

Search for High Energy & Gravitational Wave Counterparts of Fast X-ray transients detected by Einstein Probe in its first year



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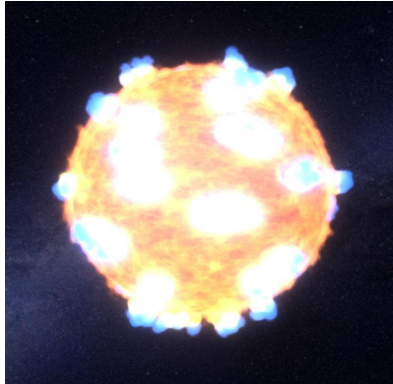
Fast X-ray Transients (FXTs)

Bright ($L_{X, \text{Peak}} \sim 10^{44} - 10^{51} \text{ erg s}^{-1}$) and Short-lived X-ray bursts lasting from **seconds to hours**. (Bauer+ (2017); Li+ (2024); O'Conner+ (2025))

Possible Progenitors:

1. Supernova Shock Breakouts

Soderberg+ (2008); Wang+ (2007);
Alp & Larsson (2020)



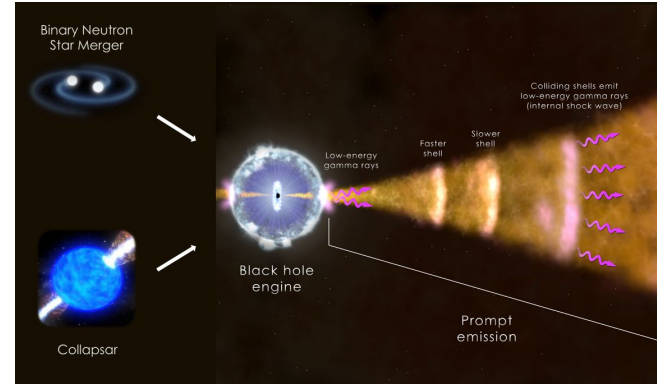
2. Tidal Disruption Events (IMBH-WD)

Jonker+ (2013); Oganessian+ (2025)



3. Gamma Ray Bursts (collapsar and merger driven)

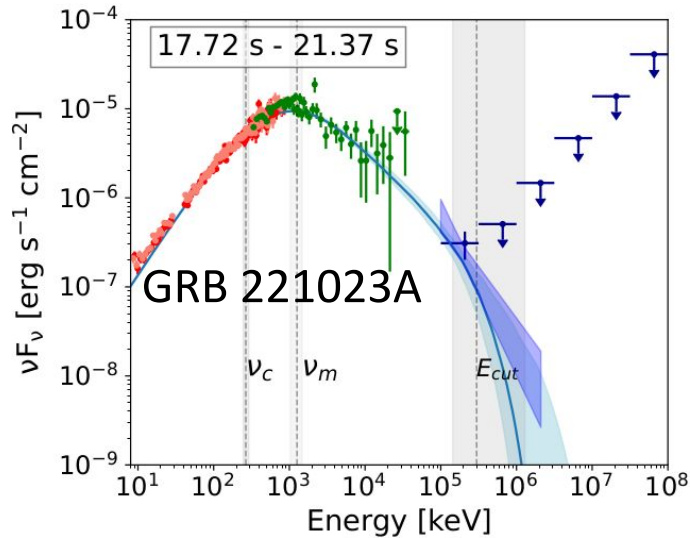
Xue + (2019); Sun+ (2019); Yin+ (2024)



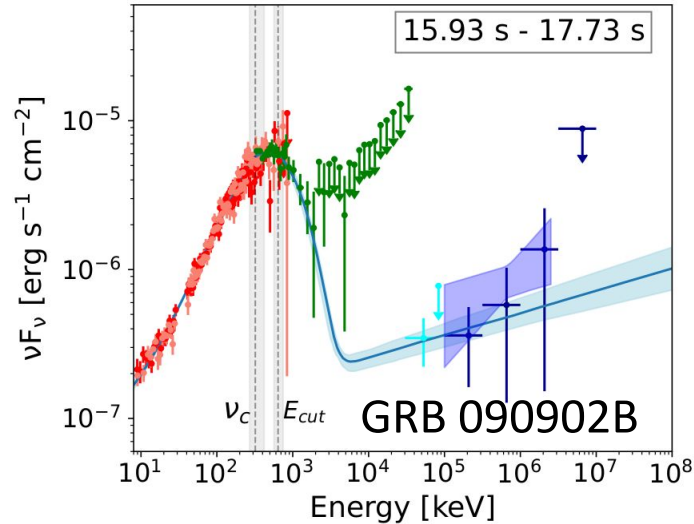
Credit:
NASA

Synchrotron & synchrotron Self-Compton (SSC) emission

- 1 High-Energy emission explained by synchrotron



- 2 High-Energy emission dominated by power law



Macera + (2025)

Einstein Probe

Launched on January 9, 2024

Search and follow-up high energy transients (Yuan + 2022)



Monitors the sky in the soft X-ray band

Triggering Instrument

Follow-up Instrument

Wide Field X-ray Telescope

EP/WXT (0.5 - 4.0 keV)

- **FoV ~ 3,600 sq. degrees**
- $F_{\text{sensitive}} \sim 2.6 \times 10^{-11} \text{ erg/s/cm}^2$ ($\Delta T \sim 1000\text{s}$)
- Angular resolution of ~ **5 arcmin**

Follow-up X-ray Telescope

EP/FXT (0.3 - 10 keV)

- Effective Area ~ 700 cm² @ 1 keV
- $F_{\text{sensitive}} \sim 5 \times 10^{-14} \text{ erg/s/cm}^2$ for ($\Delta T \sim 25 \text{ min}$)
- Angular resolution ~ **30 arcsec**

Classical FXTs before and after EP

First reported by [Soderberg+ \(2008\)](#).

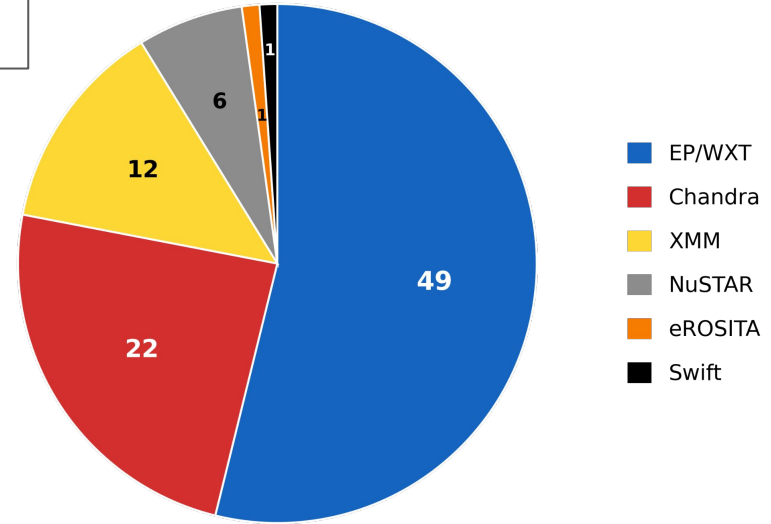
42 seen in the **archival search** in X-ray catalogs over > 20 Years

No MeV counterpart seen for any of these EP FXTs

(GCN - [36725](#), [41273](#), [41815](#); [Zhang+ \(2025\)](#))

GRBs?

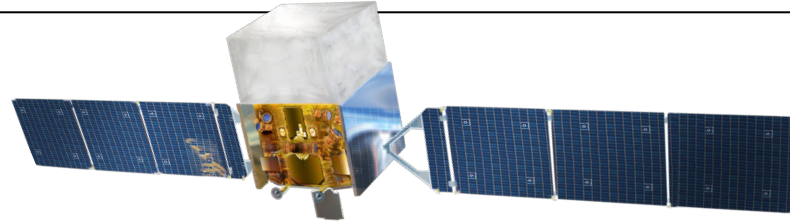
- Off-axis GRBs ([Sarin + \(2021\)](#); [Wichern + \(2024\)](#))
- On-axis GRBs, but
 - With Low Luminosity → lower peak energy ([Yonetoku+ \(2004\)](#))
 - At High redshift → lower peak energy in observer frame



[Quirola-Vázquez + \(2022, 2023\)](#)
[Alp & Larsson + \(2020\)](#)
[Grotova + \(2025\)](#)
[Soderberg + \(2008\)](#)
[Brightman + \(2026\)](#)

Fermi Telescope

Launched on June 11, 2008



Monitors the sky in the keV–GeV sky

Gamma-ray Burst Monitor

GBM (8 keV–40 MeV) (Meegan+ (2009))

- **FoV ~ 9.5 sr**
- **12 NaI and 2 BGO scintillation detectors**
- **Triggers**

Large Area Telescope

LAT (20 MeV–300 GeV) (Atwood+ (2009))

- **FoV ~ 2.4 sr**
- **Pair-conversion tracker + calorimeter**
- **Surveys the full sky in ~ 3 hrs**

