



Follow-up of ANTARES neutrino alerts

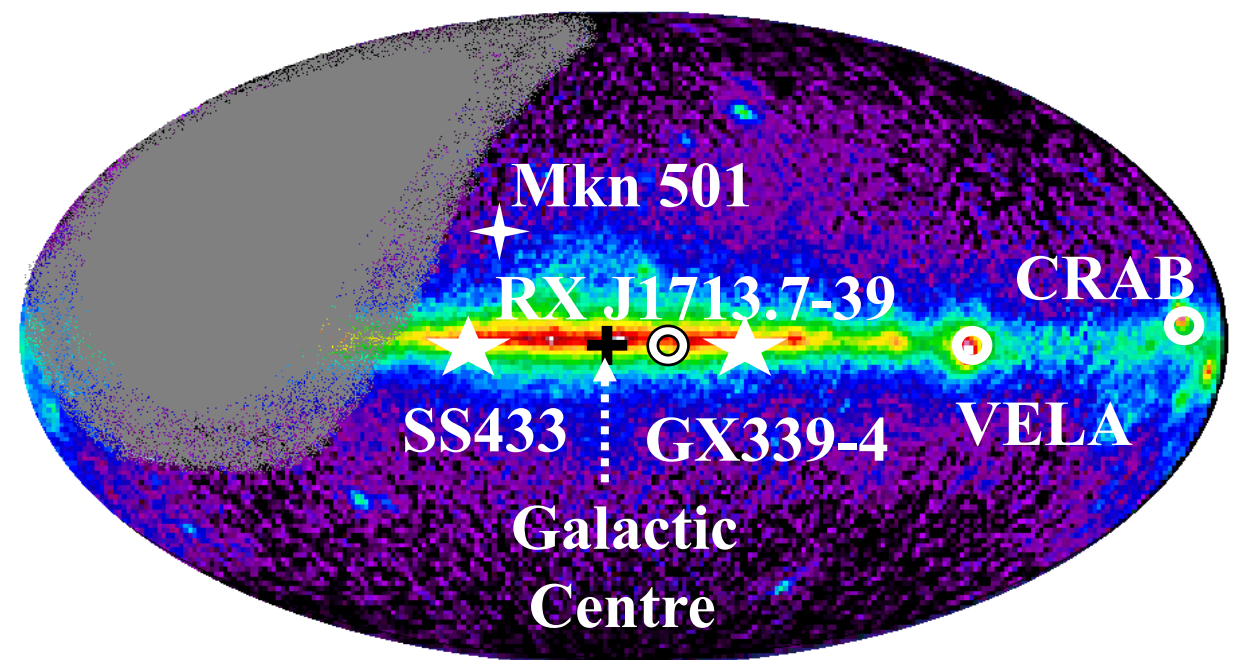
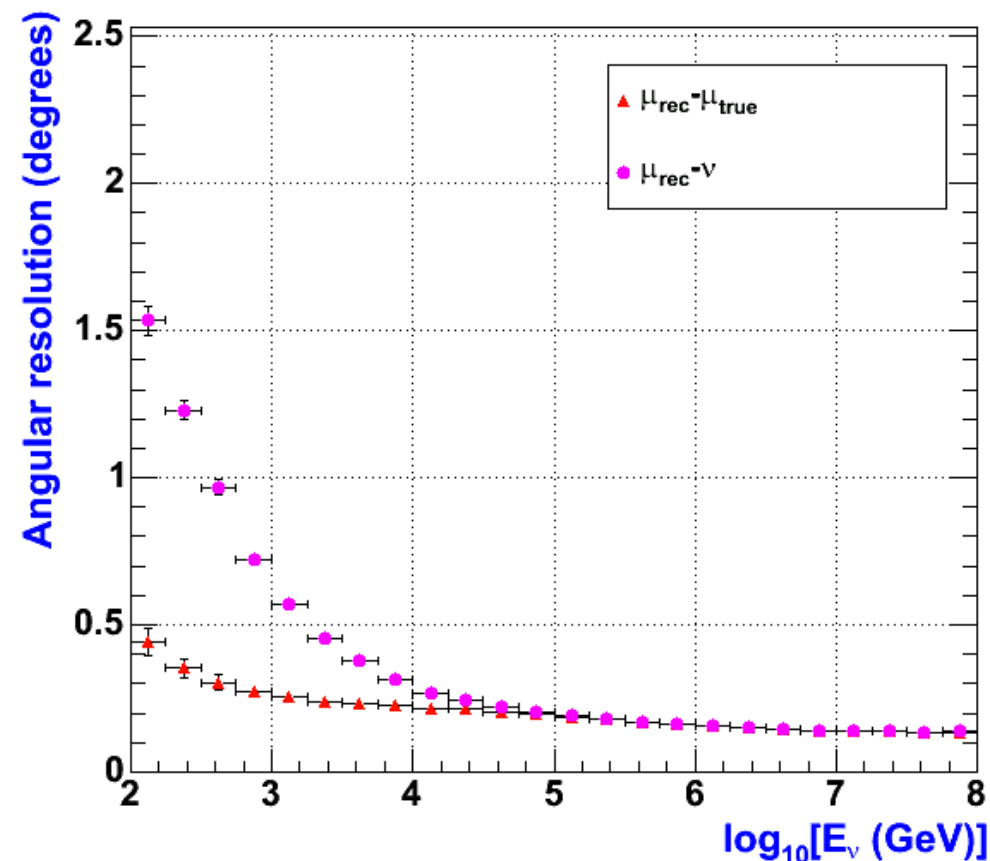
D. Dornic *CPPM*

AMON - PennState - 02/12/2015

ANTARES:

ANTARES in numbers:

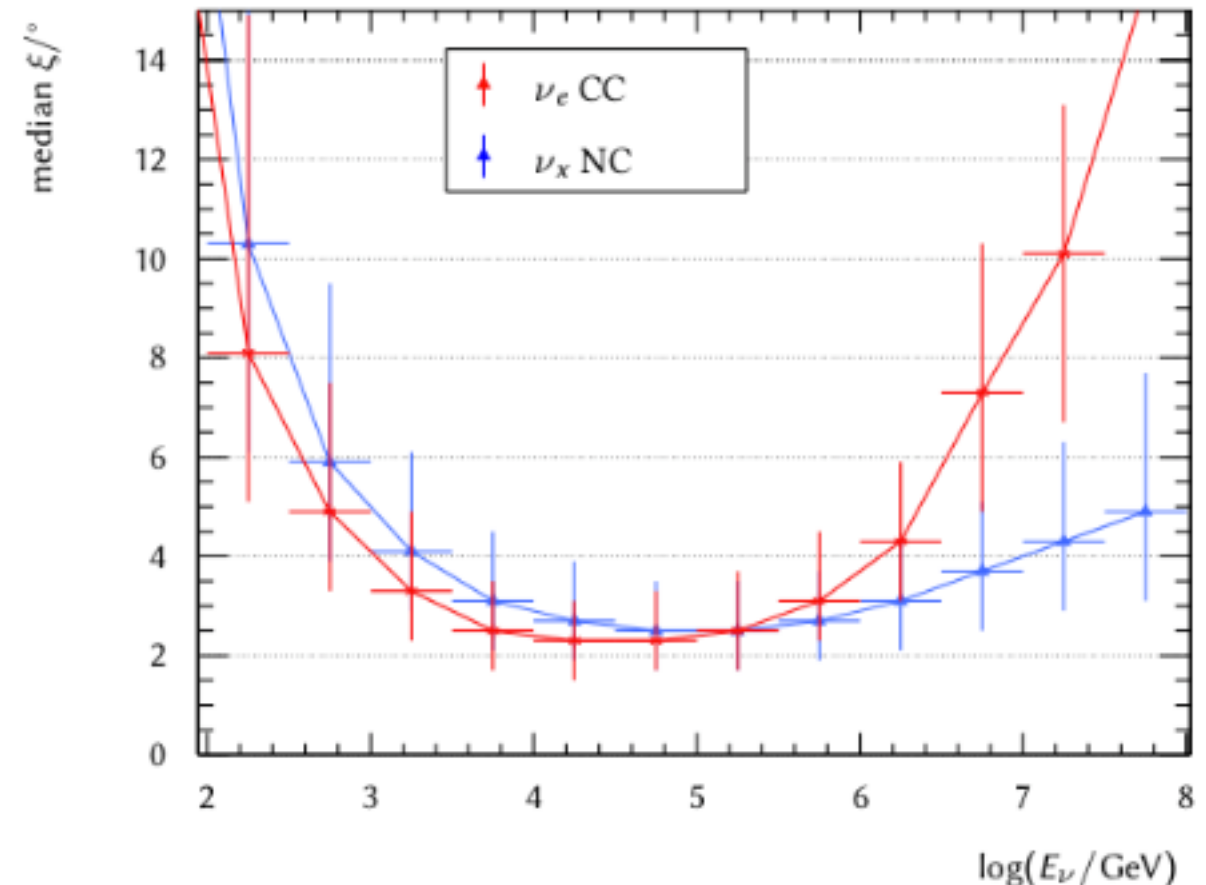
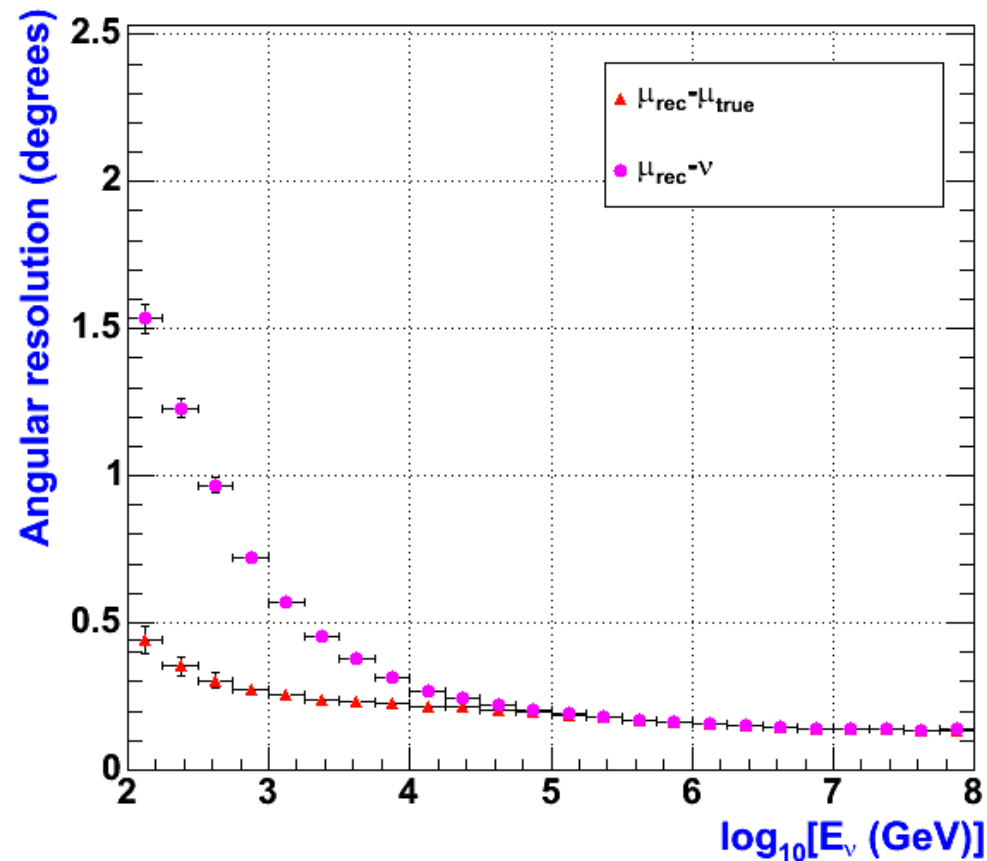
- 12-line data taking since 2008
- ~ 7500 detected neutrinos
- Angular resolution: $0.3\text{--}0.4^\circ$ (median)
- Effective area: $\approx 1\text{m}^2$ @ 30 TeV
- Visibility: $\frac{3}{4}$ of the sky, most of the galactic plane
- Real-time data processing



