Locating missing baryons from oxygen emission lines with DIOS

(Diffuse Intergalactic Oxygen Surveyor)

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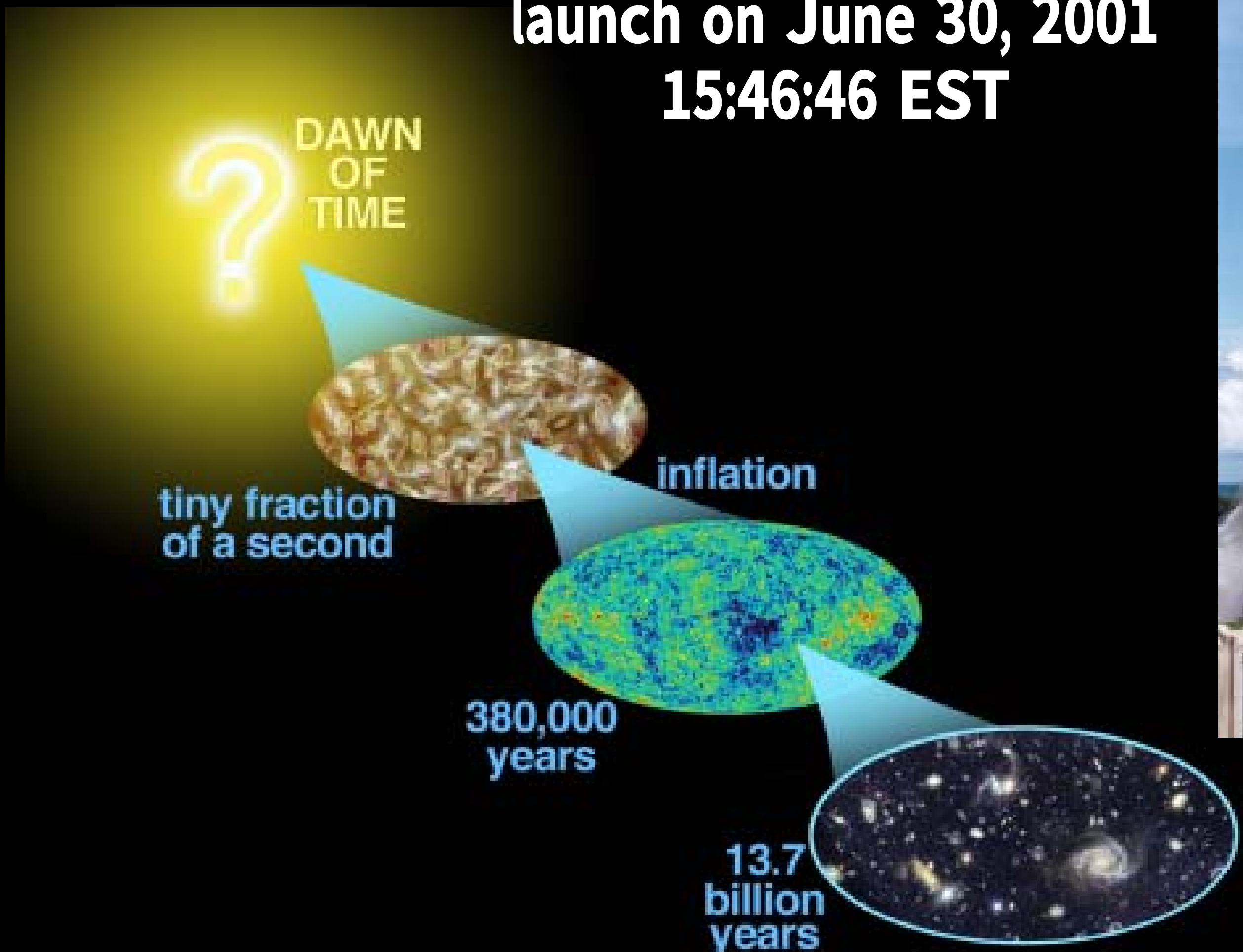
WMAP: Wilkinson Microwave Anisotropy Probe

http://lambda.gsfc.nasa.gov

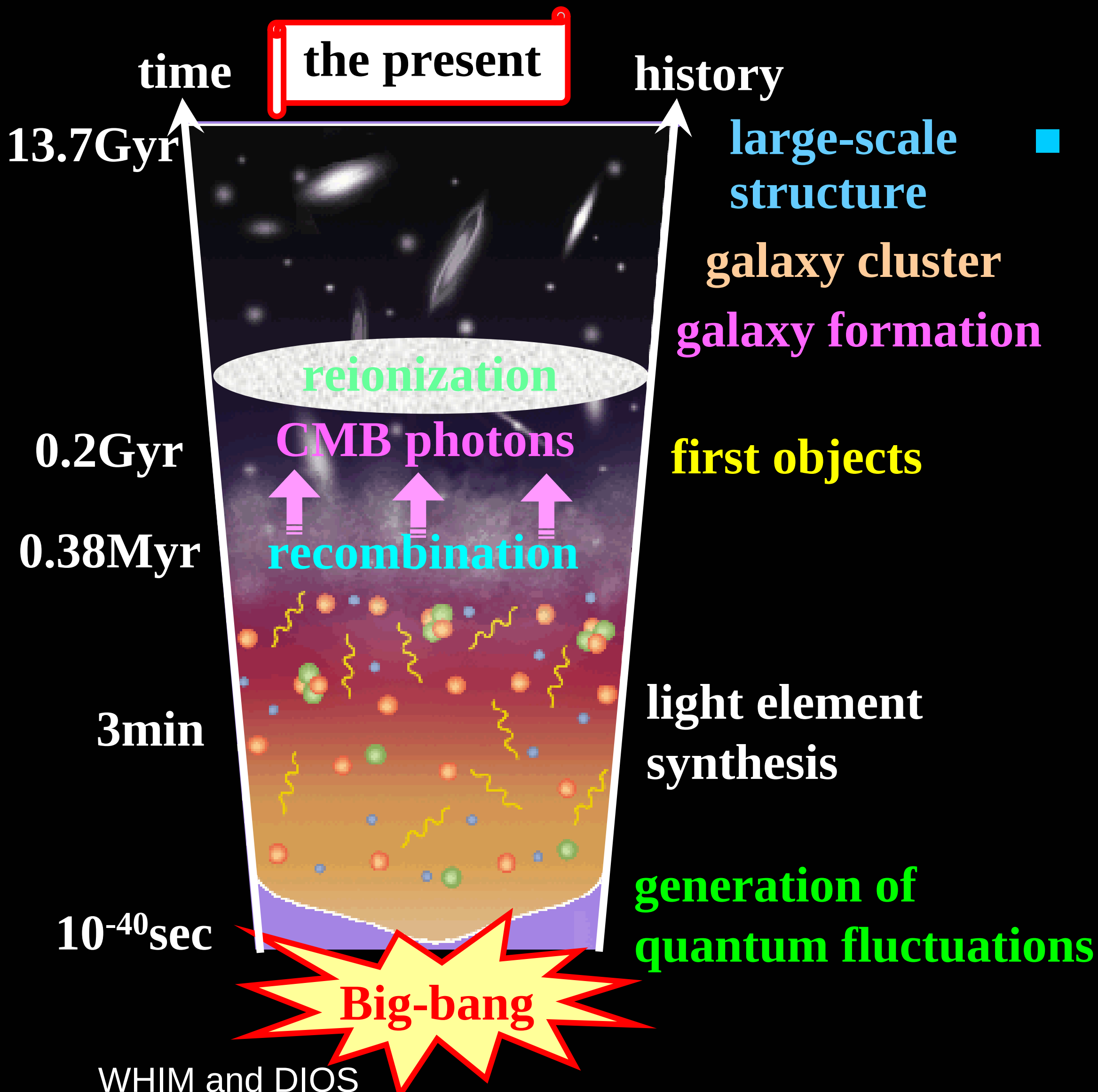
launch on June 30, 2001
15:46:46 EST



NASA/WMAP Science team

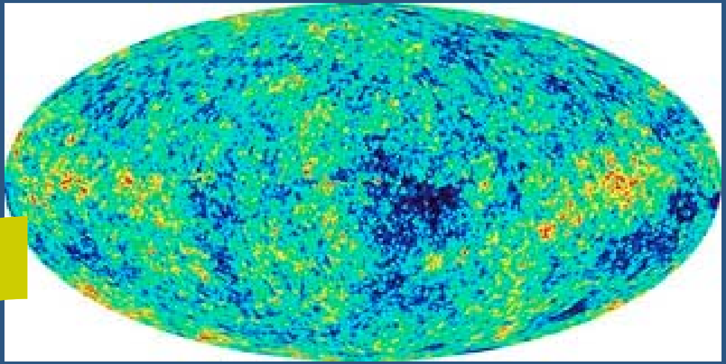
CMB: Cosmic Microwave Background

relic thermal photons from the ancient universe



- Recombination of protons and electrons = decoupling of baryons and photons
  - T=3000K
  - t=380,000 years
  - universe became neutral and thus transparent to photons

Deciphering the ancient map

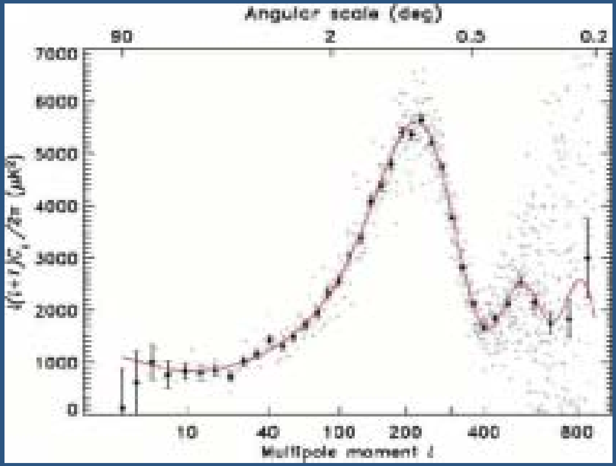


- ancient document in cipher
  - CMB all-sky map
- a cipher key
  - spherical harmonics

$$\frac{\delta T}{T}(\theta,\varphi)=\sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

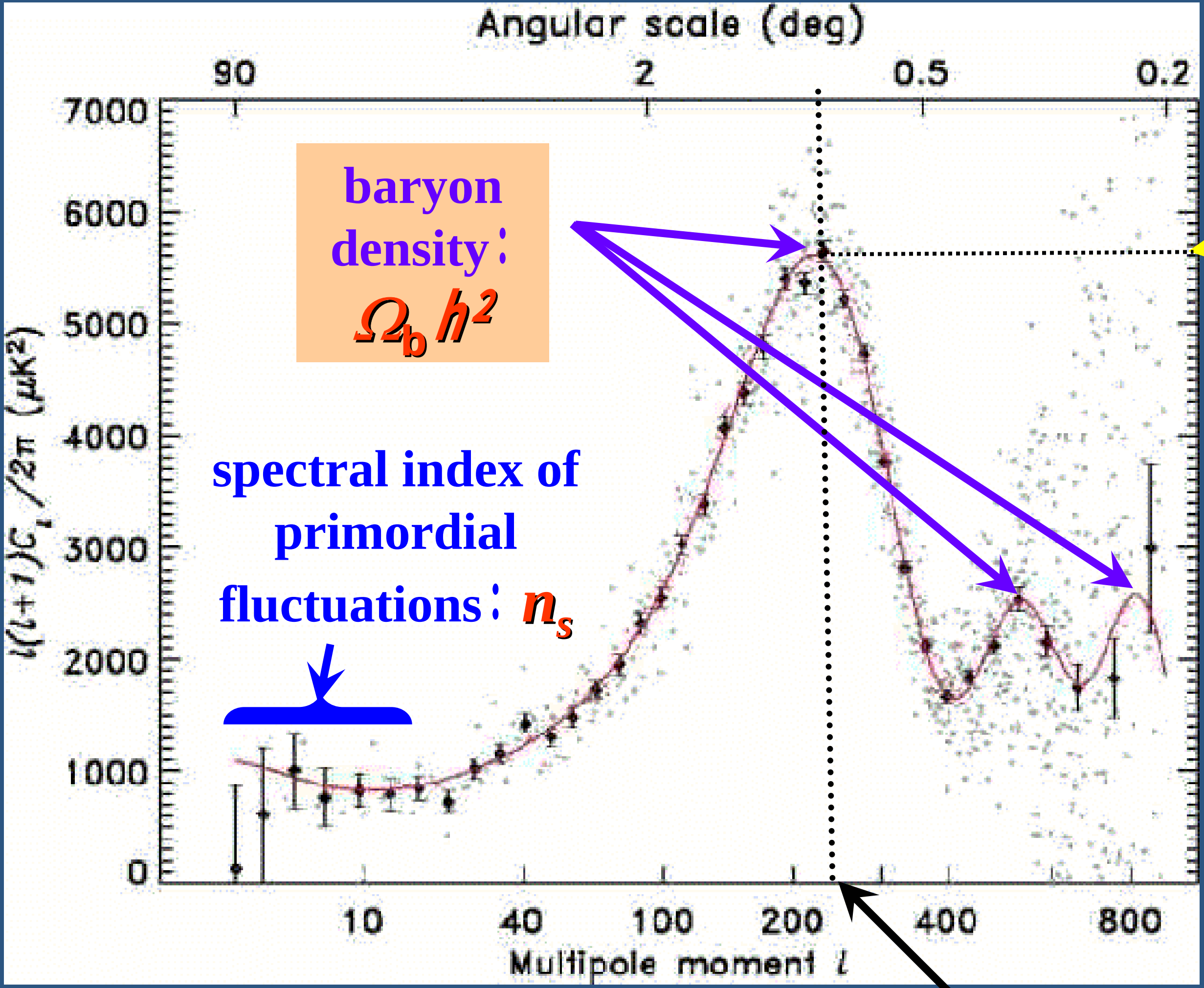
- deciphered data
  - temperature spectrum

$$C_l=\left\langle a_{lm} a_{lm}^{*}\right\rangle$$



- grammar to understand the universe
  - cold dark matter model
- imprinted information
  - age, geometry, and composition of the universe

Angular power spectrum of CMB temperature fluctuations observed by WMAP



$$\frac{\delta T}{T}(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

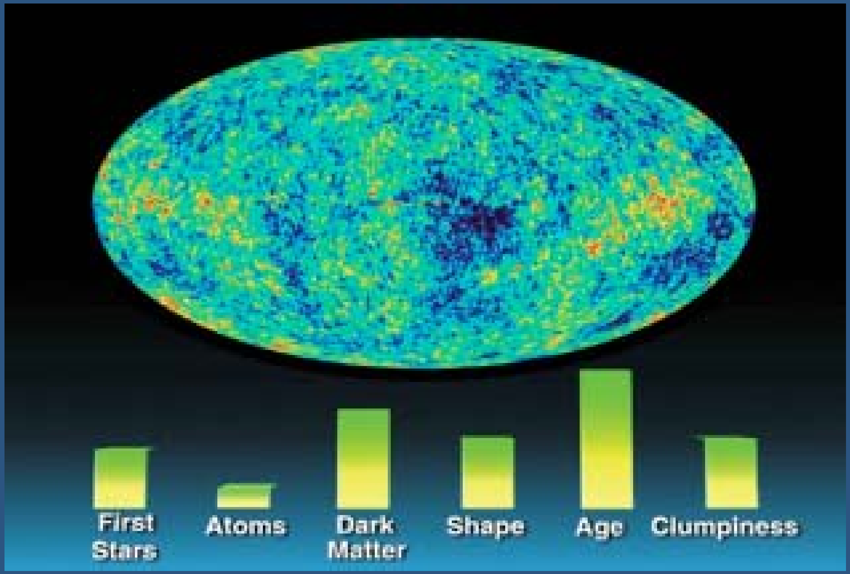
$$C_l = \langle a_{lm} a_{lm}^* \rangle$$

Spergel et al. ApJS 148(2003)175

curvature of the universe

$\Omega_K = \Omega_m + \Omega_\Lambda - 1$

What WMAP told us ?



