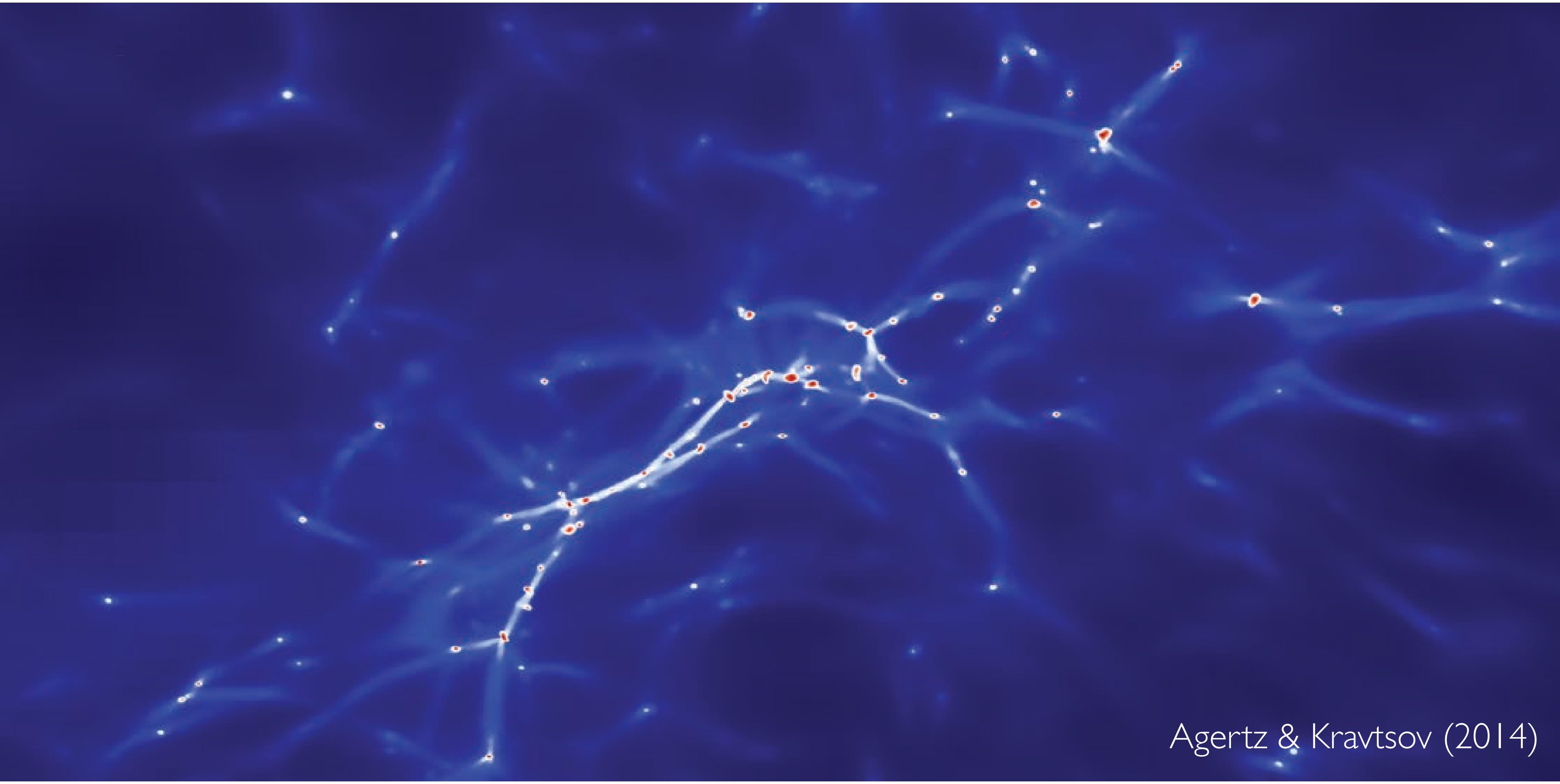
On the interplay between star formation and stellar feedback in galaxy formation simulations


Agertz & Kravtsov (2014)

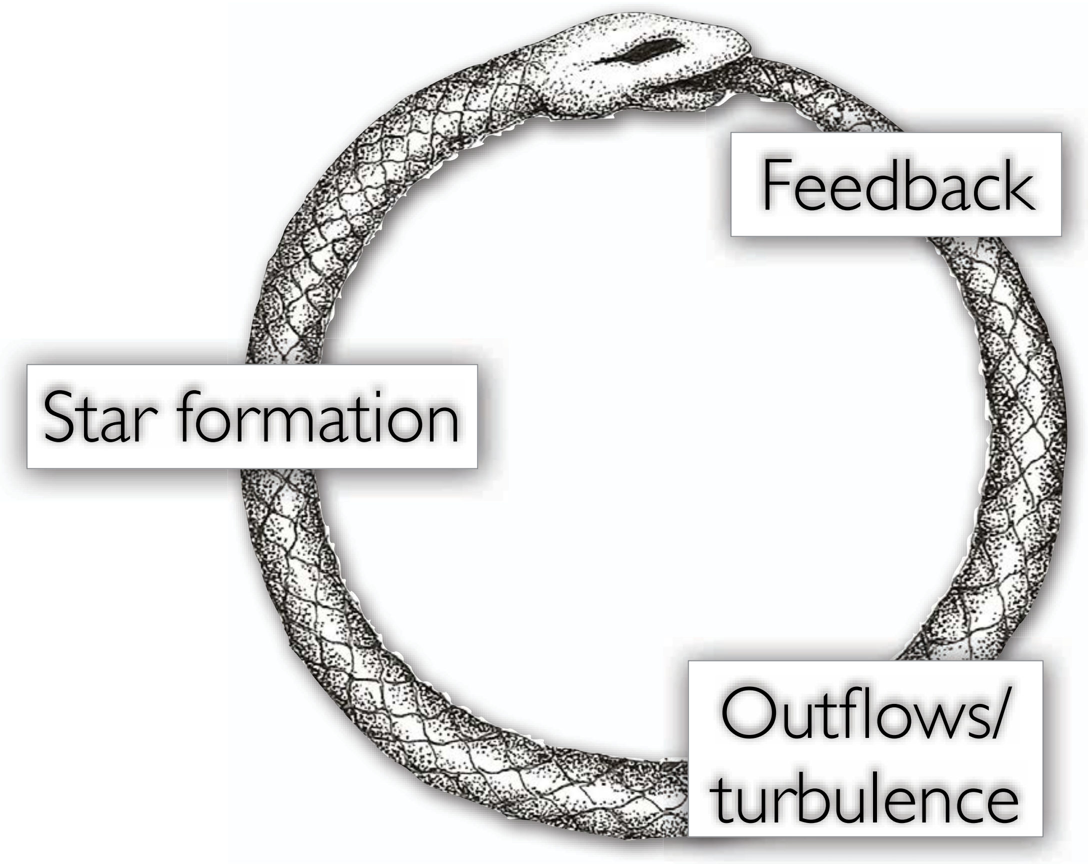
Oscar Agertz

UNIVERSITY OF SURREY

with Andrey Kravtsov, Nick Gnedin and Sam Leitner

Santa Cruz, 12 August 2014

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



Feedback

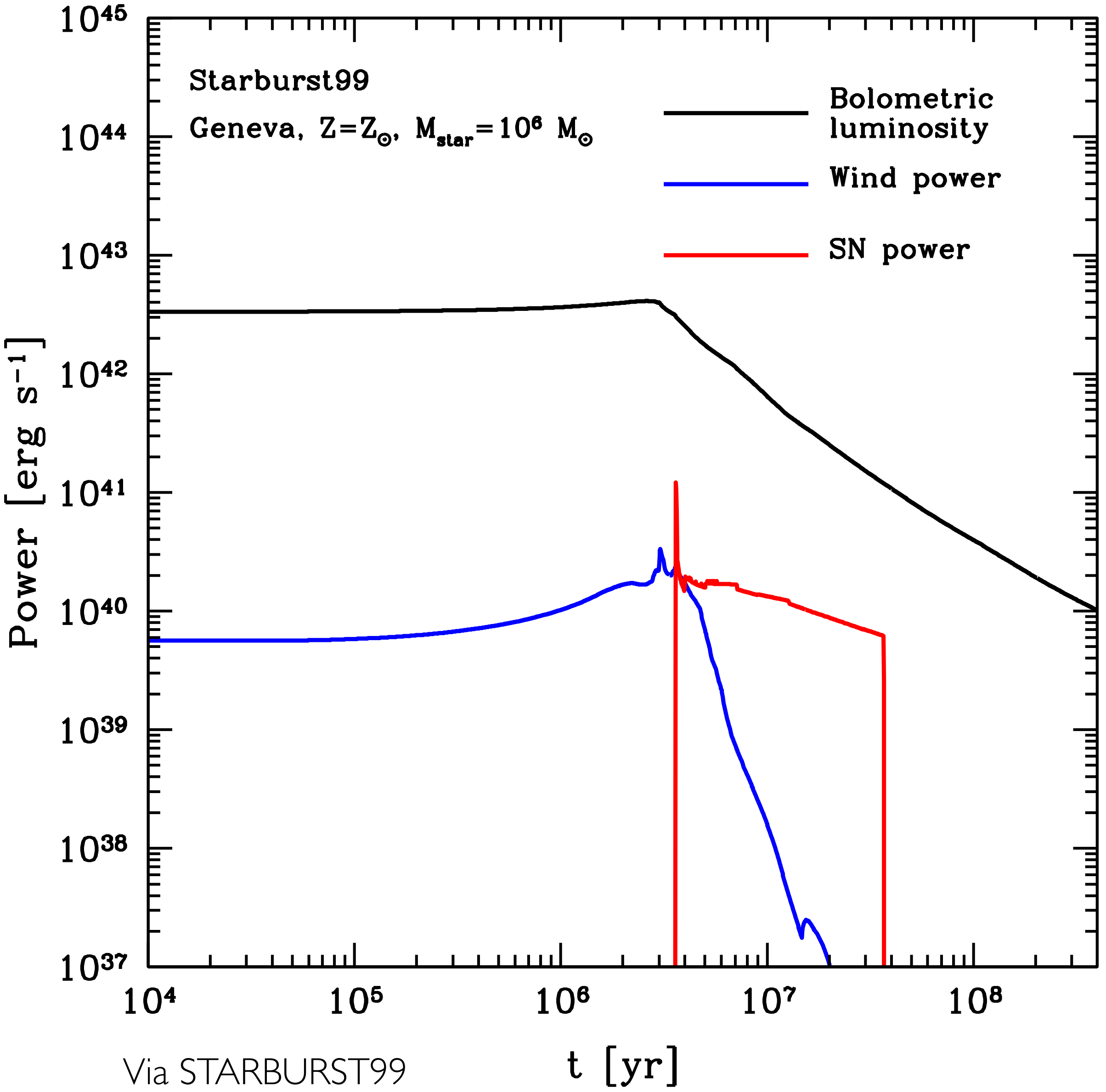
Star formation

Outflows/ turbulence

- Which models of star formation and stellar feedback achieve reasonable galactic characteristics?
- Are galaxy formation models degenerate, and if so, how can we break those degeneracies? (galactic morphologies? wind properties?)

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, 2013), Ceverino et al. (2013)*.

- 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 rates 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*)

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

- **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*).

