# Searching for high-energy neutrinos in coincidence with gravitational waves with the ANTARES and VIRGO/LIGO detectors

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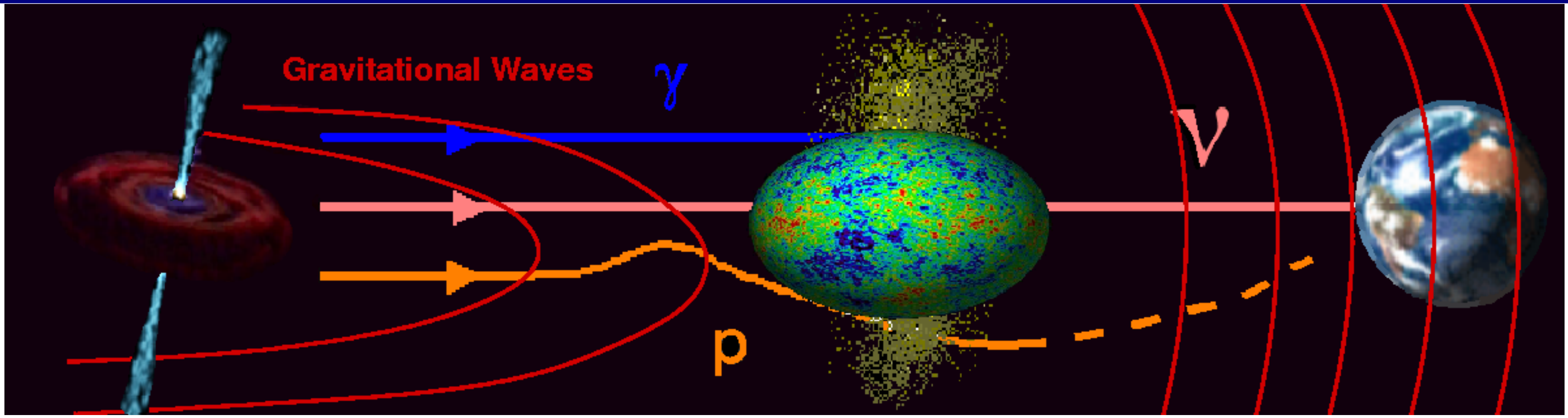
for the ANTARES Collaboration
& the GWHEN working group
(also including members of IceCube, VIRGO and LSC)

# Motivations for GW+HEN astronomy




- **Long-range messengers:** no interactions (or weak ones) with ambient matter
  no deflection by magnetic fields
- **Deep-source messengers**: carry information on the internal processes of the astrophysical engines, unaccessible through photons or hadrons
- **Plausible common sources:** **galactic** (SGRs) & **extragalactic** (GRBs: short, long, low-luminosity, choked,...)
- **Discovery potential for hidden/unknown sources**
- (difficult to detect through conventional photon/cosmic ray astronomy)

- **Main requirements for joint GW/HEN detection:**

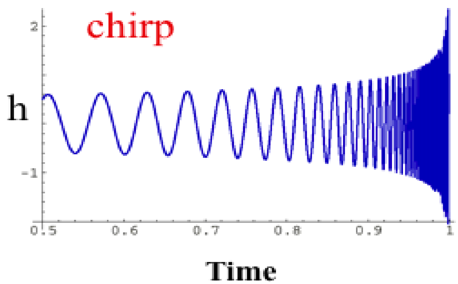
massive, compact & relativistic objects **+** sudden (< 1s) **+** baryon loaded **+** close & frequent enough

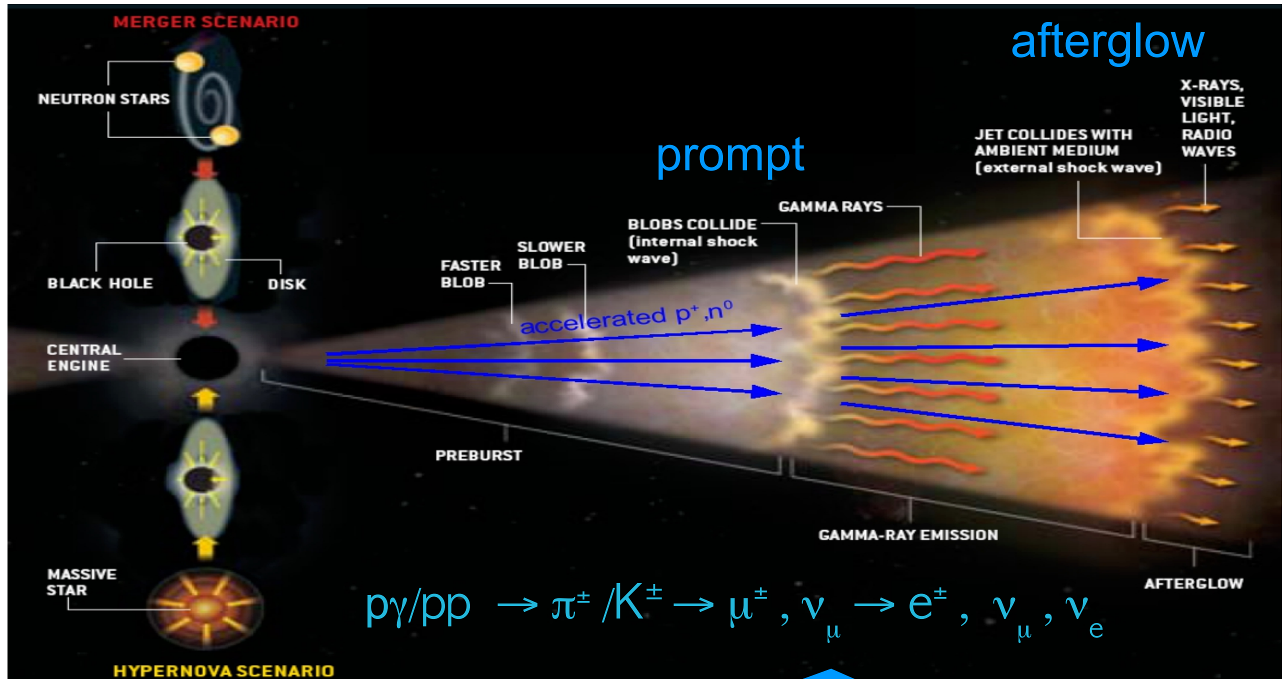
# Usual suspects: long & short GRBs

The fireball model

GW ⟷ $\Delta t$ ~ few minutes ? ⟷ HEN

**Short-Hard GRBs:**
coalescing binaries involving BH and/or neutron stars.
→ GW associated to coalescence process (inspiral)




**Long-Soft GRBs:**
associated to core-collapse supernovae (collapsars)
→ GW burst during collapse (unmodelled)
Faint ? (cosmologically distributed)

