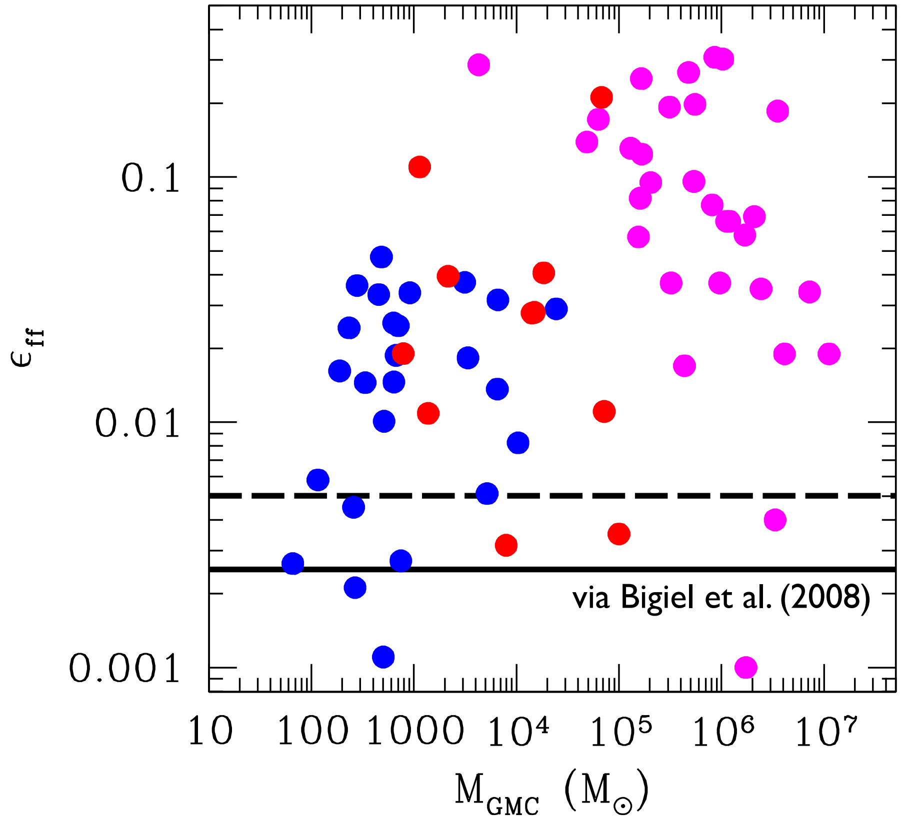
- On large scales, the efficiency of star formation is low! (THINGS: *Leroy et al. 2008*)

$$\epsilon_{\mathrm{ff}} = t_{\mathrm{ff,SF}}/t_{\mathrm{H_2,gal}} \sim 0.25\%$$

- On the scale of GMCs, it's less clear and may depend on the environment (*Evans et al. 2009, Murray 2011*), as demonstrated by simulations (e.g. *Padoan and Nordlund 2011*)

$$\epsilon_{\mathrm{ff}} \sim 0.1 - 30\%$$

- We investigate $\epsilon_{\mathrm{ff}} = 1 - 10\%$



Blue: Evans et al. (2014)
Red: Lada et al. (2010)
Magenta: Murray (2011)

Cosmological zoom-in simulations of galaxy formation

(Agertz & Kravtsov 2014)

- How does the local star formation efficiency affect the efficiency of feedback?
- **For which models do we achieve self-regulation?**
- **Are galaxy formation models degenerate, and if so how can we break those degeneracies?**

Stellar feedback driven winds are necessary to ***simultaneously*** predict observed/inferred characteristics such as:

- Cosmic star formation histories
- Stellar mass - halo mass relation
- Stellar mass - gas metallicity relation + evolution
- Kennicutt-Schmidt relation
- Flat rotation curves

The way in which this is achieved matters! I will contrast a set of different models, all including sophisticated feedback:

1. Low star formation efficiency per free-fall time: $e_{ff} = 1\%$
2. Large star formation efficiency per free-fall time: $e_{ff} = 10\%$
3. Low e_{ff} (=1%) and **boosted** supernovae feedback ($E_{SN}=5 \times 10^{51}$ erg), (Top-heavy IMF?)
4. Removing individual components of the feedback model

