The Intergalactic Medium,

with special attention to

X-ray Line Spectroscopy of the Diffuse IGM

A brief history of matter

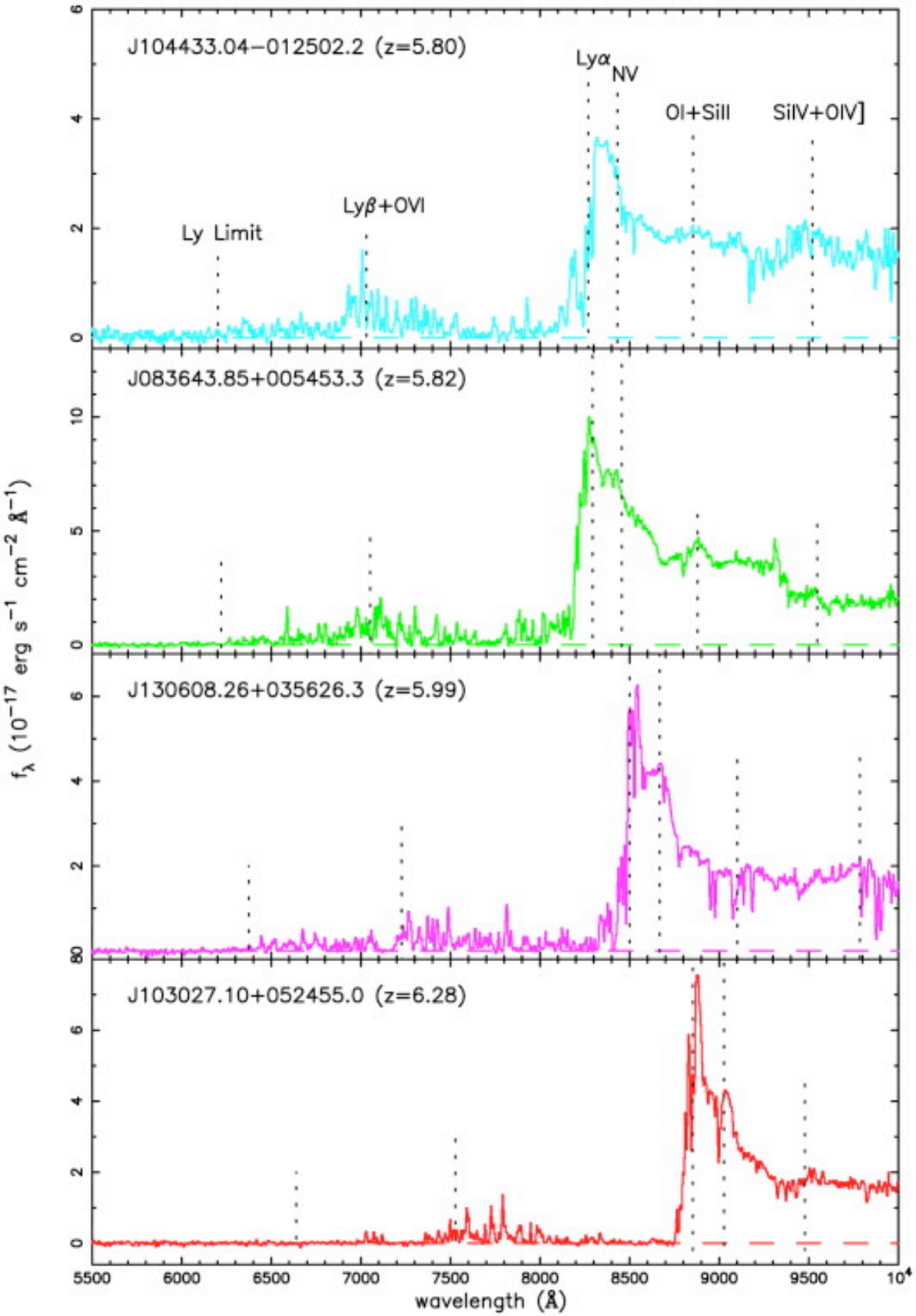
at high z, DM + fully ionized H+He, gas only;
nearly homogeneous but with small density perturbations

adiabatic expansion of the Universe cools the gas and the radiation

at $z = 1100$, recombination of H
Universe filled with nearly homogeneous DM, neutral H;
density drops as Universe expands; DM continues collapsing

out of this, stars, galaxies, clusters etc. condense,
stars starting at $z = 30$ (??)
then, at $z = 10$-6 (?): reionization, H is photoionized
by first stars, black holes

reionization: z ~ 10(?)-6



beyond z ~ 6: superposition of Lyα's renders Universe opaque

Becker *et al.*, 2001 (SDSS quasars)

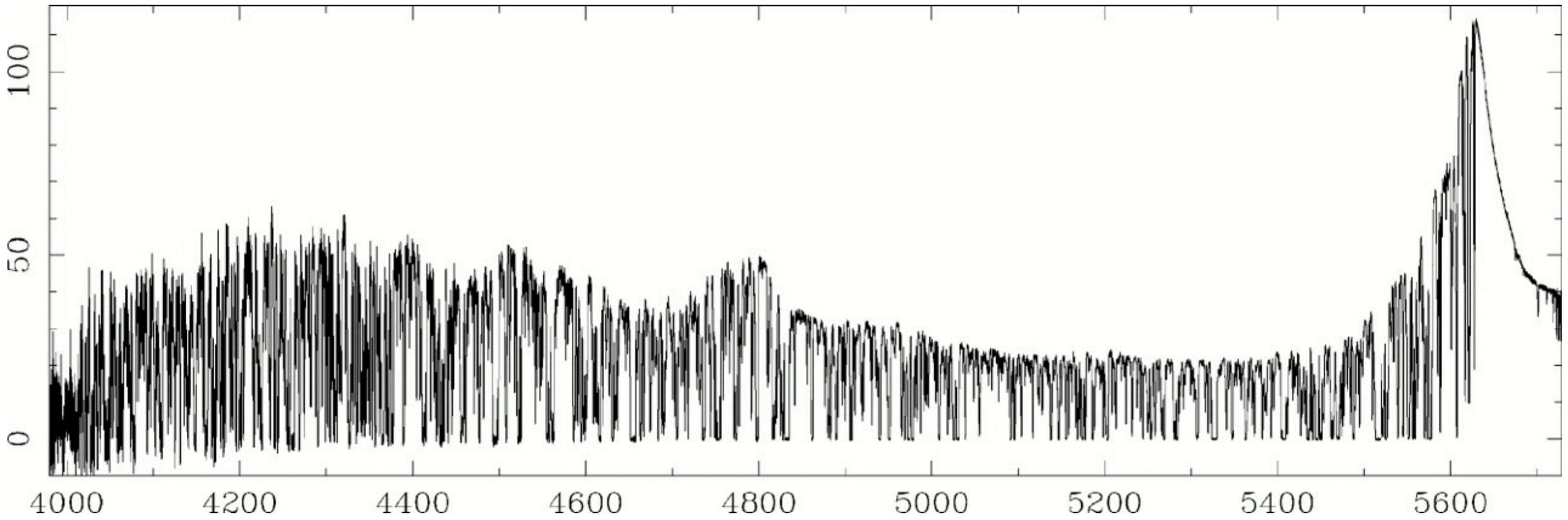
Since reionization:

continued slow gravitational collapse of DM,
followed by gas: potential wells deepen

at $z > 2$: mostly warm, photoionized H:
the Lyα forest (seen against distant quasars):
probably loose filamentary structure
(except DLA's); we see the small fraction neutral H

virialized gas in most massive DM halos
gets hotter and hotter:
up to 10^8 K in cluster ICM at $z = 0$;
Lyα forest disappears

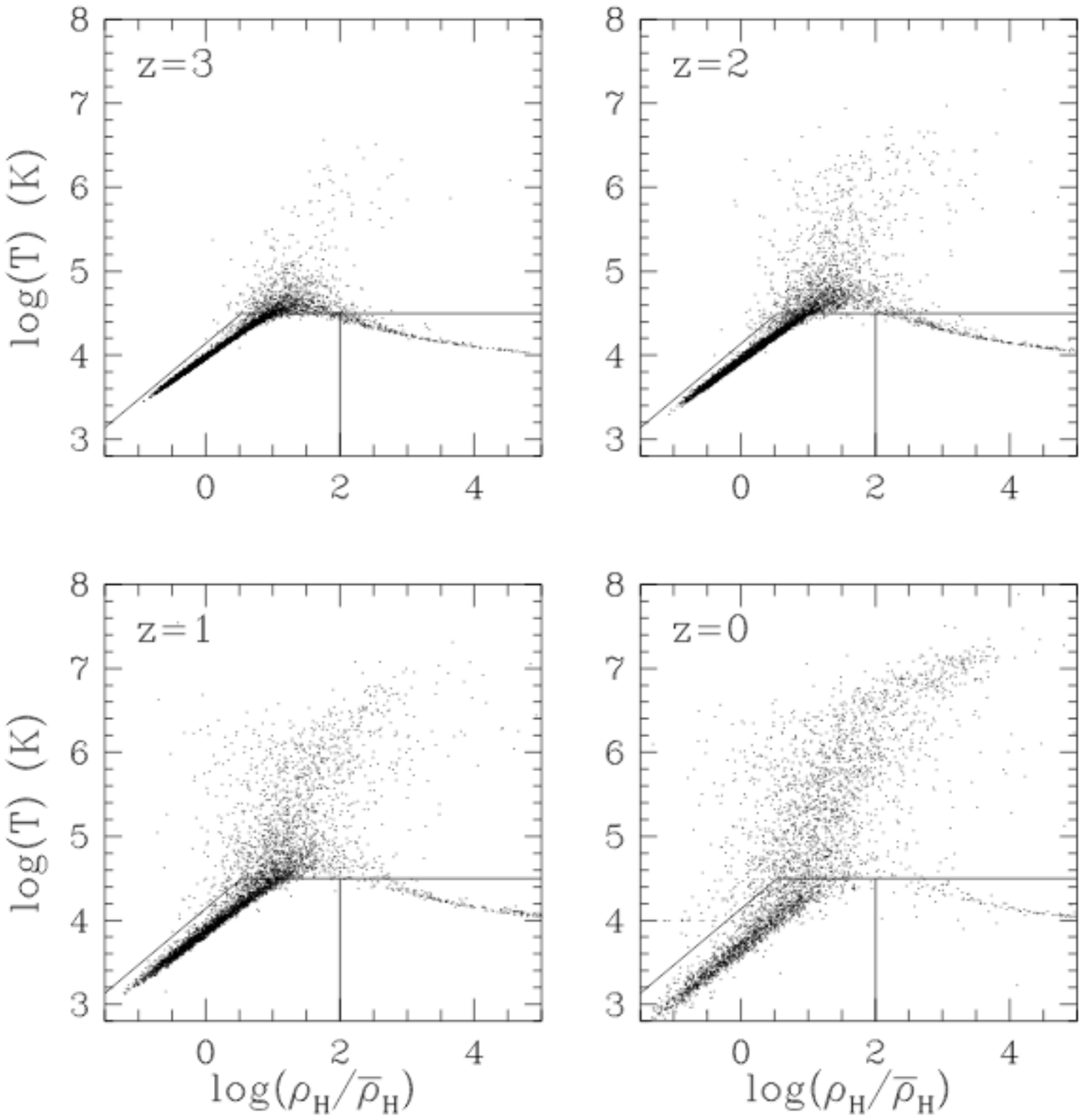
the IGM at z > 2: the Lyα Forest



QSO1422+23 (z=3.62); *Keck* HIRES 25,000 sec
(Womble *et al.* 1996)

