Searching for missing baryons via Oxygen emission lines

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Japan-US Seminar " Cosmology with the Sunyaev-Zel'dovich Effect"

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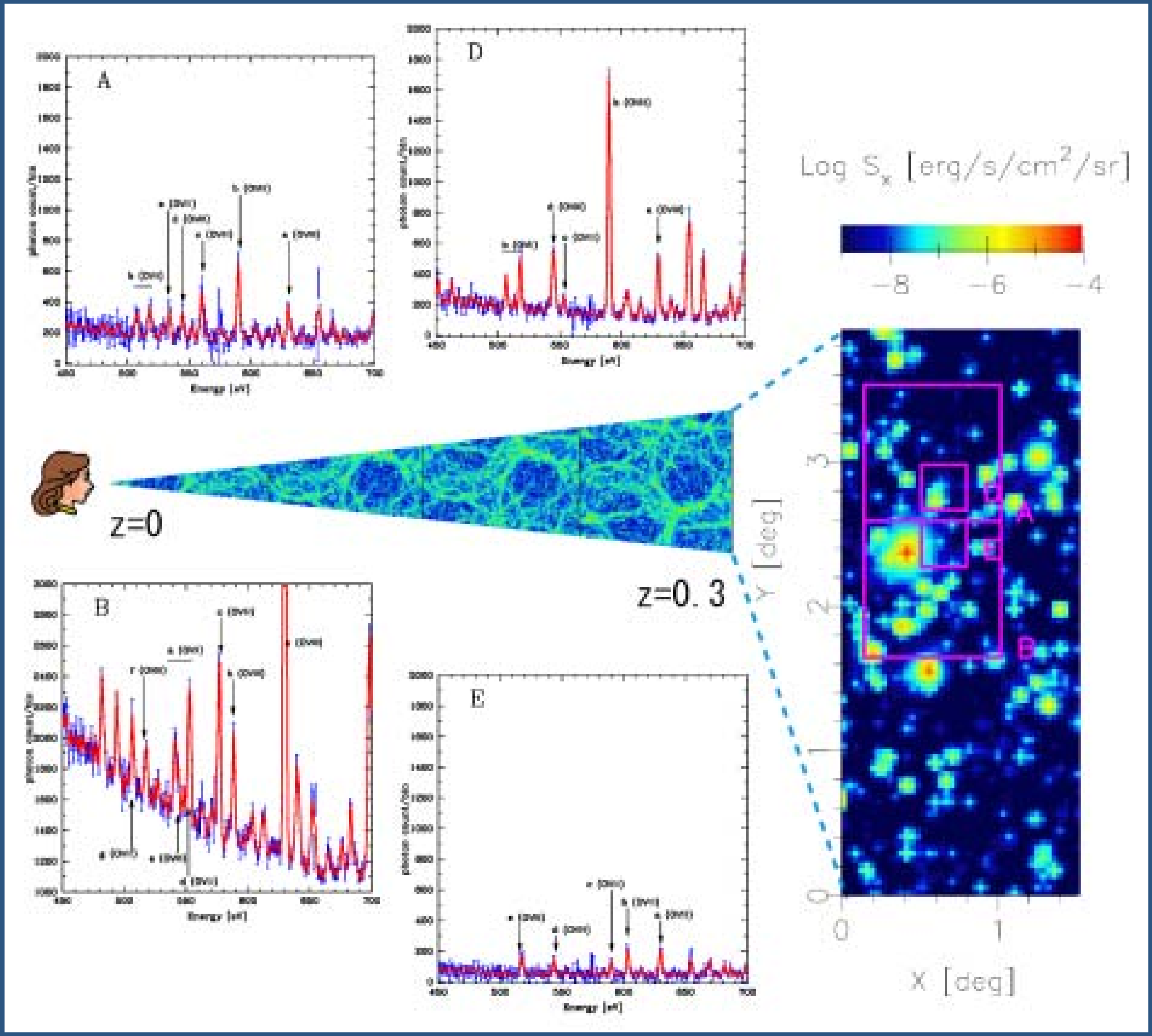
Searching for missing baryons via Oxygen emission lines (astro-ph/0303281)



Collaborators:

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Where are the baryons ?
cosmic baryon budget

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

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	...

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

- The observed baryons in the present universe amount merely to (10～50) **%** of the nucleosynthesis prediction

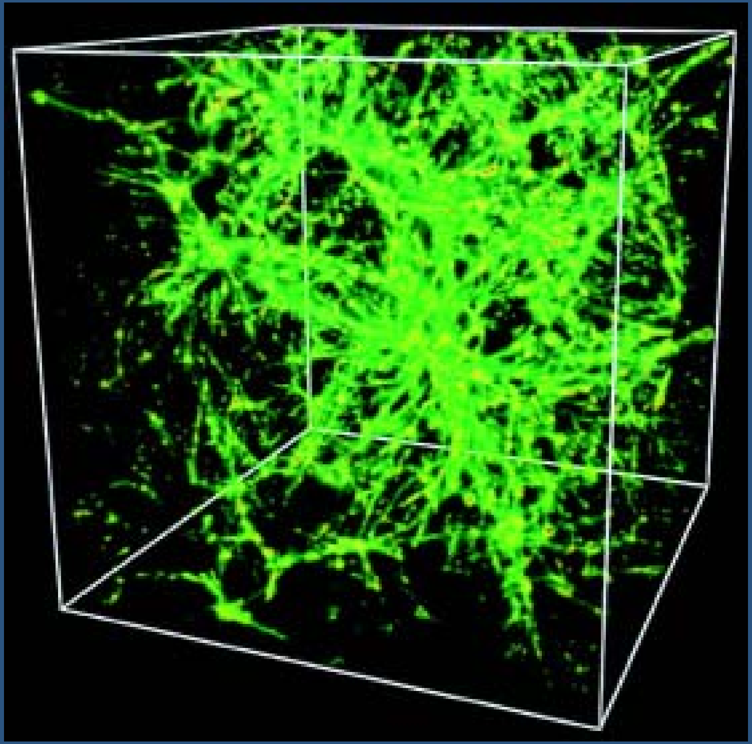
Four phases of cosmic baryons

Dave et al. ApJ 552(2001) 473

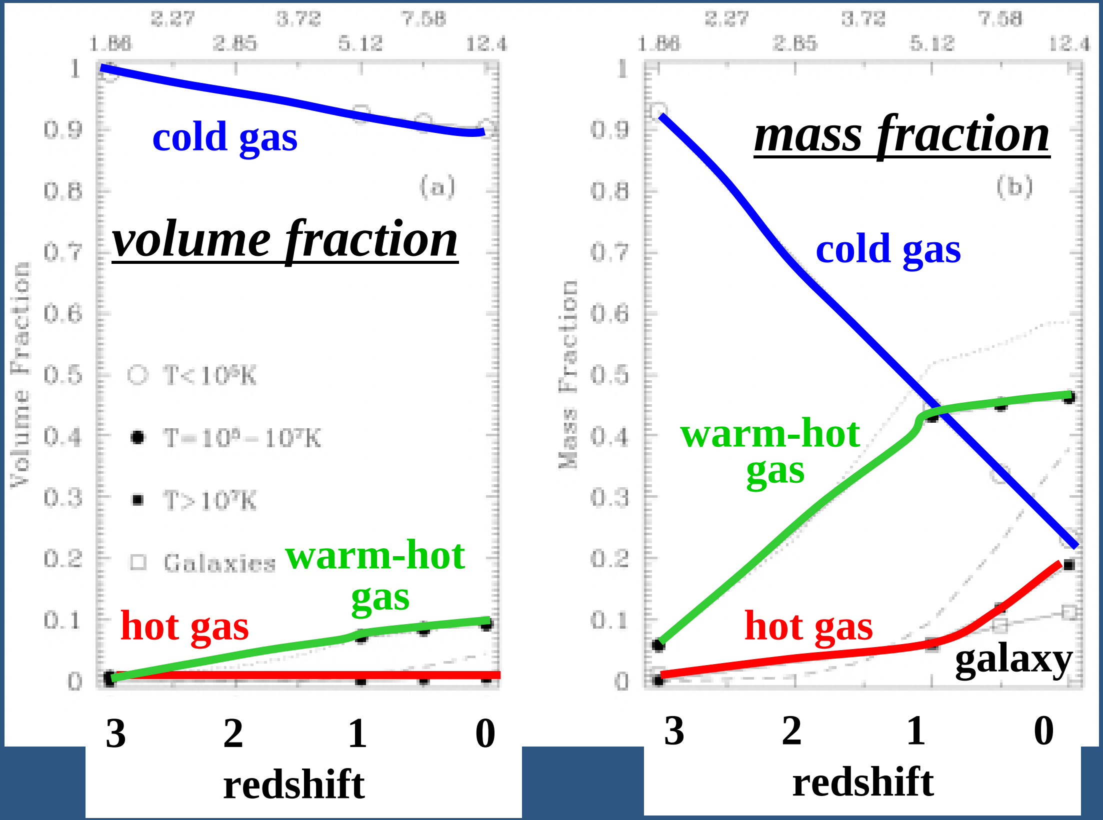
- ***Condensed:*** **δ >1000, $T<10^5$K**
  - Stars + cold intergalactic gas
- ***Diffuse:*** **δ <1000, $T<10^5$K**
  - Photo-ionized intergalactic medium
  - Ly α absorption line systems
- ***Hot:*** **$T>10^7$K**
  - X-ray emitting hot intra-cluster gas
- ***Warm-hot:*** **$10^5K<T<10^7$K**
  - Warm-hot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

Where are the baryons ?

