FLATTENING DARK MATTER CUSPS

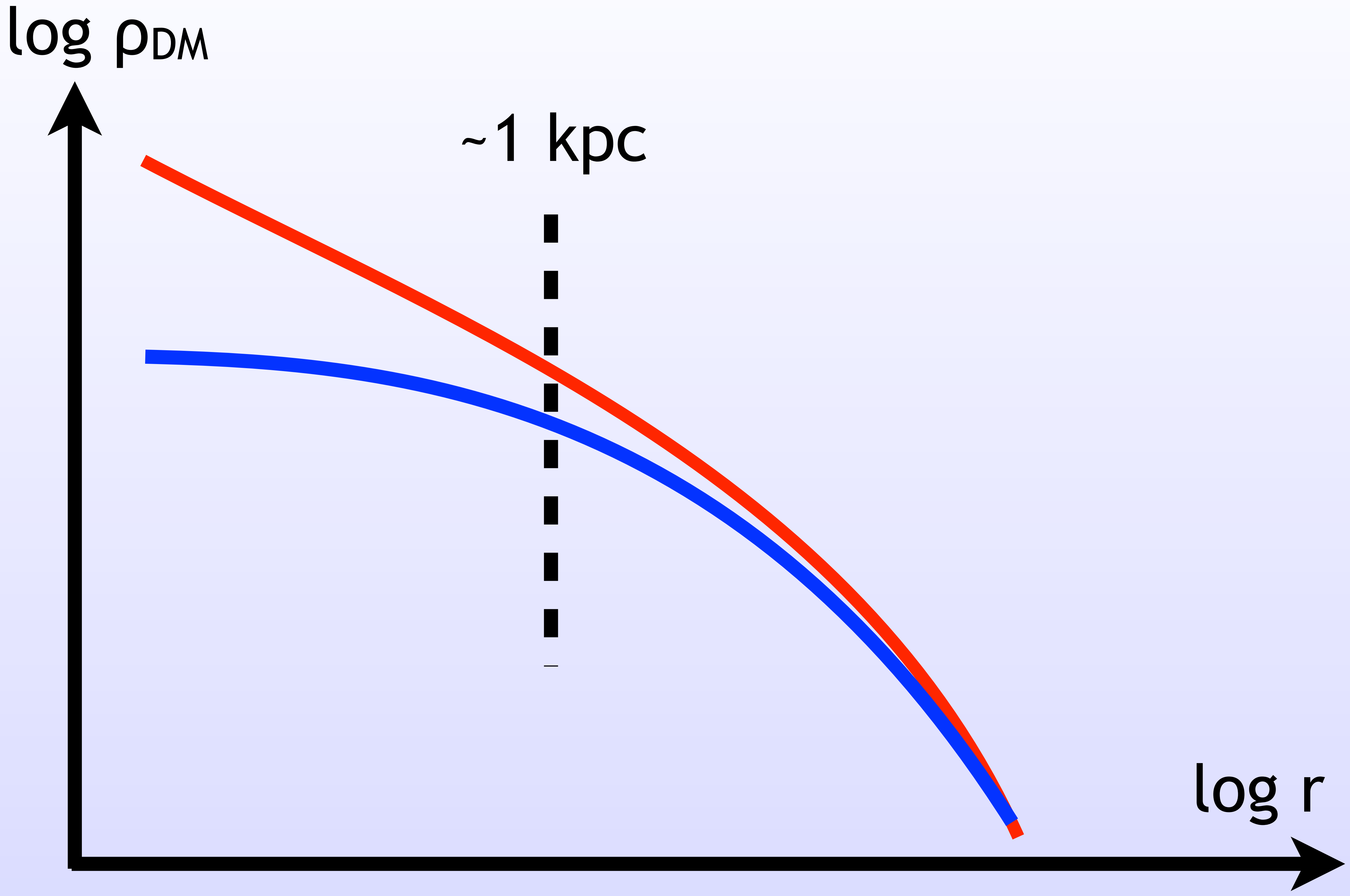
WITH

Super Nova® FEEDBACK

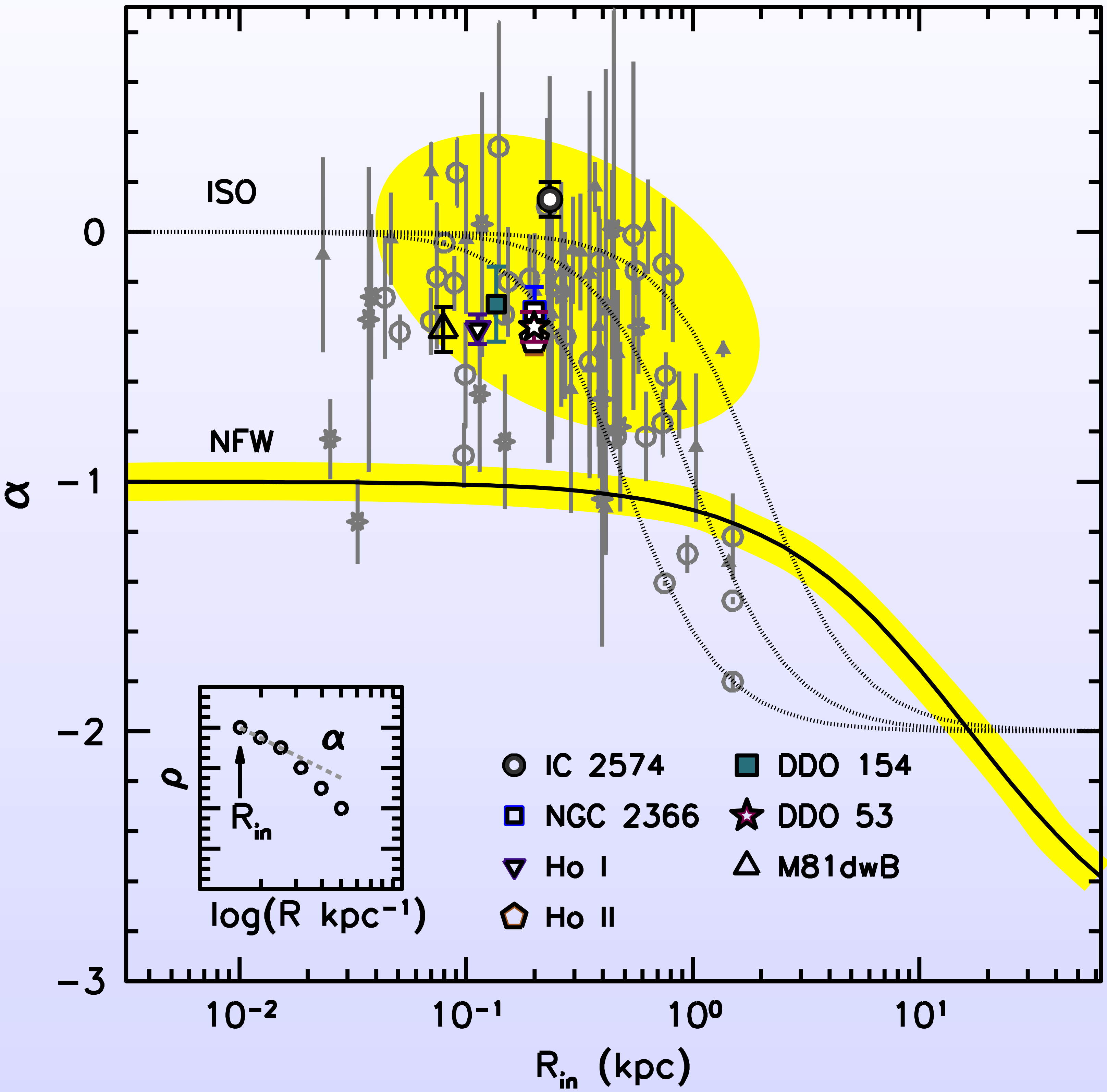
Andrew Pontzen
Oxford Astrophysics

+ Fabio Governato, Alyson Brooks, Adi Zoltov, ... + Romain Teyssier, ...
+ the Gasoline team (Wadsley/Quinn/Stadel/Stinson/Shen/Christensen/...)

Dwarf Galaxies



Dwarf Galaxies



Oh et al 2011, AJ

Governato et al 2010

Vol 463 | 14 January 2010 | doi:10.1038/nature08640

LETTERS

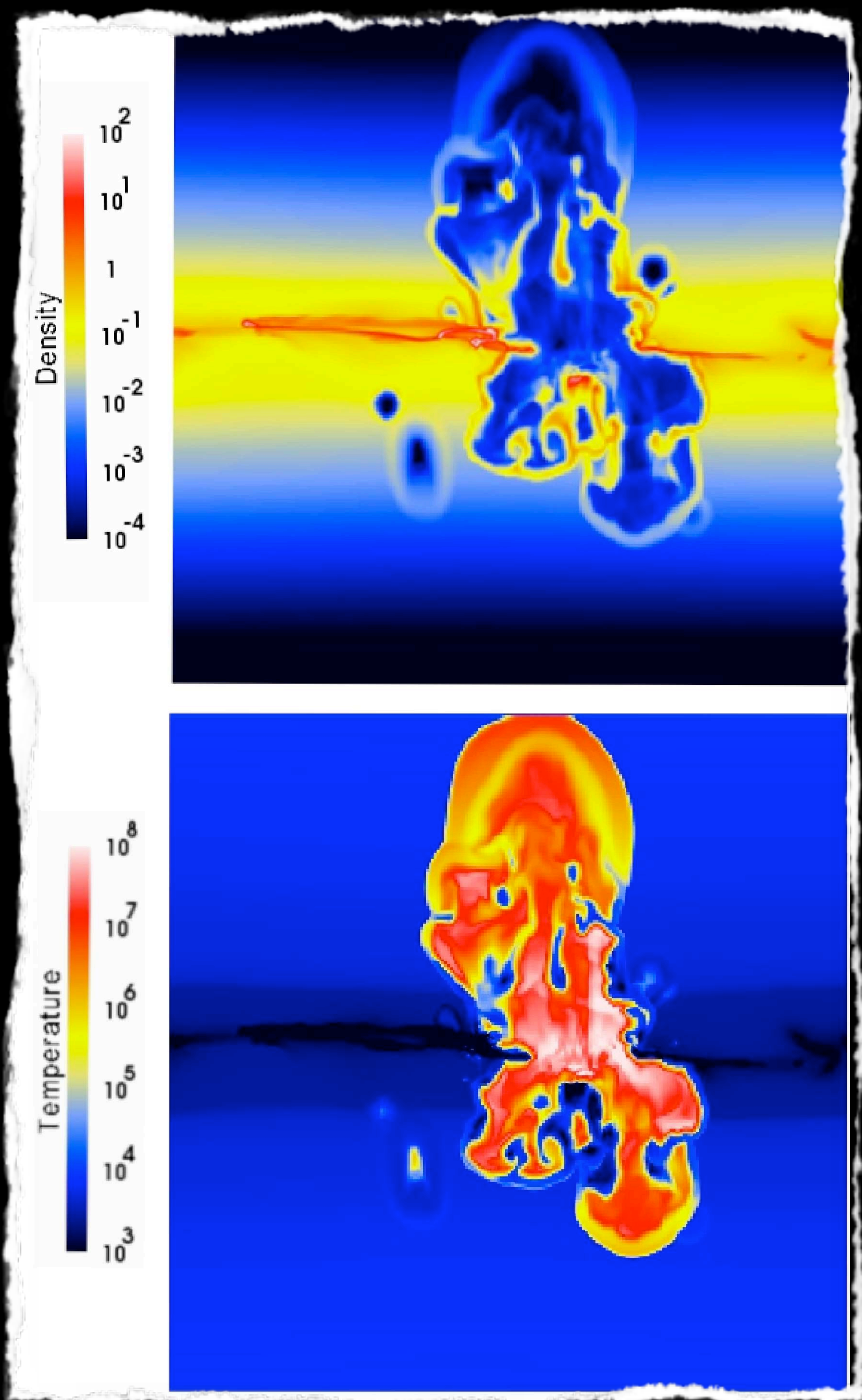
Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

F. Governato[1], C. Brook[2], L. Mayer[3], A. Brooks[4], G. Rhee[5], J. Wadsley[6], P. Jonsson[7], B. Willman[9], G. Stinson[6], T. Quinn[1] & P. Madau[8]

For almost two decades the properties of 'dwarf' galaxies have challenged the cold dark matter (CDM) model of galaxy formation[1]. Most observed dwarf galaxies consist of a rotating stellar disk[2] embedded in a massive dark-matter halo with a near-constant-density core[3]. Models based on the dominance of CDM, however, invariably form galaxies with dense spheroidal stellar bulges and steep central dark-matter profiles[4–6], because low-angular-momentum baryons and dark matter sink to the centres of galaxies through accretion and repeated mergers[7]. Processes that decrease the central density of CDM halos[8] have been identified, but have not yet reconciled theory with observations of present-day dwarfs. This failure is potentially catastrophic for the CDM model, possibly requiring a different dark-matter particle candidate[9]. Here we report hydrodynamical simulations (in a framework[10] assuming the presence of CDM and a cosmological constant) in which the inhomogeneous interstellar medium is resolved. Strong outflows from supernovae remove low-angular-momentum gas, which inhibits the formation of bulges and decreases the dark-matter density to less than half of what it would otherwise be within the central kiloparsec. The analogues of dwarf galaxies—bulgeless and

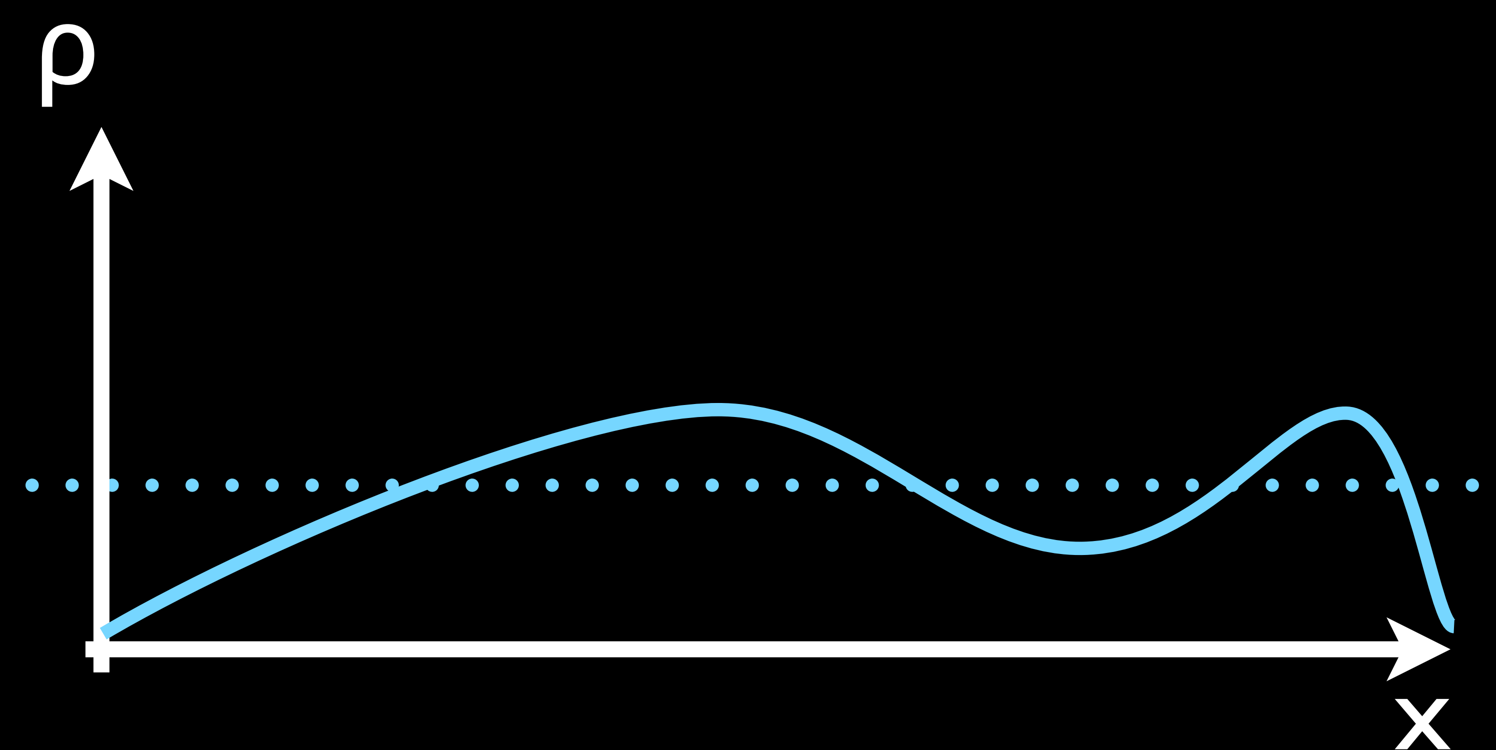
resulting feedback have been applied to the formation of high-redshift protogalaxies, leading to significant baryon loss and less concentrated systems[8,20]. Similarly, dynamical arguments[21,22] suggest that bulk gas motions (possibly supernova-induced) and orbital energy loss of gas clouds due to dynamical friction can transfer energy to the centre of the dark-matter component. Sudden gas removal through outflows then causes the dark-matter distribution to expand. These mechanisms were demonstrated to operate effectively in small high-redshift halos of total mass around $10^9 M_\odot$ ($M_\odot$ is the mass of the Sun) where they create small dark-matter cores[8]. However, such methods and the required high resolution have not been applied to cosmological hydrodynamical simulations of present-day dwarf galaxy systems ($V_{rot} \approx 60\,\mathrm{km\,s^{-1}}$). Showing that the properties of dwarf galaxies can be accurately predicted by the CDM scenario would end the 'small scale crisis' and further constrain the properties of the dark-matter particle candidate.