HEN emitted in baryon-loaded jets during prompt (TeV-PeV) & afterglow (PeV – EeV) phases

expected neutrino spectrum ~ $E^{-2}$

# More (speculative) suspects among GRBs

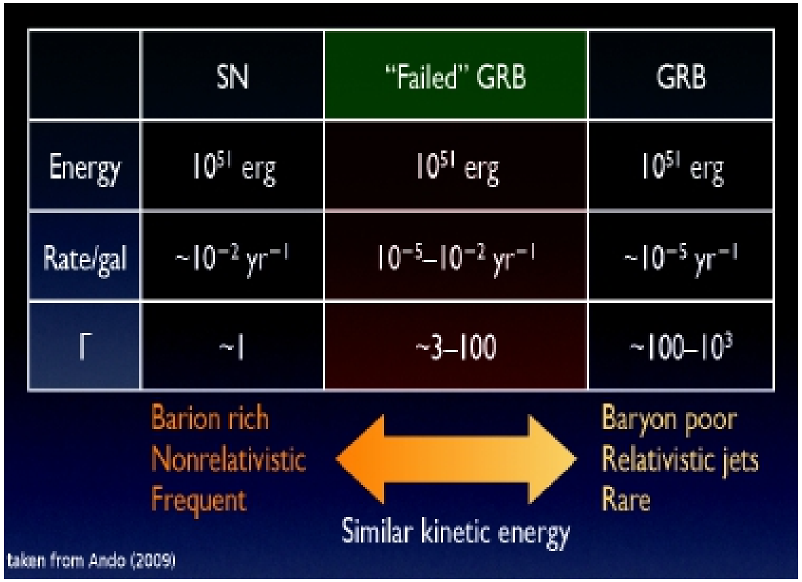
**Low-luminosity GRBs (llGRBs)**

- γ-ray luminosity few orders of magnitude smaller
- Observational evidence for llGRB/SN connection

→ produced by a particularly energetic population of core-collapse SNe ?

- larger event rate predicted in local universe

- BUT mechanism debated, presence of jets is uncertain *(Bromberg, Nakar & Piran, 2011)*

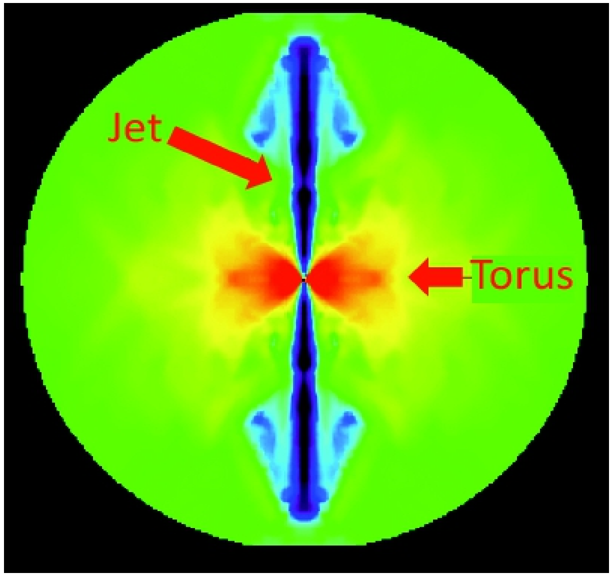


| | SN | "Failed" GRB | GRB |
|---|---|---|---|
| Energy | $10^{51}$ erg | $10^{51}$ erg | $10^{51}$ erg |
| Rate/gal | $\sim 10^{-2}$ $yr^{-1}$ | $10^{-5}$–$10^{-2}$ $yr^{-1}$ | $\sim 10^{-5}$ $yr^{-1}$ |
| Γ | ~1 | ~3–100 | ~100–$10^3$ |



**Failed GRBs:**
from mildly relativistic, baryon-rich and optically thick jets ?
→ missing link between (long) GRBs and SNe ?
*(Ando & Beacom, 2005)*

**Choked GRBs:**
successful jets unable to break through the stellar envelope ?
*(Eichler & Levinson, 1999; Mészaros & Waxman, 2001)*



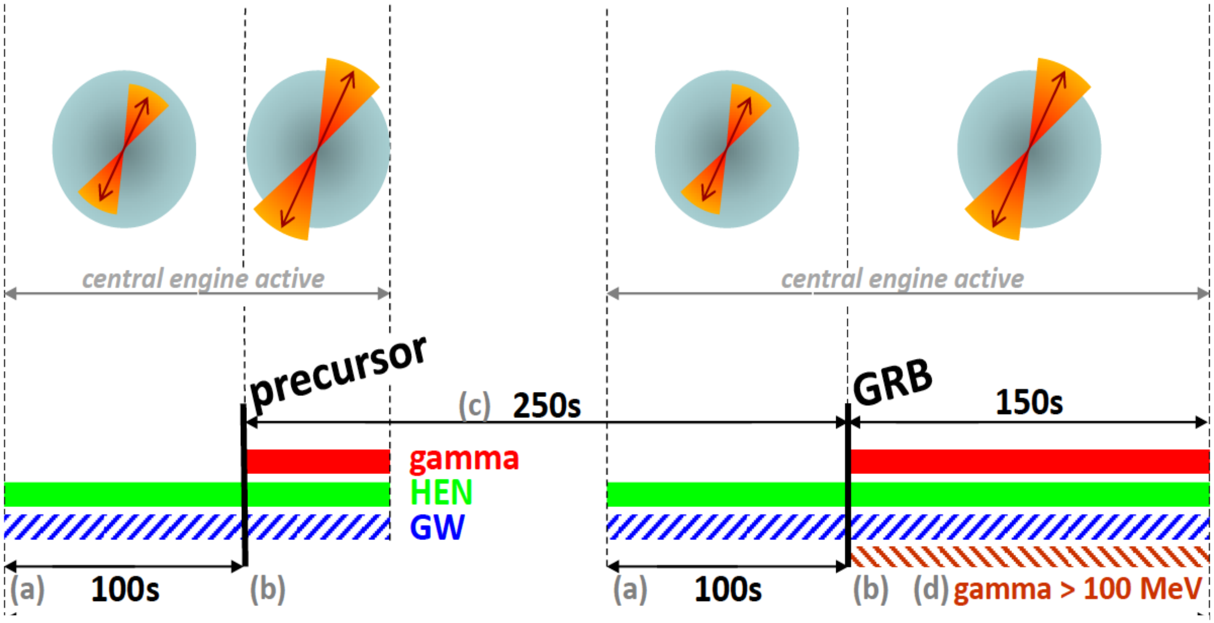


→ potentially strong HEN/GW emitters;
→ not (or difficultly) observable in photons
→ models poorly constrained and still debated

