Multi-messenger real-time analysis with the ANTARES neutrino telescope

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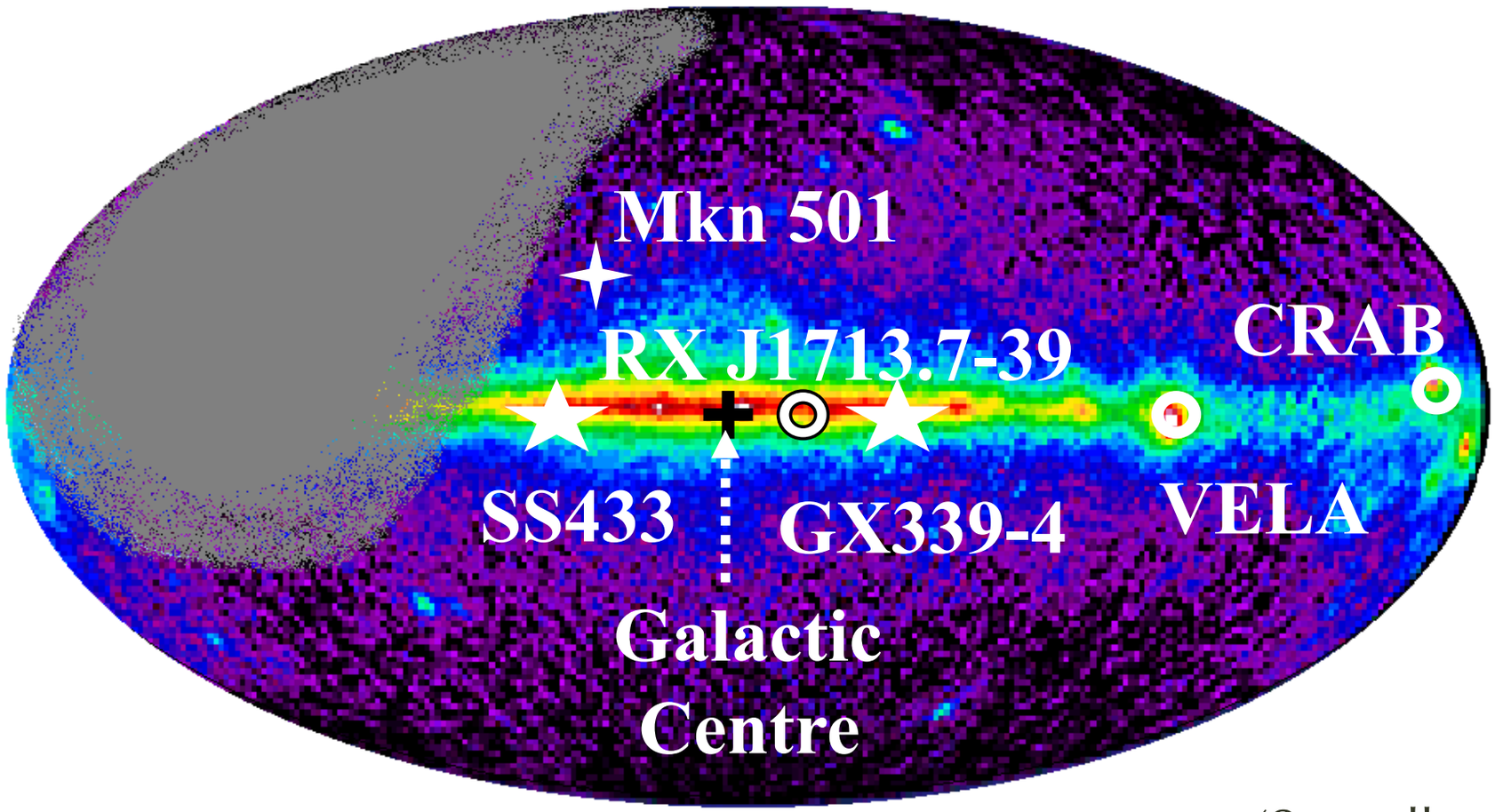
On behalf the ANTARES Collaboration

14th Rencontres du Vietnam - VHEPU - 2018

ANTARES

ANTARES in numbers:

- Stable data taking since 2008 with high duty cycle (93-96% efficiency)
- Large field of view (2π instantaneously)
- Quite good angular resolution: 0.3-0.4° (median)
- But it is also small: effective area: ≈1m² @ 30 TeV (o(12000) detected neutrinos)
- Real-time data processing

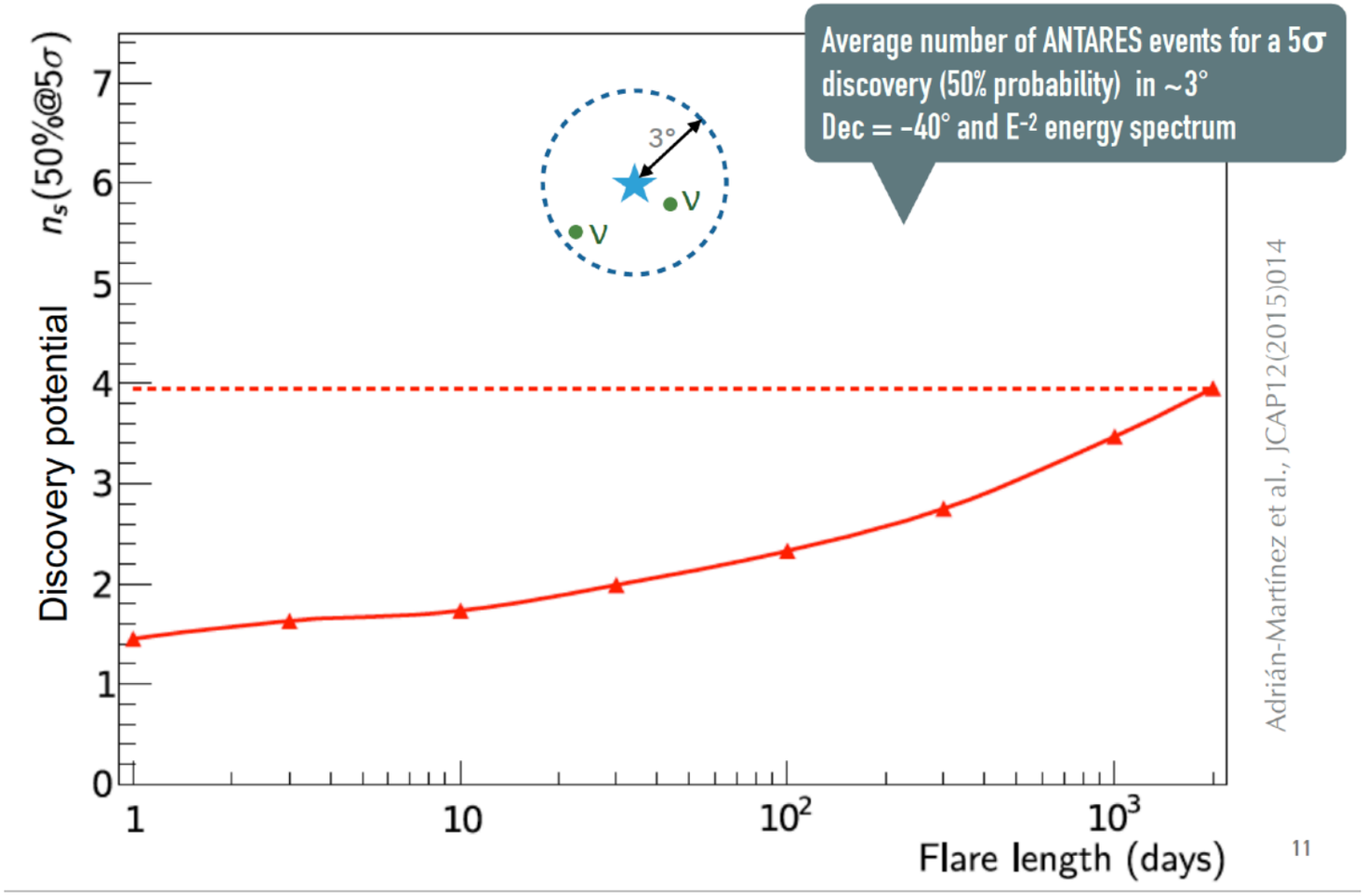


(See talk of S. Navas)

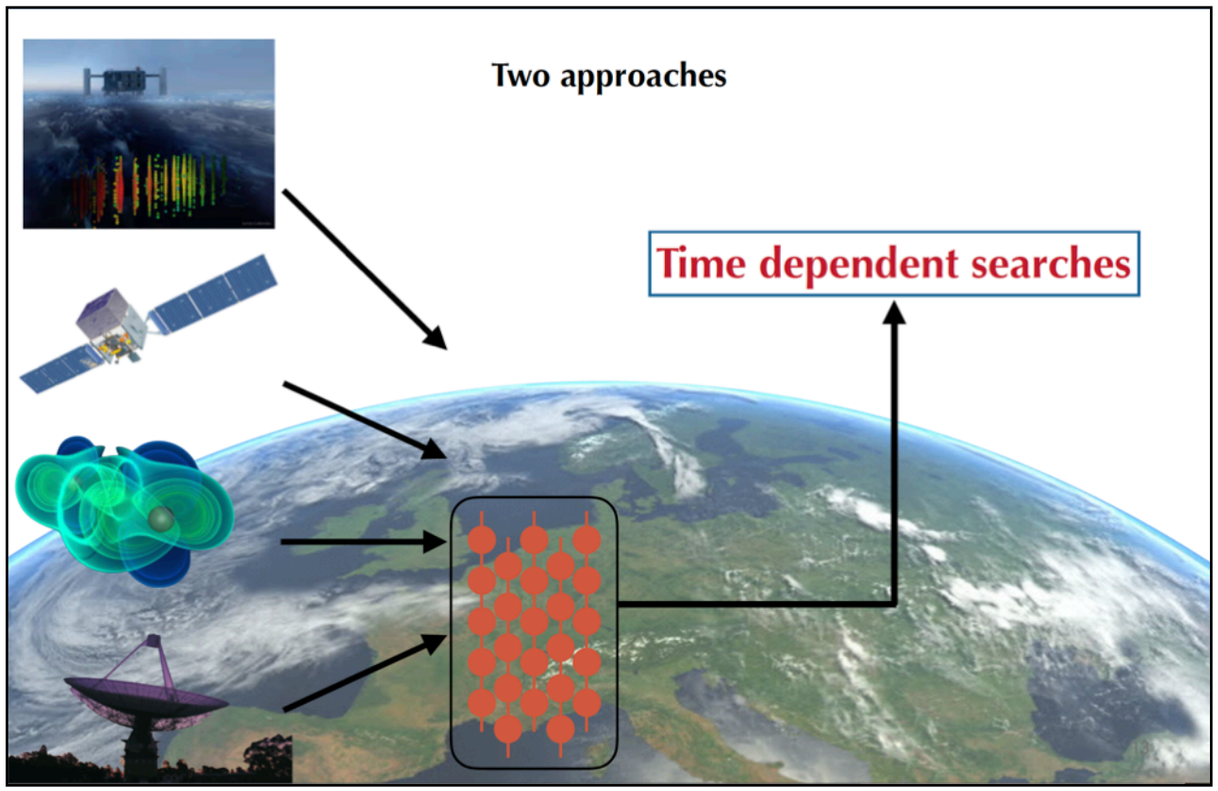
Multi-messenger programs

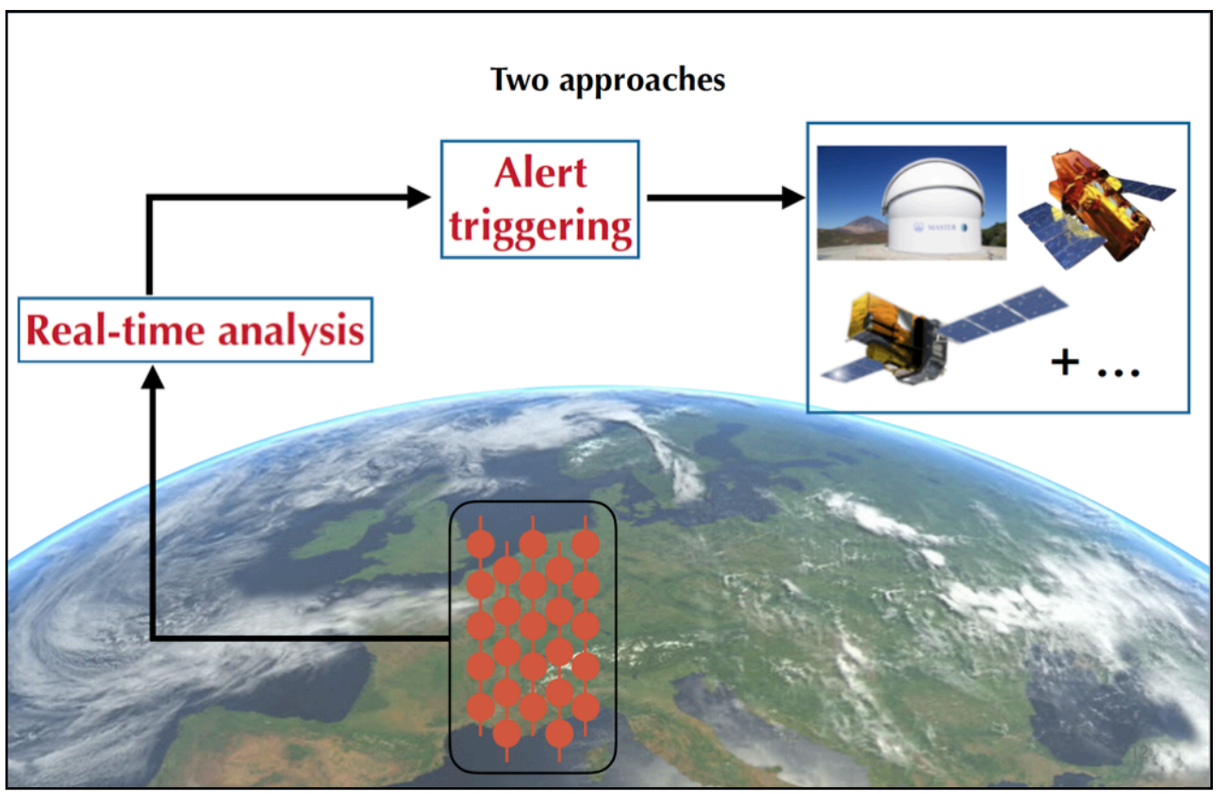
Neutrino telescopes suitable to look for transient sources:
⇒ continuously monitoring 2π sr (at least).

