# Multi-messenger programs and searches with ANTARES

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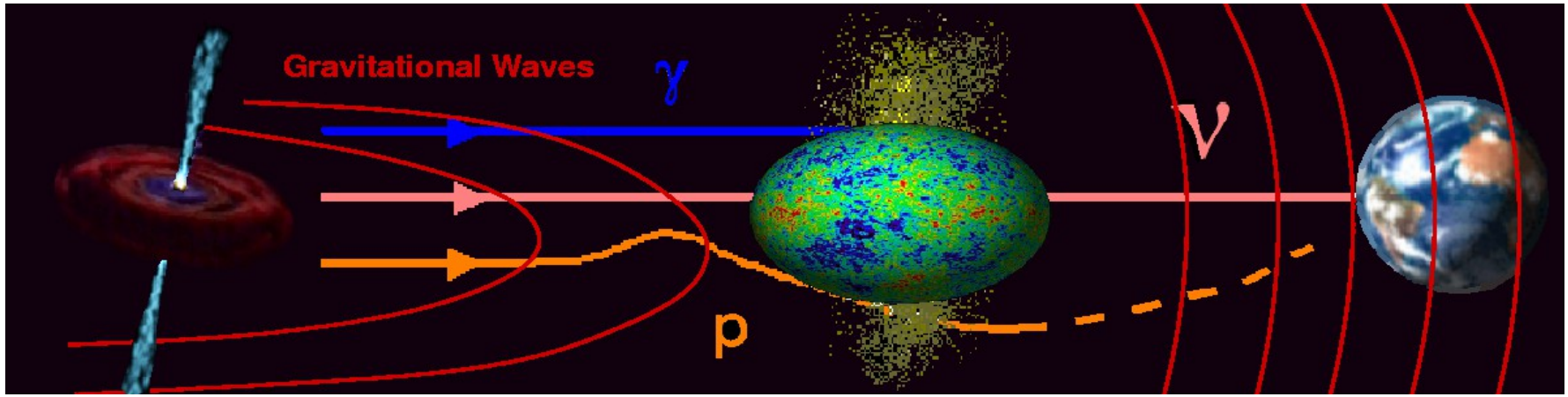
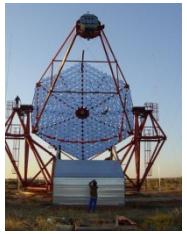
VLVNT Workshop Stockholm , 05/08/2013

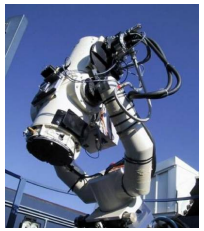
# Multimessenger astronomy, why ?

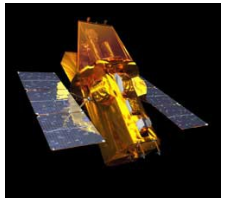



- Independant messengers → uncorellated background
  → lower quality cuts → Higher signal efficiency
- Better understanding of sources
  - Electromagnetic/Hadronic processes
  - High to Ultra High Energy Cosmic Ray accelaration Sites
  - Discovery of Gamma-ray dark sources
  - …

# Multimessenger atronomy : who ?







Radio
TANAMI

GeV-TeVγ-rays
Fermi / HESS…

UHECR
Auger

Neutrino HE
ANTARES

Optic / X-ray
TAROT, ROTSE
/ Swift, ZADKO

Gravitational
Waves
Virgo / Ligo

# Multi-messenger astronomy, how ?

**ON-LINE** (w. ANTARES fast reconstruction):

- « good events » → alerts to others :
  GCN alerts → something in ANTARES ?

→ **TATOO Program**

**OFF-LINE:**

- Follow-up of ANTARES hotspot(s)
- Use of other messengers informations, *i.e.* Maximize :

$$Likelihood\ ratio = \frac{P_{sig}(\alpha,\delta) \times P_{sig}(t)}{P_{bgd}(\alpha,\delta) \times P_{bgd}(t)}$$

**Time integrated searches**:
- Point Sources :(see J. Zornoza's talk)
- Fermi Bubbles
- Cross-correlation with catalogues

**Time triggered searches:**
- Others → ANTARES
  - GRBs (see J. Schmid's talk)
  - Micro-quasars
  - AGN flares
- ANTARES → others
  - GW emitters

# X-correlation with catalogues

$$\mathcal{N}_{\mathrm{p}}(\Delta\Omega) = \sum_{i=1}^{N}\sum_{j=1}^{n} w_i \times \hat{w}_j \times H(\Delta\Omega_{ij} - \Delta\Omega)$$

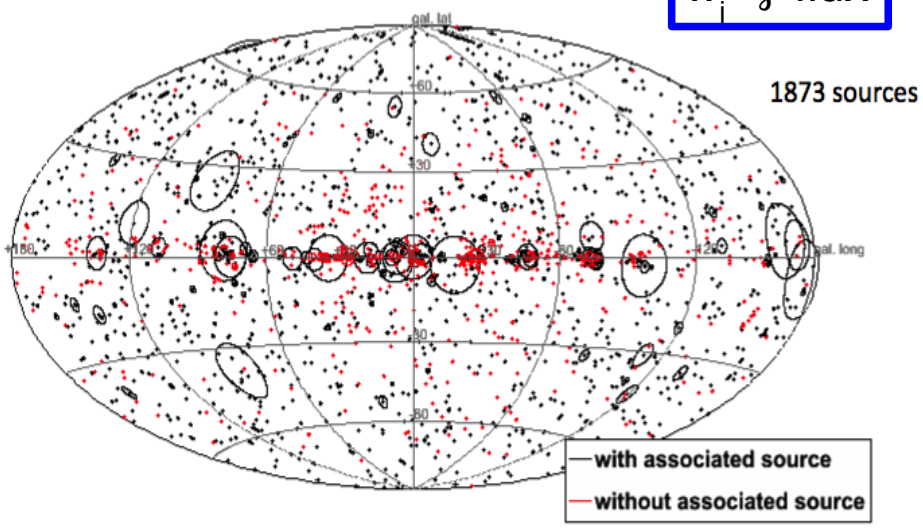
i=neutrinos

$w_i$=Number of track hits

2007-2010 PS search sample
From APJ 760 (2012) 53
3058 ν in 806 d.