# Bounding the GW-HEN time window

A case study: long GRBs

B. Baret et al., AstroPart. Phys. 35 (2011), 1-7




Observational benchmarks:

- γ-ray emission: Δt ~150 s based on the $t_{90}$ distribution in BATSE bursts (consistent with Fermi HE γ-ray emission)
- 10-20% of GRBs have precursors: $\Delta t_{precursor}$ ~250 s from BATSE GRBs

- HEN emission from internal shocks in relativistic outflow (also BEFORE it emerges from the stellar envelope, Δt ~100 s)
- GW emission associated to the activity of central engine (BH ringdown + gravitational instabilities in accretion disk + ... )

} connected to γ-ray emission

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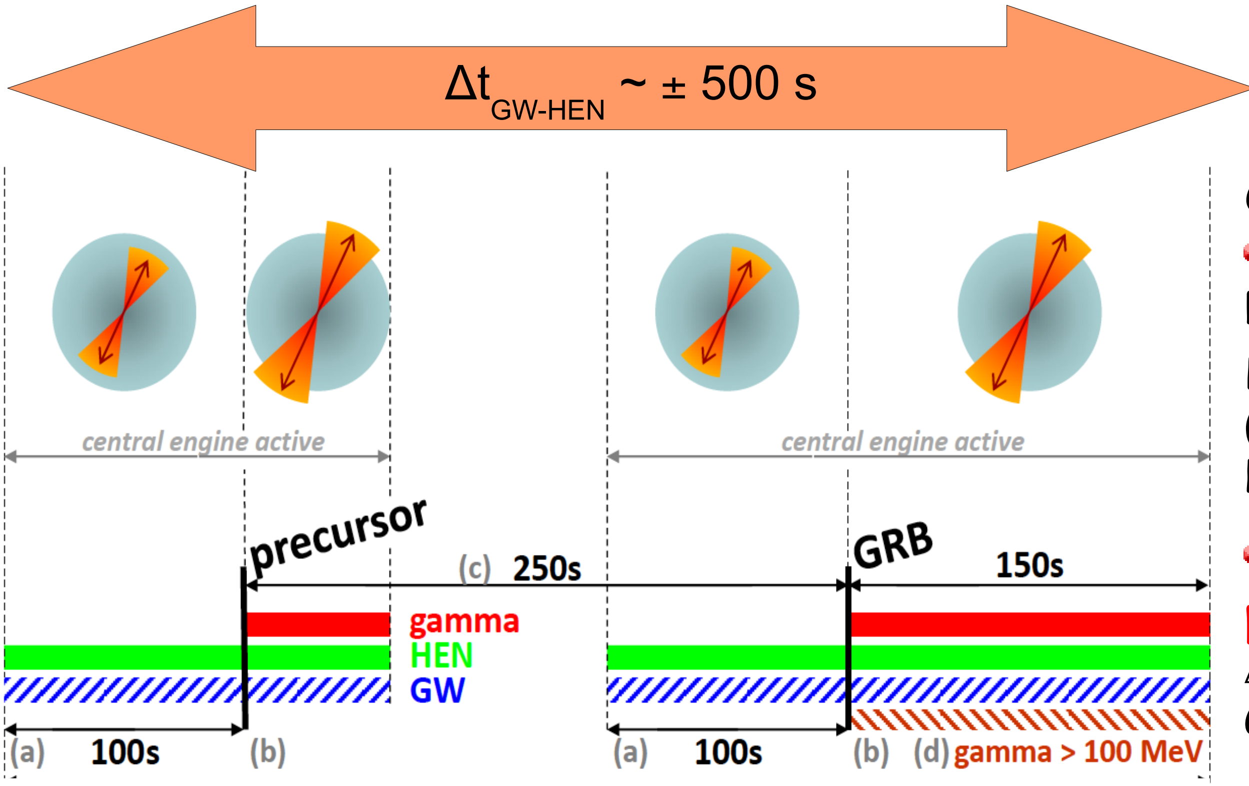


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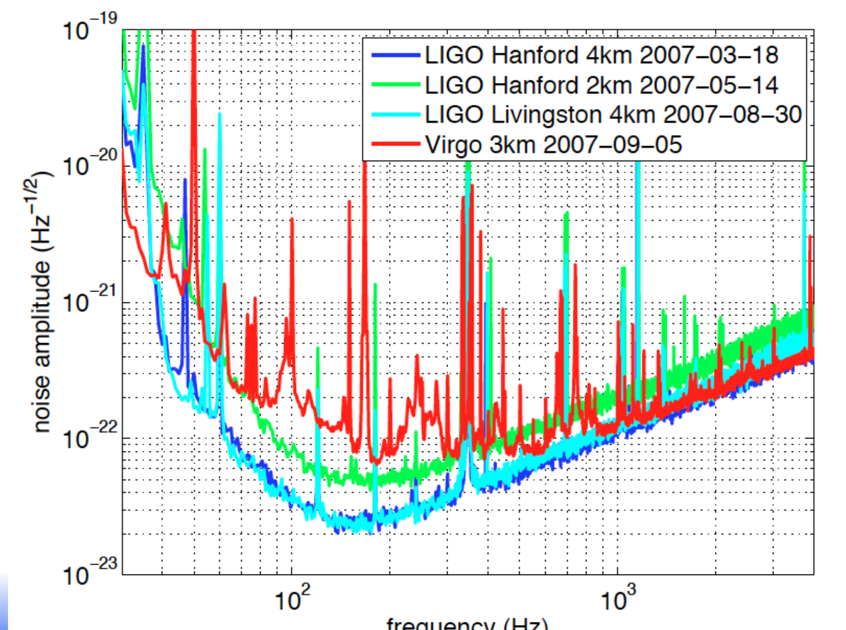
# The detectors: GW interferometers

Michelson interferometers:
suspended mirrors act as free test masses


- LIGO Hanford: 4 km (+ 2 km) arms
- LIGO Livingston: 4 km arms
- VIRGO (Pisa, Italy): 3 km arms

current sensitivity to GW amplitude

$$h = \frac{\delta L}{L} \sim 10^{-21}$$



# The detectors

Periods of concomitant data taking:

| | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|
| ANTARES KM3NeT | 5L | 10L | | 12L | | | | | KM3NeT | |
| VIRGO | VSR1 | | VS R2 | VS R3 | | | | | Advanced VIRGO | |
| LIGO | S5 | | S6 | | | | | | Advanced LIGO | |

First generation:
GW horizon for standard binary sources
~ 15 Mpc (~1 binary merger/ 100 years...)
ANTARES 5 active lines

Recent upgrades (VIRGO+/eLIGO) :
GW sensitivity ~ x 2 (expected)
Full ANTARES 12 lines, ~0,04 $km^3$ instrumented

