Coincident searches between GW+HEN with ANTARES+LIGO+VIRGO

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Outline

I. *GW+HEN Multi-messenger astronomy*

- GW and HEN
- GW+HEN common sources

II. Direct searches

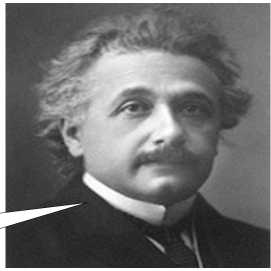
- Joint search feasibility
- First coincident search

III. ANTARES+LIGO+VIRGO data

- Search strategy

IV. Conclusions

Gravitational Waves



From General Relativity:

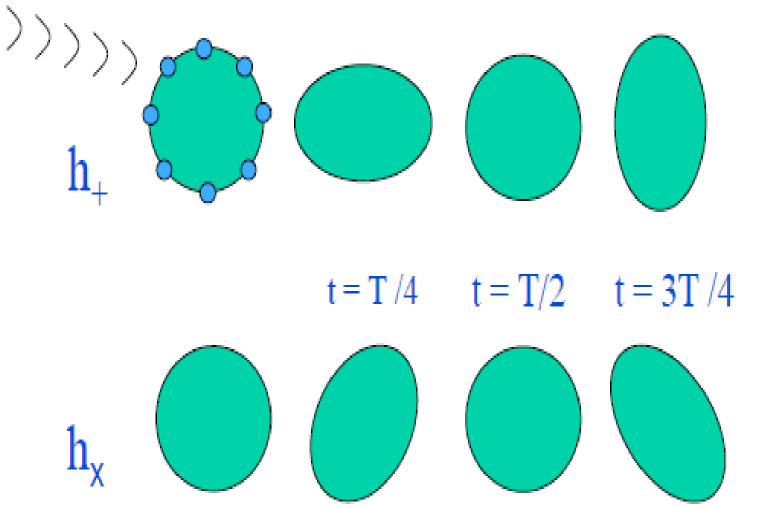
$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

Spacetime tells matter how to move, and matter tells spacetime how to curve

$$\mathbf{g} = \eta + \mathbf{h} \text{ with } |h_{\mu\nu}| << 1 \implies \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{\mu\nu} = 0$$

- Gravitational waves (GWs) are ripples in curvature caused by acceleration of masses.
- Two polarizations: hx, h+

$$\mathbf{h}(z,t) = e^{i(\omega t - kz)}\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$



- Luminosity GW:

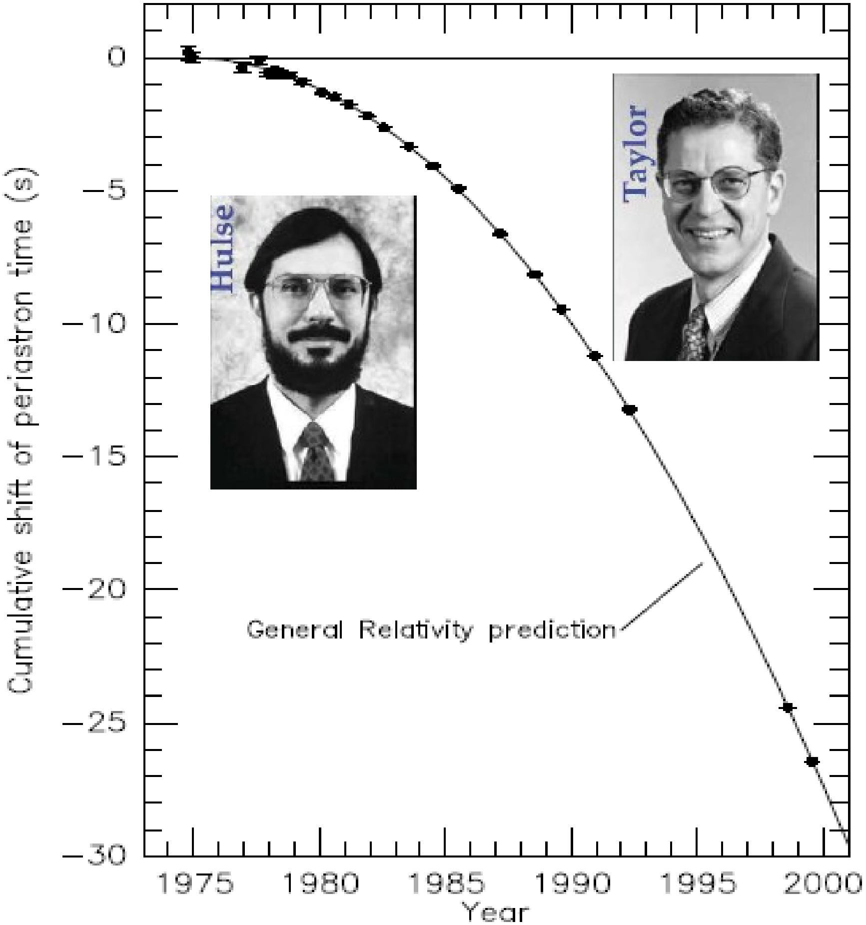
$$\mathcal{L}_{OG} = \frac{G}{5c^5}\langle \dddot{Q}_{\mu\nu}\dddot{Q}^{\mu\nu}\rangle \simeq \frac{c^5}{G}\underbrace{\epsilon^2}_{\text{asymmetric}}\underbrace{\left(\frac{R_s}{R}\right)^2}_{\text{compact}}\underbrace{\left(\frac{v}{c}\right)^6}_{\text{relativistic}}$$

Indirect evidence for gravitational radiation

- Orbital decay of PSR 1913+16
  J. M. Weisberg et al. 2010 ApJ 722 1030
  TIMING MEASUREMENTS OF THE RELATIVISTIC BINARY PULSAR PSR B1913+16

- A binary star system, (e.g NS-NS, BH-BH) should emit energy in the form of gravitational waves
- The loss of orbital energy results in shrinkage of the orbit, which is most easily observed as a decrease in orbital period

- Nobel price for Hulse&Taylor 1993



High Energy Neutrino

- Interaction of high energy particles with photons or matter
  - Protons/nuclei: pion production and decay

$p + p(\gamma) \rightarrow \pi^{\pm} + X$

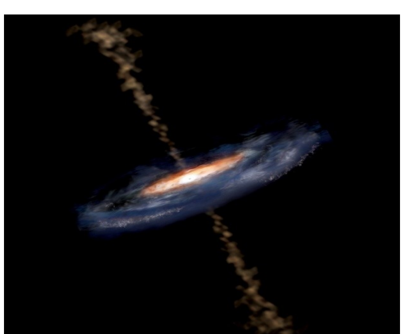
$\quad \hookrightarrow \mu + \nu_\mu$

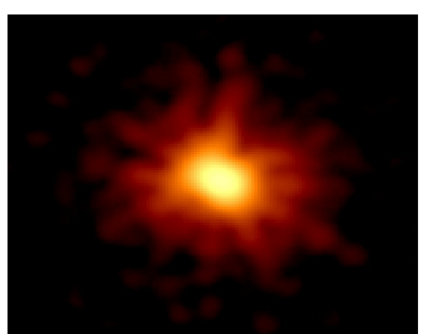
$\quad\quad \hookrightarrow e + \nu_\mu + \nu_e$

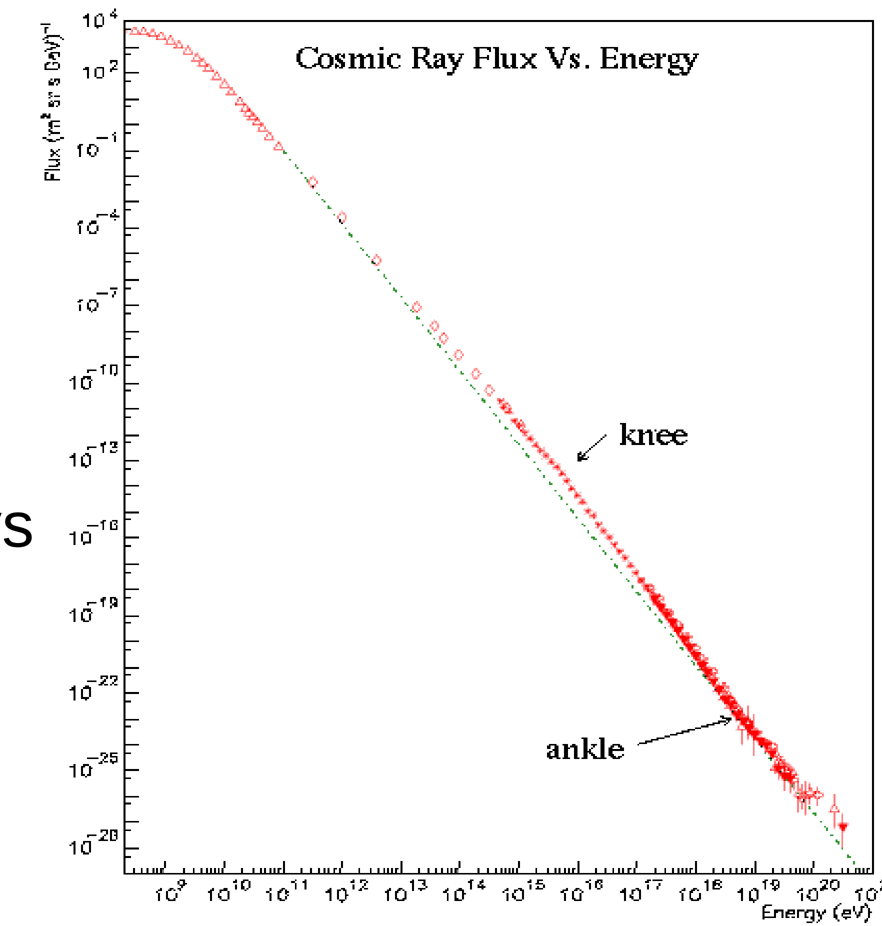
$p + p(\gamma) \rightarrow \pi^{0} + X$

$\quad \hookrightarrow \gamma + \gamma$ (TeV)

