Missing baryons at z ~ 0

the latest view from 14 QSO spectra with the Cosmic Origins Spectrograph onboard *HST*

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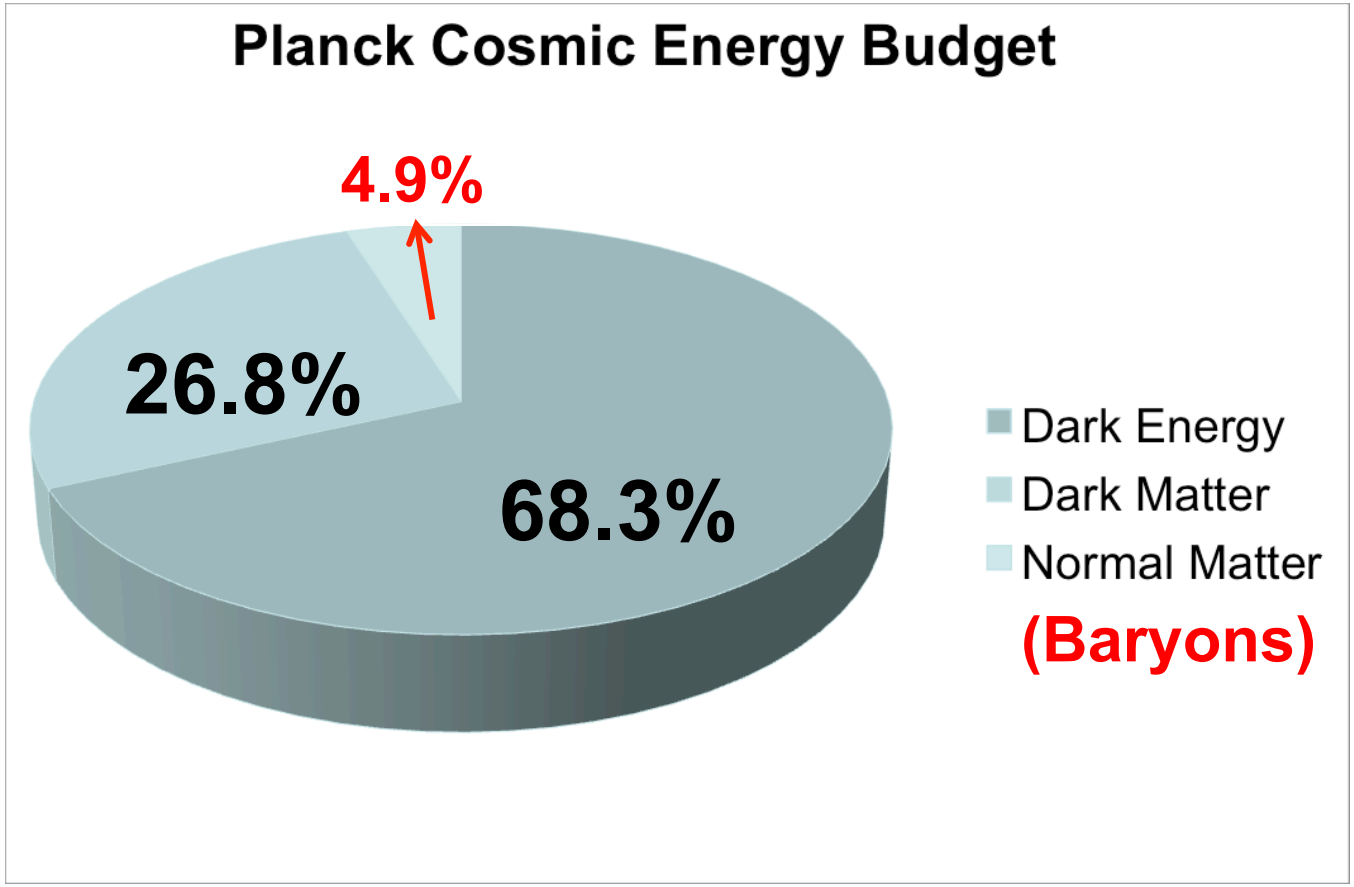
Outline:

1. Overview on the missing baryons at $z \sim 0$
2. Tools: Intergalactic medium (IGM)
3. Latest results from the COS/*HST* survey
4. Future prospects
5. Conclusions



Planck Collaboration+ 13

What are the baryons?

most visible matter in the Universe

a subatomic particle made with 3 quarks

proton, neutrons **(stars, galaxies, gas)**

predicted from the Big Bang Nucleosynthesis

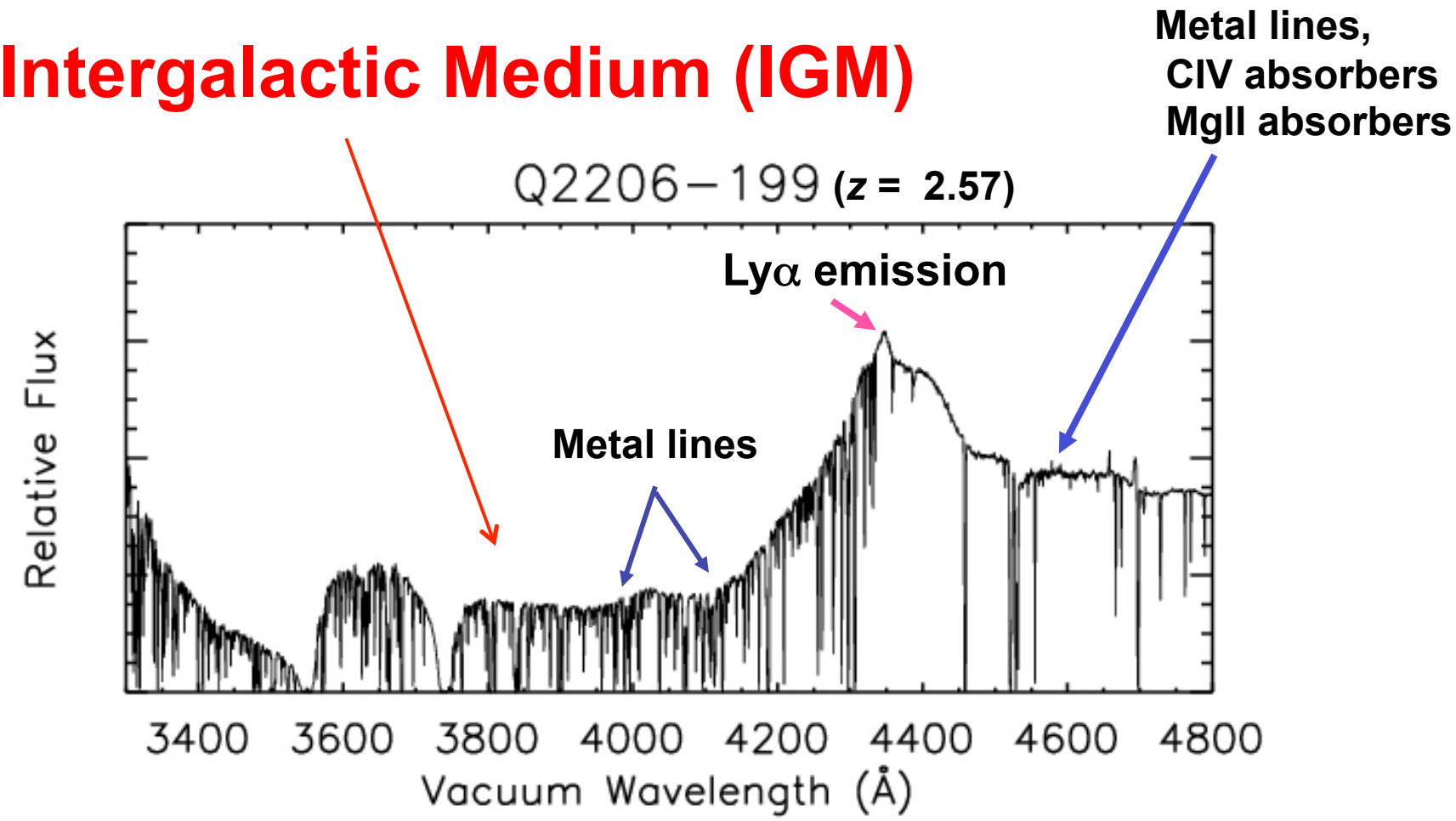
$\Omega_b h^2$ (a fraction of the critical density)

predicted: a few % of the critical density

Planck: $\Omega_b h^2 = 0.02205 \pm 0.00028$

($\Omega_b \sim 0.045$)

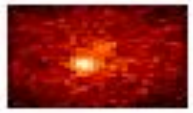
Where are the baryons?

