



Overview of ANTARES neutrino telescope: multimessenger results



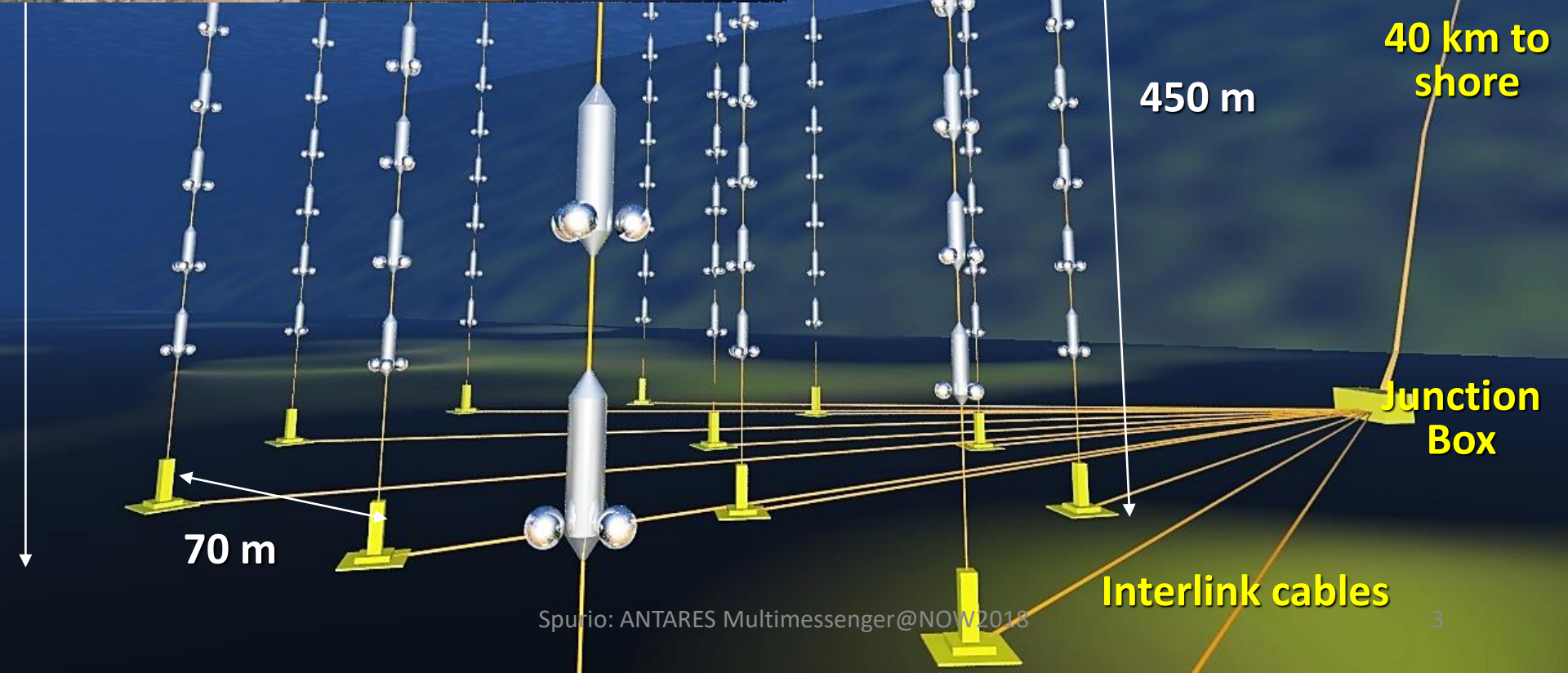
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maurizio.spurio@unibo.it





ANTARES

- Running since 2007
- 885 10" PMTs
- 12 lines
- 25 storeys/line
- 3 PMTs / storey



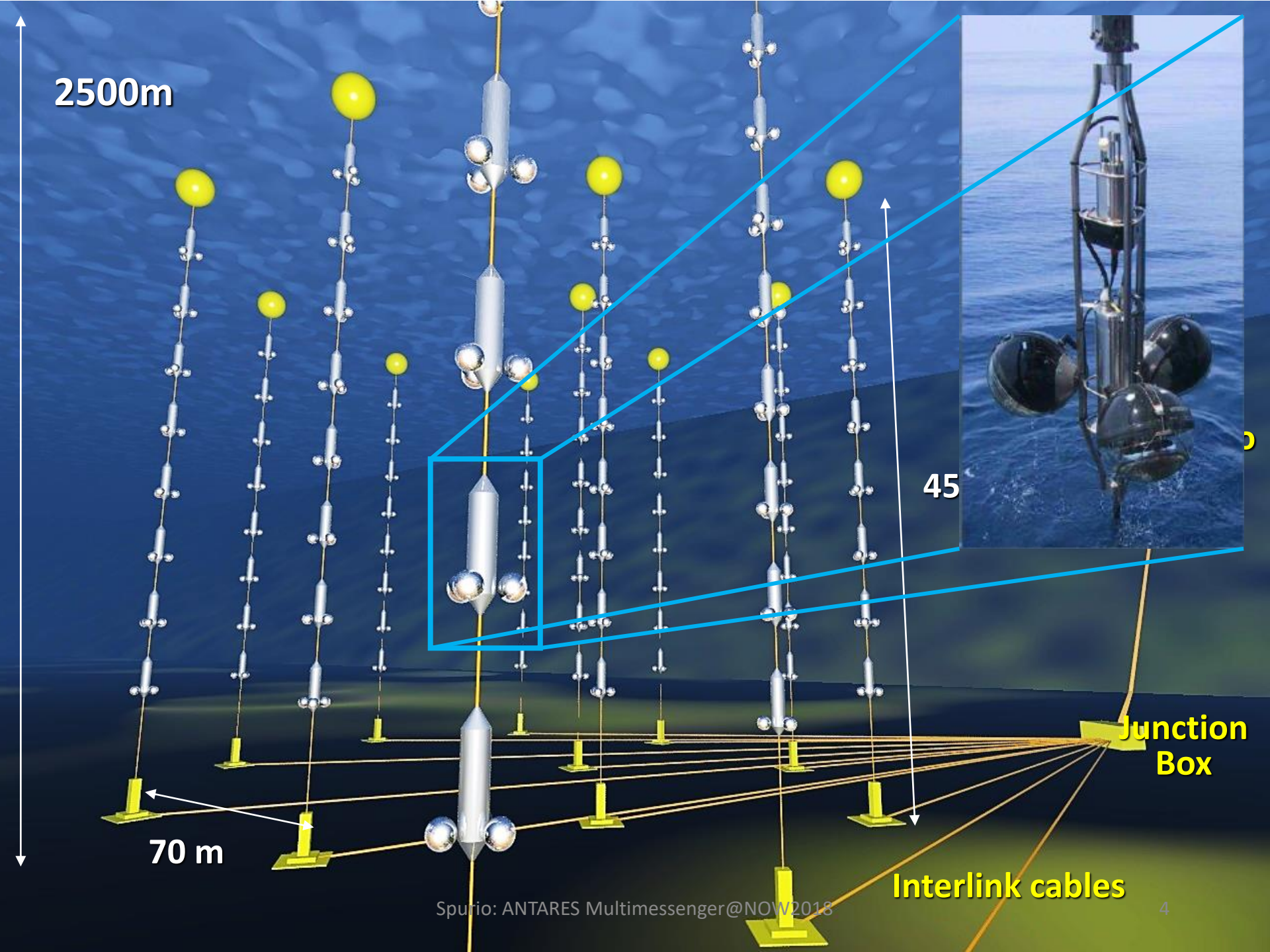
2500m

70 m

45

Junction Box

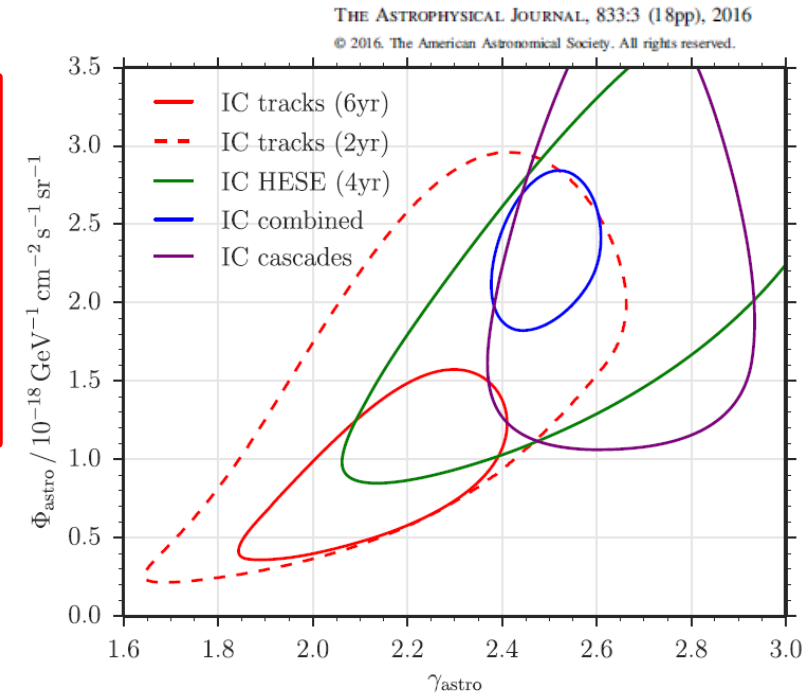
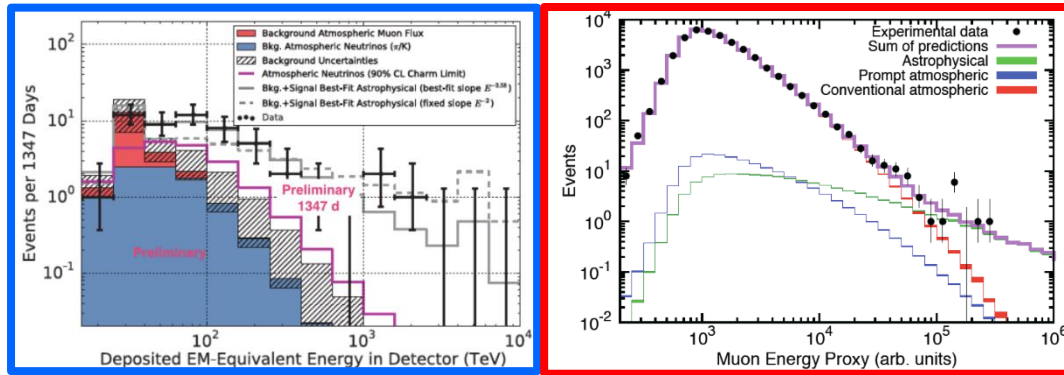
Interlink cables



Detecting cosmic neutrinos: a threefold way



(IceCube HESE and IceCube upgoing muons)



I. Point-like events, significant excess in the sky map. Based on measurement of the ν direction

II. Excess of HE neutrinos over the background of atmospheric events. Based on the estimation of the ν energy

III. Coincident event in a restricted time/direction windows with EM/ γ /GW counterparts. Relaxed ν energy/direction measurement + **transient/ multimessenger** information

I) ANTARES – Point Sources (Phys. Rev. D 96, 082001)

Sample:

- 2007 – 2015; livetime 2424 days
- Maximum likelihood method used to search for clusters of vs from sources
- Irreducible bck: **atmospheric neutrinos**
- All-flavour analysis: 7622 track-like, 180 shower-like neutrino candidates