Feedback energy injection/evolution

- 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*). Explicit model for **super bubbles**? *(Keller, Wadsley et al. 2014)*

- For most of our models, we evolve a fraction of the feedback energy using a second energy equation. **See also *Teyssier et al. (2013).***

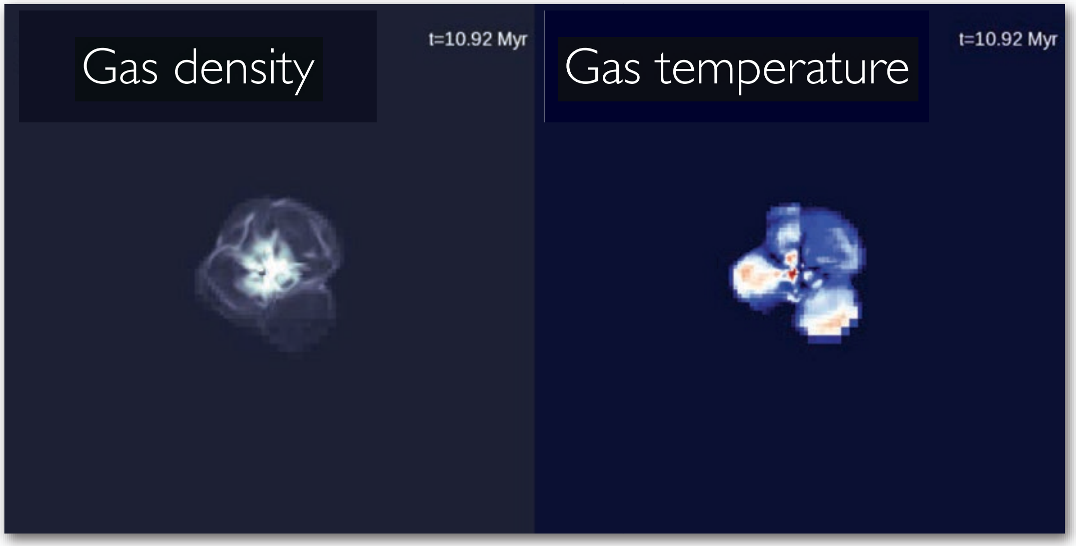
$$\frac{\partial}{\partial t}(E_{\rm fb}) + \nabla \cdot (E_{\rm fb} v_{\rm gas}) = -P_{\rm fb} \nabla \cdot v_{\rm gas} - \frac{E_{\rm fb}}{t_{\rm dis}}$$

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

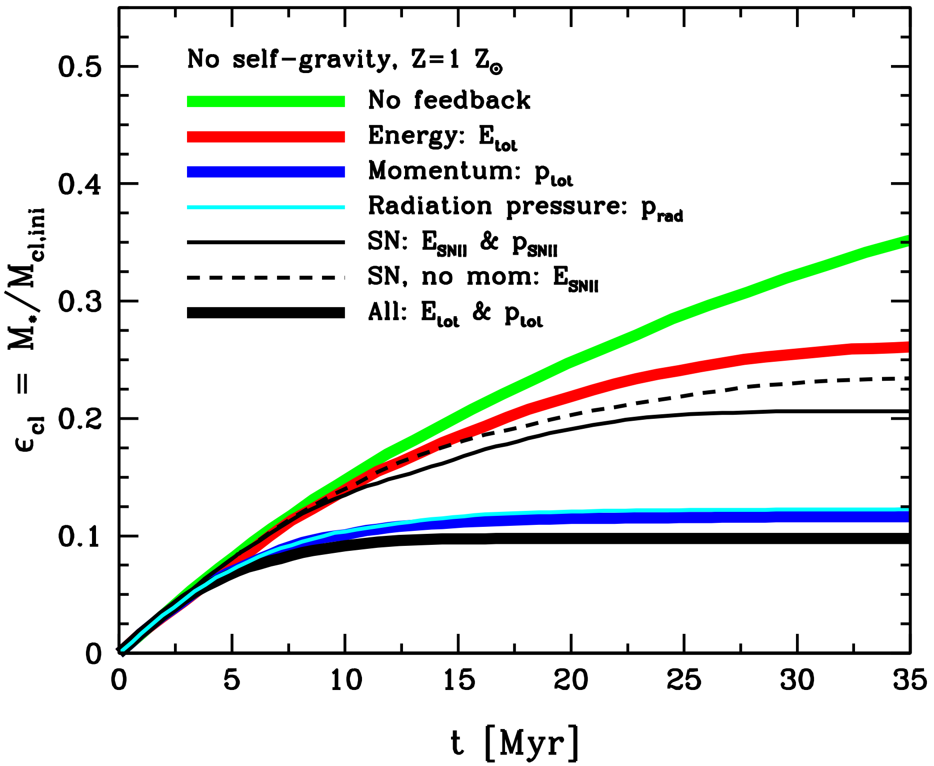
Idealized experiment at the resolution (almost) affordable in galaxy formation simulations:

The star formation efficiency in a Giant Molecular Cloud

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



Cloud star formation efficiency vs time



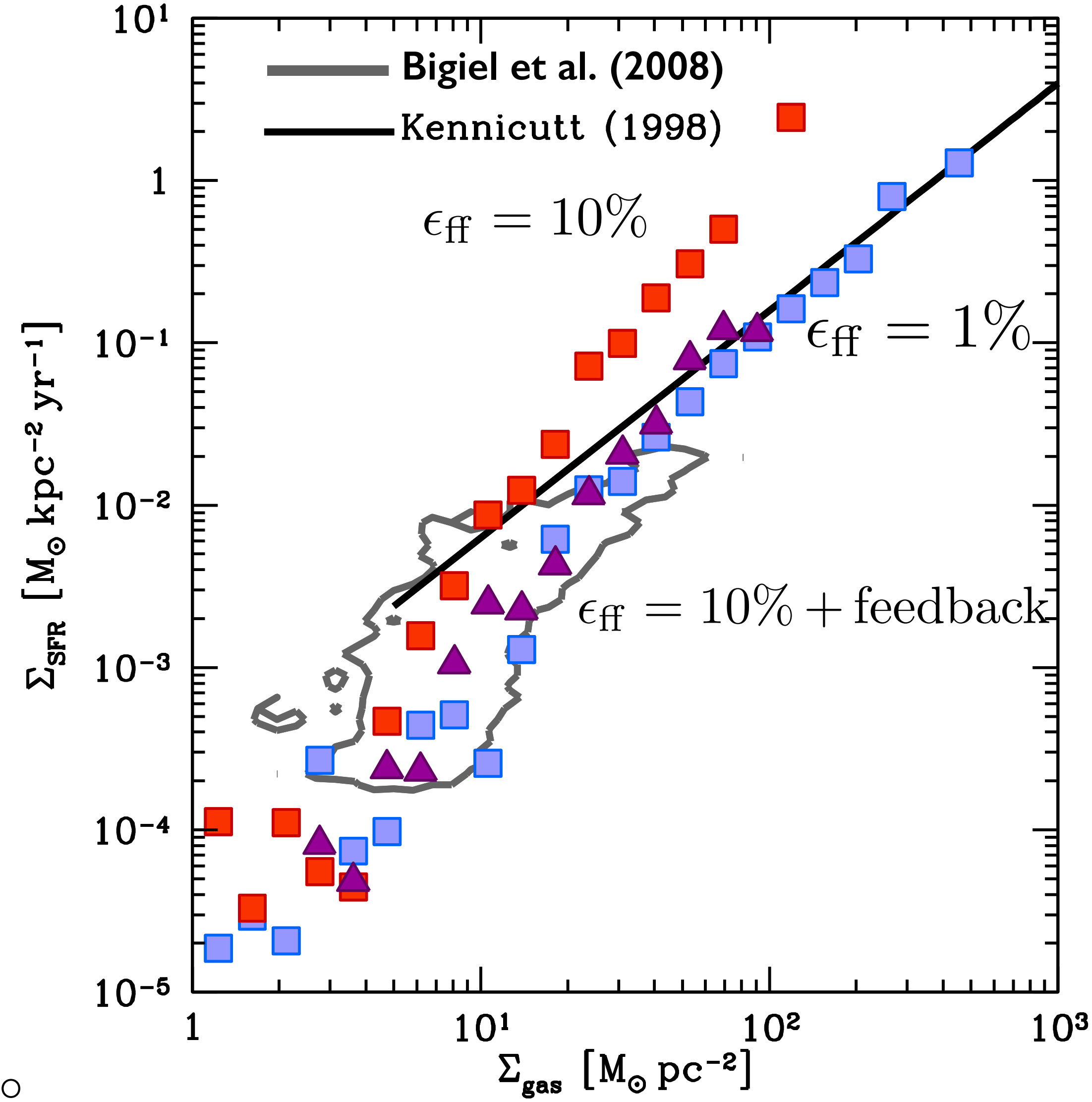
- When the full feedback model is accounted for, the results agree with luminosity weighted observed conversion efficiencies in massive Milky Way GMCs (*Evans et al. 2009, Murray 2011*)

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

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

Feedback strength and the Kennicutt-Schmidt relation

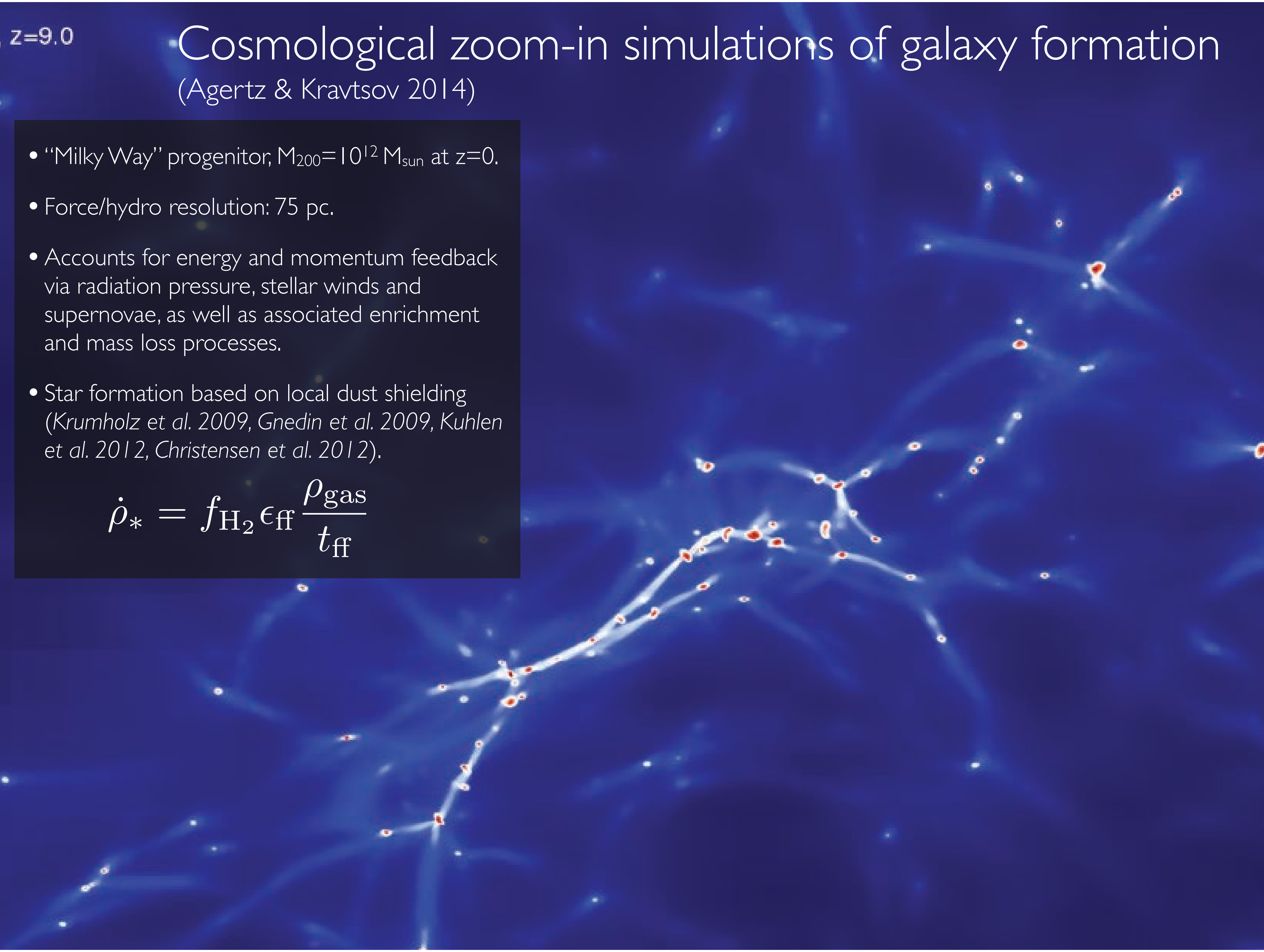
$$\dot{\rho}_* = \epsilon_{\rm ff} f_{\rm H_2} \frac{\rho_{\rm gas}}{t_{\rm ff}}$$



- Without feedback, the normalization of the Kennicutt-Schmidt relation is sensitive to the assumed star formation efficiency per free-fall time.
- Adopting our full feedback budget makes the simulated Kennicutt-Schmidt relation less sensitive to the underlying $\epsilon_{\rm ff}$, and in closer agreement to observations.

