Intergalactic matter around isolated galaxies

X-ray correlations analysis

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Outline

1. Missing baryons problem
   - Warm-Hot Intergalactic Medium (WHIM) – simulations and speculations
2. WHIM – search for the X-ray emission
   - Observational constraints
   - WHIM in the *XMM-Newton* observations
3. Preliminary *Chandra* results
   - XRB – galaxies correlations
   - Concentrated and extended emission
   - Conclusions

Where are the baryons?

$$\Omega_{\rm lum} \simeq \Omega_\star + \Omega_{\rm HI} + \Omega_{\rm X:clusters} \approx 0.014\, h_{65}^{-2}$$

$$\Omega_{\rm b} \approx (0.045 \pm 0.057) \qquad \text{(Primeval abundances D, } {}^3\text{He, } {}^4\text{He, Li)}$$

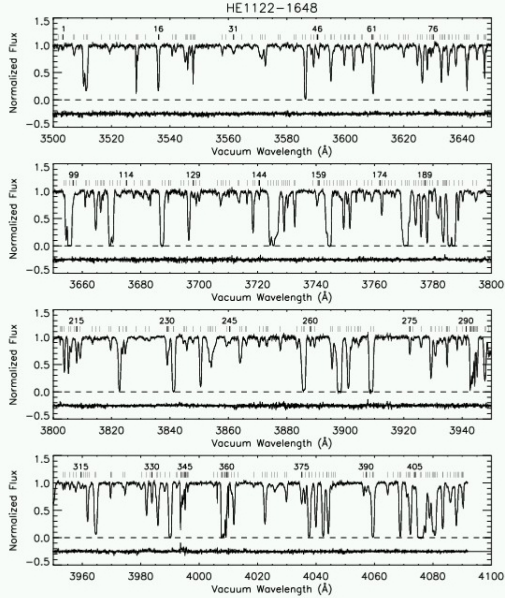
$$> 0.040\, h_{65}^{-1} \qquad (\text{Ly-}\alpha \text{ forest at } z \approx 2)$$

$$\Omega_{\rm lum} \; < \; \Omega_{\rm b} \; < \; \Omega_{\rm m} \; \approx \; 0.3$$

$\Uparrow$ Baryon deficyt

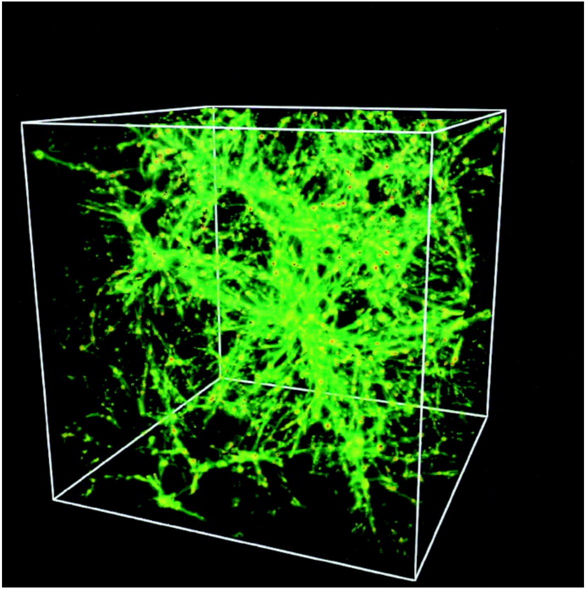
$\Uparrow$ Dark matter

Diffuse baryons at moderate redshifts



Kim, T.-S. et al. (2002)

Intergalactic matter locally



Cen & Ostriker (1999)

“Phases” of baryonic matter

- Condensed in galaxies
- Hot gas in clusters of galaxies
- Clouds producing Ly-α forest
- Warm-Hot Intergalactic Medium – WHIM

