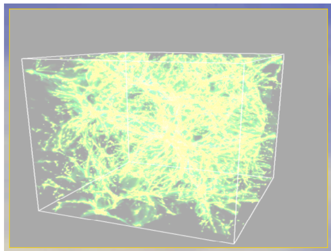

Chandra Detection of the WHIM toward Mkn 421

Fabrizio Nicastro (Harvard-Smithsonian Center for Astrophysics)

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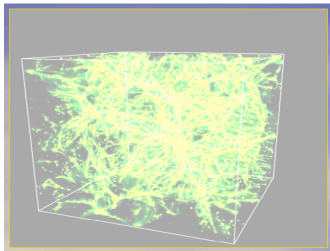
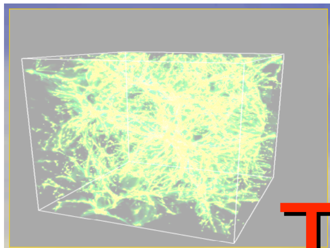


Overview

- The WHIM in X-rays and FUV: Current Status
- The WHIM along the line of sight to Mkn 421
- The WHIM in X-rays: Future Prospects



The Baryon Budget at High z

- From Observations of the Lyα Forest at z=2:

$$\Omega_b > 0.035\, h_{70}^{-2}$$

(Rauch et al., 1998; Weinberg et al., 1997)

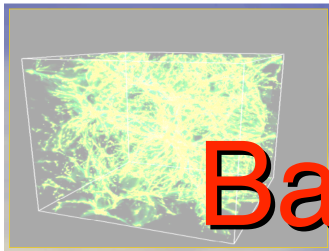
maybe conservative by a factor 2-7, due to uncertainty in the meta-galactic radiation field

- Standard Bib Bang Nucleosynthesis, combined with observed light-element ratios, gives:

$$\Omega_b = 0.039\, h_{70}^{-2}$$

(Burles & Tytler, 1998)

At High z, consistency on the estimated Baryon density



Baryons are Missing at Low z

$$\Omega_* + \Omega_{HI} + \Omega_{H_2} + \Omega_{Cl} < 0.02 \quad (2\sigma) <$$
$$< 1/2 \text{ of } z = 2 \text{ value} \quad (\text{for } h_{70} = 1)$$

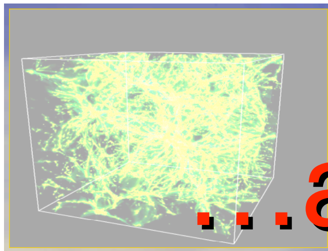
(Fukugita, Hogan & Peebles, 1997)

TABLE 3

THE BARYON BUDGET

Component	Central	Maximum	Minimum	Grade[a]
Observed at $z \approx 0$				
1. Stars in spheroids	$0.0026\ h_{70}^{-1}$	$0.0043\ h_{70}^{-1}$	$0.0014\ h_{70}^{-1}$	A
2. Stars in disks	$0.00086\ h_{70}^{-1}$	$0.00129\ h_{70}^{-1}$	$0.00051\ h_{70}^{-1}$	A —
3. Stars in irregulars	$0.000069\ h_{70}^{-1}$	$0.000116\ h_{70}^{-1}$	$0.000033\ h_{70}^{-1}$	B
4. Neutral atomic gas	$0.00033\ h_{70}^{-1}$	$0.00041\ h_{70}^{-1}$	$0.00025\ h_{70}^{-1}$	A
5. Molecular gas	$0.00030\ h_{70}^{-1}$	$0.00037\ h_{70}^{-1}$	$0.00023\ h_{70}^{-1}$	A —
6. Plasma in clusters	$0.0026\ h_{70}^{-1.5}$	$0.0044\ h_{70}^{-1.5}$	$0.0014\ h_{70}^{-1.5}$	A
7a. Warm plasma in groups	$0.0056\ h_{70}^{-1.5}$	$0.0115\ h_{70}^{-1.5}$	$0.0029\ h_{70}^{-1.5}$	B
7b. Cool plasma	$0.002\ h_{70}^{-1}$	$0.003\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	C
7′. Plasma in groups	$0.014\ h_{70}^{-1}$	$0.030\ h_{70}^{-1}$	$0.0072\ h_{70}^{-1}$	B
8. Sum (at $h = 70$ and $z \simeq 0$)	0.021	0.041	0.007	...
Gas components at $z \approx 3$				
9. Damped absorbers	$0.0015\ h_{70}^{-1}$	$0.0027\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	A —
10. Lyα forest clouds	$0.04\ h_{70}^{-1.5}$	$0.05\ h_{70}^{-1.5}$	$0.01\ h_{70}^{-1.5}$	B
11. Intercloud gas (He II)	...	$0.01\ h_{70}^{-1.5}$	$0.0001\ h_{70}^{-1}$	B
Abundances of:				
12. Deuterium	$0.04\ h_{70}^{-2}$	$0.054\ h_{70}^{-2}$	$0.013\ h_{70}^{-2}$	A
13. Helium	$0.010\ h_{70}^{-2}$	$0.027\ h_{70}^{-2}$	...	A
14. Nucleosynthesis	$0.020\ h_{70}^{-2}$	$0.027\ h_{70}^{-2}$	$0.013\ h_{70}^{-2}$	...

[a] Confidence of evaluation, from A (robust) to C (highly uncertain).



...and in our own Local Group

- > $1.5 \times 10^{12}\ M_\odot$ are needed to stabilize the Local Group (Kahn & Woltjer, 1959)

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INTERGALACTIC MATTER AND THE GALAXY

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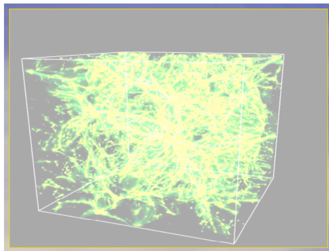
Received May 18, 1959

ABSTRACT

It is shown that the Local Group of galaxies can be dynamically stable only if it contains an appreciable amount of intergalactic matter. A detailed discussion shows that this matter consists mainly of ionized hydrogen and that stars can contribute only a small fraction to its total mass. The most likely values for the intergalactic temperature and density are found to be 5×10^5 degrees and 1×10^{-4} proton/cm^3, respectively. It is thought that this gas confines the halo. The distortion of the disk of the Galaxy, revealed by 21-cm observations, is analyzed. This effect cannot be regarded as a relic from a primeval distortion, which occurred at the time of formation of the Galaxy; a more promising explanation for it can be given in terms of the flow pattern of the intergalactic gas past the Galaxy and of the resulting pressure distribution on the halo.

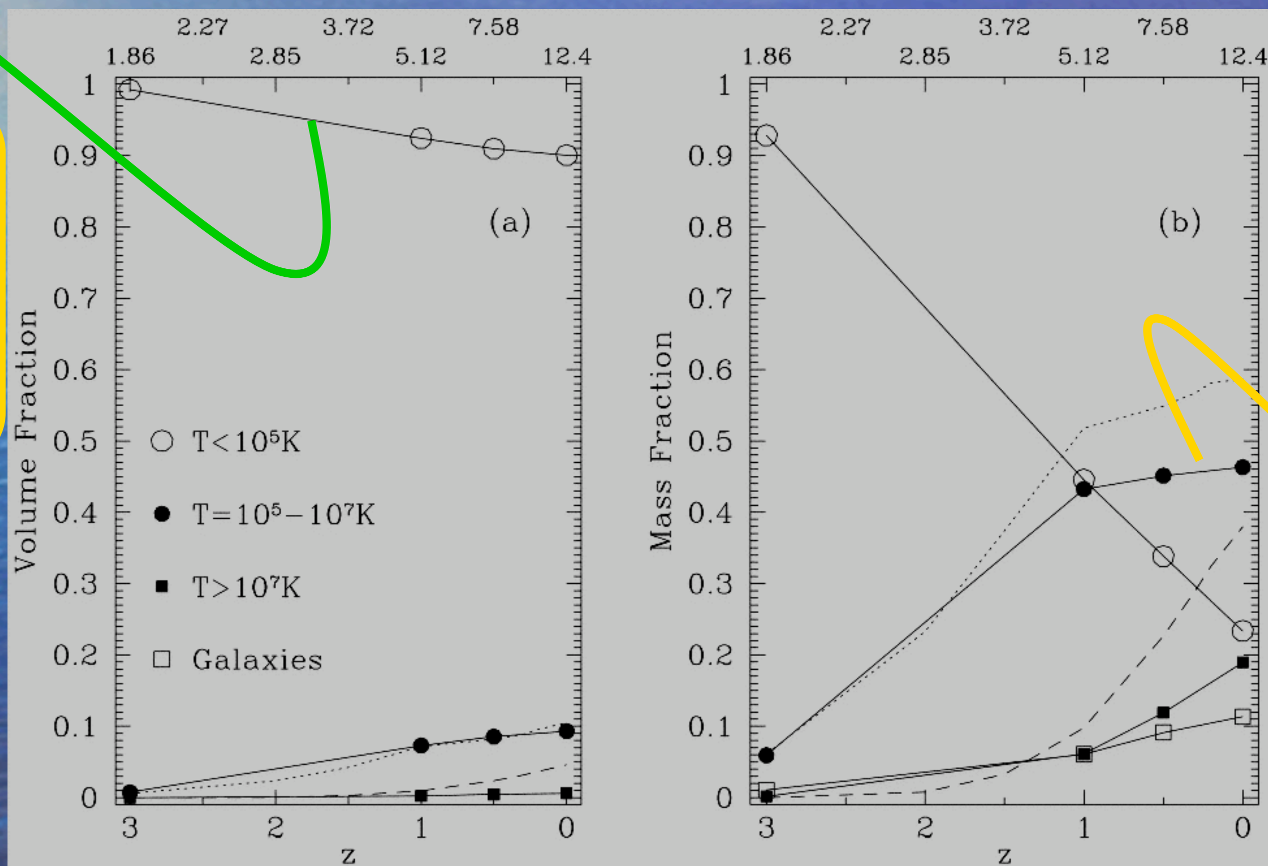


The Baryon Content in the Universe

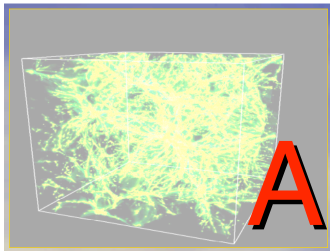
Mass Fraction vs Volume Fraction

(Cen & Ostriker, 1999)

