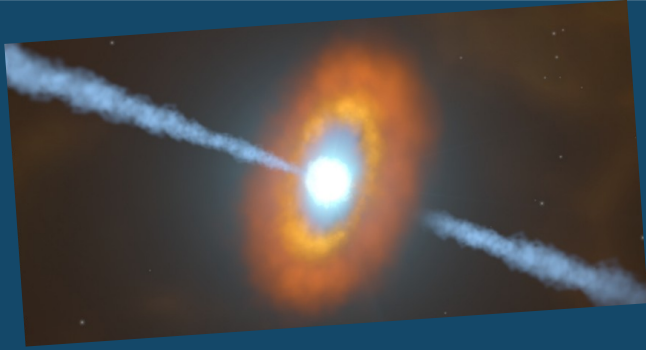


MULTI-MESSENGER ASTRONOMY IN THE MEDITERRANEAN SEA



Marta Colomer Molla
on behalf of the ANTARES-KM3NeT collaboration

"The new era of Multi-messenger astrophysics", Groningen, 28/03/2019



WHY MULTI-MESSENGER ASTRONOMY WITH NEUTRINOS?

Neutrino telescopes suitable to look for transient sources:
continuously monitoring at least half of the sky!

Studies of **transient & variable** sources:

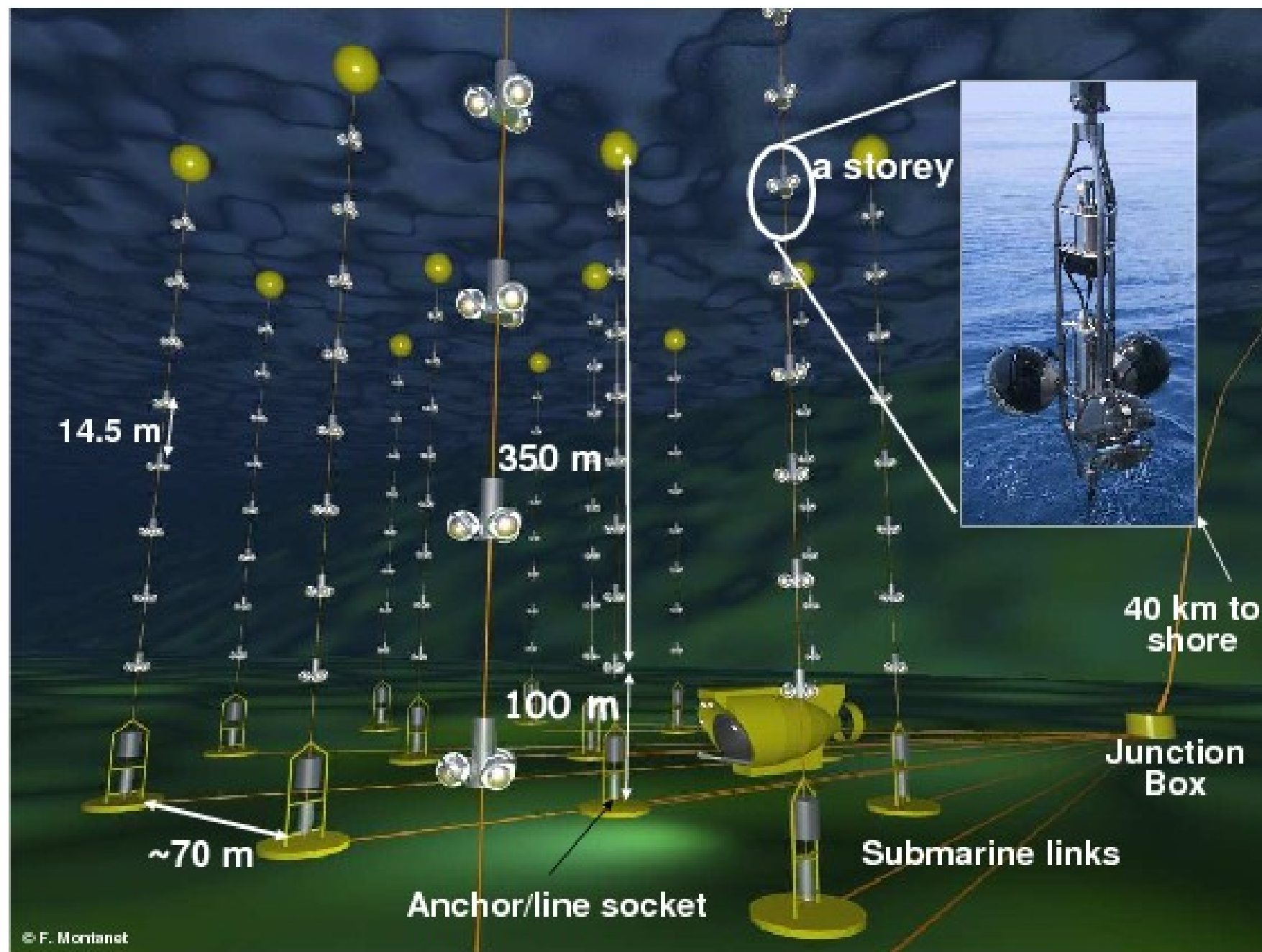
increase the sensitivity + discovery potential
(short duration allows to reduce background)

Multi-messenger studies:

increase the statistical significance
(requiring joint detection)

→ Different messengers provide different informations to
understand the astrophysical processes and phenomena

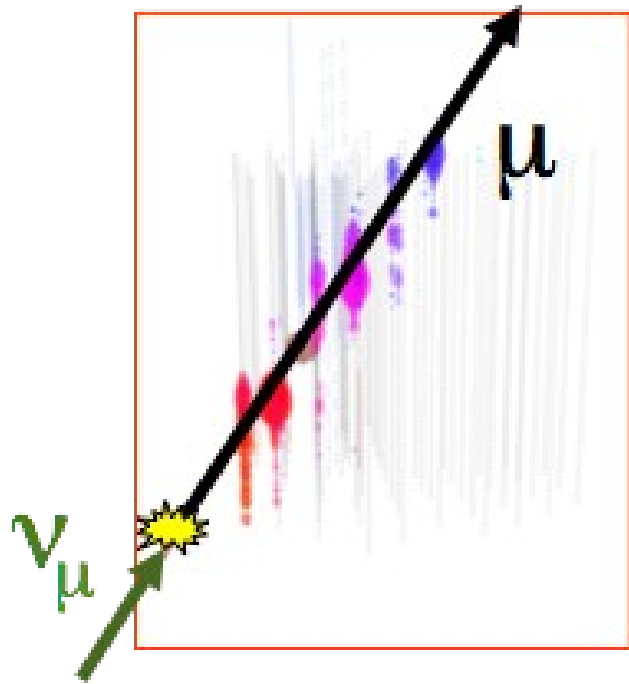
THE ANTARES NEUTRINO TELESCOPE



- Deployment completed in 2008 → More than 10 years taking data!
 - 2475 m depth in the Mediterranean sea
 - 40km offshore from Toulon
 - 12 lines, 25 storeys per line
 - 3 PMTs per storey facing 45° downwards
- Position, time and charge used to reconstruct particle direction and energy

