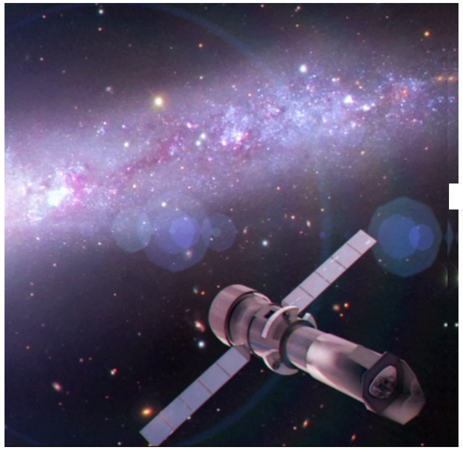
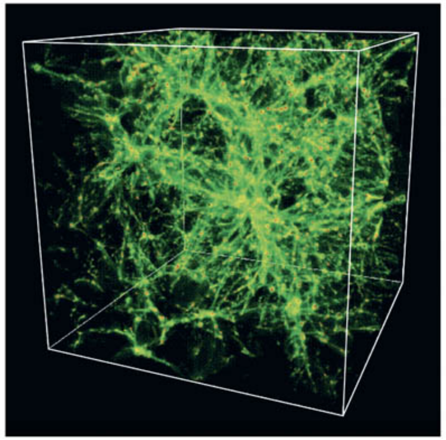
Athena: Missing baryons and beyond





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Thanks to the whole Athena & X-IFU teams

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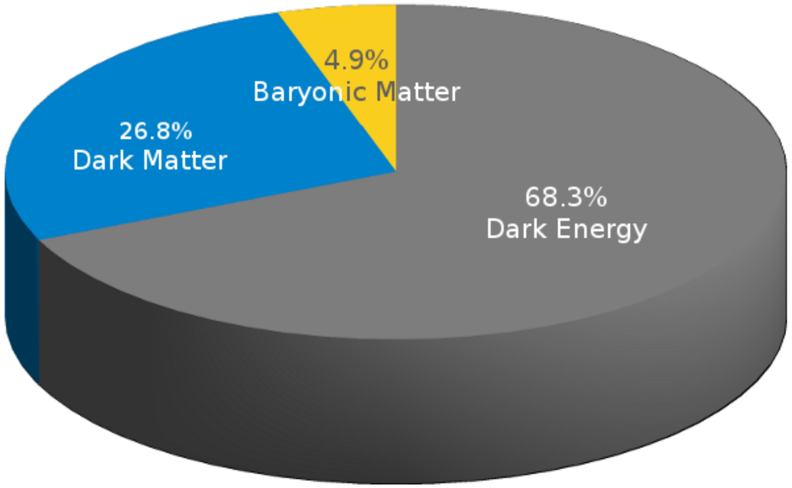
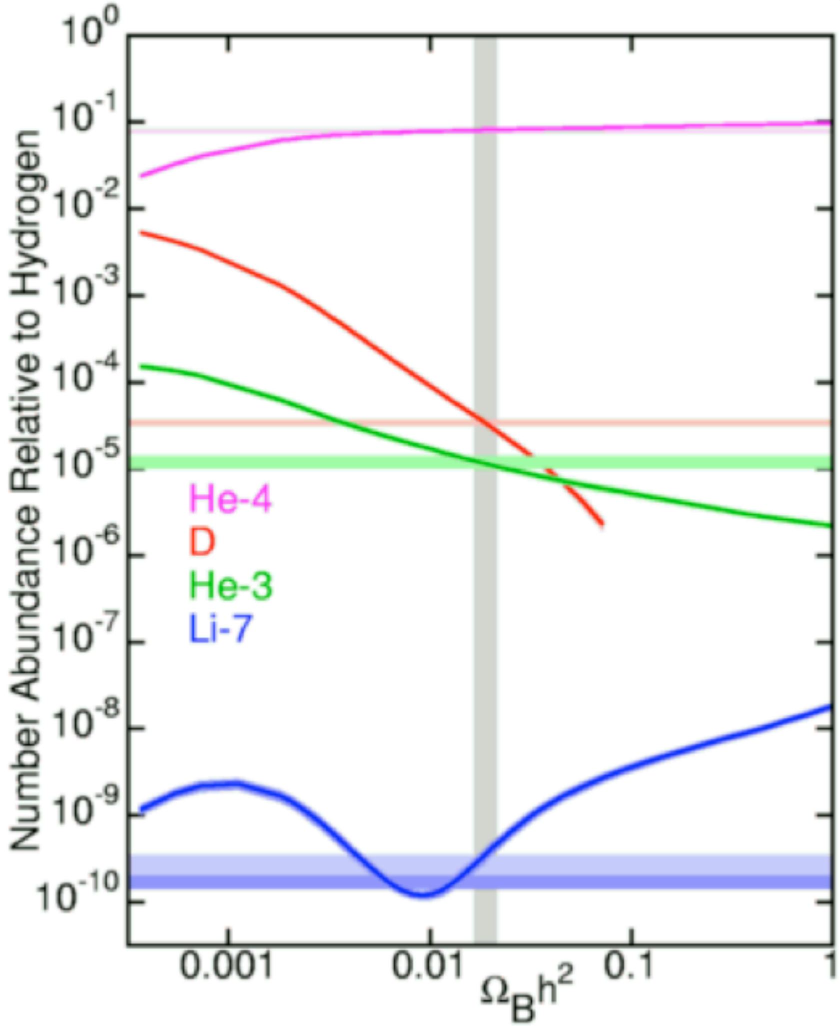
- Athena Science Study Team
- X-IFU Science Advisory Team
- Special thanks to:
  - D Barret, J Bregman, JW den Herder, A Finoguenov, J Kaastra, K Nandra, F Nicastro, L Piro E Pointecouteau

Topics

- The cosmic baryon budget
  - The baryon budget at various epochs
  - Missing baryons and the second baryon problem
  - Cosmological predictions: the Warm-Hot Intergalactic Medium (WHIM)
  - Current attempts to detect the WHIM
- Athena (Advanced Telescope for High-Energy Astrophysics)
  - Science theme, mission concept, programmatic aspects
  - The Athena/X-IFU instrument
  - Characterising WHIM filaments with Athena/X-IFU
- Beyond (ie, the 3.5 keV line in clusters)
  - Detection & Interpretations
  - Athena/X-IFU (and Hitomi/SXS)
- Outlook

How many baryons should be there?

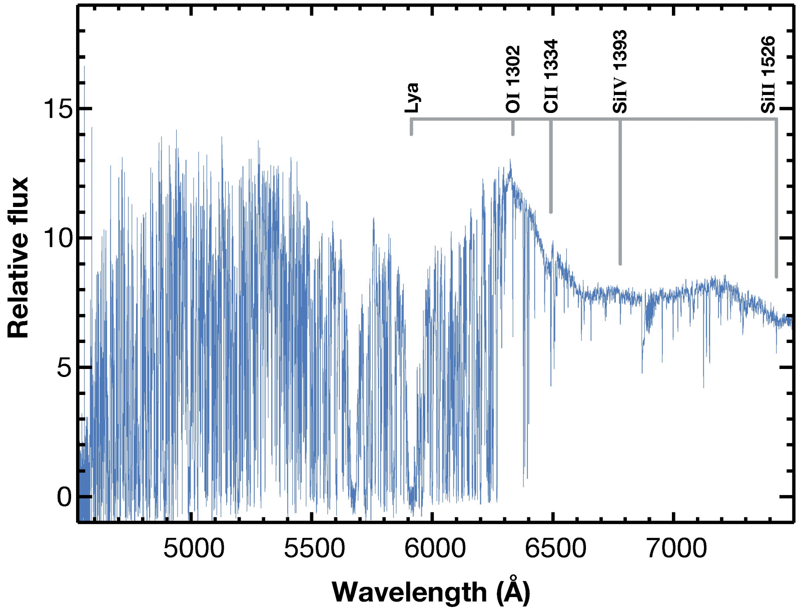




Baryon density from Big-Bang nucl
Consistent with CMB measurements

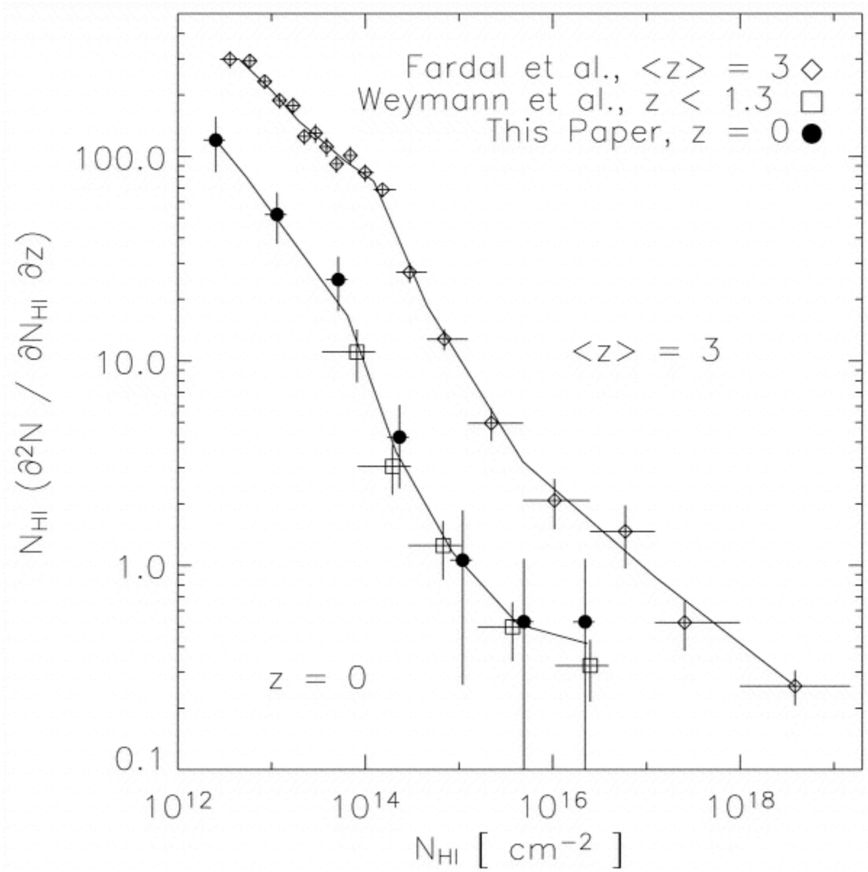
Baryons at z>2 (I)