A qualitative view at z=3

e_{ff}=10%

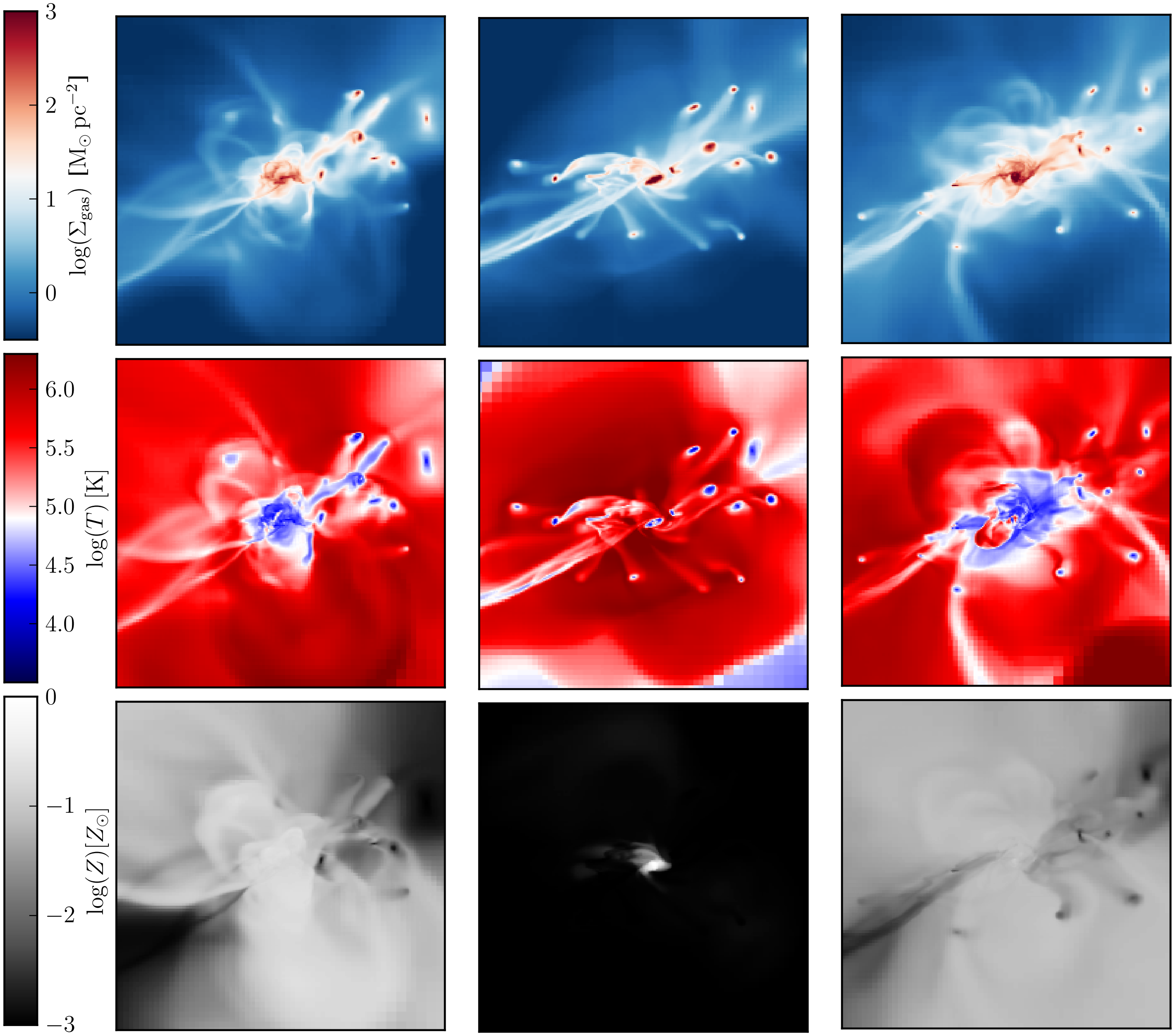
e_{ff}=1%

e_{ff}=1%, 5 × E_{SN}

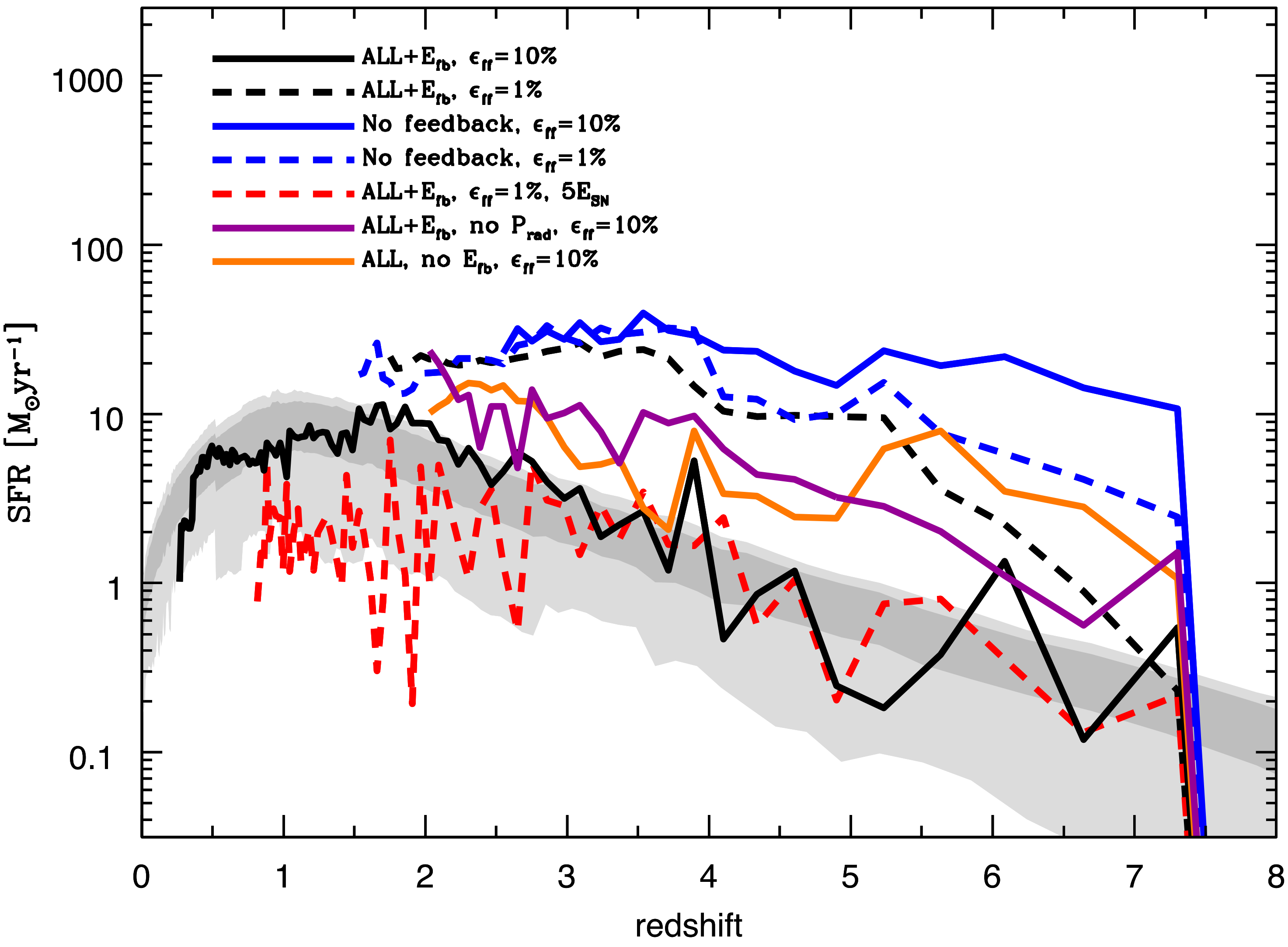
Gas density

Gas temperature

Gas metallicity



Star formation histories



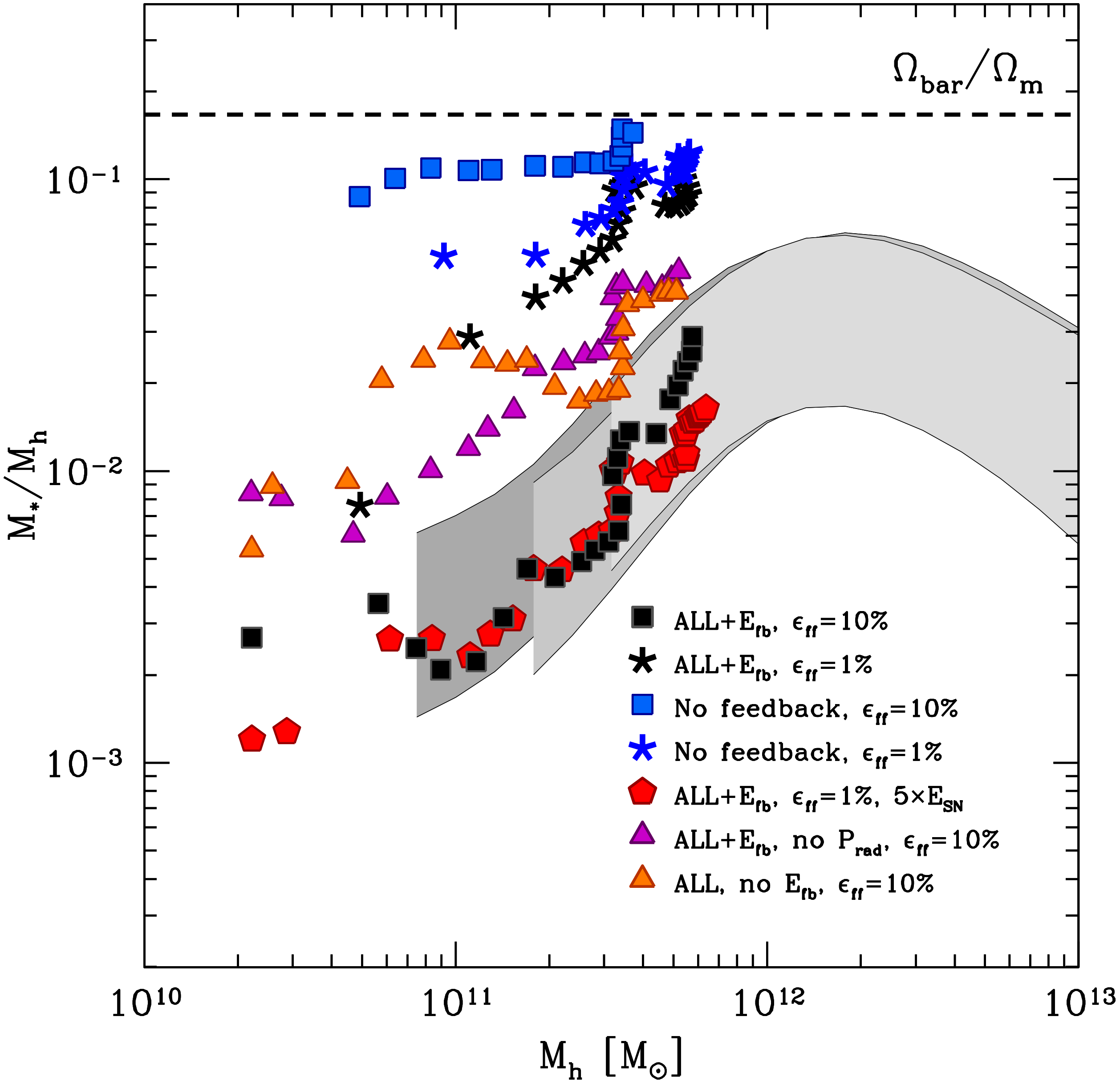
Semi-empirical data from *Behroozi et al. (2013)*