ANTARES RECONSTRUCTION PERFORMANCE

TRACKS

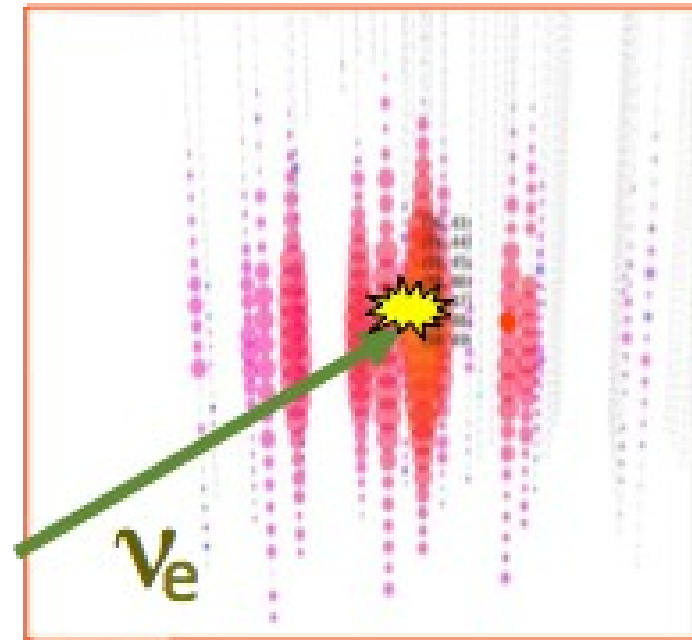


ν_μ (ν_τ) CC interactions

Neutrino can interact outside the detector

Good angular resolution:
 $<0.4^\circ$ for $E_\nu > 10\text{TeV}$

SHOWERS

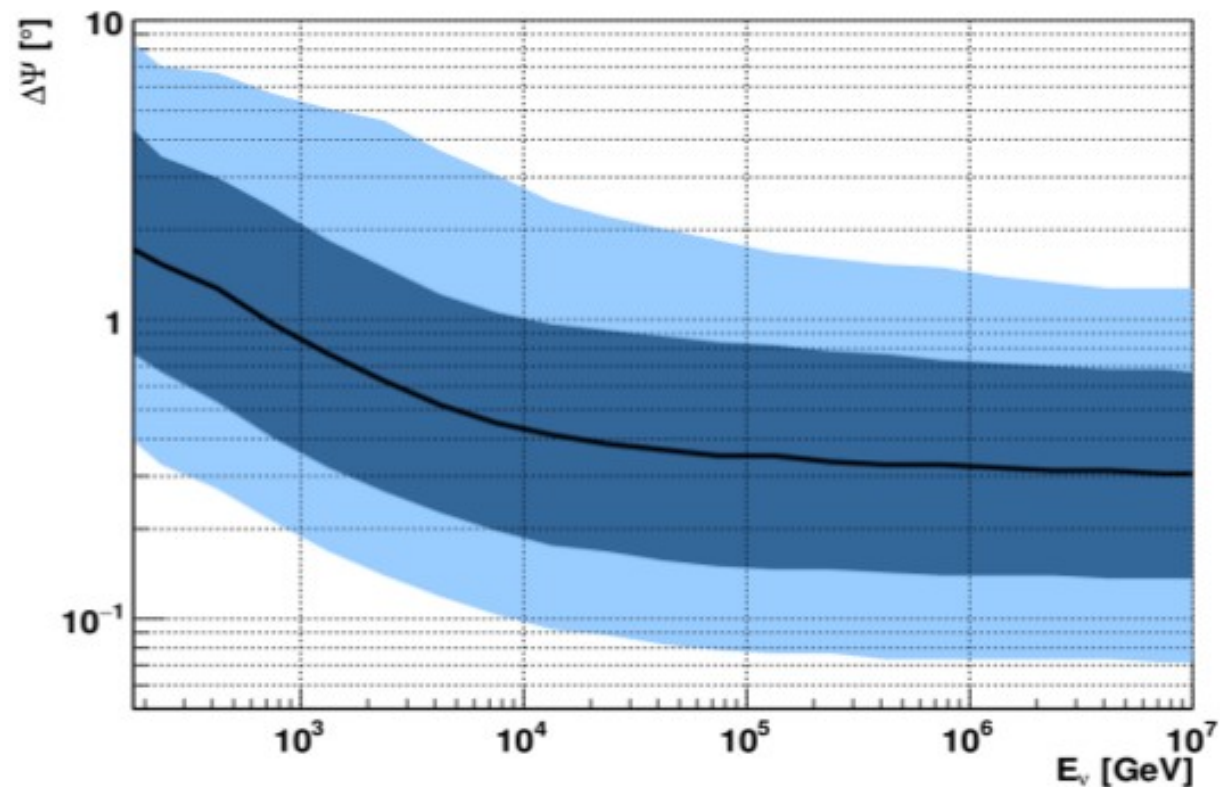


Quasi-spherical contained events

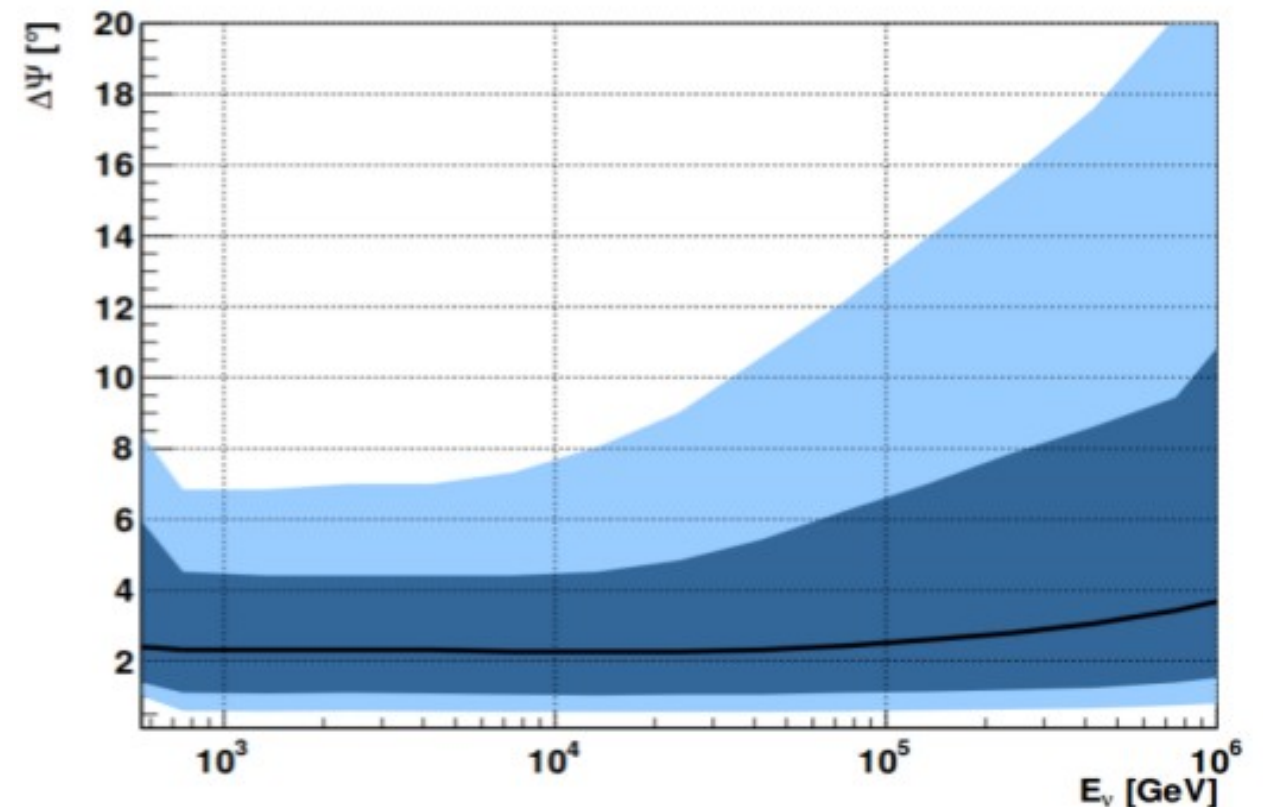
Angular resolution: $\sim 3^\circ$

Good energy resolution
(10-15%)

MEDIAN ANGULAR RESOLUTION: TRACKS



MEDIAN ANGULAR RESOLUTION: SHOWERS

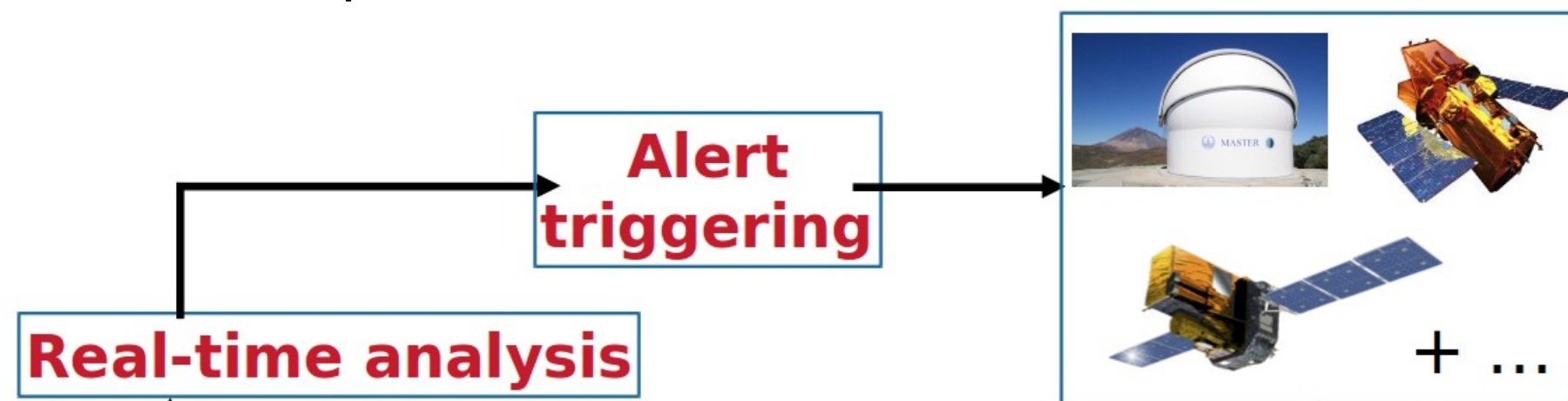


MULTI-MESSENGER PROGRAM OF ANTARES: TWO APPROACHES

- Fast neutrino online reconstruction
- Selection: HE, direction, multiplet
- Alerts sent to EM and neutrino observer partners

TAToO program

**see talk by D.Dornic



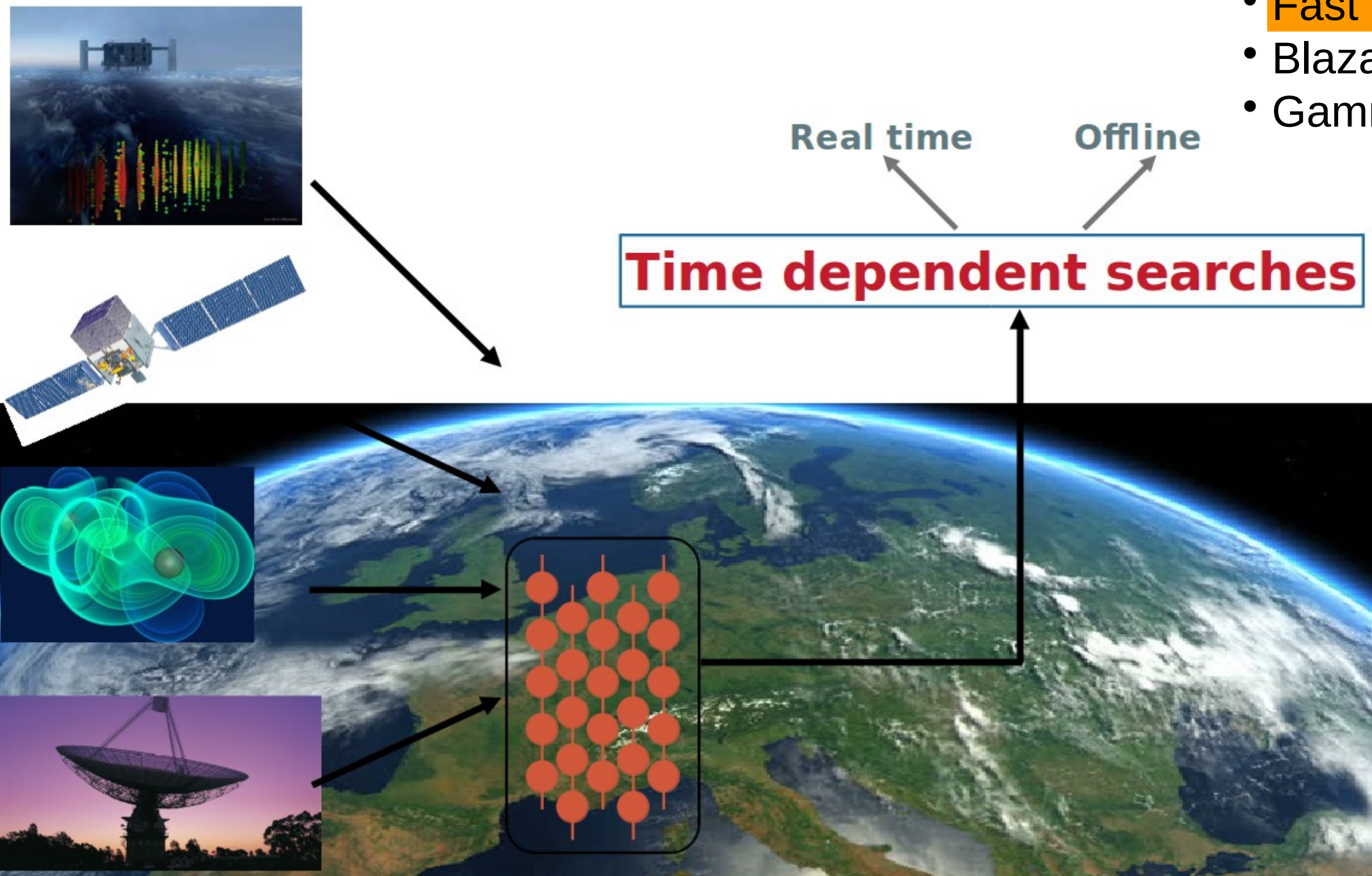
Low latency alerts (<10 sec)

