TAToO

Follow-up of high energy neutrinos detected by the ANTARES telescope

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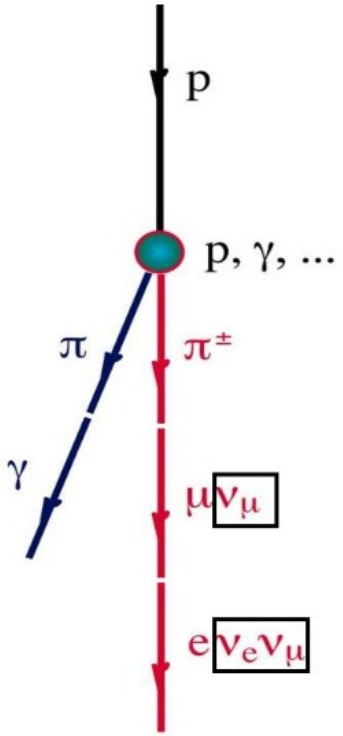
Gamma-ray bursts in the multi-messenger era

Paris, 16-19 June 2014

Motivation

Cosmic neutrinos:

- Neutrinos possibly produced in interactions of high energy nucleons with matter or radiation
- If **hadronic mechanisms**:
  High energy nucleons + hadrons ⟶ *mesons + hadrons*
  ⟶ *neutrinos and photons*
- Simultaneous emitters of neutrinos and photons
- Detection from a cosmic source would be a direct evidence of hadronic scenario

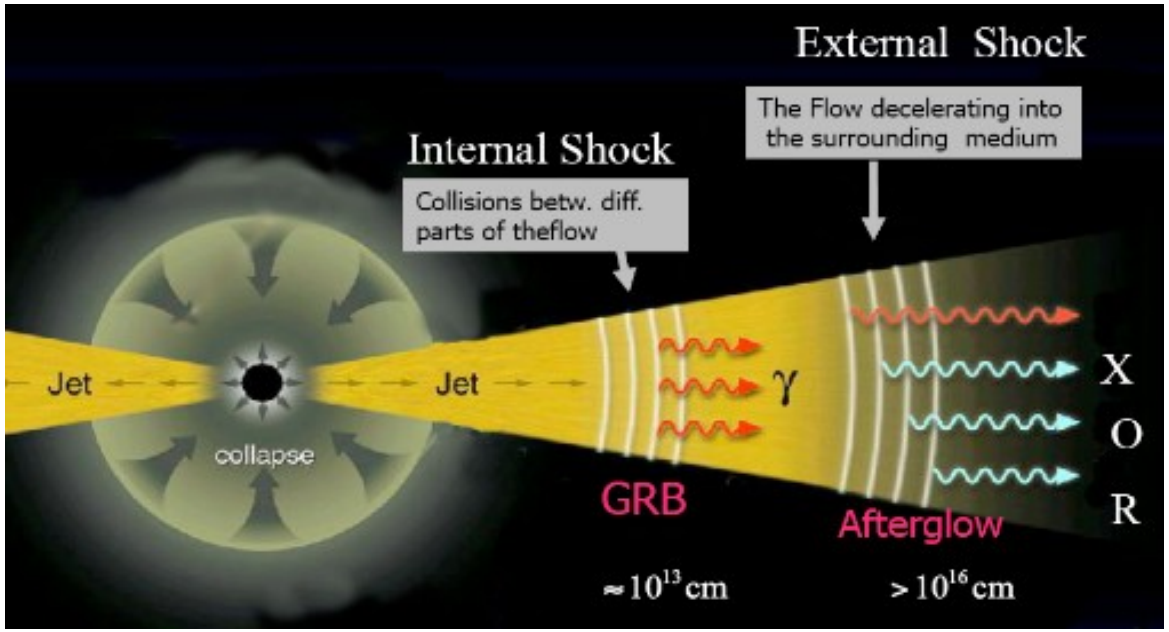


TAToO

- Multi-messenger approach: follow-up of neutrino alerts with optical/X-ray telescopes
- Enhance the sensitivity to transient sources and the discovery potential
- 1 neutrino could lead to a discovery

Example of sources

- High energy neutrinos from gamma-ray bursts and supernovae



GRB neutrinos:

relativistic jets (Fireball model)

⇨ 10 TeV–10 PeV neutrino

Meszaros & Rees, Waxman

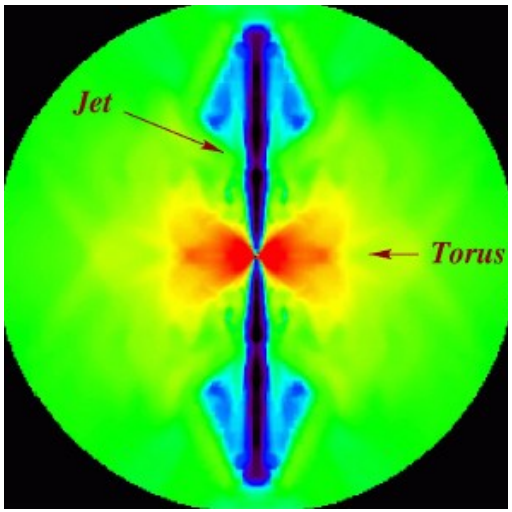
$$p\,\gamma \rightarrow \Delta^{+} \rightarrow n\,\pi^{+}$$
$$p\,p \rightarrow \pi, K$$
$$\pi^{+} \rightarrow \nu_{\mu}\,\mu^{+} \rightarrow \nu_{\mu}\,e^{+}\,\nu_{e}\,\bar{\nu}_{\mu}$$

SN neutrinos:

connection GRB-SN (chocked jet, midly relativistic)