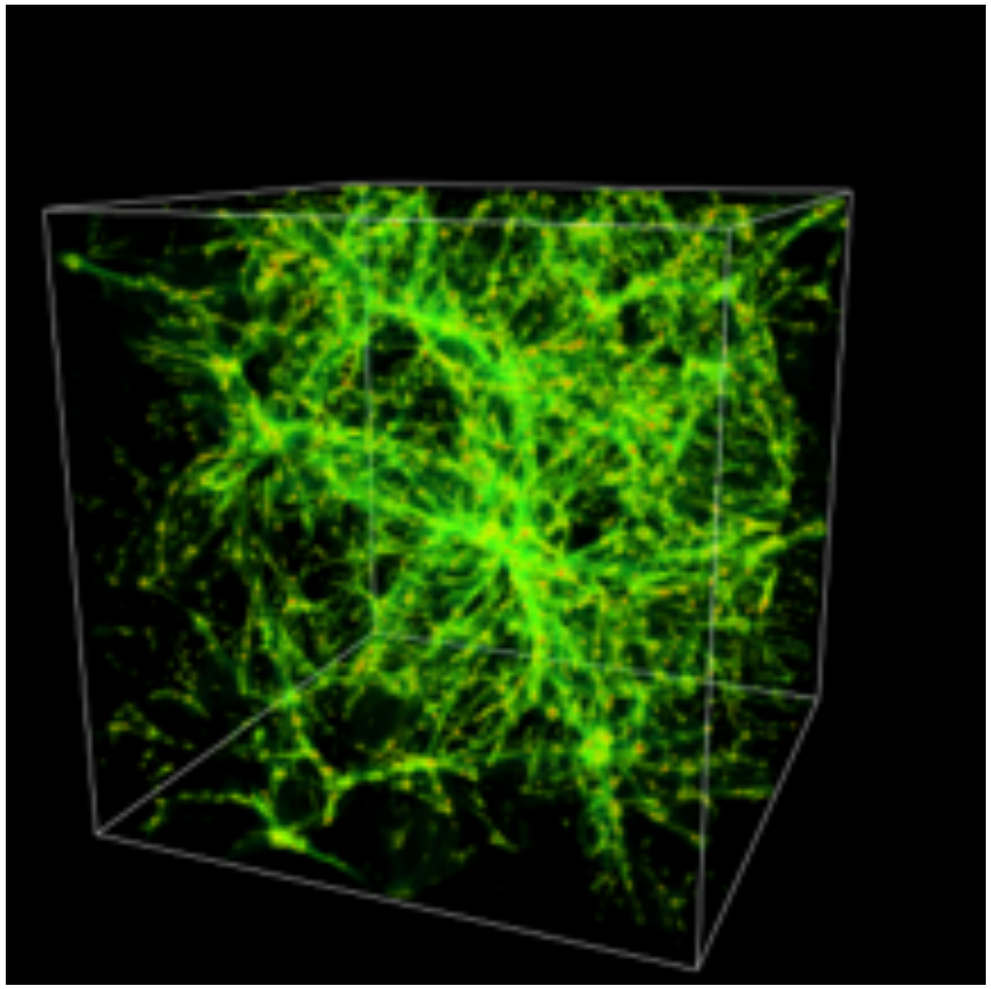
inferred cosmic baryon density: close to $\Omega_B = 0.046$
(0.046 from BBN, CMB)

evolution of the IGM towards z = 0



hydro simulations; Davé *et al.* (1999)

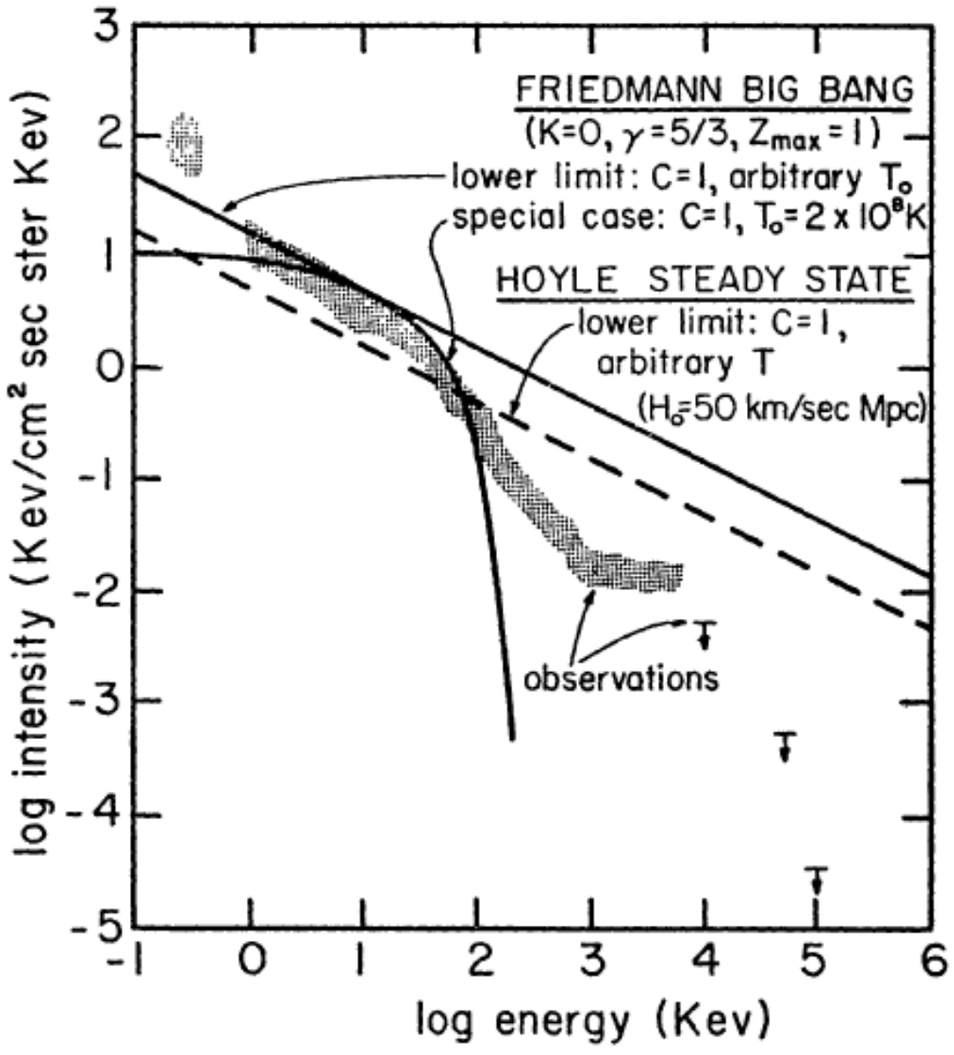
predicted current distribution of the IGM



Cen and Ostriker (1999)

locus of shocked, highly ionized gas ($T > 10^6$ K):
filaments ('WHIM')
groups, clusters at the nodes

so no diffuse universal hot IGM - but confusing history...



George Field, "*Intergalactic Matter*", *Ann. Rev. Astron. Astrophys.*, 1972:

FIGURE 1. Theoretical (lines) and observational (hatched) X-ray background spectra. The observations are from Silk (1971b). The curve represents the thermal bremsstrahlung spectrum in a big-bang (BB) model, for which the present intergalactic gas temperature is $2\times10^{8\circ}$K, assuming that the gas expanded adiabatically with $\gamma=5/3$ from $z_{max}=1$ ($T=8\times10^{8\circ}$K). The Friedmann model assumed is the flat-space model $k=0$

Narrow absorption feature in X-ray spectrum of PKS2155-304 (*Einstein* OGS, O VIII Ly α/ 653 eV; $Z/Z_O \sim 1$, $\Omega_{IGM}/\Omega_{crit} \sim 1$!)

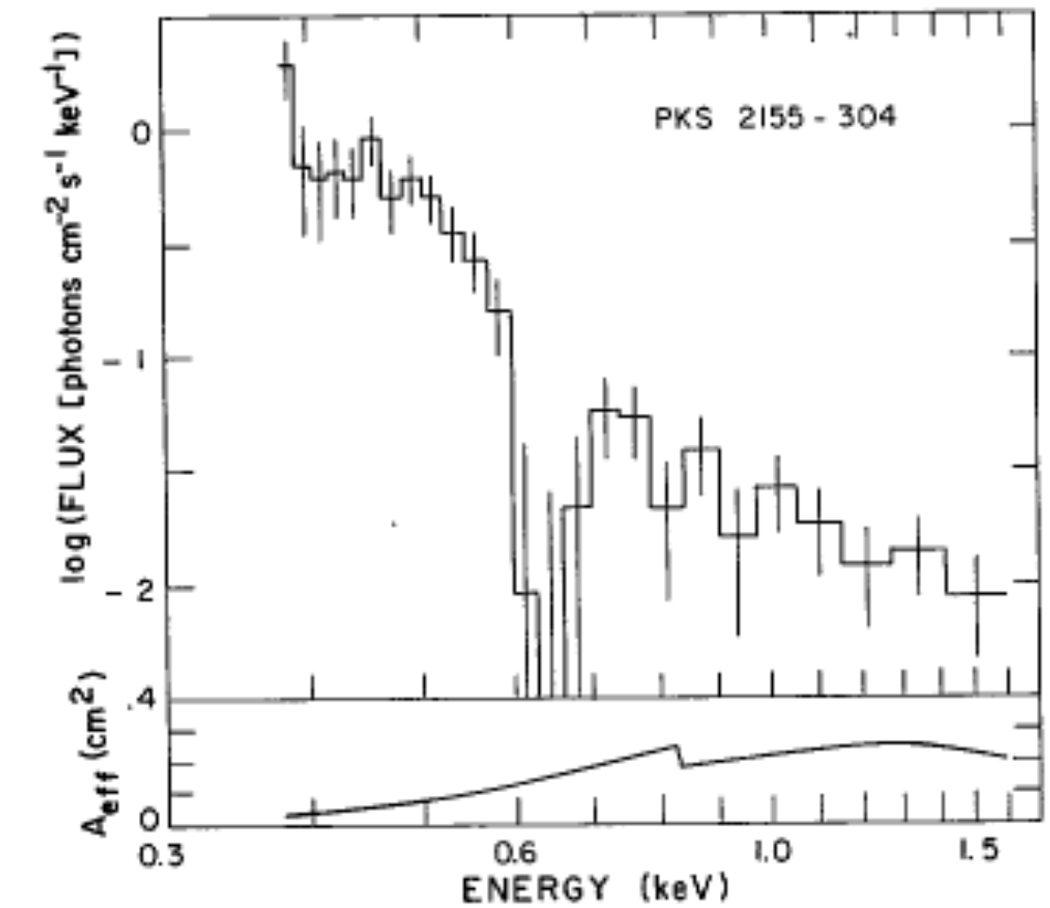
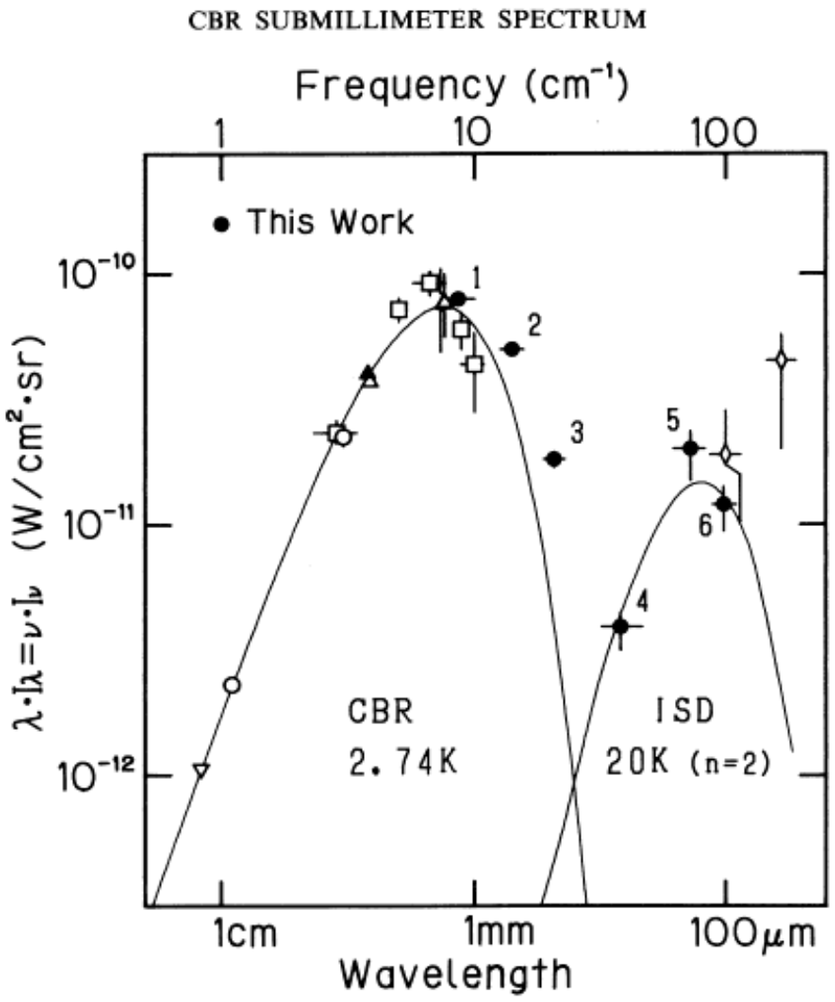


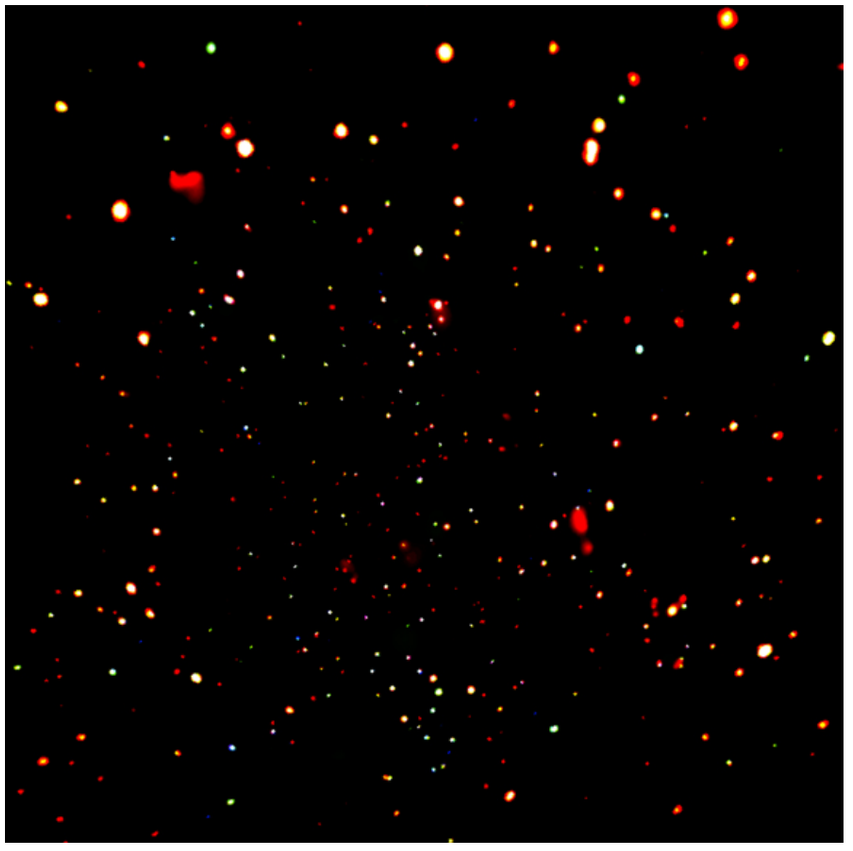
FIG. 2.—The *Einstein Observatory* OGS X-ray spectrum of PKS 2155−304 (*upper*) corrected for the efficiency of the OGS (*lower*). The 1 σ error bars are based on statistics only.