292 alerts sent to robotic telescopes **(07/2009-31/12/2018)**:

- 17 sent to Swift
- 15 sent to Integral (3 followed)
- ~20 to MWA (3 followed)
- 2 to HESS

MULTI-MESSENGER PROGRAM OF ANTARES: TWO APPROACHES

- IC neutrinos
- Auger-TA Cosmic Rays
- GWs from LVC
- Fast Radio Bursts
- Blazars: HAWC, Fermi
- Gamma-ray Bursts





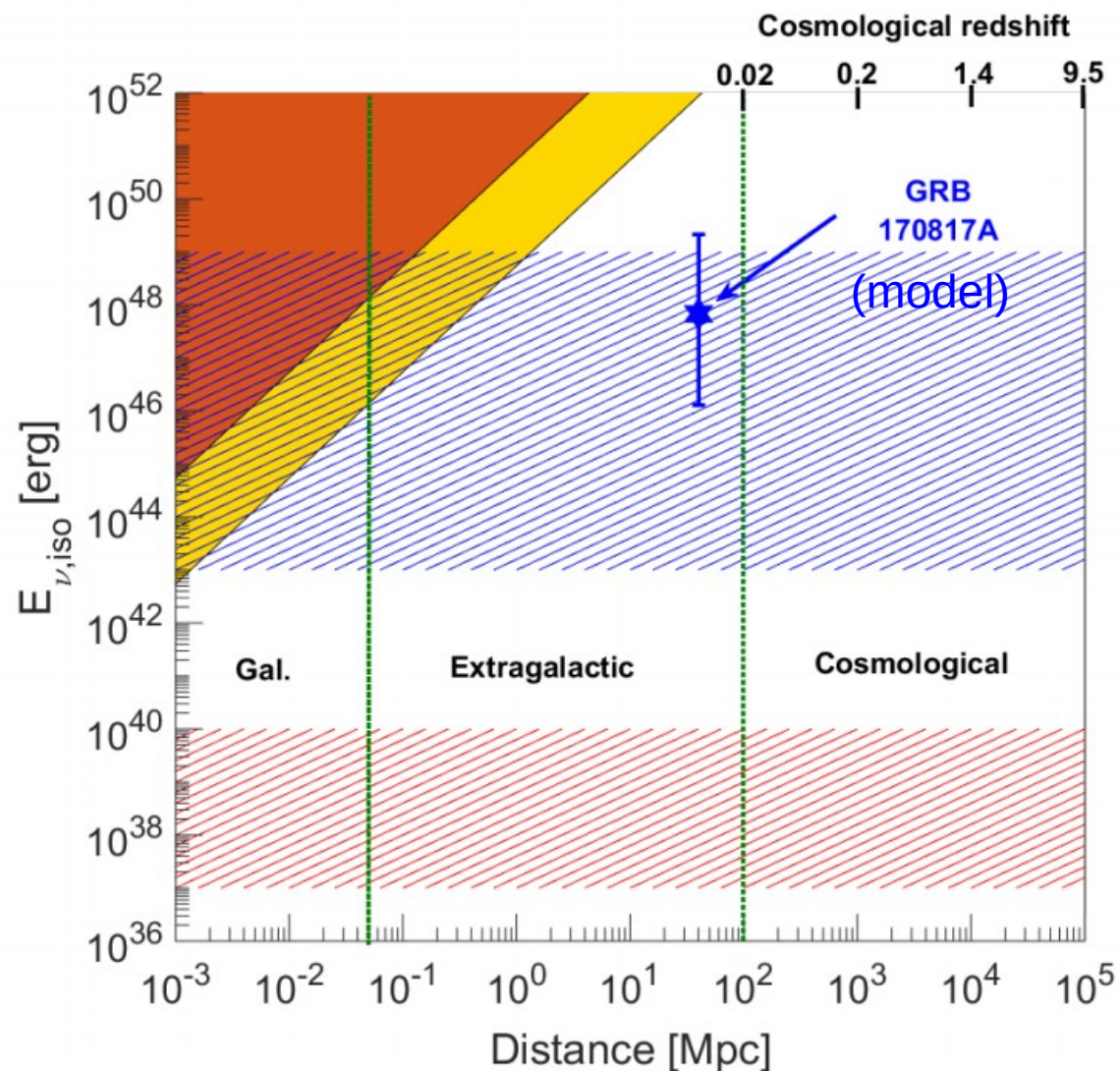
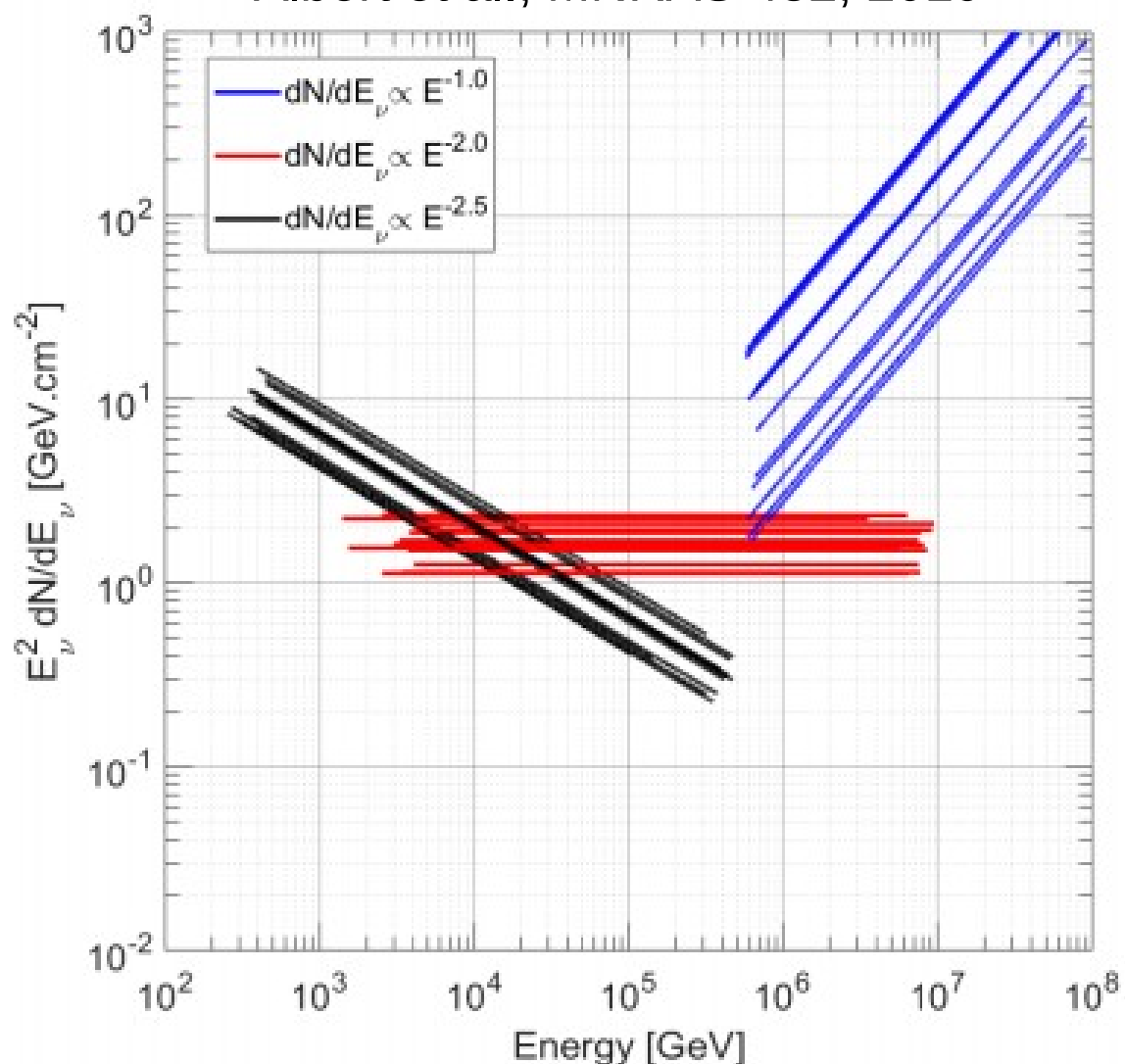
FAST RADIO BURSTS

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

- No significant correlation
- Limits on the neutrino fluence assuming different energy spectra

