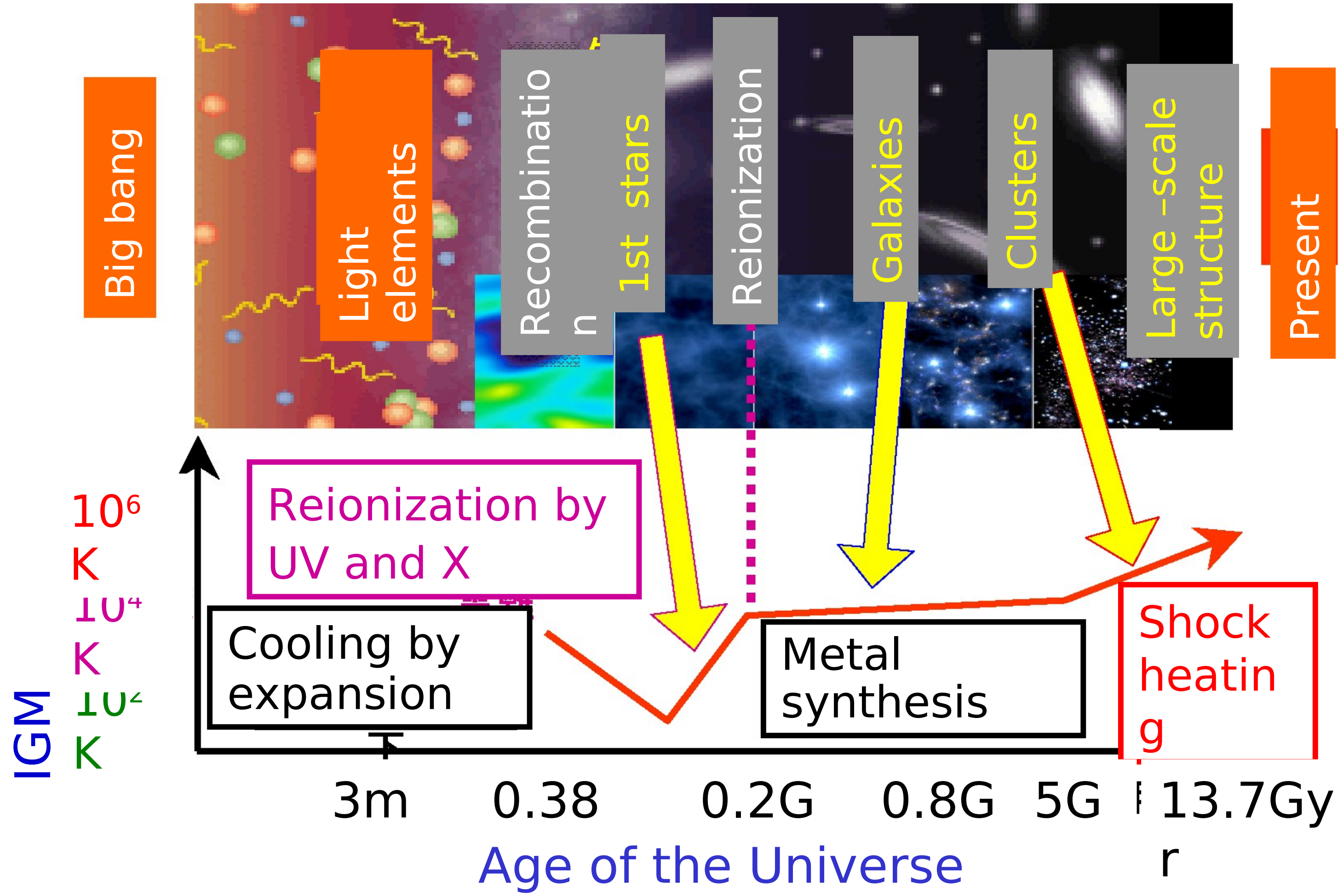
WHIM studies with IXO

T. Ohashi
Tokyo Metropolitan U.

- Science of WHIM study
- Past and present WHIM study
- IXO prospect
- Other WHIM missions

With H. Kawahara (U. Tokyo) and Y. Takei (ISAS/JAXA

Thermal history of the universe



WHIM (warm-hot intergalactic medium) will tell us the evolution of the hot-phase material in the universe

Cosmic structure

WHIM (10^5-10^7 K) traces the cosmic large-scale structure

= “Missing baryon”

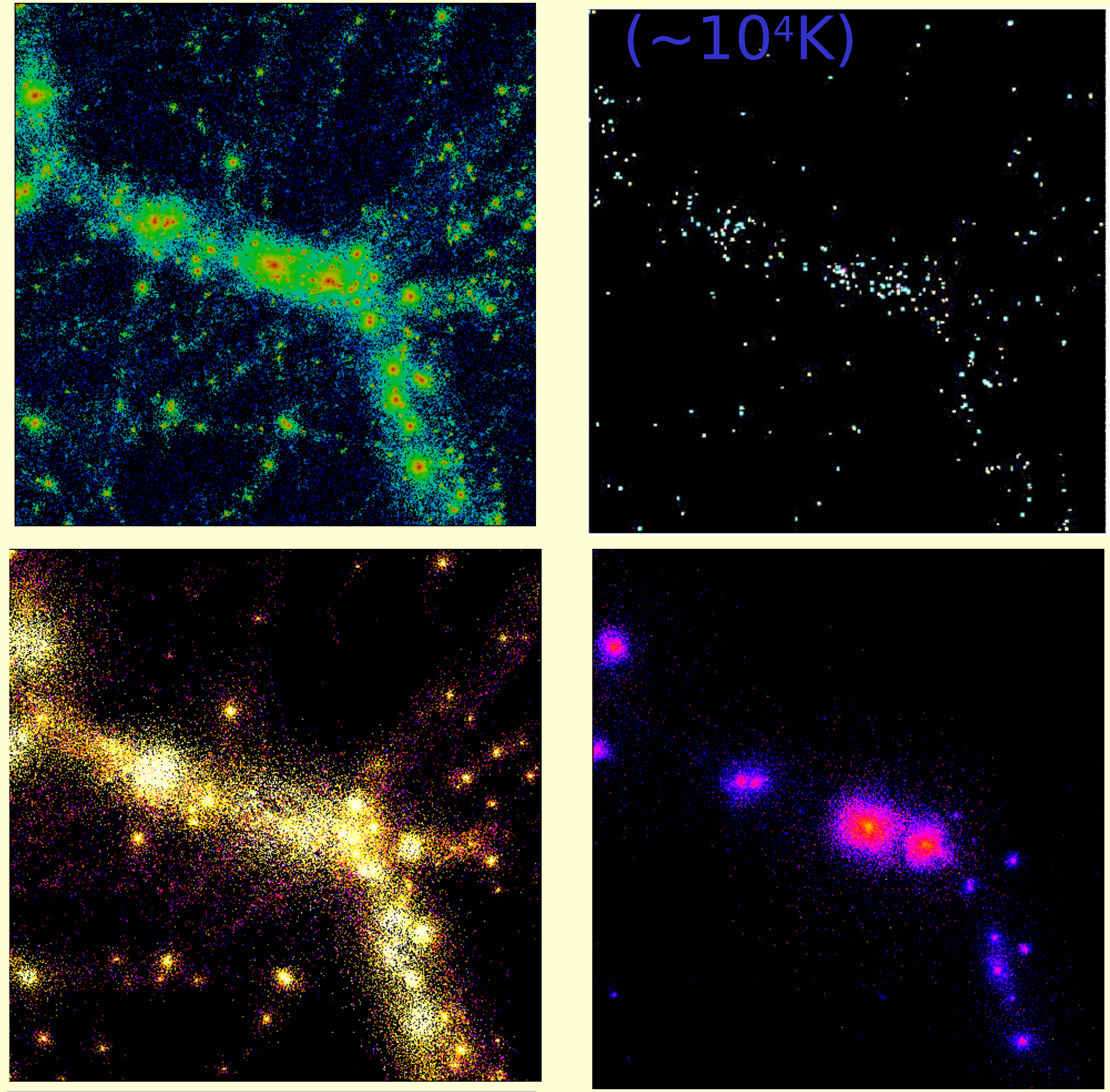
Typical matter density:

δ $(=n/\langle n_B \rangle)$ = 10 - 100

Yoshikawa et al. 2001, ApJ, 558, 520

size = 30 h^{-1} Mpc

~ 5 deg at



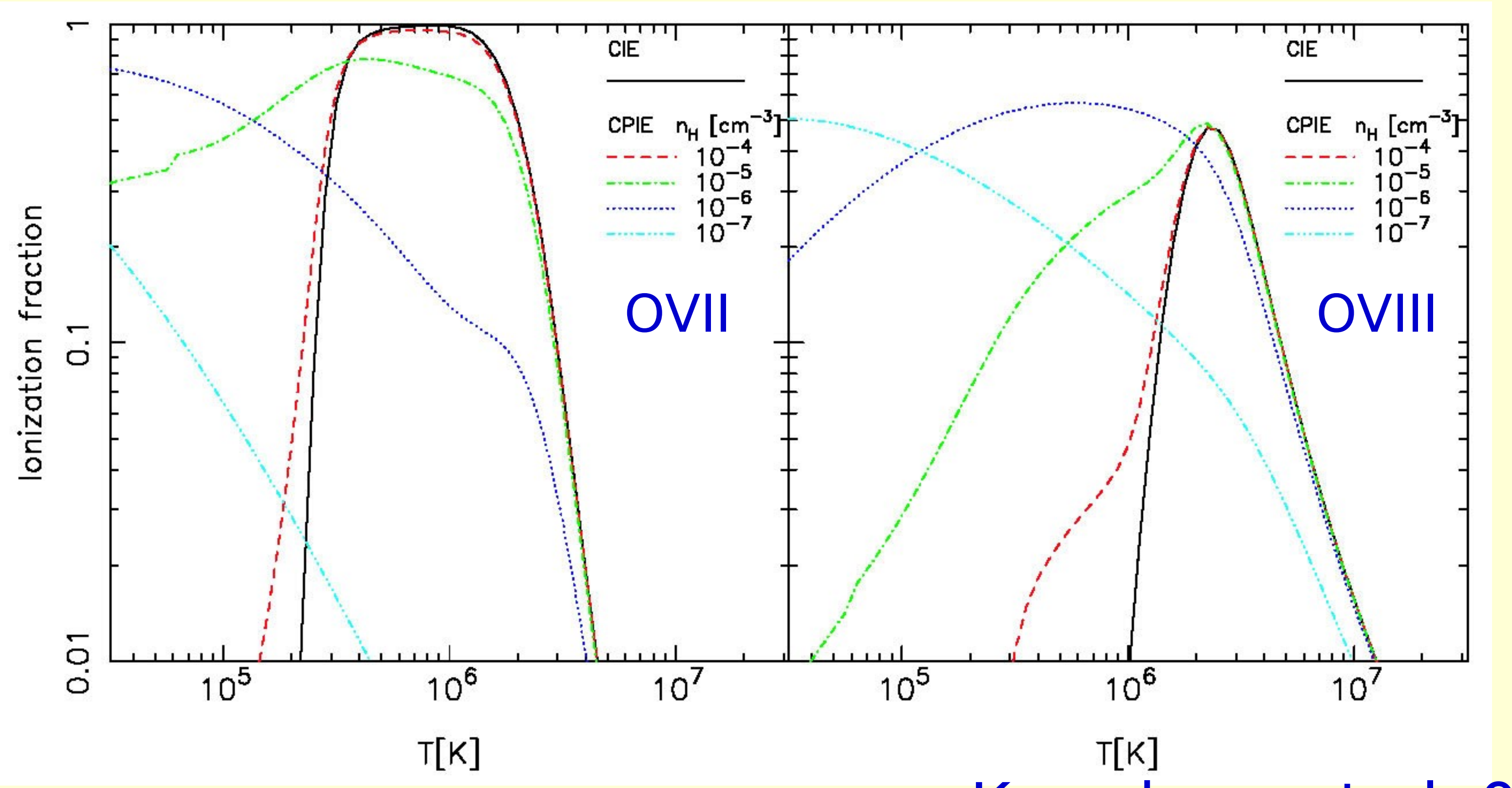
Dark matter

Galaxies ($\sim 10^4$K)

IGM (10^5-10^7K)

Cluster gas (10^7K)

Oxygen emission line

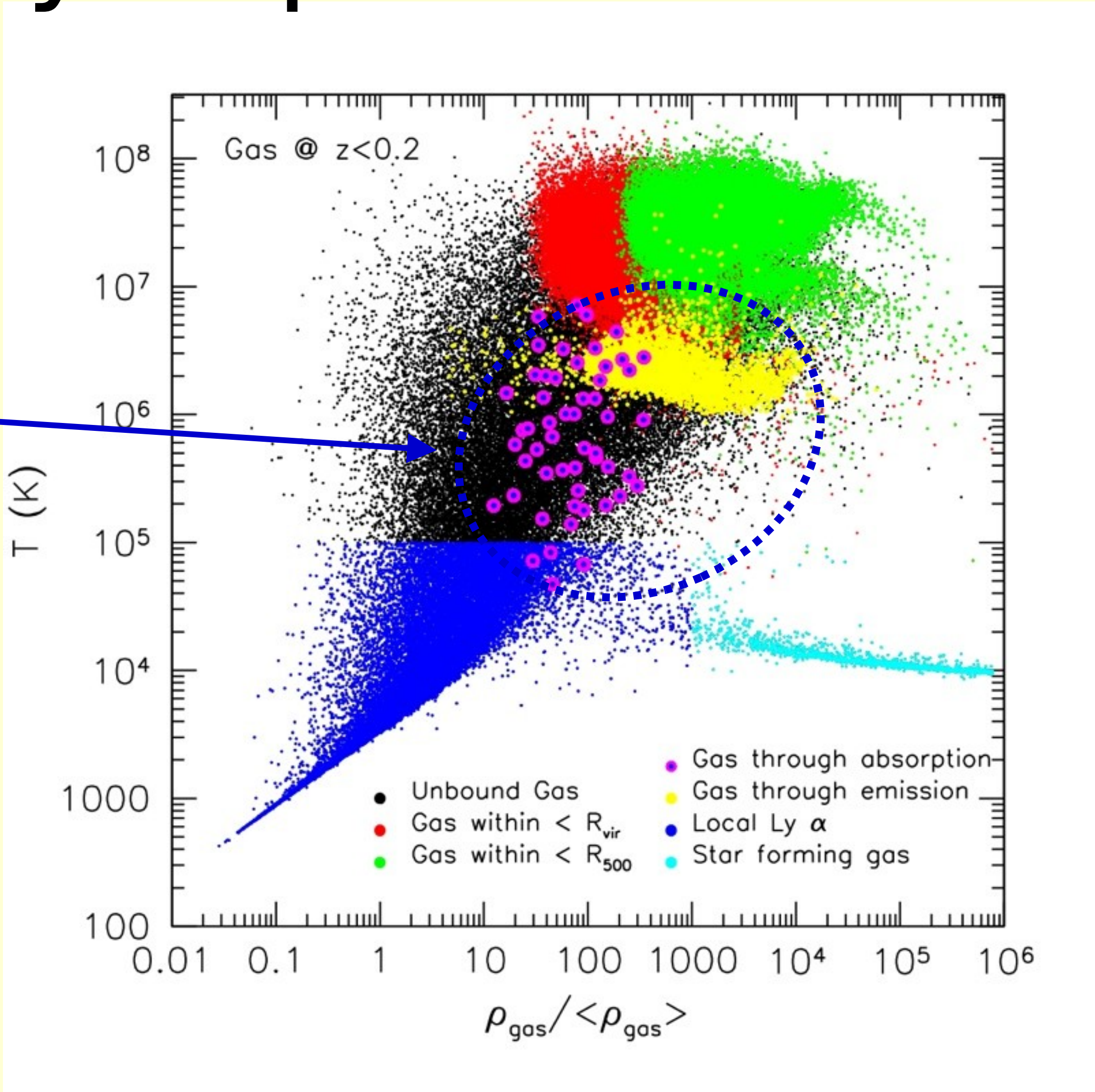


Kawahara et al. 06

- The best tool to explore dark baryon or WHIM in emission.
- Good energy resolution is essential to separate the ~100 times stronger Galactic/interplanetary emission.

Baryon phase

With X-ray absorption and emission lines, a wide area in the baryon phase space can be probed

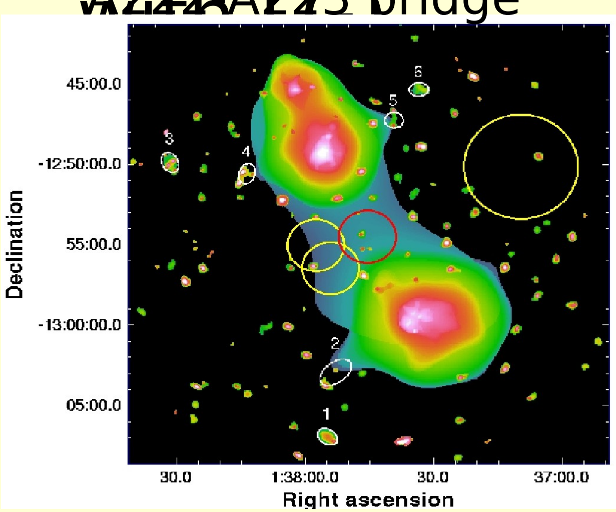


EDGE consortium

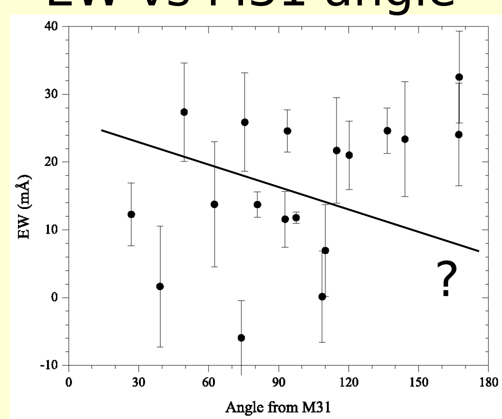
Recent XMM results

- Werner et al. 2008: X-ray bridge between A222 and A223 (z = 0.21), 15 Mpc long?
  - kT ~ 0.9 keV, δ ~ 150, continuum only
- Bregman & Lloyd-Davis 2008: N_{OVII} at z=0 favors Galactic halo rather than Local Group medium (But, line Doppler width shows $T_i > 10^{6.2}$ K and favors association

