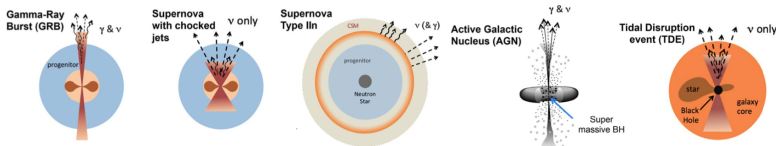
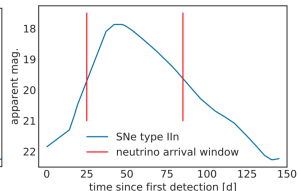
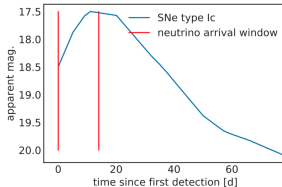
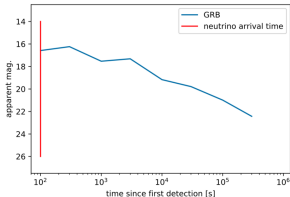


A large diversity of HEN sources...



...and of their signals

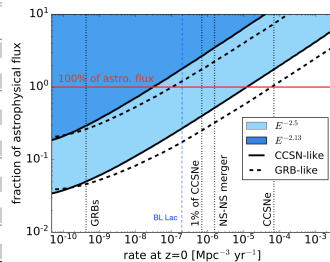
- Short duration - GRB-like - falling lightcurve, few hours
- Medium duration - SNIc BL, Kilonova - few days-weeks - **HEN before peak**
- Long duration - SuperLuminous SN, SNIIn, TDE, AGN - few months



Upper limits & Eddington bias



source class	local density [Mpc ⁻³ (yr ⁻¹)]	min. dist. [Mpc]	limit	source energy [erg]	max. fluence [GeV ⁻¹ cm ⁻²]
long GRBs	4×10^{-10}	470	< 1% (stacked)	$< 6 \times 10^{51}$	$< 4 \times 10^{-3}$
short GRBs	3×10^{-9}	220	< 32% (OFU)	$< 3 \times 10^{52}$	$< 9 \times 10^{-2}$
iGRBs	1.6×10^{-7}	64	< 100% (flux)	$< 1.5 \times 10^{51}$	$< 6 \times 10^{-2}$
SNe Ic broad.	1.4×10^{-6}	30	< 100% (flux)	$< 2 \times 10^{50}$	$< 4 \times 10^{-2}$
SNe IIn	4×10^{-6}	20	< 66% (stacked)	$< 4 \times 10^{49}$	$< 1.4 \times 10^{-2}$
SNe Ib/c	1.7×10^{-5}	12	< 32% (stacked)	$< 5 \times 10^{48}$	$< 5 \times 10^{-3}$
CCSNe	7×10^{-5}	8	< 100% (flux)	$< 4 \times 10^{48}$	$< 8 \times 10^{-3}$
FSRQs	6×10^{-10}	1000	< 17% (EHE)	$< 1.6 \times 10^{53}$	$< 3 \times 10^{-2}$
BL Lac objects	2×10^{-7}	120	< 25% (EHE)	$< 3 \times 10^{51}$	$< 2.5 \times 10^{-2}$
all AGN	10^{-3}	7	< 100% (flux)	$< 3 \times 10^{46}$	$< 8 \times 10^{-5}$
jetted TDEs	3×10^{-11}	1000	< 100% (flux)	$< 10^{54}$	$< 1.4 \times 10^{-1}$
galaxy cluster	5×10^{-6}	40	< 100% (flux)	$< 3 \times 10^{50}$	$< 3 \times 10^{-2}$
starburst gal.	3×10^{-5}	22	< 100% (flux)	$< 2 \times 10^{49}$	$< 2 \times 10^{-3}$

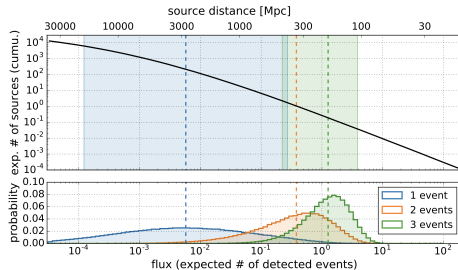


N. L. Strotjohann, PhD, <https://edoc.hu-berlin.de/handle/18452/21791>

Which alerts/objects to observe ?

