A search for a contribution from axion-like particles to the diffuse background in the keV band utilizing the Earth's magnetic field with *Suzaku*/XIS observation

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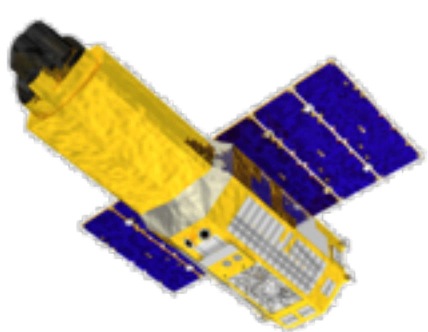

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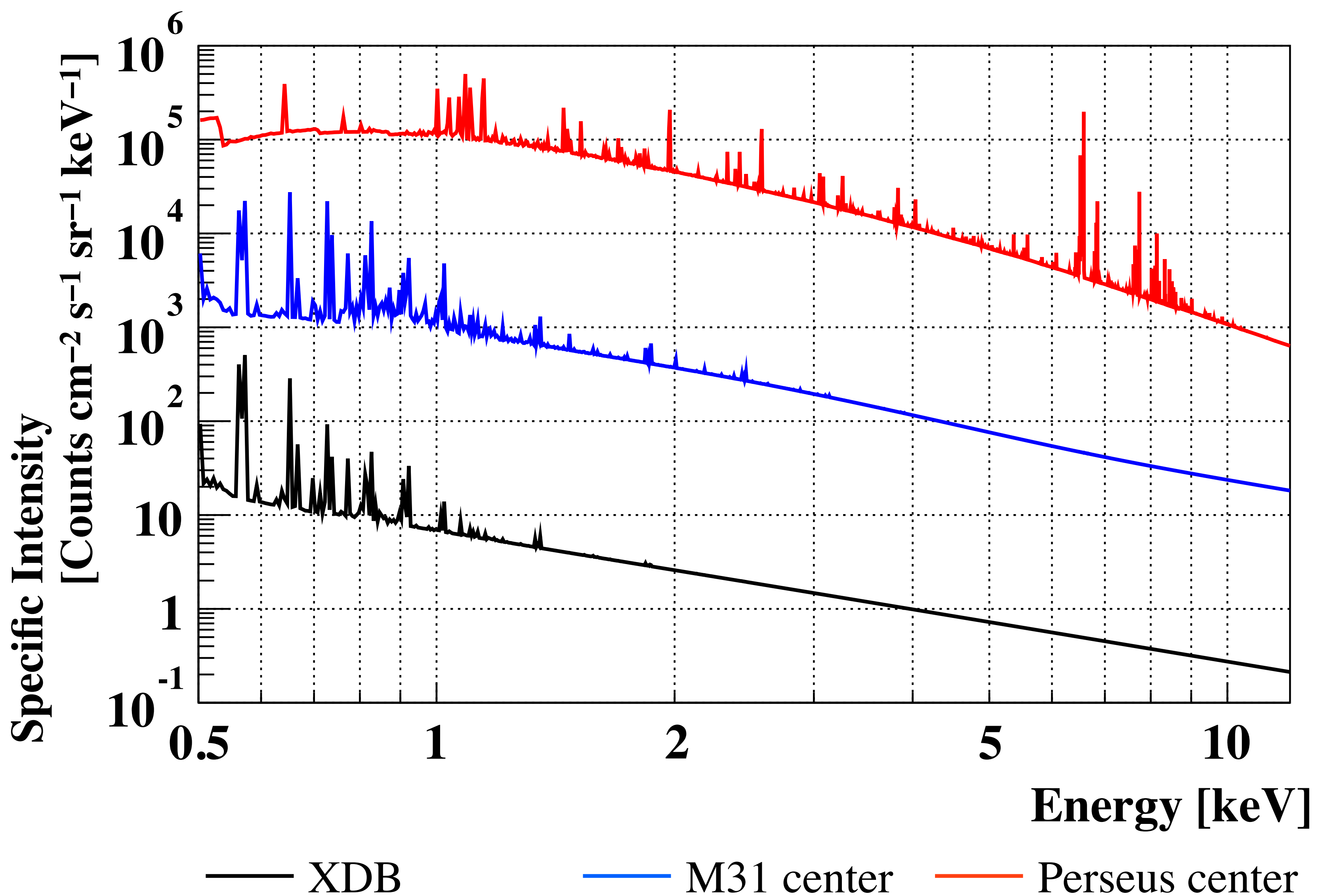
“Background” spectrum for DM search in keV band

Dark matter density: **Milky Way** < **Galaxy** < **Cluster of galaxy**

Hot plasma: **Milky Way** < **Galaxy** < **Cluster of galaxy**



Sekiya 2015

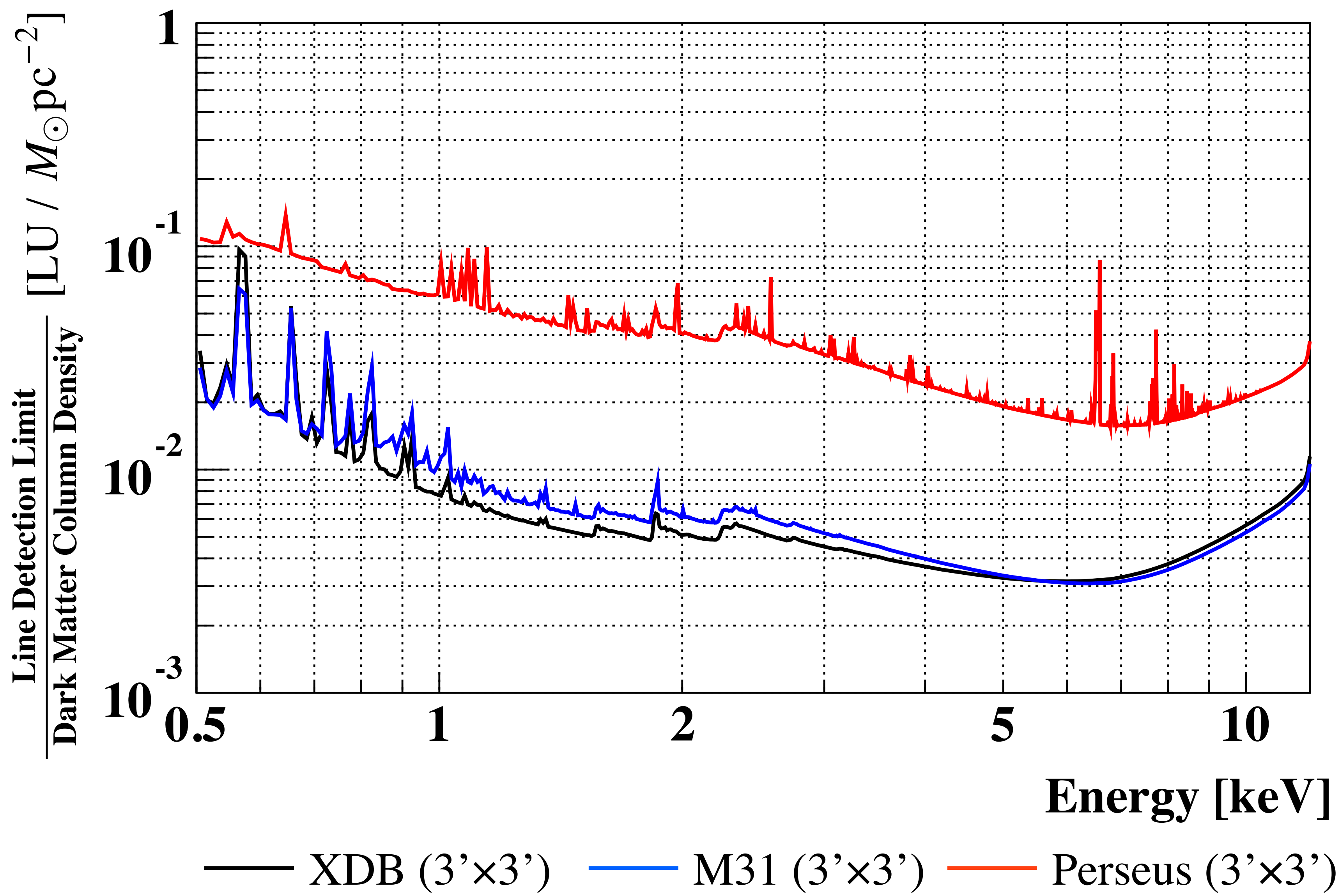
Figure 3.1 Specific intensities of the typical XDB (Yoshino et al., 2009), the center of the M31 and the Perseus cluster (Tamura et al., 2009) in the 0.5 – 12.0 keV range. Note that detector responses are not convolved.

