TAToO

Optical follow-up of high energy neutrinos detected by the ANTARES telescope

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Introduction

Why doing 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 ?

- Gamma Ray Bursts (long, short) chocked (cc-SN)
- Short & large AGN, µquasar, SGR flares

Plan

- Description of ANTARES
- Description of the real-time analysis
- TAToO: alert sending system
- First results and perspectives

I'll focus on the fast timing capabilities

The ANTARES telescope

- 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

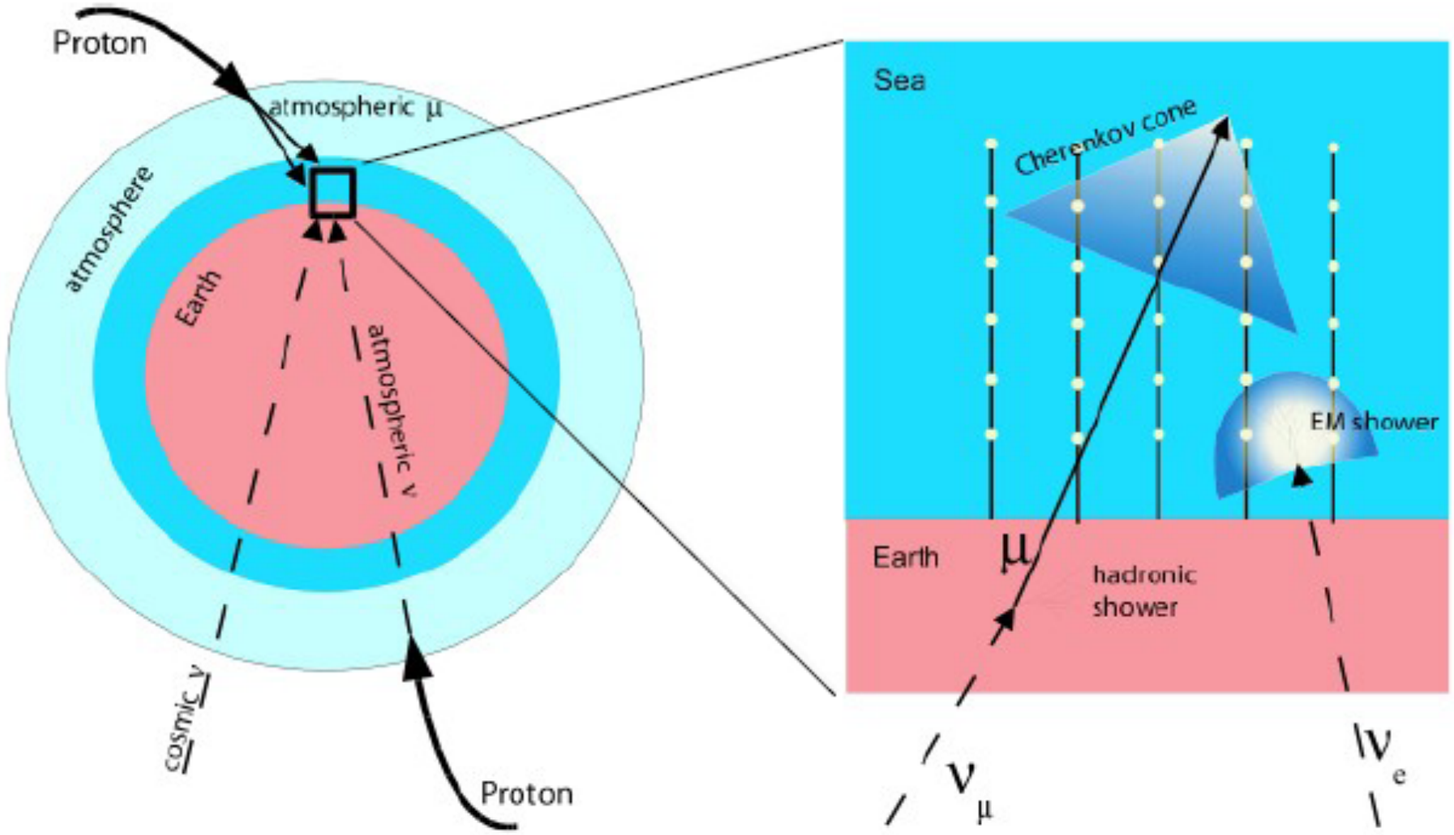
•40 km
•cable to
•shore

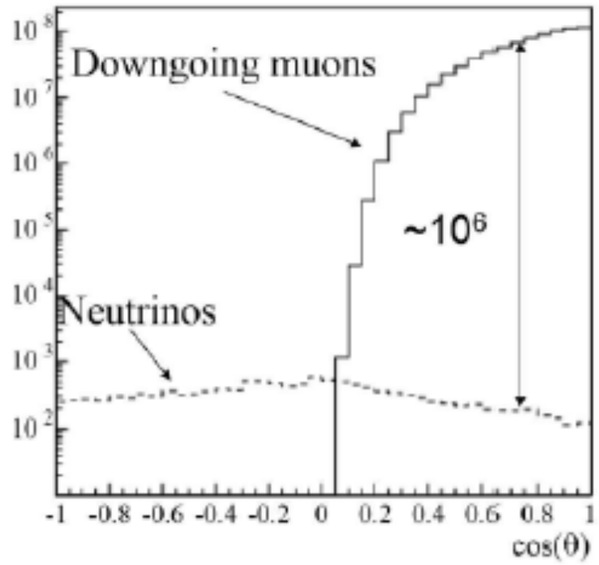
Junction Box

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

© François Montanet

Detection principle



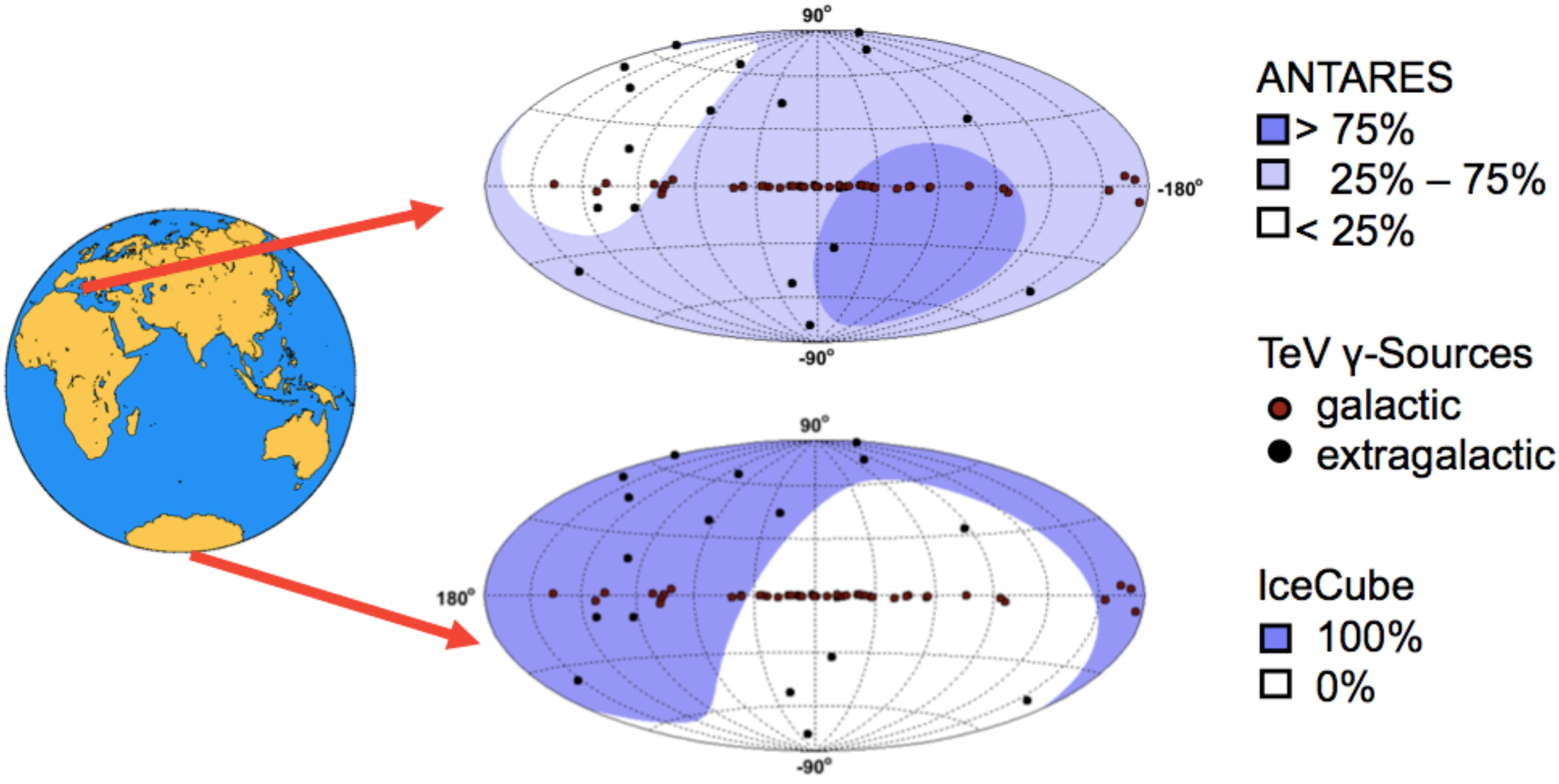


Atmospheric muons	~10 per second
Atmospheric neutrinos	few per day
Cosmic neutrinos	few per year (may be)

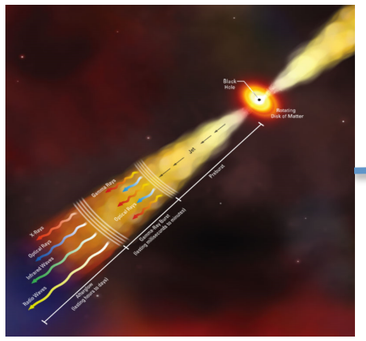
⇒ Looking for up-going events

Detecting neutrinos

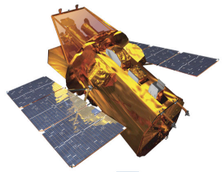
From the Mediterranean as complement to the South Pole



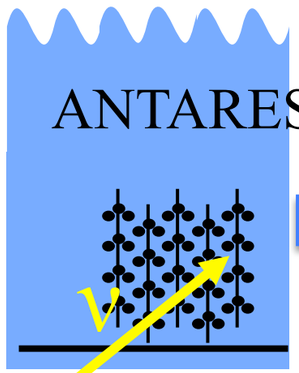
On-line framework in Antares



Transient
GRB,
AGN…



Alert
received



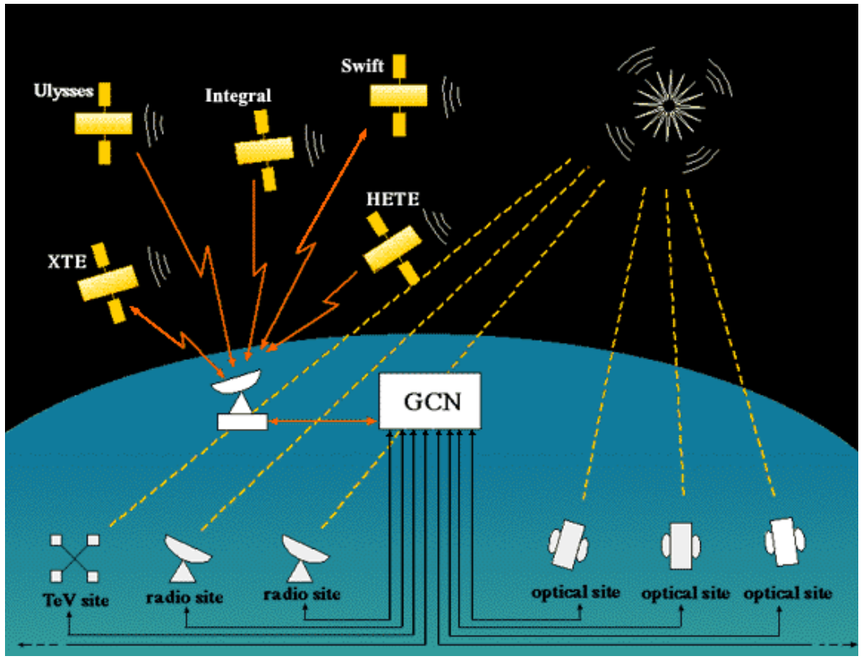
On-line transient
analysis

GRB special DAQ
Buffer data 2min without filtering
=> off-line analysis

TAToO alert
sending system

External triggers: which future?

