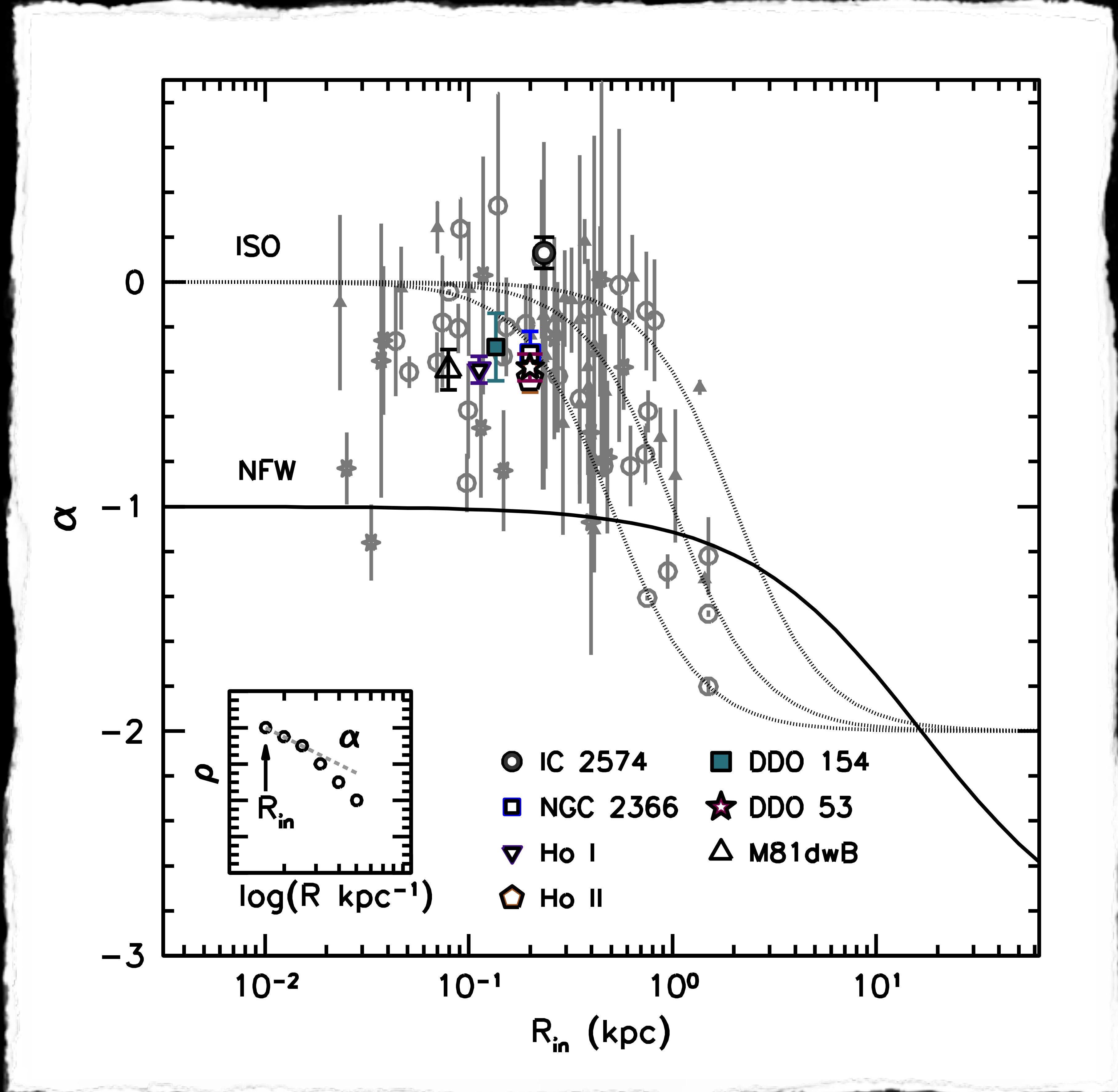
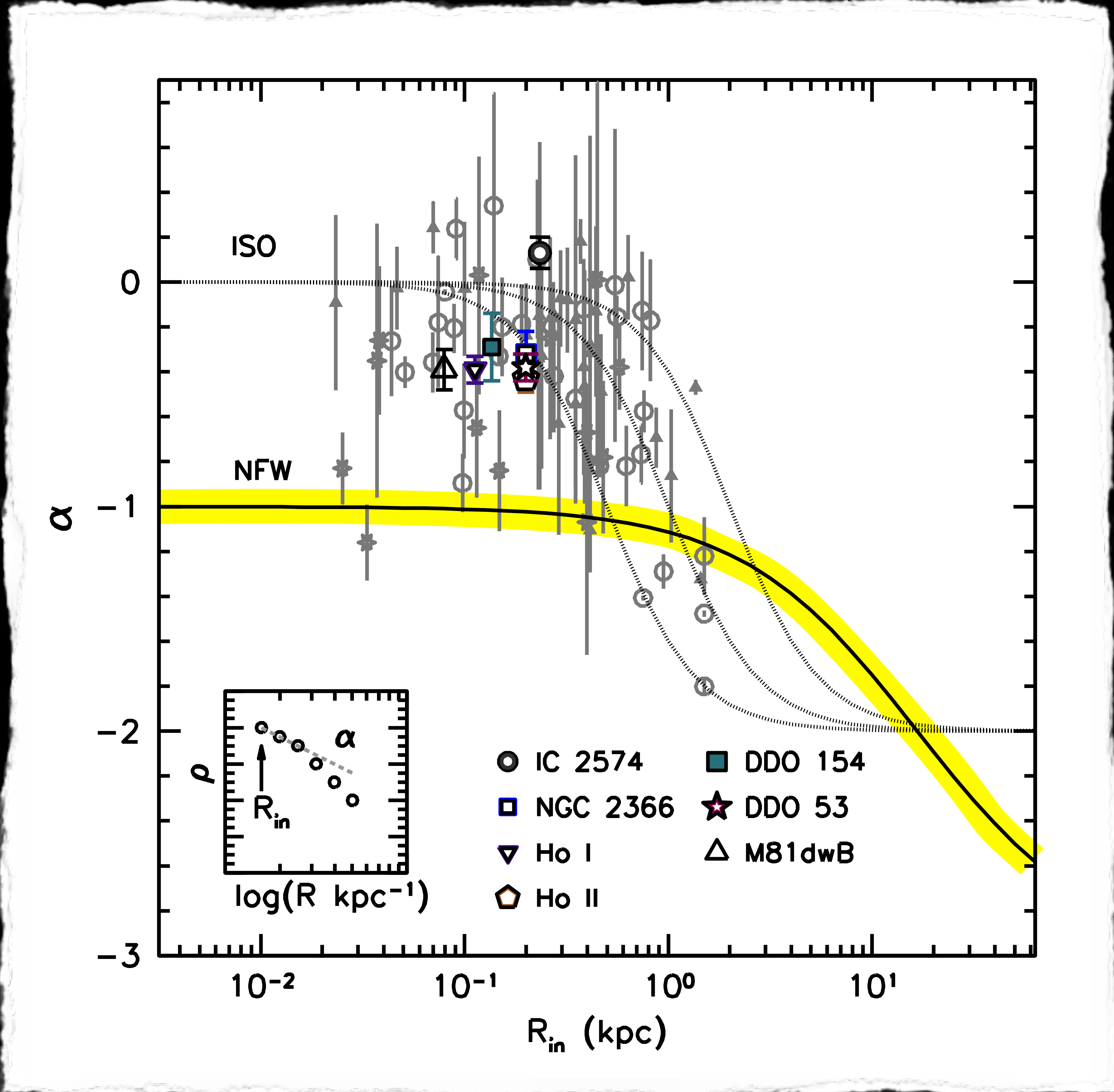
People have thought about supernova feedback being able to flatten cusps before. However, it did seem that it was hard to get it to be a strong enough effect.

This will not be a review talk – there isn't time.

Although supernova feedback has a reputation as being a 'quick fix', the mechanism I will present is not contrived – actually, it's highly generic (I hope to convince you so, anyway)



