



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

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the Virgo collaboration

5<sup>th</sup> International Workshop on Very Large Volume Neutrino Telescopes

# Outline

## I. GW+HEN Multi-messenger astronomy

- GW+HEN common sources
- GW+HEN detection

## II. Direct searches

- Joint search feasibility
- First coincident search

## III. ANTARES+LIGO+VIRGO data

- Search strategy
- Off-source results

## IV. Conclusions

# GW+HEN common sources

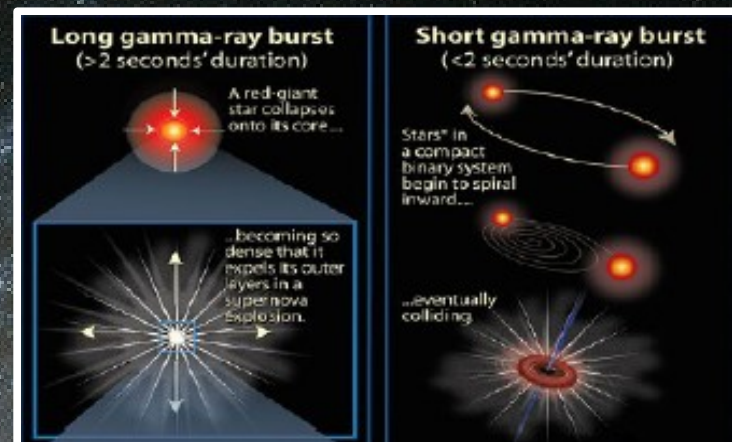
- GW+HEN:
  - Weak interaction with matter
  - No deflection by magnetic fields: travel undeflected over cosmological distances
  - Carry information on the internal processes of the astrophysical engines, unaccessible through photons or hadrons
  - Discovery potential for hidden sources (difficult to detect through photon/cosmic ray astronomy)
- What kind of source?
  - Compact, massive (tens x Solar mass)  
sudden  $\Rightarrow$  GW
  - Baryon loaded relativistic jets  
 $\Rightarrow$  Neutrino
  - e.g GRBs



# GRB case

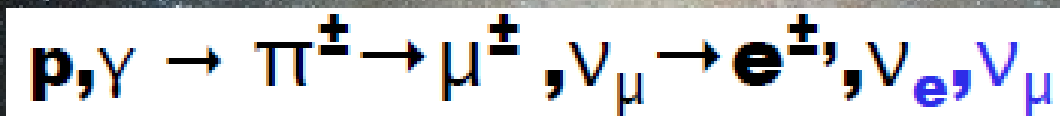
GW emission:

- Collapse or binary mergers



HEN emission:

- Acceleration of protons, followed by pp and py interactions → Neutrinos



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

Barion rich  
Nonrelativistic  
Frequent



Similar kinetic energy

Baryon poor  
Relativistic jets  
Rare

"Failed" GRB:

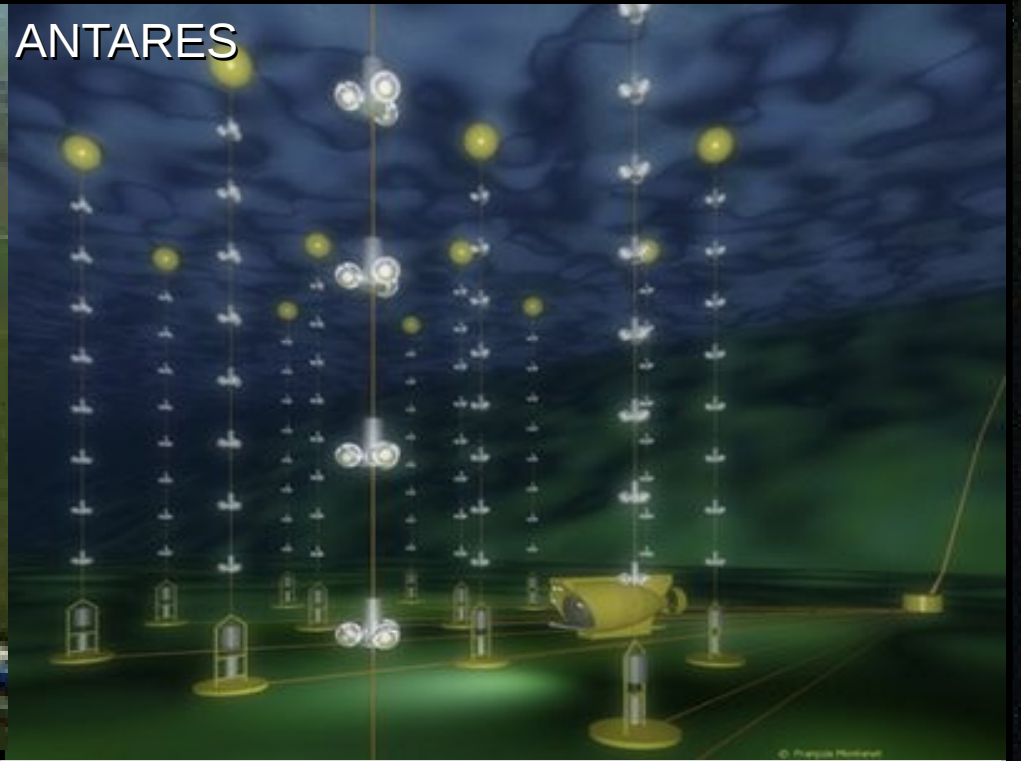
- Optically thick media: no or weak  $\gamma$ -ray
- Possibly detectable by GW+HEN

