Target of Opportunity and Multi-Messenger Programs with ANTARES

Véronique Van Elewyck

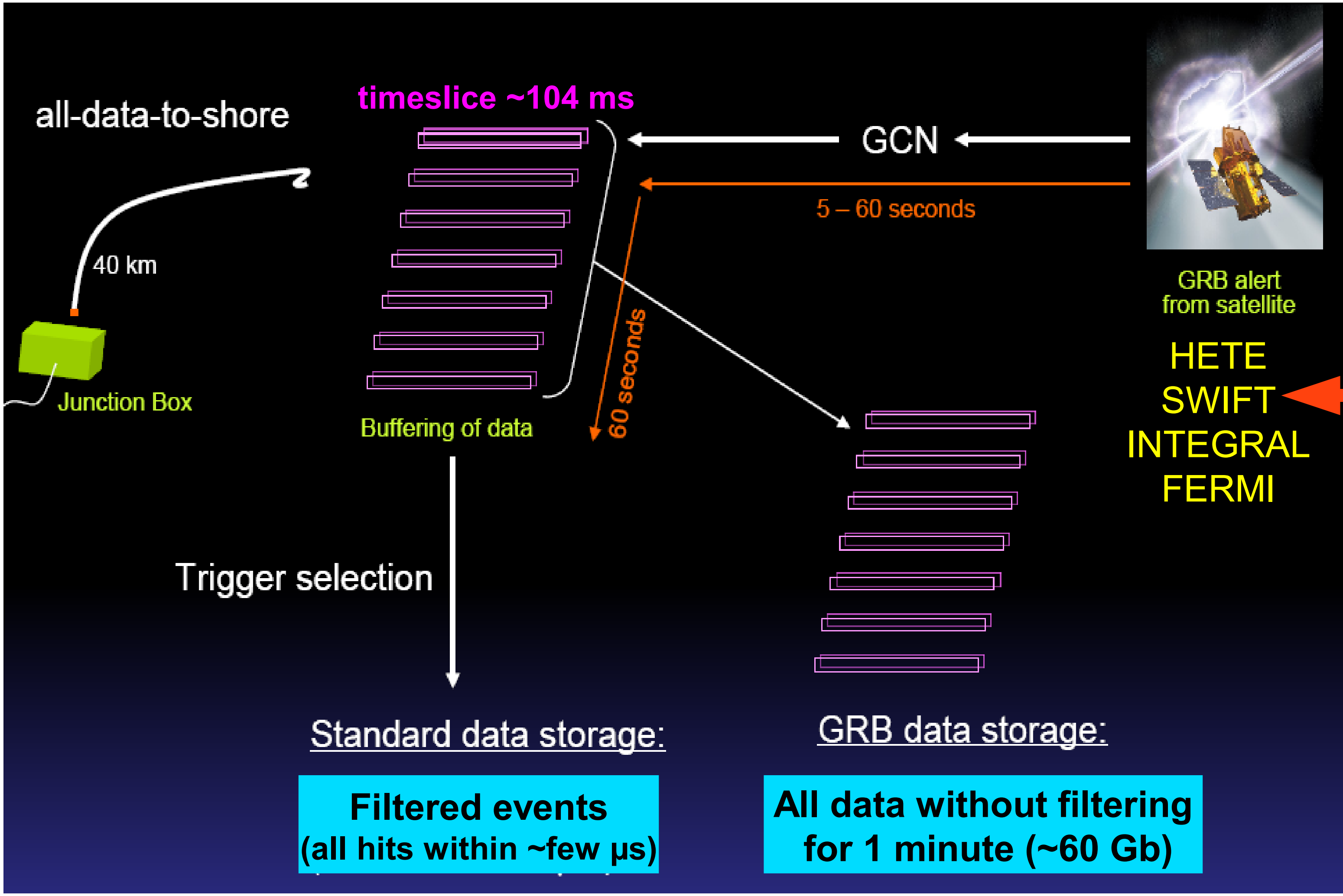
Laboratoire AstroParticule et Cosmologie (Paris)

An overview

- Externally triggered neutrino searches
  - handling of GCN alerts
  - standard searches for GRB events
  - GRBs above the horizon
- Neutrino-triggered follow-up activities
  - TAToO
- Neutrinos in coincidence with gravitational waves
  - the GWHEN project
- Other (time-uncorrelated) multi-messenger analysis
  - correlations with AUGER events
  - stacking analysis with HESS sources
- Perspectives and future plans → leave it for the discussion !

External triggers

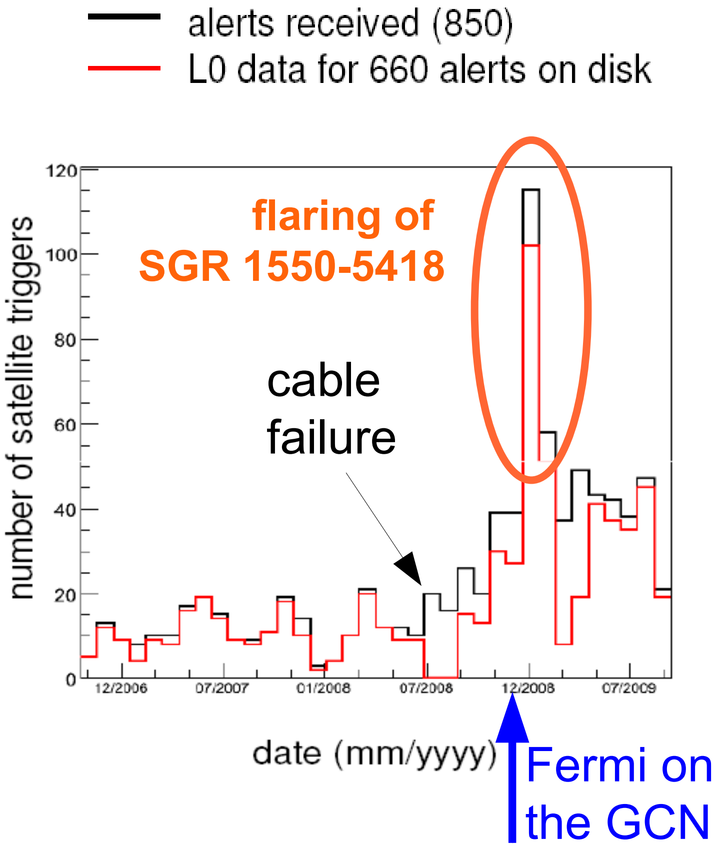
ANTARES on the Gamma Ray Burst Coordinate Network:



since this month: also subthreshold triggers (~1/day)

External triggers

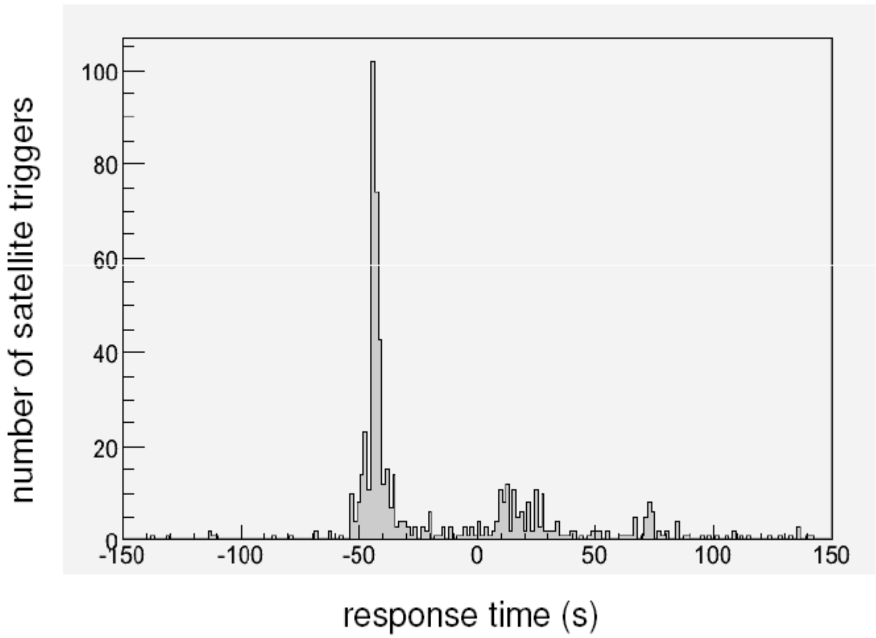
Status of GCN-triggered data taking



typical efficiency ~90%

~ 15 Tbytes of data collected

Response time



buffering allows to recover raw data prior to the alert time

External triggers: ongoing GRB analyses

General blinding policy: - the nature of the alert is hidden (GRB, other source, fake...)
- only relative times are used

-- no analysis unblinded yet --

- **Analysis of the standard data in coincidence with GCN alerts**

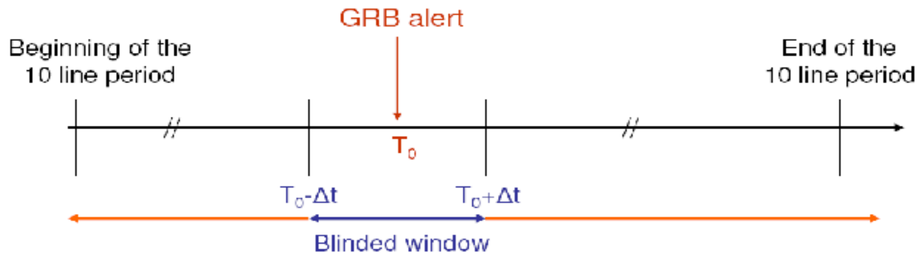
- only upward-going alerts

- blinded window: Δt = 900s

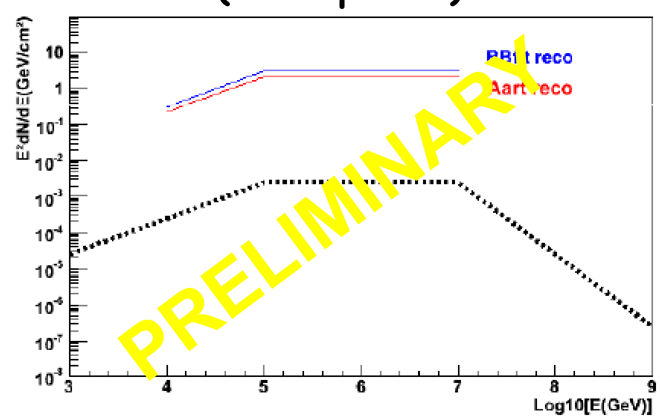
- event selection:
basic filtering (standard triggers)
+ quality cuts on the background conditions
(low baseline, small dispersion, small burst fraction)

