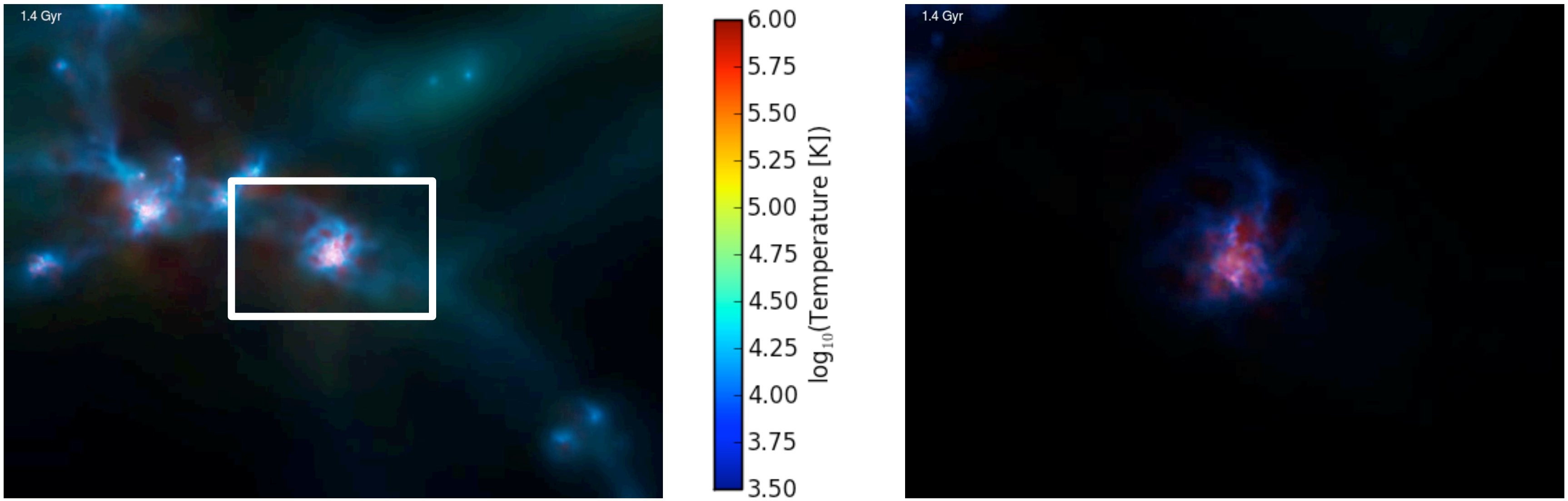
Dark Halo Response in MaGICC Simulations



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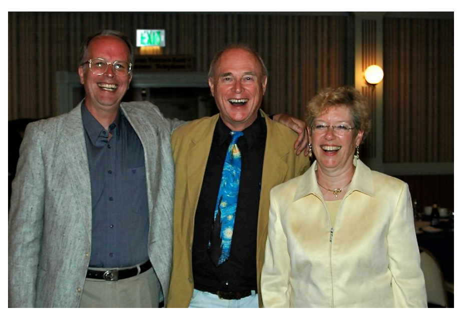
Santa Cruz Galaxy Workshop, August 12-16 2013

GOAL: Theoretical prediction for the structure of Dark Matter haloes

WHY should you care?

1) Constrain the **Nature of Dark Matter** using galaxy scale observations: i.e., dark matter density profiles.

2) Understand the **Origin of Galaxy Scaling Relations**: Tully-Fisher, Faber-Jackson, Fundamental Plane.



How does theory predict the structure of dark matter haloes?

Ingredients:

125 Mpc/h

- **Nature of the Dark Matter**
  (e.g., CDM, WDM, SIDM, ...)
- **Cosmological Parameters**
  (e.g., $\boldsymbol{\sigma_8}$, n, Ω_m, ...)

} → Dissipationless (N-body) simulations

- **Dark halo response to galaxy formation**
  (e.g., contraction/expansion/no change)

Background: Millennium Simulation

Dissipationless simulations **precisely** predict the structure of DM haloes

Millennium (Springel et al. 2005); **Via Lactea** (Diemand et al. 2007); **Aquarius** (Springel et al. 2008); **Bolshoi** (Klypin et al. 2010).

✦ **Two predictions** (**N**avarro, **F**renk, **W**hite 1997)

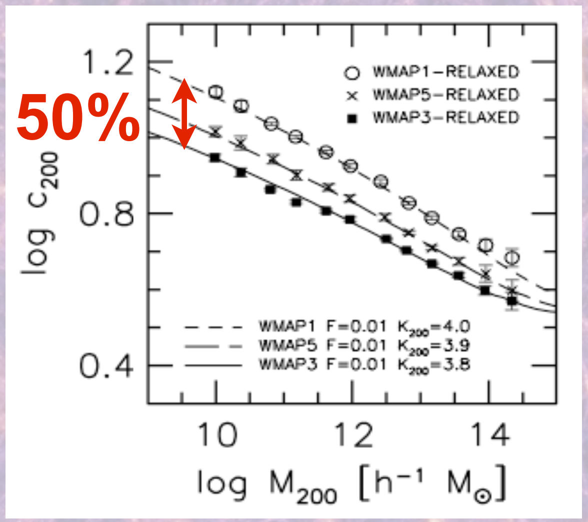
1. Universal "cuspy" density profile

$$\frac{\rho(r)}{\rho_{\rm crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

2. Concentration mass relation

$$c_{200} \equiv r_{200}/r_s \propto (M_{200})^{-0.1}$$

σ_8, n, Ω_m



Maccio, Dutton, van den Bosch 2008

✦ But, are these simulations **accurate?** (what about halo response?)

Background: Millennium Simulation

Q: How do dark matter haloes respond to galaxy formation?

Several physical process can modify the structure of DM haloes

- **Smooth and Slow Accretion: "Adiabatic Contraction"**
  - **r M(r) = const.** **(Blumenthal et al. 1986,** Barnes & White 1984)
  - Order of magnitude increase in central density possible

- **Dynamical Friction: Expansion**
  - Satellite/clumpy accretion
    (e.g., El-Zant et al. 2001; Johansson et al. 2009**)**
  - Galactic bars
    (Weinberg & Katz 2002)

- **Feedback: Expansion**
  - Strong mass outflows
    (e.g., Navarro et al. 1996; Read & Gilmore 2005)
  - Perturbations to potential
    (e.g., Pontzen & Governato 2012)

Q: How do dark matter haloes respond to galaxy formation?

A) **They don't.** Dissipationless simulations are all you need

B) **Contraction** (roughly adiabatic)
(Gnedin et al. 2004; 2011)

C) **Expansion**
(Dutton et al. 2007; 2013)

D) All of the above, AND In a predictable way!