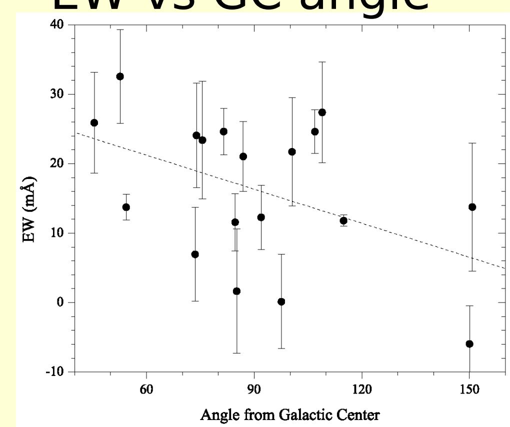
A222-A223 bridge



EW vs M31 angle

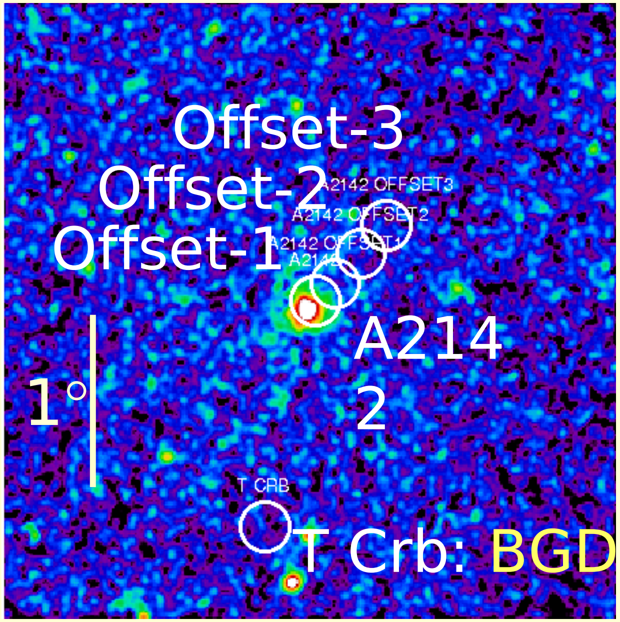


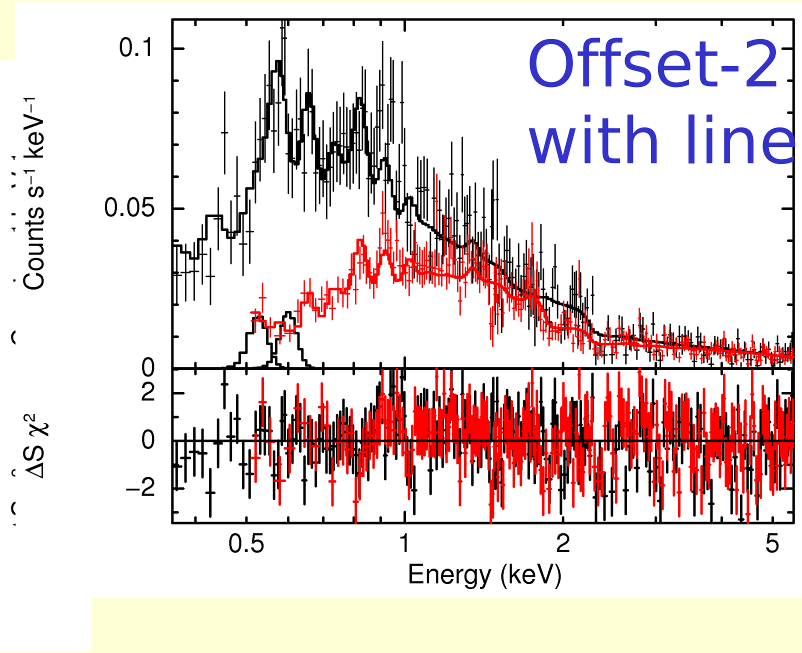
EW vs GC angle



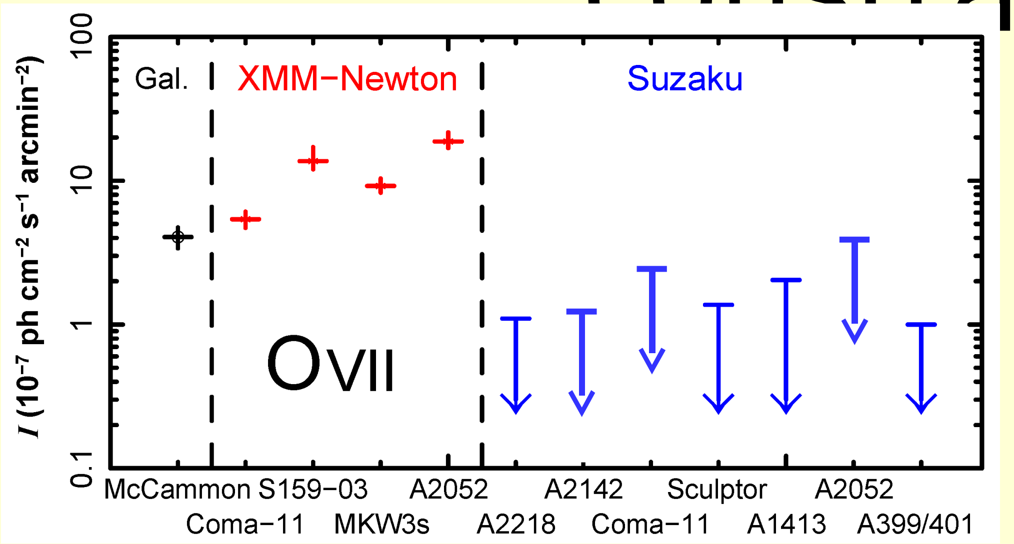
Suzaku search for WHIM

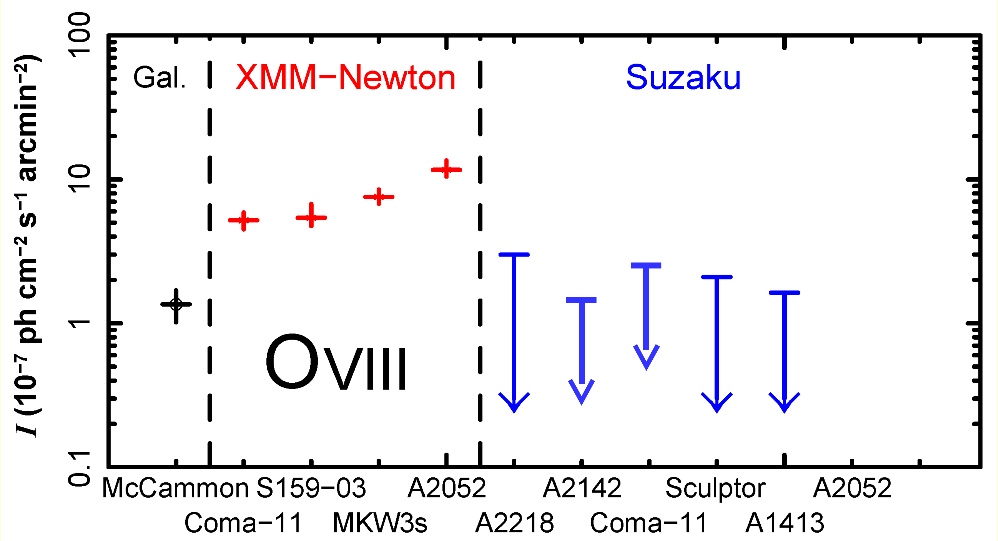
- A2142 (kT = 9 keV, z = 0.0909) offset regions
- BGD was taken at 1.4° off
- At r_{180} from A2142 (90% statitical error)
  - OVII: $7.1\pm 3.7\times 10^{-8}$ $cm^{-2}s^{-1}amin^{-2}$
  - OVIII: $9.2\pm 5.3\times 10^{-8}$ $cm^{-2}s^{-1}amin^{-2}$
- OVII flux implies δ = 250 ± 130 ($0.1Z_{\odot}$, L = 2 Mpc, 2 x10^6K)
- However, systematic error





Summary of Suzaku constraints





- Suzaku upper limits on Oxygen lines are factor of 3 -5 lower than the XMM “detection”.
- Understanding the spectrum of Galactic emission is most important
- Detector background and solar wind process also cause significant effect on oxygen measurement

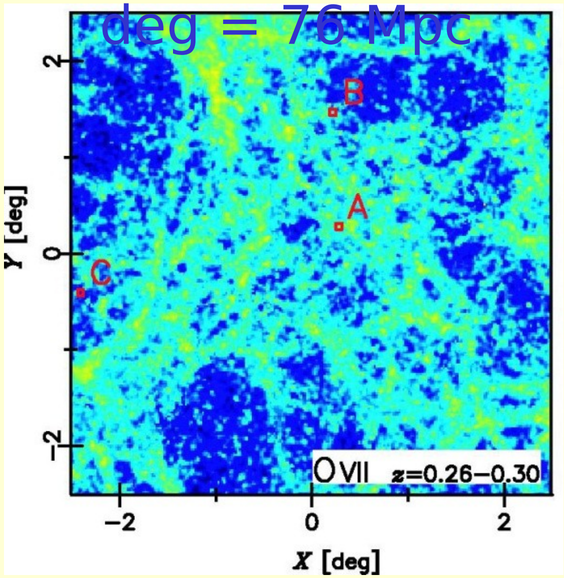
Summary of Suzaku WHIM study

- WHIM or missing baryons carry important science about structure formation and chemical/thermal evolution of the universe
- Its detection is a challenge for X-ray astronomy
- Suzaku is giving fairly low upper limits ($\delta < 300$) , but actual density around clusters is $\delta \sim 100$
- Suzaku may be able to find dense clamps of WHIM in cluster outskirts and in superclusters, which will be the first signature of WHIM

Expectation from IXO (XEUS)

- Kawahara et al. 06 computed the mock transmission spectra of the WHIM based on hydrodynamic simulation data.
  - a light-cone output for $0 < z < 0.3$
  - mock spectra for a bright source
- Cosmological Hydrodynamic Simulation (Yoshikawa et al. 01)
  - PPPM/SPH (128^3 DM and gas particles, $L_{\rm box} = 75h^{-1}$ Mpc)
  - $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.015h^{-2}$, $h = 0.7$, $\sigma_8 = 1.0$
  - note: Ω_b is ~30% smaller than