Cool (Lyα) gas dominates Volume at all z



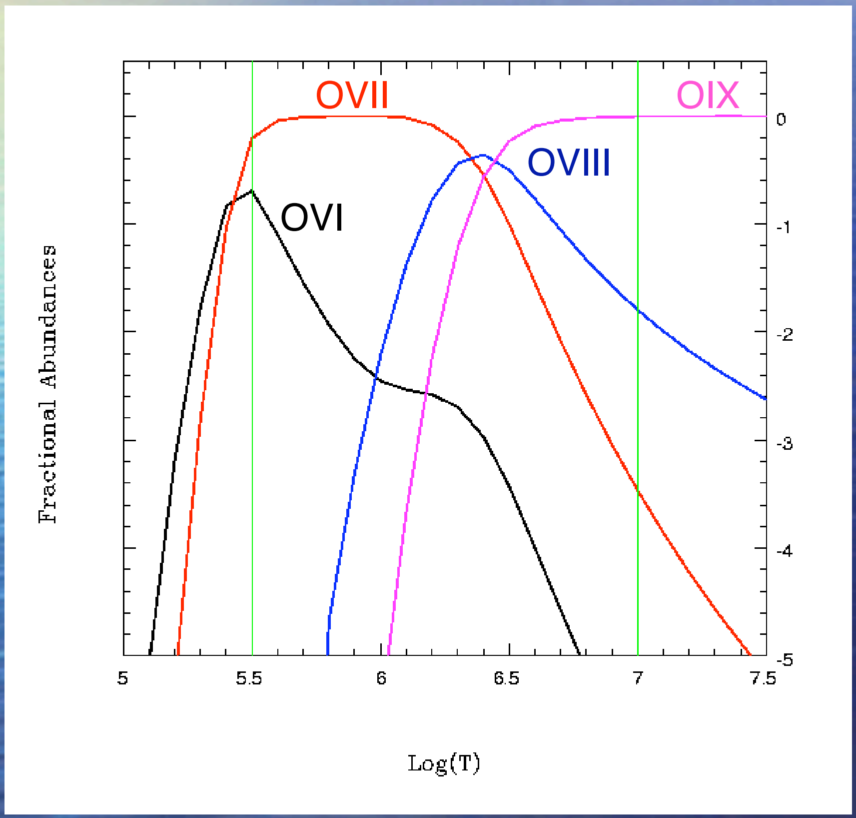
Warm-Hot gas dominates Mass at low z

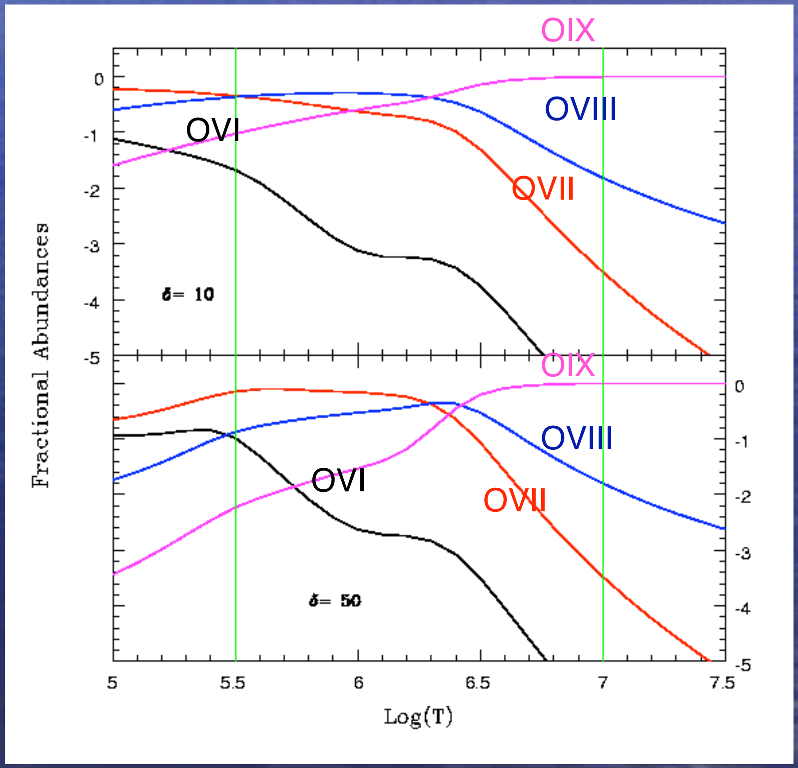


Abundant Ions in the WHIM

Collisional Equilibrium

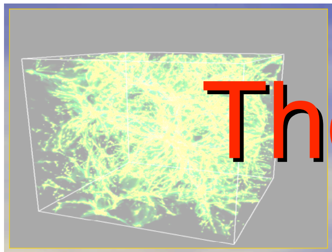
Perturbating with the XRB:
$U \sim 0.1\ \delta^{-1}$ at any z





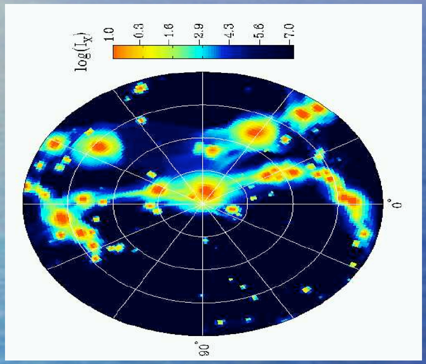
OVII, OVIII dominates

SED from Parmar et al., 1999; Boldt et al., 1987; Fabian & Barcons, 1992)