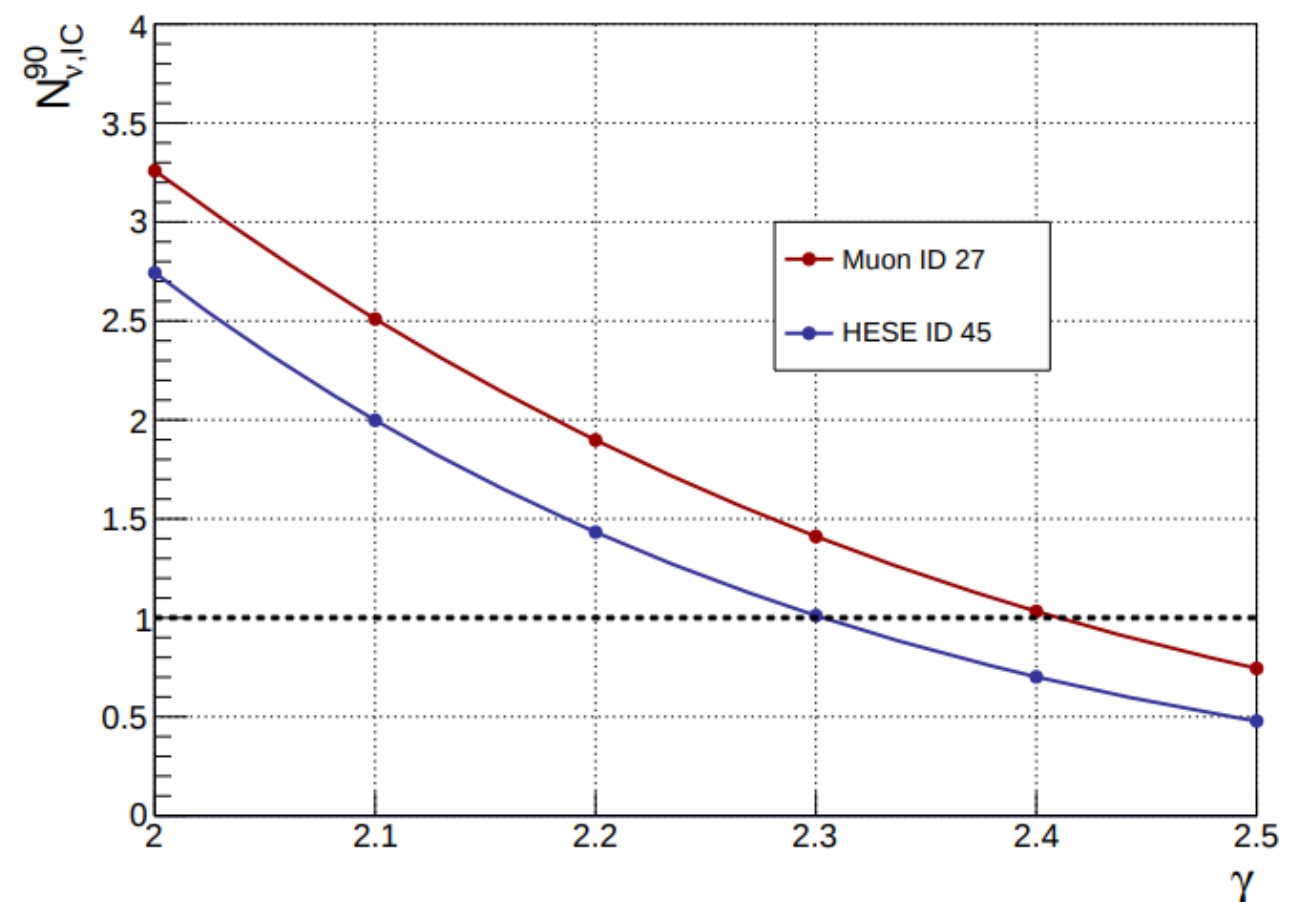
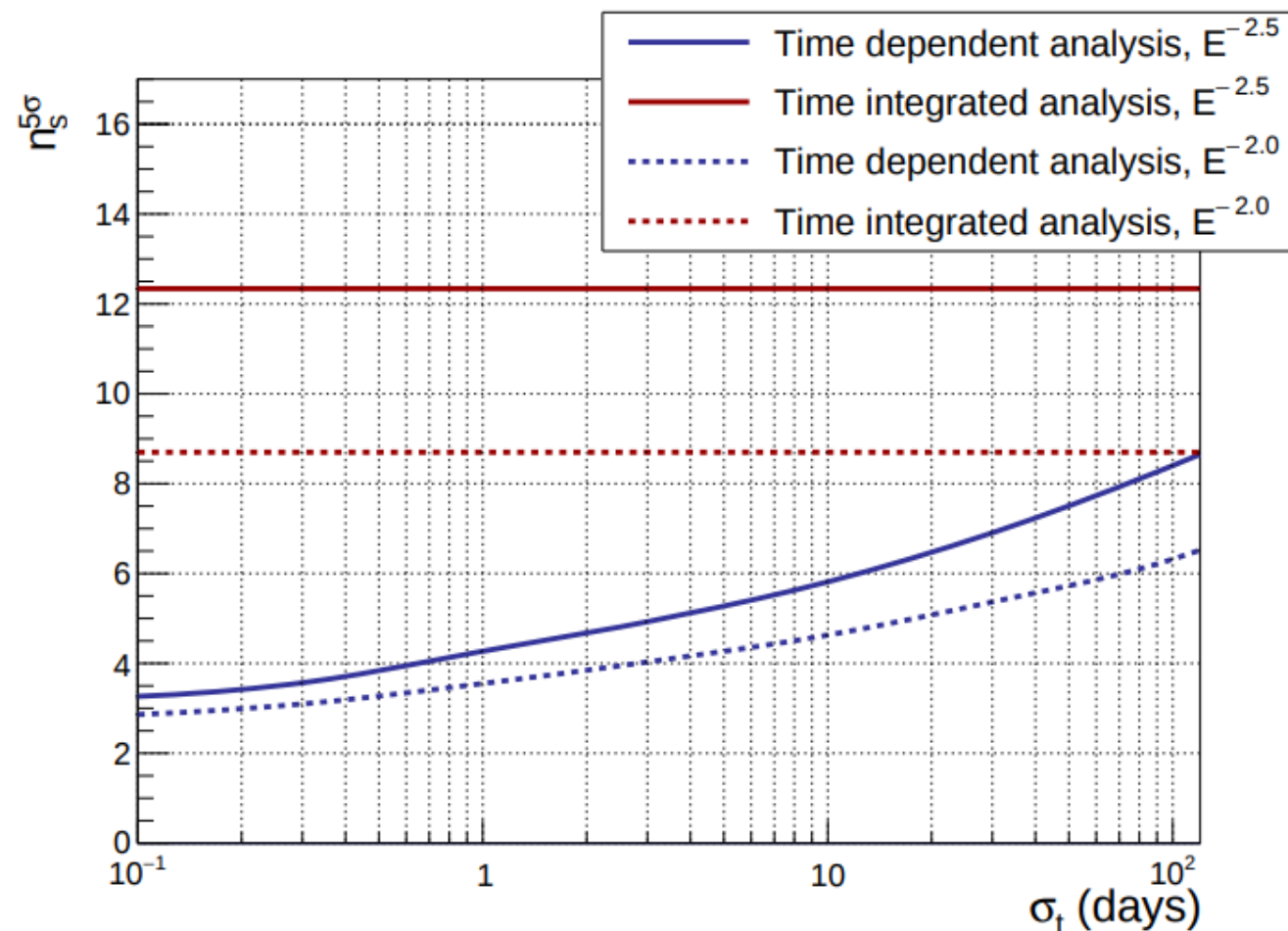
- Constraints on the TeV-PeV neutrino energy released by FRBs
- Comparison with short GRB and magnetar giant flares / soft gamma-ray repeaters models

Albert et al., MNRAS 482, 2019



TIME CORRELATIONS WITH ICECUBE EVENTS

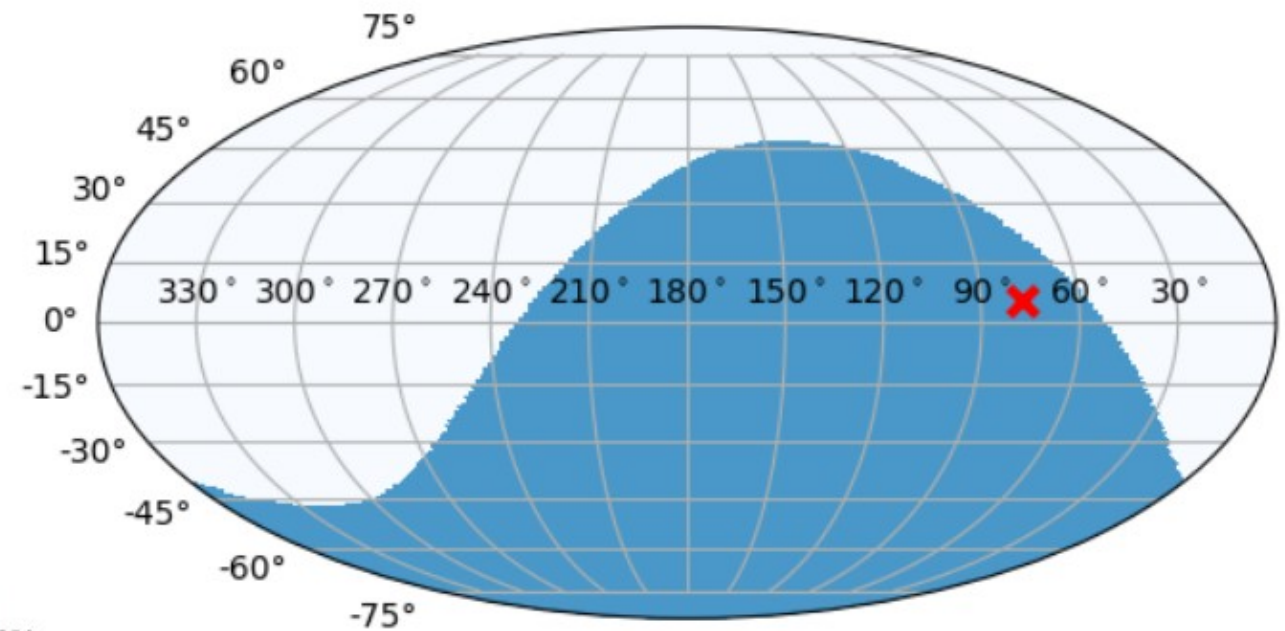
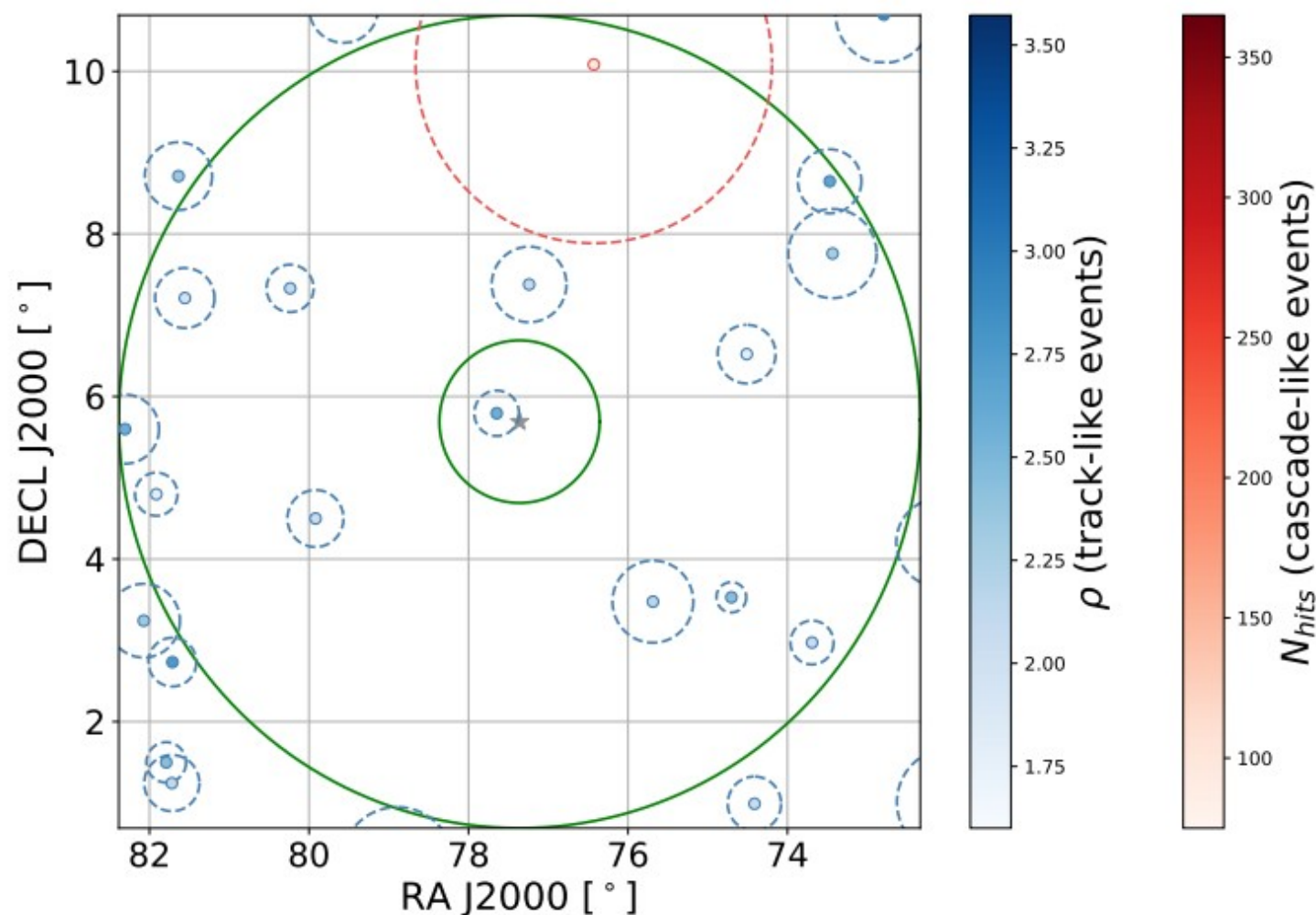
- Search for time correlations with IceCube HESE and high-energy ν_μ tracks
- Test transient origin of IceCube events
- No significant correlation (largest excess: 89% p-value post-trial)
- No event in correlation over timescale $\lesssim 3$ h
- Constraint on the spectral index of the neutrino spectrum (assuming \sim sec. transient emission)