Sensitivity of DM search in keV band

Dark matter density: **Milky Way** < **Galaxy** < **Cluster of galaxy**

Hot plasma: **Milky Way** < **Galaxy** < **Cluster of galaxy**

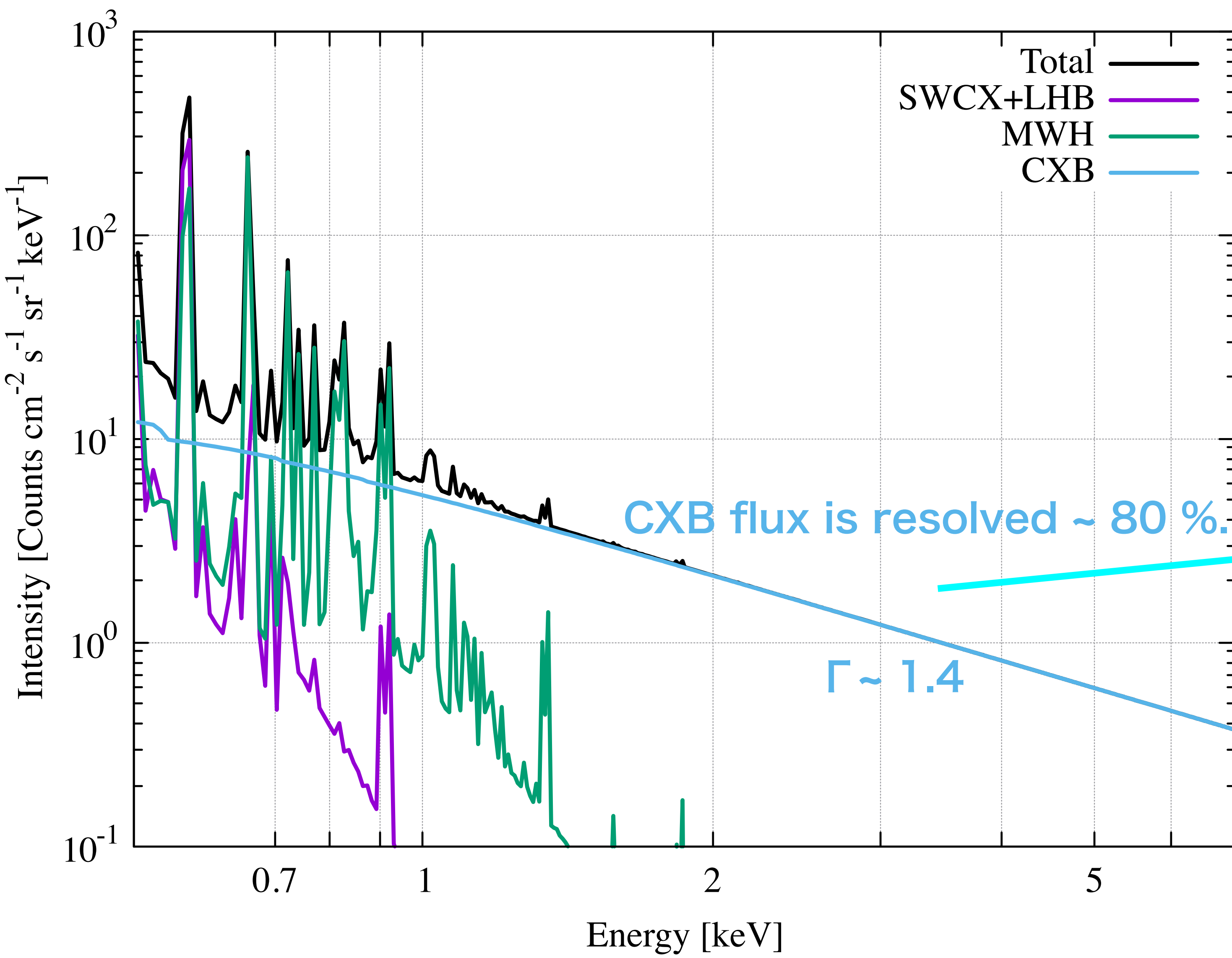
Suzaku/XIS 100ksec

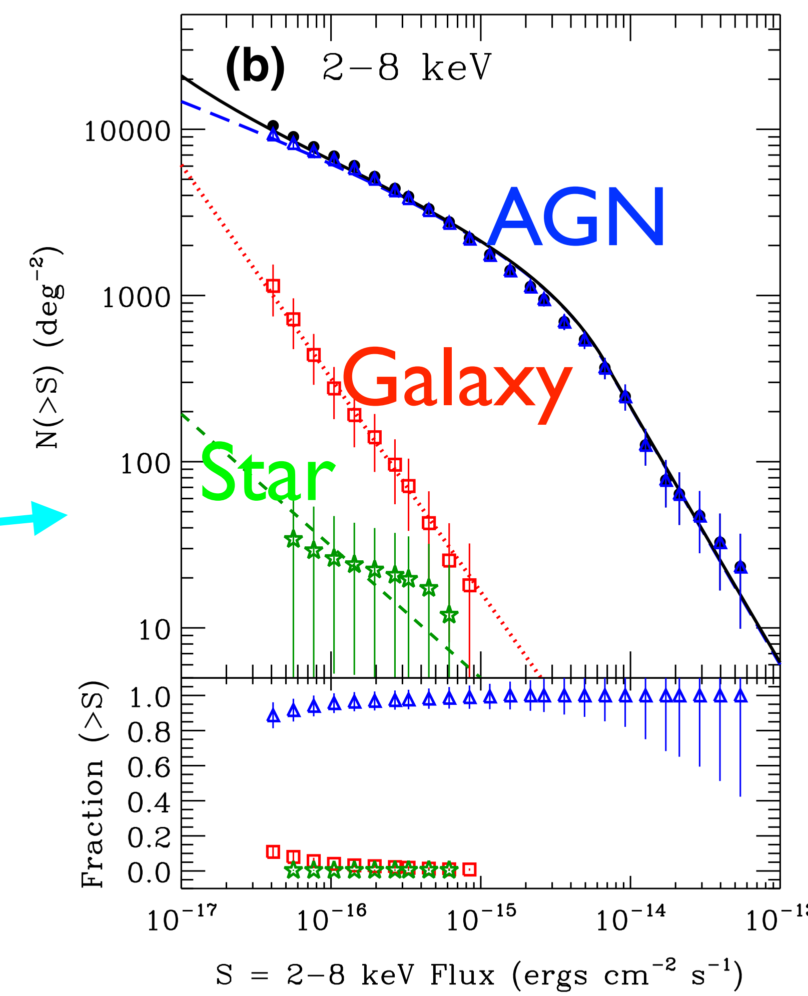


Sekiya 2015

Figure 3.6 Same as Figure 3.5 but for 3σ line detection limits normalized by their column densities.

Understanding X-ray diffuse background (XDB)





Brandt&Alexander 2015

XDB components

Solar Wind Charge Exchange + Local Hot Bubble (kT ~ 0.1 keV)

Milky Way Halo (kT ~ 0.2 keV)

Cosmic X-ray Background (extragalactic point sources)

Comparison among X-ray observatories

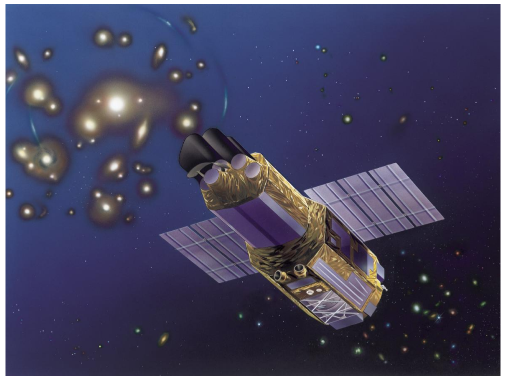
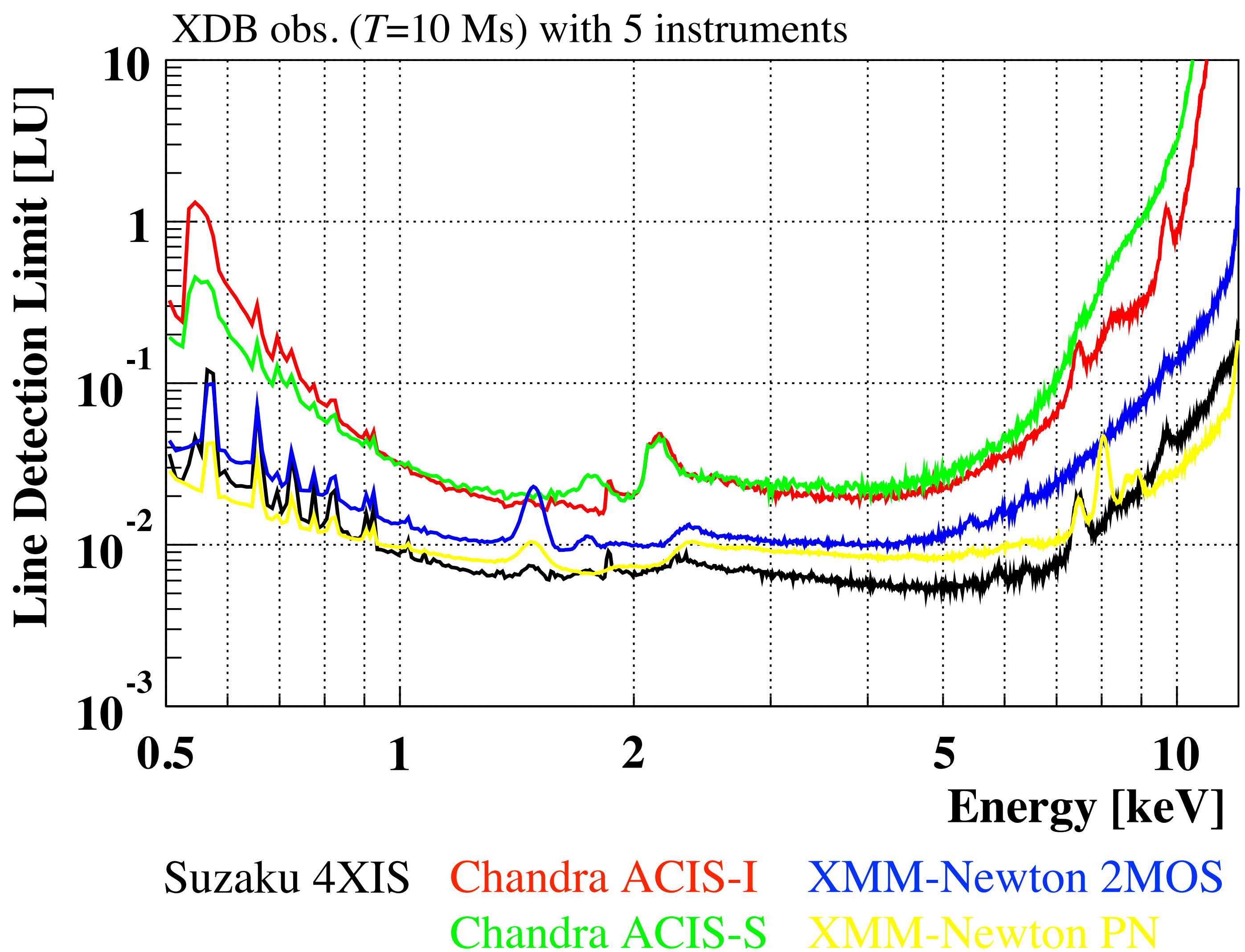