- Most gas mass is accounted for by highly-ionised Ly α absorption systems



Wolfe, AM et al. 2005
Annu. Rev. Astron. Astrophys. 43: 861-918

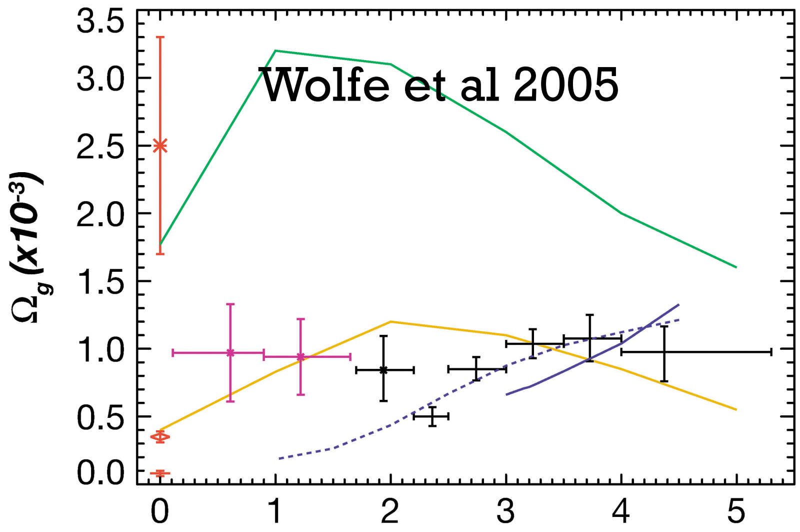
Wolfe et al 2005

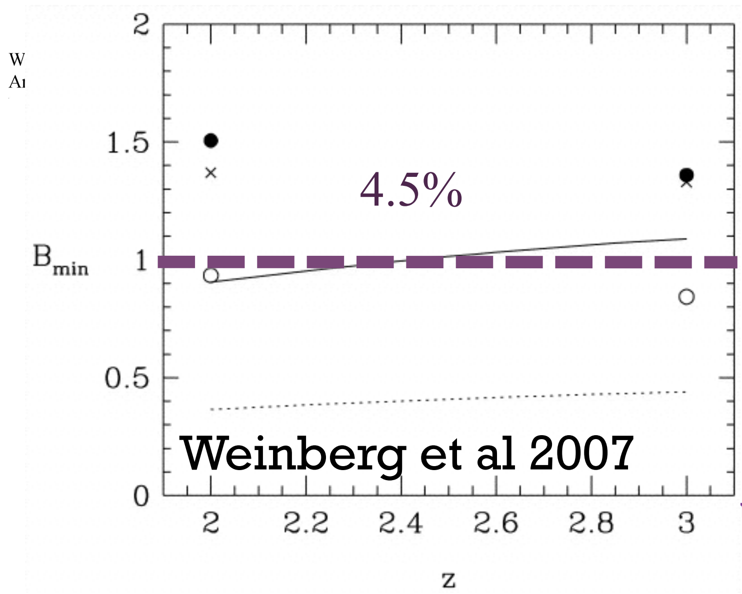


Penton et al 2004

Baryons at z>2 (II)

- Neutral gas at z>2 consistent in mass locked into stars at z=0
- Conservative ionization corrections indicate that all baryons are accounted for at z>2

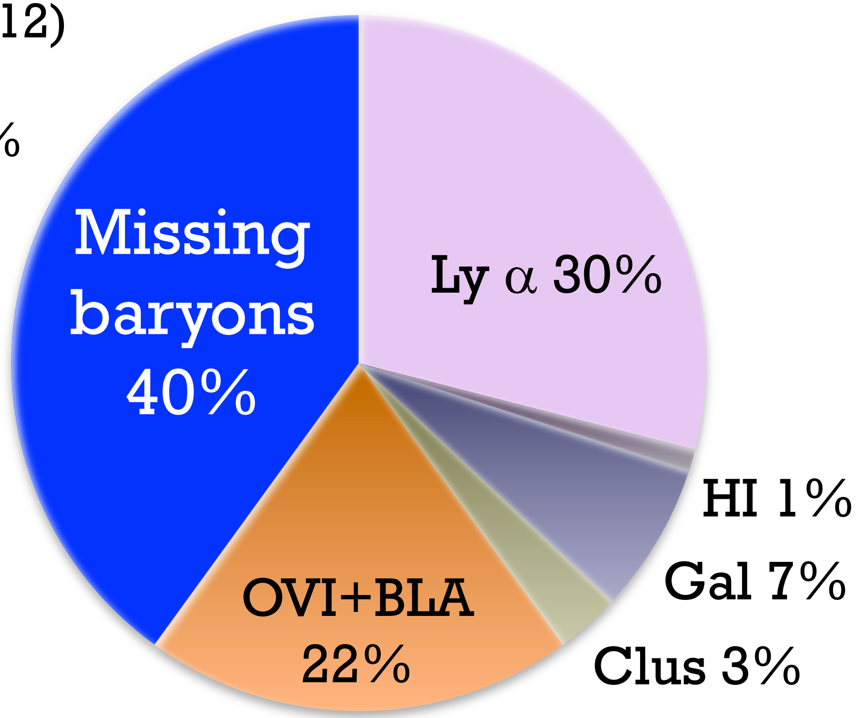




Baryon budget at low z

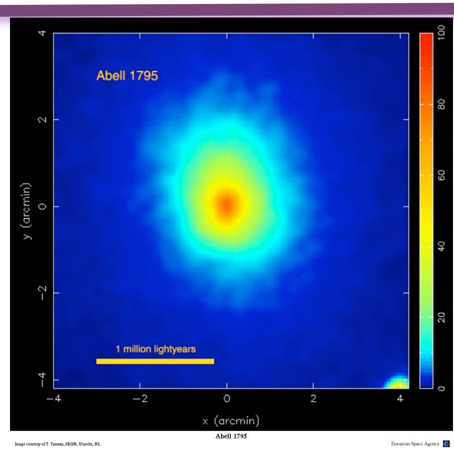
Budget from Shull et al (2012)

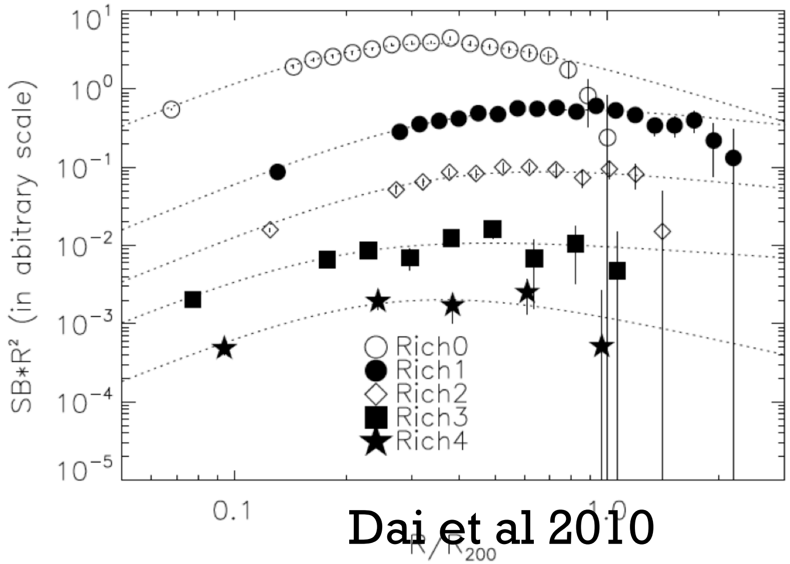
OVI+BLA uncertain 15-30%



Groups & clusters (3%)

- Clusters contain lots of X-ray emitting gas
- Baryon fraction (Ω_{gas}/Ω_{DM}~0.2) similar to cosmic
- But
  - Clusters are rare
  - X-ray gas only detected out to $R_{vir}/2$. If much extended could contribute a lot more
  - Uncertain role of groups

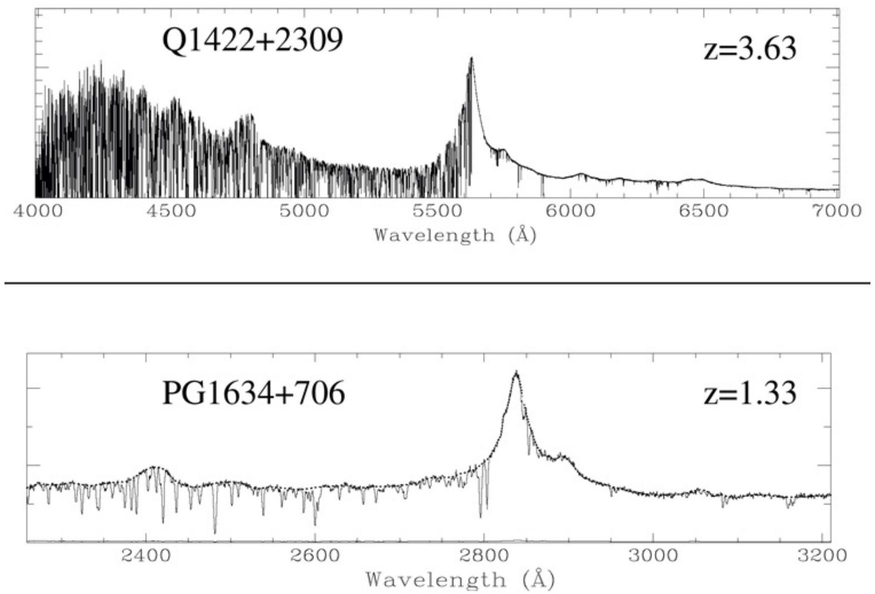


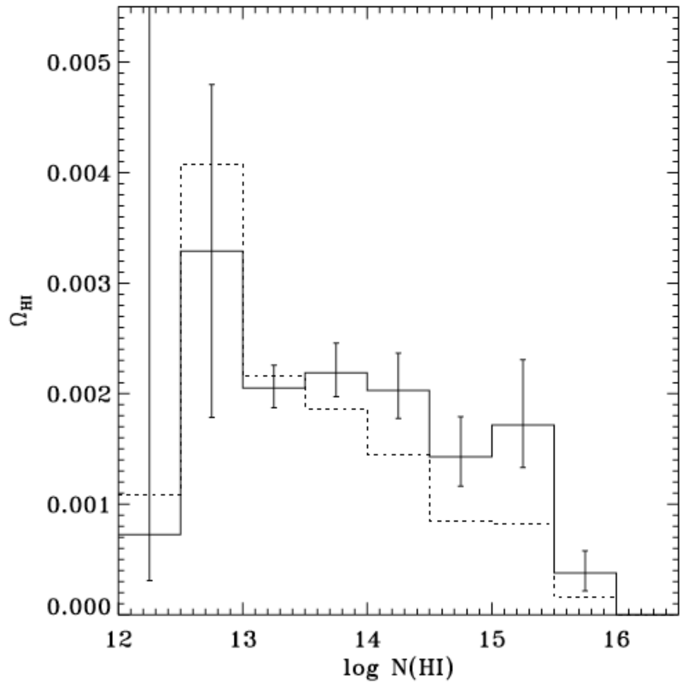


Dai et al 2010

Lyman-α absorbers at low z (~30%)

