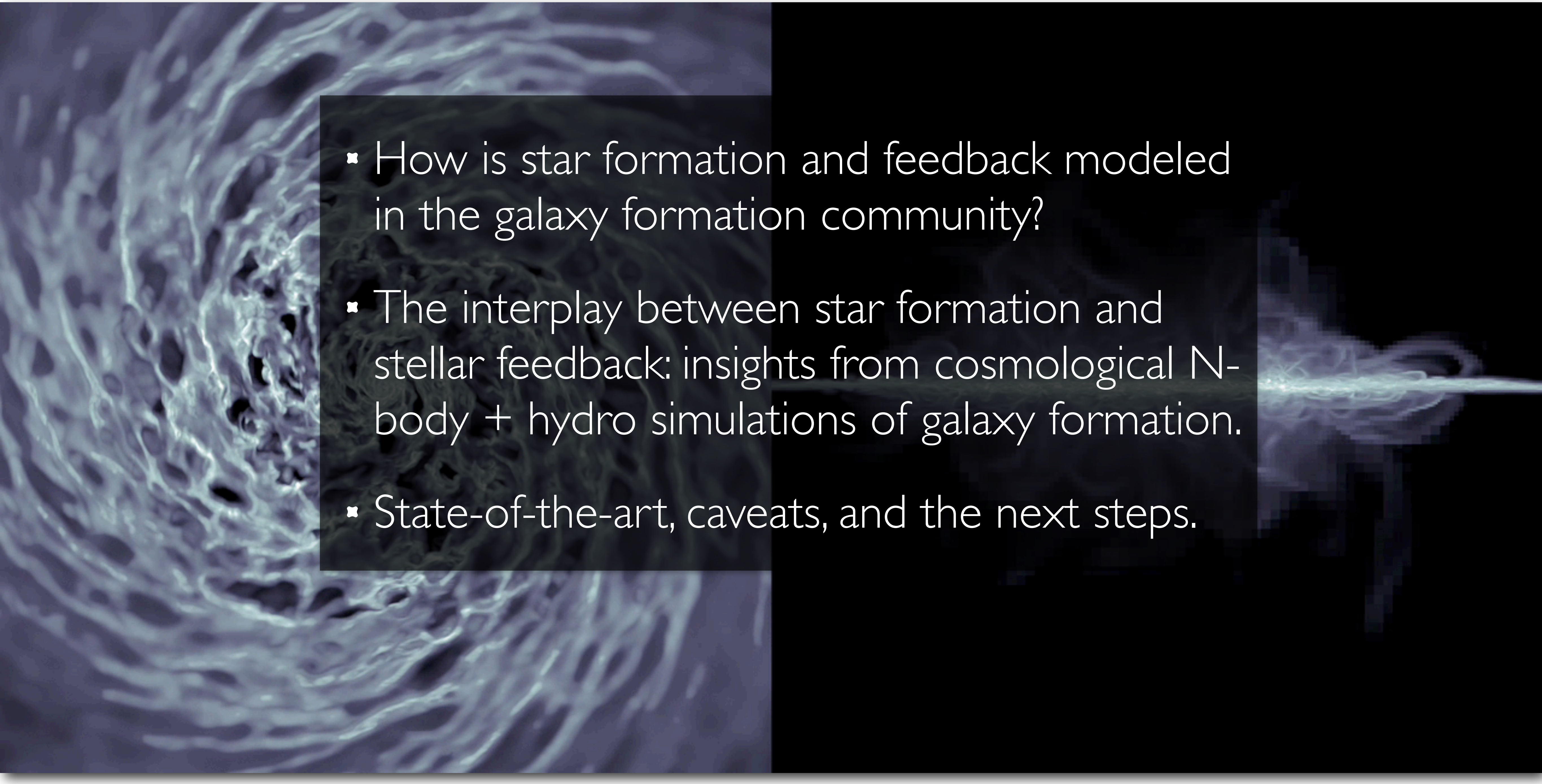
Sub-galactic scale modelling of star formation



- How is star formation and feedback modeled in the galaxy formation community?
- The interplay between star formation and stellar feedback: insights from cosmological N-body + hydro simulations of galaxy formation.
- State-of-the-art, caveats, and the next steps.

Oscar Agertz

+ Andrey Kravtsov, Nick Gnedin, Sam Leitner, Justin Read, Alessandro Romeo, Kearn Grisdale, Florent Renaud, Ramon Rey-Raposo

UNIVERSITY OF SURREY

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Stockholm
23 August, 2016

Multi-scale & multi-physics

Movies: Teyssier+ ; Agertz+13 ; Renaud+15 ; Bate ; Sabbi

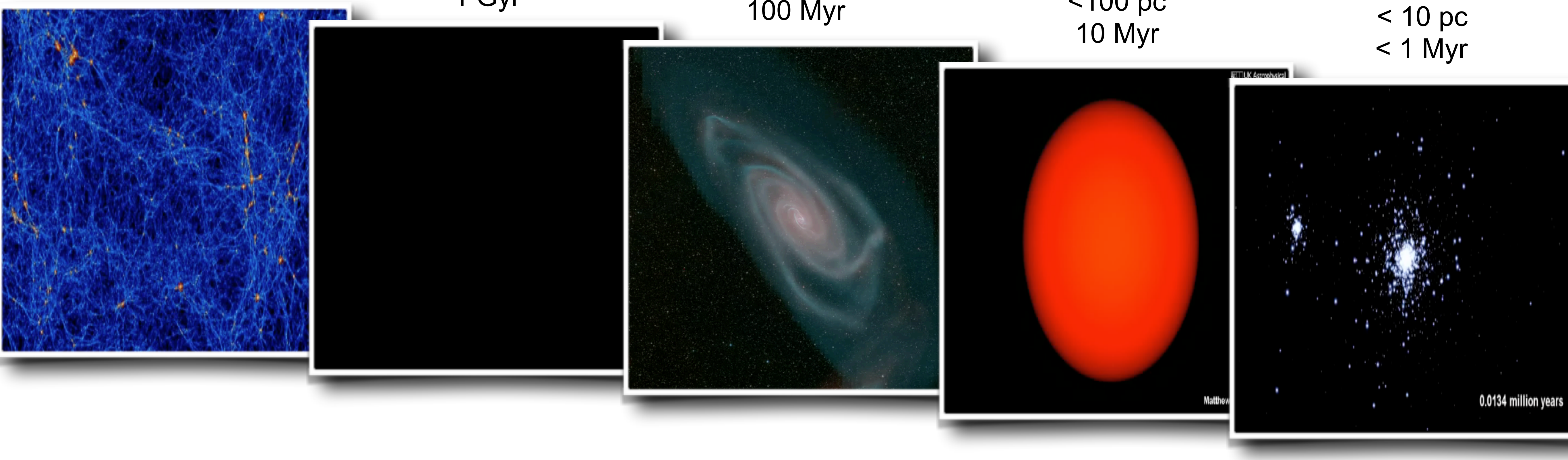
> 1 Mpc
> 1 Gyr

Mpc -> kpc
1 Gyr

10s kpc->100 pc
100 Myr

<100 pc
10 Myr

< 10 pc
< 1 Myr



gas inflows

galaxy interactions

turbulence

shear

magnetic fields

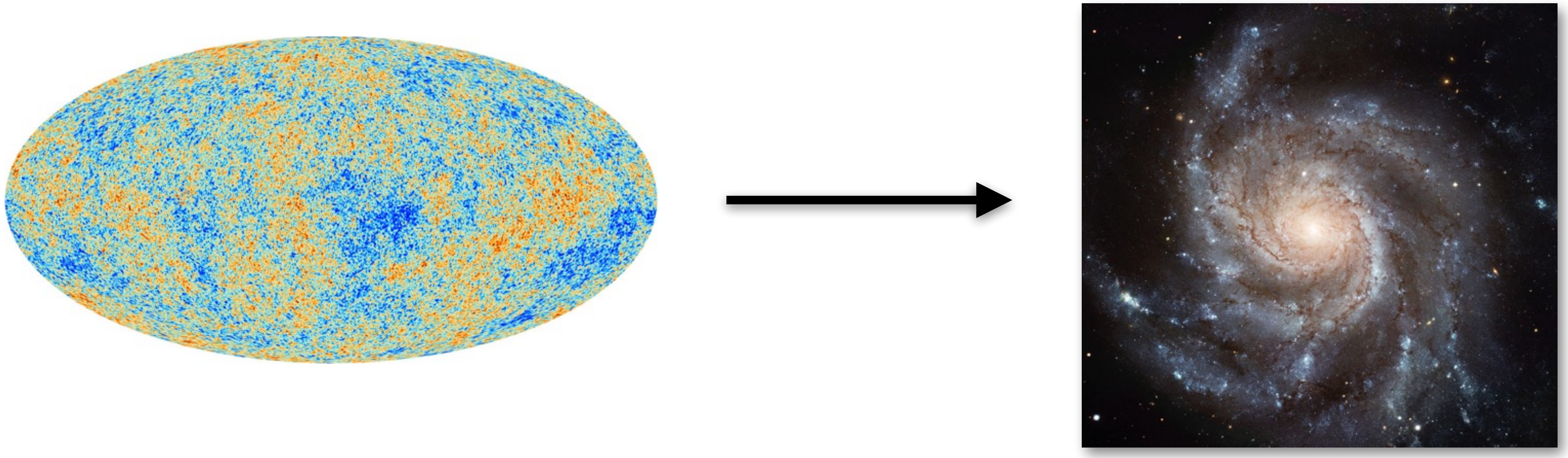
feedback

gravity

The goals

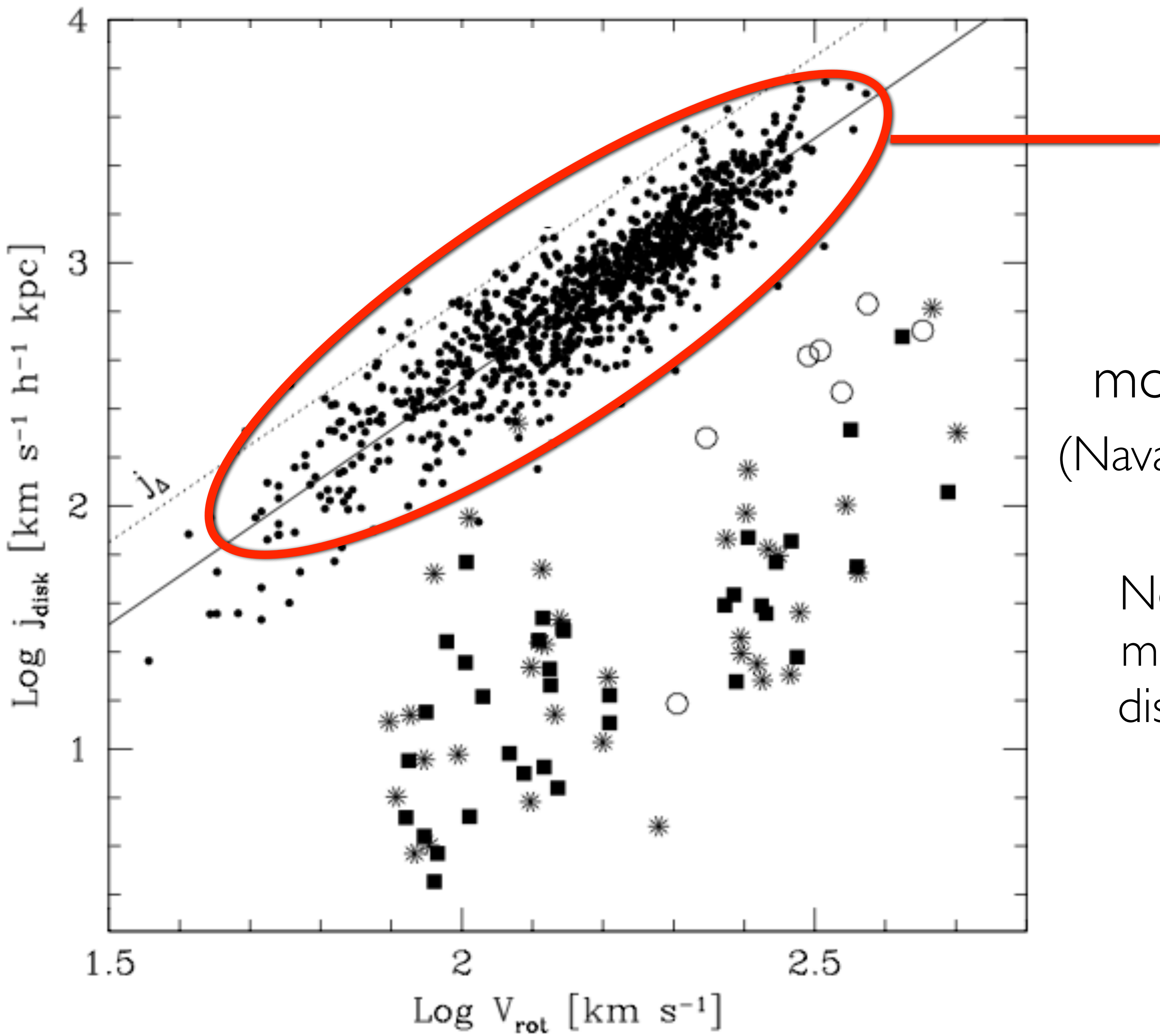
- Origin of the Hubble sequence and galactic structure
- Origin of galaxy scaling relations
- Galaxy luminosity functions and the galaxy dark matter connection
- The cosmic baryon cycle
- The physics of galactic star formation
- The role, and driver, of turbulence in the ISM

Cosmological simulations of galaxy formation are in principle optimal for this; we actually know the initial conditions!



Issues in simulations of galaxy formation:

Angular momentum



Courteau (1997)
Sb-Sc galaxies

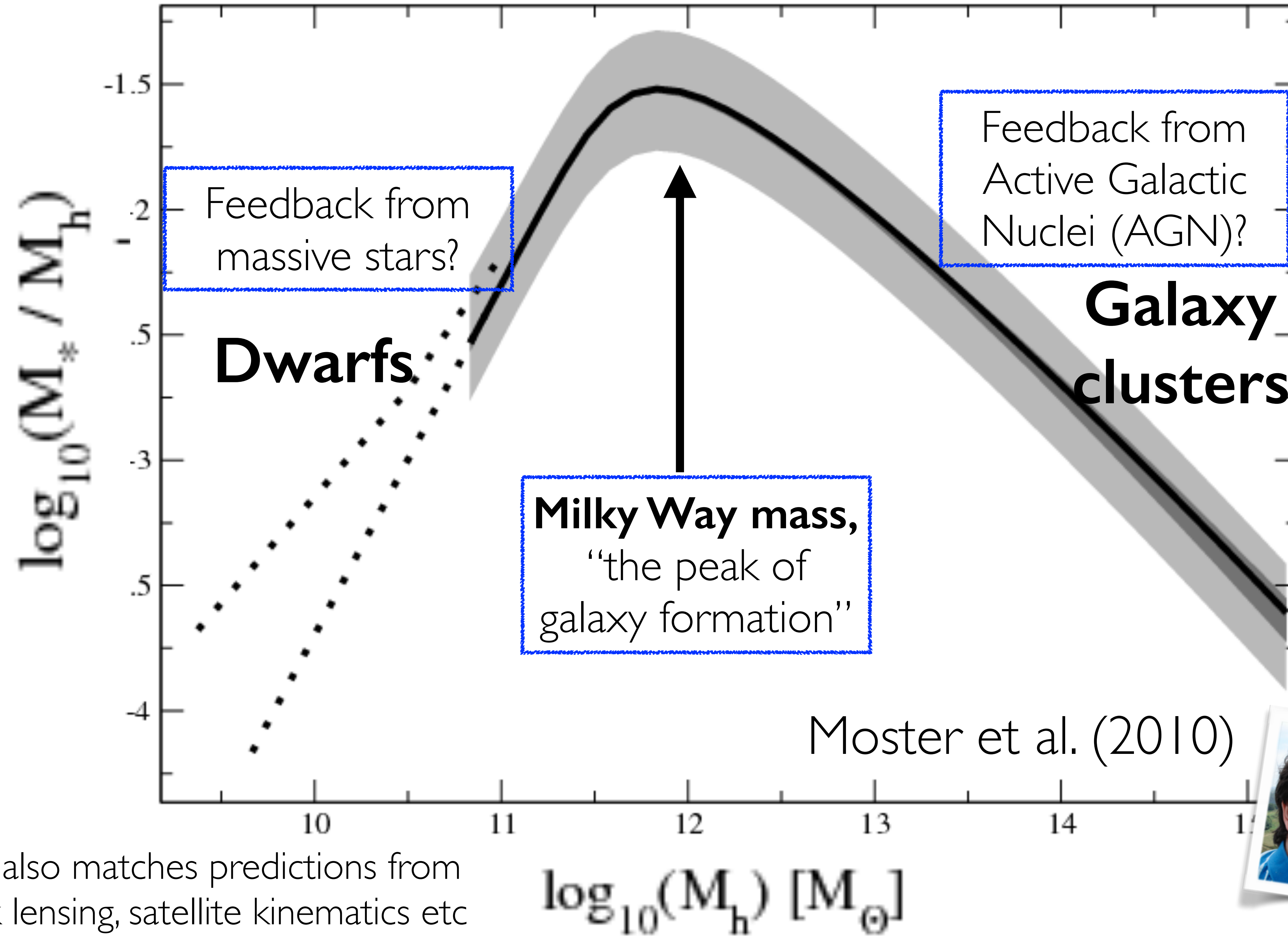
The angular momentum problem
(Navarro & Steinmetz, 2000)

Not clear ***where*** angular momentum is lost (halo, disc-halo interface, disc?)

Issues in simulations of galaxy formation:

The low efficiency of galaxy formation

$$\frac{\Omega_{\mathrm{bar}}}{\Omega_{\mathrm{m}}} \approx 17\,\%$$ -0.77



This also matches predictions from weak lensing, satellite kinematics etc

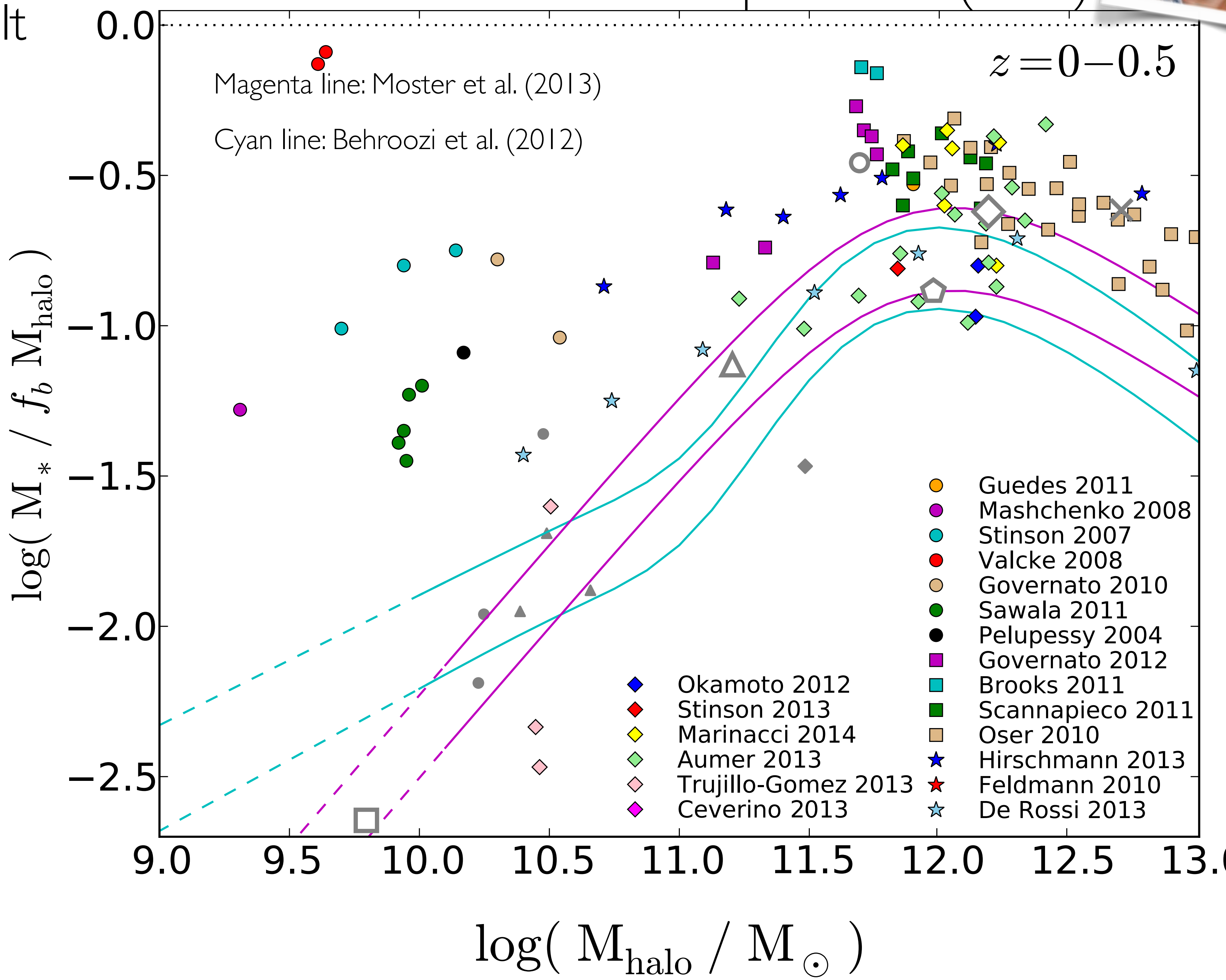
Issues in simulations of galaxy formation:

The low efficiency of galaxy formation

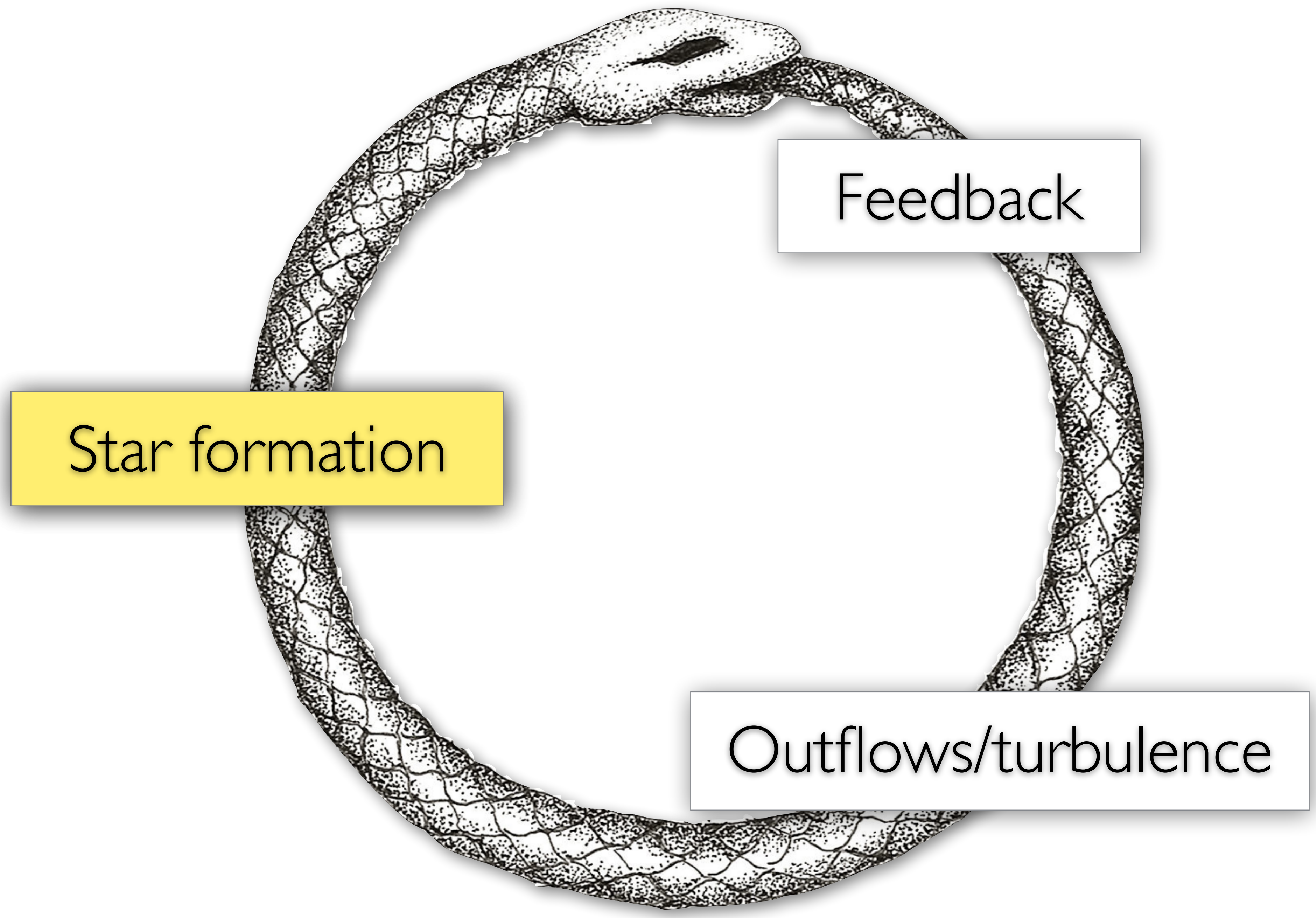
- Inefficient galaxy formation is notoriously difficult for simulations to predict.

Fraction of halo baryons locked up in stars at z=0

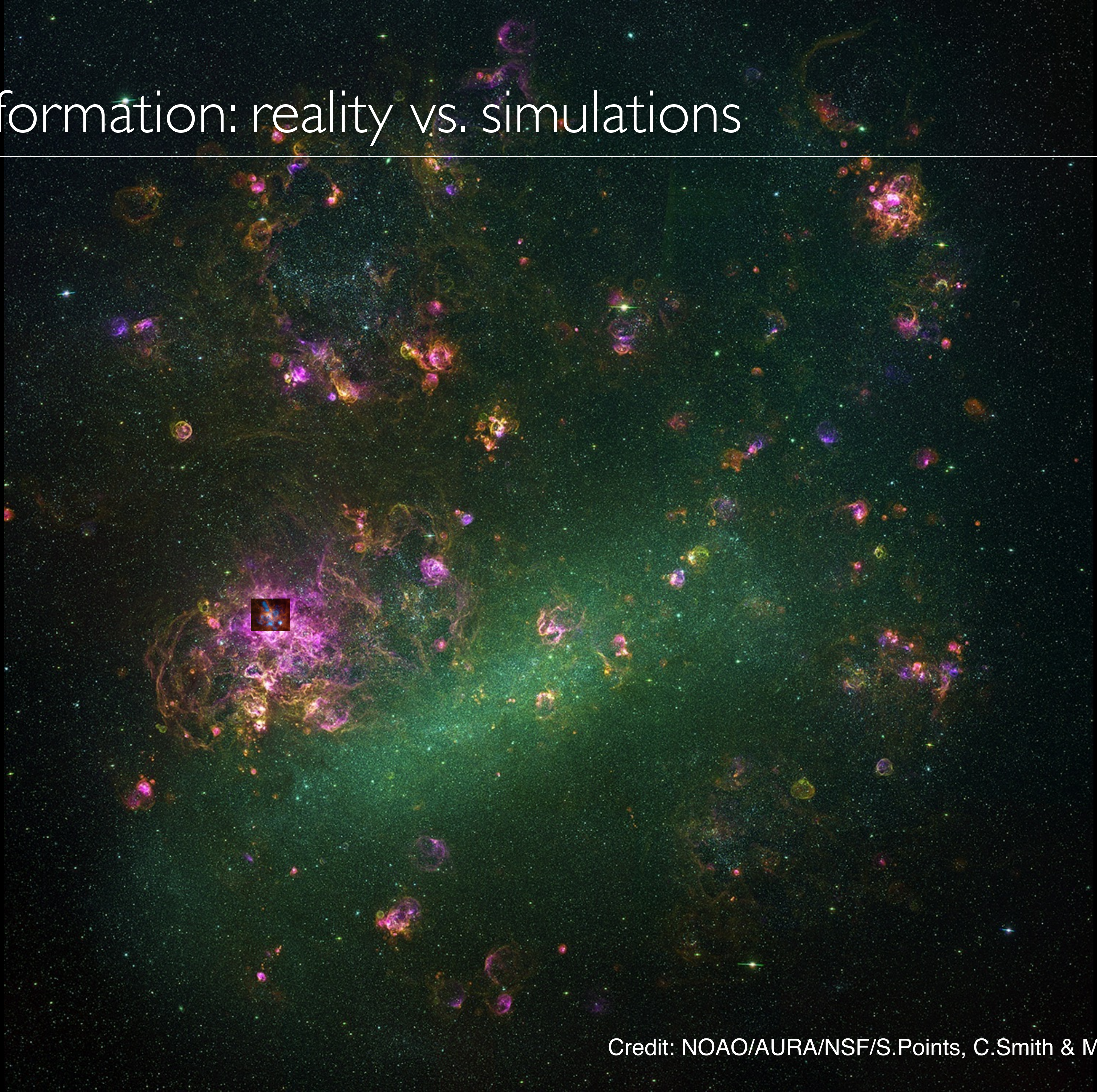
Hopkins et al. (2014)



Star formation and feedback should modelled together



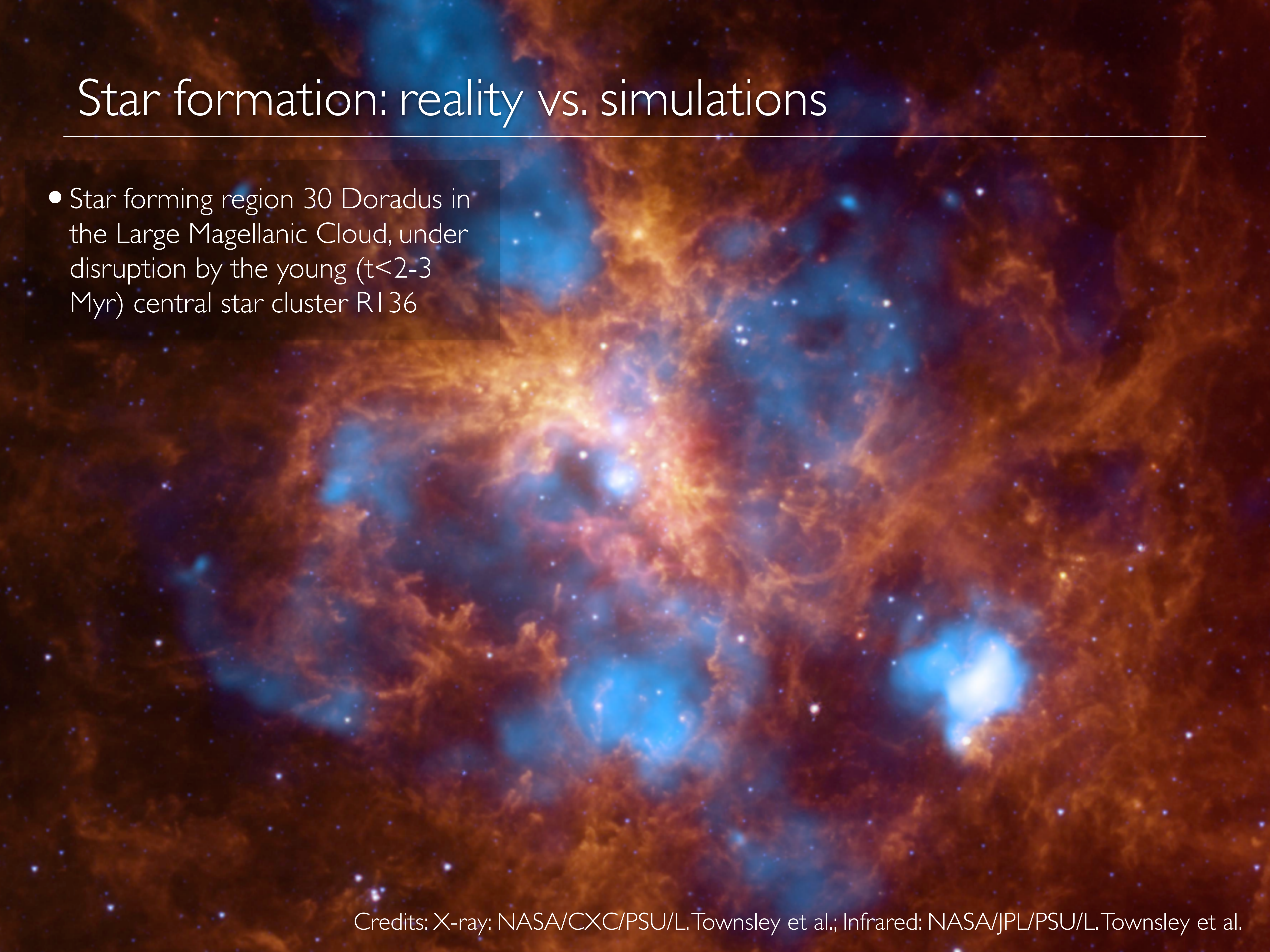
Star formation: reality vs. simulations



Credit: NOAO/AURA/NSF/S.Points, C.Smith & MCELS team

Star formation: reality vs. simulations

- Star forming region 30 Doradus in the Large Magellanic Cloud, under disruption by the young (t<2-3 Myr) central star cluster R136



Credits: X-ray: NASA/CXC/PSU/L.Townsley et al.; Infrared: NASA/JPL/PSU/L.Townsley et al.

Star formation: reality vs. simulations

10s of pc

Zoom-in simulations, e.g.
- Agertz & Kravtsov (2015,2016)
- Hopkins et al. (2014)

But mass resolution is still ~10^4 M_{sun}

~ pc

Isolated galaxy models & patches e.g.
- Renaud et al. (2013)
- Hopkins et al. (2011,2012)
- Walch et al. (2014)

Star formation: reality vs. simulations

100s of pc-kpc

Big-box simulations, e.g.

- Illustris (Vogelsberger et al. 2014)
- EAGLE (Schaye 2014)

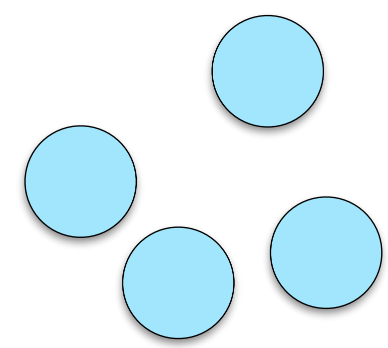
With mass resolution >10^6 M_{sun}

Models of (sub grid) star formation

$$\rho, T, v, f_{\mathrm{H}_2} \ldots$$

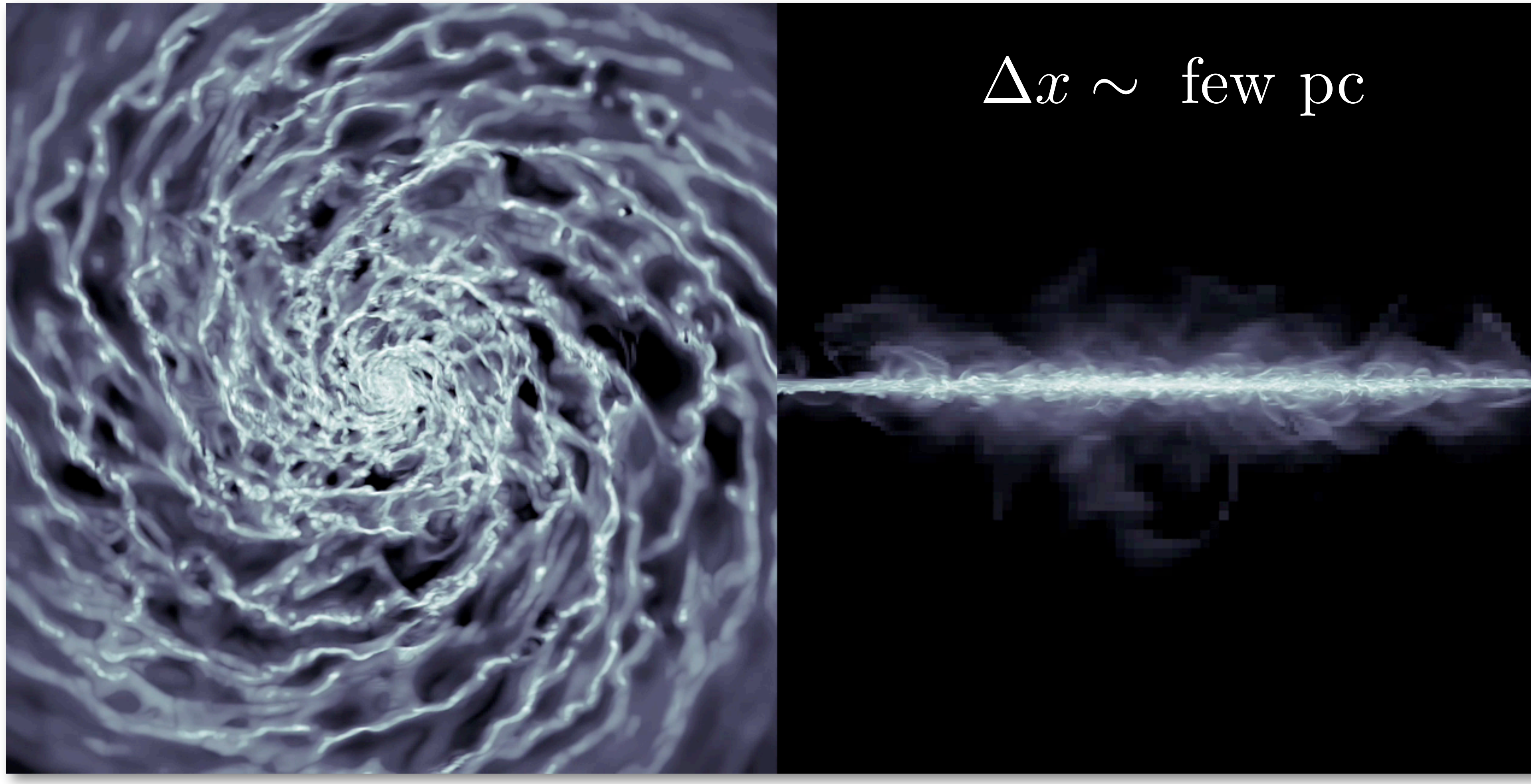
A gas
resolution
element

Mass is removed from the hydro according to a recipe, designed to model a local rate of star formation

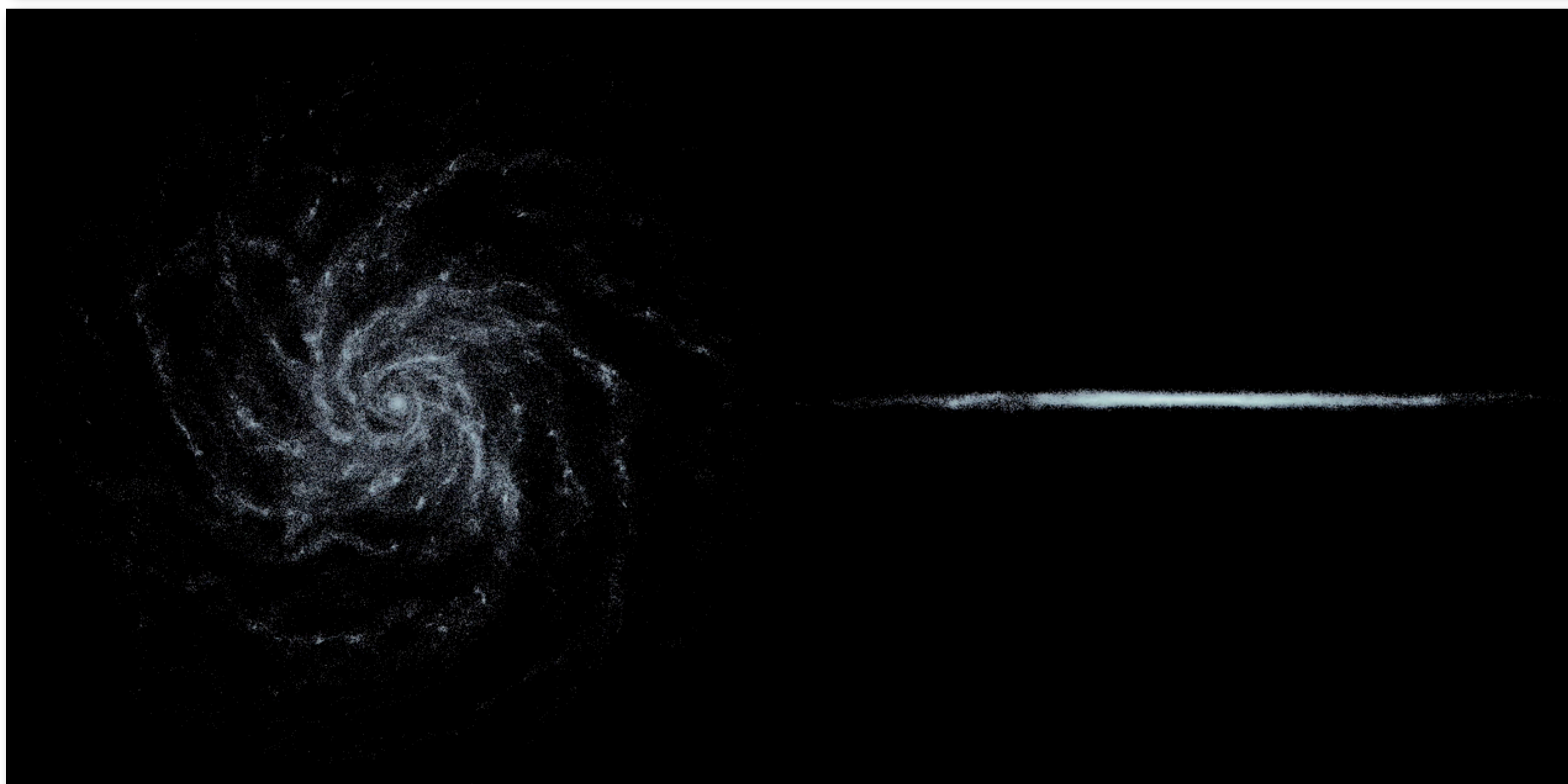


Star particles are created, and are subsequently treated a as collisonless particles that only interacts with the gas via their gravitational potential and feedback processes.

