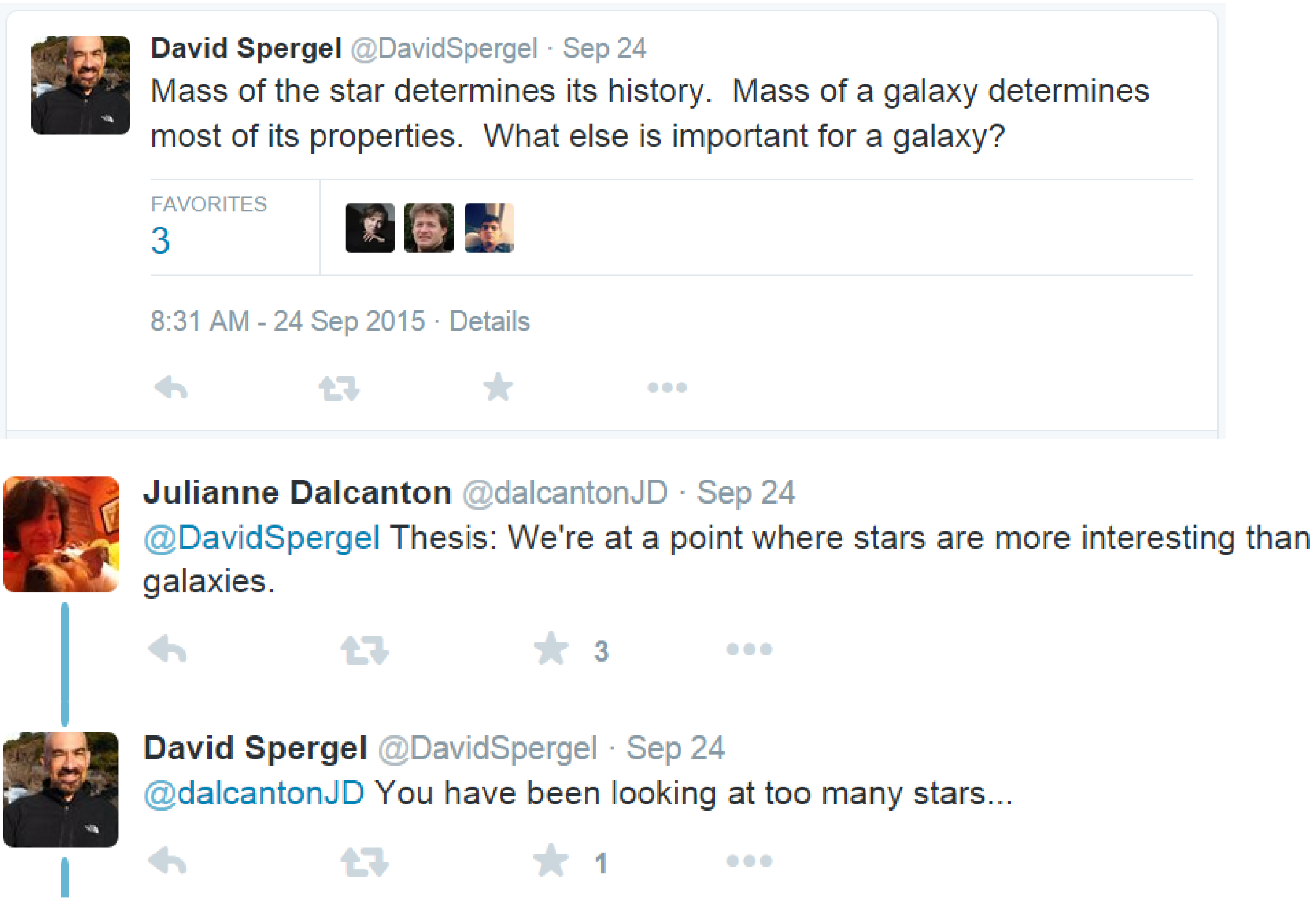
Towards a better modelling of star formation – feedback loop in galaxy formation simulations

Andrey Kravtsov
University of Chicago

the most important properties of galaxies?



David Spergel @DavidSpergel · Sep 24

Mass of the star determines its history. Mass of a galaxy determines most of its properties. What else is important for a galaxy?

FAVORITES
3

8:31 AM - 24 Sep 2015 · Details

Julianne Dalcanton @dalcantonJD · Sep 24

@DavidSpergel Thesis: We're at a point where stars are more interesting than galaxies.

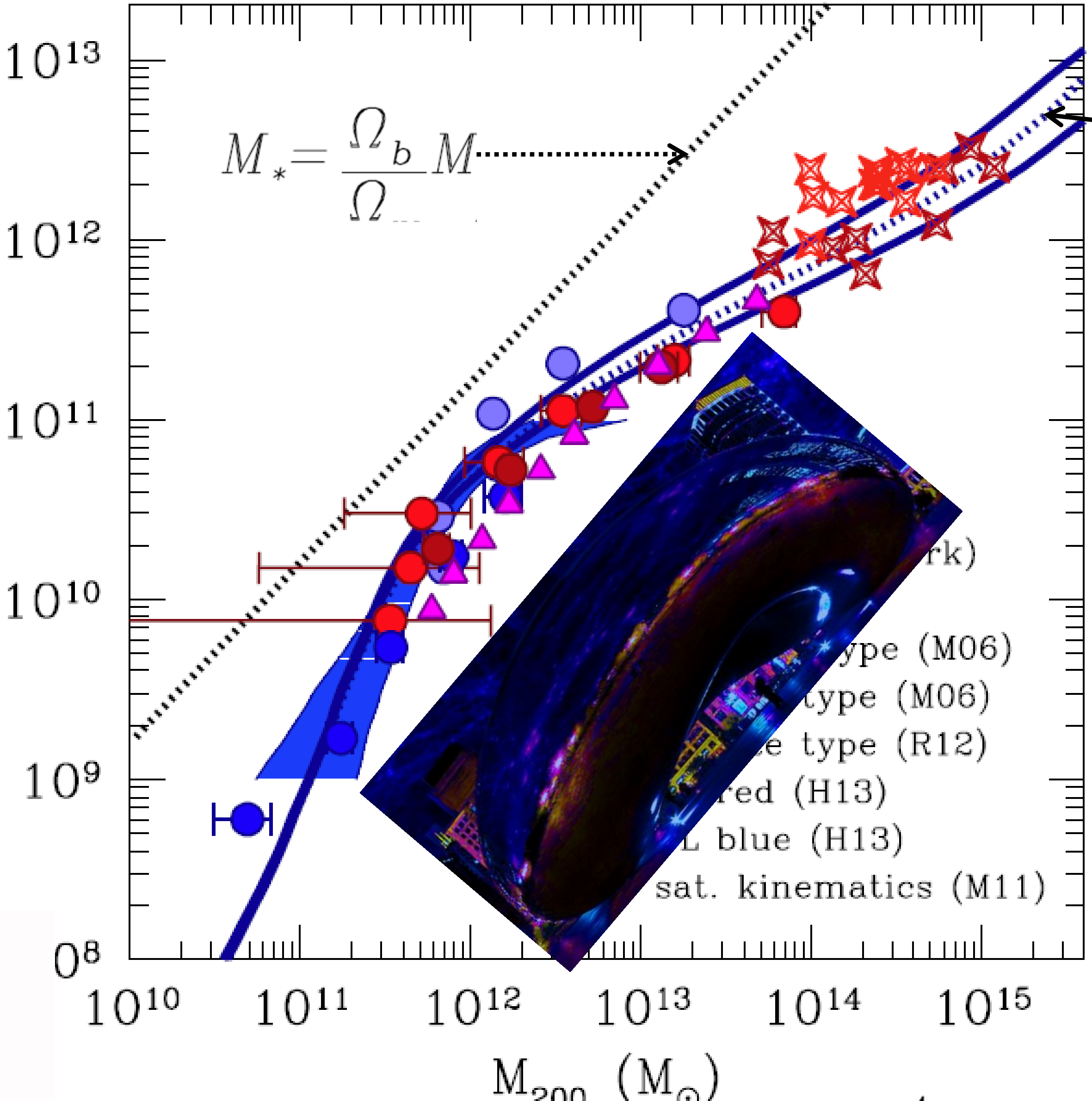
David Spergel @DavidSpergel · Sep 24

@dalcantonJD You have been looking at too many stars...

thesis: host halo mass is the most important property of galaxies

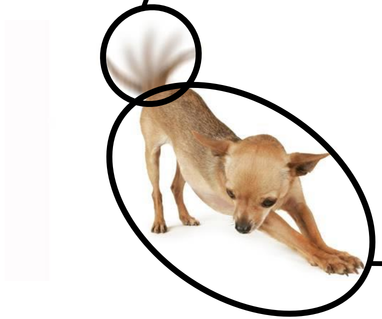
stellar mass - the most basic galaxy property – tightly correlates with host halo mass (and in this case correlation almost certainly = causation)

stellar mass of central galaxy



abundance matching using new stellar mass function of Bernardi et al. '13

Kravtsov et al. 2014



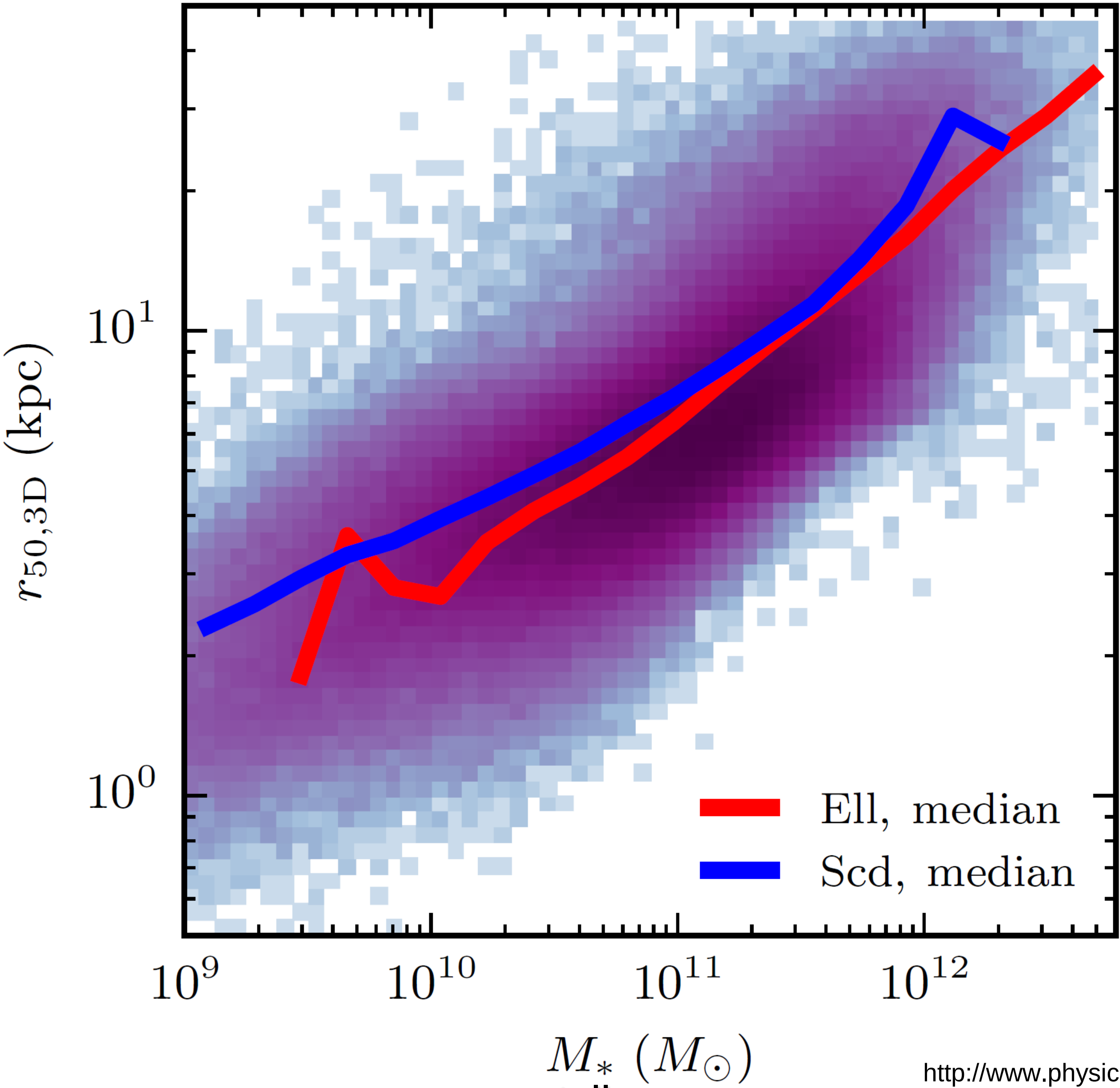
halo mass

$$M_{200} = \frac{4\pi}{3}\Delta\rho_{\rm crit}R_{200}^3$$

Galaxy size – the 2nd most basic galaxy property – correlates with stellar mass (in this case correlation almost certainly != causation)

e.g., Shen et al. 2003; Bernardi et al. 2010, 2013

3D stellar half-mass radius of galaxies



stellar mass

3D radius of late type
= projected radius
(corr. for inclination)

