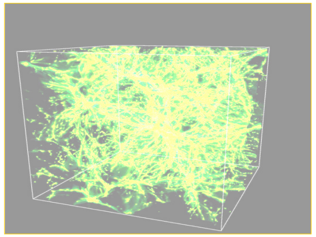
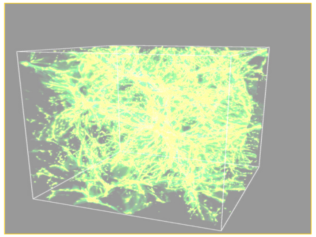


The Warm-Hot Intergalactic Medium

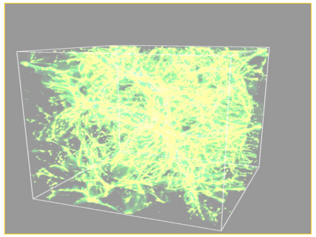
Past, Present and BRIGHT Future

Fabrizio Nicastro (CfA)
& the *Pharos* Collaboration



Overview

- *The Missing Baryons* problem
- First Ω_b^{WHIM} estimate
- *Con*-X, Estremo (New, Dios), *Pharos* & the WHIM

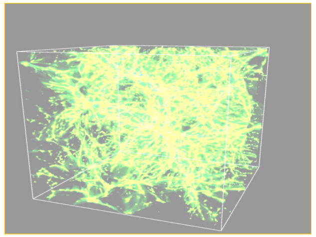


(Nicastro et al., 2005, Nature, 433, 495)

Problem: *Missing Baryons*

Table 1 **Census of baryons in the high-and low-redshift Universe**

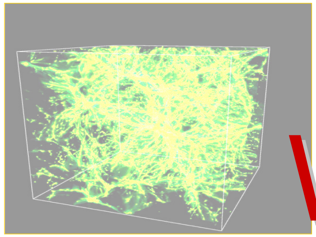
Inferred from*	Ω_b (%) for $h_{70} = 1$	% of b
BBN + D/H	(4.4 ± 0.4)	
CMB anisotropy	(4.6 ± 0.2)	
Observed at $z > 2$ in†		
Lyman-α forest	>3.5	>76
Observed at $z < 2$ in‡		
Stars	(0.26 ± 0.08)	5.7
H I + He I + H_2	(0.080 ± 0.016)	1.7
X-ray gas in clusters	(0.21 ± 0.06)	4.6
Lyman-α forest	(1.34 ± 0.23)	29
Warm + warm–hot O VI	(0.22 ± 0.03)	4.8
Total (at $z < 2$)§	(2.1 ± 0.3)	46
Missing baryons (at $z < 2$)§	(2.5 ± 0.4)	54



Why Should we Care?

(54 ± 9) % of Baryons are missing!

- Find the 'Missing Baryons' and verify theory
- Ecology of the Universe (Metal Pollution)
  - Absolute (needs UV) and Relative Metallicities.
  - Galaxy Superwinds (SN) vs AGN winds, jets
  - Nucleosynthesis
- Heating History of the Universe
- Cosmological parameters from density fluctuations of WHIM filaments (1-10 Mpc at z=0-2): > 10^3 systems needed
  - LG-WHIM is a biased measure - Need z>0 WHIM absorbers to measure Ω_b
- Local Group WHIM and Galaxy formation

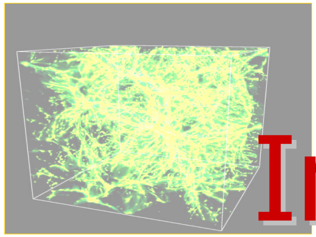


WHIM Filaments are Faint

- Size: $\Delta R \sim 1$ Mpc
- Density: $n_b \sim 10^{-6}$-10^{-5} cm^{-3}
- Temperature: $T \sim 10^6$ K ; $\xi_{OVII} \sim 1$
- Metallicity: $Z \sim 0.1 Z_\odot$

=> OVII-Forest Column Density:

$N_{OVII} \sim n_b \xi_{OVII} Z_O \Delta R \sim 2.6\mathrm{x}(10^{14}$-$10^{15})$ cm^{-2}



Instrumental Requirements

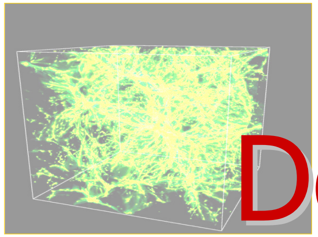
$$W_{OVII} \approx 3\times10^{-18}(1+z)^2 \mathrm{N}_{OVII} \approx 0.8-8\,(1+z)^2\,\mathrm{m\mathring{A}}$$

$$W_{N_\sigma}^{Thresh} = N_\sigma \frac{\Delta\lambda}{\sqrt{CPRE}}$$

Resolution

(Eff. Area * Res.)$^{0.5}$

$$\mathrm{N}_{OVII}^{Thres} \approx 2.3\times10^{15}\left(\frac{N_\sigma}{3}\right)\left(\frac{\Delta\lambda(\mathrm{m\mathring{A}})}{50}\right)\sqrt{\frac{500}{CPRE}}(1+z)^{-2}$$



Detectability (with Gratings)

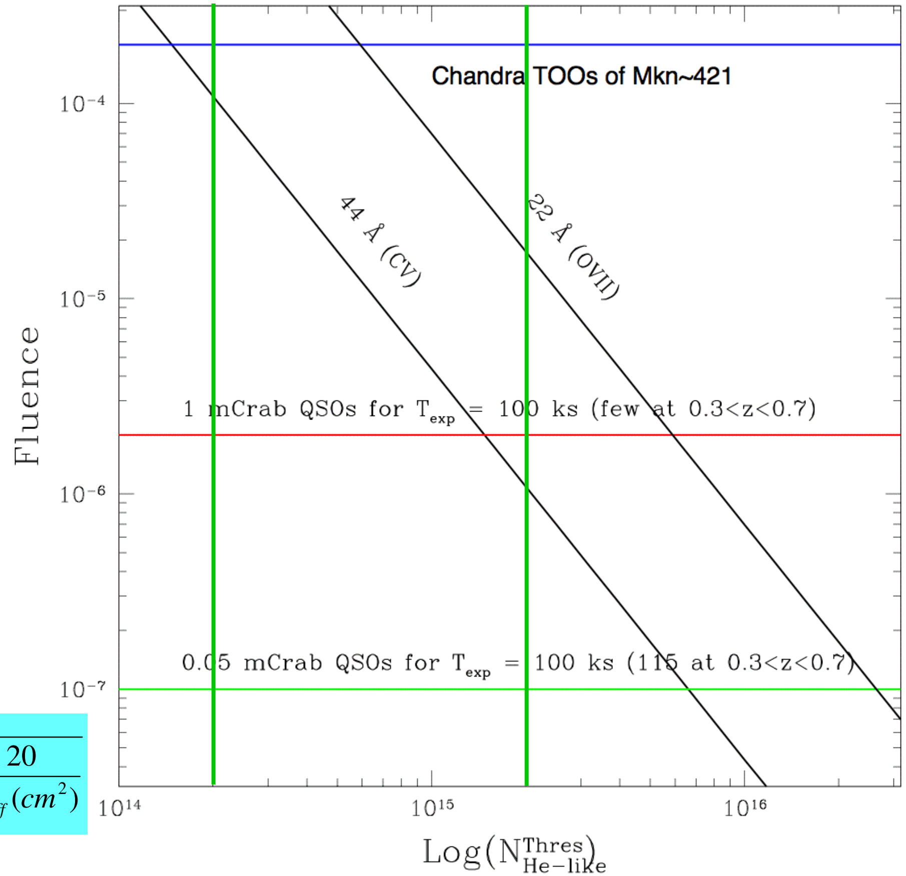
$$N_{OVII}^{Thres} \approx 2.3\times10^{15}\left(\frac{N_\sigma}{3}\right)\left(\frac{\Delta\lambda(\mathrm{m}\mathring{A})}{50}\right)\sqrt{\frac{500}{CPRE}}(1+z)^{-2}$$

$$\mathrm{CPRE} \;=\; \mathrm{f}_{\mathrm{ph}}^{\lambda} * \Delta t * A_{Eff} * \Delta\lambda$$

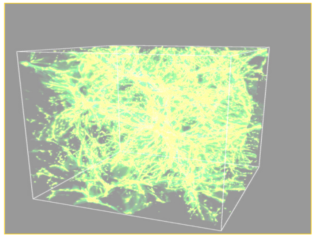
Fluence $(\Gamma=2)$

$$\mathrm{f}_{\mathrm{ph}}^{\lambda} * \Delta t = \frac{F(\lambda_1,\lambda_2)}{hc\ln(\lambda_2/\lambda_1)}$$

$$(N_{He-like}^{Thres})_{Grat} \approx 6.4\times10^{15}\left(\frac{N_\sigma}{3}\right)\left(\frac{\lambda(\mathring{A})}{25}\right)^{-2}\left(\frac{f_{ion}}{0.7}\right)^{-1}\sqrt{\frac{\Delta\lambda(m\mathring{A})}{50}}\sqrt{\frac{10^{-6}}{F(erg\,cm^{-2})}}\sqrt{\frac{20}{A_{Eff}(cm^2)}}$$



- Exceptionally high quality X-ray spectra of background AGN are needed.

