The search for the missing baryons

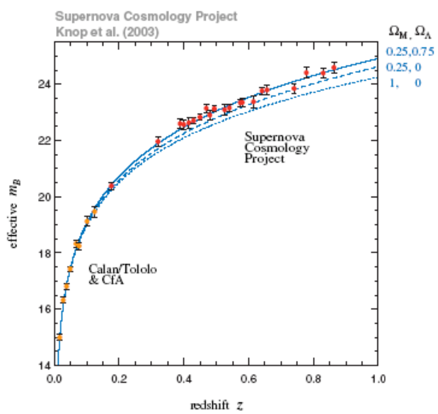
The answer,
my friend,
is blowing
in the WHIM*

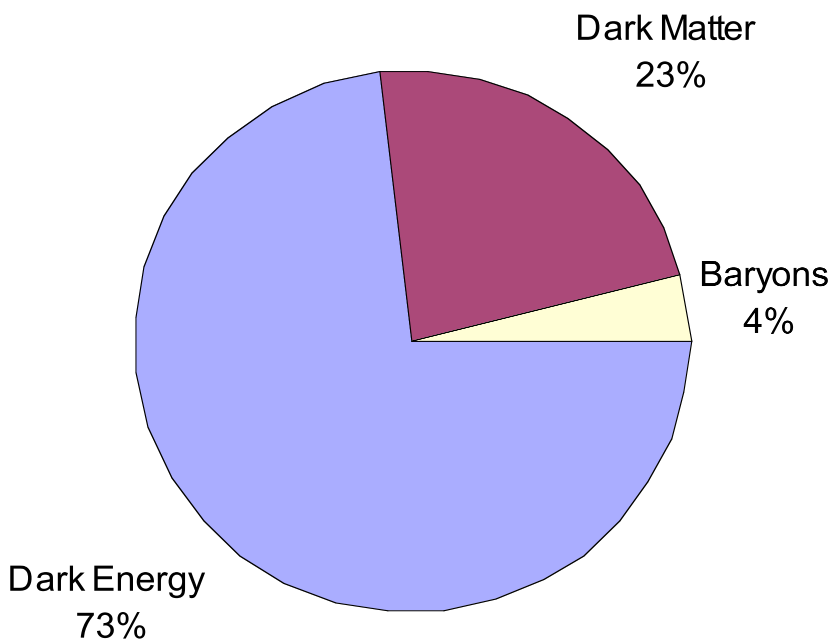
* Warm and Hot Intergalactic Medium

Theoretical ground

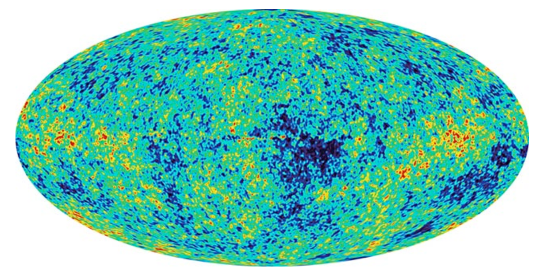
What is the Universe made of?

