X-Ray observability of WHIM and our new mission concept DIOS (Diffuse Intergalactic Oxygen Surveyor)

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"Cosmic Baryon Budget" requires missing baryon

- ✓ The observed baryons are only 10-40% of the expected valued from big-bang nucleosynthesis.

  $\Omega_{star}+\Omega_{HI}+\Omega_{H2}+\Omega_{hot\ X\text{-}ray} = 0.0068^{+0.0041}_{-0.0030}$ vs $\Omega_{BBN}=0.04$

  (Fukugita, Hogan, & Peebles 1998)

- ✓ Is there other phase of cosmological baryons?

  Star: Condensed $T<10^5$K, $\delta>1000$

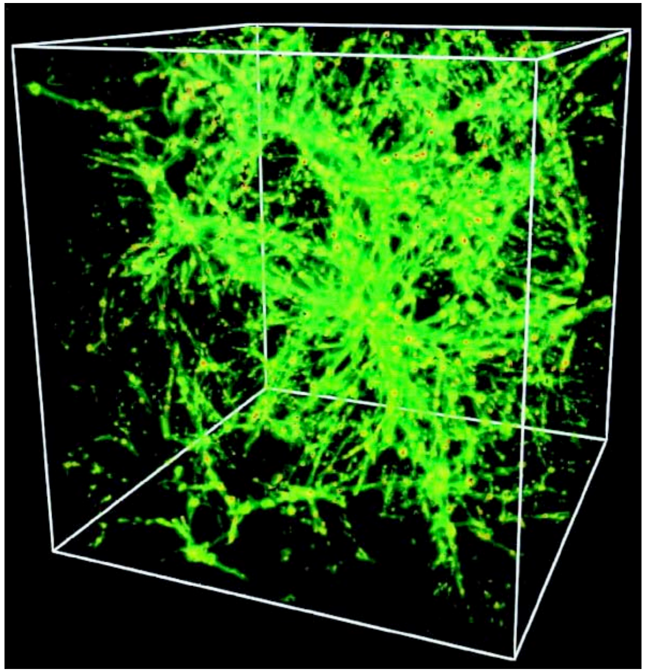
  Lyman alpha forest: Diffuse $T<10^5$K, $\delta<1000$

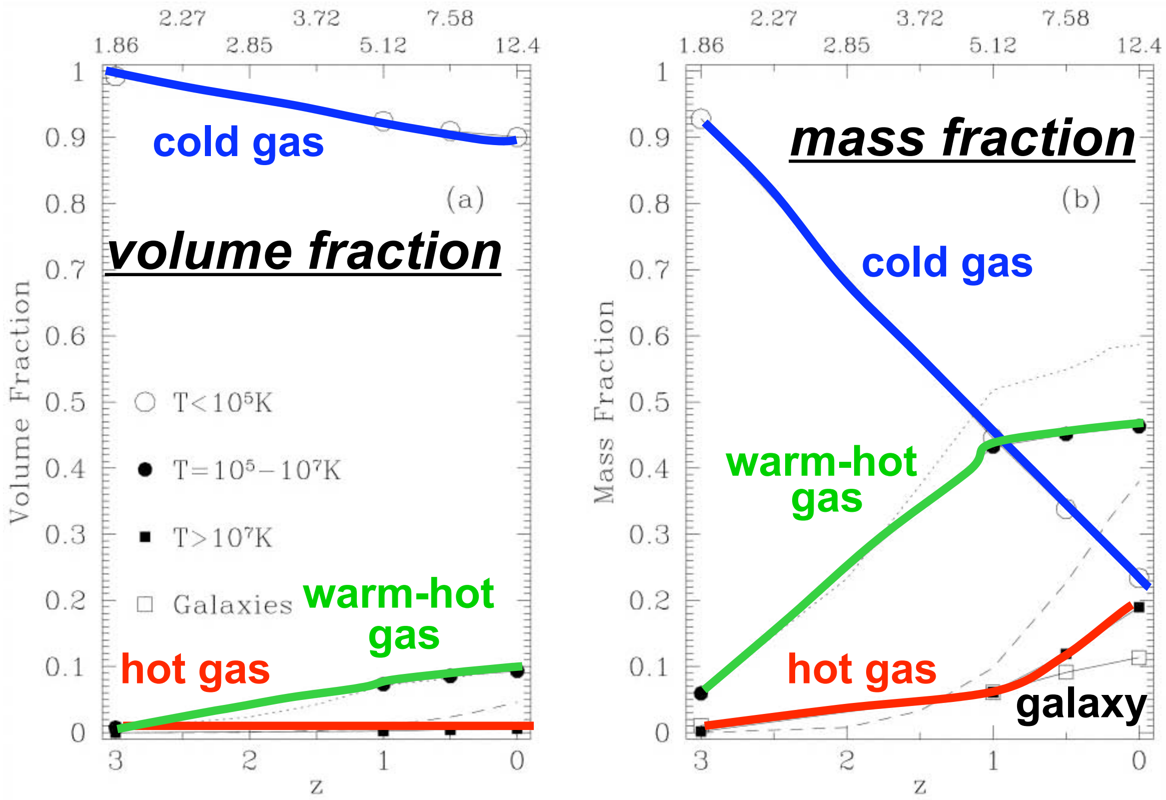
  X-ray:hot ICM $T>10^7$K

Where are missing baryons in the Universe ?

~40% of total baryons at z=0 are IGM with 10^5K<T<10^7K (Cen & Ostriker 1999)

