Searching for emission and absorption signatures of warm/hot intergalactic medium with DIOS

(Diffuse Intergalactic Oxygen Surveyor):

mock observation of cosmological simulation data

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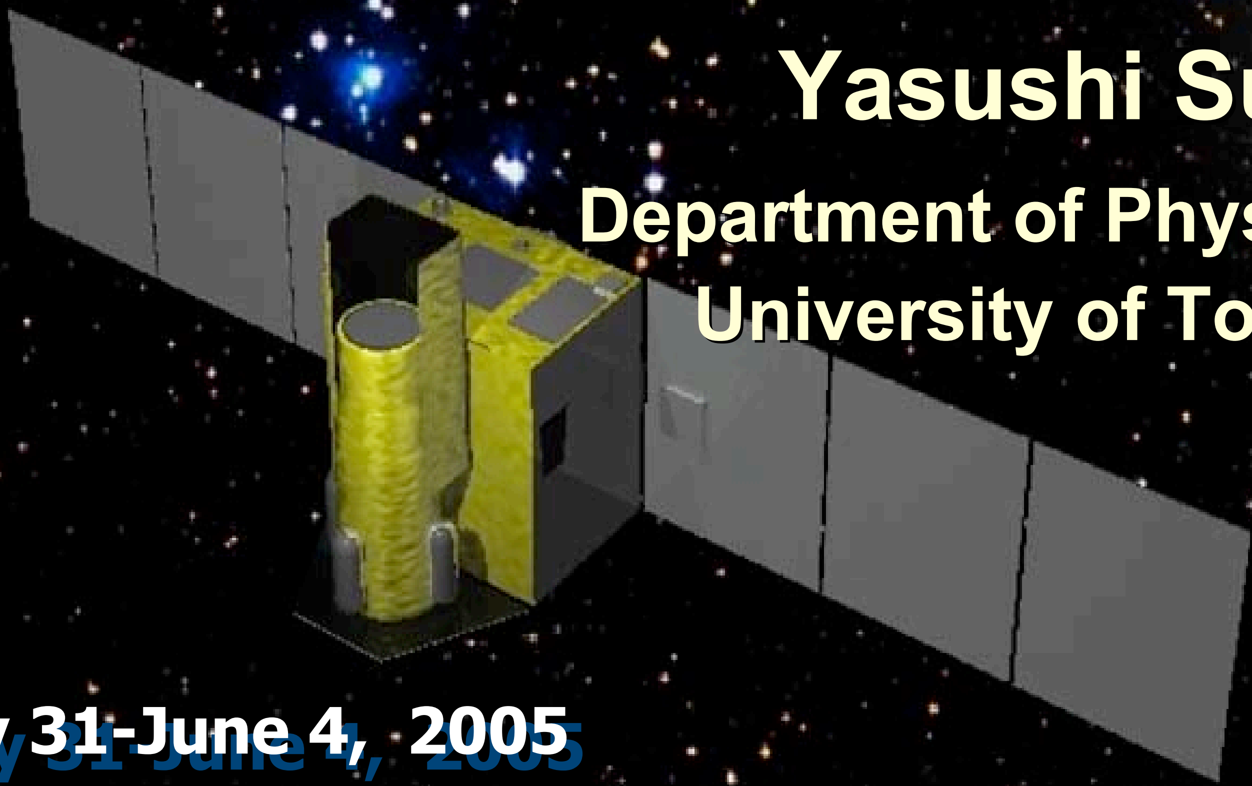
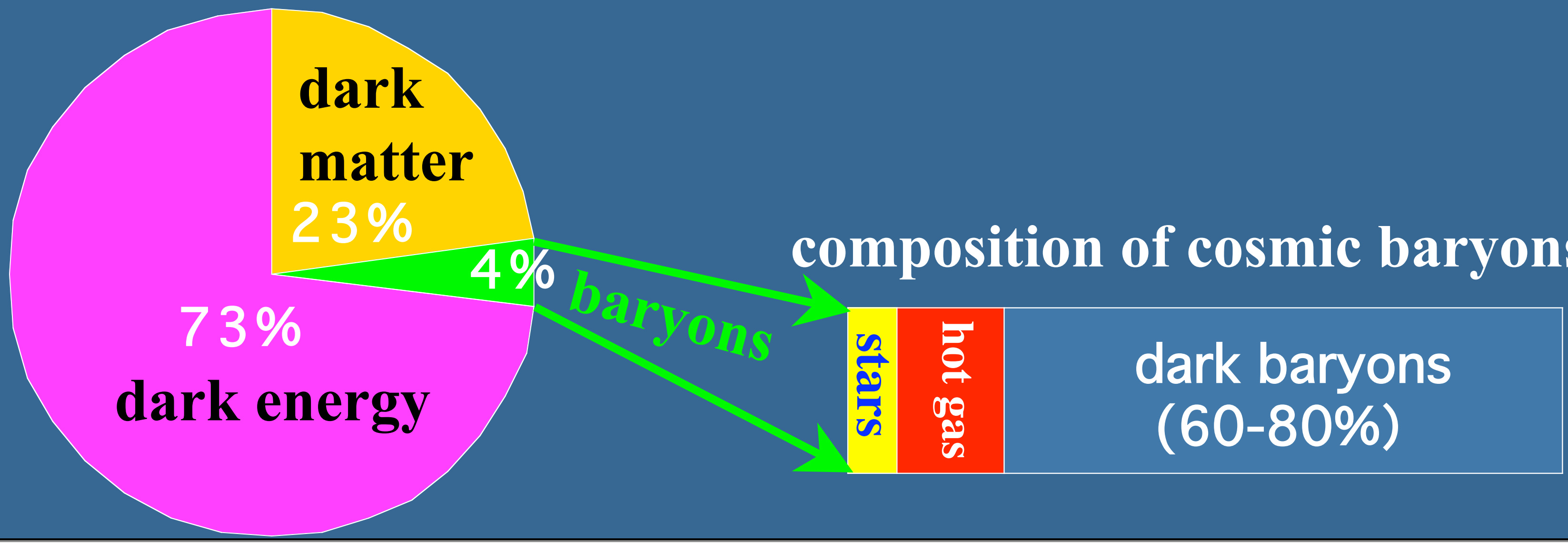


May 31-June 4, 2005

Computational Cosmology @ ICTP, Trieste

dark matter, dark energy and dark baryons



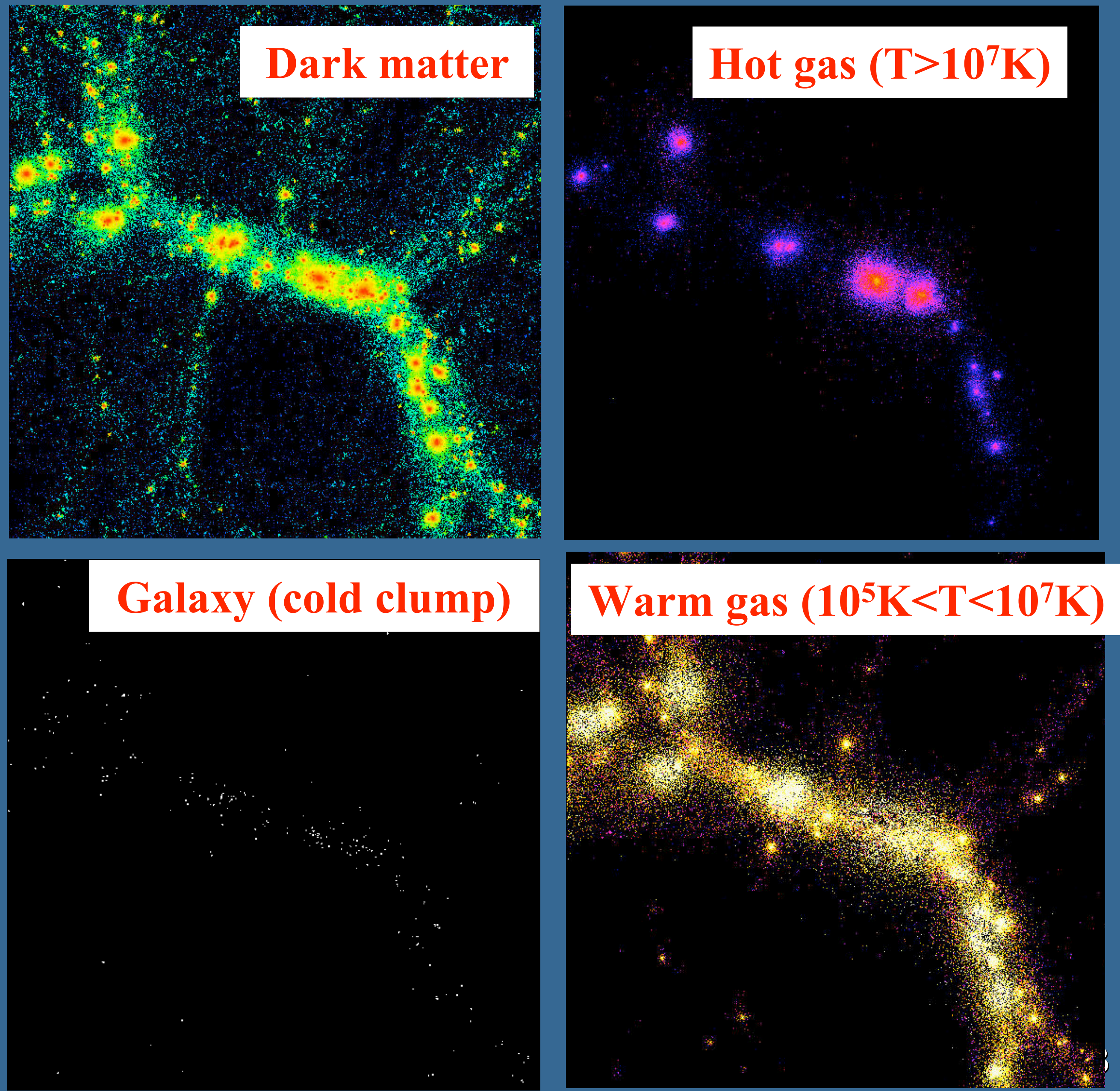
Cosmic Baryon Budget: Fukugita, Hogan & Peebles : ApJ 503 (1998) 518

Component	Central	Maximum	Minimum	Grade[a]
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	...

Simulated distribution of matter in the universe

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

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



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***)

Three complementary methods to search for dark baryons

- absorption line systems of OVI, OVII and OVIII along background QSOs in UV and soft X-ray

→ several detections reported with FUSE, Chandra, and XMM/Newton (e.g., Fang et al. 2002, Fujimoto et al. 2004, Nicastro et al. 2005)

- emission line survey (mainly of OVII and OVIII)

→ goal of DIOS (Yoshikawa et al. 2003, 2004)

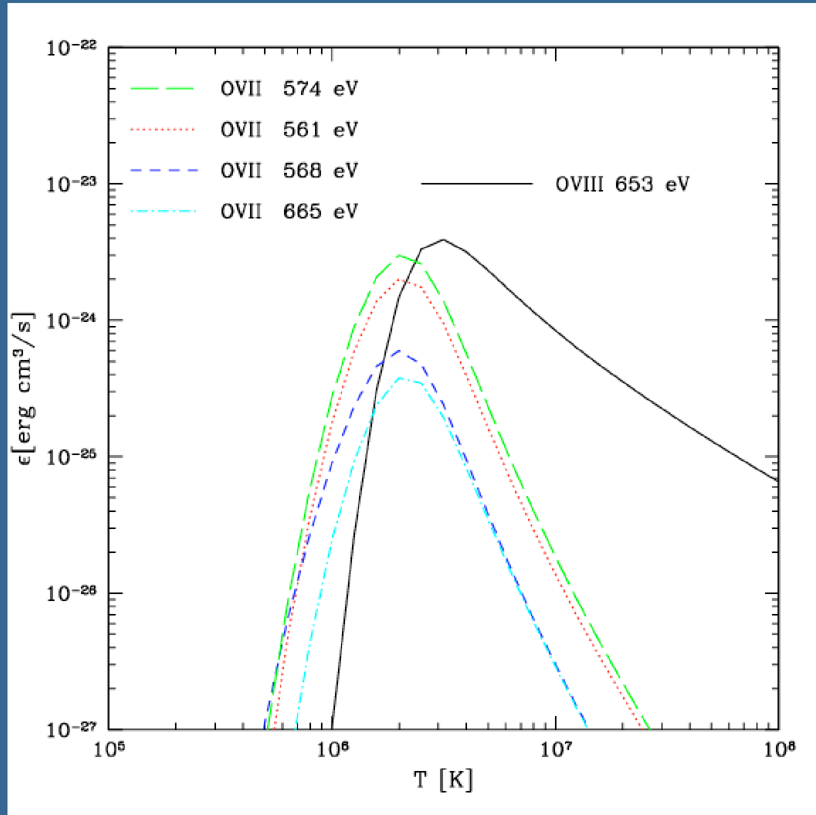
- absorption line systems along a GRB afterglow in soft X-ray

→ feasible with XEUS (X-ray Evolving Universe Spectroscopy) (Fiore et al. 2000, Kawahara et al. 2005)

Emission lines of oxygen in WHIM

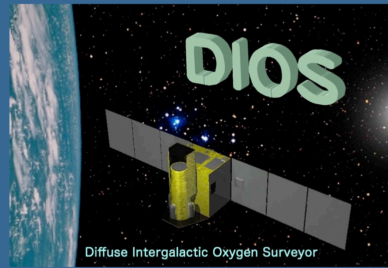
OVII (561eV, 568eV, 574eV, 665eV) , OVIII (653eV)

- **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

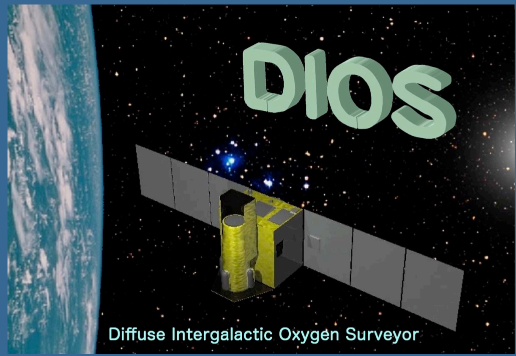


- **Good energy resolution** to identify the emission lines from WHIM at different redshifts
  - $\Delta E < 5$eV $\Rightarrow$ X-ray calorimeter using superconducting TES (Transition Edge Sensor)
- **Large field-of-view** and effective area for survey
  - $S_{eff} = 100\text{cm}^2, \Omega = 1\text{deg}^2$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

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

DIOS: Diffuse Intergalactic Oxygen Surveyor

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



- **PI: Takaya Ohashi** (Tokyo Metropolitan Univ.)
  - + Univ. of Tokyo, JAXA/ISAS, Nagoya Univ., Tokyo Metro. Univ.
- A dedicated small satellite with cost < 40M USD
- Proposed launch in **2008～2010** **(not yet approved; looking for international collaboration)**
- Unprecedented energy spectral resolution: **ΔE=2eV in soft X-ray band (0.3-1.5keV)**
- Aim at unambiguous detection of WHIM via **Oxygen emission lines**
- Estimate the dark baryon (WHIM) density contribution to the total cosmic baryon budget

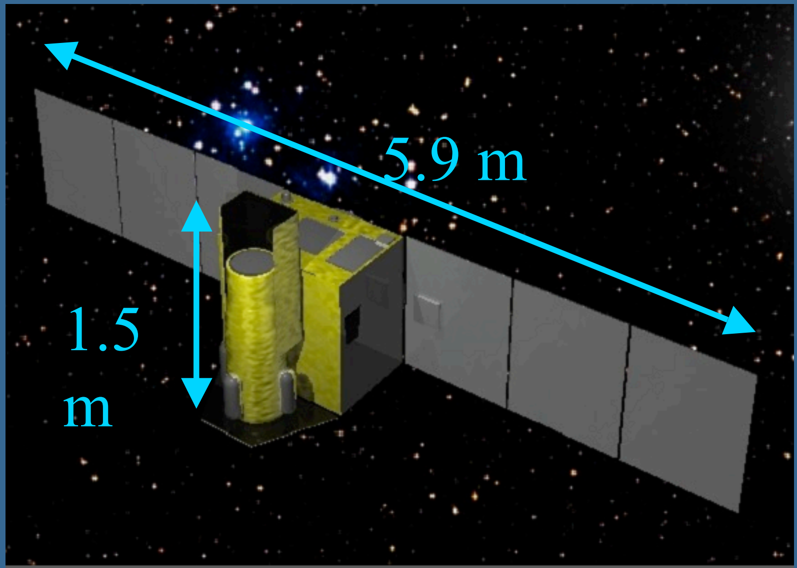
DIOS: instrument and spacecraft

Area	> 100 cm^2
Field of View	50' diameter
$S\,\Omega$	~100 $cm^2 deg^2$
Angular Resol.	3' (16^2 pixels)
Energy Resol.	2 eV (FWHM)
Energy Range	0.3 – 1.5 keV
Life	> 5 yr

