The BAHAMAS project: the CMB—large-scale structure tension

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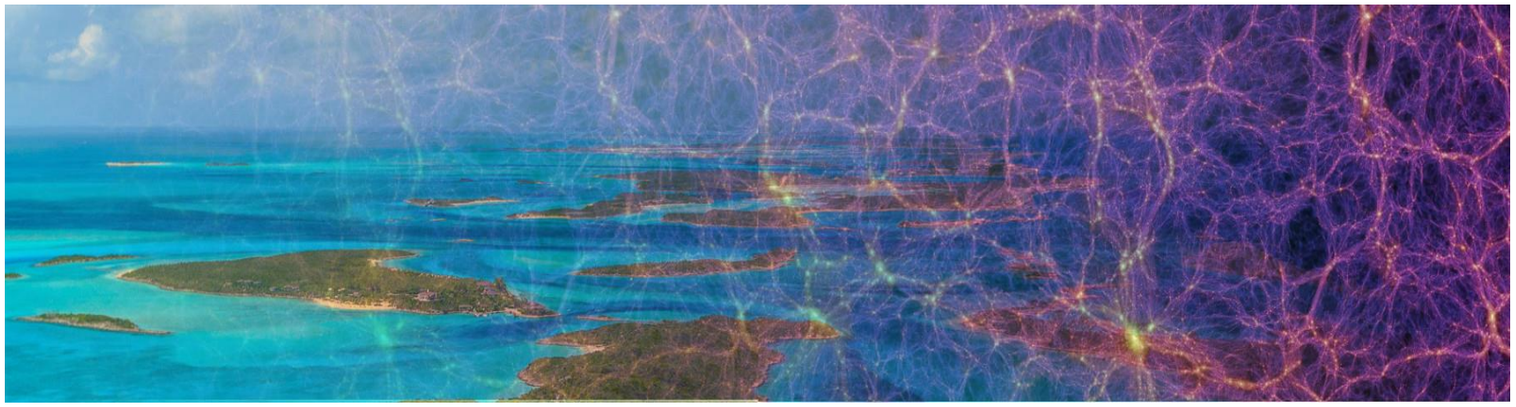
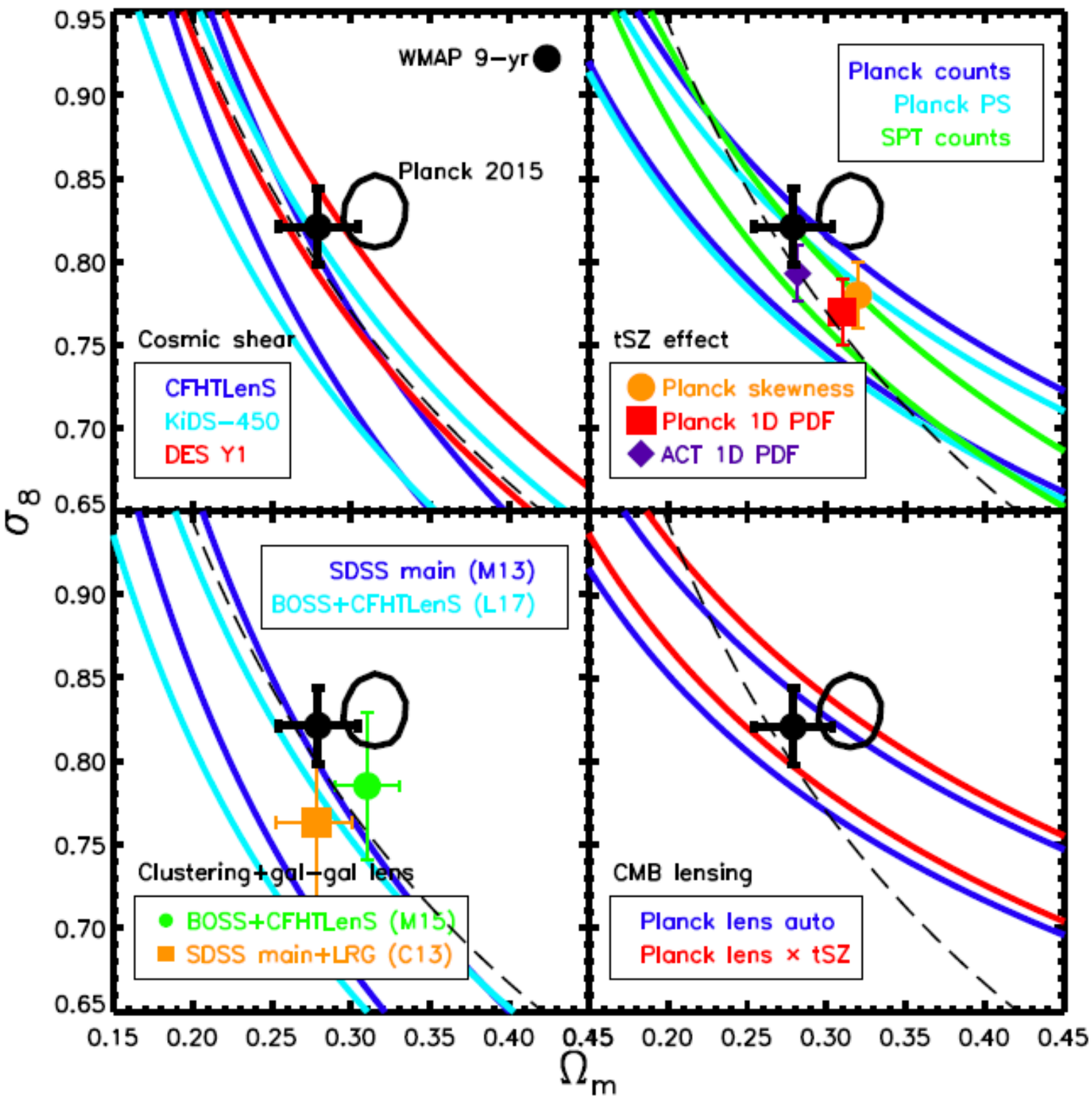


McCarthy+2018, MNRAS

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.

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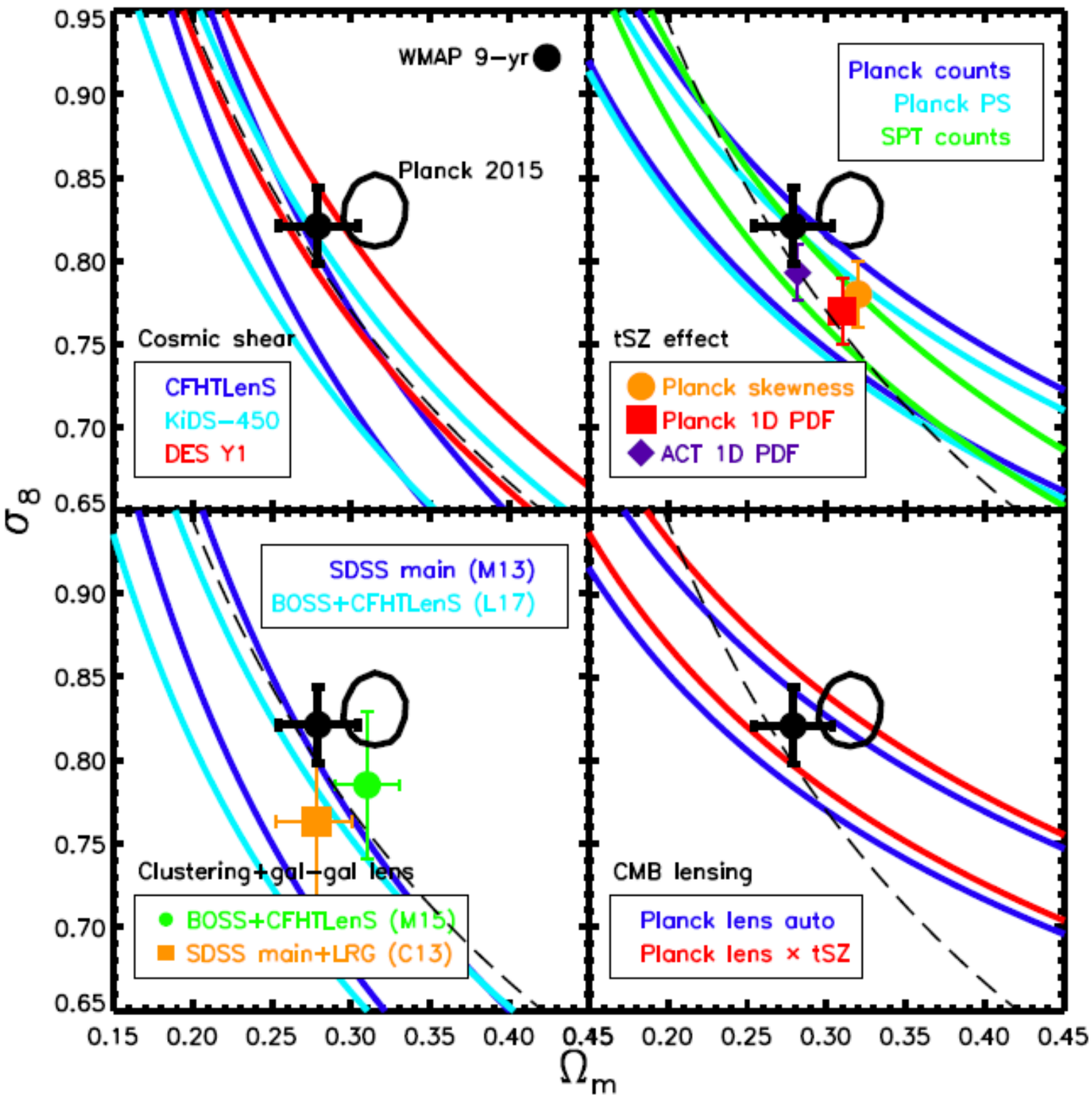