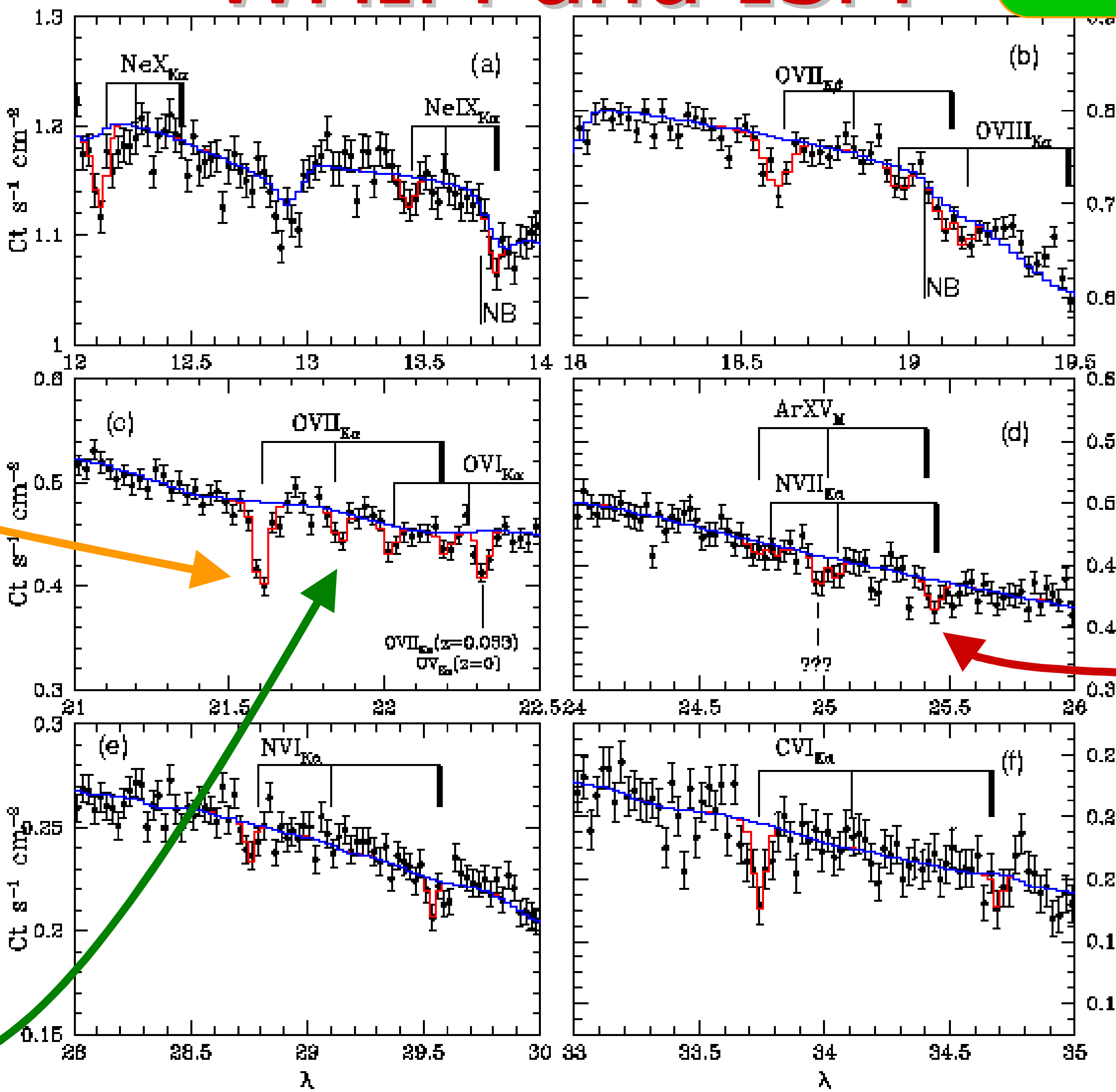


Mkn 421 (z=0.03): WHIM and ISM

Chandra TOOs:
F(0.5-2)=2x10^{-4} erg s^{-1}
CPREs=6000

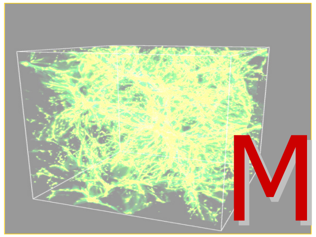
Local Group WHIM?

<z>=0.011 WHIM

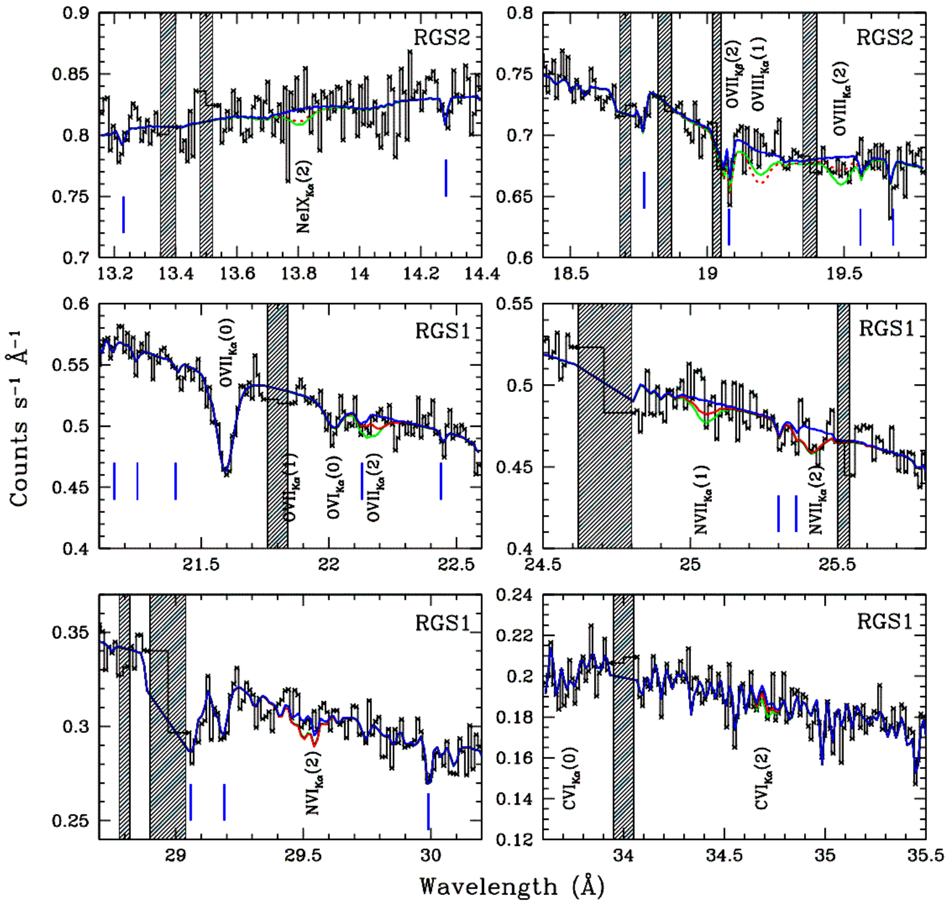


<z>=0.027 WHIM

(Nicastro et al., 2005, Nature, 433,495; Nicastro et al., 2005, ApJ; Williams et al., 2005, ApJ, in press)