- optimization strategy for upper limit (minimization of MRF) and discovery potential based on track fit quality & size of the search cone

- a posteriori: select only long GRBs (T_{90} > 2s)



Sensitivity to average burst
(2008 period)

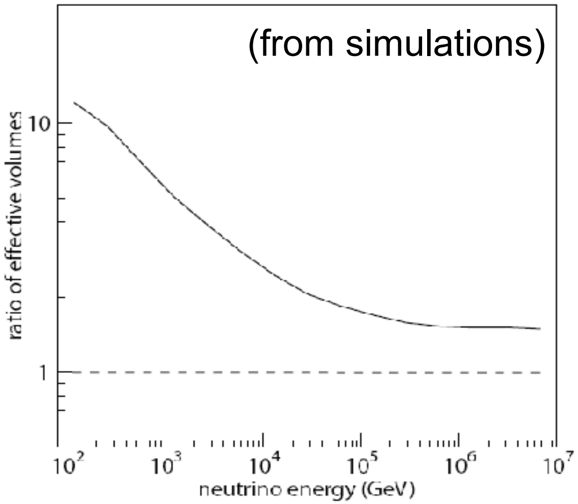


External triggers: ongoing GRB analyses

◆ **Analysis of the GRB datasets**

- dedicated filtering and reconstruction strategy:
  - 6 hits correlated in space and time with the GRB position
  - GRB position used to constrain the track fit

→ expected increase in GRB detection efficiency

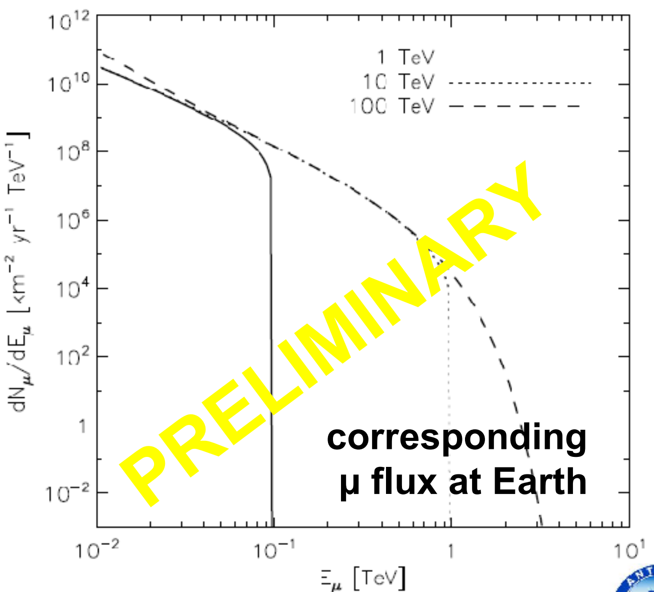


◆ « **GRBs from above** »

Idea: to detect μ's created by TeV gamma-rays originating from GRBs
(main channels: $\pi \rightarrow \mu\ \nu$ and $\gamma \rightarrow \mu^+ \mu^-$)
concentrate on down-going events

- time-correlated analysis:
study the angular correlation with GRB direction within a given time window

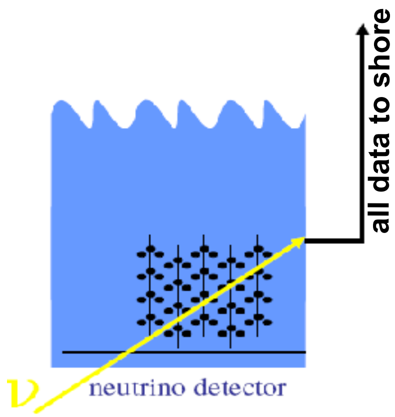
- time-independent analysis:
global excess of the μ flux in a given direction (more appropriate for steady sources)



Neutrino triggers and follow-up: TAToO

shore station

Fast online reconstruction → Trigger → alert



ANTARES

TAToO:

TAROT-ANTARES

Target of Opportunity

TAROT

(Télescope à Action Rapide pour les Objets Transitoires)

2 robotic, 25 cm-diameter optical telescopes: Calern (France) & La Silla (Chile)

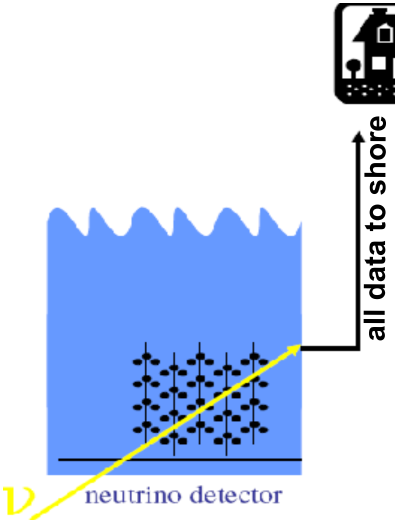
FOV: 1.86º x 1.86º

specialized in prompt-phase observations in optical wavelengths

(fast repositioning in alert mode: < 10 s)

Neutrino triggers and follow-up: TAToO

shore station



Fast online reconstruction (BBfit) → Rolling Trigger → alert

5 to 10 ms/event

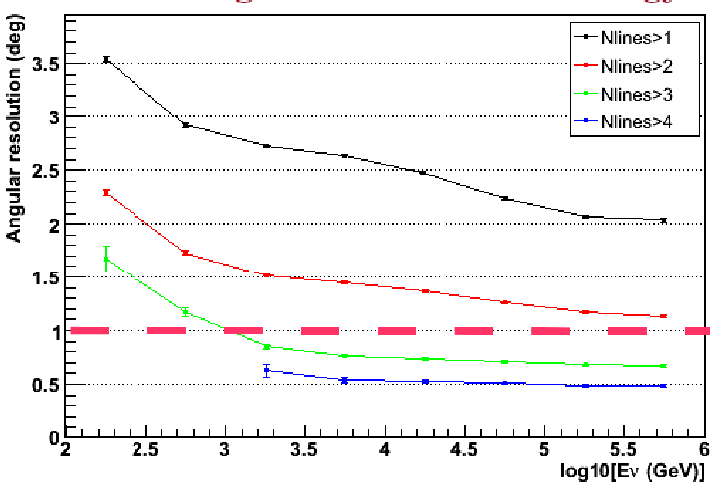
- **minimum 6 storeys triggered on at least 2 lines**
- **quality cut on the χ^2 minimisation of the muon track reconstruction (using t_{hit}'s and A_{hit}'s)**
- **dynamical positioning not included**

ANTARES

TAROT

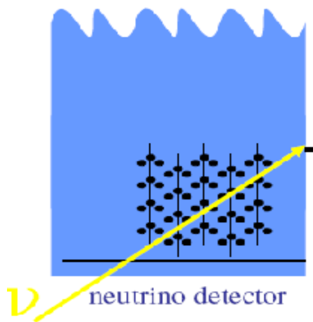
FoV: 1.86° x 1.86°

Median Angular resolution vs energy



Select events with $N_{lines} \geq 3$

Neutrino triggers and follow-up: TAToO



all data to shore

ANTARES

Fast online reconstruction → Rolling Trigger → alert → TAROT

TAROT

2 strategies:

(a) A neutrino doublet

Background estimation (ANTARES 12L):

$\Delta t = 15$ min, $\Delta\Omega = 3° \times 3°$ } single ν_{atm} : $R_{1atm} \approx 1000\ yr^{-1}$

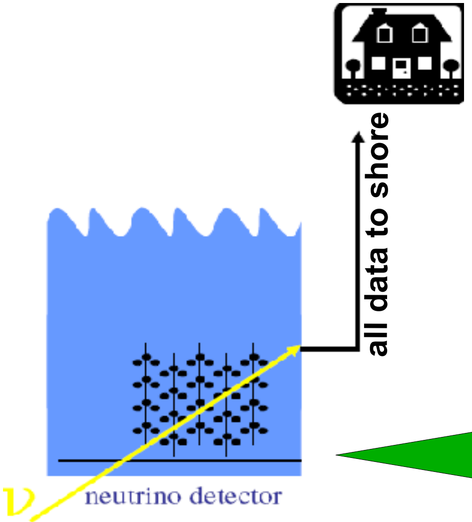
→ doublet of ν_{atm} : $R_{2atm} \approx 0.005\ yr^{-1}$

(b) One high-energy neutrino

cut in energy to eliminate the atmospheric bkg:

reconstructed $E_{\mu} \geq$ few TeV ⟷ only tracks with $N_{storeys} \geq 20$, $Q_{tot} \geq 180$ p.e.

