The Warm-Hot Phase of the Intergalactic Medium

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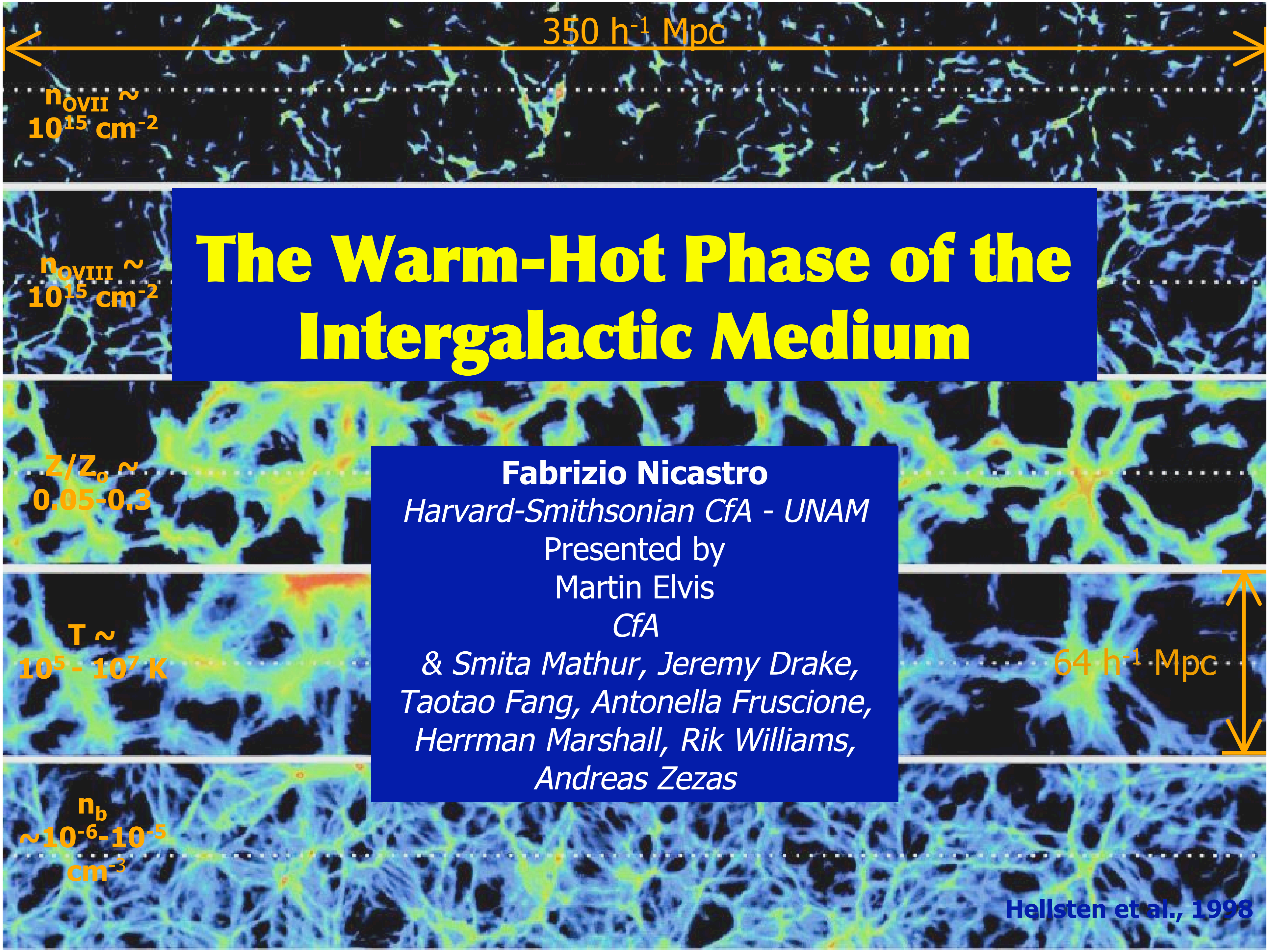


Why Should we Care?

54±9% of Baryons are missing!

- Find the 'Missing Baryons' and test theory
- Ecology of the Universe (Metal Pollution/Feedback)
  - Absolute and Relative Metallicities.
  - Galaxy Superwinds (SN) vs AGN winds, jets
  - Nucleosynthesis
- Cosmological parameters from density fluctuations of WHIM filaments (1-10 Mpc at z=0-2)
- Local Group WHIM is a biased measure

  ⇨Need z>0 WHIM absorbers to measure Ω_b

WHIM Filaments are Faint

Size: $\Delta R \sim 1$ Mpc

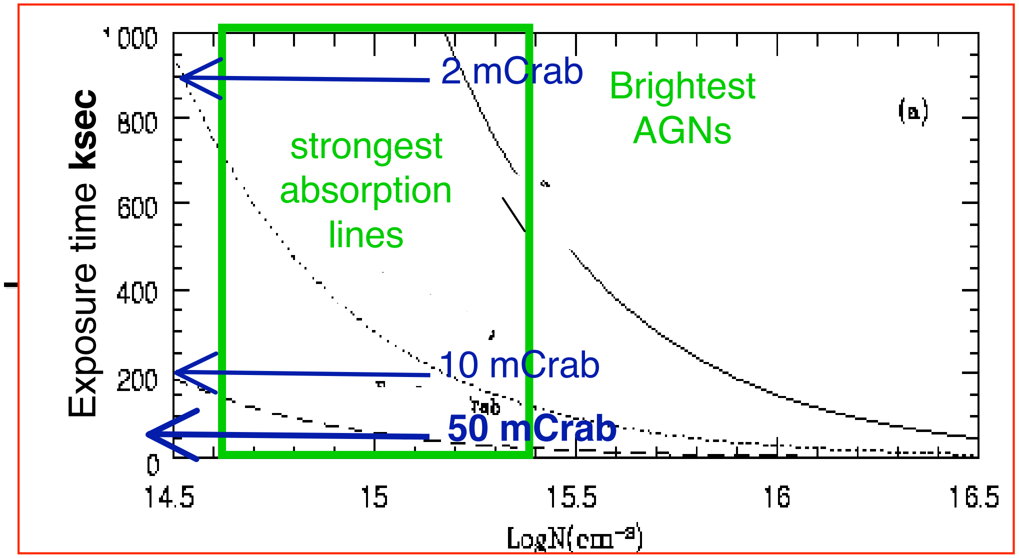
Density: $n_b \sim 10^{-6}$-10^{-5}cm^{-}

