Estimating Source Distances for High Energy Neutrinos: A Method for Improving Electromagnetic Follow-up Searches

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Abstract

A method is described for deriving a **probable distance interval** for the astrophysical source that may possibly be associated with a High Energy Neutrino (HEN) event detected with IceCube or KM3NeT.

This can be used in a **cross-matching with galaxy catalogues** to search for plausible electromagnetic counterparts. This study is intended to serve as a guide for high-energy neutrino followup campaigns.

For more information → see Reference [1]

Introduction

- Potential High Energy Neutrino (HEN) sources have diverse possible electromagnetic (EM) signals:
  - Short duration: Gamma-Ray Burst (GRB)-like, with falling lightcurve in a few hours ;
  - Medium duration: SNIc, Kilonova, with fading in few days-weeks, with HEN possibly before the EM peak ;
  - Long duration: Superluminous SN, SNIIn, Tidal Disruption Events (TDE), AGN, with fading in few months/years.
- HEN Telescopes IceCube-KM3NeT issue alerts (= notices) in real time with HEN characteristics:
  - position (ra, dec) + uncertainty, ranging from $1°$ (Tracks) to $10° - 20°$ (Cascades)
  - Energy, signalness, False-Alarm Rate (FAR) - No information on the source nature or distance
  - "Gold" events (12/yr) are 50% astrophysical - "Bronze" events (16/yr) are 30% astrophysical
- LIGO/Virgo alerts despite larger uncertainty (>100 deg^2) are more followed up than HEN alerts

⇒ Only $\approx 50\%$ of Gold IceCube alerts followed, less than 20% of Bronze alerts !

⇒ Constrain the HEN localisation/distance to improve the search for EM counterparts.

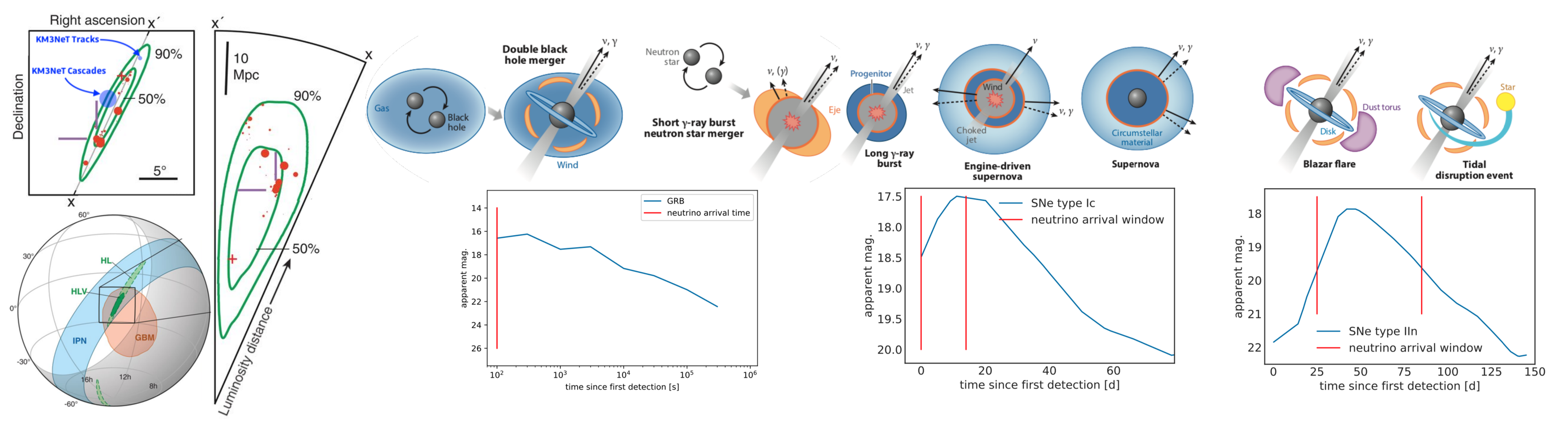

Figure 1. Compared localisation of GW170817 with Gravitational Waves (GW), with distance information, and with KM3NeT HEN if produced, with no distance information. Potential HEN sources, some of them also GW emitters (GRB, SN) but others (Blazar flares, TDE) which only emit HEN or EM, with the possible evolutions of HEN and EM emissions.