- age of the universe: 13.7 Gyr
- universe is spatially flat
- universe reionized at 0.2Gyr after Big-bang
- cosmic matter is dominated by dark matter
- cosmic energy is dominated by dark energy

Results: weighing the universe

baryons

- ordinary matter makes up merely 4 percent of the entire mass of the universe

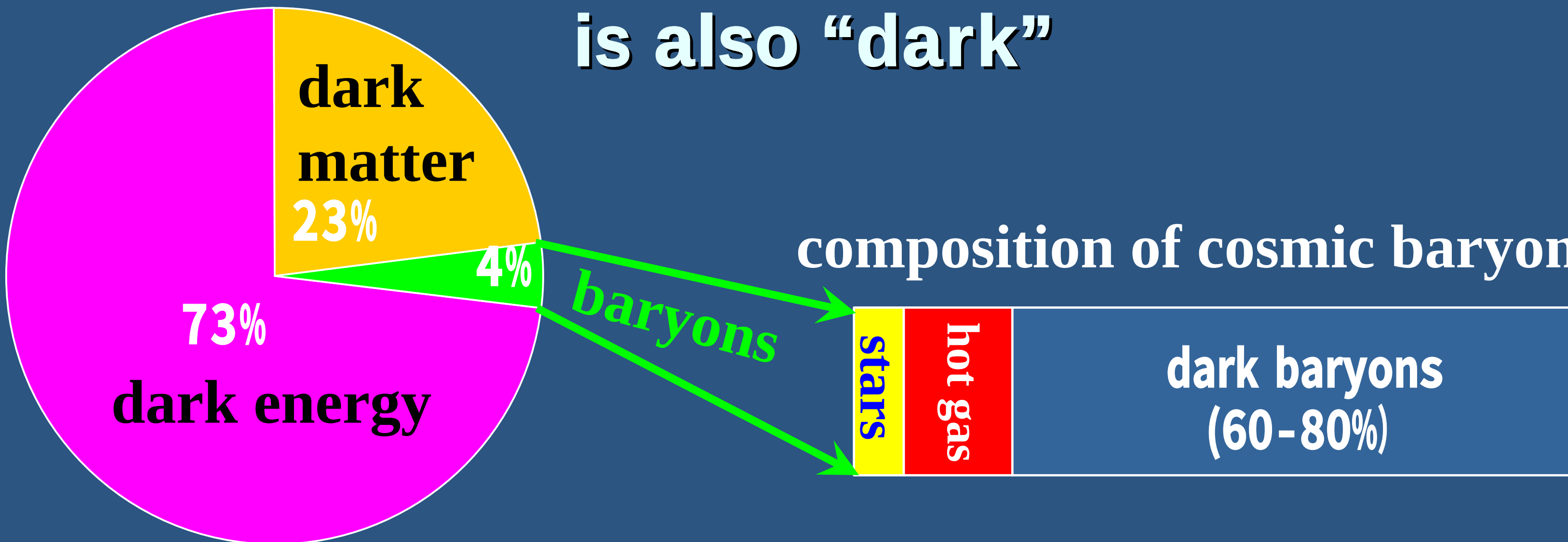
dark matter

- galaxies and clusters are surrounded by invisible mass an order-of-magnitude more massive than their visible part
- unknown elementary particles?

dark energy

- universe is dominated by even more exotic component !
- homogeneously fills the universe (unclustered)
- repulsive force (negative pressure; equation of state: $P = -\rho$)
- Einstein's cosmological constant ?

More intriguingly, most of the cosmic baryon is also “dark”



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	...

99％ of the universe is DARK

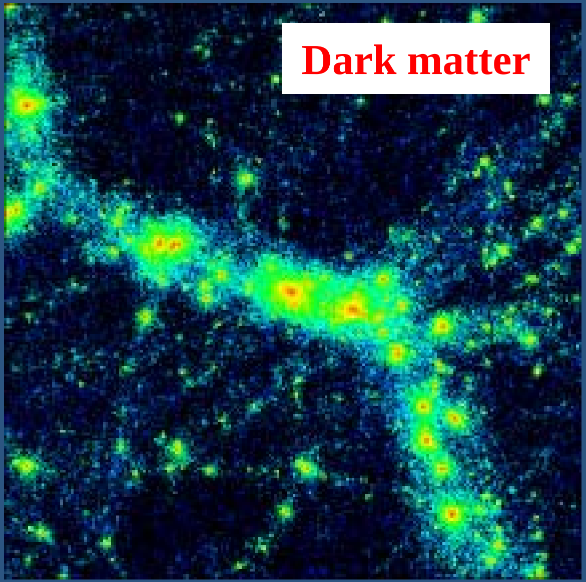
- **Quite frustrating... We finally realized that we have not yet understood 99％ of the universe at all !**

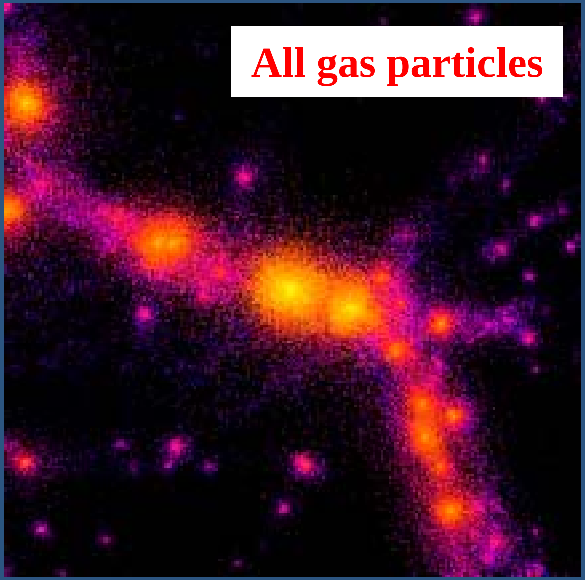
- **cosmological observations in the 20th century have identified previously unknown hierarchy of matter beyond the standard model of particle physics**
- **one needs to understand the meaning of cosmological parameters beyond mere precise estimates of their values**
- **from *how much* to *why***

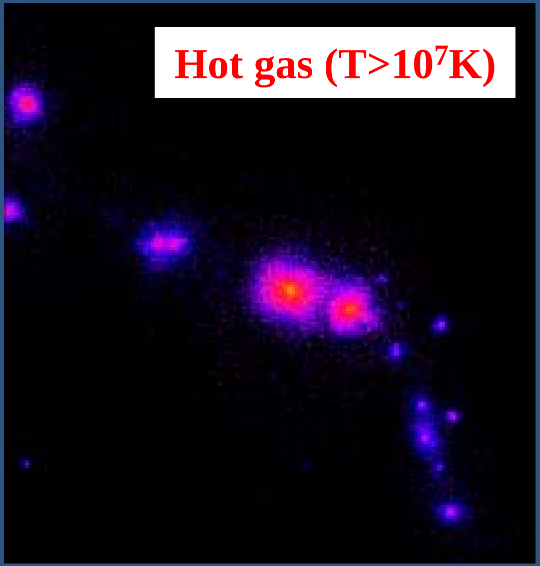
hydrodynamical simulation with gas

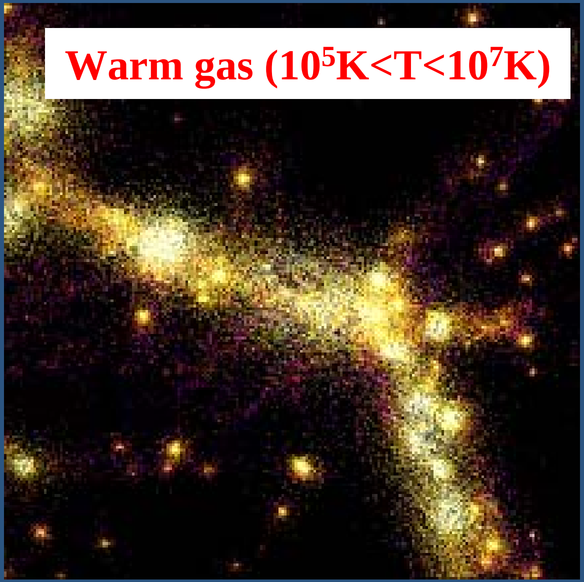
$(30h^{-1}\mathrm{Mpc})^3$ box around a massive cluster at $z=0$
ΛCDM SPH simulation

(Yoshikawa et al. 2001)









Four phases of cosmic baryons

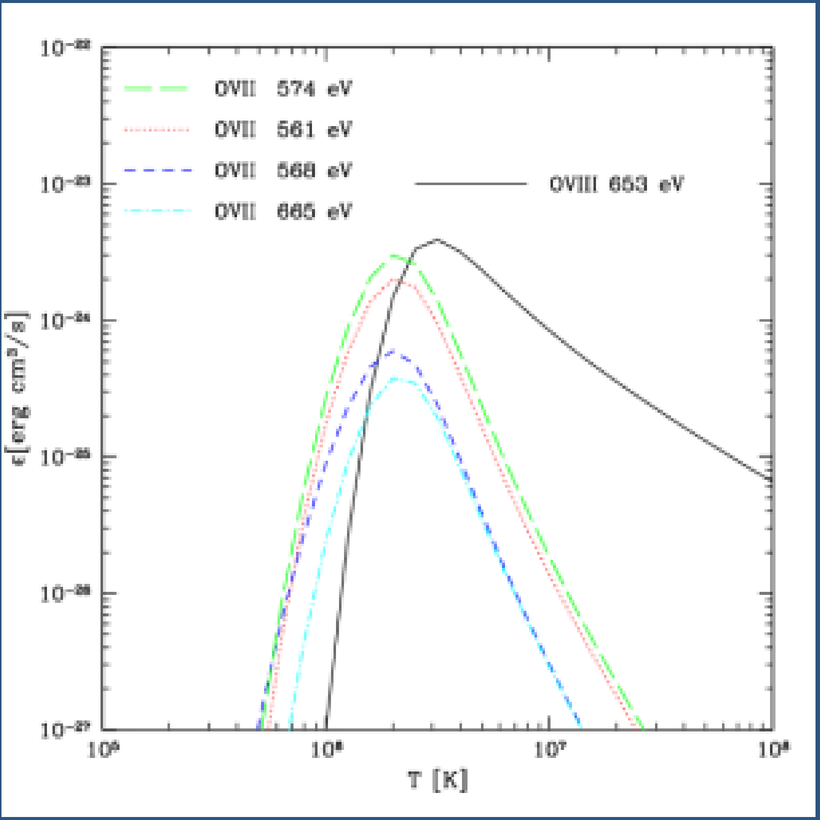
Dave et al. ApJ 552(2001) 473

- ***Condensed:*** **δ >1000, T<10^5K**
  - Stars + cold intergalactic gas
- ***Diffuse:*** **δ <1000, T<10^5K**
  - Photo-ionized intergalactic medium
  - Lyα 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***)

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***

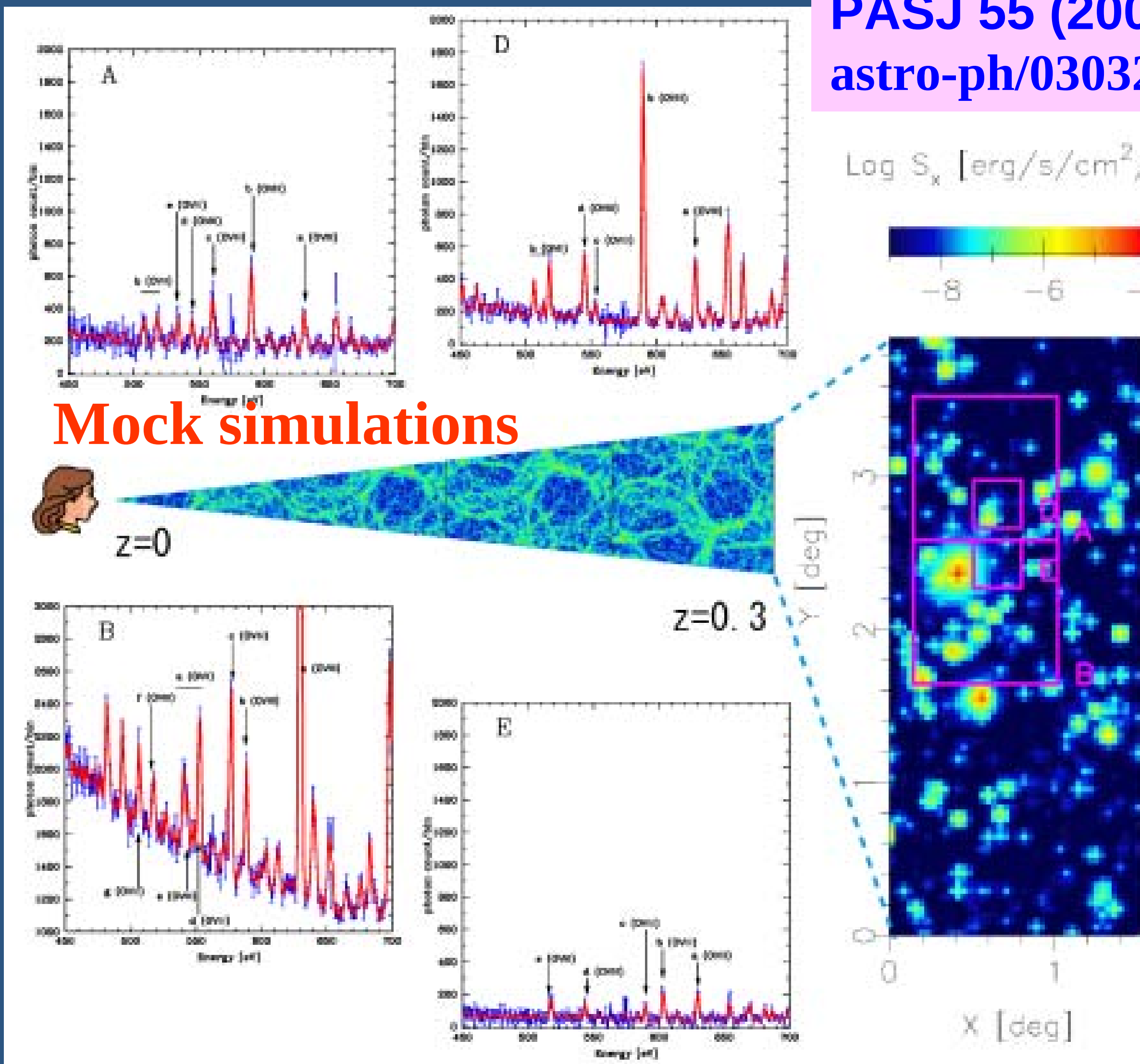
DIOS: Diffuse Intergalactic Oxygen Surveyor