Oh et al
2011, AJ



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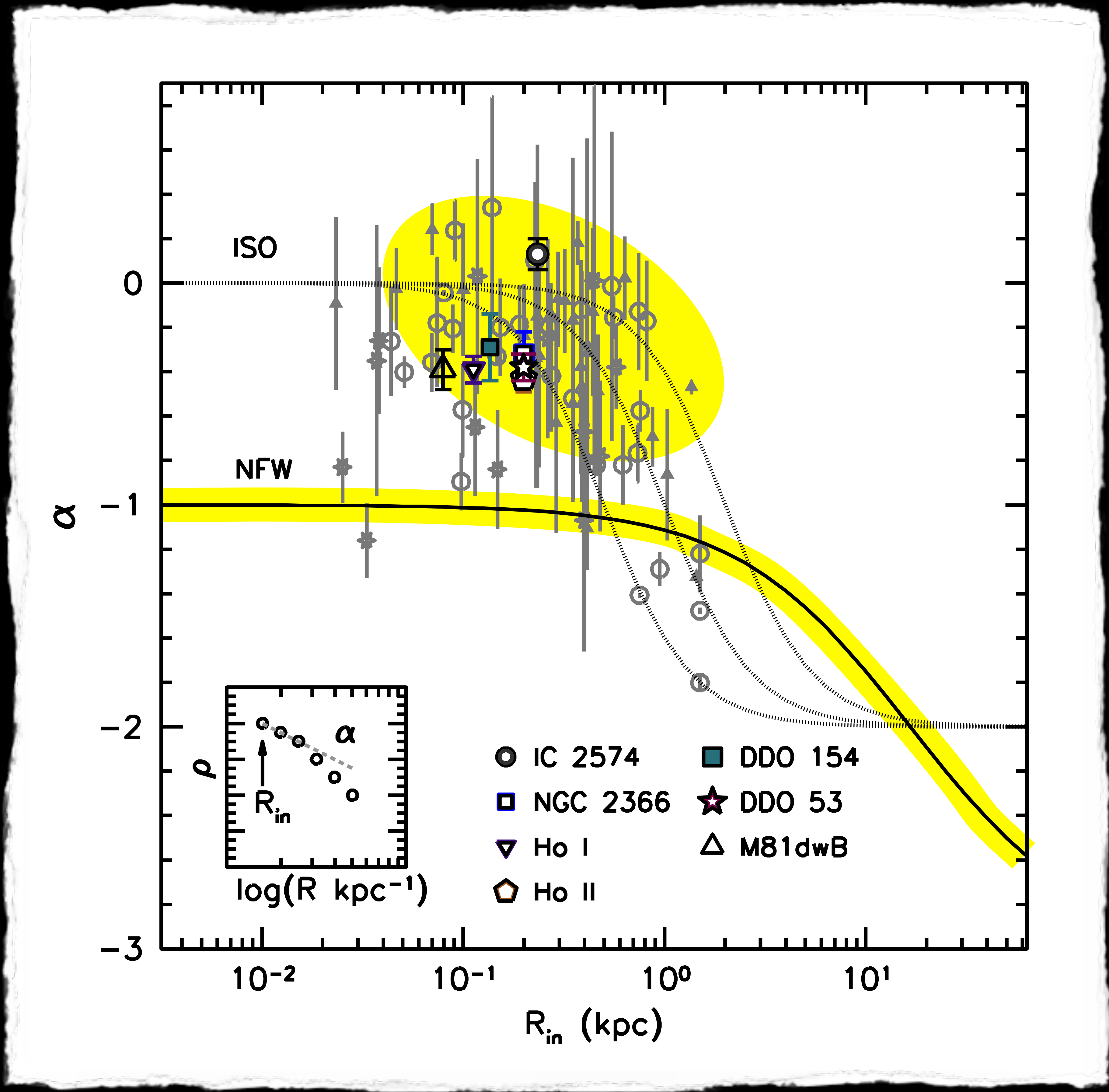
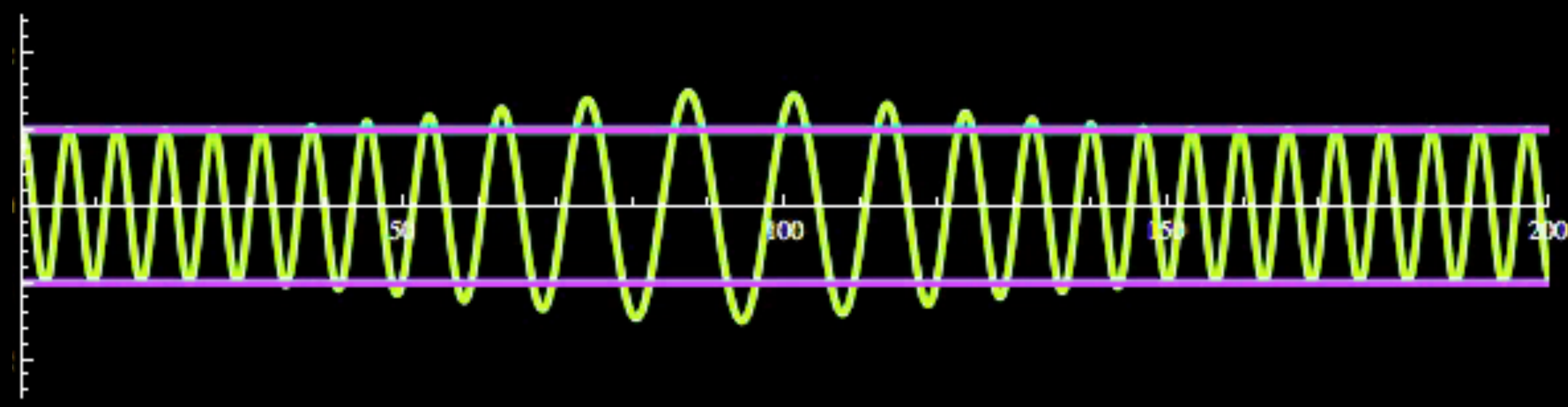


Oh et al
2011, AJ

Adiabatic

$$E_f = E_i$$



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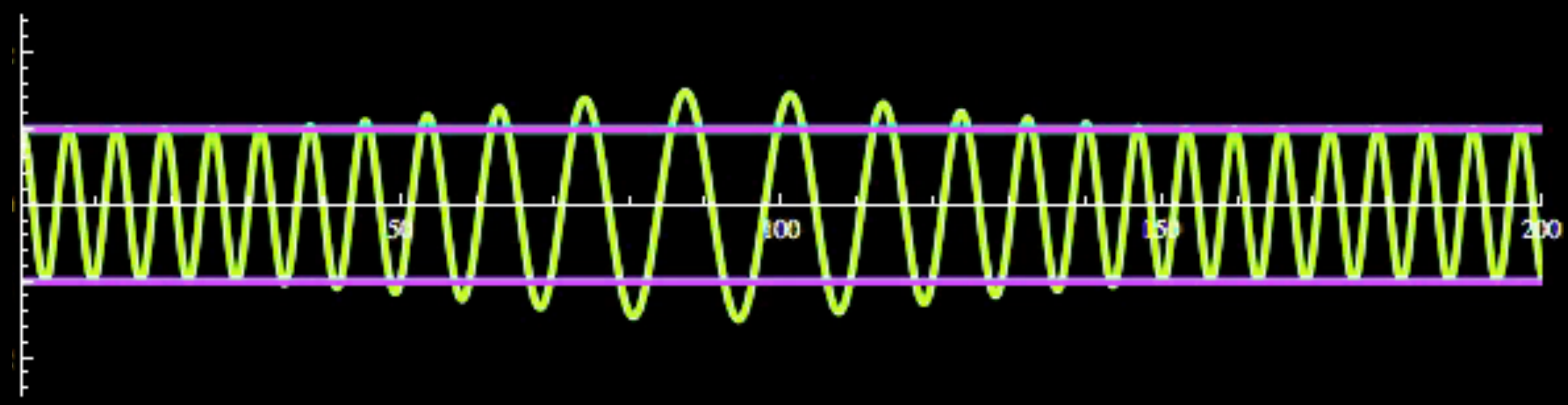
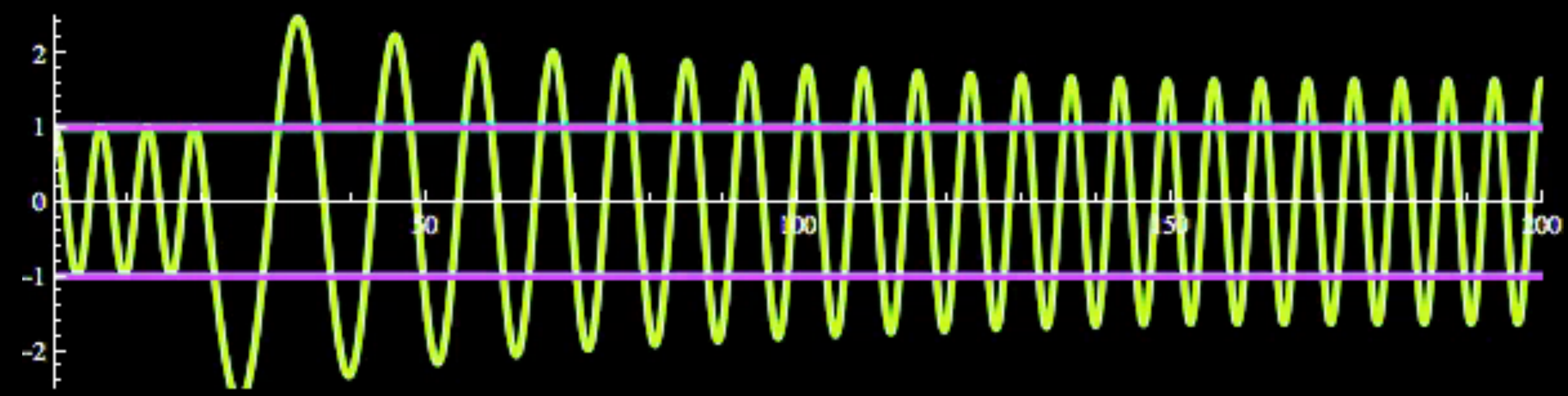


Sudden, then adiabatic

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



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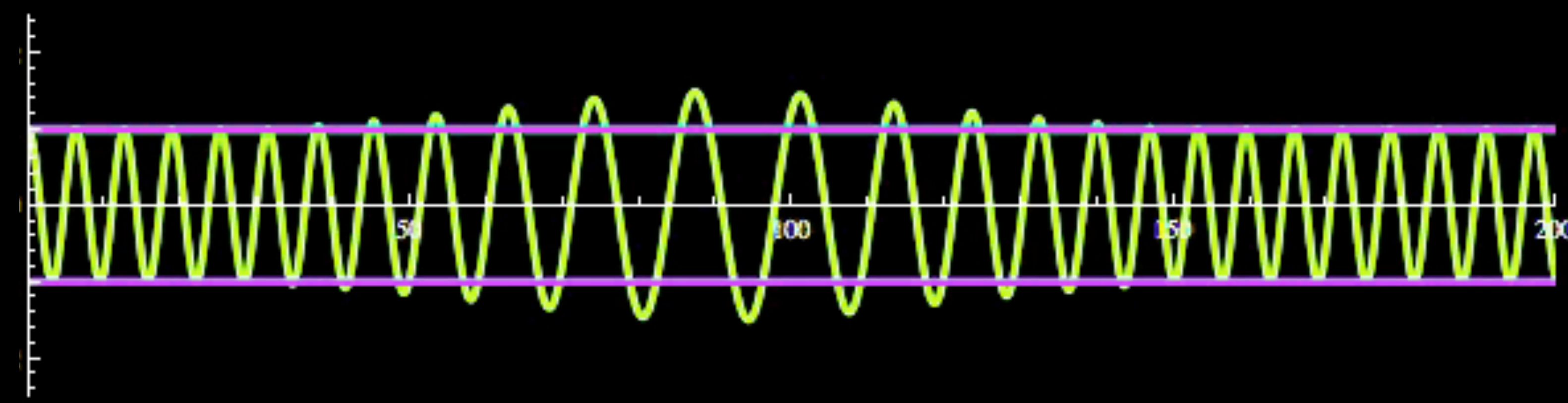