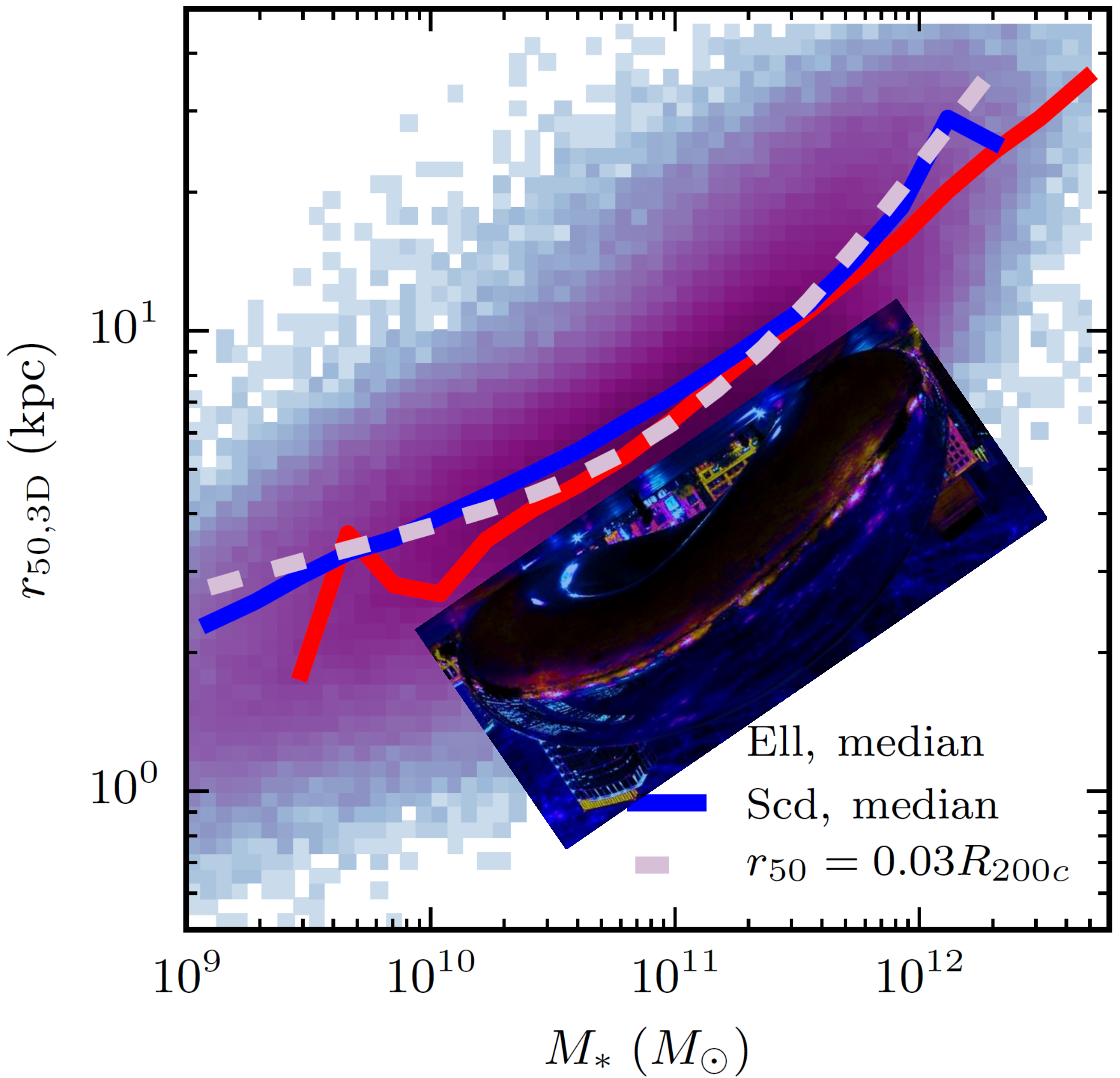
3D radius of early type
= 1.34 x projected radius

Sizes and stellar
masses from improved
SDSS photometry of
Meert, Bernardi+2015

http://www.physics.upenn.edu/~ameert/SDSS_PhotDec

Half-mass radii of galaxies are approximately proportional to the virial radius of their host halo

Kravtsov 2013; this holds across all z – e.g., Shibuya+ 2015 (see M. Ouchi's talk later today)



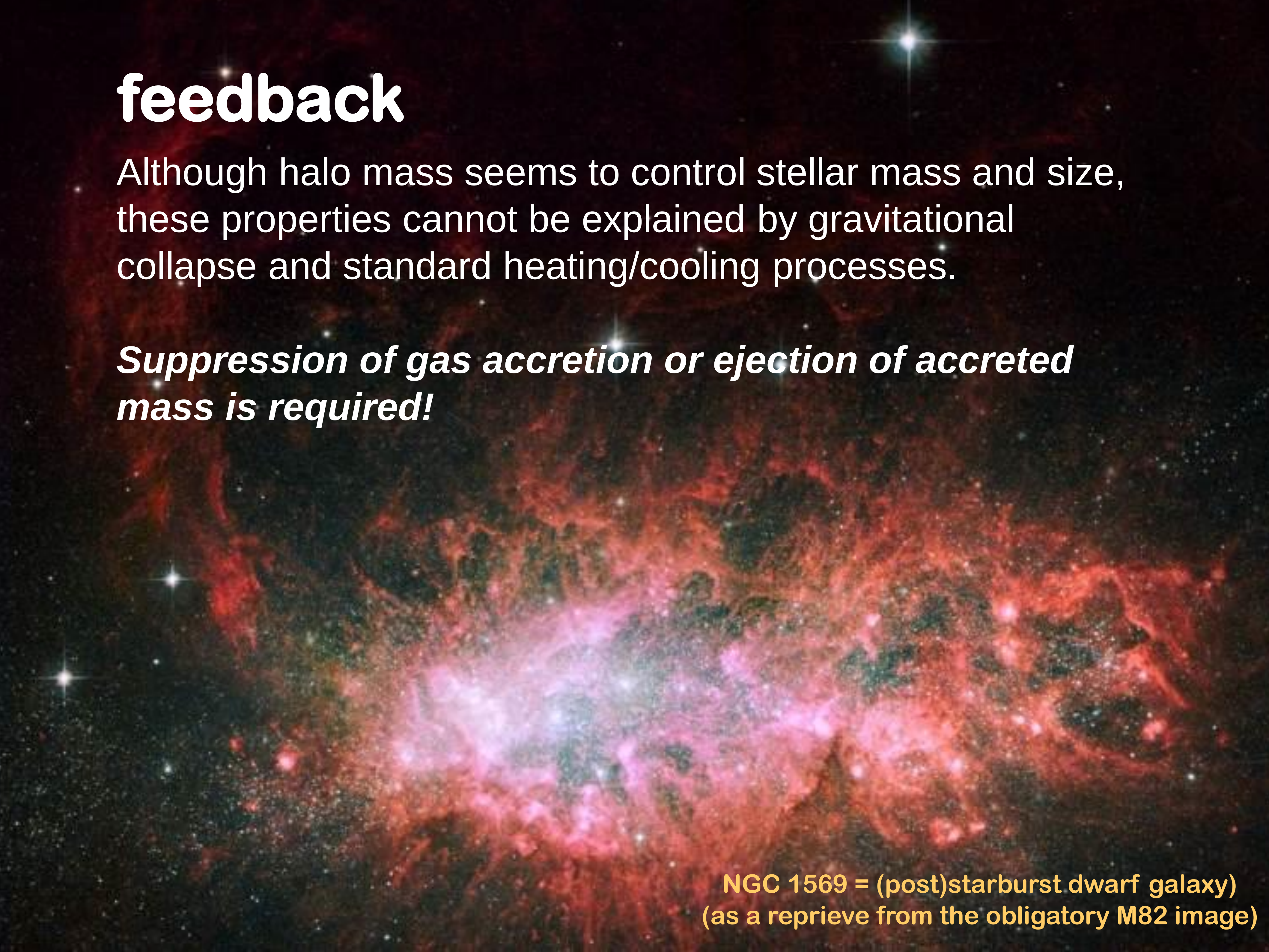
3D stellar half-mass radius of galaxies

stellar mass

feedback

Although halo mass seems to control stellar mass and size, these properties cannot be explained by gravitational collapse and standard heating/cooling processes.

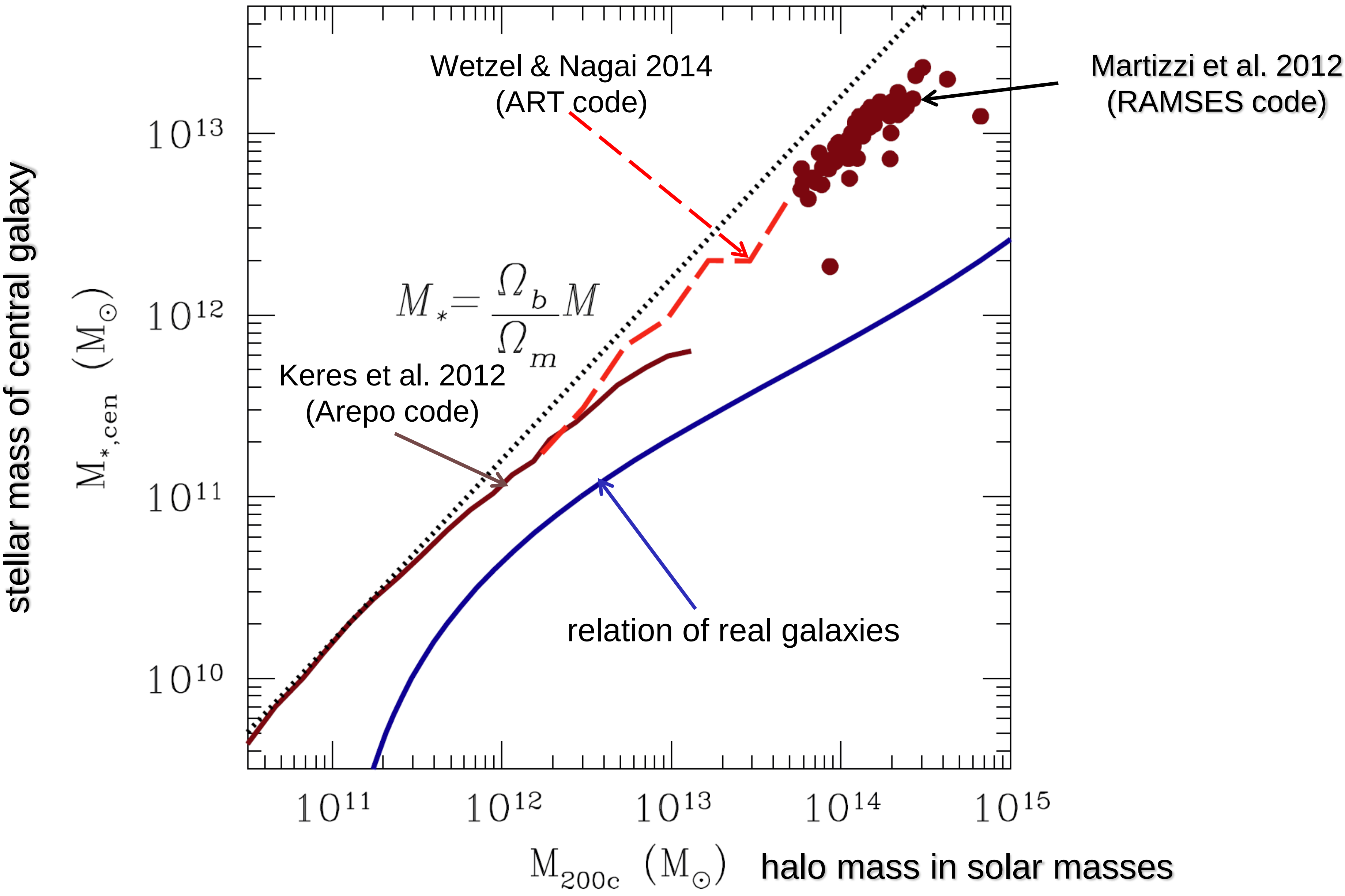
Suppression of gas accretion or ejection of accreted mass is required!



NGC 1569 = (post)starburst dwarf galaxy)
(as a reprieve from the obligatory M82 image)

M_*-M_{halo} relation of galaxies in simulations with inefficient feedback

Most simulations prior to ~2011 included basic thermodynamic processes and a recipe for stellar/AGN, but failed to reproduce a pronounced characteristic mass at $M \sim 10^{12}$ Msun indicated by observations



$$M_* = \frac{\Omega_b}{\Omega_m} M$$

stellar mass of central galaxy

halo mass in solar masses

Wetzel & Nagai 2014
(ART code)

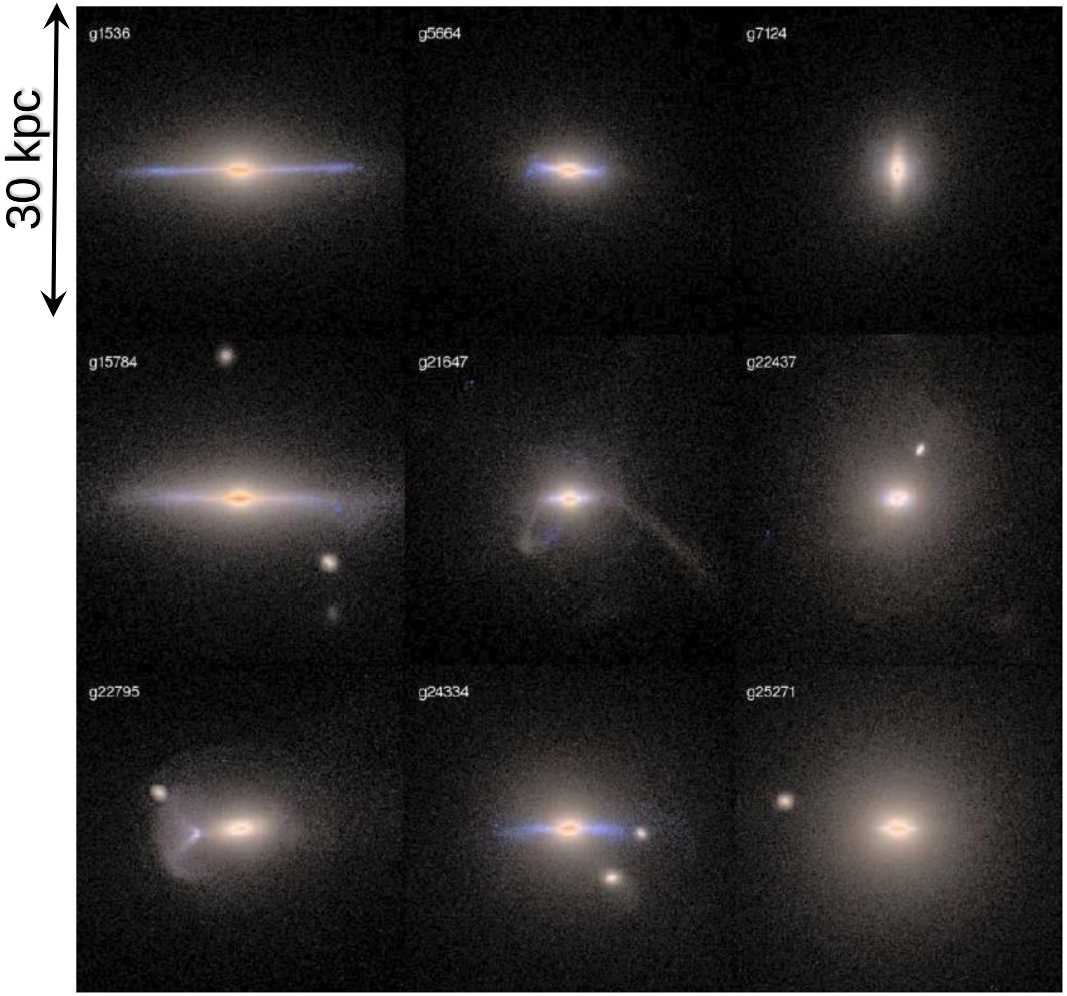
Martizzi et al. 2012
(RAMSES code)

