# The search for X-ray counterparts of gravitational wave events

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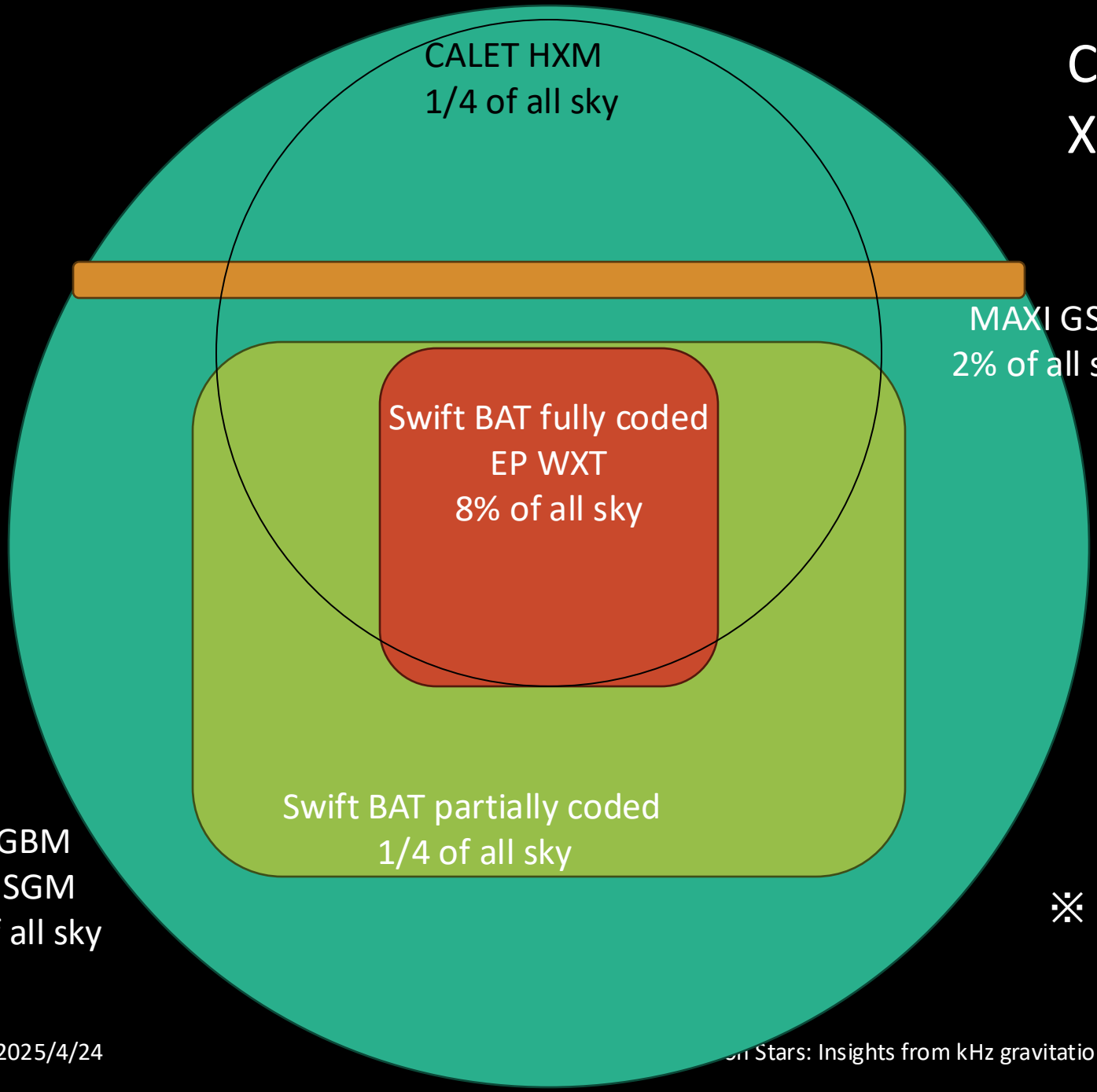
# Gravitational wave events and X-ray observations

- Purposes of X-ray observations
  - find counterparts of GW events
  - localize the position of the counterparts (for follow-up observations)
- Why X-ray (gamma-ray)?
  - large FoV
  - developed alert systems (GRBs, binaries, etc.)