- Short duration - GRB-like - **GRBs disfavored as HEN sources** (prompt phase) \Rightarrow **what about precursor/afterglow ?**
- Medium duration - SNIc, Kilonova - **mostly unconstrained**
- Long duration - SNIIn, TDE, AGN - **unconstrained**

Upper limits & Eddington bias



N. L. Strotjohann et al, <https://www.aanda.org/articles/aa/pdf/2019/02/aa34750-18.pdf>

Eddington Bias

- With only 1 neutrino $\rightarrow D \sim 0.5 - 20$ Gpc 90% (here BL Lac density, 10 events in 10 yrs for <30% detected HEN flux)
- To date, no reported multiple neutrino candidates for all Alerts (= no additional HEN found after initial IceCube alert)
- Population consists of few bright, nearby sources + many faint sources located at large distances

\Rightarrow This can be used to reduce the Search Volume in the case of a HEN signal!

HEN Alerts (AMON/IceCube/KM3NeT)



Existing Alerts - Public

- Gold Alerts : 12/yr, > 50% astrophysical - *latest* : 24/04/2024 - **Observed \approx 1/month**
- Bronze Alerts : 16/yr, > 30% astrophysical - *latest* : 19/04/2024 - **Observed \approx 1.3/month**

Other Public Alerts

- NU_EM Alerts : 2-4/yr HAWC-ICECUBE (only position + 90% radius) - **Observed rate \approx 0.7/month**
- IceCube Cascades : 8/yr, > 85% astrophysical (w. skymap) - *latest* : 26/06/2024 - **Observed rate \approx 0.5/month**

Possible Alerts - Private - MoU needed

- OFU Alerts (Optical/X-ray) : GRB/SN jets, Northern, multiplets 2 evts in 100s $\Delta\Omega < 3.5^\circ$ (ROTSE, PTF, Swift)
- GFU (γ -ray) : clusters around selected sources (MAGIC, VERITAS)

IceCube(/KM3NeT) Alert contents

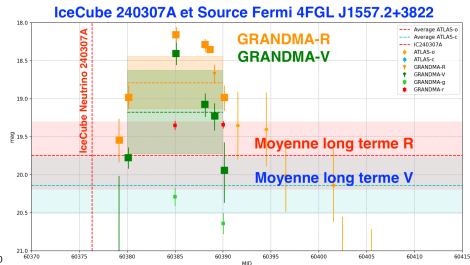
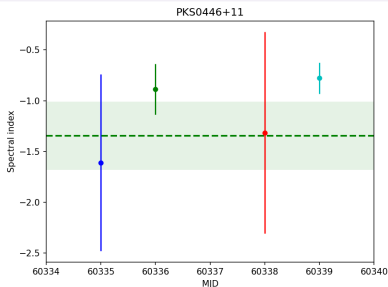
- Position + uncertainty (convertible in `fits` map) - $\lesssim 1^\circ \rightarrow 10^\circ$ (Tracks) / 20° (Cascades)
- *Signalness* + FAR (/y) + Energy

HEN Alerts followep by GRANDMA



Quite a few !