Gas density



Young stars



Grisdale, Agertz, Romeo + (2016)

Modelling of star formation in galaxy simulations

DISSIPATIONAL GALAXY FORMATION. II. EFFECTS OF STAR FORMATION

NEAL KATZ[1]

Princeton University Observatory and Steward Observatory

Received 1991 May 31; accepted 1991 December 4

also Cen & Ostriker (1992), dates back to Schmidt (1959)

$$\dot{\rho}_\star = \frac{\rho_{\rm gas}}{t_{\rm SF}} \quad \text{for} \quad \rho_{\rm gas} > \rho_0$$

and/or with other possible constraints:

$$T_{\rm gas} < T_0$$
$$\nabla \cdot v < 0$$
$$M_{\rm gas} > M_{\rm Jeans}$$

The star formation time scale if often parametrized using free-fall times and efficiencies:

$$t_{\rm SF} = t_{\rm ff}/\epsilon_{\rm ff} \longrightarrow \dot{\rho}_\star = \epsilon_{\rm ff}\frac{\rho_{\rm gas}}{t_{\rm ff}} \quad \text{with} \quad t_{\rm ff} = \sqrt{\frac{3\pi}{32 G \rho_{\rm gas}}}$$

Other developments:

Molecular hydrogen correlates with star formation:

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

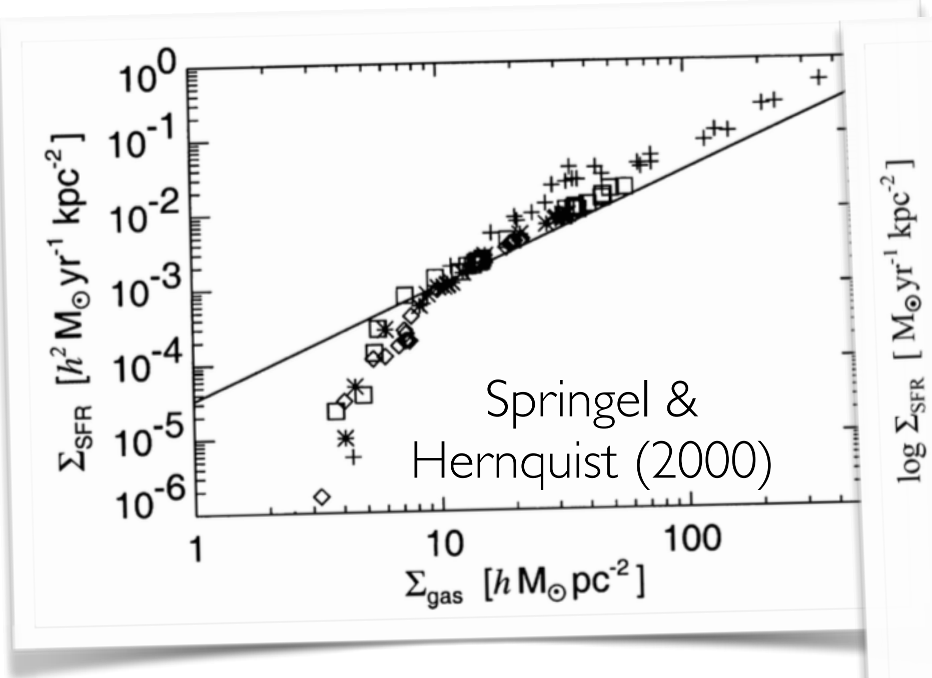
Robertson & Kravtsov (2008)
Gnedin et al. (2009)
Krumholz et al. (2009)

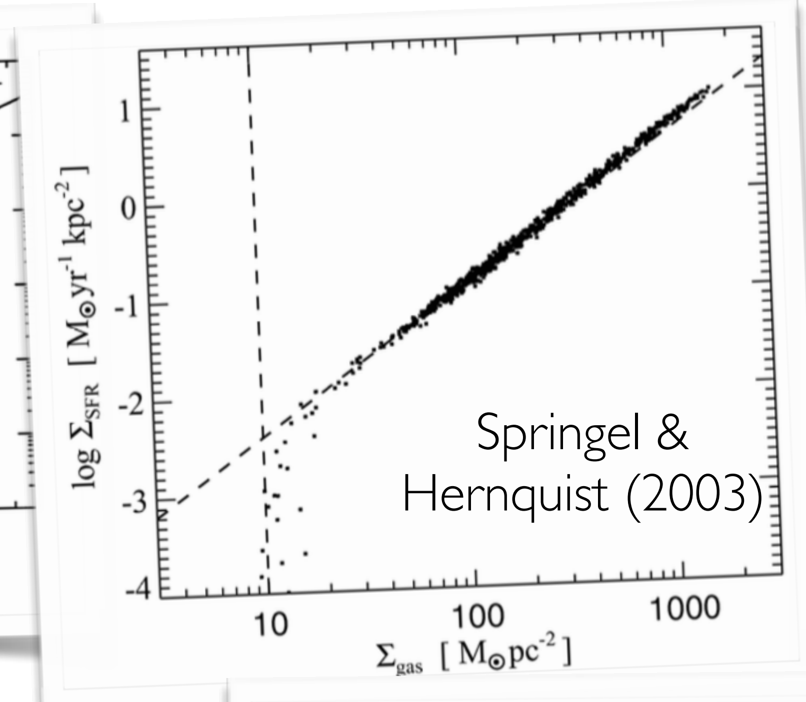
Star formation proceeds efficiently in gravitationally bound regions

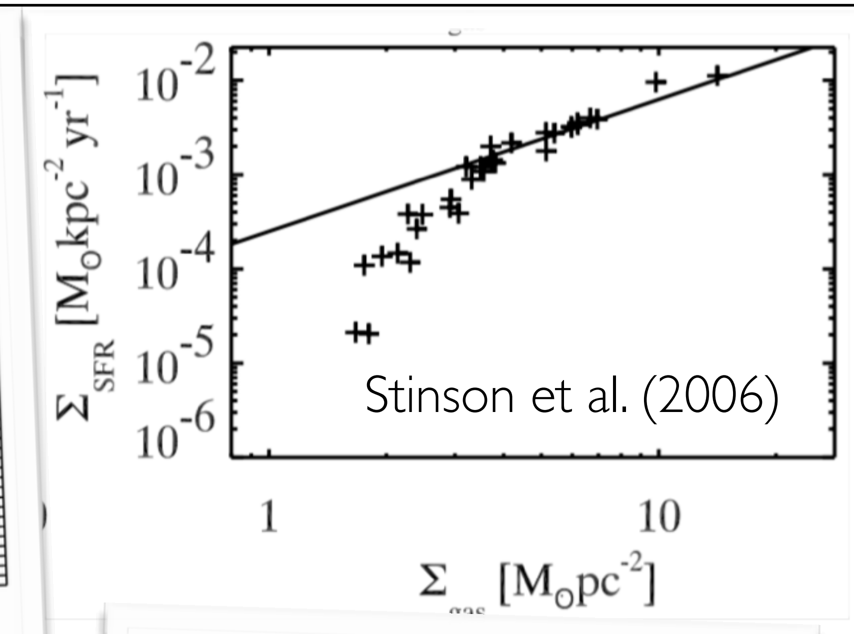
$$\alpha_{\rm vir} \lesssim 1$$
$$\alpha_{\rm vir} = 5\frac{\sigma_{\rm 1D}^2 R}{GM}$$

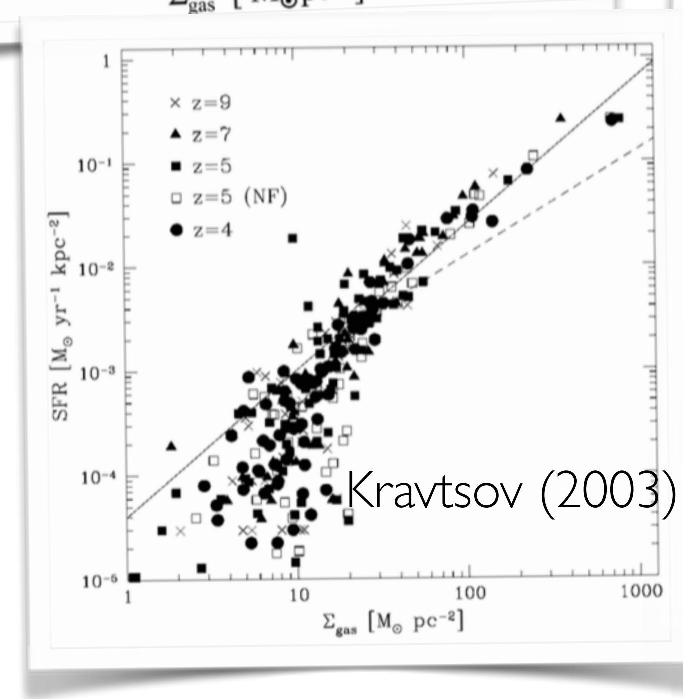
Hopkins et al. 2013
Devriendt et al.

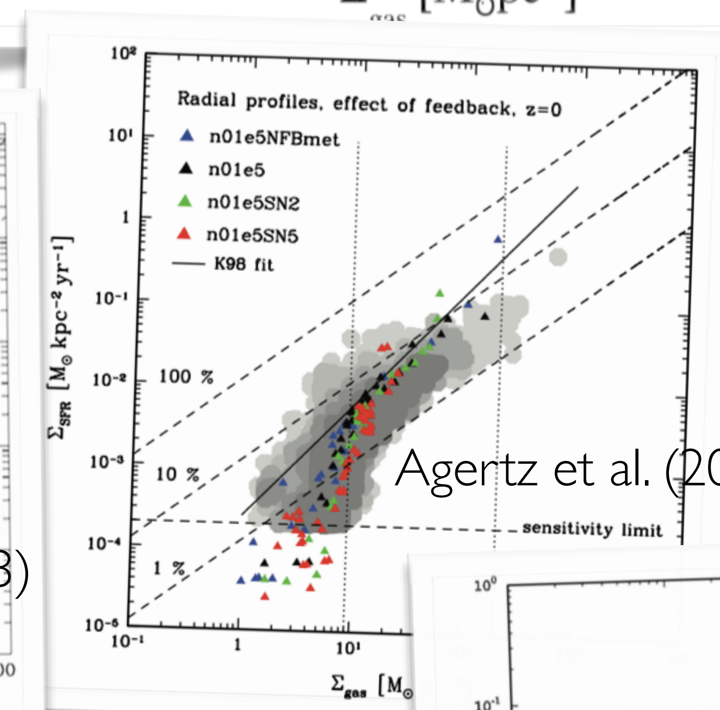
$\Sigma_{\rm SFR} - \Sigma_{\rm gas}$, the Kennicutt-Schmidt relation

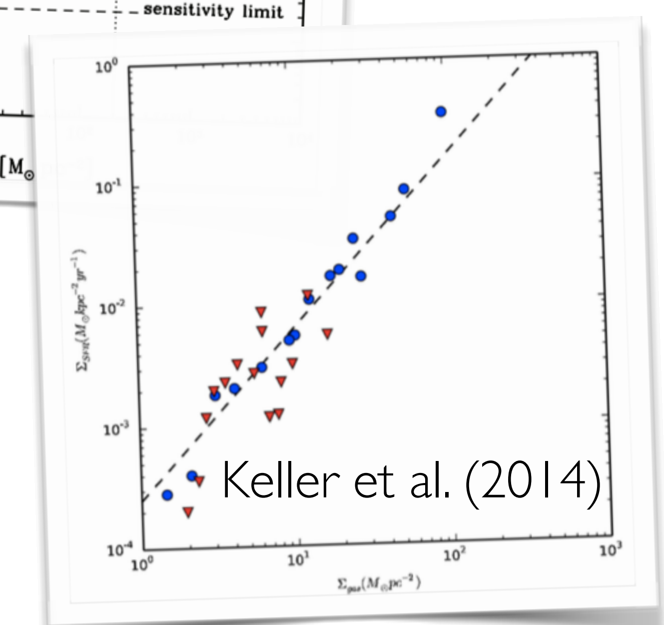












Plenty of work has gone into reproducing the observed Kennicutt-Schmidt relation (Kennicutt, 1998, Bigiel et al. 2008), both globally and measured over kpc-scale patches.

$$\Sigma_{\rm SFR} \approx 2.5 \times 10^{-4} \left(\frac{\Sigma_{\rm gas}}{{\rm M}_\odot\ {\rm pc}^{-2}} \right)^{1.4}$$

Kennicutt (1998)

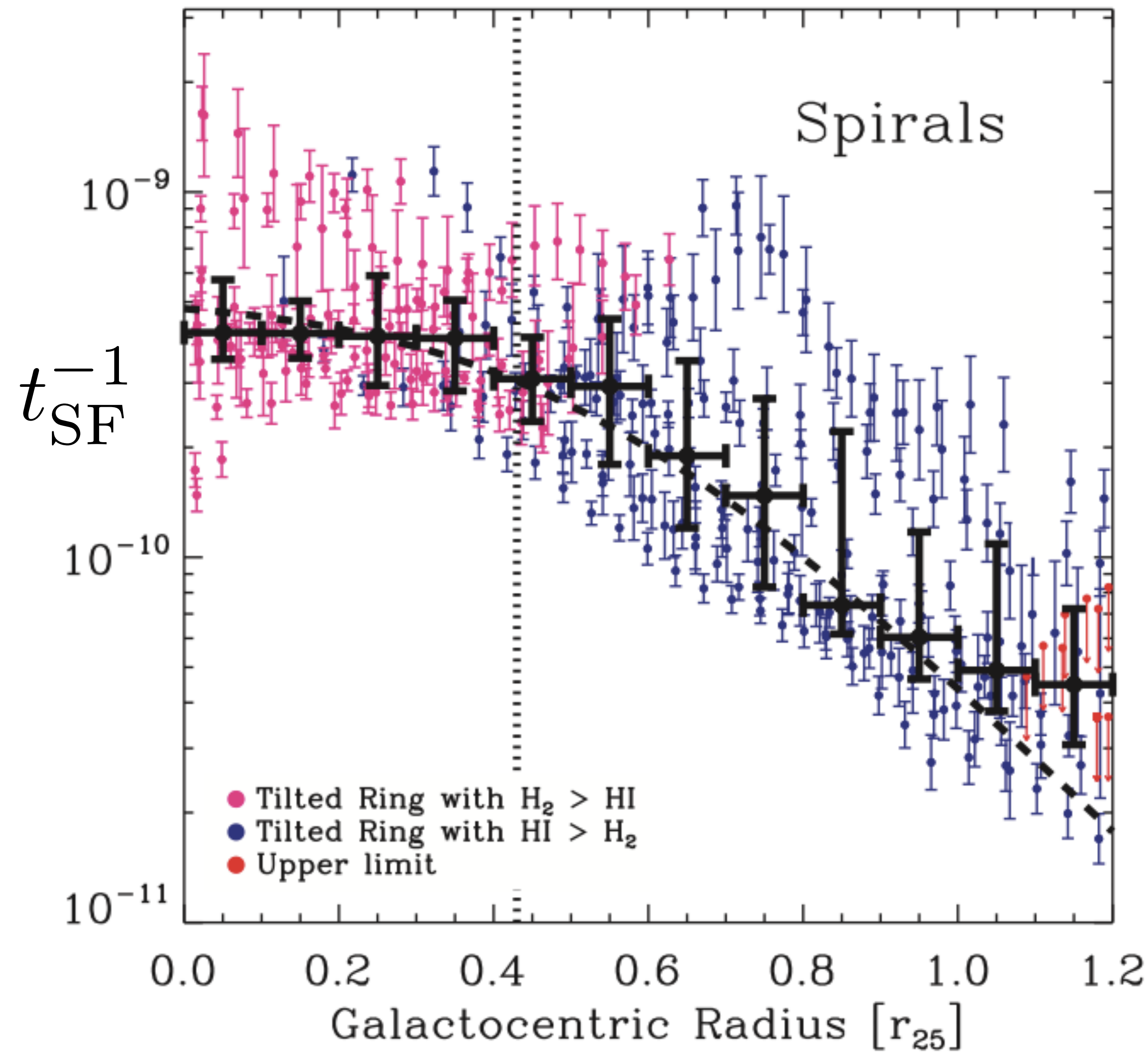
The efficiency of star formation, large scales

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

- On large scales (kpc), the depletion time in molecular gas in local spirals is long: **1~2 Gyr** (THINGS, Leroy et al. 2008)
- The free-fall time of the cold ISM is **~5-10 Myr,** making the galaxy globally very inefficient in converting gas into stars

→ $\epsilon_{ff} = t_{ff}/t_{SF} \sim 1\,\%$

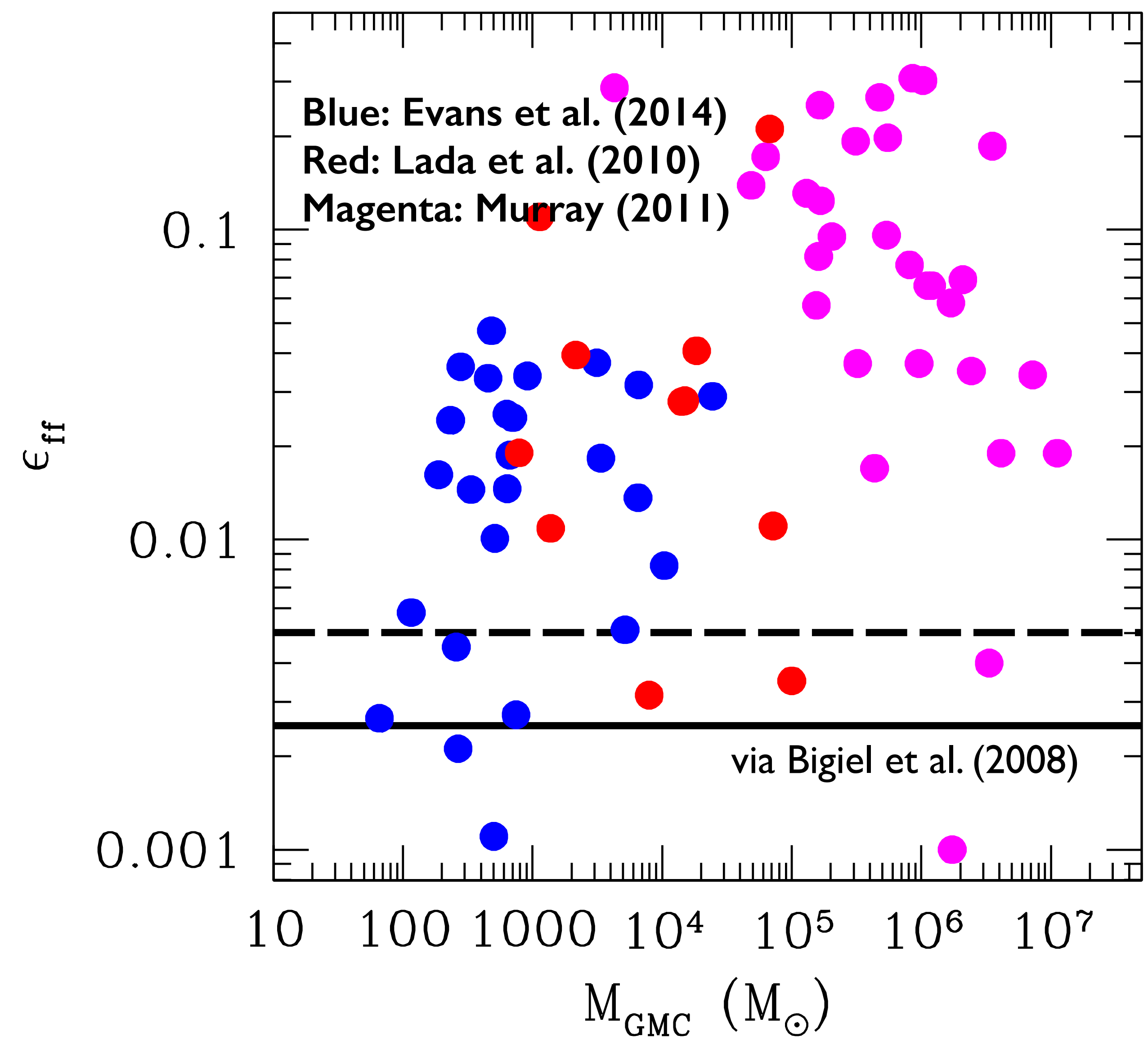
Leroy et al. 2008



The efficiency of star formation, small scales

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

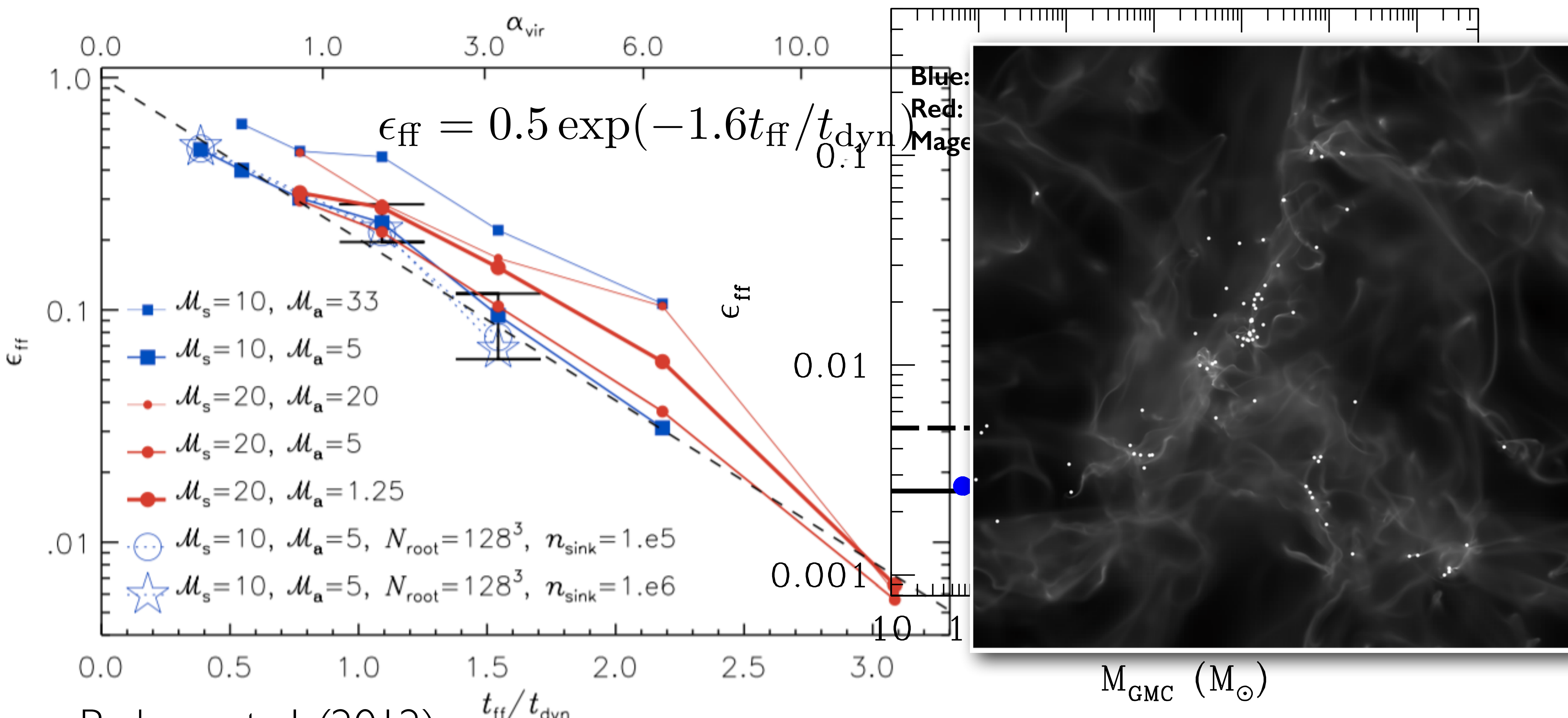
- On the scale of GMCs, it is less clear (*Heiderman et al. 2010*, *Evans et al. 2009*, *Murray 2011*) and probably depends on the environment, as indicated by simulations of super-sonic turbulence (e.g. *Padoan and Nordlund 2011*).
- Difference in turbulence properties (e.g. Renaud et al. 2012, Semenov 2015). GMC evolution (Feldmann & Gnedin, 2011)



Assuming a low efficiency on small scales gives us the observed large scale Kennicutt-Schmidt relation **by construction.** However, in order for galaxies to regulate their baryon fractions, this relation should be considered to be a **prediction** of the model, not a an input.

