# GWHEN :

OGMA Team

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Observations with Gravitational Waves
& Multimessenger Astronomy

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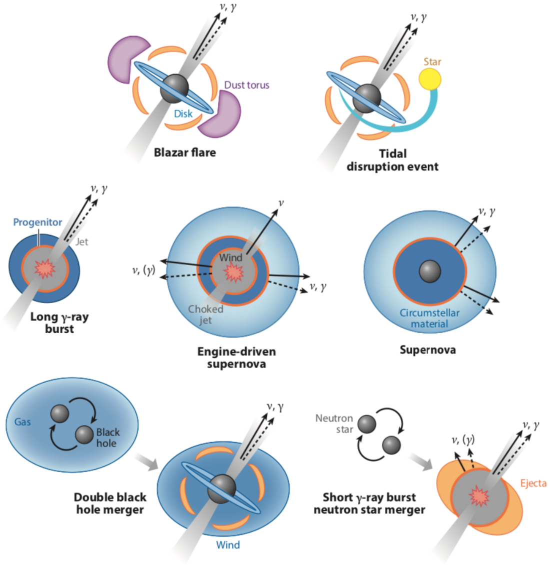
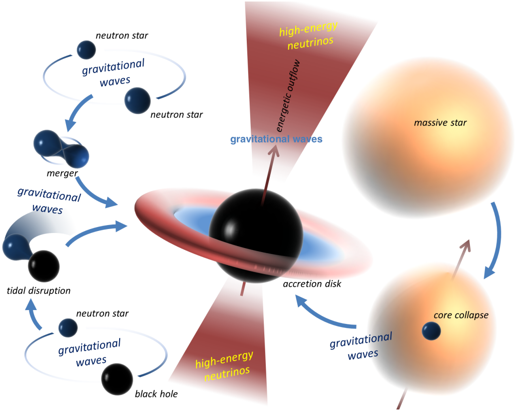
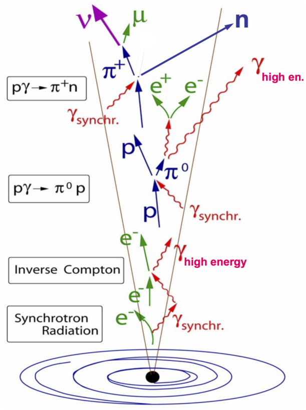
# GW, HEN and other messengers - the Cosmic-Ray Connection



# GW, HEN and other messengers - the Cosmic-Ray Connection



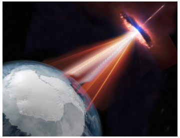

## Astronomy with GW

- Collapse/Merger ⇒ Jet ?

## Astronomy with HEN

- Cosmic-Rays → HEN produced in Jet

# GW, HEN and other messengers - the Cosmic-Ray Connection



*TXS 0506+056*

HEN Astronomy
GeV-EeV
ANTARES, KM3NET/ORCA+ARCA, ICECUBE

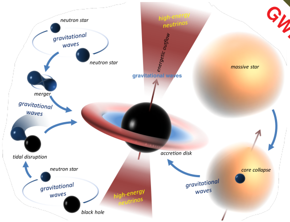
$\gamma$-ray
Astronomy
FERMI, HESS, CTA...

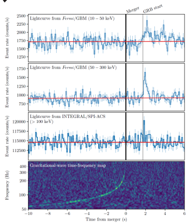
GW Astronomy
LIGO, Virgo, KAGRA

GWHEN

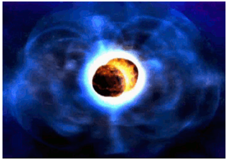
Still to be revealed

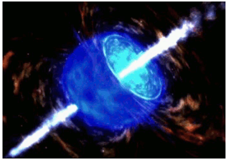
GW170817



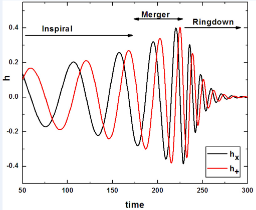
# GW, HEN and other messengers - the Cosmic-Ray Connection





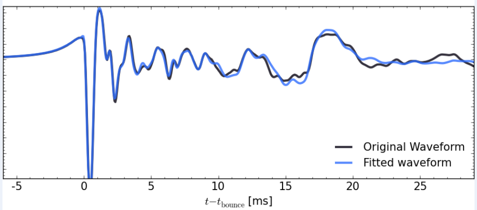
## Short Gamma-Ray Bursts (GRBs)

Merger of Black Holes/Neutron Stars

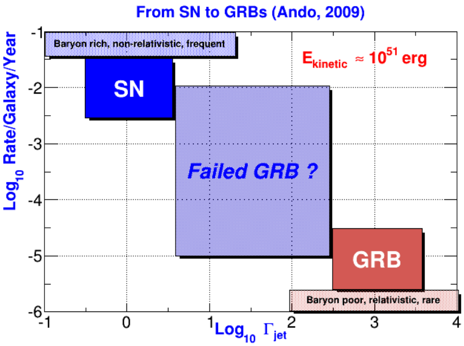


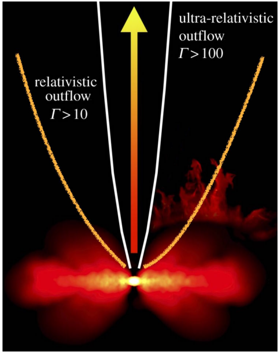

## Long GRBs

*Collapsars* - massive star collapse



# GW, HEN and other messengers - the Cosmic-Ray Connection



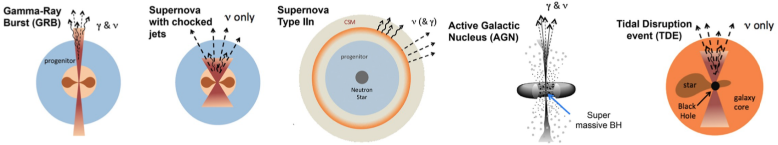




## From Supernovae to Gamma-Ray Bursts

- SNe : frequent, baryon-rich, $\Gamma \sim 1$ + emission poorly beamed
- GRBs : rare, baryon-poor, $\Gamma \gg 1$ + emission in $\theta \sim 5°$
- Failed/low luminosity GRBs : $\theta \sim 30°$ + **no/weak electromagnetic emissions - valid for Short GRBs**

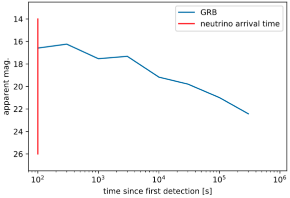
S. Ando et al., Reviews of Modern Physics 85 (2013) 1401-1420

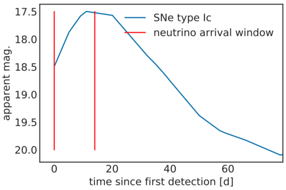
# A large diversity of HEN sources...

