First search for coincident gravitational waves and high-energy neutrinos with the ANTARES and VIRGO/LIGO detectors

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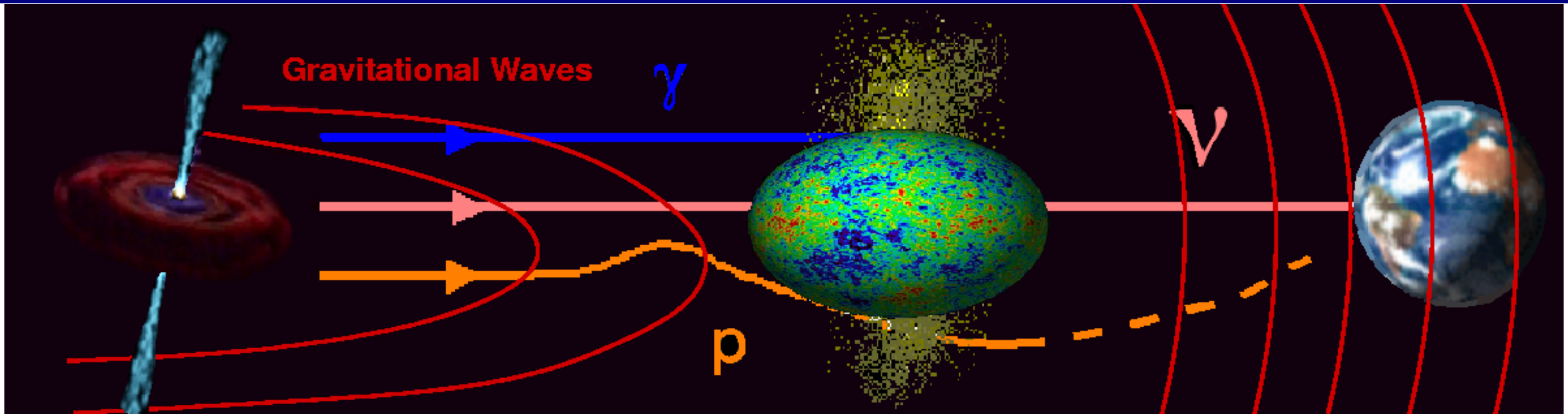
for the ANTARES Collaboration
& the GWHEN working group
(also including members of IceCube, VIRGO and LSC)

Motivations for GW+HEN astronomy



- **Long-range messengers:** no interactions (or weak ones) with ambient matter, no deflection by magnetic fields:
  GW and HEN travel undeflected over cosmological distances
- **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, failed, choked,...)
- **Discovery potential for hidden/unknown sources** (difficult to detect through photon/cosmic ray astronomy
- **Main requirements for joint GW/HEN detection:**

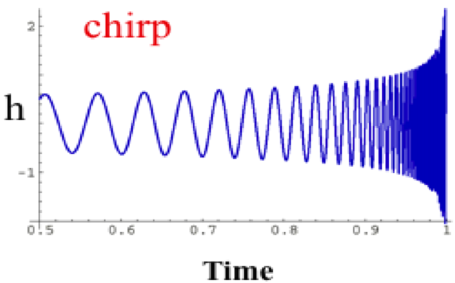
massive, compact & relativistic objects	+	sudden (< 1s)	+	baryon loaded	+	close & frequent enough

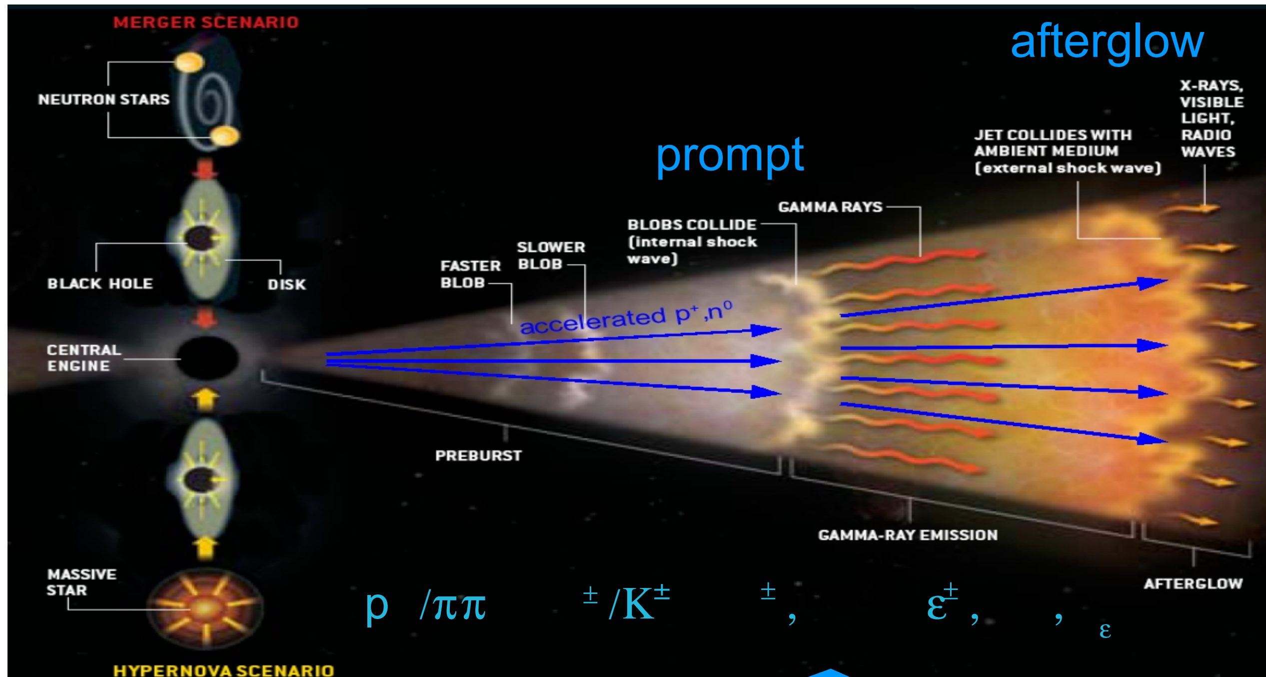
Usual suspects: long & short GRBs

The fireball model

GW $\longleftrightarrow$ $\Delta t \sim$ few minutes ? $\longleftrightarrow$ 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 (faint ?, unmodelled)

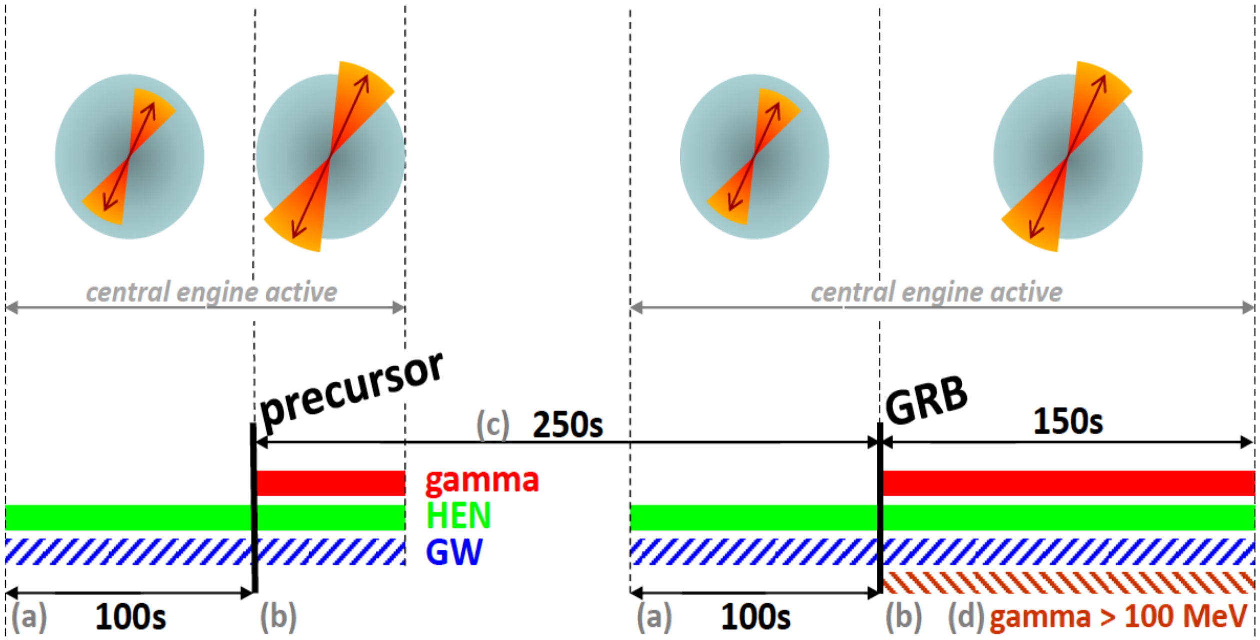
HEN emitted in baryon-loaded jets during prompt (TeV-PeV) & afterglow (PeV – EeV) phases