Sudden, then adiabatic

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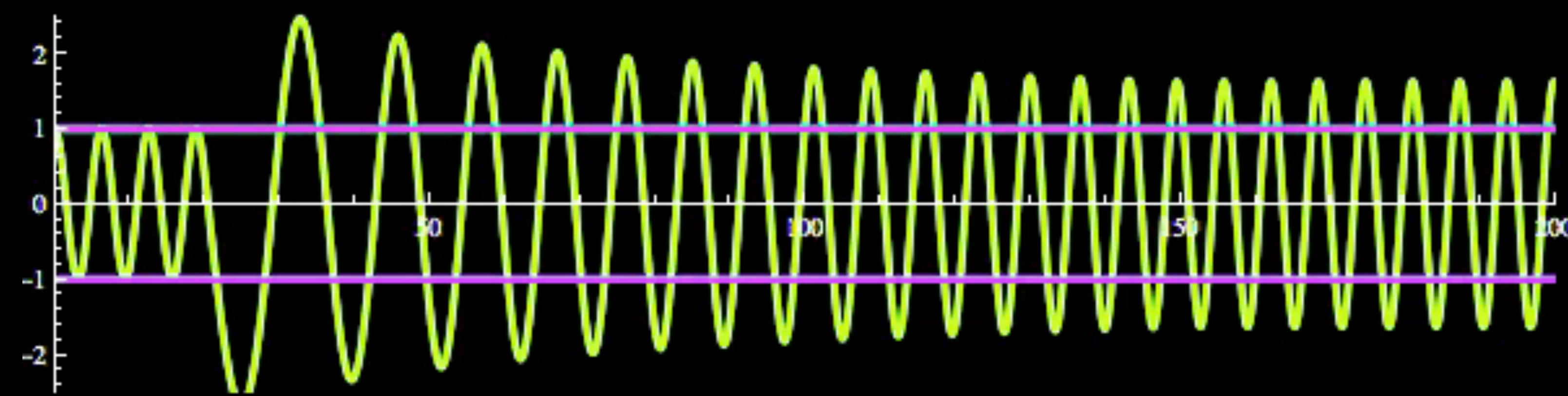
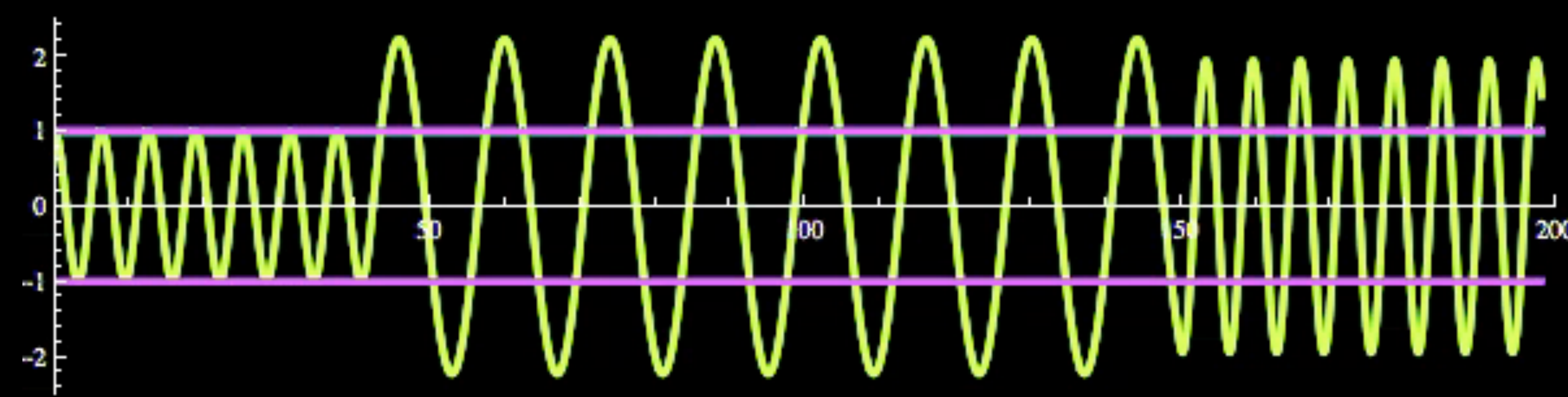


Sudden, then sudden

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



Adiabatic

$$\int_{r_{\min}}^{r_{\max}} \mathrm{d}r \sqrt{E(t) - V_{\mathrm{eff}}(r; j, t)} = \mathrm{constant}$$

The adiabatic formula is the famous conserved radial action

The instantaneous formula is a bit foreboding looking but simple to evaluate. The best thing is that a series of *small* ‘instatantaneous’ changes provably give you a final change that agrees with the adiabatic formula! So, you can apply the instantaneous formula over timesteps ~=dynamical timescale and should get the right answer.

Adiabatic

$$\int_{r_{\rm min}}^{r_{\rm max}} \mathrm{d}r \sqrt{E(t) - V_{\rm eff}(r; j, t)} = \text{constant}$$

Instantaneous

$$\Delta E = \int_{r_{\rm min}}^{r_{\rm max}} \frac{\Delta V_{\rm eff}(r; j)\mathrm{d}r}{\sqrt{E - V_{\rm eff}(r; j)}} \Bigg/ \int_{r_{\rm min}}^{r_{\rm max}} \frac{\mathrm{d}r}{\sqrt{E - V_{\rm eff}(r; j)}}$$

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Governato et al 2010

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

nature

LETTERS

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

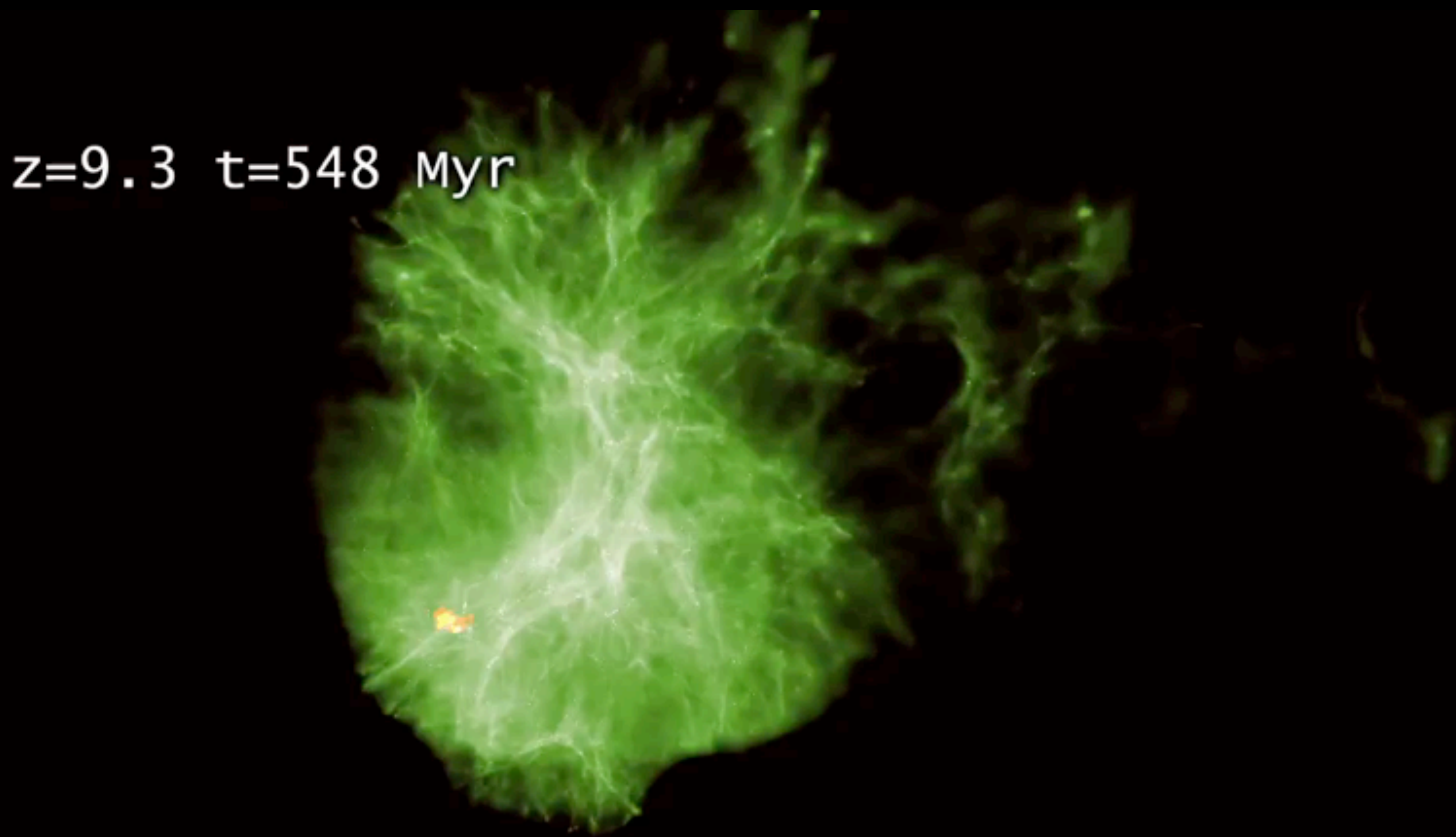
F. Governato[1], C. Brook[2], L. Mayer[3], A. Brooks[4], G. Rhee[5], J. Wadsley[6], P. Jonsson[7], B. Willman[9], G. Stinson[6], T. Quinn[1] & P. Madau[8]

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 ultraviolet field[23], star formation and supernova-driven gas heating