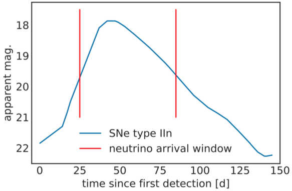



## ...and of their signals

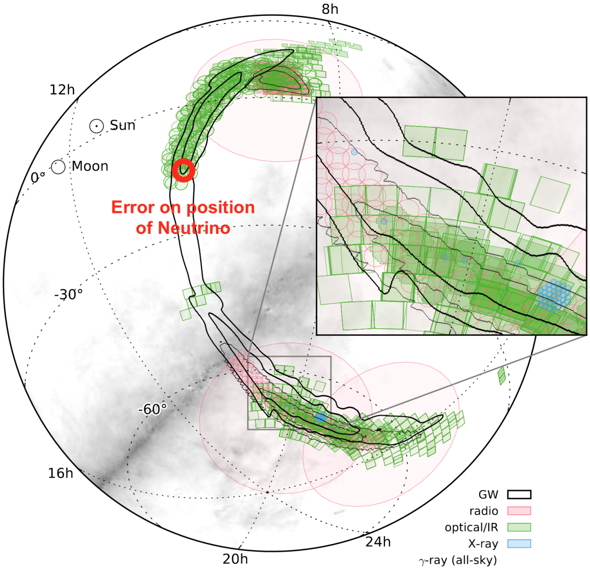
- Short duration - GRB-like - falling lightcurve, few hours
- Medium duration - SNIc, Kilonova - few weeks
- Long duration - SNIIn, TDE, AGN - few months



# GW, HEN, EM Error Boxes



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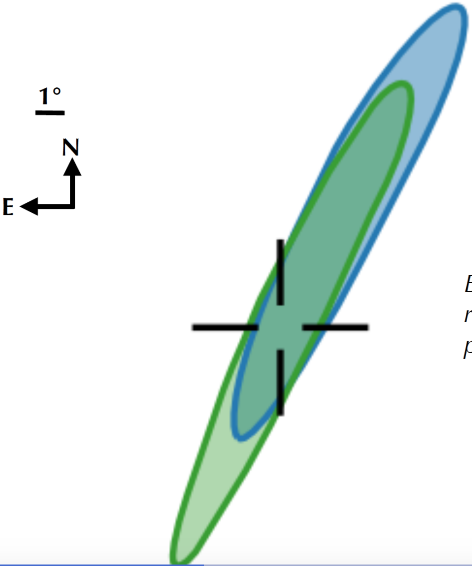
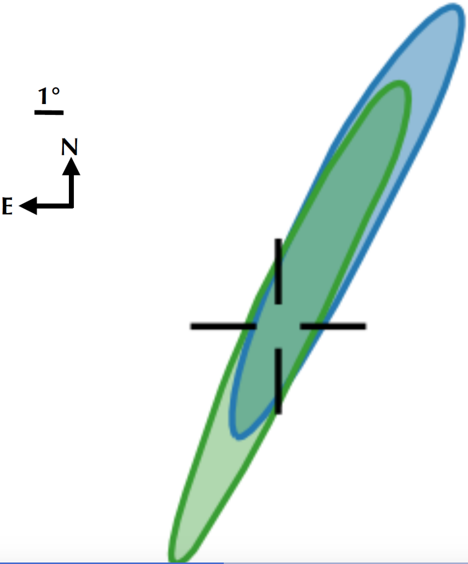
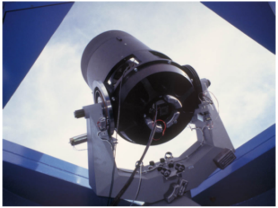