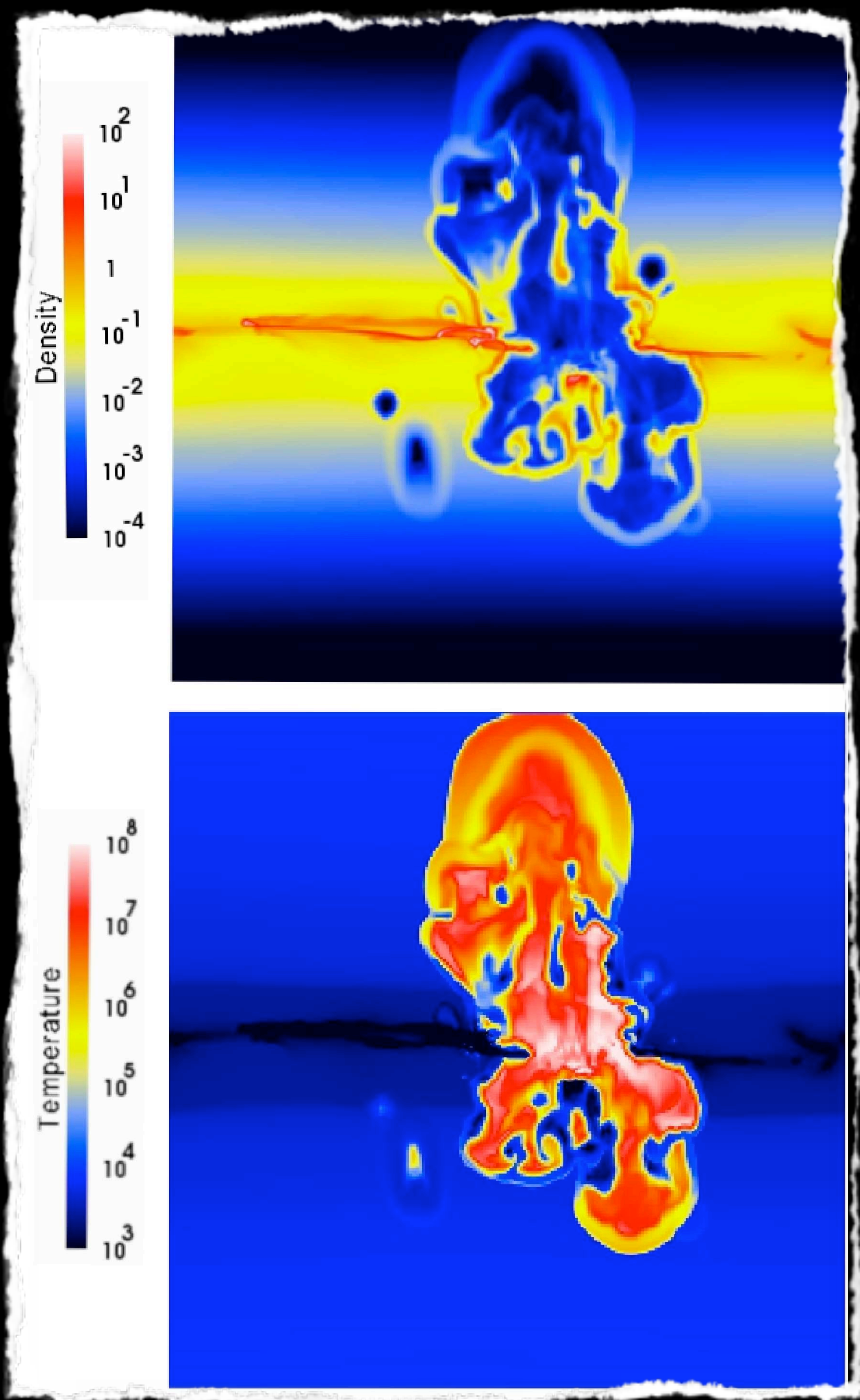
To study the formation of dwarf galaxies in a ΛCDM cosmology, we analyse a novel set of cosmological simulations. Baryonic processes are included, as gas cooling[8], heating from the cosmic ultra-violet field[23], star formation and supernova-driven gas heating



Ceverino & Klypin 09

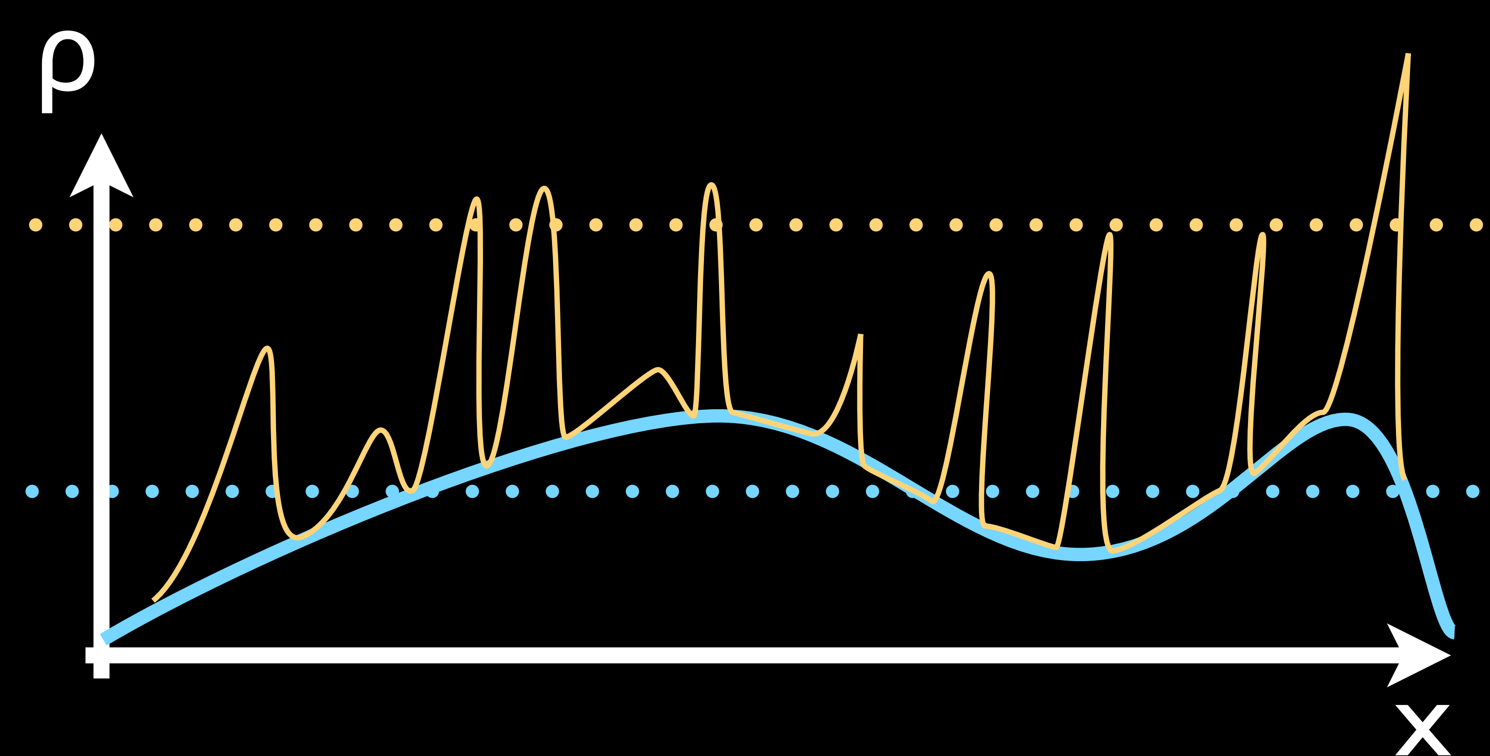
Outflows arise naturally
in high resolution
ISM models



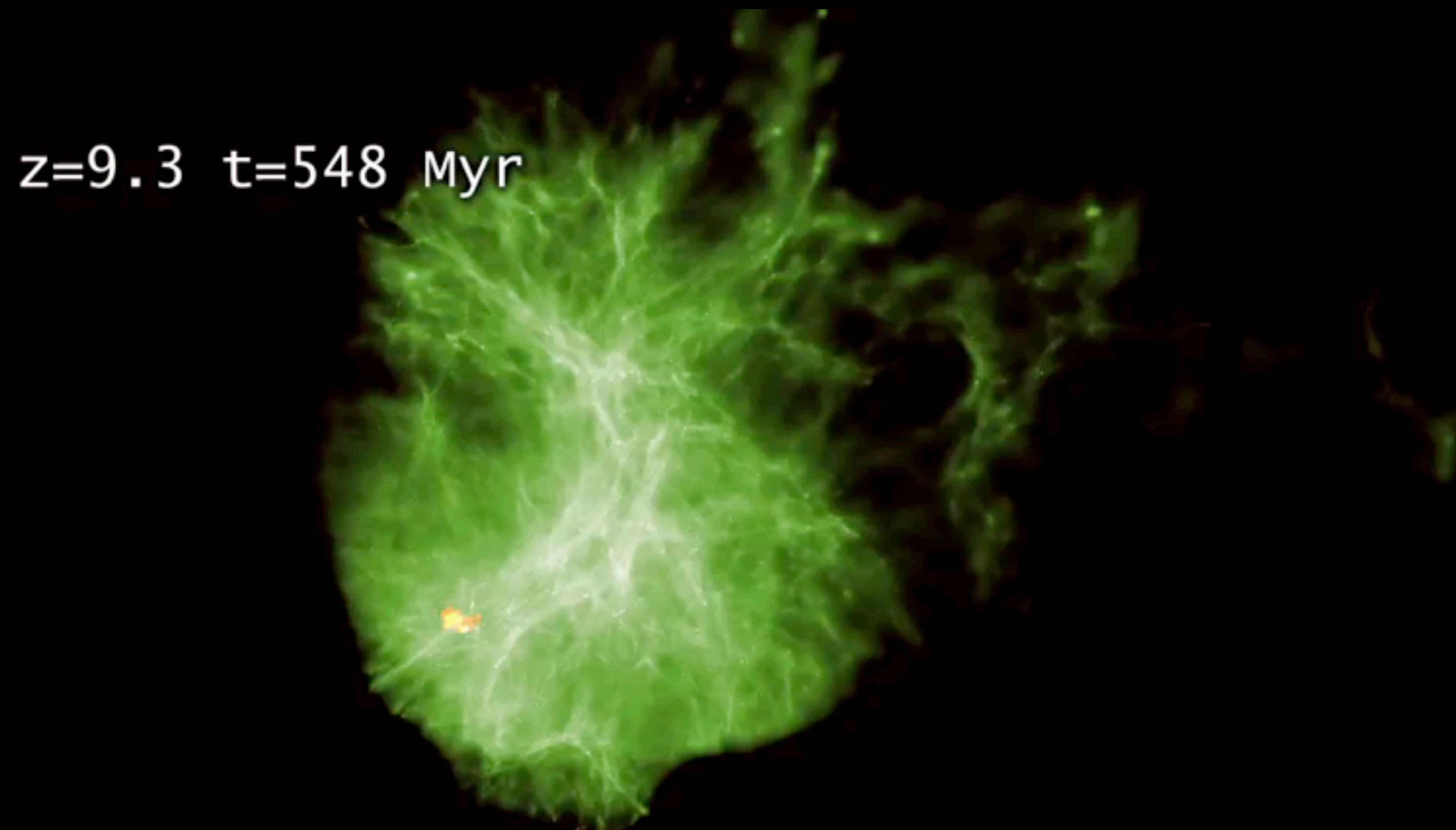


Ceverino & Klypin 09

Outflows arise naturally in high resolution ISM models



Gasoline (Wadsley/Quinn) + Metal cooling (Chen) + UV + H_2 (Christensen) + Thermal feedback

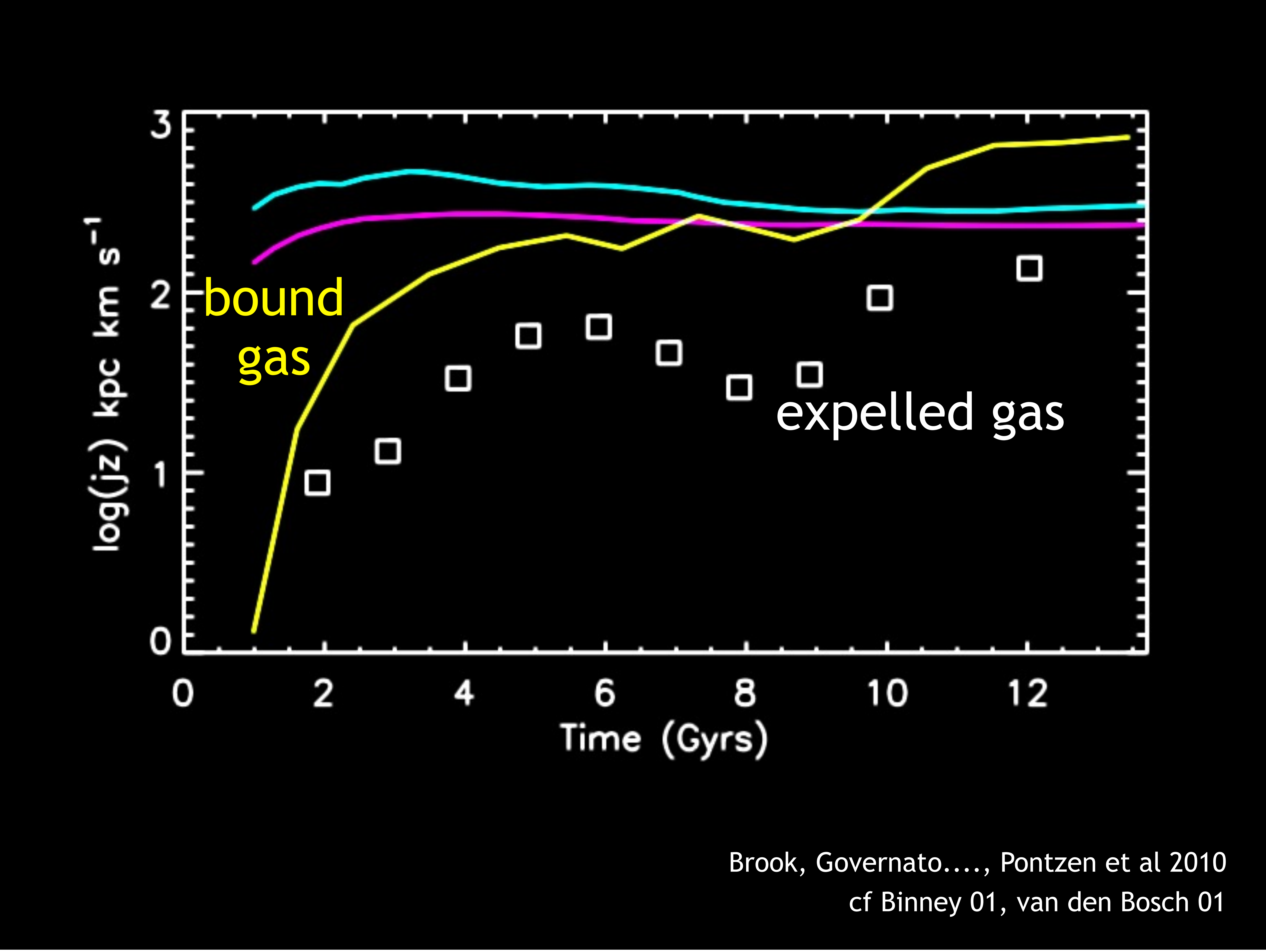


Movie by AP – available at www.cosmocrunch.co.uk

Zoom simulation.