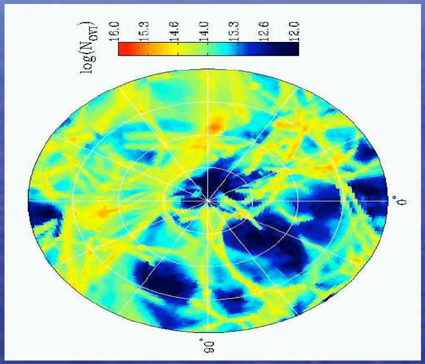


The WHIM Filament in the Local Supercluster Environment

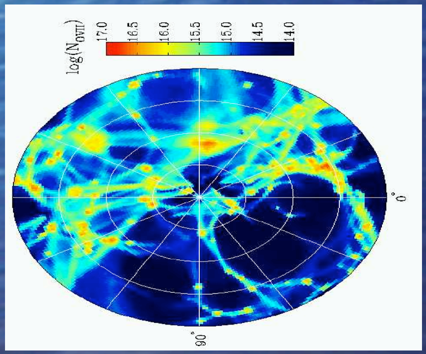
0.5-2 keV Brightness in ph/s/cm^2/sr



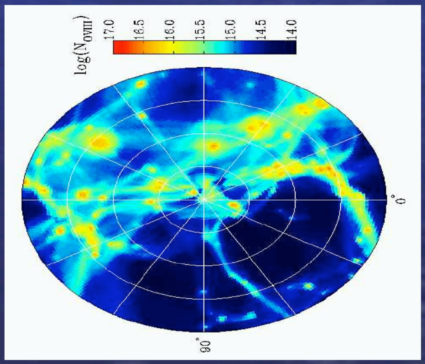
OVI column density in cm^{-2}



OVII column density in cm^{-2}

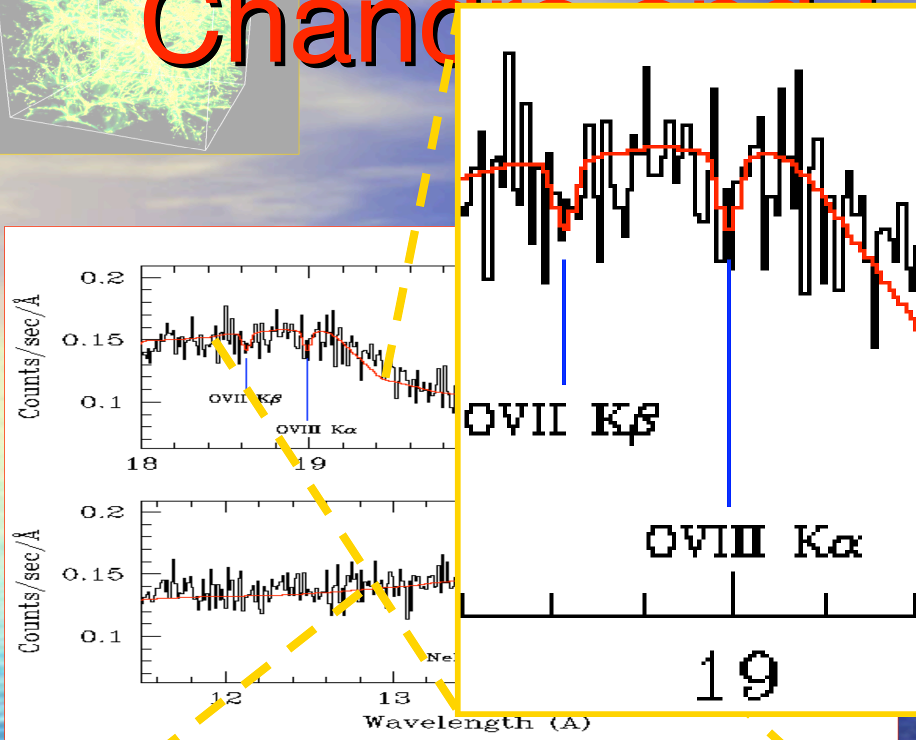


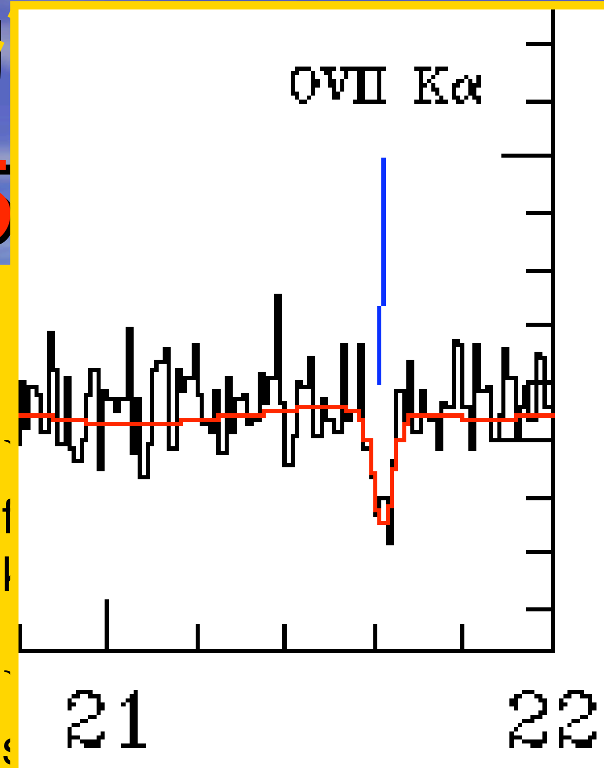
OVIII column density in cm^{-2}

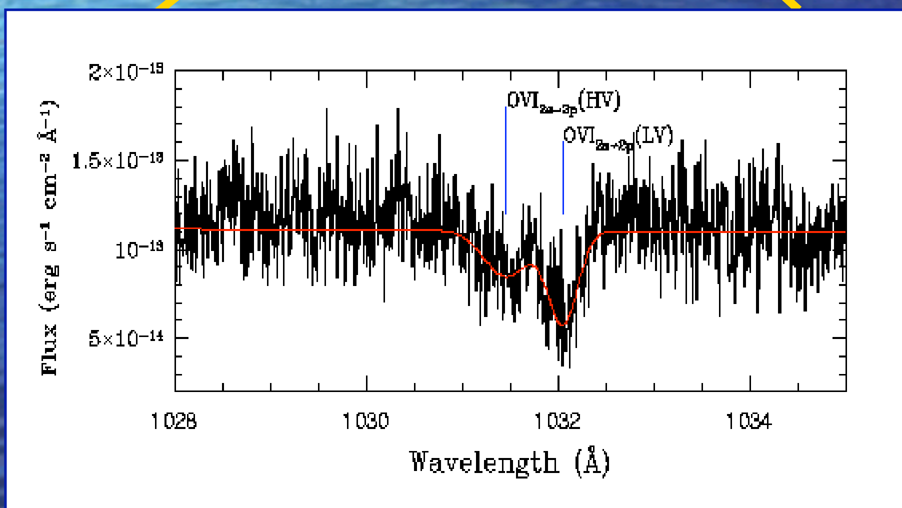


(Kravtsov, Klypin & Hoffman, 2002)

Chand… and FU… of …5







1999

-6

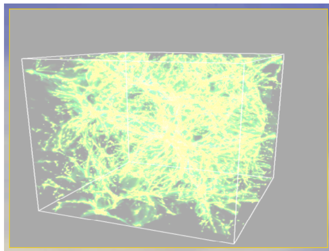
2

ns: ~

FUSE Spectrum

Resolution: $\Delta\lambda \sim 65$ mÅ (~ 20 km s^{-1} @ 1000 Å

- Observed on 24 October 1999 for ~ 39 ks



Equivalent Width Ratios Diagnostics

- All absorption Lines fall in the linear branch of the Curves of Growth (CoG)

\ EW ∝ Ion Column Density :

$$EW_{X^i} \cong 2.2 \times (\xi_{X^i}/0.4)(A_X/10^{-5})(N_H/10^{22})(f_{lu}/0.5) \quad \mathrm{eV}$$

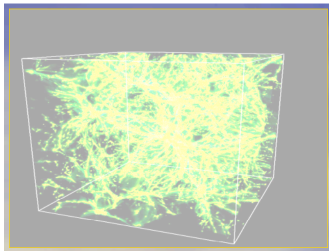
EW ratios ∝ Ionization Balance:

For 2 ions from the same element

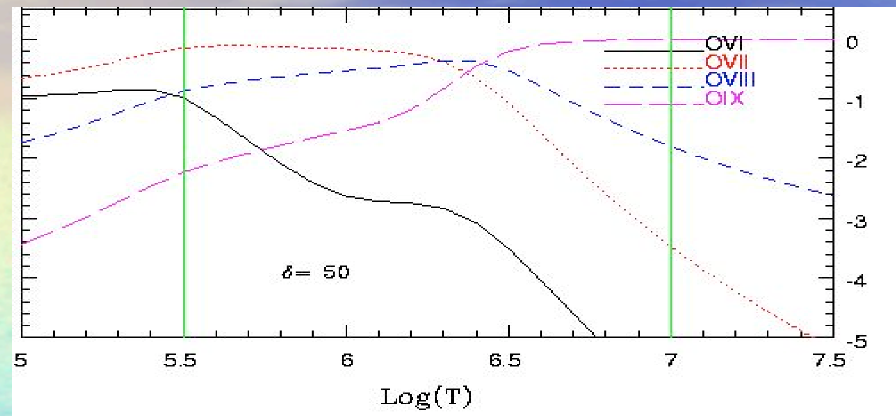
$$\frac{\xi_{X^i}}{\xi_{X^{[i+n]}}} = \frac{EW_{X^i}}{EW_{X^{[i+n]}}} \times \frac{f_{lu}(X^{[i+n]})}{f_{lu}(X^i)}$$

For 2 ions from different elements

$$\frac{\xi_{X^i}}{\xi_{Y^j}} = \frac{EW_{X^i}}{EW_{Y^j}} \times \frac{f_{lu}(Y^j)}{f_{lu}(X^i)} \times \frac{A_Y}{A_X}$$



One Line of Sight is not Enough



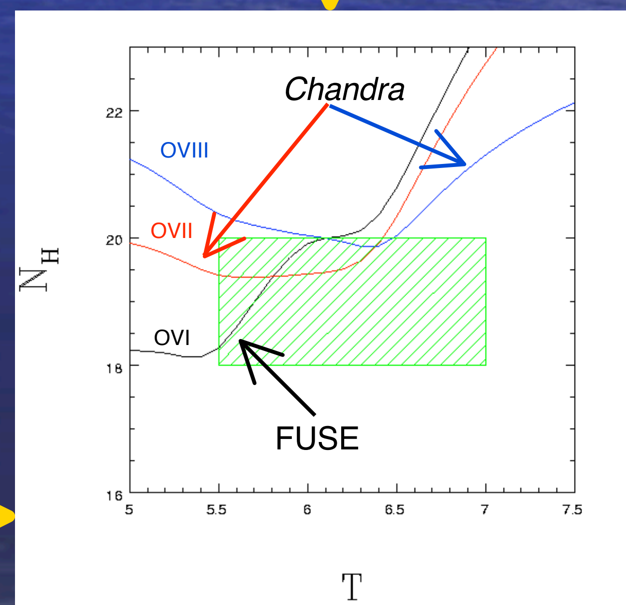
Typical WHIM Absorption Lines:
EW(OVII,OVIII) <~ 10 mÅ
EW(OVI) ~ 70 mÅ

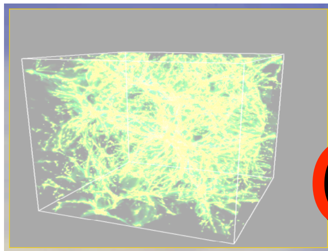
Chandra and FUSE Sensitivity

X-ray Flux = 4×10^{-10} erg/s/cm^2: Very Bright
(700 cts/res.el. At 20 Å in 60 ks *Chandra*-LETG)

UV-Flux = 5×10^{-14} erg/s/cm^2: Moderate Flux
(30 cts/res.el. In 20 ks FUSE)

