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


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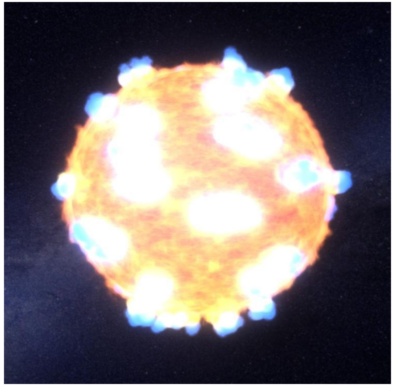
# Fast X-ray Transients (FXTs)

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

Possible Progenitors:

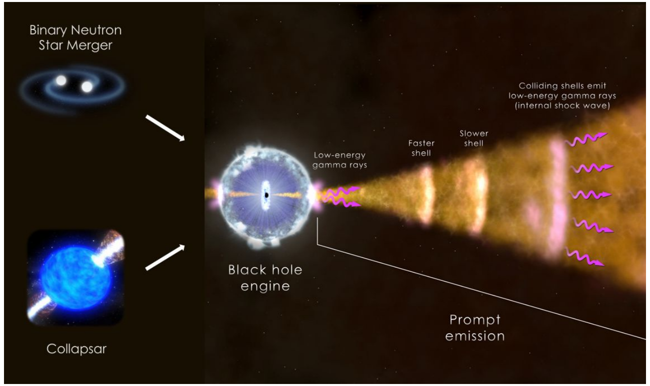
1. **Supernova Shock Breakouts**
2. **Tidal Disruption Events (IMBH-WD)**
3. **Gamma Ray Bursts (collapsar and merger driven)**

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



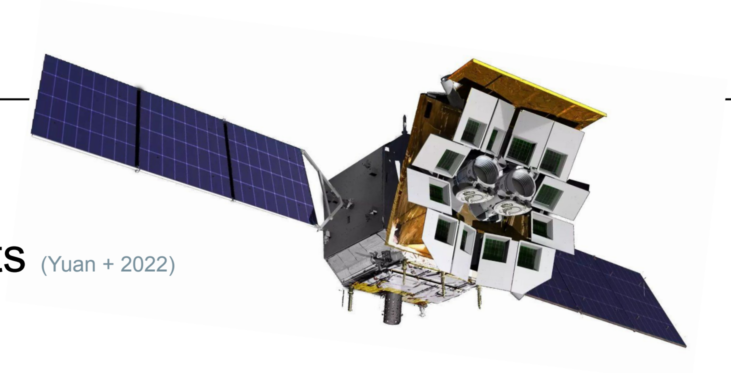
Jonker+ (2013); Oganesyan+ (2025)

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




Credit: NASA

# Einstein Probe



Launched on January 9, 2024
Search and follow-up high energy transients (Yuan + 2022)

<u>Monitors the sky in the soft X-ray band</u>

Triggering Instrument | Follow-up Instrument

**Wide Field X-ray Telescope**
**EP/WXT** (0.5 - 4.0 keV)

- **FoV ~ 3,600 sq. degrees**
- $F_{sensitive}$ ~ 2.6 x $10^{-11}$ erg/s/$cm^2$ for 1000s Exposure
- Angular resolution of ~ **5 arcmin**

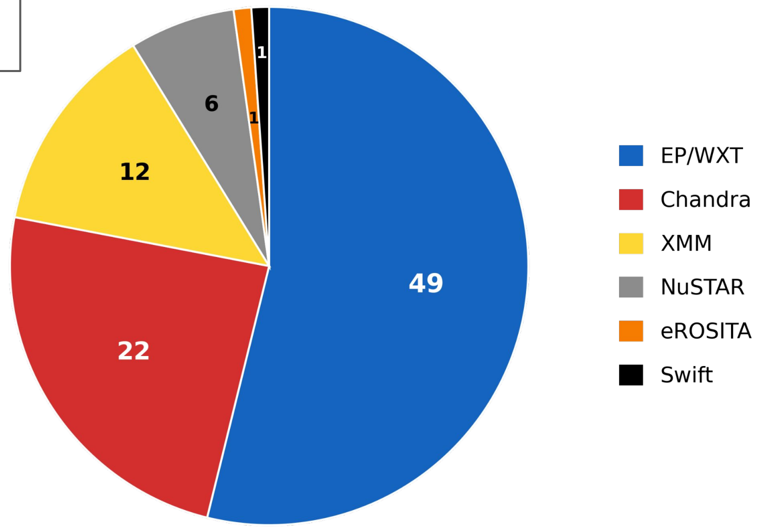
**Follow-up X-ray Telescope**
**EP/FXT** (0.3 - 10 keV)

- Effective Area ~ 700 $cm^2$ @ 1 keV
- $F_{sensitive}$ ~ **5 x $10^{-14}$ erg/s/$cm^2$** for 25 minute Exposure
- 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))



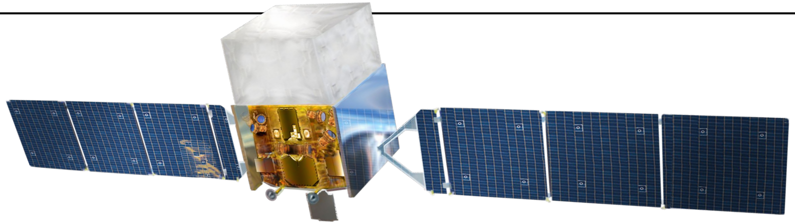

Quirola-Vásquez + (2022, 2023)
Alp & Larsson + (2020)
Grotova + (2025)
Soderberg + (2008)
Brightman + (2026)