Star formation in Milky Way-like galaxies is expected to be highly suppressed for the first 3 billion years!

"Milky Way-like galaxies form ~90% of stellar mass after z~2.5"

Leitner (2012), Behroozi et al. (2013), van Dokkum et al. (2013)

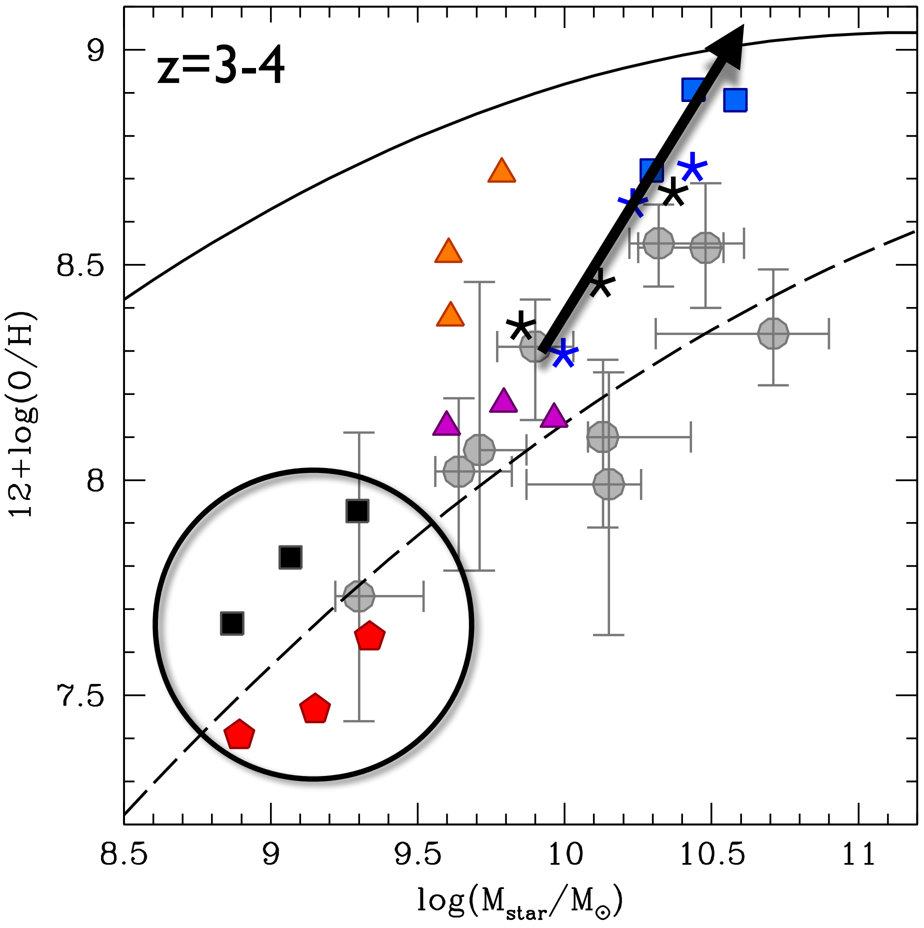
Stellar mass - halo mass relation



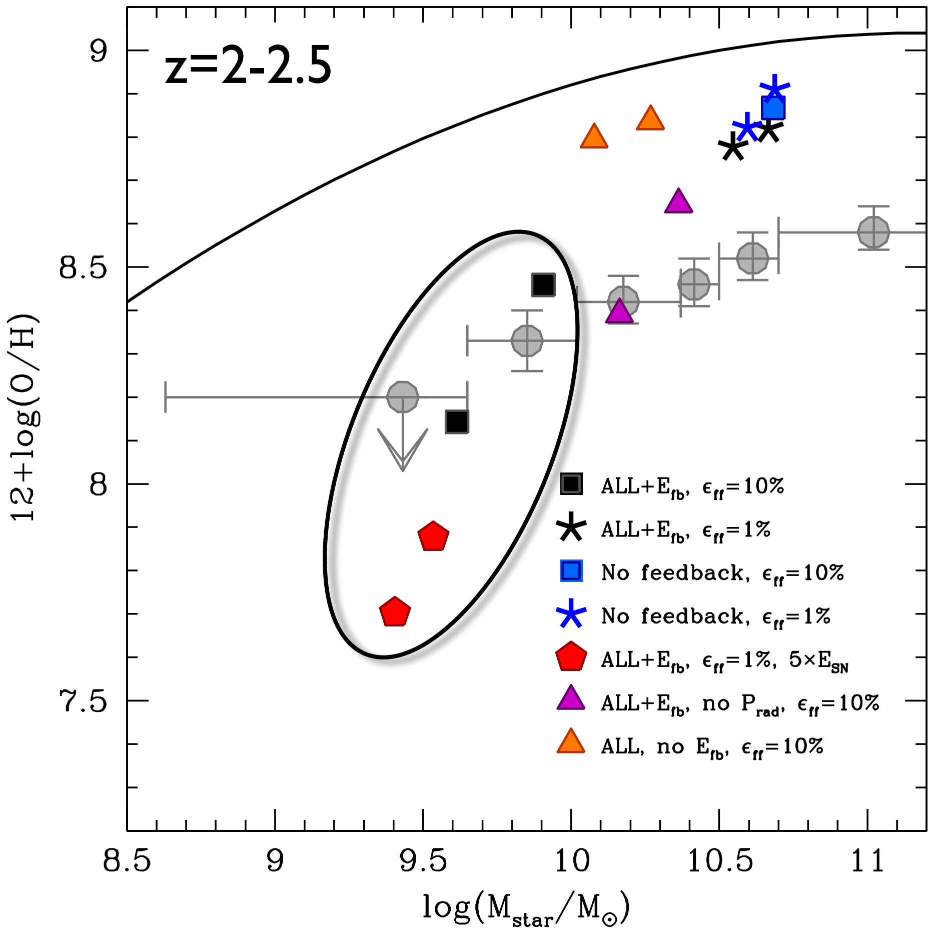
Semi-empirical data at z=3, 2 and 1 from *Behroozi et al. (2013)*