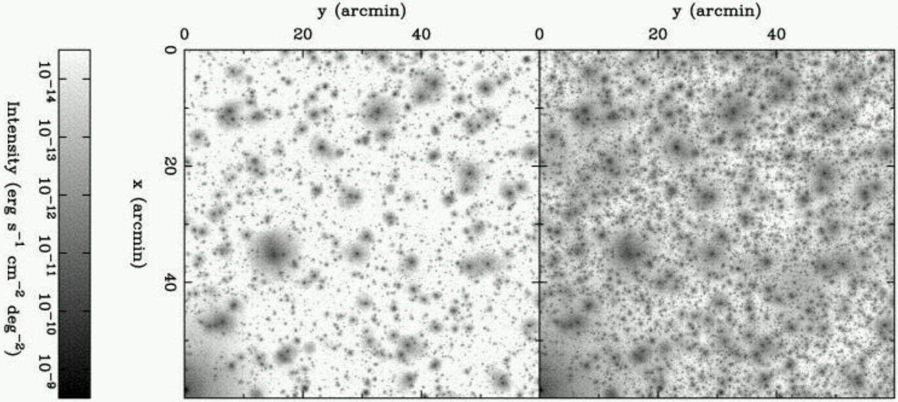
Primordial matter falling down into gravitational potential wells of galaxies (and dark matter) interacts with gas expelled from galaxies.

The medium is highly nonuniform.

Matter is heated in shocks to $10^5 - 10^7$ K.

Up to 40 % of baryons may still reside in WHIM.

WHIM – thermal emission



Croft et al. (2001)

Observational constraints

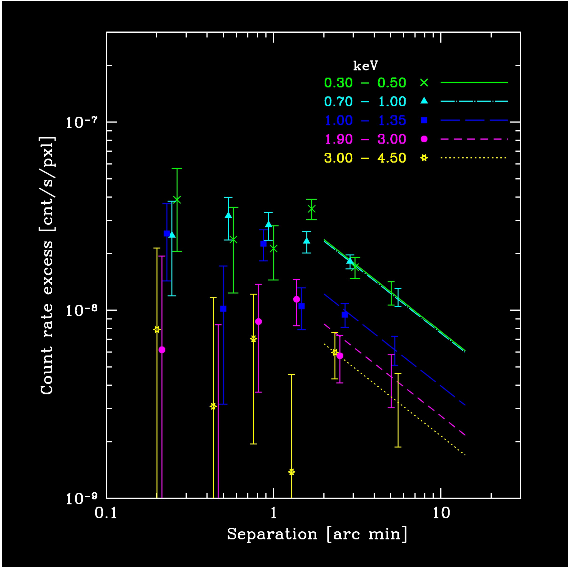
The WHIM emission is

- soft, $kT \leq 1\,\mathrm{keV}$
- strongly correlated with galaxies
- weak and superimopsed on the non-uniform XRB background generated by AGN and clusters of galaxies

How to search for the WHIM emission

- Correlate galaxy distribution with the soft XRB maps
- Use as much observational data at high galactic latitudes as possible (to improve S/N)

WHIM around galaxies – XMM results



Extended excess of the soft XRB surrounding galaxies results from the emission generated in halos around galaxies and the nonuniform distribution of galaxies.

Sołtan (2006)

X-rays emitting WHIM surrounding galaxies

$$\theta_{\rm halo} = 2' - 3' \qquad \Rightarrow \qquad (8 - 12) \cdot 10^{23}\,{\rm cm}$$

