MAXIによる
重力波対応X線放射の探索

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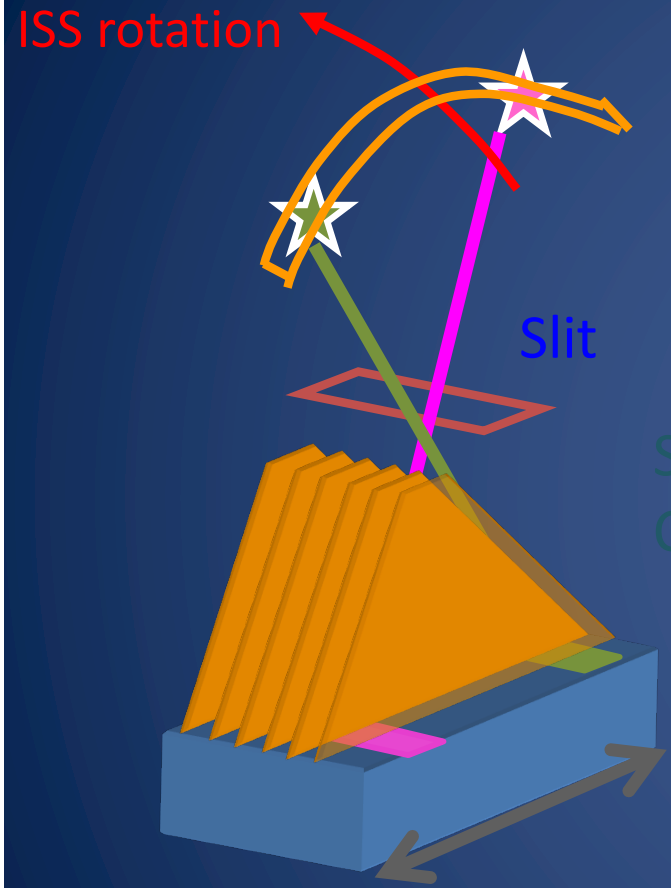
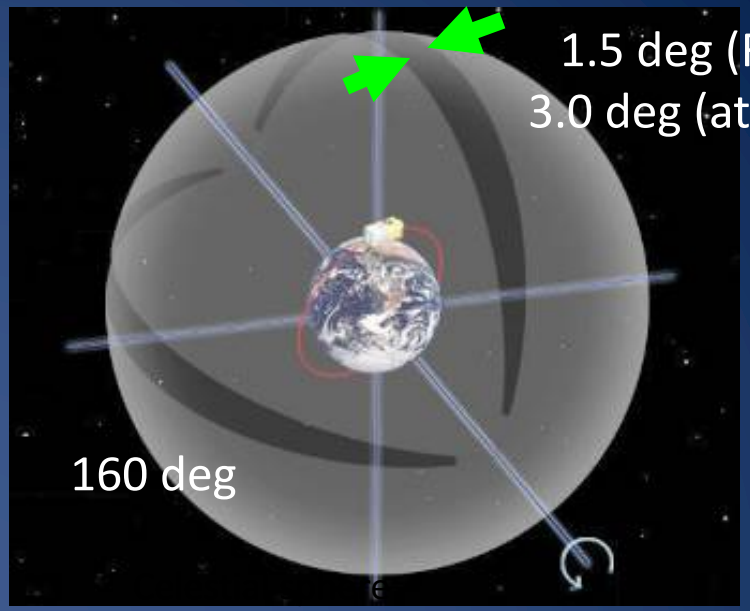
中平聡志（理研）ほかMAXIチーム

Scans with Slit + Slats collimator



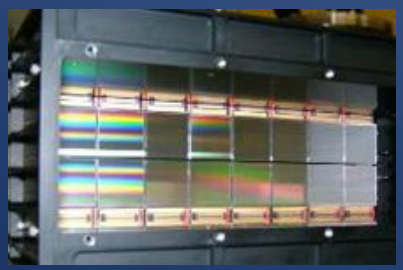
1-dimensional position sensitive detector