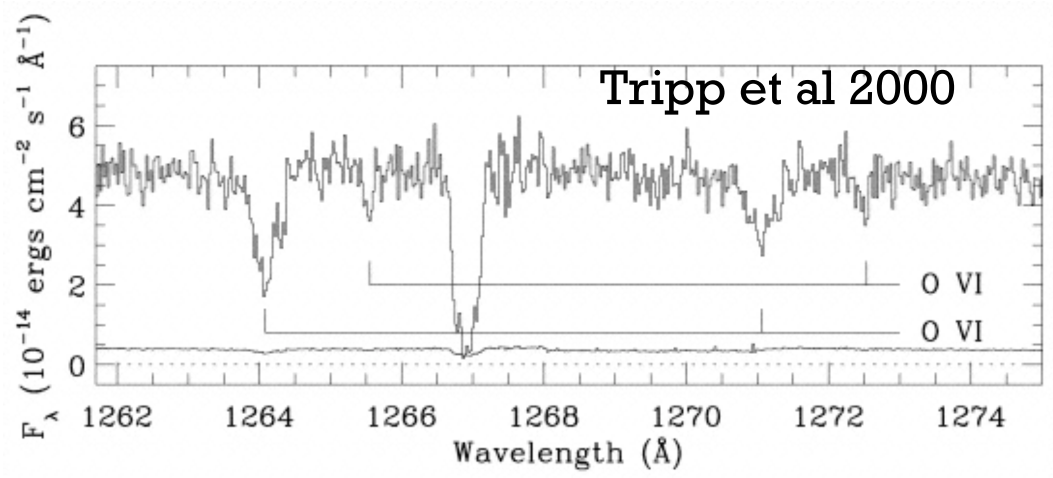
- Number of Ly α absorbers declines below z~2, then flattens
- Most of the mass is in the weakest absorption systems

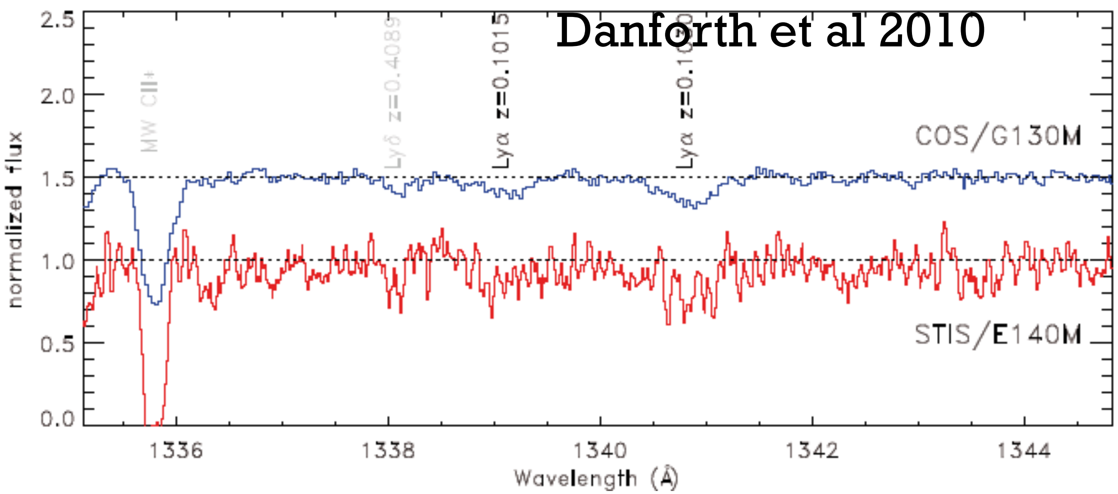




Danforth & Shull 2008

UV absorbers at low z (15-30%)

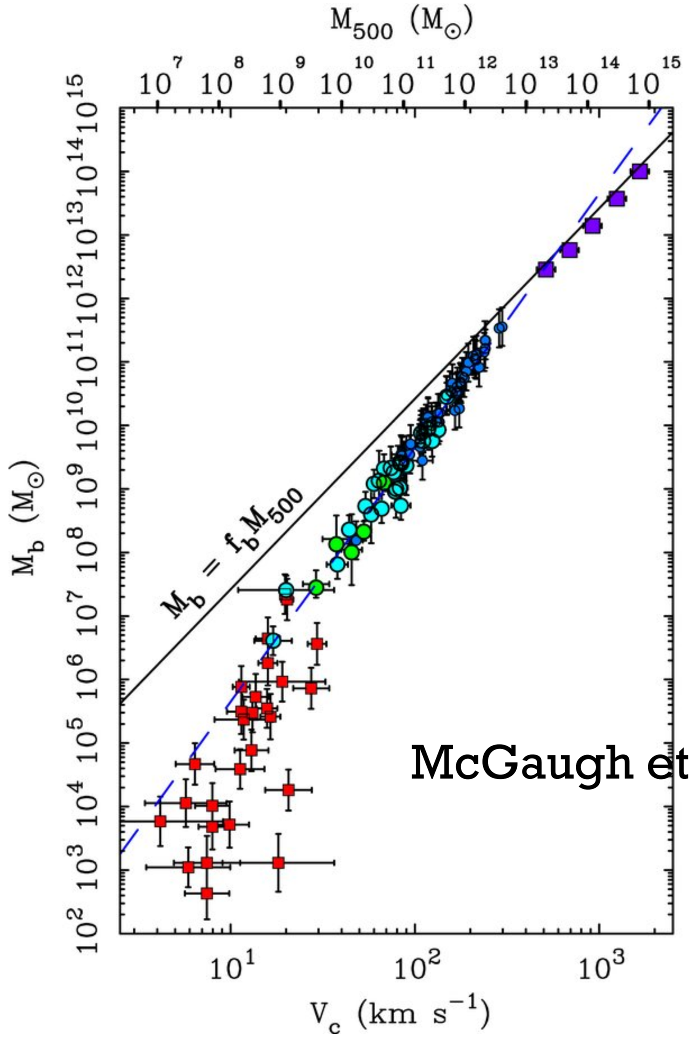




- Two flavours, but the same population:
  - OVI absorbers
    - Doublet (1031.9, 1037.6 Å), so easier to detect
  - Thermally broadened Ly α absorbers (BLAs)
    - $b_{L\alpha}$ > 42 km/s

The second baryon problem

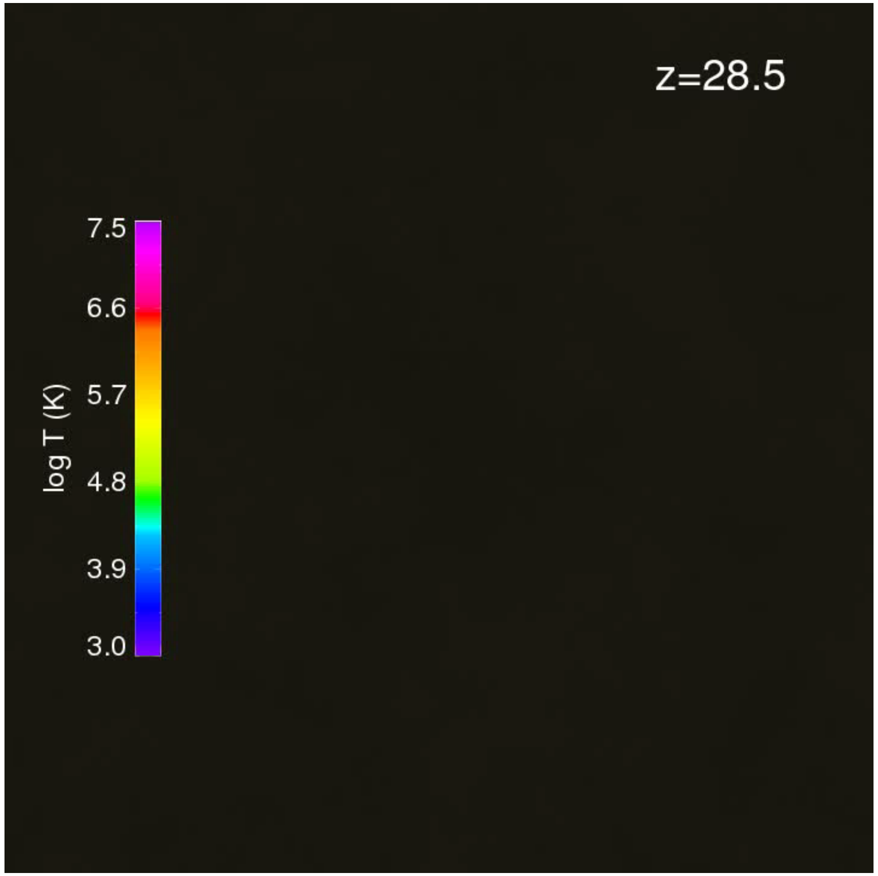
- Baryon fraction in virialised structures grows with mass
  - Reaching the cosmic value ~17% for rich clusters of galaxies
- What is the mechanism by which galaxies loss their baryons?
- The circum-galactic medium could account for up to 5% of the total baryon count