3 σ N_H detection





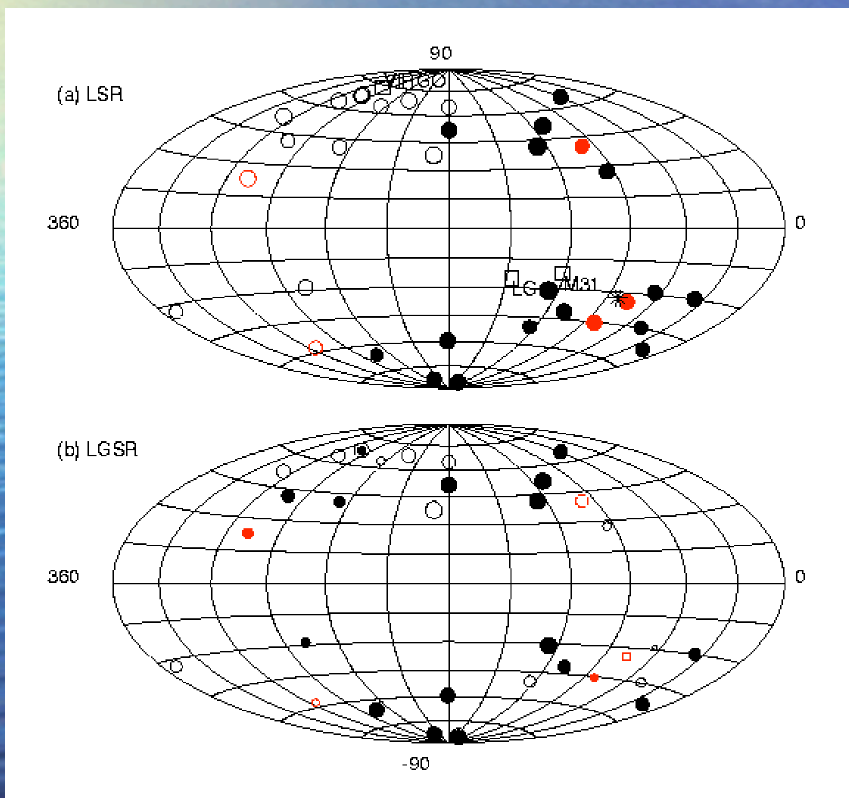
OVI Velocity Segregation

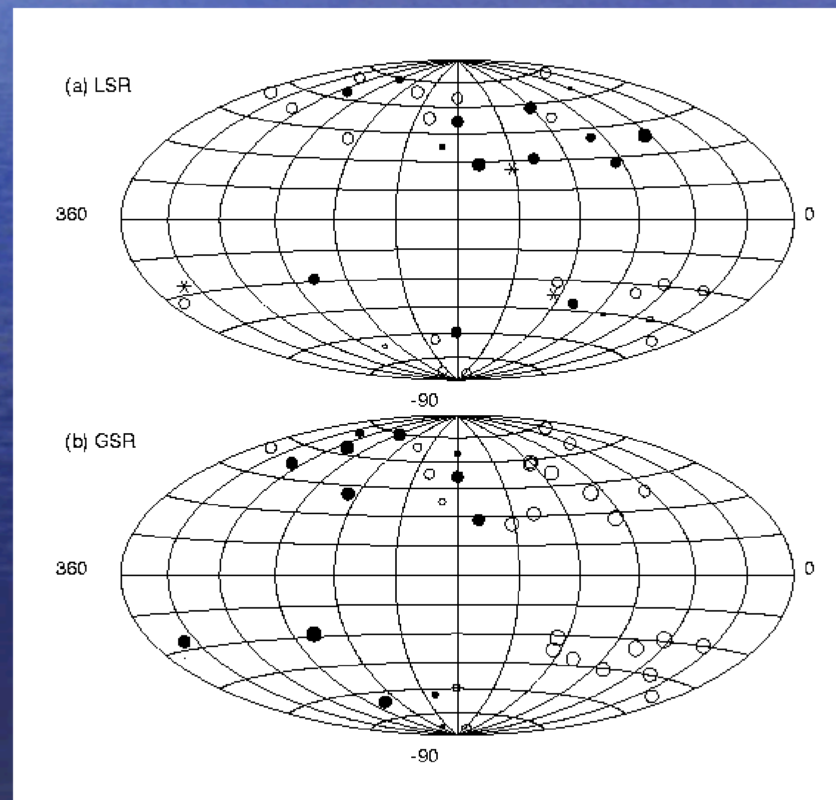
HV-OVI

Strong Segregation in the LSR

LV-OVI

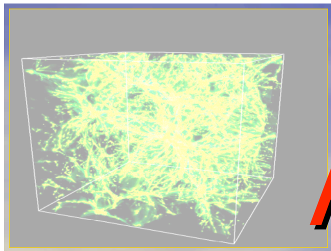
Strong Segregation in the GSR

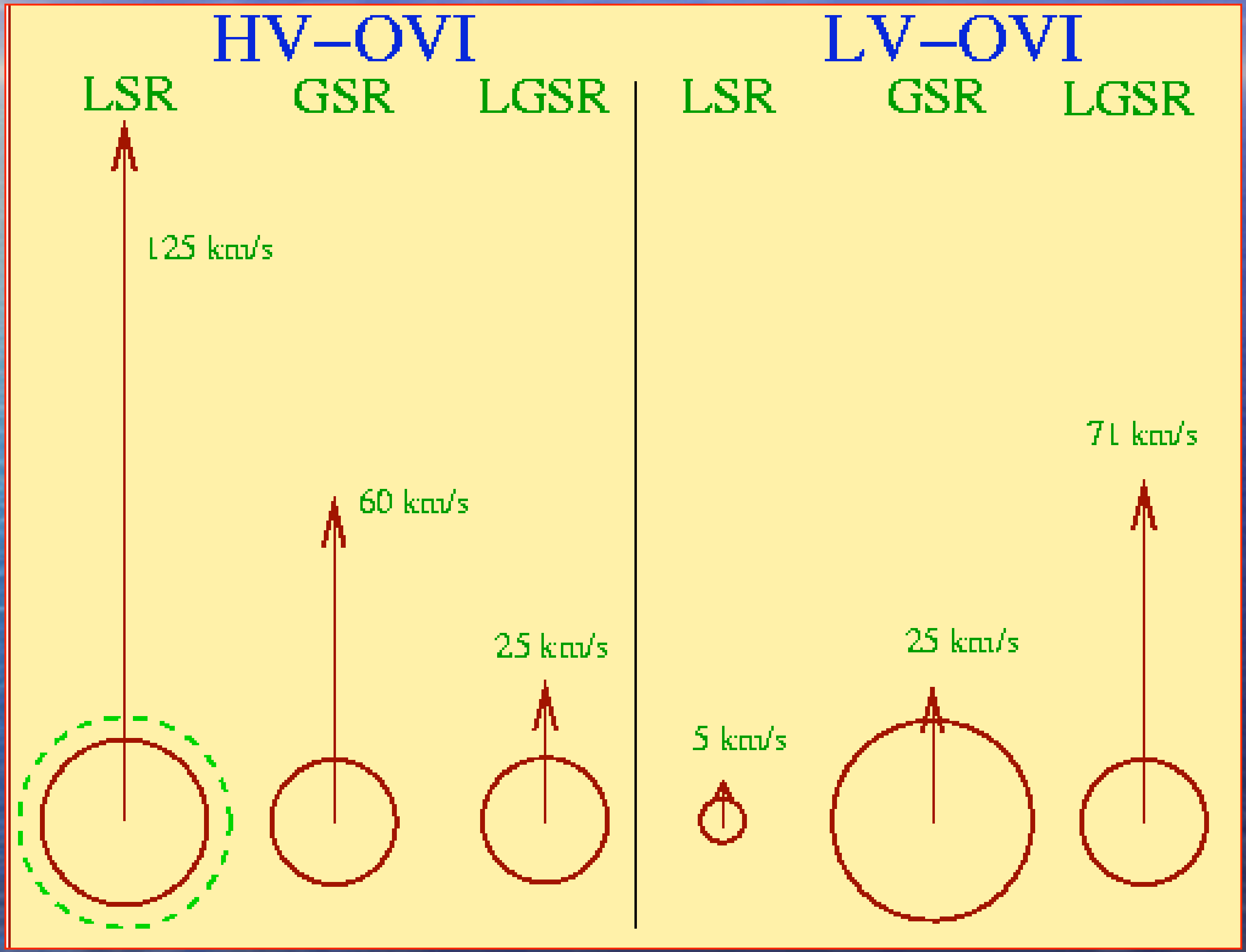




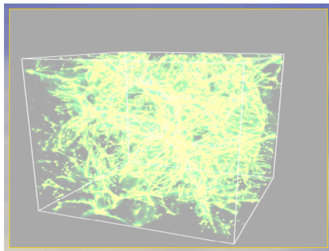
Nicastro et al, *Nature*, 421, 719

Average Velocity Vectors



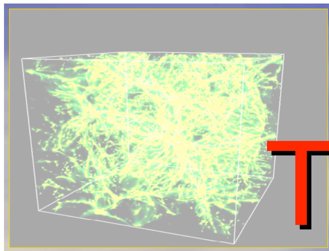


(Nicastro et al., *Nature*, 421, 719)



The Local Group WHIM

- X-Rays (Chandra and XMM-Newton): PKS 2155-304, MKn 421, 3C 273, NGC 4593, NGC 5548 (Nicastro et al., 2002, ApJ, 573, 157; Fang et al., 2003, ApJL, 586, 49)
  - ~ EW(OVII) ~ 10-15 mÅ
    - $N_{OVII} \sim 10^{16}$ cm^{-2}
  - ~ 700 counts per res. el. needed at 21.6 Å
    - (calibration sources, outbursts, or long-exposures: 0.5-1 Ms)
- Far-UV (FUSE): ~ 80-90 % of AGNs show HV-OVI: at rest in the LGSR (Nicastro et al., 2003, Nature, 421, 719; Sembach et al., 2003, ApJ, submitted)
  - 100 km s^{-1} < $|V_{LSR}|$ < 450 km s^{-1}



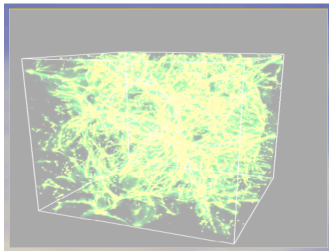
The Local Group WHIM (2)

Observation

- HV-OVI Absorbers are at rest in the LGSR
- logT = 5.8; δ = 20-30
- $[Ne/O] = 2.5\ [Ne/O]_{\odot}$
- Total Mass = $(0.6\text{-}2)\times10^{12}\ [H/O]_{0.3} M_{\odot}$

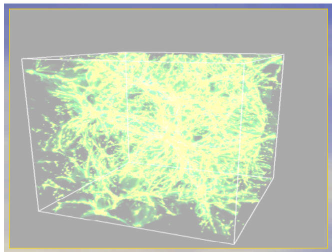
Implication

- Not in Milky Way Halo
- Fits Predictions for Warm-Hot IGM
- Dusty IGM?
- Can Bind the Local Group



WHIM Detections: 1

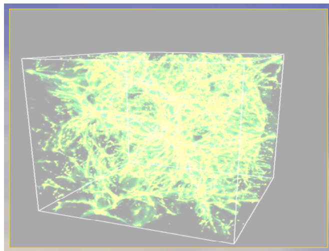
- Detecting the Local Group WHIM Filament is relatively easy, because we are in it: any direction probes ~ half filament.
- Consistently all *Chandra* or *Newton*-XMM spectra of AGN with enough statistics to detect 10 mÅ absorption lines at 21.6 Å, show OVII-OVIII Absorption by the Local Group WHIM: 6 different lines of sight.