Cosmological zoom-in simulations of galaxy formation

(Agertz & Kravtsov 2014)



- "Milky Way" progenitor, $M_{200}=10^{12}$ M_{sun} at z=0.
- Force/hydro resolution: 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 dust shielding (*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)

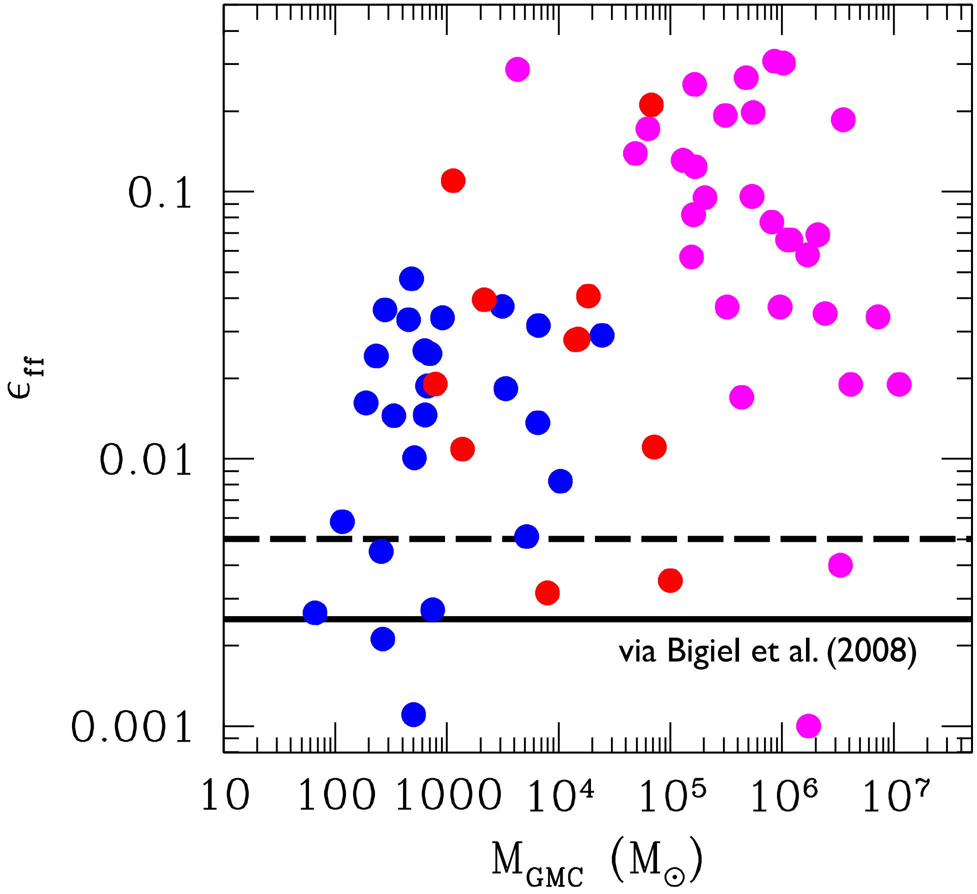
- Which models of star formation and stellar feedback achieve reasonable galactic characteristics?

- We parametrize the location star formation rate as: $\dot{\rho}_* = f_{H_2} \frac{\rho_g}{t_{SF}}$ $t_{SF} = t_{ff}/\epsilon_{ff}$

- On large (~kpc) scales, star formation is slow! (e.g. THINGS: *Leroy et al. 2008*) $\epsilon_{ff} = t_{ff,SF}/t_{H_2,gal} \sim 0.25\%$

- On the scale of GMCs, it is less clear and may depend on the environment (*Evans et al. 2009, Murray 2011*), as indicated by simulations (e.g. *Padoan and Nordlund 2011*). Could also be signs of evolution (Feldmann & Gnedin 2010)

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



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

Cosmological zoom-in simulations of galaxy formation

(Agertz & Kravtsov 2014)

- Which models of star formation and stellar feedback achieve reasonable galactic characteristics?

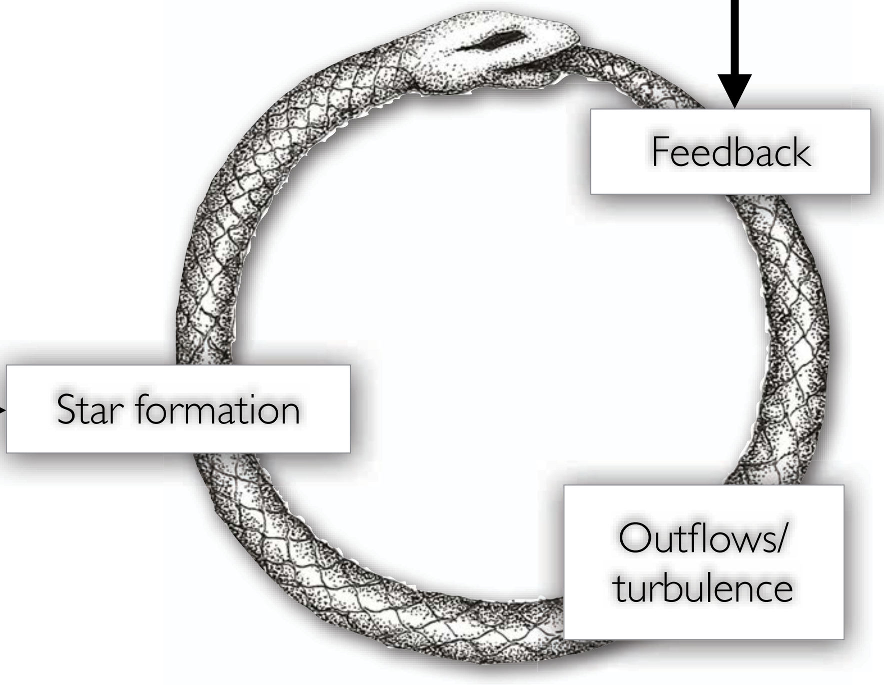
Stellar feedback driven outflow are necessary to ***simultaneously*** predict observed/inferred characteristics such as:

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

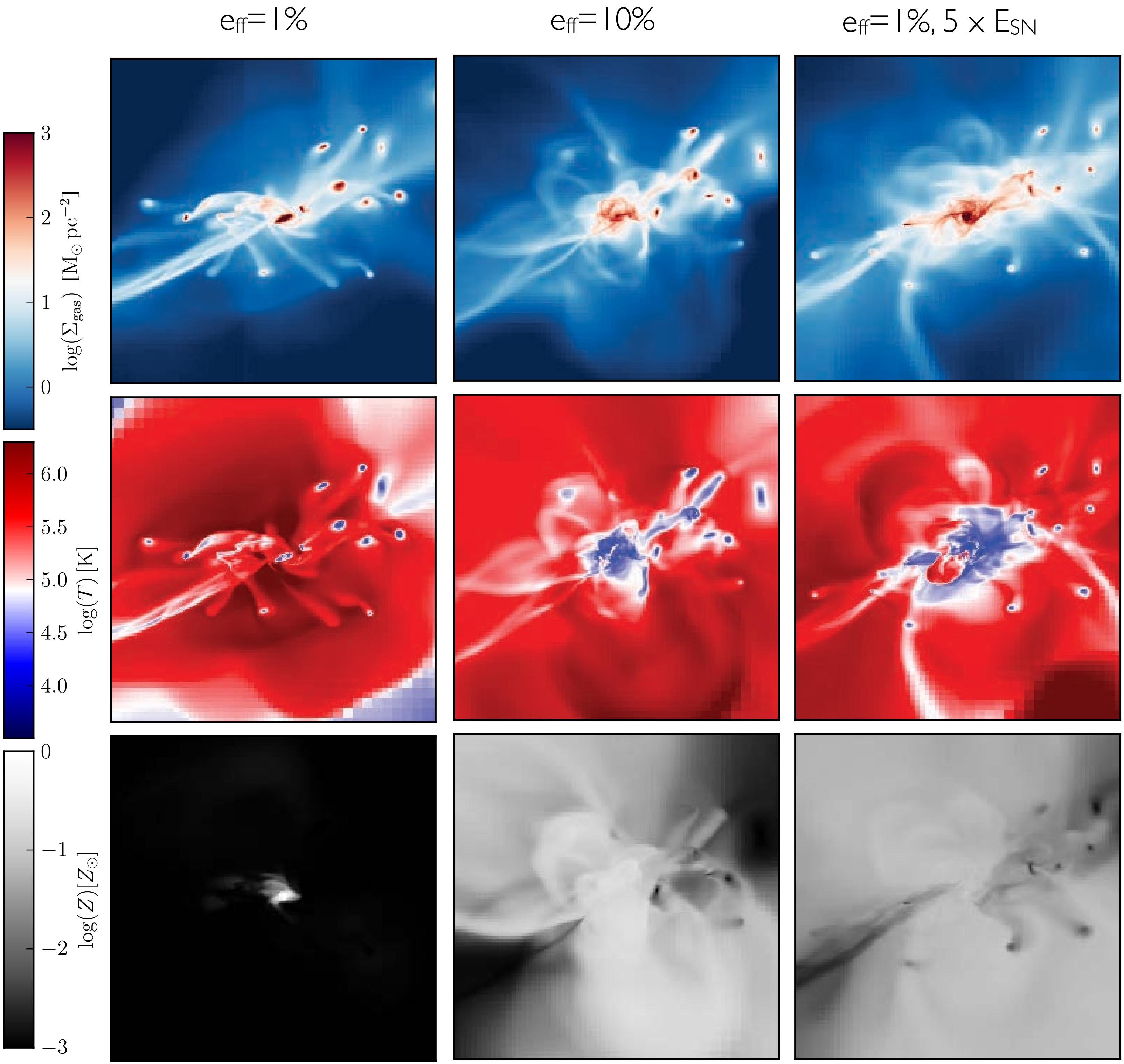
The way in which this is achieved matters!