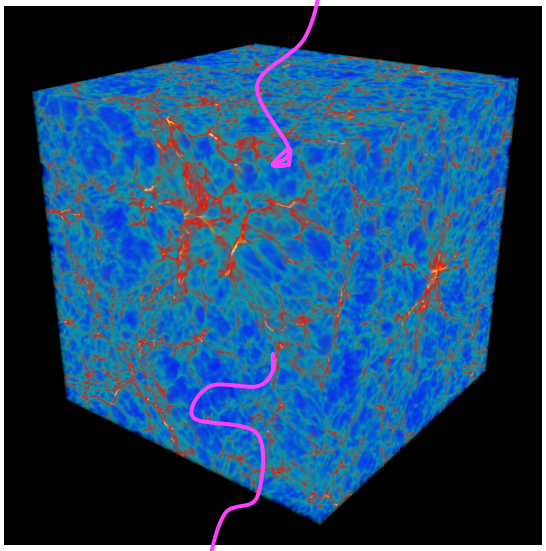


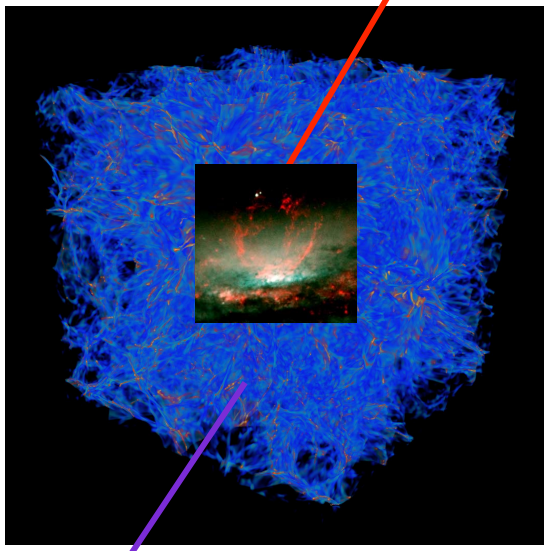
QSOs/Stars

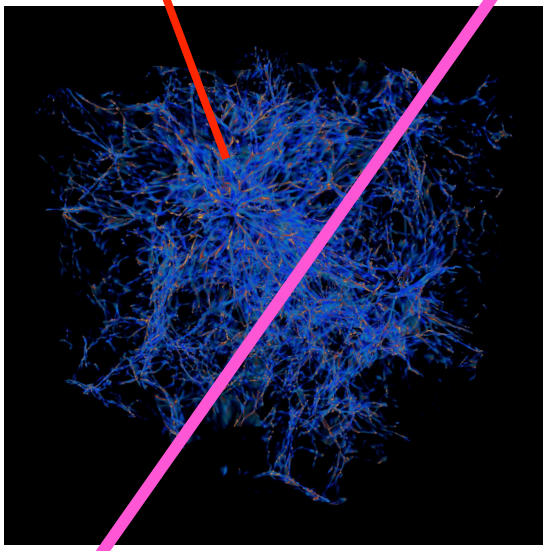
UV photons

Galaxy forming regions:
interplay between galaxies and IGM









z = 7.5

z = 4.8

z = 2.8

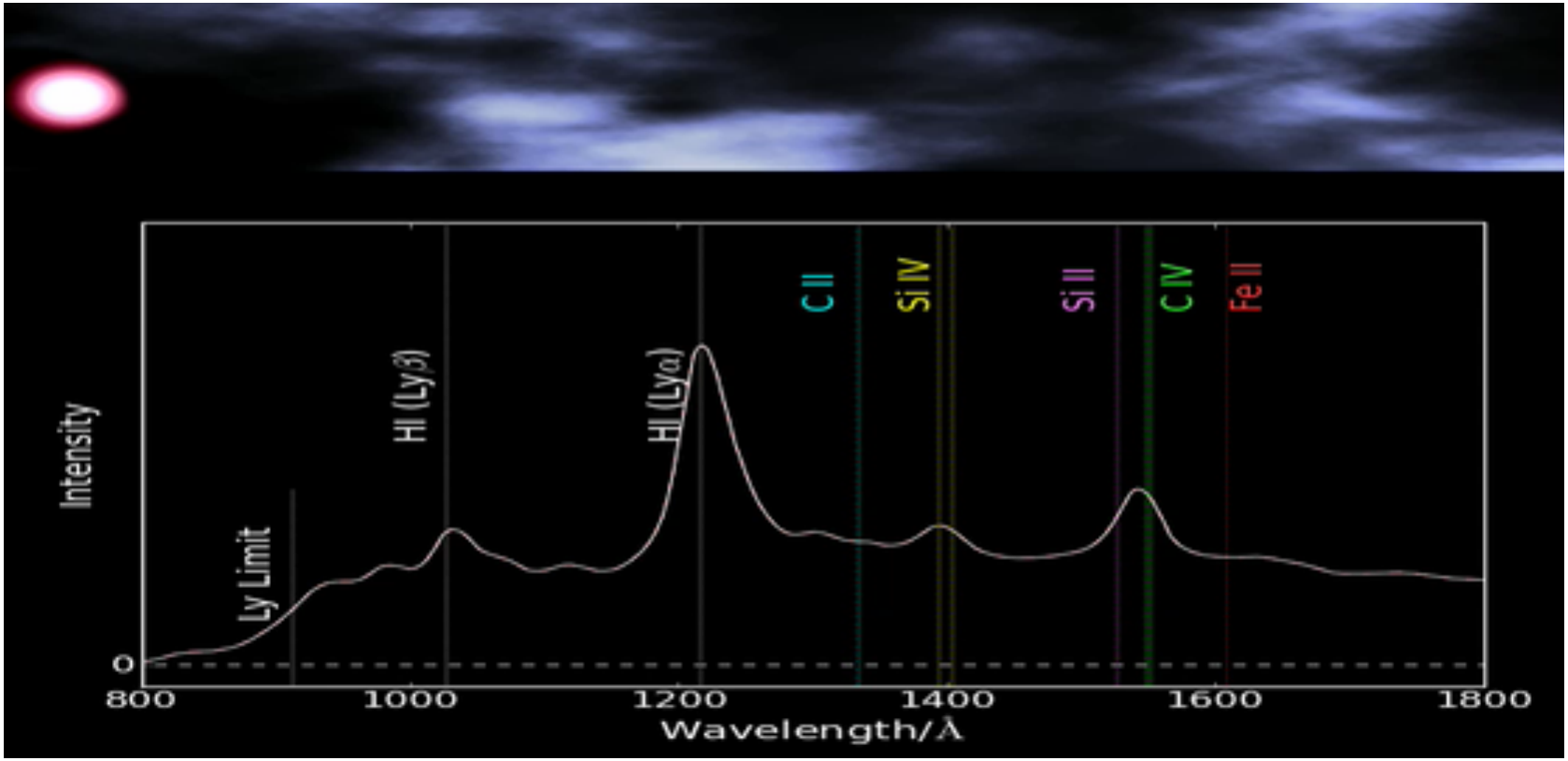
Cen's webpage

Highly ionized hydrogen, helium

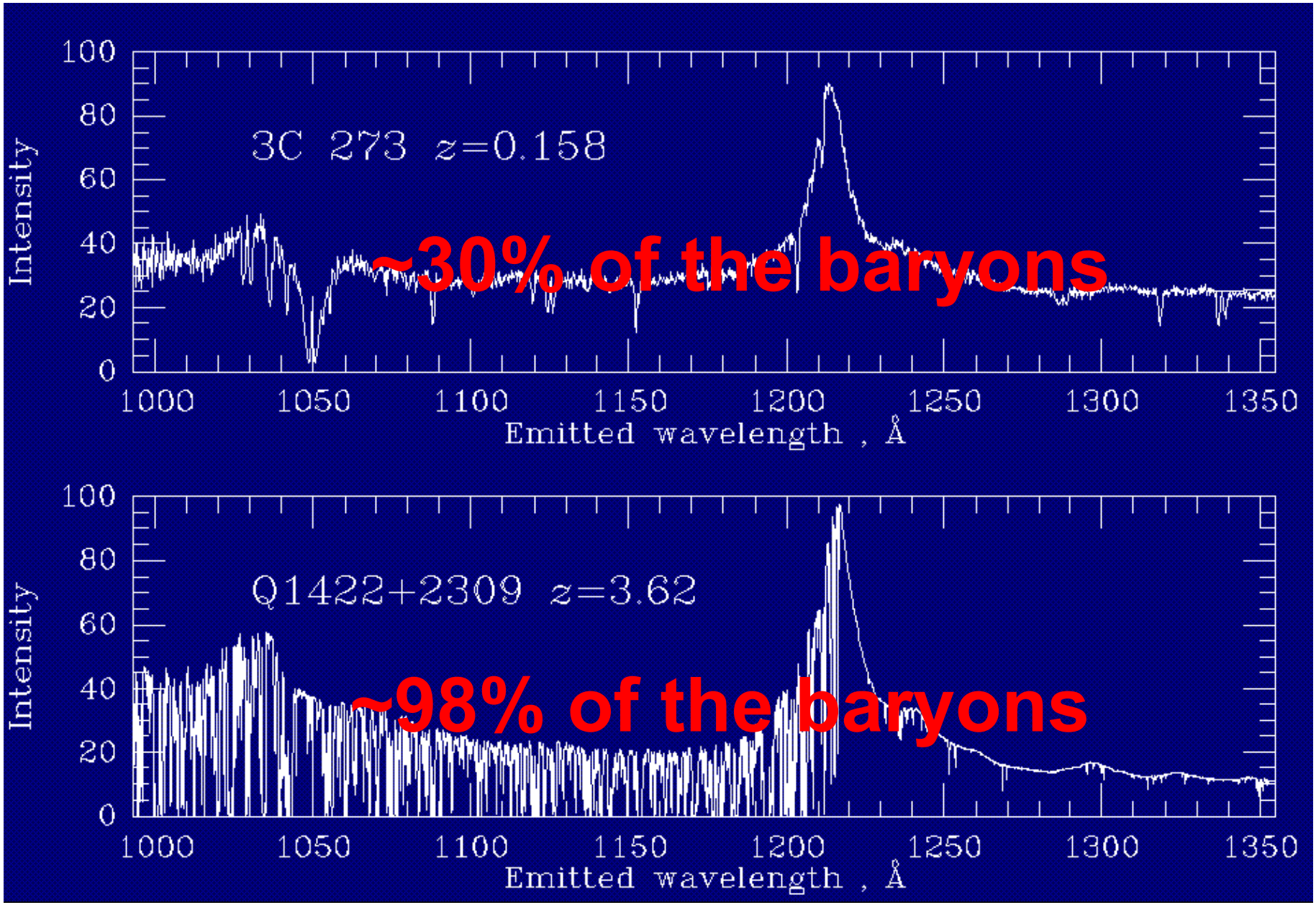
$\lambda_{abs} = \lambda_0 (1+z_{abs})$, $\lambda_o = 1215.67$ A (HI Lyα line)

Highly ionised intergalactic medium:

~ 10^4 K, photoionized by QSOs and galaxies



By A. Pontzen



Courtesy of Jannuzi

THE ASTROPHYSICAL JOURNAL, 503:518–530, 1998 August 20

THE COSMIC BARYON BUDGET (at $z \sim 0$)

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Expected: $\Omega_b \sim 0.045$
Counted: $\Omega_b \sim 0.021$ (0.007 ~ 0.041)
- **galaxies: ~ 8%**
- **intercluster medium (X-ray): ~ 10%**
- **IGM: ~ 6%**
- **Groups: ~ 30%**

THE ASTROPHYSICAL JOURNAL, 514:1–6, 1999 March 20

WHERE ARE THE BARYONS?

