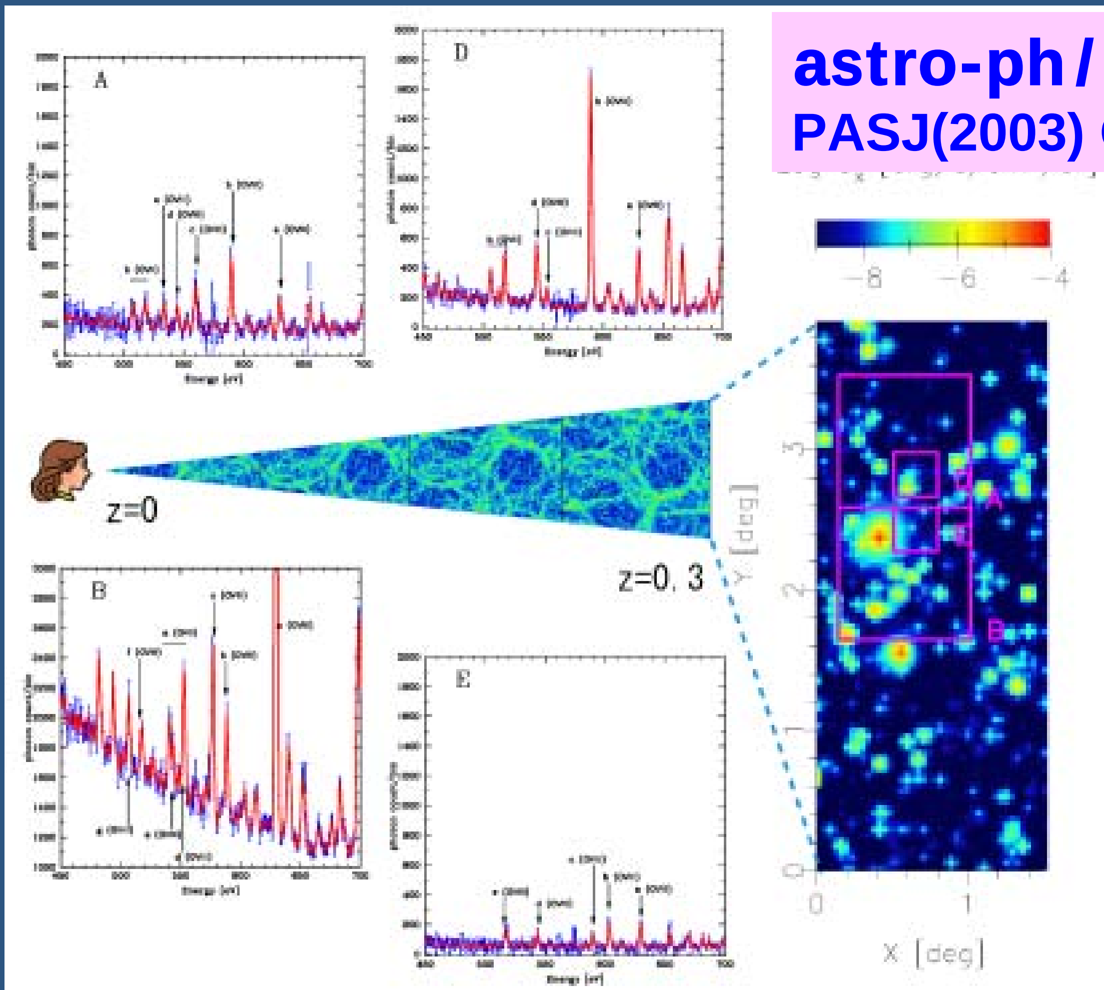
軟X線帯での酸素輝線を用いたダークバリオン探索計画

astro-ph/0303281

PASJ(2003) October issue, in press



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RESCEU 研究会@鴨川 2003年8月31日

Where are the baryons ?
cosmic baryon budget

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

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

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

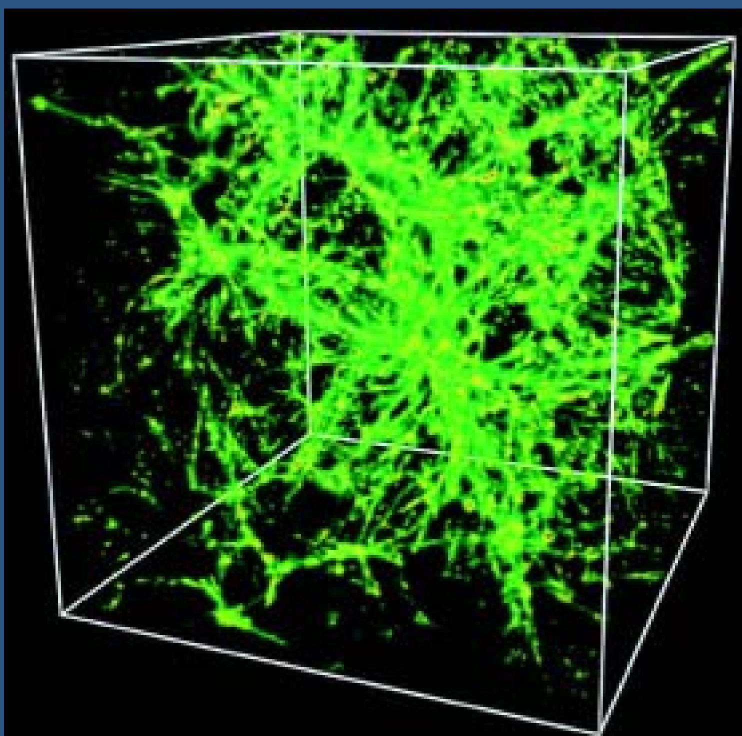
Four phases of cosmic baryons

Dave et al. ApJ 552(2001) 473

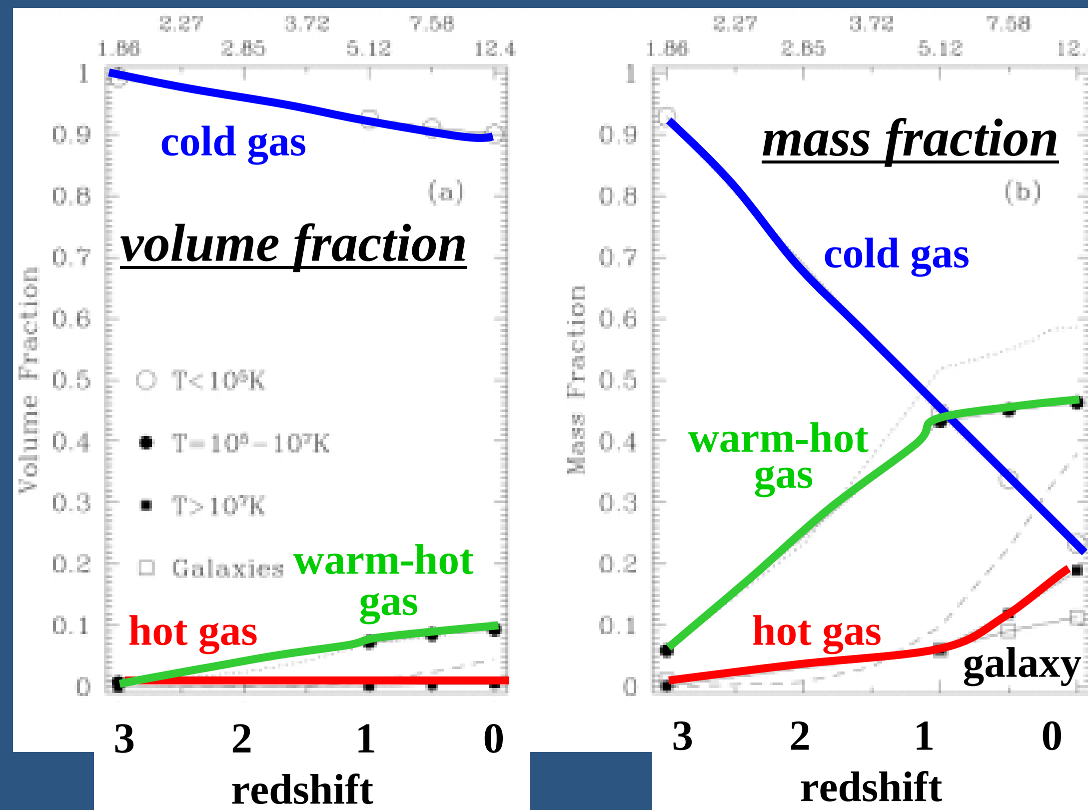
- ***Condensed:*** δ >1000, T<10^5K
  - Stars + cold intergalactic gas
- ***Diffuse:*** δ <1000, T<10^5K
  - Photo-ionized intergalactic medium
  - Ly α absorption line systems
- ***Hot:*** T>10^7K
  - X-ray emitting hot intra-cluster gas
- ***Warm-hot:*** 10^5K<T<10^7K
  - Warm-hot intergalactic medium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

Where are the baryons ?