SEARCH FOR NEUTRINOS FROM TXS 0506+56

→ No up-going muon neutrino candidate event recorded within 3° around the IC170922A direction within ± 1 h centered on the event time in the online data stream.

Abert et al., ApJL 863, L30 (2018)

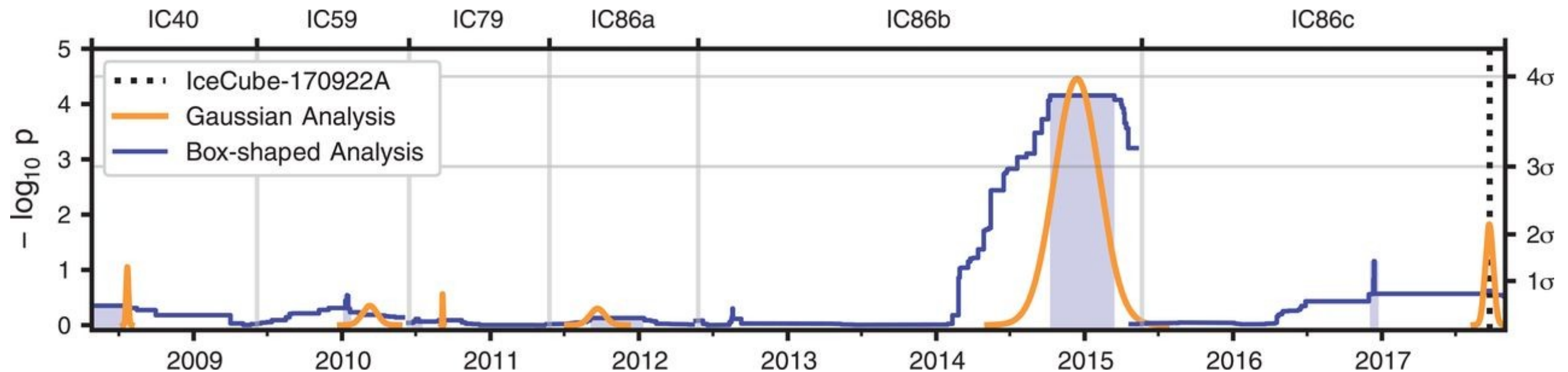


- TXS 0506+56 neutrino search with standard point-source method.
- 13 tracks and 1 shower like neutrino candidates within 5° from TXS 0506+56.
- Result using 10 yr of ANTARES data:
 - number of fitted signal events:
 $\mu_s = 1.03$
 - pre-trial p-value of 3.4%.

SEARCH FOR NEUTRINOS FROM TXS 0506+56

- ANTARES time dependent search method
- Bursting period defined by the two profiles provided by the IceCube Collaboration:
 - Gaussian flare (centered on Dec 13, 2014)
 - Box flare (centered on Dec 26, 2014)

- No signal has been found during either of the considered flares
- 13 events within 2° from the source found in data. None of them lie within either of the two flaring periods



Spectrum	$\Phi_{100\text{TeV}}^{90\%} [10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}]$	5%-95% energy range
$E^{-2.0}$	4.6	2.0 TeV – 3.2 PeV
$E^{-2.1}$	4.4	1.3 TeV – 1.6 PeV
$E^{-2.2}$	4.2	1.0 TeV – 1.0 PeV

GRAVITATIONAL WAVE FOLLOW-UPS (BINARY BLACK HOLES)

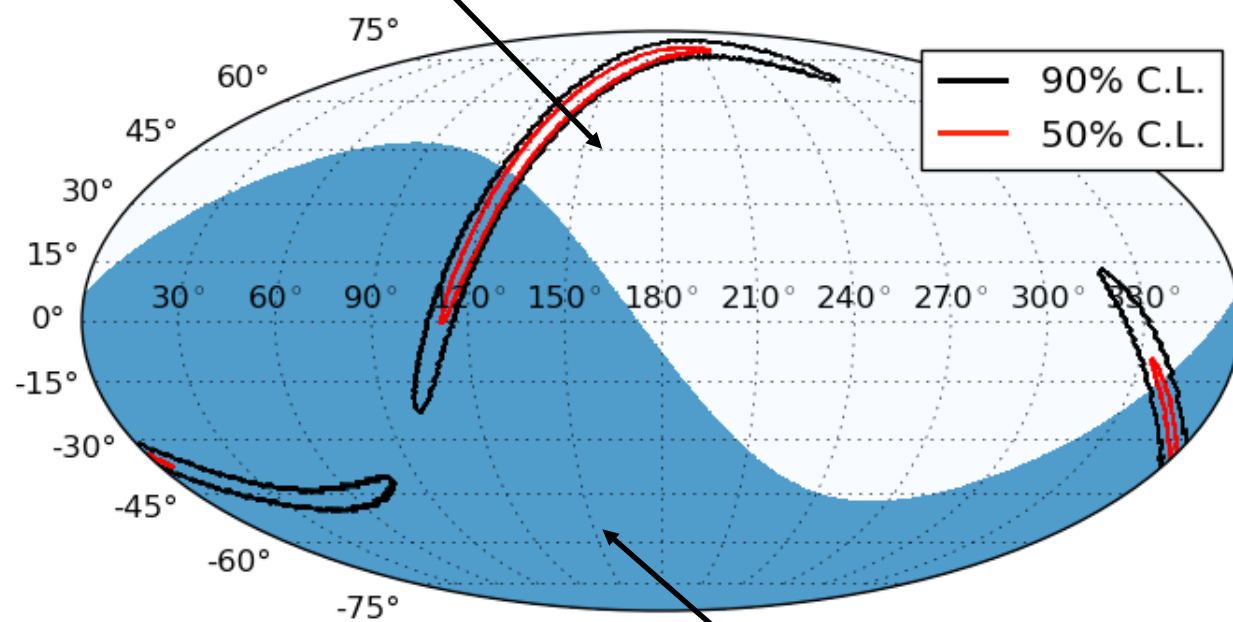
Neutrino emission coincident with BBH events.

Search (jointly with IceCube) for:

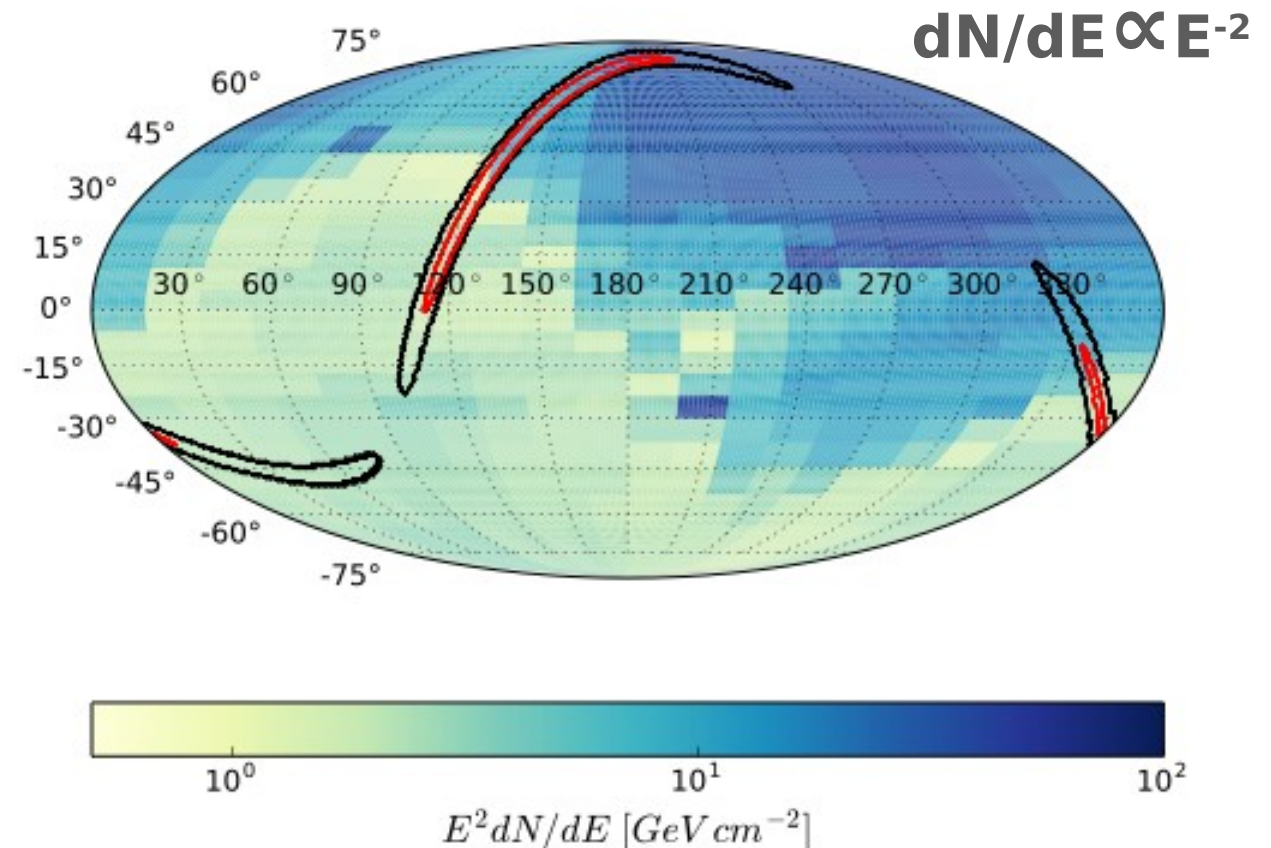
- GW150914 (*Adrian-Martinez et al., PRD 93, 12, 2016*)
- GW151226+LVT151012 (*Adrián-Martinez et al., PRD 96, 2, 2017*) → increase of sensitivity
- GW170104 (*Albert et al., EPJC 93, 77, 2017*) → full sky

ONGOING work: Update of GW offline analysis with new cataloged events

above the horizon



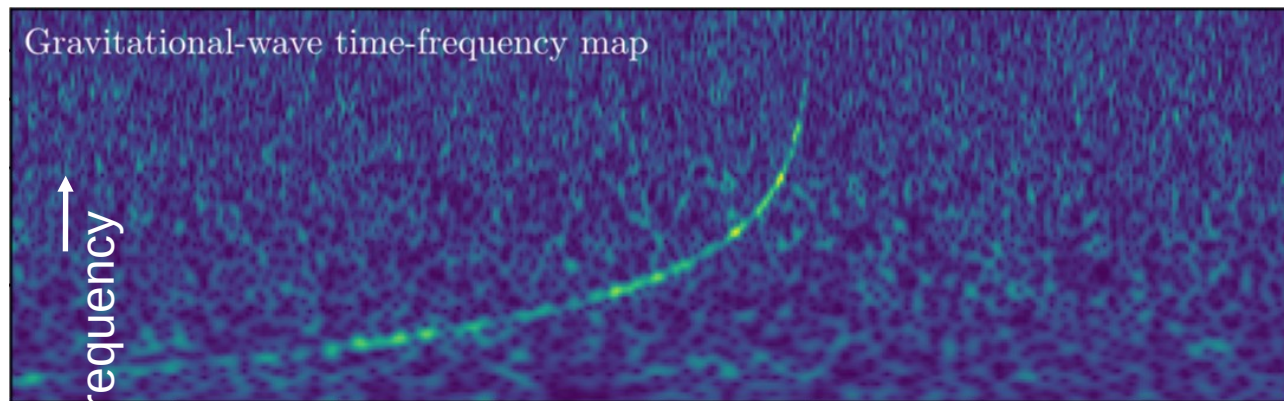
below the horizon



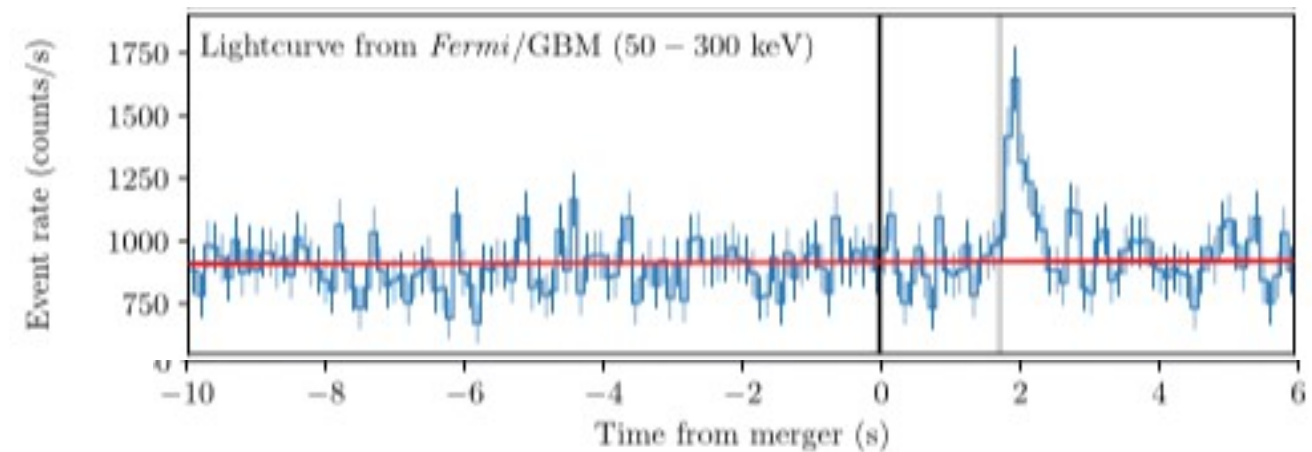
→ First analysis above ANTARES horizon (feasible for transients)

GRAVITATIONAL WAVE FOLLOW-UPS (GW170817)

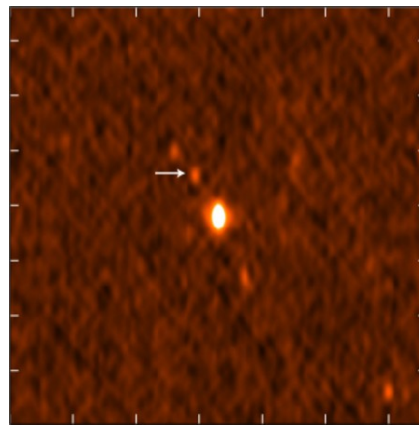
Gravitational waves



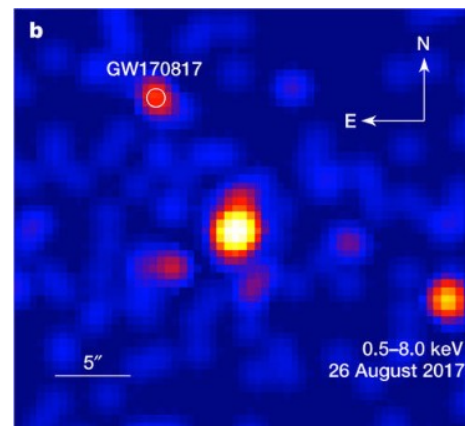
Gamma-ray



Optical



Radio



X-rays

ν ?

Expected if:

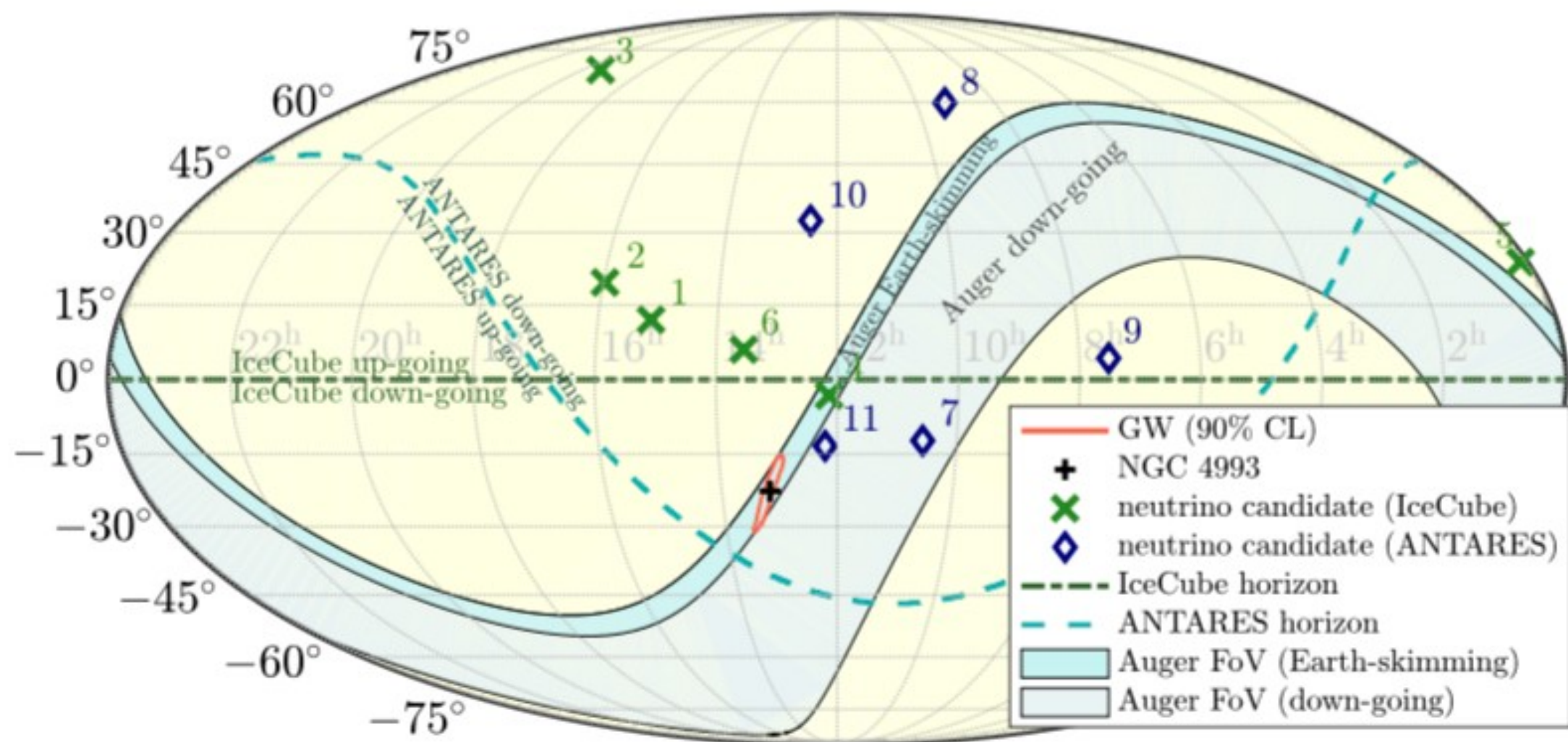
- ejection process with hadronic component
- cosmic-ray acceleration related to magnetar