What efficiency should we use?

Depends on the virial parameter, the Mach number, turbulent forcing (…)
Bound clouds form star more efficiently!

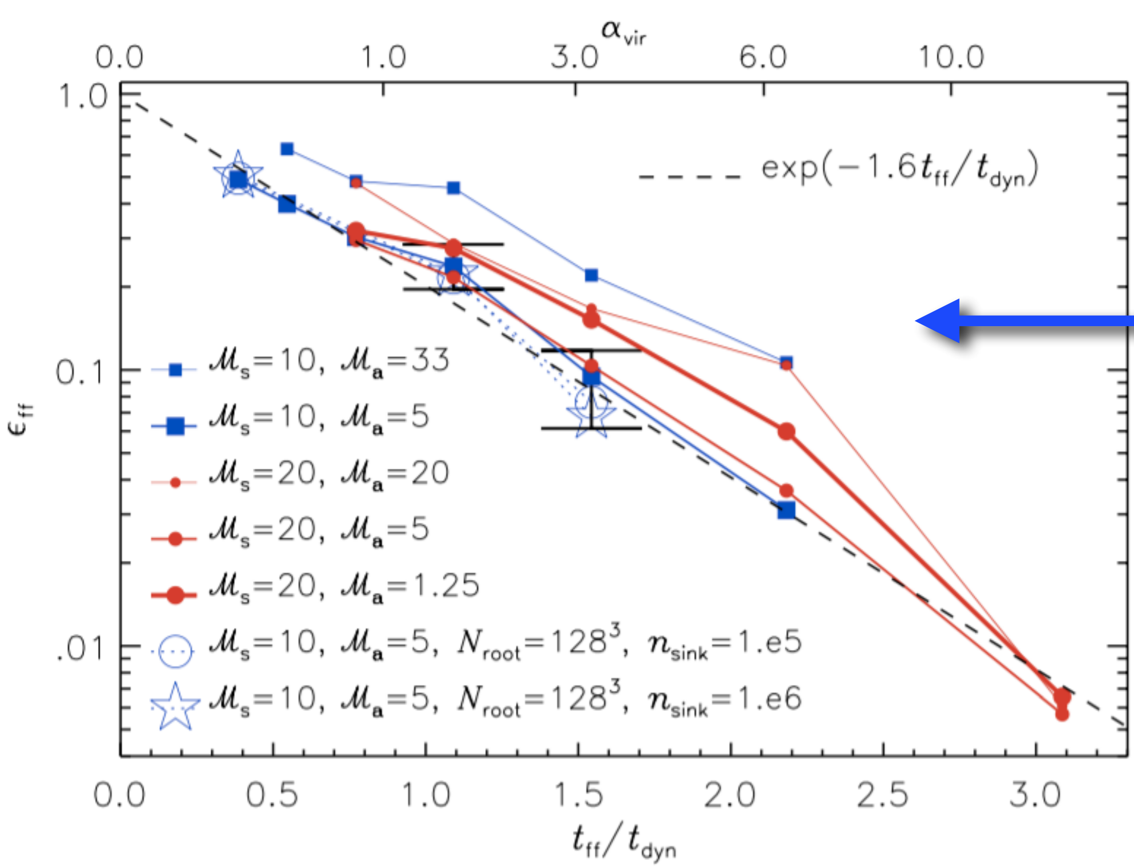


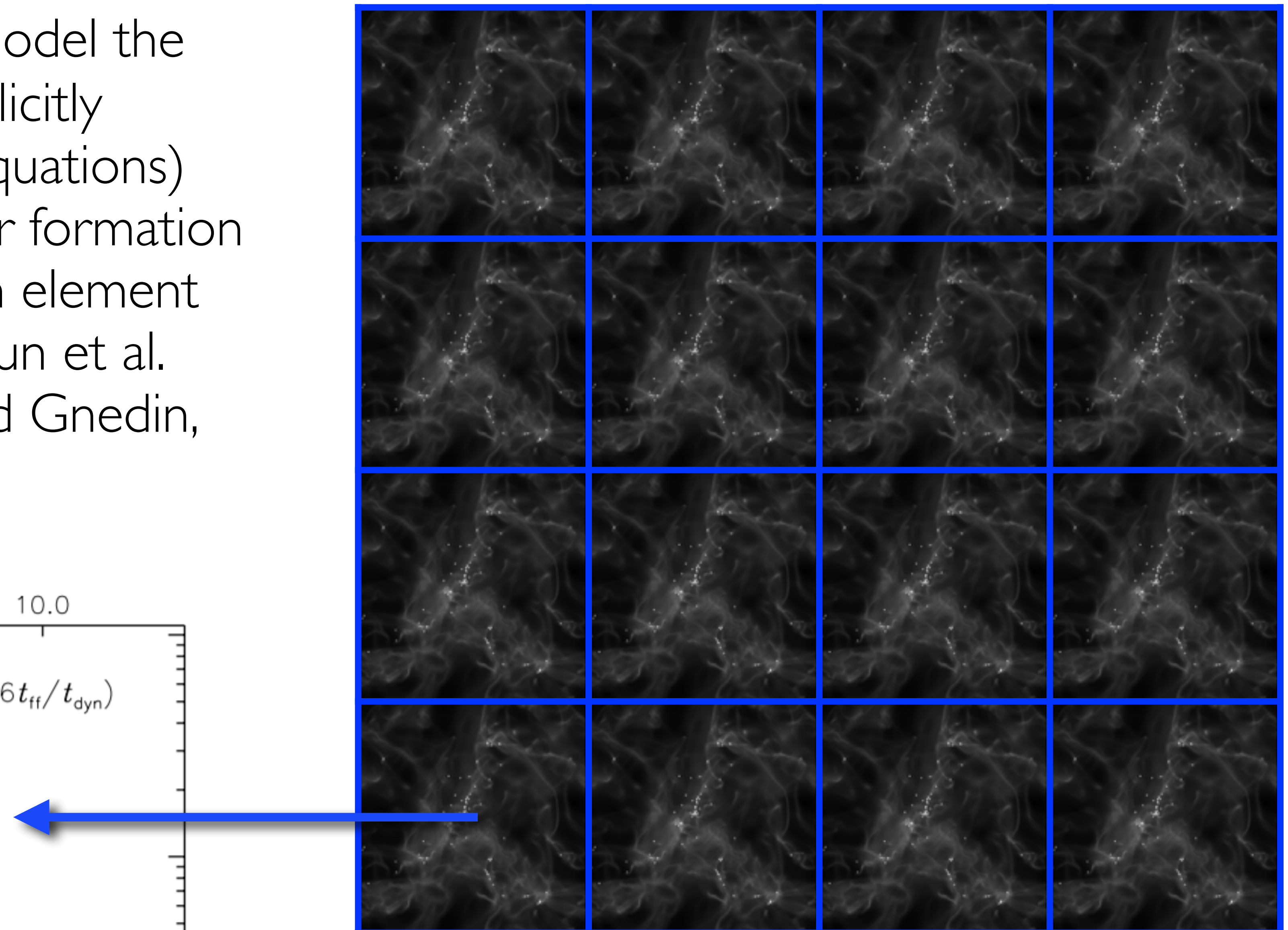
Padoan et al. (2012)

Clouds have a hierarchy of collapsing scales on different free-fall times. Excellent comparison of analytical models in Federrath & Klessen (2012) of Padoan & Nordlund, Krumholz & McKee and Hennebelle & Chabrier

What efficiency should we use?

- State-of-the-art is here to model the ***sub-resolution turbulence*** explicitly (more terms in the hydro equations) and have this predict the star formation efficiency in every resolution element (e.g. Schmidt et al. 2014, Braun et al. 2014, Semenov, Kravtsov and Gnedin, 2016)





A dynamical model for subgrid turbulence

$$\frac{\partial}{\partial t}\rho + \nabla_k v_k \rho = 0$$

$$\frac{\partial}{\partial t}\rho v_i + \nabla_k v_k \rho v_i = -\rho \nabla_i \phi - \nabla_i \left(P \quad \right)$$

$$\frac{\partial}{\partial t}E + \nabla_k v_k E = -\rho v_k \nabla_k \phi - \nabla_k v_k \left(P \quad \right) - \Lambda_{\rm net}$$

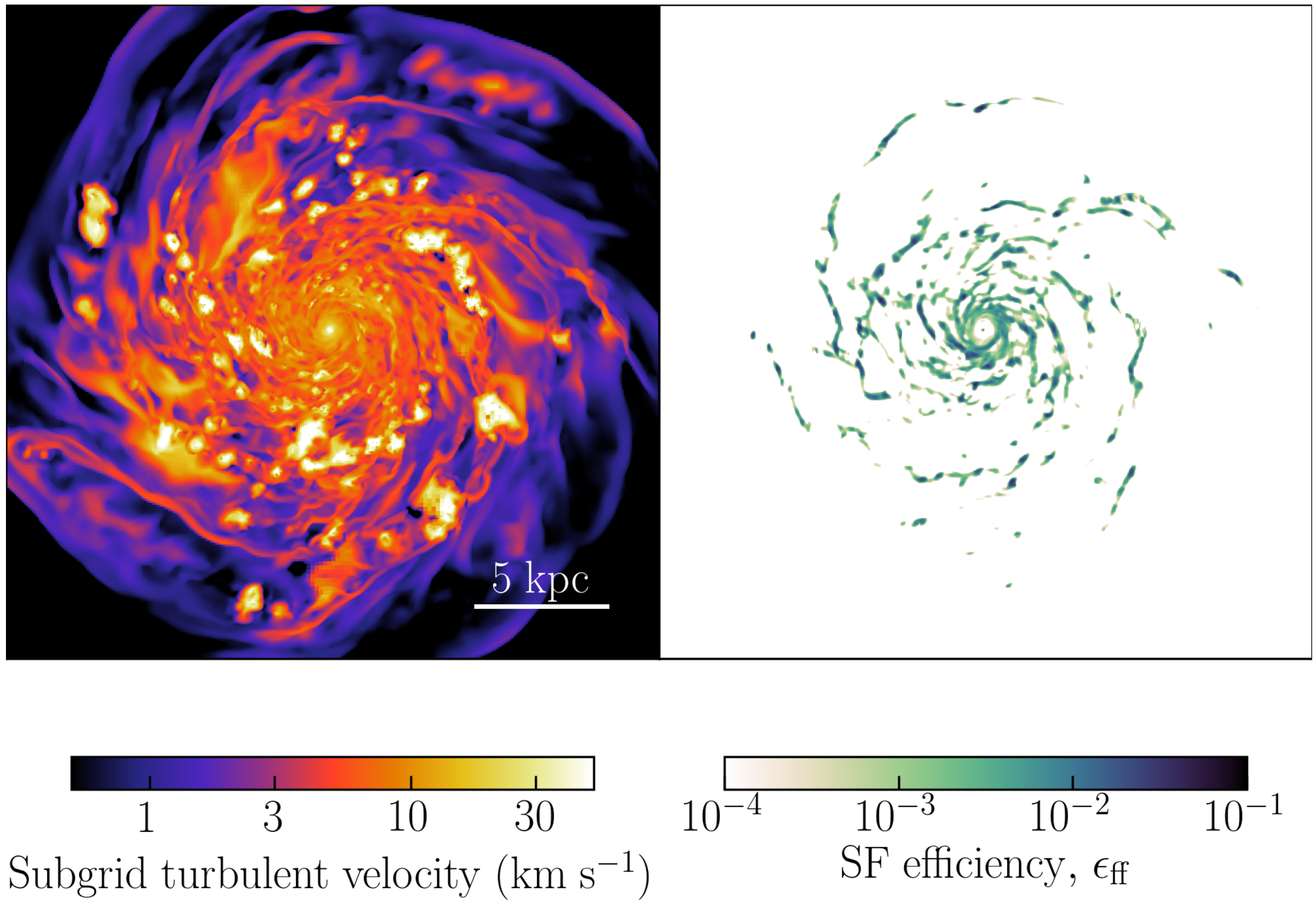
$$\frac{\partial}{\partial t}e + \nabla_k v_k e = -\Lambda_{\rm net} - P \nabla_k v_k$$

Schmidt et al. 2014
Braun et al. 2014
Semenov, Kravtsov and Gnedin, 2016

A dynamical model for subgrid turbulence

Semenov, Kravtsov and Gnedin, 2016

- Sub-grid turbulence model + stellar feedback predicts a wide range of ***instantaneous*** efficiencies, compatible with observations.
- Scatter set by environment.
- Details of stellar feedback matter still!



$$\sigma = \sqrt{\frac{2K}{\rho}}$$

$$\epsilon_{\rm ff} = 0.9 \exp\left(-1.6 \frac{t_{\rm ff}}{t_{\rm cr}}\right)$$

A dynamical model for subgrid turbulence

Semenov, Kravtsov and Gnedin, 2016

- Sub-grid turbulence model + stellar feedback predicts a wide range of ***instantaneous*** efficiencies, compatible with observations.
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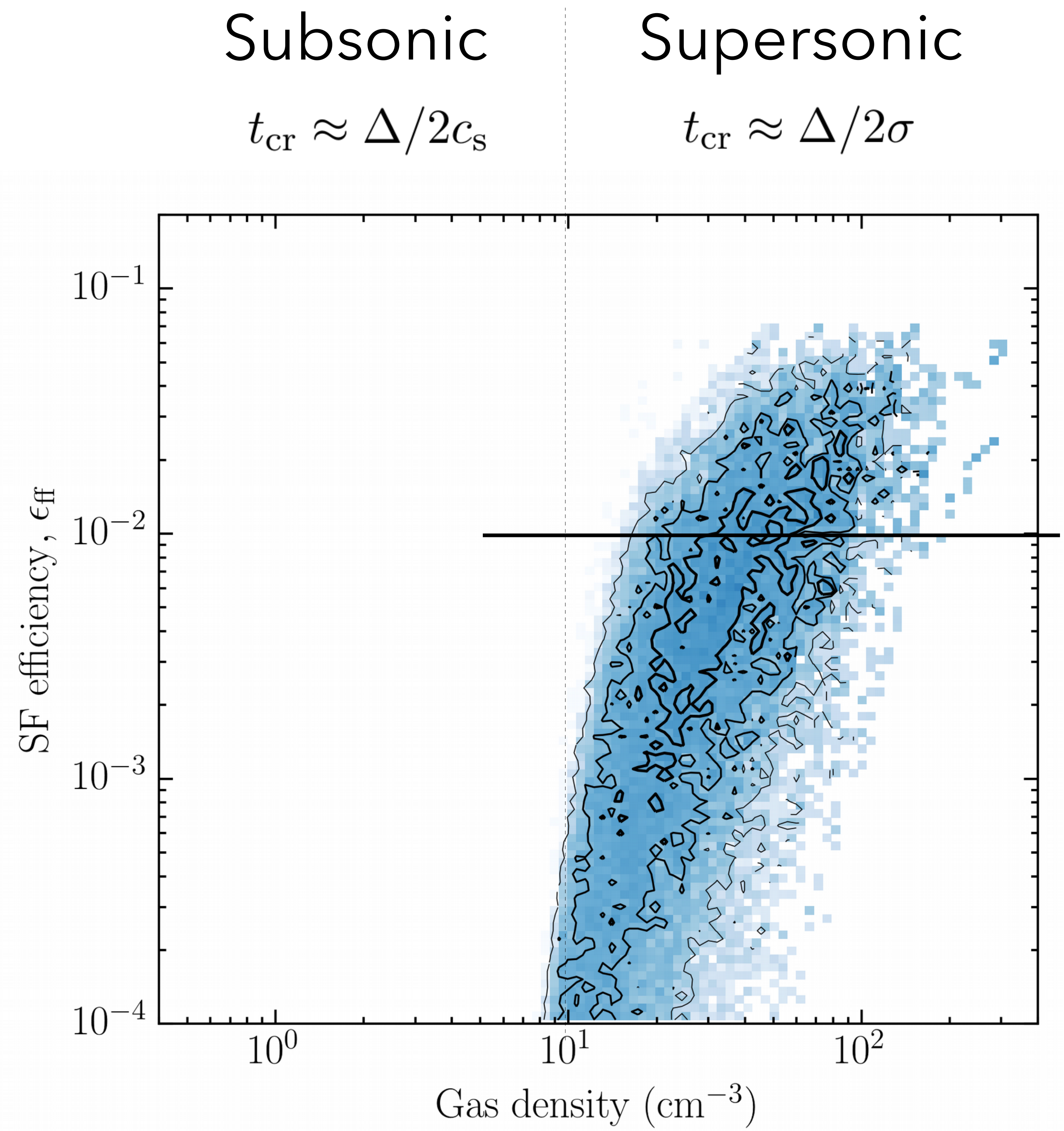
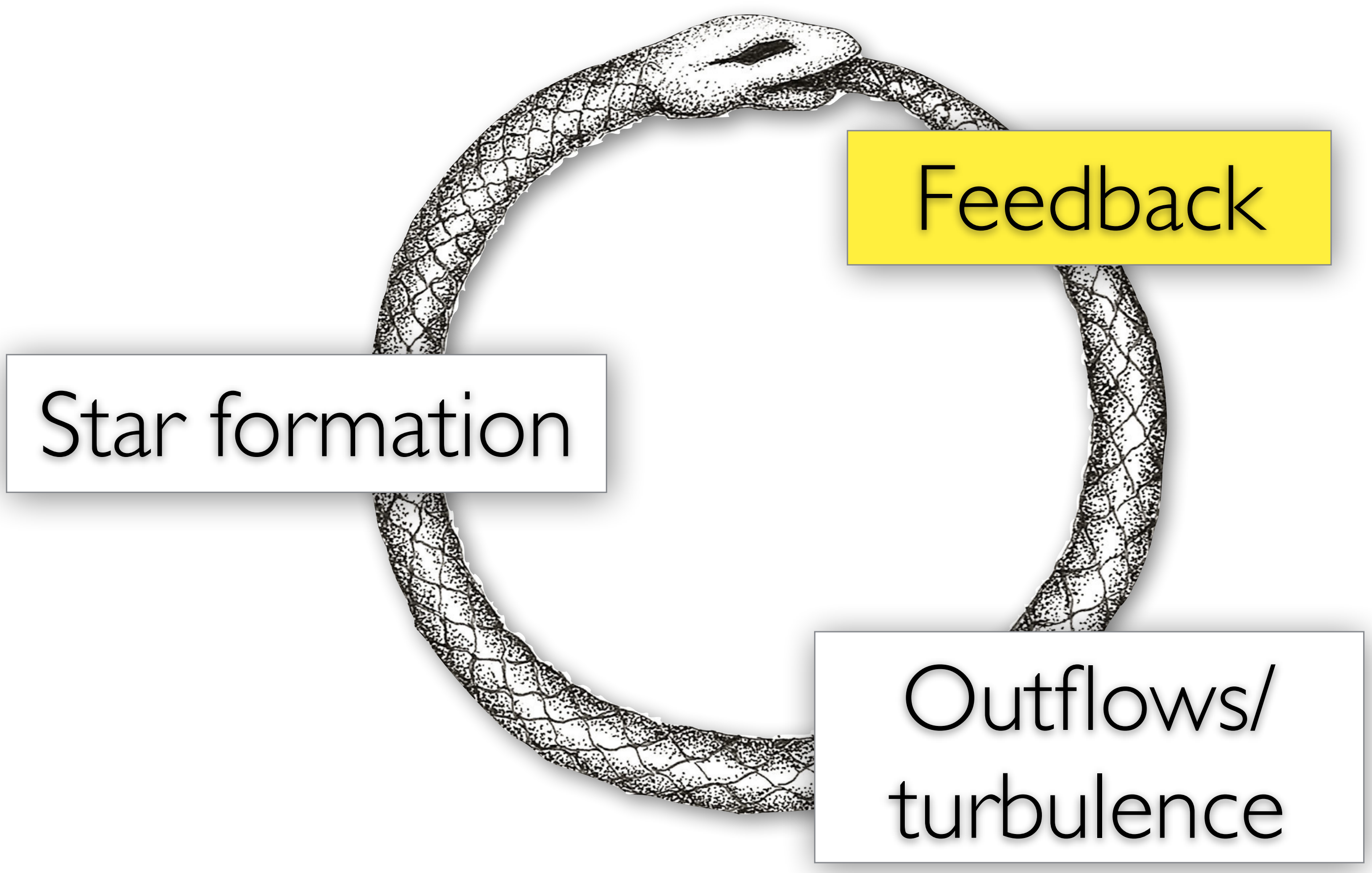