expected neutrino spectrum ~ E^{-2}

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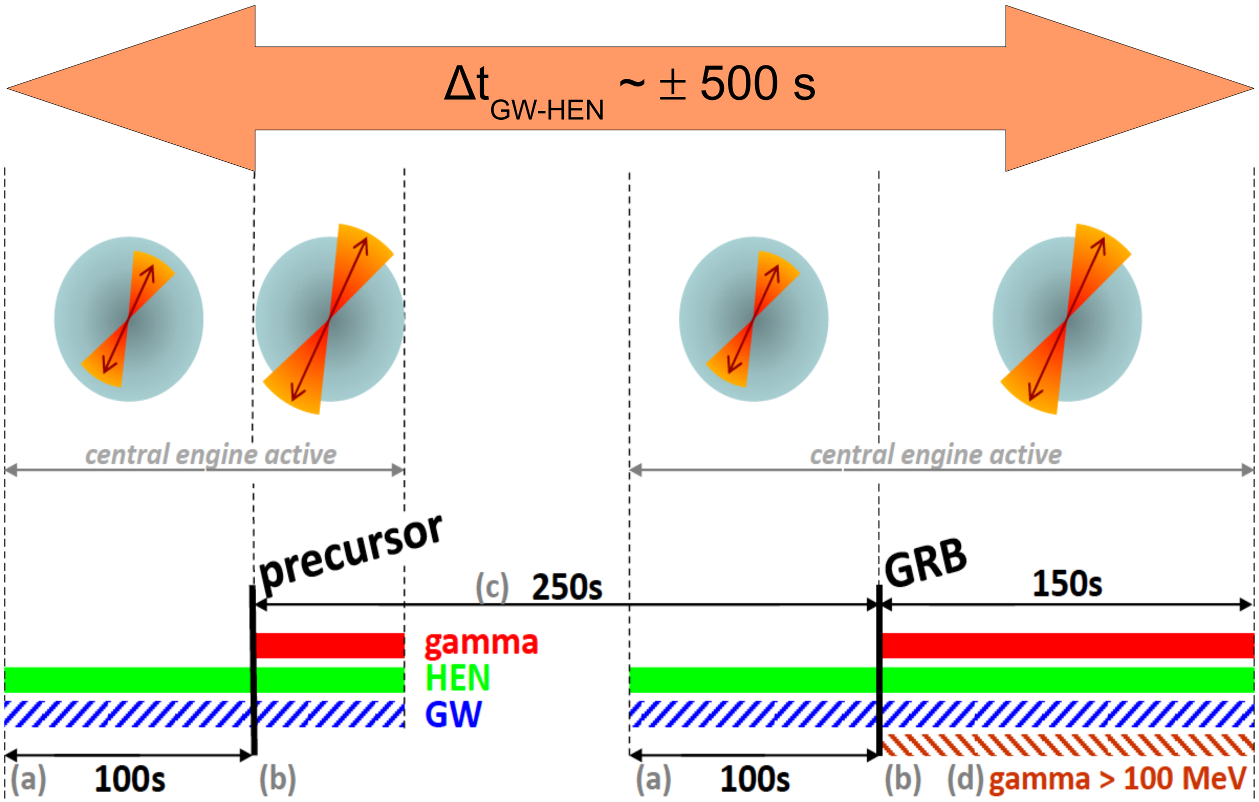

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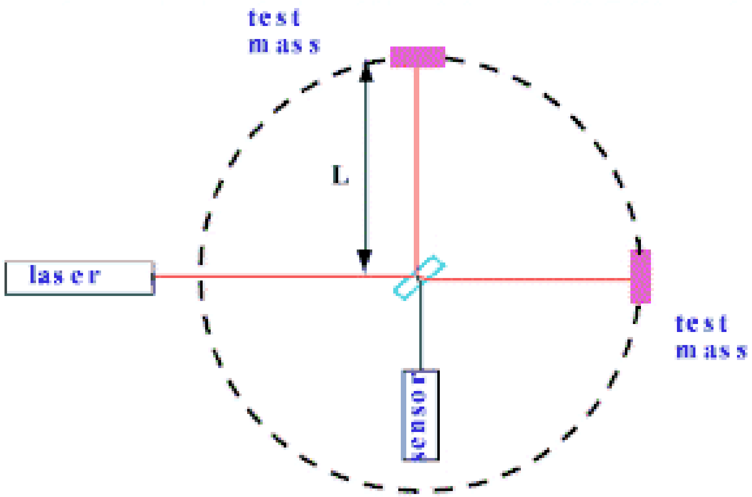
The detectors: GW interferometers

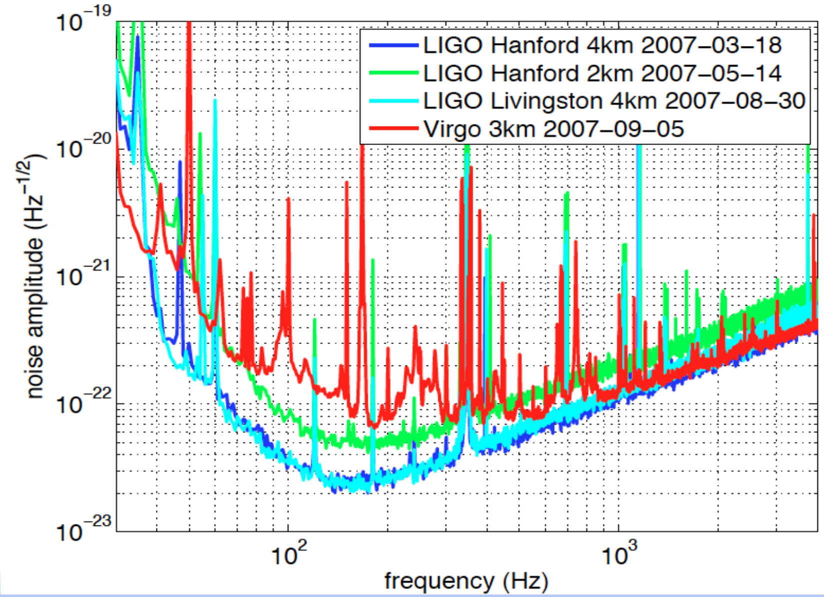
Michelson interferometers:
suspended mirrors act as free test masses



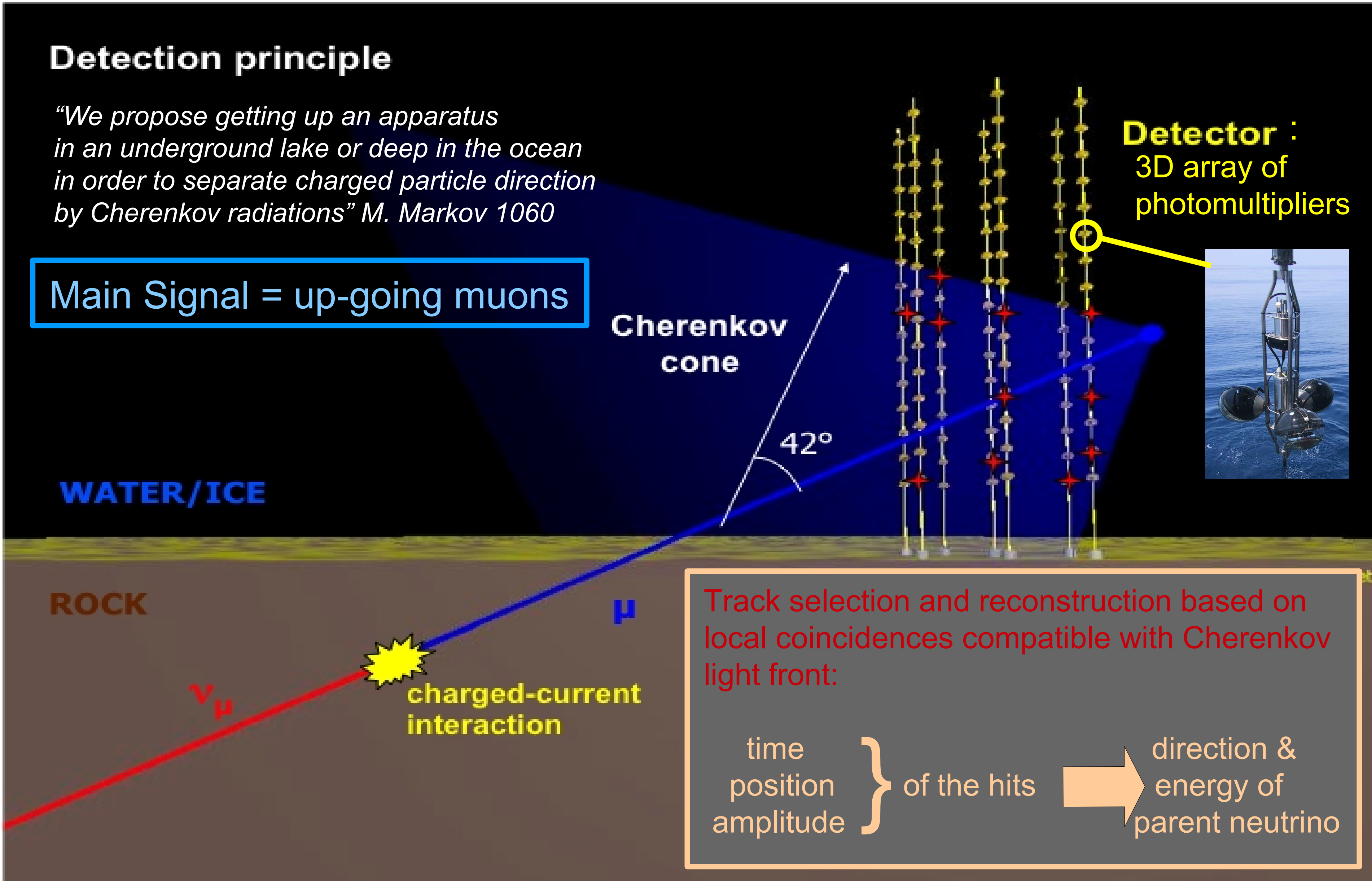
- LIGO Hanford: 4 km (+ 2 km) arms
- LIGO Livingston: 4 km arms
- VIRGO (Pisa, Italy): 3 km arms