Two theoretical approaches

✦ **Analytic**

(e.g., Mo & Mao 2004; Cole et al. 2011)

\+ you can make realistic galaxies

\- many simplifying approximations

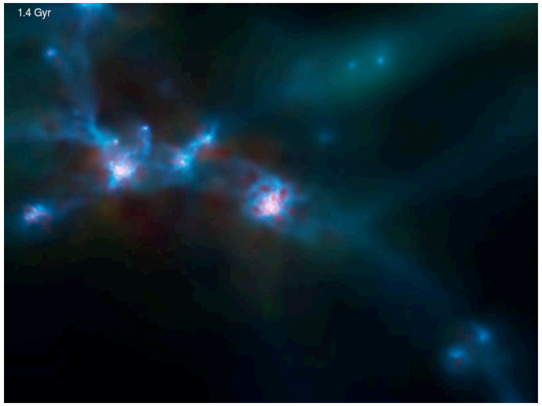
✦ **Cosmological hydrodynamical simulations**

(e.g., Gnedin et al. 2004; Abadi et al. 2010)

\+ this is the problem we want to solve

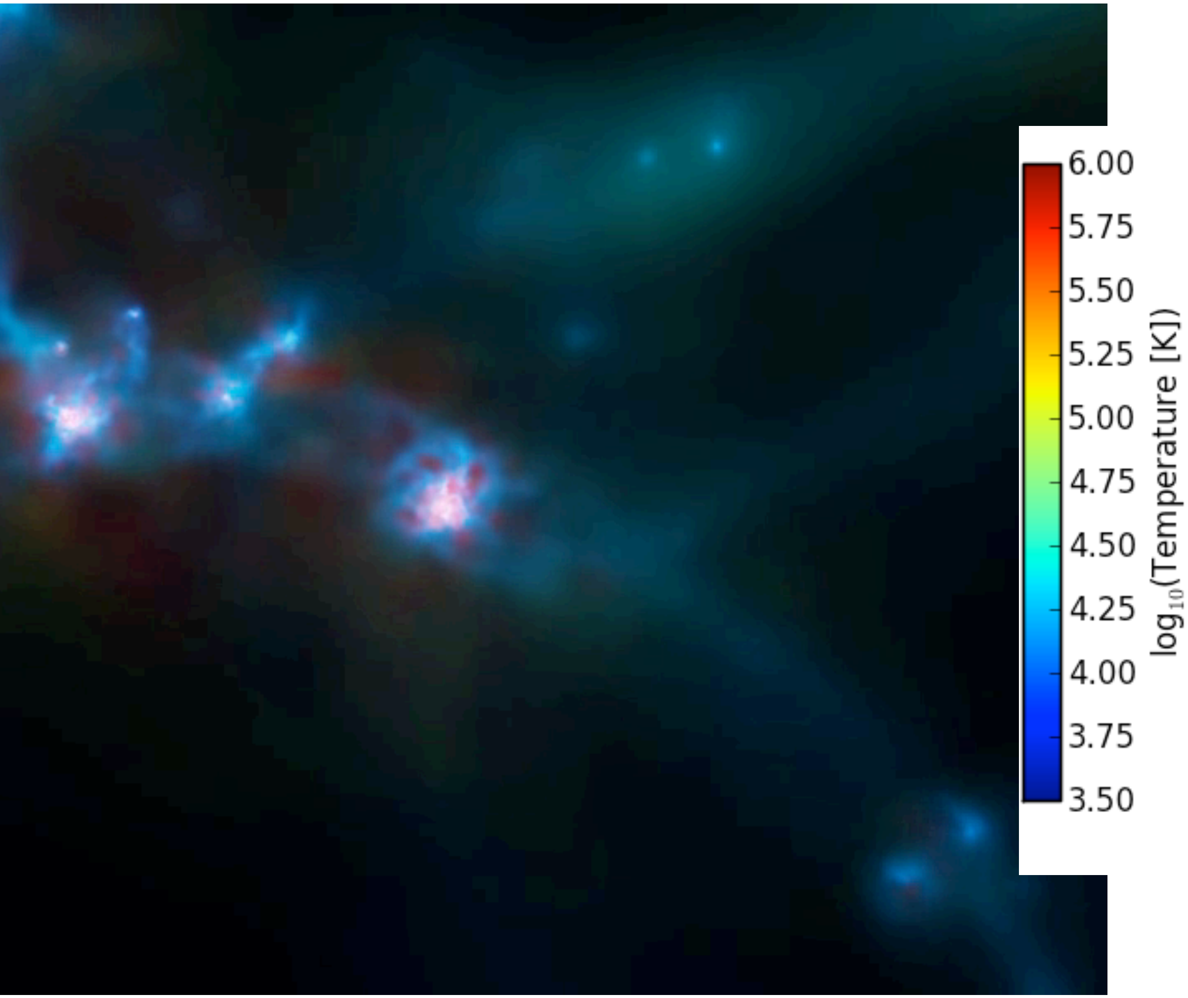
~~- galaxies are usually not realistic **(overcooling!)**~~

\+ MaGICC simulations make realistic galaxies



The MaGICC project @MPIA

Making Galaxies In a Cosmological Context



200 kpc

GASOLINE (SPH)

Metal line cooling

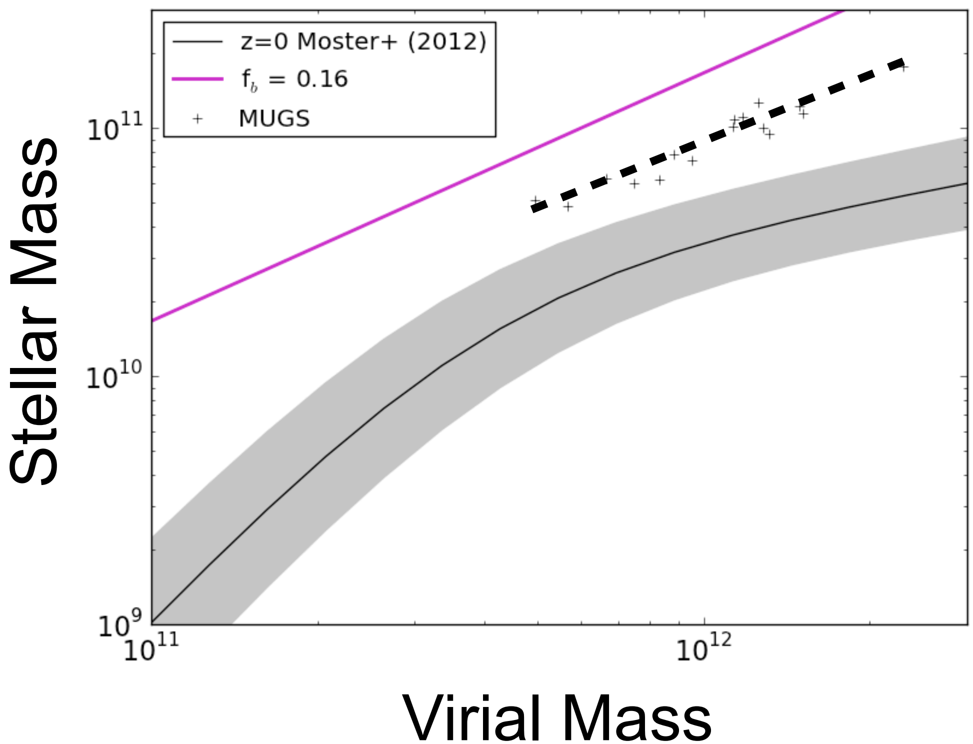
UV background

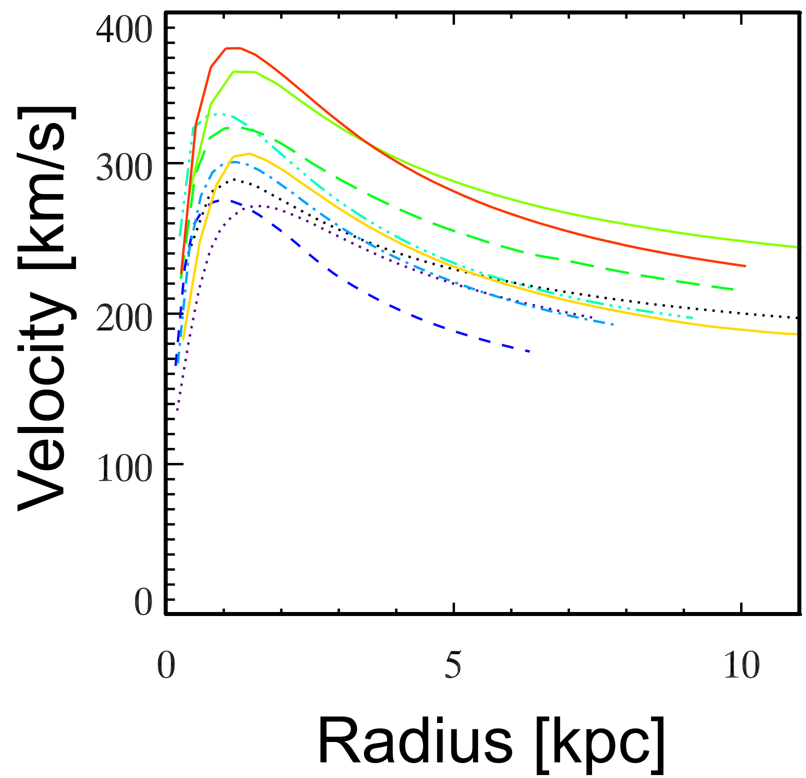
Star formation

Super Nova +Early Stellar Feedback (Stinson et al. 2013)