j=FERMI/Lat : 2FGL

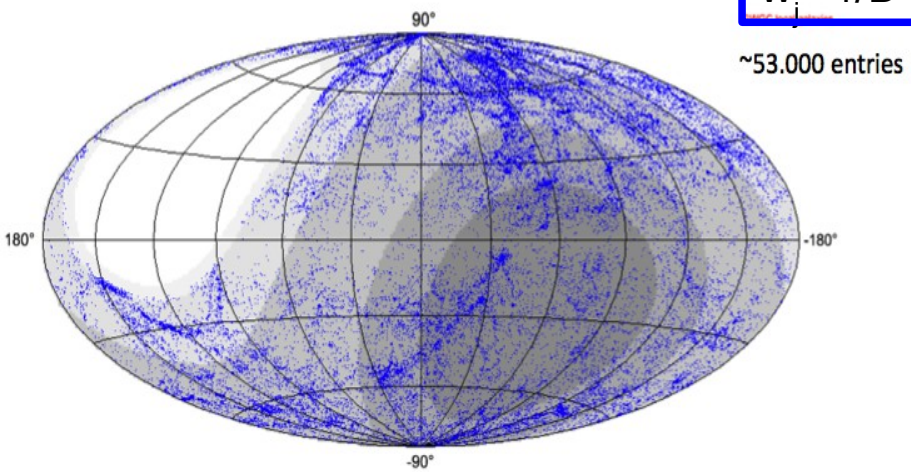
$\hat{w}_j = \gamma$ flux




**Post-trial p-value 68% for angles < 0.6deg**

j=Gazlaxy Catalog:GWGC

$\hat{w}_j = 1/D^2$




**Post-trial p-value 96% for angles < 0.3deg**

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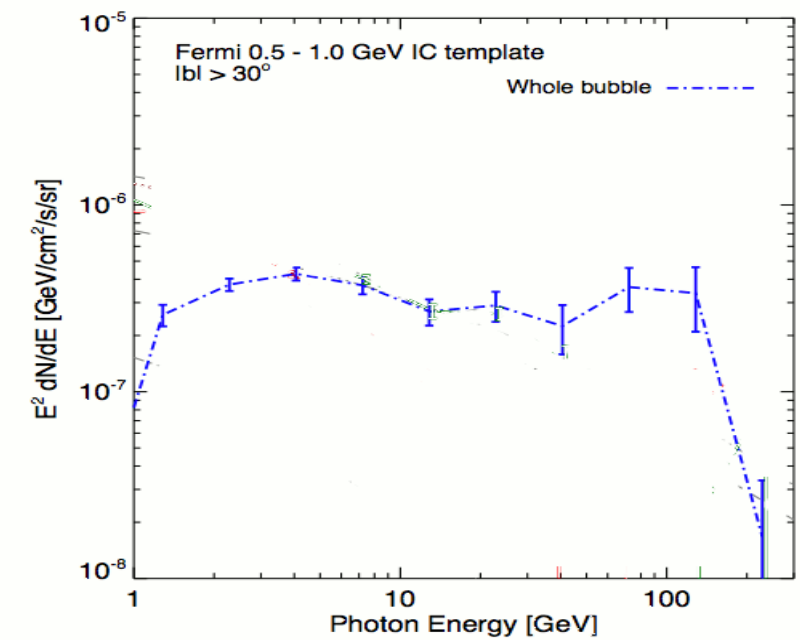
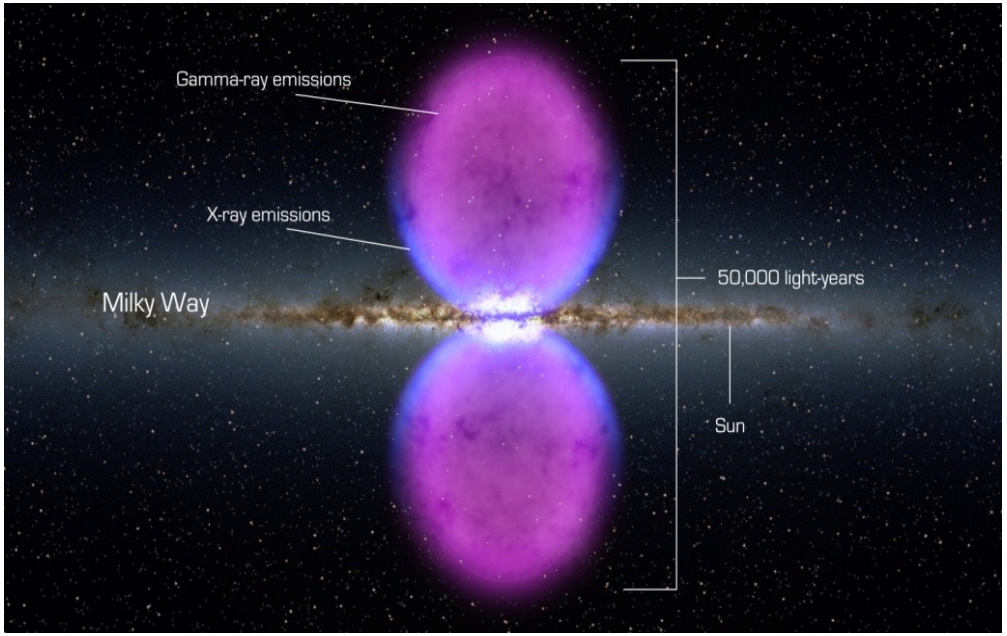
# « FERMI Bubbles »

FERMI : Extended, homogenous, hard (E-2) spectrum gamma-ray émission
⟶ M. Su, T. Slatyer, D. Finkbeiner, , ApJ 724 (2010) 1044.

Origin still debated : potentially C.R. Galactic wind interacting with ISM
⟶ Crocker & Aahronian PRL2011




2008-2011 Data : 806 d.

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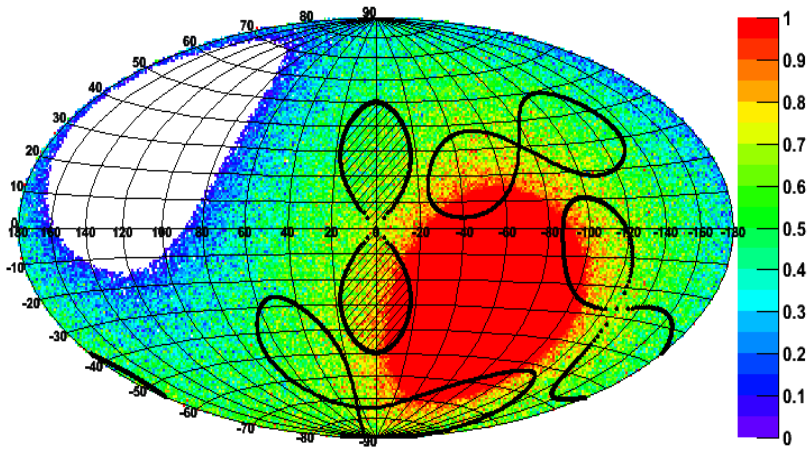
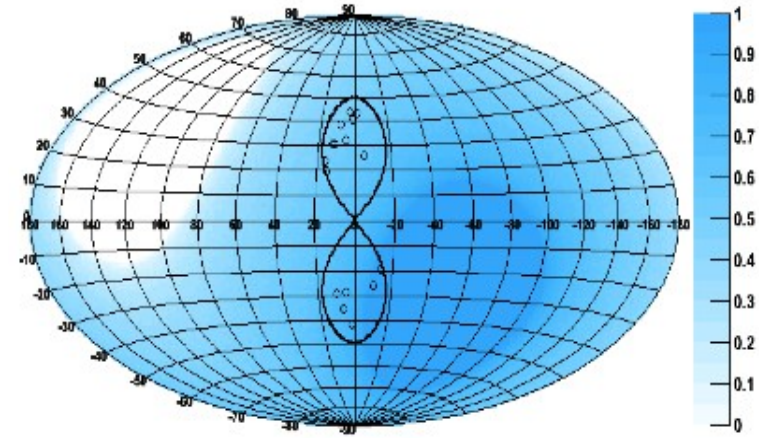
# « FERMI Bubbles »