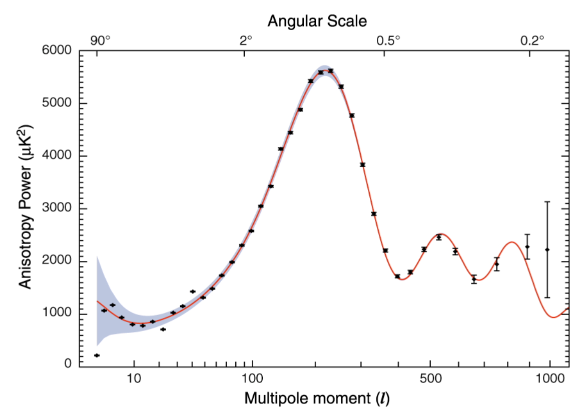
Supernovae Ia



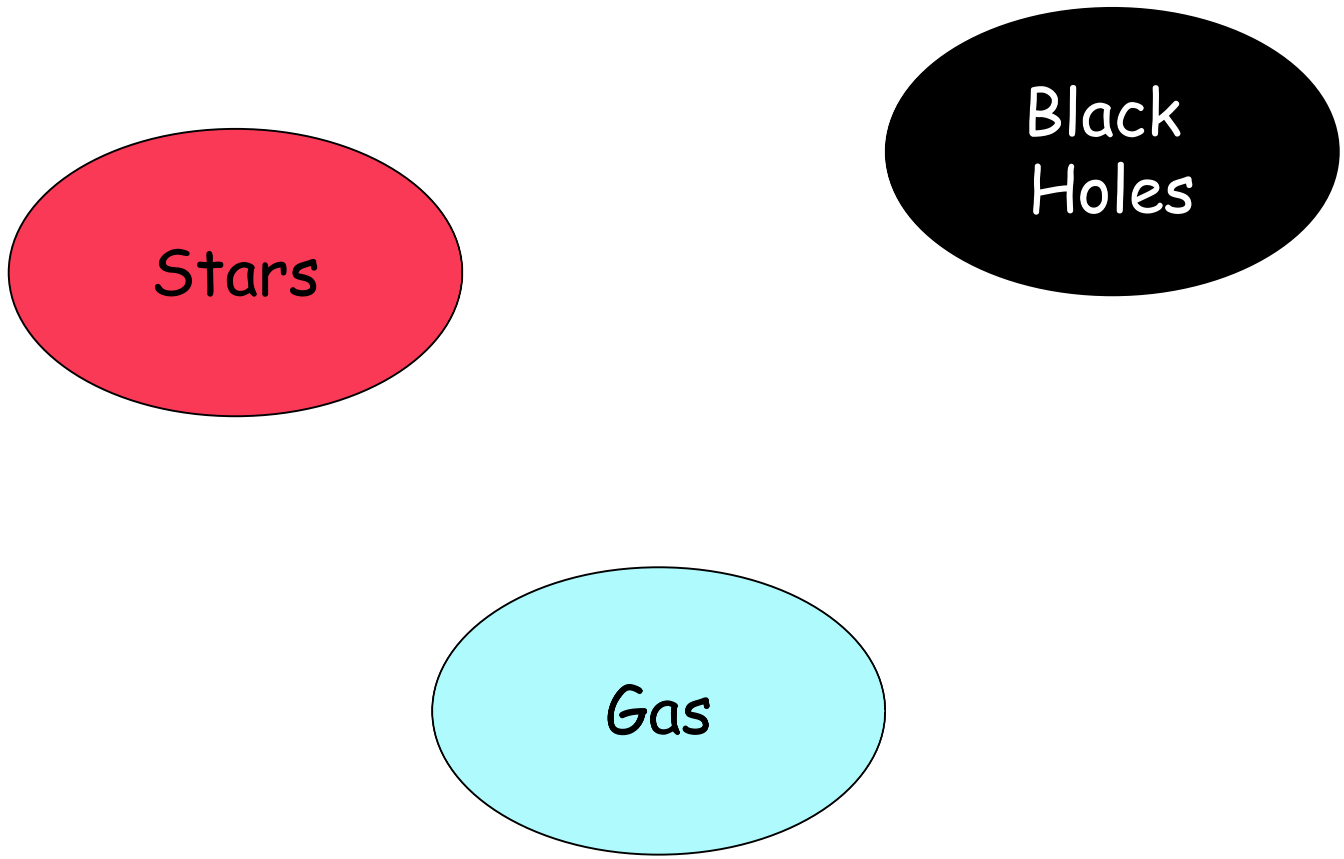


CMB anisotropies

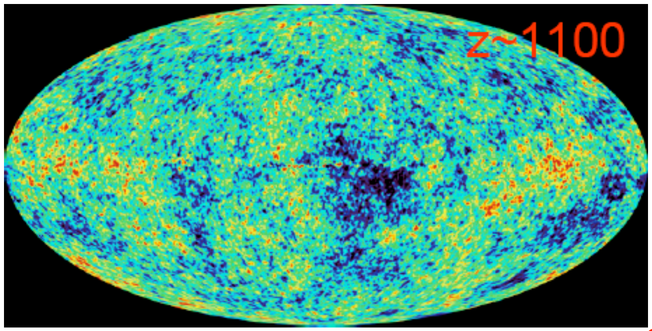




The baryon content of the Universe



From the "dark" to the observable Universe



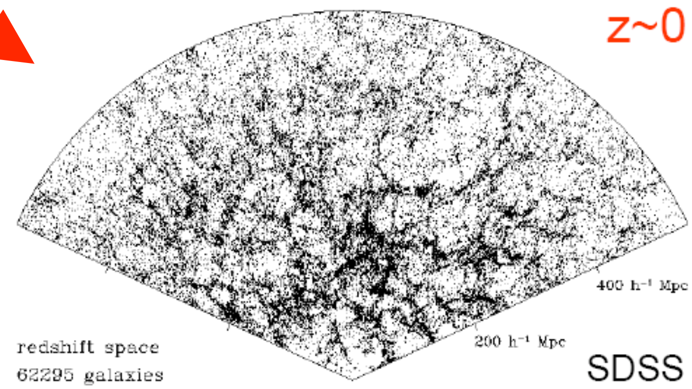
Initial conditions (density fluctuations):
- Given by the Cosmological model (Dark Matter, Dark Energy)
- Measured by CMB experiments

Dark energy: 73%
Dark matter: 23%
Baryons: 4% (1/2 missing)

?

Highly structured "baryonic" Universe:

Groups and clusters of galaxies
Filaments
Voids



The missing baryons

- Big-bang nucleosynthesis + CMB predict $\Omega_b=(4.6\pm0.4)\%$.
  - At z>2, most baryons reside in the Damped-Lyman α population, and Lyman α clouds
  - At z<2, there are very few Lyman α absorbers, and galaxies & clusters only account for $(2.5\pm0.3)\%$. Almost 50% of the baryons are missing at low z.

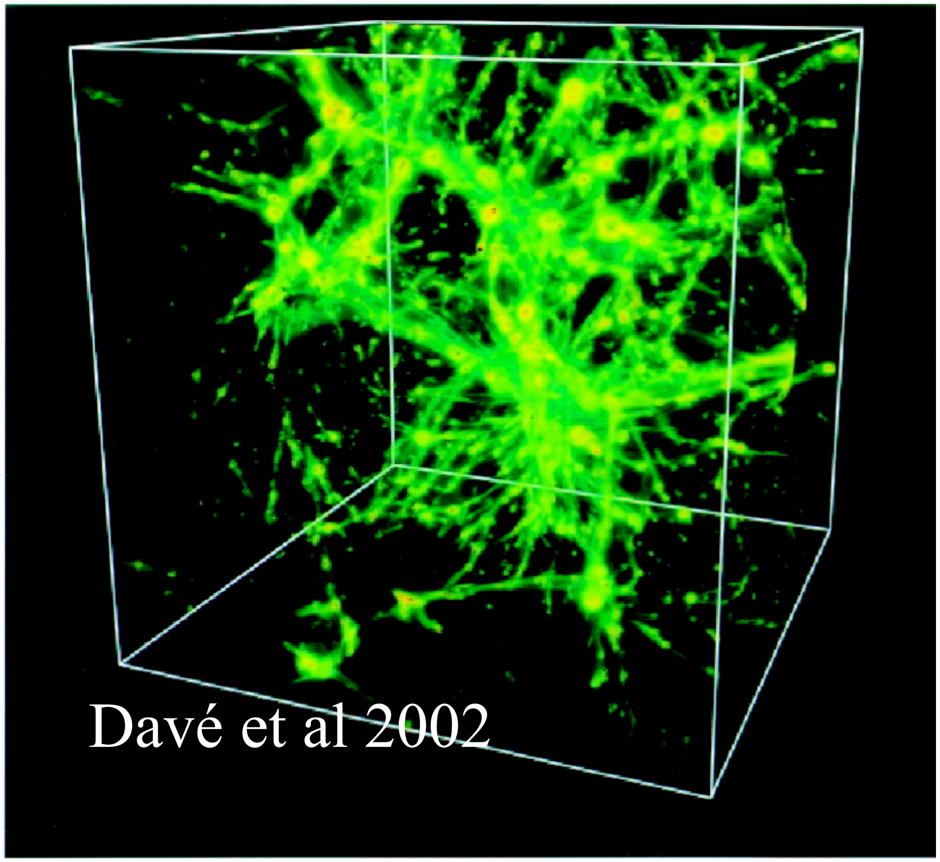
Table 1 **Census of baryons in the high-and low-redshift Universe**

Inferred from	Ω_b (%) for $h_{70}=1$
BBN + D/H*	(4.4 ± 0.4)
CMB anisotropy	(4.6 ± 0.2)
Observed at $z > 2$ in†	
Lyman-α forest	>3.5
Observed at $z < 2$ in‡	
Stars	(0.26 ± 0.08)
H I + He I + H_2	(0.080 ± 0.016)
X-ray gas in clusters	(0.21 ± 0.06)
Lyman-α forest	(1.34 ± 0.23)
Warm + warm–hot O VI	$(0.6^{+0.4}_{-0.3})$
Total (at $z < 2$)§	$(2.5^{+0.5}_{-0.4})$
Missing baryons (at $z < 2$)§	$(2.1^{+0.5}_{-0.4})$