GRB



GRB alerts are distributed via the GCN (**Gamma-ray Coordinates Network**) mainly of the SWIFT, FERMI and IPN alerts

Typical delay: ≈10-40s

False rate: ≈30-40%

ANTARES already client of the GCN for the special GRB data-taking

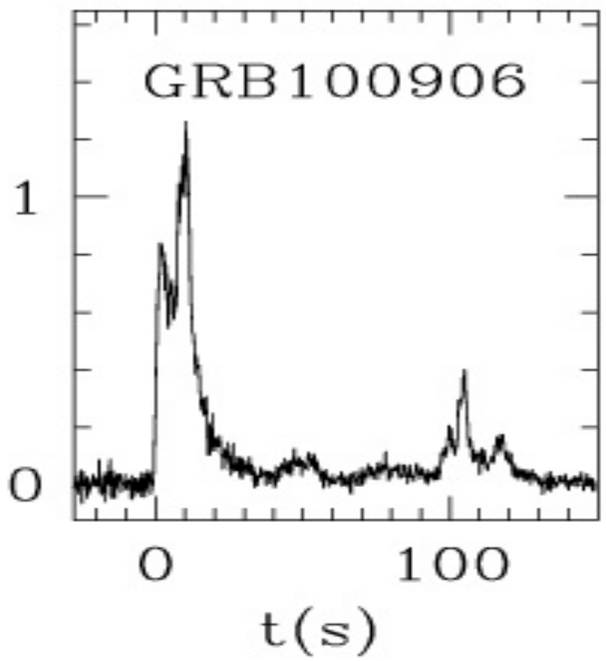


TABLE 1.1: The Various Source of GRB Locations: Current Missions

SOURCE	TIME DELAY	ERROR BOX SIZE	RATE	COMMENTS
IPN_POS	0.5-1.5 days	5-20' dia	3/month	Small FOV telescopes.
INTEGRAL_WAKEUP	60 sec	10'	1/month	Small FOV.
INTEGRAL_REFINED	60-100 sec	5'	1/month	Small FOV.
INTEGRAL_OFFLINE	60-200 sec	3-5'	1/month	Small FOV.
Swift-BAT_POS	13-40 sec(1)	1-5' dia	2/week	Fast and Small.
Swift-XRT_POS	30-80 sec(1)	5" dia	2/week	Fast and Small.
Swift-UVOT_POS	0.2-9 hrs(1)	2" dia	1/week	Fast and Small.
SuperAGILE	20-40 sec	20' dia	1/month	Small FOV.
Fermi-GBM	20 sec	4-10 deg dia	15/month	Large FOV telescopes.
Fermi-LAT	100 sec	10-30' dia	1/month	Small FOV telescopes.
MAXI_Unknown	2-200 min	1deg dia	1/month	Small FOV.
MAXI_Known	2-200 min	0.5deg dia	1/week	Small FOV.

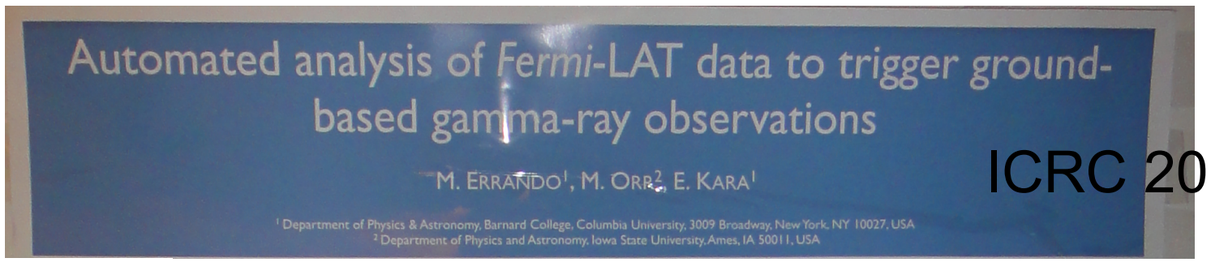
External triggers

AGN
μ-quasar

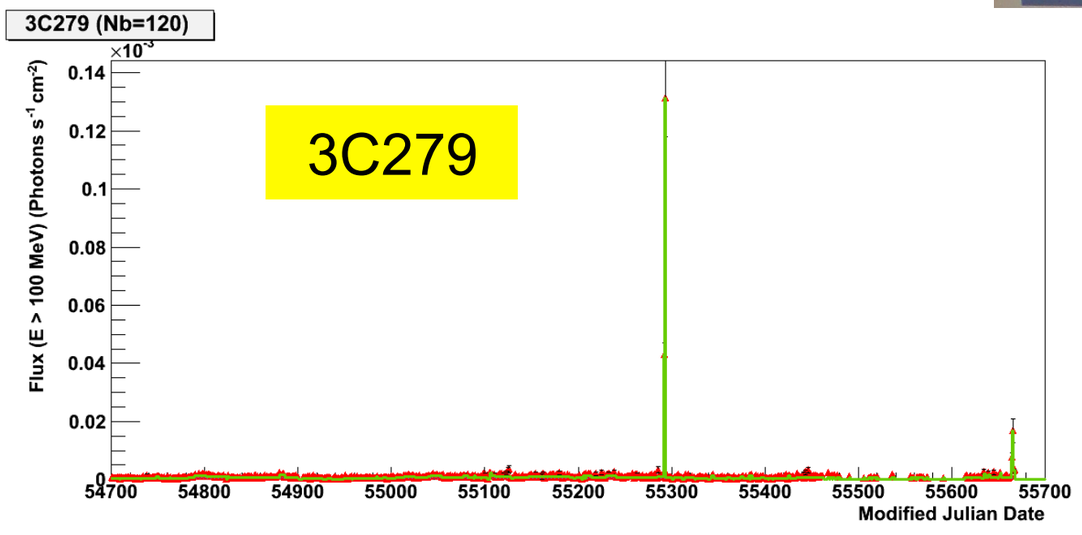
The most important discoveries are reported on the Astronomer's telegrams (A-tel)

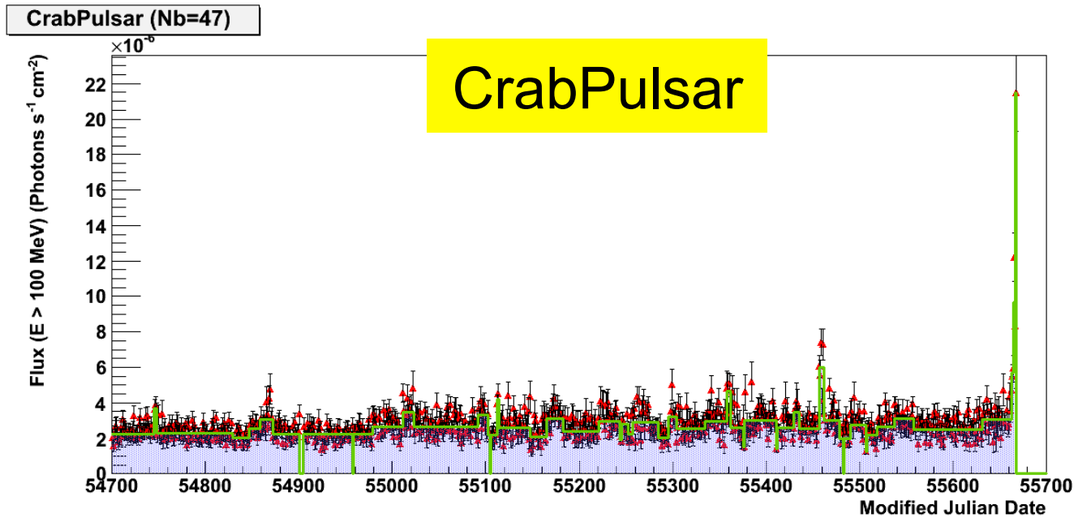
Analysis of the daily light curve for the Fermi LAT monitored source list

External Fermi on-line analysis



ICRC 2011





TAToO (alert sending program)

ANTARES Shore Station:

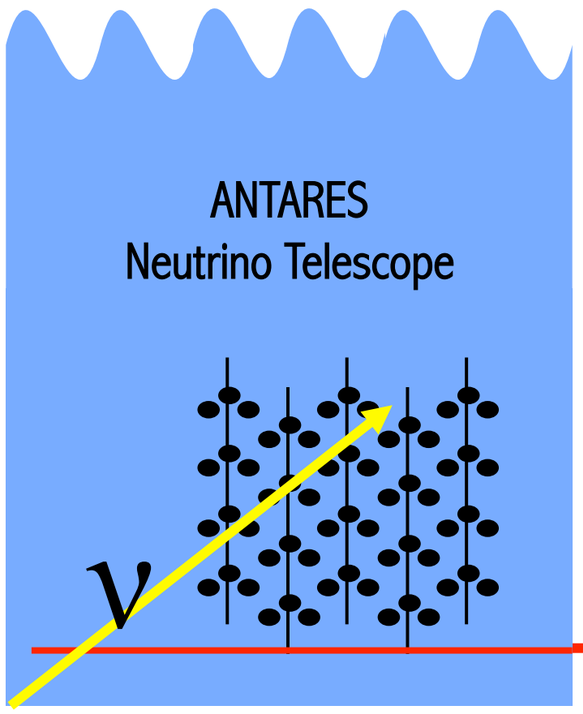
On-line reconstruction

Trigger decision

Alert message (GCN format)

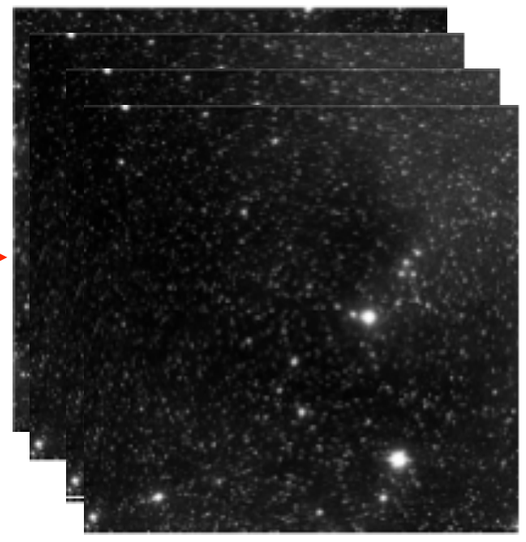
ANTARES

Neutrino Telescope



Real time

Optical telescopes



Optical images

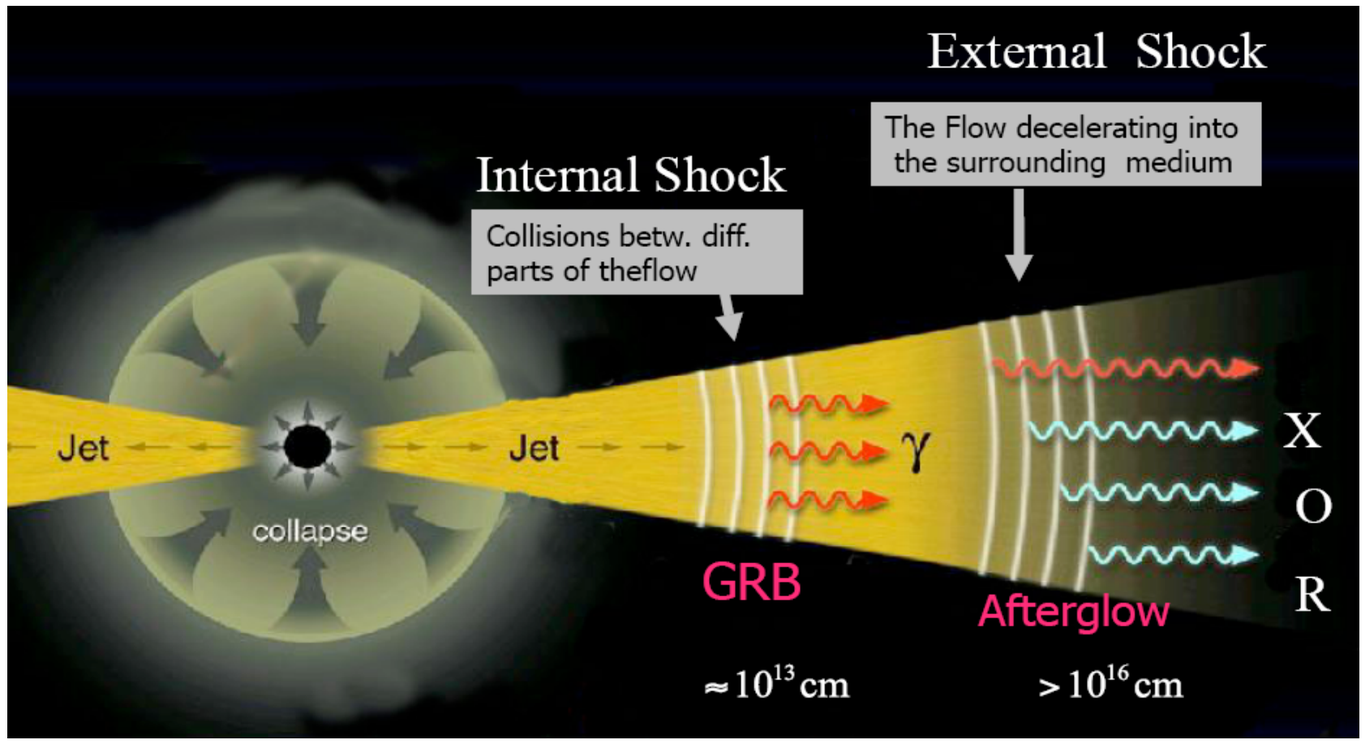
The ANTARES Telescope Neutrino Alert System