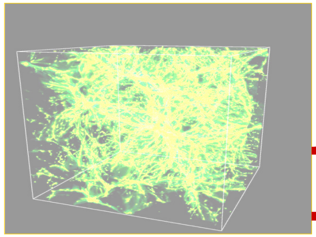
Mkn 421: XMM-*Newton*-RGS



15000 CPREs! ~ 2.5 x LETG

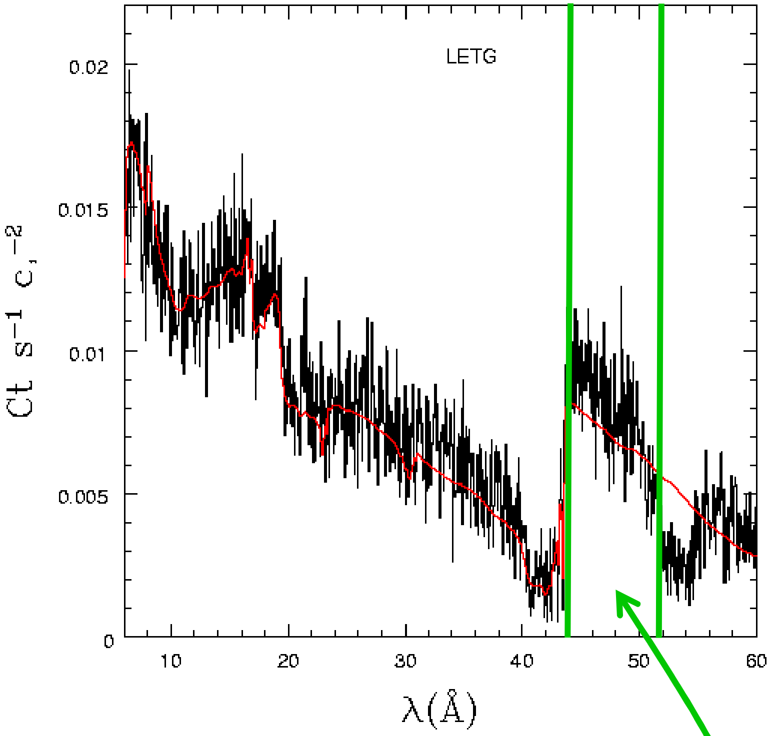
1. 20-60 % of Δz blocked by instrumental features
2. Resolution > 2 x poorer in the line wings
3. Fixed-pattern noise at λ>29 A

(Williams, Mathur, Nicastro & Elvis, 2006, ApJ, submitted)



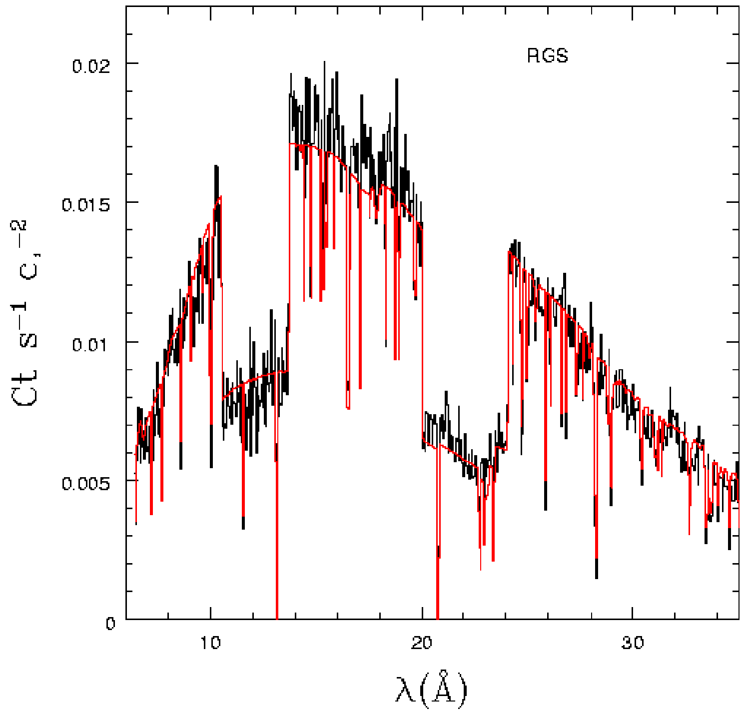
1ES 1028+511 (z=0.361)

Chandra-LETG: 149 ks
$F_{0.3\text{-}2}$ = 0.8 mCrab

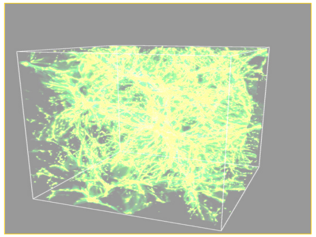


Sensitive to CV-Forest:
λ~44-52 => Δz=0.2
CPRE(20-30;44-52)=60

XMM-Newton RGS: 195 ks
$F_{0.3\text{-}2}$ = 0.5 mCrab

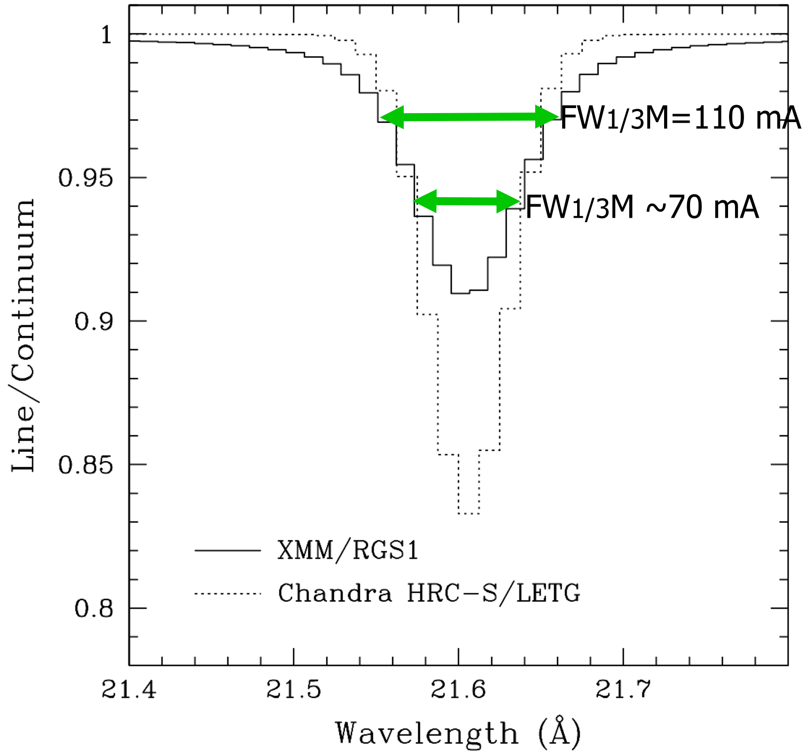


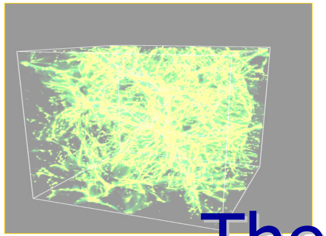
18 % of Δz(OVII) is blocked
Left-right contiguous resolution elements
Adds up to ~ 60 % blocking factor!
CPRE(20-24;30-36)=45; CPRE(24-30)=75



LETG & RGS Resolutions

R_{core}(RGS) ~ R_{core}(LETG) = 50 mA
R_{wings}(RGS) ~ 2 R_{wings}(LETG) = 140 mA