δ **~ 5 - 50**

Metallicity: $Z \sim 0.1\ Z_{\odot}$

Temperature: $T \sim 10^6$ K

➔ $\boldsymbol{f_{OVII} \sim 1}$



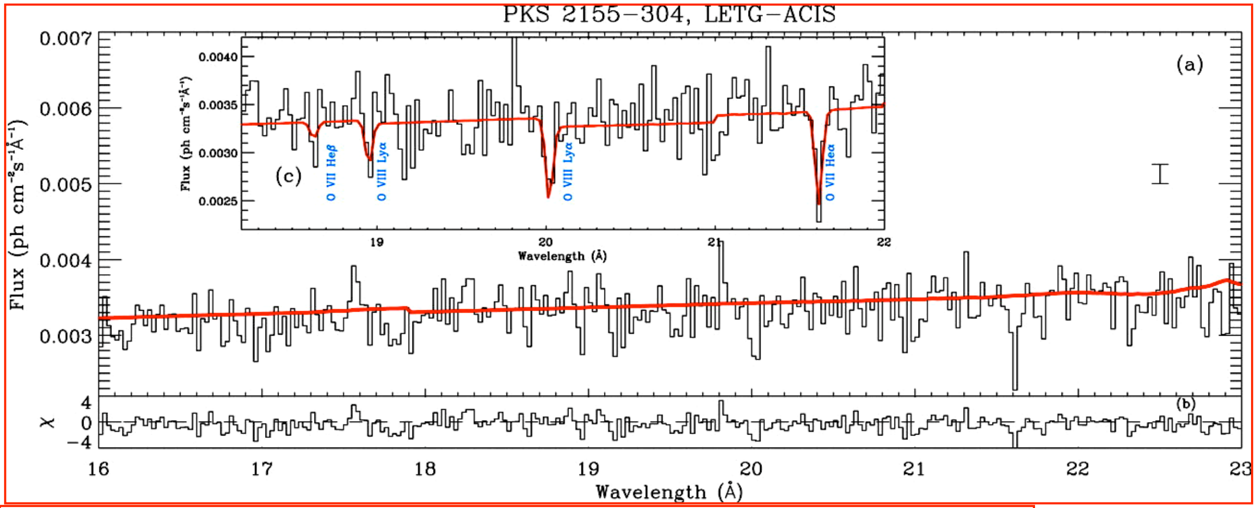
➔ OVII forest Column Density:

$\mathbf{N_{OVII}} \sim n_{OVII}\, Z_O\, \Delta R$

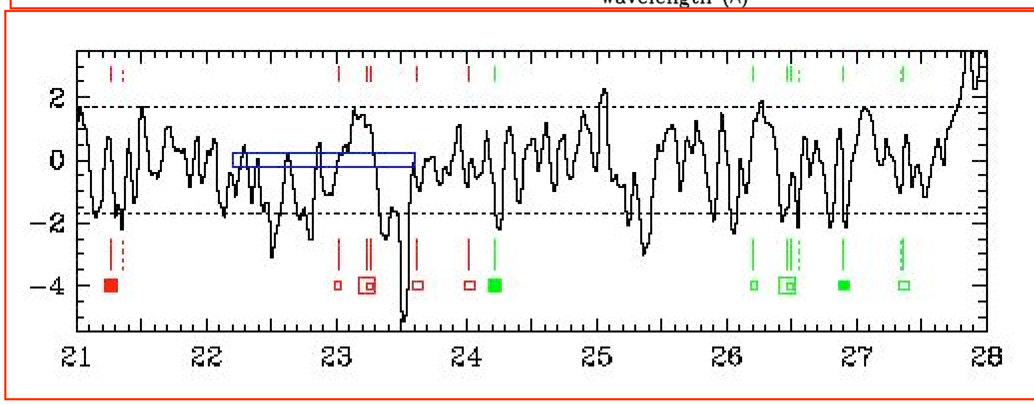
$\sim 2.6 \times (\mathbf{10^{14}}$**-**$\mathbf{10^{15}})\ \mathbf{cm^{-2}}$

$N_H \sim 3 \times (10^{18} - 10^{19})[O/H]_{0.1}^{-1}$

Studies with quiescent targets



PKS 2155-304 (z=0.116)
~ 200 CPRE*s
Fang et al., 2002



H 1821+643 (z=0.297)
500 ks ACIS-LETG
~ 50 CPRE*s
Mathur et al., 2003

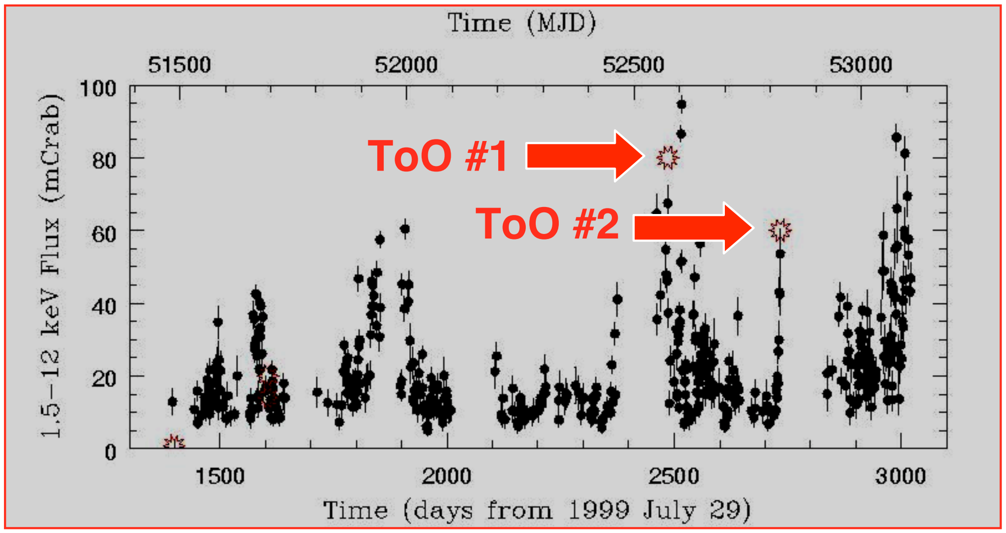
•6 QSOs with MEG: No abs. down to $N_{OVII} > 10^{16}$ cm^{-2} ➔ Z < 0.3 Z_O Fang et al., 2005

