Studying the Warm-Hot Intergalactic Medium in emission: a reprise

Athena and X-ray integral field spectroscopy

Gabriele Parimbelli

Università degli Studi di Genova

CAMELS Workshop, Flatiron Institute @NYC

Enzo Branchini *(UniGe)*
Matteo Viel *(SISSA)*
Francisco Villaescusa-Navarro *(Princeton)*
John ZuHone *(CfA Harvard)*

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Missing baryons problem and WHIM

BBN+CMB put tight constraints on baryon content (Planck 2018)

$\Omega_b = 0.0490 \pm 0.0007$

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?

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

$T \sim 10^5$-10^7 K $n \sim 10^{-6}$-10^{-4} cm^{-3}

- Emission and absorption in far UV / soft X-rays
- Difficult detection: low overdensities ($\lesssim$1000), H invisible in far UV
- Nicastro+18: detection of 2 OVII absorption systems; Kovacs+19: 17 absorption systems in distant quasar spectra

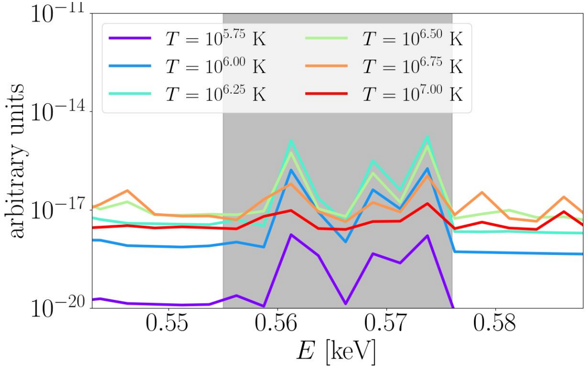
WHIM emission: integral field spectroscopy

What do we want more?

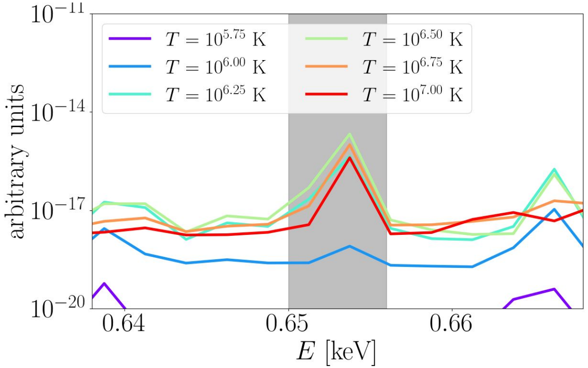
1. so far only individual detections (**physical/chemical state, baryon content information** missing)
2. detections only in absorption (**emission** missing)

Athena may allow us to detect **WHIM in emission** thanks to the possibility of performing **integral field spectroscopy**, therefore increasing the S/N of the emission signal

- already used for HI 21cm line
- metal lines (**OVII**, **OVIII**, FeXVII, NeIX, MgXII...)
- physical and chemical properties
- summary statistics: **number counts, clustering**...

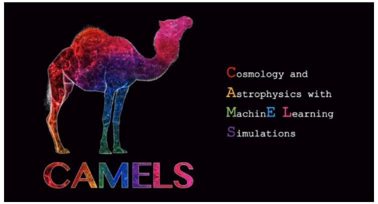


OVII



OVIII

A systematic study: the CAMELS simulations suite



Subsets:

- **CV**: “fiducial”, **cosmic variance**
- **1P**: **variations** of single parameters
- **LH**: **uncertainty on cosmo+feedback***
- \+ **IllustrisTNG-300**: **volume** effects