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

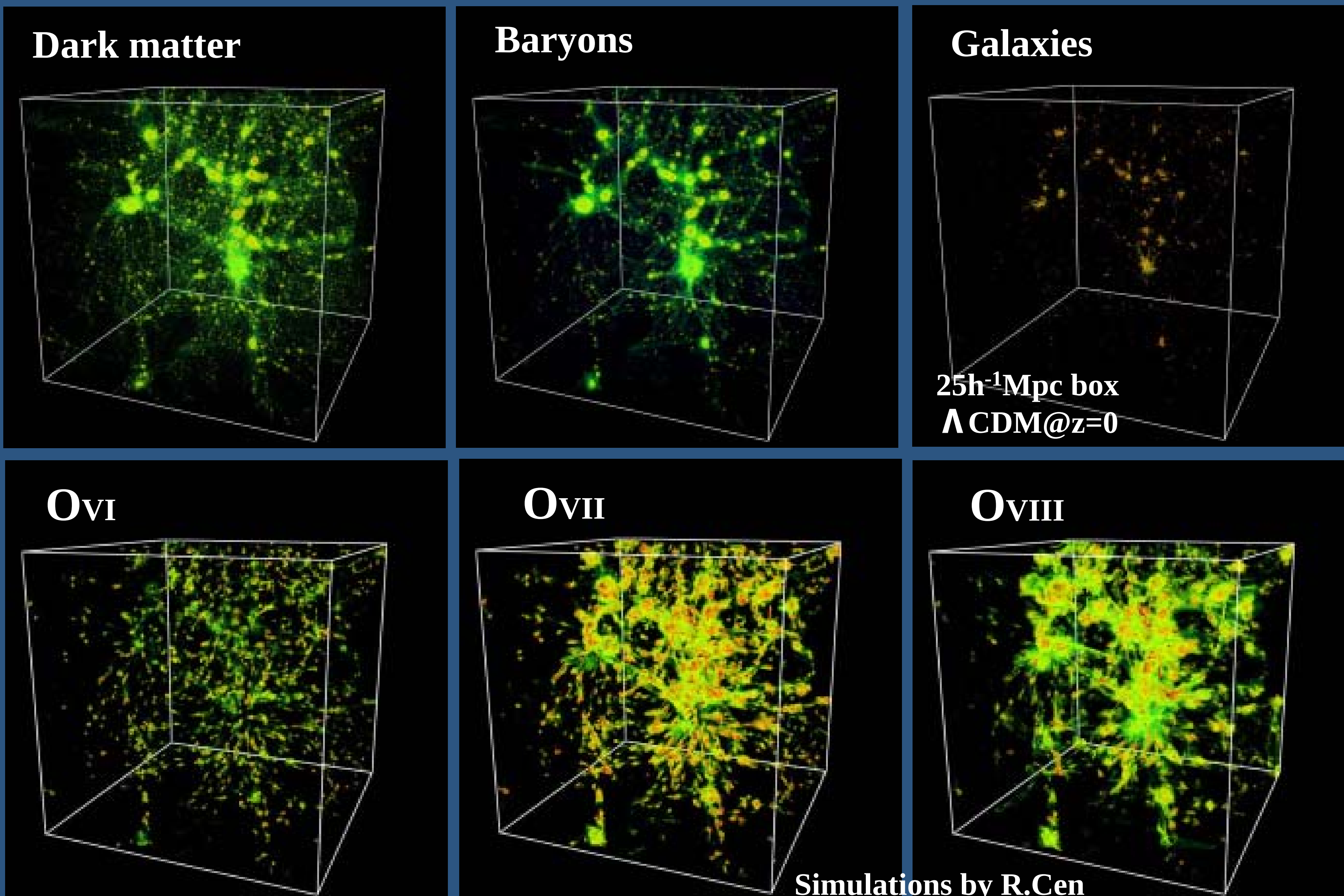


Warm/hot gas
(10^5K<T<10^7K)

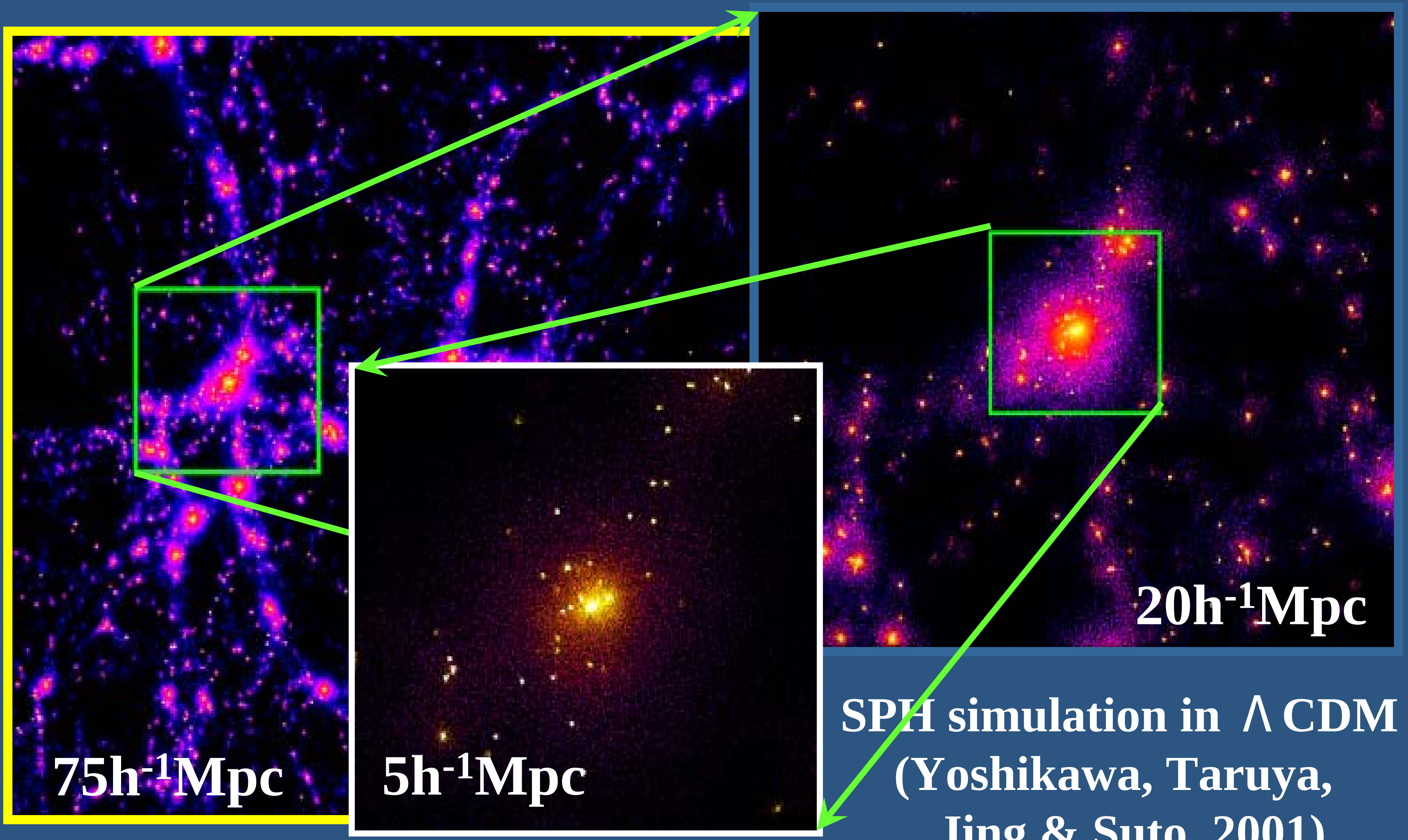


Cen & Ostriker：ApJ 514 (1999) 1

Tracing the structure with Oxygen



SPH simulation: zoom-up



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

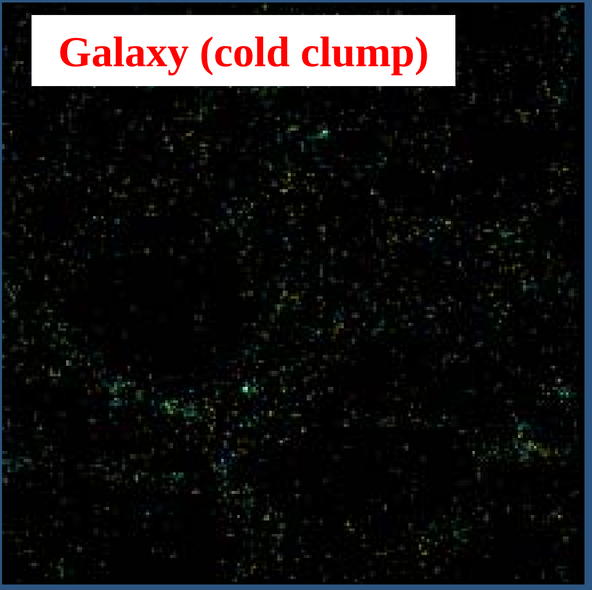
SPH simulation: movie

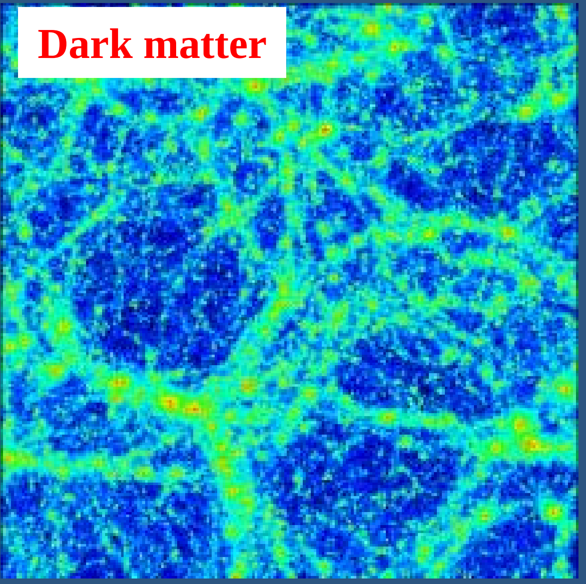
SPH simulation in ΛCDM : dark matter $\Rightarrow$ hot gas $\Rightarrow$ galaxy
(Yoshikawa, Taruya, Jing & Suto 2001)