“state-of-the-art” simulations with hierarchical merging, gas cooling, star formation, stellar feedback, and high resolution

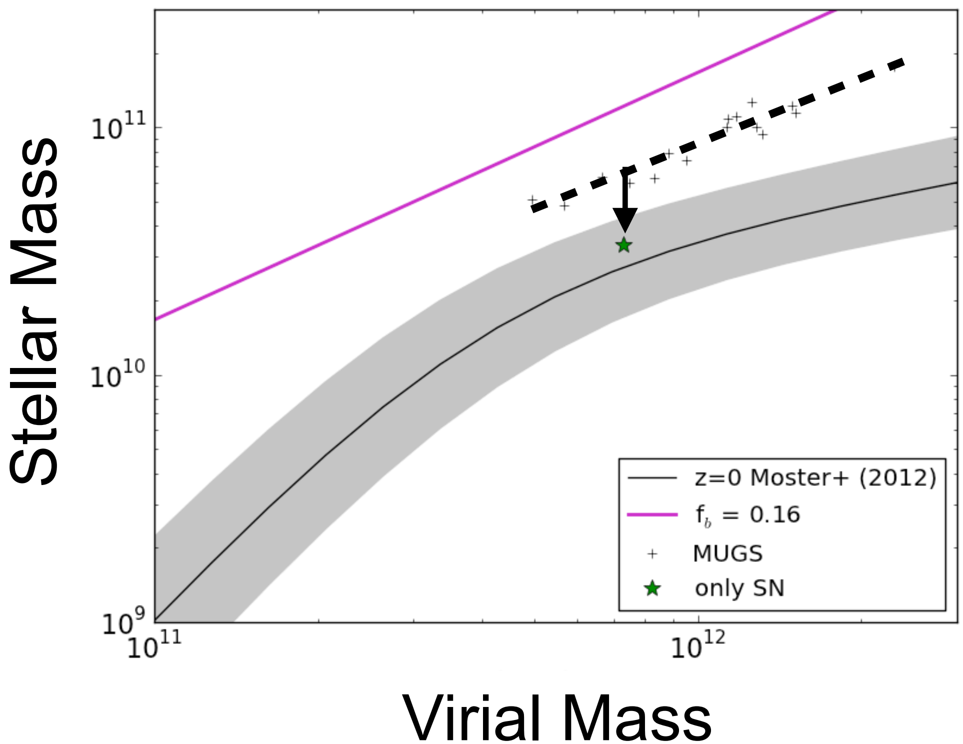
but, too many stars form... ...primarily in the center.





Solution: add more feedback

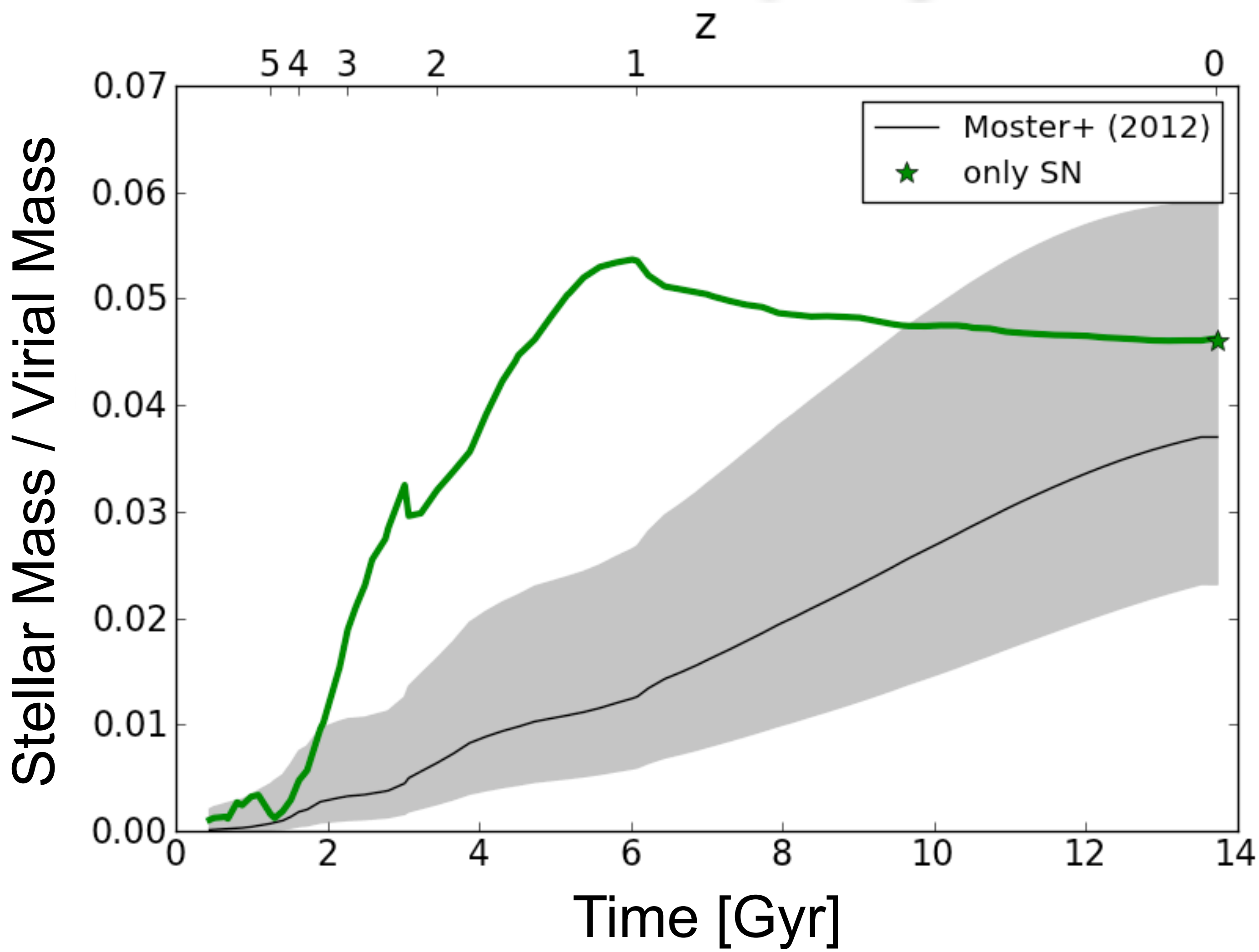
1) Chabrier instead of Kroupa IMF
2) Increased efficiency (but still < 100%)



Looks good, but...