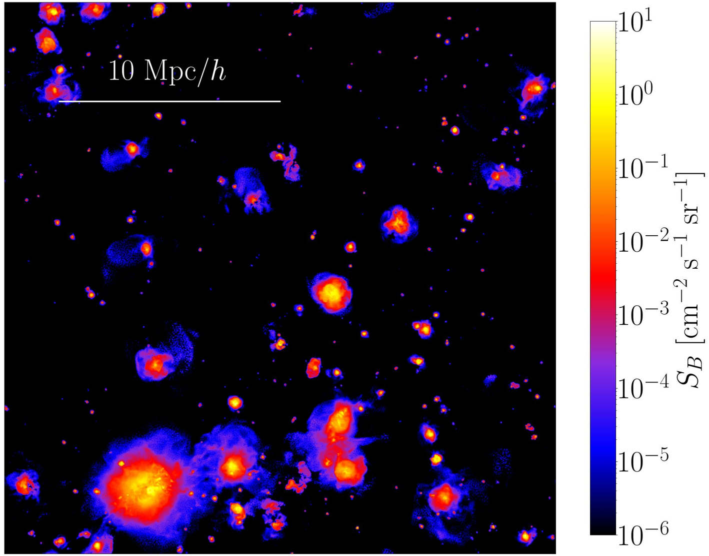
*only realizations with cosmology “close” to fiducial

Statistics:

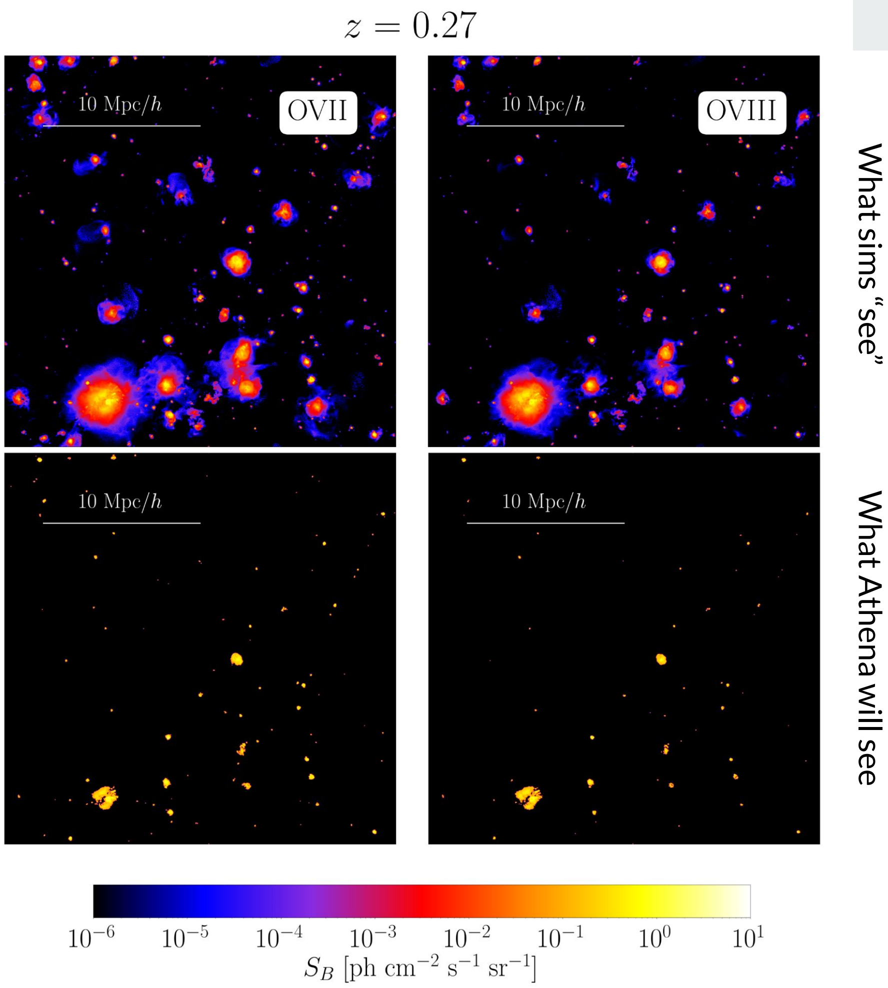
- OVII / OVIII surface brightness (S_B) maps
- S_B pixel number counts
- S_B / halo angular 2-point correlation function (2PCF)