# Comparison of FoVs of X-ray instruments




Typical FoV size of
X-ray telescopes

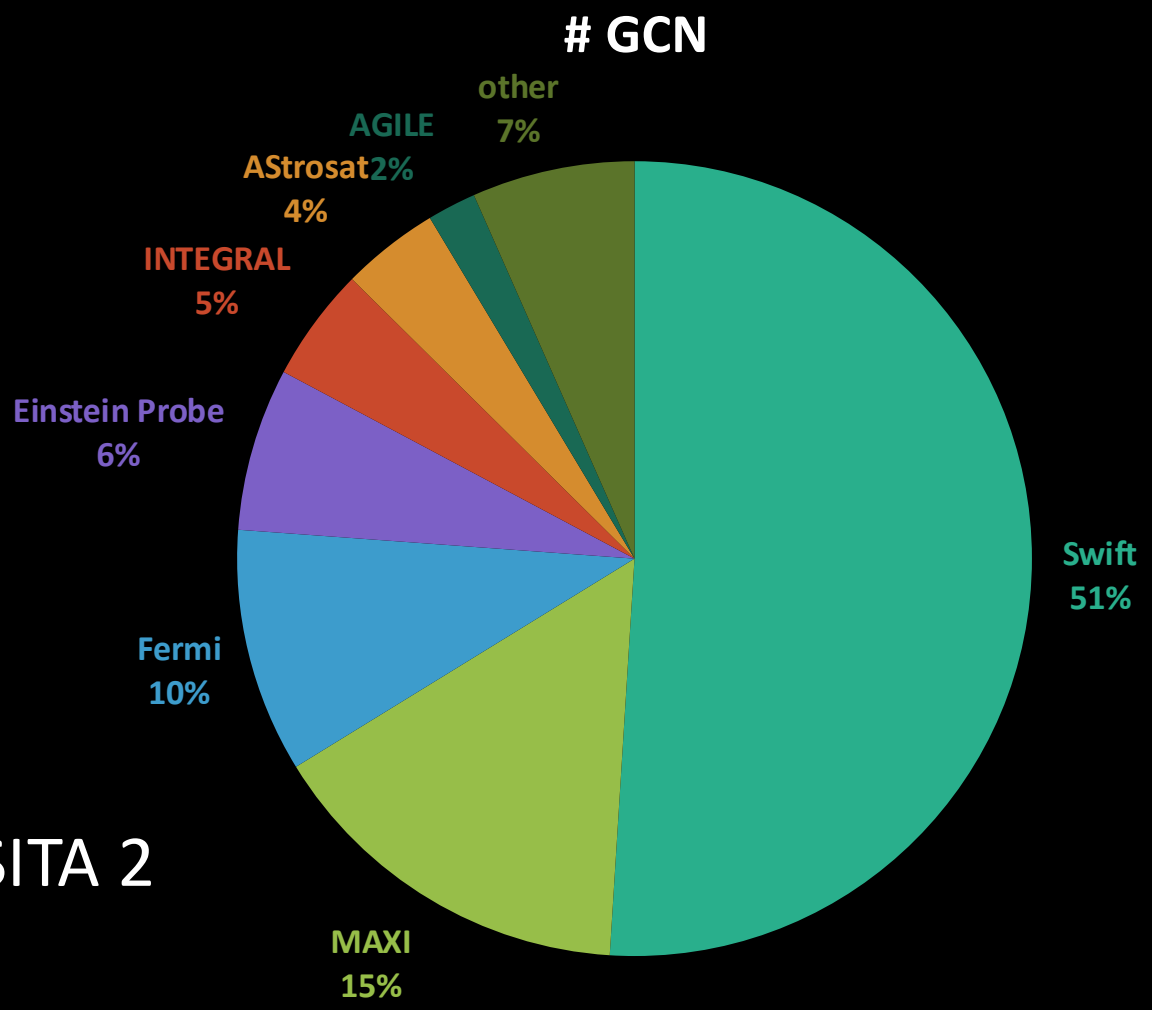
※ instantaneous FoV

# Gravitational wave events and X-ray observations

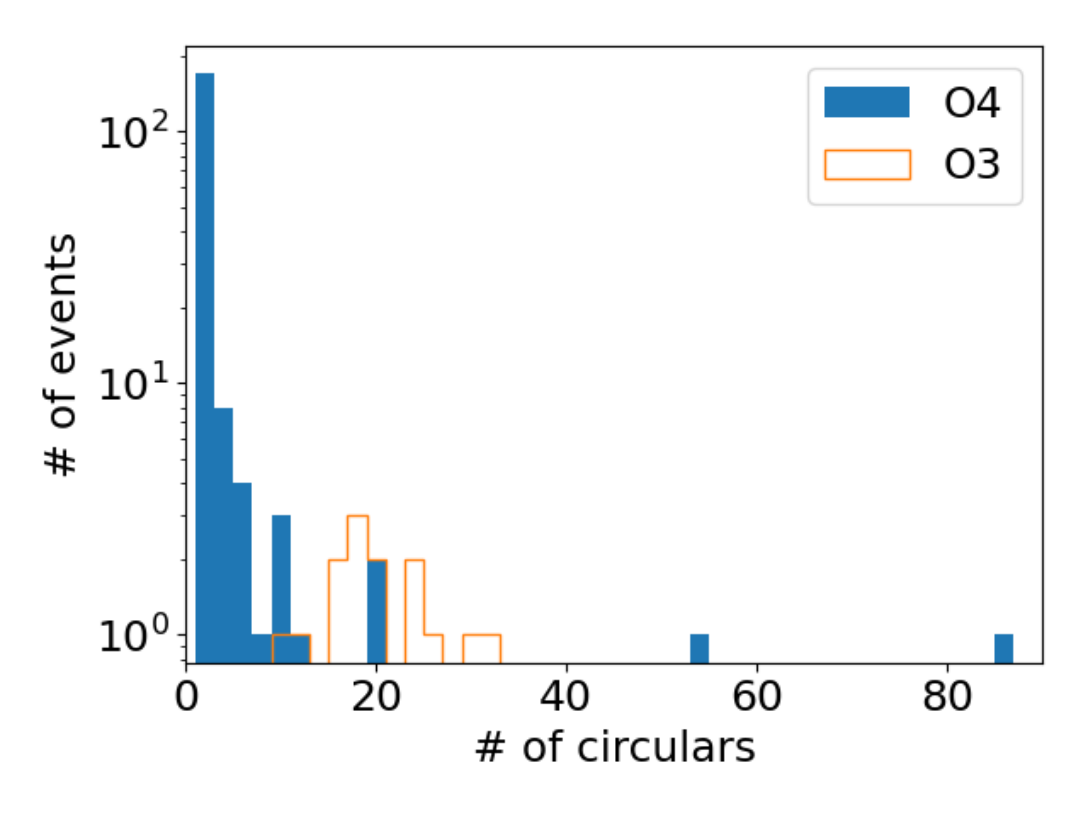
- Purposes of X-ray observations
  - find counterparts of GW events
  - localize the position of the counterparts (for follow-up observations)
- Why X-ray (gamma-ray)?
  - large FoV
  - developed alert systems
    (They are originally for GRBs, X-ray binaries, etc.)

# GCN circulars of X-ray/gamma-ray satellites (O4)

- Swift 77
- MAXI 23
- Fermi 15
- Einstein Probe (EP) 10
- INTEGRAL 7
- AstroSat 6
- AGILE 3
- CALET / Konus-wind / GECAM / eROSITA 2
- Insight-HXMT / Glowbug 1



# follow-up observations for a GW event in O3 and O4

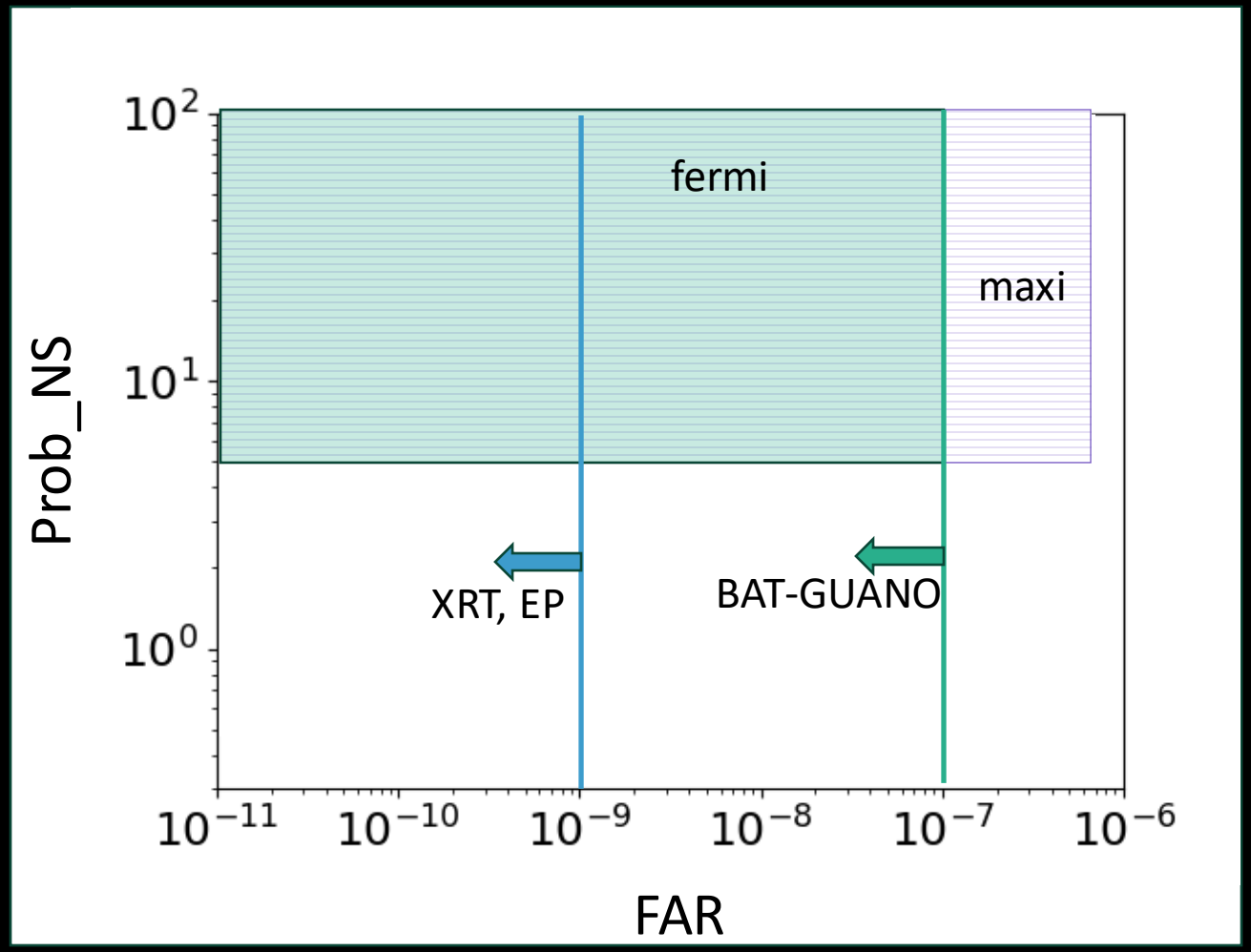



※ including the other wavelength and neutrinos

- average number of circulars for a GW event was larger in O3
- The total number of GW event has increased significantly in O4
  - Each mission made strategy to select the events to observe