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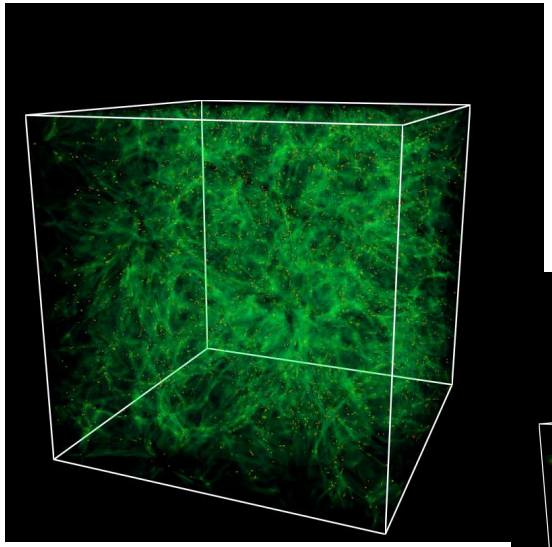
Received 1998 September 11; accepted 1998 October 29

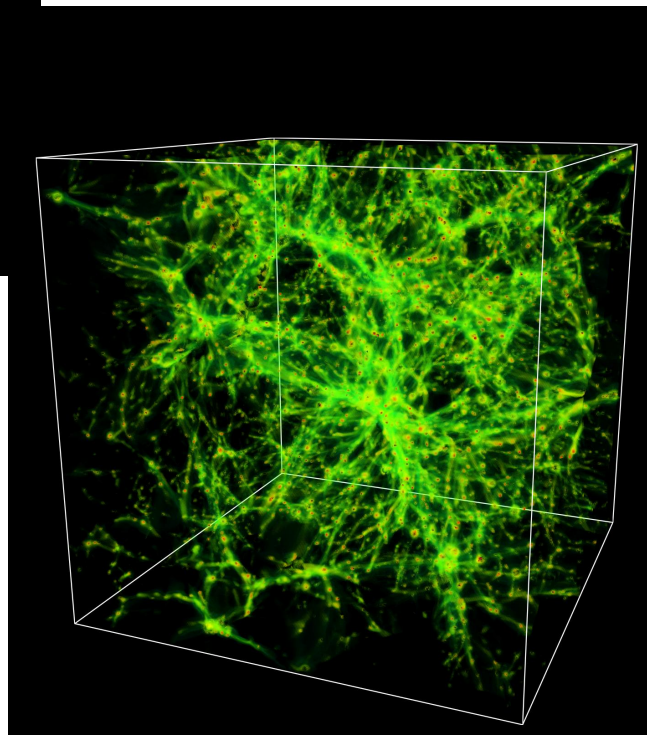
~50% of the baryons is Missing!

$z \sim 0$, IGM temperature

gravitational shock-heated (original)
galactic/AGN feedback (later)

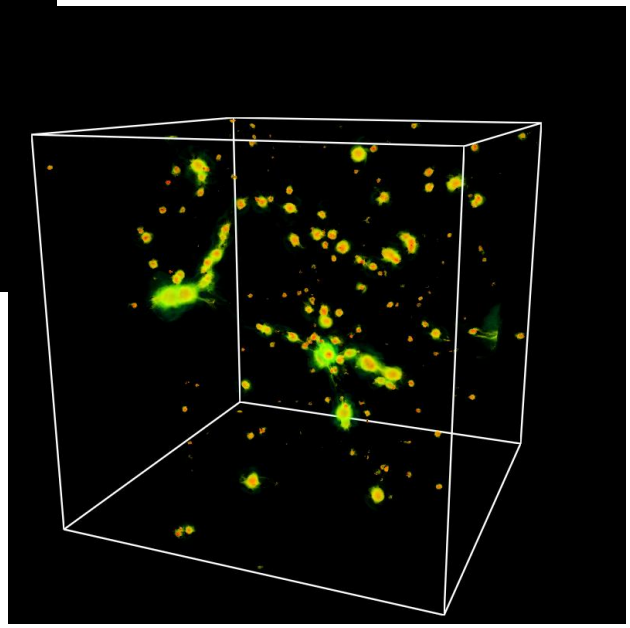


$<10^5$ K
(cool IGM)
Photoionized



$10^{5\text{-}7}$ K
(Warm-Hot IGM)
Collisionally ionized

(hot IGM)
$>10^7$ K



R. Cen's webpage

THE ASTROPHYSICAL JOURNAL, 514:1–6, 1999 March 20

WHERE ARE THE BARYONS?

In the WHIM

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ABSTRACT

New high-resolution, large-scale cosmological hydrodynamic galaxy formation simulations of a standard cold dark matter model (with a cosmological constant) are utilized to predict the distribution of baryons at the present and at moderate redshift. It is found that the average temperature of baryons is an increasing function of time, with most of the baryons at the present time having a temperature in the range of 10^5–10^7 K. Thus not only is the universe dominated by dark matter, but more than one-half of the normal matter is yet to be detected. Detection of this warm/hot gas poses an observational challenge, which requires sensitive EUV and X-ray satellites. Signatures include a soft cosmic X-ray background, apparent warm components in hot clusters due to both intrinsic warm intracluster and intercluster gas projected onto clusters along the line of sight, absorption lines in X-ray and UV quasar spectra [e.g., O VI (1032, 1038) A lines, O VII 574 eV line], strong emission lines (e.g., O VIII 653 eV line), and low-redshift, broad, low column density Lyα absorption lines. We estimate that approximately one-fourth of the extragalactic soft X-ray background (at 0.7 keV) arises from the warm/hot gas, half of it coming from $z < 0.65$ and three-quarters coming from $z < 1.00$, so the source regions should be identifiable on deep optical images.

Doublet!