3000 Msol/80 parsec resolution. Starting to resolve the cold ISM.

A rerun of the same region as Governato 2010 nature paper.



Chris Brook's work on understanding why galaxies are bulgeless. SN feedback preferentially expels low angular momentum gas.

Flores & Primack 1994

Navarro, Eke, Frenk 1996

El Zant 2001

Gnedin & Zhao 2002

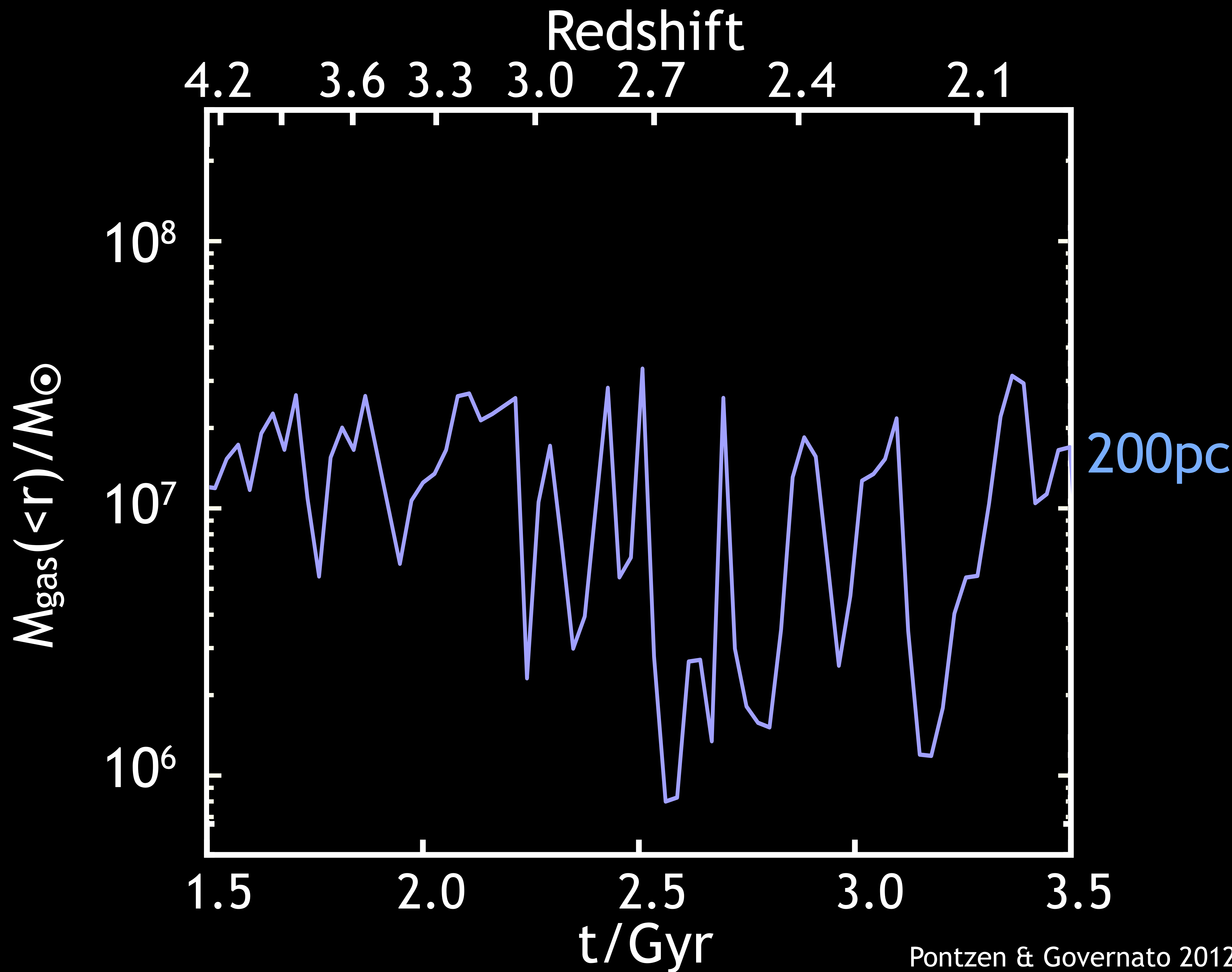
El Zant 2004

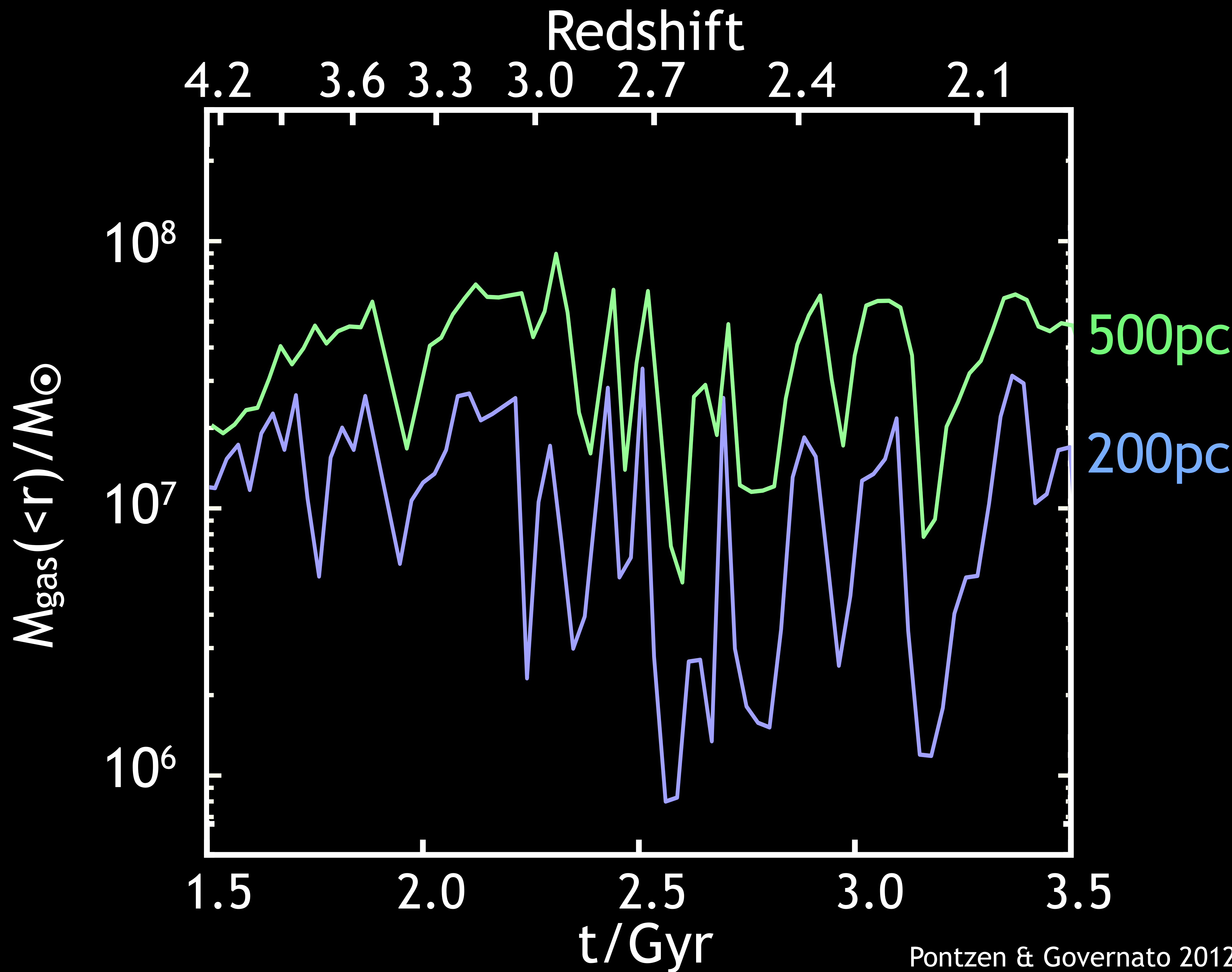
Read & Gilmore 2005

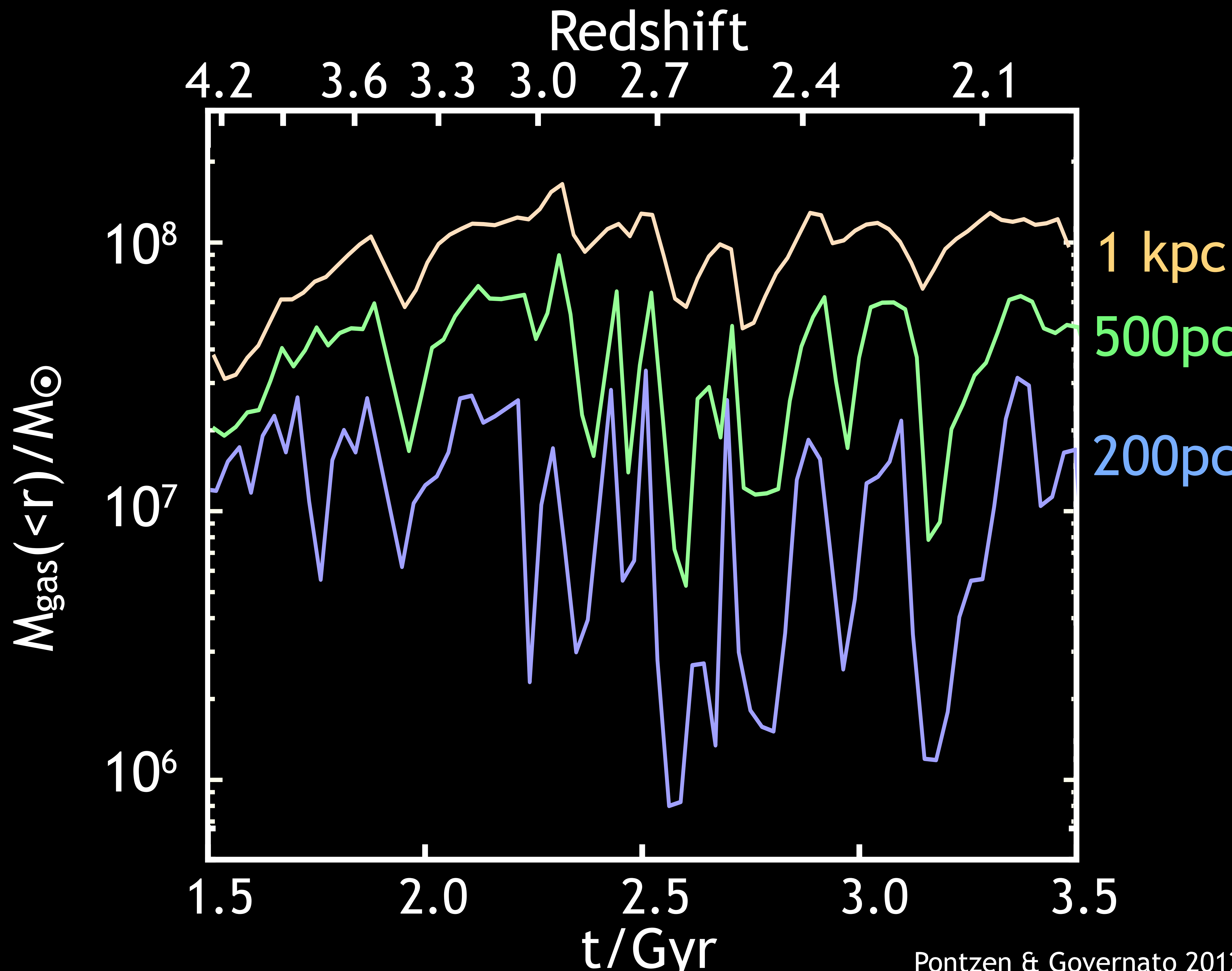
Mashchenko et al 2006/2008

Pasetto et al 2010,
Goerdt et al 2010,
Cole et al 2011

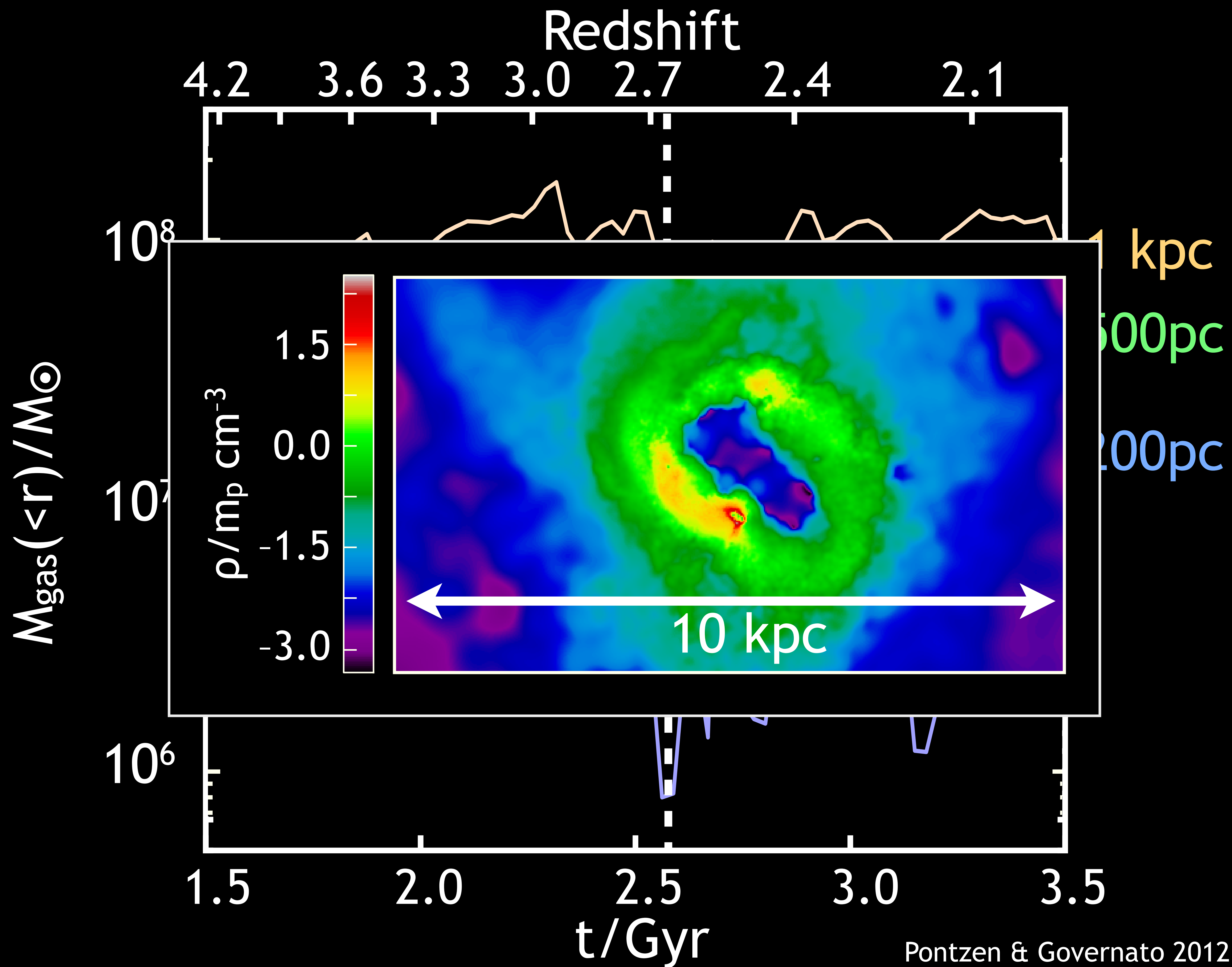
A very brief survey of some of the literature on flattening cusps


