Highlights from the ANTARES neutrino telescope
(with an attention for KM3NeT)

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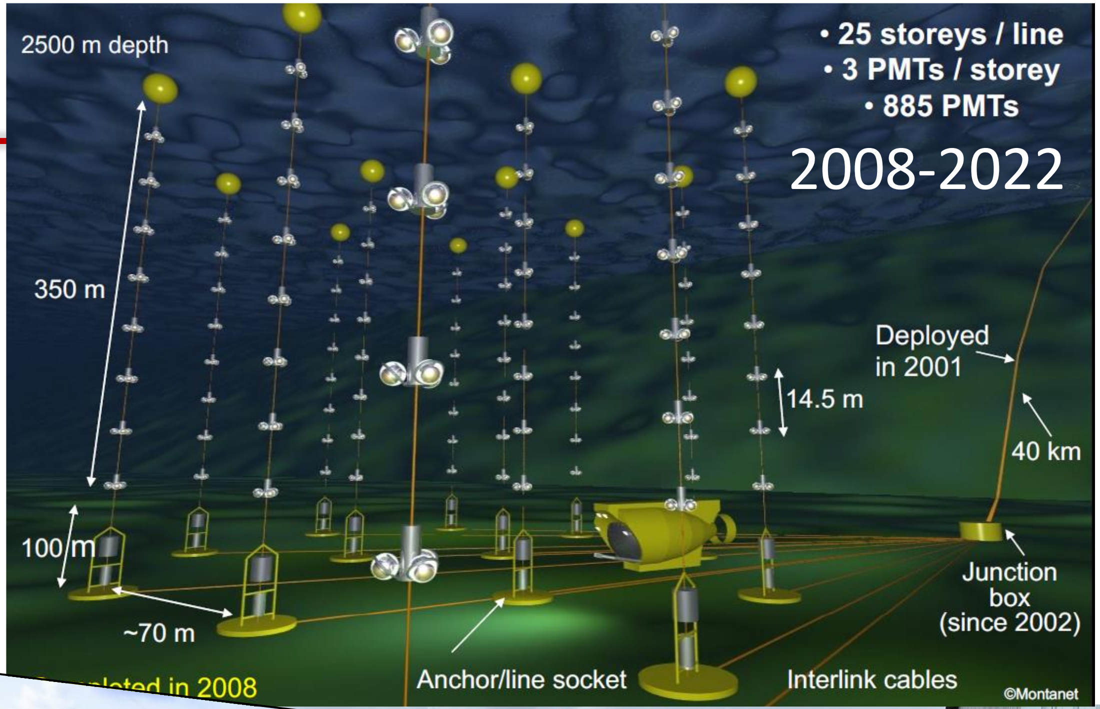
ANTARES history

📖 NIM A656(2011) 11-38

First Under-Sea neutrino telescope

Precursor to KM3NeT

- 2006 First complete detector line
- 2008 Detector with 12 lines completed
- 2022 Data taking terminated (12/2/22), and detector decommissioned (June 2022)

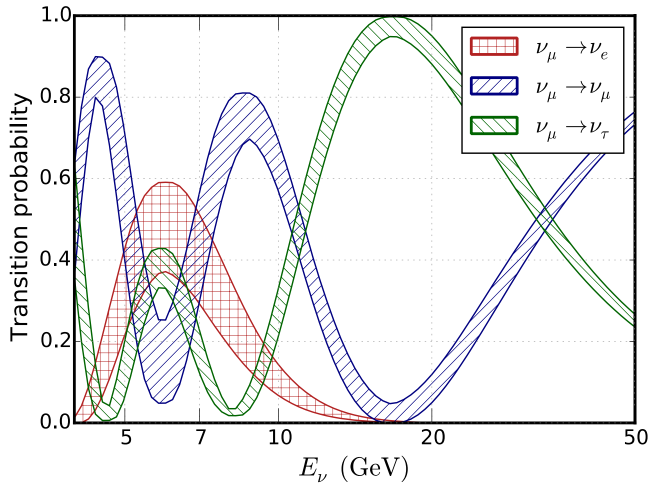


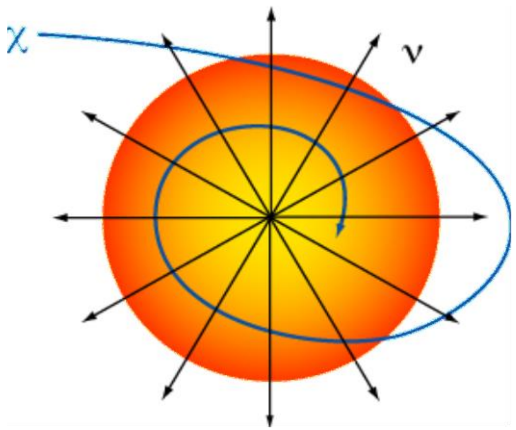
Results on cosmic ν from

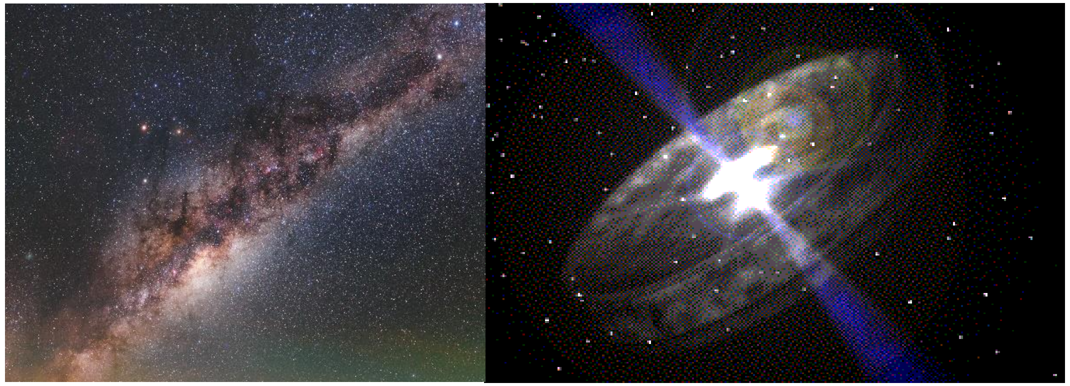
- northern hemisphere
- galactic plane
- indirect DM production

PMTs available for new experimental projects

Science with Neutrino Telescopes







Low Energy
> 10 GeV

Medium Energy
10 GeV < E_ν < 10 TeV

Galactic → Extragalactic
High Energy, E_ν > TeV → PeV

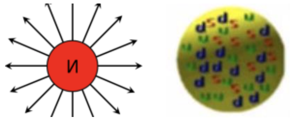
Energy

ν Oscillations

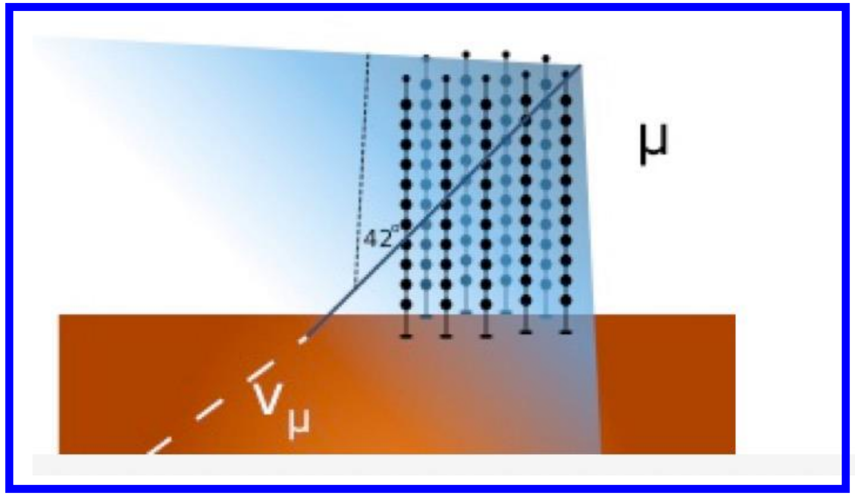
Dark matter search

ν from cosmic sources
Origin and production mechanism of HE CRs

+ Exotic searches



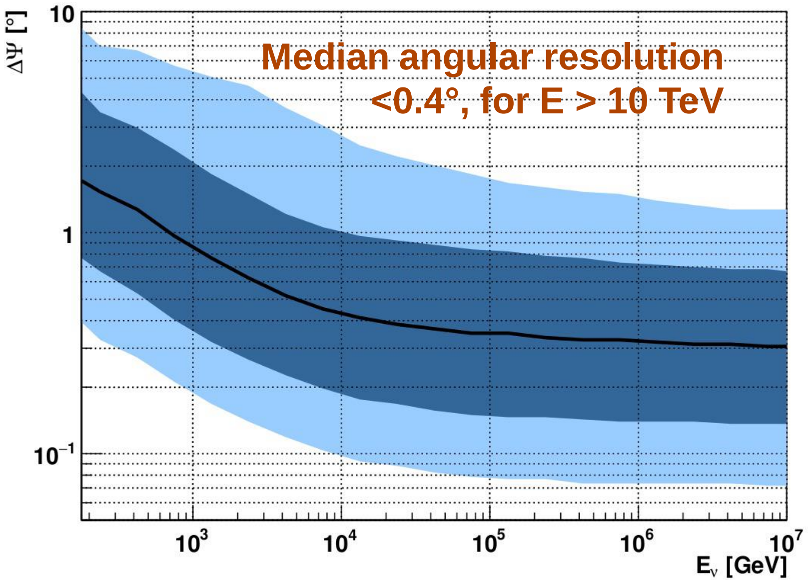
Detection principles: muon tracks (CCν_μ) + cascades (NC+ν_e)

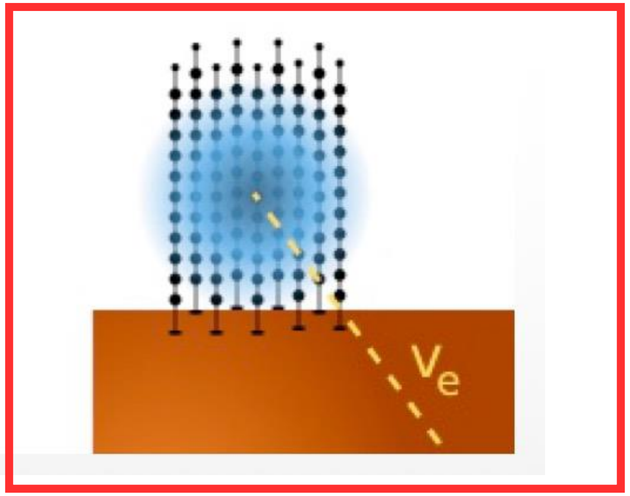


Track-like events:

ν_μ (ν_τ) CC interaction near the detector

Topology used in online analyses

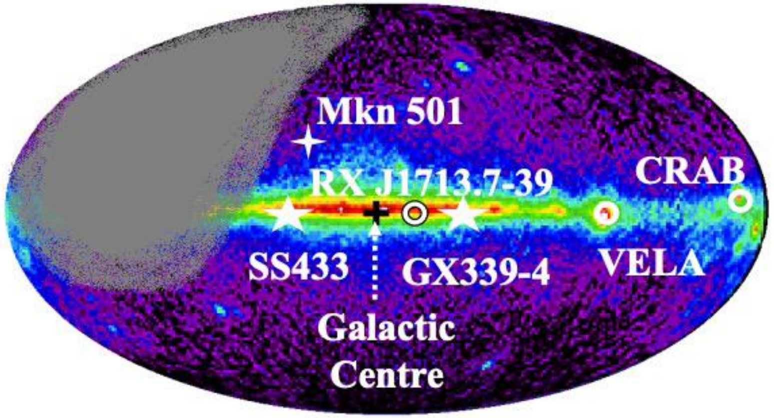




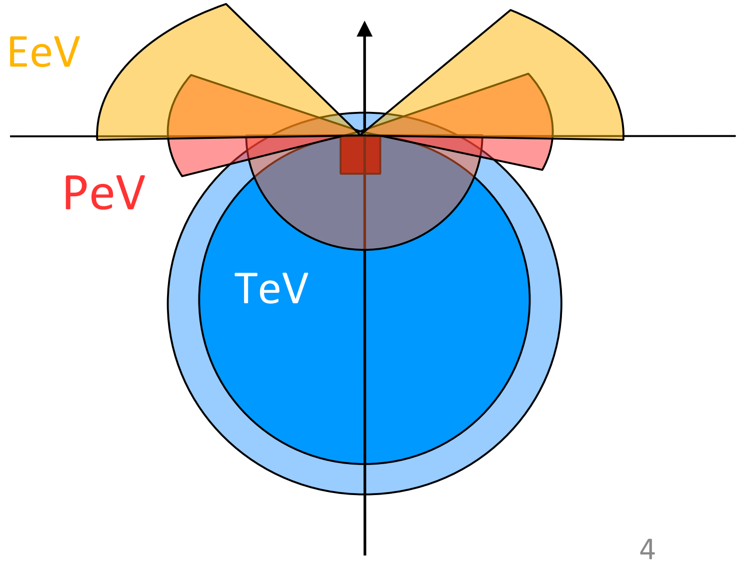
Shower-like events:

ν_e, most ν_τ CC interaction + NC inside or very close to the detector volume.

