Searching for missing cosmic baryons via Oxygen emission lines

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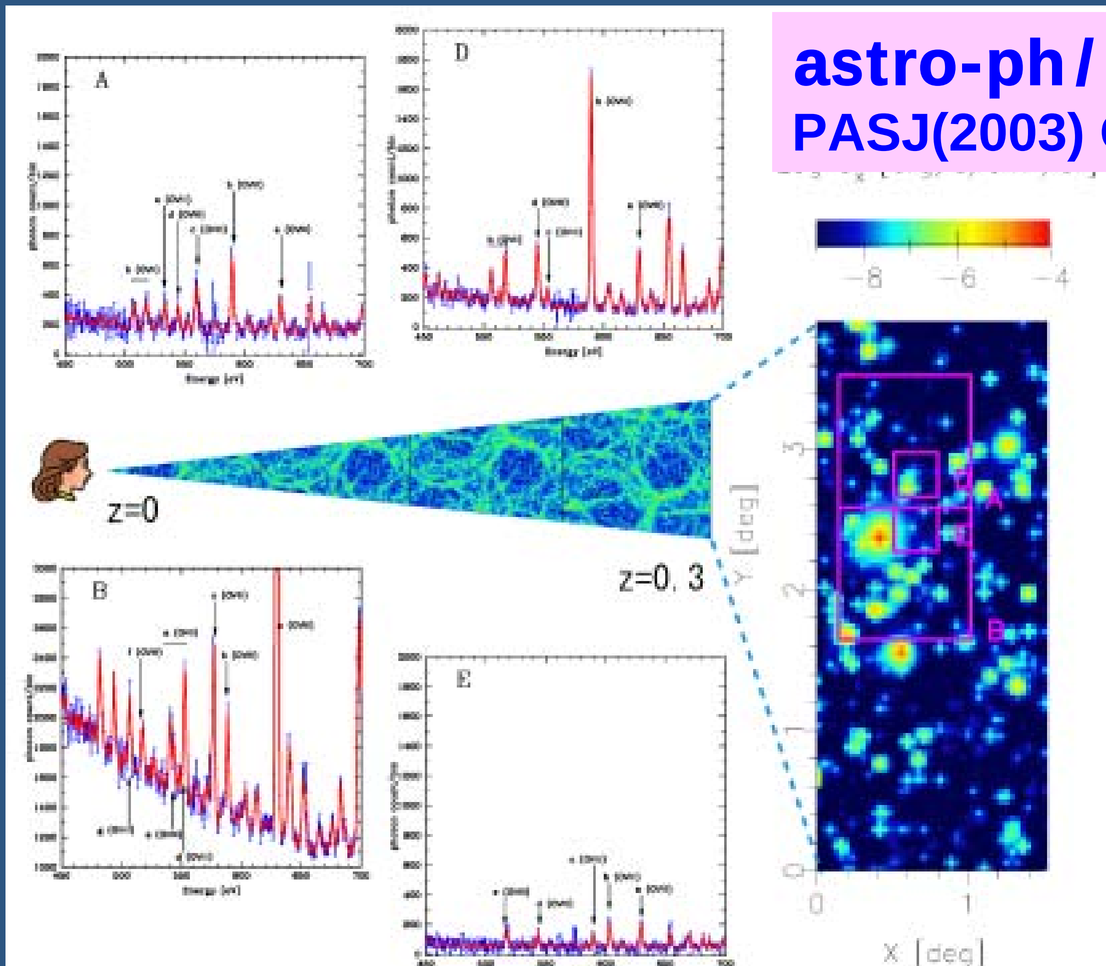

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Wednesday Seminar at Institute of Astronomy
University of Cambridge, August 13, 2003

Topics that I am currently working on (1)

1. Triaxial modeling of density profiles of dark matter halos (Jing & Suto 2002), and its application to X-ray/SZ effect (Lee & Suto 2002) and to lensing arc statistics (Oguri, Lee & Suto 2003)
2. Cosmological light-cone effect (Hamana et al. 2001)
3. Properties of Lyman break galaxies and Lyman alpha emitters from their clustering (Hamana et al. 2003)
4. Phase correlation in Fourier space from nonlinear gravitational clustering (Hikage, Matsubara & Suto 2003)
5. Topology (Minkowski functionals) of SDSS galaxy distribution (Hikage et al. 2003)
6. Morphological dependence in two- and three-point correlation functions of SDSS galaxies (Kayo et al.)

Topics that I am currently working on (2)

7. The largest-separation QSO multiple lensed images from SDSS survey (Inada et al. 2003)
8. The highest angular-resolution Sunyaev-Zel'dovich map (150GHz) and the first submm SZ map (350GHz) of RX J1347-1145 (Komatsu et al. 1999,2001; Kitayama et al.)
9. Searching for scattered light from the transiting extrasolar planet HD209458b with Subaru Suprime-Cam (Suto, Yamada, Turner et al.)
10. Detectability of missing cosmic baryons via Oxygen emission lines (Yoshikawa et al. 2003)

Where are the baryons ? cosmic baryon budget

Fukugita, Hogan & Peebles: ApJ 503 (1998) 518

$$\Omega_{star} + \Omega_{HI} + \Omega_{H_2} + \Omega_{hot\,X-ray} = \mathbf{0.0068^{+0.0041}_{-0.0030}} \quad vs \quad \Omega_{BBN} = \mathbf{0.04} \quad (h = 0.7)$$

Component	Central	Maximum	Minimum	Grade[a]
Observed at $z \approx 0$				
1. Stars in spheroids	$0.0026\ h_{70}^{-1}$	$0.0043\ h_{70}^{-1}$	$0.0014\ h_{70}^{-1}$	A
2. Stars in disks	$0.00086\ h_{70}^{-1}$	$0.00129\ h_{70}^{-1}$	$0.00051\ h_{70}^{-1}$	A–
3. Stars in irregulars	$0.000069\ h_{70}^{-1}$	$0.000116\ h_{70}^{-1}$	$0.000033\ h_{70}^{-1}$	B
4. Neutral atomic gas	$0.00033\ h_{70}^{-1}$	$0.00041\ h_{70}^{-1}$	$0.00025\ h_{70}^{-1}$	A
5. Molecular gas	$0.00030\ h_{70}^{-1}$	$0.00037\ h_{70}^{-1}$	$0.00023\ h_{70}^{-1}$	A–
6. Plasma in clusters	$0.0026\ h_{70}^{-1.5}$	$0.0044\ h_{70}^{-1.5}$	$0.0014\ h_{70}^{-1.5}$	A
7a. Warm plasma in groups	$0.0056\ h_{70}^{-1.5}$	$0.0115\ h_{70}^{-1.5}$	$0.0029\ h_{70}^{-1.5}$	B
7b. Cool plasma	$0.002\ h_{70}^{-1}$	$0.003\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	C
7′. Plasma in groups	$0.014\ h_{70}^{-1}$	$0.030\ h_{70}^{-1}$	$0.0072\ h_{70}^{-1}$	B
8. Sum (at $h = 70$ and $z \simeq 0$)......	0.021	0.041	0.007	...

- The observed baryons in the present universe amount merely to (10〜40) % of the big-bang nucleosynthesis prediction and WMAP value