* CPRE = counts per resolution element

Our Strategy: Blazars in Outburst

Chandra Cycles 4-5-6 and Newton-XMM Cycles 2-3

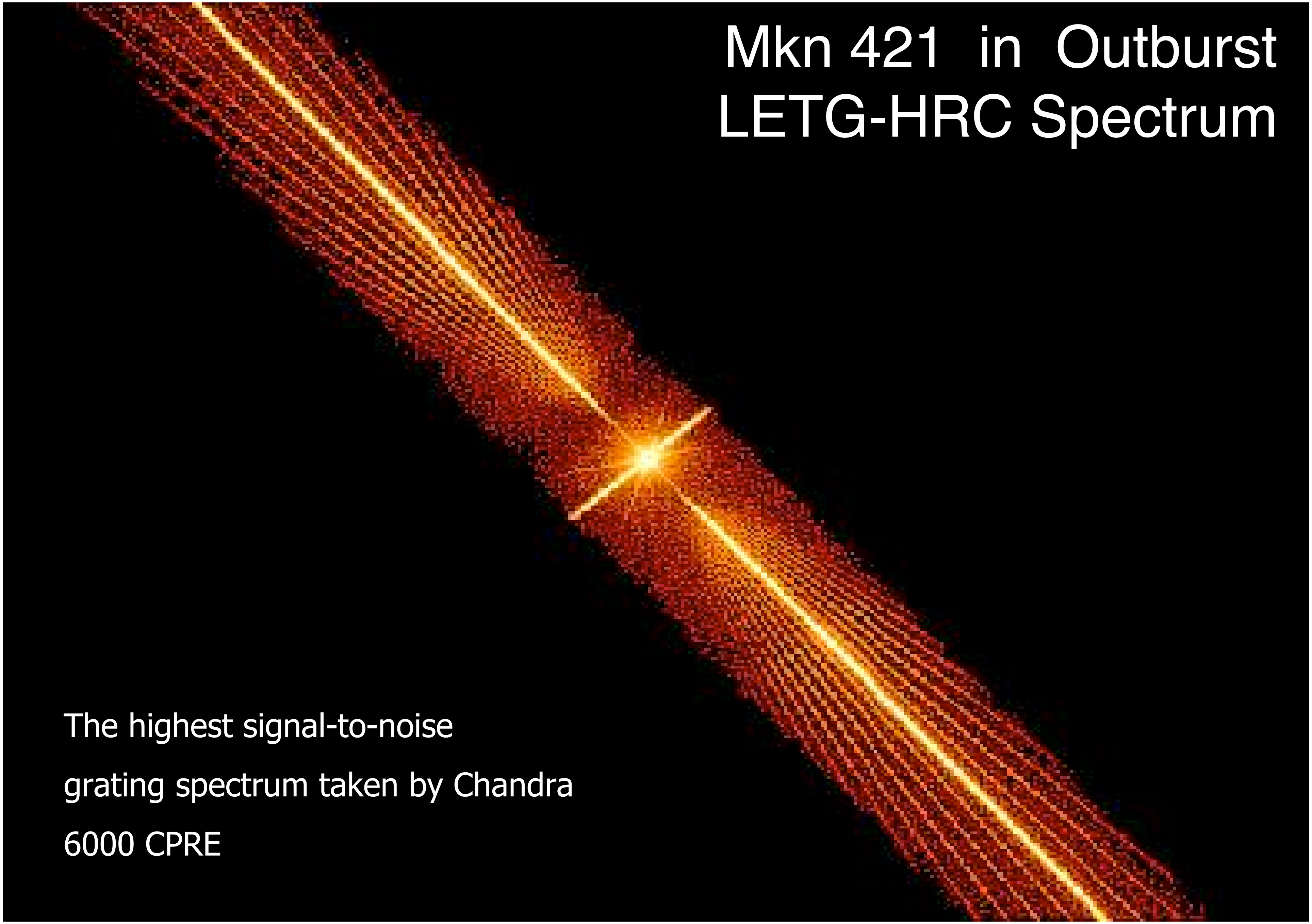
Mkn 421 (z=0.03)
RXTE ASM (0.5-12) keV light curve



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

✓1st ToO ***80mCrab*** 2002 October 27: 100 ks ACIS-LETG
✓2nd ToO ***60mCrab*** 2003 June 6: 100 ks HRC-LETG