- IC231004A - associated to SN ? T+15d
- IC231211A - PLS2047+098 - nothing
- IC240105A - PKS0446+11 - variability but T+10d - spectrum measured - under study
- IC240307A - 4FGL J1557.2+3822 - variability at T+1d
- IC240327B - 4FGL J0555.9+0030 - KNC + GRANDMA
- IC240424A - Upper Limit for Fermi J2151.3+0220





Expected Number of events vs Distance and Energy

Source - Total Isotropic Energy

$$\frac{E_{\text{iso}}^{\text{HEN}}}{4\pi D_L^2} = \int_{E_{\text{min}}}^{E_{\text{max}}} E \frac{dN}{dE} dE \propto \Phi_0$$

Detection - Average Expected Number of Events

$$\langle N_{\text{HEN}}(\delta) \rangle = \int_{E_{\text{min}}}^{E_{\text{max}}} A_{\text{eff}}(\delta, E) \frac{dN}{dE} dE \propto \Phi_0$$

Detection Probability vs Distance vs Energy

- Finally $\langle N_{\text{HEN}} \rangle = k_0(\gamma, \delta) \frac{E_{\text{iso}}^{\text{HEN}}}{4\pi D^2} \Rightarrow$ Detection probability vs $E_{\text{iso}}^{\text{HEN}}$ and Distance - depends on spectral index $E^{-\gamma}$
- Alternatively, probability for a source to be detected with $N_{\text{HEN}}^{\text{obs}} = 1, 2, 3...$ given the average $\langle N_{\text{HEN}} \rangle$
 - \Rightarrow as a function of $E_{\text{iso}}^{\text{HEN}}$
 - \Rightarrow as a function of D_L

Article \Rightarrow T.P. [A&A 674, L11 \(2023\)](#)

Constraints on origin/energy of source and ICECUBE Notices



Example 1st Notice - ICECUBE-230201A

The event was selected by the ICECUBE_Astrotrack_Bronze alert stream. The average astrophysical neutrino purity for Bronze alerts is 30%. This alert has an estimated **false alarm rate of 2.07 events per year** due to atmospheric backgrounds.

1st ICECUBE GCN - A single HEN has been detected

- Assume astrophysical origin : $N_{\text{HEN}}^{\text{obs}} > 0$
- 1 Given **FAR of alert**, and $T_{\text{obs}} \approx 3.67$ yrs (start of new Alert System) \Rightarrow mean expected background
- 2 Given $N_{\text{HEN}}^{\text{obs}} = 1$, extract UL on $\langle N_{\text{HEN}} \rangle$ (e.g. Feldman-Cousins)
 - \Rightarrow Minimum FAR $\sim 0.15/\text{yr} \Rightarrow \langle N_{\text{HEN}} \rangle_{\text{UL}} \approx 3.8$
 - \Rightarrow Minimum FAR $\sim 4.9/\text{yr} \Rightarrow \langle N_{\text{HEN}} \rangle_{\text{UL}} \approx 0.9$
- 3 Extract Minimum Distance from relationship $\langle N_{\text{HEN}} \rangle$ vs $D, E_{\text{iso}}^{\text{HEN}}$

$$D_L \geq \sqrt{\frac{k_0 \times E_{\text{iso}}^{\text{HEN}}}{4\pi \langle N_{\text{HEN}} \rangle_{\text{UL}}}}$$

Constraints on origin/energy of source and ICECUBE Notices



Example 2nd Notice - ICECUBE-230201A

IceCube sensitivity to neutrino point sources with an **$E^{-2.5}$ spectrum ($E^2 dN/dE$ at 1 TeV) (...) is **$1.3e-01 \text{ GeV cm}^{-2}$ in a 1000 second time window**. 90% of events IceCube would detect from a source at this declination with an $E^{-2.5}$ spectrum have energies in the approximate energy range **between $2e+02 \text{ GeV}$ and $1e+05 \text{ GeV}$** .**