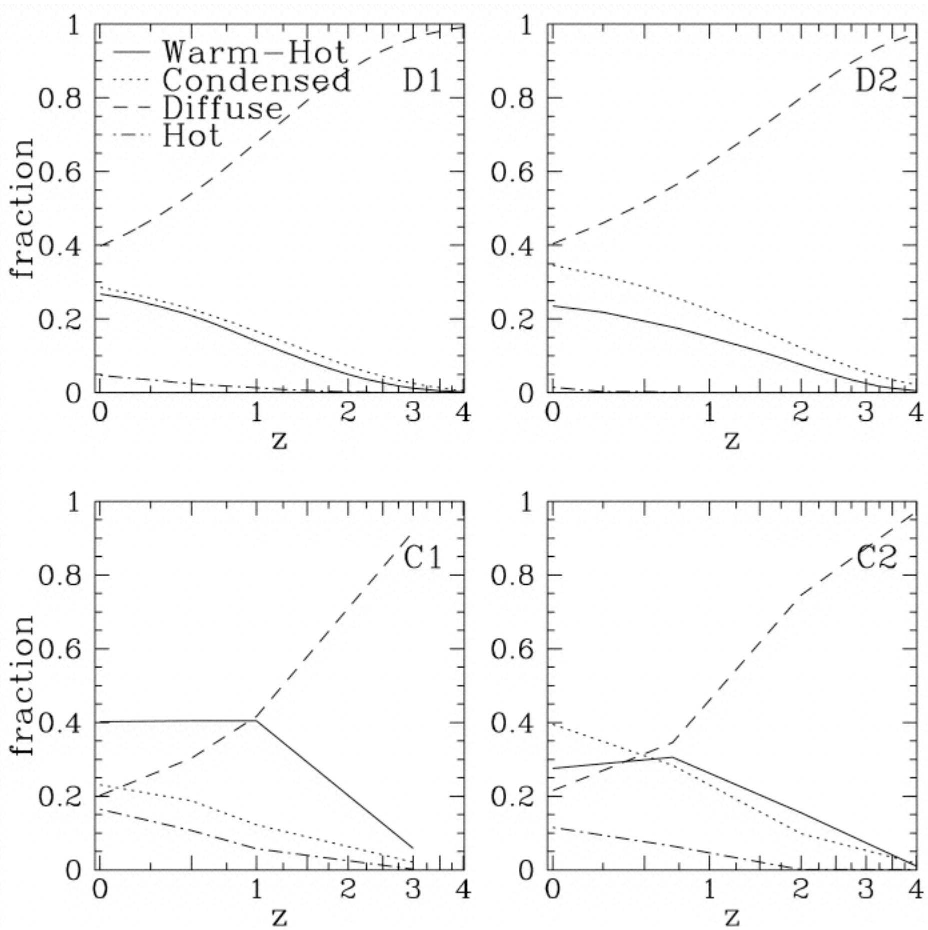
Nicastro et al 2005

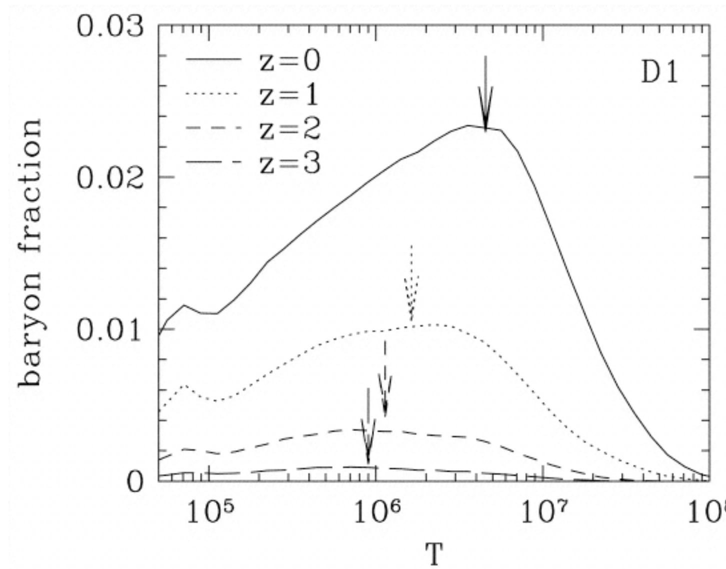
The Warm & Hot IGM

- Large fraction of baryons at T~10^5-10^7 K
- IGM hotter towards low redshift (baryons falling onto potential wells)
- Extra heating might be present due to star formation & AGNs