# GW observation strategy (GCN circulars)

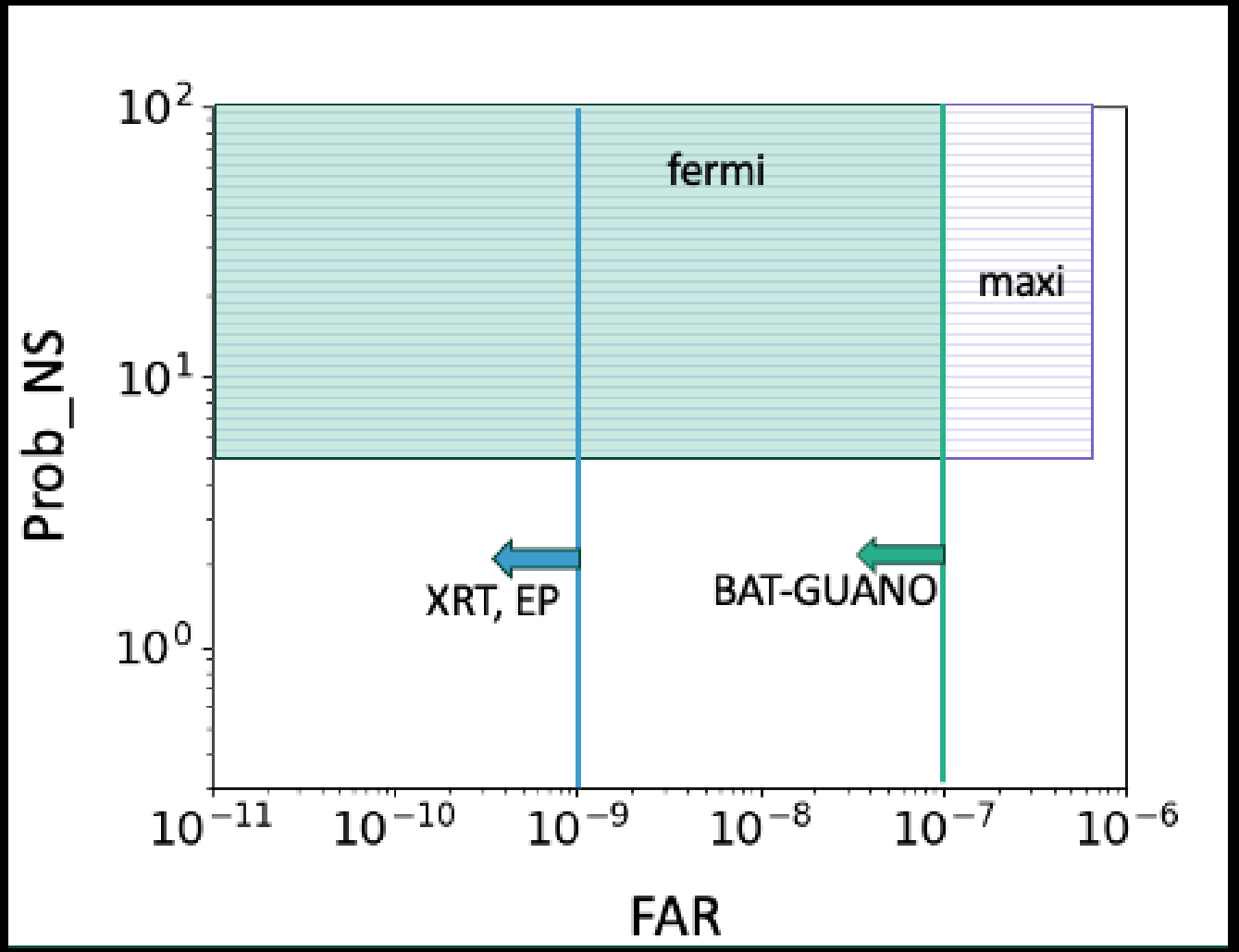
- false alarm rate (FAR) seems to be a primary standard in many missions
- Some missions use Prob_NS
- Follow-up telescopes may select well-localized events



# Swift follow-up

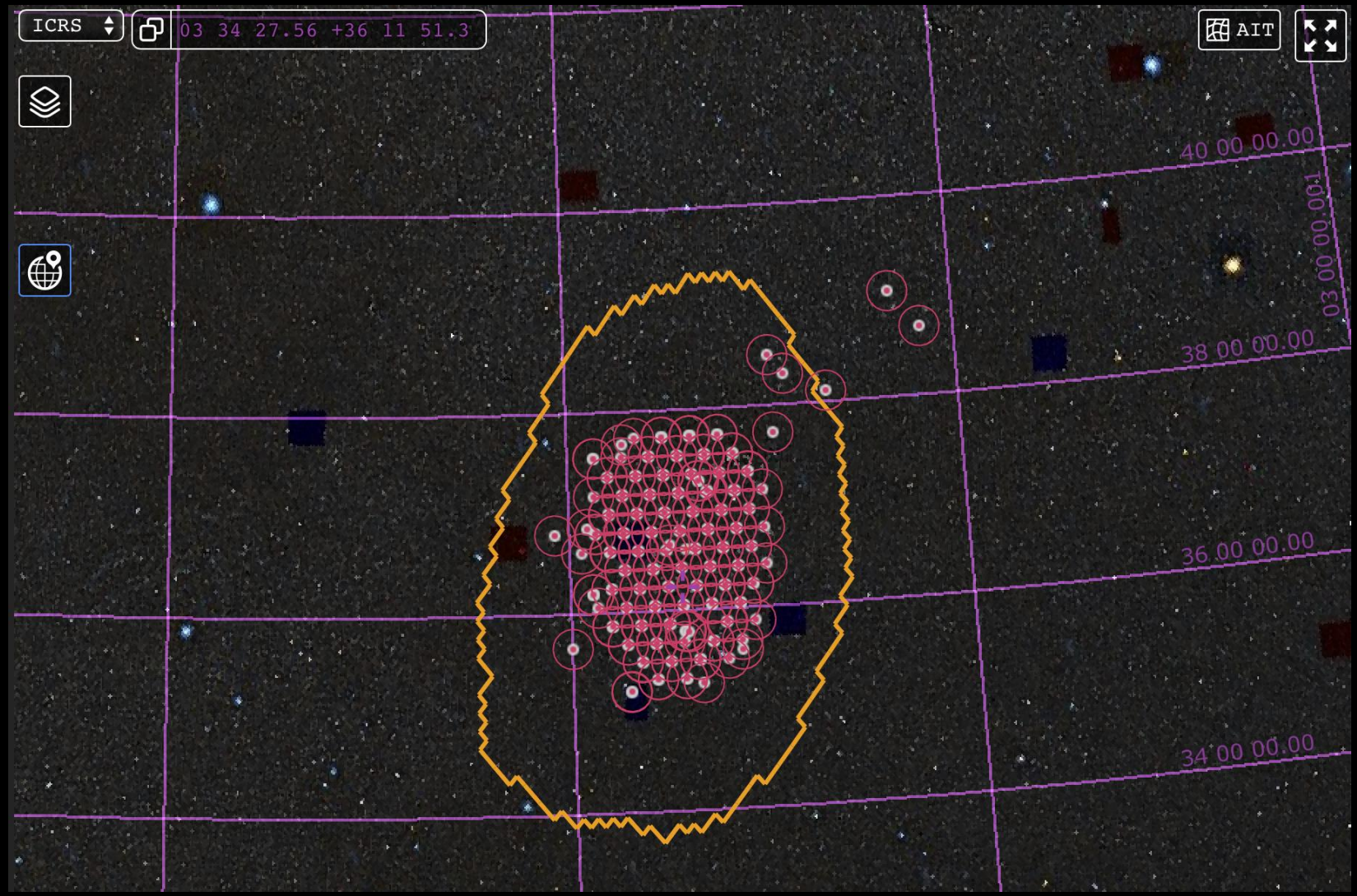
# Swift's activity related to GW events

- 77 GCN circulars
  - 60 from BAT (prompt emission)
  - 13 from XRT (follow-up)
  - 4 from UVOT (follow-up)
- XRT selected well-localized events for observation



# Swift/XRT tiled observation (S240919bn)

217 observations
for 55% probability region



# Summary of XRT follow-up

| ID | area [deg$^2$] | point | GW prob [%] |
|---|---|---|---|
| S230518h | 6 | 60 | 1 |
| S240615dg | 10.1 | 198 | 75 |
| S240915b | 17.7 | 309 | 71 |
| S240919bn | 6.6 | 217 | 55 |
| S250119cv | 13.1 | 189 | 68 |
| S250328ae | 5.3 | 97 | 68 |

follow-up at the position of candidates

S230917af(MAXI) S240422ed(EP)