Neutrino triggers and follow-up: TAToO



Fast online reconstruction → Rolling Trigger → alert

Total latency:
alert sending < 1s
repositioning < 10s

ANTARES **TAROT**

Trigger settings are tuned to send
1-2 alerts/month
(mainly from the high-energy neutrino trigger)

TAROT observation strategy:

Real time (T_0): 6 images of 3 minutes each
repeated on days T_0+1, T_0+3, T +9, T_0+27

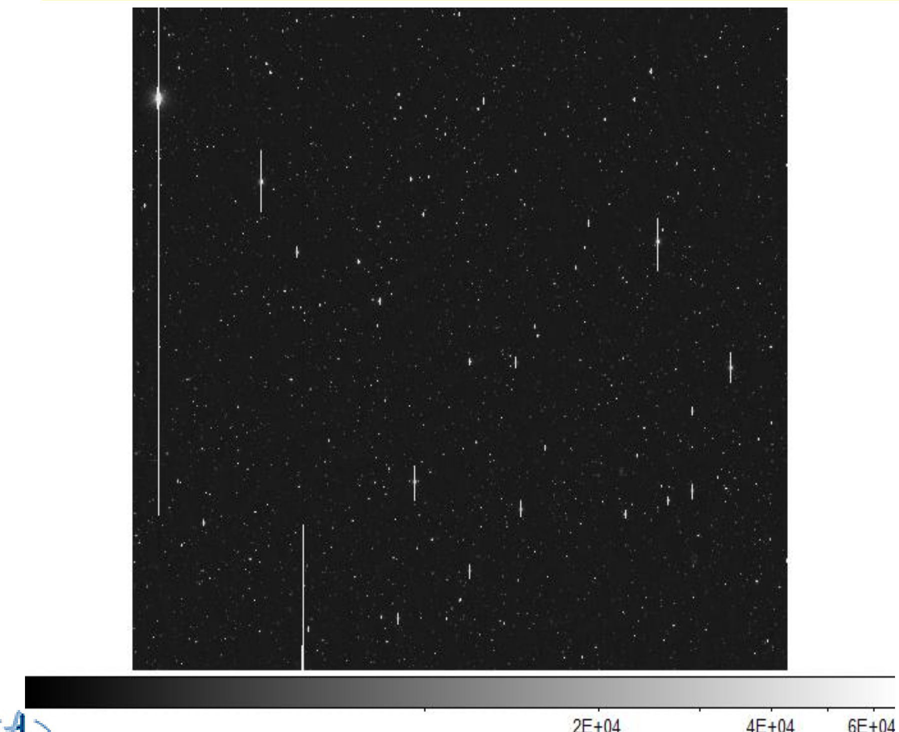
Appropriate to follow the time profile of different transient sources:
GRB afterglows (~minutes), core-collapse SNe (~days),...

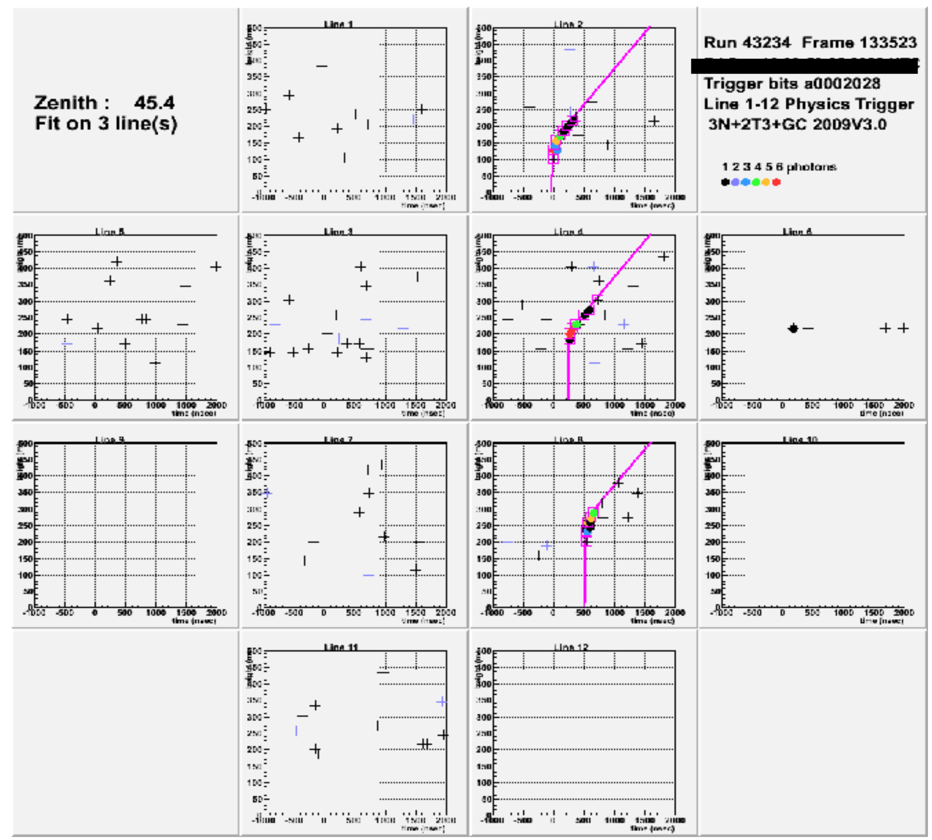
Neutrino triggers and follow-up: TAToO

TAToO Program is fully operational since February, 2009

- **Tests have been performed to validate the acquisition chain (e.g. fake alert in the direction of the Virgo cluster)**
- **alerts are being issued at the rate of 1 to 2 per month**
- **Implementation of the offline optical image analysis is ongoing**

One alert (out of 5) recorded by TAROT since the beginning of 2009

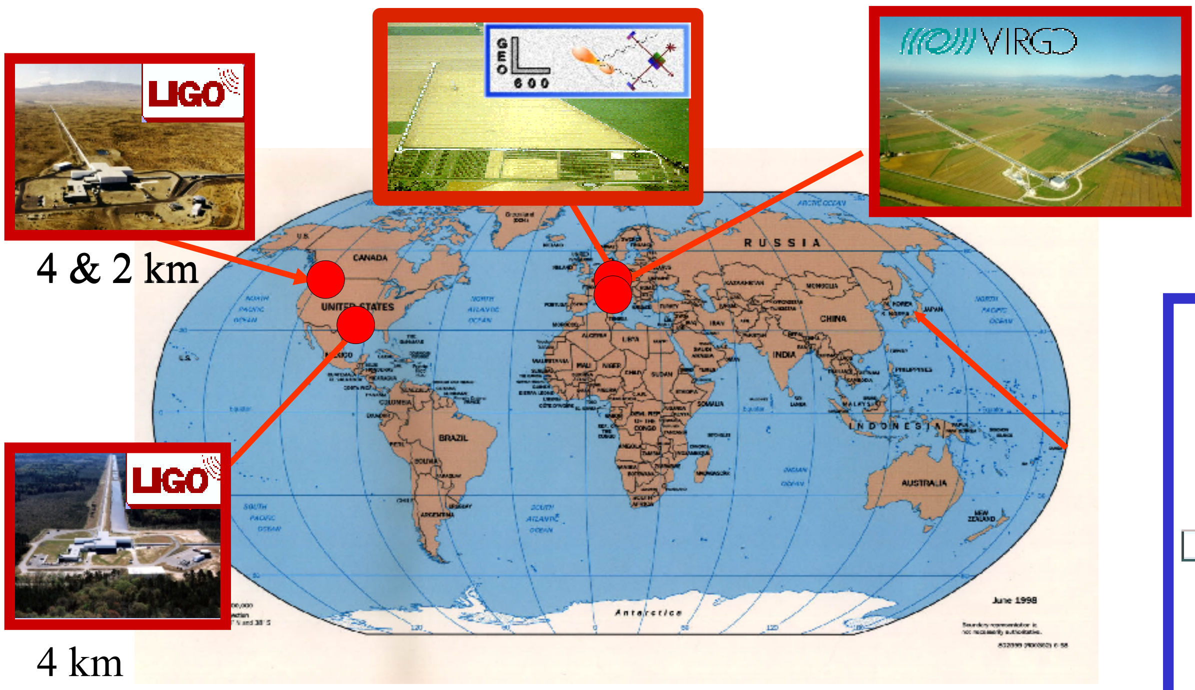




GW-HEN coincidences

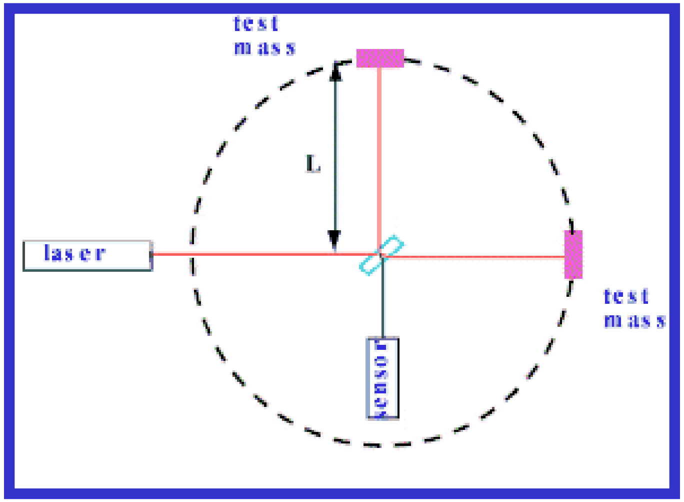
Motivations: - plausible common sources (GRBs (core collapse into BH or coalescing neutron stars), SGRs (magnetars), microquasars...)
- potential for discovery of hidden sources (e.g. failed GRBs)

The instruments:



VIRGO/LIGO/GEO now forming one single consortium

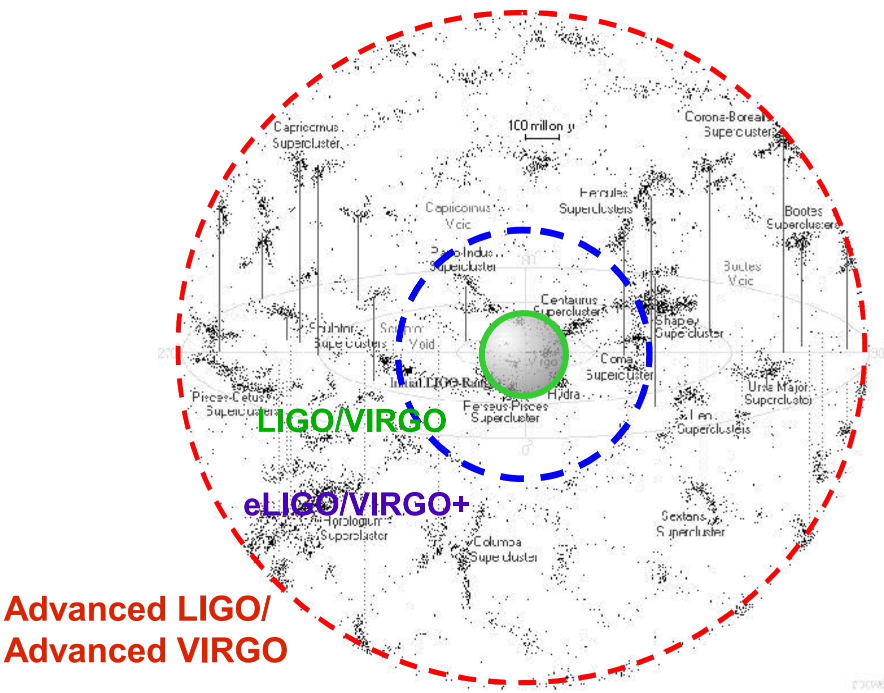
Michelson interferometers (mirrors suspended to free masses)



GW-HEN coincidences

	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
ANTARES KM3NeT	5L	10L	12L						KM3NeT	
VIRGO	VSR1		VIRGO+						Advanced VIRGO	
LIGO	LSR1		eLIGO						Advanced LIGO	

Started July 2009 !



VIRGO/LIGO detection horizon for standard binary sources: ~ 15 Mpc (~1 binary merger/ 100 years...)

current upgrades:
sensitivity x 2 → probed volume x 8

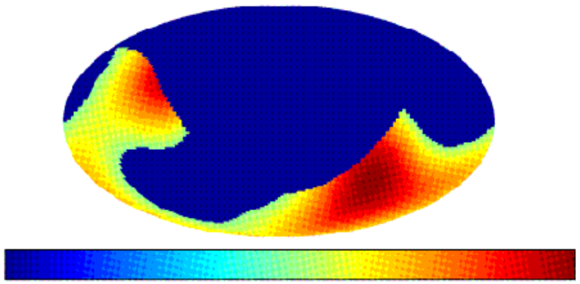
Advanced detectors:
sensitivity x 10 →probed volume x 10
(~ 1 Gpc^3,~ 40 binary mergers/yr)

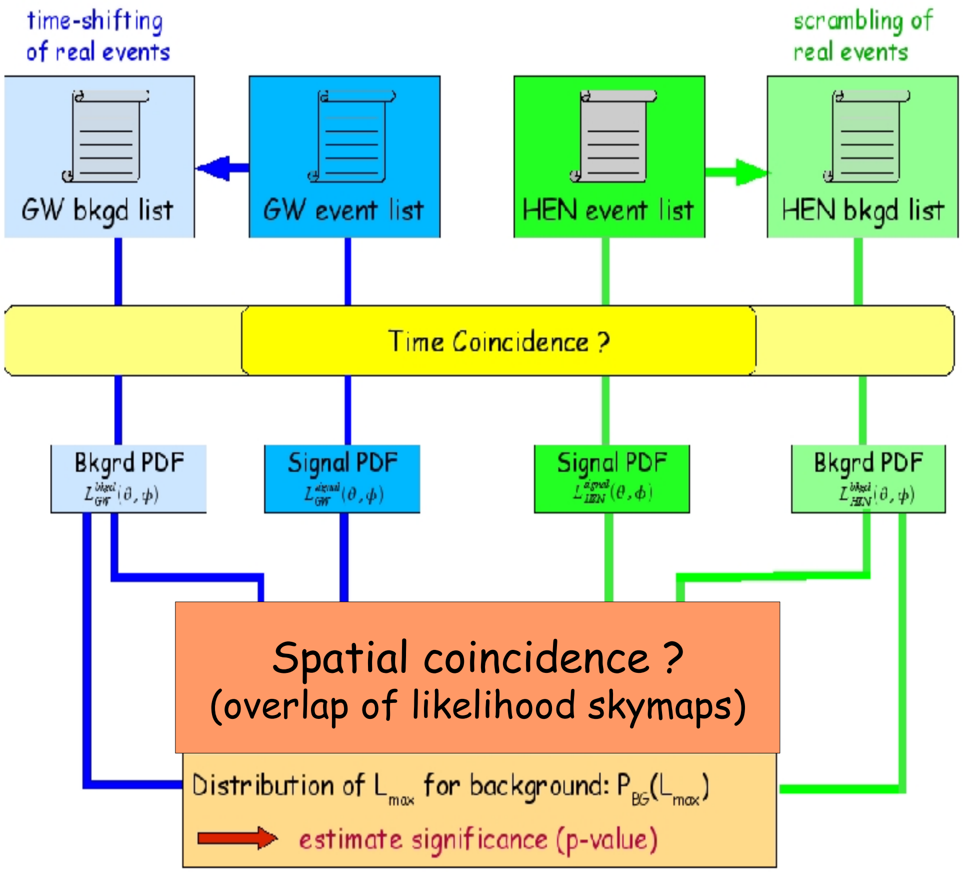
GW-HEN coincidences

Philosophy of the analysis:

size of the time window:
source/model dependant .
from preliminary studies:
false alarm rate ~ 1/500 years
for Δt ~ 1s

instantaneous sky coverage



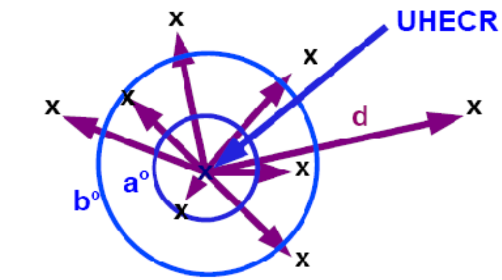


- GWHEN Workshop May 2009 at APC (Paris): http://www.gwhen-2009.org
- MoU ANTARES/VIRGO/LIGO to be signed soon
- Analyses to be launched (microquasars, GRBs)
- Discussion on the possibility of alert sending

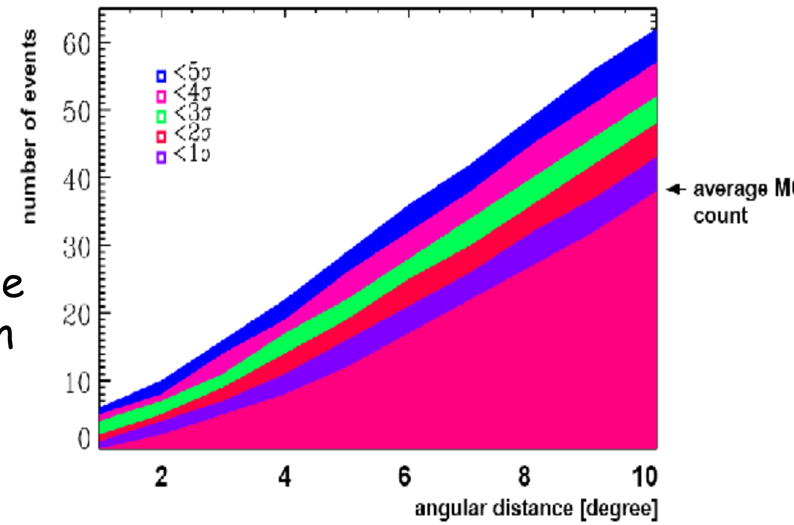
Other multi-messenger studies

- **Correlations with AUGER events**

Idea: compute an « inter-correlation » function between AUGER events and ANTARES events



look for deviations from the MC expectation under given hypotheses on the UHECR composition & propagation

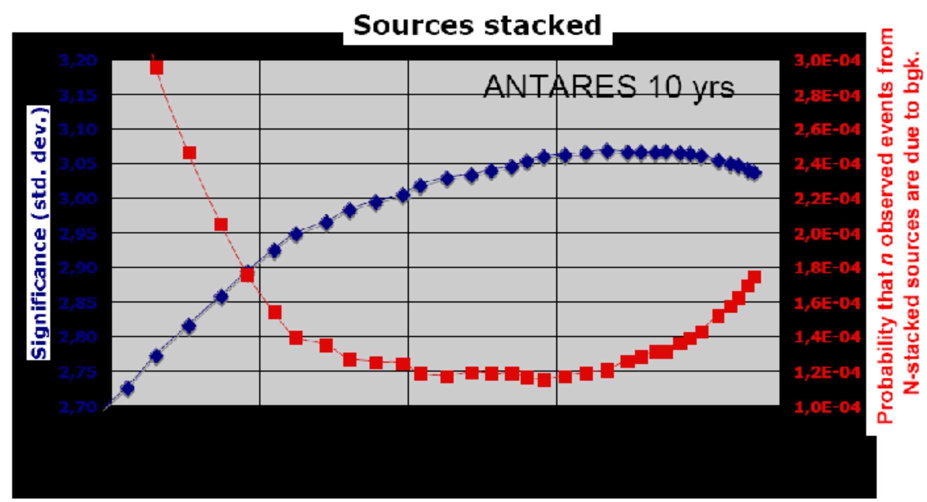


- **Correlations with HESS sources**

Idea: stack sources to benefit from the fact that the background fluctuations go as $1/\sqrt{N_{stacked}}$

stacking a sample of 23 HESS galactic sources (including extended sources divided in sub-regions)

Expected significance (probability) under the assumption that all HESS sources are hadronic