Altitude: ~ 550 km

Inclination: 30°

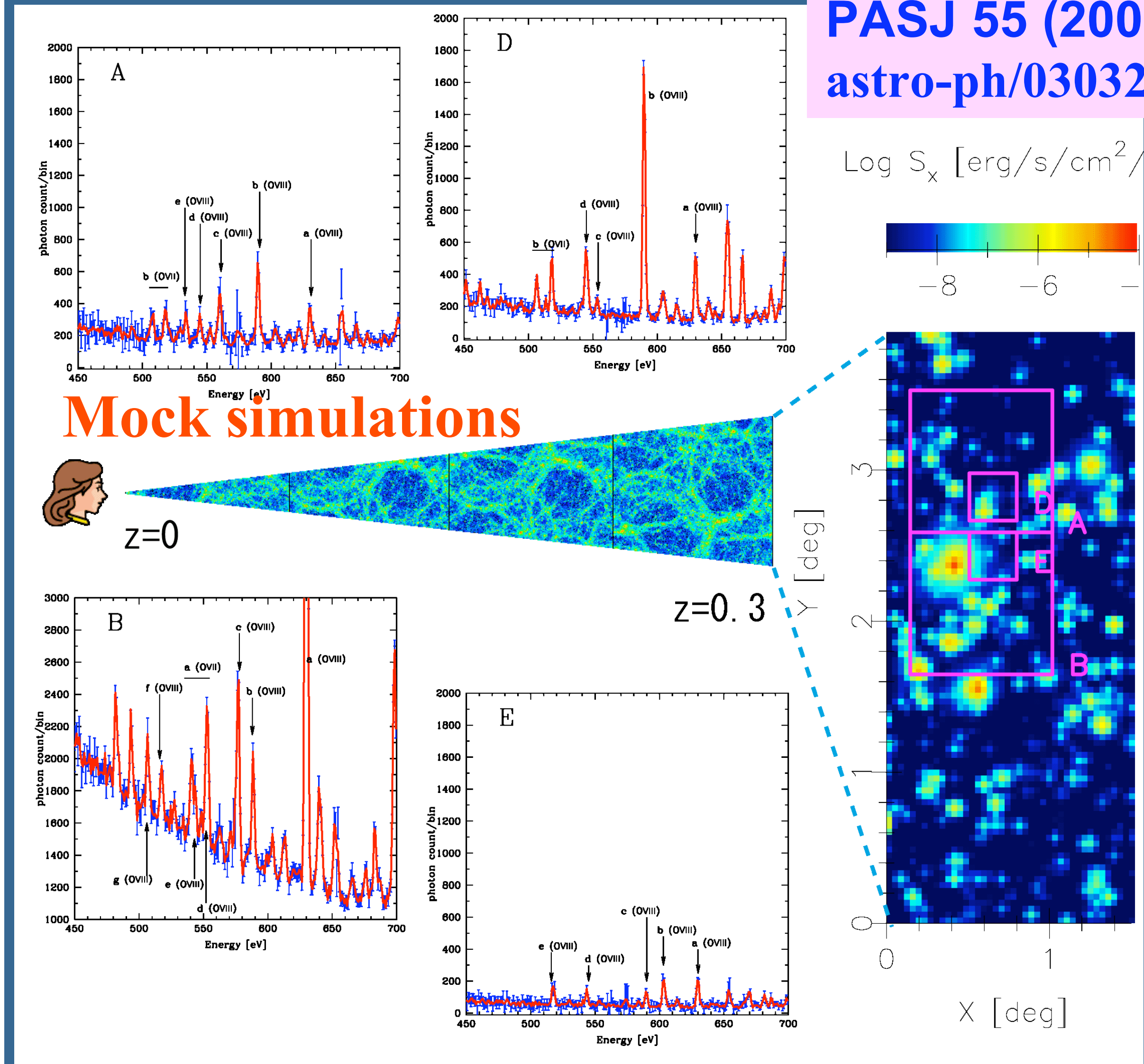
Rotation period: 95 min

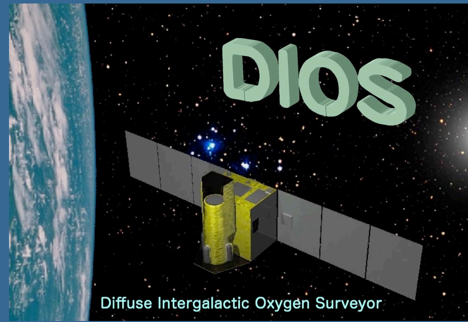


see Ohashi et al. (2004; astro-ph/0402546) for further detail

Searching for dark baryons with DIOS
(Diffuse Intergalactic Oxygen Surveyor)

PASJ 55 (2003) 879
astro-ph/0303281





Univ of Tokyo:

K. Yoshikawa

Y.Suto

JAXA/ISAS:

N. Yamasaki

K. Mitsuda

Tokyo Metropolitan Univ.:

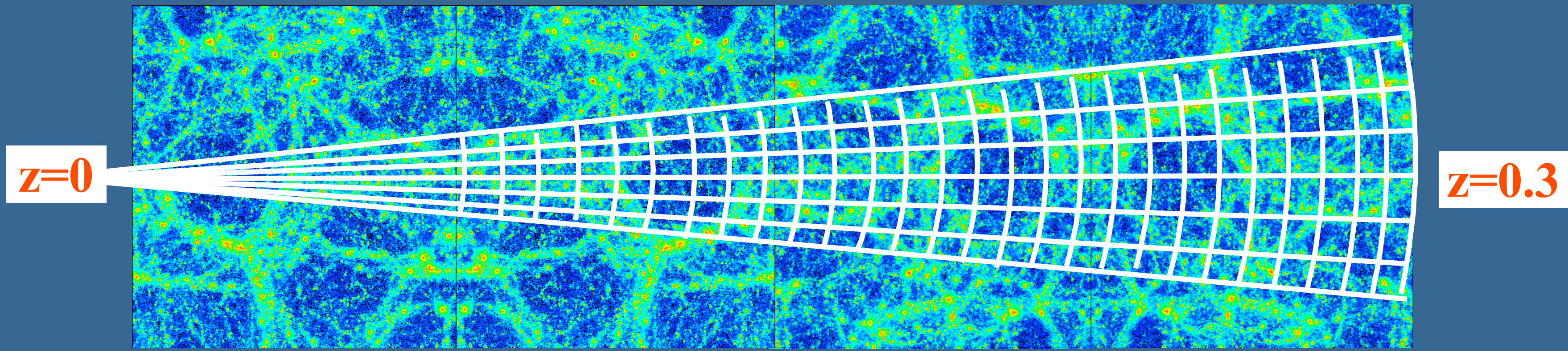
T. Ohashi

Nagoya Univ.:

Y. Tawara

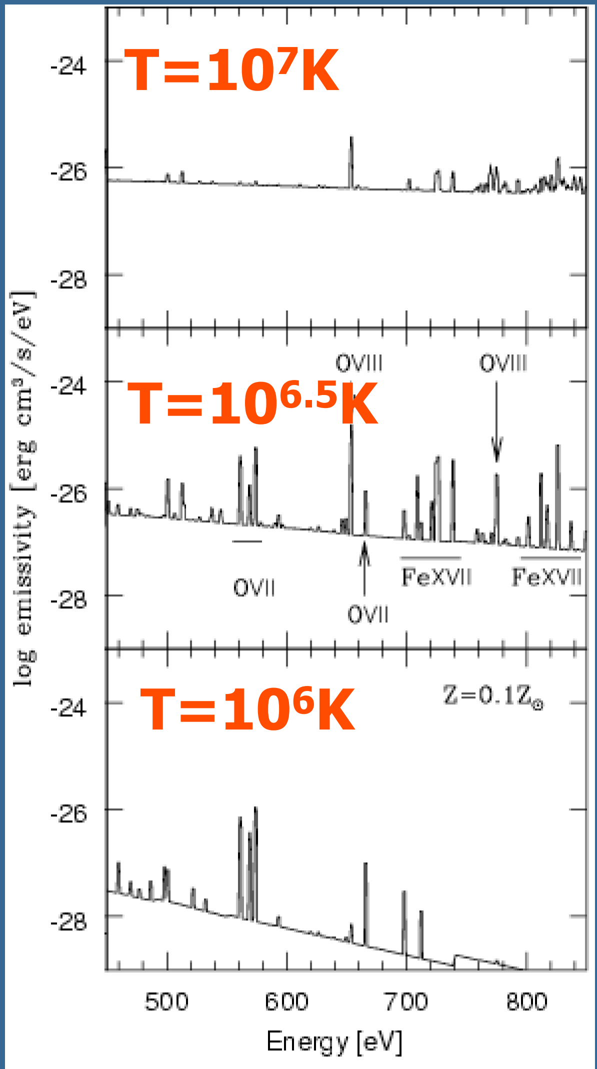
A. Furuzawa

Light-cone output from simulation



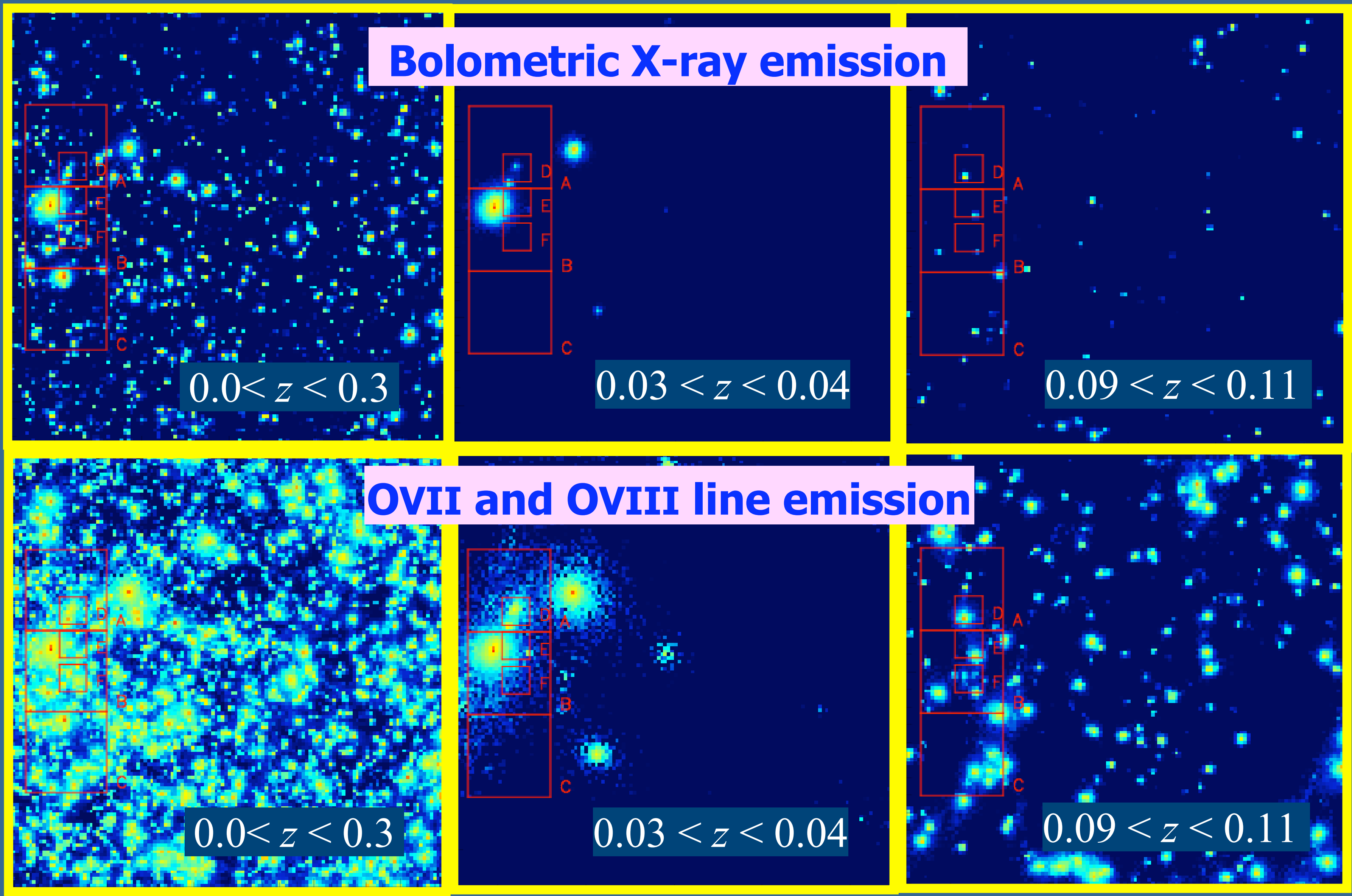
- **Cosmological SPH simulation** in Ω_m=0.3, Ω_Λ=0.7, σ_8=1.0, and h=0.7 CDM with N=128^3 each for DM and gas (Yoshikawa, Taruya, Jing, & Suto 2001)
- **Light-cone output from z=0.3 to z=0** by stacking 11 simulation cubes of $(75h^{-1}Mpc)^3$ at different z
- **5°×5°FOV mock data** in 64x64 grids on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

Creating Mock spectra from light-cone simulation output



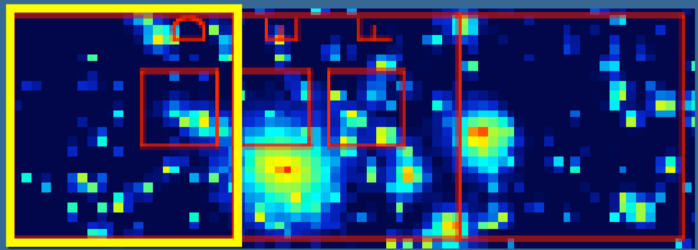
- For a given exposure time,
  - convolve the emissivity according to gas density and temperature in $(5°/64)^2$ pixels over the lightcone
  - Add the Galactic line emission (McCammon et al. 2002)
  - Add the cosmic X-ray background contribution (power-law+Poisson noise)
- Then statistically subtract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

Surface brightness on the sky



Simulated spectra: region A

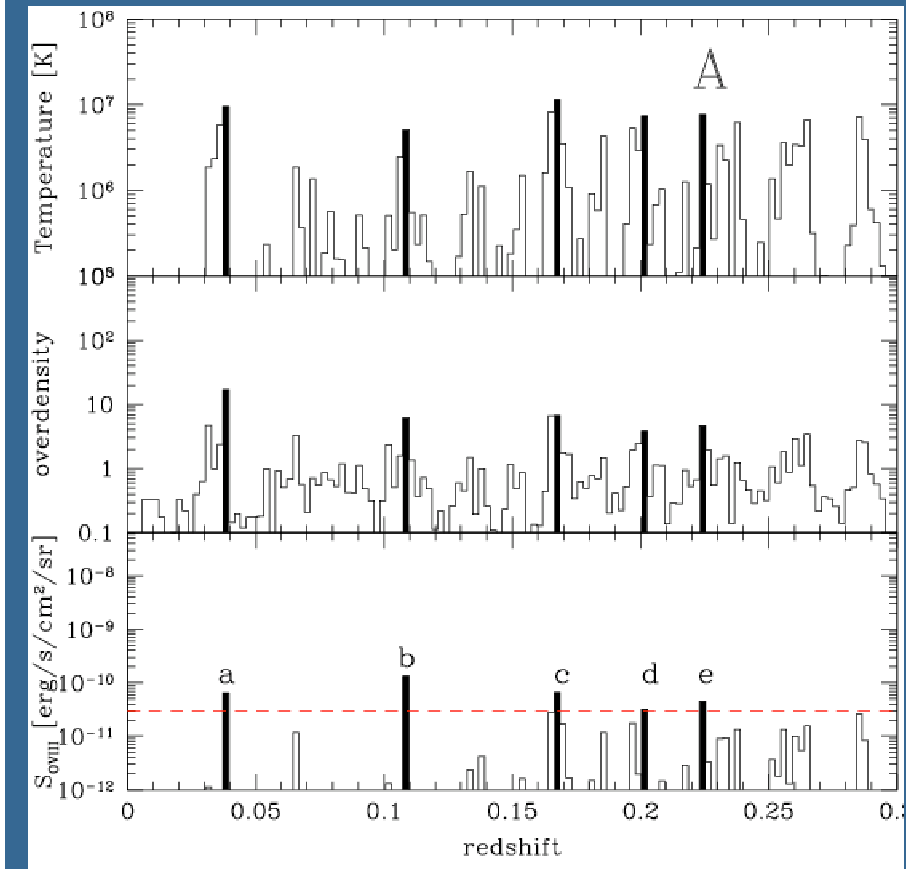
Shallow survey observation with the DIOS field-of-view (16^2pixels)