GRAVITATIONAL WAVE FOLLOW-UPS (GW170817) : ANTARES-IC-AUGER

ANTARES:

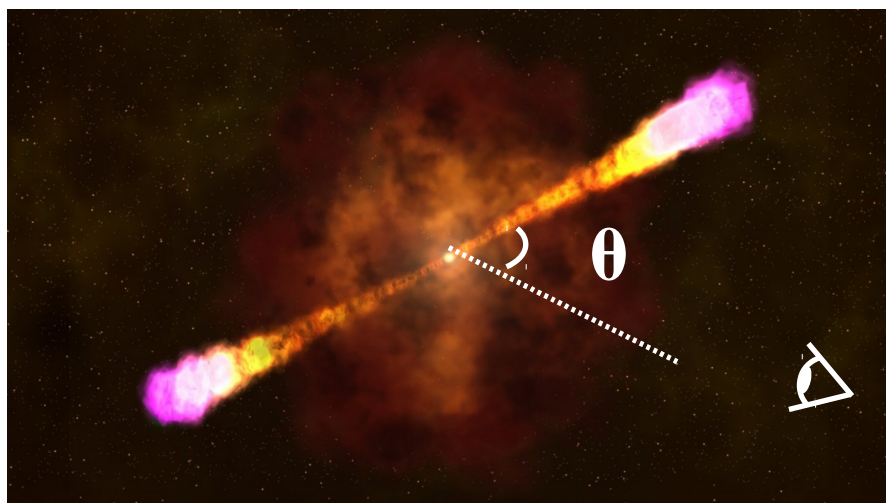
Search over ± 500 s and +14 days
Track + shower events (all flavors)

Over ± 500 s around the merger:

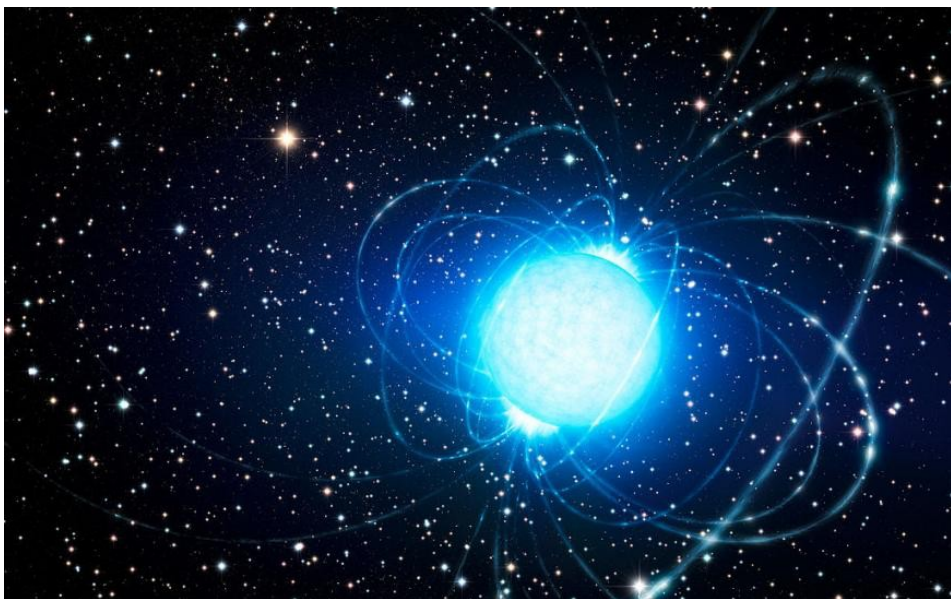


No counterpart over +14 days either

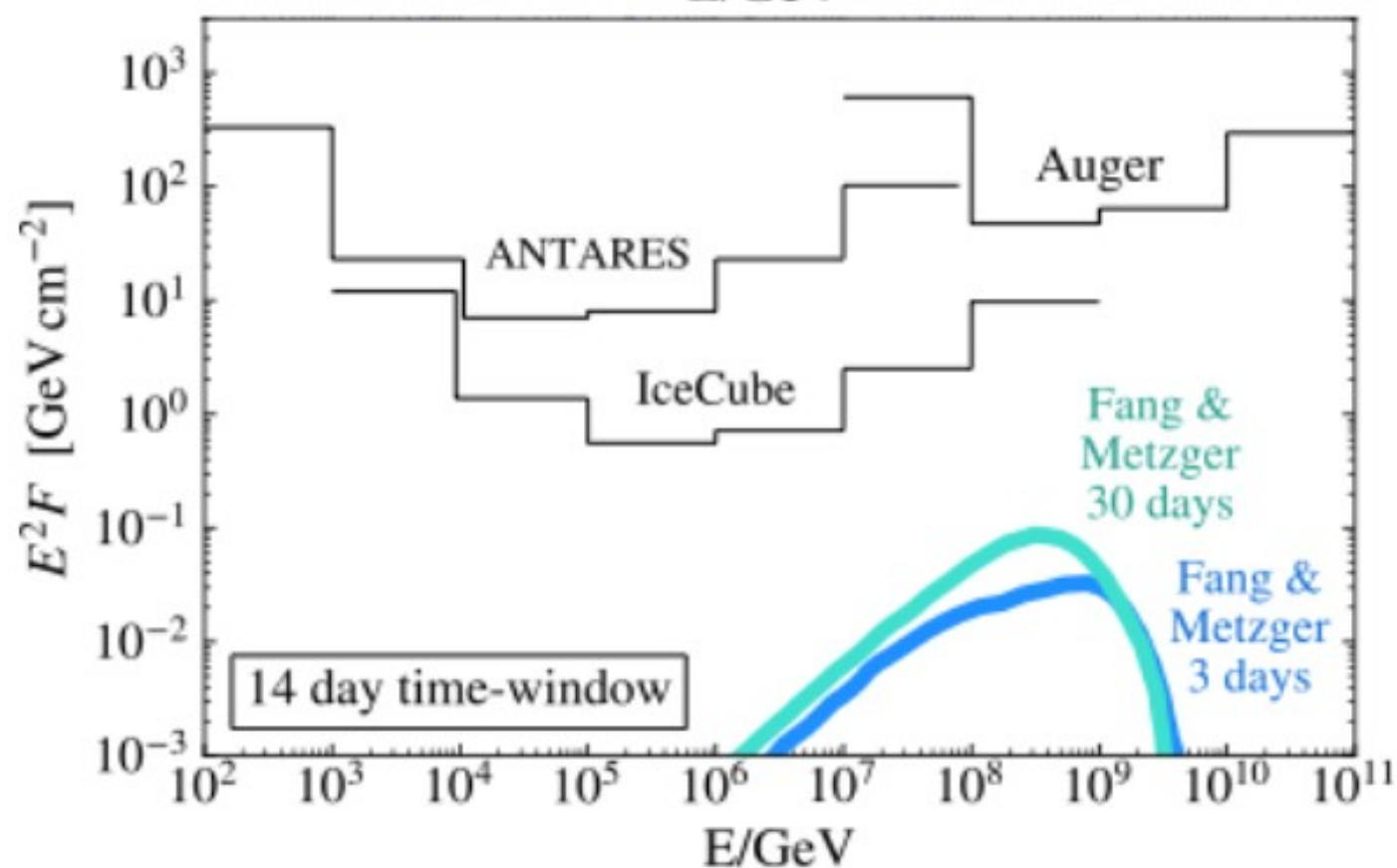
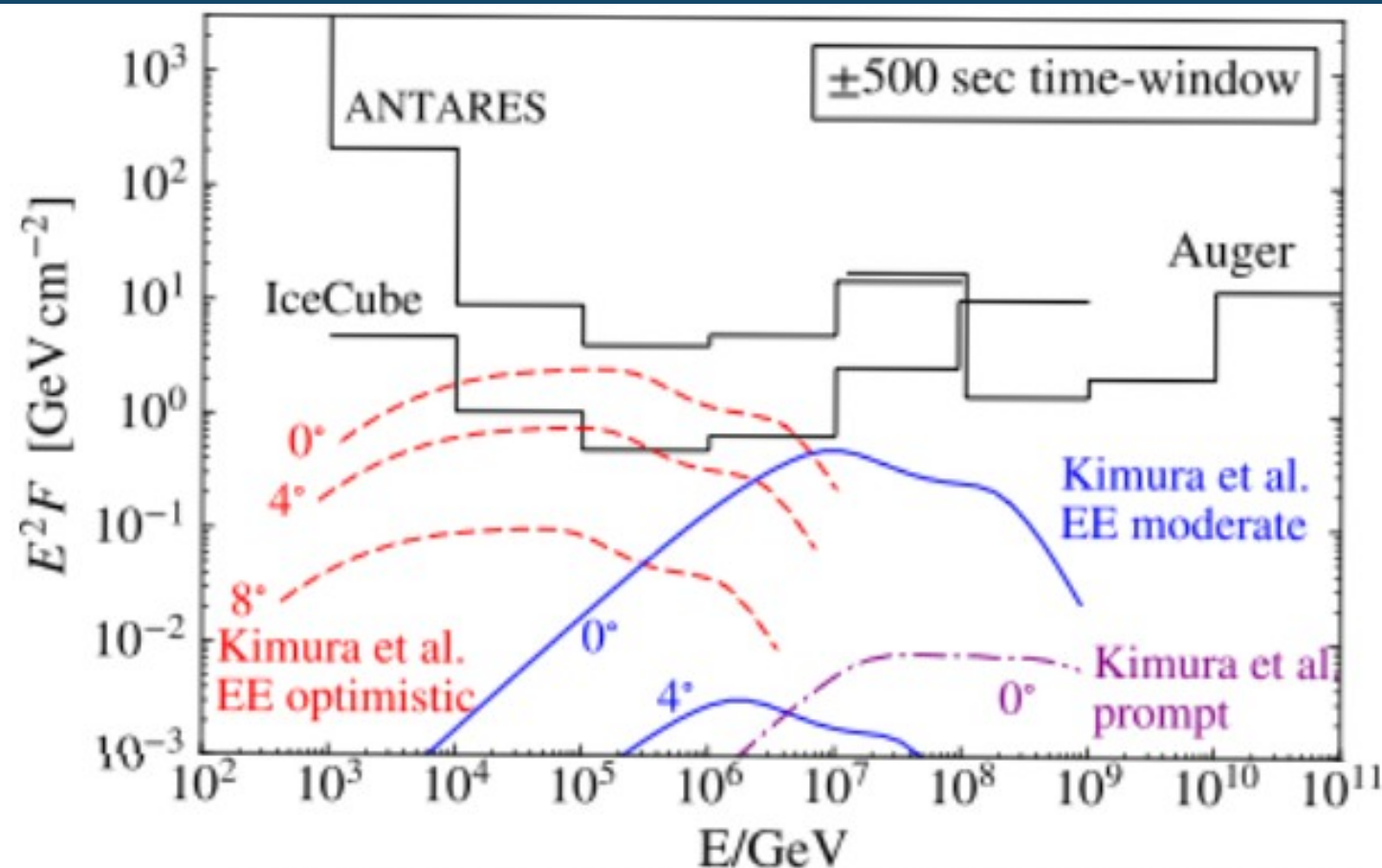
CONSTRAINTS ON THE SOURCE