current sensitivity to GW amplitude

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



The detectors: neutrino telescope



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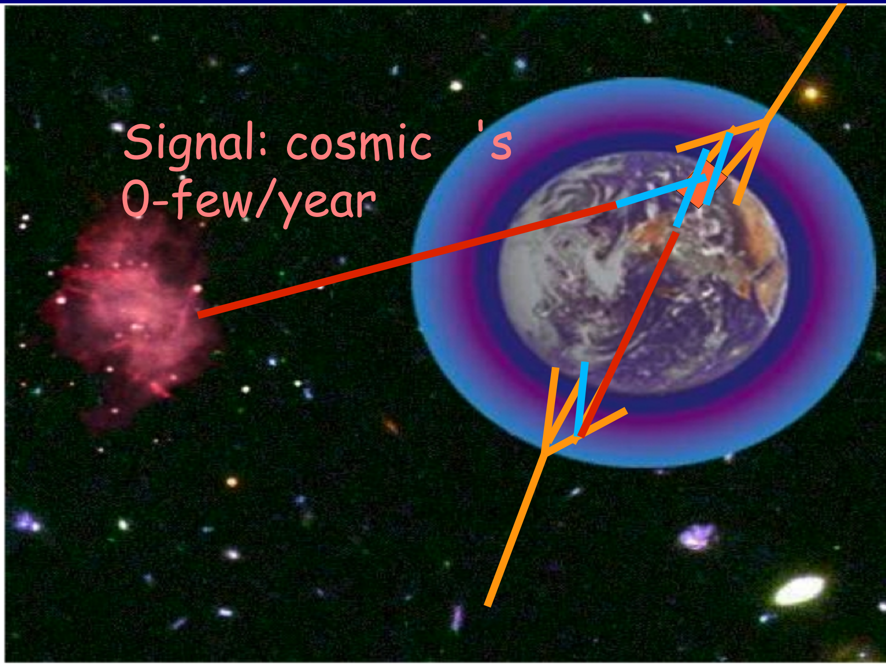


Physical backgrounds:

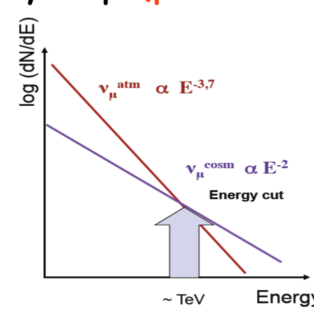
• Atmospheric muons: ~ 10^8/yr
mostly down-going (BUT can be misreconstructed as up-going)

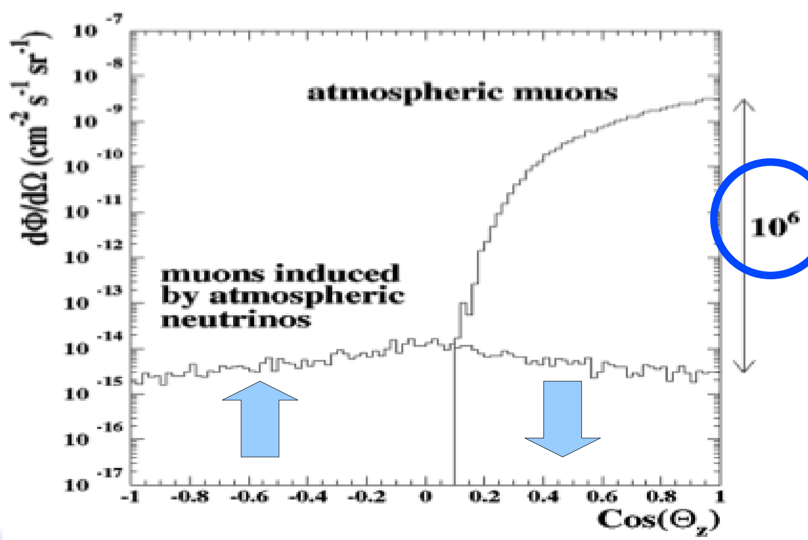
⇒ detectors are buried deep
⇒ detectors look downwards
- cut on zenith angle > 90°
- cut on track quality

• 's from atmospheric neutrinos: ~10^3/yr
irreducible background
→ cosmic neutrino identification:

⇒ localized excess in skymap (point source)

⇒ all-sky excess at high energies: (diffuse flux)

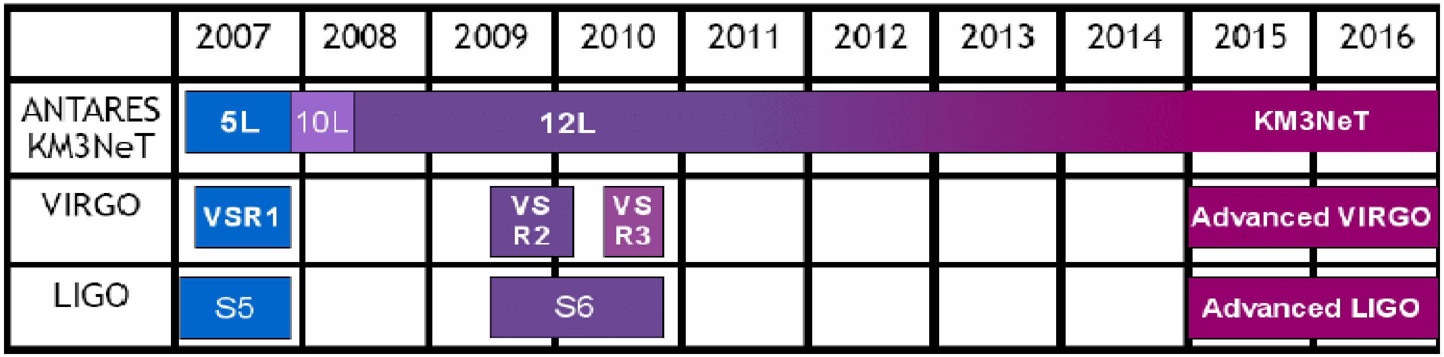




⇒ coincidence with other astrophysical signals: Multimessenger strategies

The detectors

Periods of concomitant data taking:



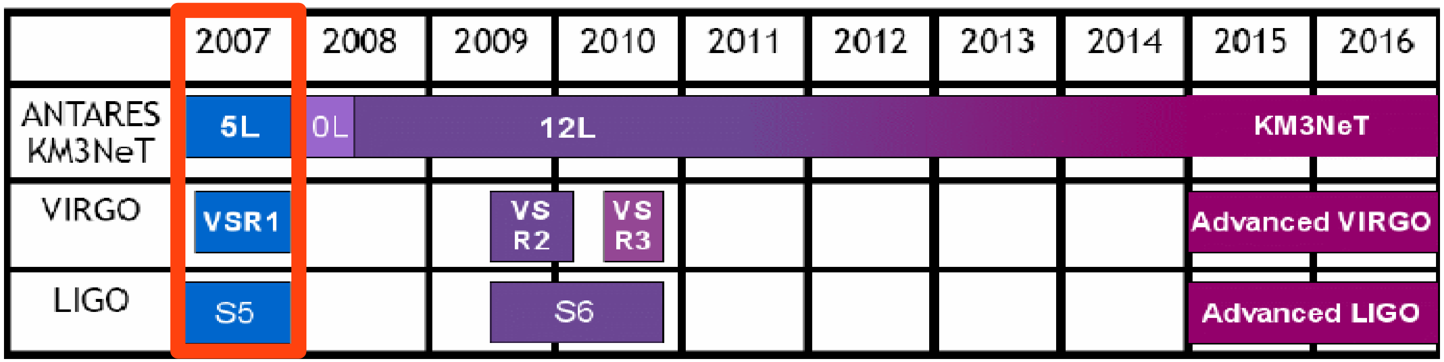
First-generation detectors:
GW horizon for standard binary sources
~ 15 Mpc (~1 binary merger/ 100 years...)
ANTARES 5 active lines

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

The detectors

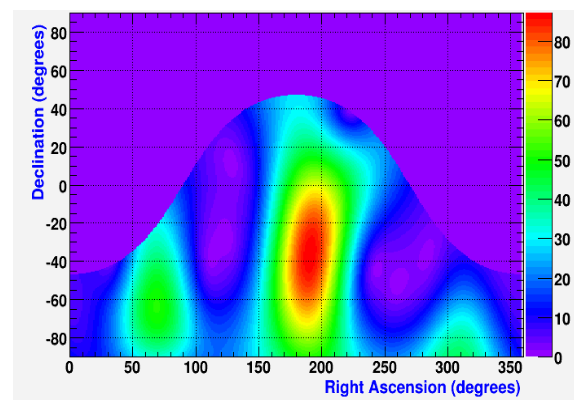
Periods of concomitant data taking:



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.