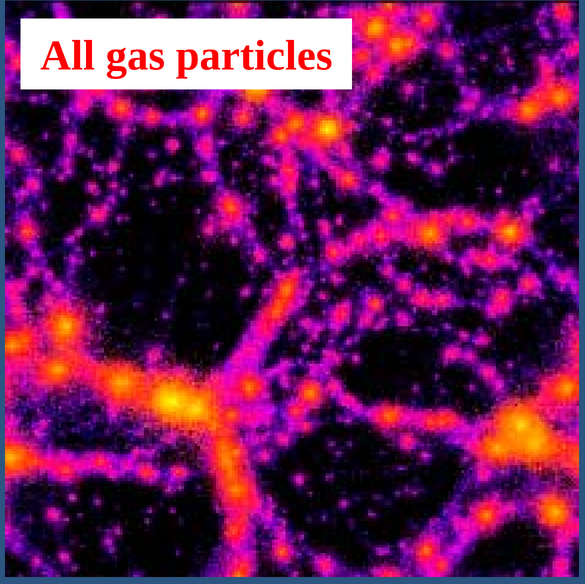
Large-scale structure in SPH simulation

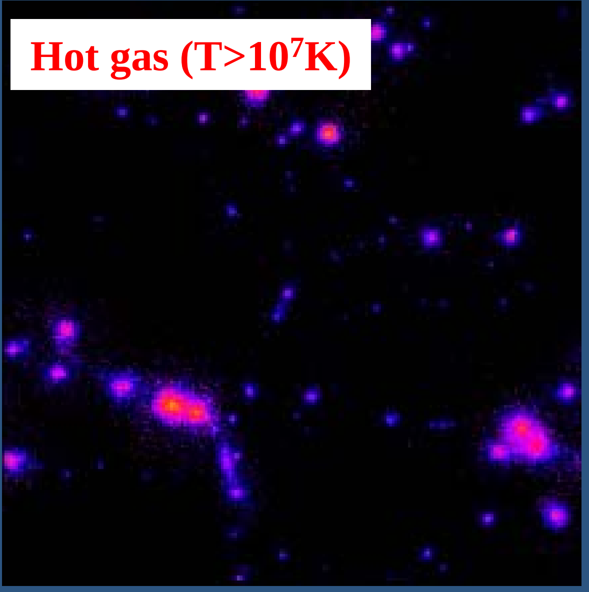
$(75h^{-1}\mathrm{Mpc})^3$ box
ΛCDM @ $z=0$
$N=128^3$:DM particles
$N=128^3$:gas particles

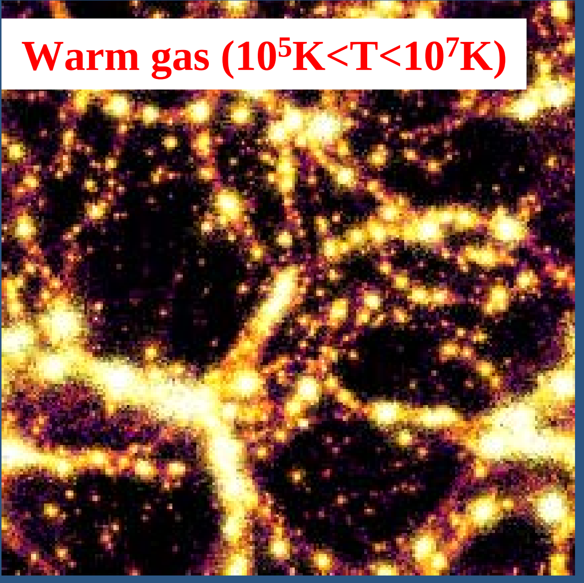
(Yoshikawa et al. 2001)







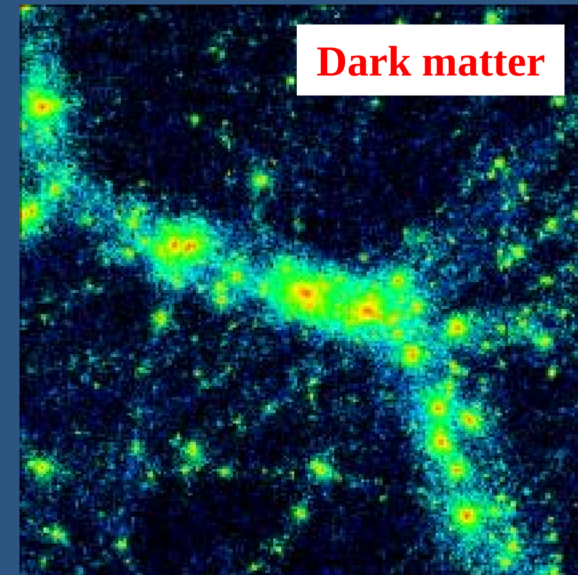


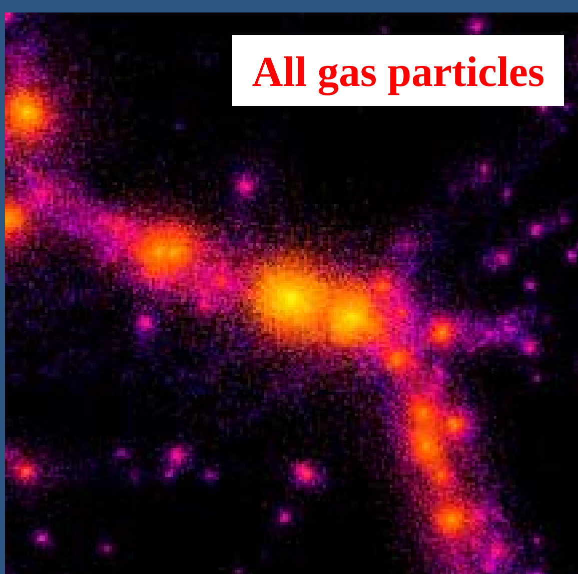


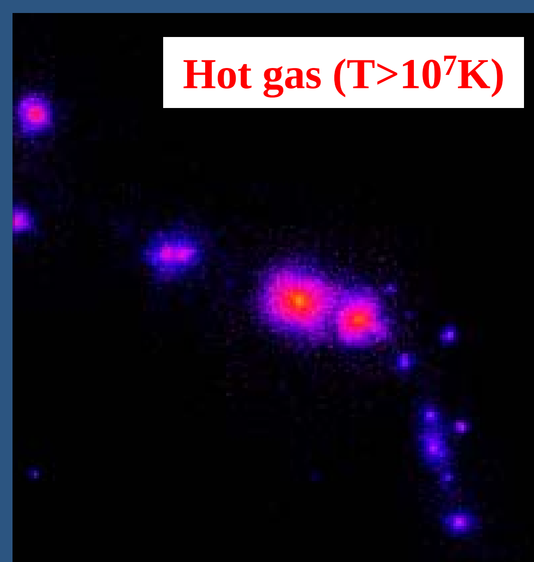
A cluster region in SPH simulation

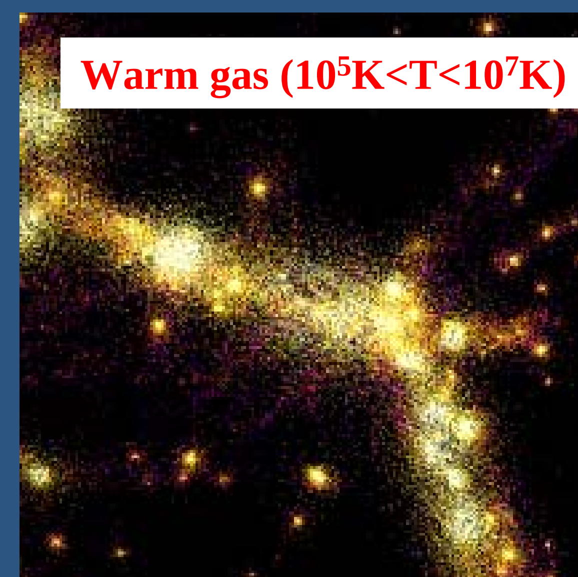
A $(30h^{-1}\mathrm{Mpc})^3$ box around a massive cluster at z=0 ΛCDM SPH simulation

(Yoshikawa et al. 2001)