2) Low **e_{ff} (=1%)** and boosted supernovae feedback (**E_{SN}=5 x 10^{51} erg**)

1) Low or high star formation efficiency per free-fall time: **e_{ff} =1%** vs **e_{ff} =10%**



A qualitative view at z=3

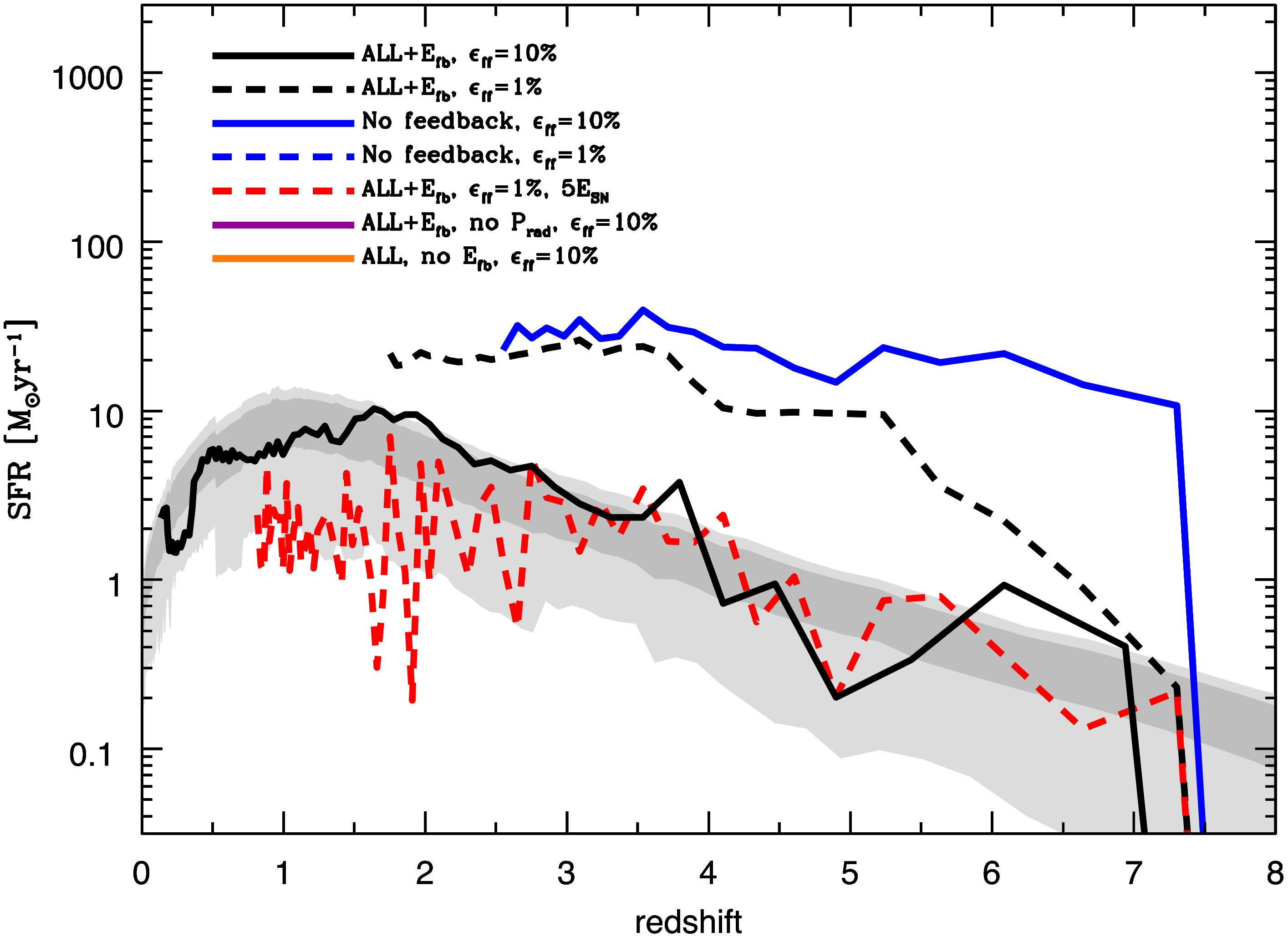


Gas density

Gas temperature

Gas metallicity

Star formation histories



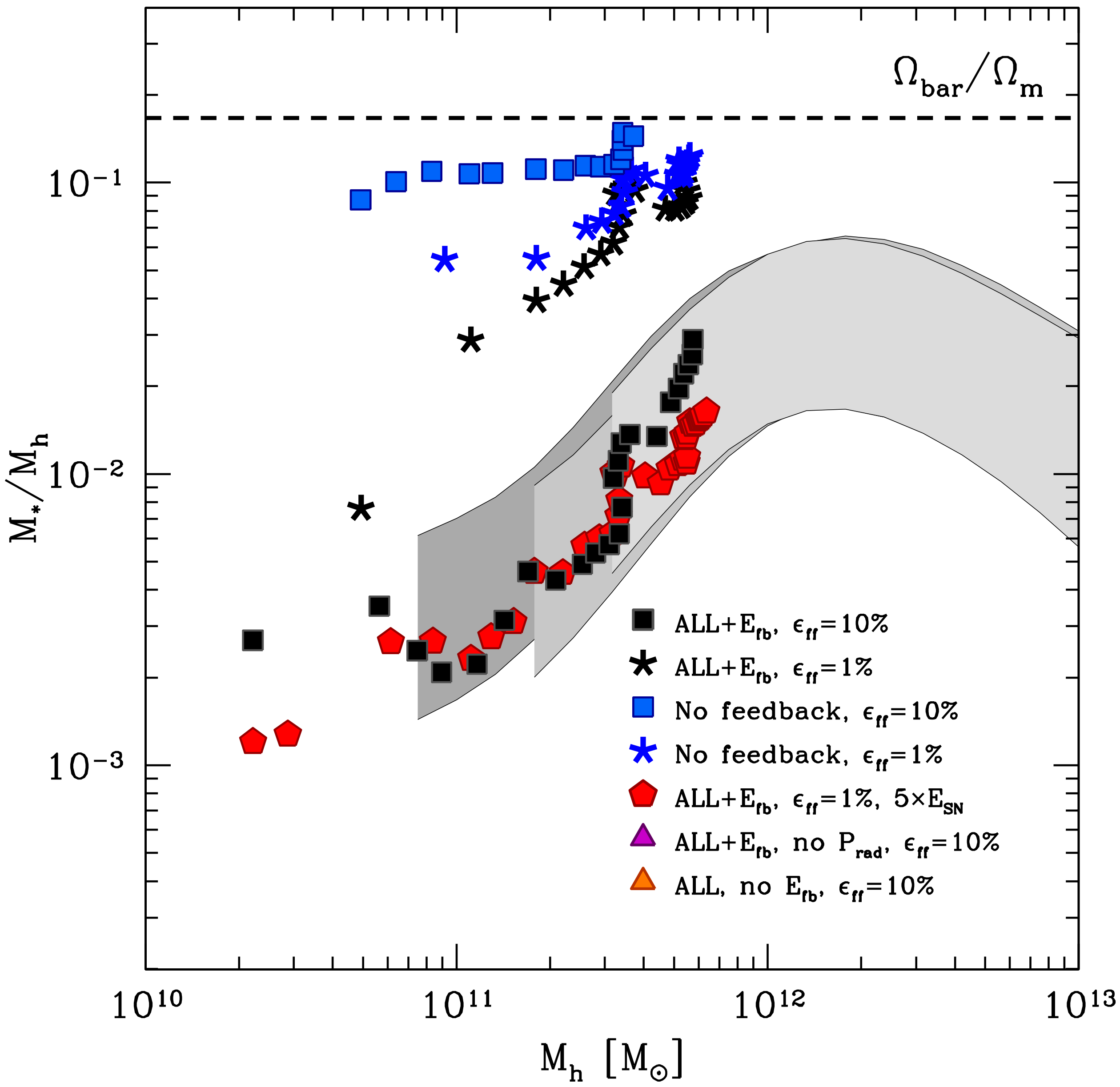
Star formation in Milky Way-like galaxies is expected to be highly suppressed for the first 3 billion years!

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

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

Semi-empirical data for a 10^{12} Msun halo from *Behroozi et al. (2013)*

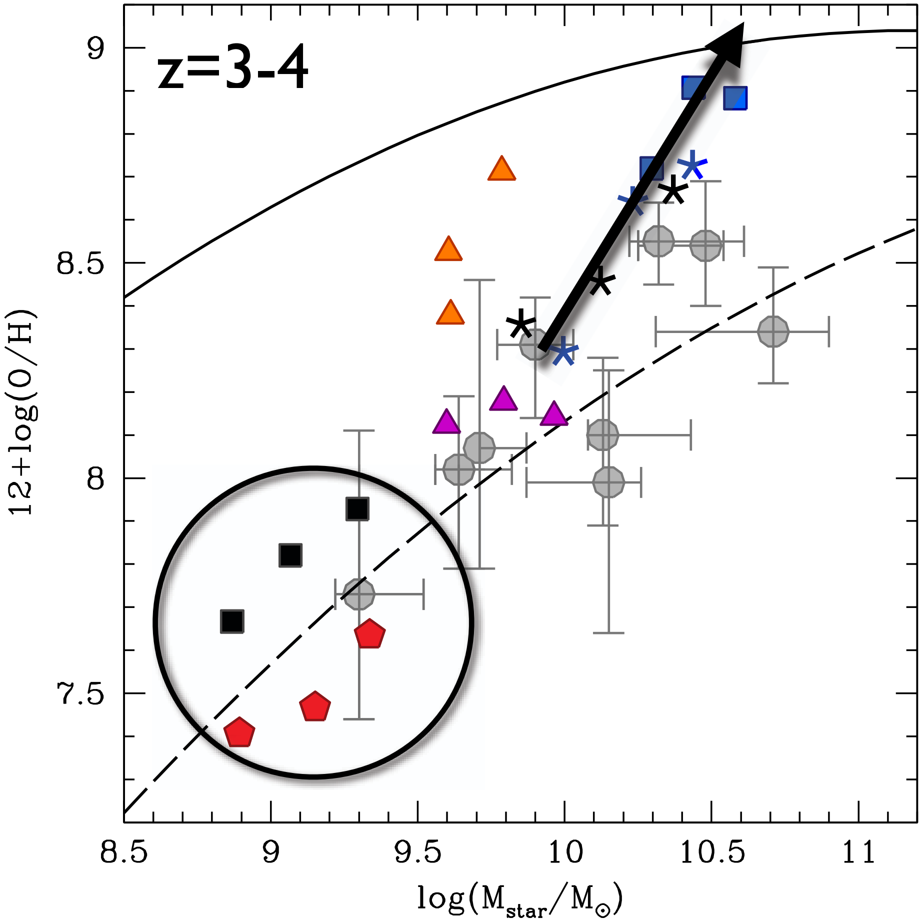
Stellar mass fraction - halo mass relation



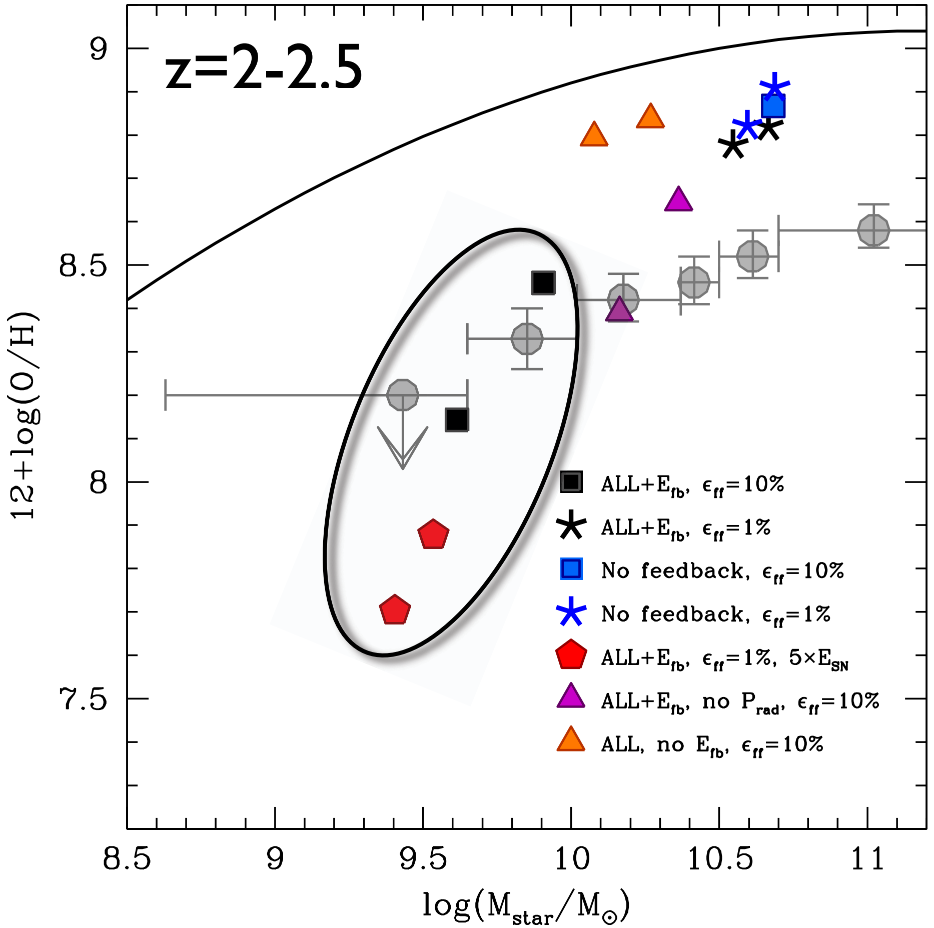
Semi-empirical data at z=3, 2 and1from *Behroozi et al. (2013)*