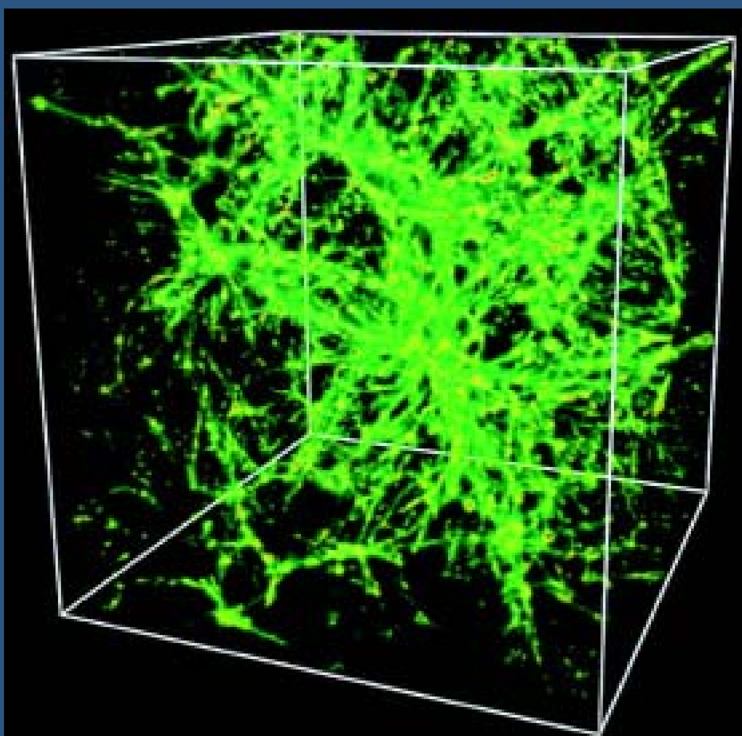
Four phases of cosmic baryons

Dave et al. ApJ 552(2001) 473

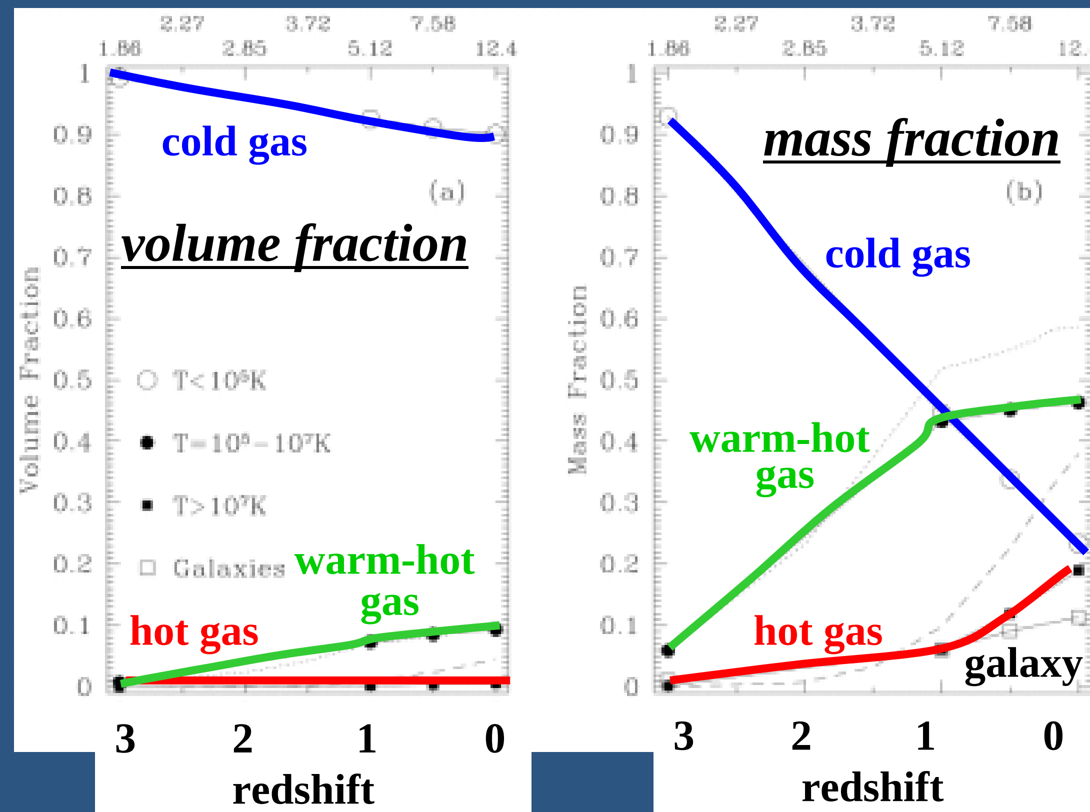
- ***Condensed:*** **δ >1000, T<10^5K**
  - Stars + cold intergalactic gas
- ***Diffuse:*** **δ <1000, T<10^5K**
  - Photo-ionized intergalactic medium
  - Ly α absorption line systems
- ***Hot:*** **T>10^7K**
  - X-ray emitting hot intra-cluster gas
- ***Warm-hot:*** **10^5K<T<10^7K**
  - Warm-hot intergalactic medium (***WHIM***)

Where are the baryons ?

- ~40% of total baryons at z=0 are Warm-Hot Intergalactic Medium (WHIM) with $10^5K<T<10^7K$

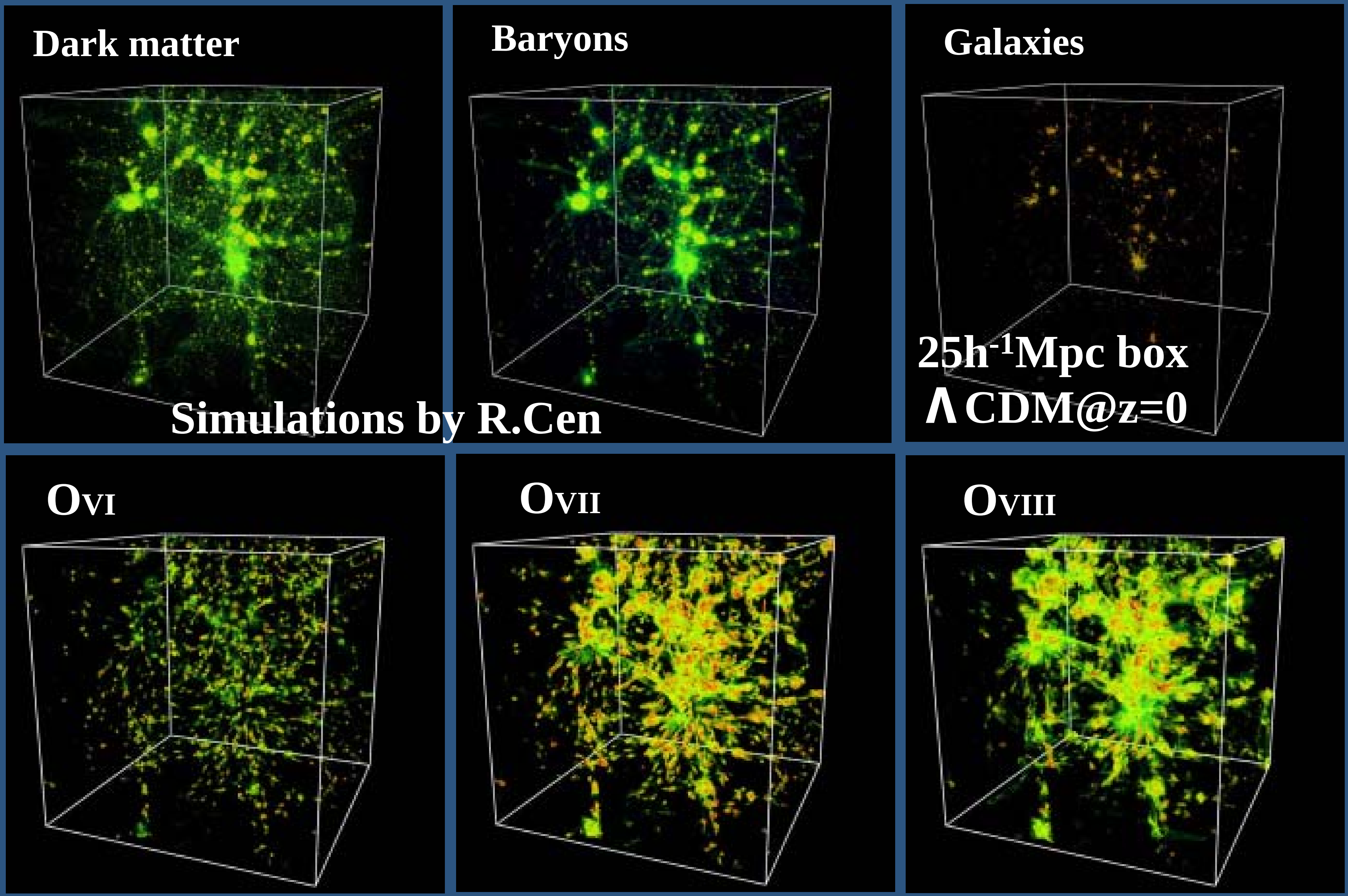


Warm/hot gas
($10^5K<T<10^7K$)



Cen & Ostriker : ApJ 514 (1999) 1

Tracing the structure with Oxygen



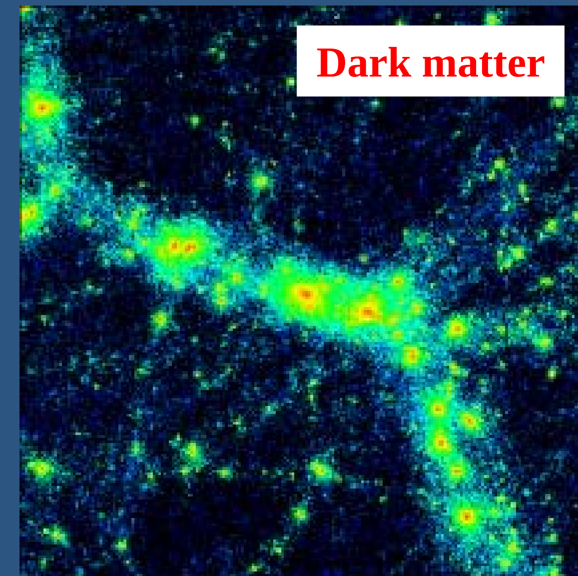
dark matter , hot gas and "galaxies"