- Better energy
- Worse angular resolution



- Visibility: ¾ of the sky (<100 TeV)
- most of the Galactic plane
- ~95% duty cycle

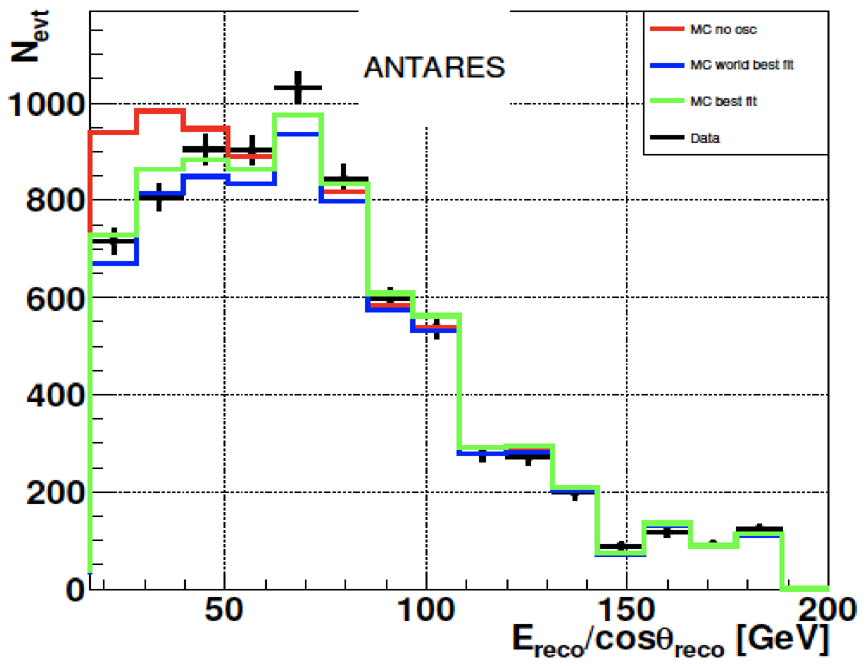


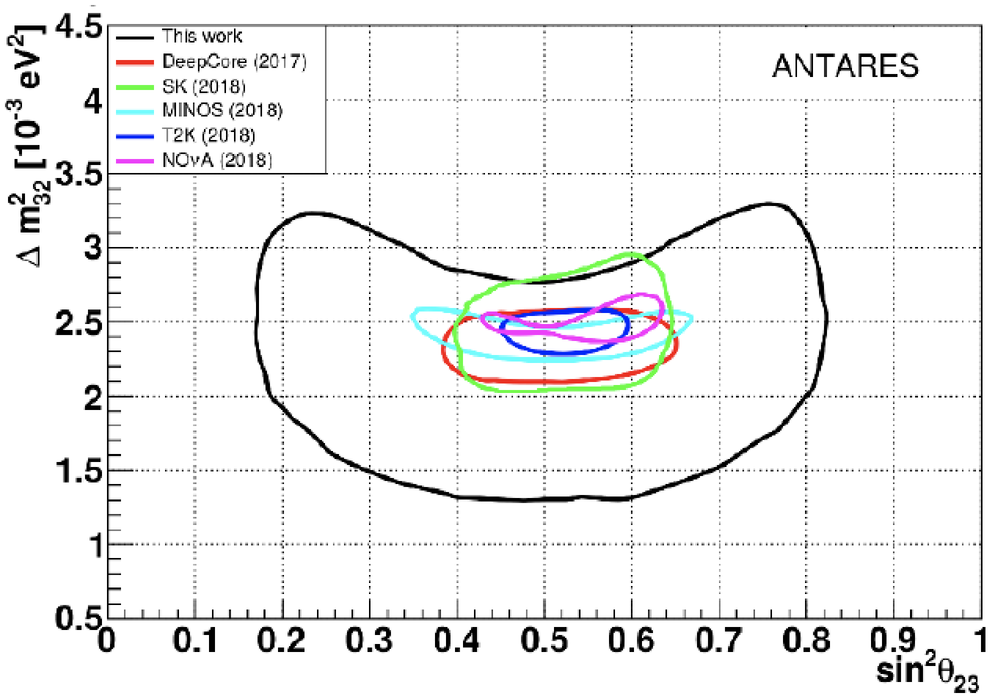
ν-oscillation (ν_μ- disappearance)

📖 J. High Energ. Phys. (2019) 2019: 113

- A binned likelihood fit (Poisson stat.) is performed in two dimensions ($\log_{10}(E_{reco})$, $\cos\theta_{reco}$)
- Priors and fitted values obtained from minimization for all the parameters of standard 3 flavor oscillations.
- No-oscillation hypothesis excluded at 4.6σ
- Data sample available on the ANTARES site

Parameter	Prior	Fit result
Δm^2_{32} [10^{-3} eV^2]	none	$2.0^{+0.4}_{-0.3}$
θ_{23} [°]	none	45^{+12}_{-11}
n_ν	none	$0.81^{+0.10}_{-0.09}$
$\nu/\overline{\nu}$ [σ]	0.0 ± 1.0	$1.10^{+0.64}_{-0.56}$
$\Delta\gamma$	0.00 ± 0.05	-0.003 ± 0.036
N_μ	740 ± 120	414^{+48}_{-24}
θ_{13} [°]	8.41 ± 0.28	8.41 ± 0.28
M_A [σ]	0.0 ± 1.0	0.0 ± 1.0

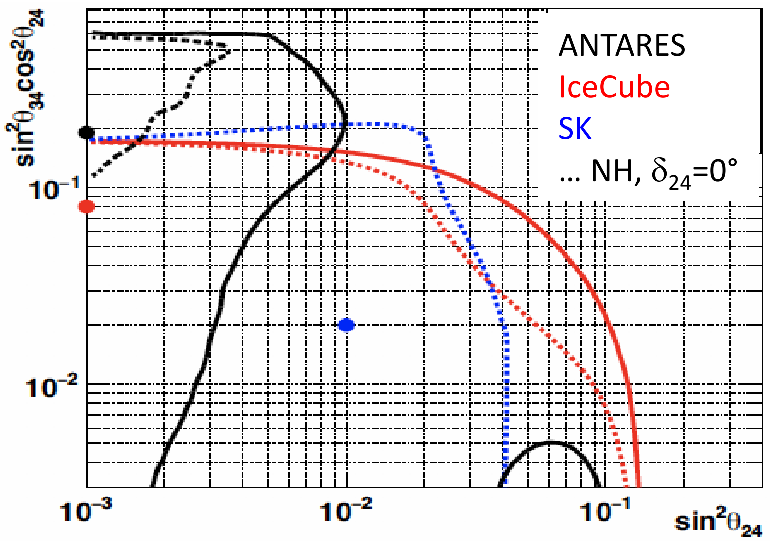




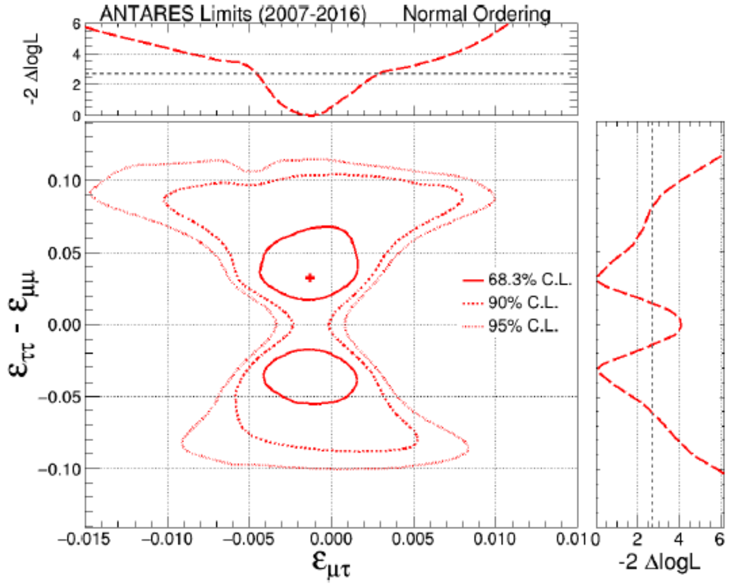
ν-oscillation studies: Sterile & NSI

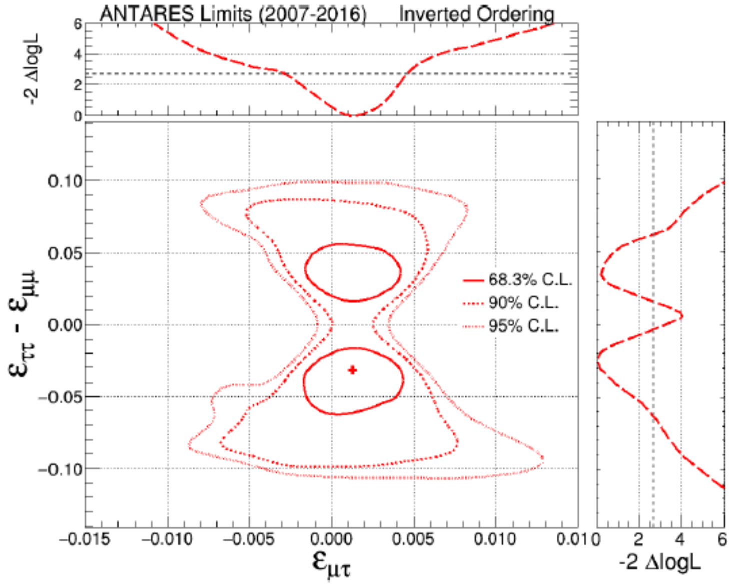
📖 JHEP (2019) 113
📖 JHEP (2022) 48

- (3+1) sterile neutrino models $\Delta m^2_{41} > 0.5\ eV^2$
- Tight complementary information to eV-scale sterile neutrino searches
- Our results (90% CL) exclude regions of the parameter space not yet excluded by other experiments.