Multi-messenger studies of transient & variable sources:
- ➤ increase the sensitivity + discovery potential (reduce the background)
- ➤ increase the statistical significance (requiring joint detection)



Multi-messenger: 2 approaches



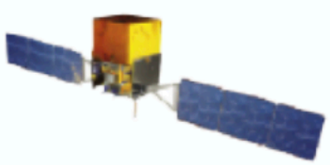


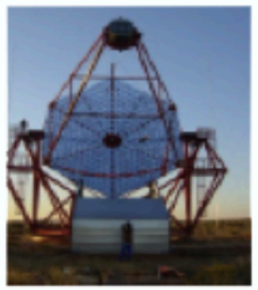
Looking in the neutrino data stream in real time or in offline for space/time correlation: IceCube neutrinos, LVC gravitational waves, PARKES/UTMOST/ASKAP fast radio bursts, Swift/Fermi gamma-ray bursts, Fermi/IACT blazars…

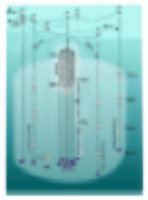
+

Reconstructing and selecting the most interesting neutrinos in real-time and send the direction to EM partners.

Multi-messenger programs





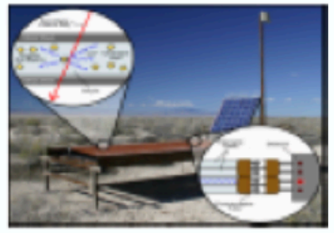


neutrinos
IceCube, GVD, SNEWS

GeV-TeV γ-rays
Fermi, HESS, HAWC, CTA

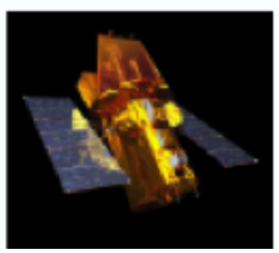
UHECR
Auger, TA

only spatial coincidence



ANTARES

Receive alerts
Generate alerts



Radio/Optic /X-ray
TAROT, MASTER, Swift, INTEGRAL, MWA

Gravitational Waves
VIRGO, LIGO

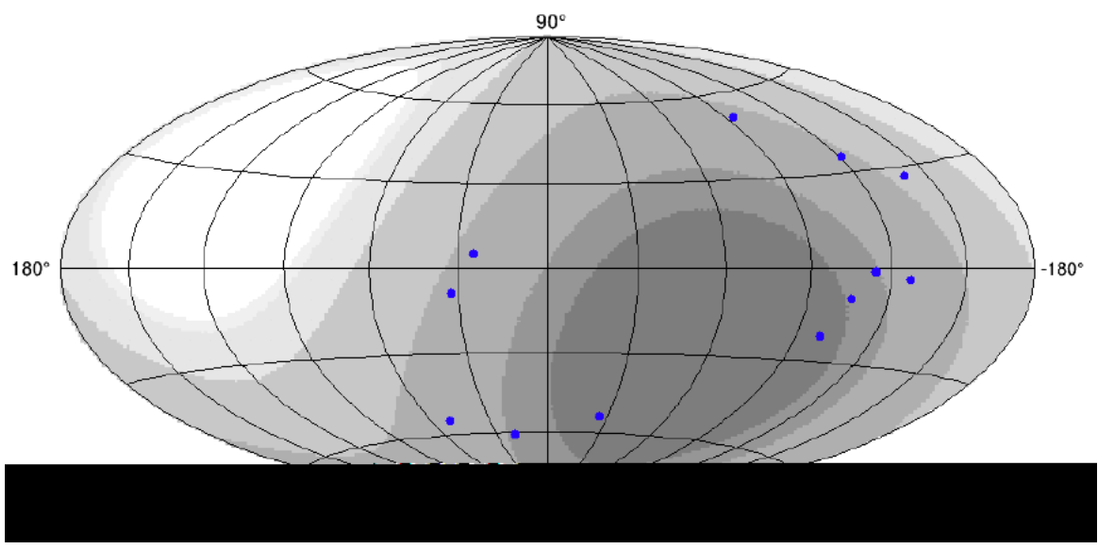
+ AMON
Astrophysical Multimessenger Observatory Network

(Cf Talk H. Ayala)

Search for Fast Radio Bursts

➤ Search for time/space correlations with fast radio bursts detected by Parkes, UTMOST and ASKAP between 2013 and 2017.

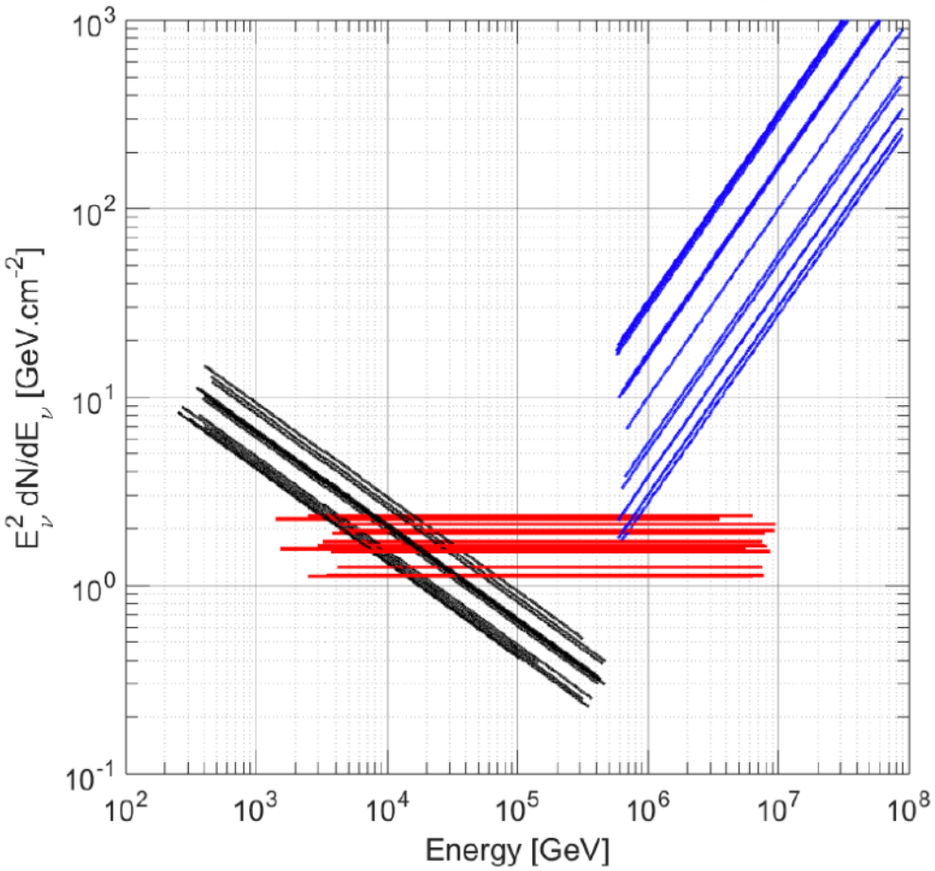
FRB	z_{DM}	T_0 (UTC)	RA (^{o})	dec (^{o})	radio telescope
131104	0.59	18:04:11.20	101.04	-51.28	Parkes
140514	0.44	17:14:11.06	338.52	-12.31	Parkes
150215	0.55	20:41:41.71	274.36	-4.90	Parkes
150418	0.49	04:29:06.66	109.15	-19.01	Parkes
150807	0.59	17:53:55.83	340.10	-55.27	Parkes
151206	1.385	06:17:52.78	290.36	-4.13	Parkes
151230	0.76	16:15:46.53	145.21	-3.45	Parkes
160102	2.13	08:28:39.37	339.71	-30.18	Parkes
160317	0.70	09:00:36.53	118.45	-29.61	UTMOST
160410	0.18	08:33:39.68	130.35	6.08	UTMOST
160608	0.37	03:53:01.09	114.17	-40.78	UTMOST
170107	0.48	20:05:45.14	170.79	-5.02	ASKAP



Since 2017, analysis in real-time for SUPERB FRBs.

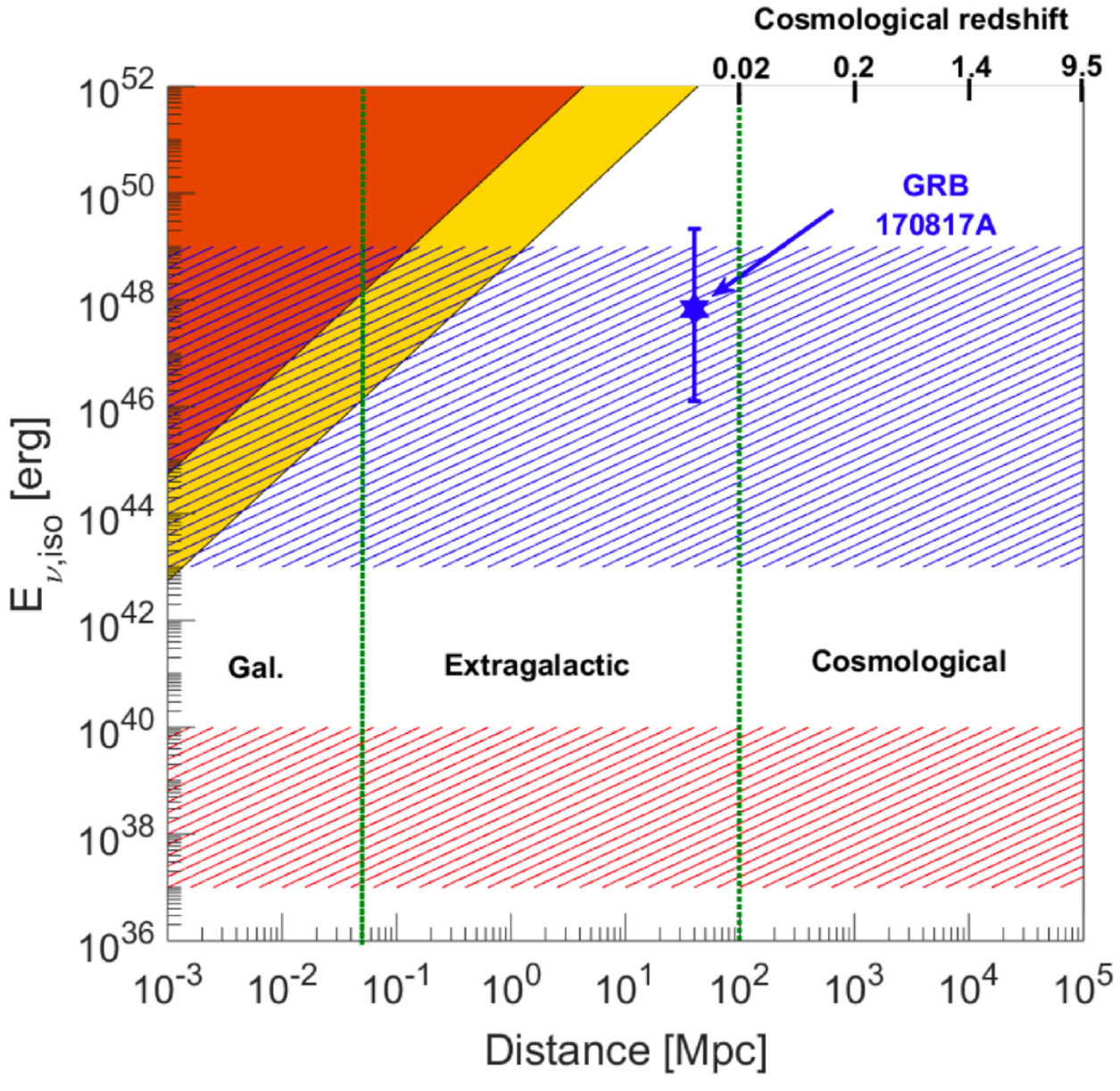
➤ No significant correlation
➤ Limits on the neutrino fluence assuming different energy spectrum.

ANTARES U.L. on the neutrino fluence (at 90% C.L.)



Albert et al., arXiv:1807.04045

Search for Fast Radio Bursts



- Constraints on the TeV-PeV neutrino energy released by FRBs
- Comparison with short GRB and magnetar giant flares / soft gamma-ray repeaters models

$$E_{\nu,iso} = \frac{4\pi D(z)^2}{1+z} \cdot F_\nu$$

FRB: no distance measured [because no optical follow-up]. Only upper-limit with DM.

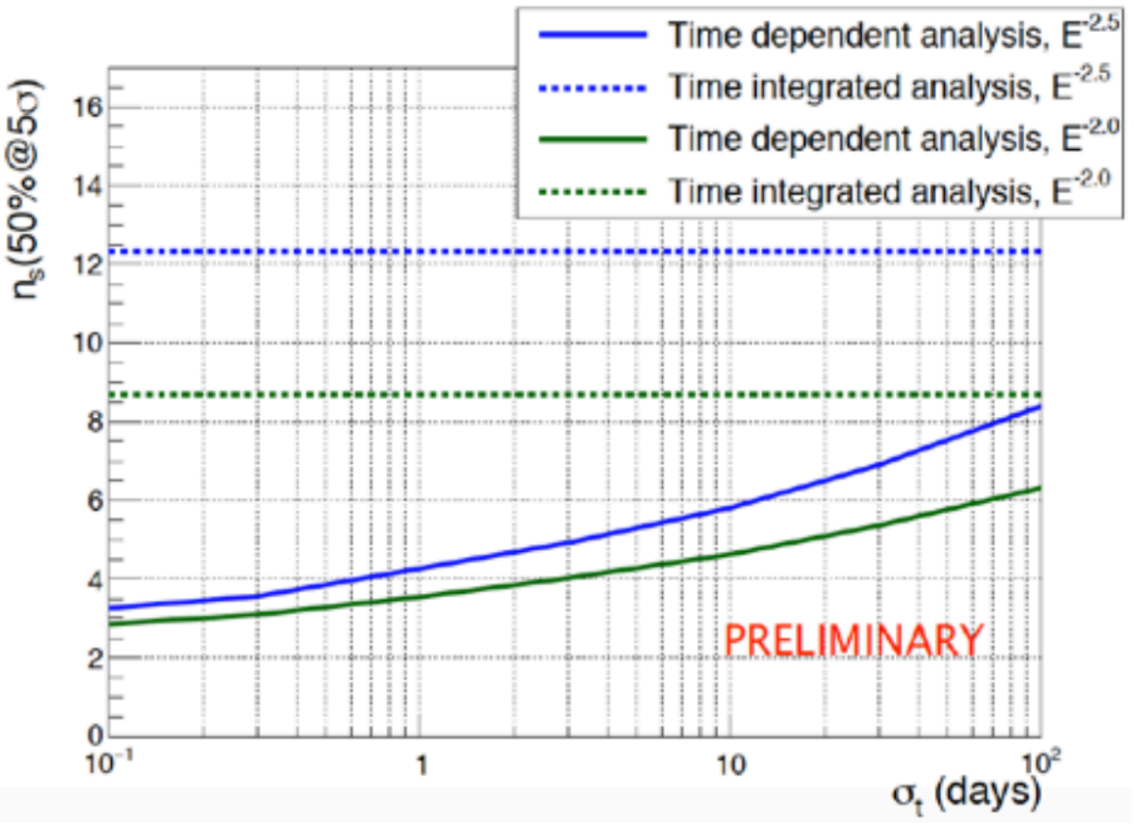
Using $R_{FRB} = 1.7\ 10^3$ /day ⇒ upper limits on the quasi diffuse flux (normalised to $E_0 = 100$ TeV), $E^2\Phi^{90\%} < 0.9, 2.0, 0.7\ 10^{-4}$ GeV cm^{-2} s^{-1} sr^{-1} for $E^{-1.0}$, $E^{-2.0}$ and $E^{-2.5}$