Possible solutions:

- 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

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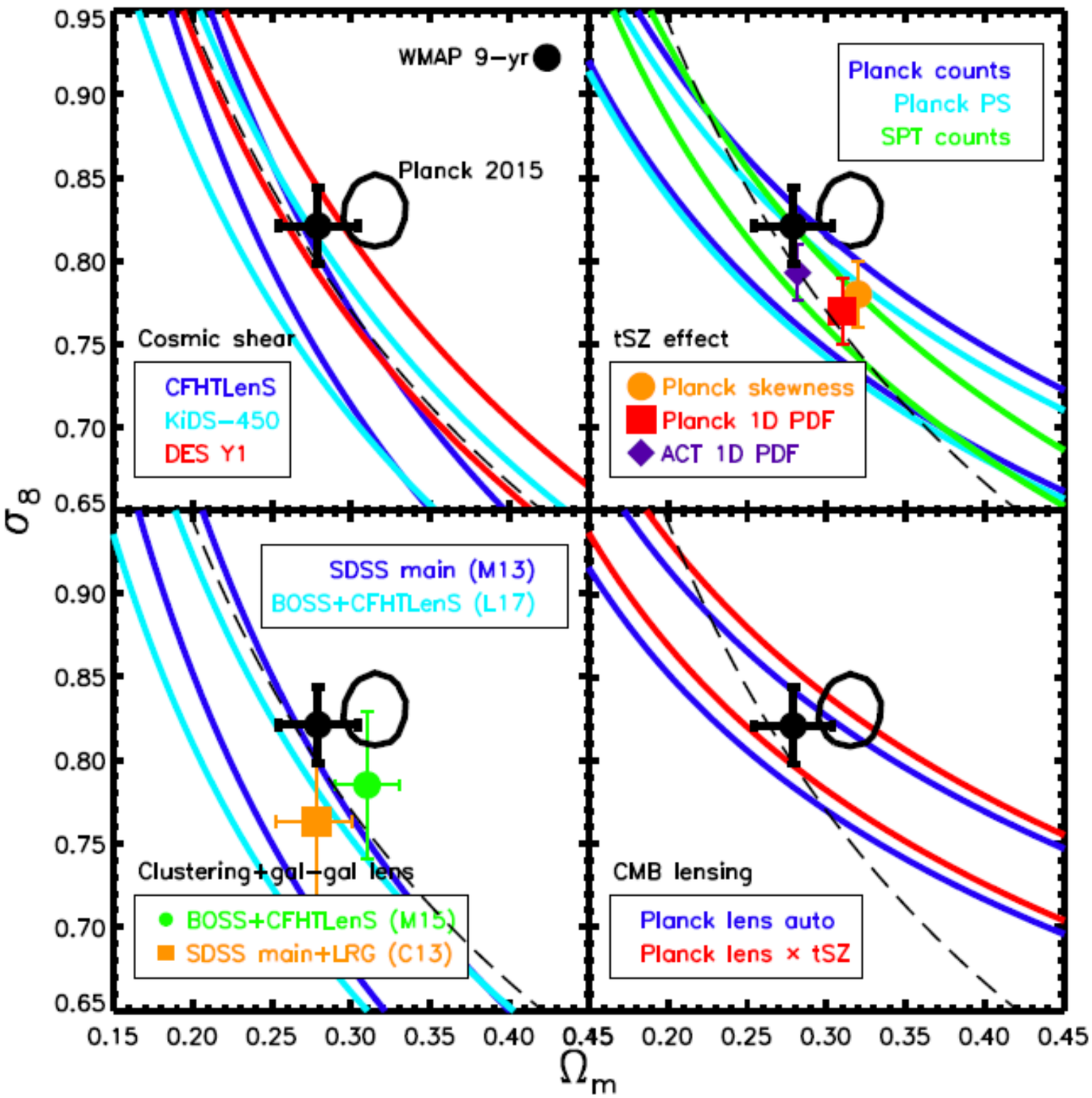

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Feedback processes can affect LSS

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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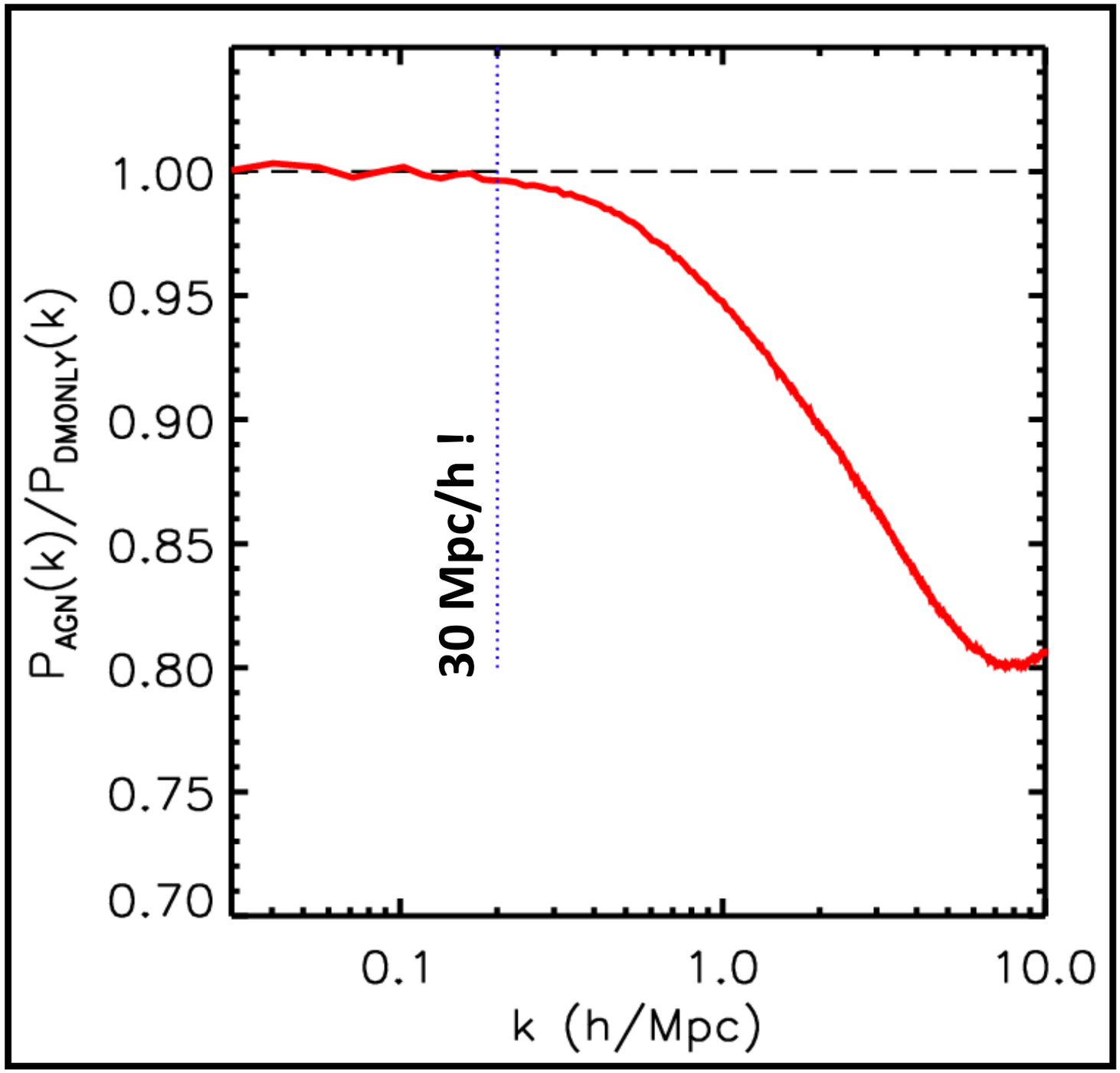

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Some possible alterations of ΛCDM