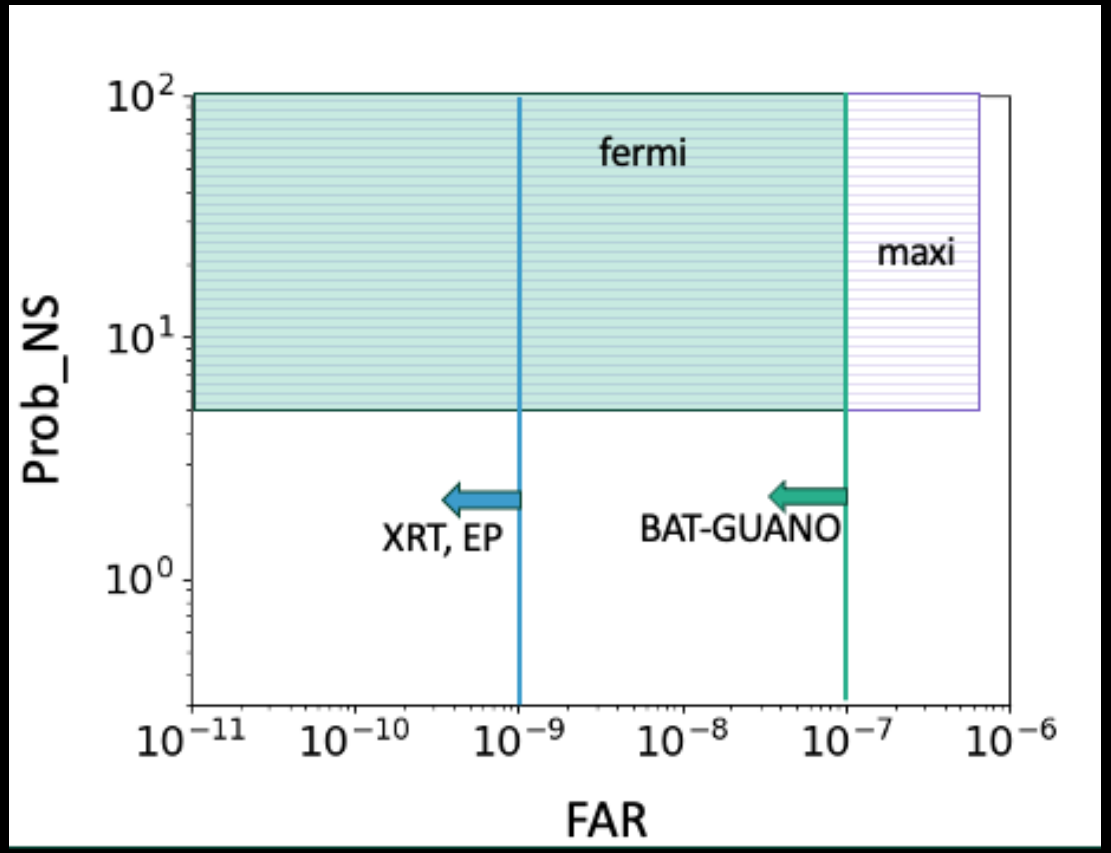
S241125n(BAT) S250223dk(BAT)

- XRT is making a lot of effort.
- Still, the numbers (or area) of follow-up is limited.
- If the error region become smaller, the observation will be complete.
- XRT takes a few days to tile
  This is because it will be darker (assuming something like X-ray afterglow), which makes it less likely to be observable
  → discuss later

# MAXI

# MAXI's activity related to GW events

- GSC coverage and start/end time of the observations are calculated automatically for all the GW alerts
  - We report the results if
    FAR< 20 per year
    and
    Prob_NS > 5%



LIGO/Virgo/KAGRA S230518h: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S230529ay: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S230627c: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S230731an: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S230802aq: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S230917af: MAXI/GSC observations
LIGO/Virgo/KAGRA S231020ba: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S231021az: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S231113bw: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S231113cd: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S231119ab: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S240422ed: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S240513cx: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S240629by: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S240711cm: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S240830gn: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S240910ci: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S240915b: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S241109bn: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S241114bi: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S241231du: Coverage and upper limit from MAXI/GSC
LIGO/Virgo/KAGRA S250201i: Coverage and upper limits from MAXI/GSC
LIGO/Virgo/KAGRA S250206dm: Coverage and upper limits from MAXI/GSC