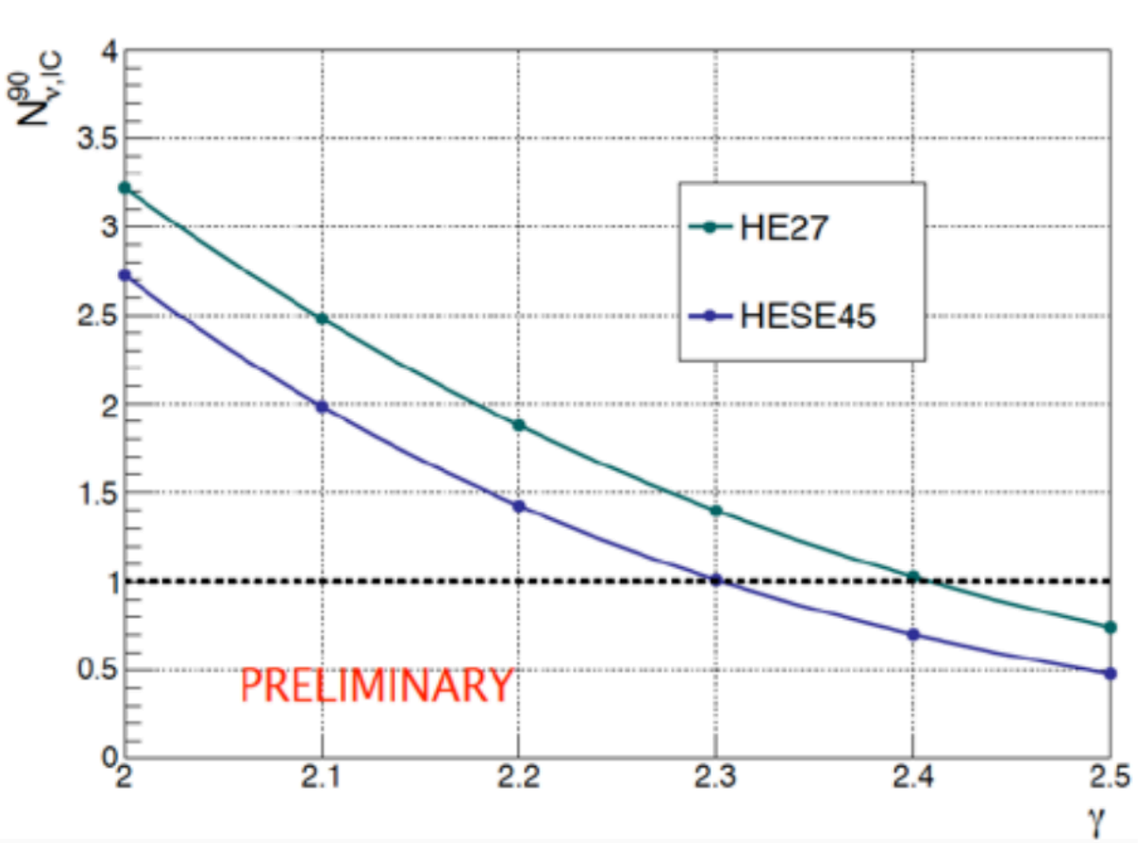
- **A polarized fast radio burst at low Galactic latitude** E. Petroff et al., MNRAS (2017) 469 (4): 4465-448
- **The SUrvey for Pulsars and Extragalactic Radio Bursts II: New FRB discoveries and their follow-up** S. Bhandari et al., MNRAS 475, 1427–1446 (2018)
- **Search for high-energy neutrinos from the fast radio bursts with ANTARES** A. Albert et al., submitted MNRAS.

Time correlations with IceCube events

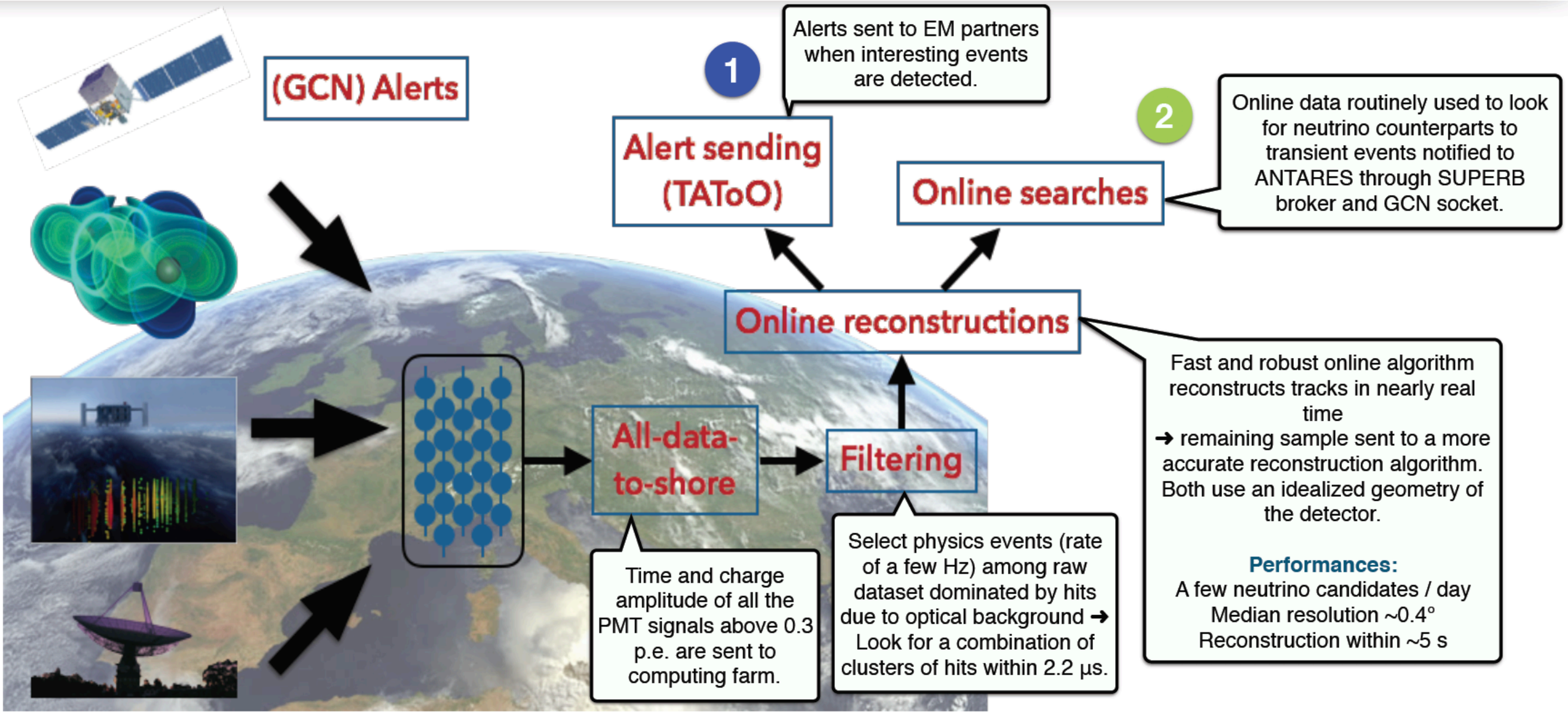
➤ Search for track+cascade time correlations [0.1; 120 days] with IceCube HESE (x 20) and high-energy ν_μ tracks (x 34) in the ANTARES field of view between 2010 and 2016.
⇒ Test transient origin of IceCube events

➤ No significant correlation (largest excess: 89% p-value post-trial)
➤ Limits on the fluence w.r.t. flare duration
➤ Constraint on the spectral index of the neutrino spectrum (assuming ~sec. transient emission)





ANTARES online system

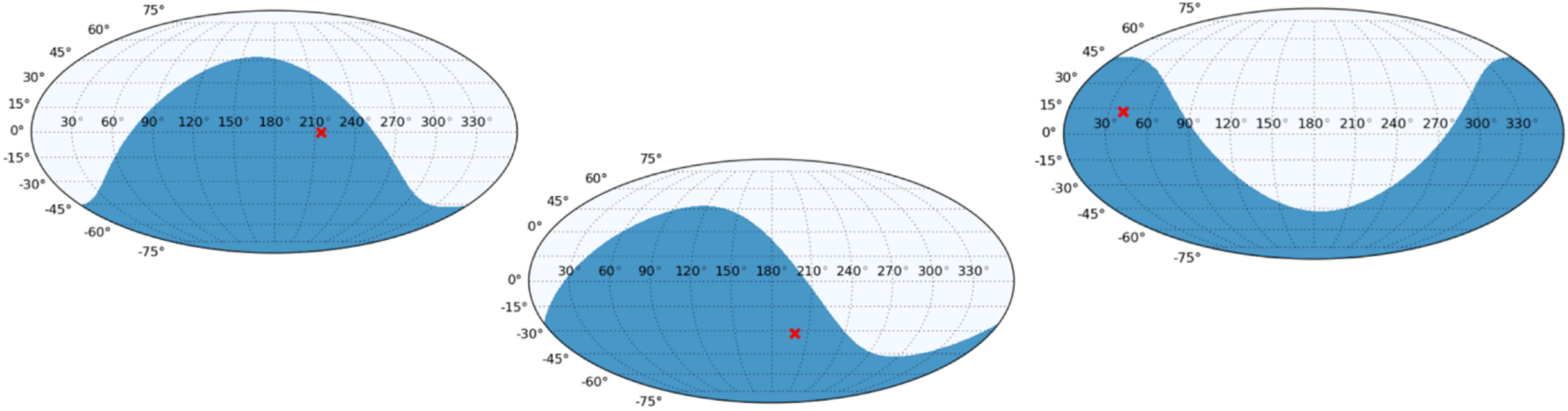


ANTARES is able to get the hits (all-data-to-shore), trigger (4 triggers) and reconstruct (2 independent algorithms) events in **~5s** !

Search for counterparts of IC neutrinos

➤ Search in real-time for neutrino counterparts of IC HESE and EHE (> 1PeV) alerts sent through AMON to the public community (GCN network)

⇒ 14 alerts sent so far: 6 analyzed, +4 retracted by IC, 4 not visible at T_0 as upgoing.



No ANTARES event found in coincidence (ROI=2°, ±500s; ±1h)
⇒ U.L. on the radiant neutrino fluence for E^{-2} and $E^{-2.5}$ spectra:

~15 GeV/cm² in [2.8 TeV, 3.3 PeV] for E^{-2}
~30 GeV/cm² in [0.4 TeV, 280 TeV] for $E^{-2.5}$

- IC171015: GCN #22019 / Atel #10584
- IC170922: GCN #21923 / Atel #10773
- IC170321: GCN #20926 / Atel #10189
- IC161103: GCN #20134 / Atel #9715
- IC160814: GCN #19885 / Atel #9440
- IC160731: / Atel #9324