(see also e.g. Moster et al. 2010, Kravtsov 2014)

Stellar mass-gas metallicity



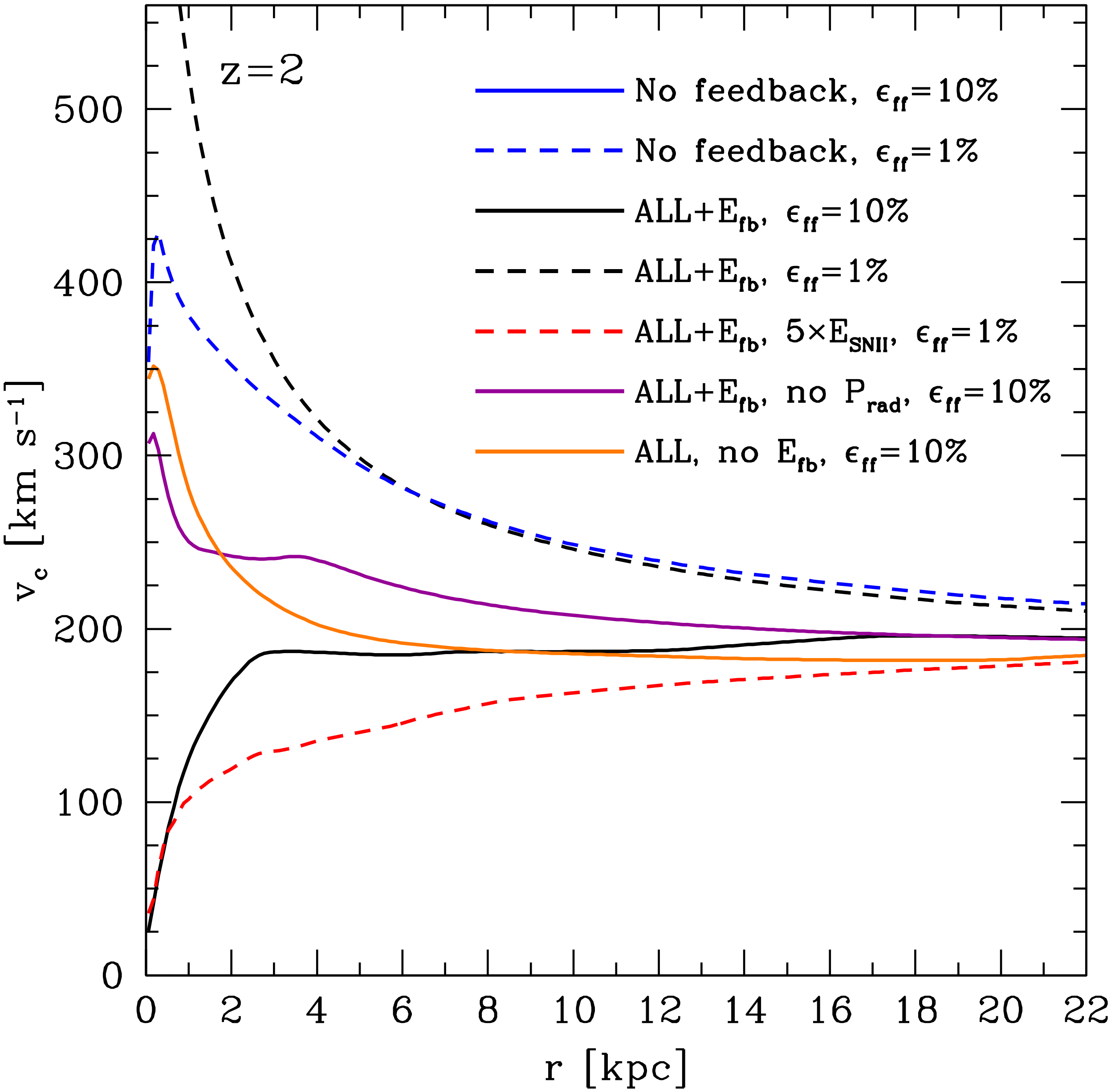
Observational data from *Maiolino et al. (2008)*



Observational data from *Erb et al. (2006)*

Without enriched winds, galaxies rapidly evolves off the observed relation, and reach the z=0 relation already at z>3. **Matching only the z=0 relation is not a sufficient metric of a successful galaxy formation model.**