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

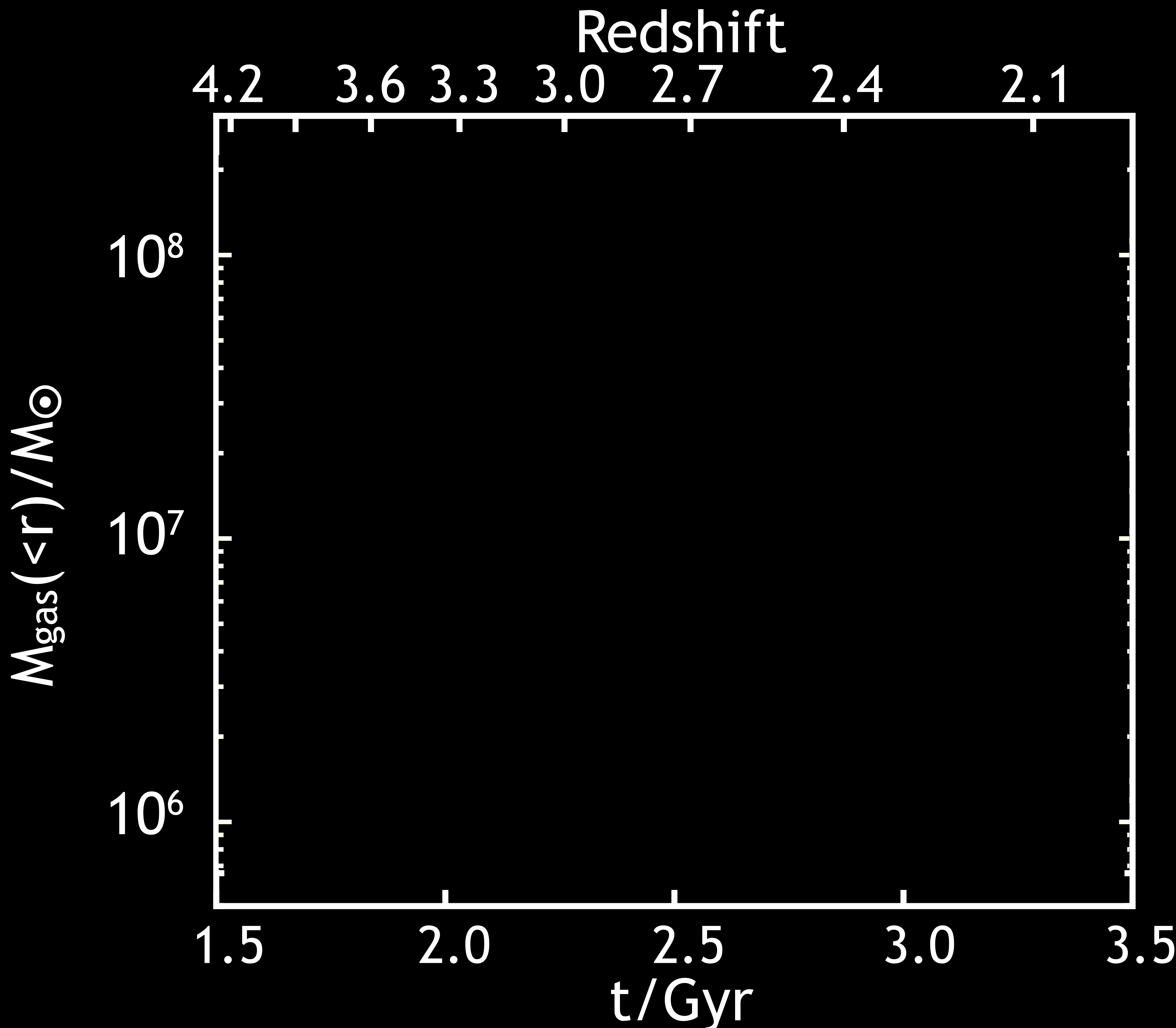


Movie by AP – download at www.cosmocrunch.co.uk

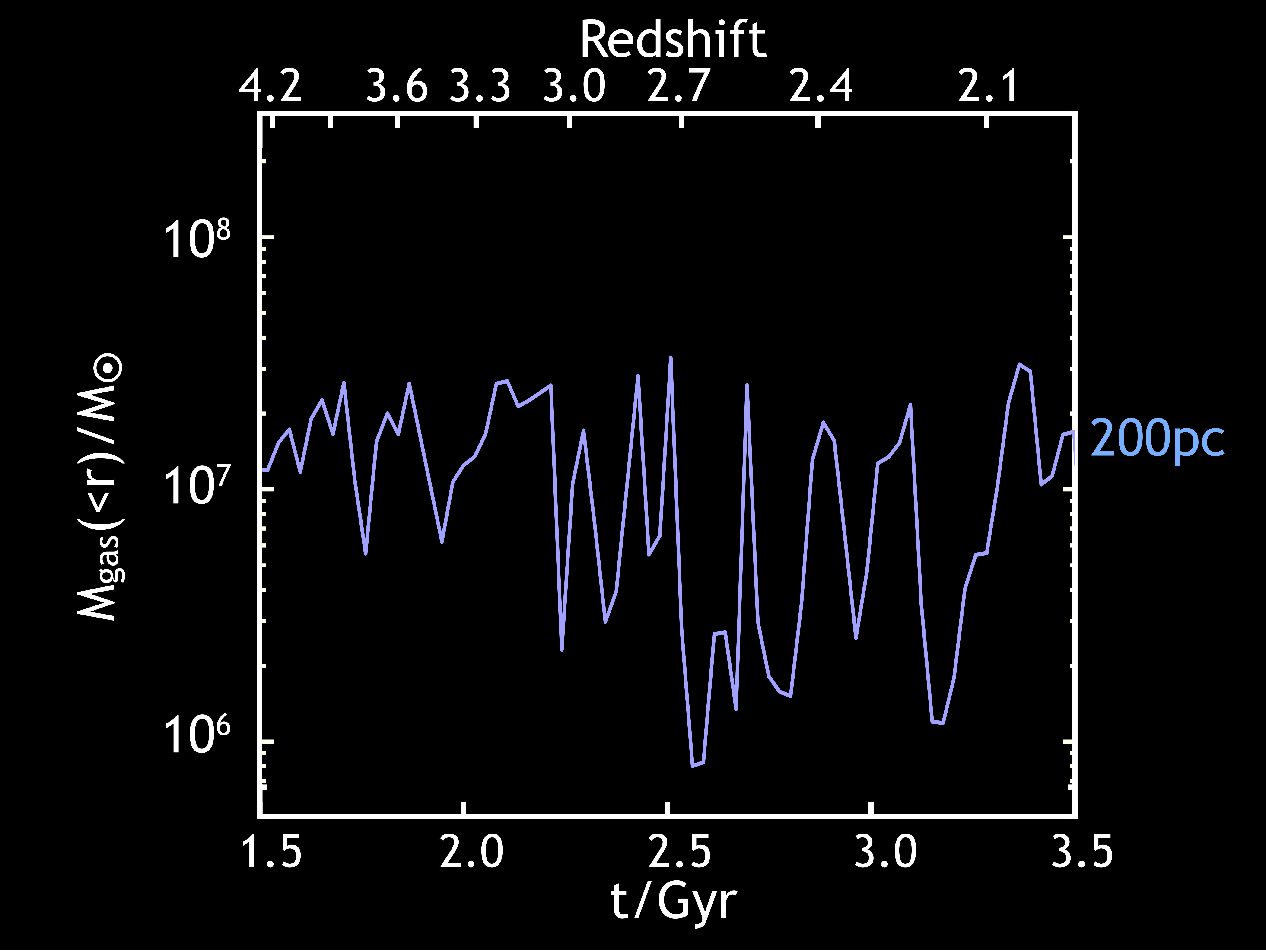
Zoom simulation.

3000 Msol/90 parsec resolution. Starting to resolve the cold ISM. Lots of work here, James Wadsley, Sijing Shen, Charlotte Christensen, many others building on gasoline codebase.

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



Rapidly changing mass interior to a given radius.
NB similarity with maschenko/wadsley work, but the new picture has no small lumps – everything coherent on kiloparsec scales – and no special resonant frequency
Also Read/Gilmore suggested the possibility of multiple epochs of outflows/condensation, in effect we are now confirming and quantifying that idea through better simulations and new mathematical modelling.



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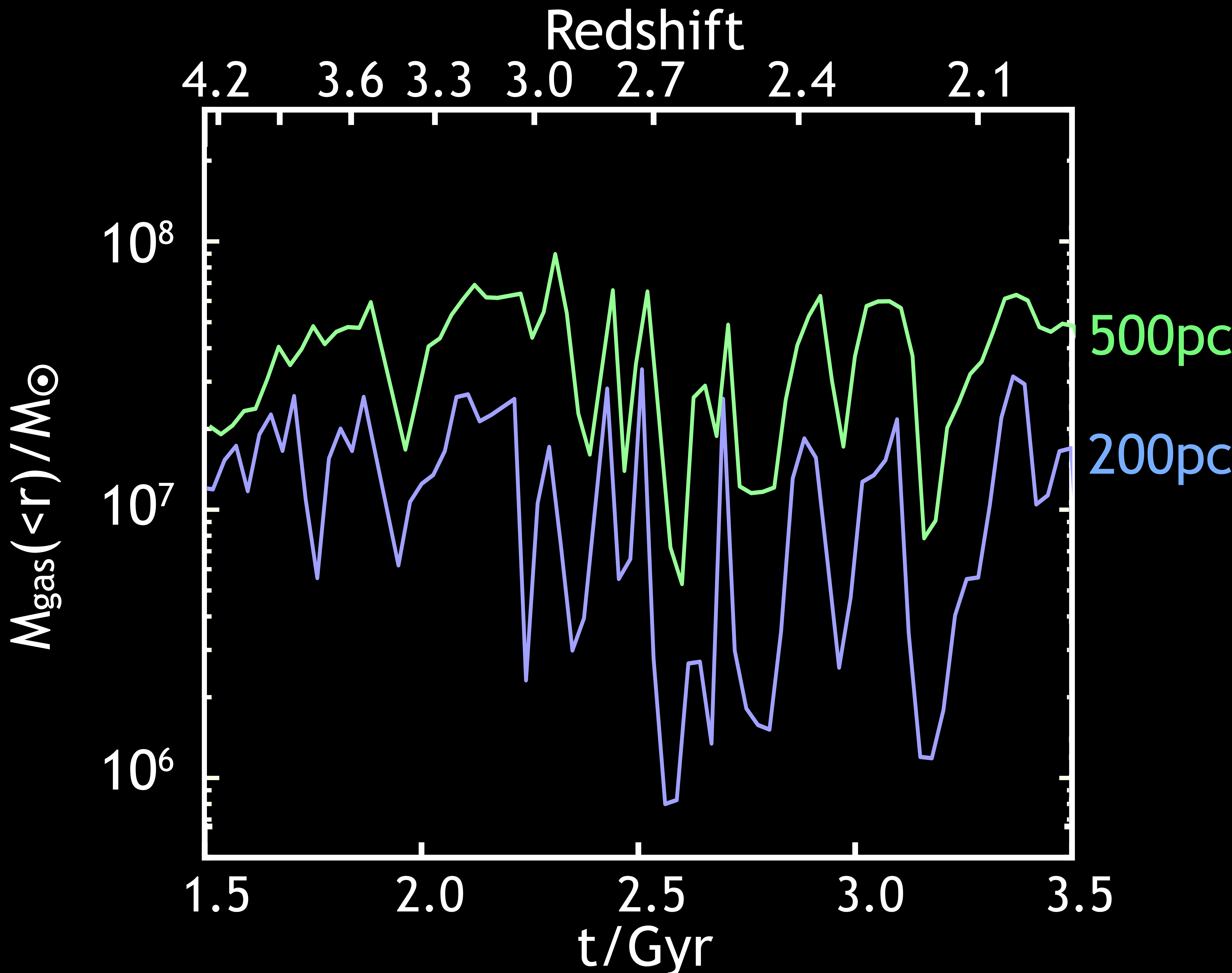