Constrain the source distance to increase the followup rate

Assuming $\frac{dN}{dE} = \Phi_0 \left(\frac{E}{E_0}\right)^{-\gamma}$, and given the effective area $A_{\rm eff}(\delta, E)$ for IceCube alerts [2]:

$$\frac{E_{\rm iso}^{\rm HEN}}{4\pi D_L(z)^2} = \int_{E_{\rm min}^{\rm obs}}^{E_{\rm max}^{\rm obs}} E\frac{dN}{dE}dE \quad \oplus \quad \langle N_{\rm HEN}(\delta)\rangle = \int_{E_{\rm min}^{\rm obs}}^{E_{\rm max}^{\rm obs}} A_{\rm eff}(\delta, E)\frac{dN}{dE}dE \quad \Rightarrow \langle N_{\rm HEN}\rangle = k_0(\gamma,\delta)\frac{E_{\rm iso}^{\rm HEN}}{4\pi D_L^2}.$$

Compute $P_{\rm obs}(N_{\rm HEN}^{\rm obs} > 0)$ and $P_{\rm obs}(N_{\rm HEN}^{\rm obs} = 1)$ depending on HEN direction, D_L and $E_{\rm iso}^{\rm HEN}$:

$$P_{\rm obs}(N_{\rm HEN}^{\rm obs} = 1) = \langle N_{\rm HEN}\rangle e^{-\langle N_{\rm HEN}\rangle},$$
$$P_{\rm obs}(N_{\rm HEN}^{\rm obs} > 0) = 1 - e^{-\langle N_{\rm HEN}\rangle}.$$

① First notice : 1 observed event

→ use FAR to get UL on $\langle N_{\rm HEN}\rangle$

$$D_L \geq \sqrt{\frac{k_0(\gamma,\delta)\times E_{\rm iso}^{\rm HEN}}{4\pi\langle N_{\rm HEN}\rangle_{\rm UL}}}.$$

→ FAR from 0.15/yr to 4.9/yr in $T_{\rm obs} \approx 4$ yrs

→ $\langle N_{\rm HEN}\rangle_{\rm UL}$ from 3.8 to 0.9

② Second notice : no additional event

→ Fluence UL in GeV/cm² for 1000s, 2 days time window

$$D_L \geq \sqrt{\frac{E_{\rm iso}^{\rm HEN}}{4\pi F_{\rm lim}\times f(\gamma, E_{\rm min}, E_{\rm max})}}$$

→ For $\gamma = 2$, $E_{\rm iso}^{\rm HEN}/4\pi D_L^2 = \Phi_0 E_0^2 \Delta t \ln\frac{E_{\rm max}}{E_{\rm min}}$

→ $\Phi_0 E_0^2 \Delta t \leq F_{\rm lim}$ yields distance limit

- Figure 3 (top) - D_L limits vs $E_{\rm iso}^{\rm HEN}$ based on first notice and the observation of 1 HEN event.
- Figure 3 (bottom) - D_L limits vs $E_{\rm iso}^{\rm HEN}$, based on second notice and Fluence UL.

⇒ Observation of 1 HEN not enough to constrain the distance within 90% distance interval.

⇒ Fluence UL bring strong contraints on the distance, especially for $E_{\rm iso}^{\rm HEN} > 10^{52}$ erg.

Taking into account Population information

Transient rate per unit time is redshift-dependent:

$$R_{\rm transients}(z) = \rho(z)\times\frac{dV_c}{dz}\times(1+z)^{-1}$$

- $\rho(z)$ = transient density rate in $1/{\rm Mpc}^3/{\rm yr}$

→ CCSN/Star Formation Rate SFR, GRB, z-independent

- dV_c/dz = differential comoving volume
- Convolve with $P_{\rm obs}(N_{\rm HEN}^{\rm obs}) = f(D_L, E_{\rm iso}^{\rm HEN})$

⇒ Probability for source at D_L with $E_{\rm iso}^{\rm HEN}$ to yield $N_{\rm HEN}^{\rm obs}$

- *Right plot* : Black = median, Green = 90% probable distance, Red = no z−dependence