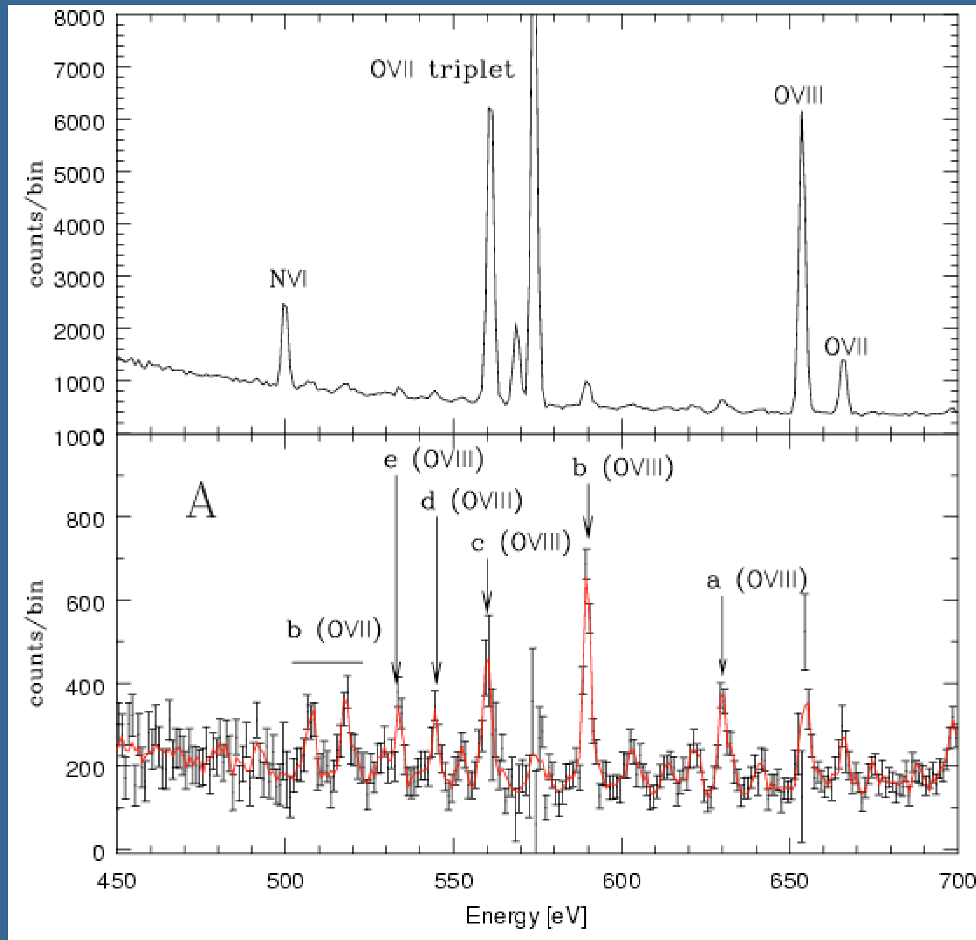


A

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

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





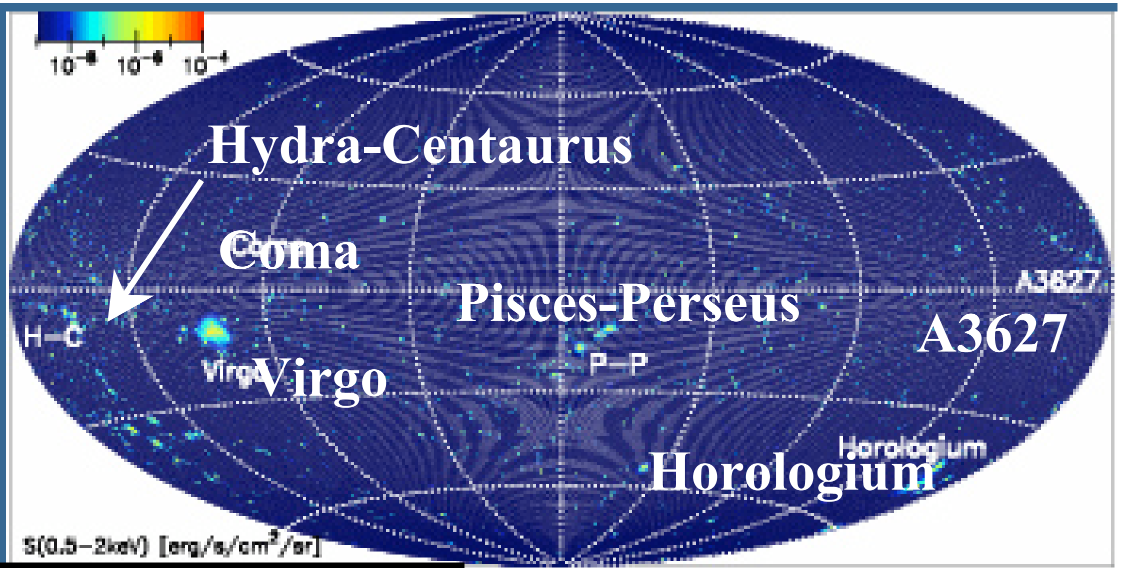
Locating the WHIM in the local universe

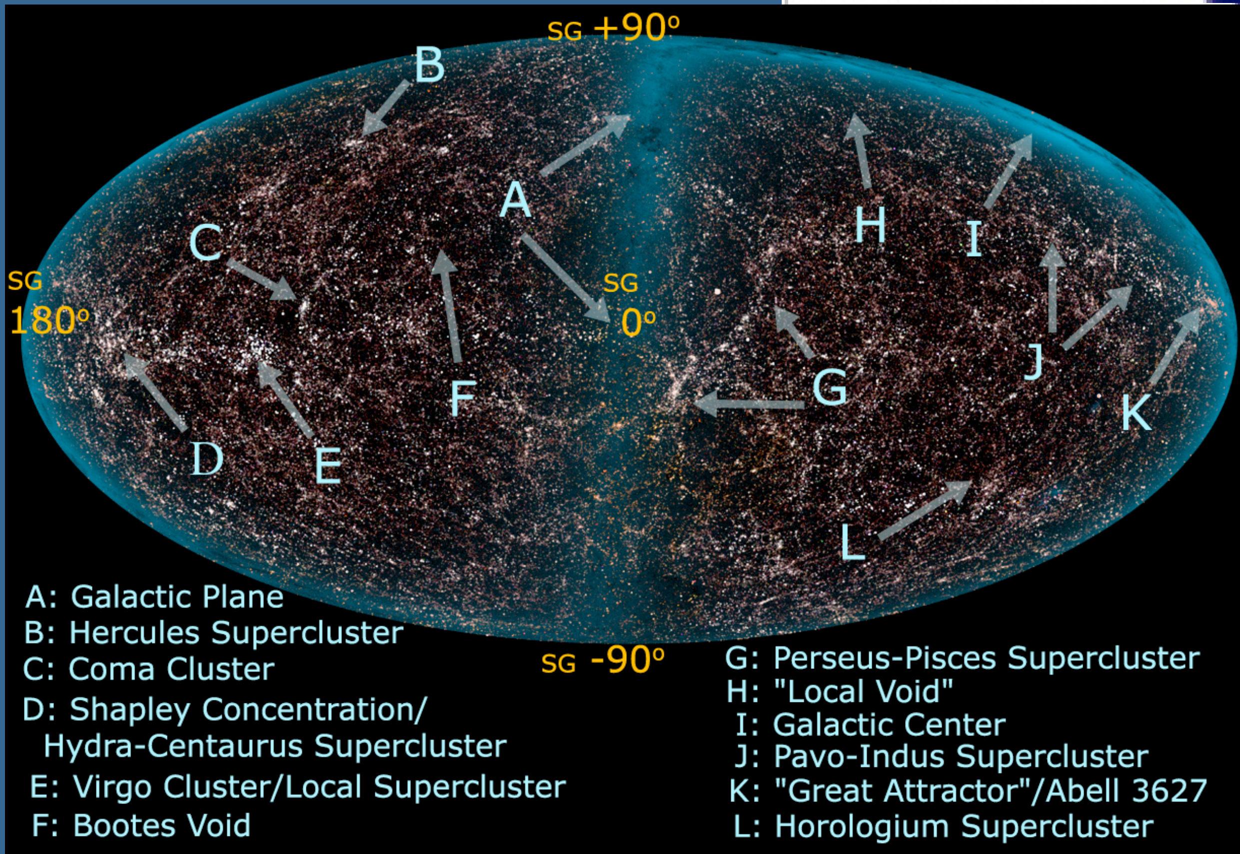
Yoshikawa, Dolag, Suto, Sasaki, Yamasaki, Ohashi, Mitsuda, Tawara, Fujimoto, Furusho, Furuzawa, Ishida, Ishisaki & Takei

PASJ 56(2004)939, astro-ph/0408140

- **Simulation by Dolag et al. (astro-ph/0310902)**
  - Initial condition: smoothing the observed galaxy density field of IRAS 1.2 Jy galaxy survey (over $5h^{-1}$Mpc), linearly evolving back to z=50
  - adiabatic run of dark matter and baryons (without cooling or feedback) in a canonical ΛCDM model
- **Independent and earlier work to consider oxygen emissions from WHIM in constrained simulations**
  - Kravtsov, Klypin & Hoffman, ApJ 571(2002)563

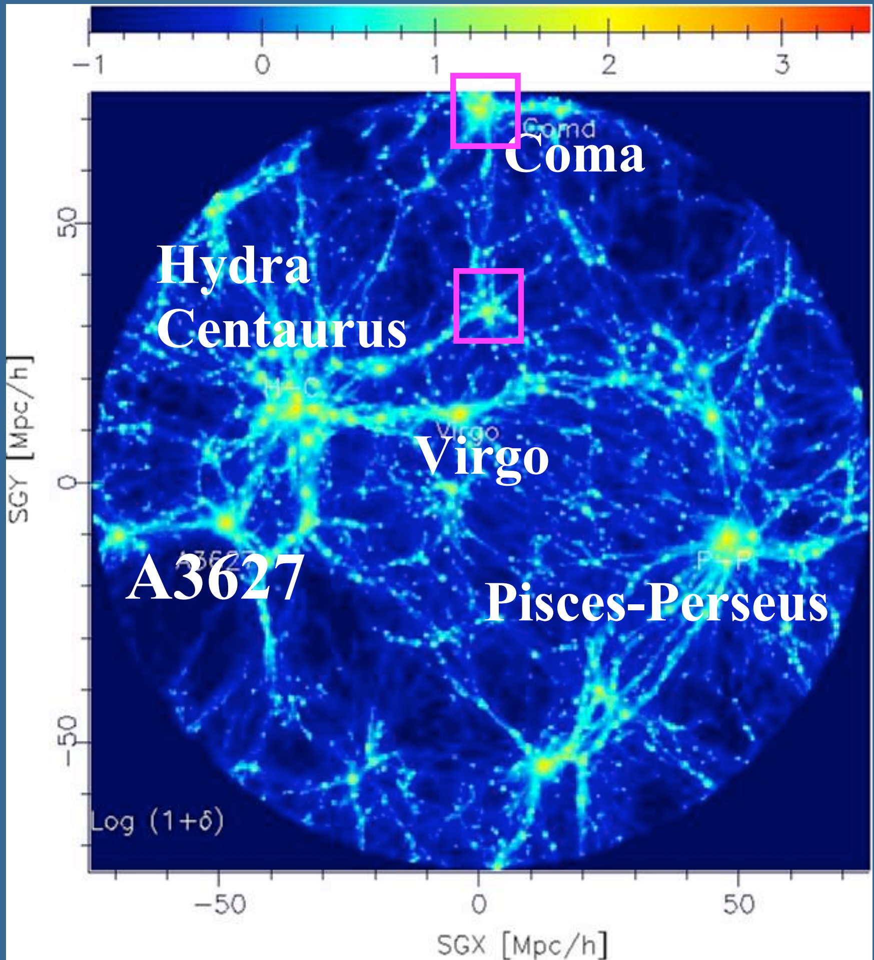
Simulated local universe vs. 2MASS map





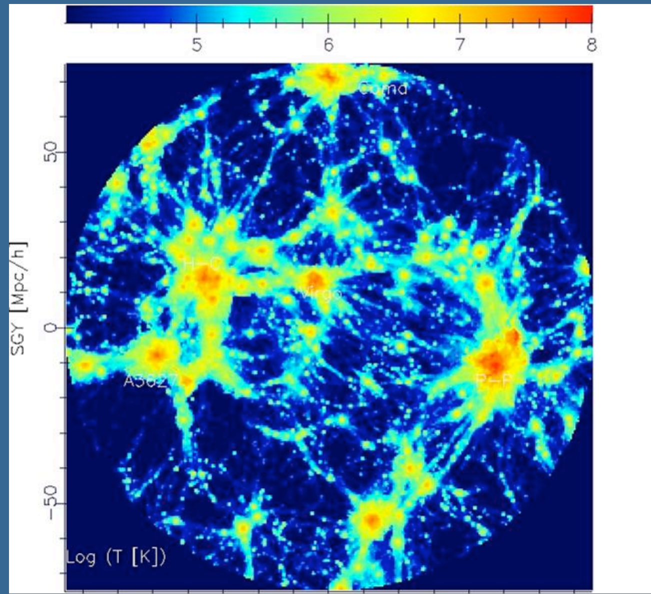
Soft X-ray map of the simulated local universe (Yoshikawa et al. 2004)

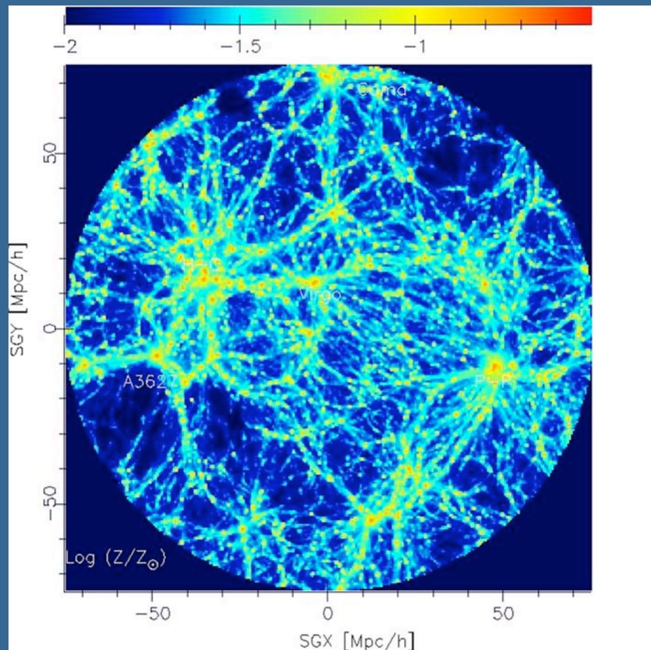
Simulated gas distribution on the supergalactic plane