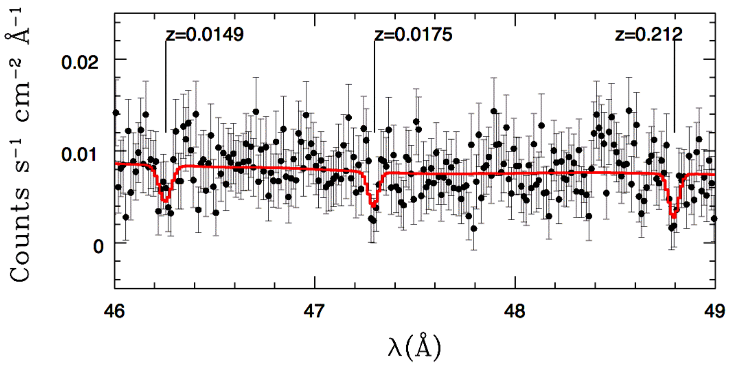




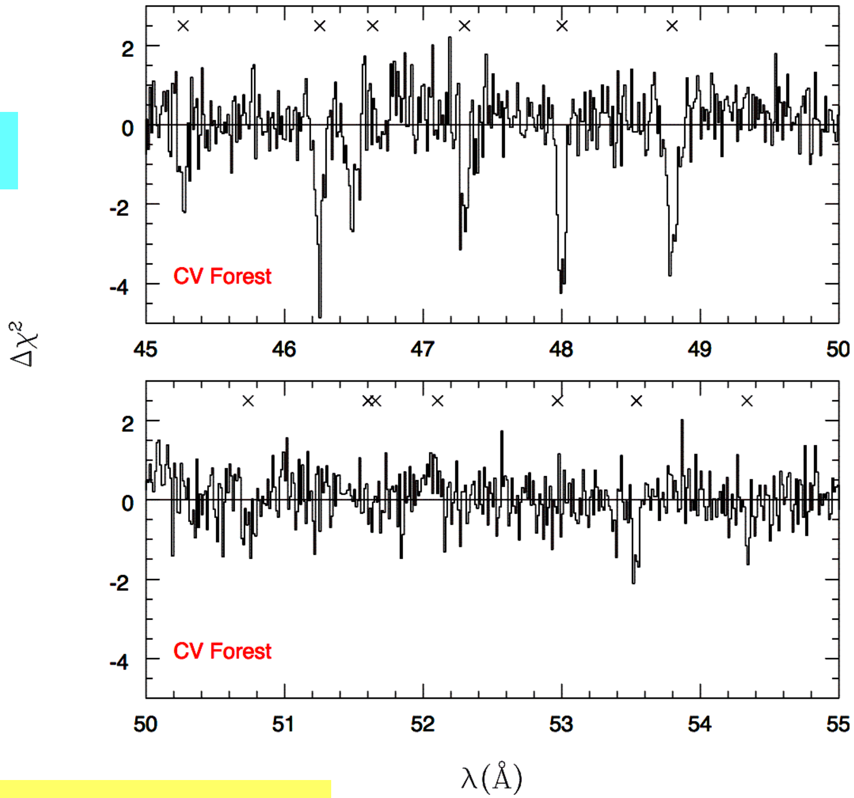
1ES 1028+511

The Best Sightline with the Best Spectrometer

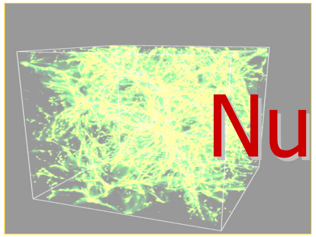
140 ks Chandra-LETG: F=3.3x10^{-6} erg s^{-1}



1.4 Ms Chandra-LETG Simulation (F=2.8x10^{-5} erg s^{-1})



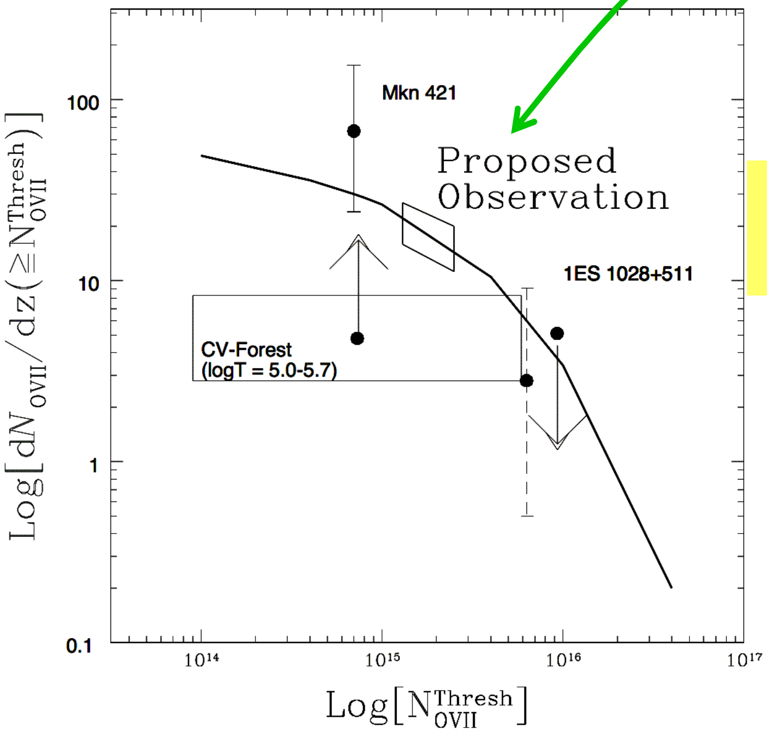
9 out of the 15 Expected Systems are Detected in CV !!!



Number Density and Cosmological Mass Density of WHIM

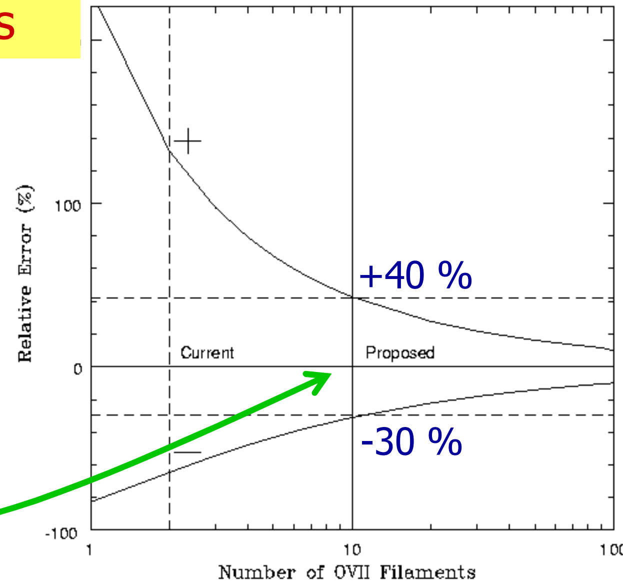
$$\Omega_b(N_{OVII} > 7*10^{14}) = \left(\frac{1}{\rho_c}\right)\left(\frac{\mu m_p \sum_i N_H^i}{d_{Mkn421} + d_{1ES1028+511}^{\rm equivalent}}\right) = 2.4_{-1.1}^{+1.9} * 10^{-[O/H]_{-1}} \%$$

Consistent with $\Omega^{missing}$ =2.5 ± 0.4

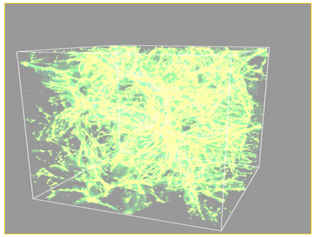


Proposed 1.4 Ms Chandra Obs

Short-term Prospects

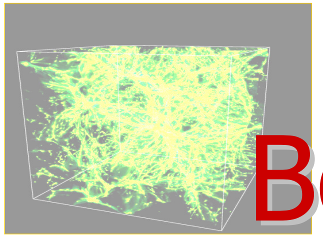


(Nicastro et al., 2005, Nature, 433, 495; Nicastro et al., 2006, in prep.)