*Error box of GW170817 reconstructed with two different pipelines (~30°²)*

# GW, HEN, EM Error Boxes



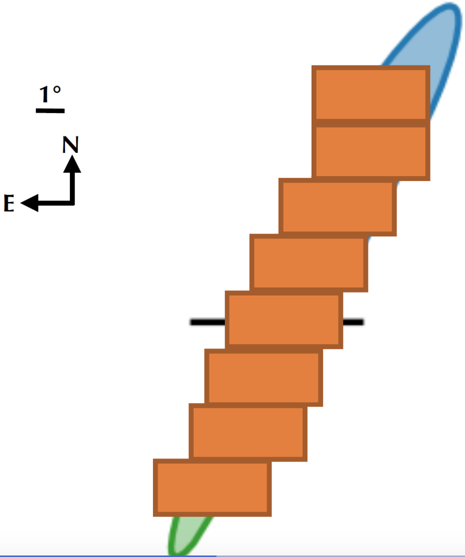

**Optical robotic telescopes**



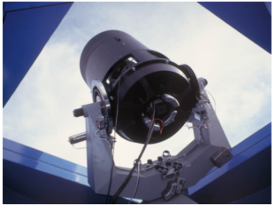
***angular resolution:***
*~arcsec*

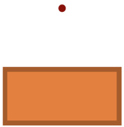
***field-of-view:***
*~square degree*

# GW, HEN, EM Error Boxes




## Optical robotic telescopes

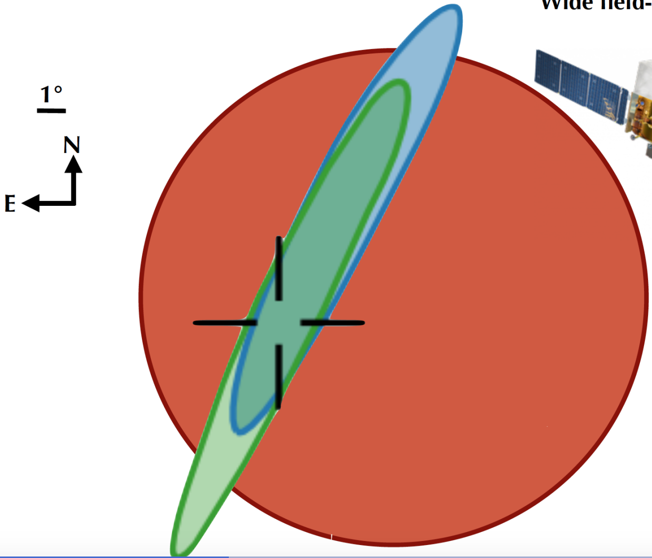




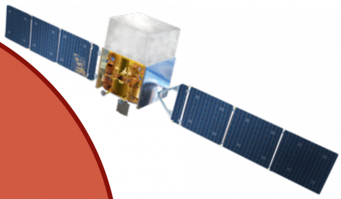
***angular resolution:***
*~arcsec*

***field-of-view:***
*~square degree*

# GW, HEN, EM Error Boxes



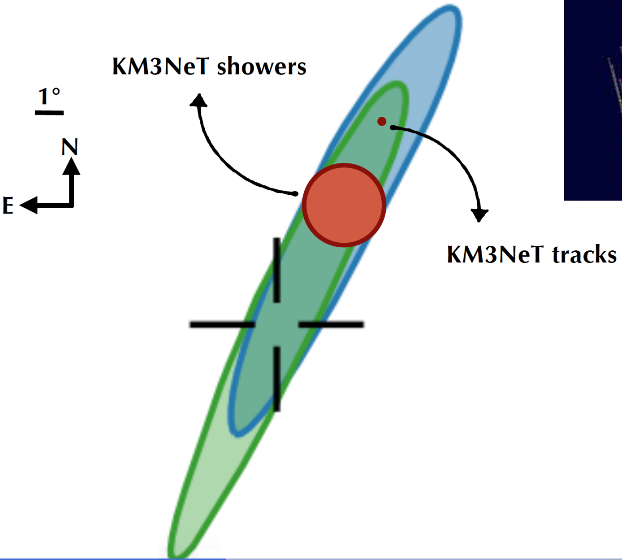

**Wide field-of-view instruments**

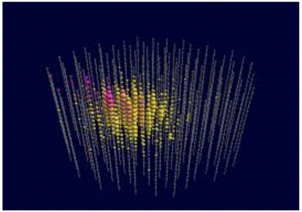


***angular resolution:***
*∼15°*

***field-of-view:***
*> 8 sr*

# GW, HEN, EM Error Boxes



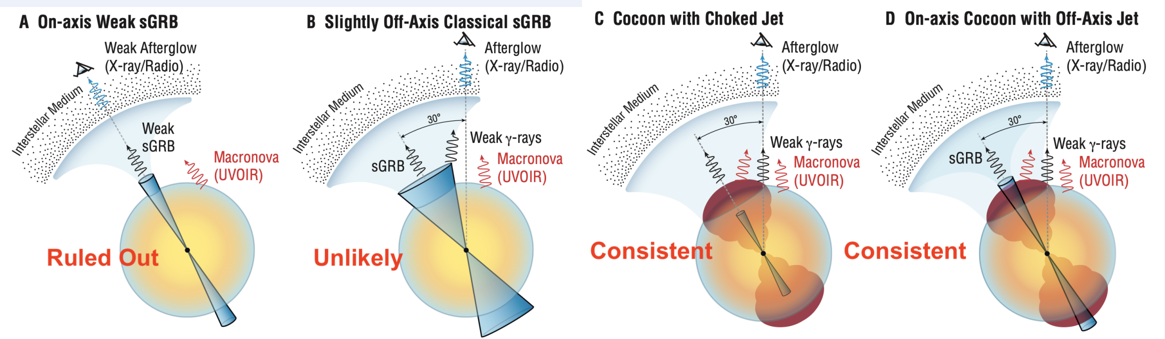



***angular resolution:***
*<deg (tracks) /*
*~deg (showers)*

***field-of-view:***
*> 2π sr*

# Astrophysical delay GW-HEN (GRBs) & sources

## GRB models from GW170817



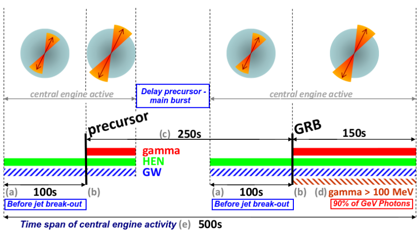

SCIENCE, 2017, Vol 358, Issue 6370 pp. 1559-1565 https ://www.science.org/doi/10.1126/science.aap9455

# Astrophysical delay GW-HEN (GRBs) & sources

## Constraints

B. Baret et al.- Astropart.Phys. 35 :1-7, 2011

- Long GRBs $\Rightarrow t_{\text{GW}} - t_{\text{GRB}} \approx t_{\text{HEN}} - t_{\text{GRB}} \in [-350s, +150s] \Rightarrow \Delta t_{GW-HEN} = \pm 500s$
- Short GRBs : $\Rightarrow \Delta t_{GW-HEN} = -3s \pm 2s$ ? **Can't find the reference !**




a) active central engine before relativistic jet has broken out of stellar envelope
b) active central engine with relativistic jet broken out of envelope
c) delay between onset of precursor and main burst
d) 90% of GeV photon emission
e) time span of central engine activity