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

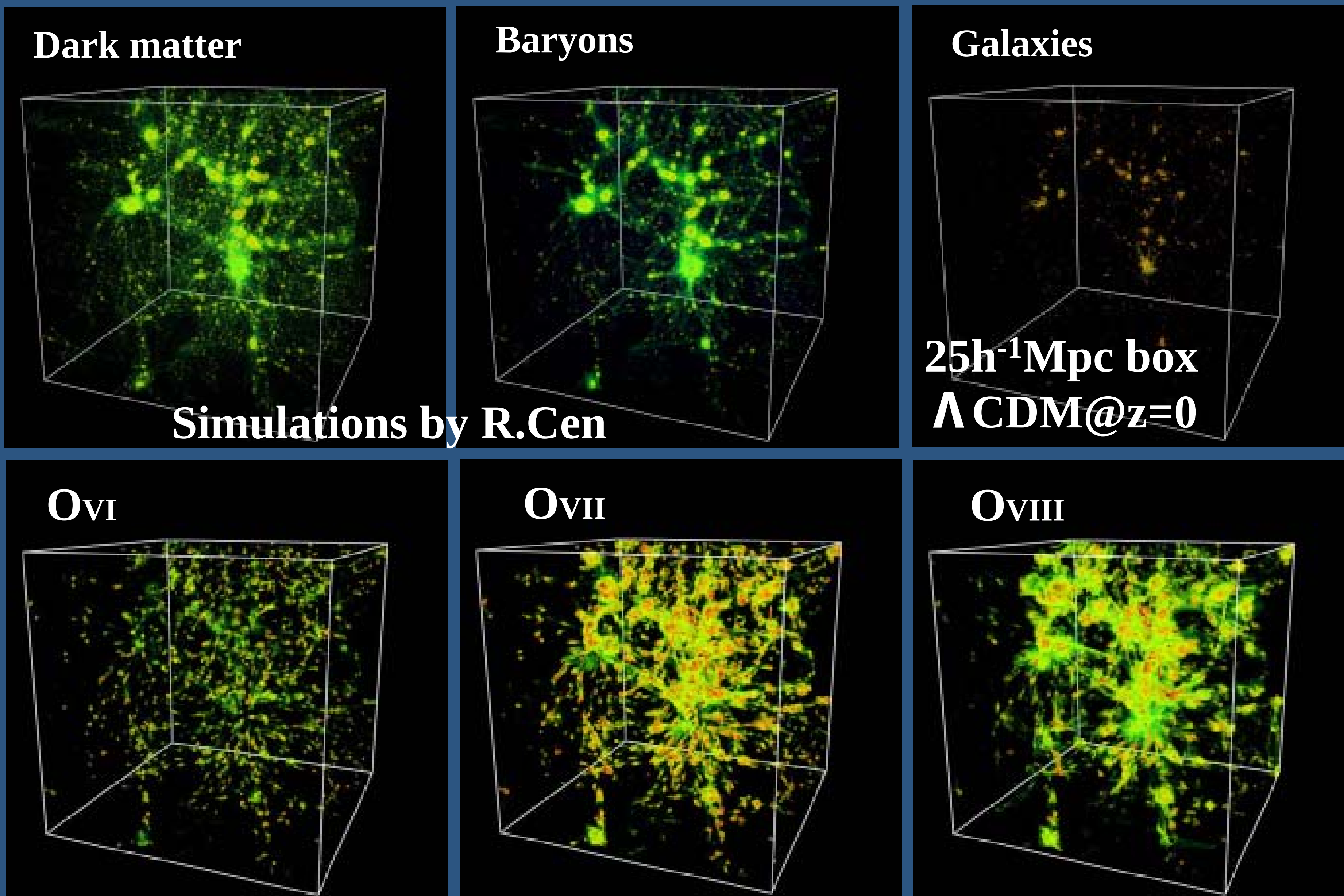


Warm/hot gas (10^5K<T<10^7K)



Cen & Ostriker：ApJ 514 (1999) 1

Tracing the structure with Oxygen



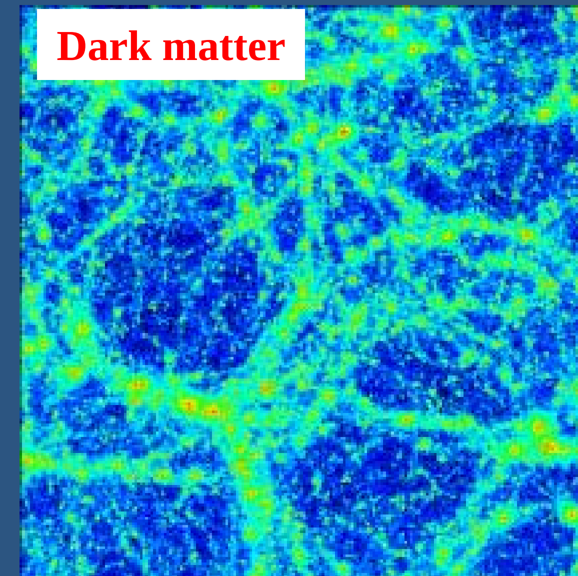
dark matter , hot gas and "galaxies"

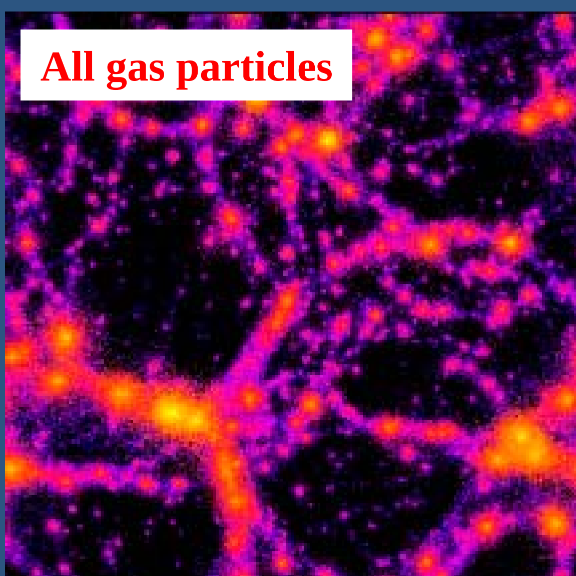
SPH simulation: Λ CDM, $(75h^{-1}Mpc)^3$ box
(Yoshikawa, Taruya, Jing & Suto 2001)

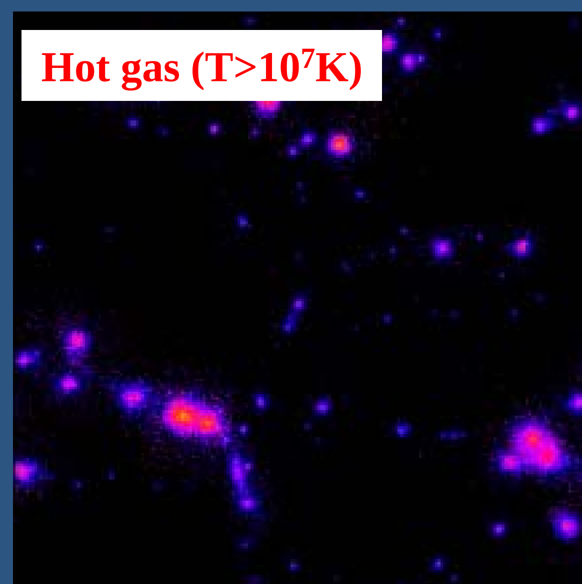
Large-scale structure in SPH simulation

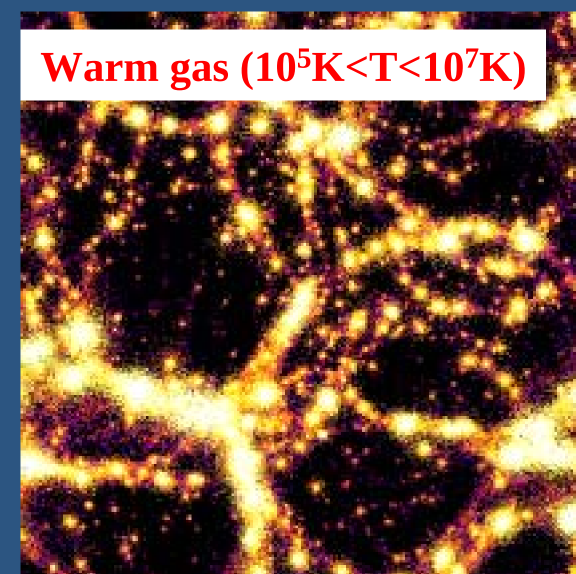
$(75h^{-1}\mathrm{Mpc})^3$ box
ΛCDM @ z=0
$N=128^3$:DM particles
$N=128^3$:gas particles

(Yoshikawa et al. 2001)