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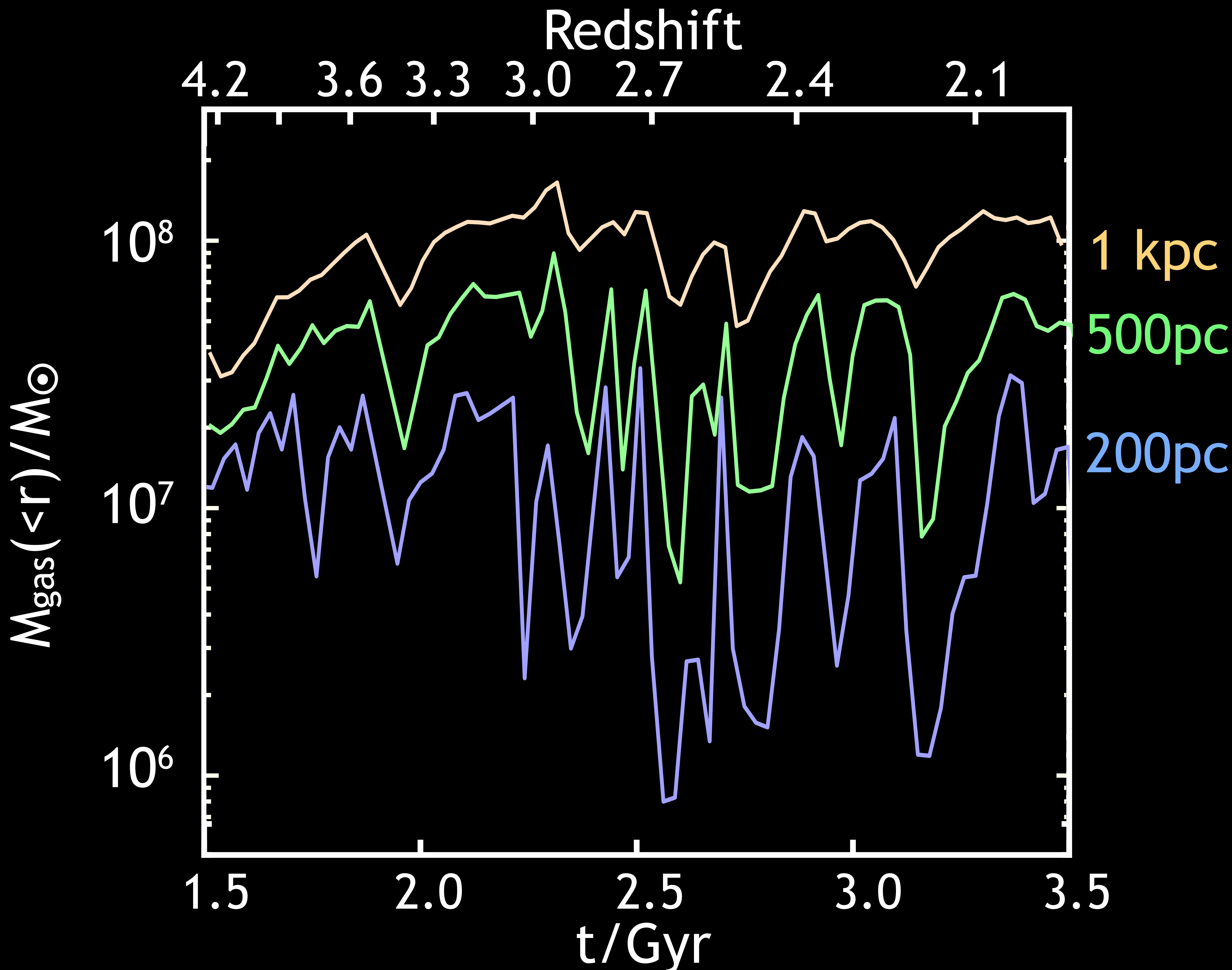

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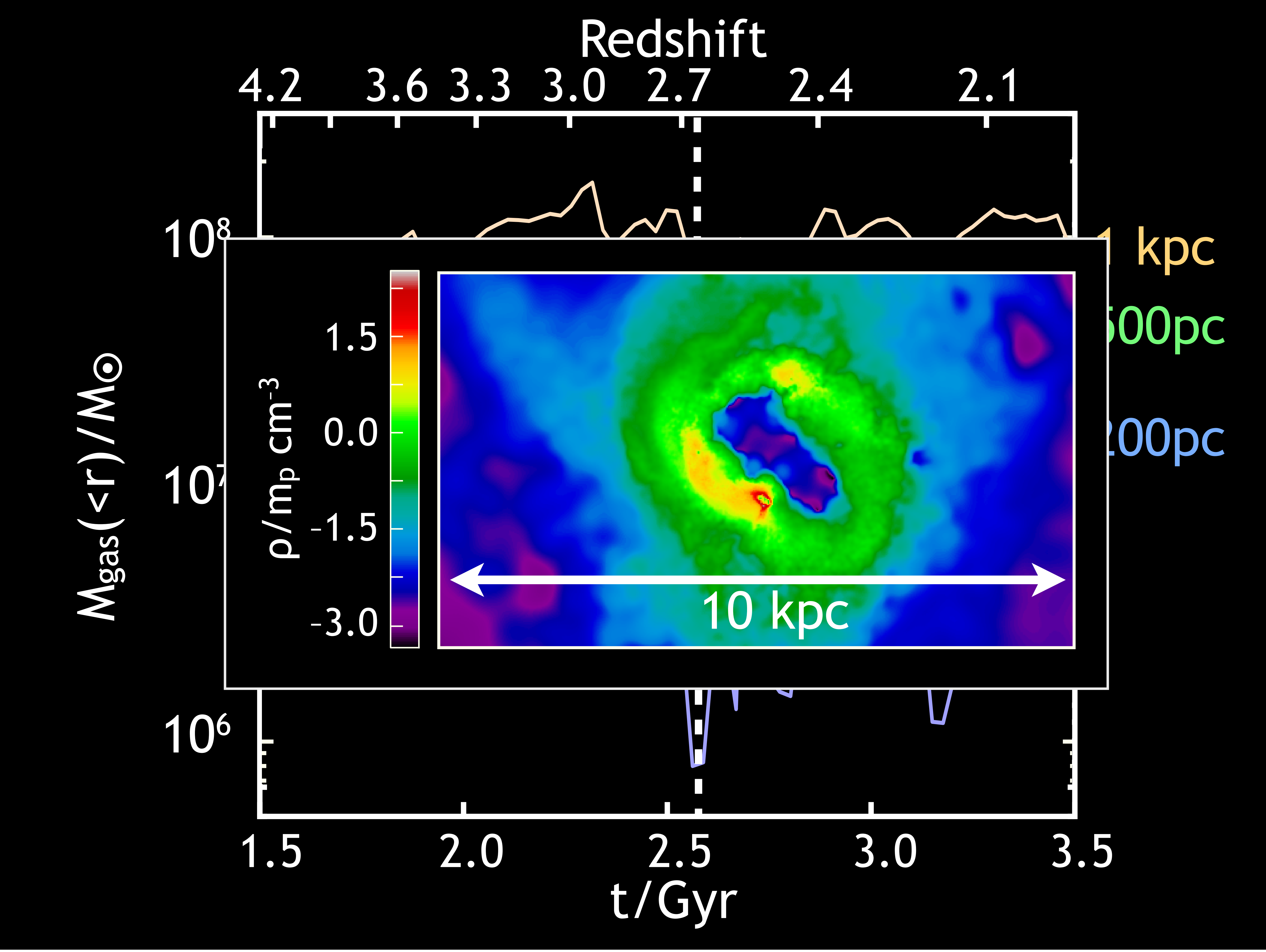

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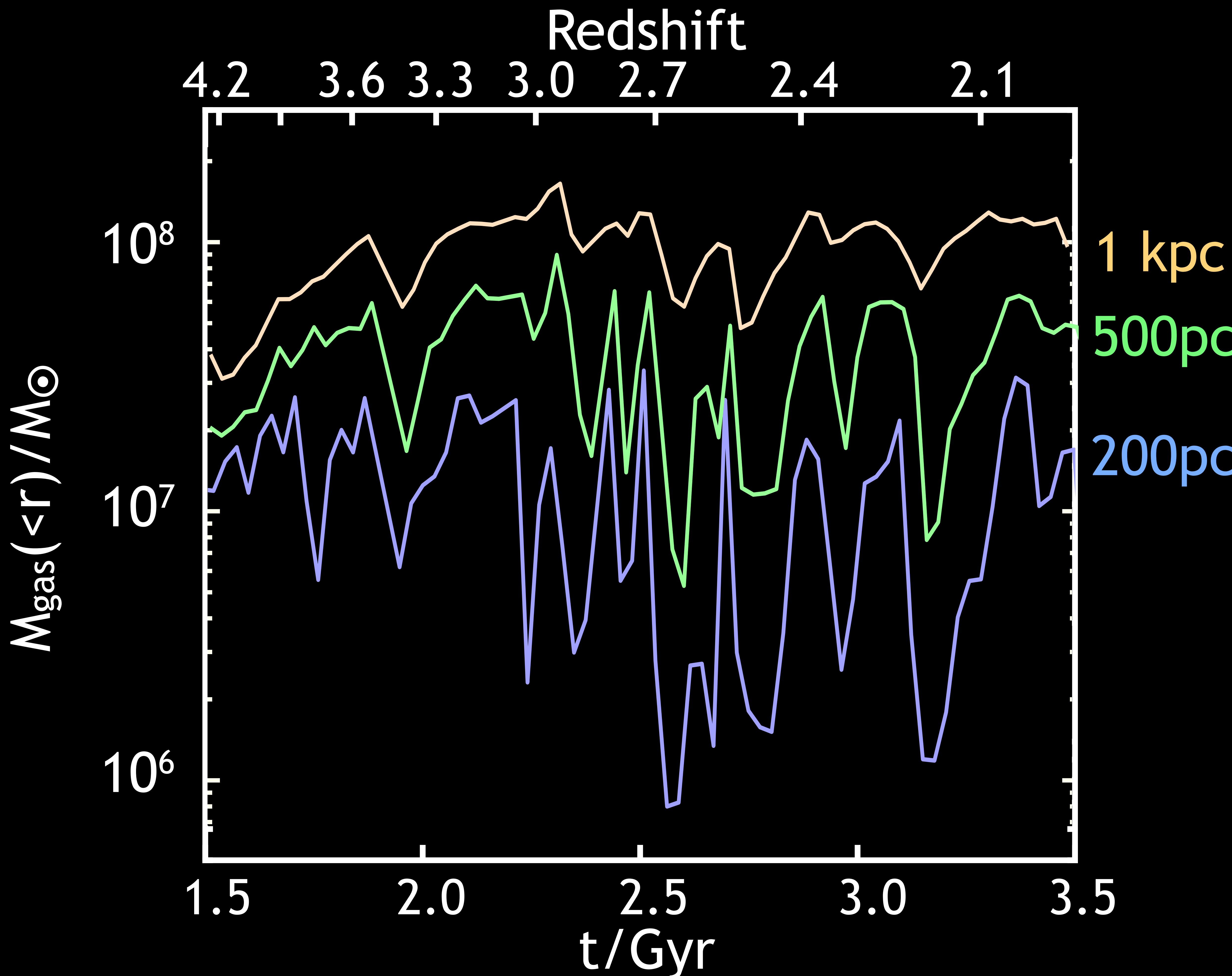