Evolution in M_{star}/M_{halo} is way off

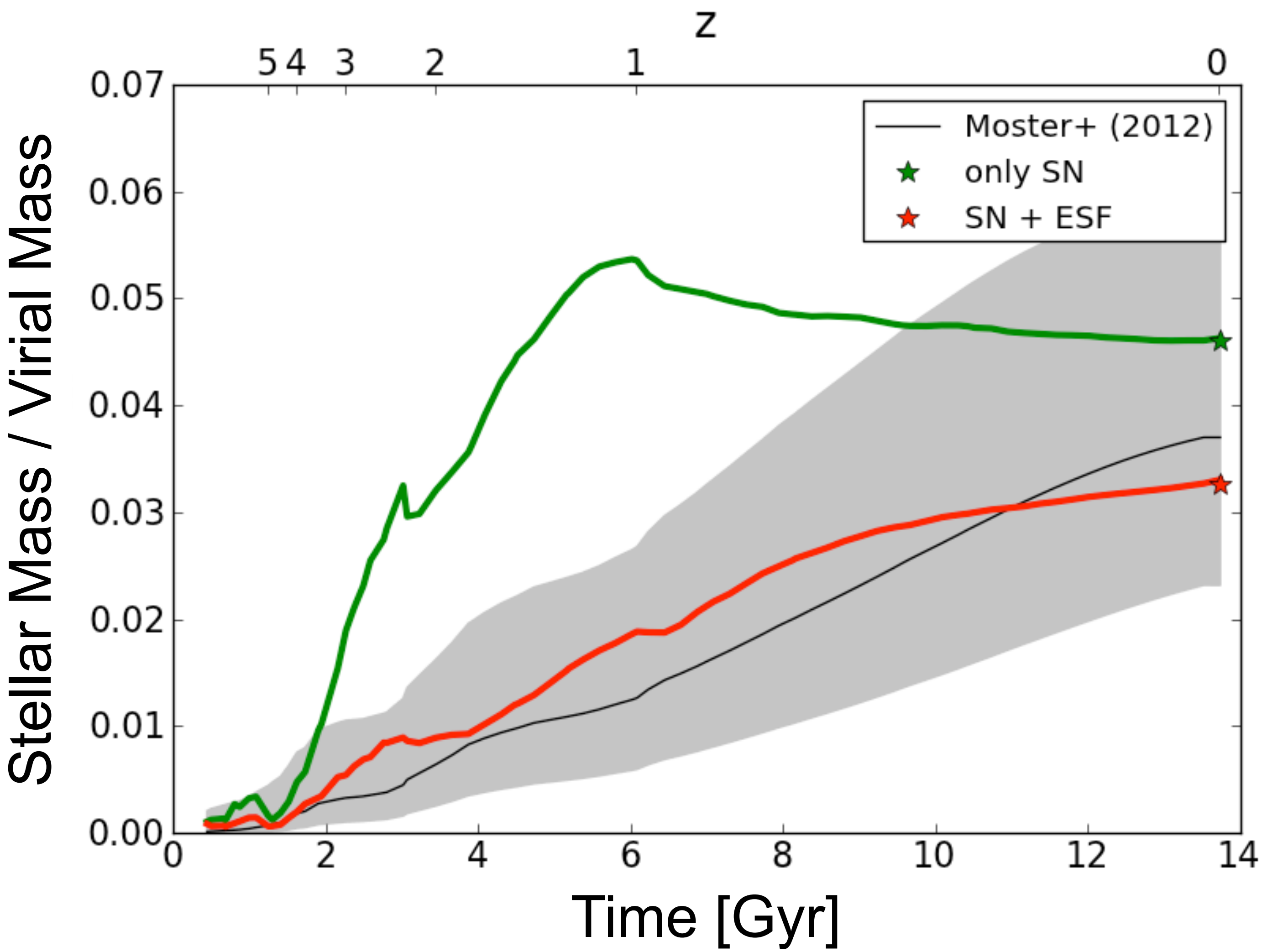
stars form too quickly!



Stinson et al. 2013, MNRAS, 428, 1295

Solution: add more feedback

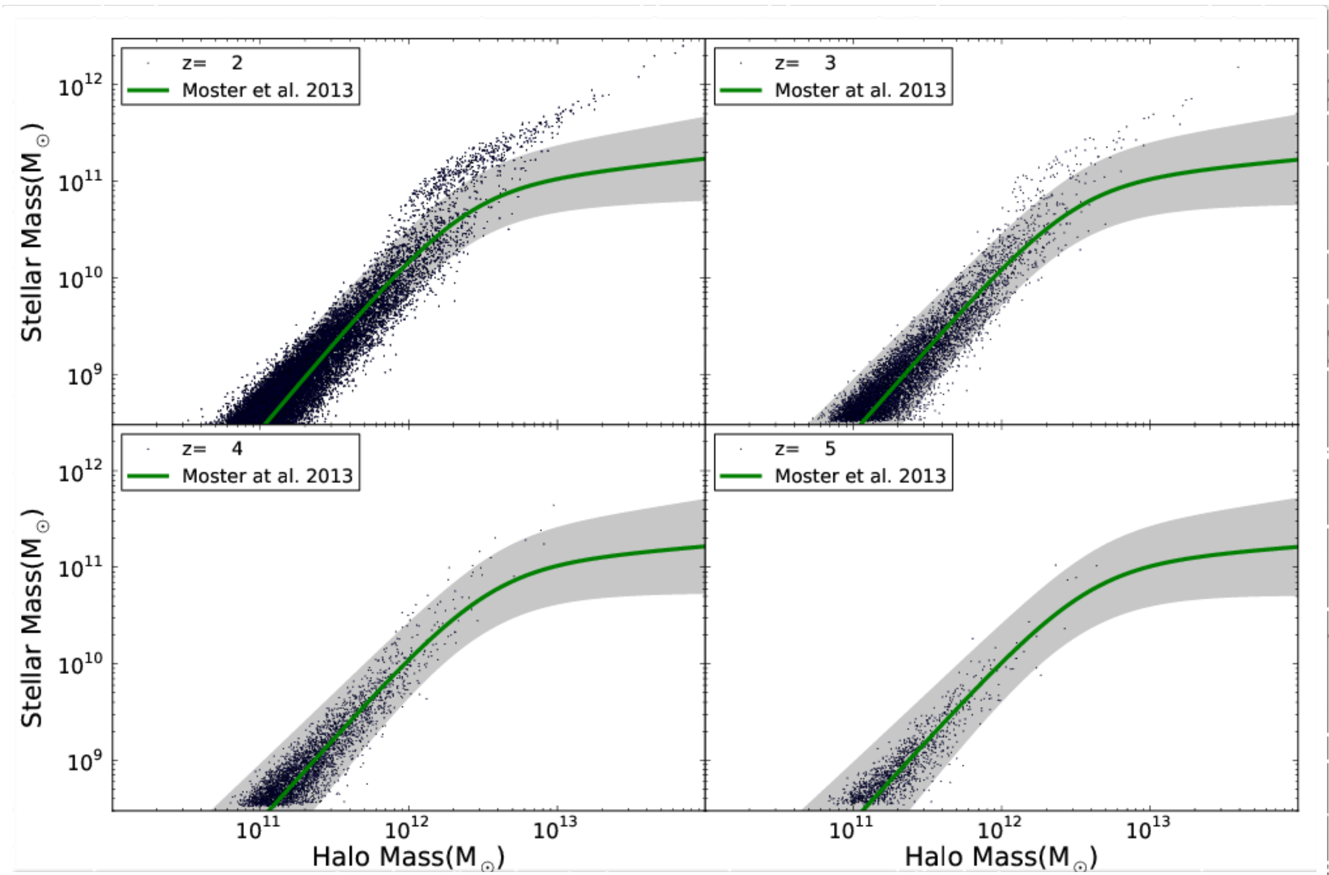
from stars before SN go off (<3 Myr)



Stinson et al. 2013, MNRAS, 428, 1295

The MaGICC Volume

stellar mass vs halo mass relation at z=2,3,4,5



512^3 particles in $(114\ \text{Mpc})^3$ volume

Rahul Kannan et al. 2013 (astro-ph:1302.2618)