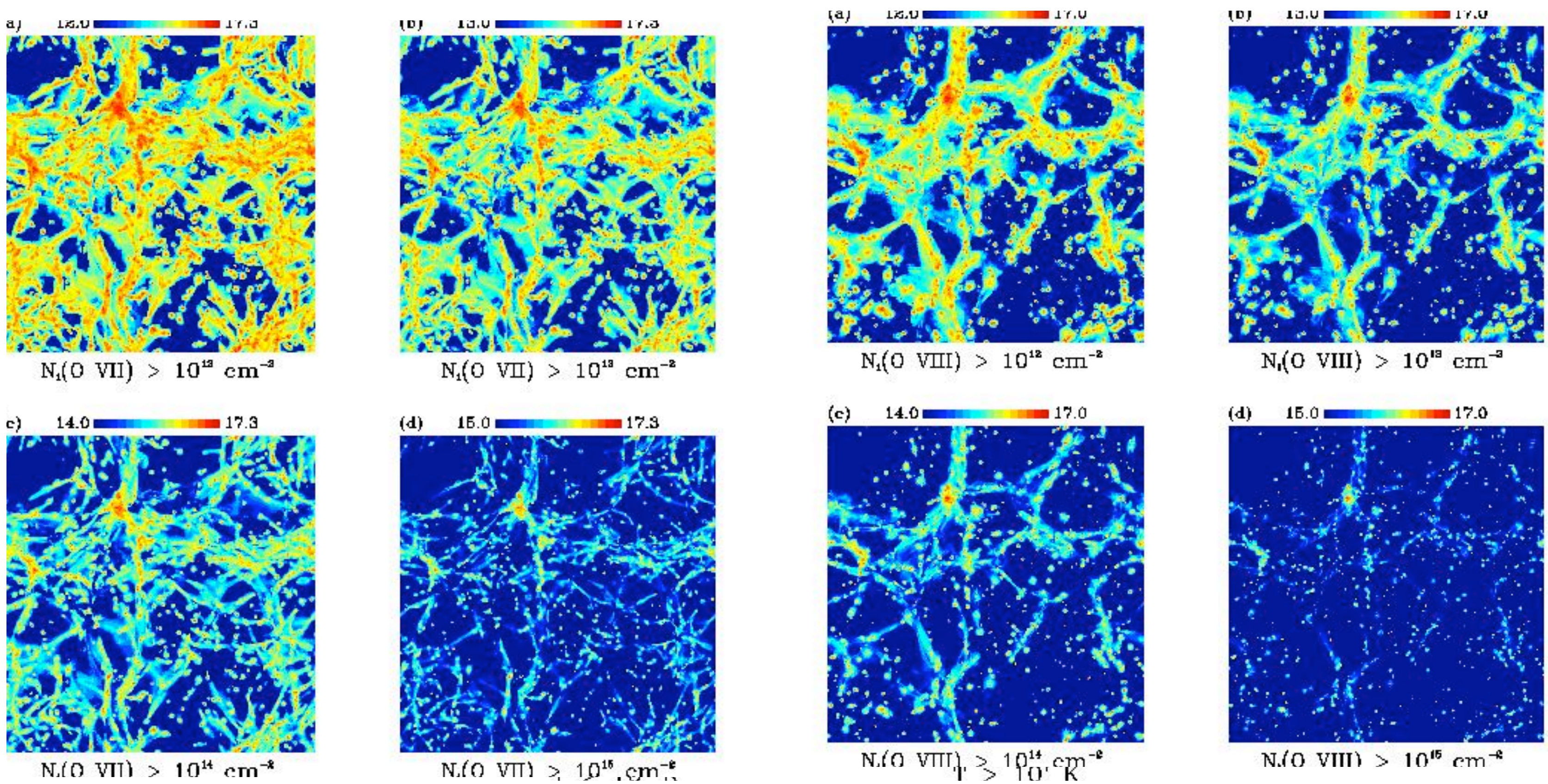
Thermal history of WHIM



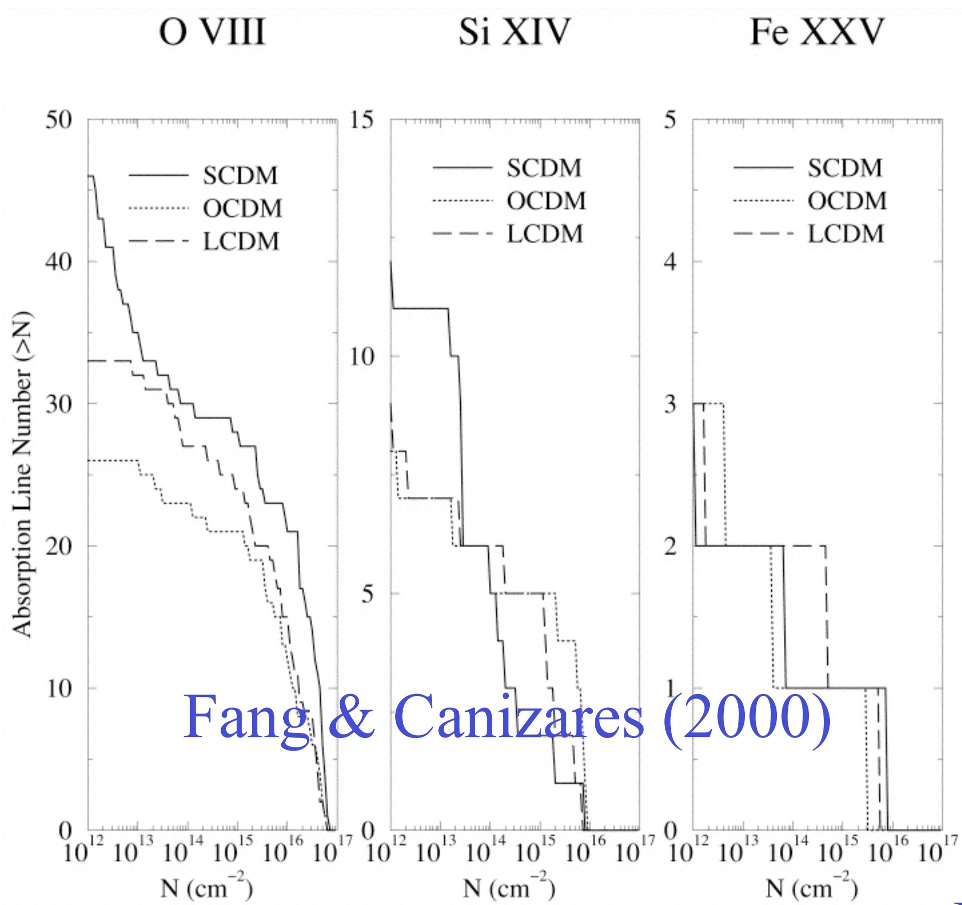


Davé et al (2001)

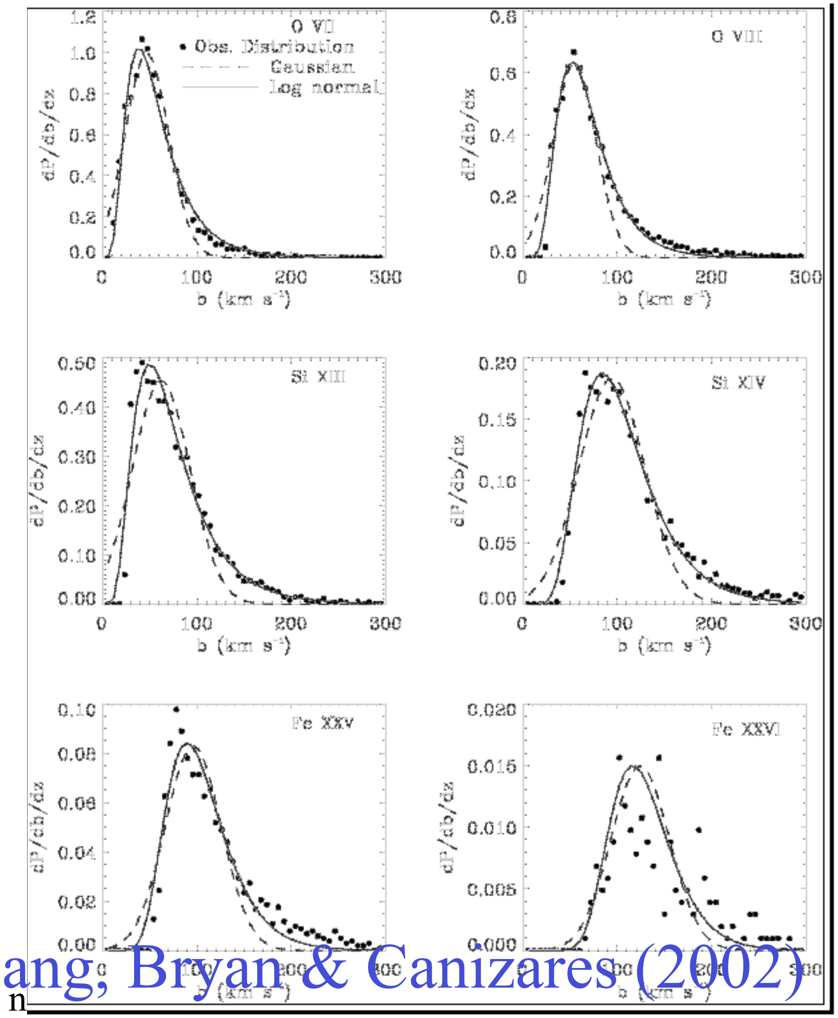
T and ion column density
(Fang, Bryan & Canizares 2002)



The distribution of absorbers



Fang & Canizares (2000)



Fang, Bryan & Canizares (2002)

Detecting the WHIM in absorption

How to detect the WHIM?

- In emission:
  - Tenuous and extended
  - Need to fight the background
  - Large sky area coverage
- In absorption:
  - Needs a bright background source
  - Detection only along specific lines of sight

Absorption versus emission

Different parameters sampled:

Hot gas emissivity $L \propto n_{gas}^2 R^3$
Absorption equivalent width $EW \propto n_{gas} R$

Different dimming effect:

$L \propto d_L(z)^{-2}$
$EW \propto (1+z)$

Absorption requires a bright background source behind.

Little cosmological dimming effect!!!

Sensitivity: equivalent width detection limit

Rule of thumb:

For a S/N>10 spectrum, sampled to ~ 2-3 channels per resolution element, narrow absorption lines can be detected with an equivalent width as small as a fraction of a channel width.

Need for:
- Large collecting area
- High spectral resolution

High-dispersion spectroscopy

XMM-Newton (RGS):

- Effective area @ 20 Ang: 100 cm^2
- Angular resolution: 15'' HEW
- Spectral resolution @ 20 Ang(1st order): 280

