The effects of galaxy formation on clustering

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SEVENTH FRAMEWORK PROGRAMME
MARIE CURIE ACTIONS

WHY MEASURE STRUCTURE?

- How structure has formed and how matter is clustered gives us information about the initial conditions of the Universe
- By comparing observations to simulations (which have known initial conditions) we can constrain cosmological models and parameters
- Powerful measures of clustering: power spectra and correlation functions

PART I

THE MATTER POWER SPECTRUM

van Daalen et al. 2011
Semboloni et al. 2012

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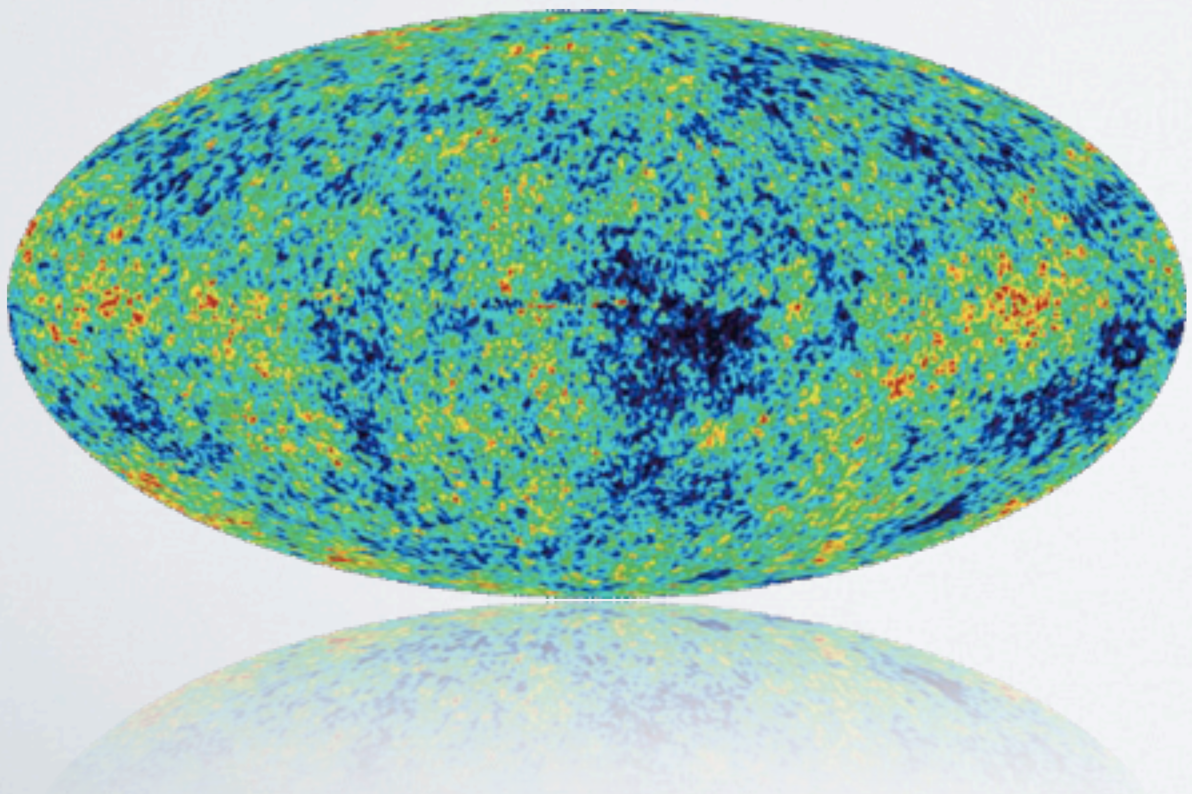

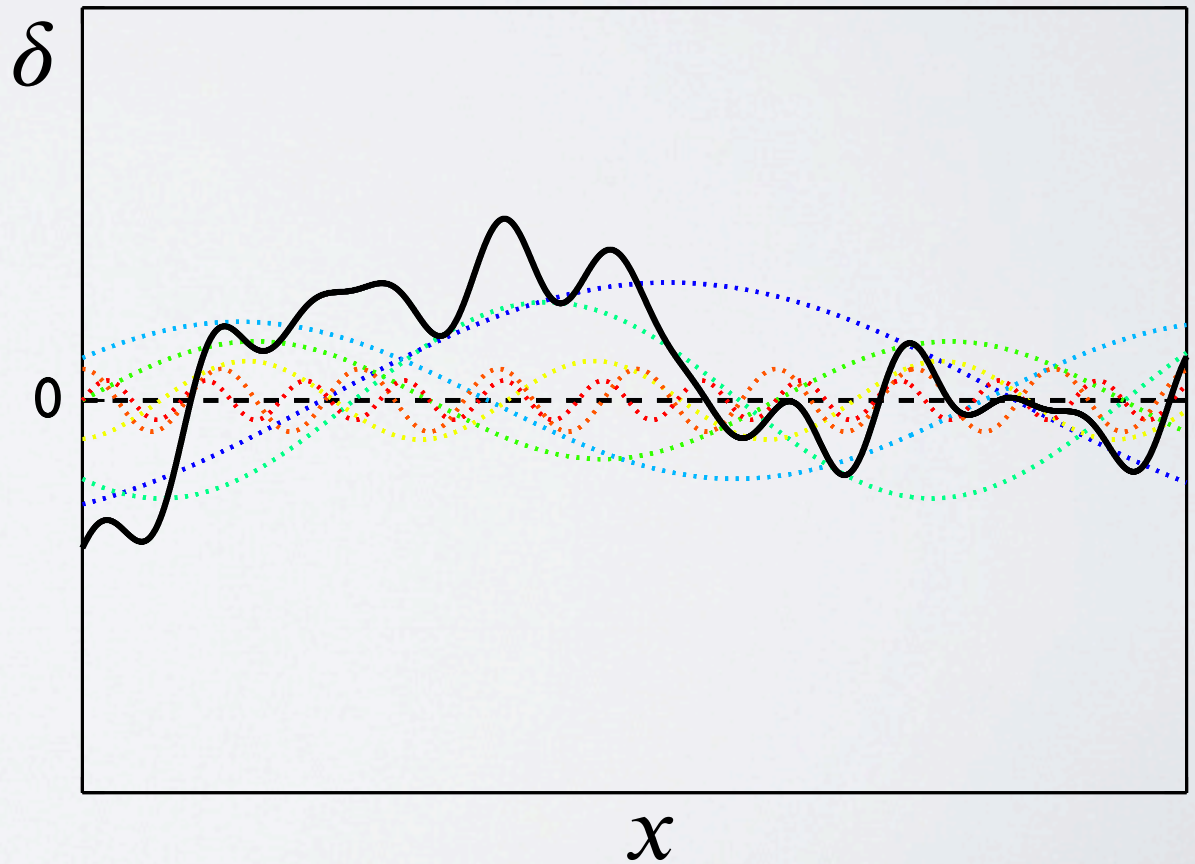

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  - Fourier counterparts: $$\delta(\mathbf{x}) = \sum_{\mathbf{k}} \delta_{\mathbf{k}}\, e^{-i\mathbf{k}\cdot\mathbf{x}}$$
  - Power spectrum: $$P(k) \equiv V \left\langle |\delta_{\mathbf{k}}|^2 \right\rangle$$ $$\Delta^2(k) \equiv \frac{k^3}{2\pi^2} P(k)$$

WEAK LENSING

- Weak lensing measures the distribution of matter through its effect on light
- Most matter is dark matter, and baryons are expected to trace it on the relevant scales
- Dark matter only simulations are therefore used to interpret weak lensing measurements
- However: studies have shown that baryons and galaxy formation can no longer be ignored

EFFECTS OF GALAXY FORMATION

- Why should galaxy formation affect the power spectrum?
  - As gas cools and forms stars and galaxies, the small-scale power increases
  - Feedback heats and redistributes the gas, which, unlike dark matter, feels pressure and thus lowers the power
  - Galaxy formation can thus affect the power on a range of scales and in different ways

- Earlier work considered cooling and weak feedback, but not AGN feedback

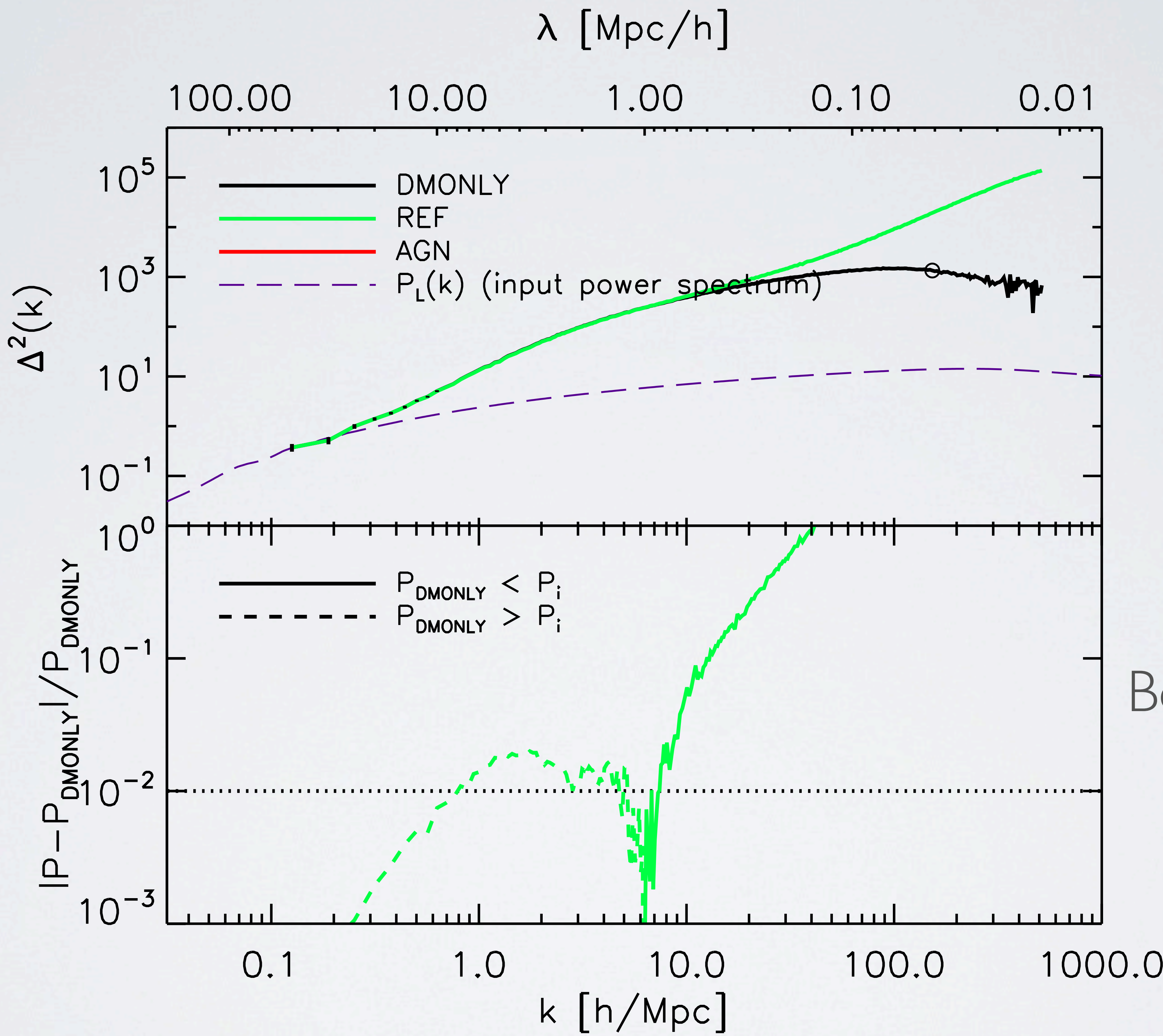
EFFECTS OF GALAXY FORMATION

- Upcoming surveys sensitive to ~1% ⇒ very precise estimates of statistics needed
- Existing models predict a ~1% decrease in power for $k = 1\text{-}10$ h/Mpc, and a great increase at smaller scales
- All these models suffer from overcooling, which some authors claim leads to conservative estimations
- However: our AGN model predicts quantitatively and qualitatively different results!

SIMULATIONS

- OWLS simulations (Schaye et al. 2010), 100 Mpc/h boxes with 2×512^3 particles, WMAP3 cosmology (but doesn't matter)
- *DMONLY*, *REF*, *AGN*
- *REF*: radiative cooling/heating, star formation, chemical enrichment, supernova feedback
- *AGN*: *REF* + AGN feedback (most realistic simulation, e.g. McCarthy et al. 2010/2011)

POWER SPECTRUM



MvD, JS, Craig Booth & Claudio Dalla Vecchia (2011)

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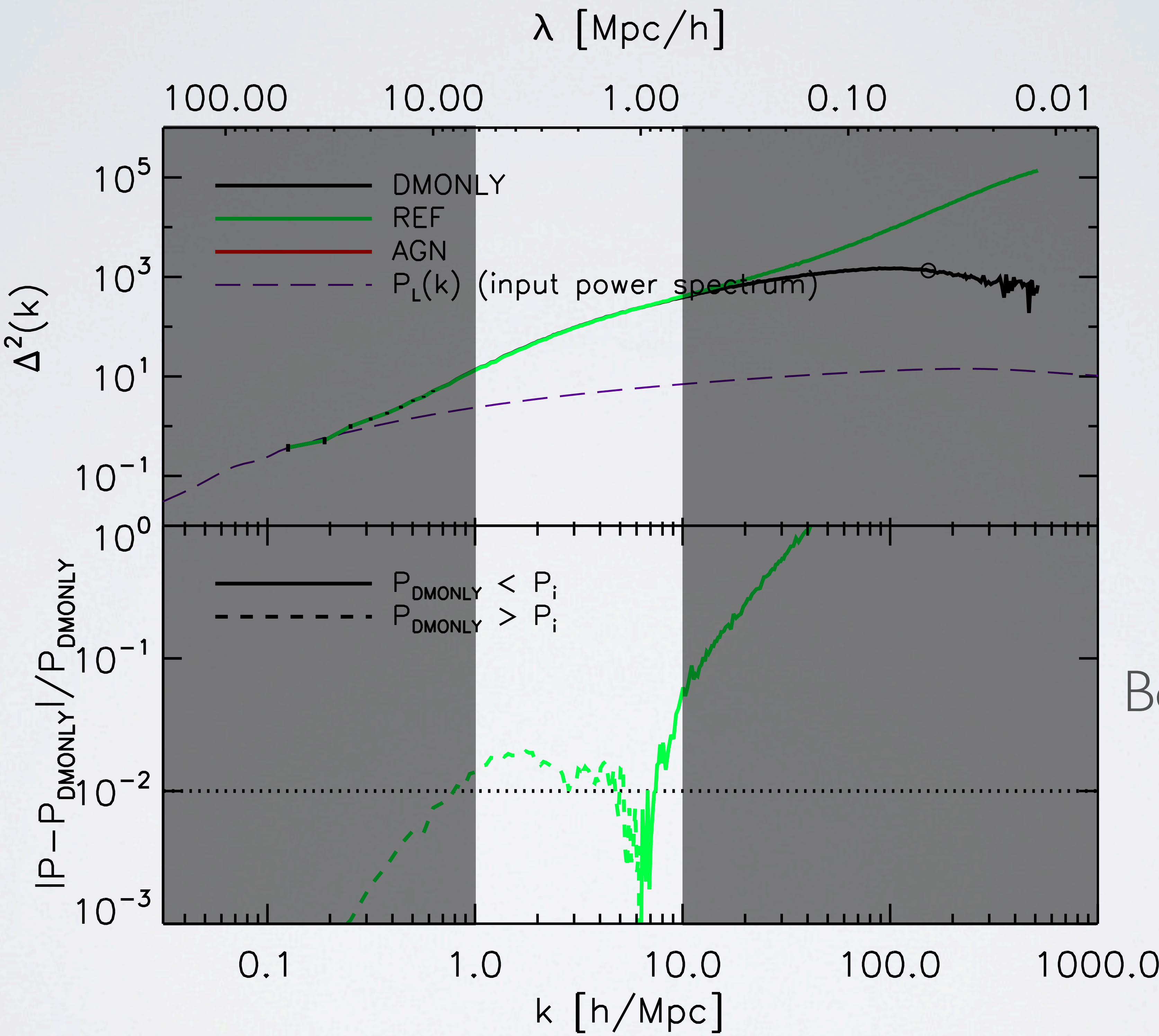