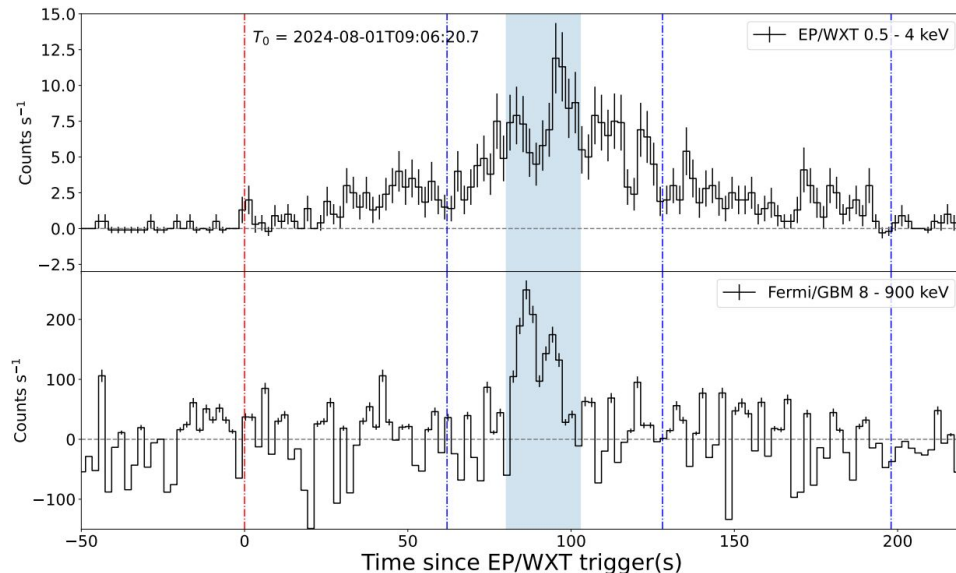
FXTs discovered by EP in 1st Year (Feb 2024 - Feb 2025)

72 FXTs reported in the first year catalog of EP extragalactic transients (Q. Wu+ (2026), *in preparation*).

We performed a systematic search for prompt γ -ray counterparts to EP FXTs.

- **23 EP FXTs** with contemporaneous detection by γ -ray satellites → **confirmed GRBs** (also see Yin+ (2024); Jiang+ (2025)).

EP240801a
S.Q. Jiang+ (2025)



FXTs discovered by EP in 1st Year (Feb 2024 - Feb 2025)

72 FXTs reported in the first year catalog of EP extragalactic transients (Q. Wu+ (2026), *in preparation*).

We performed a systematic search for prompt γ -ray counterparts to EP FXTs.

- **49** showed **no γ -ray counterparts**.

Yet, some connections with GRBs →

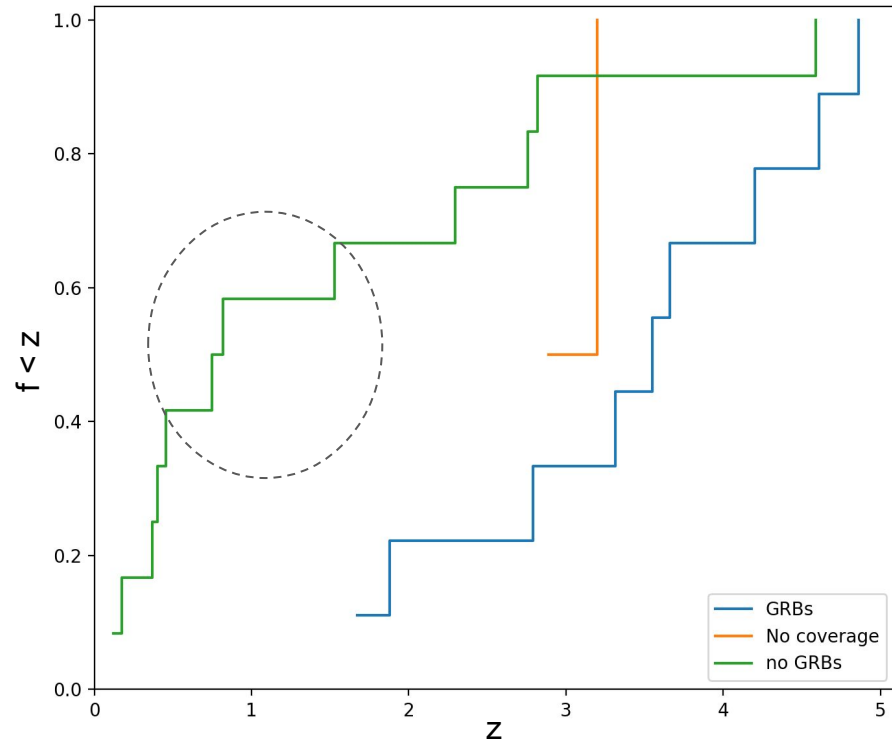
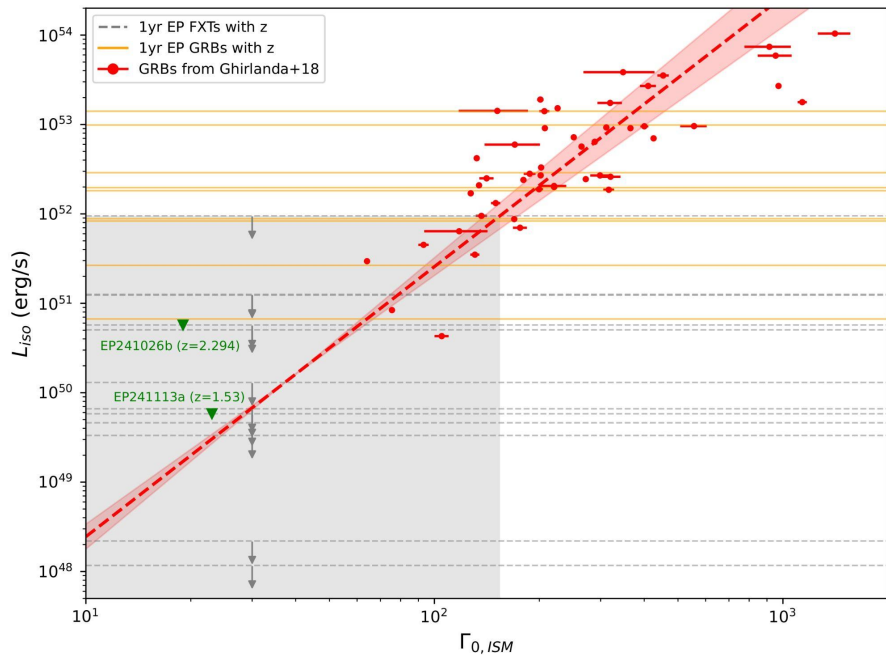
1. Late-time lightcurve resemble GRB afterglows (Sun+ 2025; Quirola-Vásquez+ 2026).
2. Broad-lined Type Ic supernovae → Collapsar (van Dalen+ 2025; Rastinejad+ 2025; van Hoof+ 2026).
3. Formation rate and luminosity function quite consistent with massive-star progenitor channel (Guo+ 2025).
4. Redshift distribution consistent with long GRBs (O'Conner+ 2025).

Category	Number of sources
GRB counterpart	23 (32%)
visible by <i>Fermi</i> /GBM	15
redshift known	9
No γ-ray counterpart	49 (68%)
visible by γ -ray satellites yet undetected	41
of which visible by <i>Fermi</i> /GBM	29
redshift known	14
Total	72

Constraints on energetics and bulk lorentz factor

From EP-only sources with **known redshift**, derived L_{iso} are in the range $L_{\text{iso}} \lesssim 1 \times 10^{48} - 9 \times 10^{51} \text{ erg s}^{-1}$

UL on L_{iso} $\rightarrow$ UL on Γ_0 (afterglow studies support)



67% EP-only events lie below closest GRB-associated event ($z = 1.673$).

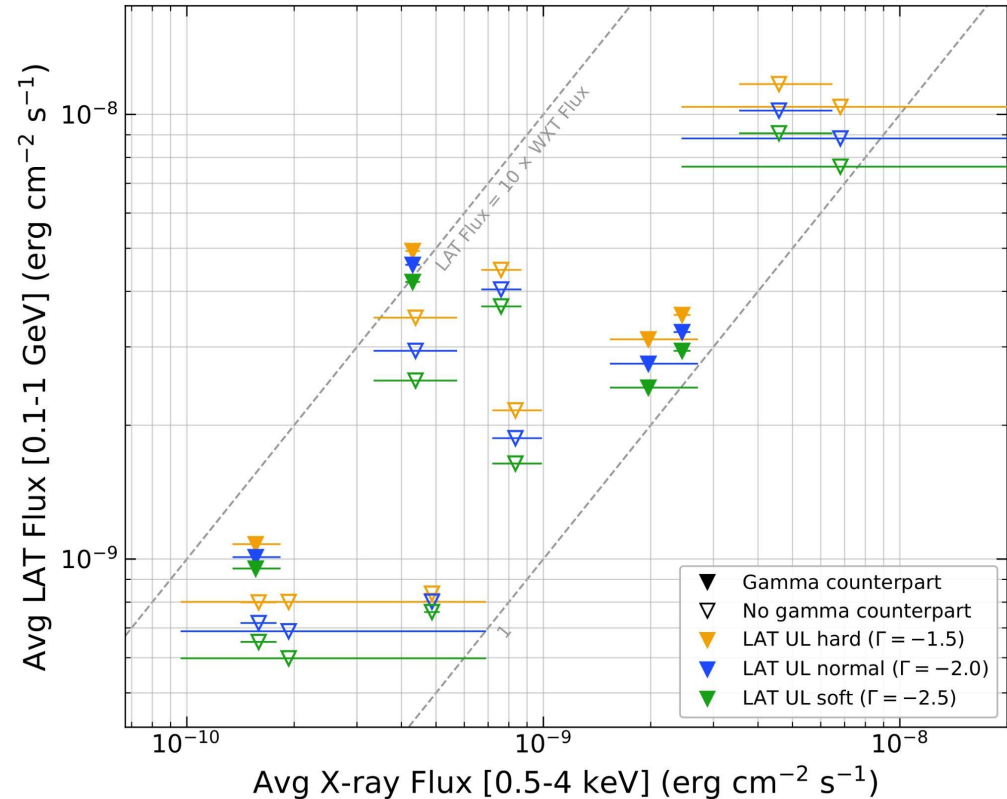
LAT Observations

12 out of 72 sources were visible by LAT

We searched for high energy emission in 0.1–100 GeV range → No emission with $> 5\sigma$.