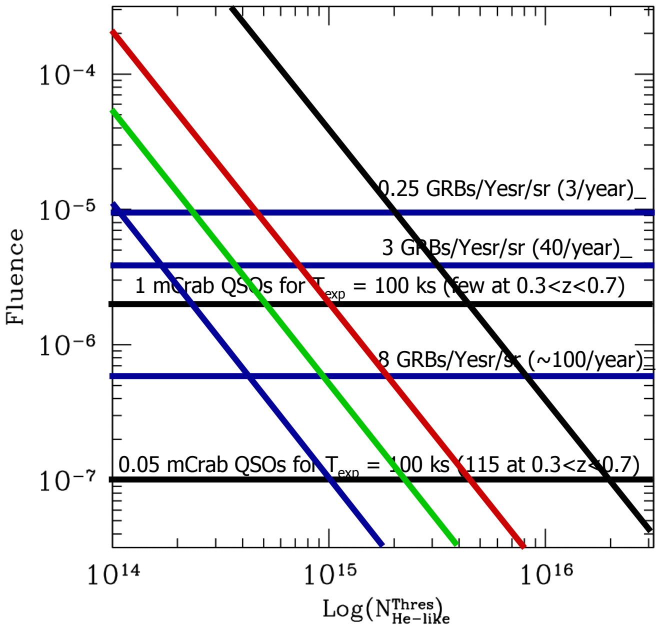
Long-Term Prospects

- Long Term: mapping the WHIM up to z~1: needs high throughput and spectral resolution.
- Tens to hundreds systems would enable:
  - Ω_b ® and d*N*/dz to better than few/tens %
  - WHIM density in galaxy *voids* vs galaxy overdensities
  - Multi-phase studies ® ® ®
- Hundreds to Thousands of Systems would enable:
  - Ω_b ® and d*N*/dz to better than few tenth of %
  - Cosmological Parameters (density fluctuations)
  - Dark-Matter Maps
  - Metallicity History: dZ/dz (Ecology of the Universe) (needs UV) ®
  - IGM/galaxy/AGN Feedback
  - Heating History of the Universe (dT/dz) ®



Best Observational strategy

$$\left(N^{Thres}_{He-like}\right)_{Pharos} \approx 3.3\times10^{14}\left(\frac{N_\sigma}{3}\right)\left(\frac{\lambda(\mathring{A})}{25}\right)^{-2}\left(\frac{f_{ion}}{0.7}\right)^{-1}\sqrt{\frac{\Delta\lambda(m\mathring{A})}{4}}\sqrt{\frac{10^{-6}}{F(erg\,cm^{-2})}}\sqrt{\frac{600}{A_{Eff}(cm^2)}}$$



Chandra-LETG: ~ 10 systems in ~ 1 Ms

Constellation-X: 100-120 los in 5 yr ==> 600-700 sys

Estremo: ~ 1500 sys in 5 yr (only 10-15 % for Ω_b)

Pharos: ~ 5000 sys in 5 yr (85 % for Ω_b)

$$\left(N^{Thres}_{He-like}\right)_{Estremo} \approx 1.5\times10^{15}\left(\frac{N_\sigma}{3}\right)\left(\frac{\lambda(\mathring{A})}{25}\right)^{-1}\left(\frac{f_{ion}}{0.7}\right)^{-1}\sqrt{\frac{\Delta E(eV)}{2}}\sqrt{\frac{10^{-6}}{F(erg\,cm^{-2})}}\sqrt{\frac{800}{A_{Eff}(cm^2)}}$$

Pharos

Pharos: (Elvis, Fiore et al. 2002 SPIE, astro-ph/0303444; F. Nicastro, M. Elvis, F. Fiore, B. Ramsey, S.S. Murray, A.Kenter, R. Kraft,K. Flanagan,E. Costa, M. Feroci, P. Soffitta, et al., 2006, SPIE, in prep.)

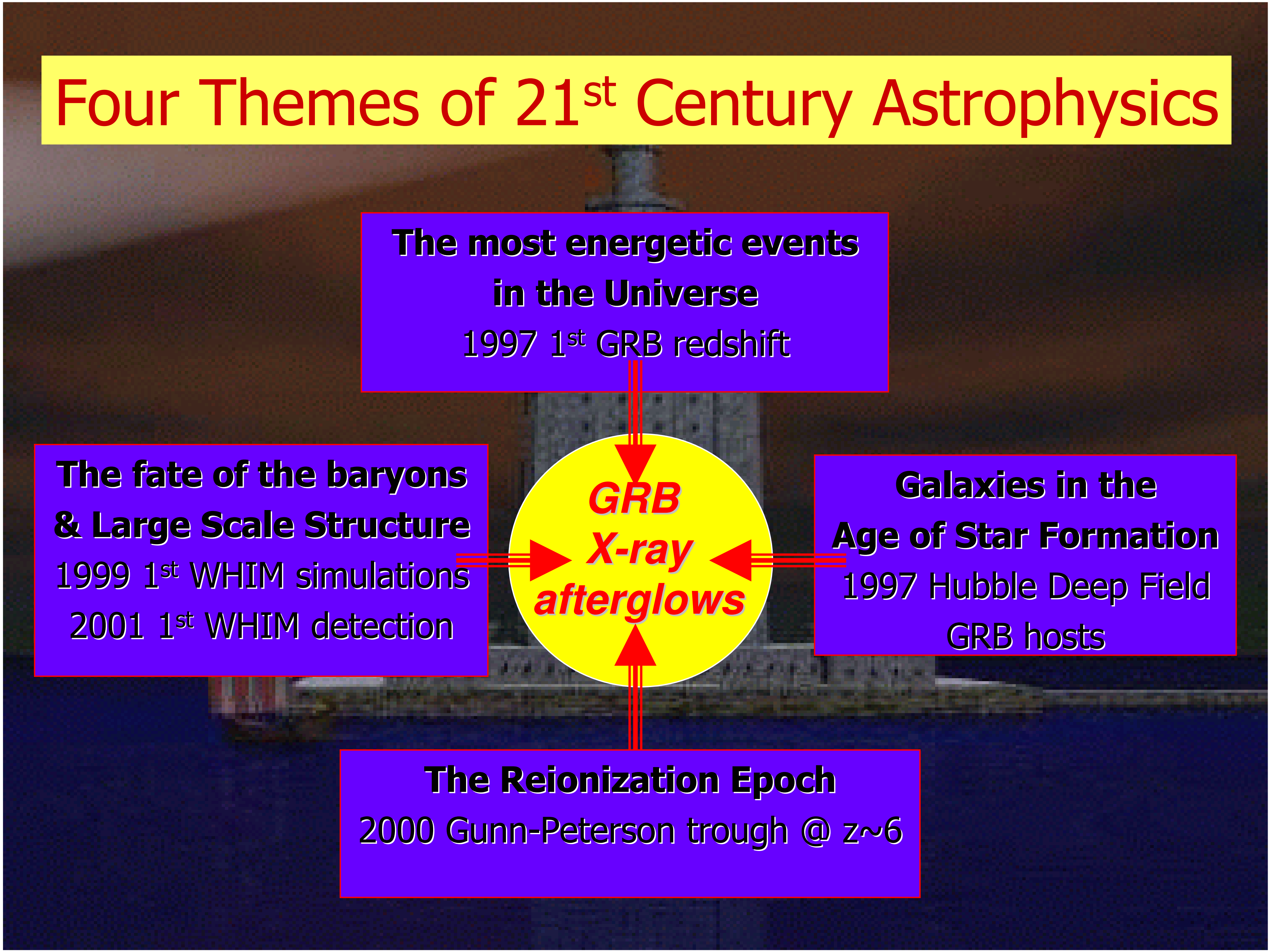
Midex concept (CfA, Obs. Rome, MIT, JHU):

R > 3000 @ E<1 keV

A = 30 x LETG

Coverage: 12-150 Å.

Slew on source in < 1 min:
about 1-5 Soft-GRB per year with $F = 10^{-5}$ erg cm^{-2}
(> 0.5 years on the brightest QSOs at z = 1-2).