Bgd estimation



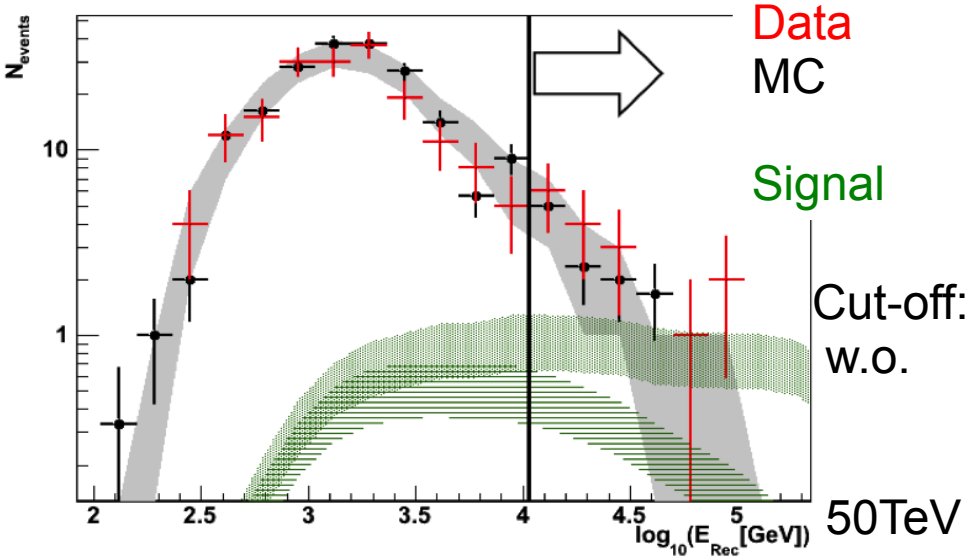
$N_{exp.}$=11

Signal region

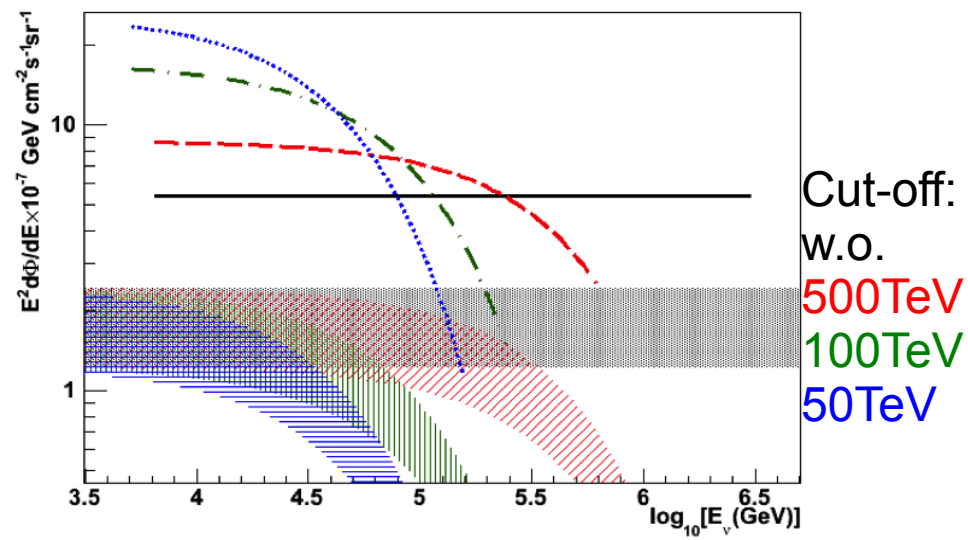


$N_{exp.}$=16 (1.2σ )

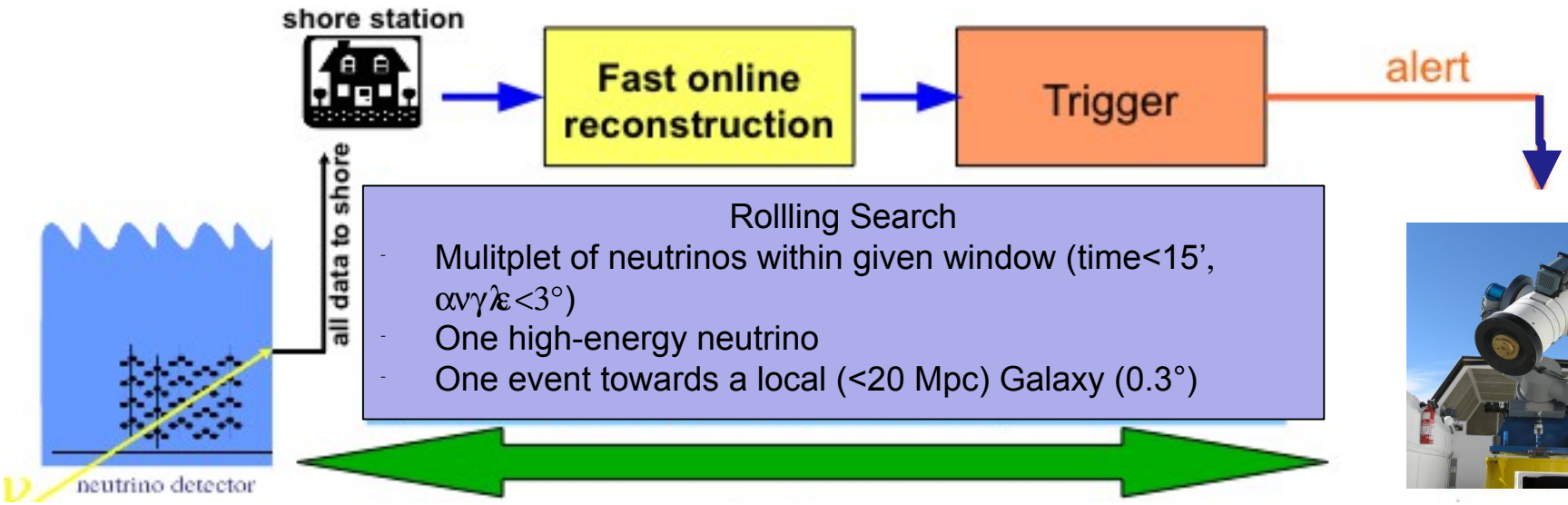
Data & MC




Flux limits



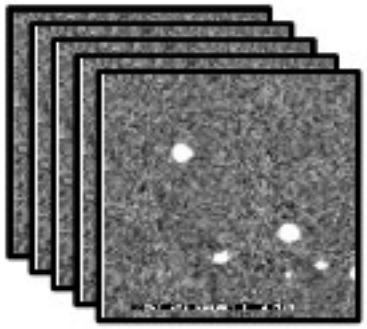
# TATOO program




Total latency: reco+trigger (<5s) alert sending (<10s) + repositioning (<5s)

optical telescopes (TAROT/ROTSE/ ZADKO/Skymapper)

- large sky coverage, high duty cycle
- no hypothesis on the nature of the source
- system active since 2009 with optical telescopes, now extended to SWIFT/XRT
- 3 types of trigger
  - Doublet (0.04/yr)
  - Single HE (12/yr)
  - Single +loc. Galaxy (12/yr)