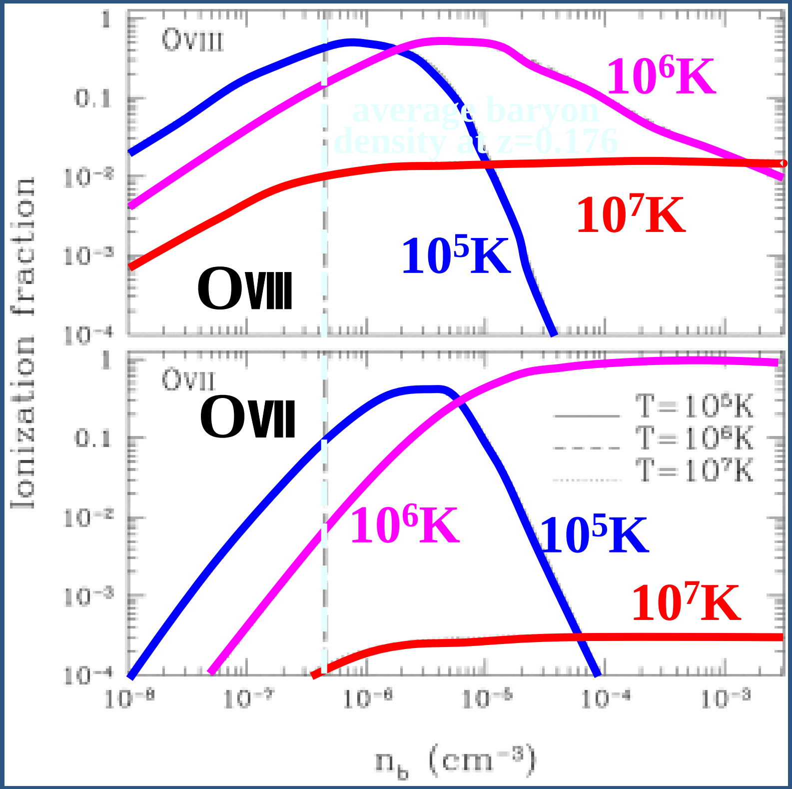


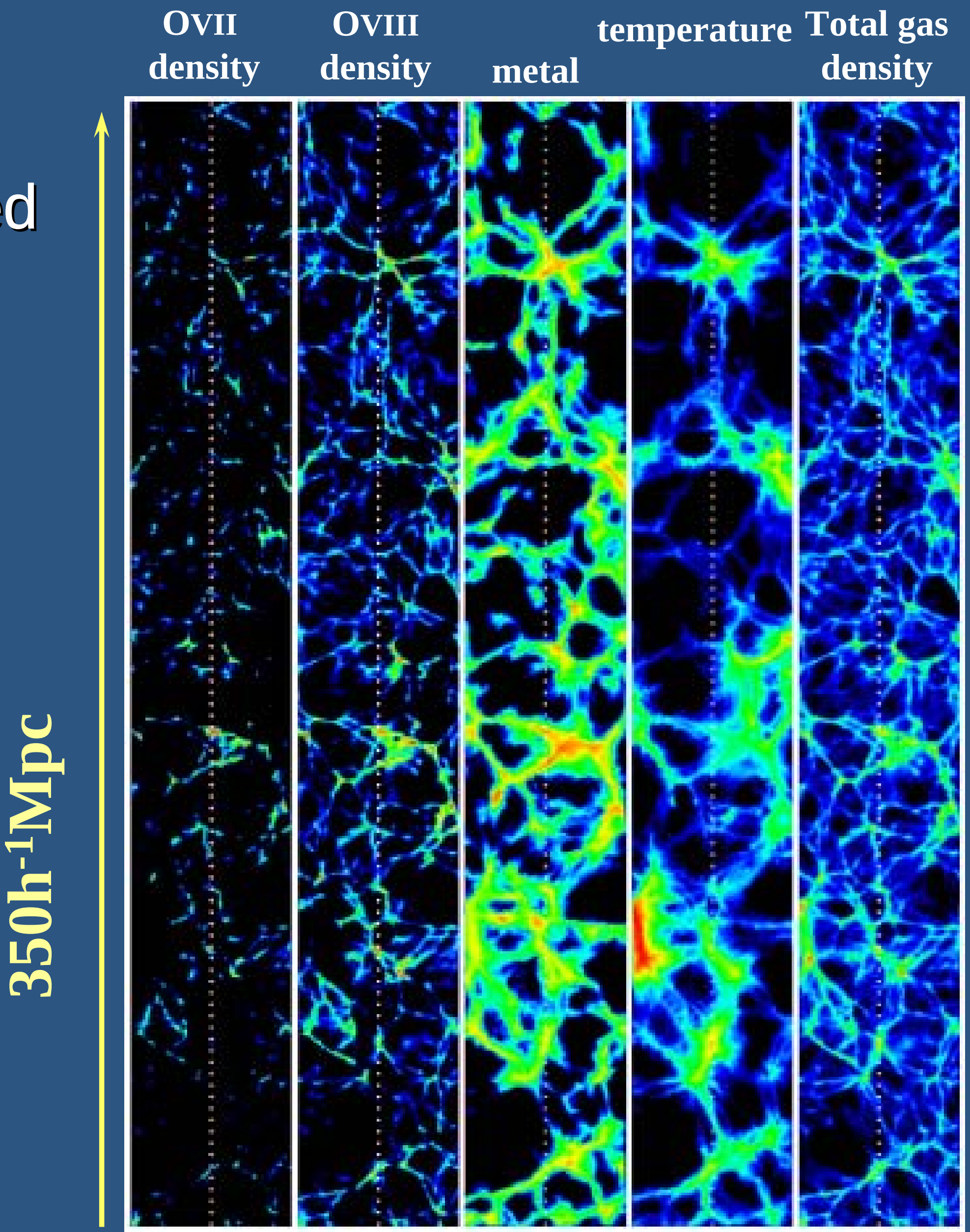
WHIM as cosmic missing baryons

- ~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

X-ray forests

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

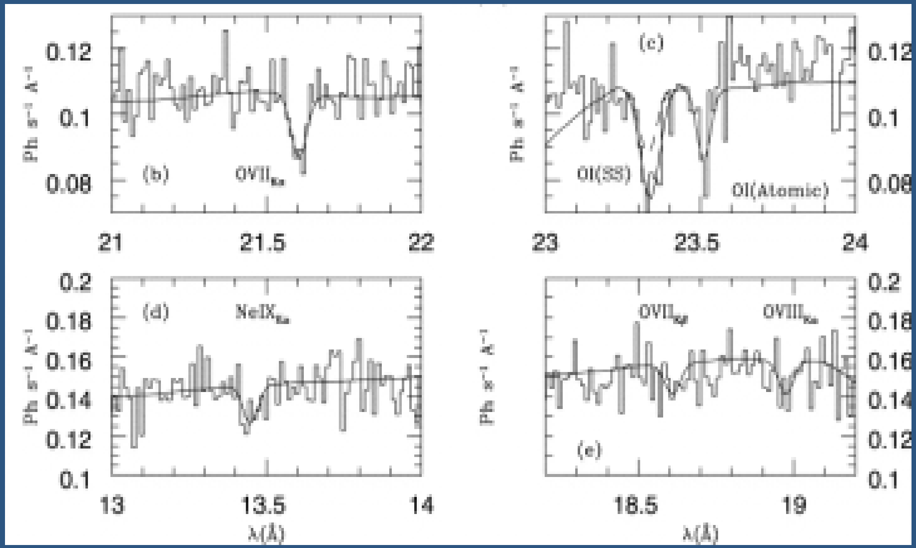




Hellsten et al. ApJ 509(1998)56

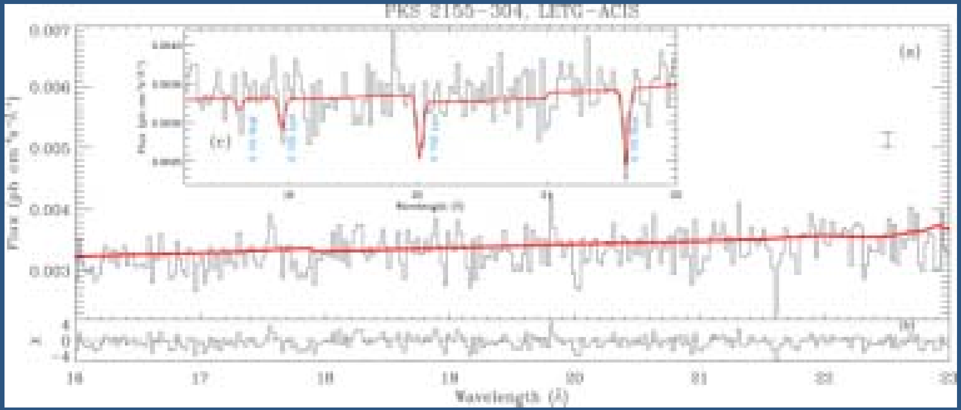
X-ray forests: shadow of WHIM

Absoption line systems of OVI, OVII, and OVIII
in the X-ray continuum spectrum 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

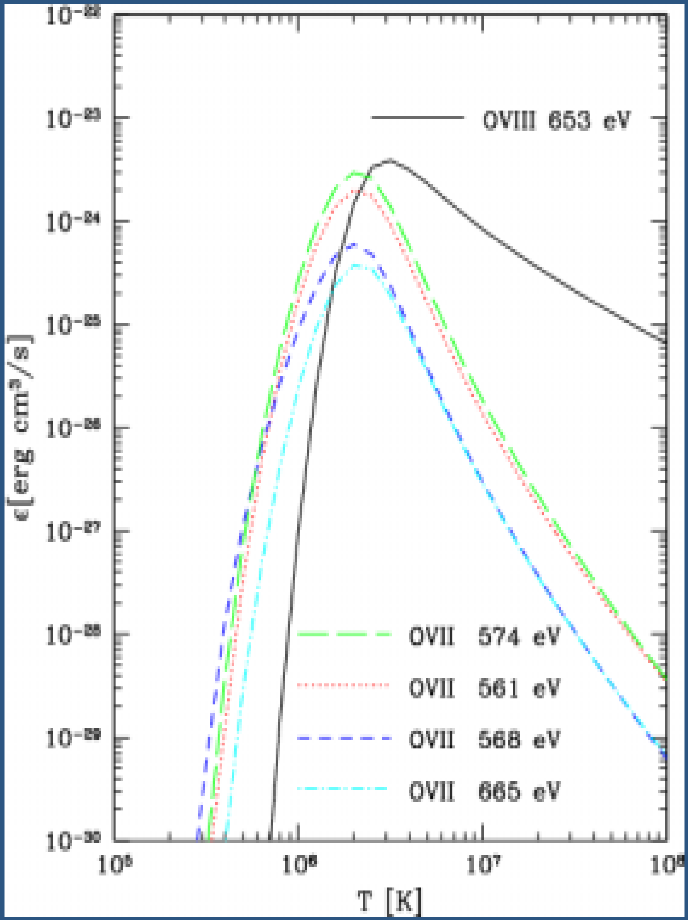
δ=50~350, T=10^6K,
L_{size}~8Mpc, z~0.06

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***



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

Metallicity models

Oxygen enrichment scenario in IGM

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

Metallicity of WHIM is currently poorly known.