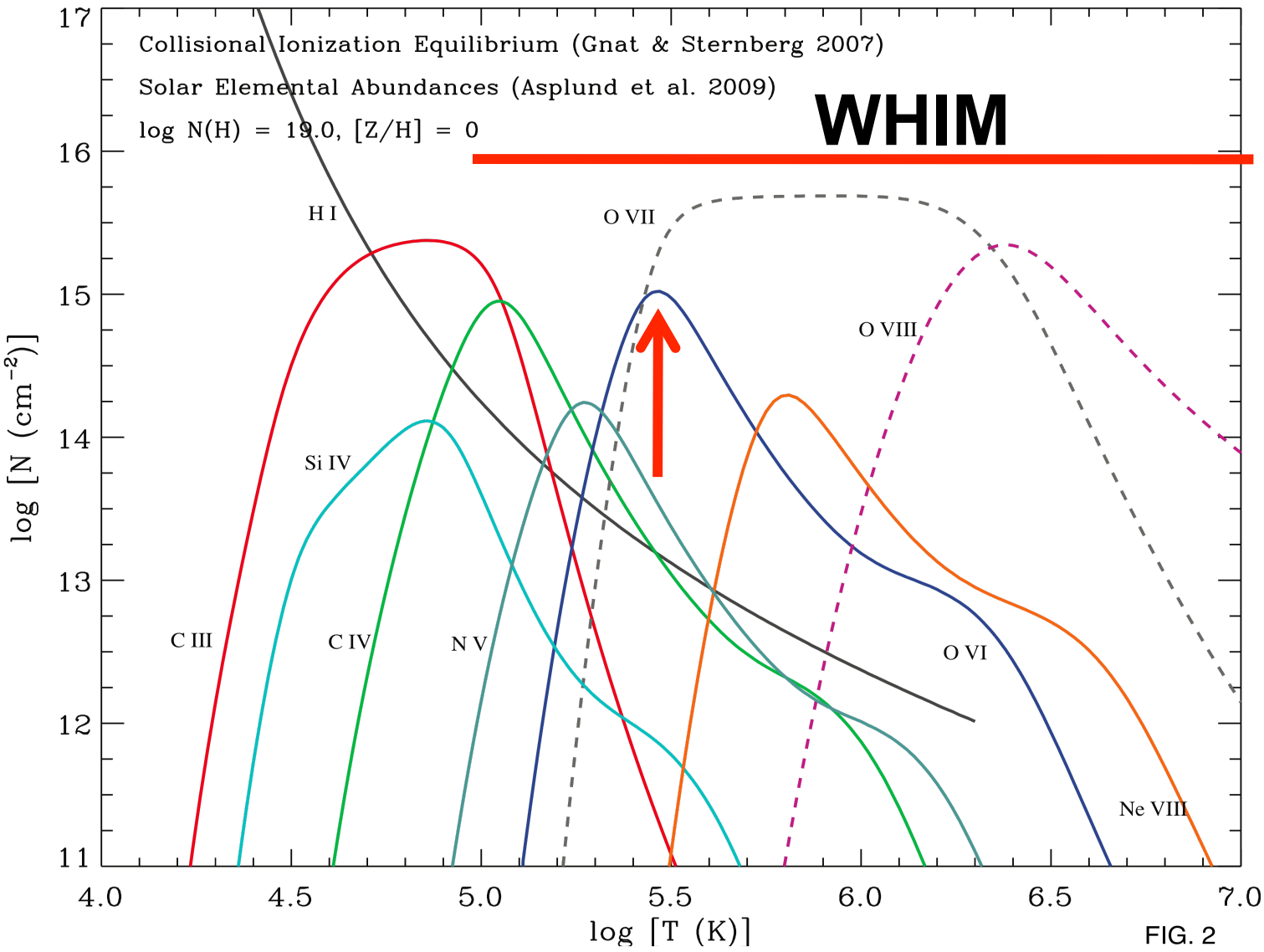
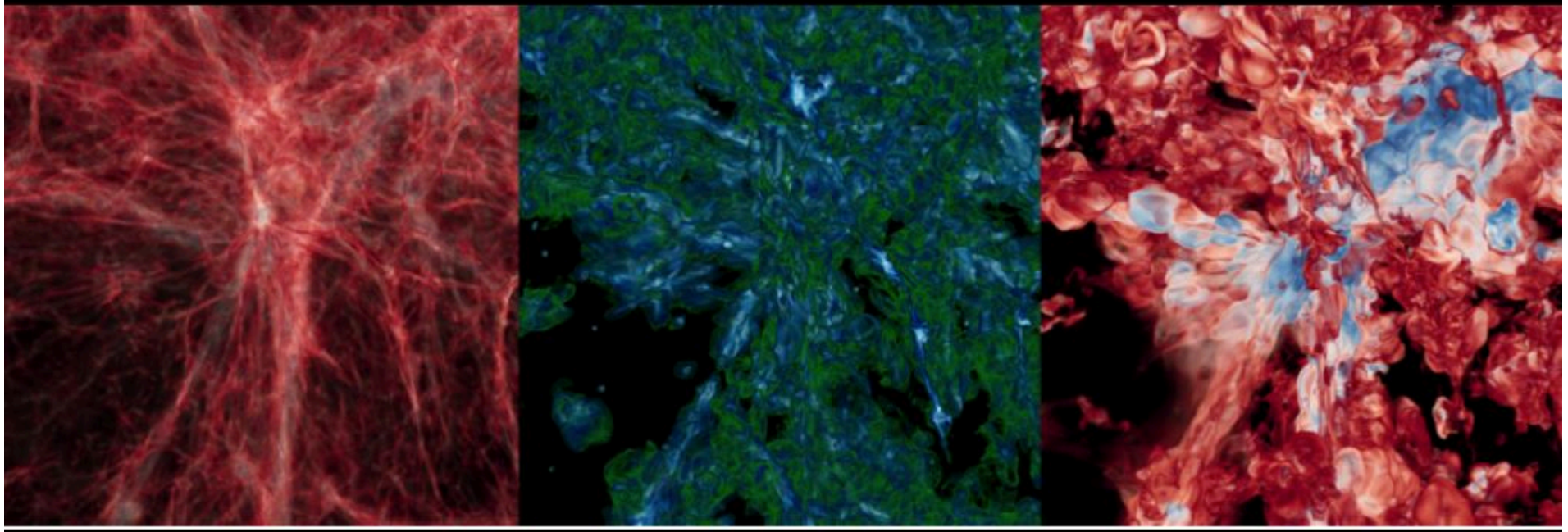

Collisional Ionization Equilibrium (Gnat & Sternberg 2007)
Solar Elemental Abundances (Asplund et al. 2009)
log N(H) = 19.0, [Z/H] = 0
WHIM
H I
O VII
O VIII
Si IV
C III
C IV
N V
O VI
Ne VIII
log [N (cm^{-2})]
log [T (K)]
17
16
15
14
13
12
11
4.0
4.5
5.0
5.5
6.0
6.5
7.0

FIG. 2

Enzo (grid-code) simulations of the low-redshift IGM structure



Gas Density

O VI Density

Temperature

10^5 K (red)
10^7 K (blue)

Britton Smith, Sam Skillman, and the Colorado IGM Theory Group

To derive Ω_b from low-*z* OVI absorbers

$$\Omega_b^{(\mathrm{O\,VI})} = \left[\frac{\mu_b H_0}{c\rho_{\mathrm{cr}}(\mathrm{O/H})_\odot}\right] \int_{N_{\mathrm{min}}}^{N_{\mathrm{max}}} \frac{d\mathcal{N}(N)}{dz} \frac{N}{Z_{\mathrm{O}}(N)\, f_{\mathrm{O\,VI}}(N)}\, dN.$$

How many OVI absorbers?

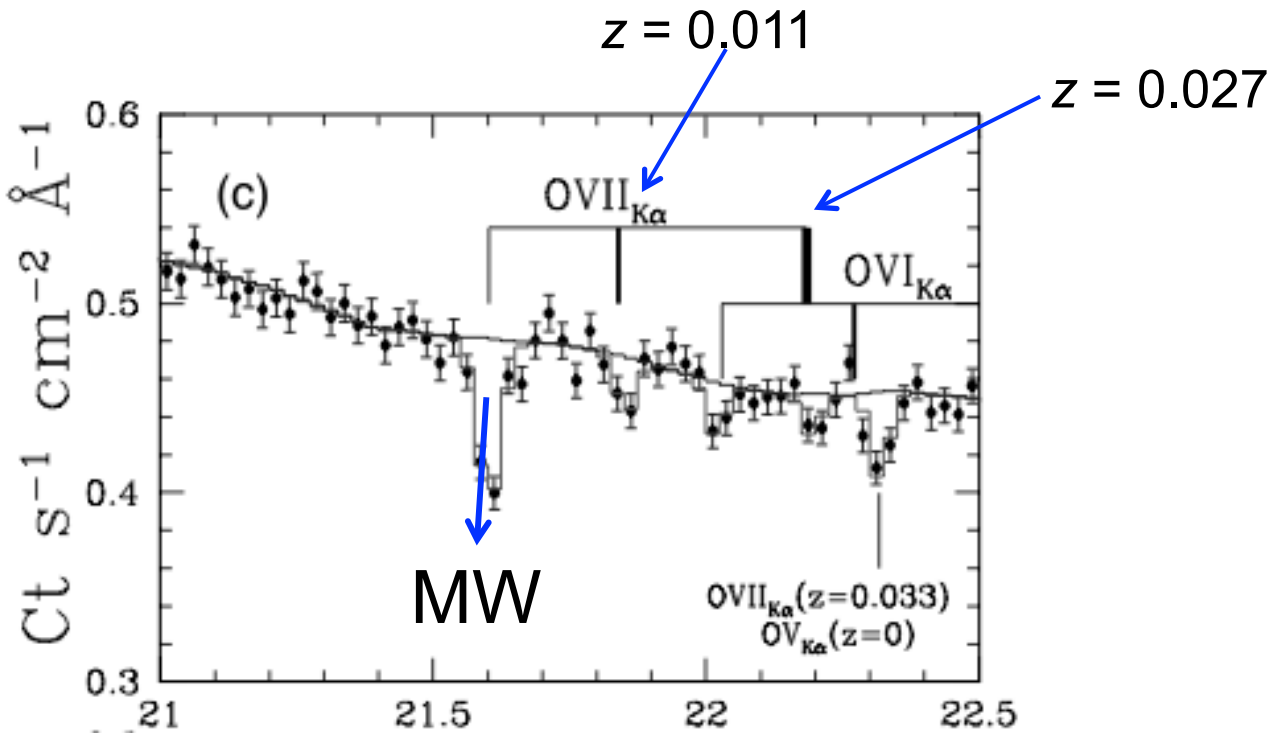
depends on the quality of spectra

What fraction of OVI to total O?

OIV, OV, OVII, OVIII?

Metallicities of OVI absorbers?