Canizares & Kruper, 1984, *Ap.J.*, **278**, L99.

* CMB spectrum shows no Compton scattering;
* High resolution X-ray imaging partly (largely?) resolves XRB:
  no dominant hot IGM.



(Crazy twist:
Matsumoto *et al.* rocket: $y = 0.02$!
M. *et al.*, 1988, *Ap.J.*, **329**, 567)



Chandra Deep Field North
(0.5-8 keV; 17 arcmin^2: ~ 500 sources)

the X-ray sky is very dark

the IGM at z = 0

total measured baryon density at z = 0: 0.005-0.03

balance must have gone into highly ionized medium; H highly ionized, but CNOFe not fully ionized (⇒X-rays)

Fukugita and Peebles 2004

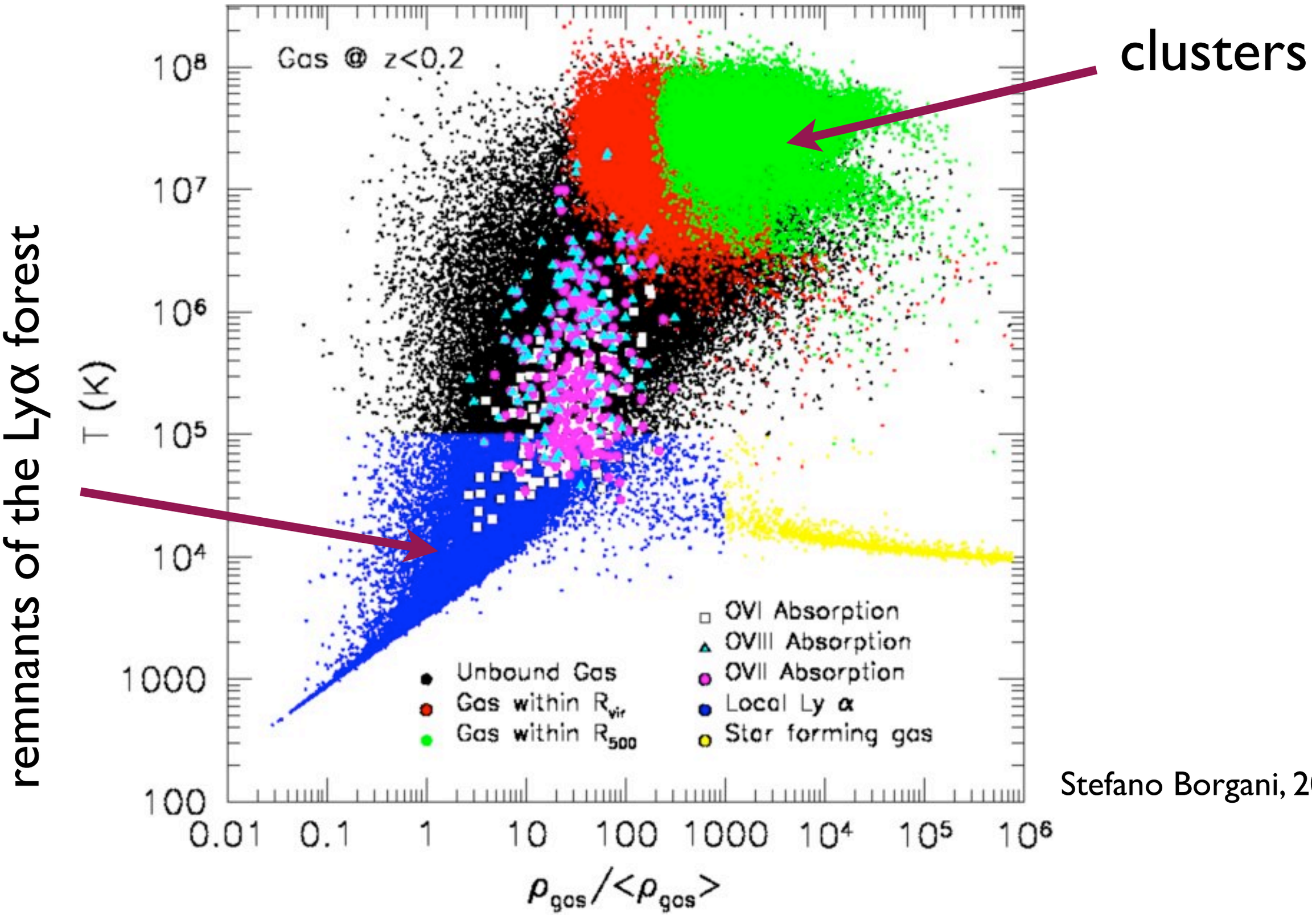
TABLE 1
THE COSMIC ENERGY INVENTORY

Category	Parameter		Components[a]	Totals[a]
1.....	Dark sector:			0.954 ± 0.003
1.1.....	Dark energy		0.72 ± 0.03	
1.2.....	Dark matter		0.23 ± 0.03	
1.3.....	Primeval gravitational waves		$\lesssim 10^{-10}$	
2.....	Primeval thermal remnants:			0.0010 ± 0.0005
2.1.....	Electromagnetic radiation		$10^{-4.3 \pm 0.0}$	
2.2.....	Neutrinos		$10^{-2.9 \pm 0.1}$	
2.3.....	Prestellar nuclear binding energy		$-10^{-4.1 \pm 0.0}$	
3.....	Baryon rest mass:			0.045 ± 0.003
3.1.....	Warm intergalactic plasma		0.040 ± 0.003	
3.1a.....	Virialized regions of galaxies	0.024 ± 0.005		
3.1b.....	Intergalactic	0.016 ± 0.005		
3.2.....	Intracluster plasma		0.0018 ± 0.0007	
3.3.....	Main-sequence stars: spheroids and bulges		0.0015 ± 0.0004	
3.4.....	Main-sequence stars: disks and irregulars		0.00055 ± 0.00014	
3.5.....	White dwarfs		0.00036 ± 0.00008	
3.6.....	Neutron stars		0.00005 ± 0.00002	
3.7.....	Black holes		0.00007 ± 0.00002	
3.8.....	Substellar objects		0.00014 ± 0.00007	
3.9.....	H I + He I		0.00062 ± 0.00010	
3.10.....	Molecular gas		0.00016 ± 0.00006	
3.11.....	Planets		10^{-6}	
3.12.....	Condensed matter		$10^{-5.6 \pm 0.3}$	
3.13.....	Sequestered in massive black holes		$10^{-5.4}(1+\epsilon_r)$	

by default

0.0053

z = 0; simulation



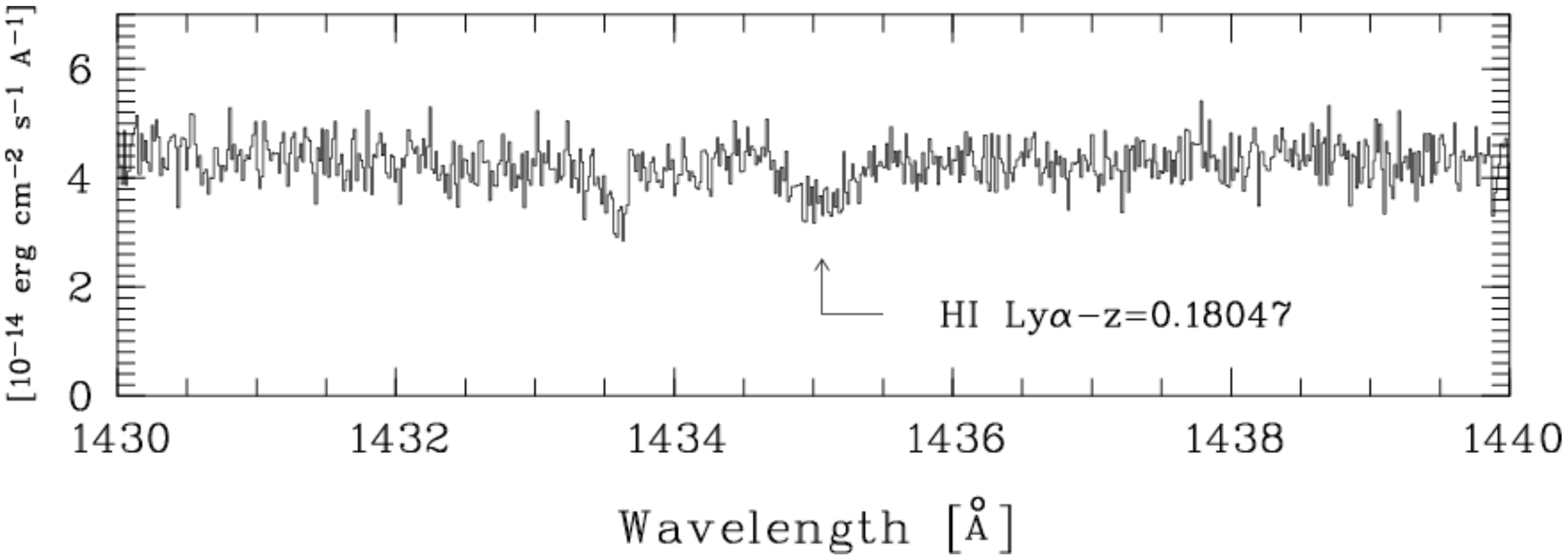
Stefano Borgani, 2004

the Warm-Hot IGM (not galaxies, not clusters)

* average density contrast $\delta \sim 10\text{-}30$
* average physical density $\delta \langle n_B \rangle = \delta \cdot 2 \times 10^{-7}$ cm^{-3} (!!)
* highly inhomogeneous: $\Delta \log n \sim 1$;
  clumping: $C = \langle n^2 \rangle / \langle n \rangle^2 \sim 100$
* average temperature $T \sim 4 \times 10^6$ K, but ranges between 10^5 and 10^7 K at each density
* metallicity?? Lyα forest, $z = 3$: $Z/Z_\odot \sim 0.01$
  Groups, clusters, $z \sim 0$: $Z/Z_\odot \sim 0.1\text{-}0.3$
  Probably strongly density-dependent