3σ upper limits derived in the 0.1–1 GeV range for three spectral shapes.

- $F_{0.1-1\text{GeV}}/F_{0.5-4\text{keV}} \lesssim 1-10$
- The upper limit can help confine the parameter space of the jet → comoving magnetic field ($\mathbf{B}'$) and Γ_0

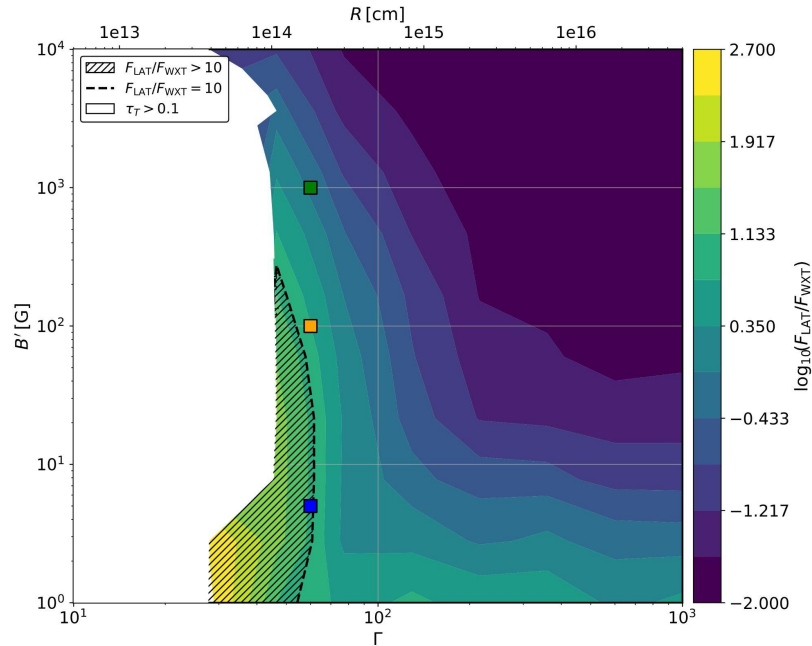


Exploring spectrum with LeHaMoC (Stathopoulos+ 2024)

Leptonic version of lepto-hadronic radiative code LeMoC

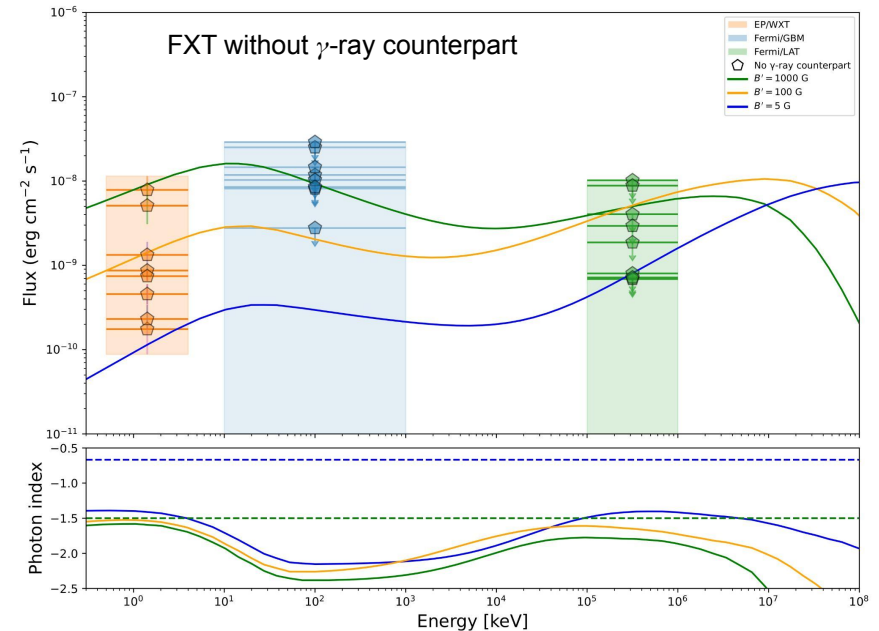
$L_{\text{iso}} = 10^{49}$ erg s $^{-1}$, rest frame $E_{\text{peak}} = 10$ keV, redshift $z = 0.2$

LAT upper limits refine the parameter space of B' and Γ_0



Representative Case: $\Gamma_0 = 60$ and $B' = 5, 100, 1000$ G

→ Absence of detected GeV emission does not rule out the presence of an additional SSC component



- **Einstein Probe transformed the FXT landscape:** 72 FXTs in the first year (double the FXTs observed in the last > 20 years). 23 confirmed GRBs and 49 without a prompt γ -ray counterpart.
- **Prompt γ -ray non-detections are constraining:** if on-axis GRBs, GBM limits favour softer and low luminosity tail of classical GRBs.
- **LAT limits reject low B' and low Γ_0 regime of parameter space:** no significant LAT detection. Upper limits do not rule out the presence of a hidden SSC component.

On ARXIV today!!!

<https://arxiv.org/abs/2610.28734>

FXTs as candidates for Gravitational Waves (GW)

Compact binary coalescences (CBC) producing a long-lived magnetars have been proposed to power a subset of FXTs (Sun+ (2019); Xue+ (2019); Quirola-Vásquez+ (2024); Becerra+ (2026)).

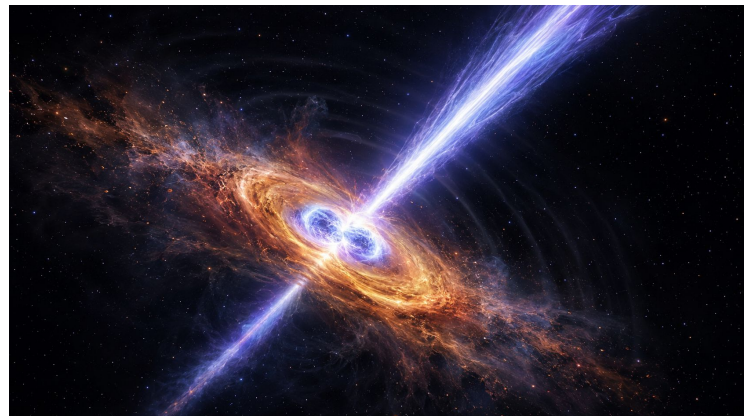
CBC also produce GW

THIS WORK! → A. Chopra+ (2026)

First systematic search for GW counterparts to EP FXTs in the second half of the 4th Ligo-Virgo-Kagra (LVK) observing run (O4b).

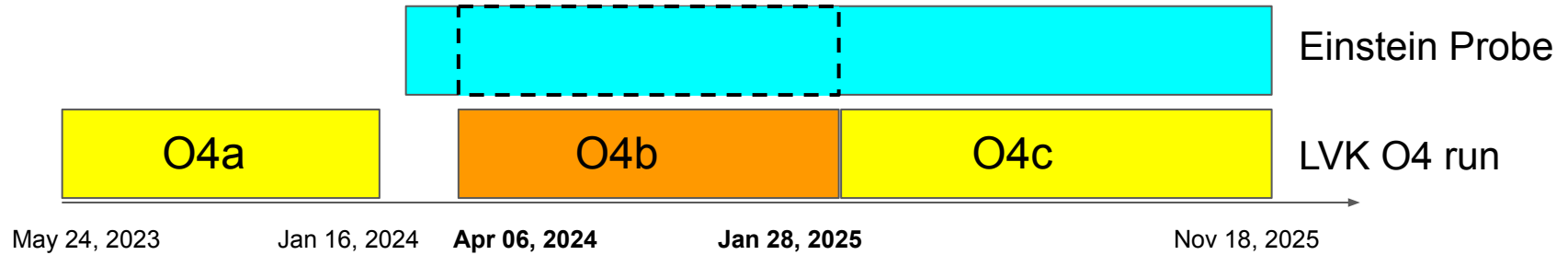
CBC believed to also power GRBs

Two FXTs detected by EP/WXT have been associated with **short GRB** → [EP250704a/GRB 250704B](#) (Fraija+ (2026)) and [EP260527a/GRB 260527A](#) (Svinkin+ (2026)).