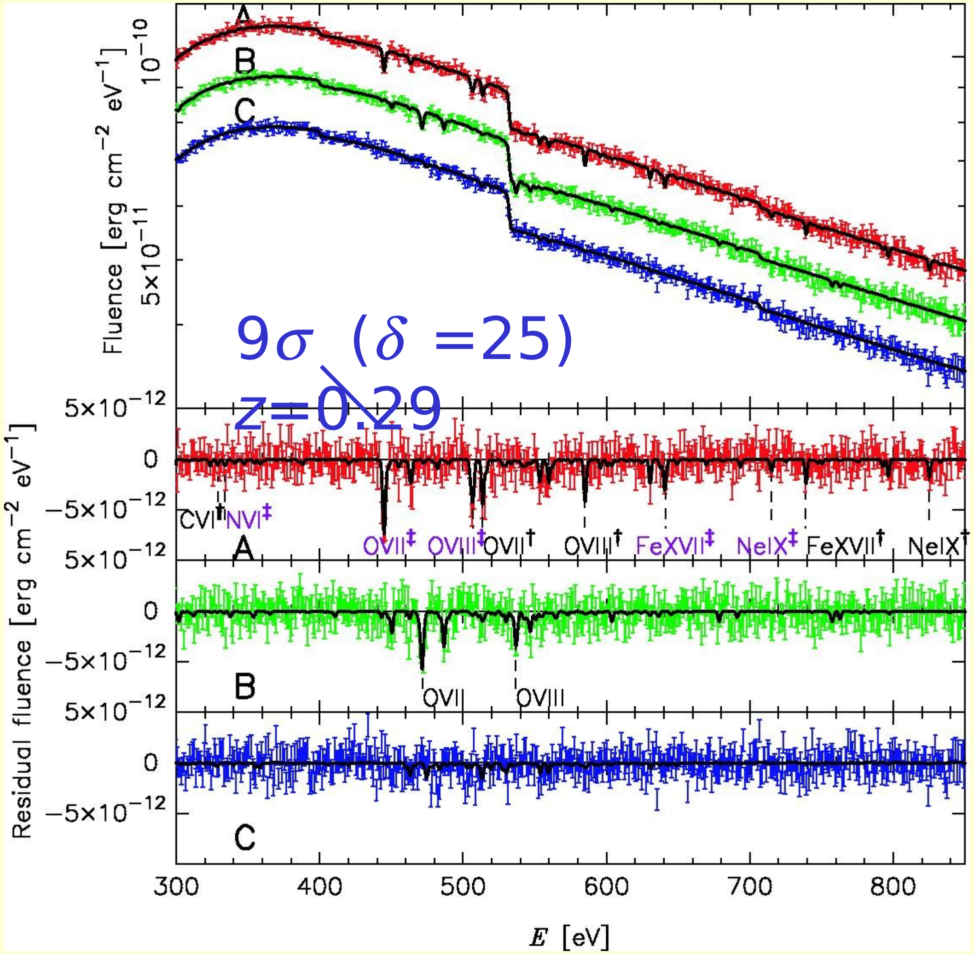
OVII: z=0.26-0.30, 5 deg = 76 Mpc



$N_{\rm OVII}=10^{15}$-10^{16} cm^{-2}

60000 cm^2 (XEUS) → 30000 cm^2 (IXO)

Simulated spectra



9σ (δ =25)
z=0.29

Background AGN
F_x= 7 $\times$ 10^{-12} erg cm^{-2}s^{-1}
(0.1-2.4 keV)
60 ksec observation with IXO calorimeter
EW = 0.05 eV detected at 3σ

Number of QSOs with F_x > 7$\times$10^{-12} cgs in 0.1-2.4 keV
~60 in z > 0.1
<u>~20 in z > 0.3</u>

$$N_{\rm OVII} = 1.3\times10^{15}(EW/0.1\,{\rm eV})\,{\rm cm}^{-2}$$

Kawahara et al. 06

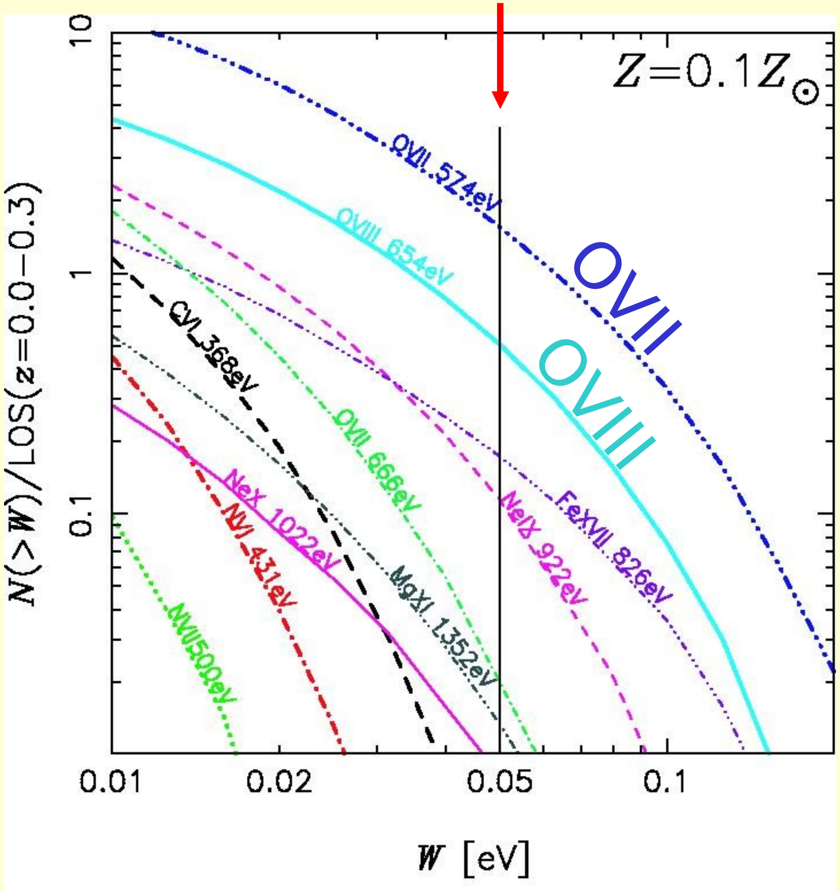
Number of WHIM clouds

Expected number of absorption systems per LOS

EW>0.05 eV
(*S/N* $\geq 3\sigma$ *with F*x > 7×10^{-12} for 60 ksec IXO)

OVII (574 eV)	1.71
OVIII (654 eV)	0.43
OVII and OVIII	0.41

0.05 eV $\approx 3\sigma$



With 60 (600) ksec observation of 20 bright AGNs at z > 0.3, 8 (~30) clouds will give us joint detection of OVII and OVIII lines

Simulation of gratings

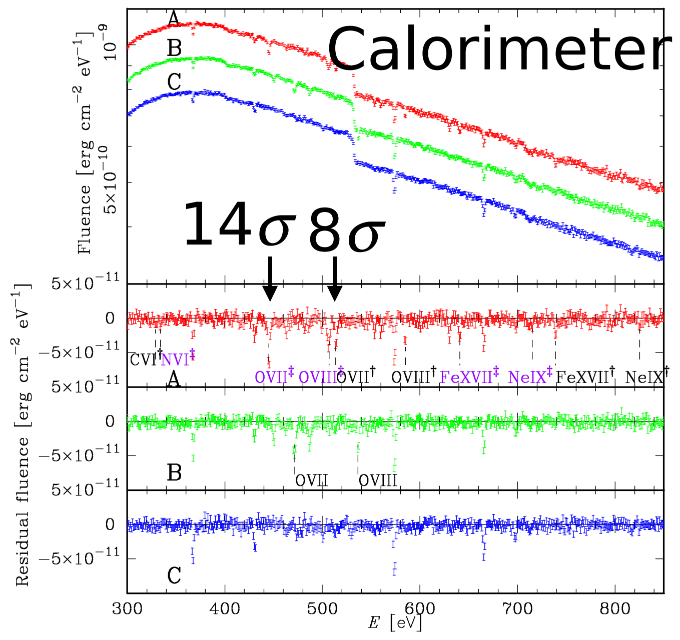
Effective area: 1500 cm^2

Energy resolution: 0.1 eV

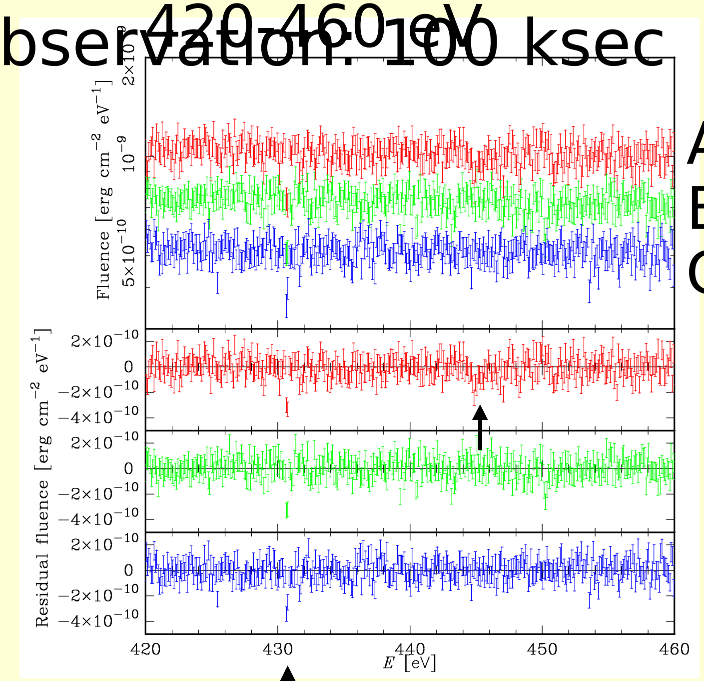
Background source:

$F_x = 2 \times 10^{-11}$ erg cm^{-2} s^{-1} (0.1-2.4 keV)

Observation: 100 ksec



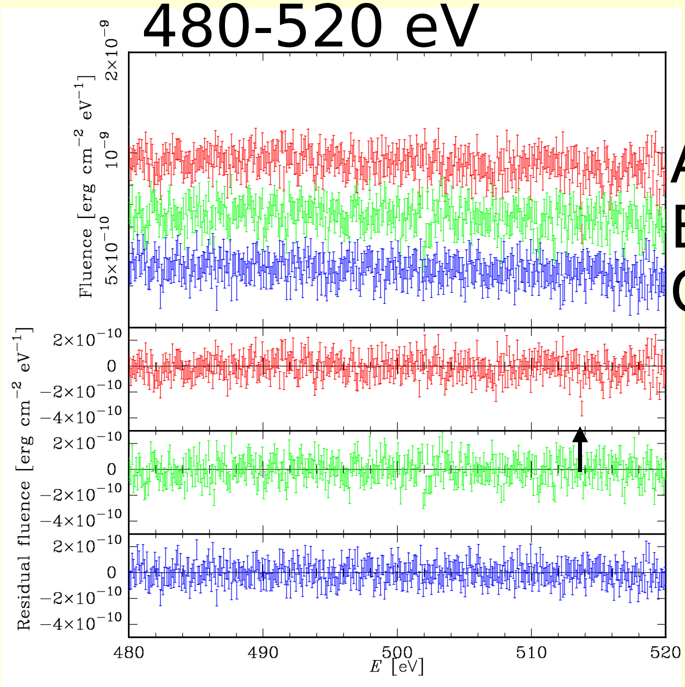
420-460 eV



Galactic

WHIM: 4σ

480-520 eV



WHIM: 5σ

Significances

E_{line} (eV)	Ion	z	Calori (σ)	Gra (σ)	Width (eV)	EW (eV)	Cloud # in z=0-0.3
445	OVII	0.29	14	4	1.2	0.16	0.1
507	OVIII	0.29	7	2	1.0	0.09	0.1
514	OVII	0.12	8	5	0.3	0.1	0.3
585	OVIII	0.12	7	4	0.5	0.12	0.05

Calorimeter gives better sensitivity, because lines have width.