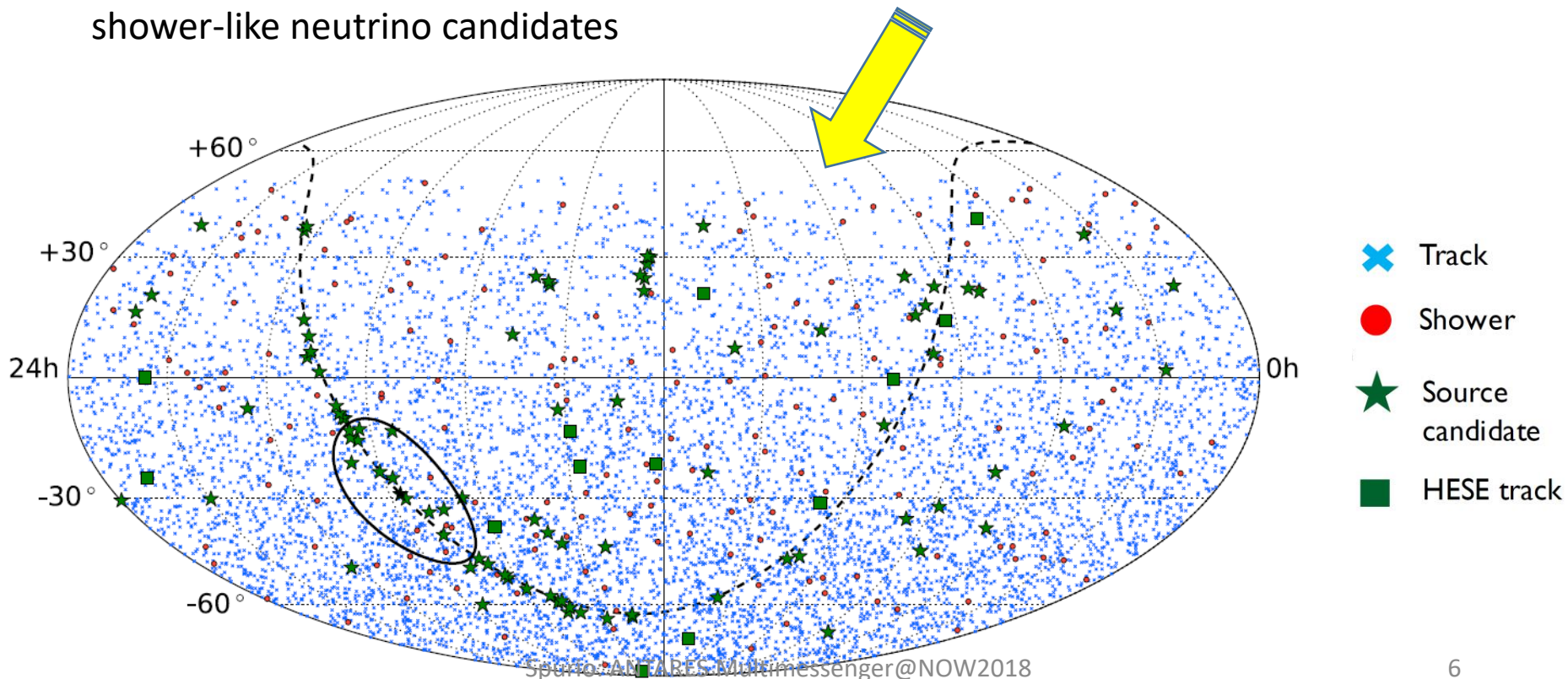
Full-sky search

1°x1° squares over ANTARES visible sky

Candidate list searches

106 known astrophysical objects (Pulsars, SNRs, ...), 13 IceCube HESE tracks

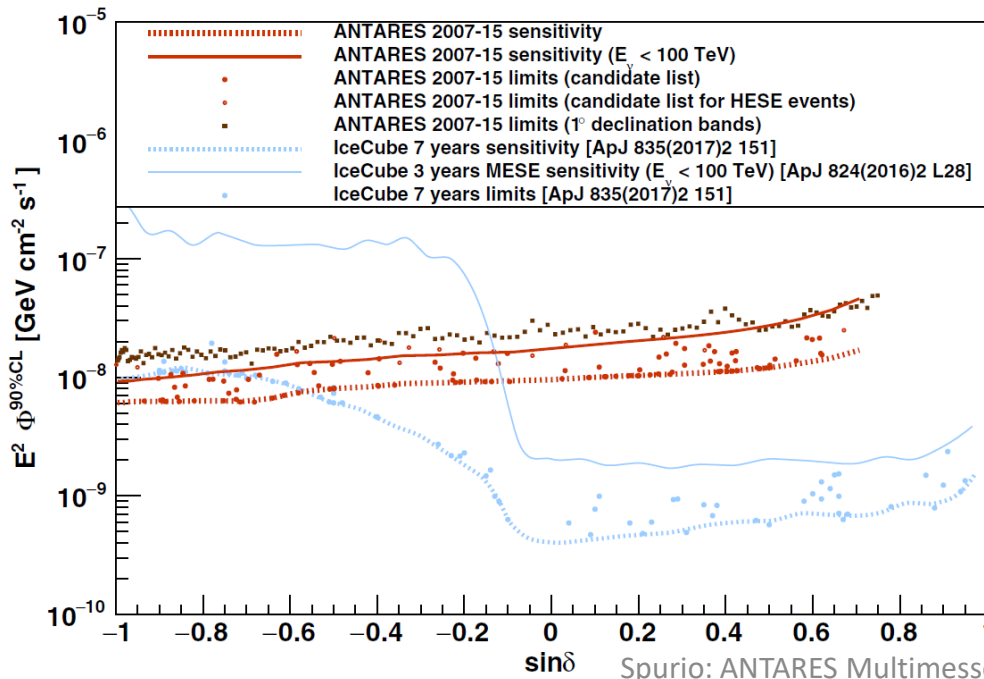
Next page 



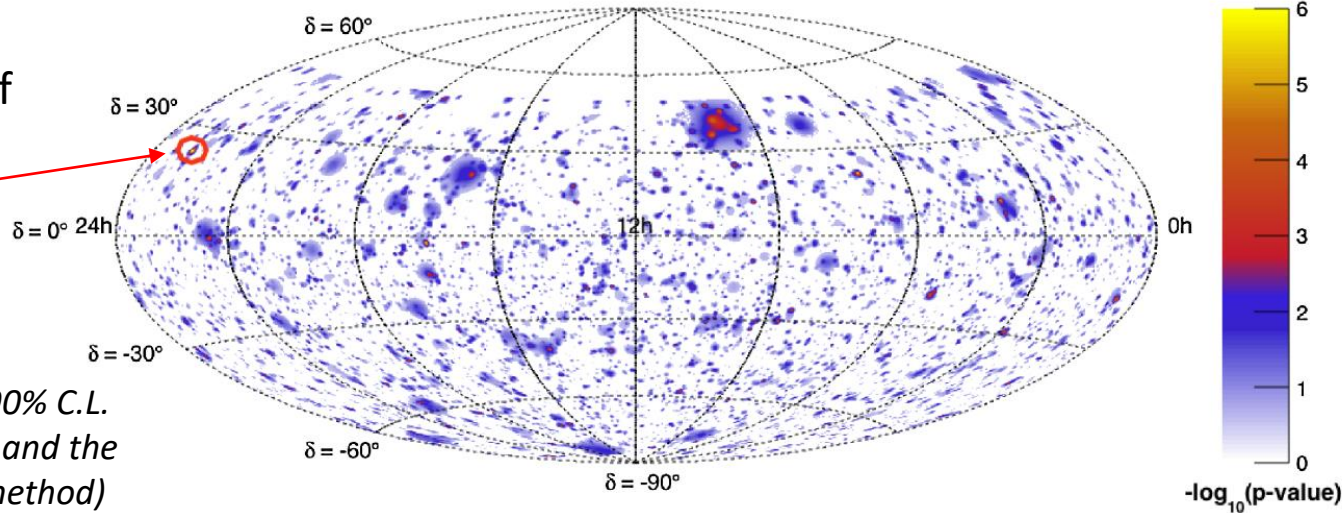
I) ANTARES – Point Sources (Phys. Rev. D 96, 082001)

Most significant cluster of the full-sky search (1.9σ post-trial significance)
 $\alpha = 343.8^\circ$ $\delta = 23.5^\circ$

Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches (Neyman method)



Spurio: ANTARES Multimessenger@NOW2018



Sky map in equatorial coordinates of pre-trial p-values

Most sensitive limits for a large fraction of the southern sky, especially at neutrino energies below 100 TeV

II) ANTARES – Diffuse flux (ApJL 853, L7 (2018))

Sample:

- 2007 – 2015; livetime 2450 days
- All-flavour analysis (track+showers)

Event selection chain + energy-related cut applied to

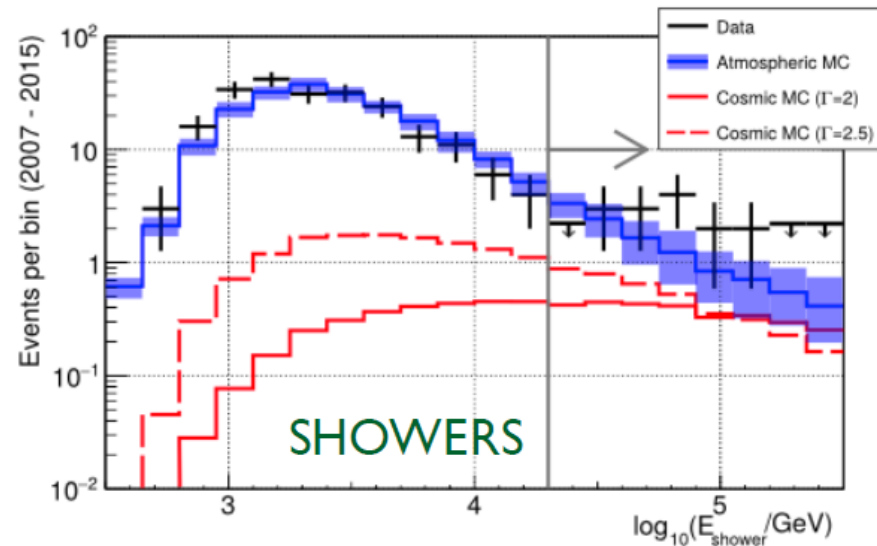
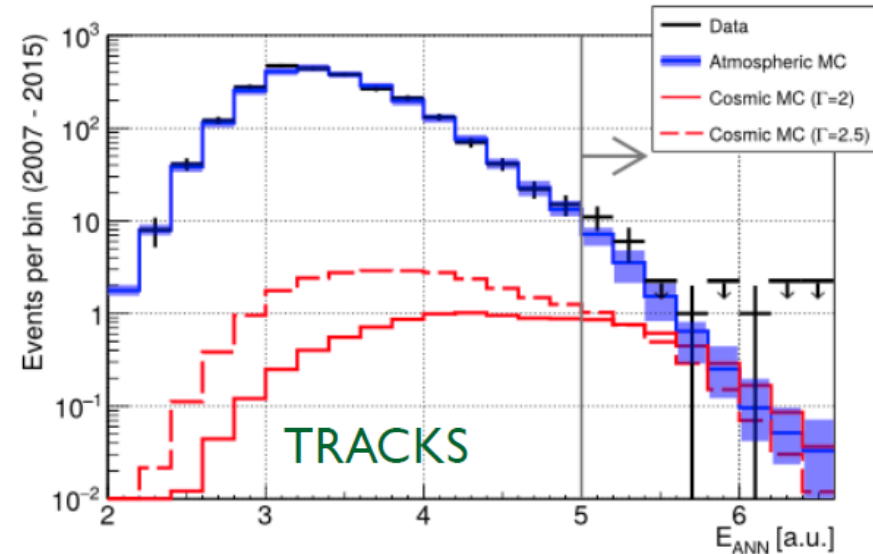
- obtain a high-purity neutrino sample
- maximise sensitivity

Signal modeled according to the IceCube flux

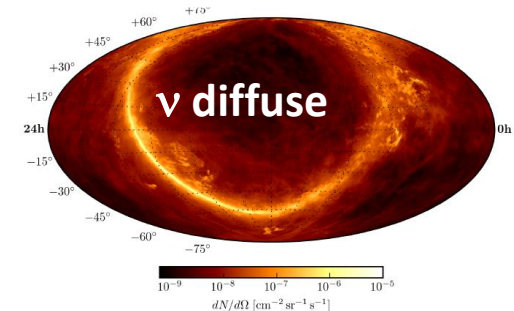
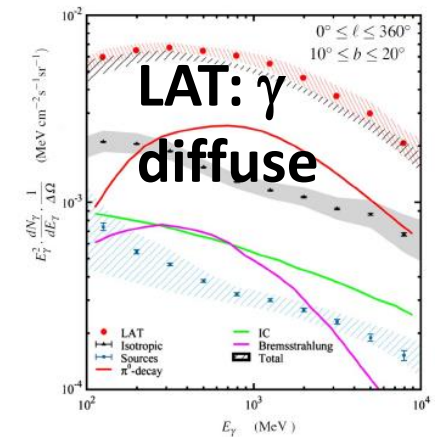
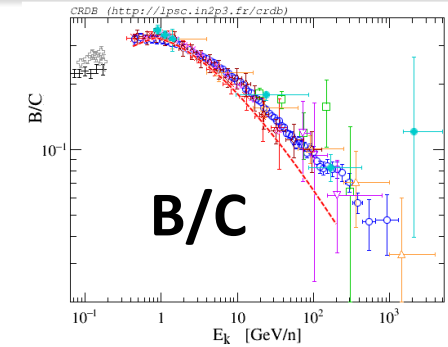
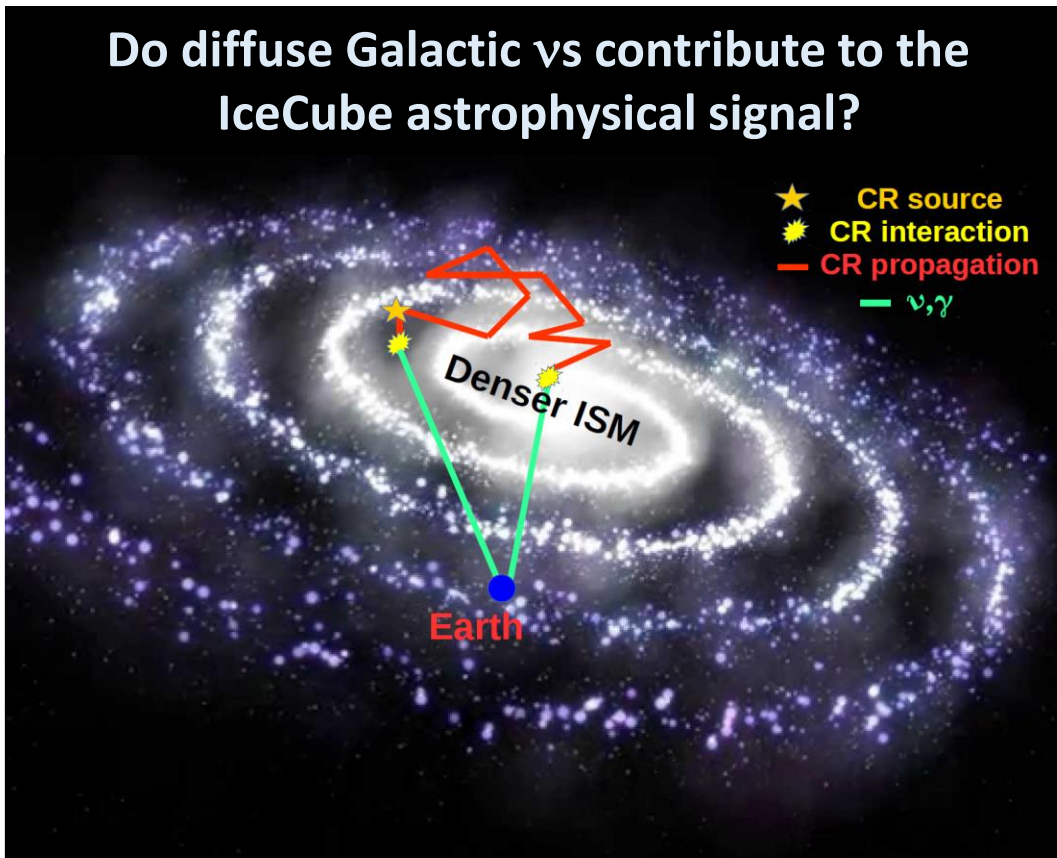
Result:

33 events (19 tracks + 14 showers) in data
 24 ± 7 (stat.+syst.) events background in MC

1.6σ excess, null cosmic rejected at 85% CL



II) CR propagation in the Milky Way: γ and ν .