Table 3.1 Summary of orbit and CCD imaging spectrometer on X-ray observatories.

Satellite	*Suzaku*	*XMM-Newton*	*Chandra*
Orbit	low earth	highly elliptical	highly elliptical
Perigee [km]	524	7.0×10^3	13.2×10^3
Apogee [km]	531	113.8×10^3	135.7×10^3
Inclination [deg]	31.38	66.17	76.9
Period [min]	95.19	2861.59	3809.54
CCD name	XIS	MOS+PN	ACIS-I (FI) ACIS-S(FI/BI)
Field of view	$17'.8 \times 17'.8$	$30'$ in diameter	$16' \times 16'$
Energy range [keV]	0.2–12	0.1–15	0.5–12
Effective area [cm^2]	390 at 1.5 keV (BI)	922 at 1 keV (2MOS) 1227 at 1 keV (PN)	380 at 4 keV
NXB *	1–10	5–100	10–1000

* In unit of $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-2}\ \mathrm{keV}^{-1}$.

Strategy for DM search with X-ray satellite



Sekiya 2015

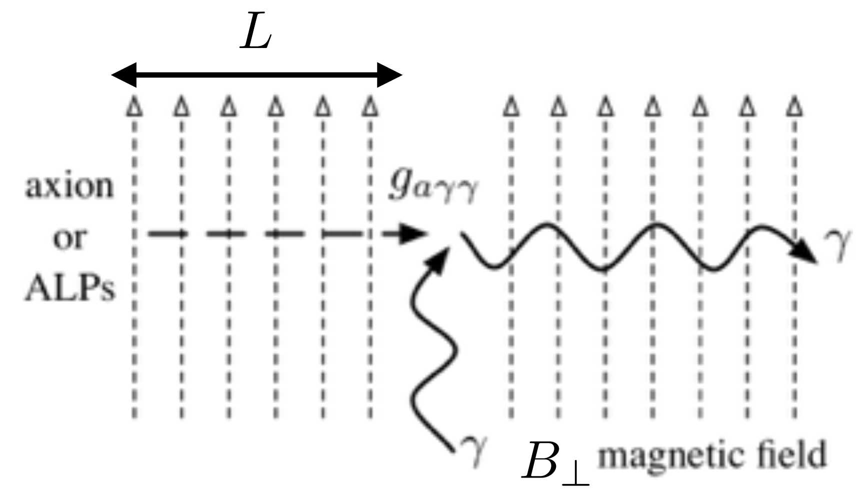
Figure 3.10 3σ line detection limits estimated from Eq.3.9 with the five CCD instrument observations of the XDB for 10 Msec of exposure time. The lowest cases for the XMM-Newton and Chandra instruments are shown.

→ XDB + Suzaku/XIS is the best way!

Axion Like Particle(ALP)-photon conversion: $P_{a\to\gamma}$

ALP-photon conversion probability in a vacuum (van Bibber+ 1989)

$$P_{a\to\gamma}(q,t) = \left(\frac{g_{a\gamma\gamma}B_\perp(t)}{2}\right)^2 2L^2 \frac{1-\cos(qL)}{(qL)^2}$$



$$\xrightarrow{qL<\pi} \left(\frac{g_{a\gamma\gamma}B_\perp(t)\,L}{2}\right)^2$$

$$q = m_a^2/2E_a$$

$g_{a\gamma\gamma}$: coupling constant

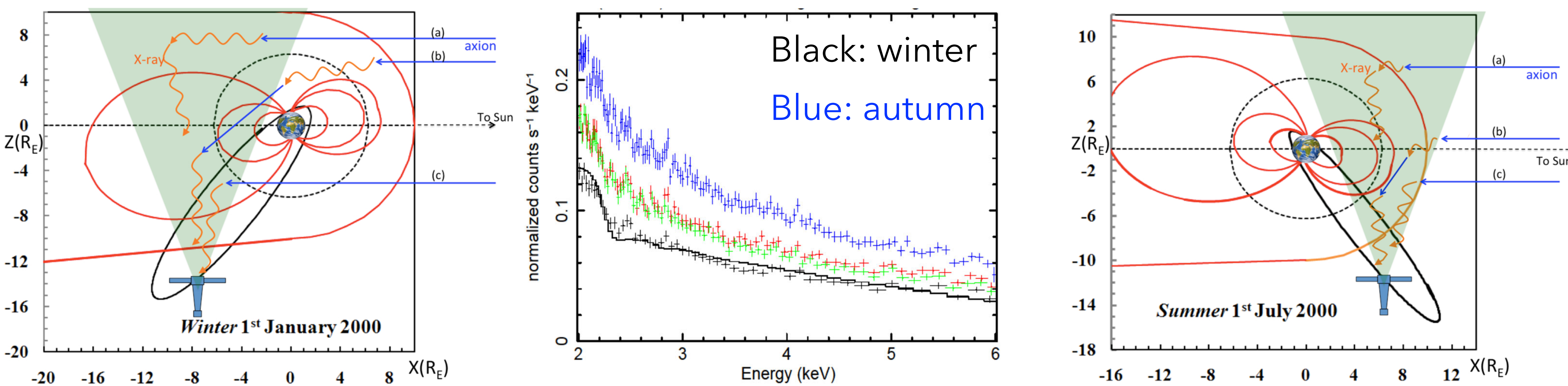
$$m_a < \sqrt{\frac{2\pi E_a}{L}} \qquad m_a < 10^{-6}\ \mathrm{eV}\left(\frac{E_a}{\mathrm{keV}}\right)^{\frac{1}{2}}\left(\frac{L}{10^4\ \mathrm{km}}\right)^{-\frac{1}{2}}$$

- $P_{a\to\gamma}$ is simply proportional to $(B_\perp L)^2$ ($qL < \pi$)
- CAST experiment: $B_\perp$ = 9.0 T, L= 9.26 m → $B_\perp L$ ~ 83 Tm (Arik+ 2014)
- Possible detection by a satellite observation using Earth's magnetic fields is claimed because a long line of sight with an order of the Earth's diameter can compensate the weak magnetic field ($B_\perp$ ~ 30 μT) (Davoudiasl & Huber, 2006)

Potential solar axion signatures with *XMM-Newton*

Fraser et al., 2014

- A seasonally varying X-ray background signal is observed.
- They conclude that this variable signal is consistent with the conversion of solar axions in the Earth's magnetic field.
- X-ray flux of 4.6×10^{-12} erg s^{-1} cm^{-2} deg^{-2} in 2–6 keV from geomagnetic conversion, which has 2.2×10^{-22} GeV^{-1} for an axion mass in the μeV, has been interpreted.



Roncadelli & Tavecchio, 2015

- The result in Fraser et al. (2014) cannot be explained by this origin from the solar ALP.
- To preserve the momentum of the photon by the Primakoff process in case of relativistic ALP, the *XMM-Newton* cannot observe because it never points toward the Sun.

→ **Instrumental background depending on its orbit? or another ALP?**

Possibility to detect X-ray originating from ALP

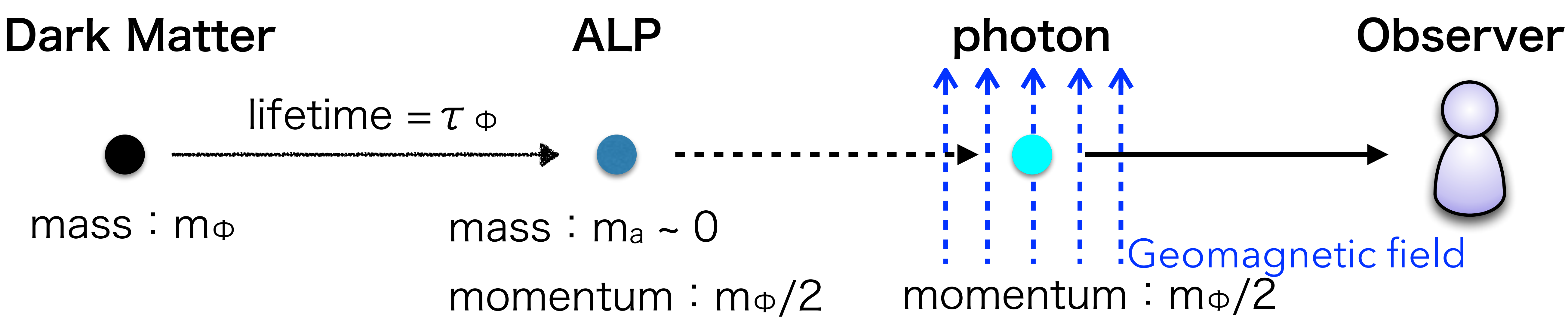
When the lifetime decaying from DM to ALP is longer than age of the universe…

(Case-A) If ALP momentum is in the keV band, we can observe the single depending on the Earth's magnetic field.

