Studying the Warm-Hot Intergalactic Medium in emission: a reprise
Athena and X-ray integral field spectroscopy

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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:

WHERE ARE THE BARYONS?

<table>
<thead>
<tr>
<th>Work</th>
<th>Count</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fukugita (1998)</td>
<td>stars+remnants, HI, H2, baryons in groups/warm plasma, MACHOs, dwarf+low-SB galaxies</td>
<td>$\Omega_b \approx 0.021$</td>
</tr>
<tr>
<td>Cen, Ostriker (1999)</td>
<td>stars, HI, H2, X-ray in clusters</td>
<td>$\geq 50%$ missing</td>
</tr>
<tr>
<td>Shull (2012)</td>
<td>galaxies, groups, clusters, CGM, Ly-α, OVI emission</td>
<td>$\sim 30%$ missing</td>
</tr>
</tbody>
</table>

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

$T \sim 10^5$-$10^7$ K \hspace{1cm} $n \sim 10^{-6}$-$10^{-4}$ 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...
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$^{-1}$
Snapshots with $z \leq 0.55$, 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 $\Omega_m$ and $\sigma_8$ 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-log$S_B$ 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
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: $R_{sp} = 2 R_{200m}$
- ~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…

$\Delta E_{\text{res}} = 4 \text{ eV}$

$\Delta \theta_{\text{res}} = 1.3'$

or both?