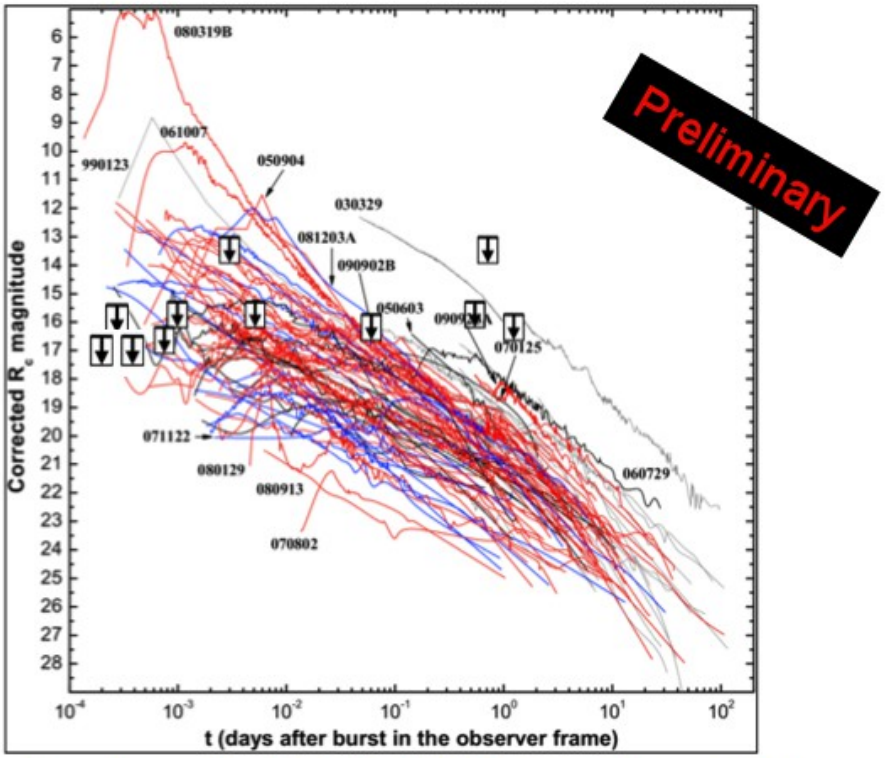
$T_0$, $T_0$ +1, 3, 9 and 27 days

📖 Astropart. Phys. 35 (2012) 530

# TATOO

- No optical coun terparts associated toa neutrino detection (model independent)
- Upper Limits in case of GRBs afterglow

| Alert | Delay (days) | U.L. Mag S/N=5 | Galactic extinction |
|---|---|---|---|
| ANT100123A | 0.64 | 11.9 | 0.2 |
| ANT100302A | 1.01 | 13.6 | 0.2 |
| ANT100725A | 8.7e-4 | 13.3 | 0.3 |
| ANT100922A | 4.7e-2 | 14.0 | 0.5 |
| ANT101211A | 0.50 | 13.0 | 0.1 |
| ANT110409A | 3.0e-3 | 18.4 | 6.7 |
| ANT110529A | 5.2e-3 | 15.6 | 1.2 |
| ANT110613A | 7.8e-4 | 17.0 | 2.3 |
| ANT120730 | 2.4e-4 | 16.7 | 0.2 |
| ANT120907 | 2.9e-4 | 15.5 | 0.2 |
| ANT121010 | 2.8e-4 | 16.5 | 0.1 |
| ANT121206 | 3.1e-4 | 16.4 | 0.2 |




Based on only detected light curves [kann2010]

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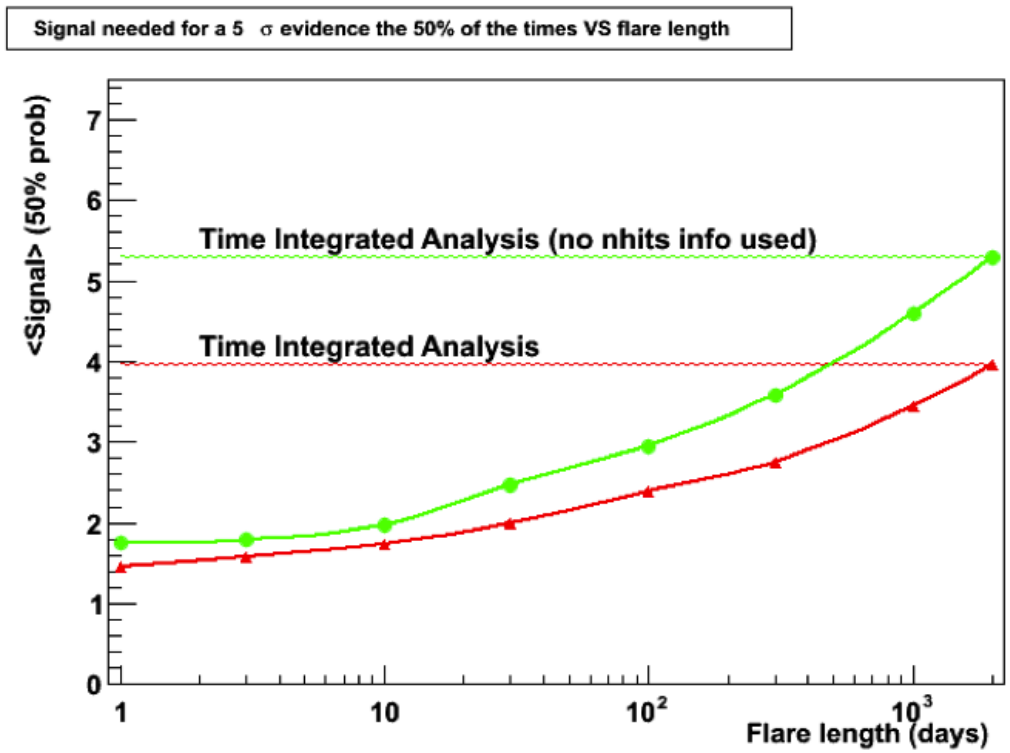
# Flaring sources

$$\textit{Likelihood ratio} \sim \frac{P_{sig}(\alpha,\delta)\times P_{sig}(t)\times P_{sig}(N_{hit})}{P_{bgd}(\alpha,\delta)\times P_{bgd}(t)\times P_{bgd}(N_{hit})}$$

