The BAHAMAS project

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BAHAMAS team in Liverpool:
Juliana Kwan (postdoc), Jaime Salcido (postdoc), Andreea Font (staff)
Students: Alberto Acuto, Shaun Brown, Egidijus Kukstas, Simon Pfeifer, Sam Stafford

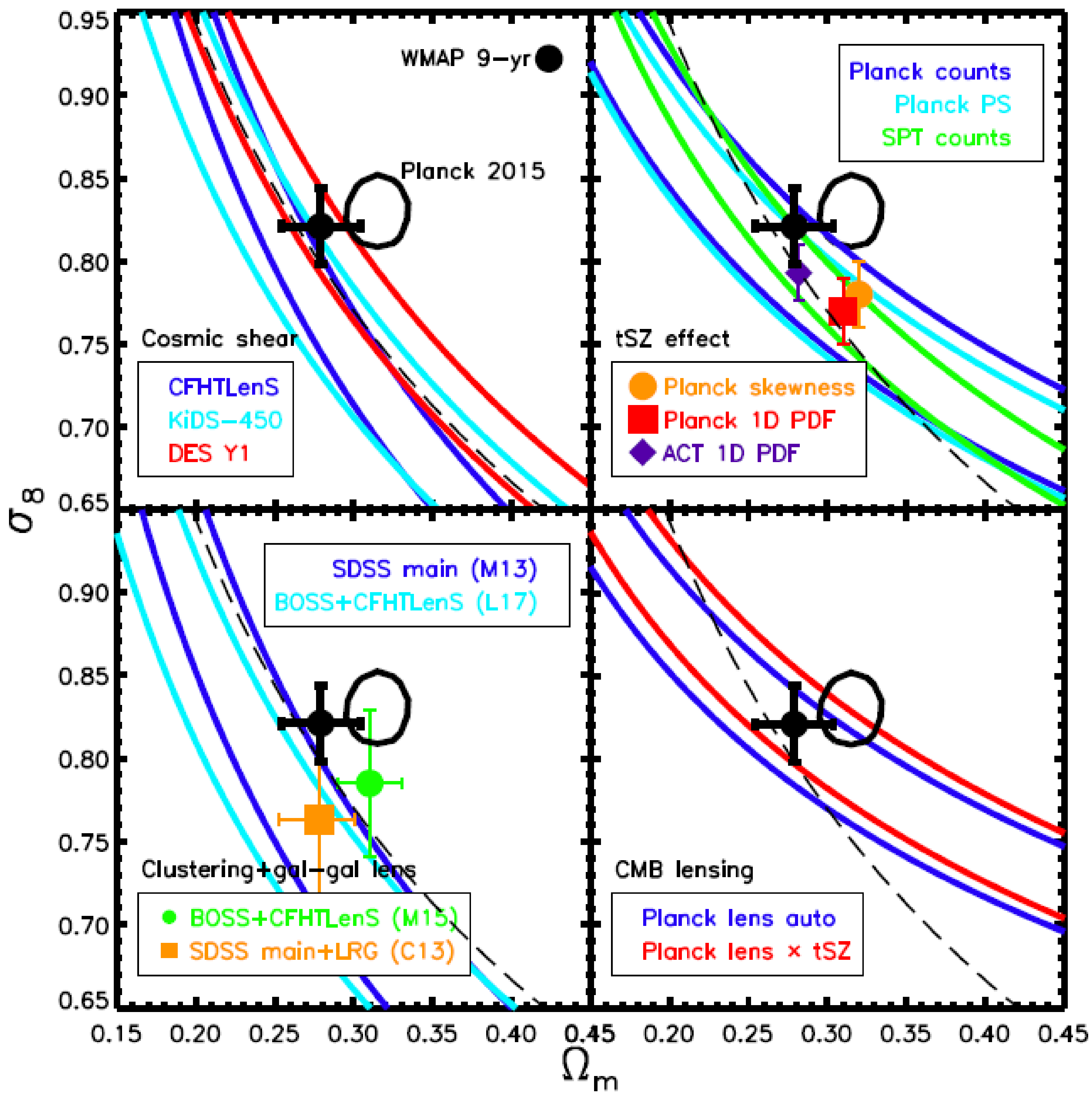
Collaborators:
Joop Schaye (Leiden), Simeon Bird (UC Riverside), Marcel van Daalen (Leiden), Joachim Harnois-Deraps (Edinburgh), Ludovic van Waerbeke (UBC)

BAHAMAS: scientific objective

Assess the evidence for physics beyond the standard model of cosmology, through *theoretically-unbiased* comparisons of cosmological simulations to large-scale structure (LSS) data.

McCarthy+2018, MNRAS

The CMB—large-scale structure tension



Ω_m = present-day matter density

σ_8 = present-day, linearly-evolved amplitude of density fluctuations on a scale of 8 Mpc/h

Solid circle – Planck 2015 constraints based on the cosmic microwave background (CMB)

Coloured curves – large-scale structure constraints ("growth of structure"). Fluctuation growth sensitive to background expansion and primordial power spectrum.

McCarthy+2018, MNRAS

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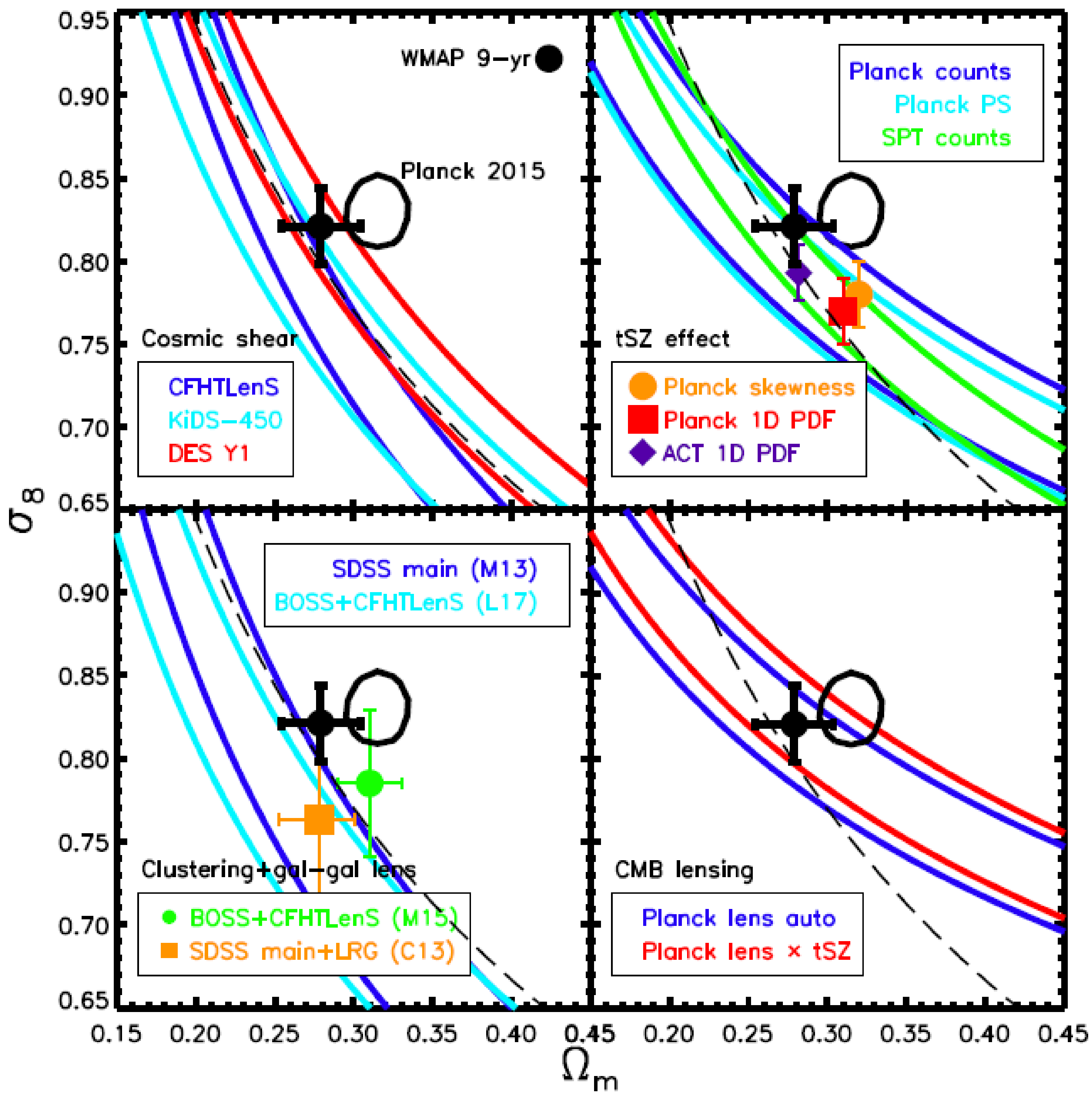


Possible solutions:

- Systematic errors in CMB measurements/analysis

- Systematic errors in LSS measurements

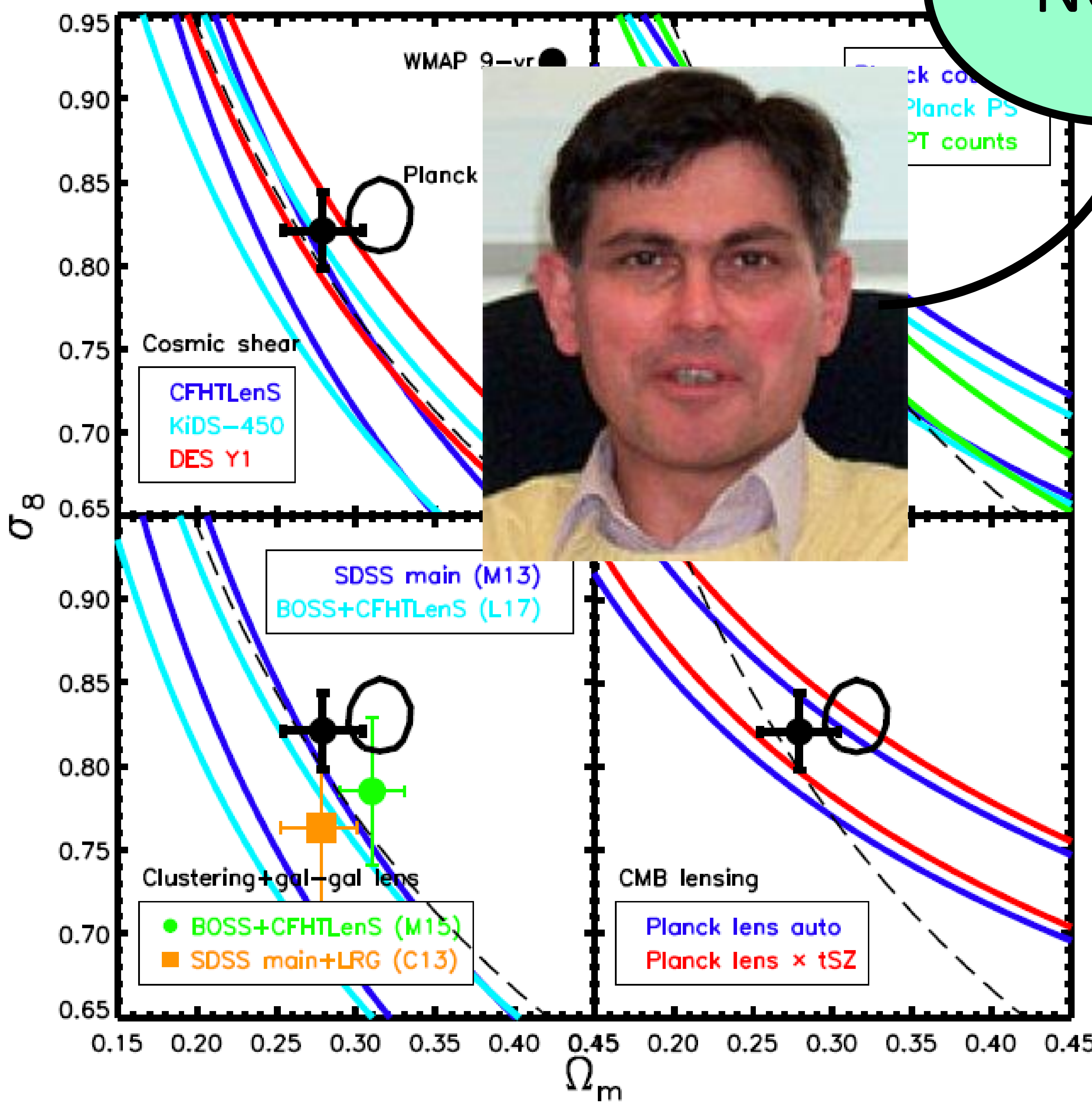
- Theoretical LSS predictions are missing relevant astrophysics

- The standard model of cosmology (ΛCDM) is incorrect

McCarthy+2018, MNRAS

The CMB—large-scale … tension

NO!!!



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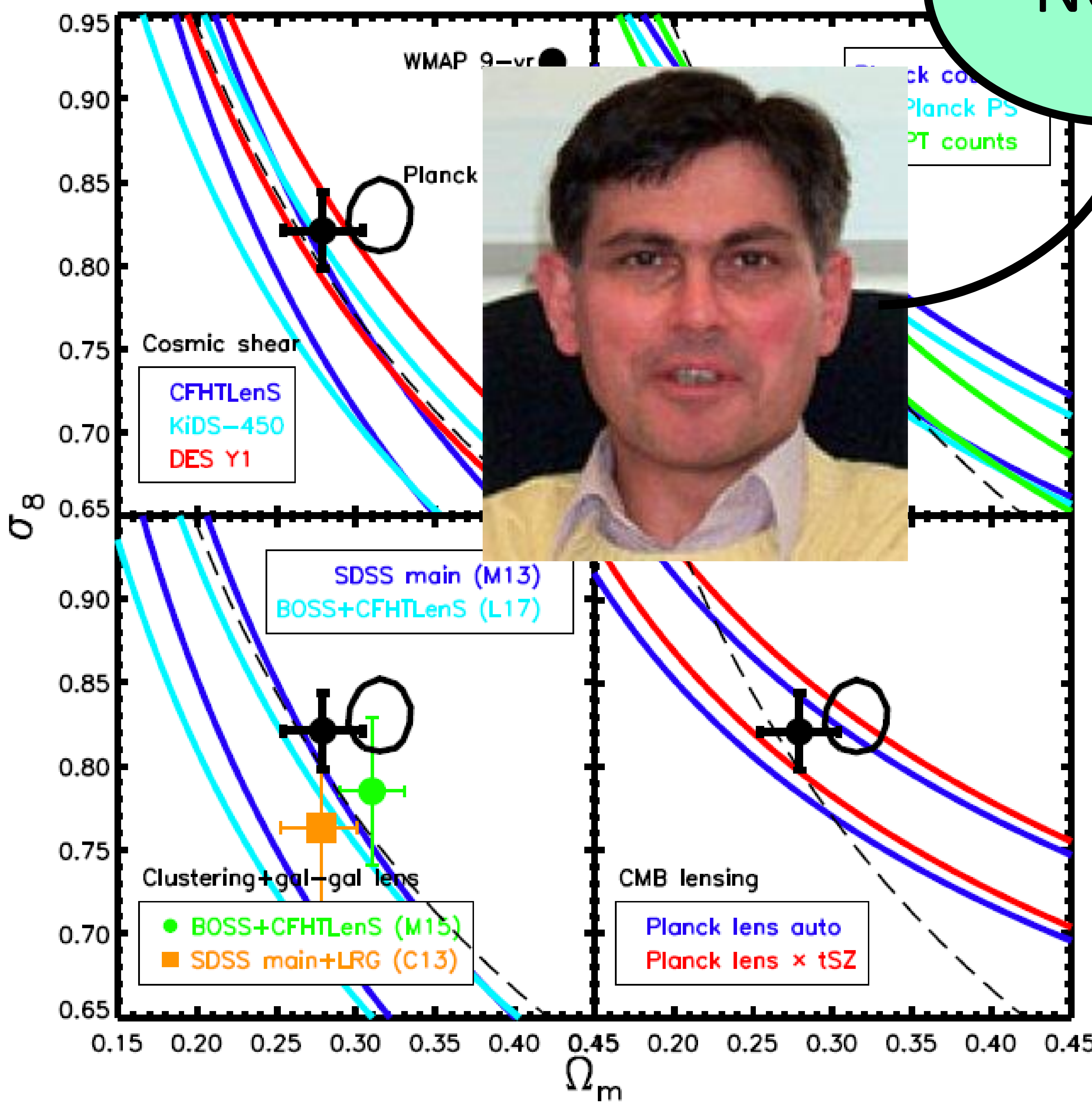

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Some possible alterations of ΛCDM

What we need are mechanisms which can **slow** the growth of structure compared to the standard model predictions.

Some options are:

- Time-varying dark energy (e.g., quintessence, k-essence)

- Modified gravity (deviations from GR on largest scales)

- Running spectral index of the primordial power spectrum

- Interesting dark matter (e.g., SIDM, decaying)

- Massive neutrinos

Some possible alterations of ΛCDM

What we need are mechanisms which can **slow** the growth of structure compared to the standard model predictions.