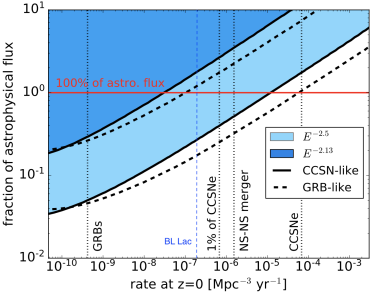
$\Rightarrow$ Short GRBs 10$\times$ less likely to have precursor

$$\text{For } z \ll 1 \; \Delta t_{\text{GW}-\text{HEN}} \approx 5.15 \left(\frac{m_i c^2}{1 \text{ eV}}\right)^2 \left(\frac{E_{\text{HEN}}}{1 \text{ TeV}}\right)^{-2} \frac{D}{1 \text{ Mpc}} \text{ ns}$$

$$\Delta t_{GW-HEN} = \frac{1}{2}\left(\frac{m_\nu c^2}{E_\nu}\right)^2 \int_0^{z_0} \frac{dz}{(1+z)^2 H(z)} - \frac{3}{2}\frac{E_\nu}{E_{\text{QG}}} \int_0^{z_0} \frac{dz(1+z)}{H(z)}$$

# Astrophysical delay GW-HEN (GRBs) & sources

| source class | local density [$Mpc^{-3}$ ($yr^{-1}$)] | min. dist. [Mpc] | limit | source energy [erg] | max. fluence [$GeV^{-1}$ $cm^{-2}$] |
|---|---|---|---|---|---|
| *long GRBs* | $4 \times 10^{-10}$ | 470 | < 1% (stacked) | $< 6 \times 10^{51}$ | $< 4 \times 10^{-3}$ |
| *short GRBs* | $3 \times 10^{-9}$ | 220 | < 32% (OFU) | $< 3 \times 10^{52}$ | $< 9 \times 10^{-2}$ |
| *llGRBs* | $1.6 \times 10^{-7}$ | 64 | < 100% (flux) | $< 1.5 \times 10^{51}$ | $< 6 \times 10^{-2}$ |
| *SNe Ic broad.* | $1.4 \times 10^{-6}$ | 30 | < 100% (flux) | $< 2 \times 10^{50}$ | $< 4 \times 10^{-2}$ |
| *SNe IIn* | $4 \times 10^{-6}$ | 20 | < 66% (stacked) | $< 4 \times 10^{49}$ | $< 1.4 \times 10^{-2}$ |
| *SNe Ib/c* | $1.7 \times 10^{-5}$ | 12 | < 32% (stacked) | $< 5 \times 10^{48}$ | $< 5 \times 10^{-3}$ |
| *CCSNe* | $7 \times 10^{-5}$ | 8 | < 100% (flux) | $< 4 \times 10^{48}$ | $< 8 \times 10^{-3}$ |
| FSRQs | $6 \times 10^{-10}$ | 1 000 | < 17% (EHE) | $< 1.6 \times 10^{53}$ | $< 3 \times 10^{-2}$ |
| BL Lac objects | $2 \times 10^{-7}$ | 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* | $3 \times 10^{-11}$ | 1 000 | < 100% (flux) | $< 10^{54}$ | $< 1.4 \times 10^{-1}$ |
| galaxy cluster | $5 \times 10^{-6}$ | 40 | < 100% (flux) | $< 3 \times 10^{50}$ | $< 3 \times 10^{-2}$ |
| starburst gal. | $3 \times 10^{-5}$ | 22 | < 100% (flux) | $< 2 \times 10^{49}$ | $< 2 \times 10^{-3}$ |



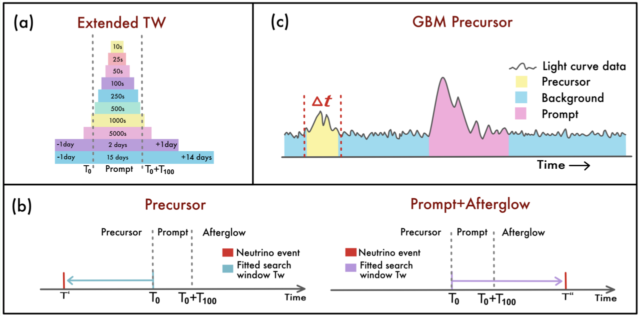

N. L. Strotjohann, PhD, https ://edoc.hu-berlin.de/handle/18452/21791

## What are the sources of HEN ?

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

# Astrophysical delay GW-HEN (GRBs) & sources

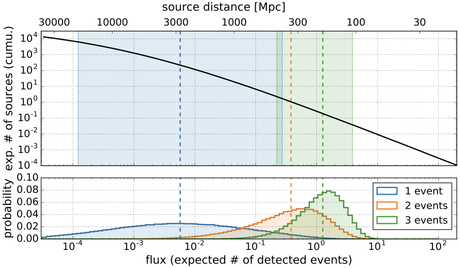
## IceCube GRB Comprehensive study - https ://arxiv.org/pdf/2205.11410.pdf




- Previous most recent search(es) used $T_{100}$ (latest - earliest) - no signal from prompt phase
- Extended Time Window = $[-1\text{day}, +14\text{days}]$ $\Rightarrow$ contrain prompt phase to $< 1\%$ of HEN flux
- Precursor/Afterglow = sample of well-localized GRBs $\Rightarrow$ From $10\%$ (HEN duration 100s) to $80\%$ (HEN duration $10^6$ s)
- GBM Precursor = Fermi-GBM prior to prompt - Stacked Precursor = well-localized bursts with no precursor

$\Rightarrow$ All GRBs $< 1\%$ prompt$\rightarrow 10^3 s$ - $< 1\%$ up to $10^4 s$

# Astrophysical delay GW-HEN (GRBs) & sources




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

## Caution - 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)

  $\Rightarrow$ Astrophysical HEN likely to be very distant

$\Rightarrow$ **Chances to detect GW counterpart ?**

# HEN Alerts (AMON/IceCube/KM3NeT)

## Existing Alerts - Public

- Gold Alerts : 12/yr, $> 50\%$ astrophysical - *latest : 29/12/2022* - **Observed ≈ 1/month**
- Bronze Alerts : 16/yr, $> 30\%$ astrophysical - *latest : 24/12/2022* - **Observed ≈ 1.3/month**