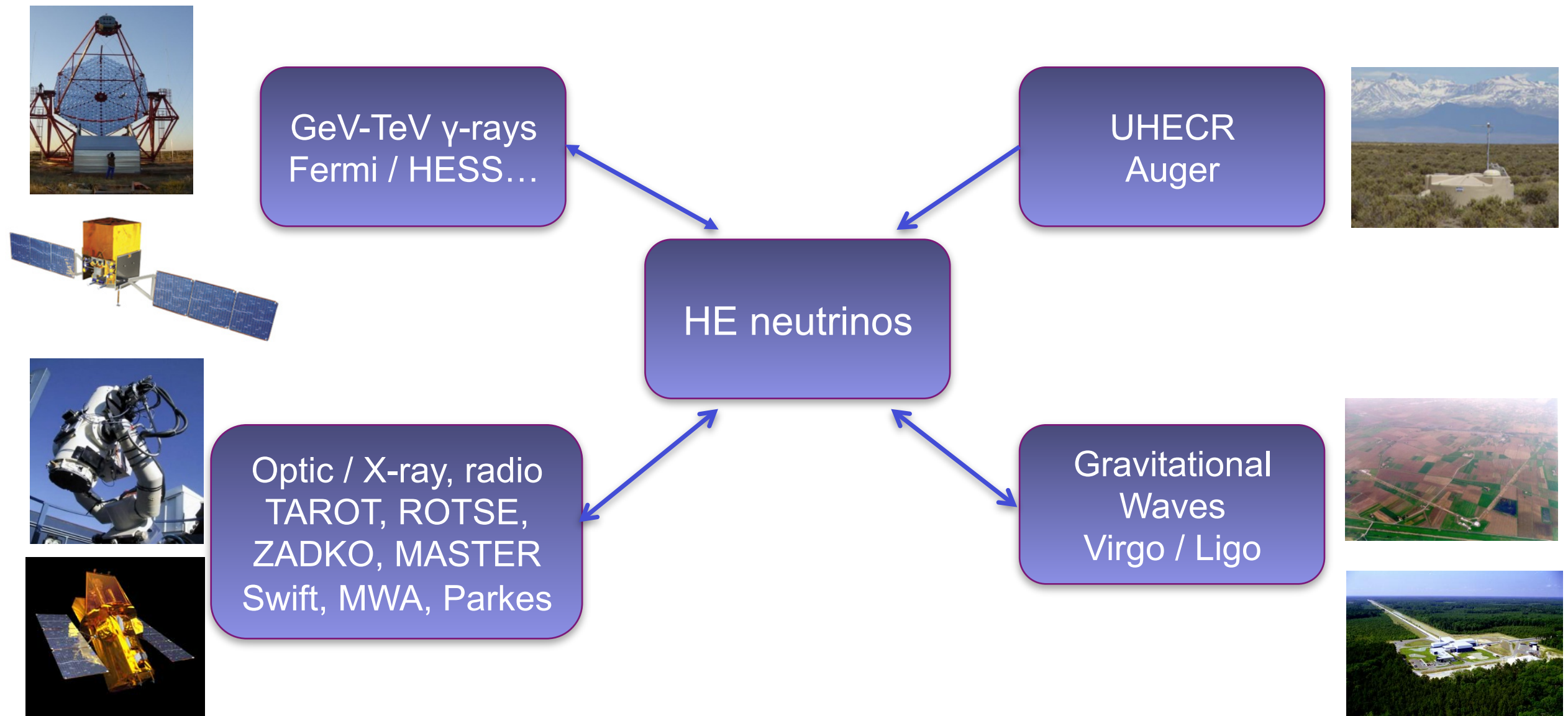
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Multi-messenger program:



+ Common ANTARES/IceCube analysis

Multi-messenger program:

Time-dependent searches:

- GRB [[Swift](#), [Fermi](#), [IPN](#)]
- Micro-quasar and X-ray binaries [[Fermi/LAT](#), [Swift](#), [RXTE](#)]
- Gamma-ray binaries [[Fermi/LAT](#), [IACT](#)]
- Blazars [[Fermi/LAT](#), [IACT](#), [TANAMI...](#)]
- Crab [[Fermi/LAT](#)]
- Supernovae Ib,c [[Optical telescopes](#)]
- Fast radio burst [[radio telescopes](#)]

Multi-messenger correlation:

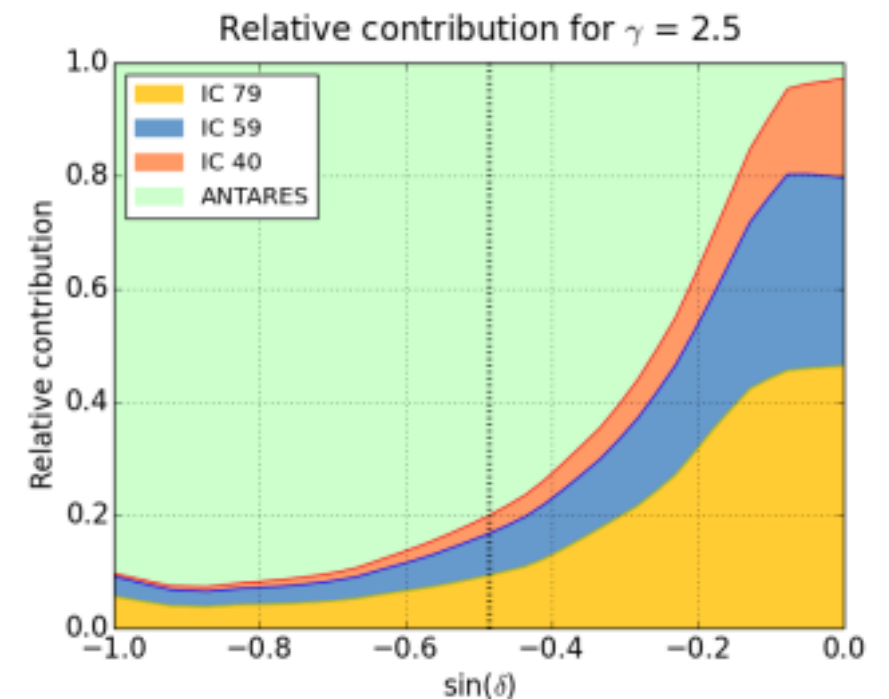
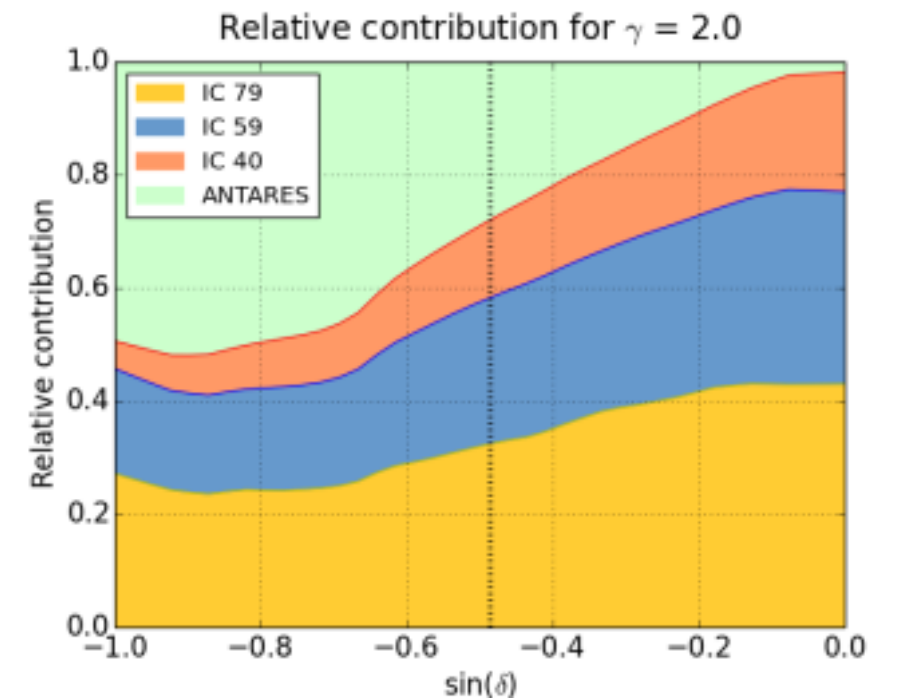
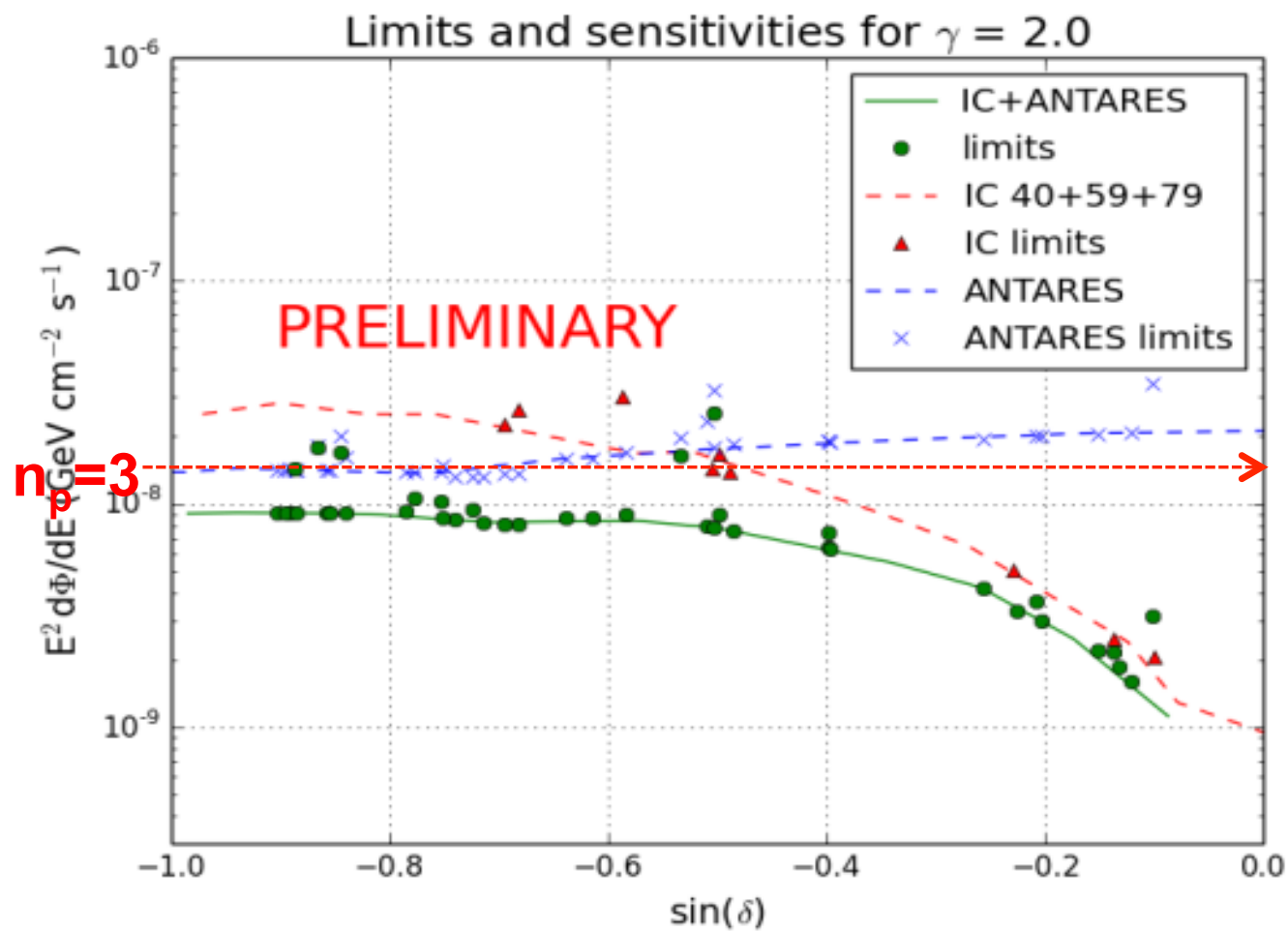
- Correlation with the UHE events [[Auger](#)]
- Correlation with the gravitational wave [[Virgo/Ligo](#)]
- 2pt-correlation with 2FGL catalogue, loc. galaxies, BH...