Other components: BLA, O VI

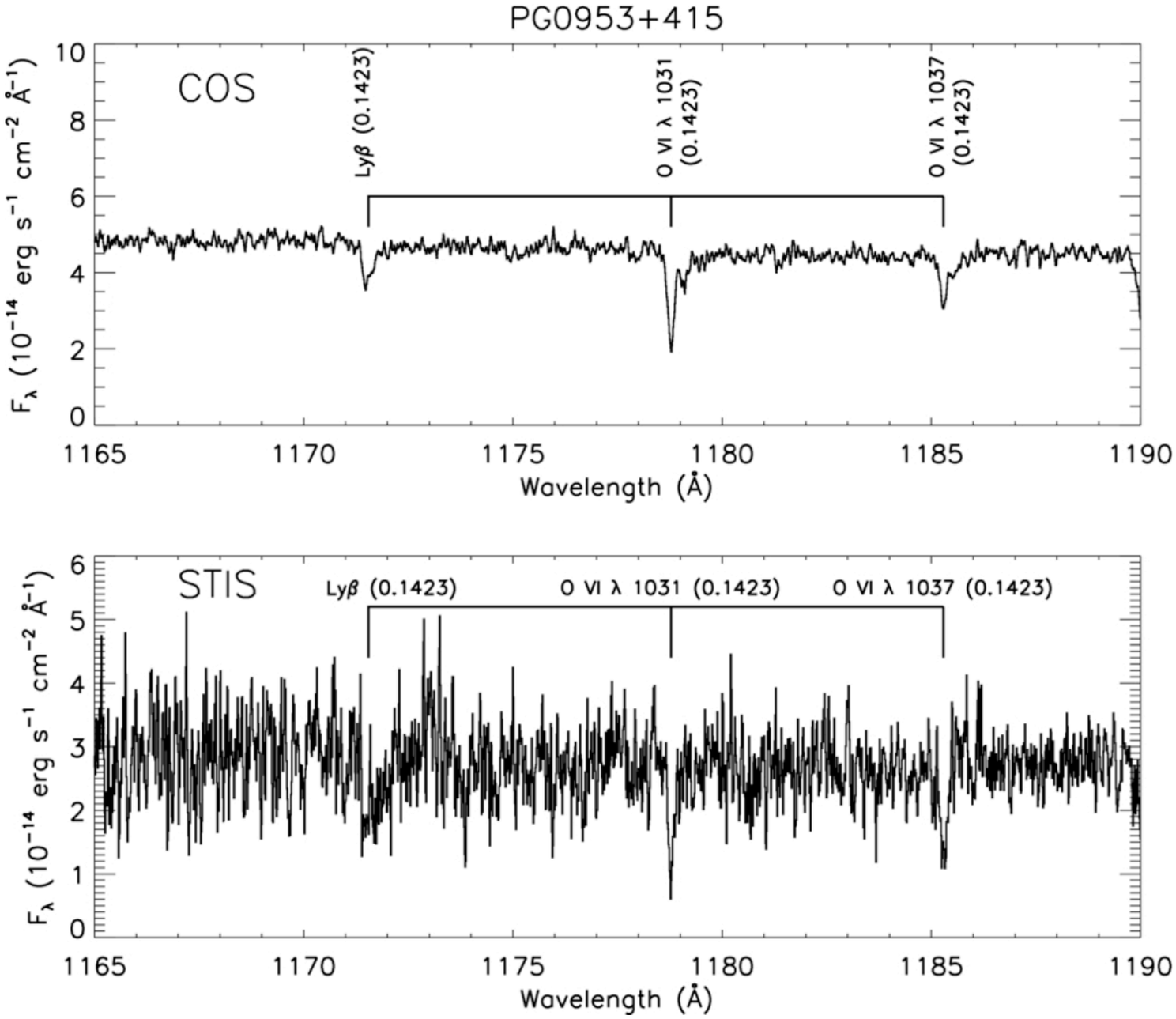
BLA: Broad Lyα Absorber; widths ~ thermal velocity at 10^6 K:



BLA in H1821+643/HST STIS;
Richter *et al.* 2006

Is this the same as the WHIM?

What is O VI ?



Savage *et al.* 2014

O VI (Li-like); $1s^2 2s$-$1s^2 2p_{1/2,3/2}$ λλ1032, 1038 Å; ubiquitous; 'easy' to detect (UV spectroscopy)

Physical state of O VI absorbers

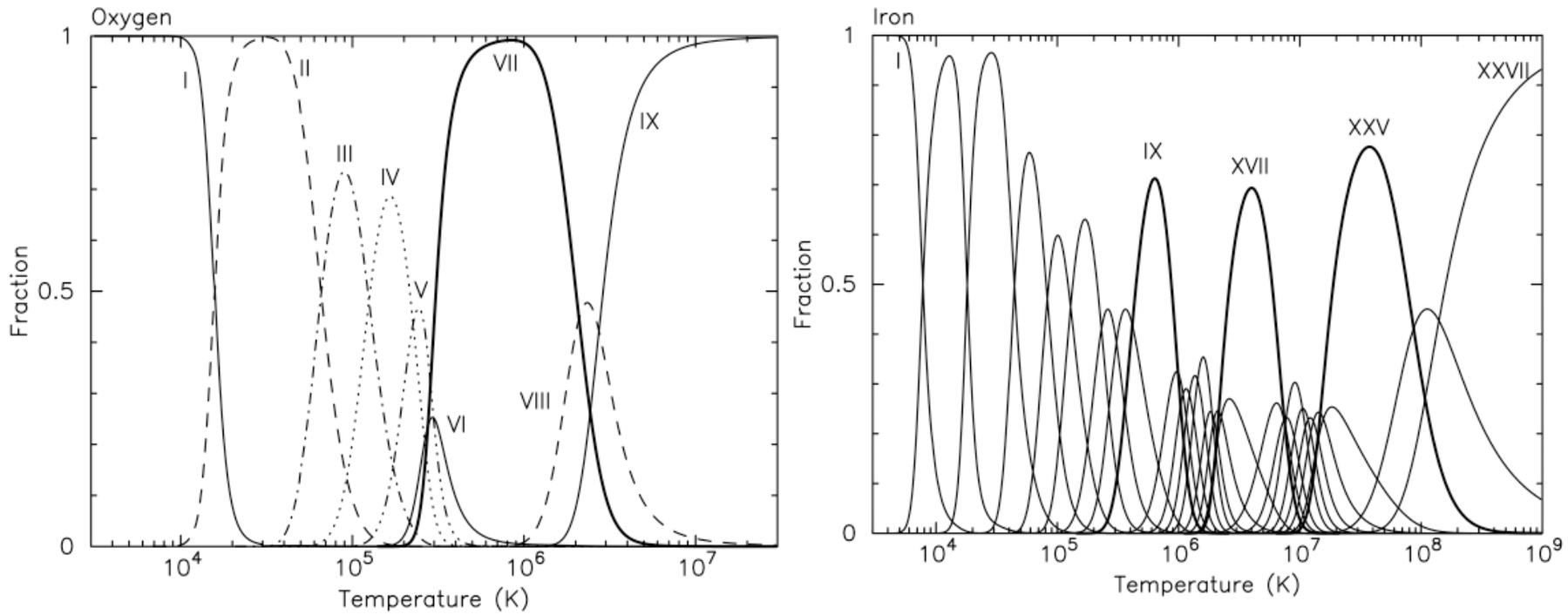


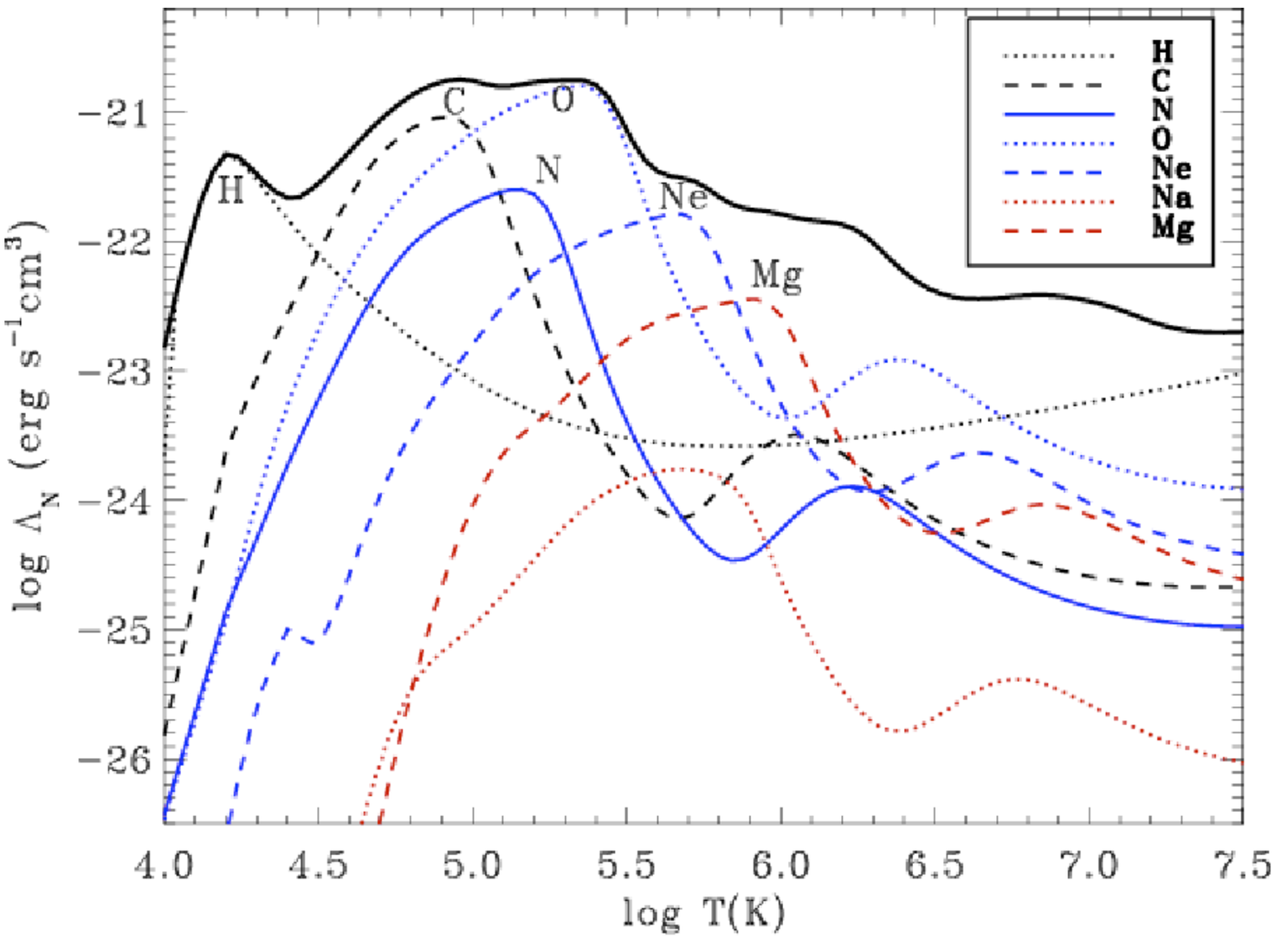
Fig. 7 Ion concentration of oxygen ions (*left panel*) and iron ions (*right panel*) as a function of temperature in a plasma in Collisional Ionisation Equilibrium (CIE). Ions with completely filled shells are indicated with *thick lines*: the He-like ions O VII and Fe XXV, the Ne-like Fe XVII and the Ar-like Fe IX; note that these ions are more prominent than their neighbours

in collisional equilibrium, appears at ~ 2-5×10^5 K

medium thermally unstable

simplest case: constant density;
unstable if $\partial\Lambda / \partial T < 0$
Famous paper: George Field 1965

O VI



radiative cooling curve; CIE; Schure *et al.* 2009

medium generally not stable when O VI is abundant:
O VI absorption traces small fraction of the baryons ($\Omega_{OVI} \sim 0.004$)

thermal instability; Kritsuk and Norman 2002

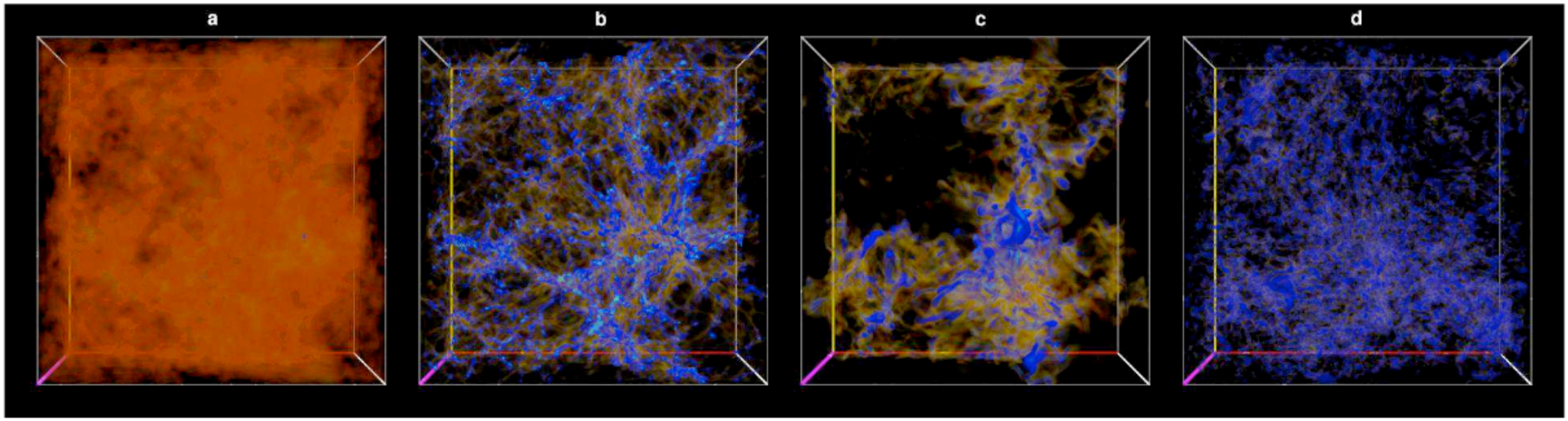


FIG. 1.— Snapshots of the gas density field (perspective volume rendering): (a) First condensation at $t = 0.07$ Myr, (b) thermal pancakes at $t = 0.1$ Myr, (c) collapse and turbulization of cellular structure at $t = 0.17$ Myr, (d) two-phase medium at $t = 1.5$ Myr (5 pc box, 256^3 grid points). The log density color coding is as follows: The dense blobs at the intersections of the filaments, $\rho > 10^{-22}$ g cm^{-3}, are light blue; the stable cold phase, $\rho \in [10^{-23}, 10^{-22}]$ g cm^{-3}, is blue; the unstable density regime, $\rho \in [10^{-23.7}, 10^{-23.0}]$ g cm^{-3}, is yellow to brown; and the low-density gas, including stable warm phase ($\rho < 10^{-23.7}$ g cm^{-3}), is a transparent red. The figure is also available as an mpeg animation in the electronic edition of the Astrophysical Journal.