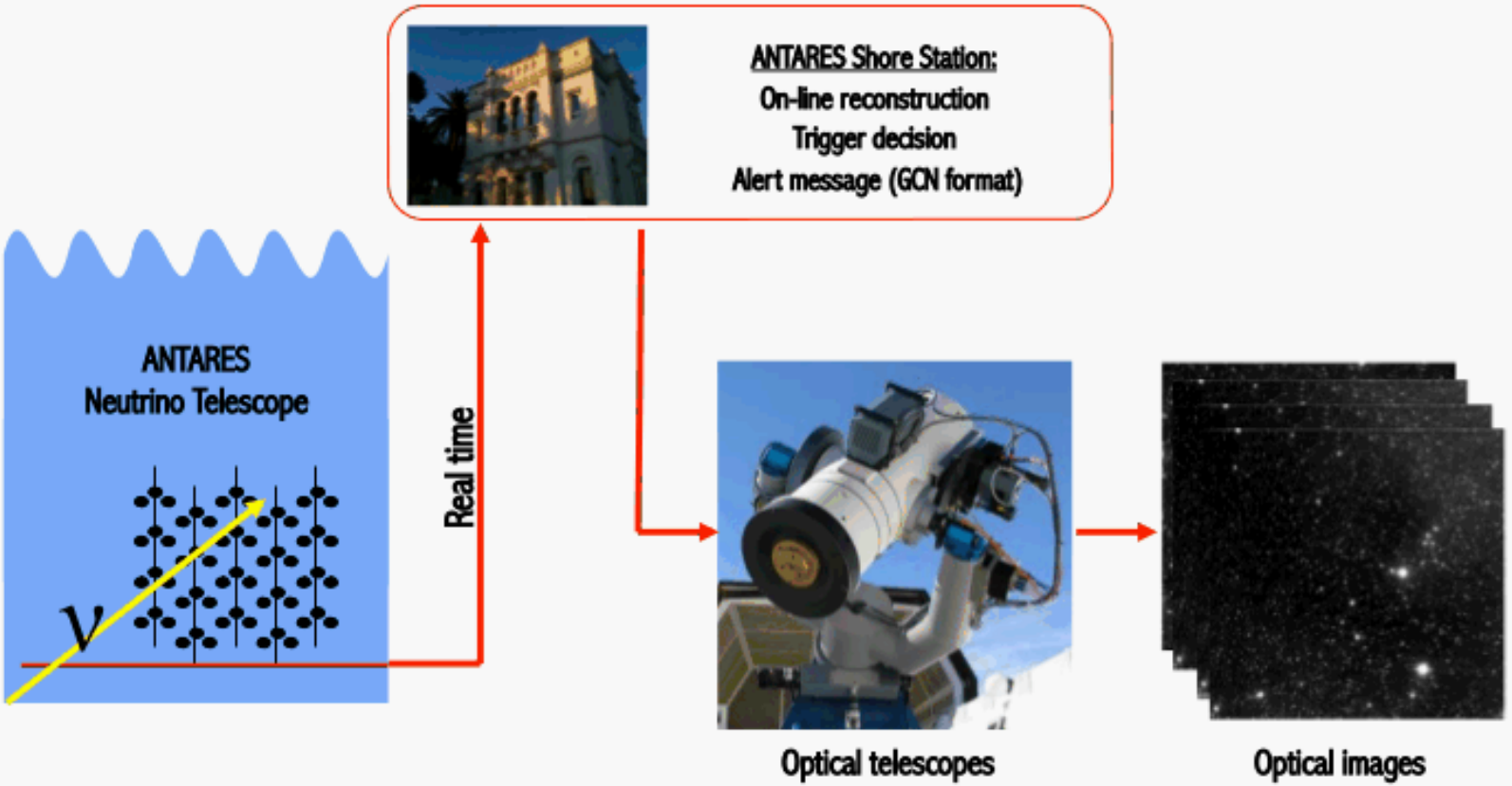
⇨ 100 GeV-10 TeV neutrino

Razzaque & al,, Ando & Beacom



TAToO

- Optical follow-up: search for an optical counterpart
- Transient sources: GRBs, SNe...



The ANTARES Telescope Neutrino Alert System
Astroparticle Physics 35 (2012) 530-536, arXiv:1103.4477

TAToO

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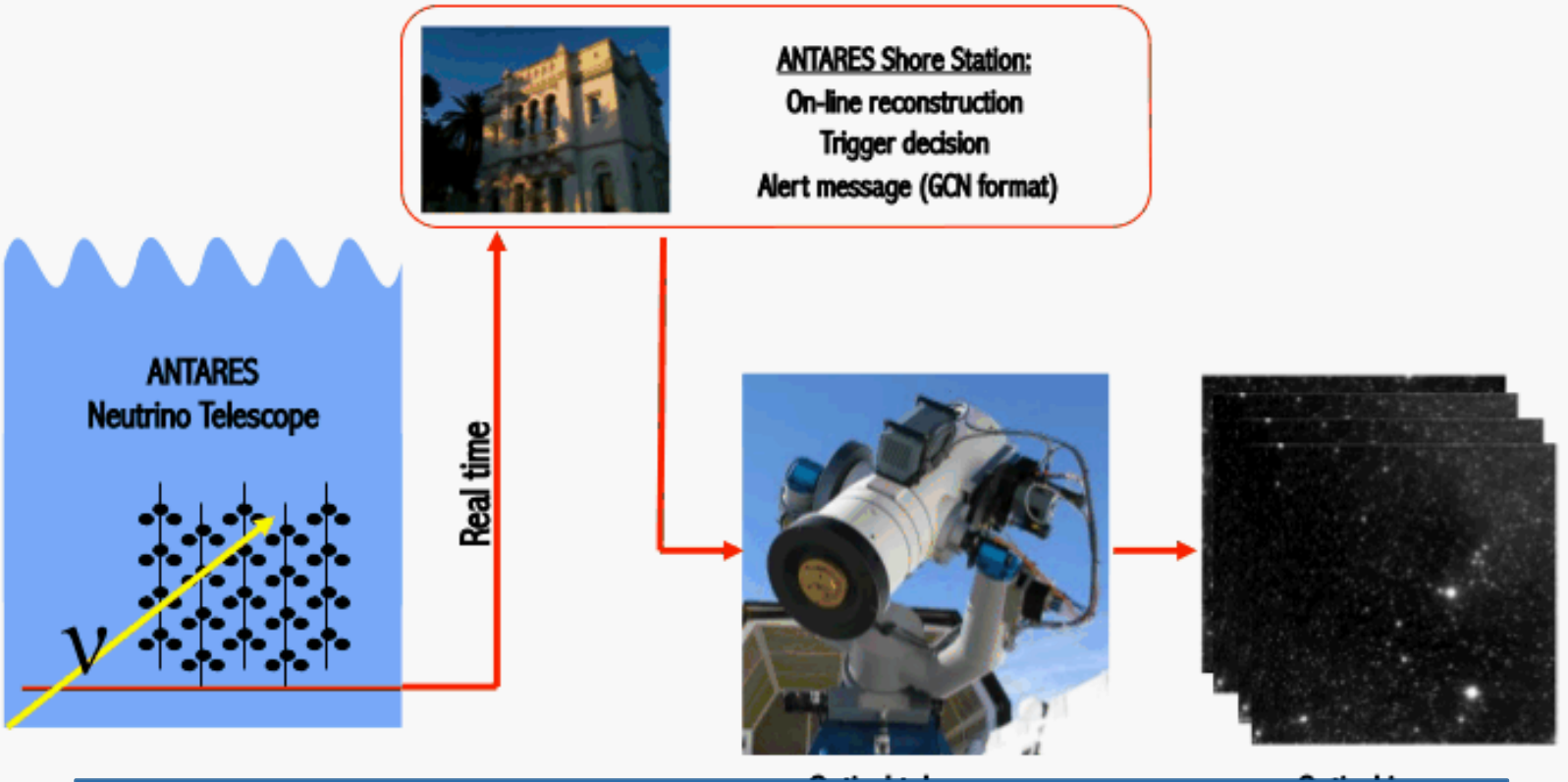