-> Warm-Hot Intergalactic Medium



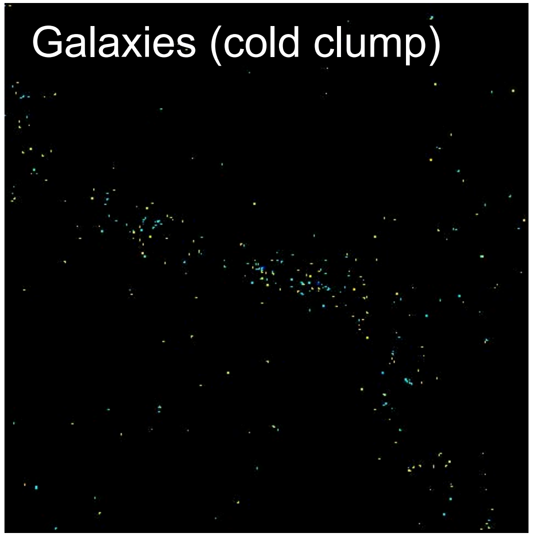


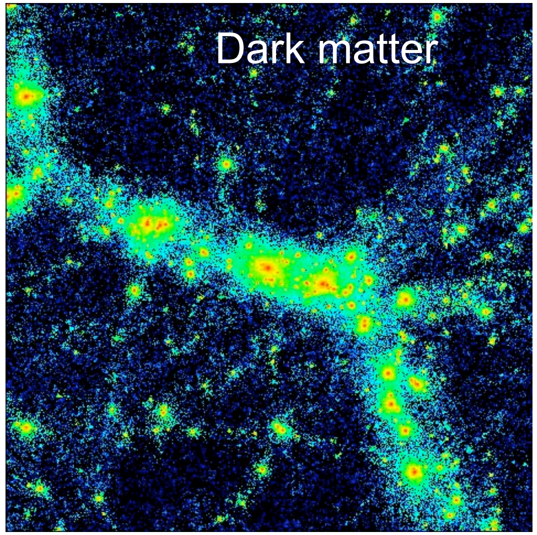
A close-up view of a filament

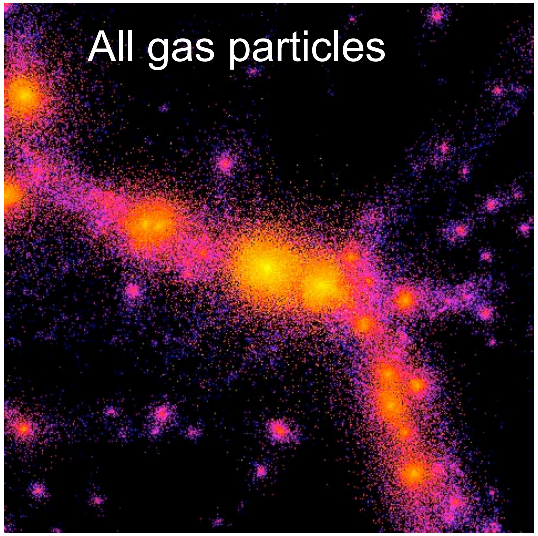
Λ CDM simulation by Yoshikawa et al. 2002

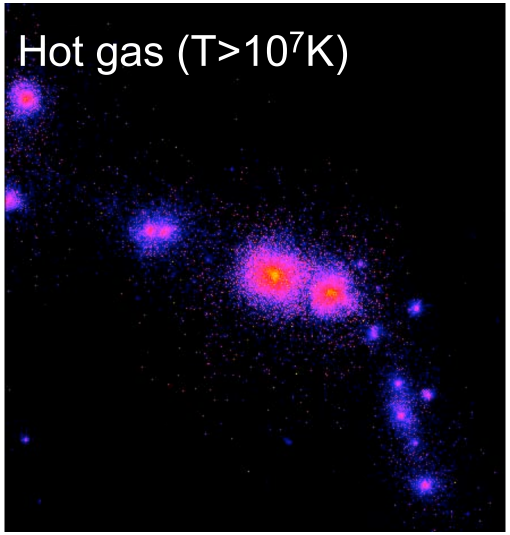
A 30 Mpc/h box around a massive cluster at z=0

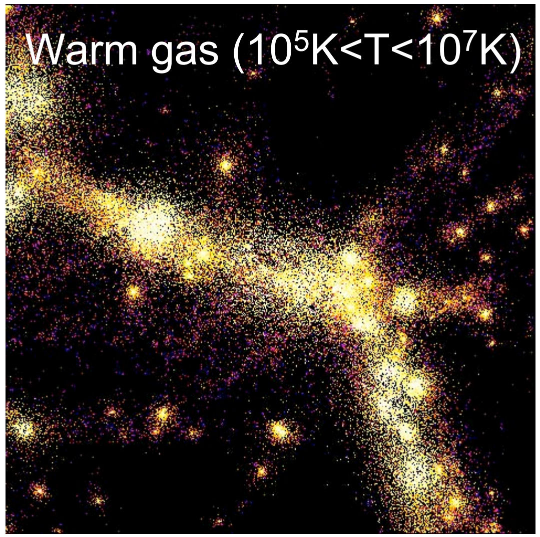
Warm gas follow dark matter very well.











How can we observe the WHIM ?

1. OVI ,OVII, & OVIII absorption lines in QSO spectra?

   New possibility: GRBs as a background sources

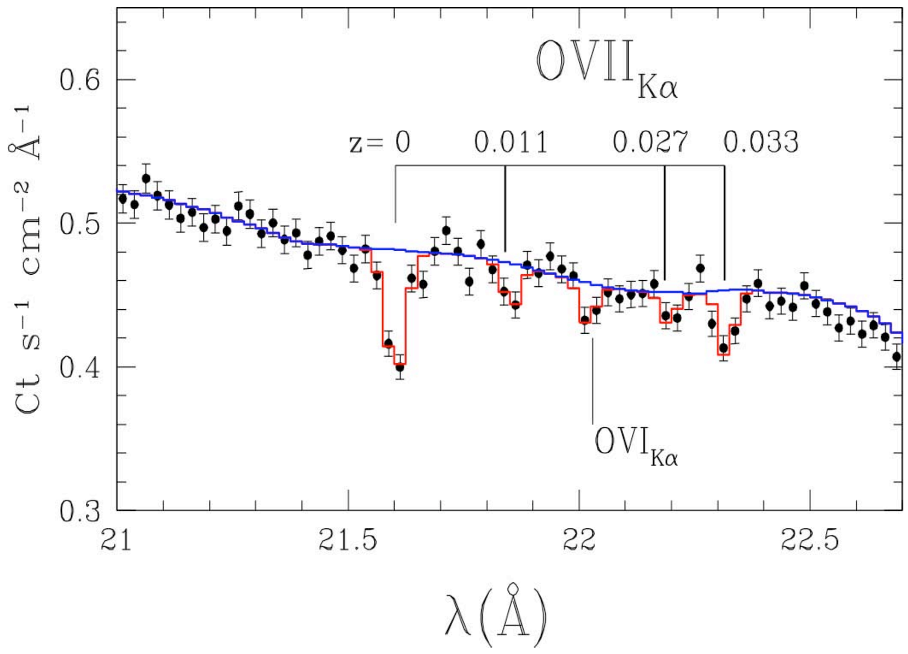
2. Bumpy soft X-ray background ?