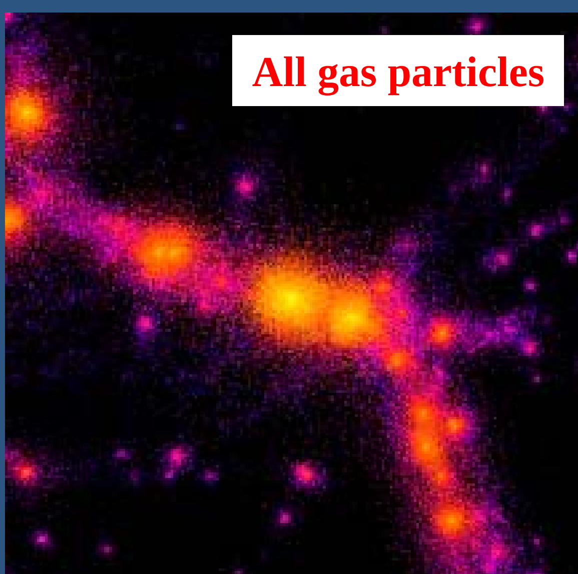
SPH simulation: ΛCDM, $(75h^{-1}Mpc)^3$ box
(Yoshikawa, Taruya, Jing & Suto 2001)

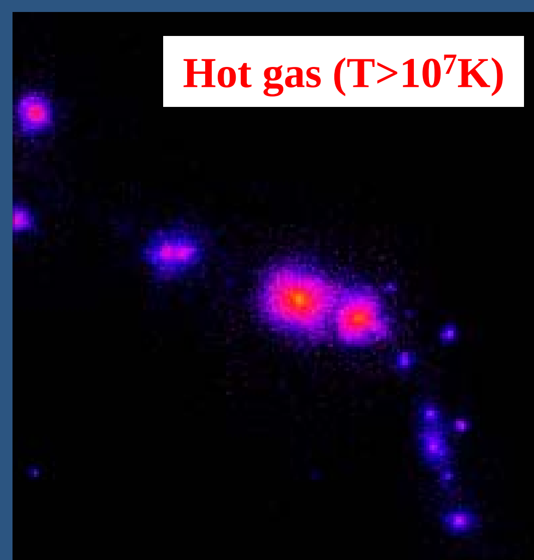
A cluster region in SPH simulation

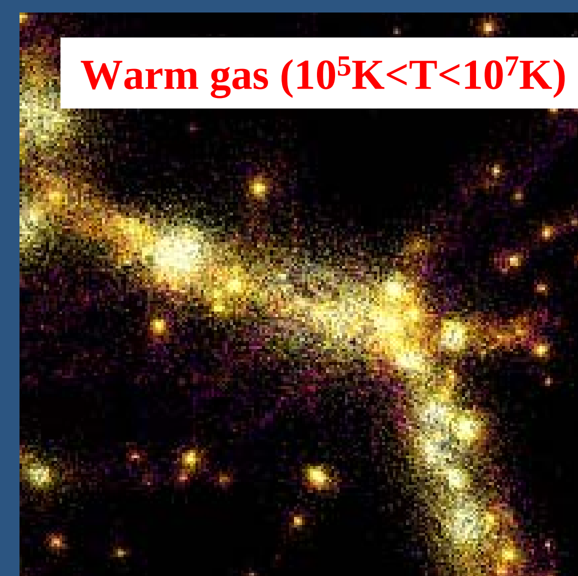
A $(30h^{-1}Mpc)^3$ box around a massive cluster at z=0 ΛCDM SPH simulation

(Yoshikawa et al. 2001)









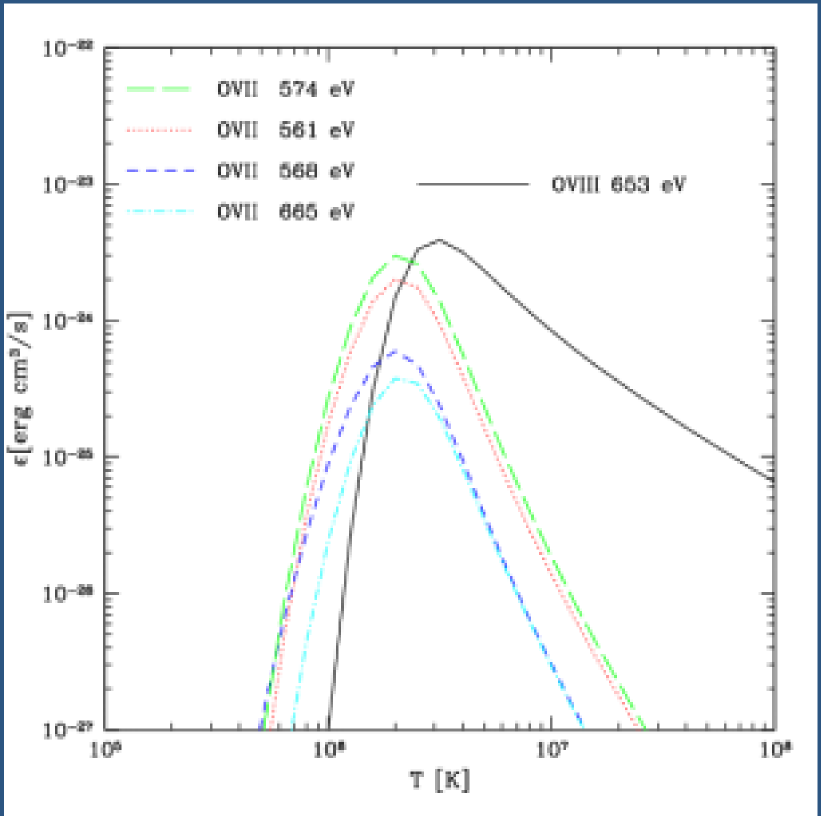
WHIM as missing cosmic baryons

- ~40% of the total cosmic baryons may exist as Warm-Hot Intergalactic Medium (WHIM) with $10^5K<T<10^7K$
- **WHIM is supposed to distribute diffusely along filamentary structures** connecting nearby clusters/ groups of galaxies
- **Direct detection of WHIM is difficult**
  - OVI absorption line systems in UV (1032Å, 1038Å doublets)
  - OVII (574.0 eV) and OVIII (653.6 eV) absorption line systems in X-ray spectra of background QSOs
  - Bumpy features in Soft X-ray background spectrum

Emission lines of Oxygen in WHIM

OVII (561eV, 568eV, 574eV, 665eV) , OVIII (653eV)

- **Why oxygen emission lines ?**
  - Most abundant other than H and He
  - Good tracers of gas around $T=10^6 \sim 10^7$ K
  - No other prominent lines in E=500-660eV
  - Not restricted to regions towards background QSOs



⇒ ***systematic WHIM survey***

Metallicity models

Oxygen enrichment scenario in IGM

Type-II SNe → galaxy wind merging → metal pollution in IGM

Metallicity of WHIM is quite uncertain

Adopted models for metallicity distribution

Model I : uniform and constant

$$Z = 0.2\, Z_{solar}$$

Model II : uniform and evolving

$$Z = 0.2\, Z_{solar}\,(t/t_0)$$

Model III : density-dependent (Aguirre et al. 2001)

$$Z = 0.005\, Z_{solar}\,(\rho/\rho_{\rm mean})^{0.33}$$ (galactic wind driven)

Model IV : density-dependent (Aguirre et al. 2001)

$$Z = 0.02\, Z_{solar}\,(\rho/\rho_{\rm mean})^{0.3}$$ (radiation pressure driven)