Additionally, in the case of the two-body decay…

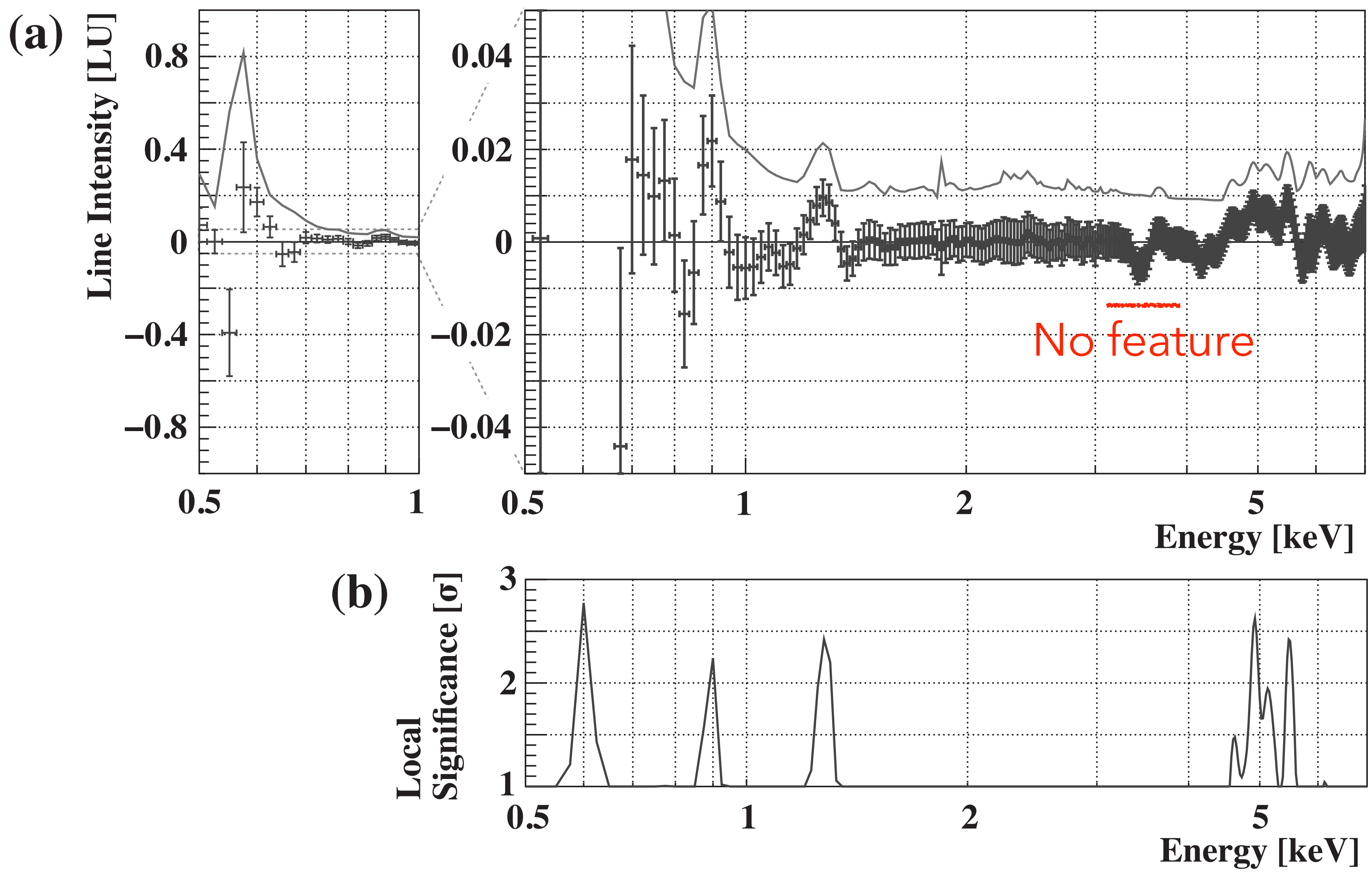
(Case-B) If DM exists in the solar system neighborhood, the observed spectrum shape is monochromatic. (e.g. Cicoli+ 2015)

(Case-C) If DM is distributed over the universe uniformly, the observed spectrum shape is continuum as a simple power-low (Γ = +0.5) created by the superposition of monochromatic lines with different cosmological redshifts. (e.g. Asaka+ 1998)



(Case-B) Detection limit of monochromatic spectrum

- From the Suzaku archive, Sekiya+ 2016 selected 187 data sets of blank-sky regions that were dominated by the X-ray diffuse background.
- Sekiya+ 2016 exhibited no significant detection of an emission line feature from dark matter.
- There is no feature on reported 3.5 keV line (e.g. Bulbul+ 2014).



Sekiya+ 2016

Possibility to detect X-ray originating from ALP

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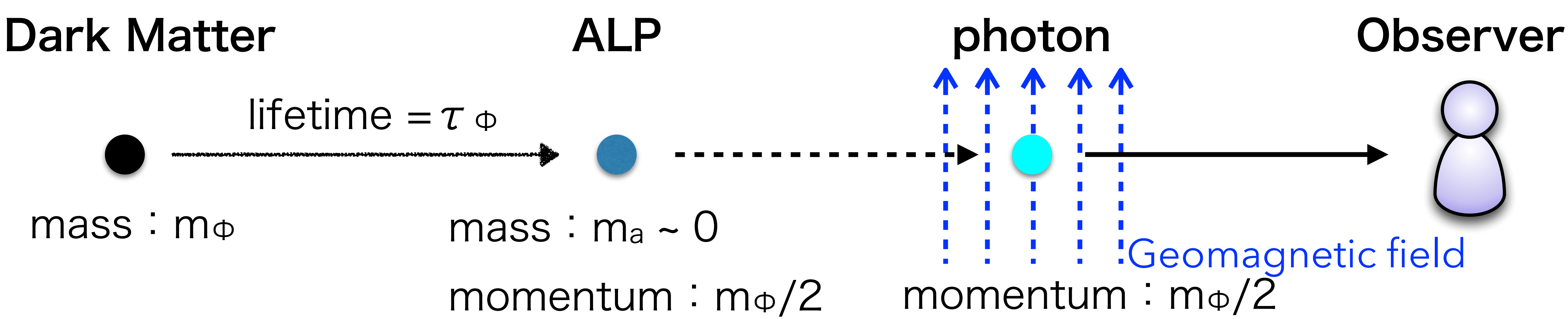


(Case-C) Continuum created by cosmological redshift

When dark matter distributed over the universe uniformly is assumed, we observe the continuum spectrum of the superposition of such monochromatic spectrum

$$I\left(E_\gamma\right) = \int_{\mathrm{l.o.s}} \frac{P_{a\to\gamma}}{4\pi m_\phi} \rho_\phi dr \times 2\delta\left(E_\gamma\left(1+z\right) - m_\phi/2\right) \quad [\mathrm{Counts\ s^{-1}\ cm^{-2}\ sr^{-1}}]$$

$$= \frac{\sqrt{2}\ P_{a\to\gamma}\ \rho_{\Phi_0}}{\pi\tau_\phi H_0 m_\phi^{5/2}}\ f\left(\frac{m_\phi}{2E_\gamma}\right)\ E_\gamma^{1/2} \qquad f(x) = \left\{\Omega_{m0} + \left(1 - \Omega_{m0} - \Omega_{\Lambda 0}\right)/x - \Omega_{\Lambda 0}/x^3\right\}^{-1/2}$$

(Asaka+ 1998)