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

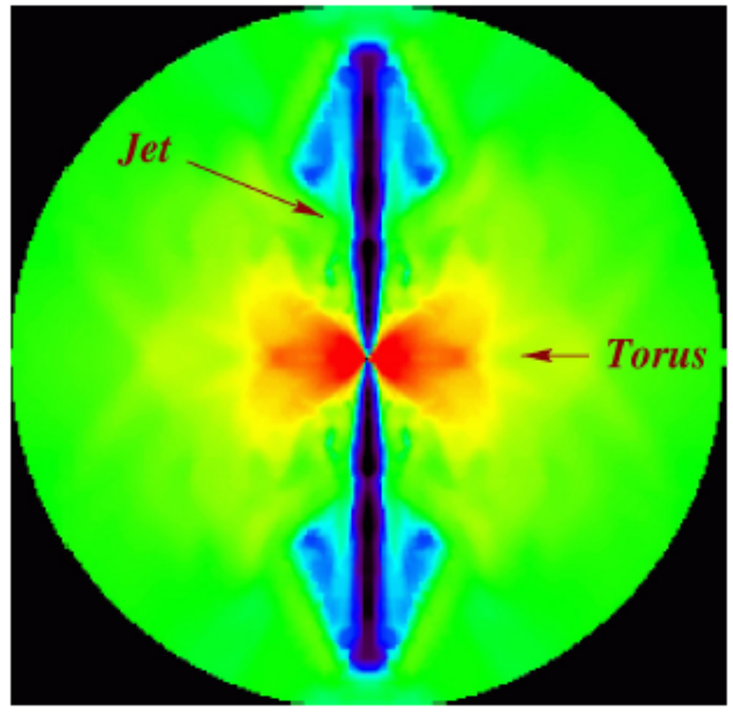
Motivation

GRB neutrinos: relativistic jets (Fireball model) => 10 TeV–10 PeV neutrino

Meszaros & Rees, Waxman



$$p\,\gamma \rightarrow \Delta^{+} \rightarrow n\,\pi^{+}$$
$$p\,p \rightarrow \pi, K$$
$$\pi^{+} \rightarrow \nu_{\mu}\,\mu^{+} \rightarrow \nu_{\mu}\,e^{+}\,\nu_{e}\,\bar{\nu}_{\mu}$$



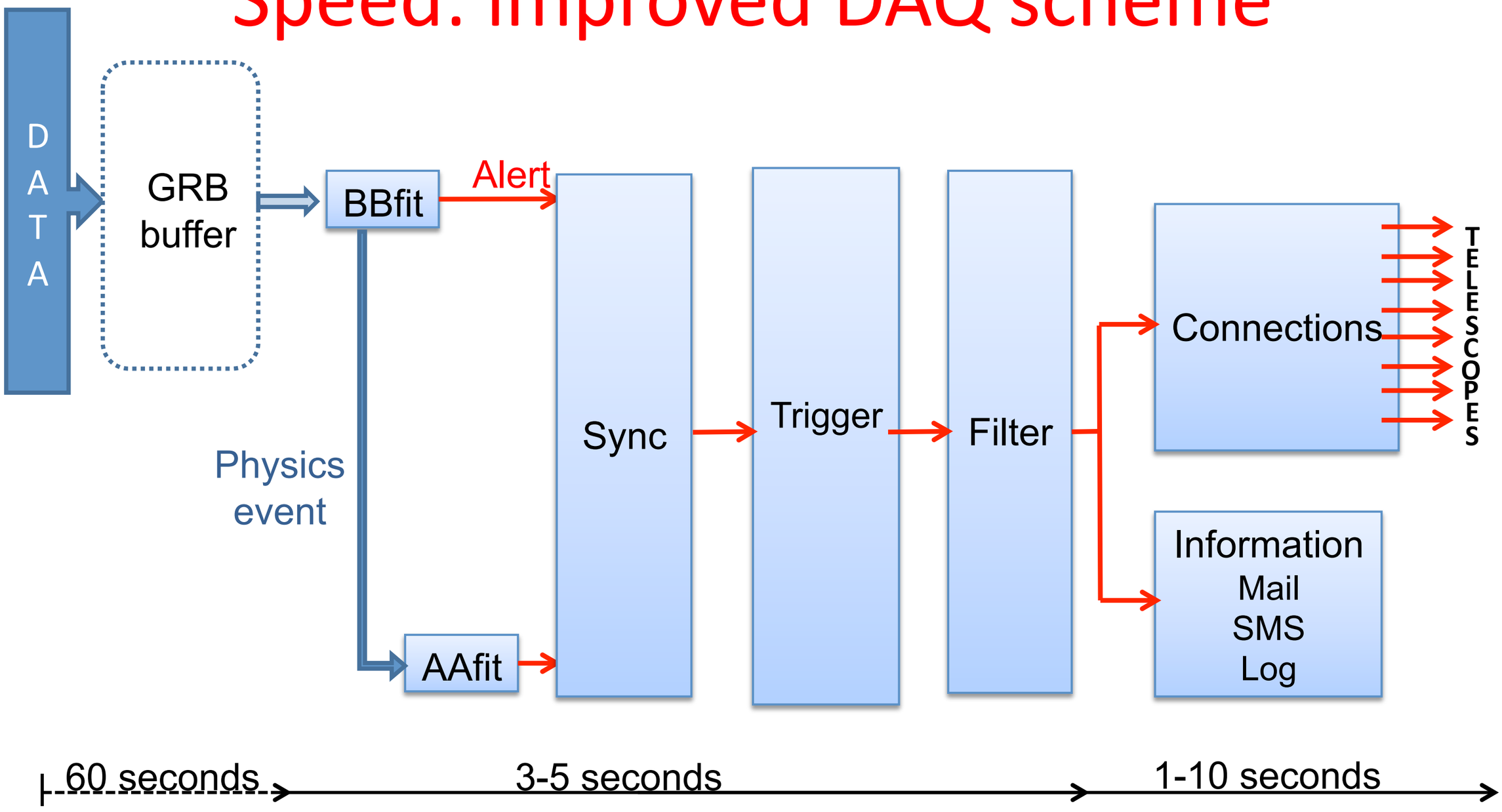
SN neutrinos: connection GRB-SN
(chocked jet, midly relativistic)
=> 100 GeV-10 TeV neutrino

Razzaque & al,, Ando & Beacom

Mission critical points

- Fast alert sending capability (GRBs, etc.)
- Good angular resolution matching the FoV of the receiving telescope
- Good sky coverage to assure follow up, i.e. as much receiving telescopes as possible
- Effective and robust image analysis

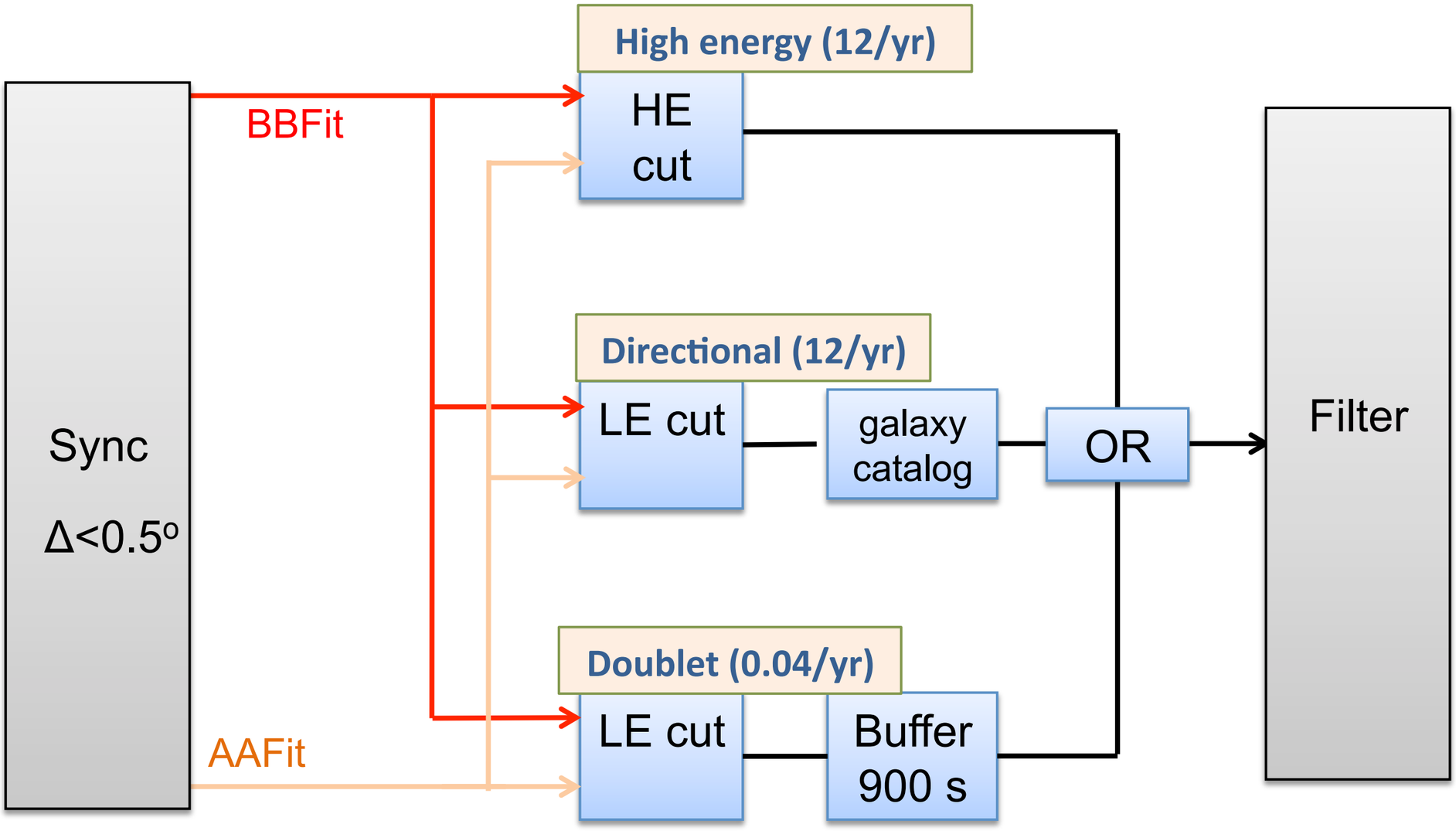
Speed: improved DAQ scheme



Previously: One minute delay due to data buffering (external GRB triggers)

→ Ability to send the alert a few seconds after the neutrino interaction

Trigger scheme and alert rates



HE

AA Trigger on :

- Cos theta > 0
- Lambda > -5.0
- N Hits > 70
- Amplitude > 200

Directional

AA Trigger on :

- Cos theta > 0
- Lambda > -5.0
- N Hits > 20
- Delta angle < 0.33°

Doublet

BB Trigger on :

- Tchi2 = 1.3 + (0.04x NDF)²

AA Trigger on :

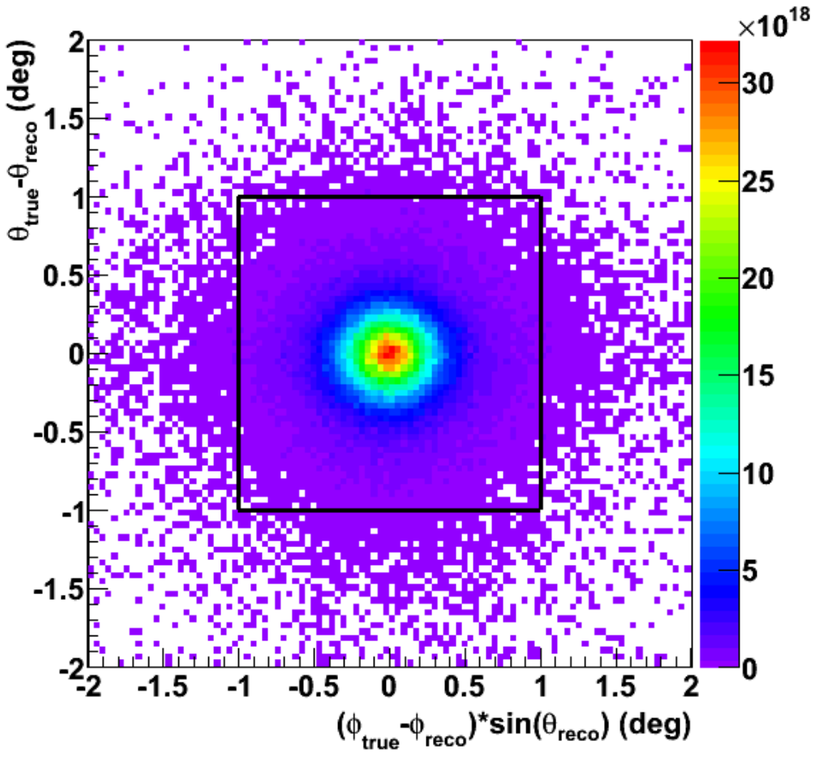
- Cos theta > 0
- Lambda > -5.2
- Delta angle < 3°

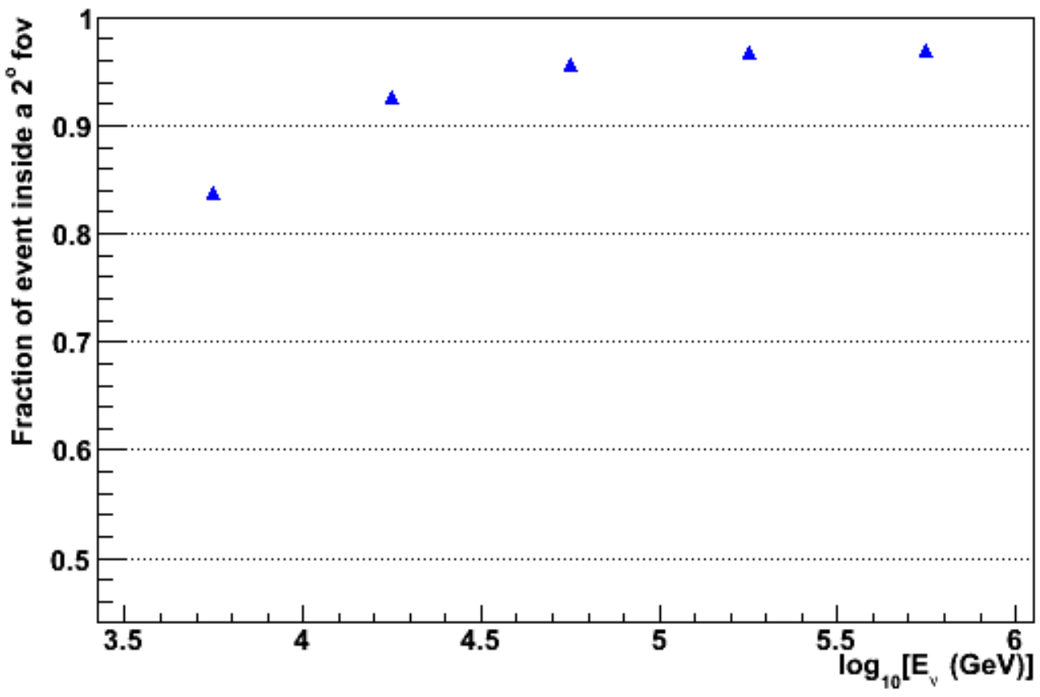
Definition of the triggers: single HE

First trigger introduced.
Rate: 1 alert / month

Efficiency: (reference AAlambda>-5.2 && AAtcosth>0)