gas density

gas temperature

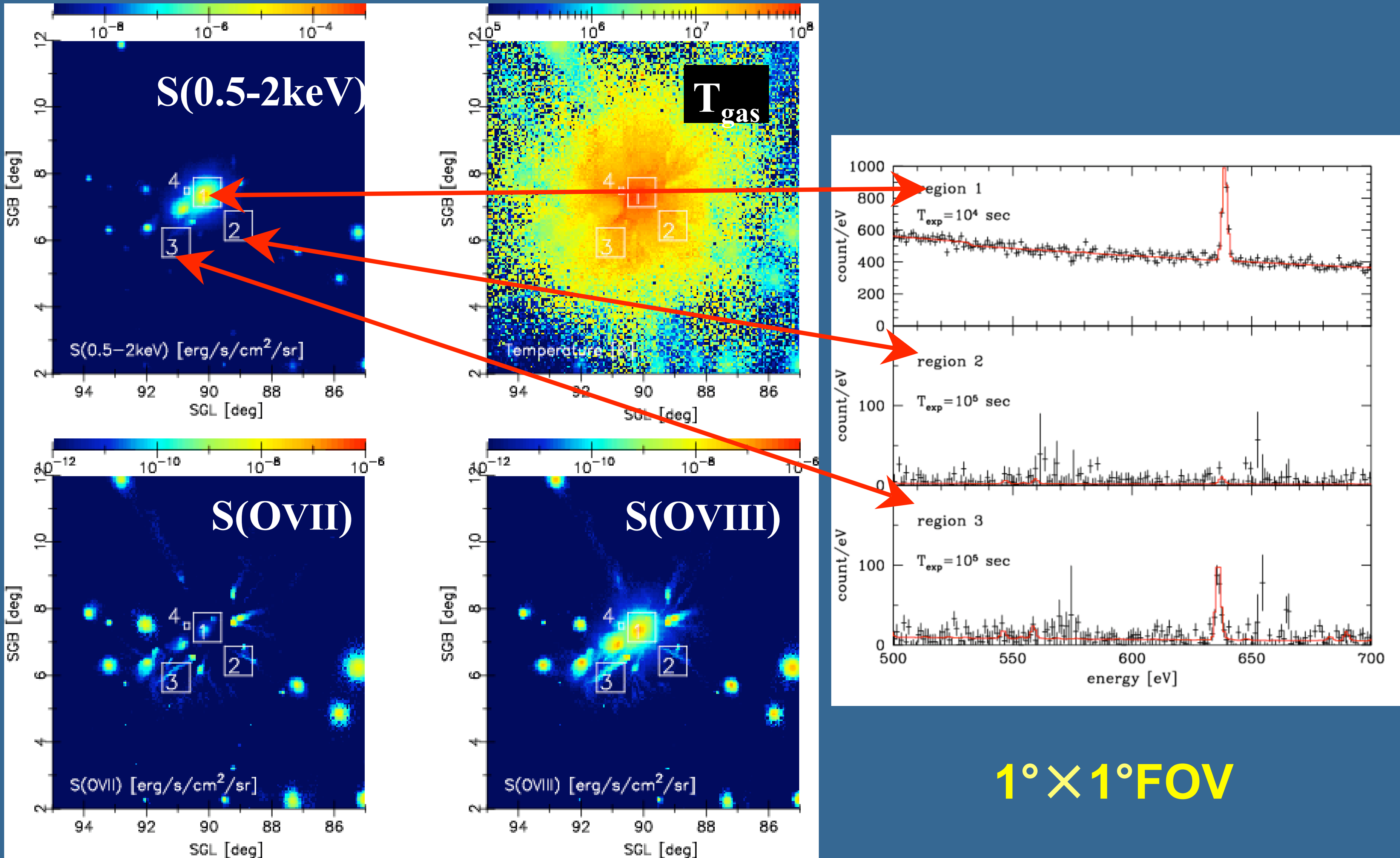




(adopted) metallicity

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

Mock observation of simulated Coma

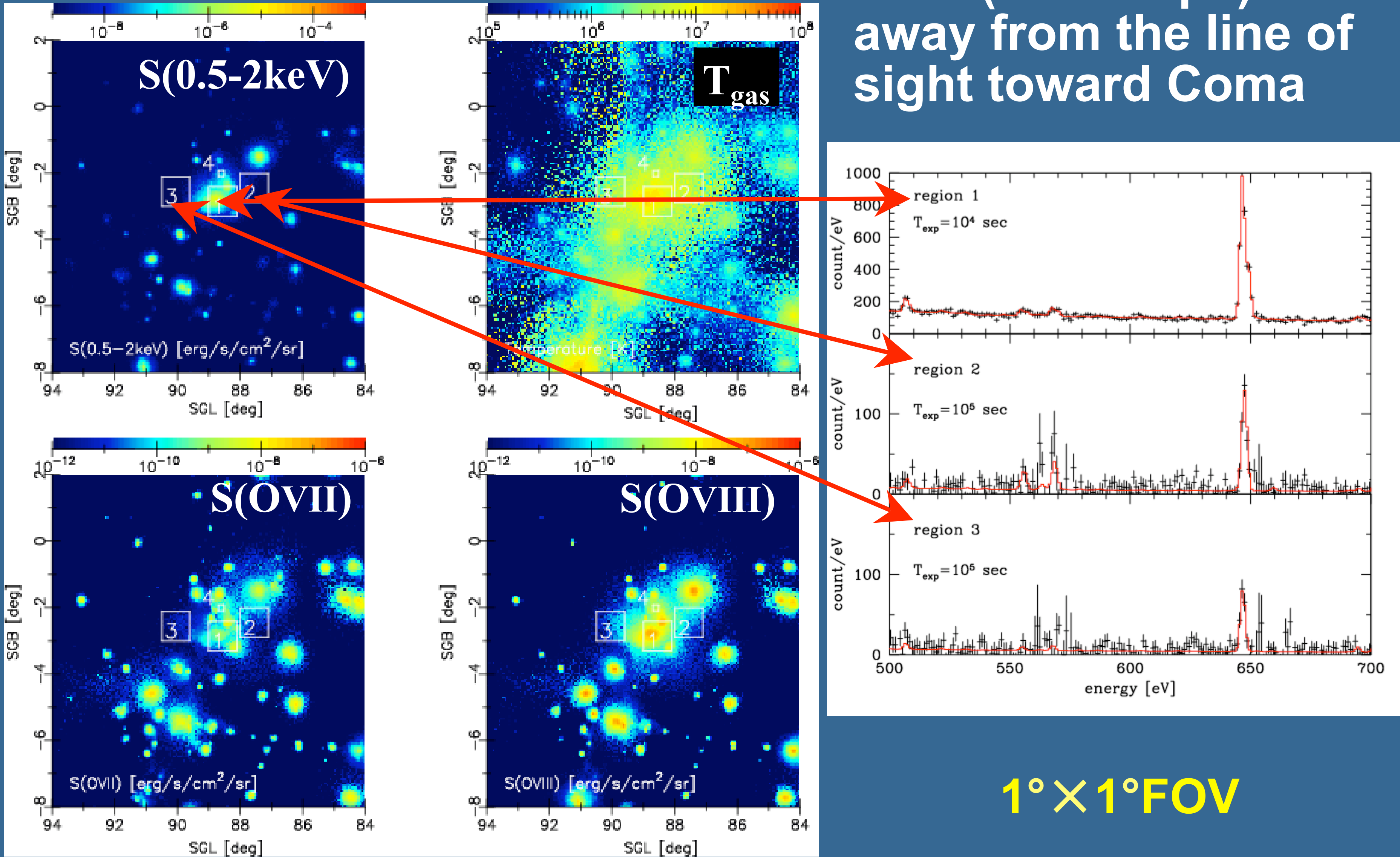


1°×1°FOV

Surface brightness map [erg $s^{-1}cm^{-2}sr^{-1}$]

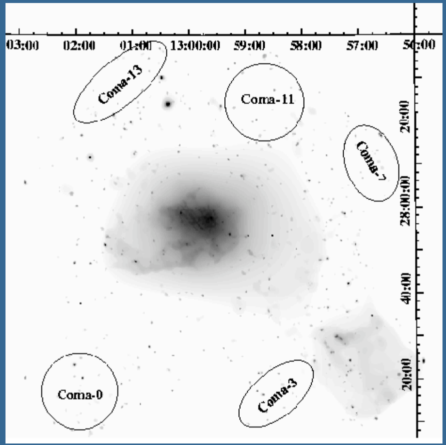
a small clump in front of simulated Coma

～10°(～5h^{-1}Mpc) away from the line of sight toward Coma



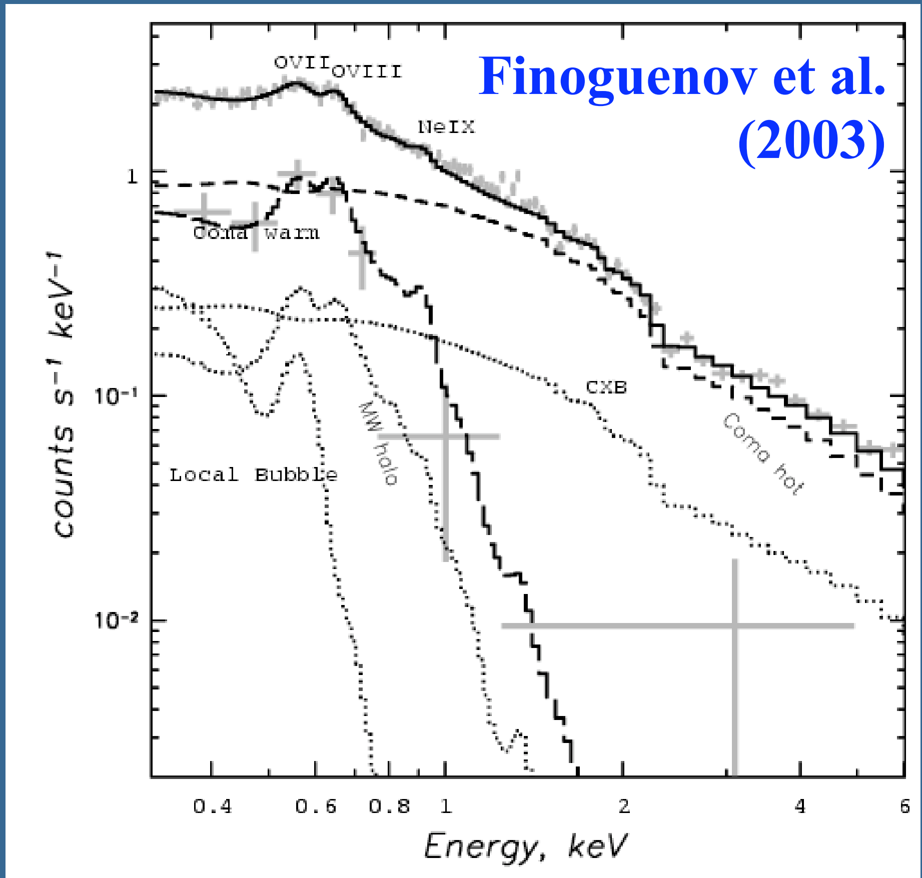
1°×1°FOV

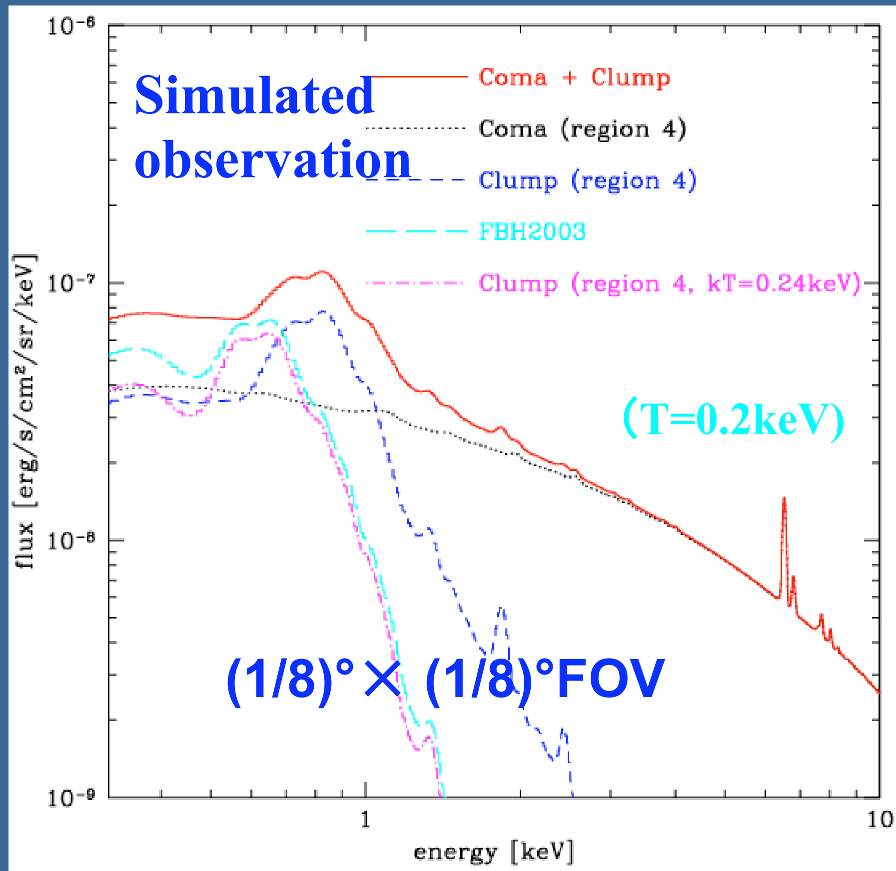
Surface brightness map [erg s^{-1}cm^{-2}sr^{-1}]



Soft X-ray excess of Coma

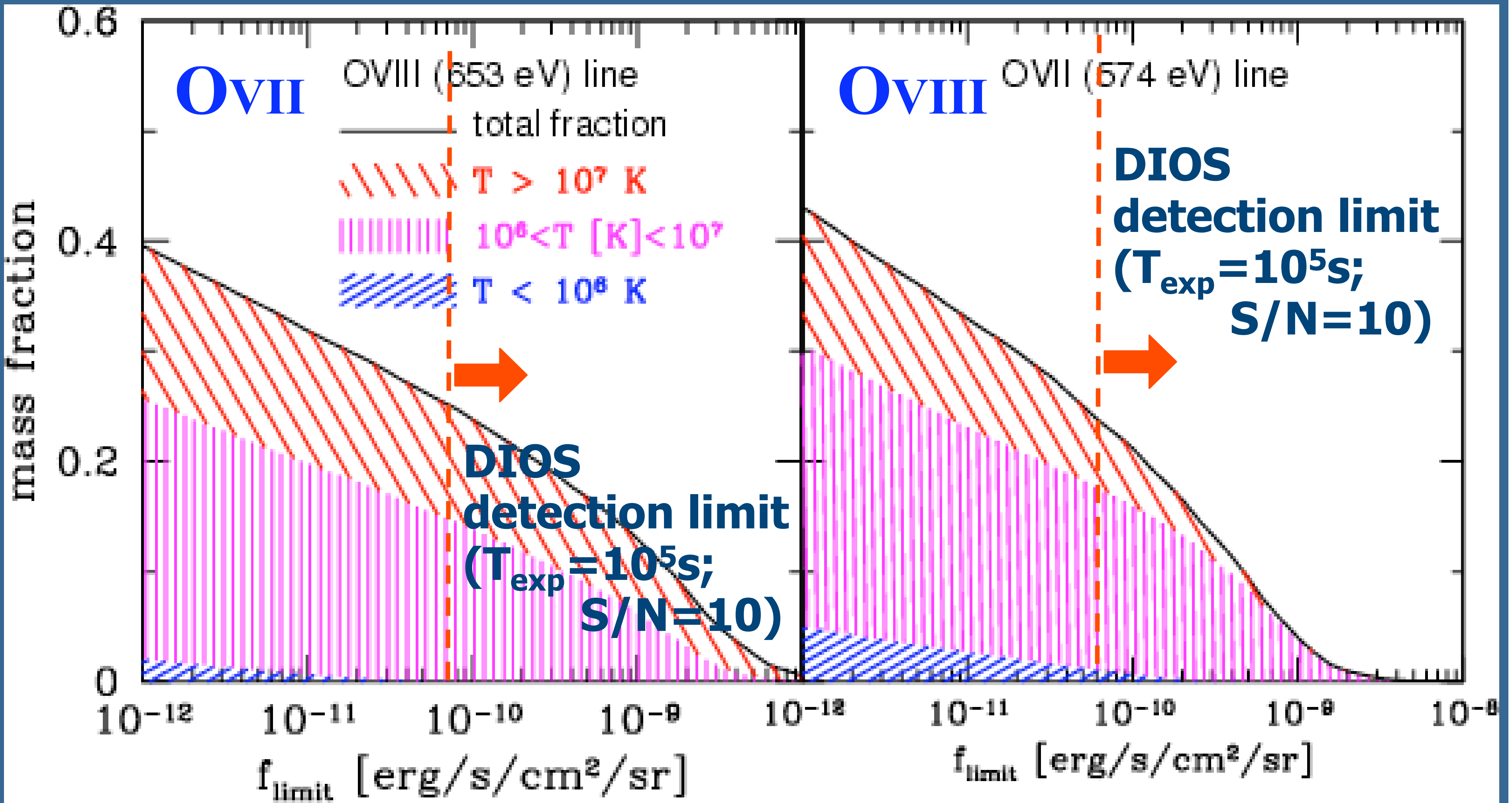
- XMM-Newton observations of the outskirts of Coma (Finoguenov, Briel & Henry 2003, A&A 410, 777)
- associated X-ray filament of 0.2keV warm gas ?
- an intervening WHIM clump along the line of sight ?