Requirements for detection

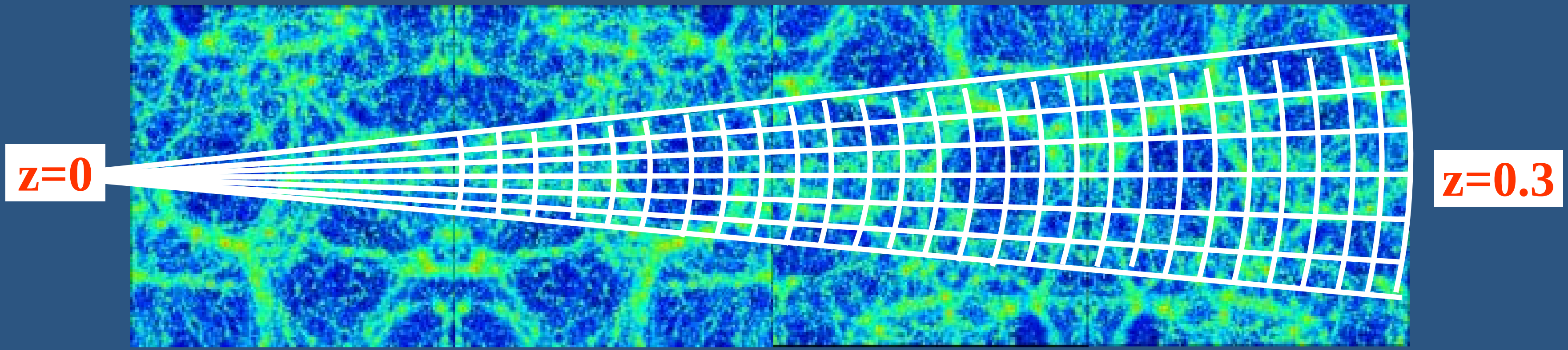
- **Good energy resolution** to identify the emission lines from WHIM at different redshifts
  - $\Delta E < 5\mathrm{eV}$ ⇒ X-ray calorimeter using superconducting TES (Transition Edge Sensor)
- **Large field-of-view** and effective area for survey
  - $S_{eff} = 100\mathrm{cm}^2$, $\Omega = 1\mathrm{deg}^2$ ⇒ 4-stage reflection telescope
- Angular resolution is not so important (but useful in removing point source contaminations)

$$\theta \approx 1^\circ \left(\frac{600\, h^{-1}\mathrm{Mpc}}{D} \right) \left(\frac{L}{10\, h^{-1}\mathrm{Mpc}} \right)$$

Comparison with other missions

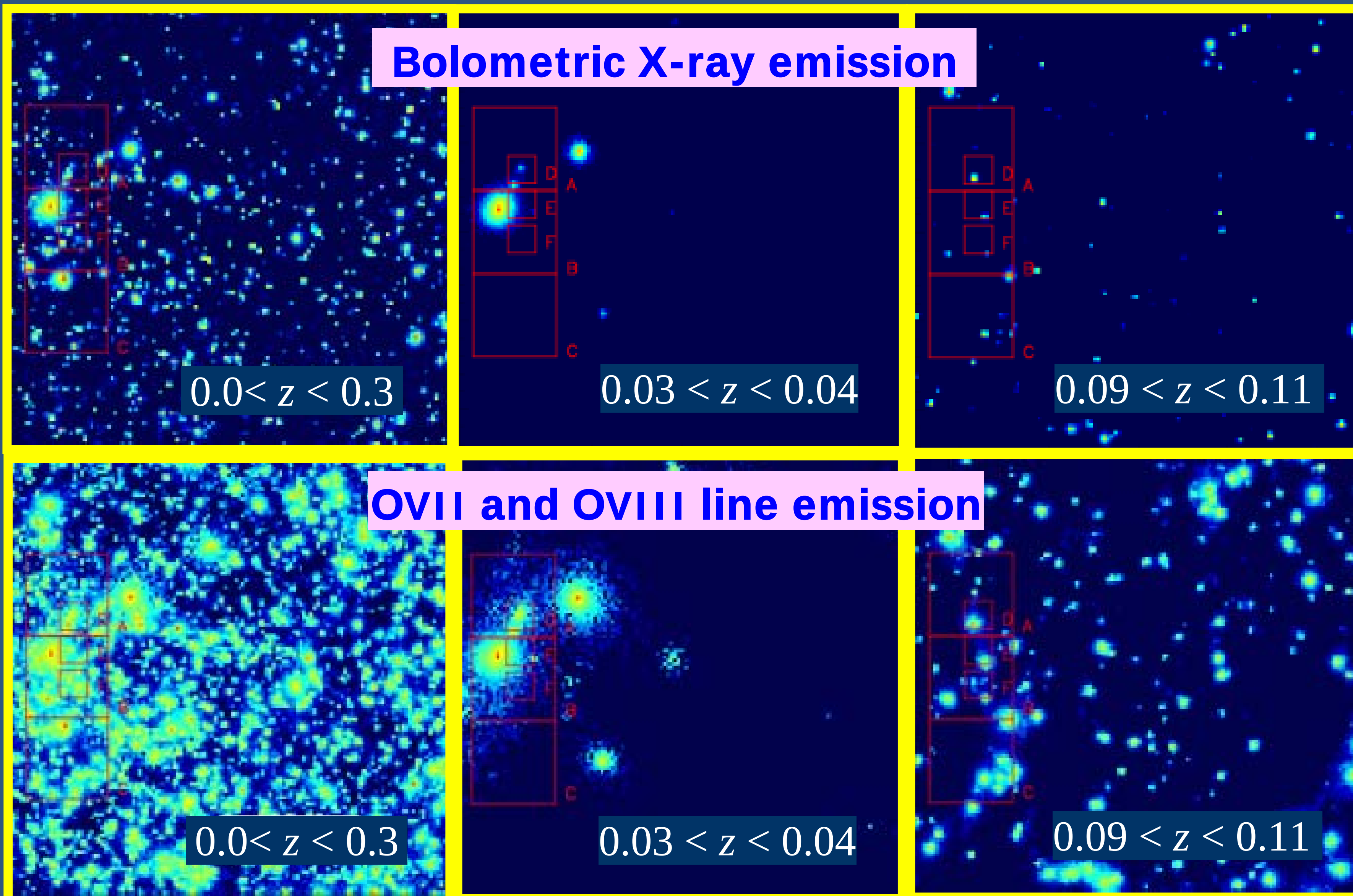
	$S_{eff}\Omega$ [cm^2 deg^2]	ΔE [eV]	f_{limit} [erg/s/cm^2/sr]
Chandra ACIS-S3	12	80	10^{-9}
XMM-Newton EPIC-pn	100	80	3×10^{-10}
Astro-E II XRS	0.23	6	2×10^{-8}
Astro-E II XIS	36	80	6×10^{-10}
XEUS-I	16.7	2	2.5×10^{-10}
our proposed detector	**100**	**2**	$\mathbf{6\times10^{-11}}$

Light-cone output from simulation

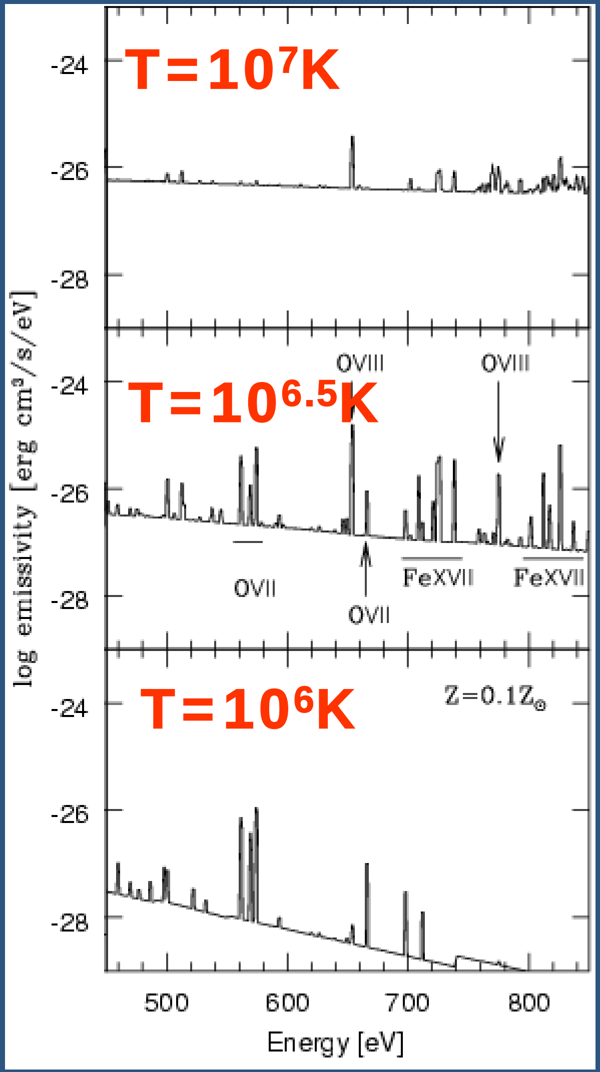


- **Cosmological SPH simulation** in Ω_m=0.3, Ω_Λ=0.7, σ_8=1.0, and h=0.7 CDM with N=128^3 each for DM and gas (Yoshikawa, Taruya, Jing, & Suto 2001)
- **Light-cone output from z=0.3 to z=0** by stacking 11 simulation cubes of $(75h^{-1}Mpc)^3$ at different z
- **5°×5° FOV mock data** in 64x64 grids on the sky
- 128 bins along the redshift direction (Δz=0.3/128)

Surface brightness on the sky

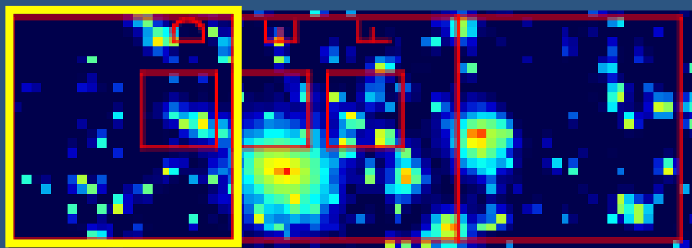


Creating Mock spectra from light-cone output



- For a given exposure time,
  - convolve the emissivity according to gas density and temperature in $(5°/64)^2$ pixels over the lightcone
  - Add the Galactic line emission (McCammon et al. 2002)
  - Add the cosmic X-ray background contribution (power-law+Poisson noise)
- Then statistically subtract the Galactic emission and the CXB and obtain the residual spectra for ΔE=2eV resolution.