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)

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

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

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

Requirements for detection

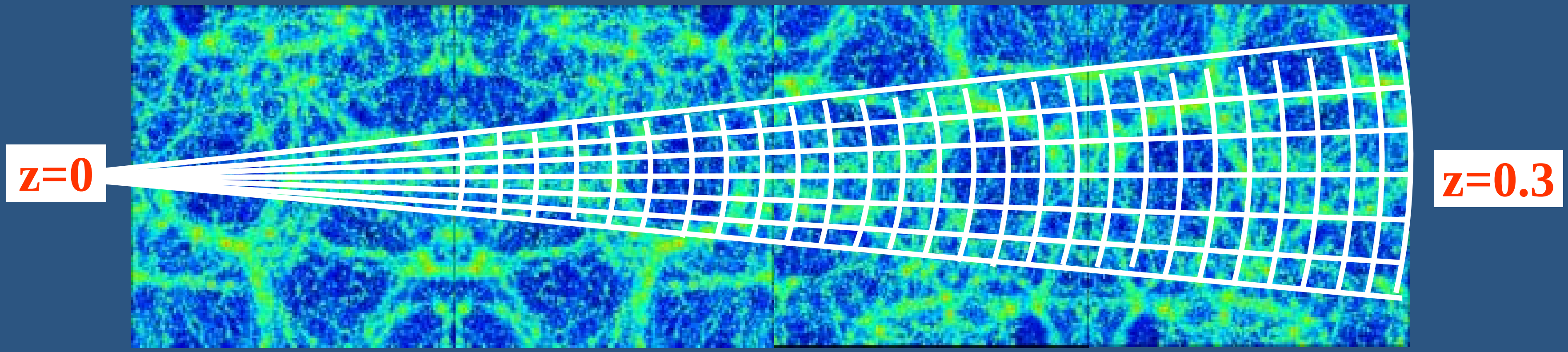
- Good energy resolution to identify the emission lines from WHIM at different redshifts
  - $\Delta E < 5$eV $\Rightarrow$ X-ray calorimeter using superconducting TES (Transition Edge Sensor)
- Large field-of-view and effective area for survey
  - $S_{eff} = 100\mathrm{cm}^2$, $\Omega = 1\mathrm{deg}^2$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

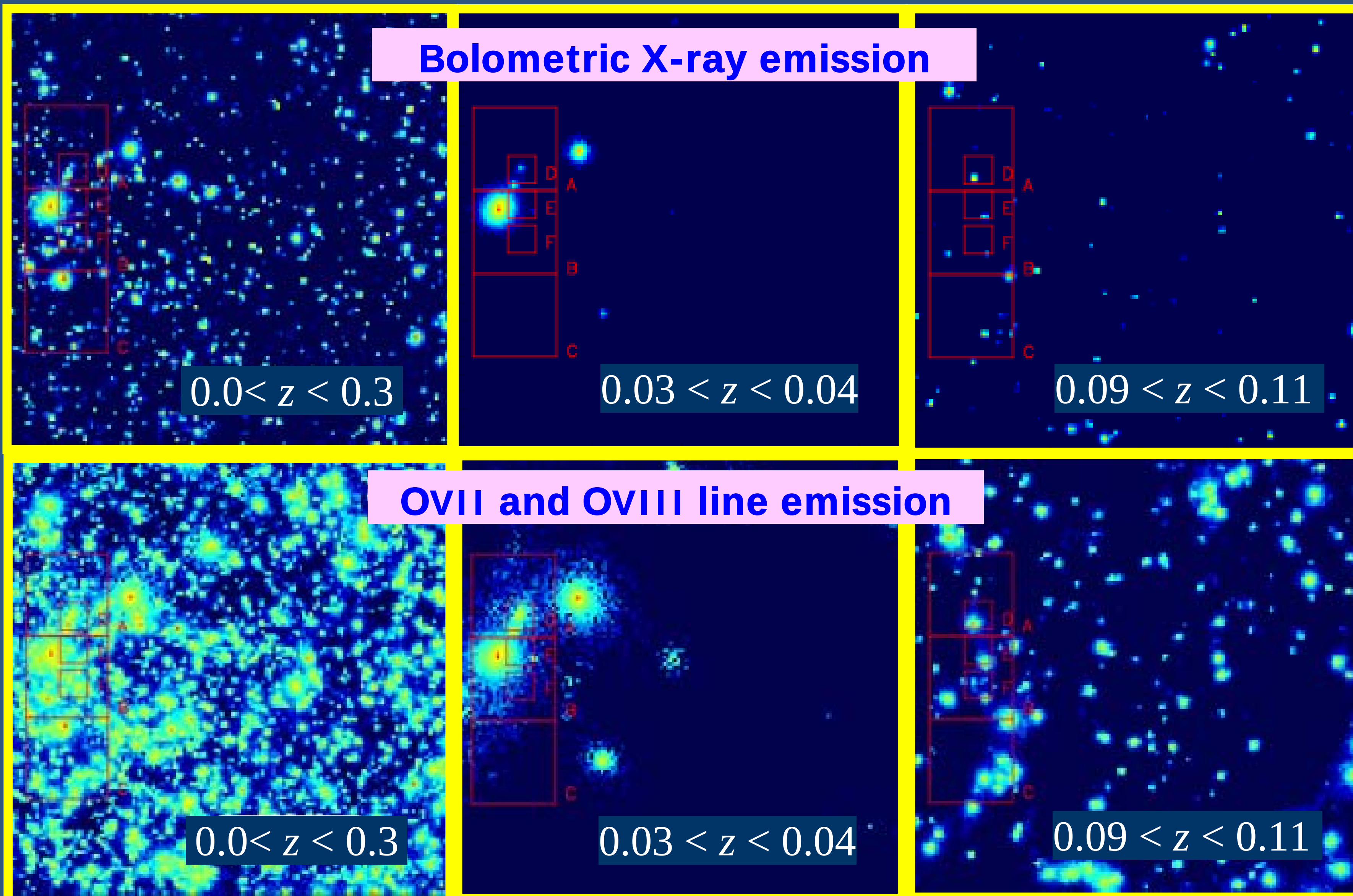
	$S_{eff}\Omega$ [cm^2 deg^2]	ΔE [eV]	f_{limit} [$erg/s/cm^2/sr$]
Chandra ACIS-S3	12	80	10^{-9}
XMM-Newton EPIC-pn	100	80	$3x10^{-10}$
Astro-E II XRS	0.23	6	$2x10^{-8}$
Astro-E II XIS	36	80	$6x10^{-10}$
XEUS-I	16.7	2	$2.5x10^{-10}$
our proposed detector	**100**	**2**	**$6x10^{-11}$**

Light-cone output from simulation

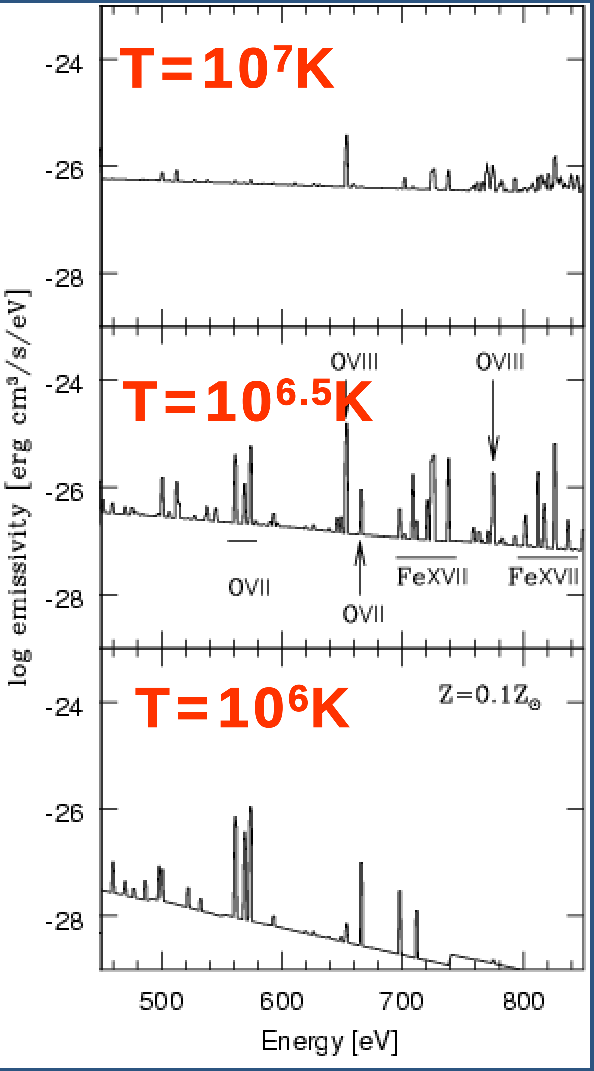


- Cosmological SPH simulation in Ω_m=0.3, Ω_Λ=0.7, σ_8=1.0, and h=0.7 CDM with N=128^3 each for DM and gas (Yoshikawa, Taruya, Jing, & Suto 2001)
- Light-cone output from z=0.3 to z=0 by stacking 11 simulation cubes of $(75h^{-1}Mpc)^3$ at different z
- 5°×5° FOV mock data in 64x64 grids on the sky
-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