Some options are:

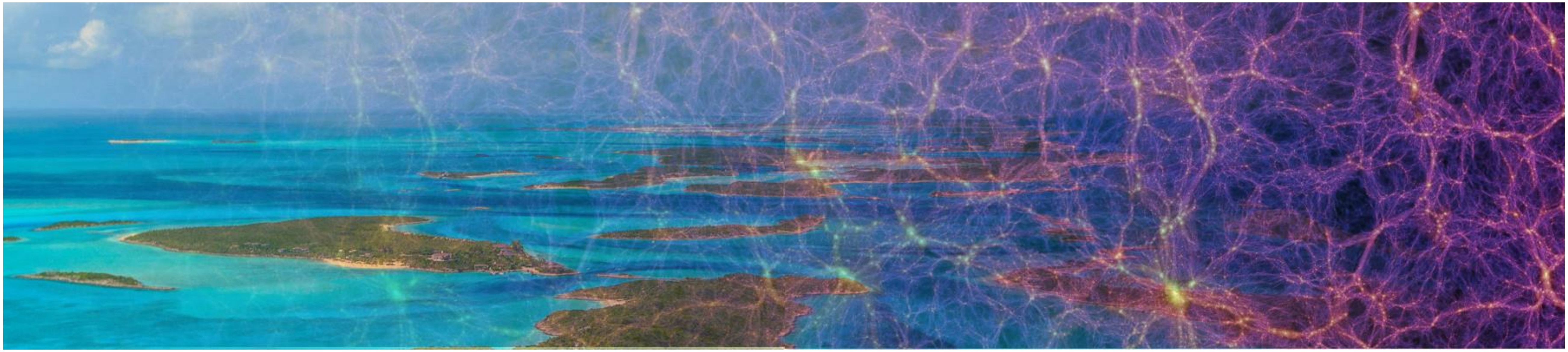
- Time-varying dark energy (Pfeifer et al. 2019, to be submitted)

- Modified gravity (deviations from GR on largest scales)

- Running spectral index of the primordial power spectrum (Stafford et al. 2019, submitted)
- Interesting dark matter (Robertson+2019)

- Massive neutrinos (McCarthy et al. 2018)

BAHAMAS: BAryons and HAloes of MAssive Systems



- Large 400 h^{-1} Mpc boxes (2×1024^3 particles) for a variety of cosmologies: **WMAP9** and **Planck 2015**, with and without massive neutrinos. Relatively fast (low res.) but lots of storage required!

- Transfer function computed with CAMB. Initial conditions at z=127 made with Simeon's modified version of Springel's N-GenIC. Modifications: 2LPT corrections and neutrino support.

- Neutrinos followed self-consistently with CDM+baryons using semi-linear method of Ali-Haimoud & Bird (2013).

- Runs with M_ν = 0.06, 0.12, 0.24, 0.48 eV. Adopt a normal hierarchy.

Feedback processes can affect LSS

Winds and jets driven by star formation and black hole accretion can eject large quantities of baryons from collapsed structures.

Gravitational back reaction on dark matter causes it to expand as well.

These effects are uncertain and normally ignored

van Daalen+2011, Springel+2017, Mummery+2017, Chisari+2018

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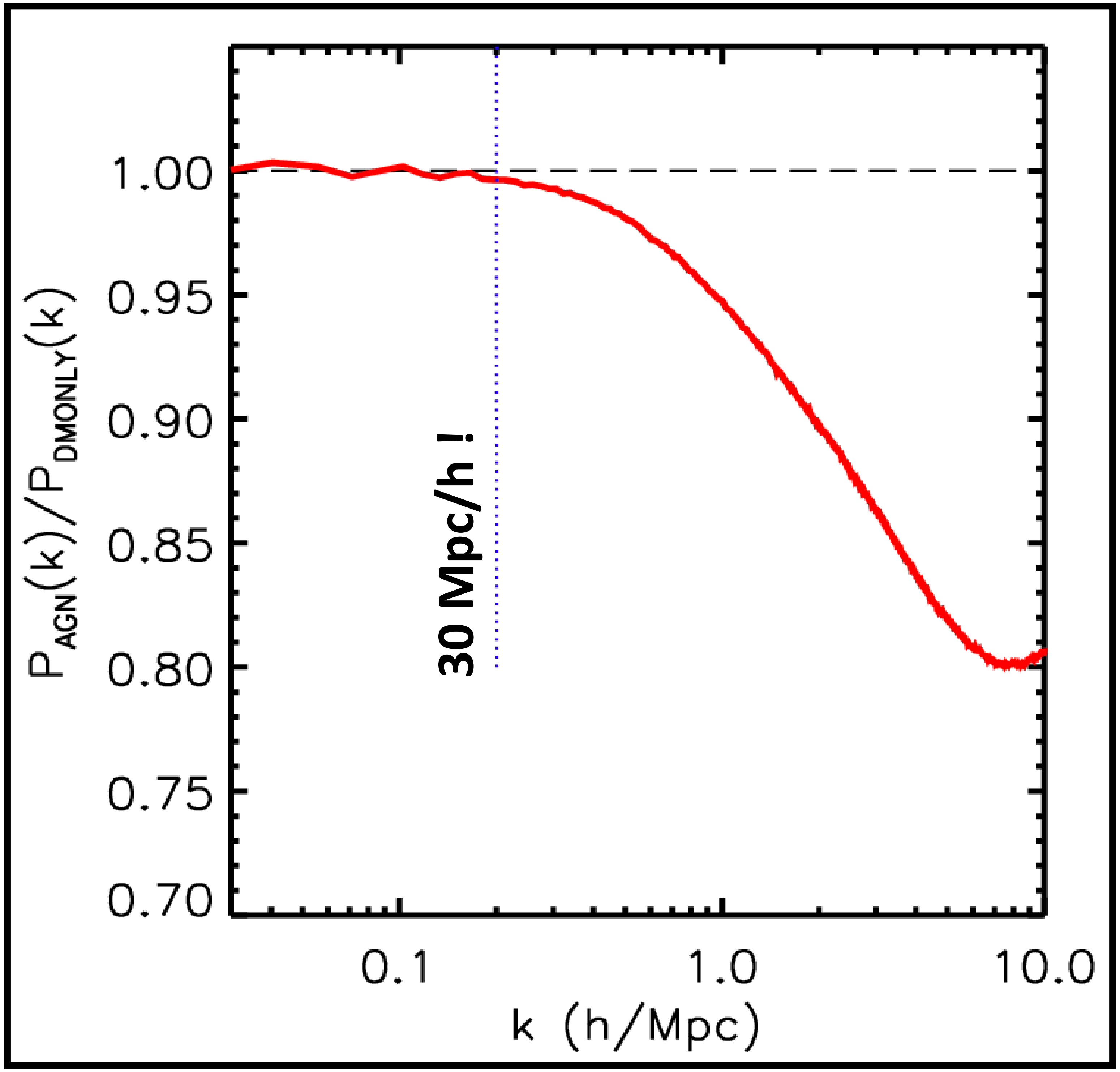