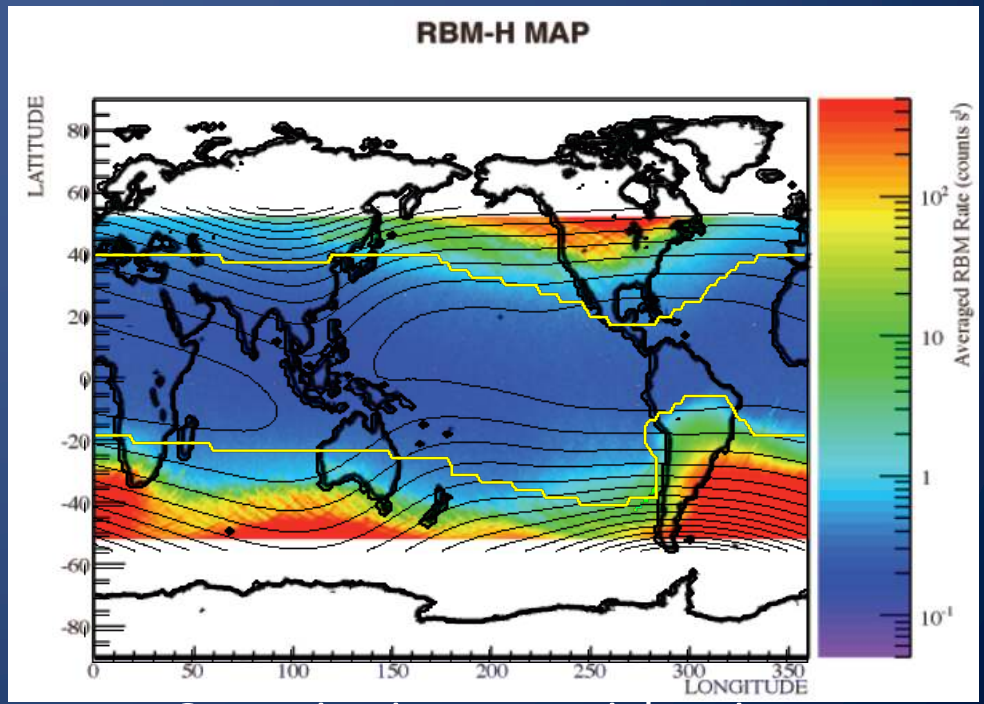


2

proportional counter

X-ray CCD

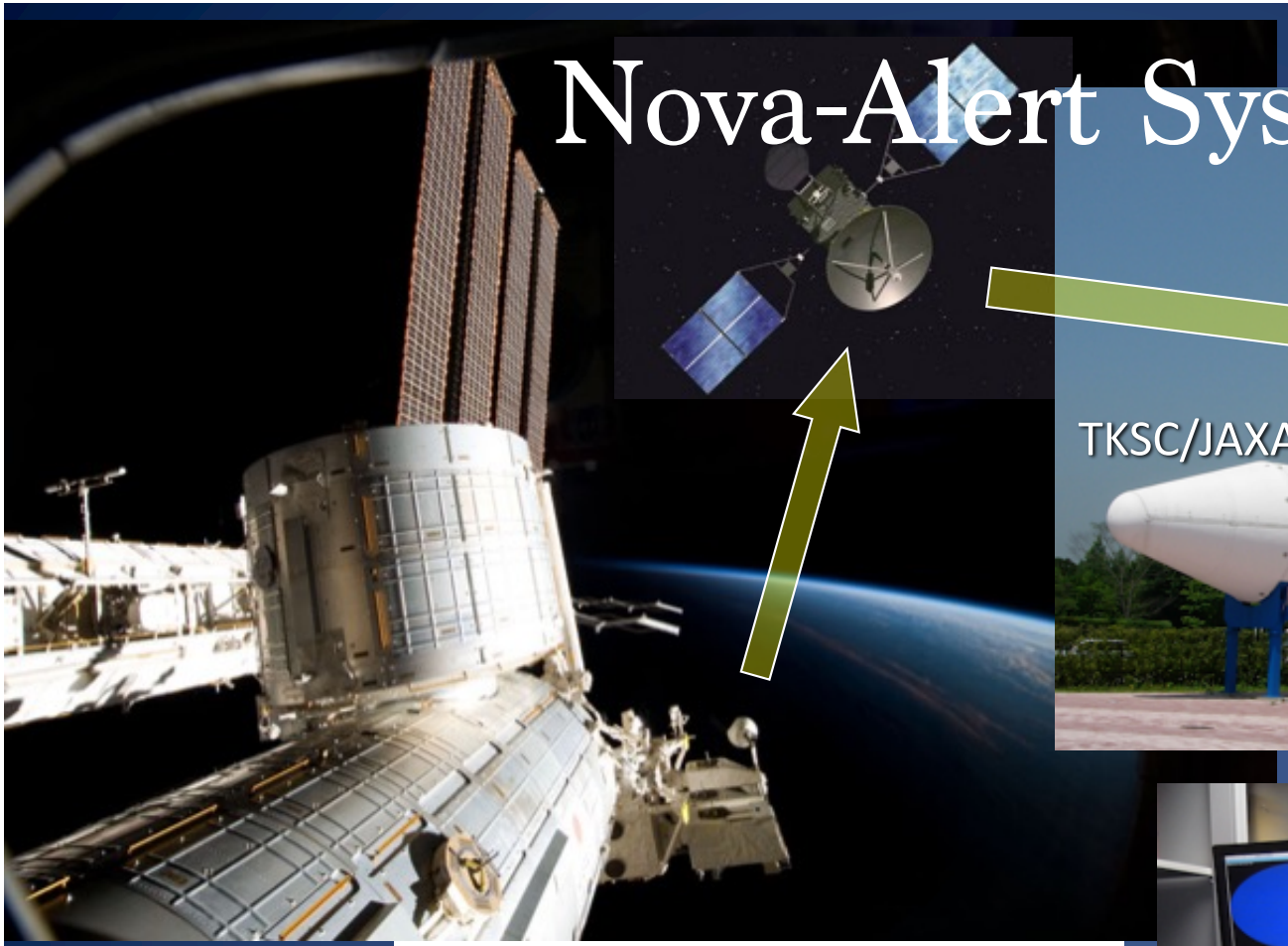




Operating in equatorial region

Nova-Alert System

Negoro+ 2016, PASJ



Nova Alert System
< 10 sec (Real)
~ 1.5 h (Stored)

RIKEN & MAXI MLs (& ATel/GCN)

Novae -- list --

ID	Image	Date	RA, Dec	com
5337375271 958473409 (Warning)		2010-05-21T10:36:34	(308.764, 37.464)	EXO 2030+375
5352037956 959732429 (Alert)		2010-06-05T00:20:14	(82.544, -66.334)	LMC X-4
5360024421 960424195 (Warning)		2010-06-13T00:29:40	(230.060, -57.227)	Cir X-1
5360277271 960453730 (Alert)		2010-06-13T08:41:55	(277.330, -24.044)	GS 1826-238
5360774677 960506625 (Alert)		2010-06-13T23:23:30	(230.037, -57.016)	Cir X-1
5363094768 960687741 (Warning)		2010-06-16T01:42:06	(52.055, -40.713)	Transient event
5365027798 [illegible] (Alert)		2010-06-18T01:28:17	(289.188, -5.447)	X-ray burst of 4U
5374277357 961659391 (Warning)		2010-06-27T07:36:16	(84.738, 26.065)	A 0535+262
5378212885 962002493 (Warning)		2010-07-01T06:54:38	(189.997, -34.181)	likely to be an XRF