Higher S/N

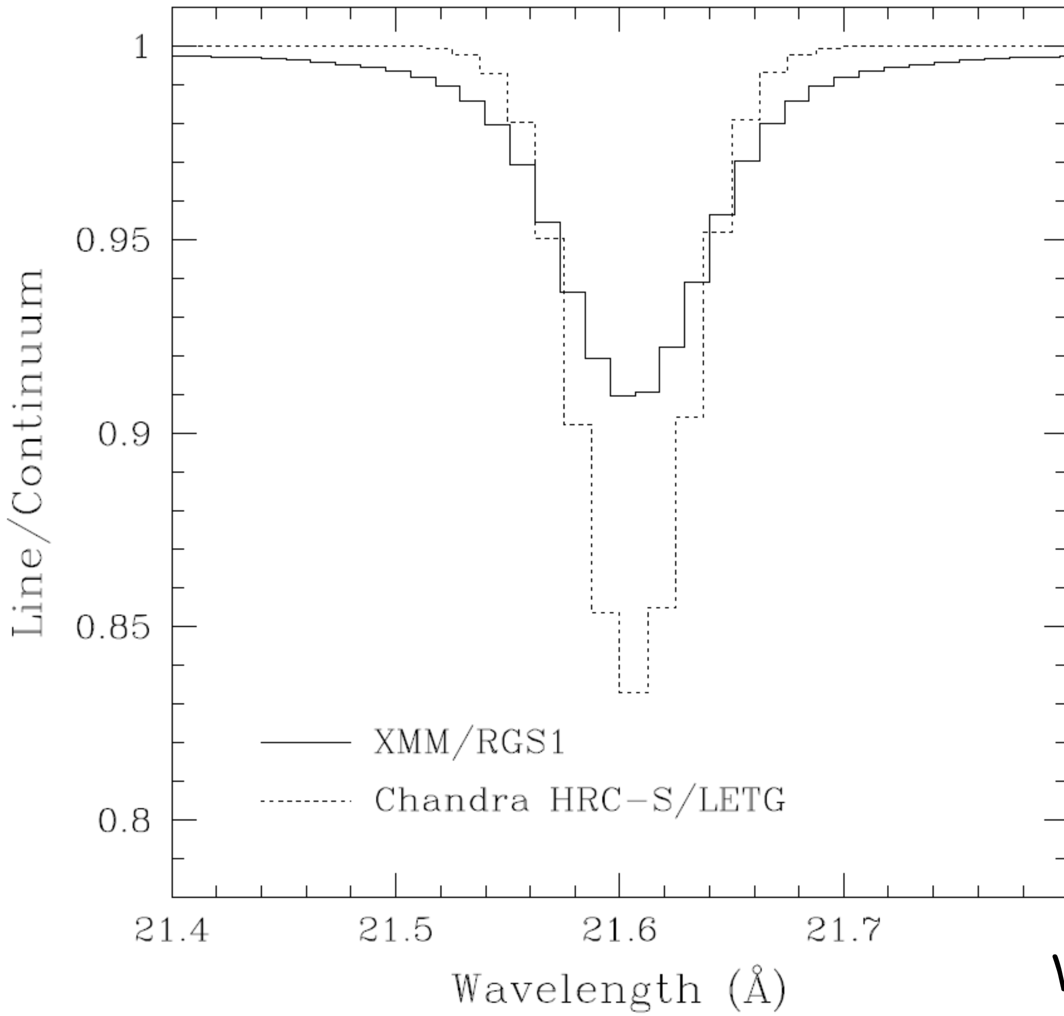
on: the

Chandra:

- Effective area @ 20 Ang: 20 cm^2
- Angular resolution: 0.5'' HEW
- Spectral resolution @ 20 Ang (1st order): 300

(Higher) spectral resolution

Spectral resolution matters!



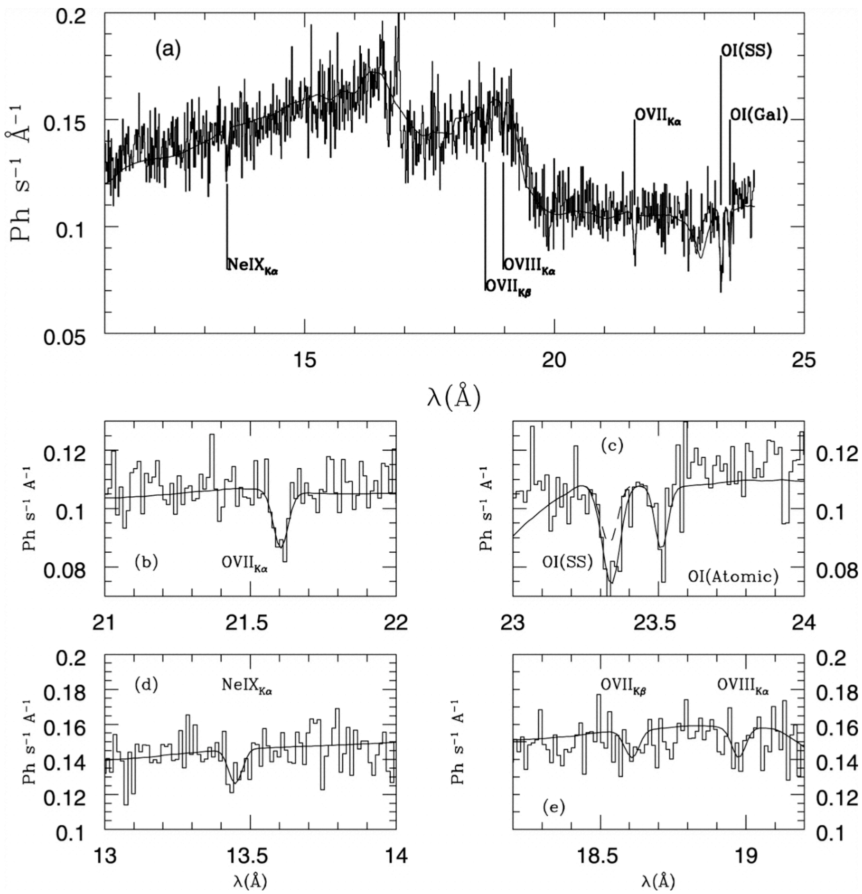
EW_λ=10 mÅ

unresolved

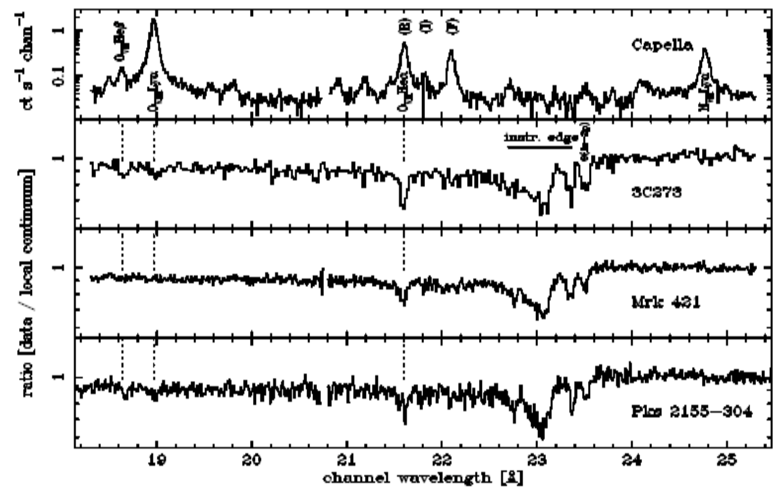
X. I

Williams et al 2007, ApJ

Early detection of the WHIM associated to the Local Group



Nicastro et al 2002



Detection of the local WHIM

Rasmussen et al 2003

Have intervening WHIM absorbers been detected?