# Detector network

VIRGO



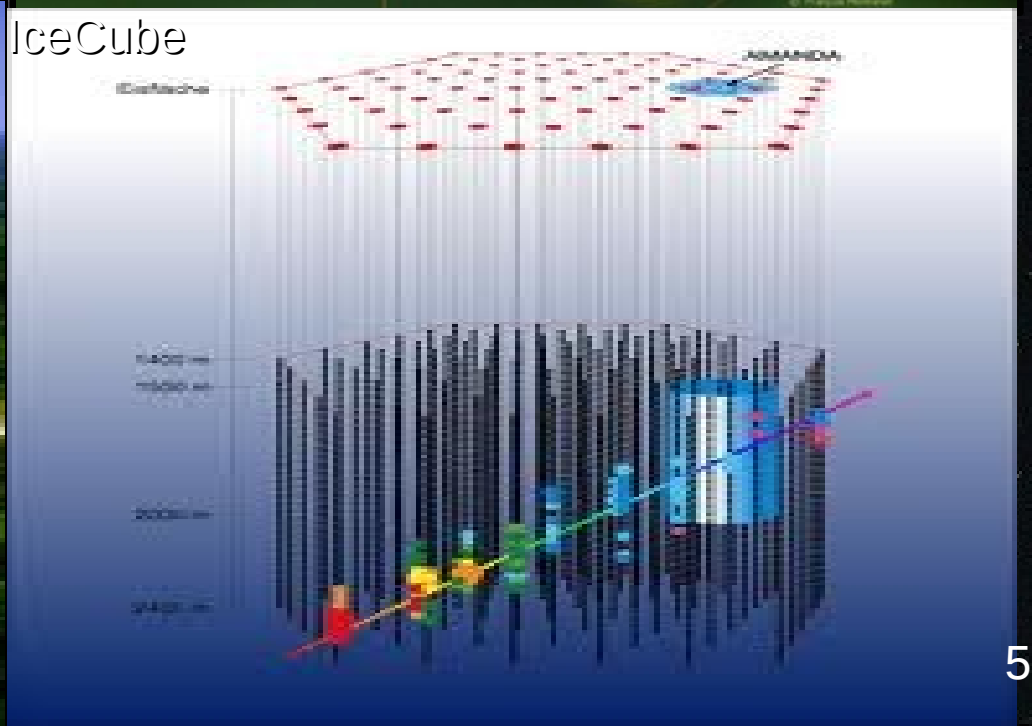
ANTARES



LIGO



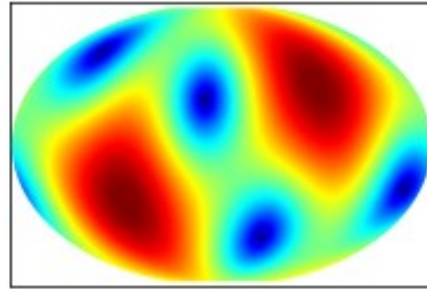
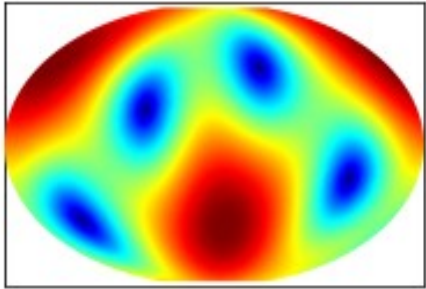
IceCube