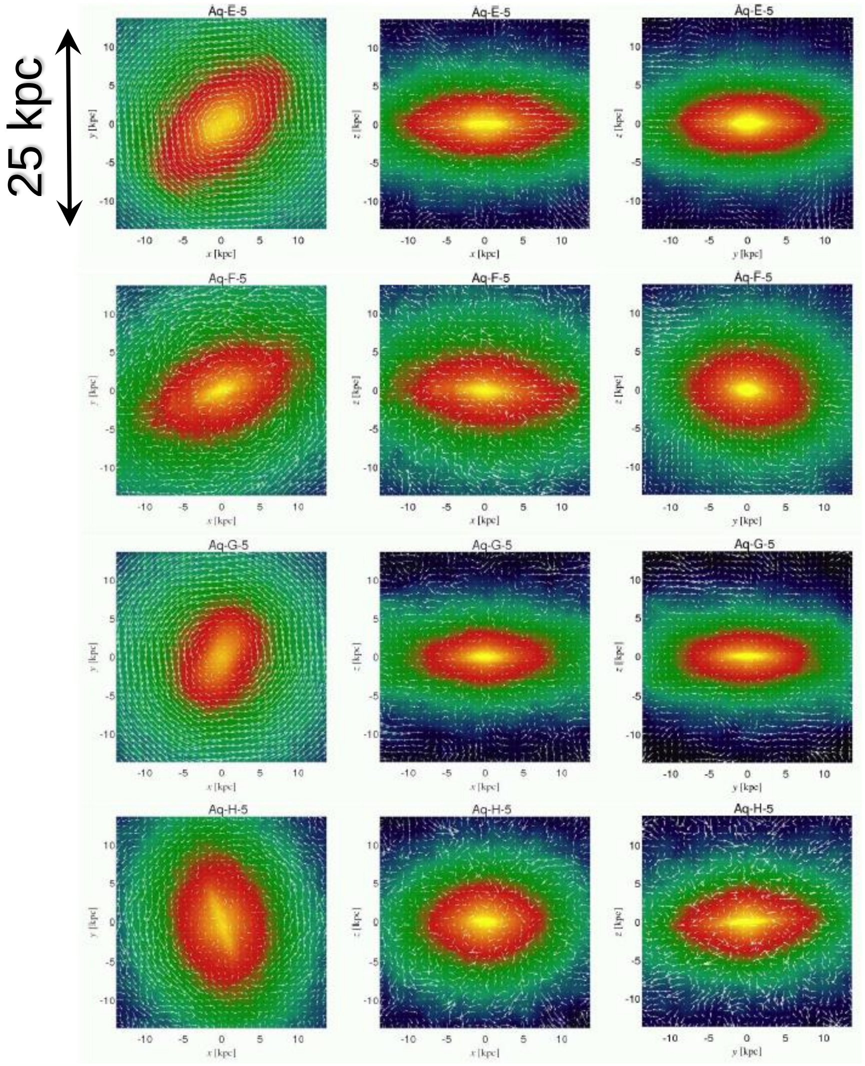
Keres et al. 2012
(Arepo code)

relation of real galaxies

wrong feedback gives wrong galaxy sizes and morphologies

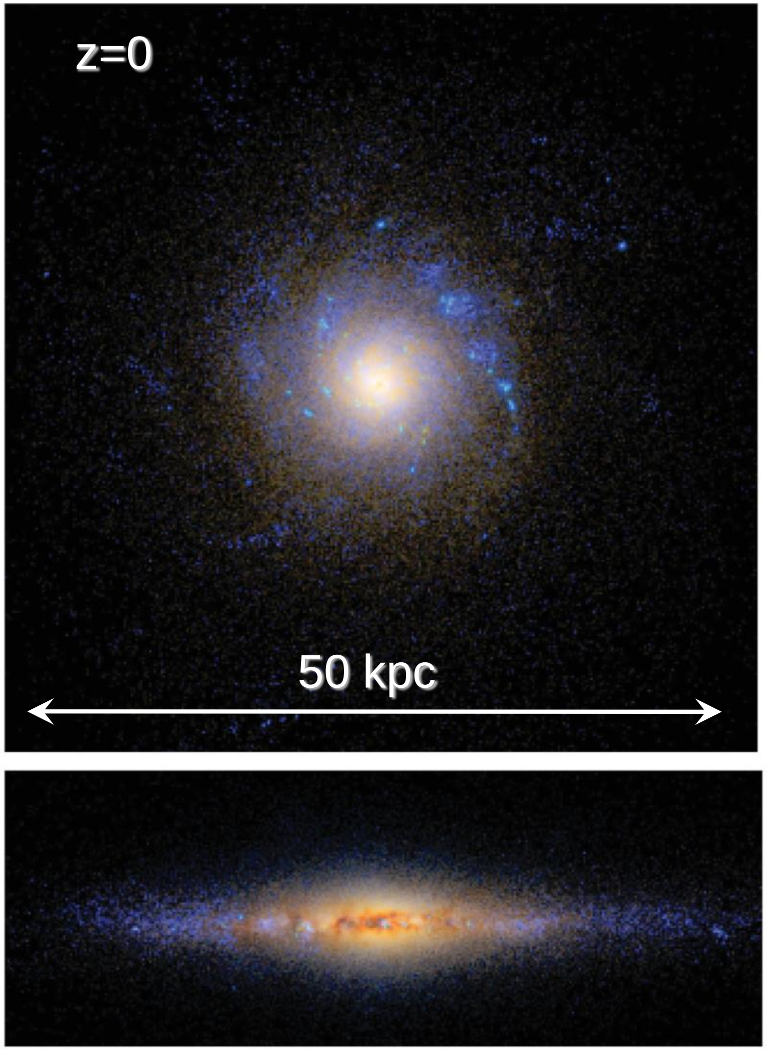
until ~2011 most simulations produced galaxies that were too massive, too compact, or dominated by spheroidal component





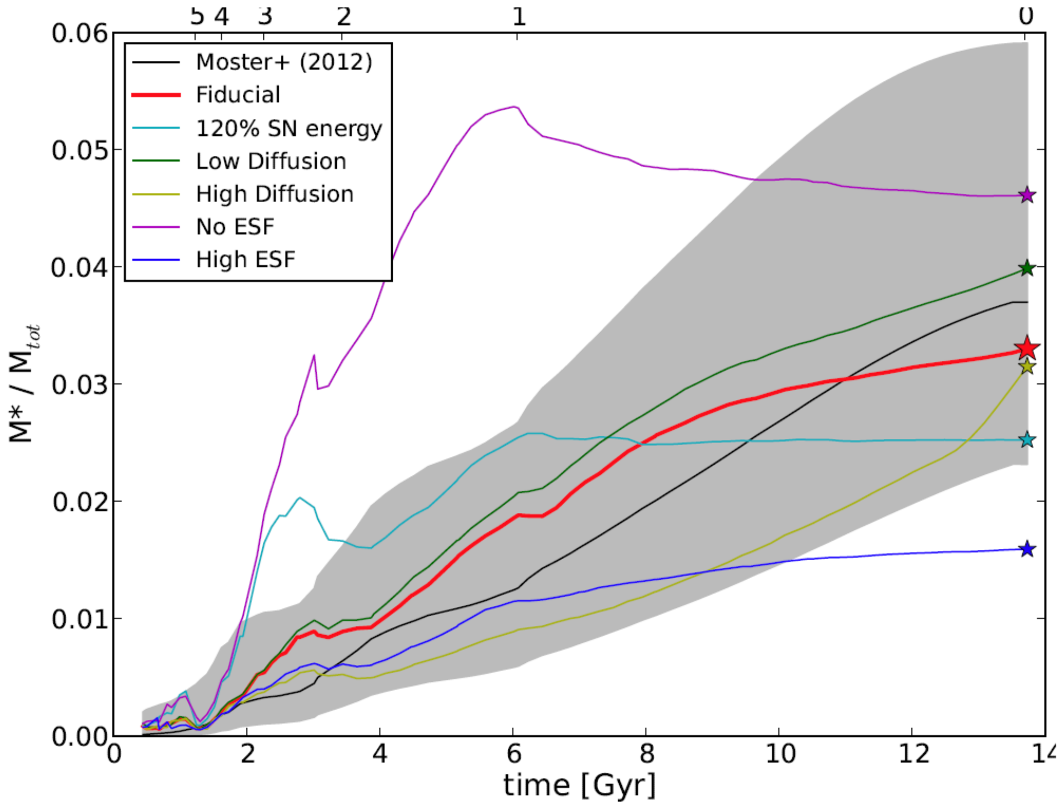
thesis # 2: galaxy formation processes (i.e., sf/feedback) must keep galaxy on the correct M*-Mhalo relation at all times

Measurements of star formation rates and stellar mass functions at z>2 in the last ~5 years have shown that simulations have been overestimating SFR and stellar masses at these z, which turned out to be the main cause of problems with size, morphology…



buildup of stellar mass (relative to total halo mass) in galaxy formation simulations with different feedback prescriptions/parameters (Stinson et al. ‘12)

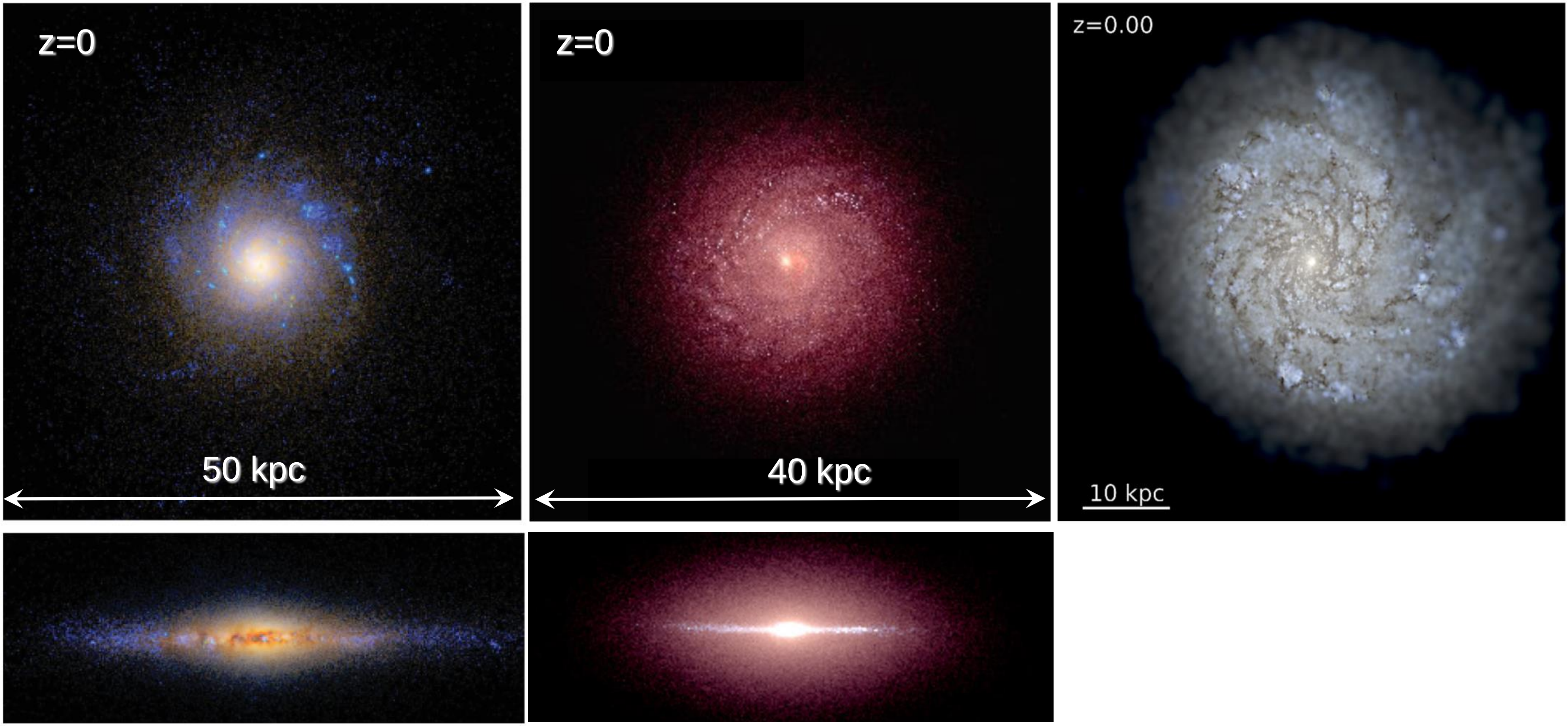
galaxy stellar mass/ current parent halo mass