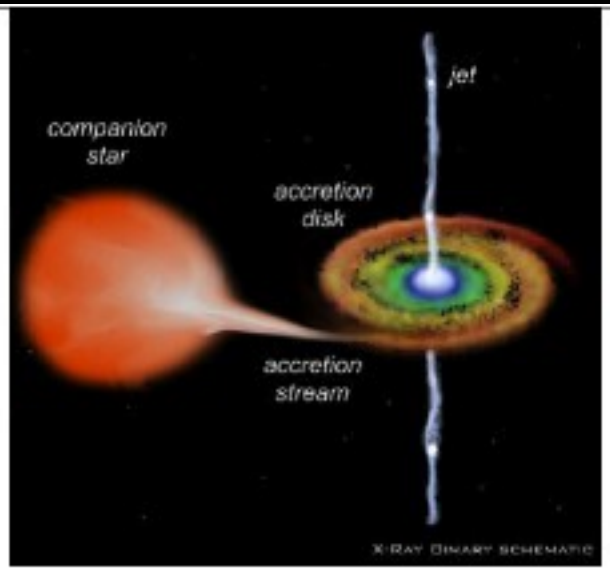
Micro-quasars

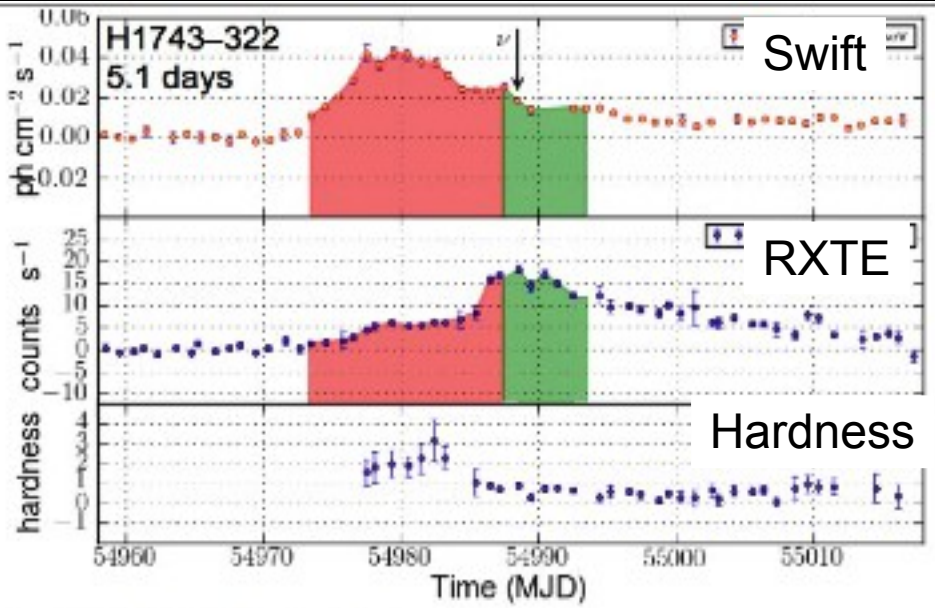
AGN




Test studies about the energy estimator $n_{hits}$ for $5\sigma$: flat flare time PDF, $\lambda$ =-5.2, $\delta$ =-30°

# Micro-quasars

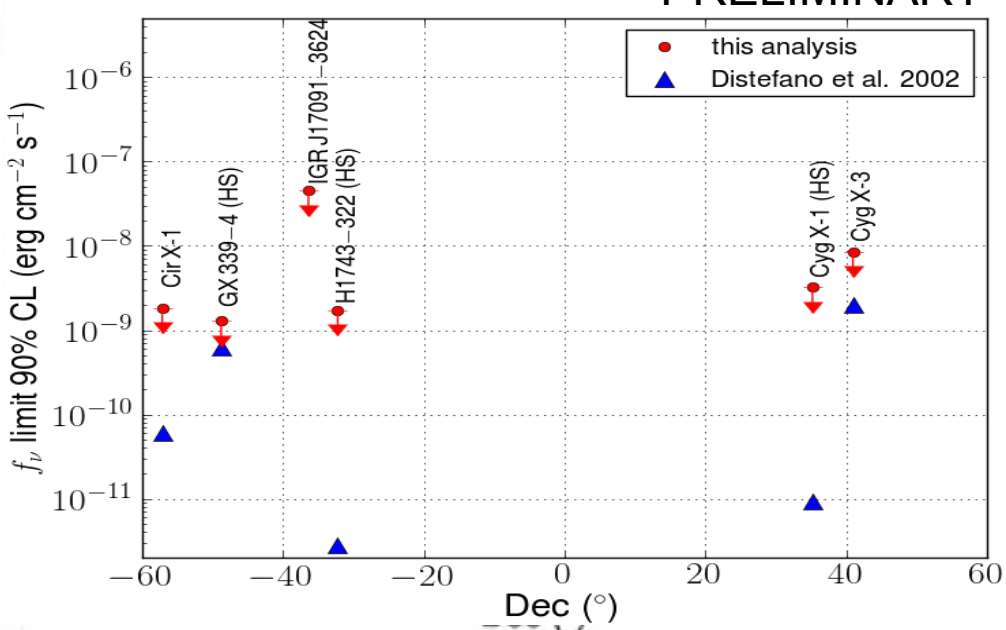



Six micro-quasars with x-ray or γ-ray outbursts in the 2007-2010 satellite data:
Circinus X-1, GX339-4, H 1743-322, IGRJ17091-3624, Cygnus X-1, Cygnus X-3

2007-2010 Data:798.5 d.
Selection of Hard state & Hard soft transition

PRELIMINARY

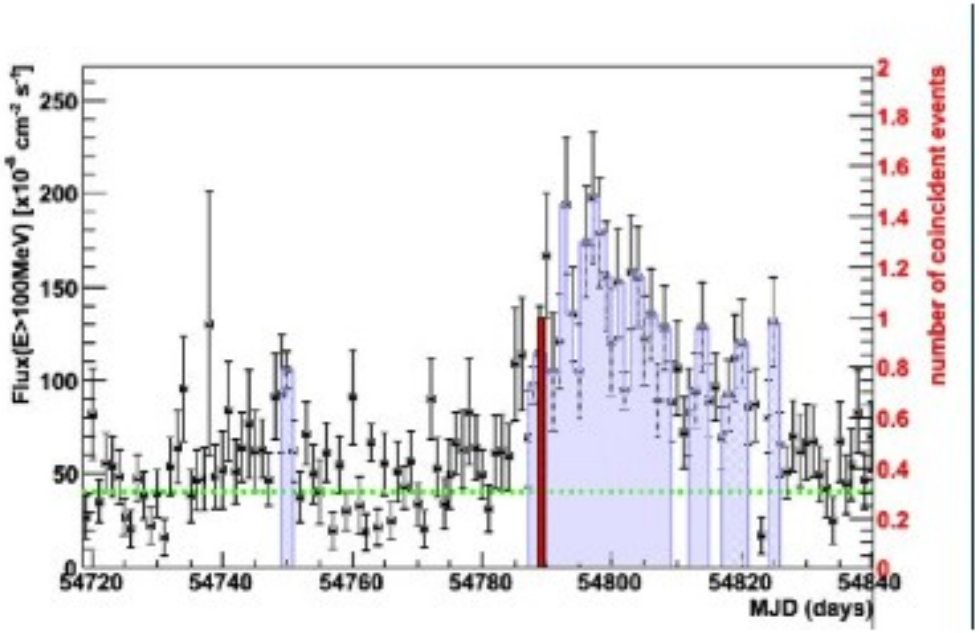


# AGN Flares 2008

10 flaring blazars in 2008:
PKS0208-512, AO0235+164, PKS1510-089, 3C273, 3C279, 3C454.3, OJ287, PKS0454-234, Wcomae, PKS2155-304

For 9 sources: 0 event

For 3C279: 1 event compatible with the source direction ($\Delta\alpha$=0.56°) and time distribution. Post trial value 10%




Number of nu necessary for disc.