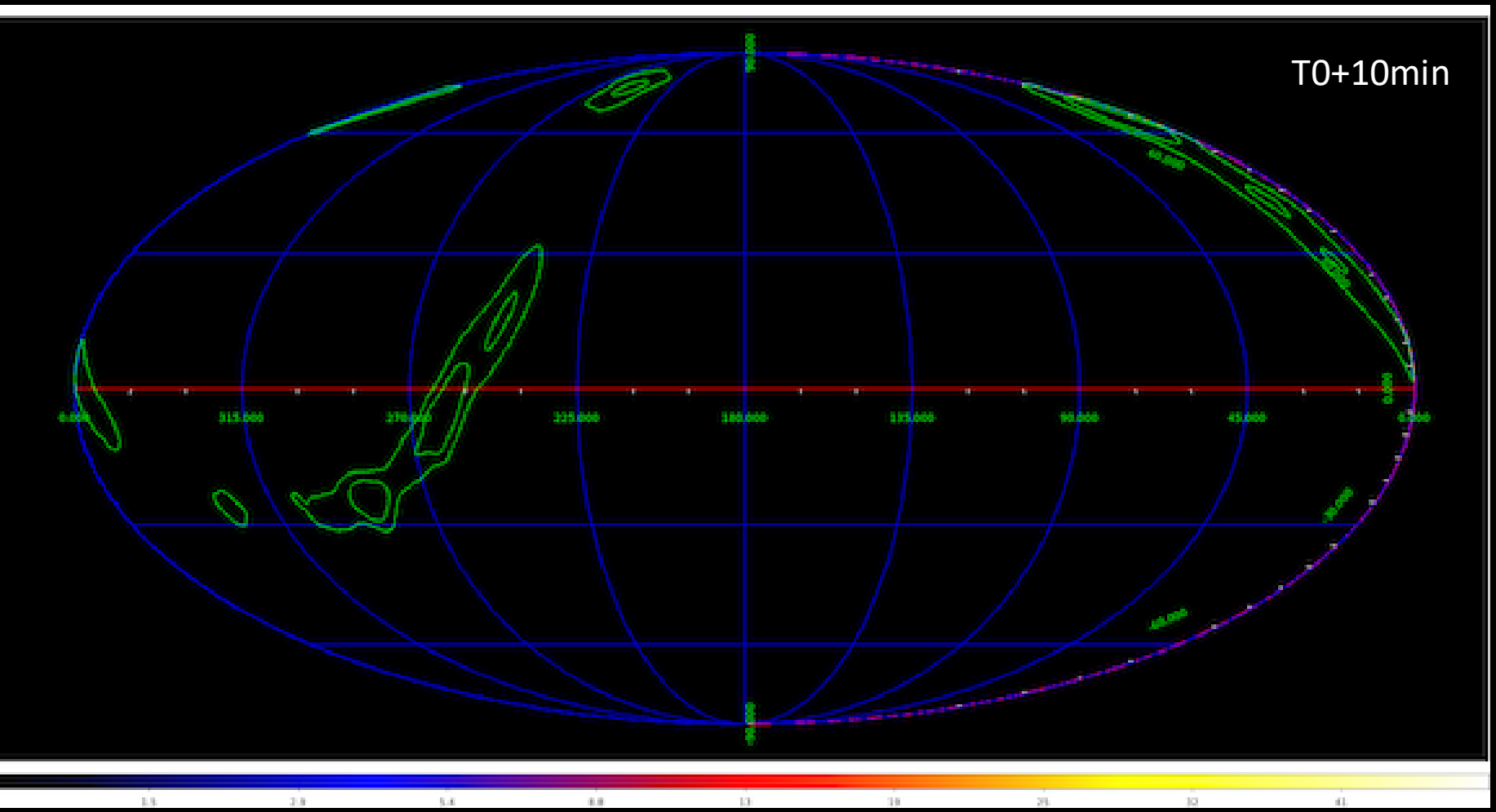
# GW event

23 GCN Circulars in O4

http://maxi.riken.jp/doc/maxi_gcn.html

# Map of X-ray photons

S250201i



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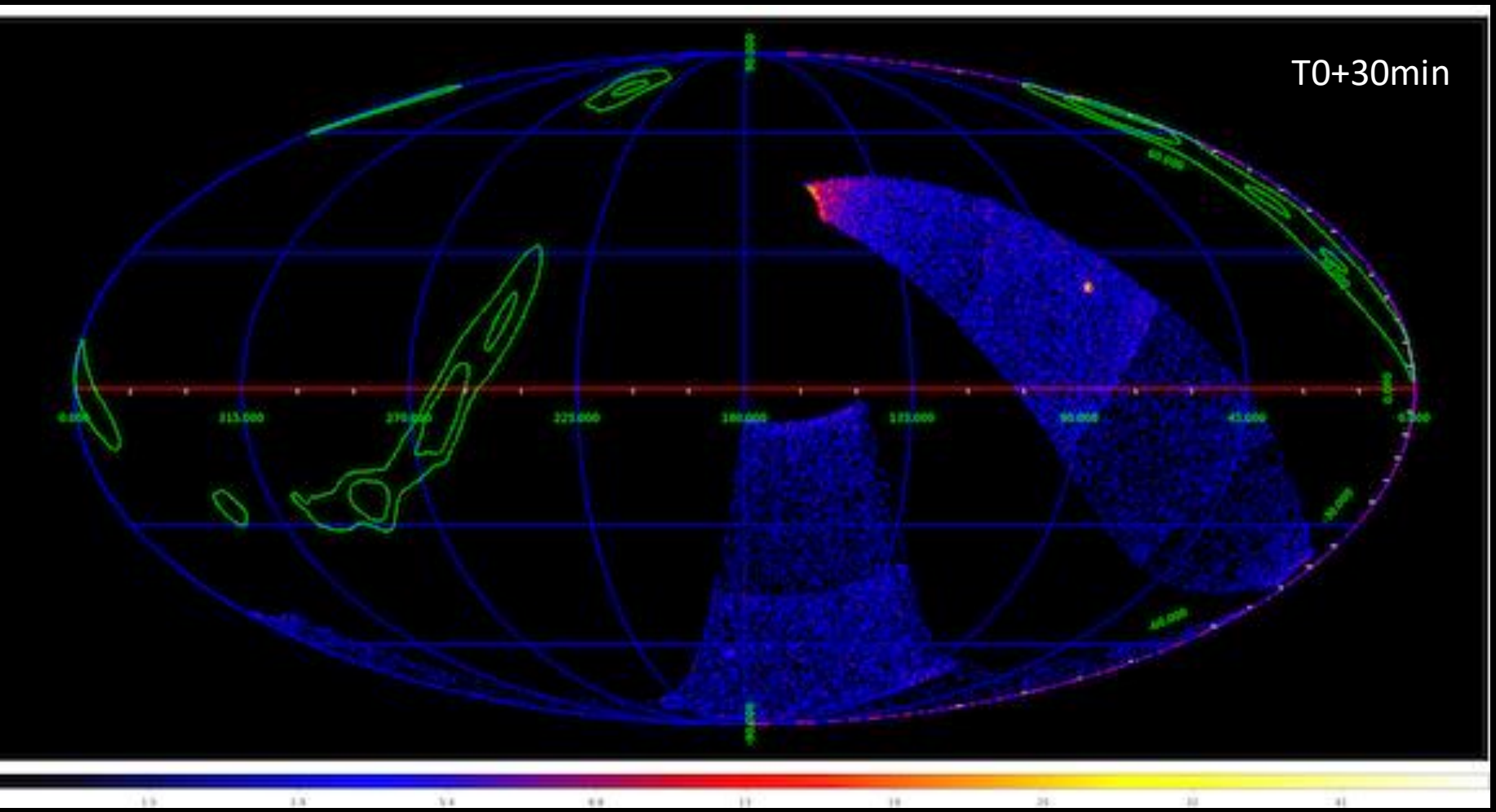
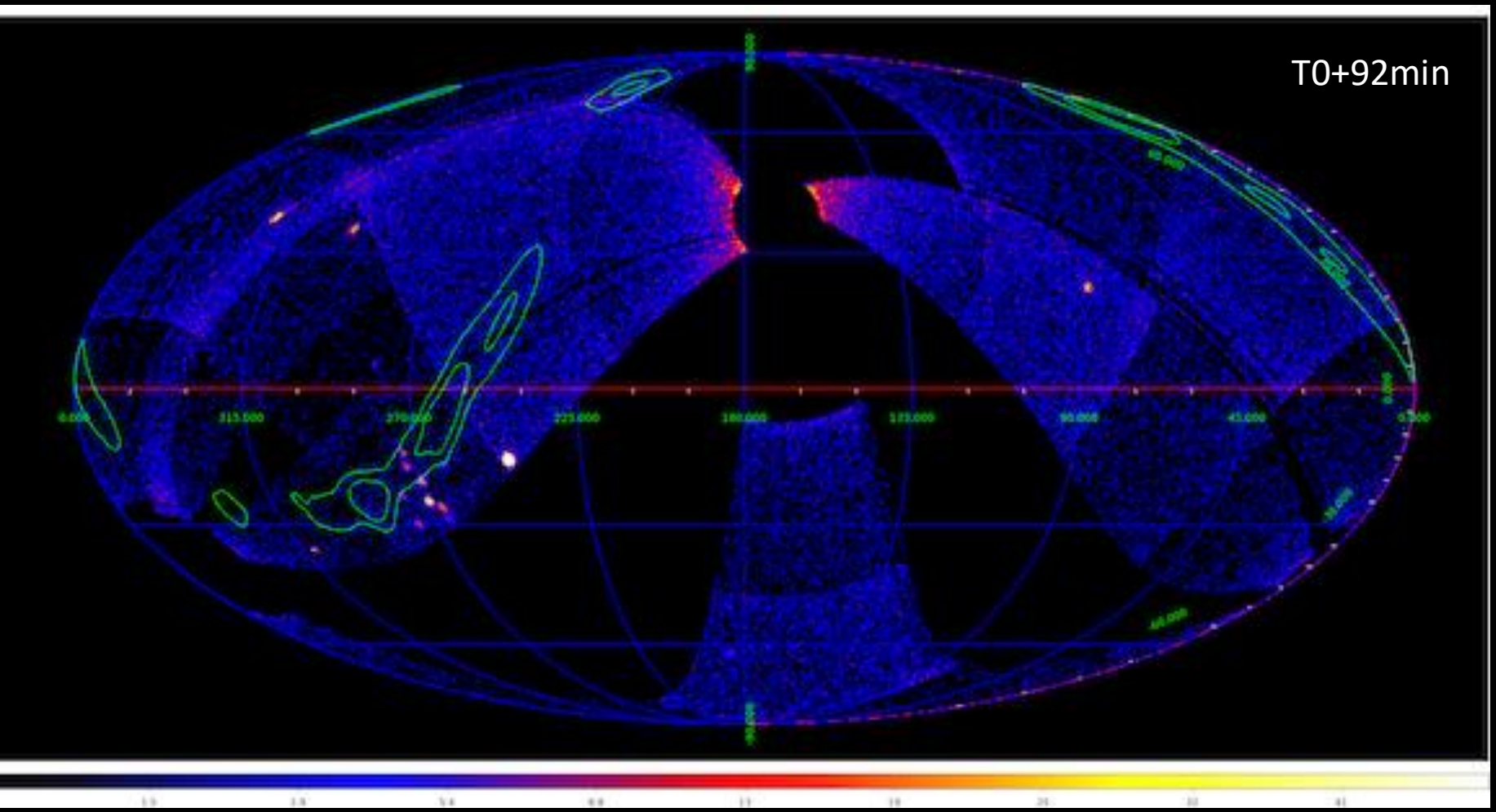
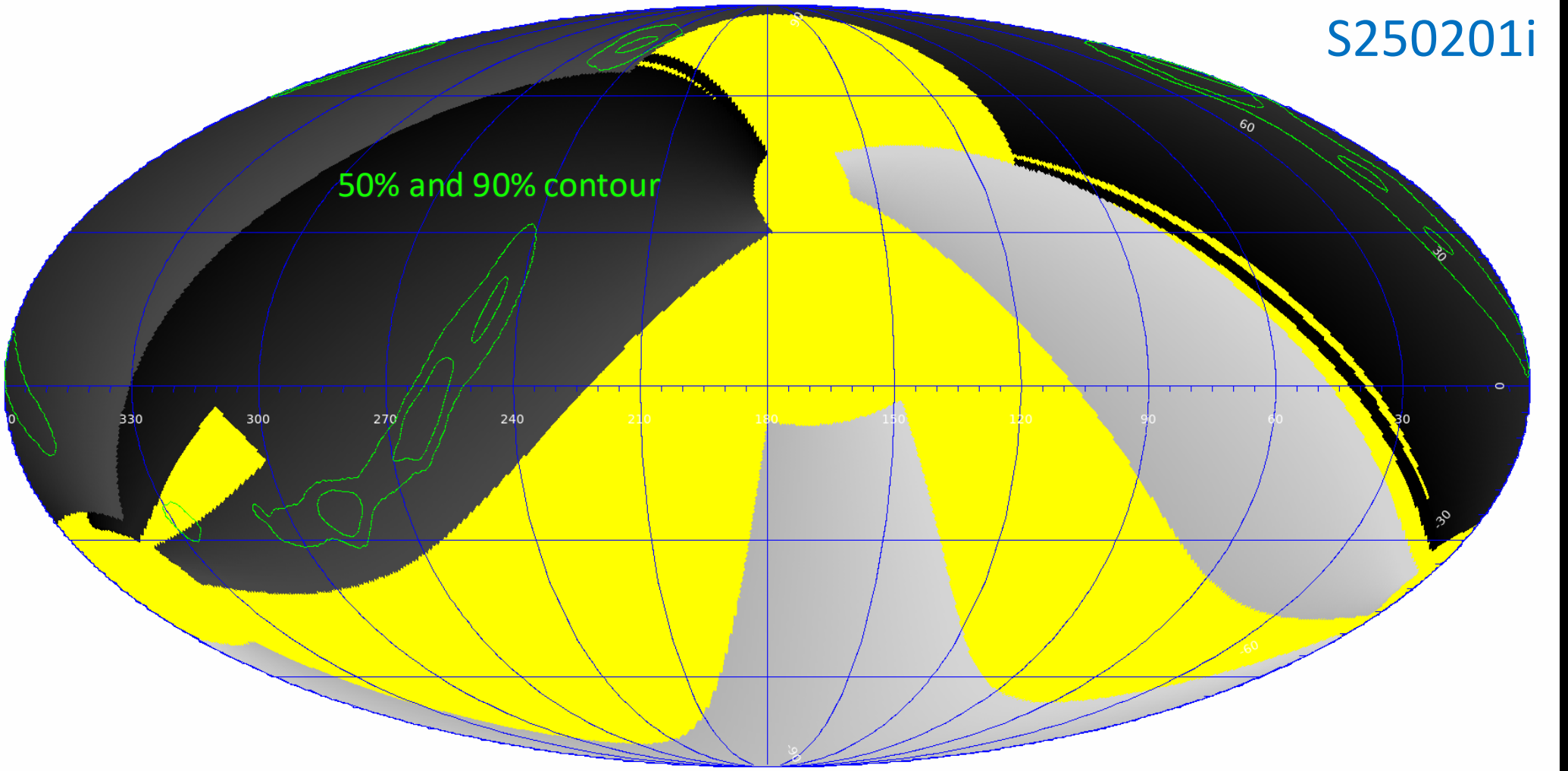