$T = 10^6 - 10^5$ K

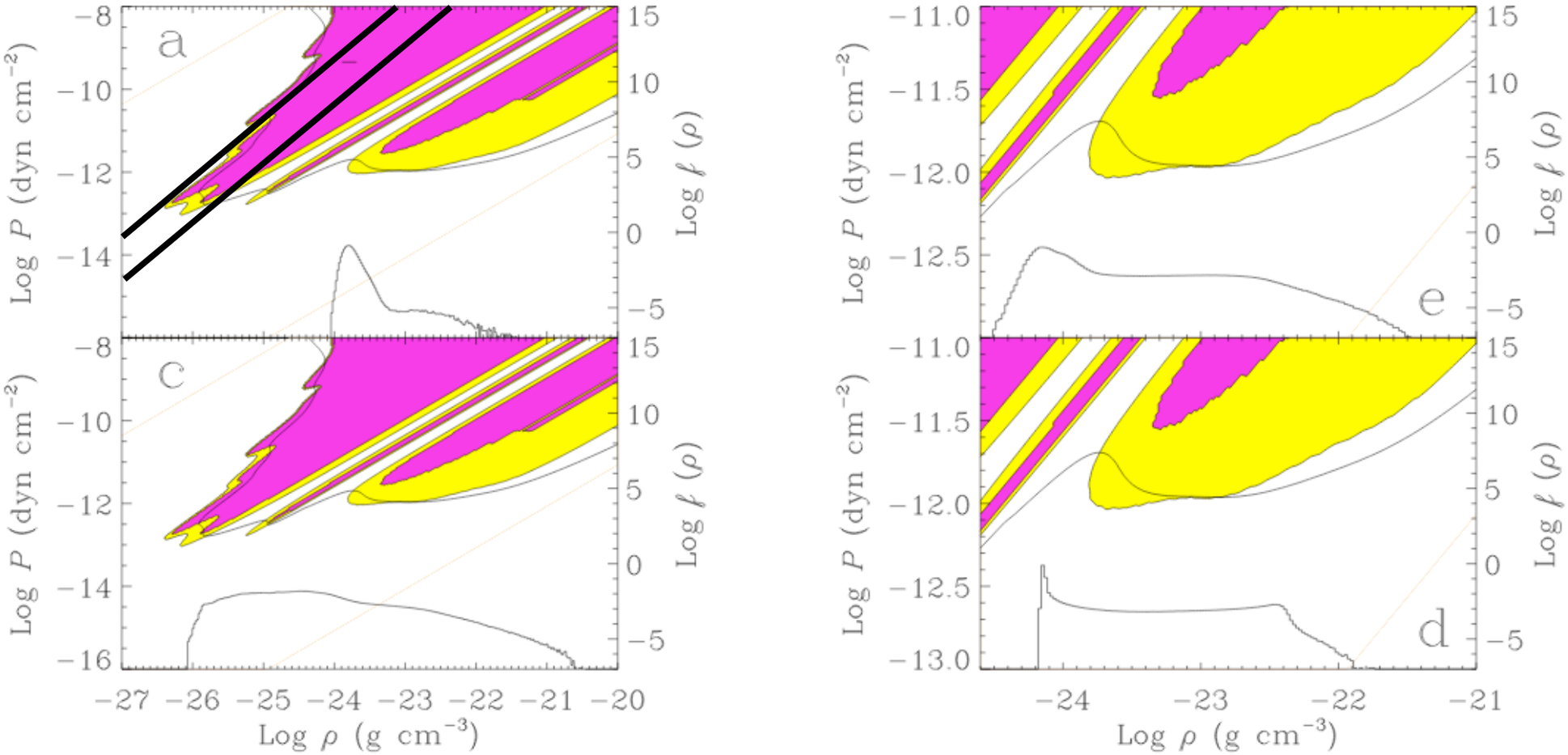
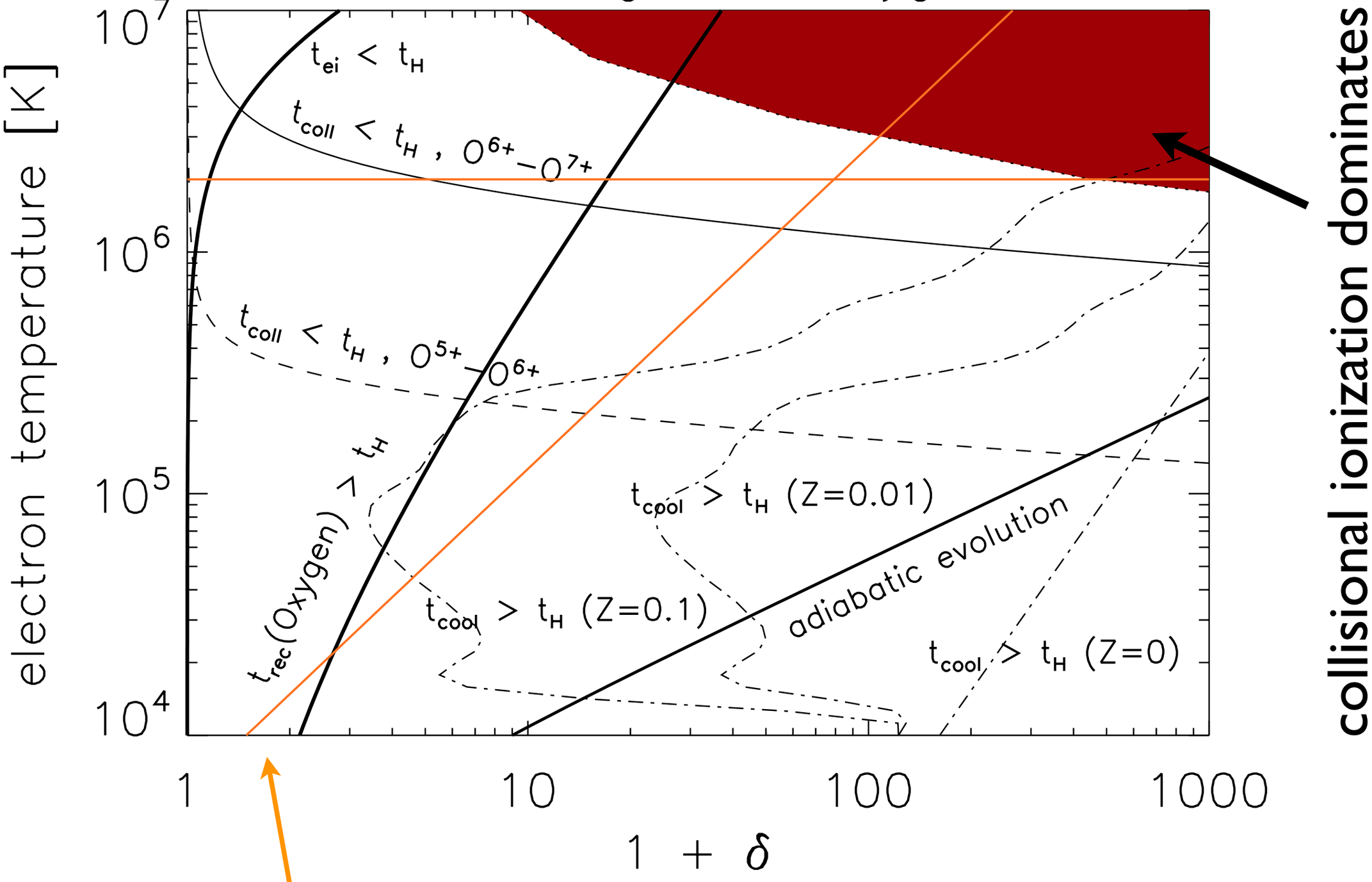


FIG. 2.— Snapshots of phase diagrams (timing and labels correspond to those in Fig. 1): (a) $t = 0.07$ Myr, (c) $t = 0.17$ Myr, (e) $t = 0.5$ Myr, (d) $t = 1.5$ Myr. The black dots show scatter plots of pressure vs. density. The "dash" at $P = 4.55 \times 10^{-10}$ dyn cm^{-2} in (a) shows the isobaric initial conditions. Background yellow-filled contours specify the part of the phase plane where isobaric mode is unstable; overlaid magenta contours are the regions of isochoric instability. The thick solid line shows thermal equilibrium curve. Density PDFs are plotted at the bottom of each panel (see scale to the right).

the Fate of Intergalactic Oxygen at z=0



The low-z, *high ionization* Intergalactic Medium

Reasons for X-rays

(highly ionized high-Z ions)

Reasons for Line Spectroscopy

(continua much too low contrast)

Reasons for Absorption Spectroscopy

(sensitive to lower-density absorbers;
sensitivity independent of z)

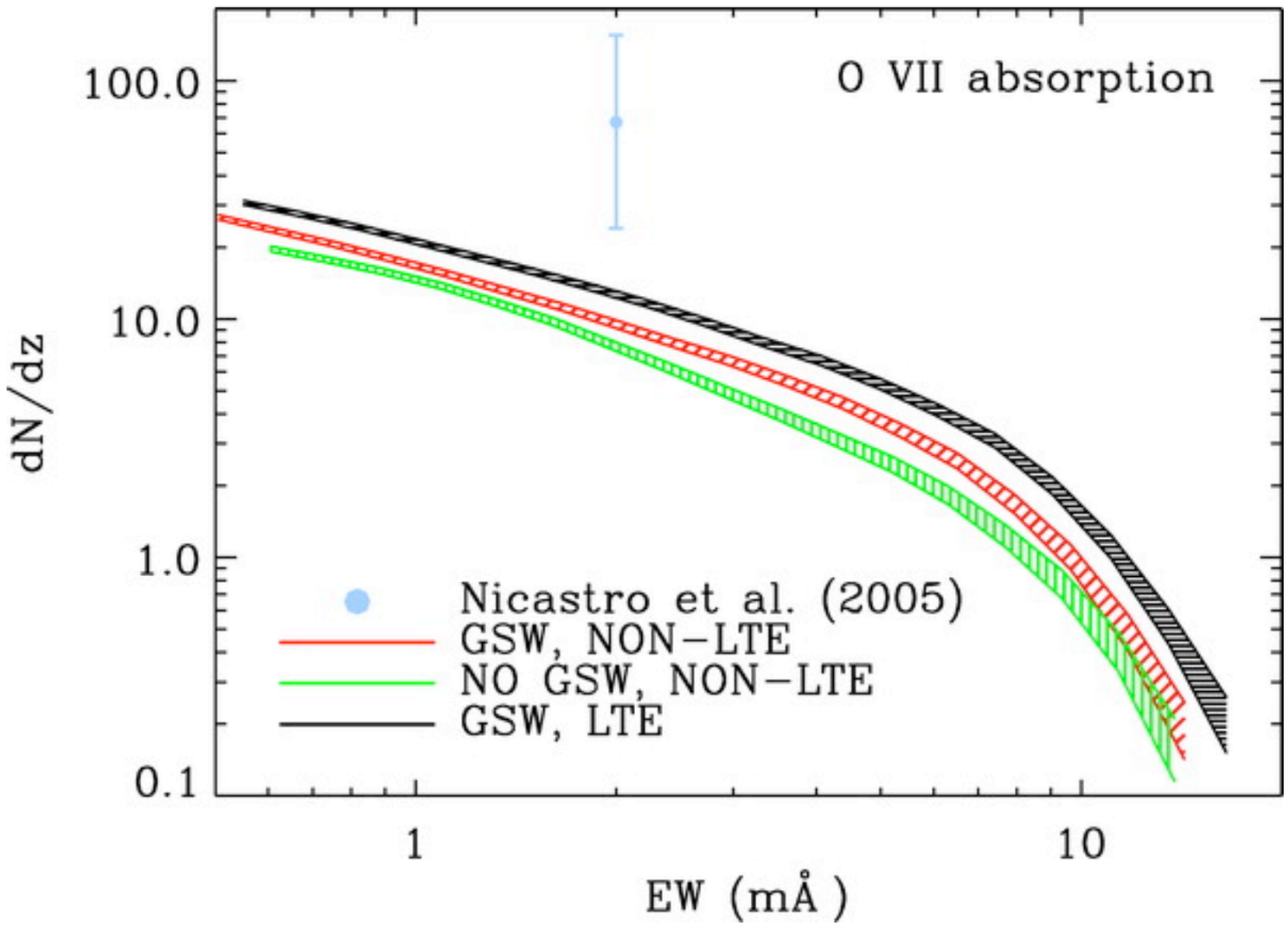
The low-z Intergalactic Medium

absorption lines will be tiny

Example: $O^{+6,+7}$ n=1-2;
thermal width $\Delta v = 23 T_6$ km/s
saturate at $N_i \sim 2\ 10^{15} (\Delta v/23 \mathrm{km/s})$ cm^{-2}, so
since $N_i \sim 3\ 10^{14}\ \delta\ (l/10\ \mathrm{Mpc})\{(Z/Z_\odot)/0.1\}$ cm^{-2}
at $\delta \sim 10$!
and EW < 30 km/sec
0.05 eV (at 500 eV) unresolved!
2 mÅ (at 20 Å)