Case study: our results around Virgo cluster

combination of absorption and emission lines

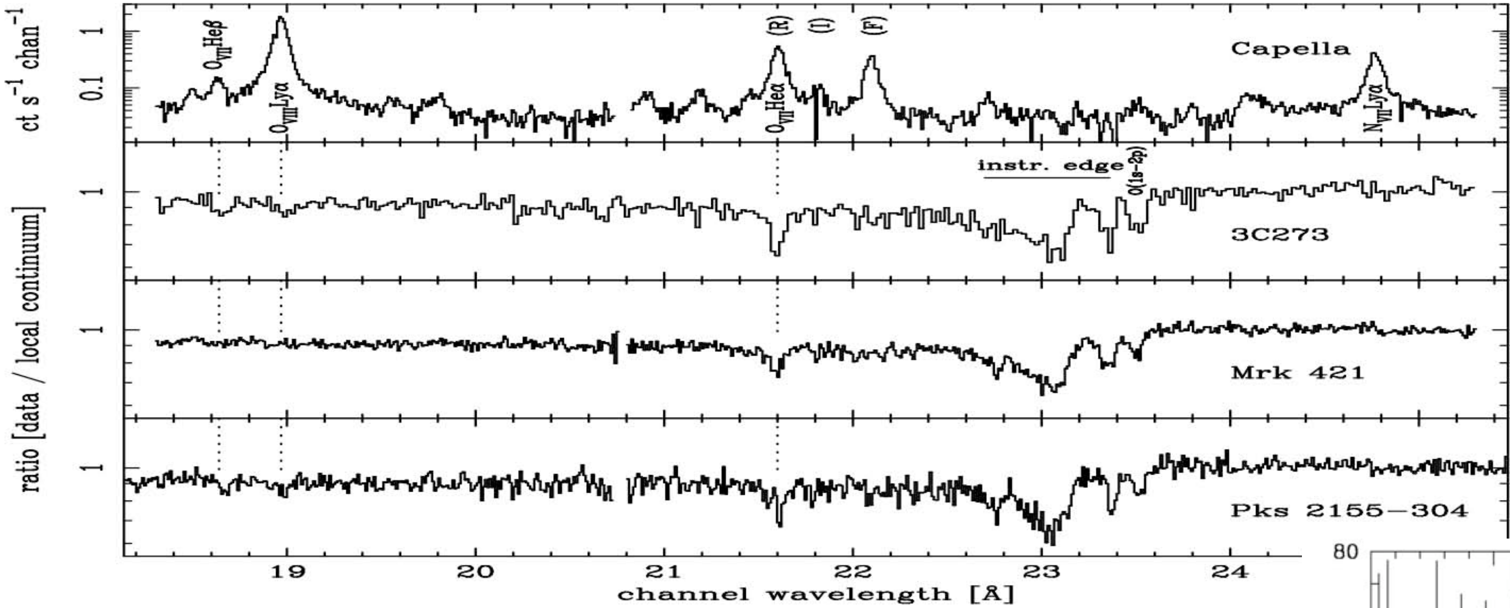
Absorption Lines towards QSO

- ✓ Mrk 421 (z=0.03) and 1ES 1028+511 (z=0.0361) show redshifted OVII absorption lines with LETG/Chandra high resolution spectra (Nicastro et al. 2005 astro-ph/0501126)
- ✓ OVI absorption lines observed by FUSE gave a lower limit of WHIM fraction in total baryonic mass as 4.8+/-0.9% at z<0.15. (Danforth & Shull 2005 astro-ph/0501054)

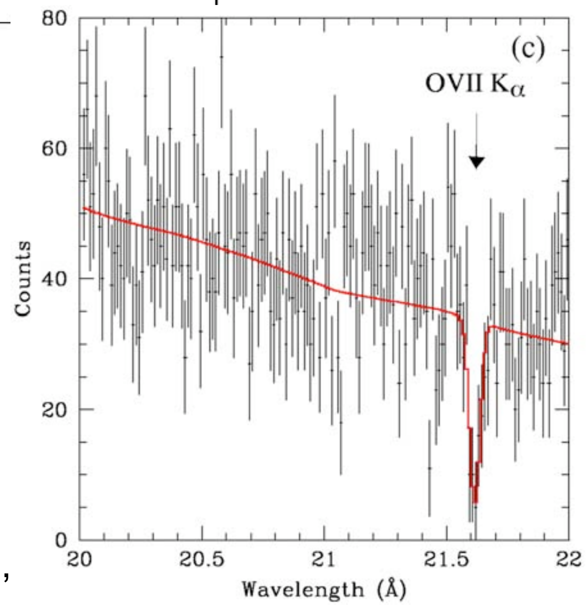


Problems of Absorption lines

- ✓ OVII, OVIII absorption lines at z=0/Local group ?
  PKS2155-304, 3C273, Mrk 421, 3C120 (Rasmussen et al. 2003)



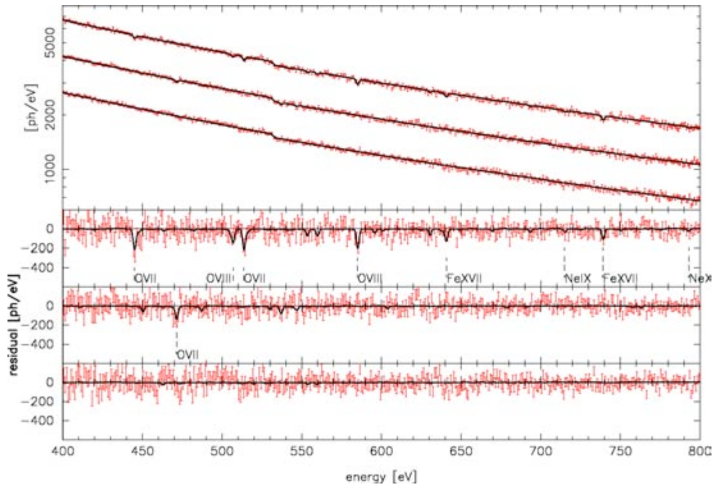
- ✓ Hot ISM also make absorption lines.
  (Futamoto et al. 2004, Yao & Wang 2005 astro-ph/0502242)