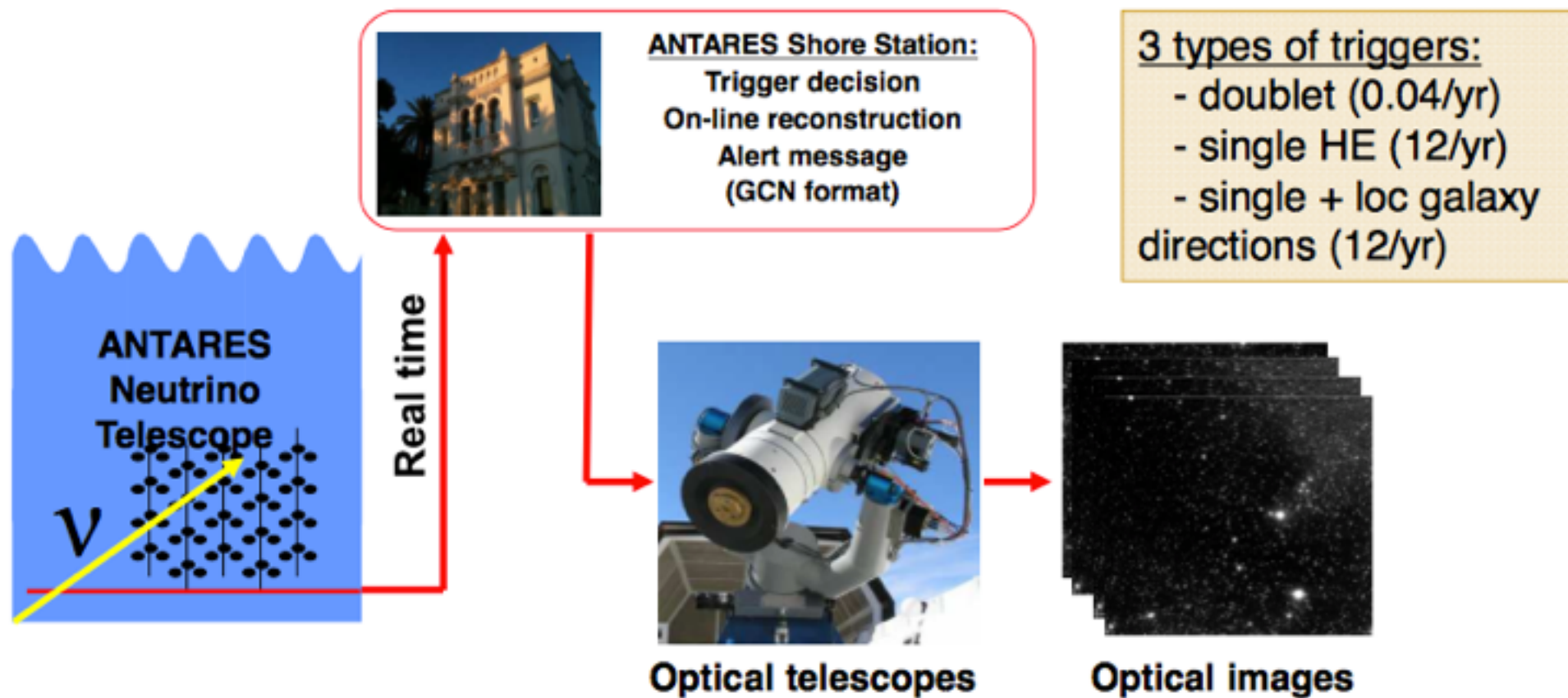
Real-time analysis:

- TAToO: follow-up of the neutrino alerts with optical telescopes [[TAROT](#), [ROTSE](#), [ZADKO](#), [MASTER](#)], X-ray telescope [[Swift/XRT](#)], GeV-TeV γ -ray telescopes [[HESS](#)] and radio telescope [[MWA](#)]
- Online search of fast transient sources [[GCN](#), [Parkes](#)]
- SNEWS: MeV neutrino from SN

Common ANTARES/IceCube analysis

Point-source analysis using the ANTARES 2007-2012 and the IC40, IC59, and IC79 samples for the Southern Hemisphere



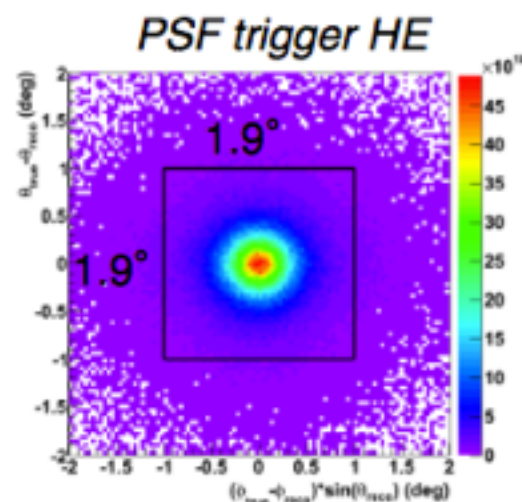


Online processing:

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

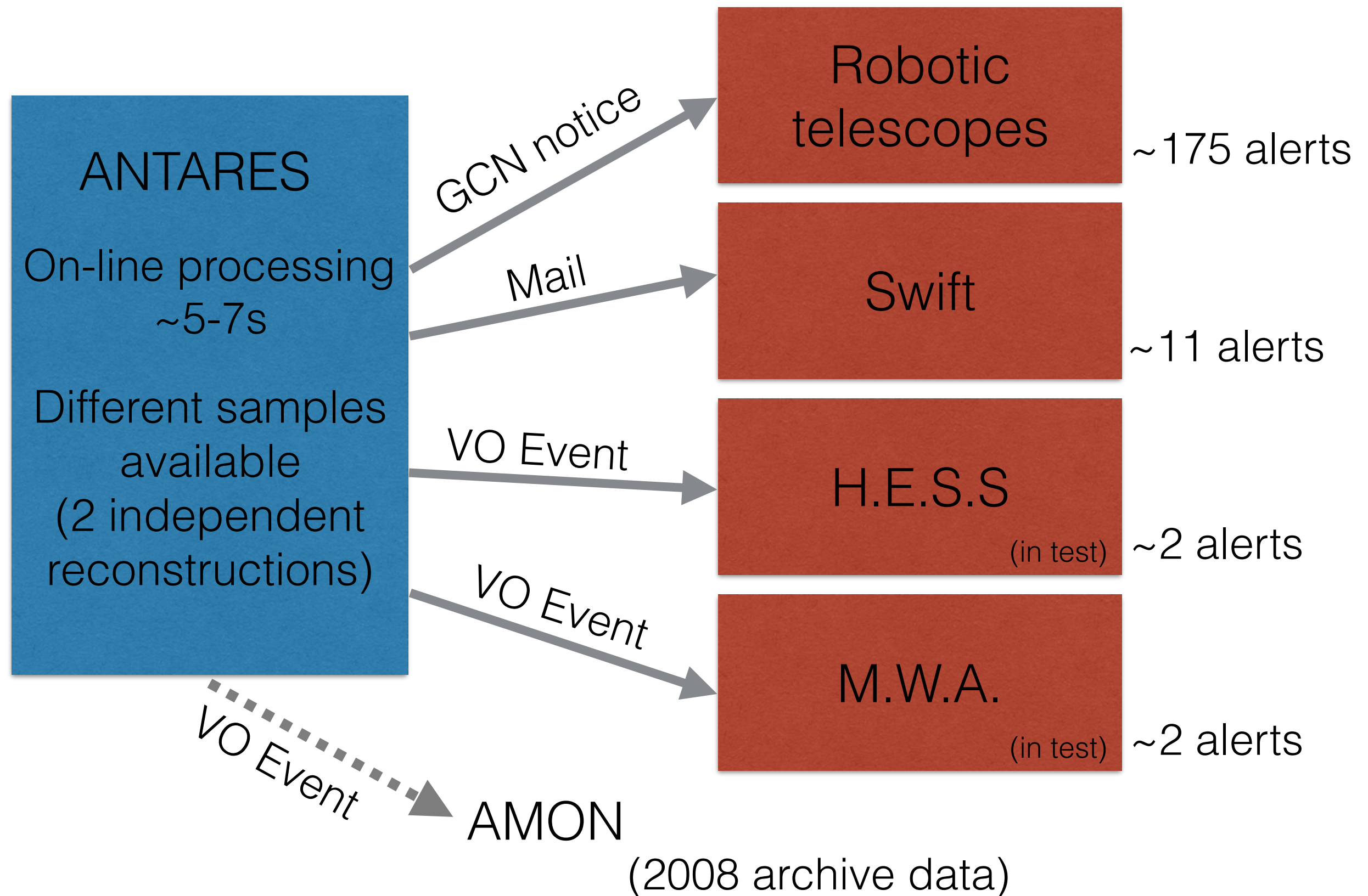
Minimum delay between the 1st image and the neutrino: ~ 20 s