The low-z Intergalactic Medium

and they will be rare; and unresolved



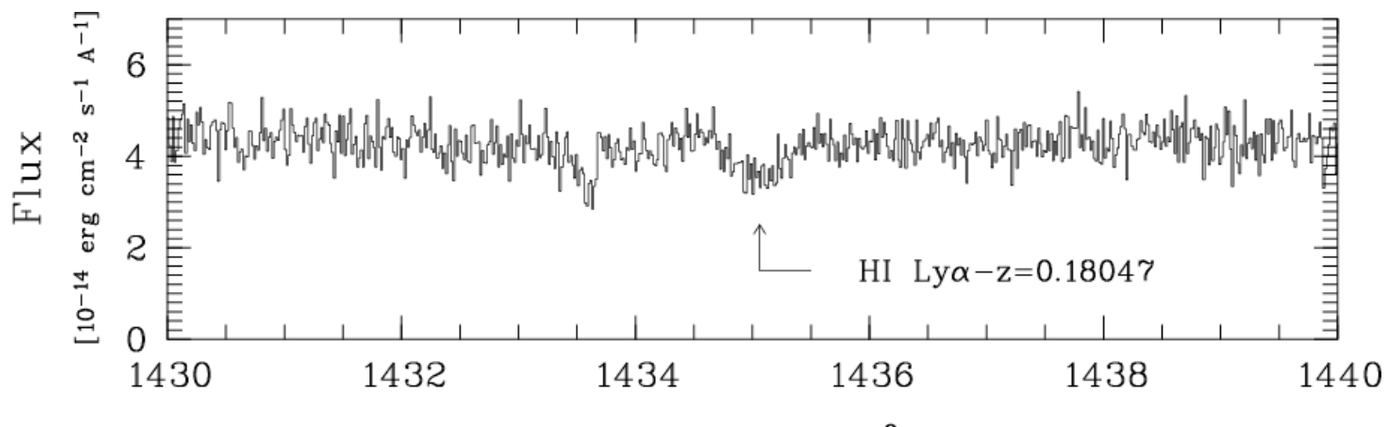
Cen and Fang 2006

NB: if n=1-2 saturated: look for n=1-3

Data: Absorption Lines

Mkn 421	z=0.01,0.027		O VII	does not appear in double exposure?	blind
H2356-309	0.03	Sculptor Wall	O VII	✓	targeted
H2356-309	0.062,0.128	Pisces-Cetus; Far Sculptor	O VII	upper limits	targeted
H2356-309	0.112, 0.167*	void	C V	0.167>z_{QSO}?	blind
PKS0558-504	0.117		O VIII	broad Lyβ?	blind
1ES1553+113	0.100, 0.124, 0.132, 0.153	5 BLA's (*)	CV, ?OVII		blind

BLA: Broad Lyα Absorber; widths ~ thermal velocity at 10^6 K:

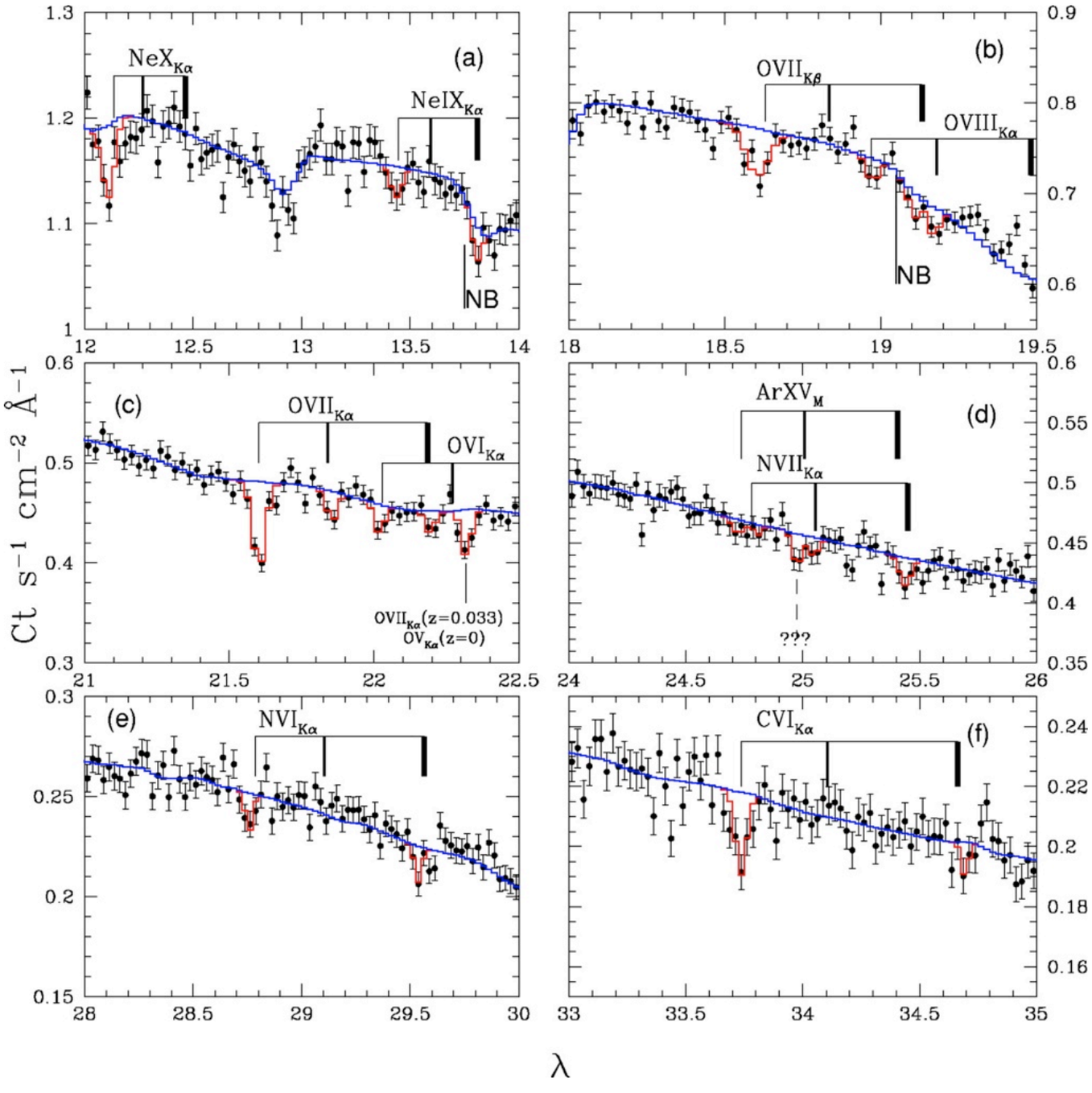


BLA in H1821+643/HST STIS; Richter *et al.* 2006

First attempt to collect enough photons:
‘flaring campaign’

Mkn 421
Nicastro et al. 2005
Chandra LETGS/ACIS

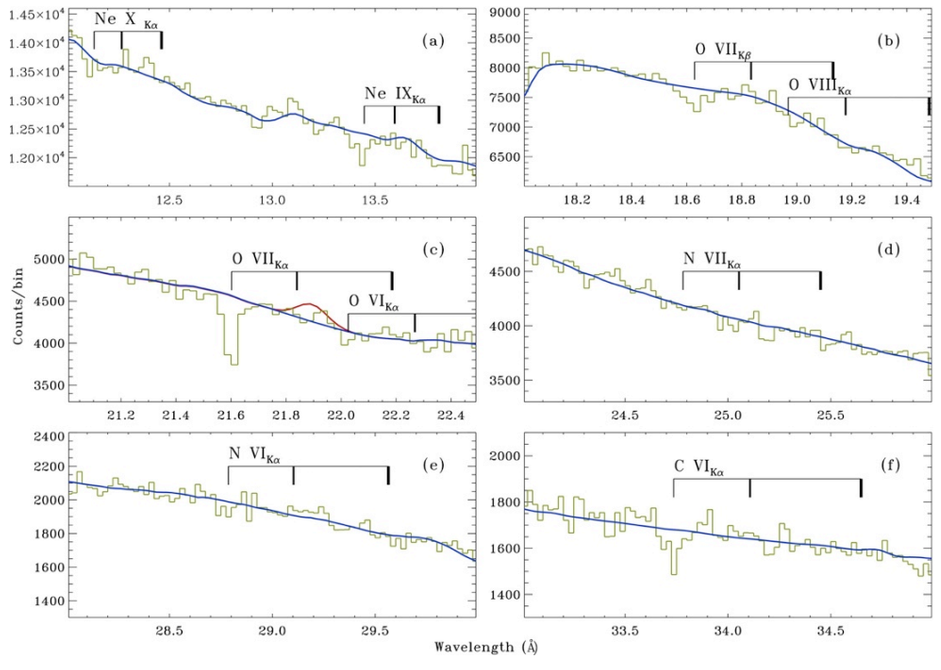
Mkn 421



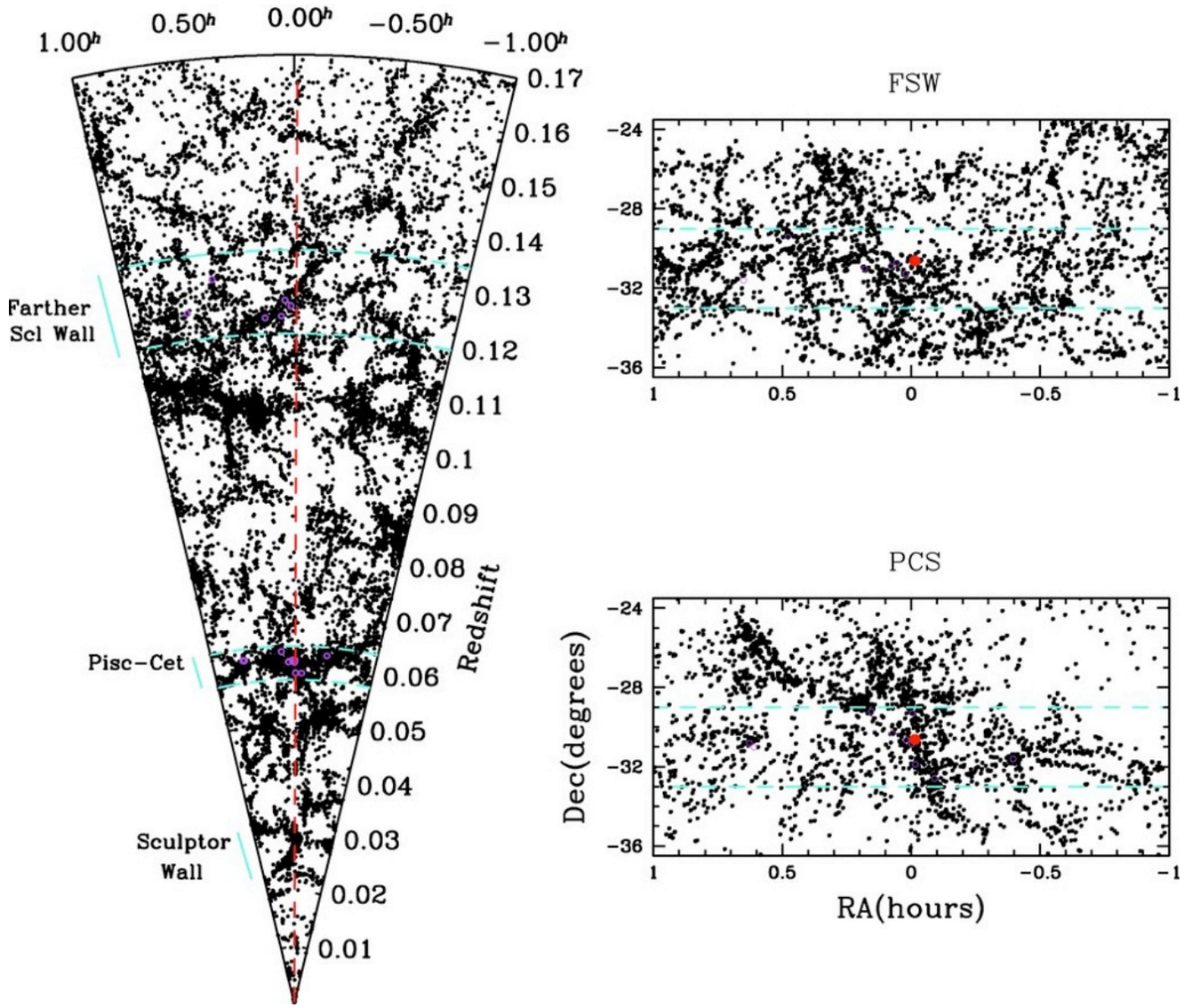
O VII n=1-2 z= 0.011 did not appear in RGS

But subtle points about LSF of LETGS and RGS well taken

Much deeper LETGS spectra do not show O VII z = 0.011 (Yao et al. 2012)