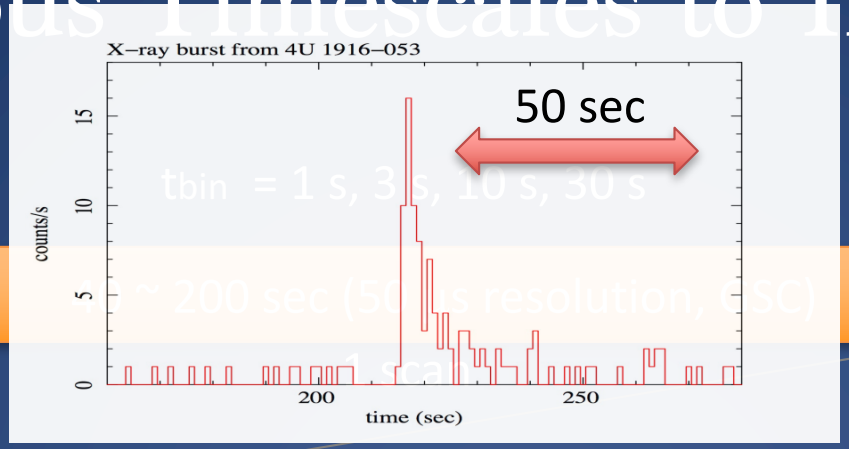
Various Timescales to Investigate

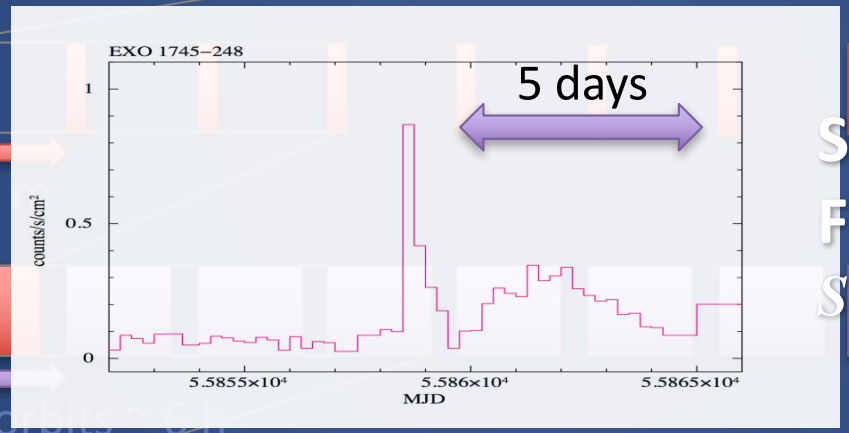
X, γ-ray bursts

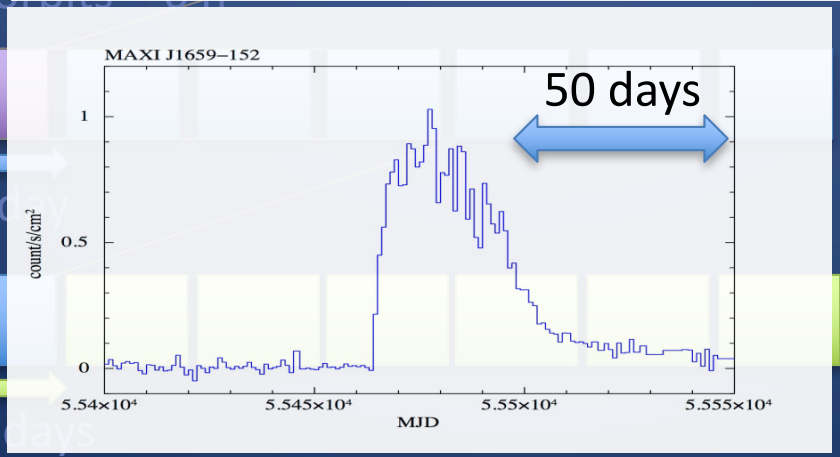
Superburst
SFXT
Star Flares

X-ray novae

AGN Flares





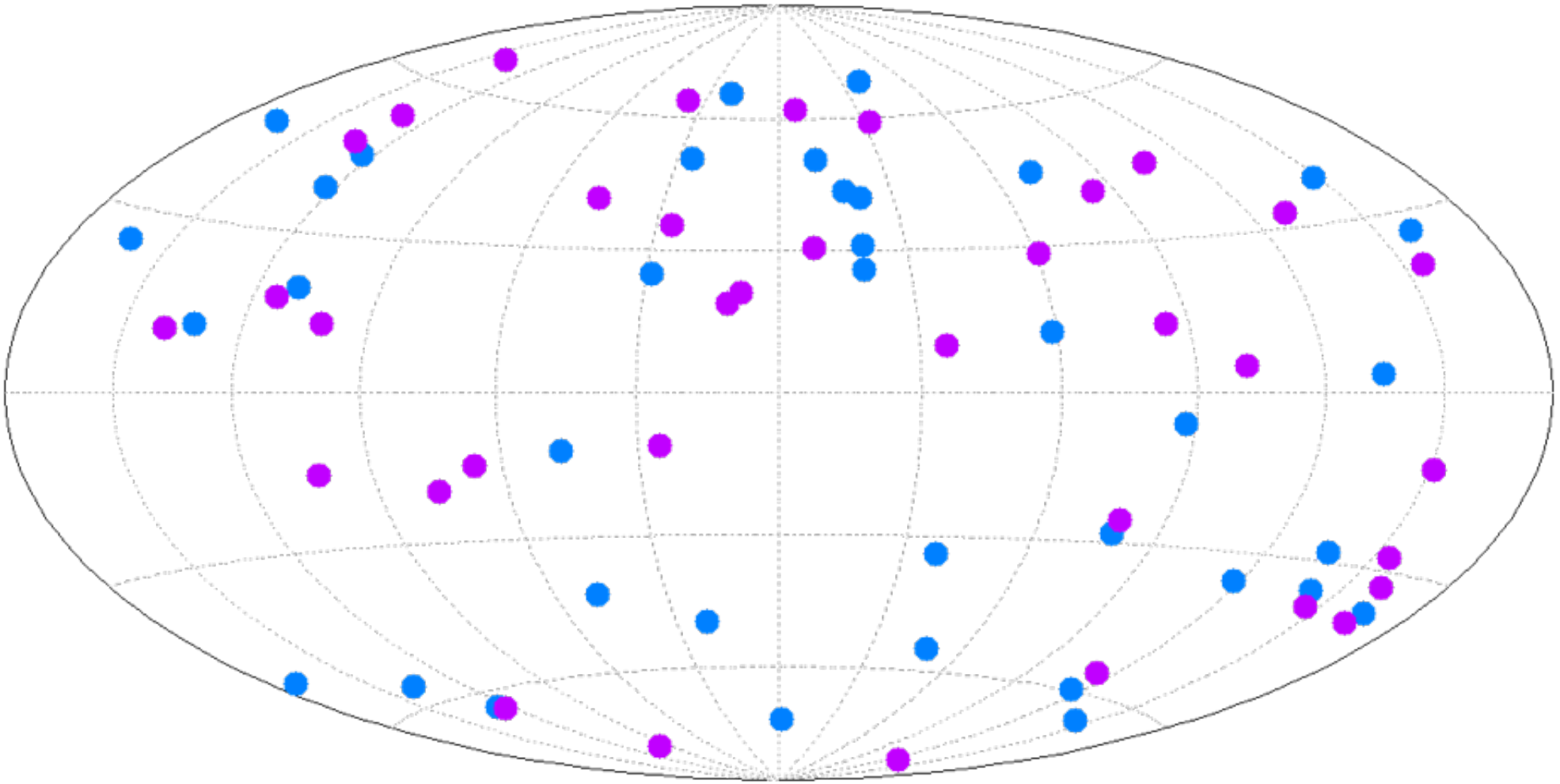


X-ray burst
From 4U 1916-053

Superburst + Outburst
From EXO 1745-248
Serino+ 2012

BH Outburst
MAXI J1659-152
Negoro+ 2010,
Yamaoka+ 2011

MAXI GRBs and transients (2—20 keV)



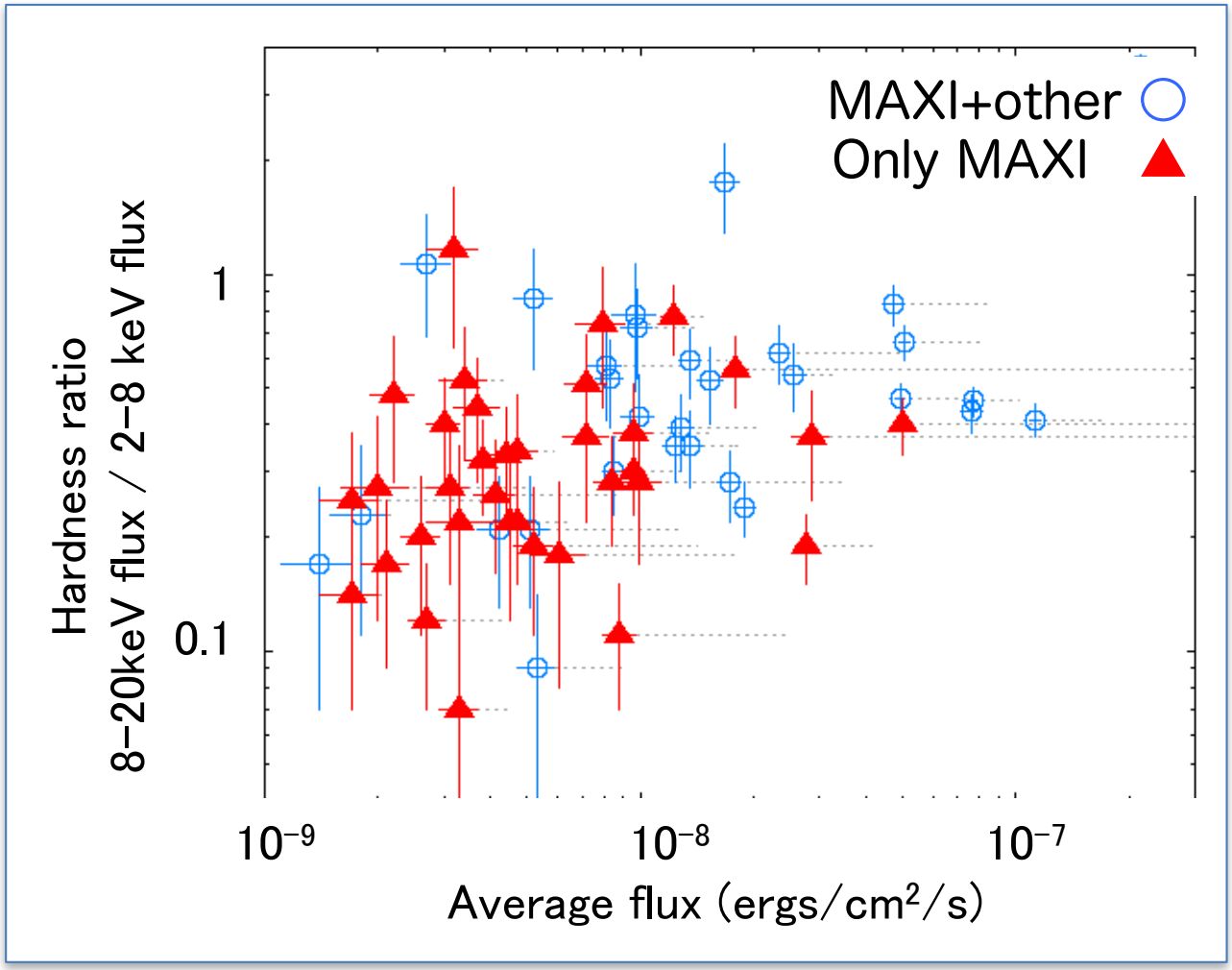
Serino et al. (2014)

http://maxi.riken.jp/grbs/

●: only MAXI (43)

●: MAXI + other (39 prompt + 7 afterglows)

Flux and Hardness



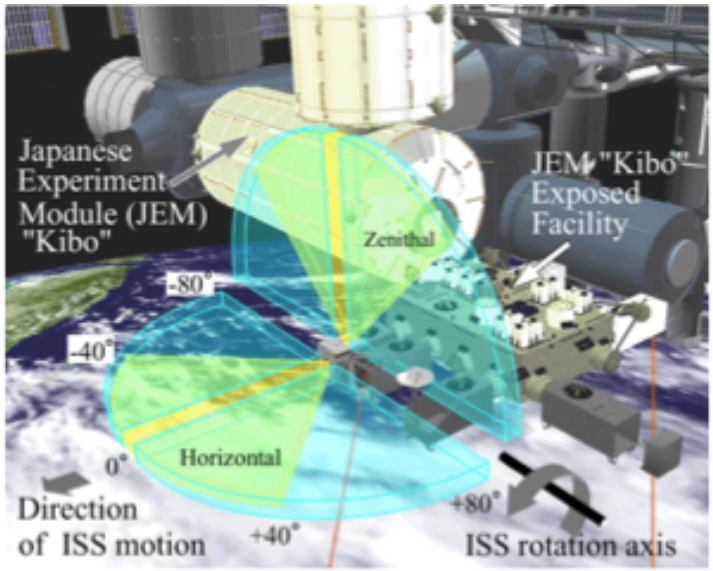
1/2 of MAXI GRBs are "Only MAXI" events

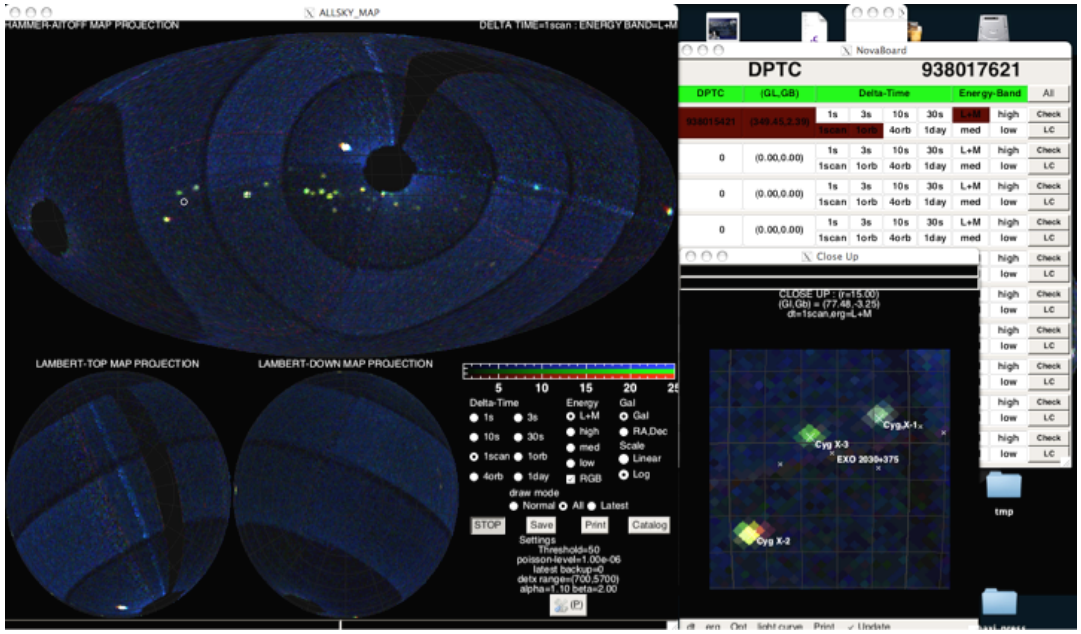
Only MAXI GRBs tend to Soft and Dim

many of them are XRFs?