**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

# 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**

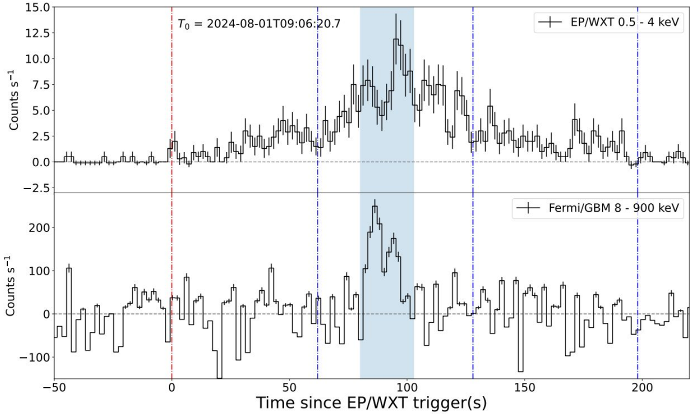
**Large Area Telescope**
**LAT** (20 MeV–300 GeV) (Atwood+ (2009))

- **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 $\gamma$-ray counterparts to EP FXTs.**

- **23** EP FXTs with contemporaneous detection by $\gamma$-ray satellites → **confirmed GRBs** (also see Yin+ (2024); Jiang+ (2025)).
- **49** showed **no $\gamma$-ray counterparts**.
  - For some, late-time lightcurve resemble GRB afterglows (Sun+ (2025); Quirola-Vásquez+ (2026)).
  - Many linked to collapsar channel through broad-lined Type Ic supernovae (van Dalen+ (2025); Rastinejad+ (2025); van Hoof+ (2026)).
  - Formation rate and luminosity function consistent with massive-star progenitor channel (Guo+ (2025)).
  - Redshift distribution consistent with that of long GRBs (O'Conner+ (2025)).




**EP240801a**
S.Q/ Jiang+ (2025)

| Category | Number of sources |
|---|---|
| **GRB counterpart** | **23 (32%)** |
| visible by *Fermi*/GBM | 15 |
| redshift known | 9 |
| **No $\gamma$-ray counterpart** | **49 (68%)** |
| visible by $\gamma$-ray satellites yet undetected | 41 |
| of which visible by *Fermi*/GBM | 29 |
| redshift known | 14 |
| **Total** | **72** |

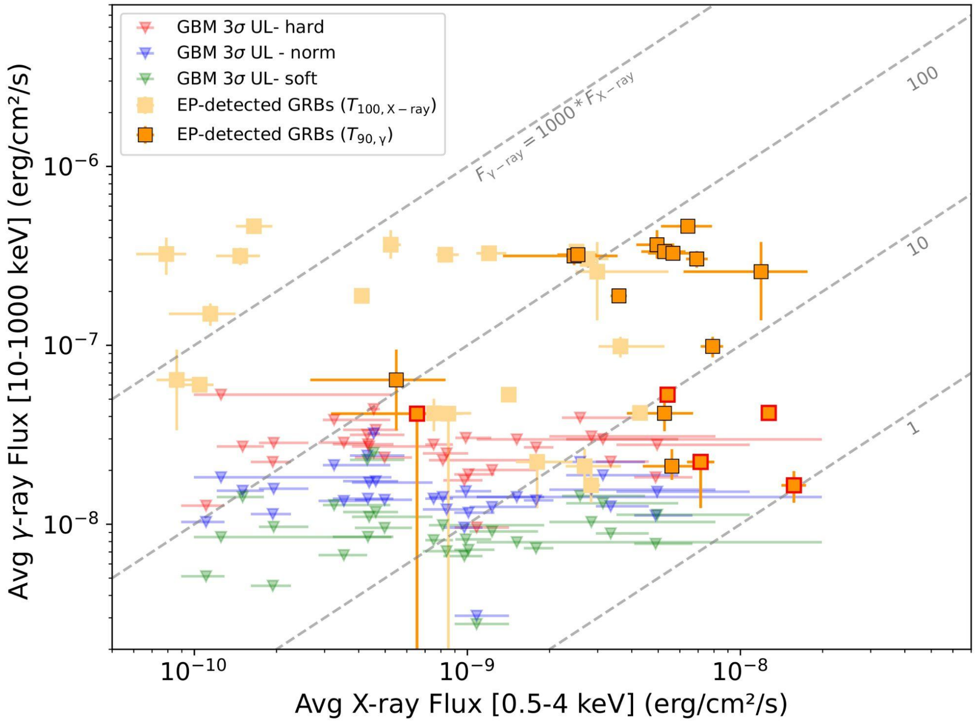
# X-ray to $\gamma$-ray flux comparison

**Non-detections:**

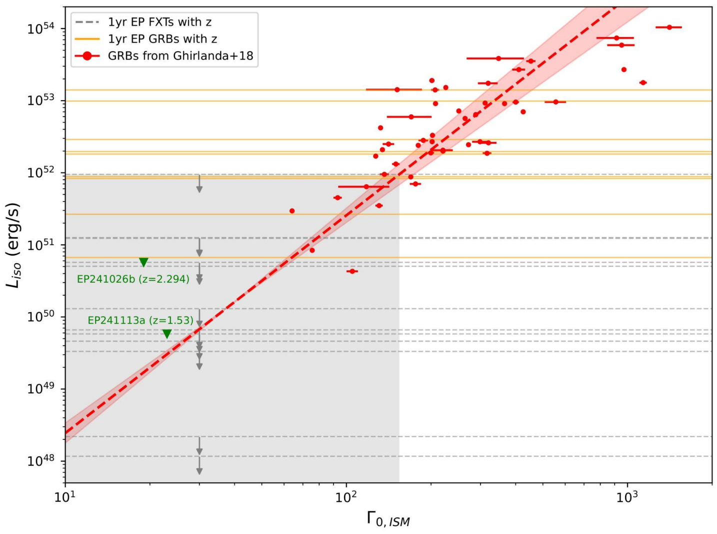
$3\sigma$ GBM upper limits derived for FXTs with no $\gamma$-ray counterparts (29 sources visible to GBM)

