Searching for cosmic missing baryons with DIOS

(Diffuse Intergalactic Oxygen Surveyor)

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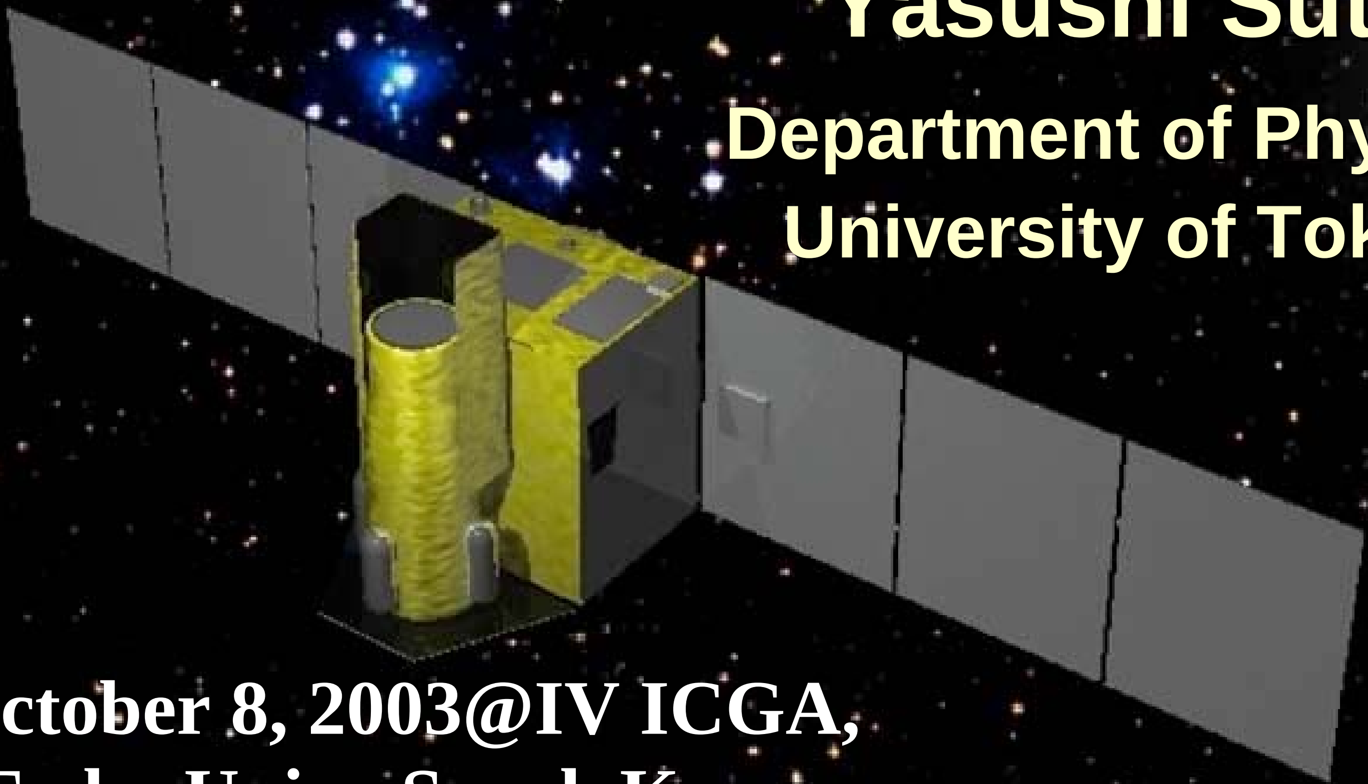

**October 8, 2003@IV ICGA,
Ewha Univ., Seoul, Korea**

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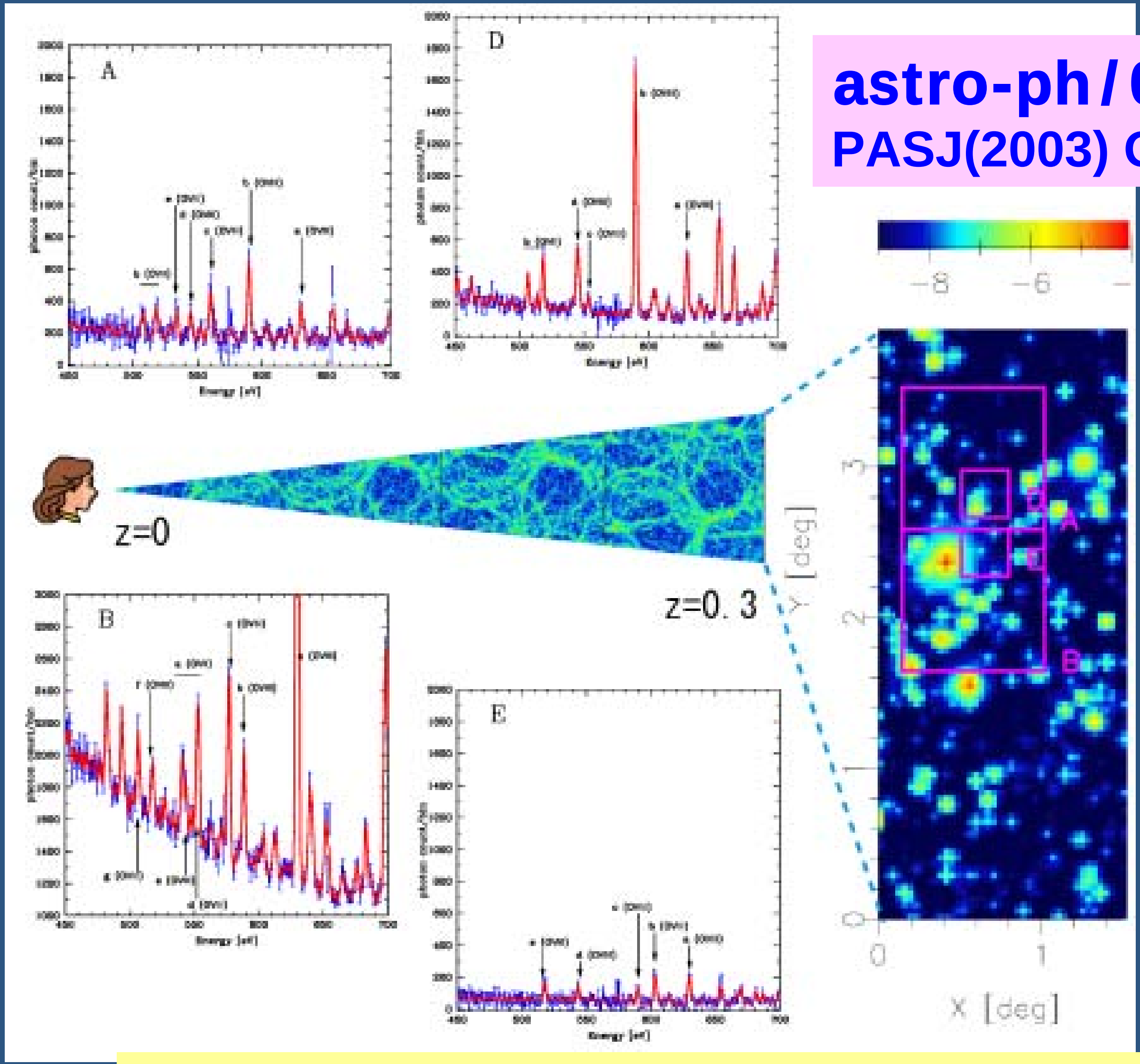

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DIOS: Diffuse Intergalactic Oxygen Surveyor

A Japanese proposal of a dedicated X-ray mission to search for missing baryons

- A dedicated satellite with cost < 40M USD to fill the gap between Astro-E2 (2005) and NeXT (2010?). Launch at Japan in 2008 (?).
- Unprecedented energy spectral resolution ΔE=2eV in soft X-ray band (0.1-1keV)
- Aim at detection of (20-30) percent of the total cosmic baryons via Oxygen emission lines
  - ΔE=2eV, $S_{eff}\,\Omega$=100 [cm^2 deg^2]
  - flux limit = 6×10^{-11} [erg/s/cm^2/str]
- PI: Takaya Ohashi (Tokyo Metropolitan Univ.)

