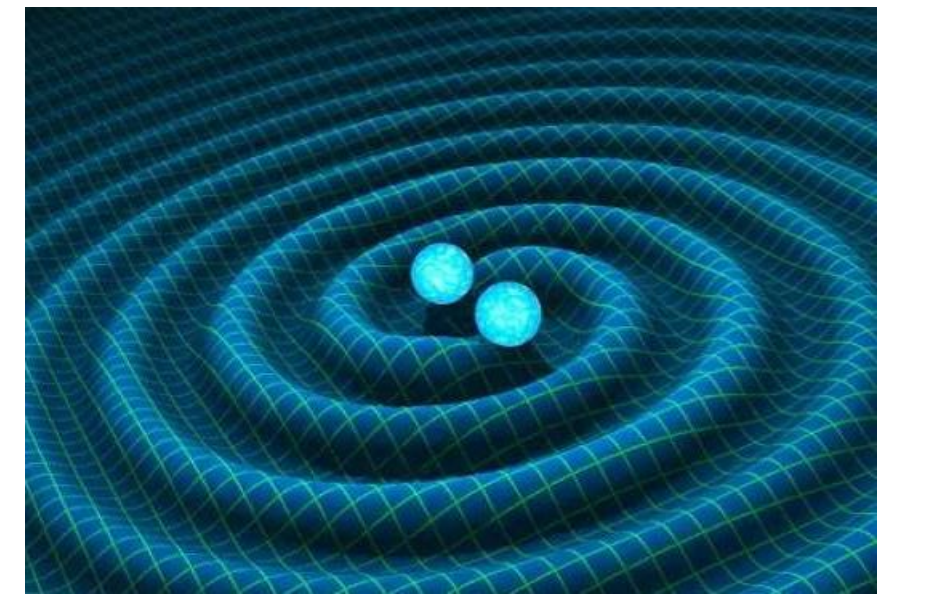


Upper limit estimation of X-ray flux for gravitational wave counterparts with MAXI