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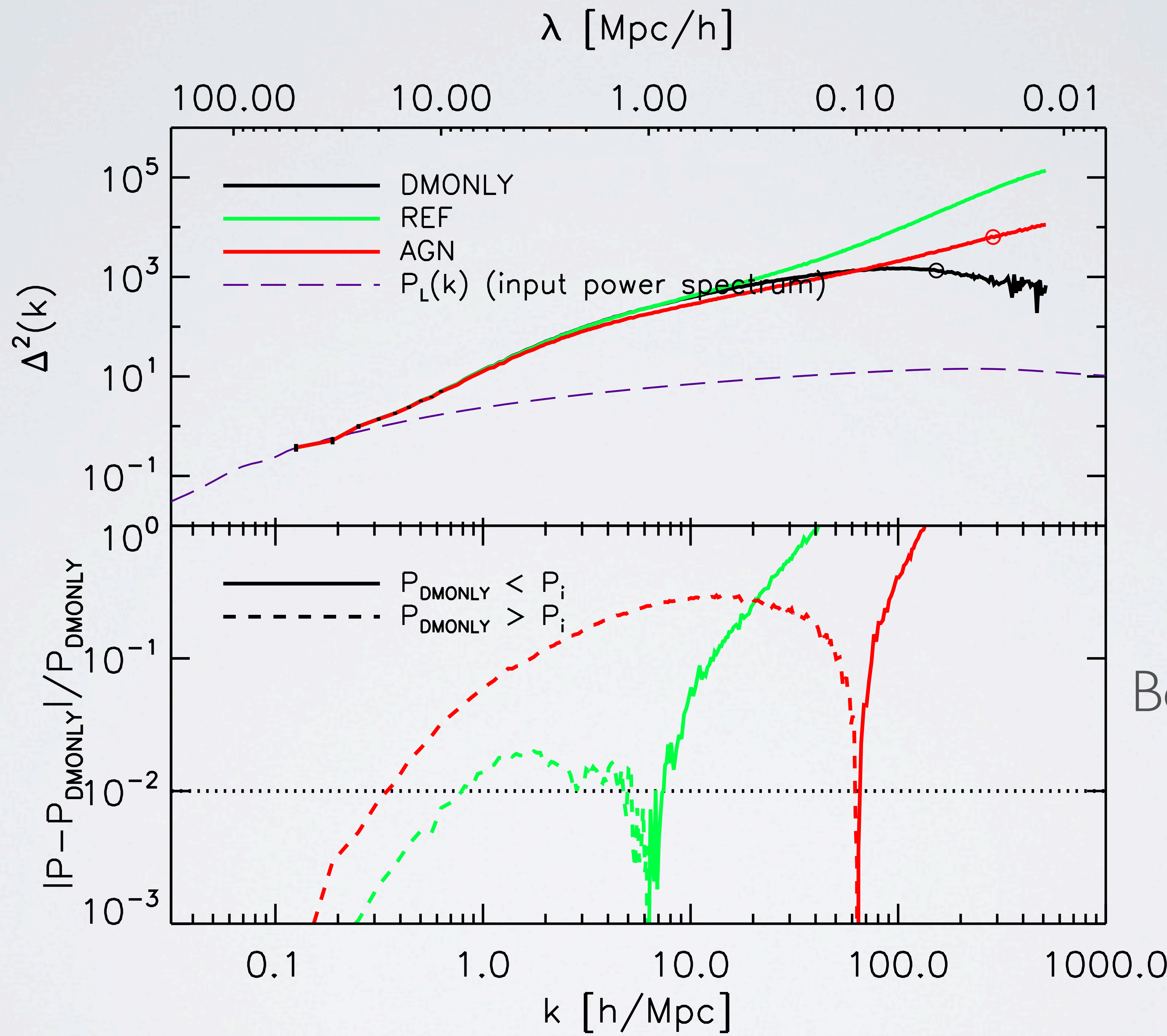

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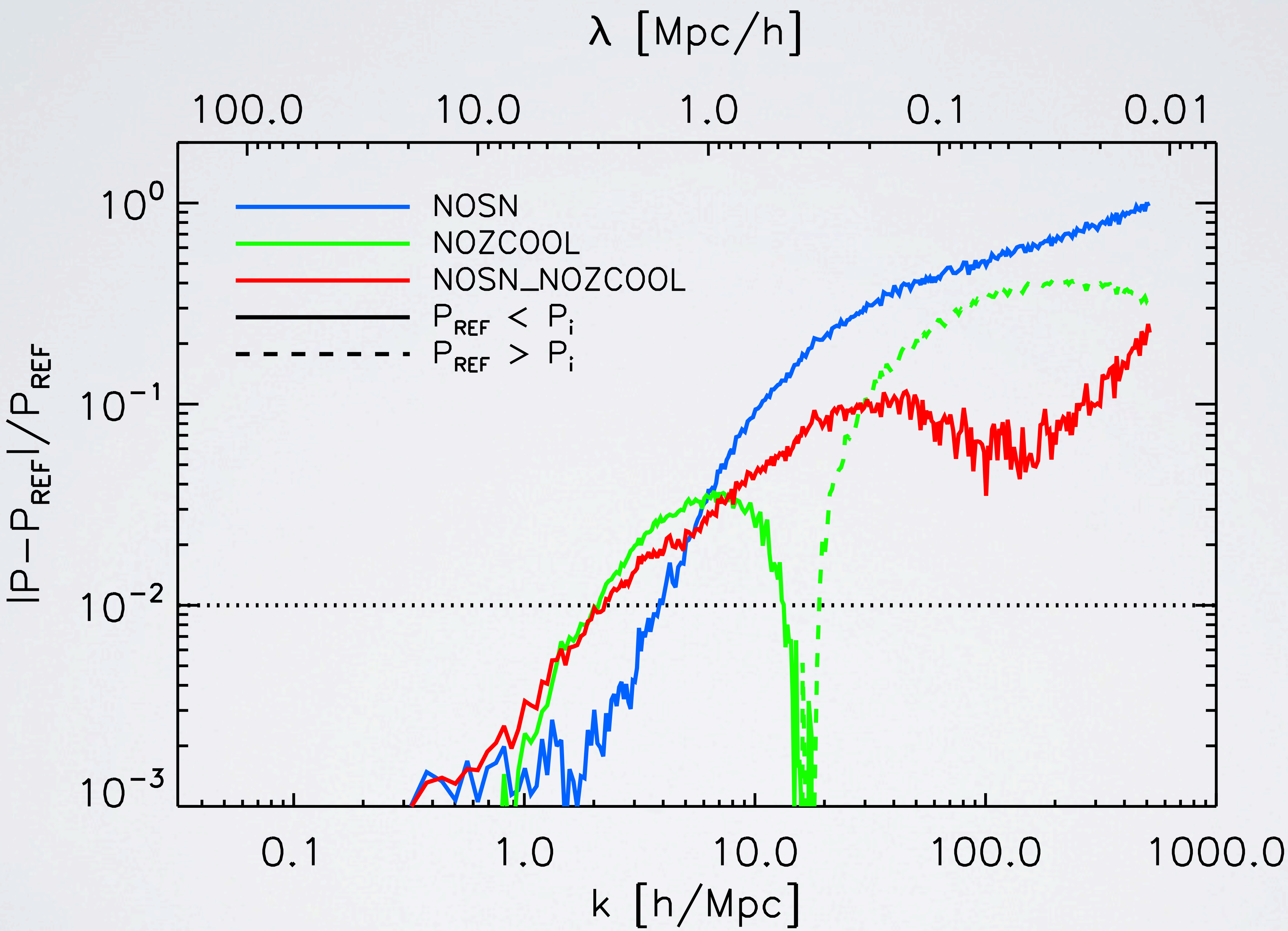
EFFECTS OF GALAXY FORMATION

VARIATIONS ON REF



EFFECTS OF GALAXY FORMATION

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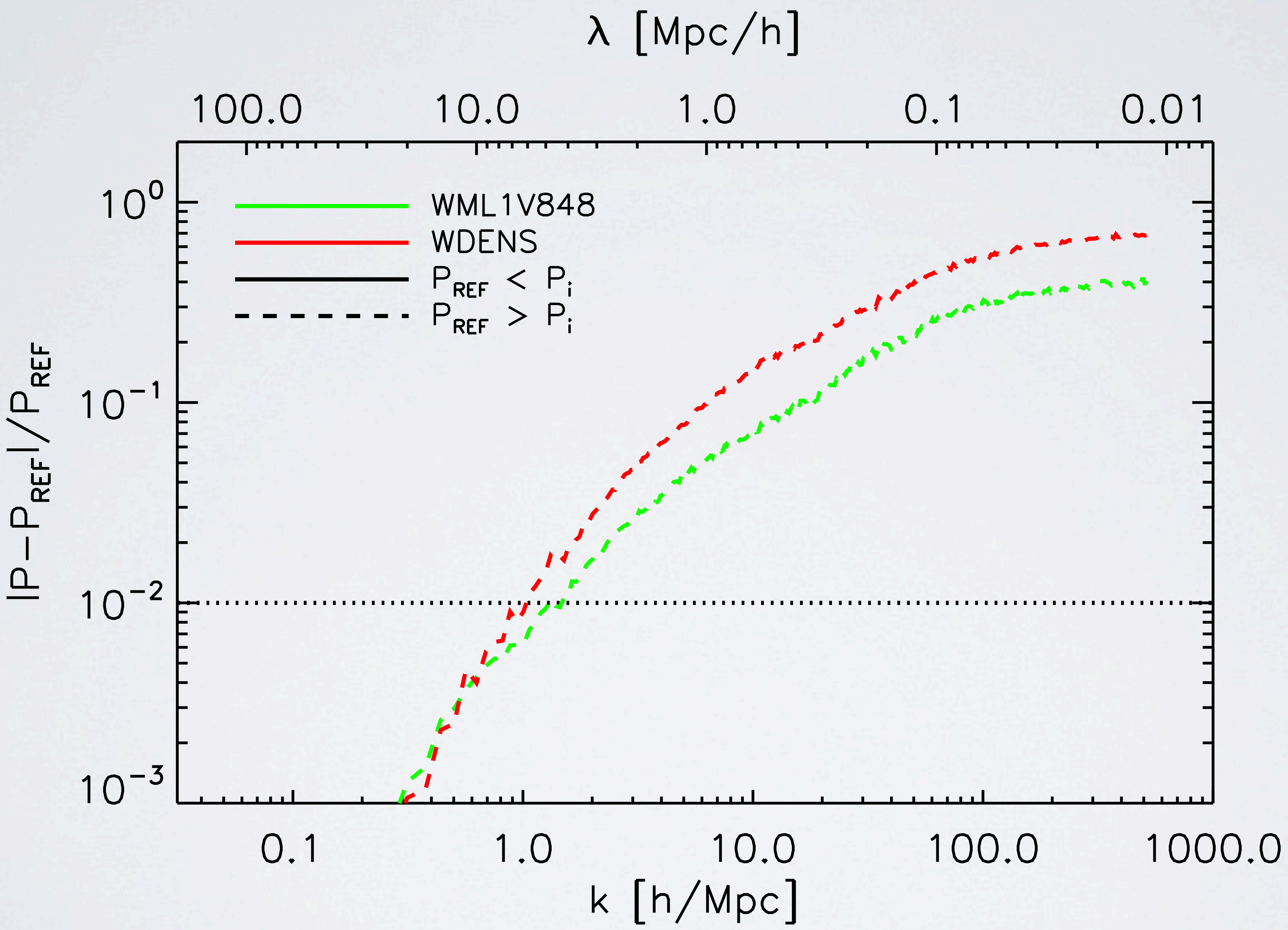

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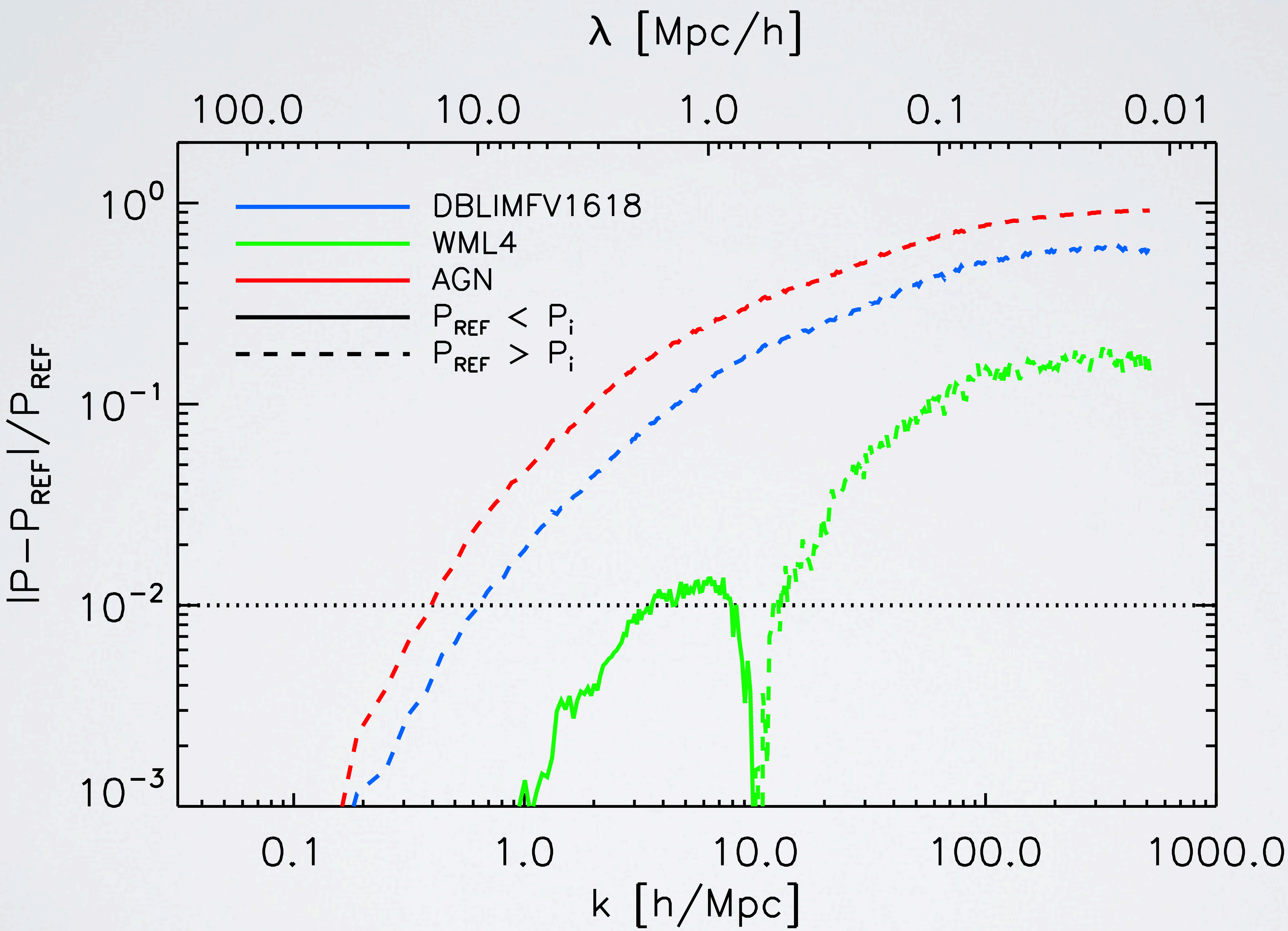

