Keep searching for the missing baryons in the local Universe

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Barolo Astroparticle Meeting

September 9th, 2021

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The missing baryon problem

BBN and CMB put tight constraints on baryon content (Planck coll., 2018)

$$\boxed{\Omega_b h^2 = 0.02242 \pm 0.00014}$$

BUT! Let's count them

Work	Count	Results
Fukugita (1998)	stars+remnants, HI, H_2, baryons in groups/warm plasma, MACHOs, dwarf+low-SB galaxies	$\Omega_b \approx 0.021$
Cen, Ostriker (1999)	stars, HI, H_2, X-ray in clusters	$\gtrsim$50% missing
Shull (2012)	galaxies, groups, clusters, CGM, Ly-α, OVI emission	$\sim$30% missing

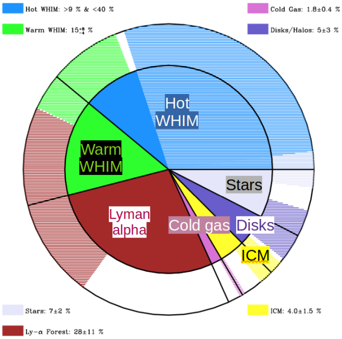
WHERE ARE THE BARYONS?

Warm-Hot Intergalactic Medium (WHIM)

Hydro-sims predict missing gas to be in a warm-hot phase and diffuse in filaments.

$$T_{\rm WHIM} \sim 10^5 - 10^7 \ {\rm K} \qquad n_{\rm WHIM} \sim 10^{-6} - 10^{-4} \ {\rm cm}^{-3}$$

Emission/absorption in far UV (OVI) and soft X-rays (OVII and OVIII)



Nicastro+18

- Difficult detection: low overdensities ($\sim 10 - 100$) and ionized H invisible in far UV
- Nicastro+18: detection of 2 OVII absorption systems
- Kovacs+19: 17 absorption systems in H 1821+643 quasar spectrum

Rationale

So far, only individual detections of "no longer missing" baryons.

How to close the problem?

1. Characterization of WHIM
   - physical and chemical properties
   - realistic modelling of emission
   - uncertainties: cosmology + feedback
2. The future (Athena)
   - spatial distribution: 2-point correlation function
   - realistic surface brightness (S_B) maps
   - emission detection forecasts

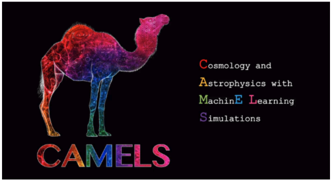
Dataset: the CAMELS project

CAMELS: state-of-the-art hydrodynamic simulations (Villaescusa-Navarro+20)

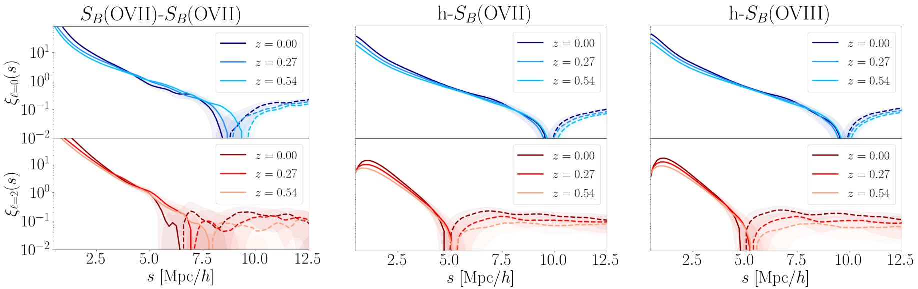
- same baryonic subgrid physics as IllustrisTNG and SIMBA
- small box ($L = 25$ Mpc/h) but more than **4,000 realizations**!
- varying cosmology, SNe and AGN feedback $\rightarrow$ we can explore feedback parameter space

Model and measurements:

- use 27 realization with same cosmology and baryonic physics (for now...)
- emissivity computed with `pyXsim` (ZuHone+16) assuming collisional equilibrium
- S_B of OVII triplet ($\sim$ 0.57 keV) and OVIII singlet (0.653 keV)
- emission maps: 5'' and 2.5 eV resolution, $S_B^{min} = 0.1$ ph/s/cm^2/sr for 100 ks observations (Athena)



2-point correlation functions

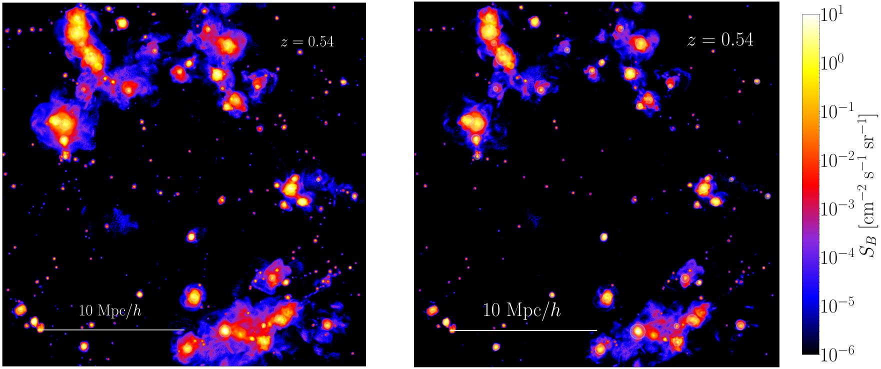


$$\xi_{AB}(s) = \langle \delta_A(x + s)\delta_B(x + s)\rangle$$

- Average on 27 realizations, shaded areas are 1-σ on the mean
- Monopole goes negative for integral constraint...
- ... but $s(\xi_{\ell=0} = 0)$ evolves with redshift
- Quadrupole goes negative where virialization onsets