Specifics:

- spectra computed with `pyXsim` (ZuHone+16)
- angular and energy resolution of **X-IFU** instrument on board of **Athena**
- 3-σ detection threshold = 0.1 ph cm^{-2} s^{-1} sr^{-1}



OVII S_B map @ z=0.27

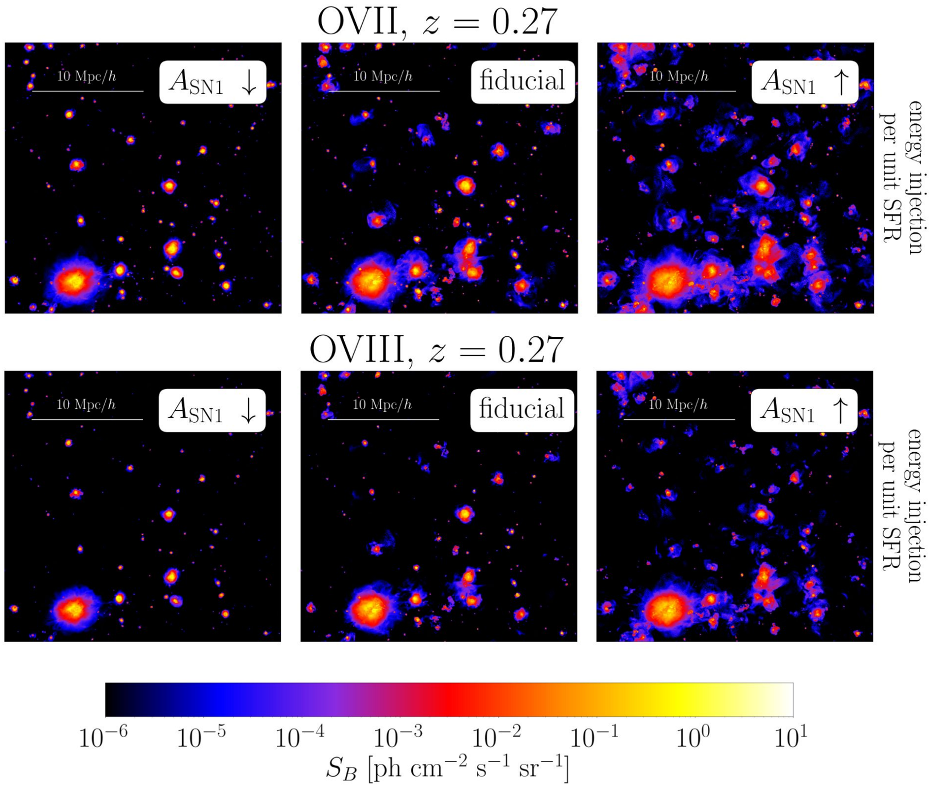


Surface brightness maps: OVII vs. OVIII

Snapshots with z $\lesssim$ 0.55, time evolution is slow and driven by halo mergers.

Filaments are missing because we neglect photoionization, see e.g. Bertone+09. However, Athena will detect only highest density regions