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

Stellar mass-gas metallicity



Observational data from *Maiolino et al. (2008)* and *Tremonti et al. (2004) (z~0.1)*



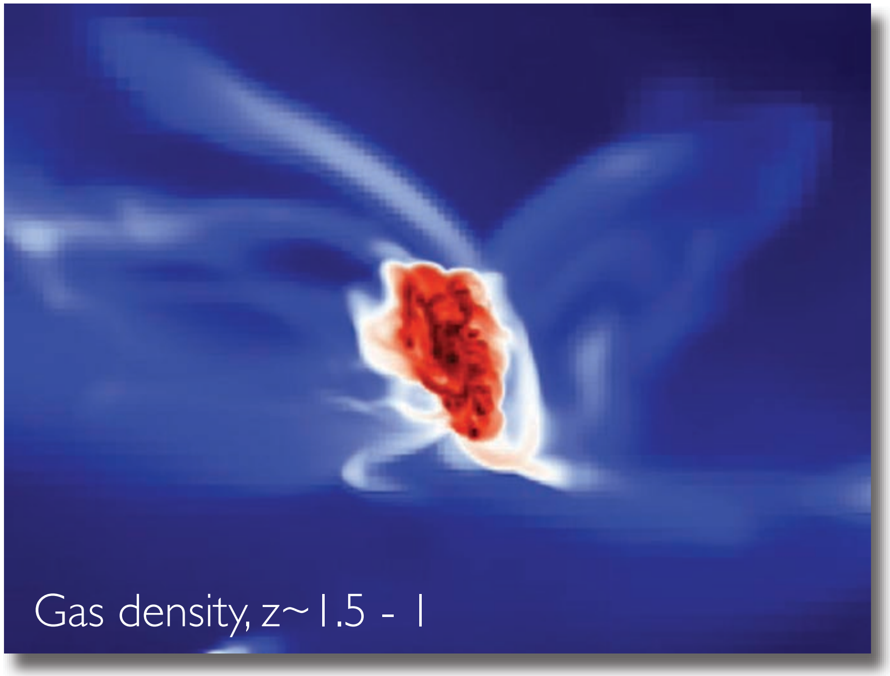
Observational data from *Erb et al. (2006)* and *Tremonti et al. (2004) (z~0.1)*

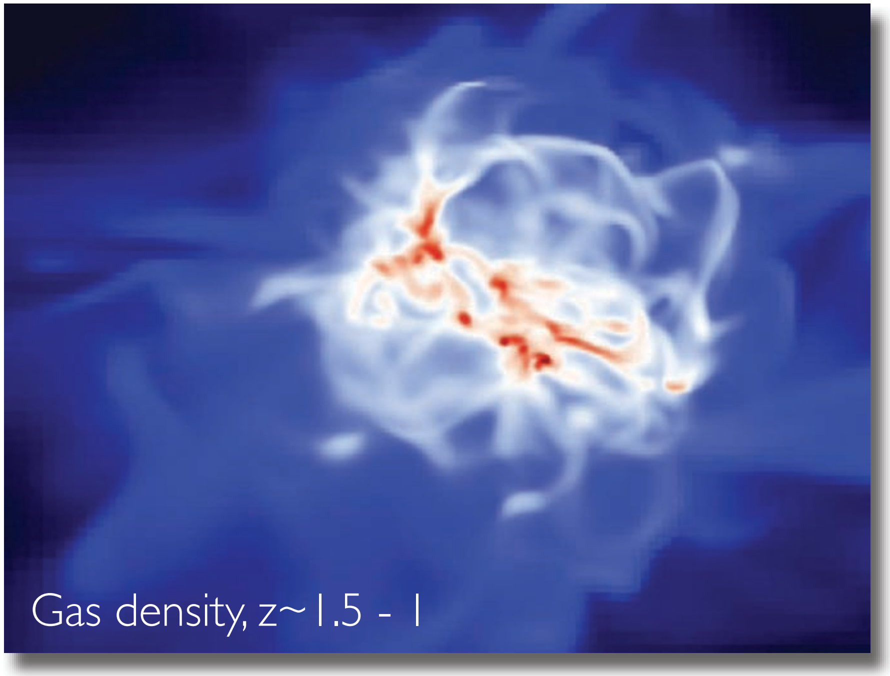
Without enriched winds, galaxies rapidly evolves off the observed relation, and reach the z=0 relation already at z>3. **Matching only the z=0 relation is not a sufficient metric of a successful galaxy formation model (see also Brooks et al. 2007).**

Breaking the degeneracies

Reasonable galactic properties are achievable by

1. correlated feedback via correlated star formation (large local efficiency per free-fall time), or
2. boosting the available energy per supernova by hand



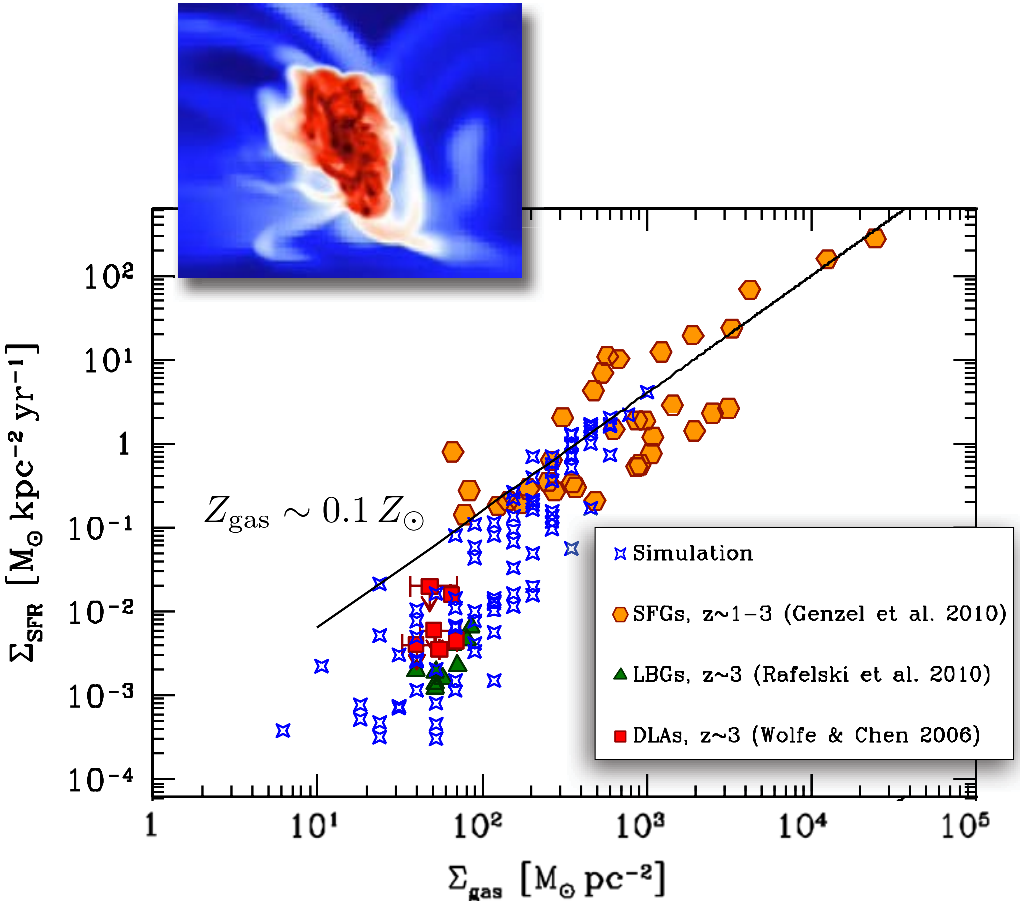


1. Fiducial (e_{ff}=10%)
Enters an epoch of disk formation by z~1 (see e.g. *Kassin et al. 2012, Elmegreen & Elmegreen 2014*)

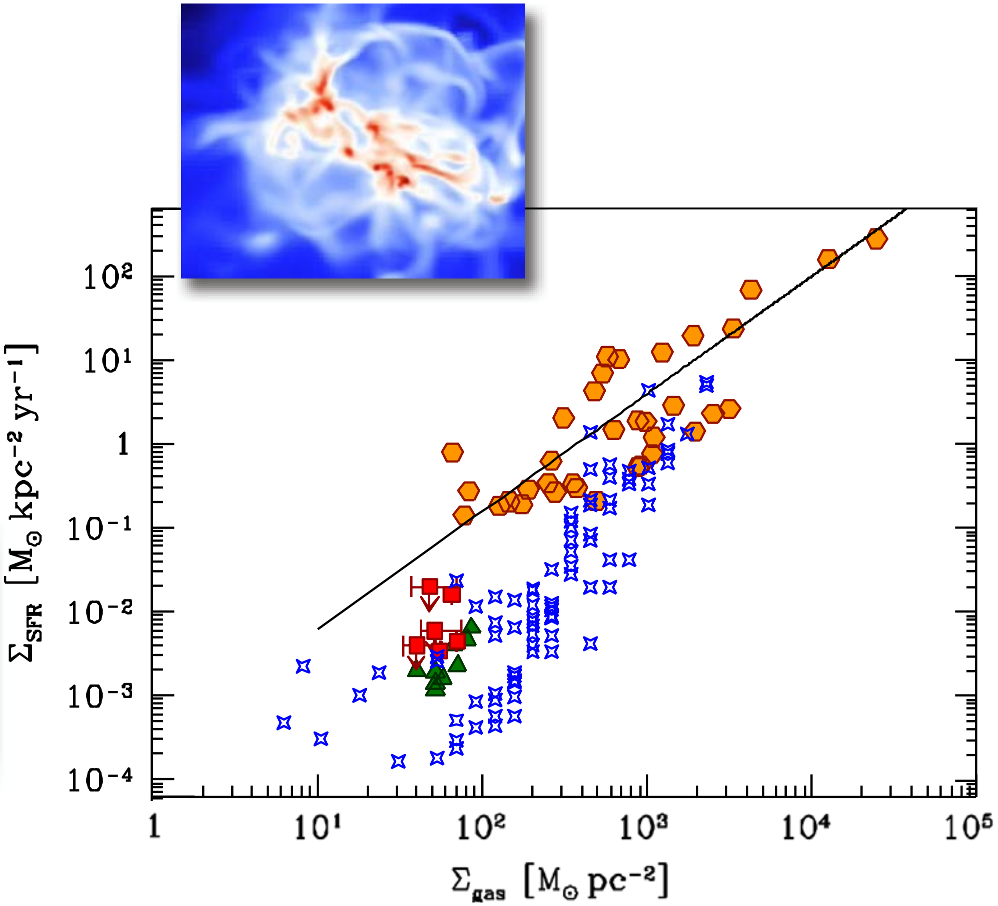
2. Boosted feedback (e_{ff}=1%, 5xE_{SN})
Vigorous galactic winds at all epochs make it impossible for the gas to settle into a cold configuration. (see also *Agertz et al. 2011, Roskar et al. 2013*),