- HEN sources
  - Supernova Remnant
  - Microquasar
  - Active Galactic Nuclei
  - Gamma-ray Burst
- Sources of the high energy cosmic rays



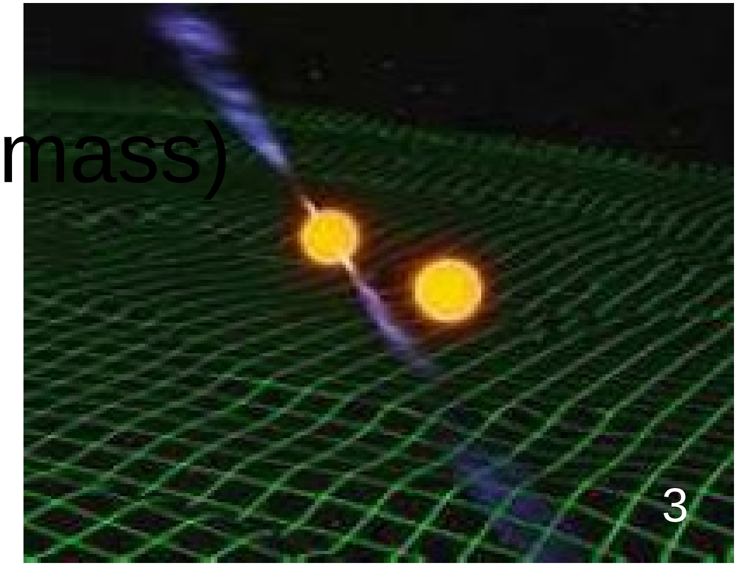




GW+HEN common sources

- GW+HEN:
  - Weak interaction with matter
  - No deflection by magnetic fields: travel undeflected over cosmological distances
  - Carry information on the internal processes of the astrophysical engines, unaccessible through photons or hadrons
  - Discovery potential for hidden sources (difficult to detect through photon/cosmic ray astronomy)

- What kind of source?
  - Compact, massive (tens x Solar mass) sudden → GW
  - Baryon loaded relativistic jets → Neutrino
  - e.g GRBs

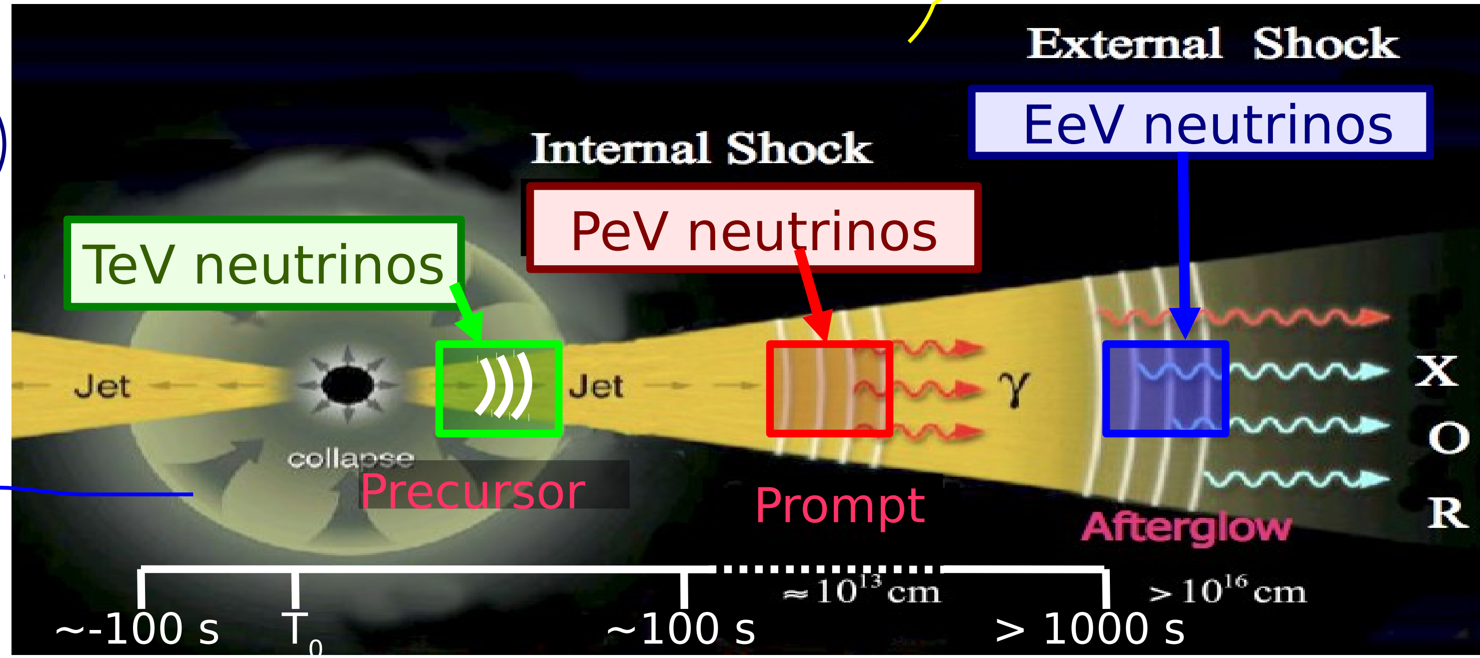


GRB case

HEN emission:
Acceleration of protons, followed by pp and pγ interactions

Fireball model:

GW emission:
Collapse or binary mergers



	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

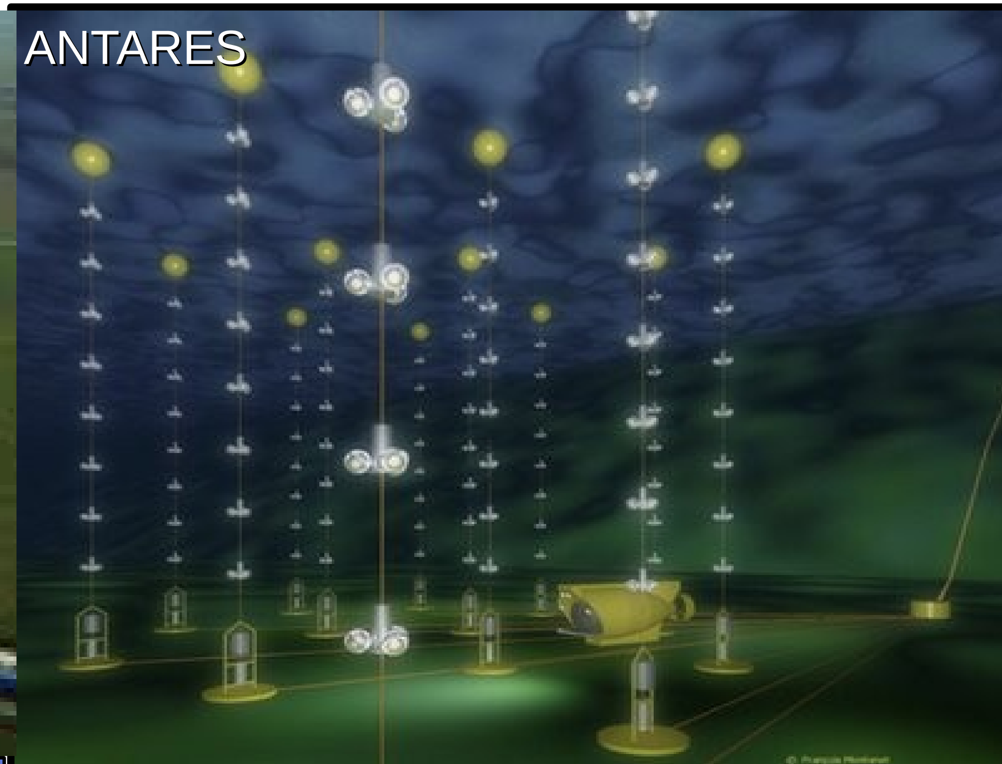
Baryon poor
Relativistic jets
Rare

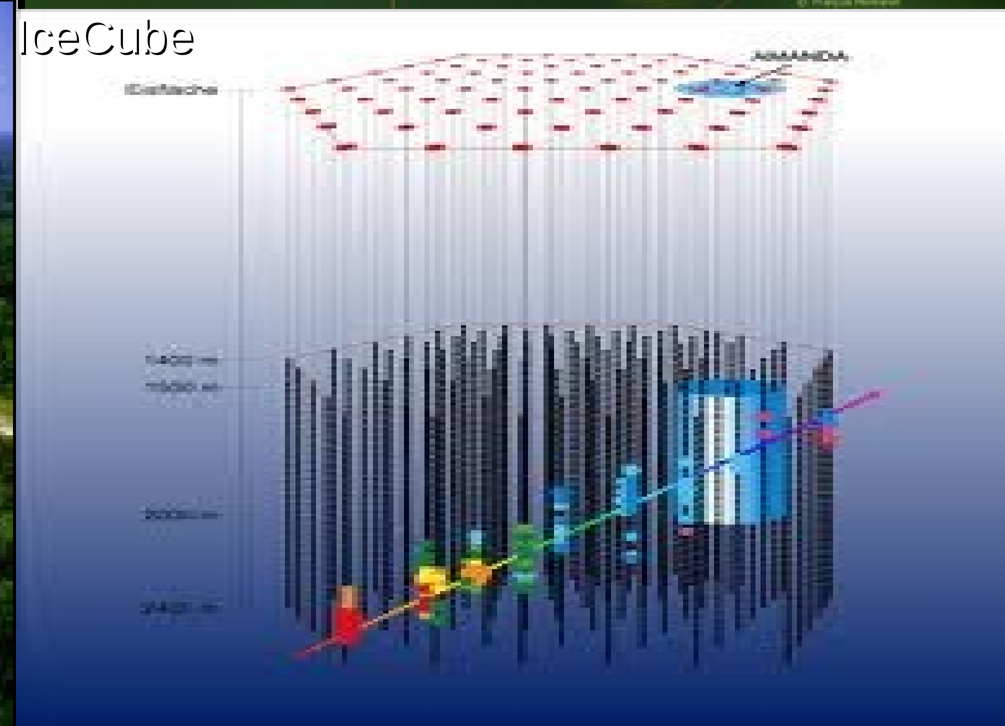
Similar kinetic energy

taken from Ando (2009)

"Failed" GRB:
- Optically thick media: no or weak γ-ray
- Possibly detectable by GW+HEN

Detector network

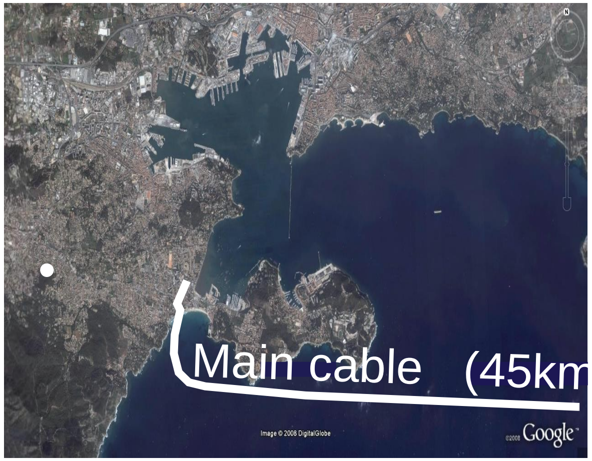


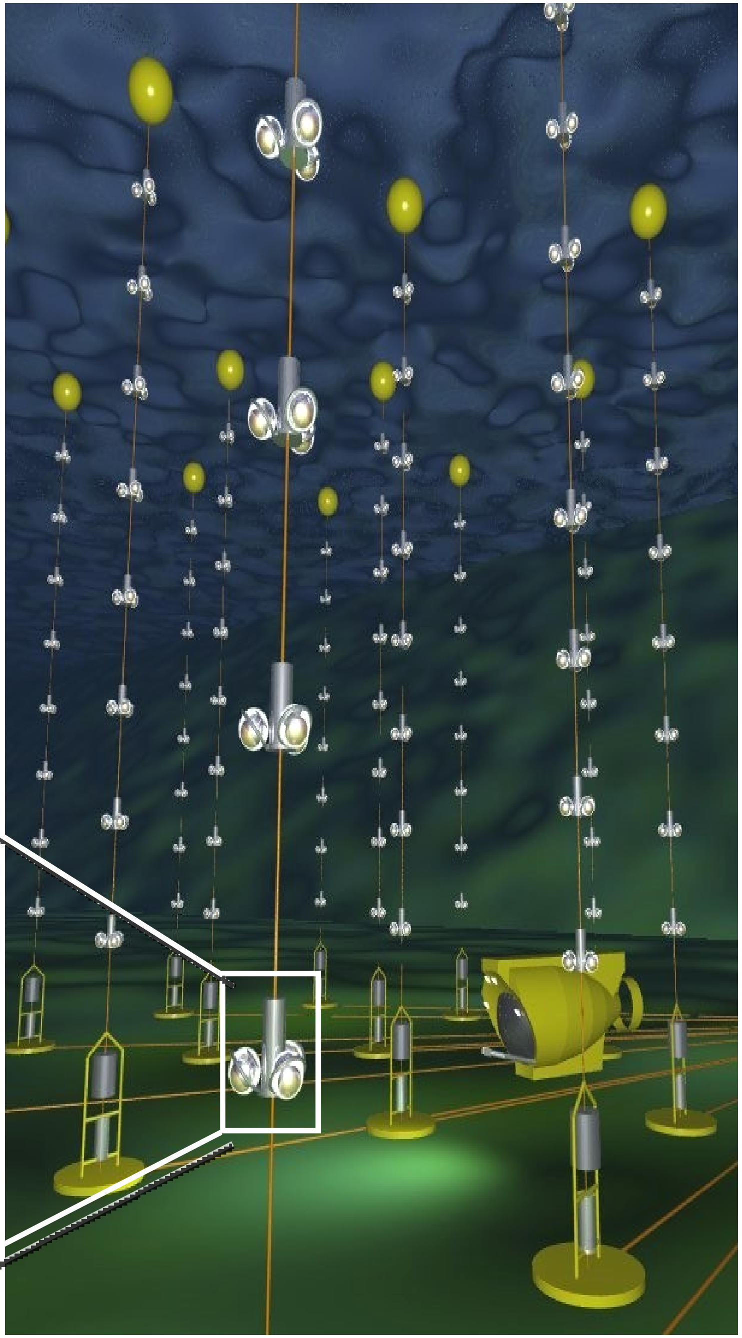


ANTARES

- 12 Lines (885 PMTs)
- Completion May 2008
- Instrumented volume: ~0.01 km^3

Shore station

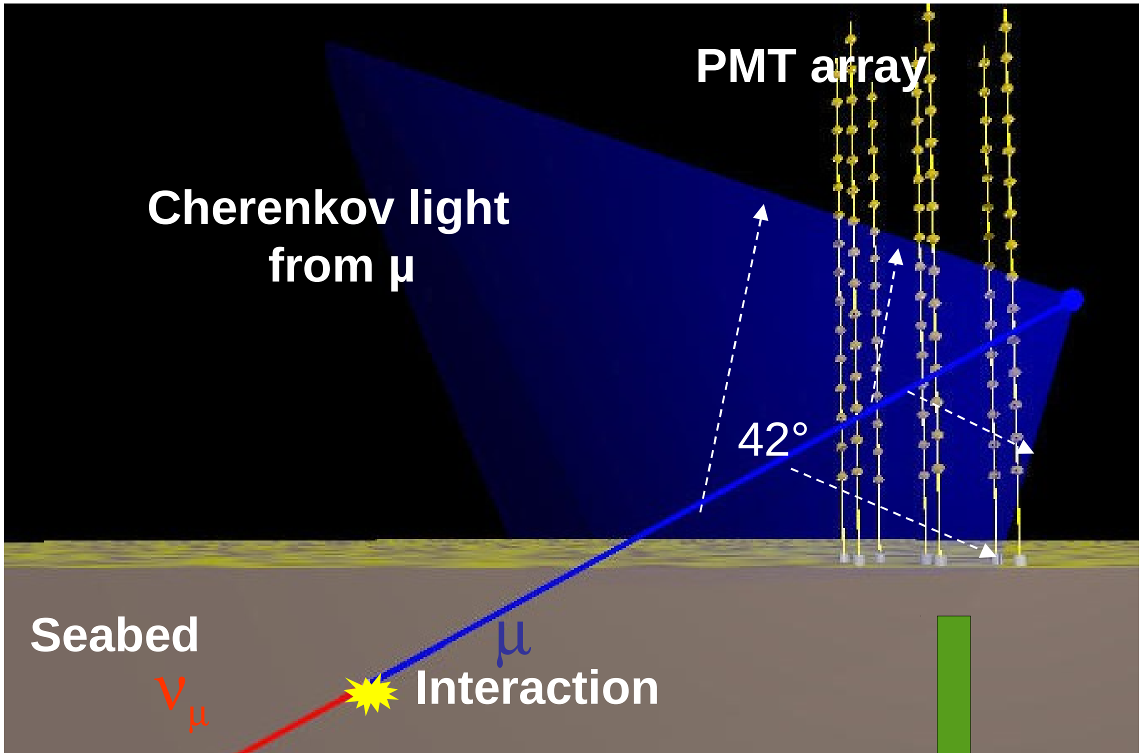




2100 m

2475 m

Antares Neutrino Telescope
Detection Principle



Neutrinos can interact with the surrounding of the detector.