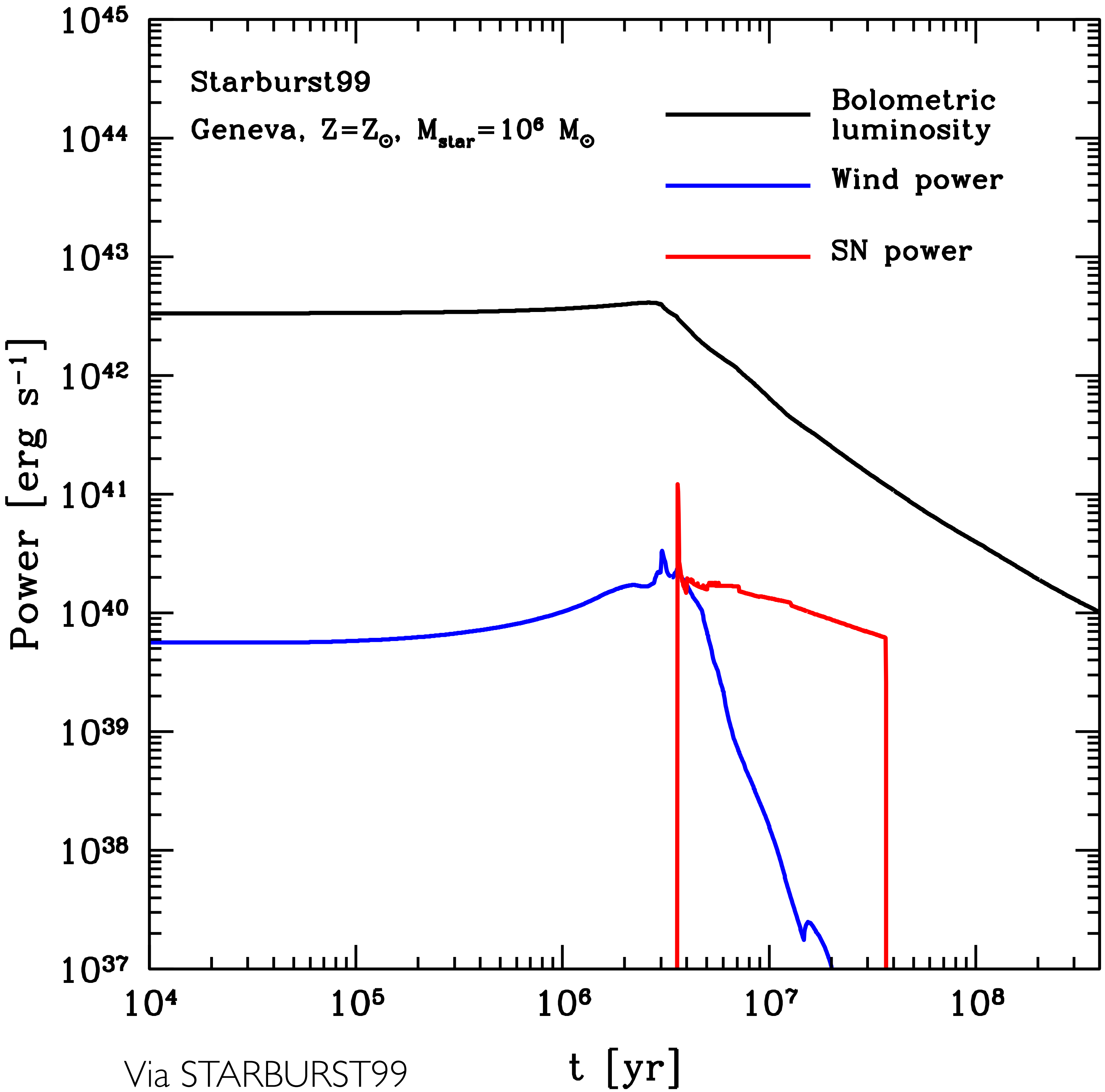
What efficiency should we use?

- Galaxy formation simulations by Hopkins et al. 2014, Agertz et al. 2015, and Devriendt et al. find that if the local free-fall time efficiency is assumed to be large in massive GMCs, feedback regulates star formation to observed rates.
- Feedback regulation will affect the entire evolution of the galaxy!



The stellar feedback budget in cosmological simulations

Agertz et al. (2013)



Via STARBURST99
(Leitherer et al. 1999)

The momentum injection rates are roughly equal!

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

NB! Cosmic rays are likely also an important component (e.g. Booth, Agertz + 2013).

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*)

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

- A slew of studies just in the past couple of years on the momentum inout from SNe: *Martizzi et al. (2015), Kim & Ostriker (2015), Vasiliev et al. (2015), Simpson et al. (2015), Gatto et al. (2015), Walch et al. (2015), Haid et al. (2016) etc.* ***See talk by Chang-Go Kim tomorrow!***

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*).

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

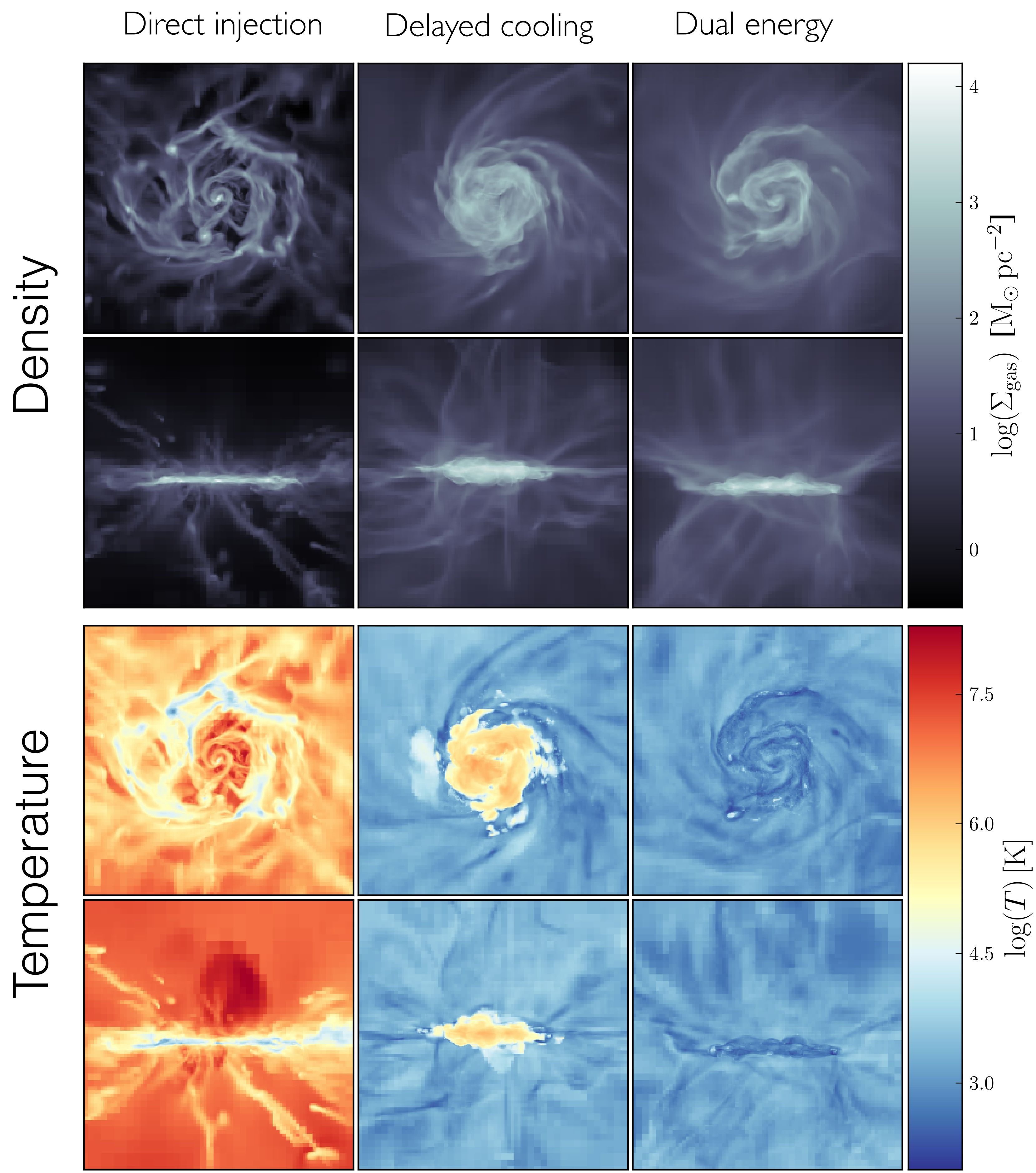
- Successful implementations of thermal feedback usually assume an extended period of **adiabatic evolution** (*Gerritsen 1997, Stinson et al. 2006, Governato et al. 2010, Agertz et al. 2011*, *Guedes et al. 2011*).

- 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 et al. 2014, 2015*), ***see talk tomorrow by Ben Keller!***

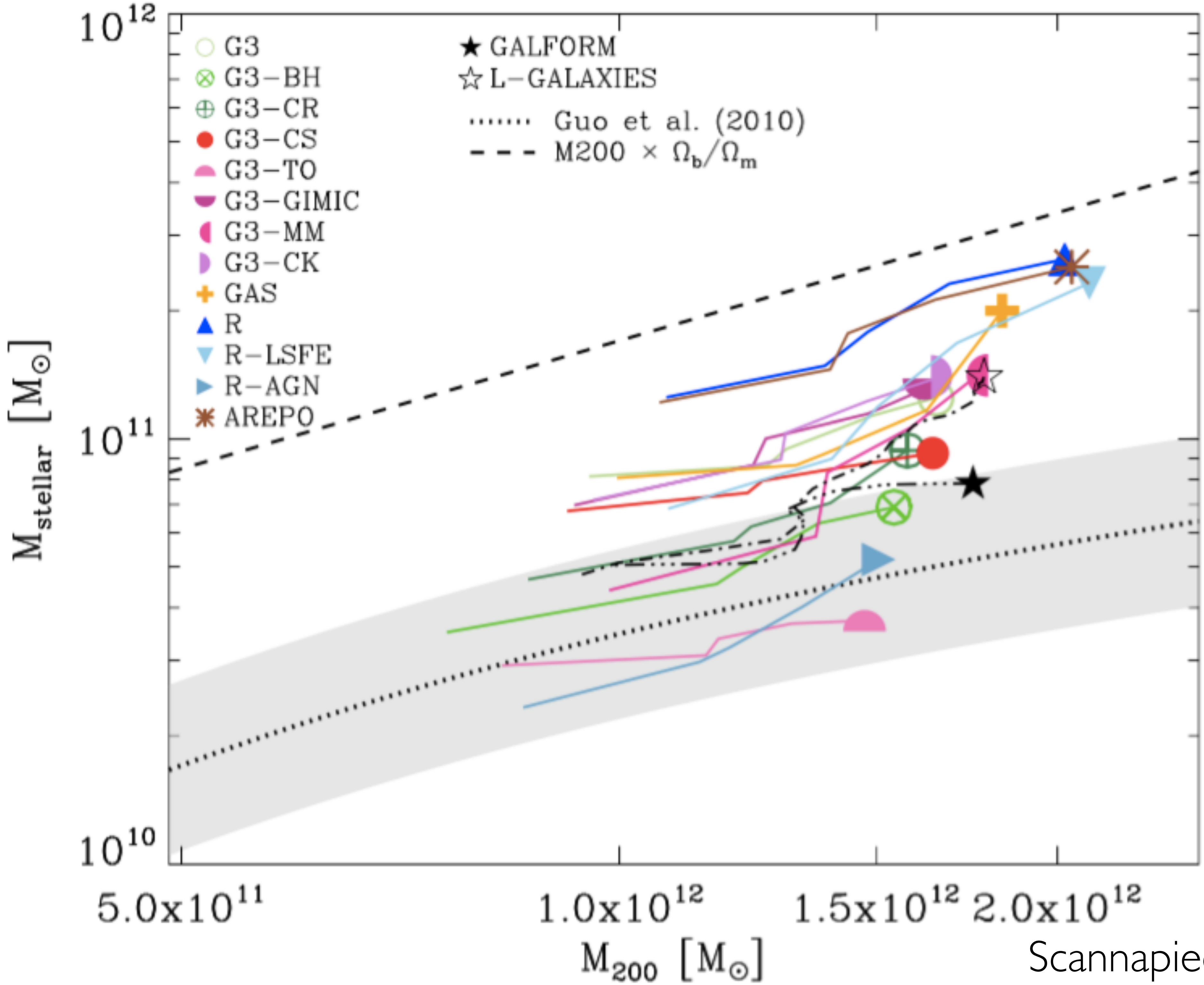
Disagreements in the community:

Same star formation and feedback, different implementations!



Disagreements in the community: implementation differences matter!

The Aquila comparison project



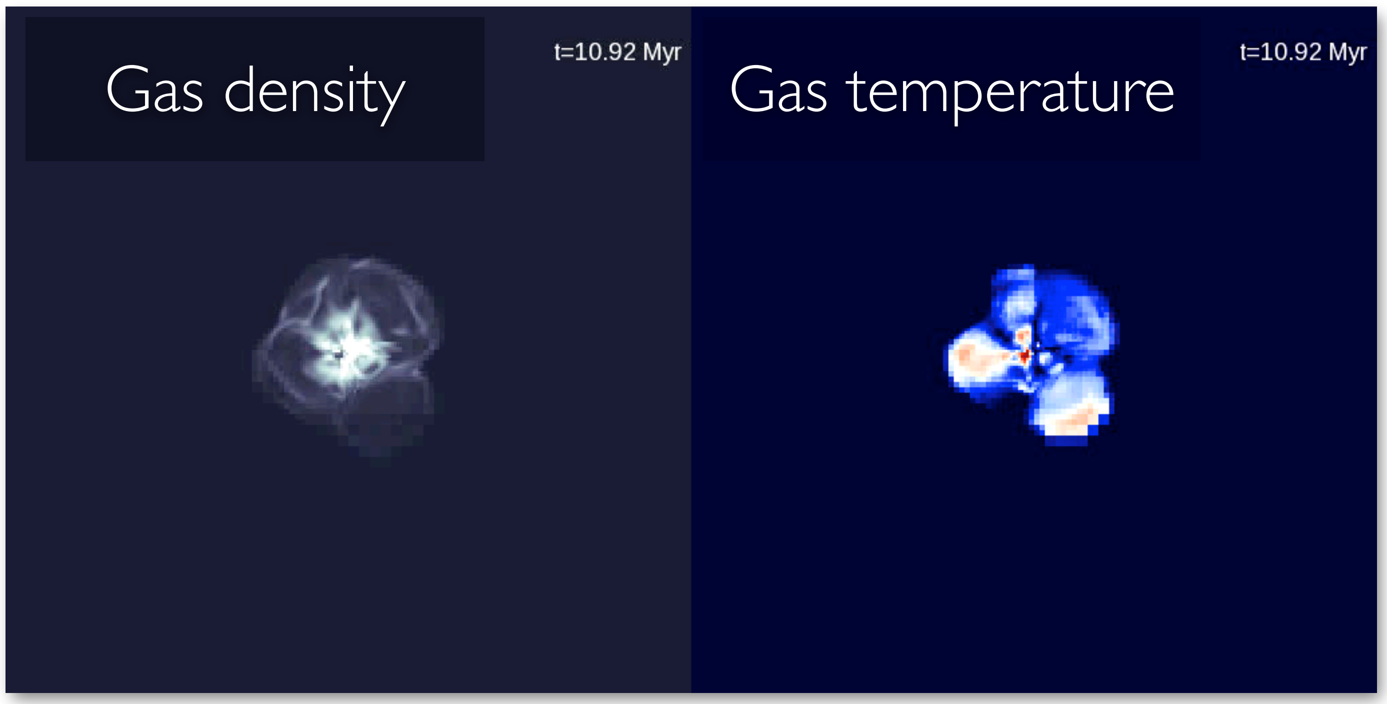
Scannapieco et al. (2012)

Calibrating feedback models on different scales is important:

The star formation efficiency in a Giant Molecular Cloud

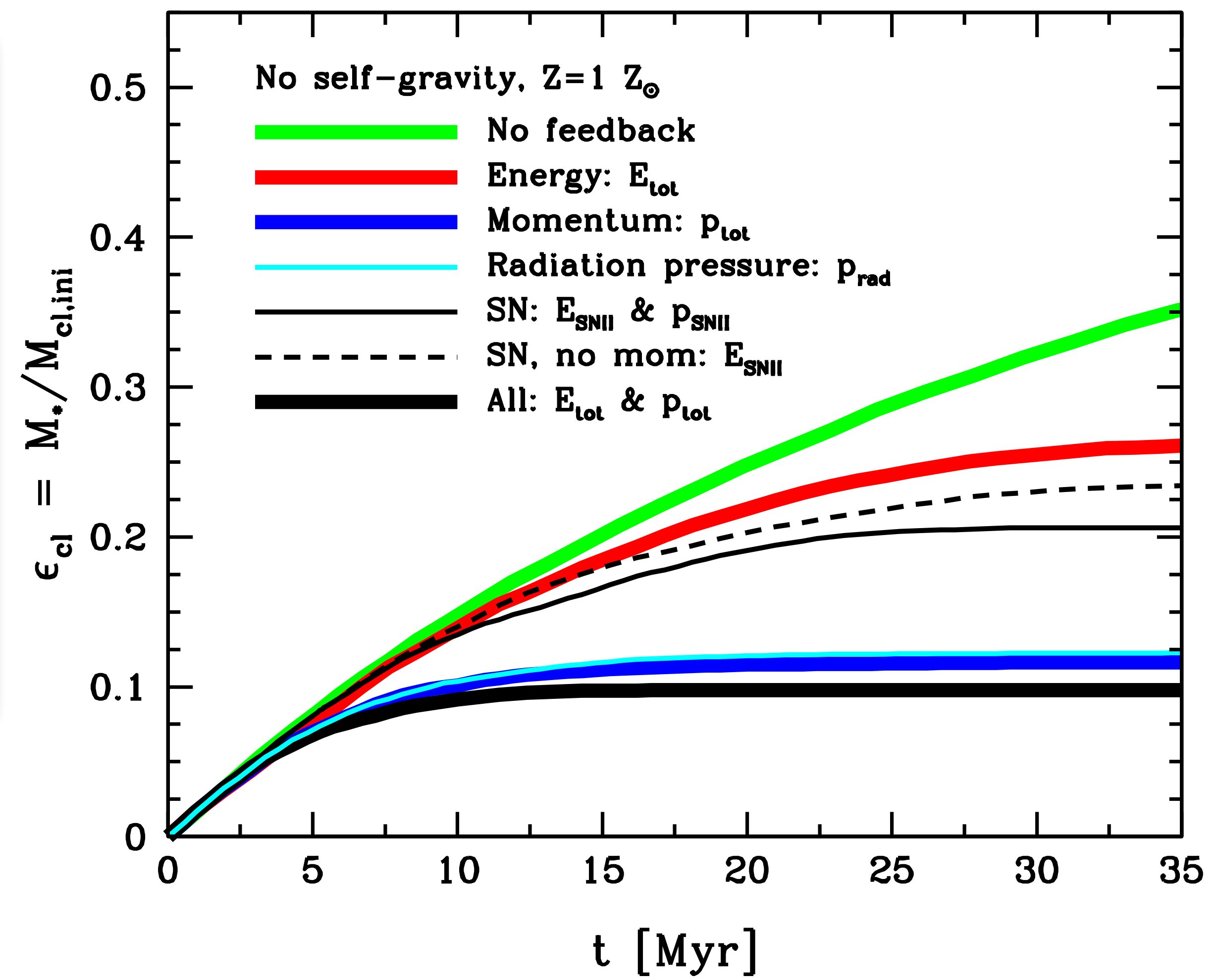
$$n_{\rm cl} = 100\,{\rm cm}^{-3} \qquad r_{\rm cl} = 50\,{\rm pc} \qquad M_{\rm GMC} \approx 10^6\,M_\odot$$

Agertz et al. (2013)



Adaptive-Mesh-Refinement code RAMSES (Teyssier, 2002)

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*)