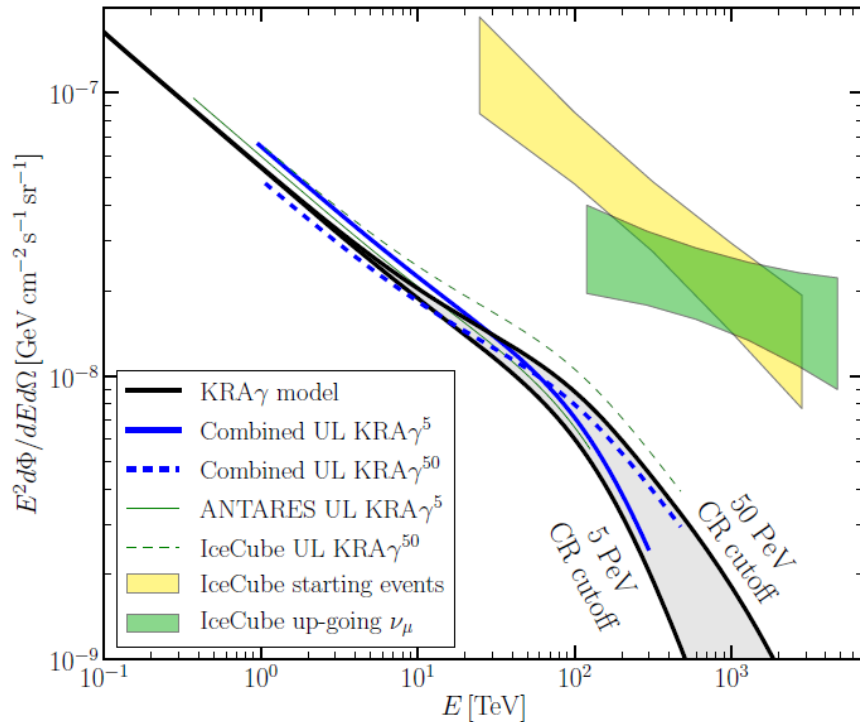


- Neutrinos allow testing **CRs propagation**
- Dense matter regions boost γ and ν fluxes
- Models can be tuned to γ and CR observations
- Northern Hemisphere optimal point of view for galactic CR

II) ANTARES+ IceCube from GP

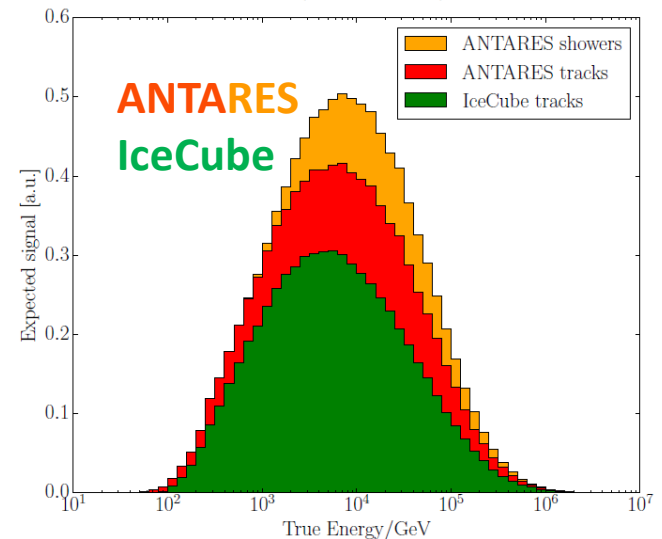
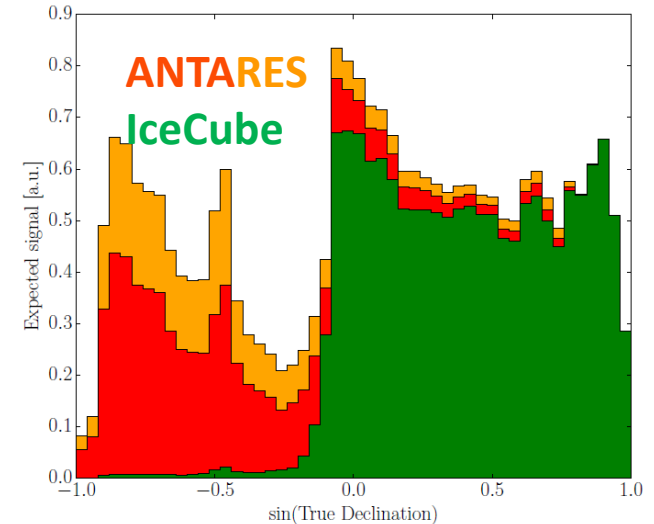
(ANTARES) PRDD96 (2017) 062001
ANTARES+IC, arXiv:1808.03531

Combined U.L. at 90% CL (blue line) on the 3-flavor neutrino flux of the KRA γ model (5-50 PeV cutoff)



Result: total flux contribution of **diffuse Galactic neutrino** emission <8.5% of the total diffuse IC astrophysical signal ($E_{\nu} > 30$ TeV) [ApJ 809:98(2015)].

Stacked expected signal vs. δ (top) and energy (bottom). Colors represents the relative contribution to the sensitivity

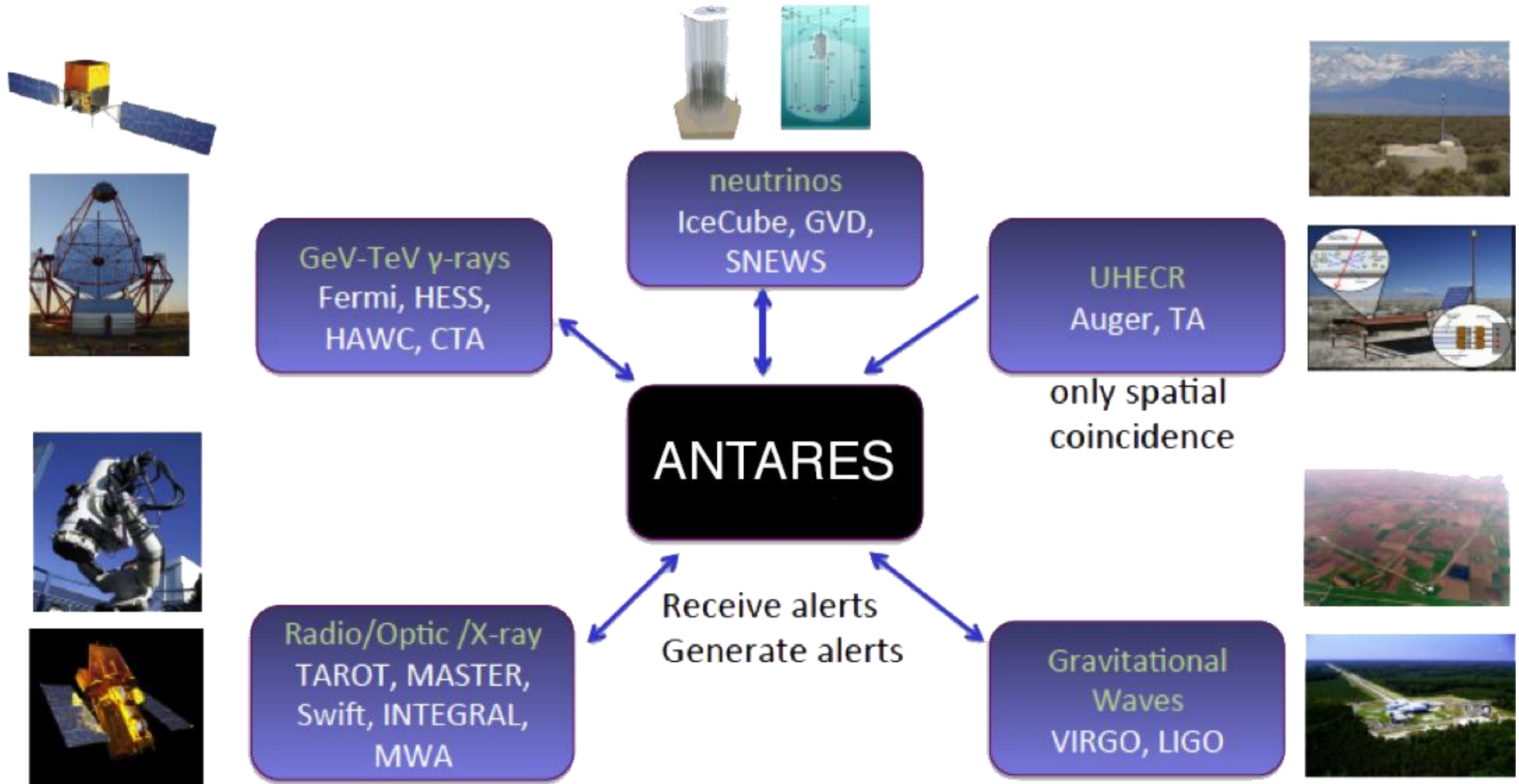


III) ANTARES – Multimessenger



* participation to **AMON** 
Astrophysical Multimessenger Observatory Network

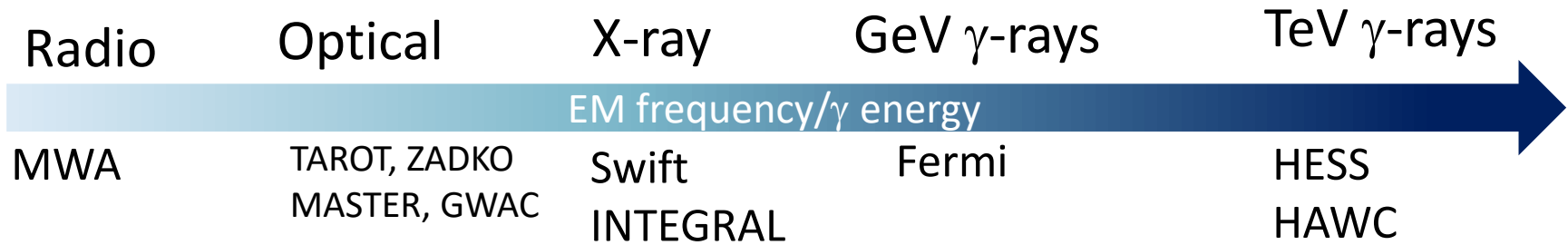
Gamma-ray Coordinates Network (GCN) <https://gcn.gsfc.nasa.gov/>



III) ANTARES multimessenger and transients

| Object(s) | Messenger | Telescope |
|---------------------------------|--|--|
| Flaring Blazars | γ -rays | FERMI/LAT |
| Flaring X-ray binaries | X & γ -rays | Swift, MAXI, RXTE/ASM, Fermi/LAT |
| Flares from Mrk 421 and Mrk 501 | γ -rays (TeV) | HAWC |
| HAWC 2-year catalog | γ -rays (TeV) | HAWC |
| Gamma Ray Bursts | γ -rays | Swift, Fermi, GCN |
| IceCube Events | ν | IceCube |
| UHECR | CRs | Auger, TA |
| Galactic Plane | CR & γ-rays | Fermi, Milagro |
| Fast Radio Bursts | Radio | SUPERB@Parkes |
| Fermi Bubbles | γ -rays | Fermi |
| Galactic Plane | CRs | HAWC |
| BH/NS mergers | Gravitational waves + EM + γ-rays+ ν | Ligo/Virgo (+ IceCube and Pierre Auger Observatory) |

ANTARES neutrino alerts



ANTARES real time alerts:

- Time to send an alert: ~ 5 s
- Track median angular resolution: 0.5°
- 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, $\sim 3-4$ ev/yr



Sent neutrino alerts

(2009-2018)

277 to robotic telescopes
 +15 to Swift
 +8 to INTEGRAL
 +22 to MWA (radio)
 +2 to HESS