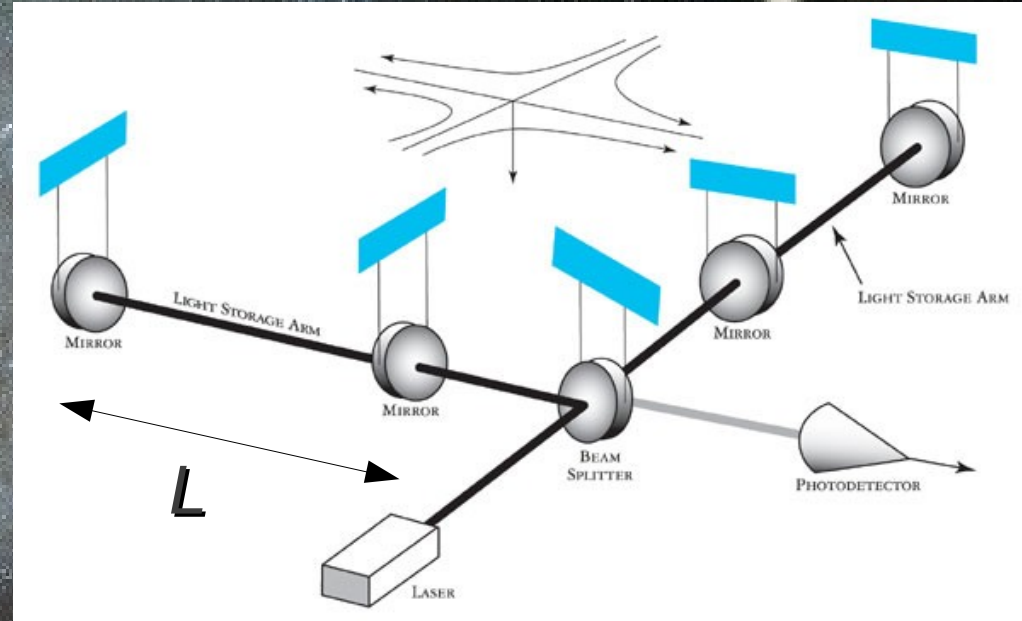
# Joint search feasibility

ANTARES+LIGO+VIRGO

Virgo  $(F_+^2 + F_\times^2)^{1/2}$  LIGO L



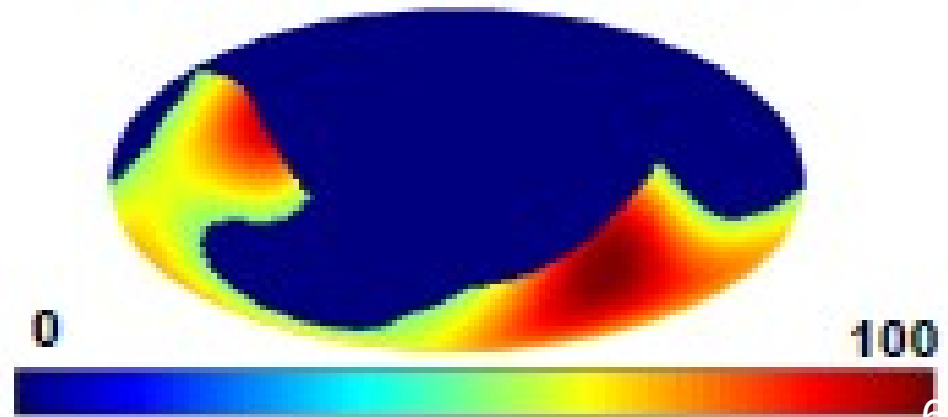
$$h(t) = \frac{\Delta L}{L} = F_+(\theta, \phi)h_+(t) + F_\times(\theta, \phi)h_\times(t) + n(t)$$



## Overlap visibility of the sky

Instantaneous common sky coverage for VIRGO + LIGO + ANTARES in geocentric coordinates

combined sky coverage  
ANTARES + VIRGO + LIGO



# Joint search feasibility (2)

ANTARES+LIGO+VIRGO

## Common observability periods

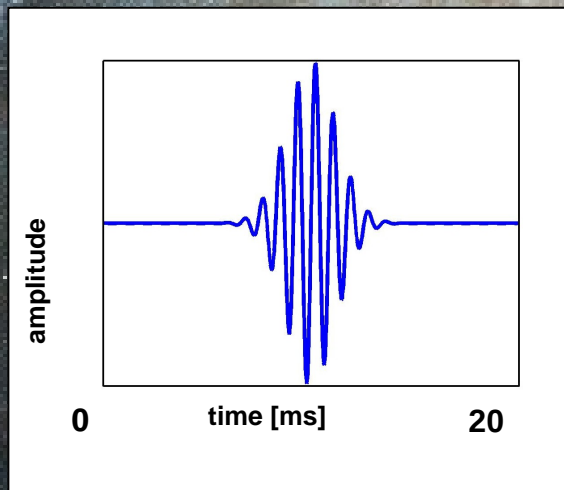
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	
ANTARES	5L	10L	12L						KM3NeT		
Ice Cube	s	22s	40s	59s	79s	Ice Cube 86 strings					
LIGO	S5			S6					Advanced LIGO		
VIRGO	VSR1		VSR2	VS R3					Advanced VIRGO		