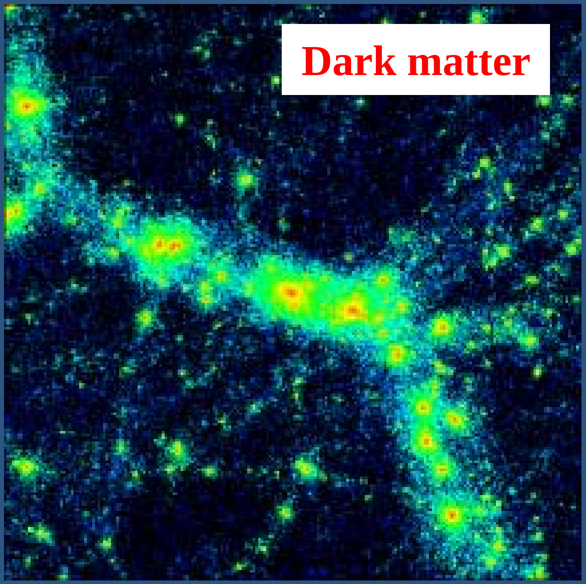


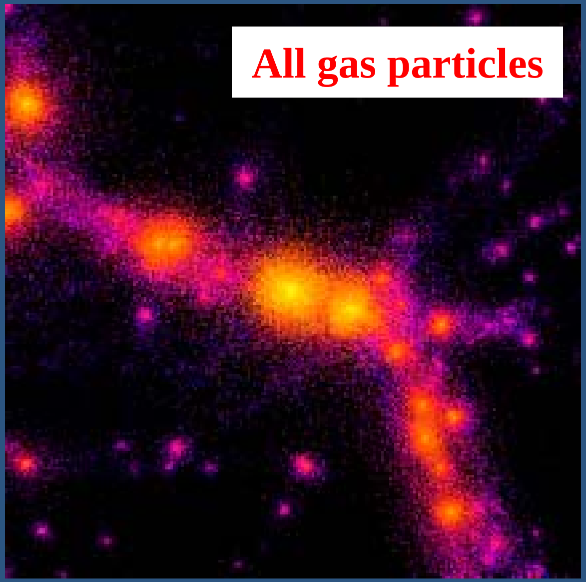


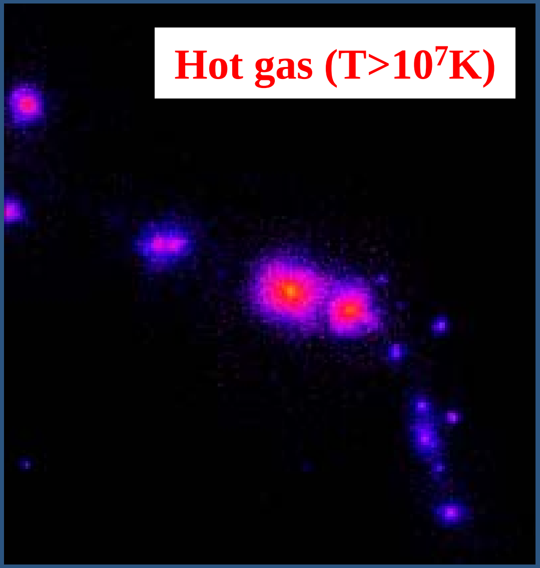
A cluster region in SPH simulation

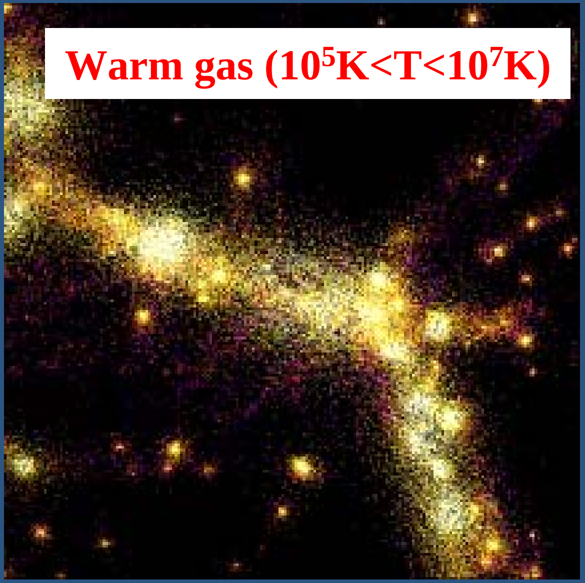
A $(30h^{-1}Mpc)^3$ box around a massive cluster at z=0 ΛCDM SPH simulation

(Yoshikawa et al. 2001)









WHIM as missing cosmic baryons

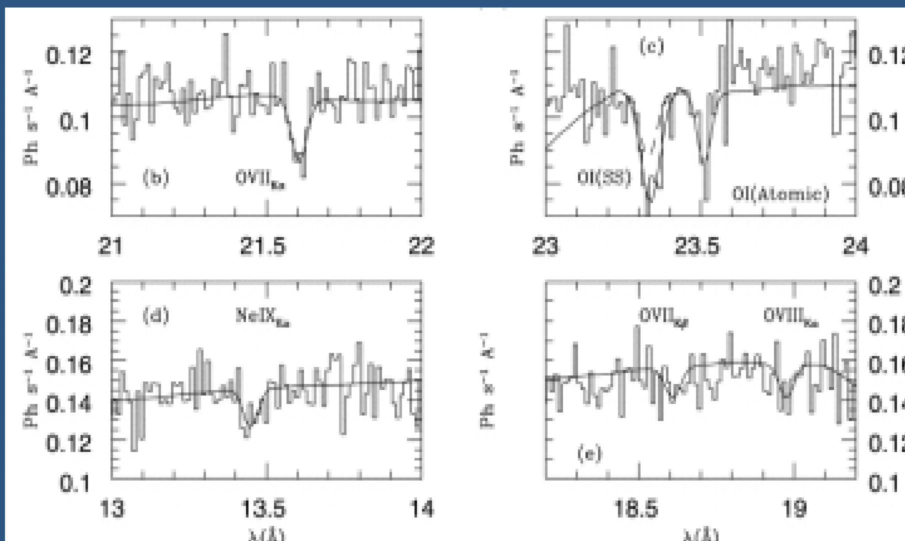
- ~40% of the total cosmic baryons may exist as Warm-Hot Intergalactic Medium (WHIM) with 10^5K<T<10^7K
- **WHIM is supposed to distribute diffusely along filamentary structures** connecting nearby clusters/ groups of galaxies
- **Direct detection of WHIM is difficult**
  - OVI absorption line systems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

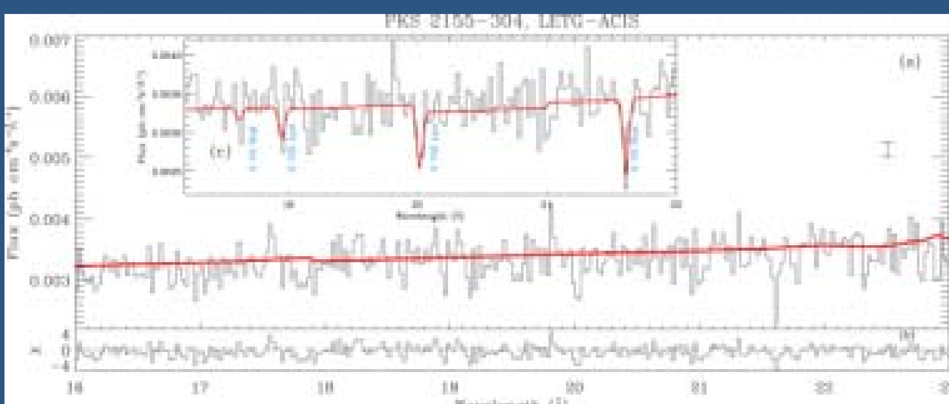
X-ray forests: shadow of WHIM

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)

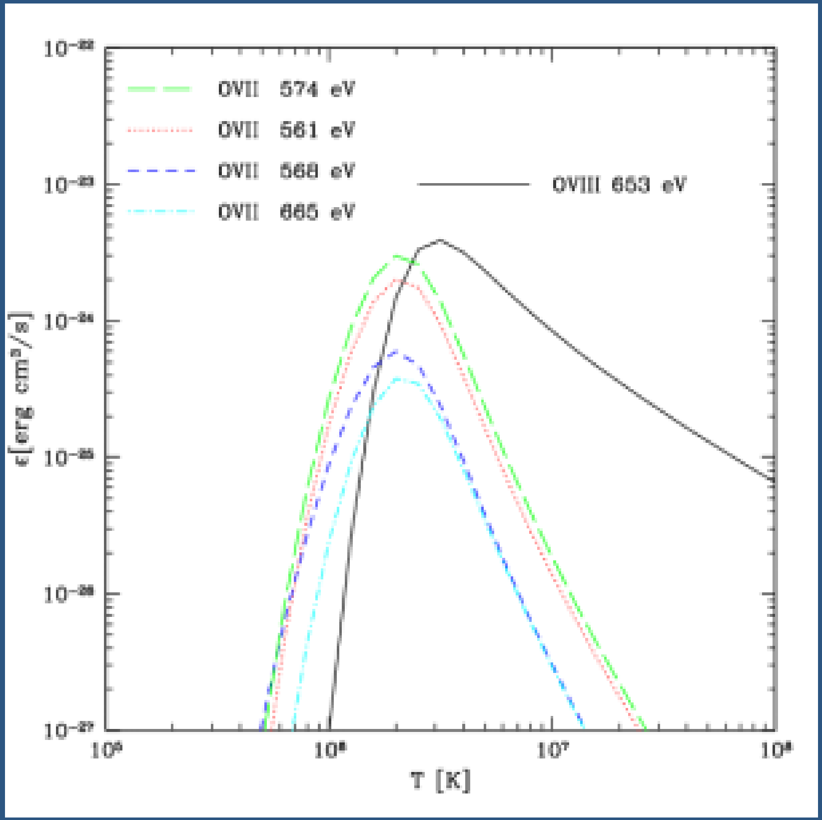
a small galaxy group
and HI Ly-a clouds

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

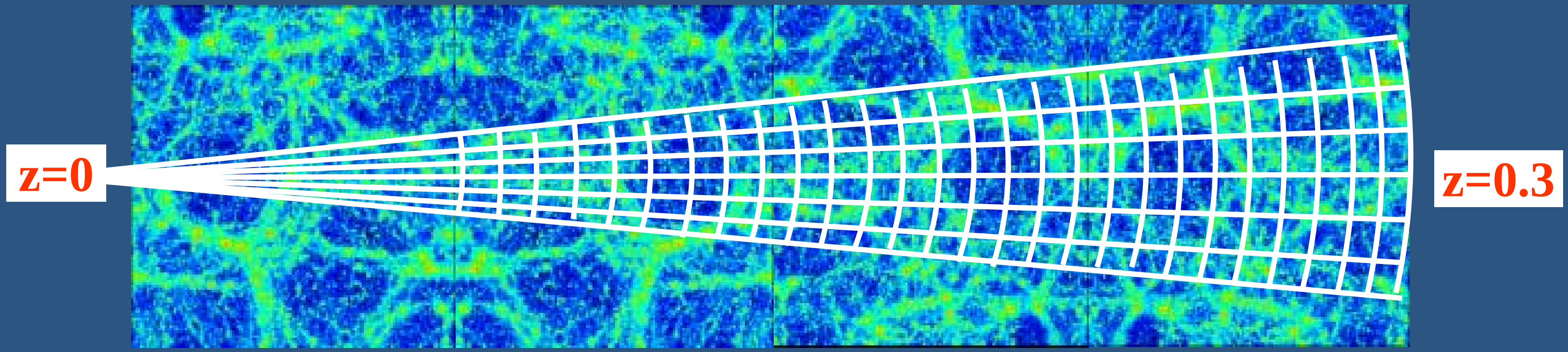
- **Good energy resolution** to identify the emission lines from WHIM at different redshifts
  - $\Delta E < 5$eV $\Rightarrow$ X-ray calorimeter using superconducting TES (Transition Edge Sensor)
- **Large field-of-view** and effective area for survey
  - $S_{eff} = 100\mathrm{cm}^2$, $\Omega = 1\deg^2$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