<u>Main detection channel:</u>

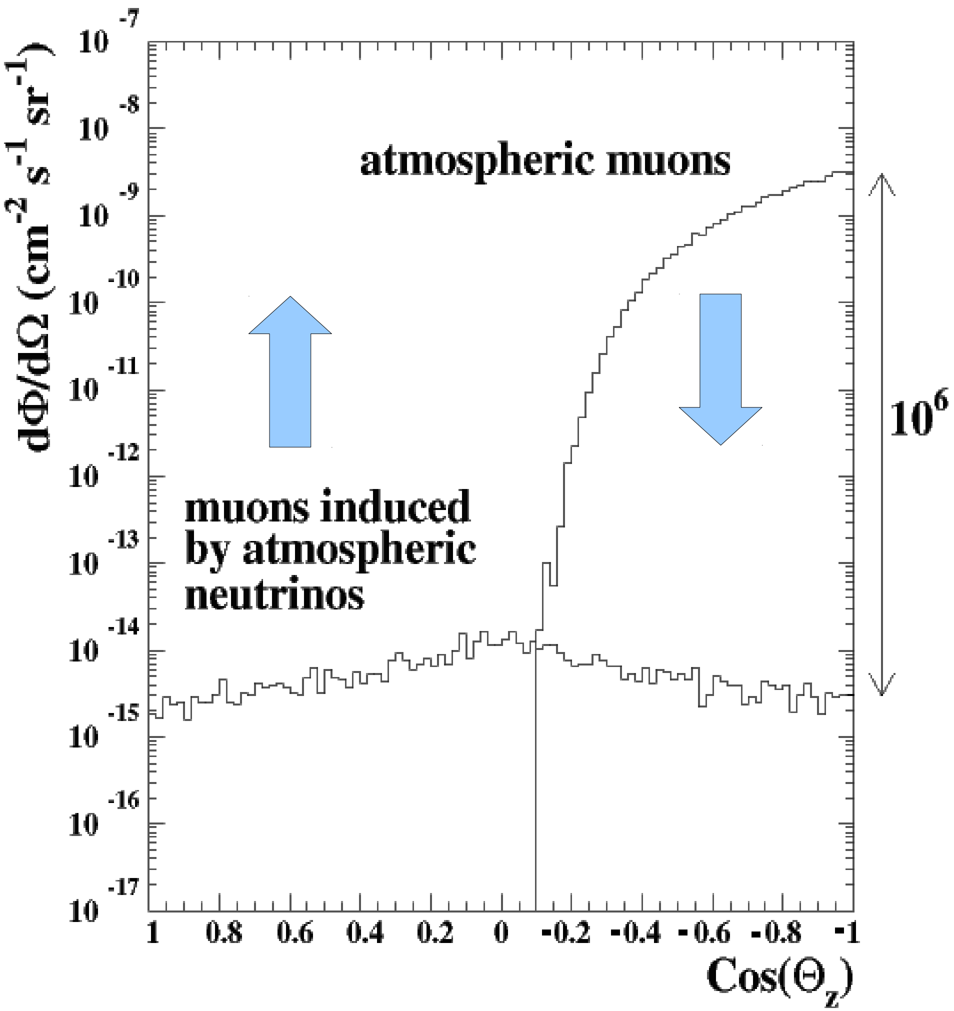
ν_μ interaction giving an ultra-relativistic μ inducing Cherenkov light in a cone (ν_e and ν_t can also be detected).

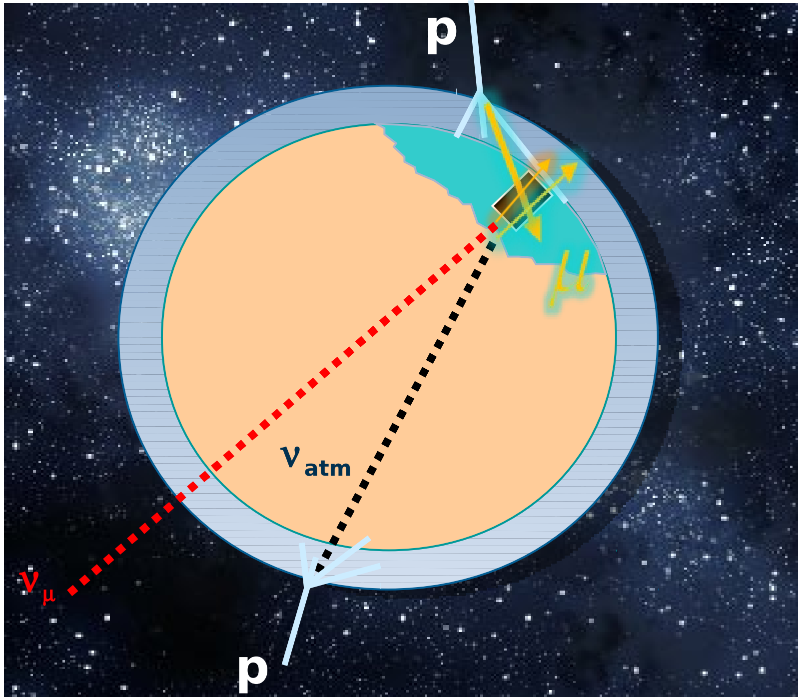
- **The main information:**
  - **Charge of the hit**
  - **Time, position of the hit**

→ Back to the neutrino (muon) track

- **Two kinds of <u>background</u> at the ANTARES site:**
  - **- Physical Background : Cosmic Rays interactions (atmospheric ν and μ).**
  - **- Optical Background: Bioluminescence and ^{40}K decay (sea environment).**

Physical Background : atmospheric muons and neutrinos





Physical background :

- Down-going muons

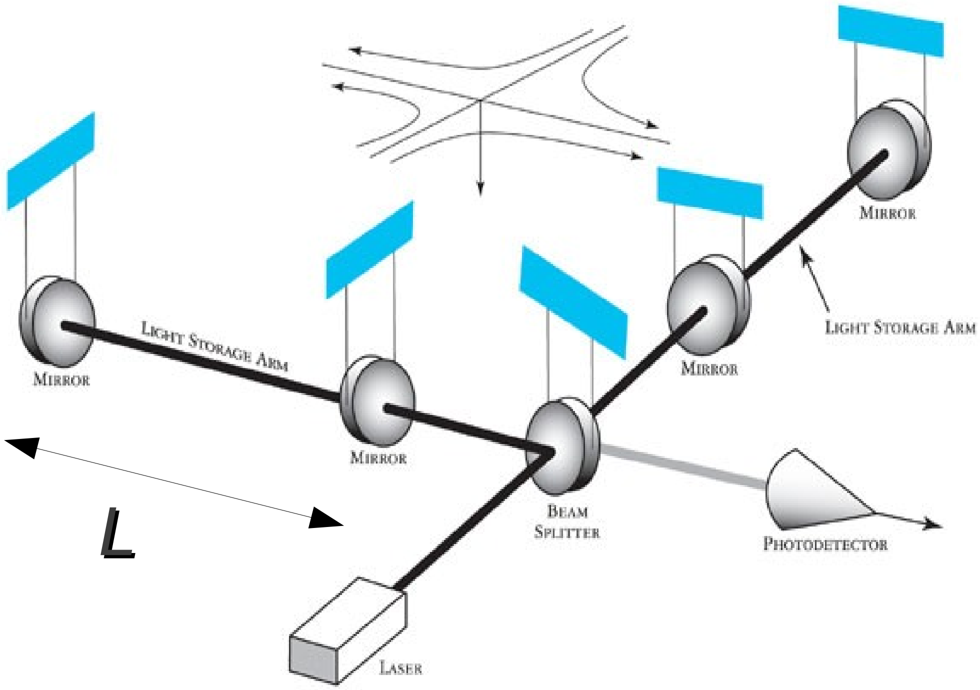
  → used to calibrate the detector

- buried deep → Shield detector
- Signal defined as up-going events

- **Cosmic vs atmospheric neutrinos: cosmic neutrinos are selected through dedicated cuts:**
  - **Search for anisotropies**
  - **Select very energetic events**
  - **Time coincidence with other messengers (e.g GW)**

GW: principle of detection

- The gravitational wave causes the time difference to vary by stretching one arm and compressing the other
- The concept is to compare the time it takes light to travel in two orthogonal directions transverse to the gravitational waves.