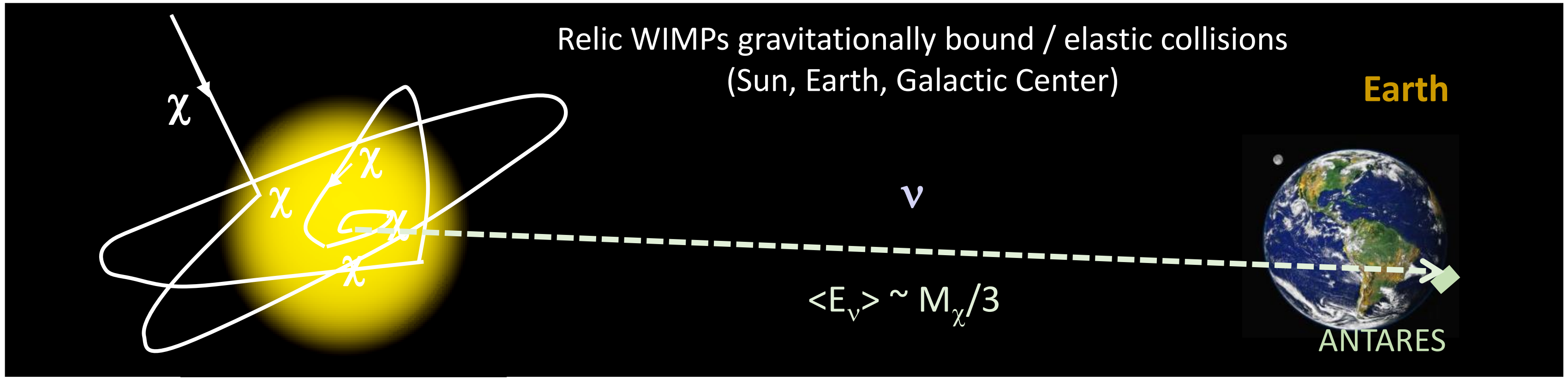


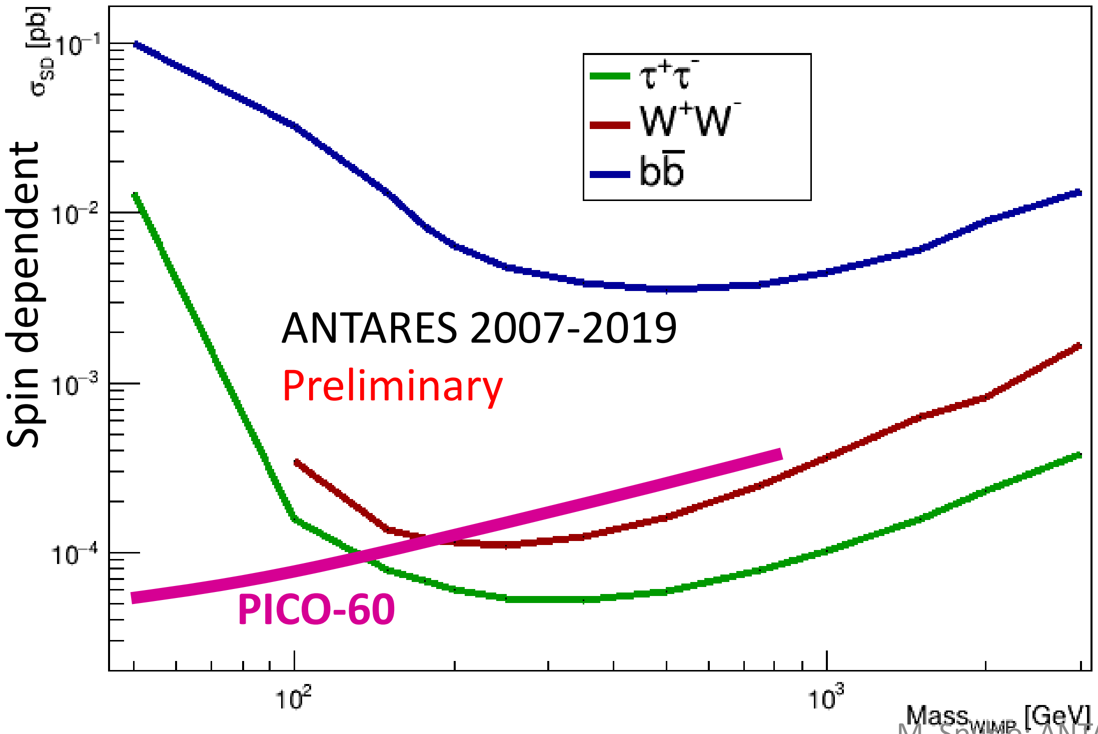
- Non-standard interactions signature in neutrino oscillation patterns are detectable
- A log-likelihood ratio test of the dimensionless coefficients $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$ does not provide clear evidence of deviations from standard interactions.
- The non-NSI hypothesis is disfavored with a significance of 1.7σ (1.6σ) for the normal (inverted) mass ordering scenario.

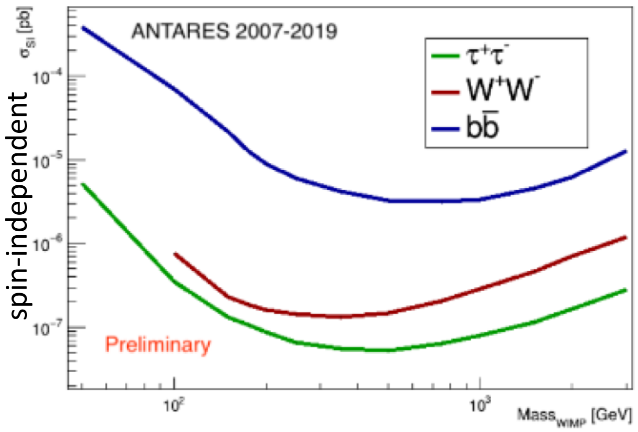




Indirect Search for Dark Matter: The Sun







📖 Earth

Phys. Dark Un., 16 (2017) 41–48

📖 Sun

Phys. Lett. B759 2016

JCAP 05 (2016) 016

JCAP 11 (2013) 032

- DM In equilibrium between capture and annihilation
- The Sun has known isotopic abundance ⇒ sensitive to WIMP-nucleon cross section for **spin-dependent** and spin-independent case (odd or even atomic number)
- Competitive limits w.r.t. direct experiment **for spin-dependent**

Dark Matter from the Galactic Center

📖 Galactic Center

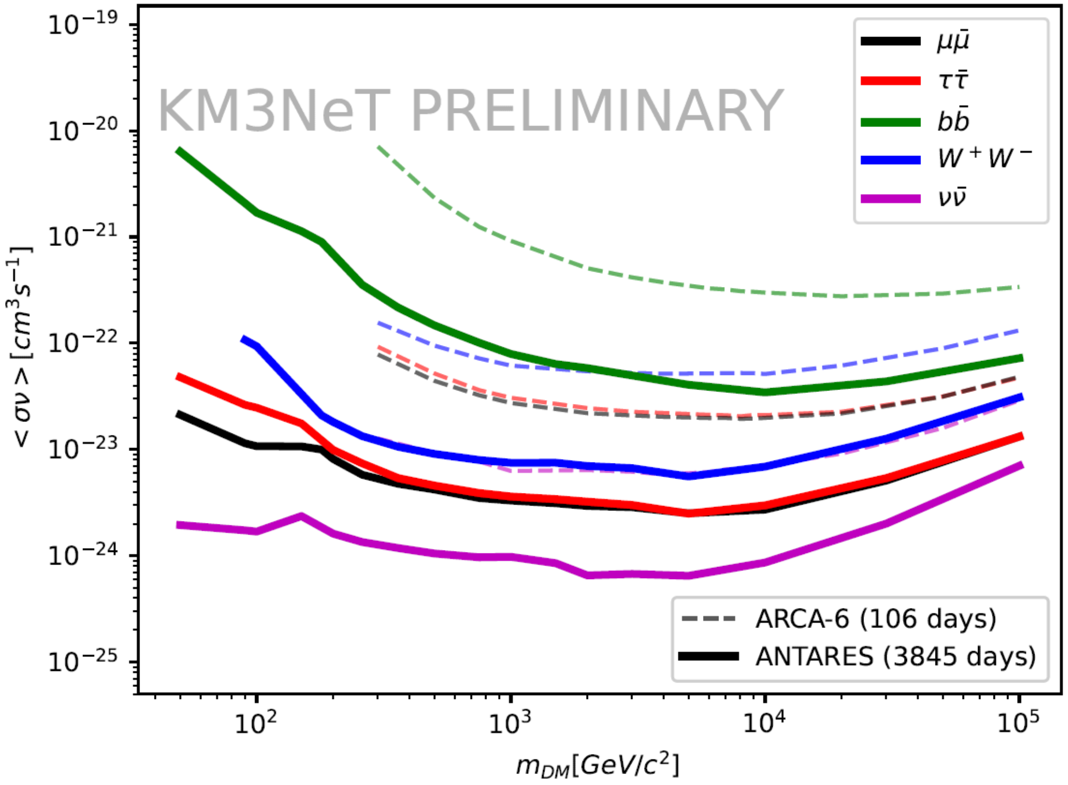
JCAP 06 (2022) 06, 028 (secluded DM)

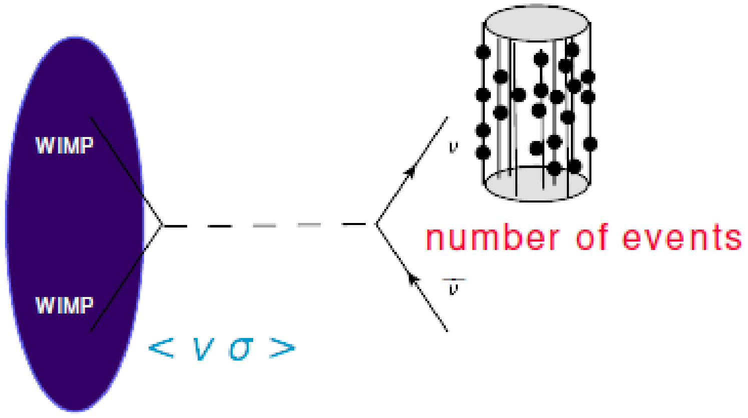
Phys. Lett. B 805 135439 (2020).

Phys. Rev. D 102, 082002 (2020) (with IceCube)