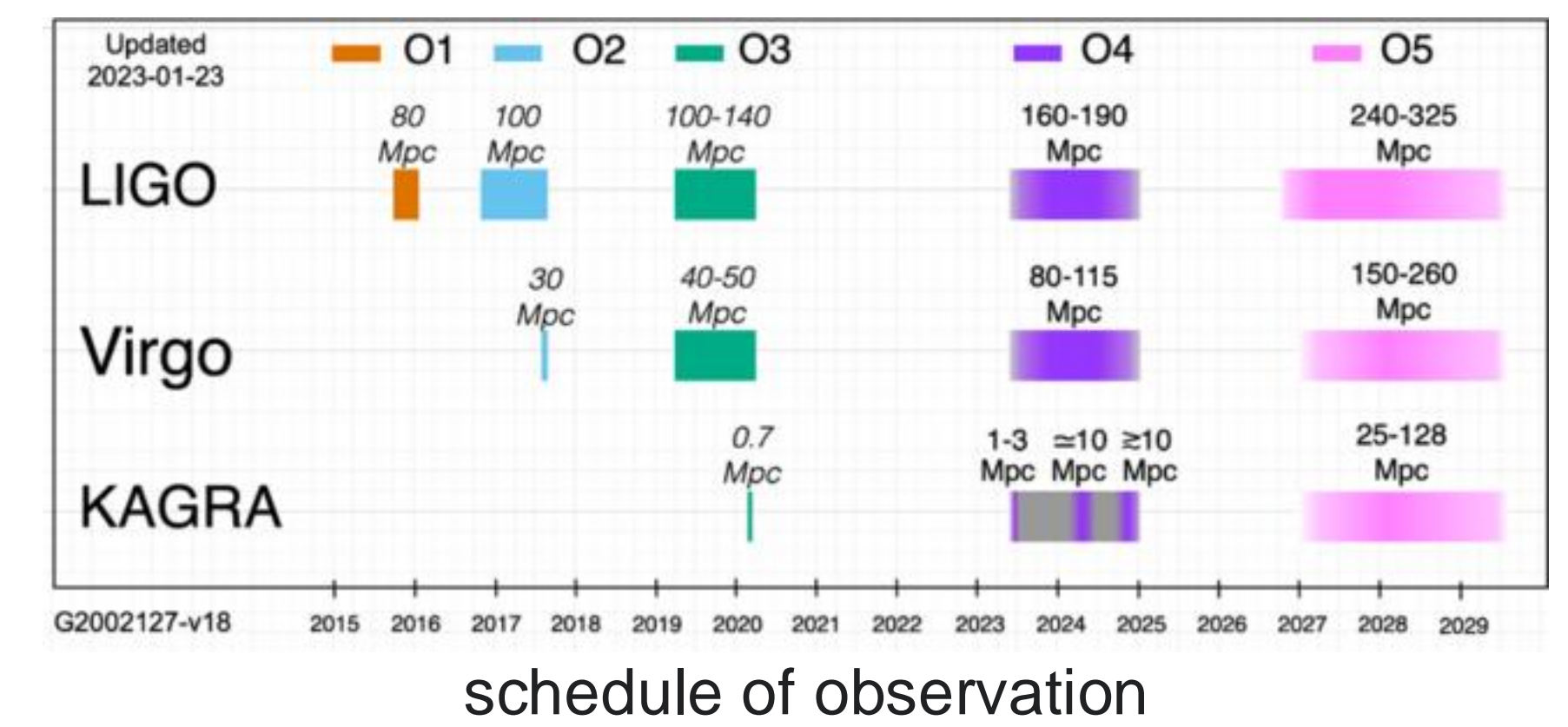
Aoyamagakuin University Yuta Kondo

Gravitational wave (GW)

- GWs are phenomenon of space-time distortion propagating in space-time.
- Major sources of gravitational waves are mergers of binary neutron stars (BNS), binary black holes (BBH), and neutron star and black hole (NSBH).
- Observing GW events, we can get information which is difficult to know from observations of electro-magnetic waves, such as mass of stars, inclination of the orbital plane, or distance to the sources.
- Now GW telescopes LIGO and Virgo are in the latter half of 4th observing run (O4b). The right figure shows schedule of the observation.



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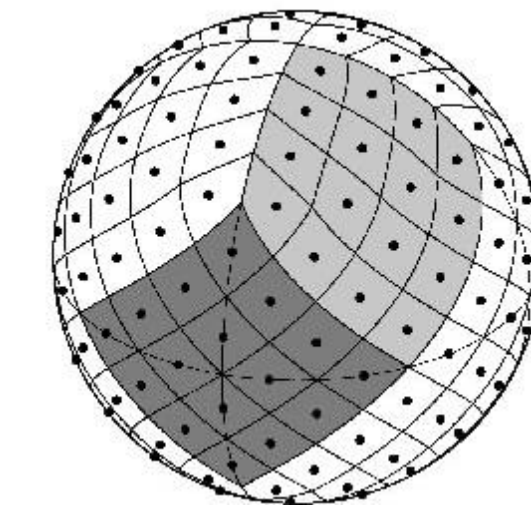


X-ray observation

- We focus on BNS and NSBH events, because they can be accompanied by short GRB, and we could see GW and X-ray simultaneously.
- MAXI had wide field of view. It makes us easy to search for fast transients such as GRBs.