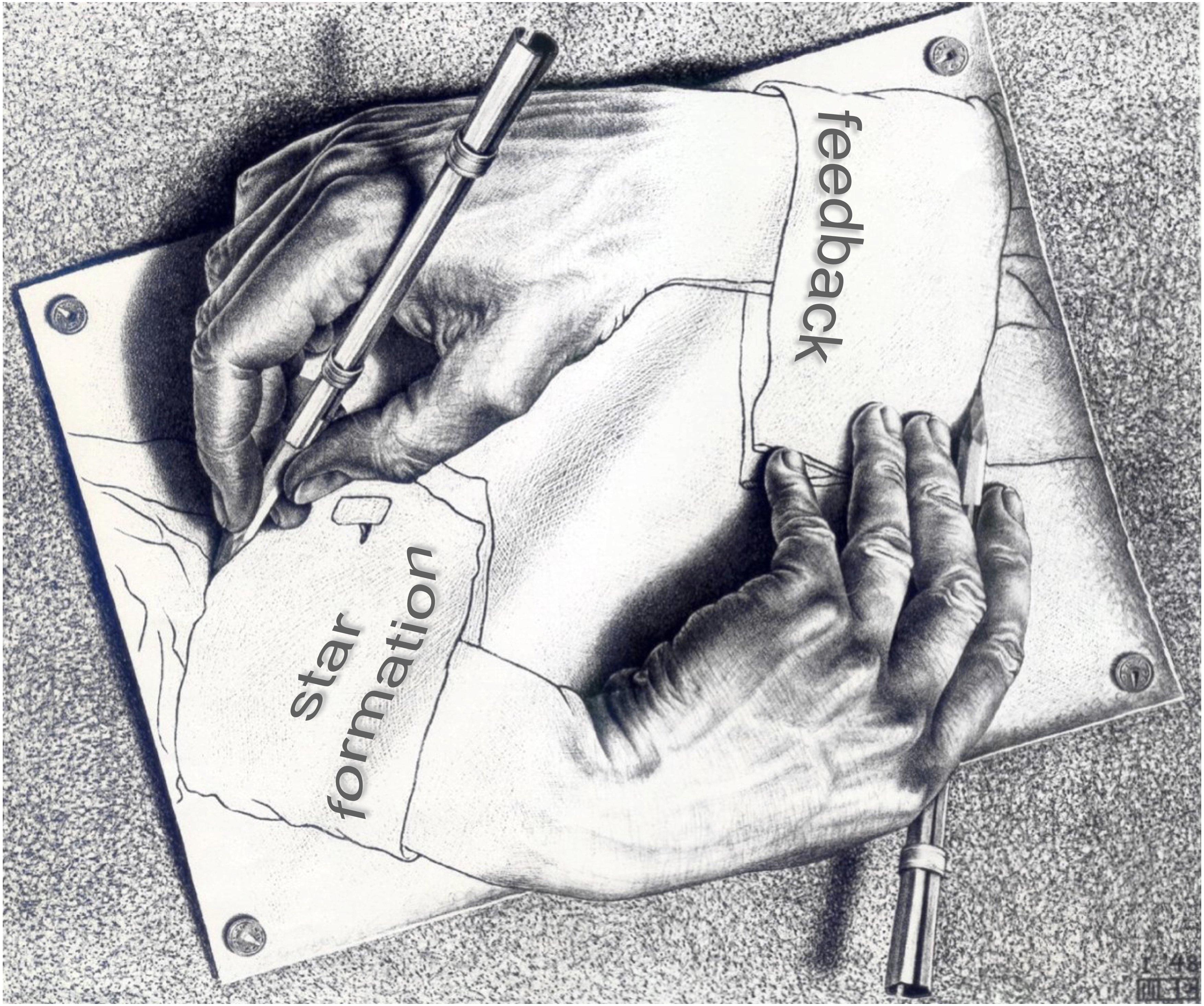
significant recent (last ~3-5 yrs) progress in modelling galaxies in simulations

Adjusting feedback implementations to conform to M*-Mhalo evolution indicated by observations improved ability of simulations to produce much more realistic galaxies, in particular, late type disks with low bulge-to-disk ratios.

Guedes+ 11; Governato+ 10,11,12; Brook+ 2012; Stinson+ 13; Hummels & Bryan ’12;
Hopkins+ 2014; Ceverino+’14; Trujillo-Gomez+ 14; Uebler+ 14;Salem+ 14; Keller+ 14, 15, 16; Agertz & Kravtsov ’15, 16



what about star formation?



M.C. Escher, “Drawing hands”, 1948

treatment of *local* star formation does influence evolution drastically

Oscar Agertz

e.g. *effects of star formation efficiency* on bulk galaxy properties are drastic because they affect efficacy of stellar feedback

(e.g., Ceverino & Klypin ‘08; Governato et al. ’10; Guedes et al. ’11;
Hopkins et al. ‘13, ’14; Agertz & Kravtsov ‘15, ‘16)

standard H_2-based star formation model

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

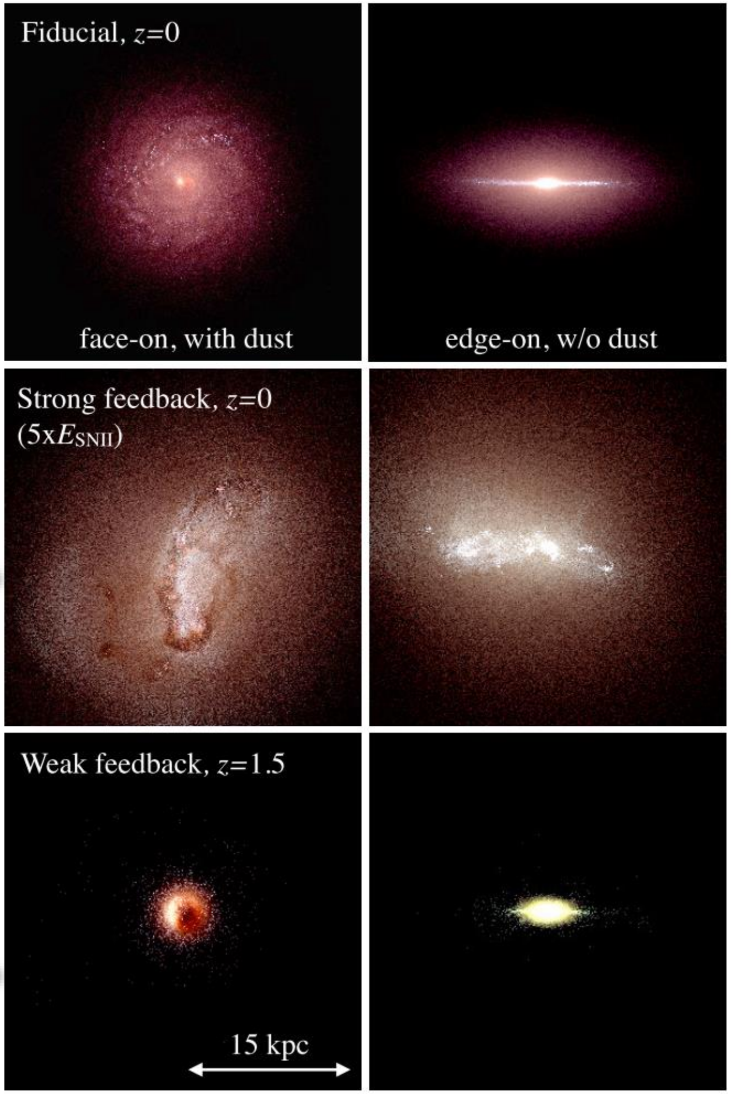
$t_{\rm ff}$ = free-fall time

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho_{\rm g}}} \propto \rho_{\rm g}^{-1/2}$$

$$\epsilon_{\rm ff} = 0.1; E_{\rm SN} = E_{\rm fid} \rightarrow$$

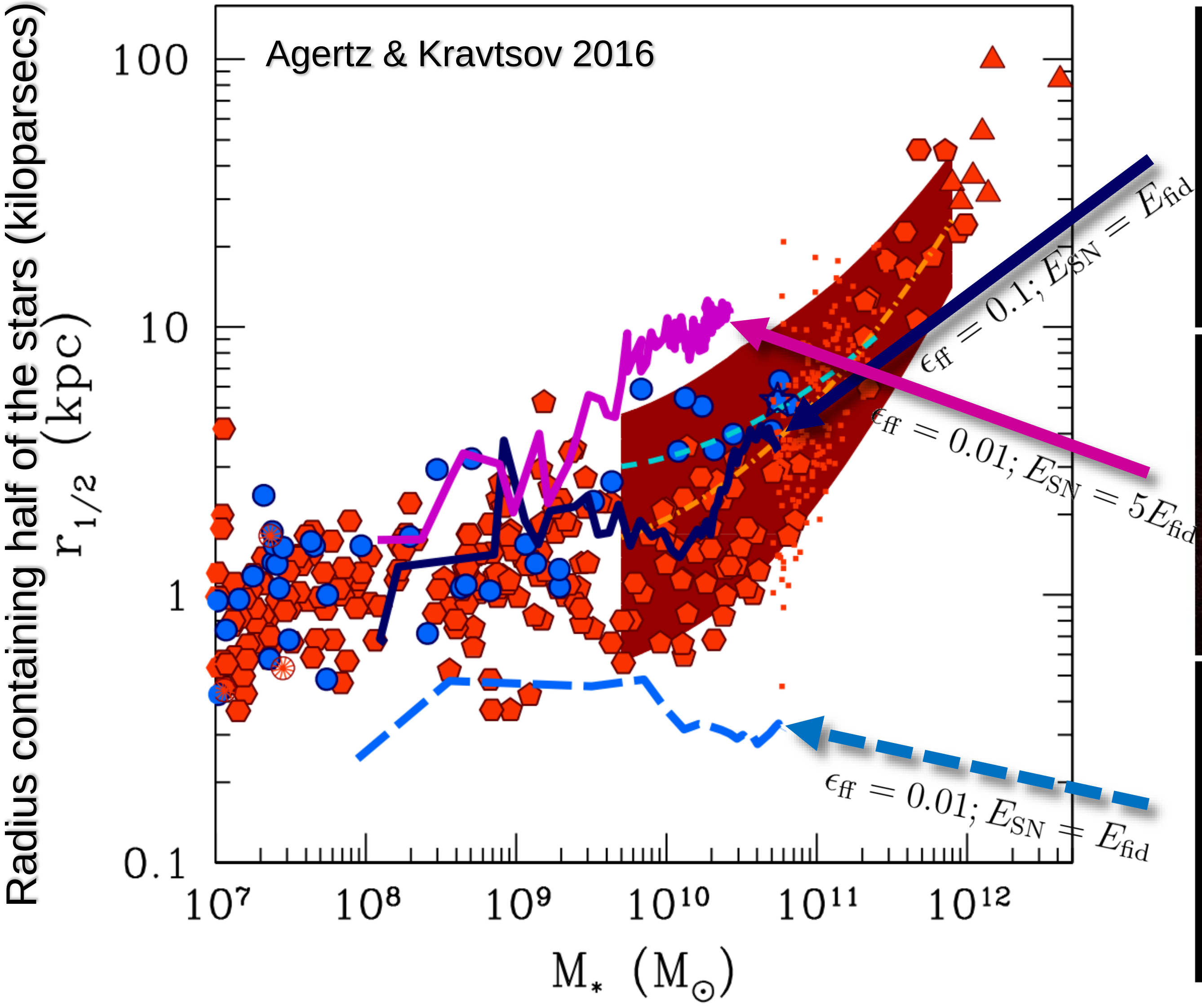
$$\epsilon_{\rm ff} = 0.01; E_{\rm SN} = 5E_{\rm fid} \rightarrow$$

$$\epsilon_{\rm ff} = 0.01; E_{\rm SN} = E_{\rm fid} \rightarrow$$

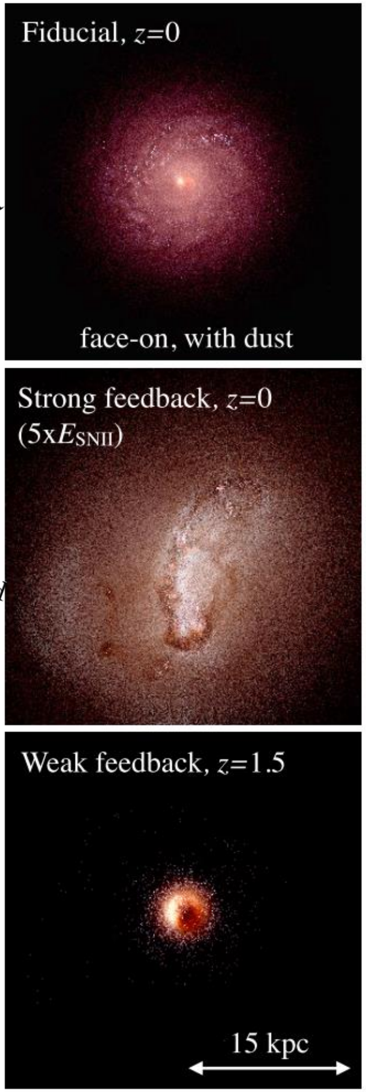


HST mockup RGB using F450W, F606W, F814W filters

A galaxy you form in a halo is sensitive to choices of feedback and efficiency



stellar mass of galaxy (in solar masses)

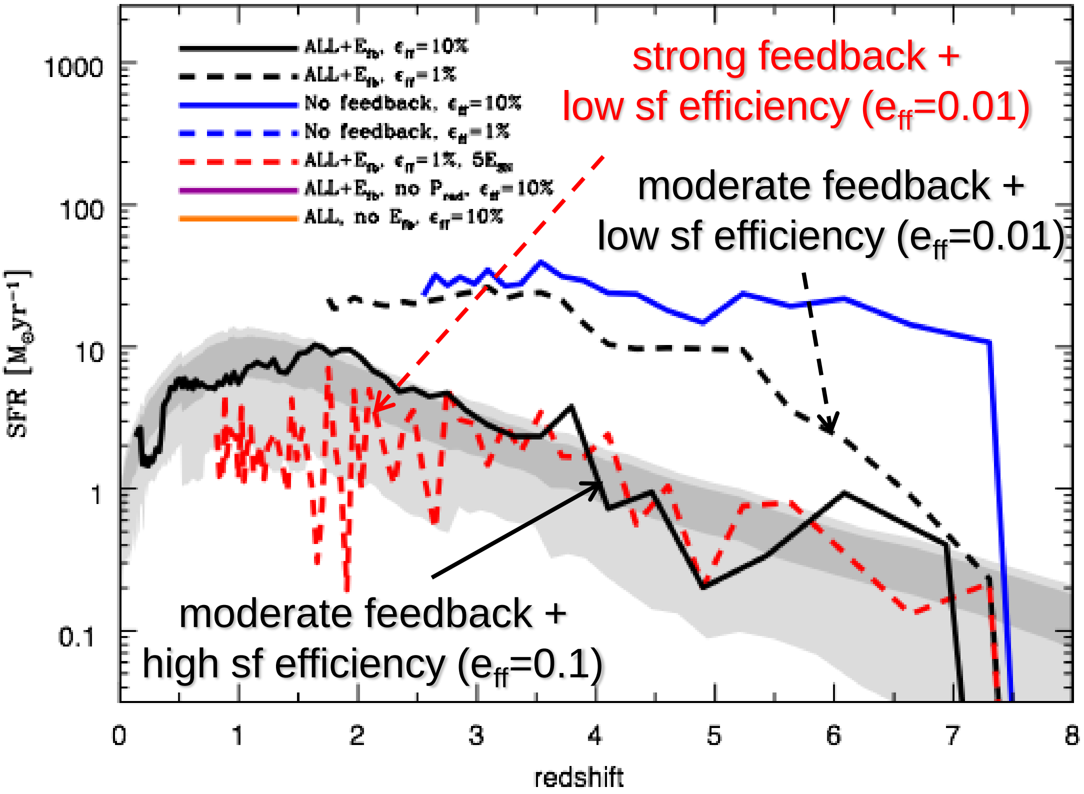


HST mockup RGB using F450W, F606W, F814W filters

Star formation history and stellar mass-halo mass relation for different sf efficiencies and feedback strengths

- Star formation history of MW-sized progenitor and corresponding evolution in M*-M plane:
- simulation that stays on the M*-Mhalo relation and SFR(t) history for halo of this mass produces a realistic late type galaxy