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

- Decaying dark matter

- Massive neutrinos

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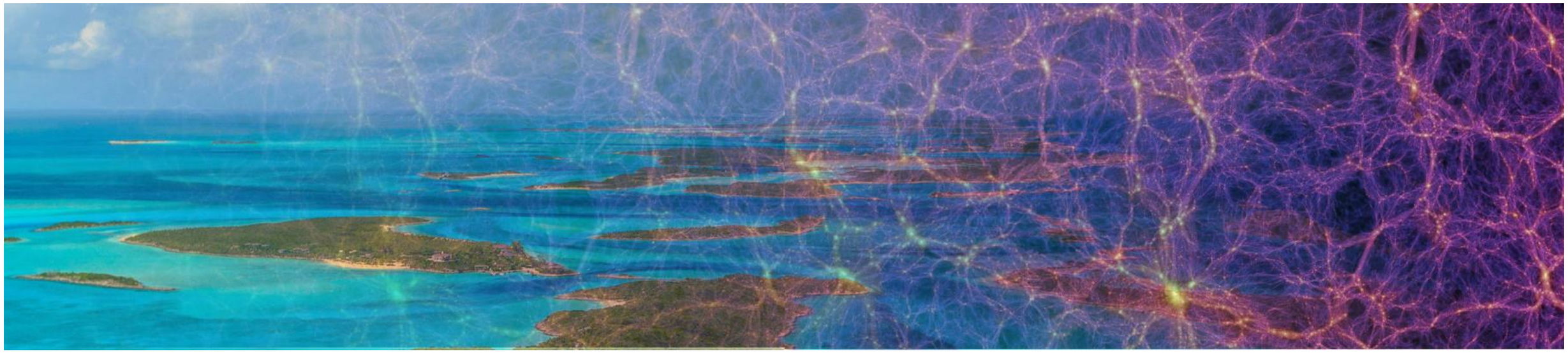
BAHAMAS: BAryons and HAloes of MAssive Systems



- Large 400 h^{-1} Mpc boxes ($2x1024^3$ 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.

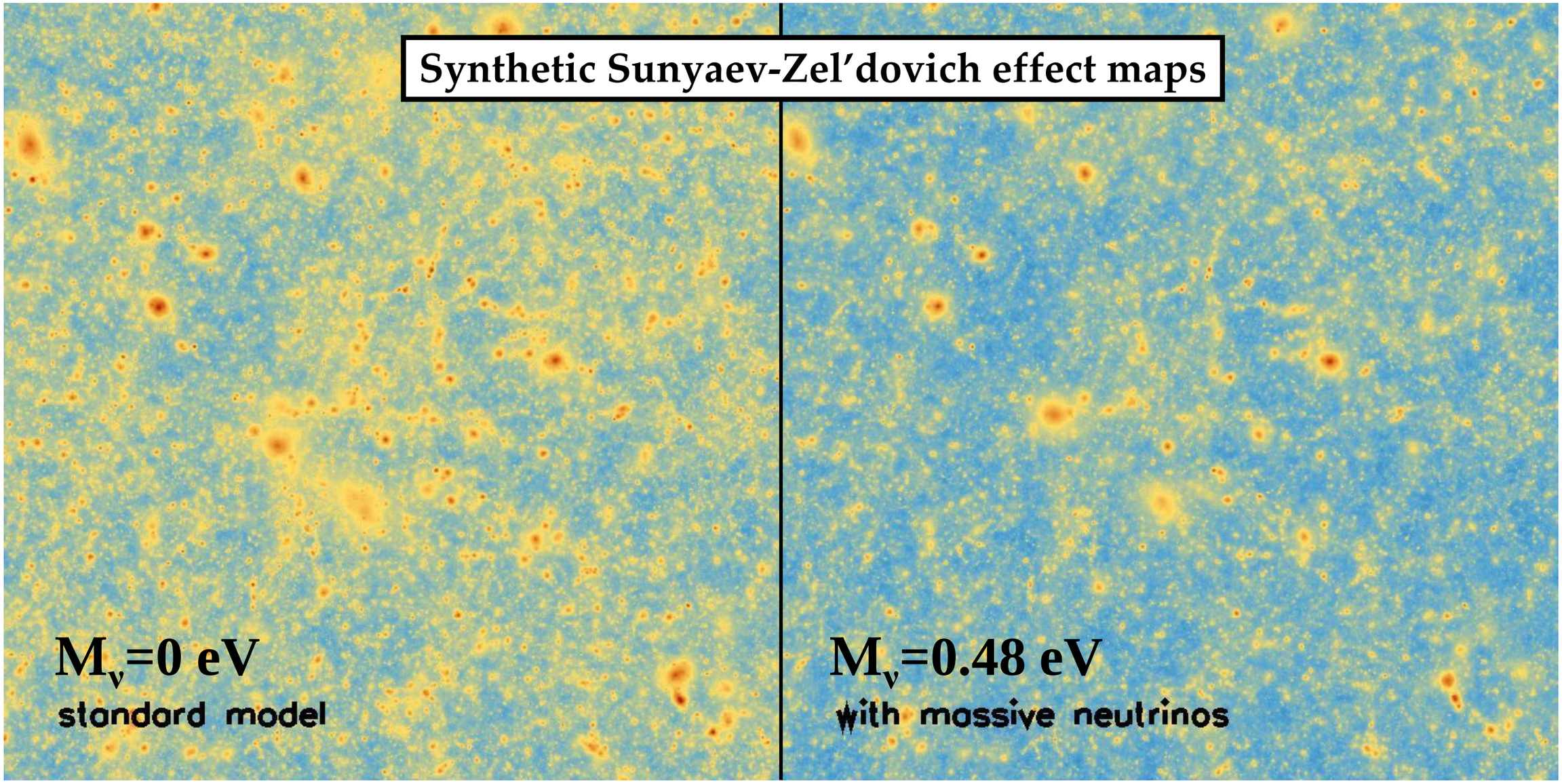
- Neutrinos followed self-consistently with CDM+baryons using semi-linear method of Ali-Haimoud & Bird (2013).

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

BAHAMAS: BAryons and HAloes of MAssive Systems

- Light cones made for gas, stars, DM, BH particles, galaxies and haloes.

- Make SZ, X-ray, cosmic shear/kappa, CMB lensing kappa maps, galaxy clustering, gal-gal lensing, etc.