Credit:
ChatGPT

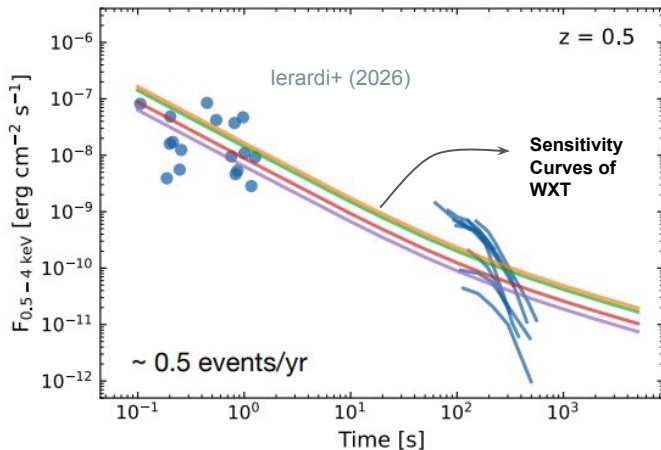
Source selection in the O4b



- **Publicly available** (General Coordinates Network and Astronomers' Telegram) EP/WXT information used → Trigger time (T_0), RA/DEC, Duration (T_{100})
- Since GRBs are followed by LVK triggered search
- We focus on FXTs without any stellar flare and GRB association → **48 FXTs**

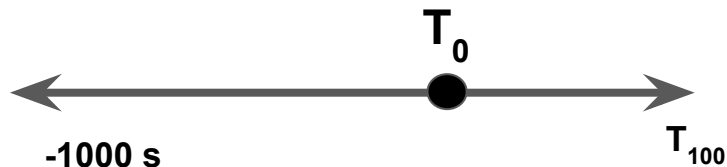
We search for GW candidates in the 5th Gravitational Wave Transient Catalog (**GWTC-5**) (The LIGO Scientific Collaboration 2026)

Search Window



For on-axis short GRB, the steep-decay phase may remain detectable by EP/WXT up to 1000 s after the prompt emission (that is coincident with the GW signal) (Ierardi+ (2026)).

For off-axis merger-driven GRB, the dissipation due to the prompt emission appears as a soft X-ray transient peaking at 10^2 – 10^3 s after the merger (Ascenzi+ (2020); Chen+ (2026)).



Or 60 s (if T_{100} is not available)

X-ray emission can occur prior to the merger in case of multiple scenarios → Resonant shattering of the neutron star (NS) crust (Tsang+ (2012)) or magnetospheric interaction between the NS and the companion (Beloborodov+ (2021); Cooper+ (2023); Sharma+ (2026)) → causing a delay in GW signal $O(1-10)$ s.

To be conservative we chose it as T_{100} that is typically ~ 10–100 s

7 Temporally coincident events!

Tells how strongly the GW event and EP FXT are correlated

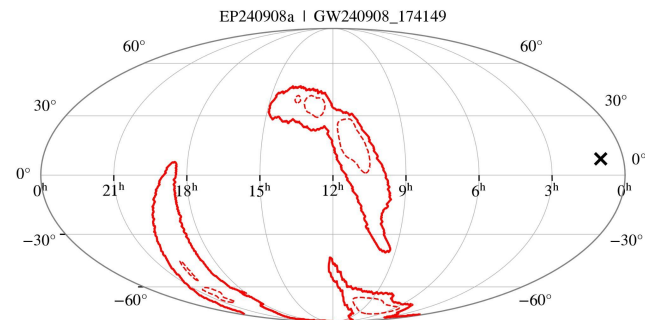
$$\Lambda = \frac{I_{\Omega}}{R_{s,c}(t_{\text{GW}}) + R_{n,c}(t_{\text{GW}}) \text{BCI}^{-1}} \longrightarrow \text{Spatial overlap}$$

Average Signal and Noise rate for GW triggers for interferometer configuration in the search window (c)

Bayes factor for coherent vs incoherent signal (whether the GW signal was real no not)

Ashton+ (2018)

$$I_{\Omega} \simeq \frac{p_{\text{GW}}(\Omega_{\text{FXT}} \mid d_{\text{GW}})}{\pi_{\text{GW}}(\Omega_{\text{FXT}}) \pi_{\text{FXT}}(\Omega_{\text{FXT}})}$$



Ranking Statistic Piotrkowski+ (2022)

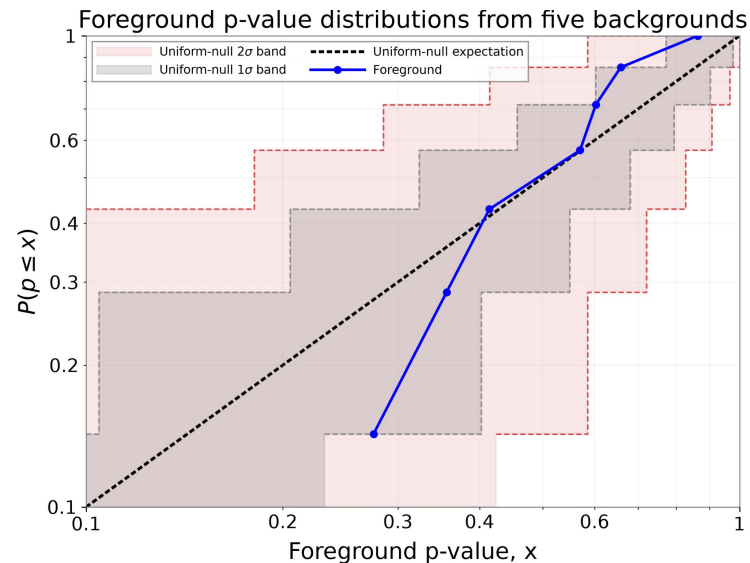
Tells how strongly the GW event and EP FXT are correlated

$$\Lambda = \frac{I_{\Omega}}{R_{s,c}(t_{\text{GW}}) + R_{n,c}(t_{\text{GW}})\text{BCI}^{-1}}$$

$\Lambda_{\text{bkg}} \rightarrow$ 1648 real O4b GW triggers with synthetic FXT positions drawn from WXT exposure. Slide each of the 48 FXT search window across each GW trigger.

$\Lambda_{\text{fg}} \rightarrow$ 7 coincident FXT-GW pairs

$$\text{p-value} = \frac{\sum \Lambda_{\text{bkg}} \geq \Lambda_{\text{fg}}}{N_{\text{bkg}}}$$

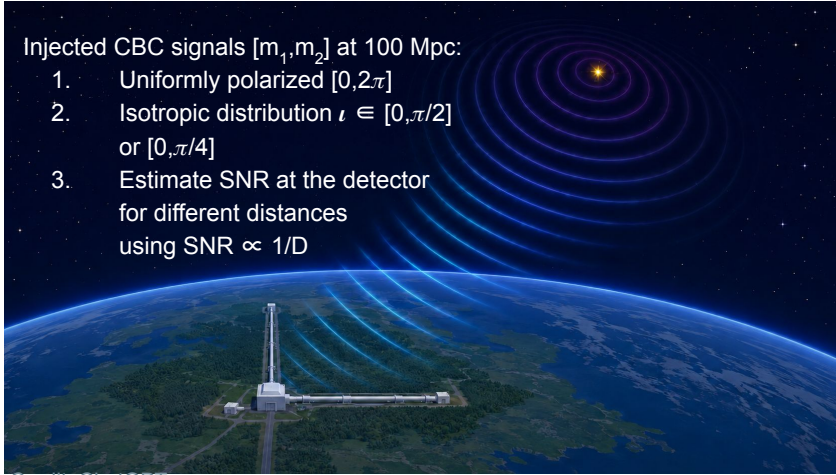


No significant association between FXTs and GW in the O4b!

Targeted Detectability Range (TDR) Ronchini, Chopra+ (2026) Published in A&A

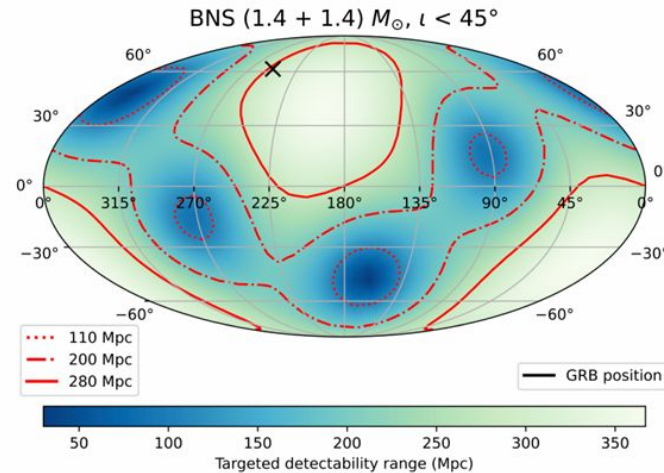
Injected CBC signals $[m_1, m_2]$ at 100 Mpc:

1. Uniformly polarized $[0, 2\pi]$
2. Isotropic distribution $\iota \in [0, \pi/2]$ or $[0, \pi/4]$
3. Estimate SNR at the detector for different distances using $\text{SNR} \propto 1/D$



Credit: ChatGPT

Detectability of a hypothetical CBC signal using **detector sensitivity at the relevant time and the sky position** of the external electromagnetic trigger.