Combination of two instruments give constraint on

Combination of Grating and Calorimeter

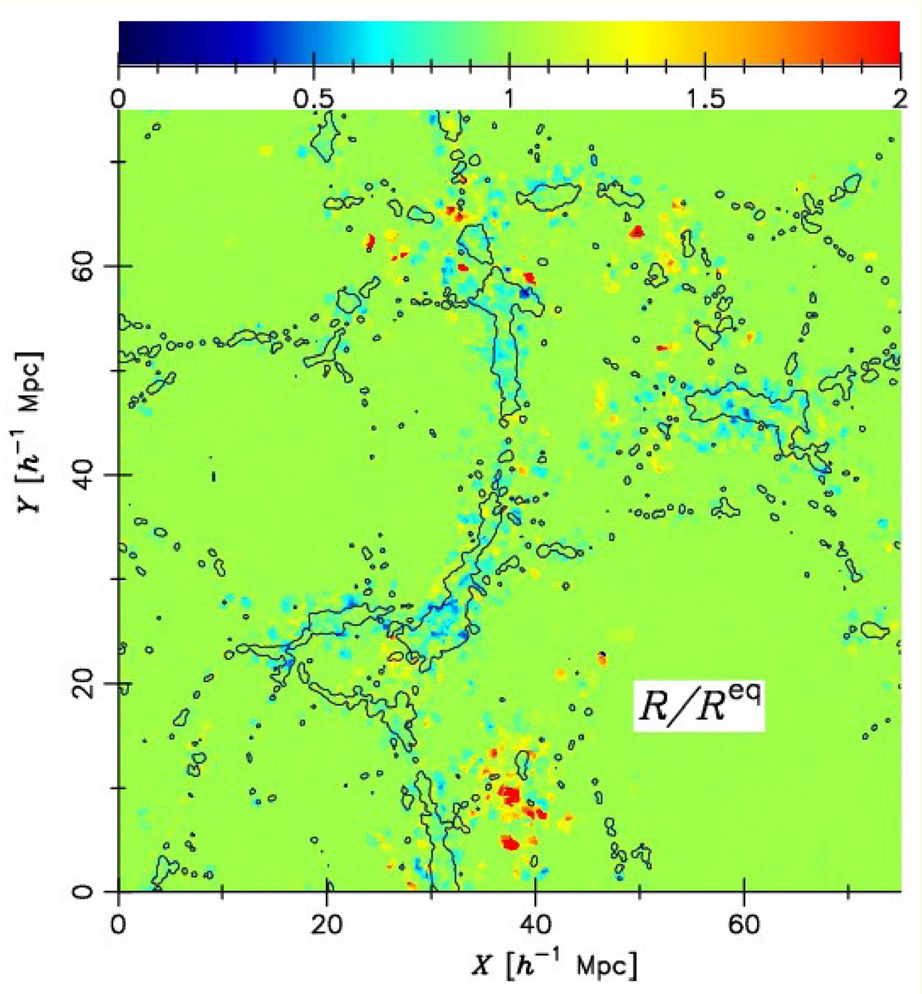
$$S/N \propto \sqrt{N/\Delta E}$$

- N = number of photons
  $N_{\mathrm{Calori}}/N_{\mathrm{Grating}} \approx 3\times 10^4\ \mathrm{cm}^2/1500\ \mathrm{cm}^2 = 20$
  $\Delta E_{\mathrm{Calori}}/\Delta E_{\mathrm{Grating}} \approx 2\ \mathrm{eV}/0.1\ \mathrm{eV} = 20$
- The two instruments offer <u>similar *S/N*</u> ratios
- Lines can be broad (100 km s^{-1} $\rightarrow \Delta E$ = 0.2 eV)
- Calorimeter is sensitive in most cases, but line profile and separation of contaminating lines with grating can constrain WHIM physics in some cases

WHIM in non equilibrium state

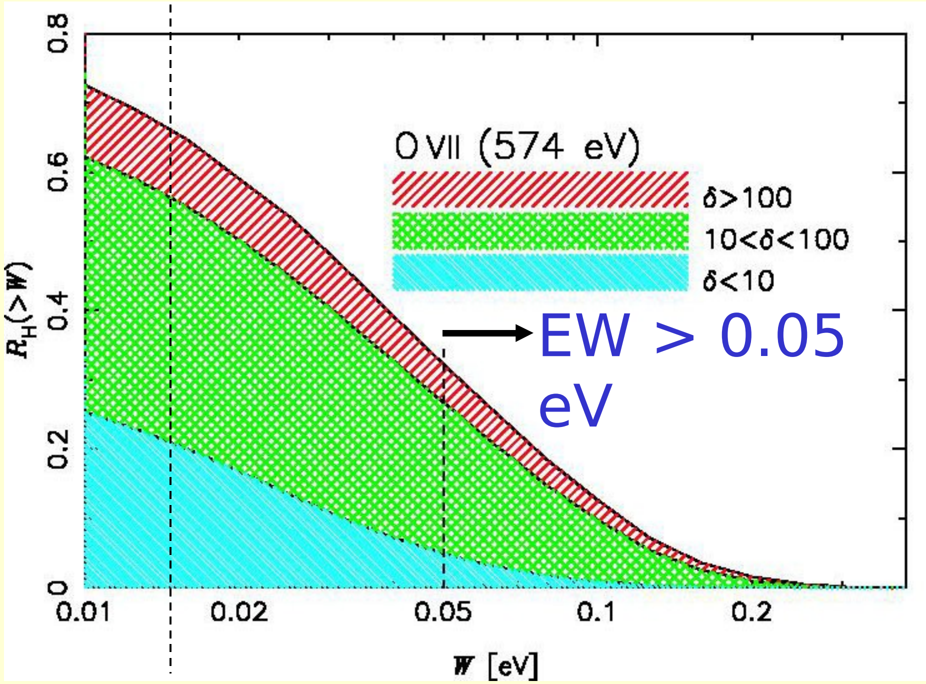
$R = F(\text{OVIII})/F(\text{OVII})$

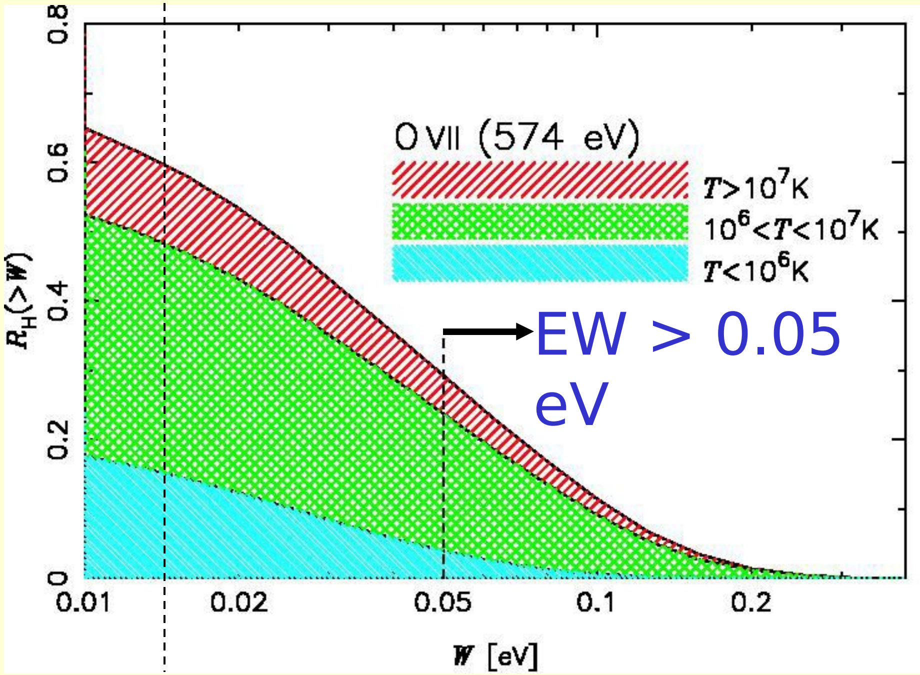
- Filaments are generally in the process of heating, so OVII line is relatively stronger than the CIE case (blue)
- If the region is immediately after a shock heating, OVIII line is stronger (red)
- Simulation should include these effects



Yoshikawa & Sasaki (2006)

Probed fraction





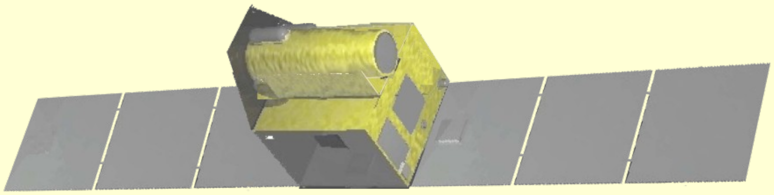
- EW = 0.05 eV (~60 ksec observation): 20-30% of baryons can be probed
- 10 times longer exposure probes ~50% of baryons
- OVII absorption can detect WHIM with T <

WHIM with IXO

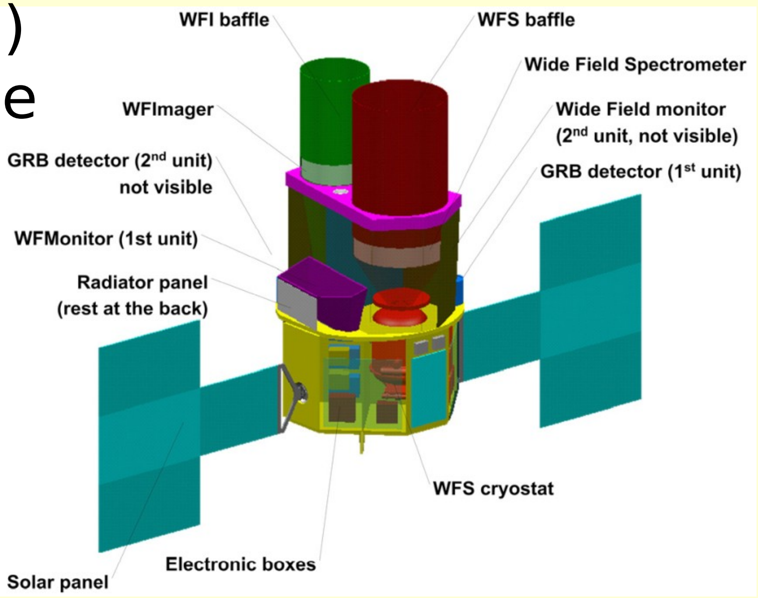
- Definitely a big jump from Chandra and XMM-Newton capabilities (with ~300 times jump in the area)
- Calorimeter is more sensitive for most cases, but combination of calorimeter and grating spectrometer may be useful in constraining WHIM motion in some cases
- Long (~ 600 ksec) observations of bright AGNs will be worth consideration