# Map of X-ray photons

S250201i



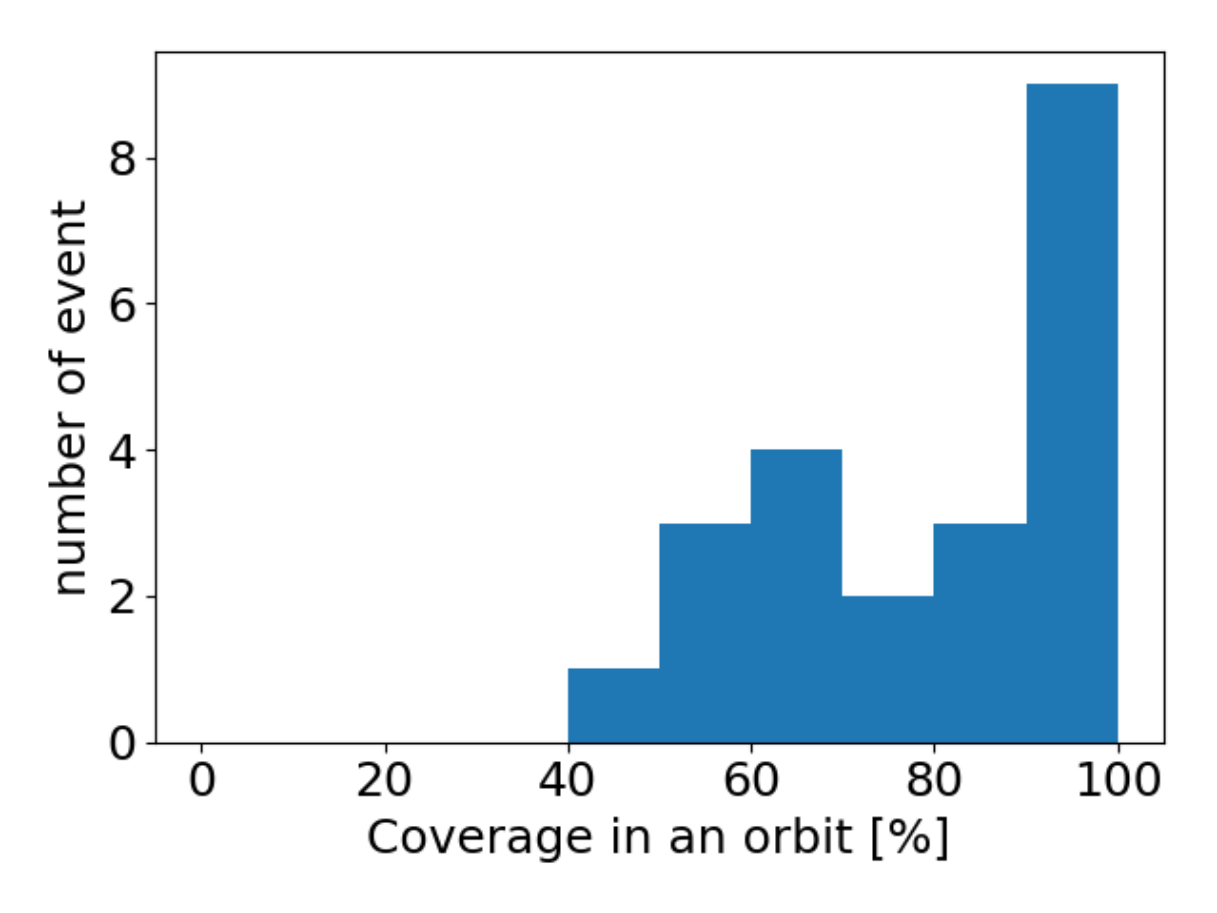
# Map of observation time




time of the observation (since GW trigger)