Method of upper limit calculation

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

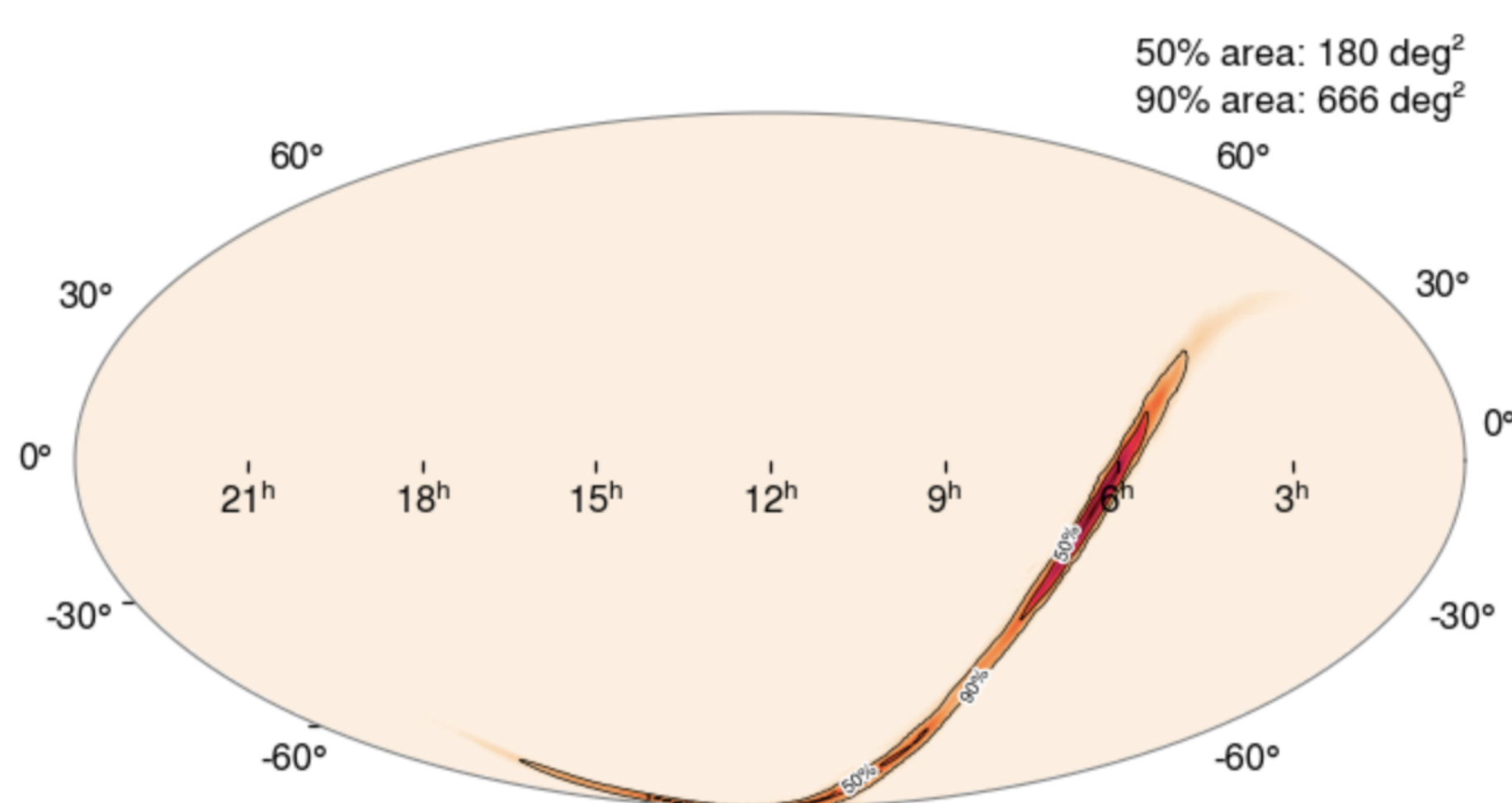


HEALPix Team
<https://healpix.sourceforge.io>

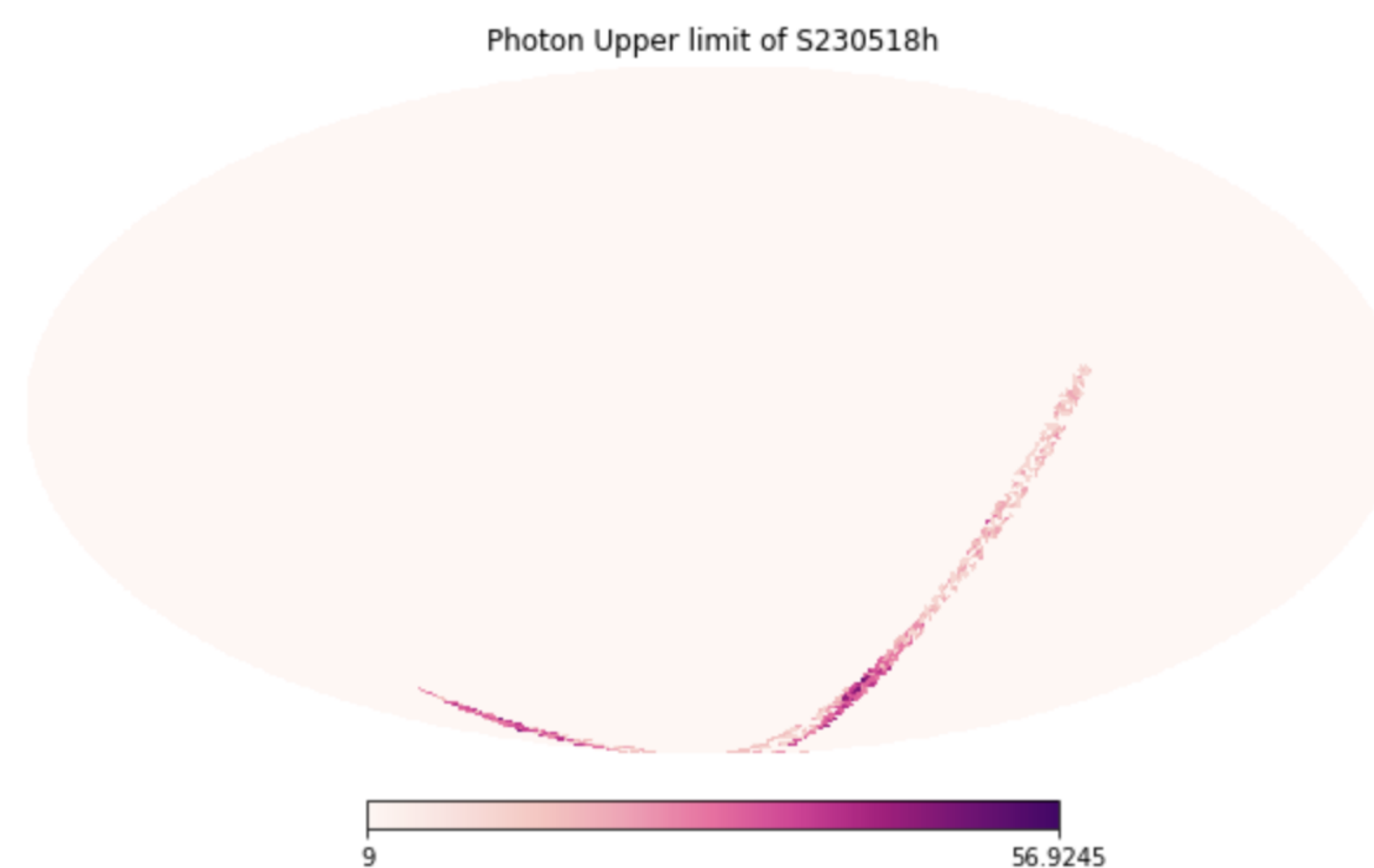
② Adjust the Nside (pixel size) of both MAXI data and pixel IDs of LIGO map in ① to 64. Usually, the spatial resolution of LIGO map is larger than MAXI's spatial resolution. Then, count the number of X-ray photons in each pixel. The number of photons per pixel is defined as the background photon count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