Yoshikawa et al. (2004)

Fraction of cosmic dark baryons detectable via oxygen emission



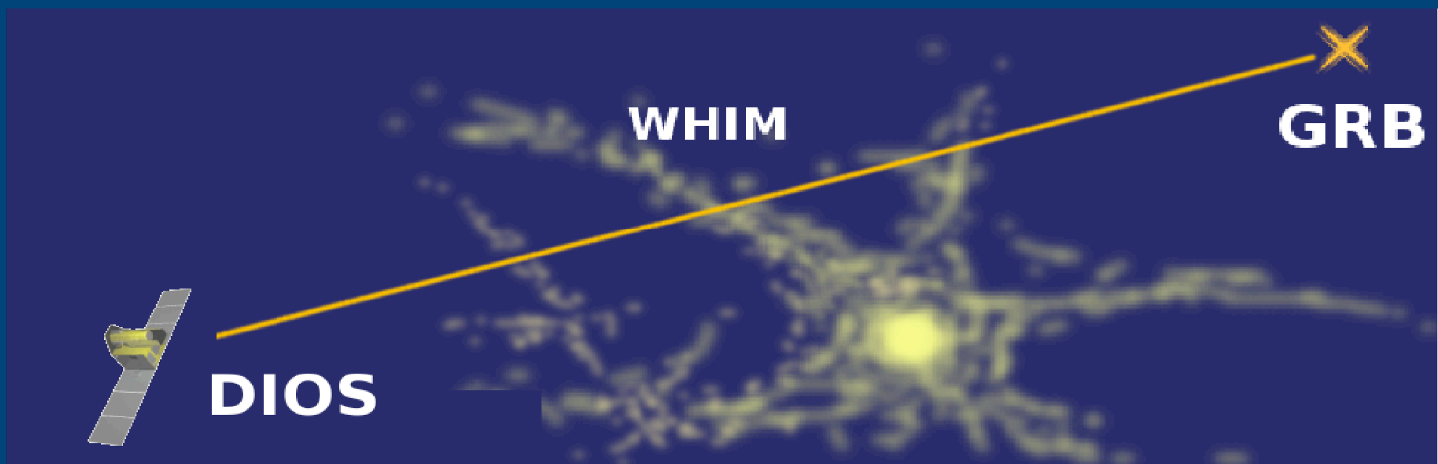
Yoshikawa et al. (2004)

Searching for dark baryons via absorption line systems in a Gamma-ray burst afterglow

H.Kawahara, K.Yoshikawa, S.Sasaki, Y.Suto, N.Kawai, T.Ohashi, N.Yamasaki & K.Mitsuda

astro-ph/0504594 (submitted to Pub.Astron.Soc.Japan 2005)

- first proposed by Fiore et al. (2000)
- can probe higher z
- can search for emission line counterparts later



Model for GRB afterglow

- Average spectrum fitted by Piro (2004)

$$F_{\mathrm{GRB}}(t,E) = F_0 \left(\frac{t}{40\mathrm{k\,sec}}\right)^{-1.2} \left(\frac{E}{1\mathrm{keV}}\right)^{-1.13} \mathrm{erg\,s^{-1}cm^{-2}keV^{-1}}$$

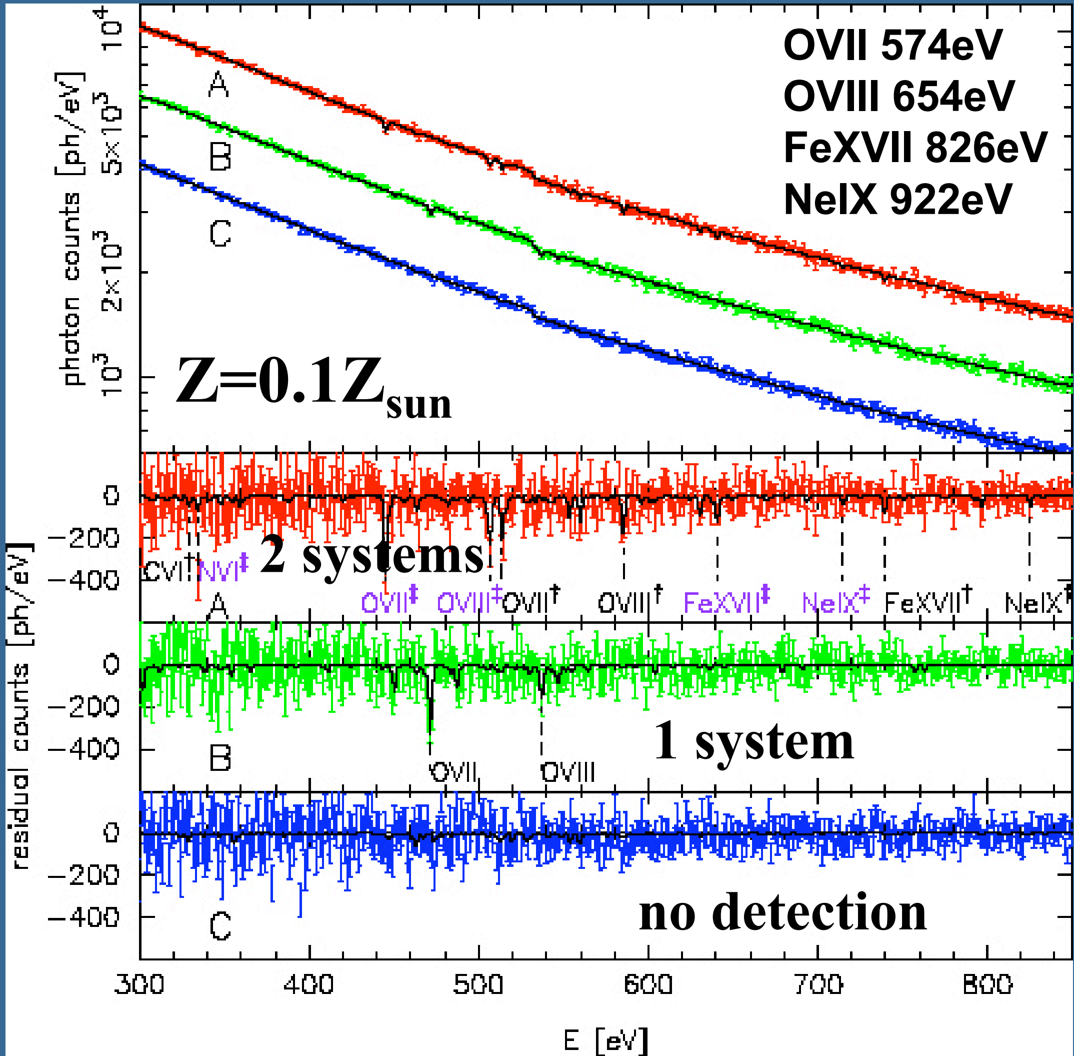
- Frequency of GRB afterglow with

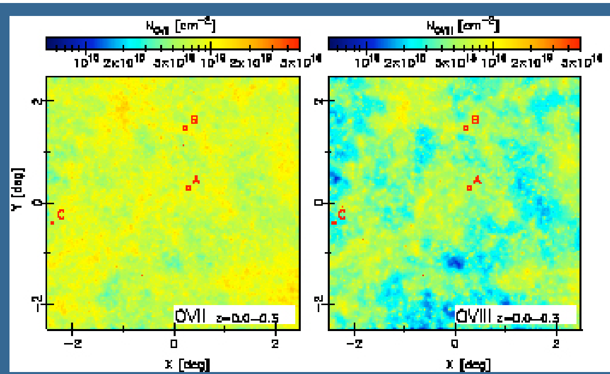
  $F>F_0=6\times10^{-11}$ erg/s/cm^2/keV

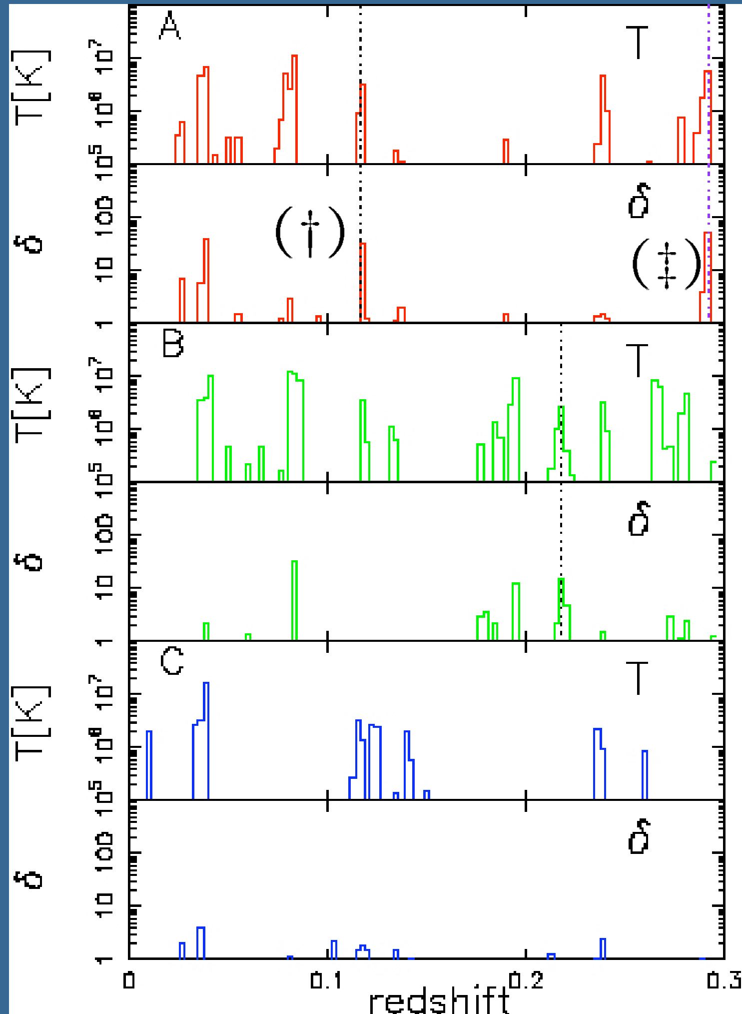
→ ～40/year/sky (from 6 years' BeppoSAX data)

- observing strategy: start of the observation and exposure time for 5000 photons/eV@500eV with XEUS (impossible with DIOS…)
  - t_i =1 hour and t_{exp} = 5ksec (for F_0)
  - t_i = 2 hour and t_{exp} = 12ksec (for F_0)
  - t_i = 1 day and t_{exp} = 15ksec (for $10F_0$)

Mock transmission spectra of a GRB afterglow



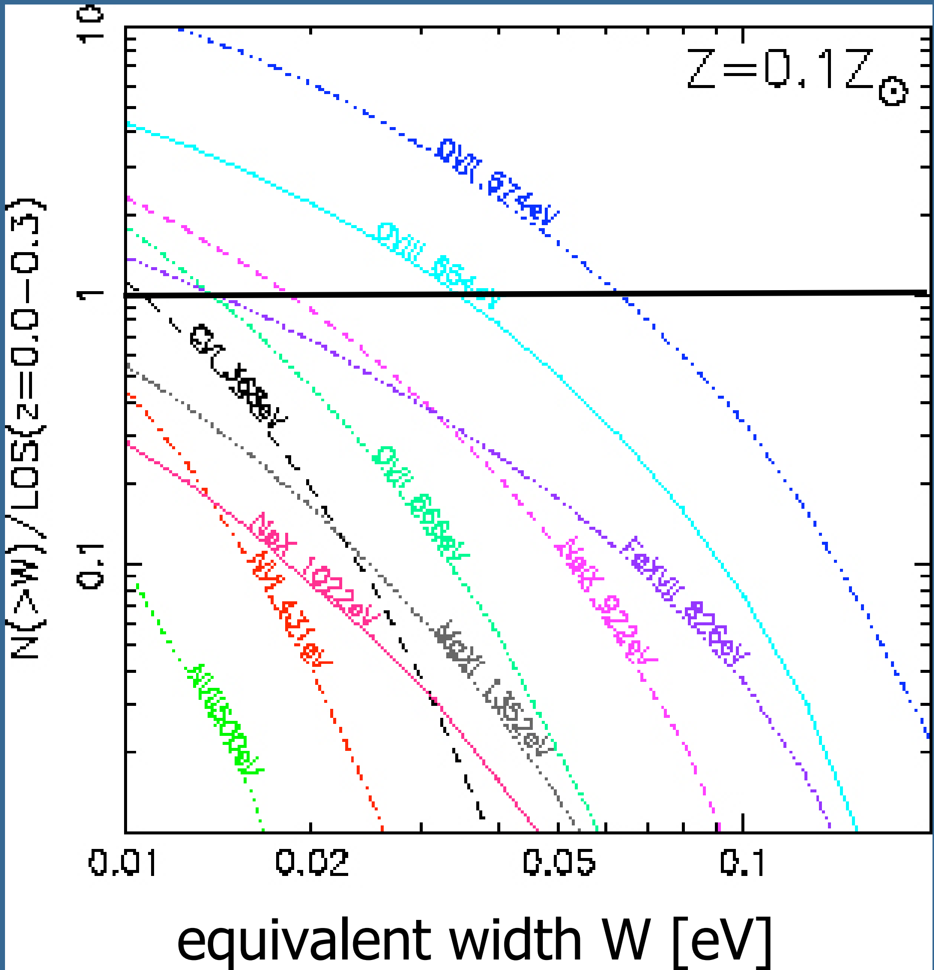


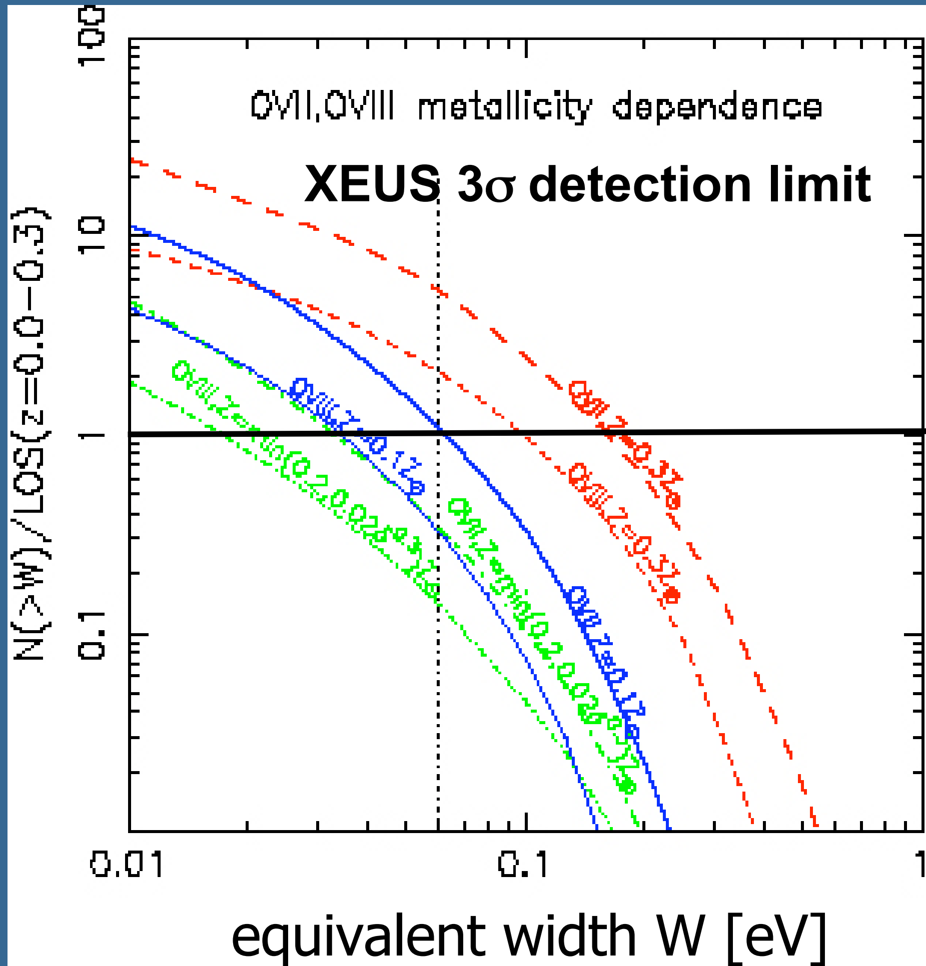


Kawahara et al. (2005)

Statistics of absorption line systems

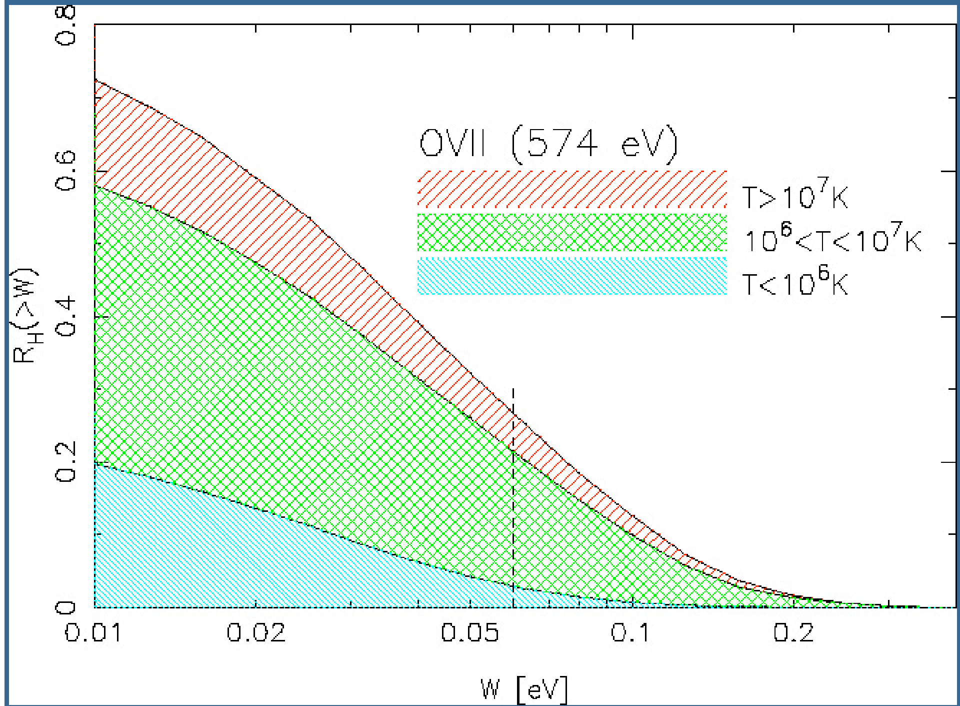
assuming collisional and photo-ionization equilibrium under CXB (Miyaji et al. 1998) and UVB (Shull et al. 1999)