**Detections:**

- Average X-ray flux (integrated over $T_{100,X\text{–}ray}$) for EP sources cannot predict presence of detectable $\gamma$-ray.
- Simultaneous X-ray flux computed over $T_{90,\gamma}$ suggest $\gamma$-ray emission is detected during enhanced X-ray activity.
  - Ratio between simultaneous $\gamma$-ray and X-ray fluxes $1<F_\gamma/F_{X\text{–}ray}<100$.
- Similar X-ray flux and lower $\gamma$-ray flux could be from an even **softer spectrum** ($E_{peak}$< 70 keV)

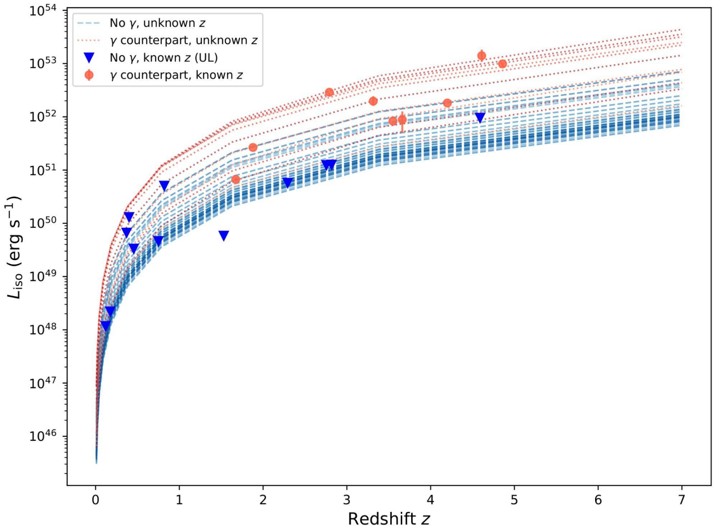


# Constraints on energetics and bulk lorentz factor



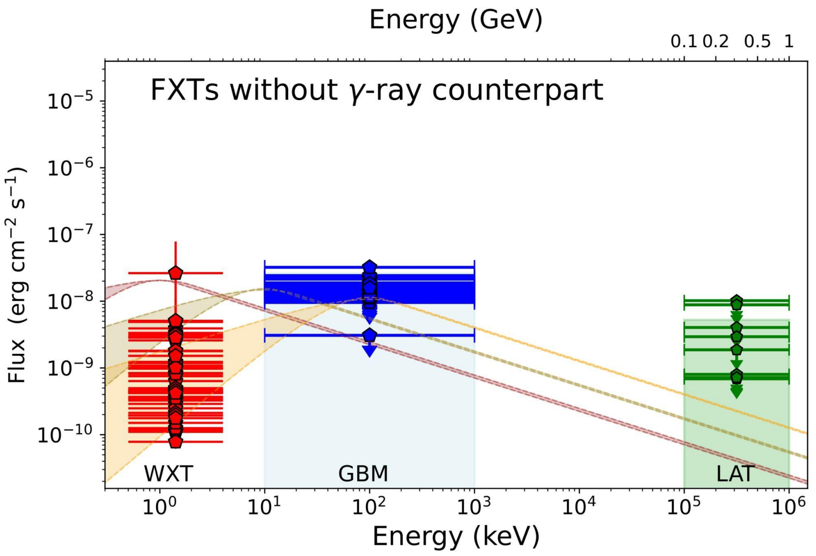

From EP-only sources with known redshift, derived $L_{iso}$ are in the range **$L_{iso} \lesssim 1\times10^{48}$–$9\times10^{51}$ erg s$^{-1}$**

- From empirical $\Gamma_0$–$L_{iso}$ correlation (Ghirlanda+ 2018) → $\Gamma_0 \lesssim 100$ for the EP-only events.
- Broadband afterglow modelling of some of these events faour an **on-axis jet with low $\Gamma_0$** (Hamidani+ (2025); Dai+ (2026); van Dalen+ (2026) *under review*)

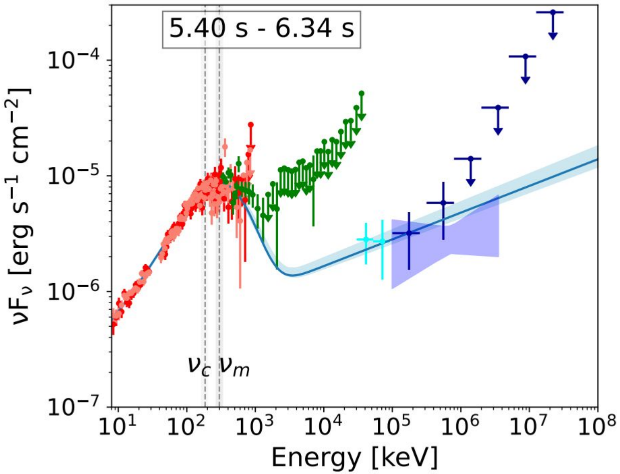



- Events with known redshift → 9 with GRB-associated and 12 with EP-only
- Median z = 3.55 for GRB-associated and z = 0.8 for EP only.
- 67% EP-only events lie below closest GRB-associated event (z = 1.673).