Breaking the degeneracies: the Kennicutt-Schmidt relation

$\Sigma_{\rm gas} - \Sigma_{\rm gas}$ at $z = 2 - 3$



1. Fiducial (eff=10%)

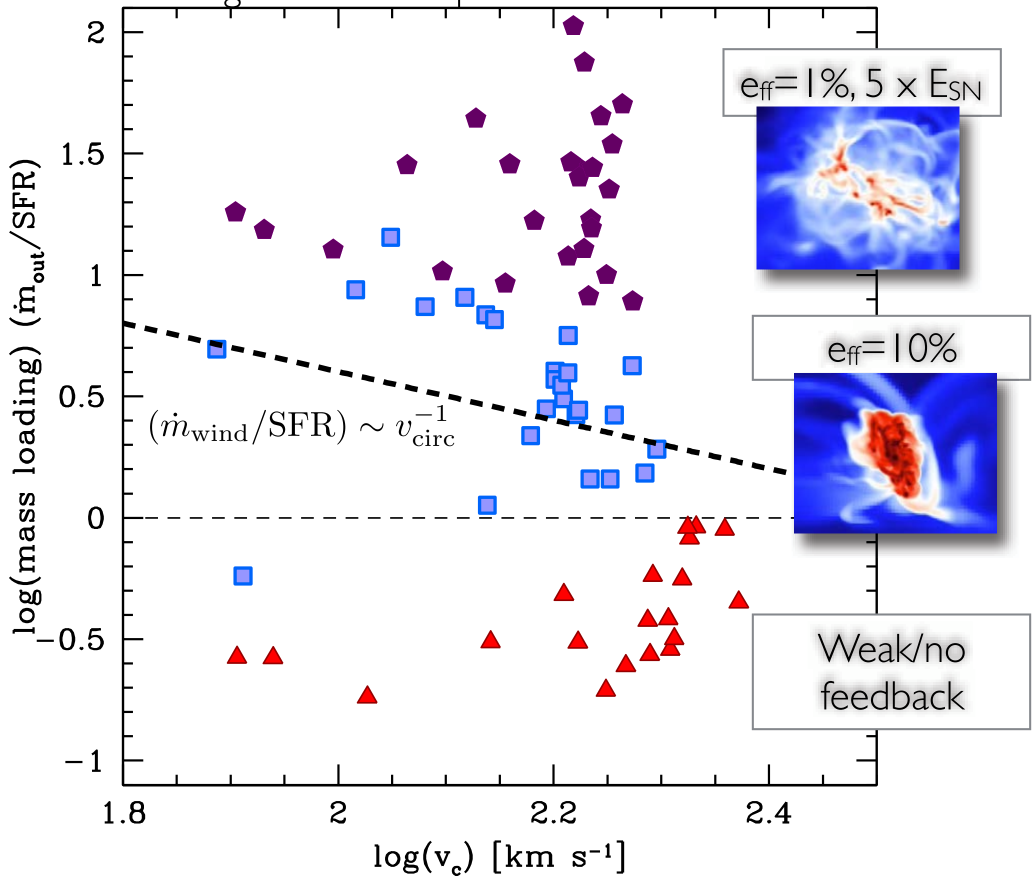


2. Boosted feedback (eff=1%, 5xE$_{\rm SN}$)

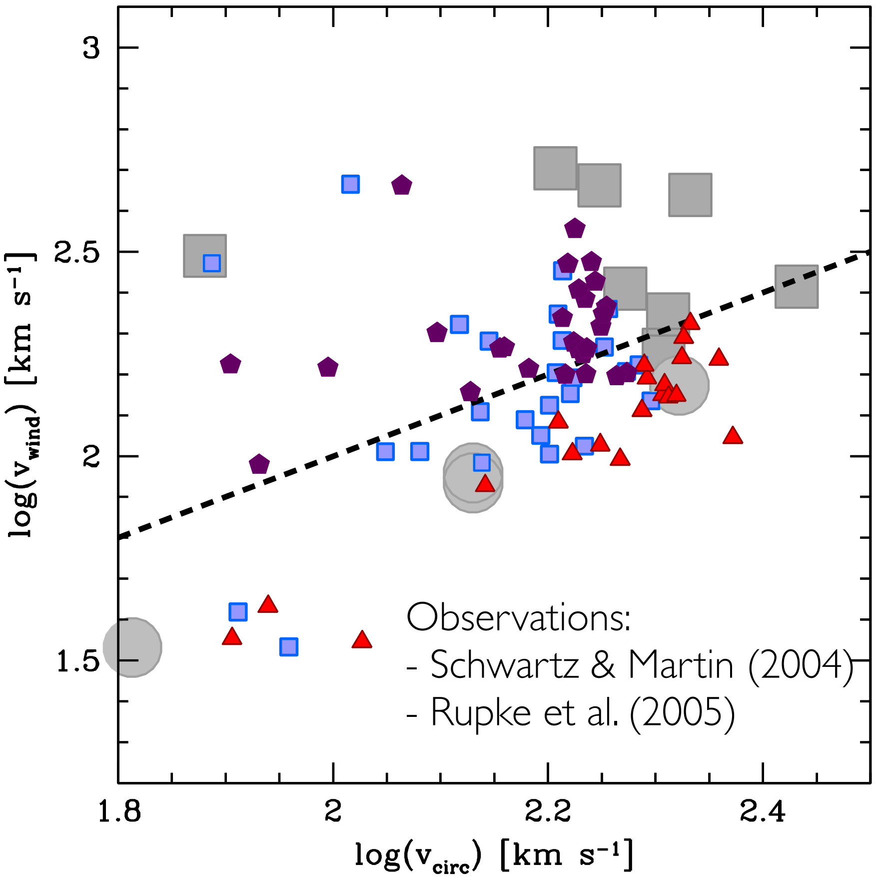
Breaking the degeneracies: Galactic winds

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

Average out to 20 kpc outside of disk for v>0



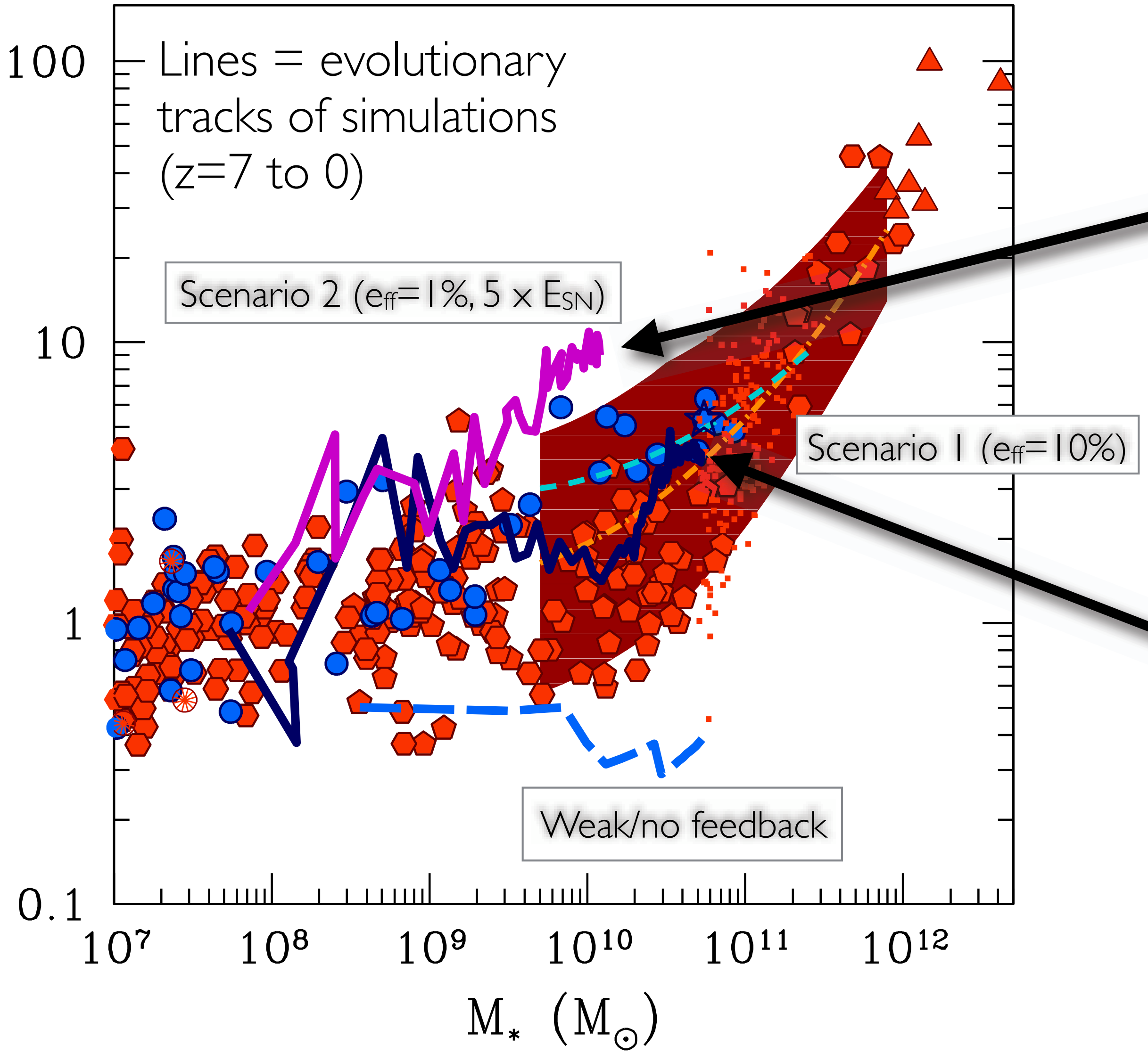
Wind velocities: $v_{\rm wind} - v_{\rm circ}$



- Different star formation - feedback cycles 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 similar in all models, although with a significant scatter.

Breaking the degeneracies: Galaxy sizes (Agertz & Kravtsov in prep.)



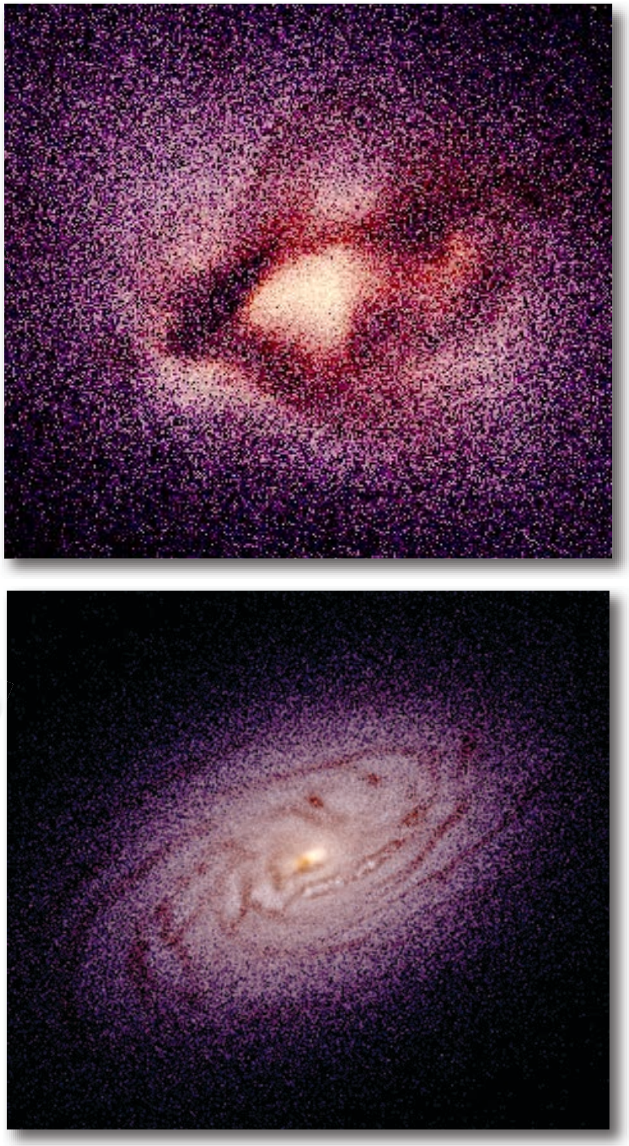
Lines = evolutionary tracks of simulations (z=7 to 0)

Scenario 2 (e_{ff}=1%, 5 x E_{SN})

Scenario 1 (e_{ff}=10%)