Multi-λ observatories linked to ANTARES for the real-time analysis

SWIFT

INTEGRAL

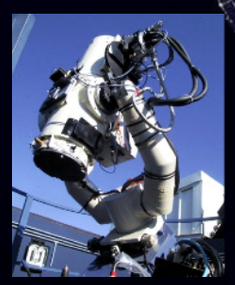
MASTER

HAWC

ANTARES

SVOM

GWAC



TAROT

HESS

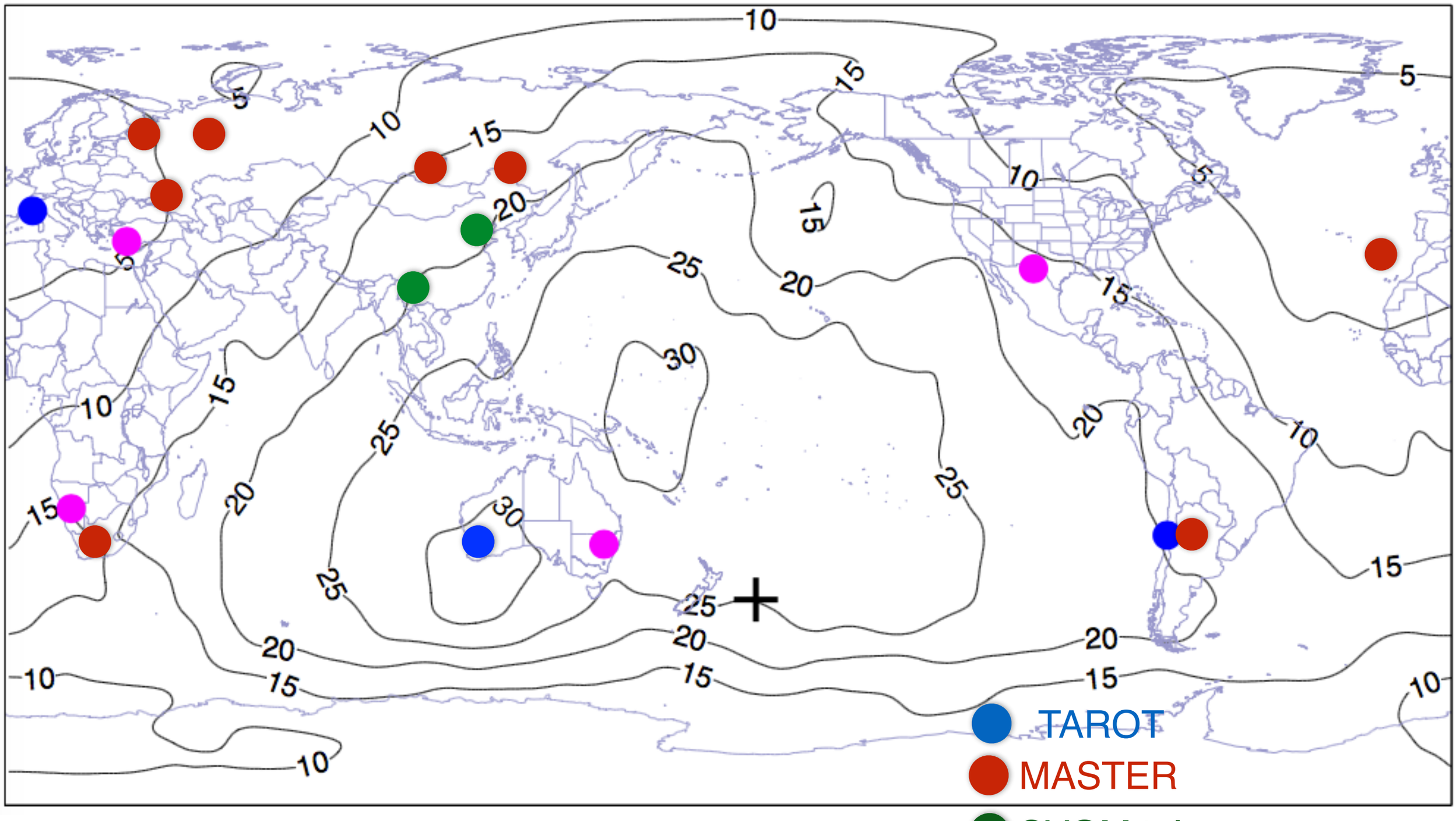
MWA

ZADKO

~~ROTSE~~

Multi-λ observatories

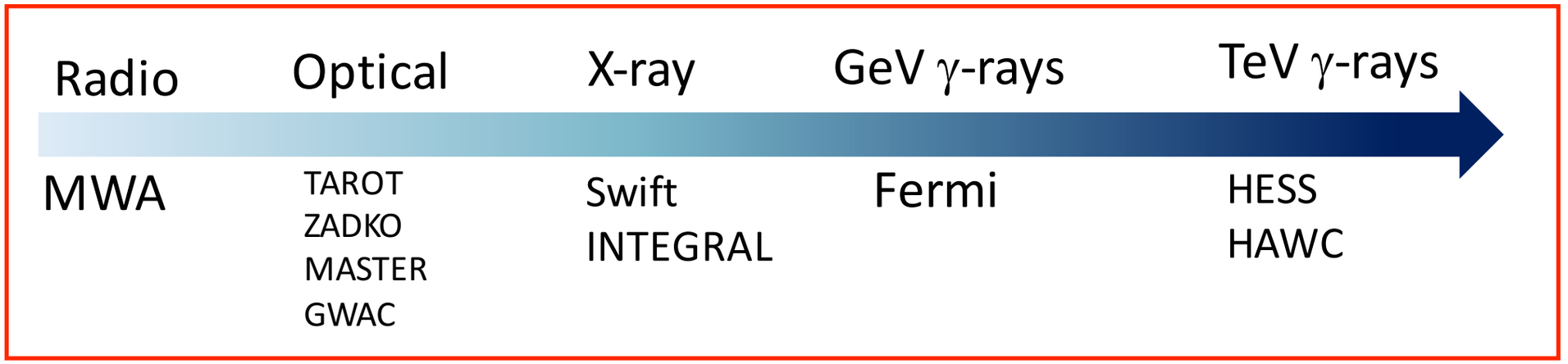
Efficiency of prompt observations vs location on the Earth



ANTARES neutrino alerts

➡ **ANTARES real time alerts:**

- Doublet of neutrinos: ~0.04 events/yr
- Single neutrino with direction close to local galaxies: ~1 TeV, ~10 events/ yr
- Single HE neutrinos: ~5 TeV, 20 ev/ yr
- Single VHE neutrinos: ~30 TeV, ~3-4 ev/yr



➡ **Statistics of the sent neutrino alerts (07/2009-07/2018)**

- 281 alerts sent to robotic telescopes [79 DIR + 202 HE]
- 15 sent to Swift
- 15 sent to Integral (4 followed)
- >20 to MWA (3 followed)
- 2 to HESS

TAToO Follow-up Summary

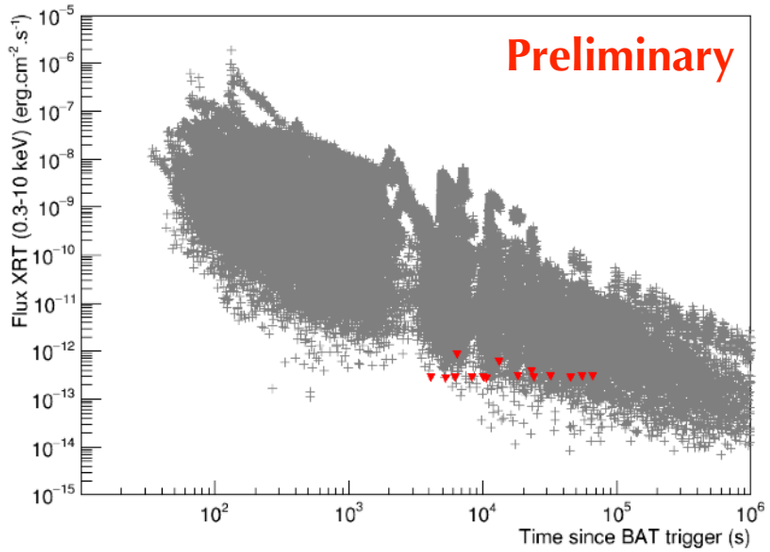
Early follow-up:

Visible: 189 alerts analyzed 01/2010-07/2018 from TAROT, ROTSE, MASTER => 27 alerts with delay <1min

X-ray: 16 alerts analyzed 06/2013-07/2018 => average delay ~5-6h

=> no transient candidate associated to neutrinos

Adrían-Martínez et al., JCAP 02(2016) 062

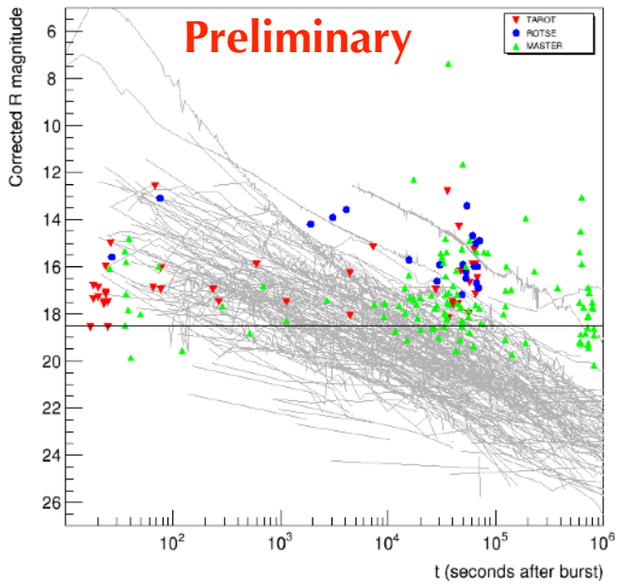


Long-term follow-up:

186 alerts with a "rather good" long-term follow-up (01/2010-07/2018)

- ➡ No SN (and no interesting transient) associated with the neutrinos
- ➡ $N_{exp}(SN) = 0.3\text{-}0.4$ for the full follow-up [SN rate=2.4 10^{-4} yr^{-1}Mpc^{-3}]

Adrían-Martínez et al., JCAP in preparation



Radio follow-up:

2 alerts followed over a year with M.W.A. (2013-14)

- ➡ No interesting transient associated with the neutrinos

Croft et al, Astrophys. J. 820 (2016) 24.

Other alerts followed in real-time with M.W.A. (2015-17)

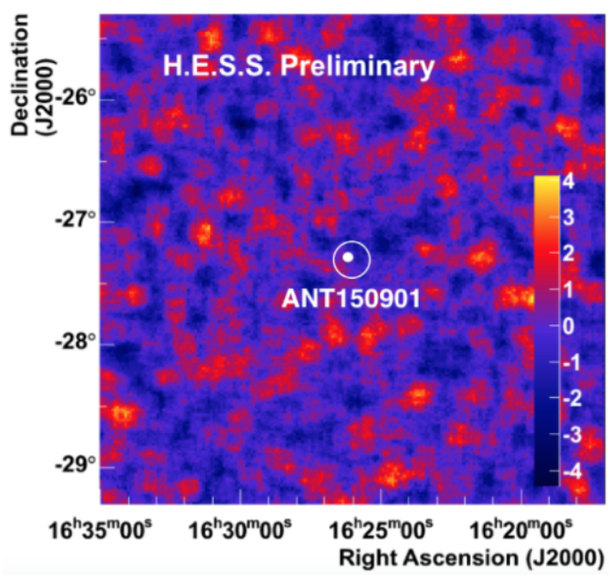
- ➡ Analysis on-going

H.E.S.S. follow-up:

2 alerts followed with very small delay (2015-2017)

- ➡ ANT150901(+2.5d), ANT170130 (+32s): No VHE candidates associated with the neutrinos

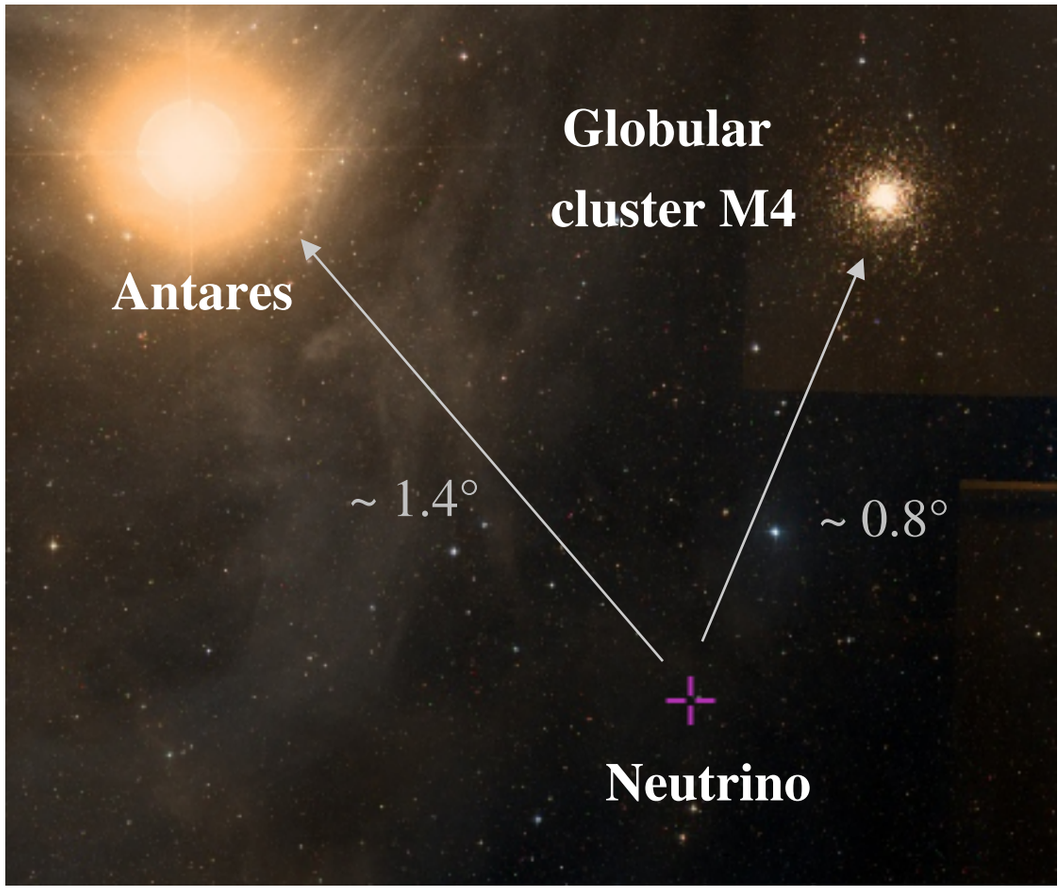
Schüssler et al., arXiv: 1705.08258



ANT150901A

<u>Alert VHE (Sept. 1, 2015)</u>
(Nhit, Amp) = (127, 356), E ~ 50 TeV
RA=246.306°; dec=-27.468°

Sent after 10 s to MASTER, Swift-XRT
➡ **Follow-up with Swift-XRT after 9h**
➡ **Follow-up with MASTER after 10h**



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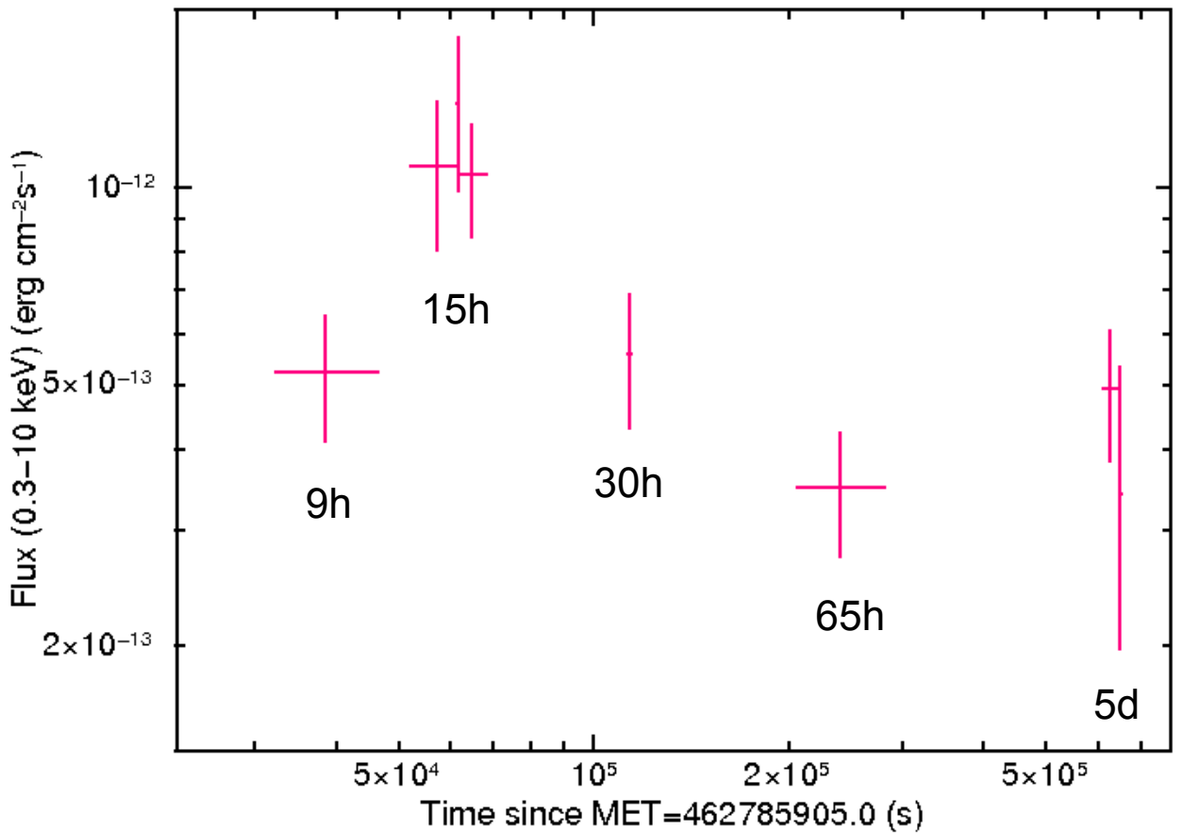
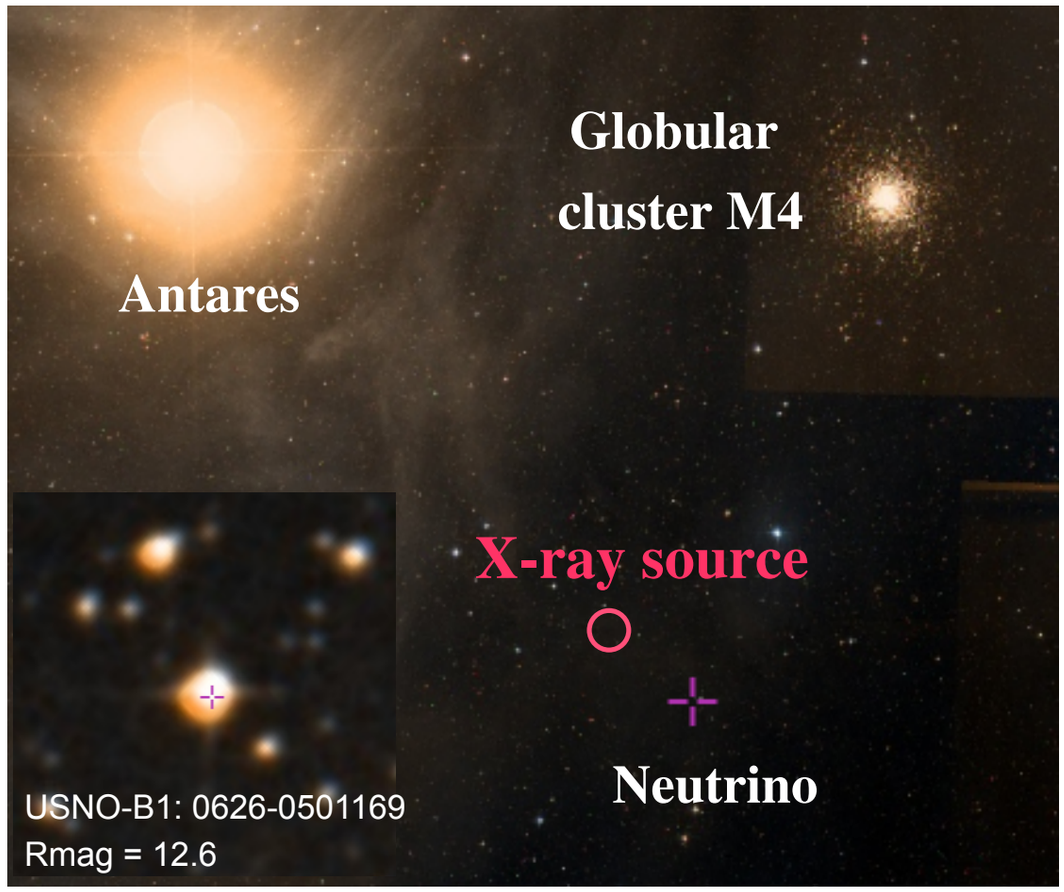