Antares Live Time (d)

Visibility

In GeV.cm$^{-2}$

High State

| Source | Vis | timePDF(MJD-54000) | LT | N(5σ) | $N_{obs}$ | Fluence U.L. |
|---|---|---|---|---|---|---|
| PKS0208-512 | 1.0 | 712-5,722-4,745-7, 750-2,753-7,764-74, 820-2 | 8.8 | 4.5 | 0 | 2.8 |
| AO0235+164 | 0.41 | 710-33,738-43,746-64, 766-74,785-7,805-8, 810-2 | 24.5 | 4.3 | 0 | 18.7 |
| PKS1510-089 | 0.55 | 716-9,720-5,726-35, 788-90,801-3 | 4.9 | 3.8 | 0 | 2.8 |
| 3C273 | 0.49 | 714-6,716-8,742-5 | 2.4 | 2.5 | 0 | 1.1 |
| 3C279 | 0.53 | 749-51,787-809, 812-5,817-21,824-6 | 13.8 | 5.0 | 1 | 8.2 |
| 3C454.3 | 0.41 | 719-51,761-5,767-9, 784-801 | 30.8 | 4.4 | 0 | 23.5 |
| OJ287 | 0.39 | 733-5,752-4,760-2, 768-70,774-6,800-2, 814-6 | 4.3 | 3.9 | 0 | 3.4 |
| PKS0454-234 | 0.63 | 743-5,792-6,811-3 | 6.0 | 3.3 | 0 | 2.9 |
| WComae | 0.33 | 726-9,771-3,790-2, 795-7,815-7 | 3.9 | 3.8 | 0 | 3.6 |
| PKS2155-304 | 0.68 | 753-5,756-8,799-801, 828-30 | 3.1 | 3.7 | 0 | 1.6 |

APP 36 (2012) 204

# AGN Flares 2008-2011

Data : 750 d.

FERMI source preselection :

- Blazars types
- Detection Significance: DS > 25 (standard threshold for discovery in FERMI, $4\sigma$)
- Variability Index: VI > 41.64 (less than 1% probability of being a steady source at month scale)
- Flux> $1 \times 10^{-9}$ photons $cm^{-2}$ $s^{-1}$ (1GeV<E<100GeV)
- $\delta < 35°$

Lightcurves :
- Likelihood block fit
- baseline+5$\sigma$
- Visual inspection

- **List of 40 sources with 86 flaring periods**, mostly dominated by 3 sources: **3C 454.3**, **4C +21.35**, **PKS 1510-08**, 3C 279, PKS 1502+106, PKS 2326-502, 3C 273, AO 0235+164, PKS 0426-380, 4C +28.07, PKS 0454-234, PKS 1329-049, PKS 0537-441, 4C +14.23, PMNJ 0531-4827, PKS 0402-362, PKS 1124-186, Ton 599, PKS 2142-75, PKS 0208-512, PKS 0235-618, PKS 1830-211, PKS 2023-07, PKSB 1424-418, PMNJ 2345-1555, OJ 287, PKS 0440-00, PKS 0250-225, B22308+34, B21520+31, PKS 1730-13, PKS 0301-243, PKS 0405-385, CTA 102, OG 050, PMNJ 2331-2148, TXS 0506+056, PKS 2320-035, PKS 0521-36 and PKS 2227-08.

- **Selection of 6 specially significant flares**: **3C 273** 55090-55092 MJD, **3C 273** 55095-55097 MJD, **3C 454.3** 55517-55521 MJD, **4C +21.35** 55316-55317 MJD, **PKS 0402-362** 55827-55829 MJD and **PKS 1510-08** 55853-55854 MJD

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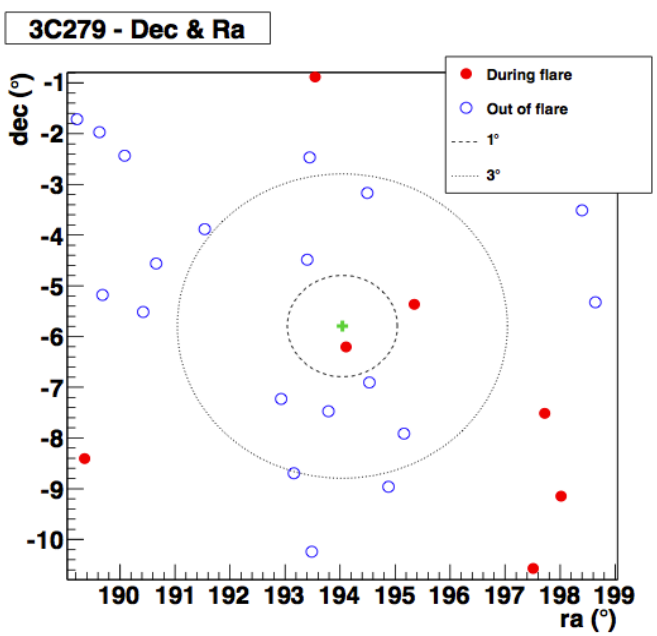
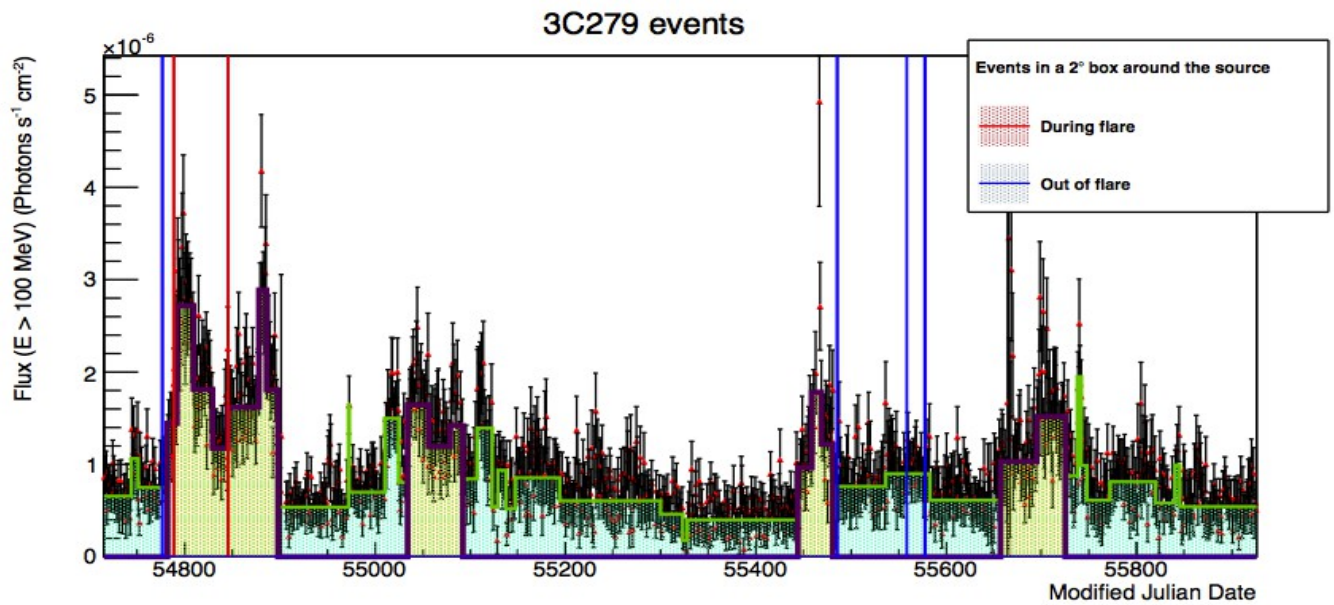
# AGN Flares 2008-2011