Phys. Let. B 769 (2017) 249

JCAP 10 (2015) 068

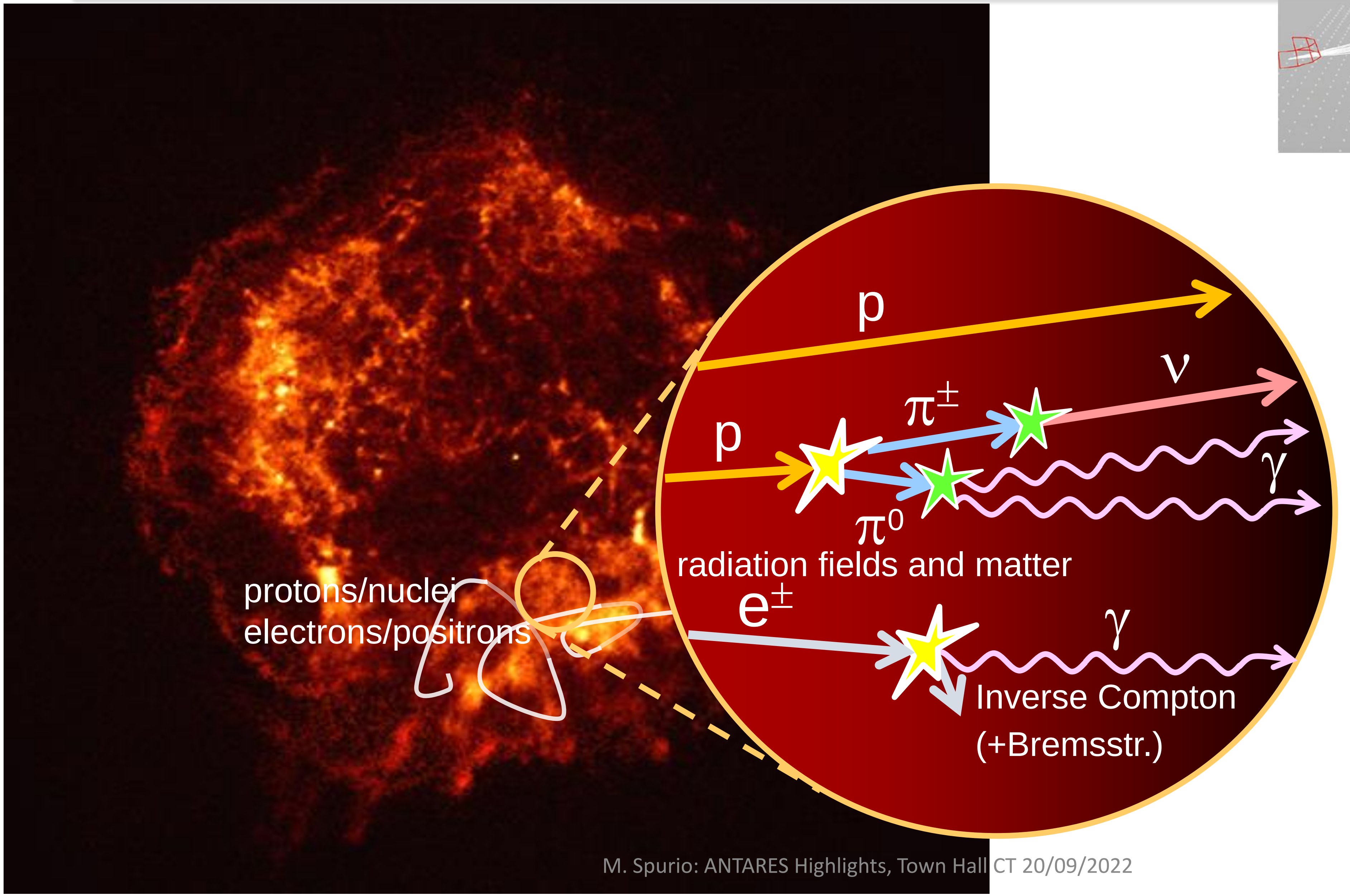


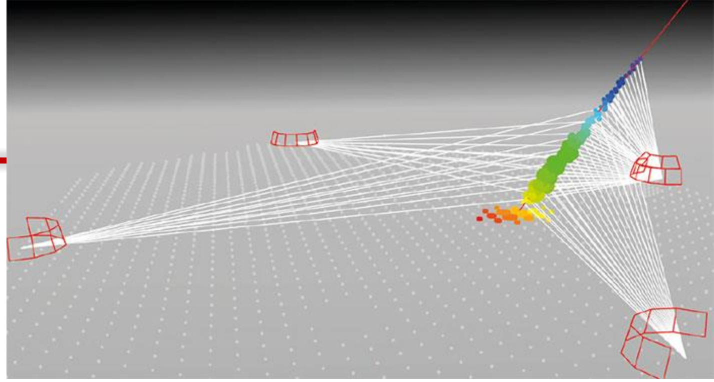


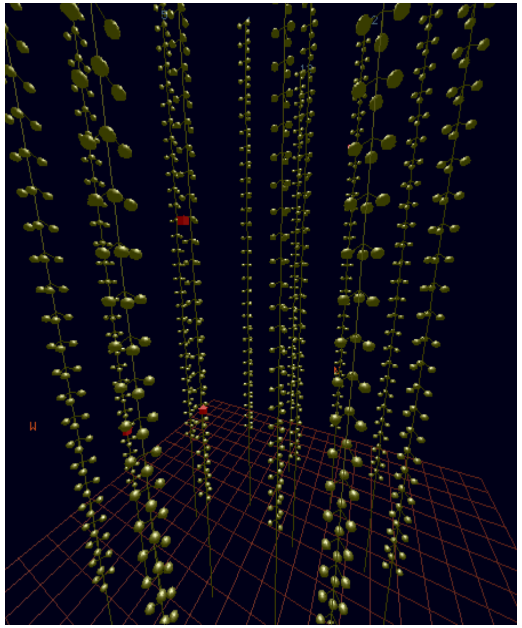
$$n = \frac{1}{2}\langle \sigma v \rangle \int_0^{M_{\mathrm{DM}}} \frac{dN}{dE} dE \, \frac{1}{4\pi} \, J \, \frac{1}{M_{\mathrm{DM}}^2} \, \mathcal{A}(M_{\mathrm{DM}}) \, t$$

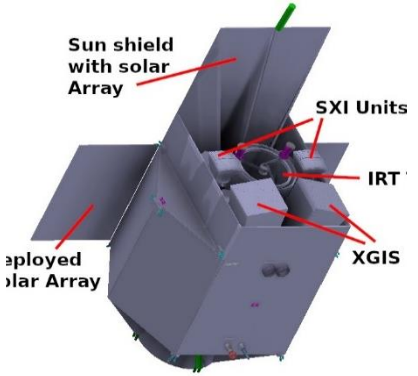
- The probability for one process to happen depends on <velocity × cross section>.
- Translate limit on flux into limit on velocity-averaged pair annihilation cross-section ⟨σv⟩.

Cosmic sources of CRs, γ-rays and ν's



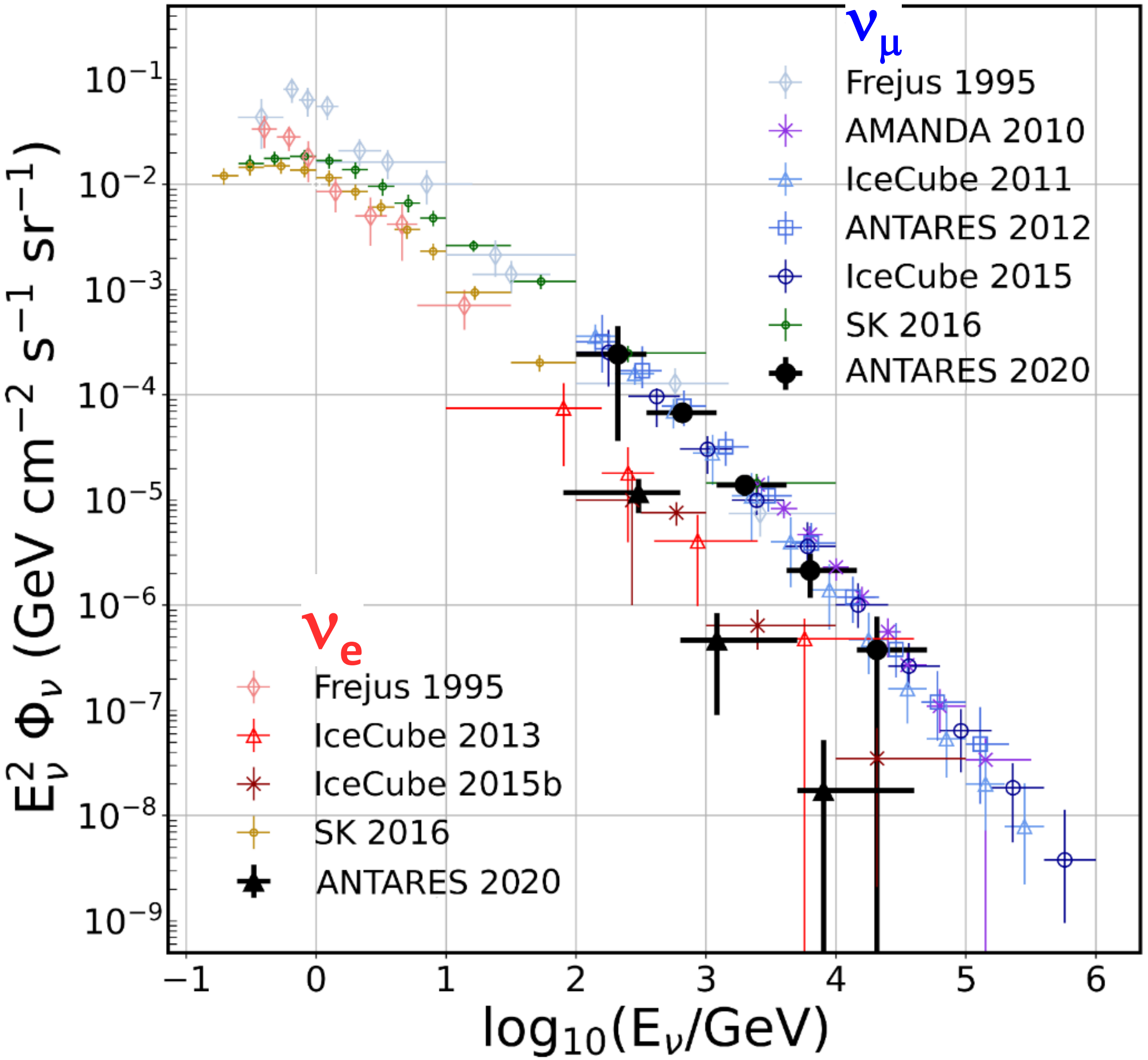




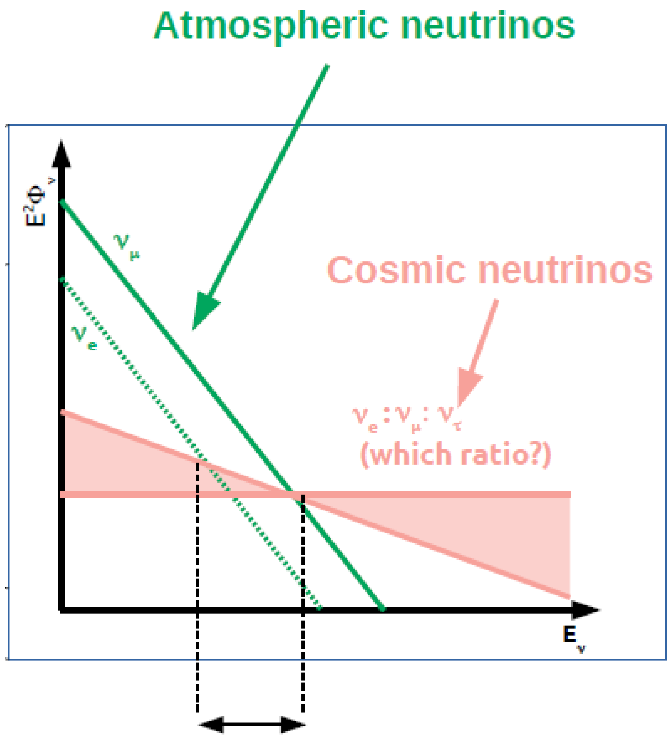


The atmospheric neutrino background

📖 EPJ 73: 2606 (2013)
📖 PLB 816: 136228 (2021)



- Atmospheric ν_μ and ν_e energy spectra can be measured
  - energy estimation
  - detector systematics