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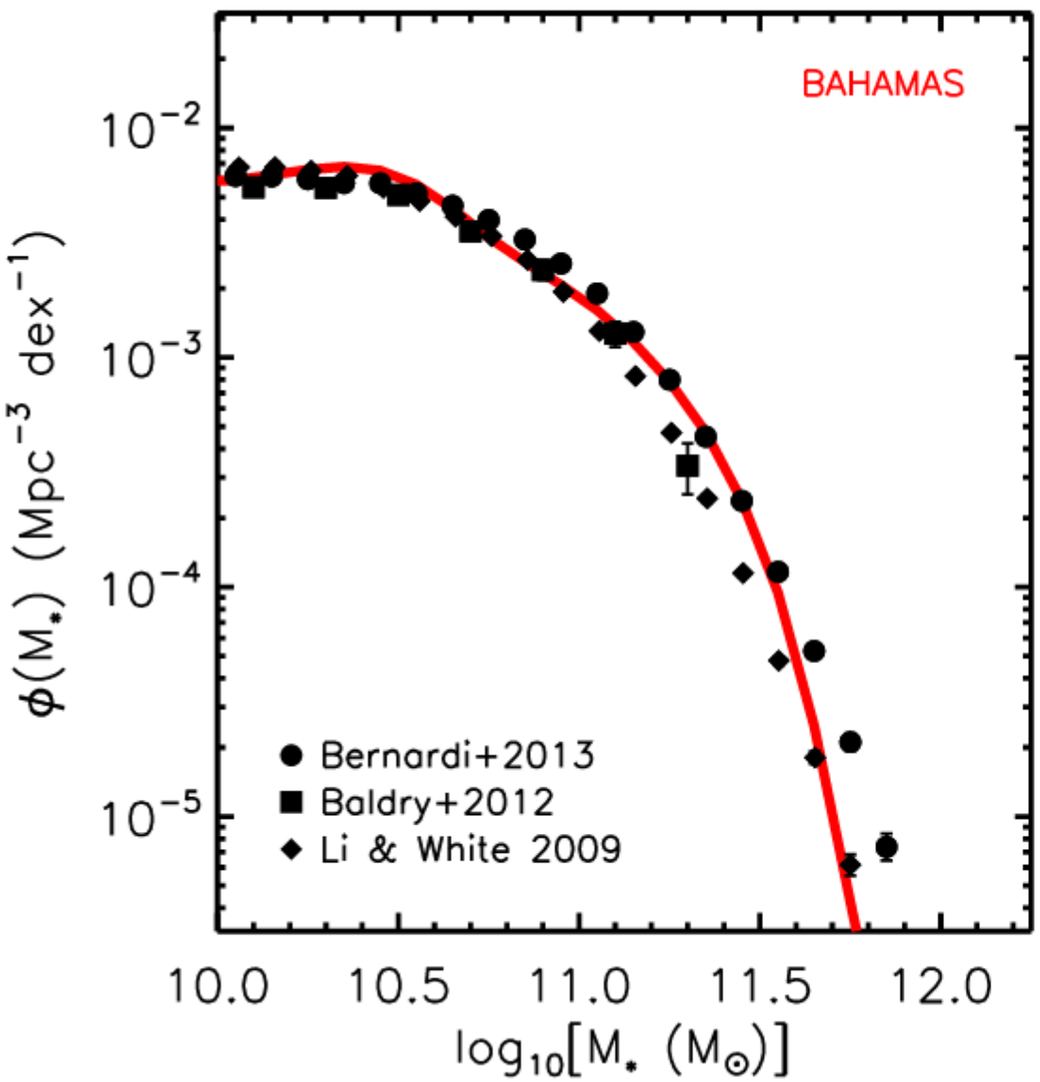
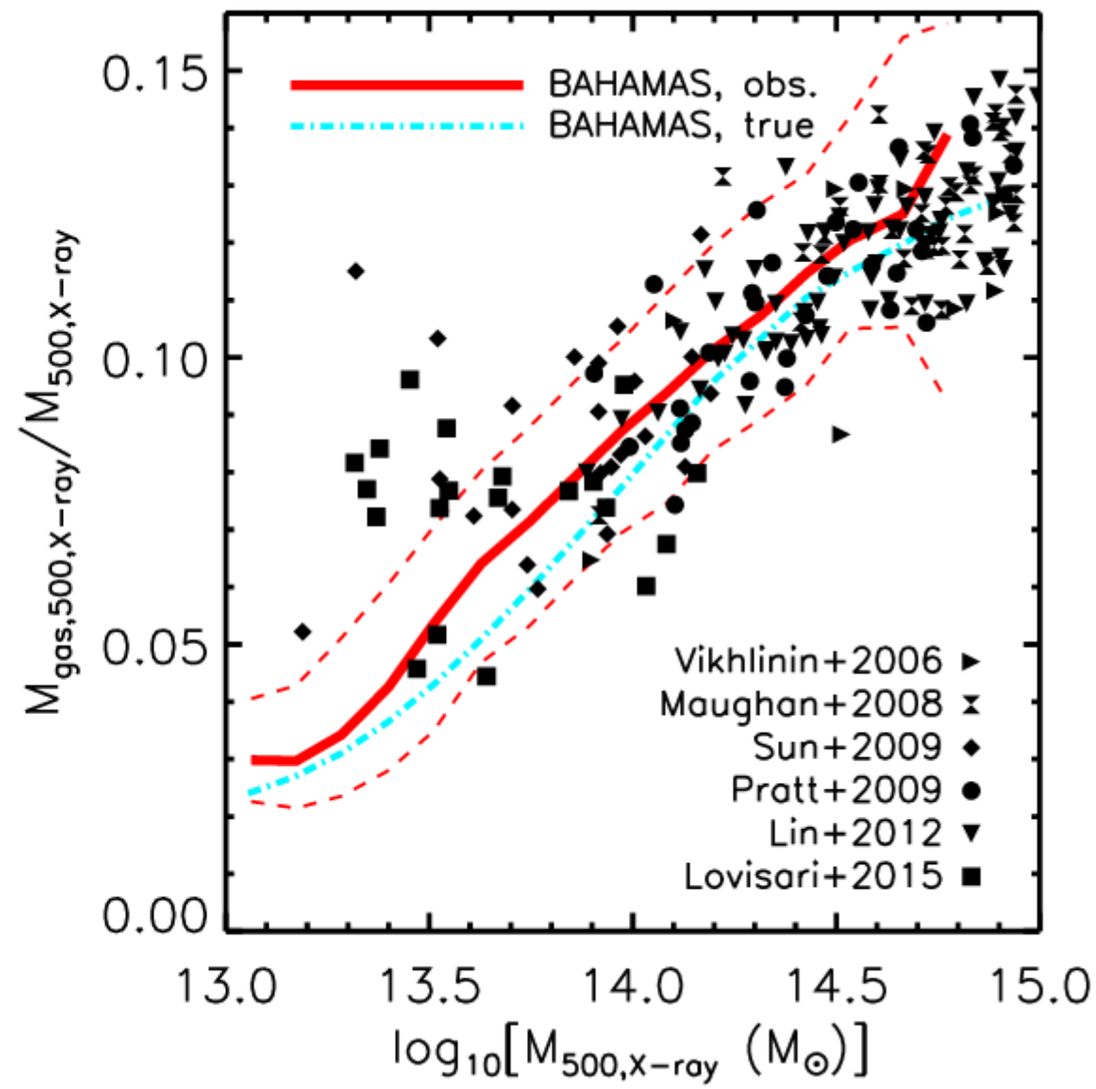
BAHAMAS: BAryons and HAloes of MAssive Systems

Distribution of stellar masses



Hot gas masses



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

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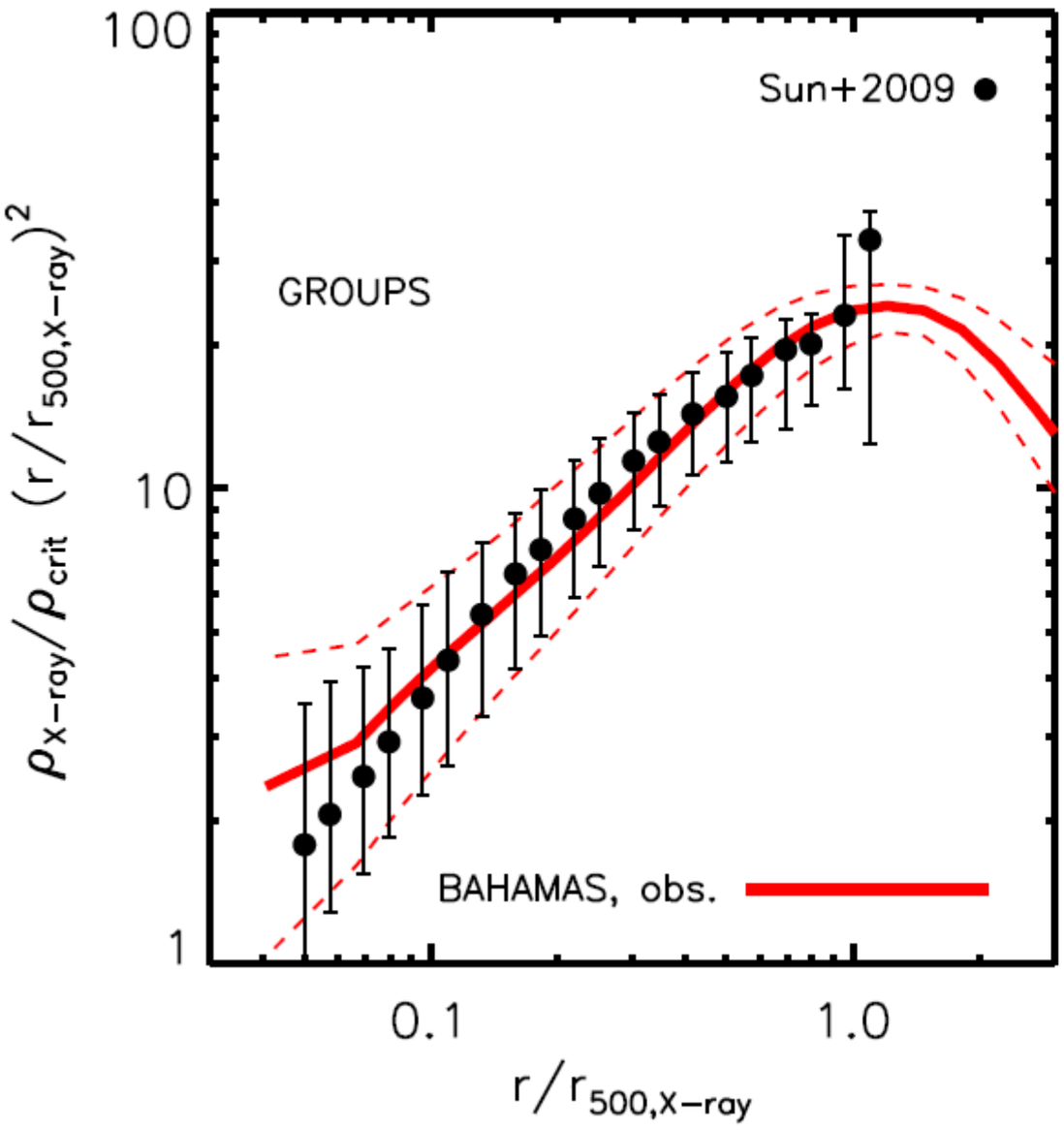
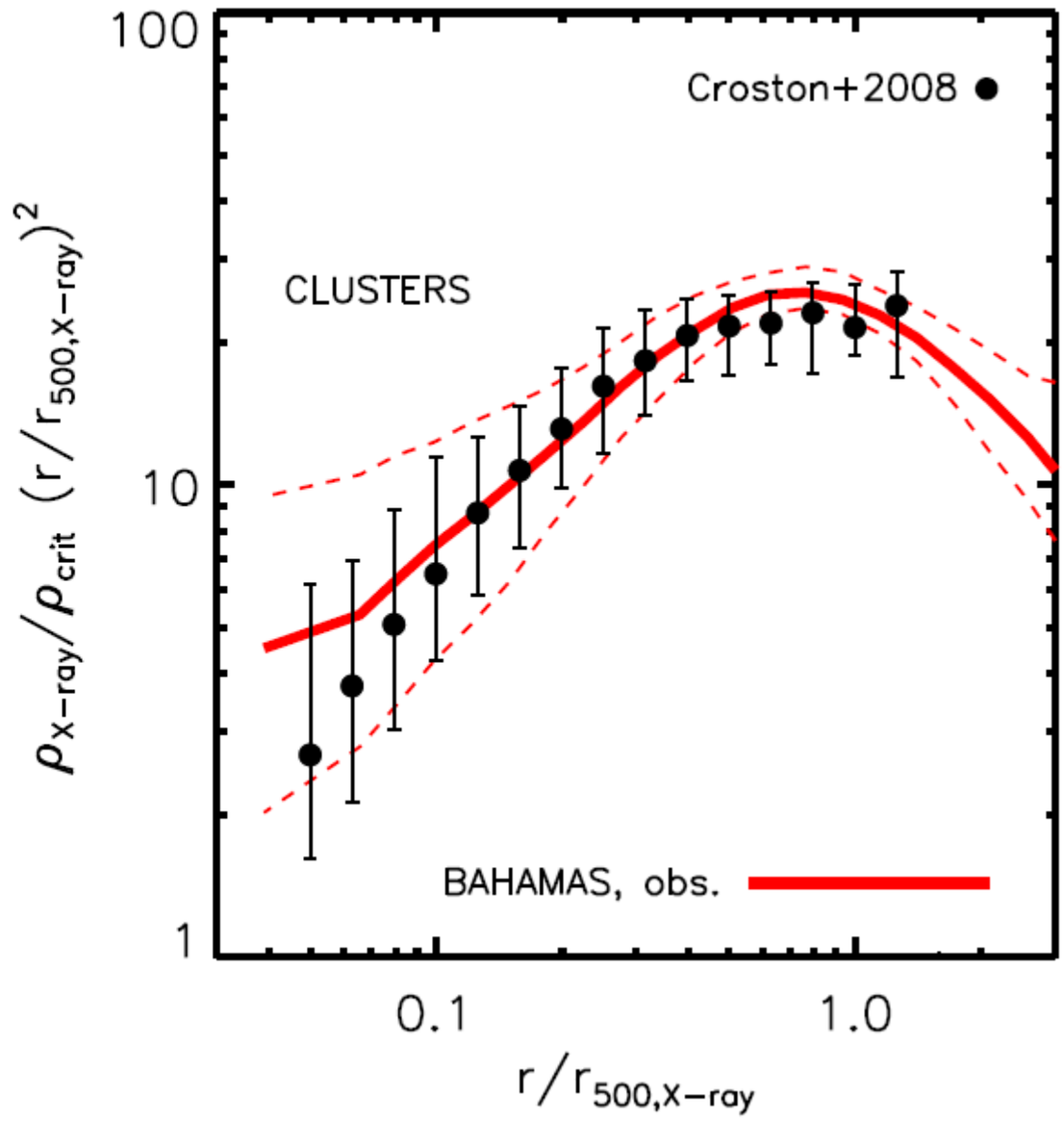
Spatial distribution of hot gas in clusters