Advantages:
- Sky coverage (> 2π sr) + high duty cycle
- Very good sensitivity
- No assumption about the nature of the source

Triggers

- **Directional:**

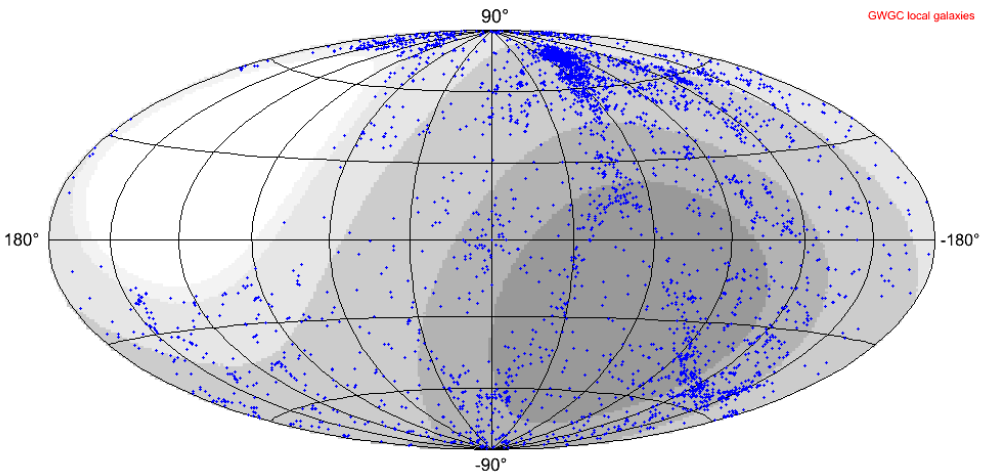
  1 neutrino in the direction (< 0.4°) of a local galaxy (< 20 Mpc)

  12 per year

- **High energy:**

  1 neutrino with E > 5-10 TeV

  12 per year



- **Doublet:**

  Two neutrinos in a 3° angle and in a time window of 15 minutes

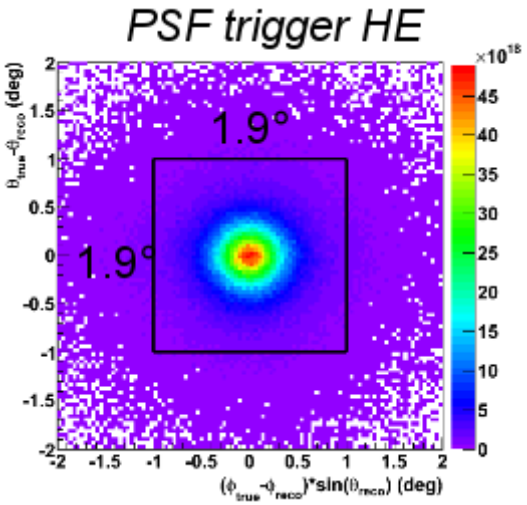
  0.04 per year

TATOO

- **Online processing:**
  - Online reconstruction + trigger: ~ **3-5 s**
  - Alert sending: ~ **1-10 s** depending on the telescope response
  - Telescope slewing: ~ **1-5 s**

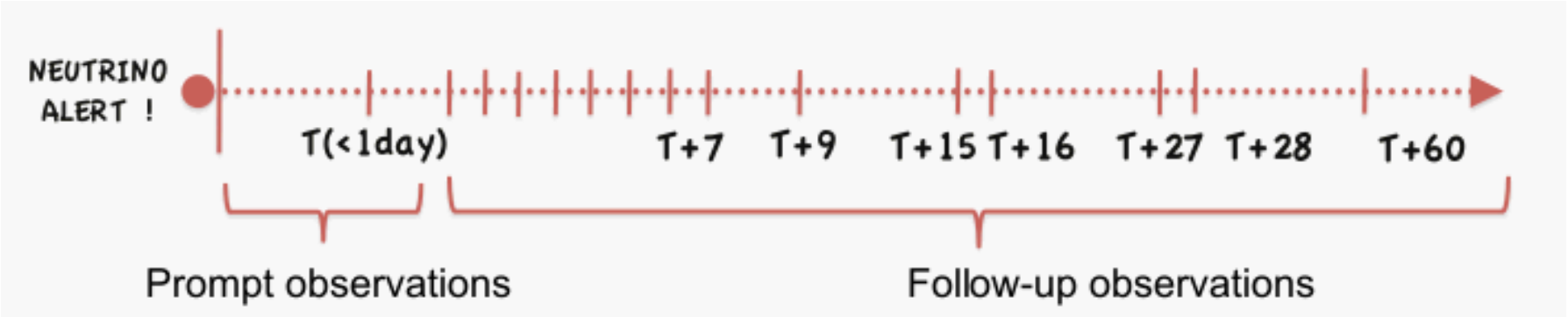
Minimum delay between the neutrino and the first image: ~ **20 s**