WB98 = 50.5%;
ATM = 3.2%;
SNk = 4.6%;
SNp = 0.2%





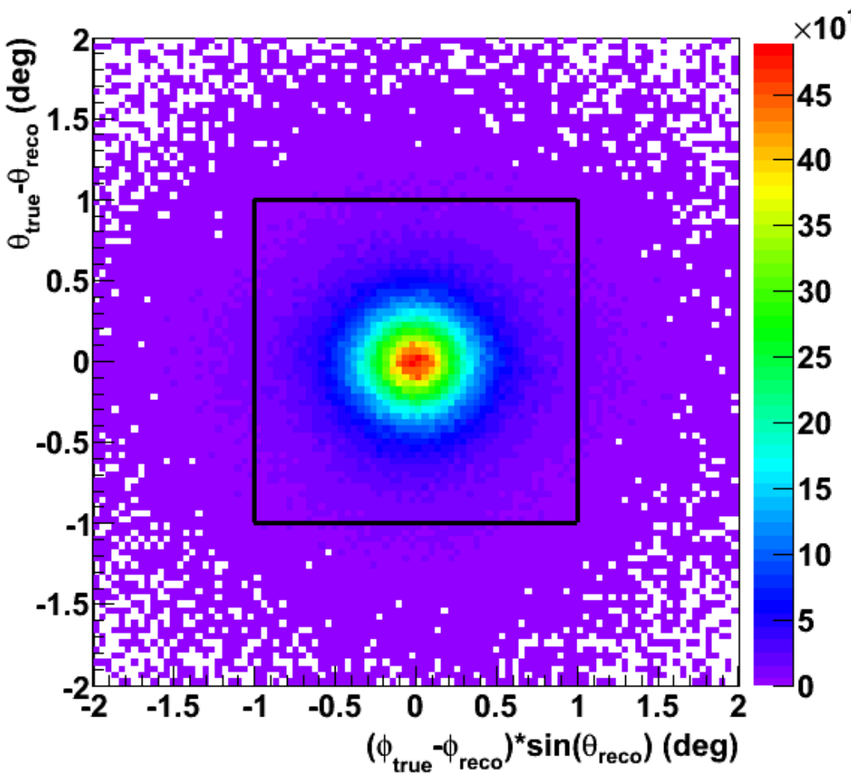
Fraction of event in FOV:

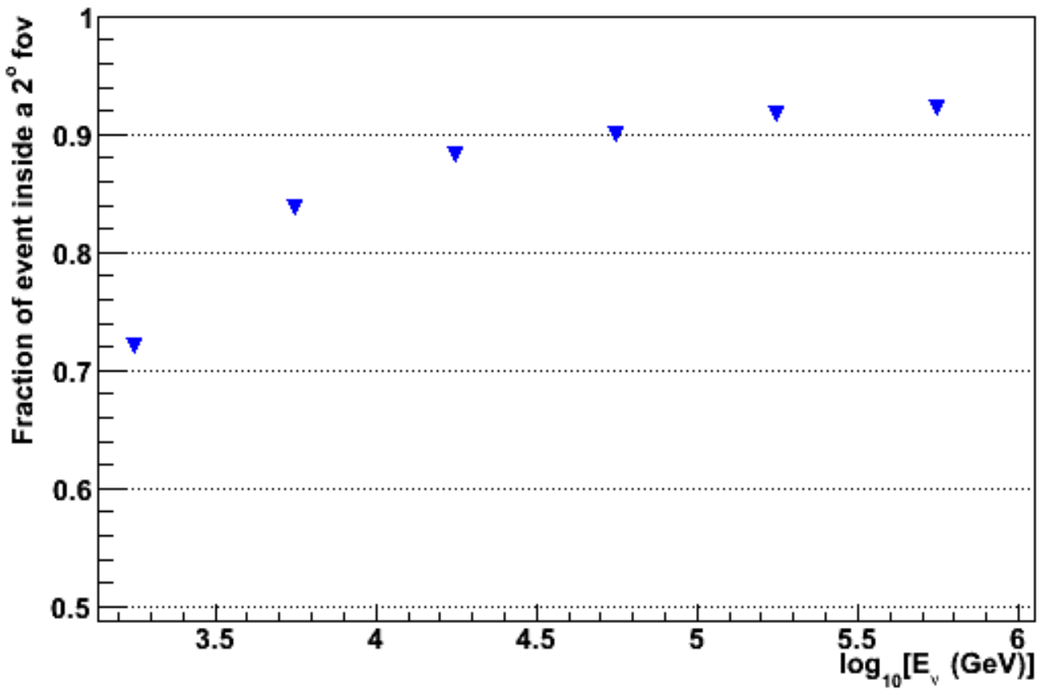
Nb events in FOV= 95.9% (WB98 model), 68% (ATM model) and 68% (SNk model)

Definition of the triggers: single dir

Trigger introduced to maximize SN discovery (Ando&Beacom)
Rate: 1 alert / month

Efficiency: (reference AAlambda>-5.2 && AAtcosth>0)
WB98 = 88.8%;
ATM = 70.6%;
SNk = 73.4%;
SNp = 65.7%

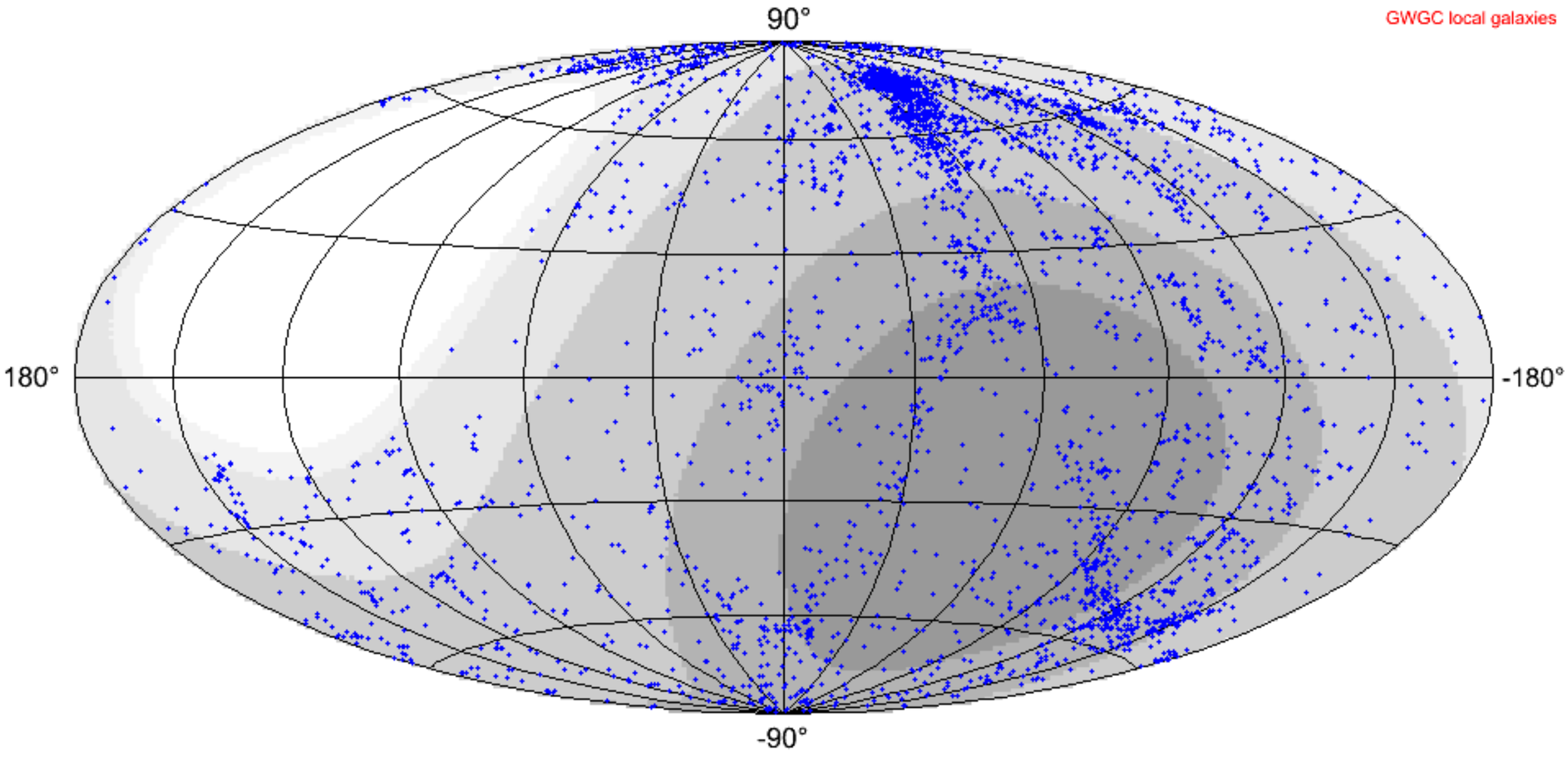




Fraction of event in FOV:
Nb events in FOV= 90.2% (WB98 model), 49.6% (ATM model) and 54.4% (SNk model)

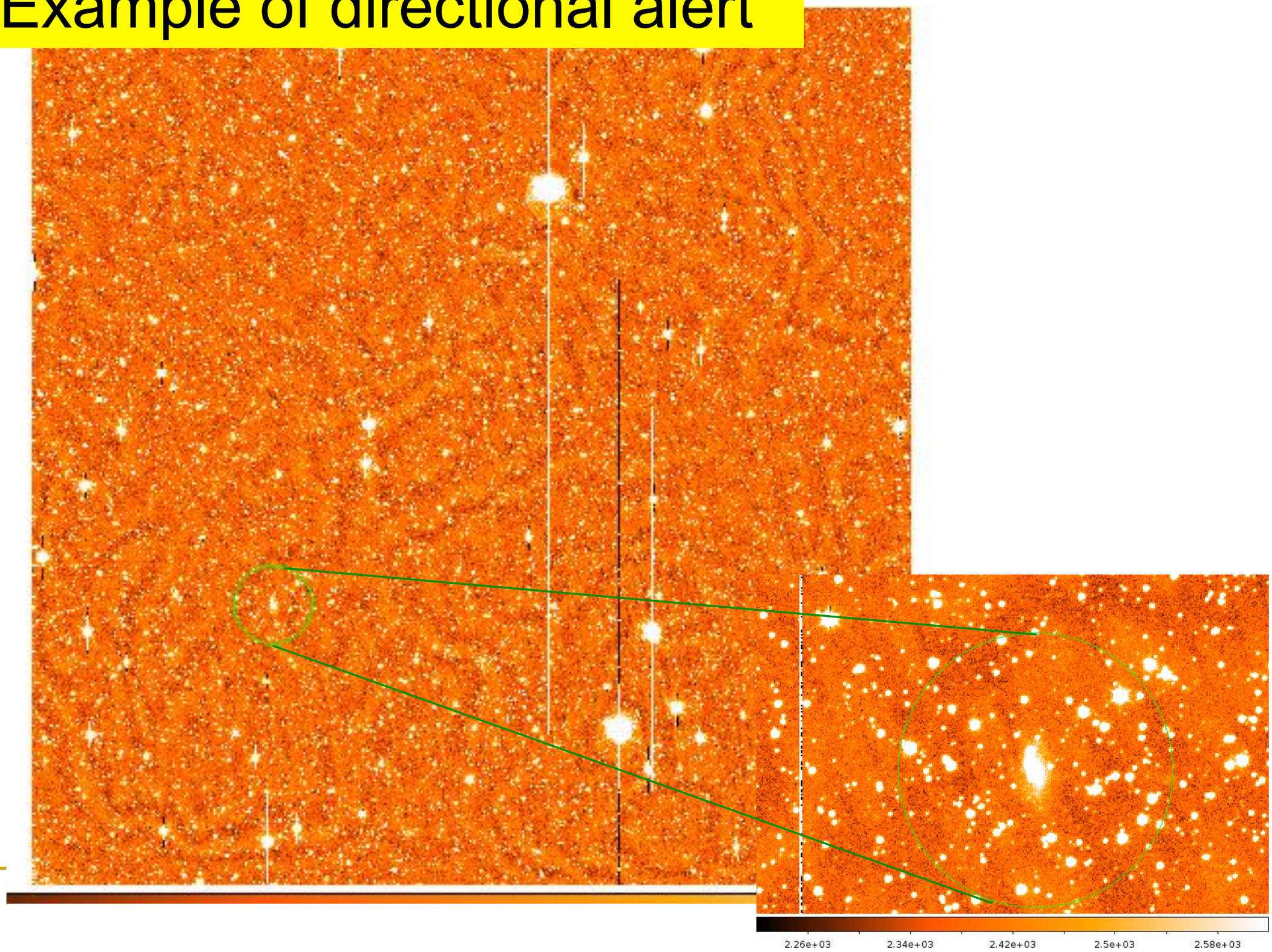
Directional trigger

<u>Selection of the local galaxies sample:</u>
GWGC catalogue (Darren White): 4404 galaxies with D < 20 Mpc