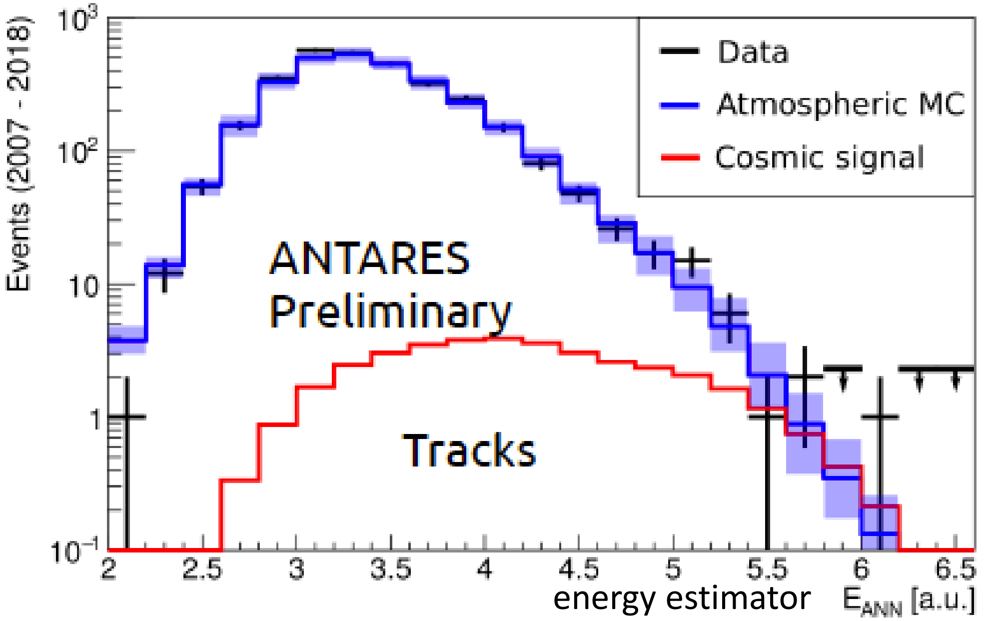
Atm./Cosmic transition: 30-200 TeV

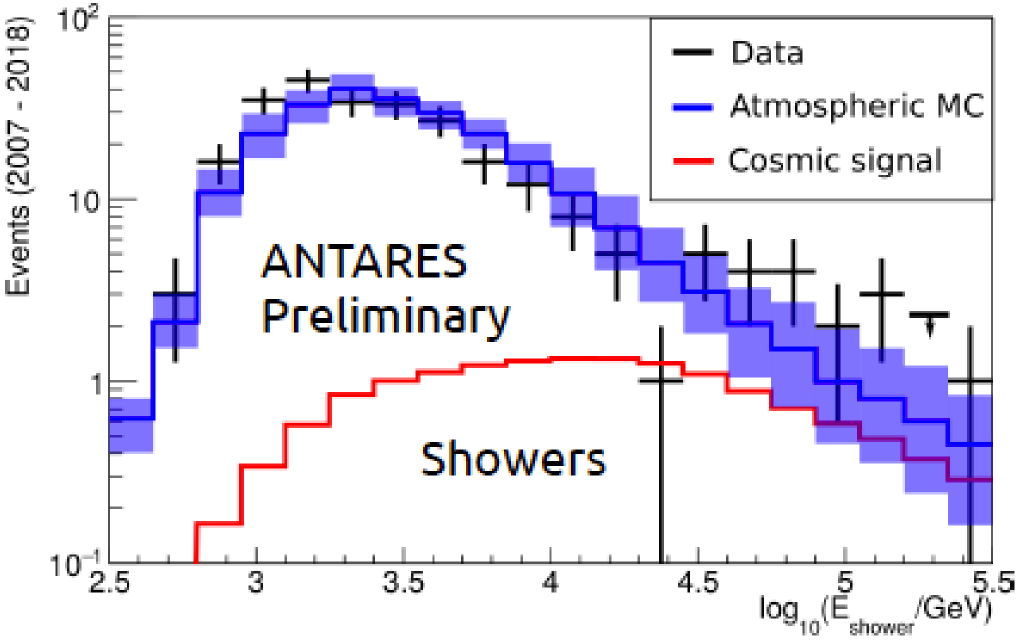
Cosmic neutrinos: diffuse flux

📖 Ap.J.Lett. 853 (2018) 1, L7
📖 https://pos.sissa.it/358/891/pdf -(ICRC 19)

Search for an excess of high-energy events w.r.t atmospheric neutrinos

- Selection cuts optimized with MRF procedure (assumed spectral index Γ=2.5)
- Look for event excess above a given E_{th} both for track & shower samples
- Data with $E > E_{th}$: **50 events (27 tracks + 23 showers)**
- Background with $E > E_{th}$ (atm. Flux=HONDA + Enberg): **36.1 ± 8.7 (19.9 tracks +16.2 showers)**
- → **1.8σ excess** of events with $E > E_{th}$, assumed as cosmic flux (red histogram)



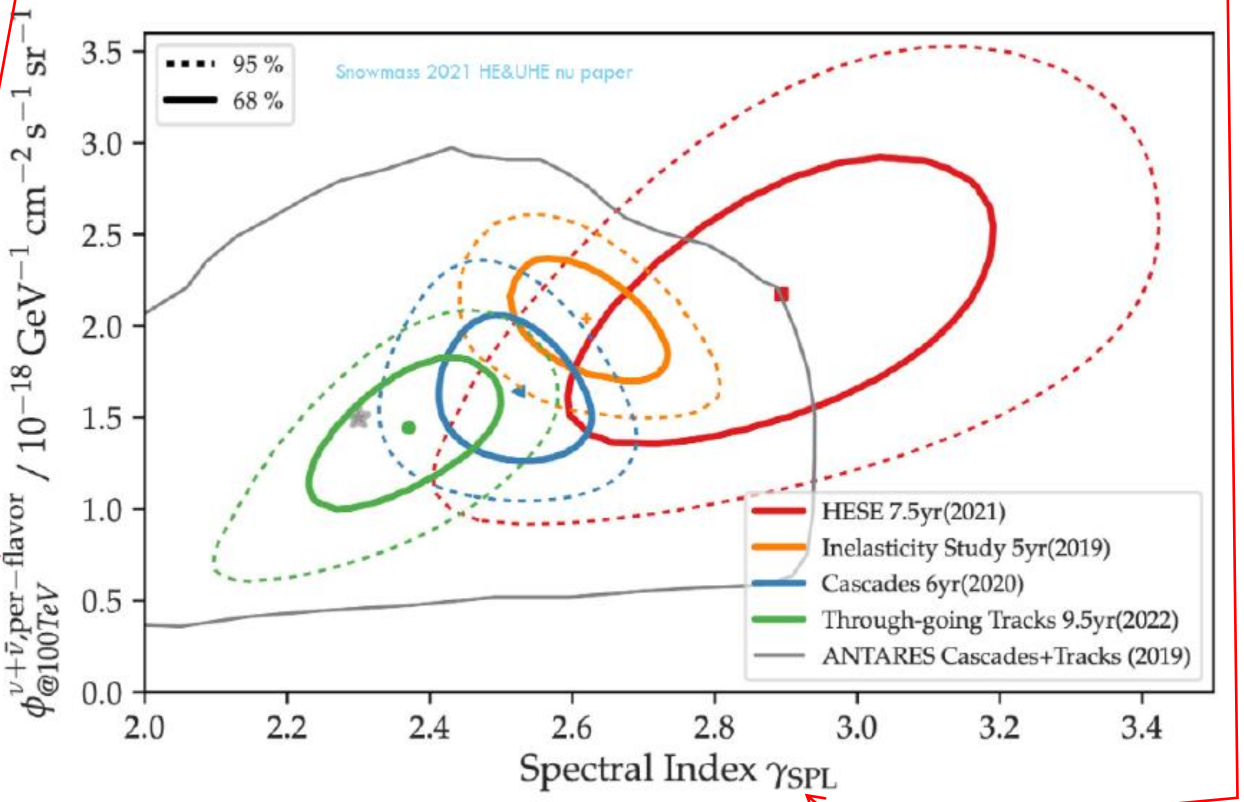


Cosmic neutrinos: diffuse flux

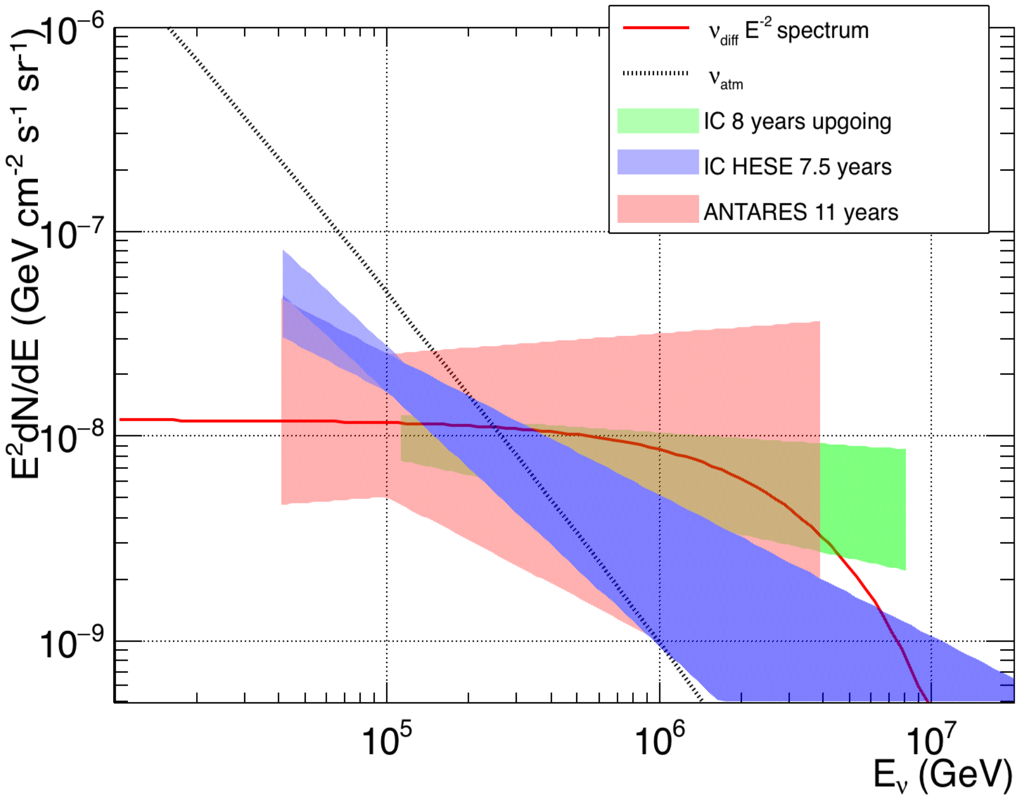
📖 Ap.J.Lett. 853 (2018) 1, L7
📖 https://pos.sissa.it/358/891/pdf -(ICRC 19)

Cosmic: Combined (tracks+showers) likelihood fitting:

$$\Phi_{100\ \mathrm{TeV}} = \Phi_0 \left(\frac{E}{100\ \mathrm{TeV}}\right)^{\gamma}$$



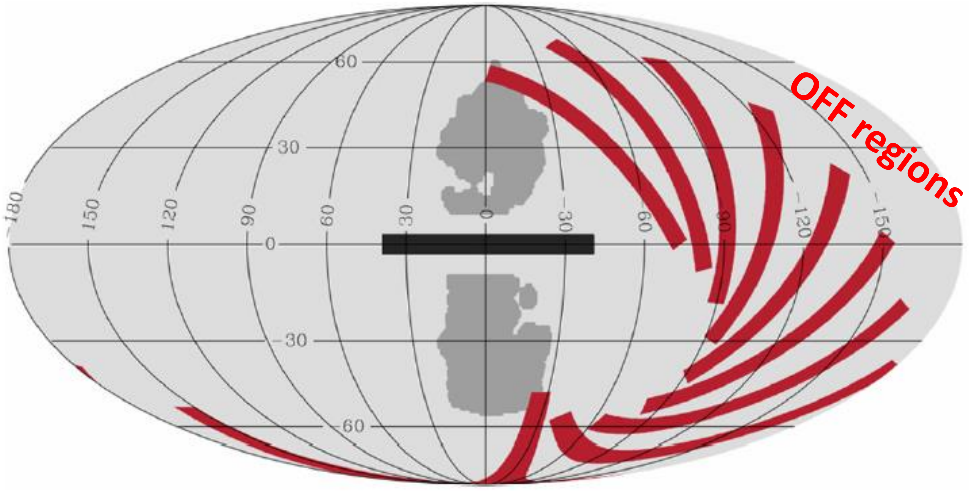
Results not really constraining… but fully compatible with IceCube



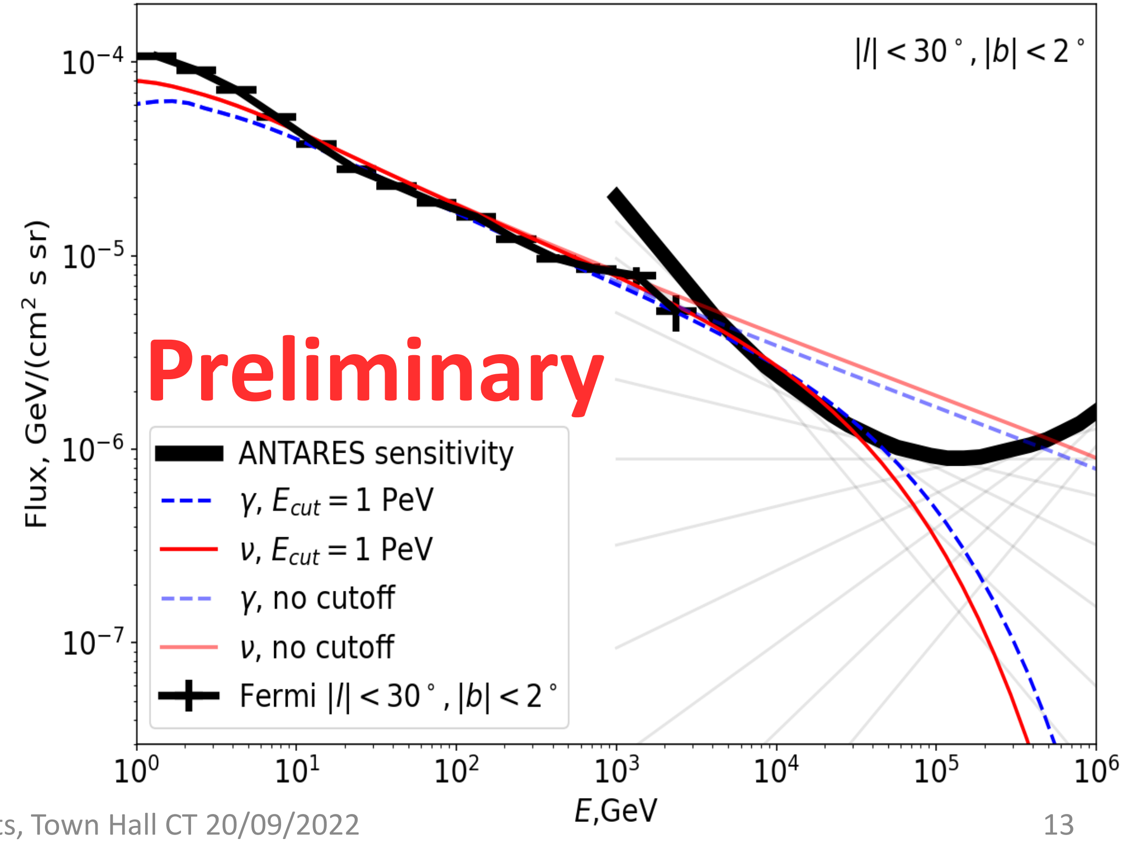
Search for diffuse flux from Galactic ridge