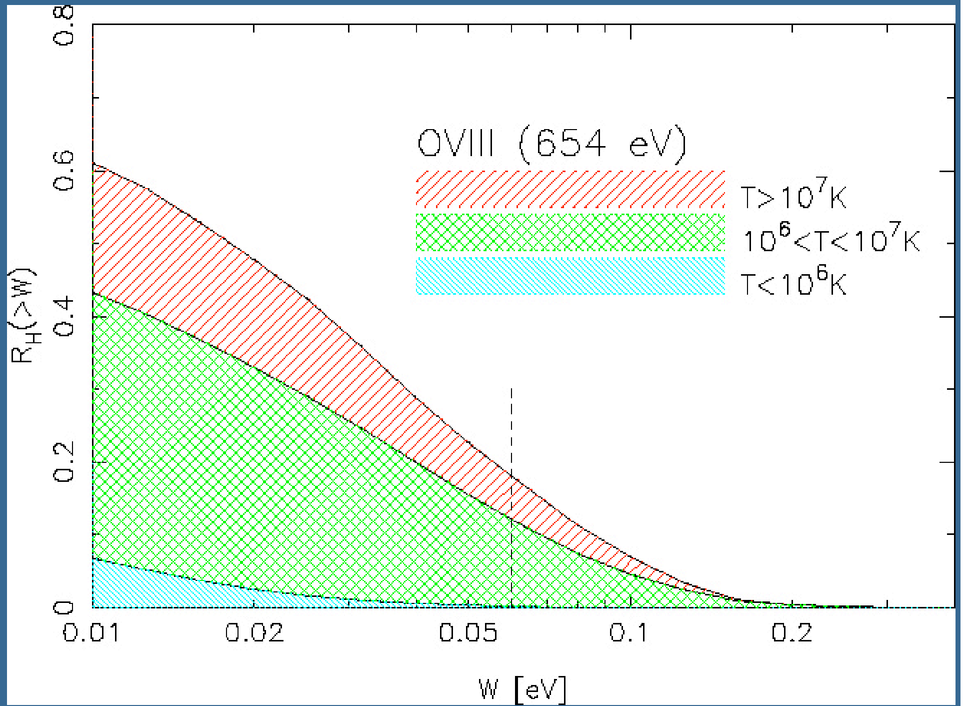




Kawahara et al. (2005)

baryon fraction detectable by absorption lines in the GRB afterglow





W: equivalent width
$R_H(>W)$: cumulative gas mass fraction

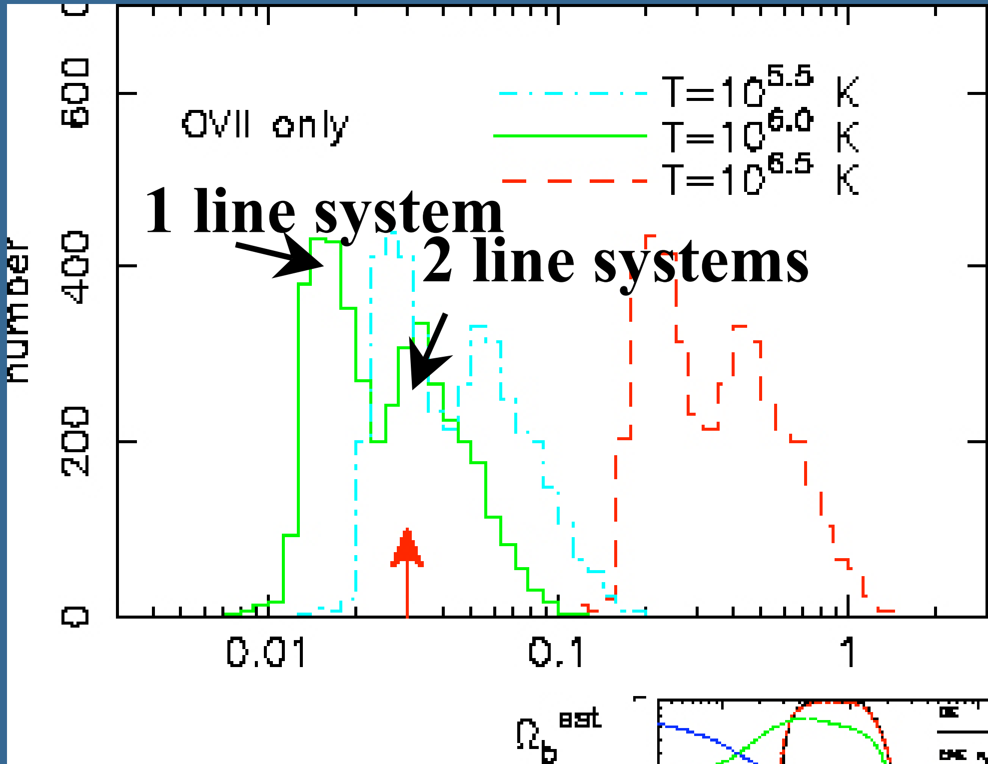
$$R_H(>W) = \frac{\sum_{i=1}^{6400} N_{H,i}^{sim}(>W)}{\sum_{i=1}^{6400} N_{H,i}^{sim}(>0)}$$

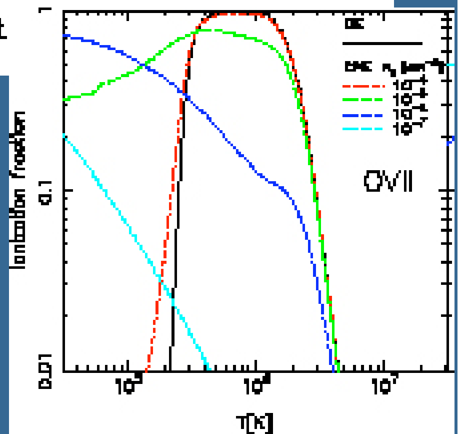
baryon density from oxygen absorption line systems in the GRB afterglow

e.g.,

$$\Omega_b^{WHIM} = (2.7^{+3.8}_{-1.9}\%) \times 10^{-[O/H]_{-1}}$$

(along Mkn421 if T=$10^{6.1}$K; Nicastro et al. 2005)





fraction of gas in baryons

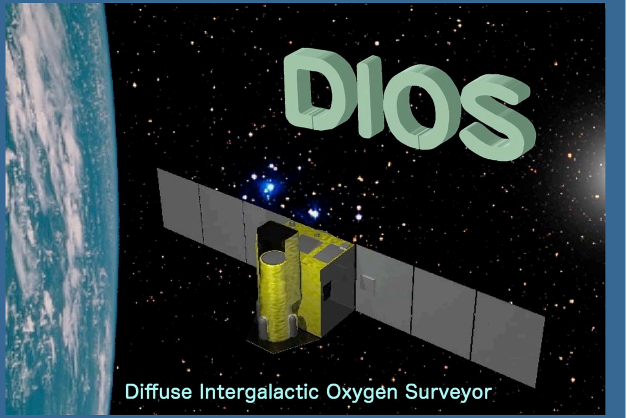
$$\Omega_b^{est} = \frac{\Omega_{gas}^{WHIM,est}(>W)}{R_H(>W)} \; \frac{1}{f_{gas}} \; \left\langle \frac{N_H^{sim}(>W)}{N_H^{est}(>W)} \right\rangle$$

undetected gas fraction

underestimate bias due to the clumpiness of WHIM

very sensitive to the assumed temperature and metallicity

Prospects for dark baryon search via WHIM spectroscopy



- **DIOS** will detect dark baryons in the form of WHIM from oxygen emission line survey (Yoshikawa et al. 2003)
  - ΔE=2eV, $S_{eff}\,\Omega$=100 [$cm^2\ deg^2$], $T_{exp}=10^5$s, S/N=10
  - flux limit = 6×10^{-11} [erg/s/cm^2/sr]
- **DIOS** will detect WHIM at outskirts of known galaxy clusters in the local universe (Yoshikawa et al. 2004)
  - origin of soft X-ray excess reported for clusters (e.g., Coma)
- **XEUS** will identify ∼ 1 OVII absorption line system along a bright GRB (40 per year) with $>3\sigma$ (Kawahara et al. 2005)
  - interesting but statistics is inevitably limited
  - estimate of baryon density is subject to big uncertainties such as temperature and metallicity …

Oxygen lines

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

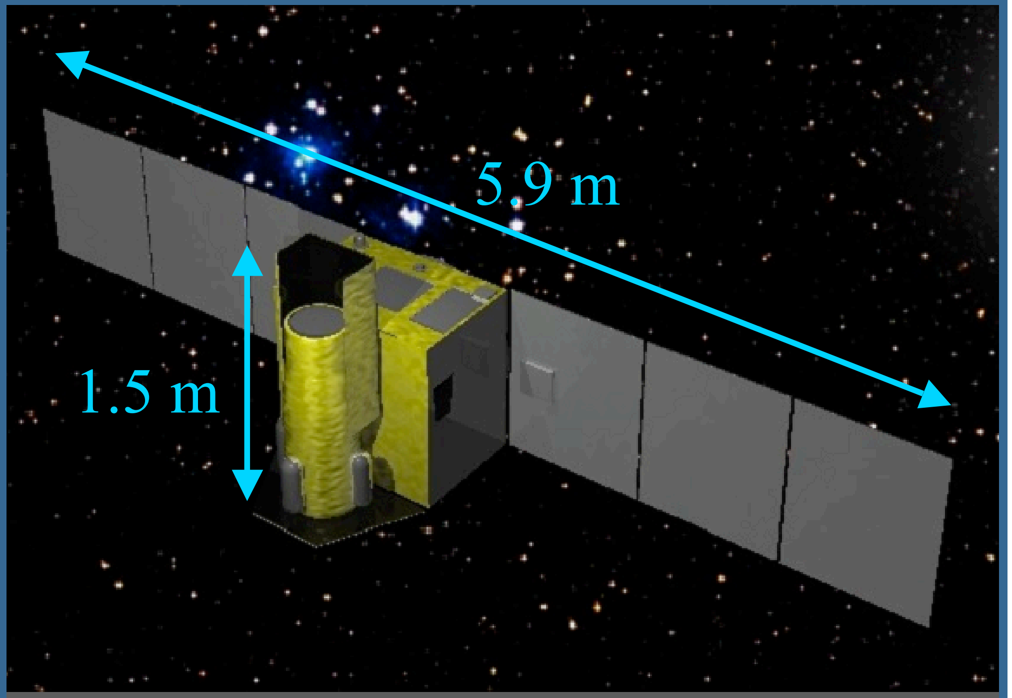
DIOS: spacecraft

Weight	Total	~ 400 kg
	Payload	~ 280 kg
Size	Launch	1.2×1.45 ×1.4 m
	In orbit	5.85×1.45 ×1.4 m
Attitude	Control	3-axis bias momentum wheel, Sun pointing in 1 axis
	Accuracy	≦10 arcsec
Power	Total	450 W
	Payload	250 W