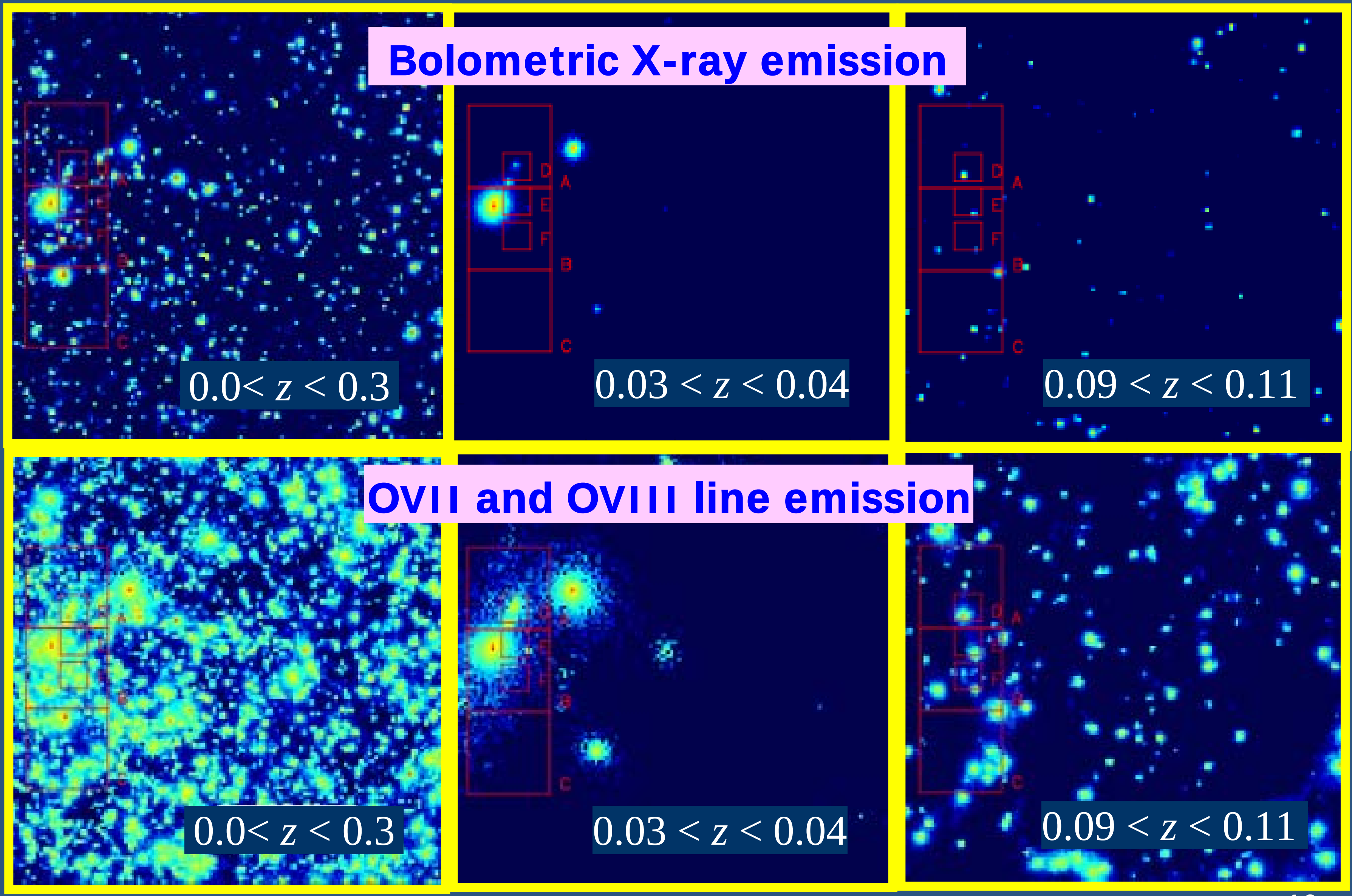
	$S_{eff}\Omega$ [cm^2 deg^2]	ΔE [eV]	f_{limit} [erg/s/cm^2/sr]
Chandra ACIS-S3	12	80	10^{-9}
XMM-Newton EPIC-pn	100	80	3×10^{-10}
Astro-E II XRS	0.23	6	2×10^{-8}
Astro-E II XIS	36	80	6×10^{-10}
XEUS-I	16.7	2	2.5×10^{-10}
our proposed detector	**100**	**2**	$\mathbf{6\times10^{-11}}$

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

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

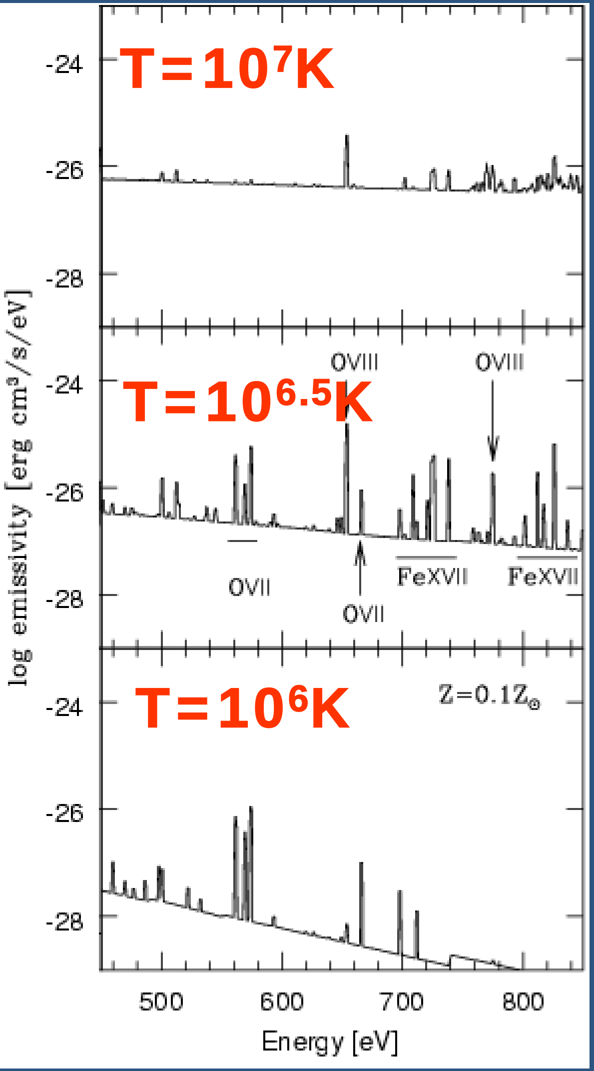
Model III : density-dependent (Aguirre et al. 2001)

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

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

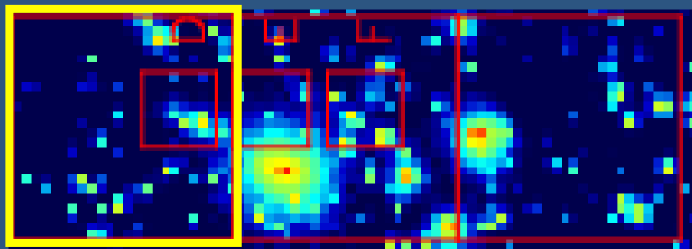
$Z = 0.02\, Z_{solar}\, (\rho/\rho_{\rm mean})^{0.3}$ (radiation pressure driven)

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 $\Delta E=2$eV resolution.