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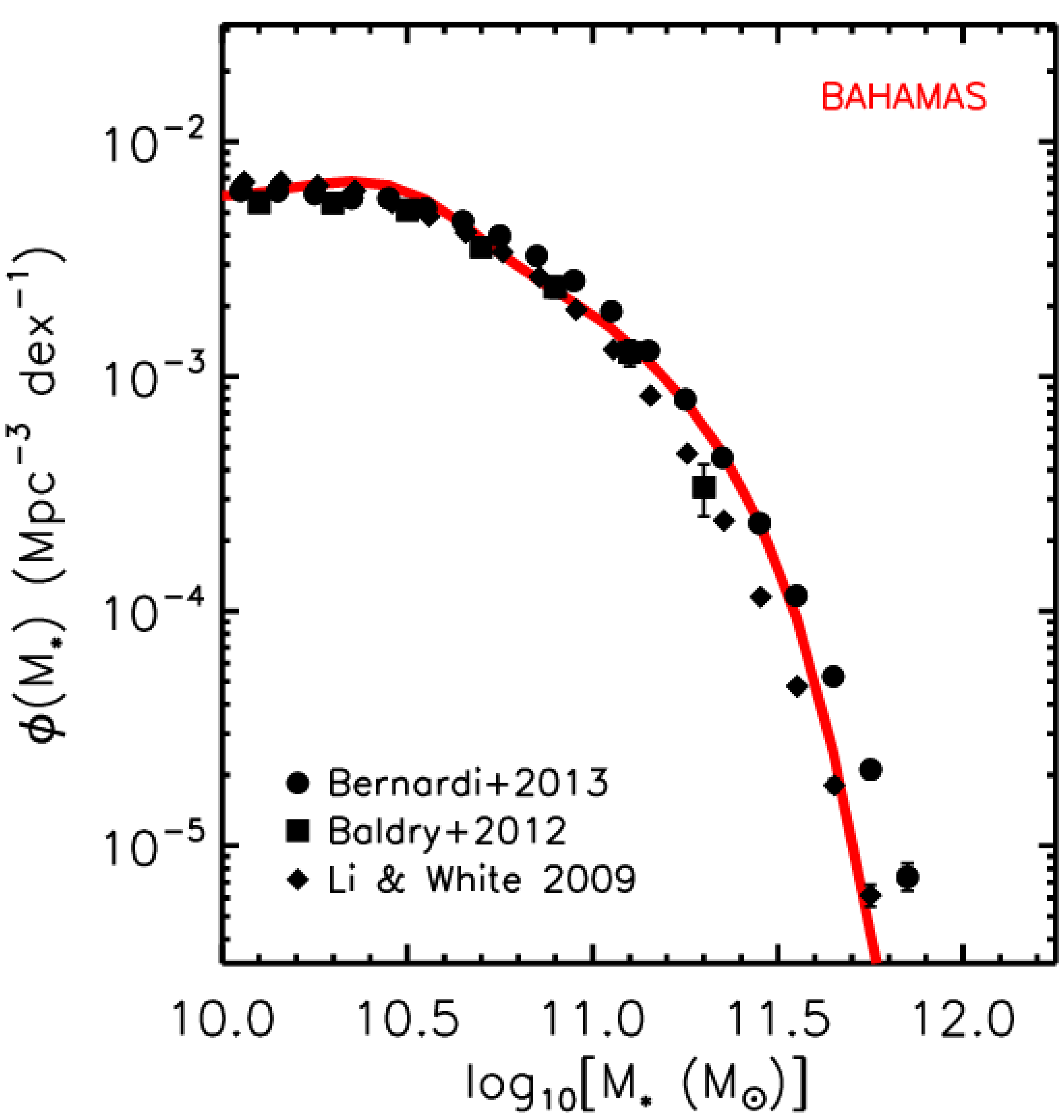
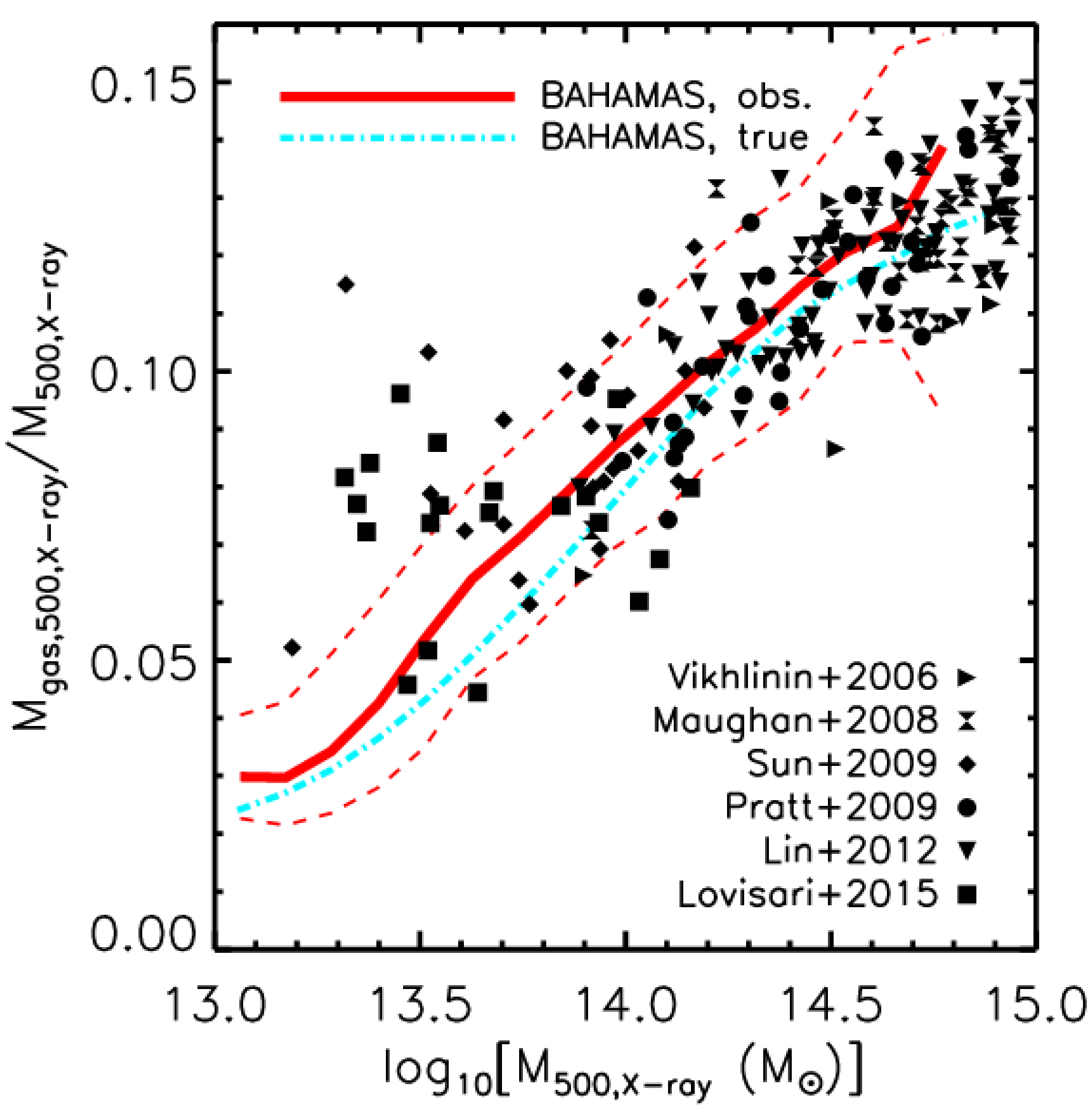
McCarthy+2017, MNRAS