XENIA/EDGE and DIOS

- TES calorimeter array with 1024 pixels
- DIOS (Diffuse Intergalactic Oxygen Surveyor, Japan) … small mission ~400 kg
- EDGE (Explorer of Diffuse emission and Gamma-ray burst Explosions) … medium size ~2000 kg
  ⇒ XENIA (Kouveliotou, Piro, den Herder) for US proposal
- Launch: 2015 or later
- Very wide field of view (~ 1deg) with 4-reflection X-ray telescope
- Energy range < 2 keV



DIOS: Japanese small satellite

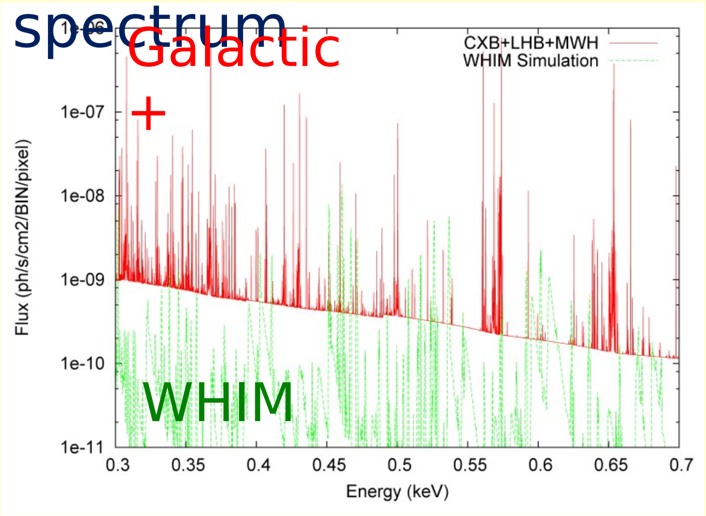


EDGE/XENIA: US-Europe-J

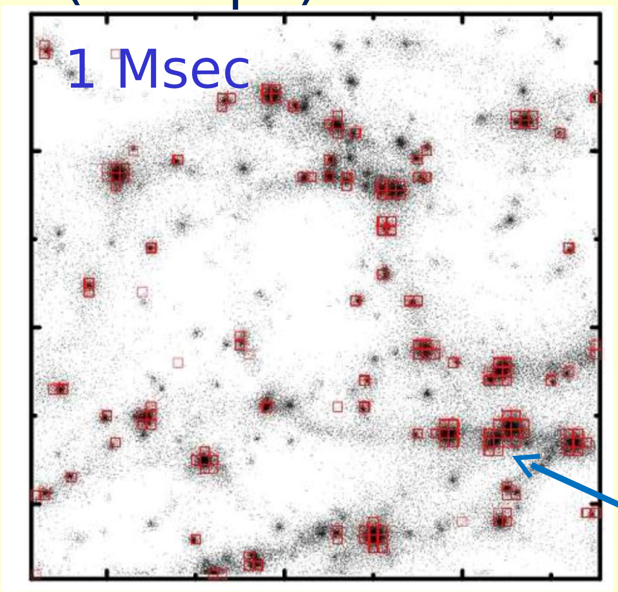
Expected results

- 0.1-1 Msec exposure with EDGE/XENIA ($S\Omega \sim 1000$ cm^2 deg^2) gives significant detection of WHIM filaments
- Combined detection of OVII and OVIII lines suppresses spurious features
- EDGE/XENIA has capability of absorption measurement against GRB afterglow → density and depth of the filament

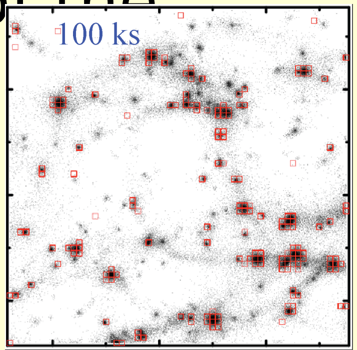
Incident spectrum



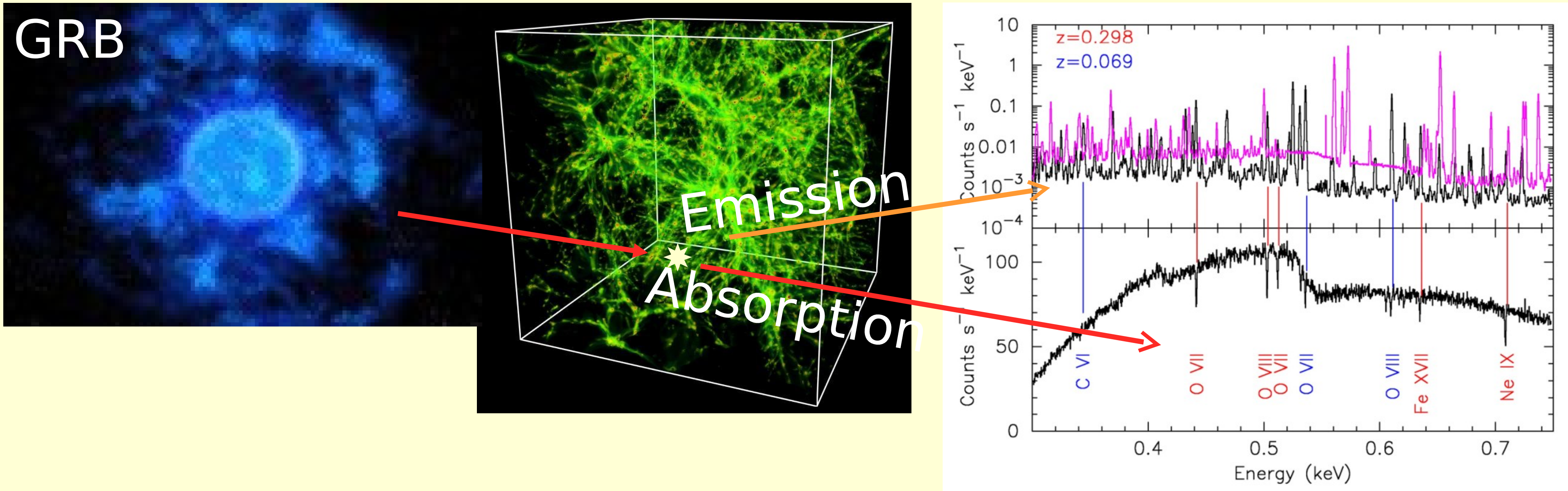
5 deg x 5 deg at z = 0.2 (60 Mpc)



OVII & OVIII >



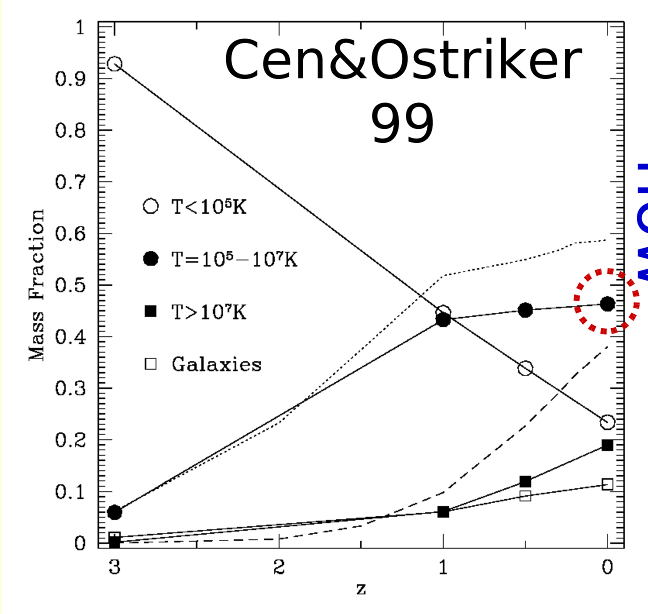
Combined measurement with Xenia



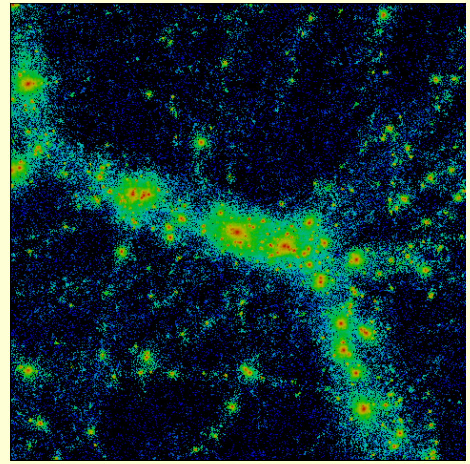
- WHIM absorption measured after ~1 min from GRB onset
- Later, emission lines from the same region will be measured
- Density, ionization state, line of sight depth of the WHIM cloud will be obtained