Gas density





Also reproduce the detailed thermodynamic profiles over a wide range of radii and halo masses.

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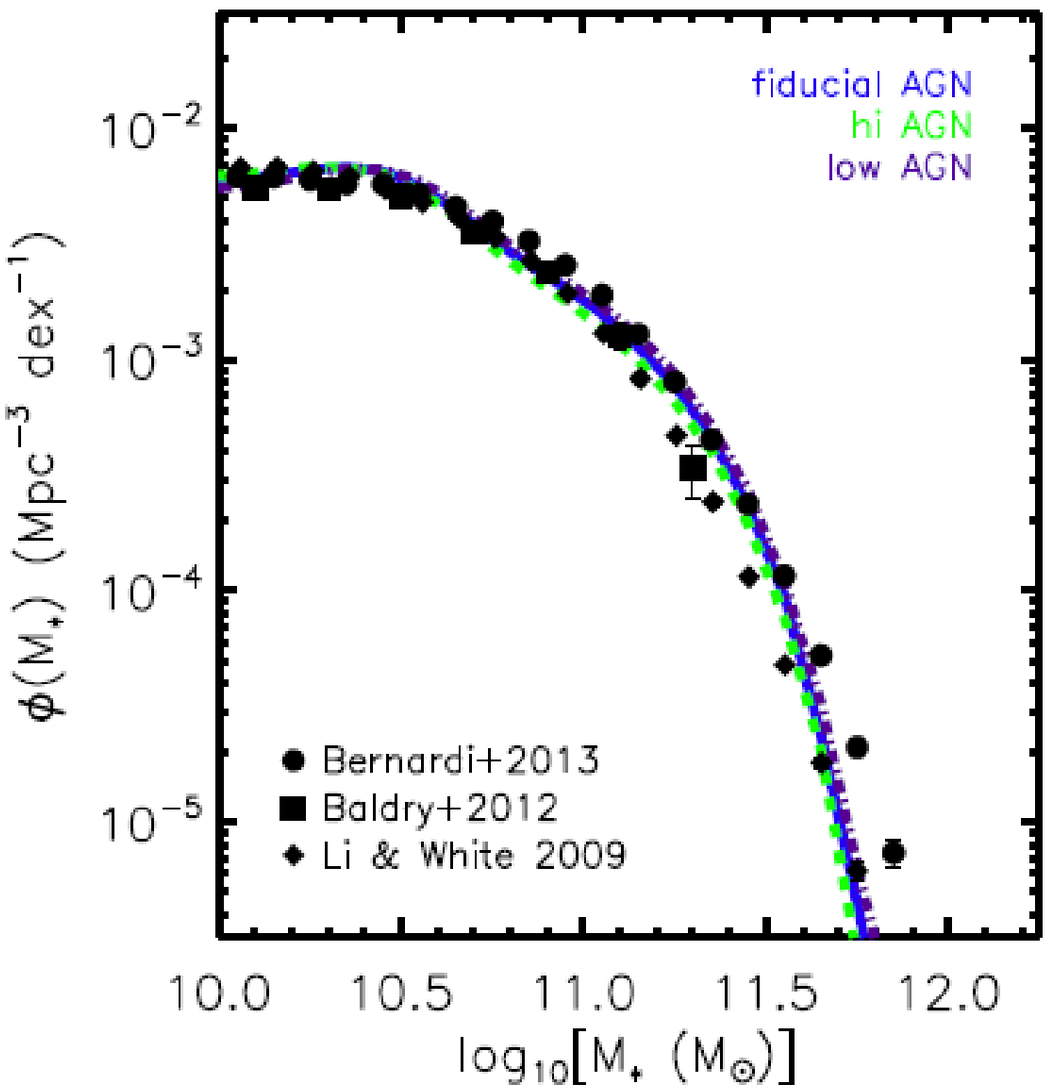
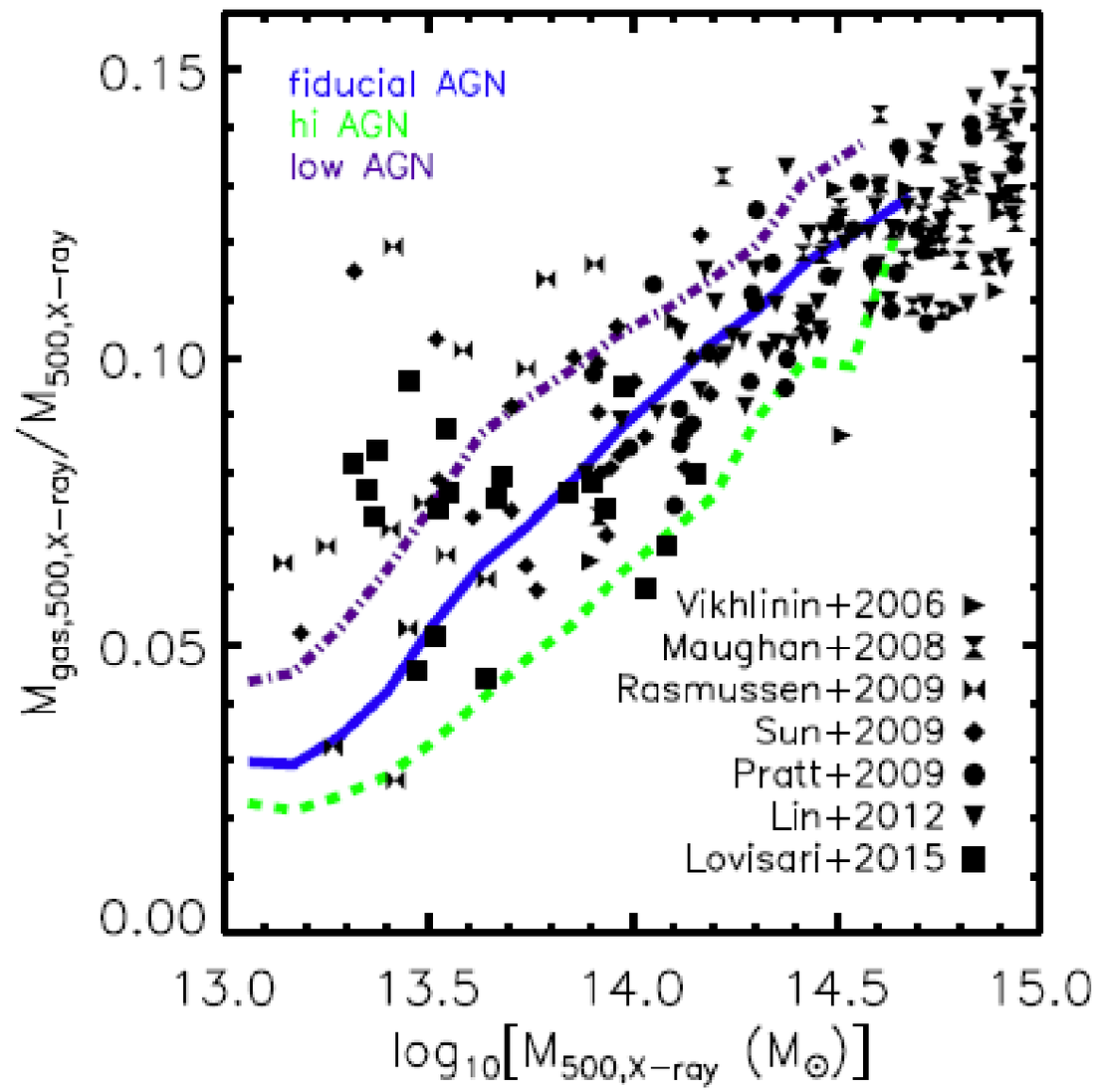
Quantifying uncertainties in feedback modelling