$$\rho_{\rm halo} = (1.6 - 2.7) \cdot 10^{-28}\,{\rm g\,cm^{-3}}$$

$$M_{\rm halo} = (3 - 7) \cdot 10^{11}\,{\rm M_\odot}$$

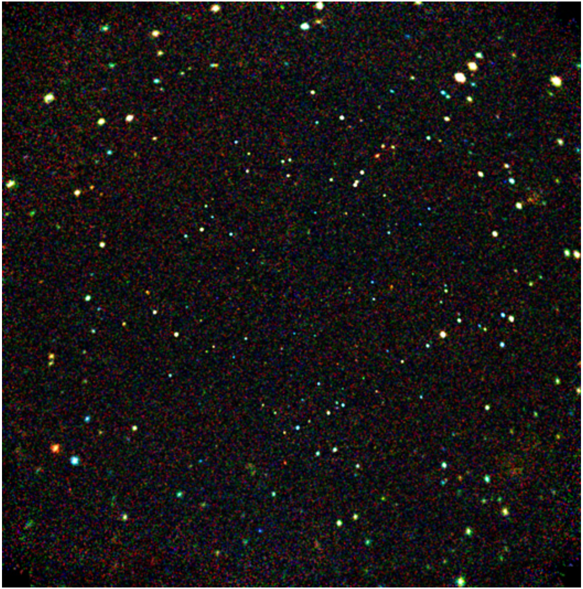
$$\rho_{\rm WHIM} = (5 - 11) \cdot 10^{-32}\,{\rm g\,cm^{-3}}$$

$$\rho_{\rm WHIM}/\rho_{\rm b} = 8 - 19\,\%$$

Weak points

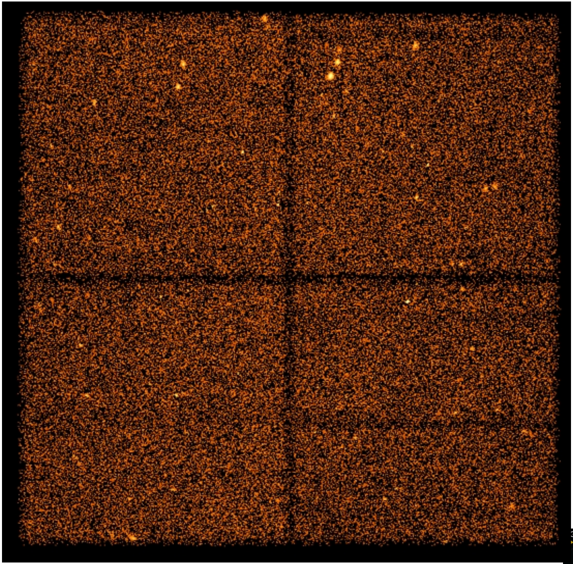
- Still low S/N (despite $\sim$ 150 pointings)
- Poor separation of the localized galaxy emission from the extended halo
- No information on the surface brightness distribution

X-ray sky - *Chandra* processed image



Giacconi et al. (2002)

X-ray sky - raw image



X-ray observational material – some statistics

- $\sim$ 180 *Chandra* ACIS pointings
- Average exposure time – 53 ks
- Total exposure time $\sim$ 9.5 Ms
- Several thousands galaxies
- 12 sq. deg.

- No strong sources
- All detected sources removed
- All known clusters removed

ACIS – AXAF CCD Imaging Spectrometer

AXAF – Advanced X-ray Astrophysics Facility

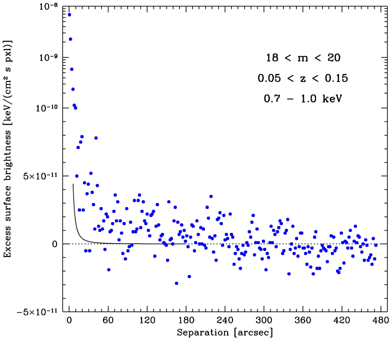
Search for WHIM using Chandra – preliminary results

Correlation of the XRB surface brightness with galaxy distribution:

- X-ray observations in 8 energy bins between 0.3 and 7 keV
- Galaxies divided in three magnitude/redshift bins

  $18 < m < 20$ or $0.05 < z < 0.15$
  $20 < m < 21$ or $0.15 < z < 0.22$
  $21 < m < 22$ or $0.22 < z < 0.28$

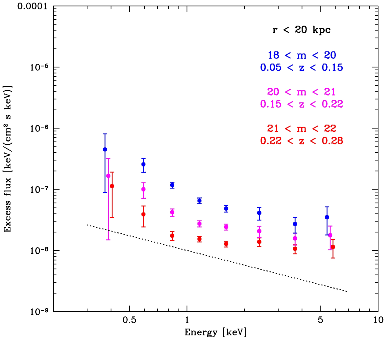
XRB around normal galaxies



20 kpc at $z = 0.10 \;\Leftrightarrow\;$ 11 arcsec.