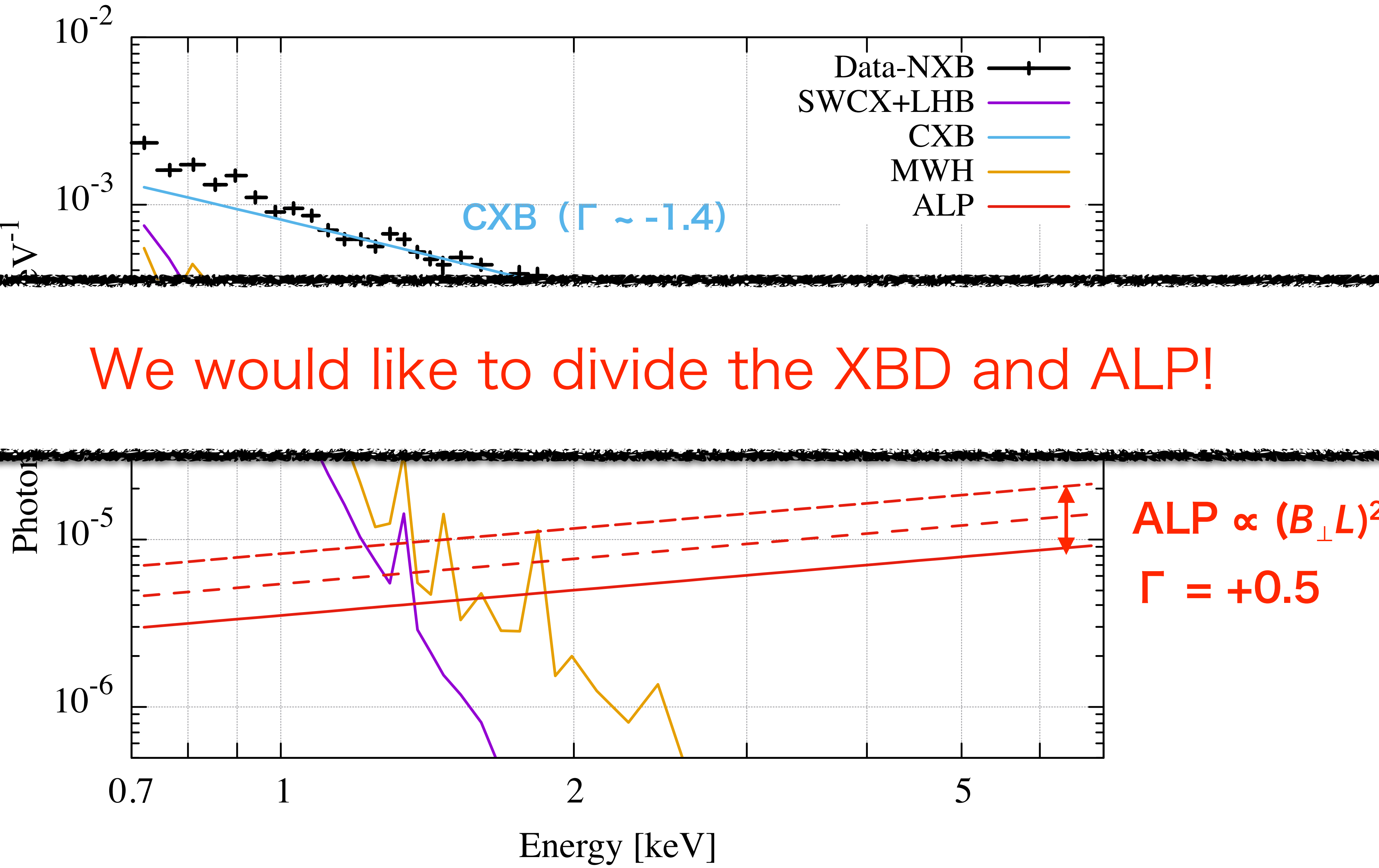
$$\propto\ g_{a\gamma\gamma}^2 \left(B_\perp L\right)^2\ \underline{E_\gamma^{1/2}}$$

In order to search for X-ray continuous emission from ALP, we selected 4 observational targets from *Suzaku*/XIS archival data of XDB from 2005 to 2015.

Field name	(Ra, Dec)	Number of observations	Exposure time
Lockman hole	(162.9, 57.3)	9 times (every year)	542.5 ks
MBM16	(49.8, 11.6)	6 times (2012-2015)	446.9 ks
SEP	(270.0, -66.6)	4 times (2009)	205.0 ks
NEP	(90.0, 66.6)	4 times (2009)	204.2 ks

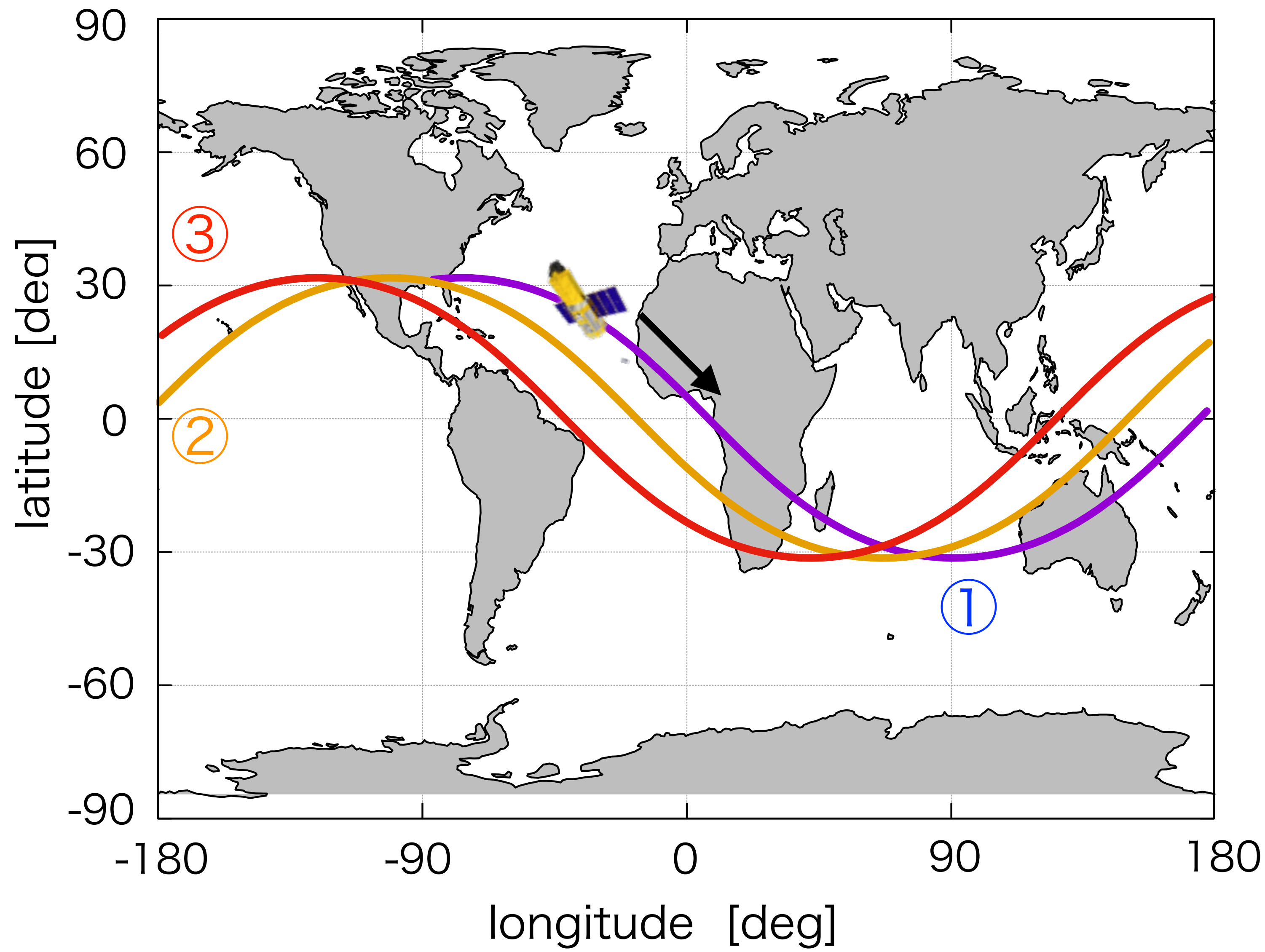
Spectral shapes of XDB and ALP

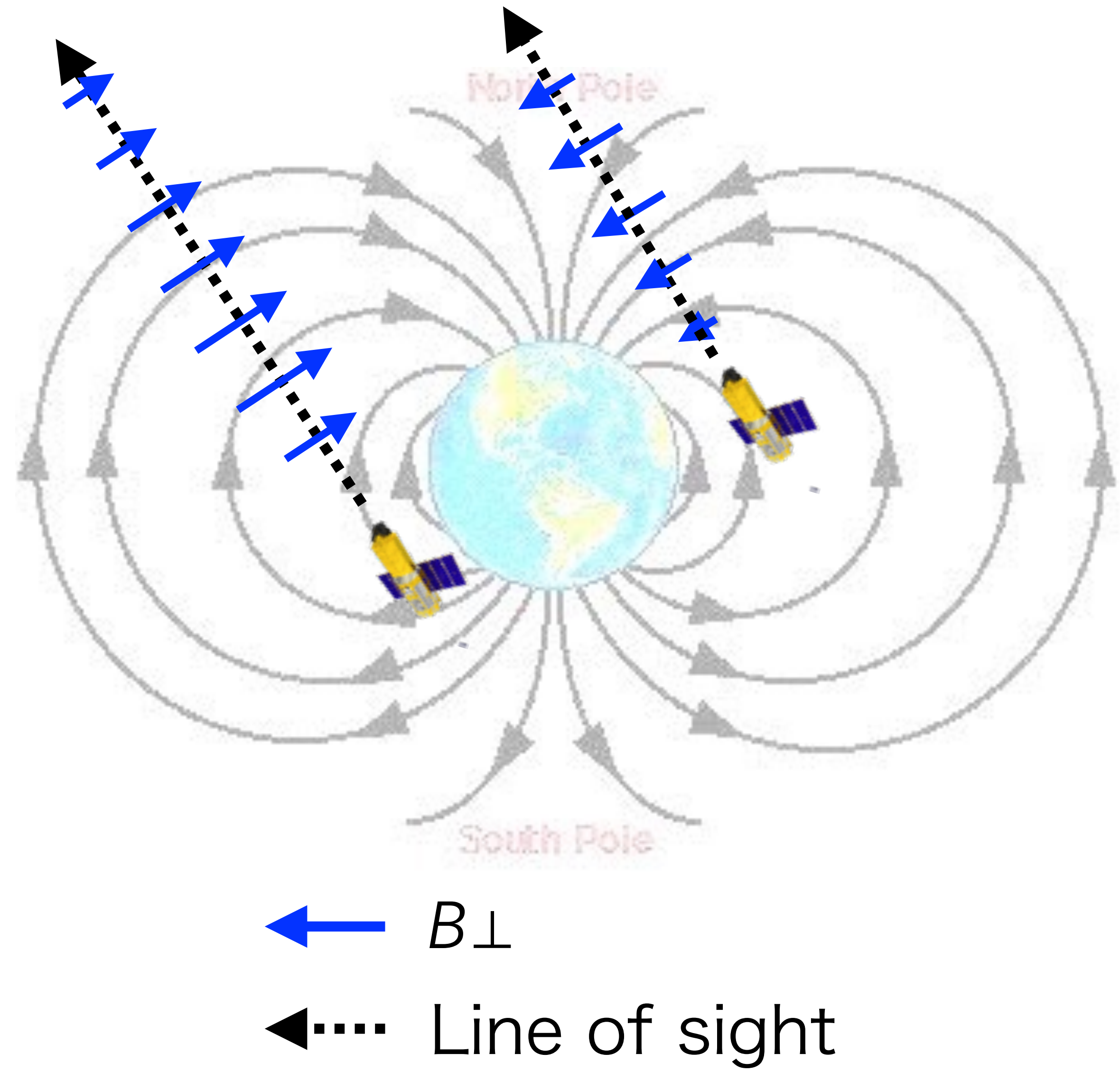
- We can estimated the surface brightness of ALP assuming the spectral shape.
- The emission model of CXB is represented by a power-law with its **photon index of Γ = -1.4** (Kushino+ 2002) above 2 keV.
- The spectral shape of ALP is transcribed as a simple power-law function whose **photon index of Γ = +0.5** due to the effect of cosmological redshift (Asaka+ 1998).