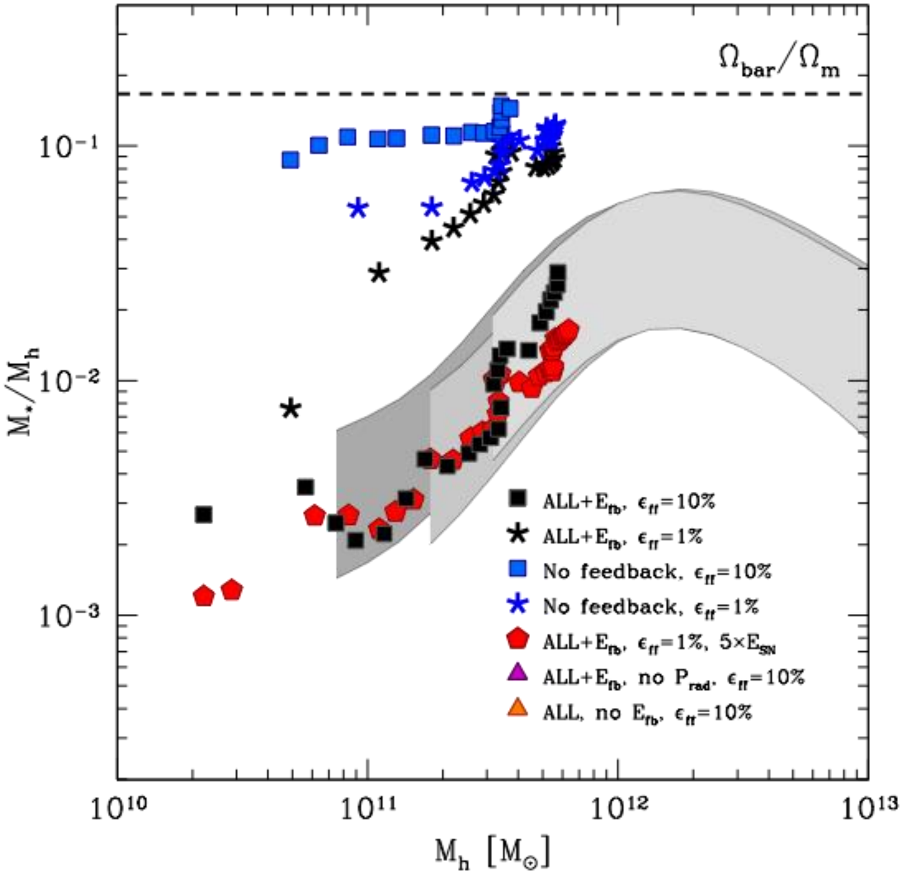
Gray bands = Semi-empirical star formation history for a 10^{12} Msun halo from abundance matching (*Behroozi et al. '13)*



strong feedback + low sf efficiency (e_{ff}=0.01)

moderate feedback + low sf efficiency (e_{ff}=0.01)

moderate feedback + high sf efficiency (e_{ff}=0.1)



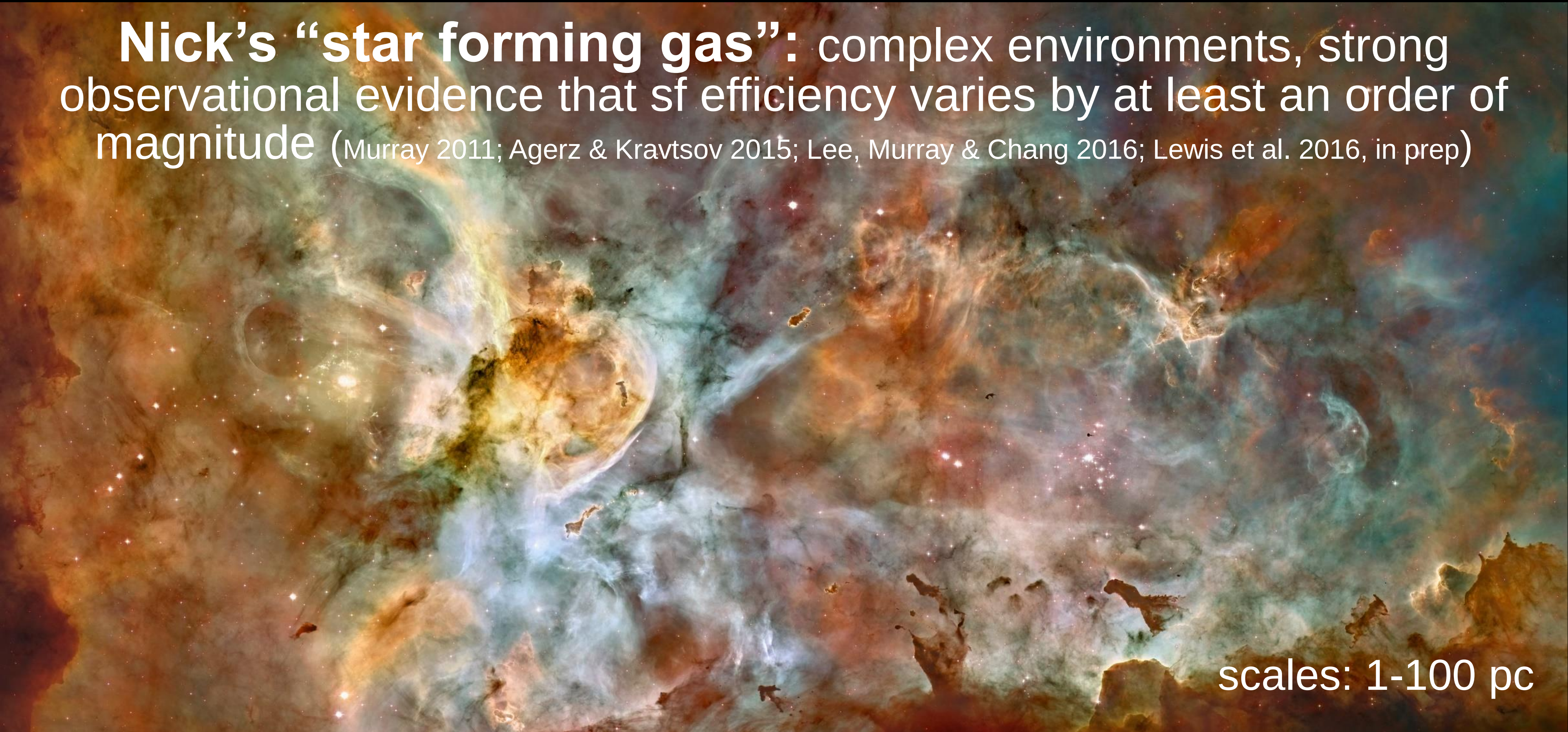
Agertz & Kravtsov 2015, arxiv/1404. 2613

Given the strong effects of star formation efficiency choice, is this:

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

- **Star formation efficiency universal** in space and time (~1-100%)

enough?

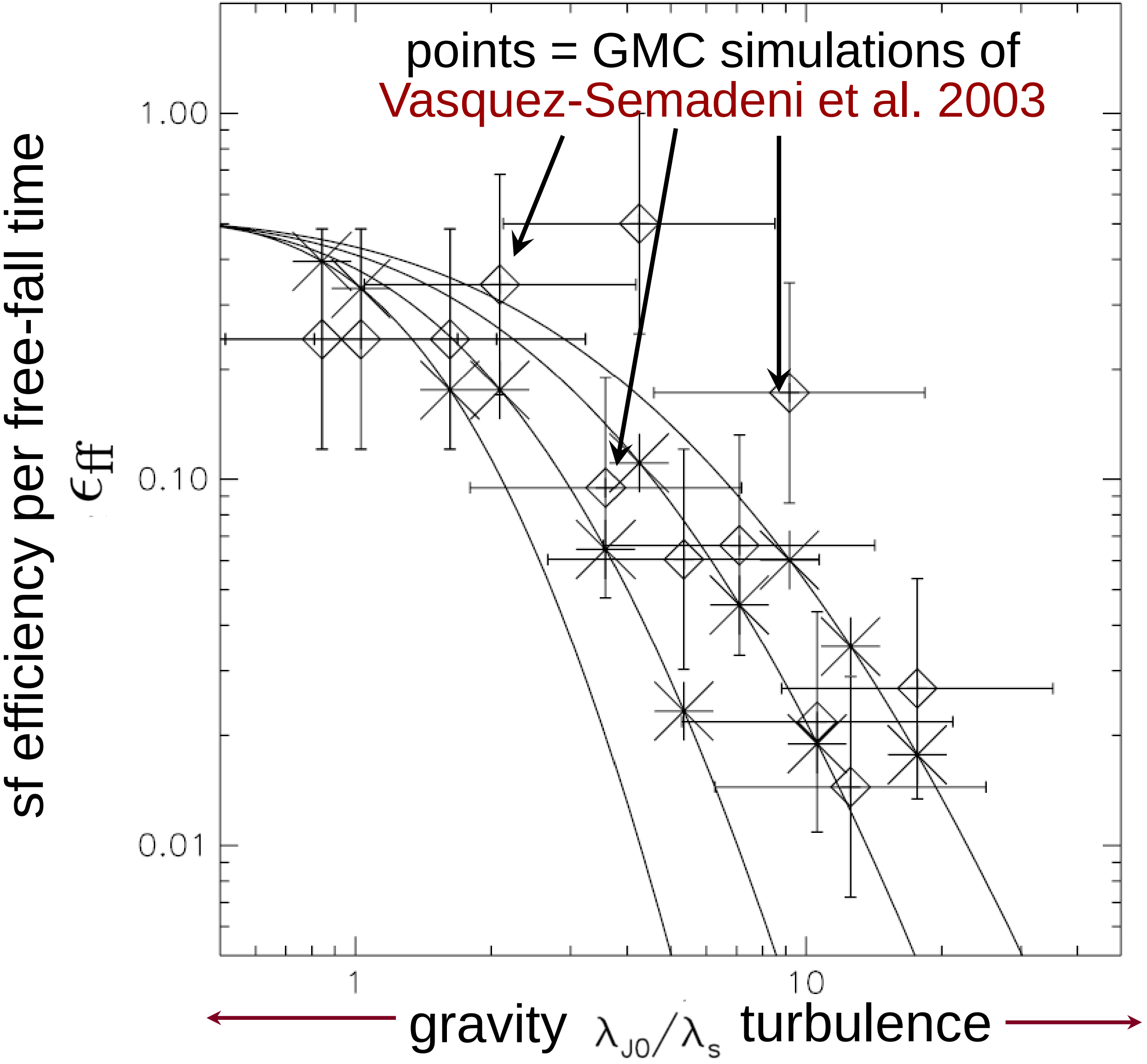


Nick’s “star forming gas”: complex environments, strong observational evidence that sf efficiency varies by at least an order of magnitude (Murray 2011; Agerz & Kravtsov 2015; Lee, Murray & Chang 2016; Lewis et al. 2016, in prep)

scales: 1-100 pc

Turbulence and star formation efficiency

Elmegreen 2002; Krumholz & McKee (2005) – turbulence-based models of star formation (cf. also Padoan & Nordlund 2011; Federrath 2014)


points = GMC simulations of Vasquez-Semadeni et al. 2003

- turbulence establishes (~log-normal) density PDF

- stars form in the densest bound regions that satisfy collapse criteria

$$x_{\rm crit} = \left(\phi_x \frac{\lambda_{\rm J0}}{\lambda_s}\right)^2$$

sonic length:

$$\lambda_s = 2R\left(\frac{c_s}{\sigma_{2R}}\right)^{1/p}$$

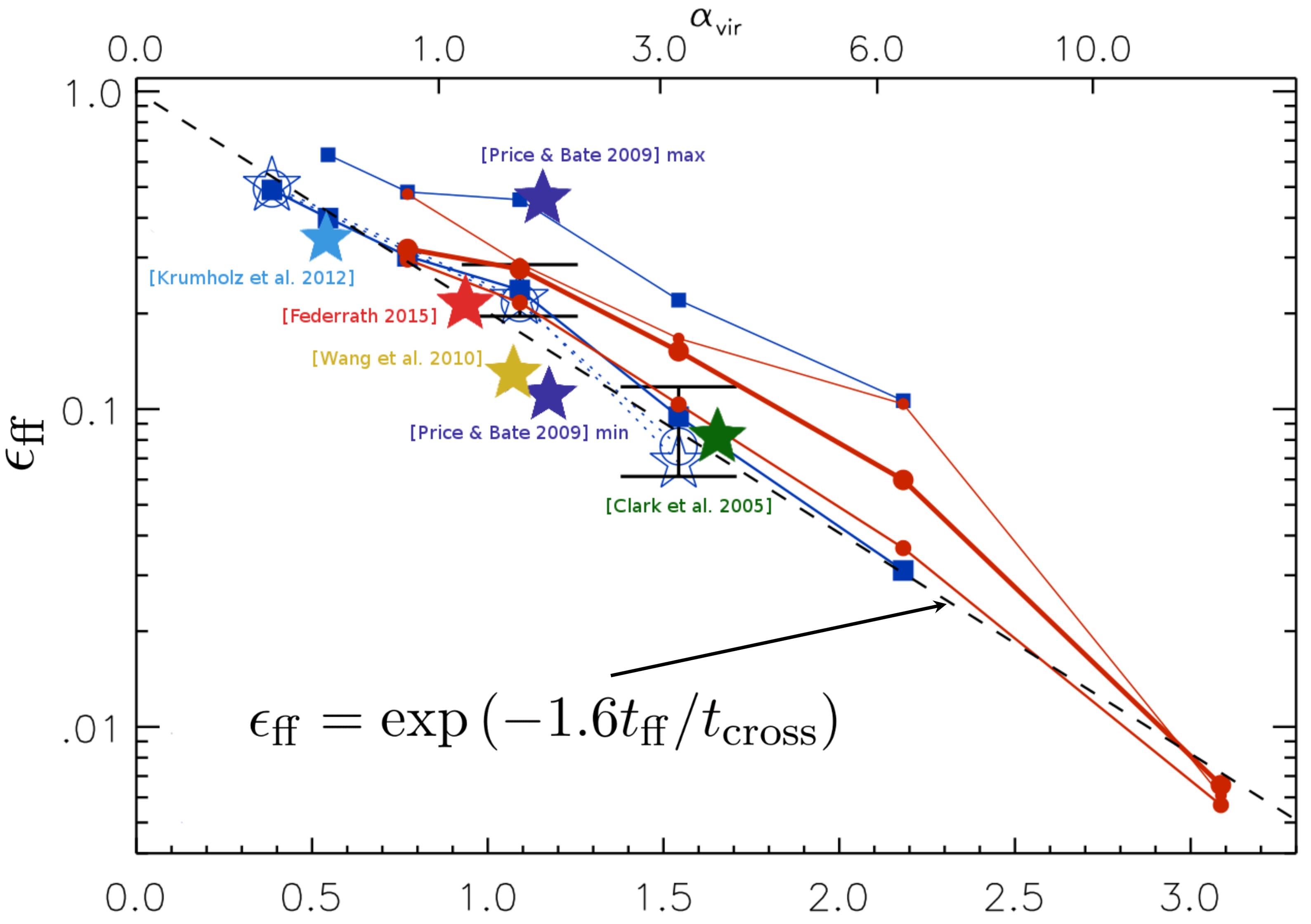
Jeans length:

$$\lambda_{\rm J0} = \sqrt{\frac{\pi c_s^2}{G\rho_0}} = 2\pi c_s\sqrt{\frac{R^3}{3GM}}$$