Surface brightness maps: changing cosmology and energy feedback



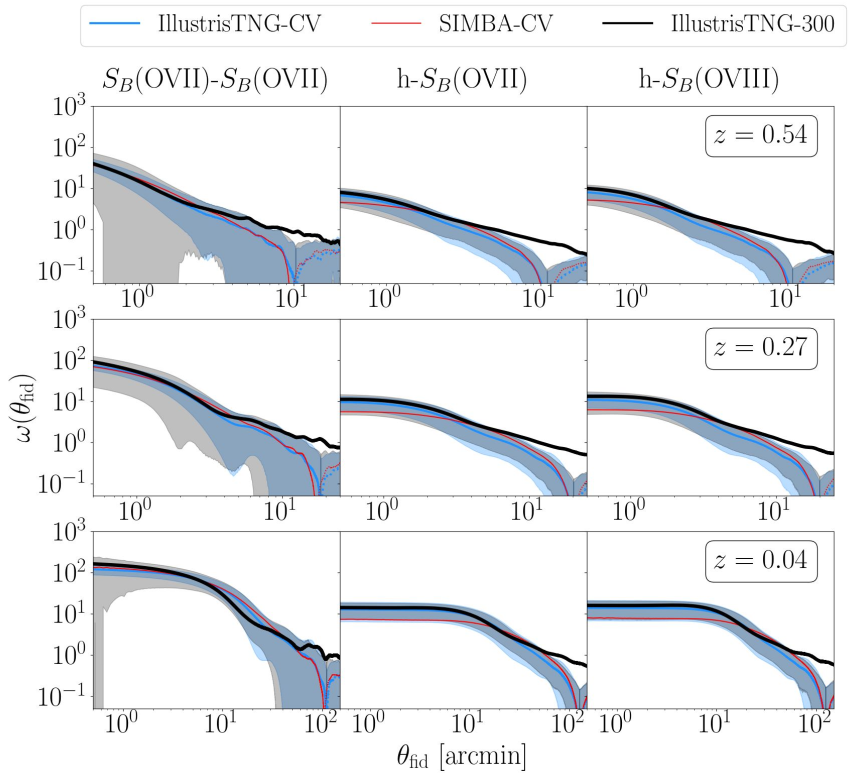
COSMOLOGY

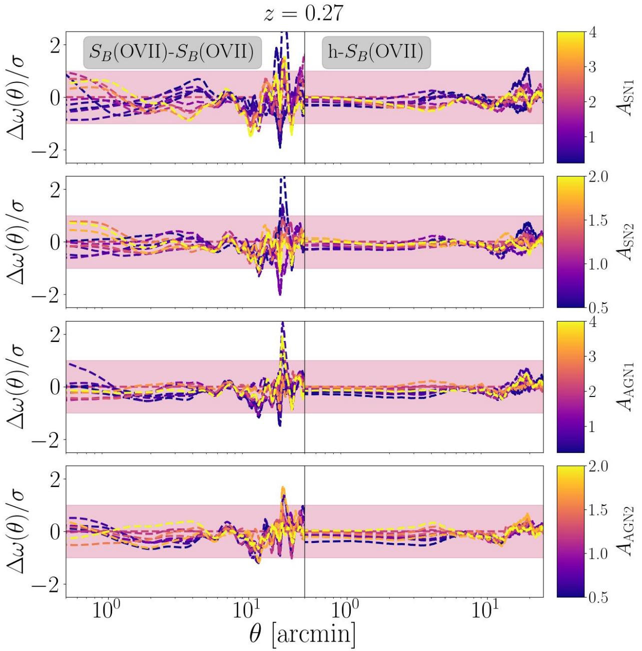
- Increasing Ω_m and σ_8 shifts emission from centers to outskirts

FEEDBACK

- Increasing energy injected by SN (see left) and SN wind speed makes emission more diffuse in outskirts (cfr. Roncarelli+12)
- Increasing AGN feedback has an opposite and less prominent effect (lack of halos of $M \gtrsim 10^{13}\,M_\odot/h$)