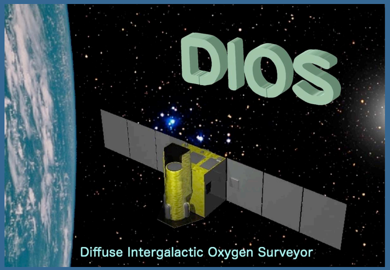
Altitude: ~ 550 km

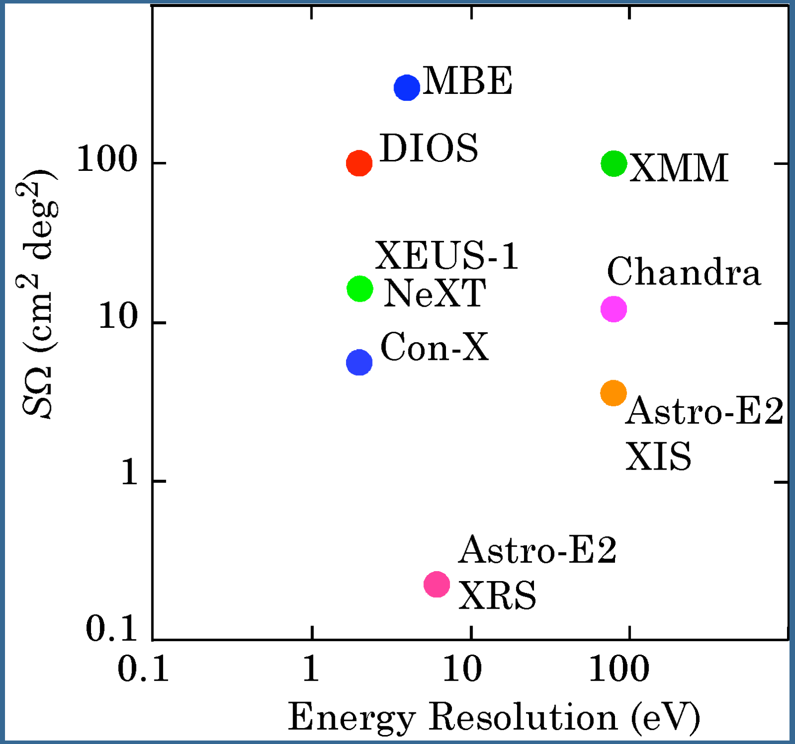
Inclination: 30°

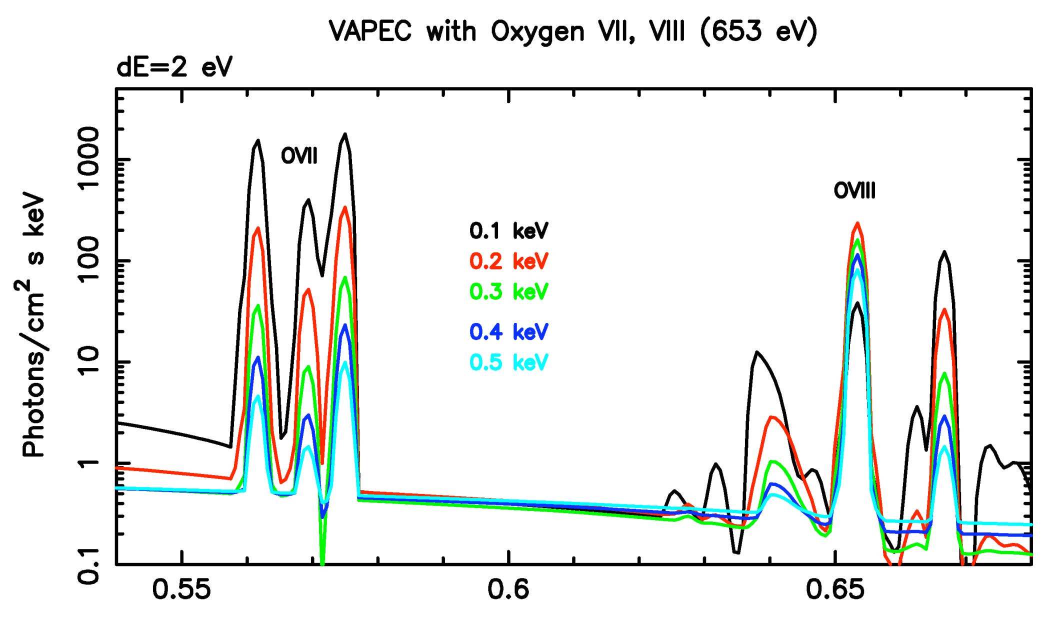
Rotation period: 95 min



DIOS: comparison with other missions

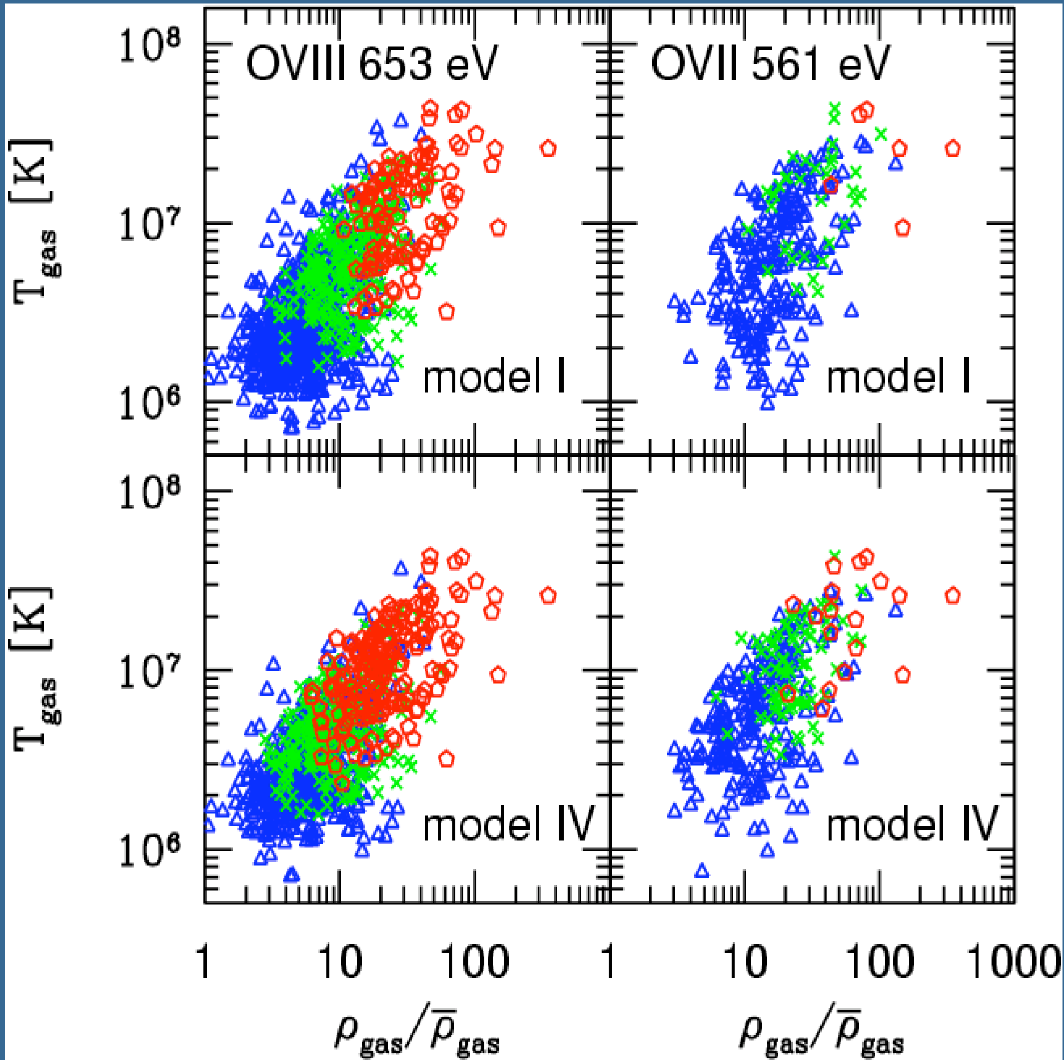






- Very high sensitivity ($S\Omega$ and ΔE) in detecting oxygen emission lines
- Intensity ratios of the lines reveal the temperature and ionization condition of WHIM

Physical properties of the probed baryons

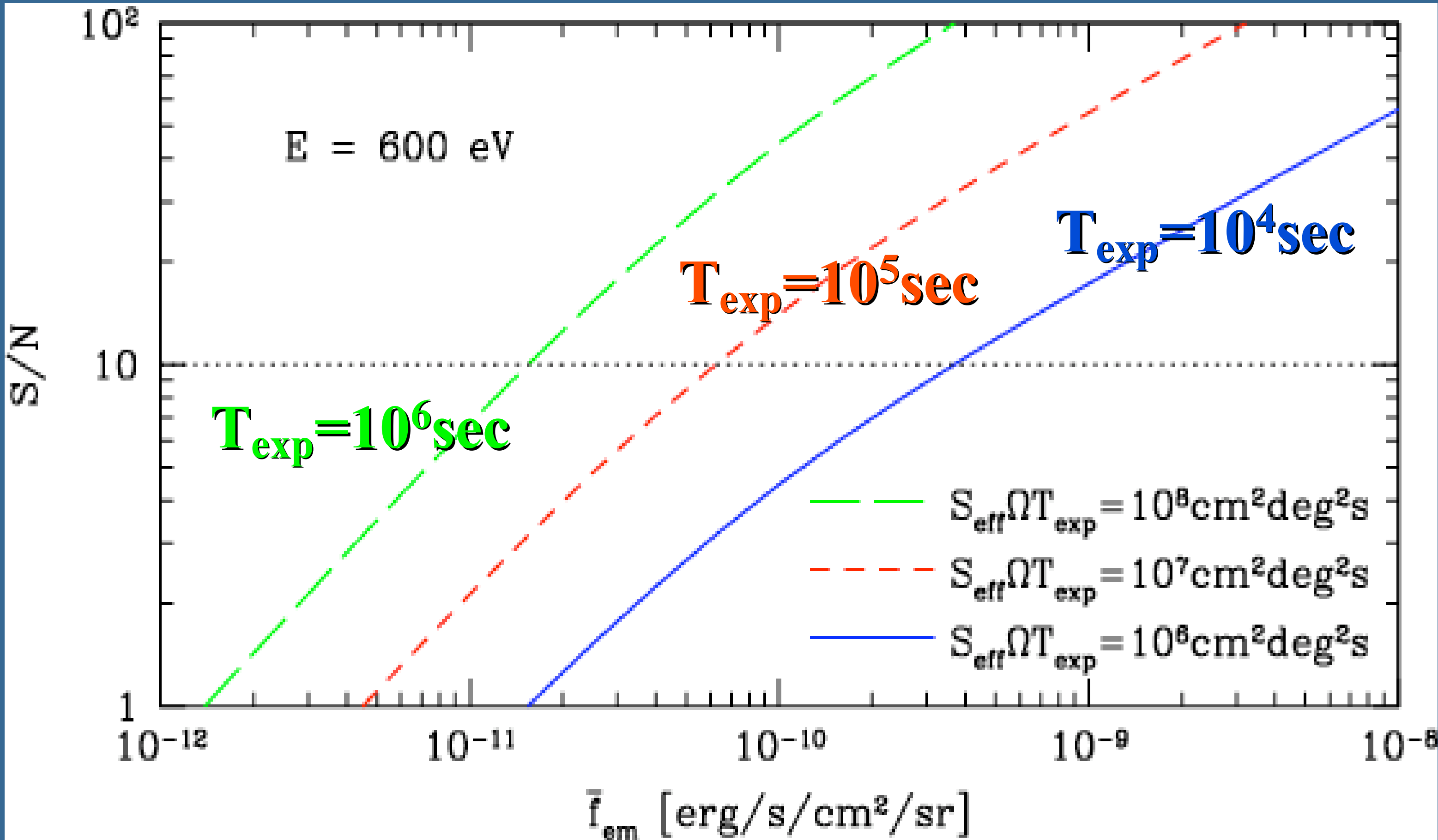


Each symbol indicate the temperature and the over-density of gas at each simulation grid (4x4 smoothed pixels over the sky and Δz=0.3/128)

- ⬠ $S_x > 3\times10^{-10}$ [erg/s/cm²/sr]
- ✕ $S_x > 6\times10^{-11}$ [erg/s/cm²/sr]
- △ $S_x > 10^{-11}$ [erg/s/cm²/sr]

Expected S/N for OVIII line

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



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

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

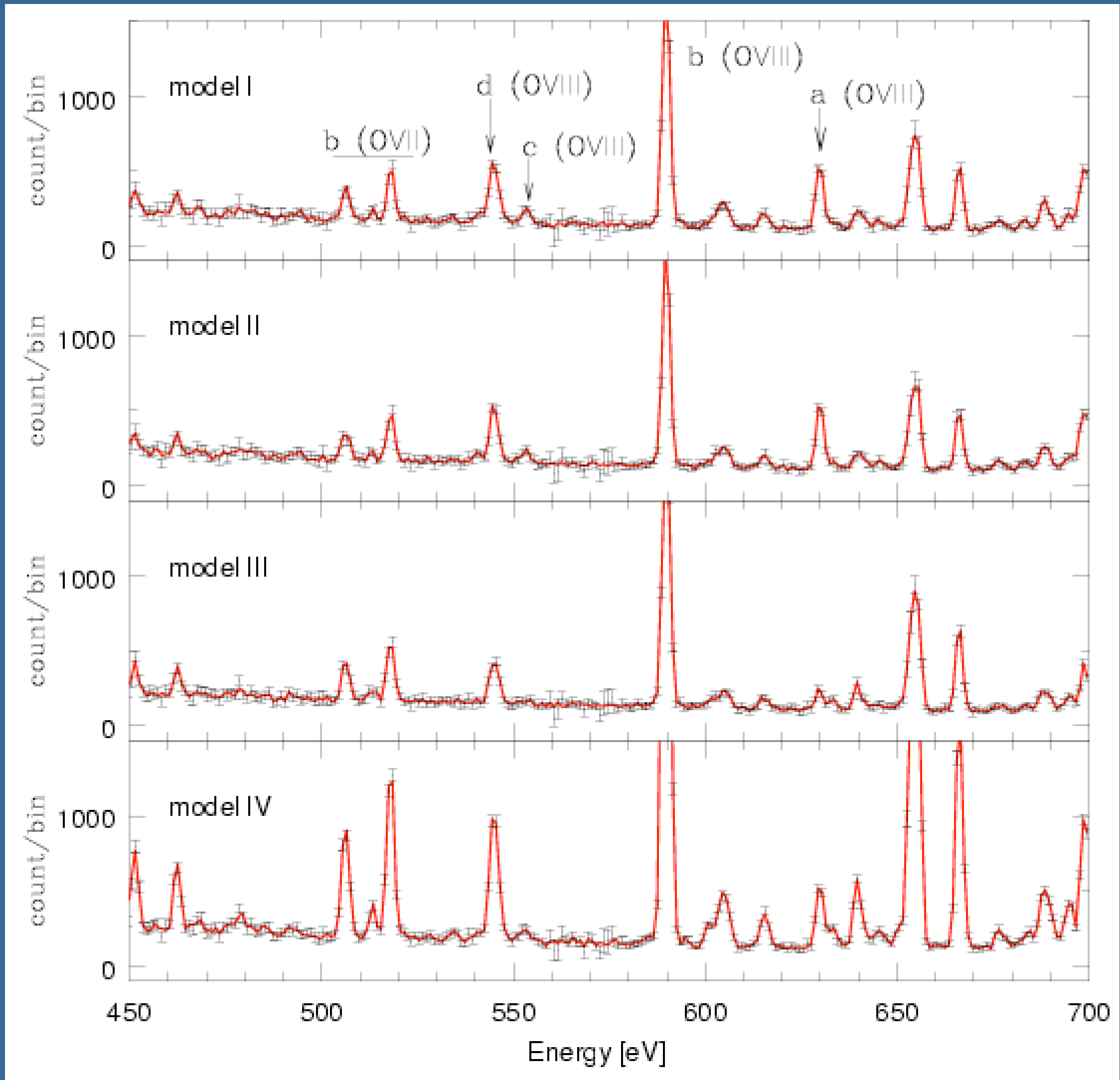
Model III : density-dependent (Aguirre et al. 2001)

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

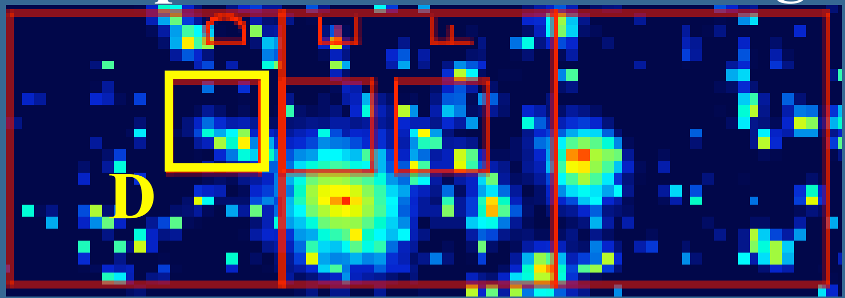
Dependence on the metallicity model



- 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

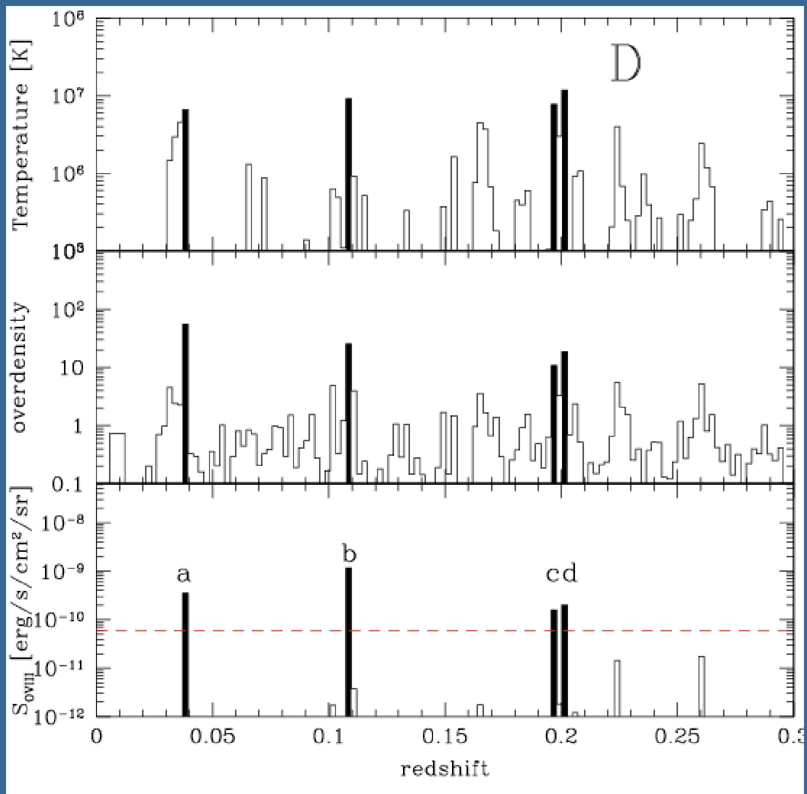
Simulated spectra: region D

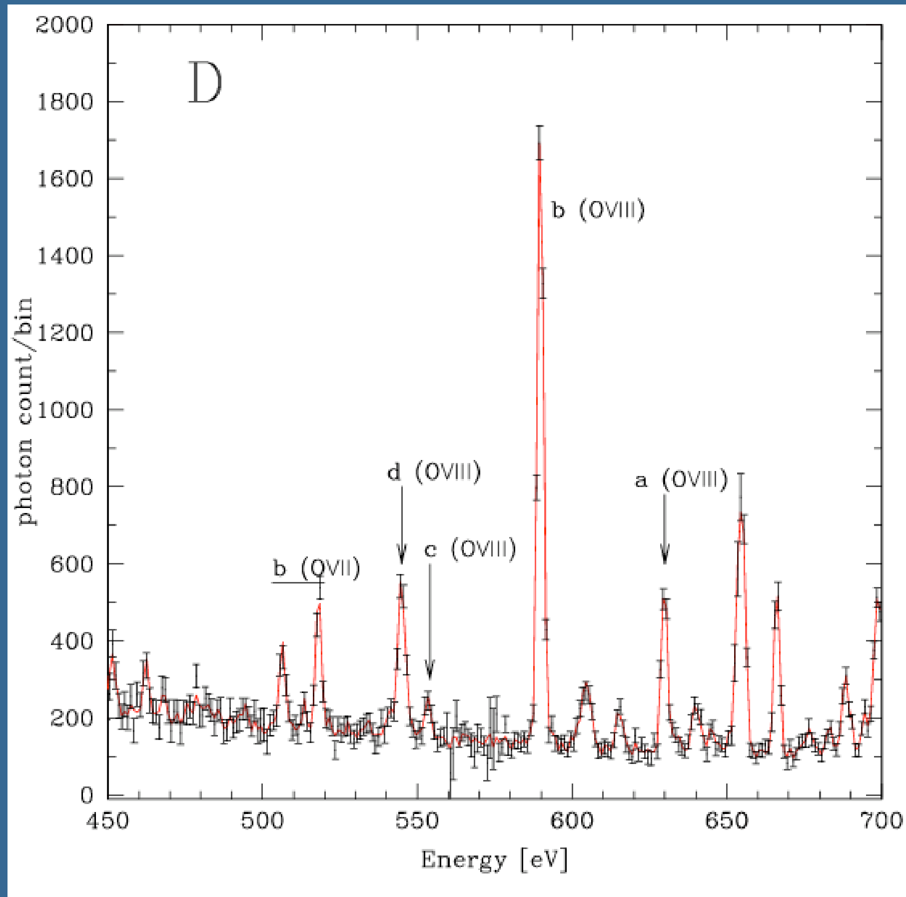
Deeper observation of targeted fields with DIOS (5^2pixels)