Angular performances:

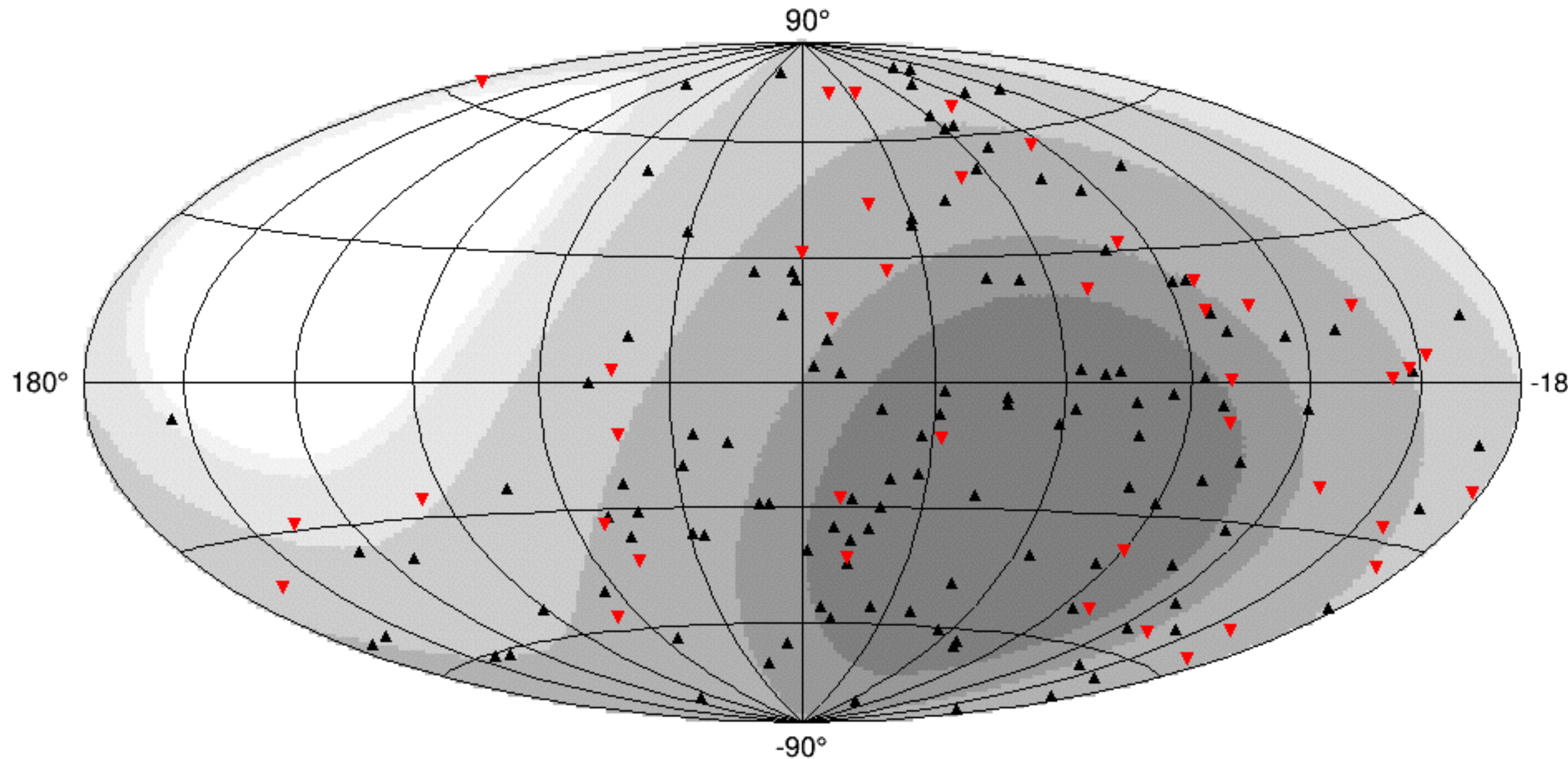


Trigger	Angular resolution	Fraction events in fov	Muon contamination	Mean energy
HE	0.25-0.3°	96% (GRB) 68% (SN)	<0.1%	~ 7 TeV
Directional	0.3-0.4°	90% (GRB) 50% (SN)	$\sim 2\%$	~ 1 TeV

Alert messages:



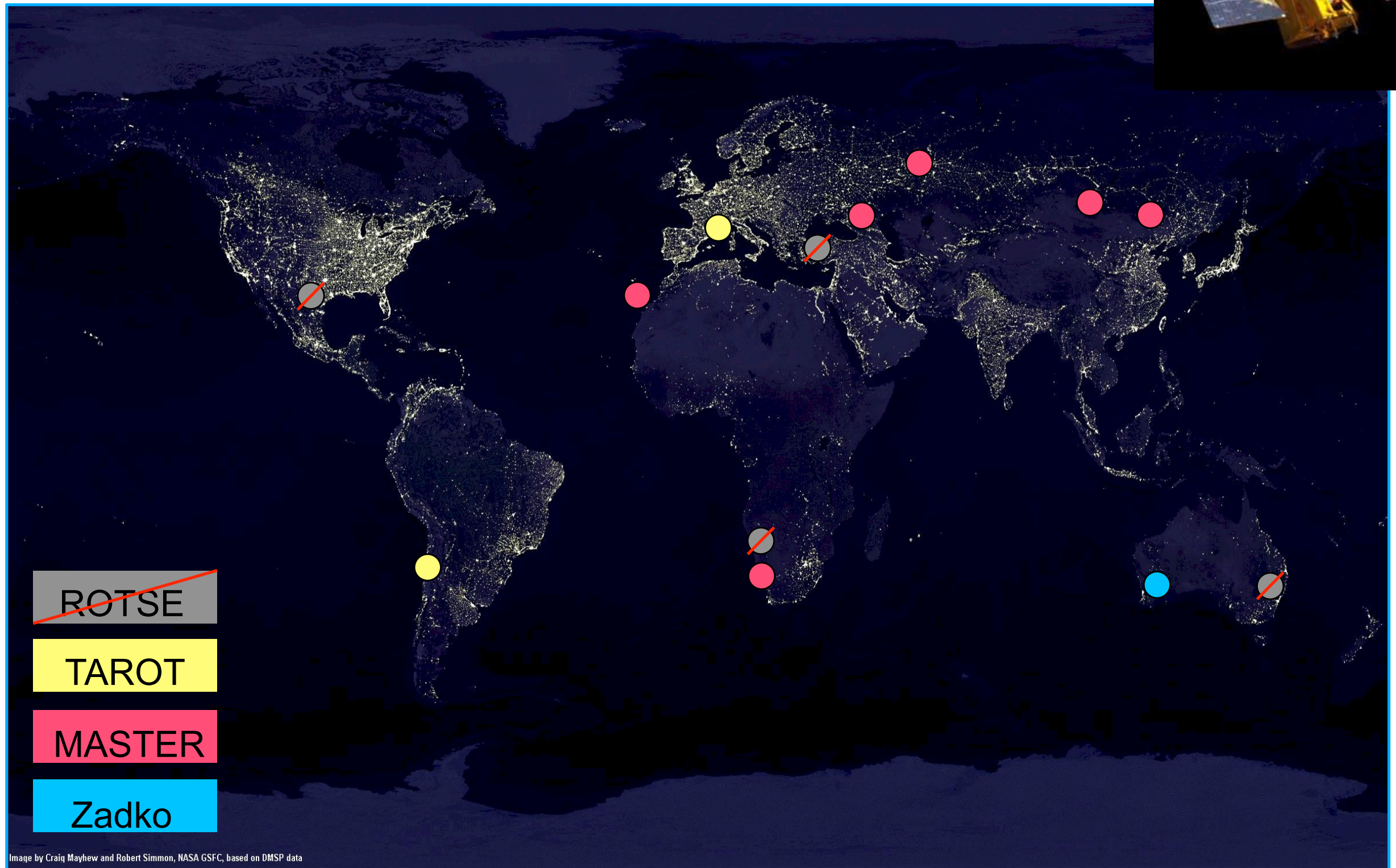
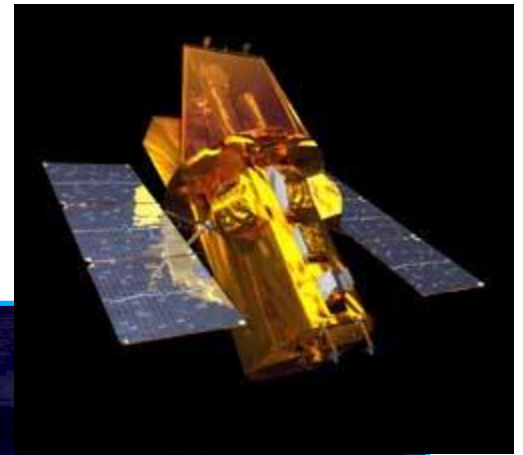
Neutrino alerts:



~175 alerts sent to the robotic telescopes
11 alerts to Swift/XRT

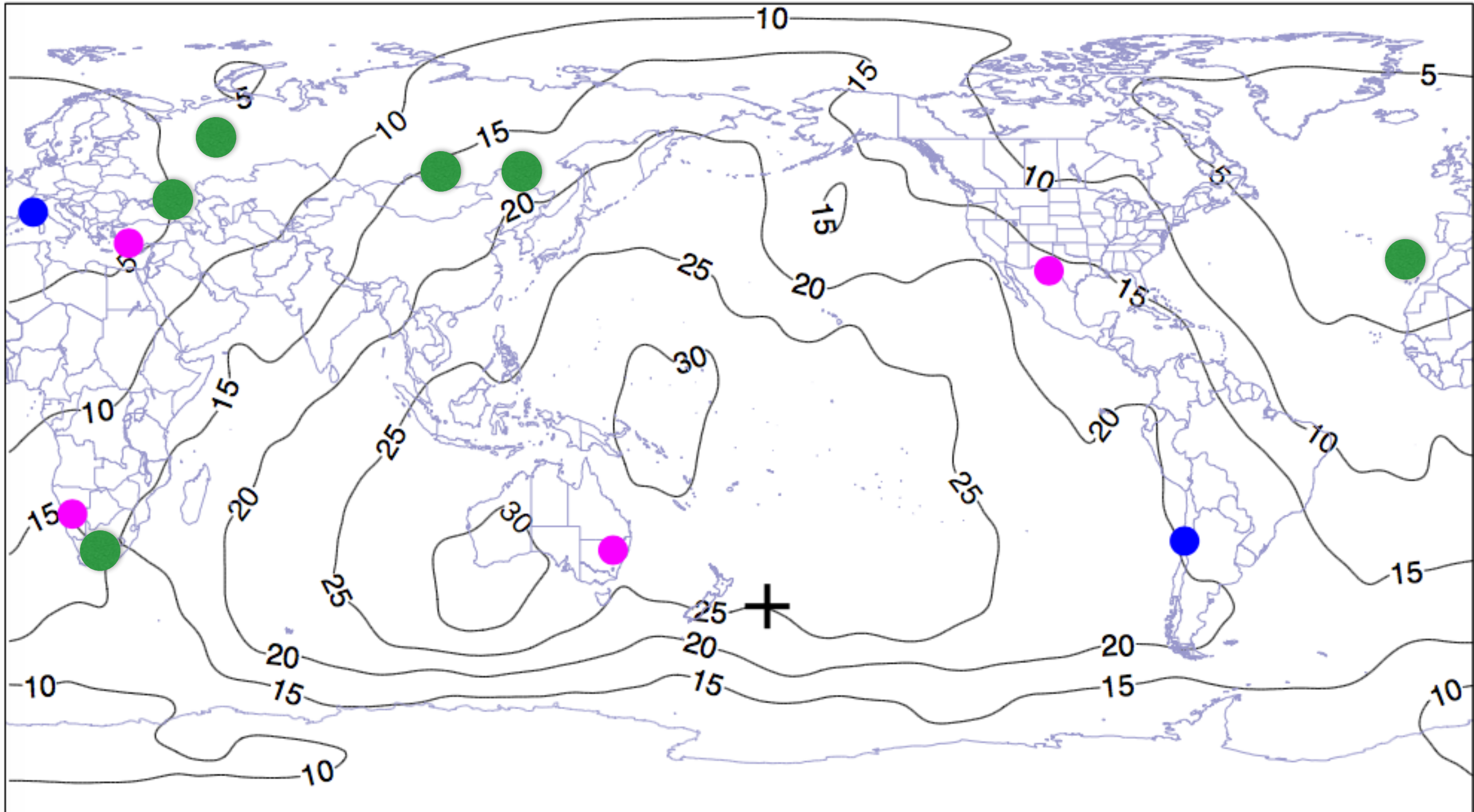
[2 triggers based on single neutrino (HE,+dir)]

Telescopes:

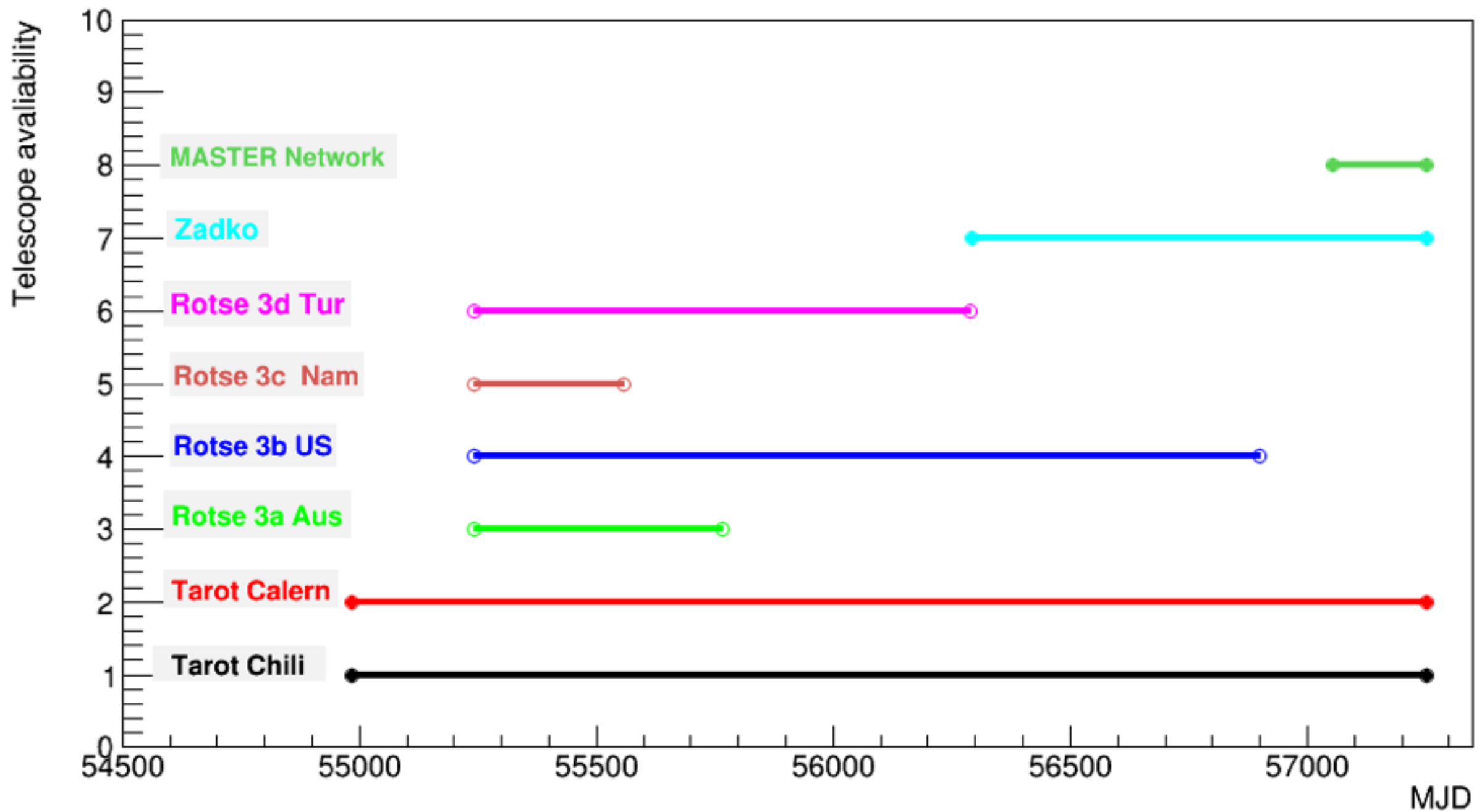


Telescopes:

Efficiency of prompt observations vs location on the Earth



Telescopes:



Main results: Model-independent searches in images

Early observations (<20h)

Visible:

42 alerts analyzed 01/2010-01/2015

=> 10 alerts with delay < 1min (best: 17s)

=> no transient candidate associated to neutrinos

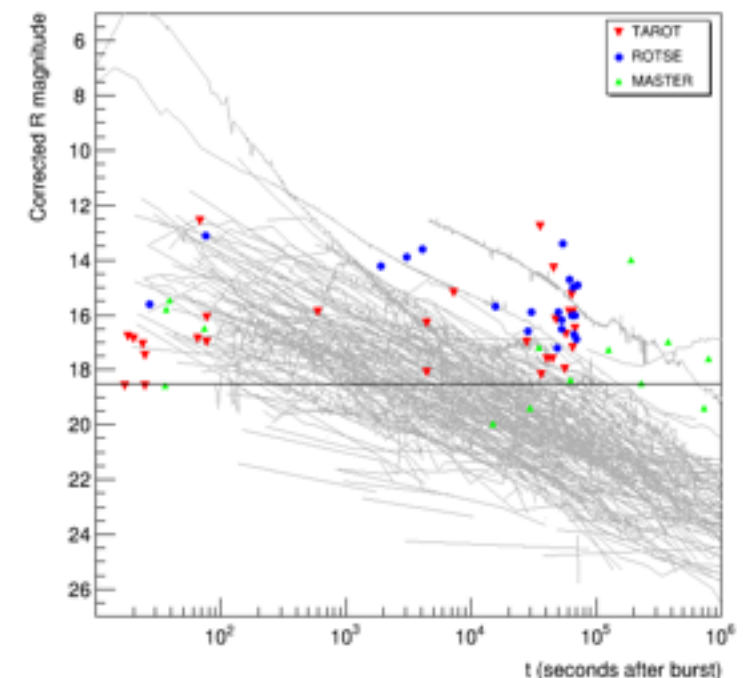
X-ray:

10 alerts analyzed 06/2013-09/2015

=> average delay ~5-6 hours

=> no transient candidate associated to neutrinos

=> constrains on origin of individual neutrinos



Mid-term observations (T+1 -> T+60 days)

80 alerts analyzed 01/2010-01/2015 (+20 ongoing)

=> no transient candidate associated to neutrinos

=> constrains on Ando&Beacon ccSN model

ANT150109A:

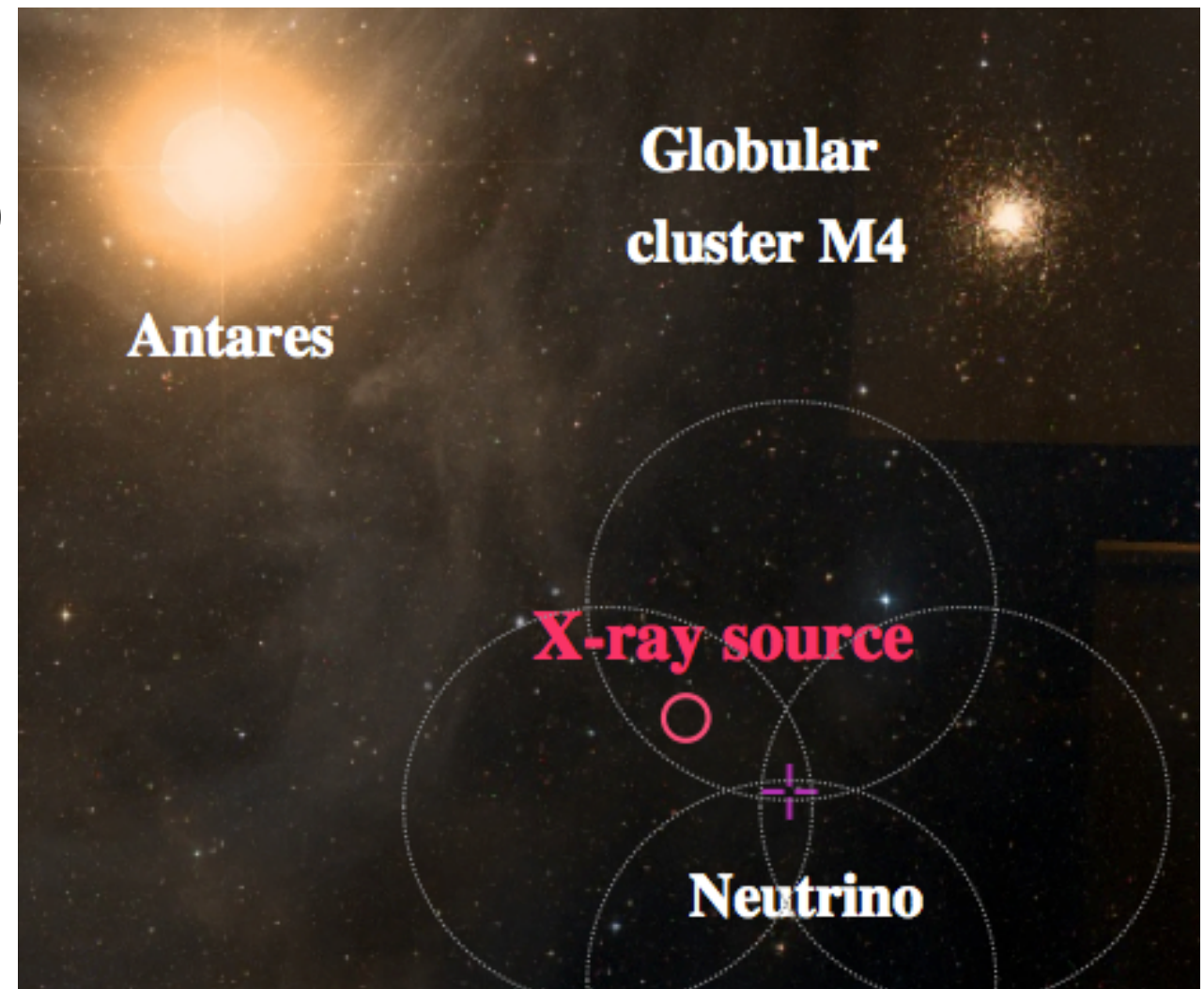
Alert "very HE" sent automatically in <10 s to TAROT, ZADKO, MASTER and Swift/XRT