➡ Emission of a GCN notice (#18231) and an ATEL (#7987) after ~24h to require more follow-up to identify the X-ray flare

ANT150901A

Great interest from the community: 15 ATels + 6 GCNs + few non-reported

➡ Neutrino
IceCube: ATel 8097

➡ Optical
Pan-STARRS: ATel 7992, 8027
SALT: ATel 7993
NOT: ATel 7994, GCN 18236
WiFes: ATel 7996
CAHA: Atel 7998, GCN 18241
MASTER: ATel 8000, GCN18240
LSGT: ATel 8002
NIC: ATel 8006
ANU: GCN 18242
GCM: GCN 18239
VLT/X-Shooter: private

➡ X-ray
Integral: ATel 7995
MAXI: ATel 8003
Swift: ATel 8124, GCN 18231

➡ Radio
Jansky VLA: ATel 7999, 8034

➡ Gamma-ray
MAGIC: ATel 8203
Fermi/GBM: GCN 18352
HESS: private
HAWC: private

=> USNO-B1.0 0626-0501169: **young accreting G-K star,** or a **binary system of chromospheric active stars (RS CVn)** undergoing a **flaring episode** that produced the X-ray emission."

Albert et al., MNRAS in preparation

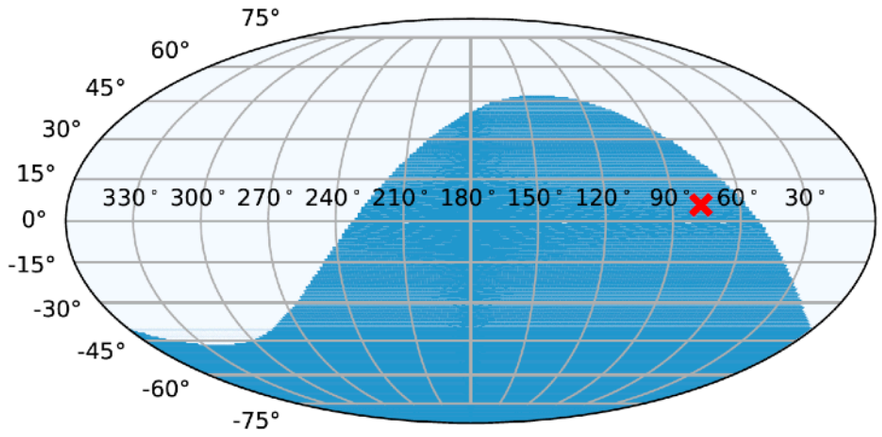
ANTARES: IC 170922 / TXS 0506+056

Online searches for ν's associated to IceCube-170922A EHE

- Direction in ANTARES: 14.2º below horizon
- Use of fast online algorithms that select only upgoing candidates

⟹ No upgoing ν candidate recorded within 3º of IceCube event and within ±1 h time-window centered on the event time. A search in ±1 d also yielded no detection (visibility 46%)

⟹ Fluence U.L. = 15 (34) GeV cm^{-2} for E^{-2} ($E^{-2.5}$) energy spectra



Atel #10773

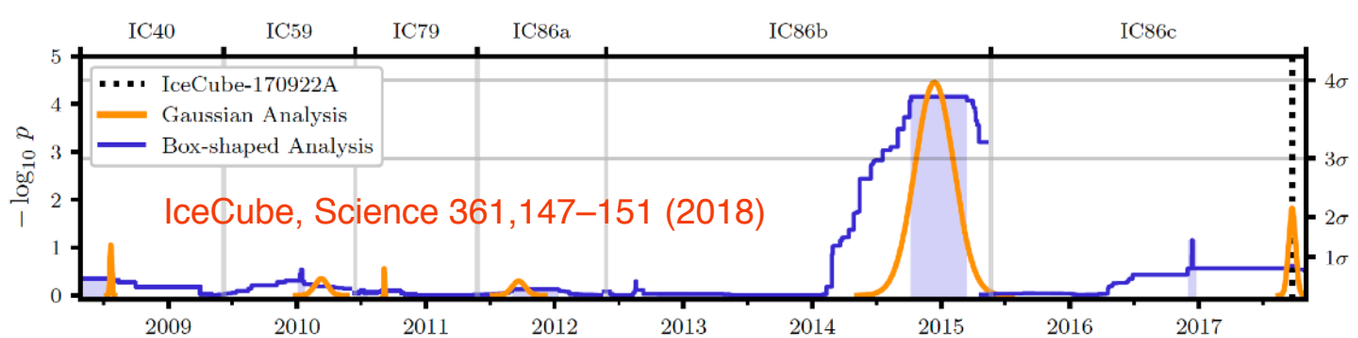
Offline time-integrated search (likelihood method used in Point Source 2007-2017)

In 3136 days: 13 tracks and 1 shower neutrinos detected within 5º (17±4 expected atmospheric bkg)
⇒ 1.03 fitted signal events

- Pre-trial p-value of 3.4% to be compatible with background only [87% post-trial]
- In the list of 107 pre-selected sources, only two have smaller p-value

Offline time-dependent search

- Two time window shapes: Gaussian (500 days) and rectangular (158 days) centered in MJD57004
- Relaxed Selection cuts which optimise the MRF with flux ~ $E^{-\gamma}$ (γ= 2.0, 2.1, 2.2)
- Expected bkg during the box expected 0.04 (4) events within 0.5º(5º) from the source



IceCube, Science 361,147–151 (2018)

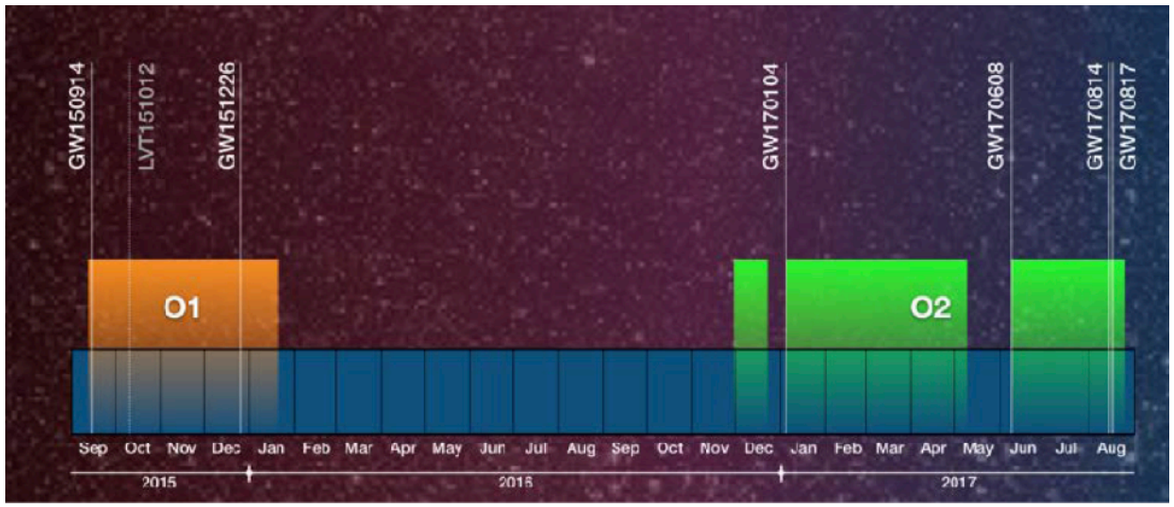
Within 2º, expected 10 bkg events [2008-2016] while 13 events found in data. None of them lies within the two flaring periods.

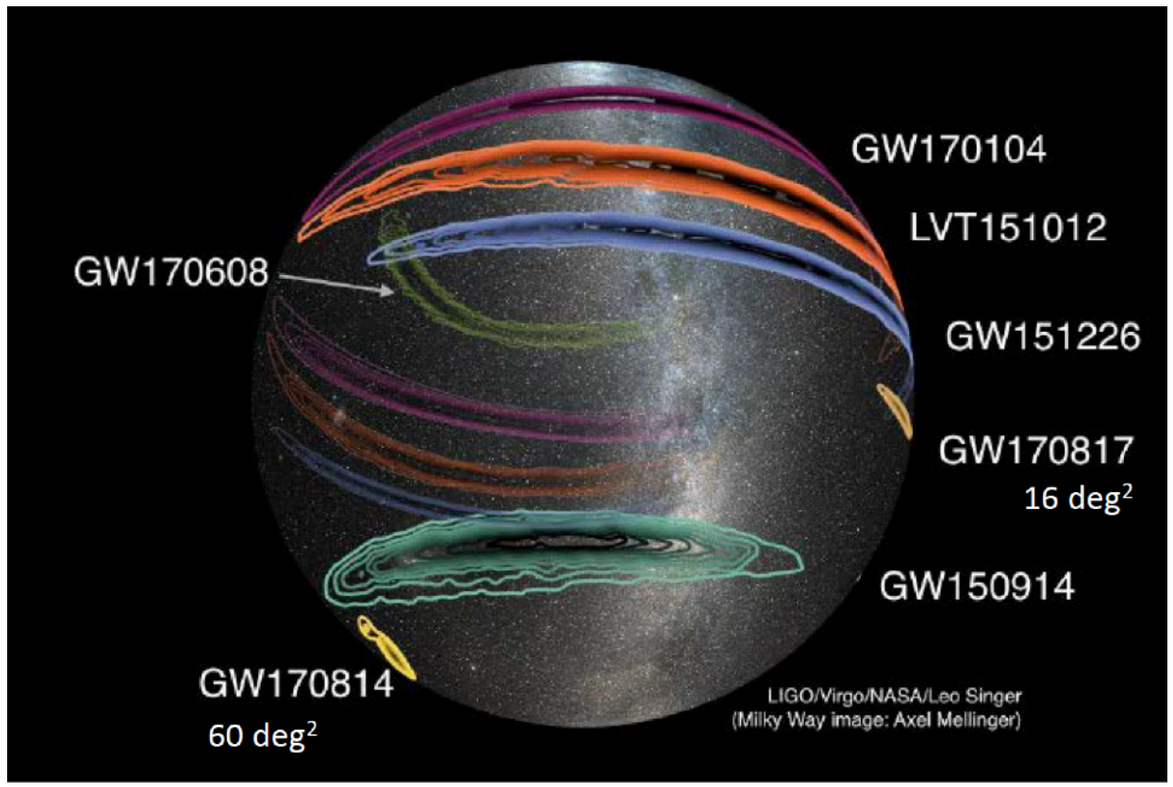
Albert et al., accepted on ApJ, arXiv:1807.04309