Advanced detectors ~2015:
GW sensitivity x 10 → probed volume x 1000
(~ 1 $Gpc^3$ for BH mergers, ~ 40 mergers/yr)
KM3NeT: (few) $km^3$ instrumented volume

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|---|---|---|---|---|---|---|---|---|---|---|
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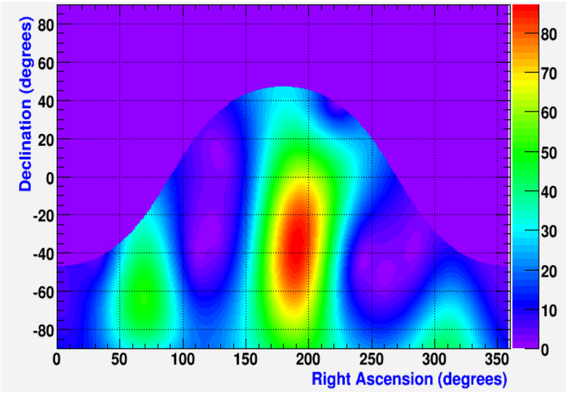
| VIRGO | VSR1 | | VS R2 | VS R3 | | | | | Advanced VIRGO | |
| LIGO | S5 | | S6 | | | | | | Advanced LIGO | |

First joint analysis:

104 days of concomitant data taking (Feb – Sept 2007)

VIRGO + LIGO + ANTARES instantaneous sky coverage ~ 30%




(equatorial coordinates)

# Joint search strategy

- GW/HEN common challenge: faint & rare signals on top of abundant noise or background events.

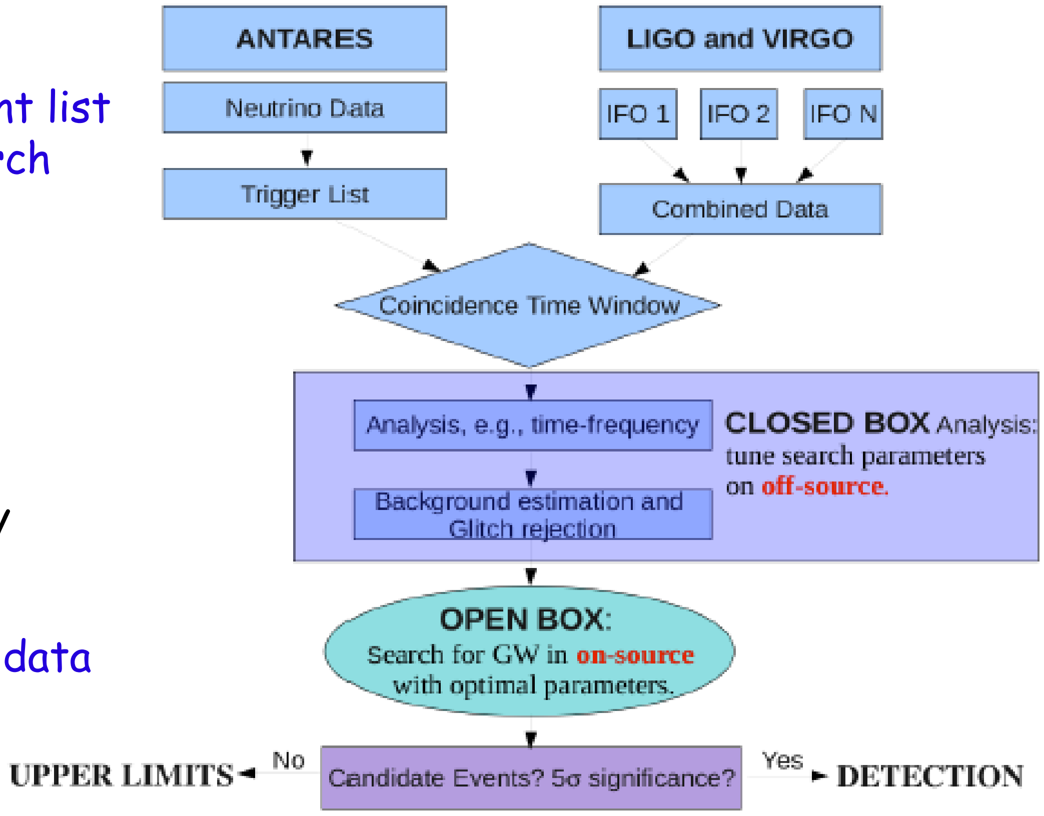
general search methodology: combination of GW/HEN event lists
+ search for coincidences in predefined time windows
( independant detectors → low combined False Alarm Rate )

- « HEN-triggered » search: HEN event list as an external input for GW burst search

- on-source coincidence time window:
•± 500 s around HEN arrival time

- GW spatial search box defined by (event-by-event) HEN angular accuracy

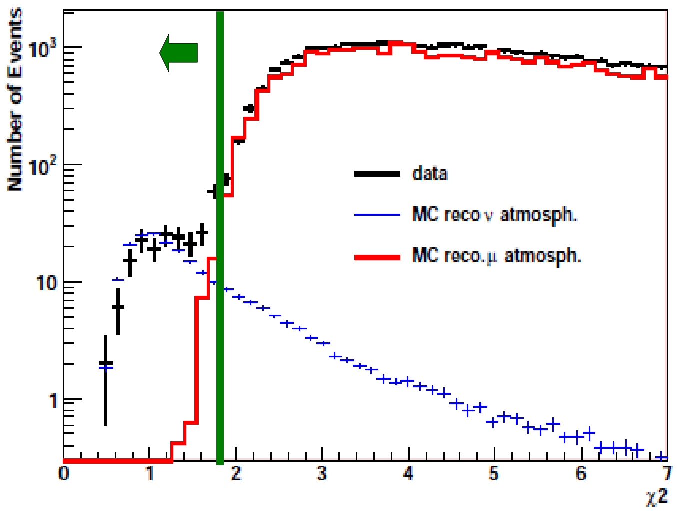
- Closed-box analysis: parameters tuned on off-source, time-shifted GW data