X-ray: Chandra spectrum of Mrk421

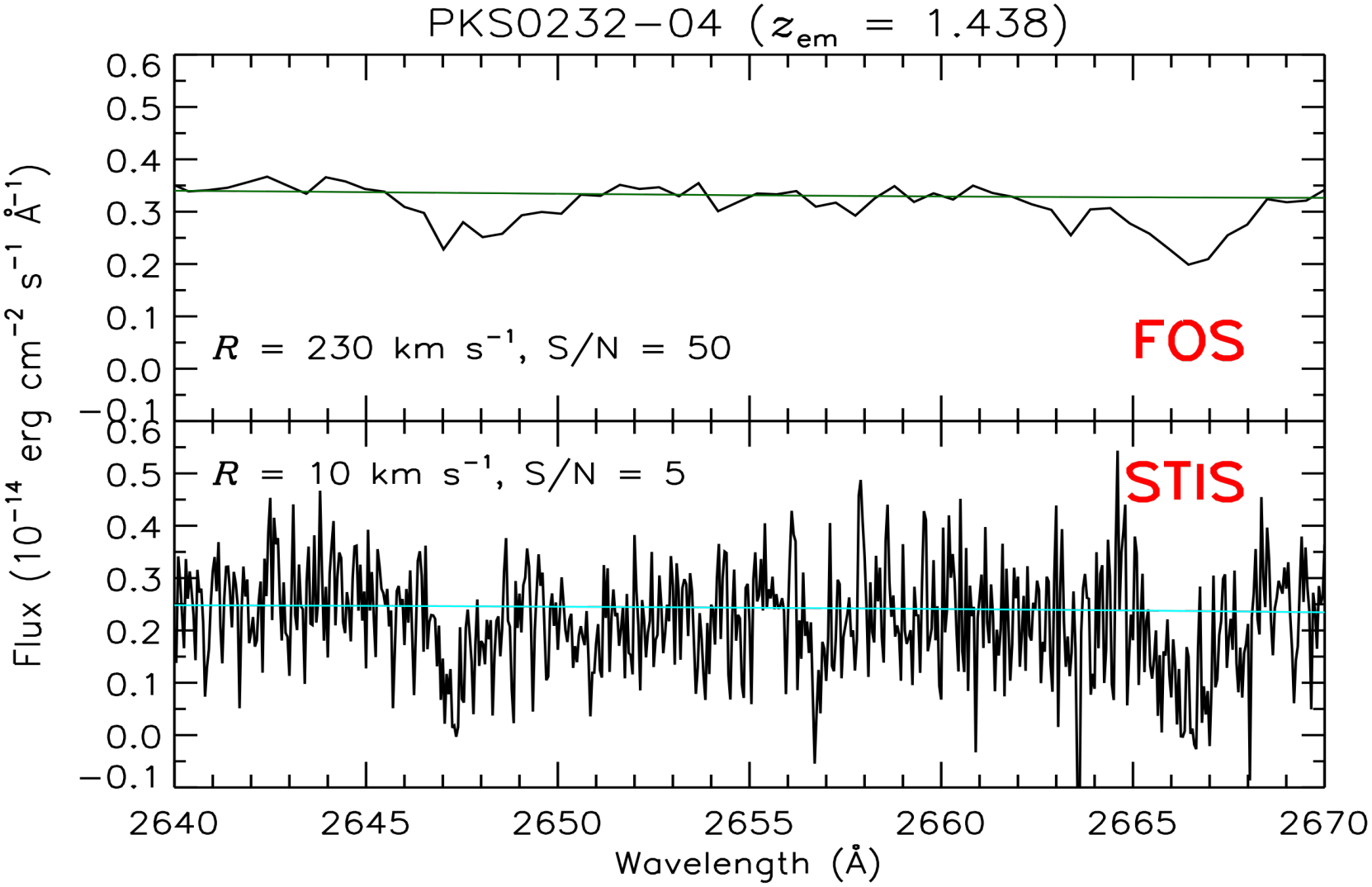


$\Omega_b \sim 0.027$ Nicastro+ 2005

NOT confirmed

NO convincing IGM OVII/OVIII

HST spectrographs: OVI (1031, 1037 A)



Tripp+ (2008): 16 QSOs with STIS/HST

low-*z* OVI statistics & ionization mechanism

51 OVI absorbers, 77 OVI components

7/28 (25%): 4.8 < log *T* < 5.6 (2 questionable)

21/28 (75%): 3.5 < log T < 4.8

~50%: either photoionized or collisionally ionized

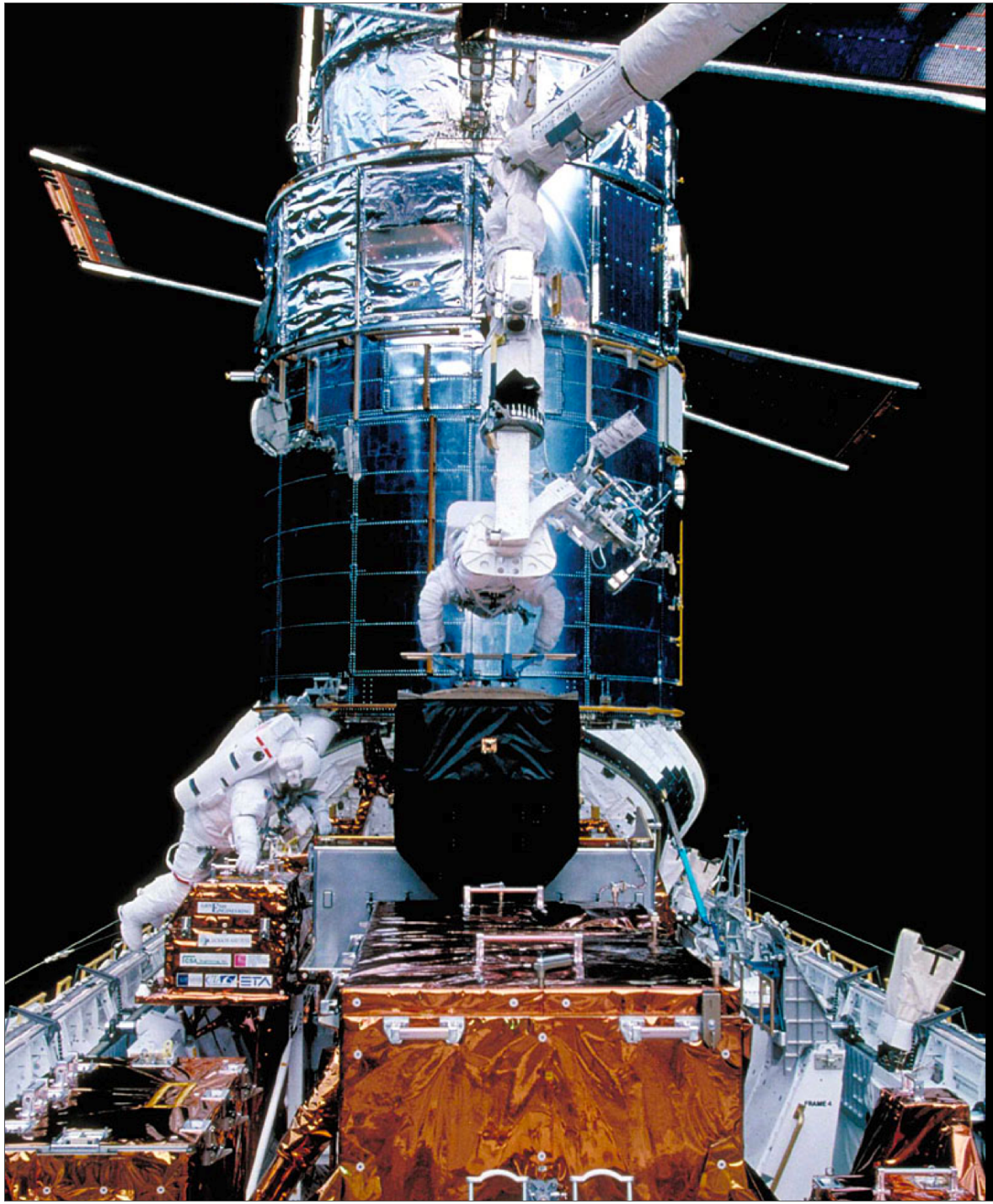
Wakker & Savage (2009): HST & FUSE

14 OVI and galaxy connection at *z* < 0.017

all OVI at closer to galaxies at ~500 kpc

1/3 photoionized, 1/3 collisionally ionized,

1/3 mixed



Next Up!

May 2009

Hubble Servicing Mission #4

Cosmic Origins Spectrograph

Wide-Field Camera-3

Shull (2009)

How many OVI absorbers at z~0?

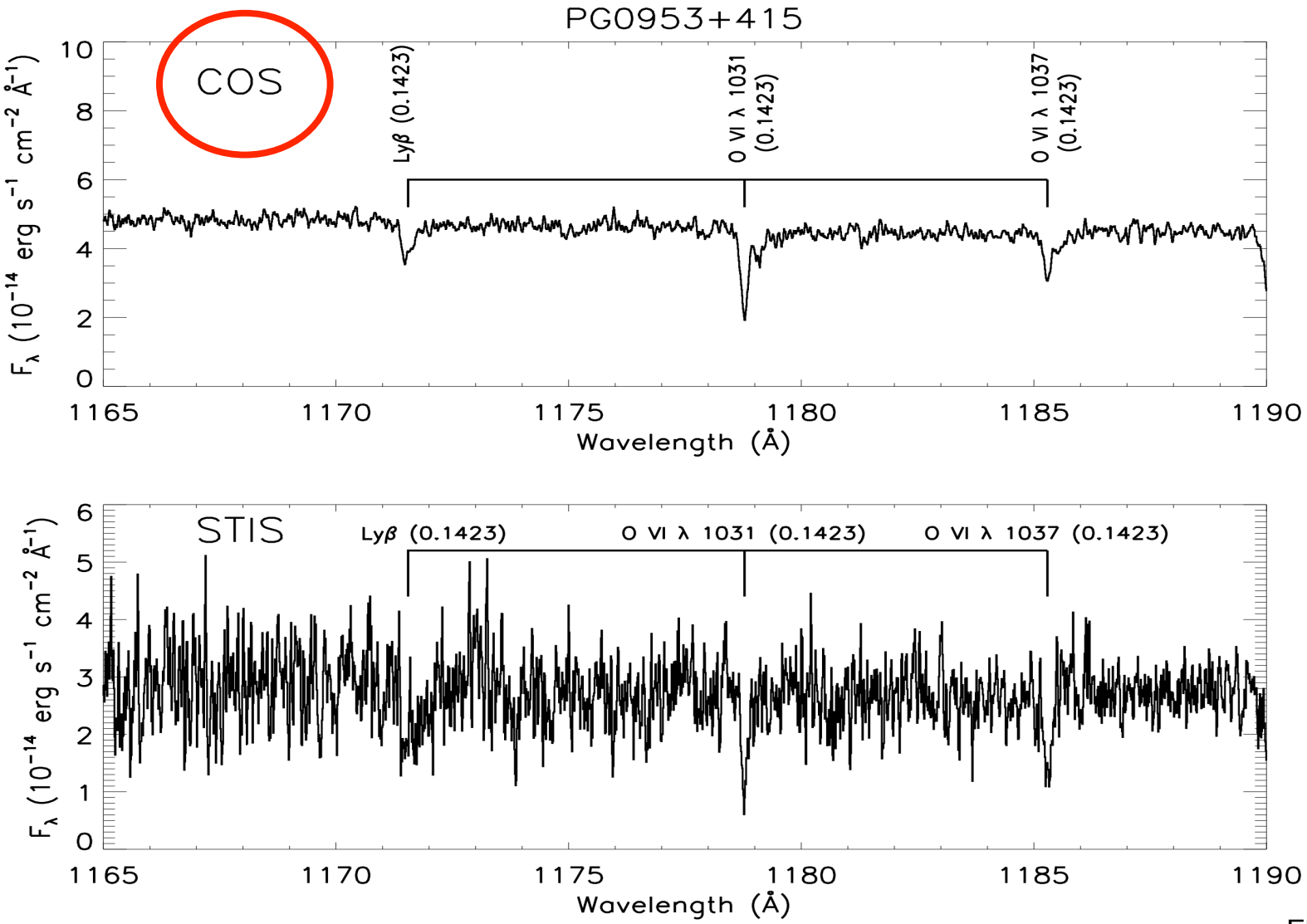
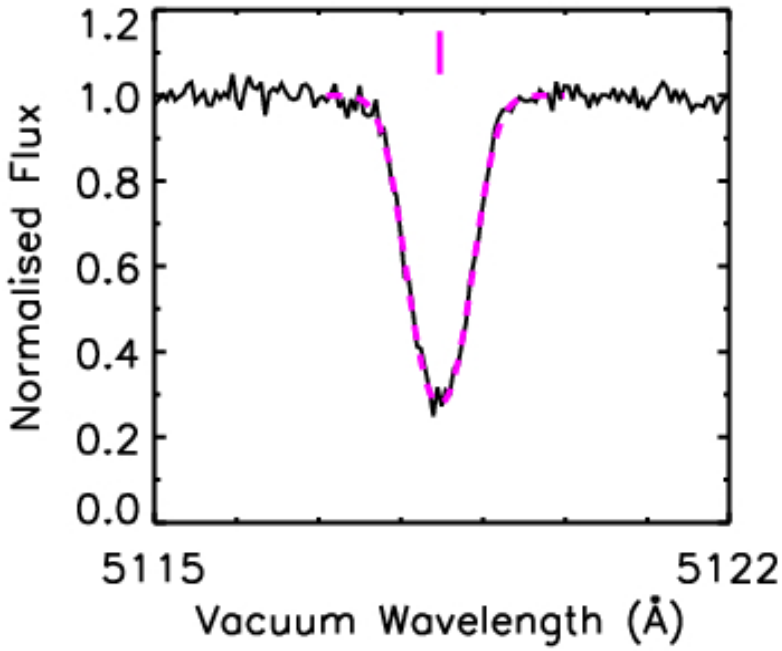