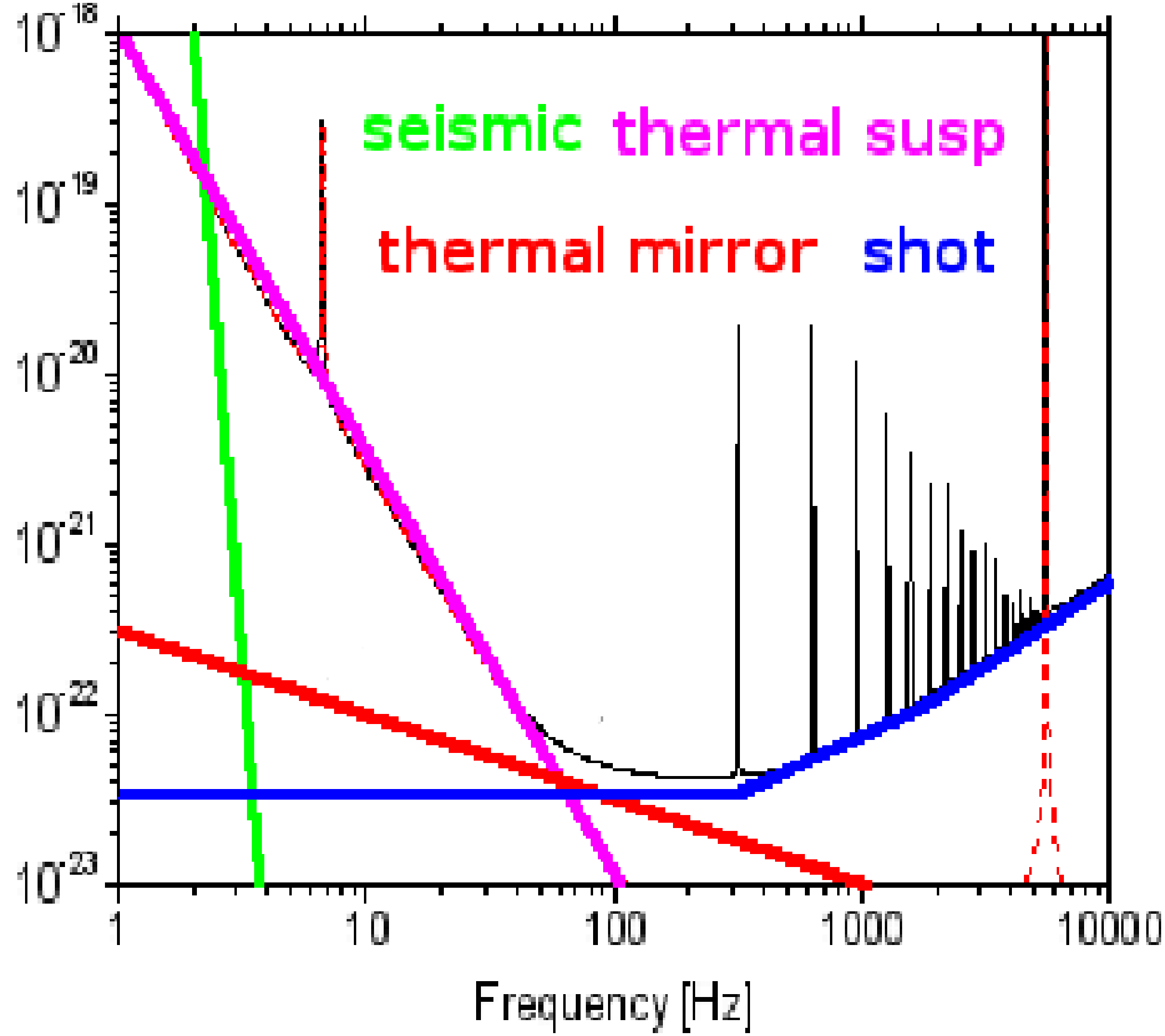


$$\frac{\Delta L}{L} = \frac{\Delta L_1 + \Delta L_2}{L} = \frac{1+\cos^2\theta}{2}\cos(2\varphi)h^{+} + \cos\theta\sin(2\varphi)h^{x}$$

GW detector noise Sources

- Sensitive frequency range:

  Few Hz to few kHz

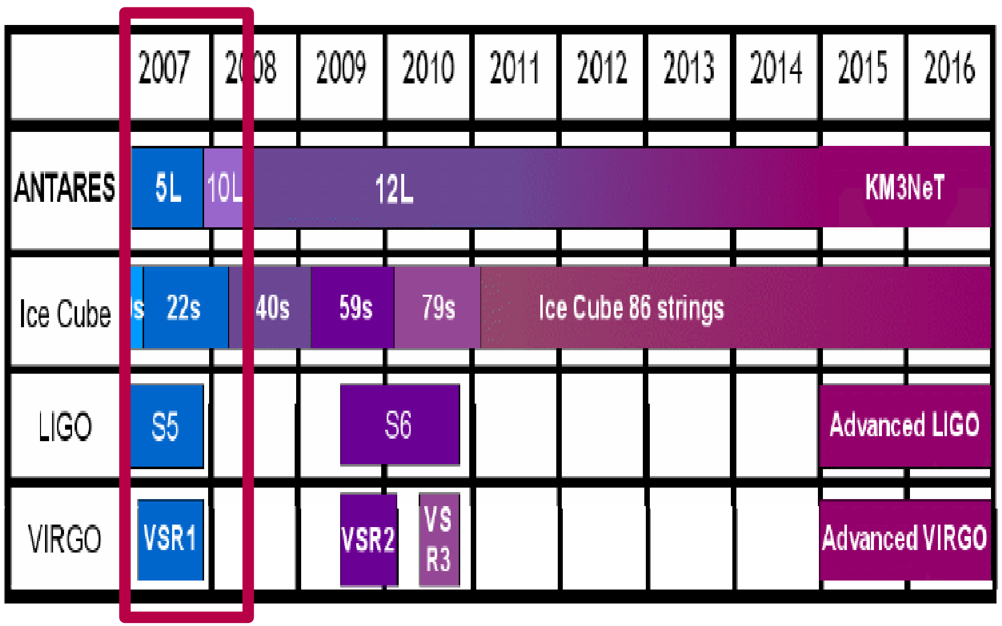


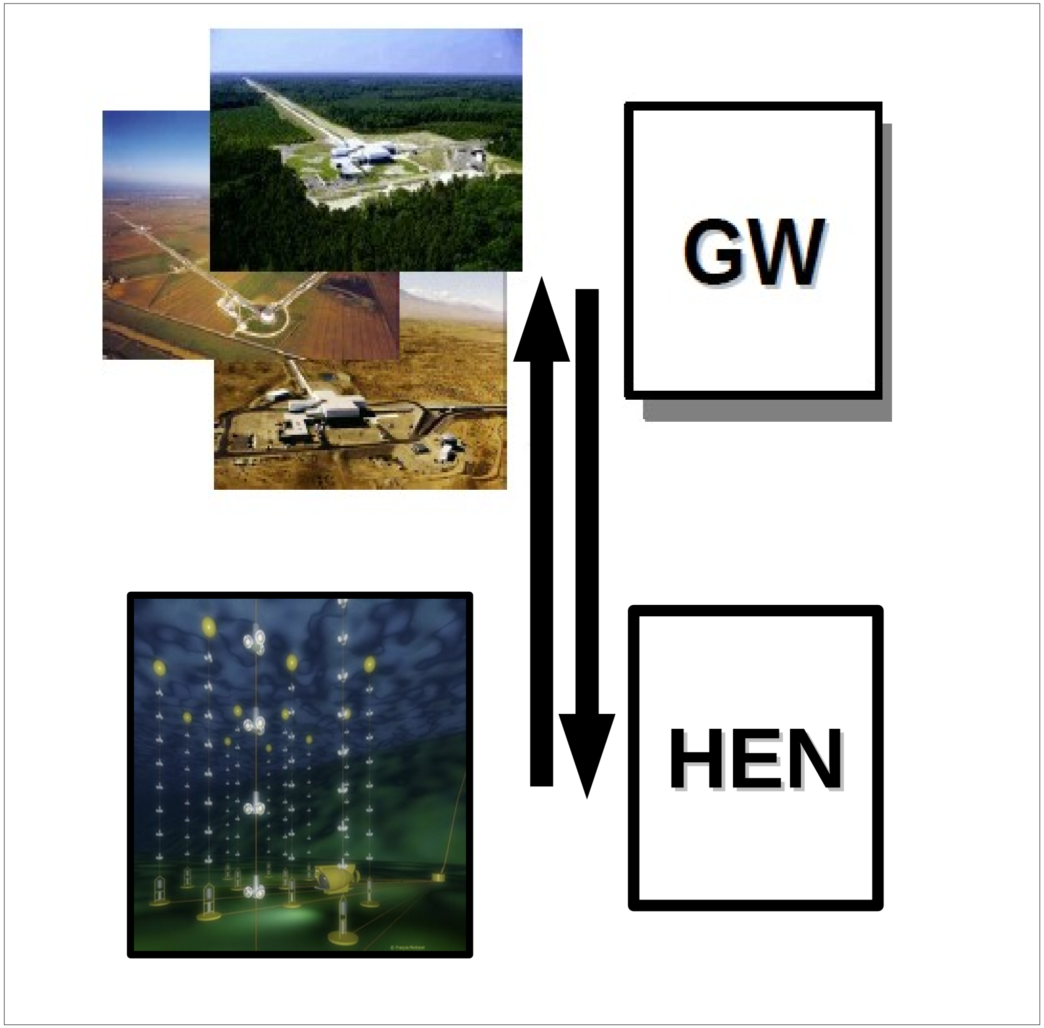
- Challenge:
  - Discriminate signal from detector noise transients (veto known artifacts)
    - Coherence in multiple detector
    - Coincidence with high energy neutrino