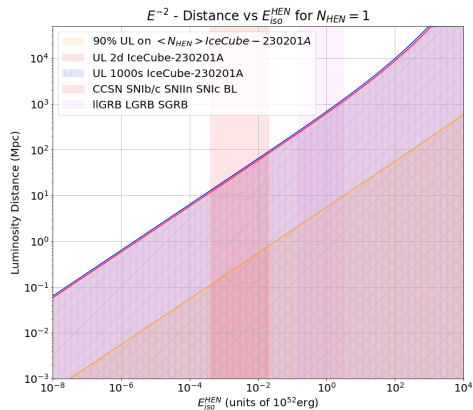
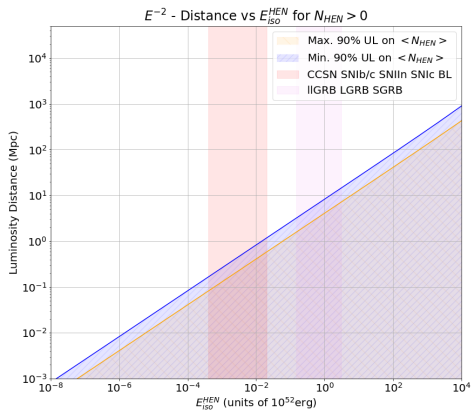
(...) The IceCube sensitivity to neutrino point sources with an **$E^{-2.5}$ spectrum ($E^2 dN/dE$ at 1 TeV) (...) ranges from **$1.5e-01$ to $1.6e-01 \text{ GeV cm}^{-2}$ in a 2 day time window**.**

2nd ICECUBE GCN - No further HEN in 1000s / 2days

- $\frac{E_{\text{iso}}^{\text{HEN}}}{4\pi D^2} = \Phi_0 E_0^2 \Delta t \int_{E_{\text{min}}}^{E_{\text{max}}} E^{1-\gamma} E_0^{\gamma-2} dE = \Phi_0 E_0^2 \Delta t \times \ln\left(\frac{E_{\text{max}}}{E_{\text{min}}}\right)$ for $\gamma = 2$
- For e.g $\gamma = 2.5 \rightarrow \Phi_0 E_0^2 \Delta t \times 2 \left(\sqrt{\frac{E_0}{E_{\text{min}}}} - \sqrt{\frac{E_0}{E_{\text{max}}}} \right)$
- 2nd Notice gives $E_{\text{min}}, E_{\text{max}}$ + limit on $F_{\text{min}} = \Phi_0 E_0^2 \Delta t$ in both time windows 1000s / 2 days \rightarrow 2 limits on Distance

$$D_L \geq \sqrt{\frac{E_{\text{iso}}^{\text{HEN}}}{4\pi F_{\text{lim}} \times \text{constante}}}$$

HEN Followup - Constraining the Observation volume



Vertical colored bands = CCSN-like - GRB-like sources ranges of maximum energies from observations

$\langle N_{HEN} \rangle_{UL} + \text{Fluence limit} \Rightarrow \text{ICECUBE Notices slightly constrain the Observation Volume}$