## Other Public Alerts

- NU_EM Alerts : 2-4/yr HAWC-IceCube + 2-4/yr Fermi-Antares (only position + 90% radius)
  - ⇒ *latest : 28/07/2022* (IceCube - HAWC) - **Observed ≈ 0.7/month**
- IceCube Cascades : 8/yr, $> 85\%$ astrophysical (with FITS skymap) ⇒ *latest : 09/09/2023* - **Observed ≈ 0.5/month**

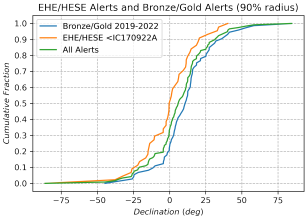
## Possible Alerts - Private - MoU needed

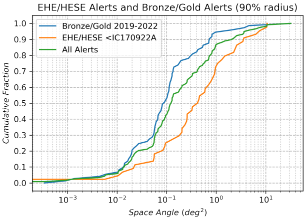
- OFU Alerts (Optical/X-ray) : GRB/SN jets, Northern, multiplets 2 evts in 100s $\Delta\Omega < 3.5^\circ$ (ROTSE, PTF, Swift)
- GFU ($\gamma$-ray) : clusters around selected sources (MAGIC, VERITAS)

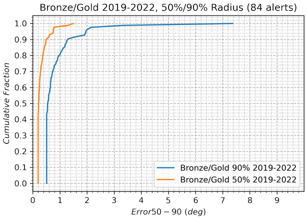
## IceCube(/KM3NeT) Alert contents

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

# How often were the HEN alerts followed ?




## December 2021 → June 2022, mostly no optical followups !

1- **11 Gold** alerts **[5/11 with possible counterparts ?]**

- ⇒ **2** with no optical followup (except MASTER) and 0 4FGL in FoV, but with 4FGL activity reported nearby - **counterpart unlikely ?**
- ⇒ **3** with no followup (except MASTER/ZTF) and ≥1 4FGL in FoV, but with Blazar radio activity/presence - **possible counterpart ?**
- ⇒ **2** with no followup and 0 4FGL in FoV - **no counterpart searched**
- ⇒ 3 with no (public) followup reported (GCN or ATel), all with No/Many 4FGL sources in FoV - **no counterpart searched**

2- **10 Bronze** alerts **[5/10 with possible counterparts ?]**

- ⇒ **2** with multiple ATel (optical, radio etc) - **possible counterparts**
- ⇒ **2** with no report despite New FERMI-LAT sources - **counterparts ?**
- ⇒ 1+1 with no report despite 4FGL sources in FoV - **no counterpart searched**
- ⇒ 3 with no report with 0 sources in FoV - **no counterpart searched**
- ⇒ 1 with no report despite SNIIn discovered - **possible counterpart not studied**

# How often were the HEN alerts followed ?

## December 2021 → June 2022, mostly no optical followups !

1- **11 Gold** alerts **[5/11 with possible counterparts ?]**

- ⇒ **2** with no optical followup (except MASTER) and 0 4FGL in FoV, but with 4FGL activity reported nearby - **counterpart unlikely ?**
- ⇒ **3** with no followup (except MASTER/ZTF) and $\geq$1 4FGL in FoV, but with Blazar radio activity/presence - **possible counterpart ?**
- ⇒ **2** with no followup and 0 4FGL in FoV - **no counterpart searched**
- ⇒ 3 with no (public) followup reported (GCN or ATel), all with No/Many 4FGL sources in FoV - **no counterpart searched**

2- **10 Bronze** alerts **[5/10 with possible counterparts ?]**

- ⇒ **2** with multiple ATel (optical, radio etc) - **possible counterparts**
- ⇒ **2** with no report despite New FERMI-LAT sources - **counterparts ?**
- ⇒ 1+1 with no report despite 4FGL sources in FoV - **no counterpart searched**
- ⇒ 3 with no report with 0 sources in FoV - **no counterpart searched**
- ⇒ 1 with no report despite SNIIn discovered - **possible counterpart not studied**

$\approx$ **1.4-2 alerts/month** with probable counterpart (only Gold/Bronze only)

+ NuEm (0.5/month)/ Cascades (0.35/month), with no (public) reports on followups
$\gtrsim$ **2 alerts/month** worth following

# Conclusions

## What we know

- BBH (with gas) or BNS/NSBH possible HEN sources
- Observed HEN source likely to be $\sim Gpc$ (except Galactic sources - CBC ?)
- GRBs (prompt) disfavored - unlike other transients

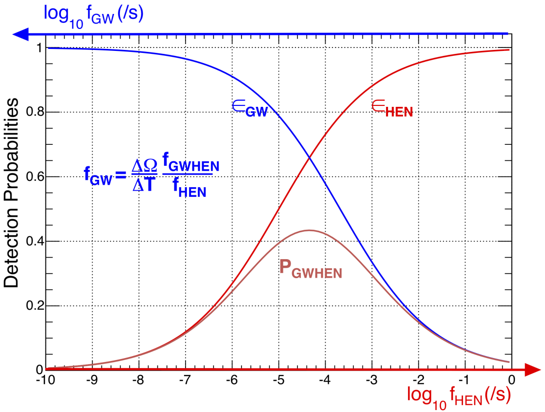
## What we don't know

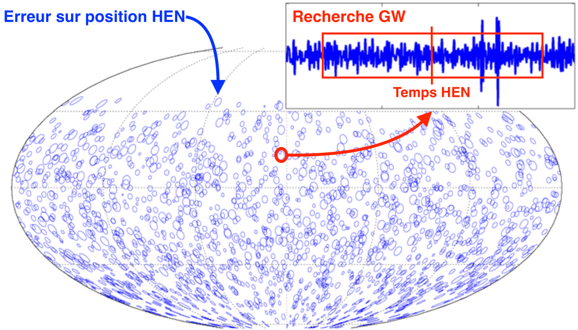
- Distance of HEN source - constraint with Galaxy Catalogues + Localization (model-dependent) ?
- Time Window from seconds to 2 weeks after merger