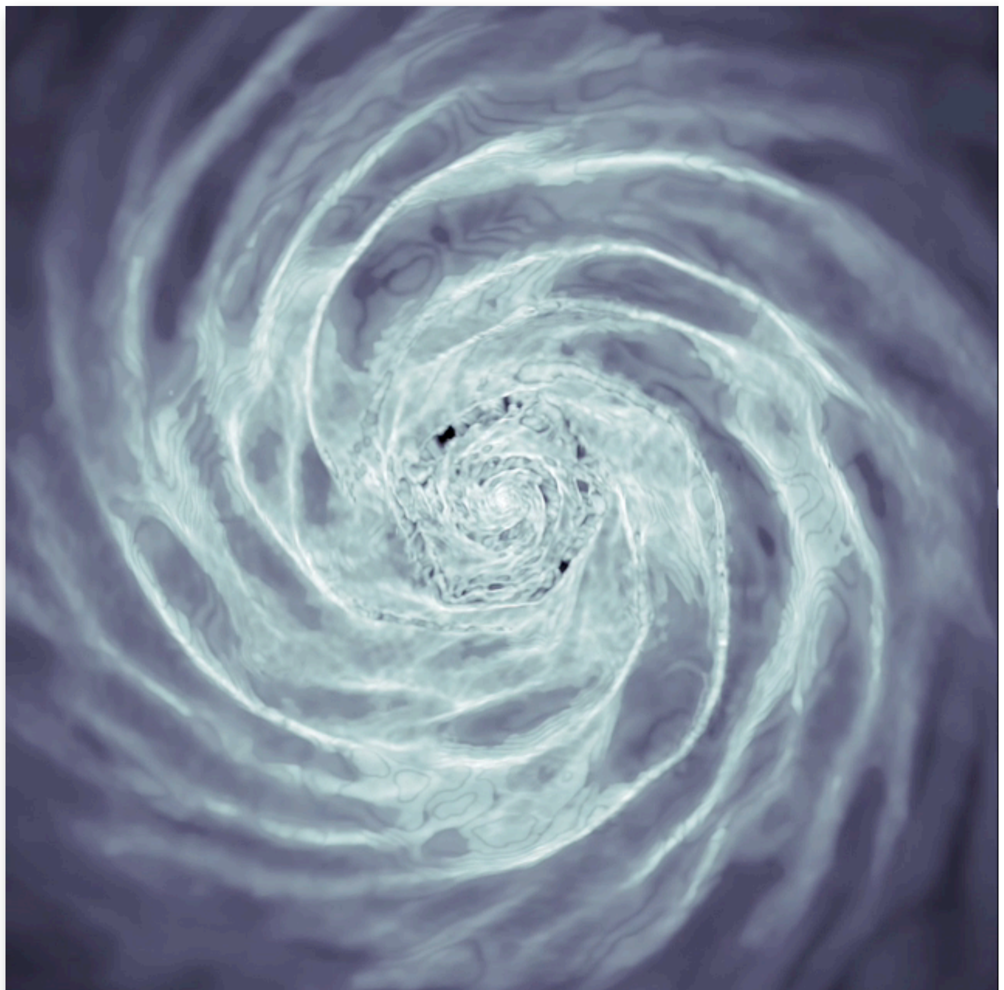
$$\langle \epsilon_{\rm ff} \rangle \approx 10\%$$

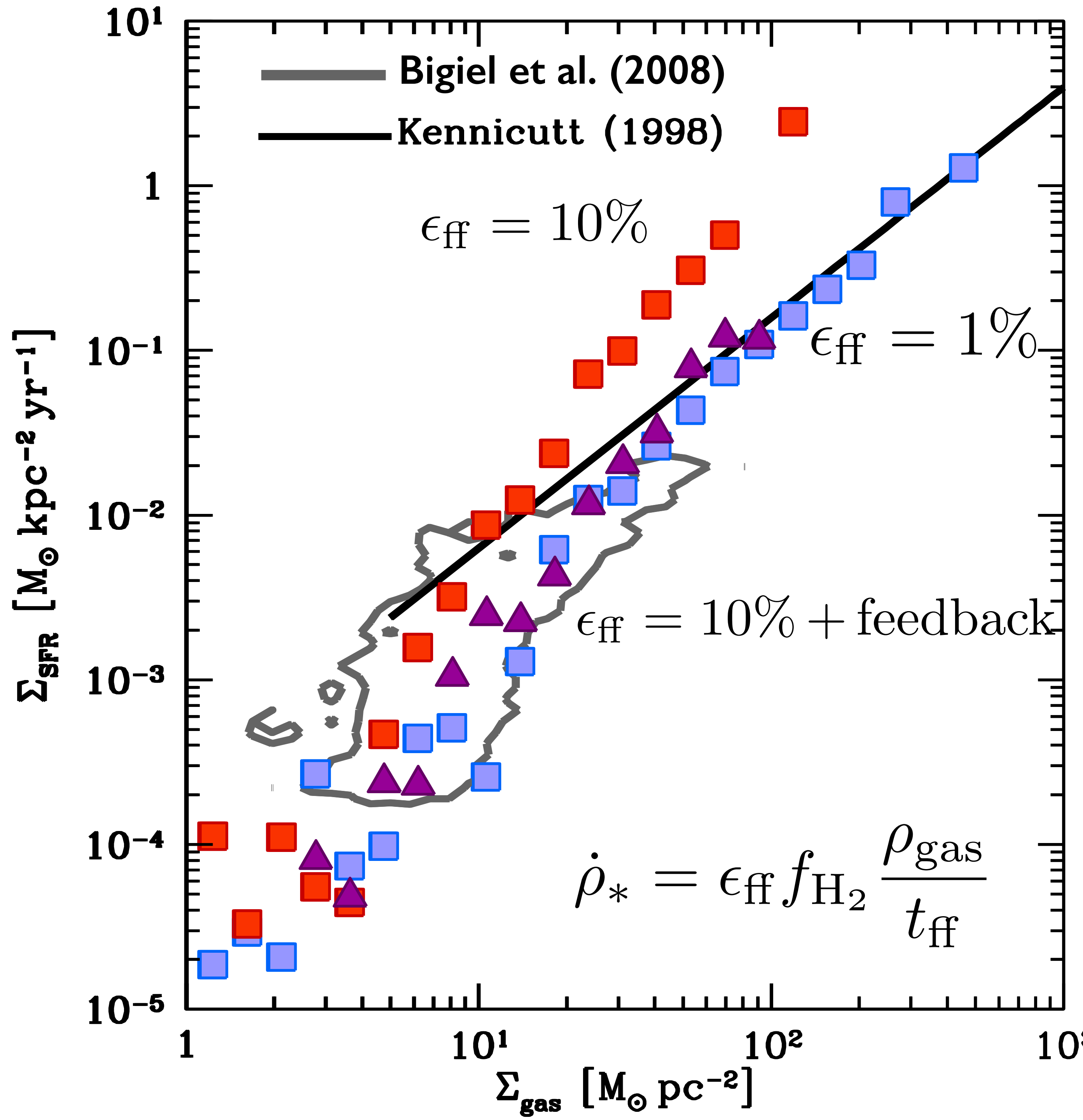
Calibrating feedback models on different scales is important:

Milky Way-like galactic disks

(Agertz et al. 2013)

Galactic star formation: the Kennicutt-Schmidt relation



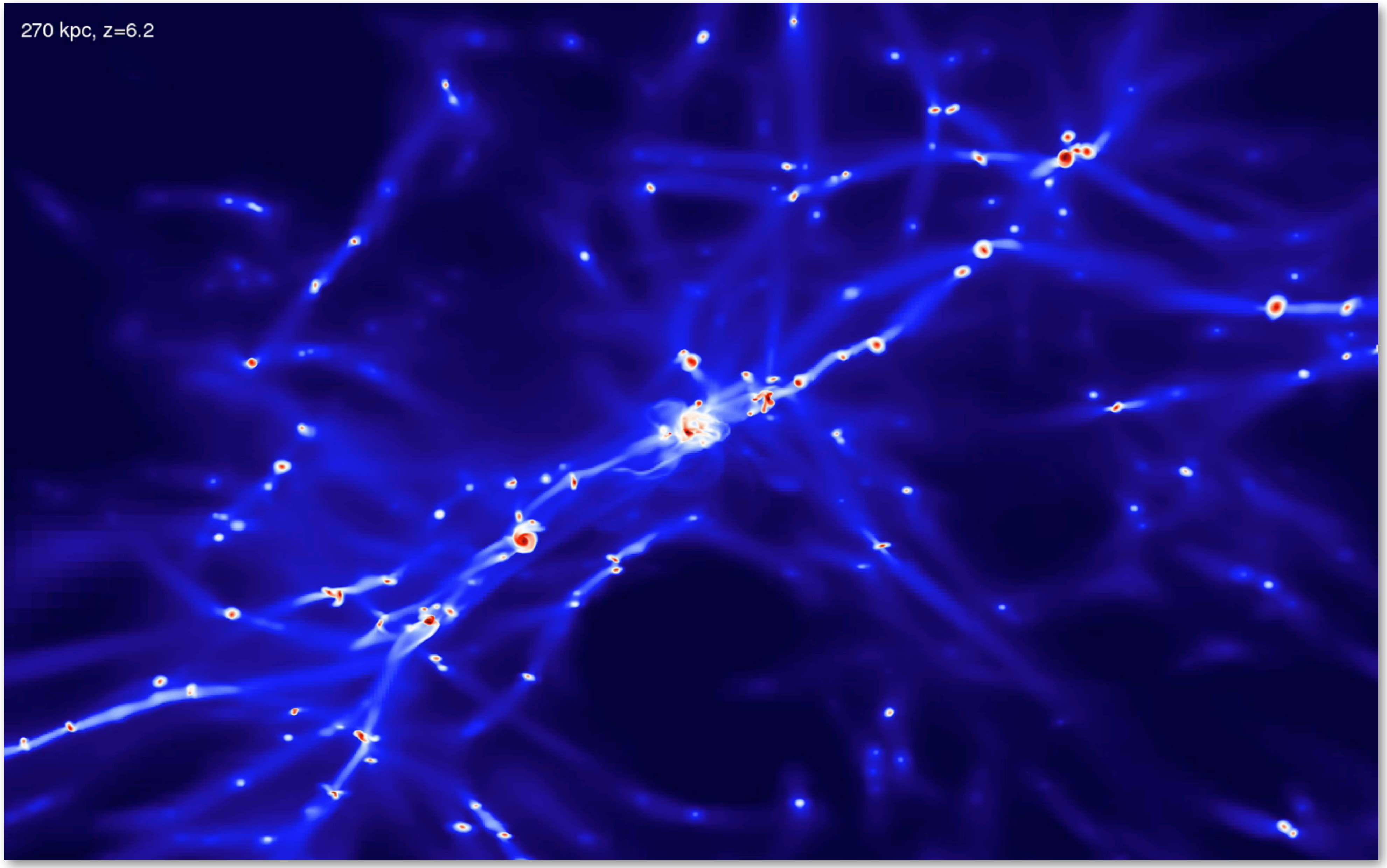


- Adopting the full feedback budget makes the simulated Kennicutt-Schmidt relation less sensitive to the underlying e_{ff}, and in closer agreement to observations.
- But which models regulate the baryon fractions via outflows?

Cosmological zoom-in simulations of galaxy formation and sensitivities to star formation modelling

- Milky Way-like progenitor, $M_{200}=10^{12}\,M_{sun}$ at z=0.
- Force/hydro resolution: 50-100 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 abundance of H_2 (*Krumholz et al. 2009, Gnedin et al. 2009, Kuhlen et al. 2012, Christensen et al. 2014*).

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



Agertz & Kravtsov (2015 & 2016)

Input vs. output, the case of galactic star formation

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

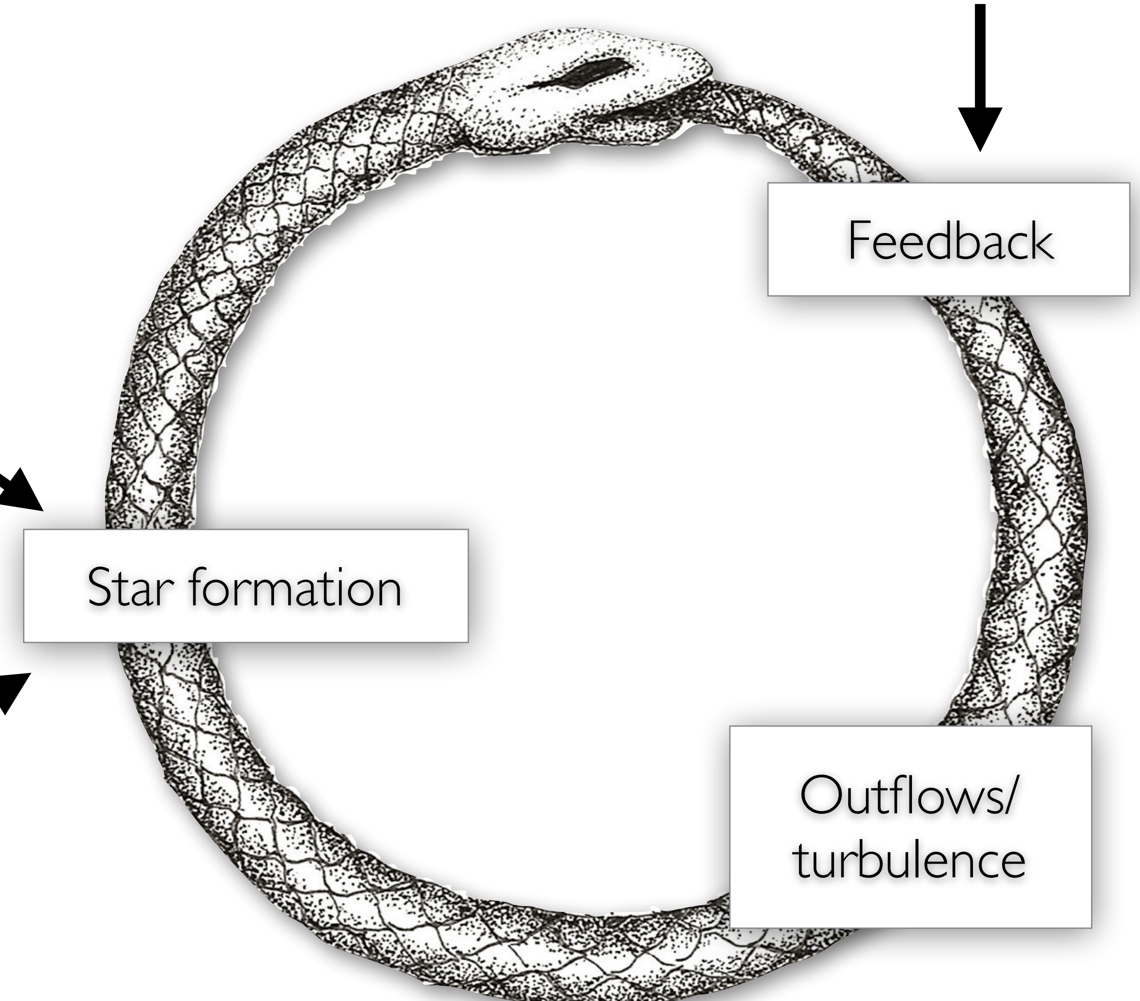
- Cosmic star formation histories
- Stellar mass - halo mass relation
- Stellar mass - gas metallicity relation + evolution
- Kennicutt-Schmidt relation
- Flat rotation curves

3) Low star formation efficiency, but extremely efficient feedback (**E_{SN}=5 x 10^{51} erg**)

The way in which correlated/strong feedback is achieved matters

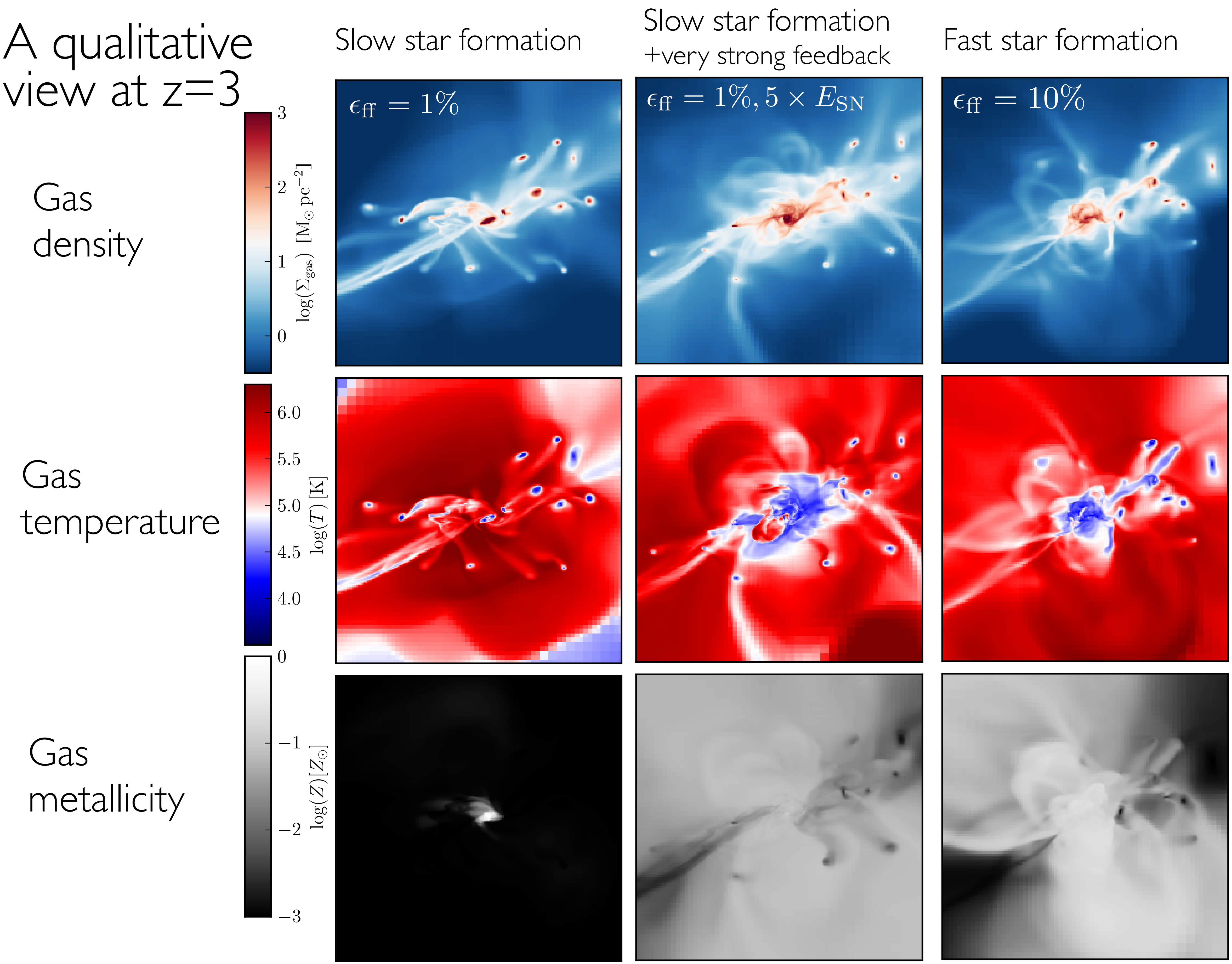
1) Low star formation efficiency (1%) **(slow/spread out star formation)**

2) High (GMC) star formation efficiency (10%) **(feedback regulated star formation)**



Agertz & Kravtsov (2015,2016)
Hopkins et al. (2014), Wetzel et al. (2016)
Governato et al. (2010)