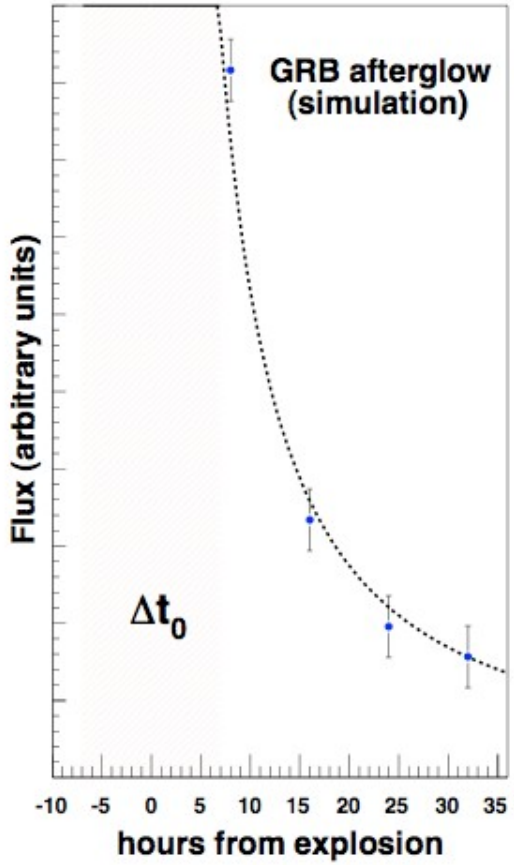
- **Angular performances:**

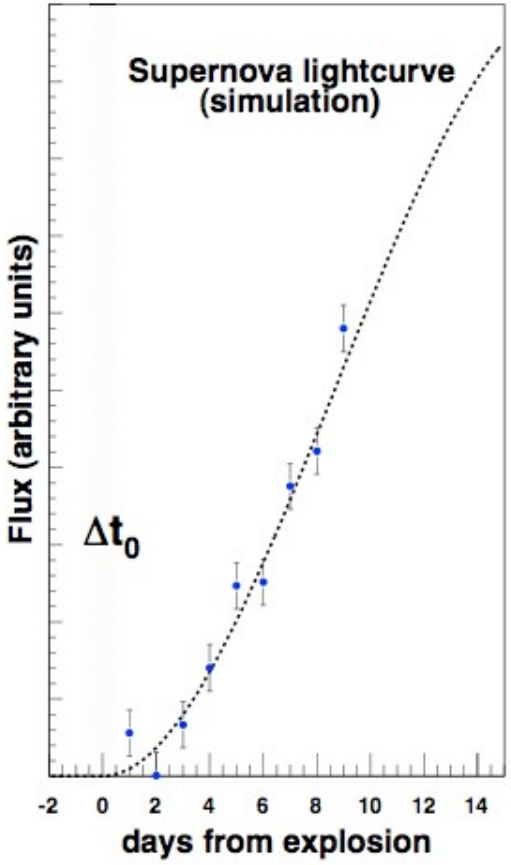


Trigger	Angular resolution	Fraction events in fov	Mean energy
HE	0.25-0.3°	96% (GRB) 68% (SN)	~ 7 TeV
Directional	0.3-0.4°	90% (GRB) 50% (SN)	~ 1 TeV

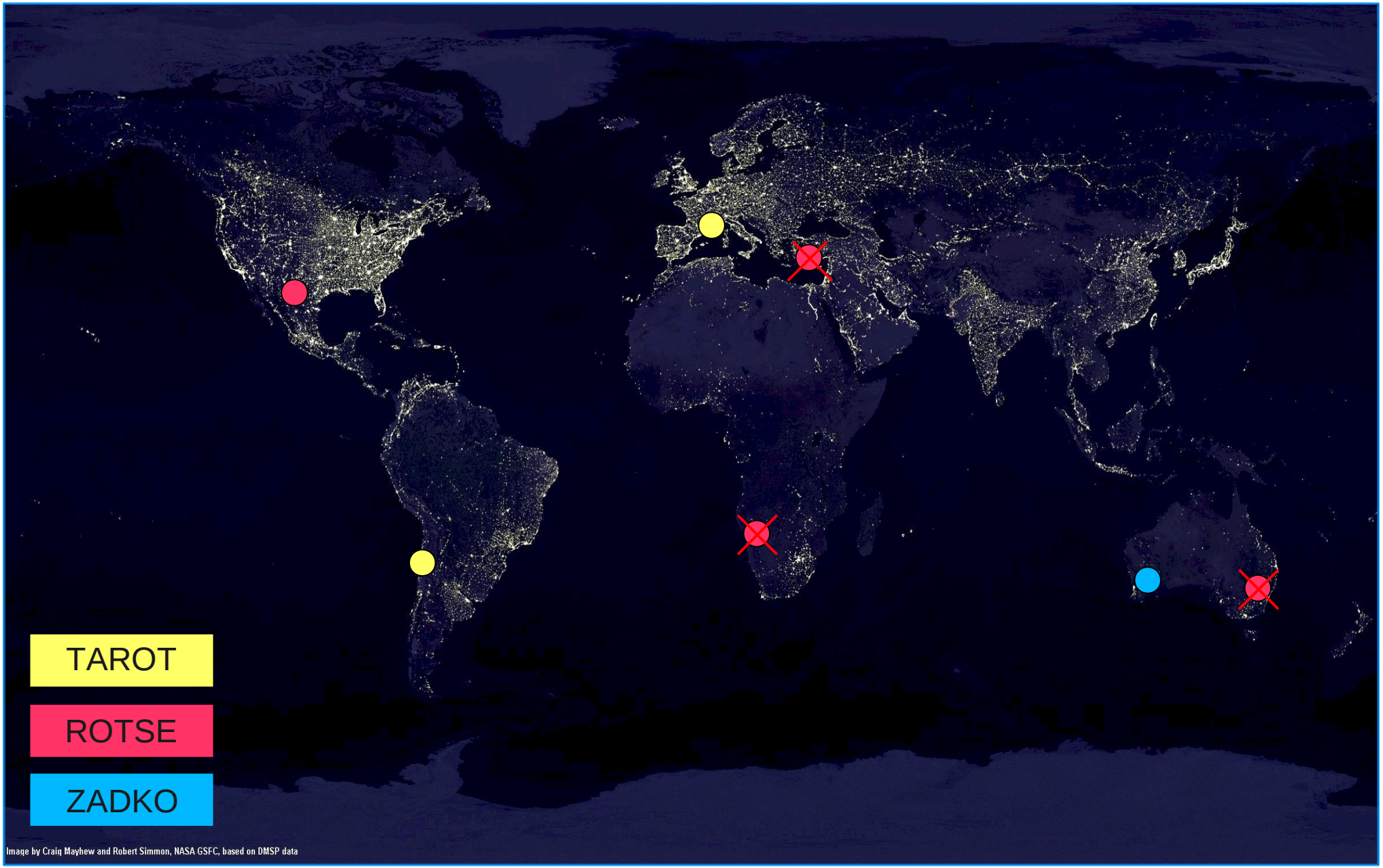
Optical follow-up strategy



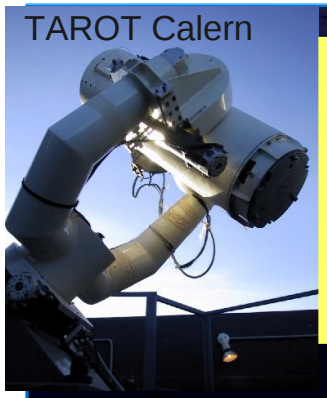




Telescopes


TAROT
ROTSE
ZADKO
Image by Craig Mayhew and Robert Simmon, NASA GSFC, based on DMSP data