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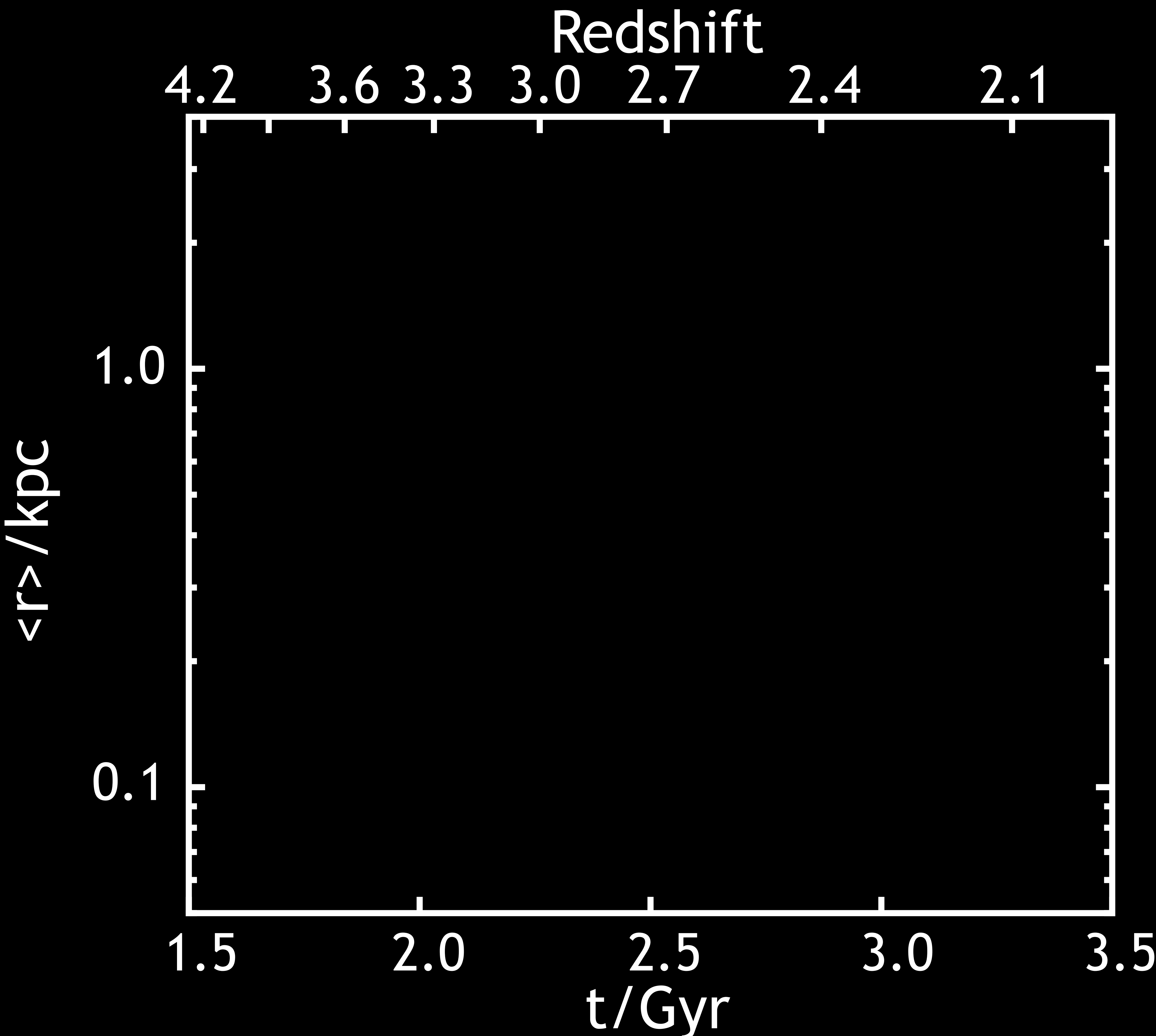
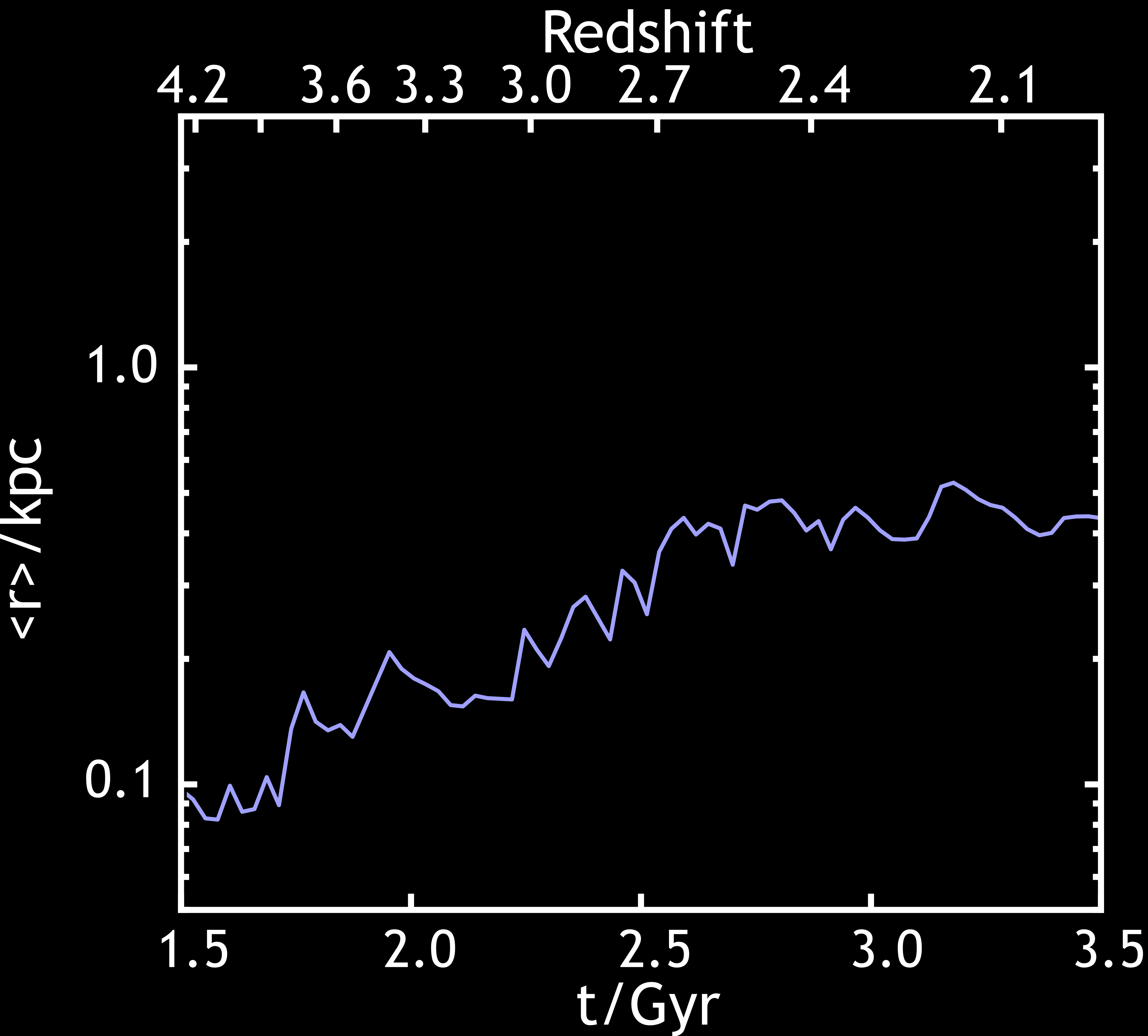


Solid lines are circular orbits migrating according to new analytic prescription

Dashed line uses adiabatic approximation - gets the wrong answer.



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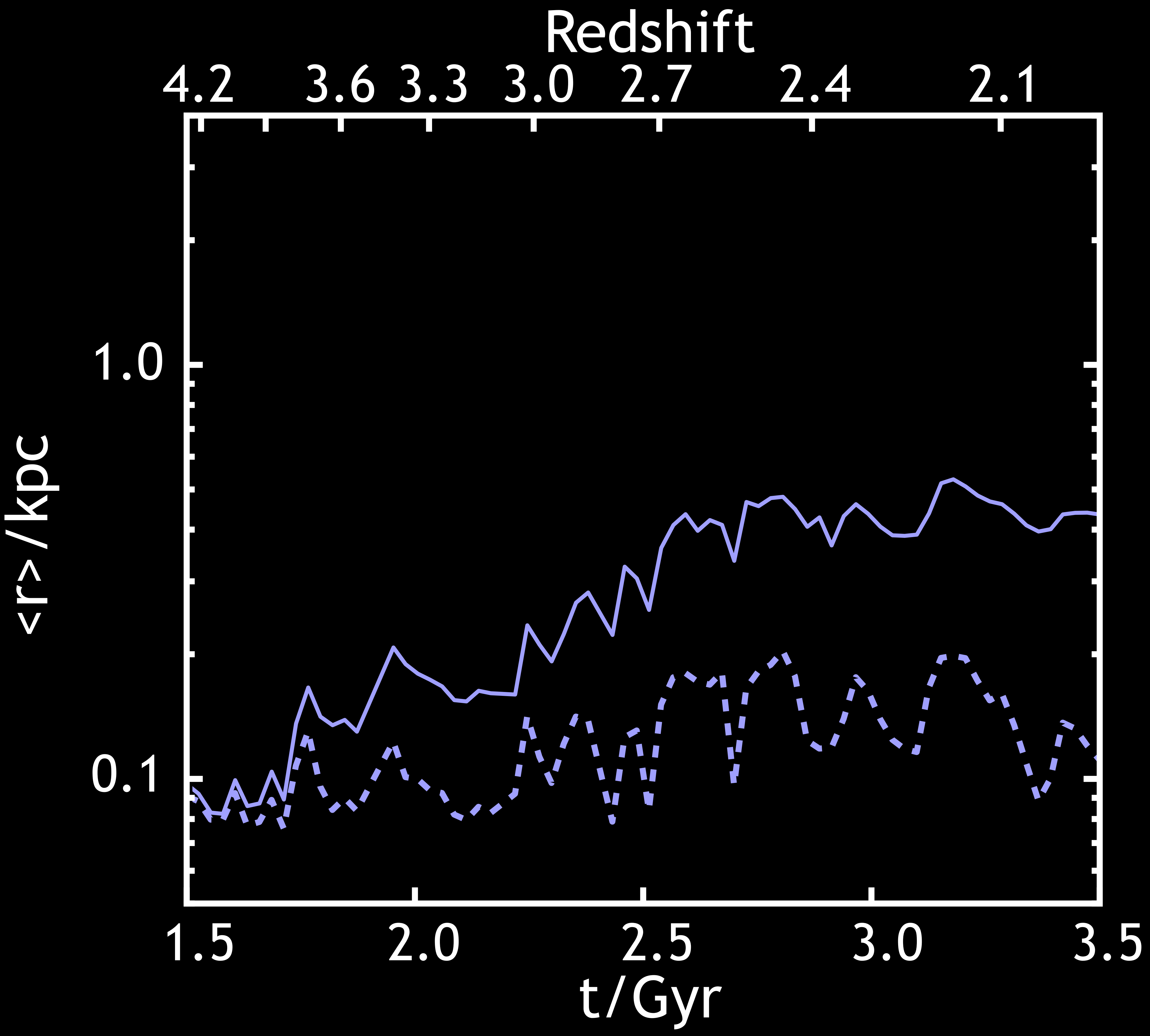