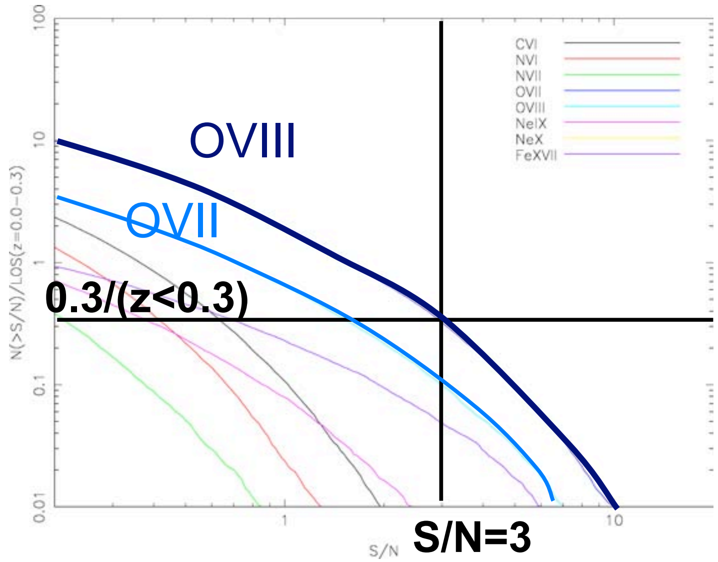


GRBs as a background source candidate

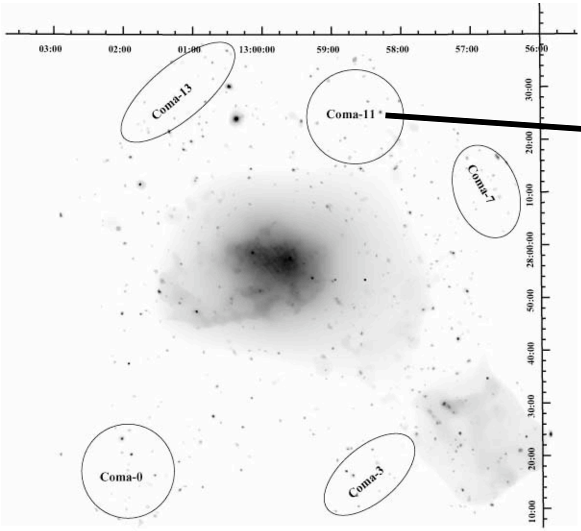
Kawahara et al. 2005 in preparation

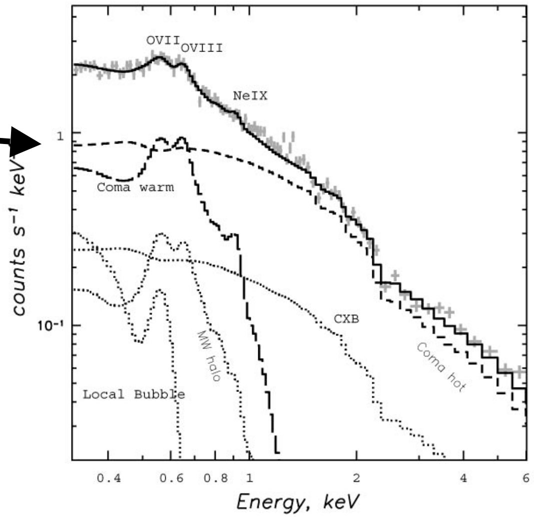
- ✓ Number of QSOs as bright as MKN421 is very small.
- ✓ GRBs are brightest X-ray objects at high z.
- ✓ Simulate a GRB spectrum with WHIM absorption:
  $F(t,E)=6\times10^{-11}\,(t/40k)^{-1.2}\,(E/1keV)^{-1.13}$ egs/s/cm^2/keV
  expected rate: 40/yr, detected 3/yr by Swift
  Obs: from 400sec after the burst.
- ✓ 0.3 OVIII absorption lines with S/N>3 detection is expected per a GRB.





Soft X-Ray excess around a cluster ?



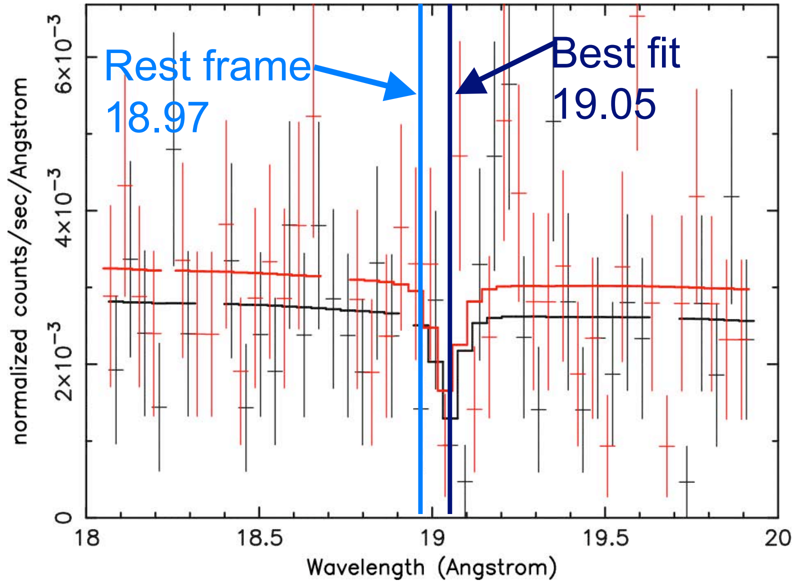


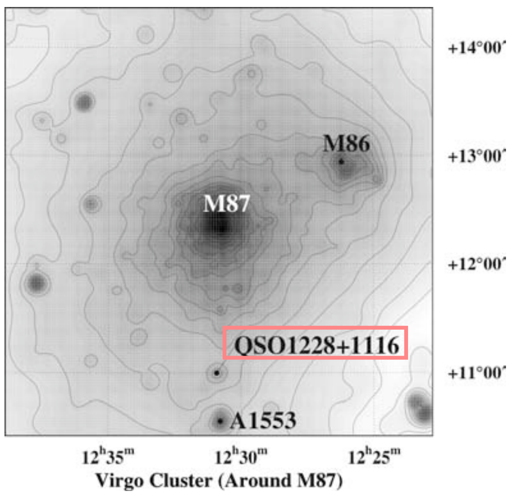
From the outer region of Coma cluster, soft emission with kT~0.2 keV and abundance of 0.1 is found.
This looks stronger than Galactic emission, which has large uncertainty in modeling. (Finoguenov et al. 2003)

Soltan et al. (astro-ph/0501275) suggest a correlation between galaxy distribution and soft X-ray background.
Excess emission of kT<0.5keV extends up to 1.5Mpc around galaxies.

Virgo cluster case (Fujimoto et al. 2004)

- ✓ LBQS 1228+1116 (z=0.237)
  83 arcmin away from M87
  - 54 ksec exposure with XMM-Newton
- ✓ 2.3 s detection of OVIII absorption line
  - cz is consistent with that of M87, 1307 km/s
  - kT>0.20 keV

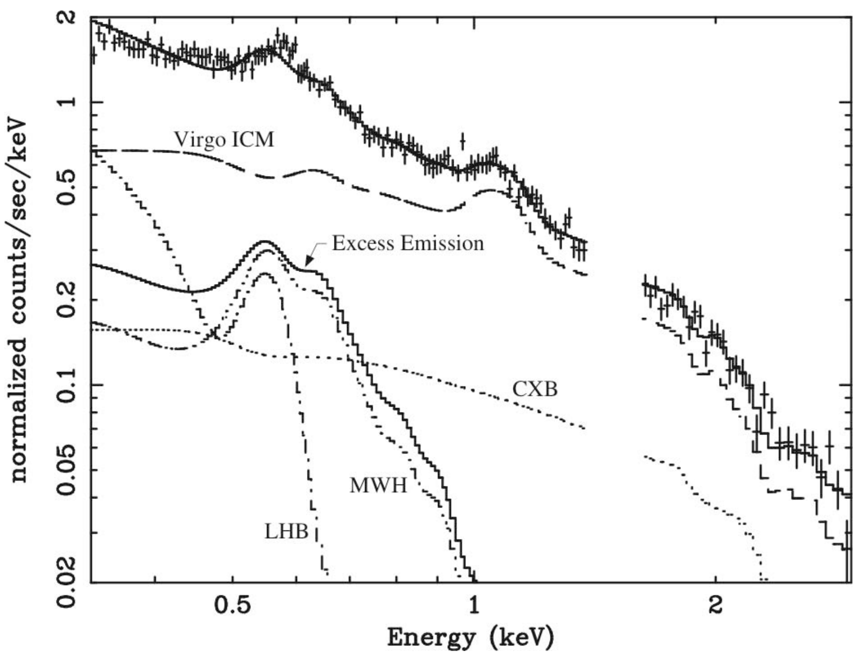




	O VIII	O VII
Energy (eV)	650.9 (+0.8 -1.9)	571.6 (fixed)
Cz (km/s)	1253 (+881-369)	--
EW (eV)	2.8 (+1.3 -2.0)	<2.8 (3σ)
N_{ion} (/cm^2)	6.2(+3.3 -4.4)x 10^{16}	<3.7 x10^{16} (3σ)

Search the Emission from Warm Gas

- ✓ The backgrounds are
  - Non X-ray particles, CXB, Vigo hot ICM(kT~2keV), local hot bubble (kT~0.07 keV), Milkyway halo (kT~0.2 keV)
  - LHB and MWH temperature are studied by Lumb et al. 2002
  - Contribution from North Polar Spur ?
- ✓ After subtracting these BGs with reasonable systematic errors, we obtained a soft X-ray emission. We treated as an upper limit of WHIM emission
- ✓ If the redshift of the Oxygen lines are measured, we can determine the origin of the soft X-ray emission.