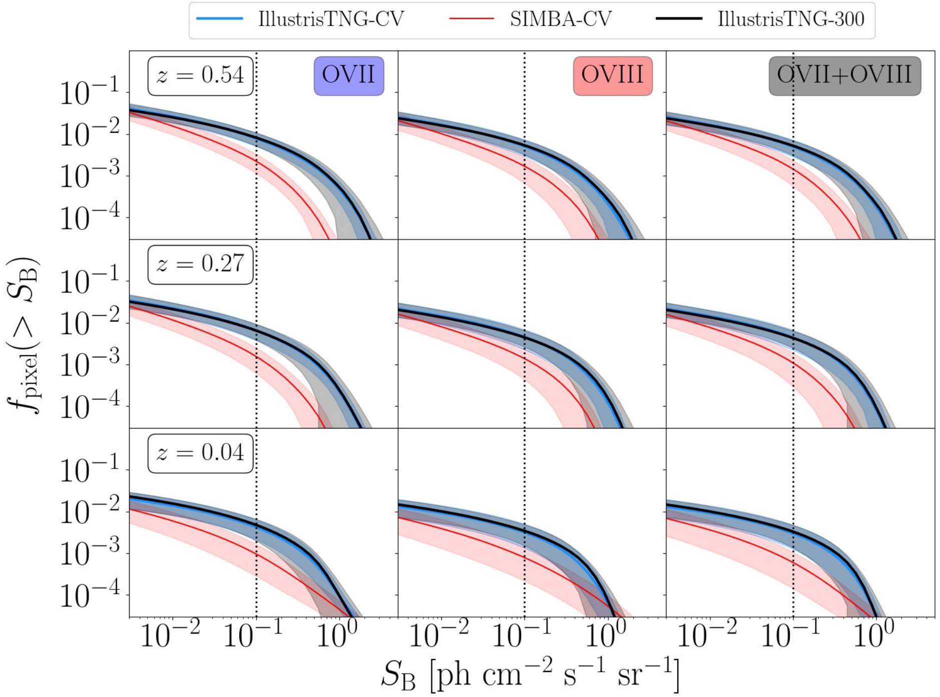
Clustering properties of the WHIM

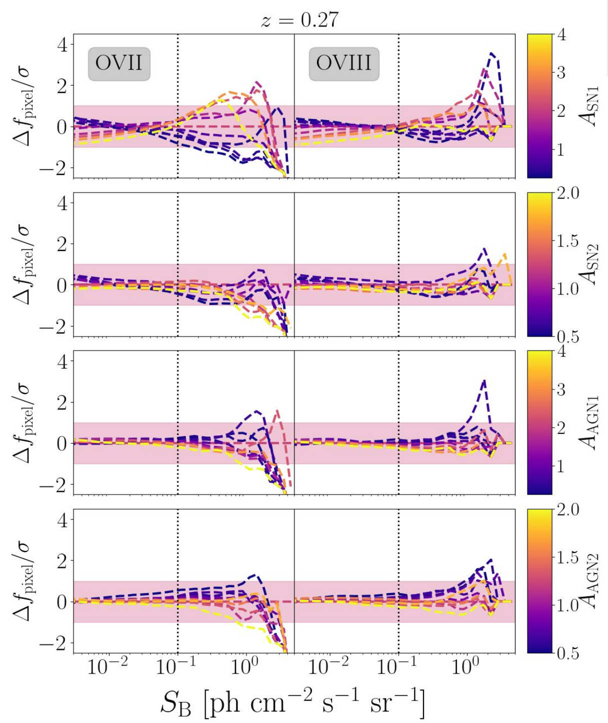




- Match at small separations for different subgrid physics!
- Evaluation of uncertainties blue is cosmic variance, grey is cosmo+astro
- Integral constraint + plateau
- Cross-correlation with halos is identical
- Cosmological dependence relevant, but very robust for extreme feedback parameters!