not observed

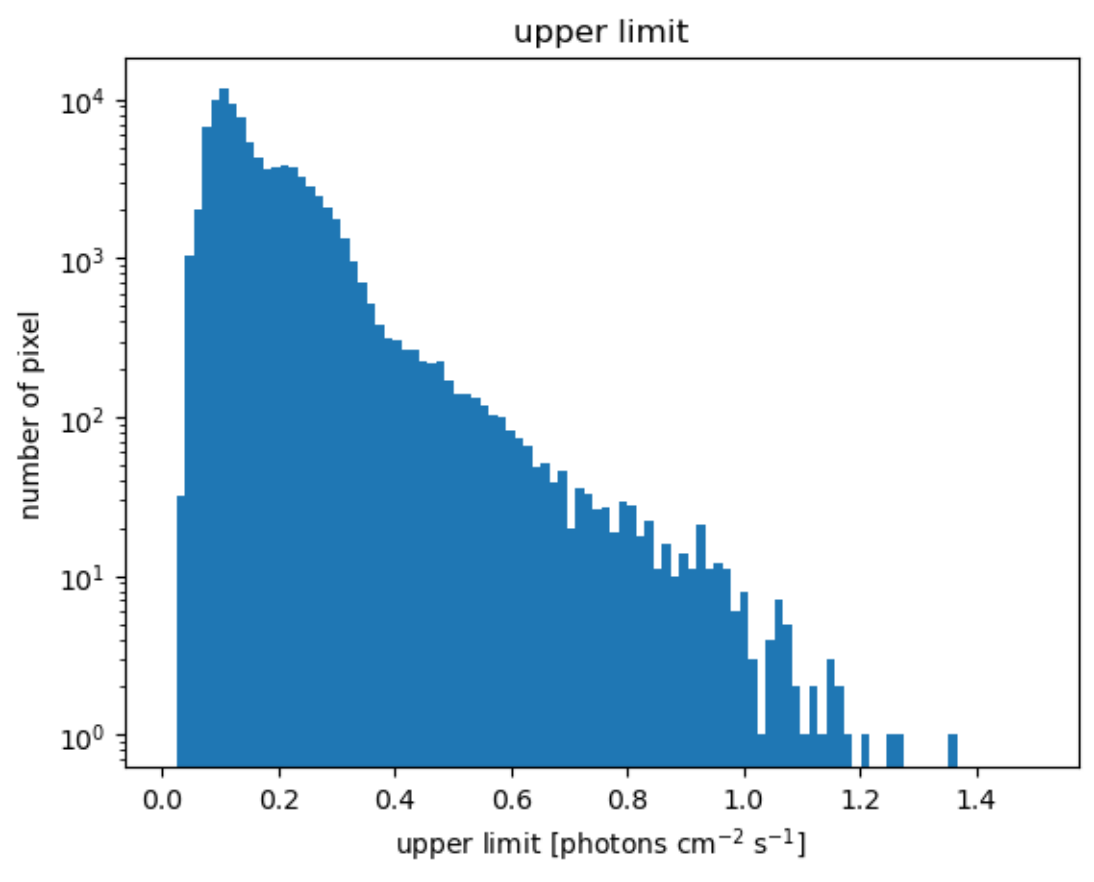
# distribution of coverage (O4)




MAXI team report

- observation status (on/off) at trigger time
- covering fraction at the trigger time
- observation coverage after one orbit

# histogram of upper limit (O4)




- mean upper limit (2-20 keV):
  0.17 photons cm$^{-2}$ s$^{-1}$
  ~ 2.3 x 10$^{-9}$ erg cm$^{-2}$ s$^{-1}$
- upper limits for each healpix pixel can be estimated from observed photon number and effective exposure at the point

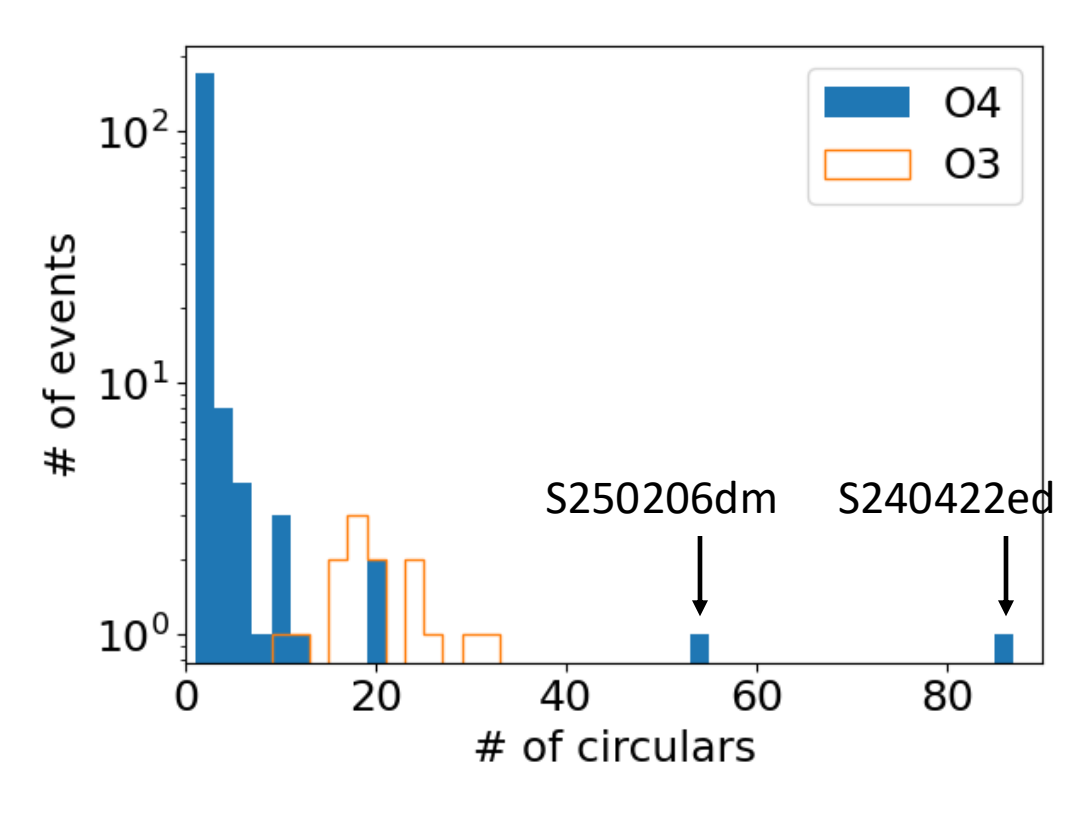
# Einstein Probe (EP)

# list of EP GCN

- S240413p: X-ray upper limits from EP-WXT for the candidate AGN counterpart
- S240422ed: X-ray Upper Limits from EP-WXT for the  Three Potential Electromagnetic Counterparts Reported So Far
- S240422ed: Early X-ray Upper Limits from EP-WXT for the LVK Sky Localization Region
- S240422ed: X-ray Upper Limits from EP-WXT for the Potential Electromagnetic Counterparts Reported by Swift and DECam
- S240422ed: X-ray Upper Limits from EP-FXT for the Potential Electromagnetic Counterparts Reported by Swift and DECam
- S240422ed: EP-FXT detection of a candidate counterpart EP240426a
- S240422ed: EP-FXT Detection of the Potential Optical Electromagnetic Counterpart AT 2024hfq Reported by DECam
- S241102br: EP-WXT X-ray follow-up and flux limits
- S241109bn: Upper limits from EP-WXT observations
- S241125n: EP-FXT follow-up observations

EP team issues GCN circulars of GW events with candidate counterparts
→ This trend applies to many observers