PN spectrum from 247 $arcmin^2$ area around the QSO

Combining the absorption lines and the excess emission

- ✓ Absorption EW: $n_{ion} \times L$
  - $n_{ion}=n_e x[O/H] x f_{ion}$
  - $f_{ion}(T)$ can be obtained by OVII/OVIII ratio
  - L can be limited by line width
- ✓ Emission Measure : $n_e n_{ion} \times V$ (V=LxS)
- ✓ Basically, baryon density and metal abundance can be solved.
  - In Virgo case, the absorption line gives
    N_{OVIII}~6×10^{16} cm^{-2},$\Delta Z<0.02$ $kT>0.2$ keV
  - Then upper limit of WHIM emission measure gives
    $n_e<6\times10^{-5}cm^{-3}(A/0.1)(f/0.4)$ and L> 9Mpc $(A/0.1)^{-2}$ $(f/0.4)^{-2}$
    (A: abundance in solar ratio)

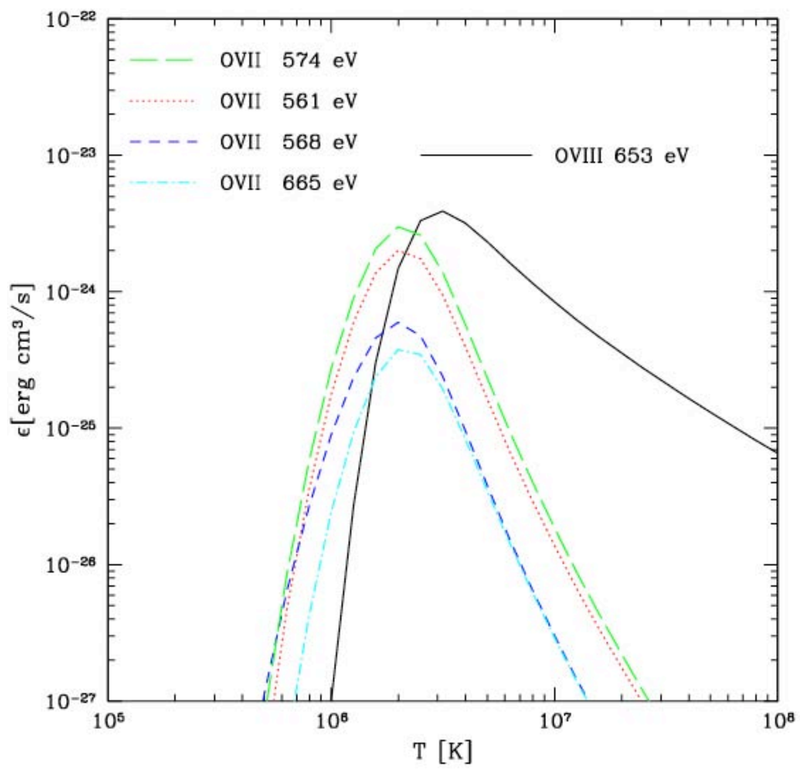
Oxygen emission lines as WHIM probe

OVII :574, 561, 568, 665 eV

OVIII :653 eV

- ✓ Why oxygen emission lines?
  - Most abundant metal
  - Good tracers at $T=10^6$-10^7K
  - Not restricted to region toward background QSO
  - With enough energy resolution, 3D map of large scale structure is obtained. Galactic component can be excluded.

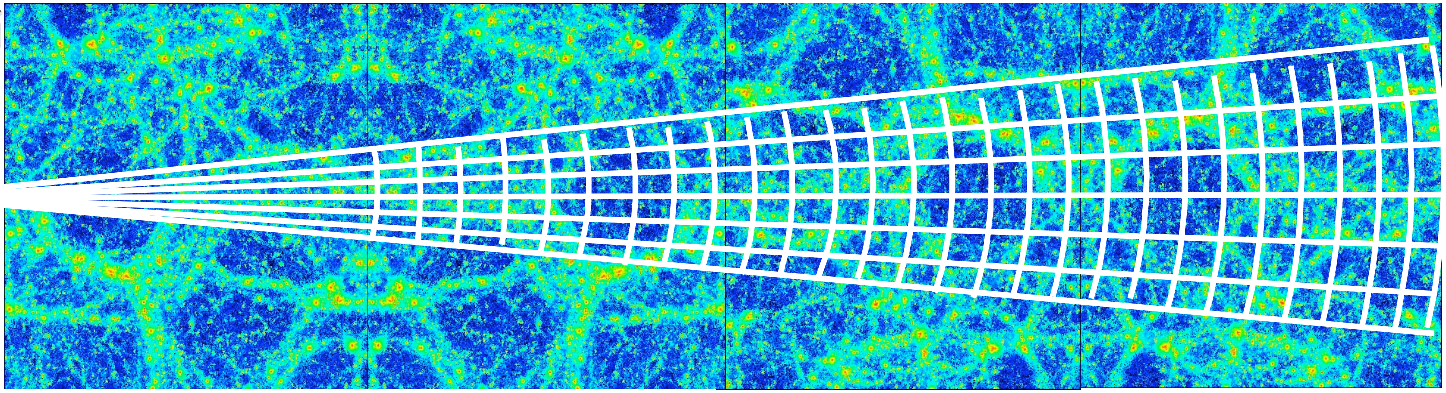
Suitable for systematic WHIM survey



Simulation for Oxygen lines from WHIM

(See Yoshikawa et al. 2003, 2004 for details)

- ✓ Cosmological SPH simulation in Ω=0.3,Λ=0.7,σ_8=1.0,h=0.7 Λ-CDM made a “Local Universe” with DM, baryon , and potential.
- ✓ Temperature is assumed to be equivalent with the potential.
- ✓ Various Metallicity models based on the density
- ✓ Convolve the emissivity (continuum and lines) over the lightcone from z=0 to z=0.3
- ✓ Add Galactic emission lines (McCammon et al. 2002) and CXB conti