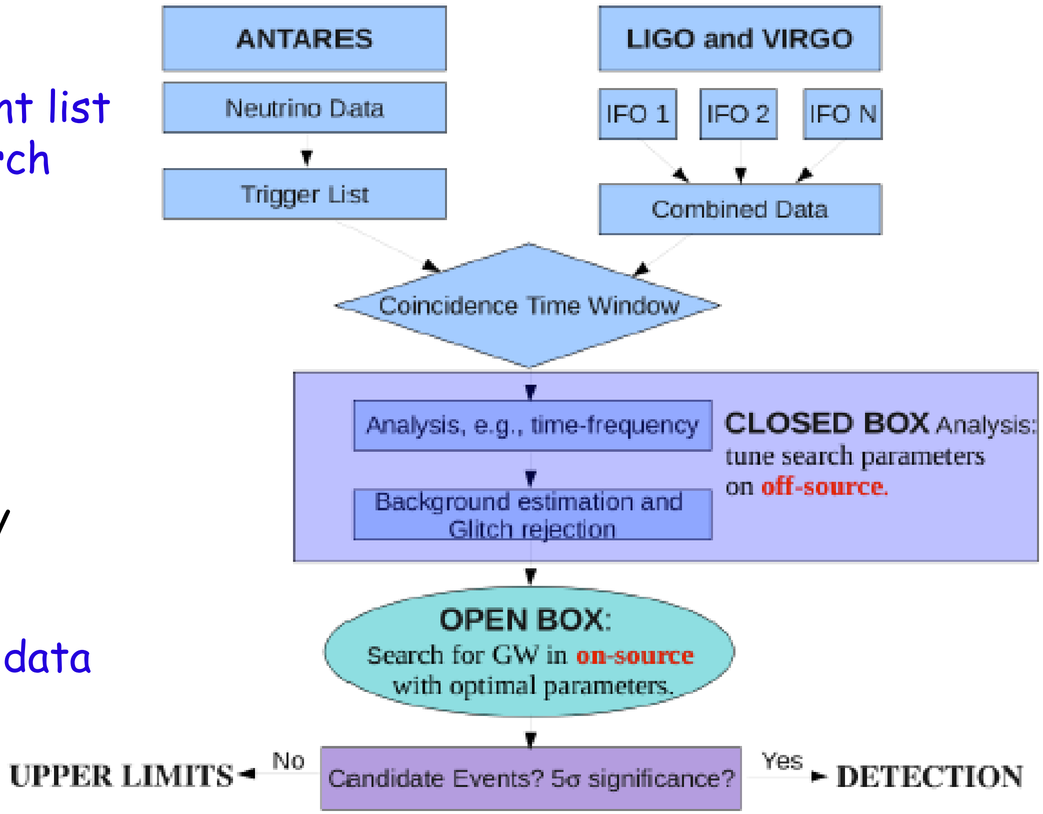
general search methodology: combination of GW/HEN event lists
+ search for coincidences in predefined time windows
(independant detectors → low combined False Alarm Rate)

- « 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

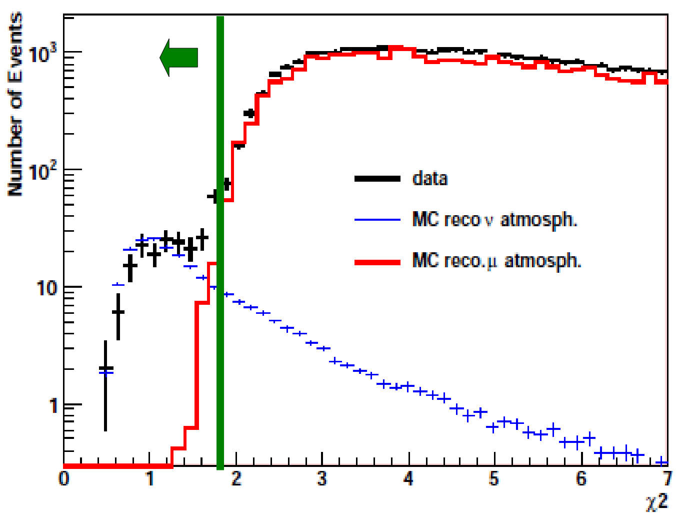
- Closed-box analysis: parameters tuned on off-source, time-shifted GW data

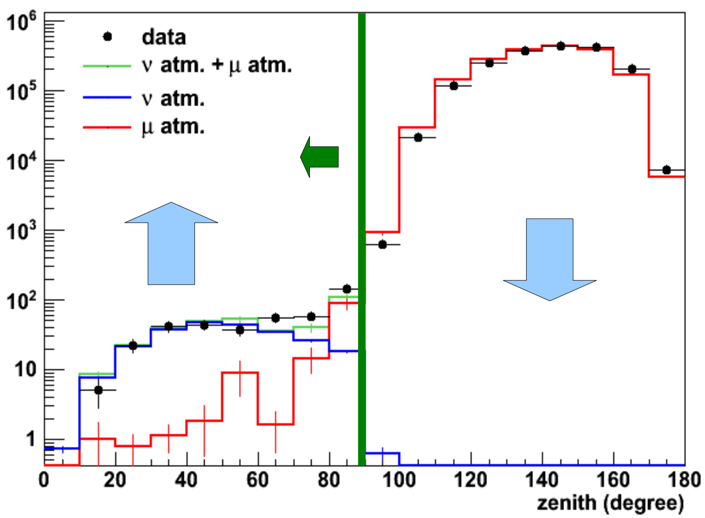


ANTARES HEN events

Hit selection and reconstruction using Bbfit: fast online algorithm

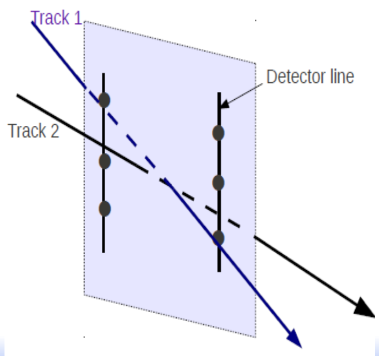
- simplified detector geometry (straight lines, 1 OM at the center of each storey)
- reconstruction algorithm based on χ^2 minimization (time residuals + charge distribution)





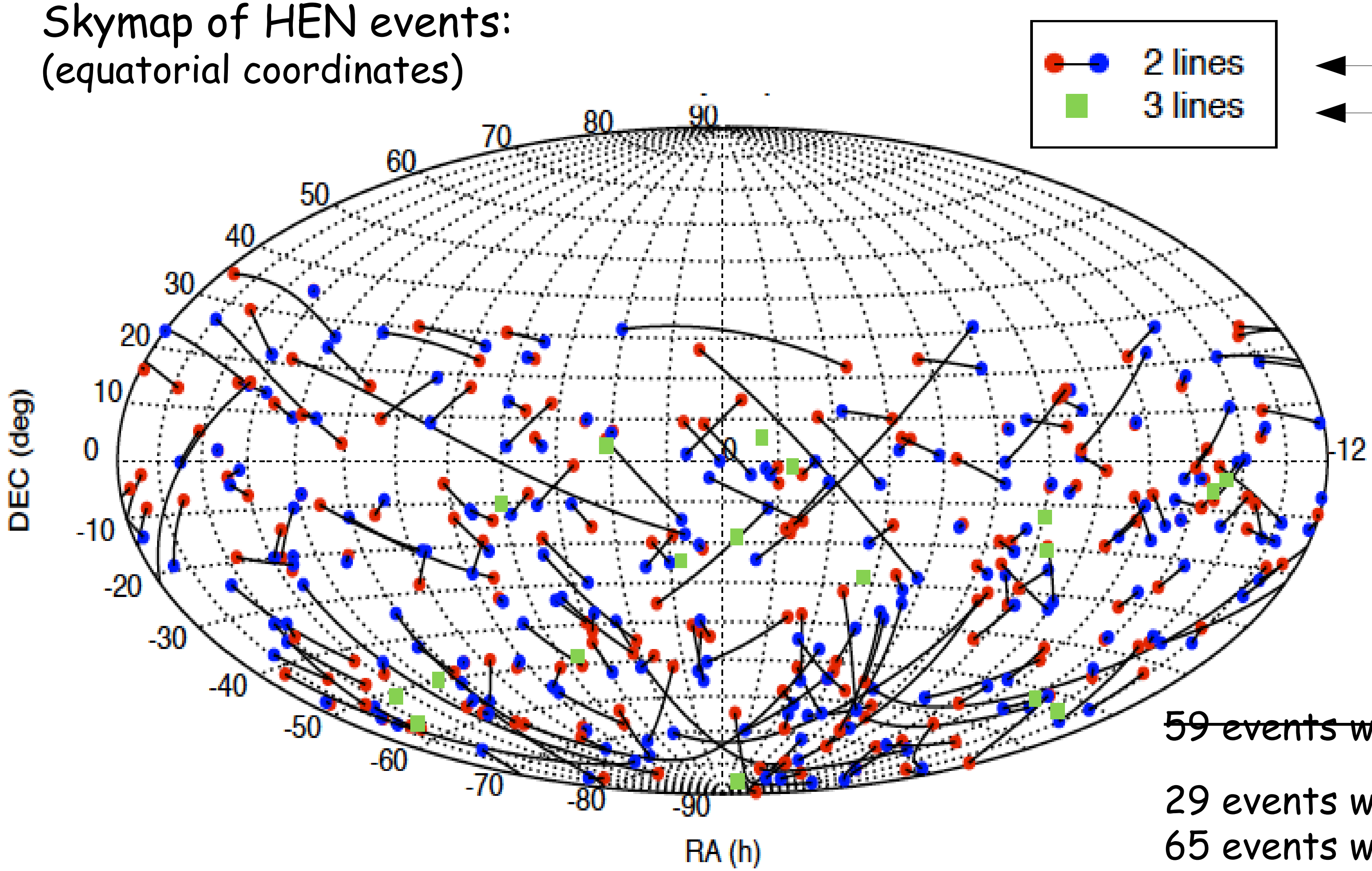
- ~20% contamination of misreconstructed upgoing atmospheric μ's in final sample