The z > 0 WHIM

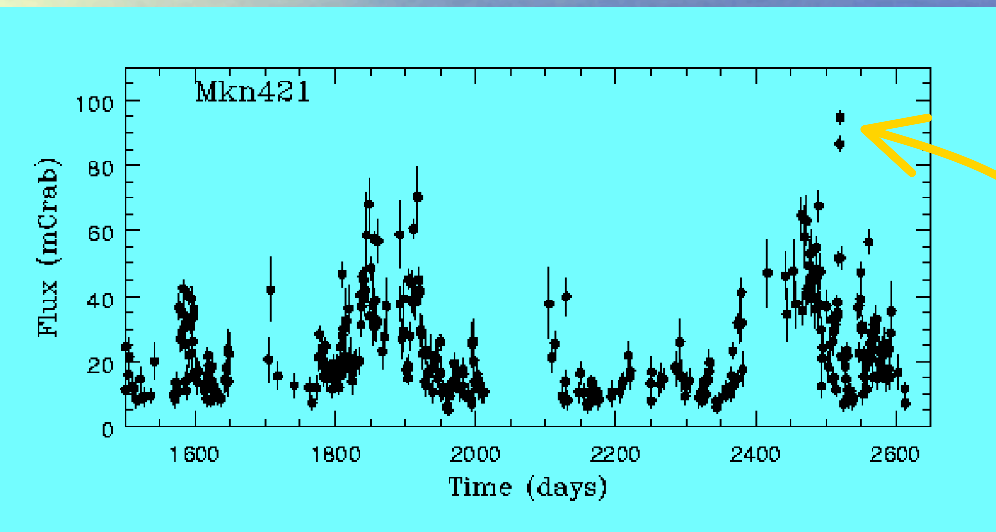
- Detecting z > 0 WHIM filaments is harder because of random orientation: lines of sight to background sources cross only a portion of the filament.
- Until very recently, only 3 tentative detections have been claimed, along 2 different lines of sight (Fang et al., 2002, Mathur et al., 2002).
- Exceptionally high quality X-ray spectra of background AGN are needed, implying exposures of Ms on the brightest blazars in their normal state.

Alternatively…



Our Strategy

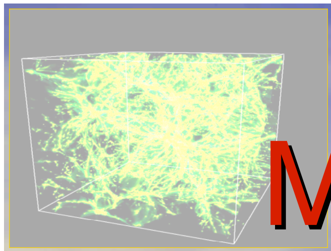
(Chandra Cycle 4 and Newton-XMM Cycle 2)



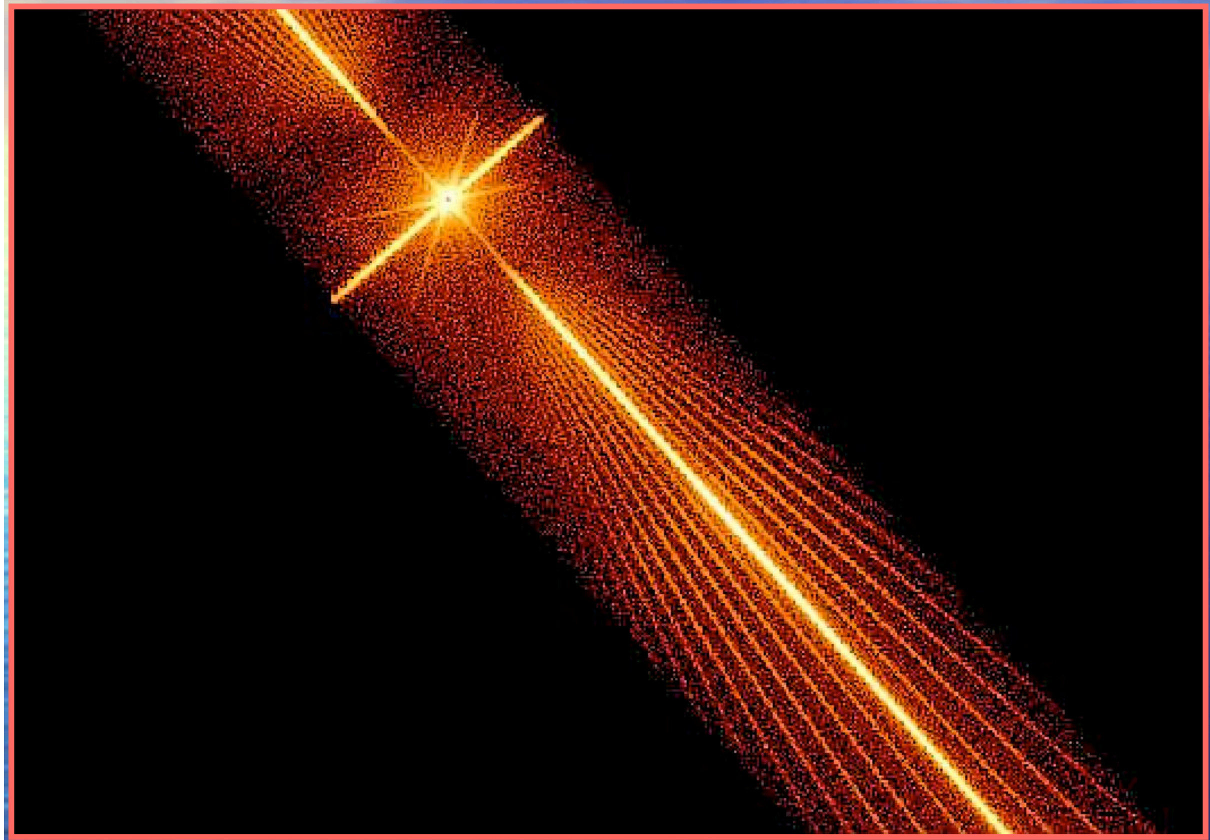
- Blazars flare to > 10 times normal
- Trigger ToO (from Rossi-XTE ASM)
- Outbursts last 1-2 weeks

⌉ 1st TOO on 2002 October 27

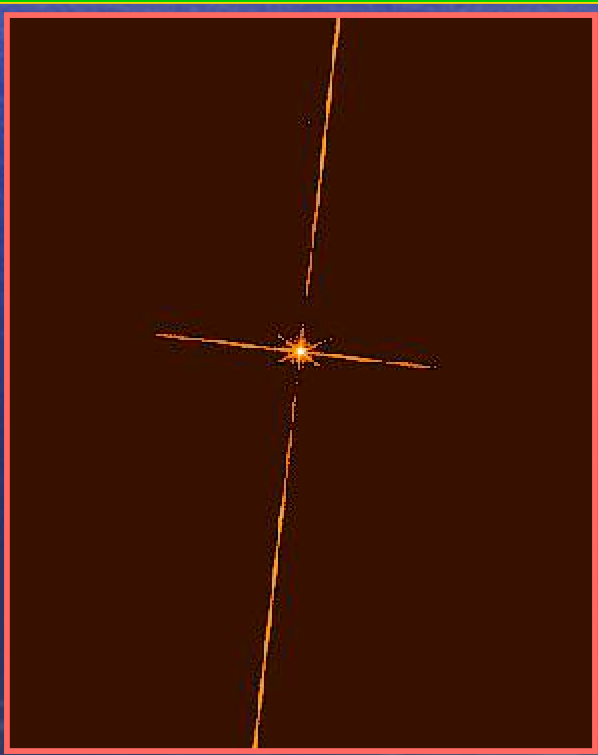
⌉ Spectacular Results!



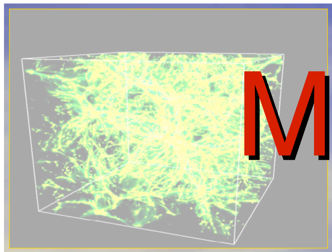
Mkn 421: Dispersed Image



The Second Brightest:
PKS 2155-304, 60 ks with *Chandra* HRC-LETG



2002, October 26-27: > 10x brighter!



Mkn 421: Chandra 1st Order Dispersed Spectrum

- F(0.5-2 keV) > 0.1 Crab
- 4.5 Mcts!!
- ~ 3000 ct/r.e., @ 21 Å

Enough to detect (at > 3σ):

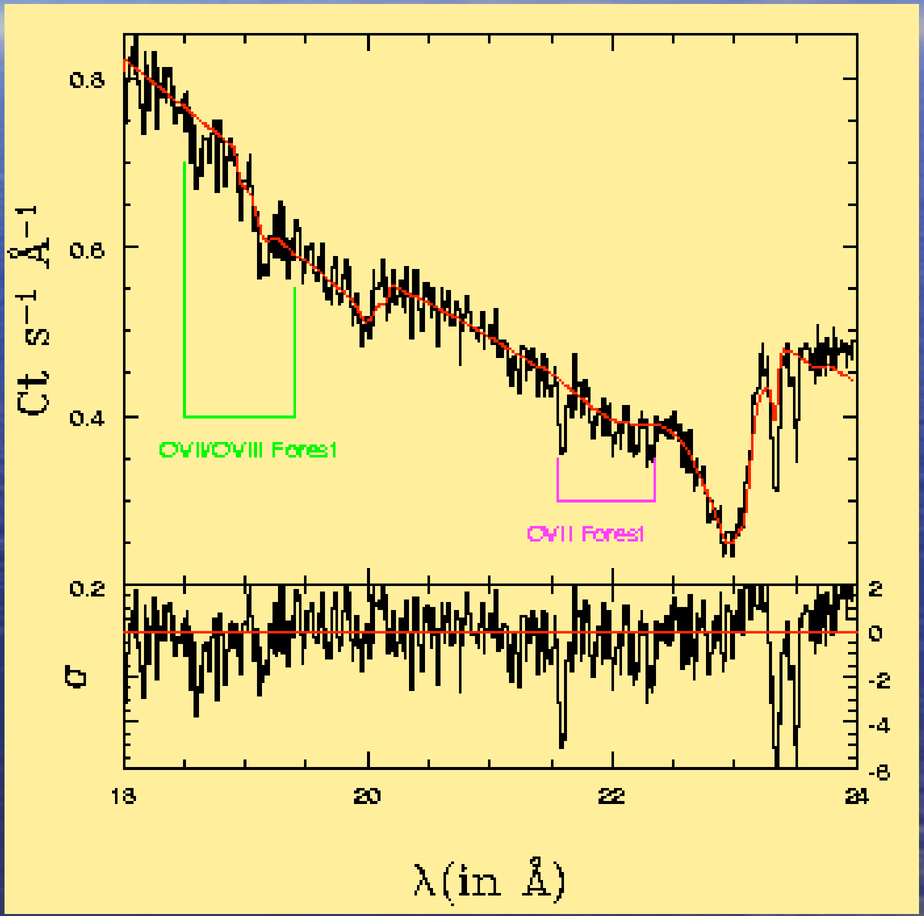
$EW_{Abs} \geq 2.5$ mÅ, @ 21 Å

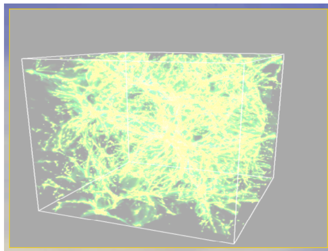
Implying:

$N_{OVII} \geq 10^{15}$ cm^{-2}

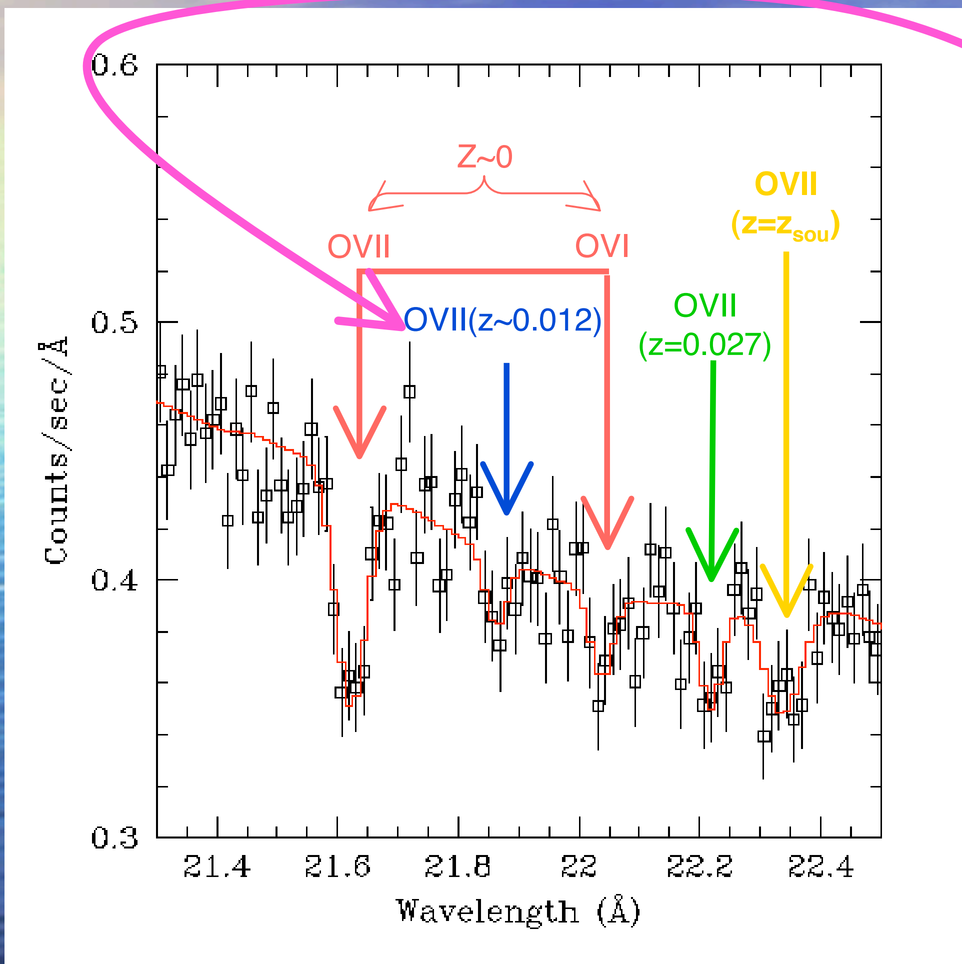
\ NH ≥ 10^{19} cm^{-2}, for $Z/Z_{\odot} = 0.1$

\ Path Lengths ≥ 1 Mpc, for δ=20





The OVII Forest



H Lyα at z = 0.01

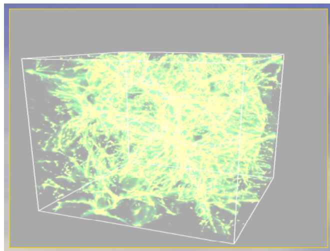
LogN_{OVII}(z=0.01) = 15 (cm^{-2})

LogN_{OVII}(0.027)= 15.2 (cm^{-2})

$$dN^{predicted}_{OVII}(z < 0.03, EW > 3.1mA) = 1.2$$

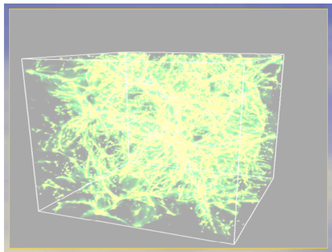
$$dN^{observed}_{OVII}(z < 0.03, EW > 3.1mA) = 2$$

dN/dz = 35-70



Summary

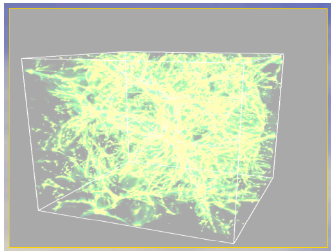
- *Chandra* ToO of Mkn 421 probes unprecedented N_{OVII} and detects 1-2 trees in the "X-ray Forest".
- Based on that detection: $dN_{OVII}/dz \sim 35\text{-}70$ (cf. $dN_{OVI}/dz = 20$, Tripp & Savage, 2000): the majority of baryons at $z < 2$.
- Alternatively, jet interaction with the ISM, up to velocities of ~ 6000 km s^{-1}



Future Prospects: Con-X and the WHIM

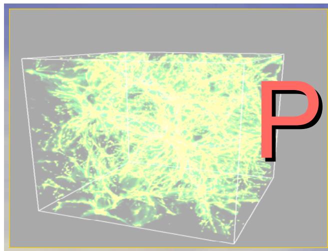
What can we learn

- Cosmology: large scale structure formation; Dark Matter distribution
- Heating mechanisms of gaseous baryons in the Universe
- Chemical history of the Universe: feedback mechanisms (refine hydrodynamical simulations)



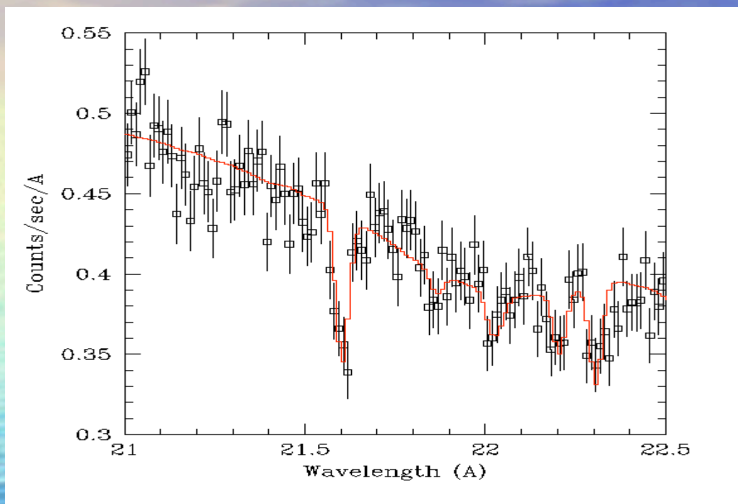
How do we learn this?

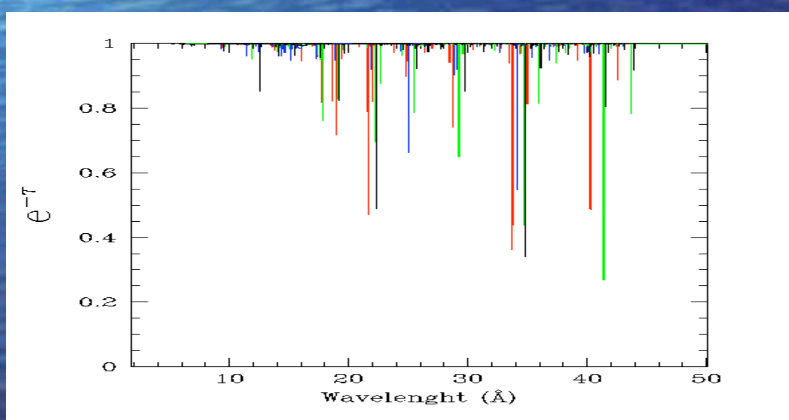
- Map the WHIM at z < 2 (Eff. Area)
- Measure dN_{WHIM}/dz (Eff. Area)
- Measure $T_{WHIM}(z)$, dT_{WHIM}/dz (Resolution)
- Measure relative contribution of photoionization (Resolution)
- Measure dZWHIM/dz (C, O, Ne, Mg, etc.) ◊ total baryonic mass (Eff. Area & Res.)

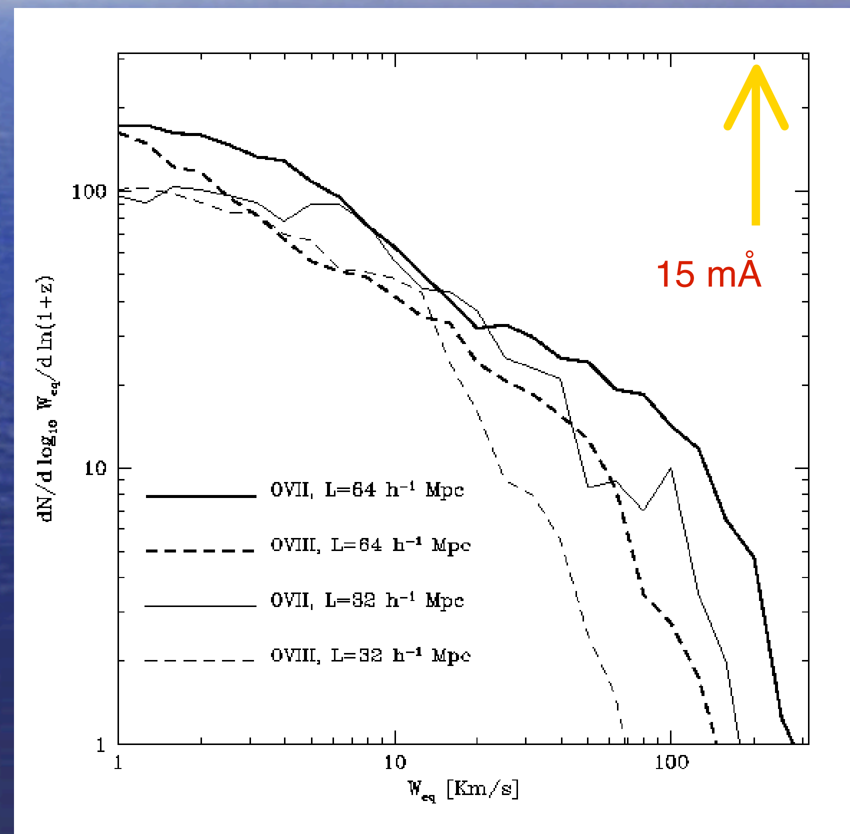


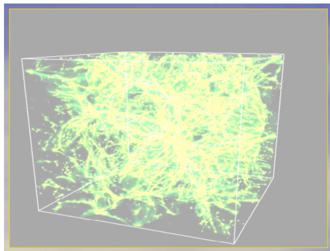
Probing the WHIM Strength: a *Constellation-X* task