EFFECTS OF GALAXY FORMATION

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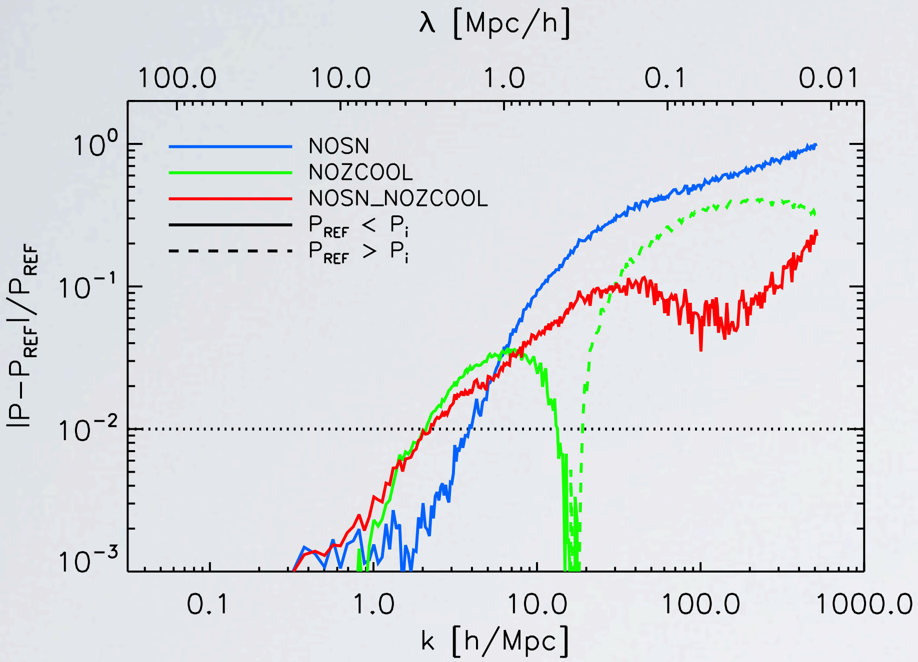
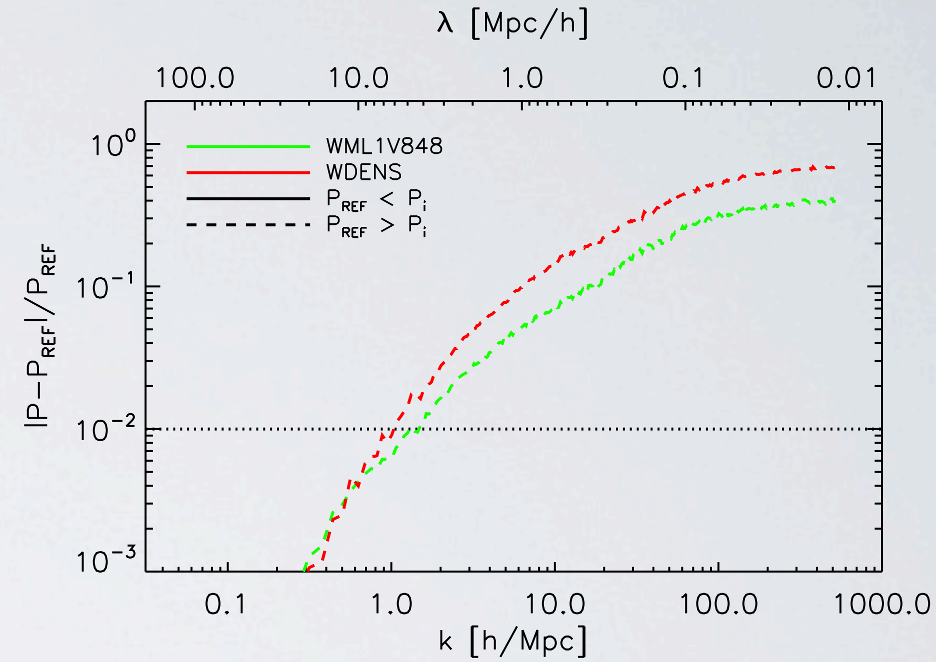
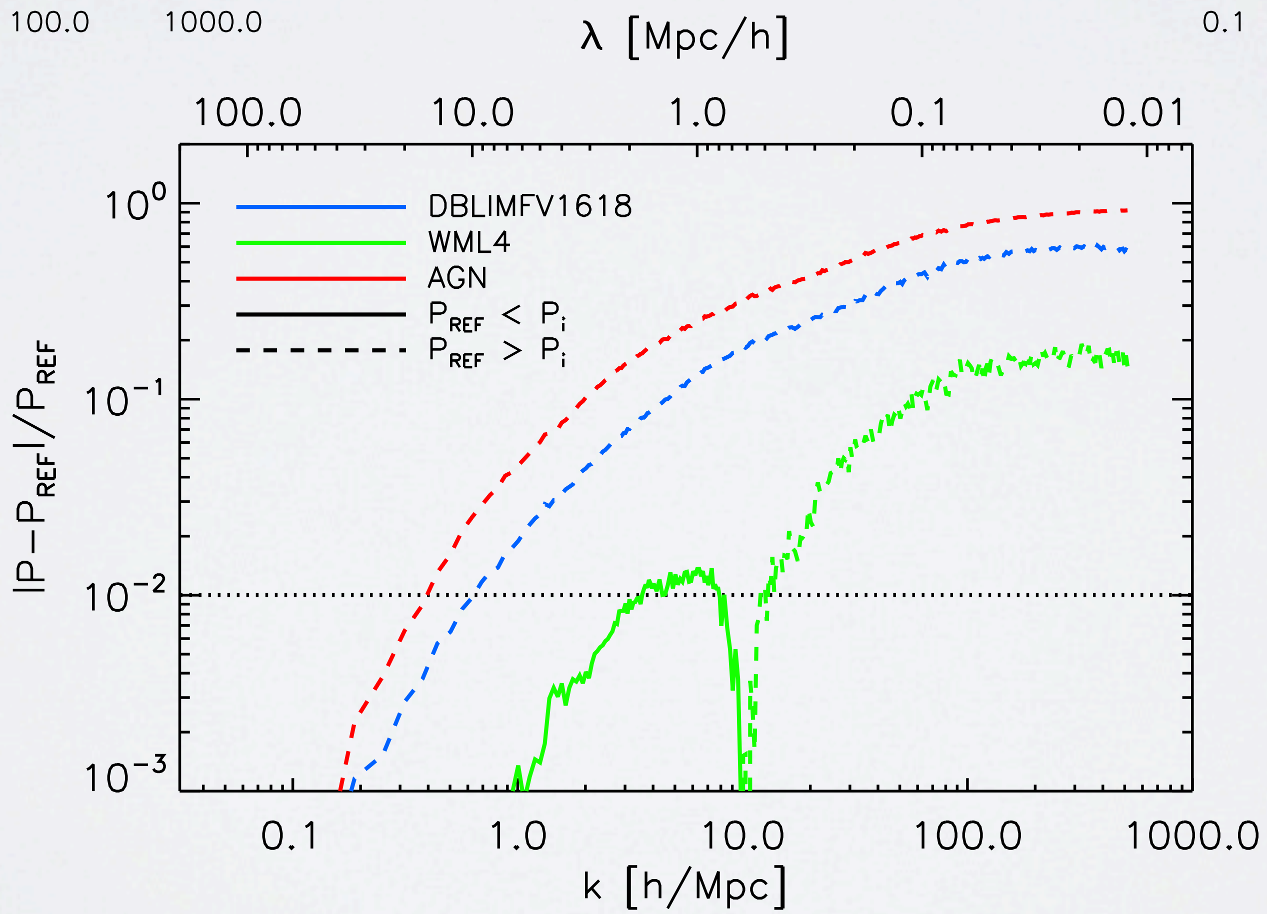
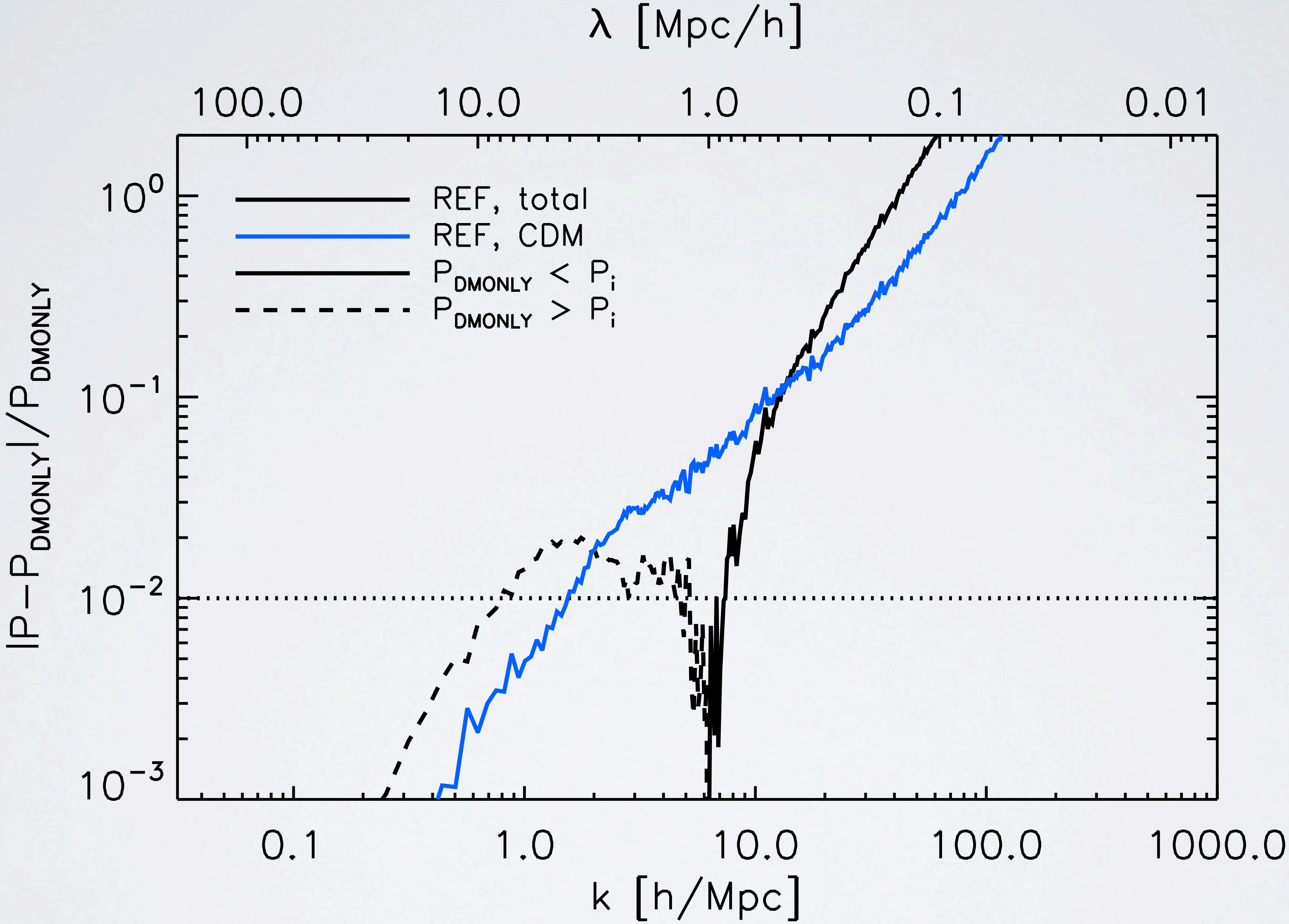






EFFECTS OF GALAXY FORMATION

BACK-REACTION



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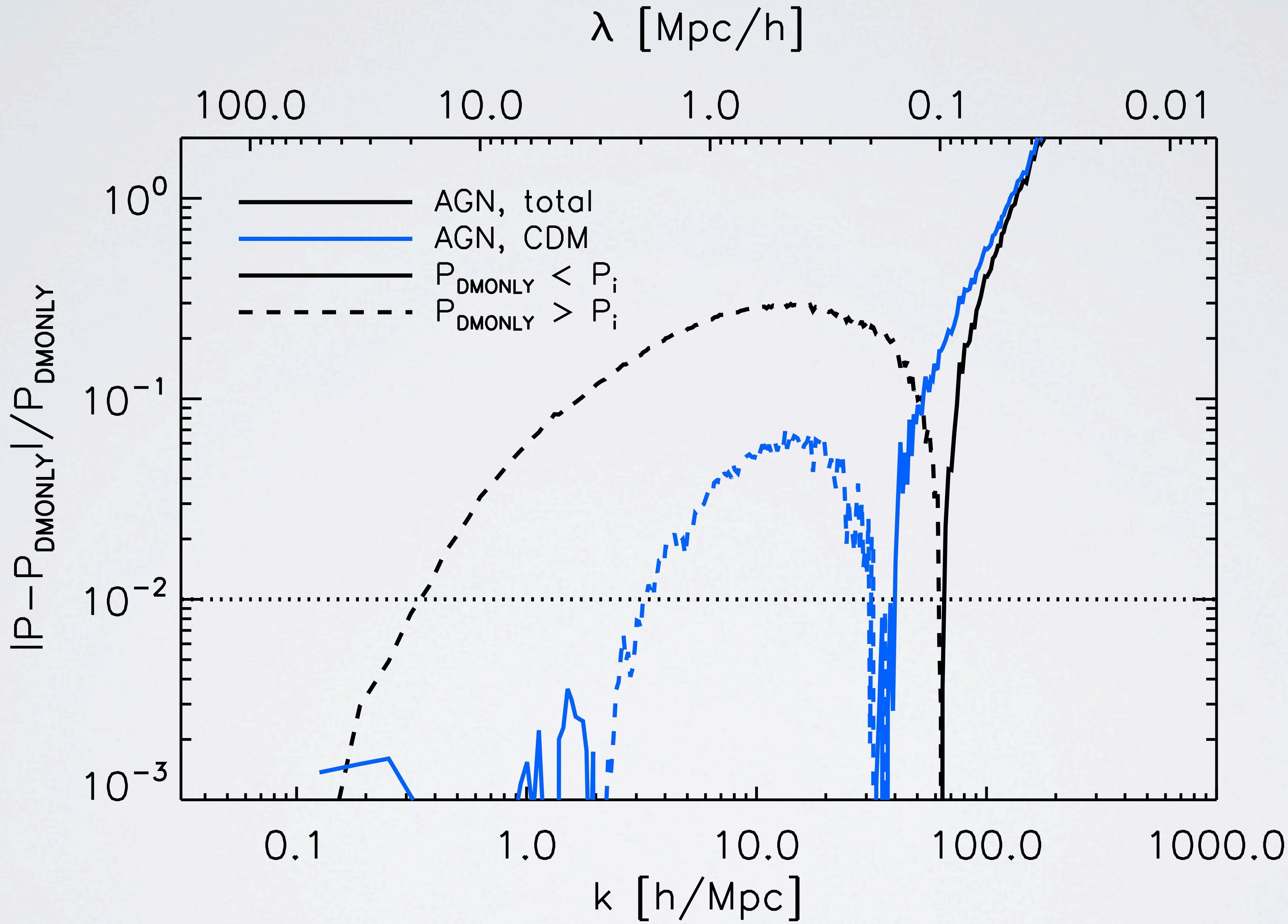