JCAP 02 (2016) 062

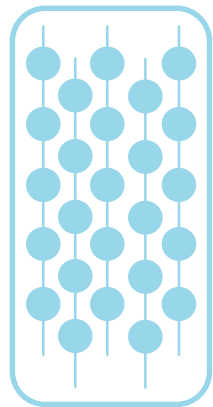


Croft S. et al, ApJ 820 (2016) 24

ANTARES – external alerts follow up

Offline studies

- Calibrated geometry
- Calibrations
- More refined tracking

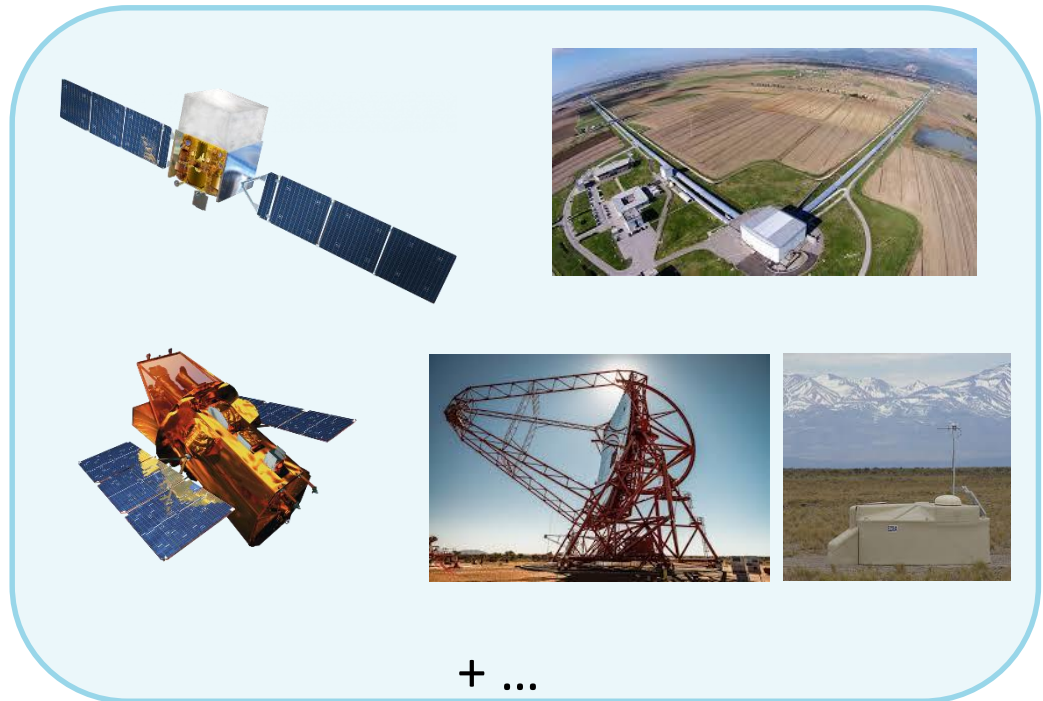


Online alert



Prompt search

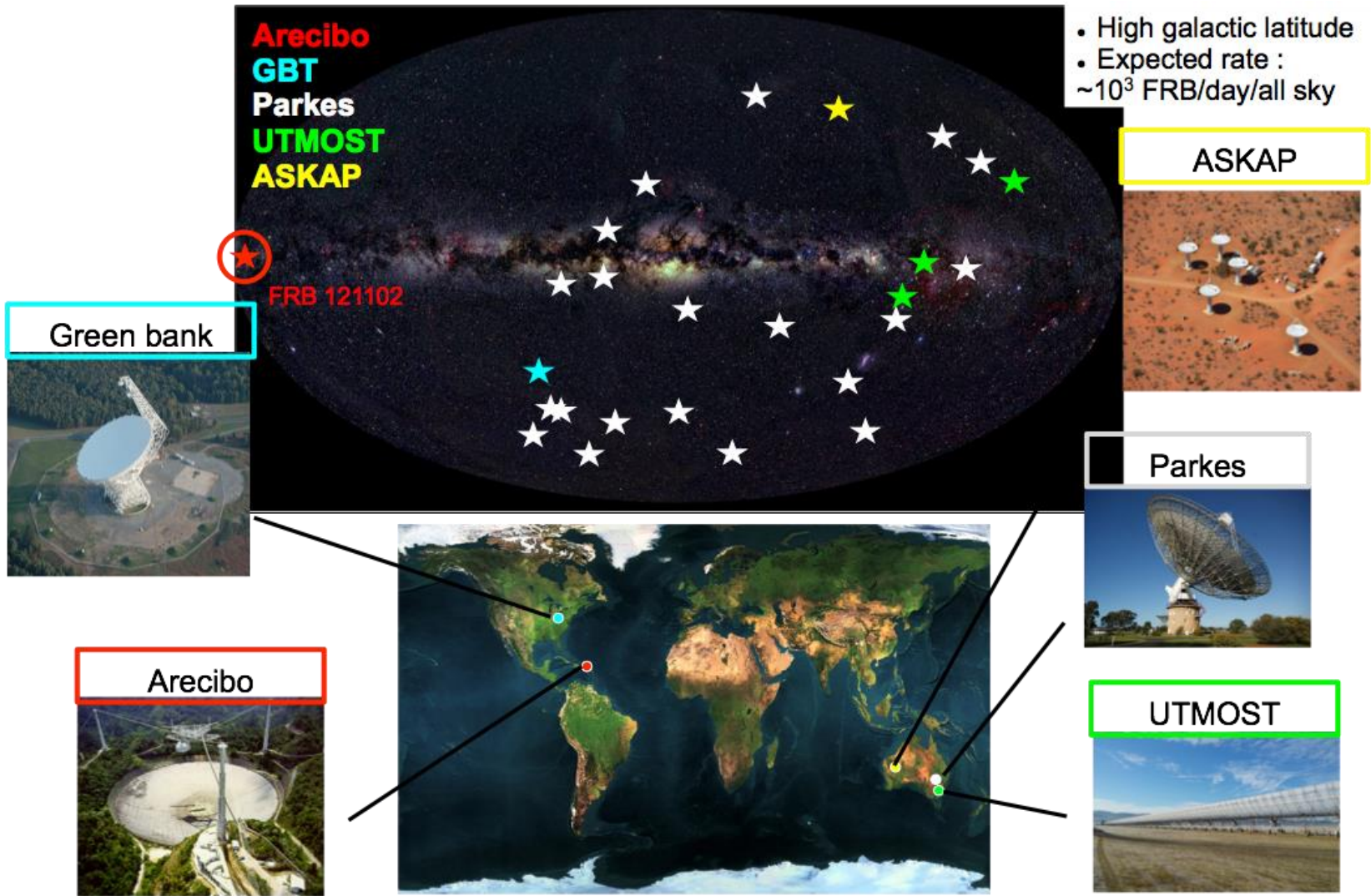
- Online tracking
- Default geometry
- Prompt response (minutes)
- (Lower trigger threshold)



Fast Radio Bursts



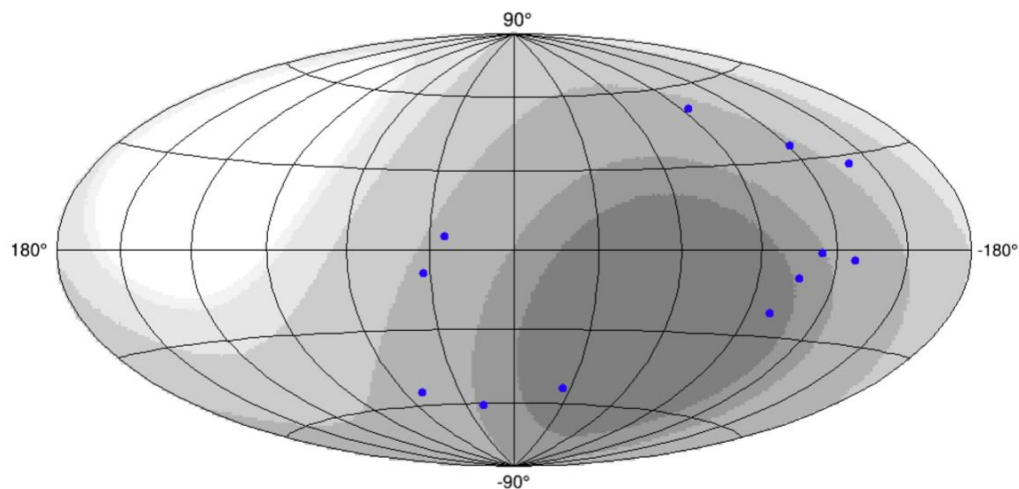
Bhandari S. et al, MNRAS, **475** (2018) 1427
Petroff E et al., MNRAS, **469** (2017) 4465



Fast Radio Burst

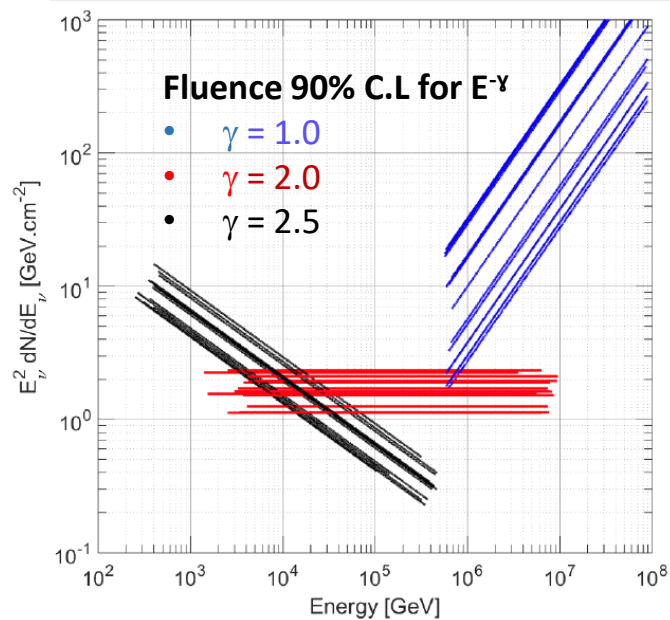


arXiv:1807.04045
Submitted to MNRAS



| FRB | z_{DM} | T_0 (UTC) | RA ($^{\circ}$) | dec ($^{\circ}$) | radio telescope |
|--------|----------|----------------|----------------------|-----------------------|-----------------|
| 131104 | 0.59 | 18:03:59 | 101.04 | -51.28 | Parkes |
| 140514 | 0.44 | 17:14:09 | 338.52 | -12.31 | Parkes |
| 150215 | 0.55 | 20:41:41 | 274.36 | -4.90 | Parkes |
| 150418 | 0.49 | 04:29:04 | 109.15 | -19.01 | Parkes |
| 150807 | 0.59 | 17:53:55 | 340.10 | -55.27 | Parkes |
| 151206 | 1.385 | 06:14:56 | 290.36 | -4.13 | Parkes |
| 151230 | 0.76 | 17:03:26 | 145.21 | -3.45 | Parkes |
| 160102 | 2.13 | 08:28:38 | 339.71 | -30.18 | Parkes |
| 160317 | 0.70 | 08:30:58 | 118.45 | -29.61 | UTMOST |
| 160410 | 0.18 | 08:16:54 | 130.35 | 6.08 | UTMOST |
| 160608 | 0.37 | 03:52:24 | 114.17 | -40.78 | UTMOST |
| 170107 | 0.48 | 20:05:45 | 170.79 | -5.02 | ASKAP |

- Jan. 2013 – Jan. 2017 analysis.
- 16 FRB (Parkes, UTMOST, ASKAP) \rightarrow 12 in the FoV during the data taking.
- ± 6 h search period in 2° .
- Event selection optimization – 1 seen neutrino = 3σ discovery.
- No events found \rightarrow limits set.

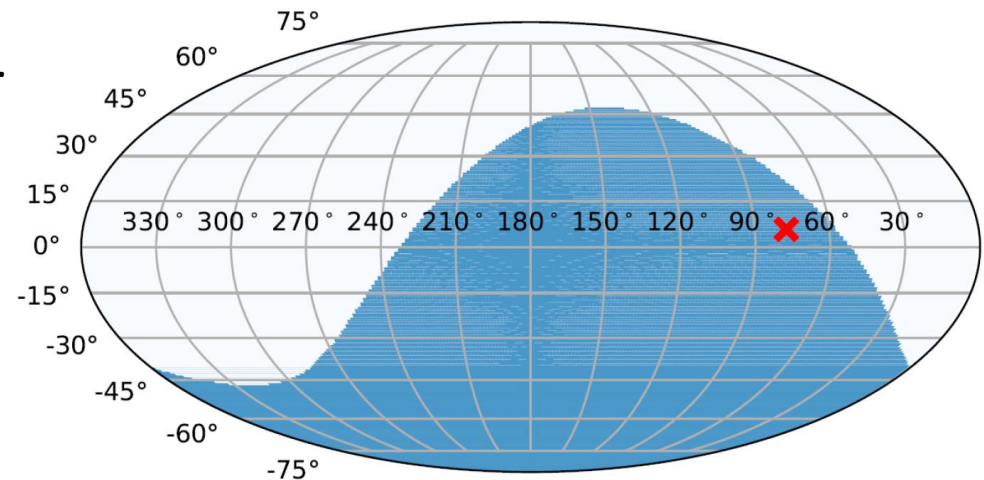


Neutrino emission from TXS 056+056: Online follow-up associated with IceCube-170922A

- On September 22, 2017 a high-energy neutrino was observed by IceCube, selected by the Extremely High Energy online filter
- γ -rays (*Fermi*-LAT, MAGIC) and other EM observations were reported, indicates that a blazar, **TXS 0506+056**, may be the source of HEN (*Science* **361**, 137 (2018)).
- IceCube find an excess of HENs at TXS 0506+056 position between 9/2014 and 3/2015 at 3.5σ , independent of the 2017 flaring episode. (*Science* **361**, 147-151 (2018)).

ApJ 863 (2018), L30

- For ANTARES, the direction of IC170922A was 14.2° below horizon.
- Use of a fast online algorithm that selects only upgoing candidates
- No upgoing ν candidate was recorded in a cone of 3° within ± 1 h (ATEL #10773, 24/9) and ± 1 day by the online reconstruction.
- ν fluence upper limit set for E^{-2} ($F < 15 \text{ GeV cm}^{-2}$ integrated from 3 TeV-3 PeV) and $E^{-2.5}$ spectra

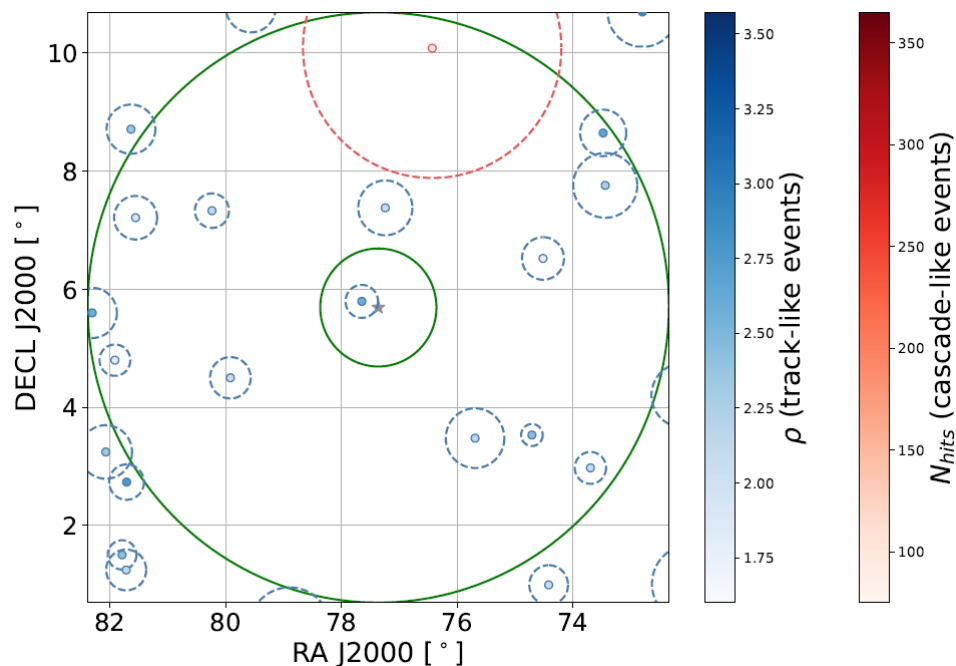


ANTARES visibility map of IC170922A in equatorial coordinates. The sky region below the horizon (=upgoing events) at the alert time is shown in blue

Neutrino emission from TXS 056+056: Time-integrated search

- The same maximum likelihood ratio used in PS searches, +2016/17 (PRD96, 082001)
- Expected background from the source in 3136 days livetime:
 - 0.23/deg² for track-like
 - 0.005/deg² for shower-like events
- # of events fitting the likelihood signal function for the source: $\mu_{\text{sig}} = 1.03$
- **Pre-trial p-value of 3.4%**
(post-trial 87%)
- 1 track (12/12/2013) 0.3° from the source position
- Flux U.L. (@100 TeV) for E⁻²: 1.6x10⁻¹⁸ GeV⁻¹ cm⁻² s⁻¹ in the range [2 TeV-4 PeV]
- In the list of 107 pre-selected sources, only two have smaller p-value

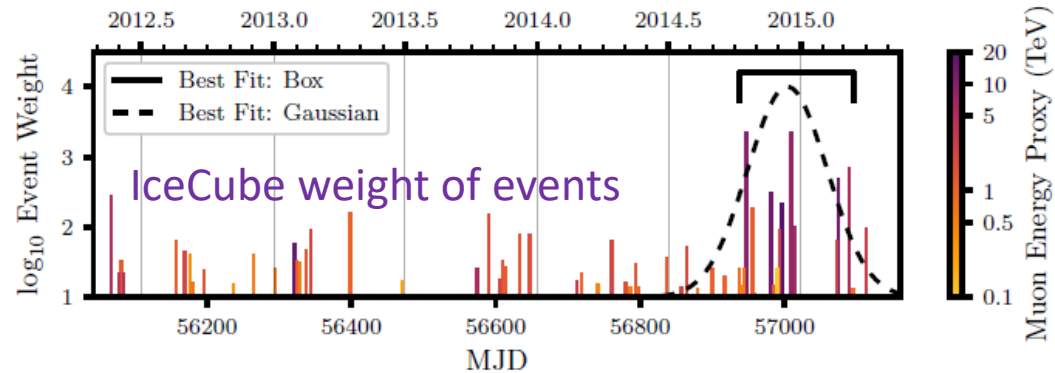
ApJ 863 (2018), L30



Distribution of the 13 tracks +1 shower events in the (RA, δ) coordinates around (radius=1° and 5°) the position of TXS 0506+056. The dashed circles around the events indicate the angular error estimate.