(Hellsten et al., 1998)



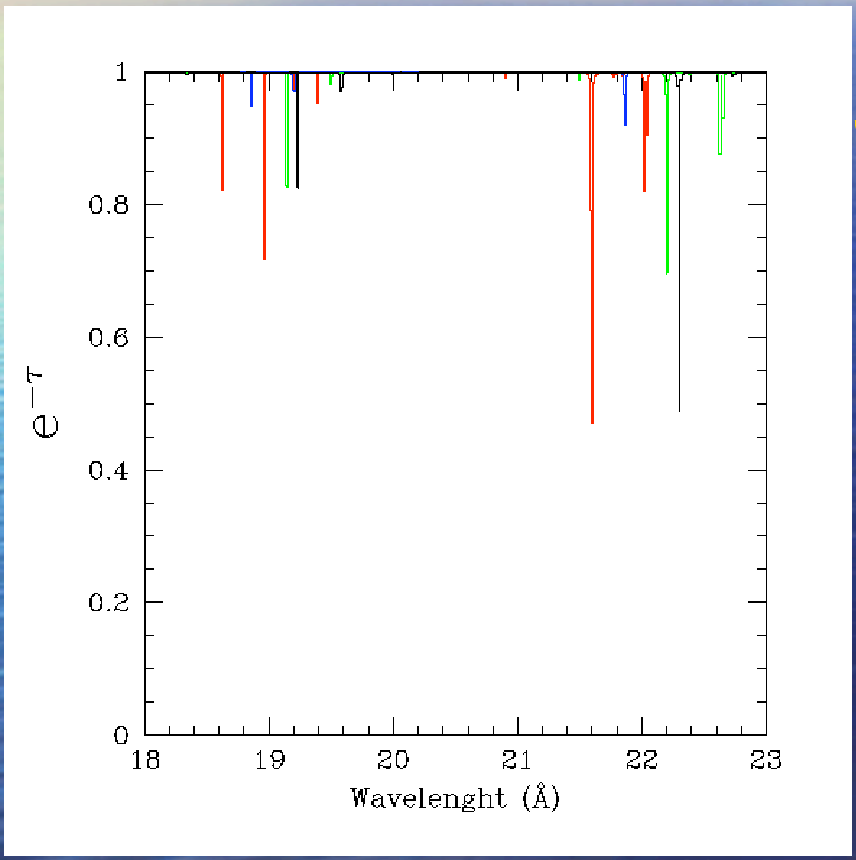


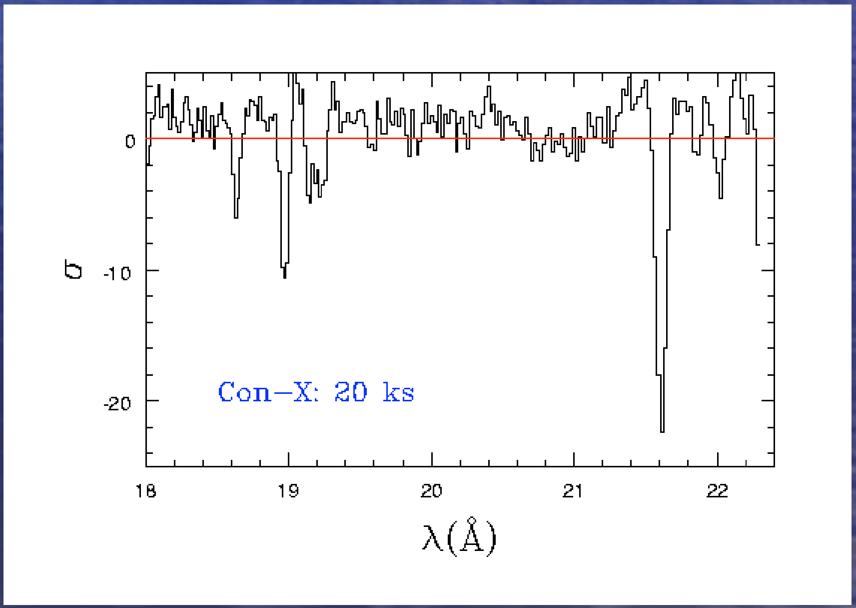


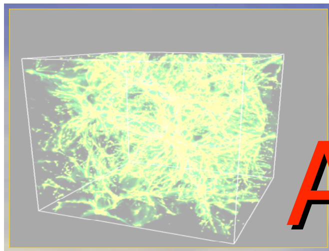


Mkn 421 through *Constellation-X*

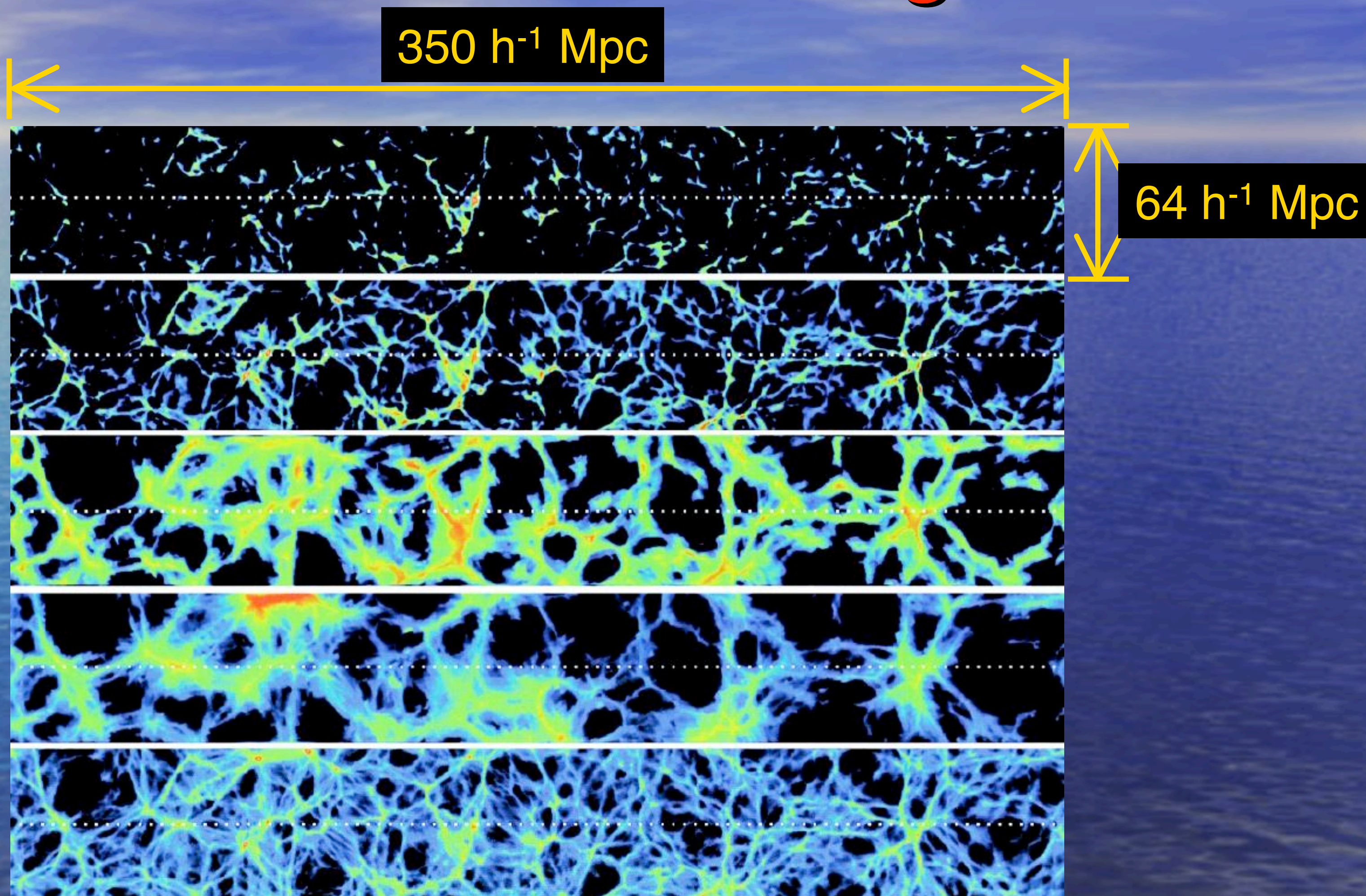
20 ks (100 mCrab)