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** **(not yet approved)**.
- Unprecedented energy spectral resolution:
  ΔE=2eV in soft X-ray band (0.1-1keV)
- Aim at detection of ～30 percent of the total cosmic baryons via **Oxygen emission lines.**

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

PASJ 55 (2003) 879
astro-ph/0303281, 0402389



Univ of Tokyo:

K. Yoshikawa

Y.Suto

JAXA/ISAS:

N. Yamasaki

K. Mitsuda

Tokyo Metropolitan Univ.:

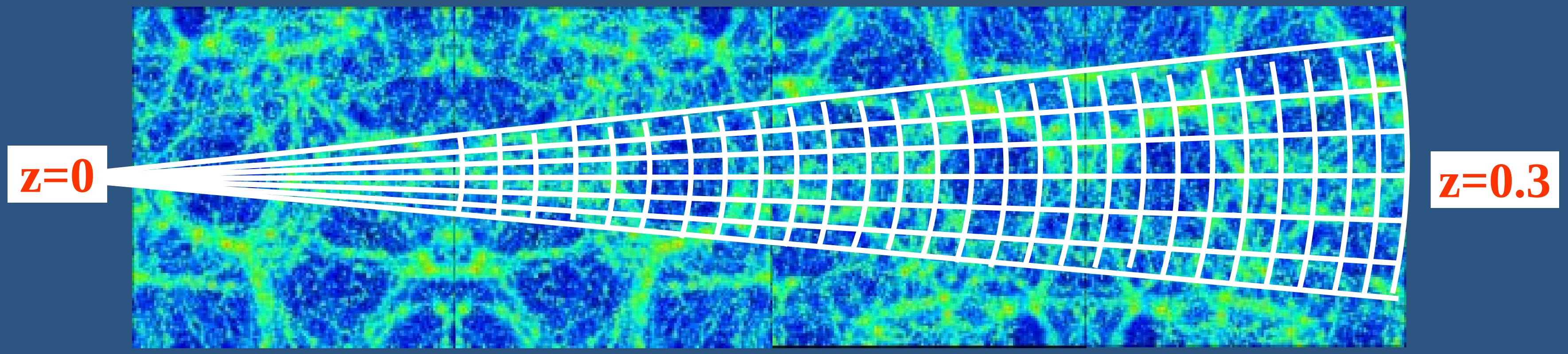
T. Ohashi

Nagoya Univ.:

Y. Tawara

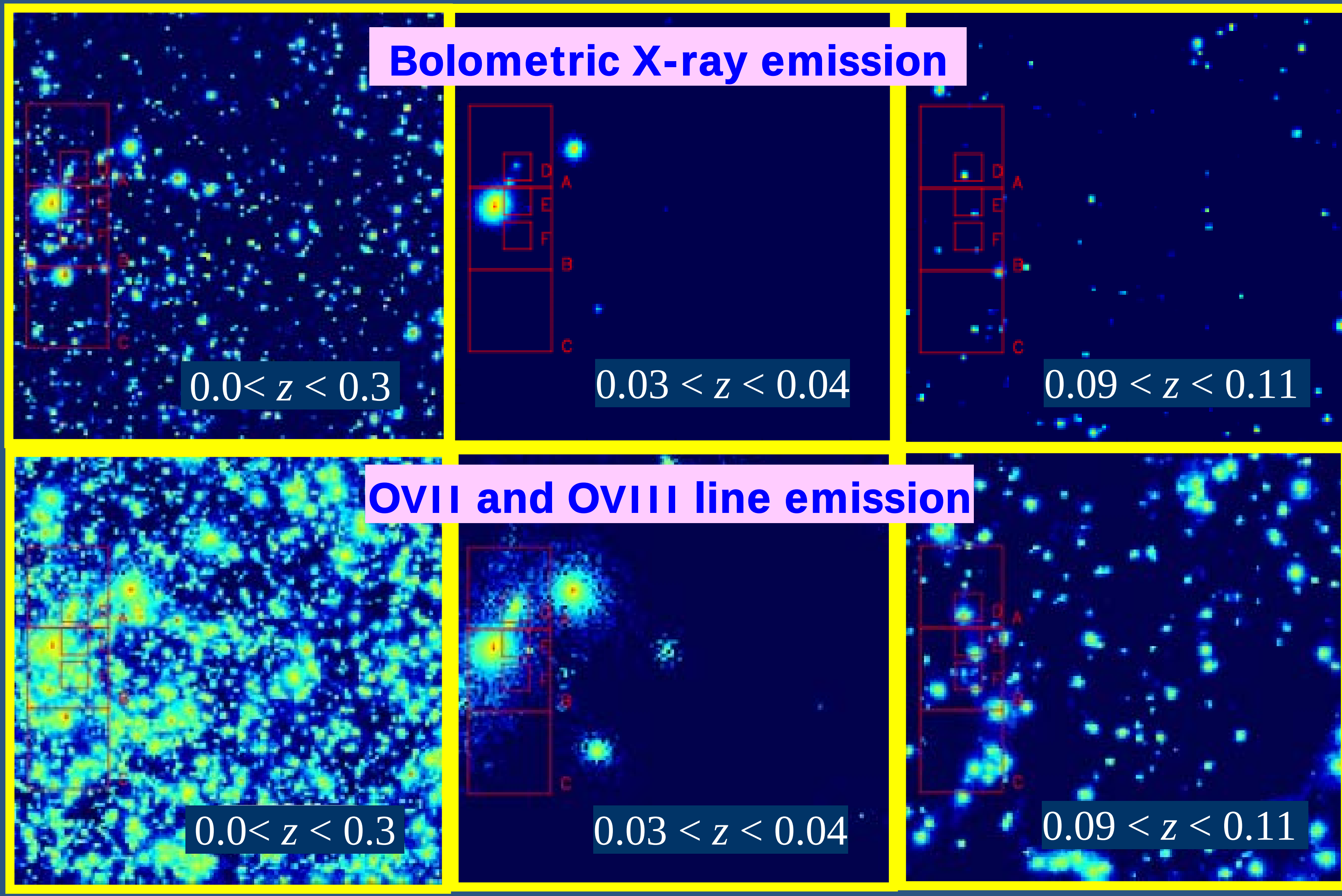
A. Furuzawa

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

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

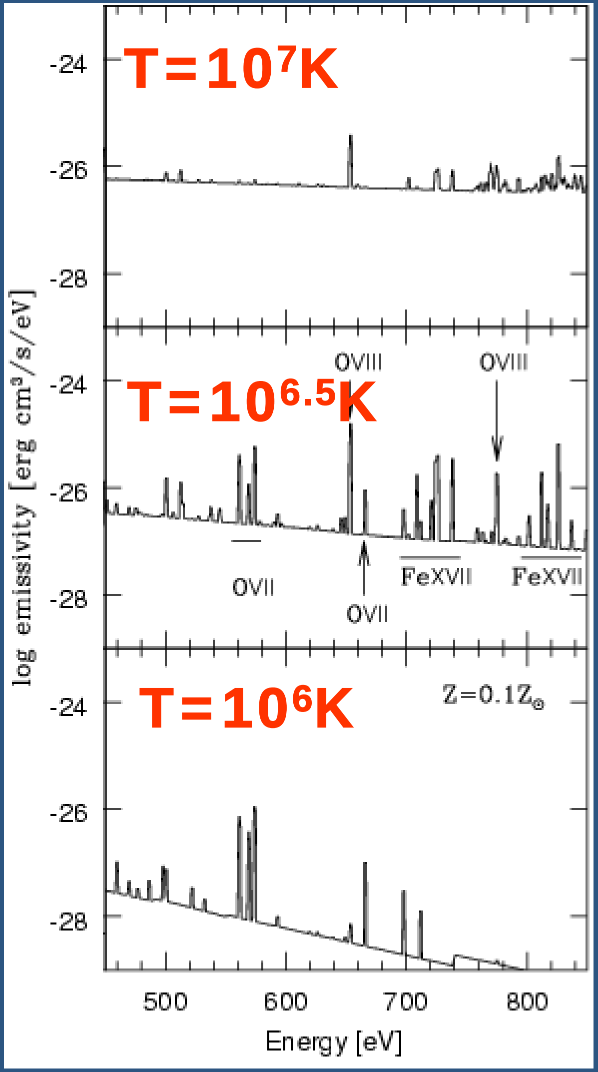
Model III : density-dependent (Aguirre et al. 2001)

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

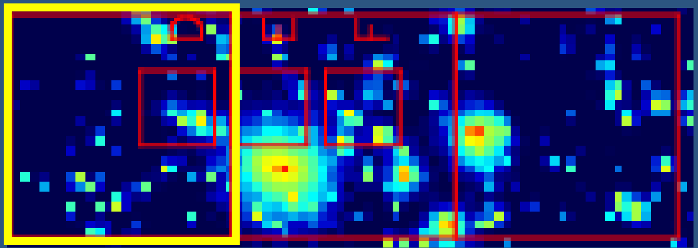
Creating Mock spectra from light-cone simulation output



- 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.

Simulated spectra: region A

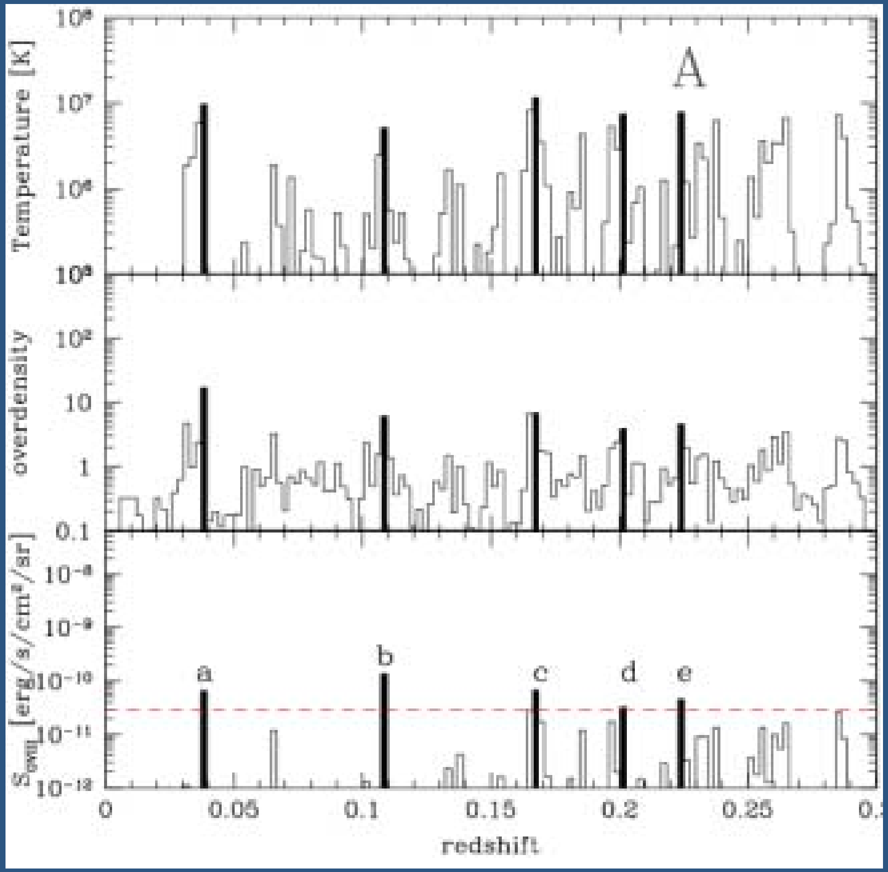
Shallow survey observation with the DIOS field-of-view (16^2pixels)