Surface brightness



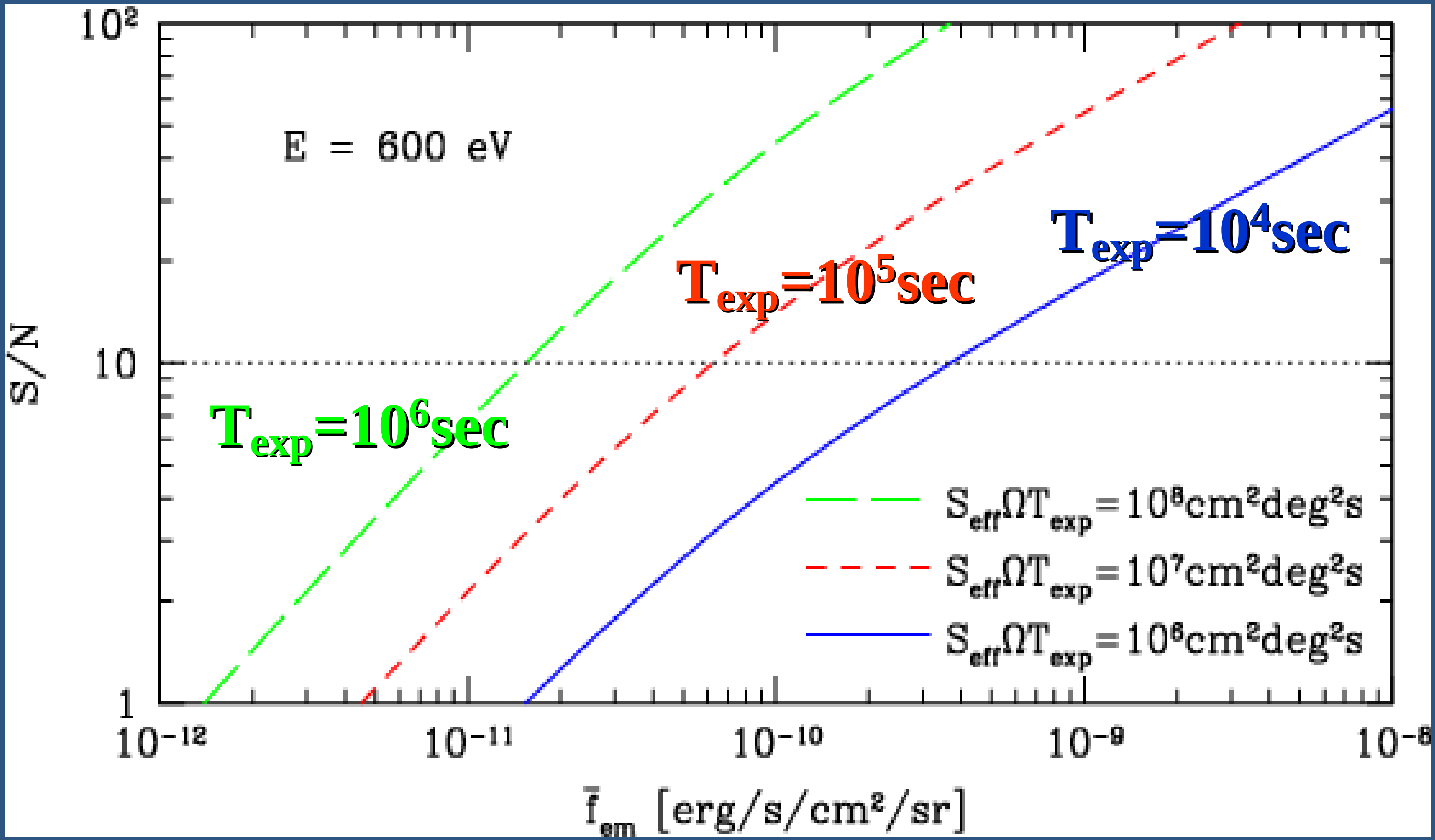
Creating Mock spectra from light-cone output



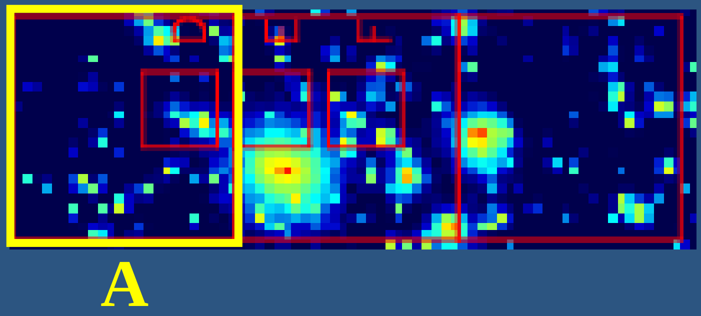
- For a given exposure time,
  - convolve the emissivity according to gas density and temperature in $(5°/64)^2$ pixels over the lightcone
  - Add the Galactic line emission (McCammon et al. 2002)
  - Add the cosmic X-ray background contribution (power-law+Poisson noise)
- Then statistically subtract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

Expected S/N for OVIII line

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

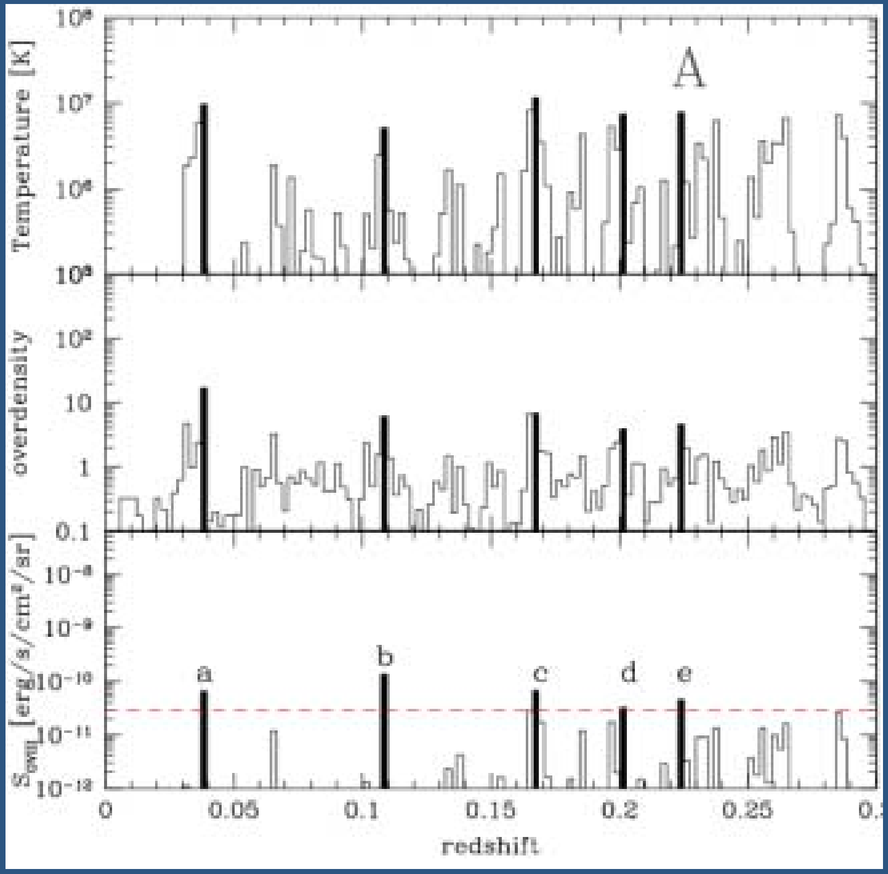


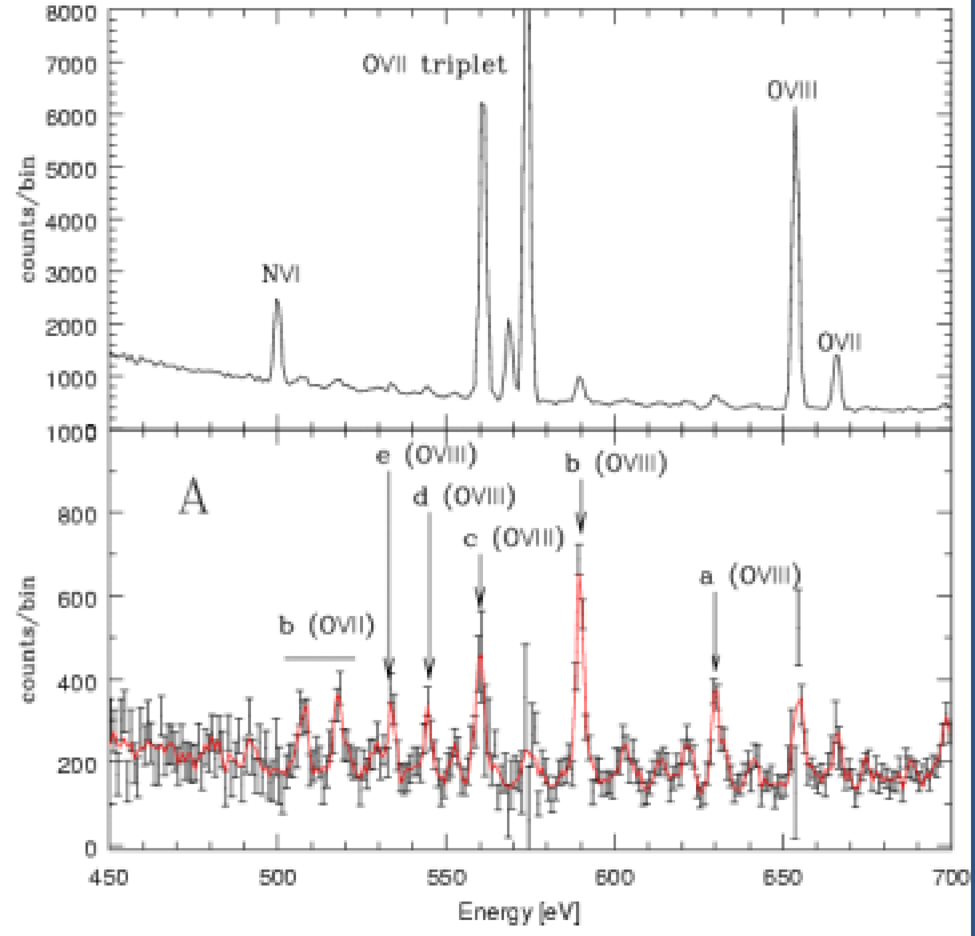
Simulated spectra: region A



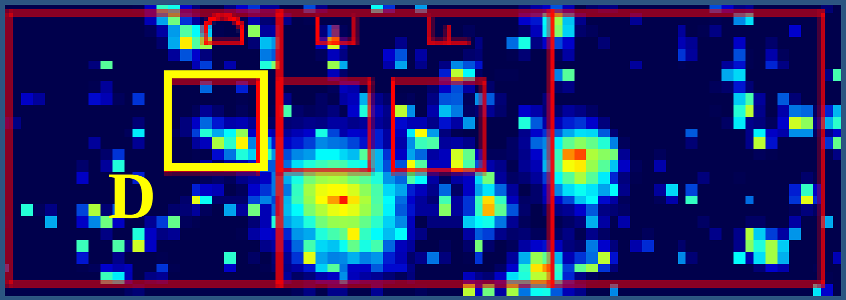
12x12 pixels (0.88 deg^2)