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 (10〜30) **%** of the big-bang nucleosynthesis prediction and WMAP value

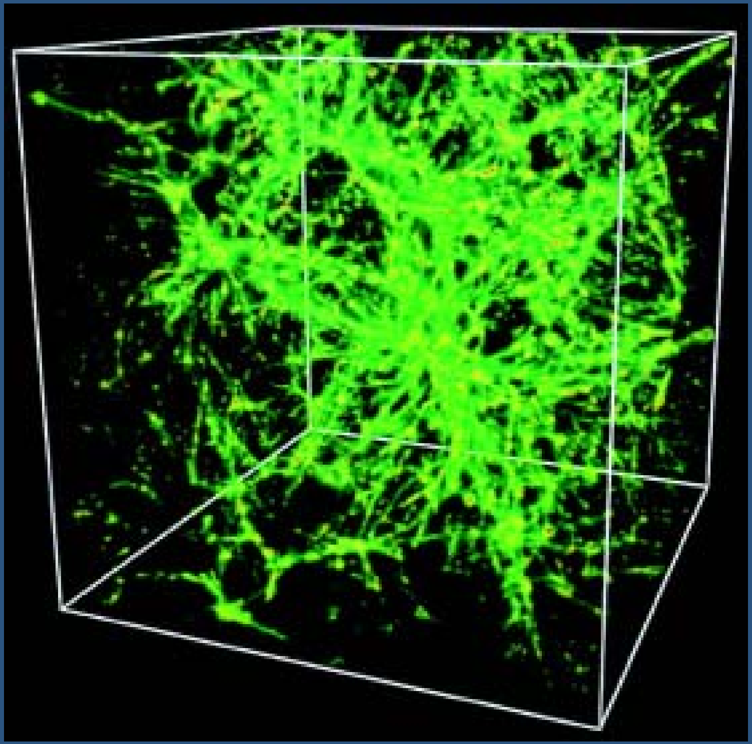
Four phases of cosmic baryons

Dave et al. ApJ 552(2001) 473

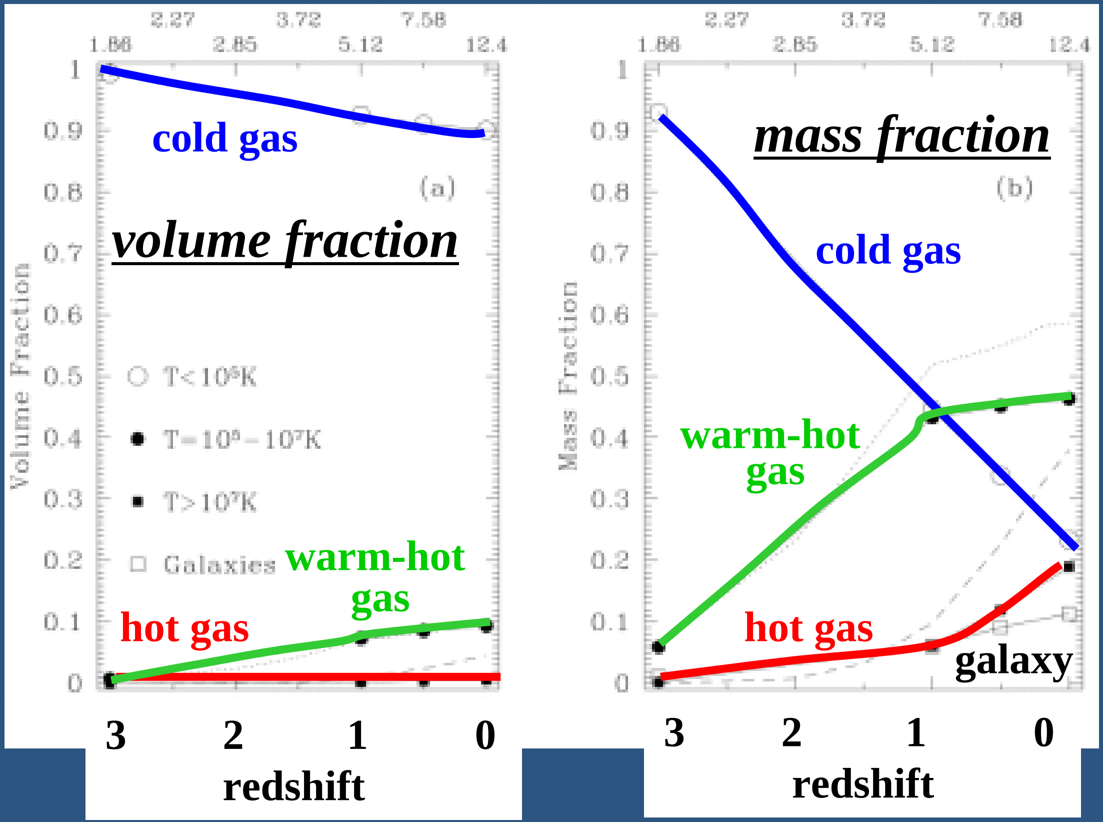
- ***Condensed:*** $\delta > 1000$, $T < 10^5$K
  - Stars + cold intergalactic gas
- ***Diffuse:*** $\delta < 1000$, $T < 10^5$K
  - Photo-ionized intergalactic medium
  - Ly α absorption line systems
- ***Hot:*** $T > 10^7$K
  - X-ray emitting hot intra-cluster gas
- ***Warm-hot:*** $10^5\text{K} <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

Where are the baryons ?

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

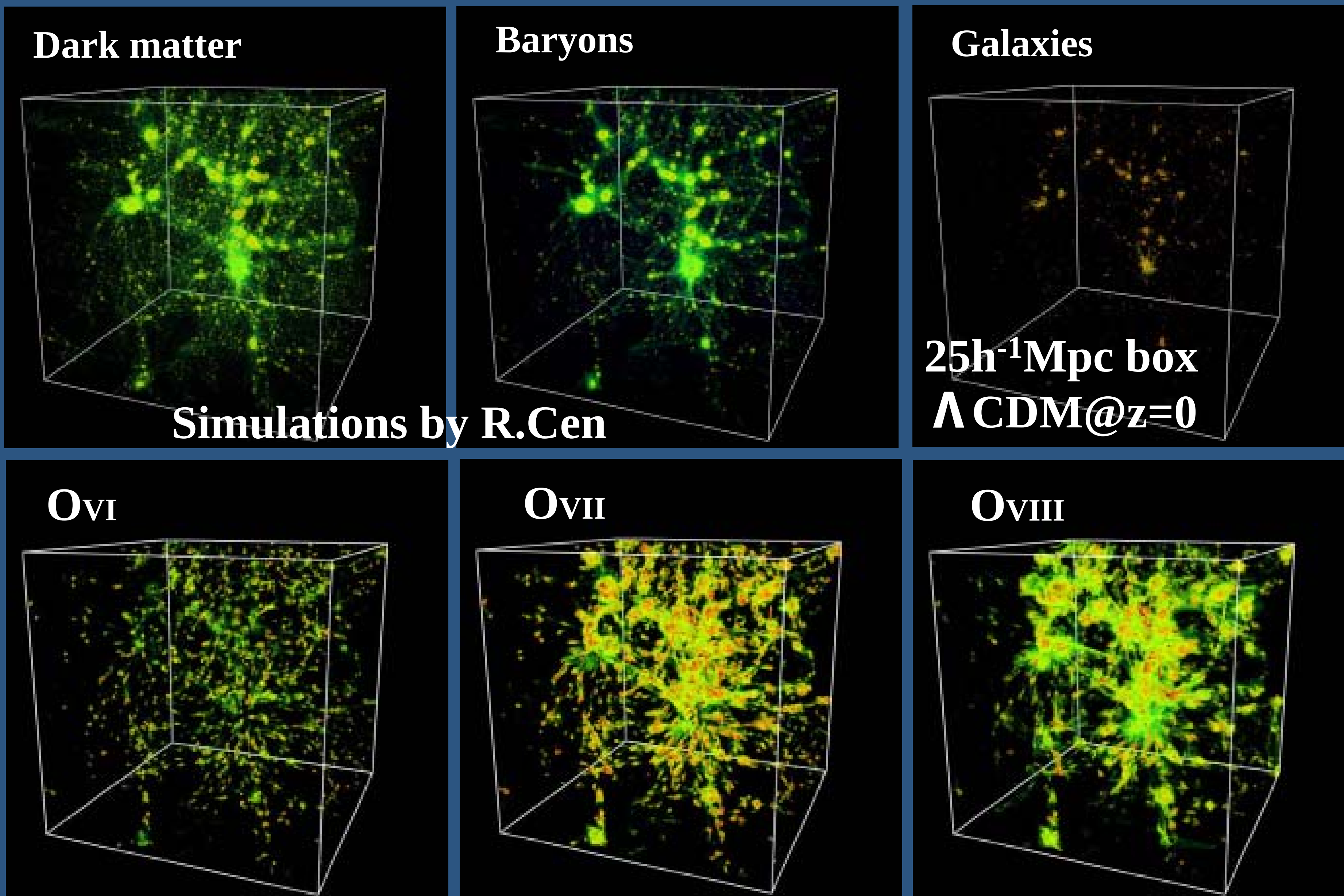


Warm/hot gas ($10^5K<T<10^7K$)