Additional runs to propagate uncertainties due in feedback calibration.

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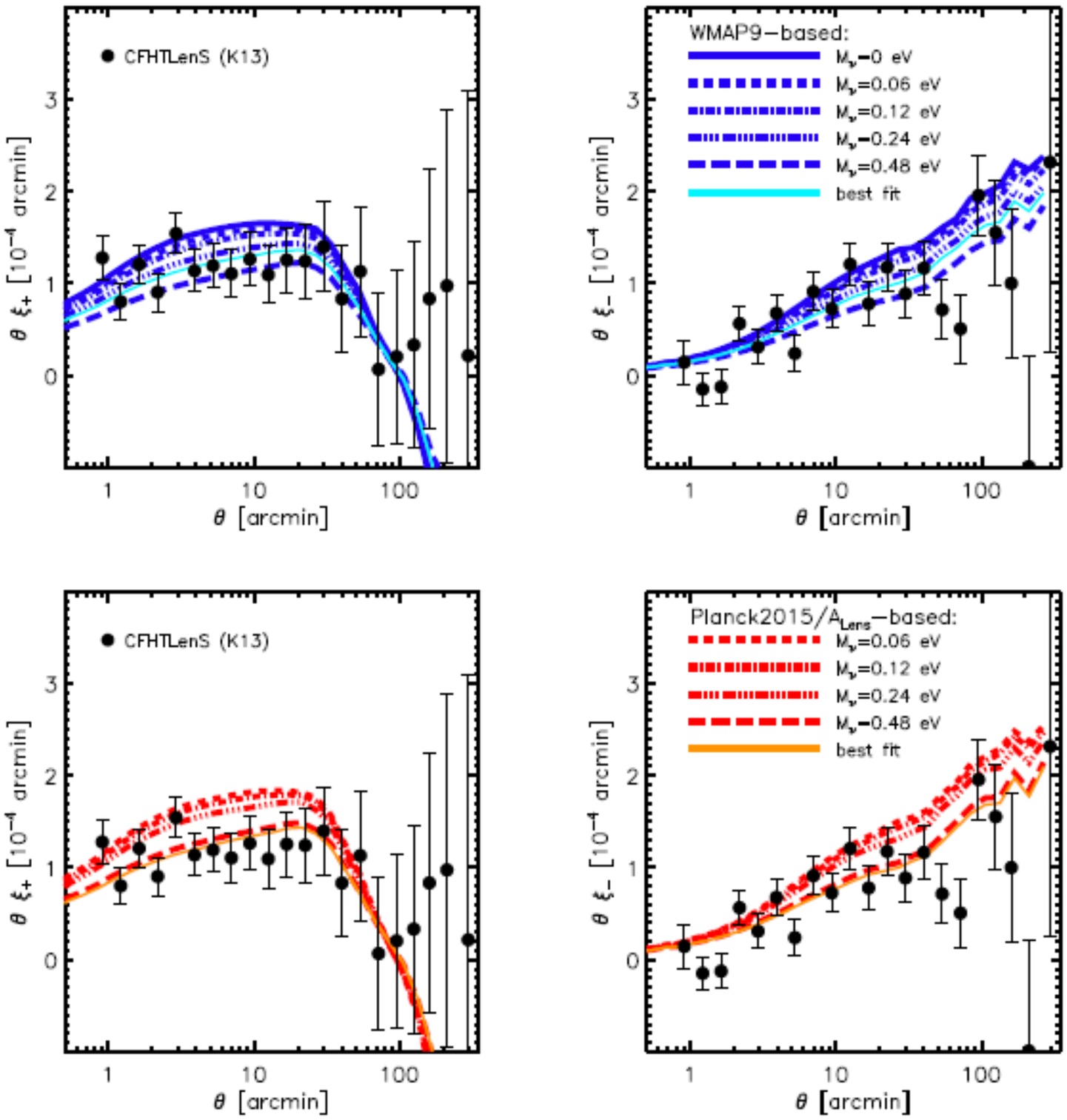
Cosmic shear