- 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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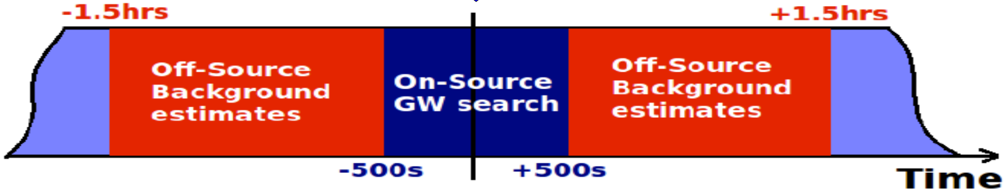
157 exploitable events
for a GW coherent search

Triggered GW search

HEN event information

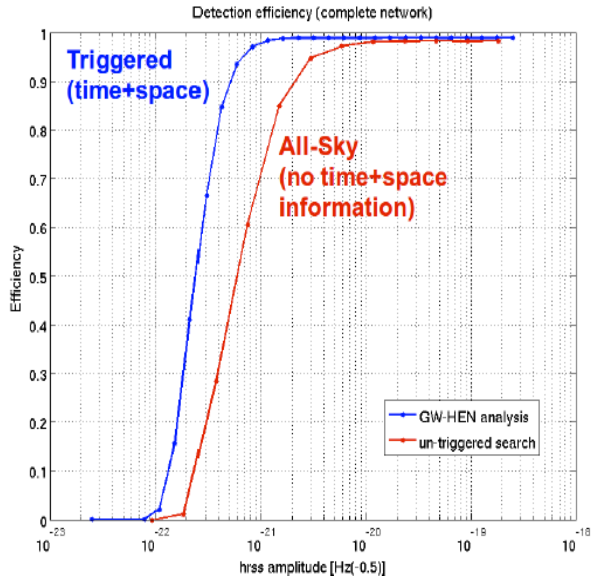
time
direction
angular accuracy
energy estimators (N_{lines},N_{hits})



- 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.



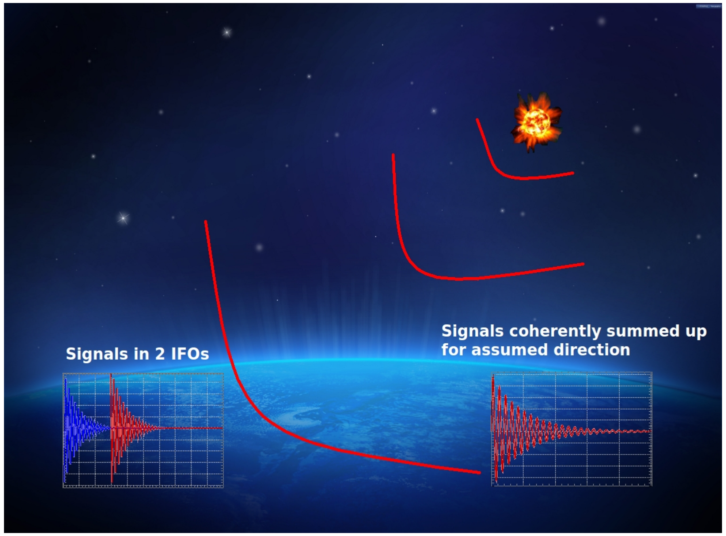
Triggered GW search

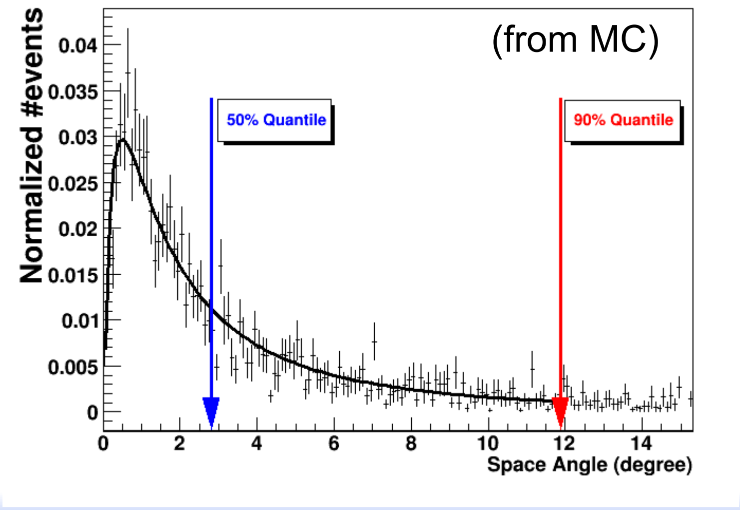
- Hanford + Livingston + Virgo data streams coherently combined → time-frequency maps

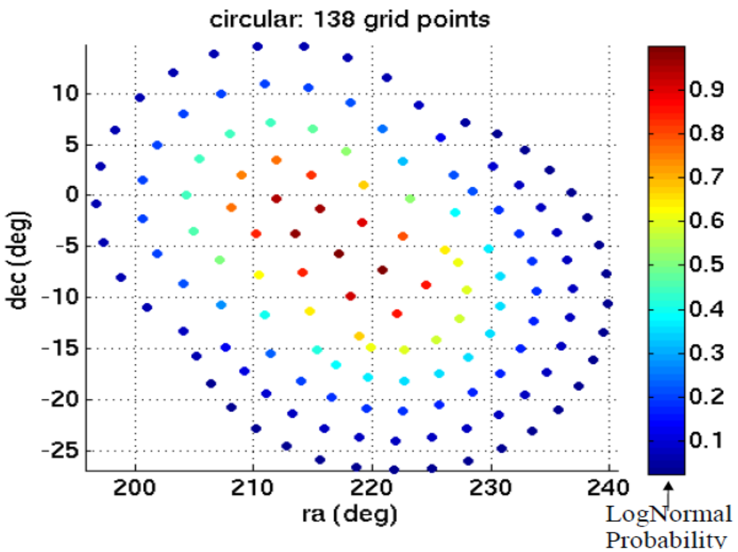
- high frequency cutoff for GW signal: 500 Hz
+ additional HF search (500 Hz – 2 kHz) for HEN events with N_{lines} = 3

- 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







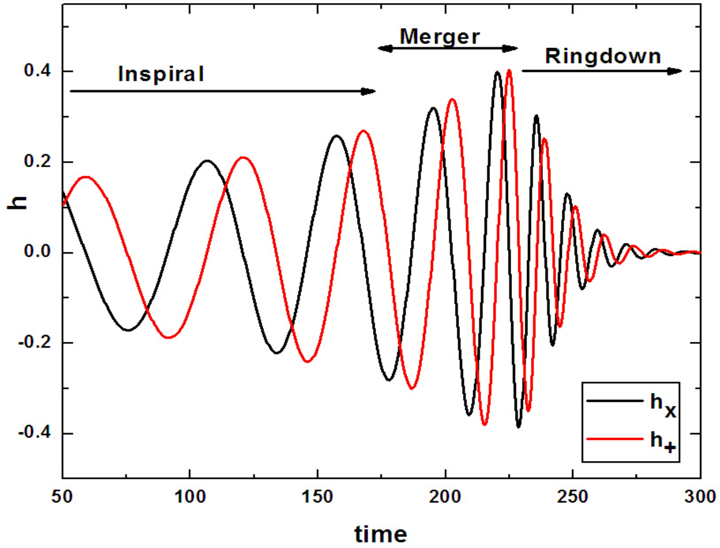
(mirror tracks are processed together)

Triggered GW search

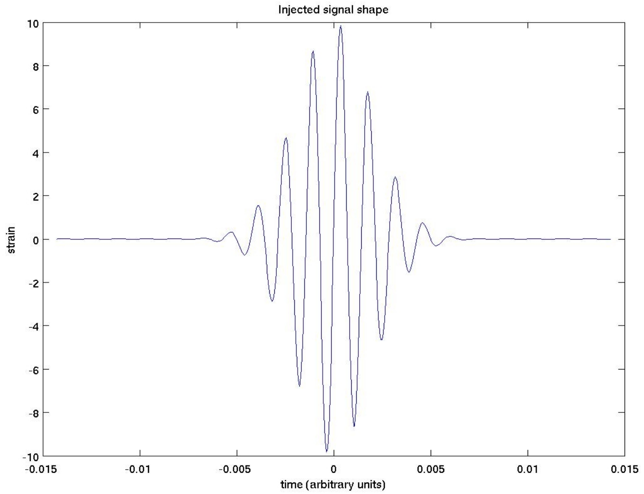
Analysis of time-frequency maps obtained from combining IFOs data streams:

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

inspiral
(binary mergers: NS-NS, NS-BH)



sine-gaussian
(generic, possibly core-collapse ?)