## Possible GW-HEN analyses

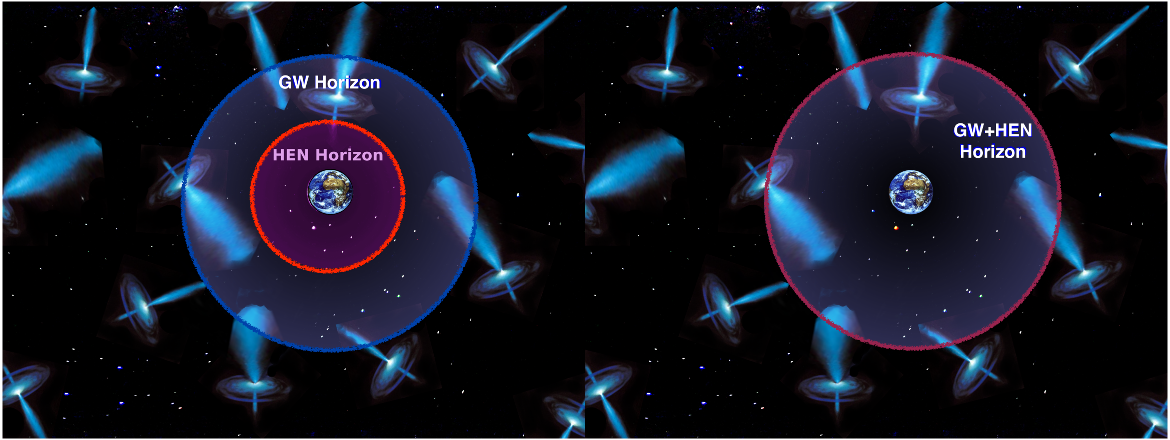
- Online - "Low" Latency Search for GW counterpart
  - $\Rightarrow$ variable Time Windows ?
  - $\Rightarrow$ Localization used as prior ?
- Offline
  - $\Rightarrow$ Subthreshold analyses - to be optimized (joint horizon)

# Conclusions



# Conclusions



# From null observations to upper limits

## Chararacteristic Energy for a given GW or HEN model

- $h_{\rm GW} = f(E^{\rm iso}_{\rm GW})$, depending on signal
- $N_{\rm HEN} = f(E^{\rm iso}_{\rm HEN})$, depending on spectrum

## Computation of limits and comparison to "observations"

- $N_{\rm GWHEN} = R_{\rm GWHEN}[1/{\rm Mpc}^3/{\rm yr}] \times V_{\rm GWHEN} T_{\rm obs} \leq 2.3$ (90%)
  $\Rightarrow R_{\rm Limits} = \frac{2.3}{V_{\rm GWHEN} T_{\rm obs}}\ 1/{\rm Mpc}^3$/yr
- Express $V_{\rm GWHEN} = f(E^{\rm iso}_{\rm GW}, E^{\rm iso}_{\rm HEN}) \propto \int_0^\infty P_{\rm GW}(E^{\rm iso}_{\rm GW}, r) \times P_{\rm HEN}(E^{\rm iso}_{\rm HEN}, r) r^2 dr$
  $\Rightarrow$ Exploration of $E^{\rm iso}_{\rm GW}, E^{\rm iso}_{\rm HEN}$
  $\Rightarrow$ Several neutrino spectra & beaming in HEN and/or GW can be studied
- Short GRBs : comparison of $R_{\rm Limits}$ with $R_{\rm binaries} \approx 10^{-5}$/Mpc$^3$/yr (used by ICECUBE)
- Long GRBs : comparison of $R_{\rm Limite}$ with $R_{\rm Core\text{-}Collapse\ Supernovae} \approx 5 \times 10^{-4}$/Mpc$^3$/yr

# Results from GWHEN 1-2 (pre-GW-discovery)

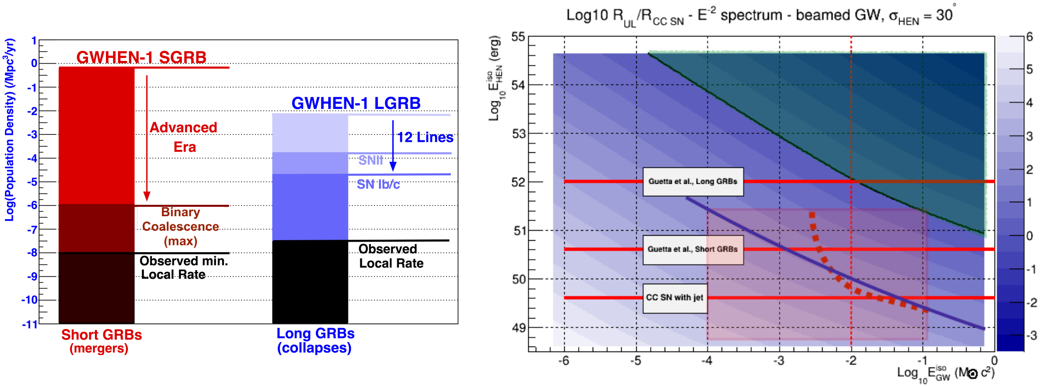



Figure – A gauche : limites obtenues sur le taux d'occurence de sources (en /volume/temps) après l'analyse des données 2007 (GWHEN-1), réalisée entre 2009 et 2012. A droite : Résultats de GWHEN-2 (données 2009-2010) avec ANTARES, comparés (en rouge) avec une analyse similaire réalisée avec ICECUBE., réalisée entre 2012 et 2015. Malgré une taille réduite, avec les mêmes hypothèses de travail sur les modèles, les résultats ANTARES sont meilleures (ligne bleue sous la ligne rouge pour $E^{\rm iso}_{\rm GW} < 10^{-2} M_\odot c^2$, zone réaliste pour l'émission GW)