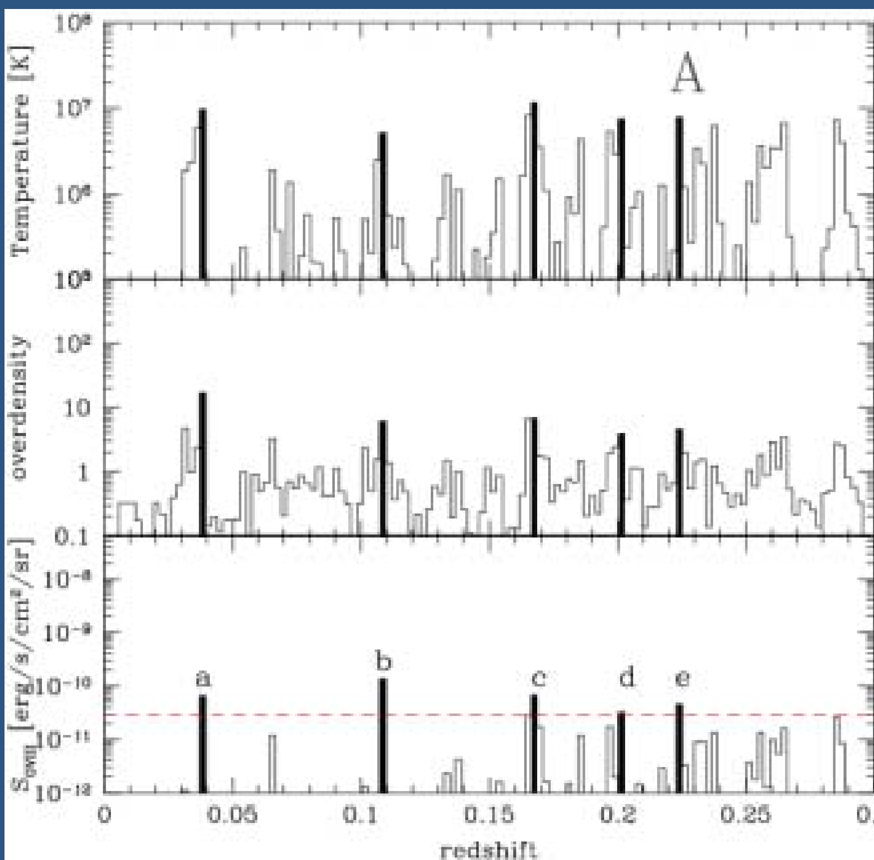
Simulated spectra: region A

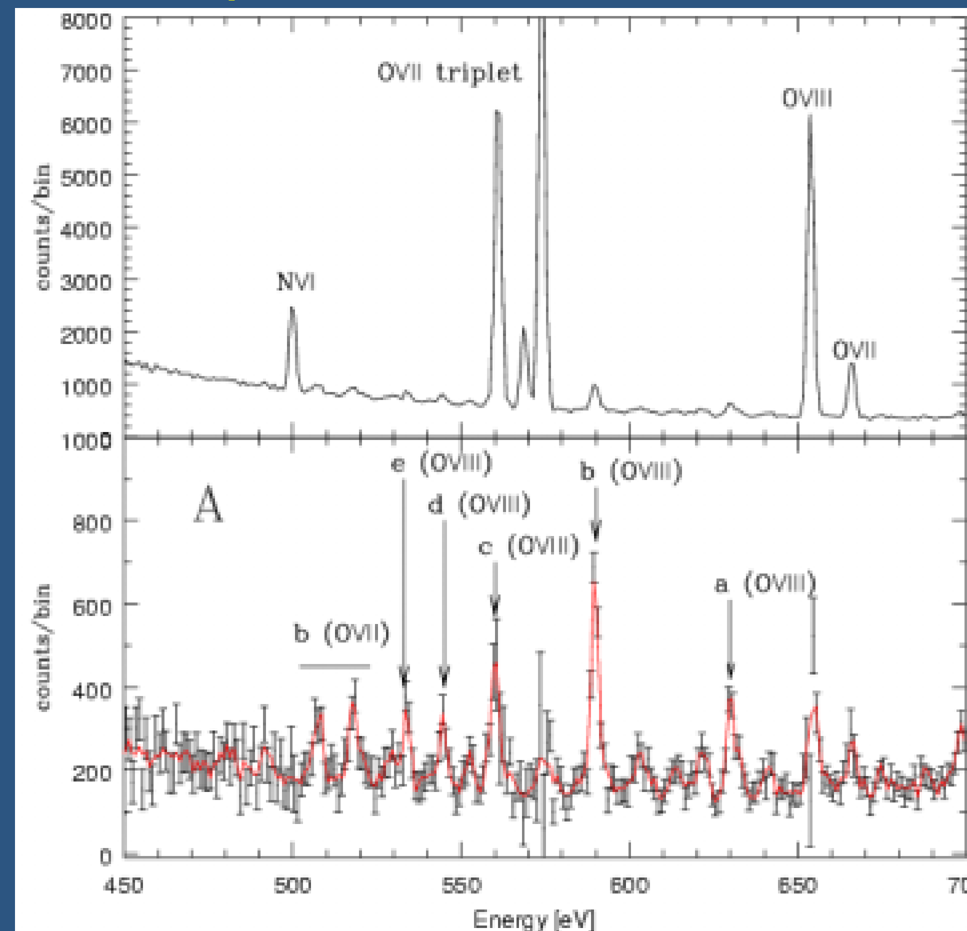


A

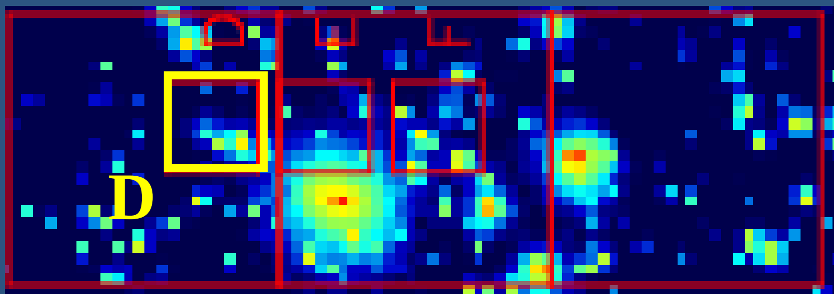
$0.94° \times 0.94° = 0.88\ \mathrm{deg}^2$