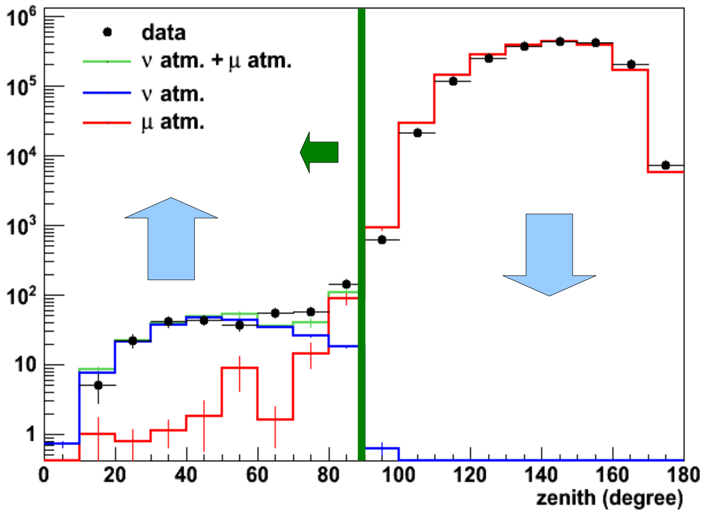


# ANTARES HEN events

Hit selection and reconstruction using Bbfit: fast online algorithm

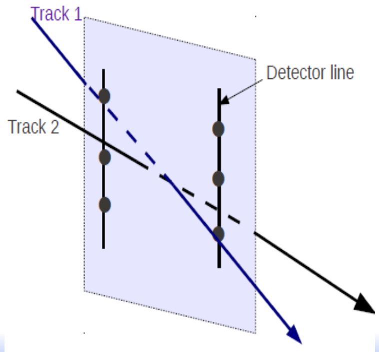
- simplified detector geometry (straight lines, 1 OM at the center of each storey)
- reconstruction algorithm based on $\chi^2$ minimization (time residuals + charge distribution)



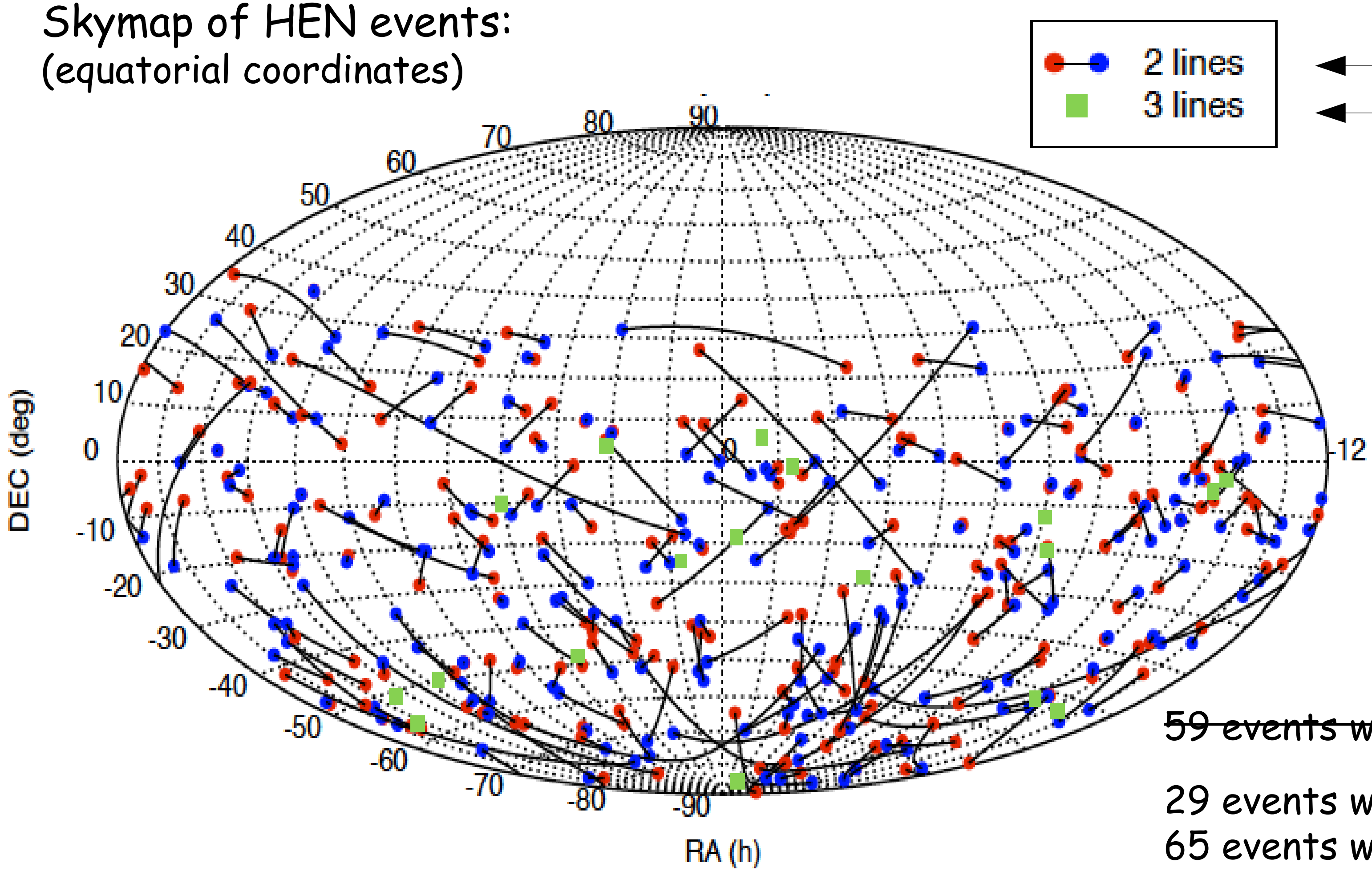

- ~20% contamination of misreconstructed upgoing atmospheric μ's in final sample

- degeneracy of events reconstructed with 2 lines: 2 mirror tracks with same zenith, different azimuths



# ANTARES HEN events

Skymap of HEN events:
(equatorial coordinates)




← 198 events (x2)
← 18 events

Among them:

~~59 events with 1 or 0 IFO~~

29 events with 2 IFOs
65 events with 3 IFOs
63 events with 4 IFOs
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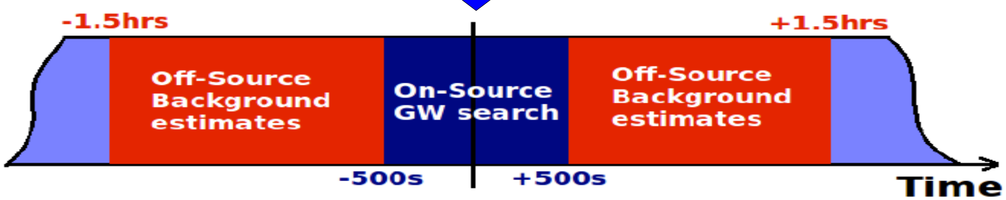
157 exploitable events
for a GW coherent search

# Triggered GW search

HEN event information

time
direction
angular accuracy
energy estimators ($N_{lines}$,$N_{hits}$)

