The Real-Time Capabilities of ANTARES

J. Brunner
The ANTARES Collaboration

ANTARES

- String-based detector;
- Underwater connections by deep-sea submersible;
- Downward-looking PMTs, axis at 45º to vertical;
- 2475 m deep.

14.5m

25 storeys,
348 m

100 m

~70 m

•40 km
•cable to
•shore

Junction Box

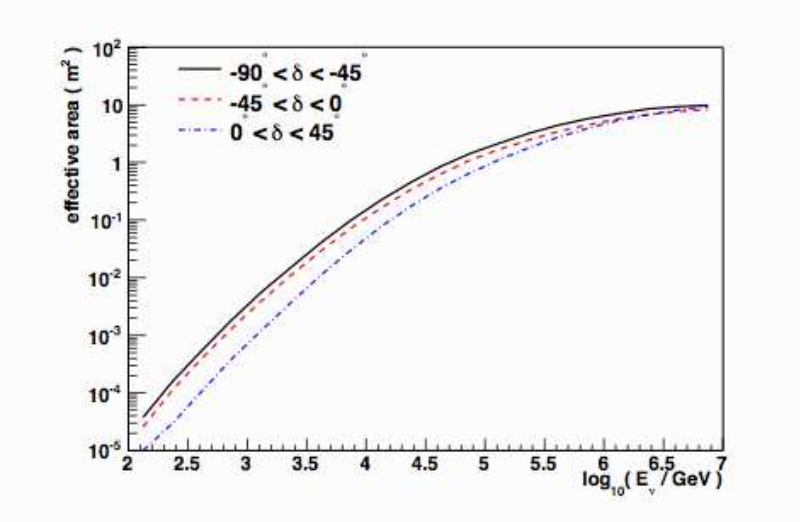
- 12 detection lines
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

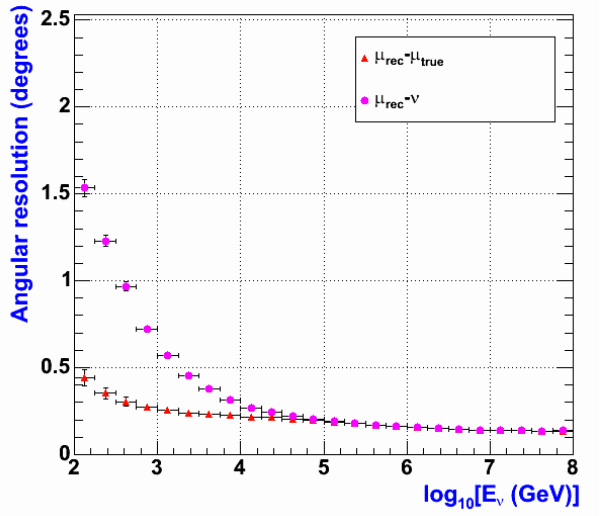
© François Montanet

ANTARES performances

ANTARES in numbers:

- *12-line data taking since 2008*
- *o(10000) detected neutrinos*
- *Angular resolution: 0.3-0.4 ° (median)*
- *Effective area: ≈1m² @ 30 TeV*
- *Visibility: ¾ of the sky, most of the galactic plane*
- *Real-time data processing*

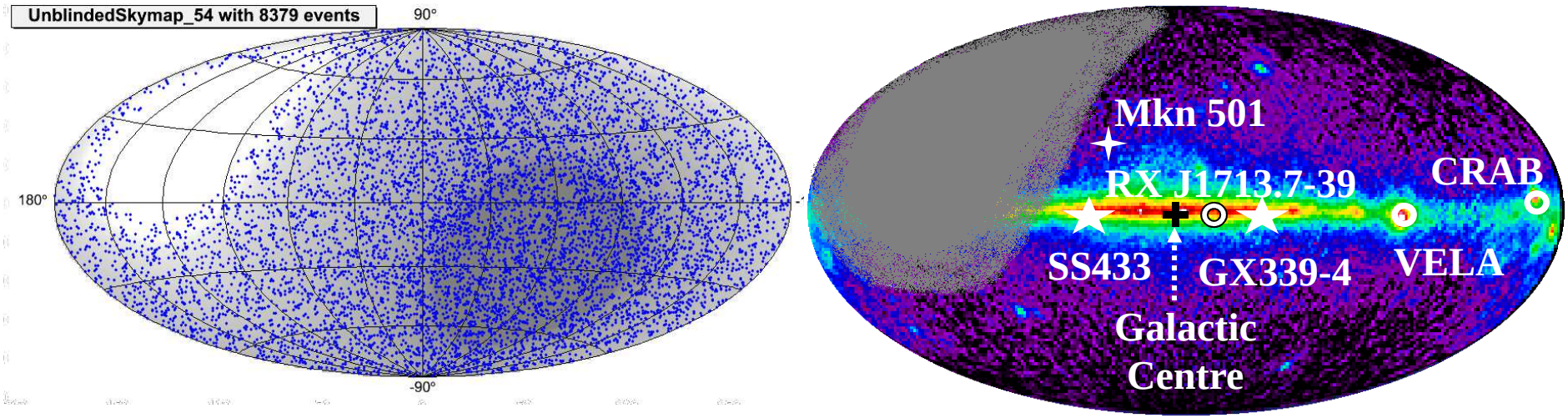




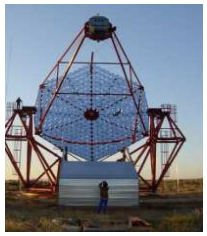
ANTARES performances

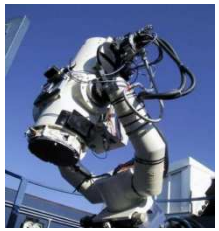
ANTARES in numbers:

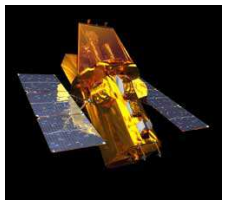
- *12-line data taking since 2008*
- *o(10000) detected neutrinos*
- *Angular resolution: 0.3-0.4 ° (median)*
- *Effective area: ≈1m² @ 30 TeV*
- *Visibility: ¾ of the sky, most of the galactic plane*
- *Real-time data processing*



Multi-messenger programs online and offline







GeV-TeVγ-rays
Fermi / HESS…

UHECR
Auger

HE neutrinos

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

Gravitational
Waves
Virgo / Ligo

Multi-messenger programs

Time-dependent searches:

- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Flares of blazars [Fermi/LAT, IACT, TANAMI…]
- Flares of the Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]

Multi-messenger correlation:

- Correlation with the UHE events [Auger]
- Correlation with the gravitational wave [Virgo/Ligo]
- 2pt-correlation with 2FGL catalogue, loc. galaxies, BH…

Real-time analysis:

- TAToO: follow-up of the neutrino alerts with optical telescopes [TAROT, ROTSE, ZADKO] and X-ray telescope [Swift/XRT]
- Online search of fast transient sources [GCN]

ANTARES as triggering lab

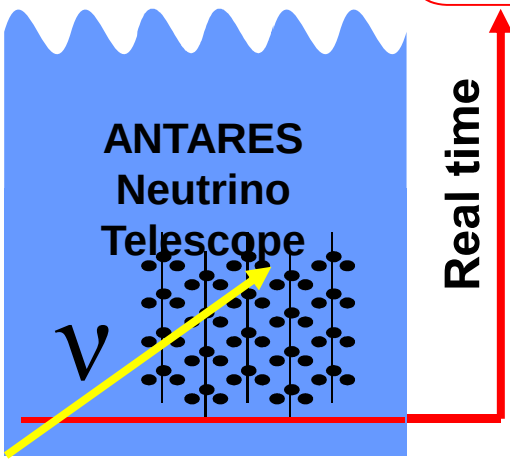
Telescopes **A**NTARES
Target **o**f **O**pportunity

Follow-up of the neutrino alerts
with optical telescopes [TAROT, ROTSE, ZADKO]
and X-ray telescope [Swift/XRT]

Optical follow-up of ν directions

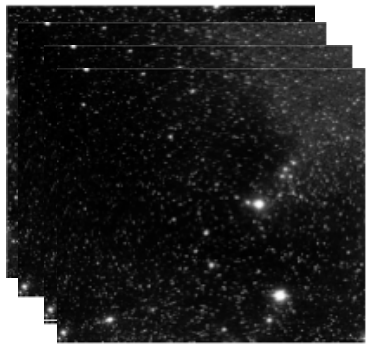
ANTARES Shore Station:
Trigger decision
On-line reconstruction
Alert message
(GCN format)

3 types of triggers:
- doublet (0.04/yr)
- single HE (12/yr)
- single + loc galaxy directions (12/yr)



Real time

Optical telescopes



Optical images

Avantages:

Sky coverage (>2π sr) + high duty cycle
Very good sensitivity (1 neutrino could yield to a discovery !!!)
No hypothesis on the nature of the source

Astroparticle Physics 35 (2012) 530-536, arXiv:1103.4477

TATooO: alert sending

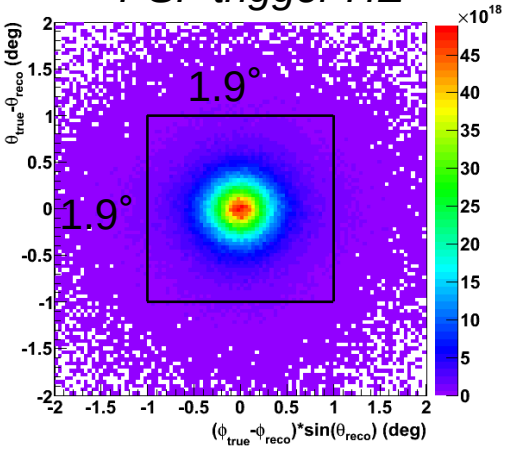
Online processing:

- Triggering & online reconstruction: ~3-5 s
- Alert transmission: ~1-10 s depending on the telescope response
- Telescope slewing: ~1-5 s