Telescopes



- Two 25 cm telescopes
- Fov 1.86°x1.86°
- Slewing time ~ 10s

TAROT

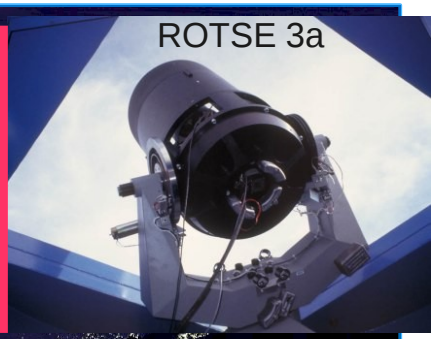
ROTSE

ZADKO

Image by Craig Mayhew and Robert Simmon, NASA GSFC, based on DMSP data

Telescopes

- Four 45 cm telescopes
- Fov 1.85°x1.85°
- Slewing time ~ 10s



TAROT

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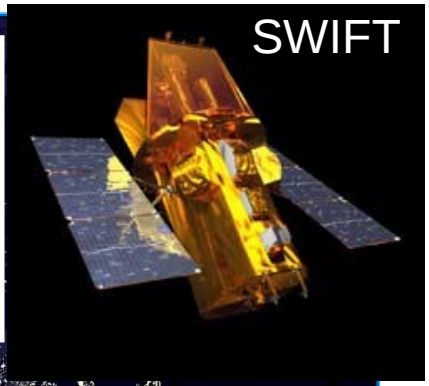
Image by Craig Mayhew and Robert Simmon, NASA GSFC, based on DMSP data

Telescopes

- One-metre telescope
- Fov 23 x 23 arcmin
- Max. Slew speed 3°/s

Telescopes

- X-ray follow-up
- Fov 23.6 x 23.6 arcmin
- 0.3-10 keV energy range



TAROT

ROTSE

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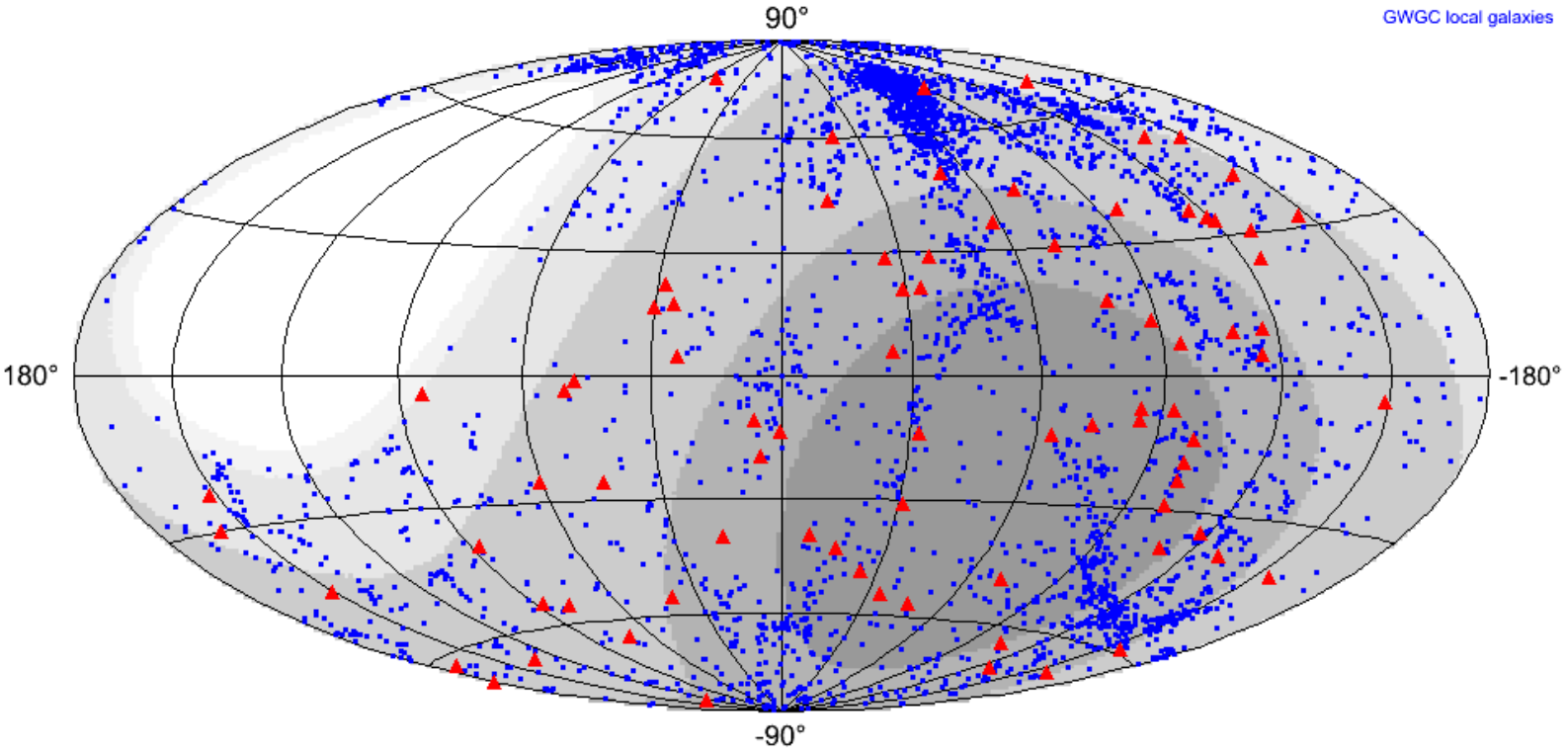
Image by Craig Mayhew and Robert Simmon, NASA GSFC, based on DMSP data