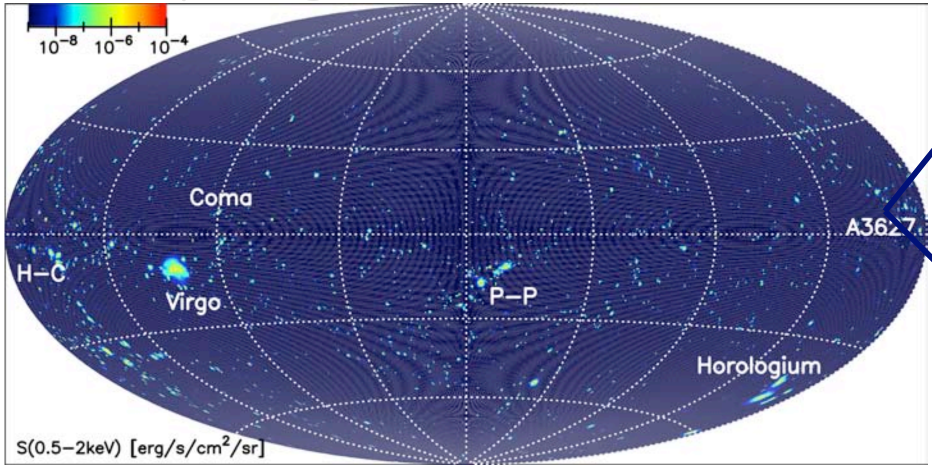


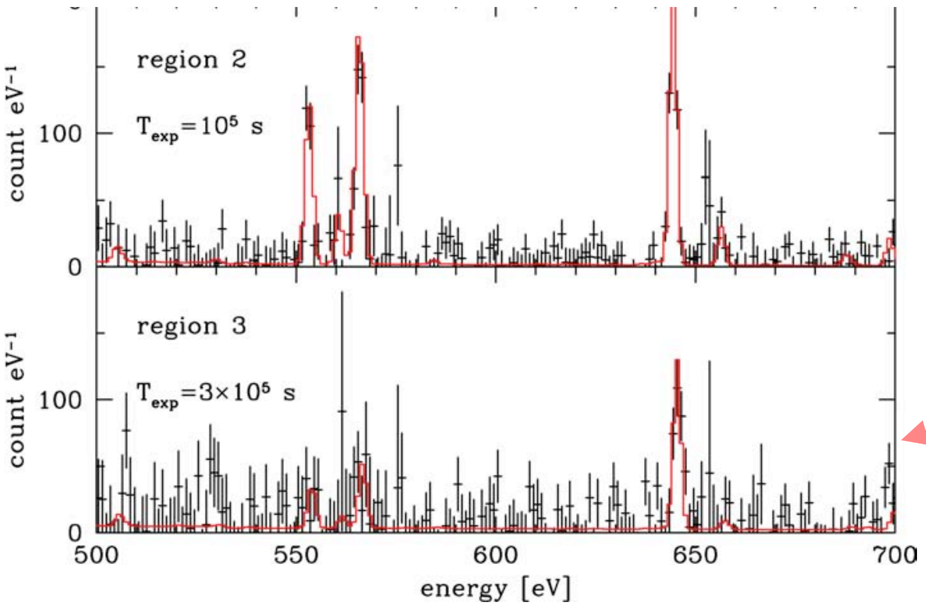
z=0

z=0.3

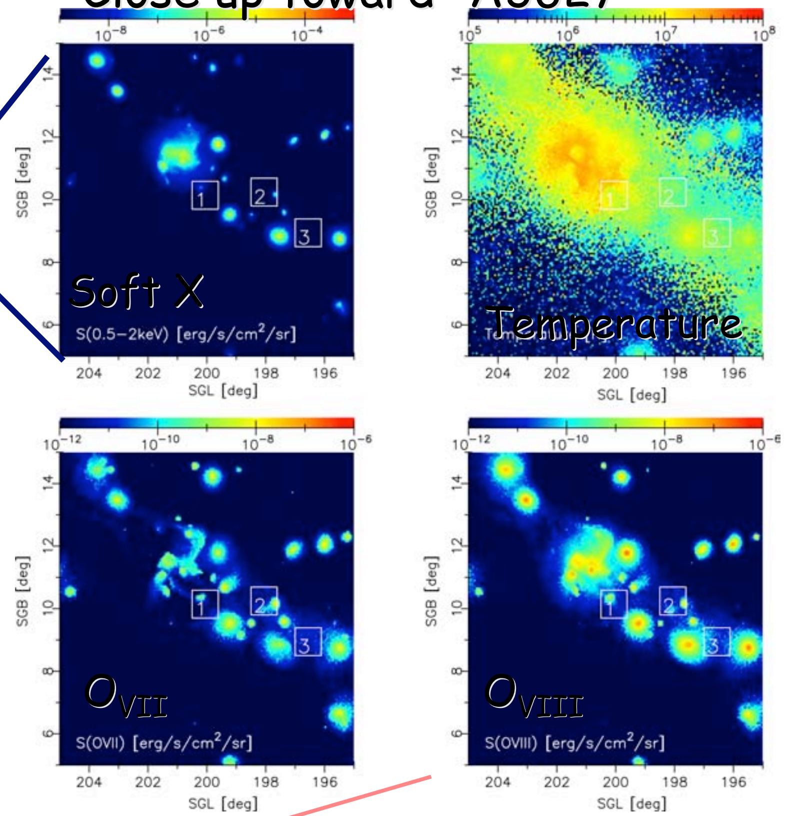
Simulated Local Universe in X-Ray

All Sky Image in 0.5-2keV band



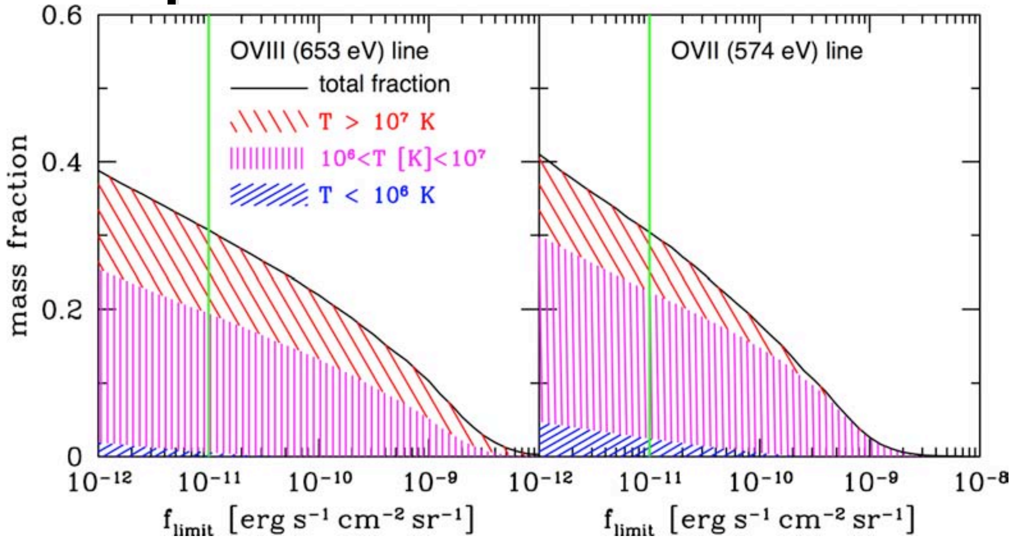


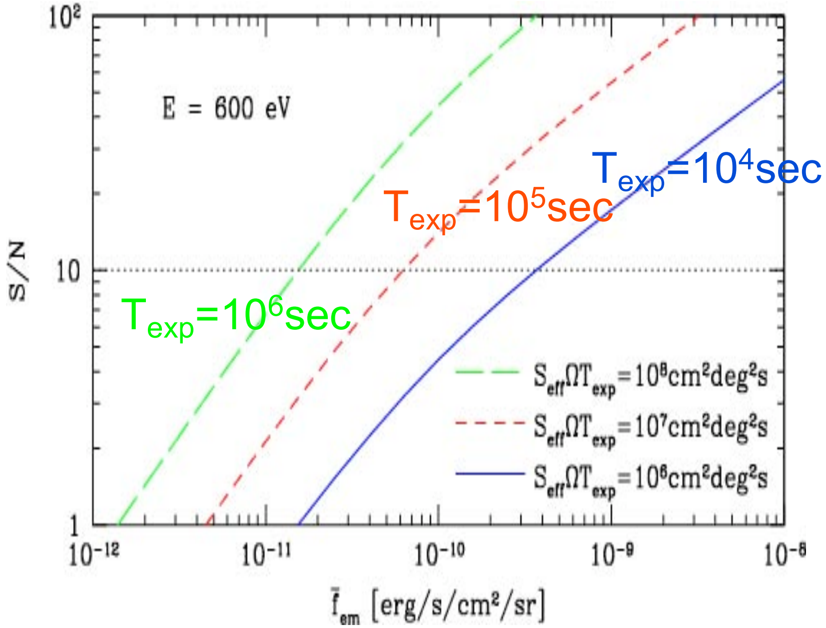
Close up toward "A3627"



Simulated spectra

Expected S/N for OVIII line

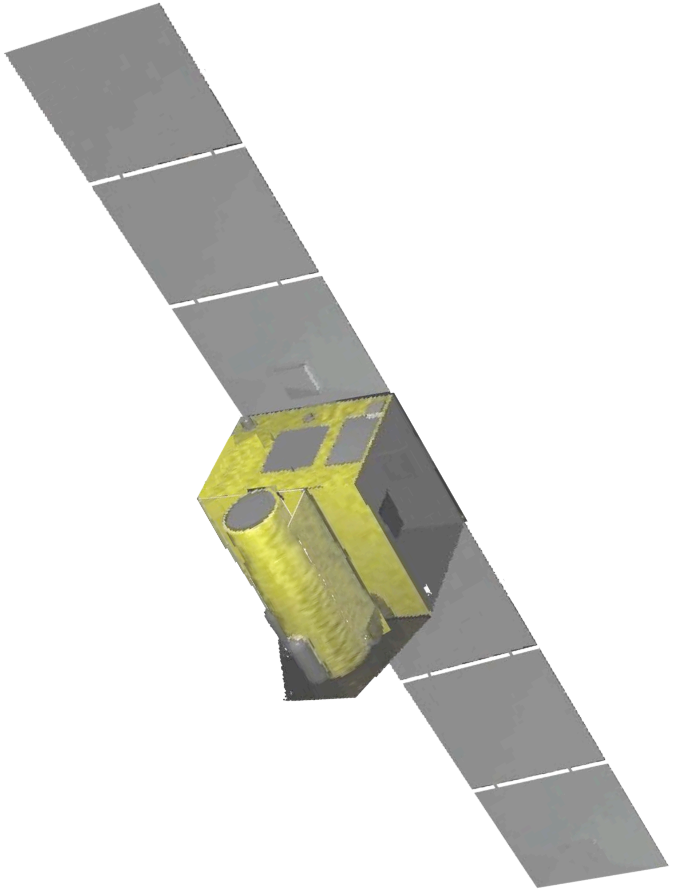




- ✓ To observe WHIM via O lines, line sensitivity of ~10^{-11} ergs^{-1}cm^{-2}sr^{-1} is required.
- ✓ S/N ratio are calcutated for ΔE=2 eV detector assuming exposure by product of area, field-of-view and time.