Only **6 sources** showed an interesting p-value:

| **p-values** (Pre-trial/Post-trial) | | | | |
|---|---|---|---|---|
| Source | $E^{-1}$ | $E^{-2}$ | $E^{-2}exp^{-E/10TeV}$ | $E^{-2}exp^{-E/1TeV}$ |
| 3C 279 | **0.17%/9.91%** | 0.33%/14.5% | 5.31%/73.5% | 6.68%/89.4% |
| PKS 1124-186 | 1.94%/54.3% | **1.07%/41.29%** | 1.68%/55.1% | 3.85%/82.2% |
| PKS 1830-211 | 2.67%/69.5% | **1.43%/52.8%** | 3.08%/72.6% | 6.64%/91.6% |
| 3C 454.3 | **3.53%/67.7%** | — | — | — |
| 4C +21.35 | **3.68%/68.9%** | — | 5.31%/73.5%% | — |
| CTA 102 | — | **4.62%/86.5%** | — | — |

(—) Those cases have a fitted signal $n_{sig} \lesssim 0.001$ and p-value$\sim$100%

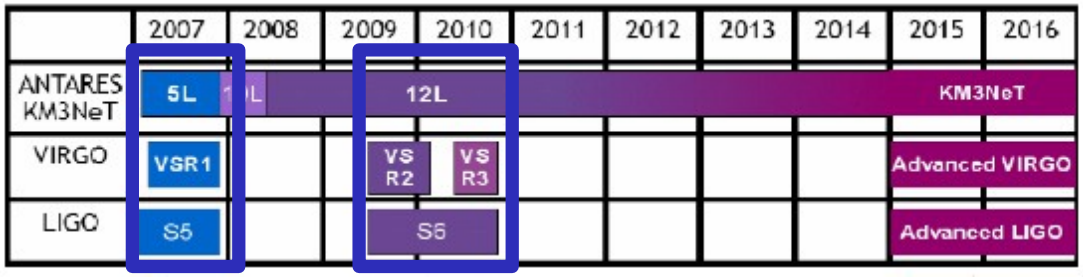


# GW+HEN

Main motivations : plausible common sources (GRBs, SGR, microquasars)
discovery potential for higgend sources (e.g. failed GRBs)

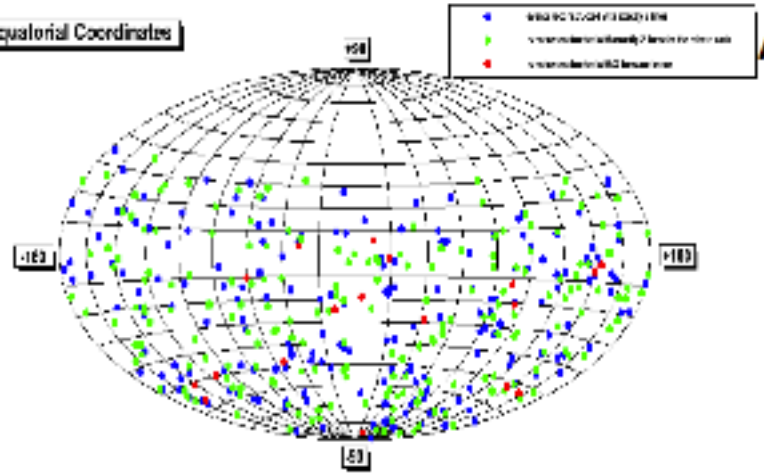
Effective collaboration (MoU) between
LSC and ANTARES
since Sept 2009



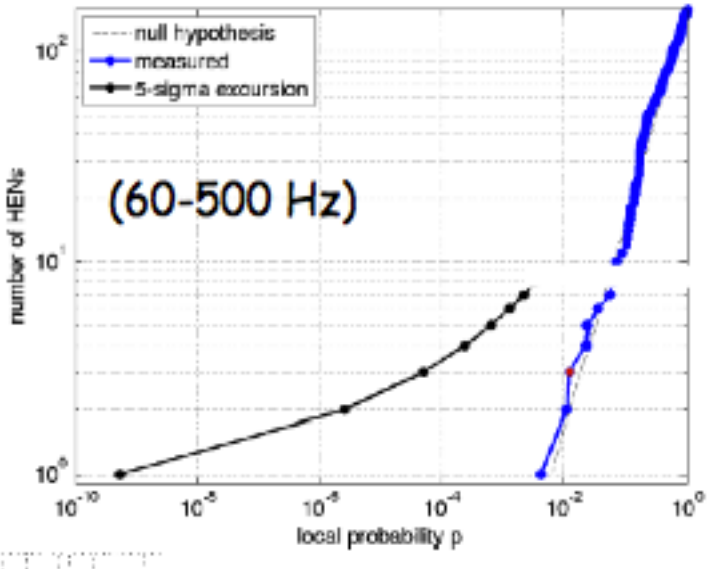

- GW/HEN common challenge: faint signals on top of abundant noise/background
- Search methodology: HEN selected events trigger the search for GW in time/space coincidence

**Phys.Rev. D85 (2012) 103004**

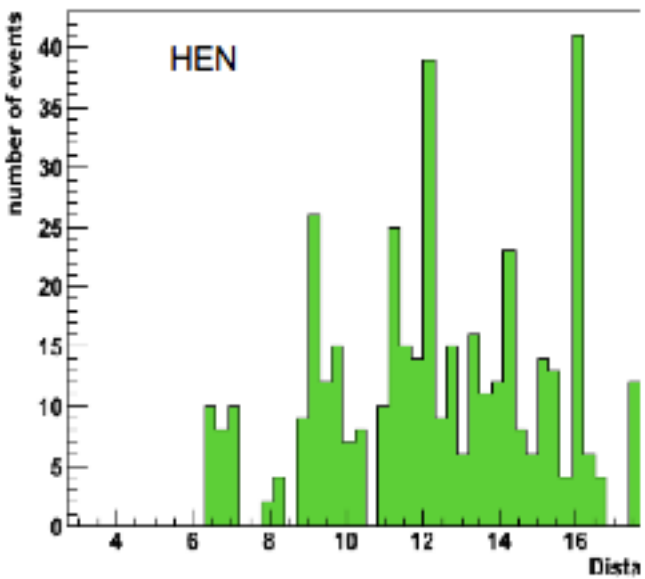
# GW+HEN 2007

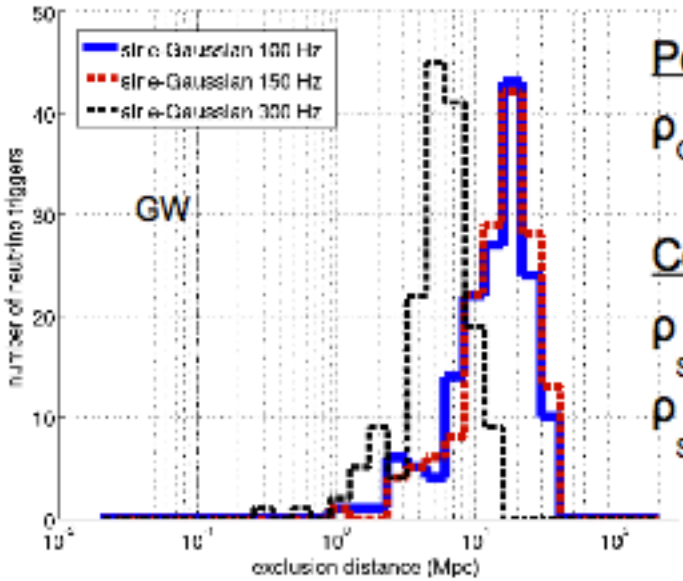



Antares Point Source search neutrino selection
→ 216 neutrino candidates, 104 d.