POWER SPECTRUM

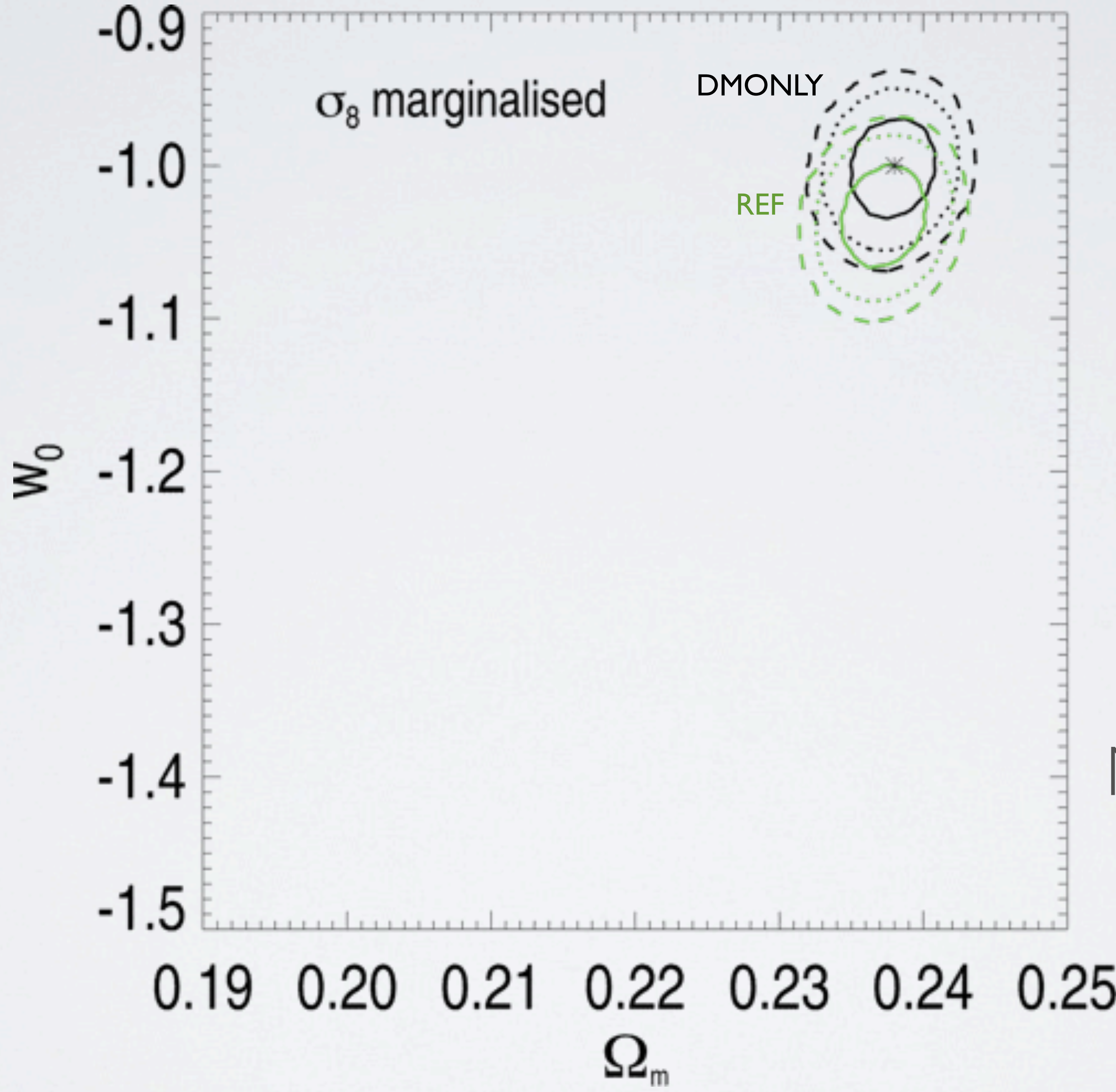
HOW DOES THIS AFFECT WEAK LENSING?

- Weak lensing needs theoretical power spectra to interpret observations

- If baryons are important on scales k<10 h/Mpc, but only dark matter is included in models, a bias is introduced

POWER SPECTRUM

EUCLID-LIKE SURVEY



Elisabetta Semboloni, Henk Hoekstra, JS, MvD & Ian McCarthy (2011)

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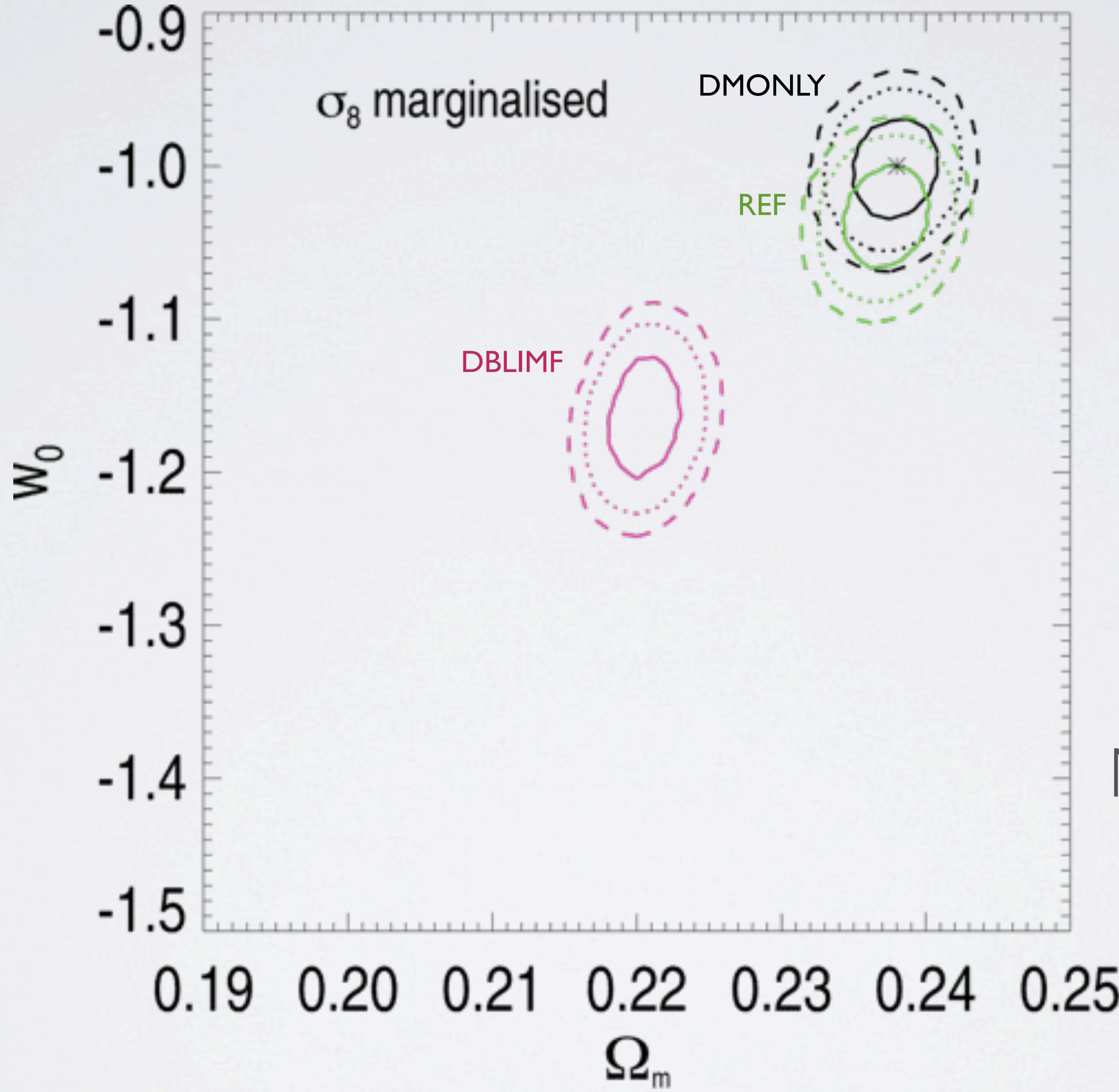

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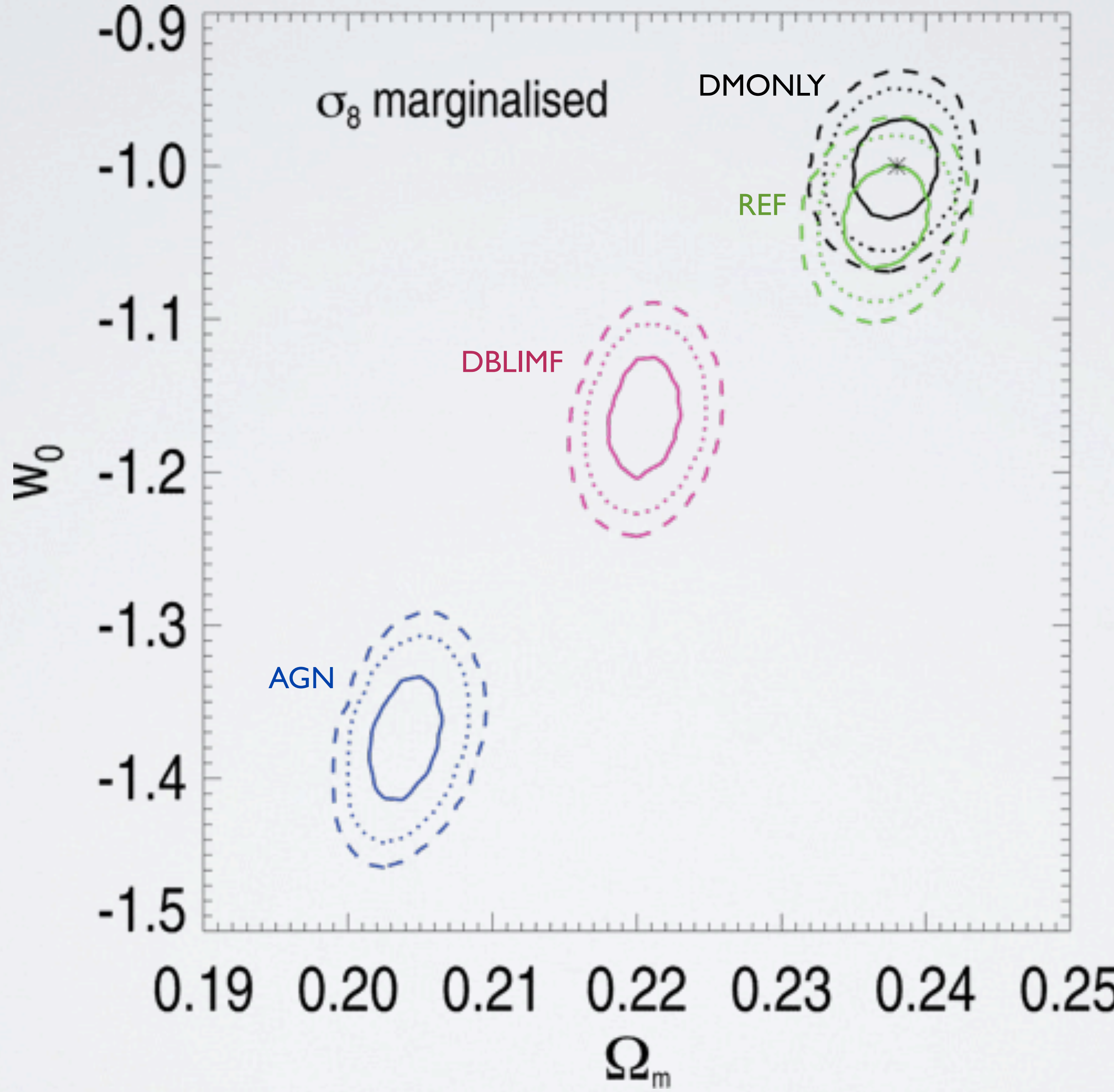

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- One solution: add a modelled distribution of the gas to the halo model (detailed observations needed!)