Redshift
4.2
3.6
3.3
3.0
2.7
2.4
2.1
10^8
10^7
10^6
$M_{gas}(<r)/M_\odot$
200pc
1.5
2.0
2.5
3.0
3.5
t/Gyr
Pontzen & Governato 2012


Redshift
4.2
3.6
3.3
3.0
2.7
2.4
2.1
10^8
10^7
10^6
M_gas(<r)/M☉
500pc
200pc
1.5
2.0
2.5
3.0
3.5
t/Gyr
Pontzen & Governato 2012

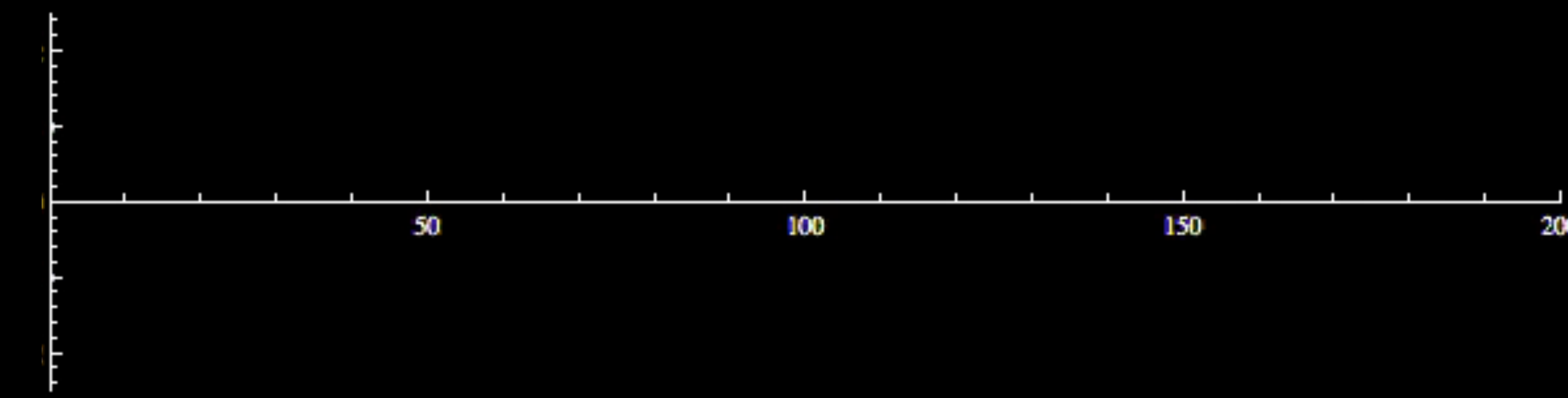


Pontzen & Governato 2012


Redshift
4.2
3.6
3.3
3.0
2.7
2.4
2.1
10^8
10^7
10^6
$M_{gas}(<r)/M_\odot$
1 kpc
500pc
200pc
1.5
0.0
-1.5
-3.0
$\rho/m_p\ cm^{-3}$
10 kpc
1.5
2.0
2.5
3.0
3.5
t/Gyr
Pontzen & Governato 2012

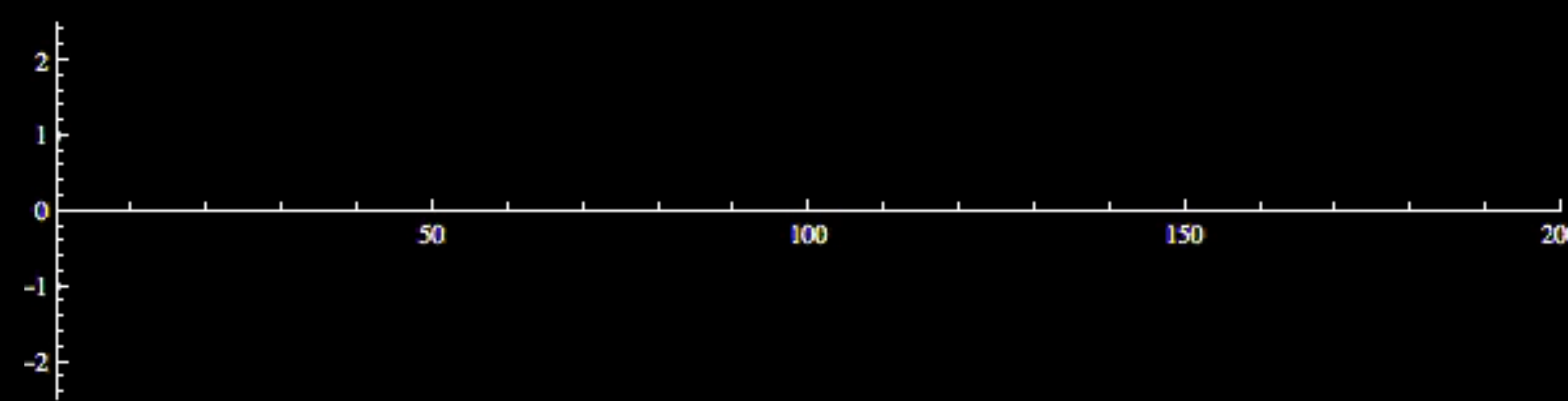
Adiabatic

$$E_f = E_i$$



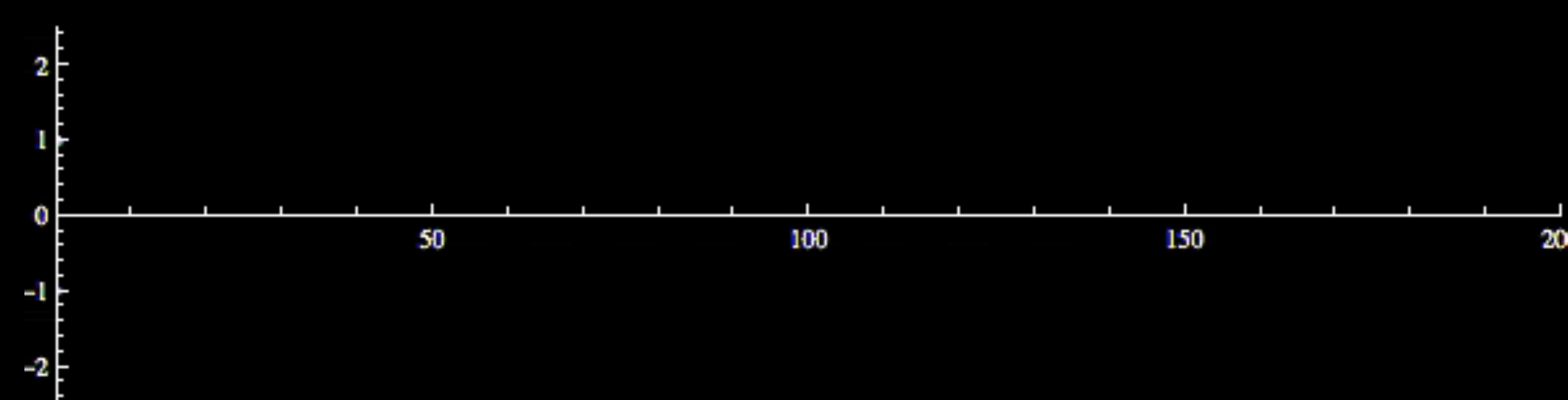
Sudden, then adiabatic

$$\frac{\langle E_f \rangle}{E_i} = \frac{1}{2}\left(\frac{\omega_1}{\omega_0} + \frac{\omega_0}{\omega_1}\right)$$



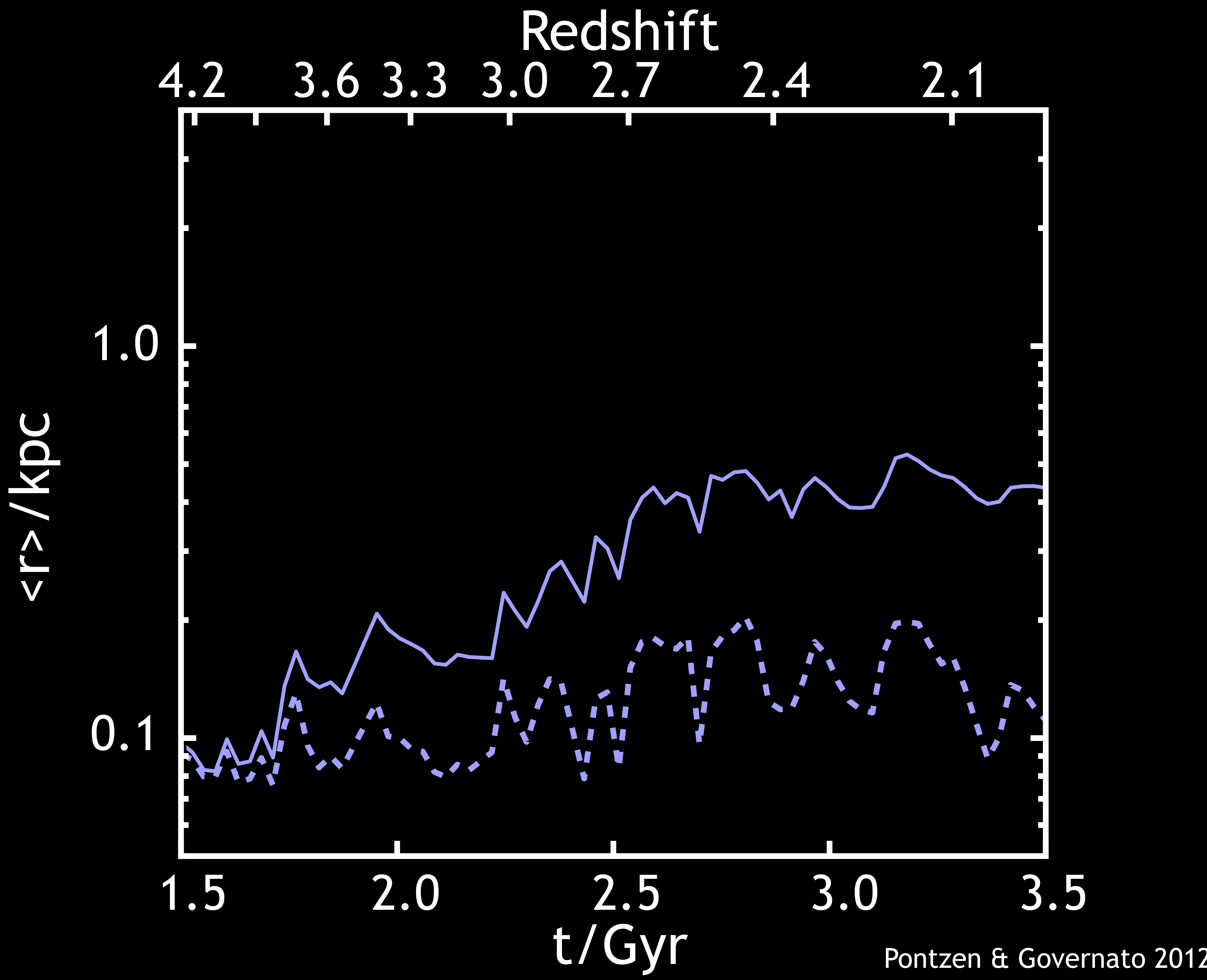
Sudden, then sudden

$$\frac{\langle E_f \rangle}{E_i} = \left(1 + \frac{1}{4}\left[\frac{\omega_1^2 - \omega_0^2}{\omega_0^2}\right]^2\right)$$



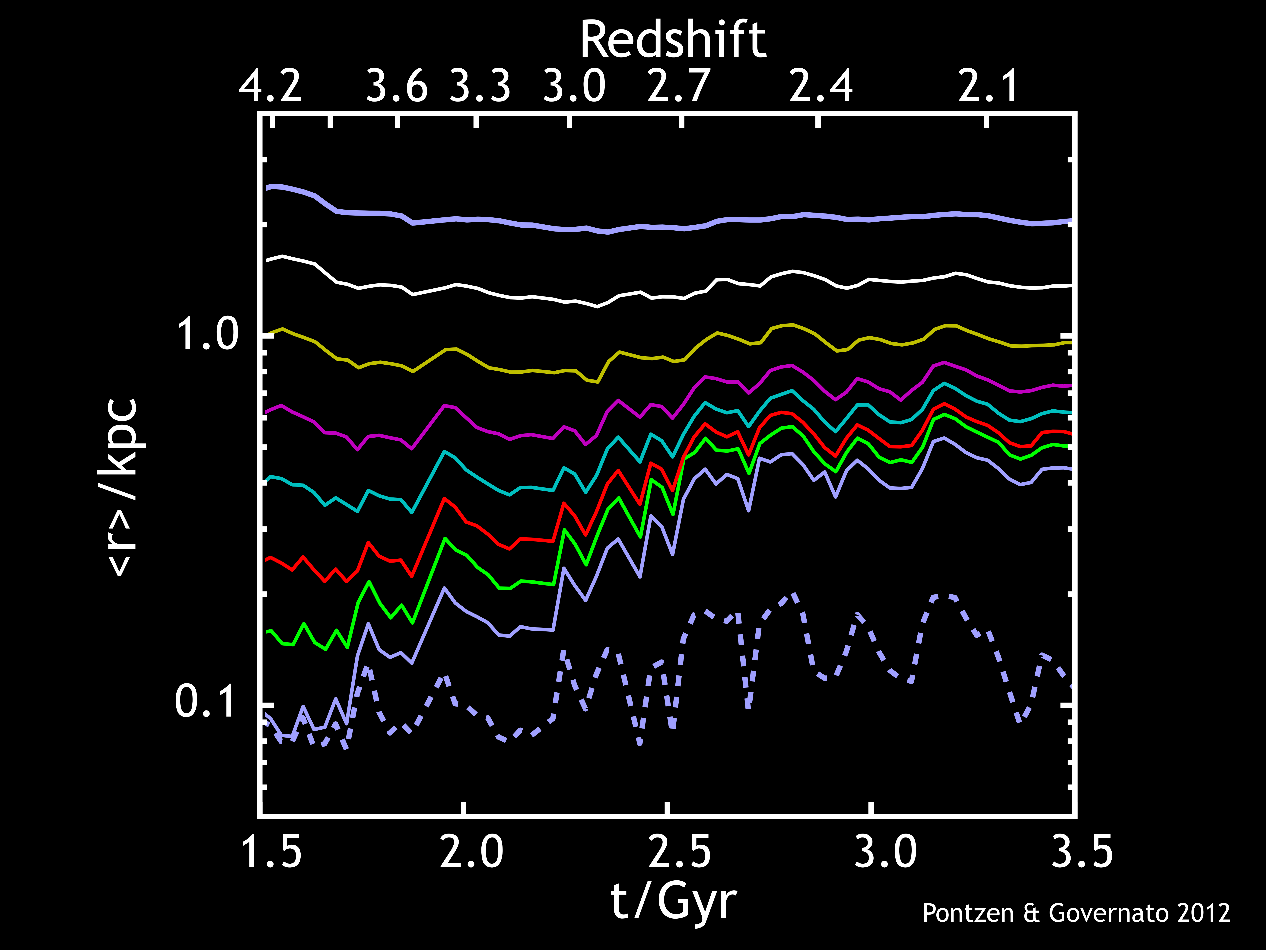
Pontzen & Governato 2012

Some videos showing what happens when harmonic oscillator potential depth changes suddenly or gradually.