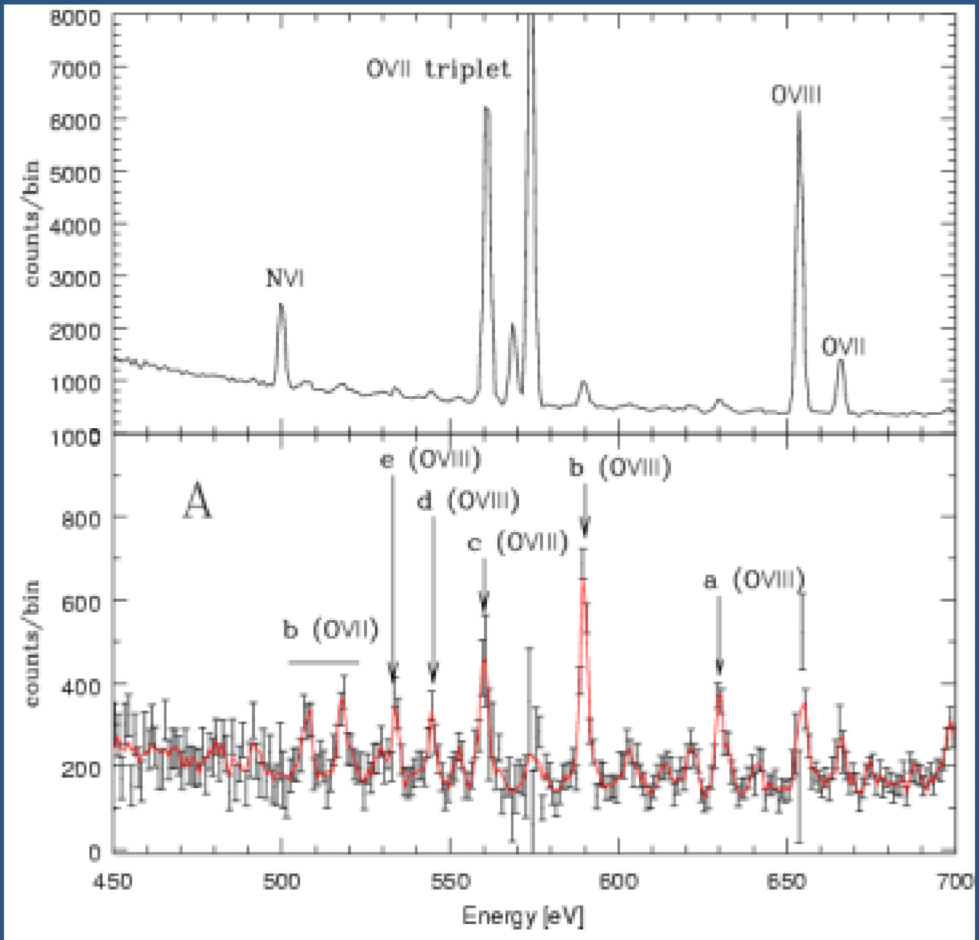


A

$0.94° \times 0.94° = 0.88\ deg^2$

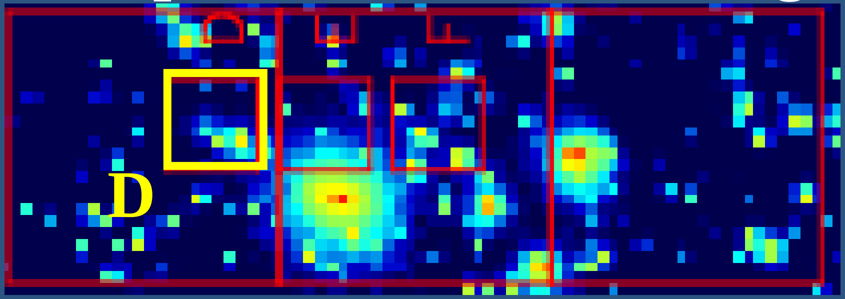
$T_{exposure} = 3x10^5 sec$





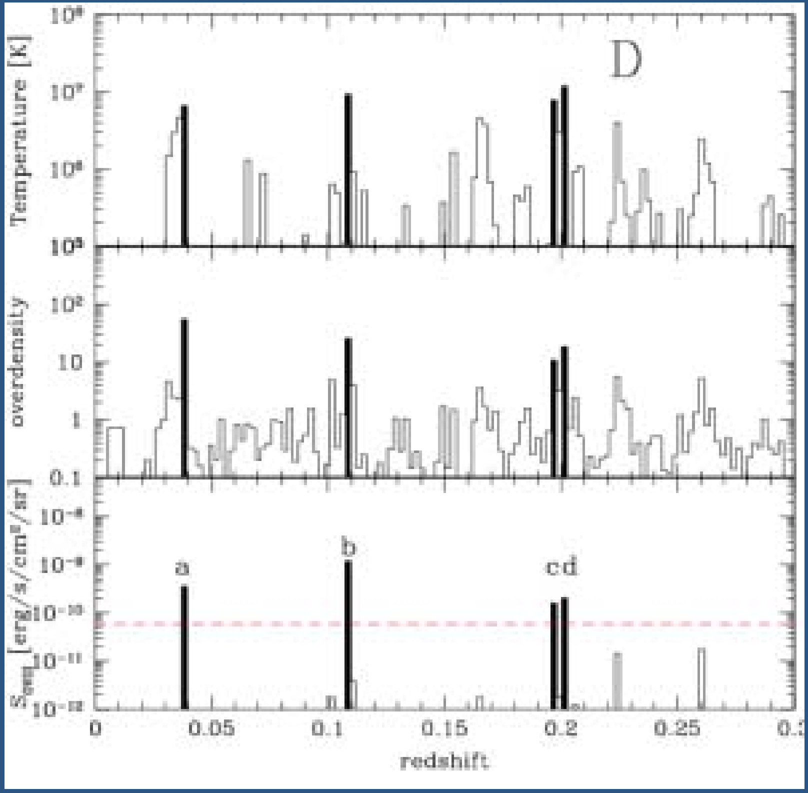
Simulated spectra: region D

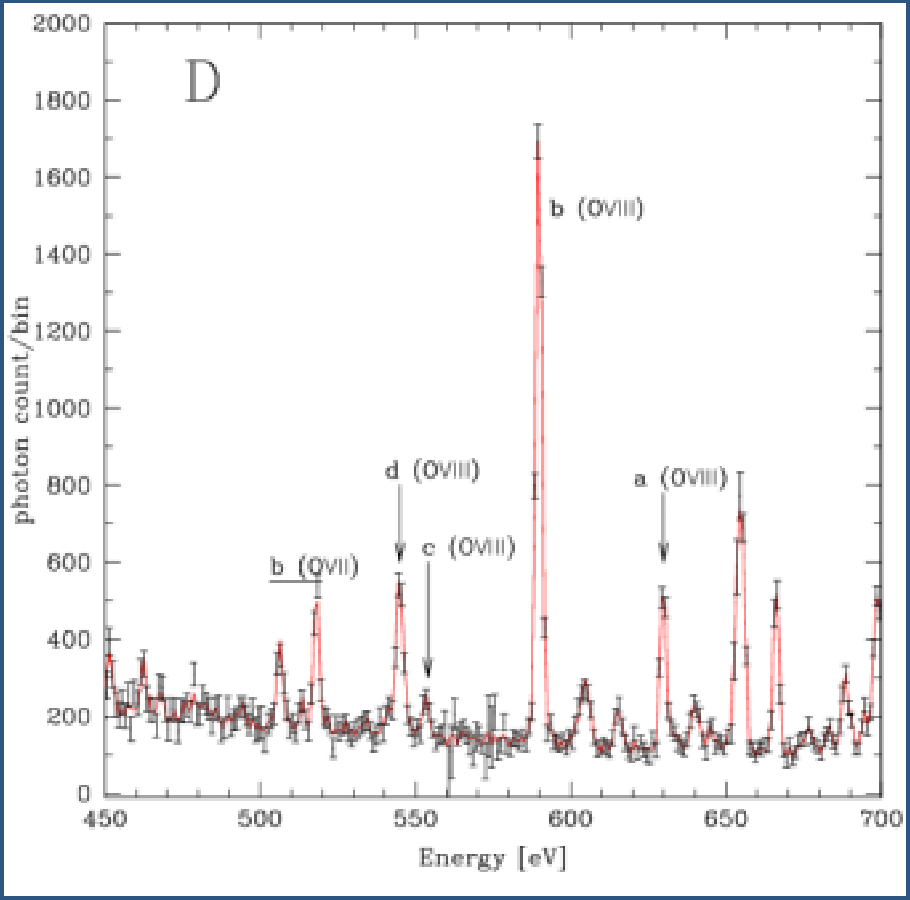
Deeper observation of targeted fields with DIOS (5^2pixels)



19'x19' = 0.098 deg^2

$T_{exposure}$ = 10^6sec

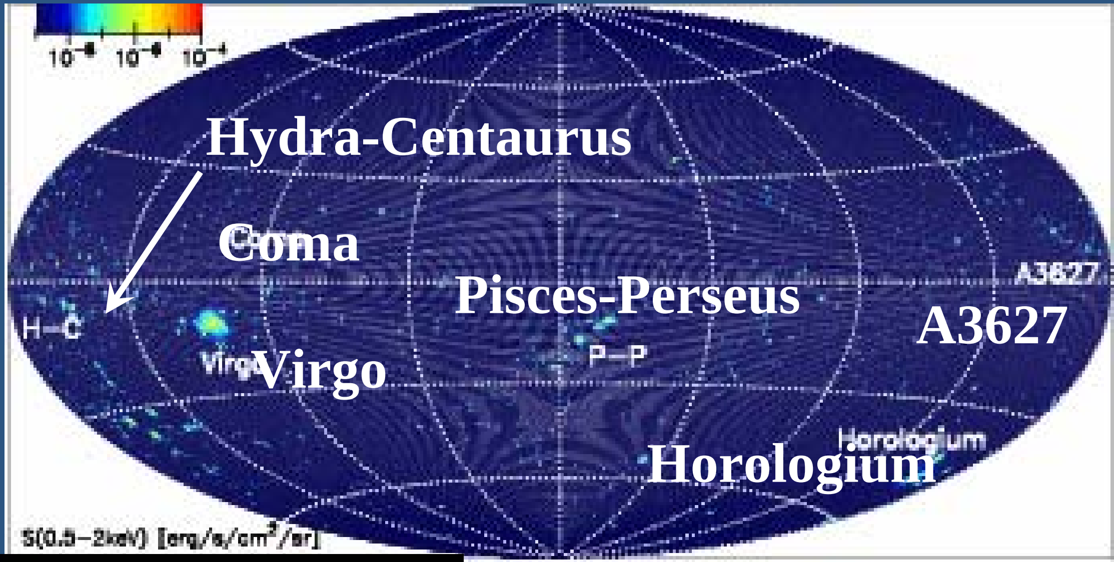




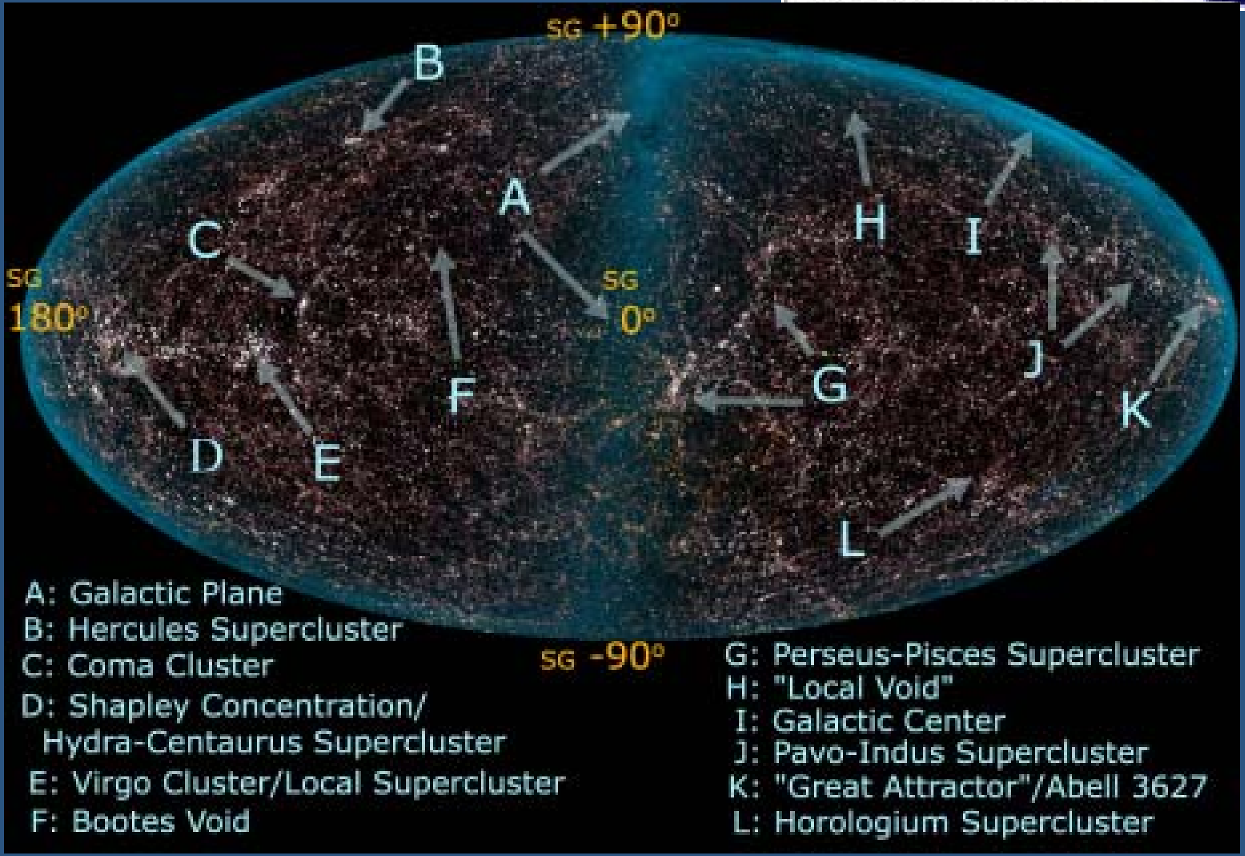
Simulating the local universe

- **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
- **Locating the WHIM in the local universe**
  - **Yoshikawa,** Dolag, Suto, Sasaki, Yamasaki, Ohashi, Mitsuda, Tawara, Fujimoto, Furusho, Furuzawa, Ishida & Ishisaki (2004), PASJ, submitted