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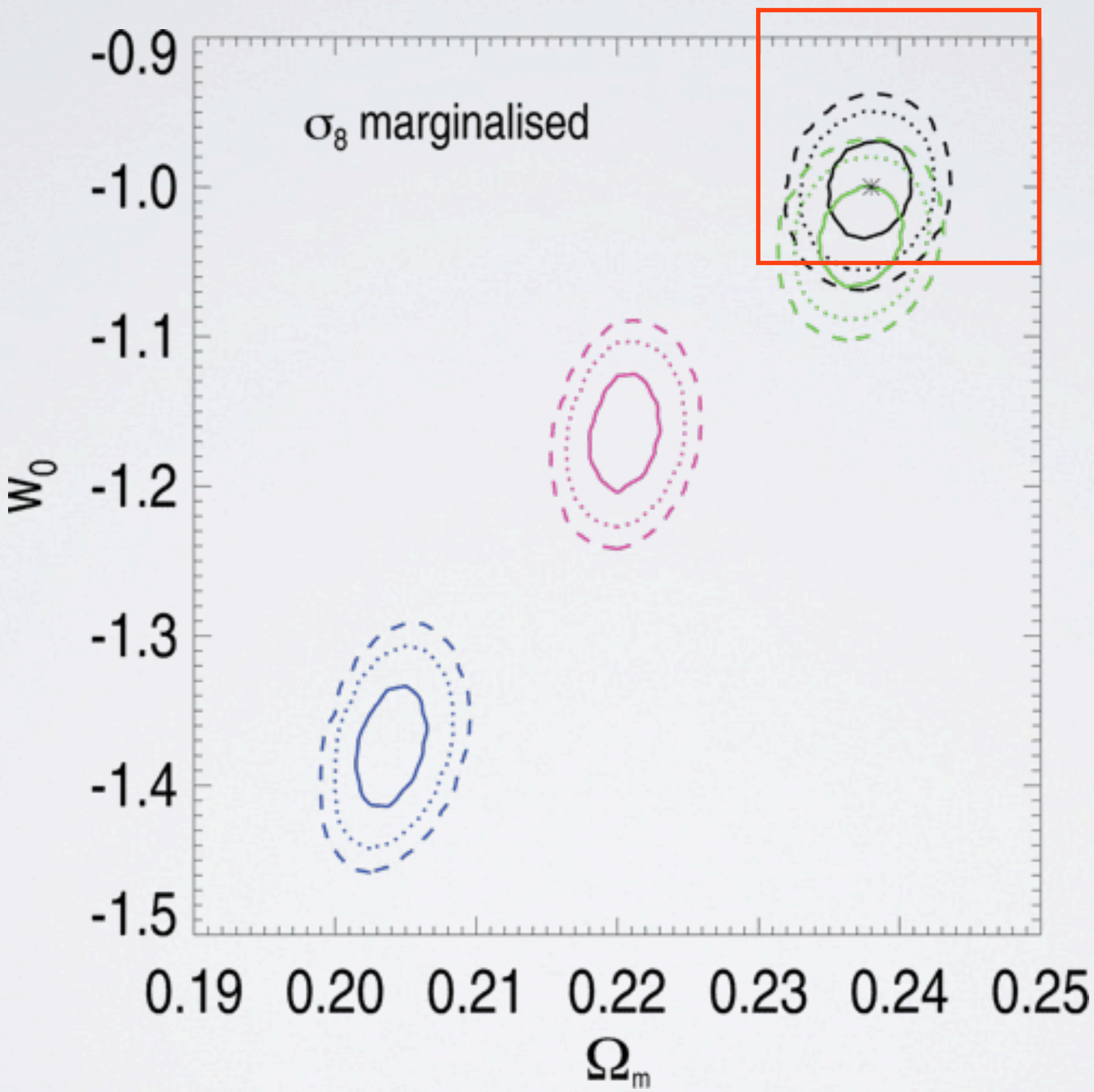

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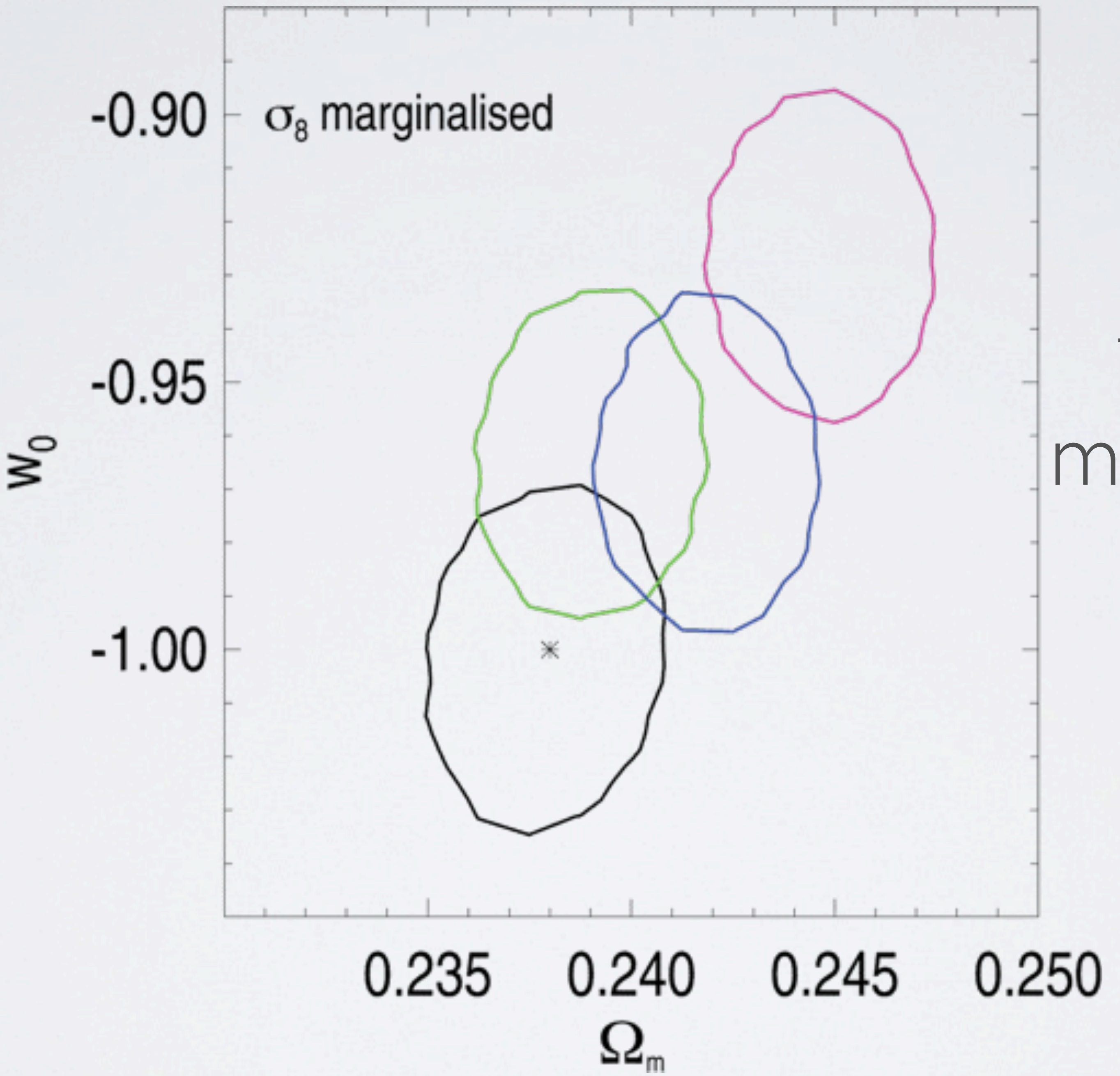

However:
this solution is
model-dependent

SUMMARY PART I

- Baryonic processes, especially AGN feedback, greatly affect the matter power spectrum, even at large scales
- Corrections can be made to reduce the (~40%!) bias, though these are (currently) model-dependent
- Better constraints on the distribution of gas in and around haloes (X-ray/SZ) are needed

van Daalen et al. 2011, arXiv: 1104.1174; Semboloni et al. 2011, arXiv: 1105.1075

PART II

THE CORRELATION FUNCTION

van Daalen et al. 2014

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- A measure of the amount of structure that has formed on a given scale/separation r

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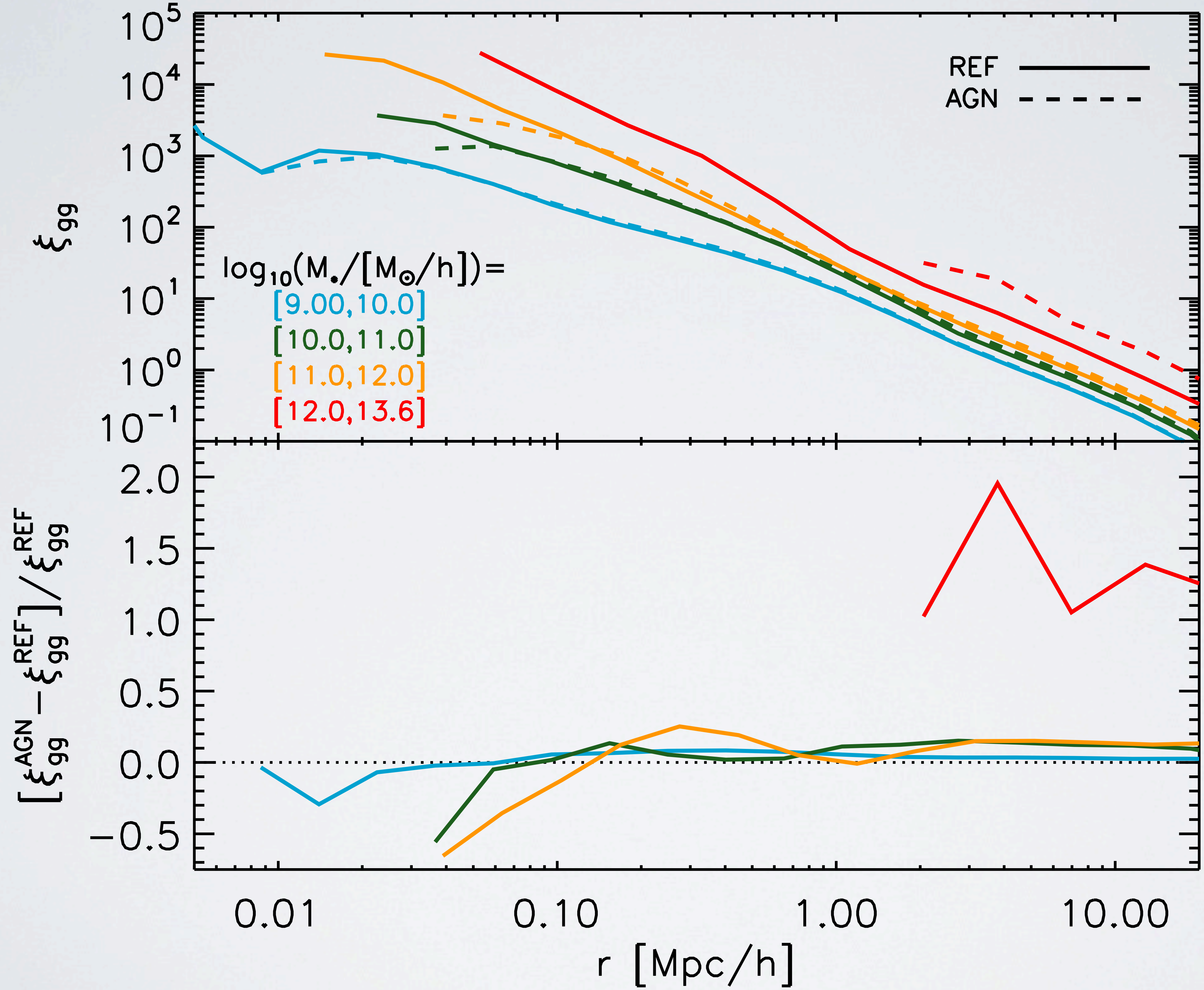
- Definitions:
  - Density fluctuations: $\delta(\mathbf{x}) \equiv \dfrac{\rho(\mathbf{x}) - \bar{\rho}}{\bar{\rho}}$
  - Galaxy correlation function: $\xi_{\rm g}(r) = \langle \delta_{\rm g}(\mathbf{r}_1)\delta_{\rm g}(\mathbf{r}_2)\rangle \quad (r = |\mathbf{r}_2 - \mathbf{r}_1|)$
    (basically counting galaxies)
  - Galaxy-mass cross-correlation function: $\xi_{\rm gm}(r) = \langle \delta_{\rm g}(\mathbf{r}_1)\delta_{\rm m}(\mathbf{r}_2)\rangle$
    (indication of the lensing signal)

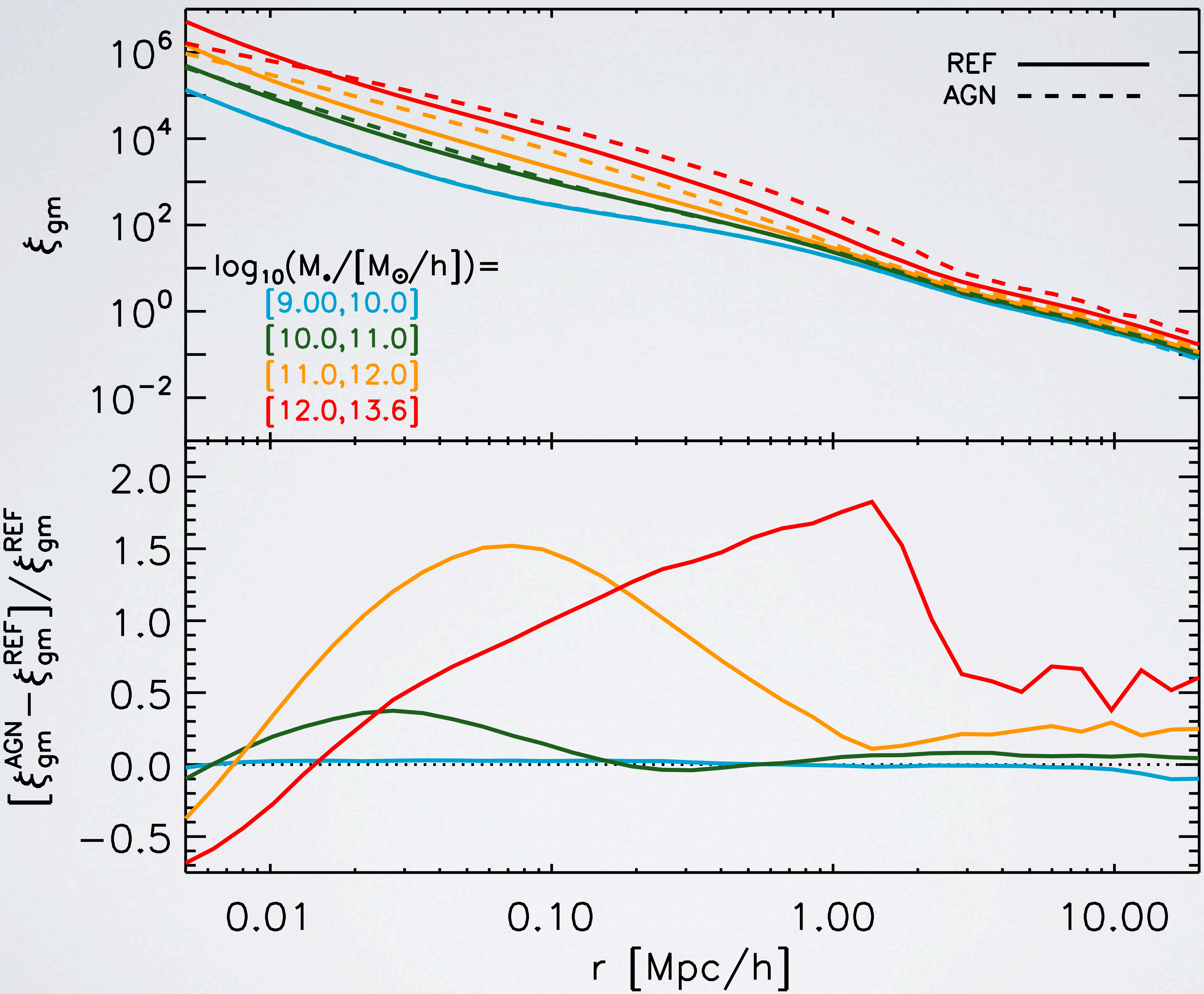
SIMULATIONS

- Cosmo-OWLS simulations: *DMONLY*, *REF, AGN* (identical initial conditions!), all WMAP7 cosmology
- *REF* contains radiative cooling/heating, star formation, chemical enrichment, supernova feedback
- *AGN* contains the same, plus AGN feedback
- 200 Mpc/h and 400 Mpc/h boxes with ε_{max}=2-4 pkpc/h