McGaugh et al 2010

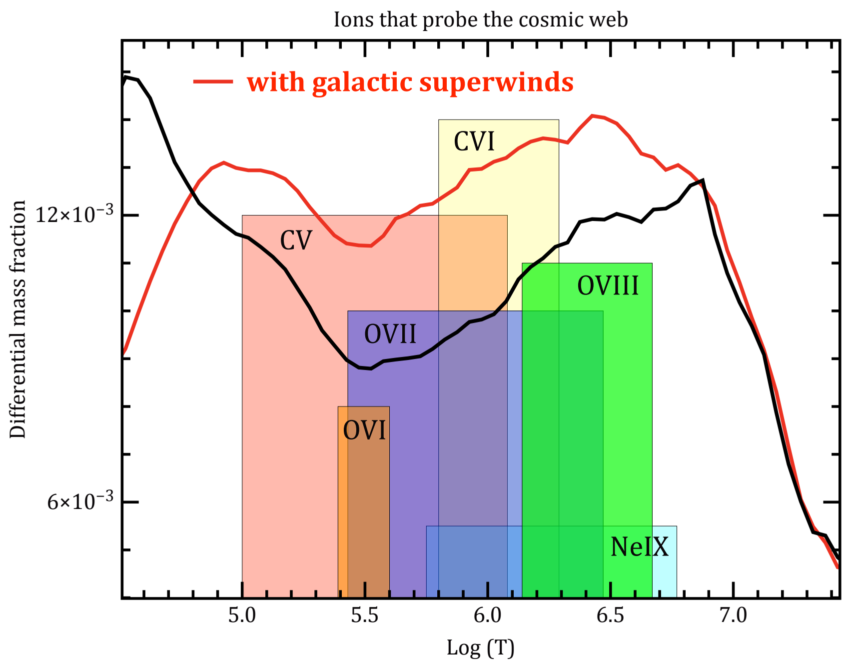
The Warm & Hot IGM (WHIM)

- Simulations show that galaxy formation is inefficient in trapping baryons in Dark Matter potential wells.
- Large fraction of baryons at T~10^5-10^7 K
  - Unvirialized
  - Filamentary distribution

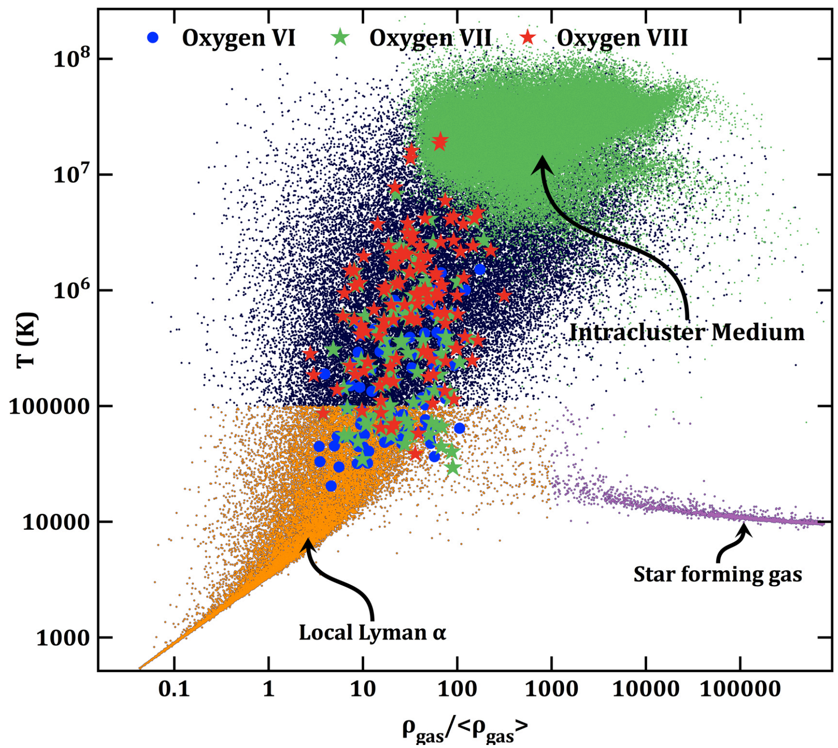


Oppenheimer et al 2009

WHIM physical state



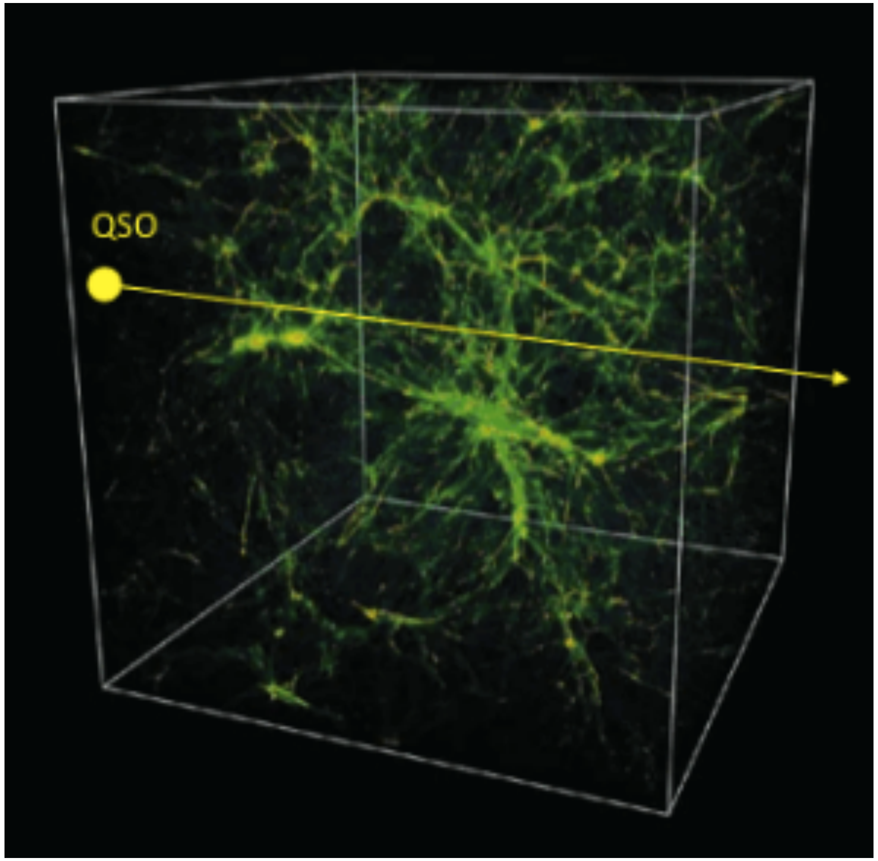
Cen & Ostriker 2006



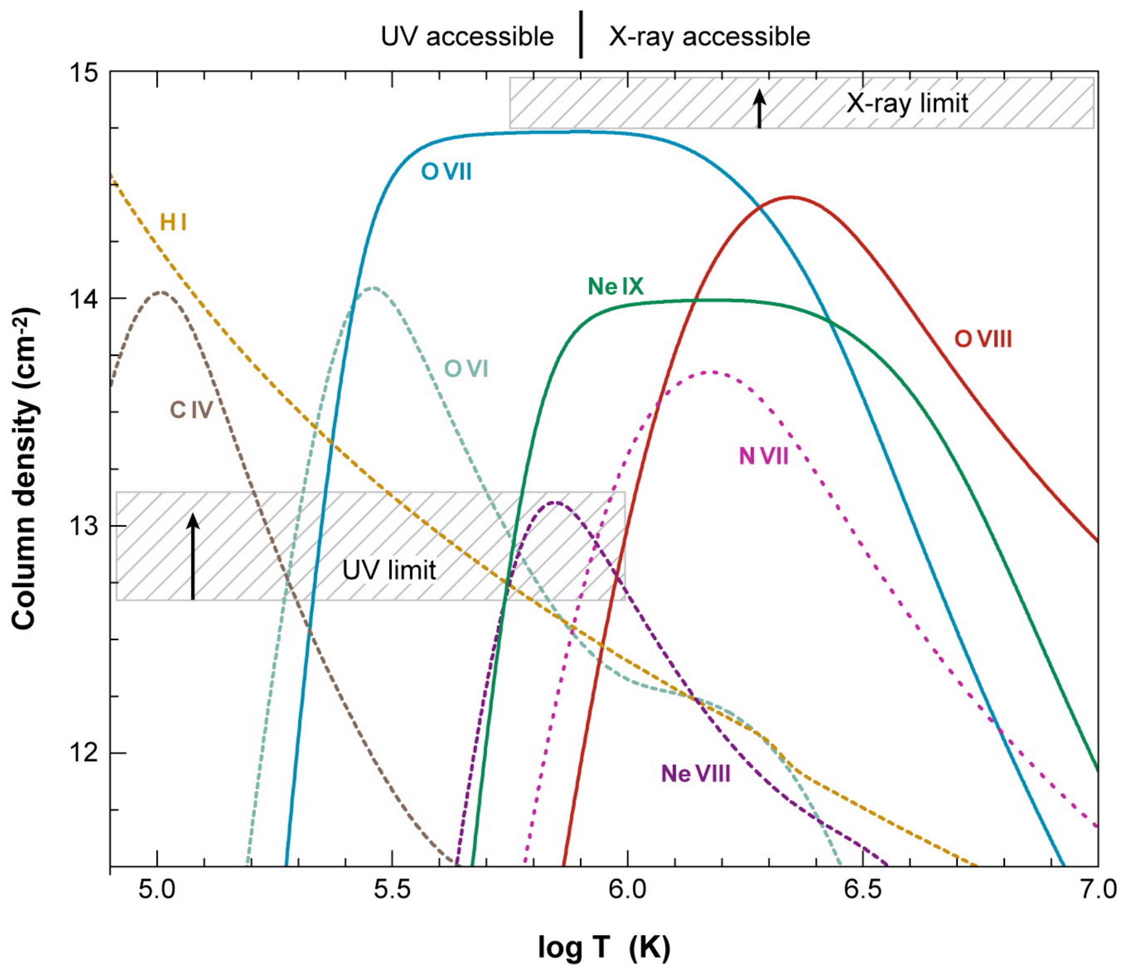
Branchini et al 2009

How to detect the WHIM?