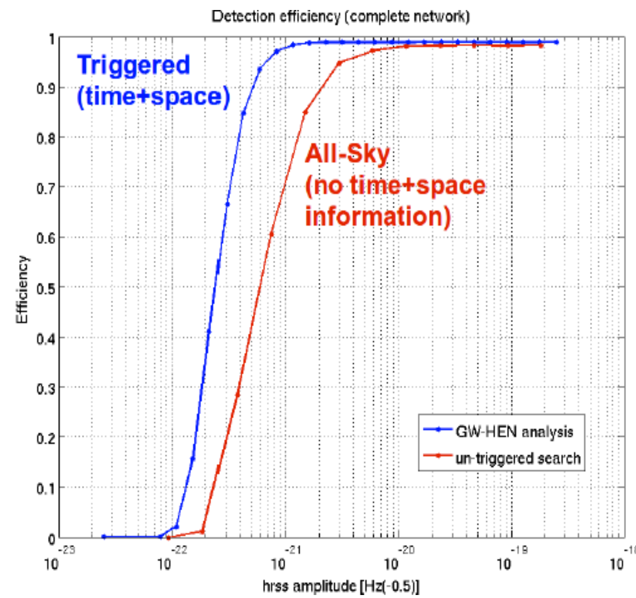



- HEN-triggered GW search using X-pipeline: analysis chain looking for unmodelled GW bursts from external triggers (e.g. GRB alerts)

- closed-box (blind) analysis: background estimation & parameter tuning on off-source region

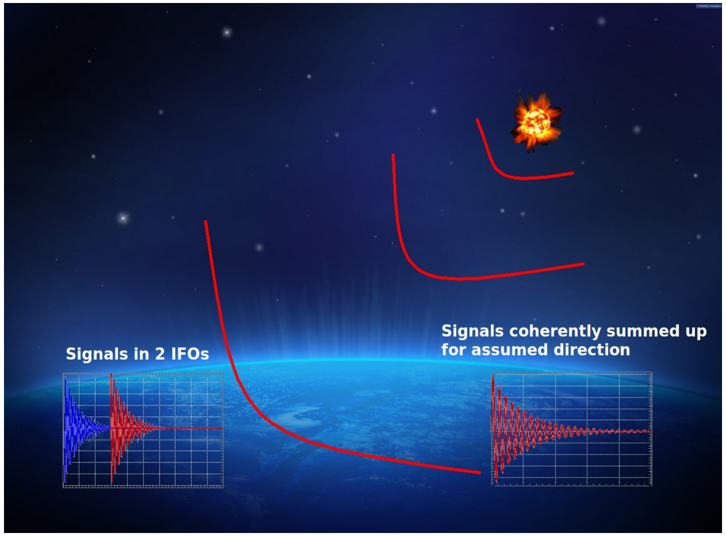
- gain in efficiency w.r.t. all-sky untriggered searches: factor 2.5 (4) at 50% (90%) C.L.

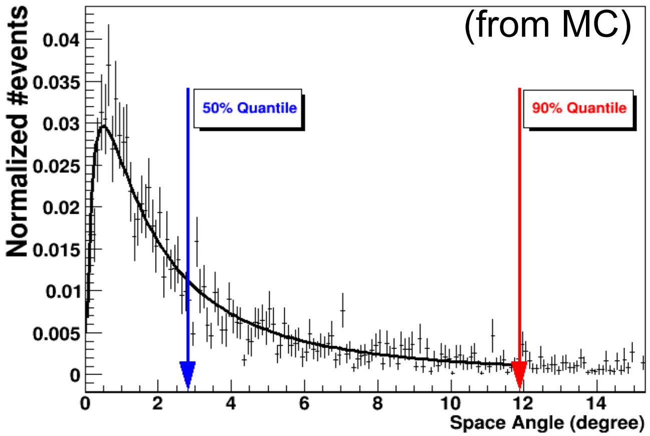
...heavy computational cost: 1 month for O(100) neutrinos



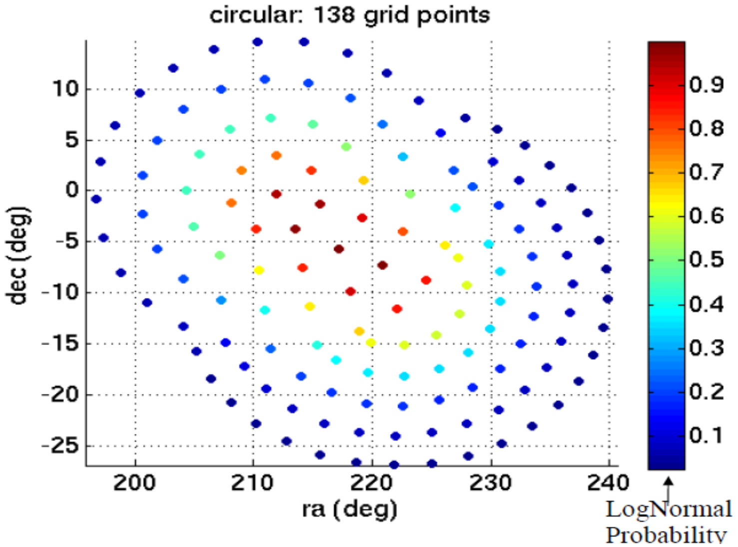
# Triggered GW search

- Hanford + Livingston + Virgo data streams coherently combined → time-frequency maps
- frequency cutoff for GW signal: 500 Hz
  + additional HF search (500 Hz – 2 kHz) for HEN events with $N_{lines}$ = 3
- assume known direction of signals
  → known delay between IFOs
- define event-by-event angular search window
  → weighted scan using log-normal parameterization of HEN PSF (in bins of declination & $N_{hits}$)




size = 90% quantile of reconstructed space angle




(mirror tracks are processed together)

# Triggered GW search

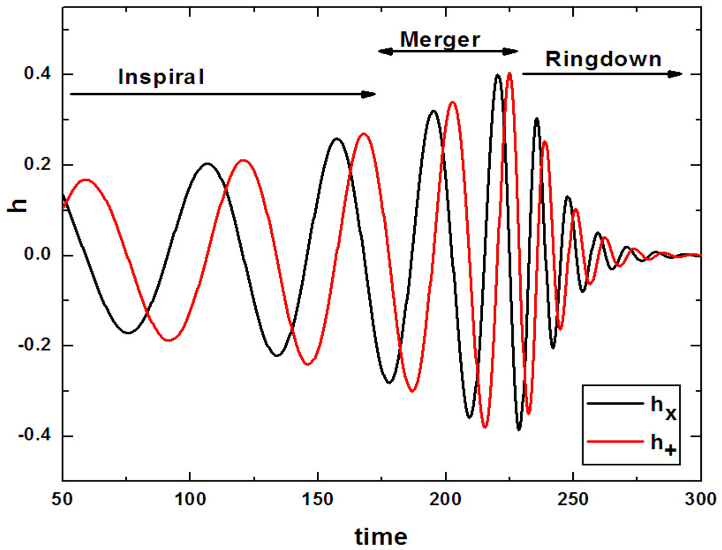
Analysis of time-frequency maps obtained from combining IFOs data streams:

- optimize thresholds using off-source background + injected template GW signals

Inspiral (binary merger)

NS(1.35 $M_o$) – NS(1.35 $M_o$)

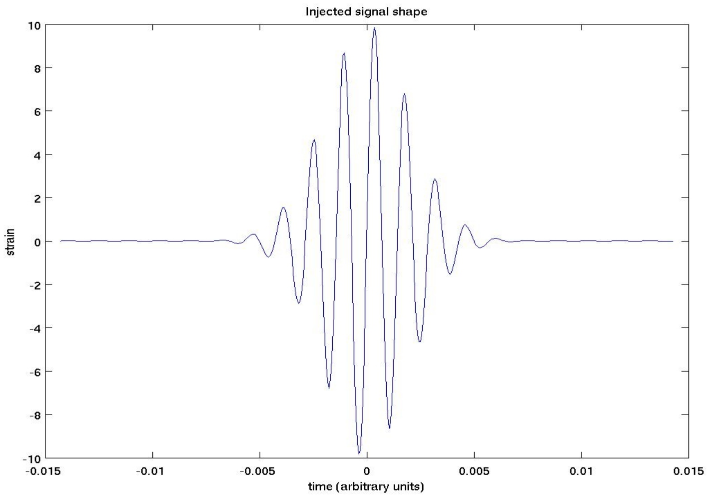
or NS(1.35 $M_o$) – BH (5 $M_o$)




Sine-gaussian

(generic, possibly core-collapse ?)

100 Hz → 1000 Hz




- estimate significance of on-source events by comparing to expected off-source distribution

  ➡ amplitude upper limits

  ➡ exclusion distances

# Coincident search results

**Search for a cumulative excess: binomial test**

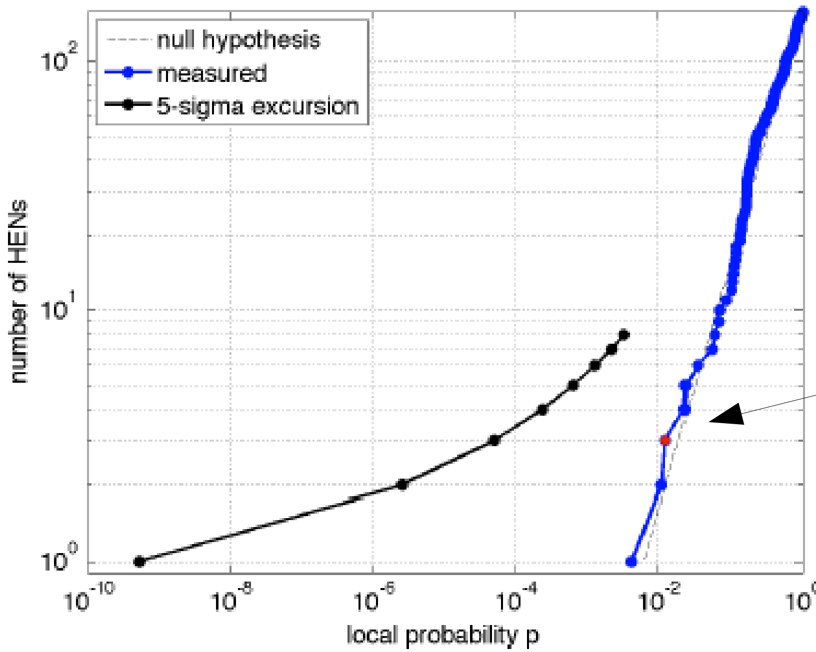
accounts for trial factor due to the large sample of tested HEN triggers:

1) compute GW false alarm probability (p-value) for each HEN trigger

2) sort by loudest event ( → by smallest p-value)

3) for the loudest 5% of events: compute binomial cumulative probability $P_{\geq i}(p_i)$: that i or more events have a p-value smaller than $p_i$

4) compare to null hypothesis (uniform distribution of p-values)




LF (60-500 Hz) search:

no significant excess found

(largest deviation from null hypothesis: occurs in 64% of pseudo-experiments under same background conditions)

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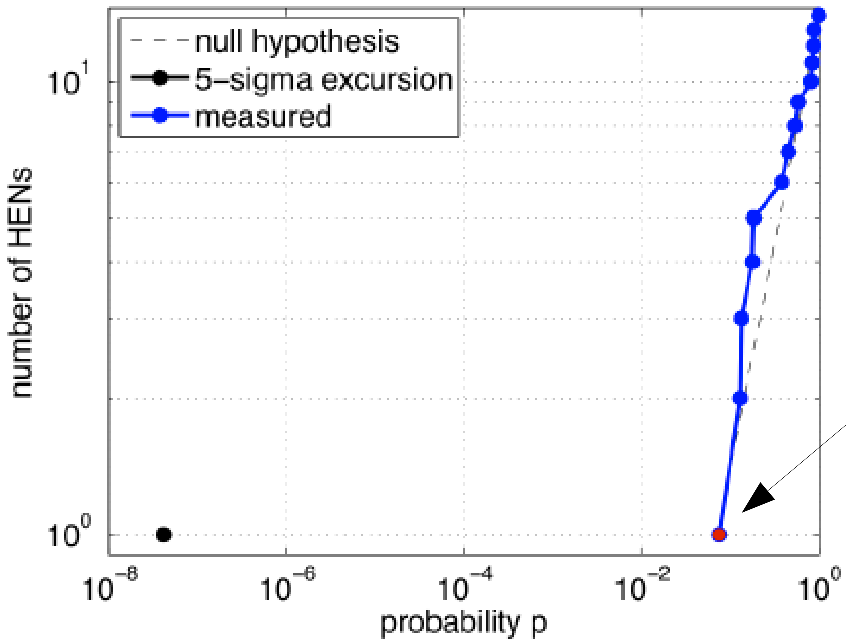



HF (500-2000 Hz) search:

no significant excess found

(largest deviation from null hypothesis: occurs in 66% of pseudo-experiments under same background conditions)