HEN Followup - Constraining the Observation volume

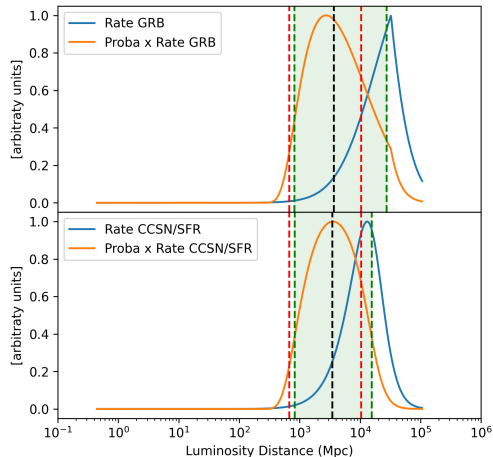


Taking into account distribution vs Redshift

- Rate of transients Mpc^3/yr is redshift-dependent

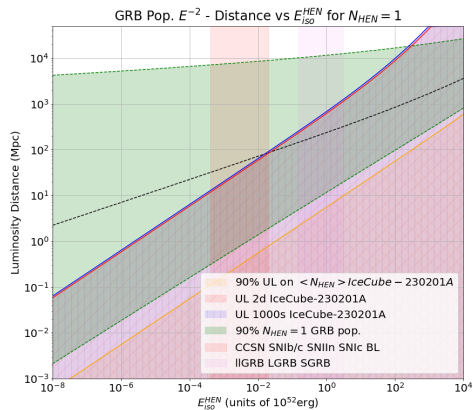
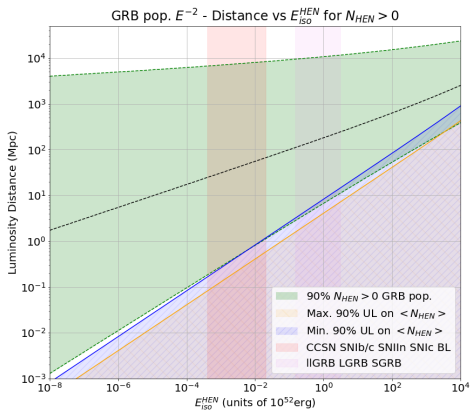
$$R_{\text{transients}}(z) = \rho(z) \times \underbrace{\frac{dV_c}{dz}}_{\text{differential comoving volume}} \times \underbrace{(1+z)^{-1}}_{\text{cosmic time dilation}}$$

- Use CCSN population (\approx Star-Formation Rate) vs Redshift or GRB, or any other rate $\rho(z)$
- Many distant & faint sources will dominate over few bright sources
- Convolve $R(z)$ with $P_{\text{obs}}(E_{\text{iso}}^{\text{HEN}}, D_L(z))$ to estimate probable position/distance of Source with $N_{\text{HEN}}^{\text{obs}} > 0$ or $N_{\text{HEN}}^{\text{obs}} = 1$



Here $E_{\text{iso}}^{\text{HEN}} = 10^{55}$ erg as example

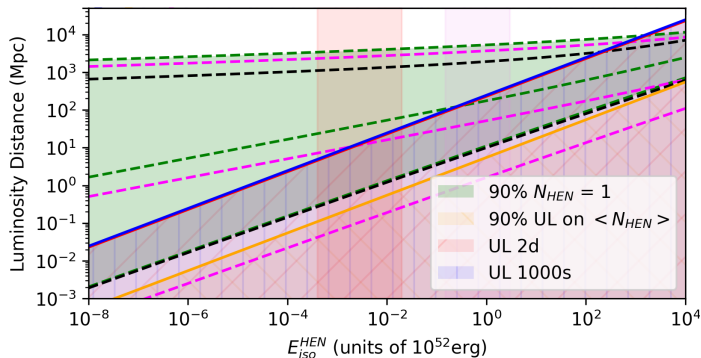
HEN Followup - Constraining the Observation volume



Dashed black line - Median distance

⇒ Population information further constrains the Observation Volume

HEN Followup - All in one plot



A&A 674, L11 (2023) for IC230306A. In **green** (lines and zone), most probable distance (90%) for a source distributed like SN, with E^{-2} . In **Black** (lines), for no z-evolution. In **purple** (lines), GRB and $E^{-2.5}$. In **yellow**, lower limit on distance after 1st alert. In **blue/red**, limit after non-observation of new HEN in 1000s / 2 days. Source it at distance in **green** zone and distance > **blue/red**. Vertical bands = indicative maximal energies for GRB ($1.5 - 30 \times 10^{51}$ erg) or SN ($4 - 200 \times 10^{48}$ erg).



Cross-match with GLADE+

Table – Distance and ranking, R , of galaxies from the GLADE+ catalogue for the cross-matching with HEN candidate IC230306A, using P_D for $E_{\text{iso}}^{\text{HEN}} \in [10^{44} \text{ erg}, 10^{52} \text{ erg}]$ or without for $E_{\text{iso}}^{\text{HEN}} = 3.3 \times 10^{49} \text{ erg}$. Only the first ten galaxies are shown. In bold we highlight those galaxies that are not ranked in the top five with no distance information. For $E_{\text{iso}}^{\text{HEN}} = 10^{52} \text{ erg}$, we show the galaxies found with or without taking into account the fluence limit provided by the ICECUBE notice. The symbol (*) indicates the galaxies present in both the low- and high-energy scans. The average $\langle R \rangle$ uses $E_{\text{iso}}^{\text{HEN}} \in [10^{44} \text{ erg} - 10^{52} \text{ erg}]$ with distance information without a fluence limit. The last two columns include the fluence limit.