Cen & Ostriker : ApJ 514 (1999) 1

Tracing the structure with Oxygen



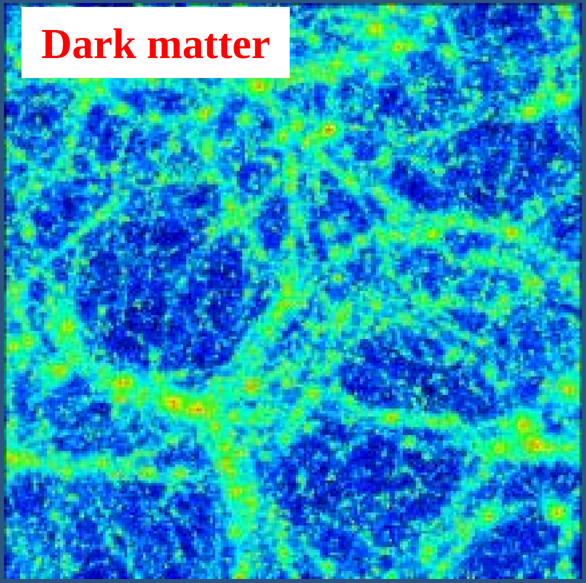
dark matter , hot gas and "galaxies"

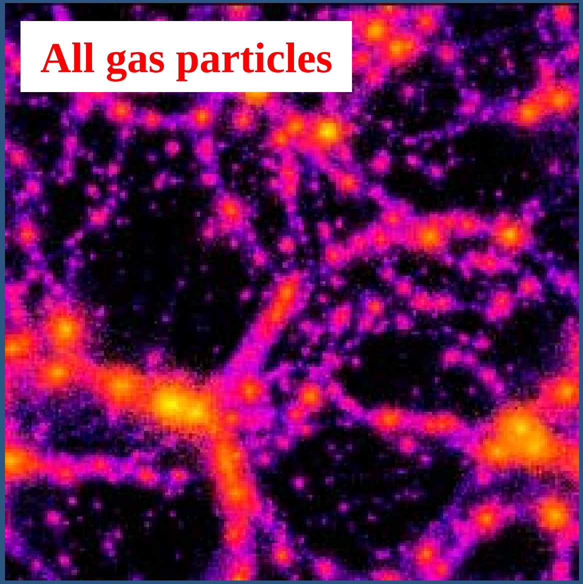
SPH simulation: Λ CDM, $(75h^{-1}Mpc)^3$ box
(Yoshikawa, Taruya, Jing & Suto 2001)

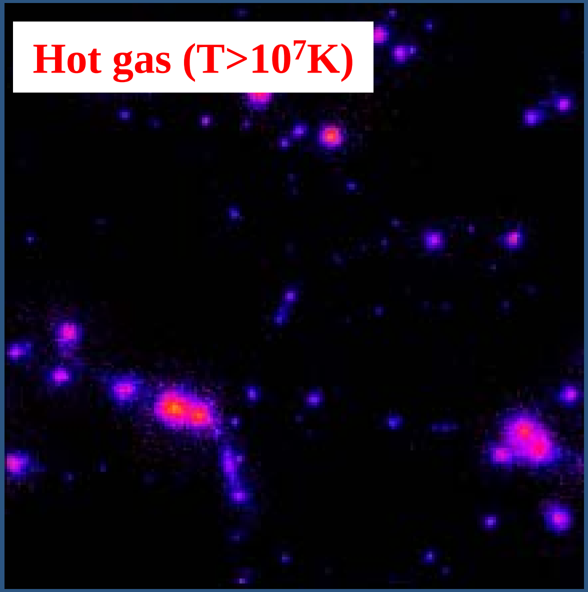
Large-scale structure in SPH simulation

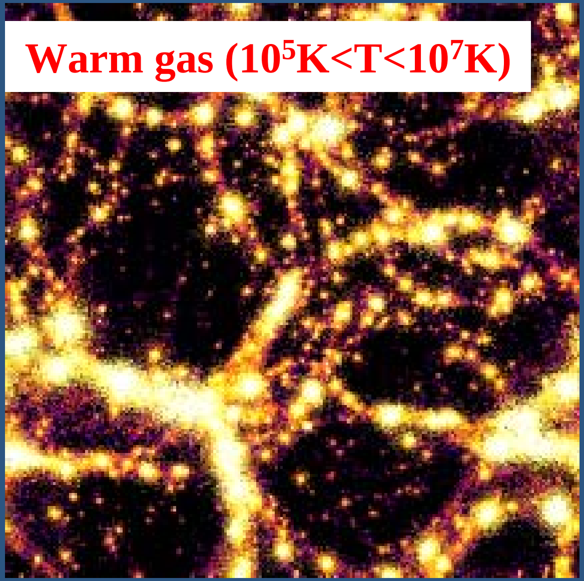
$(75h^{-1}\mathrm{Mpc})^3$ box
ΛCDM @ $z=0$
$N=128^3$:DM particles
$N=128^3$:gas particles

(Yoshikawa et al. 2001)





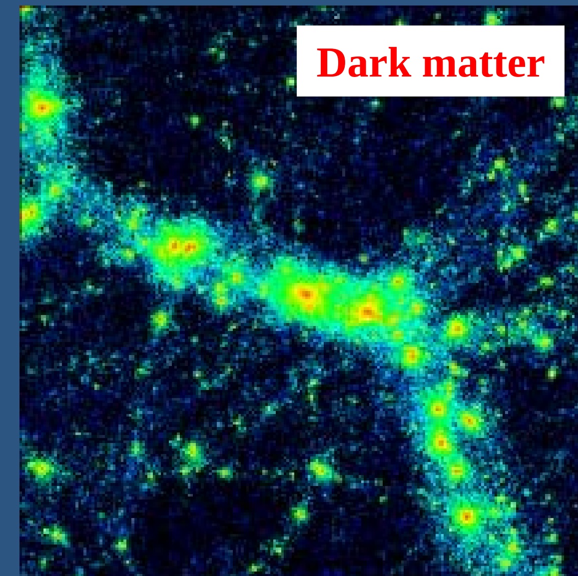


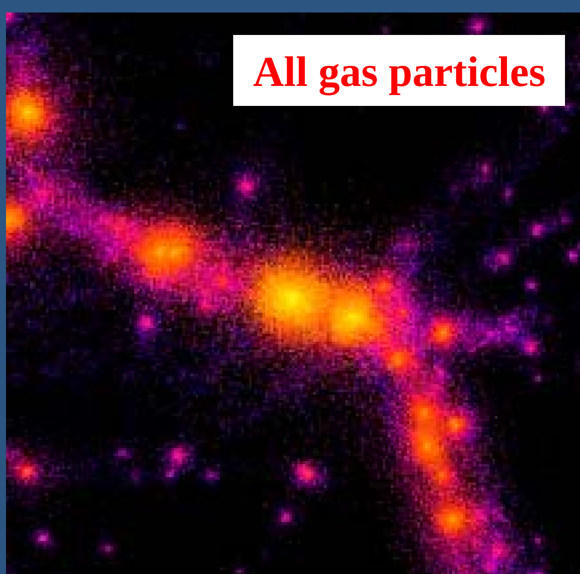


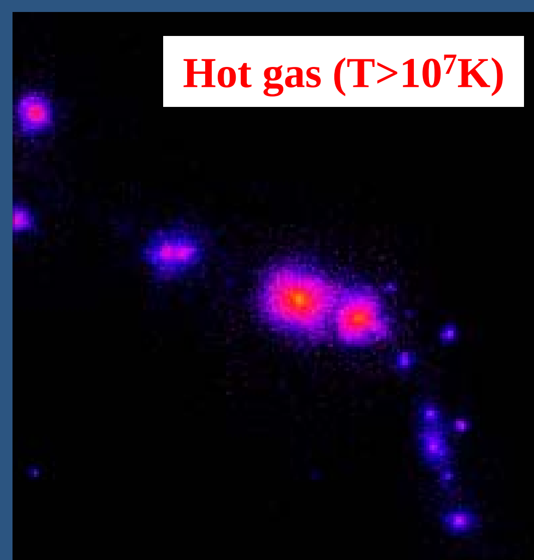
A cluster region in SPH simulation

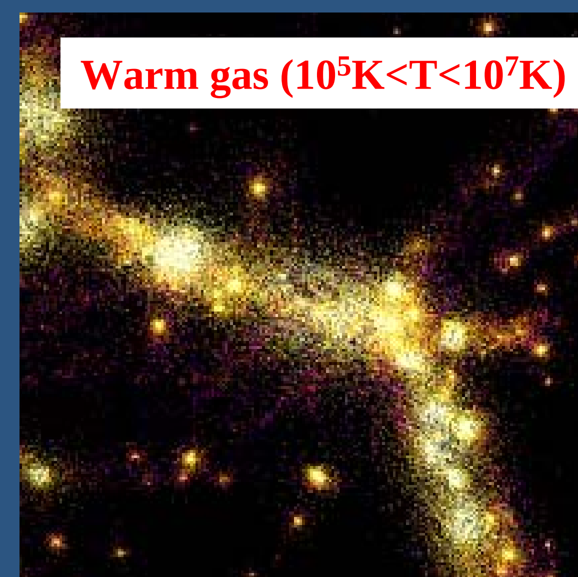
A $(30h^{-1}Mpc)^3$ box around a massive cluster at z=0
ΛCDM SPH simulation