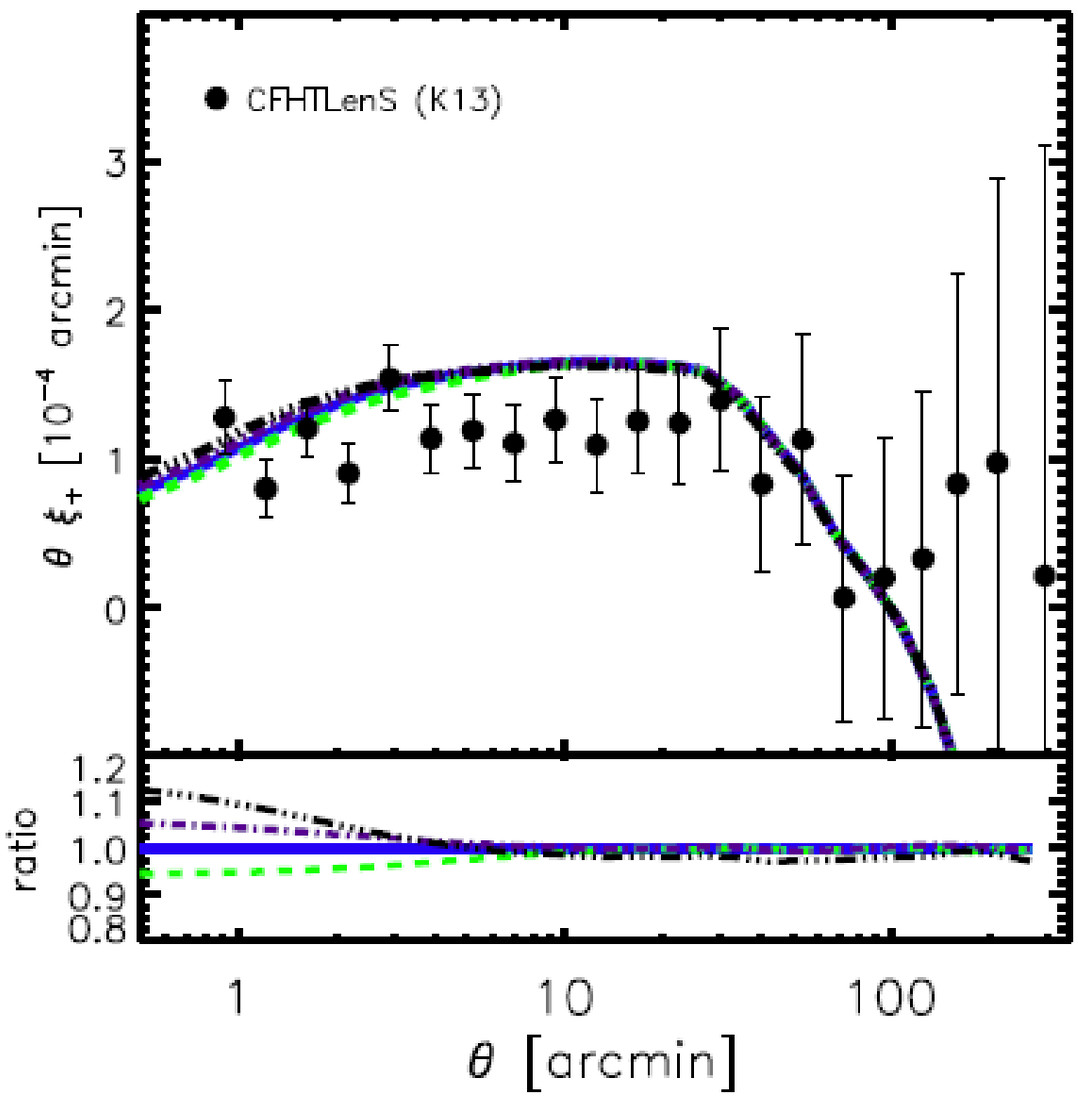


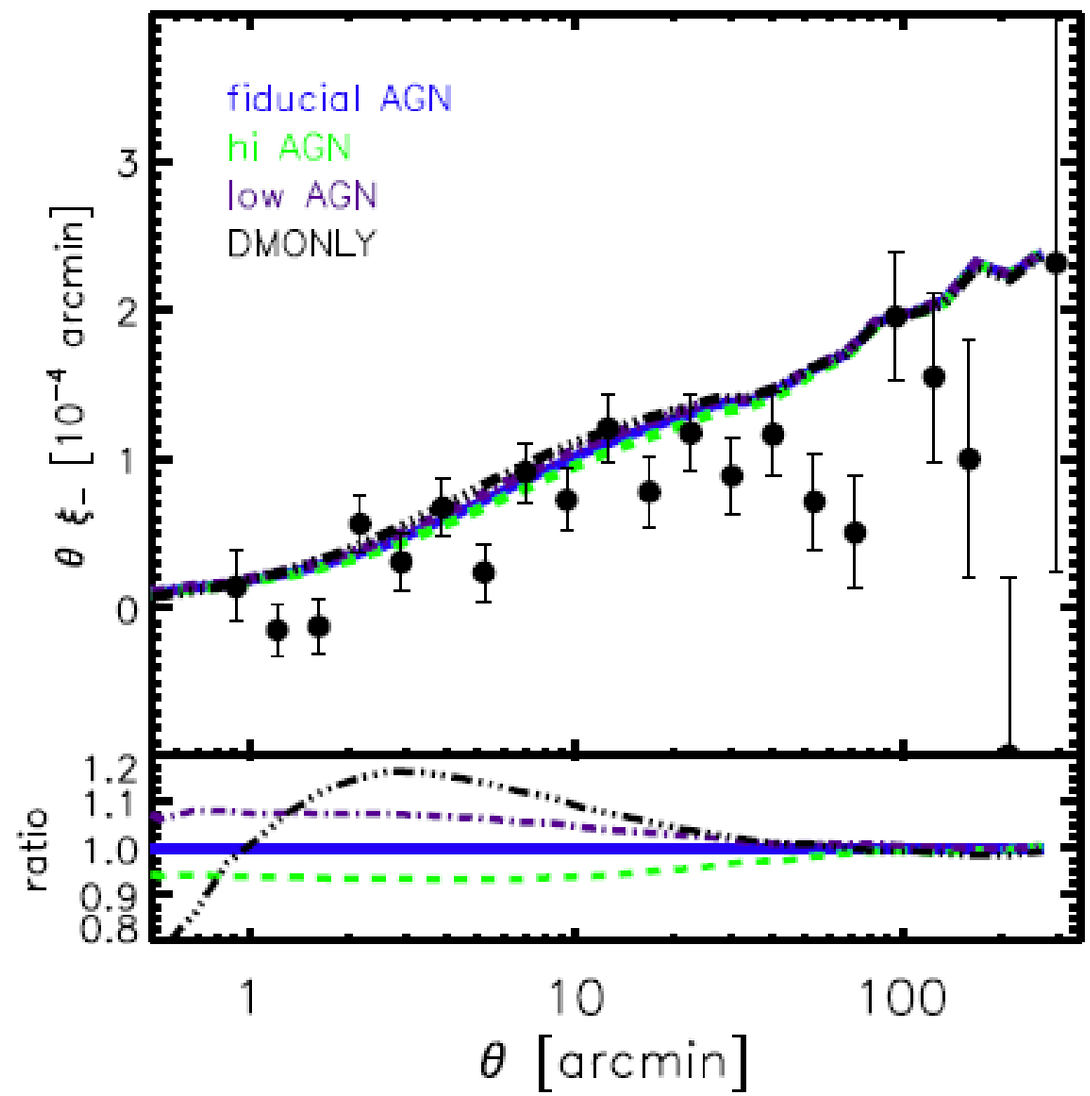
Comparison to CFHTLenS cosmic shear shape correlation functions.

Standard model with minimal neutrino mass predicts stronger correlation than observed.

True for KiDS and, to a lesser extent, DES, as well.

Feedback uncertainties (small at present)