- ✓ For reasonable observation time, $S\Omega$=100deg^{2}cm^2 is necessary

Proposed small mission --DIOS--
(Diffuse Intergalactic Oxygen Surveyor)

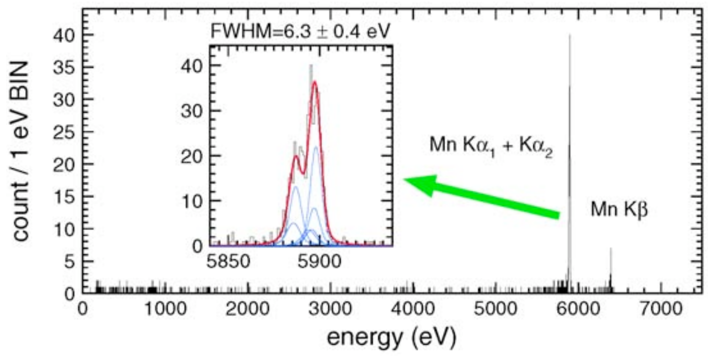
ΔE=2eV and $S\Omega$
=100cm^{2}deg^2 with
small (<400kg) satellite

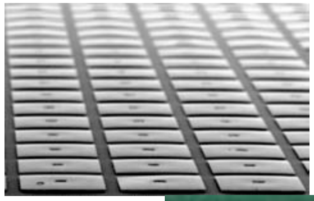


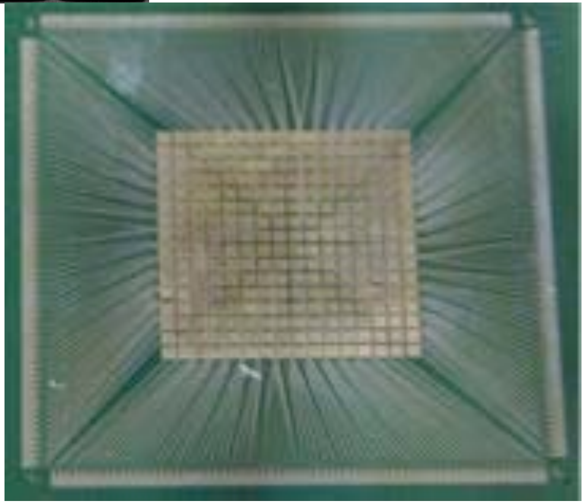
- ✓ Use TES micro calorimeter array for good energy resolution
- ✓ 4-reflecting X-ray mirror to obtain wide field-of-view
- ✓ 3D mapping of Oxygen lines of 10x10 degree^2 sky into z=0.3
- ✓ Responsible to GRB alert
- ✓ Submitted to ISAS/JAXA but review is not yet started.