END

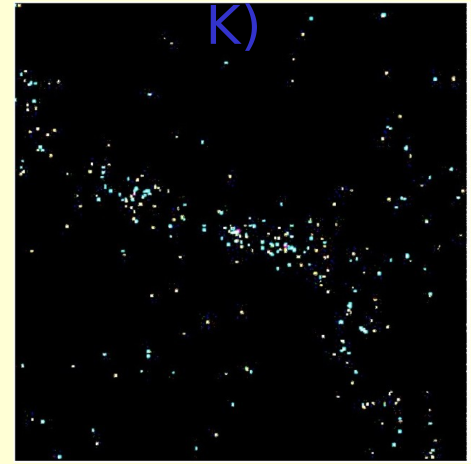
WHIM = Dark baryon



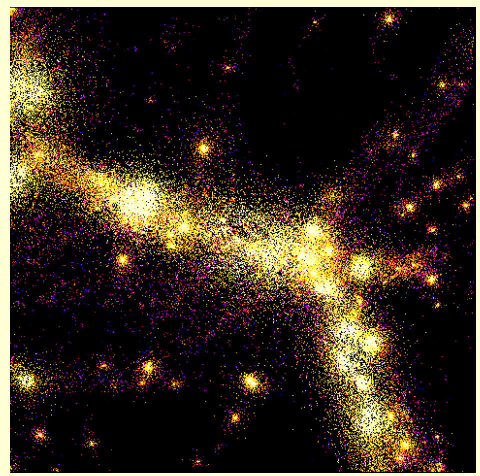
Dark matter



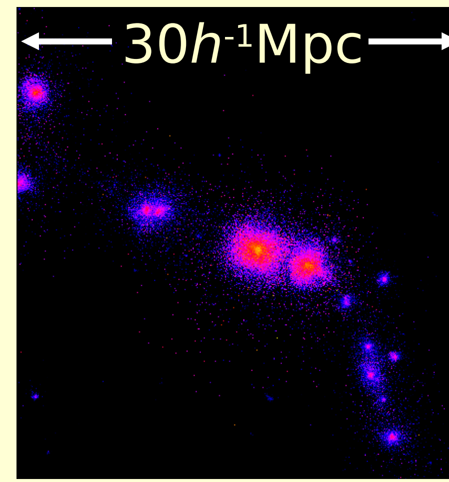
Galaxies (~10^4 K)



Yoshikawa et al.2001:



IGM ($10^{5\text{-}7}$K)



Clusters (10^7K)

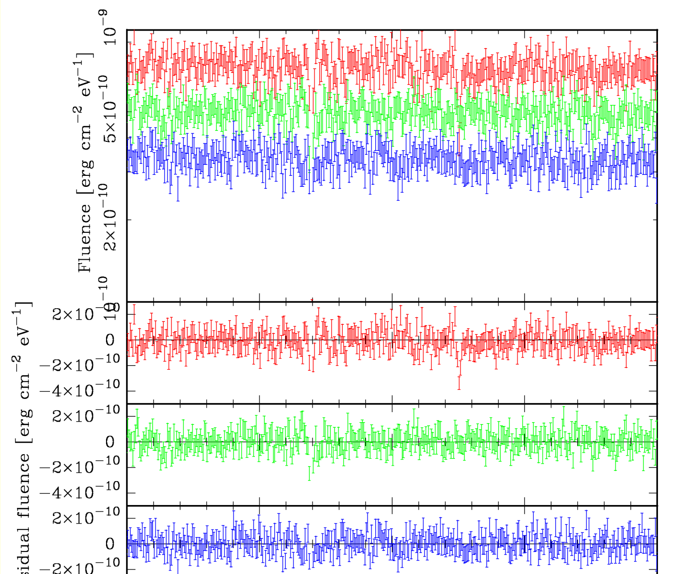
Warm-Hot Intergalactic Medium = dark baryon

WHIM with 10^5 - 10^7K traces the large scale structure

WHIM with kT > 10^6 K produces OVII and OVIII lines

Colleagues

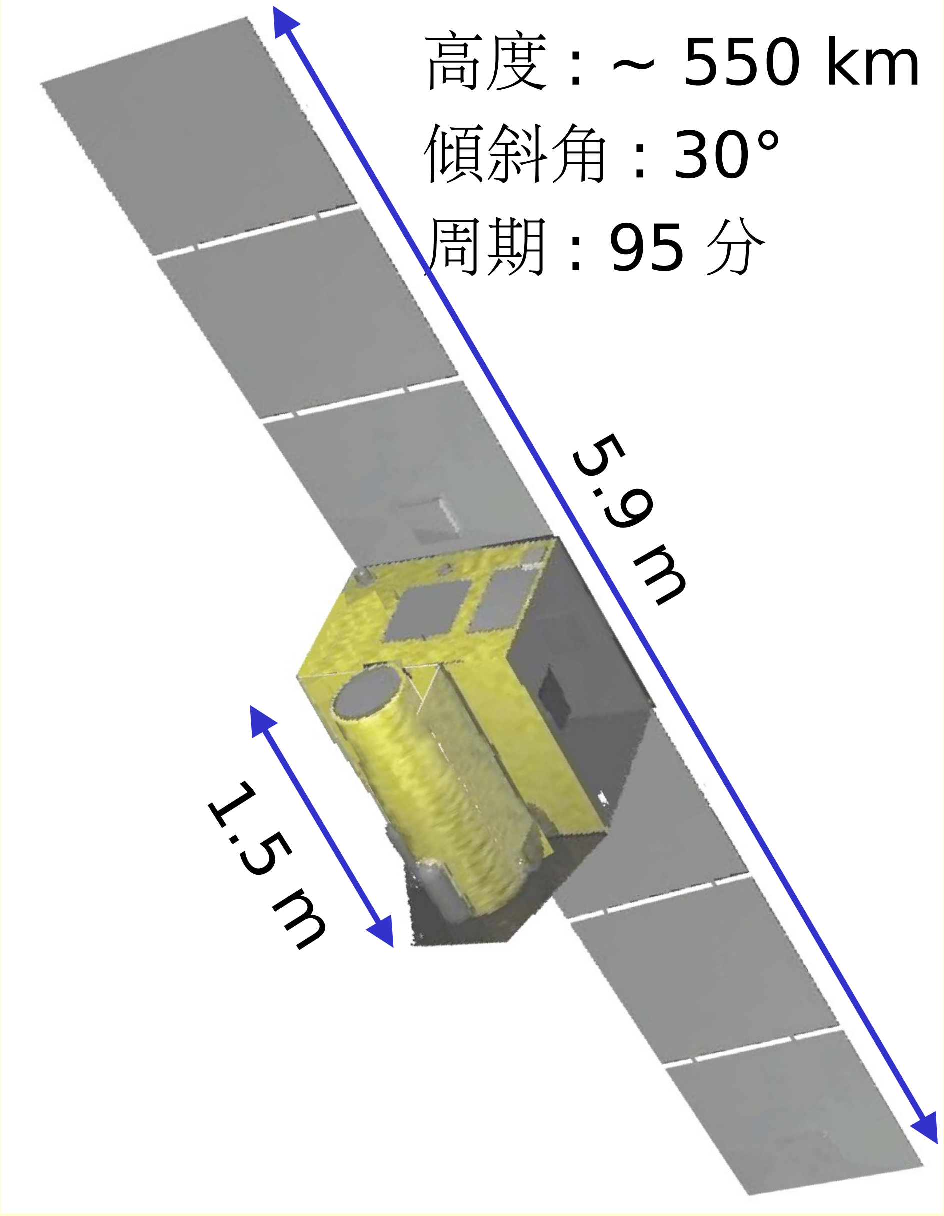
- Y. Takei (ISAS/JAXA), S. Sasaki (TMU), K. Yoshikawa (Tsukuba U), Y. Suto (U. Tokyo), C. Kouveliotou (MSFC), L. Piro (ISAF-Rome), J.-W. den



DIOS Project

- Expected launch ~2015

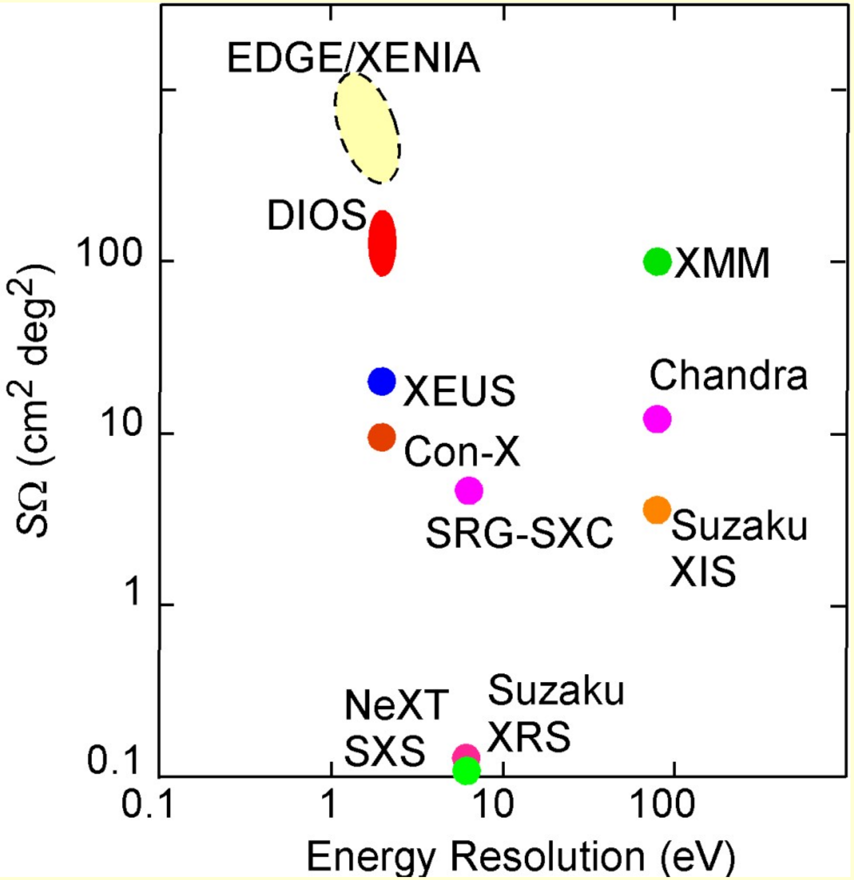
重量	全体	~ 400 kg
	観測系	~ 200 kg
大きさ	打ち上げ時	1.2×1.45×1.4 m
	軌道上	5.9×1.45×1.4 m
姿勢	制御	3- 軸制御
	精度	≦30 秒角
電力	全体	600 W
	観測系	300 W



約 20% の余裕見込む

DIOS の性能

有効面積	> 100 cm^2
視野	50' diameter
$S\Omega$	> 100 $cm^2 deg^2$
角分解能	3' (16 x 16 ピクセル)
エネルギー分解能	2 eV (FWHM)
エネルギー範囲	0.3 – 1.5 keV
ミッション寿命	> 5 yr