GALAXY - GALAXY



GALAXY - MASS



REF
AGN
ξ_{gm}
10^6
10^4
10^2
10^0
10^{-2}
$\log_{10}(M_*/[M_\odot/h])=$
[9.00,10.0]
[10.0,11.0]
[11.0,12.0]
[12.0,13.6]
$[\xi_{gm}^{AGN}-\xi_{gm}^{REF}]/\xi_{gm}^{REF}$
2.0
1.5
1.0
0.5
0.0
−0.5
0.01
0.10
1.00
10.00
r [Mpc/h]

SUBHALOES, NOT GALAXIES

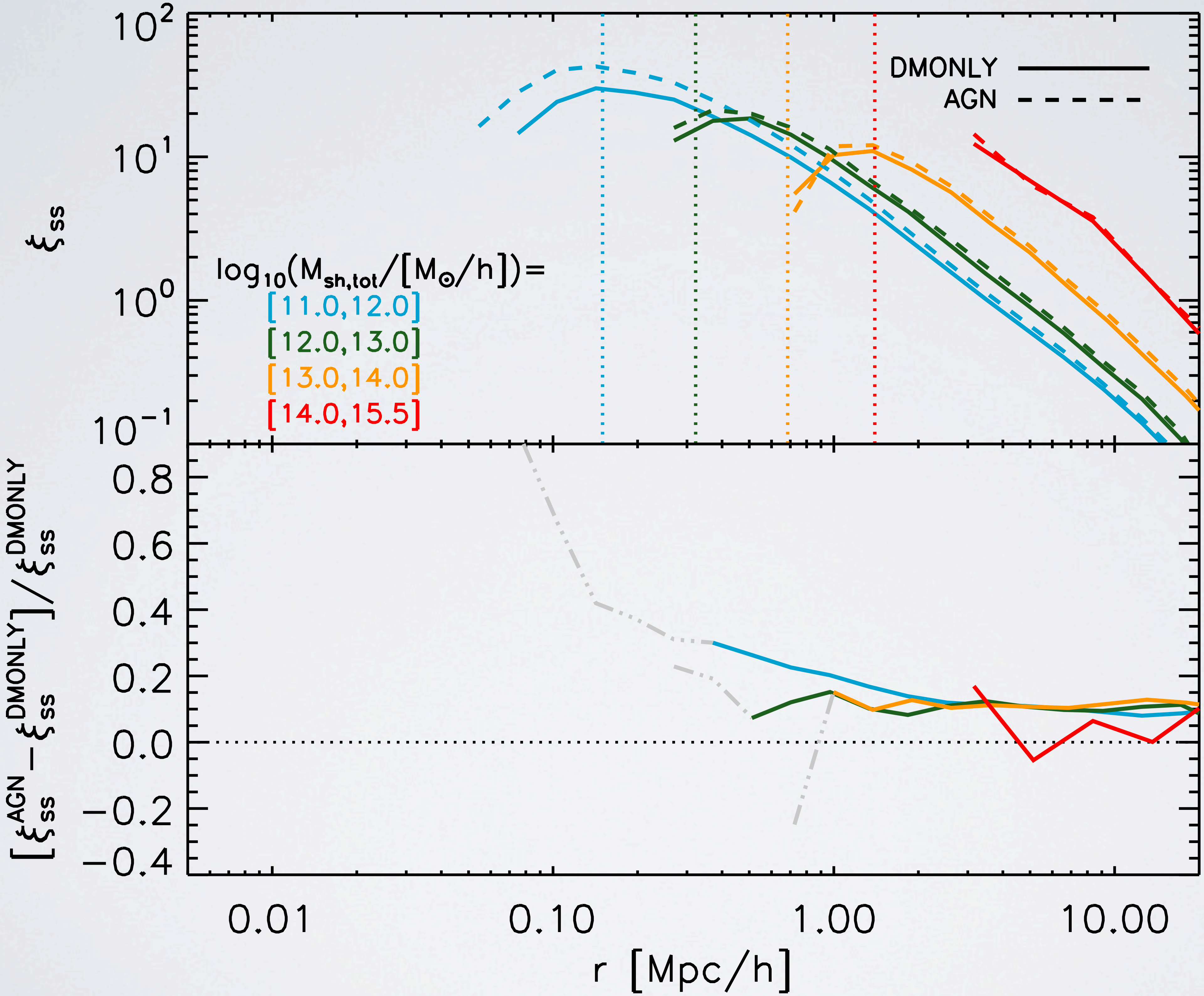
- Stellar masses highly sensitive to code, subgrid recipes and cosmology – often quite wrong in hydro simulations

- SHAM and SAMs do reproduce the M_*-M_h relation, and clustering models typically use these predictions

  ⇒ Use subhaloes instead of galaxies

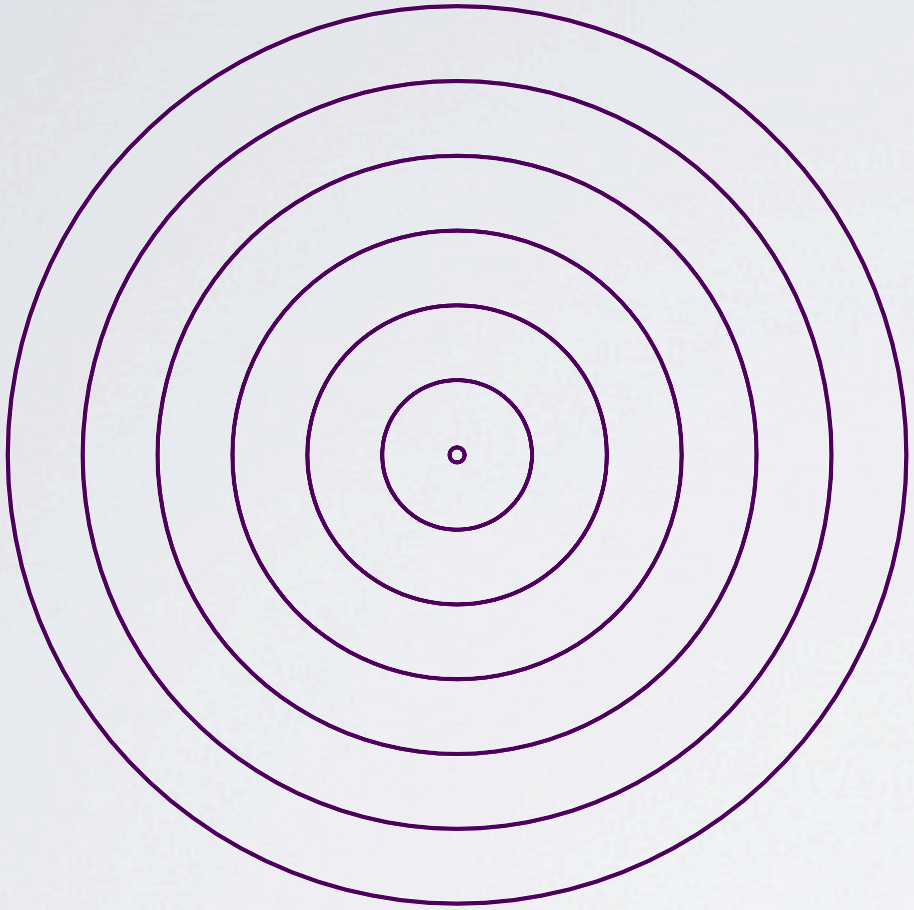
- That way, we can consider the effects of galaxy formation relative to a dark matter only scenario

SUBHALO - SUBHALO



PROFILE CHANGES

Only CDM



Also baryons

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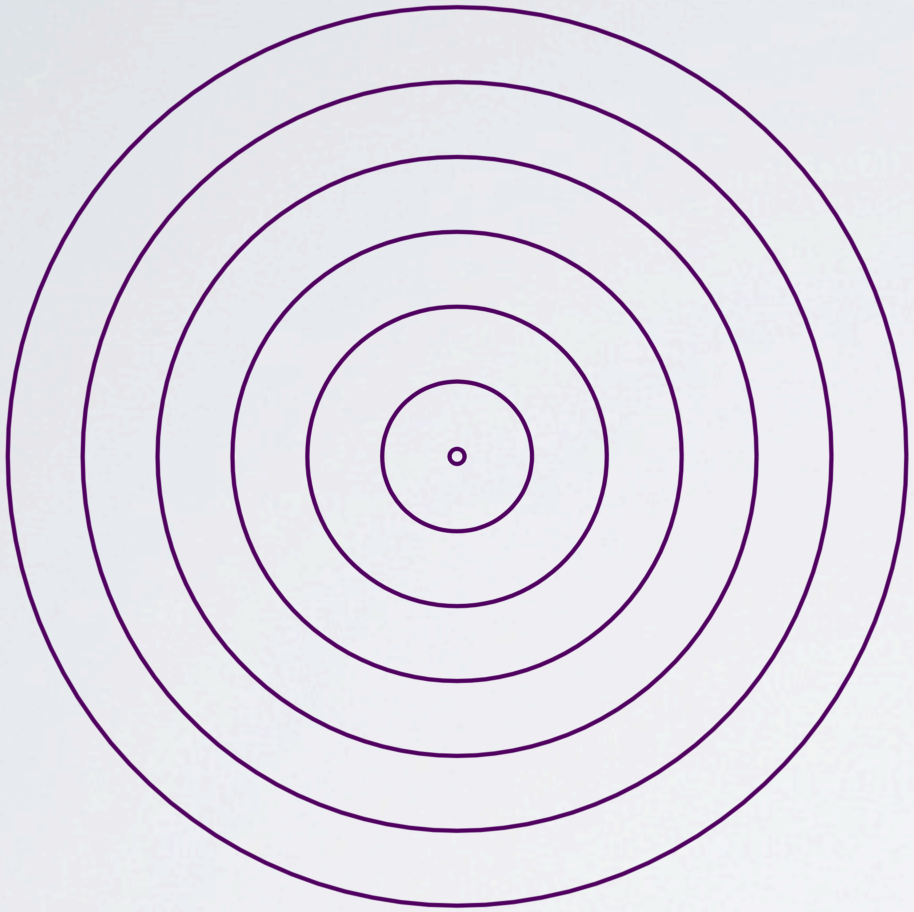

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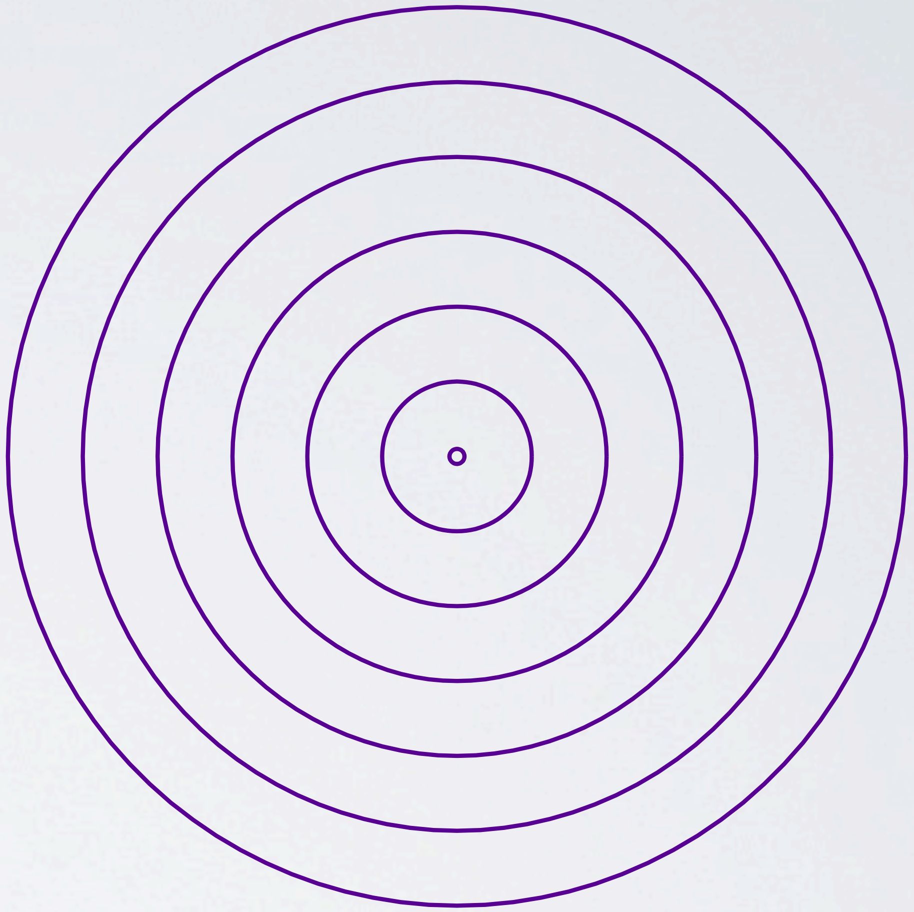

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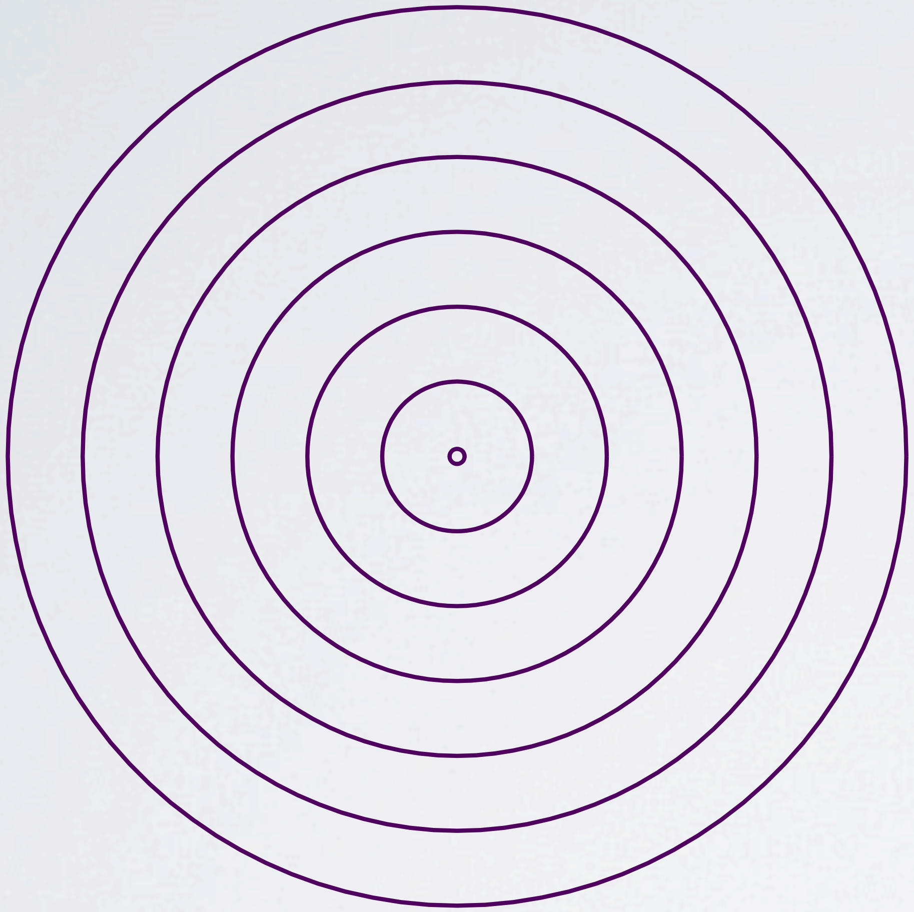