# Possibility of synchrotron self-Compton (SSC) emission




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




GRB 190114C
Macera+ (2024)

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

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

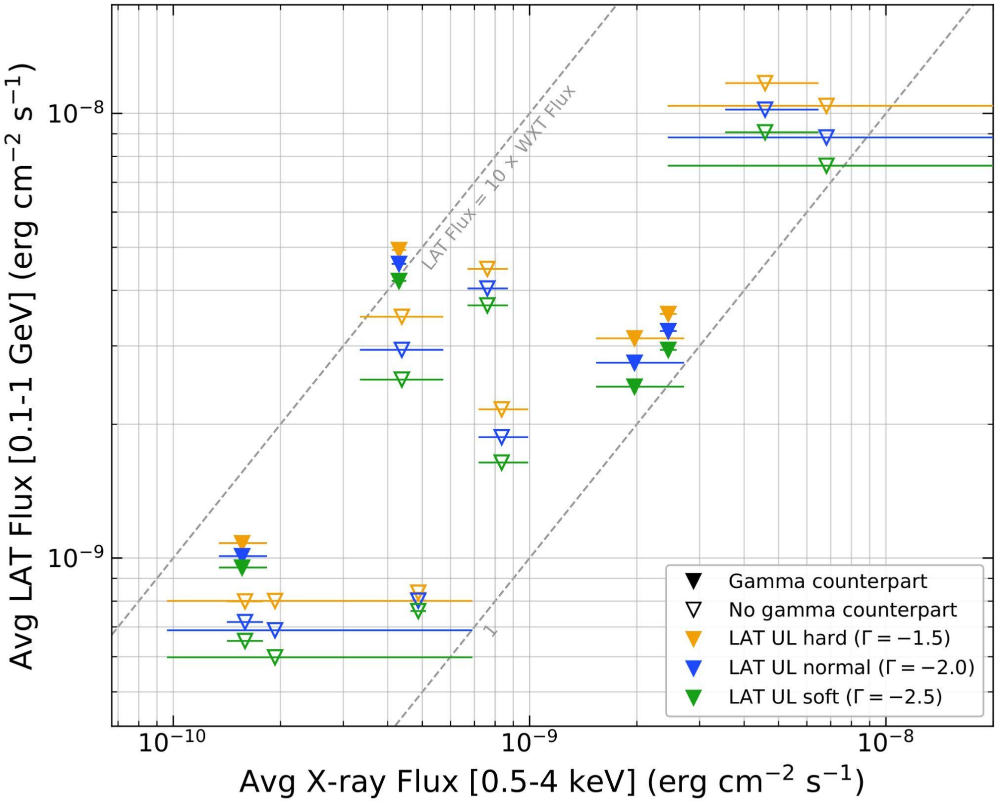
# LAT Observations

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$\sigma$.

**3$\sigma$ upper limits derived in the 0.1–1 GeV range** for three spectral shapes.

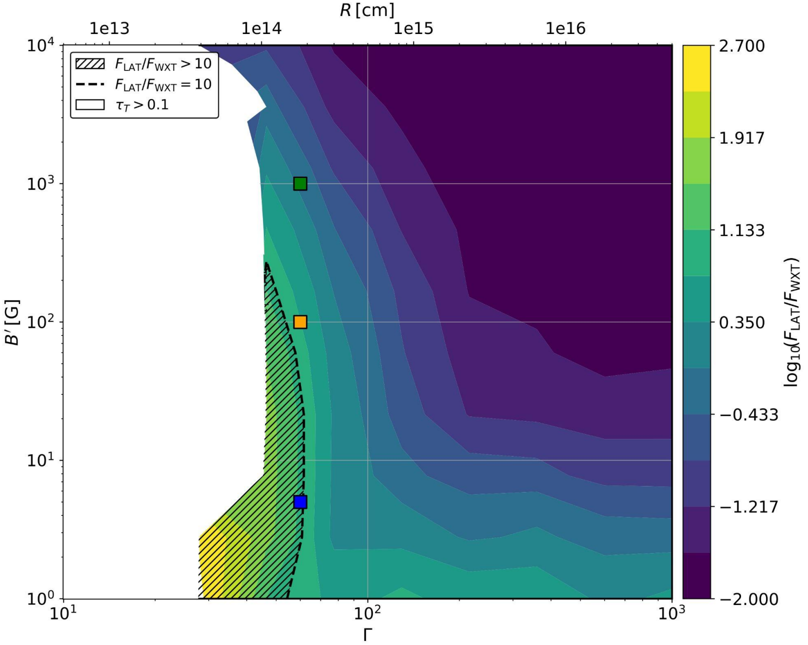
- $\mathbf{F_{0.1\text{–}1GeV}/F_{0.5\text{–}4\ keV} \lesssim 1\text{–}10}$
- The upper limit can help confine the parameter space of the jet → comoving magnetic field **(B')** and $\mathbf{\Gamma_0}$