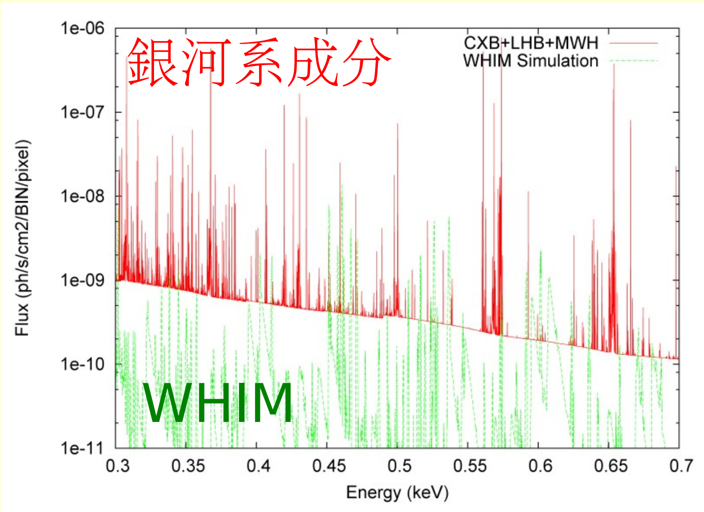


Large $S\Omega$ with good resolution

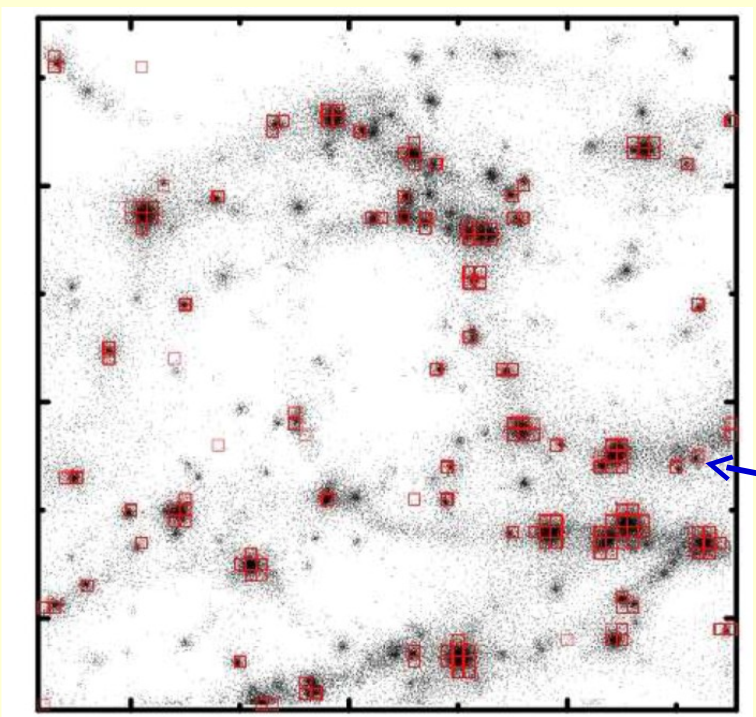
酸素の輝線で広大な WHIM をマッピング観測

観測のシミュレーション

入射スペクトル



- 数 Msec の観測を想定
- 約 100 倍強い銀河系輝線を、エネルギー分解能で分離
- OVII と OVIII の両方の輝線を測ることで信頼性向上
- 大構造フィラメントに沿う密度の高い領域を検出できる



5 deg x 5 deg at z = 0.2
 (60 Mpc)

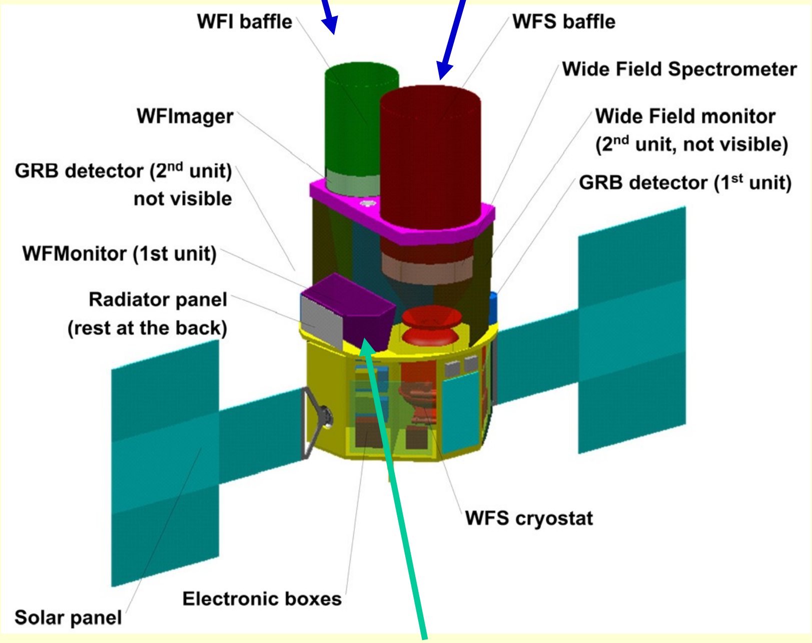
OVII & OVIII > 3σ
 δ ~100: バリオン全体の 20% 近くを検出

Xenia 計画

- DIOS を拡張、WHIM の放射と吸収を観測
- 来年米国の Decadal Survey へ PI=C. Kouveliotou (MSFC) で提案。2018 頃の打ち上げを目指す
- γ 線バースト発生後 1 分で補足
- 米国、イタリア、オランダ、日本が中心
- 4 回反射ミラー、TES カロリメータ、冷却系は DIOS の拡張モデルを搭載。カロリメータの面積は DIOS の 3-9 倍。重量約 2 トン

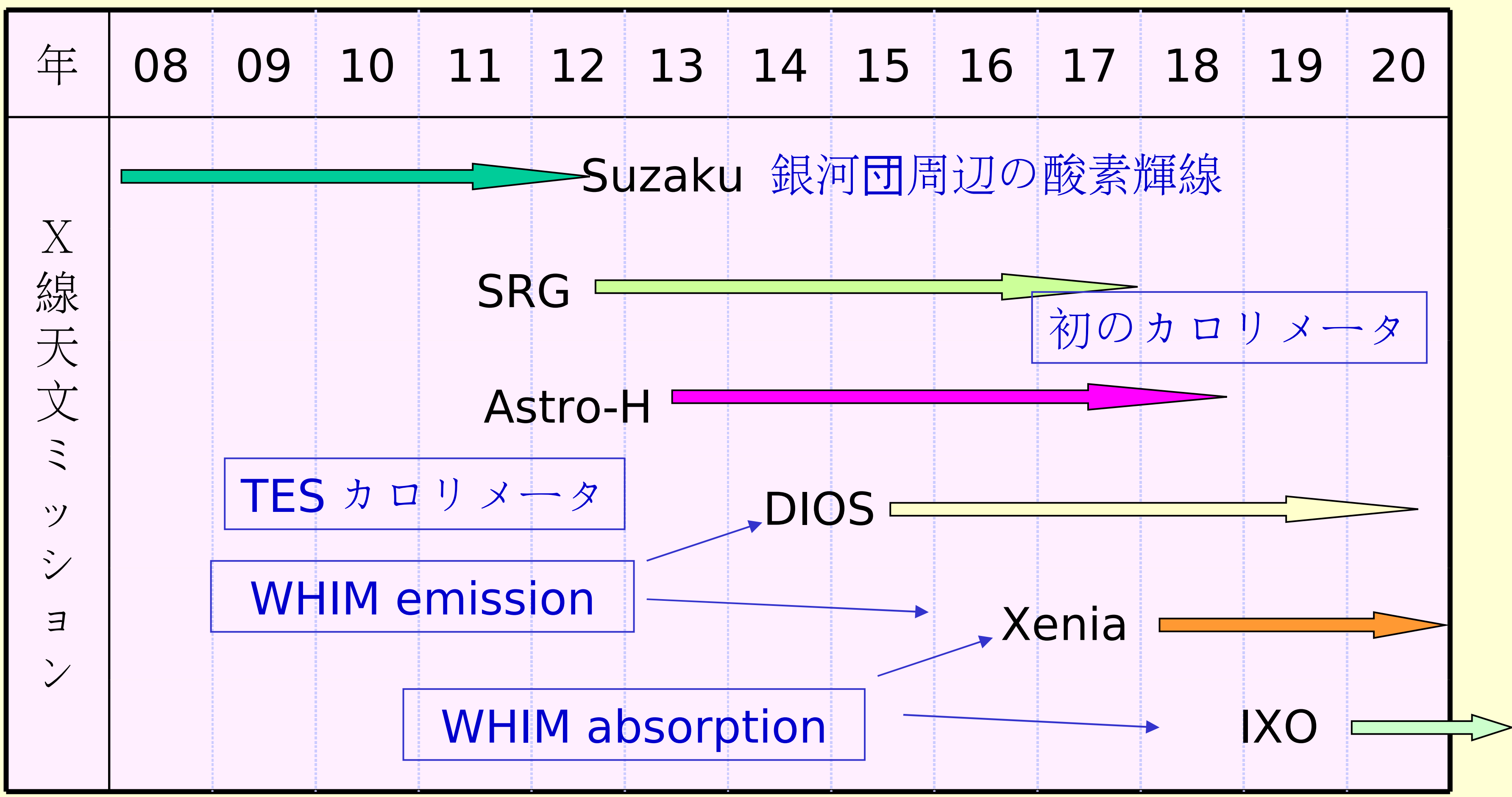
広視野 CCD

TES カロリメータ



γ 線バースト検出器

ダークバリオン攻略への道



まとめ

- 小型衛星 DIOS(~2015 年）はダークバリオン探索の先陣を切るミッション
- 大型天文衛星に無いユニークな性能で、銀河の高温ガスや銀河団ダイナミクスにも大きく貢献
- Xenia(~2018 年) で感度をあげ、放射・吸収の両面から、 WHIM の構造を物理状態を詳しく観測
- 面積 3 万 cm^2 の IXO (XEUS+Con-X 、 ~2020 年) で、吸収線観測は大幅に進展