LIGO/VIRGO GW alerts

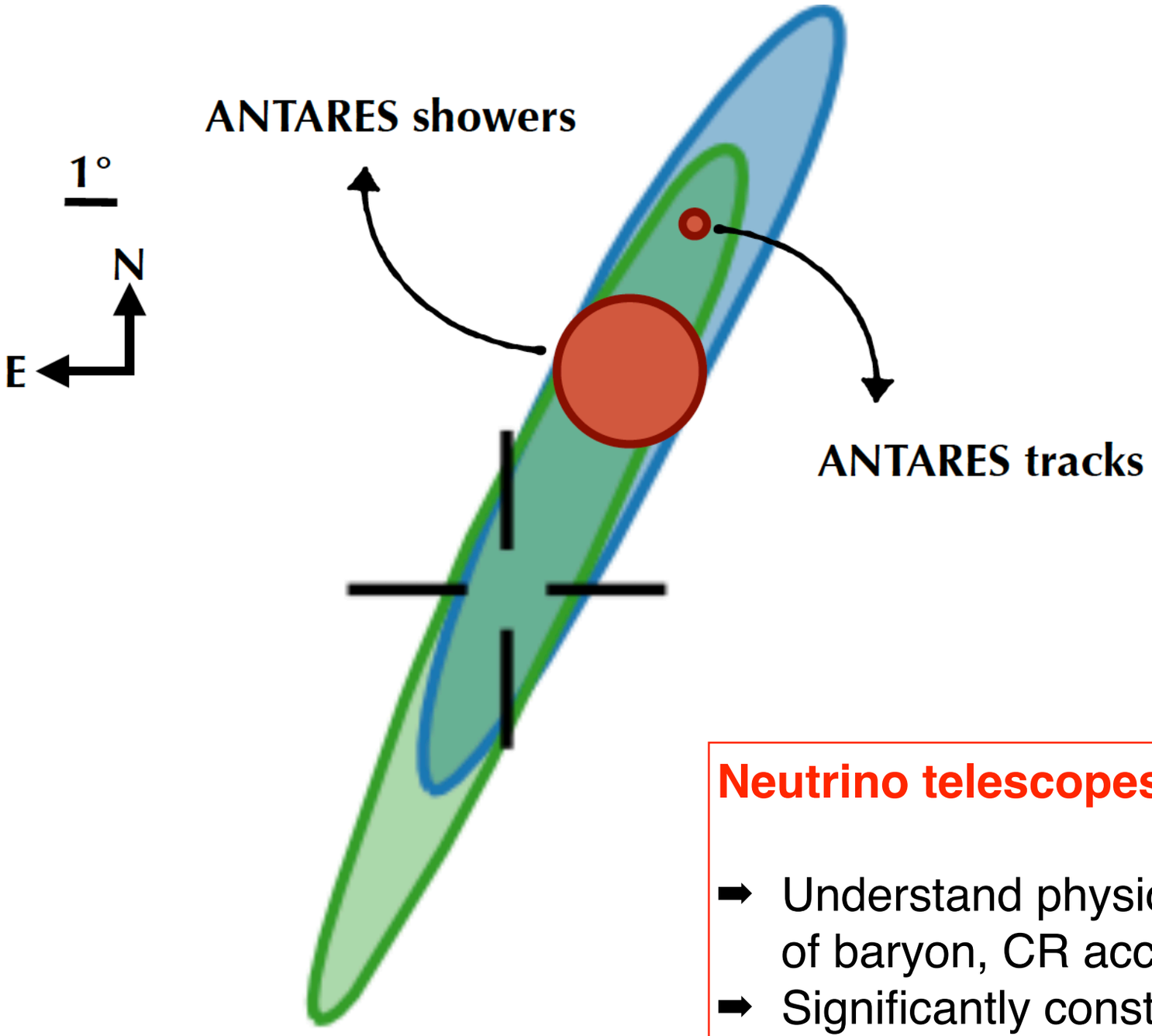
For all GW alerts, we are performing online analysis with tracks only always followed by a deeper analysis using the most refined offline data and calibration (expected gain ~2)

Run o1: 3 alerts (only the last alert GW151226 processed with small delay)
Run 02: Several alerts processed in almost real-time (stop August 25th)
=> 2 GCNs notices per alert [one with the results of the search and one with the limits]
=> Recently, we also performed down-going real-time analysis





LIGO/VIRGO GW alerts



Neutrino telescopes can:

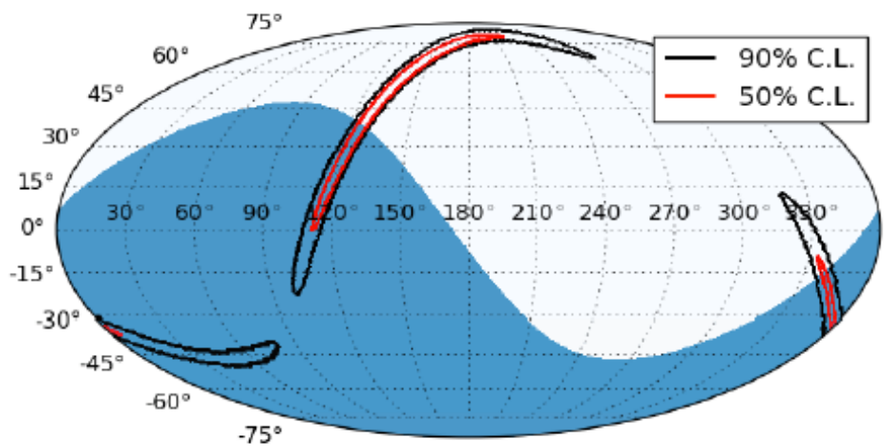
- ➡ Understand physics of the merger, jets (presence of baryon, CR acceleration)
- ➡ Significantly constrain the location of the source
- ➡ Filter sub-threshold events

Example of G268556/GW170104

GCN 20370

Considering the location probability provided by the LIGO collaboration, there is a 50.6% chance that the GW emitter was in the ANTARES field of view.

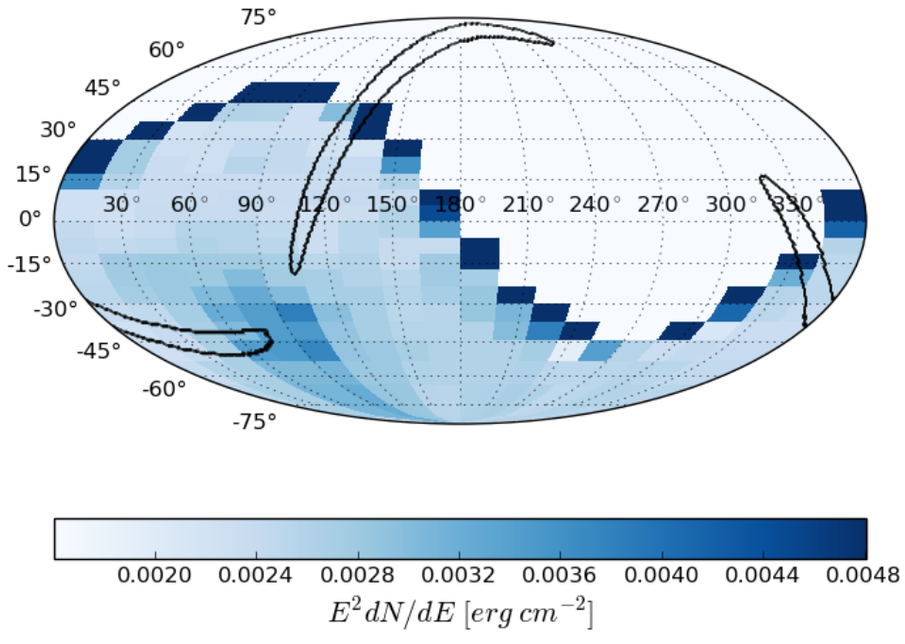
No up-going muon neutrino candidate events were recorded within the 90% contour during a +/- 500s time-window centered on the G268556 event time.

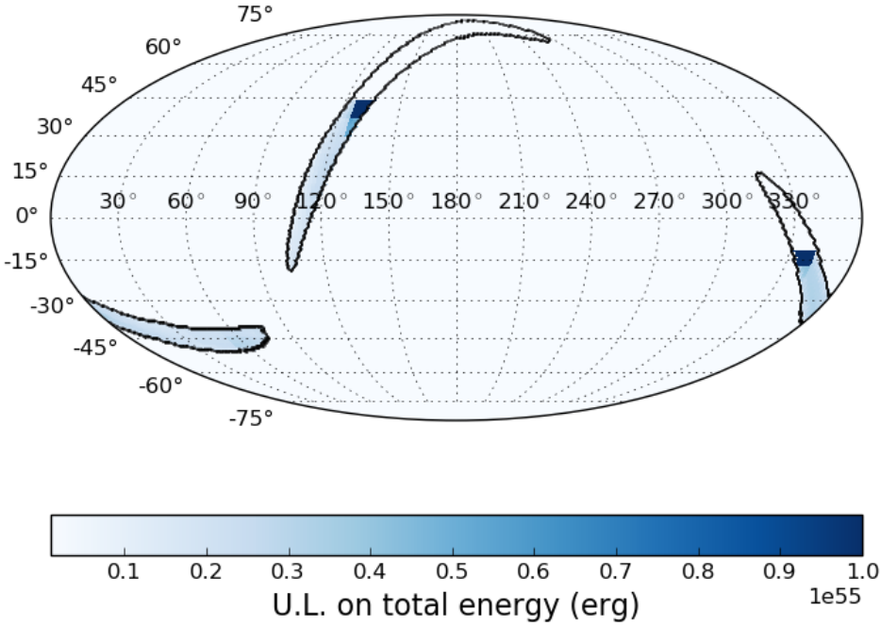


GCN 20517

Assuming a E^{-2} neutrino spectrum in the range [100 GeV-100 PeV], the neutrino fluence limits range between 1 and 3 GeV/cm^{2} depending on the source direction.

The total neutrino emission limits range between 1-10^{54} ergs.





LIGO/VIRGO GW alerts

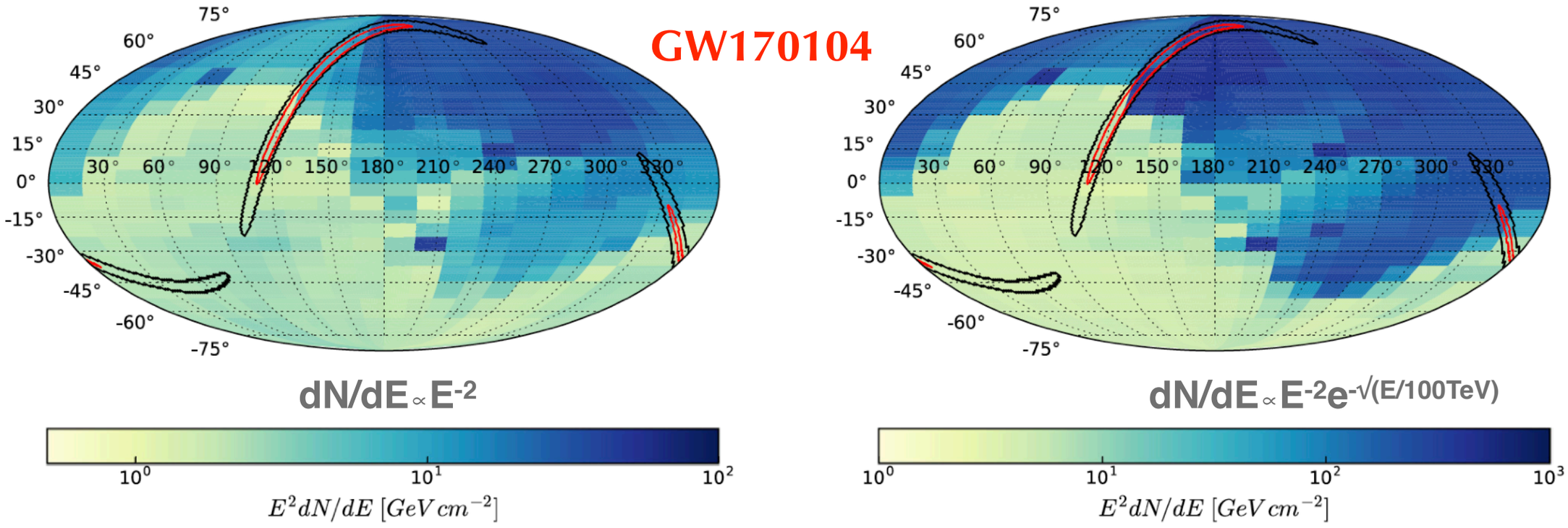
➤ Online searches for every GW alerts during O2: results to LIGO/Virgo on private GCN

➤ Offline optimized event-by-event search (jointly with IceCube) for:
(full-sky searches + optimization + combination with others neutrino telescopes)

- GW150914 (Adrian-Martinez et al., PRD 93, 12, 2016)
- GW151226 + LVT151012 (Adrían-Martinez et al., PRD 96, 2, 2017)
- GW170104 (Albert et al., EPJC 93, 77, 2017)

➤ Offline sub-threshold search (LIGO/VIRGO + ANTARES + IceCube) for o1:

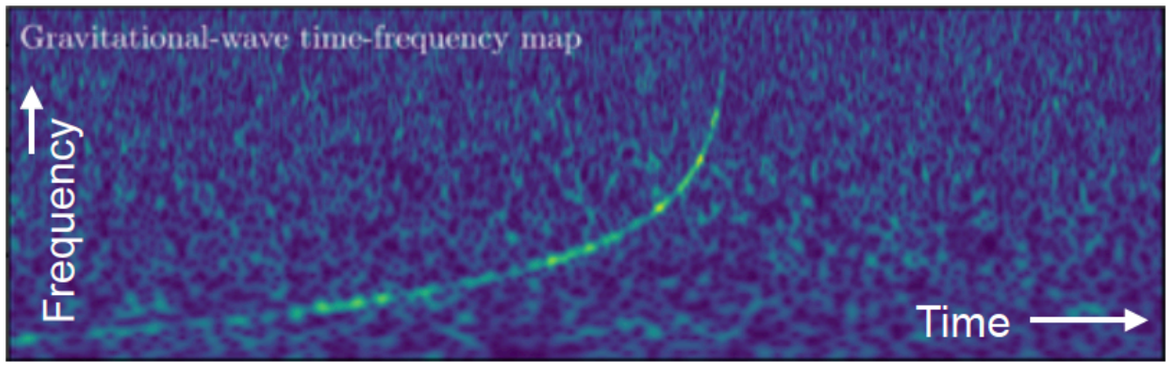
- Paper under review in the 3 collaborations.



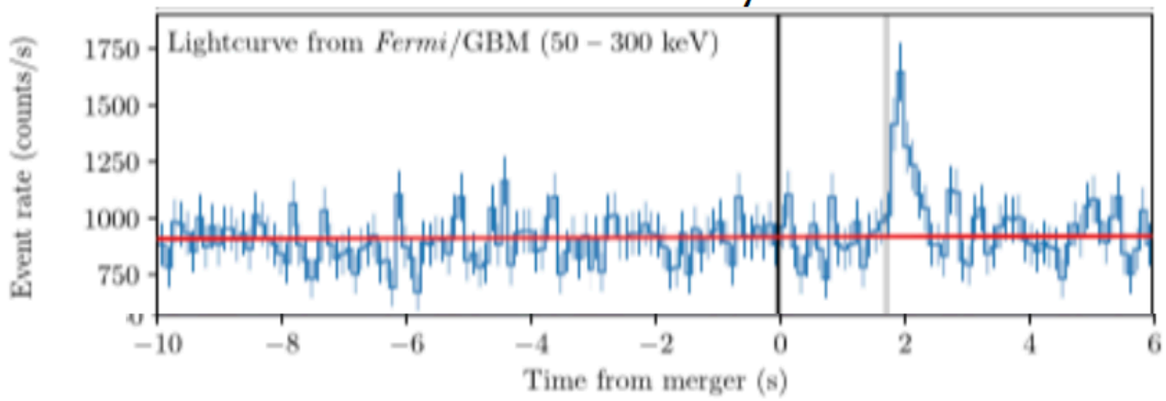
⇒ $E_{iso} < 4\ 10^{54}$ erg ($4\ 10^{53}$ at δ=-17°)

Neutrinos @ GW 170817

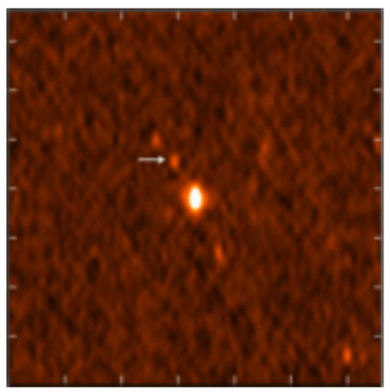
Gravitational waves



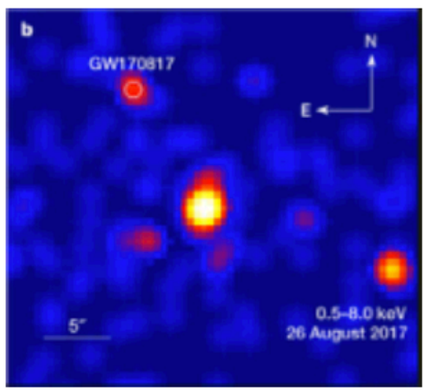
Gamma-ray



Optical



Radio

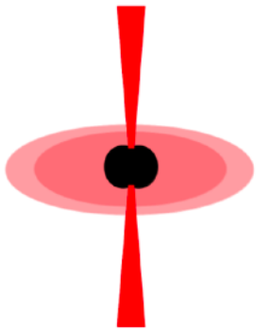


X-rays

ν ?