$T_{exposure} = 3\times10^5$ sec



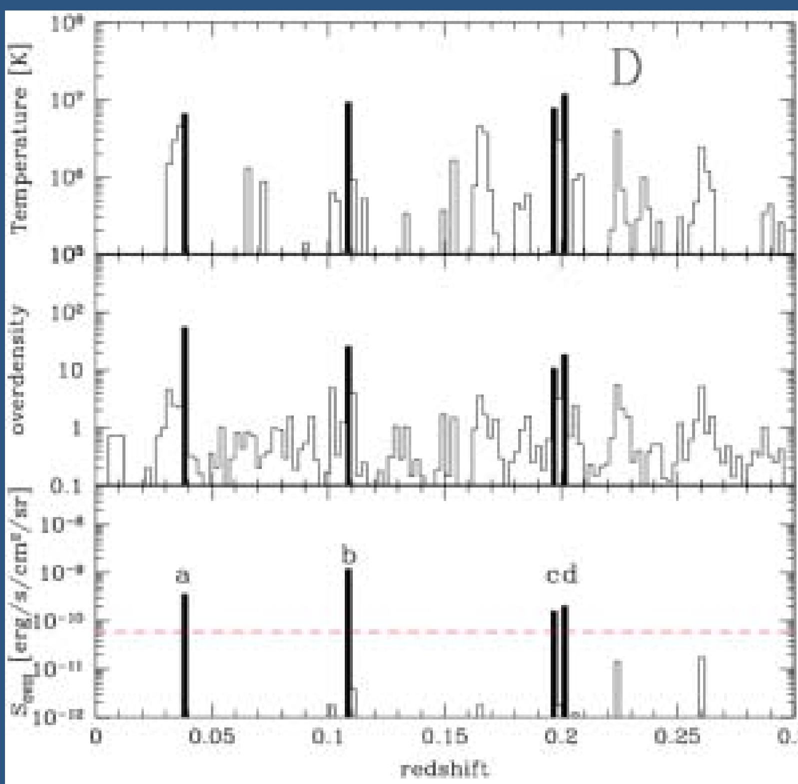


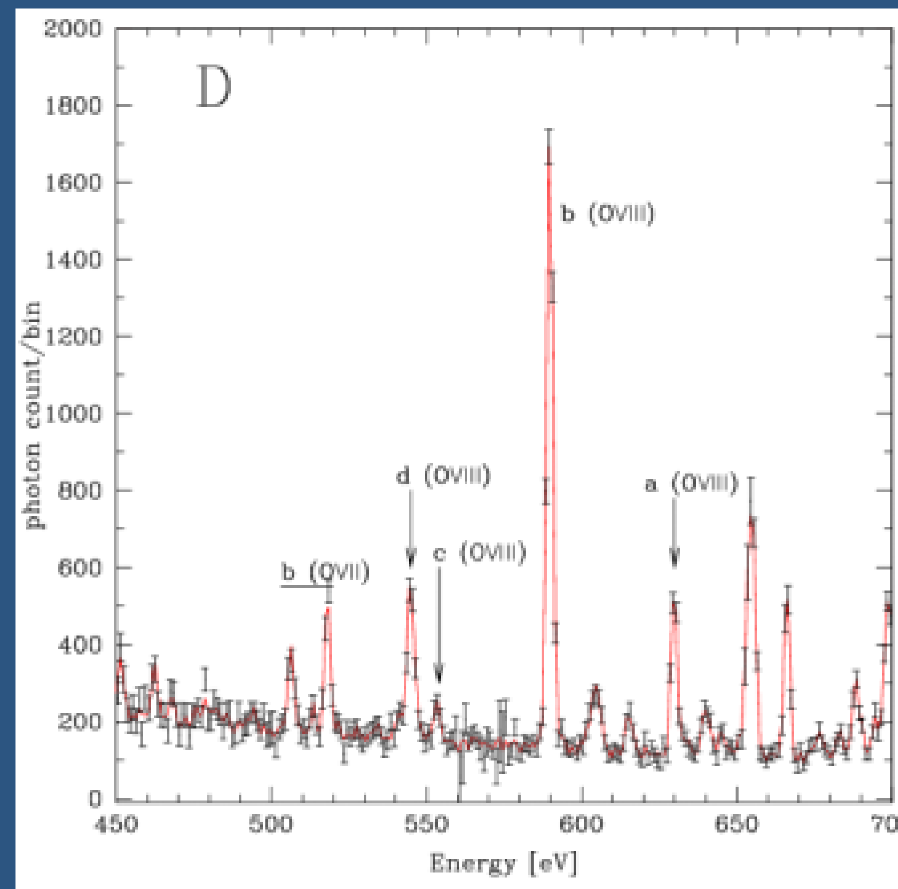
Simulated spectra: region D



$19'\times19' = 0.098\ \mathrm{deg}^2$

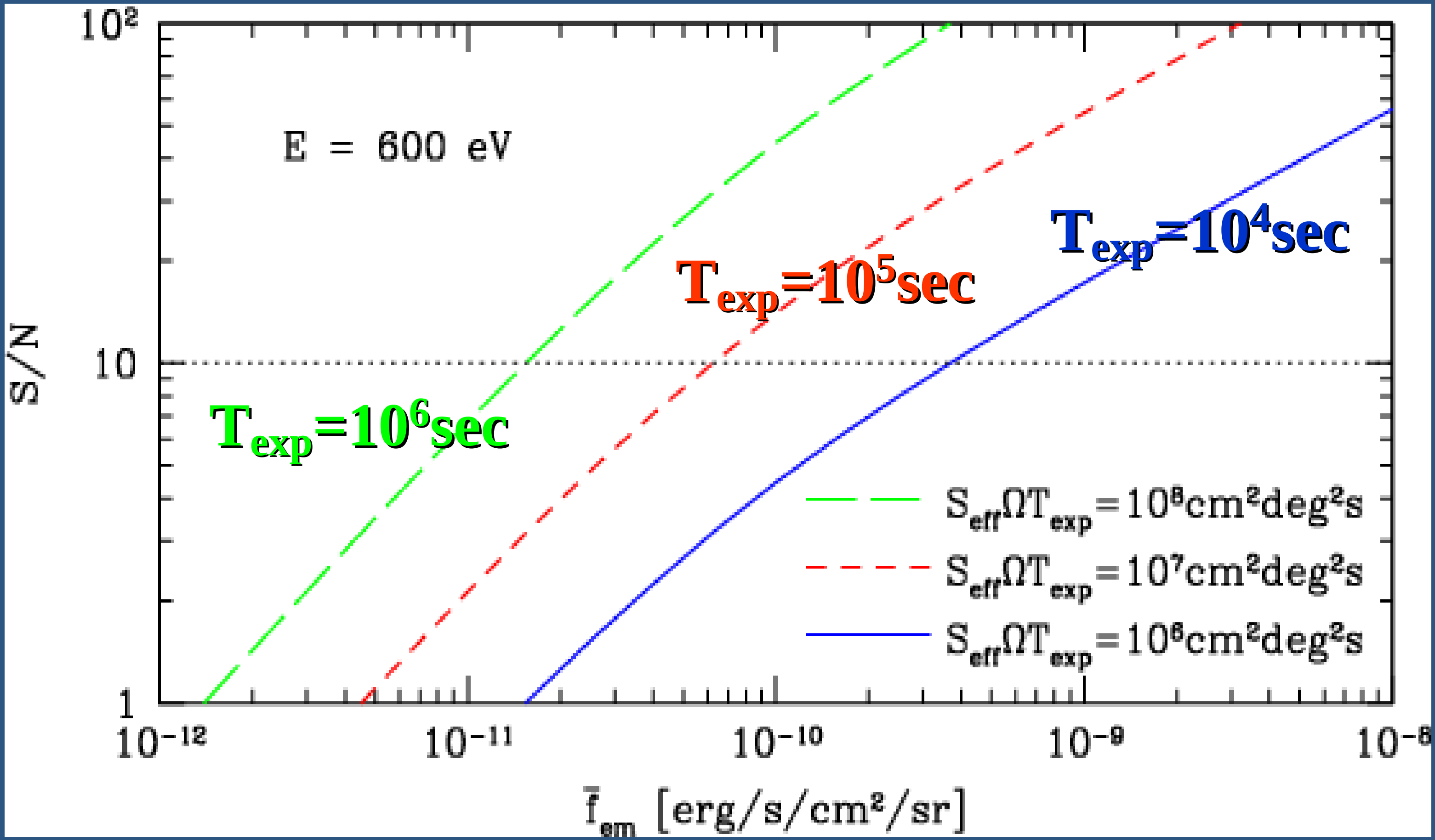
$T_{exposure} = 10^6\mathrm{sec}$



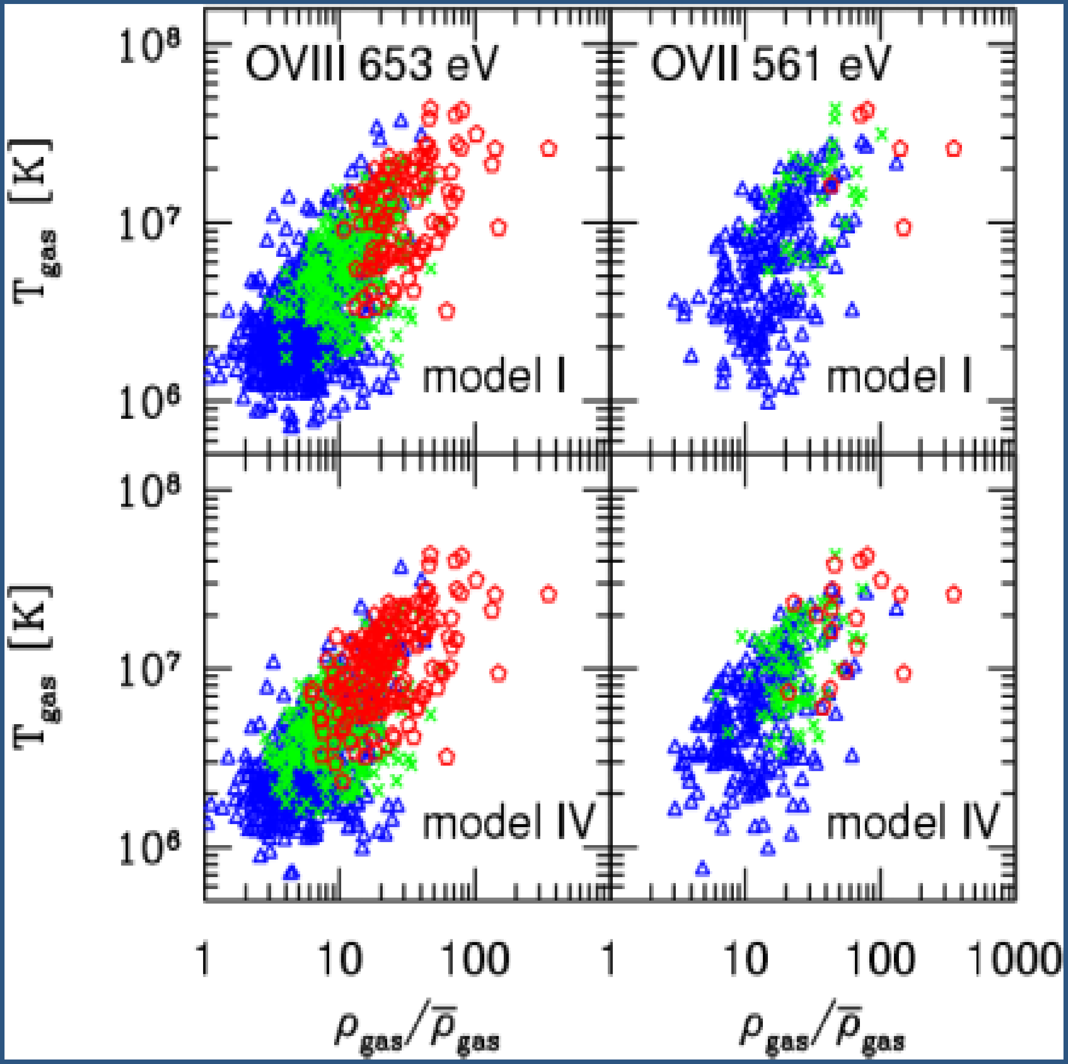


Expected S/N for OVIII line

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



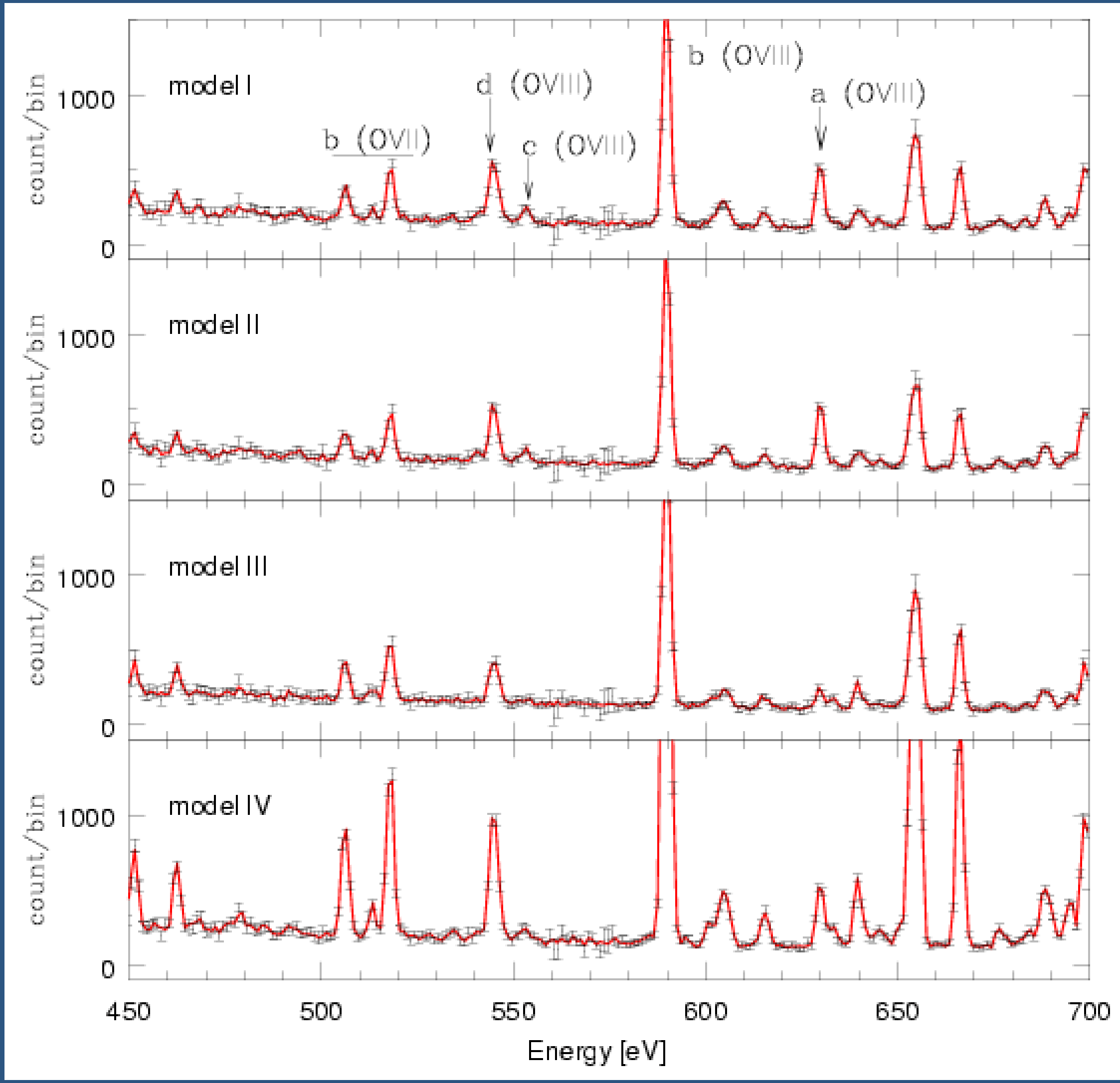
Physical properties of the probed baryons