GW+HEN joint search

ANTARES+LIGO+VIRGO

Common observability periods

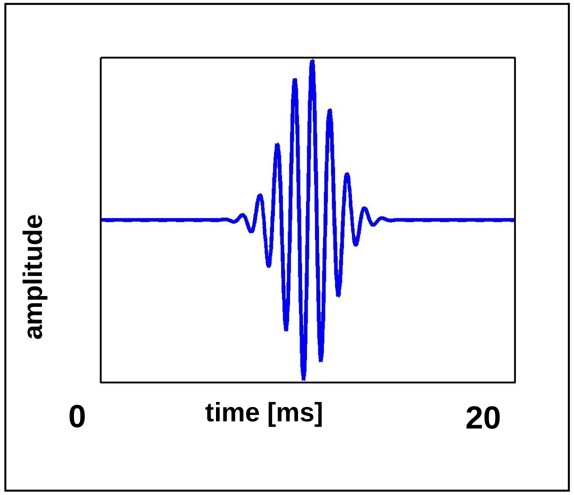




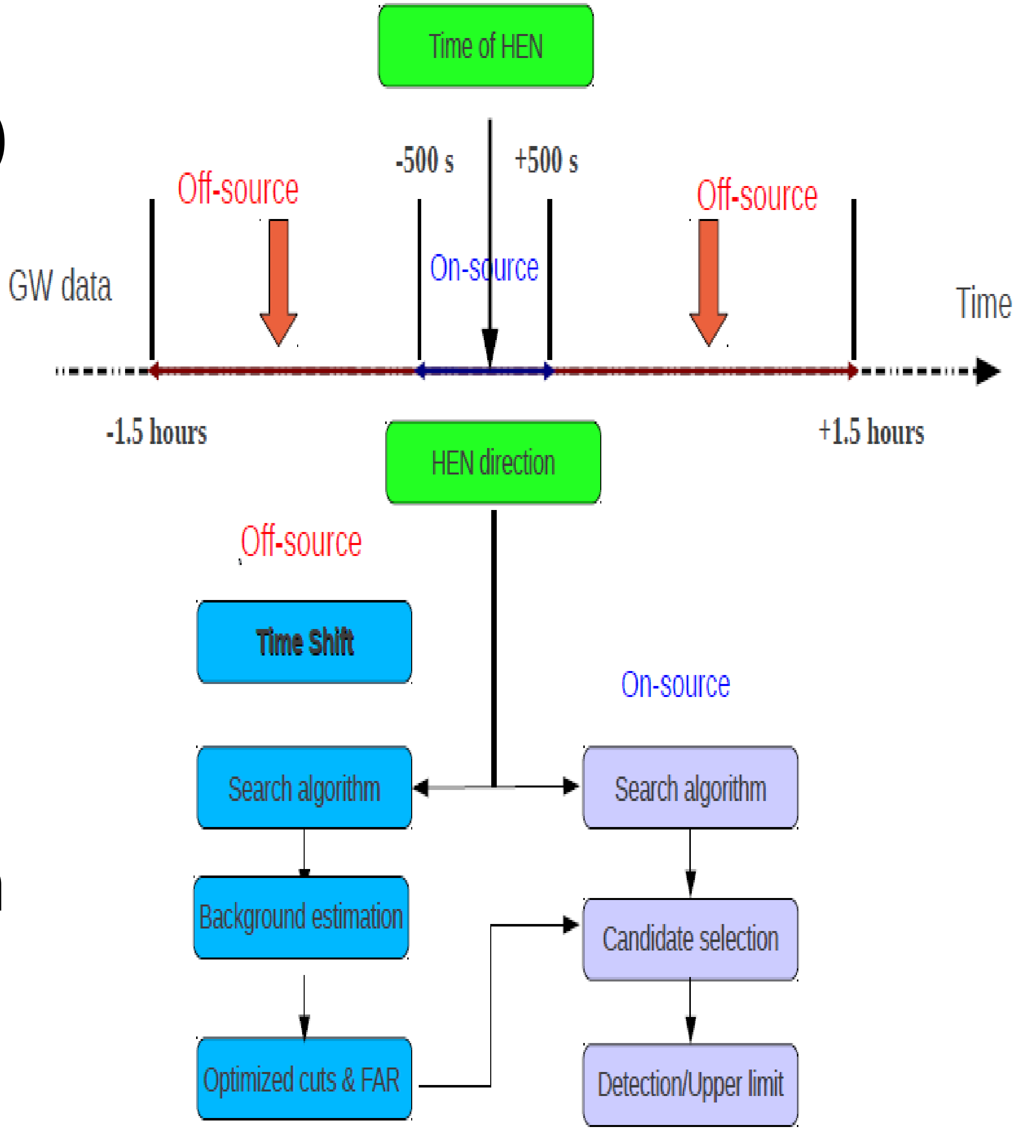
GW+HEN joint search strategy

ANTARES+LIGO+VIRGO

- 2007: 5L + S5/VSR1 (103days)
- Search for transient sources

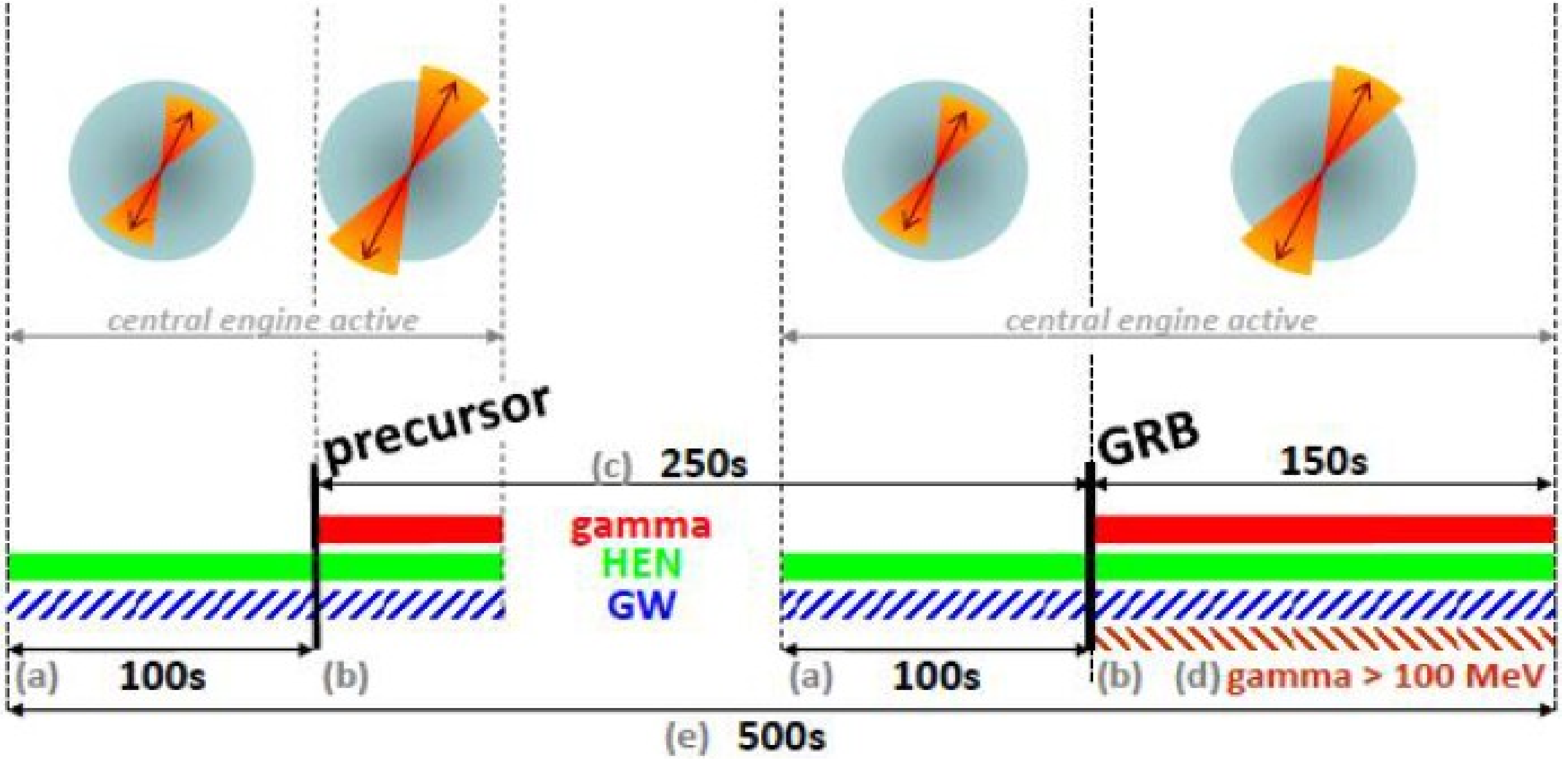


- Use HEN time and sky location as input for GW search



Time search window

Coincidence time window estimate based on GRB observation by BATSE, Swift and Fermi LAT+model of neutrino production