- All atomic spectral features are narrow: need **high spectral resolution**
- In absorption:
  - Needs a **bright background source**
  - Detection only along specific lines of sight (geometry difficult to trace)
- In emission:
  - Tenuous and extended
  - Need to fight the background
  - Large sky area coverage
- Other: halo scattering, etc.



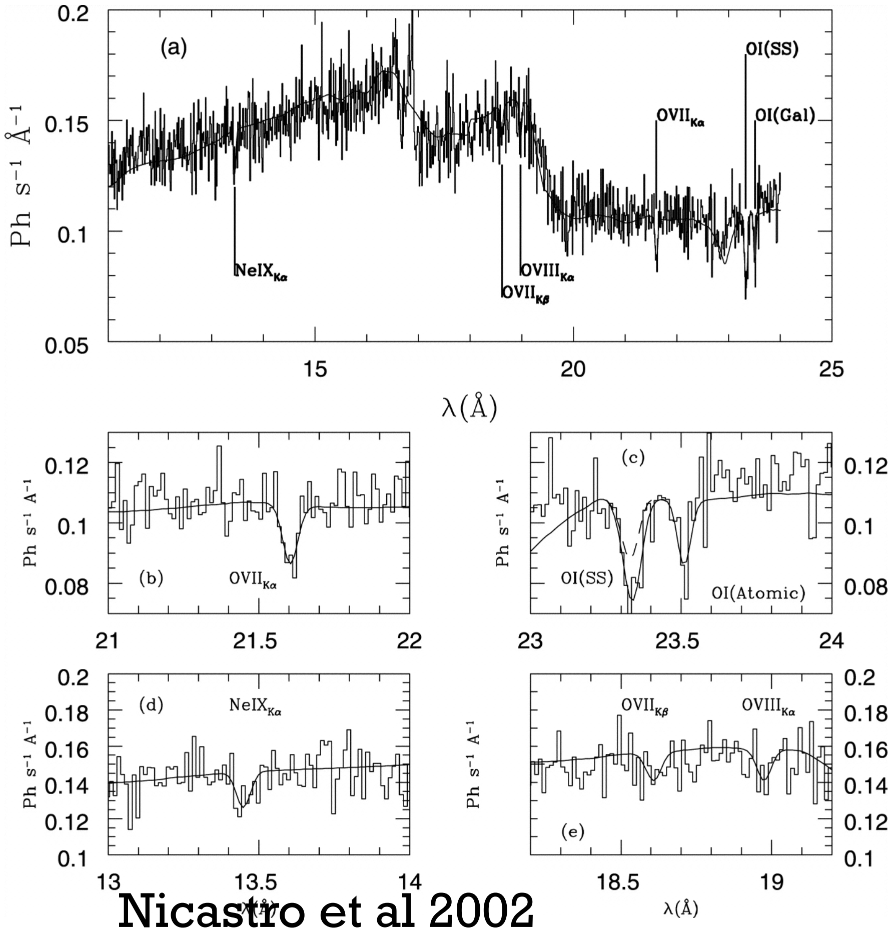
Detecting the WHIM in absorption



Bregman 2007

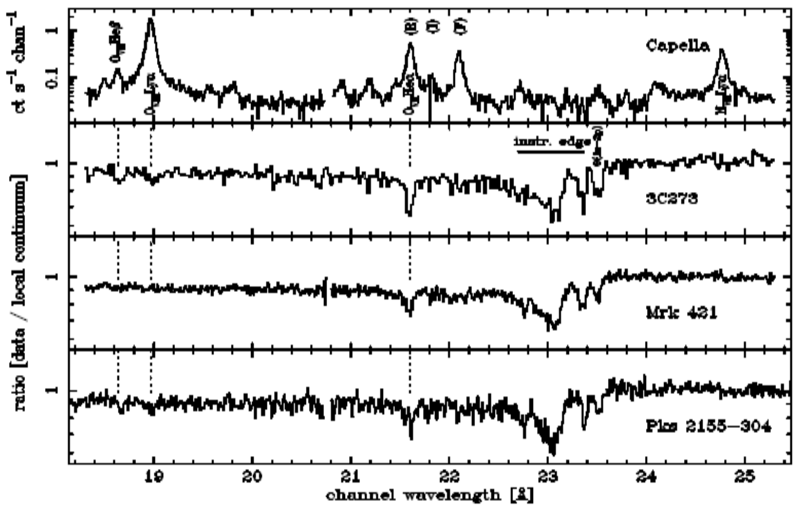
Detection of the "local" X-ray WHIM

With Chandra



Nicastro et al 2002

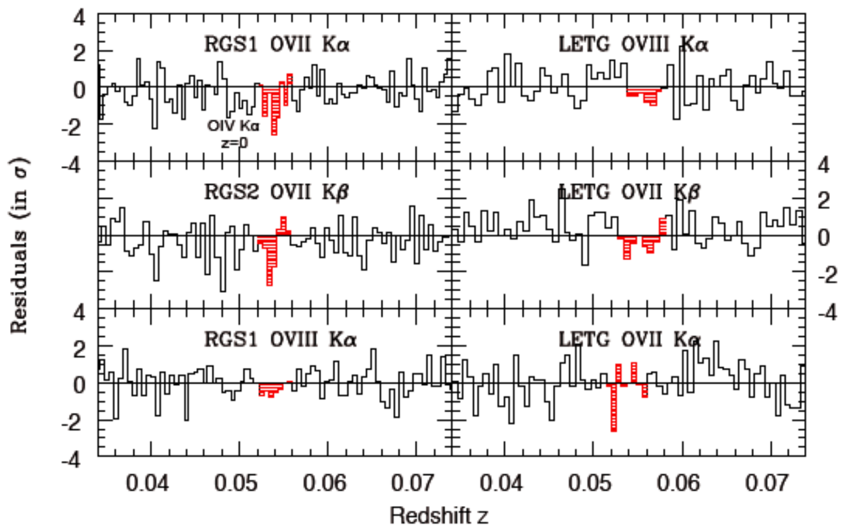
With XMM-Newton



Rasmussen et al 2003

Attempts to detect missing baryons

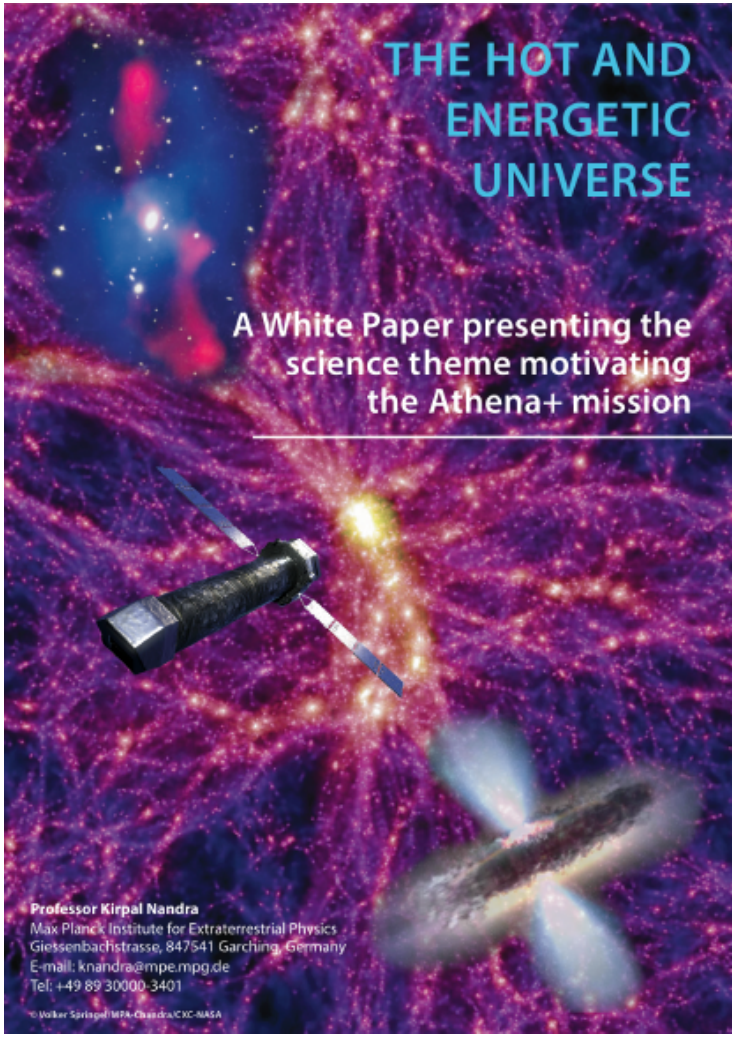
- Tentative detection of 2 WHIM filaments with Chandra against Mrk421 (Nicastro et al 2005), unconfirmed by XMM-Newton (Williams et al 2006)
- Observations of the brightest target in the sky 1ES 1553+113 (z>0.3) with Chandra and on-going XMM-Newton observations revealed 1 + 2 WHIM filaments to ~ 4-6σ significance (Nicastro et al 2013, 2016)
- Not possible to further this with current instrumentation.