Slide by M. Serino

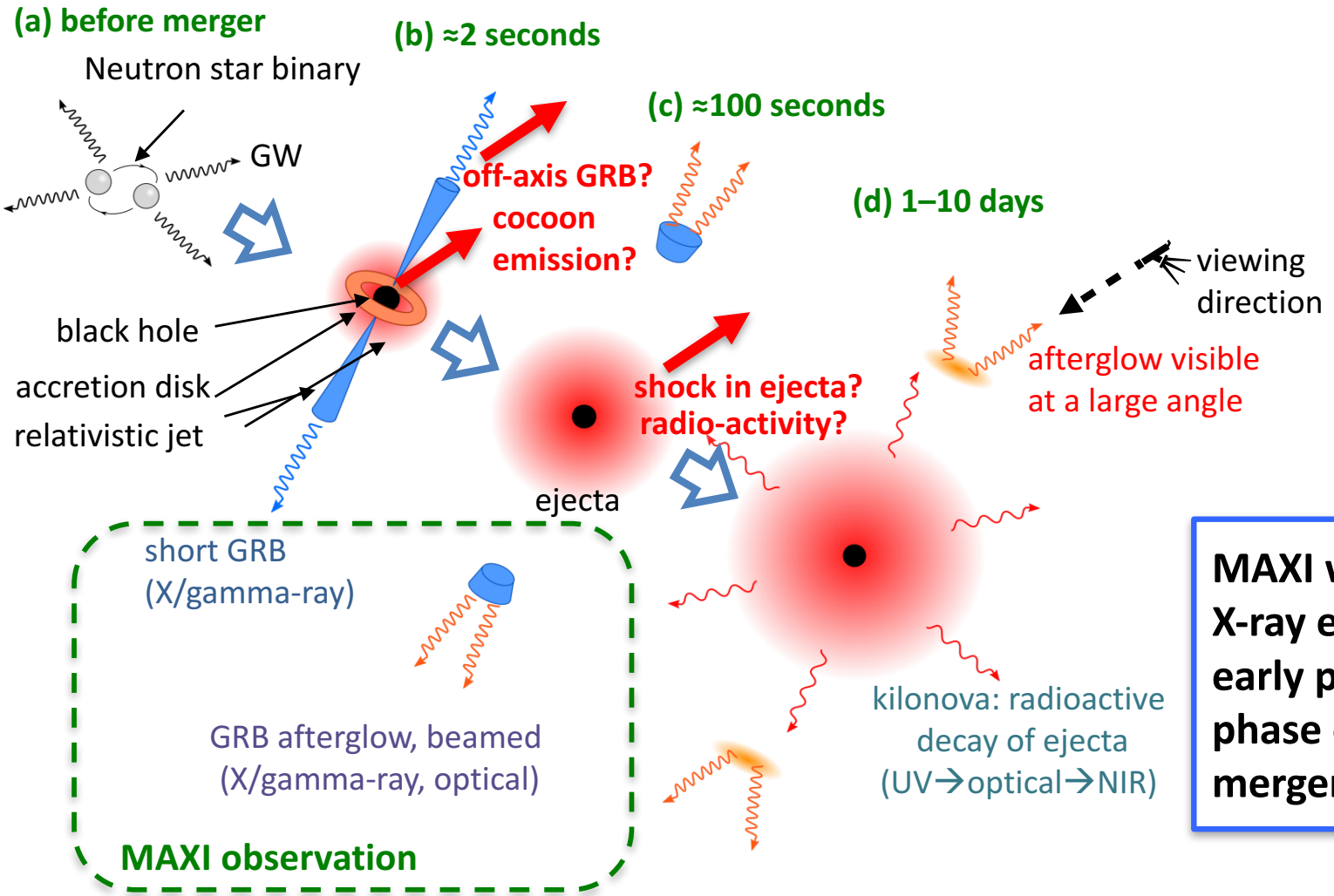
MAXI for GW event





- All-sky monitoring in one orbit (92min)
  - can cover large error area of GW event
    - ~85% of whole sky in one-orbit (92 min)
    - ~95% in one-day
  - can search the emissions before GW trigger
- Alert system (Nova) for X-ray transient event
  - framework for flash report of EM counterpart is already built

MAXI for GW event



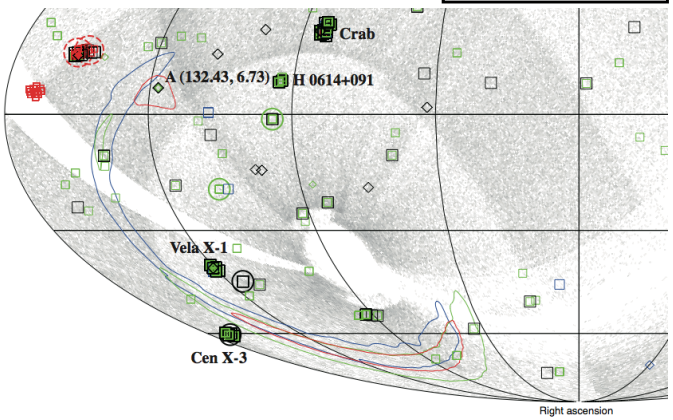
MAXI will measure X-ray emission at the early post-merger phase of neutron star merger events

Emission from Double Neutron Star Merger in time sequence and **possible X-ray emission processes**