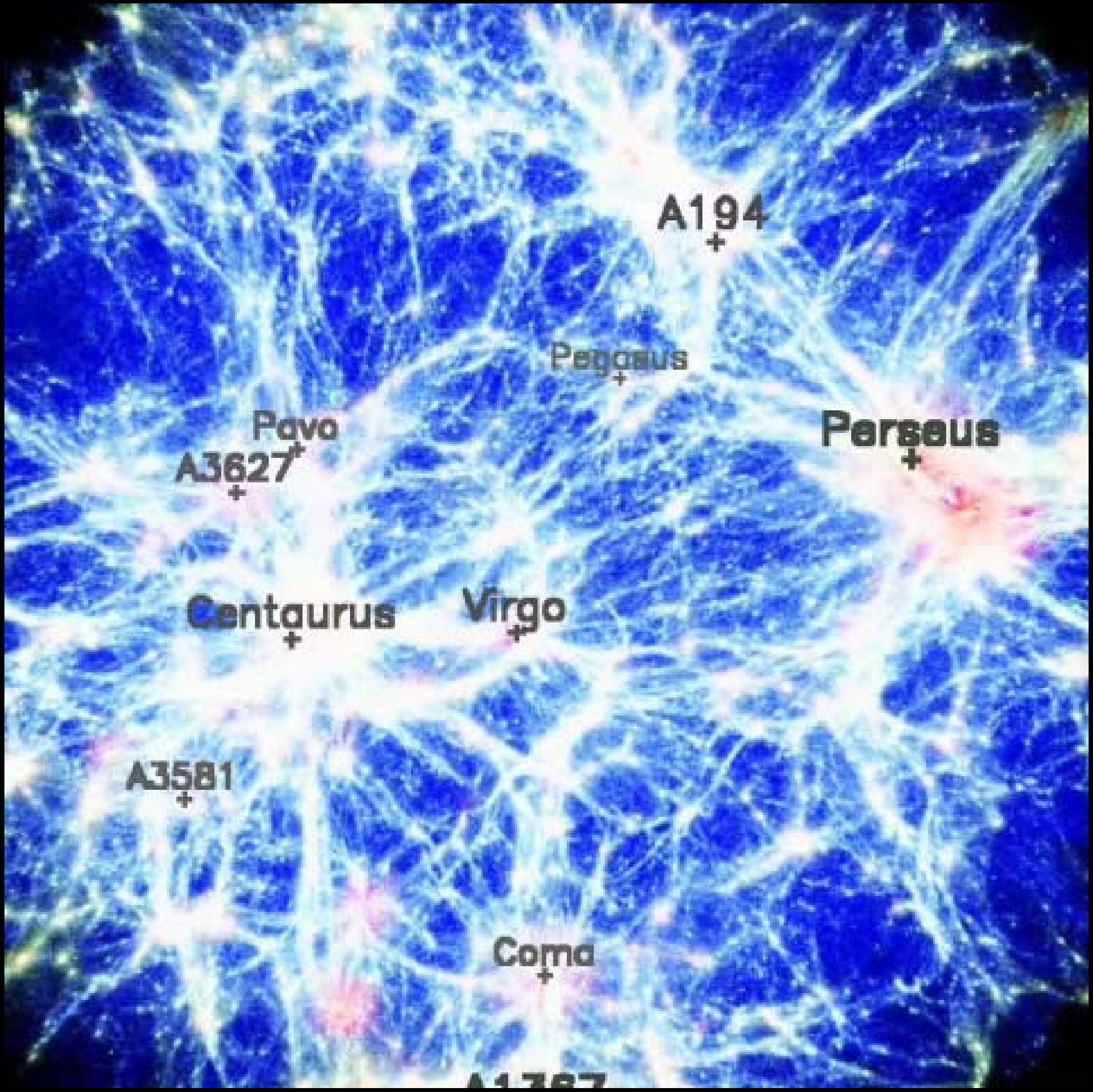
Simulated local universe vs. 2MASS map



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

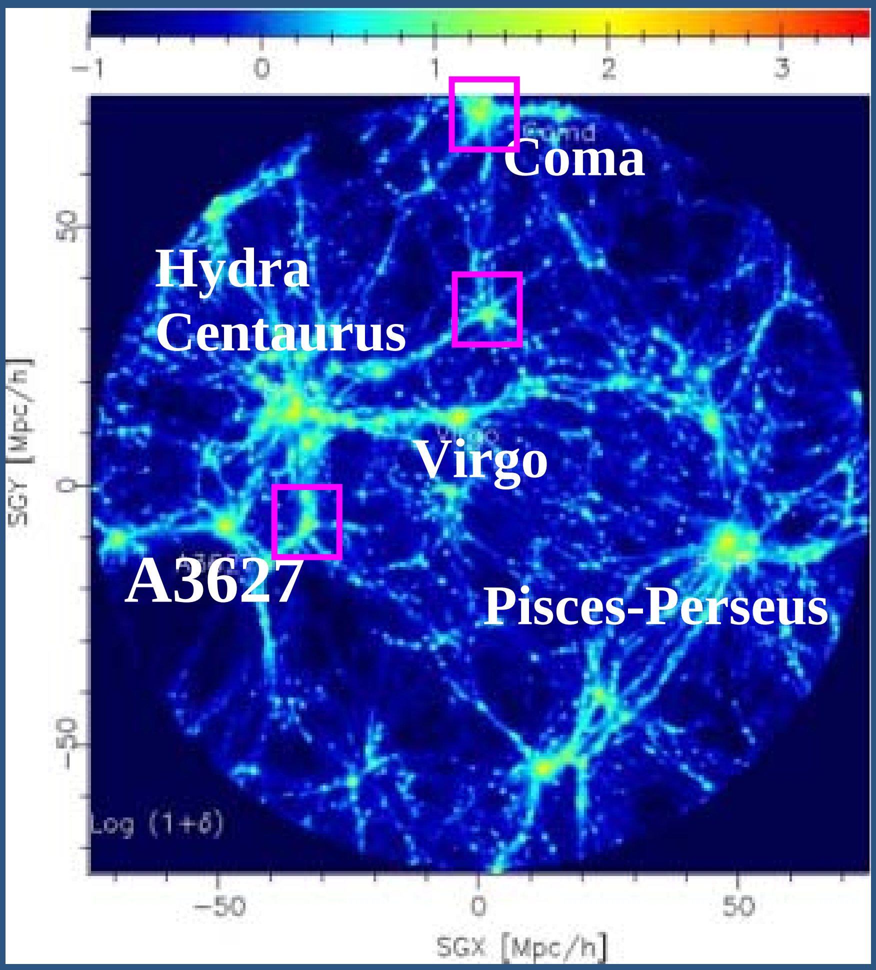


Tour of the simulated local universe



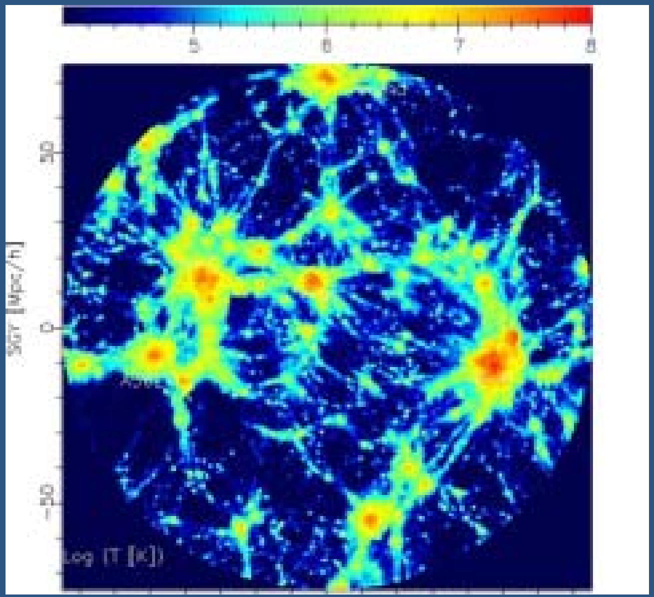
Klaus Dolag (2003)

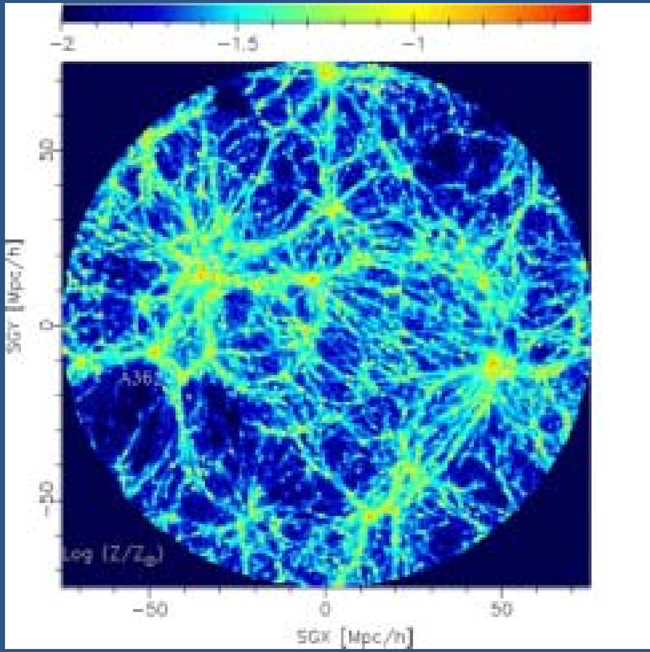
Simulated gas distribution on the supergalactic plane