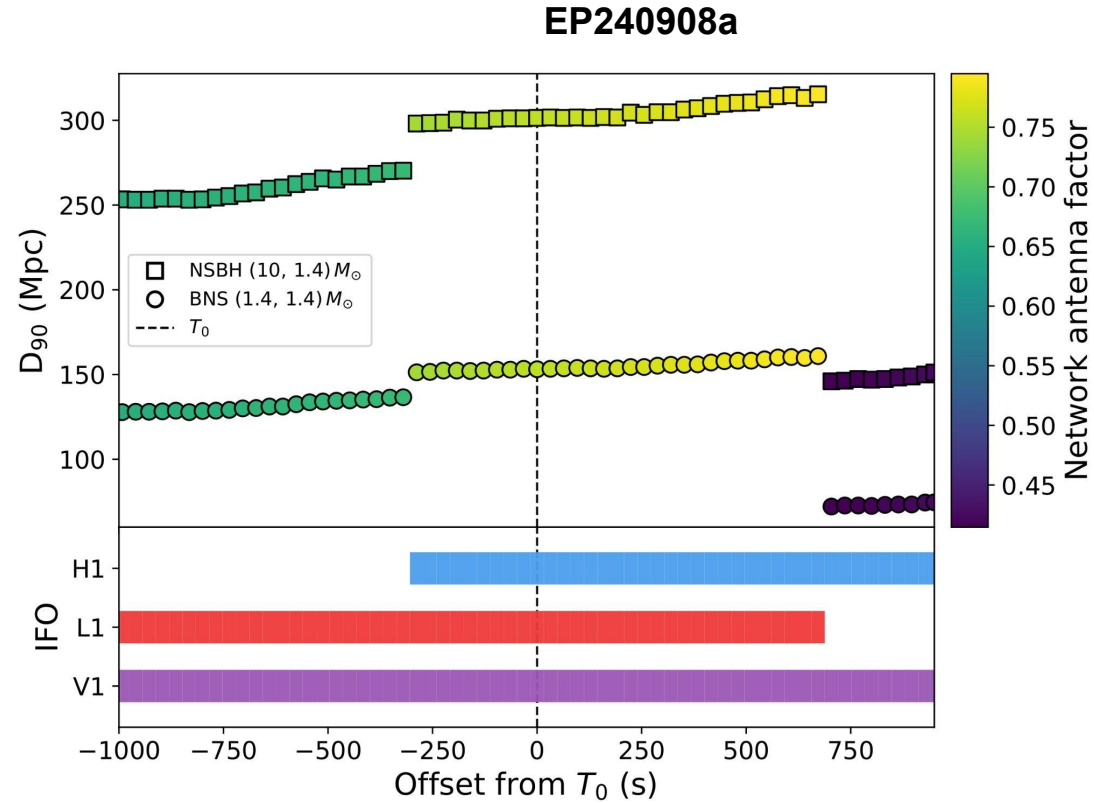


We define the exclusion distance (D_{90}) as the distance at which we retrieve 90% of the injected signals with SNR above a given threshold (we take $\text{SNR}_{\text{thresh}} = 10$).

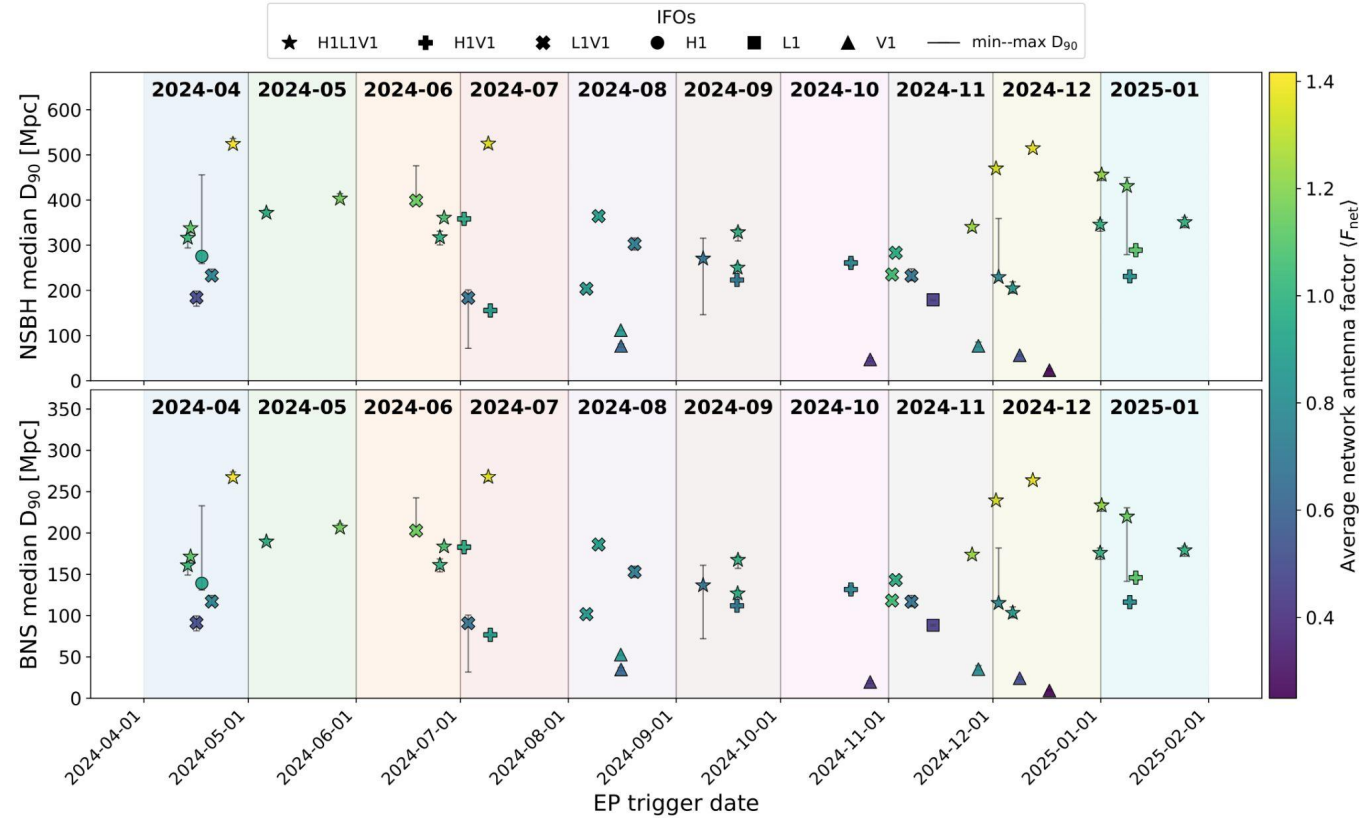
In absence of any significant GW counterpart associated with EP-FXTs, we estimate the D_{90} at which we would detect a GW signal with $\text{SNR} > 10$

Exclusion Distance for Non-Detection in GW

Large search window $\rightarrow$ the detector configuration and position of the source wrt detectors change $\rightarrow$ changing the antenna factor $\rightarrow$ changing exclusion distance (D_{90}).



Exclusion Distance for Non-Detection in GW



Average D_{90} for our entire sample for **BNS** ($m_1 = m_2 = 1.4 M_{\odot}$) is **~ 180 Mpc** and for **NSBH** ($m_1 = 10 M_{\odot}$, $m_2 = 1.4 M_{\odot}$) is **~ 350 Mpc**.

- **First systematic search of GW counterparts of FXTs** performed with 48 WXT events (non-stellar flare and non-GRB) in the **LVK O4b run**.
- No GW counterpart was found in O4b: The ranking statistic search found **no significant association for the FXT**.
- For no GW associations, TDR put constraints on a nearby CBC origins with an average D_{90} of **180 Mpc for BNS and 350 Mpc for NSBH**.
- With increasing number of detected FXTs and the upcoming LVK observations will enhance the prospects of joint FXT-GW detections.

ARXIV:

<https://arxiv.org/abs/2607.16420>

Ligo-Virgo-Kagra Activities



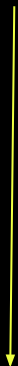
- X-Pipeline (Sutton + 2010) : Targeted GW search for long GRBs during O4b run.
- O4b GRB catalog
- Development of Targeted Detectability Range Pipeline
- TDR paper
- FXT-GW paper
- Rapid Response Team - RRT level 0 shifts (BBH candidate S251108dn)