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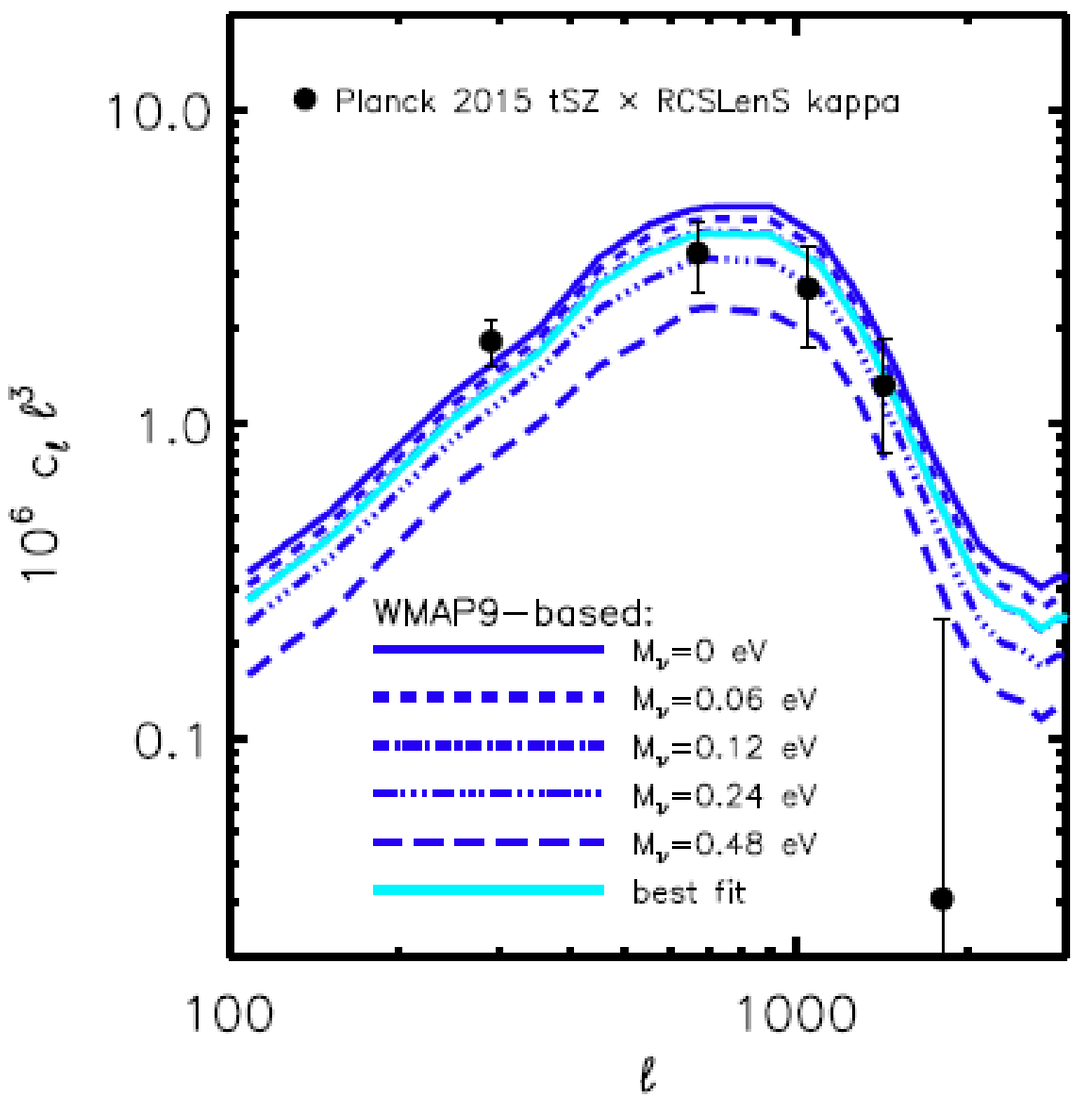
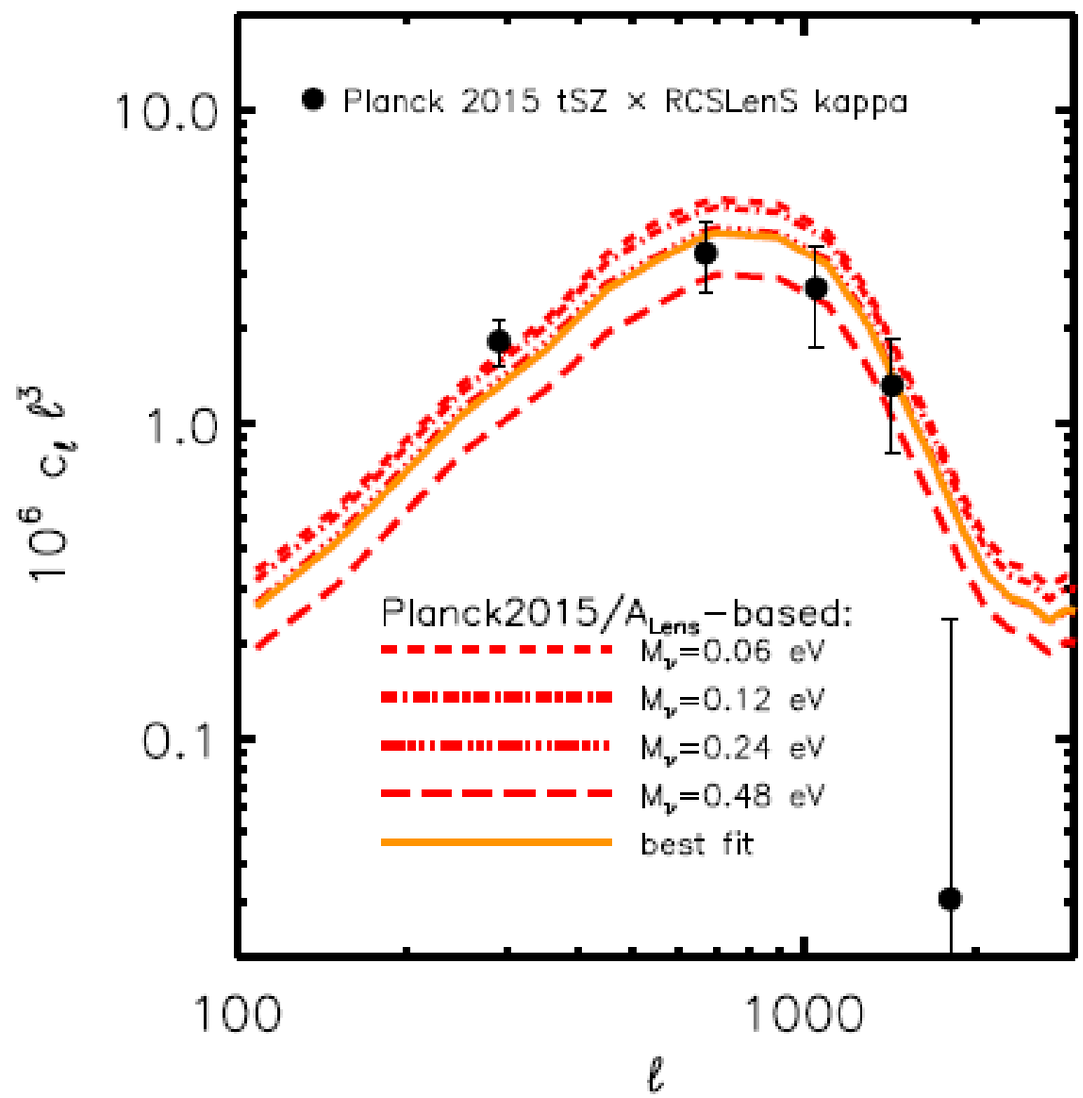
Cosmic shear-SZ cross-spectrum





Cross correlation of RCSLenS convergence map with Planck2015 SZ map.

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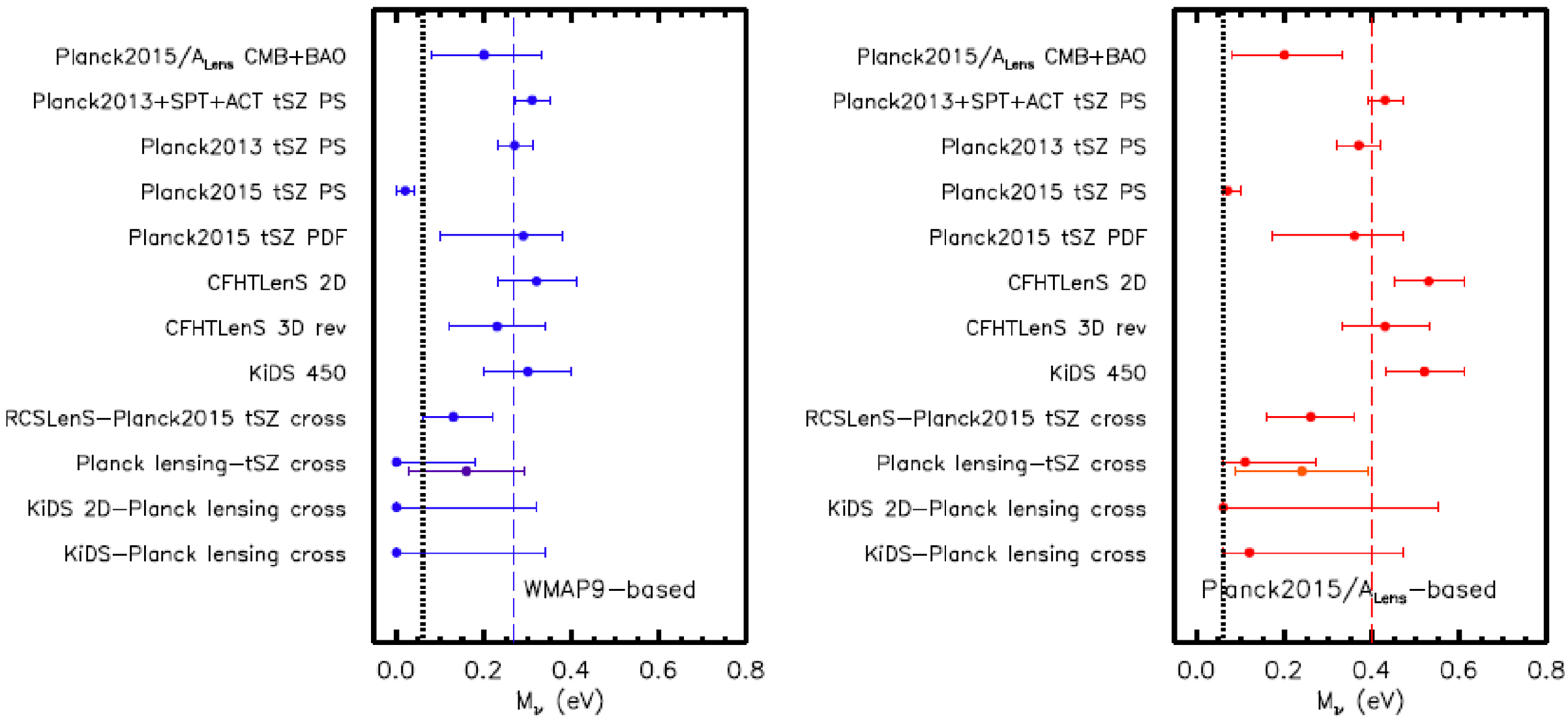
Summary of constraints



Constraints on M_ν depend on which CMB results are combined with LSS. For WMAP, a summed mass of ~0.2 eV is favoured. With Planck, ~0.4 eV.

Summary

- There is presently a tension between the CMB and LSS with regards to the joint constraint on Ω_m-σ_8. (Universe is smoother today than expected)
- The largest theoretical uncertainty is due to feedback modelling of winds/jets that expel baryons from collapsed structures.
- 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.
- We confirm that the standard model of cosmology with minimal neutrino mass (M_ν=0.06 eV) is in tension with LSS data.
- Inclusion of massive neutrinos at a level of 0.2-0.4 eV can reconcile this tension.