Minimum delay between the 1st image and the neutrino: ~20 s

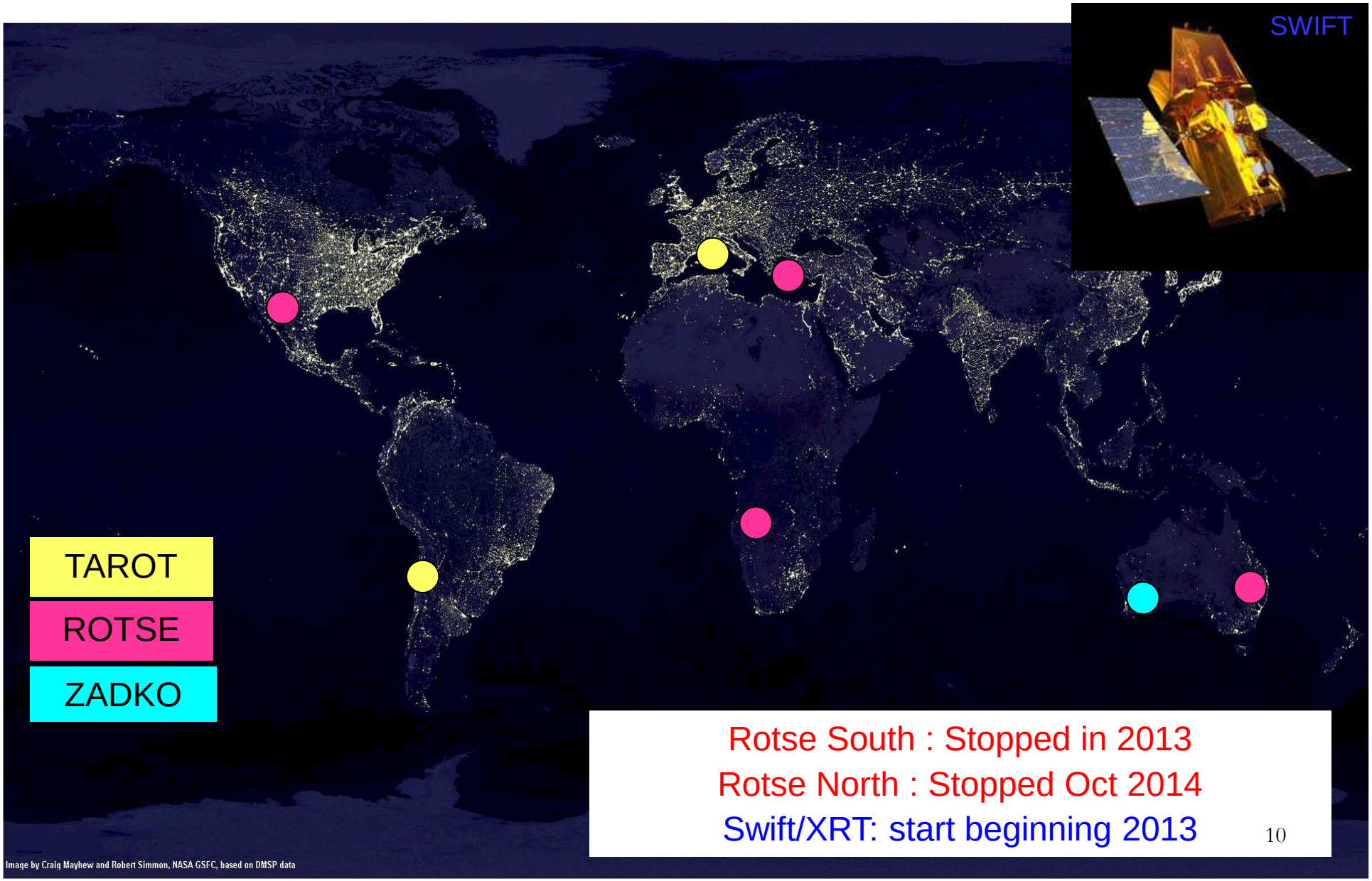
Angular performances:

PSF trigger HE



Trigger	Angular resolution	Fraction events in fov	Muon contamination	Mean energy
HE	0.25-0.3°	96% (GRB) 68% (SN)	<0.1%	~7 TeV
Directional	0.3-0.4°	90% (GRB) 50% (SN)	~2%	~1 TeV

TAToO: follow-up network

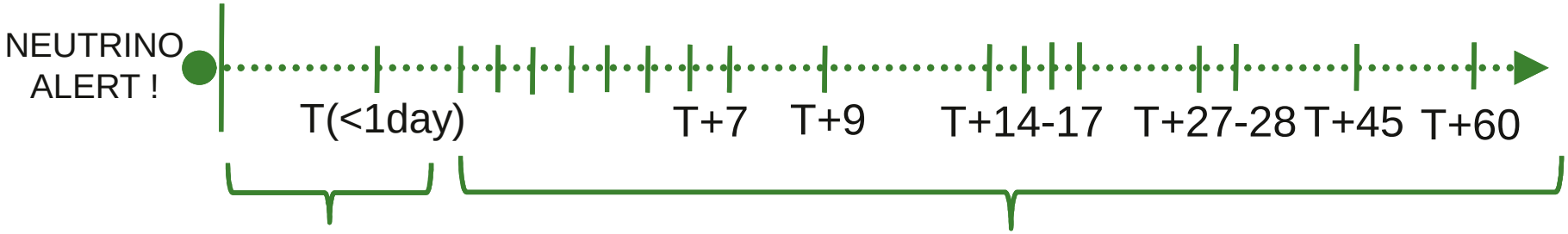


Rotse South : Stopped in 2013

Rotse North : Stopped Oct 2014

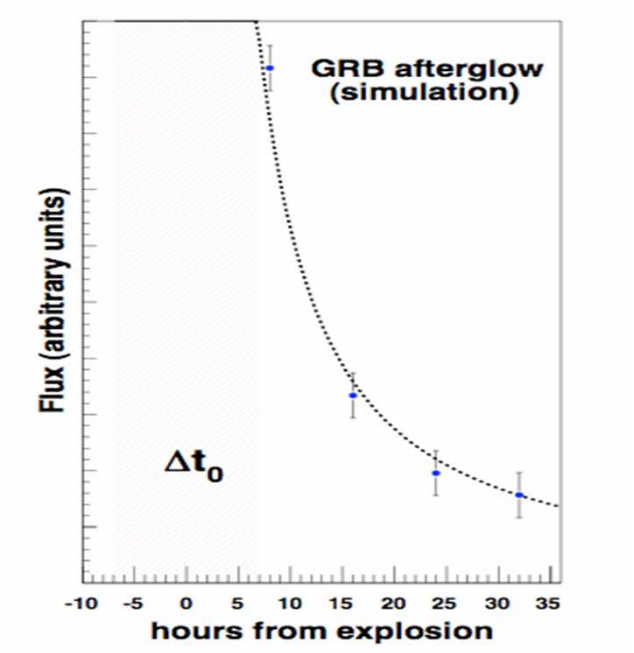
Swift/XRT: start beginning 2013

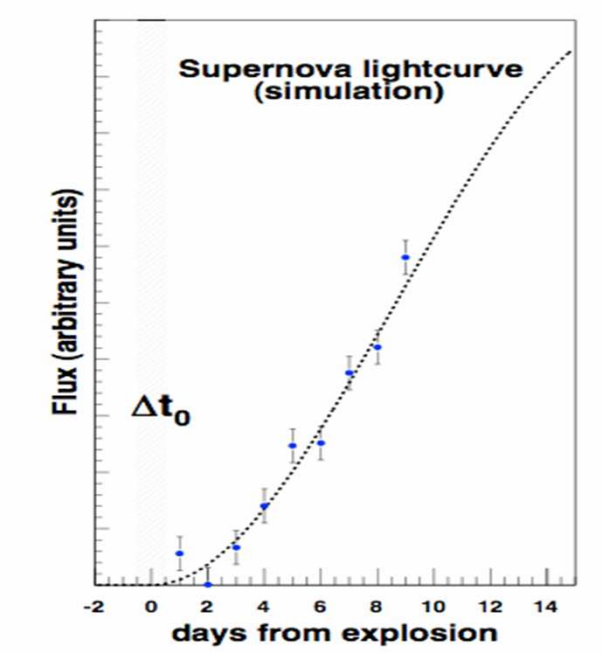
TAToO: observation strategy



Prompt observations

Follow-up observations

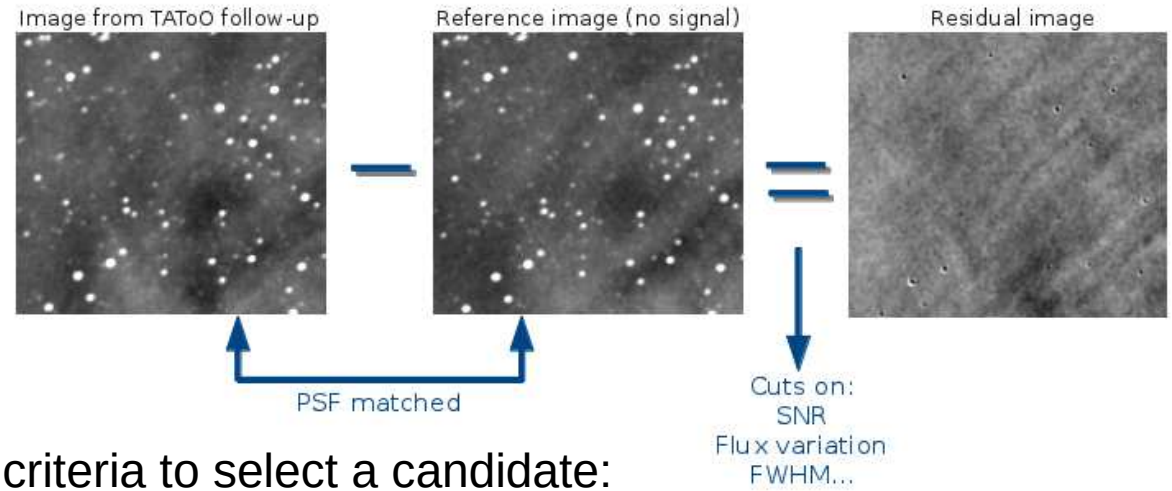




TATooO: GRB search

- High variability on the minute/hour timescale
- Images < 24h
- Analysis night by night: no co-addition

Optical counterpart search:

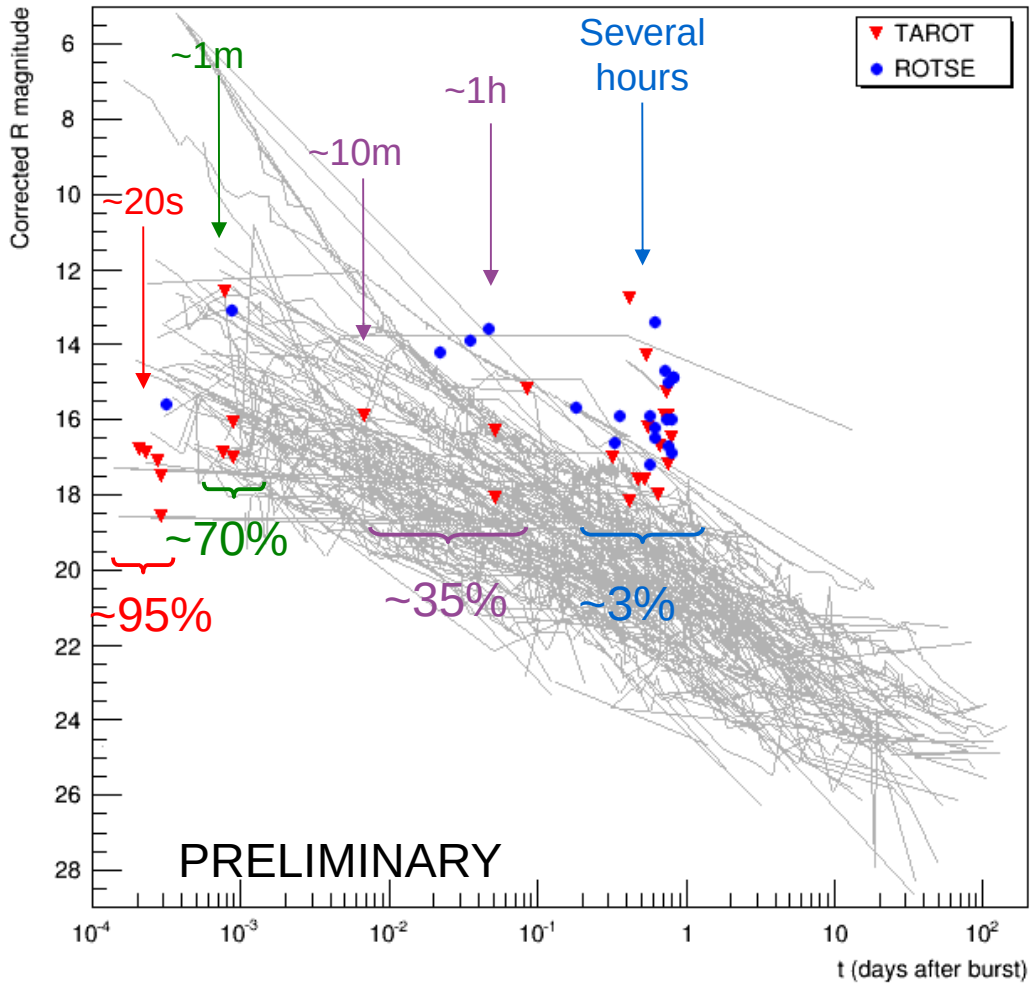


- Two criteria to select a candidate:
  1) New source
  2) Magnitude variation > 0.5
- Light curves with at least two points

TATooO: Statistics

Year	“Good” alerts	Prompt alerts
2009	3	0
2010	9	4
2011	29	11
2012	19	10
2013	22	6
2014	23	10
Total	**105**	**41**

TAToO: GRB search results



→ Comparison with optical afterglow light curves

Grey:

158 optical afterglow lightcurves detected from 1997 to 2014 (Kann).

Fast followup:

GRB excluded

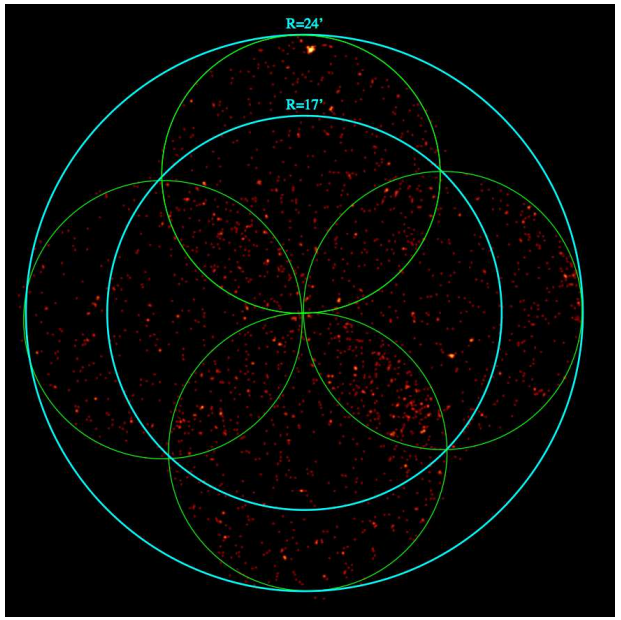
Slow followup:

no constraint

TAToO: GRB search in X-Ray

✓ Advantages: the sky is more rich and clearer signature in X-ray than in optic (less sources, more direct link with the physical processes producing neutrino)
✓ Inconvenient: quite a lot of pressure => very few alerts followed

✓ Agreement: follow-up of 6 alerts per year
✓ Event selection: sub-sample of HE TAToO events with higher energy selection => Best PSF event
✓ Image: 2 x 2 tiles of 2ks exposure each
⇒ Sensitivity: 2 10^{-13} erg/cm^2/s
⇒ 4 tiles cover 48 arcmin fov
~60-70 % of the PSF
✓ Observation strategy: 2 steps
1) Automatic response to ToO [priority 1]
=> Online analysis
2) Extension of the follow-up [priority 2]
if interesting objects found



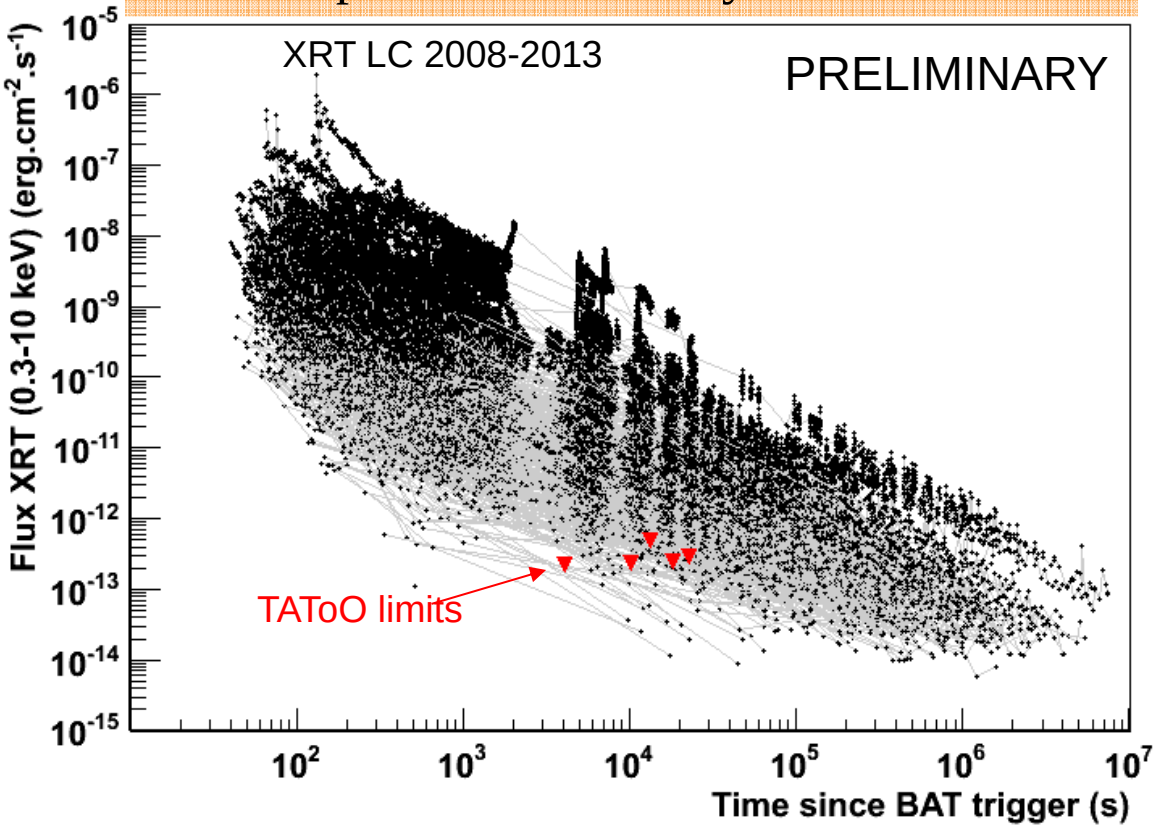
TAToO: GRB search in X-Ray

Time to send the alert: ~20 s
Time to process the alert by XRT: few hours

→ 5 alerts sent to Swift

→ No X-ray counterpart associated to our neutrino alerts

→ Upper limits on transient sources magnitude



Grey: 503 X-ray afterglow lightcurves detected by Swift/XRT from 2008 to 2013

ANTARES as Observatory

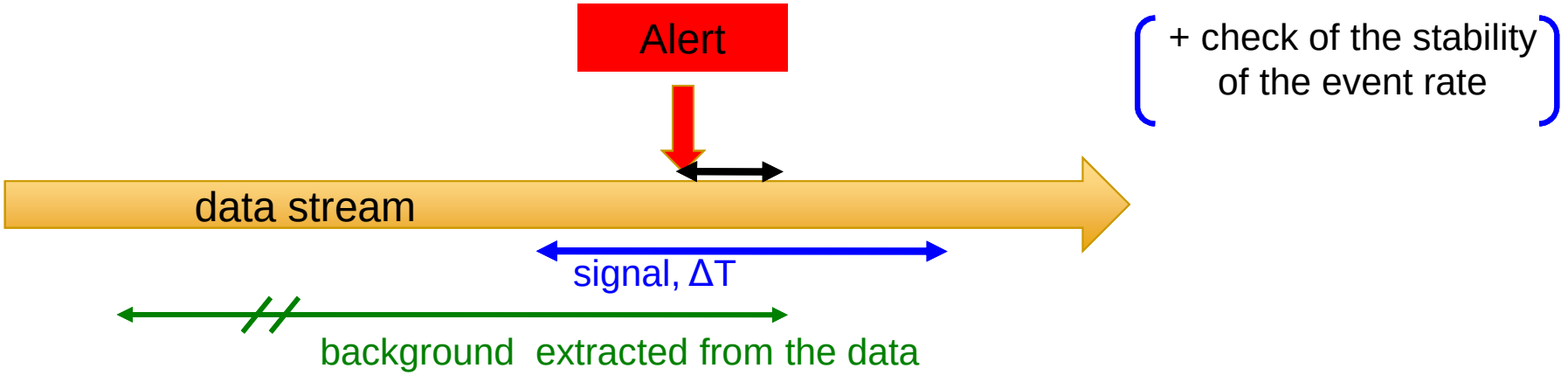
Alert receiving & on-line analysis :

- To have a fast answer to any transient astrophysical phenomena
- To have a more complete follow-up program if we find some interesting signal (for example, for a GRB, obtain the redshift or the host environment properties, or trigger TeV observation by HESS/MAGIC/VERITAS in case of a flare…)
- Generalization of the ToO program

What sources ?