Other MaGICC projects

- **Dark MaGICC** - **the effect of dark energy on galaxy structures**

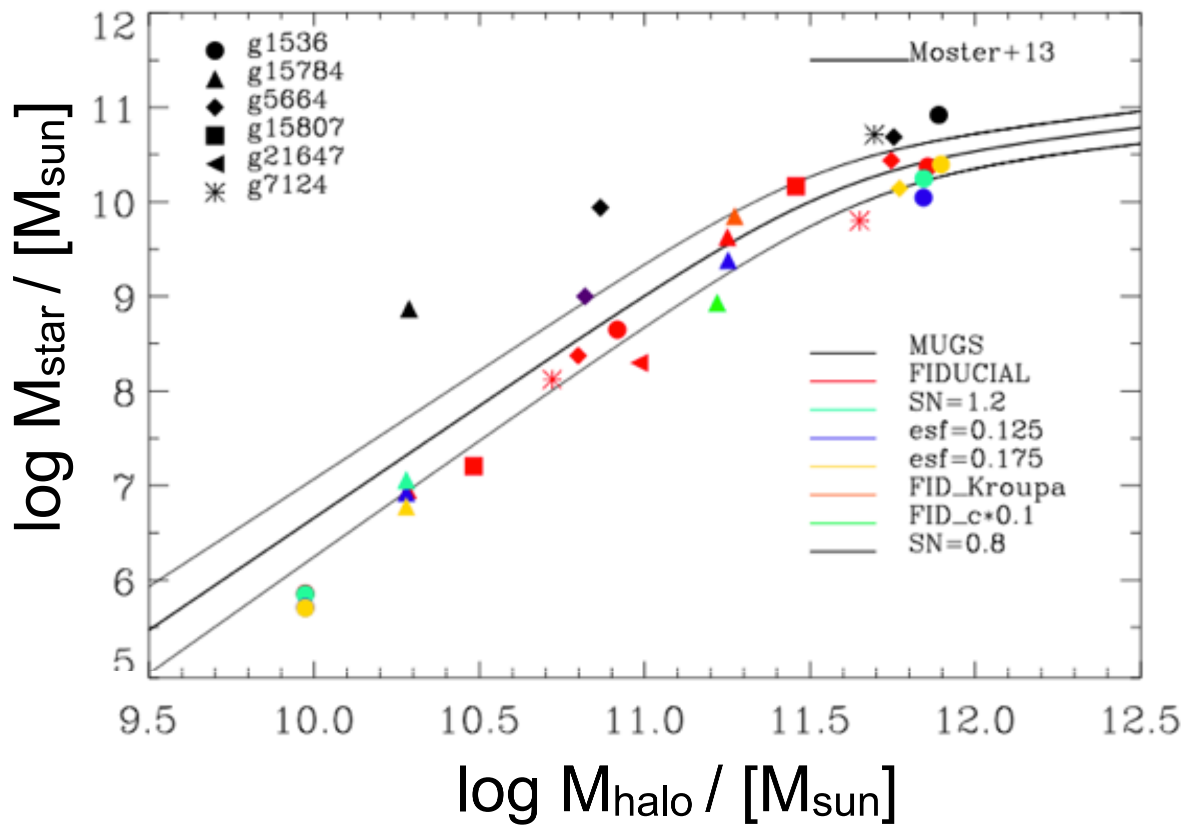
  Camilla Penzo - see next talk

- **Warm MaGICC** - **the effects of Warm Dark Matter in hydrodynamical simulations of galaxy formation**

  Jakob Herpich et al. 2013 astro-ph:1308.1088

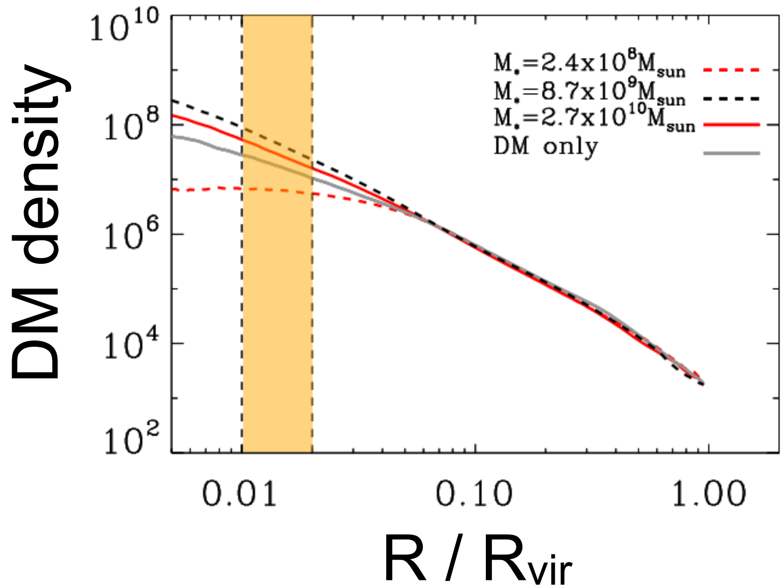
Global Properties: Stellar mass vs Halo Mass

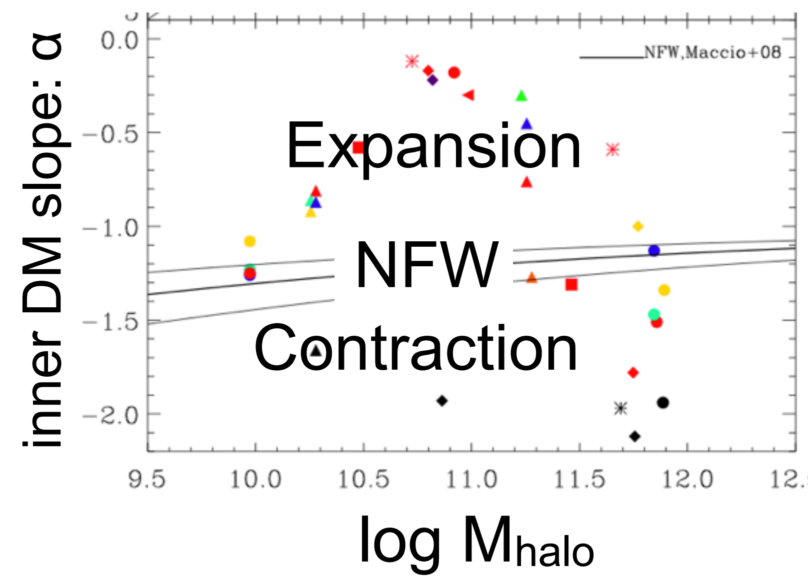
31 cosmological zoom-in simulations



Di Cintio et al. 2013, arXiv:1306.0898

Inner Dark Matter density slopes





- Fit for power-law slope, α, between 1 and 2% of R_{vir}
- No correlation with halo mass

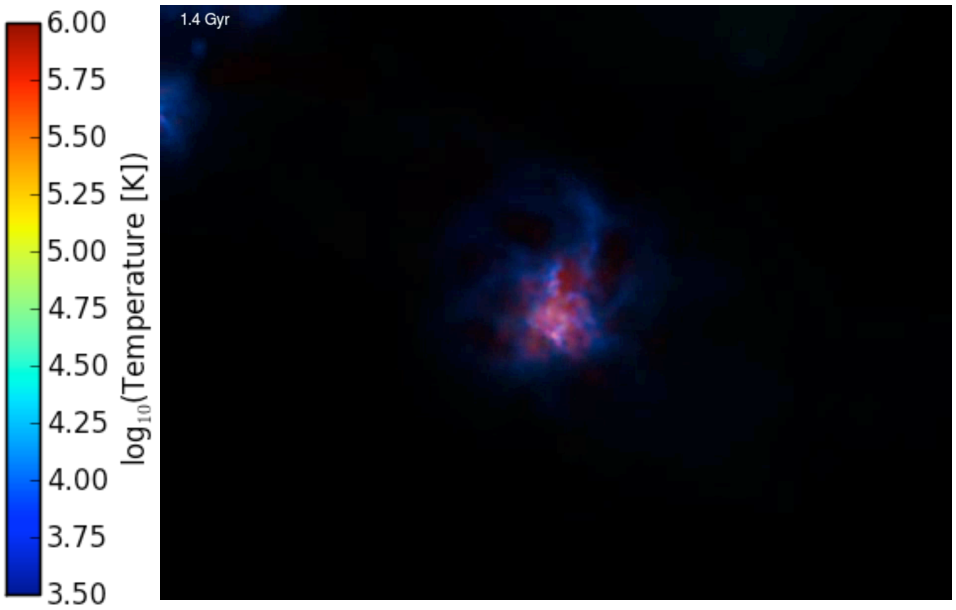
Di Cintio et al. 2013, arXiv:1306.0898

What causes halo expansion?