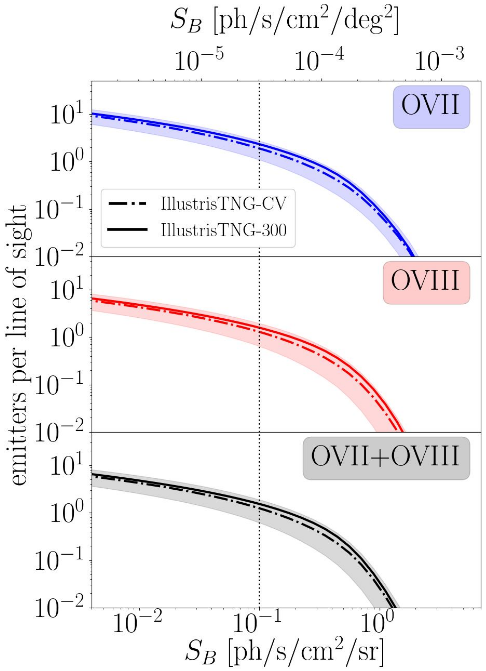
logN-logS_B from pixel number counts

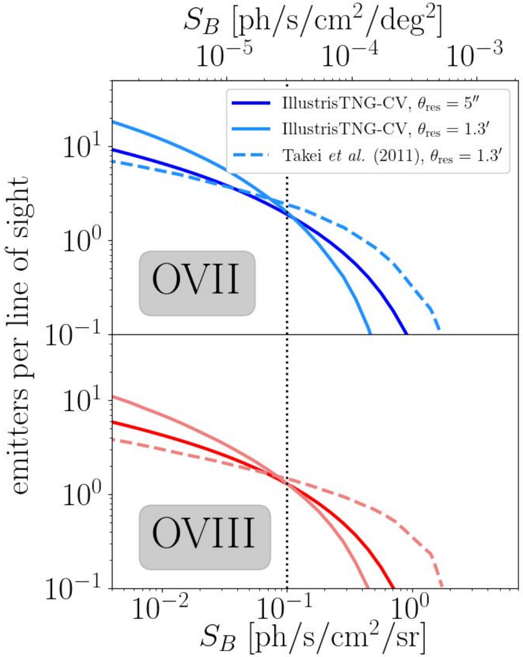




- Power-law + exp tail (similar to column density)
- Code mismatch is significant at higher z
- Volume effects are negligible
- OVIII and OVII+OVIII are almost identical
- Effect of cosmology negligible, feedback expectedly affects bright tail but with low significance

Forecasts: emitters per line-of-sight





We built a "mock lightcone" by summing up all the logN-logS_B's from available snapshots in CAMELS and IllustrisTNG-300, rescaling for the volume and dividing for the number of lines-of-sight.

We also compared different angular resolutions (cfr. Takei+11)

We forecast around 1-3 emitters per LoS (including all uncertainties and resolution) for Athena sensitivity

Conclusions

- **WHIM** is supposed to constitute the missing baryons, detected in absorption, not yet in emission
- A systematic study of **WHIM emission properties** is necessary and now possible thanks to the large suite of **CAMELS** simulations.
- We build **surface brightness** maps for OVII and OVIII lines and measure summary statistics, **testing robustness** of models, variations in cosmology and astrophysical parameters (**baryon feedback**) and **evaluating uncertainties** on measurable quantities.