We would like to divide the XBD and ALP!

Relation between *Suzaku* orbit and $(B_{\perp}L)^2$



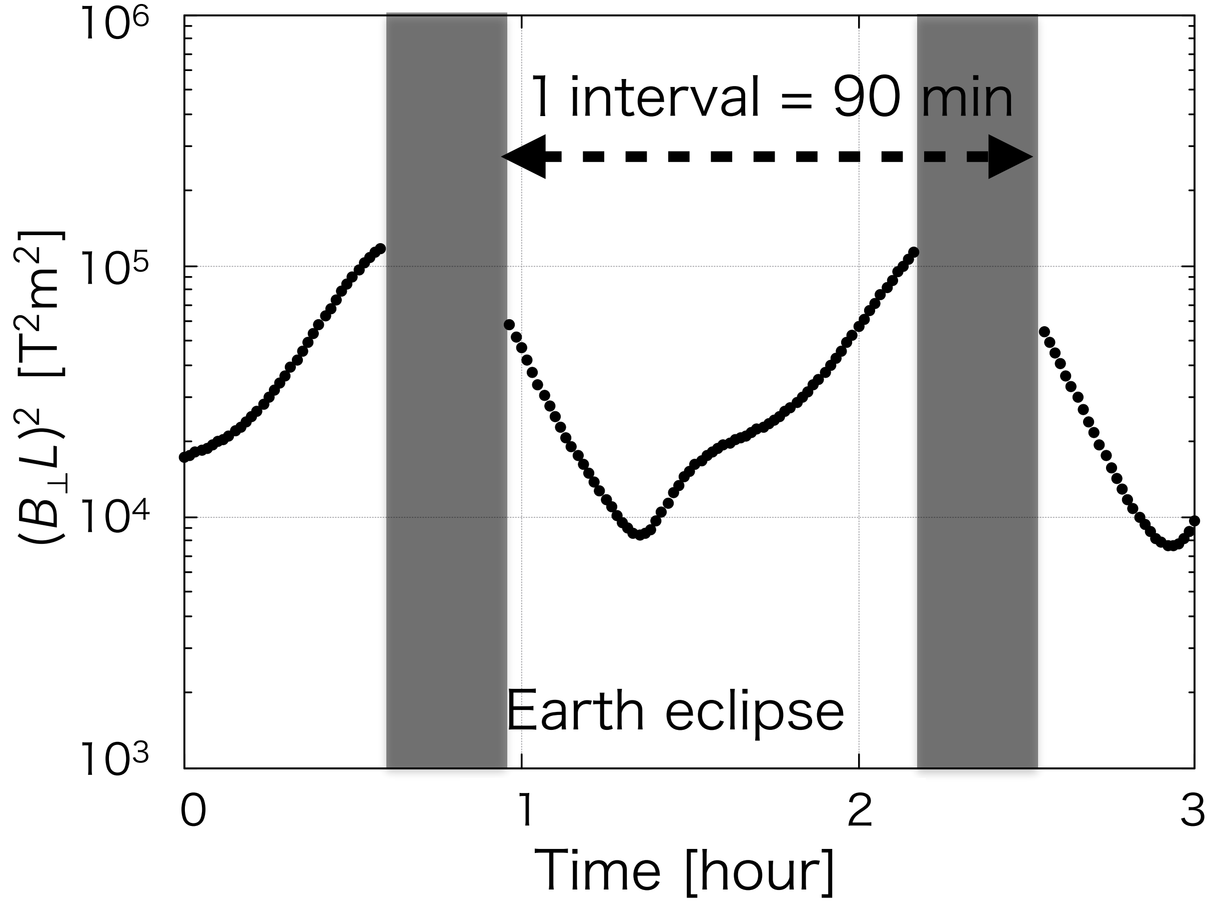


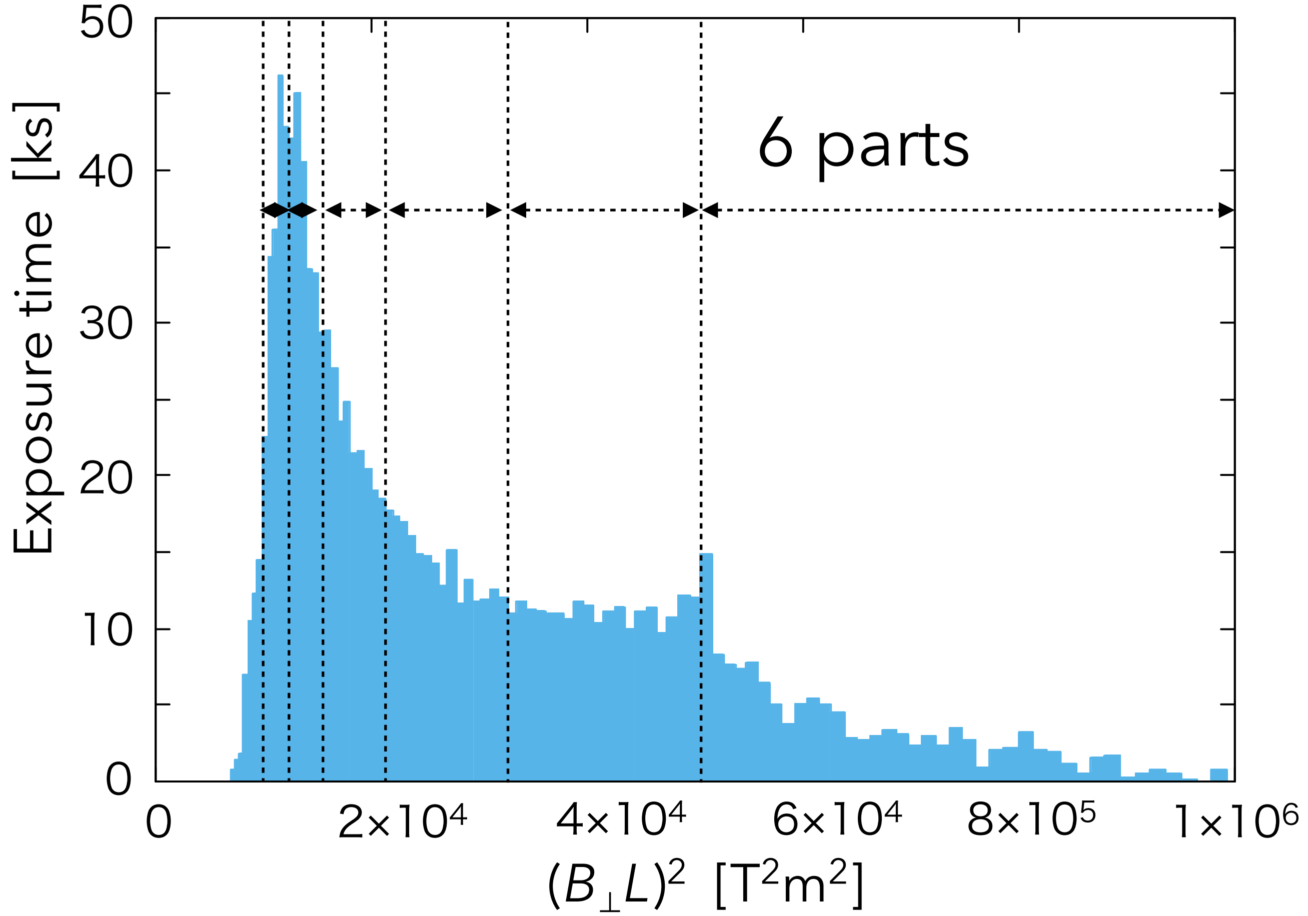
- *Suzaku* goes round the earth in ~ 90 min, and an orbital plane changes.
- Transverse magnetic field along the line of sight, $B_{\perp}$, changes with the satellite motion relative to the Earth.