D_L (Mpc) w. P_D	R no P_D	10^{52} erg no F_{lim}	$\langle R \rangle$	D_L (Mpc) 10^{52} erg	D_L (Mpc) 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	-

- For $E_{\text{iso}}^{\text{HEN}} < 10^{52} \text{ erg}$, all ranking the same (no Fluence limit) - Fluence limit discard galaxies beyond 250 Mpc/800 Mpc

⇒ *Need to finish implementing method*

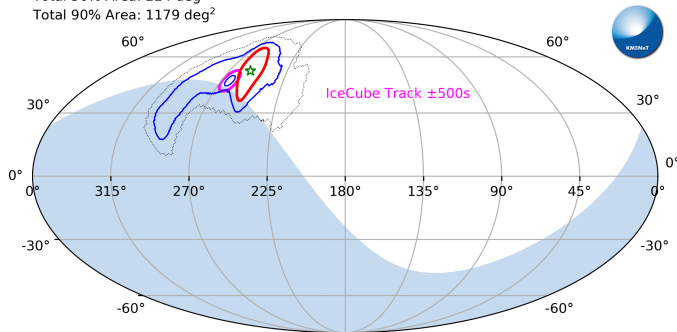
Low Significance GW + HEN Track



S240614BQ Skymap - 2024-06-14 @ 13:39:41.071 - KM3NeT/ORCA Upgoing Observability 24.1%

Total 50% Area: 224 deg²

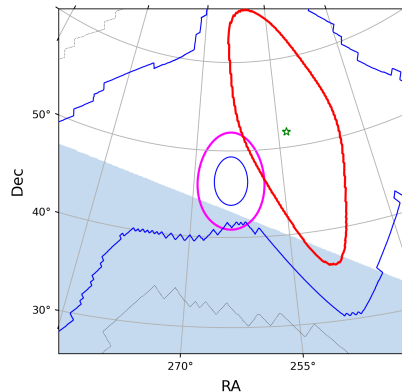
Total 90% Area: 1179 deg²



Below Horizon (Upgoing) 90% area: 450 deg²

Above Horizon (Downgoing) 90% area: 729 deg²

GW Contours at **99% 90% 50%**
KM3NeT/ORCA upgoing field-of-view



S240614bq + ICECUBE Track

- Low significance - 90% Terrestrial - 10% BBH - 740 ± 230 Mpc
- p-value HEN ≈ 0.08 [[ICECUBE Realtime GW followup site](#) → [see here](#)] \Rightarrow **What should we do?**

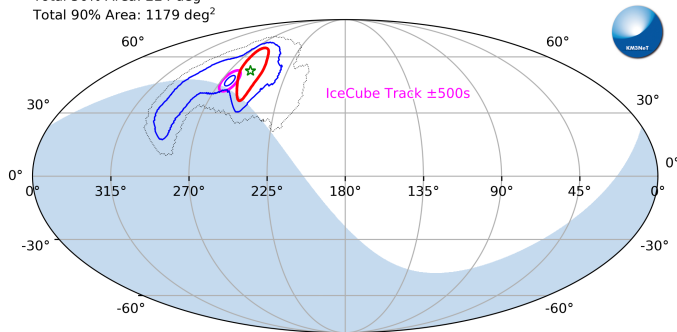
Low Significance GW + HEN Track



S240614BQ Skymap - 2024-06-14 @ 13:39:41.071 - KM3NeT/ORCA Upgoing Observability 24.1%