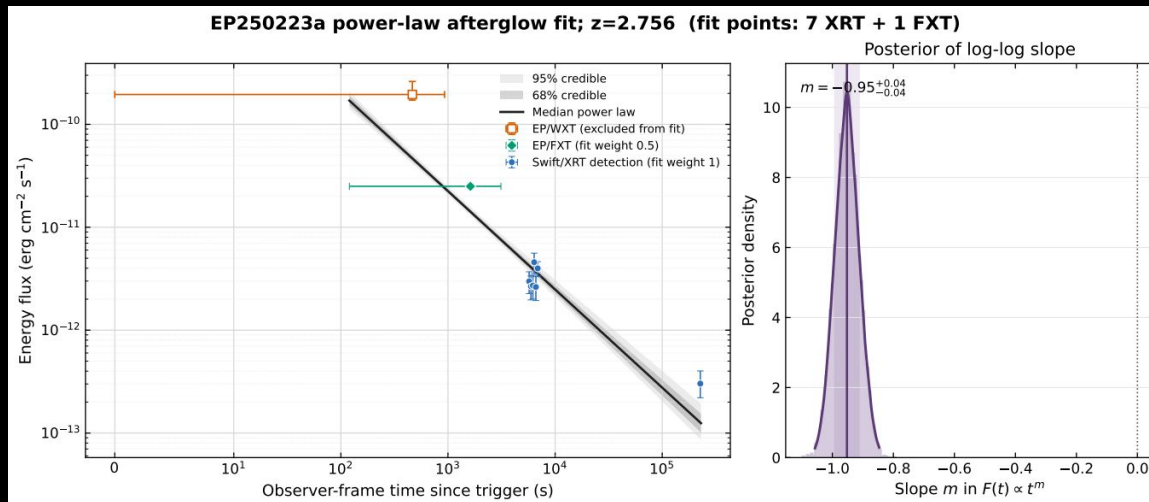
Future Work

1. Afterglows of Einstein Probe detected FXTs

Slight detour



2. Broadband afterglows of short GRBs



sGRB afterglow
modelling with
LeHaMoC

Constraints on
microphysical
parameters

Application for
FXTs as well as
sGRB follow-ups

Publications

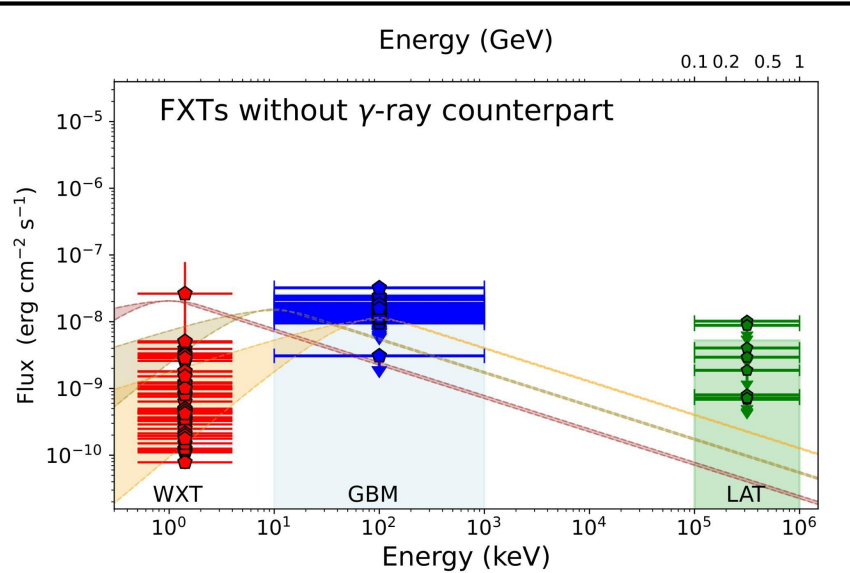
1. “Detectability of gravitational-wave counterparts of EP-FXTs observed during the LVK O4b observing run” [[A. Chopra](#), *S. Ronchini, B. Banerjee et al. (2026)*]
2. “The (missing) gamma-ray counterparts to EP events. Part I: Search for keV–GeV counterparts of Einstein Probe Fast X-ray Transients.” [*M.E. Ravasio, [A. Chopra](#), P.G. Jonker et al. (2026)*]
3. “Gravitational wave detectability range informed by external messengers.” [*S. Ronchini, [A. Chopra](#), T. Dal Canton et al. (2026)*]
4. “X-ray flares in gamma-ray bursts at high and very-high energies.” [*P. Tiwari et al. (2026)*, including *A. Chopra*]
5. “The ultra-fast afterglow of GRB 260226A.” [*B. Banerjee et al. (2026)*, including *A. Chopra*]
6. “Search for gravitational-wave counterparts to gamma-ray bursts observed during the second half of the fourth observing run (O4b).” [*LVK Collaboration – In preparation*]
7. “The geometry of lunar gravitational wave detection.” [*J. Tissino et al. (2026)*, including *A. Chopra*]

Participations

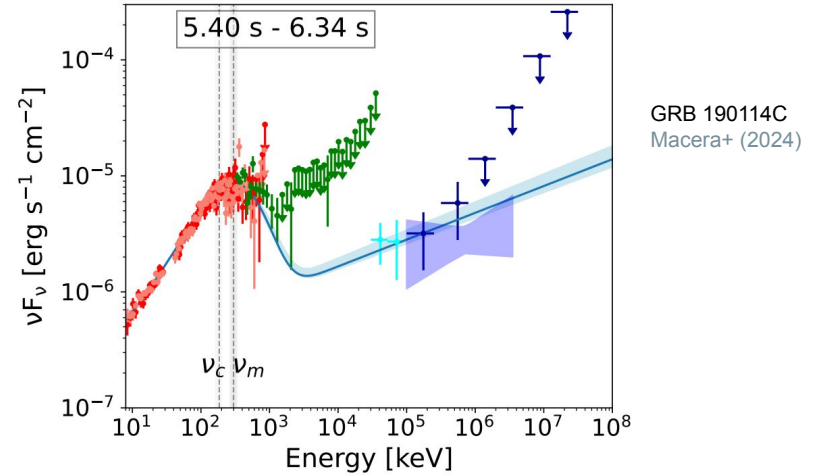
1. **Conference:** TeVPA 2026, Tendo, Japan, 30 August–4 September 2026. [Talk]
2. **Workshop:** Third-Generation Gravitational-Wave Detectors: The View from Latin America, São Paulo, Brazil, 29 June–3 July 2026.
3. **School:** 9th ICE-CSIC Summer School on Multimessenger Astrophysics, Barcelona, Spain, 6–14 July 2026.
4. **School:** School on Astroparticle and Multimessenger Astrophysics, São Paulo, Brazil, 15–26 June 2026.
5. **Journal peer review:** Served as a referee for Monthly Notices of the Royal Astronomical Society: Letters (MNRAS Letters).

EXTRA SLIDES

Possibility of synchrotron self-Compton (SSC) emission



For FXTs, LAT observations can help in constraining the presence of the prompt SSC emission.



In a standard synchrotron + SSC scenario, SSC component peaks at $E_{\text{SSC,peak}} \propto \gamma_m^2 \cdot E_{\text{sync,peak}}$

1. SSC emission seen in prompt phase of GRBs (Macera+ (2024))
2. For typical long GRBs $\rightarrow$ SSC component is expected to peak in the TeV band (see, Nava+ (2021)).
3. For combination of low bulk lorentz factor and lower $E_{\text{sync,peak}}$ $\rightarrow$ SSC peak shifts to lower energies

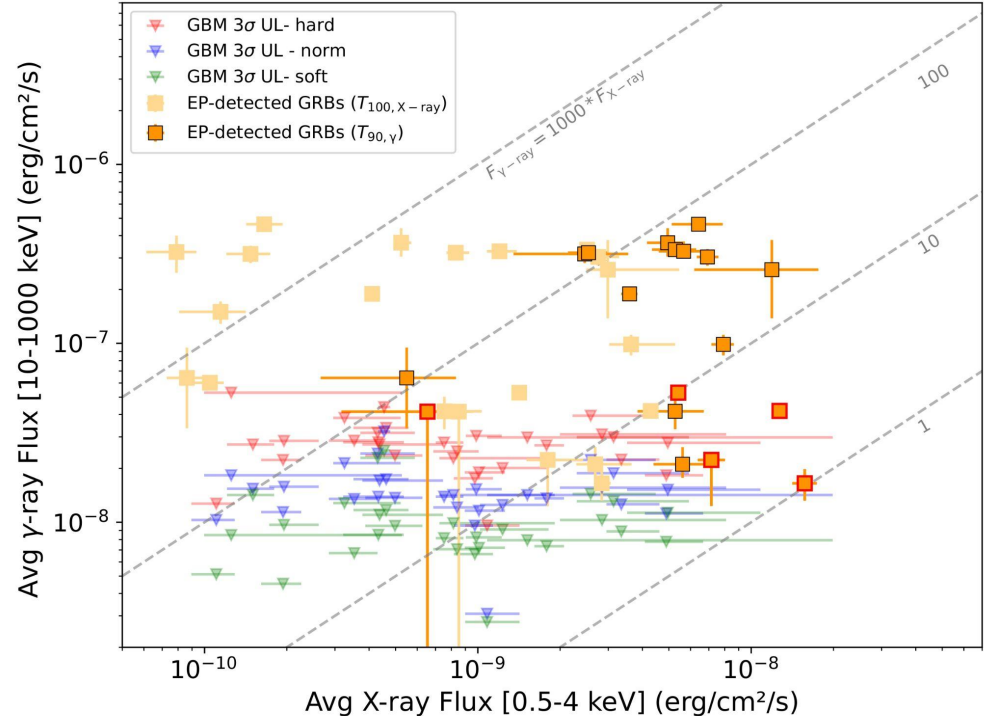
X-ray to γ -ray flux comparison

Non-detections:

3σ GBM upper limits derived for FXTs with no γ -ray counterparts (29 sources visible to GBM)

Detections:

- γ -ray produced during **enhanced X-ray activity**.
- Simultaneous γ -ray and X-ray fluxes $1 < F_{\gamma}/F_{\text{X-ray}} < 100$.
- Similar X-ray flux and lower γ -ray flux could be from an even **softer spectrum** ($E_{\text{peak}} < 70$ keV)