  ⟶ $(B_{\perp}L)^2$ changes depending on the observation time zone

Classification of dataset by $(B_\perp L)^2$

Example of Lockman hole observation

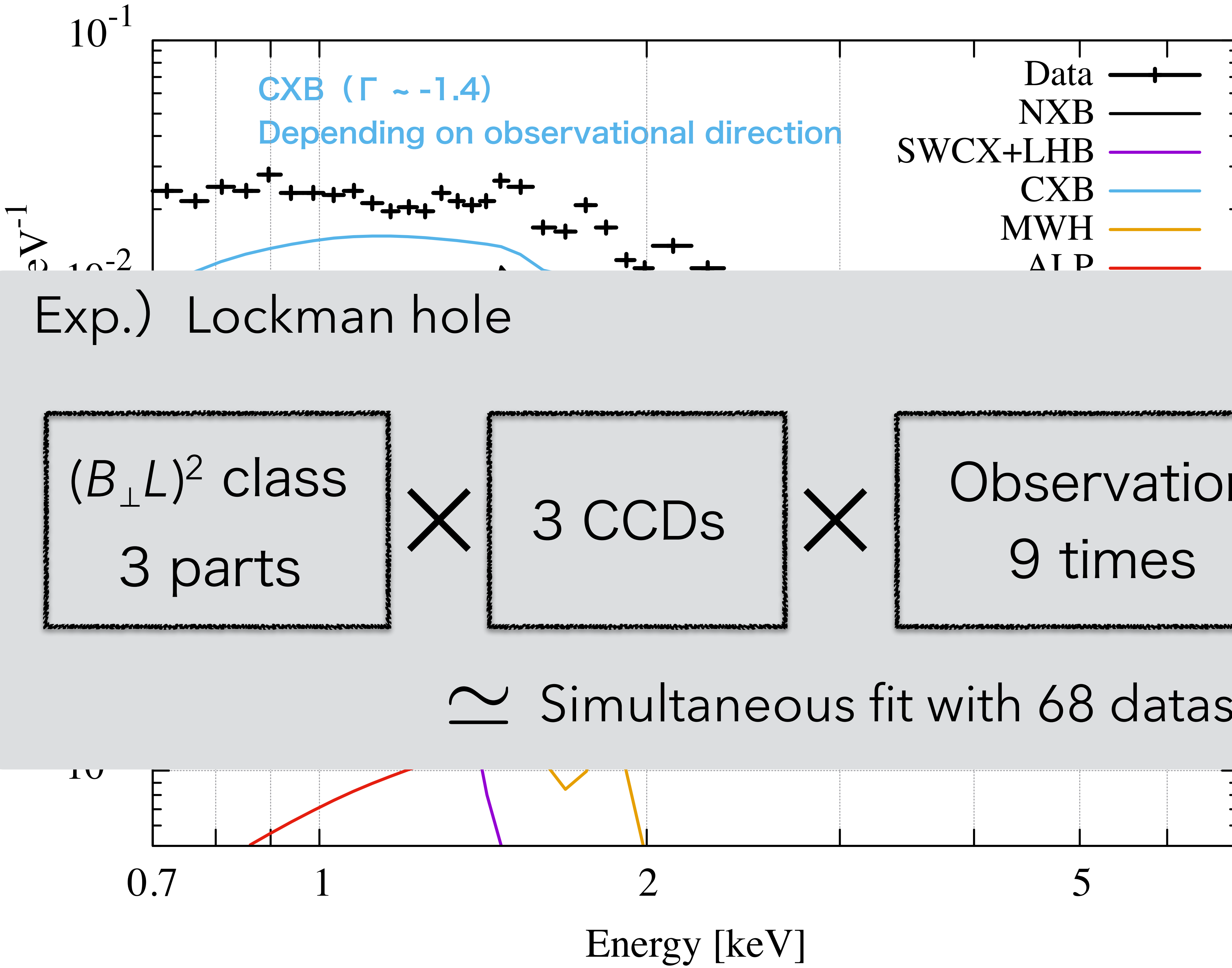




- The location of *Suzaku* every 60 seconds for XDB observation
- $B_\perp$, the transverse magnetic field along the line of sight estimated by IGRF-12
- $(B_\perp L)^2$ integrated to $6R_E$
- Maximum: $B_\perp L$ ~ 300 Tm, Average: $B_\perp L$ ~ 140 Tm

Observed spectrum (including detector response)

Consider systematic errors of CCD characterization and NXB fluctuation (~ 30%)