Time: 2015/09/01 07h38m25s UT

RA (J2000): 16h 25m 42s (246.3064d)

DEC (J2000): -27d 23m 24s (-27.4684d)

Uncertainty of 18 arcmin (radius, 50% containment)



Neutrino:

run/ev: 81802/377262

$\Lambda = -4.29$

$T_{\chi^2} = 1.2$

$\cos\theta = 0.85$ (31.8d)

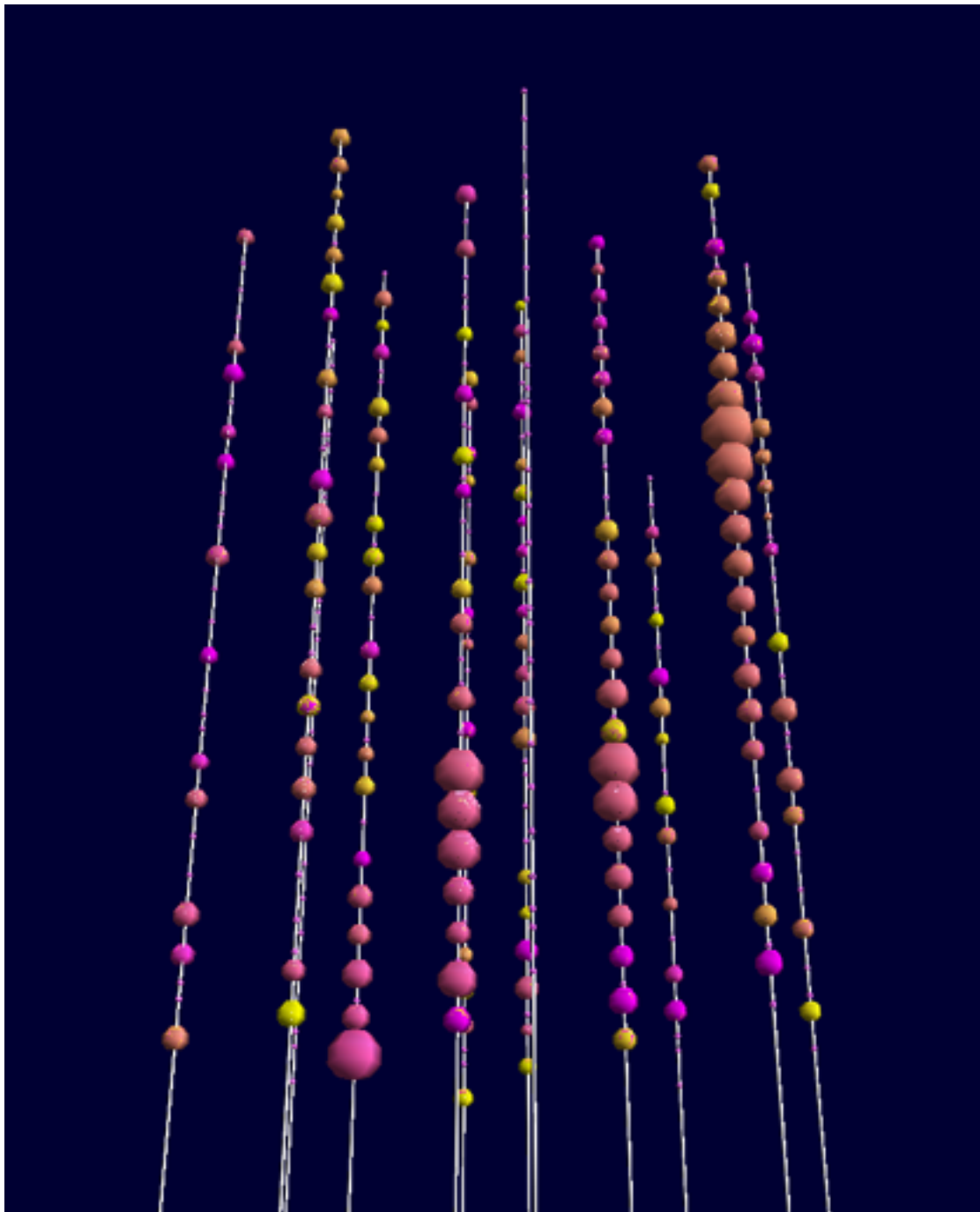
Diff BB-AA = 0.14deg

$N_{\text{hit}} = 127$

Amp = 356

$N_{\text{line}} = 8$

No other muon event in
5deg around the source



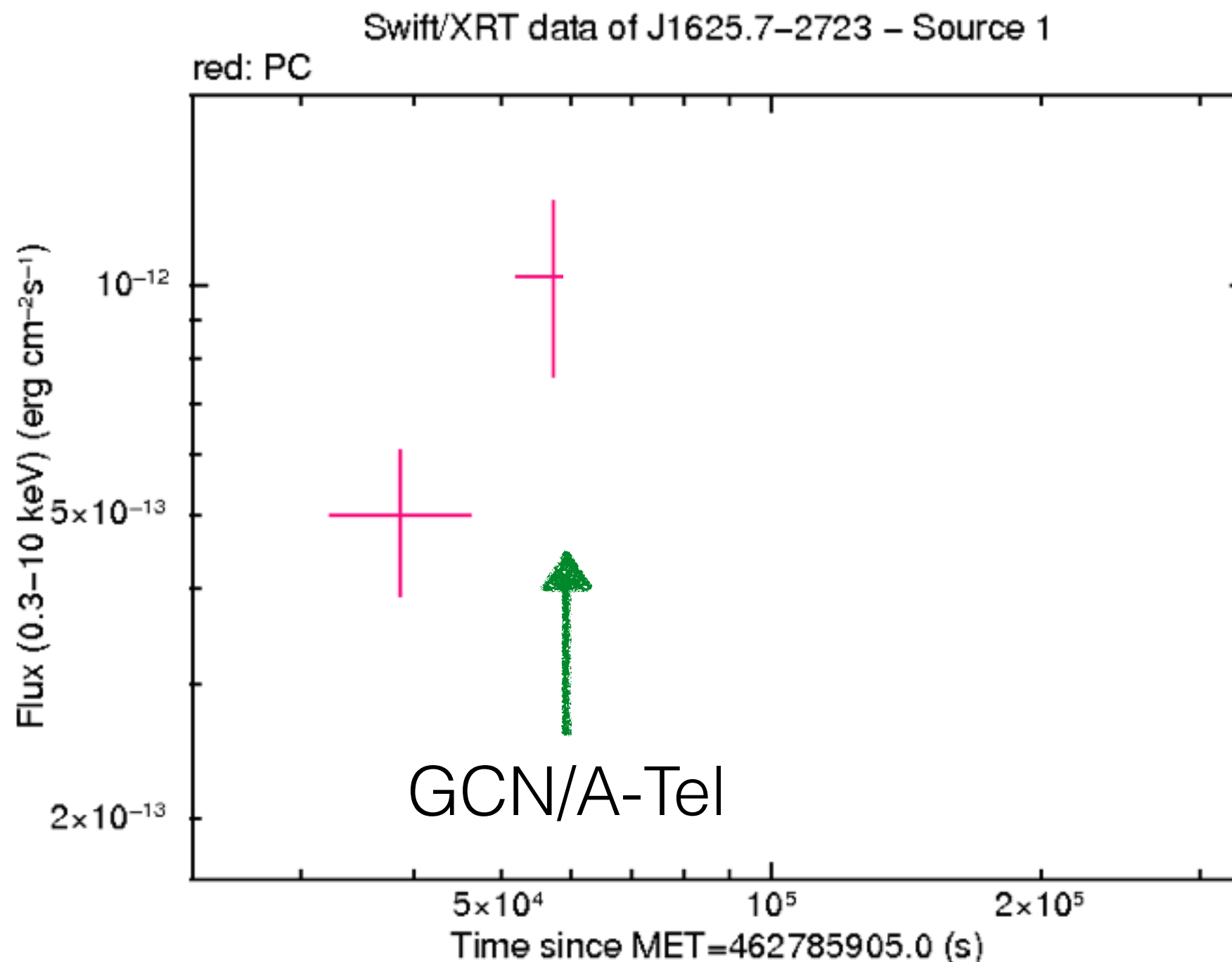
With MC Nu events: $\langle E \rangle > 60$ TeV

Follow-up with Swift/XRT:

8 sources in the field,
5 catalogued/ 3 new
(2 not passing cuts)

#	RA (J2000)	Dec (J2000)	Err ₉₀ ¹	Detection Flag ²	Exposure	Notes	Vizier
	16h 26m 02.12s	-27° 18' 14.8"	2.4'' *	Good	6.8'	2.7 ks	The source is brighter than the RASS limit.