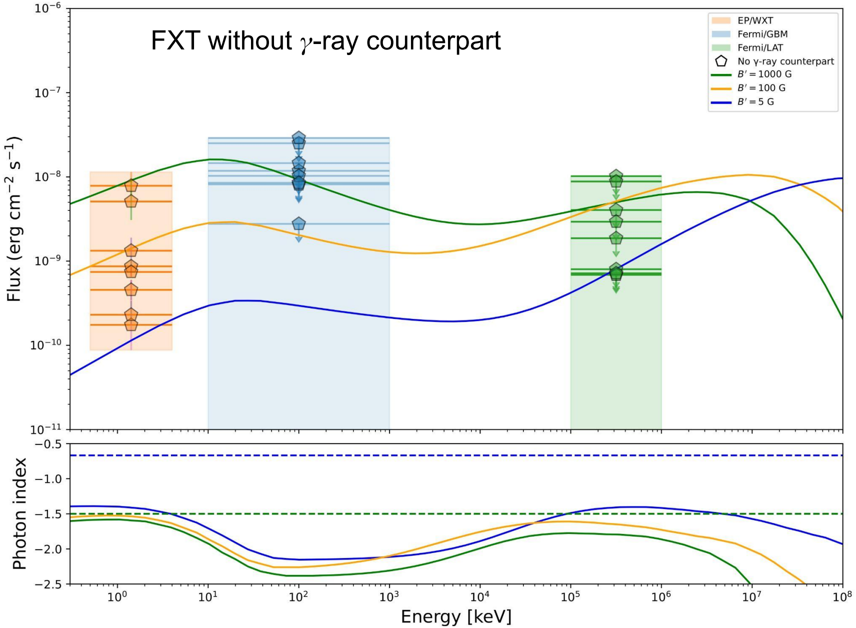
# Exploring spectrum with LeHaMoC (Stathopoulos+ 2024)

## Leptonic version of lepto-hadronic radiative code LeMoC

$L_{iso}$ = $10^{49}$ erg s-1, rest frame $E_{peak}$ = 10 keV, redshift z = 0.2
LAT upper limits refine the parameter space of B' and $\Gamma_0$




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**



# 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)).

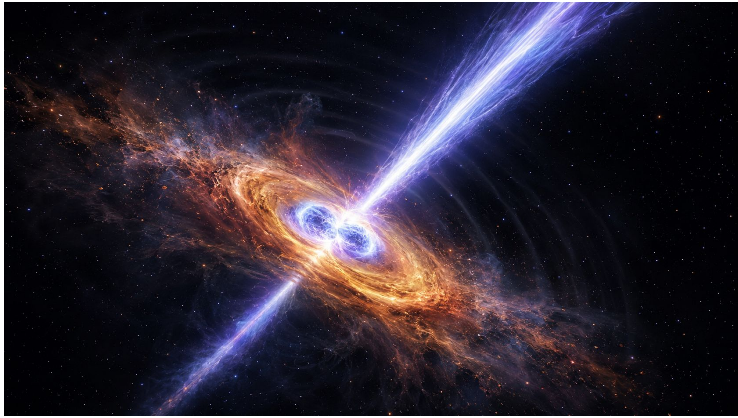
CBC also produce GW

**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).

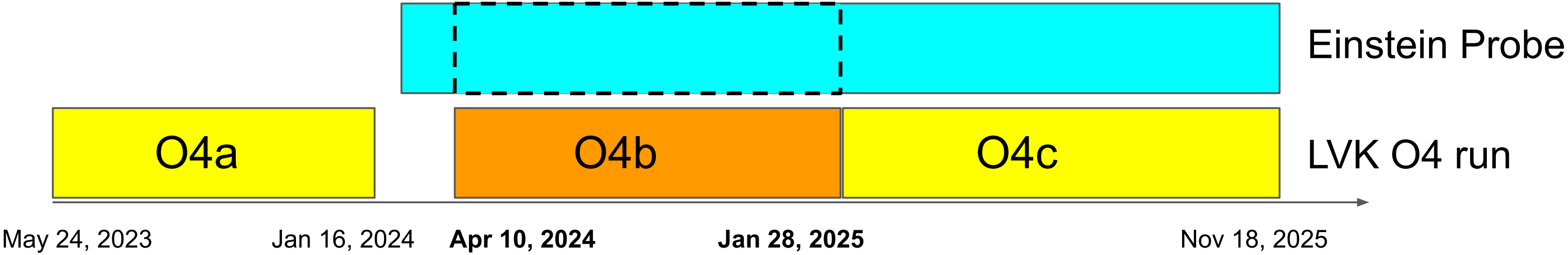
CBC believed to also power short GRBs

**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

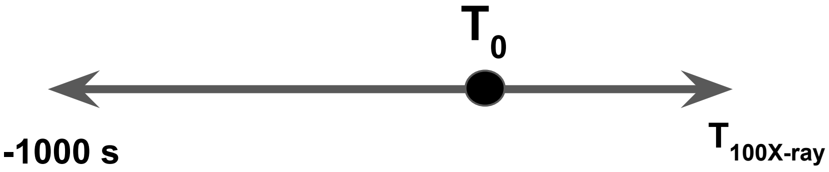
# Source selection in the O4b




- **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 → **47 FXTs**

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



# Ranking Statistic Piotrzkowski+ (2022)

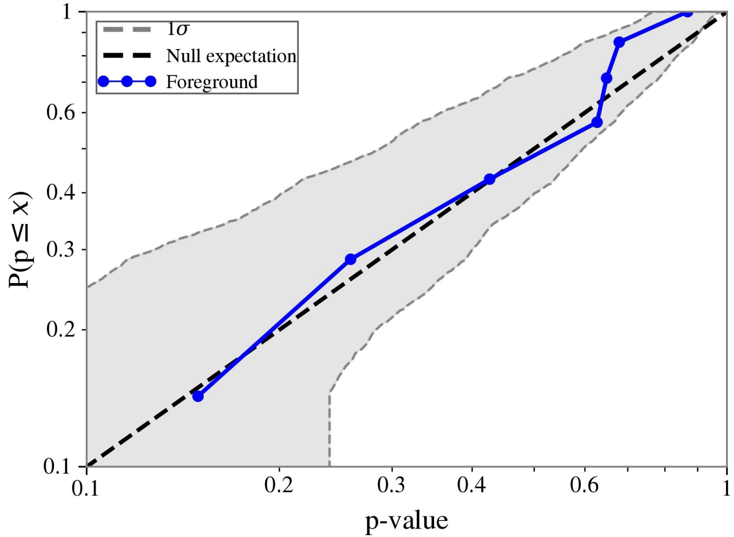
Tells how strongly the GW event and EP FXT are correlated