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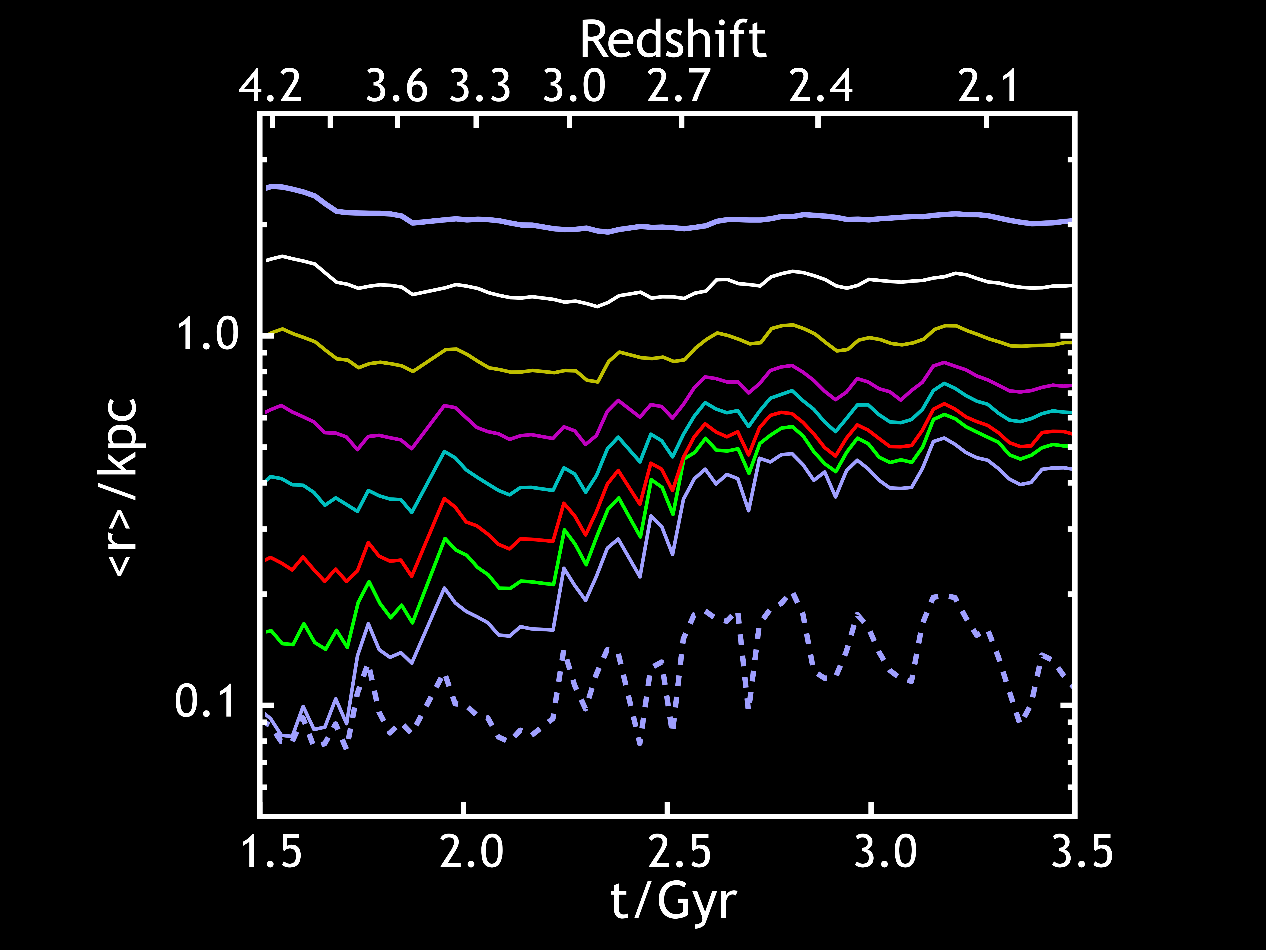

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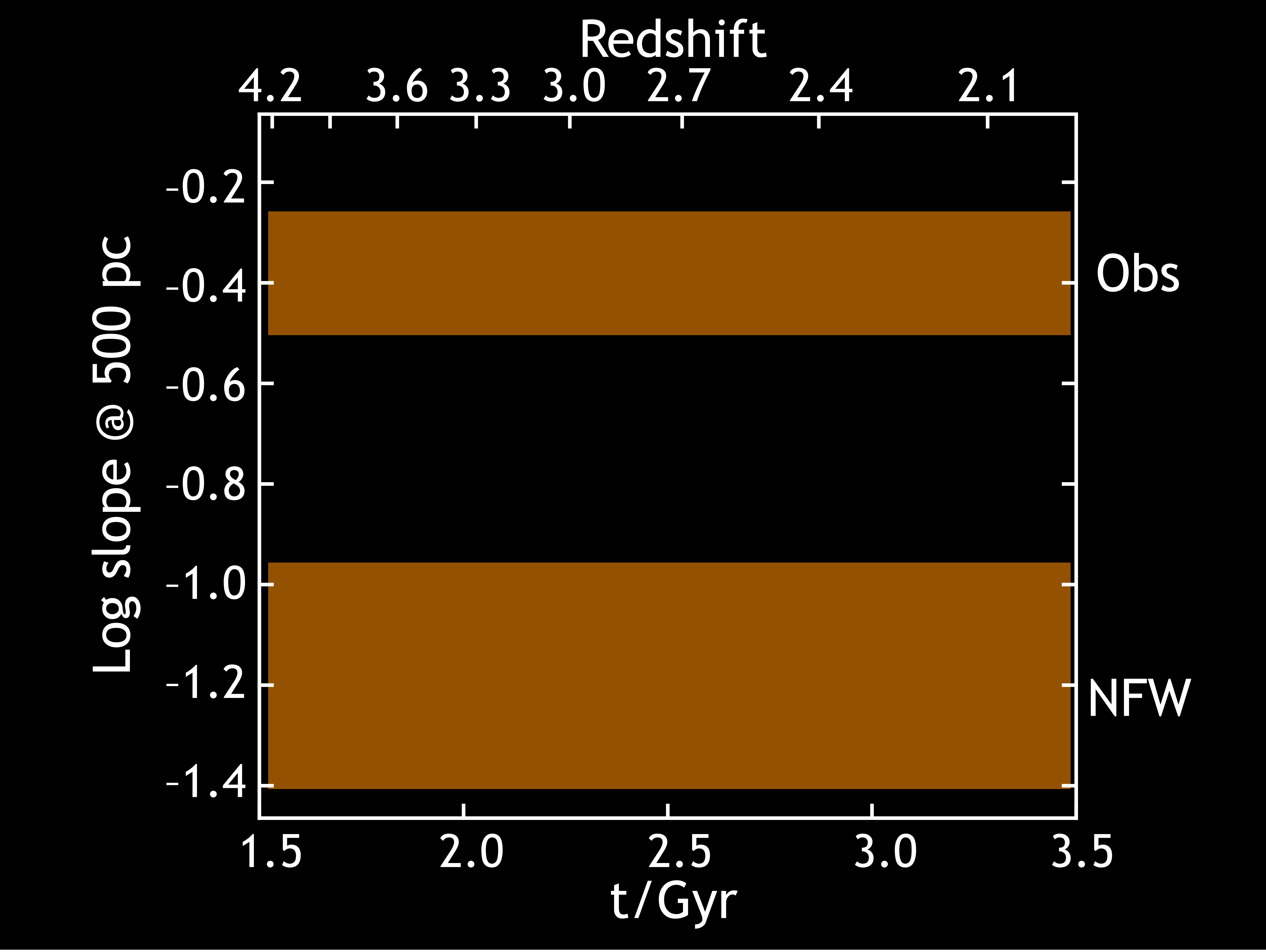
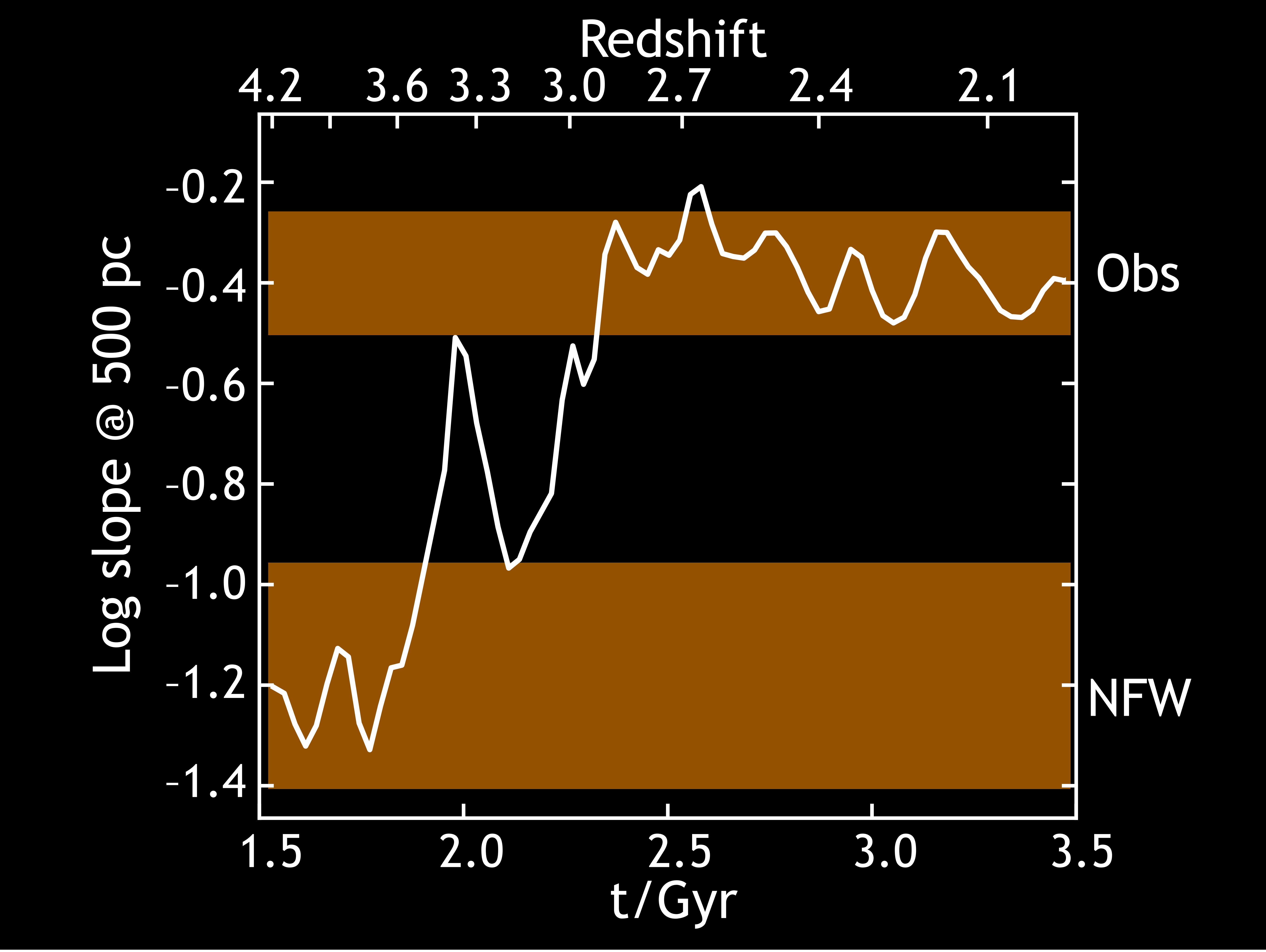