Neutrino emission from TXS 056+056: Search for neutrinos in the 2015 bursting period

ApJ 863 (2018), L30



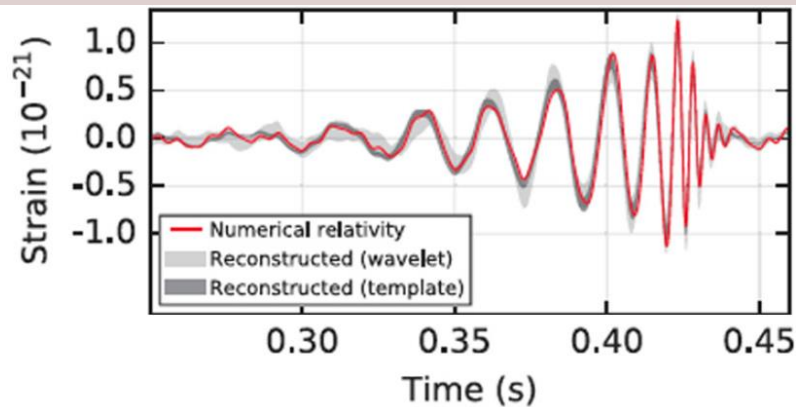
- The IceCube time-dependent analysis contains a significant excess (two time-window shapes) centered on MJD 57004
- We use a time-dependent analysis (developed to correlate ν 's to X-rays and γ -rays as in JCAP04 (2017), 019) that reduces by a factor of 2-3 the signal required for a discovery with respect to a time-integrated search
- Time window defined by the IceCube Gaussian- and box-shaped flares
- Relaxed cuts: more low-energy events accepted both in signal and background (background a x4 factor higher)
- Results: **no events found during flares**. Within 2° from the source, 10 background events expected, 13 events found in data. None of them lies in the flaring period.

Gravitational Waves (GW) + HE Neutrinos (HEN)

Short GRB

(Merger of Black Holes/Neutron Stars)

- **GW: 100 Mpc**
[LIGO/VIRGO, ApJL, L21 (2016)]

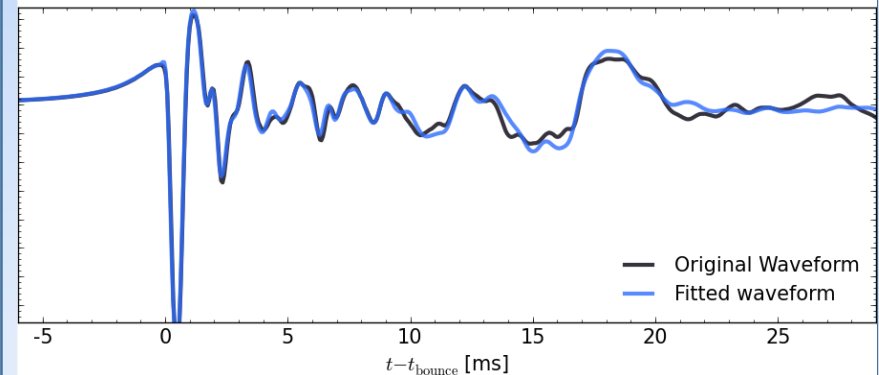


- **HEN: 10 Mpc (ANTARES)**
 [ANTARES, JCAP 06 (2013) 006]

Long GRB

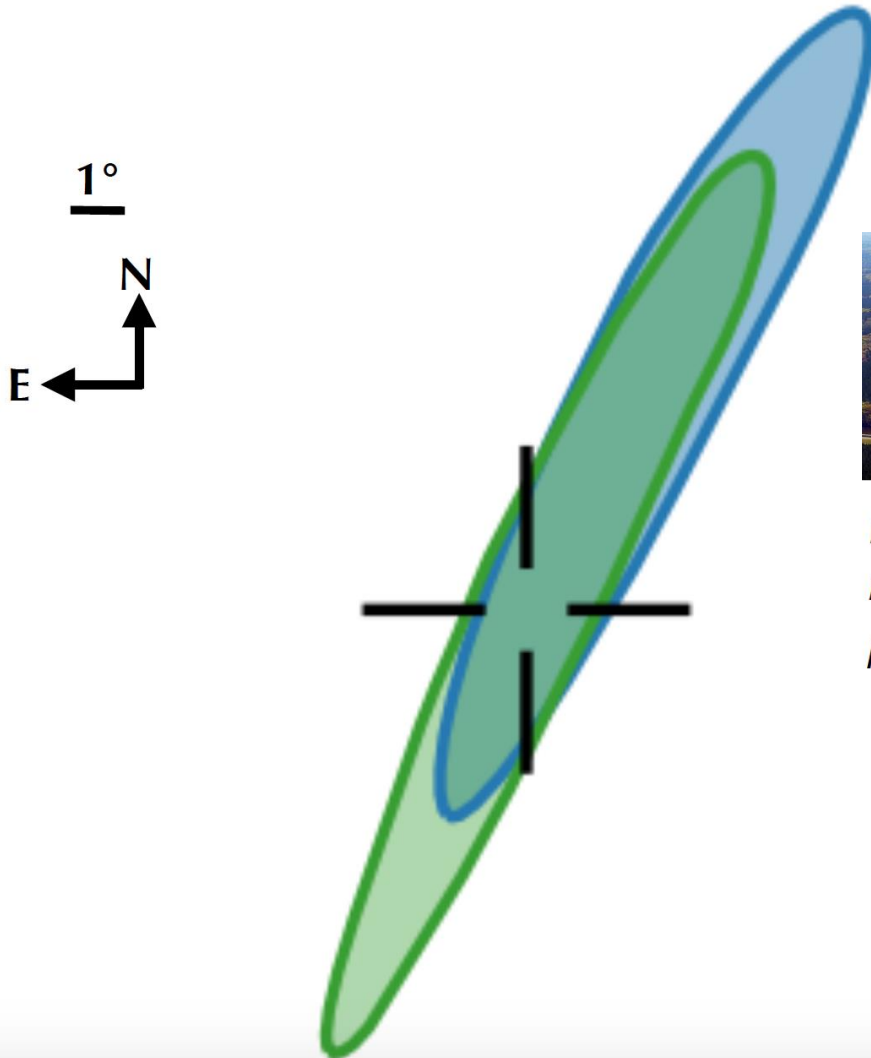
(Collapsars - massive star collapse)

- **GW : realistically Mpc**
[e.g. Gossan et al., PRD93 042002 (2016)]



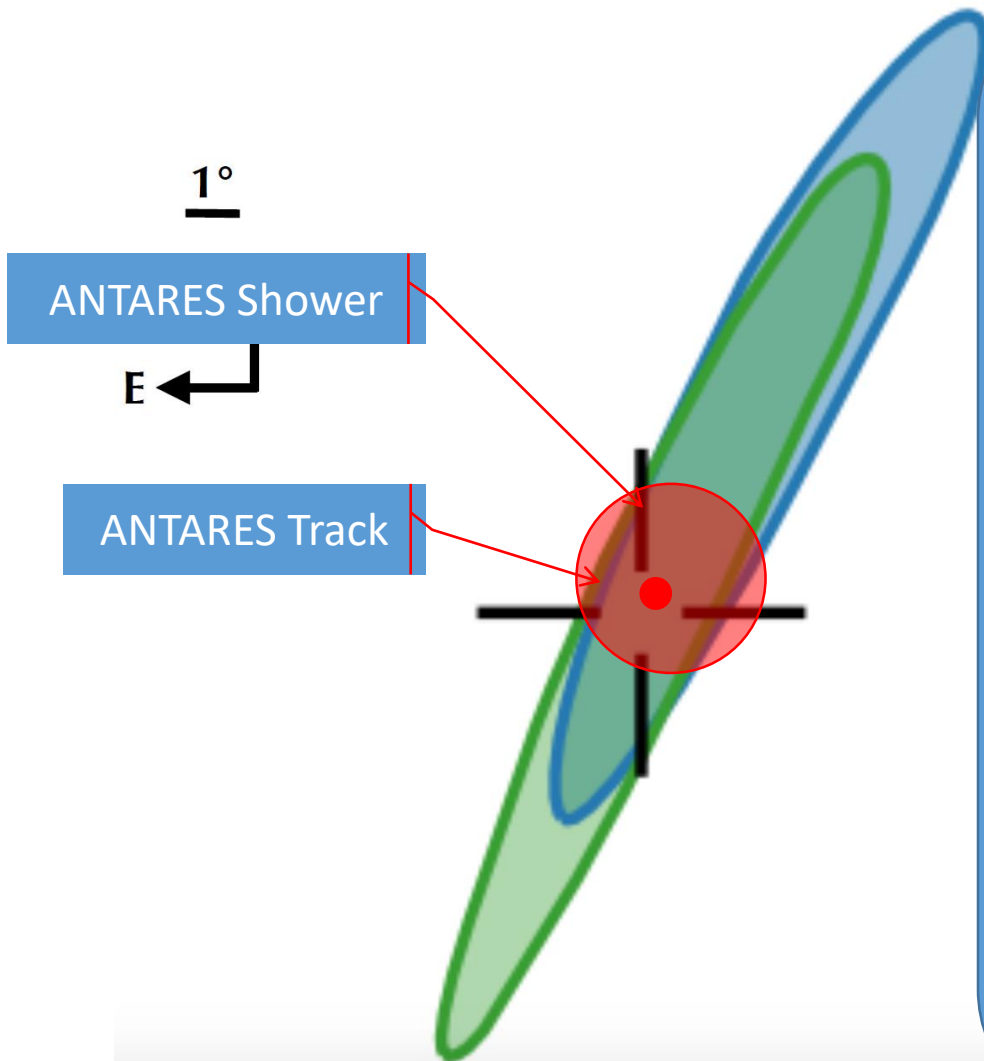
- **HEN 20 Mpc (ANTARES)**
 [ANTARES, JCAP 06 (2013) 006]

Gravitational Waves (GW) + HE Neutrinos (HEN)



*Error box of GW170817
reconstructed with two different
pipelines ($\sim 30^{\circ 2}$)*

Gravitational Waves (GW) + HE Neutrinos (HEN)

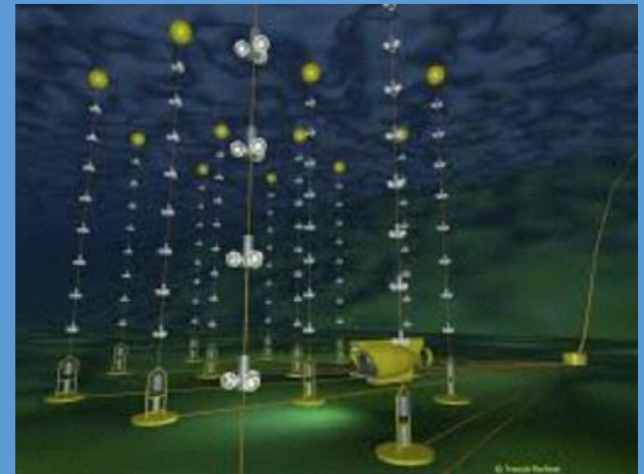


ANTARES (2020)-
KM3NeT(>2020)

Field-of-view: 2π sr

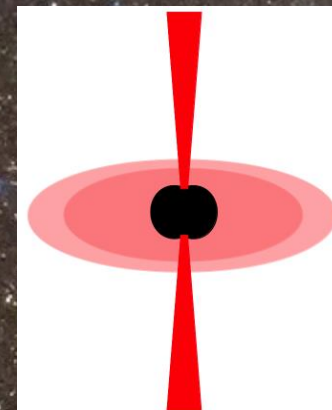
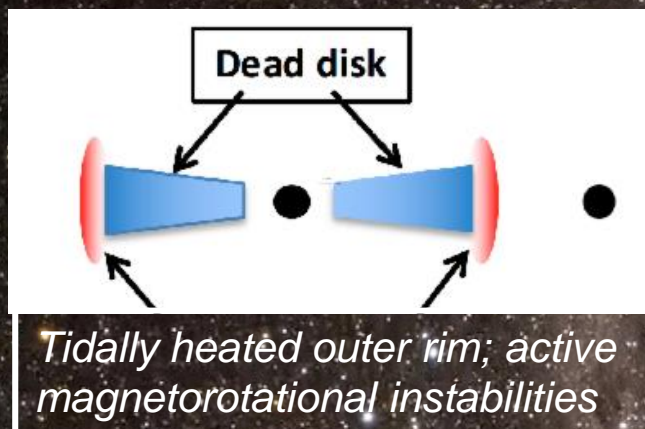
Angular resolution:

- $<0.5^\circ$ (tracks)
- 2° - 3° (showers)






Searching for HEN from BBH coalescences (O1-O2)

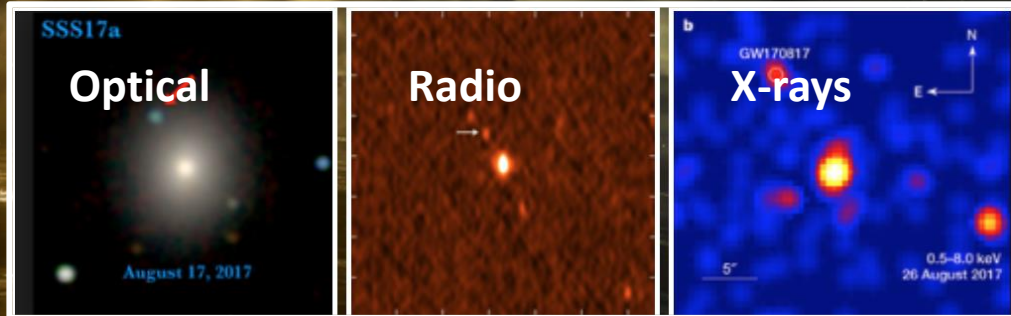
HEN emission coincident with GW signals expected ?
If hadronic/magnetic environment



Different ANTARES analyses, no HEN +GW, Upper Limits produced:

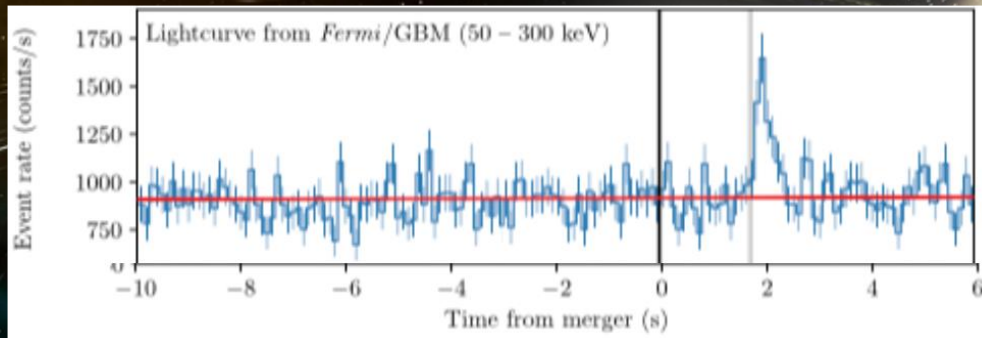
- **GW150914 (with IC):** HEN emission < 20% of GW energy;  PRD93 (2016) 122010
- **GW151226+LVT151012 (with IC):** upgoing, HEN emission < 1-15% of GW energy;  PRD96 (2017) 022005
- **GW170104:** first full sky search, optimization.  EPJC 77(2017) 911

Binary NS Mergers and HEN?

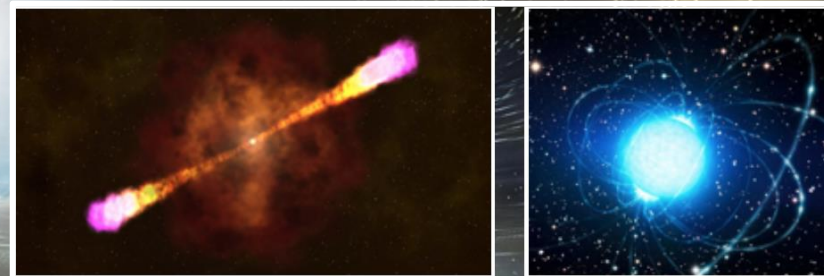
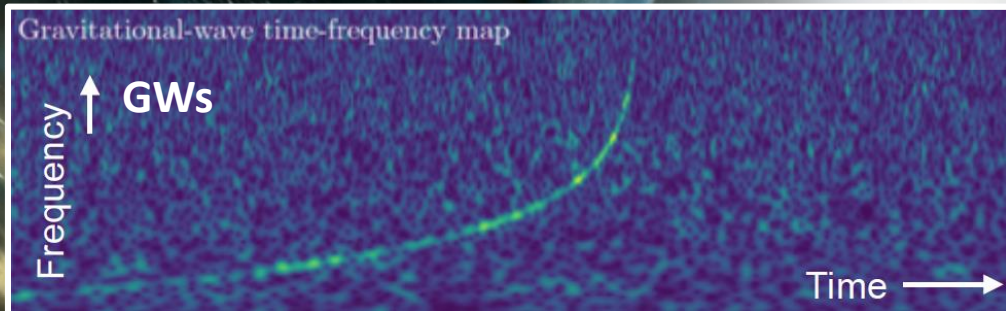


GW170817

ν ?



- Prompt neutrino production on-axis
- Off-axis scenario, neutrino-production related to the extended γ -ray emission (Kimura et al. 2017).
- (Later) Extended emission from a relativistic wind with its rotational energy, (Fang&Metzger. ApJ 2017).



GW170817 followup : constraints on the source - prompt emission (+ AUGER, IceCube)

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<https://doi.org/10.3847/2041-8213/a90aed>



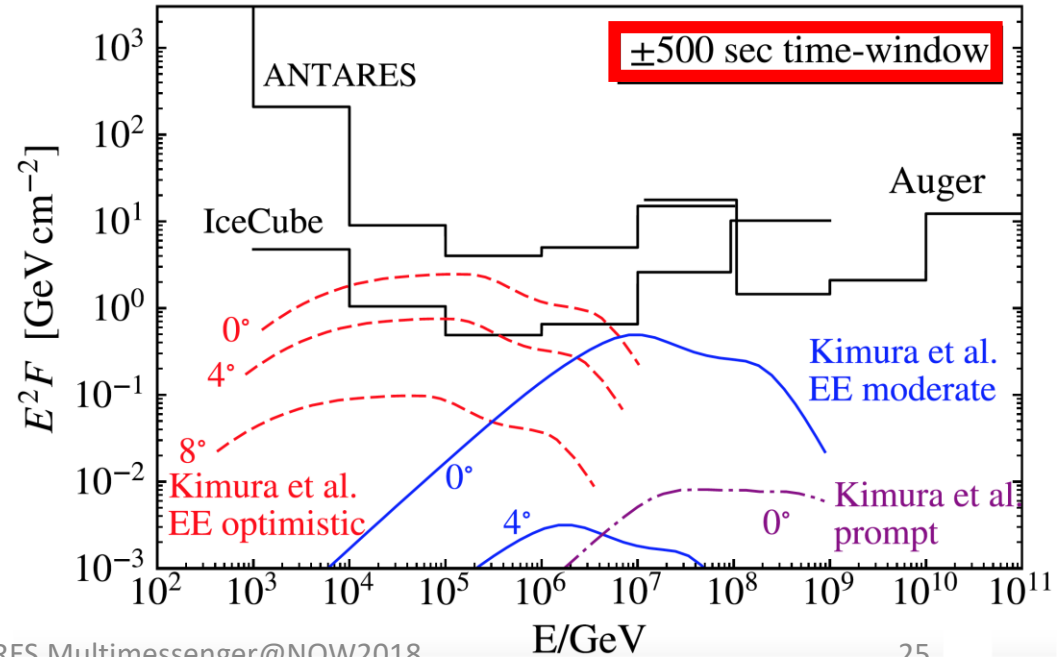
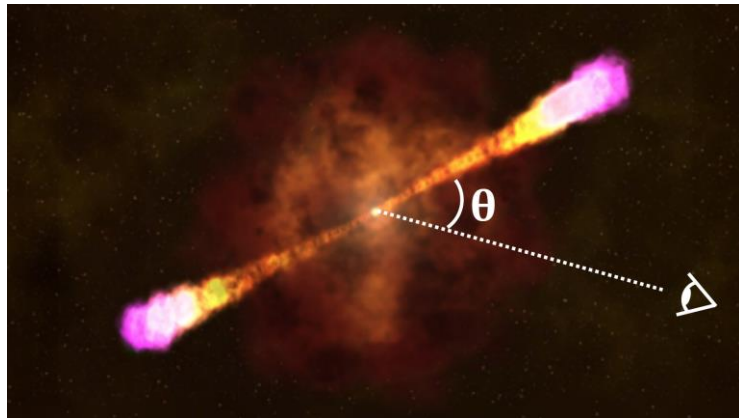
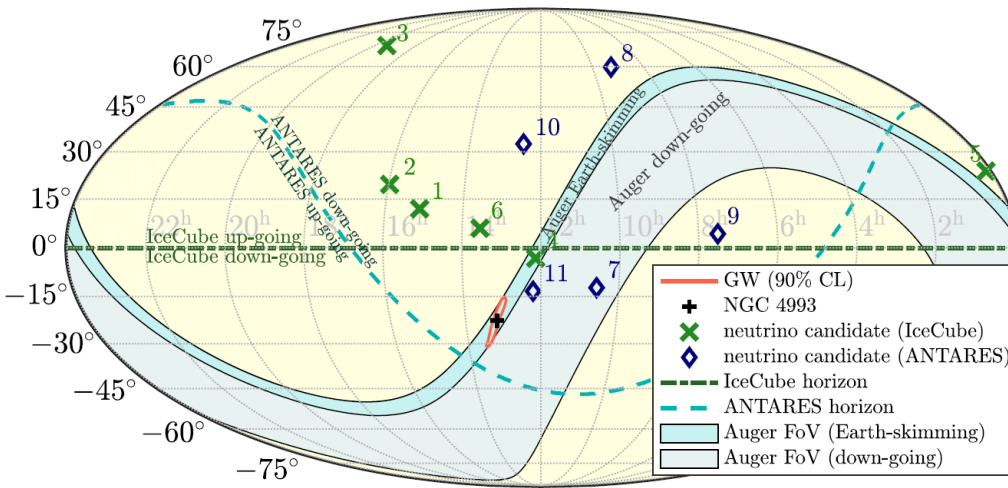
Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration, and LIGO Scientific Collaboration and Virgo Collaboration
 (See the end matter for the full list of authors.)

ApJL 850:L35 (2017)

(multimessenger): ApJL 848 L12 (2017)

GW170817: Neutrino limits
 (fluence per flavour: $\nu_x + \bar{\nu}_x$)



GW170817 followup : constraints on the source - extended emission (+ AUGER, IceCube)

THE ASTROPHYSICAL JOURNAL LETTERS, 850:L35 (18pp), 2017 December 1
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<https://doi.org/10.3847/2041-8213/aa9aed>



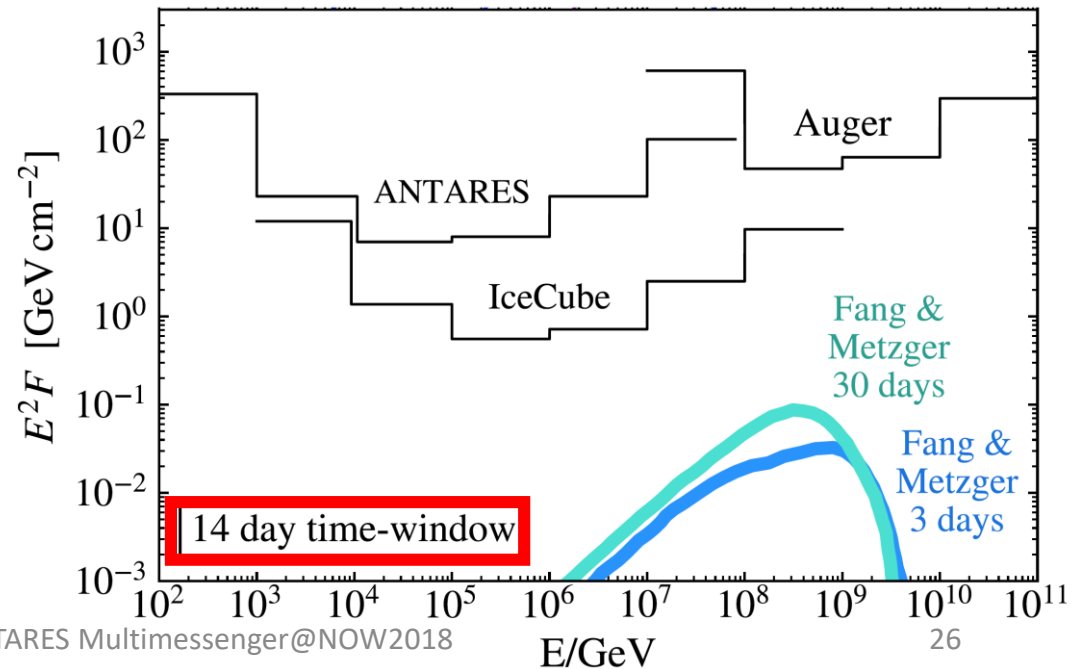
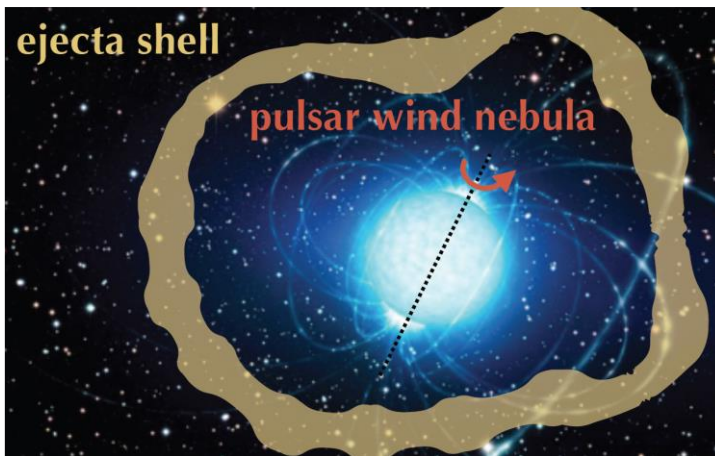
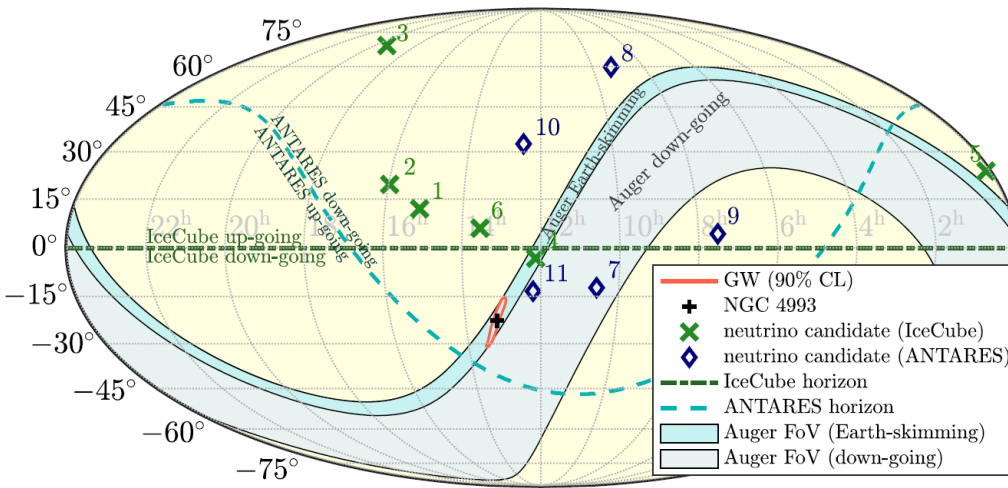
Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration, and LIGO Scientific Collaboration and Virgo Collaboration
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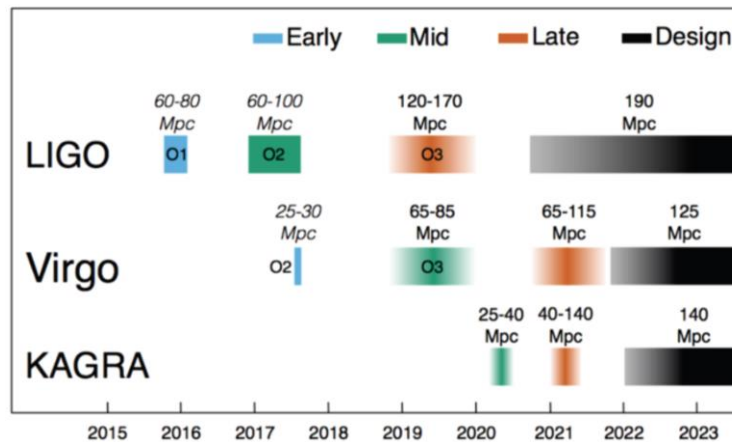
ApJL 850:L35 (2017)