PLB 760 (2016) 143
ApJ 868 (2018) L20
new paper in preparation

- A neutrino signal is expected from the Galactic Ridge, as suggested by gamma-ray data
- ν flux relates to the spectrum of primary CRs, if CR flux does not have a cut-off below 1 PeV
- Analysis in 2016 (7 y data 2007-2013) gives limits close to expectation without cutoff
- Using the full ANTARES dataset, we expect a sensitivity below the extrapolated gamma-ray



Galactic ridge:
$|l| < l_{ridge} \approx 30\text{-}40°$ and $|b| < b_{ridge} \approx 2\text{-}3°$

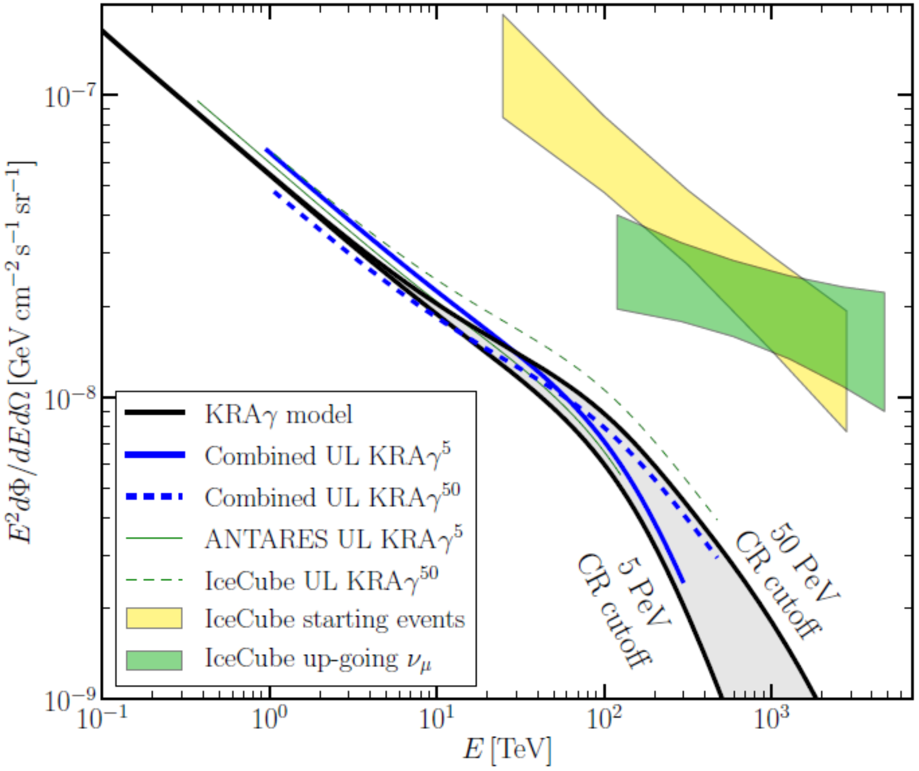


Search for diffuse flux from Galactic ridge

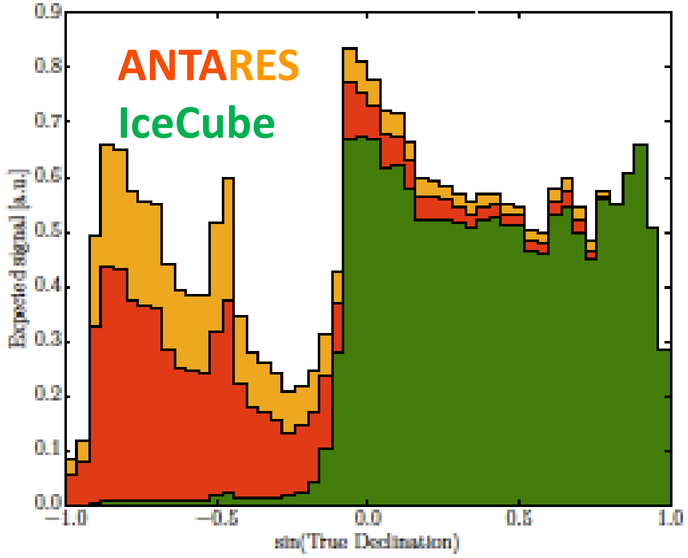
📖 Phys. Rev. D 96, 062001 (2017)
📖 ApJL 868, L20 (2018), with IC

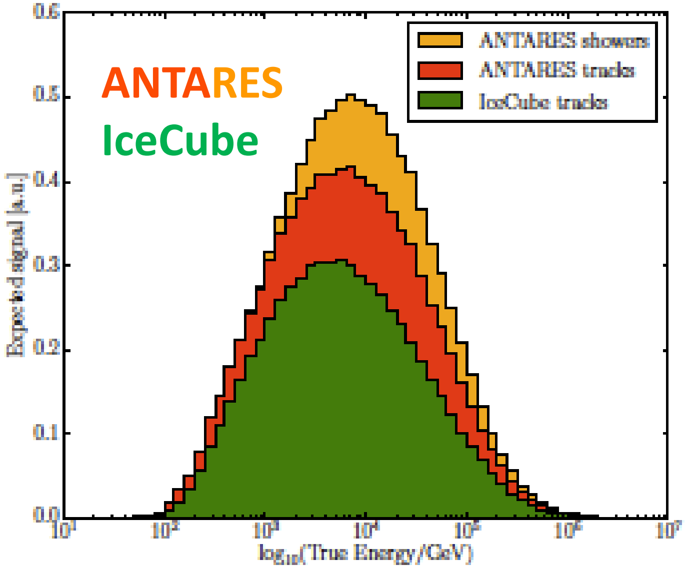
- Improved knowledge of the primary CR spectrum in the knee region in the last years
- Searches (also in combination with IceCube) using a template model (KRA) of cosmic ray diffusion
- **Result**: total flux contribution of **diffuse Galactic neutrino** emission <9% *of the total diffuse IC signal* (E_ν> 30 TeV)

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



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



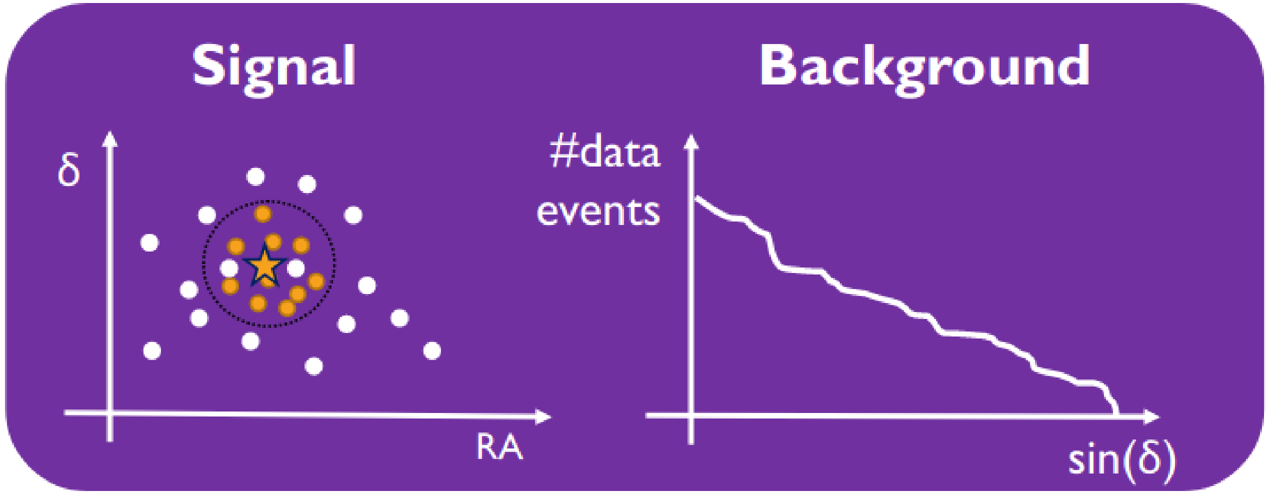


Search for cosmic sources: tracks+cascades

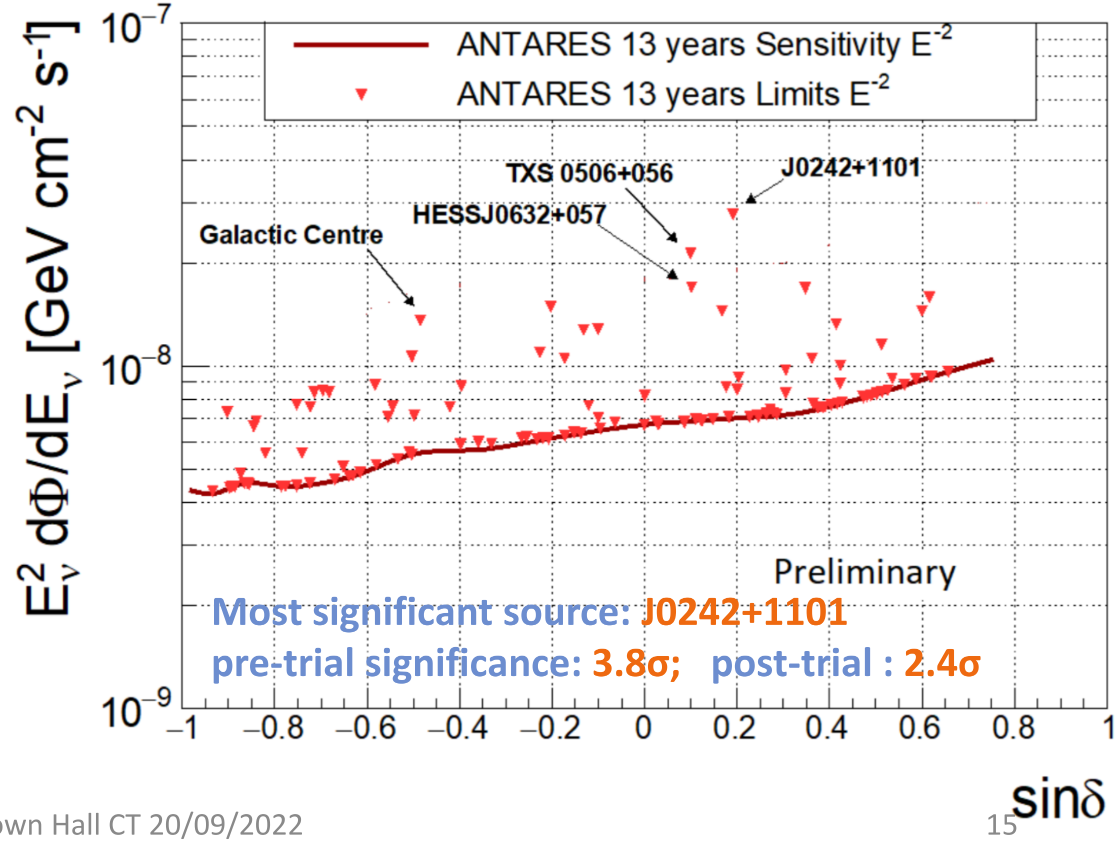
PRD 96, 082001 (2017)
PoS(ICRC2021)1161

- Search in data for spatial clustering of events with respect to atmospheric (~isotropic) foregrounds
  - Self-clustering of neutrinos
  - Following templates for emission (point-source, extended, diffuse)