Circular velocities



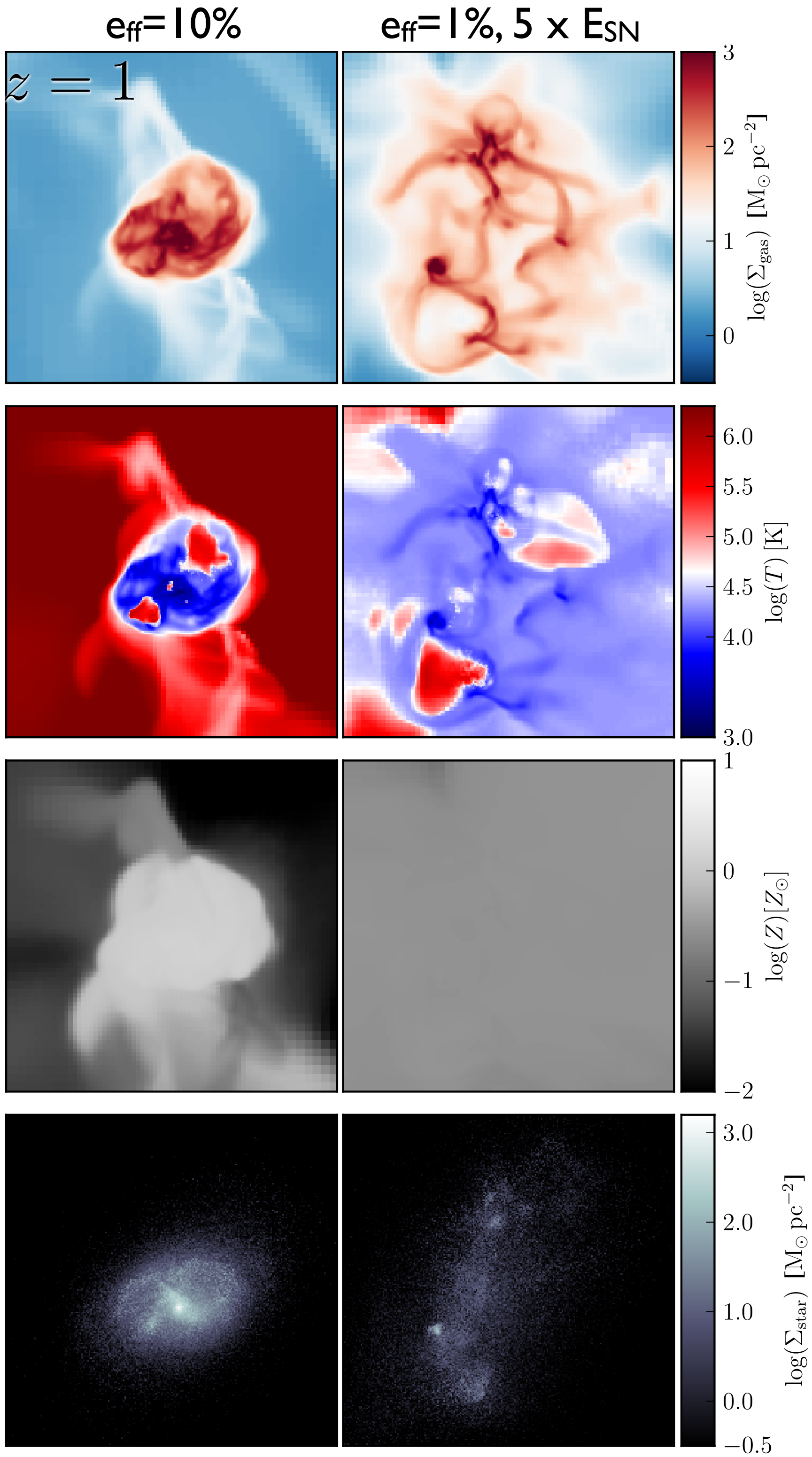
- Low angular momentum material is continuously blown out in the two models which match all other data, leading to flat/rising rotation curves.

Breaking the degeneracies

- Reasonable galactic properties are achievable by
  1. making feedback more correlated using a high local star formation efficiency per free-fall time, or
  2. by "by hand" by boosting the available supernova energy.

- **The fiducial model enters an epoch of disk formation by z=1** (see e.g. HST data: *Kassin et al. 2012, Elmegreen & Elmegreen 2014*) where outflows mainly lead to a fountain.

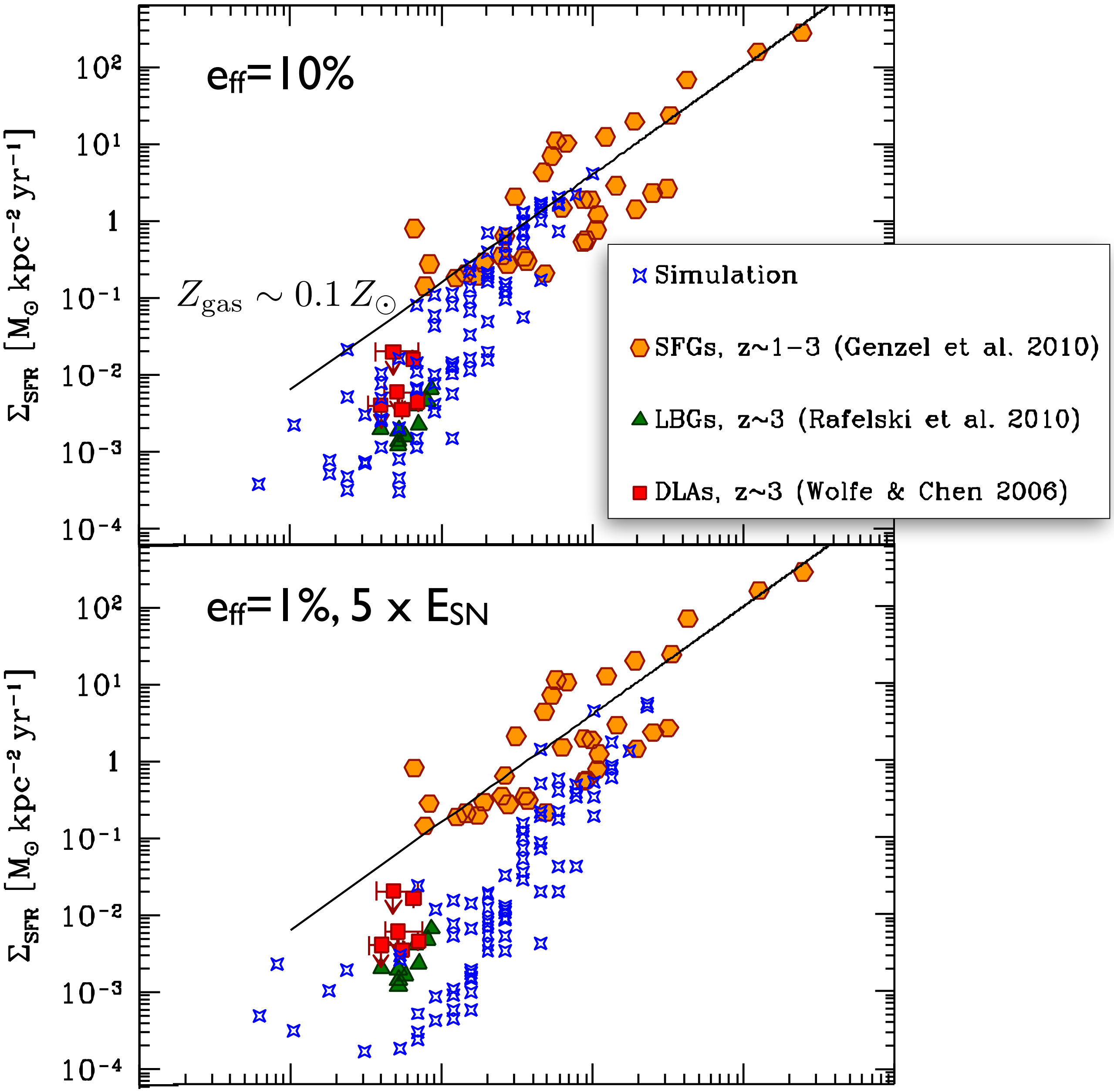
- **Boosting feedback to achieve global scaling relations destroys the galaxy** (see also *Agertz et al. 2011, Roskar et al. 2013*), illustrating a different star formation - feedback loop.