[1](#)
[Hide details]



Follow-up with MASTER:

MASTER telescopes are our main optical follow-up facility.
(very large field of view 4dx2d)

First observation with SAAO at **T+35100s**

=> found a lot of transient sources because presence of M4

Continuous follow-up since the first day with 2 telescopes in south Africa and Canarias (filter R and now filter B and V)



=> No variation of the flux (<3%)

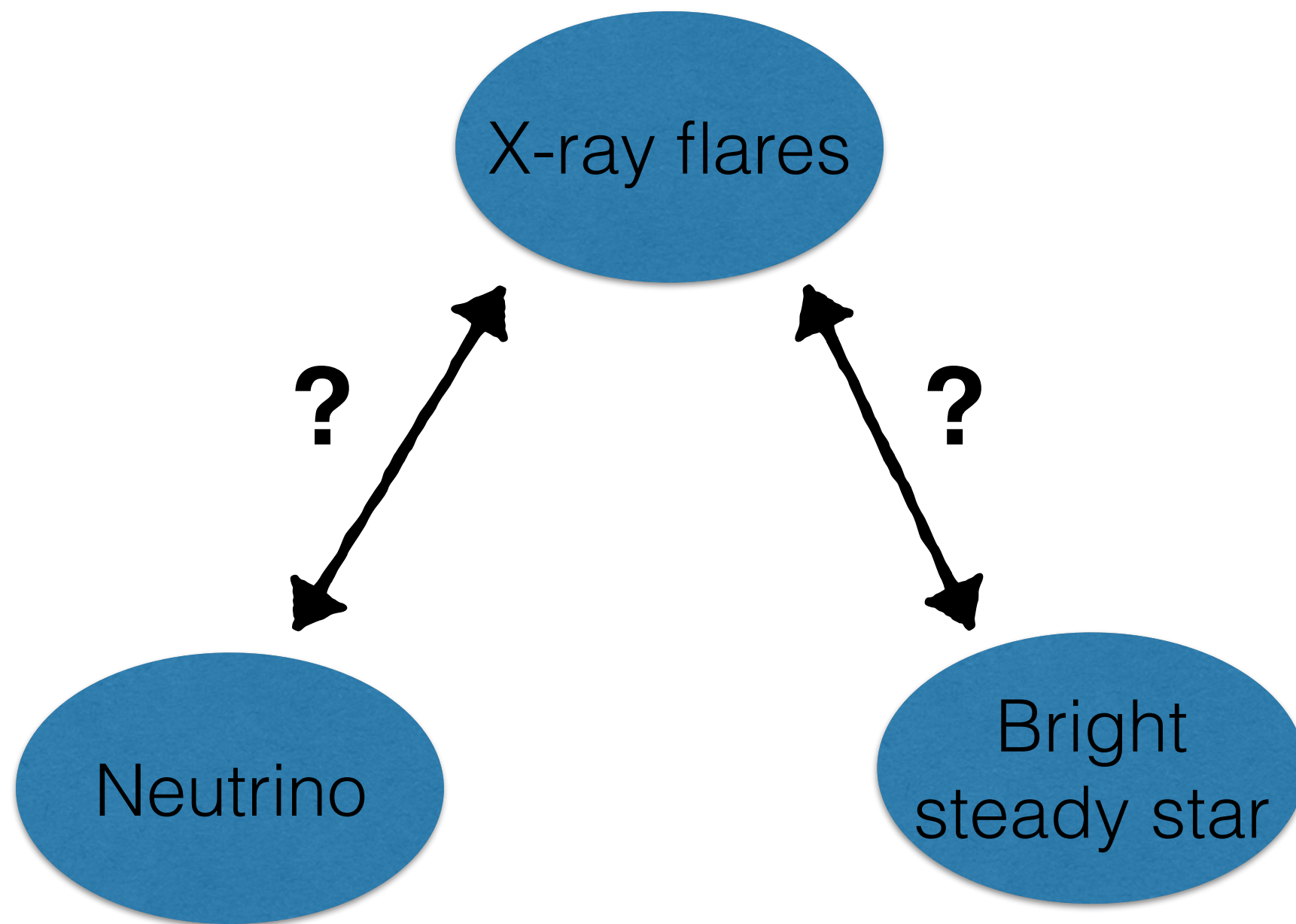
Antares star (Alpha Scorpii)

Closest to Earth Globular cluster M4 (NGC 6121)
with binary millisecond-pulsar PSR 1620-26
(Dornic et al. Atel#8000)

USNO-B1.0 0626-0501169
← and Swift XRT position

MASTER-SAAO ANTARES
neutrino alert 150901.
(Dornic et al Atel#7987) observations. 2x2 deg.

Main questions:

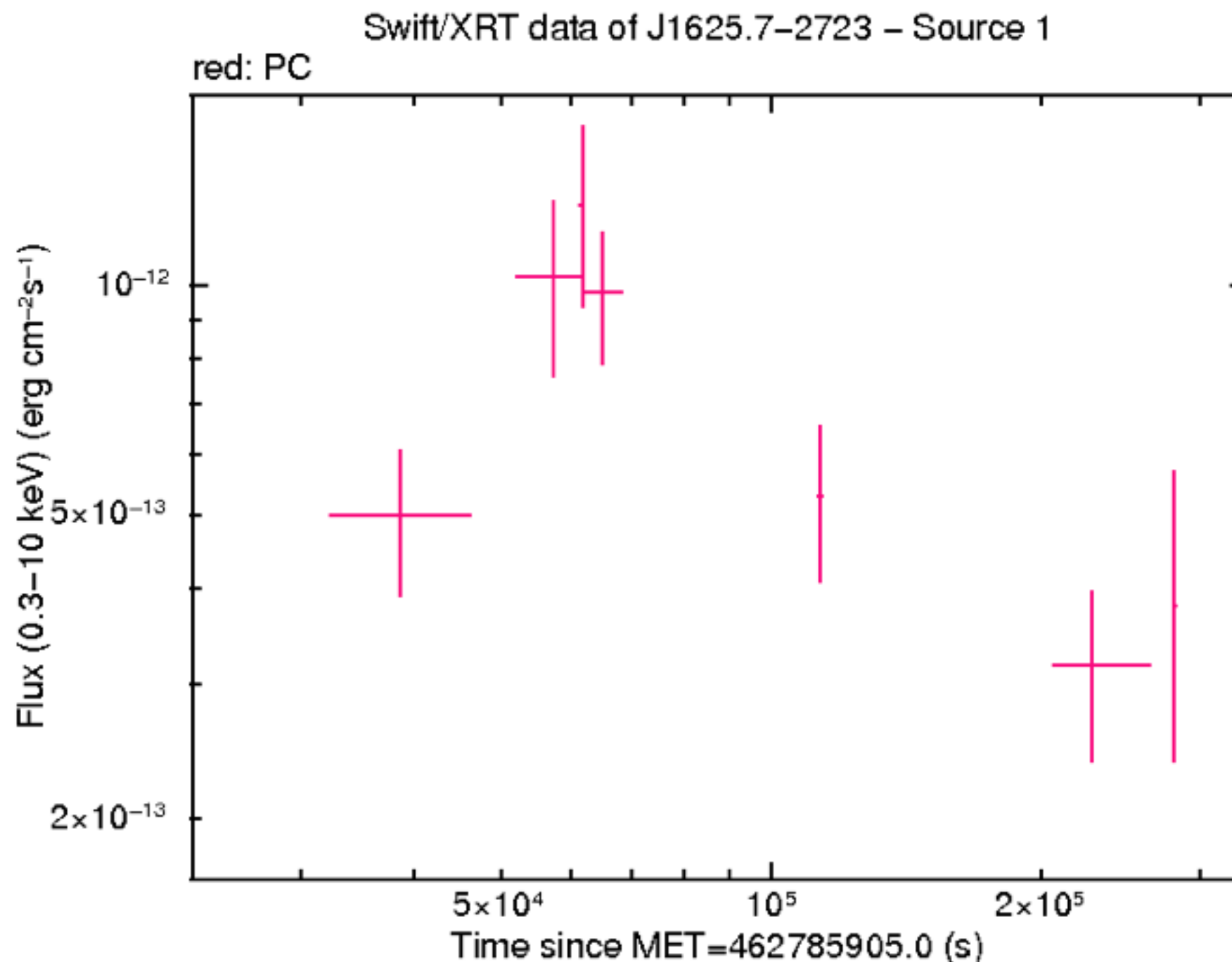


=> Request more multi-wavelength observations

Follow-up with Swift/XRT:

#	RA (J2000)	Dec (J2000)	Err ₉₀ ¹	Detection Flag ²	Exposure	Notes	Vizier
1	16h 26m 02.12s	-27° 18' 14.8"	2.4'' *	Good	6.8'	2.7 ks	The source is brighter than the RASS limit.

[1](#)
[Hide details]



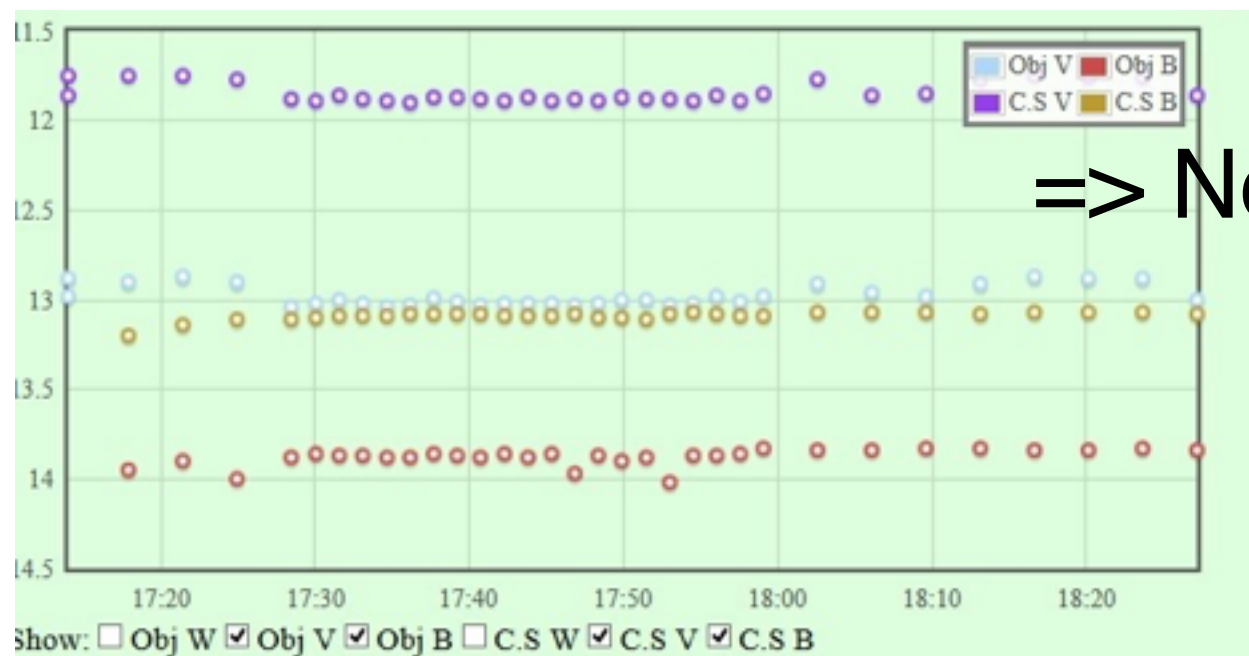
MASTER follow-up: (atel #8000)

MASTER-SAAO from 2015-09-01 17:23:48 unfiltered (w=0.2B+0.8R USNOB1 calibrated)
up to 2015-09-01 20:25:18 18.5-19.8 (180s), 20.6 (540s)

MASTER-SAAO from 2015-09-03 17:13:59 m_B_lim=19.1(180s), 19.6(540s)
up to 2015-09-03 21:21:59 m_V_lim=19.3(180s), 19.9sum(540s)
m_R_lim=18.4-19.0(60-180s), 19.7-20.3(540s-1800s)
m_I_lim=17.5-18.0(180s), 18.5(540s)

MASTER-IAC from 2015-09-01 21:02:44 unfiltered m_lim=18.7-19.2(180s), 19.8(540s)
up to 2015-09-01 21:17:34

MASTER-IAC from 2015-09-03 20:08:40 m_B_lim=19.8(180s)
up to 2015-09-03 22:09:12 m_V_lim=18.6(180s)



=> No color variation

Multi-wavelength observations

=> Necessary to characterize the star and test the association between X-ray flare and the bright star

16 Atels telegrams + 6 GCN notices:

- * MASTER, Pan-STARRS, SALT, NOT, WiFeS, Kepler 2, CAHA, LSGT, Nishi-Harina NIR, VLT/Xshooter, IRIS...
- * MAXI, Integral, GBM
- * Jansky VLA
- * IceCube

Not reported LAT, HESS, HAWC

Contacts with RATIR, GROND, Chandra...