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

  ➡ amplitude upper limits

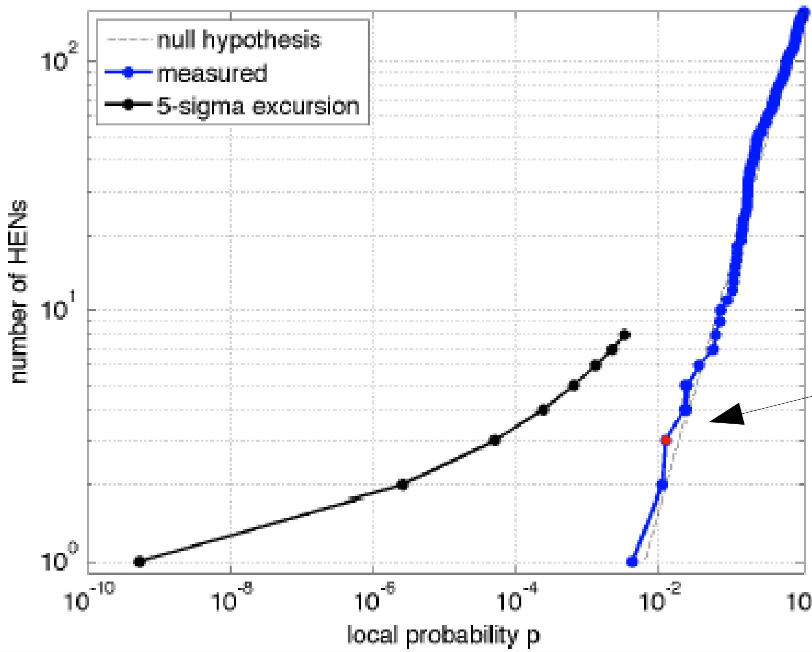
  ➡ exclusion distances

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 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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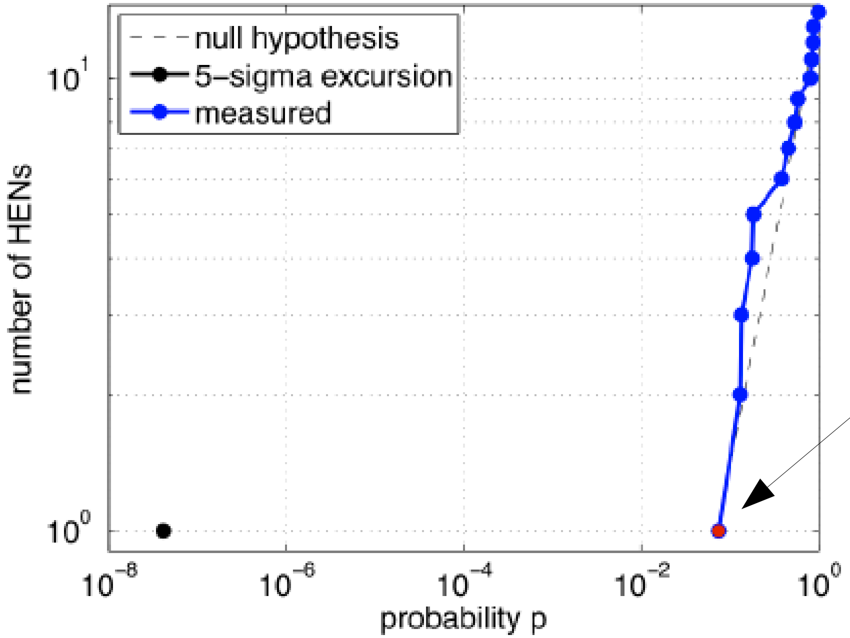


LF (500-2000 Hz) search:

no significant excess found

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

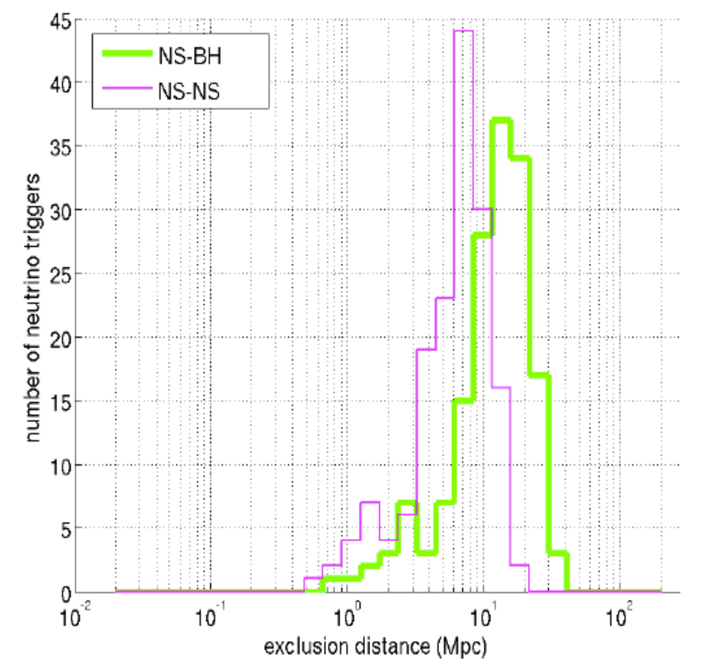
Coincident search results

Exclusion distances

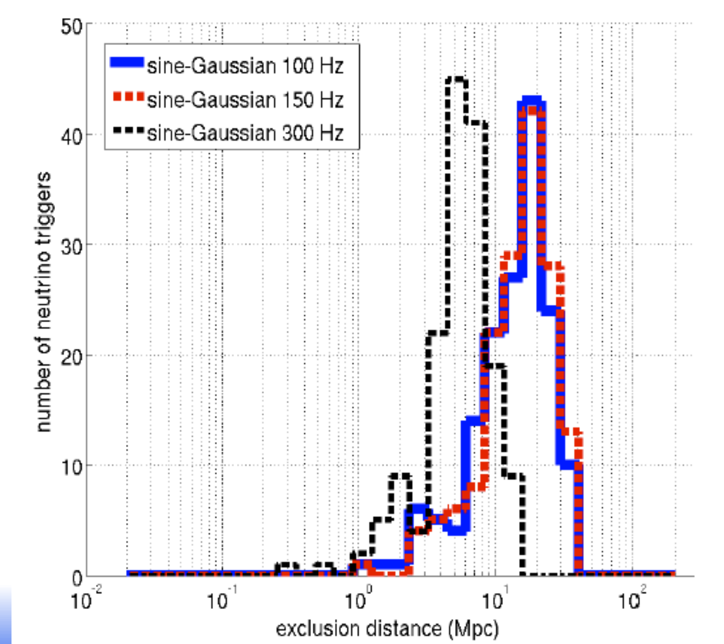
Estimate the detection horizon for each injected GW template signal:

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:

Typical GW horizon for inspiral ~ 5-10 Mpc



Typical GW horizon for sine-gaussian ~ 5-20 Mpc
(assuming total emitted energy $E_{GW} = 10^{-2} M_{Sun} c2$)



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:

e.g. on the population of common sources within observation horizon:

No event found → $N_{GWHEN} \leq 2.3$ at 90% C.L. in $T_{obs} = 104$ days

→ constrains the density of joint GW+HEN emitters: $\rho_{GWHEN} = N_{GWHEN}/(V_{GWHEN}\, T_{obs})$

effective volume:
depends on GWHEN horizon
$d_{GWHEN} = \min(d_{HEN}, d_{GW})$

- Next step: analyze data from 2009-2010: ANTARES 12L/LIGO S6/VIRGO VSR2-3
  - new GW software (suitable for joint simulations)
  - new HEN reconstruction strategy (smaller error boxes)

  → first fully optimized GWHEN search

  → probe realistic astrophysical models of common source population (e.g. long GRBs) ?