(multimessenger): ApJL 848 L12 (2017)

*GW170817: Neutrino limits
 (fluence per flavour: $\nu_x + \bar{\nu}_x$)*

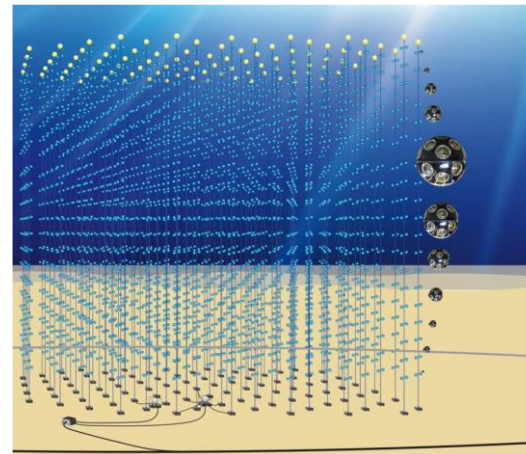
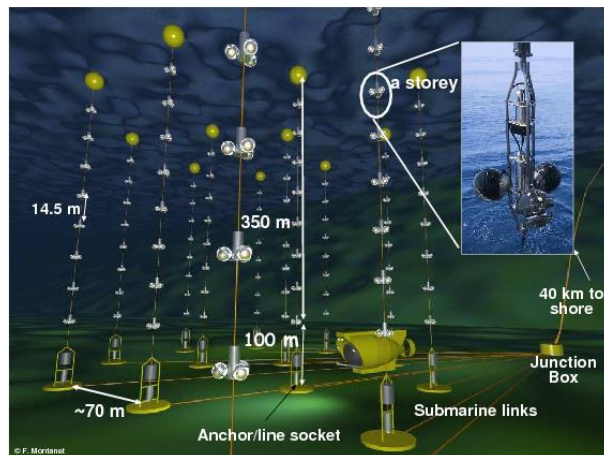


Next GW + HEN observations



Exciting period ahead for Multi-Messenger Astronomy

- Run O3 will start early 2019. Possibly several alerts/week
- Neutrino follow-ups: ANTARES (up to early 2020), KM3NeT (2020), IceCube + AUGER + BAIKAL



ANTARES can also study (not covered here...)

Neutrino oscillations and NMH:

- *Phys. Lett. B* 714 (2012) 224
- ... Works on going

Indirect Dark Matter searches

- *Phys. Lett. B* 759 (2016) 69-74
- *Phys. Lett. B* 769 (2017) 249
- *Physics of the Dark Universe* 16 (2017) 41
- JCAP05(2016)016

Magnetic Monopoles:

- *JHEP* 07 (2017) 054

Sea and Earth Science

- *Scientific Reports* 7(2017): 45517
- *Jou. Geophysical Research* 122(2017) 2291
- *Ocean Dynamics* 64 (2014)507–517
- *PLoS ONE* 8(2013): e67523
- *Deep-Sea Research I* 58(2011)875

During operation on the ANTARES/
KM3NeT site, last summer

ANTARES – Dark Matter

(Sun) Phys. Lett. B 759 (2016) 69-74

(GC) Phys. Lett. B 769 (2017) 249

(Earth) Physics of the Dark Universe 16 (2017) 41

WIMPs accumulate in massive celestial objects (Sun, Galactic Centre, ...)

- Neutrinos could be produced in WIMP-WIMP annihilation
- Clean signal and low expected background

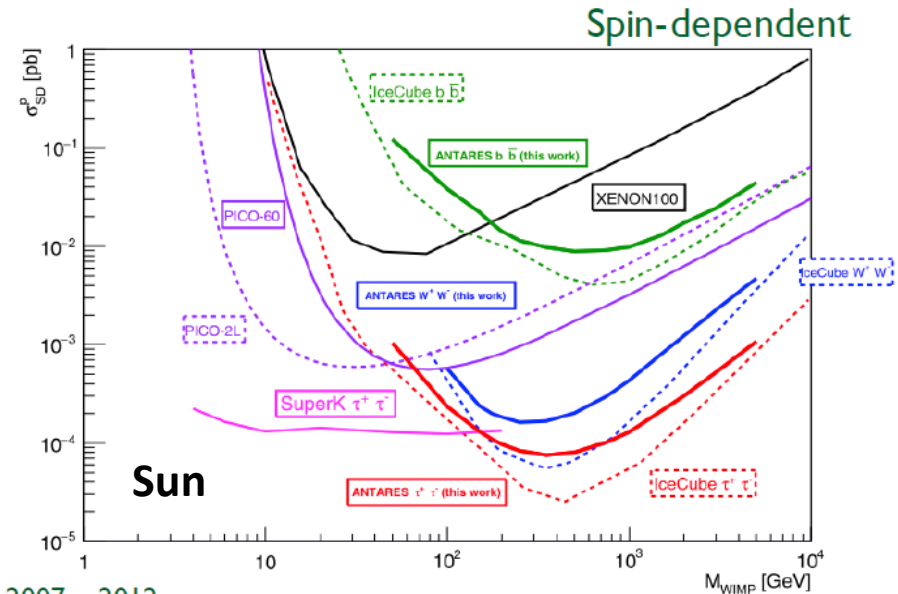
Ingredients used in the analysis:

- Signal energy spectra for each considered WIMP mass and annihilation channel:

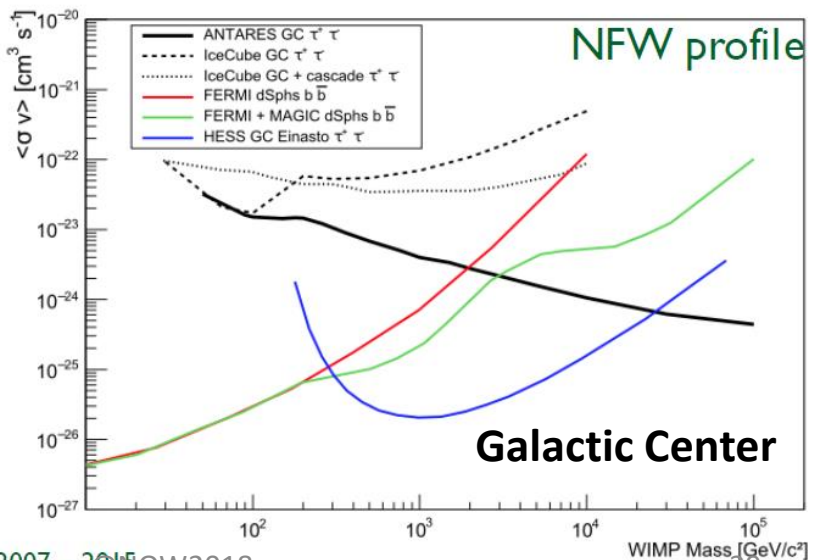
$$WIMP + WIMP \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, \bar{\nu}\nu$$

- Spatial distribution of dark matter in the source:
 - Point-like (Sun)
 - NFW, Burkert, McMillan halos (GC)

- **No excess** above background observed;
- Upper limits derived, as a function of the WIMP mass and annihilation channel on
 - spin-(in)dependent WIMP-nucleon scattering cross-section (**Sun**)
 - thermally averaged annihilation cross-section (**Galactic center**)



2007 – 2012

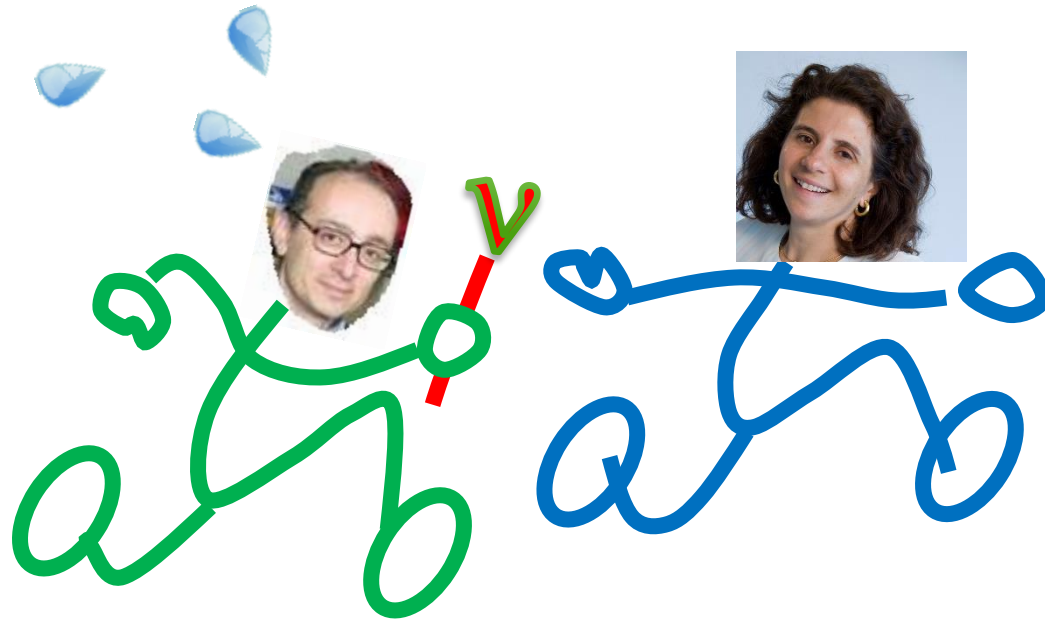


Summary and Perspectives

- ANTARES: more than 10 years of continuous data taking!
... and still stably ongoing!
- ANTARES Data taking continues up to the end of GW O3
 - Then, KM3NeT in the Mediterranean Sea
- Solid results from various searches of astrophysical neutrino emission.
 - (point-like, diffuse, extended regions, dark matter, ...)
- **Active multi-messenger program:**
 - Neutrino alerts distribution, participation to GCN and AMON
 - External alerts reception, prompt analysis
 - Offline multi-messenger analysis.
 - Combined analyses with IceCube (point sources, galactic plane, time correlation...).
- Best practice and multi-messenger collaborations ported to KM3NeT!
- Neutrino astronomy is on its way to increased sensitivity and full sky coverage
- Neutrinos are an indispensable ingredient of multi-messenger astronomy
- Neutrino telescopes also offer opportunities for precision measurements in neutrino physics



Thank you!