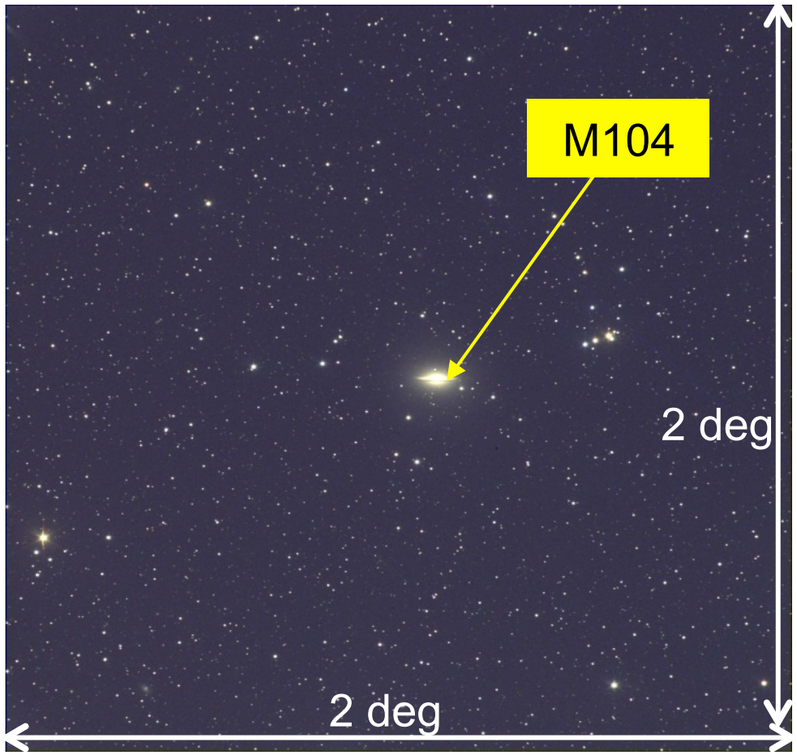


Angular distance galaxy-event < 0.33deg => 1 alert / month

Example of directional alert



Wide FoV optical telescopes



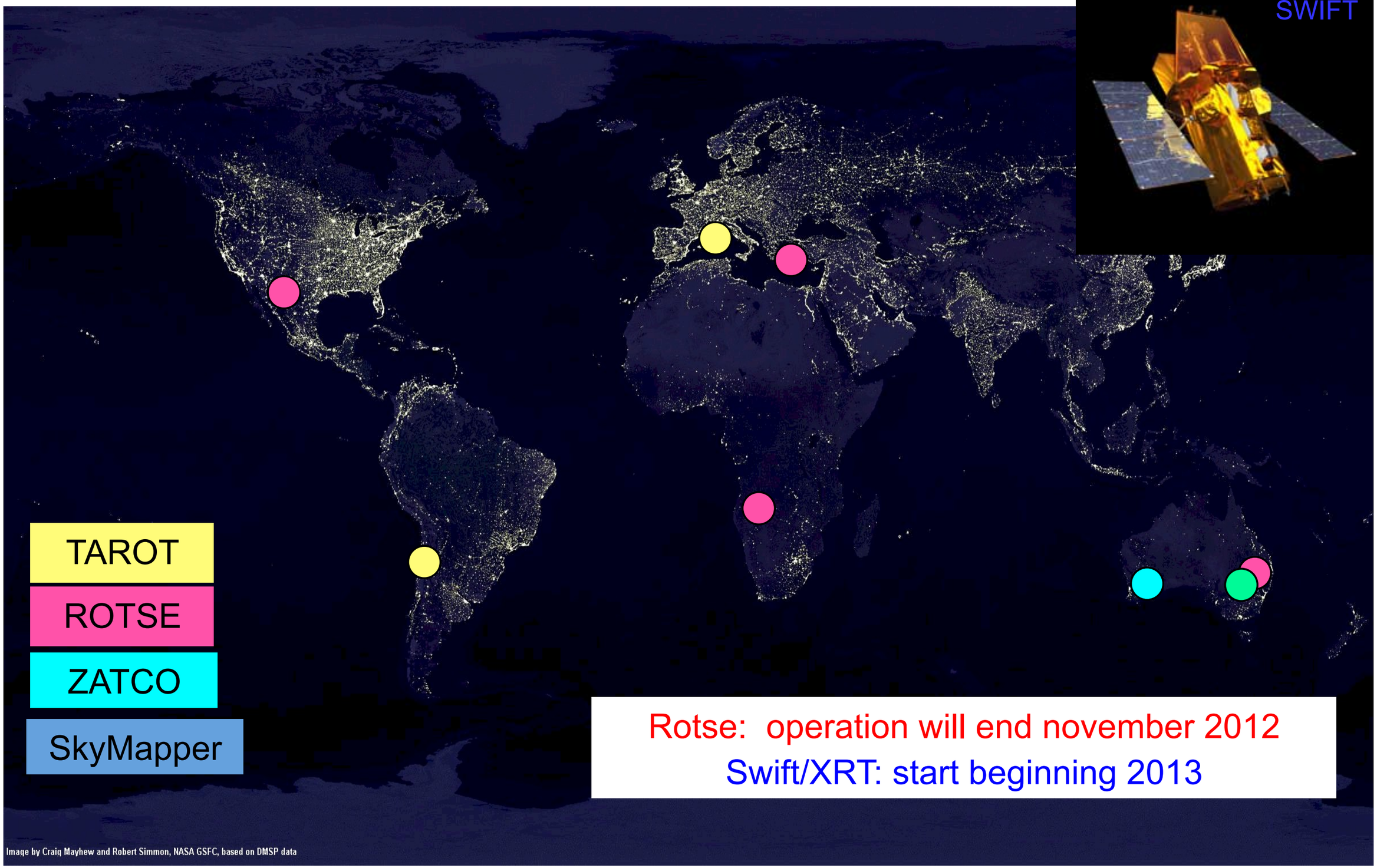
- Rather special requirements
- Limited choice of available telescopes

TAROT: two 25 cm telescopes

-fov 1.86° x 1.86°

- Magnitude V<17 (10s), V<19 (100s)
- sleewing time ~ 10s

Telescope network connect to TAToO



Follow-up efficiency

Follow-up efficiency = P(ra,dec) visibility $_{\text{optic Tel}}$ x P(ra,dec) visibility $_{\text{neutrino Tel}}$

P(ra,dec) visibility $_{\text{optic Tel}}$

Conditions on alert coordinates to be instantaneously visible :

- Direction elevation > 7°
- Sun elevation < 0
- Moon elevation < 0 ||

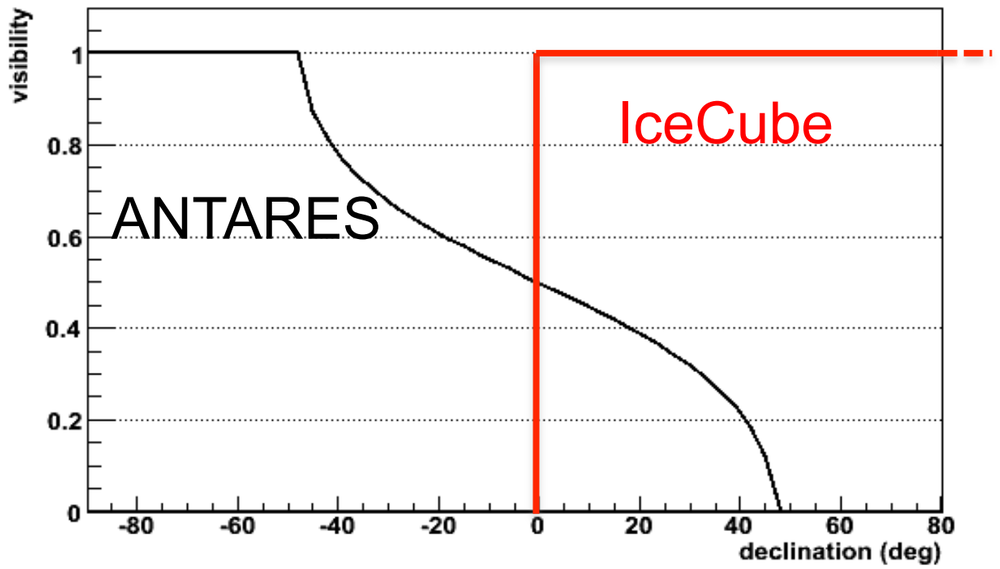
(moon elevation > 0 && dmoon > 25°)

Not considered:

- Atmospheric effects (20-30% efficiency loss)
- Maintenance periods (10-20% efficiency loss)