$$\Lambda = \frac{I_\omega}{1 + (BCI)^{-1}}$$

→ Probability density at source position (spatial coincidence between GW and WXT trigger)

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

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




$\mathbf{\Lambda}_{\text{fg}}$ → Coincident GWTC-5.0 Events

$\mathbf{\Lambda}_{\text{bkg}}$ → From 1000 random sets of RA/DEC and GWTC-5.0 Events

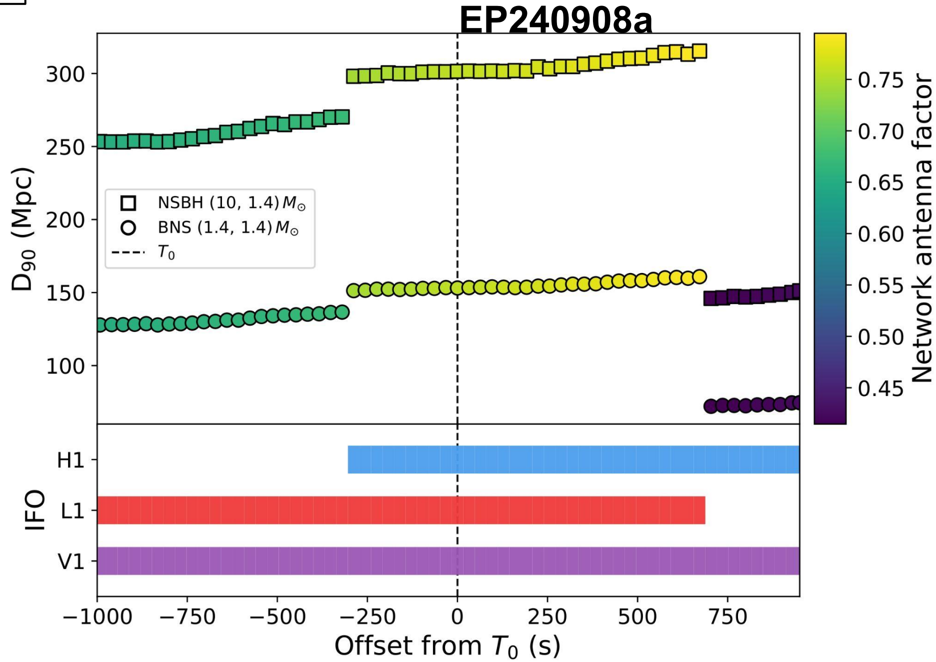
**No significant association between FXTs and GW in the O4b!**

# Exclusion distance for non-detection in GW

**Targeted Detectability Range** (S.Ronchini, **A. Chopra**+ (2026))
Detectability of a hypothetical CBC signal using detector sensitivity at the relevant time and the sky position of the external electromagnetic trigger.

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

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**.



# Summary

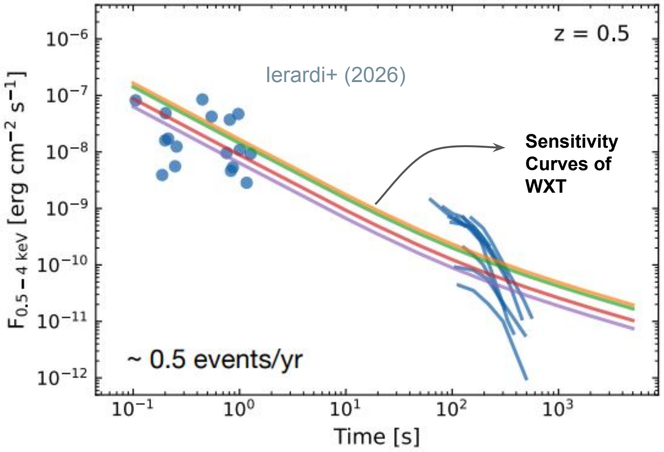
- **Einstein Probe transformed the FXT landscape**: 72 FXTs in the first year (double the FXTs observed in the last > 20 years). 23 confirmed GRBs and 49 without a prompt $\gamma$-ray counterpart.
- **Prompt $\gamma$-ray non-detections are constraining**: if on-axis GRBs, GBM limits favour softer and low luminosity tail of classical GRBs.
- **LAT limits reject low B' and low $\Gamma_0$ regine of parameter space**: no significant LAT detection. Upper limits do not rule out the presence of a hidden SSC component.

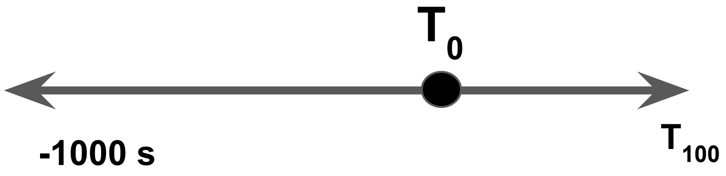
- First systematic search of GW counterparts of FXTs performed with 47 WXT events (non-stellar flare and non-GRB) in the LVK O4b run.
- No GW counterpart was found in O4b: The ranking statistic search found no significant association for the FXT.
- For no GW associations, TDR put constraints on a nearby CBC origins with an average $D_{90}$ pf 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.