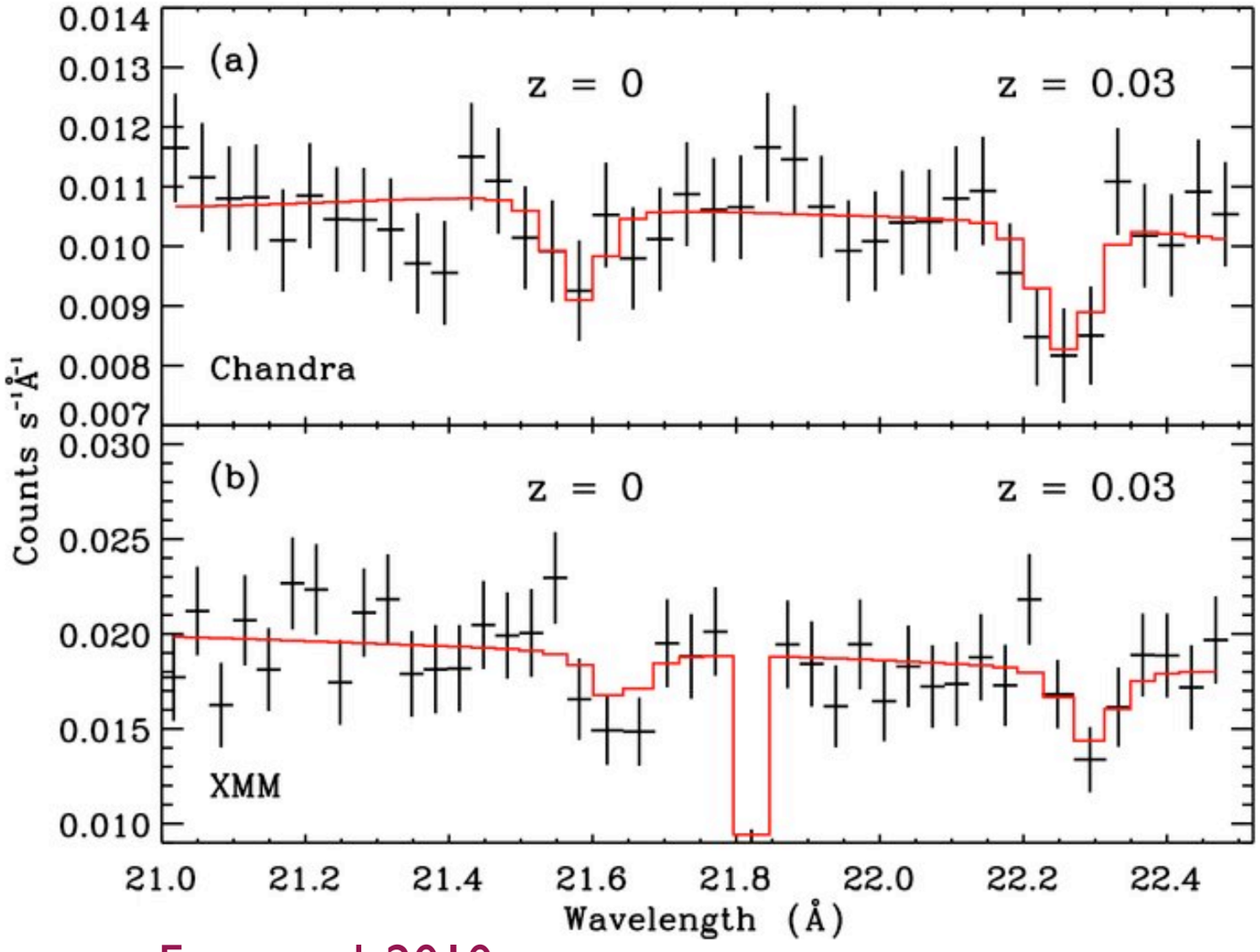


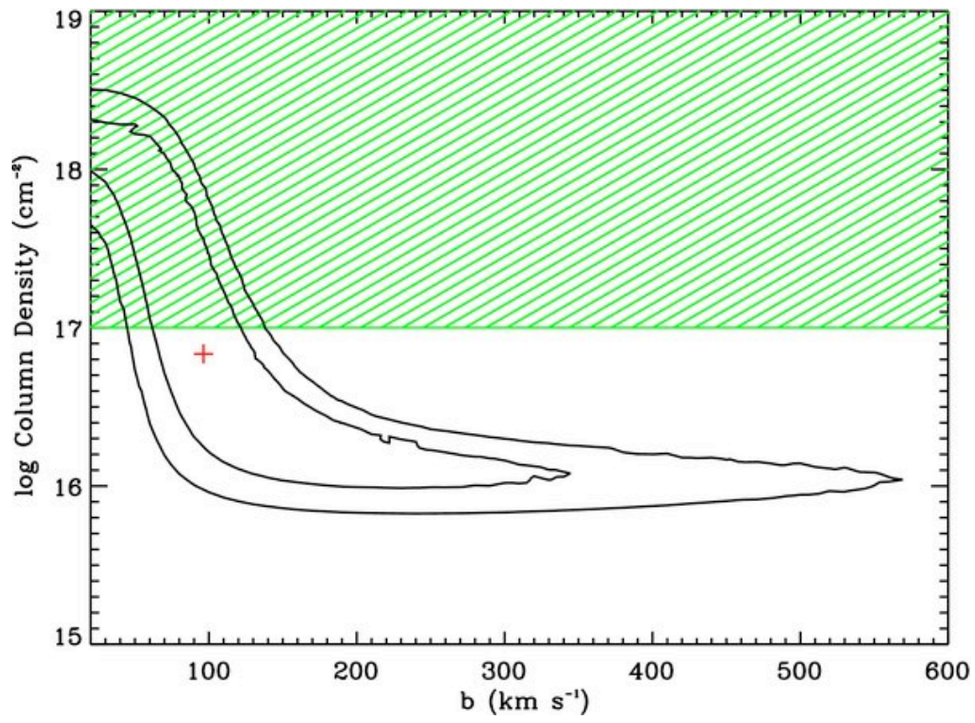
H2356-309: Sculptor Wall



Zappacosta et al. 2010

H2356-309: Sculptor Wall

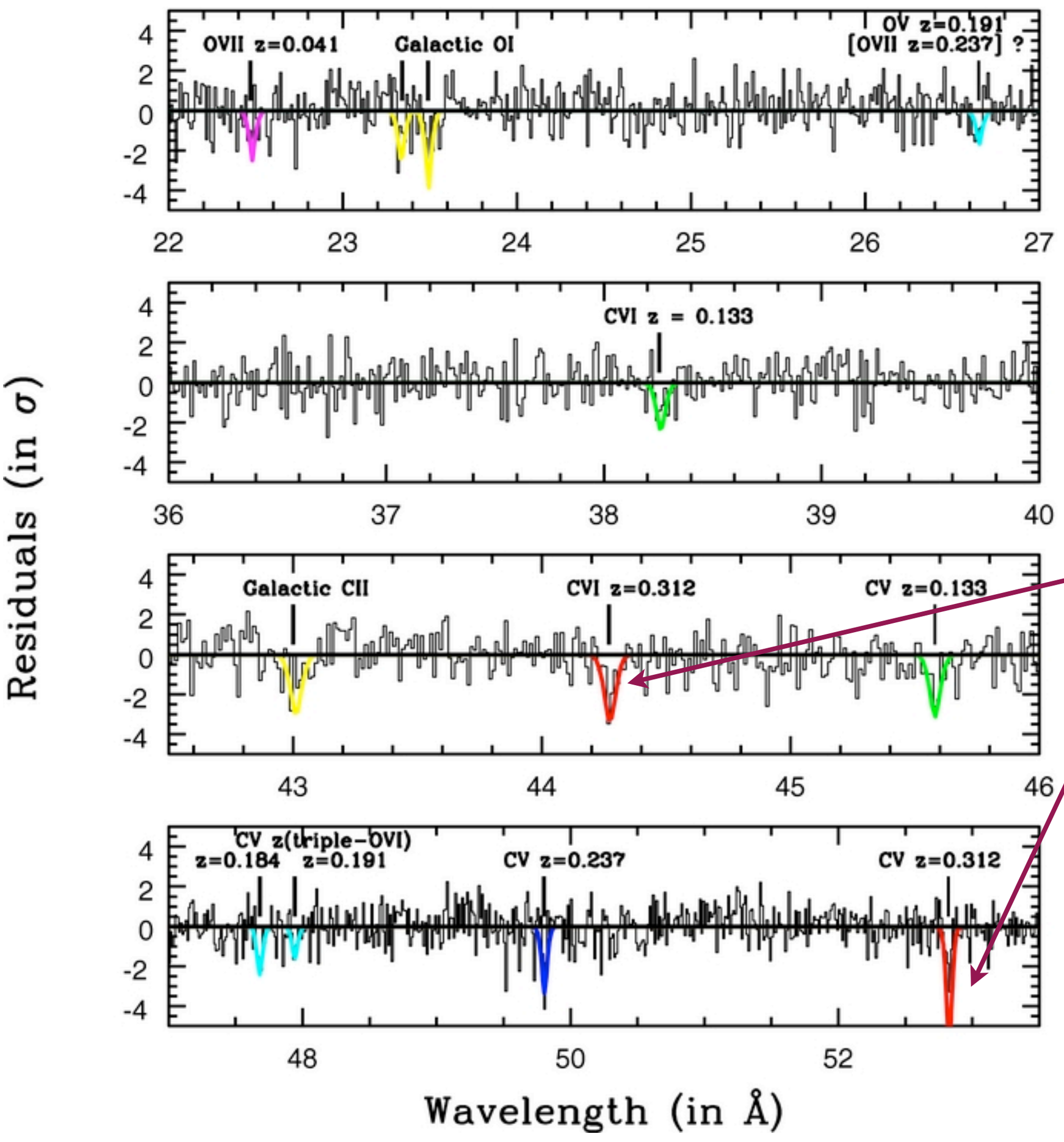




Fang et al. 2010

$$n = 6 \times 10^{-6} (\mathrm{cm}^{-3}) \times \frac{N_{\mathrm{O\,VII}}}{2 \times 10^{16}\ \mathrm{cm}^{-2}} \left(\frac{f_{\mathrm{O\,VII}}}{1}\right)^{-1} \left(\frac{Z}{0.1\ Z_{\odot}}\right)^{-1} \left(\frac{L}{15\ \mathrm{Mpc}}\right)^{-1}.$$

so $\delta \sim 30$ (but could be single galaxy halo)



IES1553+113
Chandra LETGS
Nicastro *et al.* 2013

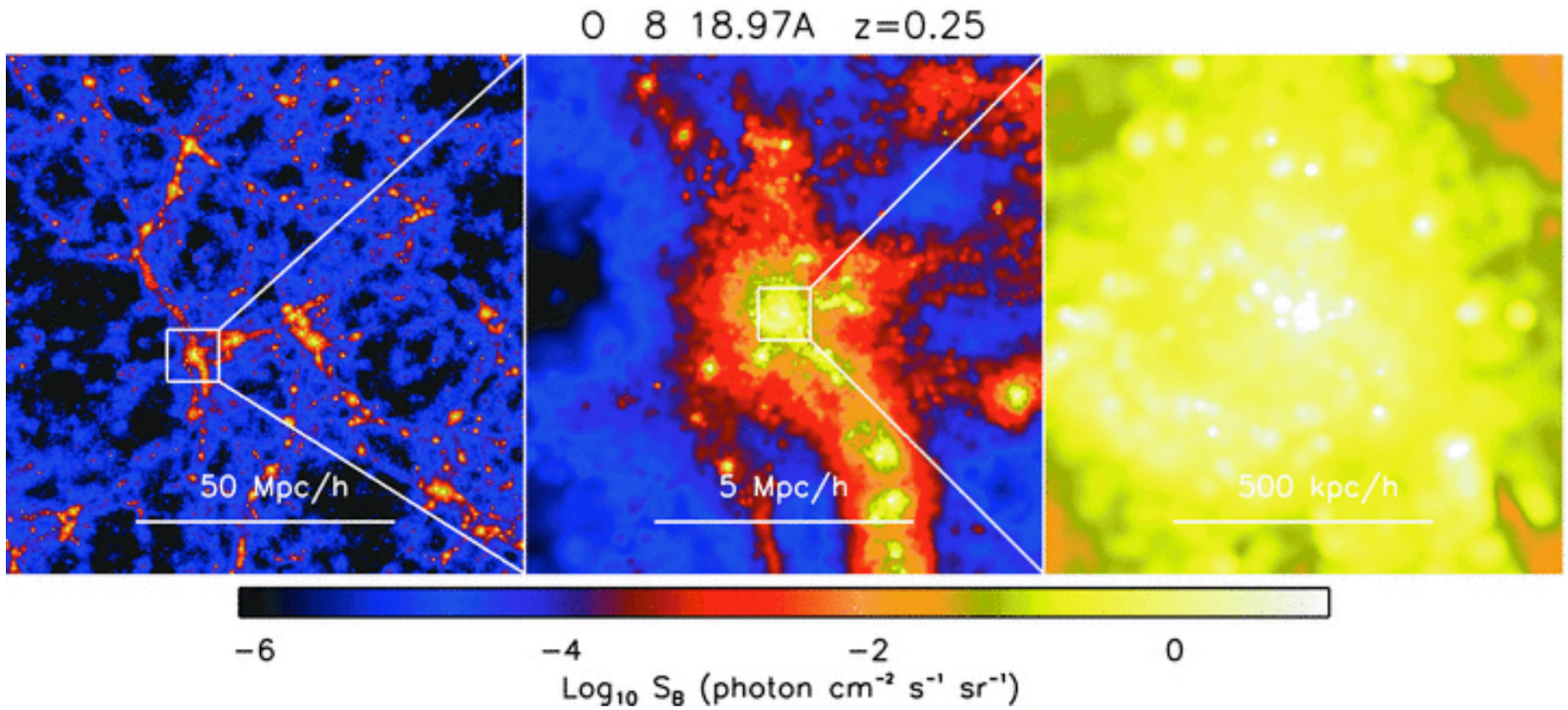
C V, VI n=1-2

also BLA, OVI
at z = 0.312

in the meantime, we have found ample evidence for galactic outflows/winds: local metal 'pollution'

Likely we'll find this first in X-ray absorption-

but then no Ω_B!