Fast transient sources [few seconds to few minutes]: GRB, SGR…
=> Phenomena detected by X-ray satellites (Swift, Konus…)
=> Alerts distributed by the GCN to the whole world

Online physics analysis



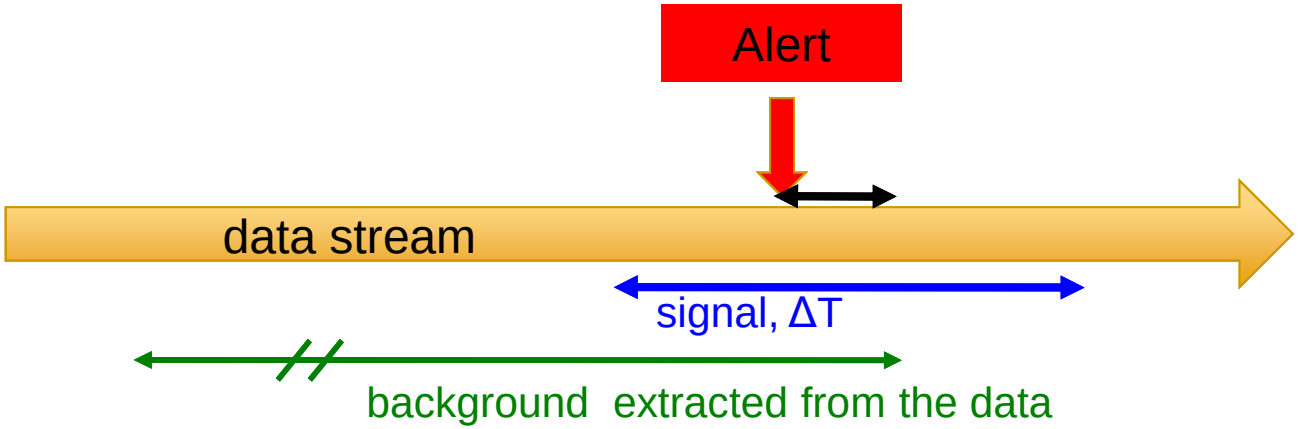
Information available in real-time?

- BBFit and AAFit events (after a pre-filtering of BBFit, i.e. 1ev/min)
- Sub-sample of selected TAToO events
- GCN notices for Fermi/GBM, Swift/BAT, Integral, IPN (Konus-Wind…)

Simplifications with respect to an offline analysis ?

- Nominal ANTARES detector geometry
- Online charge calibration
- Few data quality parameters
- Not final parameters for the transient (not always the most refined position, nature, duration…)

Online physics analysis



+ check of the stability of the event rate

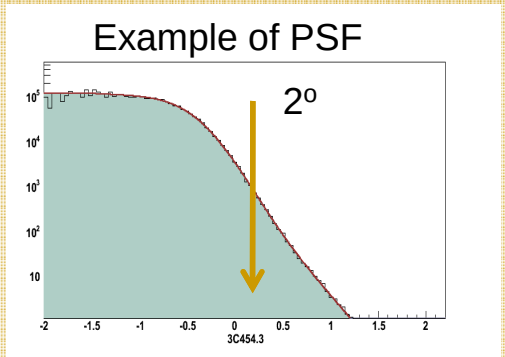
Case of GRB: ongoing: binned analysis

⇒ Time window: Max(T90,1000s) search window: [T_0-250s,T_0+750s]

⇒ Search cone: Max(2° ,Fermi GBM error)

⇒ Event selection: upgoing + Λ>-5.4

+ agreement between the 2 reconstructions



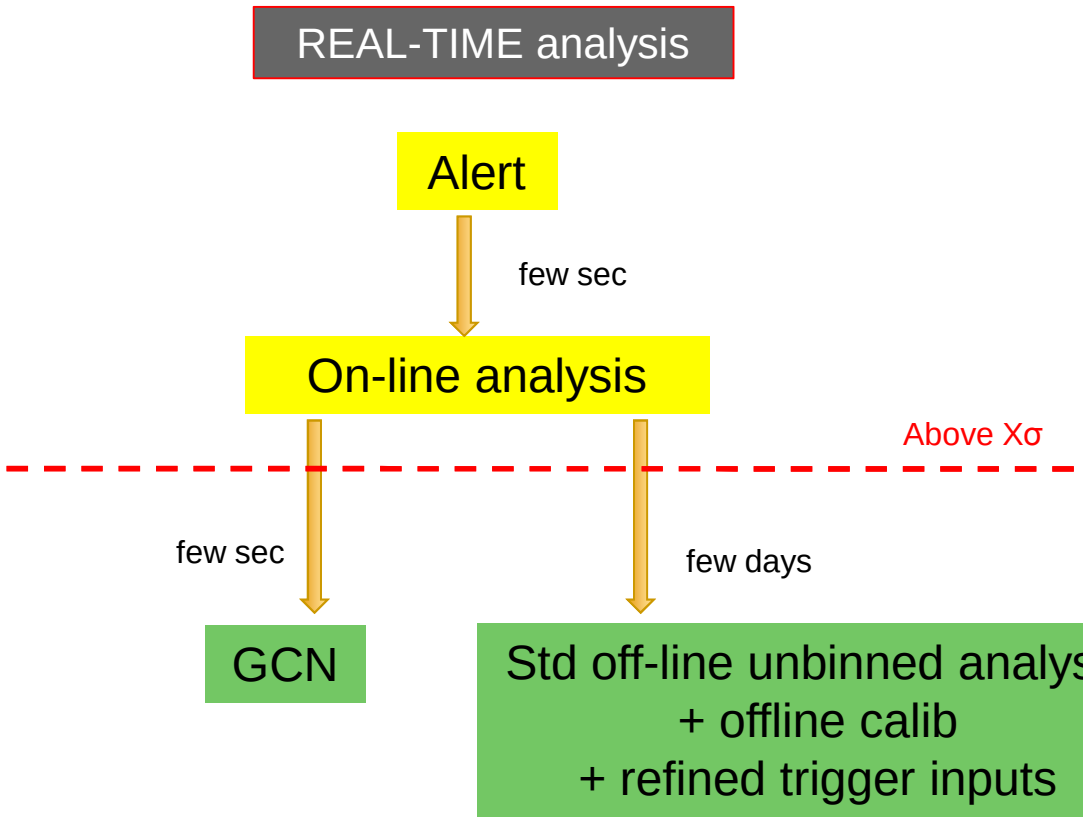
Online physics analysis

```
========================================= NOTICE ==========================
PKT INFO:   Received: LT Wed Oct  2 10:54:48 2013
 Type= 61   SN= 12    Illegal type!
 Hop_cnt= 0
 PKT_SOD= 39283.00 [sec]   delta=5.00 [sec]
 Trig#=  572742,  Segnum= 0
 TJD=    16567
 SOD=    39268.51 [sec]   delta=19.49 [sec]
 RA=      75.06 [deg] (J2000)
 Dec=     -75.73 [deg] (J2000)
 Error=  3.00 [arcmin, radius, statistical only]
 Inten=  4625 [cnts]
 Peak=   176 [cnts]
 Int_Time=1.024 [sec]
 Phi=    -24.76 [deg]
 Theta=    7.34 [deg]
 Trig_Index=  146
 Soln_Status= 0x83
 Rate_Signif= 12.60 [sigma]
 Image_Signif= 6.78 [sigma]
 Bkg_Inten=   29662 [cnts]
 Bkg_Time=    39252.89 [sec]   delta=15.62 [sec]
 Bkg_Dur=     8.00 [sec]
 Merit_Vals= 1  0  0  0  2  -3  0  0  3  0
 This is a rate trigger.
 A point_source was found.
 This does not match any source in the on-board catalog.
 This does not match any source in the ground catalog.
 This is a GRB.
 Since the IMAGE_SIGNIF is less than 7 sigma, this is a questionable detection.
```

```
Trigger number 572742
Ra 75.0612  Dec -75.7266
Error 3
T0  2013-10-2 10:54:28
Comment This is a GRB.
```

```
GCN trigger id: 572742
Nb signal  : 0
Nb background : 4.2e-5
Stability  : [ 3.8e-5    4.1e-5   4.0e-5   5.0e-5   4.2e-5 ]
=============================================================
Window low time limit : -250 s
Window high time limit: +750 s
Lamda limit  [>]      : -5.4
Cos theta limit  [>]  : 0
Angle limit  [deg]    : 2
```

Online physics analysis



⇒ Method well adapted to study individual GRB

OFFLINE analysis

Apply stacking method for the new dataset at one or two years basis (cf AGN's flare or GRB analysis)
+ special analysis