Total 50% Area: 224 deg²

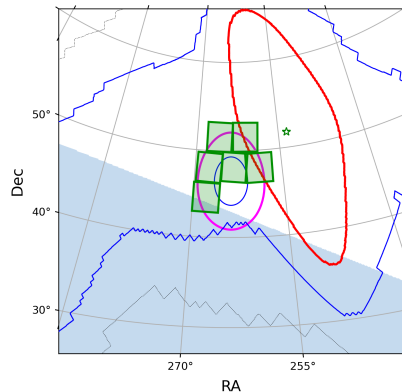
Total 90% Area: 1179 deg²



Below Horizon (Upgoing) 90% area: 450 deg²

Above Horizon (Downgoing) 90% area: 729 deg²

GW Contours at **99% 90% 50%**
KM3NeT/ORCA upgoing field-of-view



S240614bq + ICECUBE Track

- Low significance - 90% Terrestrial - 10% BBH - 740 ± 230 Mpc
- p-value HEN ≈ 0.08 [[ICECUBE Realtime GW followup site](#) → [see here](#)] \Rightarrow **What should we do? Tiling for HENs?**

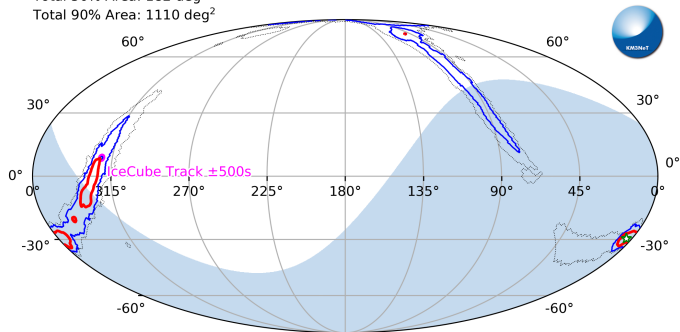
High Significance GW + HEN Track



S240601CO Skymap - 2024-06-01 @ 23:10:04.023 - KM3NeT/ORCA Upgoing Observability 60.2%

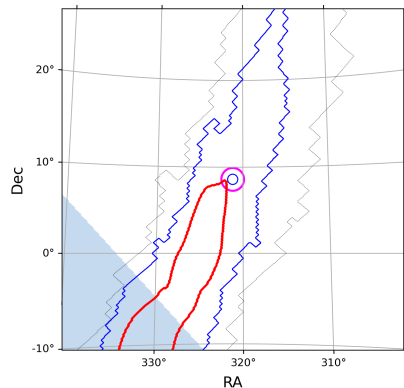
Total 50% Area: 182 deg²

Total 90% Area: 1110 deg²



Below Horizon (Upgoing) 90% area: 570 deg²
Above Horizon (Downgoing) 90% area: 540 deg²

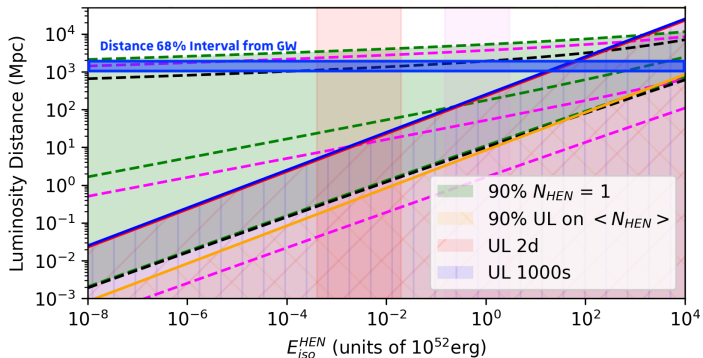
GW Contours at **99% 90% 50%**
KM3NeT/ORCA upgoing field-of-view



S240601co + ICECUBE Track

- BBH 1-2 Gpc
- p-value HEN $\approx 0.06 - 0.08$ [\rightarrow [see here](#)] \Rightarrow **What should we do ?**