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

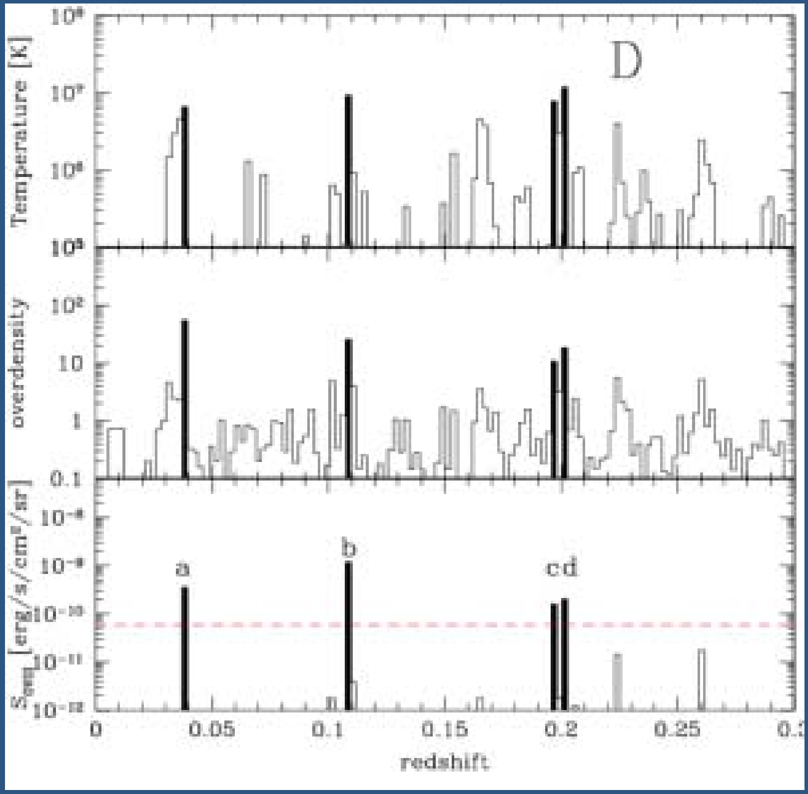


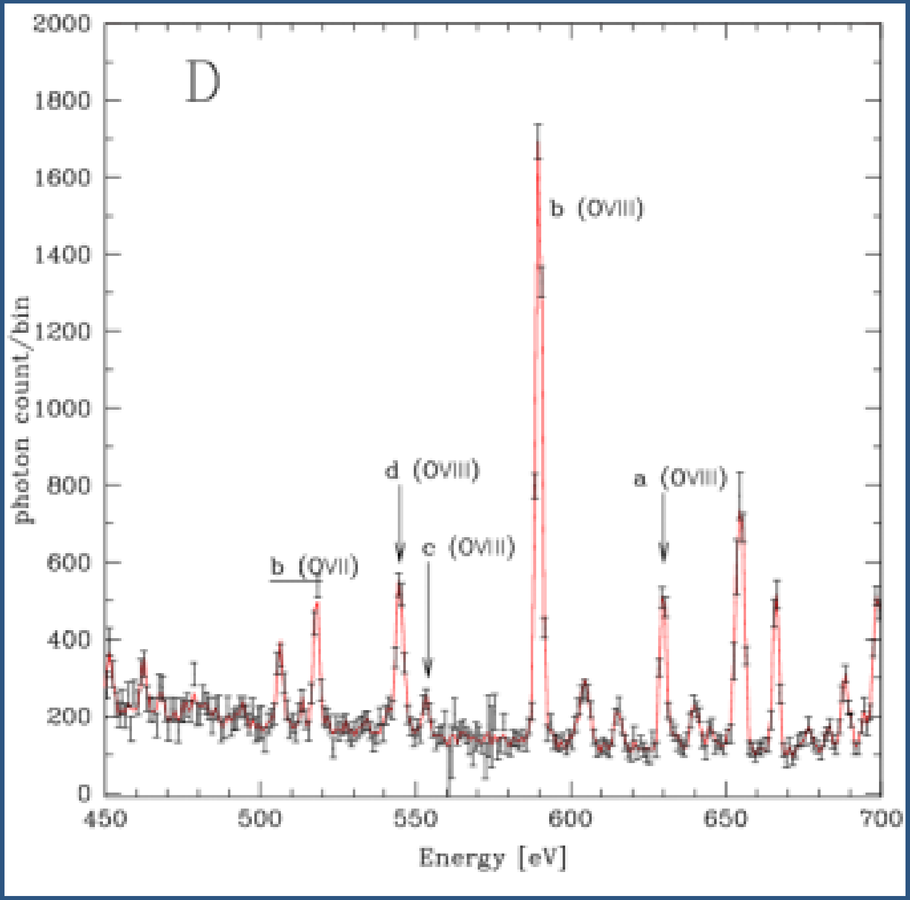


Simulated spectra: region D

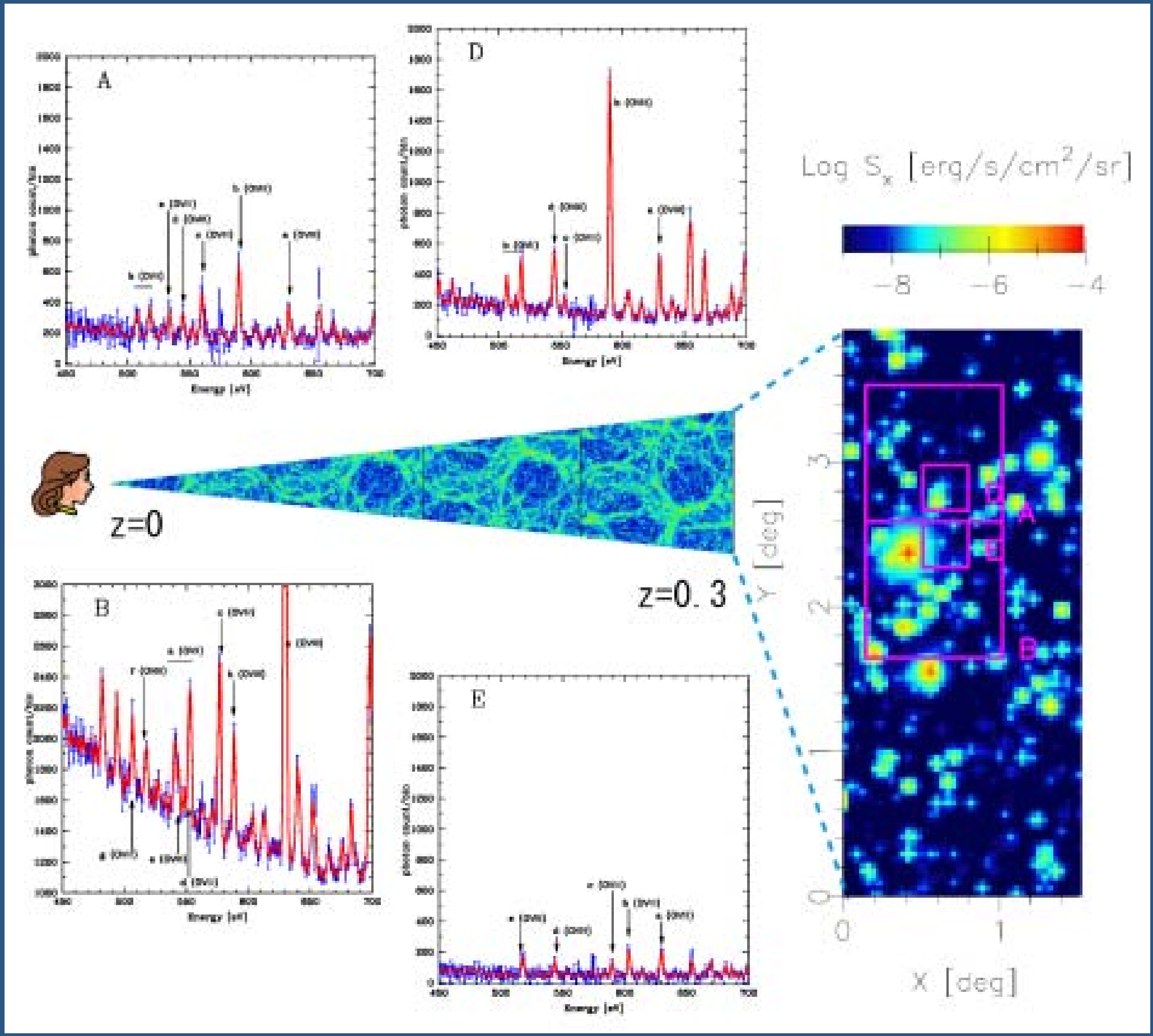


4x4 pixels (0.098 deg^2)
$T_{exposure}$=10^{6}sec





Searching for missing baryons via Oxygen emission lines (astro-ph/0303281)