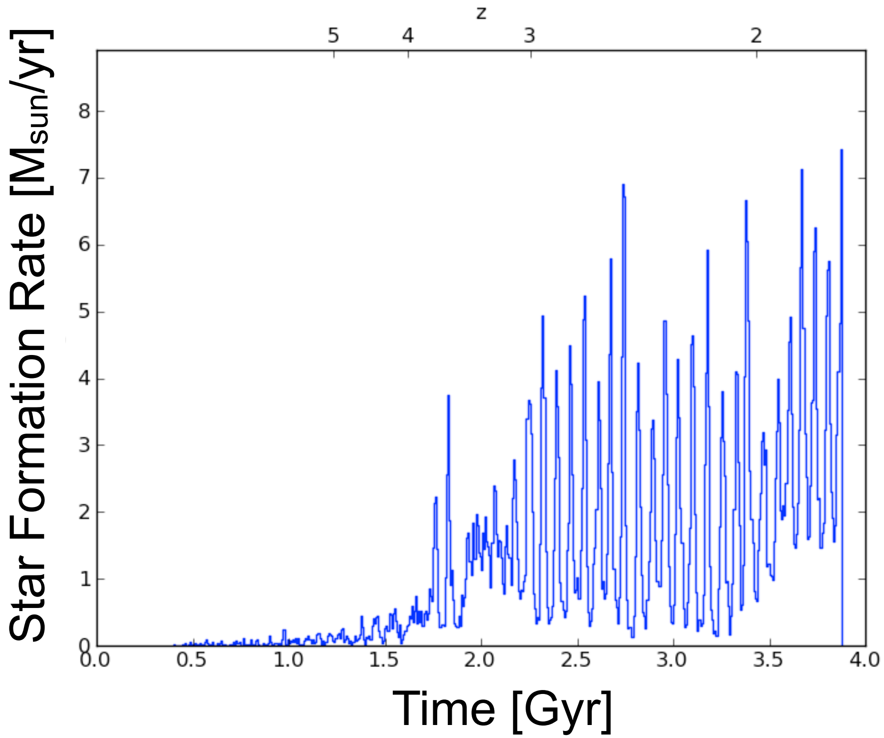
Bursty star formation ⇒ feedback drives gas flows

⇒ rapid fluctuations in potential depth ⇒ halo expansion

(Pontzen & Governato 2012)