# Joint search strategy

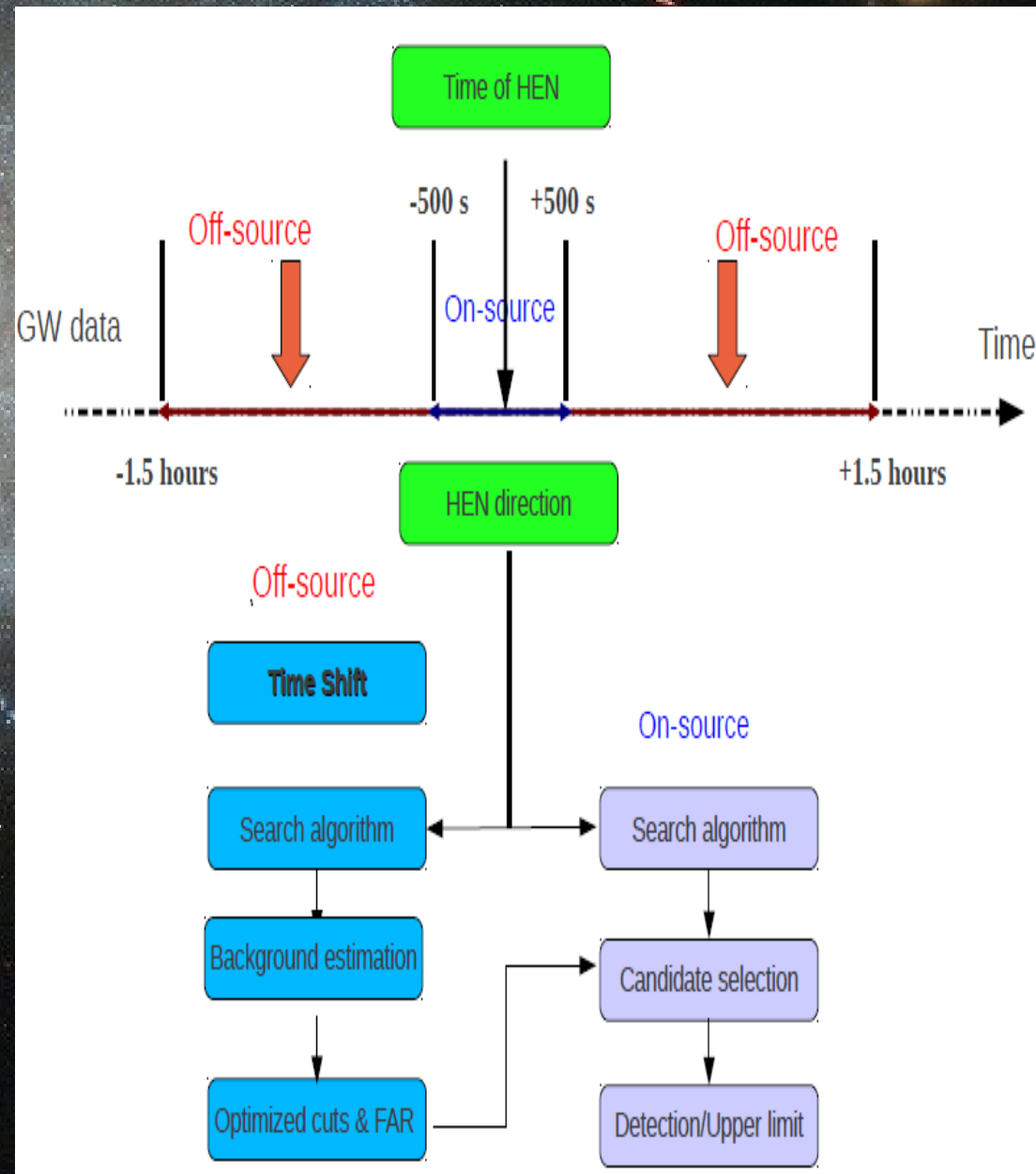
## ANTARES+LIGO+VIRGO

### Concomitant data

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



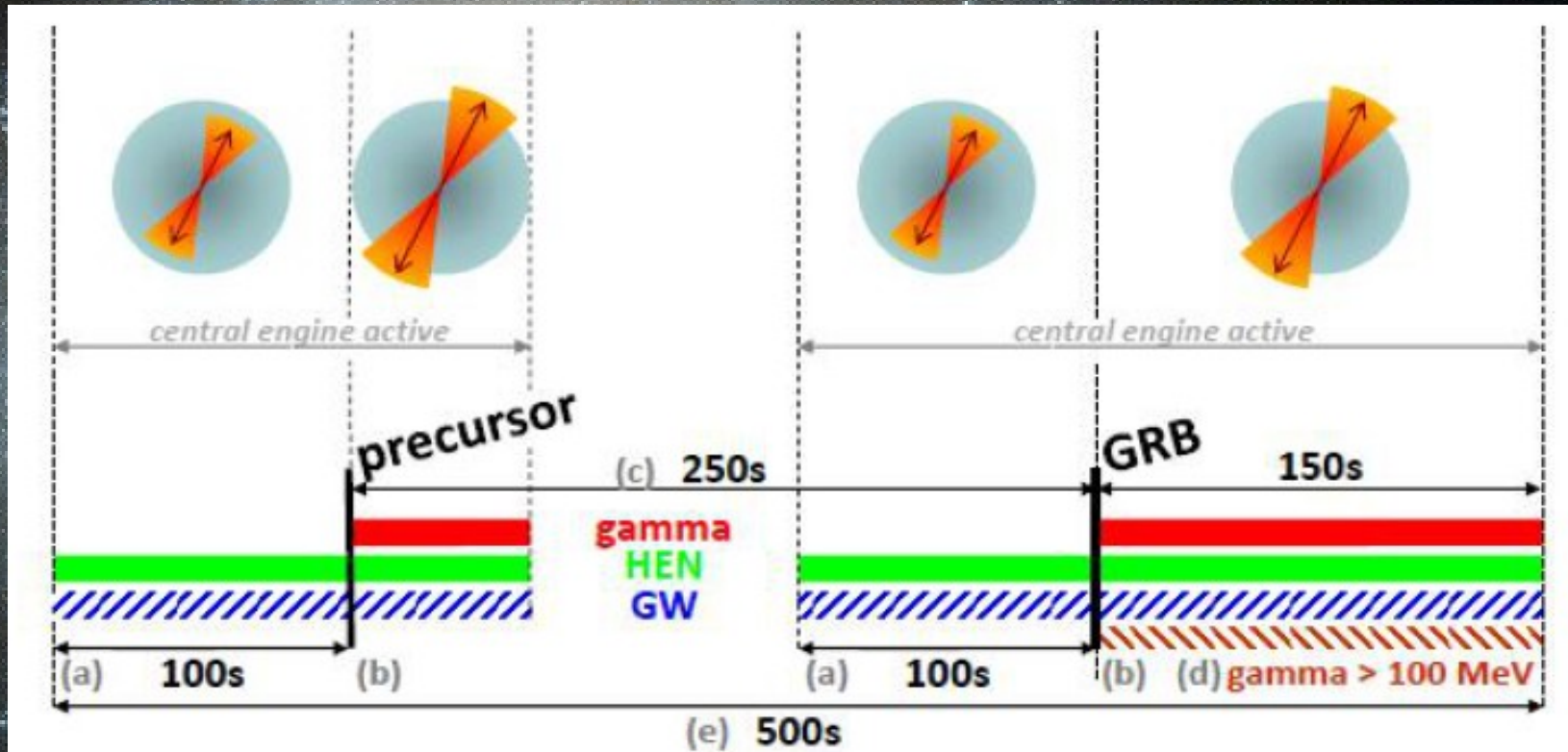
- Use HEN time and sky location as input for GW search