Data set 13 year (from Jan 2007 to Feb 2020); Livetime: 3845 days



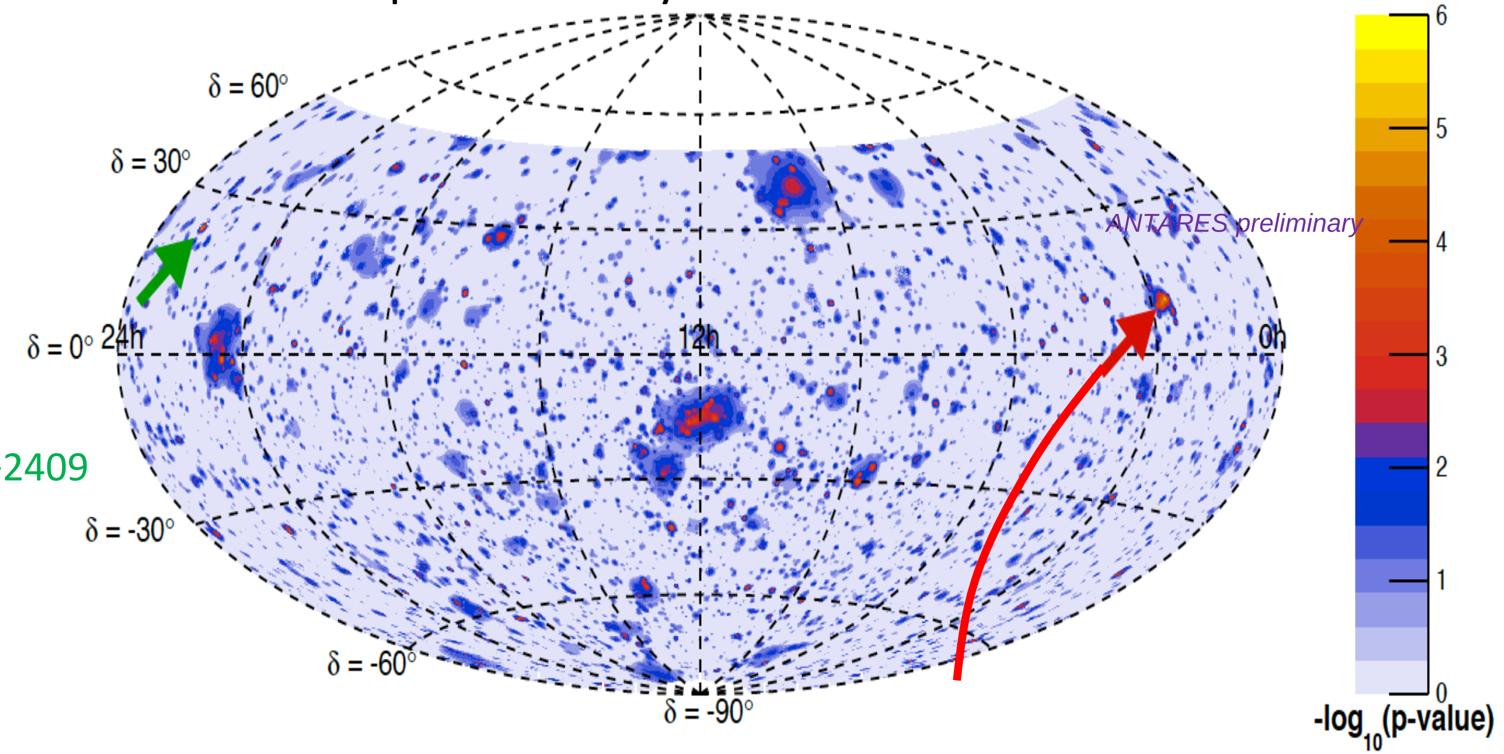
Using a pre-definite candidate-list search: 121 investigated sources



Search for cosmic sources: tracks+cascades

PRD 96, 082001 (2017)
PoS(ICRC2021)1161

Data set 13 year (from Jan 2007 to Feb 2020); Livetime: 3845 days
Search for an excess of events from a particular sky direction



2nd most significant cluster:
RA=343.8° δ=+23.5°
Pre-trial: 4.2 σ
Close to blazar MG3 J225517+2409

The most significant cluster:
RA=39.6° δ=+11.1°
Pre-trial: 4.3 σ (48% post)
Within 1 degree of J0242+1101

With a unbinned full-sky search

Catalog-based searches (stacking sources)

ApJ 911 (2021) 48
PoS(ICRC2021)1164

- Based on Promising associations between IceCube neutrinos and radio galaxies [Plavin+,ApJ 894 (2020) 101; ApJ 908 (2021) 157]
- Likelihood based stacking approach using data from 11 years (2008-2017)

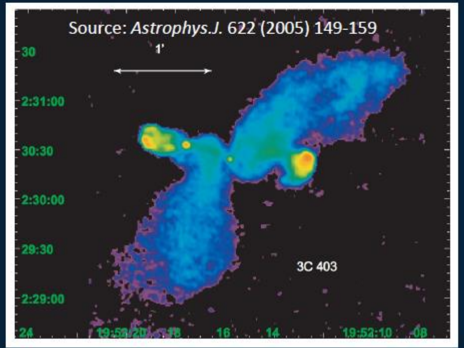
CATALOG	PRE-TRIAL	POST-TRIAL	DOMINANT SOURCE
Fermi 3LAC All Blazars	0.19	0.83	
Fermi 3LAC FSRQ	0.57	0.97	
Fermi 3LAC BL Lacs	**0.088**	**0.64**	**MG3J225517+2409**
Radio-galaxies	**4.8 10^{-3}**	**0.10**	**3C403**
Star Forming Galaxies	0.37	0.93	
Obscured AGN	0.73	0.98	
IC HE tracks	0.05	0.49	

1.6 σ

BLLac MG3 J225517+2409

p-value: 3.8σ
chance probability ($N_{sources}$ = 1255) = 1.4σ

Radio galaxy 3C403



p-value: 3.7σ
chance probability ($N_{sources}$ = 56) = 2.5σ

- Association with blazars of the 5th Roma-BZCat catalog as for IC events in [Buson+, ApJ 933 (2022) 2, L43]: **work in progress**

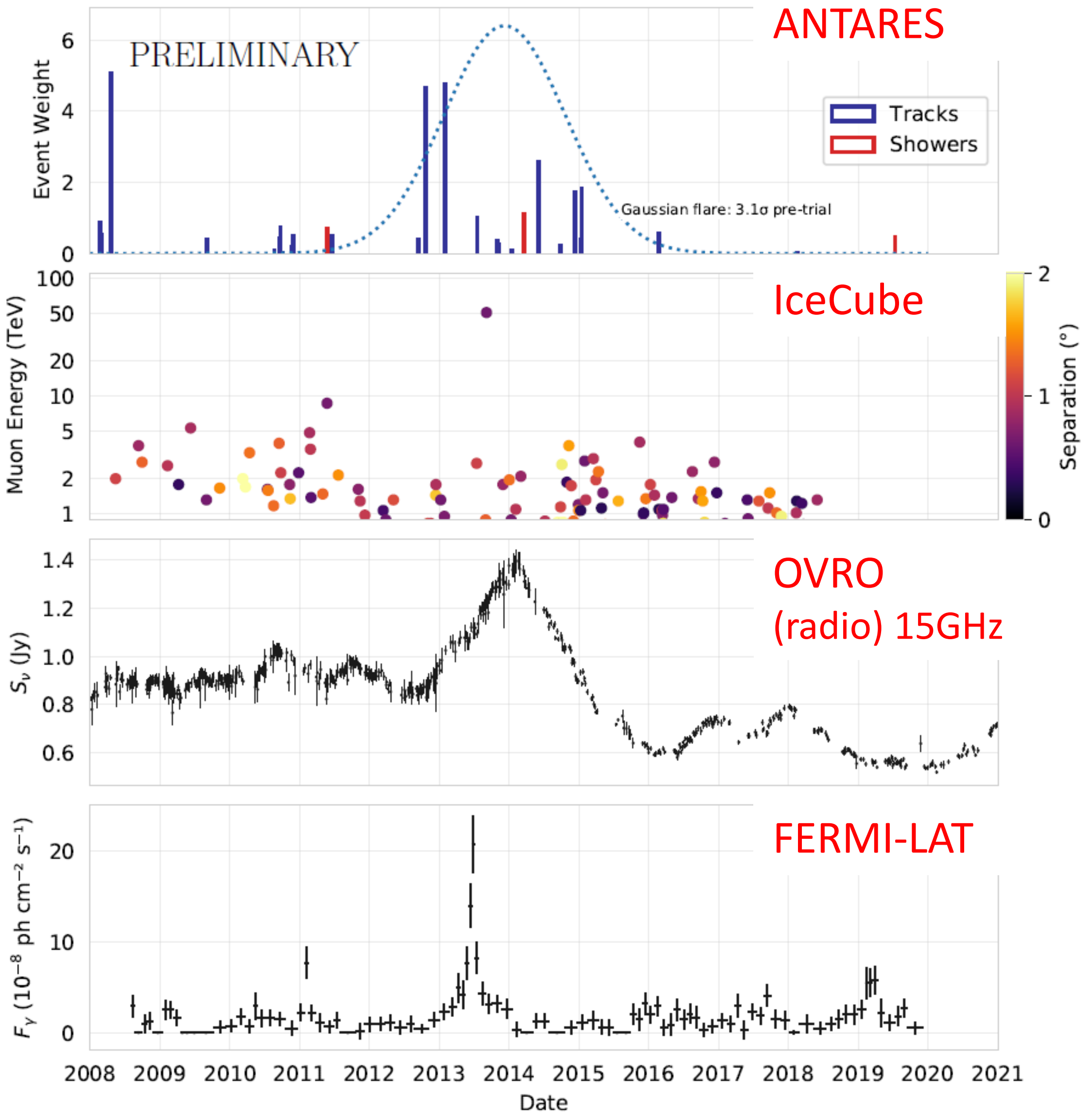
Notable case of J0242+1101 (PKS0239+108)

PoS(ICRC2021)972

Intriguing overlap in time of the flaring emission in radio, γ-ray and neutrino found from the direction of the blazar **J0242+1101** studied from **2008 to 2021**.