Weak/no feedback

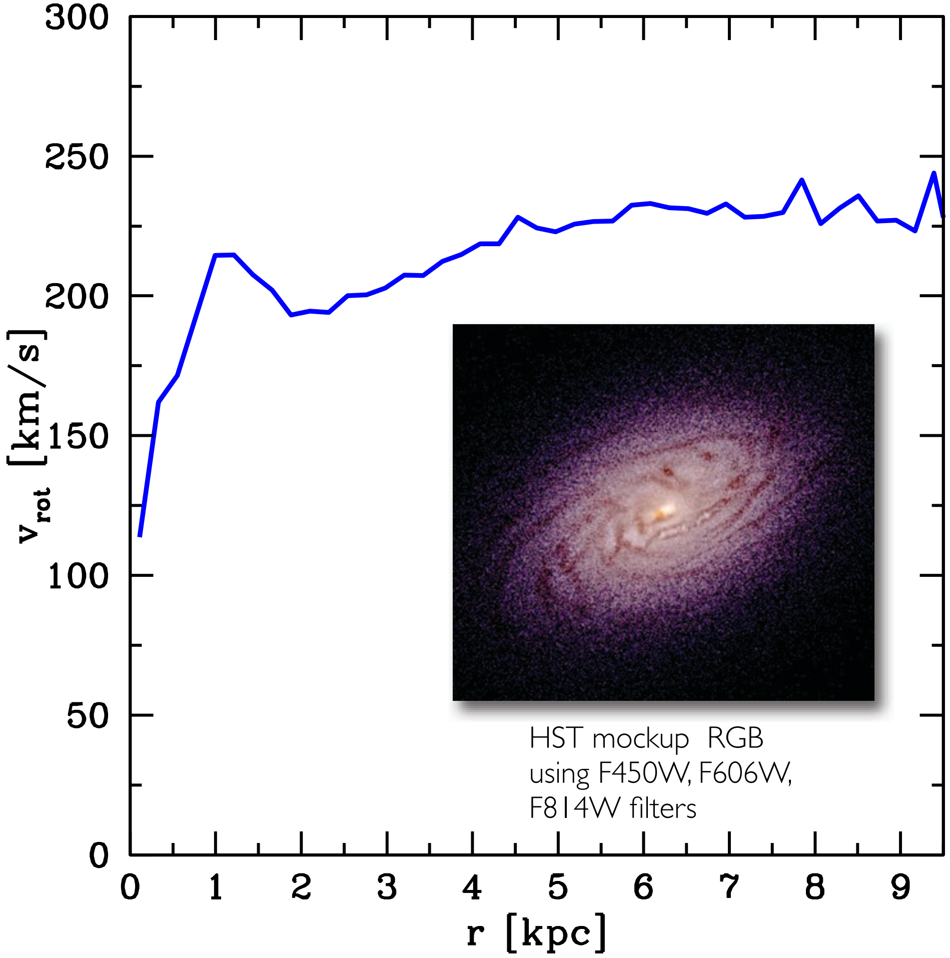
Observational data from Misgeld & Hilker (2011), Leroy et al. (2008), Zhang et al. (2012), Bernardi et al. (2012). Szomoru et al. (2013)



HST mockup
RGB using F450W, F606W, F814W filters

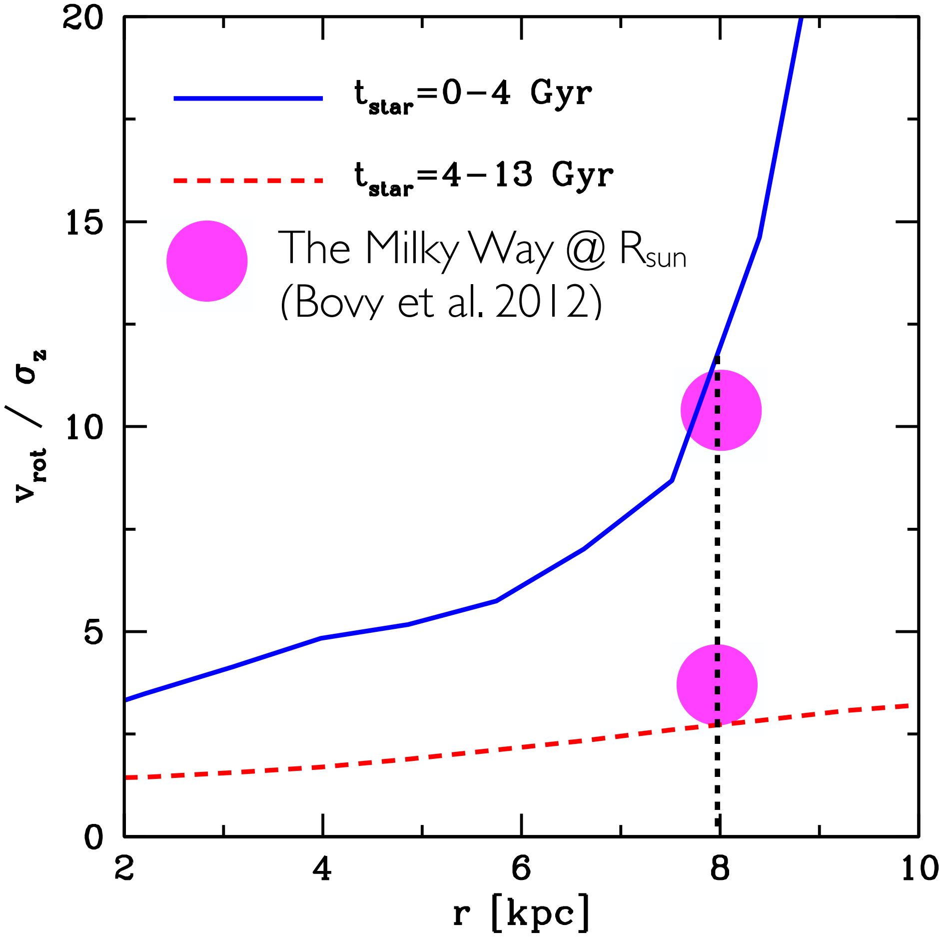
Thin and thick disks at z=0

Stellar rotational velocity



HST mockup RGB using F450W, F606W, F814W filters

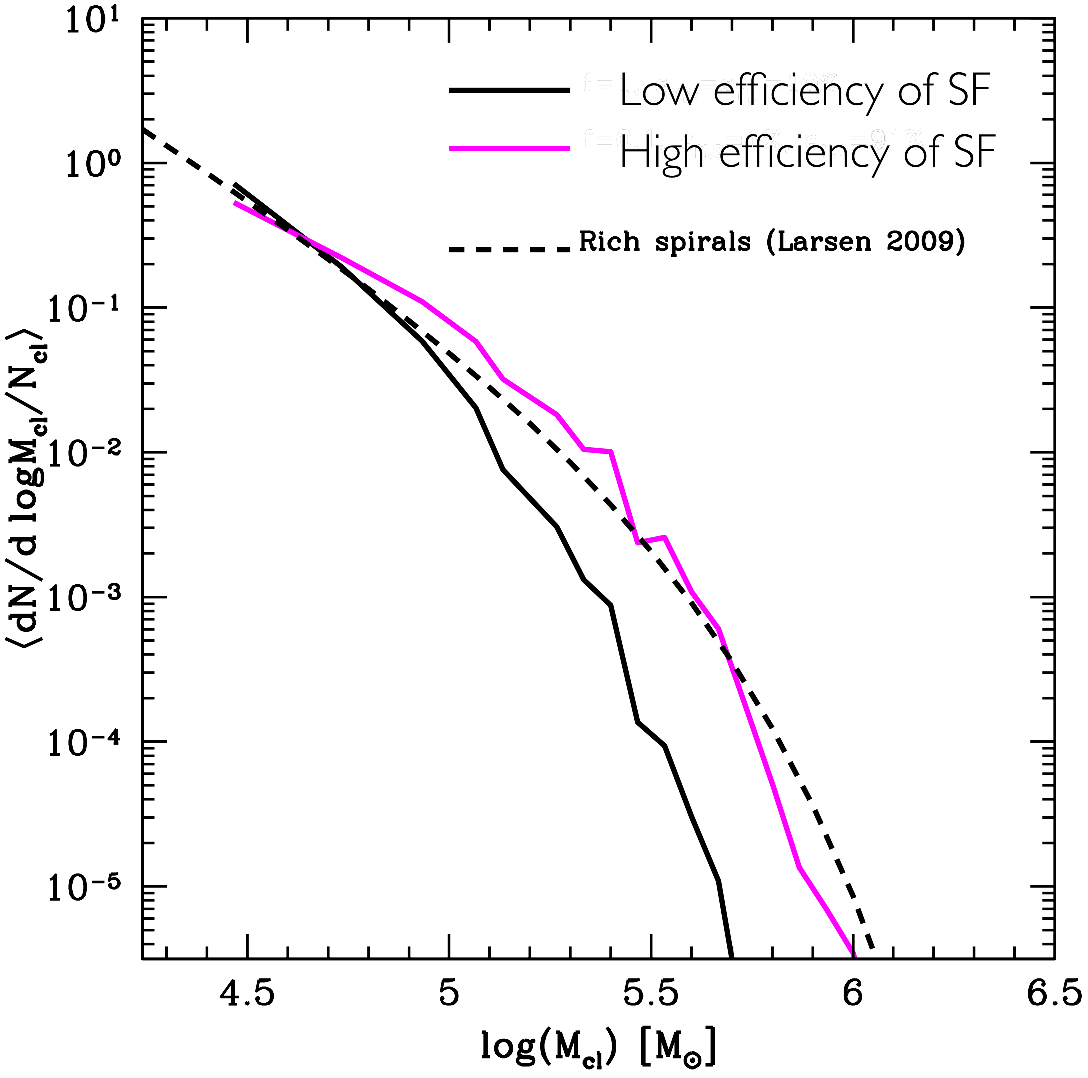
Stellar rotational velocity/ vertical velocity dispersion



Agertz et al. (in prep)

Correlated star formation and the strength of feedback

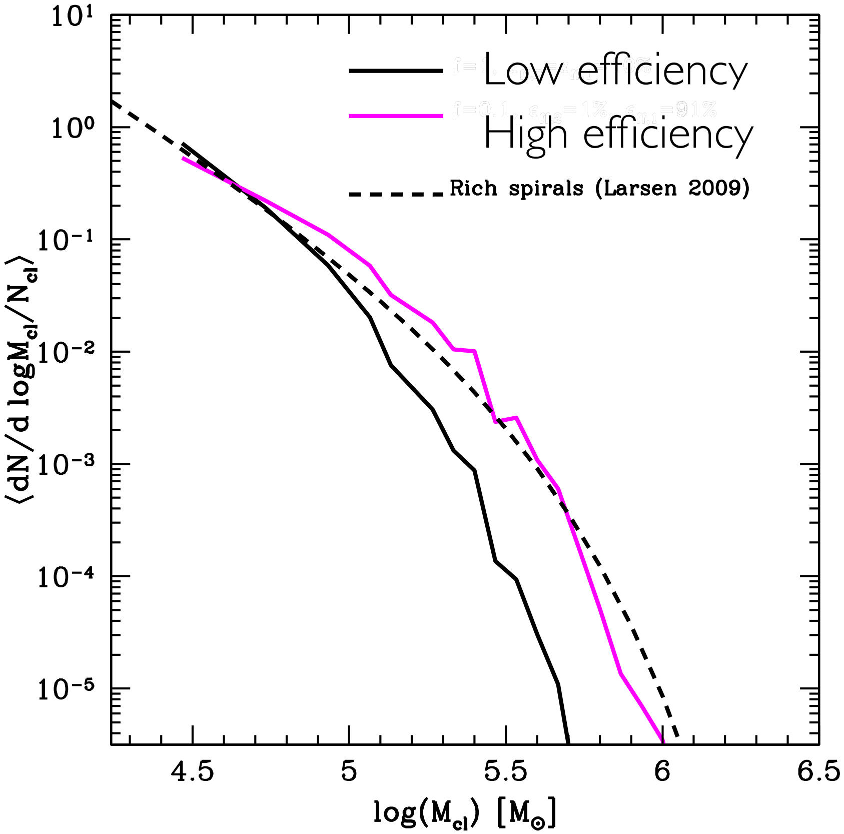
- The local star formation efficiency, coupled with stellar feedback, must ultimately make predictions on the mass function of young star clusters.
- Galaxy formation simulations still poorly resolves the gas density PDF relevant for star formation. Choices of star formation efficiency/model is applied on ~10-100 pc scales! A connection should be made to detailed models of star formation in super-sonic turbulence (e.g. *Krumholz & McKee 2005, Padoan & Nordlund 2011, Hennebelle & Chabrier 2011*).
- What about cosmic rays?