Mkn 421 in Outburst
LETG-HRC Spectrum



The highest signal-to-noise

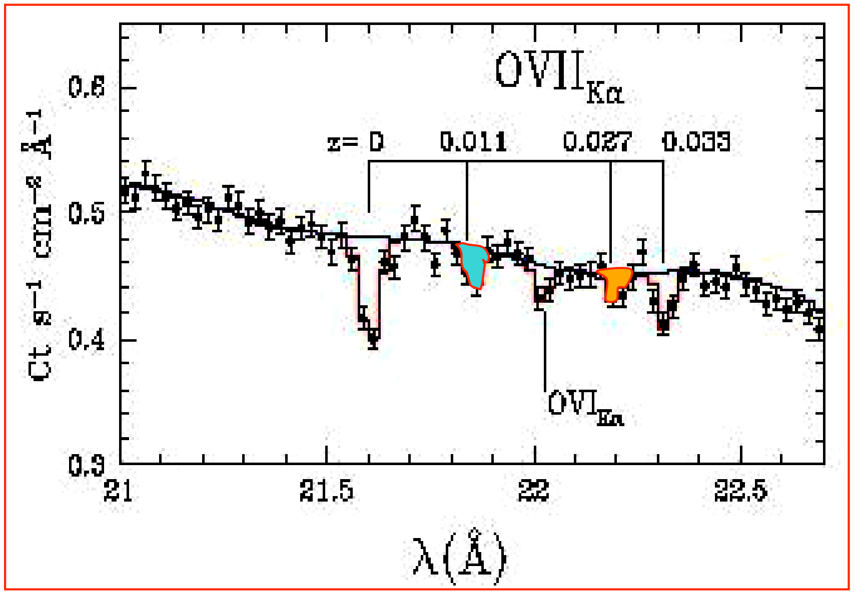
grating spectrum taken by Chandra

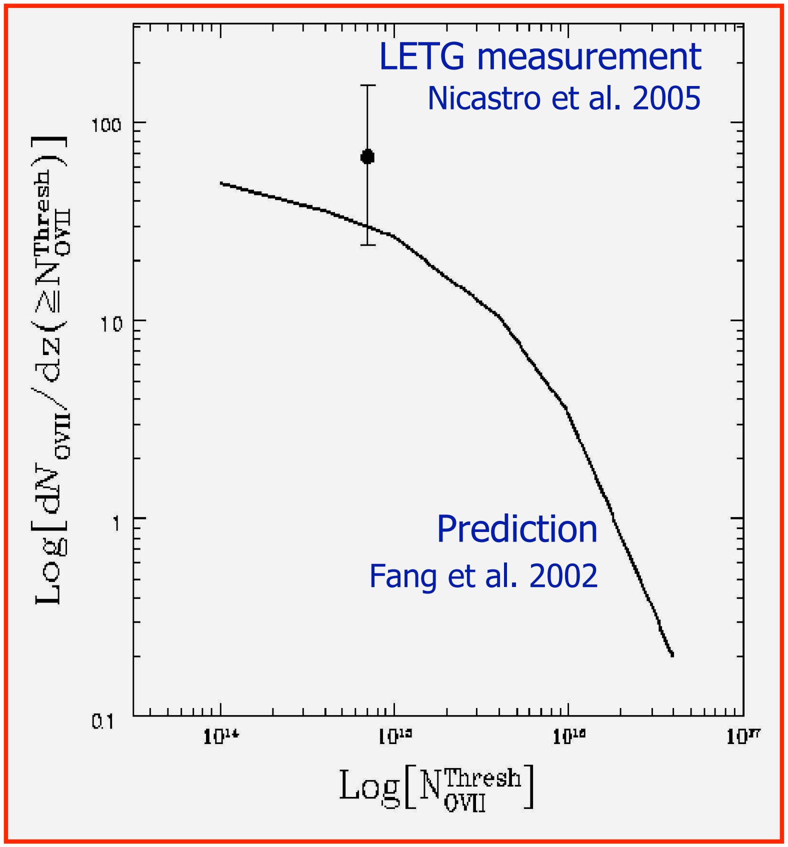
6000 CPRE

WHIM at z > 0: Mkn 421 (z=0.03)

Nicastro et al., 2005, *Nature* 433, 495

9 z>0 lines: 2 systems
z=0.011 (3.5σ), 0.027 (4.9σ)

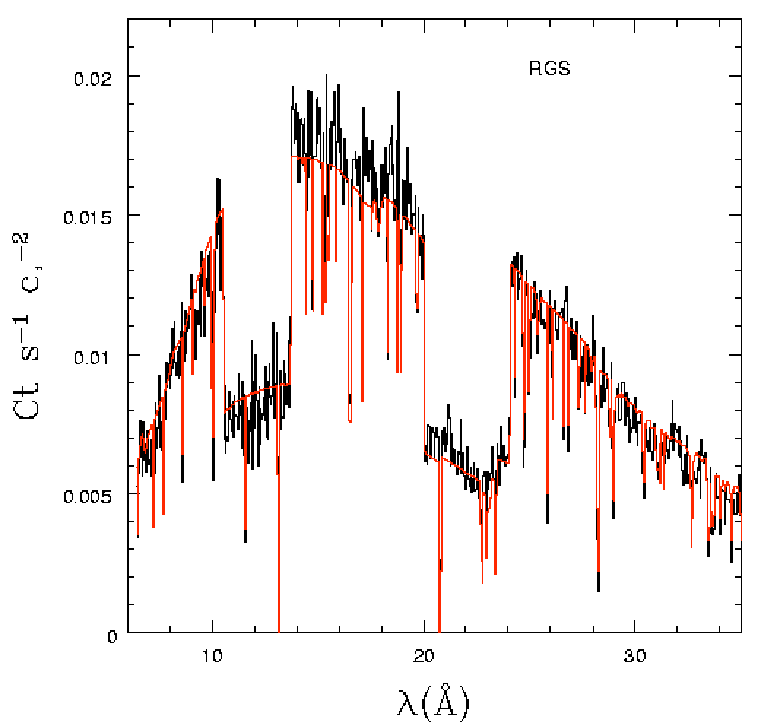




1ES 1028+511: RGS

higher redshift z=0.361

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



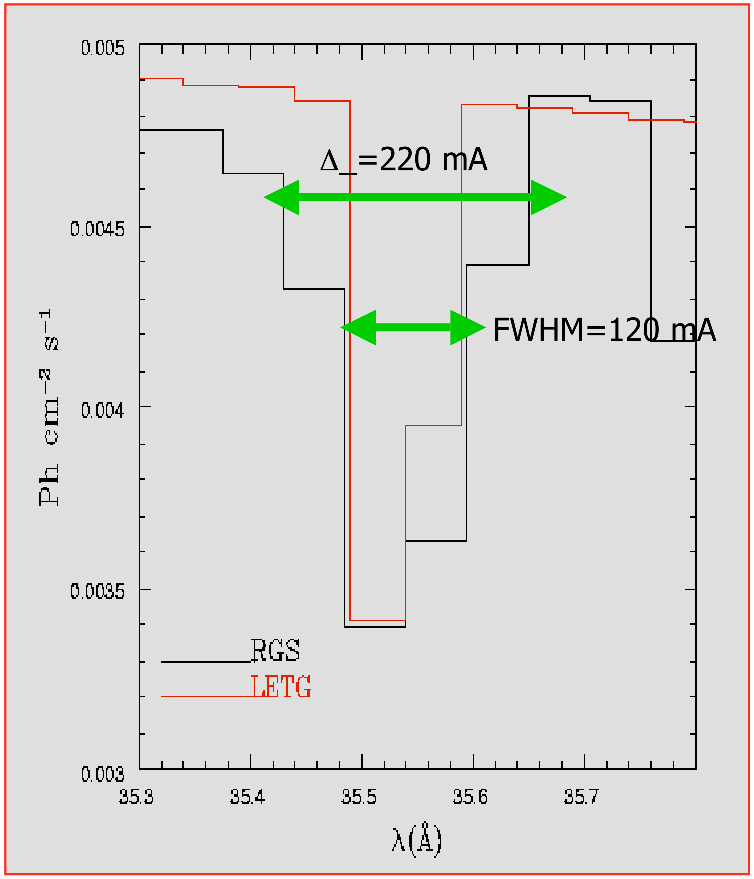
18 % of RGS Δz(OVII) is blocked
Left-right contiguous resolution elements add up to ~ 60 % RGS blocking factor