From Nicastro (2016)

Advanced Telescope for High-Energy Astrophysics

- Second Large (L) mission of ESA Cosmic Vision 2015-2035
- Science theme: The Hot and Energetic Universe
  - How does ordinary matter assemble in the large-scale structures?
  - How do black holes grow and shape galaxies?
- In addition:
  - Fast ToO capability to study transient sources
  - Observatory science across all corners of Astrophysics

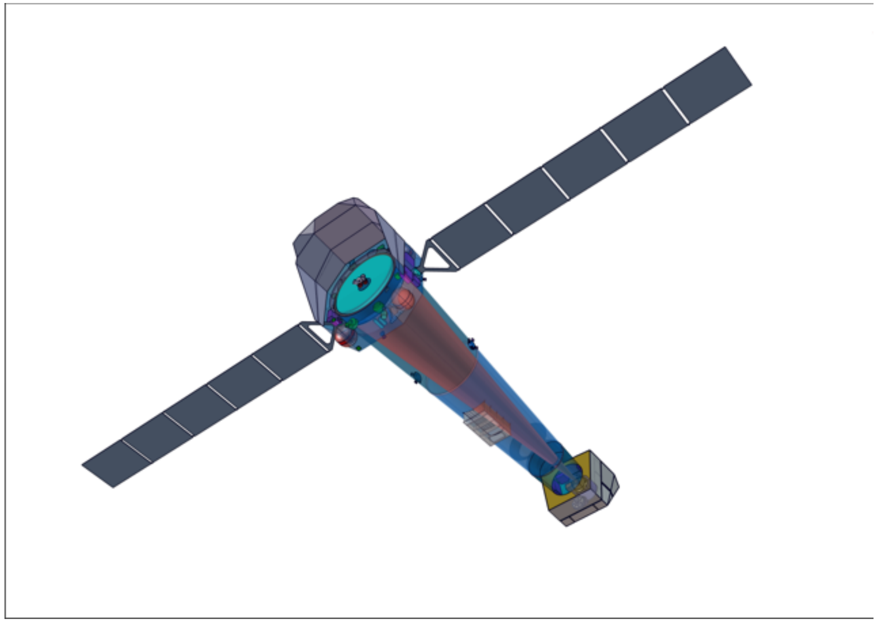


Athena Science Requirements

Parameter	value	enables (driving science goals)
Effective area at 1 keV	2 m^2	Early groups, cluster entropy and metal evolution, WHIM, high redshift AGN, census AGN, first generation of stars
Effective area at 6 keV	0.25 m^2	Cluster energetics (gas bulk motions and turbulence), AGN winds & outflows, SMBH & GBH spins
PSF HEW (< 8 keV)	5'' on axis, 10'' off axis	High z AGN, census of AGN, early groups, AGN feedback on cluster scales
X-IFU spectral resolution	2.5 eV	WHIM, cluster hot gas energetics and AGN feedback on cluster scales, energetics of AGN outflows at z~1-4
X-IFU FoV	5' diameter	Metal production & dispersal, cluster energetics, WHIM
X-IFU background	< 5 10^{-3} counts/s/cm^2/keV (75%)	Cluster energetics & AGN feedback on cluster scales, metal production & dispersal
WFI spectral resolution	150 eV	GBH spin, reverberation mapping
WFI FoV	40' x 40'	High-z AGN, census AGN, early groups, cluster entropy evolution, jet-induced cluster ripples
WFI count rate	80% at 1 Crab	GBH spin, reverberation mapping, accretion physics
WFI background	< 5 10^{-3} counts/s/cm^2/keV (75%)	Cluster entropy, cluster feedback, census AGN at z~1-4
Recons. astrometric error	1'' (3s)	High z AGNs
GRB trigger efficiency	40%	WHIM
ToO reaction time	< 4 hours	WHIM, first generation of stars

Athena mission concept

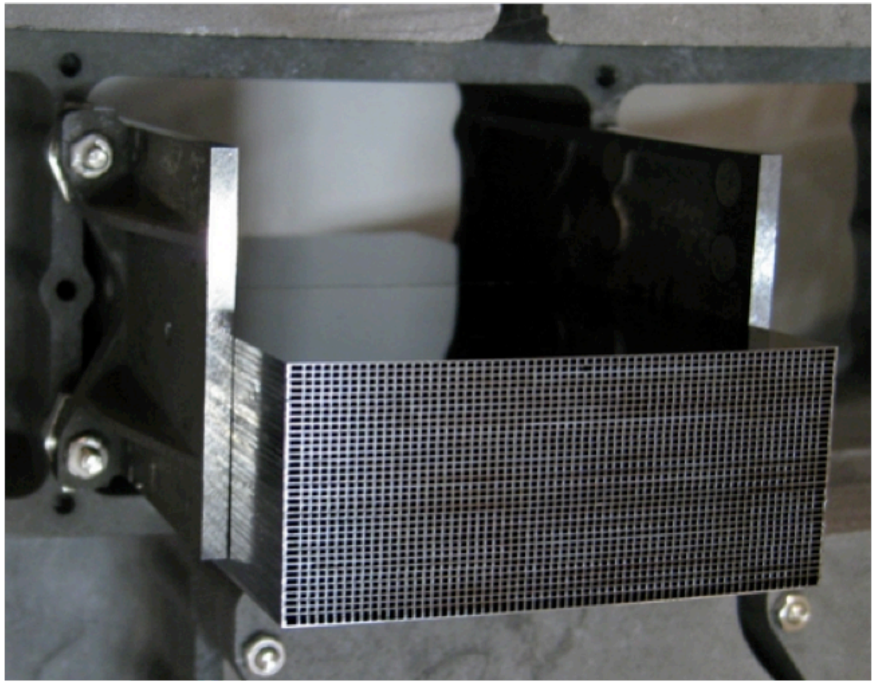
- Single telescope, using Si pore optics. 12m focal length
  - WFI sensitive imaging & timing
  - X-IFU spatially resolved high-resolution spectroscopy
- Movable mirror assembly to switch between the two instruments
- Launch 2028, Ariane 64
- L2 halo orbit (TBC)
- Lifetime > 5 yr



Athena concept, ESA CDF

The Athena telescope

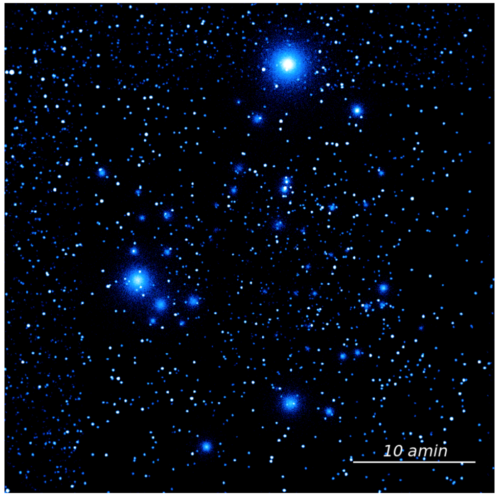
- Light-weight Si-pore optics:
  - 5” HEW on-axis
  - Graceful degradation off-axis, <10” @ 15’
  - 2 m^2 effective area @ 1 keV, with 3.6 m aperture diameter
  - Limited vignetting at 1 keV
- Athena optics development:
  - Grazing incidence optics, Wolter-I type (paraboloid-hyperboloid), largely with conical approximation
  - Vigorous development programme at ESA and industry.

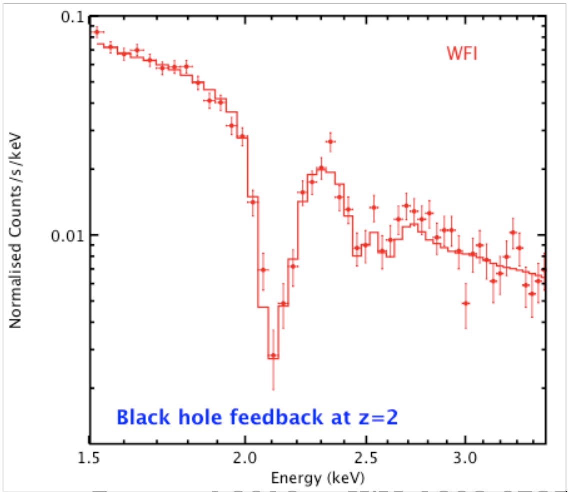


Willingale et al 2013, arXiV: 1308.6785

Wide Field Imager (WFI)

- Based on Si detectors, using Active Pixel Sensors based on DEPFETs.
- Key performances;:
  - 120-150 eV spectral resolution,
  - 3” pixel size (PSF oversample)
  - Field of view: 40’x40’
  - Separate chip for fast readout of brightest sources
  - Readout speed up to ~30 MHz
- Consortium led by MPE, with other European partners and NASA
- Optimized for sensitive and wide imaging and intermediate resolution spectroscopy, up to very bright sources





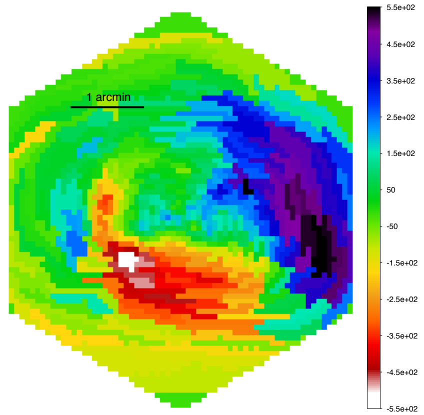
Rau et al 2013, arXiV: 1308.6785

X-ray Integral Field Unit (X-IFU)

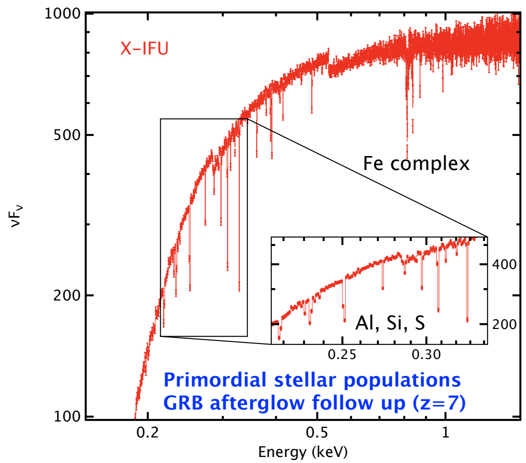
- Cryogenic imaging spectrometer, based on Transition Edge Sensors, operated at 50 mK featuring an active cryogenic background rejection subsystem

- Consortium led by CNES/IRAP-F, with SRON-NL, INAF-IT and other European partners, NASA and JAXA.