Association star/X-ray flare

Multi-wavelength observations => characterisation of the star

NOT: 2.5m La Palma + FIES spectro: 3x400s + NOT IR cam: 4x120s

[Atel 7994](#)

=> Young accreting G-K star undergoing a flaring episode

SALT: [Atel 7993](#)

=> Rapidly rotating late K-early M type star

=> Chromospheric activity + marginal evidence of periodicity 6.5-8.9h

WiFeS: ANU 2.3m Australia [Atel 7996](#)

=> Spectrum shows late-type (K5-K7) dwarf star

=> Periodicity of ~1.5 days -> may be binary activity

CAHA: 2.2m (+BUSCA) & 3.5m (+TWIN) Spain [Atel 7998](#)

=> non detection of HeI and H-lines rules out classical T Tauri star

Association star/X-ray flare

Multi-wavelength observations => characterisation of the star

Jansky VLA: radio 1-2 GHz (T+2.6 days), FOV=30arcmin

Atel 7999

=> No variability down to 200 microJy + No new source

=> Assuming distance of 140 pc, X-ray luminosity= $2 \cdot 10^{30}$ erg/s and
radio luminosity = $3 \cdot 10^{15}$ erg/s/Hz

=> Consistent with RS CVn binary system or a rapidly rotating young
stellar object

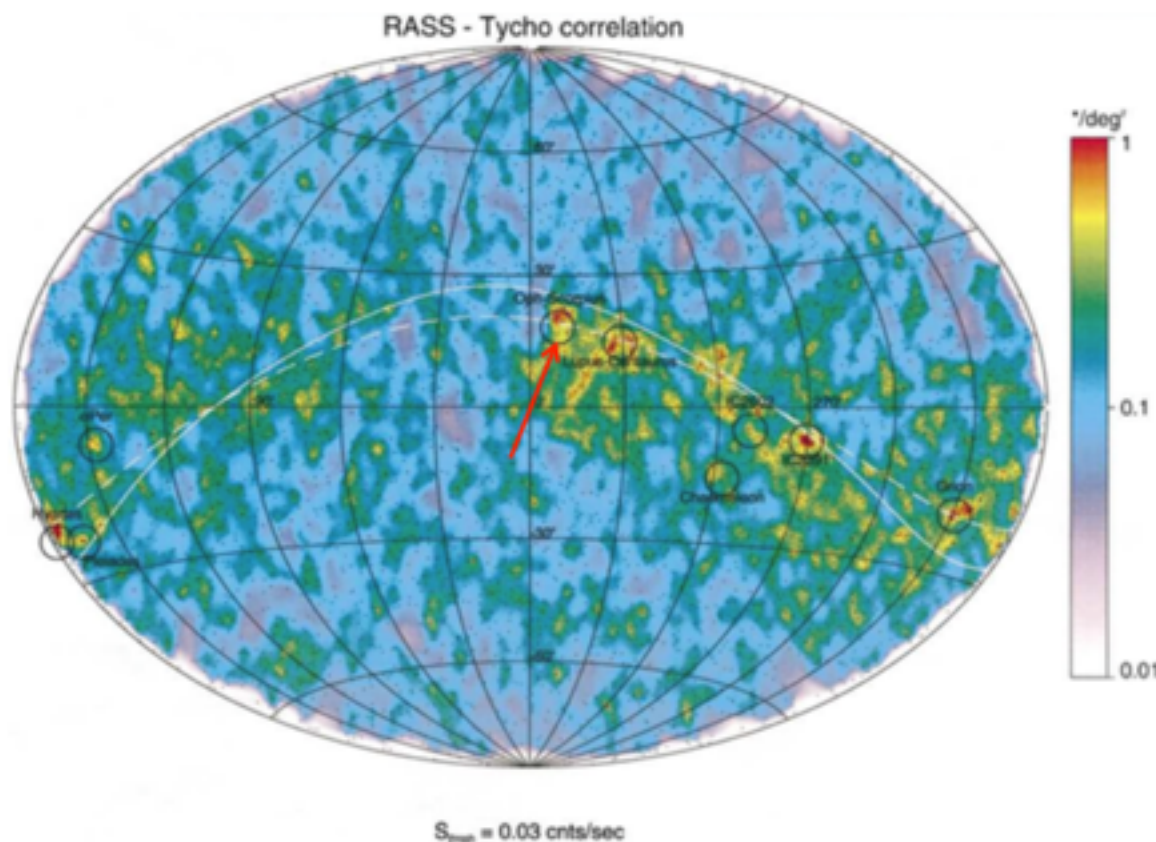
=> Bright star associated to the X-ray flare (100-150pc).

Age: ~10 Myr - Mass: ~0.75 M_{sun}

**=> Therefore, very low probability of being associated to
the neutrino**

Association star/X-ray flare

Computation of the chance association probability



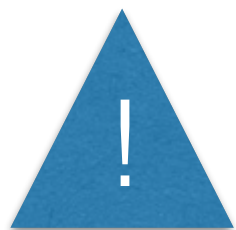
ROSAT catalogue
($<300\text{pc}$ & star $10^3 L_{x,o}$)

Rho Ophiuchi SFR

=> enhanced X-ray
star density

=> 0.5-0.75 star per
square degree.

=> few flares per yr



To be refined: pbm ROSAT catalogue not really
adapted. (Try stellar formation code of Besancon)

Case of the globular cluster M4

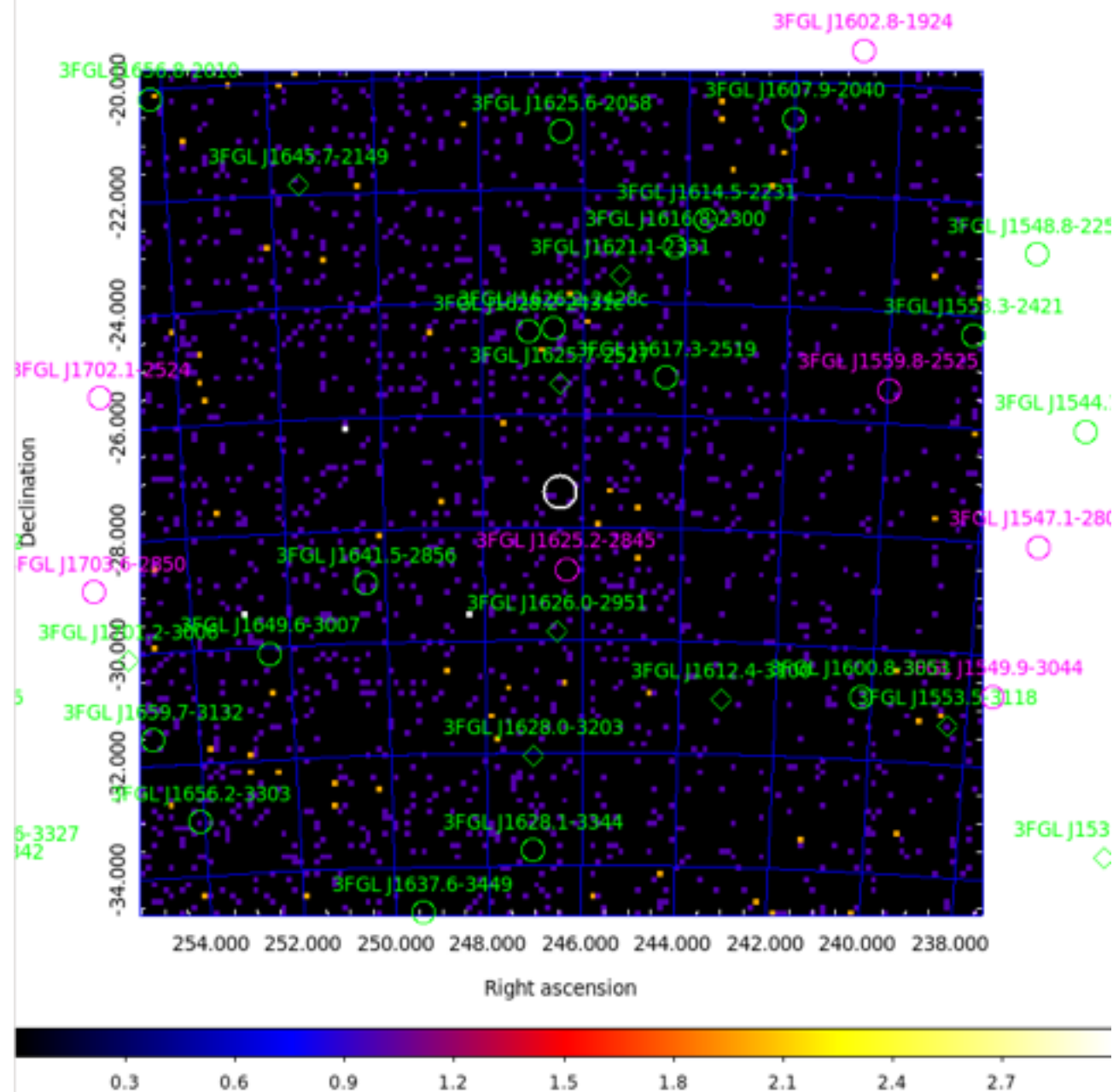
M4: closest globular cluster from Earth (2.2kpc) at around 0.8 degree from the neutrino location (still inside the 90% error box)



Contains millisecond pulsars and massive black hole.
=> interesting objects with known relativistic acceleration

Fermi/LAT

no catalogued source find in
the neutrino error box



(A. Brown)

HESS

ToO proposal (cat. A)
Night 03-04 September:
HESS II+3 HESS I (112 min)
elevation = 37.5-60.2deg
=> No source detected in
the fast analysis (only
HESS1)
=> For the refined results,
we have to wait few weeks

HAWC

HAWC: no transient

Summary

- Strong multi-messenger program
- TAToO program working stably since 2010 with capabilities to send alerts in <10 s and 0.3° error box
- Efficient collaborations with TAROT, ROTSE, ZADKO, MASTER, Swift
- **1st GCN/A-Tel notice send by ANTARES in real-time**
 - => Real-time follow-up is the key
 - => very positive answers of the astronomer community (>20 multi-wavelength observatories)
 - => Excellent test case to optimize future follow-up (neutrino, GW...).