CPRE(20-24;30-36)=45; CPRE(24-30)=75

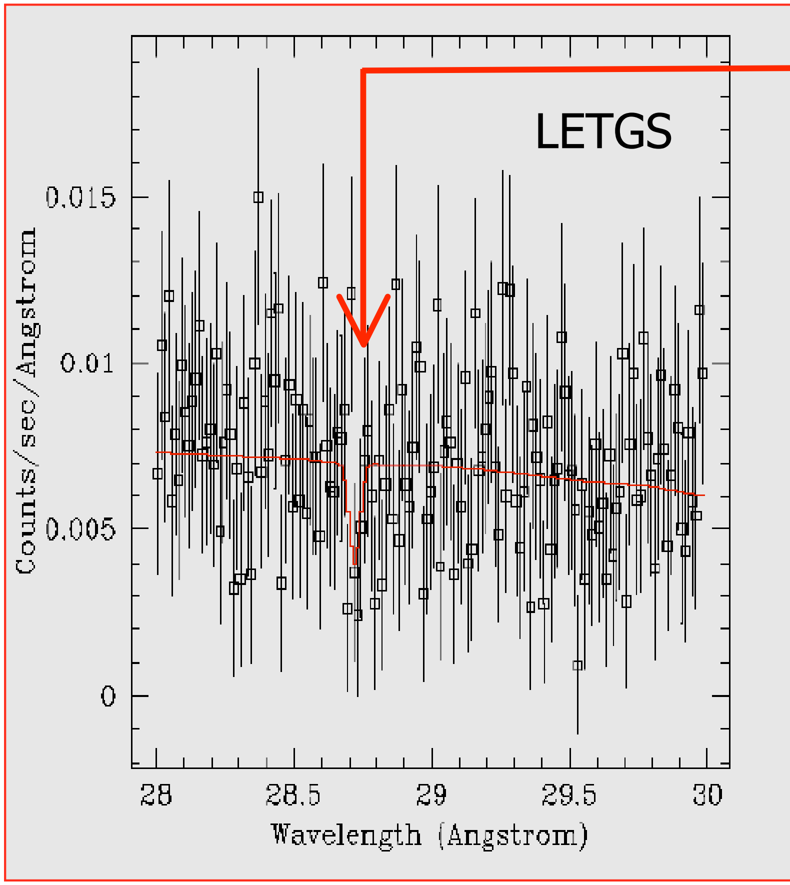
LETG & RGS Resolutions

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

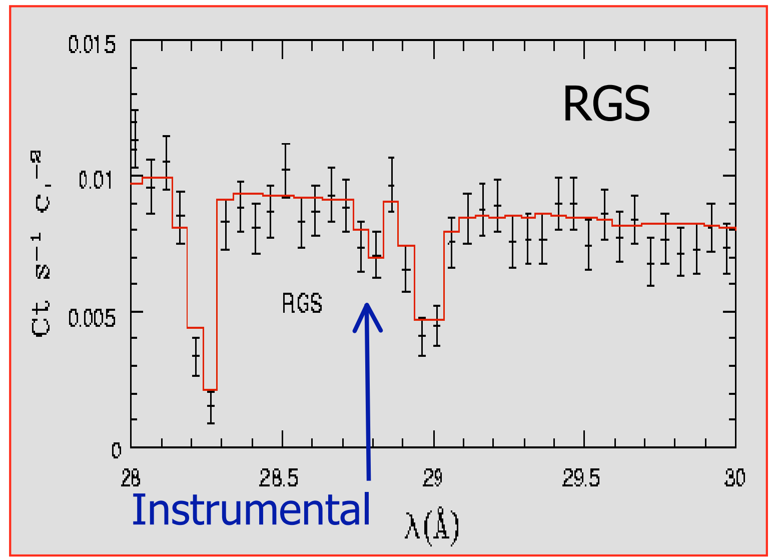
R_{wings}(RGS) ~ 2 R_{wings}(LETG) = 110 mA



1ES 1028+511 Chandra: OVII ?



$OVII_{K\alpha}(z=0.330)$ **?**
EW=32±13mA
$N_{OVII}=(6.3\pm2.6)\times10^{15}\ cm^{-2}$

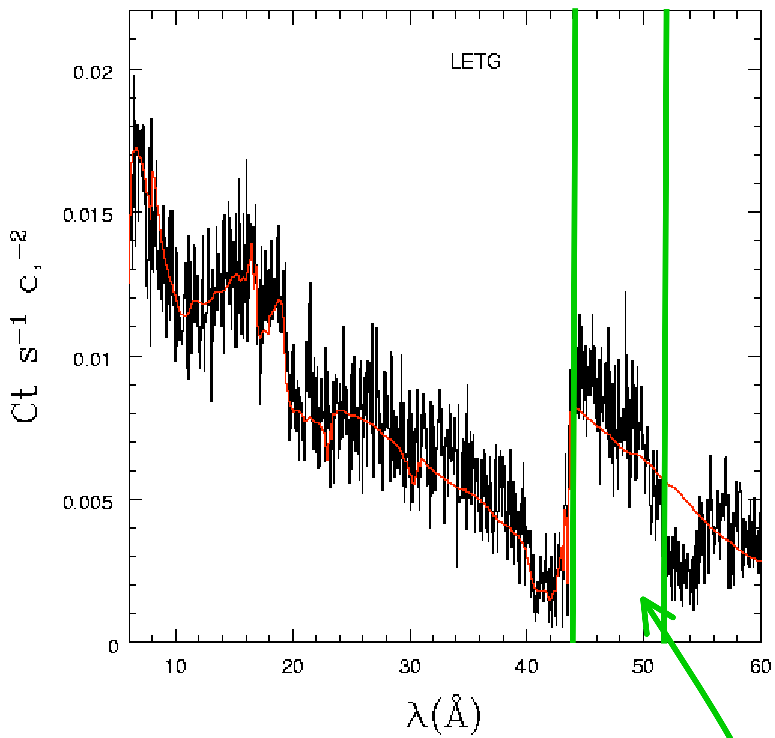


1ES 1028+511 in Outburst: CV

$z=0.361$

Chandra-LETG: 149 ks

$F_{0.3\text{-}2}$ = 0.8 mCrab



Sensitive to CV-Forest:

λ ~ 44-52 A ➔ Δz=0.2

CPRE(20-30;44-52)=60

Advantage of long-wavelength coverage

$$N^{Thres}_{He-like} \approx 1.1\times10^{18}\left(\frac{N_\sigma}{3}\right)\left(\frac{\Delta\lambda(\text{m}\mathring{A})}{50}\right)\sqrt{\frac{500}{CPRE}}\,\lambda^{-2}$$

➔threshold

$N_{CV}/N_{OVII} \sim 3.5$

$$N^{2\sigma}_{OVII} > (5.0-9.3)\times10^{15}\ \text{cm}^{-2}$$
$$N^{2\sigma}_{CV} > (1.6-2.9)\times10^{15}\ \text{cm}^{-2}$$