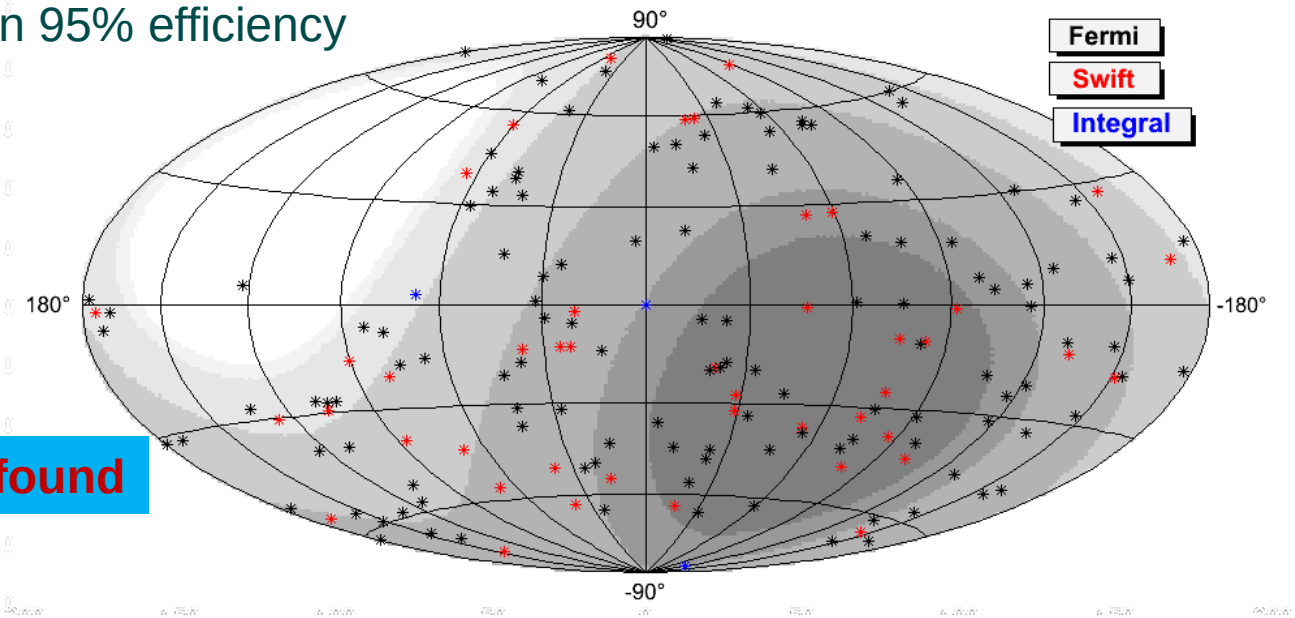
⇒ Method well adapted to study GRB population

Online physics analysis - Results

September 2013 to May 2014 : 224 GCN alerts analysed

- 57 Integral → 55 analyzed
- 44 Swift → 43 analyzed
- 123 Fermi GBM → 114 analyzed

212/224 → more than 95% efficiency



No correlated neutrinos found

ANTARES as Observatory

Alert receiving & raw data buffering

1) **GRB alerts via GCN**

   - store 2min of unfiltered raw data
   - Operational since 2008
   - physics analysis based on these low-threshold data still to come

2) **SuperNovae via SNEWS**

   - Store unfiltered coincidence data (L1) for 30min
   - Operational since Feb 2012
   - No alert yet

Summary and perspectives

✓ ANTARES : Most sensitive neutrino telescope in the TeV range for the southern sky

$\Rightarrow$ No cosmic signal yet (but taking data until at least 2016)

✓ Many coincident searches with other messengers

Off-line : GRBs, micro-quasars, blazars, unknowns

On-line : optical and gamma follow-up

✓ For transient sources and fast variable sources, transition to real-time analysis

AMON participation

Participation to AMON program endorsed by the MoU
Recall here statement made on AMON workshop 2013 – still valid

✓ 1st phase: off-line training
=> provide the dataset of 2008
(or scrambled dataset for more recent dataset)

✓ 2nd phase: real-time analysis
=> Provide real-time muon neutrino events with a latency of o(20s) with an angular resolution of o(0.4°). 4-5 neutrinos per day [check of detector stability + 2 independent tracks reconstruction]

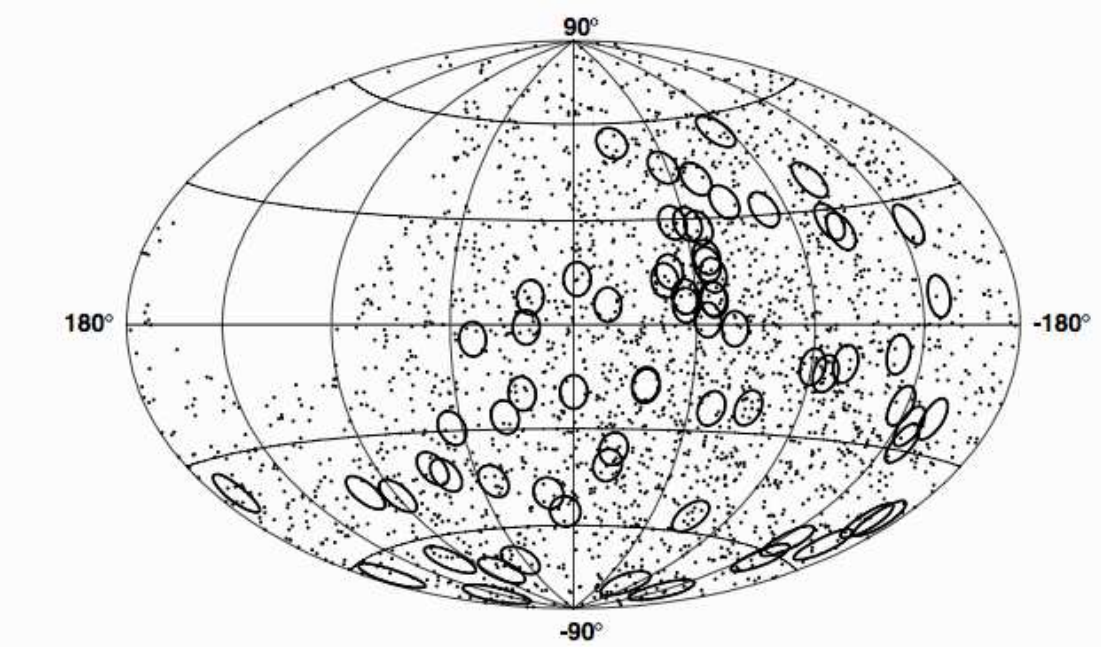
Need to define the format for data transfert, PSF model…
Event format : VOEvent ?

Backup

Multi-messenger correlation

- Correlation with the UHE events [Auger]
- Correlation with the gravitational wave [Virgo/Ligo]
- 2pt-correlation with 2FGL catalogue, loc. galaxies, BH…]

Correlation with Auger UHE events



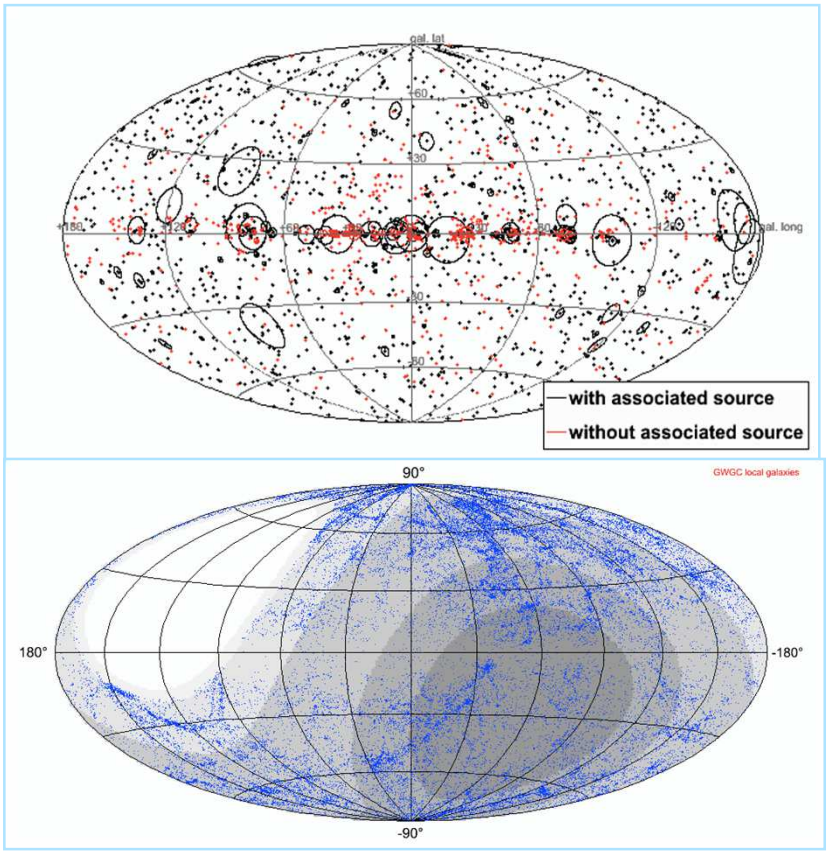
Analysis performed with 2007-08 data:
- Antares: 2190 events
- Auger: 69 events

⇒ Optimum search in a cone of 4.9º around each Auger sources
⇒ No correlation observed (deficit at 1.4 sigma)
⇒ Upper-Limit: 5.010^{-8} GeV.cm^{-2}.s^{-1}

S. Adrián-Martínez et al. ApJ 774 (2013) 19

2-pt correlation [2007-10]

2-pt correlation function: $N_p(\Delta\Omega) = \sum_{i=1}^{N}\sum_{j=1}^{n} w_i \times w_j \times H\left(\Delta\Omega_{ij} - \Delta\Omega\right)$



ANTARES: nHit weights

2FGL: gamma-ray flux (1-100GeV)