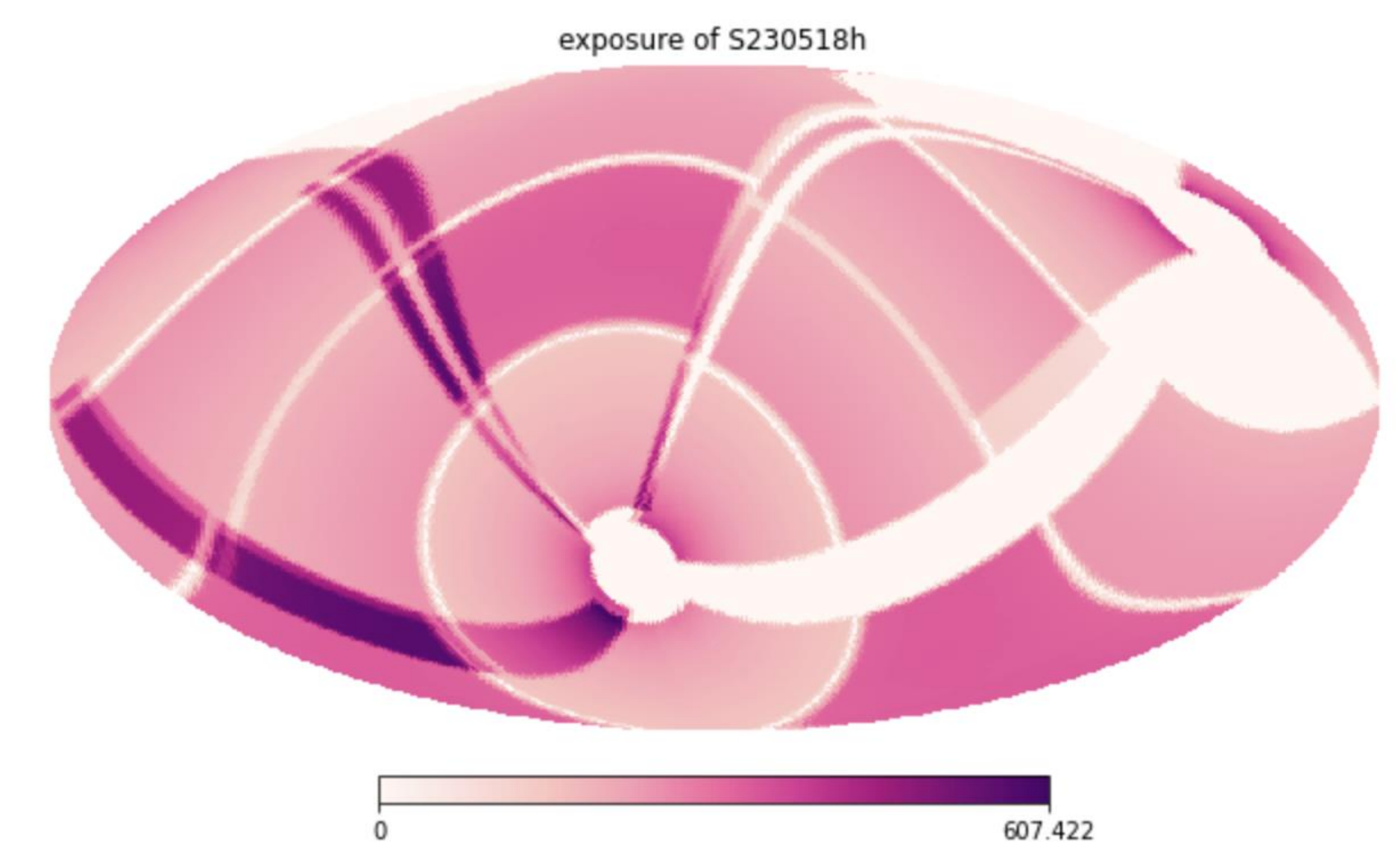
④ Get flux (photons/cm²/s) by dividing C_{src} by MAXI's effective exposure of the pixel.