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

Barion rich
Nonrelativistic
Frequent

Similar kinetic energy

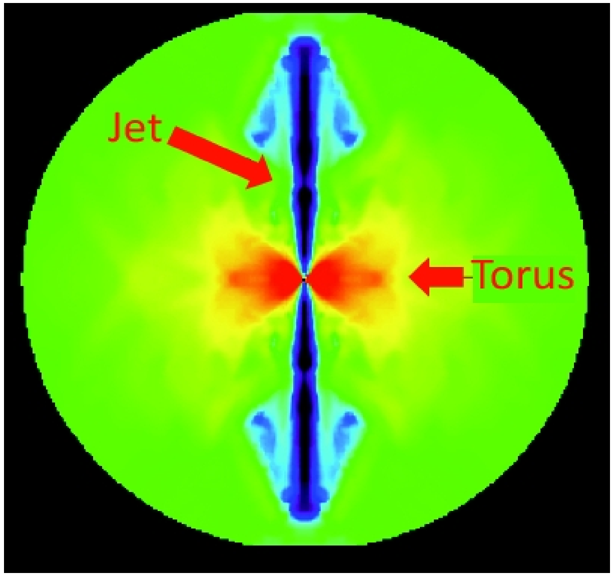
Baryon poor
Relativistic jets
Rare

taken from Ando (2009)

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

Choked GRBs:
successfull 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



Estimations of source population

ρ_{GWHEN} for SGRB and LGRB

- $\rho_{\mathrm{GWHEN}}^{\mathrm{SGRB}} = 1.1 \times 10^{-2}/\mathbf{Mpc^3/yr}$

  $\Rightarrow$ to be compared with **typical merger rates**...
- $\rho_{\mathrm{GWHEN}}^{\mathrm{LGRB}} = 1.0 \times 10^{-3}/\mathbf{Mpc^3/yr}$

  $\Rightarrow$ to be compared with **typical star collapse rates**...

Binary merger Rates

- $\rho_{\mathrm{merger}} \lesssim 1.5 \times 10^{-6}/\mathbf{Mpc^3/yr} \approx \rho_{\mathrm{SGRB}}$

  $\Rightarrow$ `B. Belczynski et al., arXiv:1106.0397v1`
- $\rho_{\mathrm{GWHEN}}^{\mathrm{SGRB}} = 1.1 \times 10^{-2}/\mathrm{Mpc^3/yr}$
- Need **4 order of magnitudes !**
- With $T_{\mathrm{obs}} \sim 1\mathrm{yr}$, need improvement of factor 10 on d_{HEN}

  $\Rightarrow$ Not possible with 2009-2010 12 Lines data

  $\Rightarrow$ **Need bigger km^3 HEN telescope and Advanced GW interferometers...**

Type II/Type Ib/c SN Rates

- $\rho_{\mathrm{SNII}} \approx 2 \times 10^{-4}/\mathbf{Mpc^3/yr}$

  $\Rightarrow$ `G. Bazin et al., A&A, 2009`
- $\rho_{\mathrm{SN\ Ibc}} \approx 2 \times 10^{-5}/\mathbf{Mpc^3/yr}$

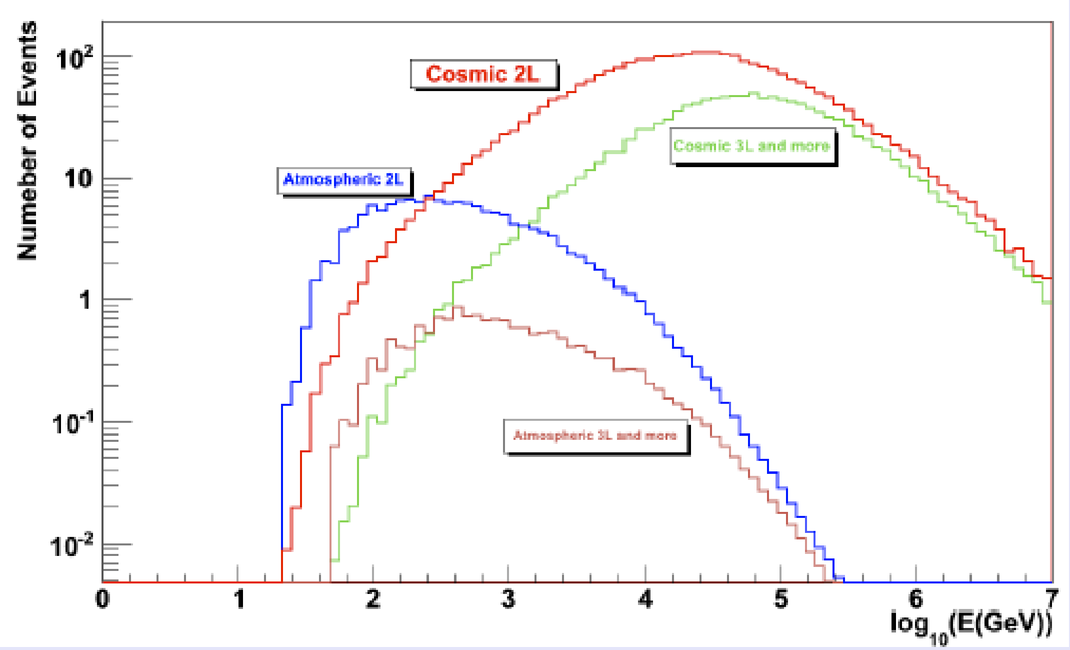
  $\Rightarrow$ `D. Guetta et al., ApJ, 2007`
- $\rho_{\mathrm{GWHEN}}^{\mathrm{LGRB}} = 1.0 \times 10^{-3}/\mathrm{Mpc^3/yr} \Rightarrow$ only need a factor 5-50...
- With $T_{\mathrm{obs}} \sim 1\mathrm{yr}$, need improvement of only up to factor 2 on d_{HEN}

  $\Rightarrow$ **Seems feasible with 2009-2010 data ! !**

Extended high-frequency search

3Lines HEN for an extended High-Frequency Search

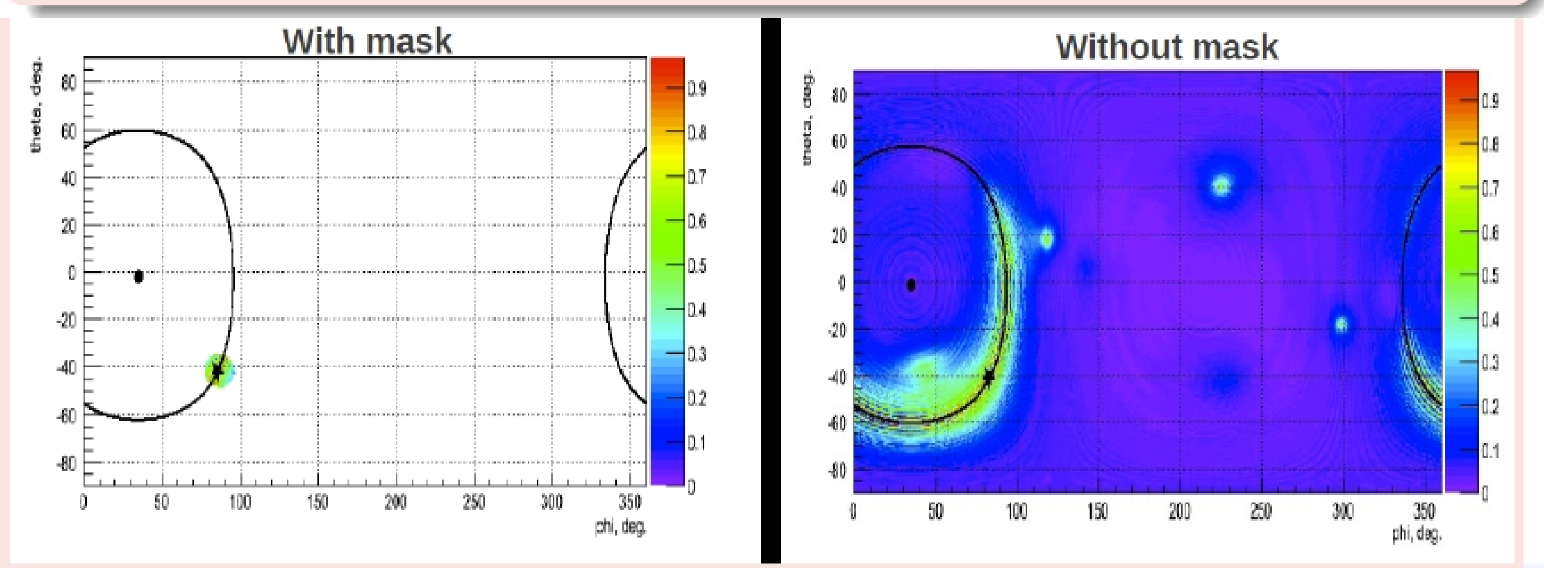
- Additional search from 500Hz up to 2kHz for the 14 3 Line events
- Misreconstructed muons : 12.3% (2L) vs 3.7% (3L) (wrt atm. ν)
- 3L events more energetic