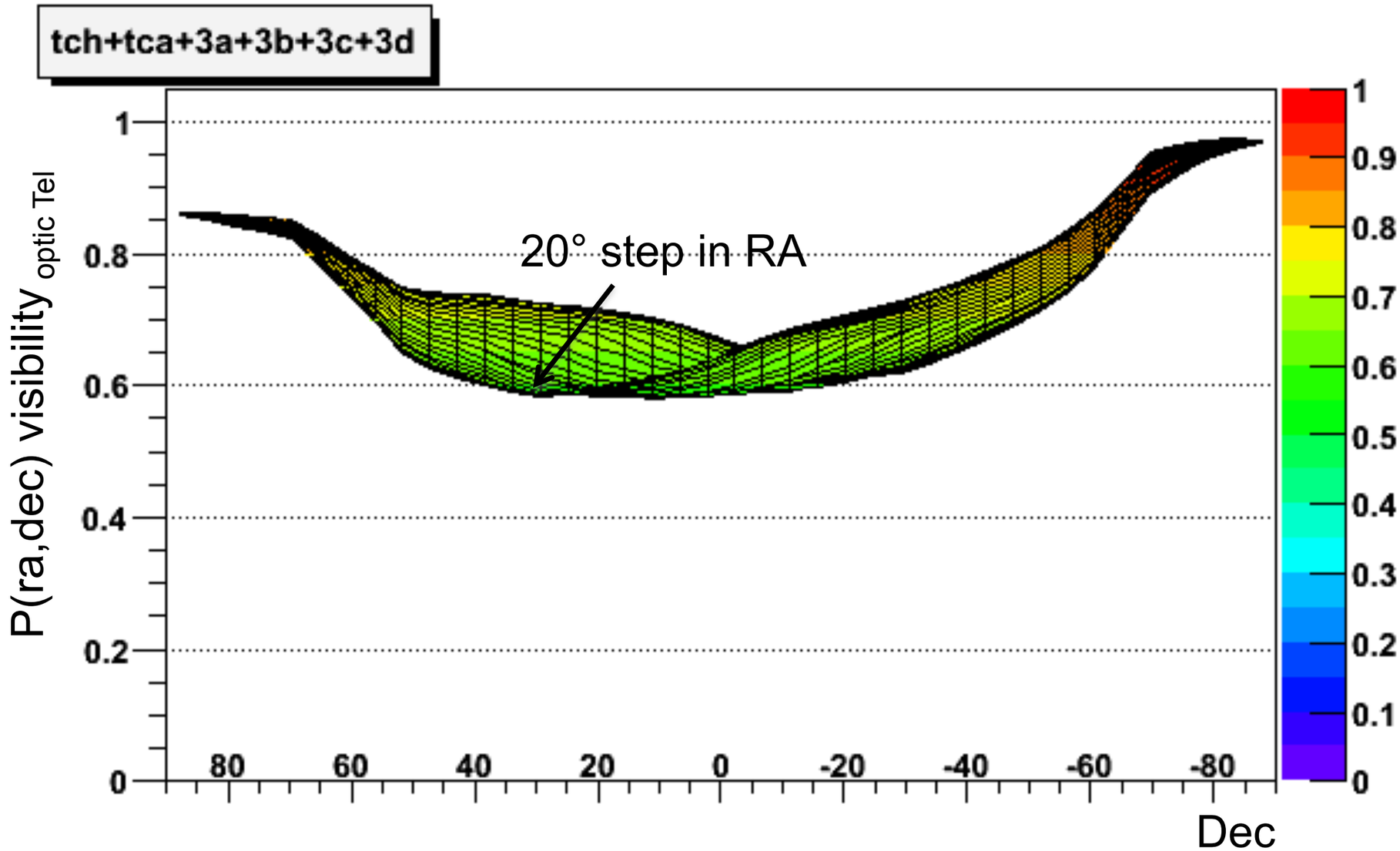
→ Optimistic values

P(ra,dec) visibility $_{\text{neutrino Tel}}$



Efficiency: Optical telescopes

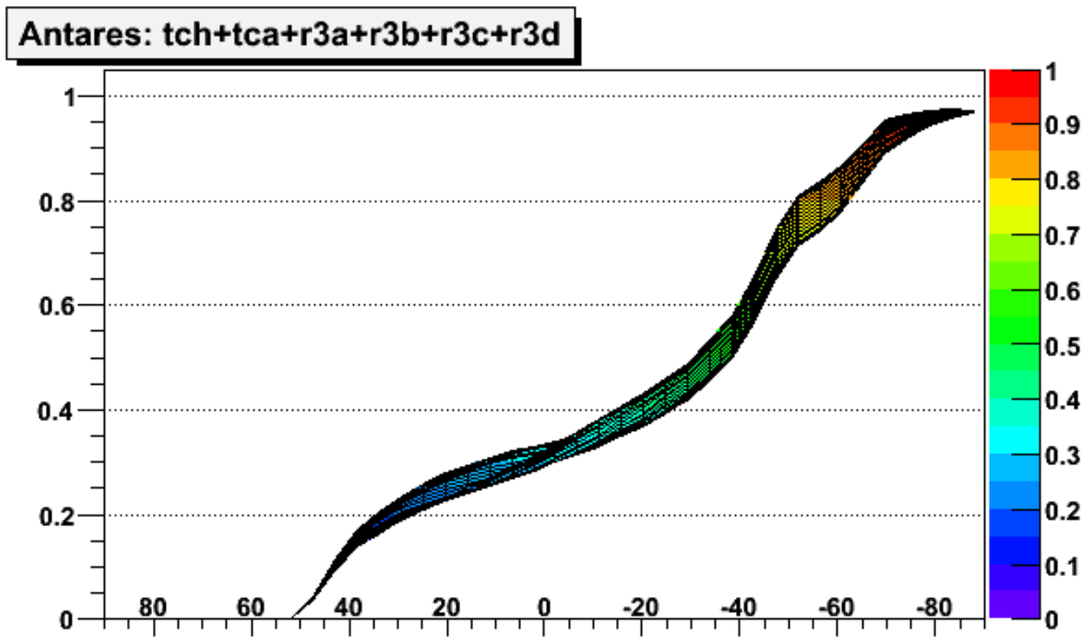
2 Tarot + 4 Rotse



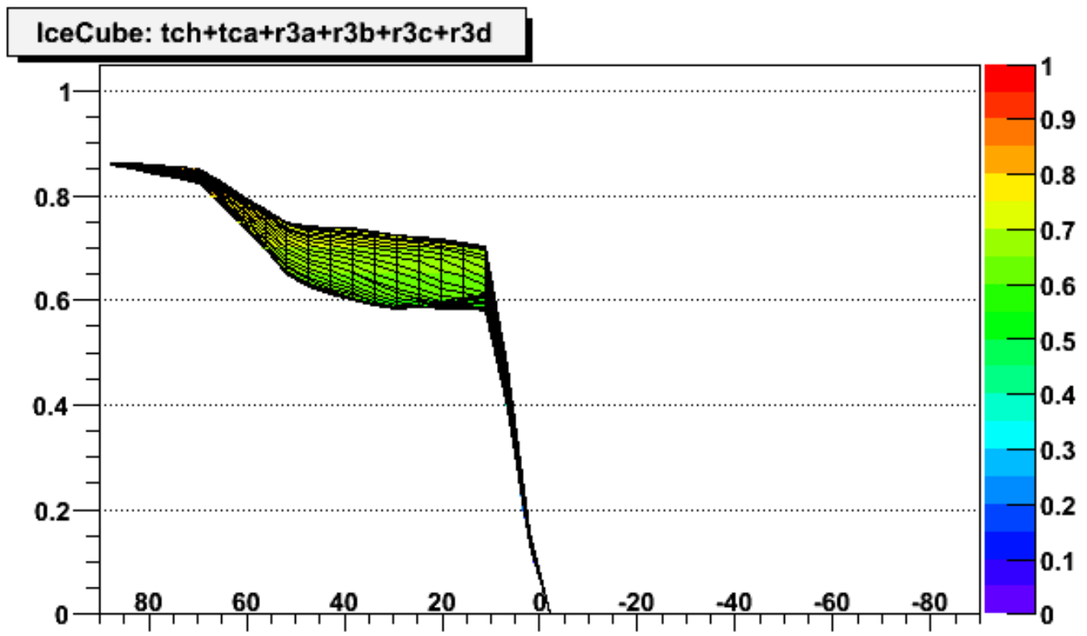
Combined efficiency

2 Tarot + 4 Rotse

ANTARES



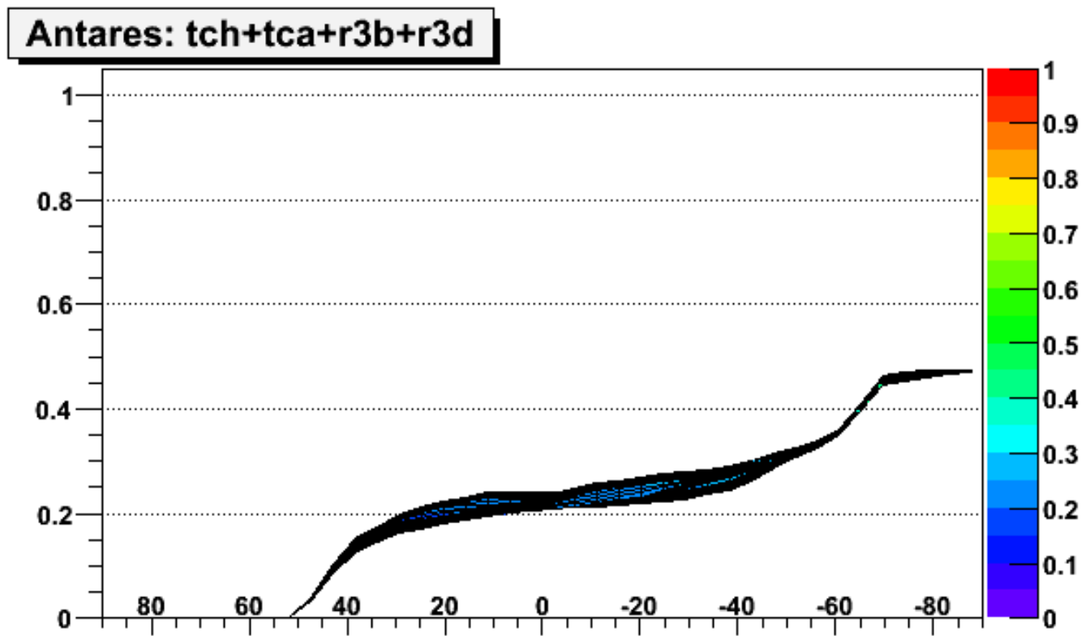
IceCube



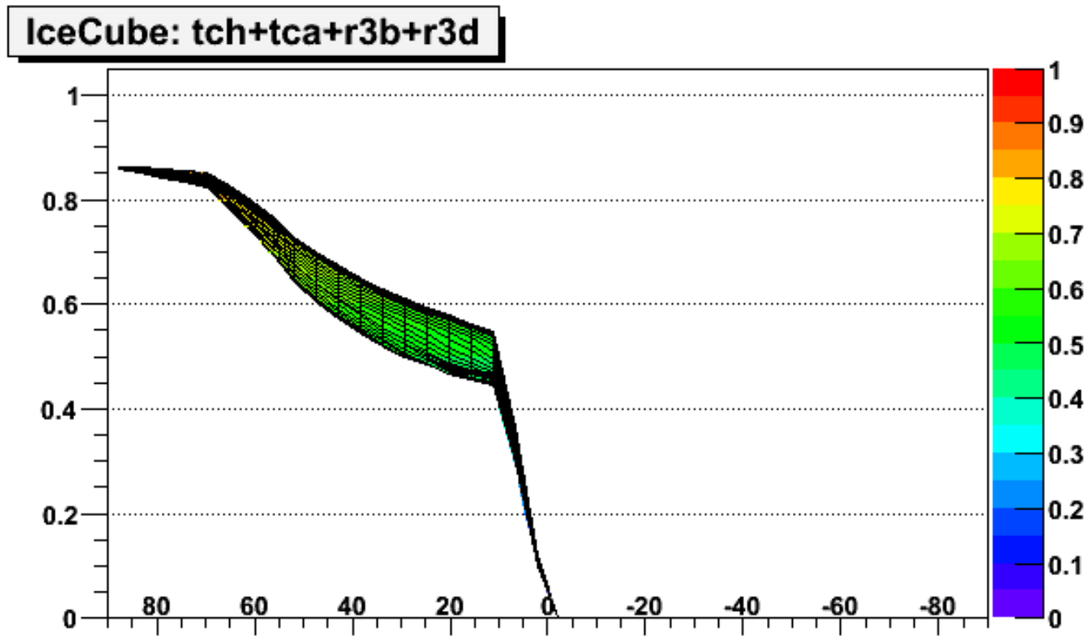
Combined efficiency after 11/2012

2 Tarot + Rotse 3b + Rotse 3d
(US) (Turkey)

ANTARES

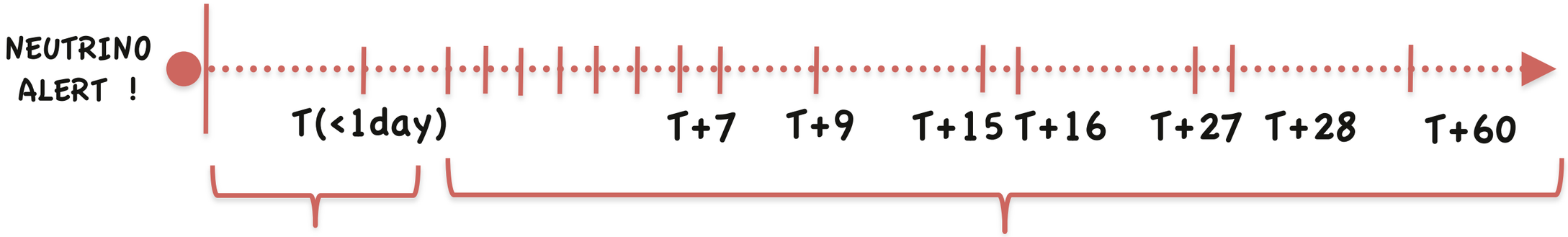


IceCube

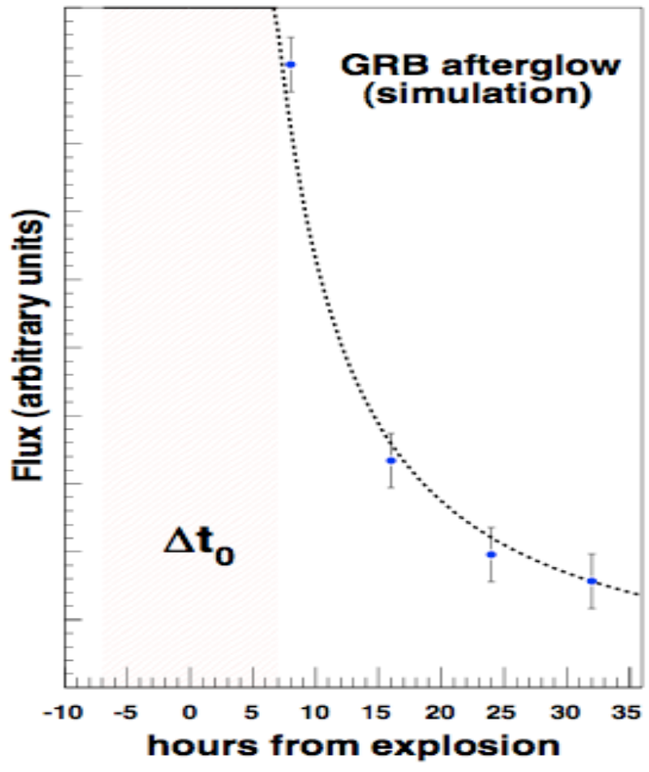


To maintain the capacity of the fast alert response, we need to find some telescopes in the South hemisphere: Zadko, SkyMapper, Bootes-4, Trappist…
For a long term follow-up (SN…), one telescope per hemisphere is sufficient. Only increase the sensitivity