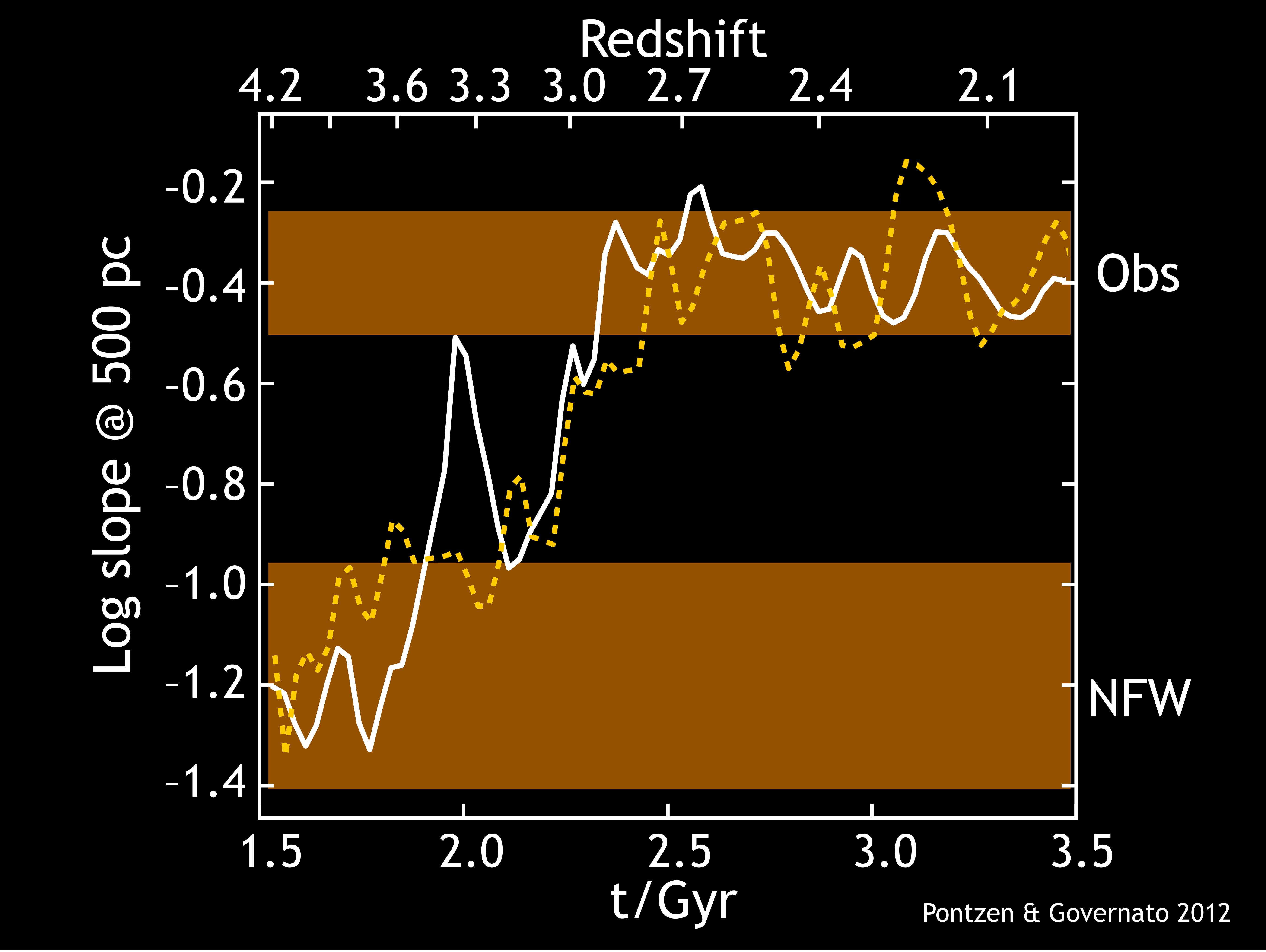
Solid lines are circular orbits migrating according to new analytic prescription

Dashed line uses adiabatic approximation - gets the wrong answer.



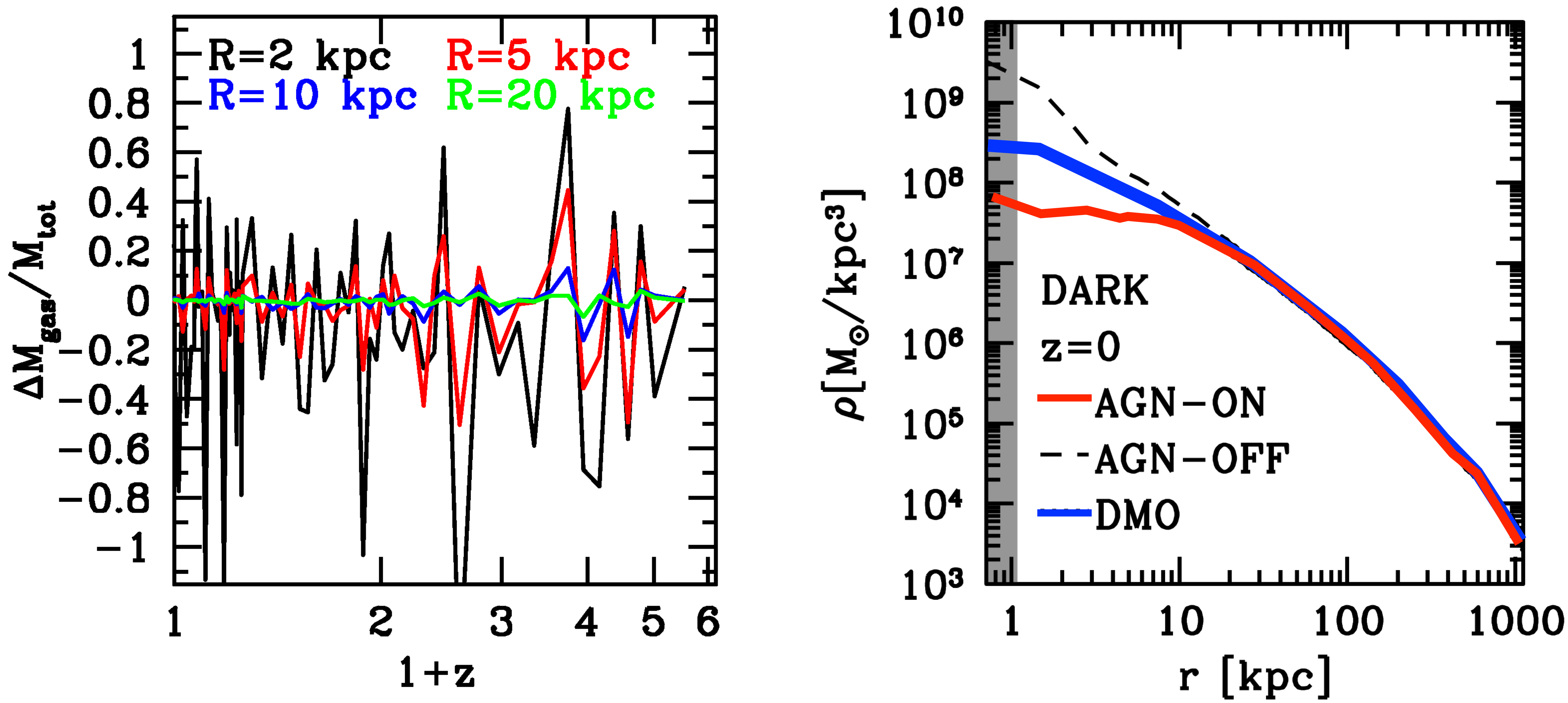
Solid lines are circular orbits migrating according to new analytic prescription

Dashed line uses adiabatic approximation – gets the wrong answer.



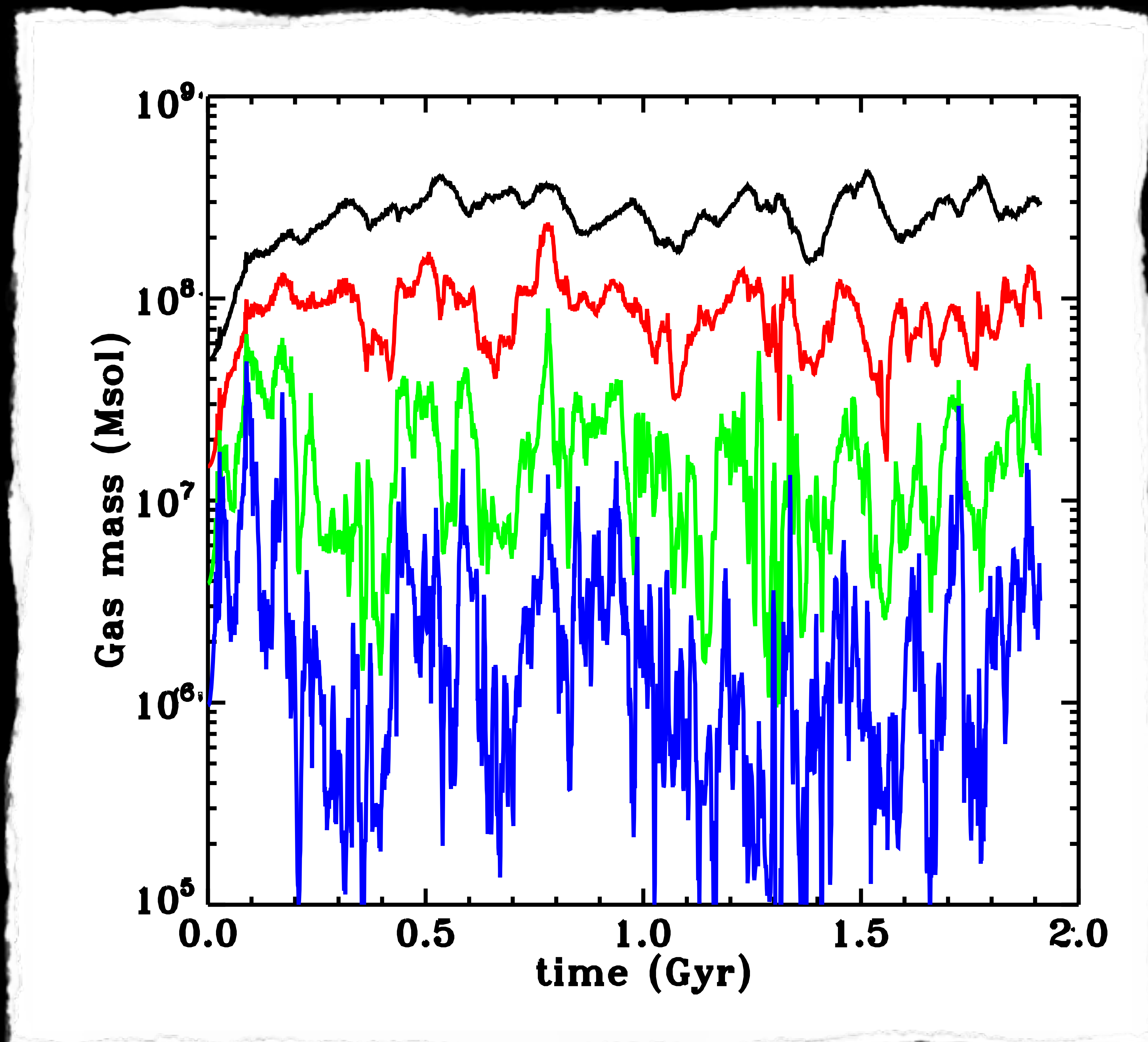
Solid line is analytic prescription. Flattening agrees well with actual simulation (dashed line)

So the questions now should be: is the underlying hydrodynamics realistic? How do the cores scale with mass of the galaxy?



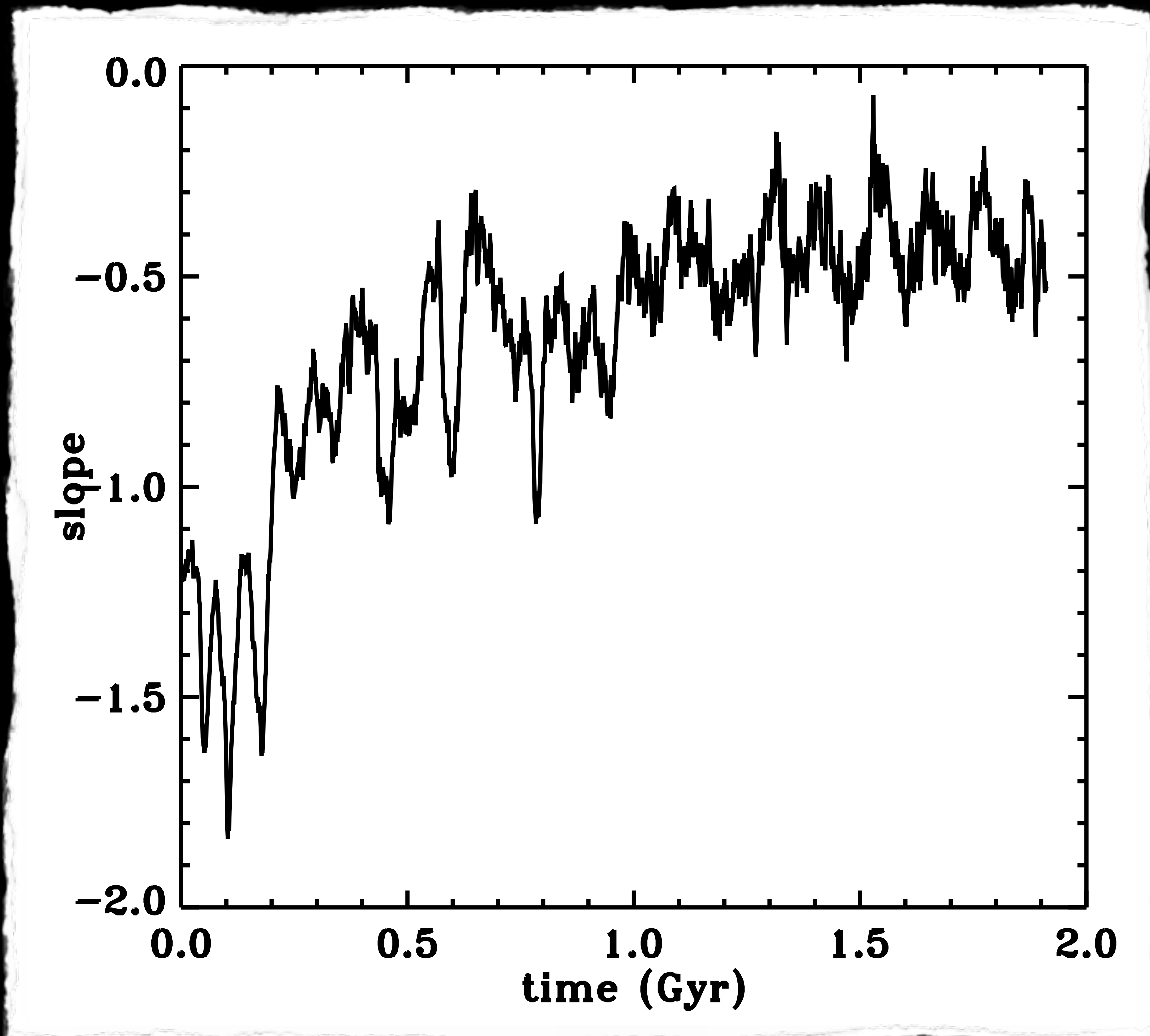
Martizzi et al arXiv 1112.2752

Same process going on to create ~10kpc cores in BCGs. 10^14 Msol virial mass zoom AMR simulation by Martizzi et al.