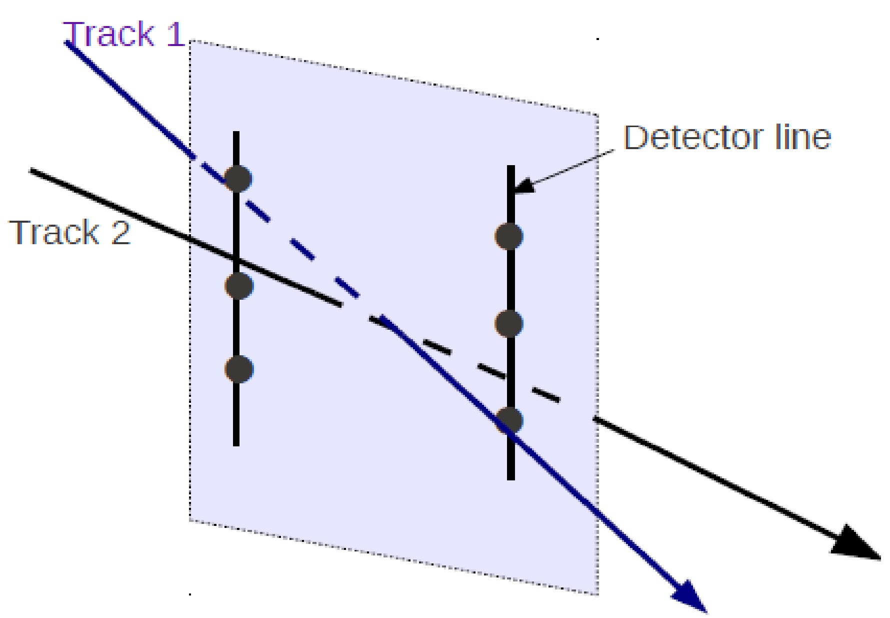
$\Delta t_{GW+HEN} = \pm 500s$

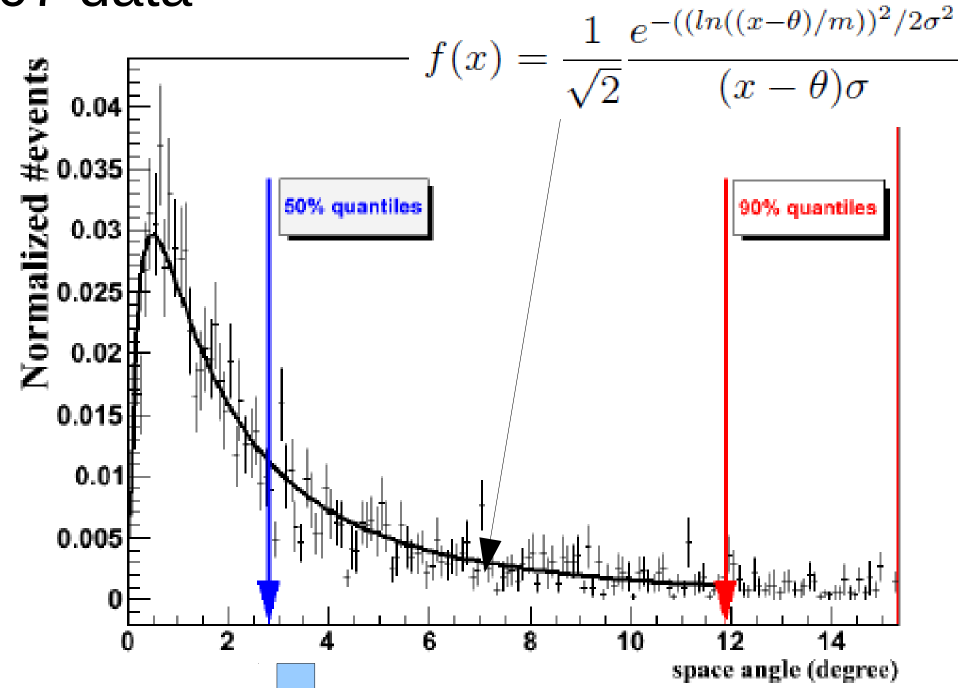
Baret et al. / Astroparticle Physics 35 (2011) 1–7

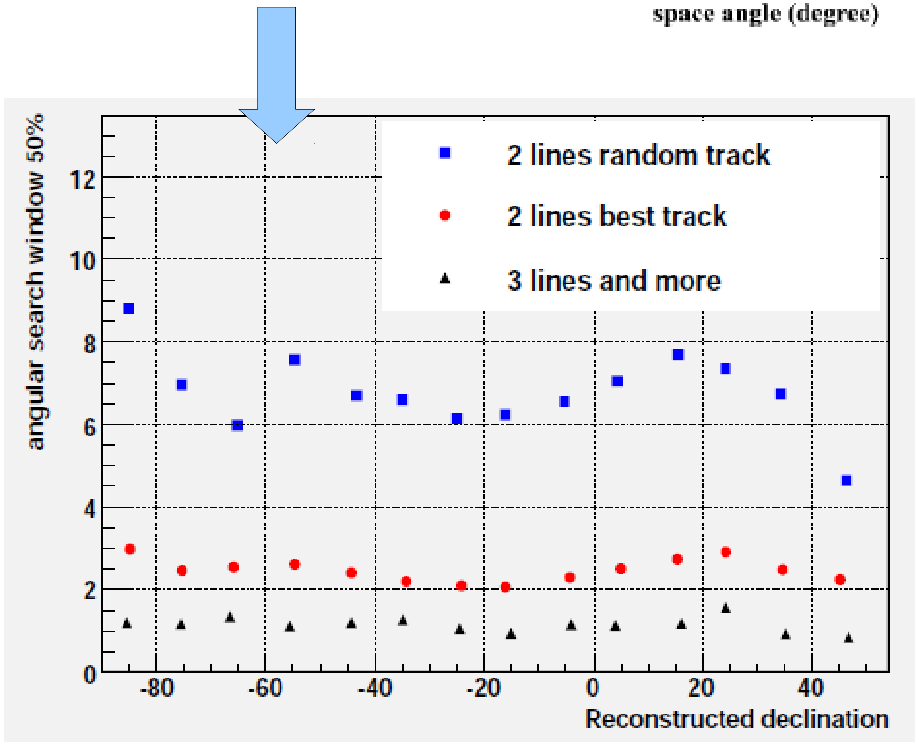
Space search window

ANTARES 2007 data

- reconstruction method based on χ^2 minimization*
  - Select only the direct photons (unscattered)
  - Ignore the detector geometry (events reconstructed with 2L have two mirror solutions)
- Optimization for an E^{-2} flux