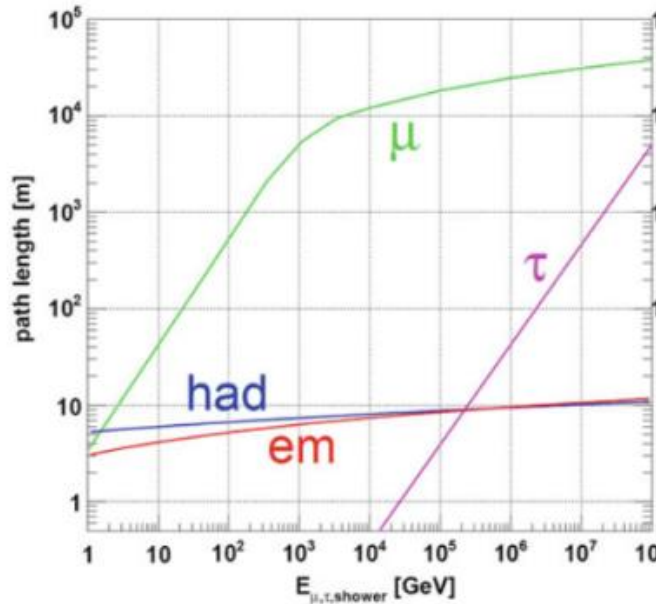


Spares

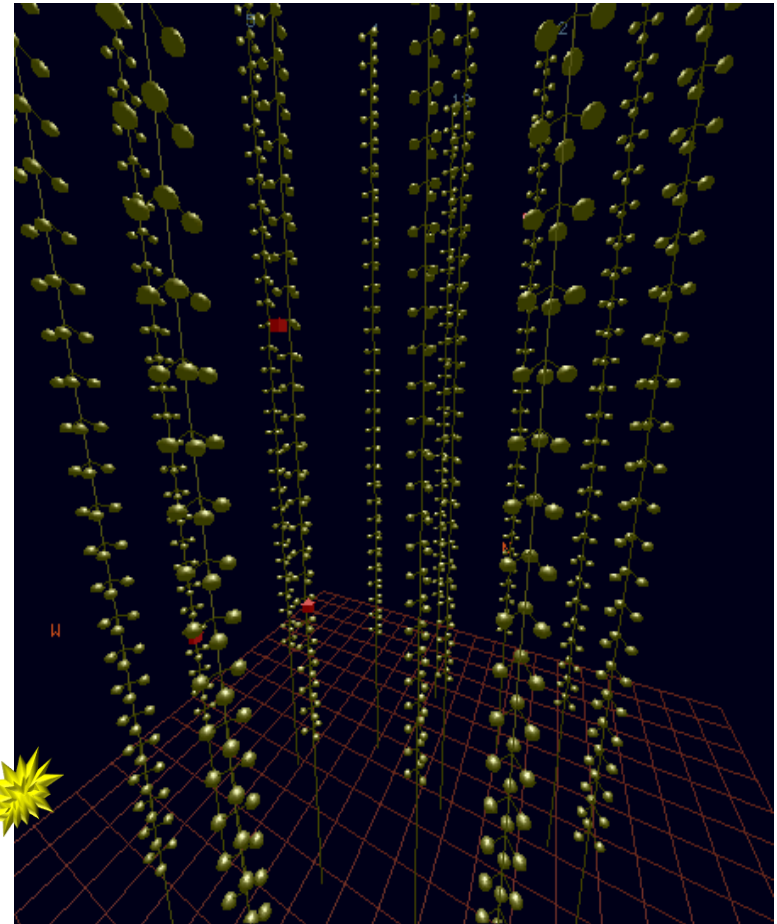
A neutrino telescope



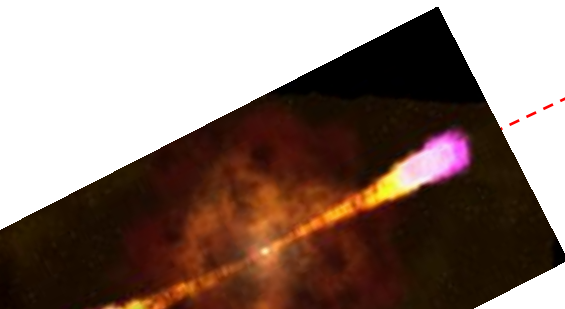
Length of secondary charged particles



- Tracks (**CC ν_μ**): Long pattern in the detector
- Cascades (**CC ν_e + NC**): Short pattern (point like)

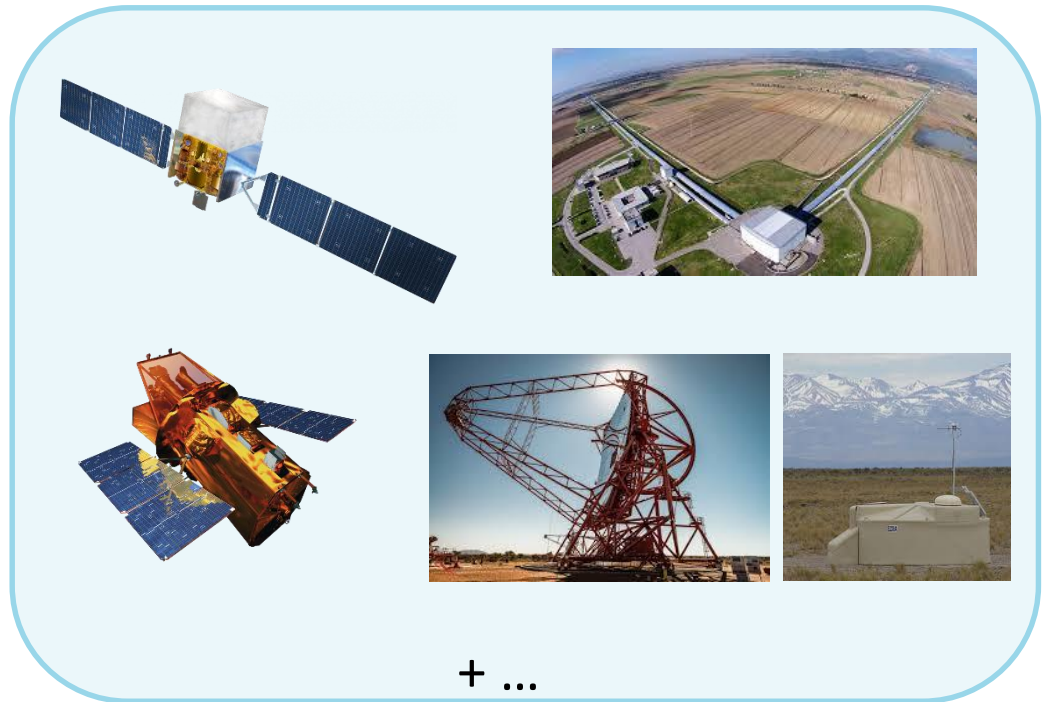
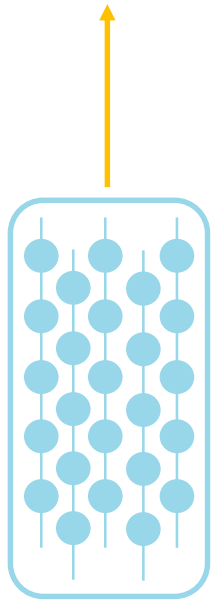


- Track/cascade direction reconstructed from time-space correlation between *hits* produced by Cherenkov photons
- Event energy reconstructed from amplitudes



ANTARES real time neutrino alerts

Real-time analysis \longrightarrow Alert triggering



follow-up

Performances:

- Time to send an alert: ~ 5 s
- Median angular resolution: 0.5°



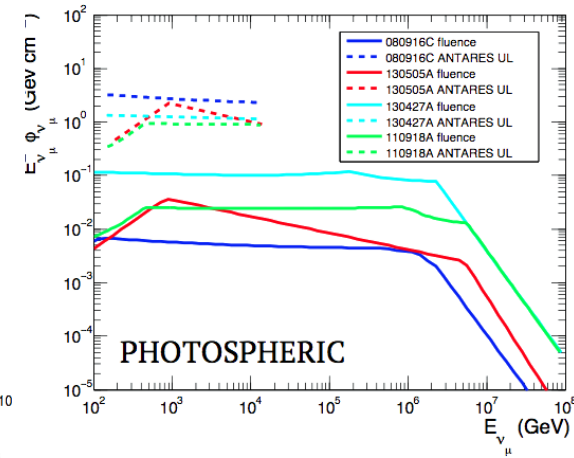
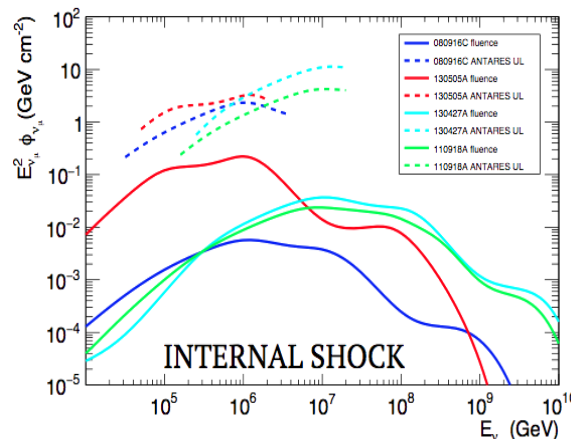
4 bright GRB selected:

GRB080916C, GRB110918A, GRB130427A and GRB130505A

Upper limits

Two model investigated:

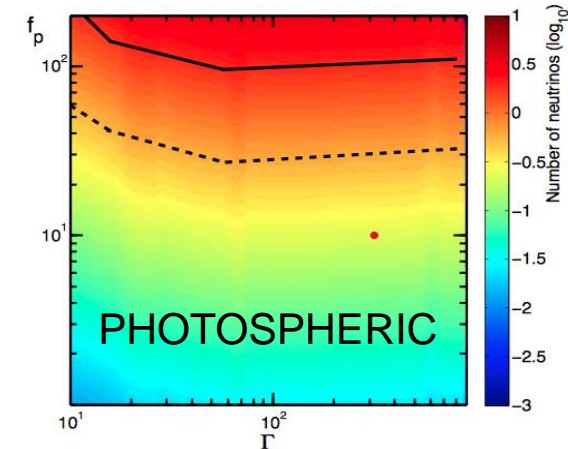
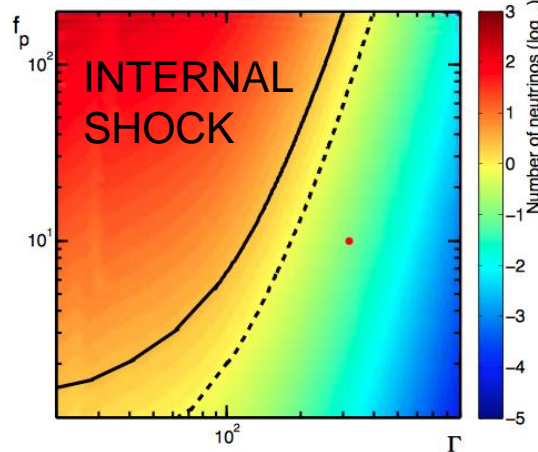
- photospheric
- internal shock



Constraints

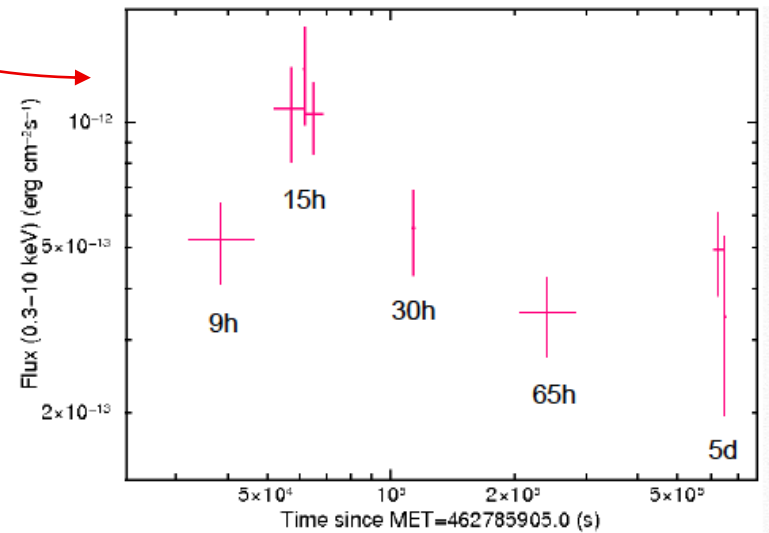
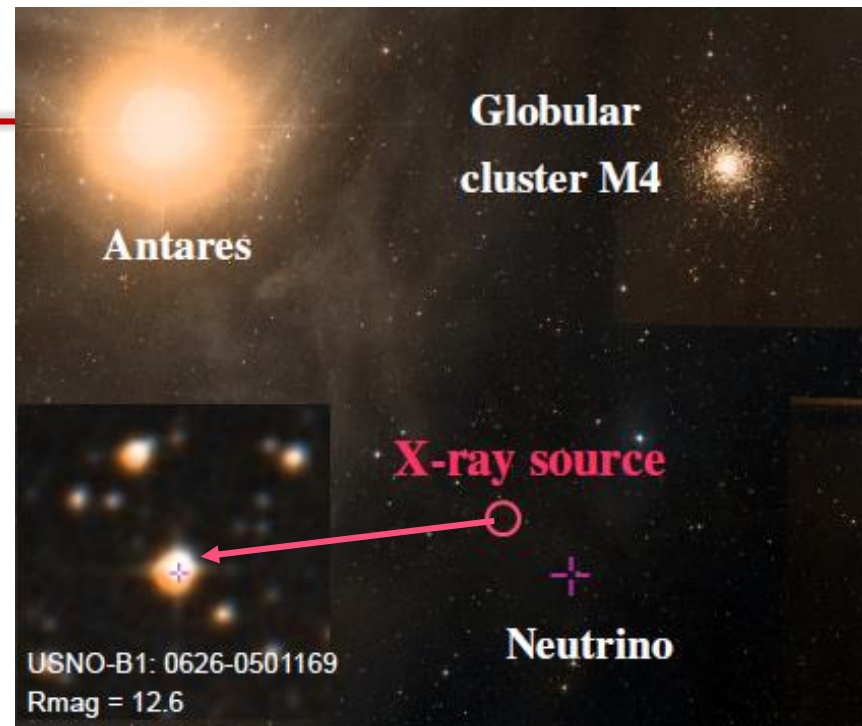
on baryonic fraction, f_p , and Lorentz factor Γ

- 90% C.L. (solid line)
- 50% C.L. (dashed line)



ANT150901A (ATEL#7987)

- **ANTARES** Alert VHE (Sept. 1, 2015)
 $E \sim 50$ TeV; RA=246.3°; $\delta = -27.4^\circ$
- Sent after 10 s to MASTER, Swift-XRT
- Unknown, relatively bright and variable X-ray source- $(0.5-1.4) \times 10^{-13}$ erg cm $^{-2}$ s $^{-1}$ detected by Swift XRT 9h after the ATEL
- Great interest in the community (15ATels+6 GCN)
- Later, the X-ray source associated with a **young accreting G-K star**, or a binary system of active stars undergoing a **flaring episode** with X-ray emission.
- H.E.S.S.: No VHE transient source
 $\Phi(E > 320\text{GeV}; 99\% \text{C.L.}) < 2.7 \times 10^{-8} \text{m}^{-2} \text{s}^{-1}$



Gravitational Waves (GW) + HE Neutrinos (HEN)