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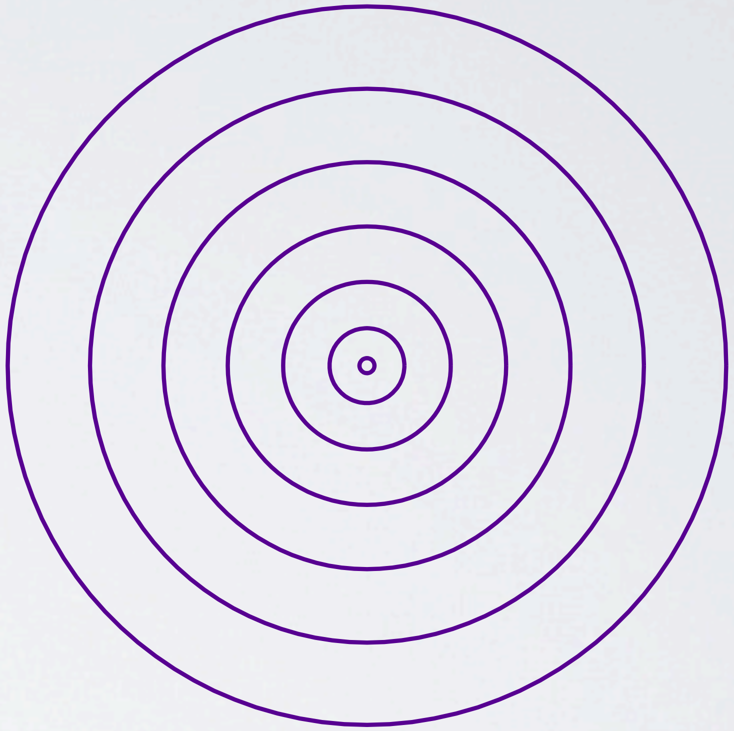

Baryons make the profile more concentrated

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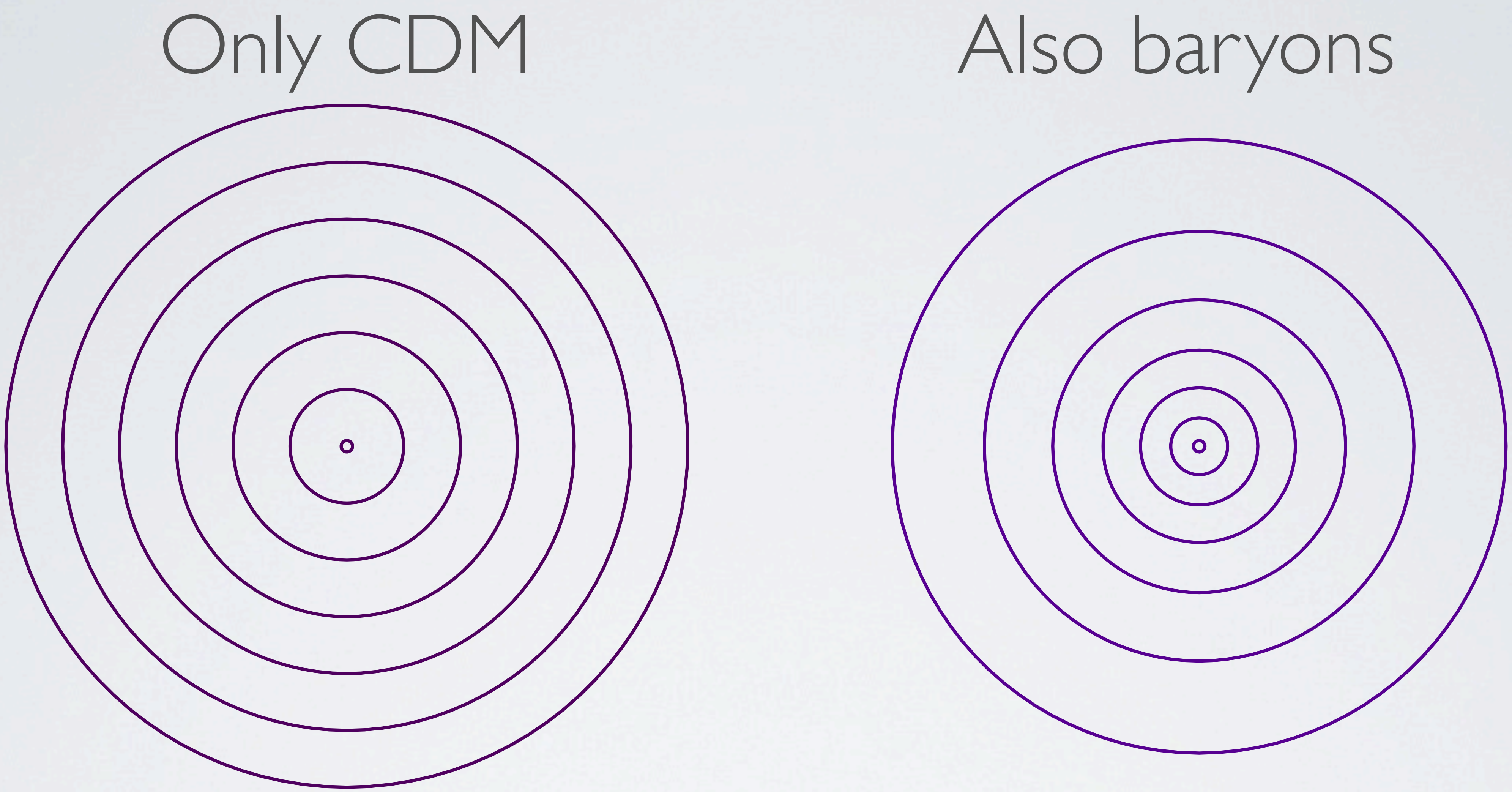
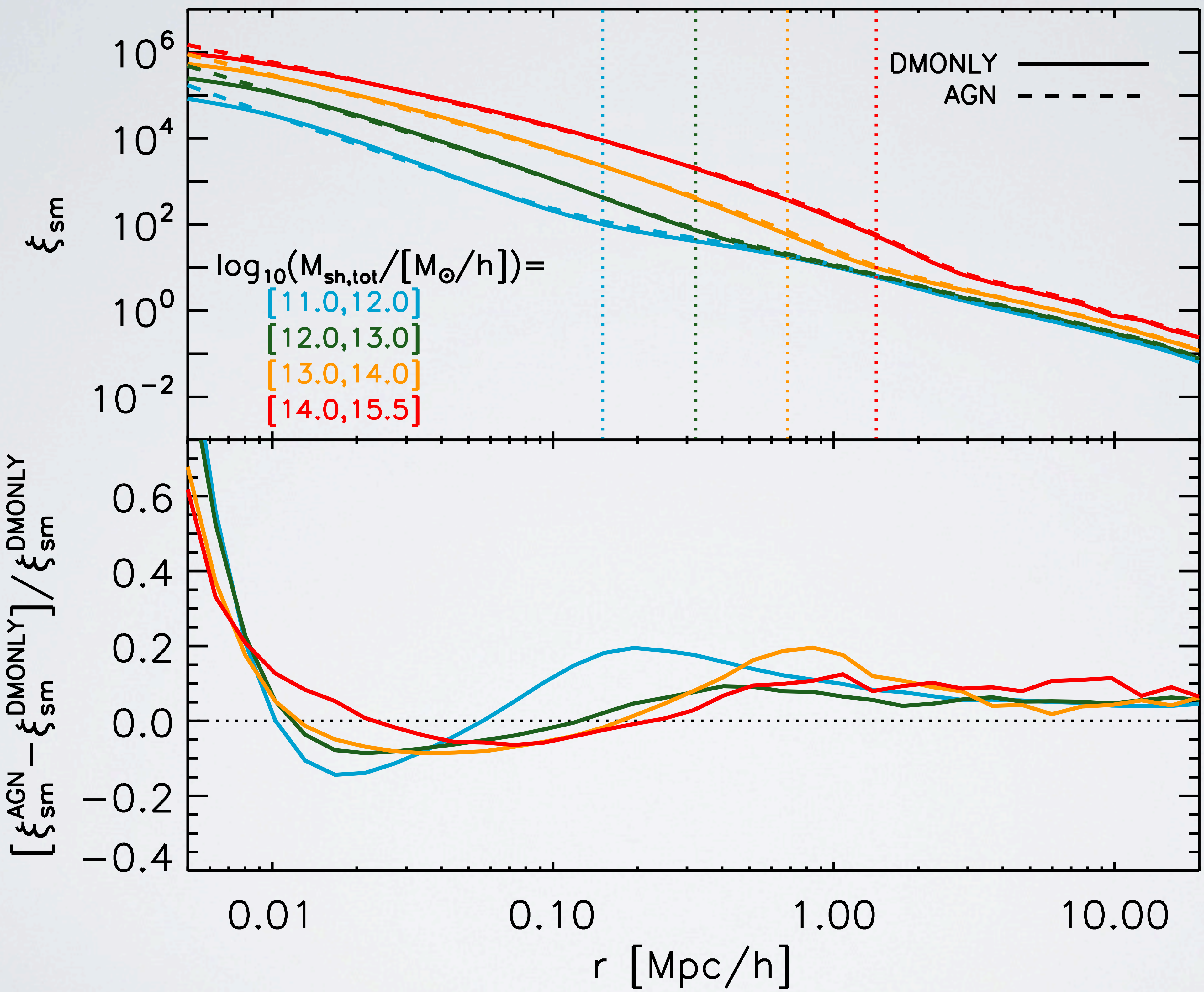


Baryons make the profile more concentrated

Efficient feedback partly negates this!

SUBHALO - MASS



LINKING SUBHALOES

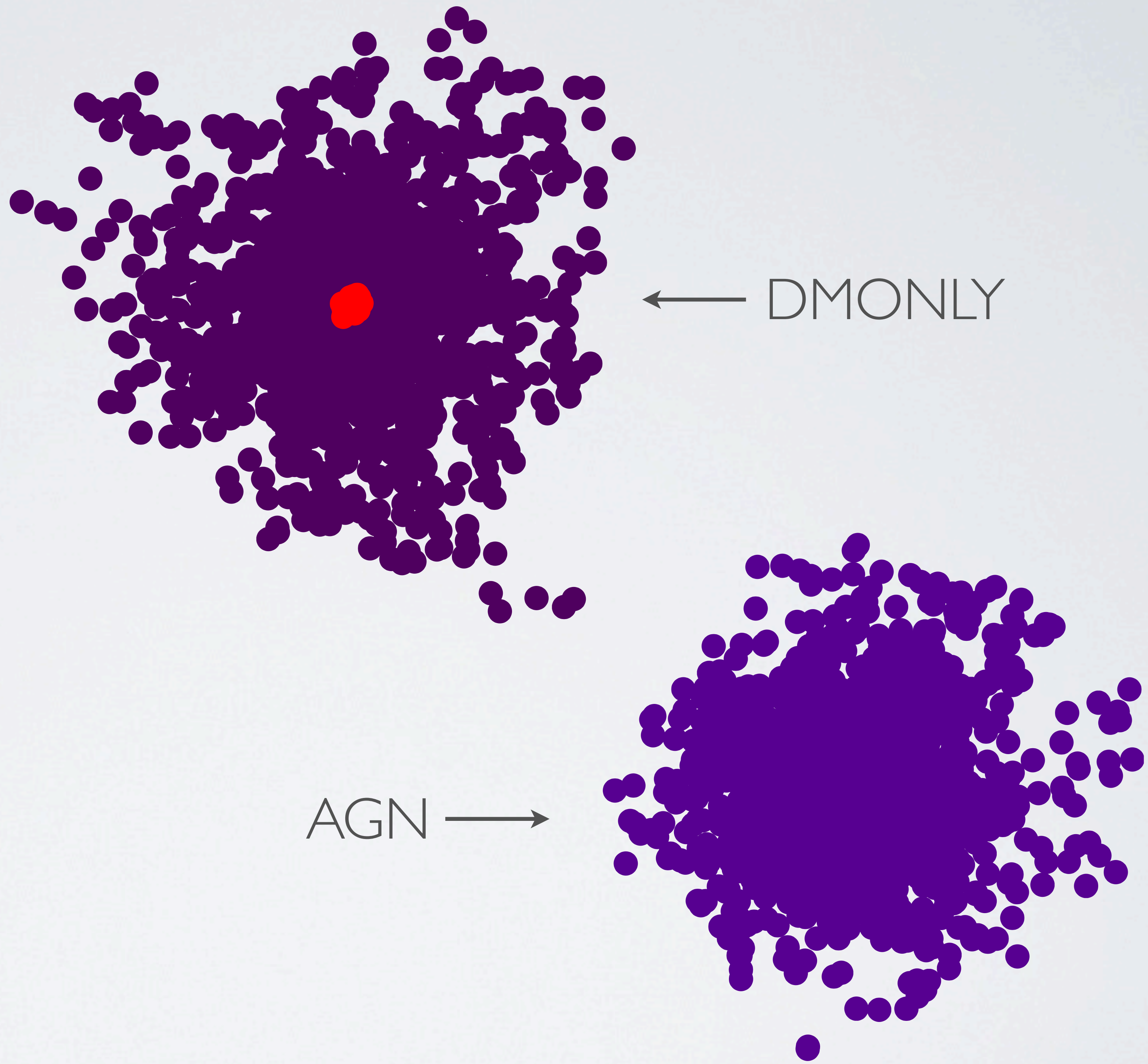
- Feedback lowers the mass of objects, but we may be able to account for this mass-dependently (e.g. Velliscig et al. 2014)

- What part of the effect we see is due to the masses changing?