Breaking the degeneracies: the Kennicutt-Schmidt relation

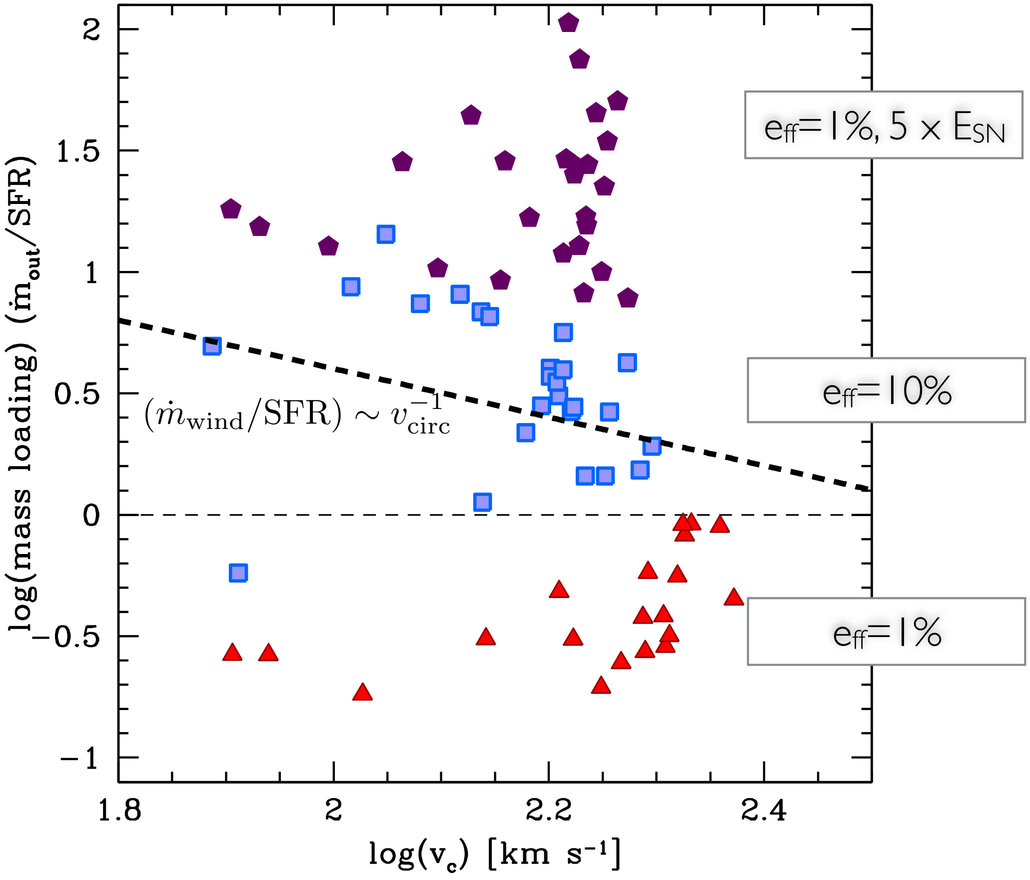
$$\Sigma_{\rm gas} - \Sigma_{\rm SFR}$$

- The fiducial model match the z=2-3 observations.
- The low surface density turn-off is driven by the gas metallicity in the disk's outskirt (see also *Gnedin et al. 2009, Krumholz et al. 2009*).
- Boosted feedback removes metals very (too?) efficiently, leading to a possible **over-suppression** of star formation at this epoch.



Breaking the degeneracies: Galactic winds

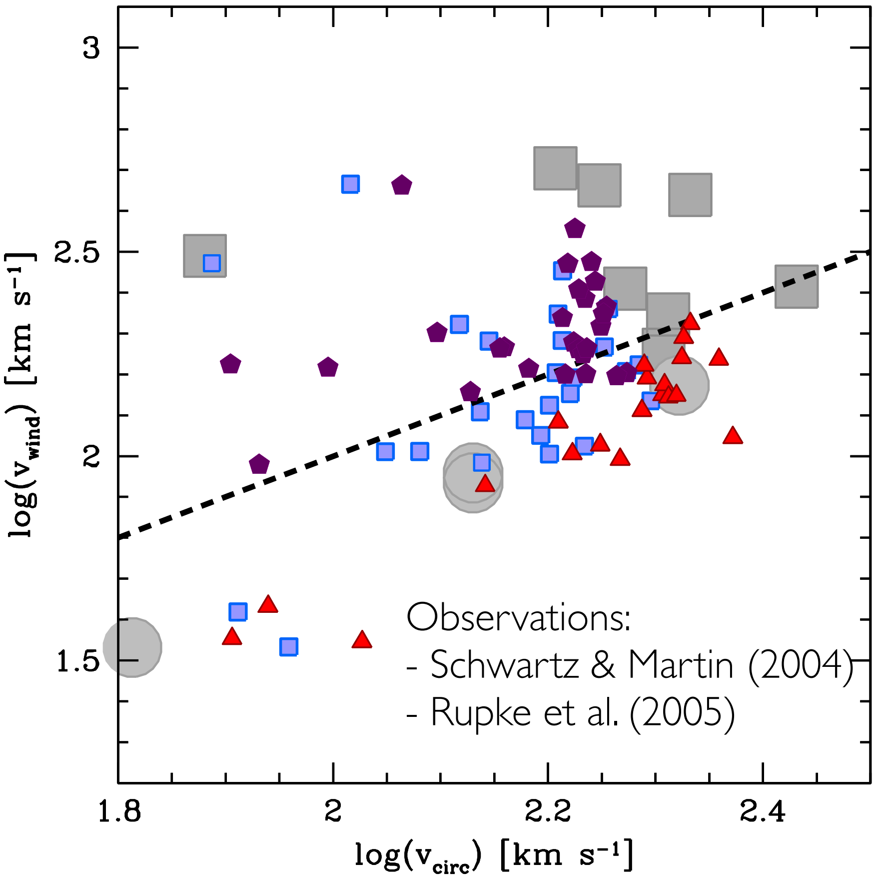
Mass-loading: $(\dot{m}_{\rm wind}/{\rm SFR}) - v_{\rm circ}$



- Different star formation - feedback loops predict dramatically different mass loading factors.

- NB: note comparison to hydro-decoupled "momentum-driven" winds claimed to be necessary to explain the galaxy luminosity function (e.g. *Oppenheimer & Dave 2006*).

Wind velocities: $v_{\rm wind} - v_{\rm circ}$



- Wind velocities similar in all models, although with significant scatter.

Caveats, uncertainties and points for discussion

- Galaxy formation simulations poorly resolves the gas density PDF relevant for star formation. Choices of star formation efficiency/model is applied on ~100 pc scales, and its connection to detailed models of star formation must be understood (e.g. *Krumholz & McKee 2005, Padoan & Nordlund 2011, Hennebelle & Chabrier 2011*).

- Does an H_2 based star formation model matter?