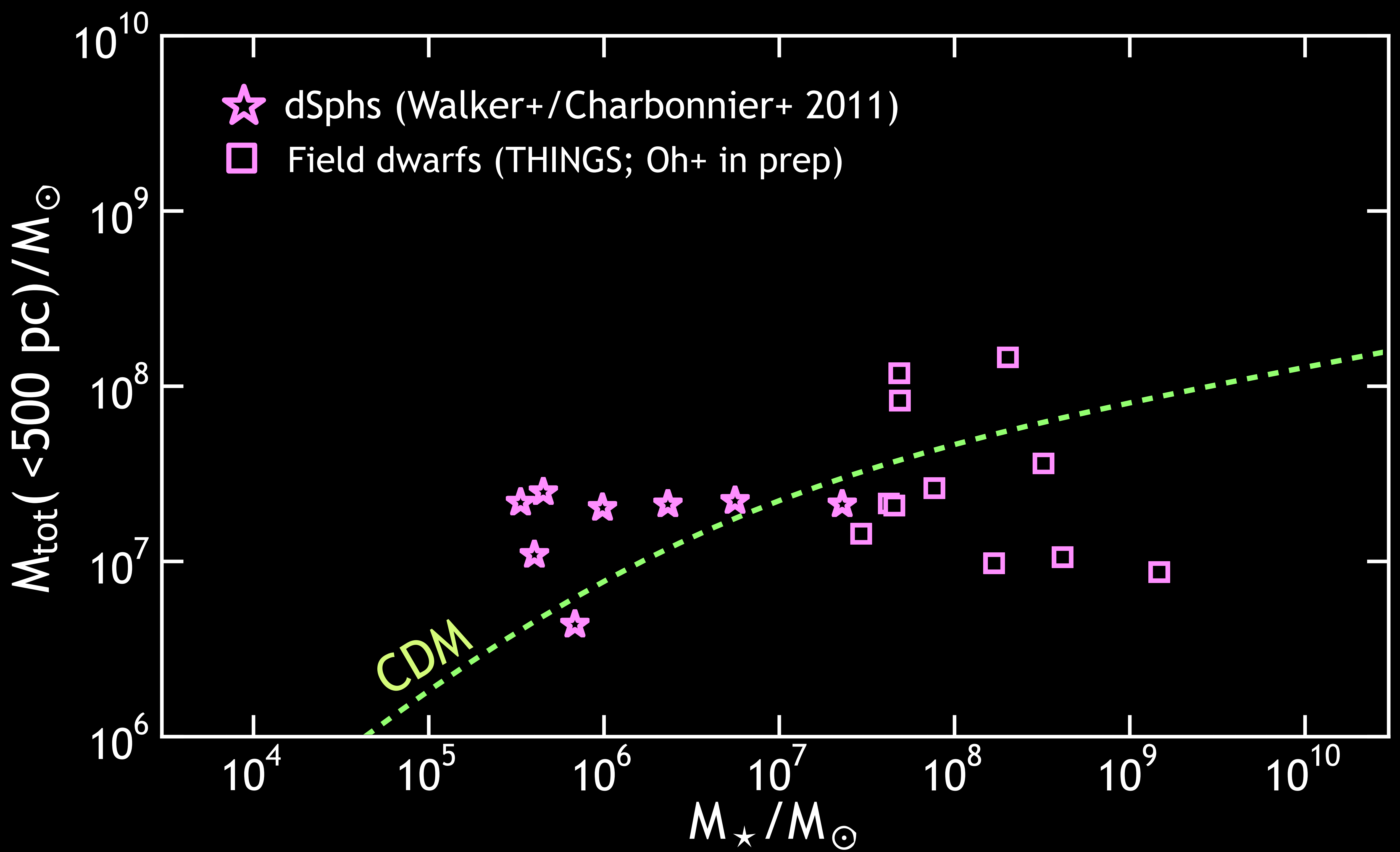
Teyssier & Pontzen in prep 2012

New SN feedback in Ramses gets mass fluctuations in Mvir ~ 10^10 Msol dwarf galaxy isolated run.



Teyssier & Pontzen in prep 2012

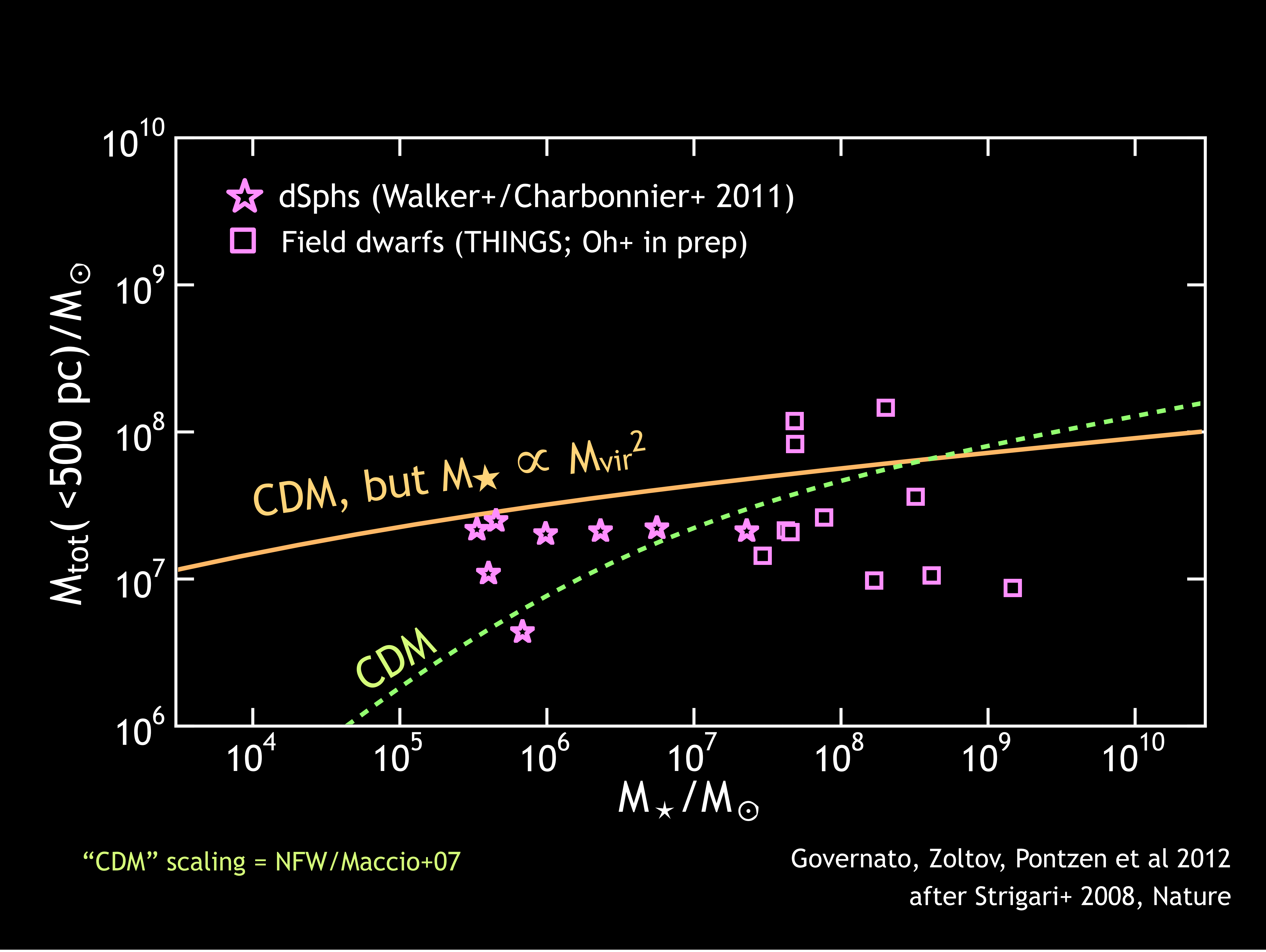
And the cusp flattens out.



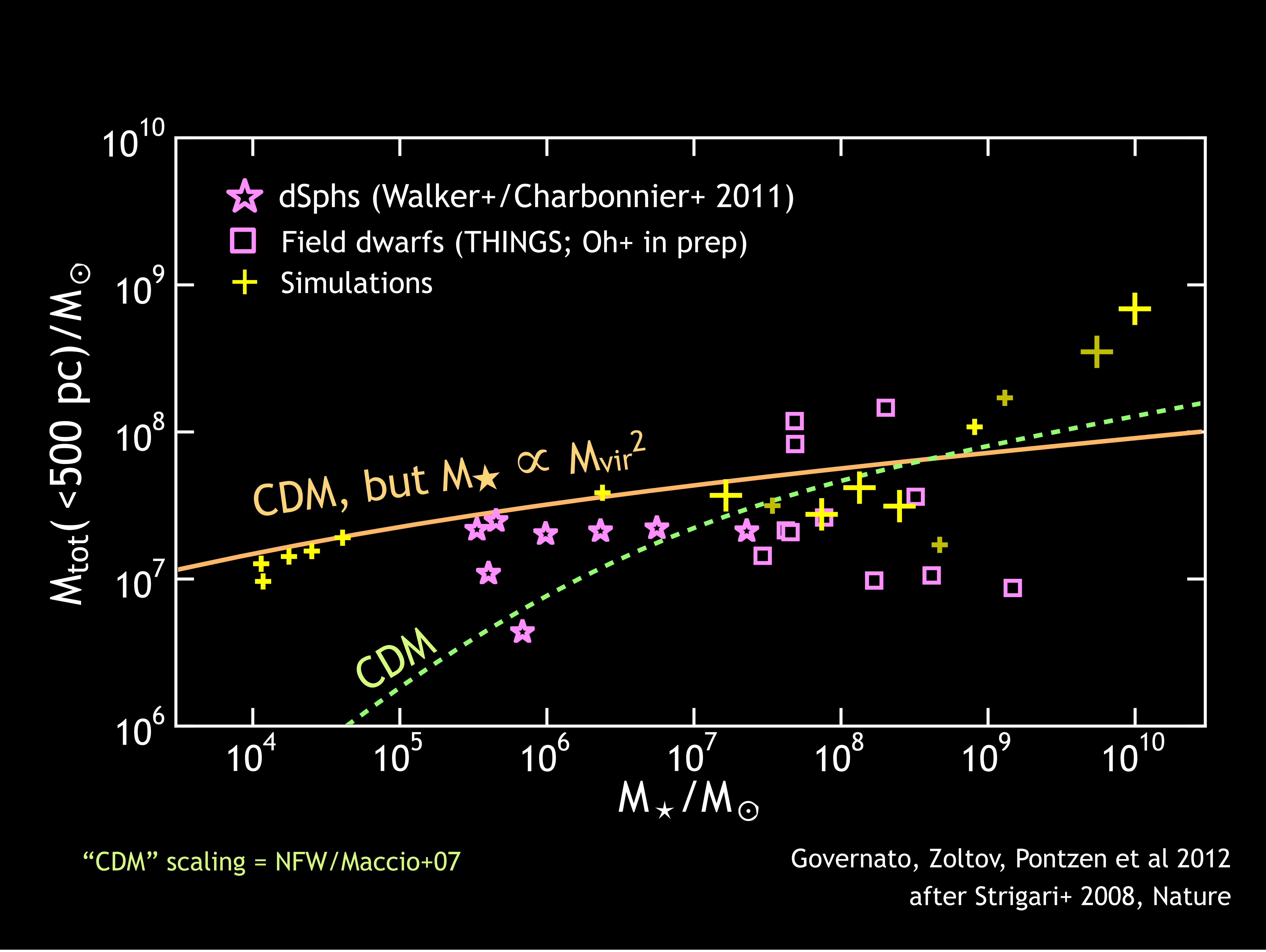
"CDM" scaling = NFW/Maccio+07

Governato, Zoltov, Pontzen et al 2012
after Strigari+ 2008, Nature

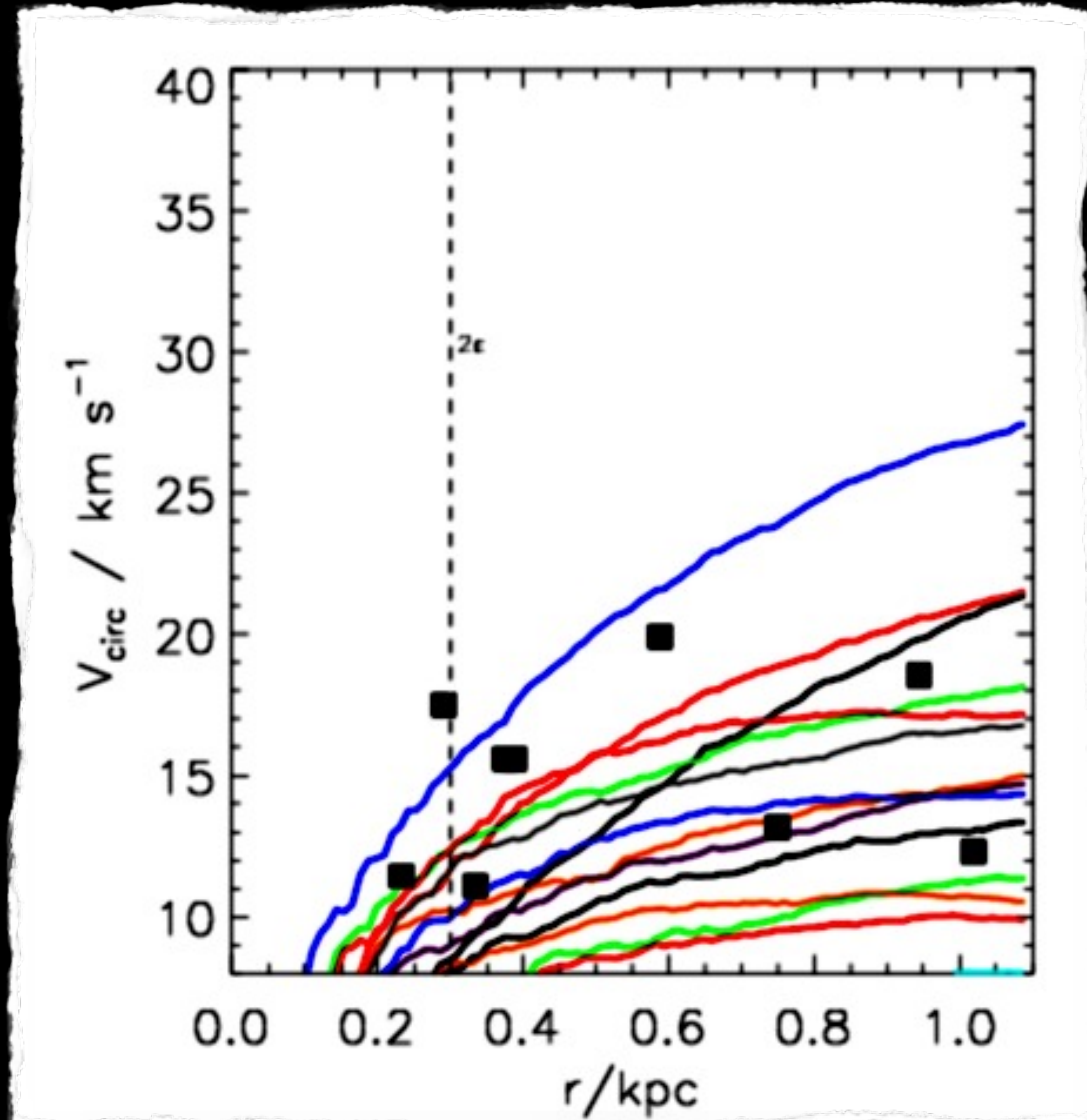
Strigari relation explained by steep scaling of stellar mass with virial mass at feint end.
(Anticiapted by Strigari+08 but not always remembered in literature.)



Strigari relation explained by steep scaling of stellar mass with virial mass at feint end. (Anticiapted by Strigari+08 but not always remembered in literature.)