Results of recent turbulent GMCs simulations

Padoan, Haubolle, Nordlund 2012 ApJ 759, L27

SF efficiency ⟶



t_{ff}/t_{cross}

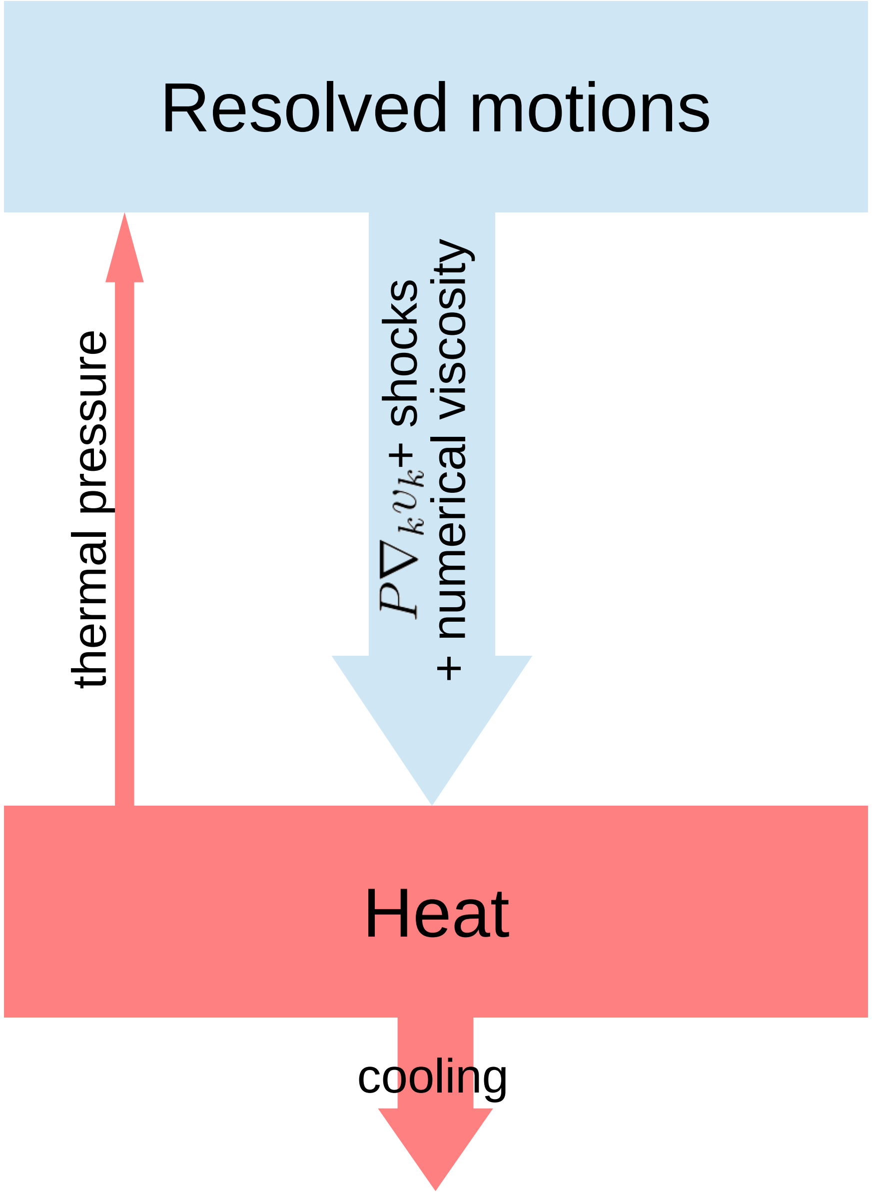
⟵ gravity

turbulence ⟶

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

$$t_{cross} = \Delta/2\sigma$$

energy exchanges in a standard hydro simulation



Resolved motions

thermal pressure

$P\nabla_k v_k$+ shocks
+ numerical viscosity

Heat

cooling

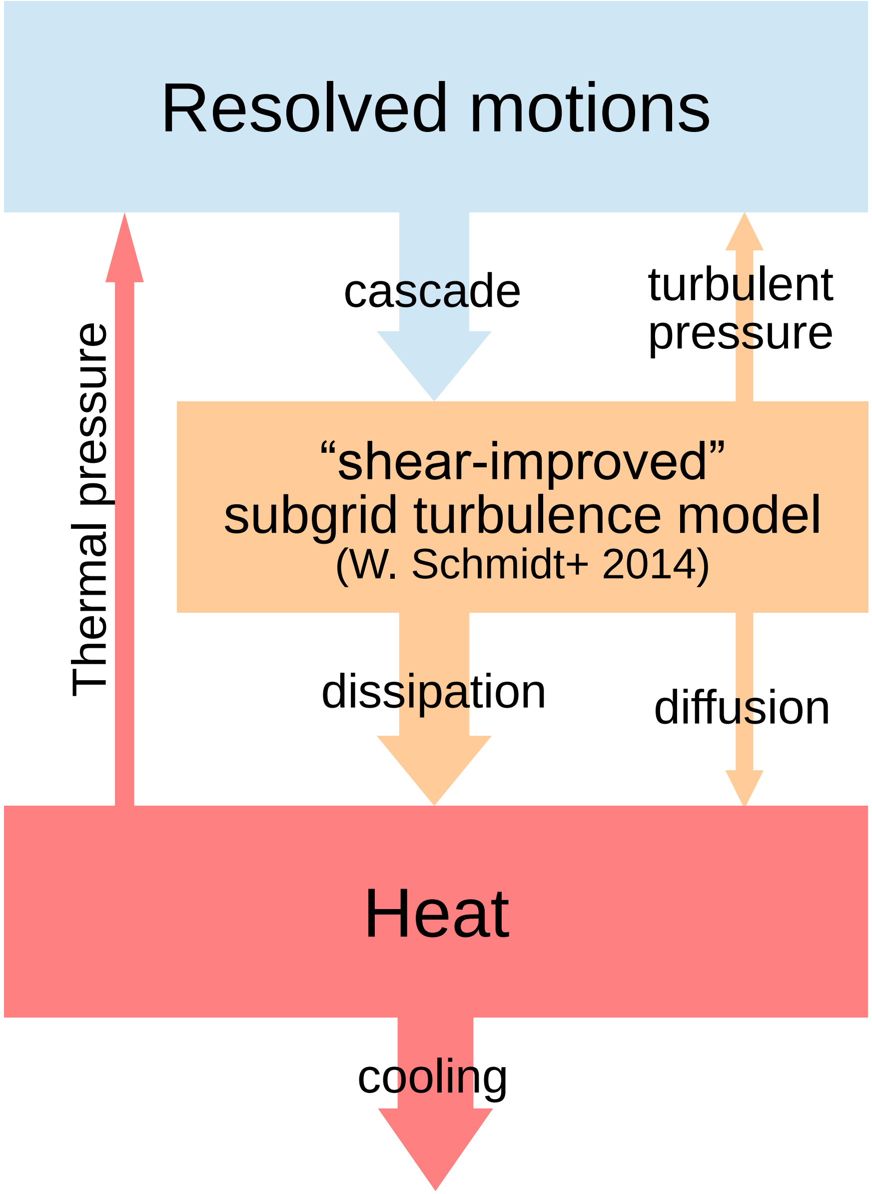
$$\frac{\partial}{\partial t}\rho + \nabla_k v_k \rho = 0$$

$$\frac{\partial}{\partial t}\rho v_i + \nabla_k v_k \rho v_i = -\rho \nabla_i \phi - \nabla_i P$$

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

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

introduce **subgrid turbulence** as a mediator between resolved motions and thermal energy



Resolved motions

cascade

turbulent pressure

“shear-improved” subgrid turbulence model (W. Schmidt+ 2014)

Thermal pressure

dissipation

diffusion

Heat

cooling

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

$$\frac{\partial}{\partial t}\rho v_i + \nabla_k v_k \rho v_i = -\rho\nabla_i\phi - \nabla_i\left(P+\frac{2}{3}K\right) + \nabla_k\tau_{ki}$$

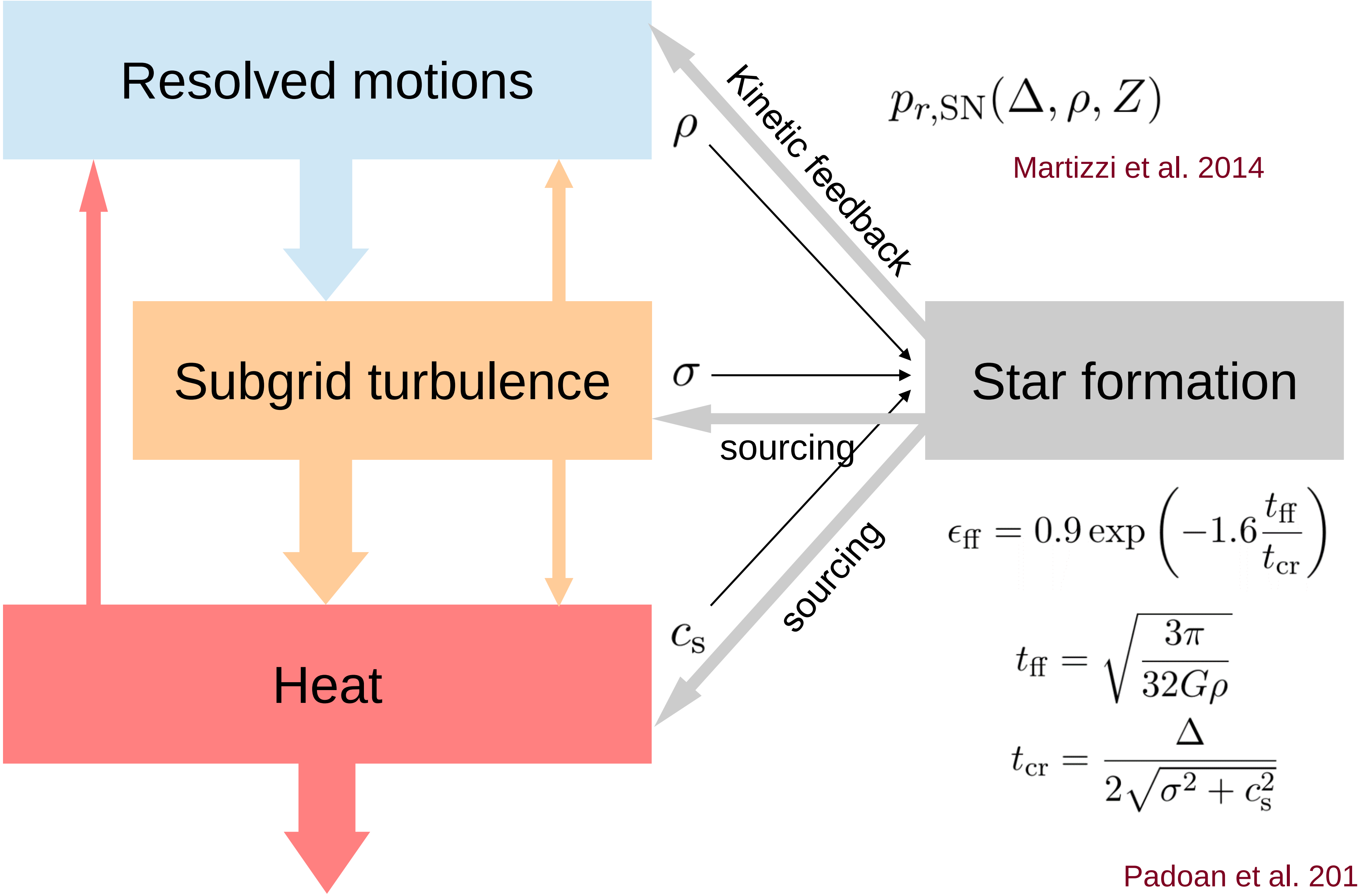
$$\begin{aligned}\frac{\partial}{\partial t}E + \nabla_k v_k E = {} & -\rho v_k\nabla_k\phi - \nabla_k v_k\left(P+\frac{2}{3}K\right) - \\ & - \Lambda_{\mathrm{net}} + \nabla_k v_i\tau_{ki} + \nabla_k\left(\mathfrak{F}_k^{(K)} + \mathfrak{F}_k^{(e)}\right)\end{aligned}$$

$$\frac{\partial}{\partial t}K + \nabla_k v_k K = \tau_{ki}\nabla_k v_i - \epsilon - \frac{2}{3}K\nabla_k v_k + \nabla_k\mathfrak{F}_k^{(K)}$$

$$\sigma = \sqrt{\frac{2K}{\rho}}$$ - subgrid turbulent velocity

$$\frac{\partial}{\partial t}e + \nabla_k v_k e = \epsilon - \Lambda_{\mathrm{net}} - P\nabla_k v_k + \nabla_k\mathfrak{F}_k^{(e)}$$