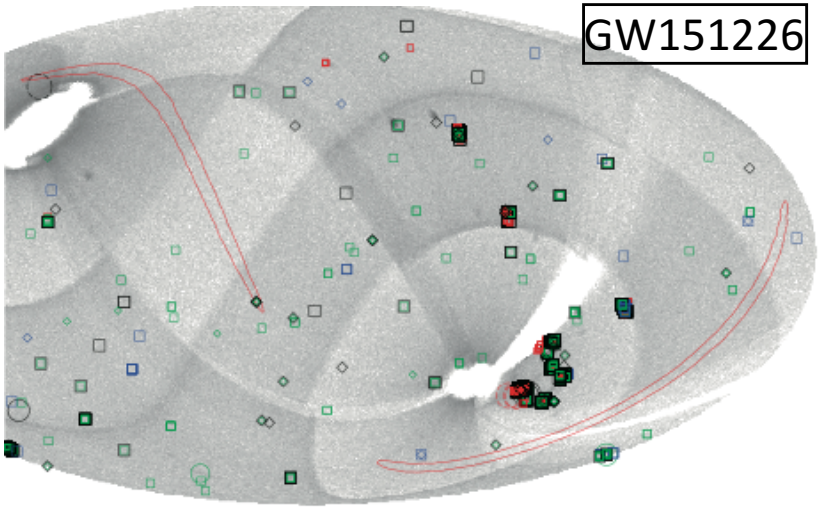
Framework of GW Analysis

- Nova-Alert system is always running regardless of GW event or not

GW150914

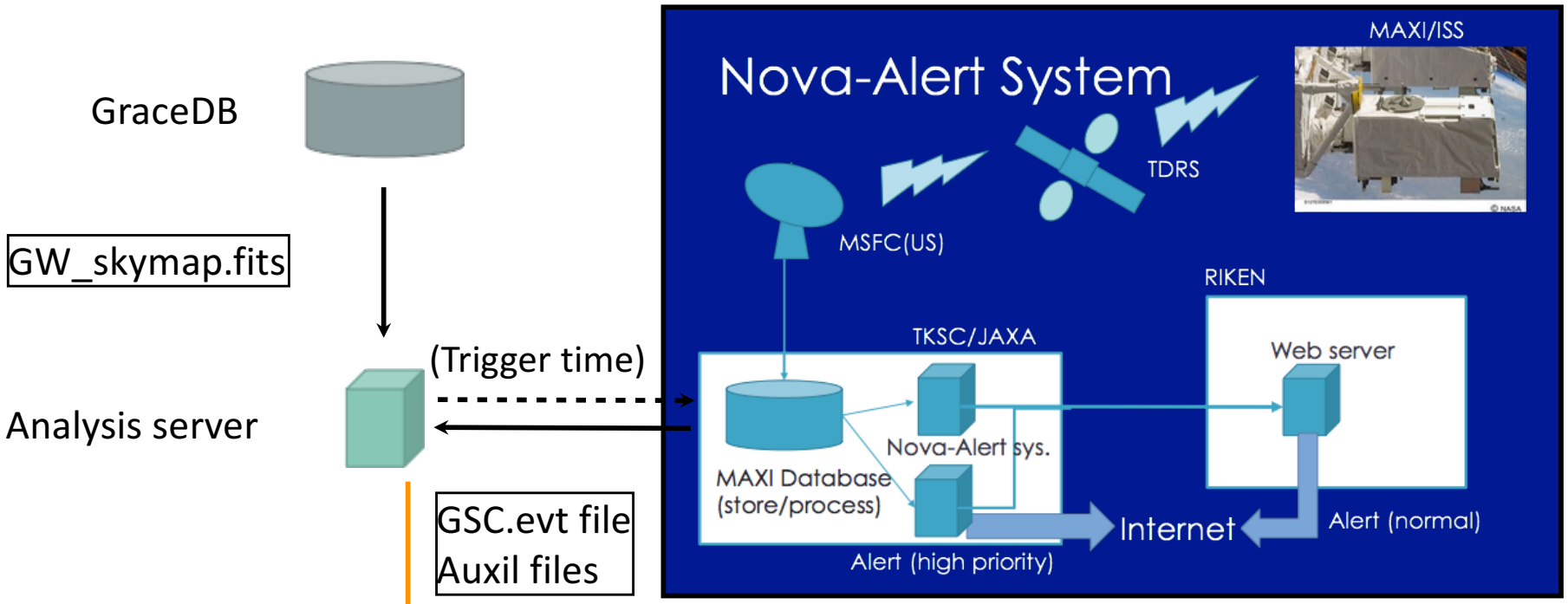


GW151226



- Search weak candidate and calculate X-ray flux upper limits from MAXI/GSC observation in the error region of GW event when we receive the GW skymap data from GraceDB

Framework of GW Analysis



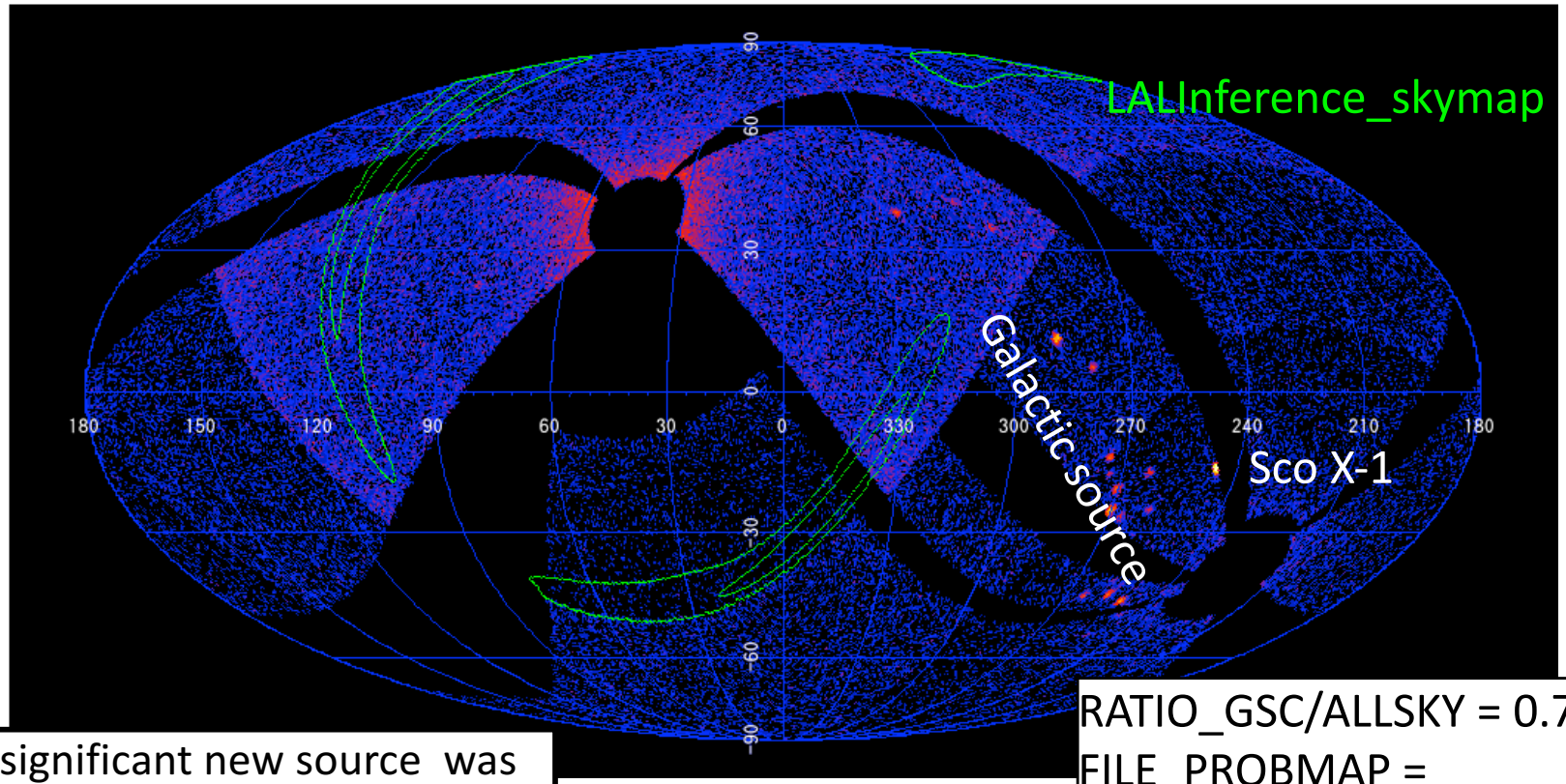
- convert GSC.evt to healpix (time, counts) format from photon data format
- make skymap of GSC in GW error region (and check any candidates).
- calculate covering ratio of GSC observation to the GW error region
- calculate upper limits of the GSC observation from the background counts in each (heal)pixels