Perspectives for 2009-2010 data analysis

GW Pipeline : Coherent Wave Burst

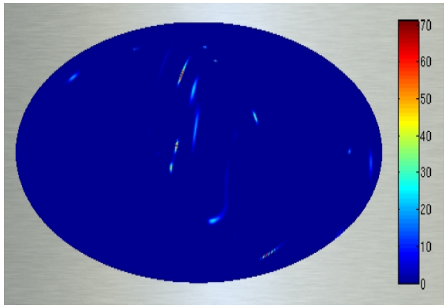
- « skymask cWB »= same analysis as cWB
  - ⇒ but restricted to a limited time segment and a small sky area defined by a mask
- Segment and mask computed from neutrino candidate
  - ⇒ event time ± 500s, position + lognormal fit of the angular search window
- Enable joint search for 2-detector networks :
  - ⇒ Events are reconstructed over a ring in the sky
  - ⇒ Mask application allows to select events in this ring consistent with the neutrino direction



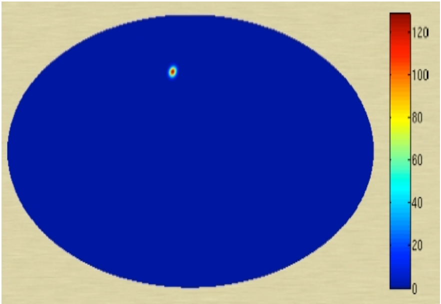
Joint analysis strategies

Ongoing: ANTARES 12L/LIGO S6/VIRGO VSR2&3 (2009-2010)

- independent lists of GW and HEN candidates
- search for time-coincident events
- test spatial correlation by combining GW/HEN likelihood skymaps



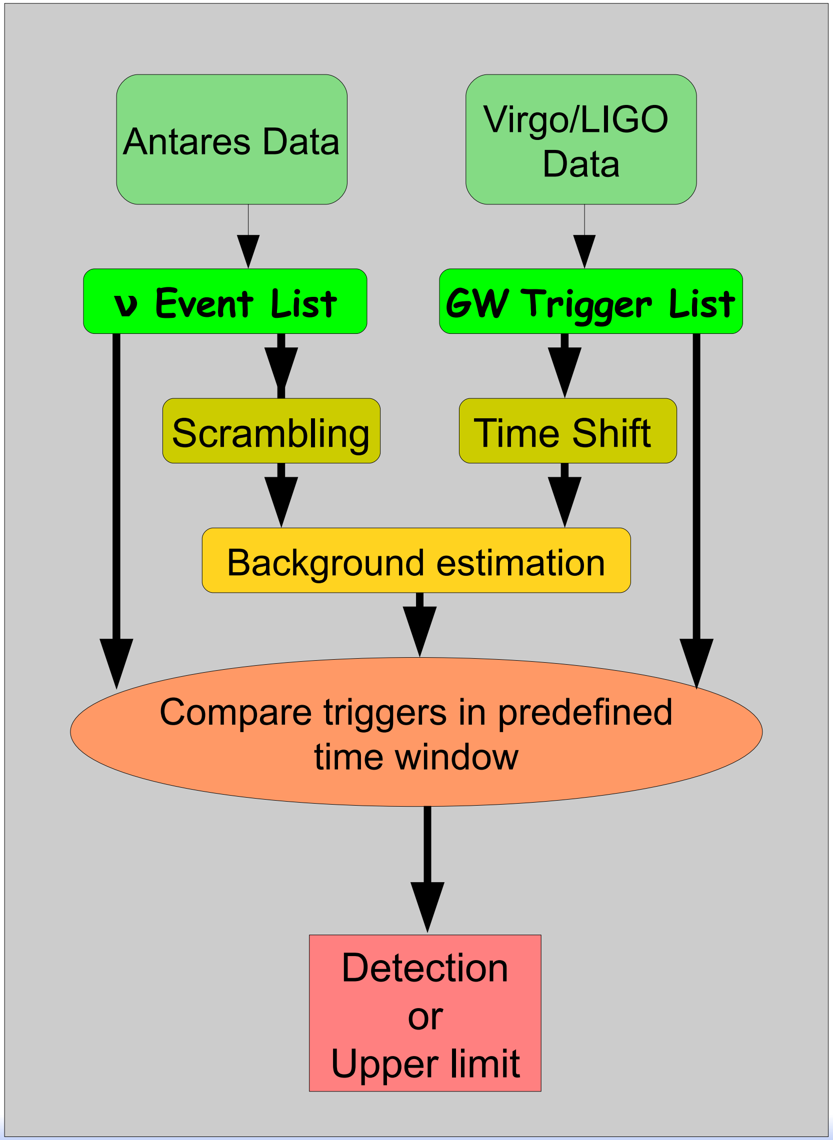
VIRGO/LIGO coherent analysis



HEN telescope typical PSF

- estimate significance by comparing to the distribution of accidental coincidences obtained with time-shifted GW data streams & scrambled (or simulated) HEN event lists

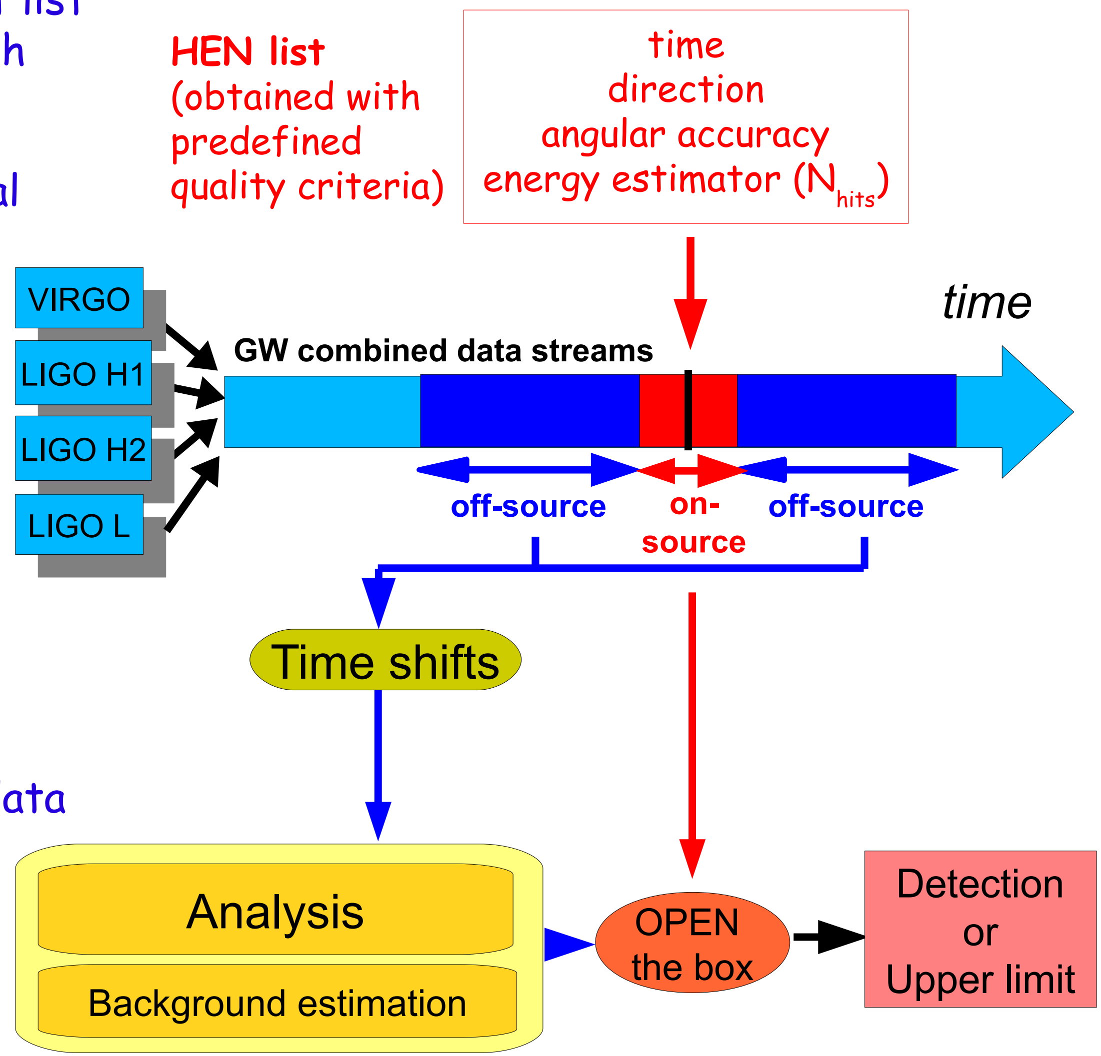
★ Allows full optimization of selection strategies !
critical parameter: combined false alarm rate
FAR(coinc) = T x FAR(GW) x FAR(HEN)



Joint analysis strategies

- ANTARES 5L /LIGO S5/VIRGO VSR1 (2007) data analysis

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



✯ uses specific analysis chain looking for unmodelled GW bursts from external triggers (e.g. GRB alerts): X-pipeline
P. Sutton et al., New J. Phys. 12 (2010)
(a variant with inspiral templates also being developed: STAMP)

◆ on-source 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

◆ high computational cost:
O(100) neutrinos O(month) processing with X-pipeline

✯ *Analysis nearly completed*