Upper limit estimation of X-ray flux for gravitational wave counterparts with MAXI

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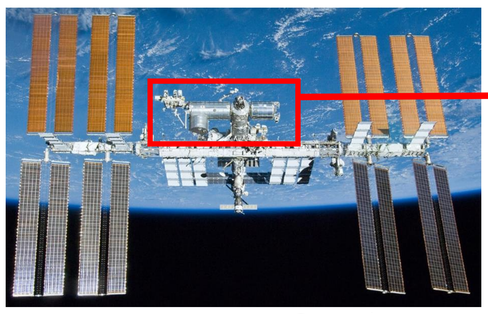
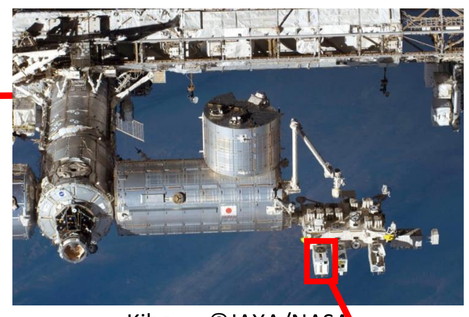
MAXI (Monitor of All-sky X-ray Image)

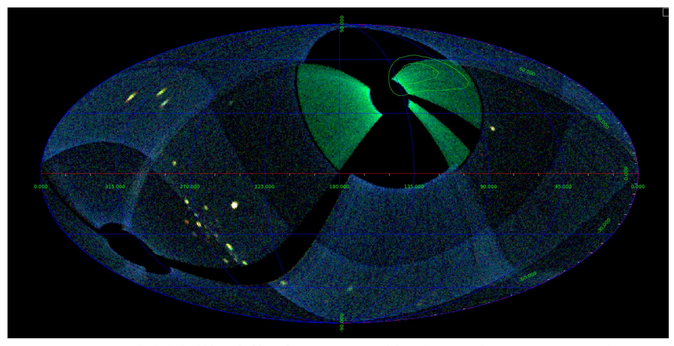
- MAXI is X-ray mission on the Japanese Experiment Module "Kibo" of ISS
- It can observe X ray transients such as X-ray bursts, GRBs, variable X-ray stars, black hole transients, etc.
- There are 2 types of cameras:
  - GSC (Gas Slit Camera)
    - GSC is sensitive to **2-20keV.** It has larger field of view and larger effective area.
  - SSC (Solid-state Slit Camera)
    - SSC is sensitive to **0.7-7keV**. It has higher spectral resolution and position resolution.
- MAXI covers 85% of all-sky in 92 minutes and almost 100% of all-sky in 2 weeks.
- Wide field of view makes it easy to search for fast transients.



ISS ©JAXA/NASA



Kibo ©JAXA/NASA



MAXI's All-sky map (1 day observation)

MAXI ©JAXA/NASA

Method

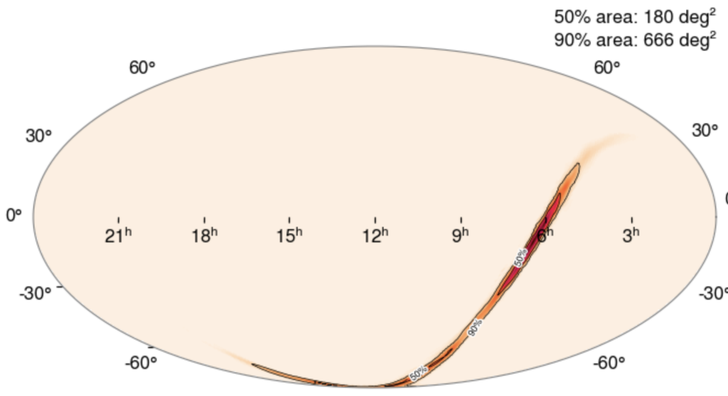
HEALPix Team
https://healpix.sourceforge.io

① Examine the pixel IDs (by HEALPix) of the 90% credible region of gravitational wave events, provided by LIGO.