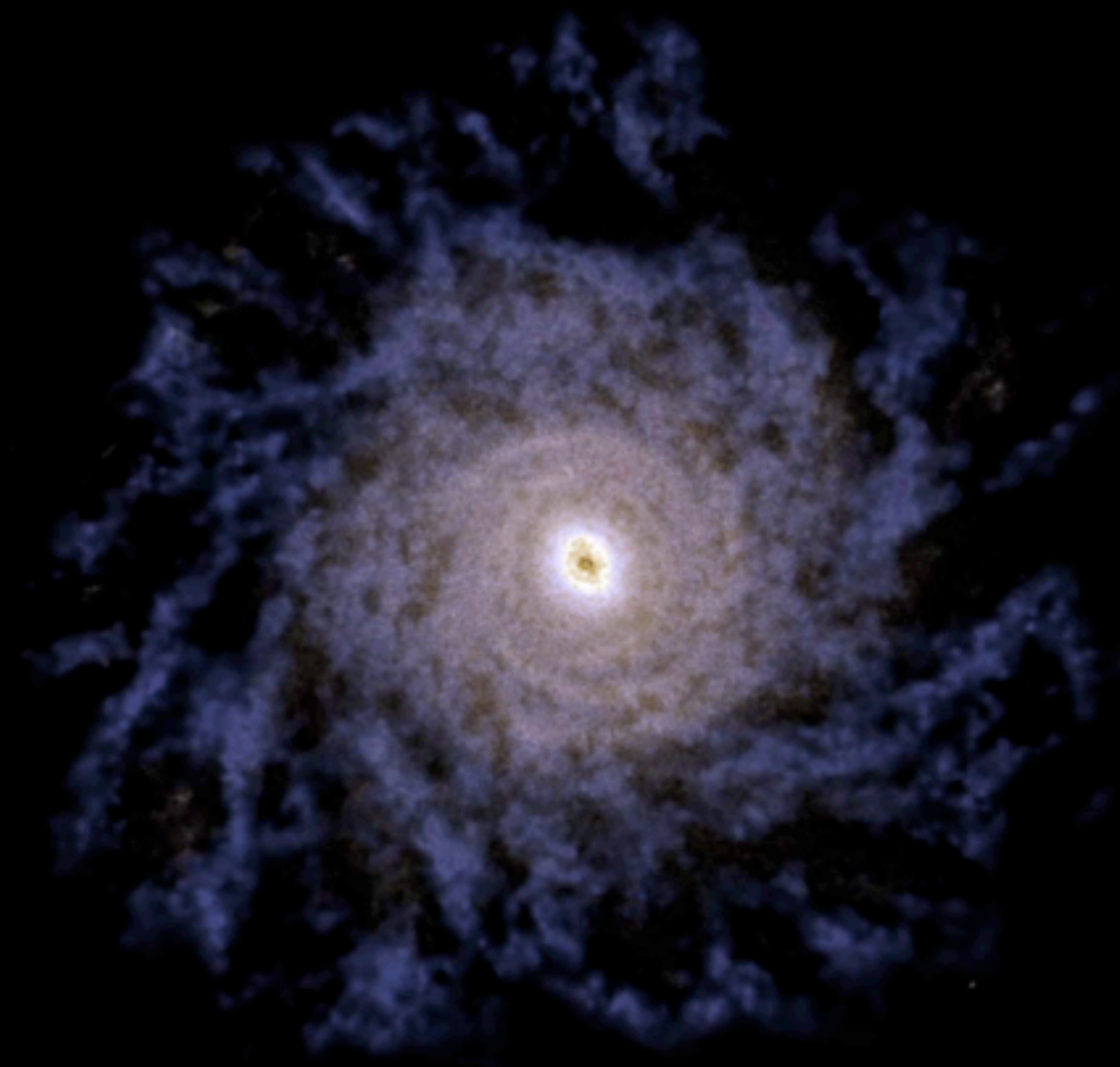


Strigari relation explained by steep scaling of stellar mass with virial mass at feint end. (Anticiapted by Strigari+08 but not always remembered in literature.)



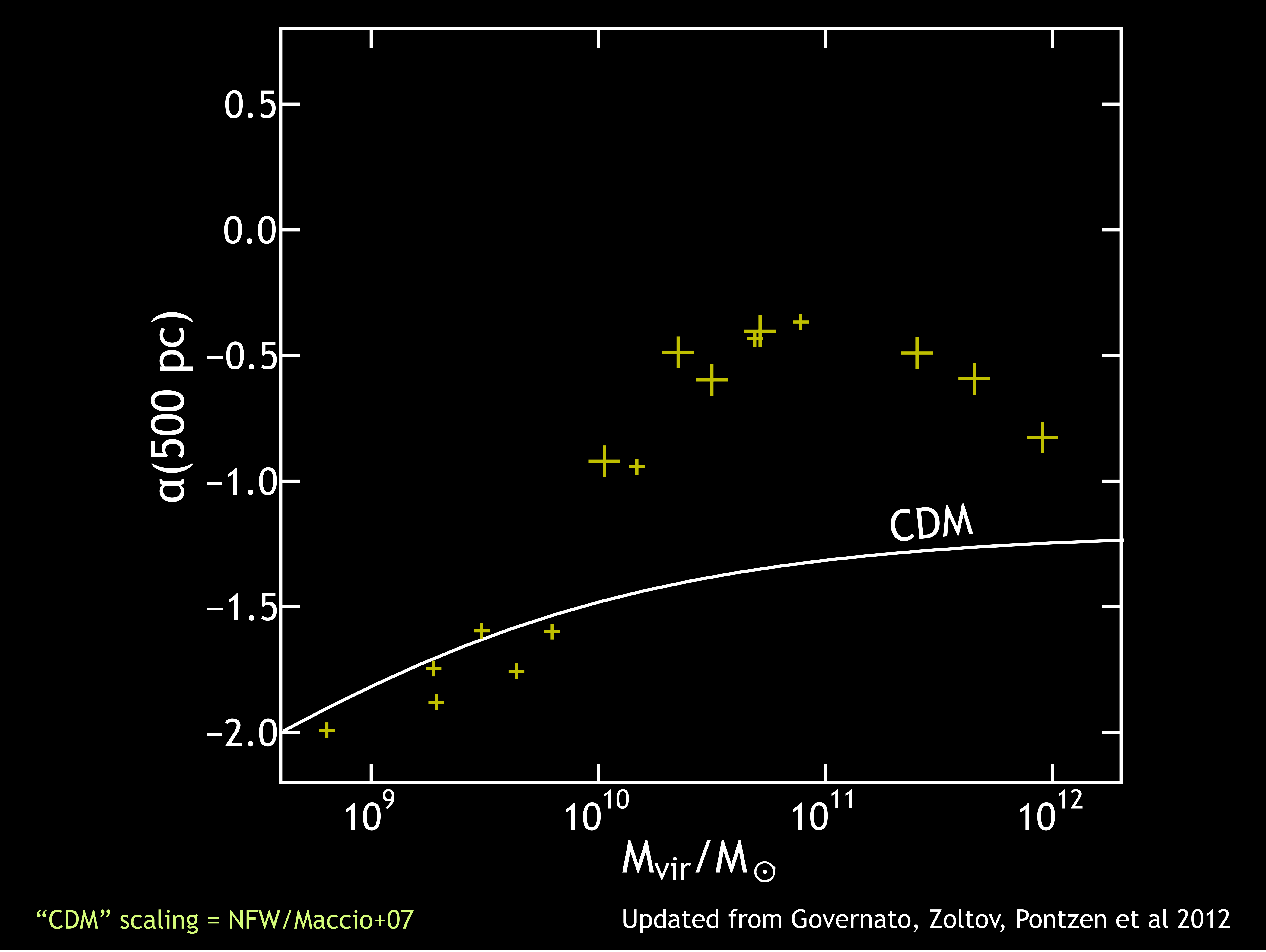
Zoltov & Brooks in prep 2012

Now running Milky Way-mass objects. Dwarf satellite rotation curves looking healthy - work by Adi Zoltov and Alyson Brooks.

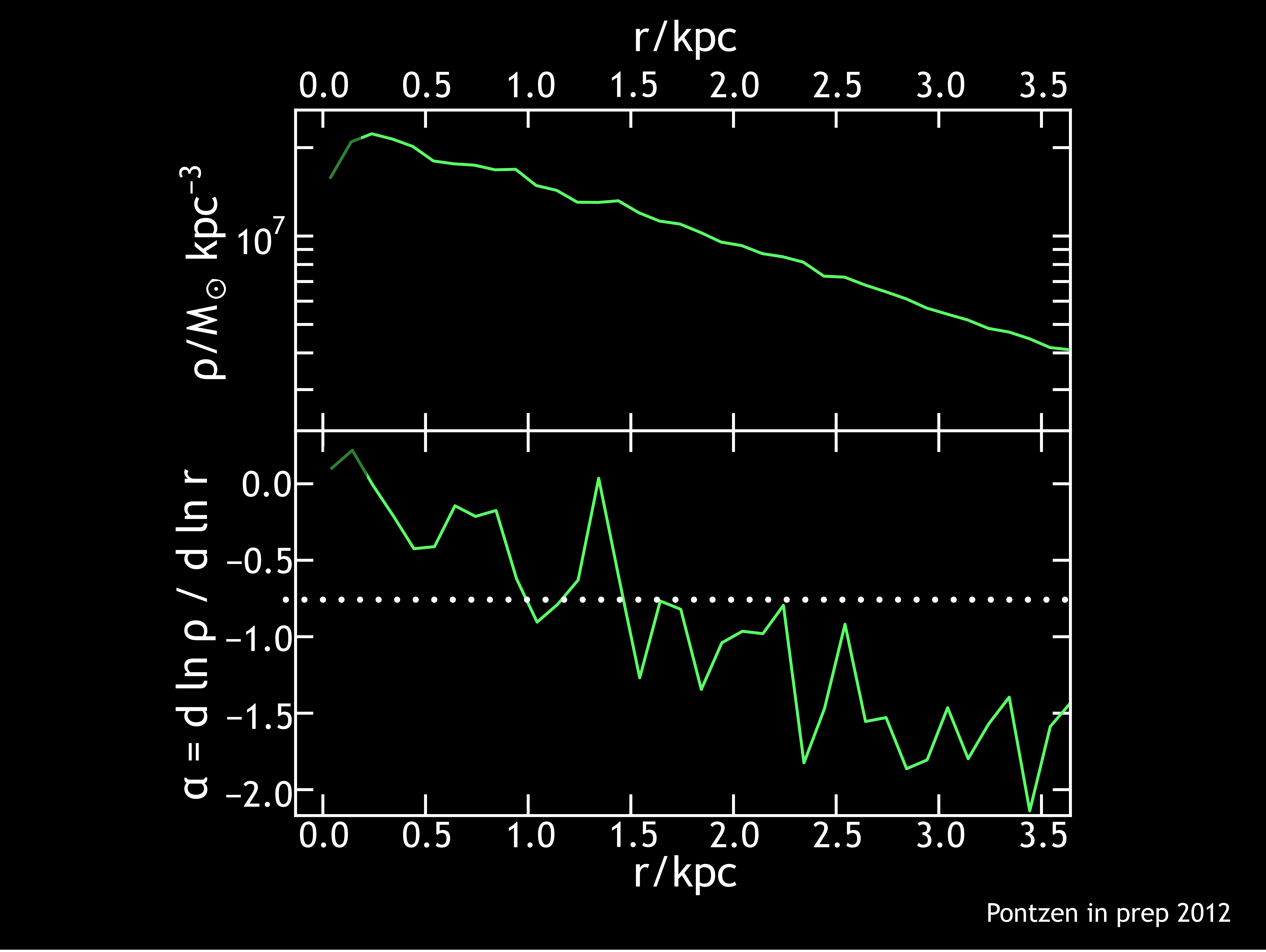


Movie by AP for *BBC Stargazing Live*
– available at www.cosmocrunch.co.uk

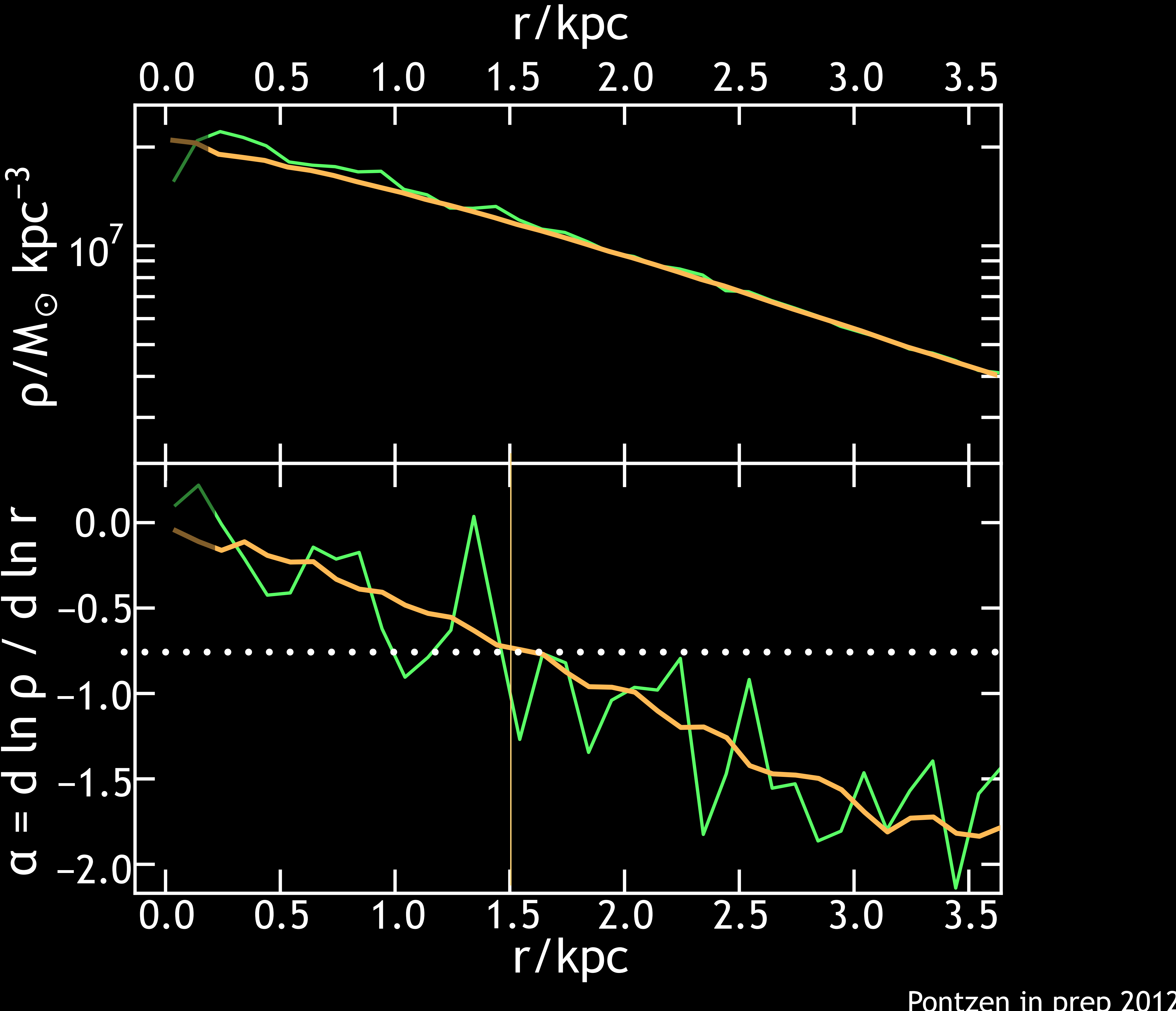
A pretty movie.