A qualitative view at z=3



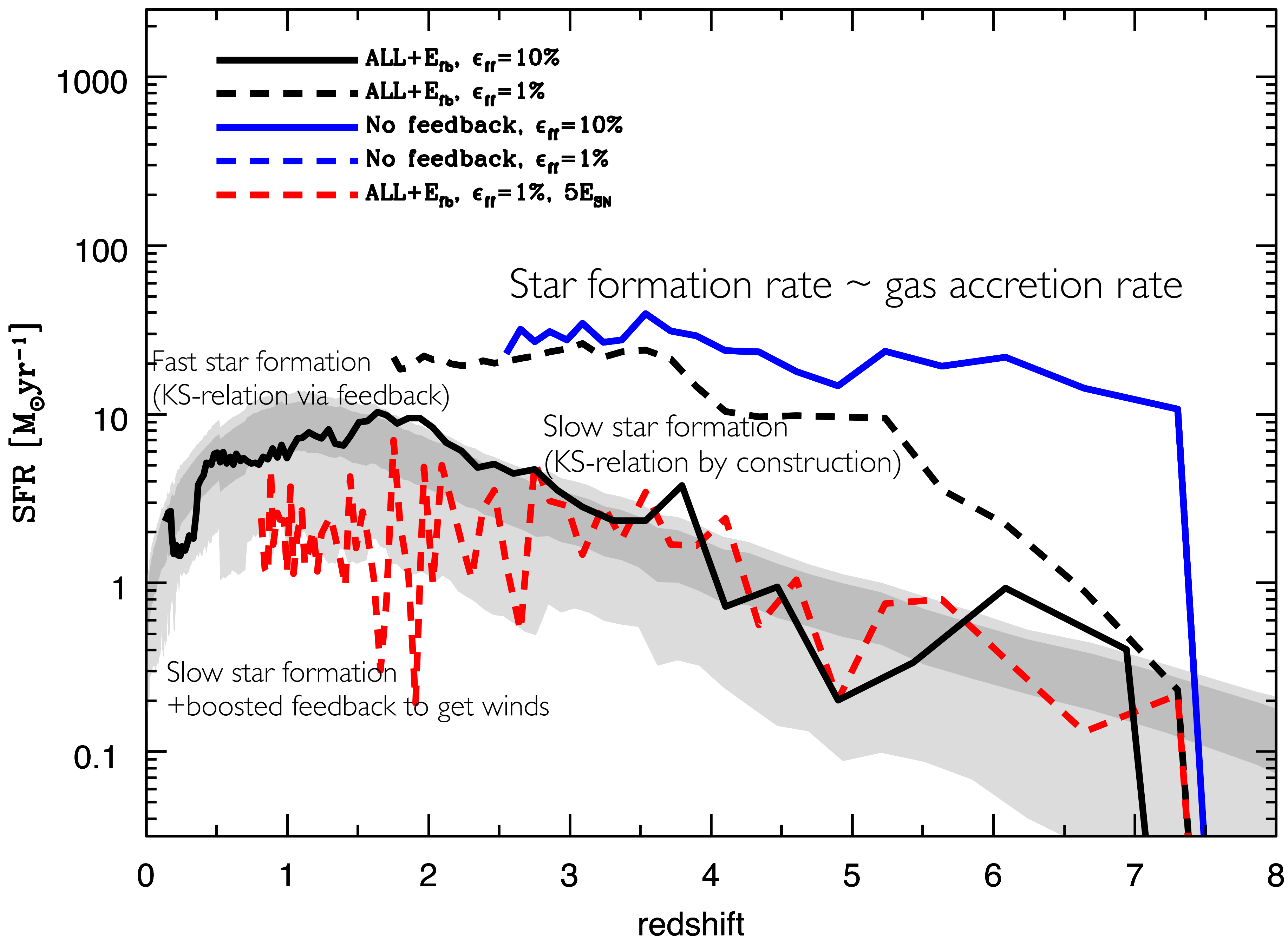
Star formation histories

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

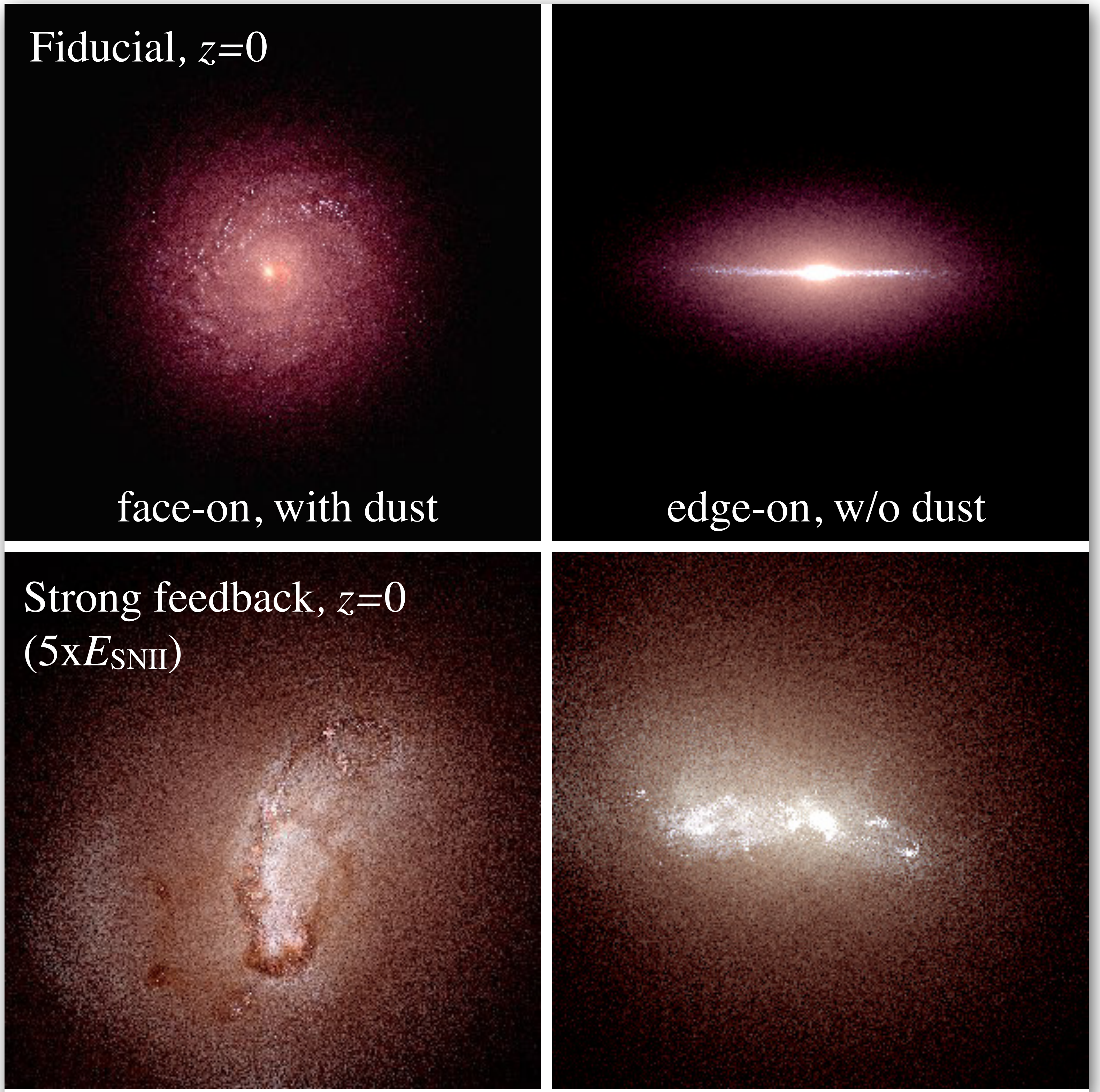
Star formation in Milky Way-like galaxies is expected to be highly suppressed for the first 3 billion years!

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

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



Internal properties differ significantly!



SDSS mockups (g,r,i)
Agertz & Kravtsov (2016)

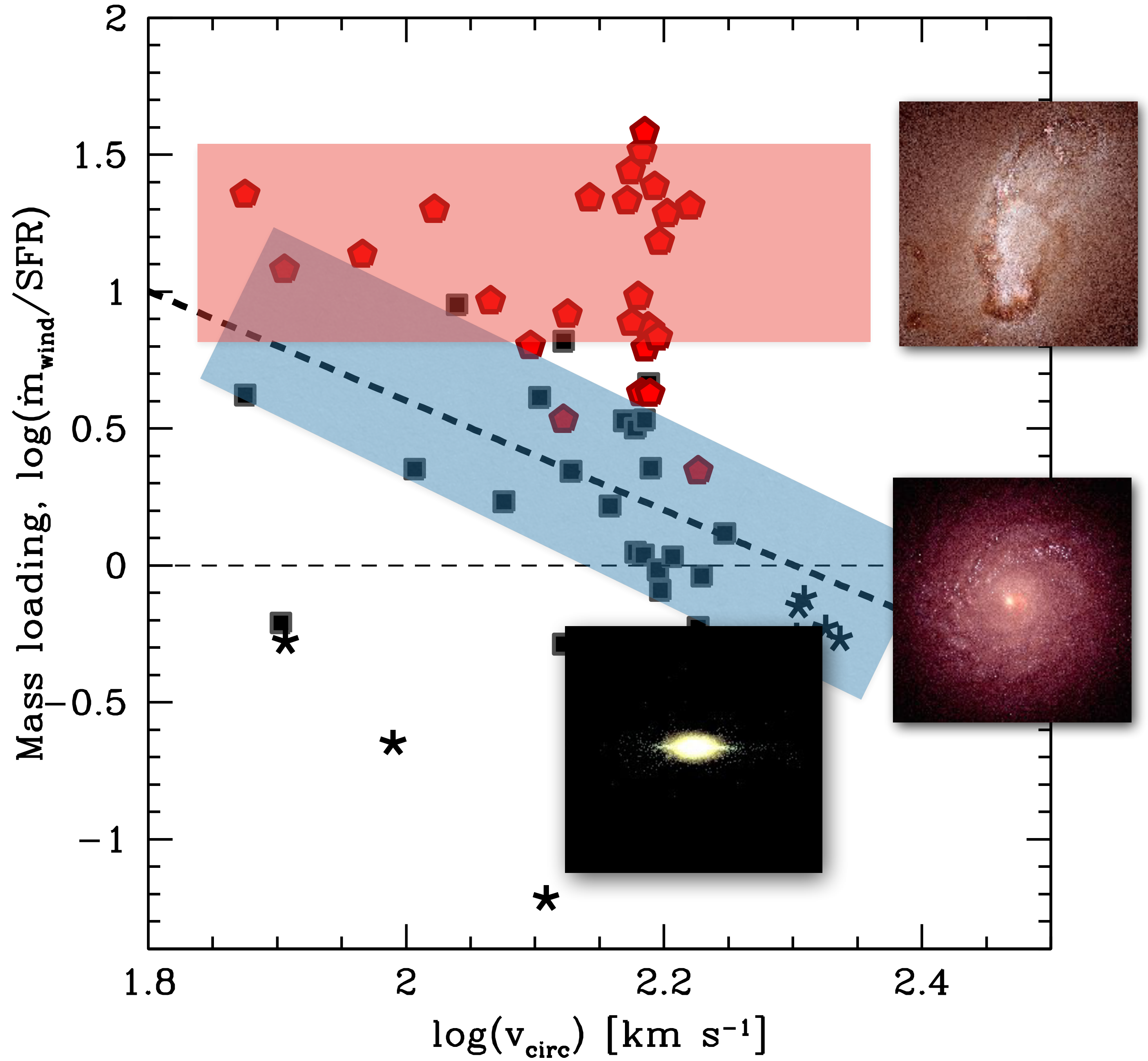
Identical initial conditions!

Galactic winds as emergent phenomena (not put in by hand!)

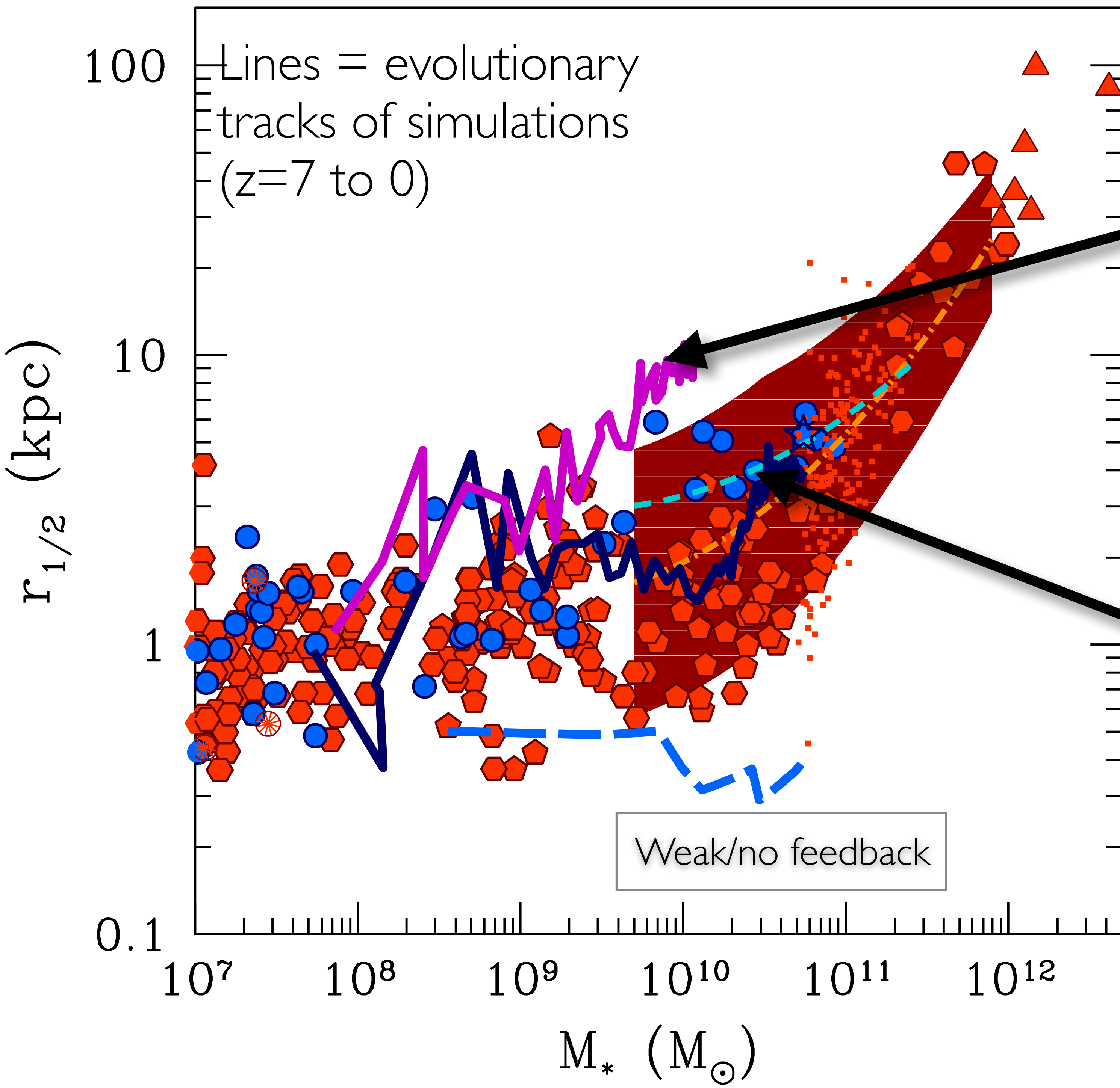
Mass-loading:

Measured at r=20 kpc for v>0

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



Galaxy sizes (Agertz & Kravtsov 2016)



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

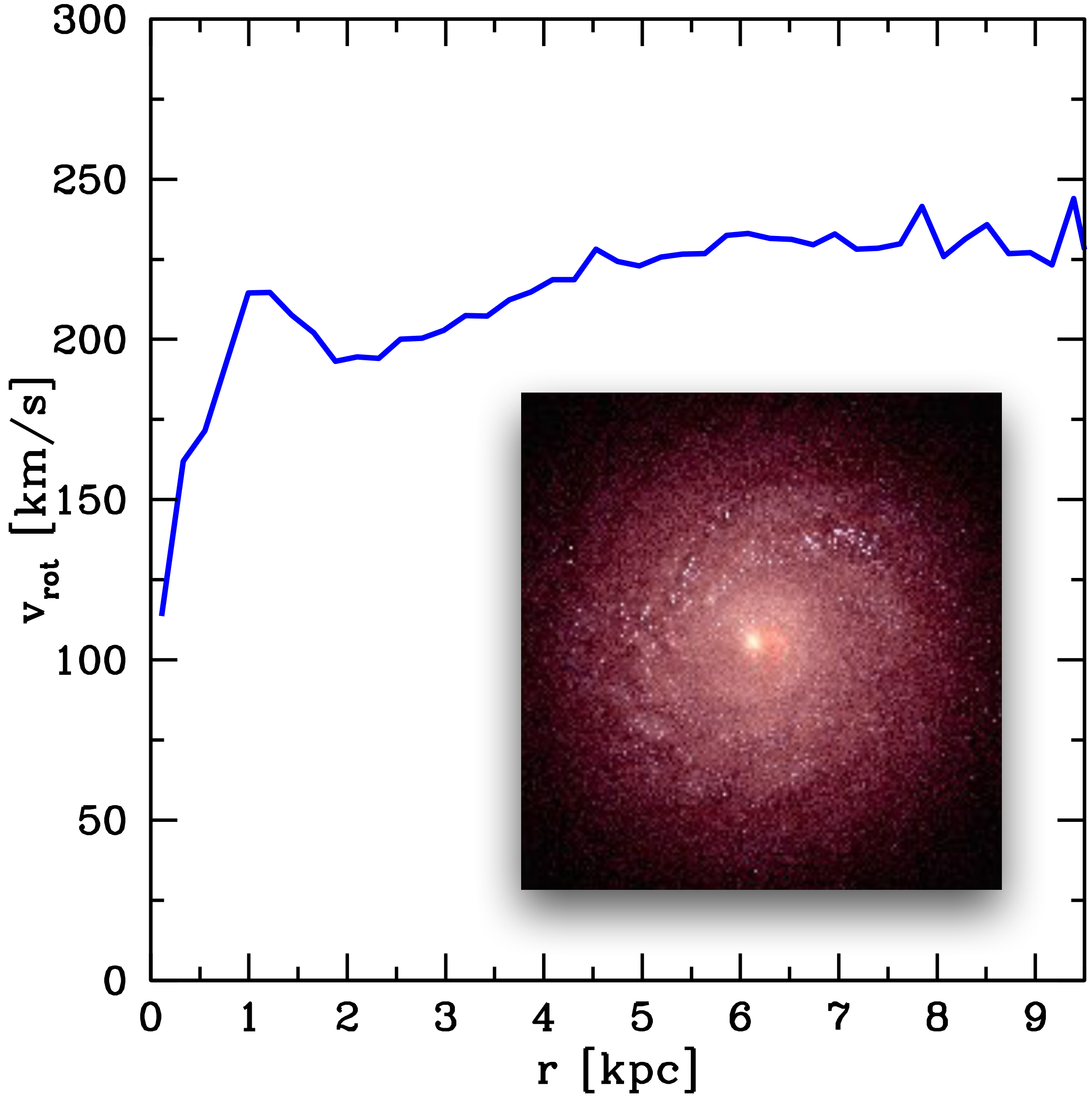
Grows as

$$r \propto M_\star^{0.3}$$

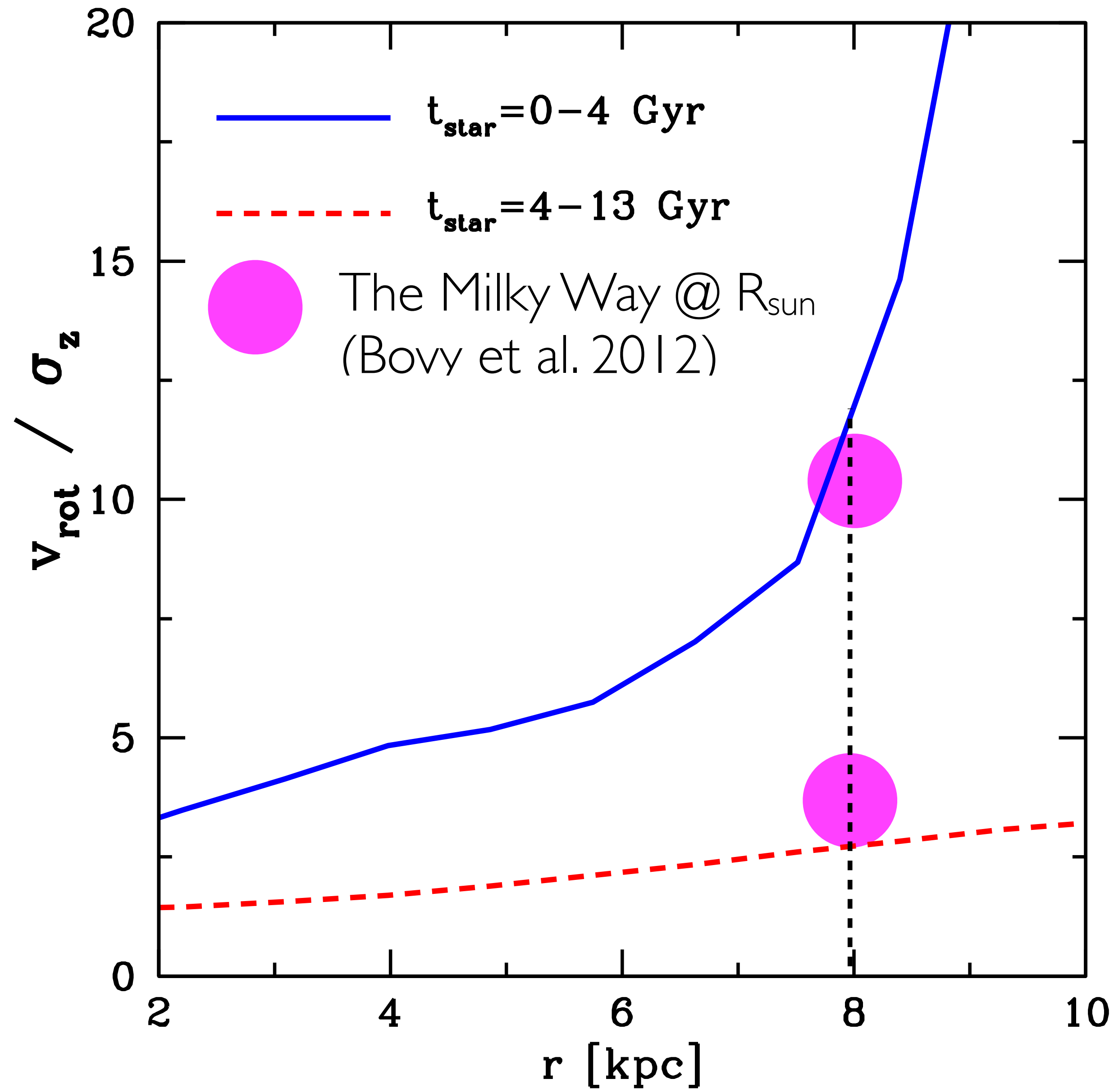
great match to CANDELS (Patel al. 2013)

Thin and thick disks at z=0 (Agertz & Kravtsov 2015)