1873 sources

Post-trial p-value 68% for angles < 0.6˚

ANTARES: nHit weights

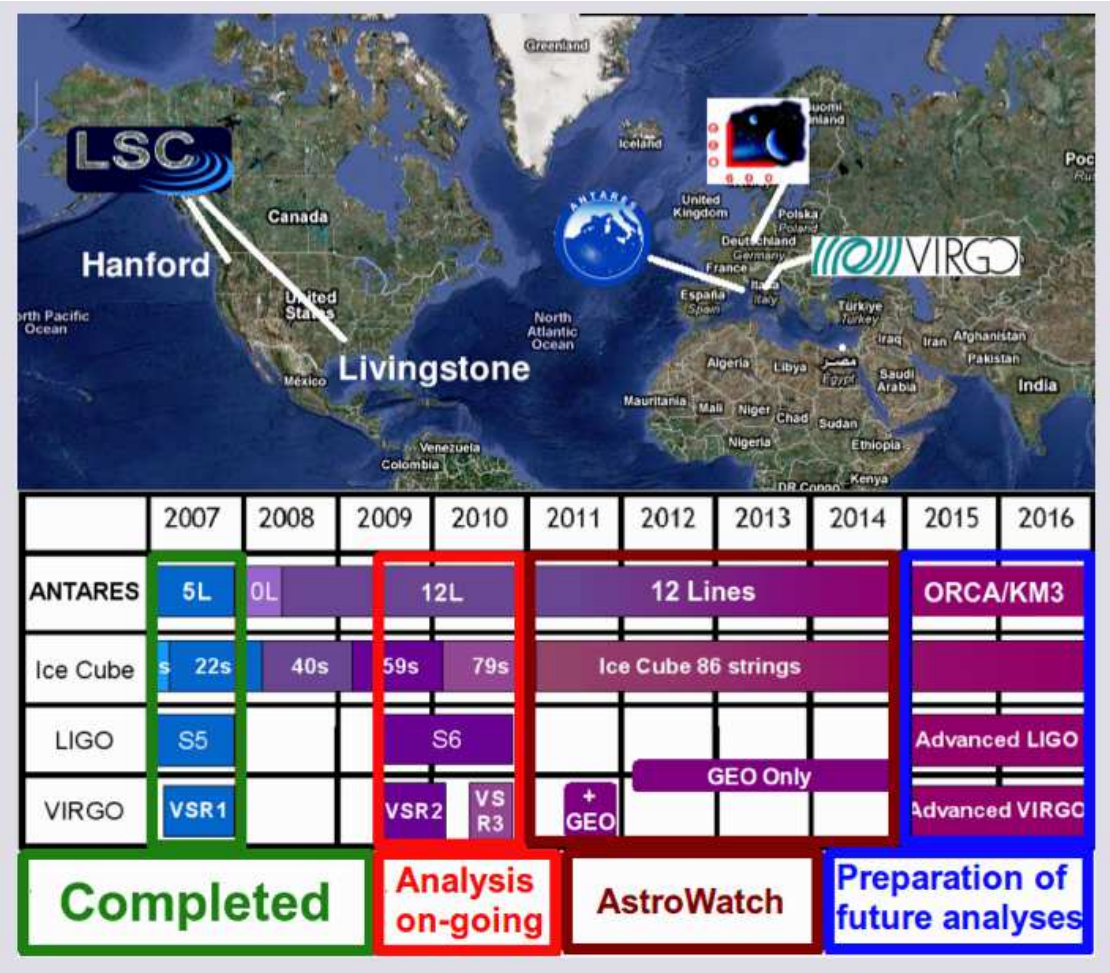
GWGC: D^{-2} weighting

~53000 loc. gal.

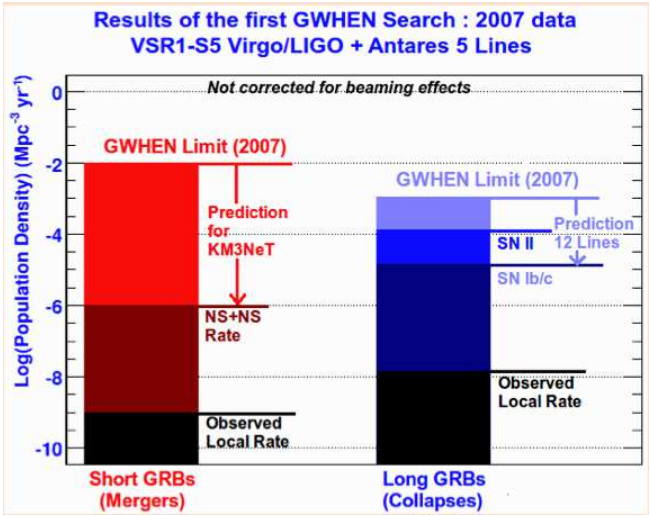
Post-trial p-value 96% for angles < 0.3˚

F. Schüssler, ICRC2013

Correlation with Virgo/Ligo GW



1st search 2007 data:



S. Adrian-Martinez et al., JCAP 06 (2013) 008

2nd search 2009-10 data:

- Optimized event selections on both side
- Improved likelihood analysis

T. Pradier, ICRC2013

Time dependent searches

- GRB [Swift, Fermi, IPN]
- Micro-quasar and X-ray binaries [Fermi/LAT, Swift, RXTE]
- Flares of blazars [Fermi/LAT, IACT, TANAMI…]
- Flares of the Crab [Fermi/LAT]
- Supernovae Ib,c [Optical telescopes]

Search for ν from GRB

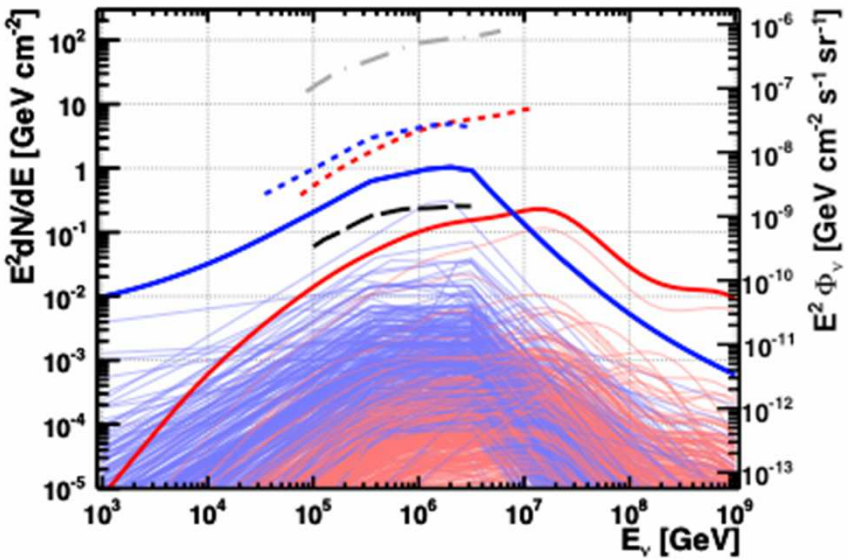
o *Analysis of GRBs from late 2007 – 2011: 296 long GRBs,*
Total prompt emission: 6.6 hours
Information from FERMI/SWIFT/GCN

o GRB simulations of expected neutrino fluence:NeuCosmA [Hümmer et al. (2010)] and Guetta [Guetta et al. (2004)]

o Likelihood analysis & quality cut optimized for NeuCosmA & highest signal discovery probability

o No events found within 10° window from GRB
Expected: 0.48 (Guetta), 0.061(NeuCosmA)

PRELIMINARY



Grey: first ANTARES limit (40 GRBs, 2007)
📖 JCAP 03(2013) 006

Black: IceCube IC40+59 (215 GRBs)

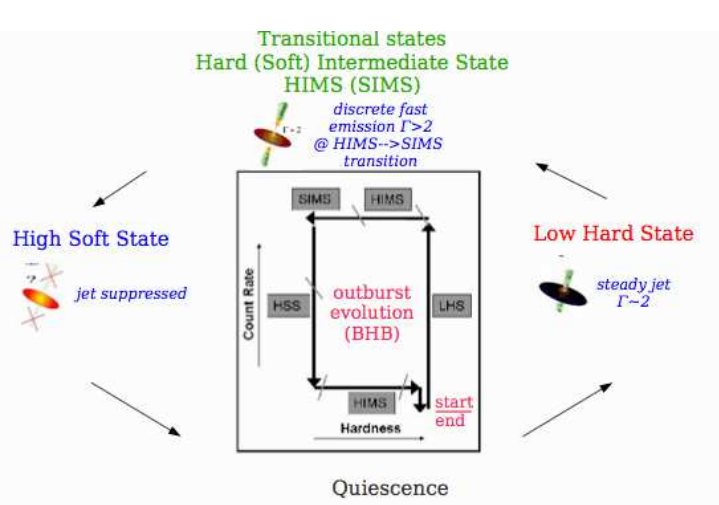
o *Dedicated analysis for very peculiar: GRB080916C, GRB110918A, GRB130427*

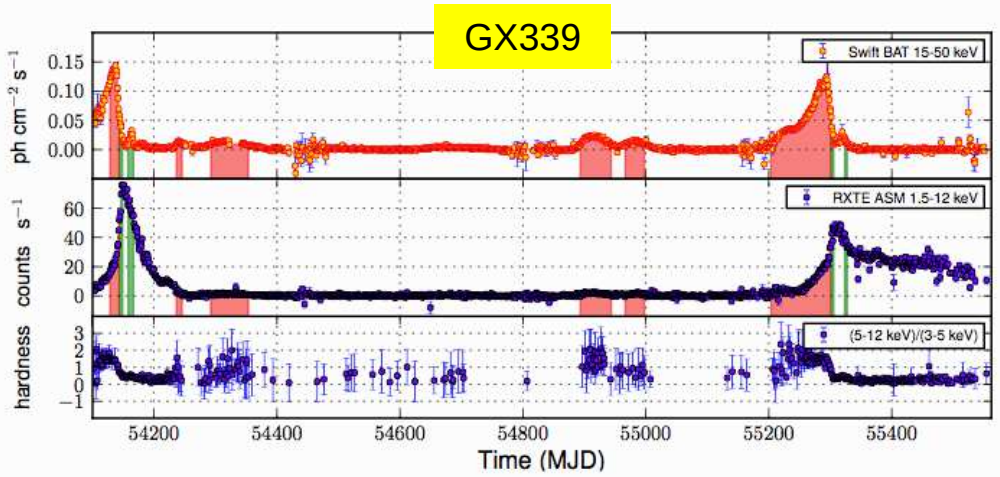
Search for ν from microquasars

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

Analysis of the 6 micro-quasars:

- For 4 black hole binaries *ν*-search split in two:
  - During hard X-ray states : “slow” steady jet
  - During transition hard→soft : “fast” discrete ejection
- Cyg X-3 : γ-ray outburst using Fermi/LAT data
- Cir X-1 : X-rays + orbital phase/jet connection