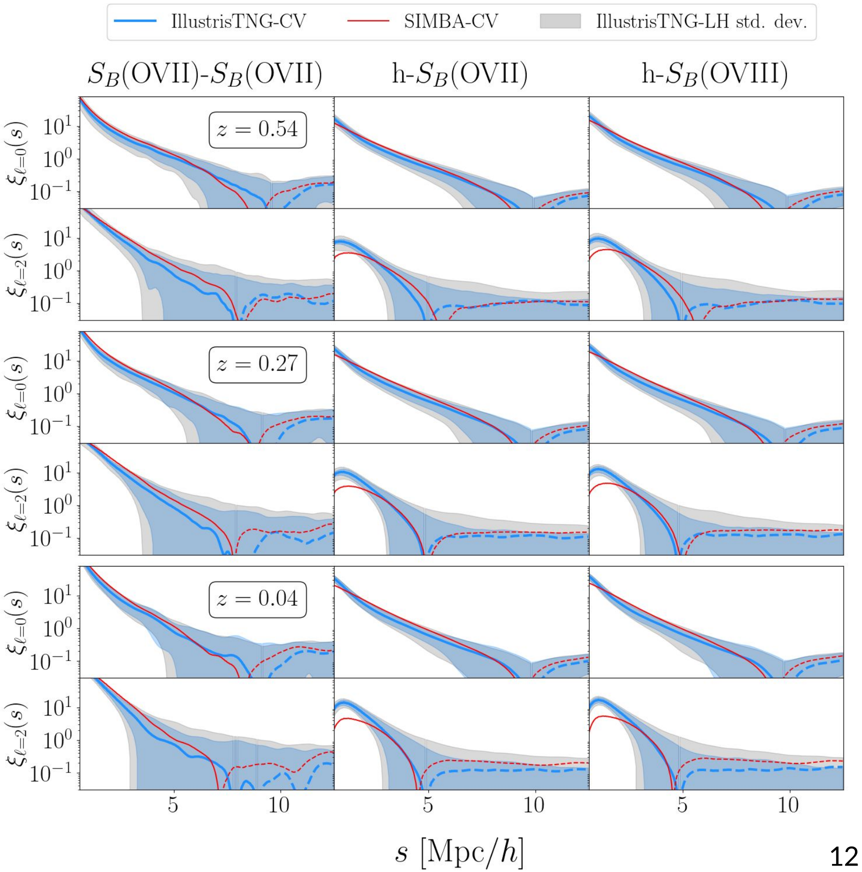
- TAKE-AWAYs:
  - **Correlation functions** are robust w.r.t. changes in cosmology and feedback; **pixel number counts** show some low-significance dependence on SN feedback.
  - **Uncertainty on baryonic feedback parameters** dominates the error budget in bright regions.
  - We foresee **1-3 WHIM detections per LoS** with Athena specifics (but independently from angular resolution!)
- FUTURE WORK:
  - adding NeIX, FeXVII, MgXII lines
  - SZ effect (Moser et al., 2022)
  - level-field inference with machine learning (also why I'm here…)

THANKS FOR YOUR ATTENTION

BACK-UP SLIDES

3D clustering of the WHIM

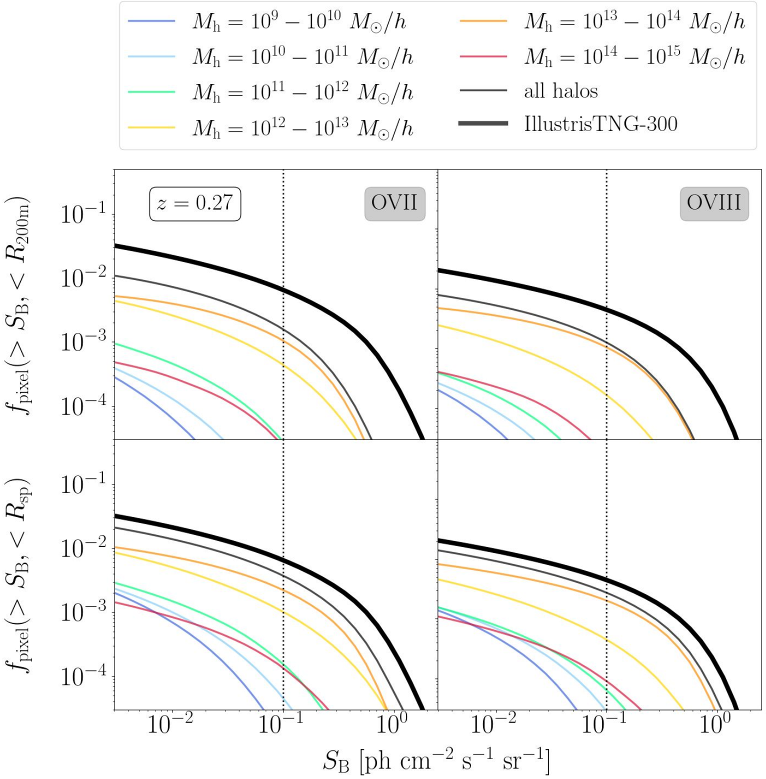
- Monopole (l=0): isotropic clustering
  - integral constraint turnaround
  - redshift evolution
- Quadrupole (l=2): gas motion
  - -: coherent infall motion
  - +: virialized non-linear motions