LIGO/Virgo Circulars

This process was prepared for O2 run

In case of GW170104

GSC skymap at one-scan with GW 90(50)% error region

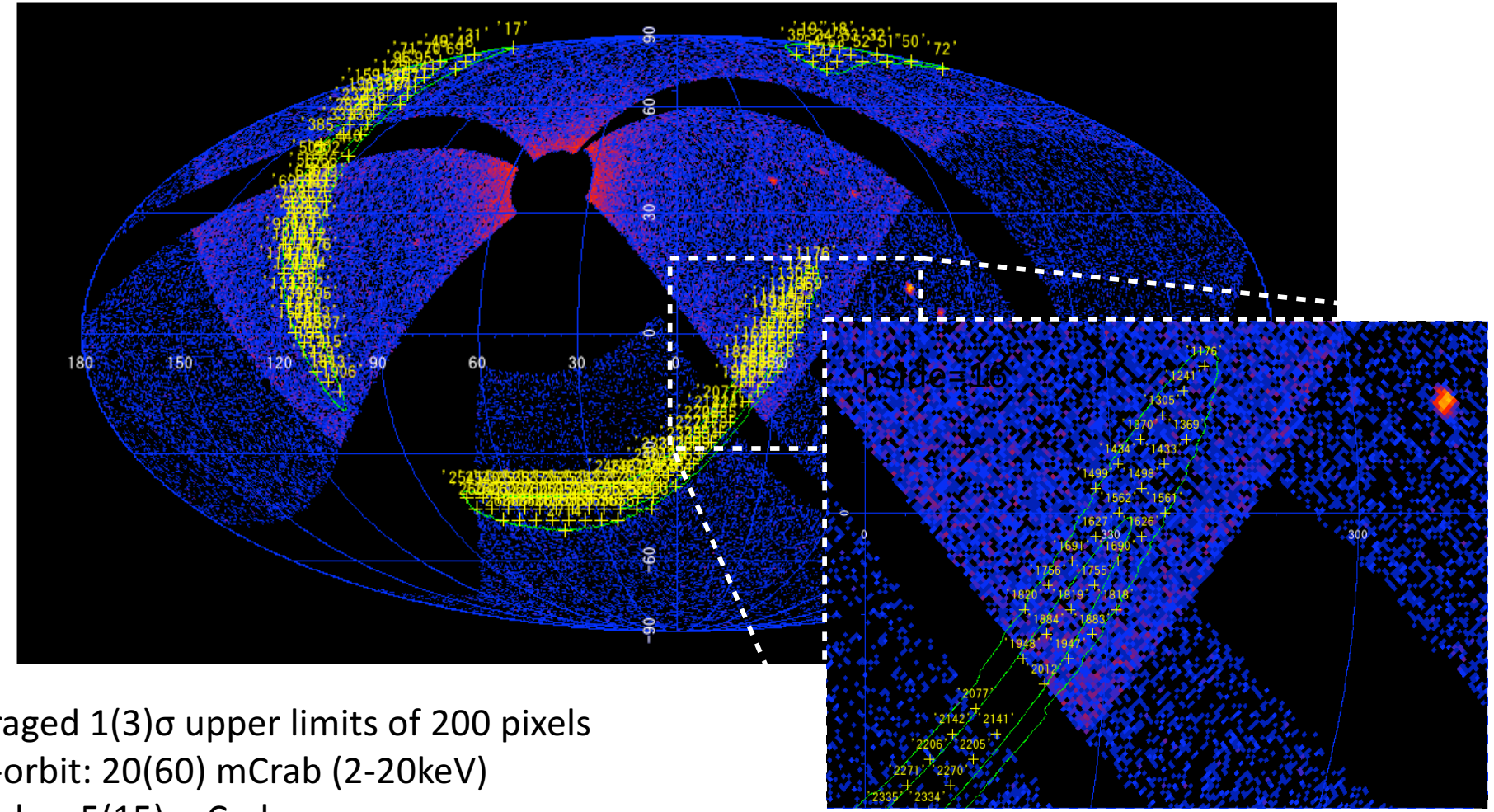


No significant new source was found in these images.

RATIO_GSC/ALLSKY = 0.779
FILE_PROBMAP = LALInference_skymap.fits
RATIO_GW/ALLSKY = 0.050
RATIO_GSC/GW = 0.933

- make skymap of GSC in GW error region and check any candidates.

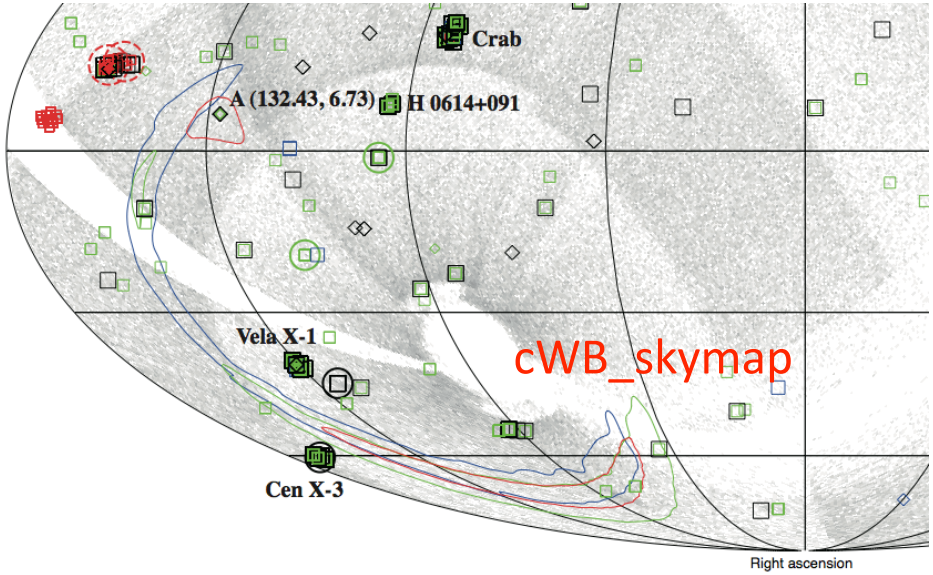
case of GW170104



Averaged 1(3)σ upper limits of 200 pixels
one-orbit: 20(60) mCrab (2-20keV)
one-day: 5(15) mCrab
estimated from background fluctuation (Serino et al., 2017)

- calculate upper limits of the GSC observation from the background counts in each circular regions with the radii of 2.°0

“X-ray upper limits of GW150914 with MAXI”



Nova-search
◇ 1-orbit trigger event
□ 4-orbits trigger

PASJ accepted (Kawai et al.)

- Triggered at 2015/09/14 09:50:45 UTC
- Scan in the GW error region started T0+4 to +25 min
- Scan in one-orbit covered 95% of cWB skymap region by 6 GSC cameras
- Nova-Alert detected no significant variability with 3 σ in the GW error region.

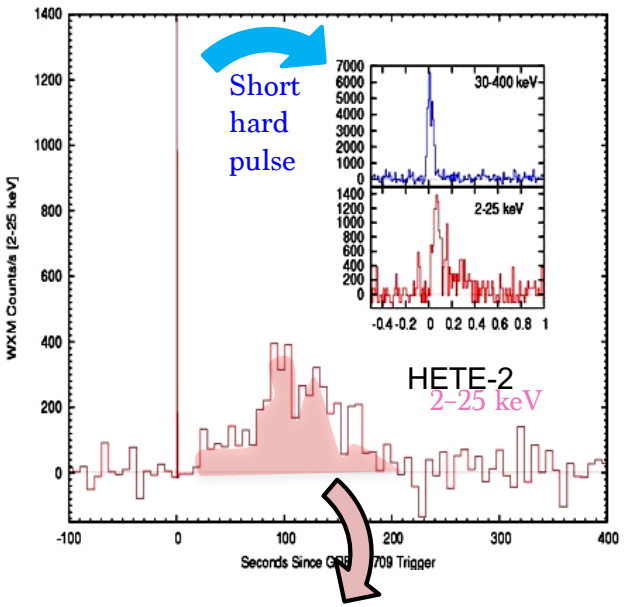
“X-ray upper limits of GW150914 with MAXI”

Table 2. Upper limits for the X-ray flux and radiated energy obtained by MAXI/GSC.

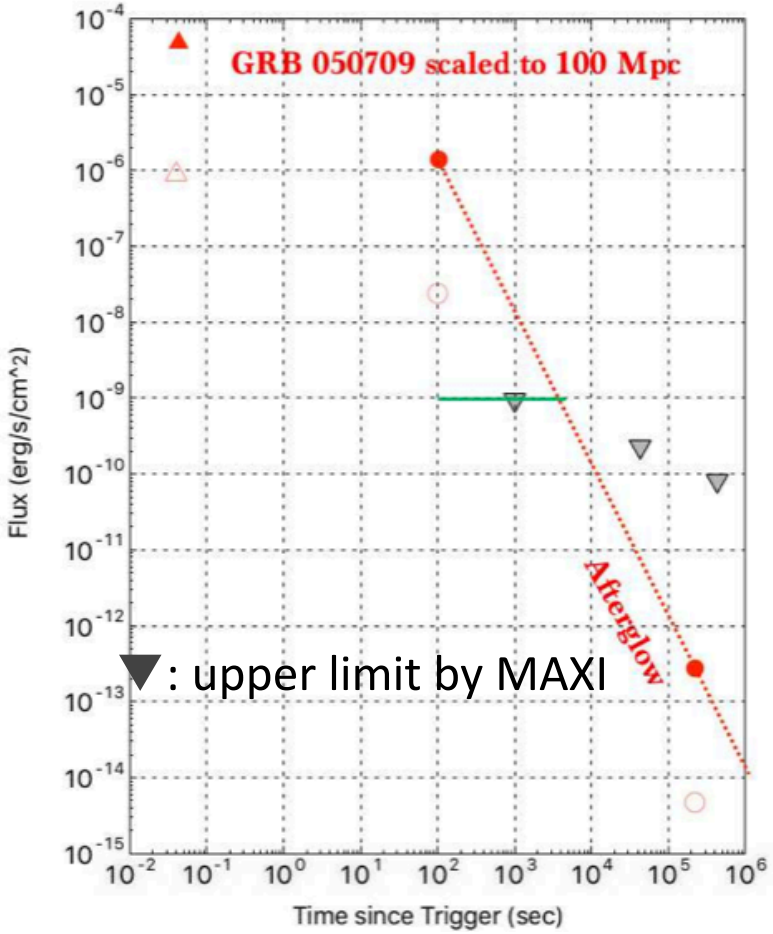
	Timescale (s)	Flux (2–20 keV) (erg s^{-1} cm^{-2})	Luminosity * (erg s^{-1})	Radiated Energy (erg)	E_X/E_{GW}
1 orbit	1000	$< 9.5 \times 10^{-10}$	$< 1.9 \times 10^{46}$	$< 1.9 \times 10^{49}$	$< 3.5 \times 10^{-6}$
1 day	8.6×10^4	$< 2.3 \times 10^{-10}$	$< 4.6 \times 10^{45}$	$< 4.0 \times 10^{50}$	$< 7.4 \times 10^{-5}$
10 days	8.6×10^5	$< 0.8 \times 10^{-10}$	$< 1.6 \times 10^{45}$	$< 1.4 \times 10^{51}$	$< 2.6 \times 10^{-4}$