1ES 1028+511: CV Forest

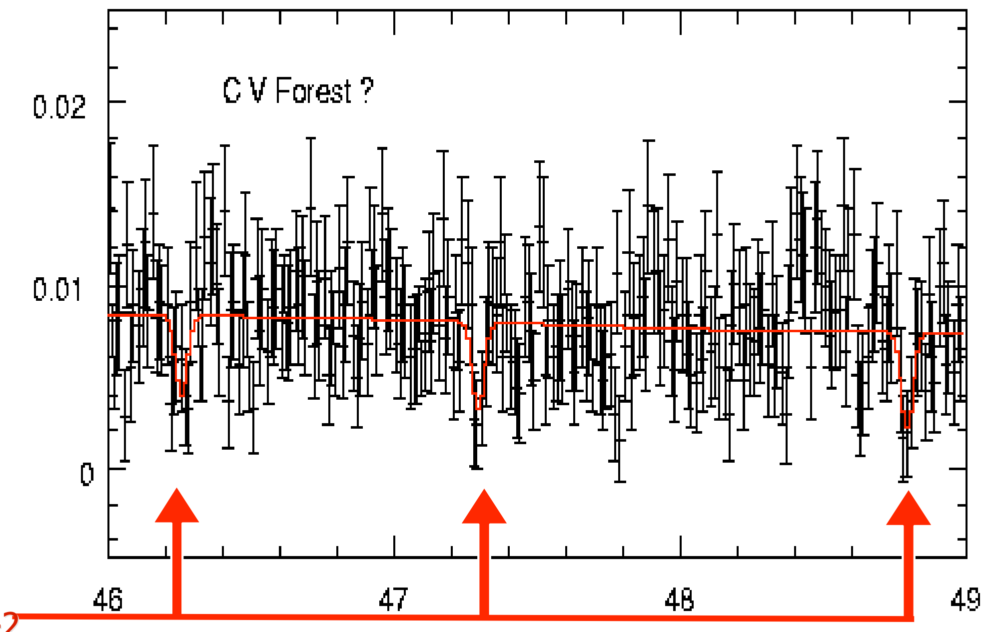
- $N_{OVII}^{Exp}(z_{CVI})=N_{CV}^{obs}\ 10^{[O/C]}\ f_{OVII}/f_{CV}$
- f_{CV} peaks at logT = 5.3 in coll. eq. and $f_{OVII}/f_{CV}(\log T=5.3)$ = 0.04/0.84=1/21

Assuming Solar [O/C] ➔

$N_{OVII}(z=0.149, 0.175, 0.212)$

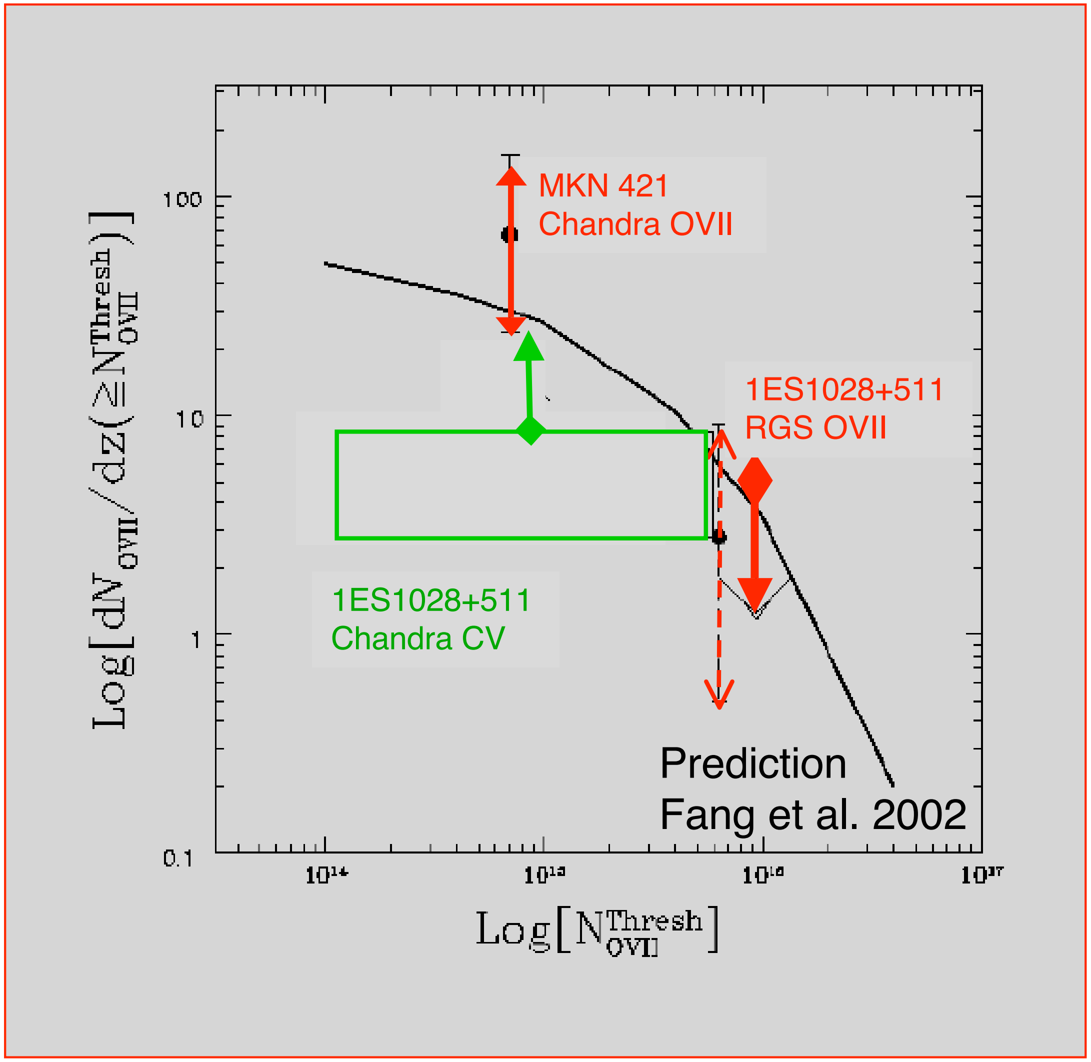
$= (2.9, 3.1, 3.5)\ \times 10^{14}\ cm^{-2}$

$\leq 1/18\ N_{OVII}^{2-}$



➔ Consistent with no OVII detections for logT=(5.0-5.7)

Number Density of OVII WHIM



$\Omega_b (N_{OVII}, > 7\text{x}10^{14}\ \text{cm}^{-2})$

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

- Mkn421 (2 Filaments.): z=0.03

$$\Omega_b(N_{OVII} > 7*10^{14}) = \left(\frac{1}{\rho_c}\right)\left(\frac{\mu m_p \sum_i N_H^i}{d_{Mkn421}}\right) = \mathbf{2.7}^{+3.8}_{-1.9} * 10^{-[O/H]_{-1}} \%$$

- Mkn421 + 1ES1028+511 (3 Filaments):