Rotational velocity of young stars

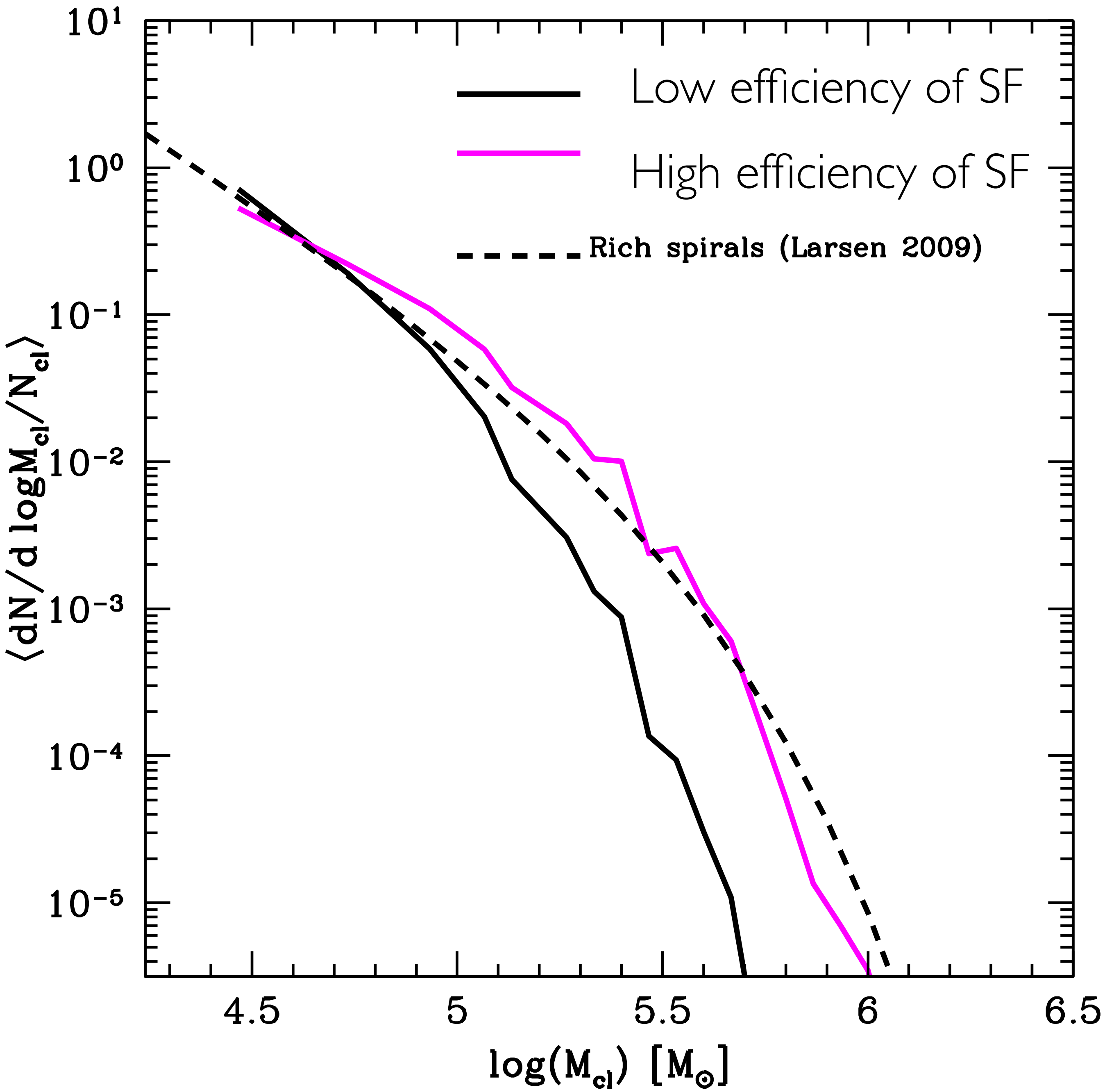


Stellar rotational velocity/ vertical velocity dispersion

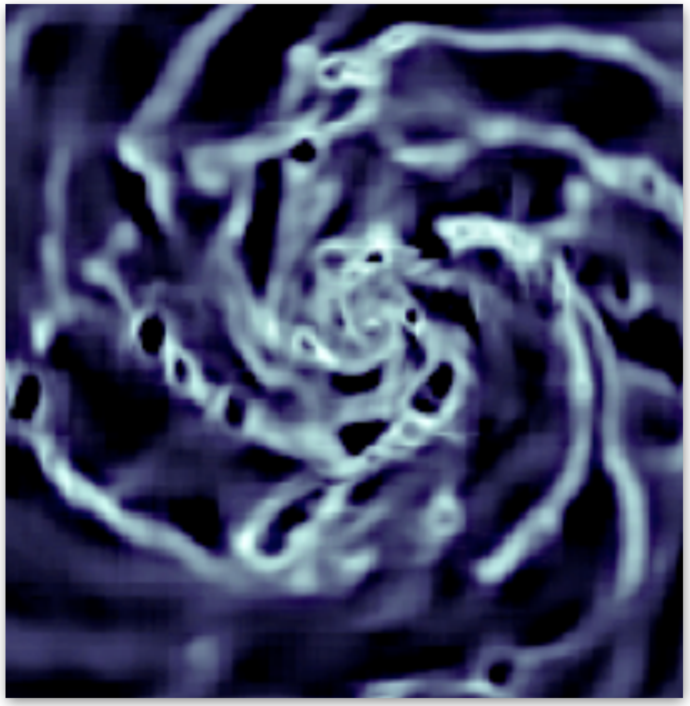


Appears when dx <50-100 pc. In the current model, only 1/3 of the disk mass is in a kinematically thin disk.

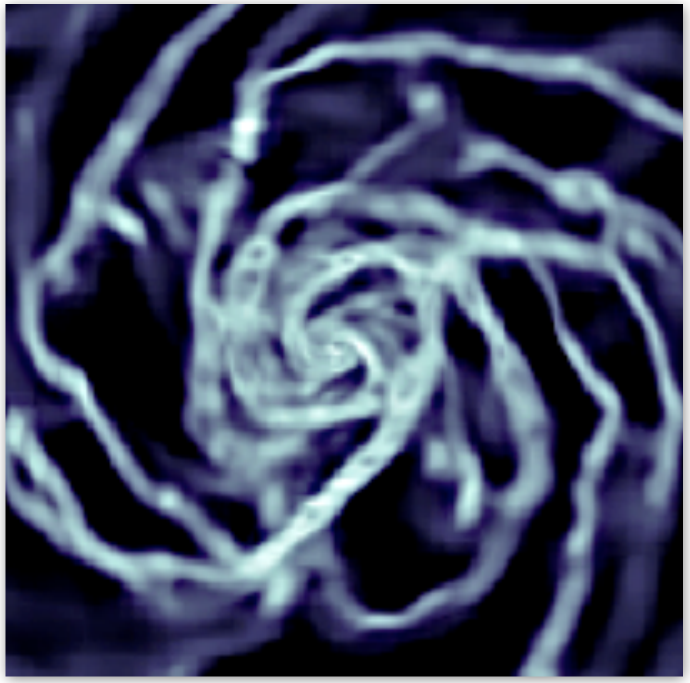
Correlated star formation and the strength of feedback



c.f. Milky Way:
30 % of ongoing star formation comes from 6 % of the GMCs (Murray 2011).

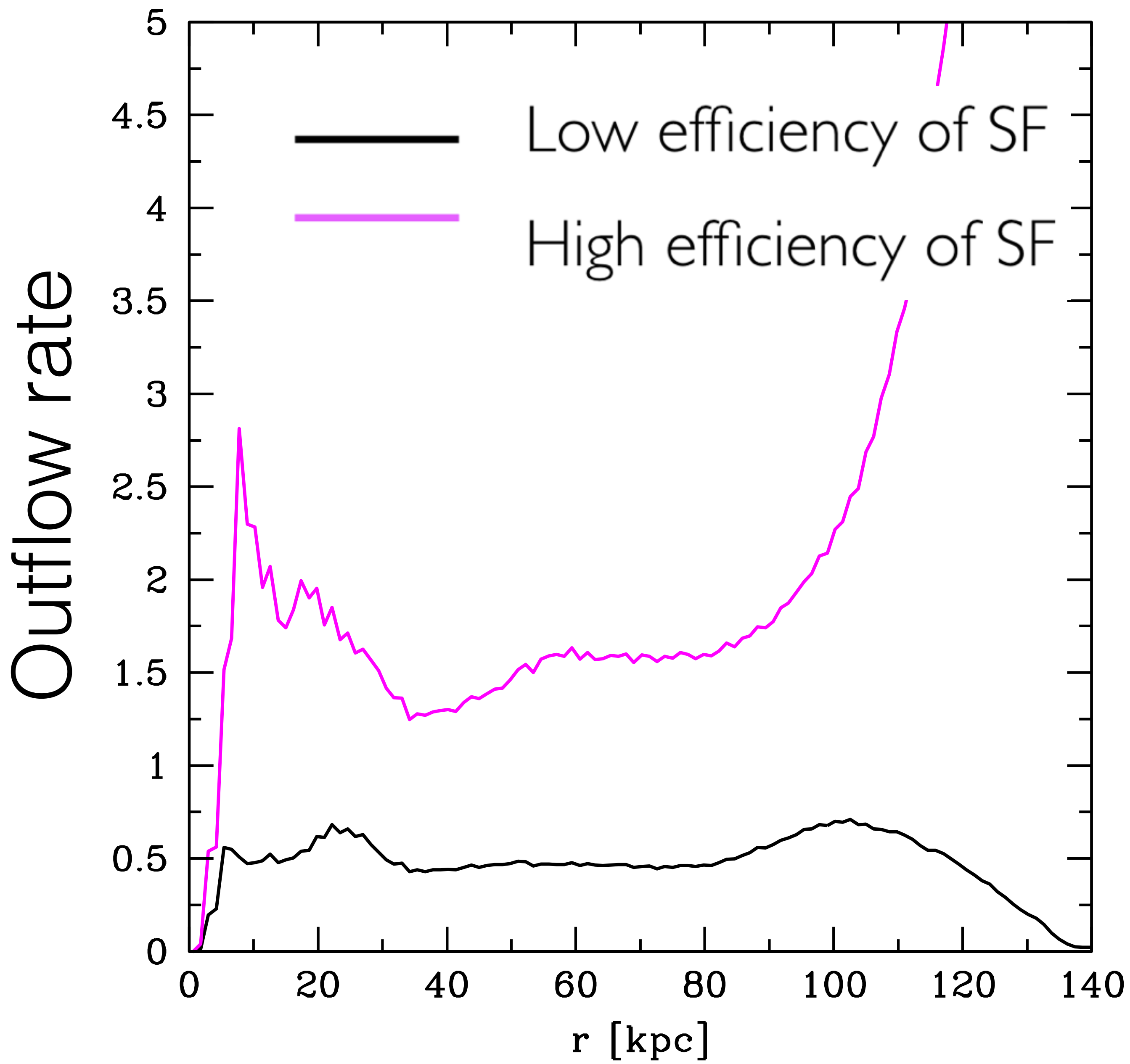


High efficiency of star formation



Low efficiency of star formation

Correlated star formation and the strength of feedback



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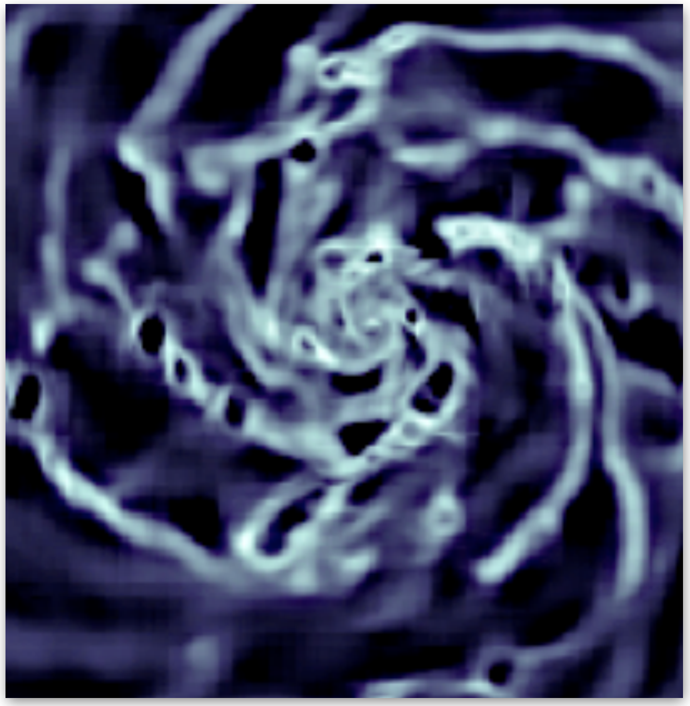

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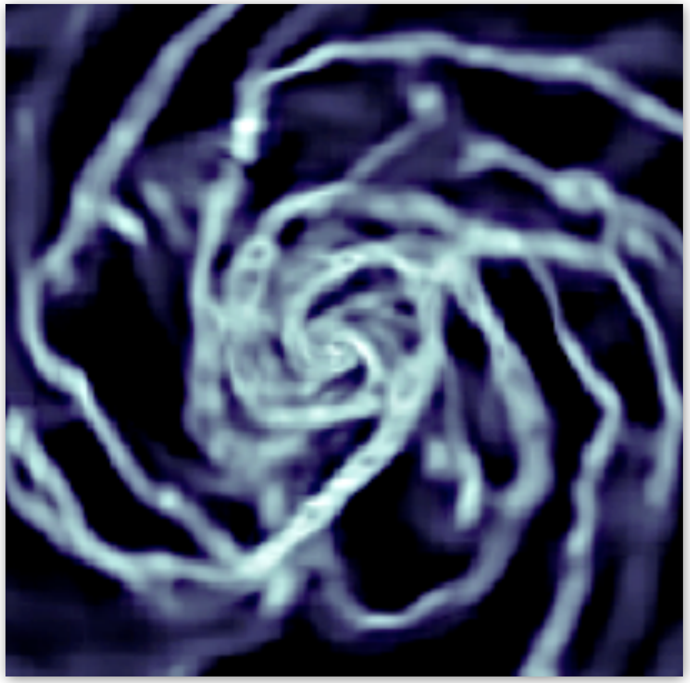
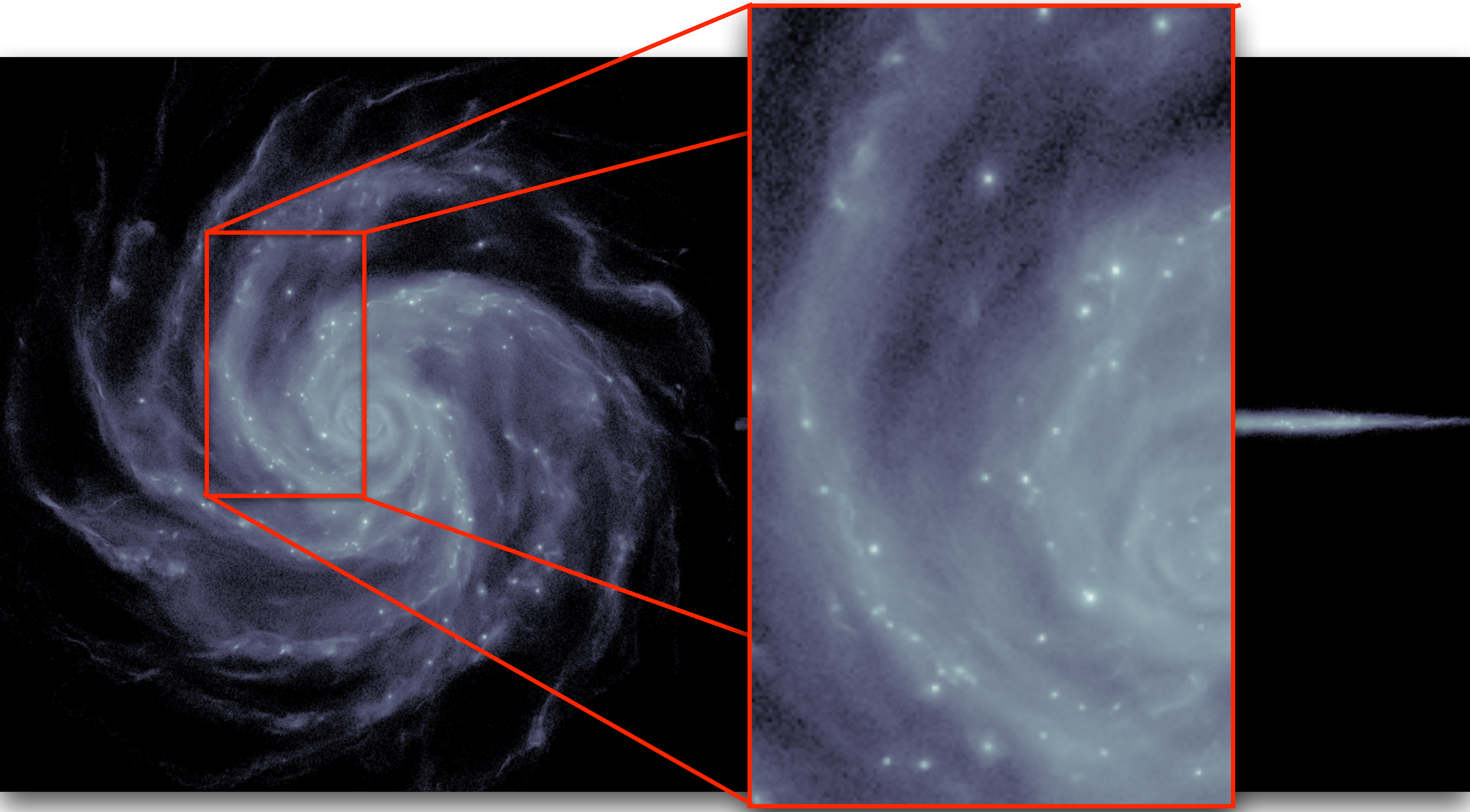


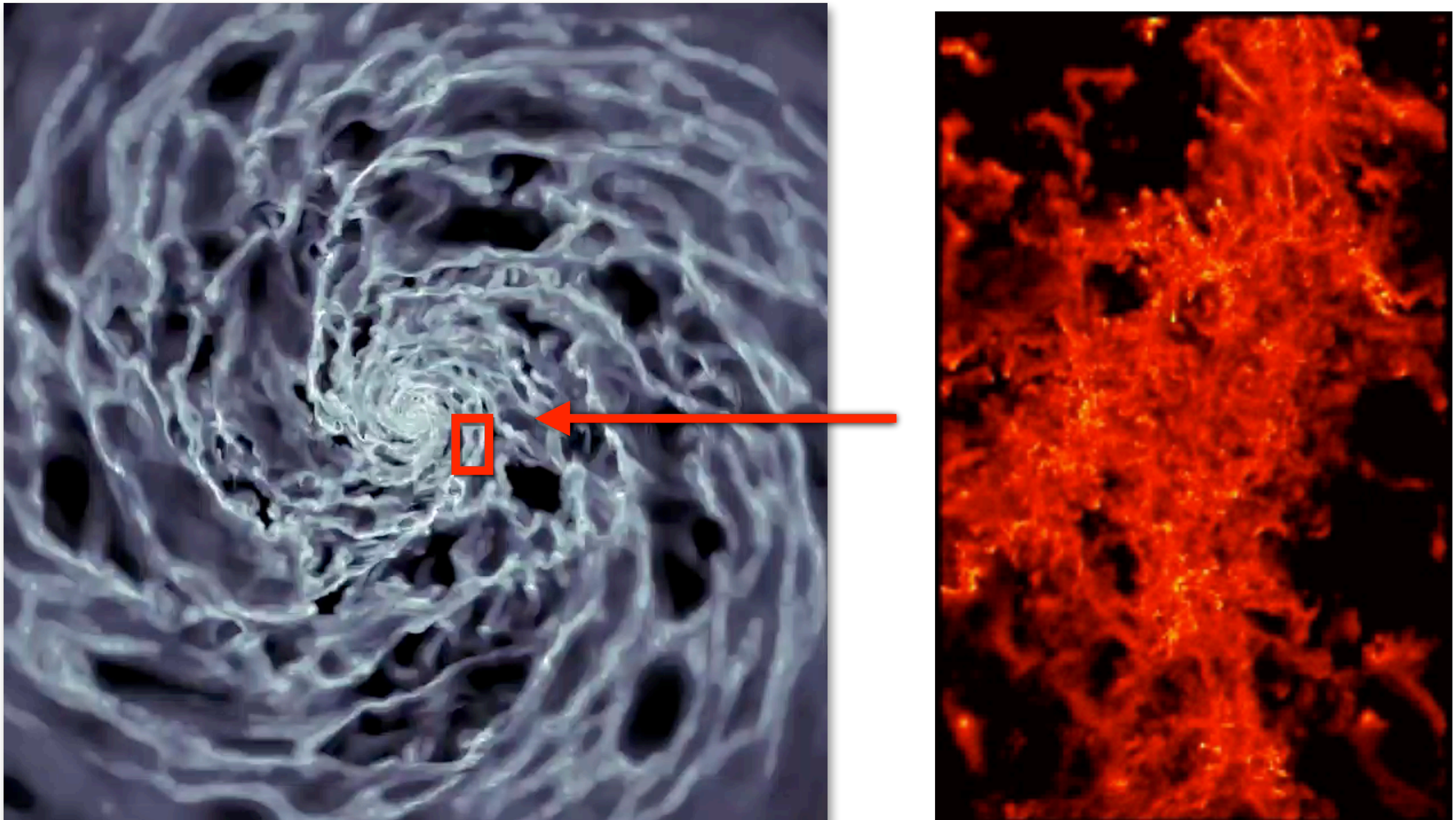
Low efficiency of star formation

The fields of galaxy formation and star formation are merging



Agertz et al. (in prep)

The fields of galaxy formation and star formation are merging



Rey-Raposo, Agertz et al. (in prep)
Smilgys & Bonnell (2016)

Summary

- Star formation models in hydrodynamical simulations of galaxy formation have remained more or less unaltered for > 2 decades. Improved numerical resolution now makes it possible to model star formation in cold molecular gas, almost on cloud scales.

- Feedback from massive stars have received a lot of attention, much driven by the effort to understand the inefficiency of galaxy formation and the existence of extended disc galaxies. Modern results are encouraging, with simulations reproducing a wide array of observables.

- Further scale coupling will allow us to better constrain free parameters, and to understand the connection between massive star clusters and their impact on ISM turbulence and outflows.