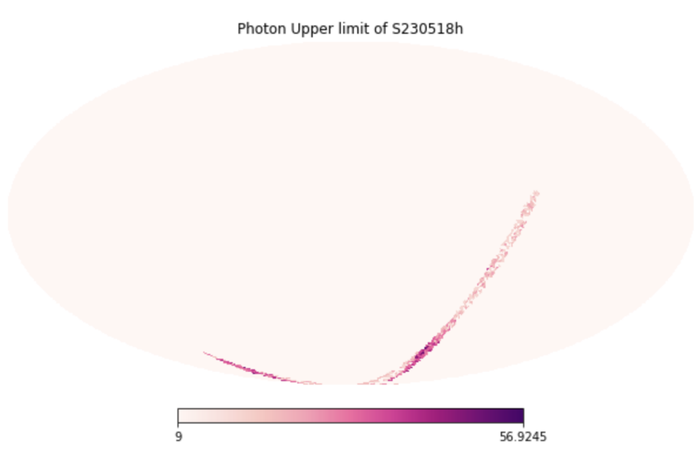
② Adjust the Nside (pixel size) of both MAXI data and pixel IDs of LIGO map in ① to 64. Usually, the spatial resolution of LIGO map is larger than MAXI's spatial resolution. Then, count the number of X-ray photons in each pixel. The number of photons per pixel is defined as the background photon count C_{bg}.

③ From the number of events C_{bg}, use $C_{src}(N, C_{bg}) = N\left(\frac{N+\sqrt{8C_{bg}+N^2}}{2}\right)$ to find an upper limit for the count number C_{src}(the number of photons generated by a gravitational wave event). We calculated 3σ upper limit, So N=3. (Sugita et al., 2018)

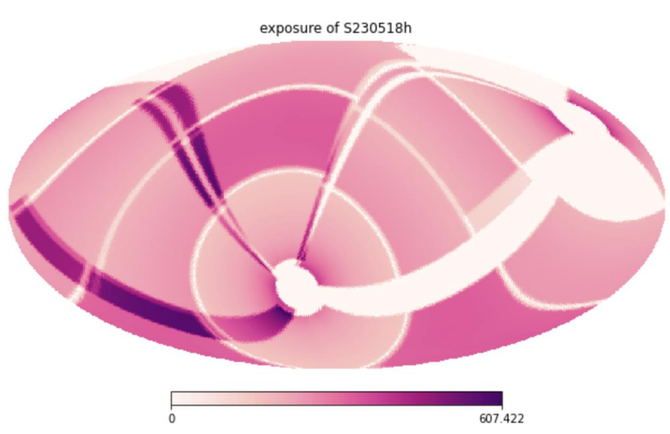
④ Get flux ($\mathrm{photons/cm^2/s}$) by dividing C_{src} by MAXI's effective exposure of the pixel.