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

Consistent with $\Omega_{\text{missing}} = 2.5 \pm 0.4\ \%$

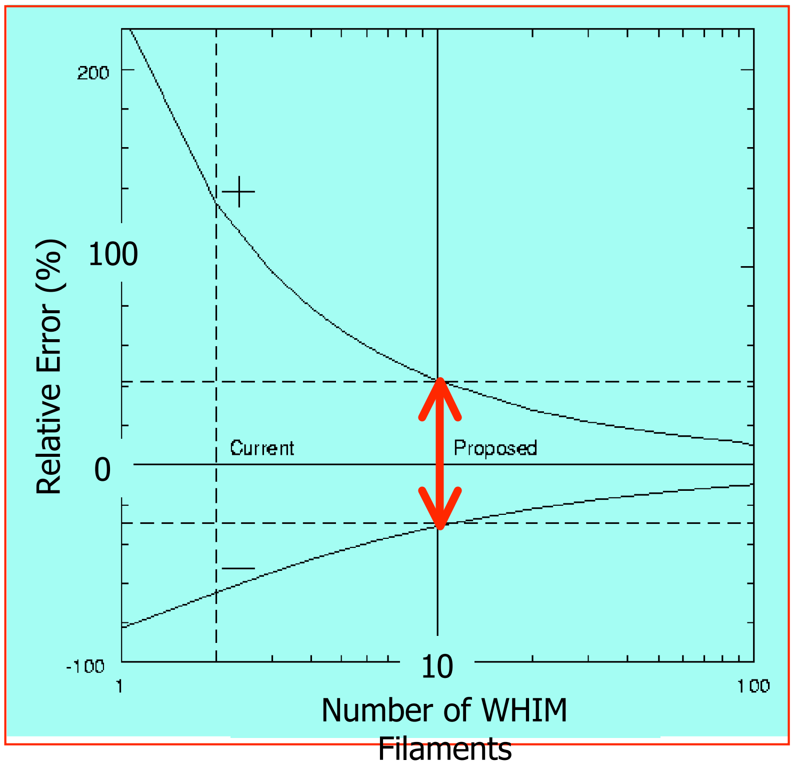
WHIM at z>0 to date

- 3 OVII + 3 CV detections (2 lines of sight)
- Consistent* with:
  - dN/dz predictions ~10 x OVI dN/dz
  - number of missing baryons Ω_b~2.5%

  * within large uncertainties due to the low statistics

Short-Term Prospects

•GOAL: ***Reduce Ω_b and dN/dz uncertainties to ~35%***
(same as other baryonic components in the Universe)
from current (+140,-70)%



TOOs: key strategy to *detect* the WHIM
But...Mkn 421 is unique
Long integrations on previously identified ***high-z*** sightlines are more promising

Long-Term Prospects

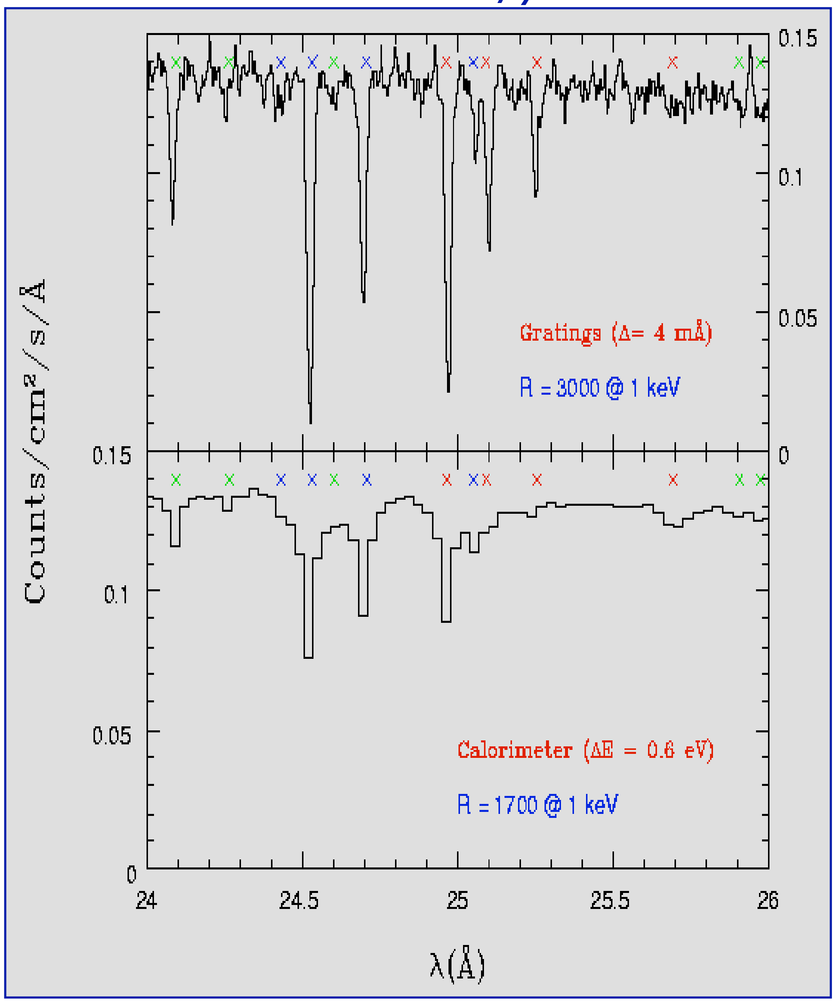
- Long Term: map the WHIM up to z=1-2
  - needs high X-ray throughput and spectral resolution
- ➔ Hundreds to Thousands of Systems:
  - Metallicity History (Ecology of the Universe)
  - IGM/galaxy/AGN Feedback
  - Heating History of the Universe (dT/dz)
  - Dark-Matter Maps
  - Cosmological Parameters (density fluctuations)
- Constellation-X *R* > 2.5 x LETG, A = 50 x LETG
- XEUS *R* ~ 2.5 x LETG, A = 750 x LETG
- *Pharos MIDEX* ***R* ~ 10 x LETG**, A = 10 x LETG
  - *Fast* (~1 min) targeting of GRB afterglows: Crab strength sources
  - no >1keV response: small mirror, mission