Four Themes of 21st Century Astrophysics
The most energetic events in the Universe
1997 1st GRB redshift
The fate of the baryons & Large Scale Structure
1999 1st WHIM simulations
2001 1st WHIM detection
GRB X-ray afterglows
Galaxies in the Age of Star Formation
1997 Hubble Deep Field
GRB hosts
The Reionization Epoch
2000 Gunn-Peterson trough @ z~6

PHAROS: Mission Concept

Rapid Response to GRBs ~ 30 seconds

Catch X-ray afterglows while bright after 20min ~ 60 times fainter

Half-sky X-ray coded masks ~1arcmin (SuperAgile technology)

- **CMOS hybrid 0th-order detectors**
  - **Refine pointing to arcsec**
  - **Position telemetered to the ground immediately**
- **High resolution: R>3000 at E<1 keV (~10 x Chandra, XMM)**
  - **Detect faint absorption lines**
  - **Low column density systems** much more common
  - **Abundances from many lines in same system**
  - **Resolve thermal widths, internal galaxy motions: e.g. spiral arms**
  - **Detect emission lines from z=10-20 sources**
- **Short focal length (~2 m) X-Ray Replica mirror < 1.5 keV**
  - **Small moment of inertia: rapid slewing**
  - **More rigid form: better PSF: HPD=10" (goal 5")**
  - **More area/kg (A_{eff}=2000 cm^2, M<200 kg, including supports)**
- **Out-of-plane grating onto μchannel-plate detectors**
  - **Higher resolution (R>3000 at E<1 keV), efficiency (30 %)**

Pharos: Rapid X-Ray-rich GRB Trigger & Location

- **Problem:** require <1armin location + acquisition in 0.5-1 minutes *and* require quasi-4π coverage: *conflicting goals*
- **Solution:** trigger in the 5-30 keV with 2 1-D Coded Masks

t=0 s

Trigger

5-30 keV 'light'

ASM Coded Mask

1' localization in 0.5-1 s

t=1-15 s

Rapid rough slew
to 1' location

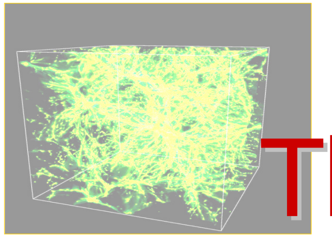
0.1-1 keV (5" mirror – Con-X technology): short focal length reduces moment of inertia, $I=mR^2$
(factor 25 for 2 m vs. 10 m) [2 m$, 2.5 yr]

GRB trigger must be on-board & autonomous: 5-30 keV triggers X-ray rich [SuperAgiles: light! 80 kg]

X-ray spectrometer starts to take data R>6000 @ <0.5 keV:
Out-of-plane Reflection Gratings