# follow-up observations for a GW event in O3 and O4

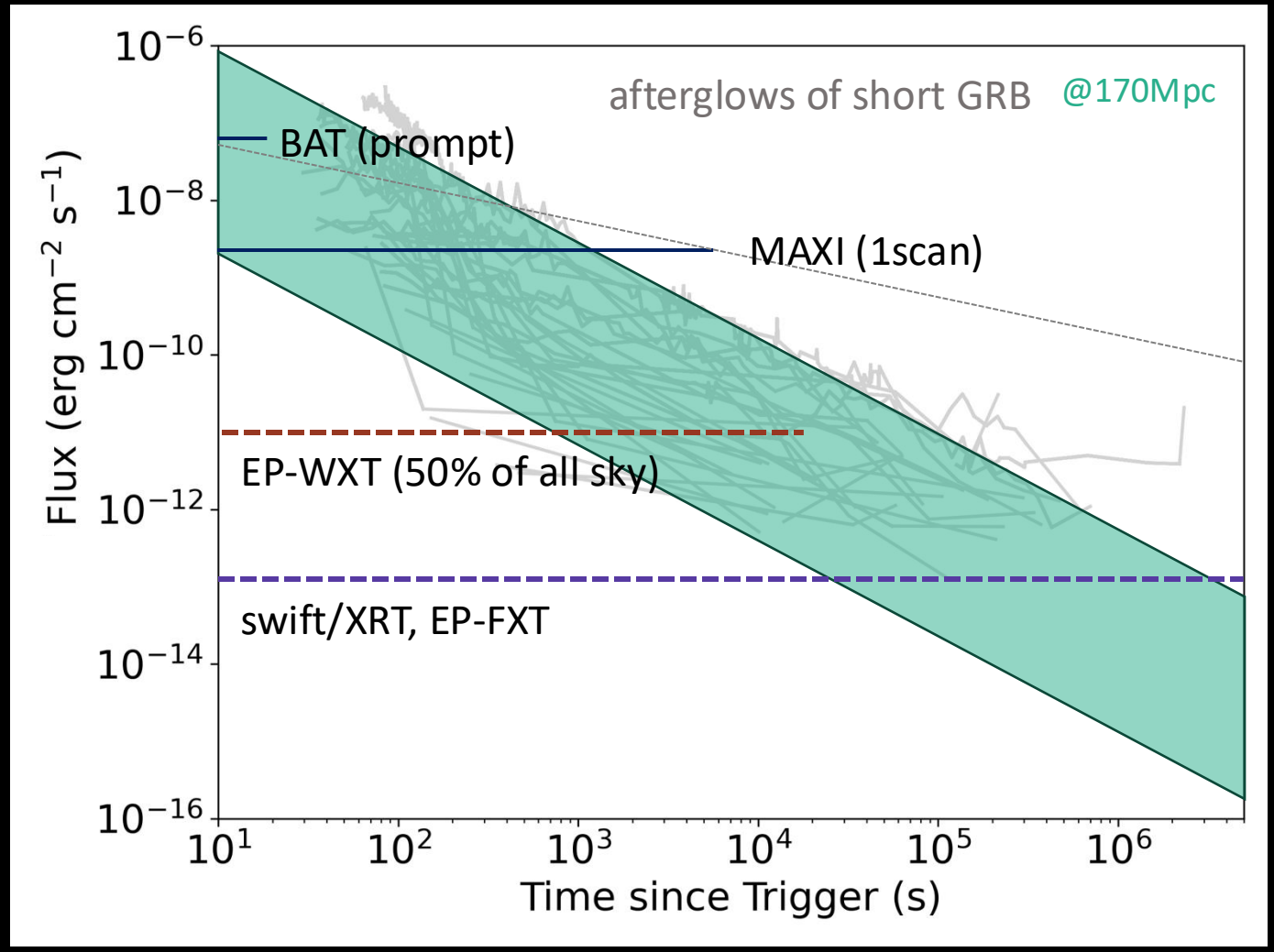



※ including the other wavelength and neutrinos

- in O4 Most of follow-up observers focused on **special** events
- S240422ed:
  probability of NSBH >99%
- S250206dm:
  probability of HasNS >99%

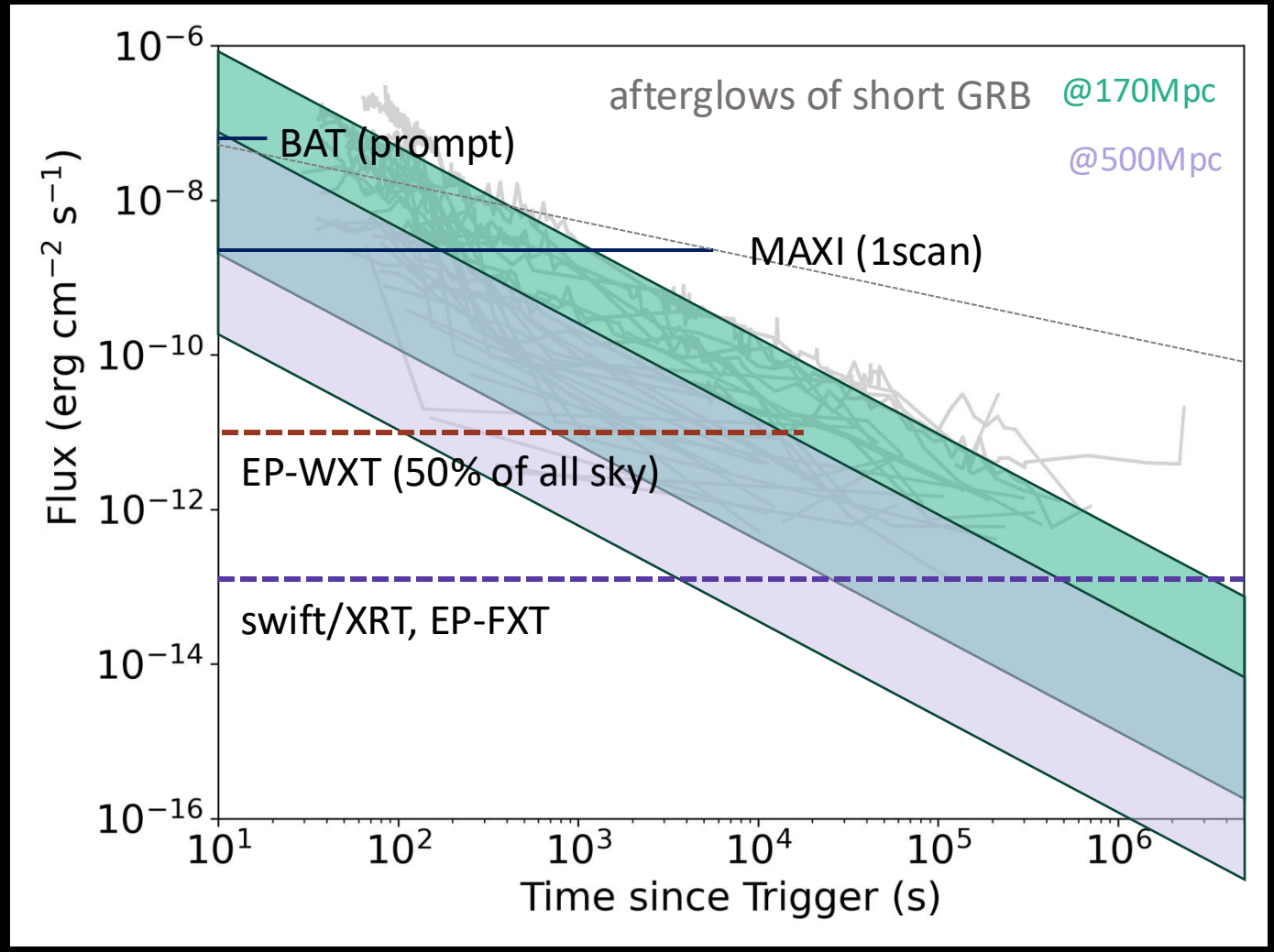
# observation time and sensitivity

- Assuming lightcurves of short GRBs



# observation time and sensitivity

- Assuming lightcurves of short GRBs
  - MAXI can detect bright source at 170Mpc, but it is hard to detect 500Mpc sources
  - EP-WXT can detect most of sources at 500Mpc
  - The sources decay below typical sensitivity of swift/XRT or EP-FXT after several days for 500Mpc



# Summary

- X-ray instruments with large FoV and follow-up telescopes are complementary
- What we hope for the future GW observations
  - It is important to increase the number of samples by being able to see far away
    - We need more sample for statistical study
  - For follow-up observations narrow region is essential
    - We expect well-localized events with 3 or more GW telescopes
  - In addition to Swift, EP and SVOM can also be automatically follow-up
    - if they can find prompt emissions, we can expect early follow-ups