Backup slides

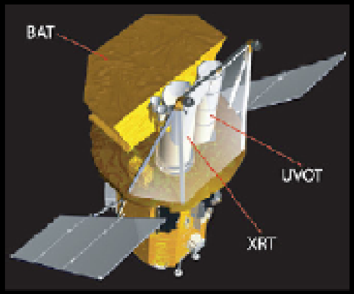
Véronique Van Elewyck

Laboratoire AstroParticule et Cosmologie (Paris)

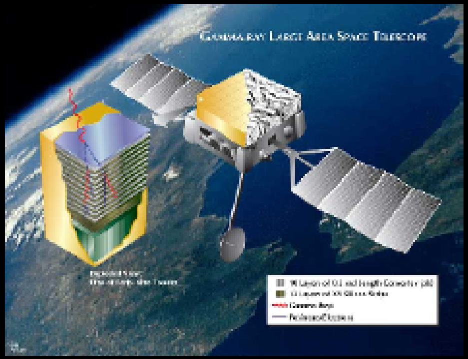
Time delays

GRB alerts from three satellites

INTEGRAL

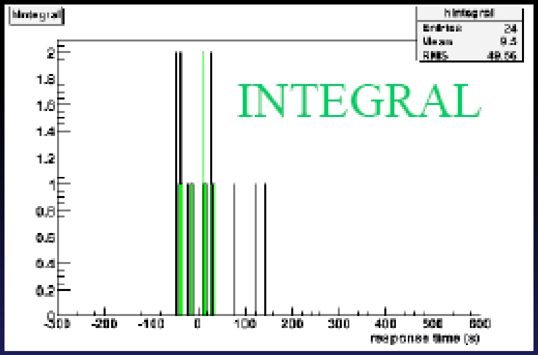


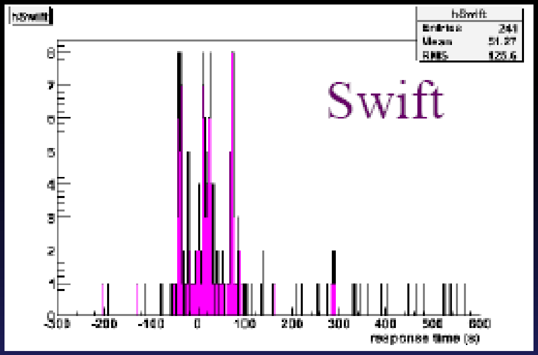
Swift

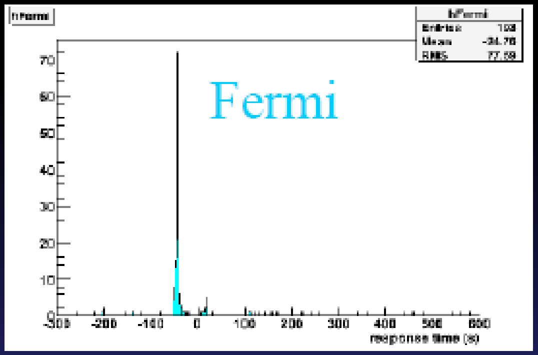


Fermi

Response time = time delay – buffering time







From February 2007 to May 2009

Credit: S. Escoffier

External triggers: ongoing GRB analyses

Optimization strategy

Set an upper-limit ⇒ Minimize the Model Rejection Factor in order to improve the sensitivity:

$$MRF = \frac{\overline{\mu}_{90}(n_b)}{n_s}$$

10 lines detector: 112_c00_s00.det + n31098.root

Atmospheric muons and neutrinos background:

Standard ANTARES production

Source: neutrino signal:

Simulation with a fixed direction $(\cos\theta\ ,\ \phi) = (0.4\ ,\ \pi)$

In order to optimize the sensitivity, we will use only events reconstructed with **at least 2 lines**.

2 reconstruction strategies: **BBfit & Aart**

2 parameters: **$\Delta\theta$, track fit quality**

Credit: D. Dornic

External triggers: ongoing GRB analyses

Optimization strategy

Set a discovery ⇒ put cuts in order to have the maximum signal in the cone compare to a background signal at the level of 3 or 5σ (kind of MDP)

10 lines detector: 112_c00_s00.det + n31098.root

Atmospheric muons and neutrinos background:

Standard ANTARES production

Source: neutrino signal:

Simulation with a fixed direction $(\cos\theta\ ,\ \phi) = (0.4\ ,\ \pi)$

In order to optimize the sensitivity, we will use only events reconstructed with **at least 2 lines**.

2 reconstruction strategies: **BBfit & Aart**

2 parameters: **$\Delta\theta$, track fit quality**

Credit: D. Dornic

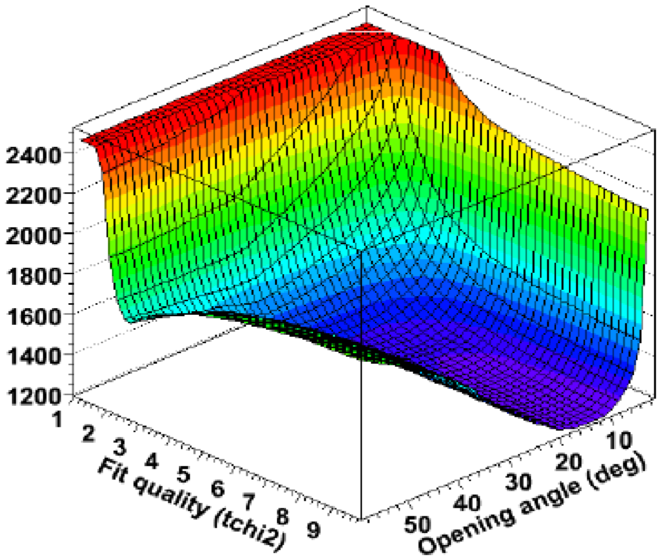
External triggers: ongoing GRB analyses

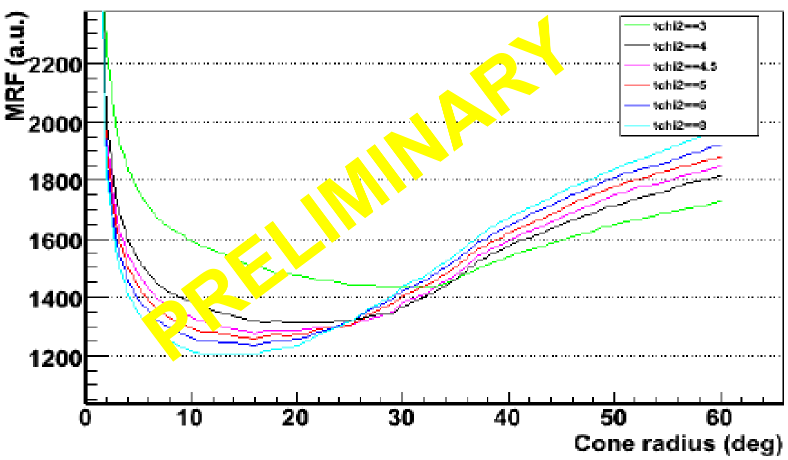
U.L. Optimization (Δθ,fit quality)

Minimization of the MRF:

- Signal events: simulation of a fixed source ($\cos\theta=0.4$, $\varphi=\pi$)
- Background events: atm neutrino + muons productions

BBfit reconstruction





($\Delta\theta=16°$, tchi2<4.3)

Credit: D. Dornic

External triggers: ongoing GRB analyses

Stability of the optimization

Effect on the choice of the simulated direction

Different directions:

$(\cos\theta , \phi) = (0.2 , \pi)$

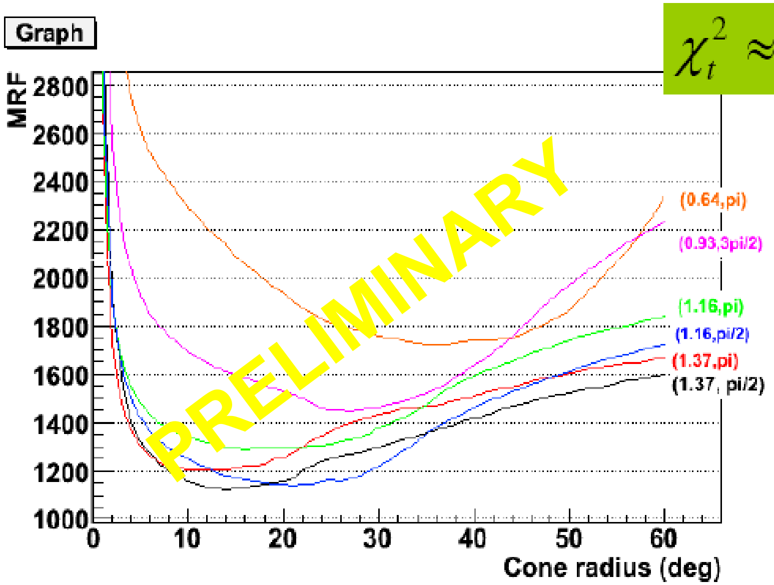
$(\cos\theta , \phi) = (0.4 , \pi)$

$(\cos\theta , \phi) = (0.8 , \pi)$

$(\cos\theta , \phi) = (0.2 , \pi/2)$

$(\cos\theta , \phi) = (0.4 , \pi/2)$

$(\cos\theta , \phi) = (0.6 , 3\pi/2)$



$\chi_t^2 \approx 4.5$

An angular cut at 20° seems robust to the choice of the direction

Credit: D. Dornic

External triggers: ongoing GRB analyses

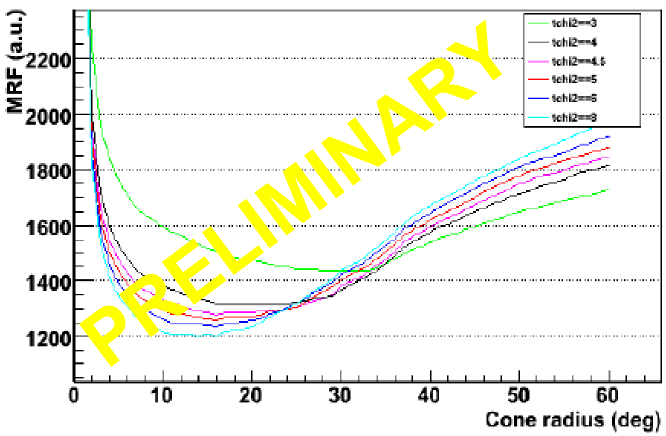
Credit: D. Dornic

Stability of the optimization

Effect on the number of atm muons

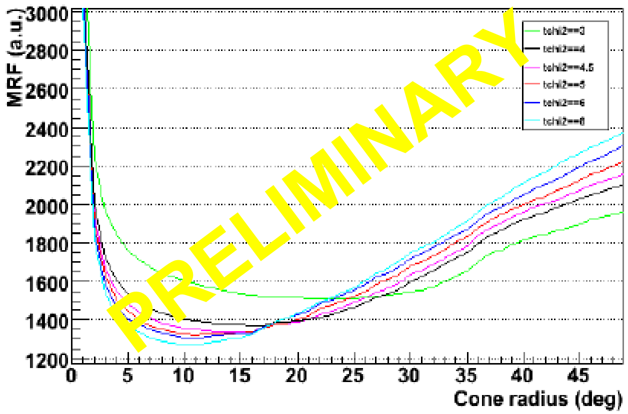
If the MC of the atmospheric muons is wrong by a factor 2, it has little change in the choice of the angular window