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

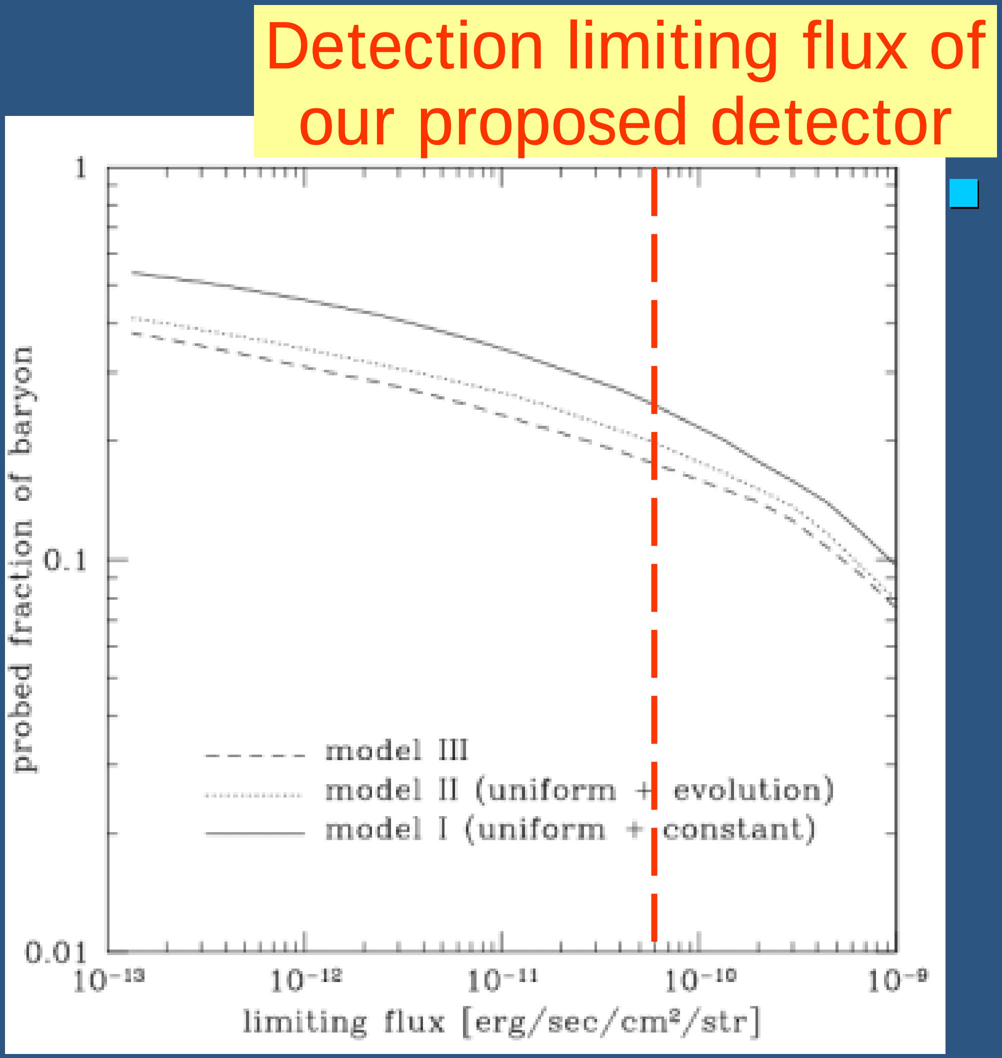
- **$S_x > 3\times10^{-10}$ [erg/s/cm^2/sr]** (red pentagon)
- **$S_x > 6\times10^{-11}$ [erg/s/cm^2/sr]** (green cross)
- **$S_x > 10^{-11}$ [erg/s/cm^2/sr]** (blue triangle)

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)

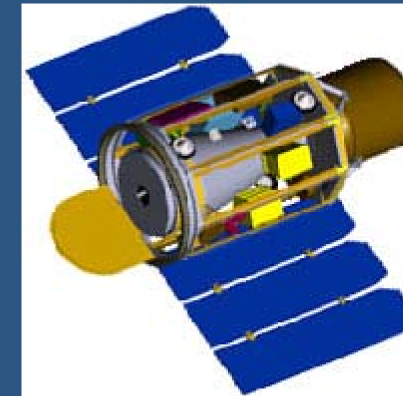


- Our proposed mission (flux limit = 6×10^{-11} [erg/s/cm^2/str]) will be able to detect (20-30) percent of the total cosmic baryons via Oxygen emission lines **in principle**.

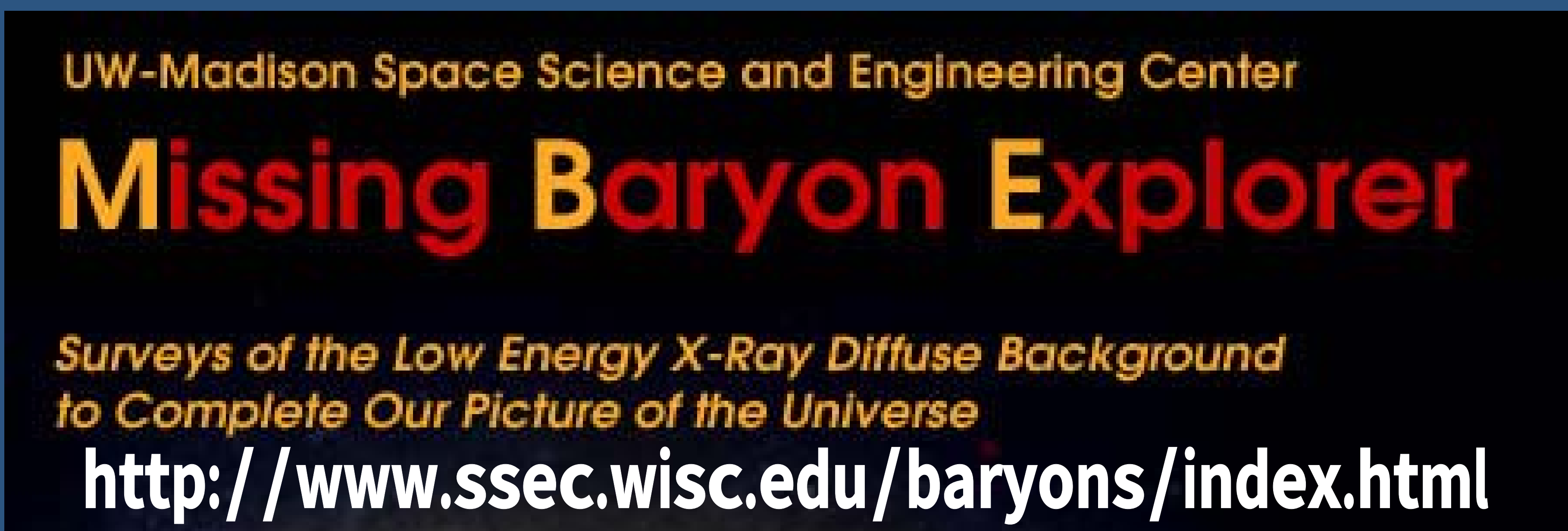
Detectability of Warm-Hot Intergalactic Medium via Oxygen emission lines

- 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.
  - $\Delta E=2\text{eV}$, $S_{eff}\,\Omega=100$ [$\text{cm}^2\ \text{deg}^2$]
  - 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 ?