gas density

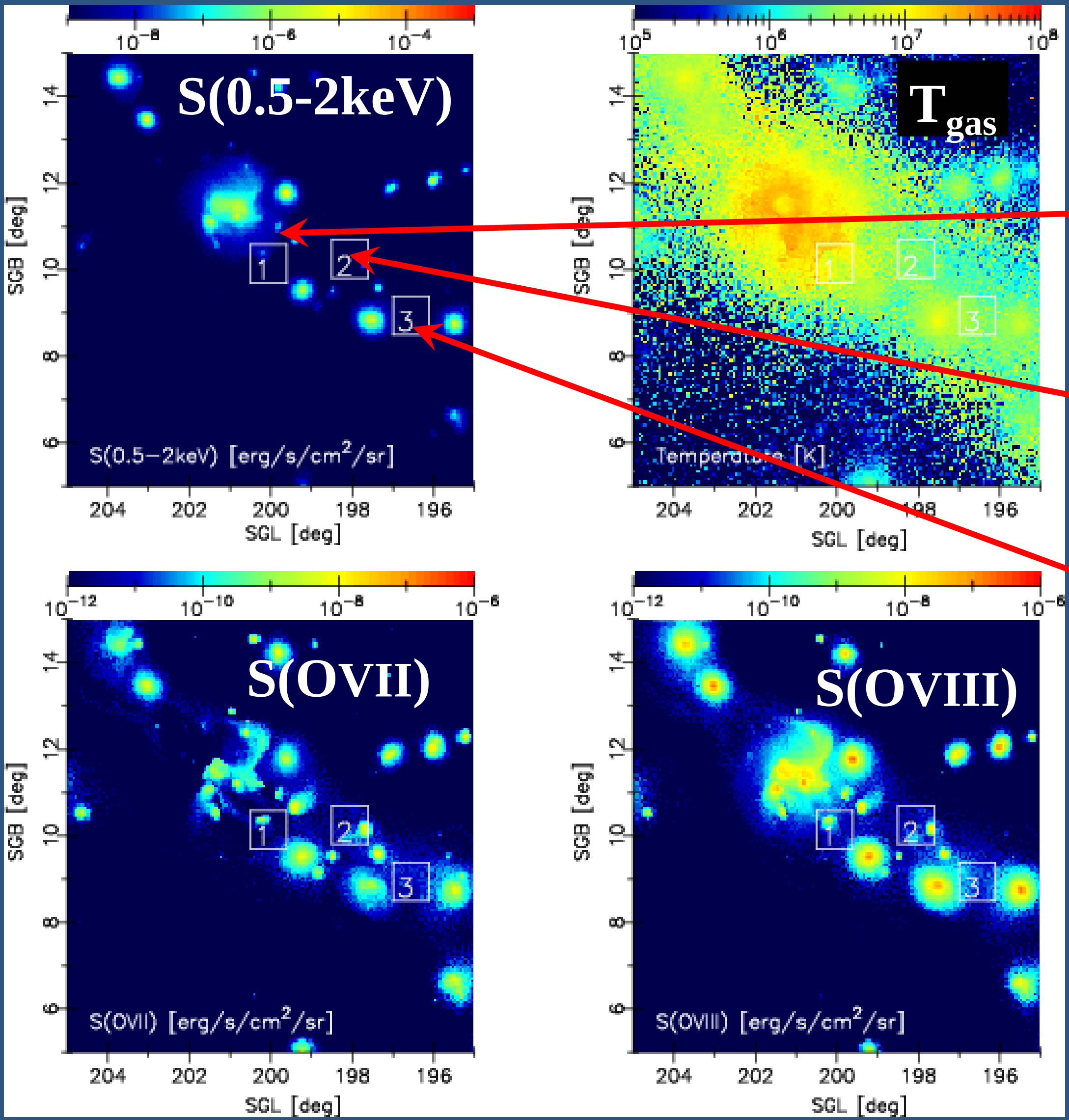
gas temperature

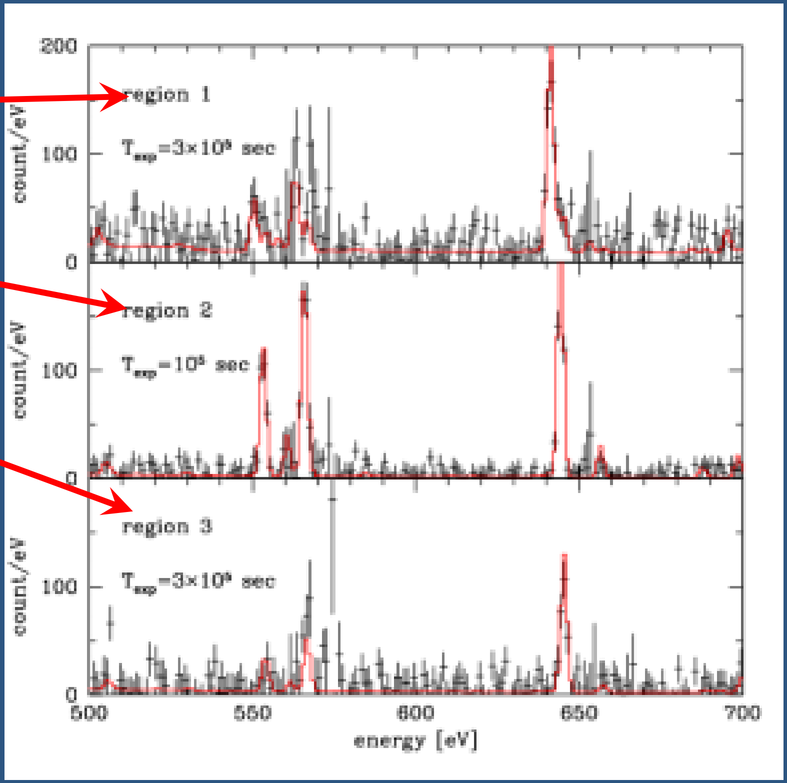




(adopted) metallicity

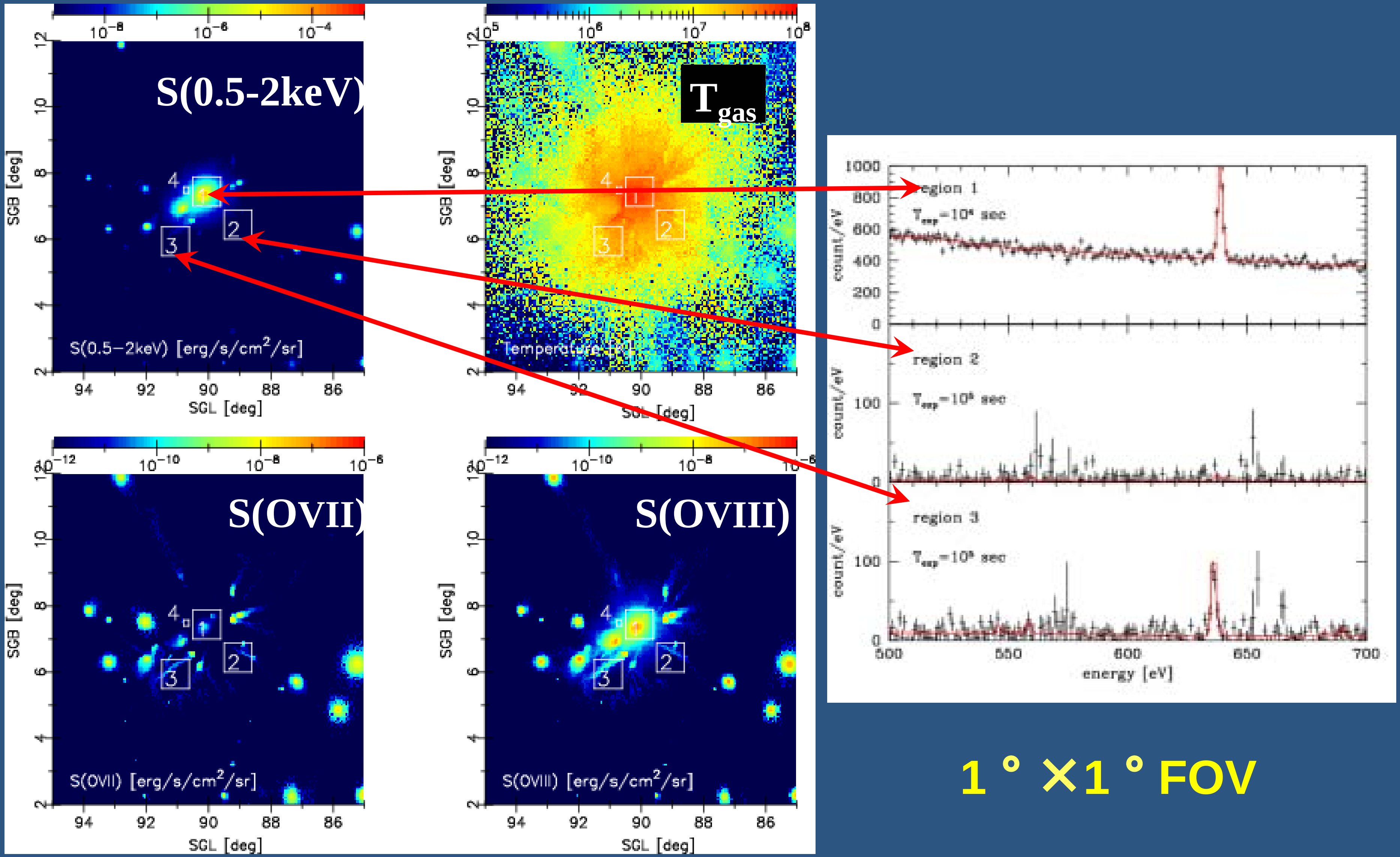
Mock observation of X-ray filament extending around simulated A3627





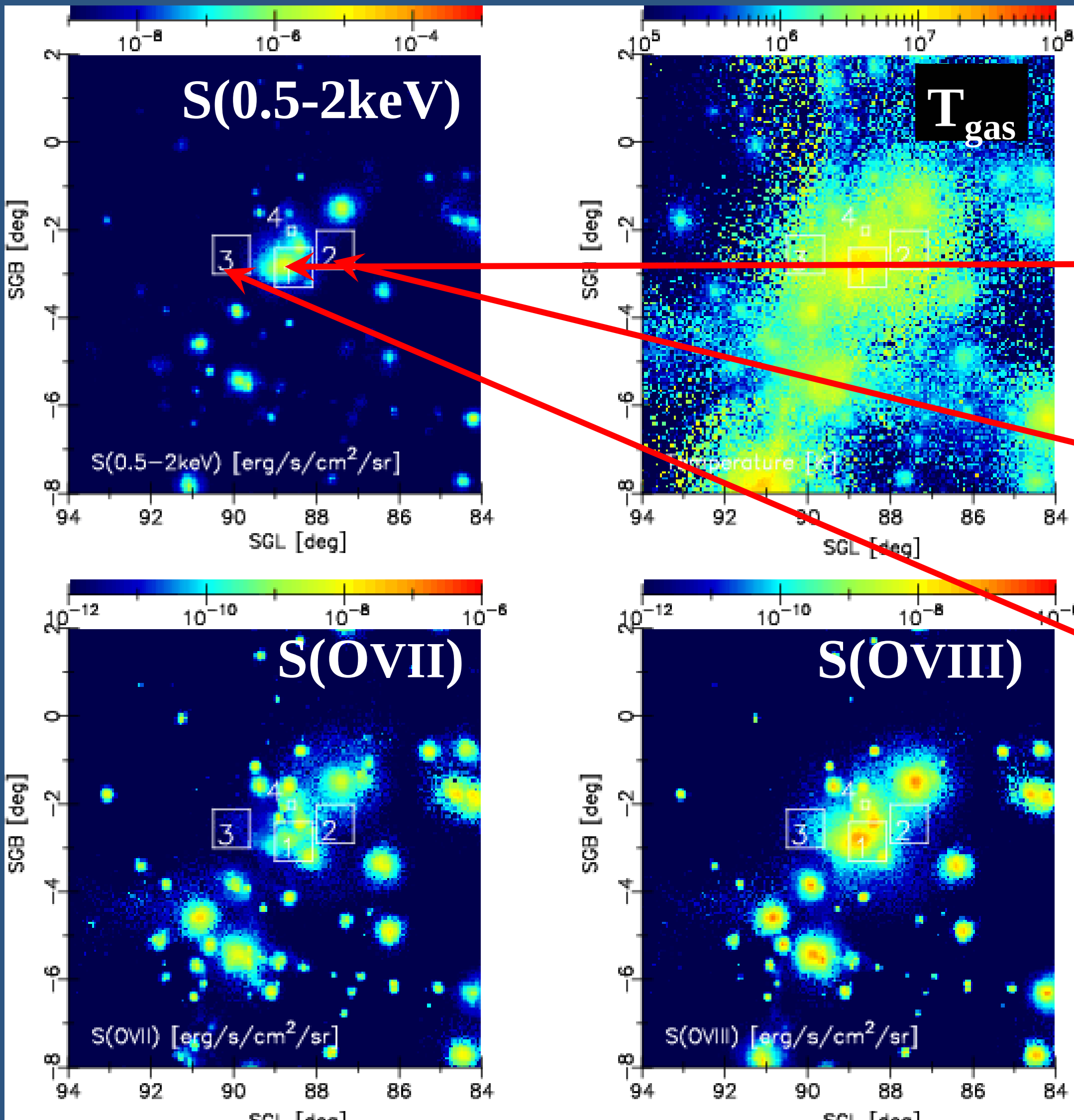
1°×1° FOV

Mock observation of simulated Coma

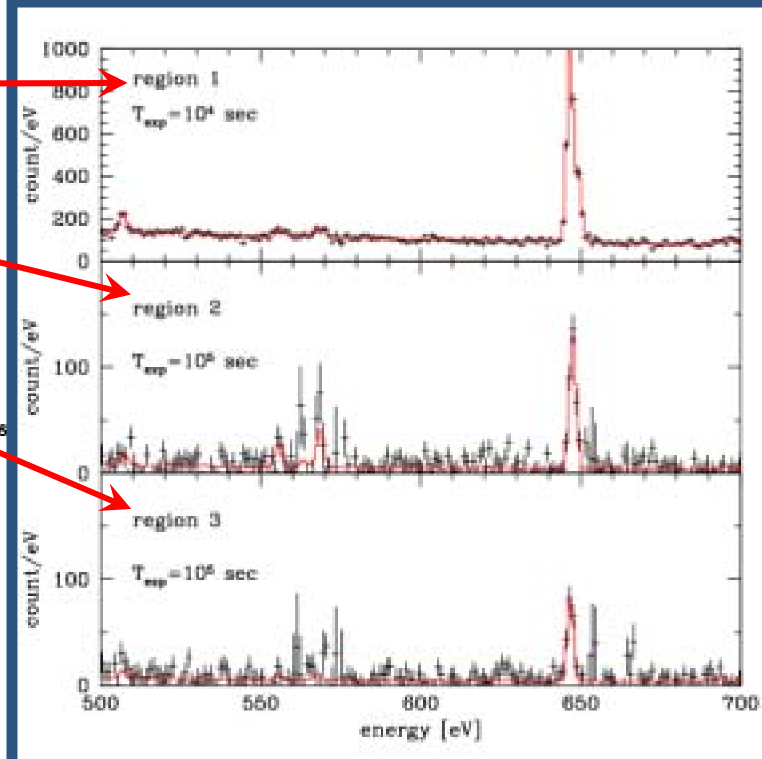


1°×1°FOV

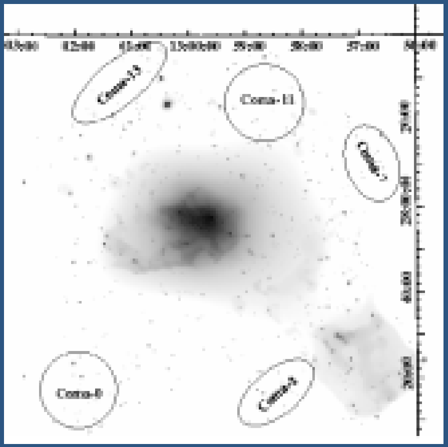
a small clump in front of simulated Coma