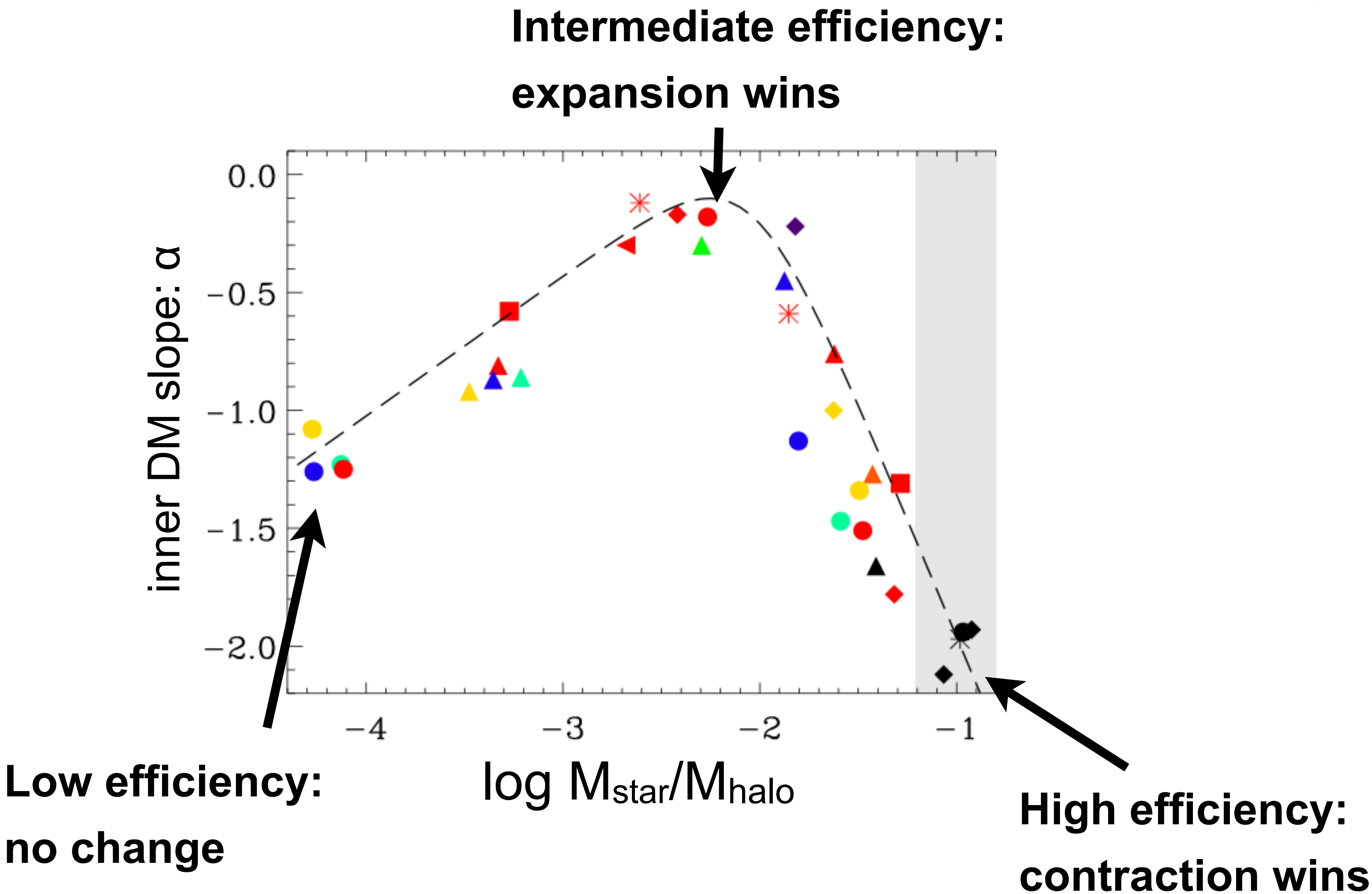


MaGICC - Stinson et al. 2013



DM slope correlates with star formation efficiency

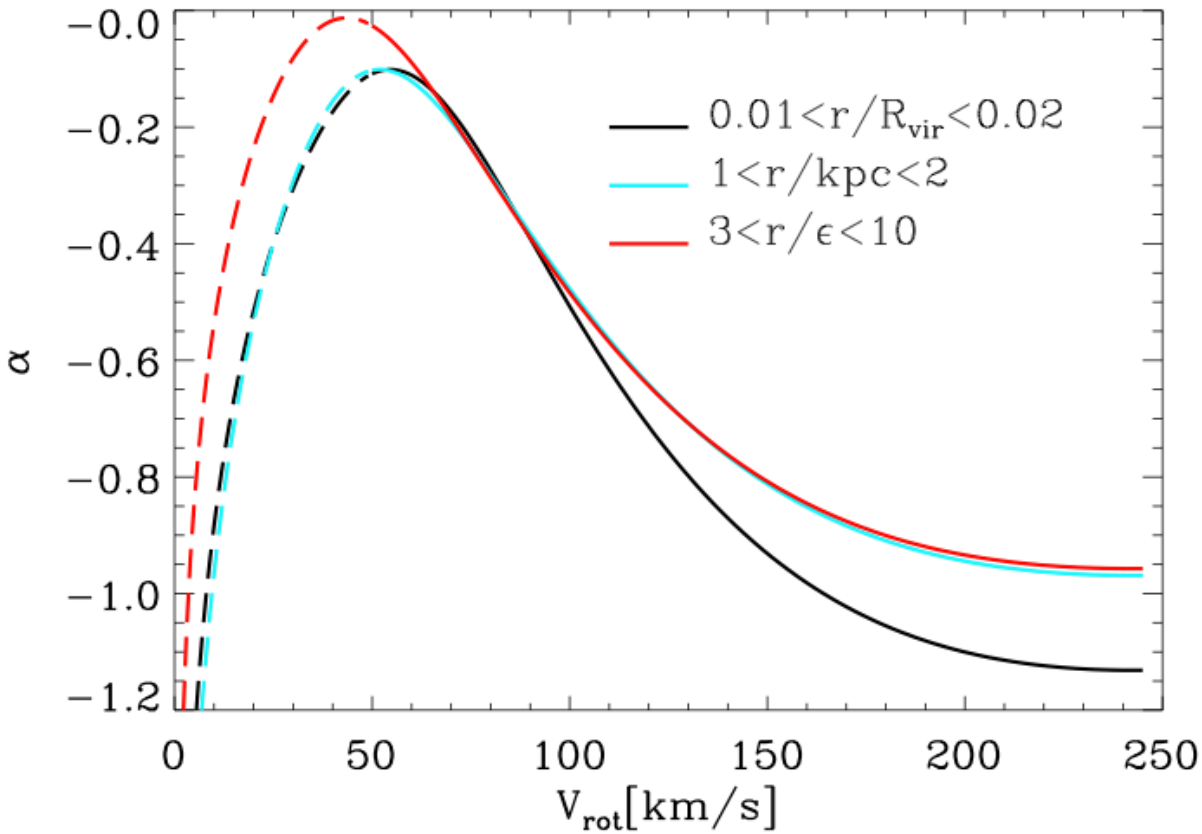
Competition: inflows (contraction) vs **outflows** (expansion)



Di Cintio et al. 2013, arXiv:1306.0898

What mass scales are most effected?

Use abundance matching and TF relation



Di Cintio et al. 2013, arXiv:1306.0898

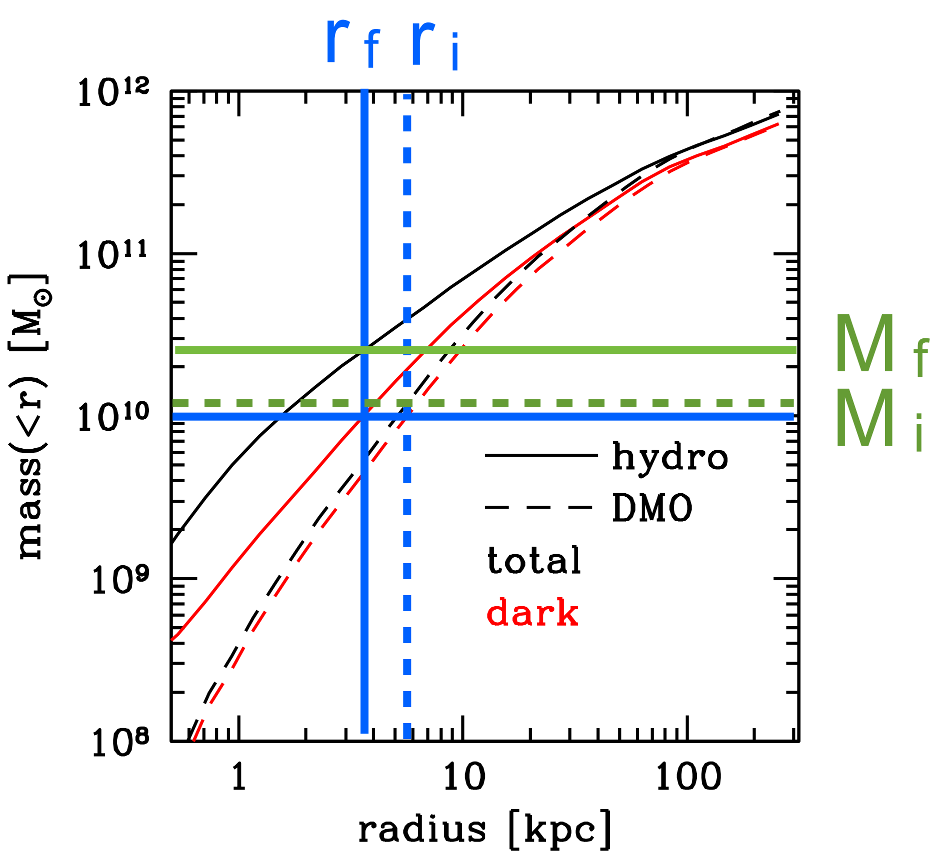
Characterizing dark halo response

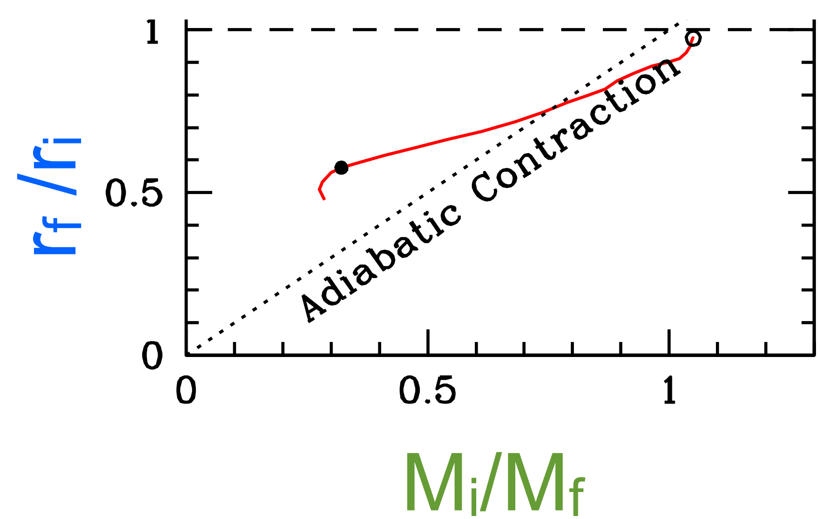
- **Follow a mass shell of dark matter**