- Choice of star formation efficiencies, coupled with feedback, must ultimately make predictions on the mass function of young star clusters. The slope and characteristic masses may differ!

- The feedback physics is still not complete. What about cosmic rays?

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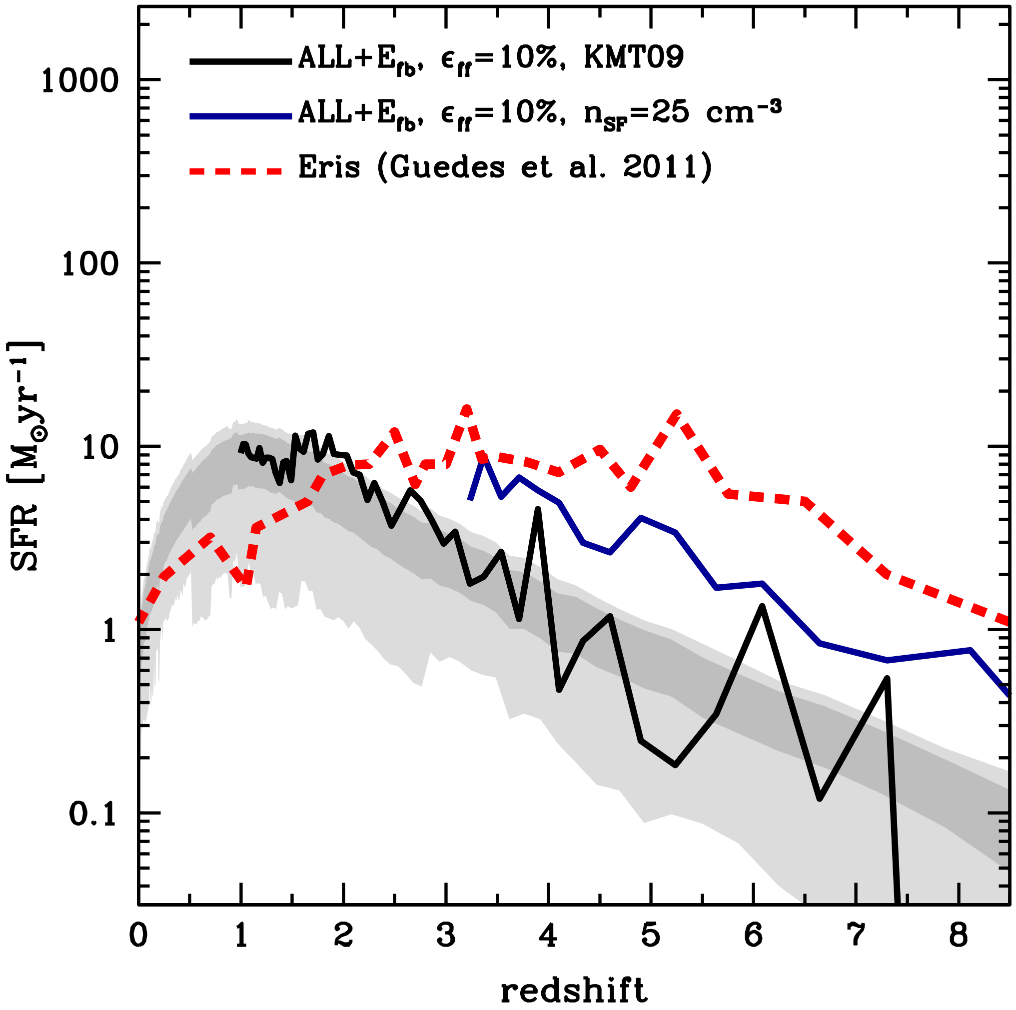

see also Christenen et al. (2012)

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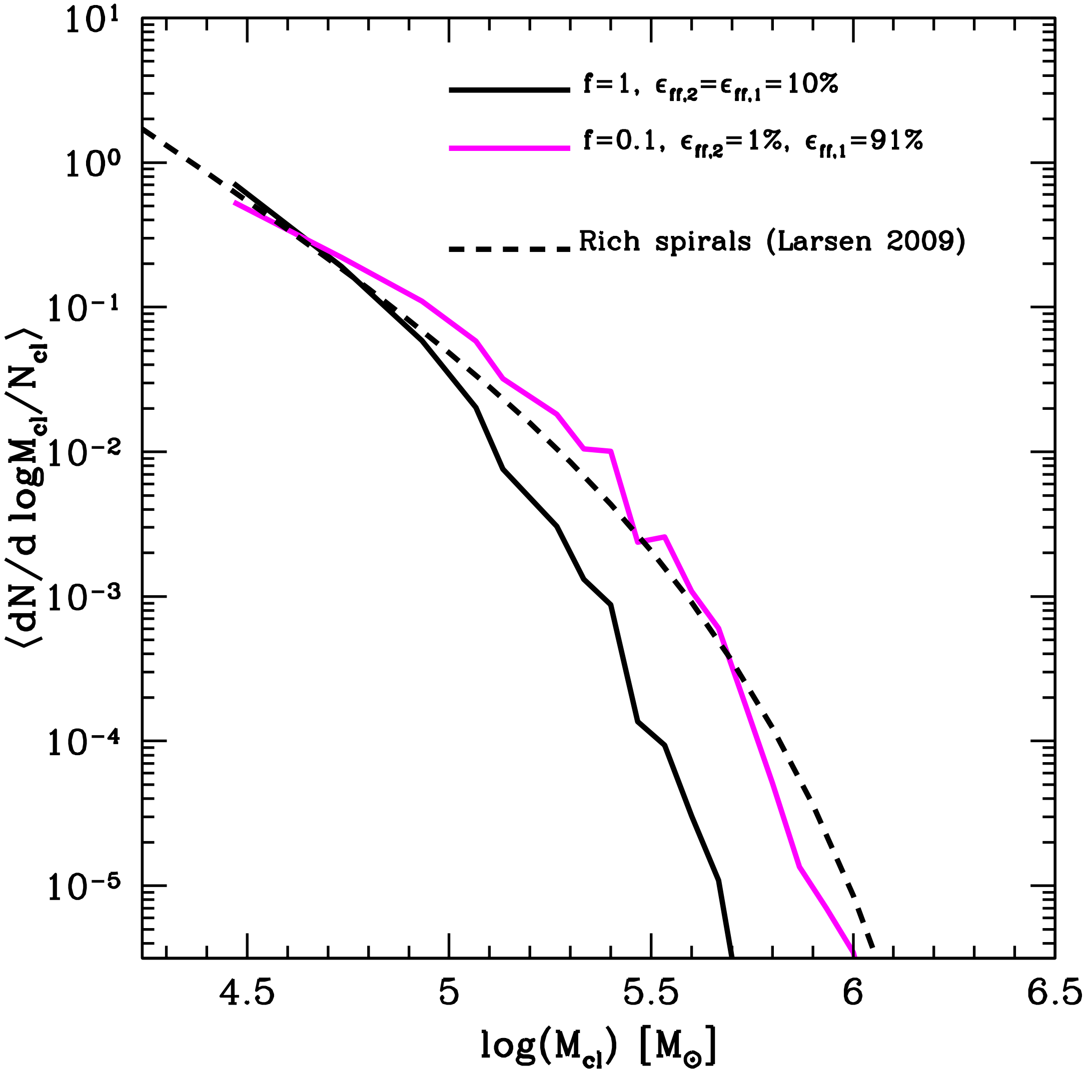