The controversy around Mrk 421

- Detection of two WHIM absorbers with Chandra/LETGS:
  - Nicastro et al 2005, ApJ, 629, 700
  - Nicastro et al 2005, Nature, 433, 495
- XMM-Newton (437 ks) unable to confirm or discard these absorbers
  - Williams et al 2006, ApJ, 642, L95
- XMM-Newton (955 ks) <u>rejects</u> the presence of these absorbers
  - Rasmussen et al 2007, ApJ, 656, 129

Two WHIM absorbers towards Mrk 421 with *Chandra* LETGS

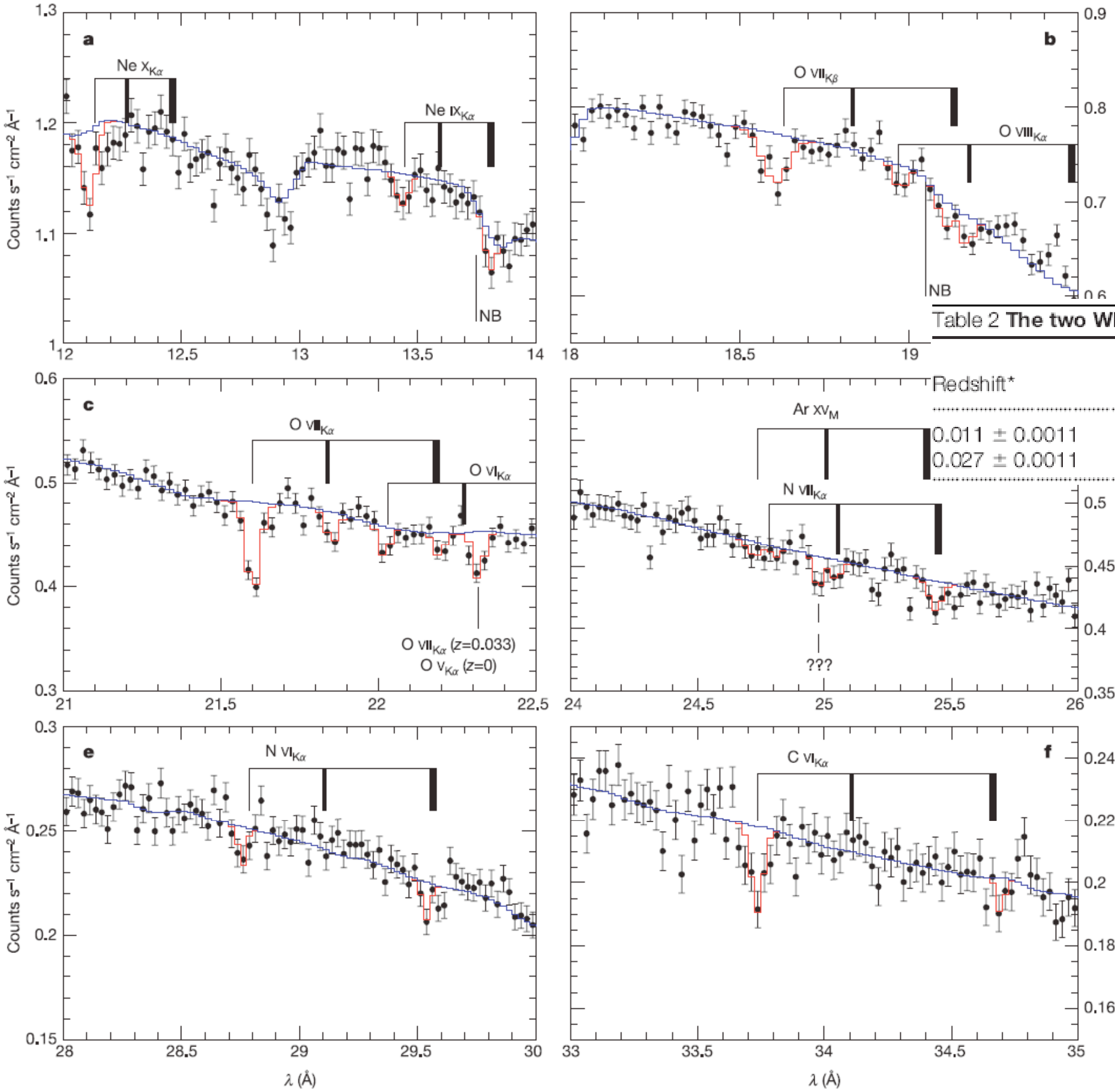


Table 2 **The two WHIM filaments along the line of sight to Mkn 421**

Redshift*	$>2\sigma$ ion detections†	Probability of exceeding F‡	Conservative significance‡	Sum of lines significance§
0.011 ± 0.0011	O VII, N VII	5.9×10^{-4}	3.5σ	5.8σ
0.027 ± 0.0011	O VII, N VII, N VI	1.3×10^{-6}	4.9σ	8.9σ

$$\Omega_{WHIM}=(2.7_{-1.9}^{+3.8})\%$$

Nicastro et al 2005a
Nicastro et al 2005b

XMM-Newton confirmation?