A Random Line of Sight…



N_{OVII} ~ 10^{15} cm^{-2}

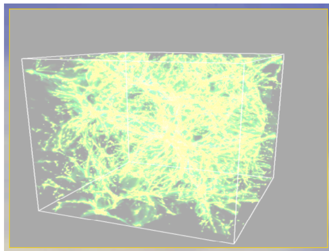
N_{OVIII} ~ 10^{15} cm^{-2}

$Z/Z_{\odot}$ ~ 0.05-0.3

T ~ $10^{5.5}$ - 10^{7} K

n_b ~ 10^{-6}-10^{-5} cm-3

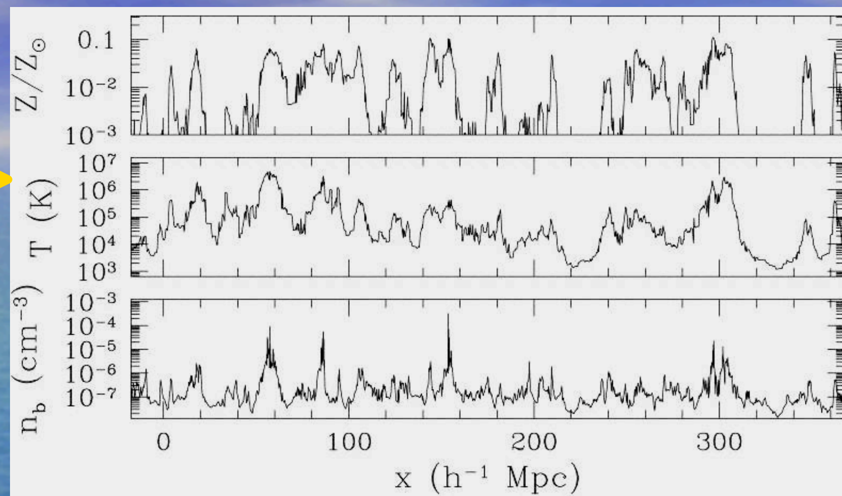
(Hellsten et al., 1998)



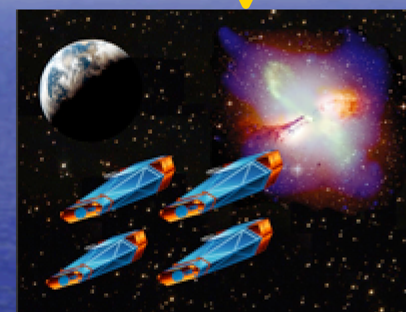
The WHIM through *Constellation-X*

Background QSO

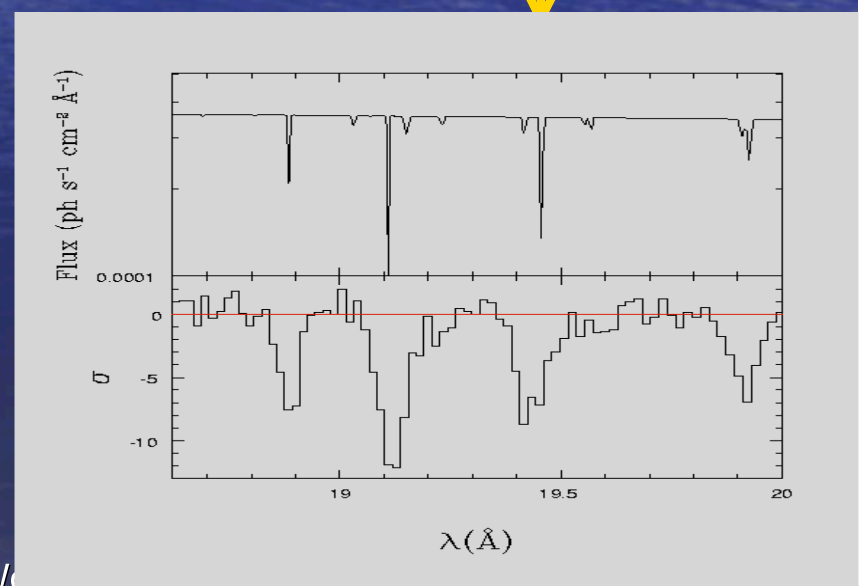
1 mCrab

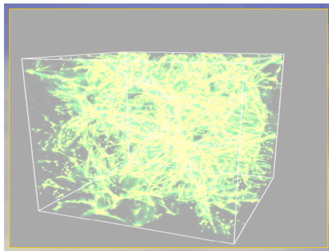


100 ks



ConX

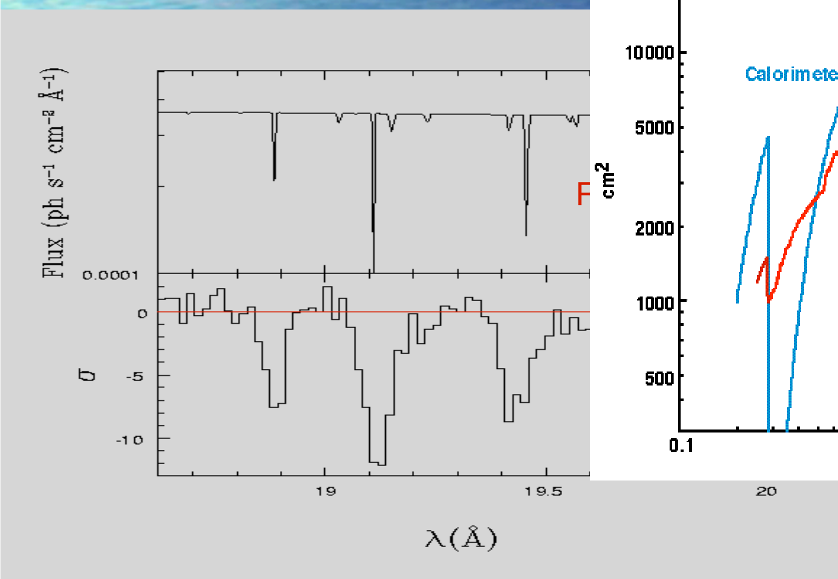


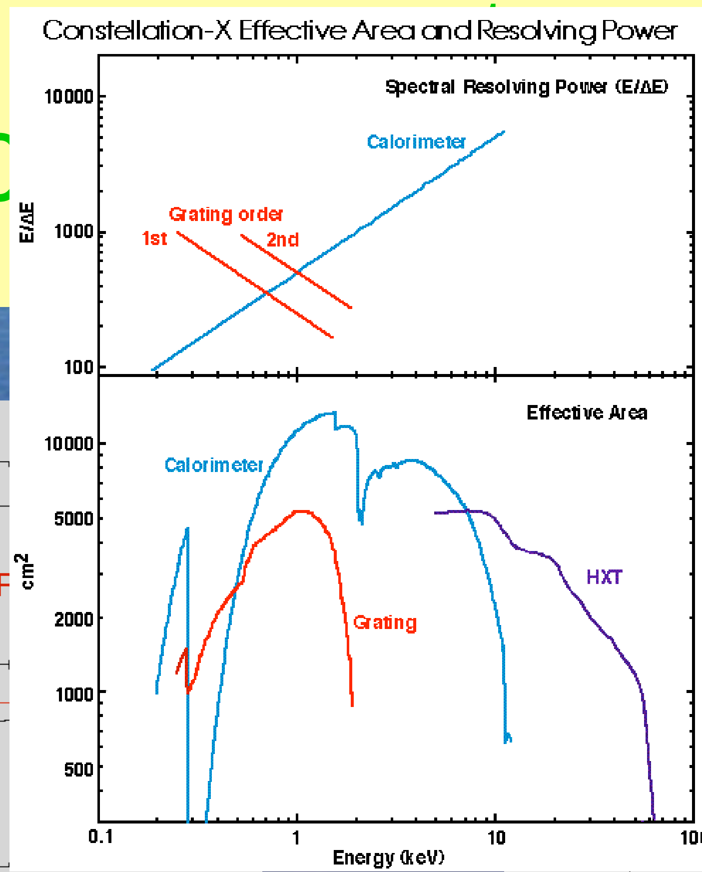


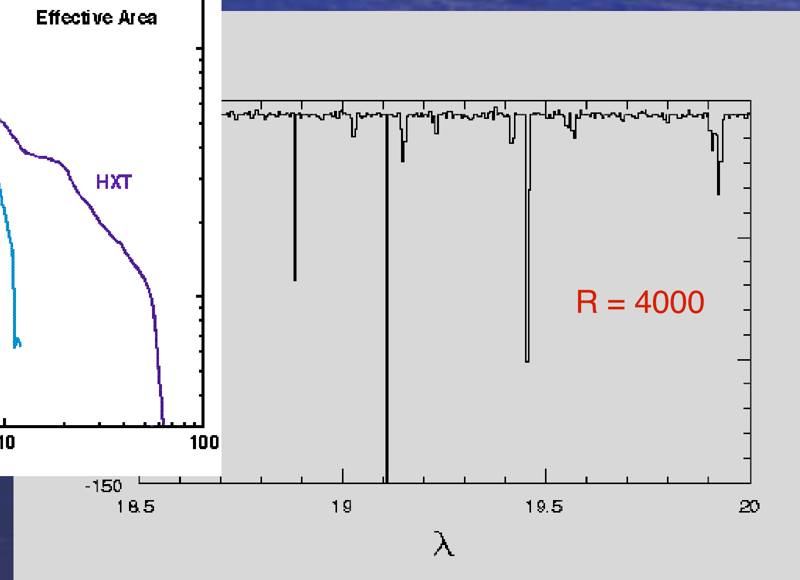
However…Physics need Resolution

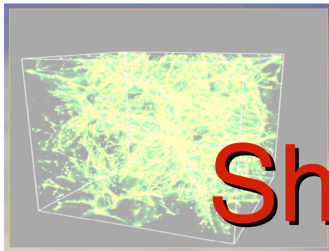
$\Delta v_O(T=10^6\ K)$

◊ FWHM ~ 60 … 00





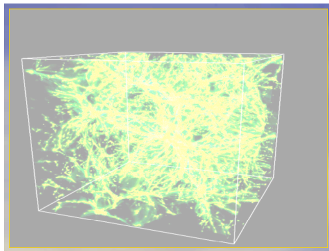




Short and Long Term Prospects

- Next 2-4 years: collect data from 12 sightlines towards blazars in outburst: up to $z = 0.5$: \ dN_{WHIM}/dz, Ω_b, $T_{WHIM}(z<0.5)$, dT_{WHIM}/dz, dZ/dz

- Long Term: mapping the WHIM up to z=2: needs high throughput and spextral resolution in X-ray: *Constellation-X* ($R > 1000$, $A = 2000\ cm^2$)



The Detection of the Missing Baryons in the Local Universe

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S. Bianchi

Oss. Arcetri:
C. Cecchi Pestellini

My 1-yr old Twins!

Giulia and Sara