std



($\Delta\theta$=16°, tchi2<4.3)

$N_\mu \times 2$



($\Delta\theta$=11°, tchi2<6.4)

External triggers: ongoing GRB analyses

Credit: D. Dornic

Sensitivity BBfit vs Aart

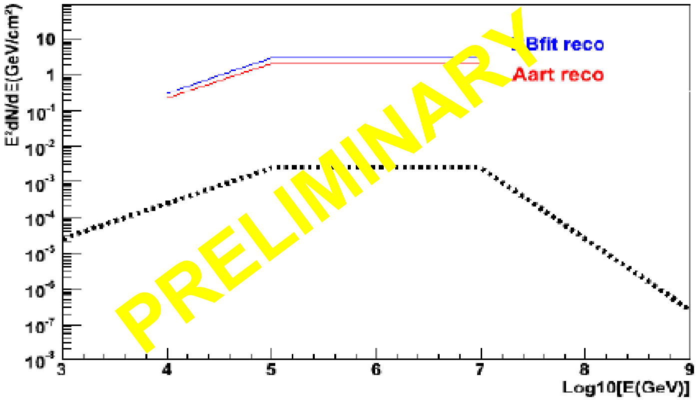
Upper limit:

$$U.L. = \frac{\bar{\mu}_{90}(n_b)}{n_s}\phi_s(E)$$

n_b can be extracted from the data in the same direction of the alert

Average WB	BBfit	Aart
Normalization f_ν (GeV.m^{-2}.s^{-1})	0.833	0.833
Energy range (90% event)	10TeV - 3PeV	
Expected background event	0.13	0.027
Expected signal event	0.0020	0.0027
MRF	1280	905

30%



- Aart strategy better performance than BBfit at HE
- BBfit is globally less efficient for the selection of multi-line events
- Angular resolution of the Aart strategy is largely better

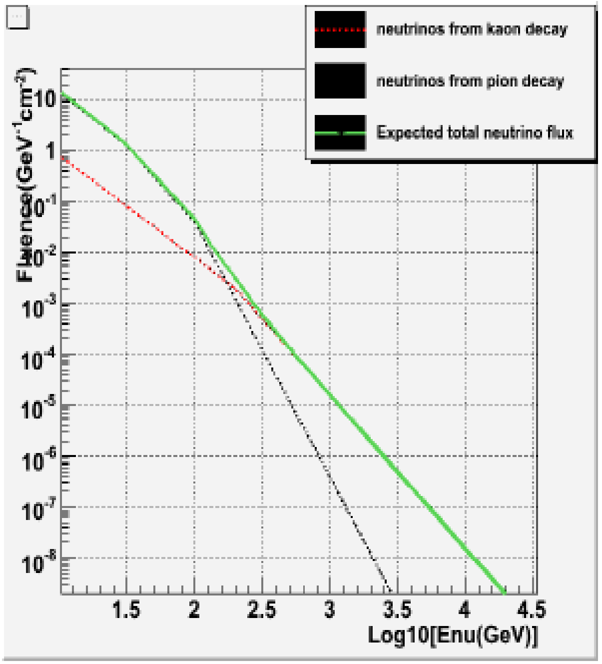
Neutrino from failed GRB

Ando & Beacom model

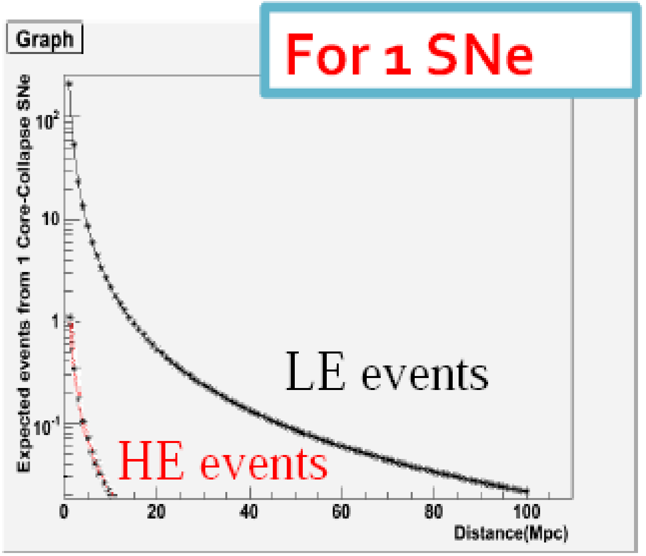
(PRL 95,061103(2005))

Protons accelerated in midly relativistic jet (Γ~3)

p-p interaction → Mesons → Neutrinos



Expected neutrino signal



Using estimation:

1 Core collapse SNe/ yr/ 10 Mpc

→ 0.4 SNe detected per year in ANTARES

Stacking of HESS sources

List of HESS gal. sources @ Mar '09 - point-like only

	sources to be stacked	Other name	n^{on}	n^{bg}	$(S/N)_i$
1	HESSJ1702-420		1,36	0,15	1,11
2	HESSJ0835-455	Vela X	1,11	0,46	0,88
3	HESSJ1632-478	IGR J16320-4751 ?	0,81	0,19	0,81
4	HESSJ1626-490		0,61	0,19	0,69
5	HESSJ1514-591		0,54	0,19	0,63
6	HESSJ1616-508		0,51	0,19	0,61
7	HESSJ1841-055		0,44	0,10	0,60
8	HESSJ1731-347		0,43	0,13	0,57
9	HESSJ1825-137		0,41	0,11	0,57
10	HESSJ1614-518		0,46	0,19	0,57
11	HESSJ1420-607	PSR J1420-6048?	0,45	0,19	0,57
12	HESSJ0534+220		0,32	0,07	0,51
13	HESSJ1809-193		0,33	0,11	0,49
14	HESSJ1813-178		0,32	0,11	0,49
15	HESSJ1908+063		0,27	0,09	0,45
16	HESSJ1837-069		0,26	0,10	0,43
17	HESSJ1418-609		0,29	0,19	0,42
18	HESSJ1857+026		0,20	0,09	0,37
19	HESSJ1023-575		0,22	0,19	0,34
20	HESSJ1745-290	Sgr A*/Sgr A East ?	0,19	0,13	0,34
21	HESSJ1640-465	WR 20a; RCW49 Westerlund 2;	0,18	0,17	0,30
22	RCW86	SN 185?	0,18	0,19	0,30
23	HESSJ1427-608	G338.3-0.0 ?; 3EG J163 4702 ?	0,18	0,19	0,29
24	HESSJ1634-472		0,14	0,19	0,24
25	HESSJ1718-385	PSR J1718-3825 ?	0,13	0,14	0,24
26	HESSJ1708-410	G23.3-0.3 / W41?	0,12	0,15	0,24
27	HESSJ1834-087	G8.7-0.1 / W30 ?; PSR J1803-2137 ?	0,11	0,10	0,23
28	HESSJ1804-216	IGR J16358-4726 ?; G337.2+0.1 ?	0,11	0,12	0,23
29	HESSJ1303-631		0,09	0,19	0,16
30	HESSJ1800-240	3EG J1744-3011 ?	0,06	0,12	0,15
31	HESSJ1745-303	G006.1-006; (W 28)	0,07	0,13	0,15
32	HESSJ1912+101	PSR J1913+1011	0,05	0,08	0,15
33	HESSJ1714-385	CTB 37A	0,06	0,14	0,13
34	HESSJ1858+020	LS 5039	0,04	0,09	0,11
35	HESSJ1826-148	PSR B1259-63	0,04	0,11	0,10
36	HESSJ1302-638	G0.9+0.1	0,05	0,19	0,09
37	HESSJ1747-281		0,04	0,13	0,09
38	HESSJ0632+057	Monoceros ?	0,02	0,09	0,06
39	HESSJ1713-381	W 28; GRO J1801-2320	0,02	0,14	0,05
40	HESSJ1801-233	CTB 37B (G348.7+0.3)?	0,02	0,12	0,05