# GWHEN O1

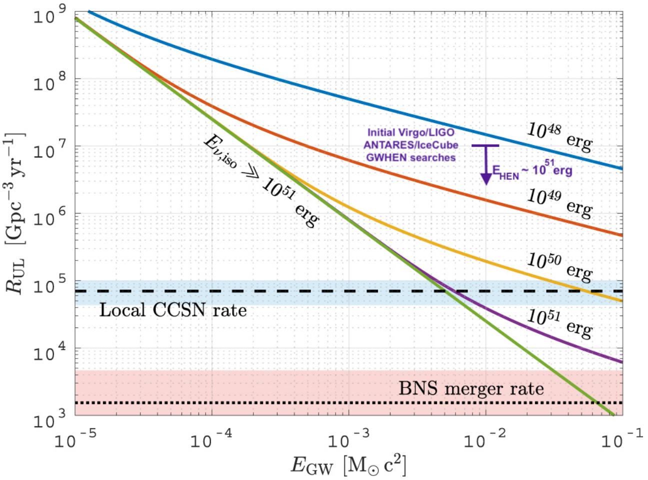
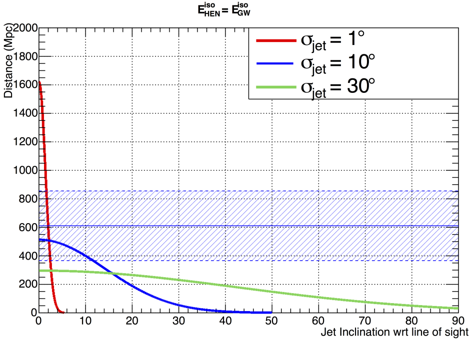



Figure – Limites obtenues après la recherche ICECUBE/ANTARES utilisant les données VIRGO/LIGO prises pendant O1 (2015-16), publiée en 2019.

# GWHEN - Possible astrophysical constraints on jet



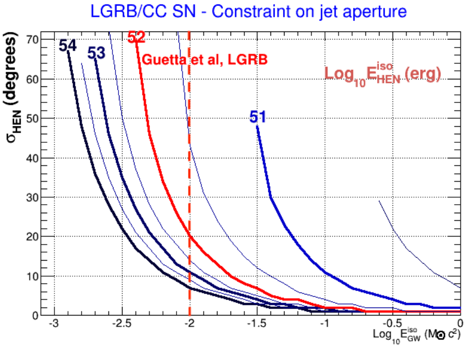
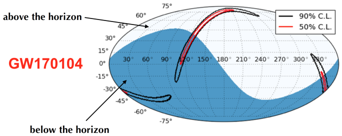
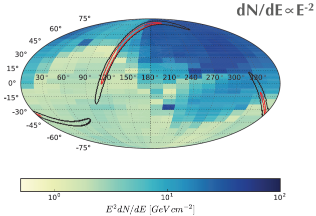
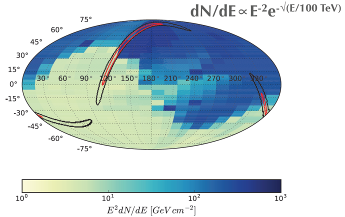




Figure – Cas de GW170104 - A gauche : Contraintes sur la distance de la source en fonction de l'inclinaison du jet (par rapport à la ligne de visée) pour $E^{iso}_{HEN} = E^{iso}_{GW} = 10^{54}$ erg, pour différentes ouvertures du jet : $\sigma_{jet} = 1°$ (rouge), $10°$ (blue), typiques des sursauts gammas courts (GRB), et $30°$ (vert), attendue dans le cas de GRB de faible luminosité (région exclue sous la courbe). La région en bleu montre la distance estimée à partir du signal GW et son incertitude. En fonction de l'énergie HEN supposée, on peut donc contraindre inclinaison et ouverture du jet [Résultats présentés en Réunion ANTARES, mais non publiés au final]. A droite, contrainte sur l'ouverture du jet, pour spectre GRB long, en supposant 100% des supernovae avec jets (GWHEN-2).

# Searching for HEN for BBH/NSBH/BNS coalescences during O1/O2



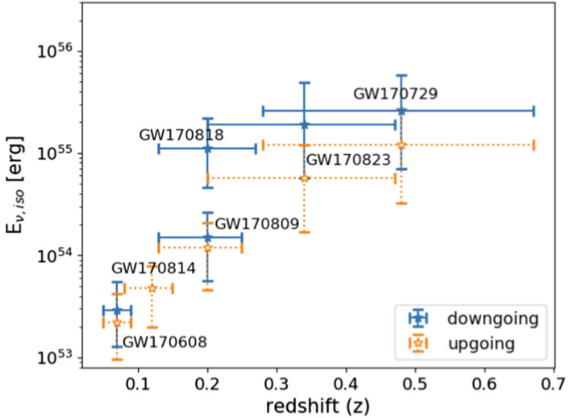




## Different analyses - only tracks (quicker, better localization) [Offline]

- O1 / GW150914 : online reco., no optimization - HEN emission < $0.2 - 20\%$ of GW energy
- O1 / GW151226+LVT151012 : upgoing, optimization - HEN emission < $1 - 15\%$ of GW energy
- O2 / GW170104 : first full sky search + optimization

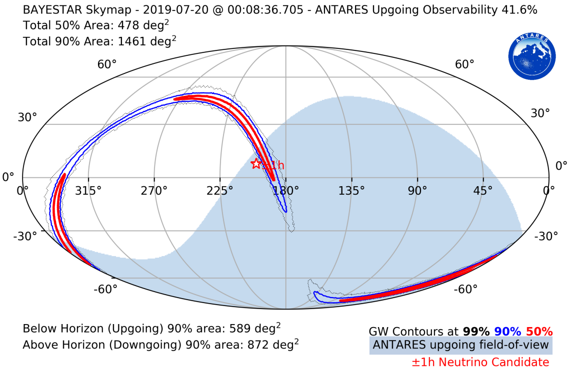
# Searching for HEN for BBH/NSBH/BNS coalescences during O1/O2