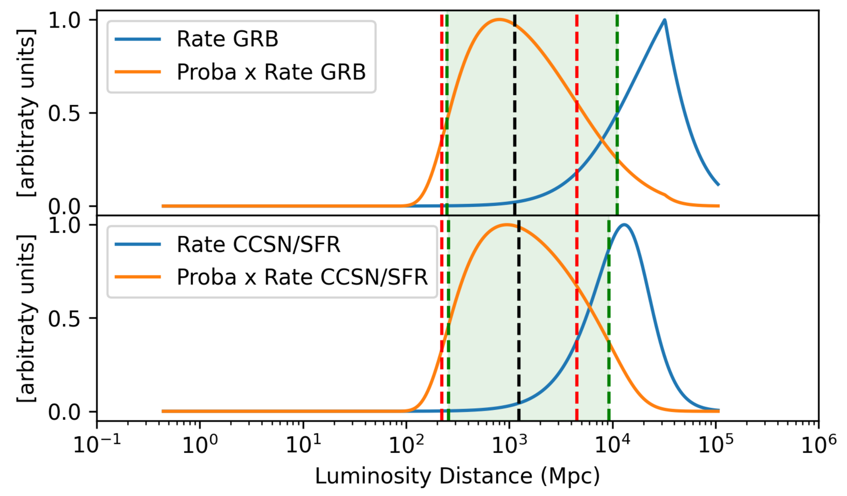

Figure 2. $P_D(D_L)$ for $E_{\rm iso}^{\rm HEN} = 10^{55}$ erg, given that $N_{\rm HEN}^{\rm obs} = 1$

⇒ $N_{\rm HEN}^{\rm obs}$ allows to define a 90% interval for the distance for each D_L, $E_{\rm iso}^{\rm HEN}$, which depends on :

- the HEN direction (through the effective area),
- the HEN spectral index assumed, the population, either SFR, GRB, or z−independent.

Using information from IceCube circulars

Let's look at the probable 90% distance interval and constraints in the case of the IceCube event IC230306A, a Gold event of 176 TeV detected on 6 March 2023 [see comments in adjacent red frame].