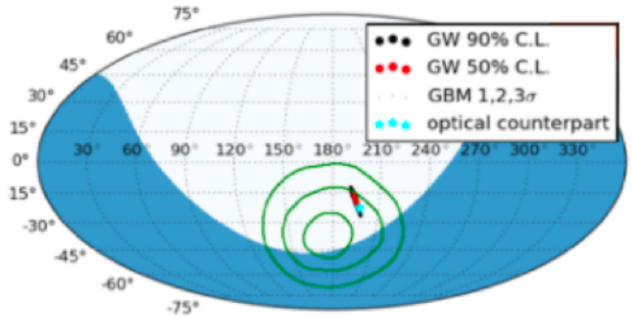
Expected if:
- **ejection process with hadronic component;**
- **Cosmic-ray acceleration related to magnetar**

Neutrinos @ GW 170817

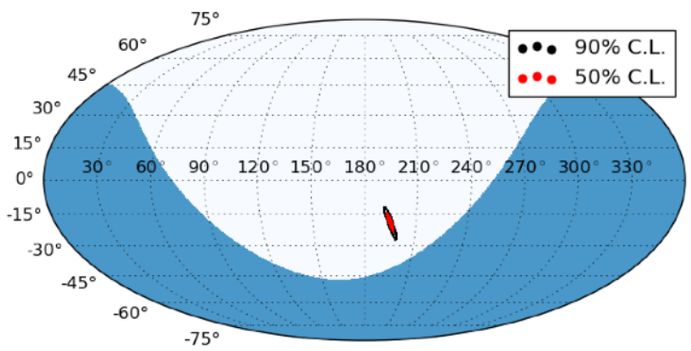


1st notice: t_c+40min
2nd notice: t_c+5h
(+VIRGO localization)

1st GCN 7h after alert
Search below horizon
No HEN counterpart



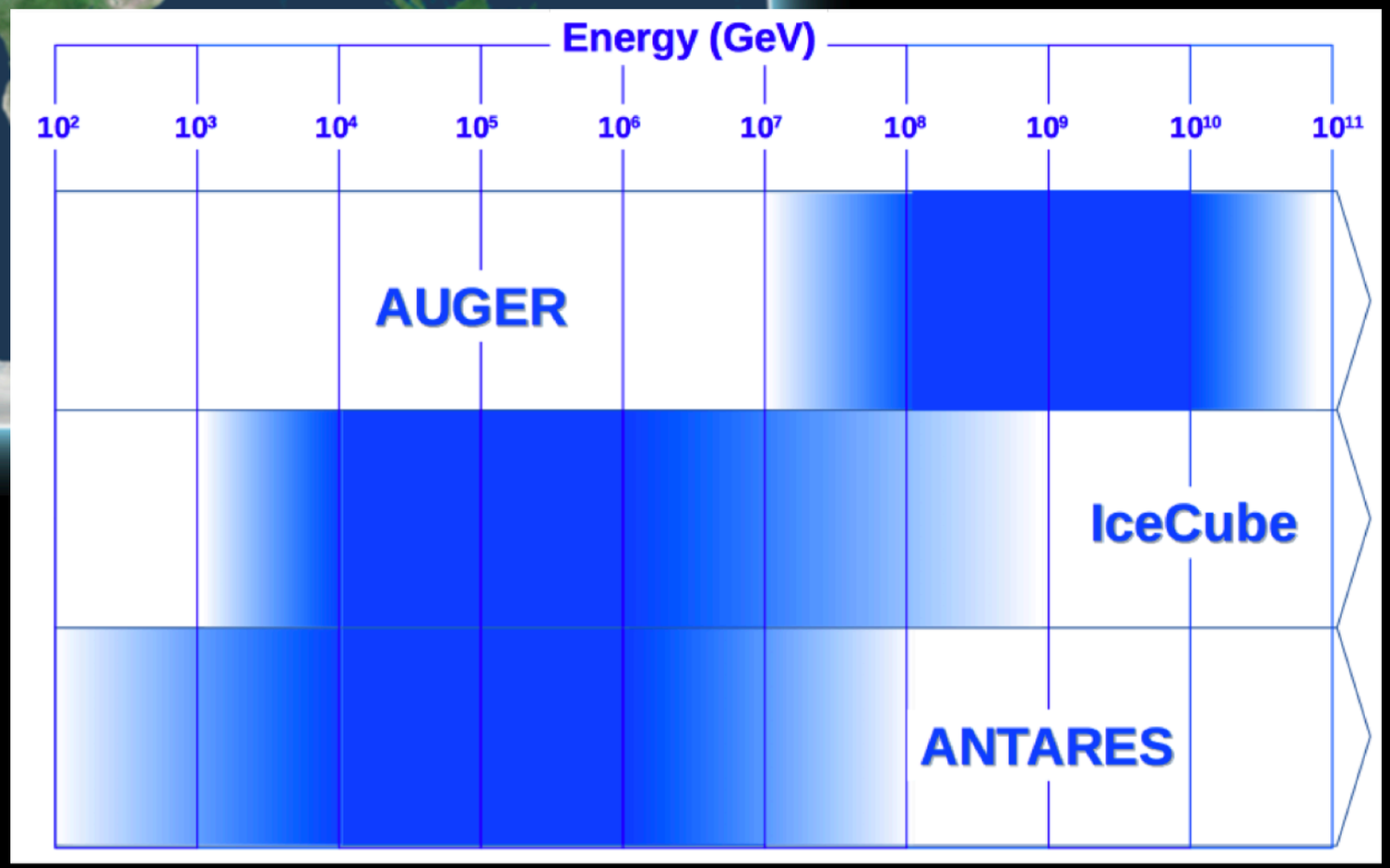
2nd GCN 4d after alert
Search above horizon
No HEN counterpart



Public announce by LVC 60d after alert
Offline optimized search
No HEN counterpart
⇒ ANTARES/IC/Auger/LVC paper
⇒ MMA paper

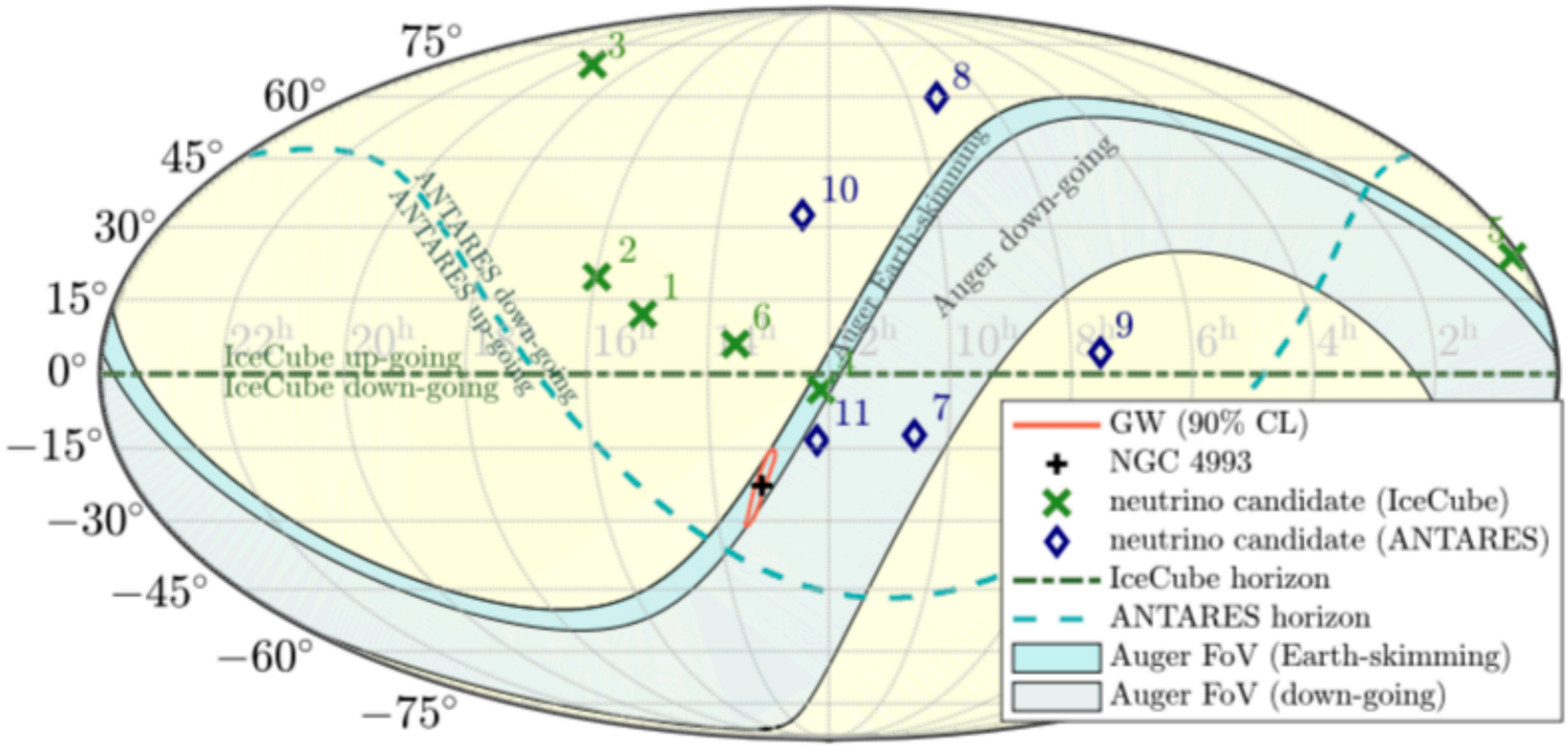
Neutrinos @ GW 170817

Albert et al. (ANTARES, Auger, IceCube & LIGO/Virgo), ApJL, 850, 2 (2017)



Neutrinos @ GW 170817

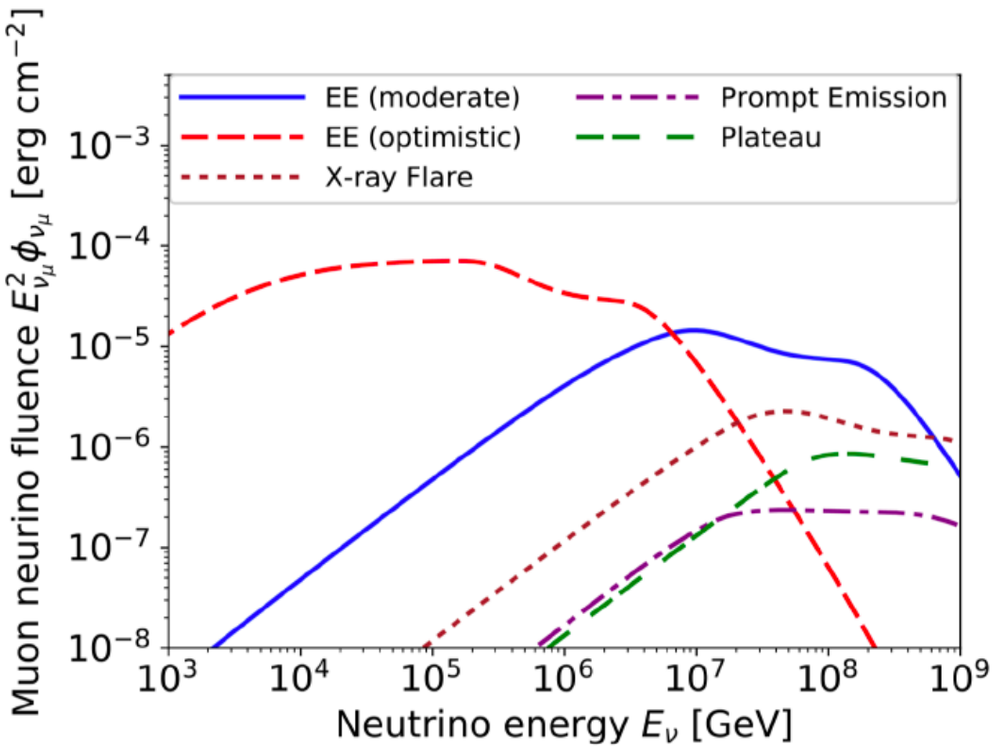
1) Search over ± 500s around the merger



Albert et al., ApJL, 850, 2 (2017)