The WHIM at *R*~3000 with Pharos

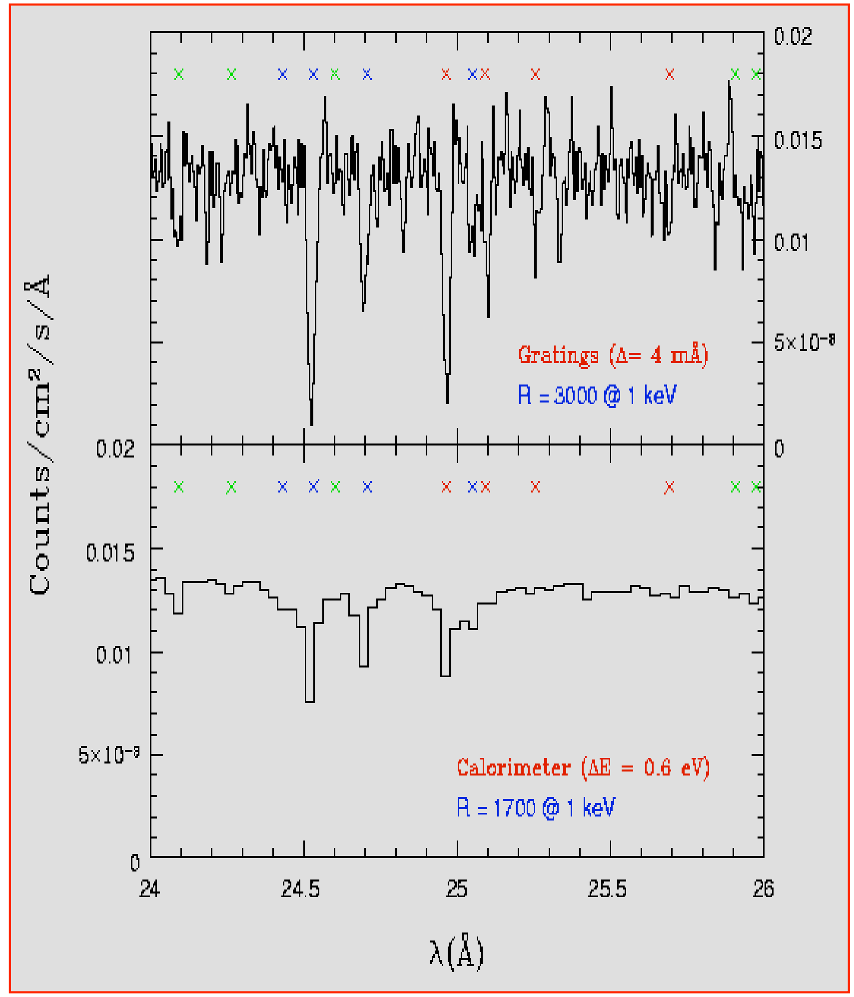
- **Weaker lines**
  - multiple ions - *b* parameter
    - ⇨ Ionization Temperature
  - more elements: Relative abundances
    - ⇨Type 1 vs Type 2 SN enrichment
- **Resolve line widths:** *more physics*
  - Turbulent/infall velocities
  - Thermal Temperature
    - ⇨In equilibrium? Heating mechanism

The WHIM with Pharos

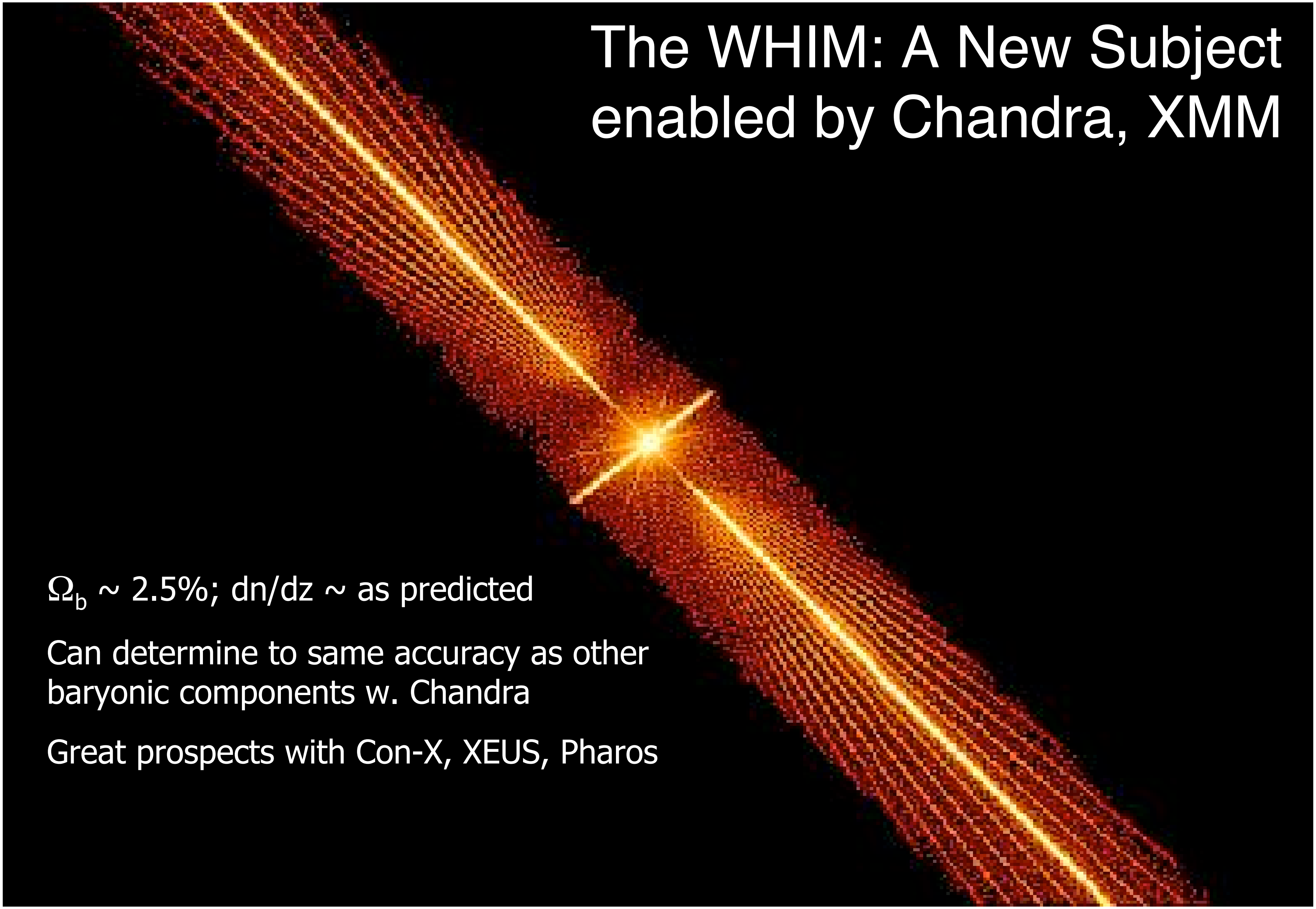
Fluence(2-10 keV) = 10^{-5} ergs cm^{-2}
~ 10 GRBs/year



Fluence(2-10 keV) = 10^{-6} ergs cm^{-2}
~ 100 GRBs/year



The WHIM: A New Subject enabled by Chandra, XMM



Ω_b ~ 2.5%; dn/dz ~ as predicted

Can determine to same accuracy as other baryonic components w. Chandra

Great prospects with Con-X, XEUS, Pharos