t=30 s

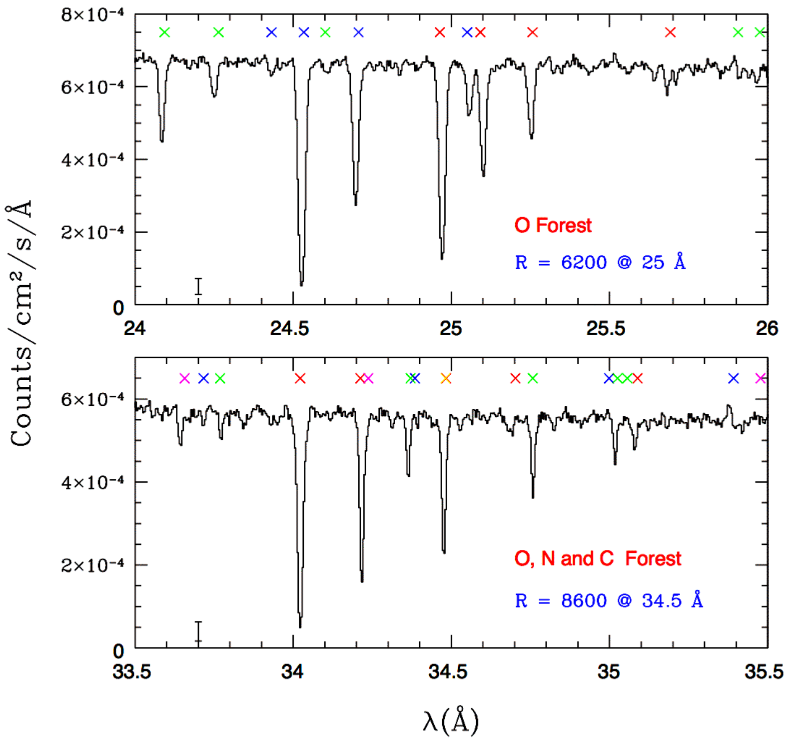
Fine slew
to <1 arcmin position



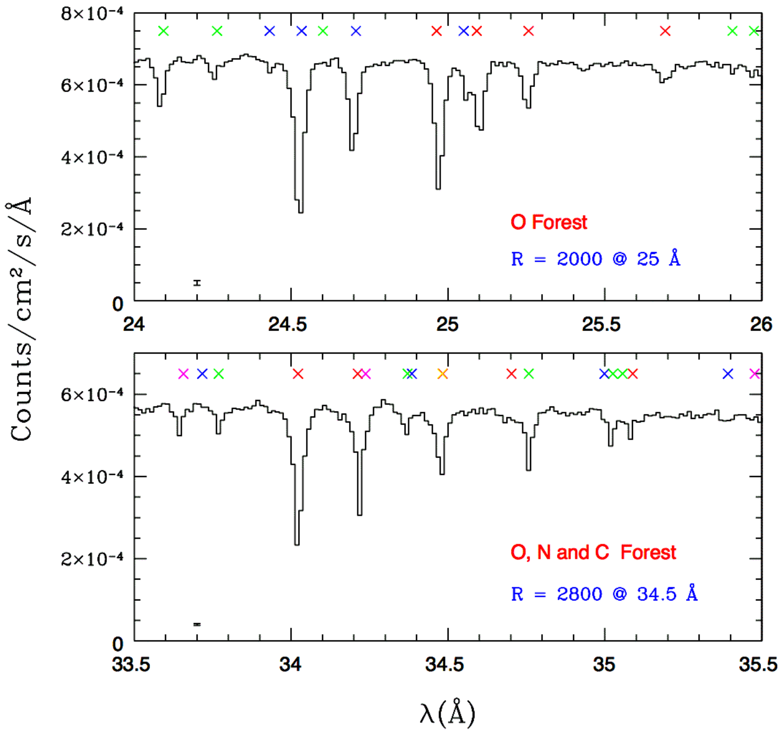
The X-Ray Forest with *Pharos*

$F_{0.5\text{-}2}(\mathrm{GRB}) = 10^{-5}$ erg s^{-1}

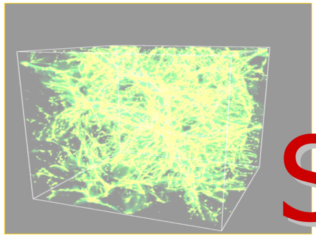
$\Delta\lambda$=4 mA



$\Delta\lambda$=12.5 mA

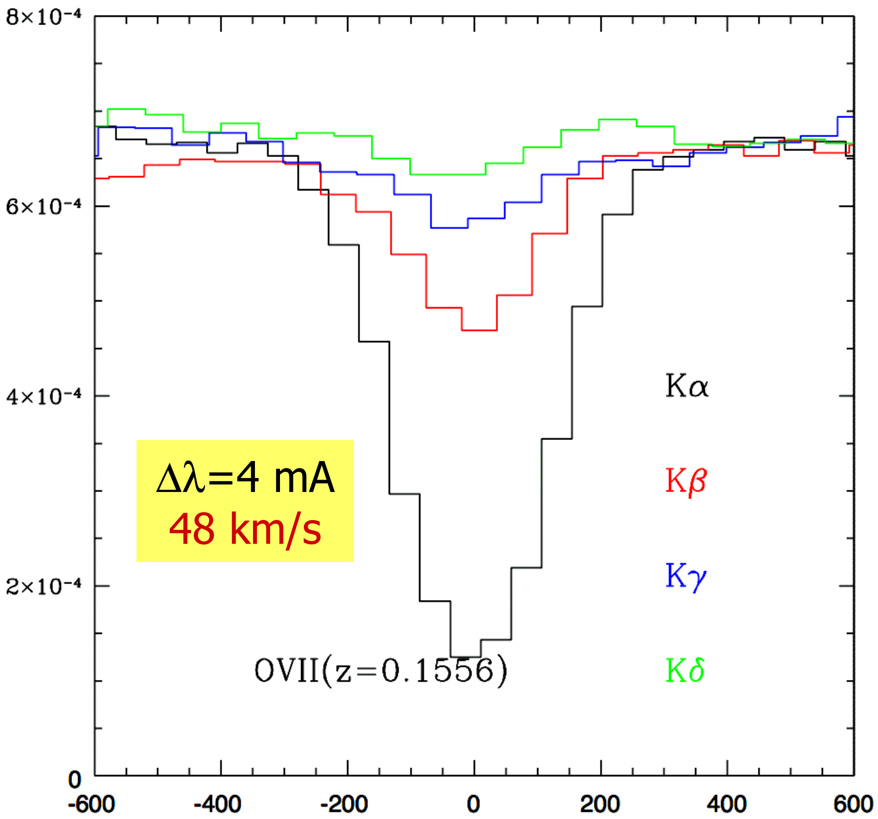


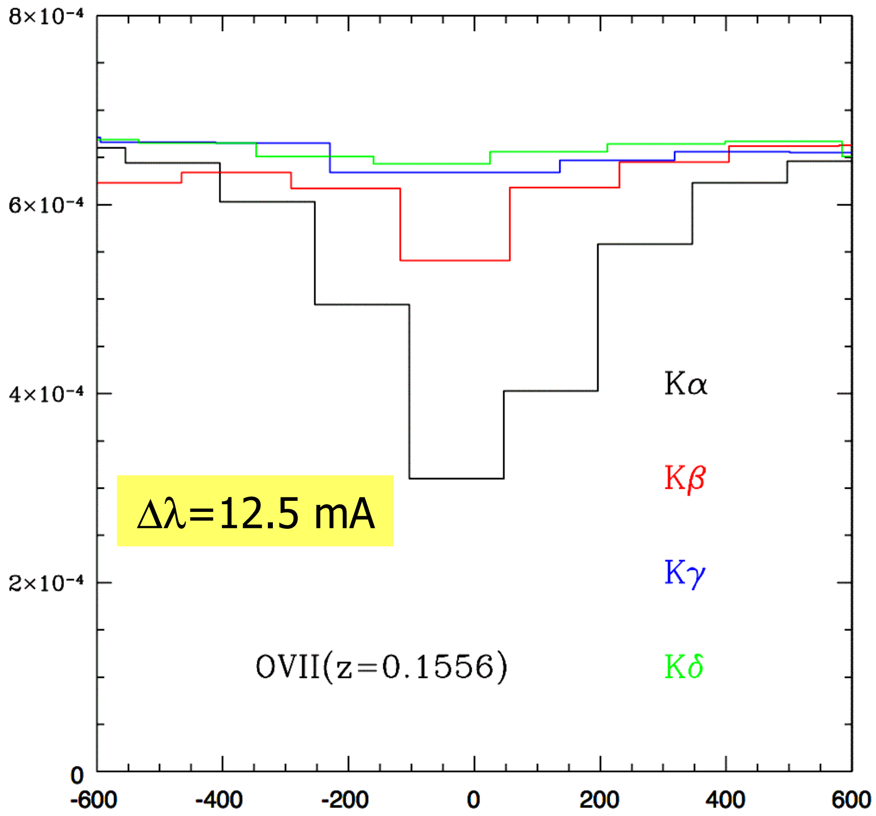
R>1000 at 12 A guarantees detection of > 80 % OVII systems



Saturated lines: b and N_{ion}

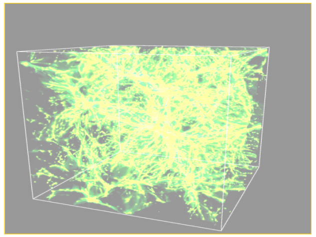
$N_{OVII} = 5 \times 10^{15}$; $b = [(b_{therm})^2 + (b_{turb})^2]^{0.5} = 48$ km/s



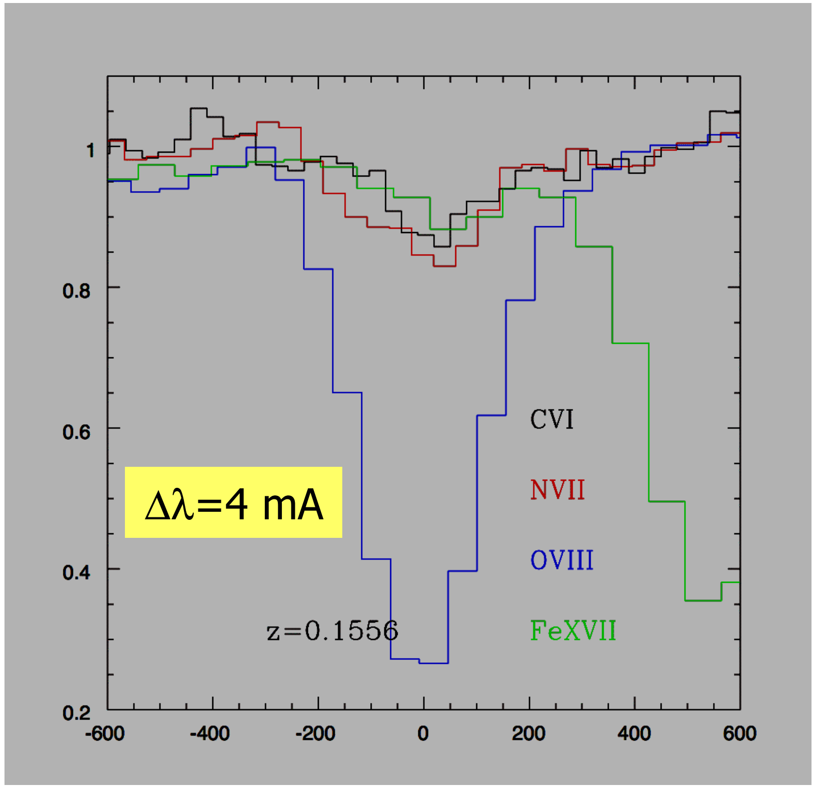


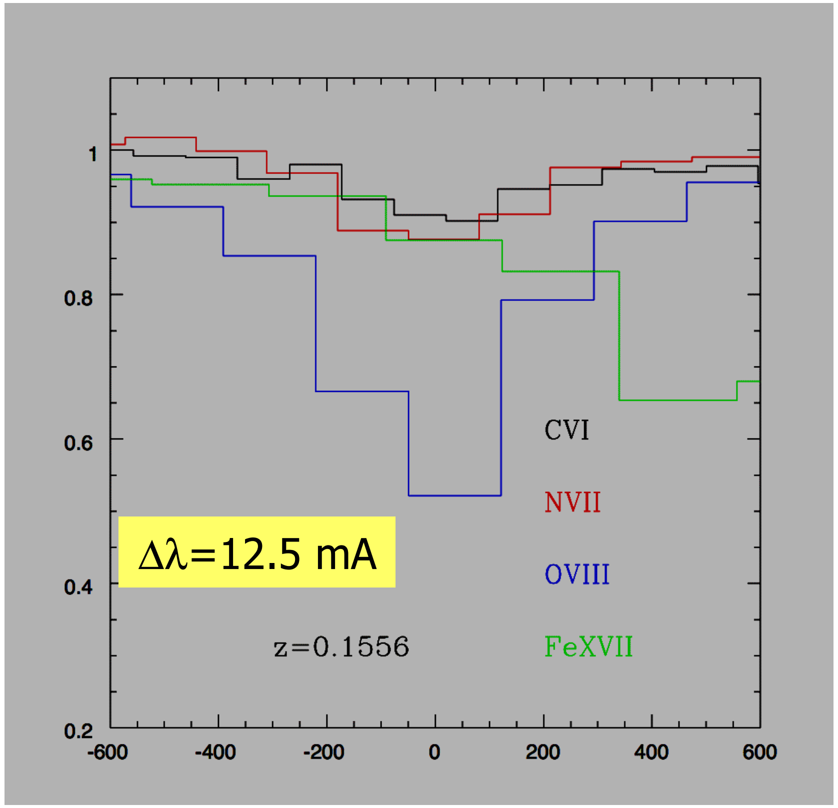
R=1000 at 12 A allows N_{ion}-b decoupling only for brightest OVII systems
Higher R needed!