～10° (～5h⁻¹Mpc)
away from los
toward Coma

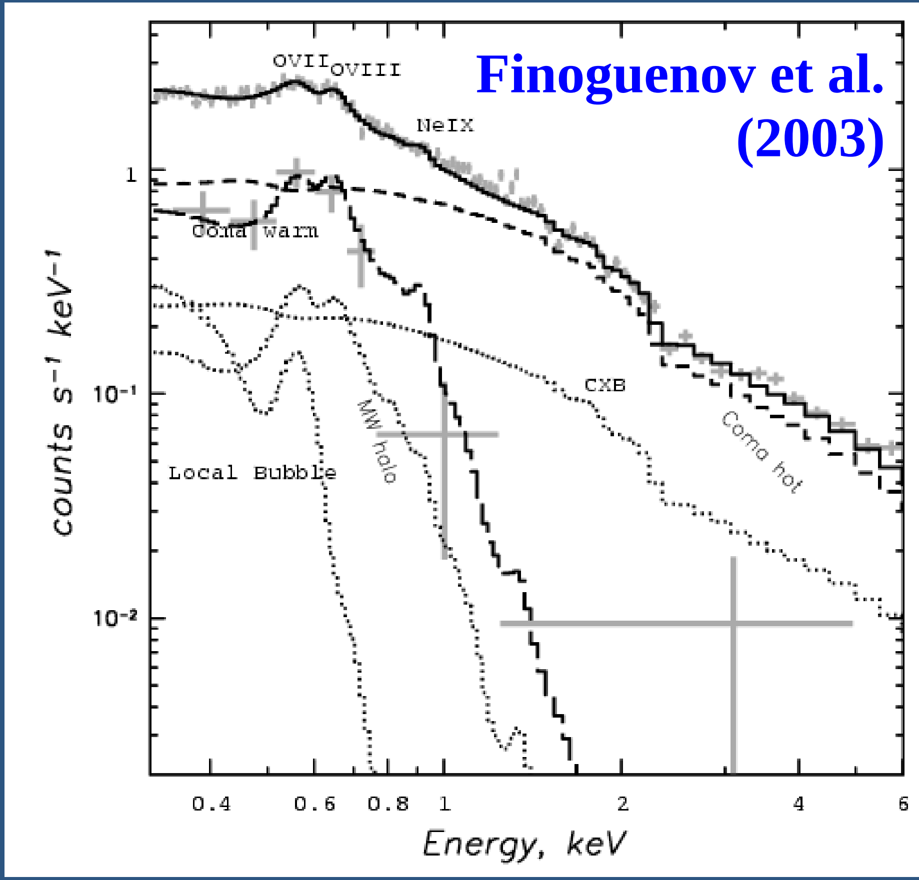


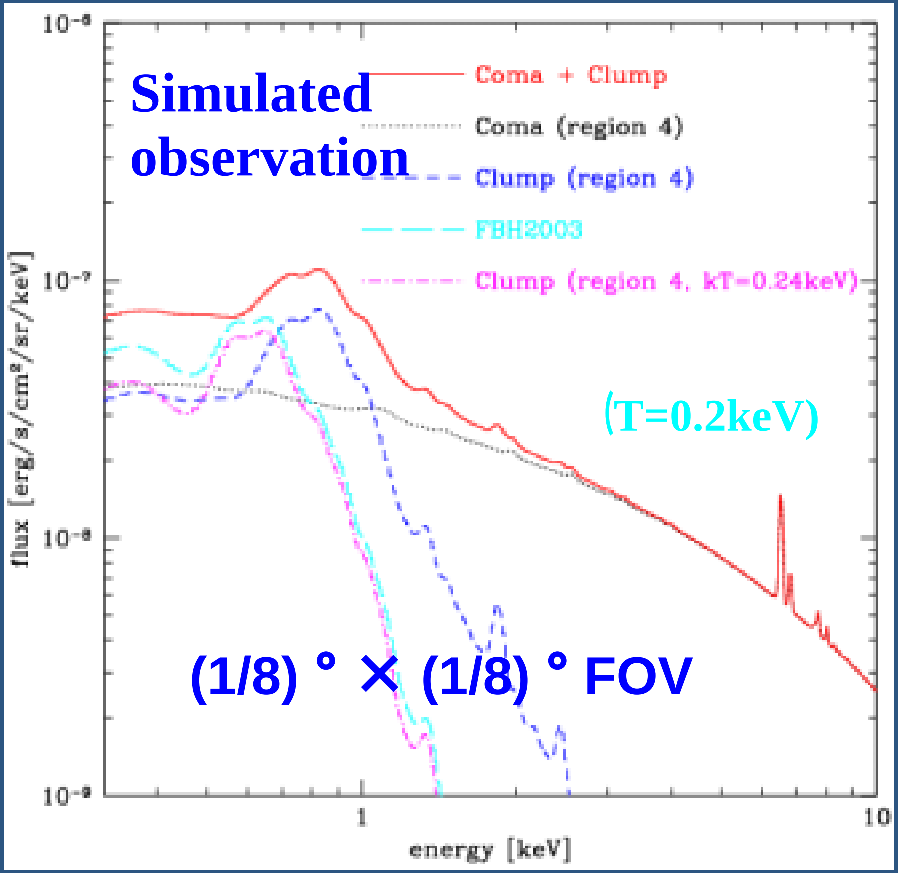
1°×1° FOV



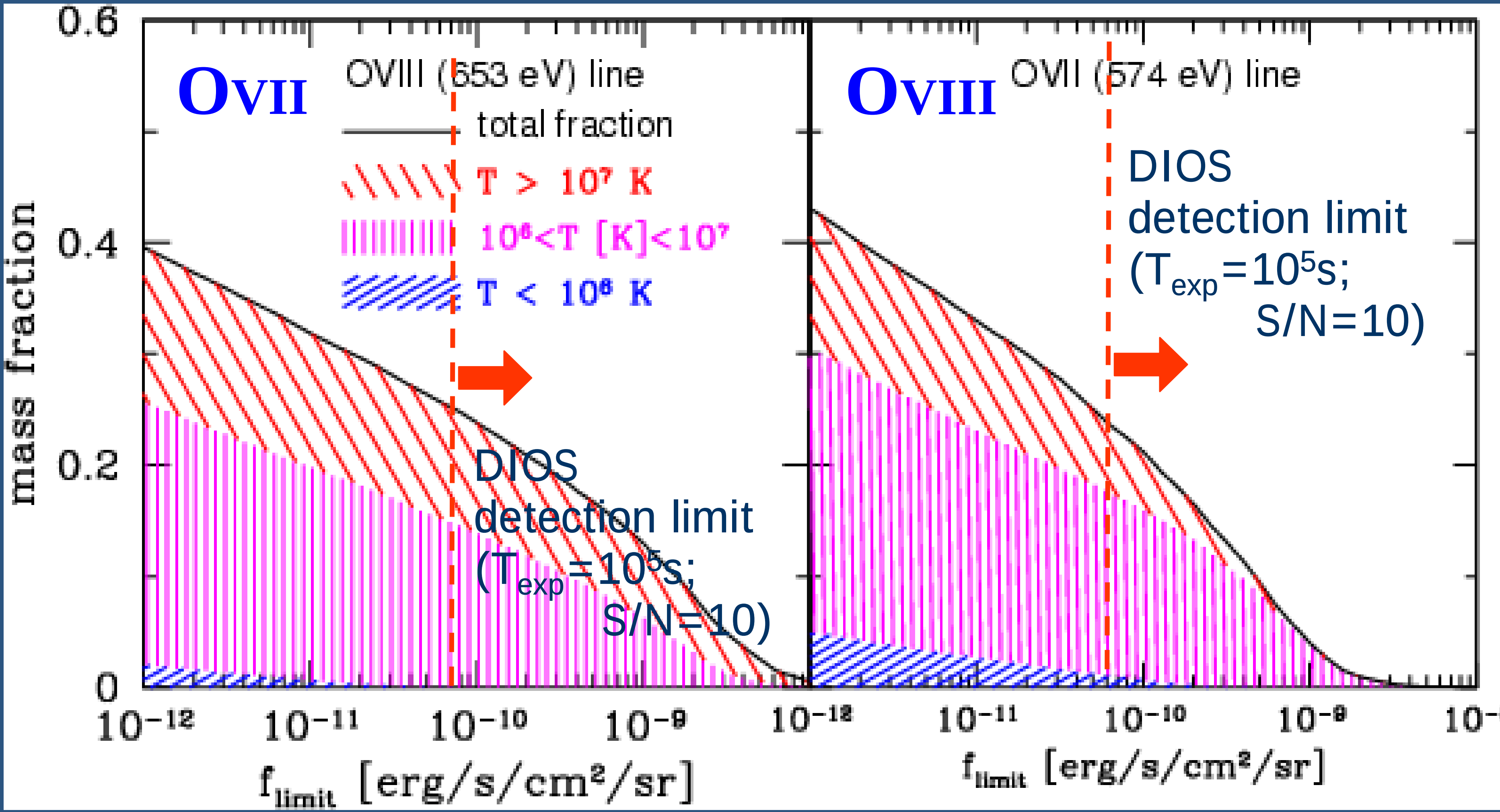
Soft X-ray excess of Coma

- XMM-Newton observations of the outskirts of Coma (Finoguenov, Briel & Henry 2003, A&A 410, 777)
- X-ray filament of 0.2keV warm gas ?

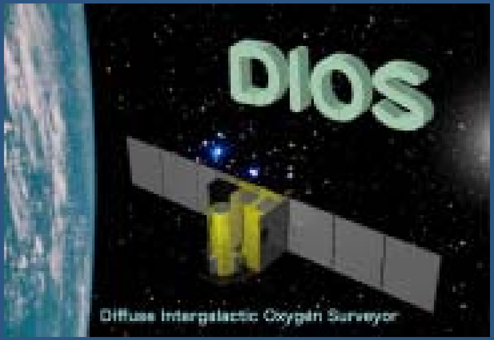




Fraction of cosmic baryons detectable via oxygen emission

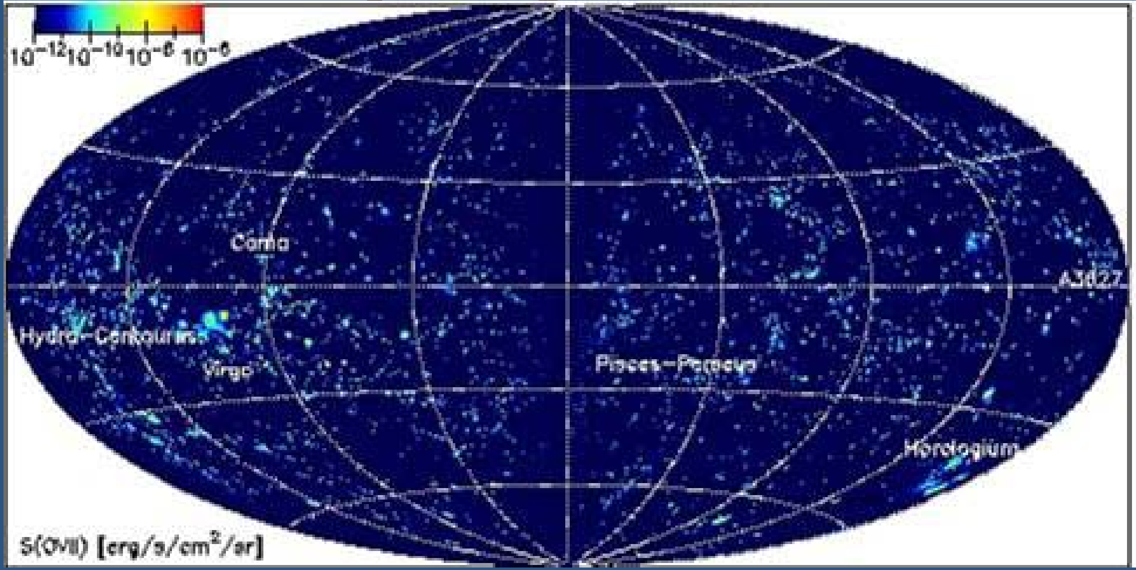


Locating Warm-Hot Intergalactic Medium via Oxygen emission lines



- Mock spectral observations of oxygen emission lines (Yoshikawa et al. 2003, 2004)
- **DIOS will be able to locate ～30 percent of the total cosmic baryons directly**
  - 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/str]
- Things remain to be checked
  - Validity of the collisional ionization equilibrium ?
  - Strategy to quantify the fraction of WHIM; targeted observations vs. blank survey
  - Sciences with DIOS other than WHIM search

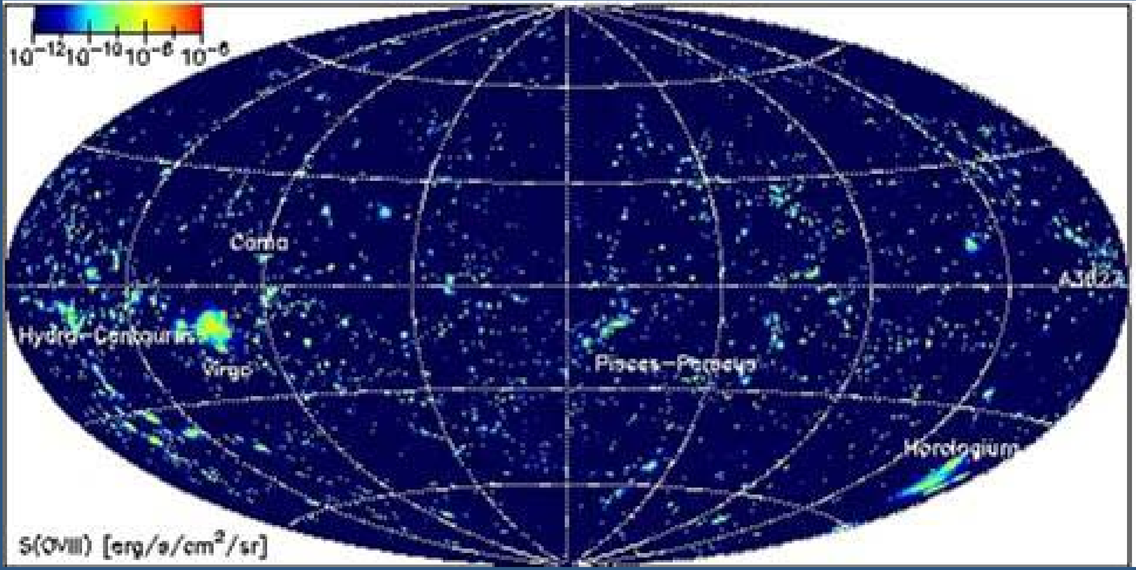
Oxygen emission in supergalactic coordinates



OVII

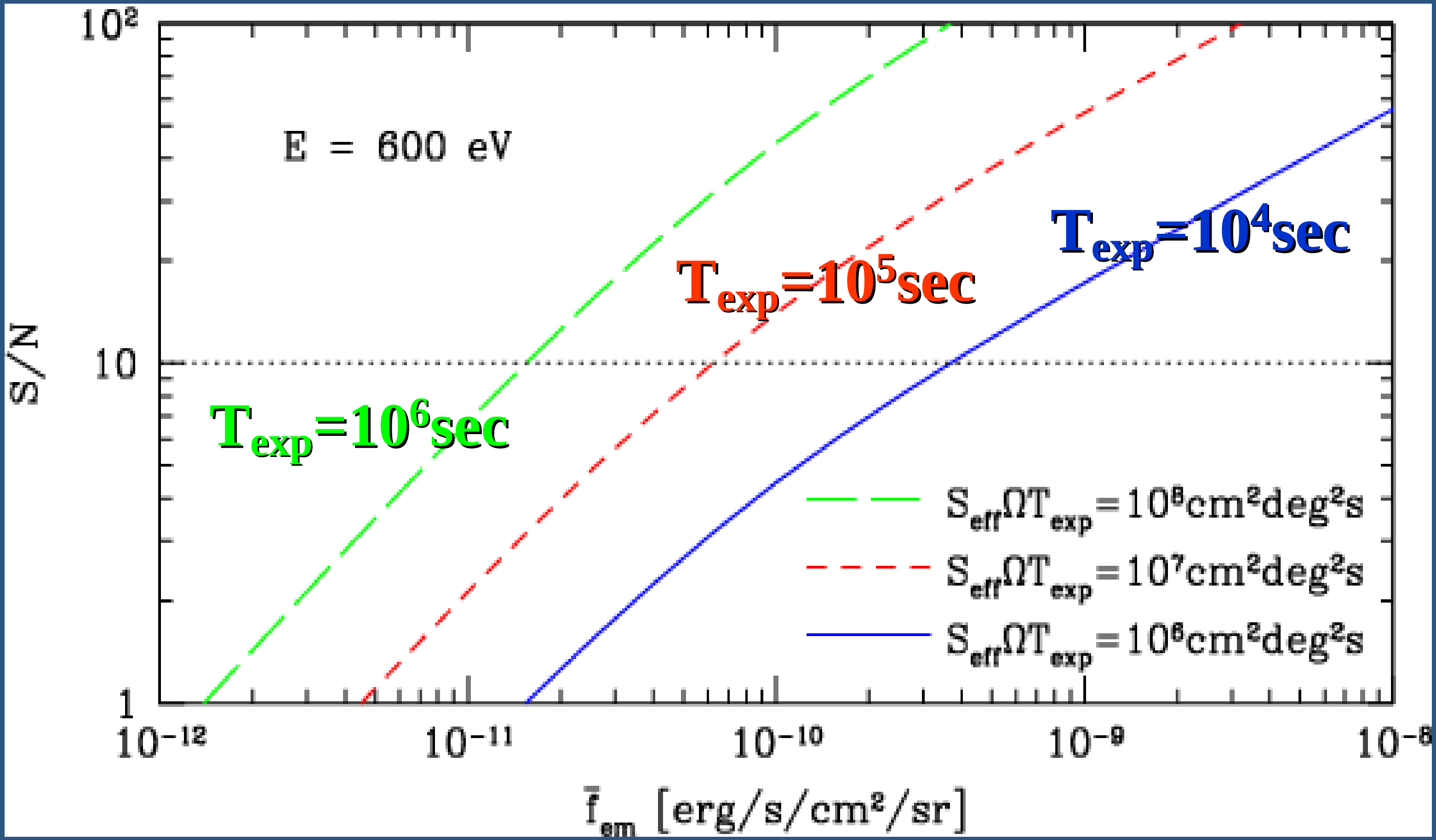
soft X-ray

OVIII



Expected S/N for OVIII line

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



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

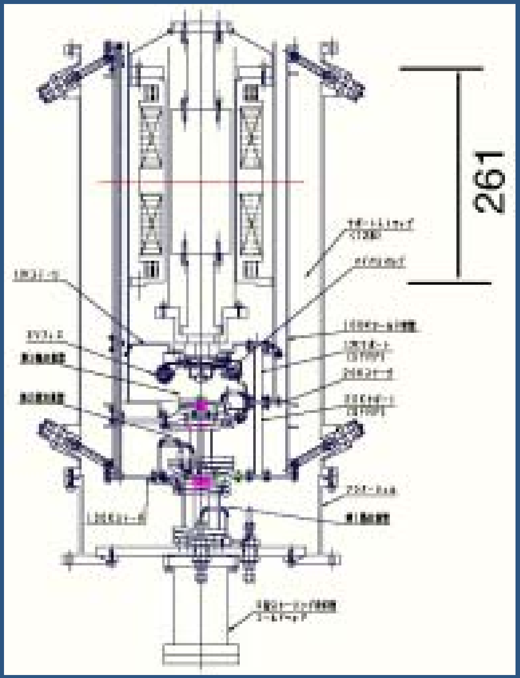
Requirements for detection

- **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)