BAHAMAS: BAryons and HAloes of MAssive Systems

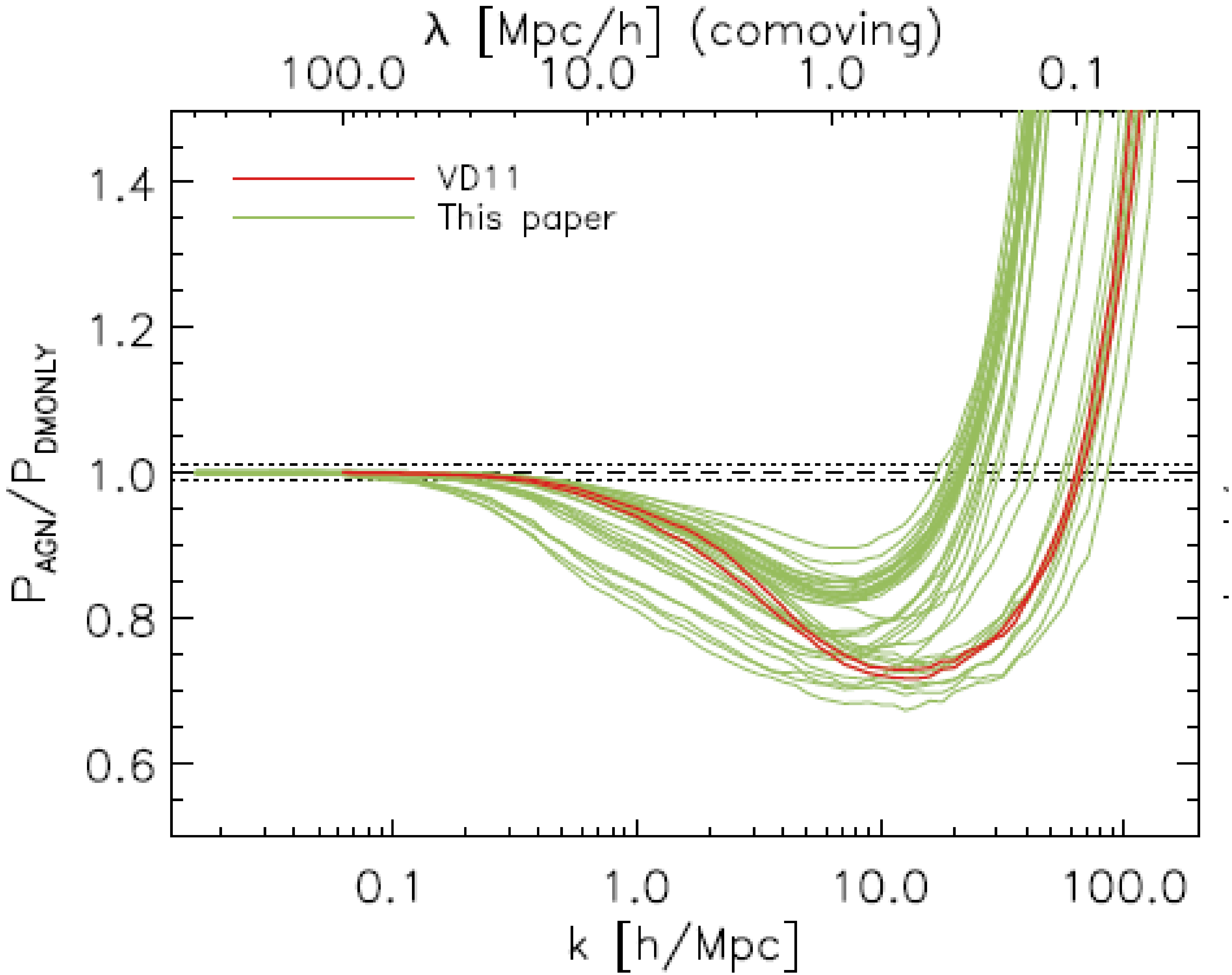
Distribution of stellar masses



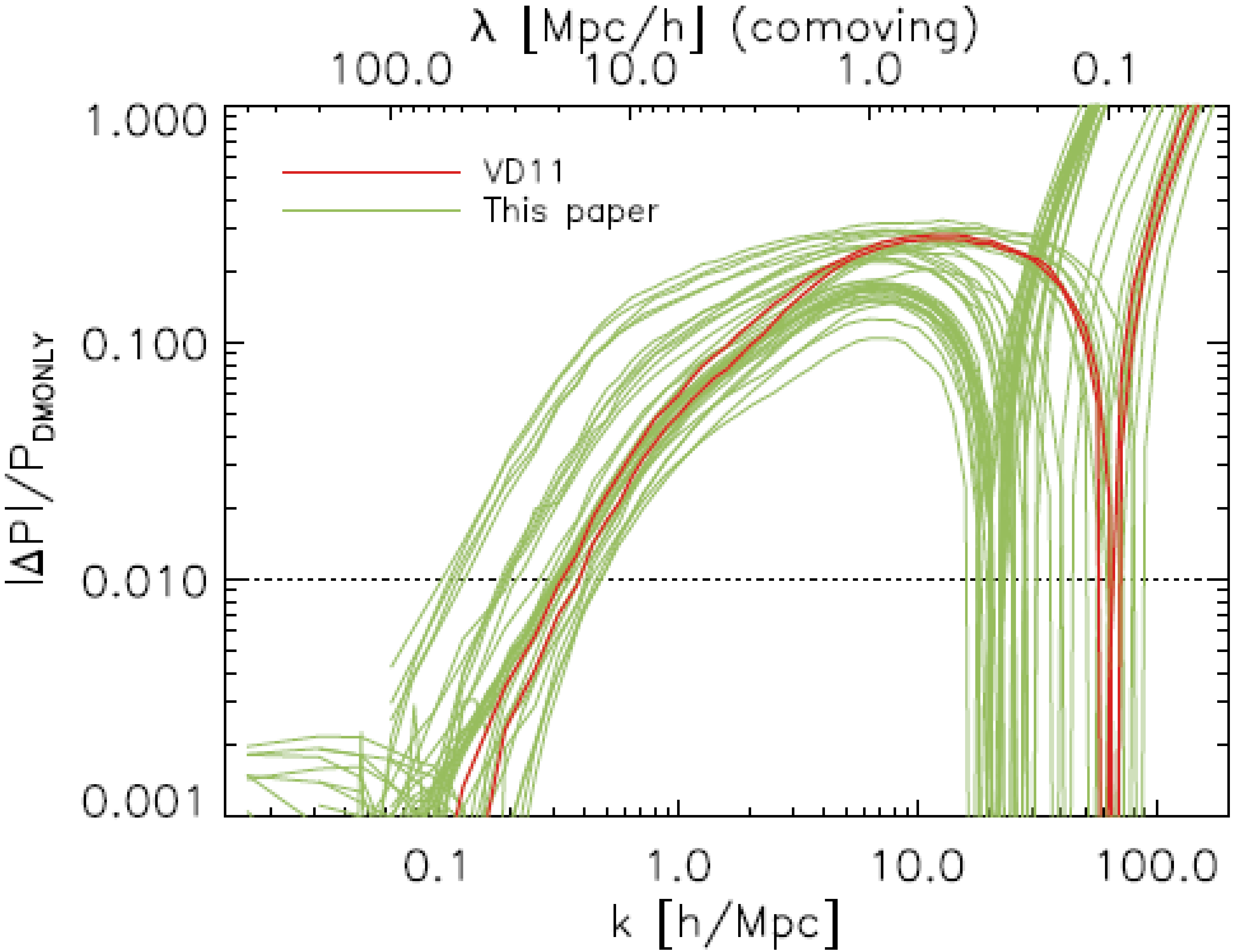
Hot gas masses



Hydro simulations reproduce the observed baryon content of collapsed structures. Realistically captures suppression of matter power spectrum.



van Daalen, McCarthy, Schaye 2019



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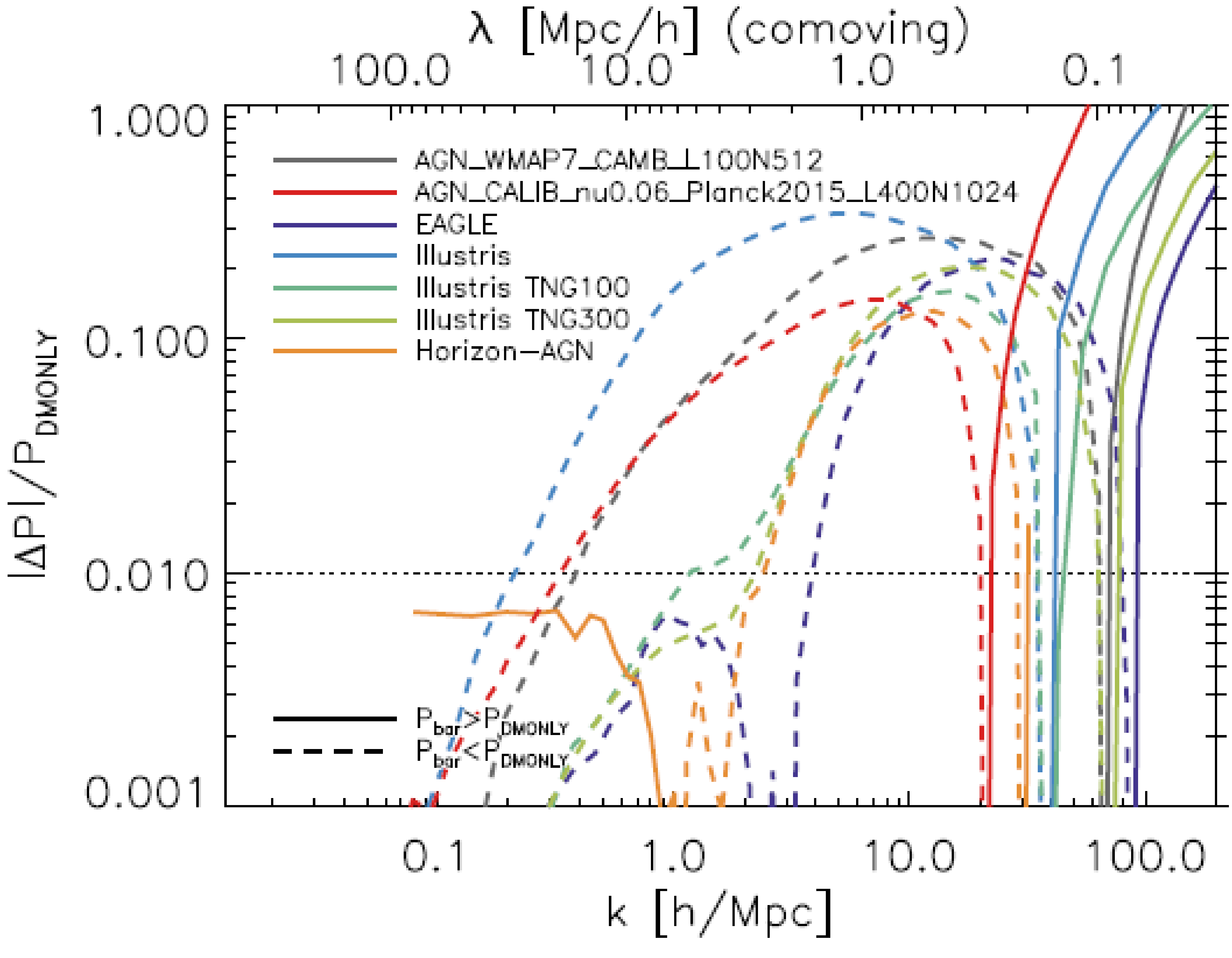
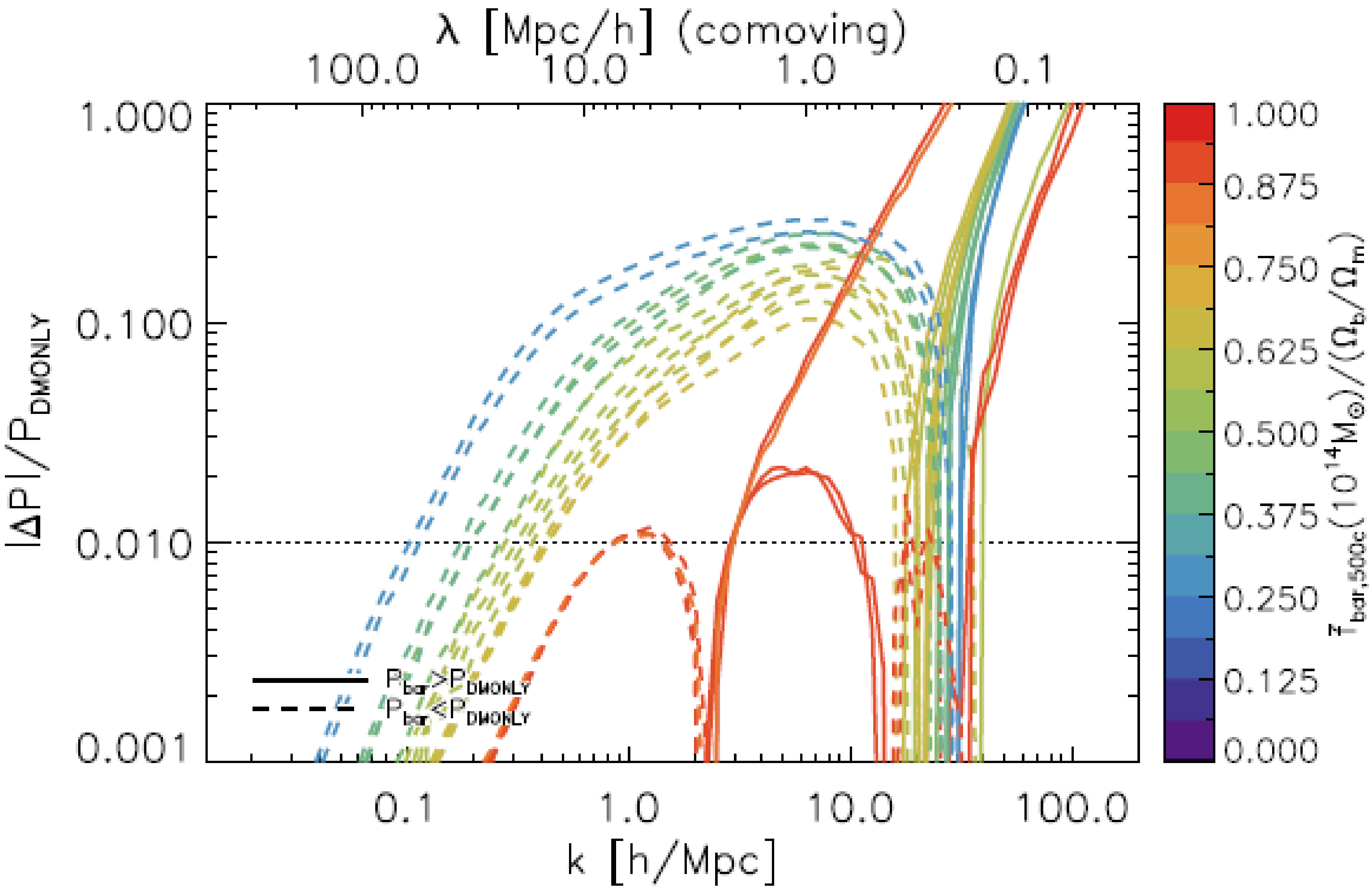