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



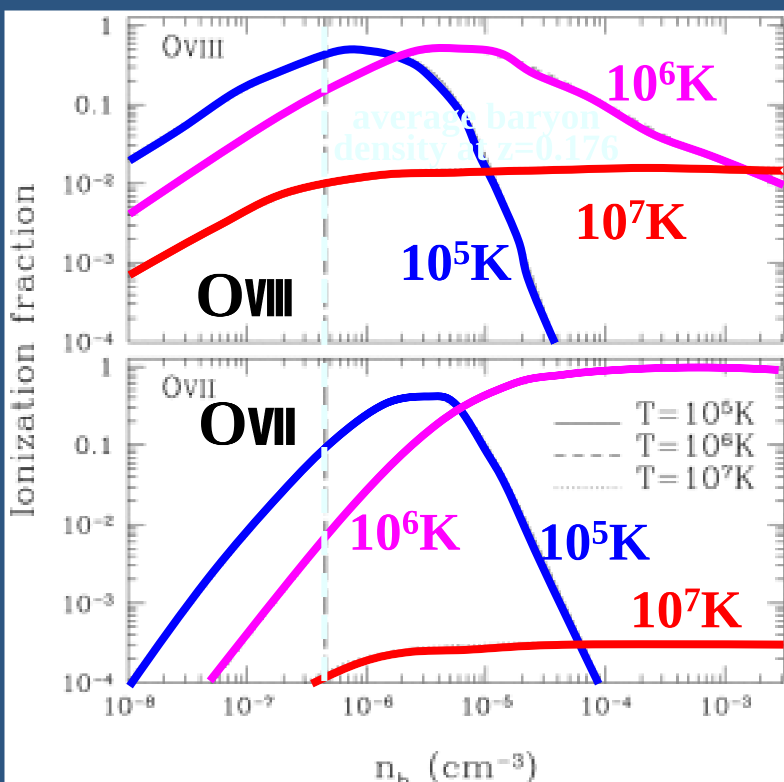
http://www.ssec.wisc.edu/baryons/index.html

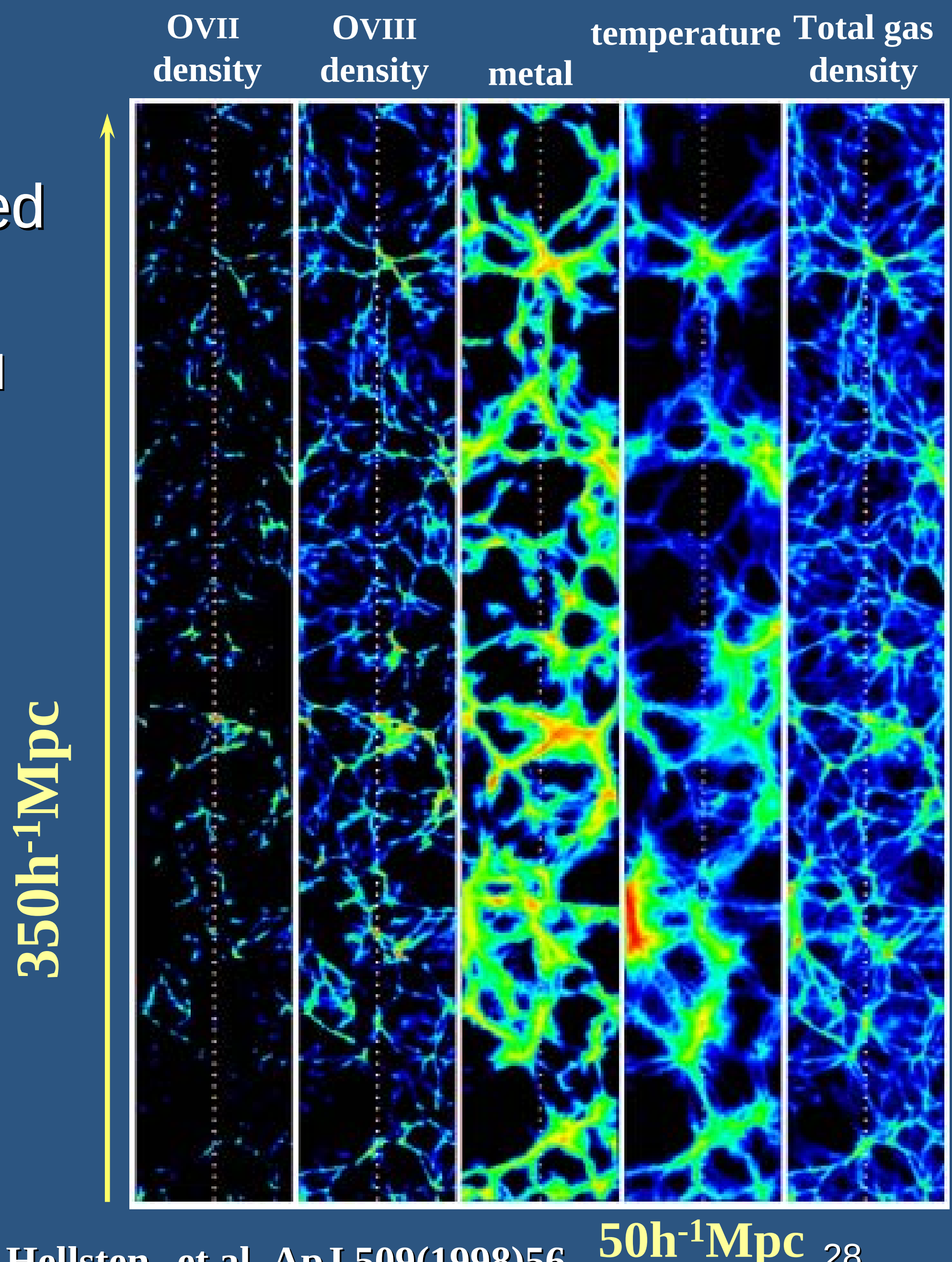
Our plan

- A dedicated satellite with cost < 30M USD to fill the gap between Astro-E2 (2005) and NeXT (2010?).
- Launch at Japan in 2008 (?).
- Details to be determined at a meeting on September 10, 2003 at ISAS.
- Need to organize a serious working group to explore all possible aspects of the expected scientific outcome.
- Everyone interested in this project is very welcome to join us.

X-ray forests: simulation

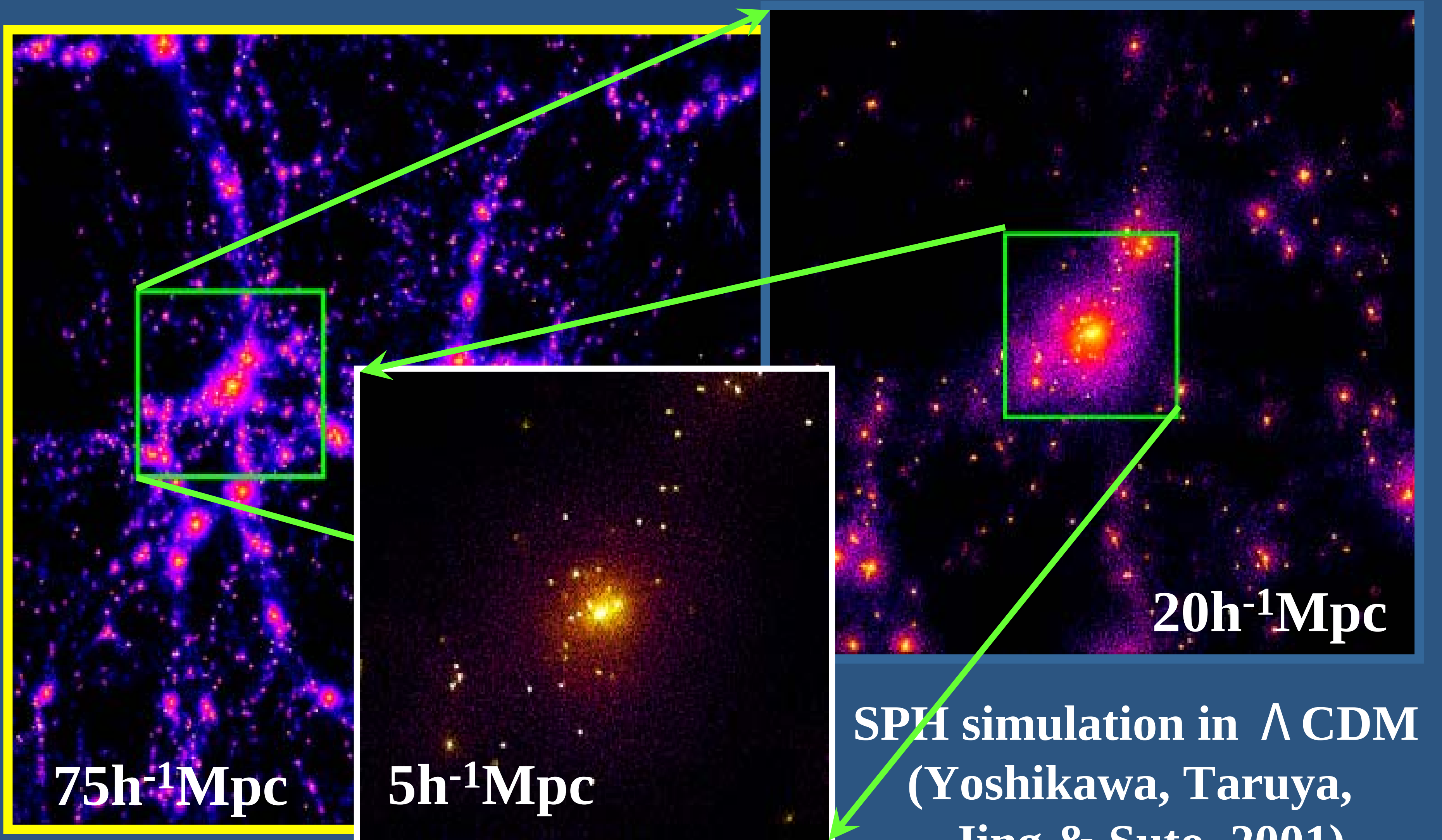
- Oxygen emission lines ionized by X-ray background
- High-density regions ⇒ OVII
- Connecting filaments ⇒ OVIII





Hellsten et al. ApJ 509(1998)56

SPH simulation: zoom-up



SPH simulation in ΛCDM (Yoshikawa, Taruya, Jing & Suto 2001)