① 90% region of gravitational waves (S230518h) ©GraceDB



②③ the count number C_{src}



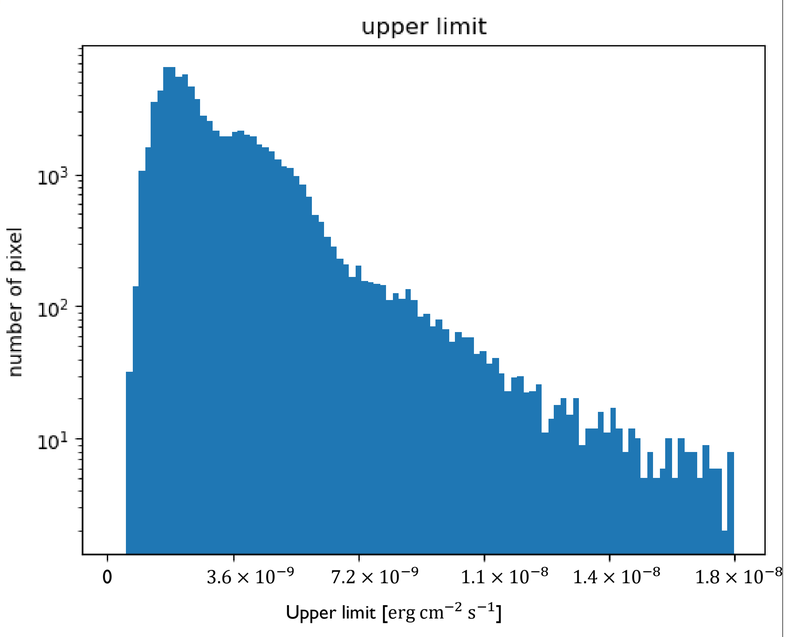
④ MAXI's exposure map in 92 minutes

Result

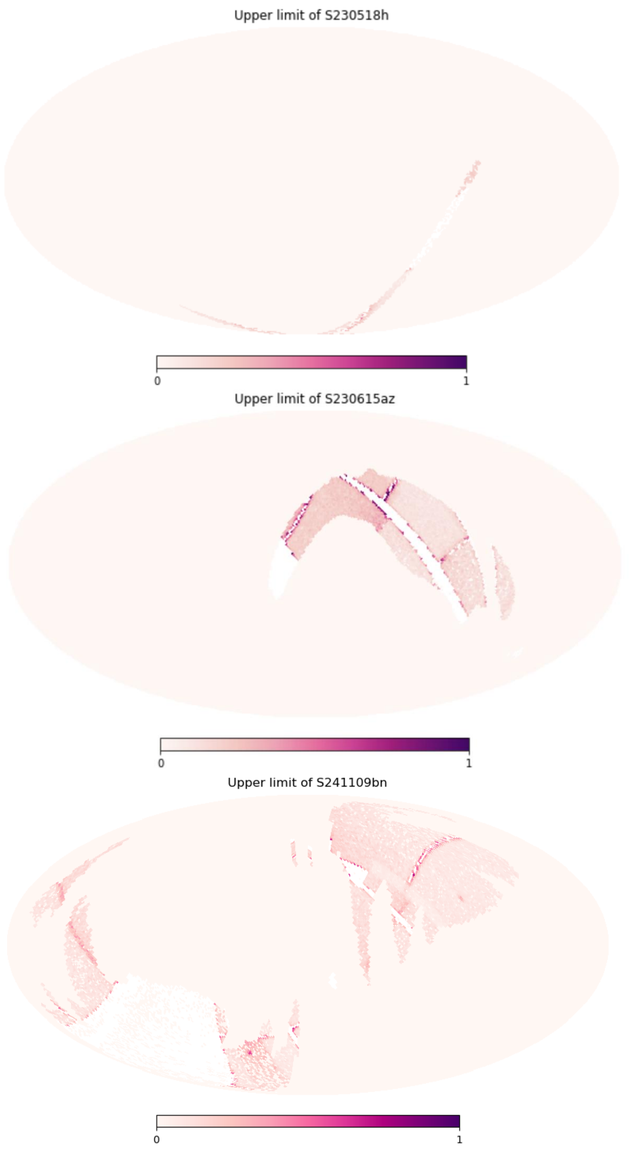
We investigated the upper limit of 21 GW events in O4a and O4b with FAR < 20 per year and have Prob NS > 5% (or Unknown). Table 1 shows the list of the events.

Table 1. A list of GW events of our sample

Researched Event	FAR [$\mathrm{year^{-1}}$]	Prob NS	Coverage [%]	GCN number
S241109bn	1/2225	NSBH(72%)	68	38151
S240915b	1/100	NSBH (14%)	100	37520
S240910ci	1/100	NSBH (31%)	51	37448
S240830gn	1/50	NSBH (11%)	65	37358
S240711cm	19.8	Unknown	72	36850
S240629by	1/100	NSBH (8%)	80	36792
S240513cx	4.2	NSBH (10%)	41	36454
S240422ed	1/ 1.0e+5	NSBH (99%)	100	36238
S231204bz	10.6	Unknown	99	35130
S231119ab	12.3	Unknown	82	35019
S231113cd	5.2	Unknown	53	35017
S231021az	7.3	NSBH (26%)	86	34871
S231020ba	1/25	NSBH (8%)	90	34852
S230917af	14.5	Unknown	100	34725
S230802aq	1.4	NSBH (6%)	62	34314
S230731an	1/100	NSBH (18%)	95	34303
S230729cj	3.8	NSBH (39%)	77	
S230627c	1/100.	NSBH (49%)	64	34088
S230615az	4.7	NSNS (85%)	66	
S230529ay	1/160	NSBH (62%)	91	33893
S230518h	1/98	Unknown	70	33823



This histogram is distribution of upper limits of each pixel in 21 event (77984 pixel). Most of the data have upper limits less than $2 \times 10^{-8}\mathrm{erg/cm^2/s}$.
An average value of upper limit is $4 \times 10^{-9}\ \mathrm{erg/cm^2/s}$.



White region : 90% region but MAXI couldn't observe. The border region with large flux upper limit is due to a small exposure.