(Yoshikawa et al. 2001)









WHIM as missing cosmic baryons

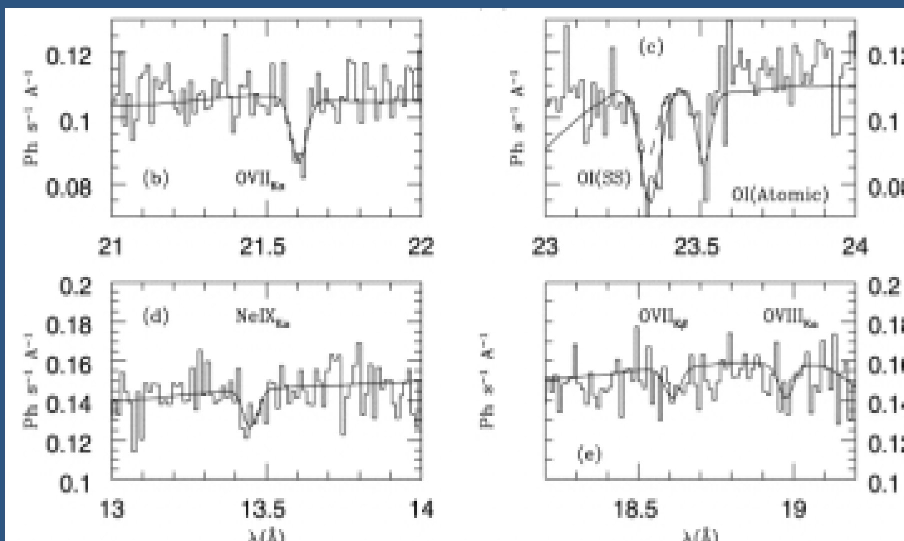
- ~40% of the total cosmic baryons may exist as Warm-Hot Intergalactic Medium (WHIM) with 10^5K<T<10^7K
- **WHIM is supposed to distribute diffusely along filamentary structures** connecting nearby clusters/ groups of galaxies
- **Direct detection of WHIM is difficult**
  - OVI absorption line systems 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

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

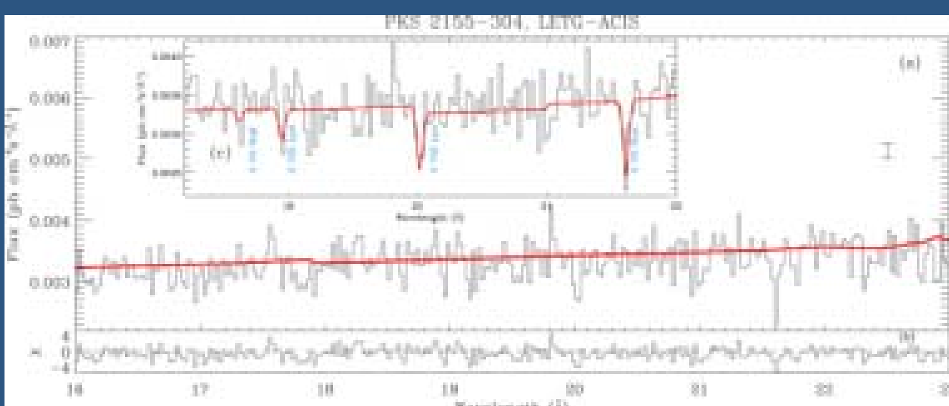
X-ray forests: shadow of WHIM

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)

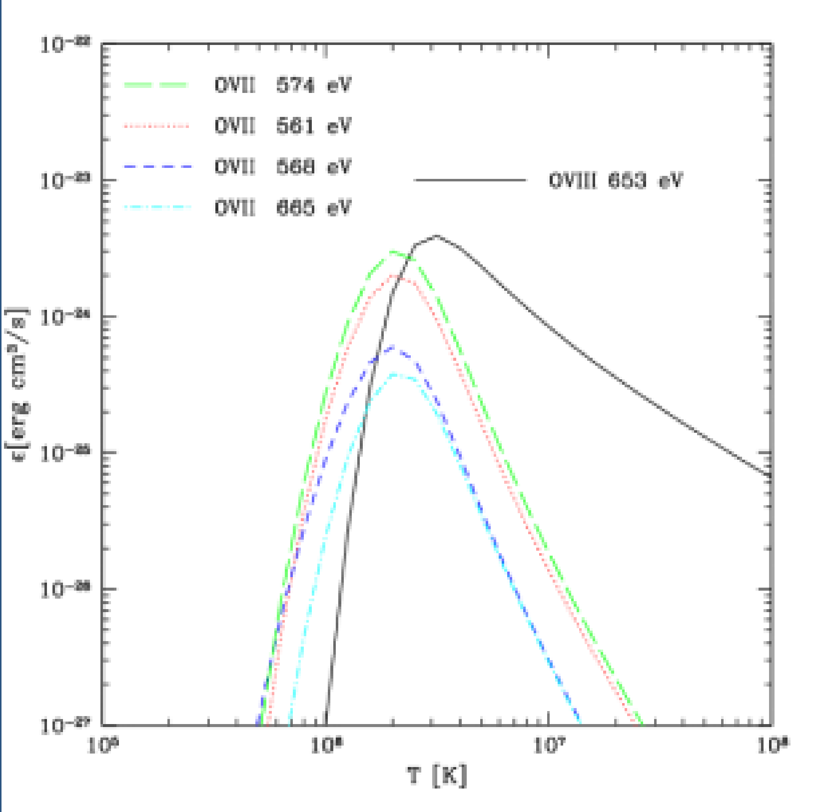
a small galaxy group
and HI Ly-a clouds

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

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***

Requirements for detection

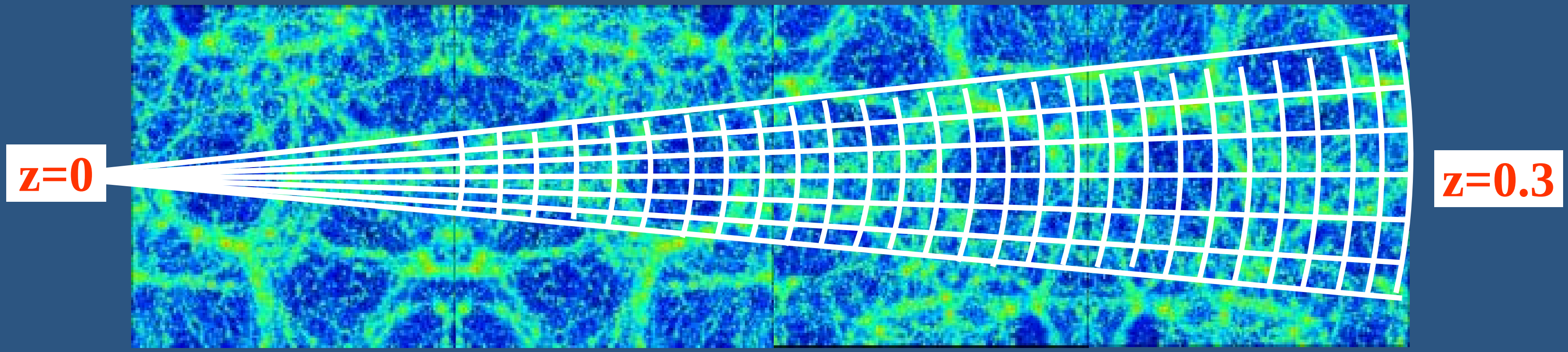
- **Good energy resolution** to identify the emission lines from WHIM at different redshifts
  - $\Delta E < 5\text{eV}$ ⇒ X-ray calorimeter using superconducting TES (Transition Edge Sensor)
- **Large field-of-view** and effective area for survey
  - $S_{eff} = 100\text{cm}^2, \Omega = 1\text{deg}^2$ ⇒ 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