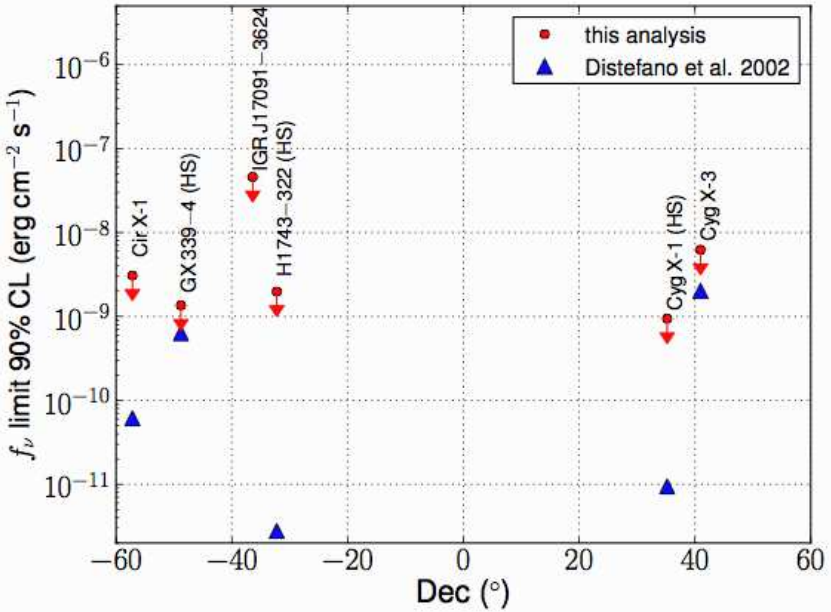




Search for ν from microquasars

No neutrino found in time coincidence with microquasars
=> Upper-limit on the neutrino flux (F.C. 90%)

	n_{sig}	livetime	fluence u.l.$^{90\%C.L.}$
Cir X-1	0	100.5	16.9
GX 339−4 (HS)	0	147.0	10.9
GX 339−4 (TS)	0	4.9	19.7
H1743−322 (HS)	0	84.6	9.1
H1743−322(TS)	0	3.3	30.3
IGR J17091−3624	0	8.5	21.3
Cyg X-1 (HS)	0	182.8	14.1
Cyg X-1 (TS)	0	18.5	6.0
Cyg X-3	0	16.6	5.7

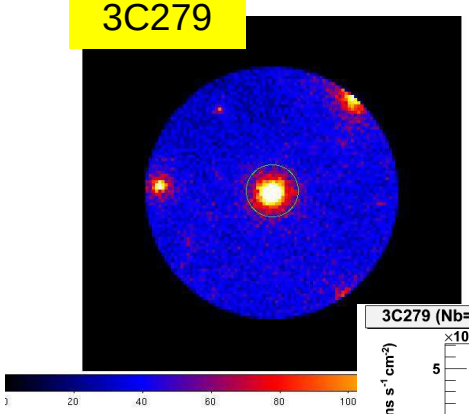


Model: Levinson, Waxman (2001), Distefano (2002) assuming a flux

$$\phi \approx E^{-2} e^{-\sqrt{E/100TeV}}$$

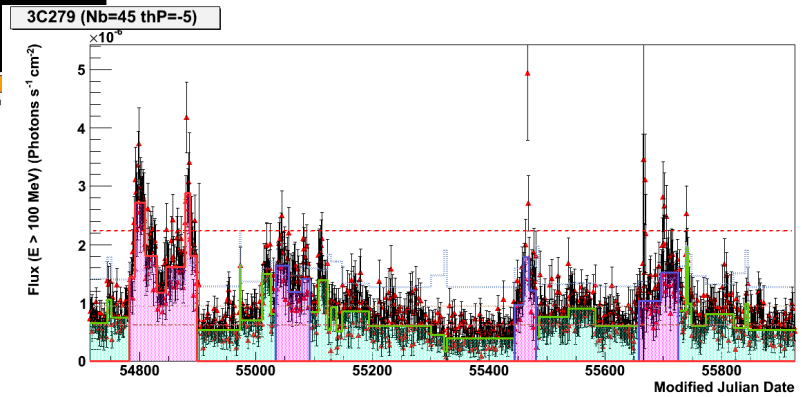
Search for ν from AGN flares

3C279

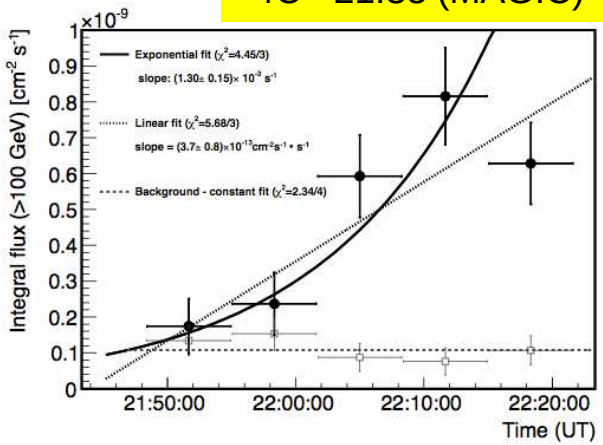


Analysis of Fermi data:

- *Counting map + lighcurve (2deg)*
- *Denoising LC (Maximum Likelihood Block method)*
- *Selection of significant flares*



4C +21.35 (MAGIC)



First analysis: selection of 10 Fermi flaring blazars [2008]:

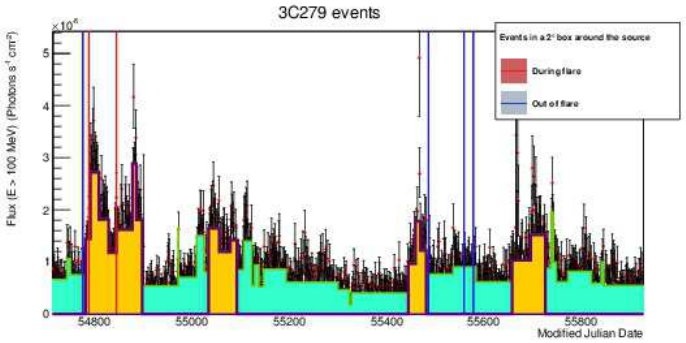
=> Astropart. Phys. 36 (2012) 204

Updated analyis: selection of Fermi flaring blazars [2008-2012] flaring TeV blazars (HESS/MAGIC/VERITAS)

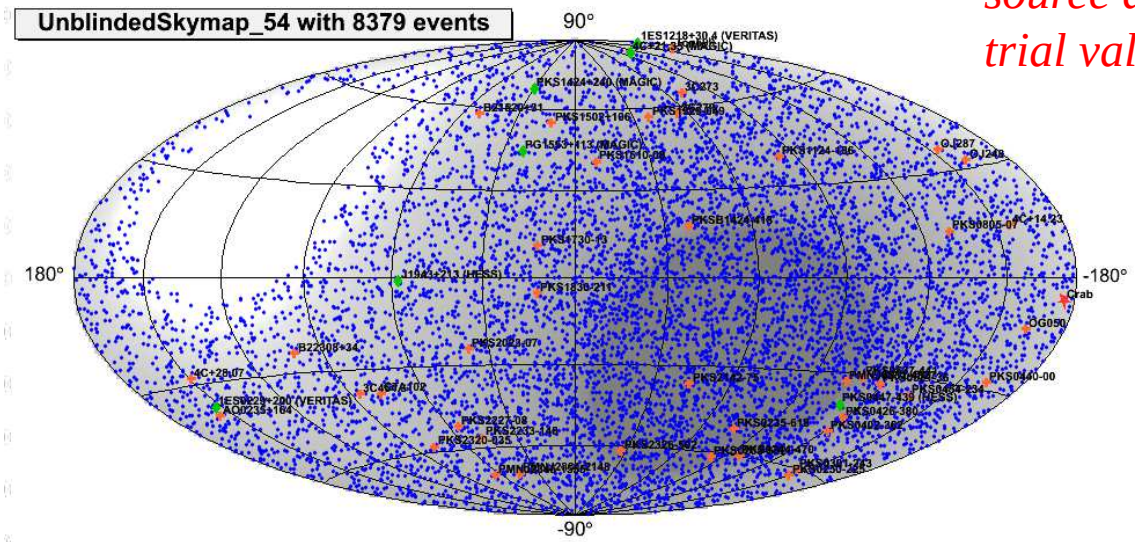
=> D. Dornic, A. Sanchez-Losa ICRC2013 - Paper in preparation

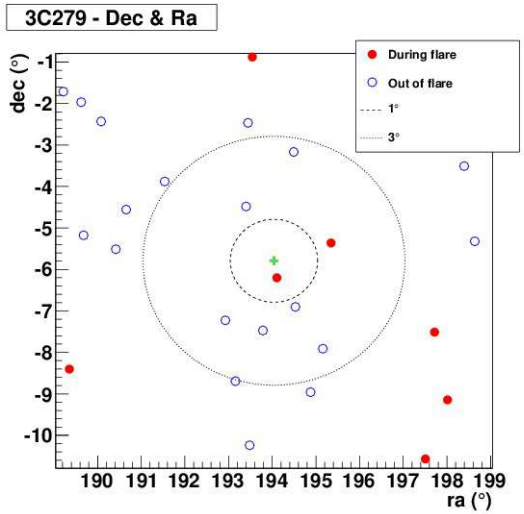
Search for ν from AGN flares

Unbinned searches performed [2008-2012]:
→ *For 42 Fermi sources: no significant cluster*
→ *For the 8 TeV flares: no significant correlation*

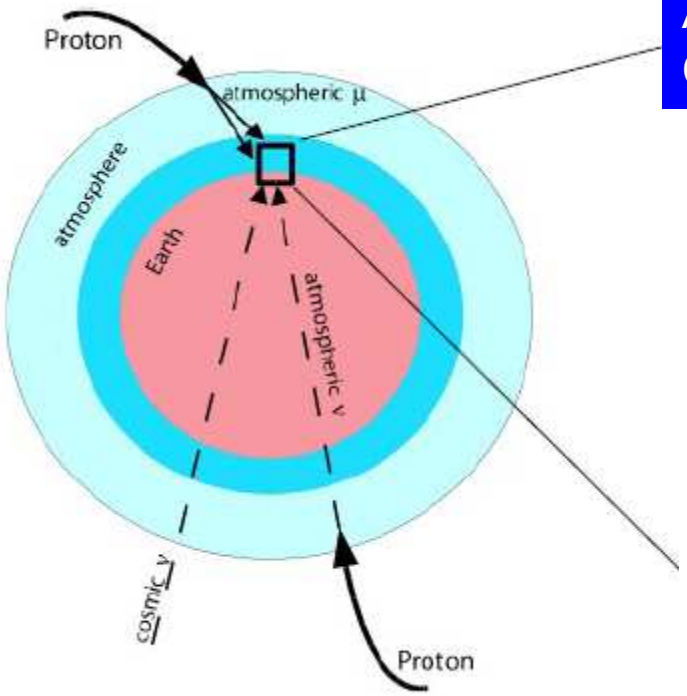


→*For 3C279: 2 events compatible with the source direction and time distribution. Post trial value 10%*