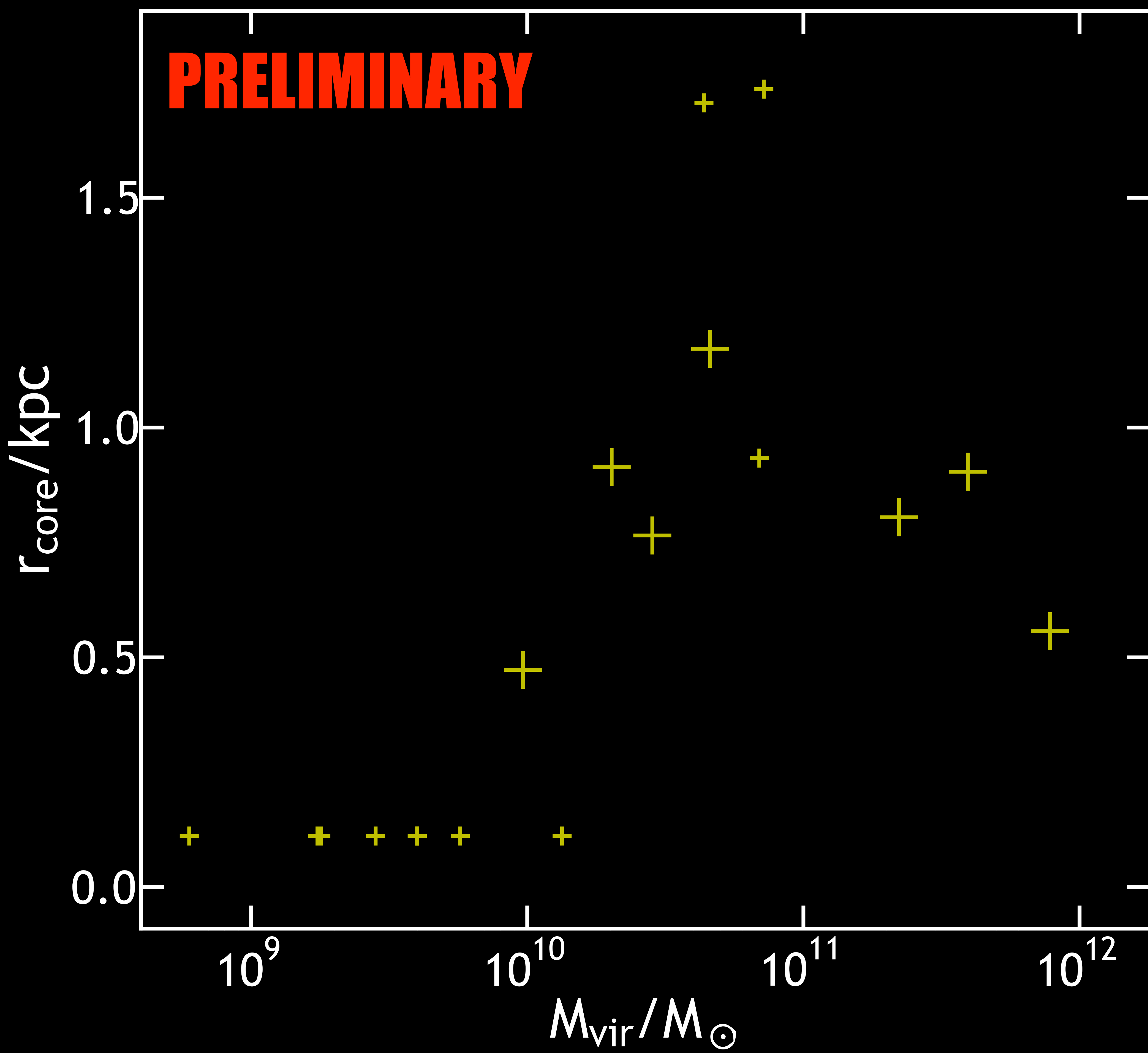
At high mass (not in Governato et al paper), profiles look cuspier again. Can we understand this?



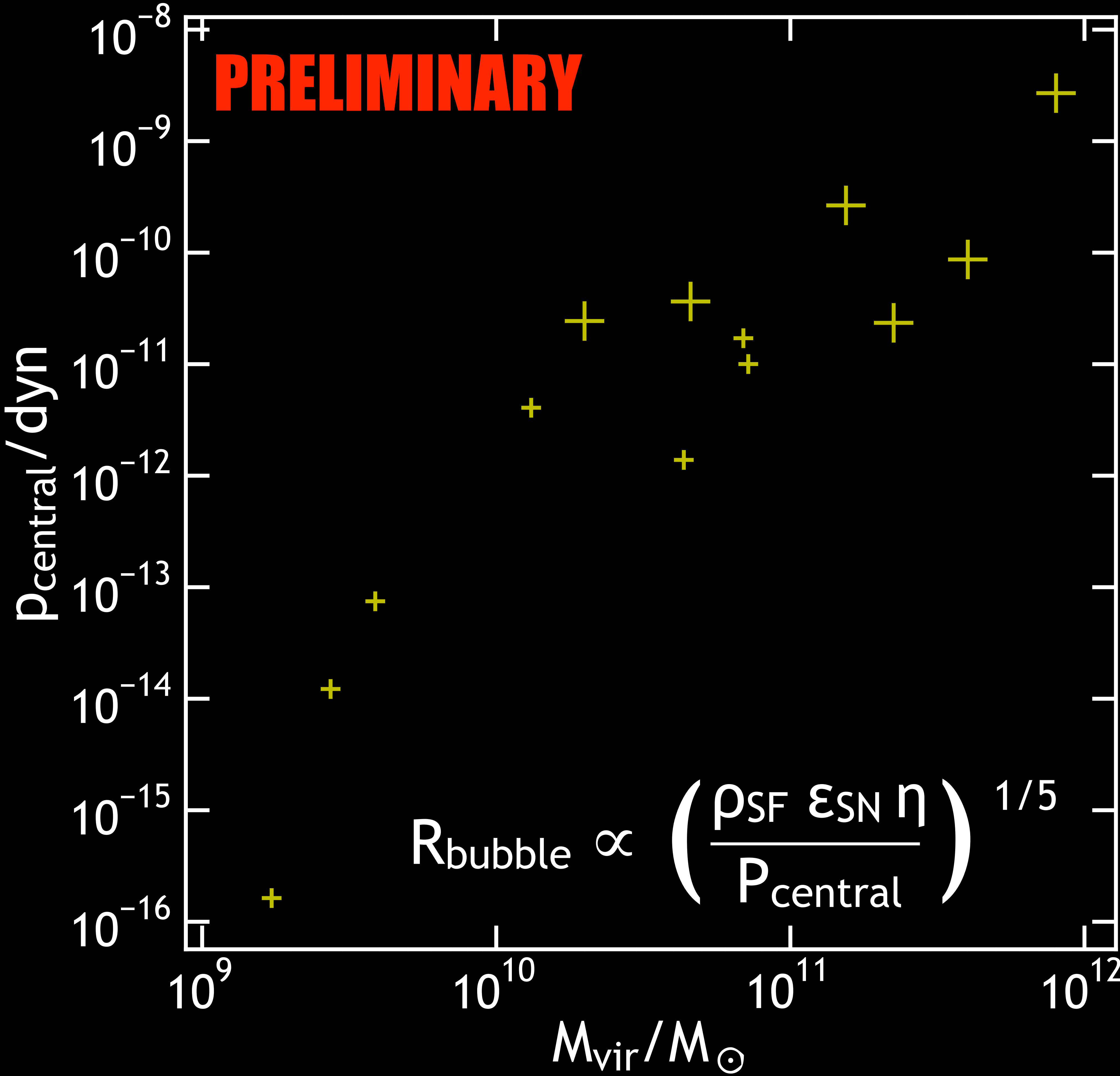
Coming soon – a new way to make optimal use of information in halo snapshot.
Equivalent to time-averaging over several outputs, but much faster (~3 minutes per 10 million particles on 4 cores)



Coming soon – a new way to make optimal use of information in halo snapshot.
Equivalent to time-averaging over several outputs, but much faster (~3 minutes per 10 million particles on 4 cores)

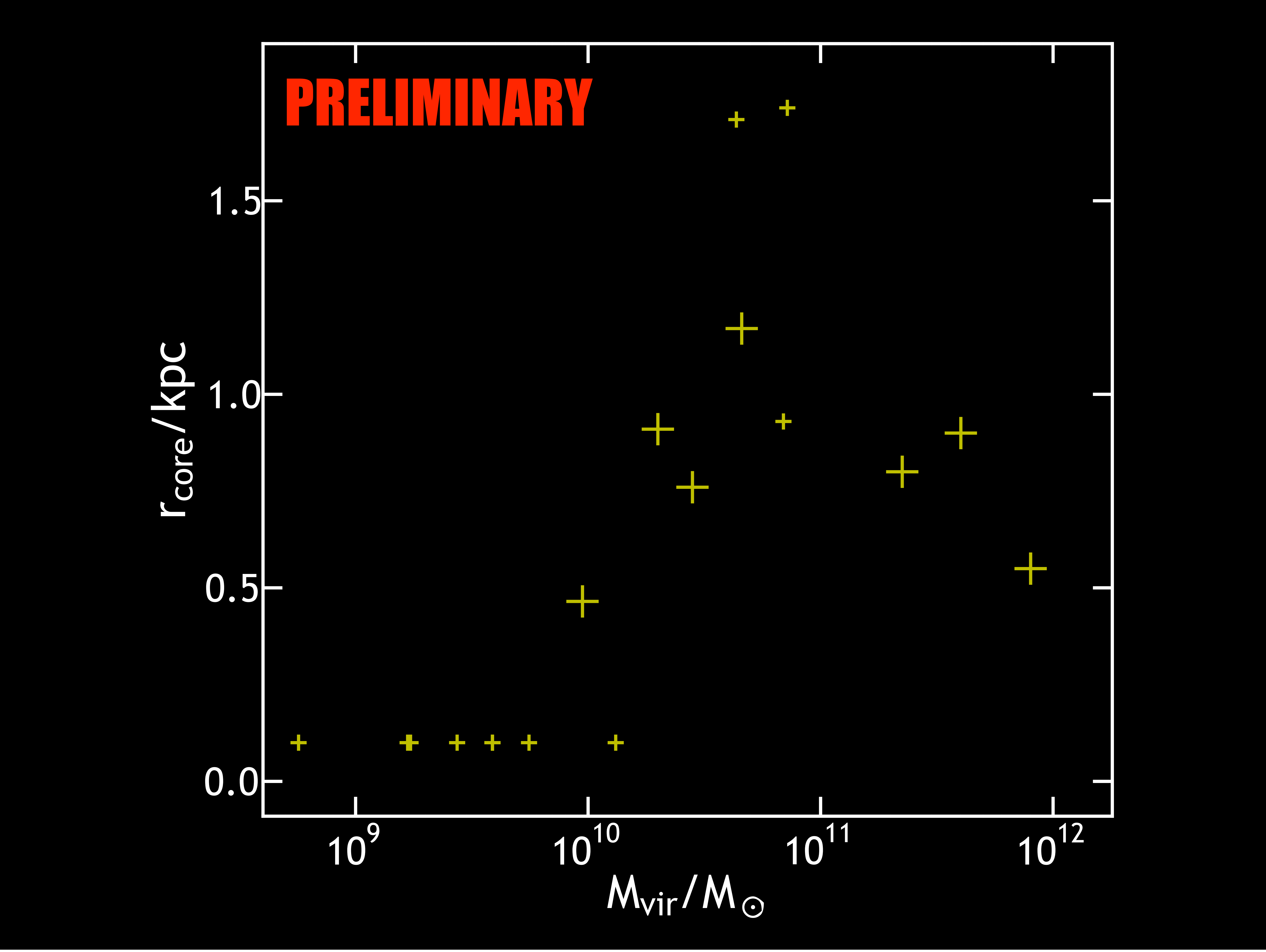


Low mass objects have no core, because no (or little) SF
High mass objects have small cores. Why?



Pressure in disk opposes bubble expansion during SF burst.

(But of course things like fraction of cloud converted into stars, η, could also scale with pressure, so more work needed here.)

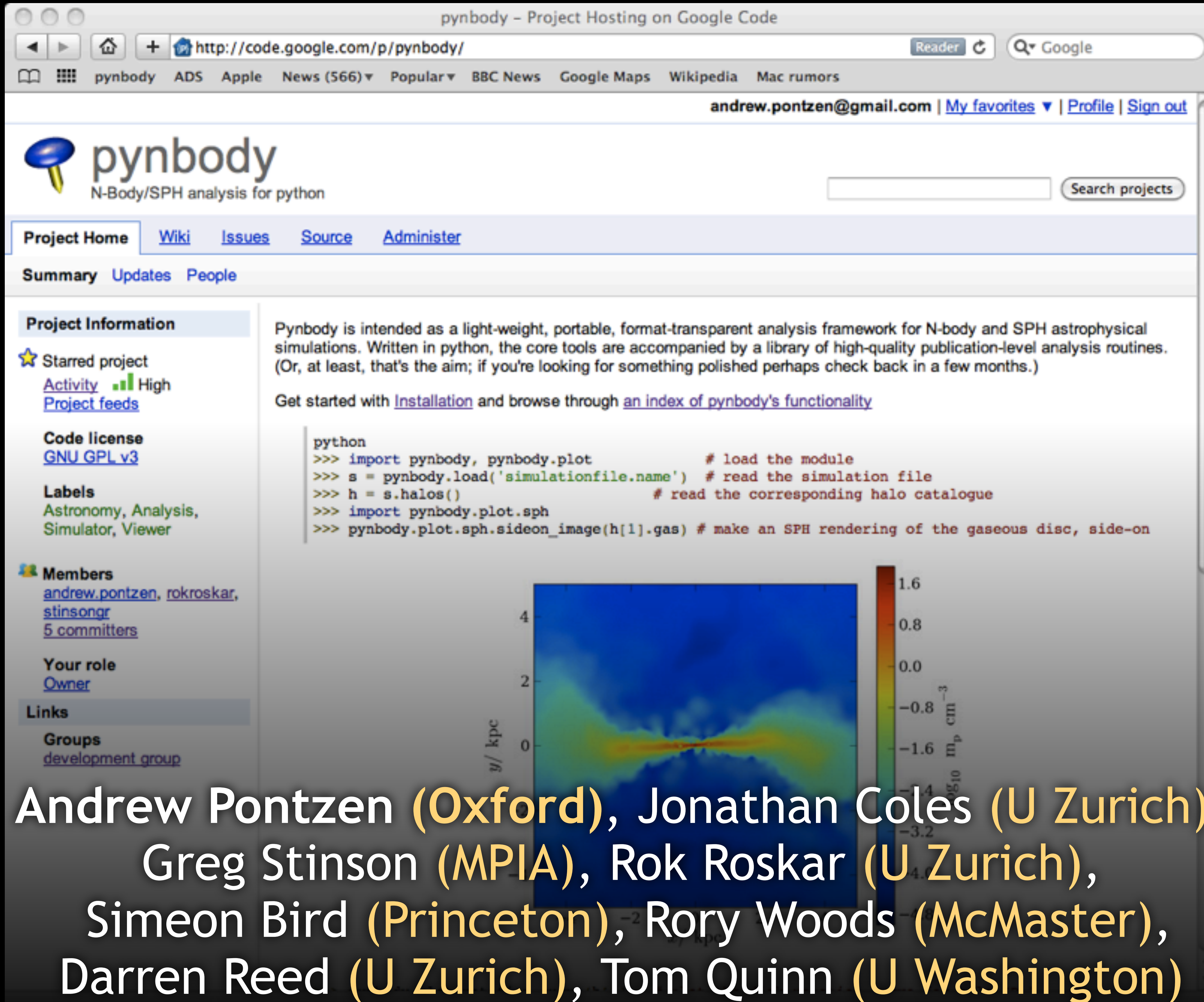


PRELIMINARY investigation of scalings suggests this accounts for the reduction in core size.

But when does AGN feedback come in? These runs do not include BHs.

- New irreversible model quantitatively accounts for DM core-creation from rapid cycles of SN-driven baryonic expansion/ collapse (no resonance required);
- Reproducing result in AMR → increase confidence in hydrodynamics (w/Teyssier);
- Scalings are reasonable so far;
- Satellites more complicated but signs are good (Zoltov/Brooks).

Andrew Pontzen, Oxford



Andrew Pontzen (Oxford), Jonathan Coles (U Zurich),
Greg Stinson (MPIA), Rok Roskar (U Zurich),
Simeon Bird (Princeton), Rory Woods (McMaster),
Darren Reed (U Zurich), Tom Quinn (U Washington)

pynbody.googlecode.com