FIG. 1

Voigt profile fitting



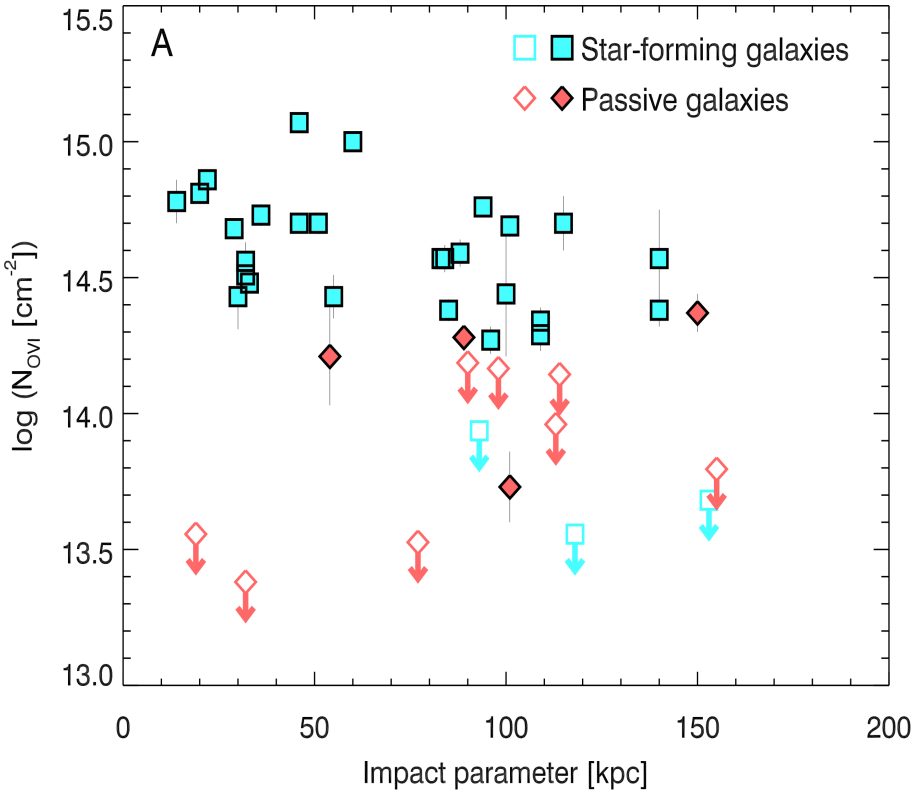
1. column density *N* (cm^{-2})
2. line width *b* (km/sec)

$$b^2 = \frac{2kT}{m} + b_{\rm tur}^2$$

If 2 lines are cospatial, T & $b_{\rm tur}$ are measured

COS high-S/N (> 30) OVI survey at 0 < z < 0.5

1. OVI absorbers from 14 bright QSOs
2. Blind survey, a typical sightline



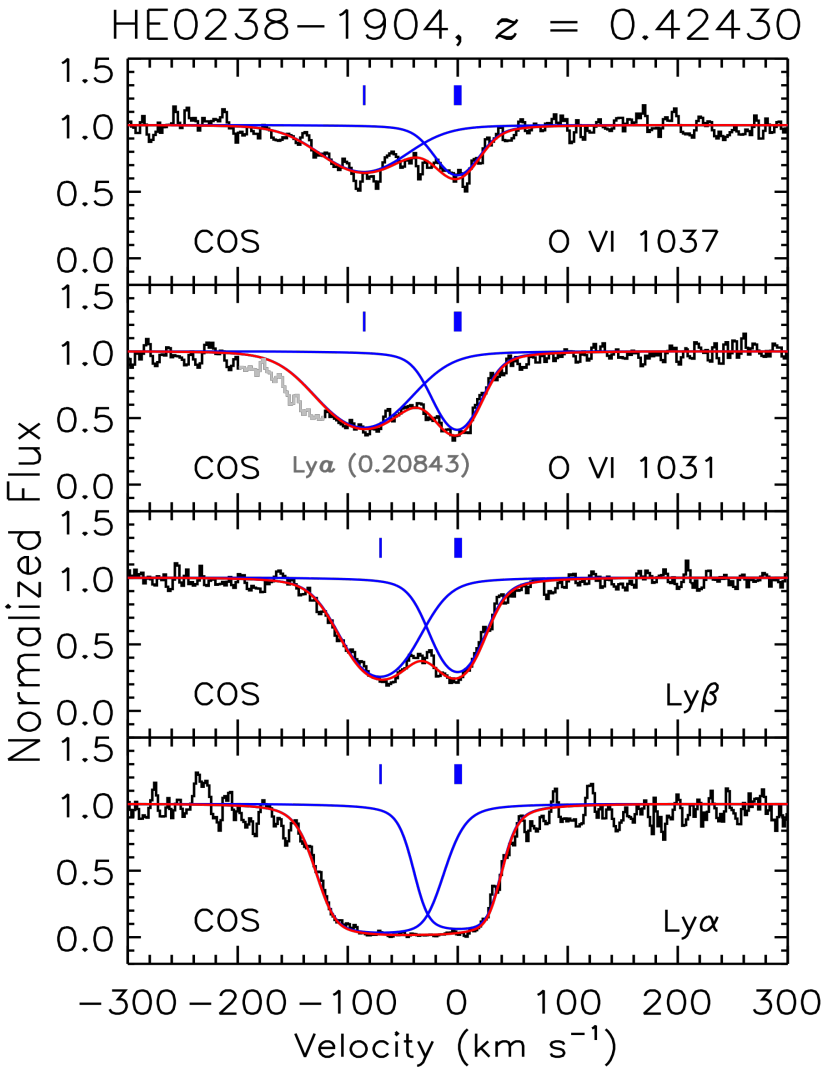
COS-Halo survey

39 QSO+Galaxy pairs

L ~ L* galaxies

IGM OVI is in the CGM

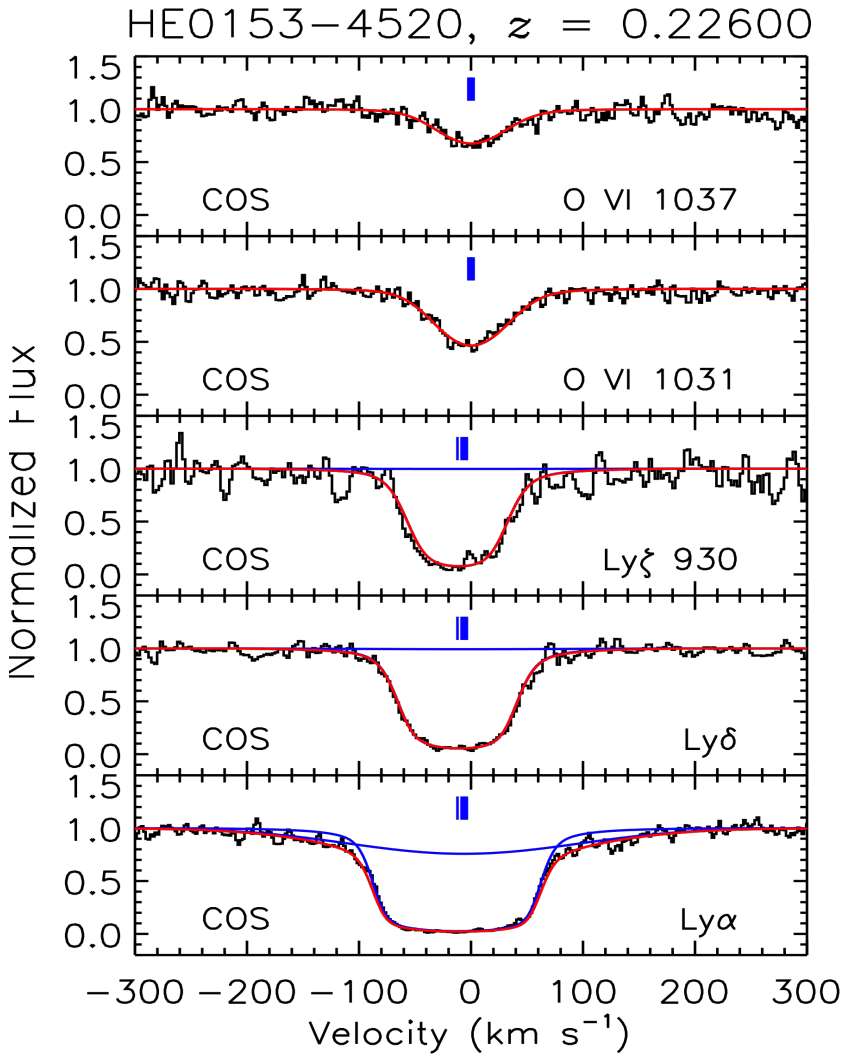
Tumlinson+ (2011, 2013)