- Key performance parameters:
  - 2.5 eV energy resolution <7 keV
  - FoV 5' diameter
  - Pixel size <5"



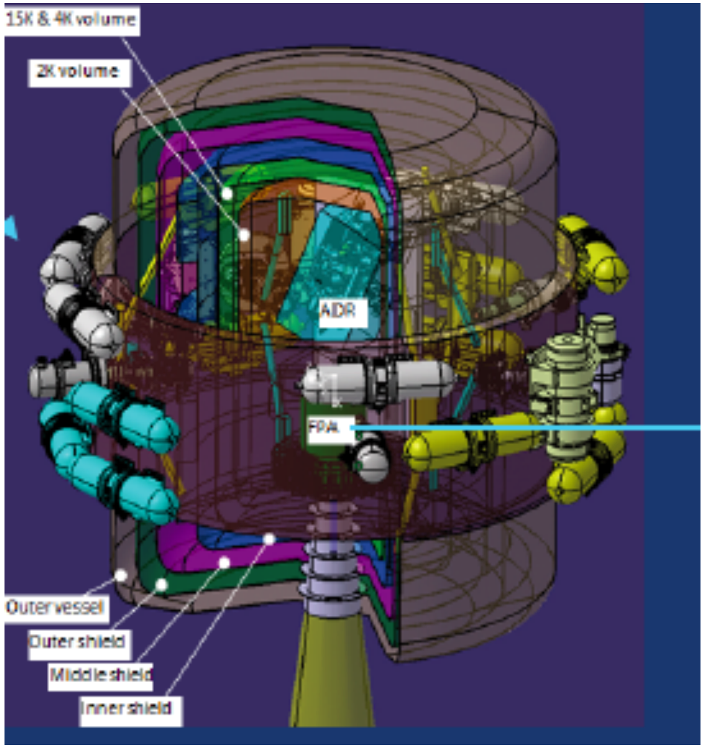
E. Pointecouteau, P. Peille, E. Rasia, V.Biffi, S. Borgani, J. Wilms



Barret et al 2013, arXiV: 1308.6784
http://x-ifu.irap.omp.eu/

The Athena X-ray Integral Field Unit (X-IFU)

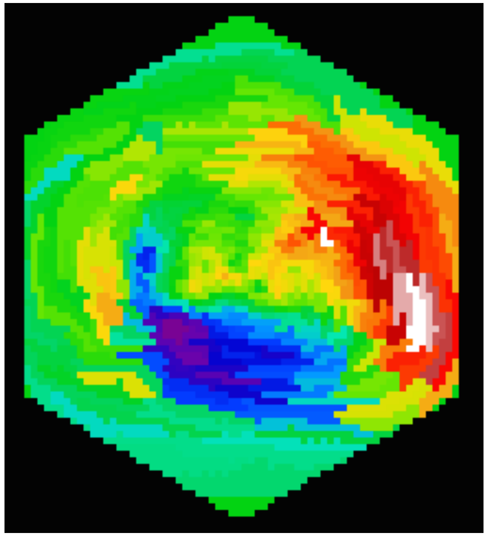
- Cryogenic imaging spectrometer:
  - based on Transition Edge Sensor
  - operated at 50 mK
  - multi-stage cooling chain
  - active cryogenic background rejection subsystem
- Consortium led by CNES/IRAP-F, with SRON-NL, INAF-IT and other partners in Belgium, Finland, Germany, Poland, Spain Switzerland and international partners (NASA and JAXA)
- Optimised for:
  - Spatially resolved X-ray spectroscopy
  - High-resolution spectroscopy



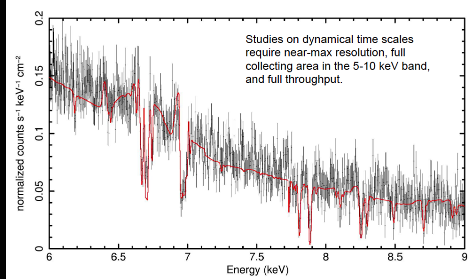
Barret, den Herder, Piro et al 2013, arXiv:1306.6784

The Athena X-IFU science capabilities

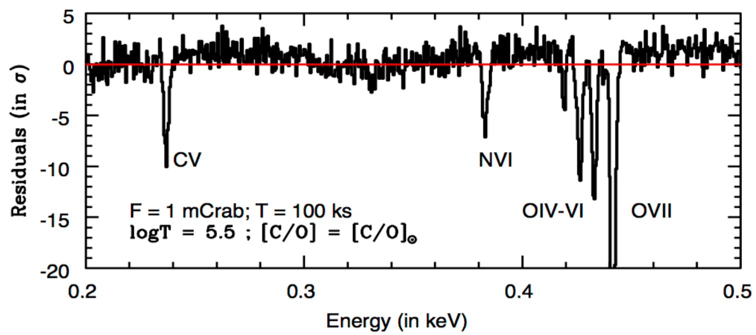
- 3D mapping of hot cosmic gas through spatially resolved spectroscopy
- Weak spectroscopic line detection (mostly absorption lines)
- Physical characterization of the HEU: plasma diagnostics (using multiplets), AGN reverberation and spins, BHXB reverberation, AGN outflows, stellar mass outflows, Solar Wind etc.



Peille, Pointecouteau et al (priv comm)

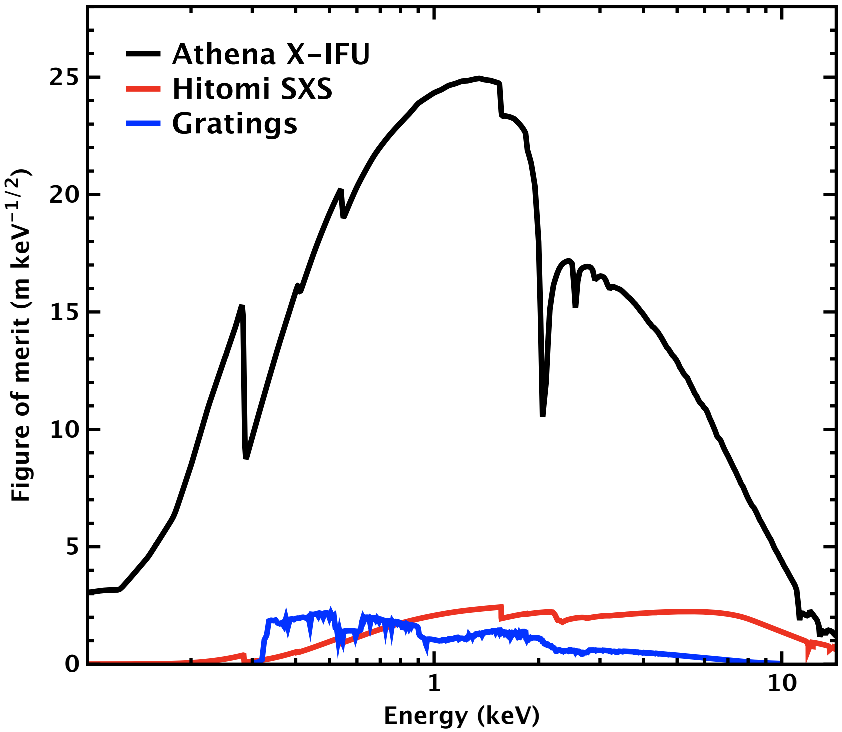


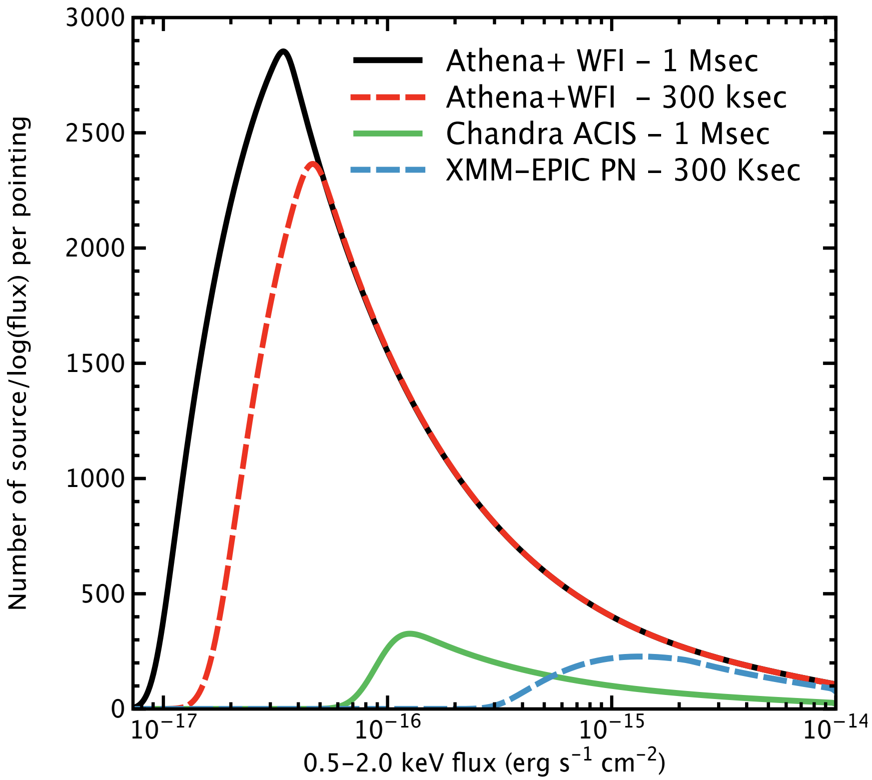
Miller et al (2015)



Nicastro (priv comm)