TES calorimeter array

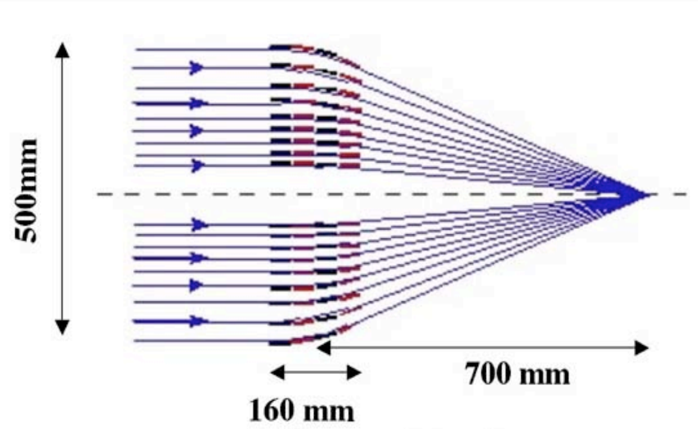
- Astro-E2/XRS is 3.6mm square, but we need 1cm square array. XRS -type detector is hard to be enlarged more than 64 pixels..
- TES (Transition Edge Sensor) uses transition between superconducting and normal phase as a thermometer.
- It will be a prototype of NeXT Soft X-ray Spectrometer.
- 16x16 array format TESs has been fabricated and tested.
- Signal multiplexing is under developing (AC bias & multi-input SQUID)

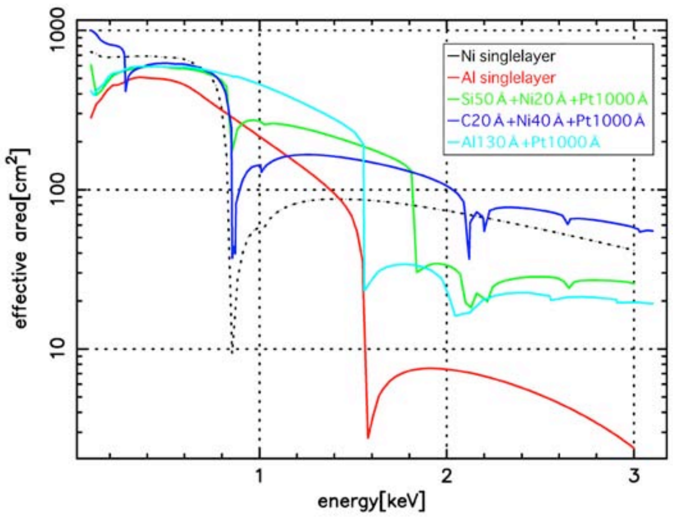






4-stage X-ray mirror

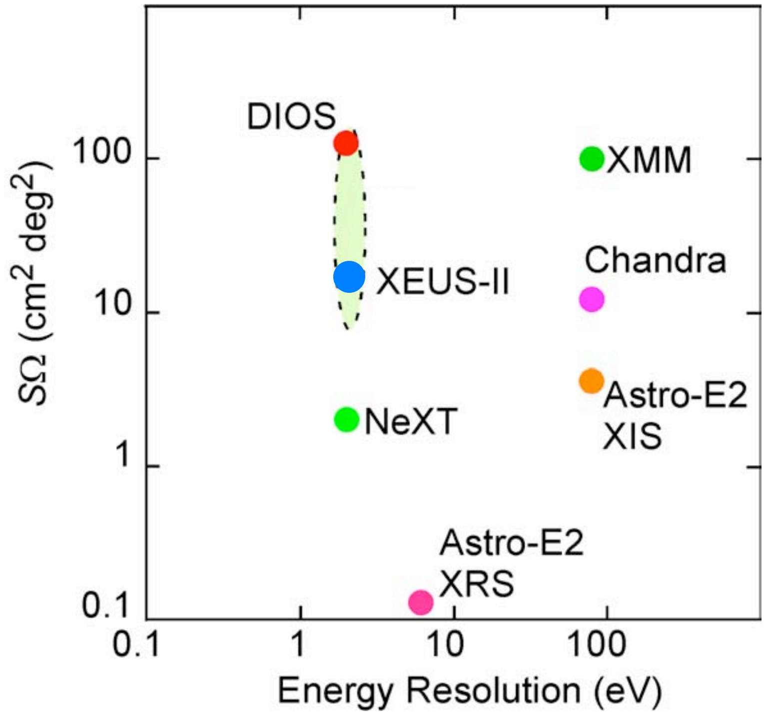




- ✓ Standard 2-stage Walter mirror Larger area requires longer focal length and smaller fov for finite-size detector.
- ✓ 4-reflecting optics: 500mm diameter mirror with wide fov (50′) with short focal length (70cm). Compact and suitable to small mission
- ✓ Angular resolution of 3′ is not so good, but enough to observe diffuse emission
- ✓ Energy range:up to 1.5 keV
  - Cover Mg K line
- ✓ Fabrication test has been started at Nagoya Univ.

DIOS Performance

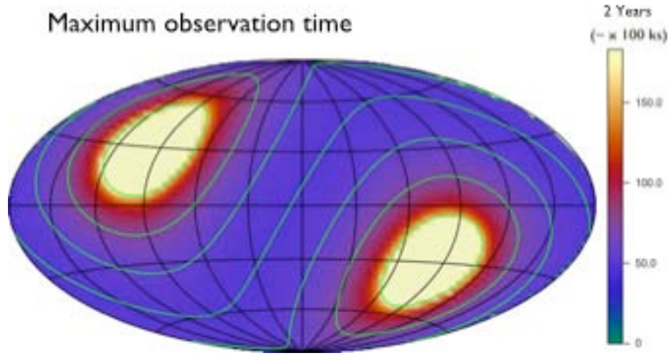
Effective area	~200 cm^2 @0.6keV
Field of view	50' diameter
SΩ	~100 $cm^2 deg^2$
Angular resolution	3' (16 x 16 pix)
Energy resolution	2 eV (FWHM)
Energy range	0.1 - 1.5 keV
Mission life	> 5 yr

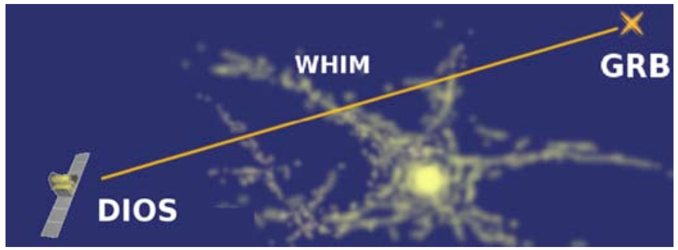


Larger SΩ than that of XEUS-II

Observation Plan

- ✓ Survey observation:
  10x10 degree squares with
  100ks exposure -> WHIM,
  1/4 sky with 1ks ->hot ISM
- ✓ Pointing observation :
  selected clusters, QSOs
- ✓ Response to GRB alerts <500sec
  - Uplink commands via full time access to the internet with ORBCOMM spacelink.





~10 GRBs/year with
$F(t,E)=5\times10^{-12}\,(t/40ks)^{\wedge 1.2}\,(E/1keV)^{-1.1}$
$(erg/cm^{2}/sec/keV)$

Summary

- ✓ Warm-hot IGM (10^5K<T<10^7K) is the most plausible missing baryon candidate.
- ✓ X-ray will be a window to the missing baryon. Oxygen line mapping will reveals the large scale structure of baryons in the Universe
  - Contamination from the Galactic hot gas should be excluded.
  - Complementary studies of emission and absorption lines will give us the density and metallicity of WHIM
- ✓ For that purpose, fine spectroscopy by non-dispersive method and large field-of-view are essential.
  Not a large X-ray observatory but an alternative approach like DIOS is required.