Nicastro

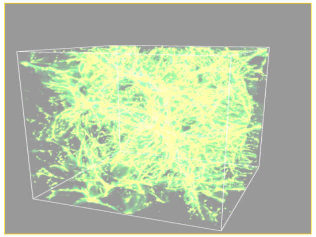


Relative Metallicity



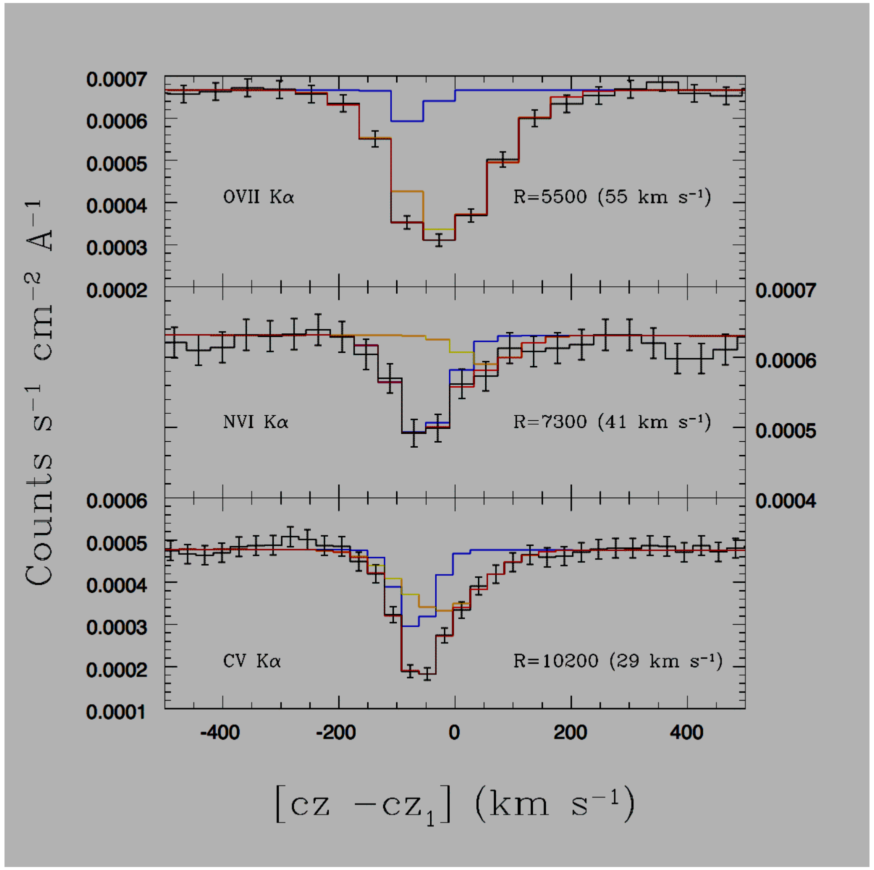


Needs R > 3000 at 12.4 A



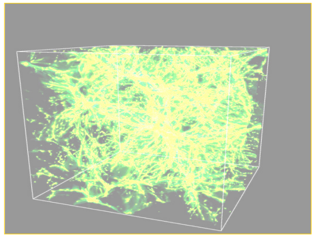
Multiphase WHIM

Δλ=4 mA

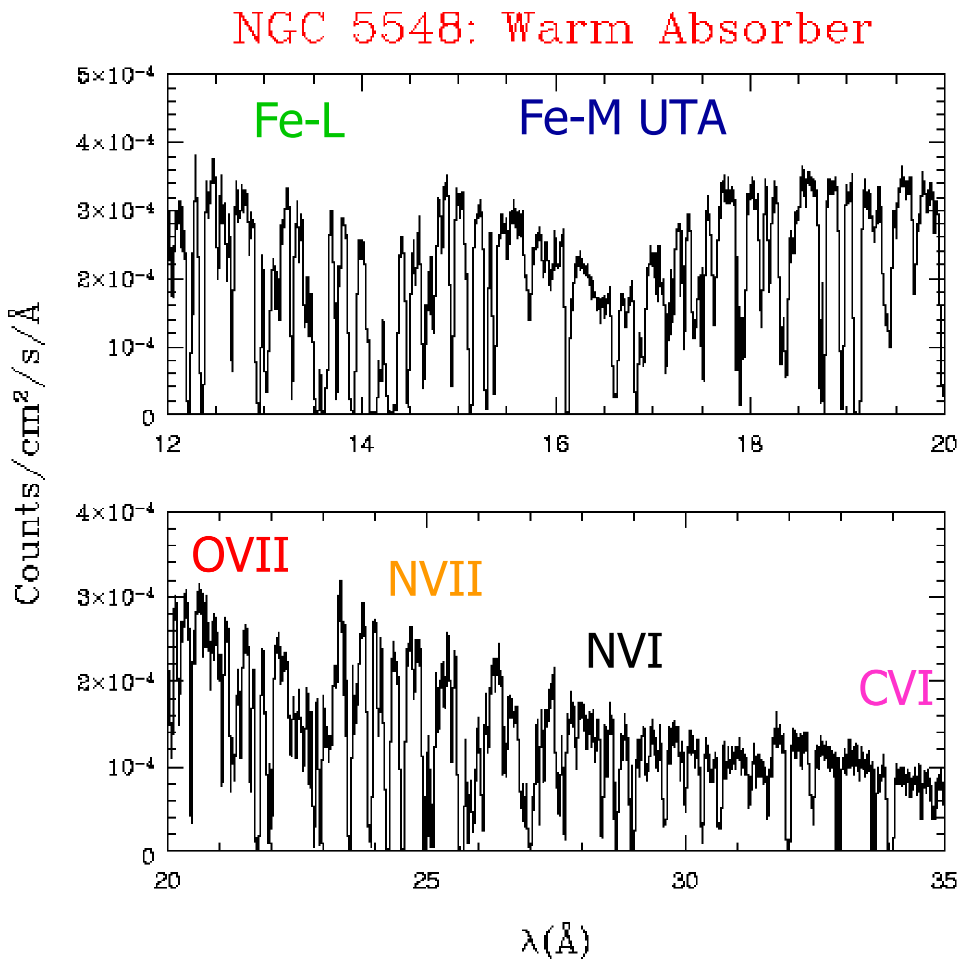


2 WHIM phase in pressure eq. Total extension 2.2 Mpc along the line of sight

Start to be resolved at R>3000 at 1 keV



AGN Warm Absorbers with *Pharos*



500 ks

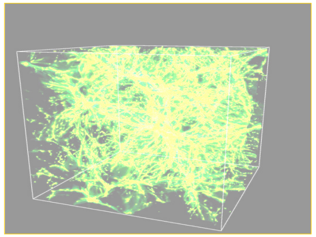
F_{2-10} = 1 mCrab

N_H = = $3x10^{20}$

Pharos: Summary

- GRB afterglows combine 4 themes of early *21st Century astrophysics*:
  - The **fate of the baryons** & large scale structure 1999
  - The **most energetic events** in the Universe 1997
  - Galaxies in the **age of star formation** 1997
  - The **recombination epoch** 2000

- Pharos, with $R>3000$ at $E<1$ keV, opens up all of these new areas of physics and astrophysics
- A small, short, soft X-ray telescope is enough
- *Rapid GRB trigger* & *autonomous slewing* essential, but straightforward
- Pharos is a natural MIDEX-class successor to Swift



Conclusions

- First WHIM Filaments Detected with Chandra-LETG (XMM data cannot confirm/rule-out: insufficient quality)
- Ω_b and dN/dz consistent with predictions and with total number/mass of missing baryons, although with large uncertainties
- *Chandra* can reduce the uncertainties down to ~ 30 % with ~ 1-2 Ms exp

- WHIM future studies rely on high-resolution spectrometers:
  - Gratings better than calorimeters for WHIM absorption studies
- R>=3000 @ E< 1 keV (50 km/s <==> O thermal velocity) enables:
  - Accurate Ion column density measurements for 80 % of H-like and He-like C, N, O and Ne ==> Ionization correction and relative metallicity ==> accurate Ω_b estimates
  - Accurate temperature estimates ==> measures of internal turbulence and local bulk motion for C, N and O
  - Minimizes of confusion due to overlapping lines from different systems
  - Starts resolving phases