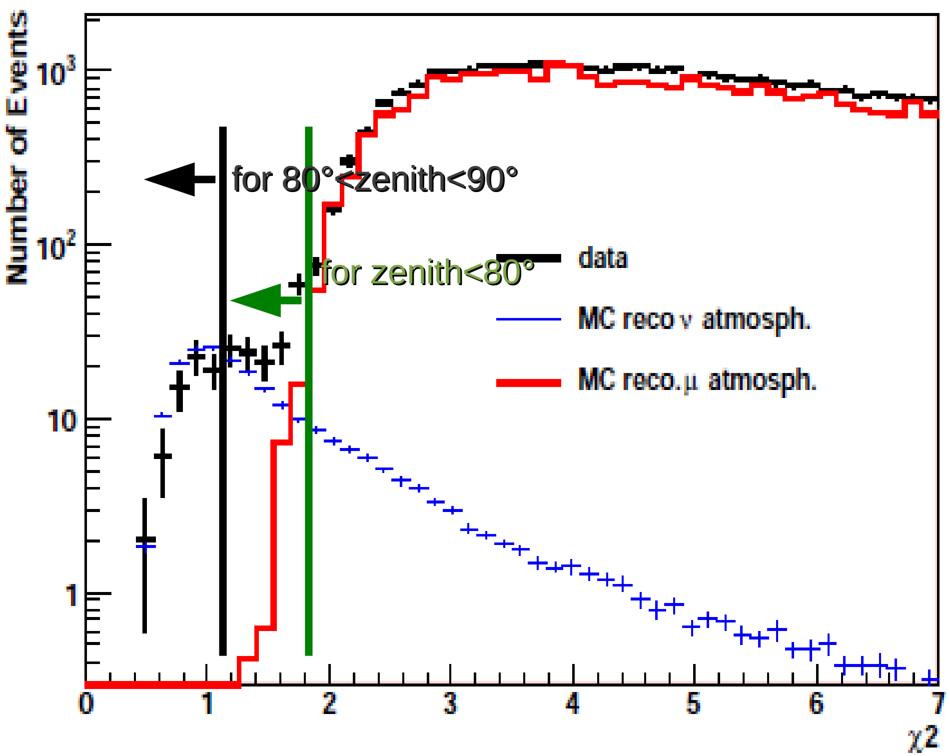


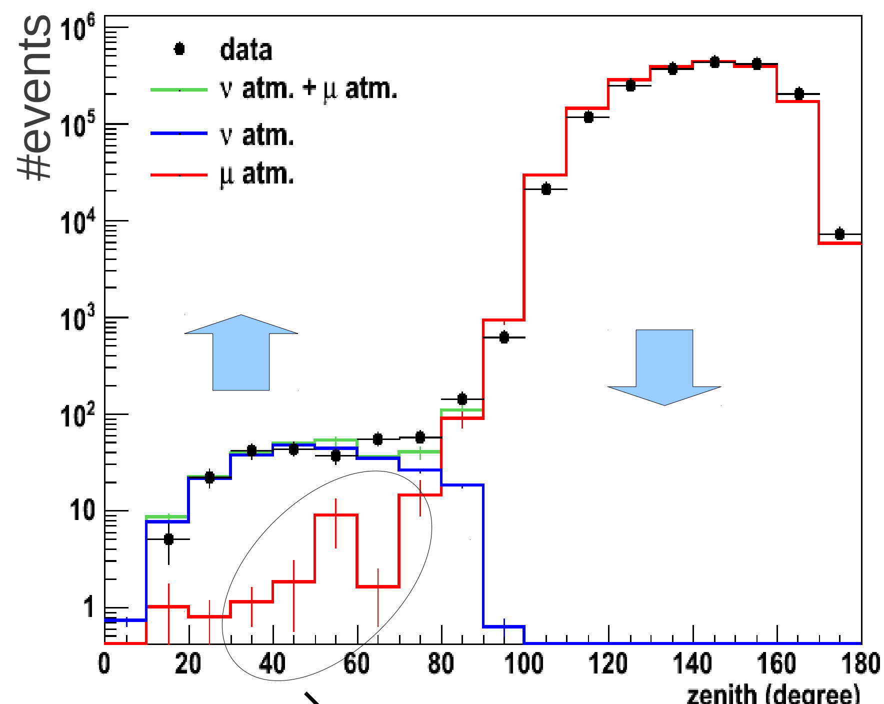


*Astroparticle Physics 34 (2011)652–662

HEN selection criteria

- Upward going events in the detector
- Cut on the quality of the reconstructed muon track
- Selection of HEN based on the number of photons in the event.



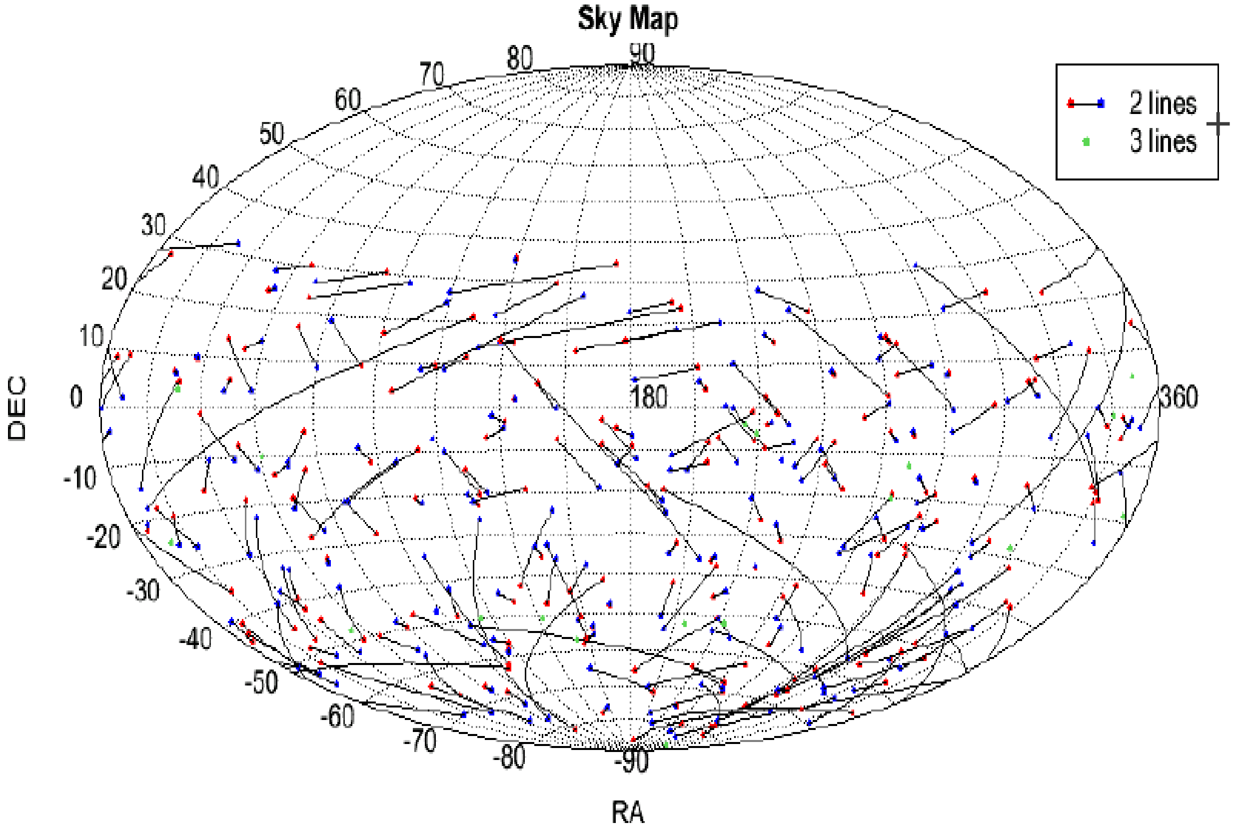


Downgoing atmospheric muons reconstructed as upgoing

Final HEN set

- 216 neutrino candidates (198 with mirror tracks)
- Each candidate is characterized by its:
  - Arrival time t_{HEN}
  - Sky location (RA, Dec)
  - Error box ASW_{HEN}

SkyMap of the selected events in equatorial coordinates



GW coherent search

- Combine data from many IFOs
- Select data segments in Δt_{HEN+GW} window around the t_{HEN}
- Use X-pipeline* for the GW search

reconstructed from **2 Lines**

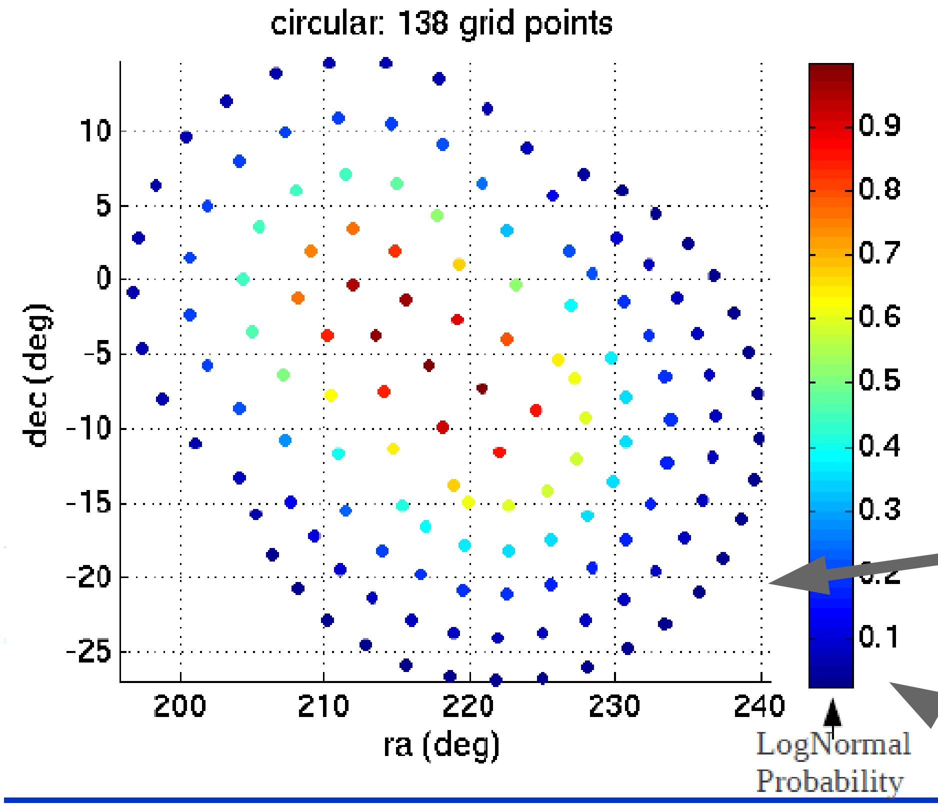
# neutrinos	4 IFOs	3 IFOs	2 IFOs
143	60	58	25

55 triggers cannot be analyzed because there aren't enough IFOs in network.

reconstructed from **3 Lines** + more

# neutrinos	4 IFOs	3 IFOs	2 IFOs
14	3	7	4

4 triggers cannot be analyzed because there aren't enough IFOs in network.



- At least two GW detectors are required to enable background estimation via time shifts
- Use HEN error box for GW search

$$f(x) = \frac{1}{\sqrt{2}} \frac{e^{-((ln((x-\theta)/m))^2/2\sigma^2}}{(x-\theta)\sigma}$$

* P. Sutton et al 2010 New J. Phys. 12 053034

Conclusion

- First joint search has been completed with ANTARES (5L) LIGO+VIRGO (S5+VSR1)
  - Review ongoing
  - No detection
  - astrophysical implications under study

- Ongoing data analysis
  - ANTARES (12L) + LIGO+VIRGO (S6+VSR2-3)
    - Expect O(1000) HEN candidates
    - Improved track reconstruction algorithm
    - Improved angular resolution < 0.5°
    - Use specific GW pipeline

- Future:
  - Km3net neutrino telescope: Sensitivity x 50
  - Advanced Virgo & Advanced LIGO: Sensitivity x 10
    - Horizon 200 Mpc