van Daalen, McCarthy, Schaye 2019 (see also Chisari+2018)



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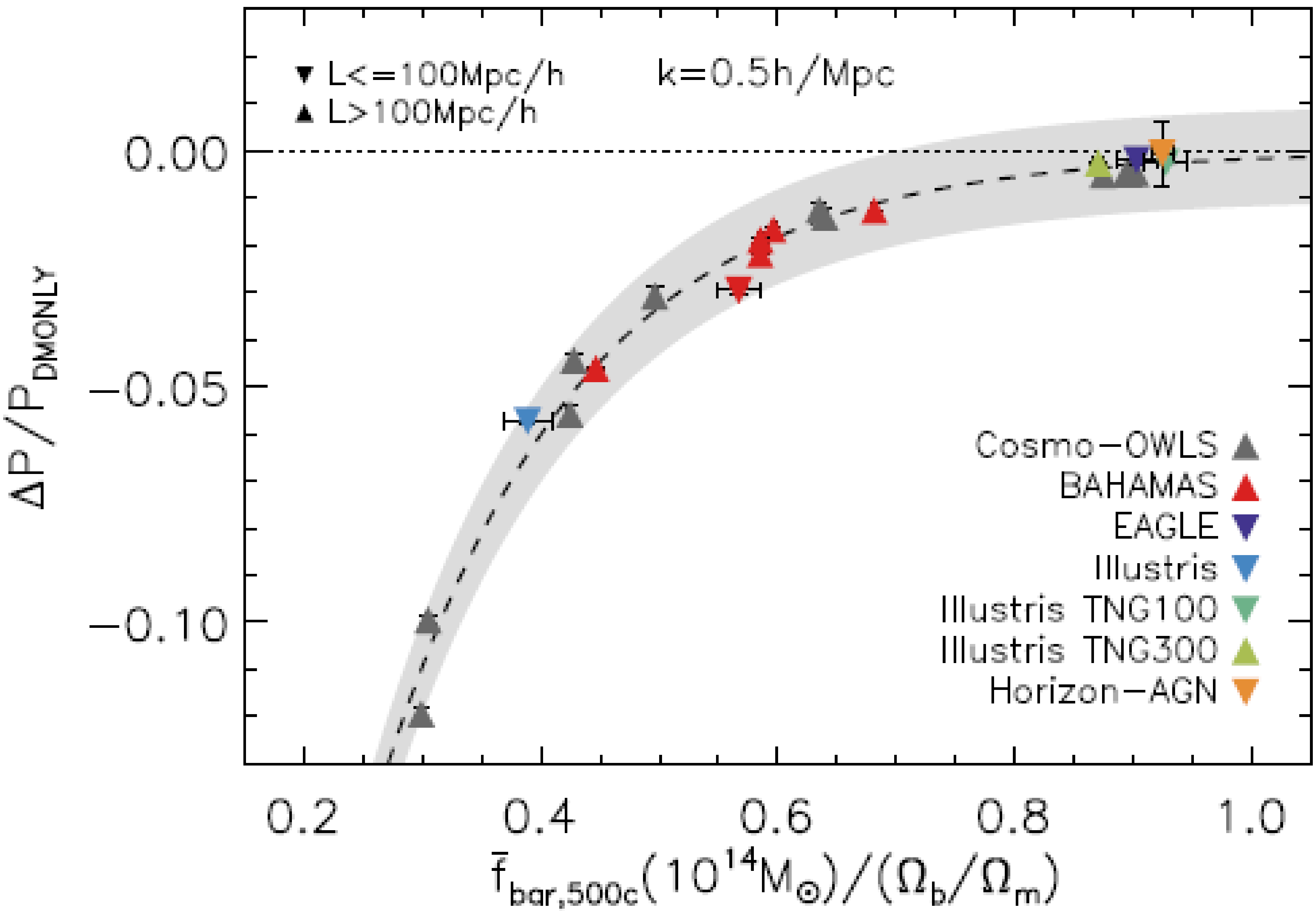