FXT-GW

# EXTRA SLIDES

# Search Window




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

<u>For on-axis short GRB</u>, 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)).

<u>For off-axis merger-driven GRB</u>, 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))

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

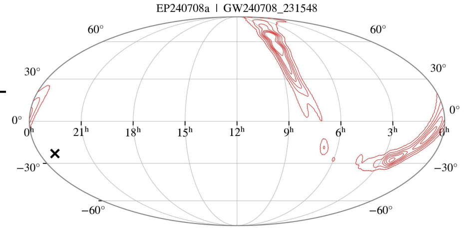
# Temporally coincident events

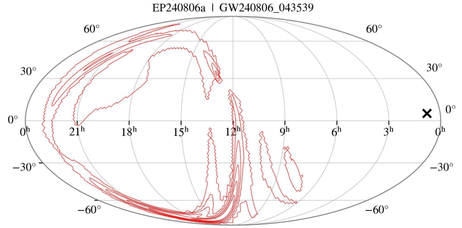
All-sky GW Superevents in GWTC-5.0* in the EP-FXT search window for temporal and spatial coincidence

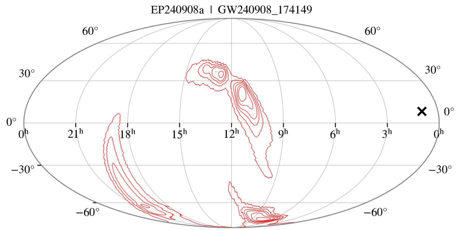
* https://zenodo.org/records/20276130

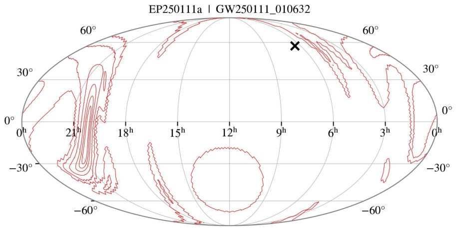
| EP_event | $T_{0,\mathrm{EP}}$ [UTC] | Superevent_ID | Offset ($T_{\mathrm{GW}} - T_0$) [sec] | FAR [$\mathrm{yr}^{-1}$] | SNR | Pipeline | IFOs |
|---|---|---|---|---|---|---|---|
| EP240708a | 23:28:23 | S240708ex | -754.7 | 448.27 | 8.0 | gstlal | H1L1V1 |
| EP240806a | 04:47:53 | S240806f | -733.8 | 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 |

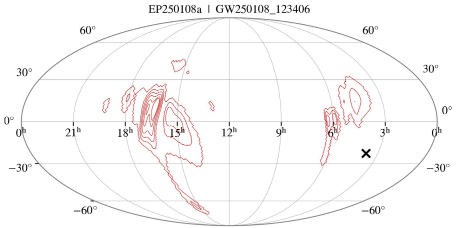
Probability of having 7 or more random temporal coincidence ~ **17%**