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



②③ the count number C_{src}



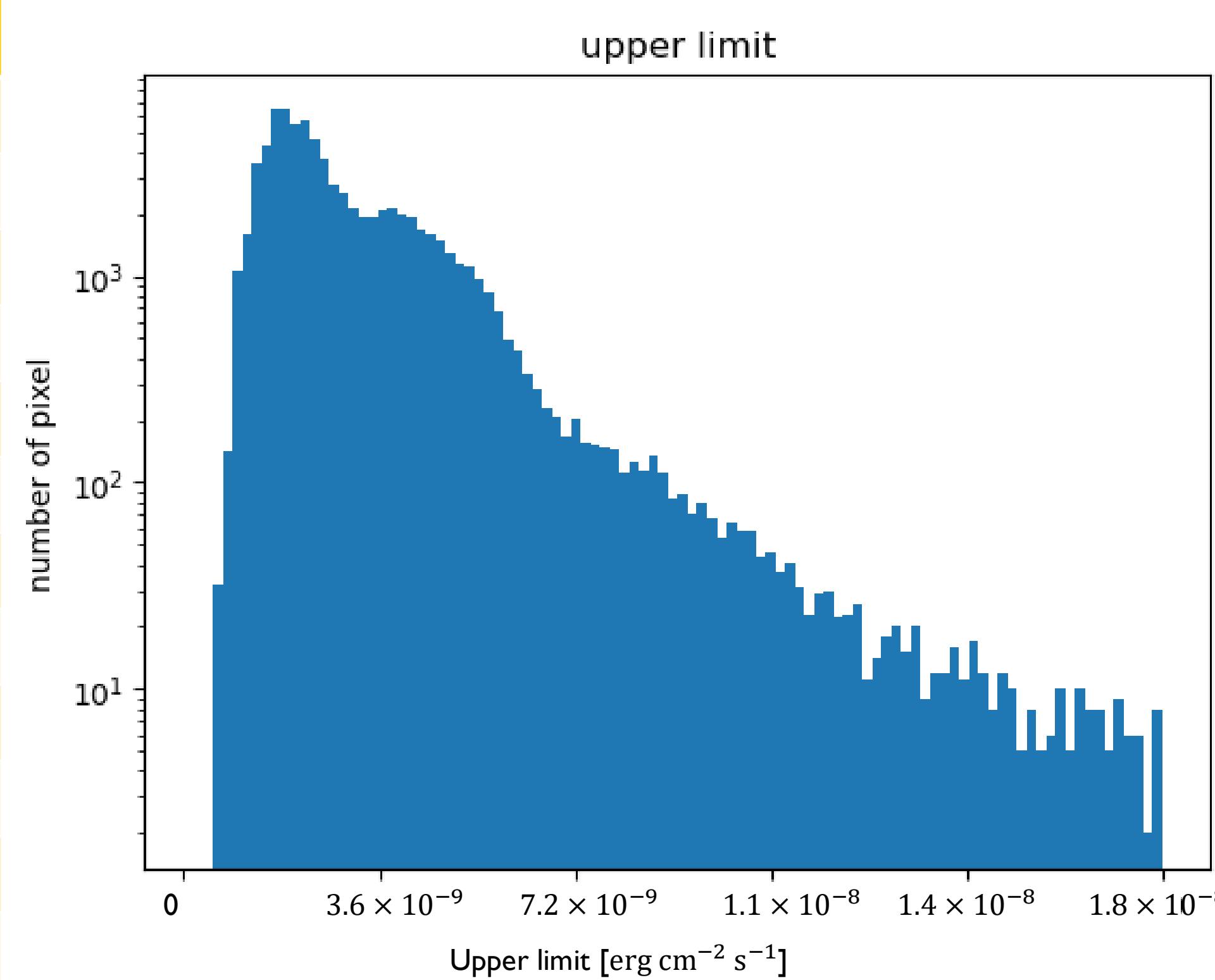
④ MAXI's exposure map in 92 minutes

Result

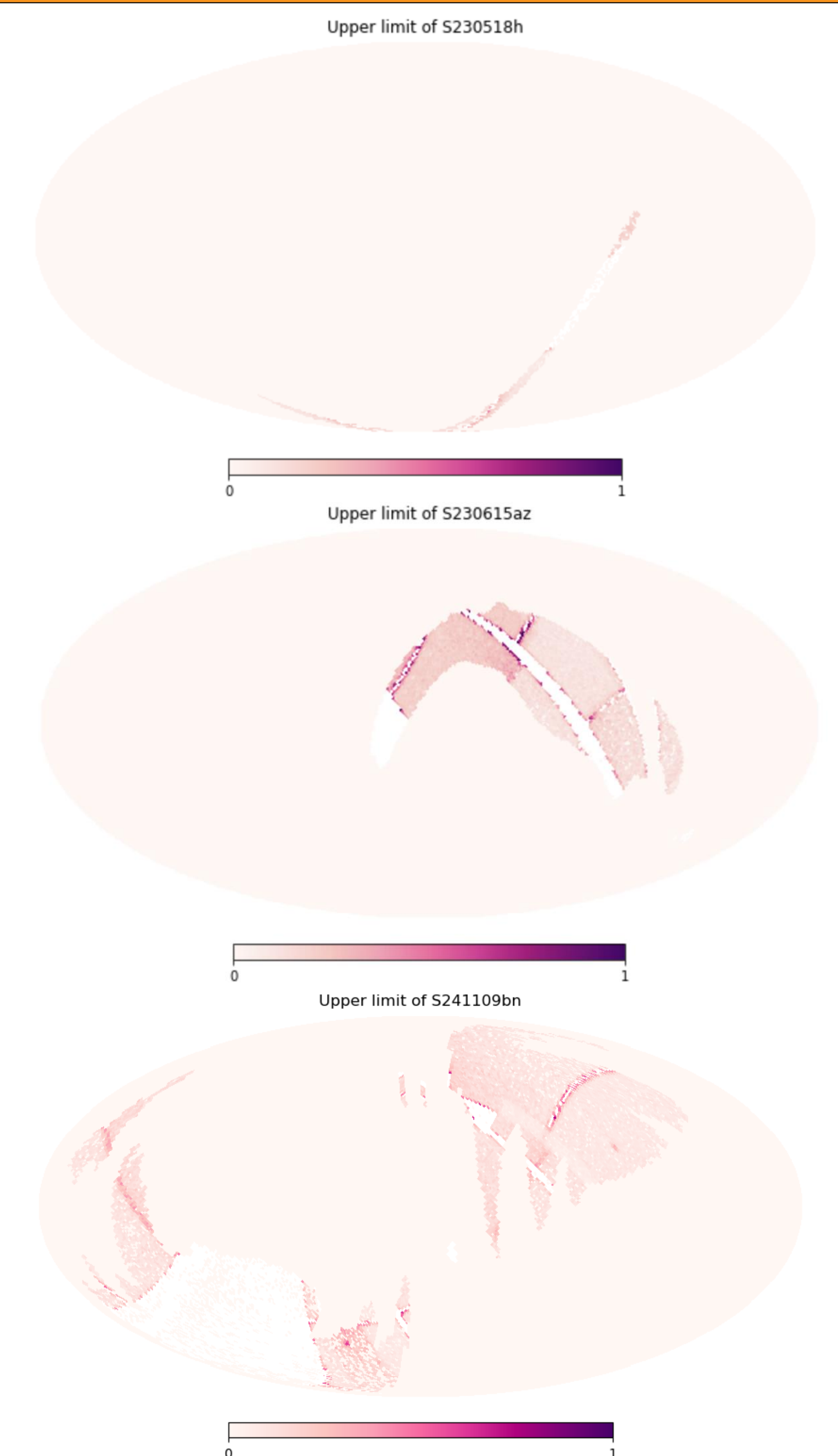
We investigated the upper limit of 21 GW events in O4a and O4b with FAR < 20 per year and have Prob NS > 5% (or Unknown). Table I shows the list of the events.

Table I. A list of GW events of our sample

Researched Event	FAR [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 2×10^{-8} erg/cm²/s. An average value of upper limit is 4×10^{-9} erg/cm²/s.



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