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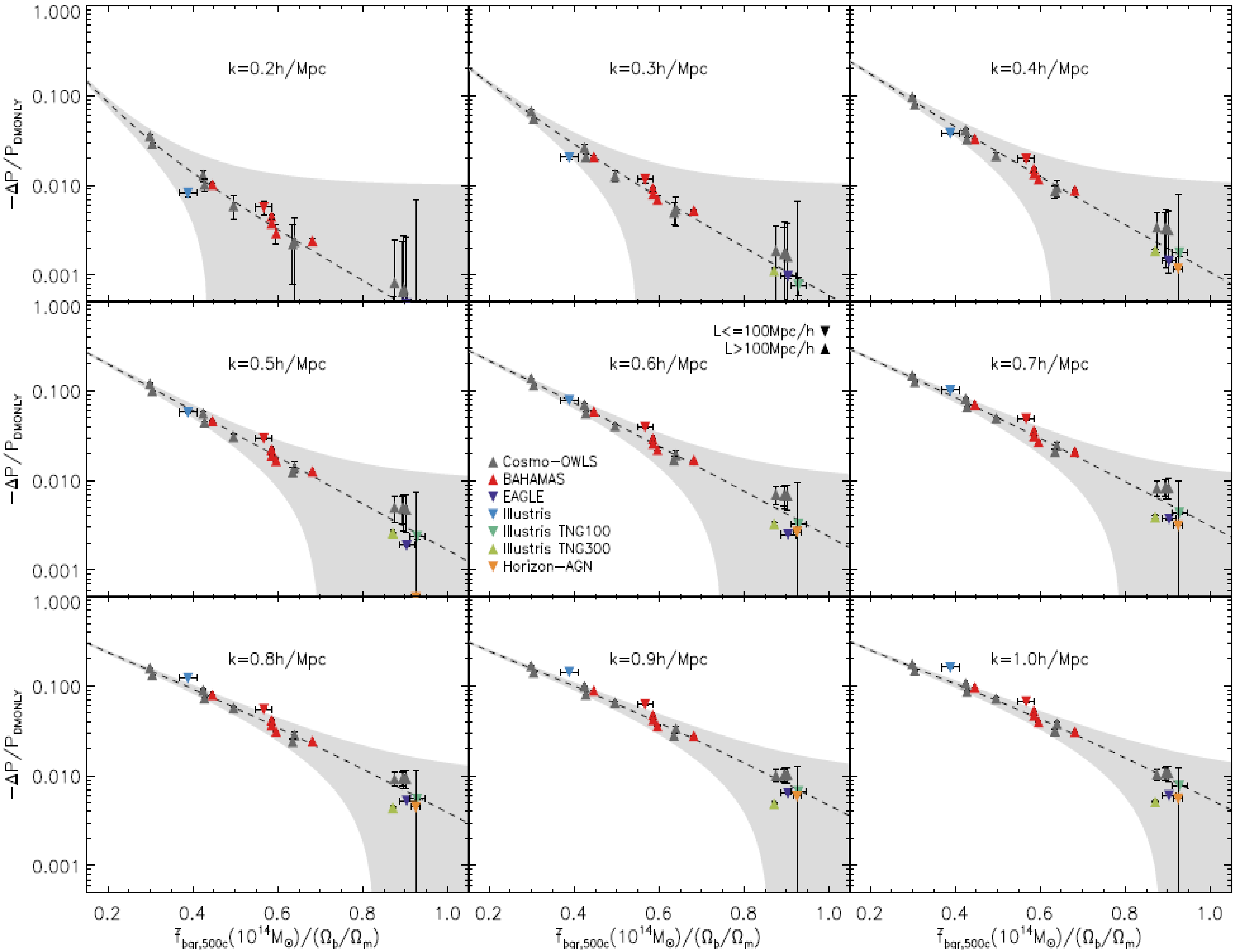
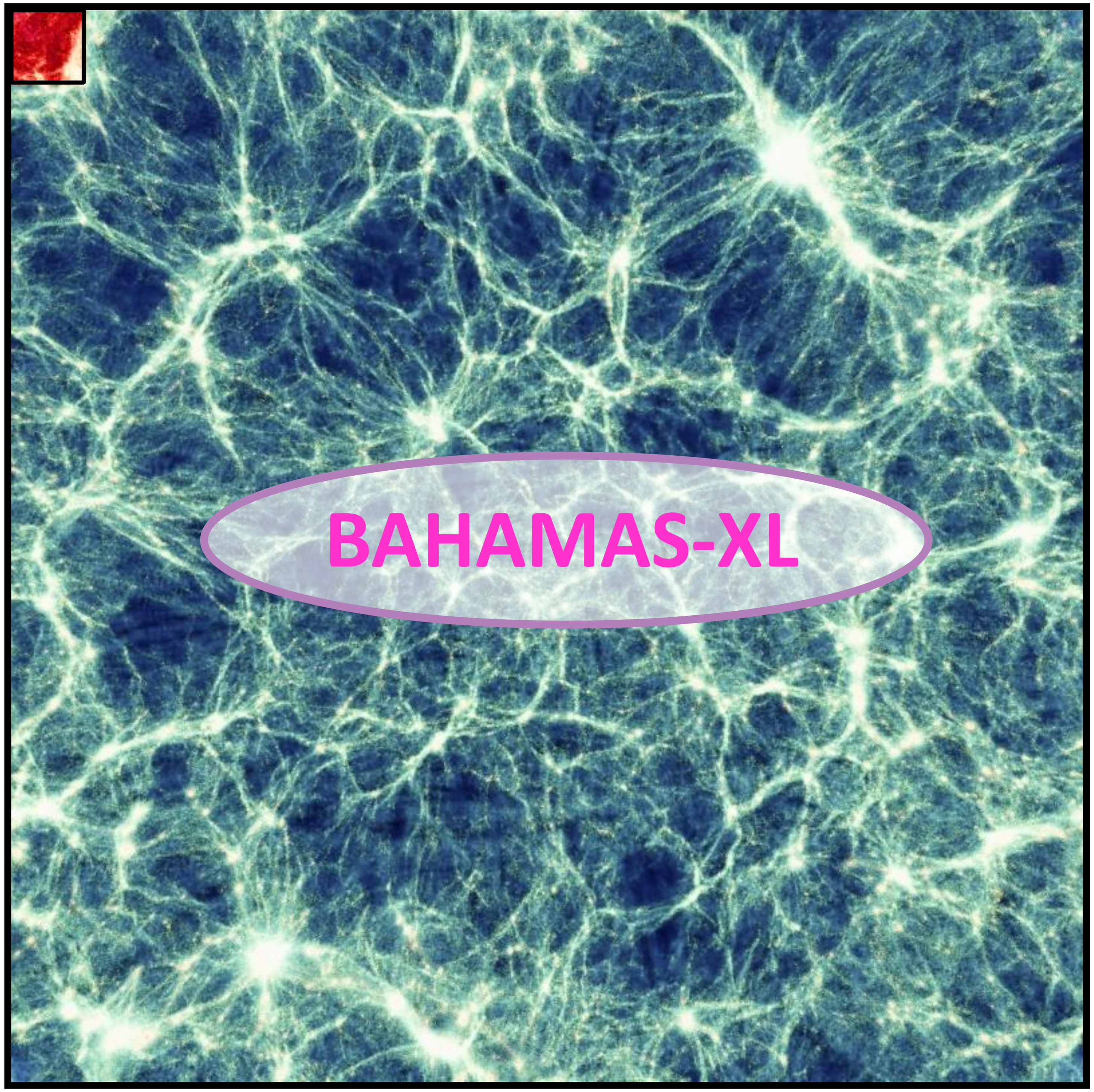

k=0.2h/Mpc
k=0.3h/Mpc
k=0.4h/Mpc
k=0.5h/Mpc
k=0.6h/Mpc
k=0.7h/Mpc
k=0.8h/Mpc
k=0.9h/Mpc
k=1.0h/Mpc
L<=100Mpc/h
L>100Mpc/h
Cosmo-OWLS
BAHAMAS
EAGLE
Illustris
Illustris TNG100
Illustris TNG300
Horizon-AGN
$-\Delta P/P_{DMONLY}$
$\tilde{f}_{bar,500c}(10^{14}M_{\odot})/(\Omega_b/\Omega_m)$
1.000
0.100
0.010
0.001
0.2
0.4
0.6
0.8
1.0

BAHAMAS-XL:
Emulating the observable Universe

Large cosmological volumes

EAGLE→



<u>HUGE</u> volumes needed for upcoming LSS surveys.

Just one of our sims will be amongst the largest ever carried out (vol. ≈3000 times larger than EAGLE). We will do 100-200 such simulations.

BAHAMAS-XL

- Existing BAHAMAS is too small for upcoming surveys. Both in volume and in cosmological landscape. Not easy to combine with observations to constrain cosmology.

- Right now, BAHAMAS is mainly used to inform the halo model formalism when it comes to cosmology.

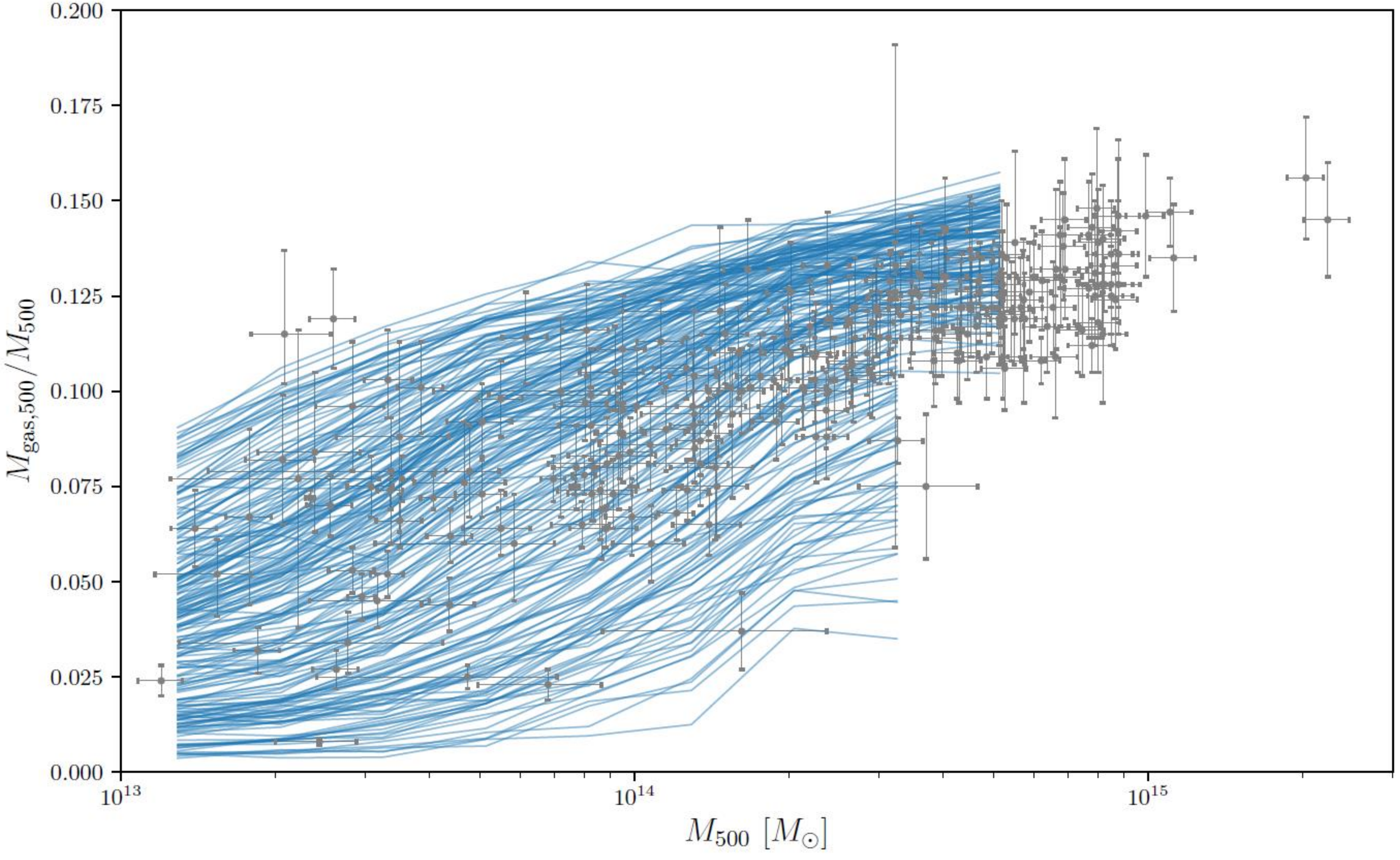
- What is required is a large "grid" of large-volume simulations, like MiraTitan, Euclid simulations, Aemulus, etc. but with full hydrodynamics and feedback calibration.