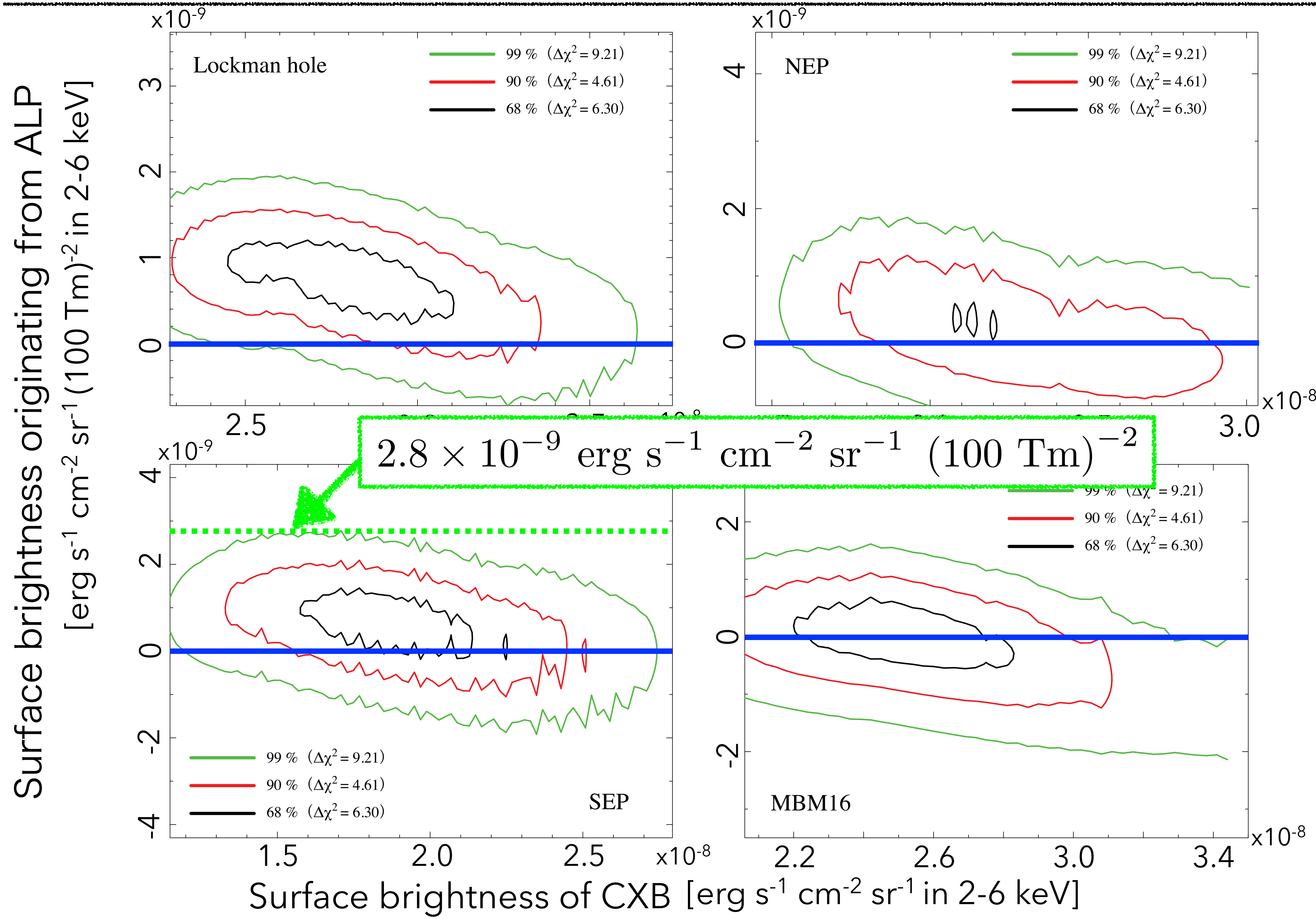


Exp.) Lockman hole

$(B_{\perp}L)^2$ class 3 parts × 3 CCDs × Observation 9 times

$\simeq$ Simultaneous fit with 68 dataset

Surface brightness correlation between ALP and CXB

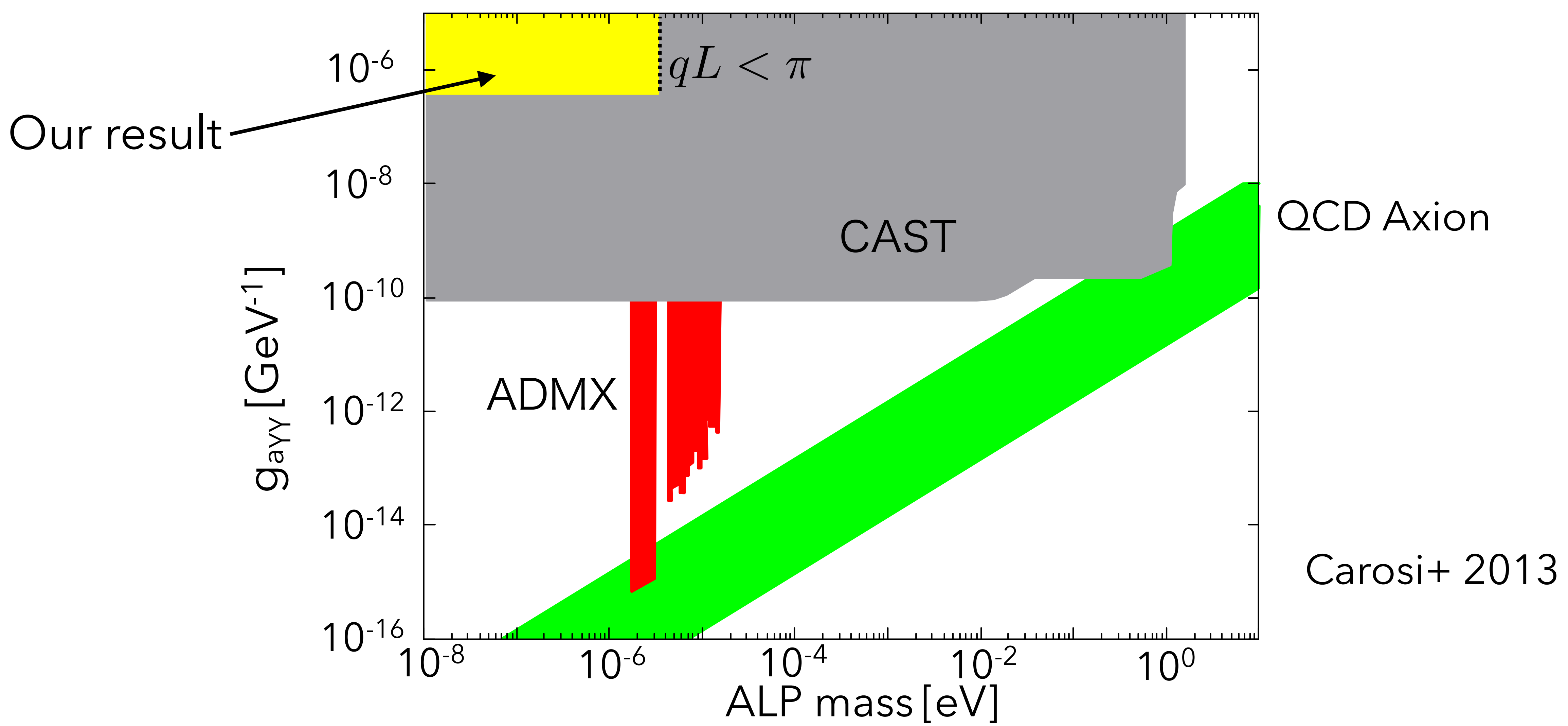


ALP-photon coupling constant (continuum emission)

$$I(E_\gamma) \propto g_{a\gamma\gamma}^2 (B_\perp L)^2 E_\gamma^{1/2}$$ (Asaka+ 1998)

$$g_{\alpha\gamma\gamma} < 4.4 \times 10^{-7}\ \mathrm{GeV}^{-1} \left(\frac{m_\phi}{10\ \mathrm{keV}}\right)^{-\frac{5}{4}} \left(\frac{\tau_\phi}{4.32\times10^{17}\ \mathrm{s}}\right)^{1/2} \left(\frac{B_\perp L}{100\ \mathrm{Tm}}\right)^{-1} \left(\frac{\rho_\phi}{1.25\ \mathrm{keV\ cm}^{-3}}\right)^{-1/2} \left(\frac{H_0}{2.20\times10^{-18}\ \mathrm{s}^{-1}}\right)^{1/2} \left(\frac{f}{1.92}\right)^{-1/2}$$

$$f(x) = \left\{\Omega_{m0} + (1-\Omega_{m0}-\Omega_{\Lambda0})/x - \Omega_{\Lambda0}/x^3\right\}^{-1/2}$$



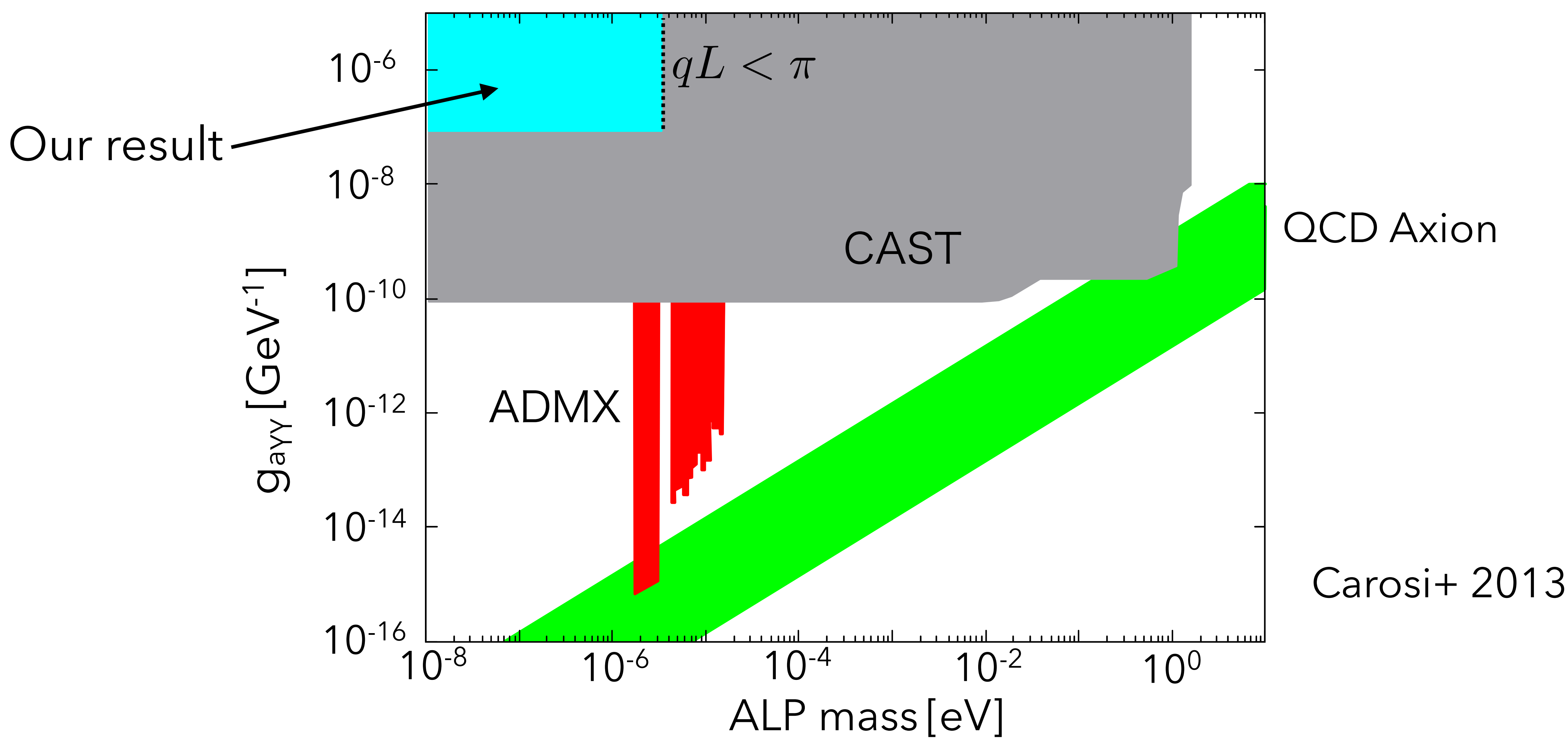
ALP-photon coupling constant (line emission)

- Estimated $P_{a\to\gamma}$ for 187 observations (31 Ms) used by Sekiya+ 2016
- X-ray line detection limit by Sekiya+ 2016 converted into monochromatic spectrum originating from ALP.

$$g_{\alpha\gamma\gamma} < 8.4 \times 10^{-8}\ \mathrm{GeV}^{-1} \quad (1 < m_\phi < 14\ \mathrm{keV})$$

$$\left(\frac{B_\perp L}{140\ \mathrm{Tm}}\right)^{-1} \left(\frac{I_{\mathrm{line}}}{0.02\ \mathrm{L.U.}}\right)^{2} \left(\frac{\tau_\phi}{4.32 \times 10^{17}\ \mathrm{s}}\right)^{1/2} \left(\frac{S_\phi}{50\ M_\odot \mathrm{pc}^{-2}}\right)^{-1/2}$$

$\mathrm{L.U.} = \mathrm{photons\ s^{-1}\ cm^{-2}\ sr^{-1}}$



Summary

We proposed a novel method to uncover ALP origin photons by space observatory using the Earth's magnetic field in the X-ray background.

The systematic uncertainty of NXB such as The NXB characterized by the relative position of the earth and the satellite, and time fluctuation from seconds to years are evaluated.

We did not detect any possible continuous emission from ALP.

In the keV band, we can search a unknown signature …

- Assuming of spectral shape
- Depending the environmental parameter (BL etc…)