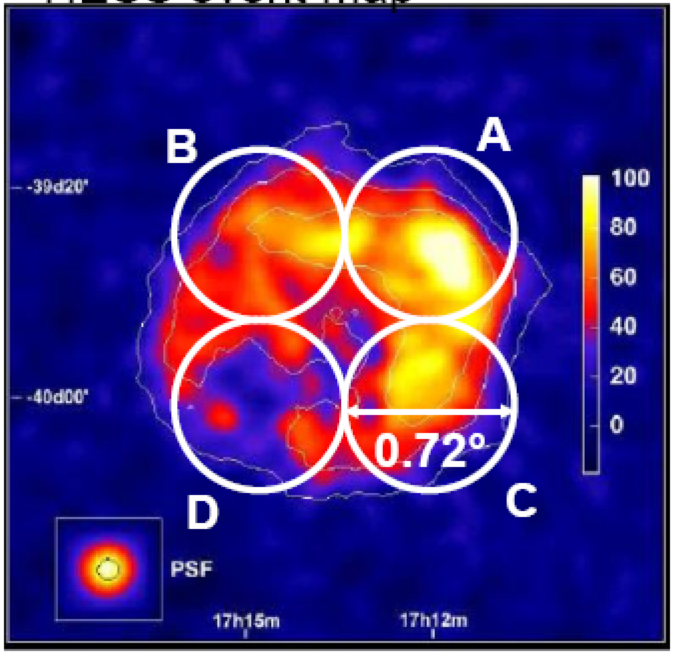
Neutrino evts (E>1 TeV) over 10 yrs

Bgk evts over 10 yrs (in a 0.3° ang. bin around the src position)

Credit: F. Lucarelli

Extended sources: RX1713.7-3946

HESS event map



4 sub-regions

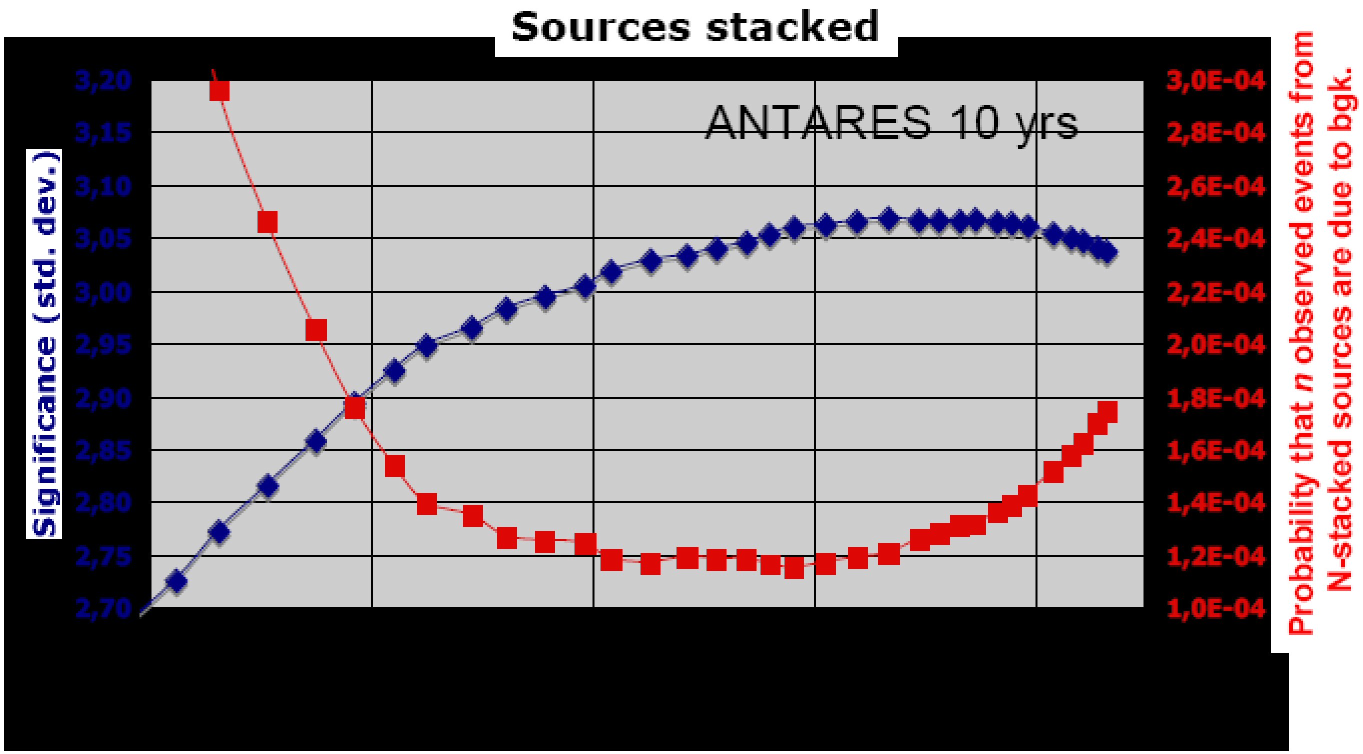
	n^{on}	n^{bg}	$(S/N)_i$
RX1713 (sub-reg. A)	0,79	0,21	0,79
RX1713 (sub-reg. B)	0,59	0,21	0,66
RX1713 (sub-reg. C)	0,61	0,21	0,67
RX1713 (sub-reg. D)	0,55	0,21	0,63

Credit: D. Dornic

External triggers: ongoing GRB analyses

Stacking of HESS gal. srcs (pt.-like+ext.)

Expected significance (probability) under the assumption that all HESS sources are hadronic

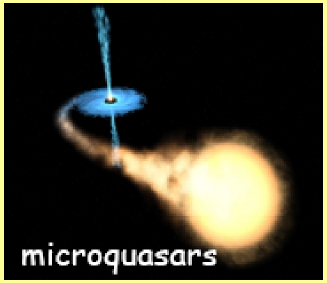


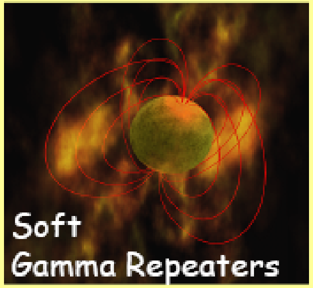
Credit: D. Dornic

Plausible GW-HEN sources

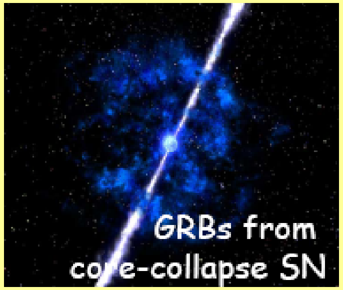
The usual suspects

Galactic sources





Extragalactic sources



- **Microquasars:** radio-emitting X-ray binaries with relativistic jets (D~few kpc, Γ~ 1-20)
  → GW in blob accretion/ejection phases
  → HEN from jets (if hadronic component)
  HEN & GW (ejection) signals correlated[1]

- **SGRs:** X-ray pulsars with soft gamma-ray flaring activity (plausibly magnetars)
  → GW from star deformation during outburst
  → HEN from GRB-like, hadron-loaded flares
  correlated signals, possibly within reach of present detectors [2]

- **Short-Hard GRBs:** associated with NS-NS or NS-BH mergers
  → GW associated to coalescence process
  → HEN produced during burst [3]

- **Long-Soft GRBs:** core-collapse supernovae (collapsars)
  → strong burst of GW during collapse & pre-GRB phase
  → HEN emitted during GRB prompt and afterglow phases [4]

- **Low-luminosity GRBs:** associated to extremely energetic, possibly rotating and jet-driven SNs
  → possibly stronger GW signal but fainter HEN signal [5]

- **Failed GRBs:** mildly relativistic, optically thick, baryon-rich jets
  → possibly strong HEN signal; not observable in photons [6]

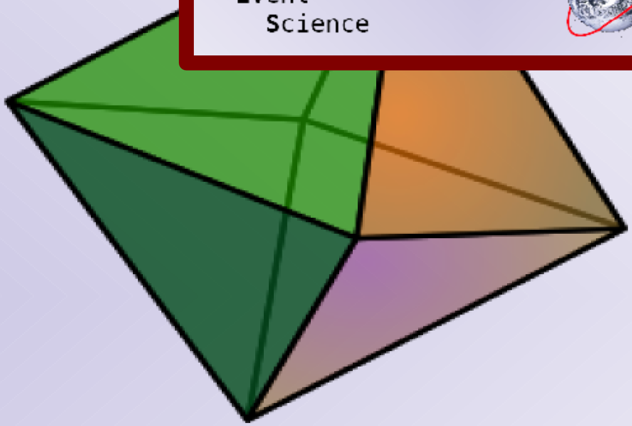
- **Others...?**

External triggers and alerts

- GRB triggered searches: a mission dedicated to multi-messenger astronomy ?

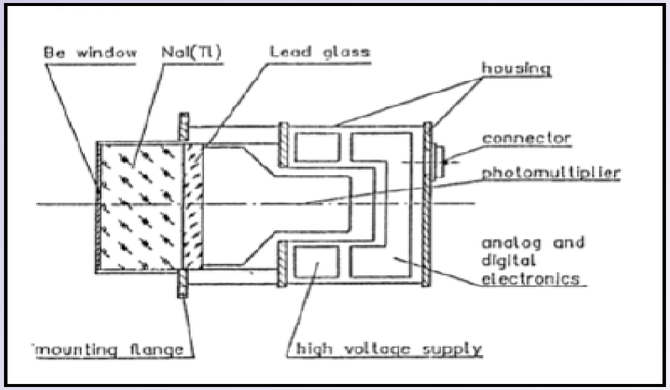
A GWHEN Mission

- All-sky, all the time
  - Booster launch into high-apogee orbit
  - Low, stable background
- Real-time alerts
  - Onboard position calculation
- Brighter bursts
  - Konus-grade sensitivity fine
  - 100 GRB year^{-1} goal
- Cheap
  - NaI + PMT
  - No position-sensitive detectors
- Sub-arcmin positions
  - ?



HERMES

- High-Energy Reconnaissance for Multimessenger Event Science



Failed and low-luminosity GRBs

Unrevealed supernova-GRB connection?