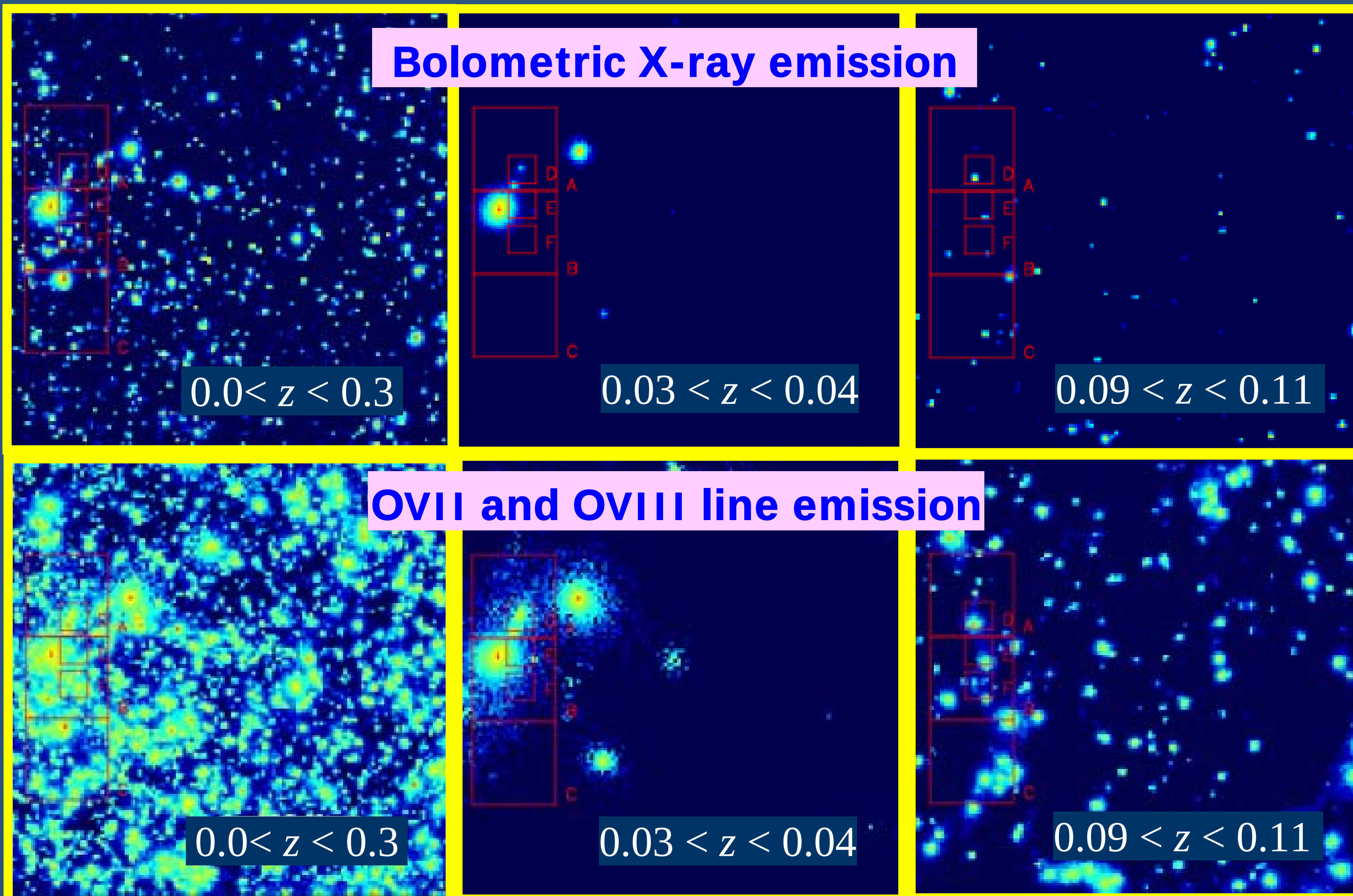
	$S_{eff}\Omega$ [cm^2 deg^2]	ΔE [eV]	f_{limit} [erg/s/cm^2/sr]
Chandra ACIS-S3	12	80	10^{-9}
XMM-Newton EPIC-pn	100	80	$3\text{x}10^{-10}$
Astro-E II XRS	0.23	6	$2\text{x}10^{-8}$
Astro-E II XIS	36	80	$6\text{x}10^{-10}$
XEUS-I	16.7	2	$2.5\text{x}10^{-10}$
	**100**	**2**	$\mathbf{6x10^{-11}}$

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 $(75h^{-1}\mathrm{Mpc})^3$ 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



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

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

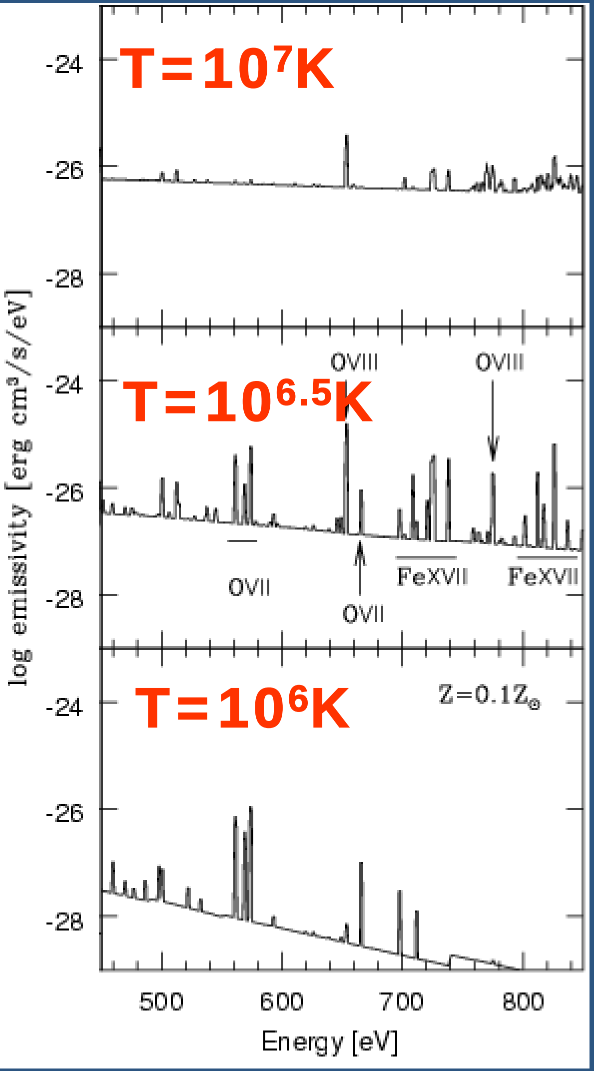
Model III : density-dependent (Aguirre et al. 2001)

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

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

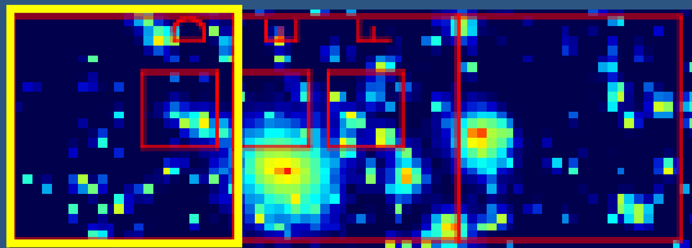
$$Z = 0.02\, Z_{solar}\, (\rho/\rho_{\rm mean})^{0.3}$$ (radiation pressure driven)

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.