- Investigate by linking subhaloes between different simulations

LINKING SUBHALOES

(1) Flag 50 most-bound CDM particles



LINKING SUBHALOES

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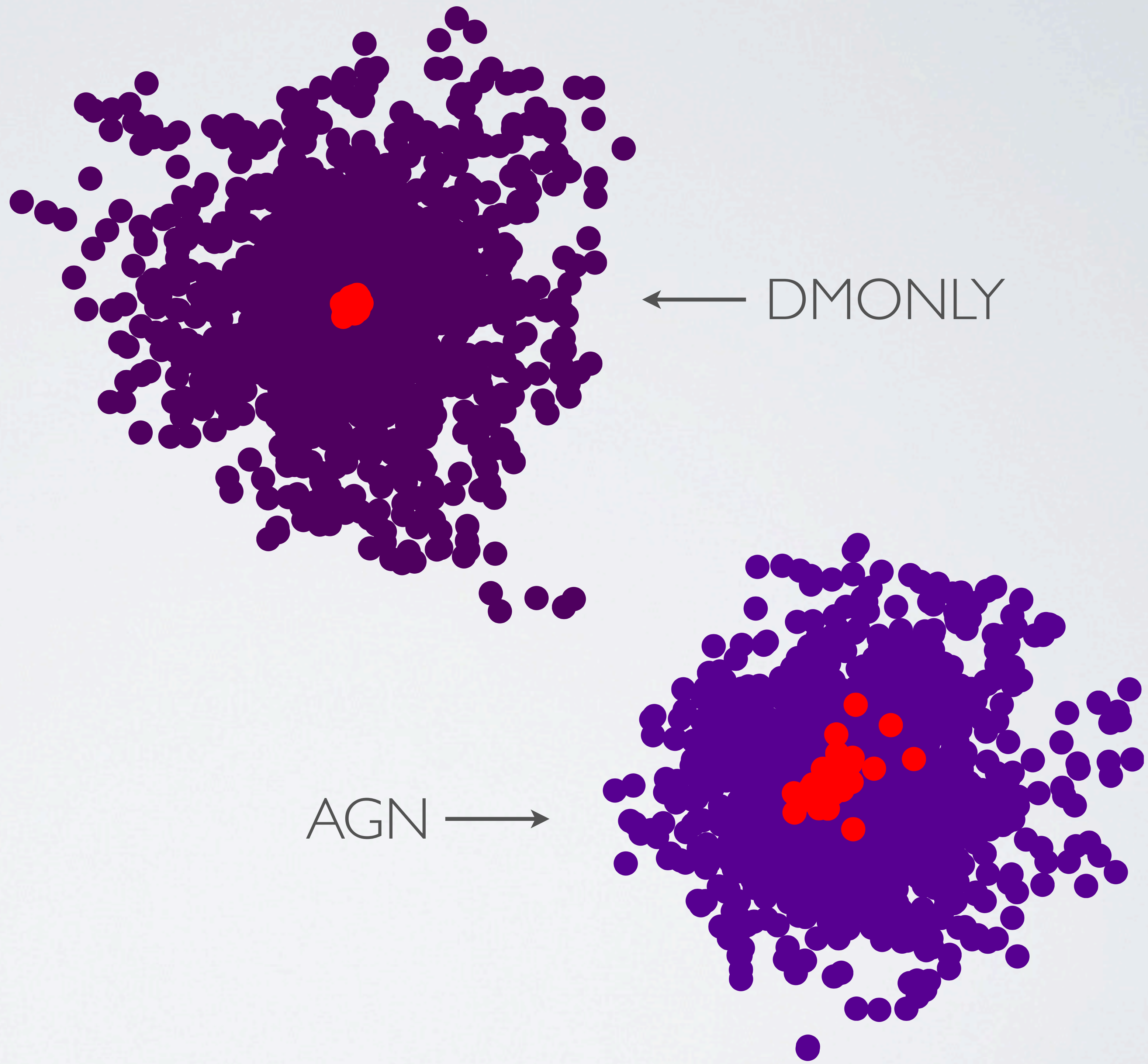

LINKING SUBHALOES

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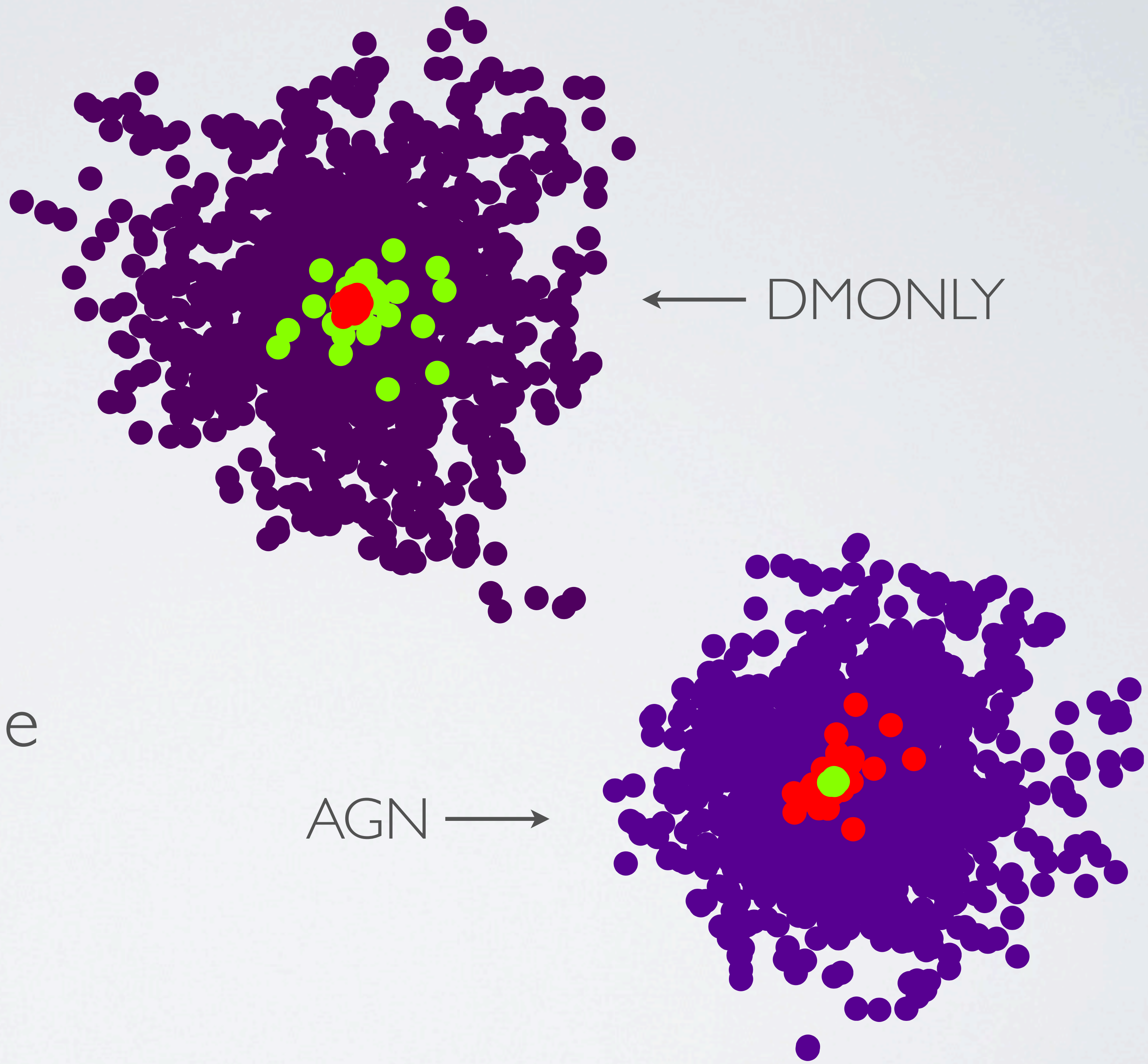
(3) Confirm link if the reverse is true

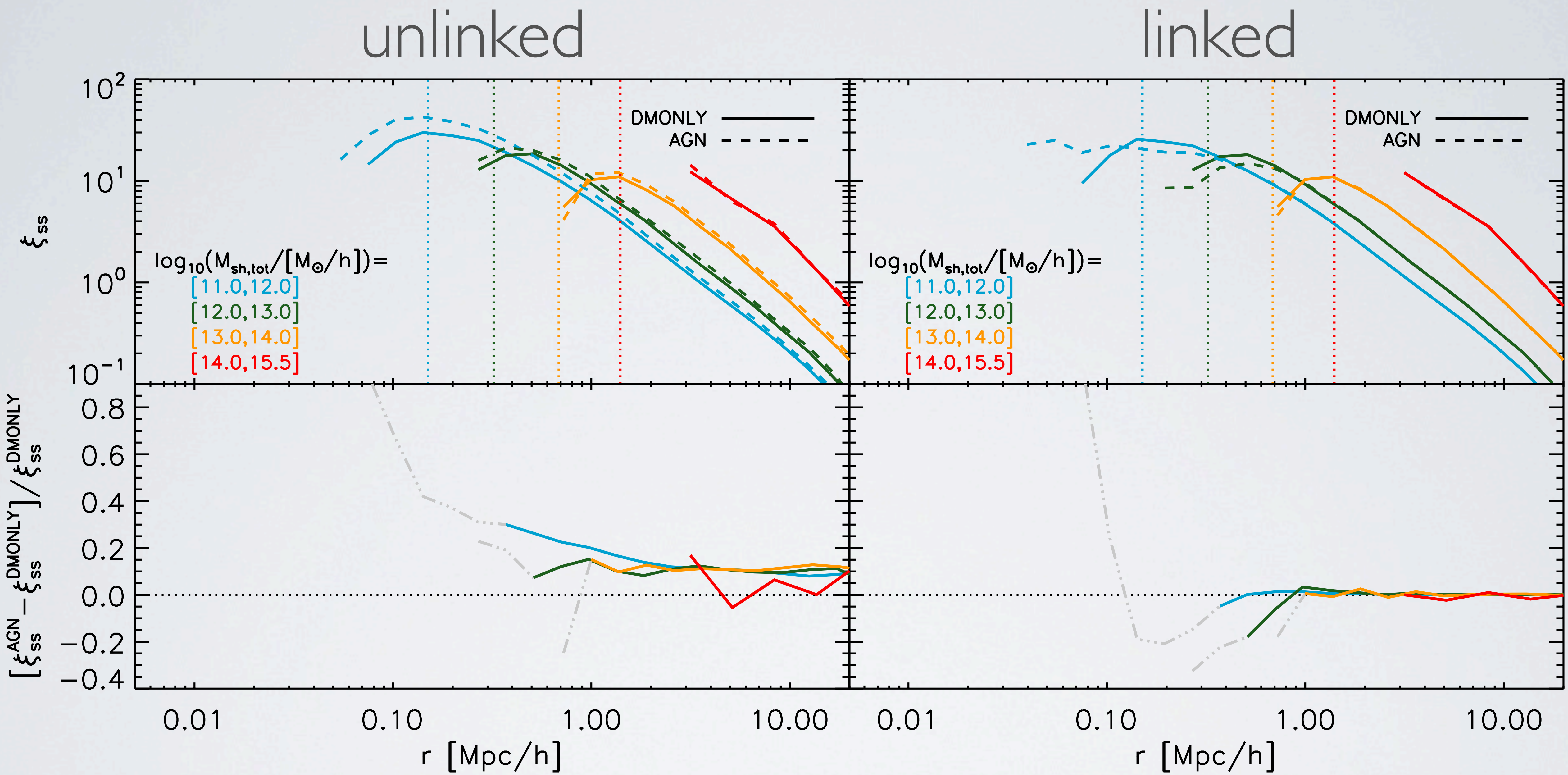


LINKING SUBHALOES

- Linked fraction is ~98% for the lowest-mass subhaloes, typically >99%

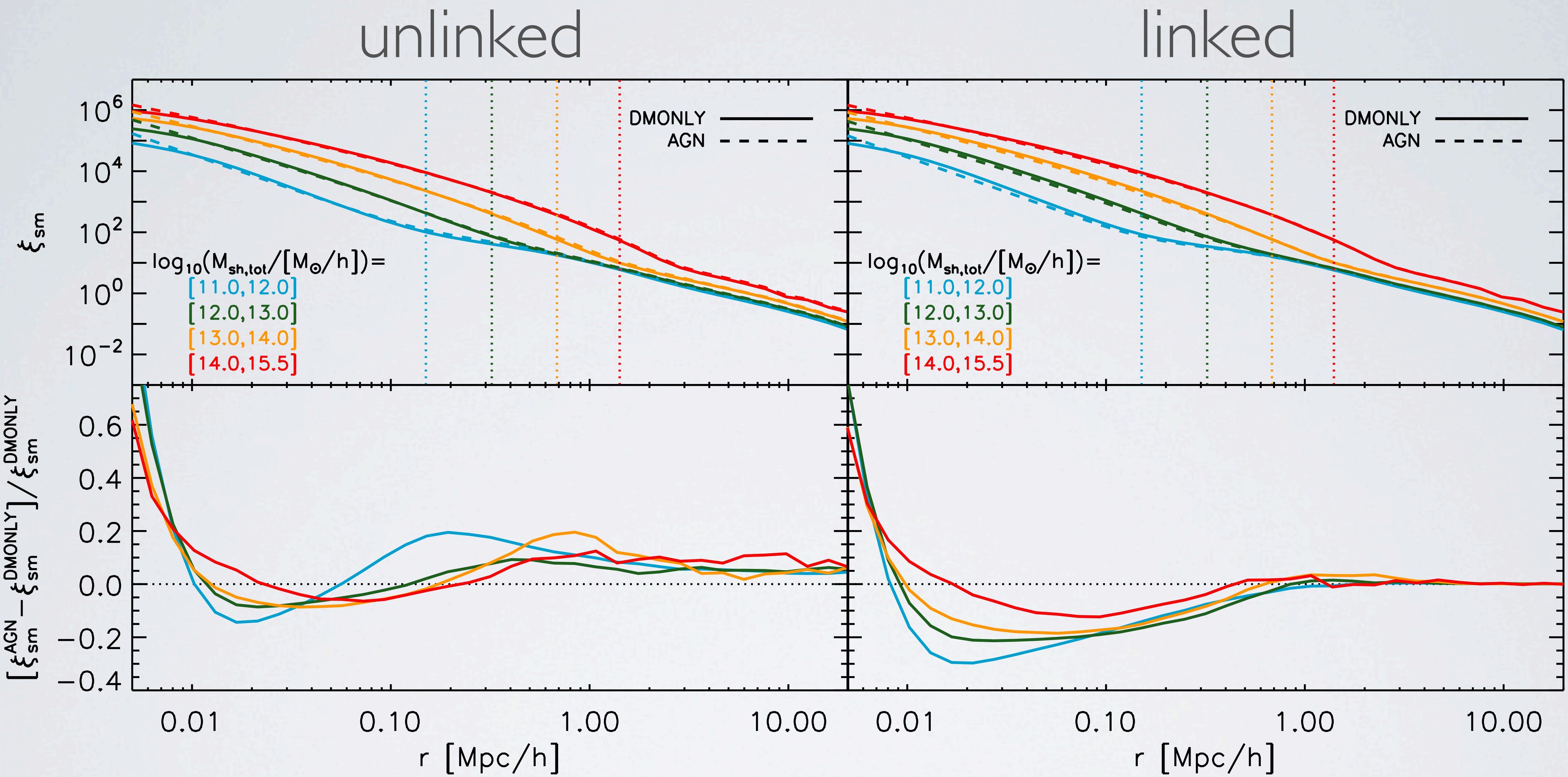
- Calculate correlation functions again, but now selecting by DMONLY mass → effectively removes the mass change!

SUBHALO CLUSTERING



Effect goes away entirely for $r \gtrsim 2r_{\rm vir}$!

SUBHALO - MASS



Change of subhalo profiles still important!

SUMMARY PART II

- Galaxy formation changes clustering a lot, both by changing the masses of objects and the overall distribution of mass
- When mass-selecting objects, account for the mass change due to galaxy formation or be biased by ~10%
- For the clustering of matter, accounting for the change in profiles/large-scale gas distribution is most important (out to beyond even r_{vir}!)

van Daalen et al. 2014, arXiv: 1310.7571