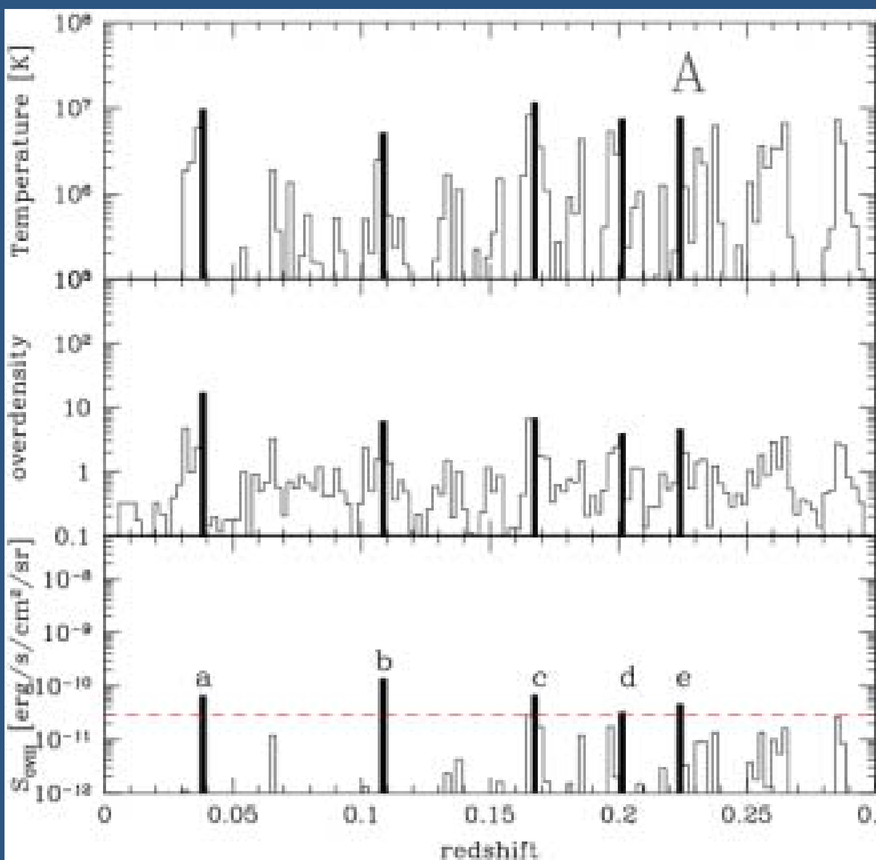
Simulated spectra: region A

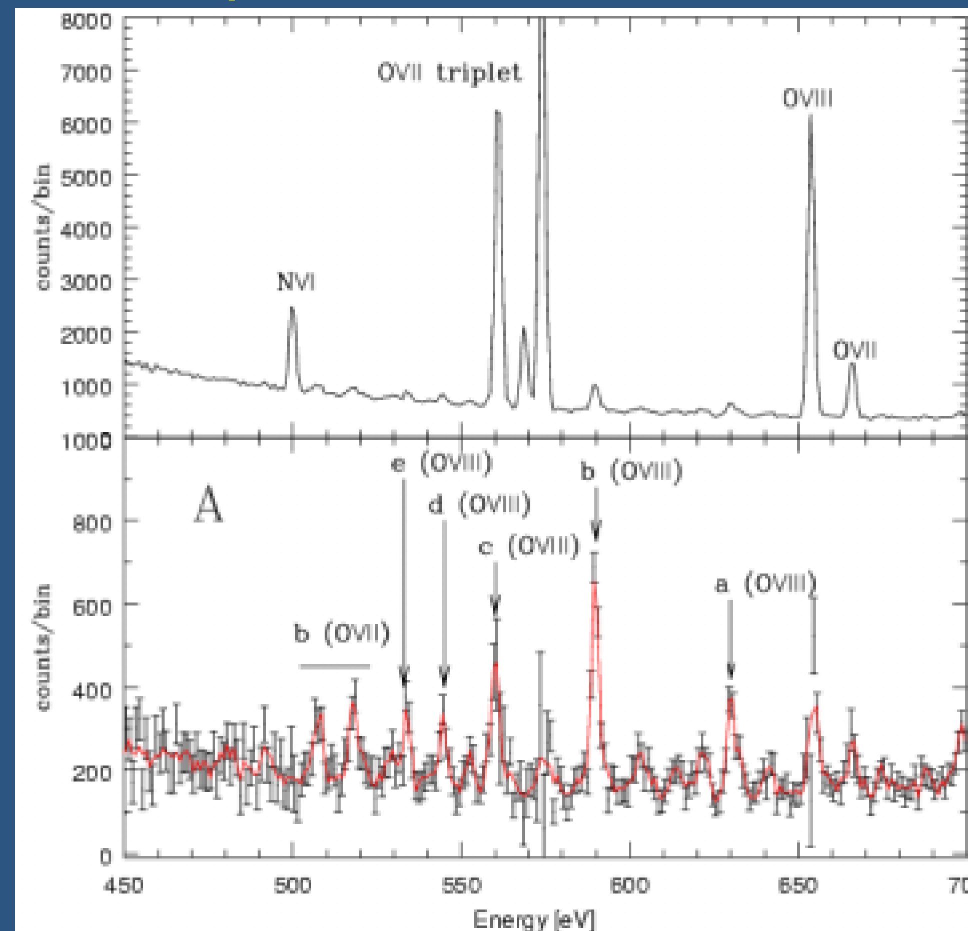


A

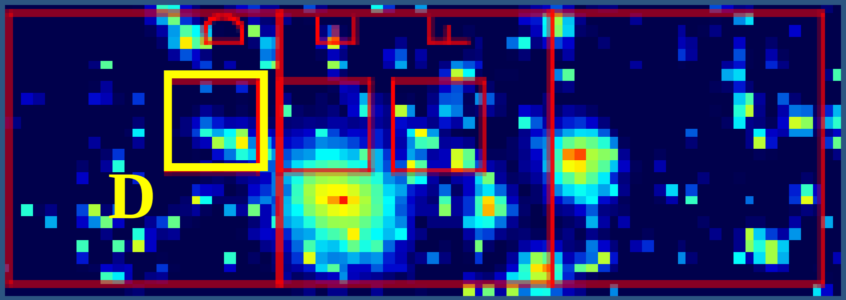
0.94 ° × 0.94 ° = 0.88 deg^2

$T_{exposure}$= 3x10^{5}sec



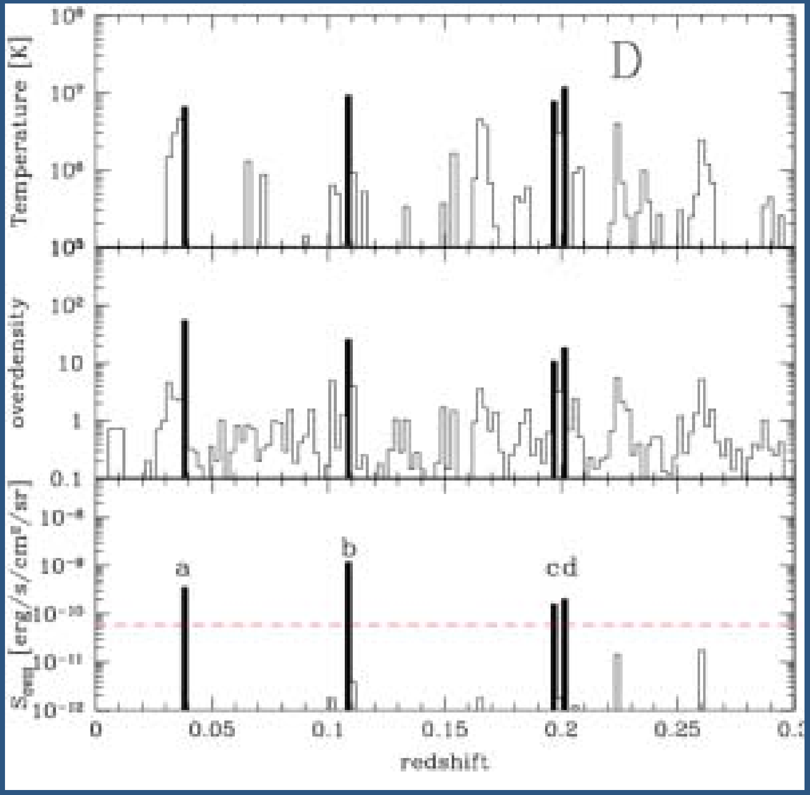


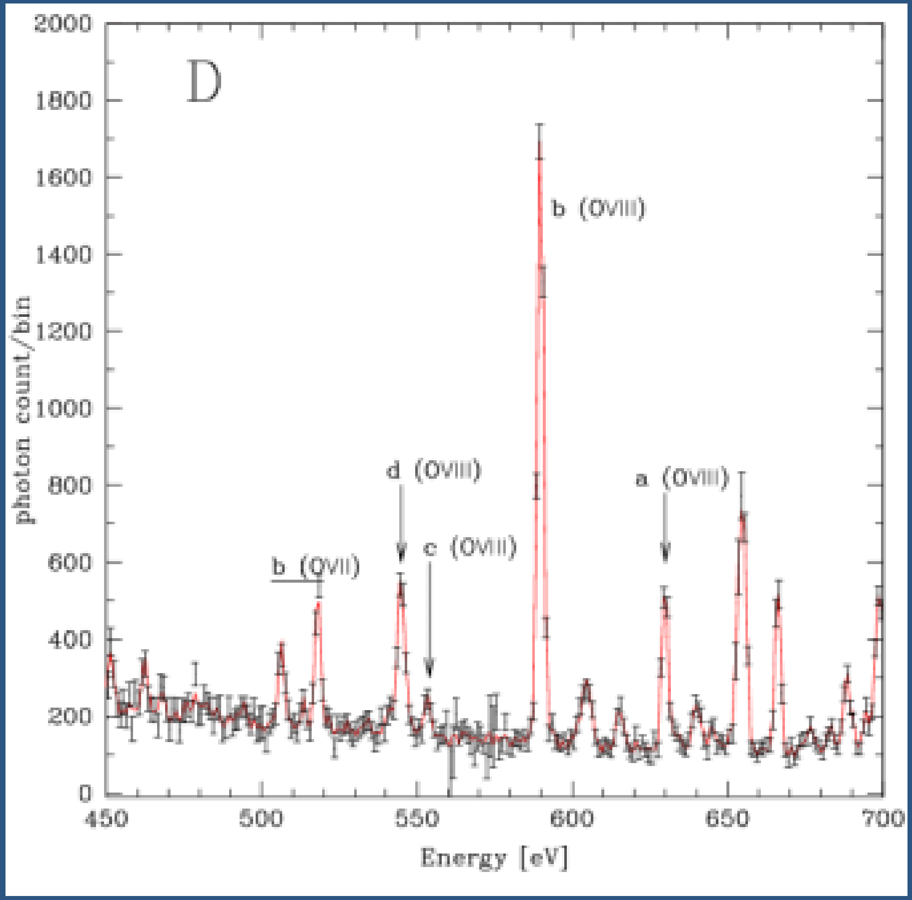