If GW events are associated with short GRBs like GRB 050709, MAXI will be able to detect X-ray emissions (especially extended emission) in one-orbit scan

GRB050709 Villasenor et al. 2005



Prompt Extended Afterglow

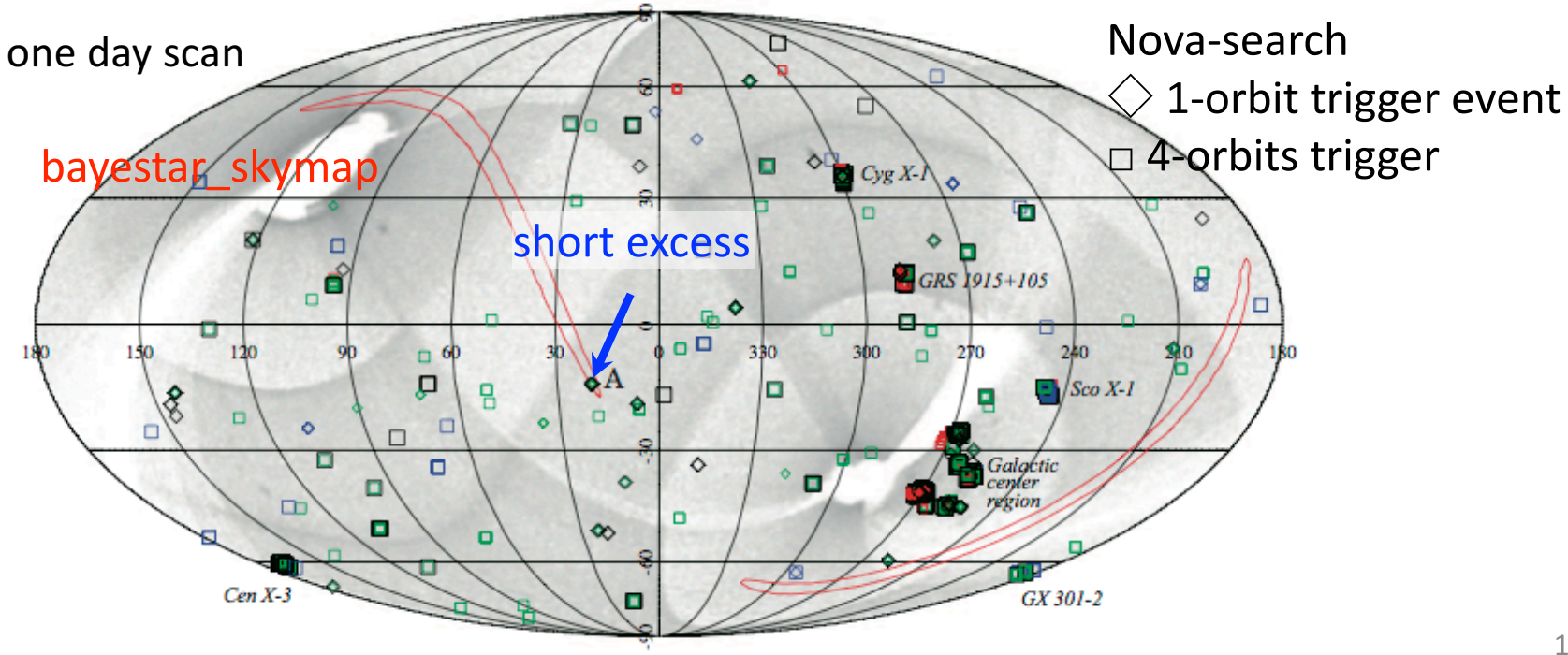


- Calculate the X-ray upper limits in 3 timescales and estimate luminosity from distance of 410 Mpc

“X-ray upper limits of GW151226 with MAXI”

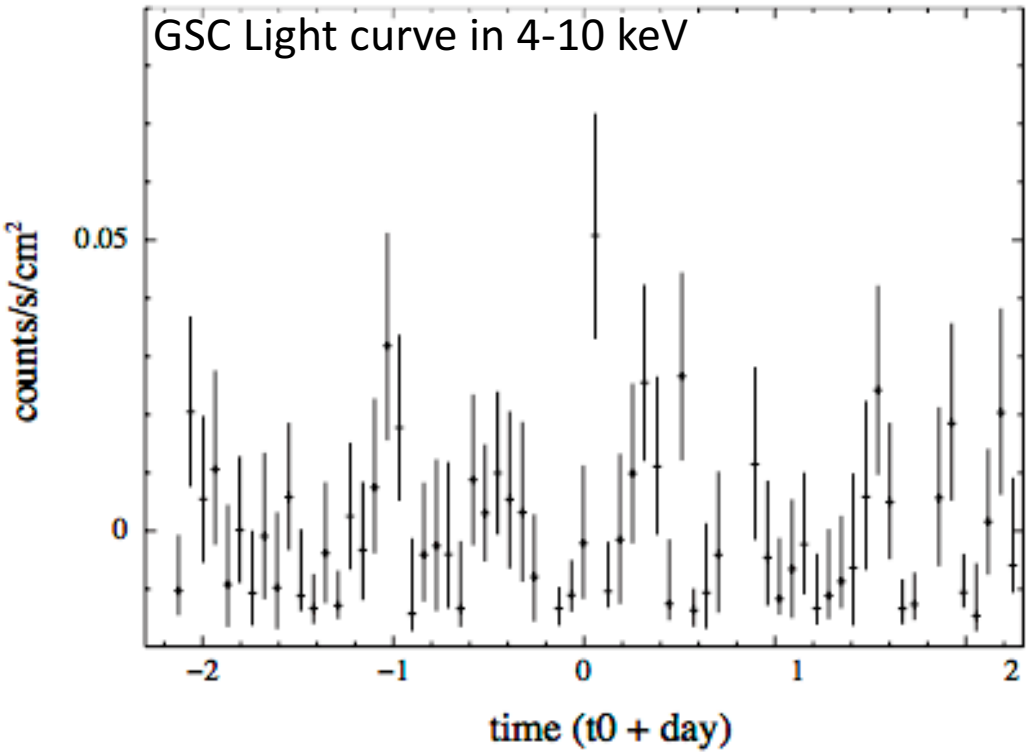
PASJ accepted (Serino et al.)

- Triggered at 2015-12-26 03:38:53.648 UTC
- At the trigger time, GSC was observed in the GW error region: cover 1% of the region at that time
- Scan in one-orbit covered 84.8% of bayestar skymap region by 6 GSC cameras
- Nova-Alert detected a short excess event with a low significance (2.85σ) from T0+5257 to 5260 sec



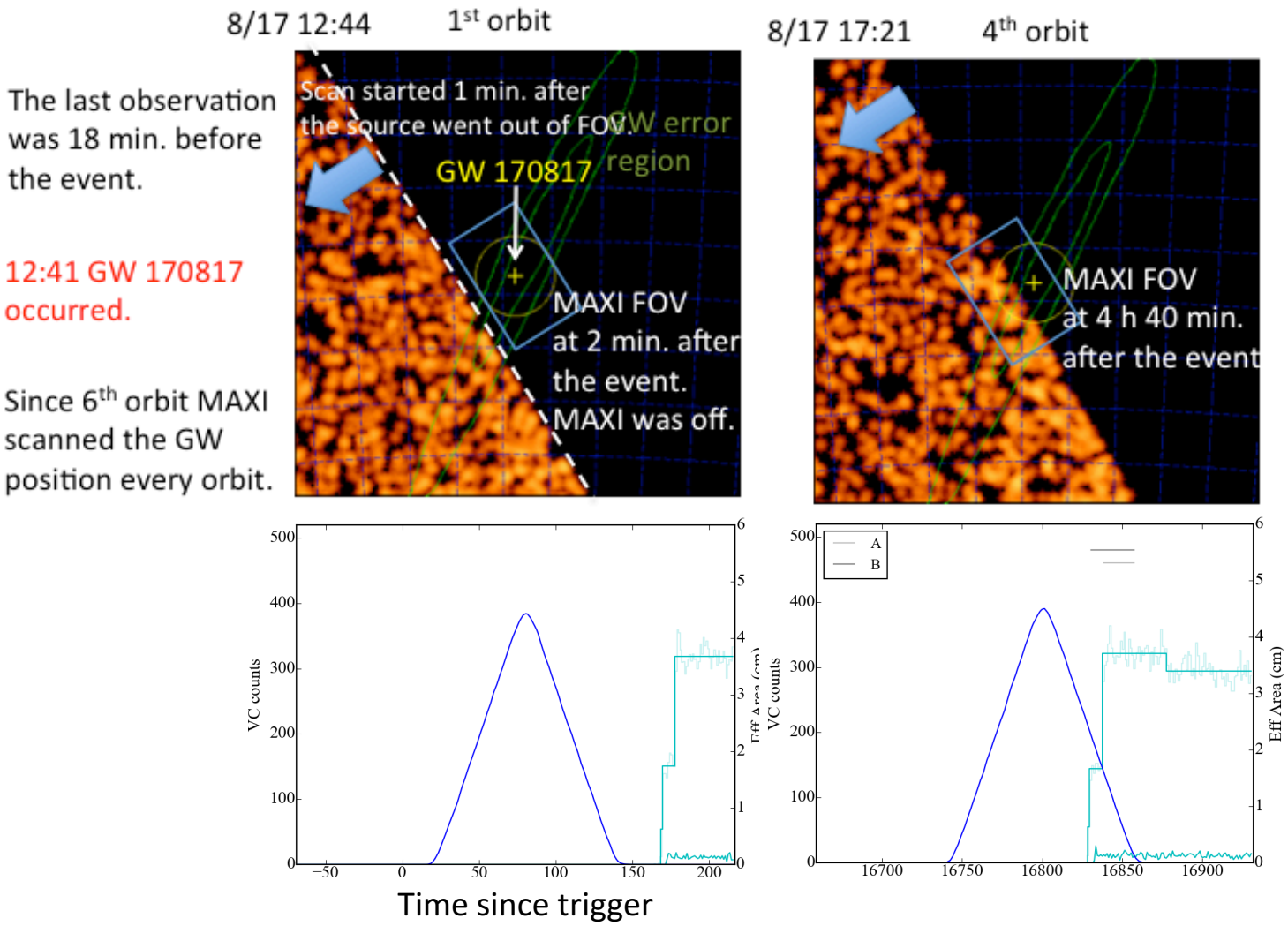
“X-ray upper limits of GW151226 with MAXI”