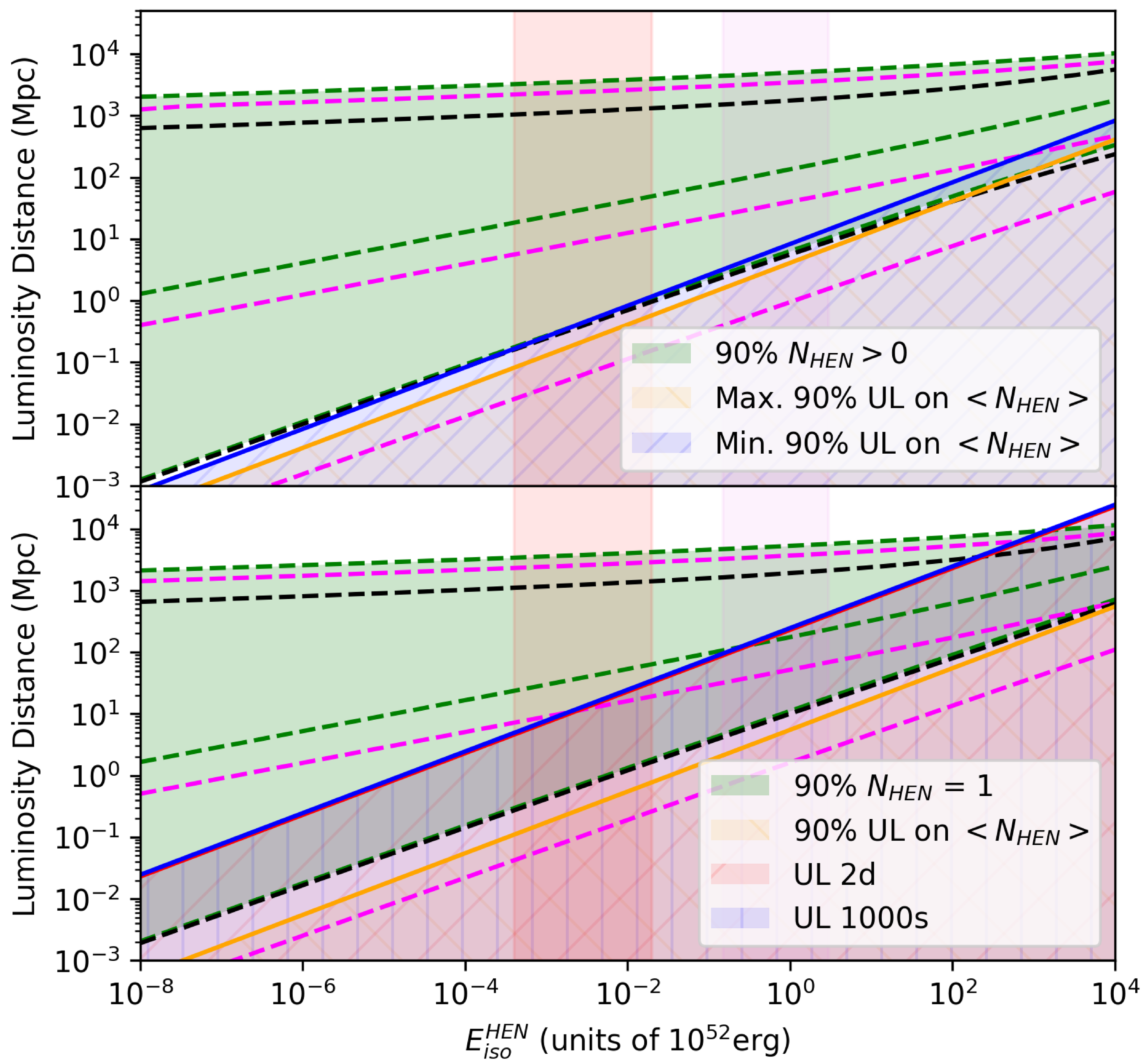

Figure 3. Top: 90% distance interval after 1st notice $N_{\rm HEN}^{\rm obs} > 0$, CCSN/SFR population and spectral index $\gamma = 2$, in green. Yellow and blue region = excluded after 1st notice, given max. and min. UL on $\langle N_{\rm HEN}\rangle$, depending on FAR of the alert. Bottom: Same quantities after 2nd notice reporting fluence limits in 1000s and 2 days time windows. *Colored vertical bands* = ***maximum*** E_{iso}^{HEN} *for different sources - GRBs =* $1.5\times10^{51} - 3\times10^{52}$ *erg, SN =* $4\times10^{48} - 2\times10^{50}$ *erg. Green dashed line = median distance. Magenta lines = modified 5%-95% interval for a GRB-population together with* $\gamma = 2.5$. *Black lines = population with no redshift evolution and* $\gamma = 2$.

Galaxy Catalogue Cross-Match for IC230306A

Ranking score defined for each galaxy of a catalogue for each $E_{\rm iso}^{\rm HEN}$, given its position and distance:

$$P_{\rm Galaxy}(E_{\rm iso}^{\rm HEN}) = P_{\rm loc}(\alpha_{\rm Galaxy}, \delta_{\rm Galaxy})\times P_{\rm D}(D_{\rm Galaxy}),$$

- $P_{\rm loc}(\alpha_{\rm Galaxy}, \delta_{\rm Galaxy}) \propto e^{-\frac{\Delta\theta^2}{2\sigma^2}}$, with $\Delta\theta$ galaxy-HEN angular separation, and σ = uncertainty based on 50% / 90% HEN containment errors of the observed HEN event.
- $P_{\rm D}(D_{\rm Galaxy})$ = convolution of transient rate & detection probability (Figure 2).

For the cross-match, the Glade+ Galaxy Catalogue [3] is used.

Table 1. Distance and ranking, R, of galaxies from the Glade+ Galaxy Catalogue cross-match with HEN IC230306A, using $P_{\rm D}$ for $E_{\rm iso}^{\rm HEN} \in [10^{44}{\rm erg}, 10^{52}{\rm erg}]$ or without for $E_{\rm iso}^{\rm HEN} = 3.3\times10^{49}{\rm erg}$. Only the first ten galaxies are shown. **In bold**, galaxies not ranked in the top five with no distance info. For $E_{\rm iso}^{\rm HEN} = 10^{52}{\rm erg}$, galaxies with/without Fluence limit. $(*)$ indicates galaxies present in the low- and high-energy scans. Average $\langle R\rangle$ uses $E_{\rm iso}^{\rm HEN} \in [10^{44}\ {\rm erg} - 10^{52}{\rm erg}]$ with distance information without a fluence limit. Last two columns with Fluence limit.