Simulated spectra: region D



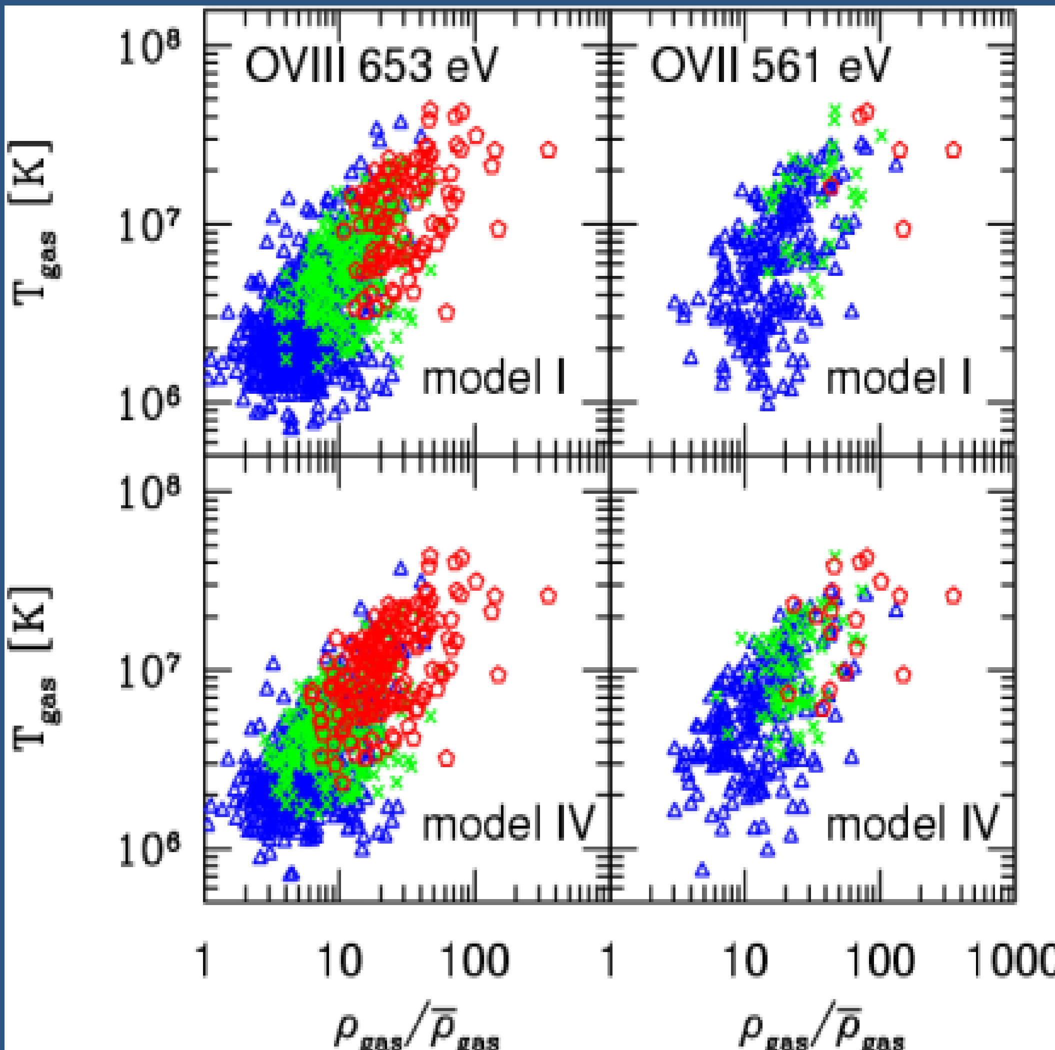
19'x19' = 0.098 deg^2

$T_{exposure} = 10^6 sec$





Physical properties of the probed baryons



Each symbol indicate the temperature and the over-density of gas at each simulation grid (4x4 smoothed pixels over the sky and Δz=0.3/128)