## O2 Catalogue BBH Signals [Offline]

- Tracks and Showers !
- Downgoing + Upgoing

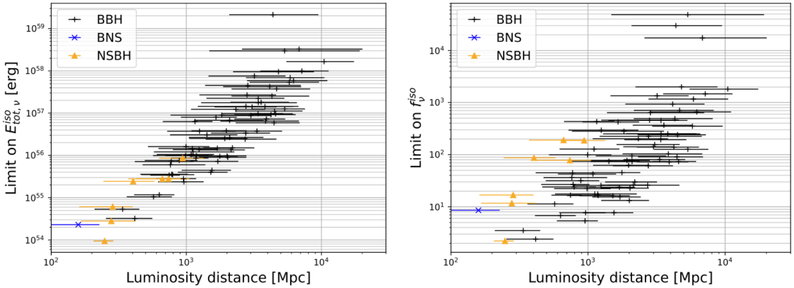
# Searching for HEN for BBH/NSBH/BNS coalescences → O3→ O4




## O3 - S190720a - BBH at ∼1 Gpc [Online]

- ±1h ANTARES Neutrino Candidate outside of 90% Contour
- GCN25120

# Searching for HEN for BBH/NSBH/BNS coalescences



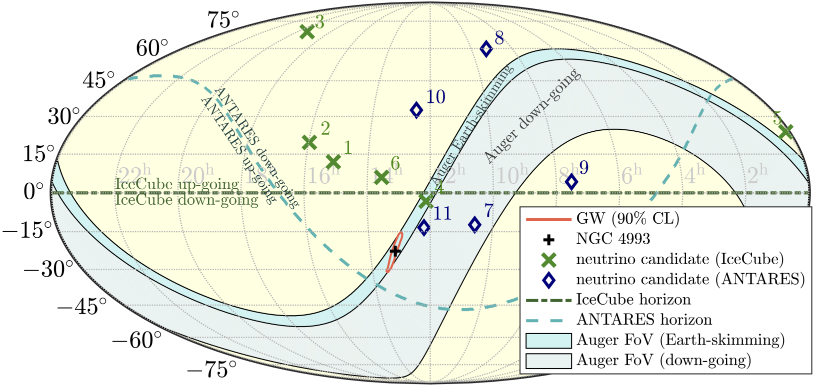

(a) $E^{\rm iso}_{\rm tot,\nu}$ (b) $f^{\rm iso}_{\nu}$

**Figure 3**: 90% upper limits on the total energy $E^{\rm iso}_{\rm tot,\nu}$ emitted in neutrinos of all flavours (left) and on $f^{\rm iso}_{\nu} = E^{\rm iso}_{\rm tot,\nu}/E_{\rm rad}$ (right) as a function of the source luminosity distance, assuming an $E^{-2}$ spectrum and isotropic emission. The horizontal bars indicate the 5-95% range of the luminosity distance estimate, and the markers/colours correspond to the different source categories.

## O3 - Catalogue [Offline]

- Preliminary, still unpublished

# GW170817 HEN followup



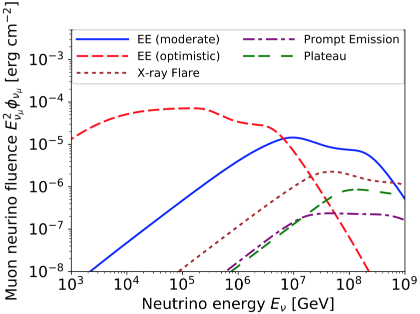

Search over $\pm500$s (map) + extended search on 14 days

First search with both Tracks AND Showers !

Publication by ANTARES, AUGER, ICECUBE, VIRGO/LIGO (Click for paper !)

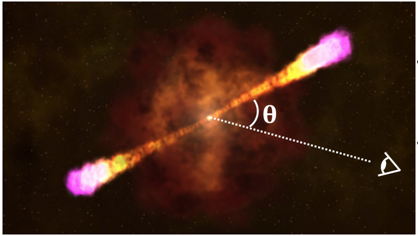
Unfortunately limit on $E_{\mathrm{HEN}}^{\mathrm{iso}} > E_{\mathrm{GW}}$

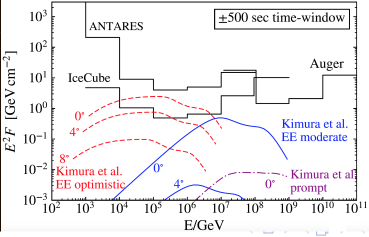
# GW170817 HEN followup : constraints on the source - prompt emission



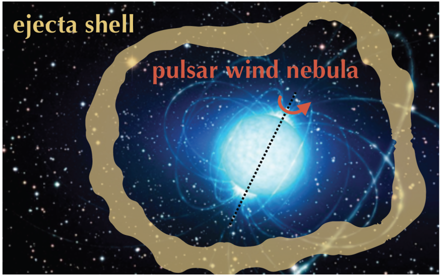

- Extended GRB emission
  - $\Rightarrow$ Lower $\Gamma$
  - $\Rightarrow$ Higher meson efficiency
- Jet viewed off-axis

Kimura et al., 2017



# GW170817 HEN followup : constraints on the source - extended emission




- Magnetized NS with high spindown power
- Magnetar + ejected material
  - $\Rightarrow$ Cosmic Ray acceleration
  - $\Rightarrow$ HEN production
- Corrected with $F_{\text{off}}(E) = \eta F_{\text{on}}(E/\eta)$
  - $\rightarrow \eta = \delta(\theta_{\text{obs}}) - \delta_0$
  - $\rightarrow \delta(\theta_{\text{obs}}) = [\Gamma(1 - \beta\cos(\theta_{\text{obs}} - \theta_{\text{jet}}))]^{-1}$

Fang & Metzger, 2017