D_L (Mpc) with $P_{\rm D}$, no $F_{\rm lim}$ $E_{\rm iso}^{\rm HEN} = 3.3\times10^{49}$erg	R no $P_{\rm D}$, no $F_{\rm lim}$ 3.3×10^{49}erg	R $P_{\rm D}$, no $F_{\rm lim}$ 10^{52} erg	$\langle R\rangle$ $P_{\rm D}$, no $F_{\rm lim}$ $[10^{44}\ {\rm erg} - 10^{52}{\rm erg}]$	D_L (Mpc) $P_{\rm D} + F_{\rm lim}$ 10^{52} erg	D_L (Mpc) $P_{\rm D} + F_{\rm lim}$ 10^{53} erg
202.2	3	1	1	426.7 (*)	1208.6
150.0	1	2	2	701.4 (*)	842.4
106.7	2	6	4	418.9	1080.4
426.7 (*)	**10**	3	3	306.0	861.3
140.7	**6**	7	5	437.7	859.4
170.9	7	5	5	386.8	1131.9
234.3	9	4	7	307.0	-
88.6	5	9	8	468.1	-
701.4 (*)	>10	>10	>10	660.6	-
35.1	4	9	9	567.2	-

- Ranking with distance+localisation is different from localisation-only (1st, 2nd columns)
- With increasing energy, selected galaxies are increasingly distant.
- For $E_{\rm iso}^{\rm HEN} \in [10^{44}, 10^{51}{\rm erg}]$, the selected galaxies are identical.
- For $E_{\rm iso}^{\rm HEN} \gtrsim 10^{52}$erg, galaxies beyong 250 Mpc must be discarded because of Fluence limit.
- For $E_{\rm iso}^{\rm HEN} \gtrsim 10^{53}$erg, distance limit is 800 Mpc: only handful of galaxies left in this case.

⇒ **Method for galaxy-targeted HEN followup, e.g. using GRANDMA Telescope Network [4]**

$1^{\rm st}$ notice T_0: average ranking for $E_{\rm iso}^{\rm HEN} \in [10^{44}\ {\rm erg}, 10^{52}{\rm erg}]$ ⇒ valuable time saved

$2^{\rm nd}$ notice $T_1 \approx T_0 + 1.5$ days: low-energy (e.g. 10^{49}erg) and high energy ranking (e.g. 10^{52}erg)

Conclusions - Glade+ completeness and cross-match probability

- Precious information from Notices issued after a HEN alert: Number of HEN observed, Fluence limit.
- Additional information on the source: maximal energy, spectral index, population z-dependence.

- Up to 50 Mpc - Catalogue complete - 30-70% source presence probability with cross-match
- Up to 130 Mpc - 90% of total B-band K_s-band luminosity → 35-70% ×-match probability
- Up to 250 Mpc (400 Mpc) - 50% of total B-band (K_s-band) luminosity - 25-40% ×-match probability
- Beyond 800 Mpc - 20% complete - 15-30% presence probability → 3-6% with cross-match
- HEN sources: 10 Mpc (NGC1068) to 1.8 Gpc (TXS0506+056) - GW170817 40 Mpc (envisaged)

⇒ Reasonable/feasible to look for association with close catalogued galaxies.

Distance-constrained cross-matches will save valuable time to catch EM counterparts to HEN !

References

[1] T. Pradier. Estimating source distances for high energy neutrinos (...). A&A Letter to the Editor 2023 (accepted) arXiv:2304.00831.

[2] IceCube. IceCube HEN Track Alerts [https://gcn.gsfc.nasa.gov/doc/IceCube_High_Energy_Neutrino_Track_Alerts_v2.pdf], 2019.

[3] G. Dálya et al. Glade+ : an extended galaxy catalogue for multimessenger searches (...) - arxiv:2110.06184. *MNRAS*, 514-1:1403–1411, 2022.

[4] D. A. Kann et al. GRANDMA and HXMT Observations of GRB 221009A (...) - arXiv:2302.06225. *ApJL*, 948(2):L12, May 2023.