2) Search over ± 14 days around the merger

Neutrinos @ GW 170817

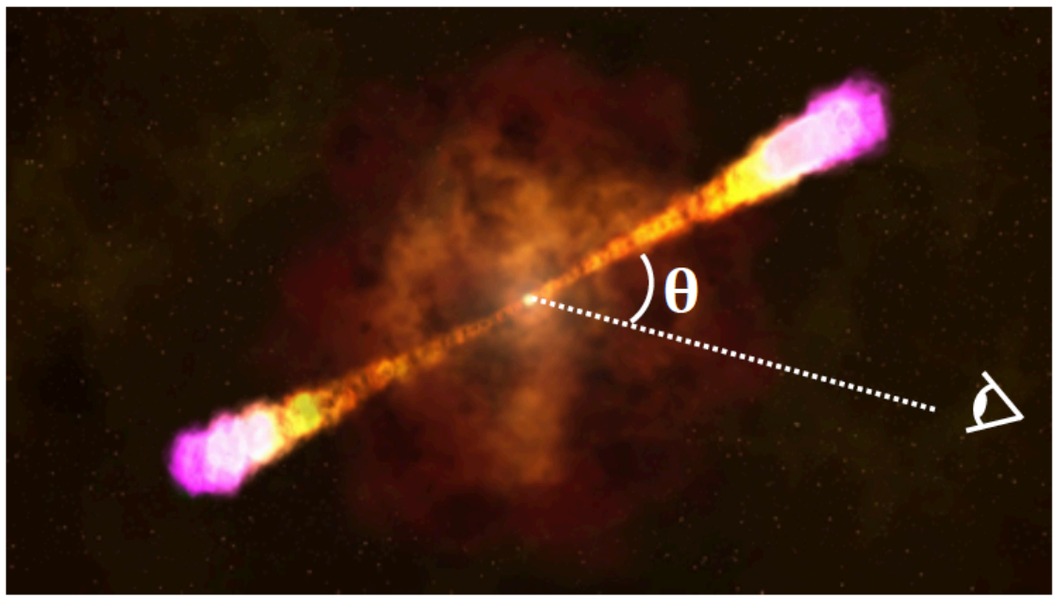


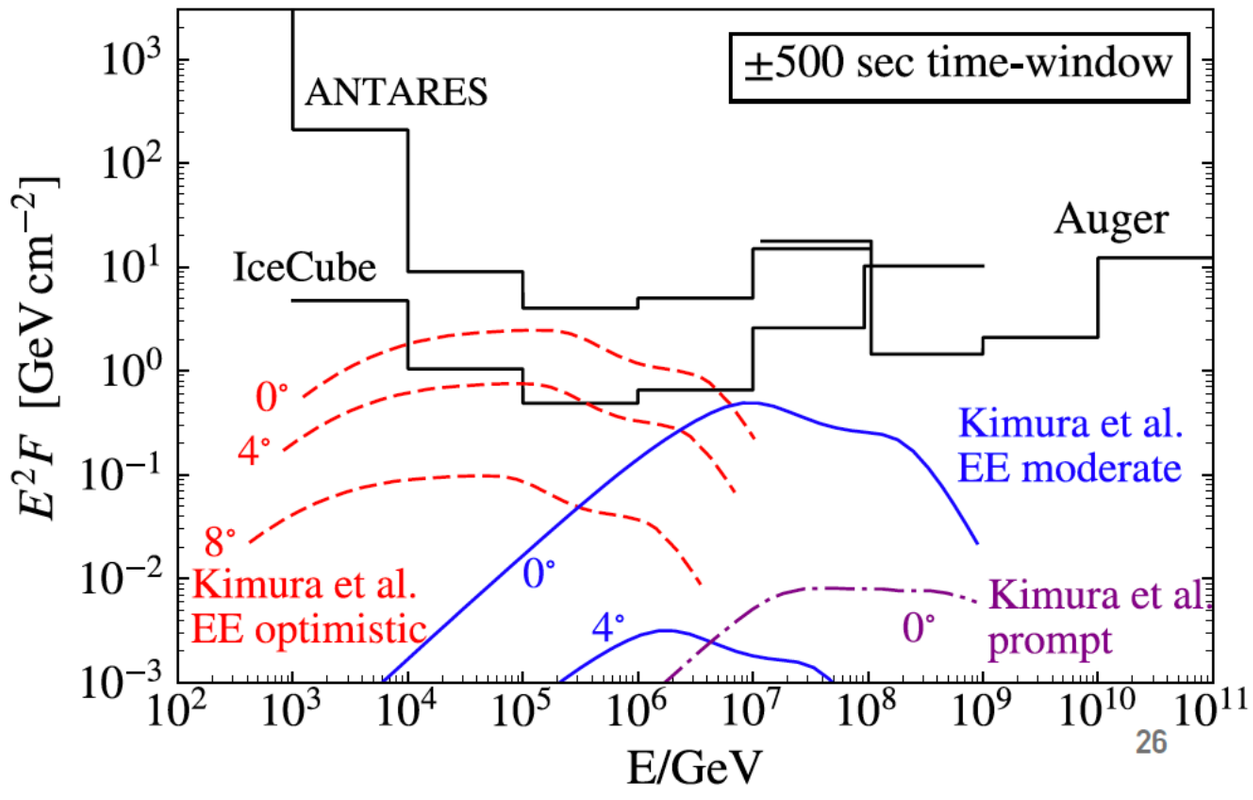
➡ Neutrino emission related to the prompt/ extended high-energy emission

➡ Assuming relativistic jet viewed off-axis

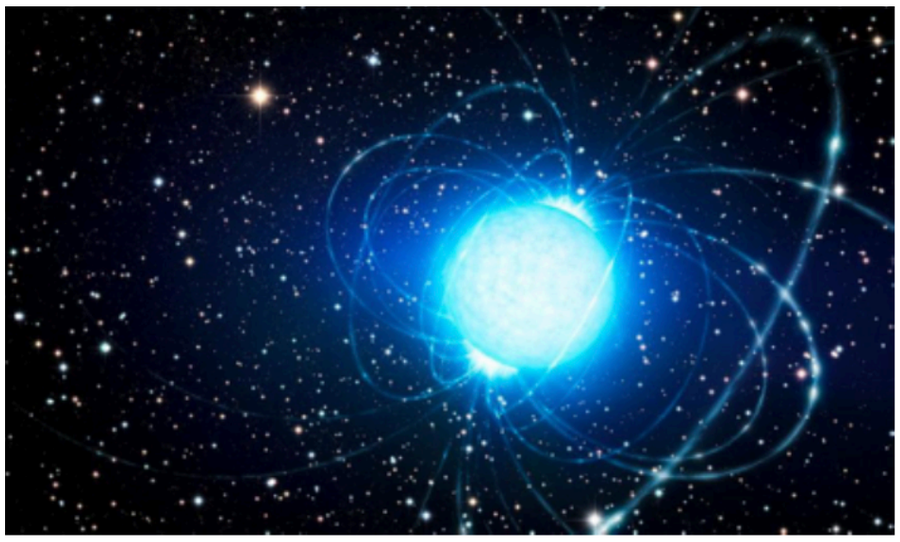
➡ Extended GRB emission: Lower Γ ⟹ Higher meson production efficiency

(Kimura et al., 2017)





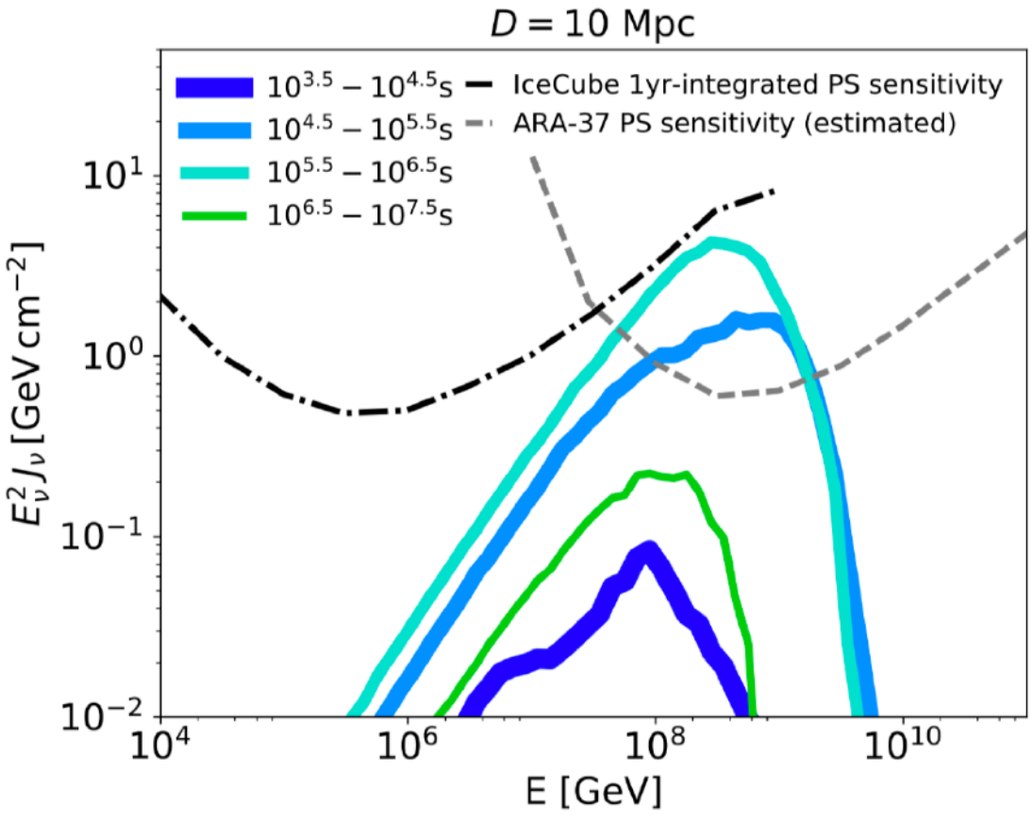
Neutrinos @ GW 170817

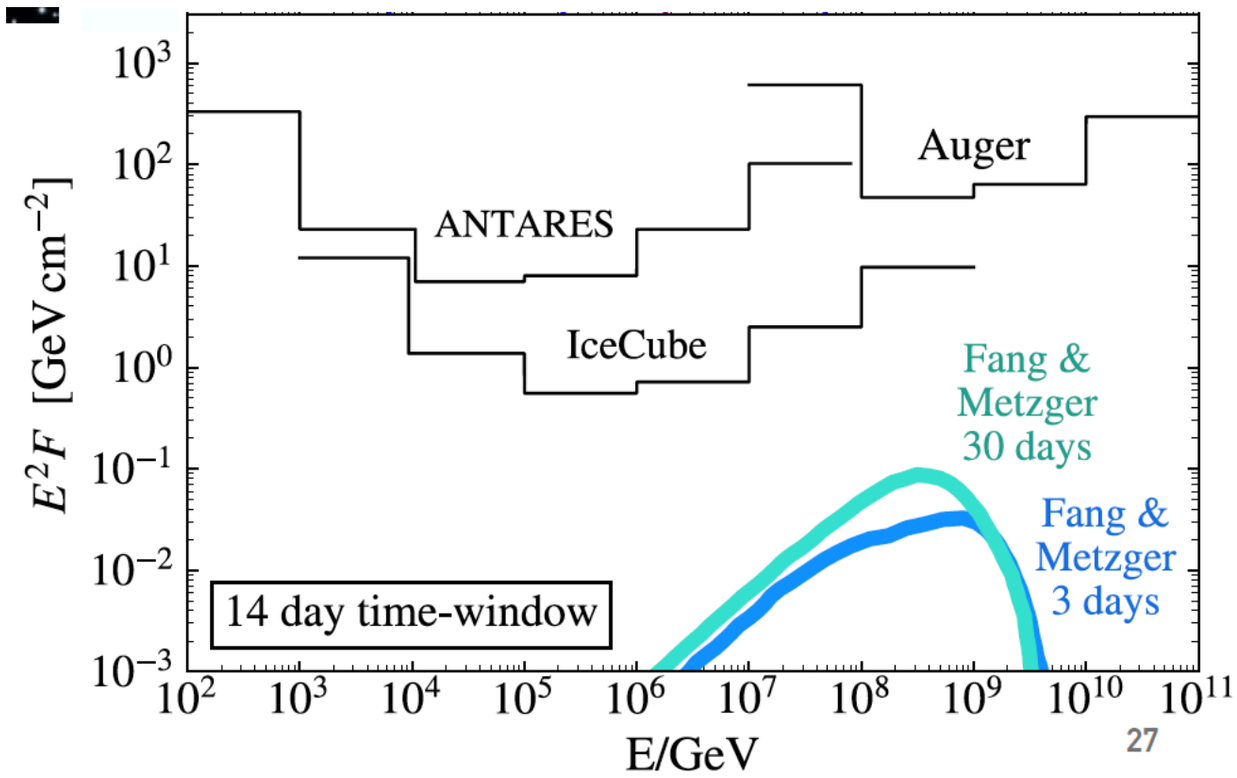


➤ Neutrino emission related to ejecta material from the merger over several days

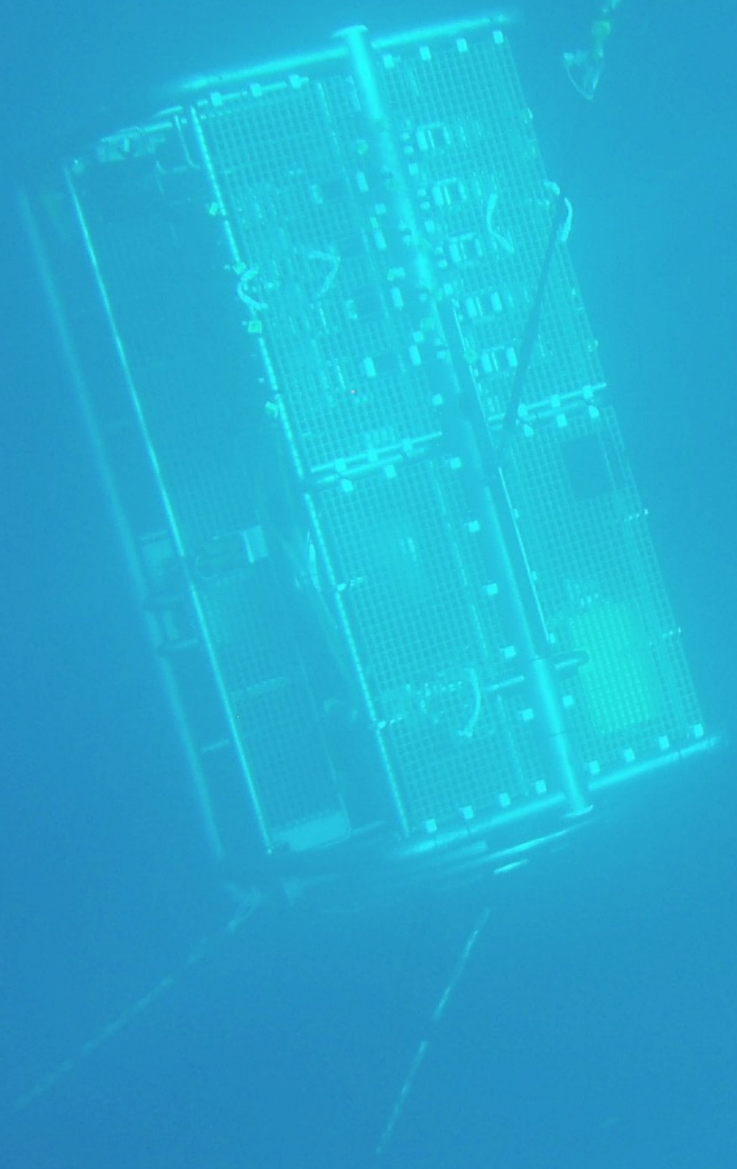
➤ Assumes formation of a magnetar ➙ powers relativistic wind (CR acceleration)

Fang & Metzger, 2017





Summary



- ANTARES: 12 years of continuous and stable data-taking
- Small excess in all diffuse analysis (final ANTARES sensitivity <=> IC signal flux)
- Competitive results on the Southern sky

(Cf Talk S. Navas)

- <u>Multi-messenger effort:</u>
  - EM follow-up of our neutrino alerts,
  - Real-time GRB/FRB searches,
  - Follow-up of GW/IC candidates,
  - Offline time/space correlations,
  - Combined analysis with IC (PS, GP)

- ANTARES will be decommissioned in 2020, with smooth transition to KM3NeT
- KM3NeT is under construction in Europe (2 sites South of Italy and South of France).

(Cf Talk A. Domi)

In the KM3NeT Fr site, few months ago...