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

DIOS: instrument summary

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	**0.1 - 1 keV**
Life	**> 5 yr**



Mechanical coolers
+ ADR: < 100 mK

Initial cooling
~ 3 months

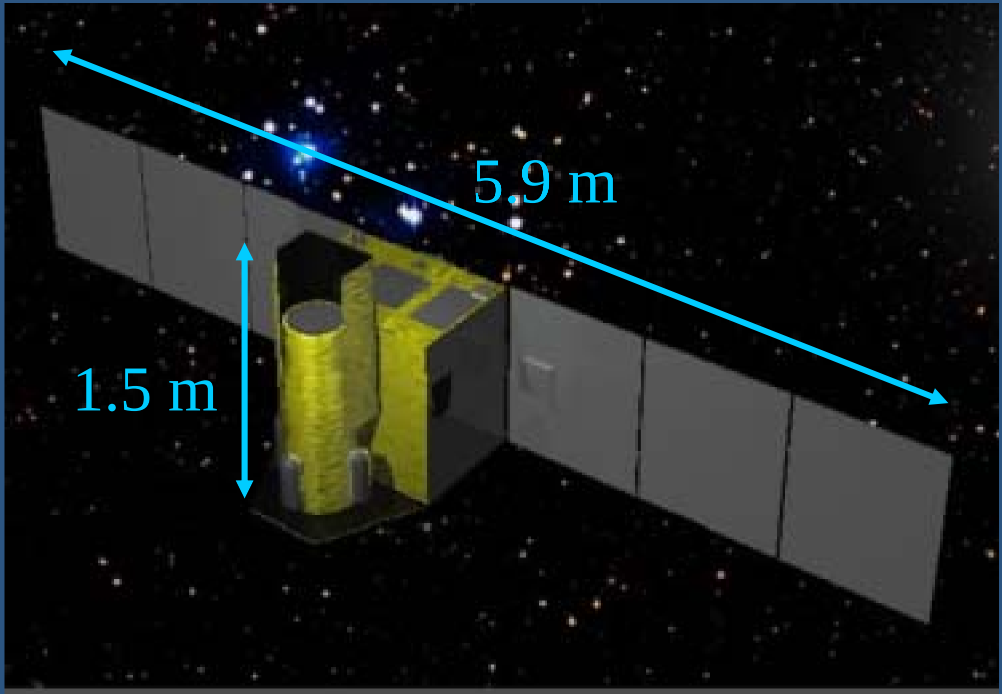
DIOS: spacecraft

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

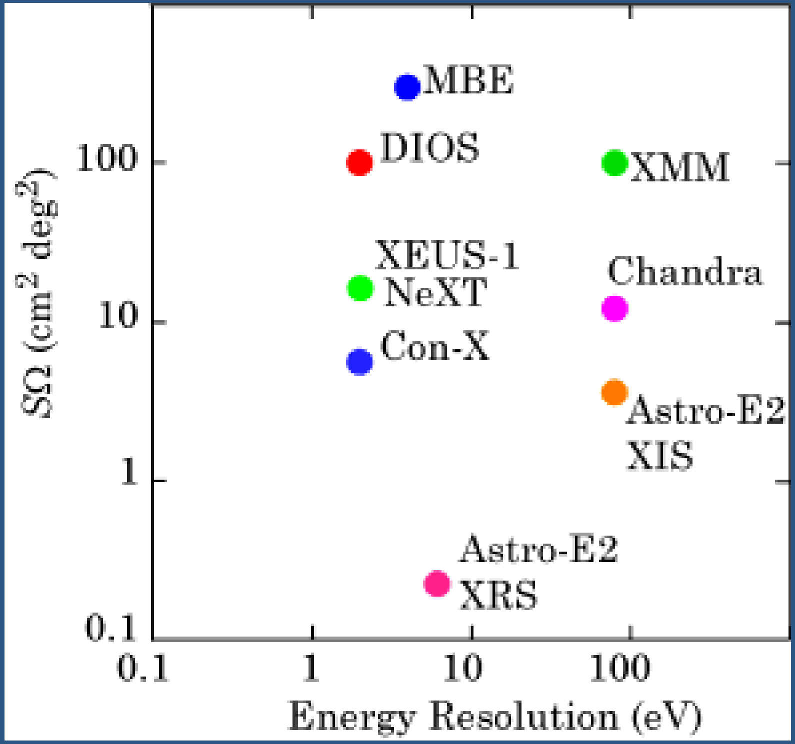
Altitude: ~ 550 km

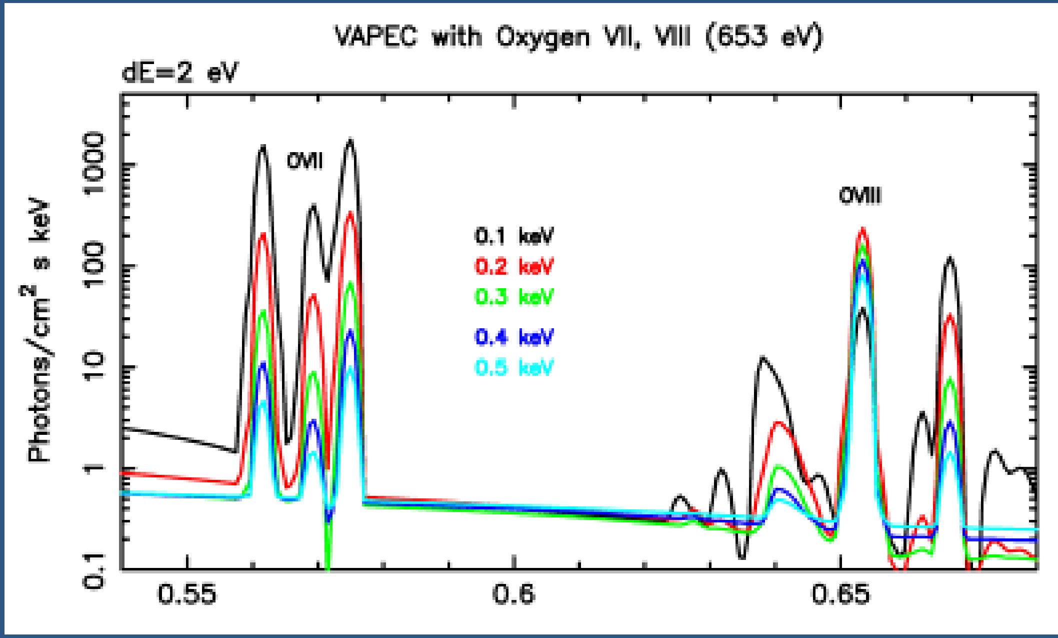
Inclination: 30 °

Rotation period: 95 min



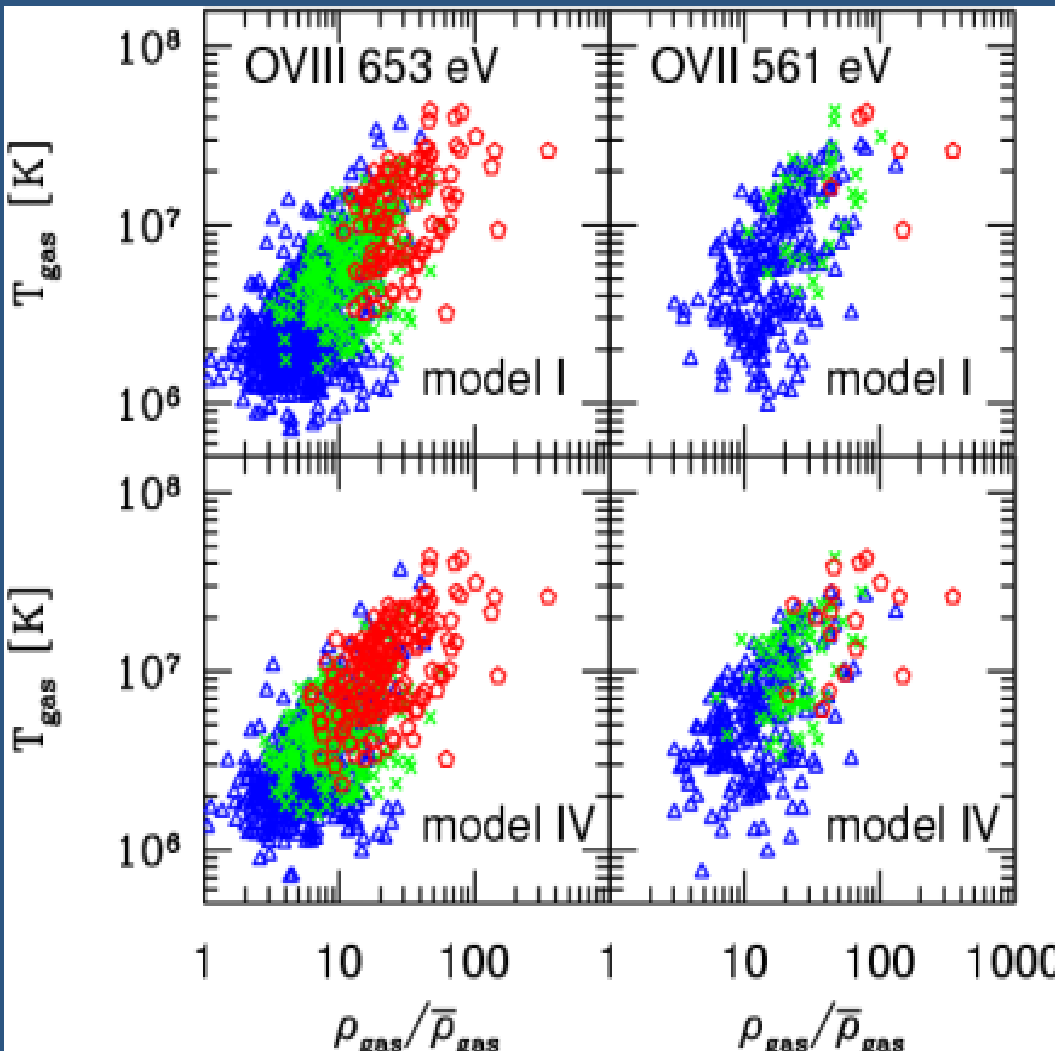
DIOS: comparison with other missions





- 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

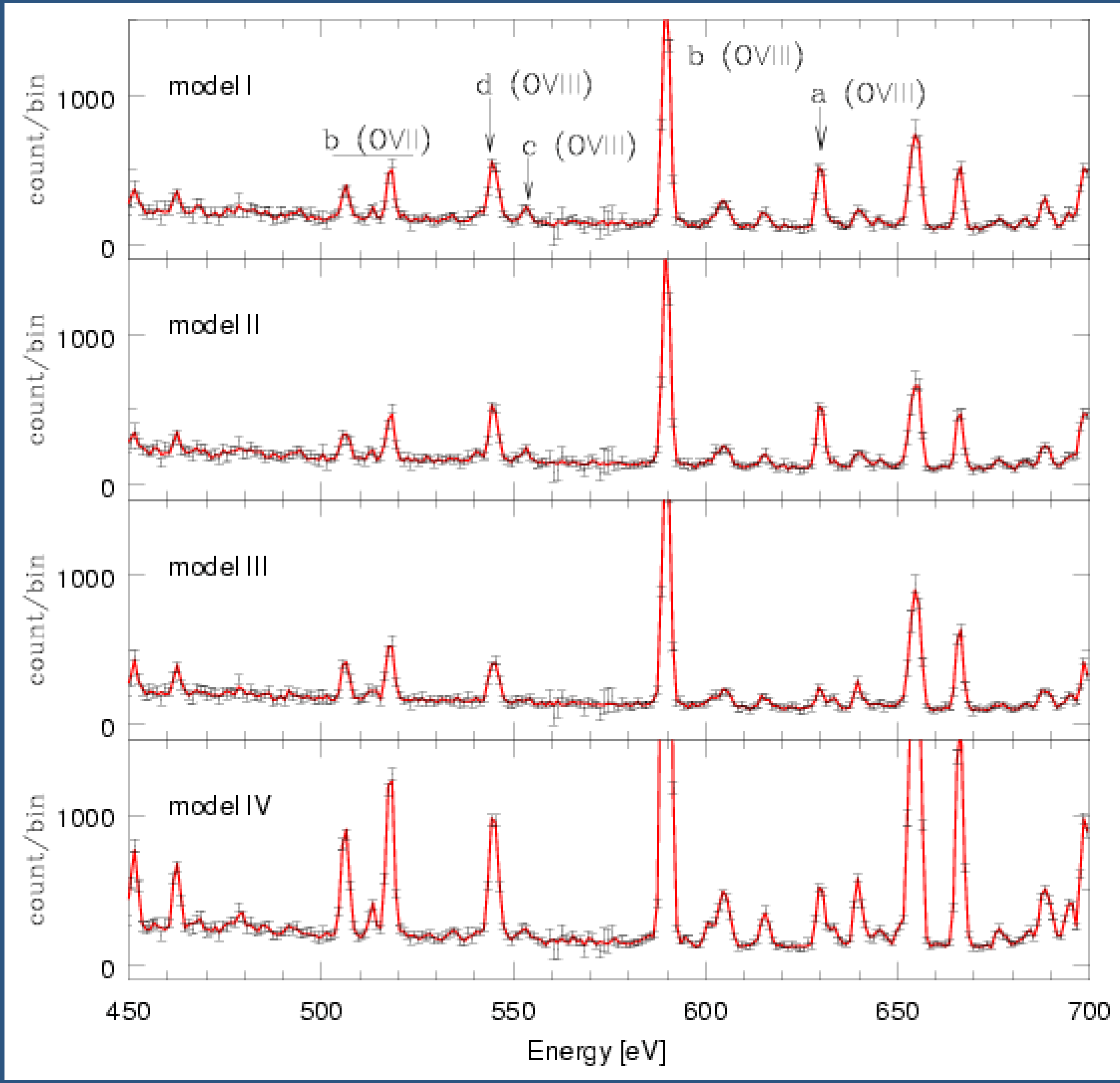
Physical properties of the probed baryons



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)

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