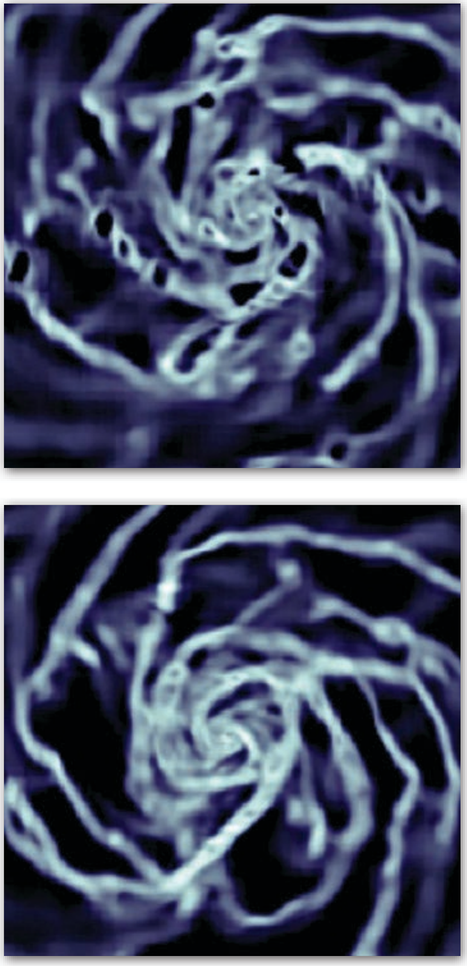


Agertz et al. (in prep)

Correlated star formation and the strength of feedback

- The local star formation efficiency, coupled with stellar feedback, must ultimately make predictions on the mass function of young star clusters.
- Galaxy formation simulations still poorly resolves the gas density PDF relevant for star formation. Choices of star formation efficiency/model is applied on ~10-100 pc scales! A connection should be made to detailed models of star formation in super-sonic turbulence (e.g. *Krumholz & McKee 2005, Padoan & Nordlund 2011, Hennebelle & Chabrier 2011*).
- What about cosmic rays?

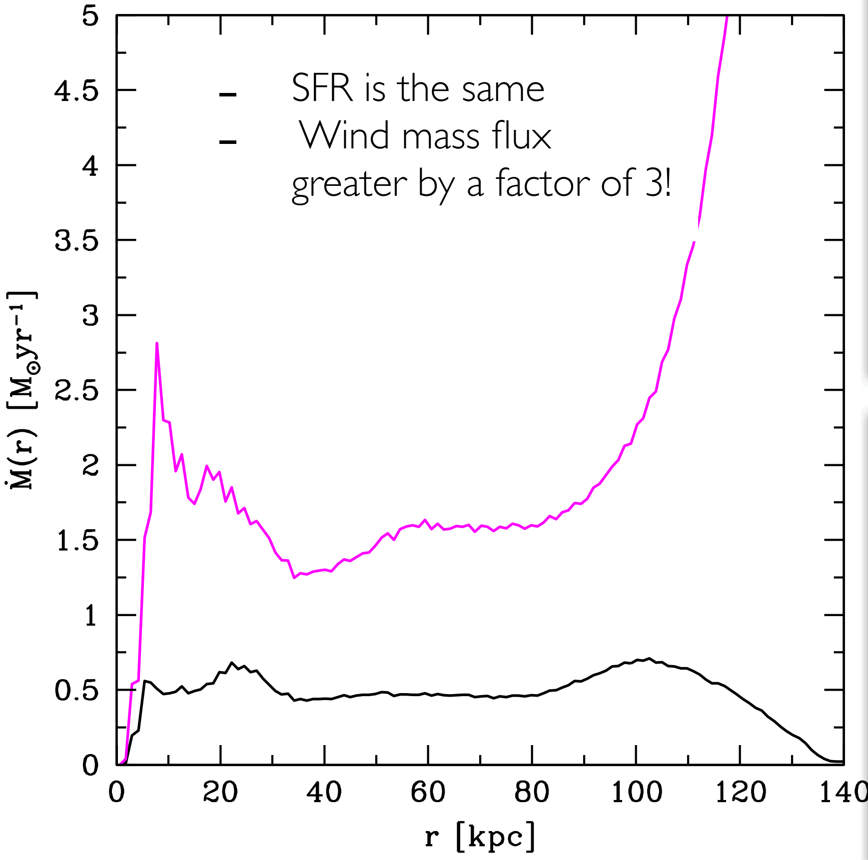




Agertz et al. (in prep)

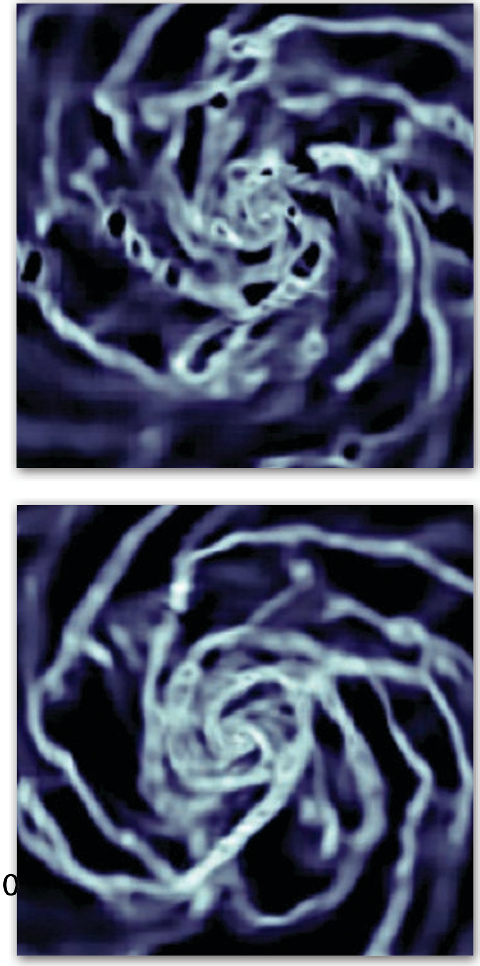
Correlated star formation and the strength of feedback

- The local star formation efficiency, coupled with stellar feedback, must ultimately make predictions on the mass function of young star clusters.
- Galaxy formation simulations still poorly resolves the gas density PDF relevant for star formation. Choices of star formation efficiency/model is applied on ~10-100 pc scales! A connection should be made to detailed models of star formation in super-sonic turbulence (e.g. *Krumholz & McKee 2005, Padoan & Nordlund 2011, Hennebelle & Chabrier 2011*).
- What about cosmic rays?



– SFR is the same

– Wind mass flux greater by a factor of 3!



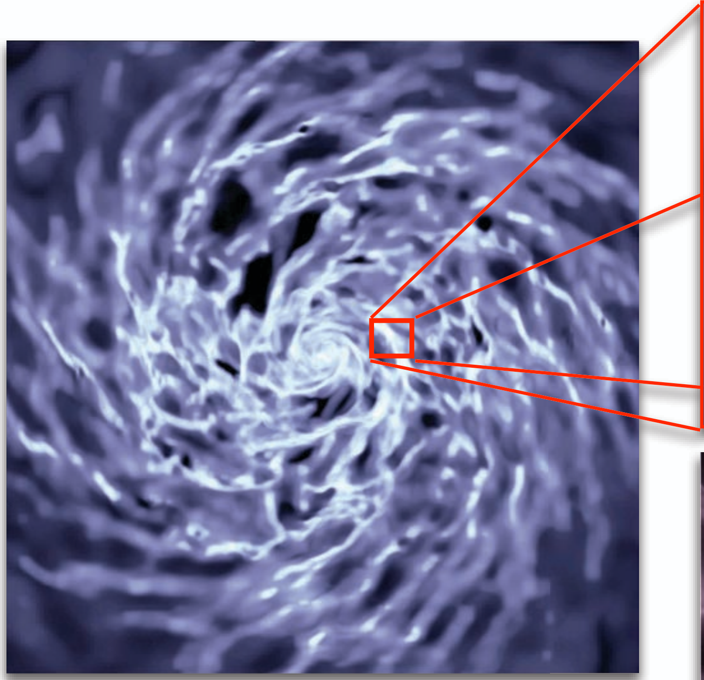
Agertz et al. (in prep)

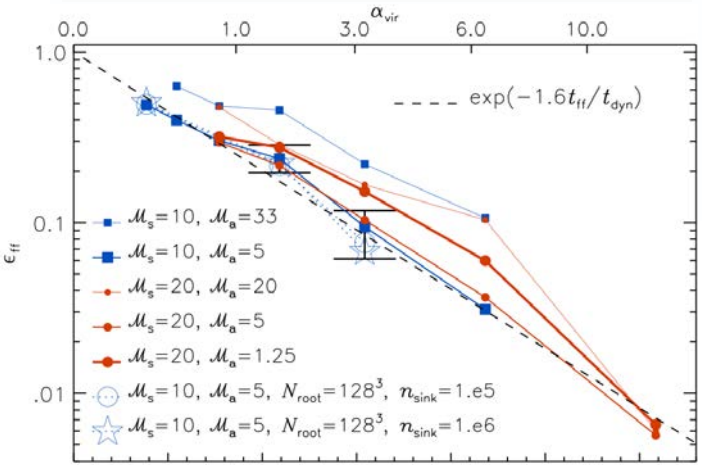
Correlated star formation and the strength of feedback

- The local star formation efficiency, coupled with stellar feedback, must ultimately make predictions on the mass function of young star clusters.

- Galaxy formation simulations still poorly resolve the gas density PDF relevant for star formation. Choices of the star formation efficiency/model is applied on ~10-100 pc scales! A connection should be made to detailed models of star formation in super-sonic turbulence (e.g. *Krumholz & McKee 2005, Padoan & Nordlund 2011, Hennebelle & Chabrier 2011*).

- What about cosmic rays?

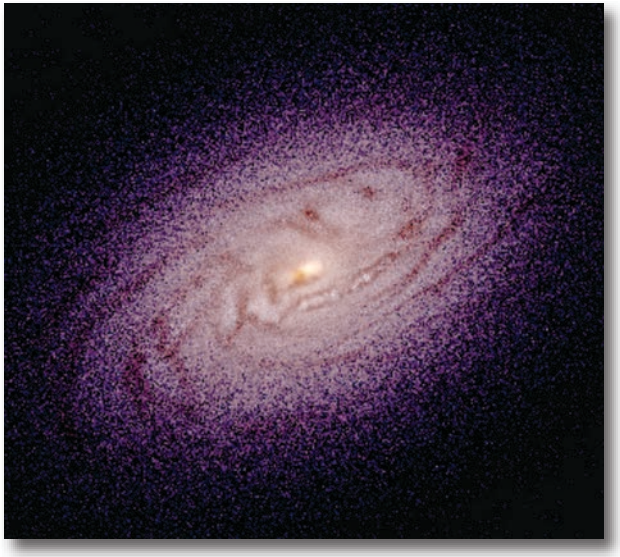




Padoan et al. 2012

Conclusions

- The way in which the galactic baryon cycle is established is not only controlled by the imposed kind, and strength, of feedback, but also by how correlated star formation events are (super-bubbles?).
- 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 (can) arise when star formation is feedback regulated and galactic outflows set the baryons fraction. This occurs when:
  1. The local star formation efficiency is large enough to generate coherent outflows
  2. More energy is given to the ISM by hand per stellar population
- The degeneracy can be broken by more detailed comparisons to data, e.g. the Kennicutt-Schmidt relation, wind properties, galaxy sizes, morphologies. **The strength of stellar feedback is not simply a knob to turn; too strong feedback destroys all signs of a cold gas/stellar disk** (see also e.g. Roskar et al. 2013)



HST mockup
RGB using F450W, F606W, F814W filters