TAToO: status

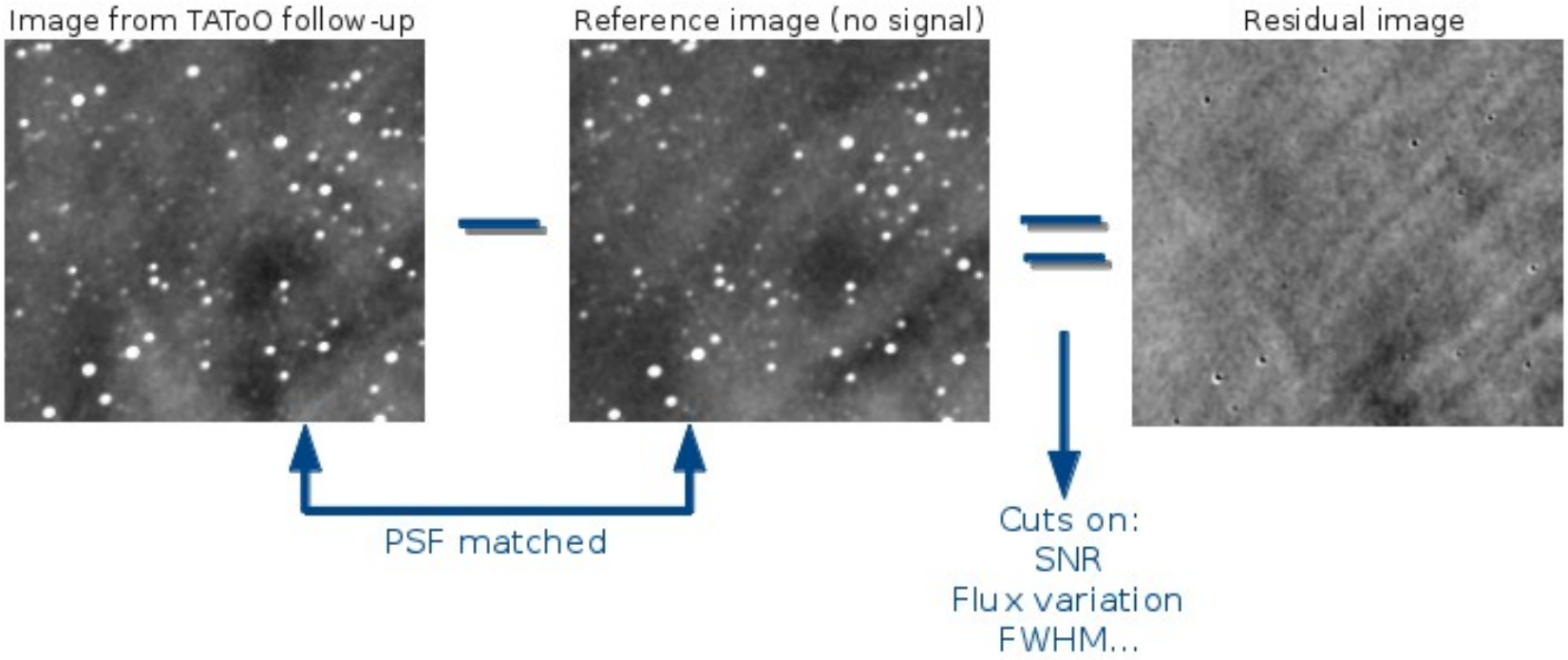
Since 2009:

- **108** alerts sent:
  - **11** not followed (telescope maintenance, too close to the Sun...)
  - **97** followed by at least 1 telescope and at least 1 night
  - **90** followed by at least 1 telescope and at least 3 nights



Optical counterpart search

- Analysis based on the image subtraction:



- Development of a new pipeline for image analysis

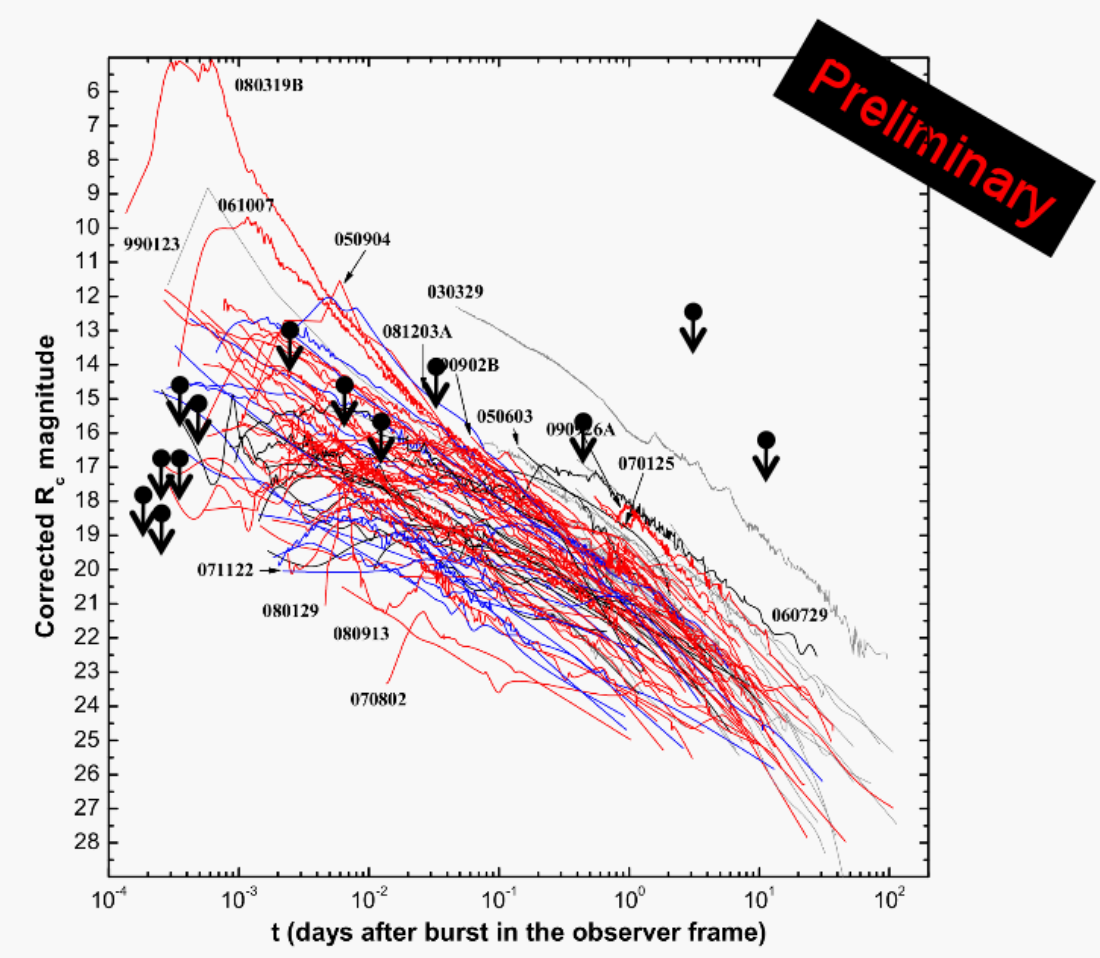
Prompt analysis: results

Hypothesis: neutrino emission simultaneously with photons

→ No transient optical counterpart associated with a neutrino detection

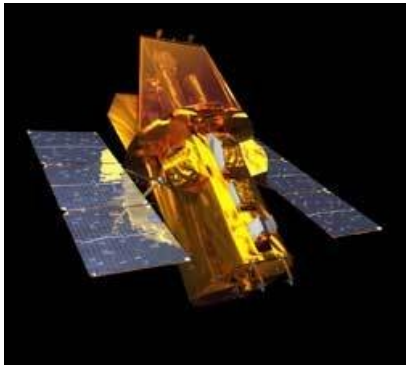
→ Upper limits on transient sources magnitude