Emission maps

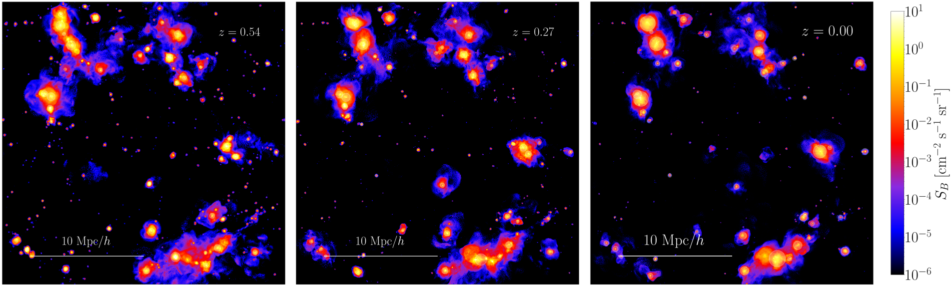
Distribution of OVII and OVIII at fixed redshift



- OVII traces more halo outskirts
- OVIII is more concentrated in halo centers

Emission maps

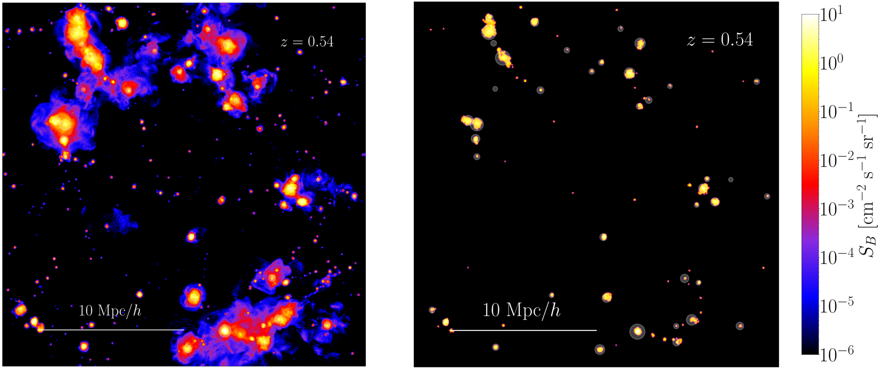
Redshift evolution of OVII



- Redshift range is narrow, so weak evolution
- Mainly driven by halo mergers

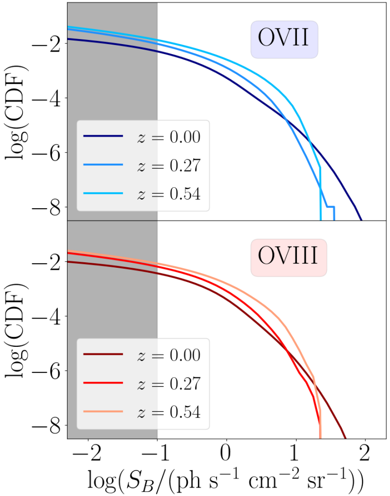
Emission maps

Surface brightness cut (Athena)



- $S_B^{min} = 0.1$ ph/s/cm^2/sr for 100 ks observation
- Detectable WHIM only in zones internal or close to (relatively massive) halos

Cumulative density function



- Fraction of pixels above the a certain detection threshold (0.1 ph/s/cm^2/sr for 100 ks observation)
- Clear trend: high emission tail grows at low redshift (mergers)
- With this threshold $>$ 1% of pixels will contain a detection
- **To-do**: dependence on feedback parameters and other WHIM properties (metallicity, SFR, winds, AGN...)

Conclusions

Aim and method

- Characterization WHIM in emission, physical processes
- Exploitation of immense amount of data of CAMELS hydro sims
- Exploration of effects of cosmology and degeneracies with baryon feedback (SN and AGN winds)
- Study of cross-correlations to identify highest signals
- Building of realistic surface brightness maps for future detection of emitting systems, prediction of number of emitters in the field-of-view (1° at $z \approx 0.5$)

Take-home messages

- **2PCFs**: measure of spatial distribution, chaotic motion, infall and virialization of gas; weak redshift evolution
- **Maps and CDFs**: detectable emission comes from highest overdensities (most massive halos) for both OVII and OVIII; highest emission at low z

THANKS FOR YOUR ATTENTION