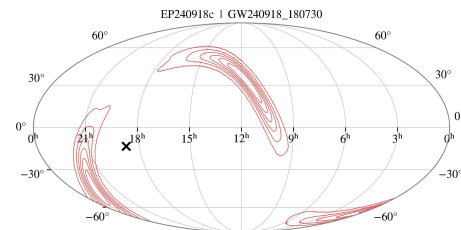
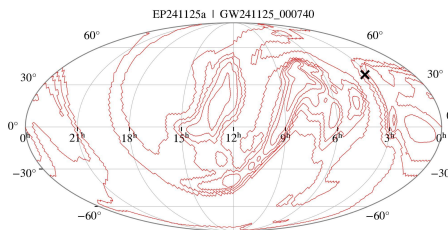
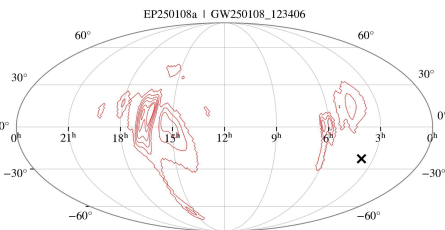
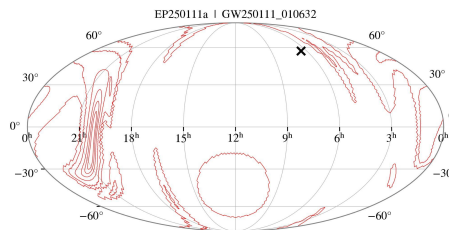
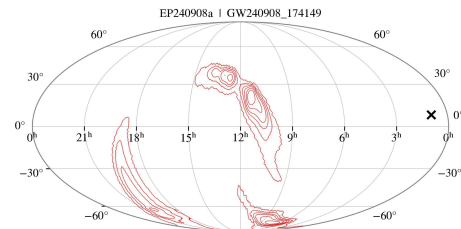
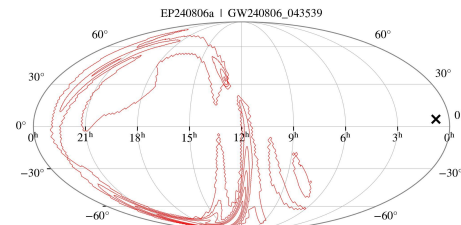
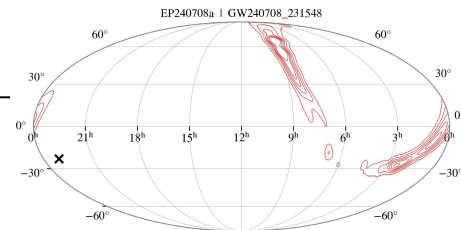
Temporally coincident events

All-sky GW Superevents in GWTC-5.0* in the EP-FXT search window for temporal and spatial coincidence

* <https://zenodo.org/records/20276130>

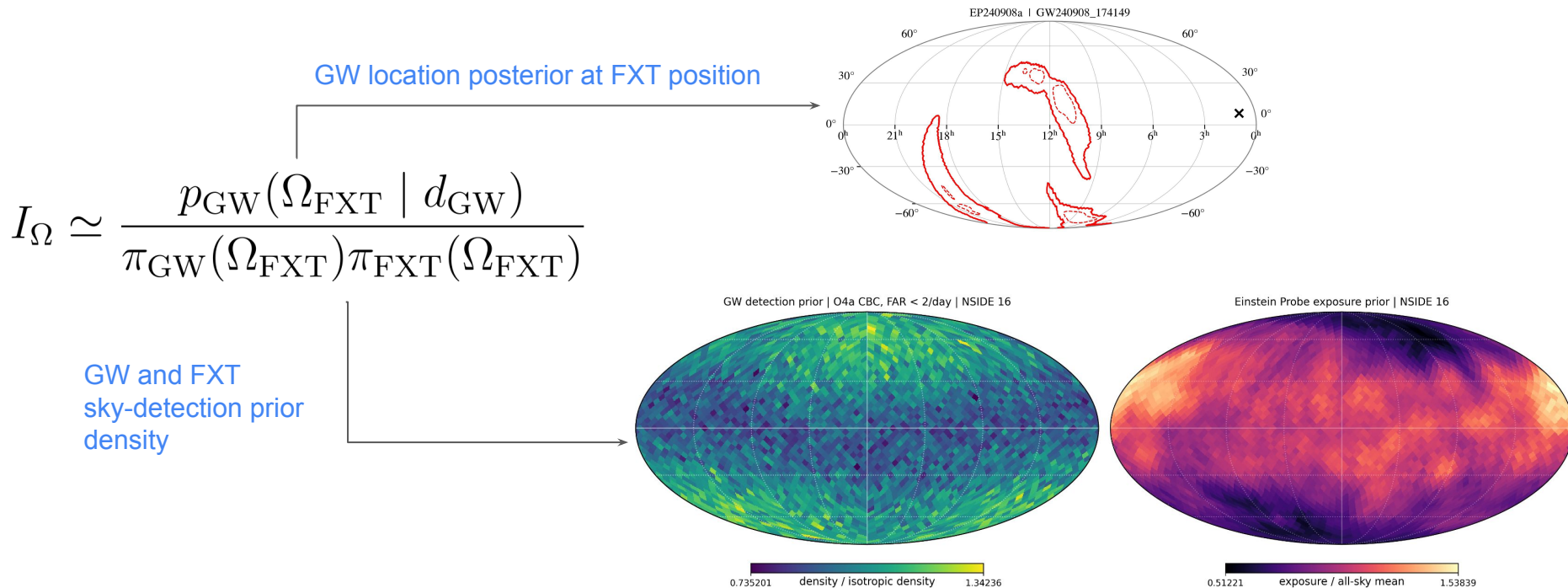
EP_event	$T_{0,EP}$ [UTC]	Superevent_ID	Offset ($T_{GW} - T_0$) [sec]	FAR [yr ⁻¹]	SNR	Pipeline	IFOs
EP240708a	23:28:23	S240708ex	-754.7	448.27	8.0	gstlal	H1L1V1
EP240806a	04:47:53	S240806f	-733.8	1.91	8.4	pycbc	L1V1
EP240908a	17:28:27	S240908fo	+802.2	3.08	8.9	MBTA	H1L1V1
EP240918c	18:06:47	S240918gi	+43.8	233.51	6.8	pycbc	H1L1
EP241125a	00:06:06	S241125fj	+94.9	316.67	9.0	MBTA	H1L1V1
EP250108a	12:30:28	S250108dc	+218.1	297.42	9.3	MBTA	H1L1V1
EP250111a	01:20:24	S250111cg	-831.1	155.18	8.8	MBTA	H1V1

Probability of having 7 or more random temporal coincidence ~ 17%



7 Temporally coincident events!

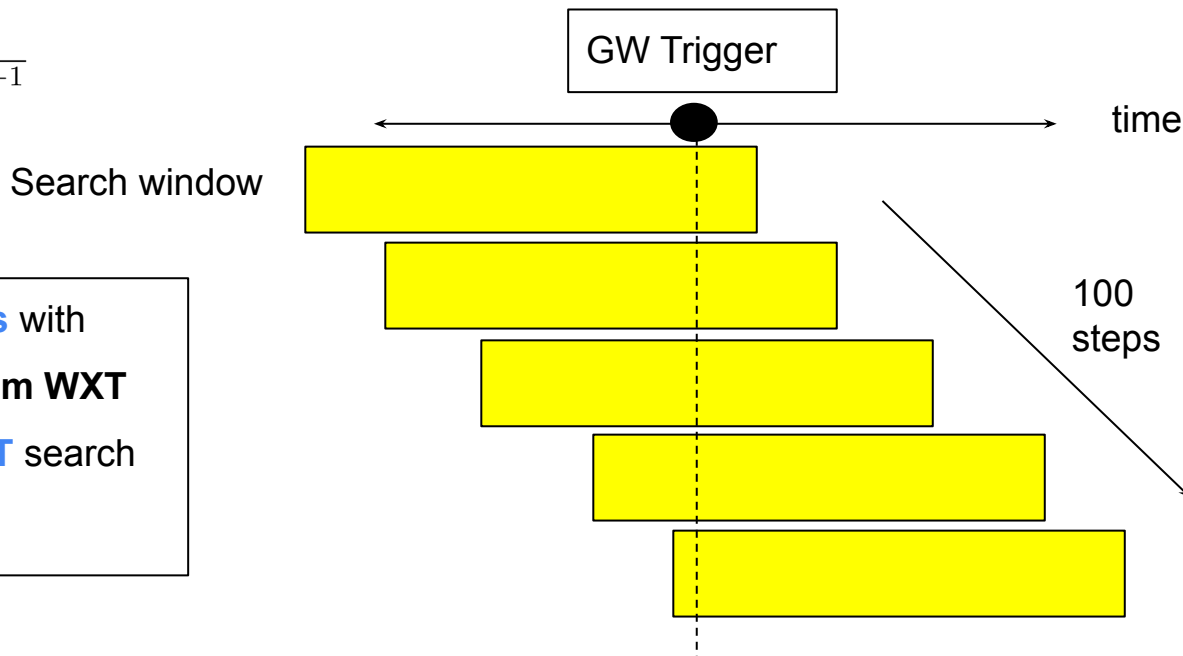
Quantifying the localization agreement of the sky positions of GW-FXT pairs