# Time search window

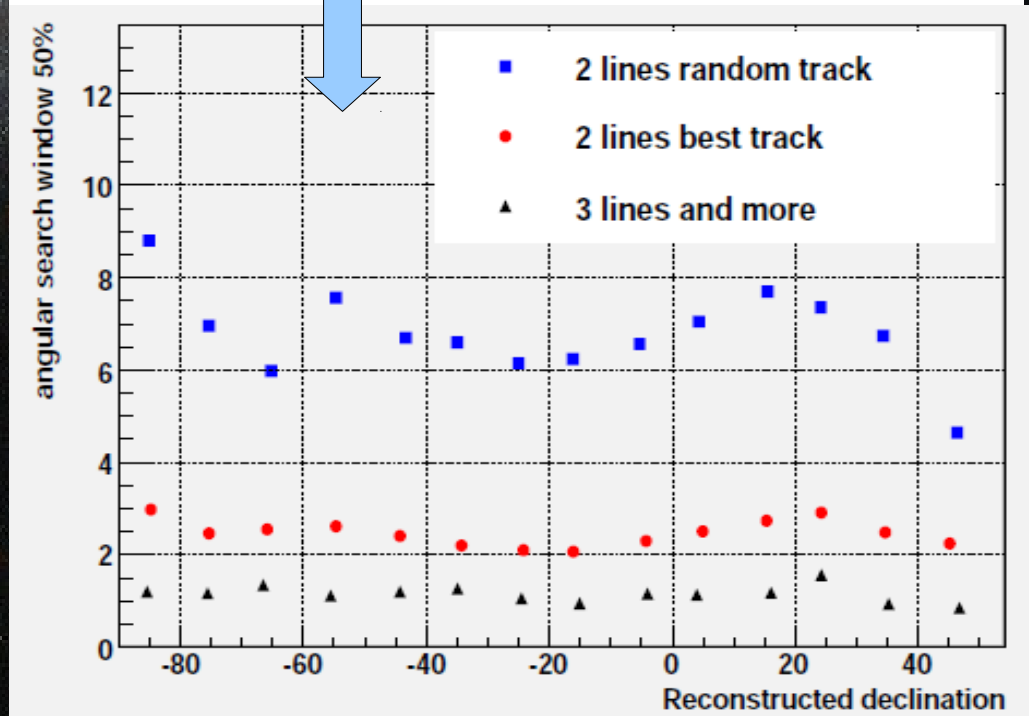
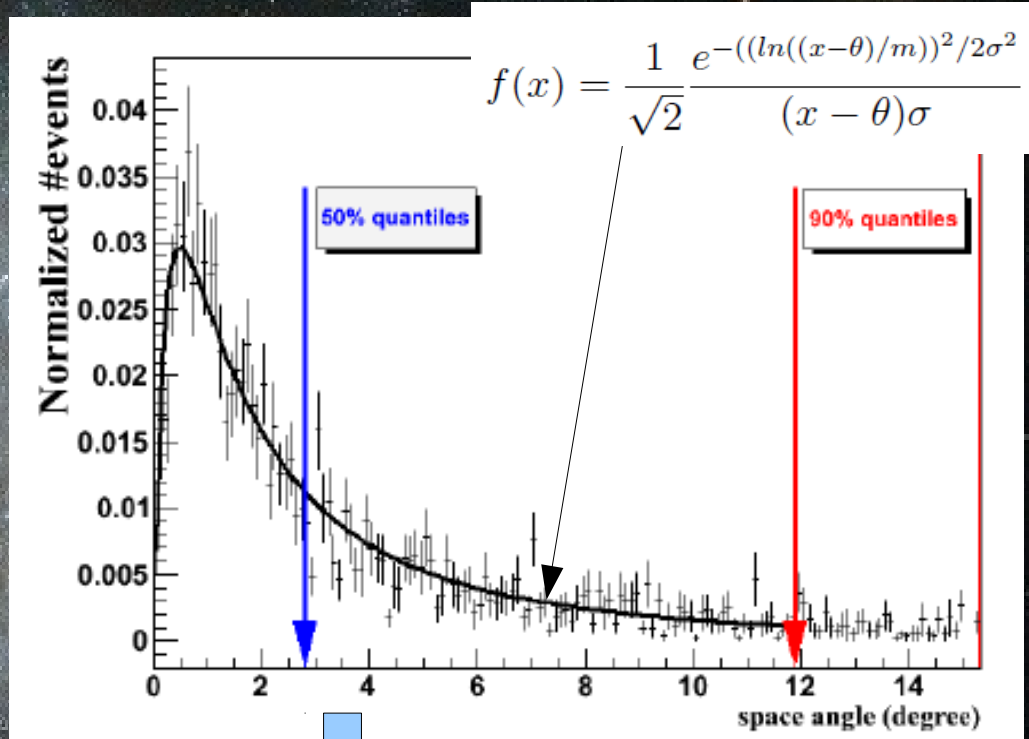
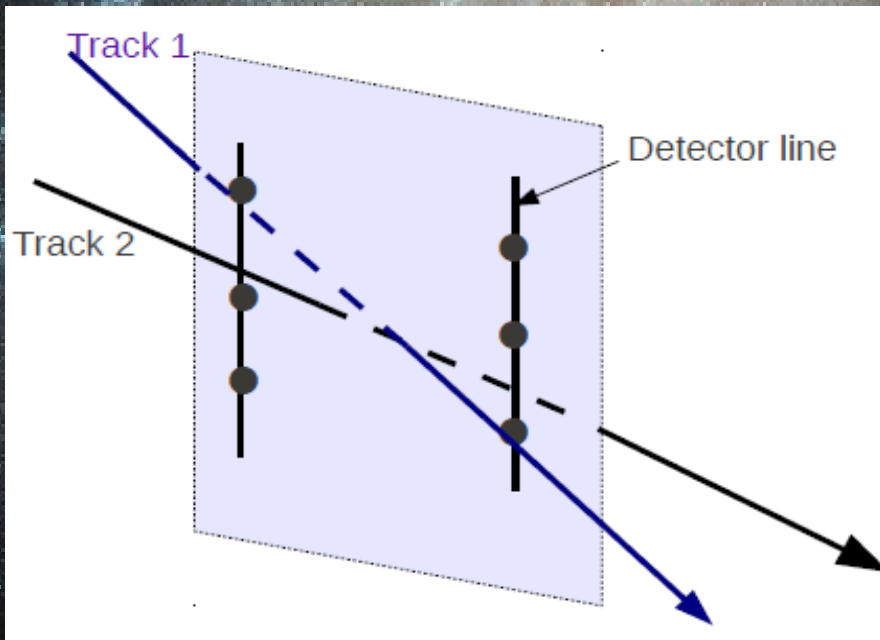
Coincidence time window estimate based on GRB observation by BATSE, Swift and Fermi LAT