turbulence-based star formation model



Resolved motions

Subgrid turbulence

Heat

Star formation

Kinetic feedback

sourcing

sourcing

ρ

σ

c_{s}

$p_{r,\mathrm{SN}}(\Delta, \rho, Z)$

Martizzi et al. 2014

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

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

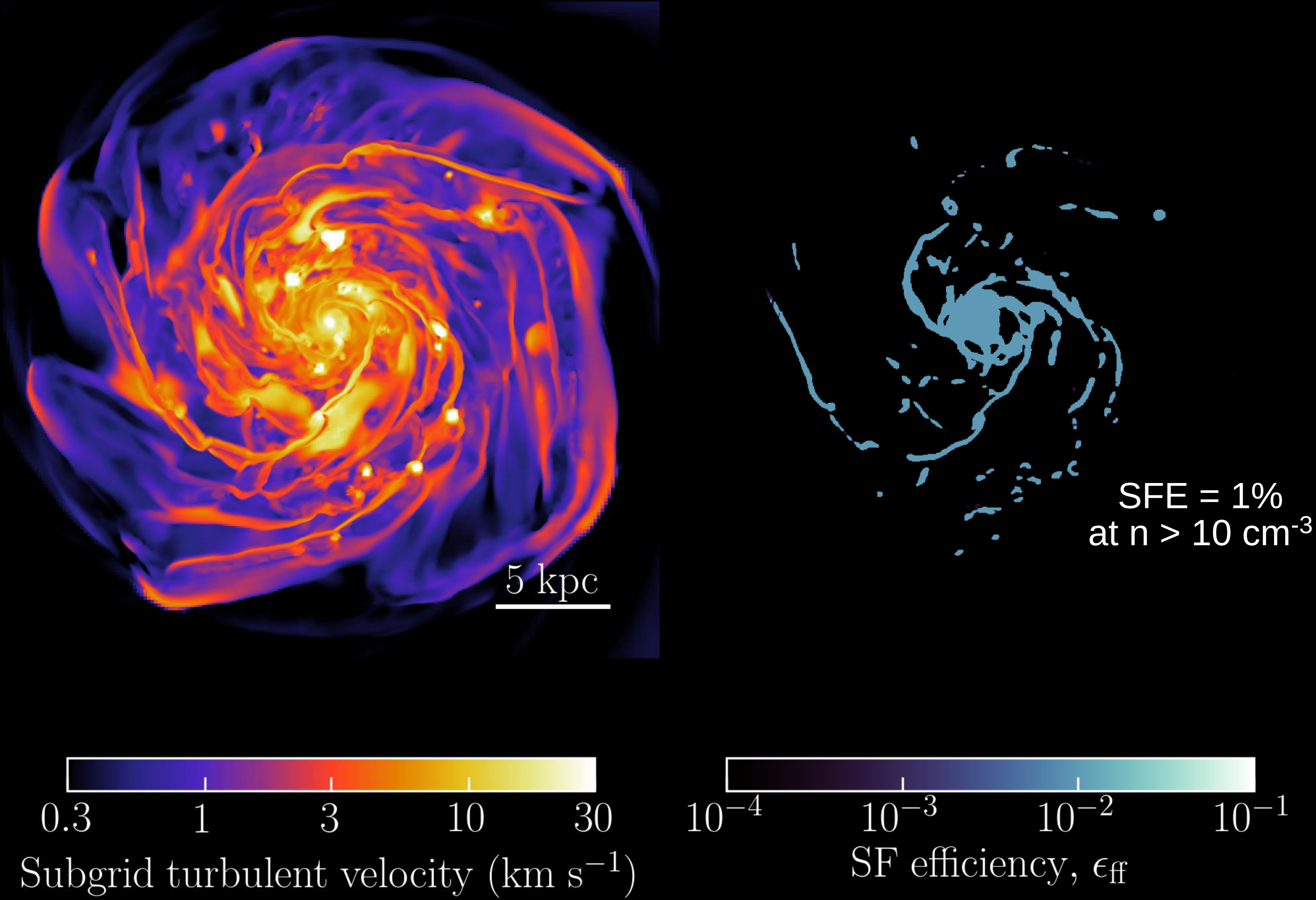
$$t_{\mathrm{cr}} = \frac{\Delta}{2\sqrt{\sigma^2 + c_{\mathrm{s}}^2}}$$

Padoan et al. 2012

Milky Way-sized isolated disk

see poster by Vadim Semenov

- Adaptive mesh refinement ART code + subgrid turbulence-based star formation efficiency
- AGORA project initial conditions: $M_{\mathrm{disk}} \sim 4.3\mathrm{x}10^{10}$ $M_{\mathrm{sun},}$ $f_{\mathrm{gas}} = 0.2$; $\Delta = 40$ pc (also checked $\Delta = 20, 10$ pc)



SFE = 1%
at n > 10 cm^{-3}

Non-universal star formation efficiency

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

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

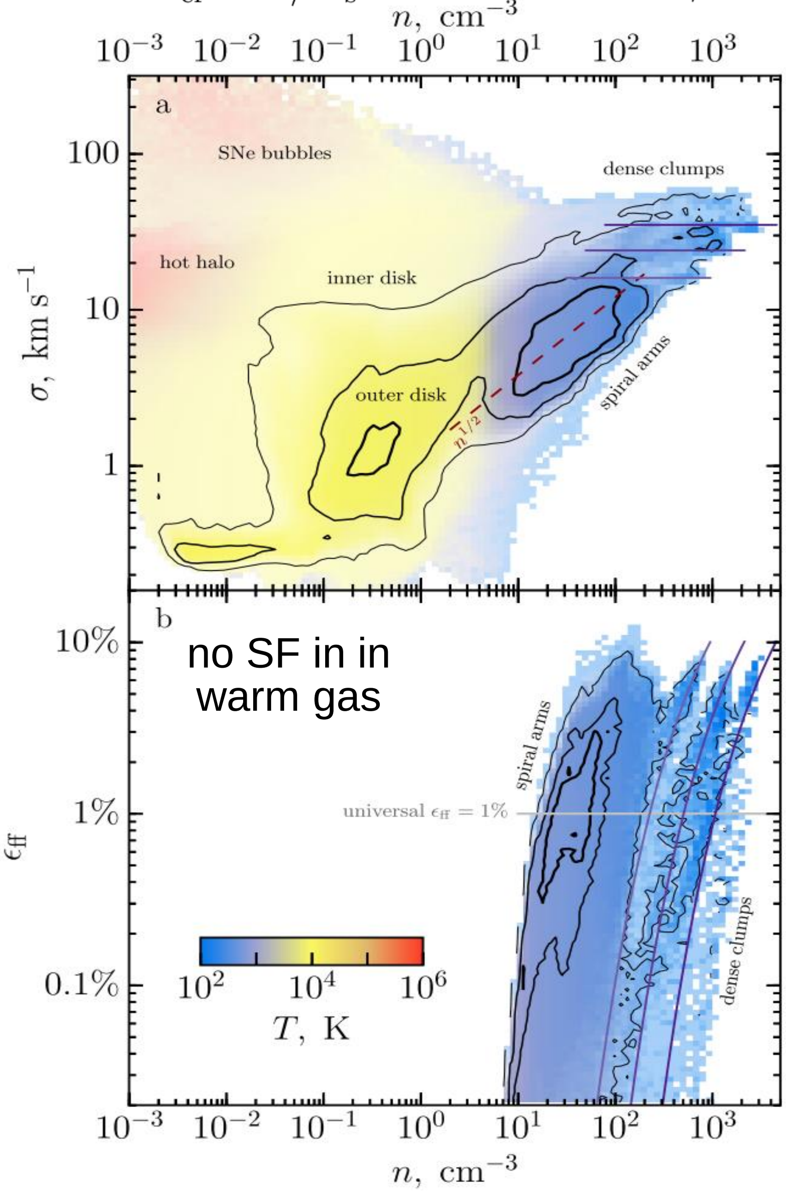
$$t_{\rm cr} = \frac{\Delta}{2\sqrt{\sigma^2 + c_{\rm s}^2}}$$

warm, subsonic

$t_{\rm cr} \approx \Delta/2c_{\rm s}$

cold, supersonic

$t_{\rm cr} \approx \Delta/2\sigma$



no SF in in warm gas

Wide variation due to scatter in σ

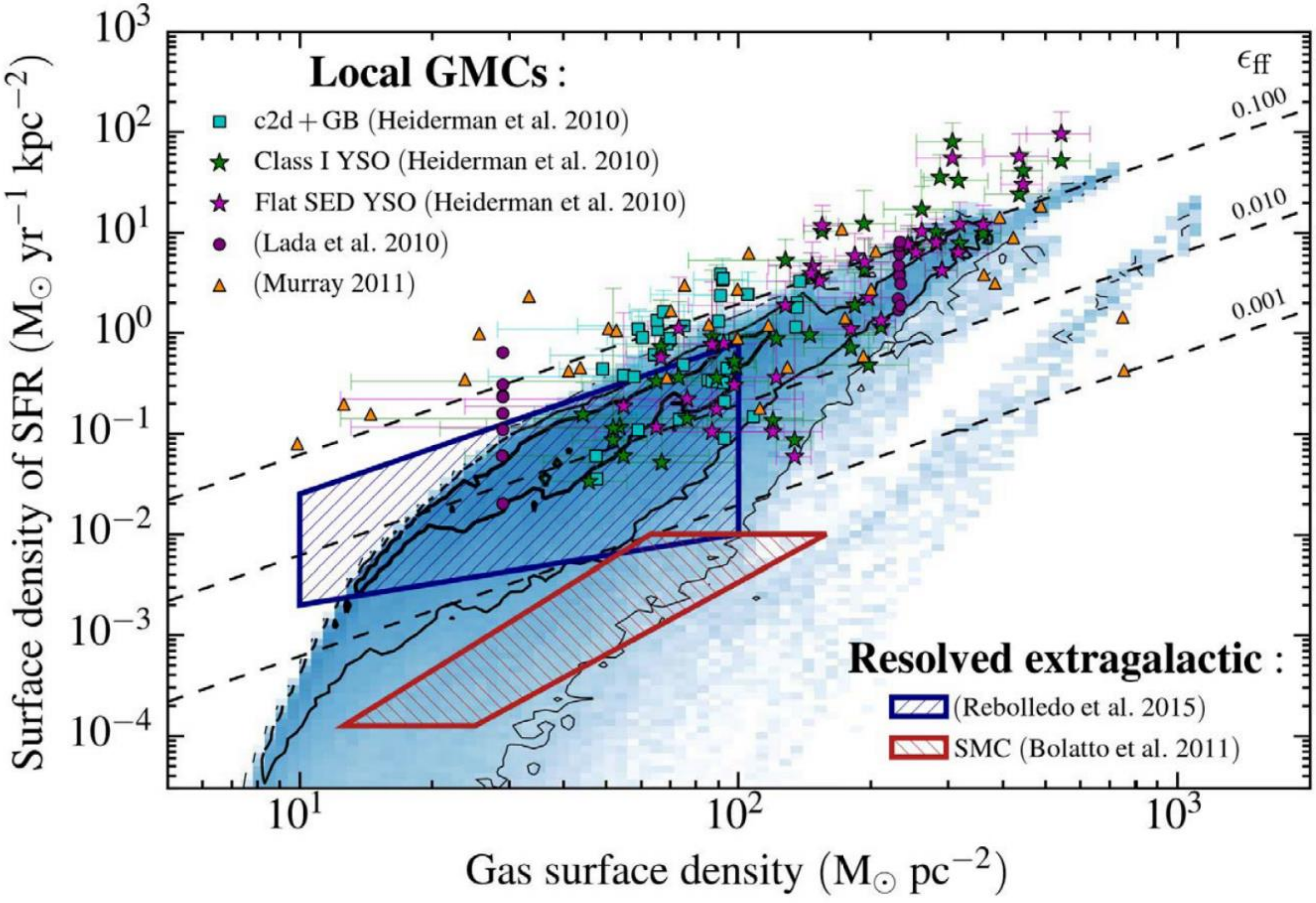
- Density threshold
- Average eff ~ 1%
- Wide variation of eff

contours in the model pdf: 5, 15, 30%

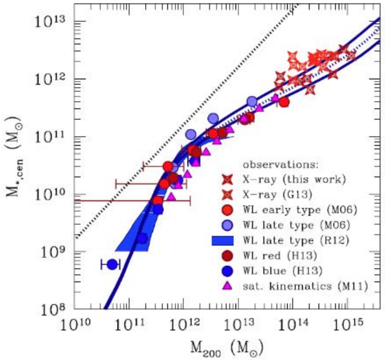
comparison with observed star formation in molecular clouds

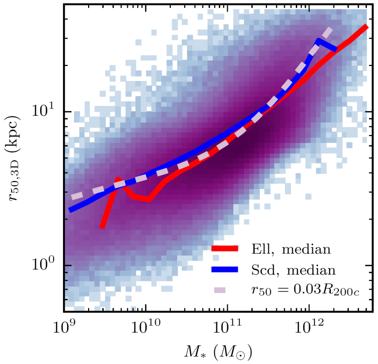
The model model stochastic ε_{ff} as a function of local ISM properties

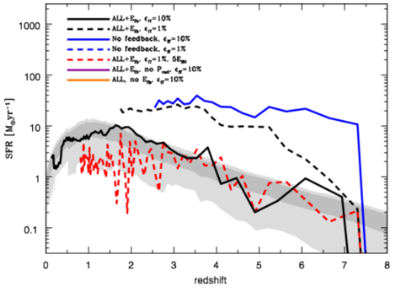
Semenov, Kravtsov & Gnedin, 2016
ApJ in press (arxiv/1512.03101)
(see poster for more details)