$$M_{dm,f}\,(r_f) = M_{dm,i}\,(r_i)$$

f - Hydro

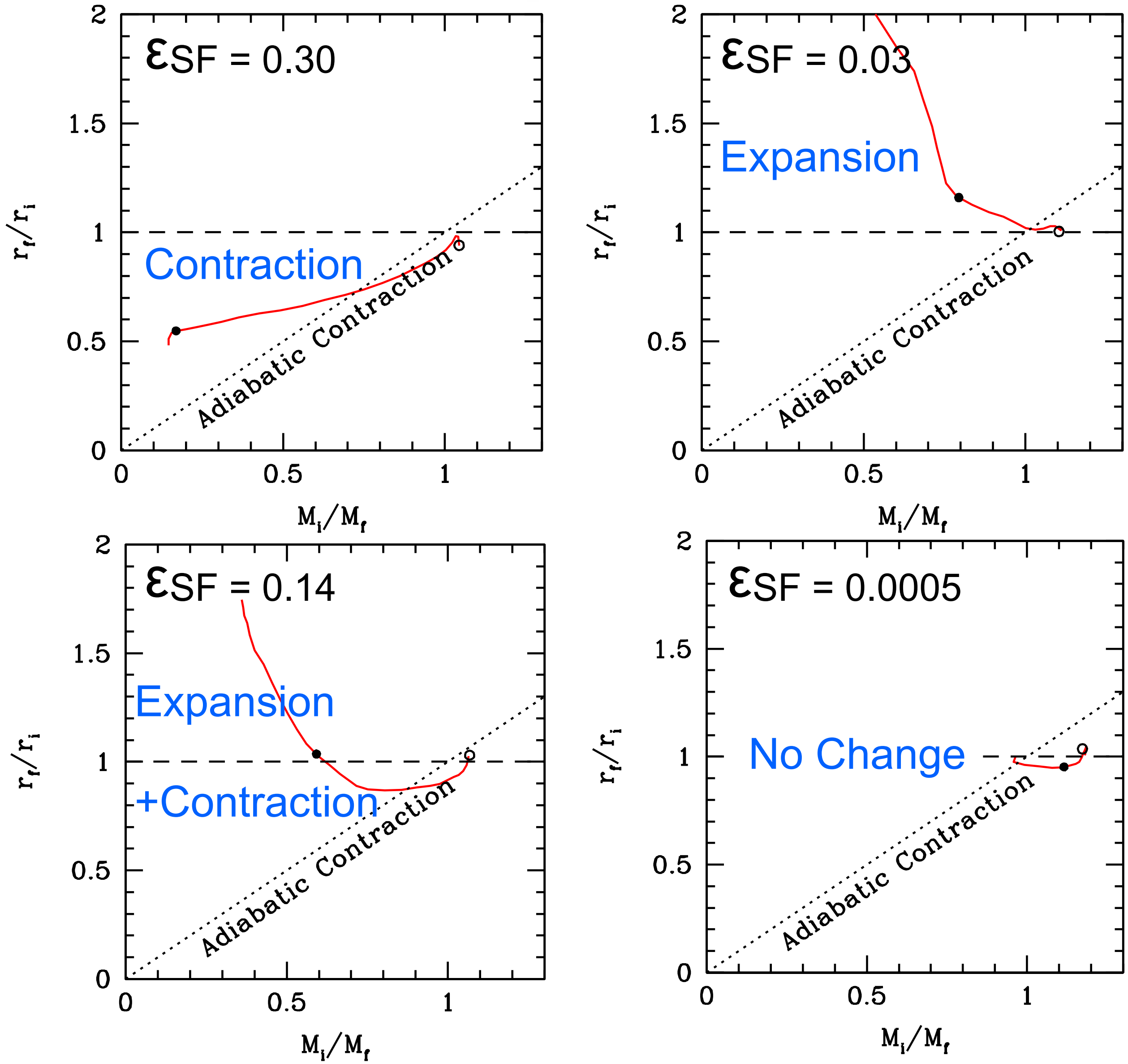
i - Dark Matter only





Dutton et al. in prep

Characterizing dark halo response



Dutton et al. in prep

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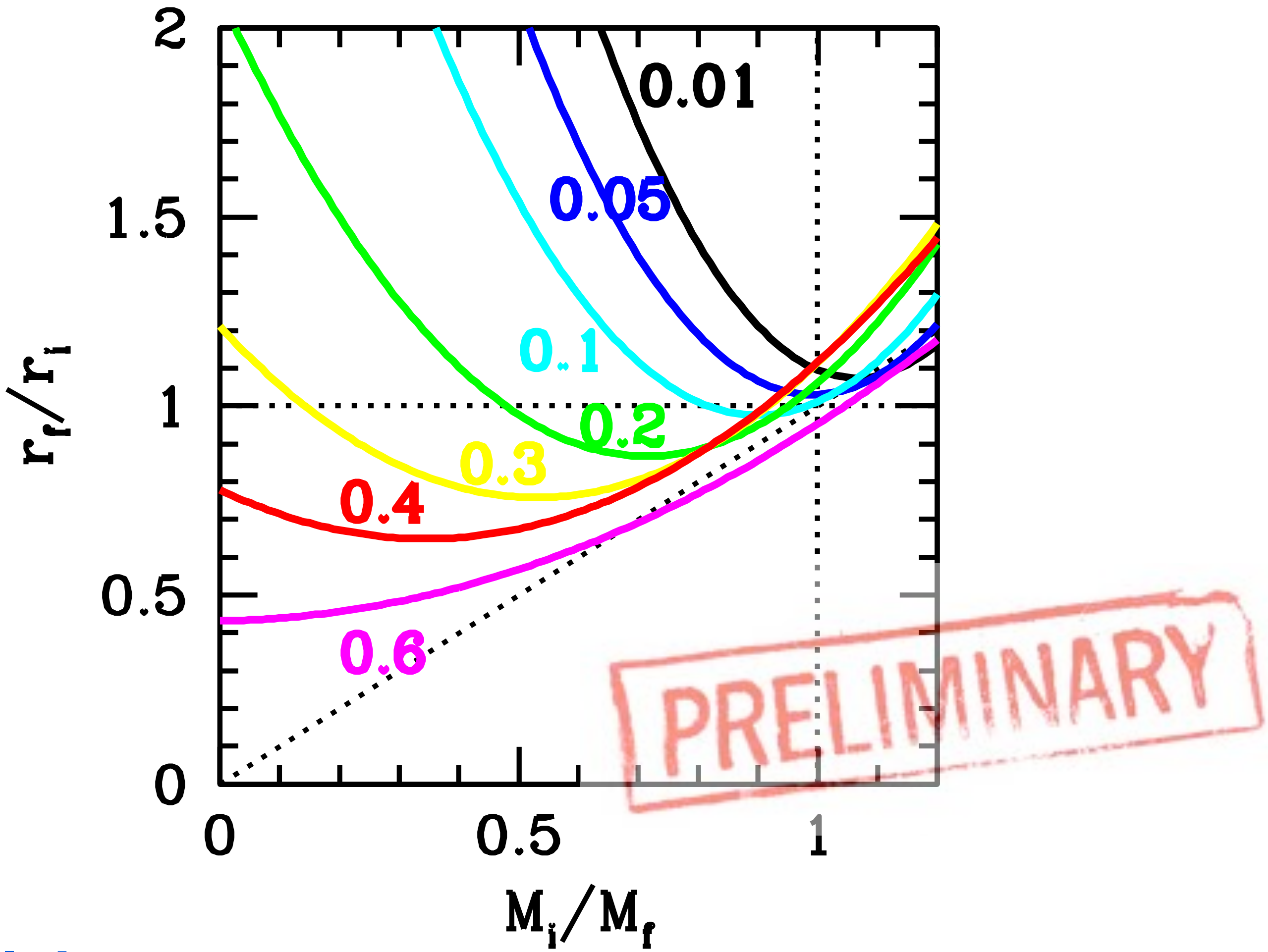
Halo response is correlated with integrated star formation efficiency

$\varepsilon_{SF} = (M_{star} / M_{vir}) / (\Omega_b / \Omega_m)$



Dutton et al. in prep

How do dark matter haloes respond to galaxy formation?

- **Response is correlated with star formation efficiency** **(Di Cintio et al. 2013; Dutton et al. in prep)**

★ contraction (steep cusps) at high efficiency $\varepsilon_{SF} > 0.30$

★ expansion (cores) at low efficiency $\varepsilon_{SF} < 0.10$

★ no change (NFW) at very low efficiency $M_{vir}/M_{star} > 10\,000$

$$\varepsilon_{SF} = (M_{star} / M_{vir}) / (\Omega_b / \Omega_m)$$