Alert	Delay since trigger	U.L. Mag S/N=5
ANT100123A	**15h**20m15s	12
ANT100302A	**24h**20m8s	15.7
ANT100725A	0h**01m**15s	14.5
ANT100922A	**1h**08m06s	14.0
ANT101211A	**12h**03m30s	15.1
ANT110409A	0h**04m**17s	18.1
ANT110529A	0h**07m**33s	15.6
ANT110613A	0h**01m**08s	17.0
ANT120730A	0h00m**21s**	17.6
ANT120907A	0h00m**25s**	16.9
ANT121010A	0h00m**24s**	18.6
ANT121206A	0h00m**27s**	16.9



Based on only detected light curves [kann2010]

X-ray follow-up with SWIFT



Follow-up with SWIFT

X-ray follow-up: complementary informations to optical signals

→ The X-ray sky is rich in variable and transient sources

→ Fast response: increase sensitivity to fast transient sources (GRBs)

Strategy:

MoU 6 with alerts/yr

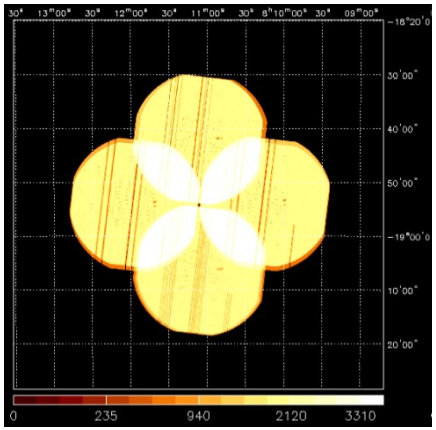
Only HE triggers with higher energy selection

2x2 tiles with 2ks exposure each

⇒ Sensitivity: 2.10^{-13} erg.cm^{-2}.s^{-1}

⇒ 4 tiles cover 48 arcmin fov

~60-70 % of the PSF



Observation strategy:

1) Automatic response to ToO (priority 1) → online analysis

2) Follow-up only if an interesting candidate is found (priority 2)

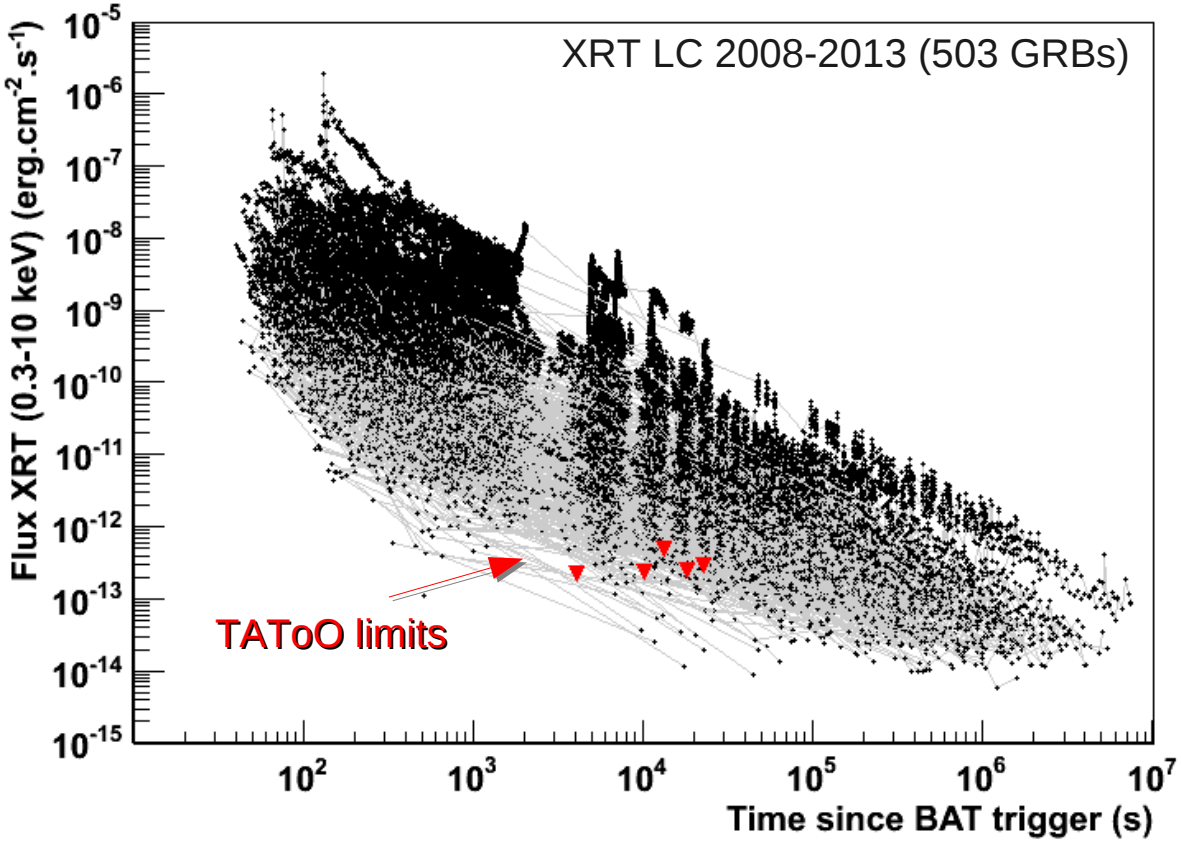
Image processing: Phil Evans (Leicester University)

Follow-up with SWIFT: results

⇒ 5 alerts sent to the XRT since June 2013
After a delay of: 23s / 25s / 18s / 18s / 24s
Processing after: 1h08 / 6h24 / 5h06 / 6h43 / 5h36

⇒ **No X-ray counterpart associated to a neutrino detection**

In case of GRB: compare with the afterglow lightcurves detected by Swift/XRT



Summary

- TAToO works well since 2009
  - More than 100 alerts sent

- Optical follow-up:
  - Prompt analysis done: no counterpart associated to a neutrino detection

- X-ray follow-up:
  - Operational since 2013
  - 5 alerts sent to the XRT: no X-ray counterpart

Derive upper limits on transient sources magnitude

BACK UP

Image analysis

Telescope site

Image correction :

- Bias, dark subtraction
- Flat-fielding
- Fringe correction

Astrometry / photometry :

- SExtractor : catalogue of extracted sources
- SCAMP : astrometric calibration
- Le PHARE : photometric calibration

Co-addition :