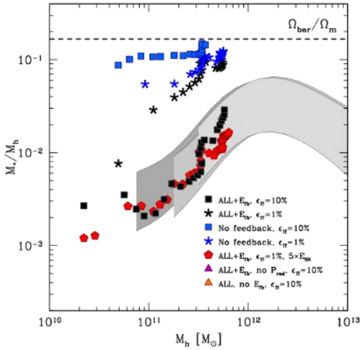


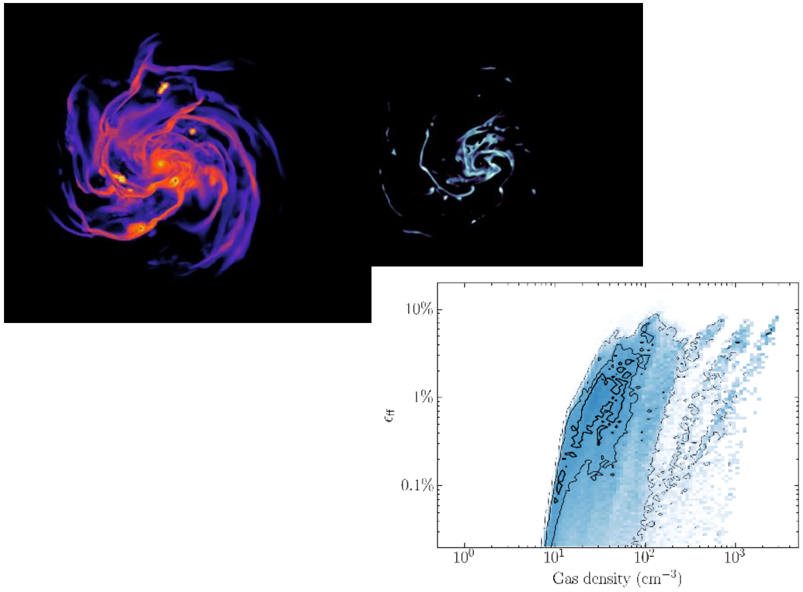
Summary







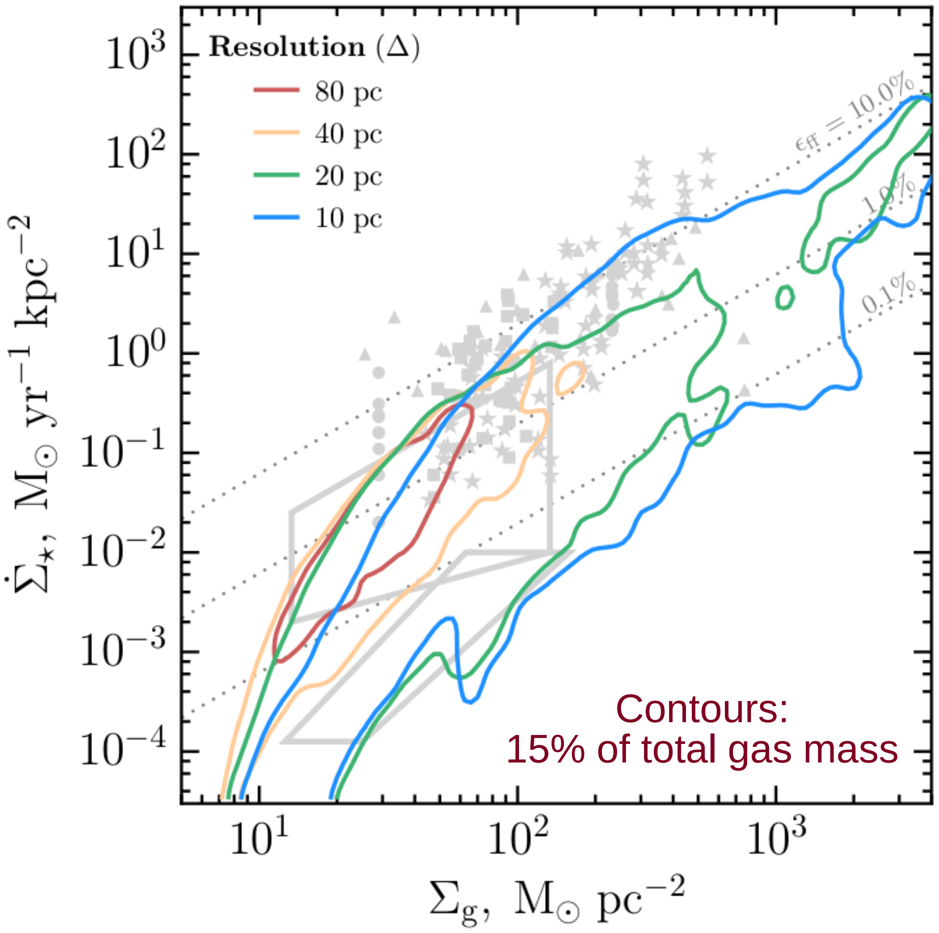




- Halo mass controls the baryon budget of galaxies at all z
- it also appears to control the actual stellar mass and sizes of galaxies, but in a complicated nonlinear way
- Simulations indicate that realistic late type galaxies form only when galaxies follow evolution of M*-Mhalo and SFR(t) derived from observations.
- This is achieved by making feedback efficient, but the way star formation is distributed and how efficient it is matters!
- We need to go beyond the simple universal efficiency star formation model!
- First attempt to do this (see Semenov et al. poster) indicates wide variation of ε_{ff} due to its high sensitivity to local density and turbulent velocity predicted by simulations of star formation in GMCs

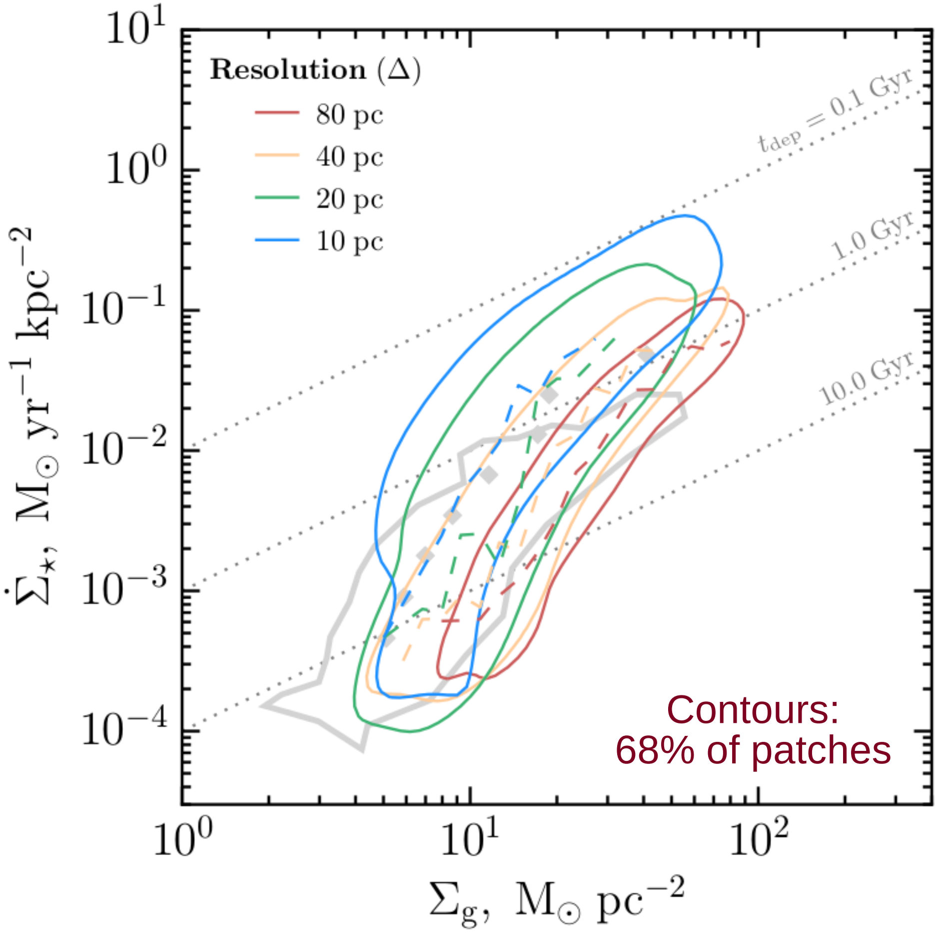
Resolution study

SFRs on cell size scale



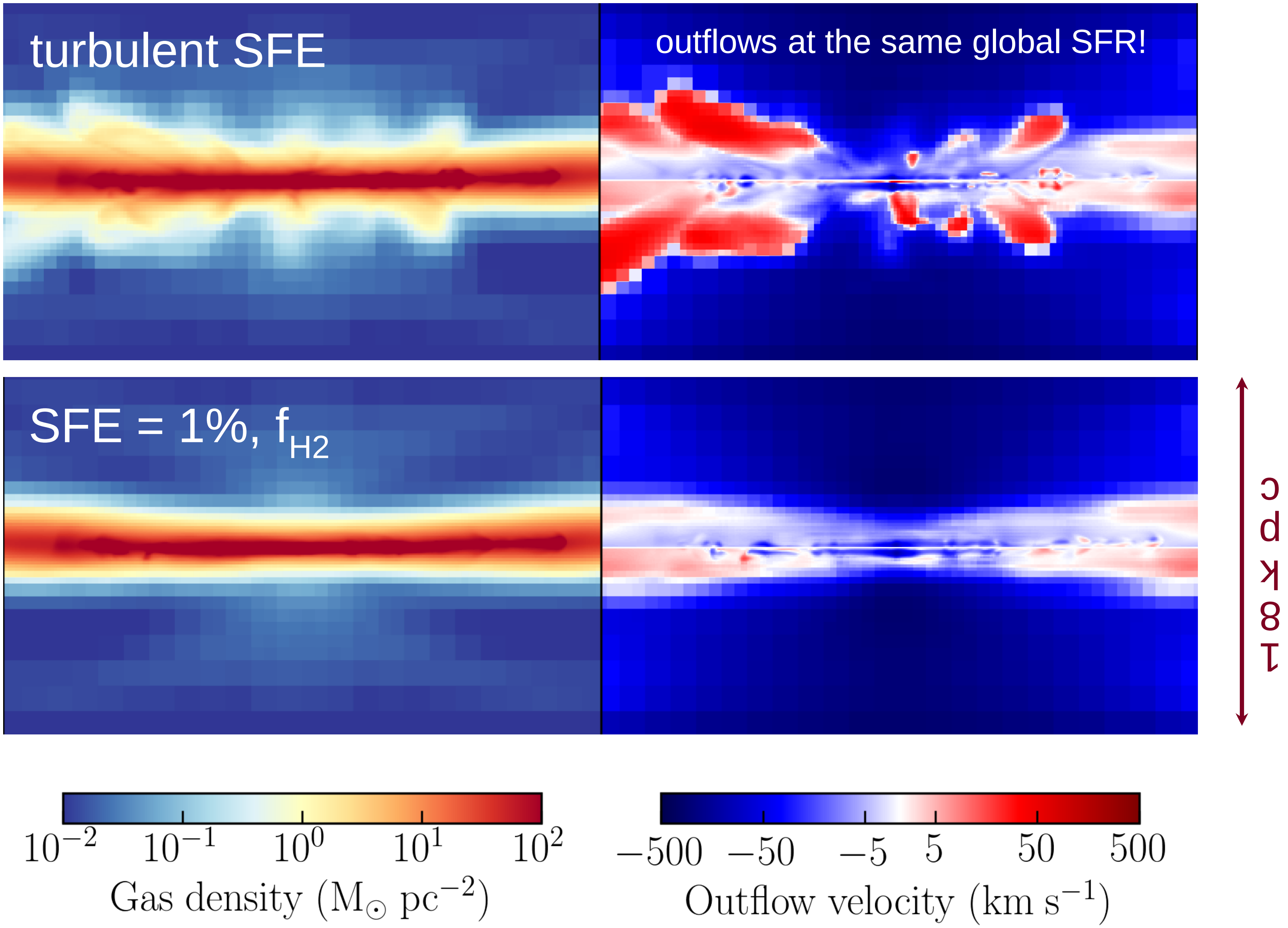
Contours:
15% of total gas mass

SFRs on kpc scale



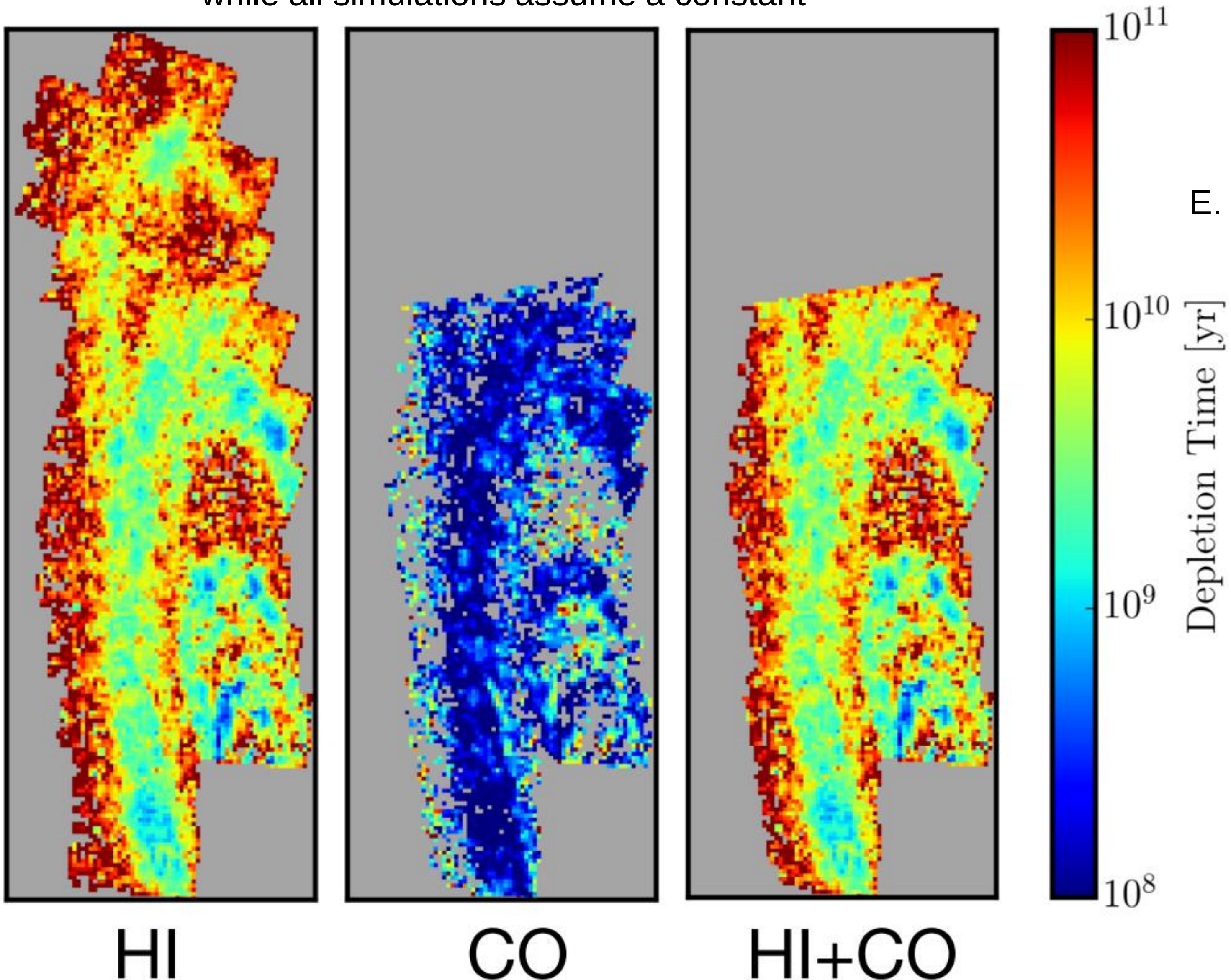
Contours:
68% of patches

Why SFE variation matters



Observational constraints like these should help to improve modelling of star formation in simulations

Strong variation of gas depletion time on 100 pc scales in M31
while all simulations assume a constant



Alexia Lewis' talk

See also
E. Schinnerer et al. 2013
for M51

Lee, Murray 2016
For MW