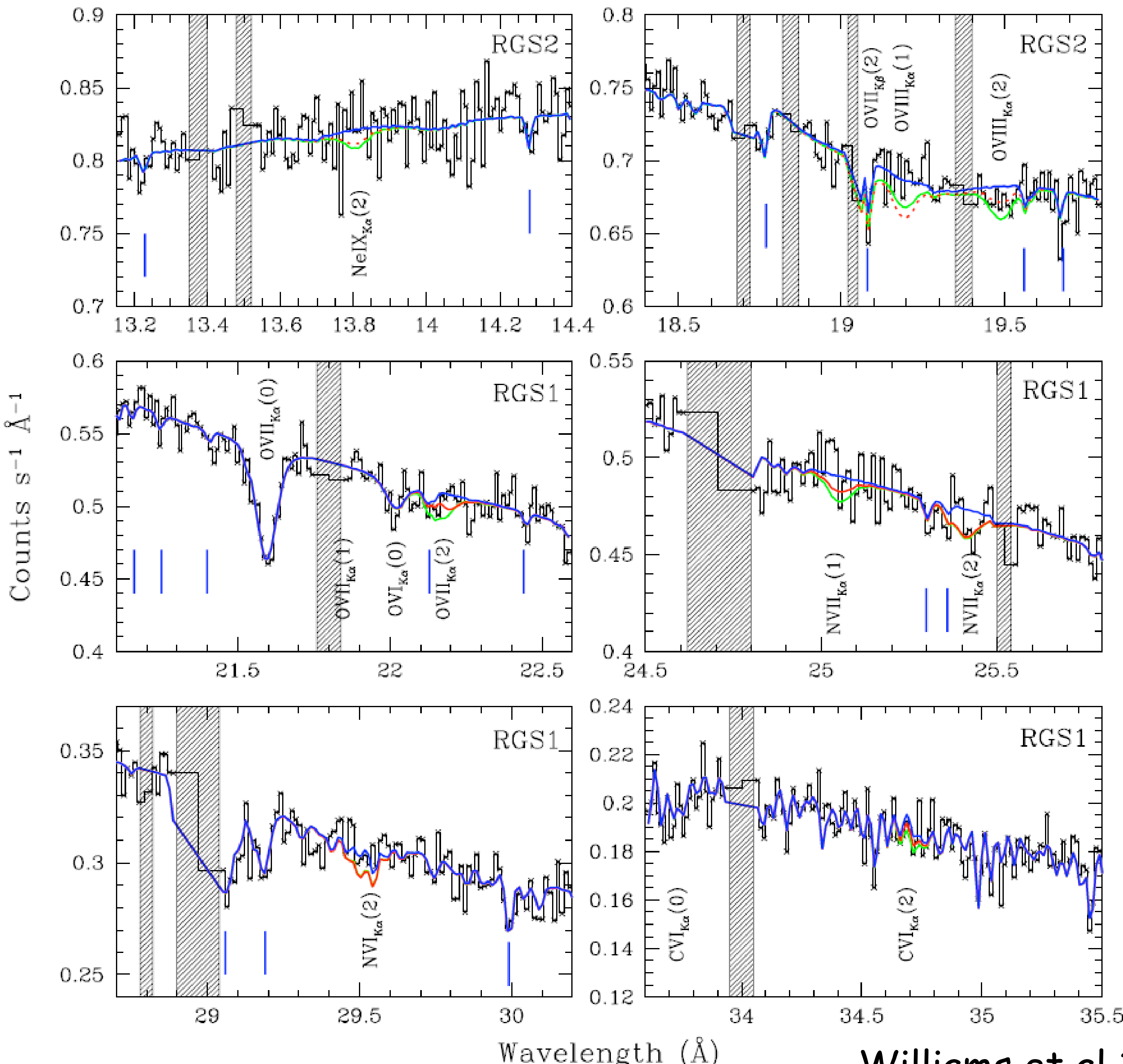
Williams et al 2006

"Despite the long exposure time neither of the two intervening absorption systems is seen, though the upper limits derived are consistent with the Chandra equivalent width measurements."

437 ks exposure

Line	λ^{a} Å	z^{a}	$W_{\lambda,\mathrm{N05a}}{}^{a}$ mÅ	$W_{\lambda,\mathrm{R1}}{}^{b}$ mÅ	$W_{\lambda,\mathrm{R2}}{}^{b}$ mÅ	$W_{\lambda,\mathrm{R1+R2}}{}^{b}$ mÅ
Ne IX$_{K\alpha}$	13.80 ± 0.02	0.026 ± 0.001	< 1.5	< 5.2	< 1.9	< 2.9
O VII$_{K\beta}$	19.11 ± 0.02	0.026 ± 0.001	< 1.8	< 2.5	< 2.1	< 1.5
O VIII$_{K\alpha}$	19.18 ± 0.02	0.011 ± 0.001	< 4.1	< 7.6	< 5.8	< 4.1
O VIII$_{K\alpha}$	19.48 ± 0.02	0.027 ± 0.001	< 1.8	...	< 3.9	...
O VII$_{K\alpha}$	21.85 ± 0.02	0.011 ± 0.001	$3.0^{+0.9}_{-0.8}$	...	...	...
O VII$_{K\alpha}$	22.20 ± 0.02	0.028 ± 0.011	2.2 ± 0.8	< 3.9	...	...
N VII$_{K\alpha}$	25.04 ± 0.02	0.010 ± 0.001	1.8 ± 0.9	< 3.0	< 6.0	< 4.4
N VII$_{K\alpha}$	25.44 ± 0.02	0.027 ± 0.001	3.4 ± 1.1	< 4.3	< 4.2	< 3.5
N VI$_{K\alpha}$	29.54 ± 0.02	0.026 ± 0.001	3.6 ± 1.2	< 3.8	< 8.7	< 3.4
C VI$_{K\alpha}$	34.69 ± 0.02	0.028 ± 0.001	2.4 ± 1.3	< 5.5	< 5.2	< 4.2

- "This appears to result from (1) the larger number of narrow instrumental features caused by bad detector columns,
  (2) the degraded resolution of XMM/RGS as compared to the Chandra/LETG, and (3) fixed pattern noise at & 29Å.
- The non-detection of the WHIM absorbers by XMM is thus fully consistent with the Chandra measurement."



Williams et al 2006, ApJ

Absorbers rejected by XMM-Newton?

Rasmussen et al 2007

955 ks of data

Careful data reduction & alaysis

- *Localized gain anomalies*
- *Transient, high duty-cycle pixel reads*
- *Cross-talk pixels-pickup of synchronously sampled analog signal of high dark current pixels*
- *Changes in source spectrum in the presence of finite spacecraft drift*

TABLE 3

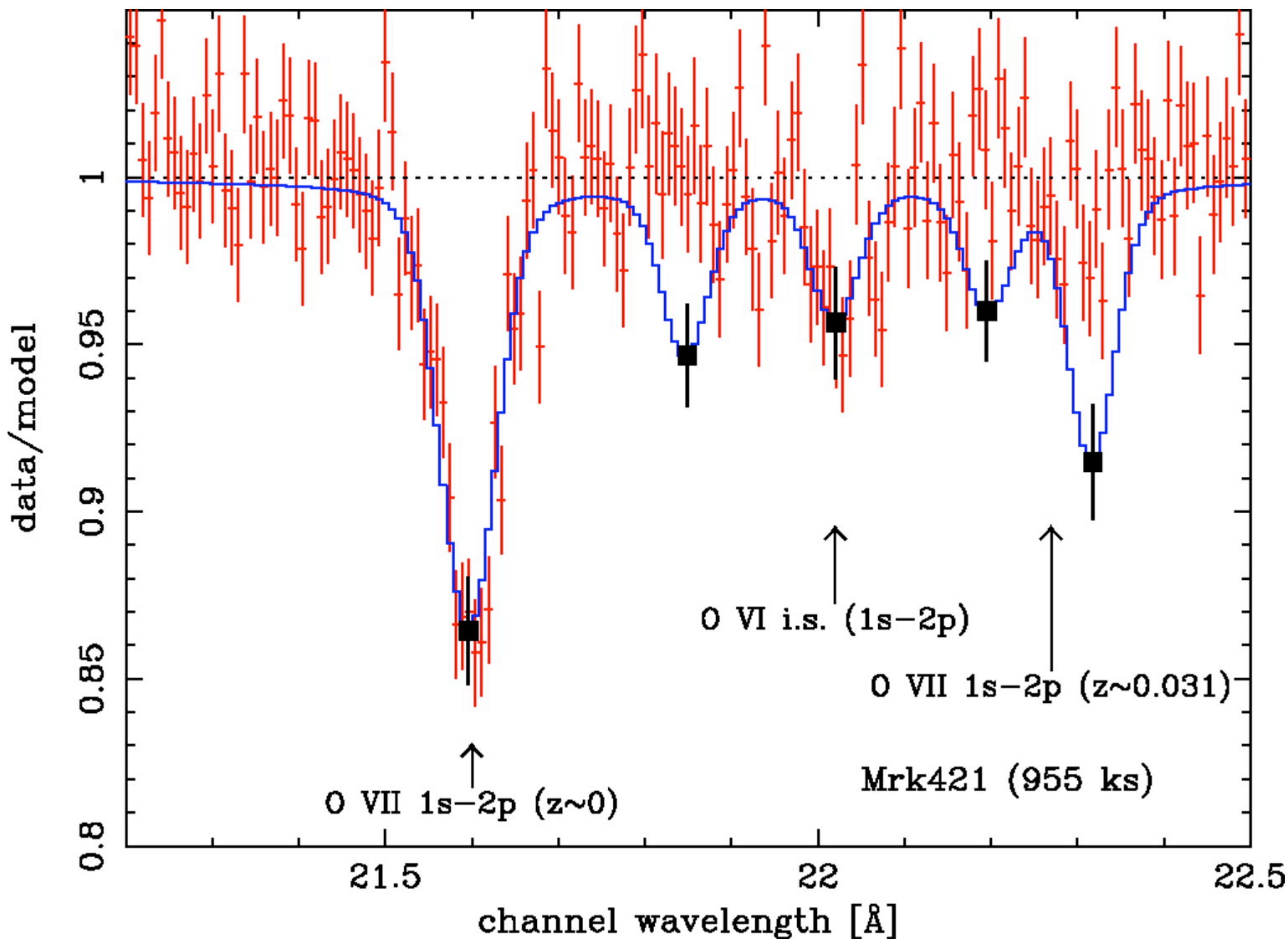
JOINT FITTING RESULTS AND LINE DETECTION LIMITS FOR DATA

Feature	λ_{meas} [a]	$\Delta\lambda$ [a]	ID [b]	z	W_λ [a]
1.	21.598	±3	O VII	≡0	$13.1^{+1.0}_{-1.0}$
2.	22.023	±10	O VI	0.0003 ± 0.0005	$3.3^{+1.3}_{-1.3}$
3.	22.300	±17	(O VII)	0.0325 ± 0.0008	$2.6^{+1.3}_{-1.3}$