Tells how strongly the GW event and EP FXT are correlated

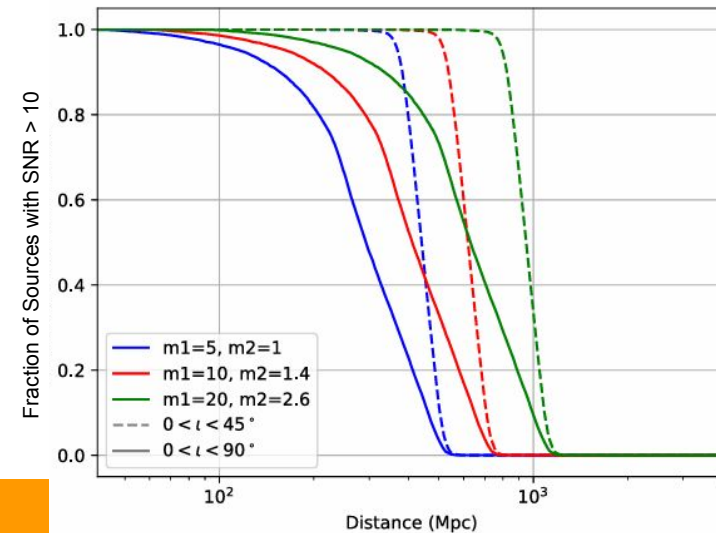
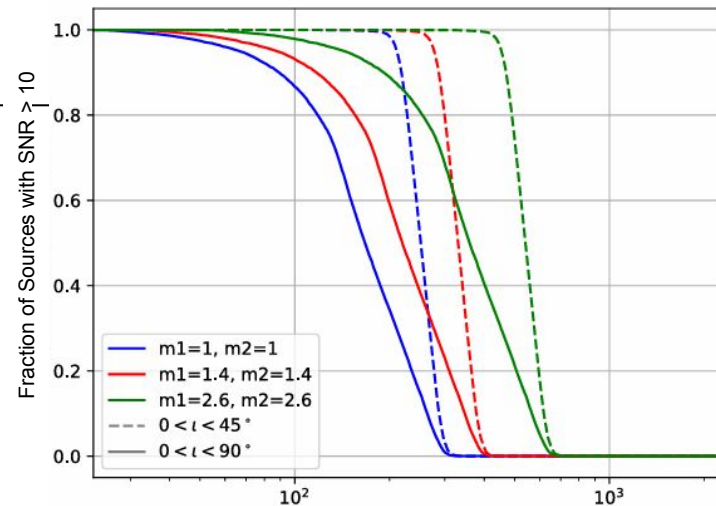
$$\Lambda = \frac{I_{\Omega}}{R_{s,c}(t_{\text{GW}}) + R_{n,c}(t_{\text{GW}})\text{BCI}^{-1}}$$

$\Lambda_{\text{bkg}} \rightarrow$ **1648 real O4b GW triggers** with synthetic **FXT positions drawn from WXT exposure**. Slide each of the **48 FXT** search window across each GW trigger.



Range Map & Efficiency Curves

We define the Targeted Detectability Range as the distance where 90% of the injections have an $\text{SNR} > 10$



B. Optimal and Matched-filter SNR

$$\text{SNR}_{opt}^2 = \langle h|h \rangle = 4 \int \frac{|h(f)|^2}{S_n(f)} df$$

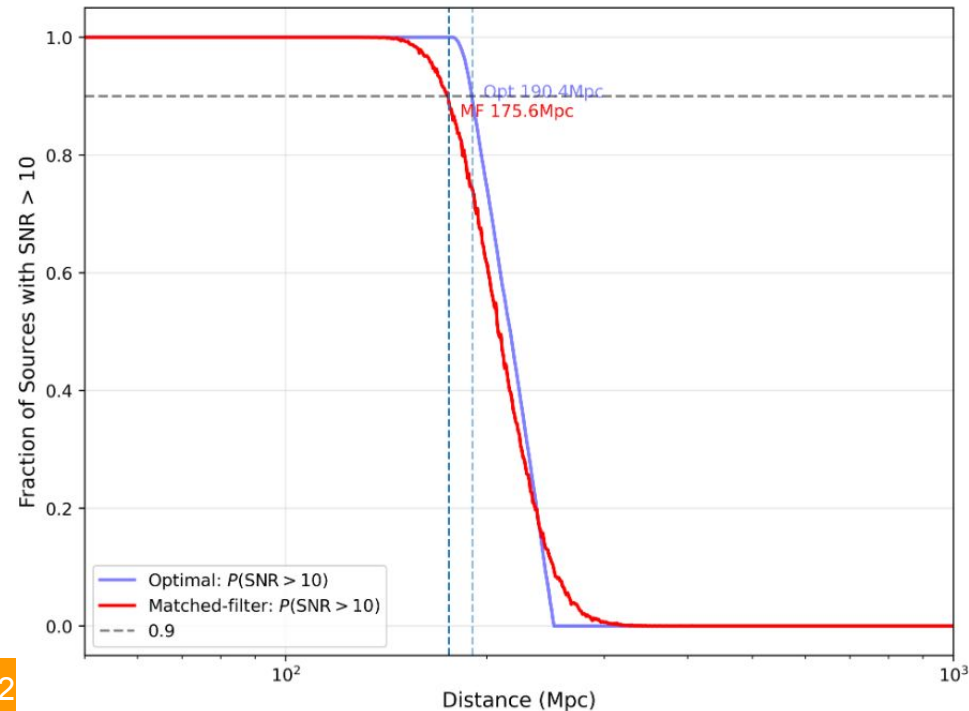
Optimal SNR is the ideal SNR which gives the total strength of the signal power weighted by the detector sensitivity @ each frequency

$$\text{SNR}_{mf} = \frac{\langle s|h \rangle}{\sqrt{\langle h|h \rangle}}$$

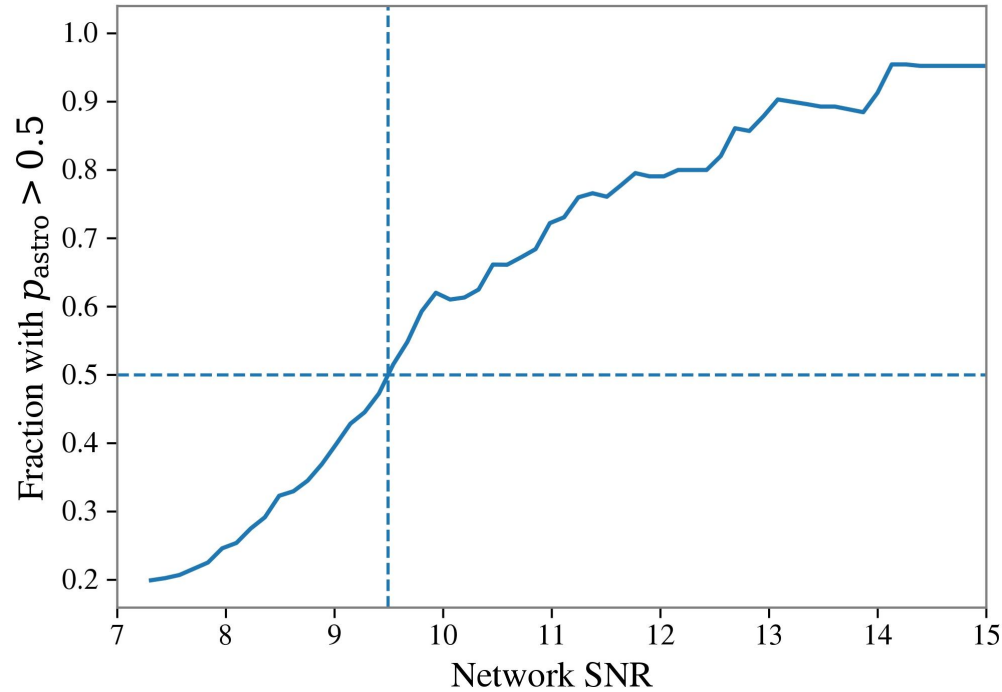
Matched-filter SNR compares how well the data matches the signal, accounting for noise. Most robust way of defining the Exclusion distance

Detector data $s(f) \sim h(f) + n(f)$

Where $h(f) \rightarrow$ signal waveform; $n(f) \rightarrow$ detector noise

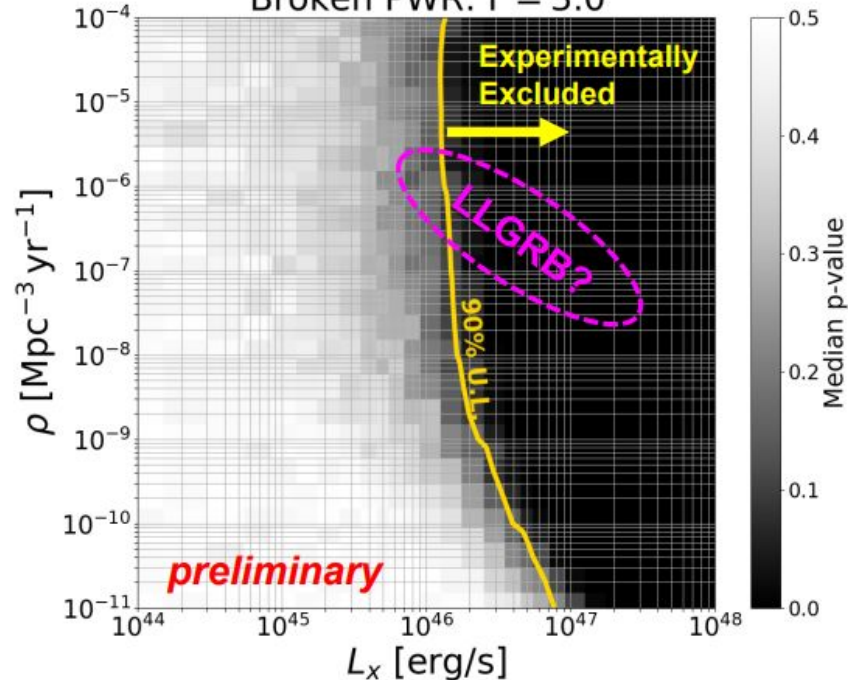


Choice for the SNR Threshold



Short time scale
transients (10^3 s)

Broken PWR: $\Gamma = 3.0$



Short time scale ($\pm 10^3$ s)