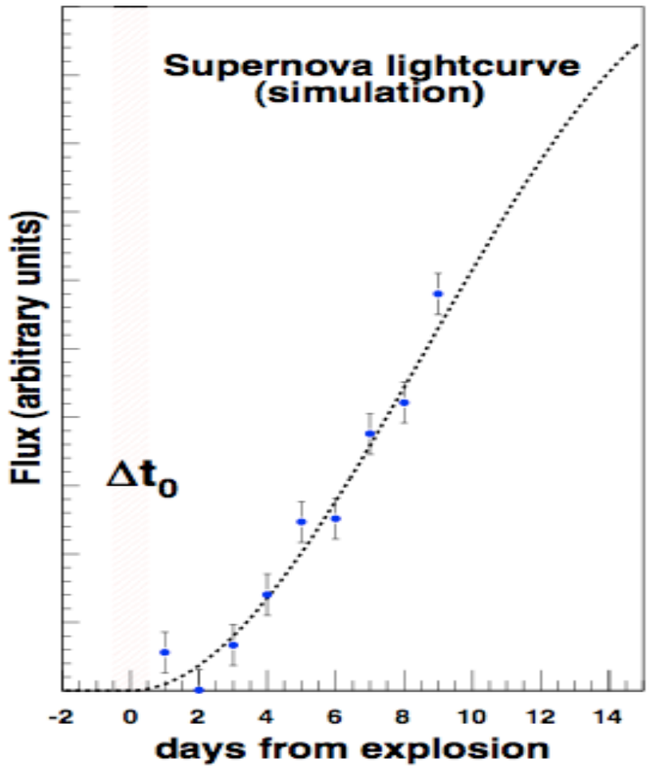
Optical follow-up strategy



Prompt observations



Follow-up observations



Statistics: optical follow-up

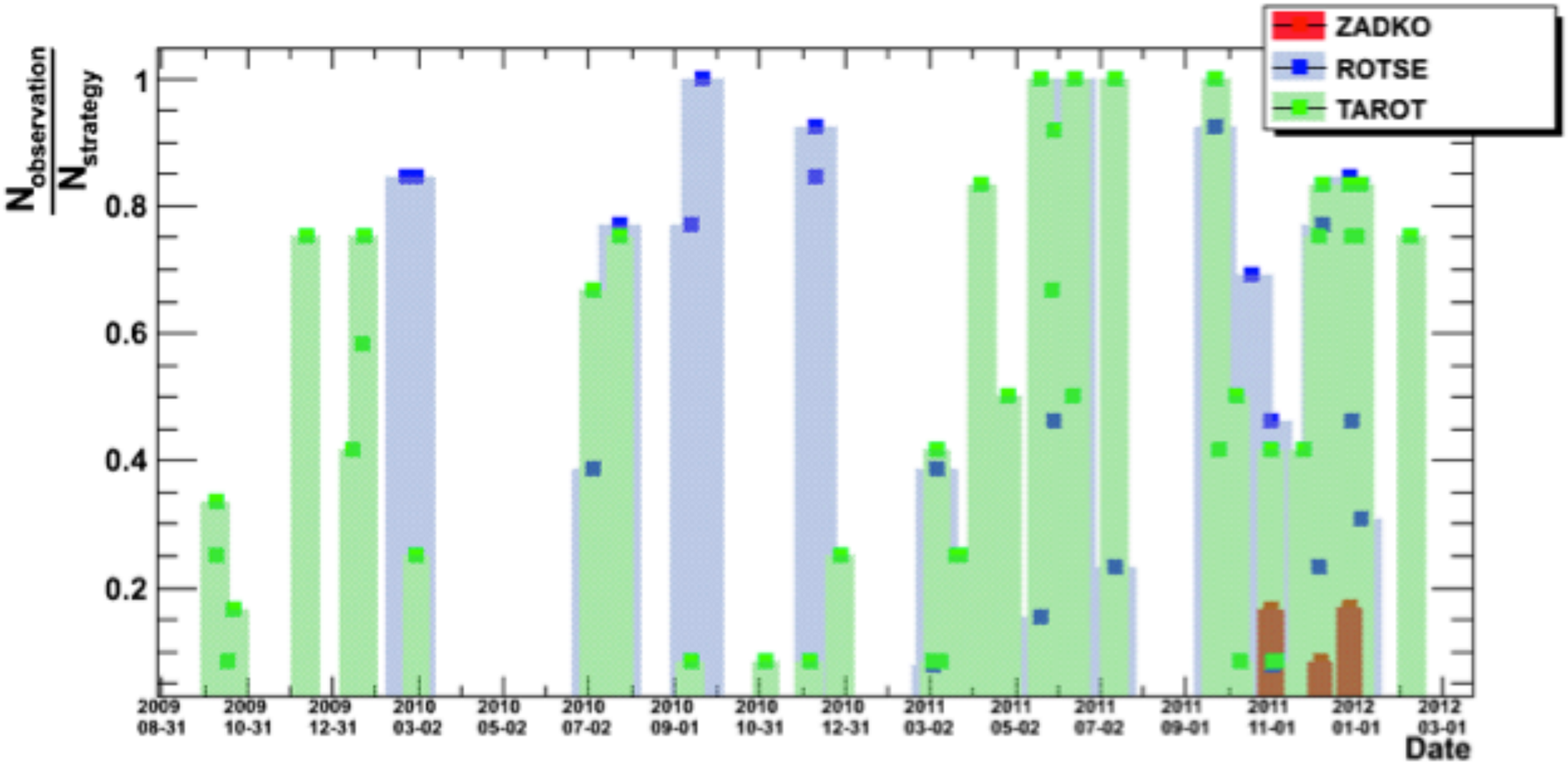
Since the beginning of TAToO : $\varepsilon^{total} = N_{observation}/N_{strategy}$ ~ 40%

2009 : 32%
(5 alerts)

2010 : 82 %
(13 alerts)

2011 : 72%
(27 alerts)

Stratégie: 14 nuits pour
TAROT et ROTSE



Optical counterpart search

2 independent software chains based on the image subtraction:

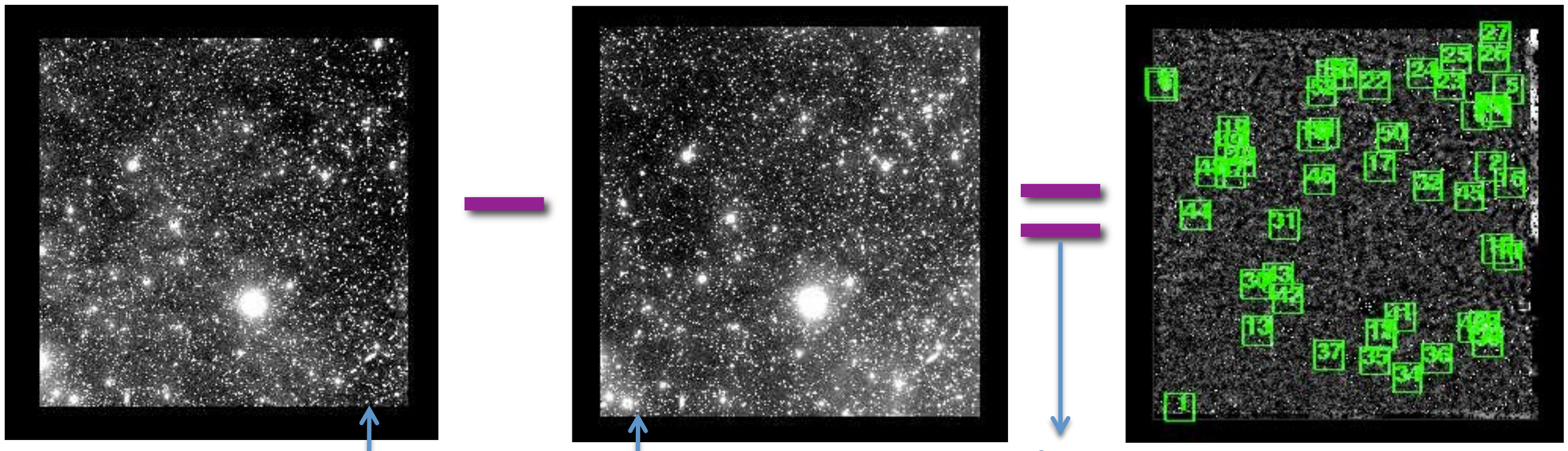
- SNSL / LAM adapted to the TAROT/ROTSE image quality
- ROTSE SN pipeline

➔ New standard pipeline in development (A. Mathieu)

Image from TAToO Follow-Up

Reference Image (No signal)

Residual Image



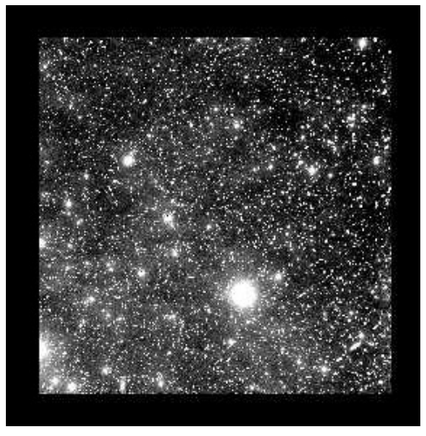
PSF matched

Cuts on :
SNR
Flux variation
FWHM ...

Optical counterpart search

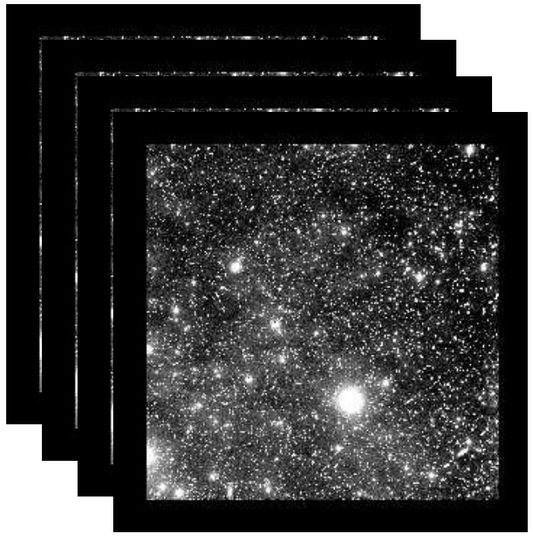
- Image co-adding enhances the sensitivity to faint sources
- Co-added analysis undertaken when enough images are available

Image by image

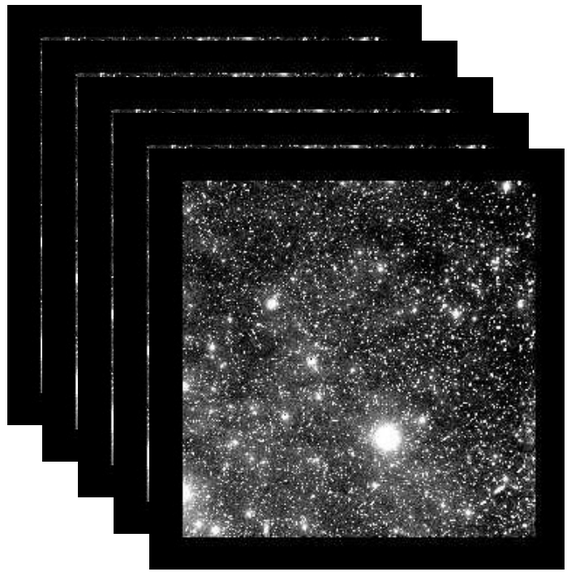


- Limiting magnitude ~ 15 mag
- Search for a variable signal on the scale of few seconds..

Coadd 4 Images



Coadd 8 Images



- Limiting magnitude ~ 16 mag
- Search for a transient signal on the scale of few minutes

Prompt analysis: alerts

Alert	Telescope	Number of images	Exposure	Observation time since trigger
ANT100123A	Rotse 3c	15	60 s	15h20mn15s
ANT100302A	Rotse 3b	11	20 s	24h20mn8s
ANT100725A	Rotse 3c	30	20 s	0h01mn15s
ANT100922A	Rotse 3a	24	20 s	1h08mn06s
ANT101211A	Rotse 3c	6	60 s	12h03mn30s
ANT110409A	TarotChili	6	180s	0h04mn17s
ANT110529A	TarotChili	6	180s	0h07mn33s
ANT110613A	TarotChili	6	180s	0h01mn08s
ANT120730	TarotChili	25	180s	0h00mn21s
ANT120907	TarotChili	20	180s	0h00mn25s
ANT121010	TarotChili	24	180s	0h00mn24s
ANT121206	Rotse 3b	30	60s	0h00mn27s

Prompt analysis: results

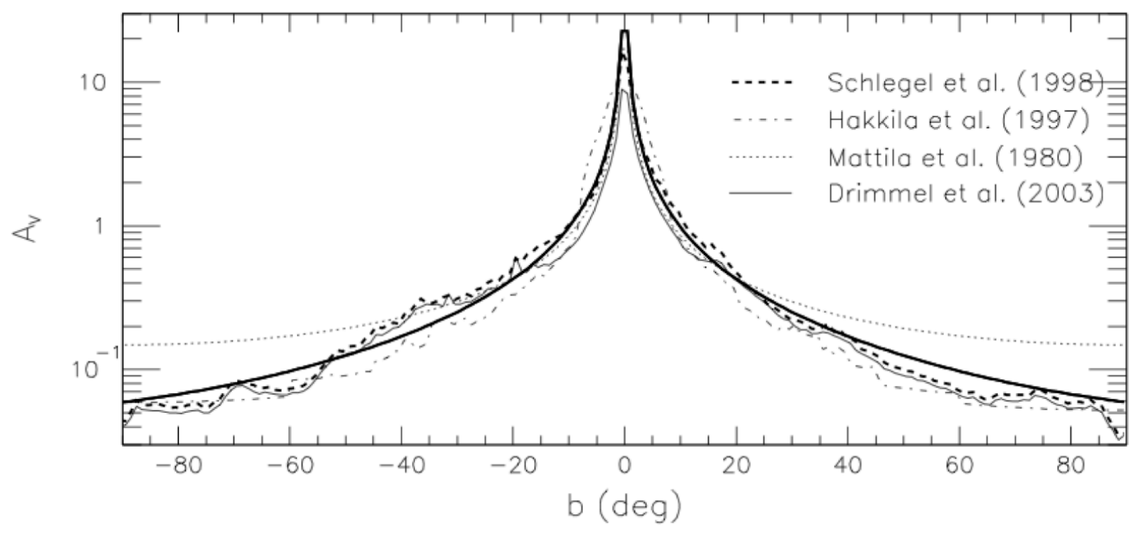
Preliminary

=> No transient optical counterpart associated to a neutrino detection (model independant)

→Derive upper limits on transient sources magnitude

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

Correction from galactic extinction



Av correction as a function of the galactic elevation (Schlegel maps)