# Exclusion distances

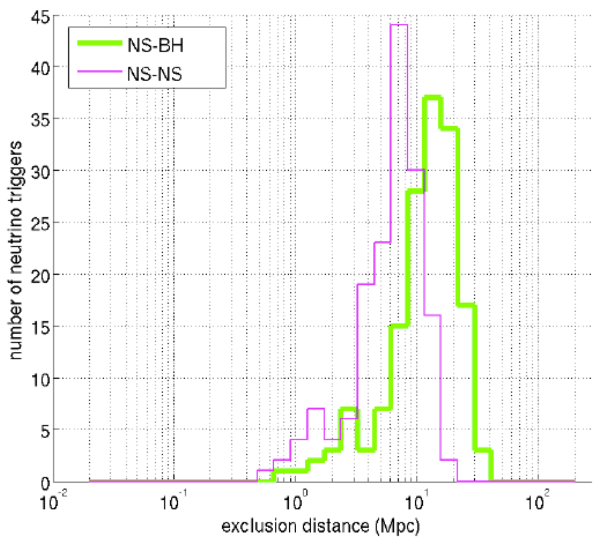
Estimate the detection horizon for each injected GW template signal:

1) vary the amplitude of injected signal

2) determine the threshold amplitude for producing, in 90% of the cases, a louder event than observed in data

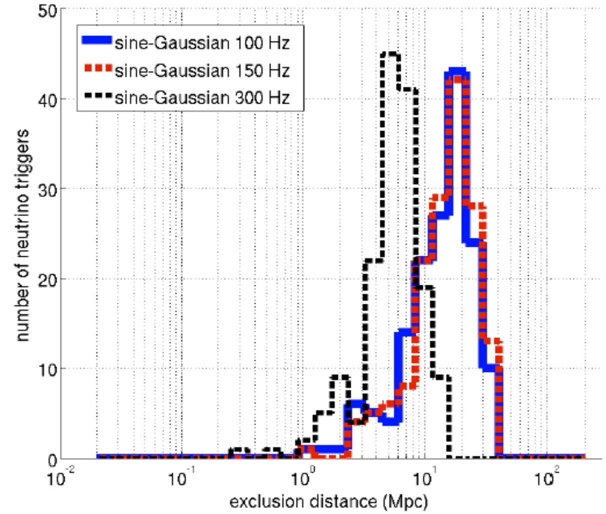
3) convert amplitude → distance:

Inspiral (short GRB)




Typical GW horizon ~ 5-10 Mpc
Typical HEN horizon ~ 4 Mpc

sine-gaussian (long GRB)
(assuming standard siren $E_{GW} = 10^{-2}\, M_O\, c^2$)




Typical GW horizon ~ 5-20 Mpc
Typical HEN horizon ~ 12 Mpc

# Conclusions and perspectives

- First joint search for HEN and GW performed with (sub-optimal) detectors ANTARES 5L + LIGO S5 + VIRGO VSR1:

  No evidence for coincident events found

- Common sources of GW and HEN are likely to exist !

combined GW+HEN observations can provide new constraints on astrophysical mechanisms:

$N_{GWHEN} \leq 2.3$ at 90% C.L. in $T_{obs}$ = 104 days within $d_{GWHEN}$

→ limits on the population density of joint GW+HEN emitters:

- Short GRB-like: $\rho_{GWHEN} \leq 10^{-2}$ Mpc$^{-3}$ yr$^{-1}$

  ...to be compared with estimated density of NS-NS mergers:

  $\rho_{NS\text{-}NS} \approx 10^{-6}$ Mpc$^{-3}$ yr$^{-1}$ (Kalogera et al. 2004 ; Belczynski et al. 2011)

- Long GRB-like: $\rho_{GWHEN} \leq 10^{-3}$ Mpc$^{-3}$ yr$^{-1}$

  ...to be compared with estimated density of Type II/Ibc core-collapse SN :

  $\rho_{SNII} \approx 2 \times 10^{-4}$ Mpc$^{-3}$ yr$^{-1}$ (Bazin et al. 2009)

  $\rho_{SNIbc} \approx 2 \times 10^{-5}$ Mpc$^{-3}$ yr$^{-1}$ (Guetta & Valle 2007)

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  ...to be compared with typical rate of NS-NS mergers:

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- Long GRB-like: $\rho_{GWHEN} \leq 10^{-3}$ Mpc$^{-3}$ yr$^{-1}$ → **requires 2x increase in $d_{GWHEN}$**

  ...to be compared with typical rate of Type II/Ibc core-collapse SN :

  $\rho_{SNII} \approx 2 \times 10^{-4}$ Mpc$^{-3}$ yr$^{-1}$ (Bazin et al. 2009)

  $\rho_{SNIbc} \approx 2 \times 10^{-5}$ Mpc$^{-3}$ yr$^{-1}$ (Guetta & Valle 2007)

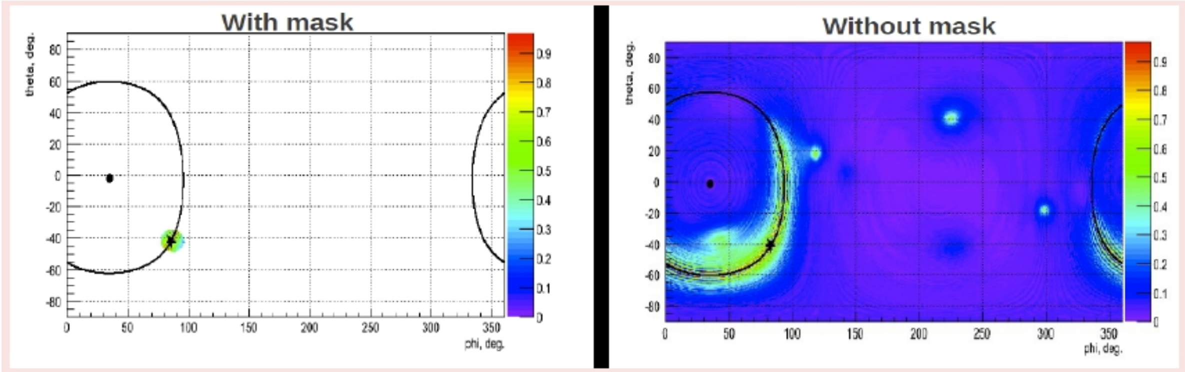
# Conclusions and perspectives

- Next step: 2009-2010 concomitant data sample
  ANTARES 12L + LIGO S6 + VIRGO VSR2-3

➡ Larger detectors : ~x2 in nominal sensitivity

➡ Improved HEN reconstruction strategy (no doublets, sub-degree angular resolution)

➡ New GW pipeline: cWB : coherent Wave Burst (all-sky coherent search algorithm)
+ time window $\Delta t = \pm 500s$
+ skymask provided by the HEN angular sarch window :
  - lower computational cost (O(1000) neutrinos)
  - allows to constrain direction for data analyzed with 2 ITF




➡ Joint optimisation of the selection cuts based on a fixed rate of accidental coincidences (or False Alarm Probability)

...time to probe astrophysical models of source populations (e.g. long/choked GRBs) ?
Stay tuned for the outcome of the analysis !