Short excess in the GW error region



- (R.A., Dec): (19.913, −14.480 deg) with error of elliptical circle 0.46°,0.49° (+systematic 0.1°)
- X-ray flux: $5.1^{+2.1}_{-1.8} \times 10^{-2}$ counts cm^{-2}s^{-1} ~43 ±16 mCrab

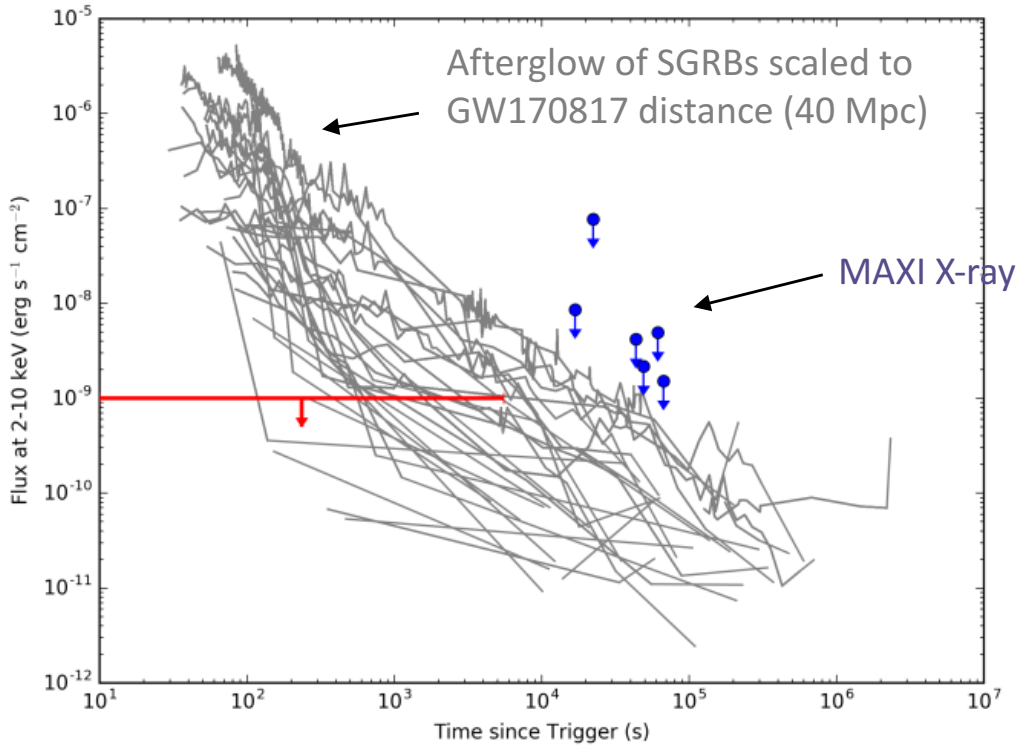
Observation of GW170817



- MAXI set the earliest X-ray upper limit at 4.6 hours after the GW event.
  - MAXI was not able to observe GW170817 for 4.6 hours after the GW trigger due to operational constraints that affect 15% of the sky in a orbit.

Observation of GW170817

MAXI X-ray upper limits for GW170817

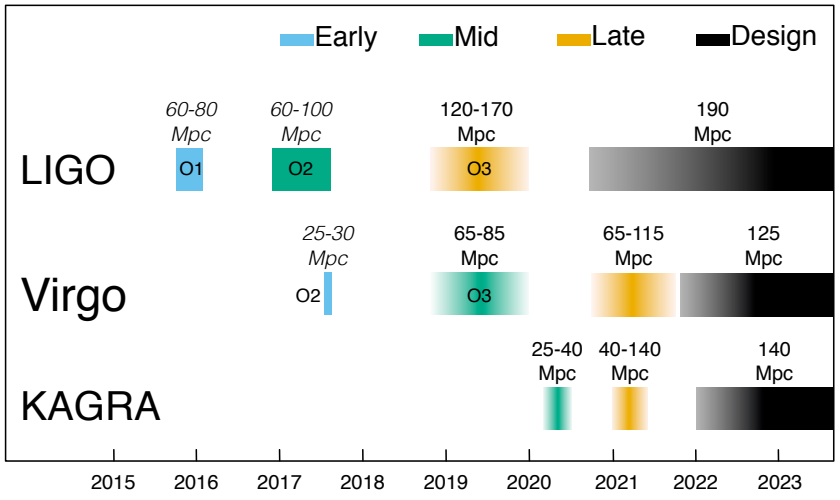
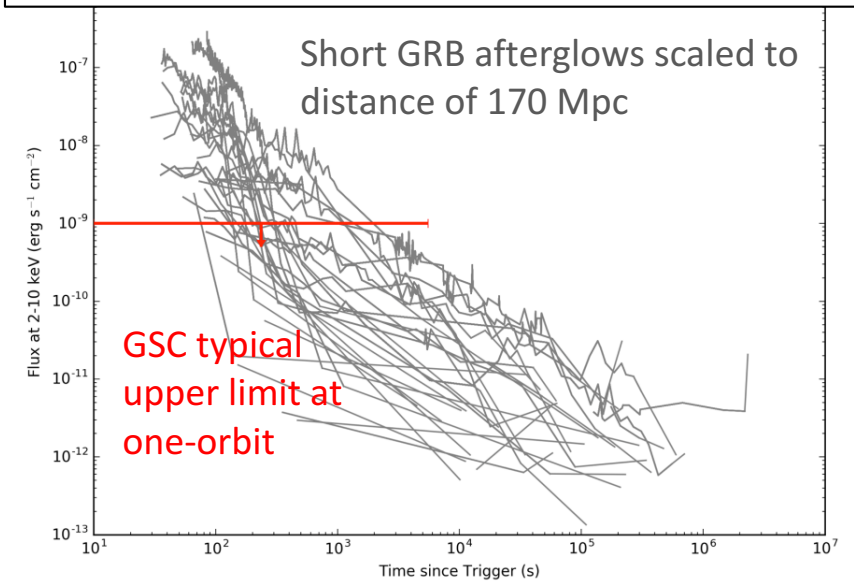


- MAXI upper limit for GW 170817 was reported in Multi-messenger paper
- MAXI had sufficient sensitivity to measure the “extended” X-ray emission of “typical” SGRBs, if MAXI would observed the source within an orbit. The sky coverage in an orbit was 85% of the whole sky.

Toward O3

- The LIGO/Virgo GW detectors will be upgraded at the next observing run (O3: one year run from fall 2018) to double the horizon distance (or ×8 event rate) .
- ≈100 GW events are expected including >≈10 double neutron star mergers in O3. In addition, Japanese GW detector KAGRA will be operational in 2019–2020.
- MAXI scans 85% of the whole sky area in a orbit (92 min), ready to search for X-ray counterparts for every GW event even if its localization error is large.
- MAXI can detect the afterglow from a SGRB at 170 Mpc (LIGO horizon for double neutron star merger at O3), and will test the emission models for GW events.

The horizon distance of the GW detectors for double neutron star merger events at the planned observing runs.



Detectability of GSC to SGRB afterglow from 170 Mpc