Log T = 3.48 +0.38 -3.48

b_{tur} = 23 ± 1 km/sec

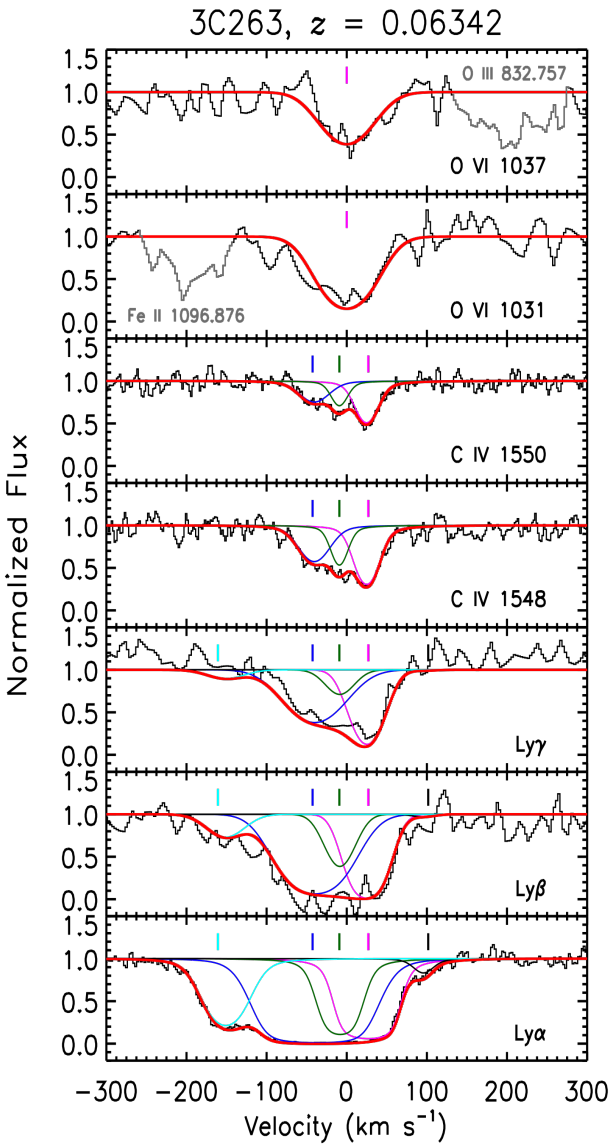
aligned, photoionized



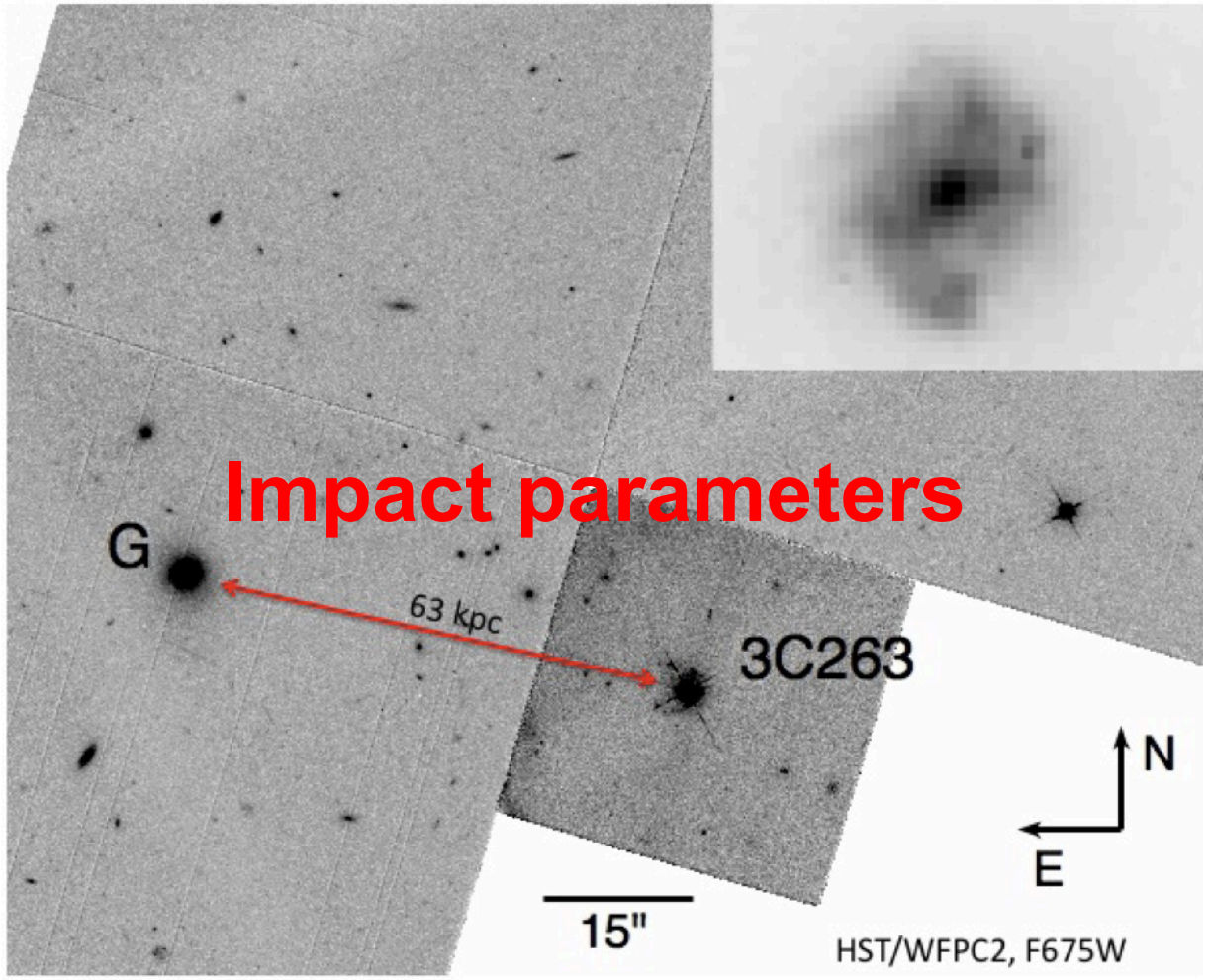
Log T = 6.14 +0.08 -0.10

b_{tur} = < 10 km/sec

collisionally ionized



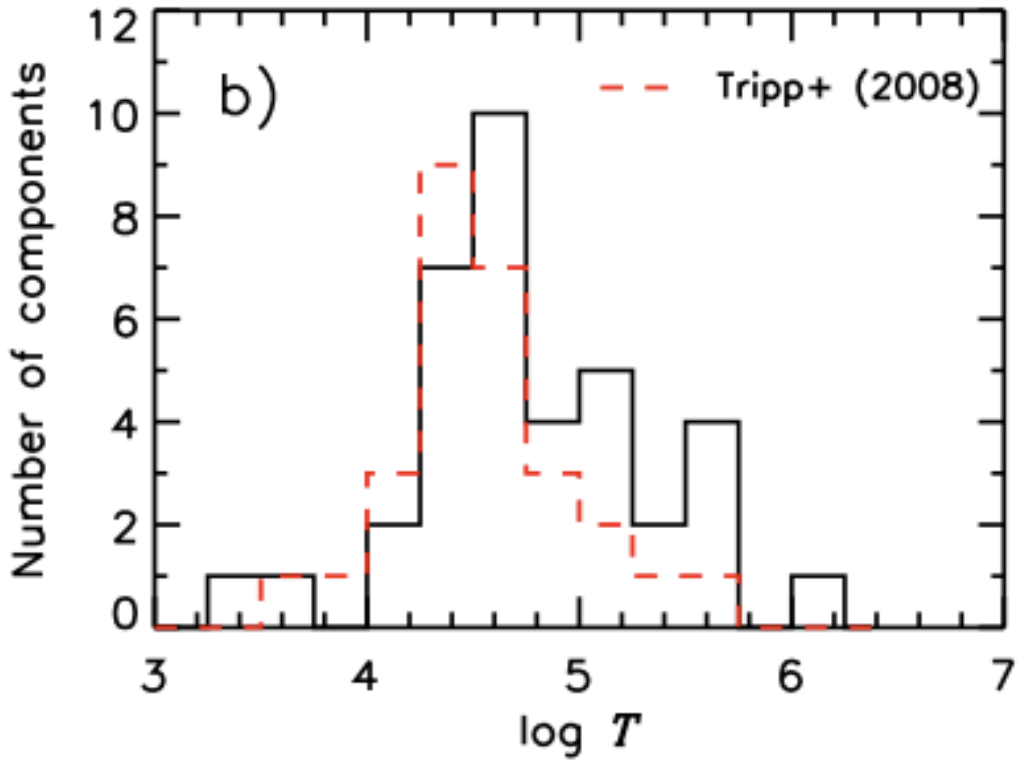
0.31 L*, about solar metallicty

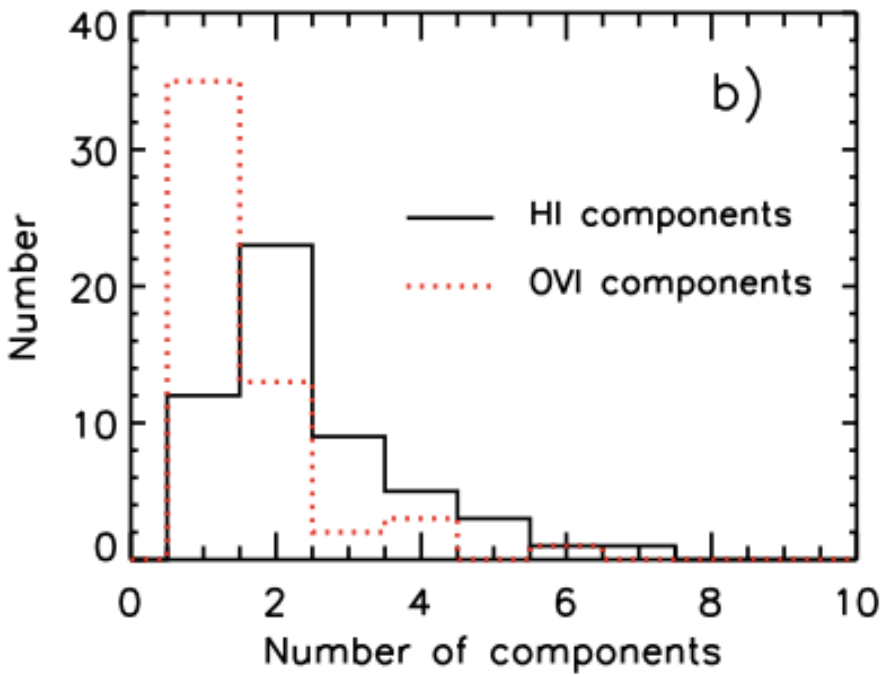


galactic halo: circumgalactic medium

Savage+ 2012

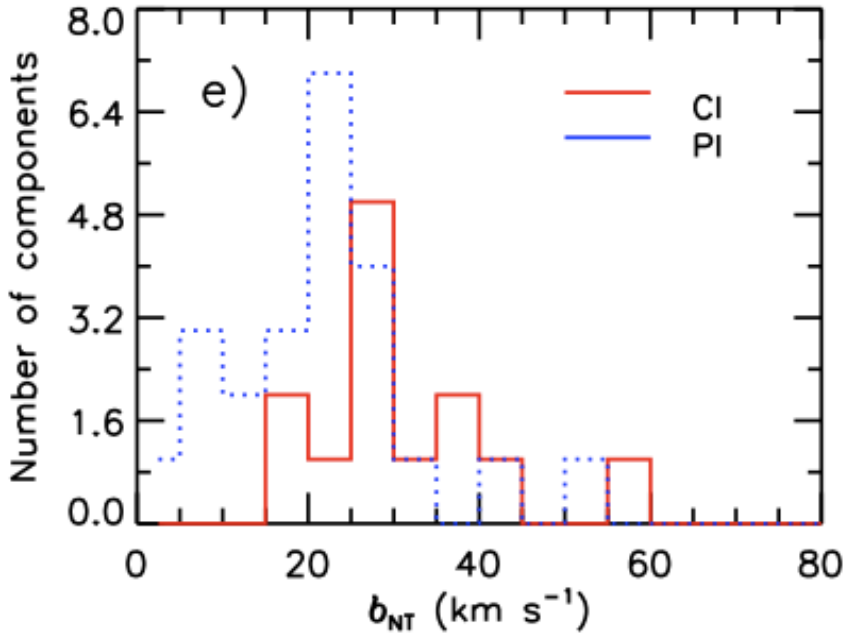
1. 54 OVI absorbers from 14 bright QSOs
2. 85 OVI components, 133 HI components
3. 31/45 (69%) photoionized, < 10^5 K
4. 14/45 (31%) collisionally ionized, > 10^5 K





~50%:

1 OVI + 1 or 2 HI components

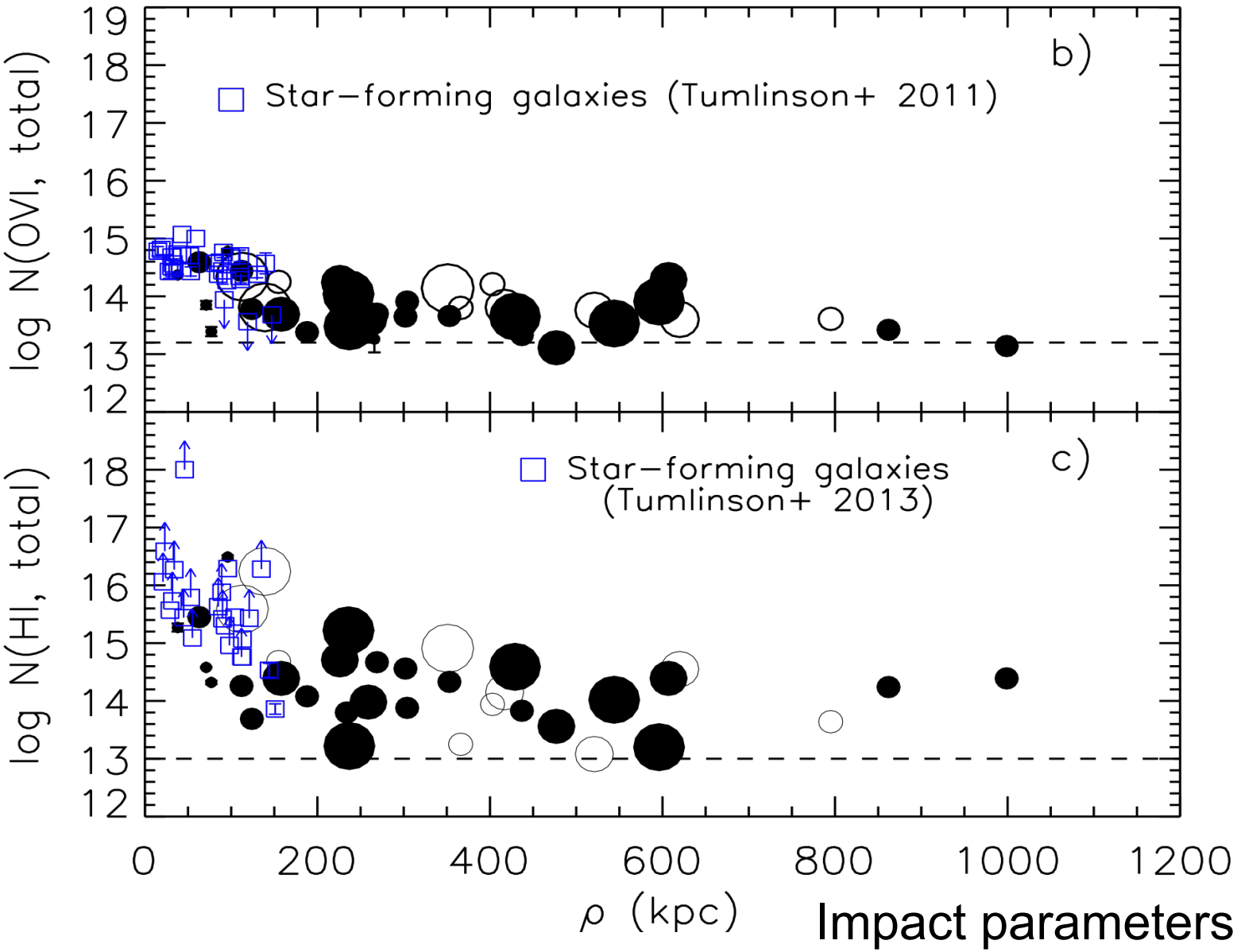


COS blind OVI survey

source	Ω_i/Ω_b (%)
Galaxies	9±3
Hot ICM	4±1.5
Aligned OVI	4.1±1.1
Non-aligned OVI	?
Cool IGM	28±11
Warm IGM	14±7
Hot IGM	?
Total observed	**65±24**
Total expected	**100**

~30% is still missing!

Relation between OVI and Galaxies



Where are collisionally ionized OVI absorbers?

Galaxy survey at $z < 0.15$ down to $L_{lim} < 0.1L^*$

5 collisionally ionized OVI absorbers

a small spiral-rich group at $\rho < 2$ Mpc

What is the future?

Without any upcoming UV facilities planned
in the next 10-20 years

While COS is working:

1. A few more high S/N spectra
2. QSOs at larger impact parameters
3. QSOs at higher redshifts

Deep imaging around QSOs

to search for low-L galaxies
to refute the classical WHIM

Conclusions “One thing to take”:

COS blind OVI survey from 14 QSOs

source	Ω_i/Ω_b (%)
Galaxies	8±3
Hot ICM	4±1.5
Aligned OVI	4.1±1.1
Non-aligned OVI	?
Cool IGM	28±11
Warm IGM	14±7
Hot IGM	?
Total observed	**65±24**
Total expected	**100**

~30% is still missing!