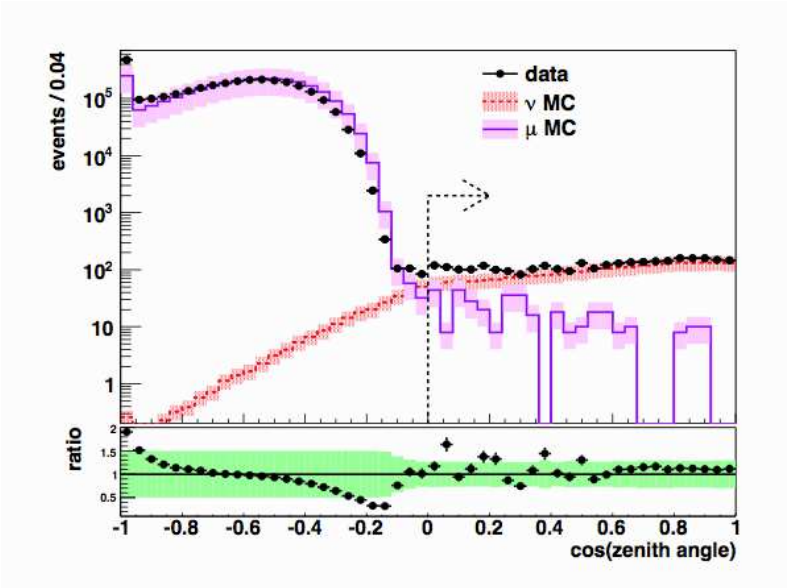




Background suppression



Atmospheric muons	~10 per second
Atmospheric neutrinos	few per day
Cosmic neutrinos	few per year (may be)

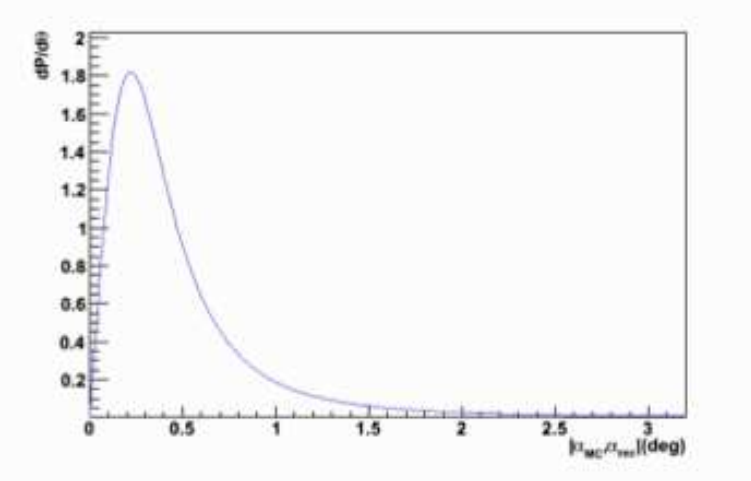


⇒ *Atm muons: quite easy to remove (zenith +quality cuts)*
⇒ *Atm neutrinos: irreducible isotropic background, low energy*

Neutrino search method

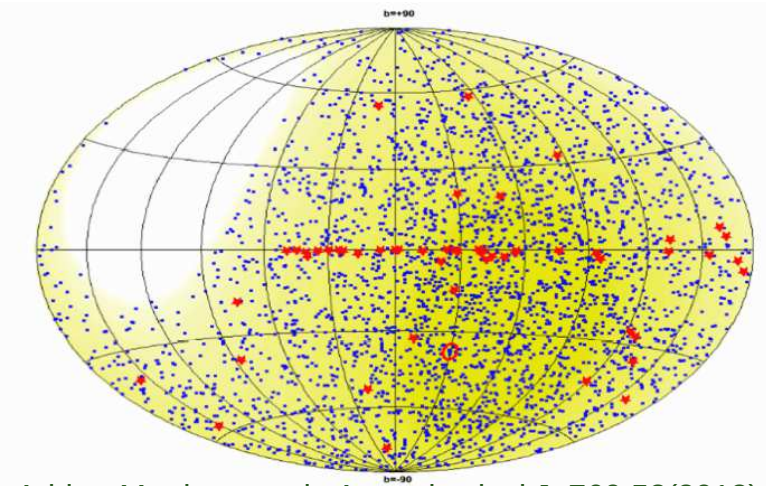
***Neutrino source**: quite high energy and sharp directional distribution, possible specific time distribution*

=> ***Search of clusters in space with a high energy content*** *(adding the information of energy allows to gain ~25% discovery potential)*



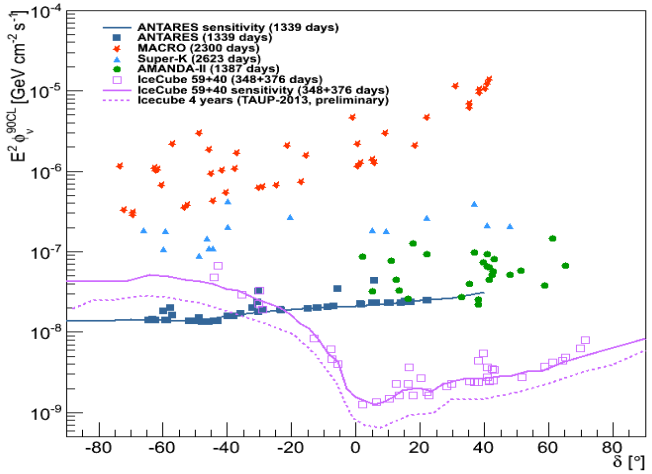
2 types of point-source analysis:
- All sky search: significant cluster
  => 8-10 ν per source @ 5σ discov

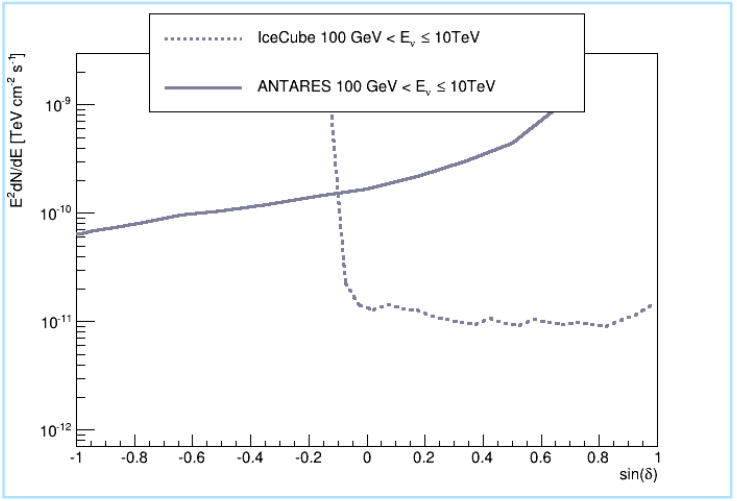
- Candidate list: 50 most promising sources
  => 5-6 ν per source @ 5σ discov

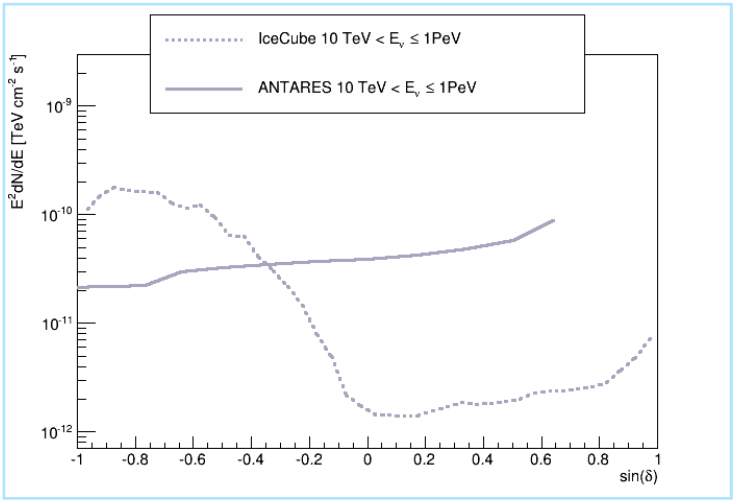


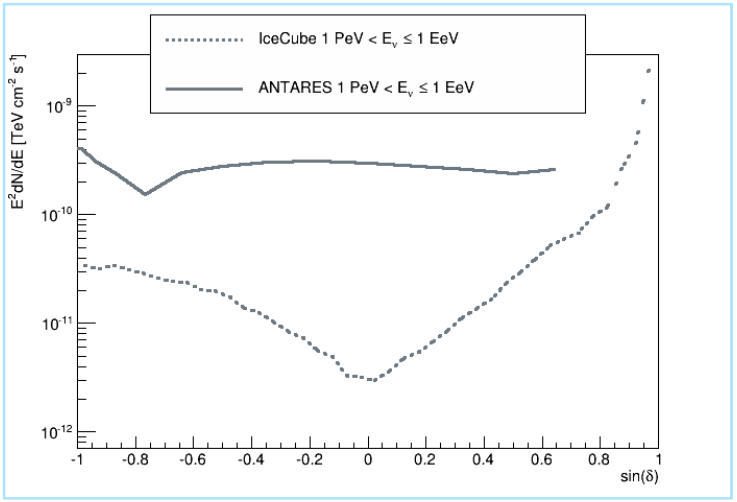
S. Adrian-Martinez et al., Astrophysical J. 760:53(2012)

Point-source sensitivities









Neutrino search method

2 types of point-source analysis:
- All sky search: significant cluster => 8-10 neutrinos per source
- Candidate list: 50 most promising sources => 5-6 neutrinos per source

Adding the time information:
=> 2-3 ν per source @ 5σ discov
=> Increase sensitivity by a factor 2-3

=> For a very short transient (GRB), only 1 ν per source is sufficient !!!

Analysis for micro-quasars, flares of AGN, supernovae, magnetar, GRB…