- SWarp : resampling and co-adding images

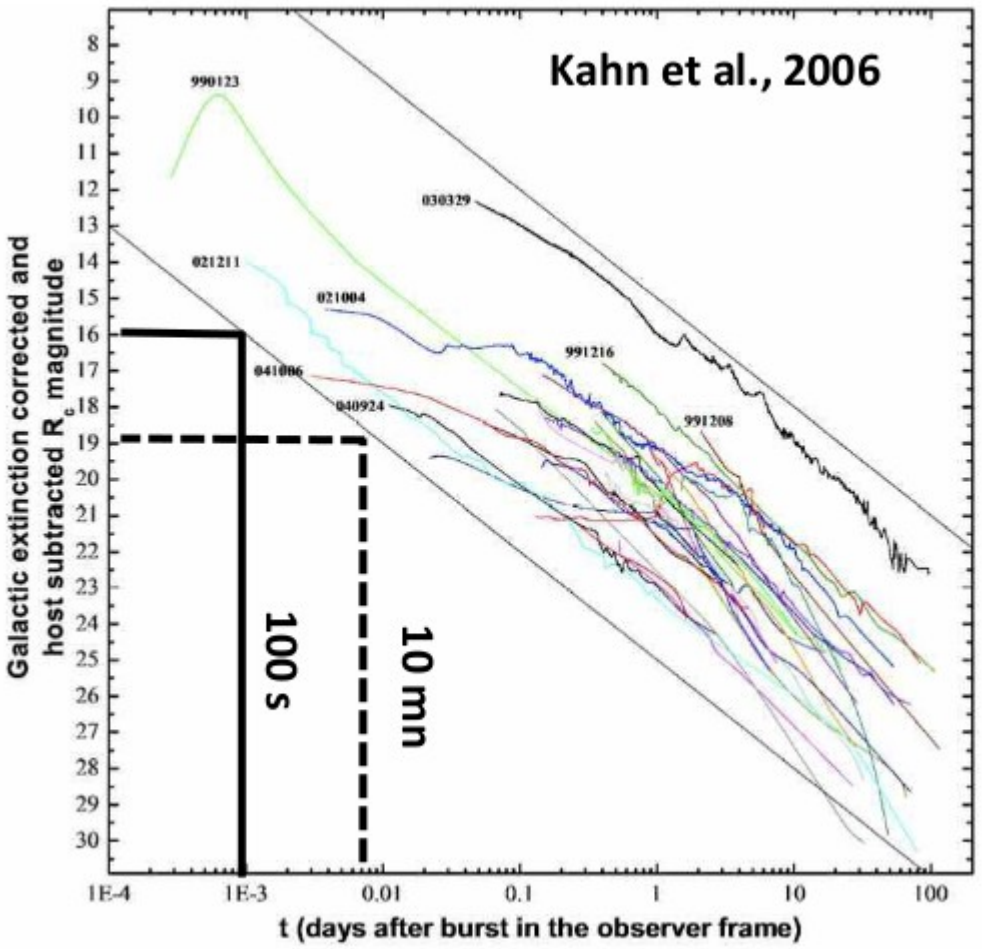
Subtraction :

- Reference selection
- Pixel by pixel

Residuals inspection :

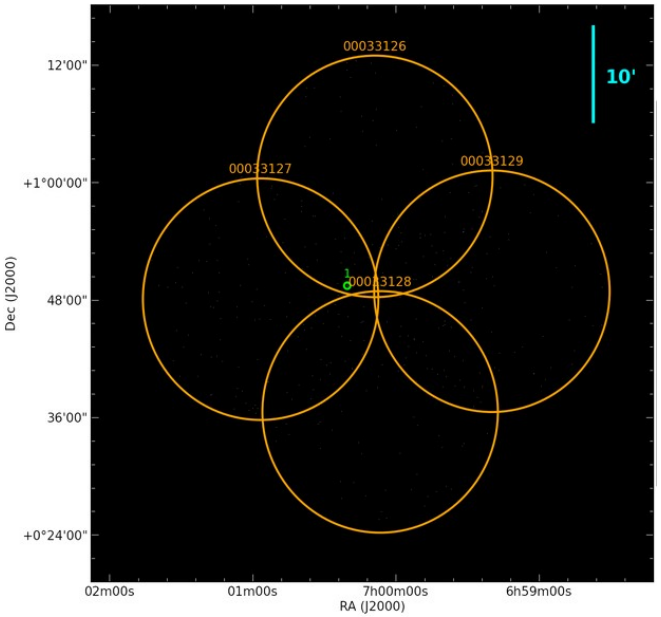
- Visual scan
- Comparison with catalogues
- Light curve scan

Telescopes response



Follow-up with SWIFT: example

Alert 2014/01/24:



J0700.2+0049: Swift observation summary

Mission:	ANTARES	**Sun distance:**	152.50°
ANTARES RA:	105.040°	**Sun angle:**	10.62 [hr](East of Sun)
ANTARES Dec:	+0.811°	**Moon distance:**	98.14°
ANTARES Err:	21.0 arcmin	Visibility of this field.	
T0:	2014-01-23 12:55:47 UT	**First slew:**	2014-01-23 16:36:42 UT
Galactic:	213.20° +2.31°	**First observation:**	2014-01-23 16:36:54 UT
Galactic N_H:	4.35×10^{21} cm^{-2}	**First analysis:**	2014-01-24 00:09:58 UT
Galactic E(B-V):	NED unavailable		

#	RA (J2000)	Dec (J2000)	Err_{90}[1]	Detection Flag[2]	Dist from ANTARES pos	Exposure	Notes	Vizier
1 [Hide details]	07h 00m 20.41s	+00° 49′ 27.2″	5.6″	Good	2.8′	1.3 ks		

- Mean XRT rate: 9 (±3) $\times 10^{-3}$ ct s^{-1}
- Peak XRT rate: 9 (+3, +3) $\times 10^{-3}$ ct s^{-1}
- RASS PSPC 3-σ upper limit: 0.03 ct s^{-1} (PSPC count-rate)
- Mean XRT rate converted to PSPC: 9 (±3) $\times 10^{-3}$ ct s^{-1}
- Peak XRT rate converted to PSPC: 9 (+3, +3) $\times 10^{-3}$ ct s^{-1}
- Mean XRT flux: 3.3 (±1.1) $\times 10^{-13}$ erg cm^{-1}s^{-1}
- Peak XRT flux: 3.3 (+1.1, +1.1) $\times 10^{-13}$ erg cm^{-1}s^{-1}
- Products: Light curve | Spectrum |
- Expected serendipitous sources: ~0.5 [What is this?]

If an uncatalogued source is found, 2 questions are asked to identify the afterglow:

1) Is the source “bright”?

2) Is the source fading?

⇒ No counterpart