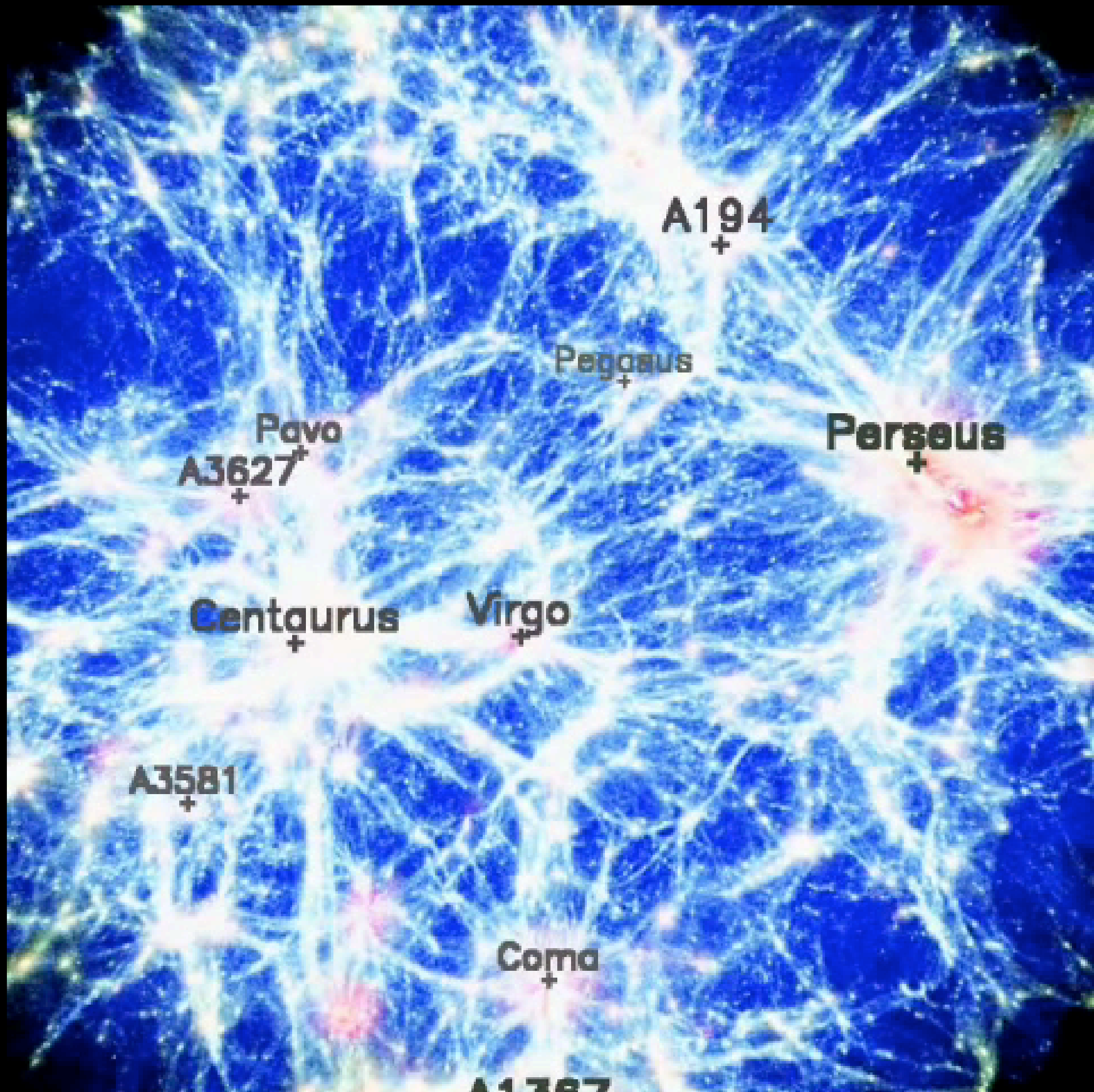
19′x19′ = 0.098 deg^2

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



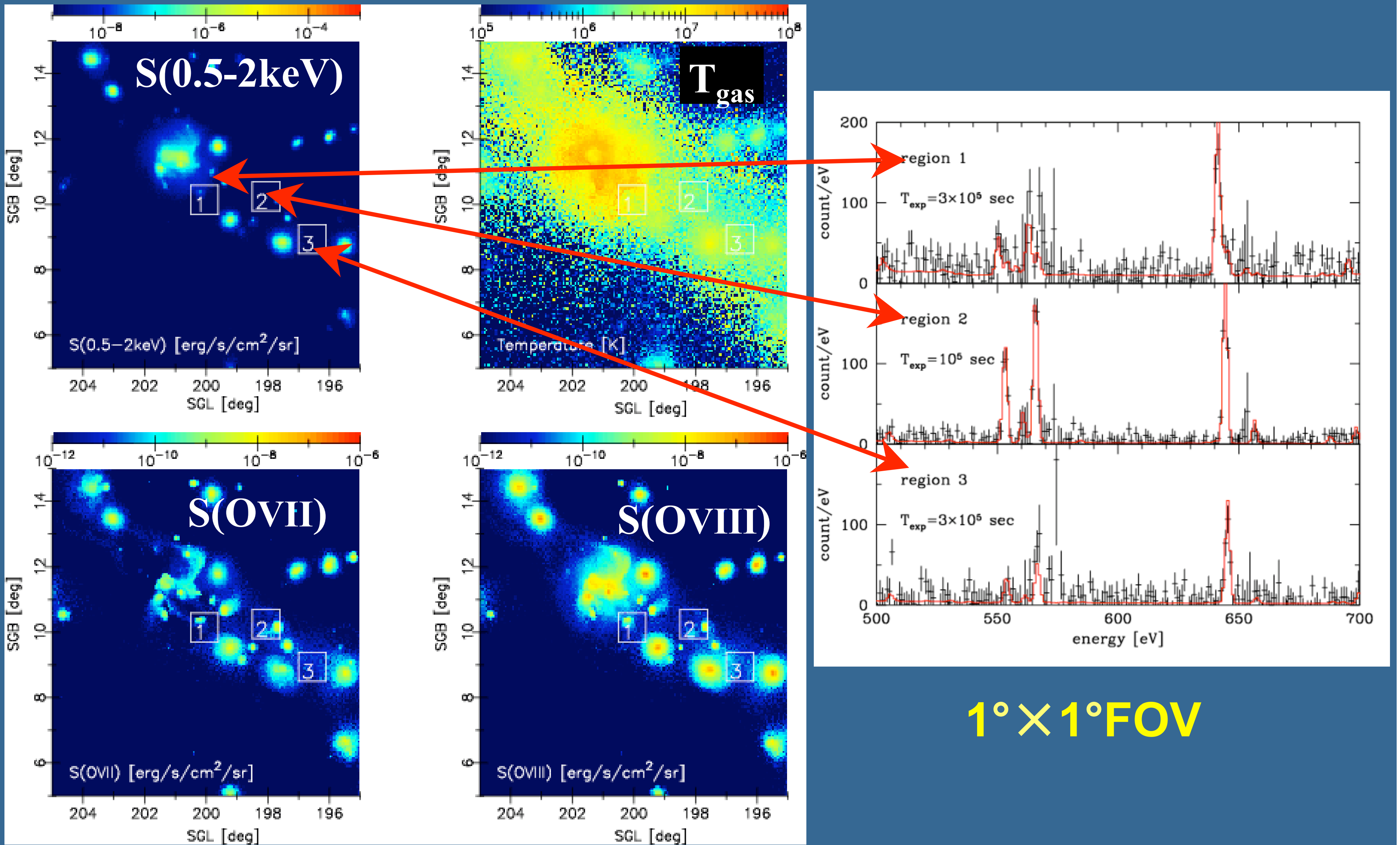


Tour of the simulated local universe



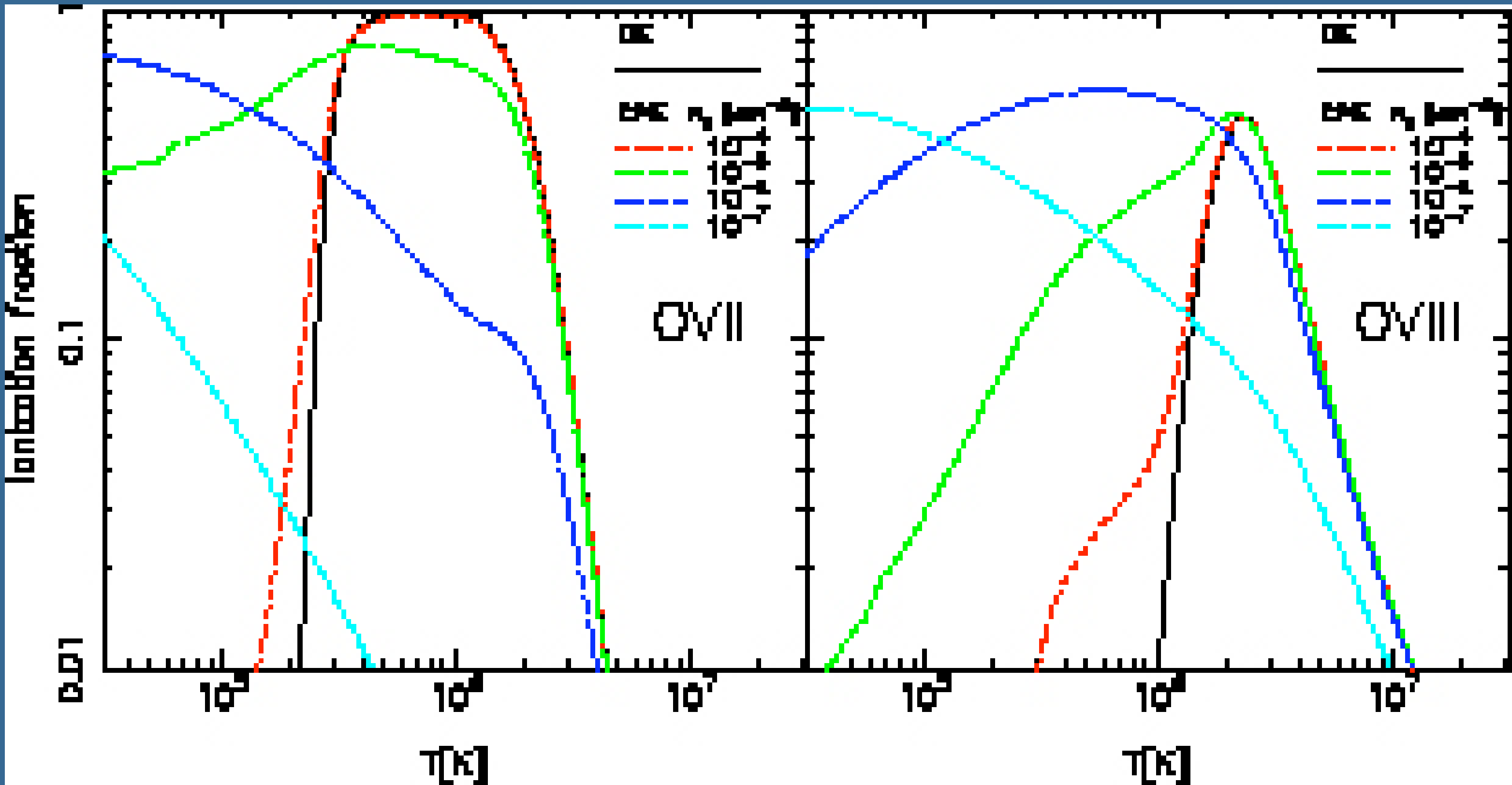
Klaus Dolag (2003)

Mock observation of X-ray filament extending around simulated A3627

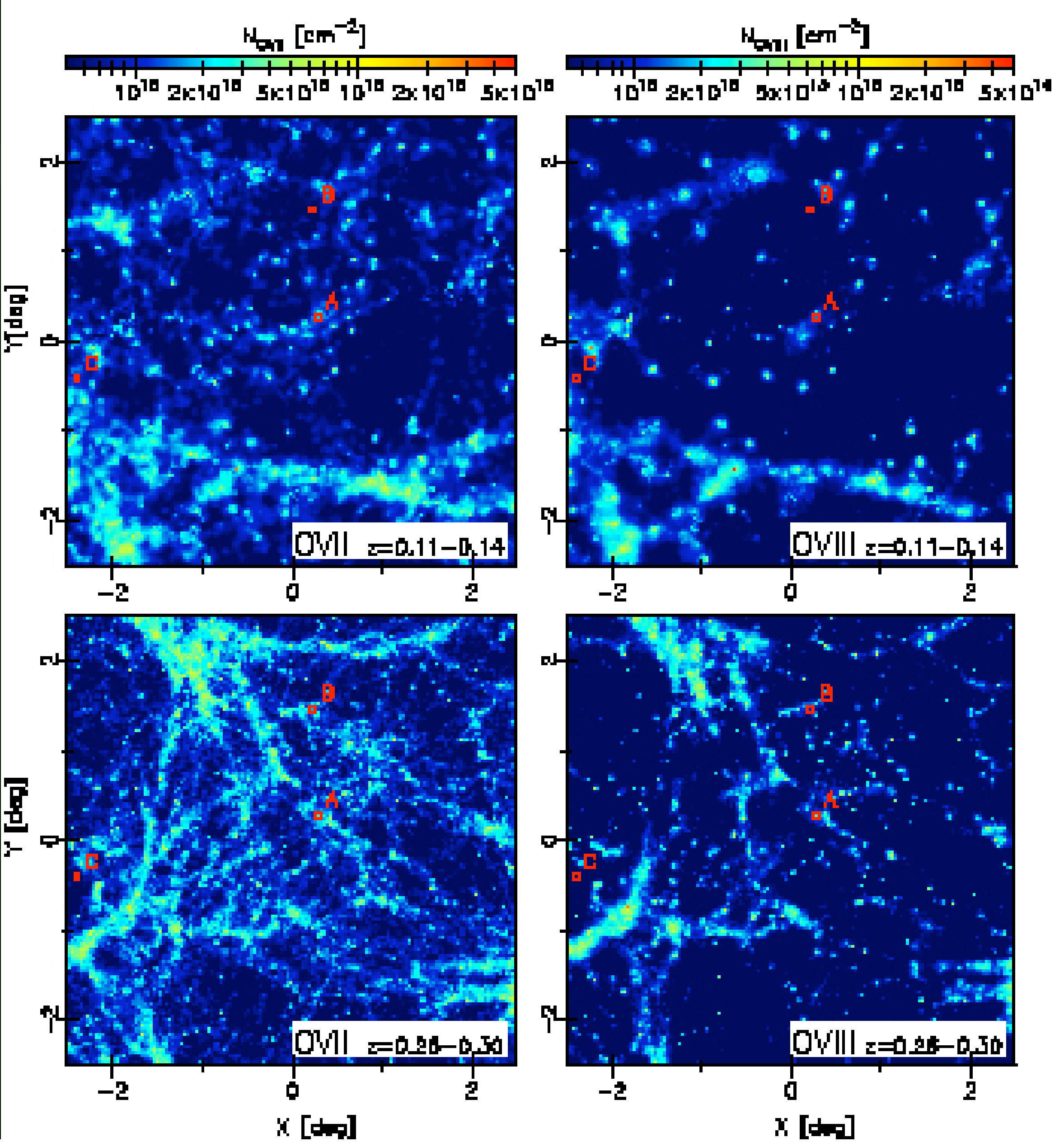


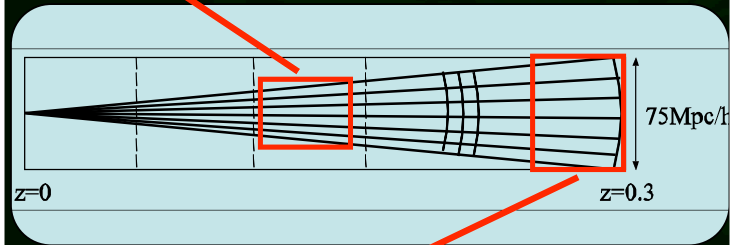
1°×1°FOV

Ionization fraction of oxygen



Oxygen column density map





吸収体数のcumulative distribution
(1視線方向z=0-0.3あたり, 6400視線方向平均)

吸収線	3σ以上の吸収体数/１視線方向
OVII 574eV	1.06個
OVIII 654eV	0.23個
OVII & OVIII	0.21個