Neutrino emission related to the prompt/extended high-energy emission (**Kimura et al., 2017**)



Fang & Metzger 2017:
Magnetar + ejected material from the coalescence:
↳ HE cosmic ray acceleration
↳ HE neutrino production





CONCLUSIONS:

- Multi-messenger astronomy era ! GWs + neutrinos
- Broad multi-messenger program - joint effort
- Increases discovery potential of neutrino telescopes
(by observing the same source with different probes)
- Refines detection efficiency (relaxed cuts if time coincidence required)
- Hopefully: High significance multi-messenger detections with neutrinos soon! (KM3NeT is coming)

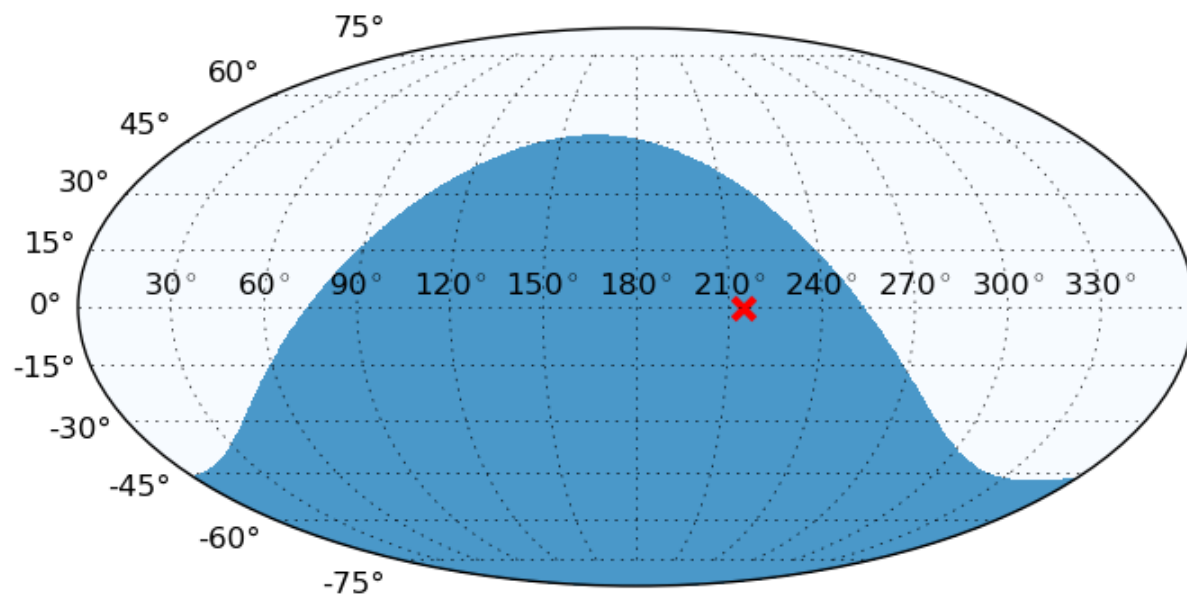
SEARCH FOR COUNTERPARTS TO ICECUBE ALERTS

- Search in real-time for neutrino counterparts to IceCube HESE+EHE ($>1\text{PeV}$) alerts sent through AMON to the public community (GCN network) since 03/2016

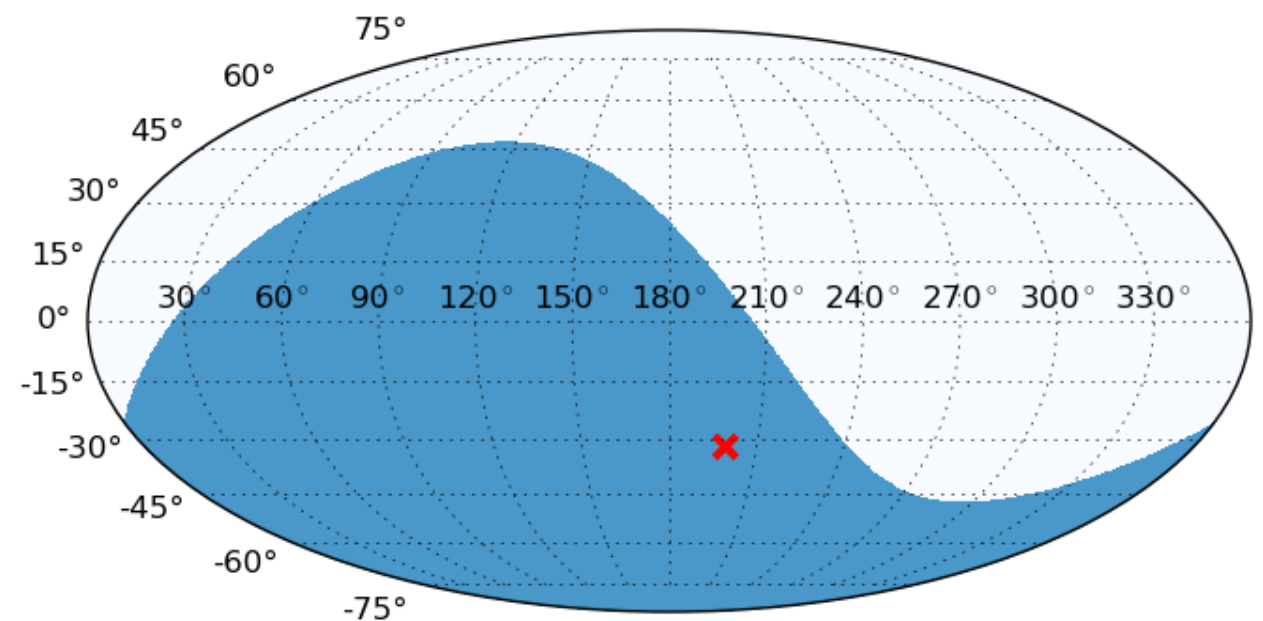
=> 18 alerts sent so far

=> 8 analyzed, + 5 retracted by IC, 5 not visible at the time of the alert as upgoing.

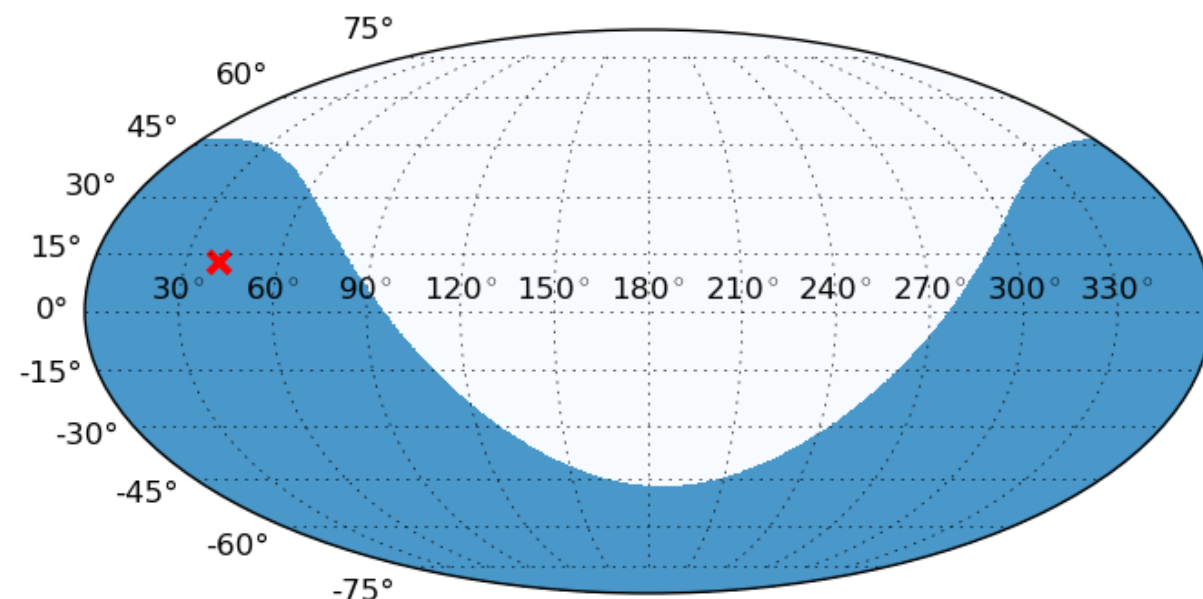
IC160731



IC160814



IC161103



No ANTARES event found in coincidence (ROI=2°, $\pm 500\text{s}$; $\pm 1\text{h}$)

⇒ 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 $E^{-2.5}$

KM3NET PERSPECTIVES

- Search for upgoing neutrinos at $\delta=-23\text{deg}$, $\text{RoI}=30\text{deg}^2$, within $\pm 500\text{s}$
(GW170817 ANTARES like optimization on the 3σ significance)

PRELIMINARY

- - Kimura optimistic
- Kimura moderate
- - Kimura prompt
- Cocoon model