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

# Space search window

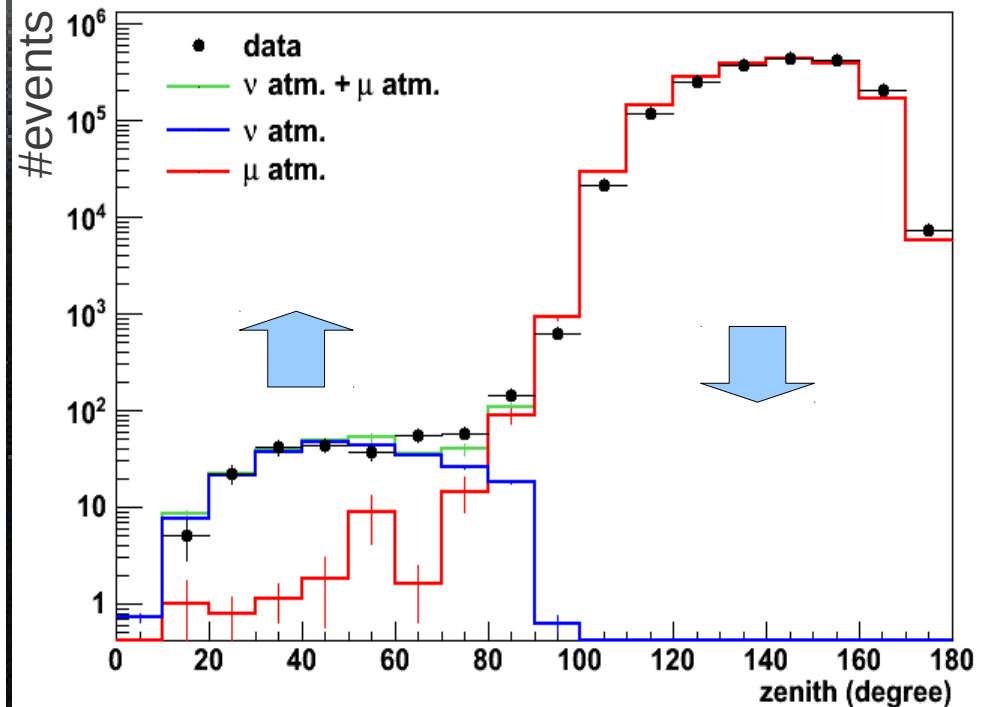
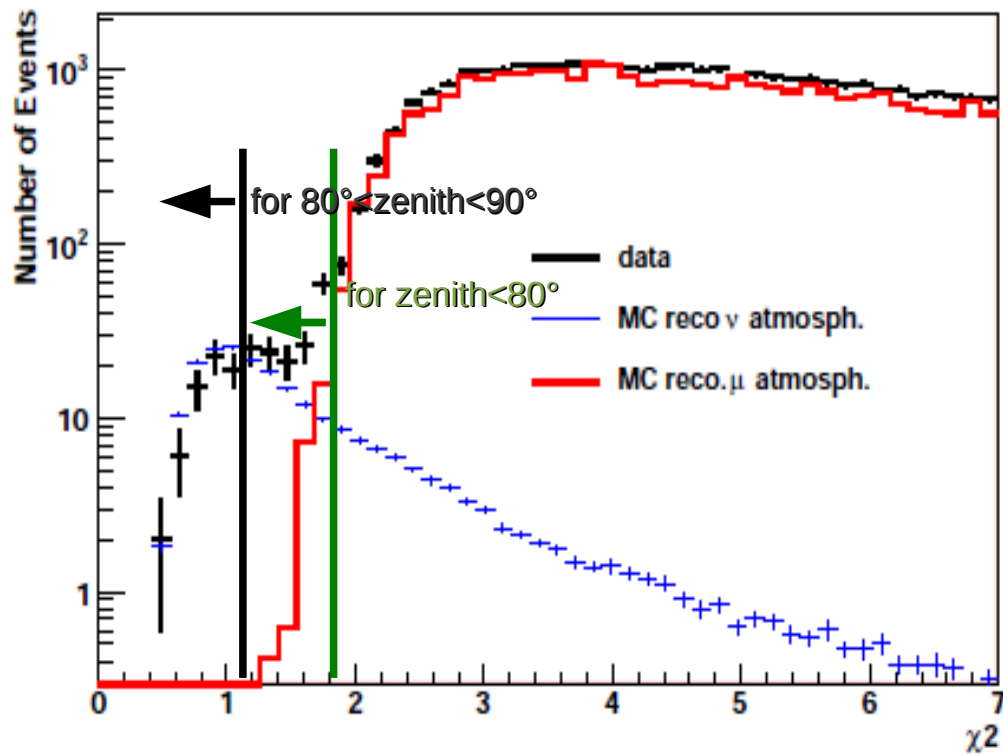
- reconstruction method based on  $\chi^2$  minimization\*
  - Select only the direct photons (unscattered)
  - Ignore the detector geometry (events reconstructed with 2L have two mirror solutions)
- Optimization for an  $E^{-2}$  flux