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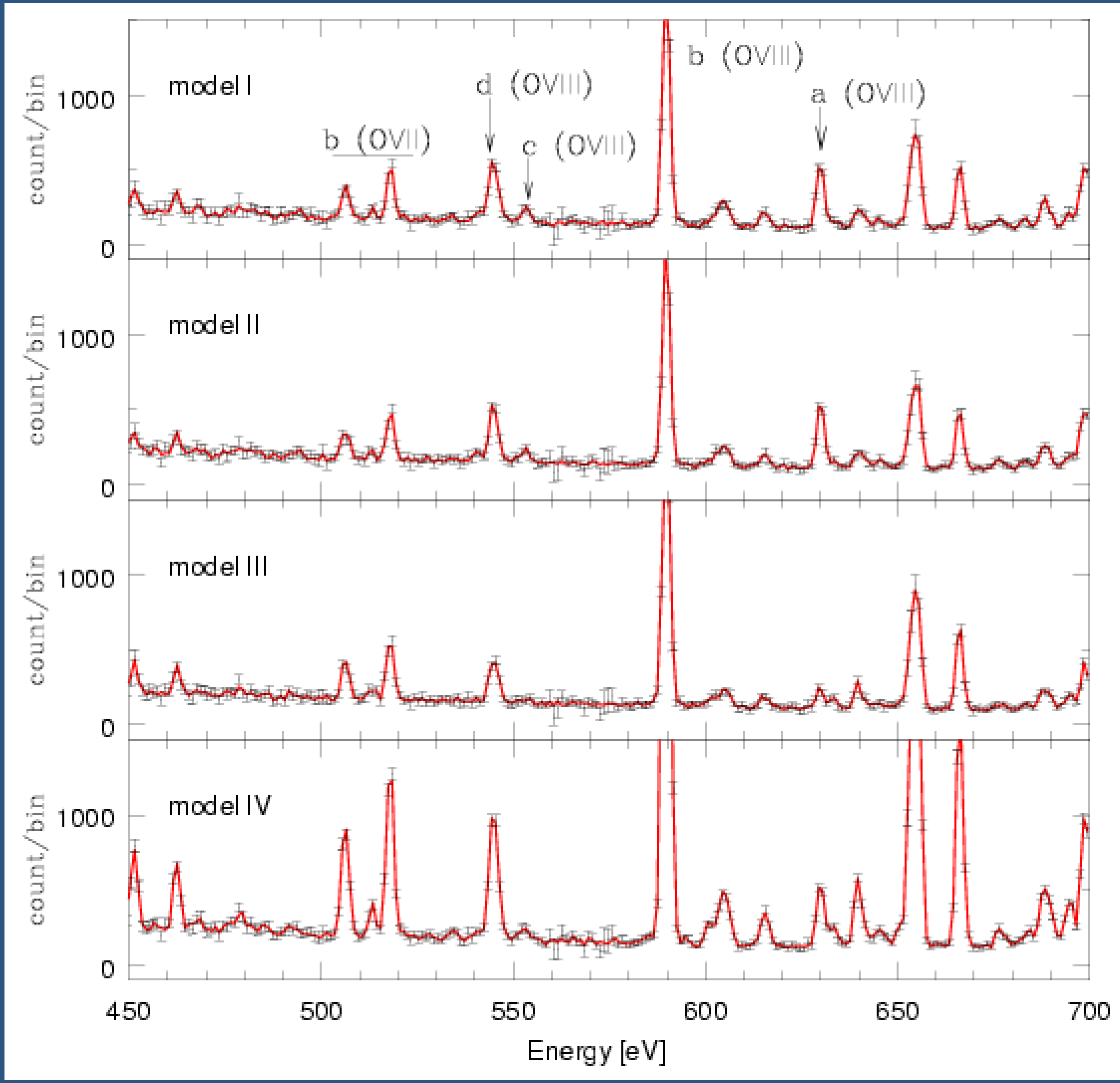
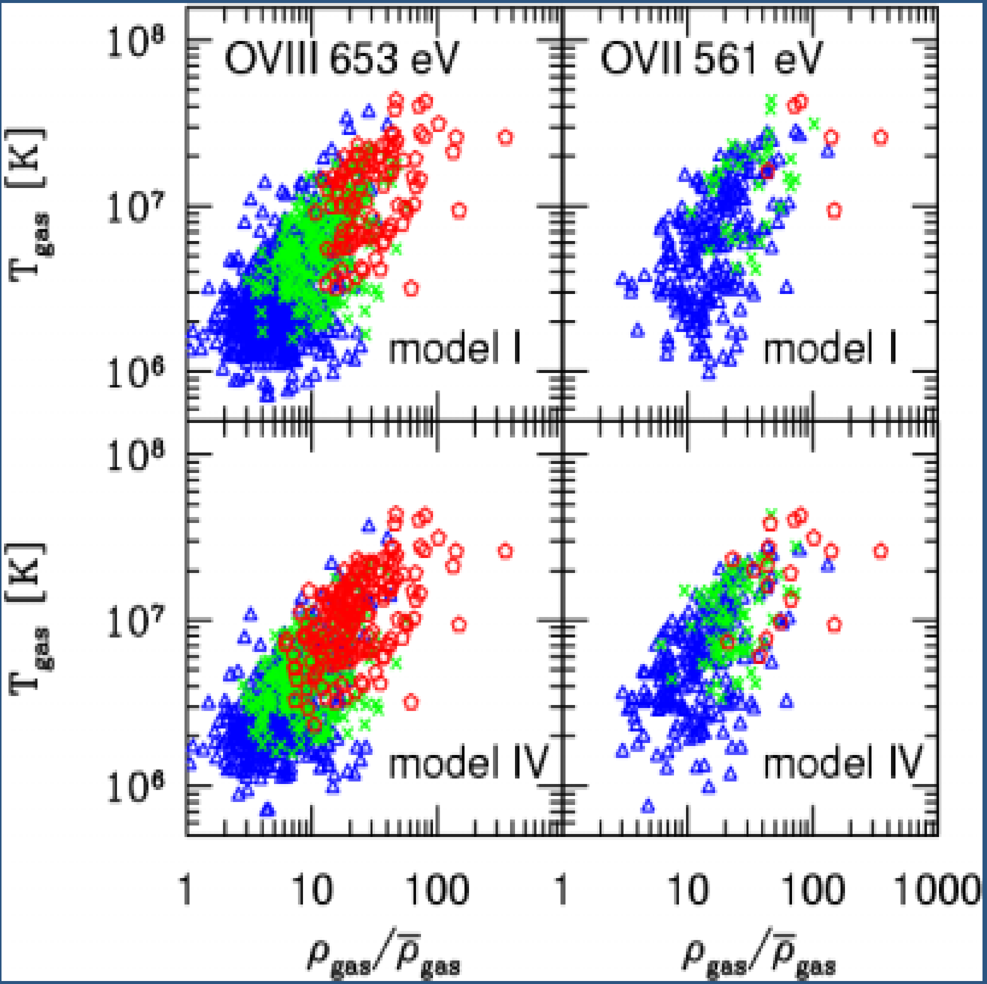
Dependence on the metallicity model



- 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

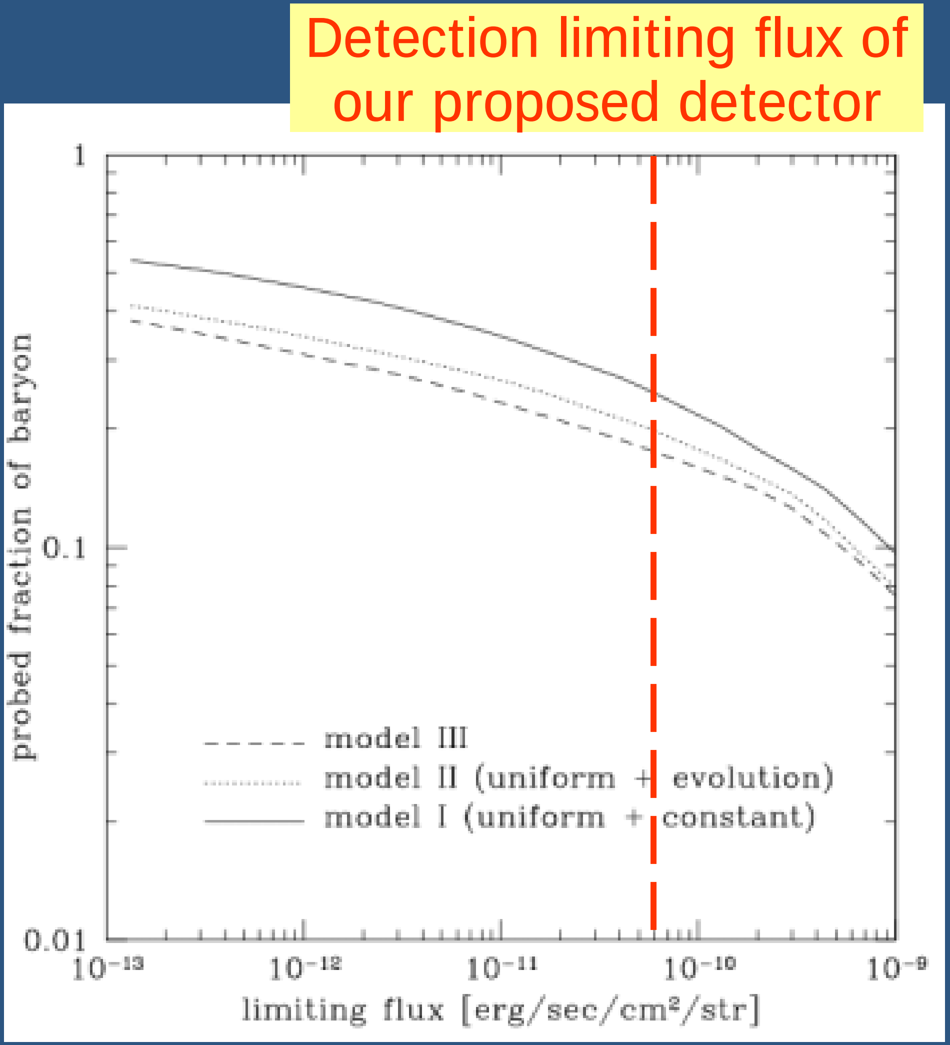
Physical properties of the probed baryons



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]

Probed fraction of WHIM



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

Summary

- The detectability of Warm-Hot Intergalactic Medium is extensively examined with mock spectra from cosmological SPH simulation data.
- With our proposed mission (DE=2eV, S_{eff} W=100 [cm^2 deg^2], flux limit = 6×10^{-11} [$erg/s/cm^2/str$]) , (20-30) percent of the total cosmic baryons will be detected via Oxygen emission lines in principle.
- Things remain to be checked
  - Validity of the collisional ionization equilibrium ?
  - How to properly identify the oxygen lines from the background