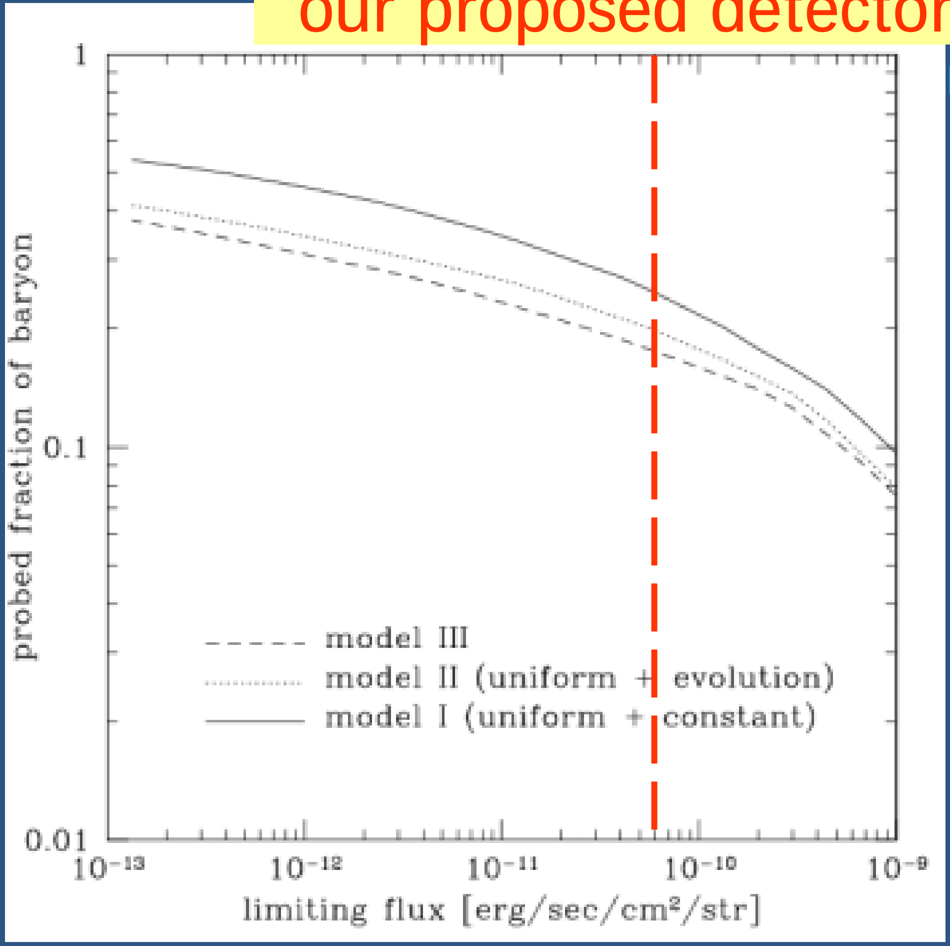
$S_x > 3\times10^{-10}$ [erg/s/cm^2/sr]

$S_x > 6\times10^{-11}$ [erg/s/cm^2/sr]

$S_x > 10^{-11}$ [erg/s/cm^2/sr]

Expected fraction of WHIM detectable via Oxygen emission lines (in principle)

Detection limiting flux of our proposed detector



- Our proposed mission (flux limit = 6×10^{-11} [erg/s/cm^2/str]) will be able to detect (20-30) percent of the total cosmic baryons via Oxygen emission lines **in principle**.

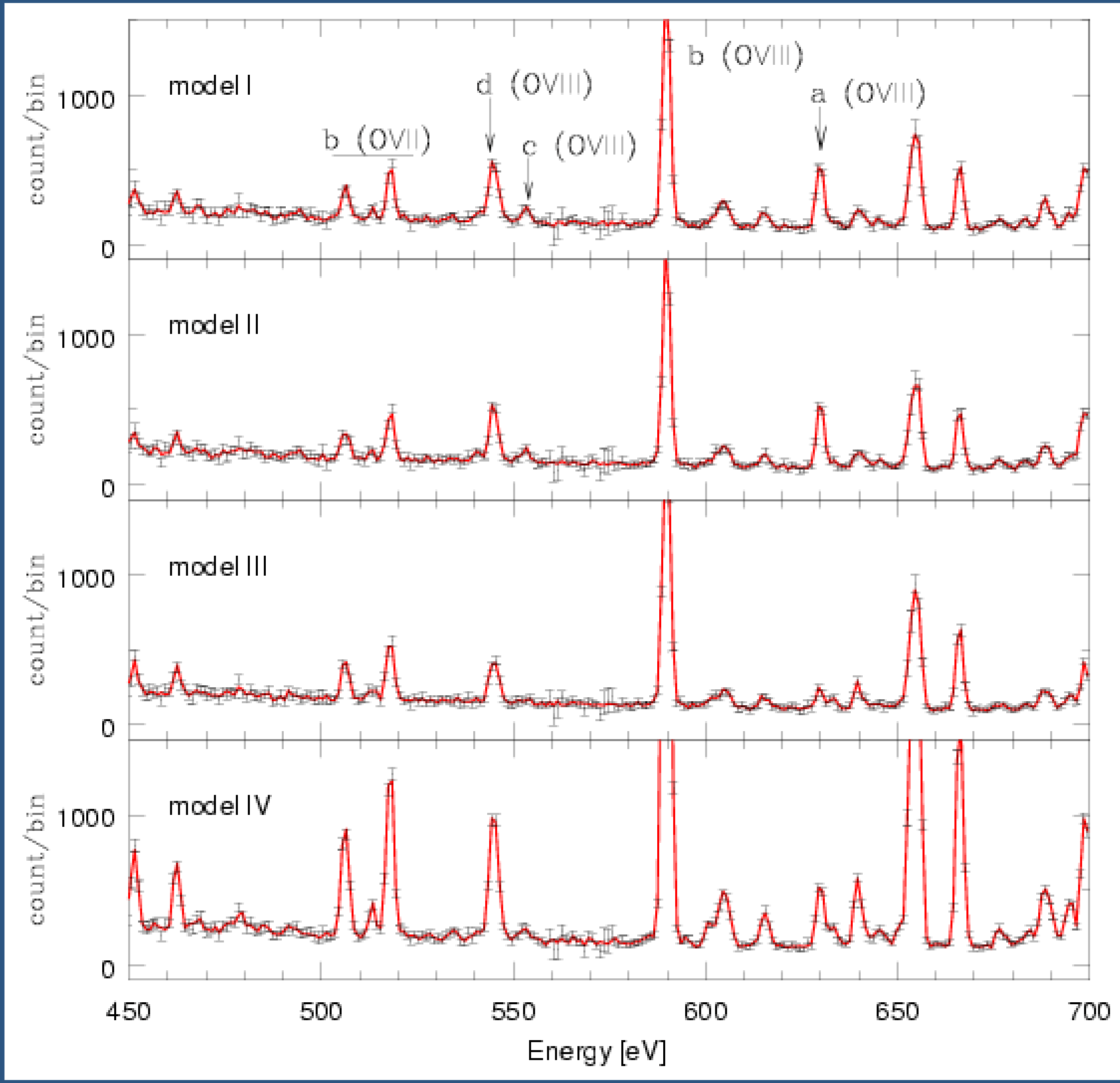
Detectability of Warm-Hot Intergalactic Medium via Oxygen emission lines

- Mock spectra from cosmological SPH simulation
- **With our proposed mission (20-30) percent of the total cosmic baryons will be detected via Oxygen emission lines** in principle.
  - $\Delta E = 2\text{eV}$, $S_{eff}\ \Omega = 100$ [$\text{cm}^2\ \text{deg}^2$]
  - flux limit = 6×10^{-11} [$\text{erg/s/cm}^2\text{/str}$]
- Things remain to be checked
  - Validity of the collisional ionization equilibrium ?
  - How to properly identify the oxygen lines from the background/noises in reality ?

Oxygen lines

O VII	$1s^2 - 1s2s\ (^3S_1)$	561eV	22.1 Å
O VII	$1s^2 - 1s2p\ (^3P_1)$	568eV	21.8 Å
O VII	$1s^2 - 1s2p\ (^1P_1)$	574eV	21.6 Å
O VIII	1s – 2p (Ly α)	653eV	19.0 Å
O VII	$1s^2 - 1s3p$	665eV	18.6 Å
O VIII	1s – 3p (Ly β)	775eV	16.0 Å
Ne IX	$1s^2 - 1s2s\ (^3S_1)$	905eV	13.7 Å
Ne IX	$1s^2 - 1s2p\ (^3P_1)$	914eV	13.6 Å
Ne IX	$1s^2 - 1s2p\ (^1P_1)$	921eV	13.5 Å