Agertz & Kravtsov (in prep)

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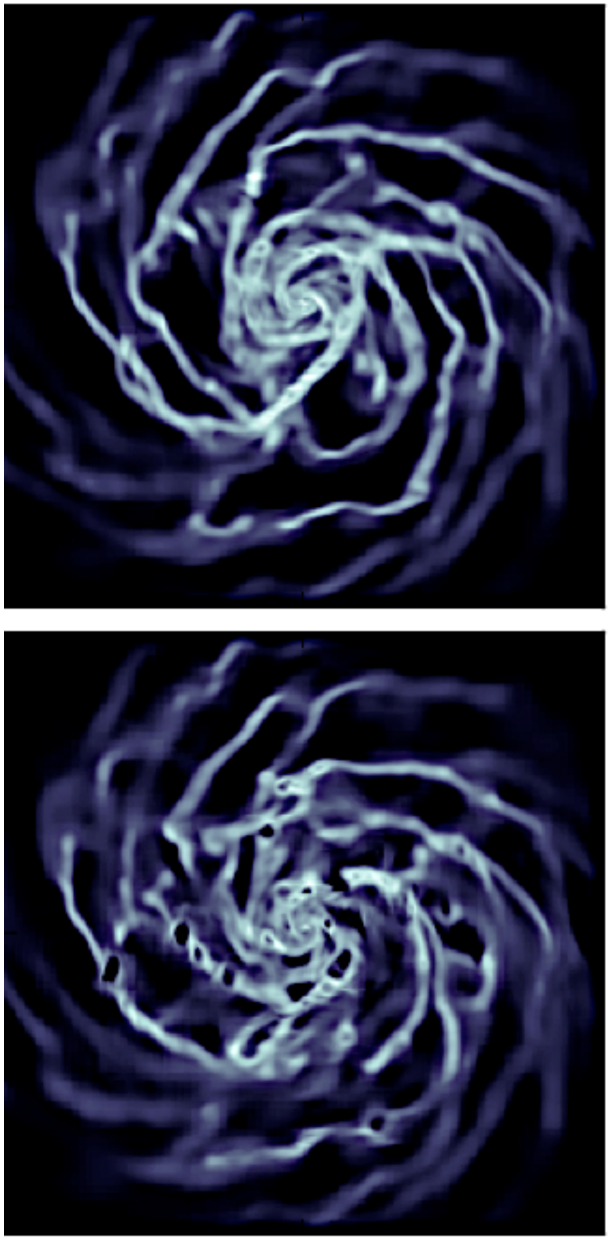

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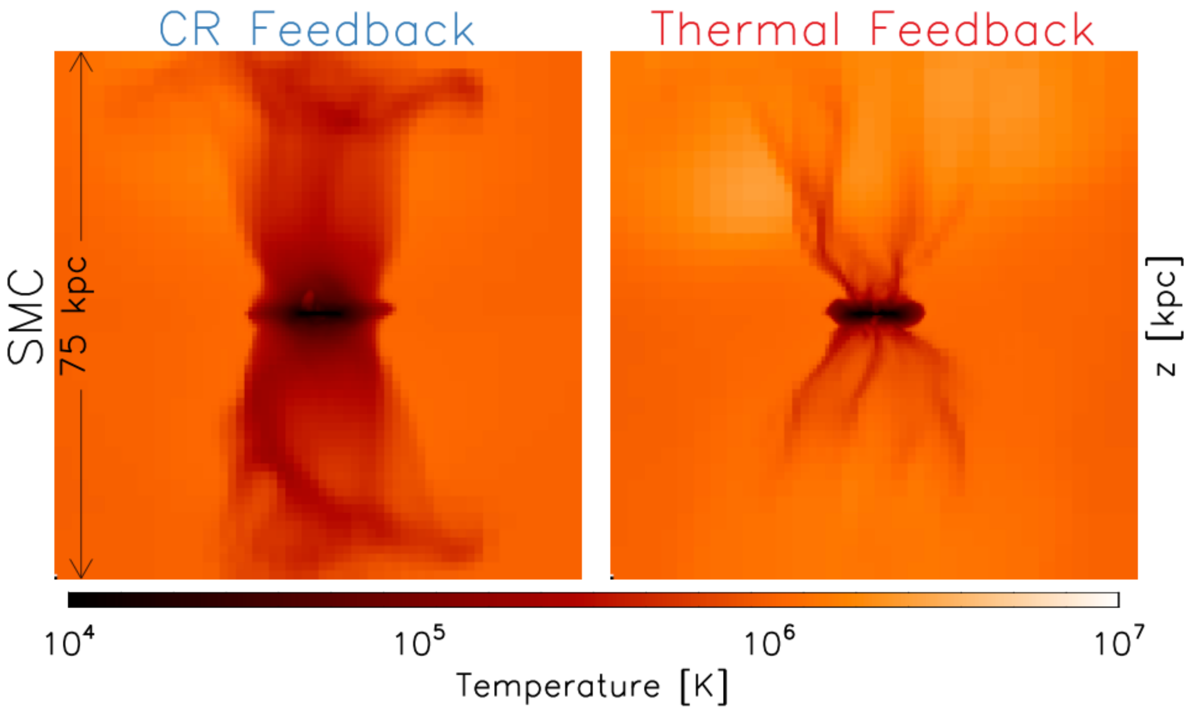
- The feedback physics is still not complete. What about cosmic rays?

- Accounted for in RAMSES by adding an advection-diffusion equation for the cosmic ray energy (Booth et al. 2013).

- Drives colder outflows compared to thermal feedback, which may discriminate feedback models

- Simulated cosmic ray driven winds have a strong effect on star formation histories and baryon fractions of low mass galaxies.



see also Jubelgas & Springel (2006), Ensslin (2007), Hanasz et al. (2013), Salem & Bryan (2013)

Conclusions

- The interplay between the underlying star formation model and the choice of stellar feedback model in simulations of galaxy formation is complex, and must be tested case by case.
- For a galaxy formation model accounting for stellar winds, radiation pressure, supernovae type II and Ia, in a time-dependent fashion, observed galaxy scaling relations arise when star formation is feedback regulated. This occurs when:
    1. The local e_{ff} is large (e_{ff}>10%), or
    2. More energy is given to the ISM by hand per stellar population (top heavy IMF?)
- The degeneracy can be broken with more data, here the Kennicutt-Schmidt relation, wind properties, and disk morphology.
- Simulations are state-of-the-art (dx~75 pc), but still operate on too large scales. More work necessary to "connect the scales" with modern star formation models.