	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

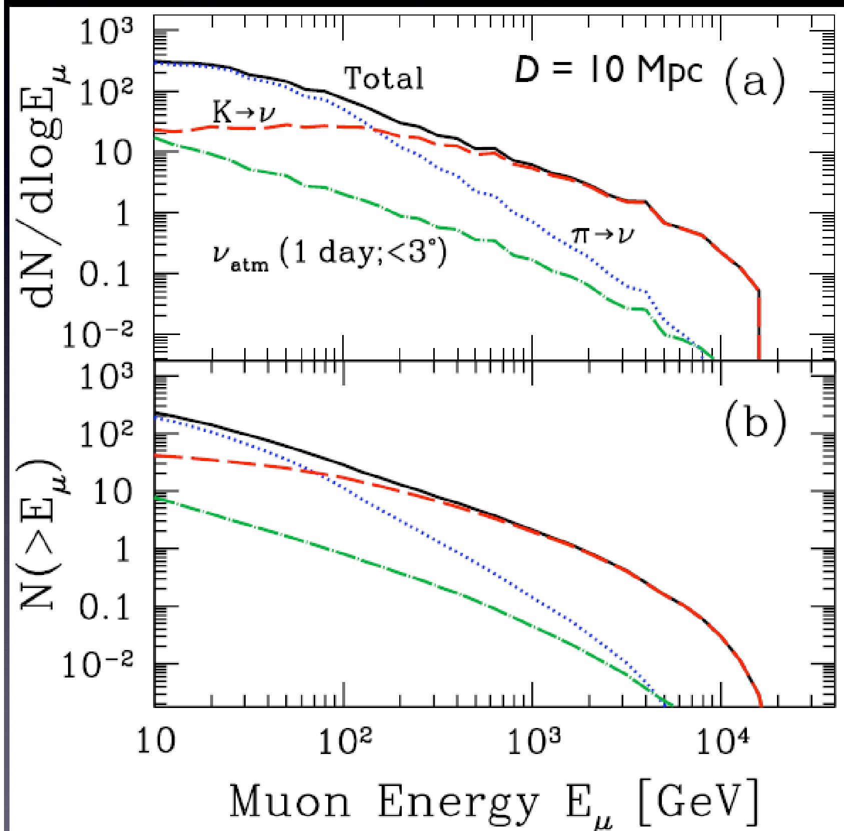
Baryon poor
Relativistic jets
Rare

- Evidence of mildly relativistic jets:
  Kulkarni et al. 1998; Berger et al. 2003; Totani 2002; Granot & Ramirez-Ruiz 2004; van Putten 2004; Soderberg et al. 2004, 2006, 2008, etc.

Failed and low-luminosity GRBs

Events at km^3 detectors

Ando & Beacom, *Phys. Rev. Lett.* **95**, 061103 (2005)



- Kaon contribution dominates
- Expected events above 100 GeV:
  - ~30 @ 10 Mpc
  - ~3 @ 30 Mpc
- These events cluster within 10 s time and 3° angular bins
  - Extremely low background

Low-energy neutrinos

Conclusions 1

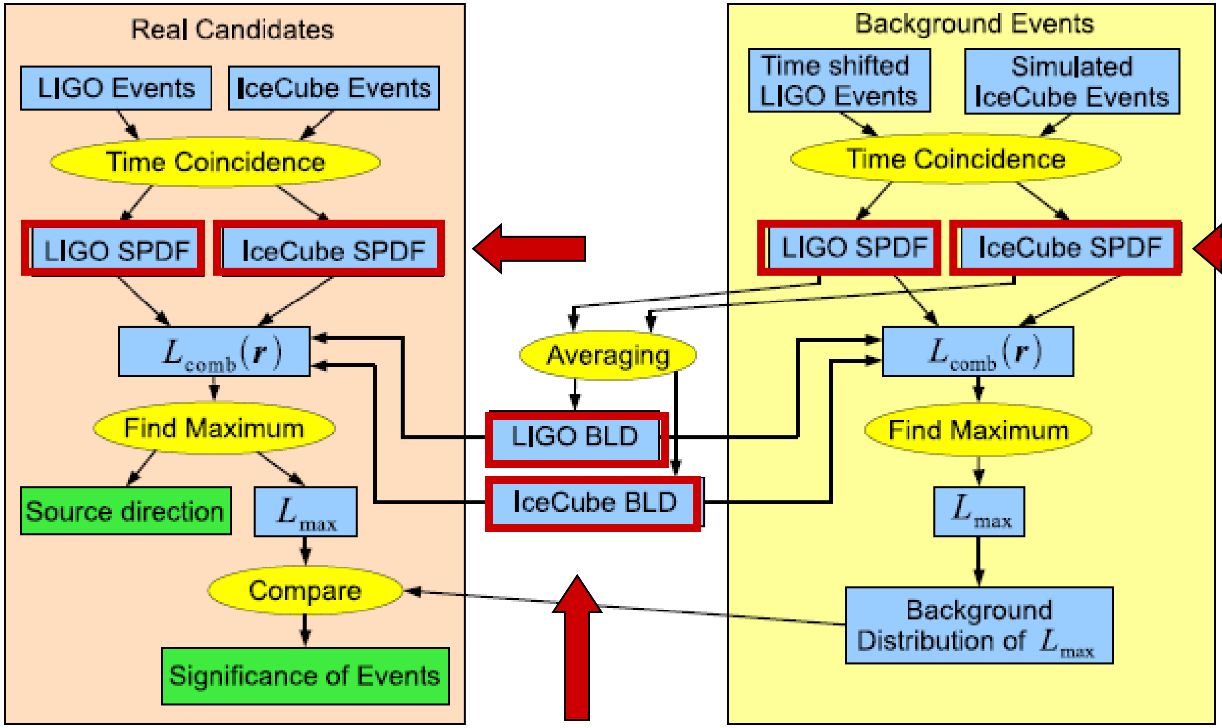
- Stellar collapse is promising source for GW/HEν
- Baryon-rich (failed) GRB
  - Rate can be very large
  - Good for neutrino production
- For the model with $E_K = 3 \times 10^{51}$ erg and $\Gamma = 3$, we expect ~30 neutrino events at km^3 detectors from a 10-Mpc burst
- Kaon decays give important contribution than π decays

Conclusions 2

- Supernova rate in the Galaxy is ~1–3 century^{-1}
- Supernova rate in the local Universe is ~1–3 yr^{-1} (within 10 Mpc)
- But it could be much larger because of
  - Starbursts (M 82, NGC 253) around 3 Mpc
  - Virgo cluster around 17 Mpc
- Good fraction might be associated with jets
- If 10%, then $R_{\text{failed GRB}} \sim 10$ yr^{-1} within 30 Mpc

LIGO - Ice Cube coincidence analysis

Cf. **Search method for coincident events from LIGO and IceCube detectors,**
Y. Aso, Z. Marka, C. Finley, J. Dwyer, K. Kotake, S. Marka
Class.Quant.Grav.25:114039,2008; arXiv:0711.0107 [astro-ph]



<u>2 ingredients:</u>

spatial probability distribution functions (SPDF) or PSFs

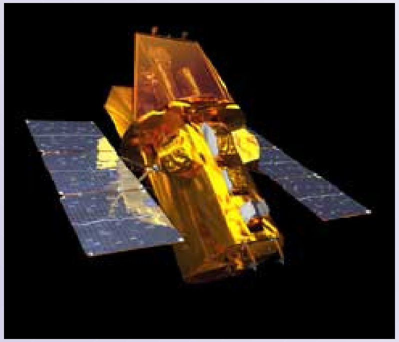
Background Likelihood distributions

External triggers and alerts

- GRB triggered searches:

High-Energy Photonics

- *Swift*
  - Best sensitivity (but few short bursts)
  - Arcsec localizations (incl. external triggers)
  - Sees 1/8 of sky
- *Fermi*
  - GBM positions >degrees
  - Sees 1/2 of sky
  - LAT data for few (albeit very interesting) bursts
- IPN
  - All-sky, all the time
  - Brightest bursts
  - Poor localizations
  - Delayed by ~day from burst

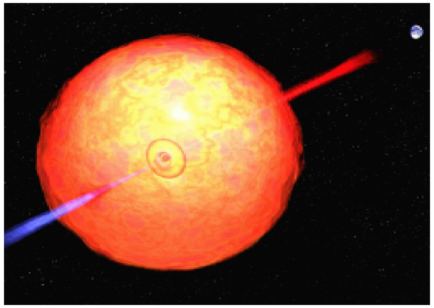


External triggers and alerts

From the GW point of view:

LSC How astrophysical triggers help VIRGO

- Know time of event
  - Search within an astrophysically motivated time window.
    - GRB bursts: [-120,+60] s
    - GRB inspirals: [-5,+1] s
  - Higher detection probability at fixed false alarm probability.
- Often know sky position
  - Only look there!
  - Can account for time delay, antenna response of instrument in consistency tests
- Frequency range
  - Frequency-band specific analysis of the data set (e.g., SGR QPOs)
- Progenitor type
  - Model-dependent searches can be performed in some cases, e.g., matched-filter for inspiral signal for short hard GRBs.



- Sensitivity improvement:
  - Often a factor of ~2-3 in amplitude / 4-10 in energy.

GW-HEN 2009.05.20 Sutton: Review of GW Data Analysis G0900455-v1 #13

Alert sending: current latency for non-triggered searches ~ 30 min

Perspectives:

- New optical instruments coming online soon: ROTSEMapper, Sky

SkyMapper

(5.7 deg^2, Southern sky survey with opportunities for ToO, 2009-2014)

- Also consider ToO with X-ray (meilleure precision sur T0 Sne,
- + grande profondeur de champ), radio telescopes (? utilité ?) ?

  - HEN → GW alerts: to be implemented
    (no real need for short latency as the whole GW data streams are registered)

  - GW → HEN alerts: current GW latency (~30 min) is an obstacle for ANTARES
    - improve latency from the GW side (down to ~10 min...)
    - enlarge ANTARES raw data buffer (→ hour ?)