- Strong pointlike excess of the XRB flux at small separations (Note change of scale at 10^{-10} keV/(cm^2 s pxl); pxl = 2×2 arcsec).
- Weak extended emission (black curve represents contribution of the central source due to PSF).

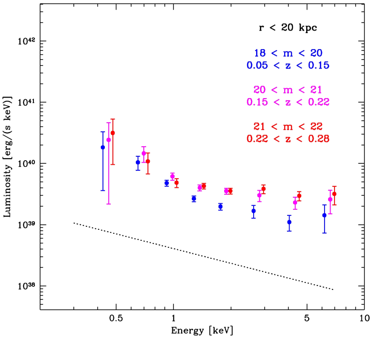
Galaxies – pointlike X-ray emission



- Average spectrum of emission generated within 20 kpc from the galaxy center in three magnitude/redshift samples.
- Dotted line indicates power law with photon index $\Gamma = -1.8$.

Error bars represent 2σ uncertainties.

Normal galaxies – X-ray luminosities



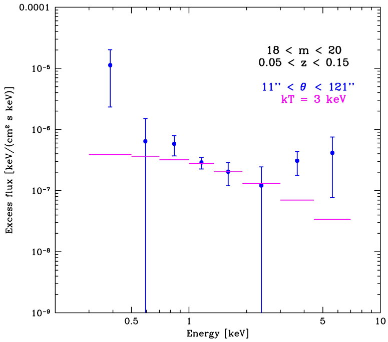
- Average galaxy luminosities generated within 20 kpc in three magnitude/redshift samples.
-

m	$L_{0.5-2\,\mathrm{keV}}$ [erg/s]
18 – 20	$5.7 \cdot 10^{39}$
20 – 21	$8.4 \cdot 10^{39}$
21 – 22	$7.5 \cdot 10^{39}$

- Note a possible hardening of spectra for more distant galaxies.

Dotted line indicates power law with photon index $\Gamma = -1.8$.
Error bars represent 2σ uncertainties.

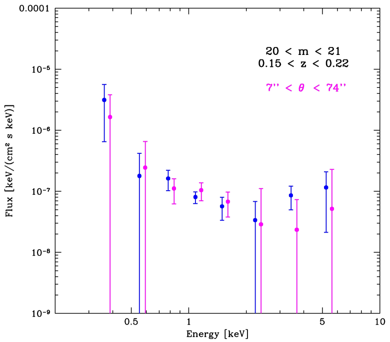
Galaxies – X-ray halo emission



- Average flux generated in the halo around galaxies between 20 and 220 kpc.
- Thermal optically thin plasma emission with $kT = 3\,\mathrm{keV}$; metal abundances $Z = 0.25\,Z_\odot$ (arbitrary normalization).
- Note excess in the low energy bin of $0.3 - 0.5\,\mathrm{keV}$.

Error bars represent 2σ uncertainties.

Halo emission – local vs. distant



- Average flux generated in the halo around galaxies between 20 and 220 kpc (pinki symbols).
- Halo emission in the $18 < m < 20$ sample scaled to the $20 < m < 21$ sample (blue symbols).
- Low S/N ratio in the lowest and highest energy bins do not allow for assessment of the WHIM evolution.

Error bars represent 2σ uncertainties.

Conclusions and prospects for the future

- WHIM is visible, but it's really faint
- *Chandra* and *XMM-Newton* observations are in good agreement
- In the soft XRB WHIM emission dominates over the galactic contribution
- WHIM contributes substantially to the soft XRB

- Large data volume $\Rightarrow$ very high sensitivity

  $S_{th} < 10^{-17}\,\mathrm{erg\,s^{-1}cm^{-2}}$ $[0.5 - 2\,\mathrm{keV}]$ – point sources
- How to improve S/N ?

  More data – not likely

  Individual treatment of each observation; careful subtraction of instrumental effects