\*Astroparticle Physics 34 (2011)652–662

# HEN selection criteria

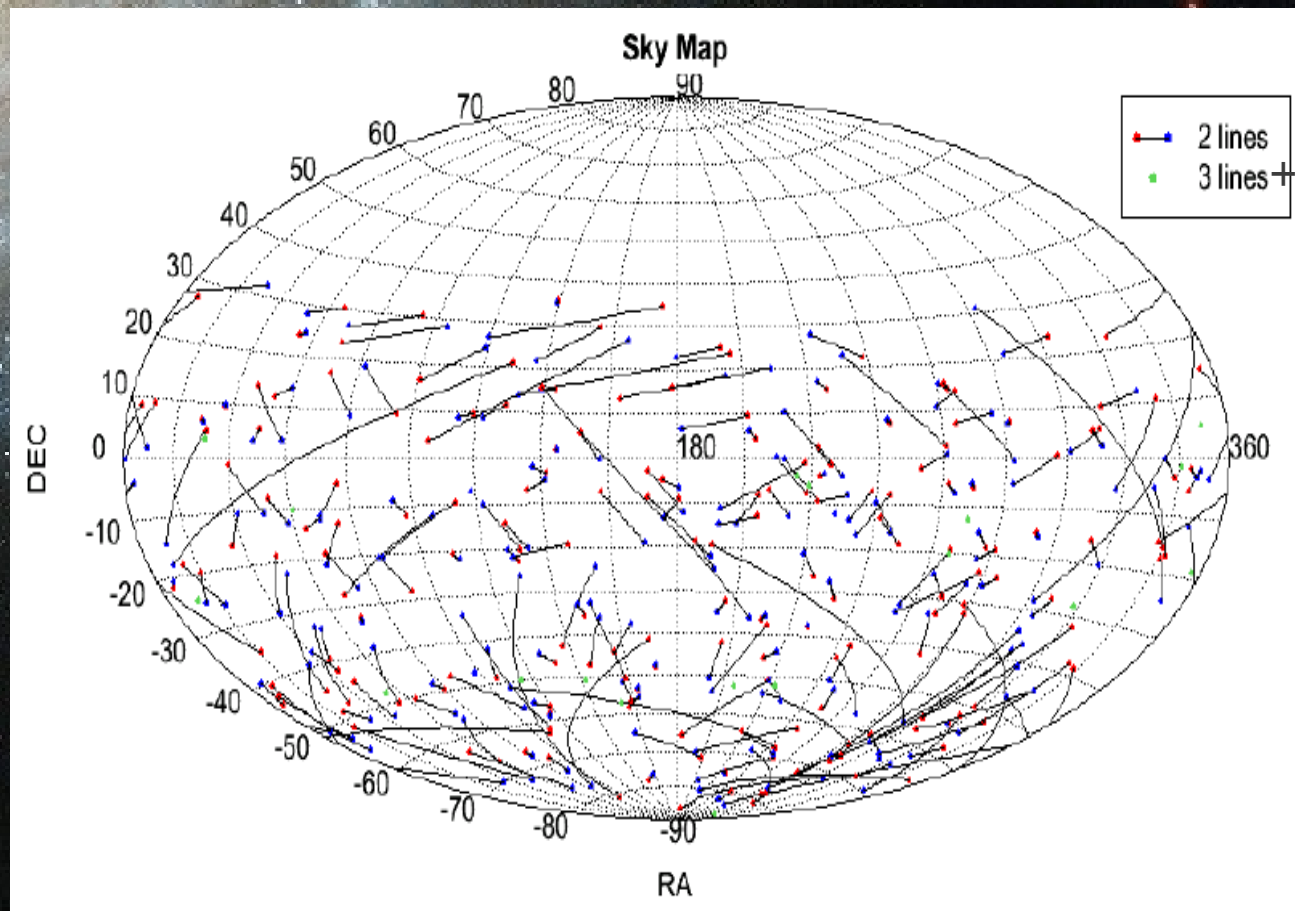
- Upward going events in the detector
- Cut on the quality of the reconstructed muon track
- Selection of HEN based on the number of photons in the event.



# Final HEN set

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

SkyMap of the selected events in equatorial coordinates



# GW coherent search

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

## reconstructed from 2 Lines

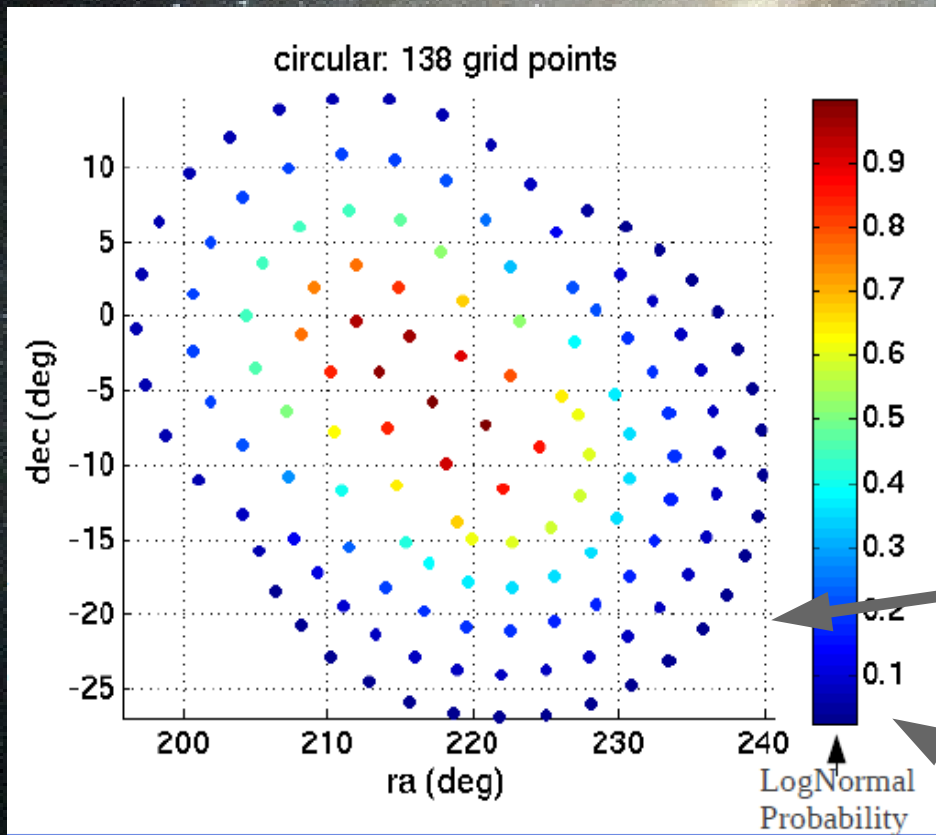
# neutrinos	4 IFOs	3 IFOs	2 IFOs
143	60	58	25

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.