High Significance GW + HEN Track



S240601co + ICECUBE Track

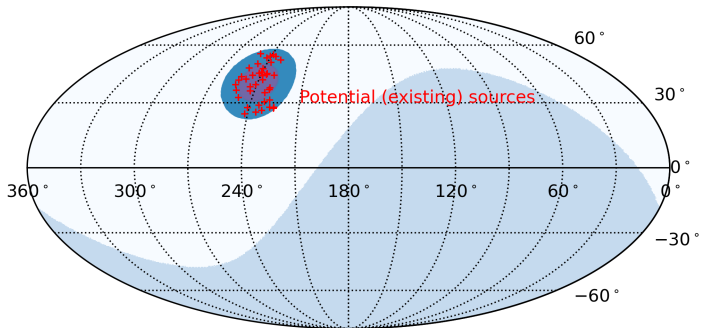
- Distance consistent with only 1 HEN

⇒ **Observe even if BBH?**

Poorly localized HEN GOLD Track



IC240307A Gold Track



Gold ICECUBE Track

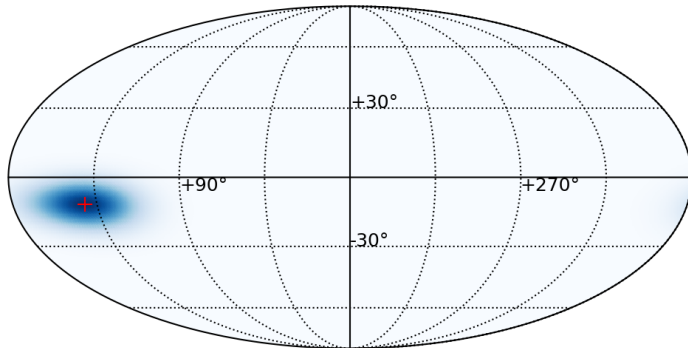
- 15° error $\Rightarrow \approx 40$ 4FGL possible counterparts !
- Fermi 4FGL sources generally listed in ICECUBE Circular (if a few - not here)

\Rightarrow **What to do ? ATLAS/ZTF Forced Photometry on all possible sources ?**

Poorly localized Cascade



IceCube-Cascade 26/06/2024 04:49:28 UT



ICECUBE Cascade

- 31° error
- Fermi 4FGL sources not listed by ICECUBE

⇒ **What to do ? ATLAS/ZTF Forced Photometry on all possible sources ?**



ICECUBE Track alerts

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Observe 4FGL sources within error box ? Only the closest ? Or depending on variations in last XX days ?

ICECUBE Cascade alerts

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Observe 4FGL sources within error box ? Only the closest ? Or depending on variations in last XX days ?

Low significant GW + ICECUBE Tracks

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Threshold on p-value HEN ? On GW FAR ? GW type ?

High significant GW + ICECUBE Tracks

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Threshold on p-value HEN ? On GW type ?

Discussions



ICECUBE Track alerts

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Observe 4FGL sources within error box ? Only the closest ? Or depending on variations in last XX days ?

ICECUBE Cascade alerts

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Observe 4FGL sources within error box ? Only the closest ? Or depending on variations in last XX days ?

Low significant GW + ICECUBE Tracks

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Threshold on p-value HEN ? On GW FAR ? GW type ?

High significant GW + ICECUBE Tracks

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Threshold on p-value HEN ? On GW type ?



ICECUBE Track alerts

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Low significant GW + ICECUBE Tracks

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
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High significant GW + ICECUBE Tracks

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Threshold on p-value HEN ? On GW type ?



ICECUBE Track alerts

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- Observe 4FGL sources within error box ? Only the closest ? Or depending on variations in last XX days ?

ICECUBE Cascade alerts

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
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Low significant GW + ICECUBE Tracks

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Threshold on p-value HEN ? On GW FAR ? GW type ?

High significant GW + ICECUBE Tracks

- Search for counterpart ? depending on size of error box ? threshold ? Automatic tiling ?
- Threshold on p-value HEN ? On GW type ?