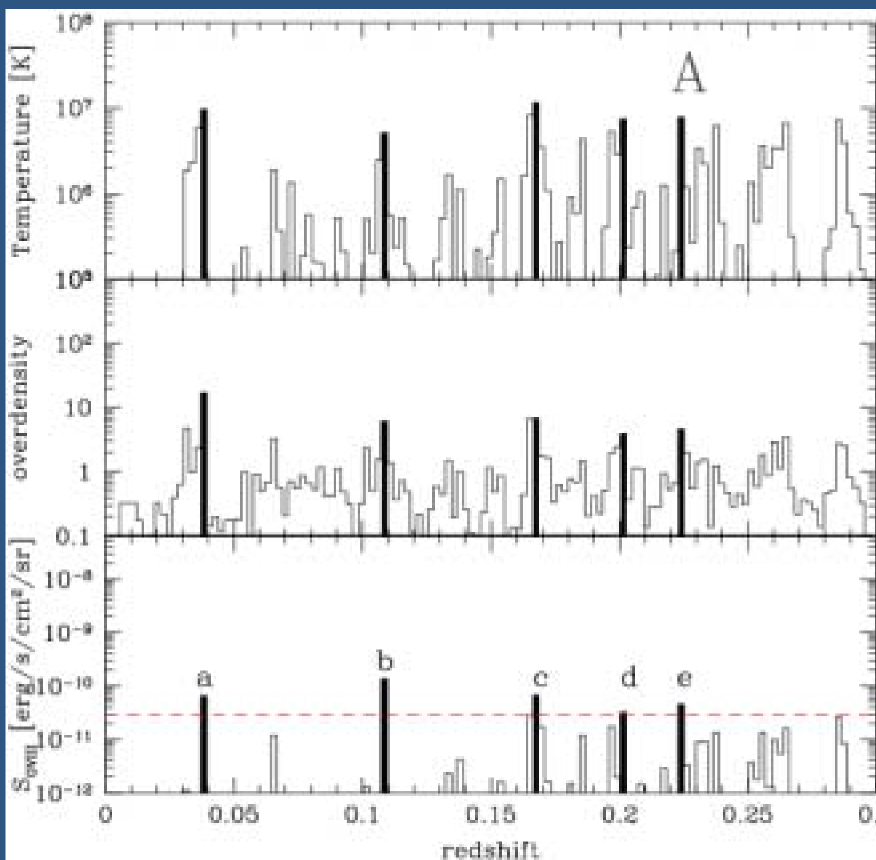
Simulated spectra: region A

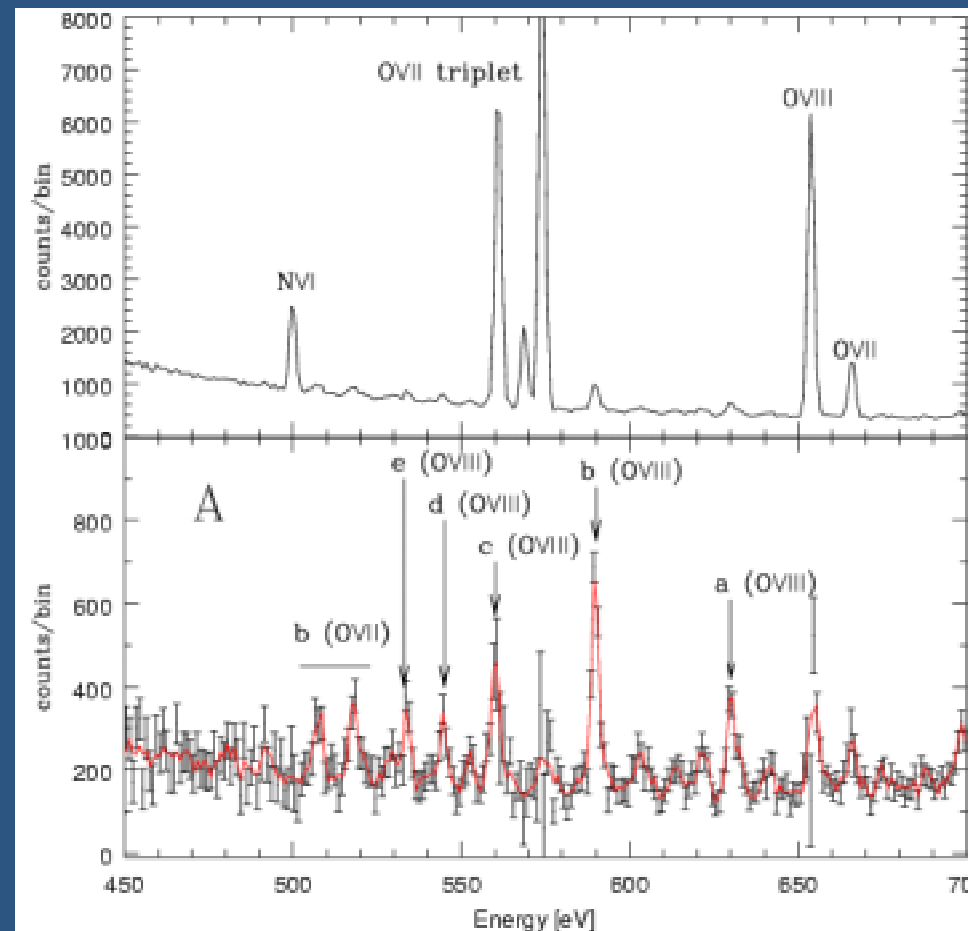


A

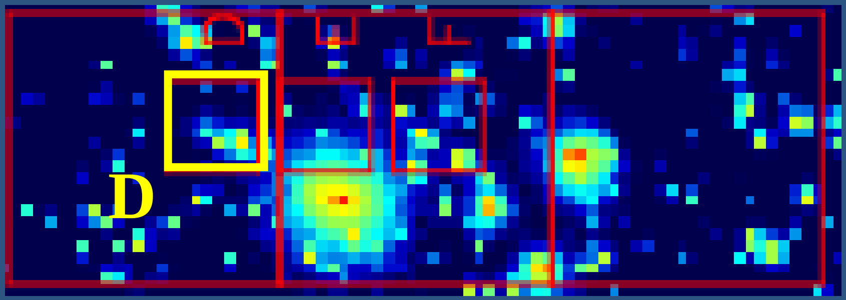
$0.94° \times 0.94° = 0.88\ \mathrm{deg}^2$