Nondetections

	λ_{input} [e]	$\Delta\lambda$ [e]	ID [b]	z [e]	W_λ [a]
1.	21.85	±20	(O VII)	$0.011^{+0.001}_{-0.001}$	$0^{+1.3}_{-1.4}$
2.	22.20	±20	(O VII)	$0.028^{+0.001}_{-0.001}$	$0^{+1.4}_{-1.3}$
3.	22.32	±20	(O VII)	$0.033^{+0.001}_{-0.001}$	$0^{+1.0}_{-1.7}$

"The deep continuum spectrum of Mrk 421 is well enough understood that it allows us to detect real absorption lines of equivalent width >1.9 mÅ with 99% confidence. "


data/model
1
0.95
0.9
0.85
0.8
21.5
22
22.5
channel wavelength [Å]
O VII 1s−2p (z~0)
O VI i.s. (1s−2p)
O VII 1s−2p (z~0.031)
Mrk421 (955 ks)

Rasmussen et al (2006) conclude:

The non-detection of intervening absorption (…) is probably not surprising.

The a priori probability, as predicted by recent cosmological gas dynamics simulations, of having an intervening filament with a column density that is (…) detectable with the current instrumentation, is relatively small. For Z =0.1 $Z_\odot$, out to z(Mrk 421)= is 0.05–0.2 for Log(N_i) > 15.0 and 14.6.

The **most uncertain** parameter in these calculations is the **absolute oxygen abundance**, which can currently not be calculated with confidence from first principles.

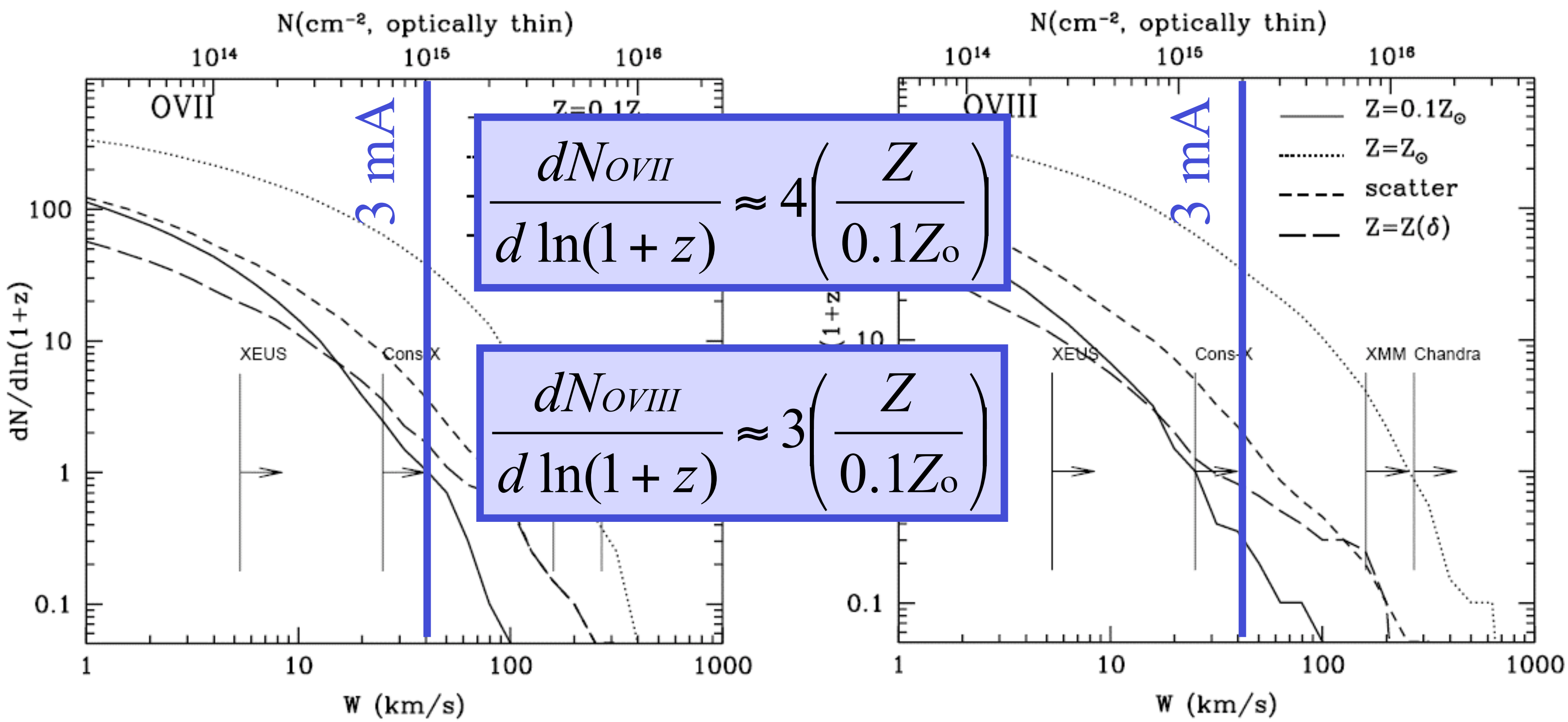
The detection of the "missing baryons" remains a challenge, best addressed with higher resolution, higher sensitivity spectrometers.

What can XMM-Newton do regarding the WHIM?

Boundary conditions

- "<u>Serendipitous</u>" search (do not target WHIM associated to groups/clusters)
- Need to go for a <u>secure</u> detection, i.e., expect a significant number of absorbers (span a significant Δz)
- Metal abundance <u>unpredictable</u> (nothing can be done about it)

Expected # of absorbers



$$\frac{dN_{OVII}}{d\ln(1+z)} \approx 4\left(\frac{Z}{0.1Z_{\odot}}\right)$$

$$\frac{dN_{OVIII}}{d\ln(1+z)} \approx 3\left(\frac{Z}{0.1Z_{\odot}}\right)$$

Need to cover $\Delta z \sim 1$ with >10,000 counts/50 mÅ

(similar quality to a 500 ks spectrum of Mrk 421)

Is that feasible with XMM-Newton?

Possible single target searches

Source	Redshift	Exp Time (Ms)	# absorb
3C 279	0.53	1.5	2.9
Pks 0637	0.65	5	3.5
3C 454.3	0.86	5	4.3
3C 380	0.69	10	3.7

Can XMM-Newton detect intervening WHIM filaments?

- Extremely interesting topic.
- Extremely challenging for current instrumentation, but feasible.
- Metallicity always a concern