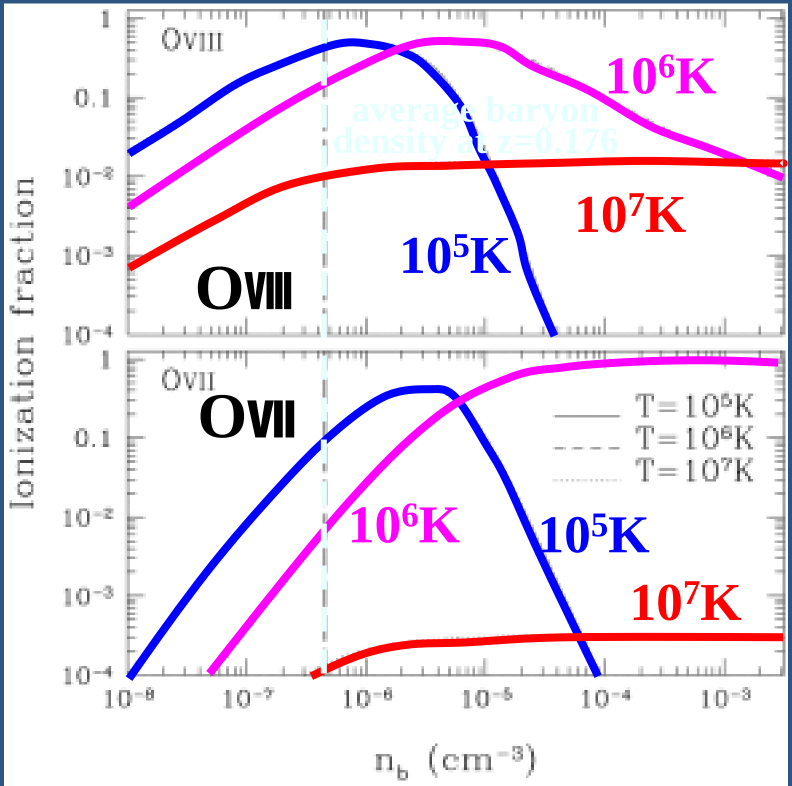
Dependence on the metallicity model

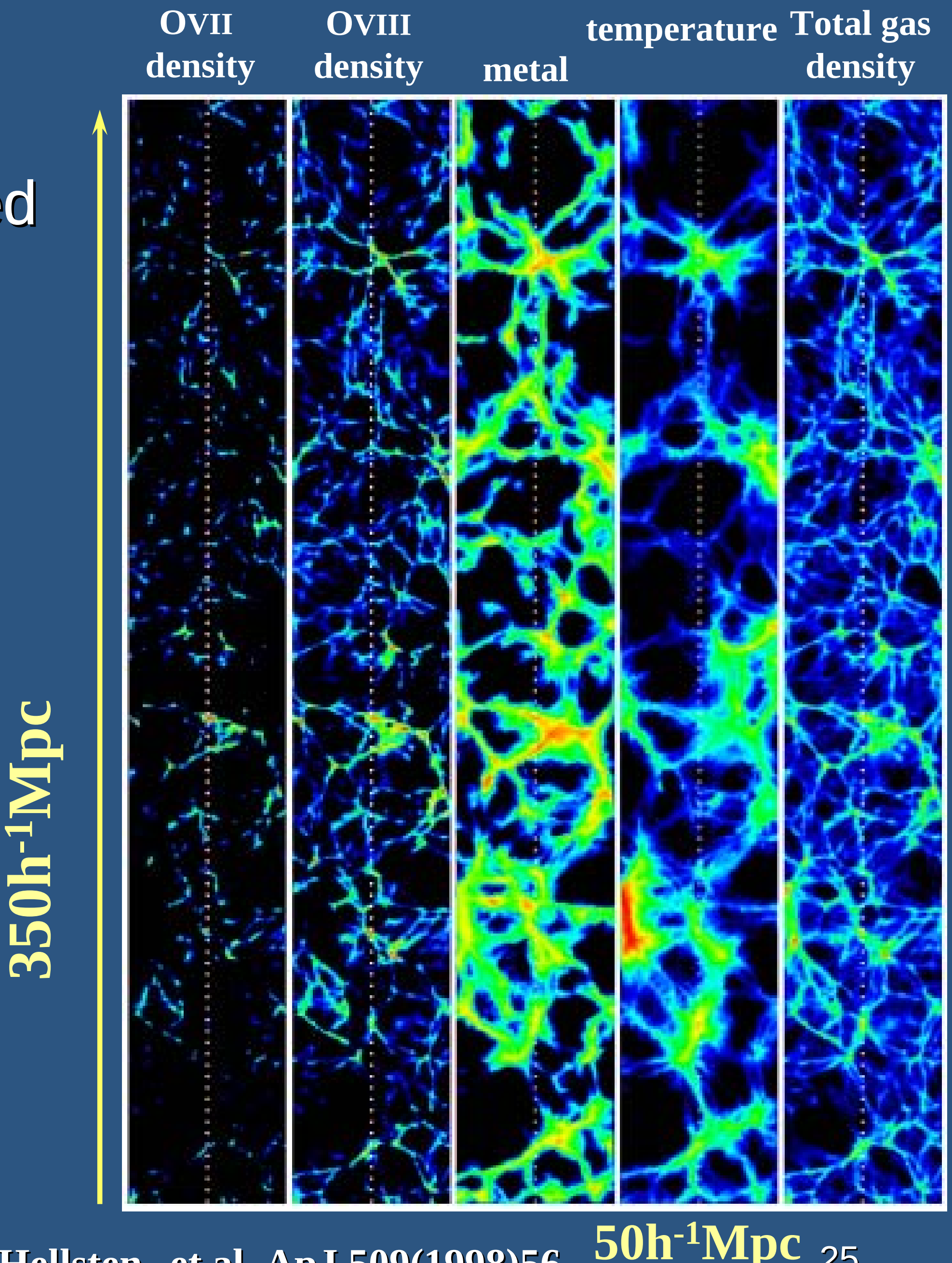


- We have adopted model I (constant 0.2 solar metallicity) so far
- Density-dependent metallicity models show stronger emission lines.
- ⇒ WHIM will be unambiguously detected with our proposed mission

X-ray forests

- Oxygen emission lines ionized by X-ray background
- High-density regions ⇒ OVII
- Connecting filaments ⇒ OVIII

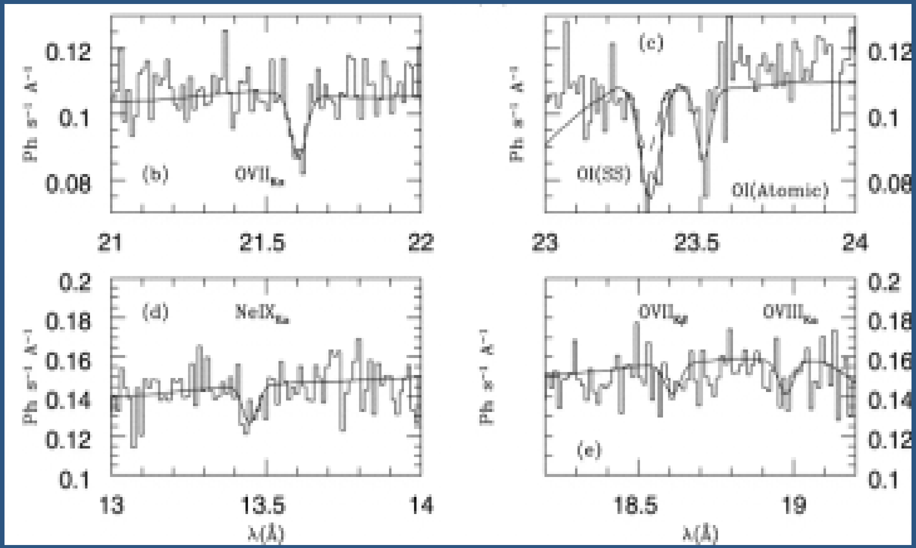




Hellsten et al. ApJ 509(1998)56

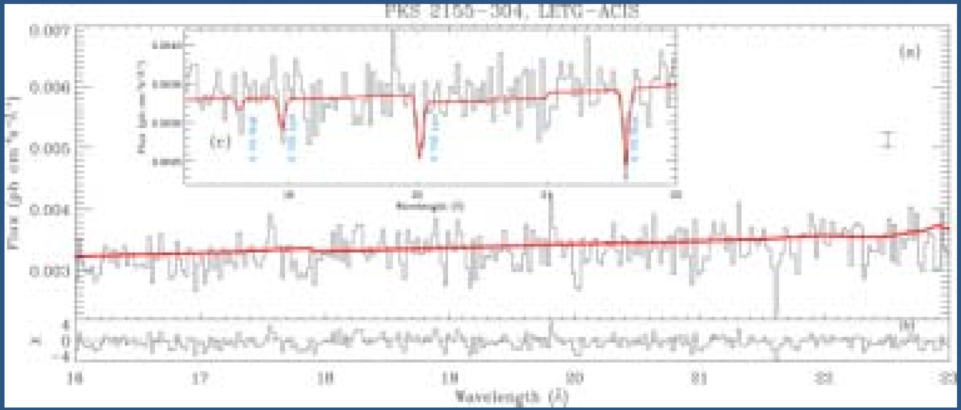
X-ray forests: shadow of WHIM

Absoption line systems of OVI, OVII, and OVIII in the X-ray continuum spectra of background quasars



Nicastro et al. (2002)

δ=60, T=10^6 K,
L_{size}~3Mpc, z~0



Fang et al. (2002)

a small galaxy group
and HI Ly-a clouds

δ=50~350, T=10^6K,
L_{size}~8Mpc, z~0.06