Bertone, Schaye *et al.* 2010

Conclusion/Absorption:

experimental picture heterogeneous;
confirms expectations from modeling;
independent confirmation (let alone measurements)
will be very tough

Absorption: The Future

much larger area (> 3000 cm^2); much higher R (> 3000)
microcal no good
even so, will remain sparse (surface density of
F > few 10^{-11} cgs QSO, *especially at z > 0.1*)
auxiliary data absolutely crucial (other bands; galaxy surveys; EMISSION LINE SPECTROSCOPY ?)

few remarks on emission lines

IGM extremely low density: average $\delta \sim 10\text{-}30$

WHIM does emit X-rays (thermal and recombination emission, both discrete and continuum), but extremely faint.

Contrast problem in presence of continuum sources and detector B/G: focus on line emission (contrast $E/\Delta E$); in practice: O VII, VIII

Therefore need imaging spectrometer, small ΔE, large $A_{eff} \cdot \Omega$ ('grasp')

X-ray line emission from the IGM

Most of the medium in strange state: photoionized, possibly out of ionization equilibrium, but mechanically heated (no other analog in astrophysics); line emissivity still dominated by collisional excitation:

$T \sim 2.10^6$ K:

$$< I > \sim (1/4\pi)\, C\, <n_e>^2\, l A\, \Lambda_i\, (T_e)$$

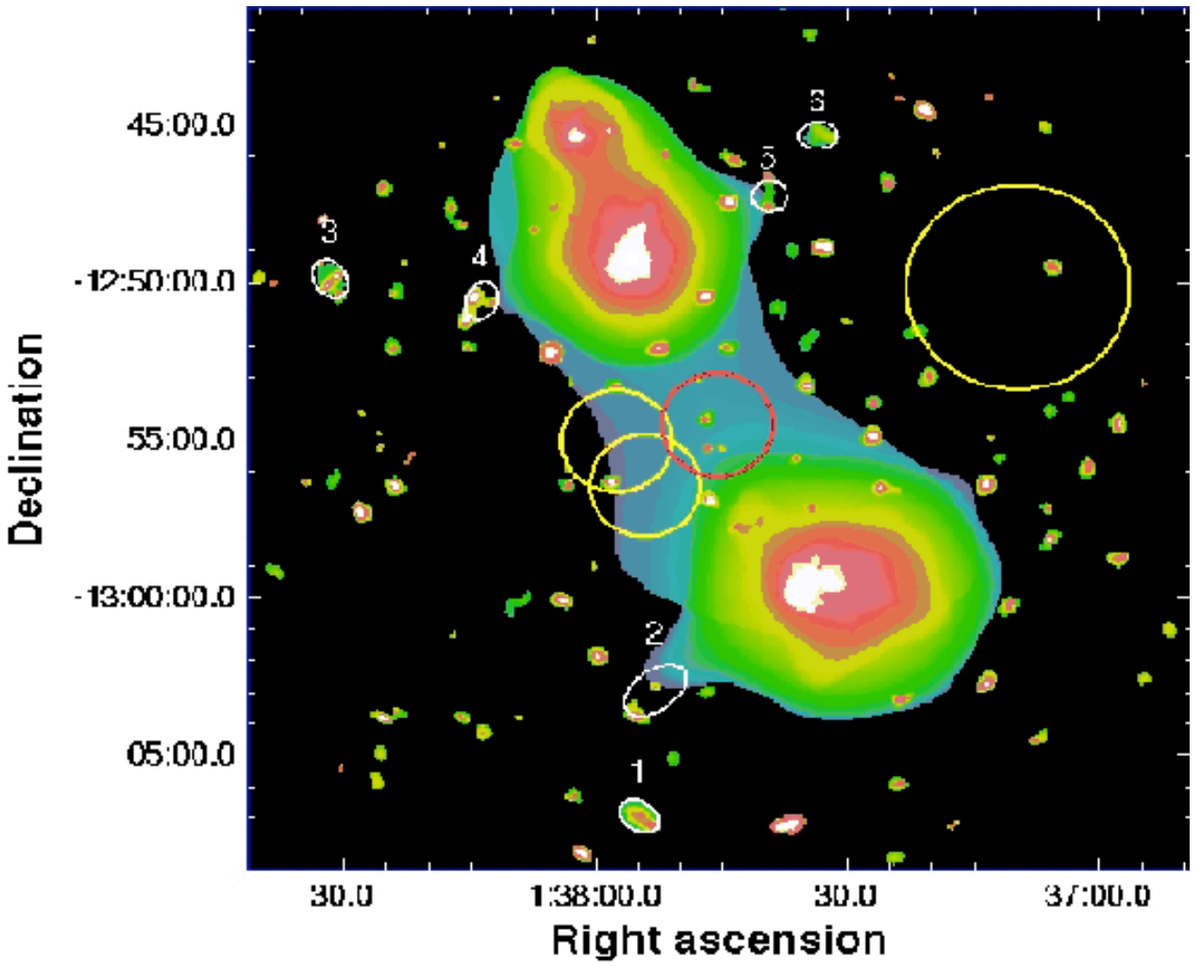
~ 0.1 photon cm^{-2} s^{-1} sr^{-1} **EXTREMELY FAINT!**

($l \sim (1/3)(c/H_0)$, $A \sim 0.1$ Solar)

NB: also get photoexcitation by CXB- rate comparable to collisional rate; with He-like $n = 1$-2 'triplet', get both optical depth *and* volume emission measure!

What do we know?

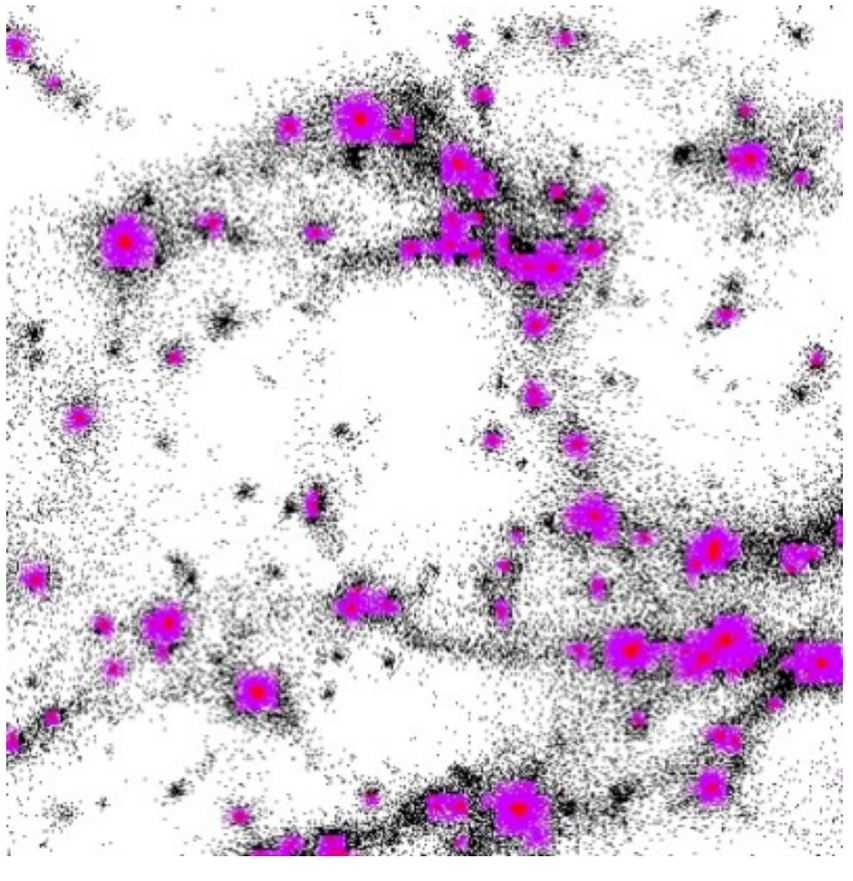
A possible filament between A222, 223



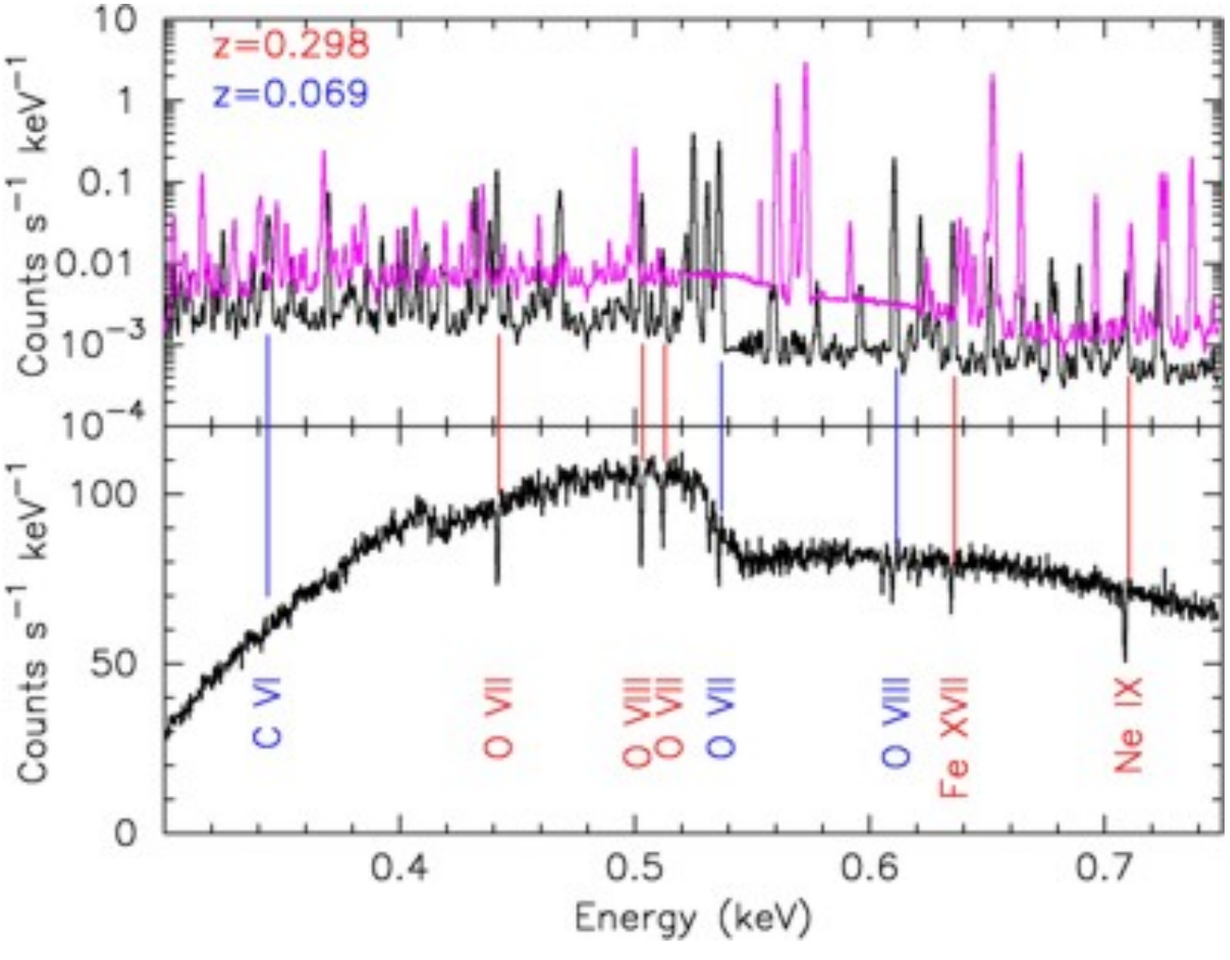
Werner *et al.* 2008; XMM EPIC 0.5-2 keV;
kT ~ 0.9 keV, n ~ 3 x 10^{-5} cm^{-3} (δ ~150)

- *Origin; DIOS*: cryogenic imager (soft band, large FOV, large area)
- ΔE = 2.5 (1.5) eV
- $A\Omega$ = 300 cm^2 deg^2 at 0.5 keV
- fast repointing on GRB afterglows: absorption spectra (GRB are renewable resource, not enough AGN)

- thermal O line emission: ~ 10^{-3} counts/sec



courtesy Yoh Takei/ISAS



Conclusion/Emission:

maybe even harder than absorption

not a natural problem for Athena