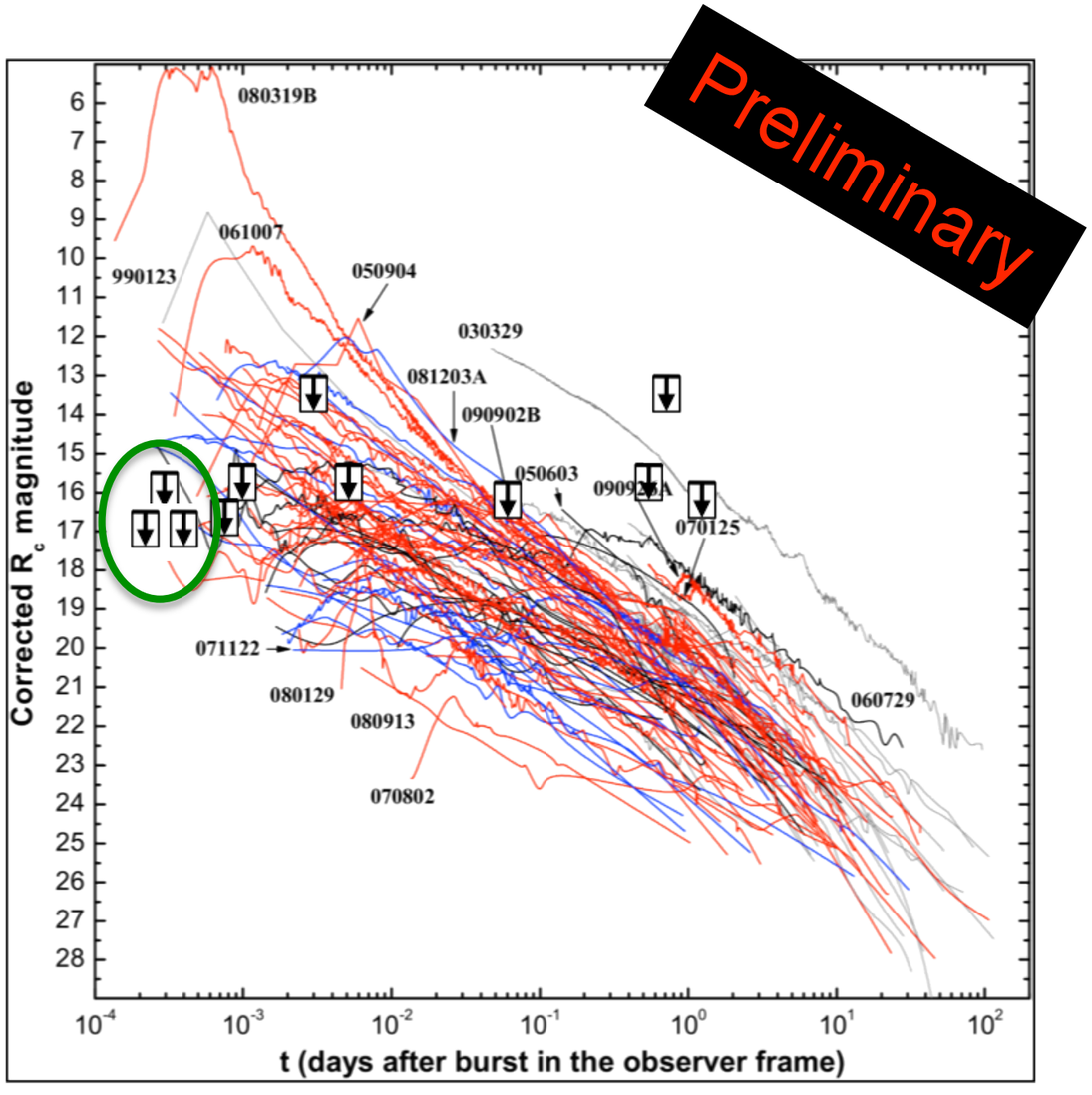
Prompt analysis: GRB case

Hypothesis: neutrino emission simultaneously with gamma rays

→ Consider GRB Light Curves/apparent magnitudes in the litterature

→ Derive optical detection efficiency with our limits

Alert	P_{miss} (%)
ANT100123	100
ANT100302	100
ANT100725	60
ANT100922	98
ANT101211	98
ANT110409	90
ANT110529	77
ANT110613	45
ANT120730	20
ANT120907	15
ANT121010	15
ANT121206	15

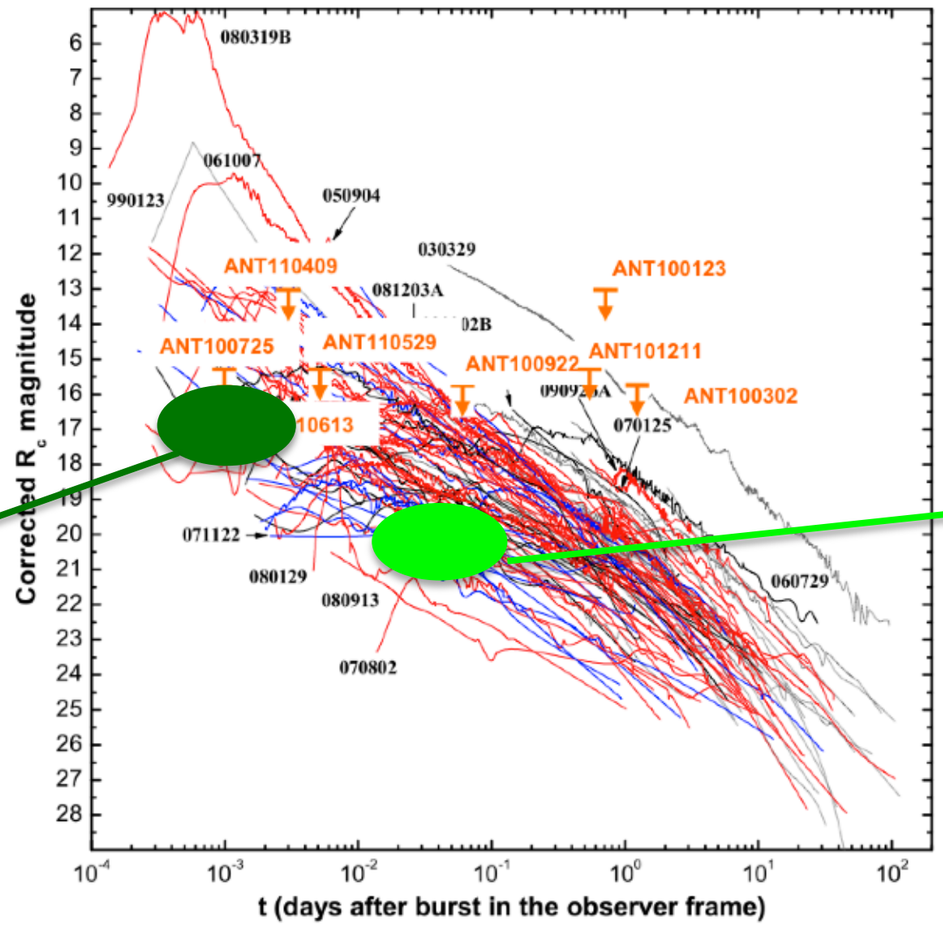


Method based on only detected light curves [kann2010] :

Robotical telescope networks

-Today situation: Rotse end in nov 2012 (Tarot future OK)

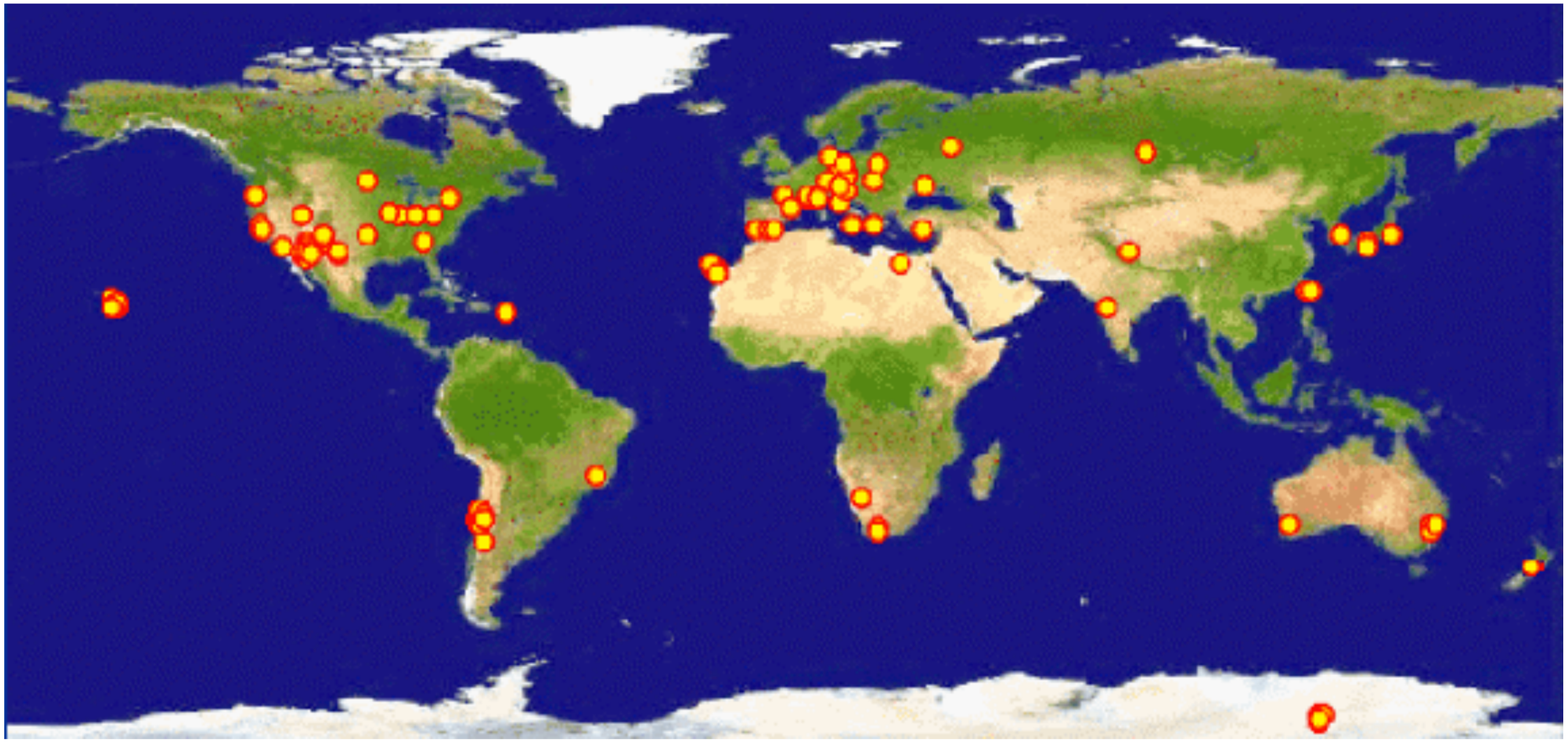
Small robotic telescopes (~30-60cm)located all around the word capable to answer in the minute timescale with a sensitivity of M 16-17



Medium robotic telescopes (~1m), with a sensitivity of M 20-21. Capable to answer in the hour timescale (1 or 2 per hemisphere) => but important pressure + limited fov

Robotical telescope networks

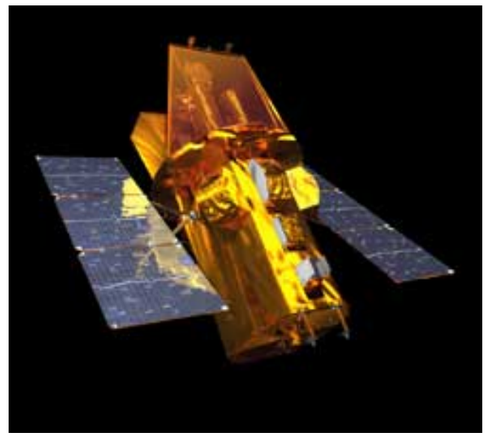
-Today situation: Rotse end in nov 2012 (Tarot future OK)



To maintain the capacity of the fast alert response, we need to find some telescopes in the South hemisphere: Zadko, SkyMapper, Bootes-4, Trappist…

For a long term follow-up (SN…), one telescope per hemisphere is sufficient. Only increase the sensitivity

Swift/XRT



X-ray follow-up: complementary information to optical signals; fast response: increased sensitivity to GRBs

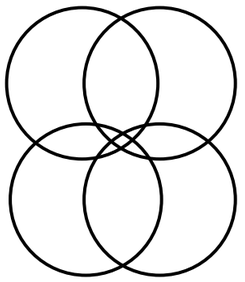
Swift/XRT: 0.2-10keV but small fov=23.6arcmin

Strategy: 6-7 alerts per year

=> only HE triggers (best PSF: 0.3-0.4°@ 1sigma)

=> 4 pointings: 72% of the events in fov (assuming ~E^{-2})

=> 2ks observation



Observations:

1) Automatic response to ToO (priority 1)=> on-line analysis

2) Follow-up for several days (priority 2) only if interessting candidate found (high or decreasing flux)

System operational, wait for an alert

Summary

➔ TAToO alert system operational since 2009:
- alert sending delay ~20s with 0.3-0.5^{o} precision
- 75 alerts send: 59 with follow-up > 2 nights

➔ Image analysis performed with 2 independent pipelines (SNLS + Rotse)
- Prompt analysis done: no candidate
- Follow-up analysis in progress: no SN candidat in ~10 alerts

=> Move to a more standard pipeline

➔ Present: TAROT, ~~Rotse~~, Zadko + Swift/XRT
Near future: Pan-Starrs, Gaia…
Future: Flash telescope, EVENT project…

➔ In complement, ANTARES is part of AMON