- Now gearing up for a grid of ~100 volumes with 1 Gpc/h (or 800 Mpc/h) with 2500^3 (or 2048^3) particles. Run with calibrated EAGLE code or SWIFT.

- Spanning standard model parameters plus massive neutrinos, w(a), and running. Incorporating a feedback parameter in the grid (AGN heating temperature) might also be doable.

- Develop emulators for ***observable*** quantities (e.g., tSZ-lensing-galaxy cross)

BAHAMAS-XL calibration



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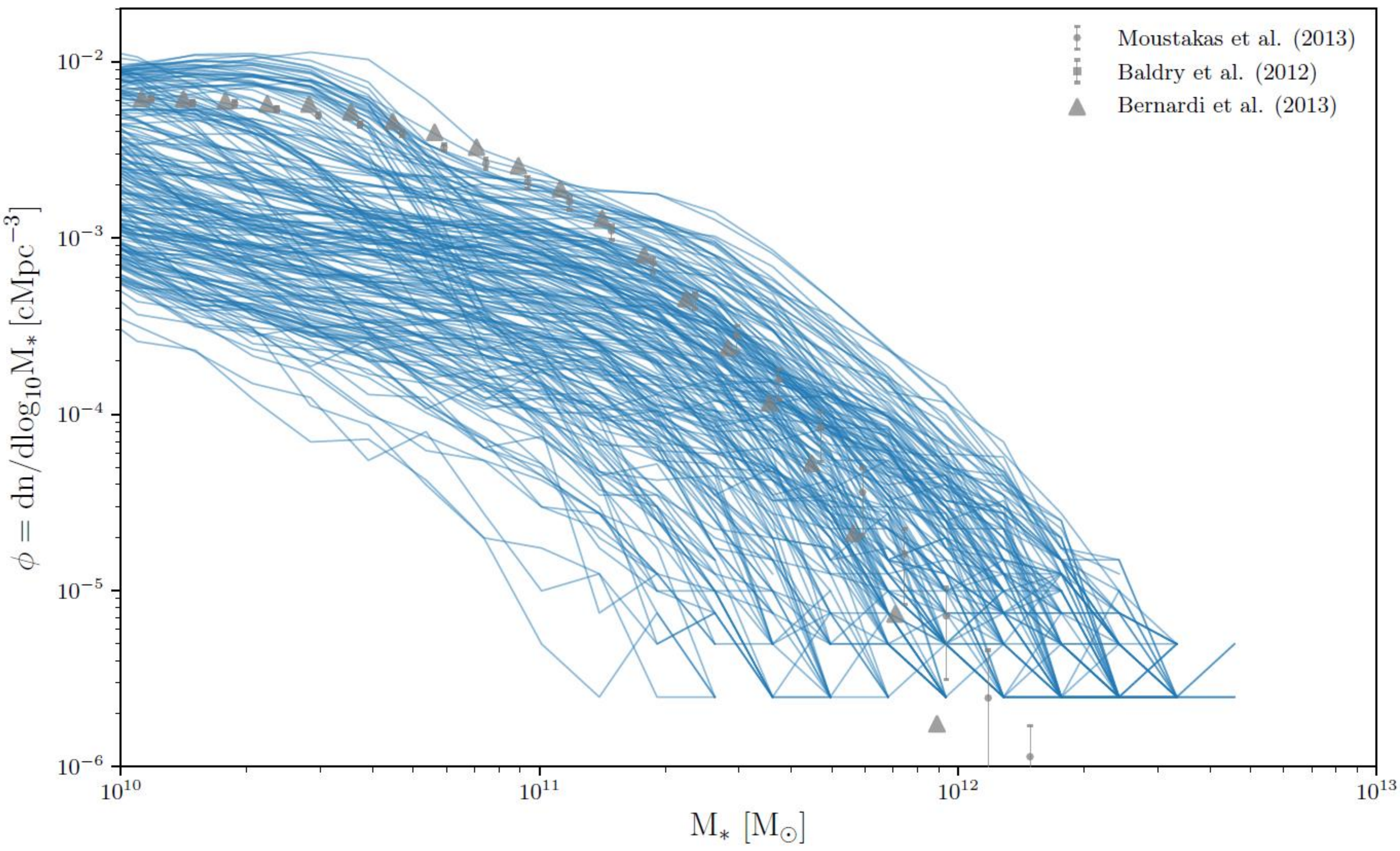

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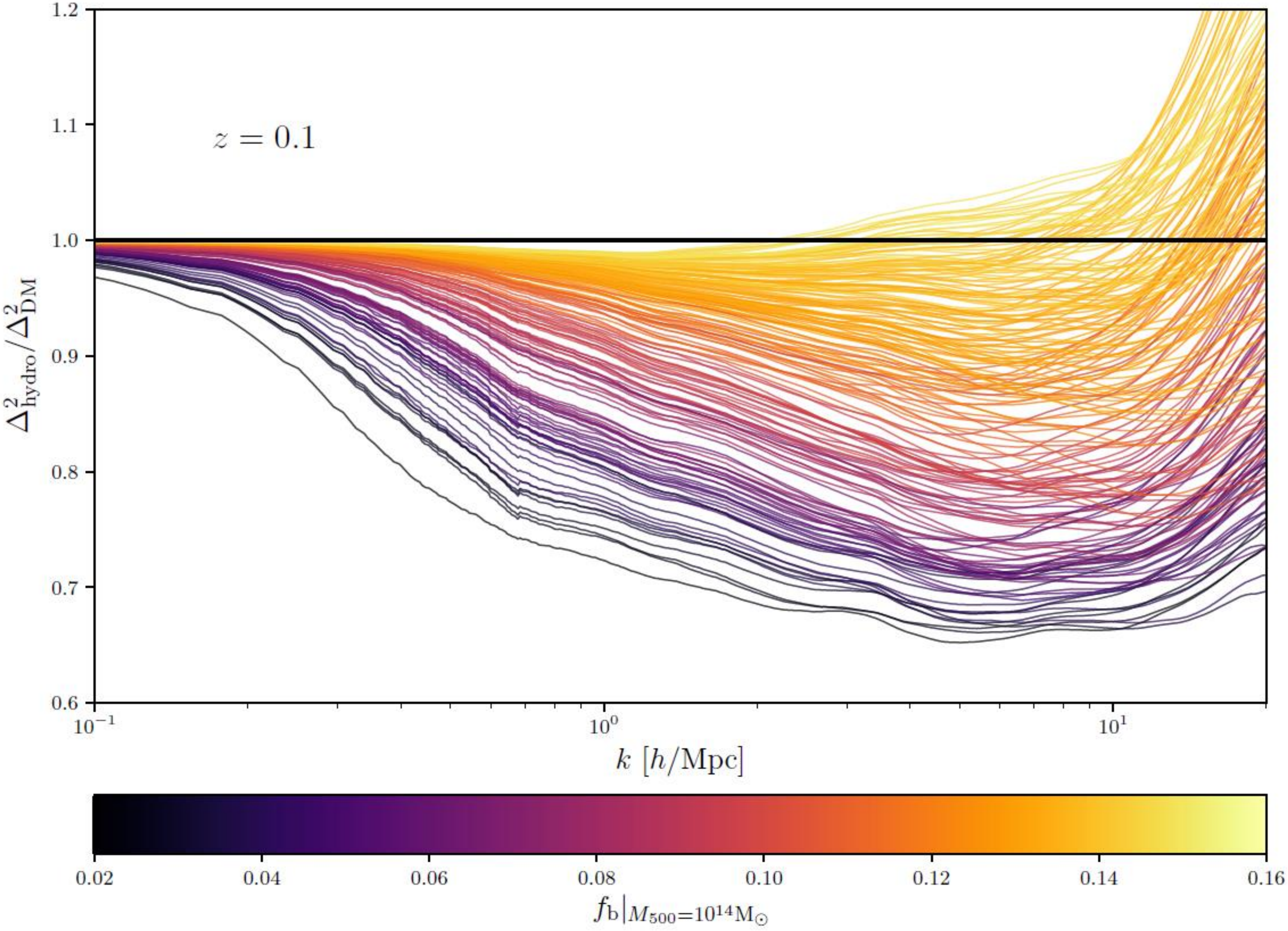

Summary

- There is presently (maybe) a tension between the CMB and LSS with regards to the joint constraint on Ω_m-σ_8.

- The largest theoretical uncertainty is due to feedback modelling of winds/jets that expel baryons from collapsed structures. **Estimates of the baryon fraction at group and low-mass cluster scale are HUGELY important for LSS predictions (including cluster counts).**

- We have created a new suite of simulations called **BAHAMAS** that incorporates these effects in a realistic way. We make consistent comparisons of CMB-based cosmologies with LSS data. **Maps available!**

- Prelim results: Massive neutrinos can reconcile this tension, but running of $\mathbf{n_s}$ and **w(a)** cannot.

- **BAHAMAS-XL** will overcome current limitations, by providing very large volumes needed for LSS surveys, many volumes spanning a range of cosmologies, and emulation on a wide range of observables.