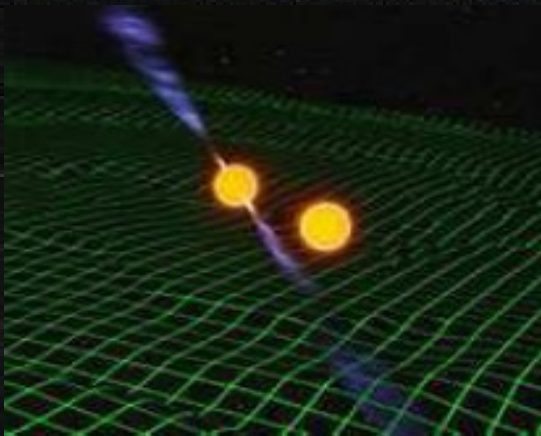


- At least two GW detectors are required to enable background estimation via time shifts
- Use HEN error box for GW search

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

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

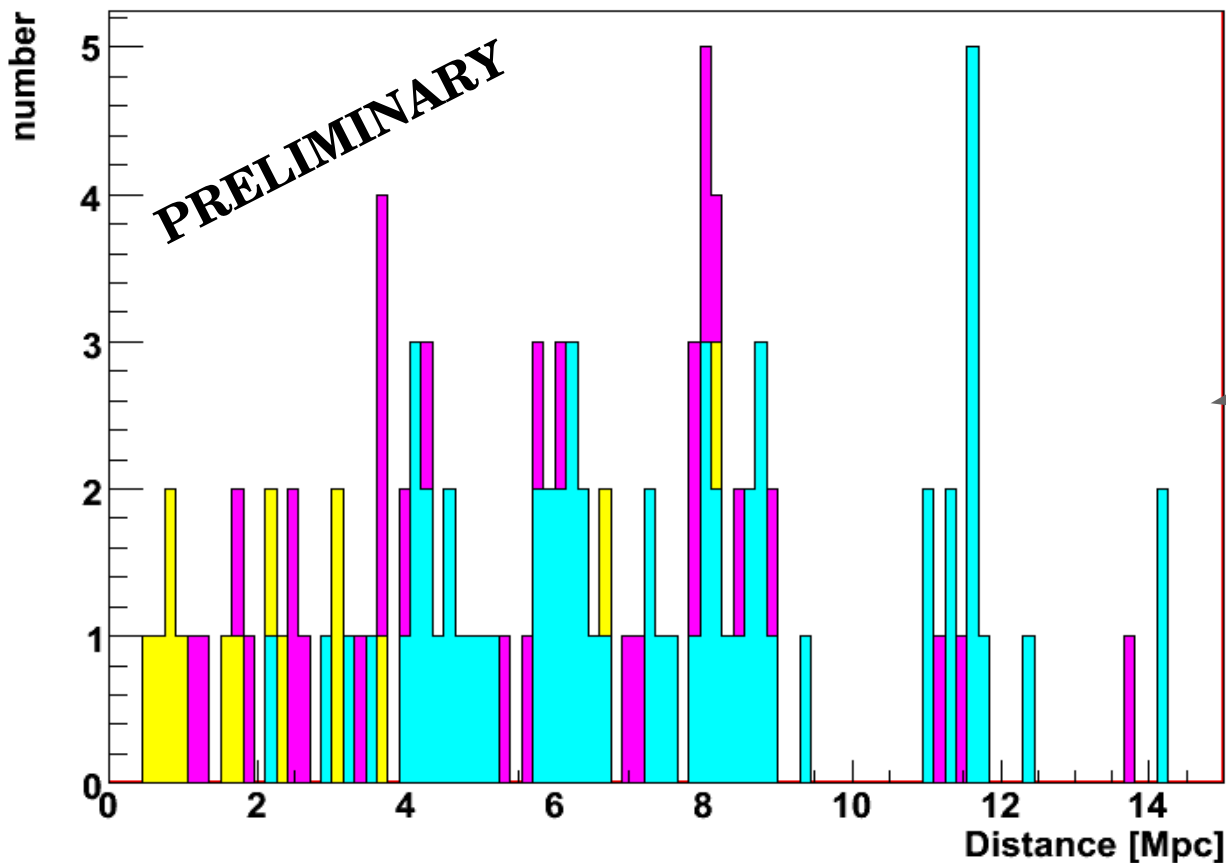
# Off-source results e.g NS-NS binary



[ I. DiPalma et al, TAUP 2011 ]

- Estimates of the sensitivity of the joint search

NS(1.35Msun)-NS(1.35Msun) all networks



- 2 detectors in network:  
mean = 4.4 Mpc
- 3 detectors in network:  
mean = 6.0 Mpc
- 4 detectors in network:  
mean = 7.6 Mpc

Distances within which the analysis has a detection probability  $\geq 90\%$  at a 1% per-neutrino false alarm probability

# 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  $< 0.4^\circ$
    - Use specific GW pipeline
  - IceCube-22+LIGO+VIRGO