Exclusion distances (long GRBs)




Population density limits :

$\rho_{GWHEN} \leq 10^{-3}$ Mpc$^{-3}$ yr$^{-1}$

Core collapse SN models :

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

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

JCAP06(2013)008

# Optimization of the joint search sensitivity

**Objective: maximize the number of "observable" sources**

- Write the number of detectable GWHEN sources as follows

$$\mathcal{N}_{\mathrm{gw}\nu}(\Lambda,\rho) \propto \int_0^\infty 4\pi r^2 dr \, \frac{1}{r^2}\epsilon_\nu(\Lambda)\epsilon_{gw}(\rho; E_{gw}, r),$$

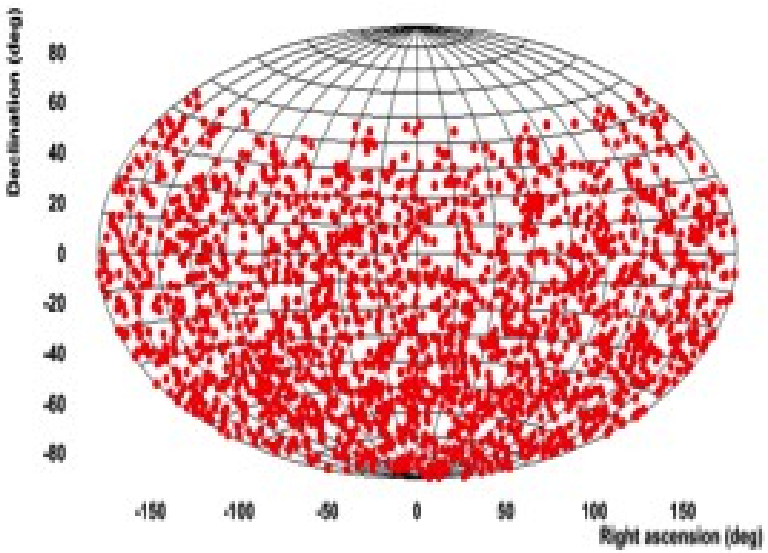
- $\epsilon_{gw}(\rho; E_{gw}, r)$ and $\epsilon_\nu(\Lambda)$ are the efficiencies for a given model
- Approximate GW efficiency as a step function

$$\mathcal{N}_{\mathrm{gw}\nu}(\Lambda,\rho) \propto \epsilon_\nu(\Lambda) D(\rho).$$

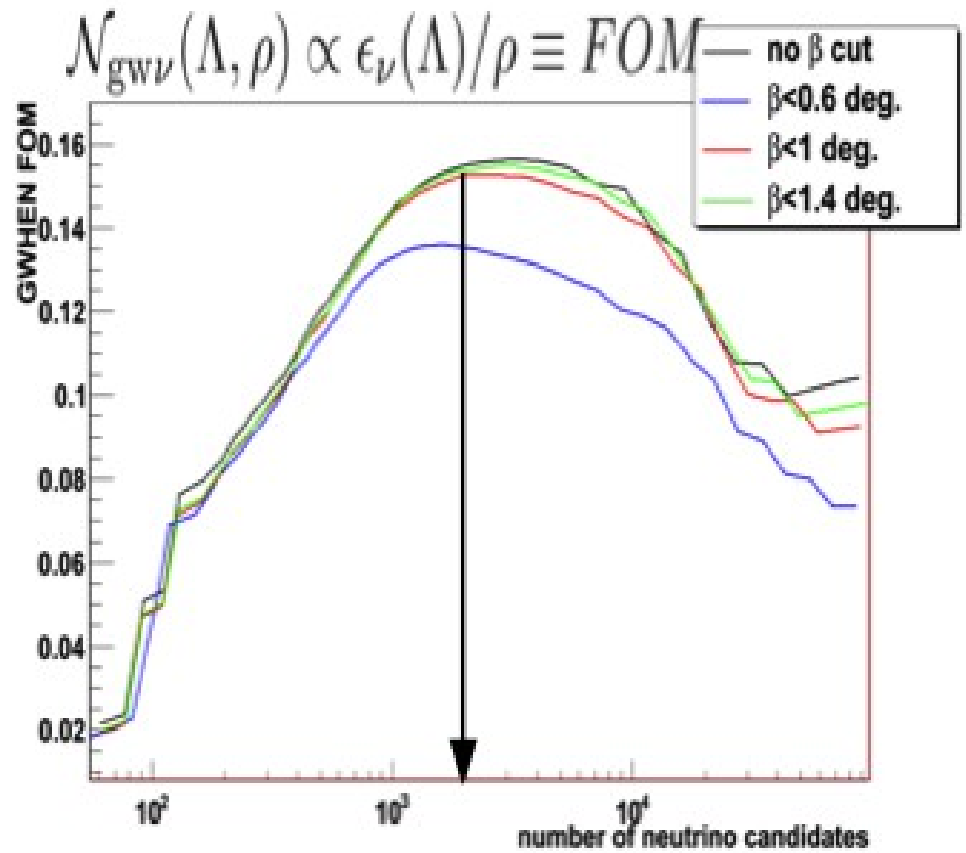
- $\rho$ is inversely proportional to horizon distance

$$\mathcal{N}_{\mathrm{gw}\nu}(\Lambda,\rho) \propto \epsilon_\nu(\Lambda)/\rho \equiv FOM$$

# GW+HEN 2009




- Better detectors, better nu reco, better GW pipeline...
- 129 days of common data taking
- Joint optimisation of the number of detectable sources




1986 neutrino candidates

Sensitivity
&
Discovery potential

→ x7 w.r.t. 2007

Final test statistics : $P_{GW}(\rho) x P_{GW}(N_{hit}) x P(\text{spatial overlap})$

# Conclusion

ANTARES has a wealth of multi-messenger programs :

Almost on-line :

- TATOO : sending alerts to robotic telescopes and Swift for follow-up
- Fast reaction to (model indpt) Fermi and Swift alerts almost ready

Offline :

- Large scale and time integrated searches : PS,X-corellations Fermi bubbles...
- Externally time triggered searches : GRBs, micro-quasars, AGNs
- Triggering other messenger detectors : GW , HESS

- No (significant) excess yet but stay tuned !