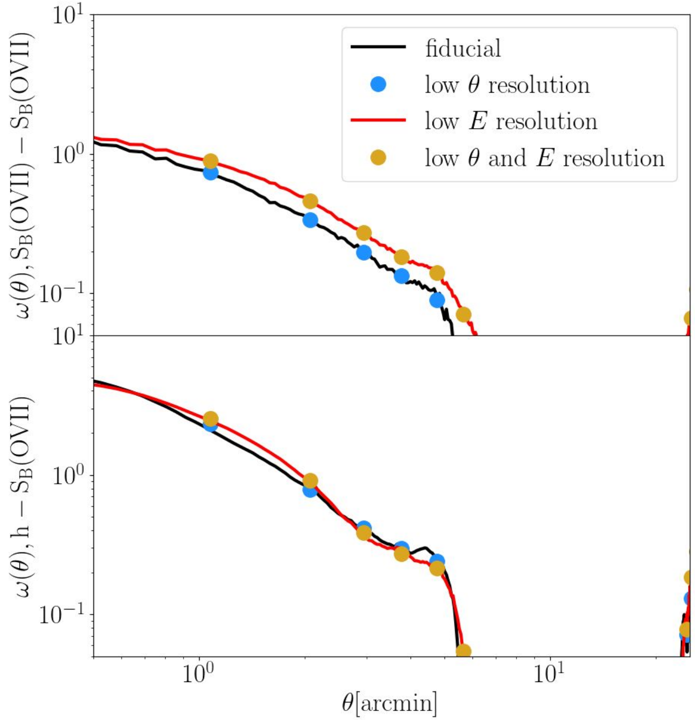
Where does the emission come from?

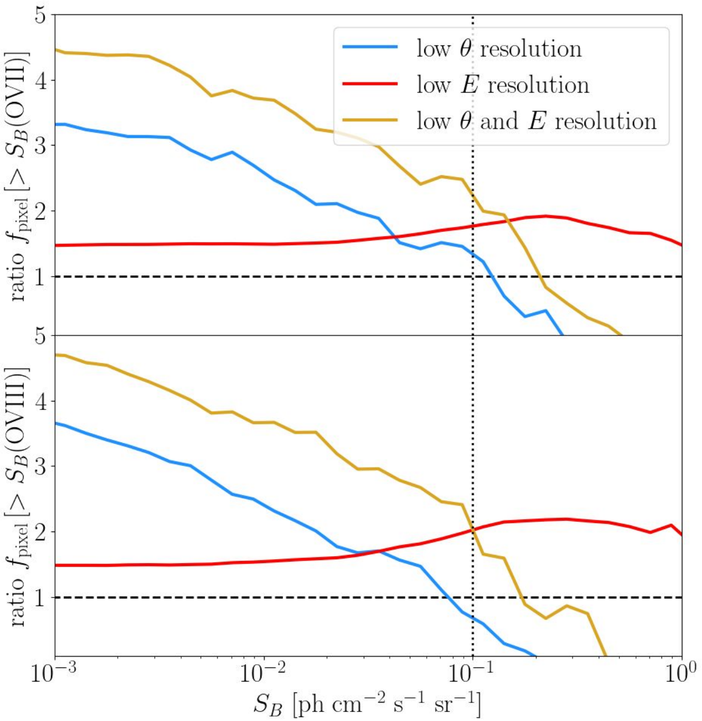
Center of halos? Outskirts? Which kind of halos?
Helpful for future focused searches!
We use IllustrisTNG-300 (more numerous and more massive halos)

- Halo radii are loosely defined:
  - **virial radius**: R_{200m}
  - **splashback radius**: $R_{sp} \approx 2\, R_{200m}$
- ~50% of the emission comes from regions outside the virial radius; ~30% of the emission comes from outside the splashback radius
- Halos in mass range 10^{12}-10^{14} $M_\odot/h$ dominate (only 8 halos with $M > 10^{14}$ $M_\odot/h$)



Effect of energy/angular resolution





What if…

ΔE_{res} = 4 eV
$\Delta\theta_{res}$ = 1.3'

or both?