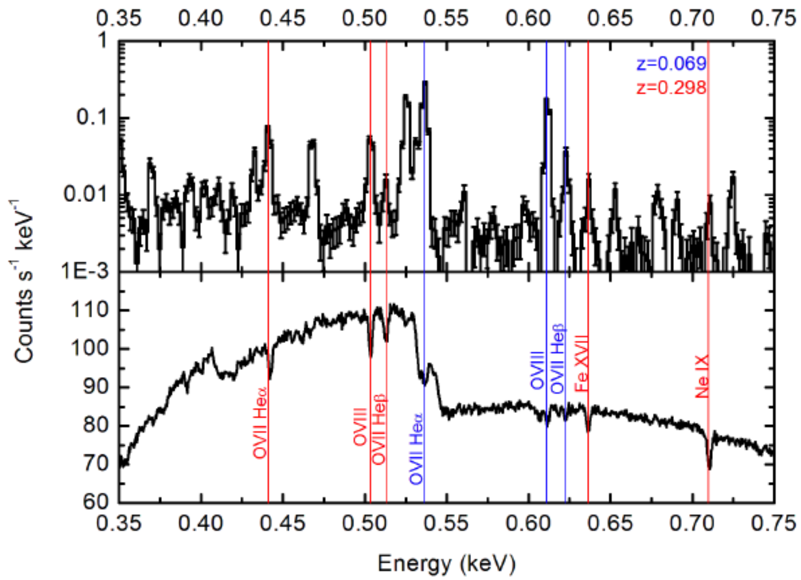
Athena: a revolutionary observatory





Characterising the WHIM with Athena/X-IFU

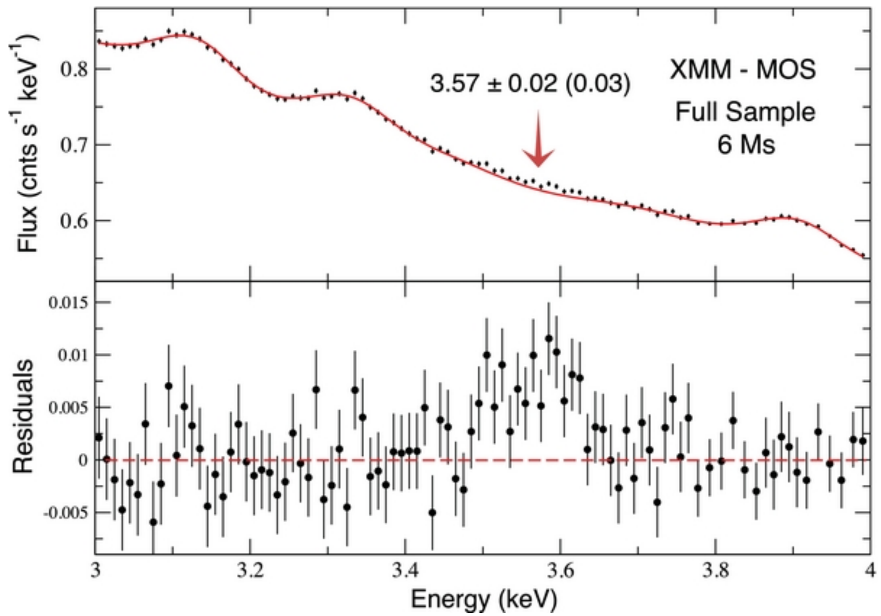
- Objectives:
  - Measure the local WHIM baryon density to < 10% accuracy
  - Test evolution up to z~0.8 (models predict a flat distribution)
  - Characterise metal abundances in 30% of the filaments
- By means of the detection of ~200 WHIM filaments in absorption against bright AGNs and GRB afterglows
- Detection of a fraction of them in emission, after the GRB afterglow has faded away



Finoguenov, Kaastra et al 2013
+ Nicastro, Piro, Wilms, Brandt, Dauser

The 3.5 keV line: Detection

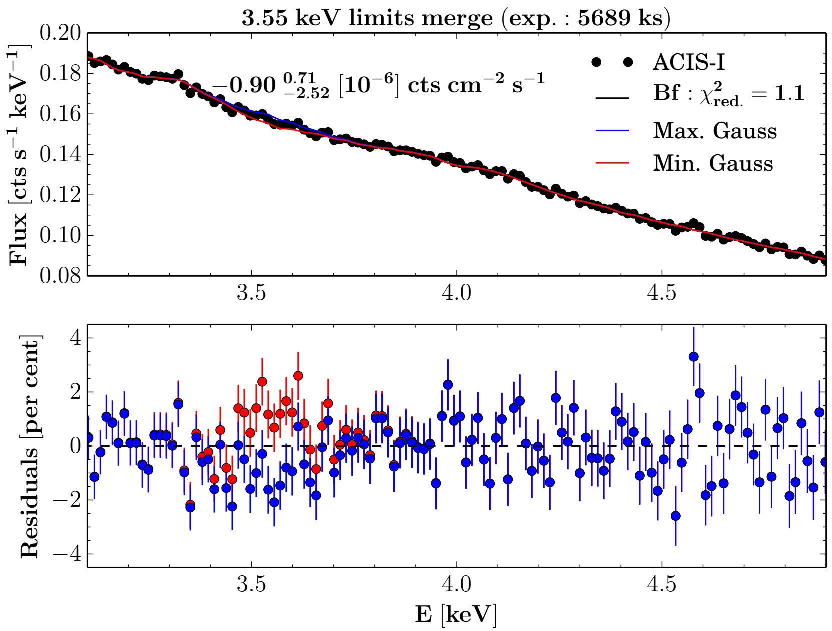
- Bulbul et al (2014) detect a weak emission line at 3.5 keV in the stacked spectrum of 73 galaxy clusters observed with XMM-Newton.
  - The line is only 1 eV in equivalent width, while the spectral resolution is > 100 eV
  - The line is visible in the spectrum of the brighest galaxy cluster (Perseus)
- Boyarsky et al (2014) reported a similar detection from the Andromeda galaxy
- Decay of sterile neutrinos with mass ~7.1 keV ?



Bulbul et al 2014

The controversy is on: is it real?

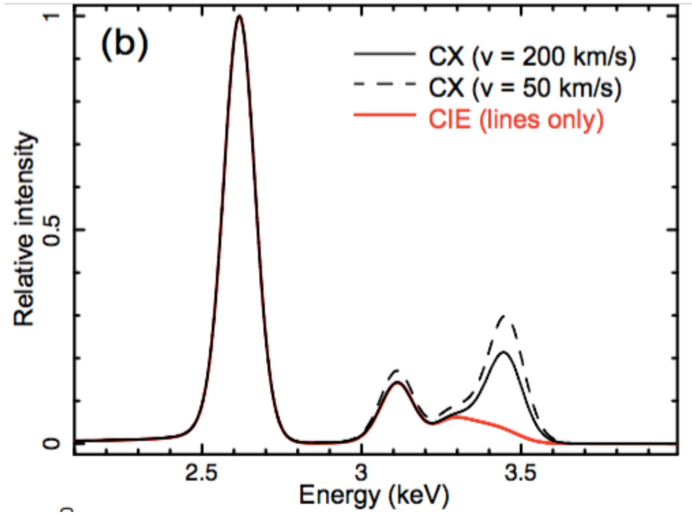
- Detections:
  - Urban et al (2015). Use Suzaku data, line detected at 3.51 keV (but energy is radially dependent) in Perseus, but not in Coma, Virgo and Ophicus clusters.
  - Iakubovsky et al (2015) detect (2σ) this feature at 3.55 keV in 8/19 clusters individually
- Non-detections: Malyshev et al (2014), Anderson et al. (2015), Tamura et al (2015), Carlson et al (2015), Sekiya et al. (2015).

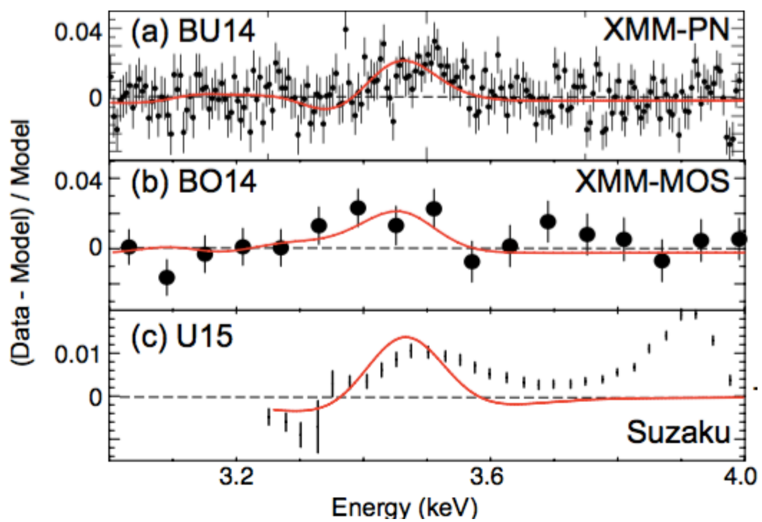


Hofman et al 2016
33 clusters with Chandra
Non-detection

If real, what is it?

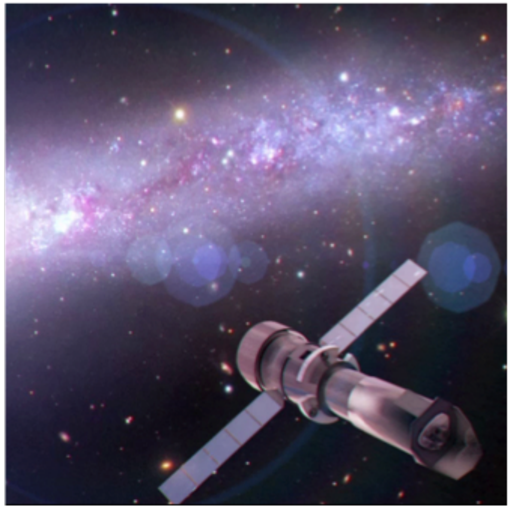
- Jeltema & Profumo (2014) proposed to be K XVIII or Cl XVII
  - But Bulbul et al (2015) argue that the atomic data are incorrect.
- Gu et al (2016) propose atomic lines from S XVI from n≥9 to the ground state, excited by Charge Exchange from neutral H.
  - Central AGN could provide the energetic H atoms
- And, of course, the decay of sterile neutrinos of m=7.1 keV





How do we settle the issue?

- We need both:
  - Large numbers of photons
  - Spectral resolution (~eV)
- The JAXA Hitomi satellite was launched in February 2016, with an X-ray calorimeter on board (resolution~5 eV)
  - Unfortunately, the S/C was lost in March 2016
  - But it had taken 160 ks of data of the Perseus cluster, above 3 keV. Data being analysed.
- Otherwise, wait for Athena/X-IFU (2028)



Outlook

- Athena will be a unique and powerful X-ray observatory mission to study the Hot and Energetic Universe
- High-resolution X-ray spectroscopy with Athena X-IFU will characterise the Warm-Hot Intergalactic Medium
- And hopefully find the missing baryons.
- It may also detect weak decay lines from DM particle candidates, if they fall in the several keV range.

- Follow Athena on
  - Web www.the-athena-x-ray-observatory.eu
  - Twitter: @athena2028
  - Facebook: The Athena X-ray Observatory
  - Athena Community Office email: aco@ifca.unican.es
    - Drop us a message if you want to receive the Athena Community Newsletter