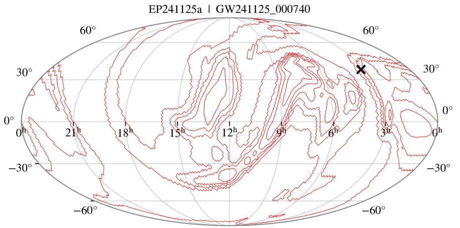


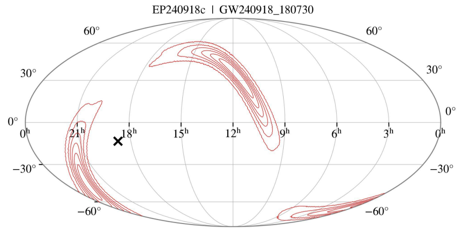



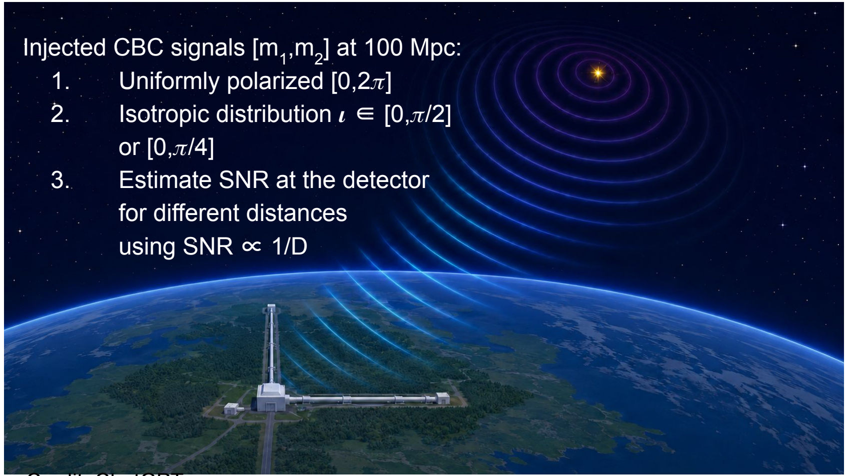



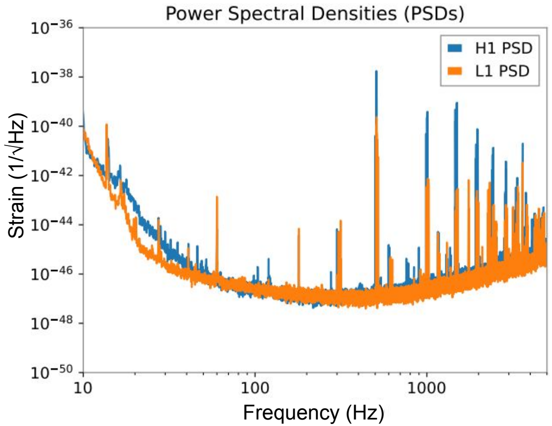



# Targeted Detectability Range (TDR) (Ronchini, **Chopra**+ (2026))




Credit: ChatGPT

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

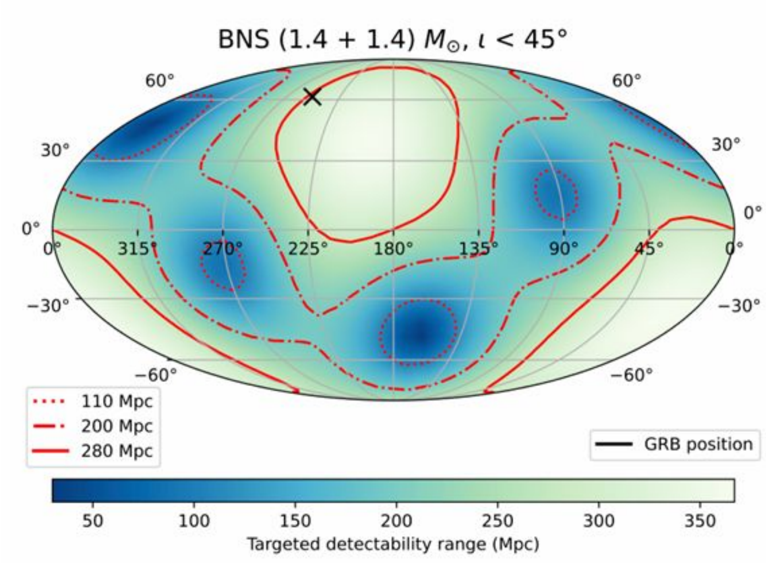


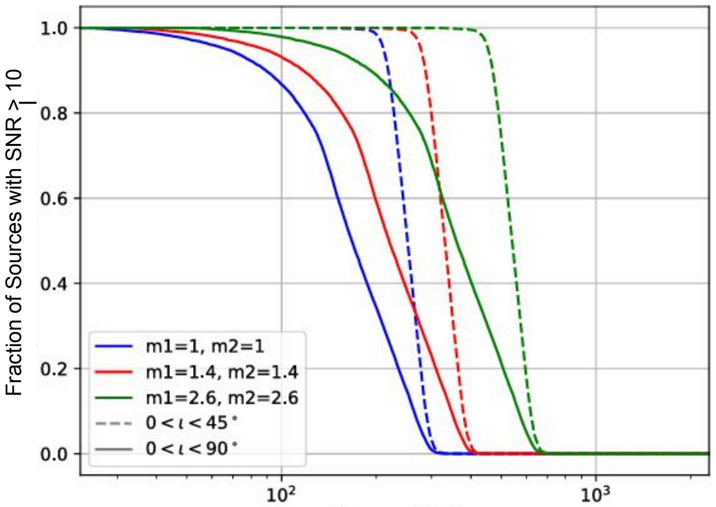

We define the exclusion distance ($D_{90}$) as the distance at which we retrieve 90% of the injected signals with SNR above a given threshold (we take $SNR_{thresh}$ = 10).

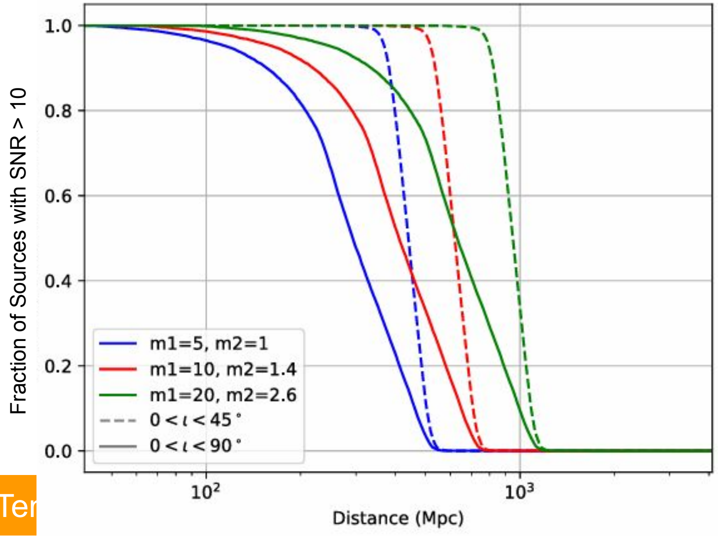
**In absence of any significant GW counterpart associated with EP-FXTs, we estimate the $D_{90}$ at which we would detect a GW signal with SNR>10**

- Estimate the Exclusion Distance

We define the Targeted Detectability Range as the distance where 90% of the injections have an SNR>10



# B. Optimal and Matched-filter SNR

Detector data **s(f) ~ h(f) + n(f)**

Where h(f) → signal waveform; n(f) → detector noise

$$\mathrm{SNR}^2_{opt} = < h|h > = 4 \int \frac{|h(f)|^2}{S_n(f)}\, df$$

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

$$\mathrm{SNR}_{mf} = \frac{< s|h >}{\sqrt{< h|h >}}$$

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