$T_{exposure} = 3\mathrm{x}10^5\mathrm{sec}$



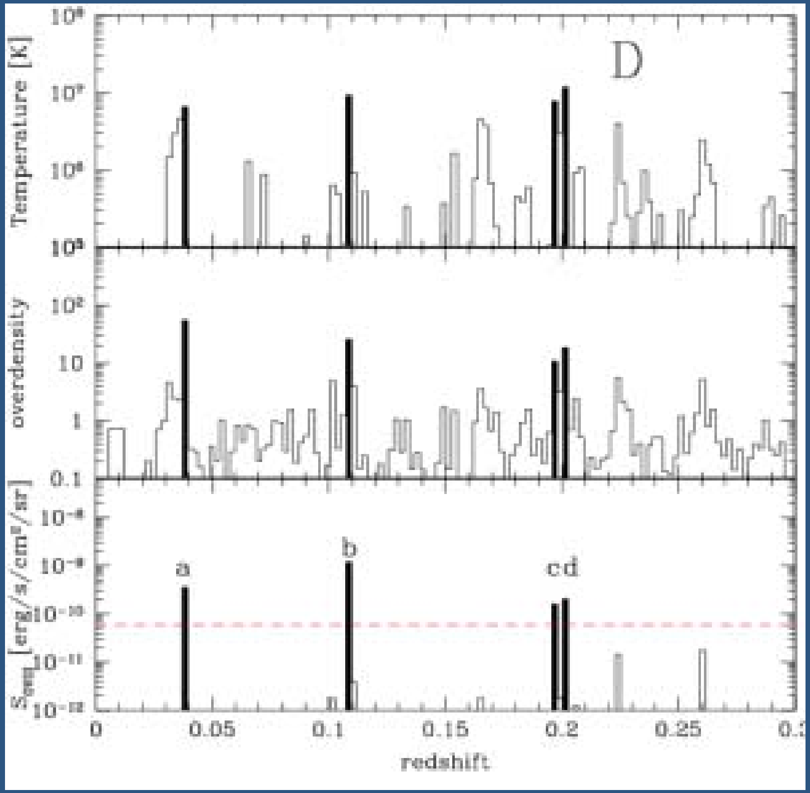


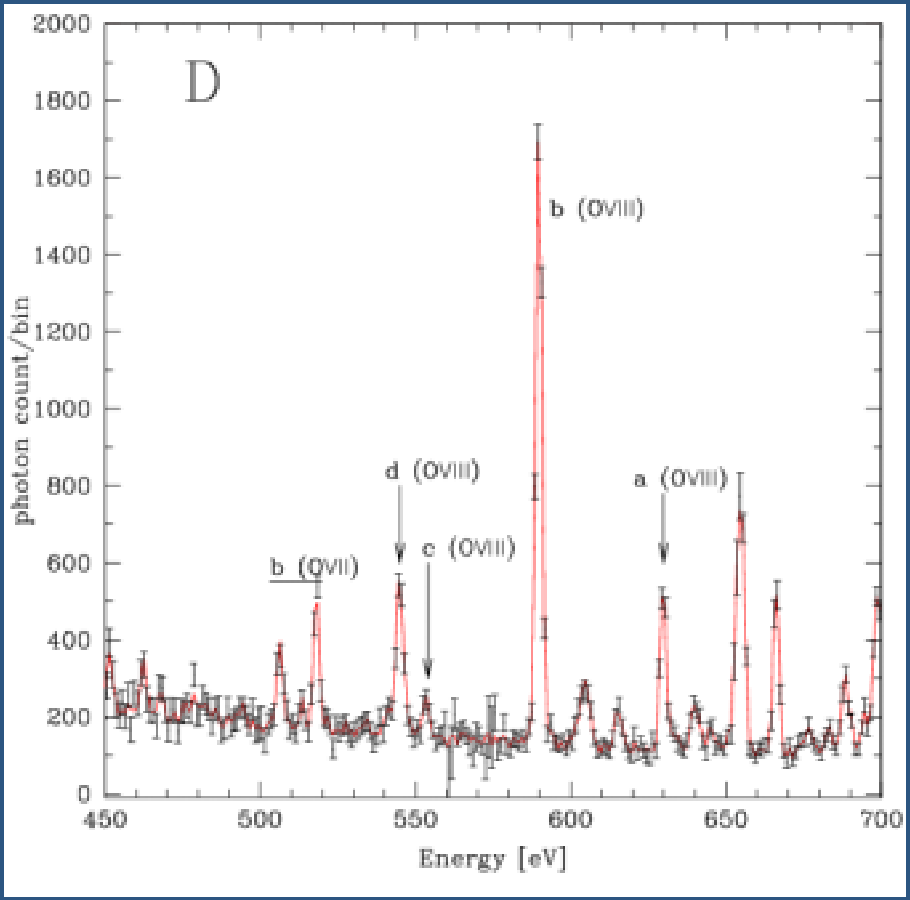
Simulated spectra: region D



19'x19' = 0.098 deg^2

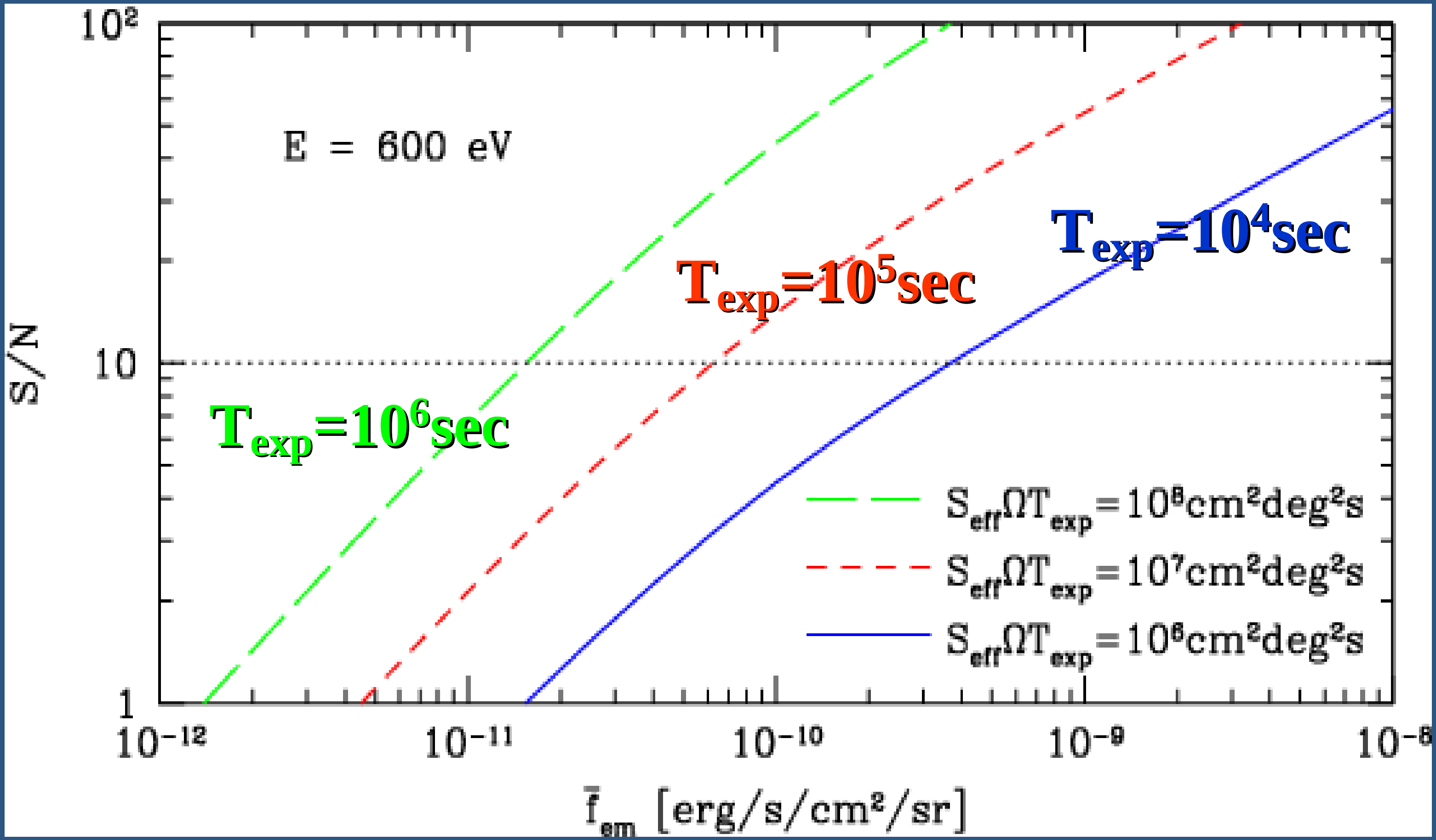
$T_{exposure} = 10^6$ sec



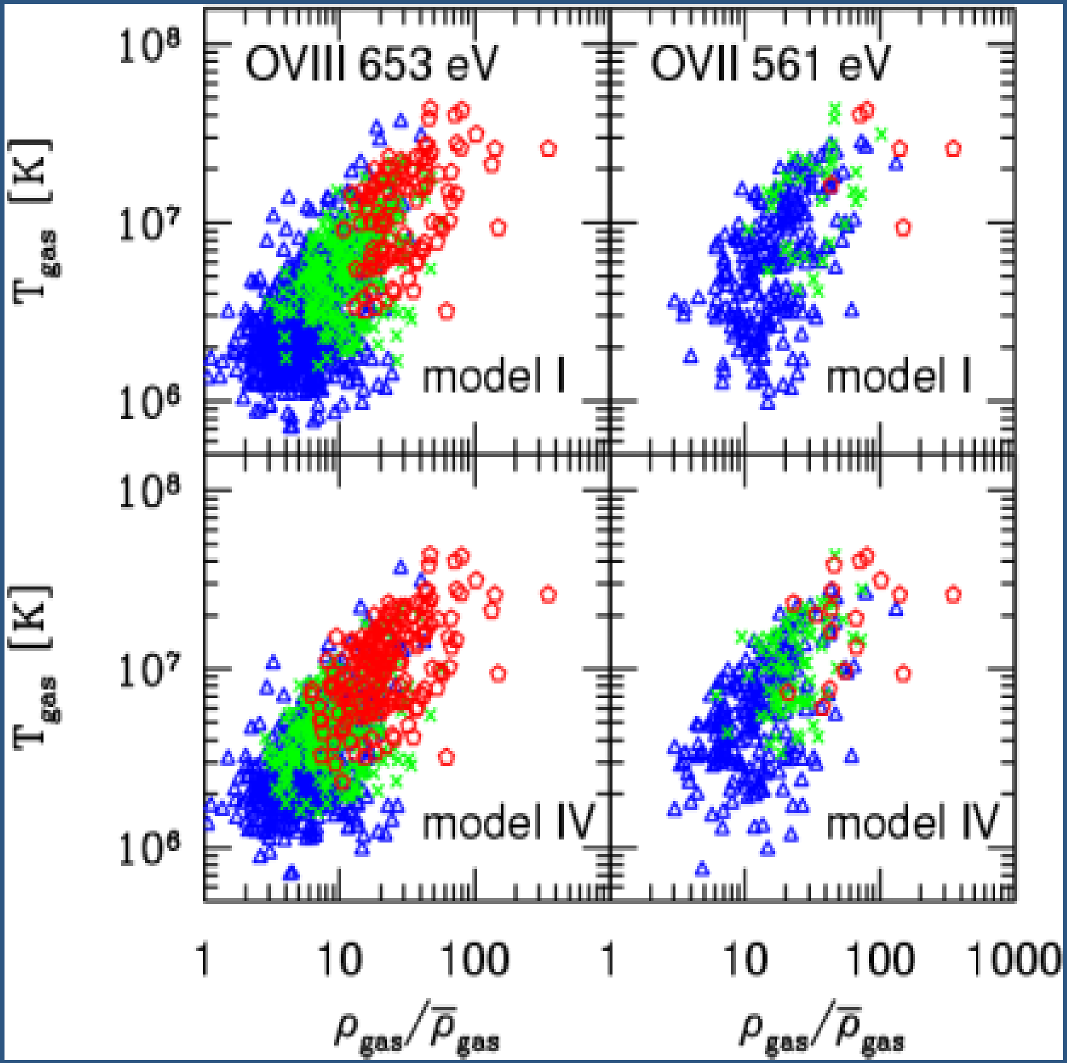


Expected S/N for OVIII line

Assuming the detector of $S_{eff}\Omega = 100\ cm^2deg^2$ and ΔE=2eV



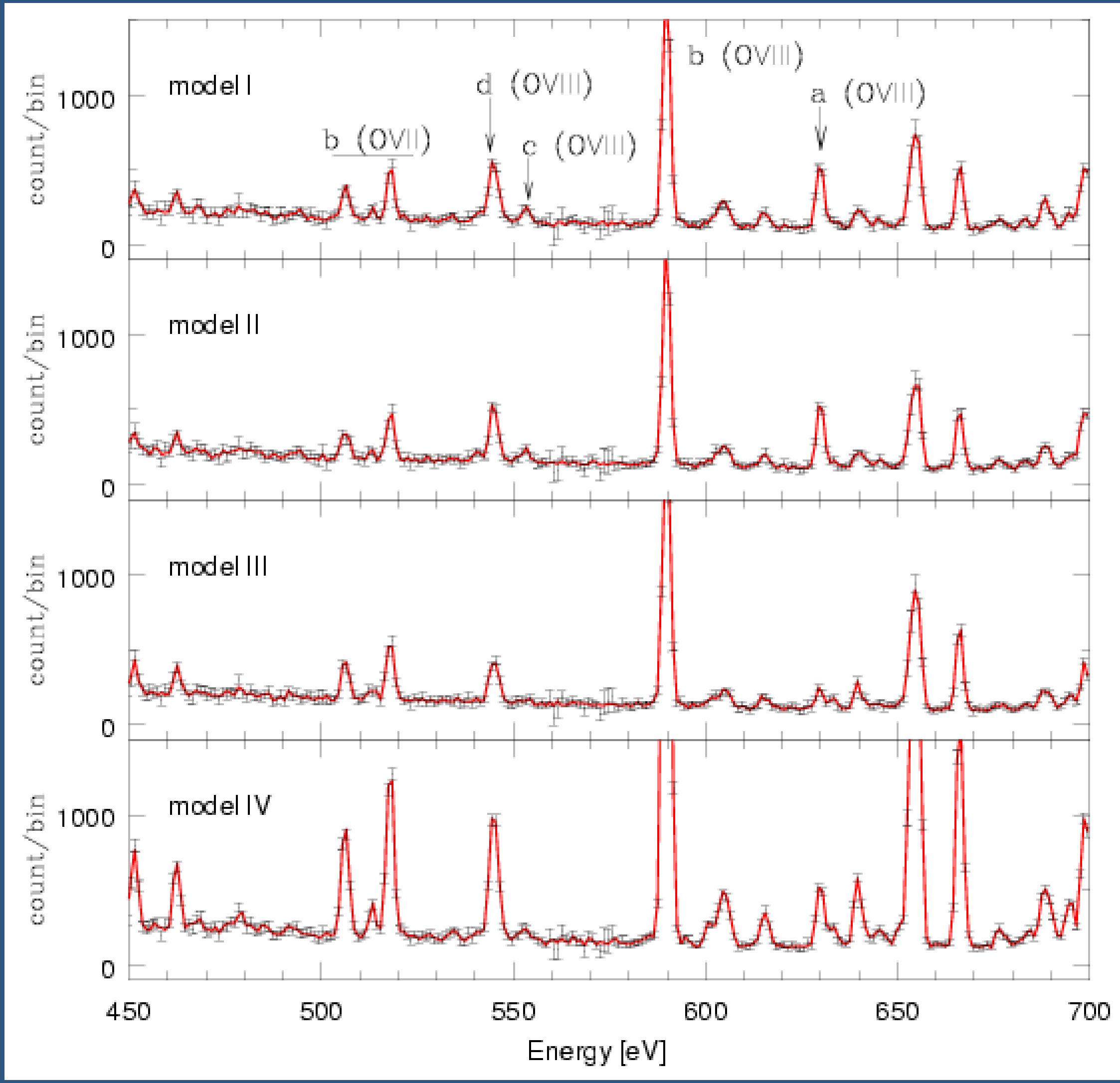
Physical properties of the probed baryons



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)

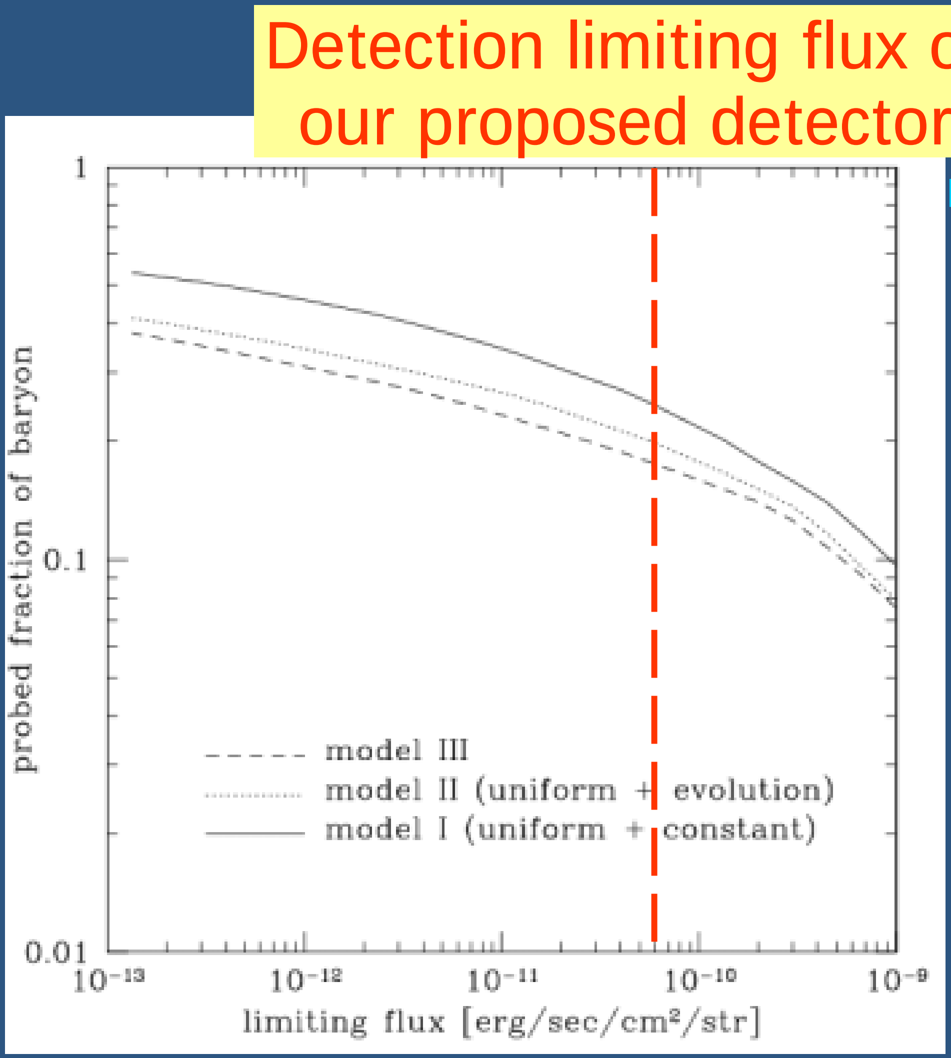
- ⬠ $S_x > 3\times10^{-10}$ [erg/s/cm^2/sr]
- × $S_x > 6\times10^{-11}$ [erg/s/cm^2/sr]
- △ $S_x > 10^{-11}$ [erg/s/cm^2/sr]

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

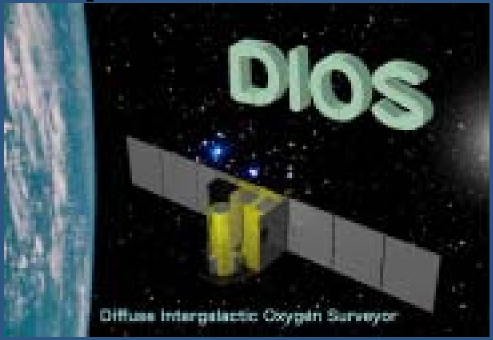
Expected fraction of WHIM detectable via Oxygen emission lines (in principle)



- 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**.

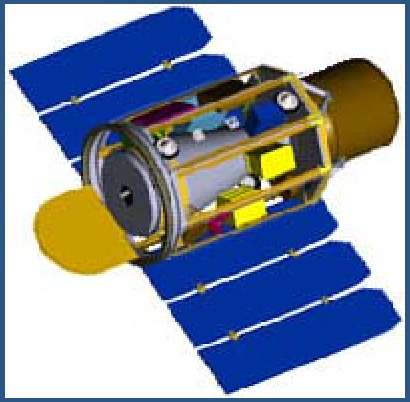
Detectability of Warm-Hot Intergalactic Medium via Oxygen emission lines

- 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.
  - $\Delta E = 2\mathrm{eV}$, $S_{eff}\ \Omega = 100$ [cm^2 deg^2]
  - flux limit = 6×10^{-11} [$erg/s/cm^2/str$]



- Things remain to be checked
  - Validity of the collisional ionization equilibrium ?
  - How to properly identify the oxygen lines from the background/noises in reality ?

MBE: a competing proposal



- PI: Wilt Sanders (UW-Madison SSEC)
- X-Ray Calorimeter Telescope Development
  - UW-Madison, NASA/GSFC, Lockheed-Martin
- Spacecraft: Spectrum Astro SA-200S Bus
- Time schedule: the concept study start is in November 2003, and launch is scheduled for August 2007.
- Cost: $118.96M in FY2003 USD

UW-Madison Space Science and Engineering Center

Missing Baryon Explorer

Surveys of the Low Energy X-Ray Diffuse Background to Complete Our Picture of the Universe

http://www.ssec.wisc.edu/baryons/index.html