Solid line is analytic prescription. Flattening agrees well with actual simulation (dashed line)



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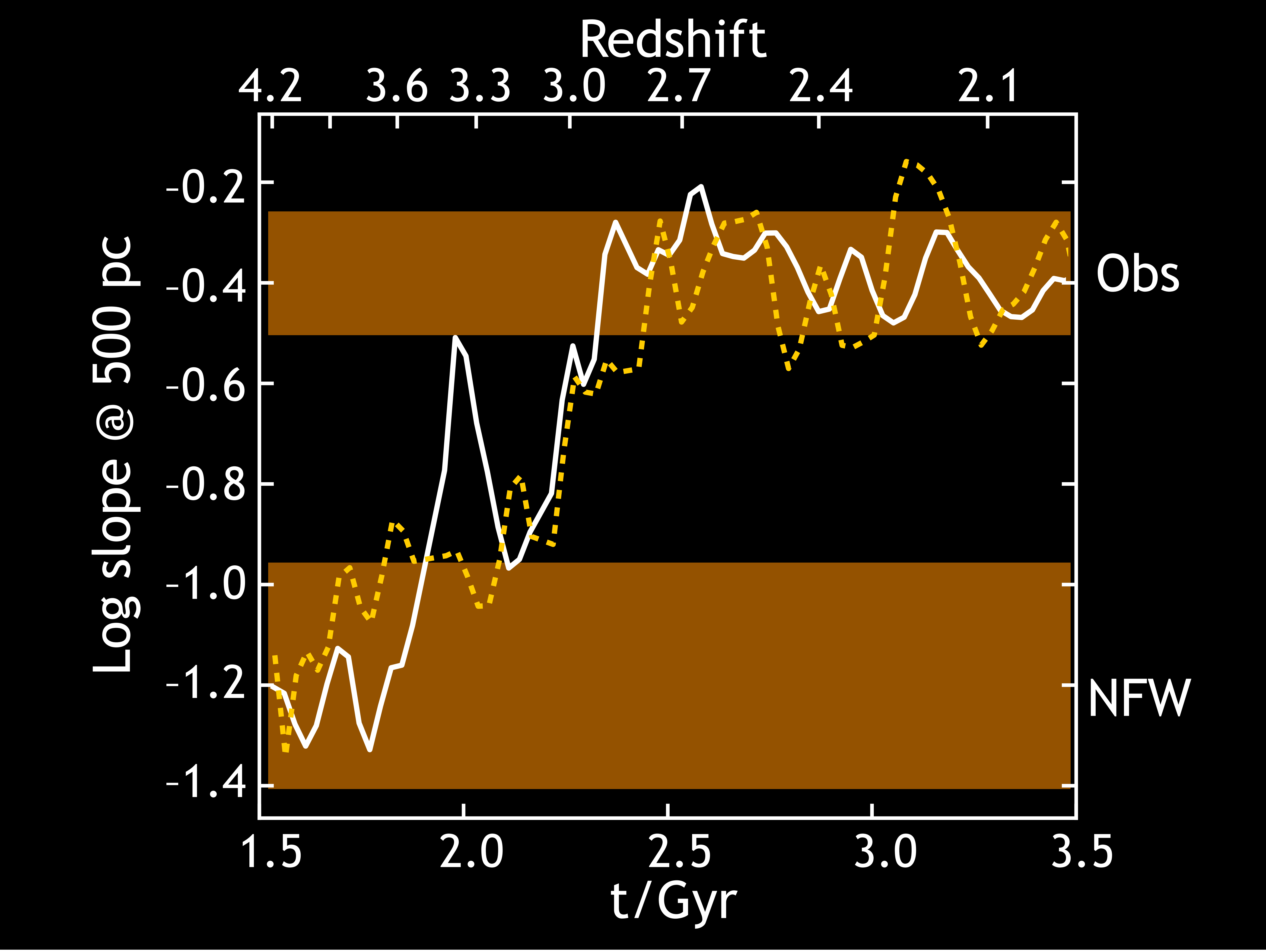

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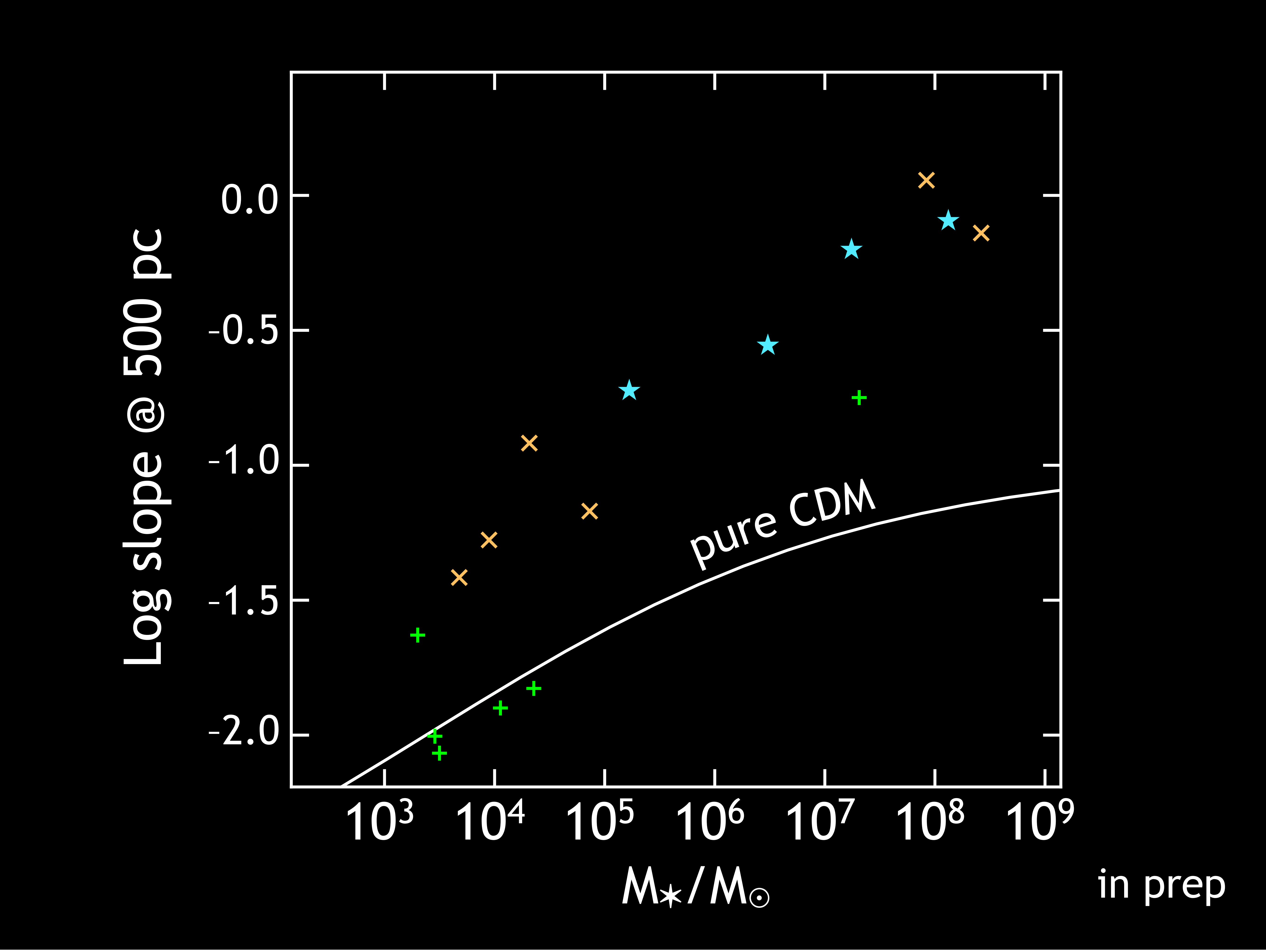

Smaller objects do not have enough star formation to create cores. Classical dwarfs yes, ultra-faints no.

What to take home

- **New model quantitatively accounts for DM core-creation** from rapid cycles of SN-driven baryonic expansion/collapse;
- **Intrinsically irreversible** unlike previous adiabatic modelling;
- **Does not invoke resonance** or long-lived clumps.

Pontzen & Governato, arXiv:1106.0499

Andrew Pontzen, IoA Cambridge