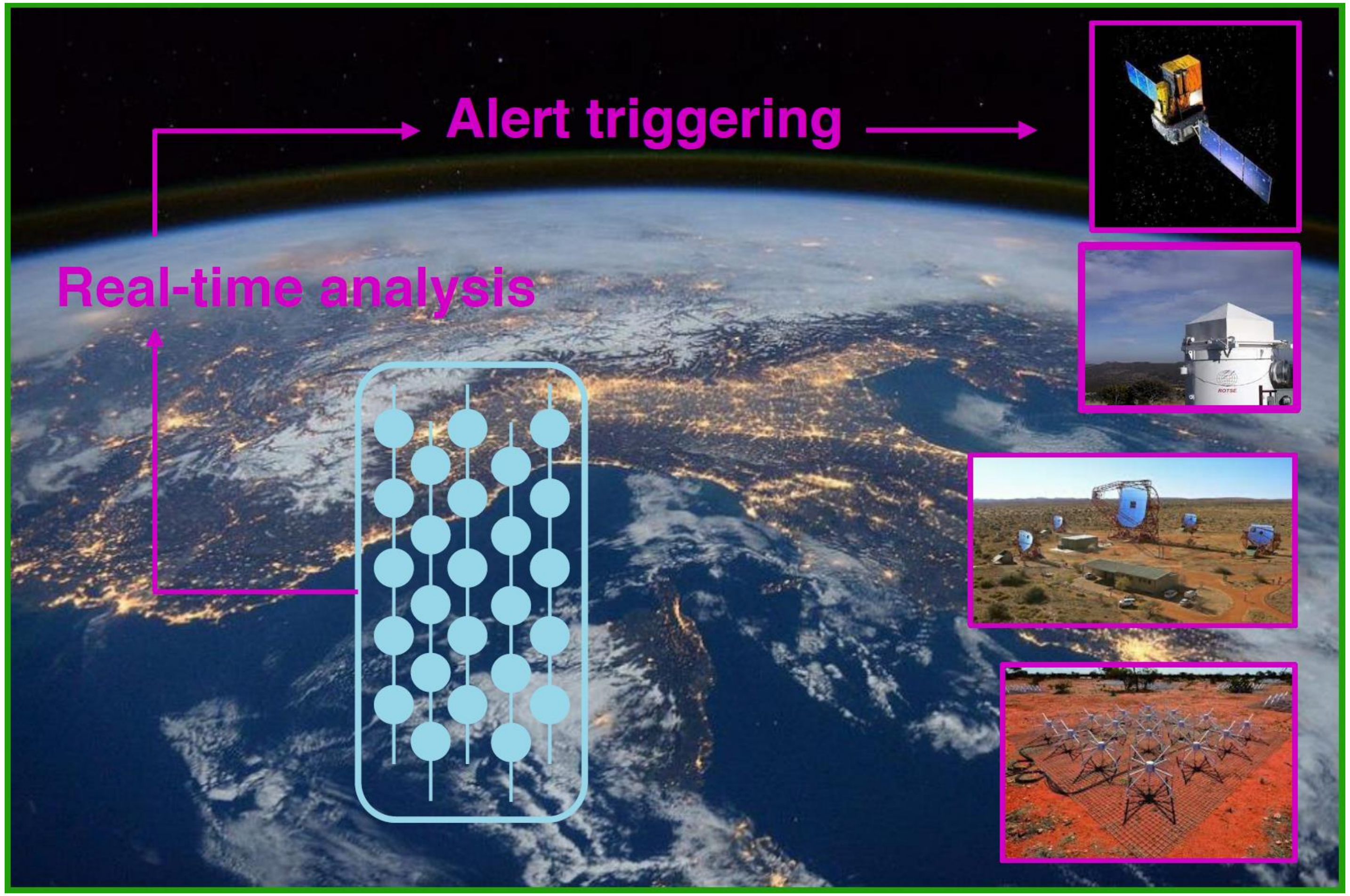
- First panel: weighted time distribution of the ANTARES tracks (showers) within 5°(10°) from J0242+1101 and best-fit Gaussian time profile.
- Second panel: weighted time distribution of the Ice-Cube tracks closer to J0242+1101 than 50% angular error. Weight=energy of each event. The color scale indicates the event angular distance from the source.
- Third panel: OVRO (Owens Valley Radio Observatory) radio light-curve @15 GHz for J0242+1101.
- Fourth panel: adaptive binned γ-ray light-curve obtained from Fermi LAT data for J0242+1101.

Chance probability of the multi-messenger association under study.



Multi-messenger approaches: sending alerts

📖 APP 35 (2012) 530–536



Alert system (**TAToO: Telescopes and Antares Target of Opportunity**) operating since 2009:

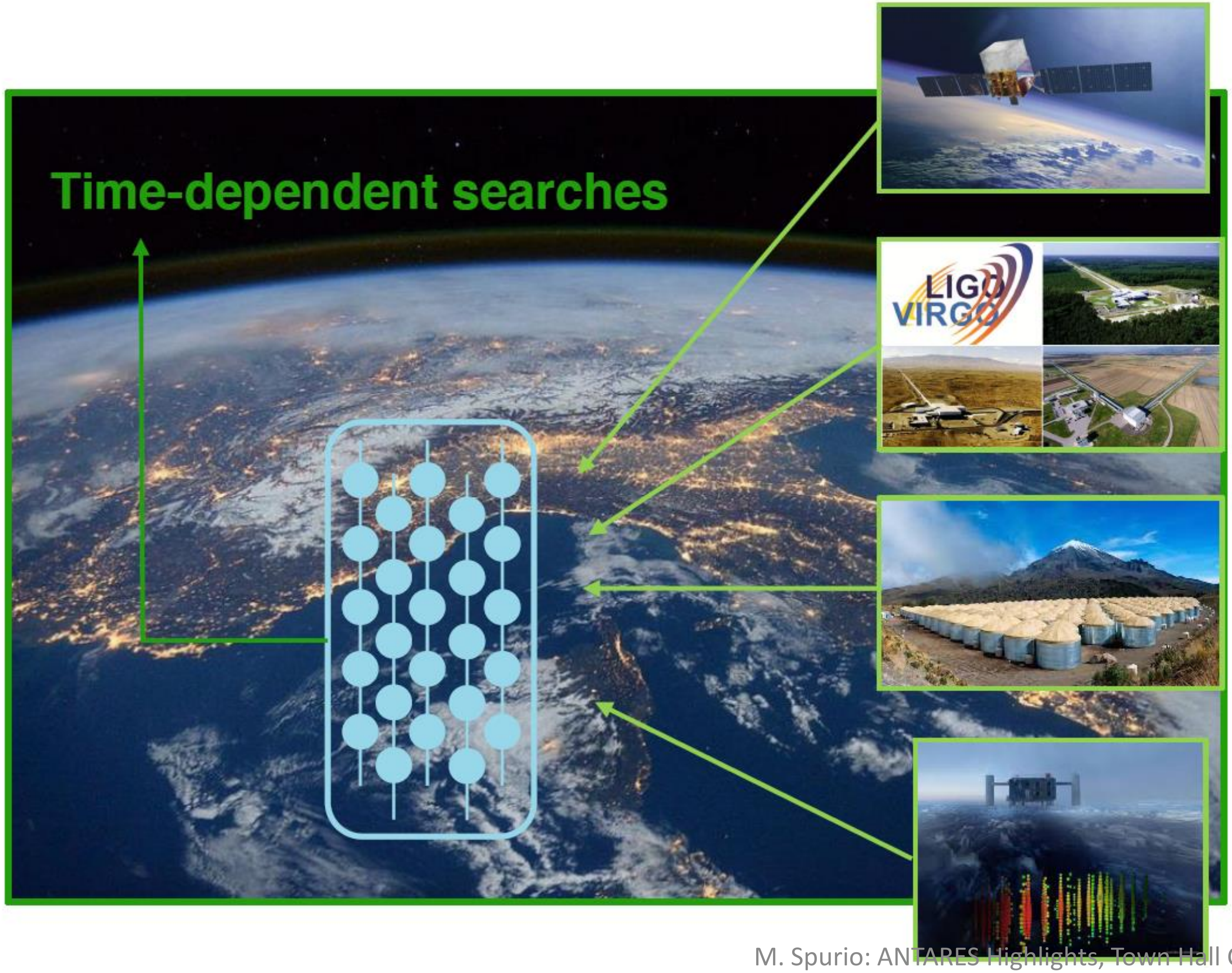
- **High energy (HE)**: single neutrino with an energy ≥ 5 TeV. **Rate: ~1/month**

- **Very high energy (VHE)** : single neutrino with an energy ≥ 30 TeV. **Rate: ~3-5/year**

- **Directional trigger**: single neutrino from the direction (≤ 0.4°) of a local galaxy (≤ 20 Mpc). Mainly introduced to enhance the chance to detect a local CCSN. **Rate: ~1/month**

- **Doublet trigger**: at least two neutrinos coming from close directions (≤ 3°) within a predefined time window (15 min). **No doublet trigger ever been issued**

Multi-messenger approaches: receiving alerts



Follow-up of IceCube neutrinos:

- 115 IceCube events received, 37 analyzed (7 HESE, 3 EHE, 10 gold and 17 bronze)
- No ANTARES candidates found compatible with any of the IceCube alerts
- 90% confidence level upper limits on the neutrino fluence

Dedicated offline follow-up of IC events:

- TXS0506+056 (**ApJL 863 (2018) 2, L30**)
- AT2019dsg and AT2019fdr (**ApJ 920 (2021) 1, 50**)
- HESE and EHE events (**ApJ. 879 (2019)2, 108**)

Follow-up of LIGO/Virgo GWs

- No candidates associated with GWs

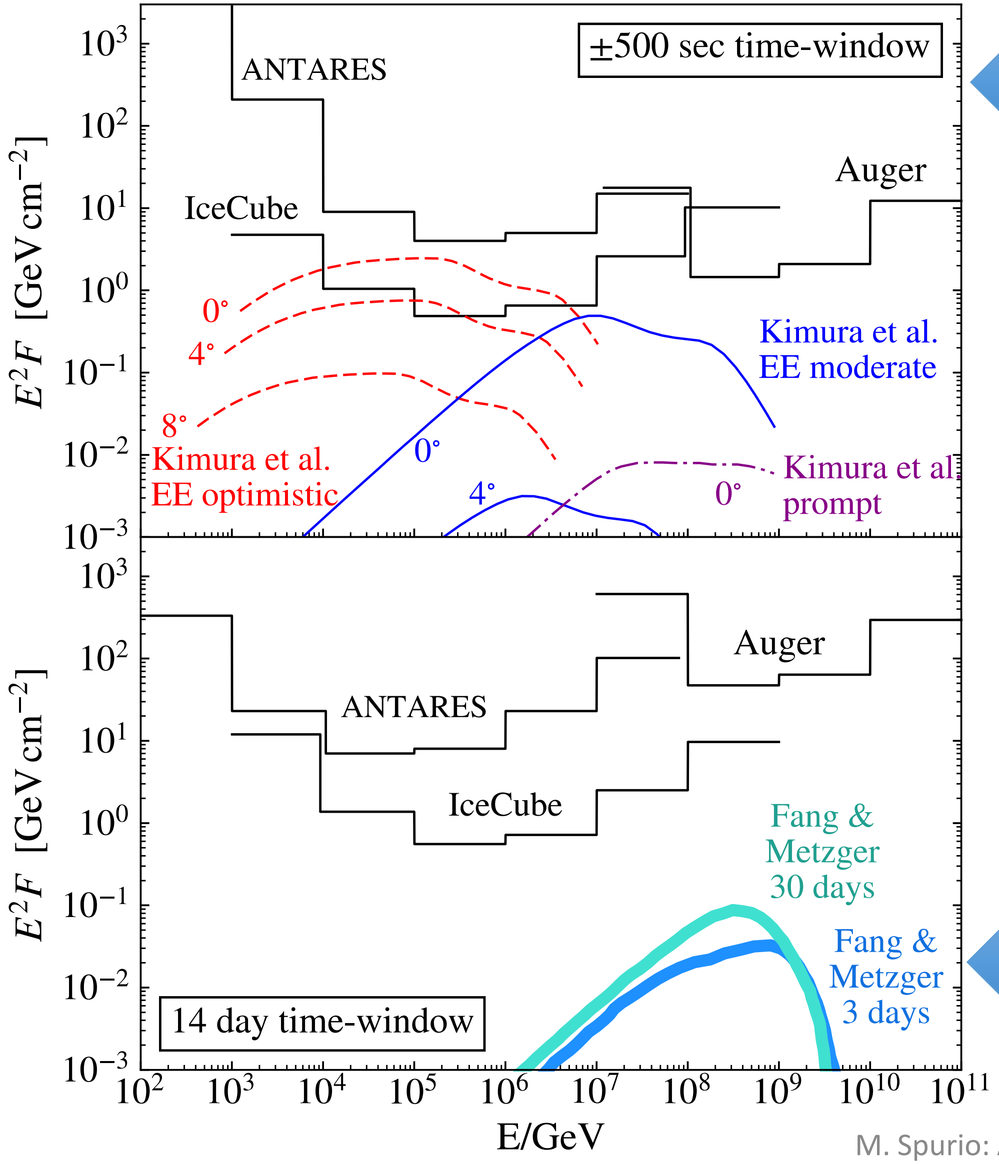
Follow-up of Fermi-GMB and Swift GRBs

Follow-up of HAWC alerts

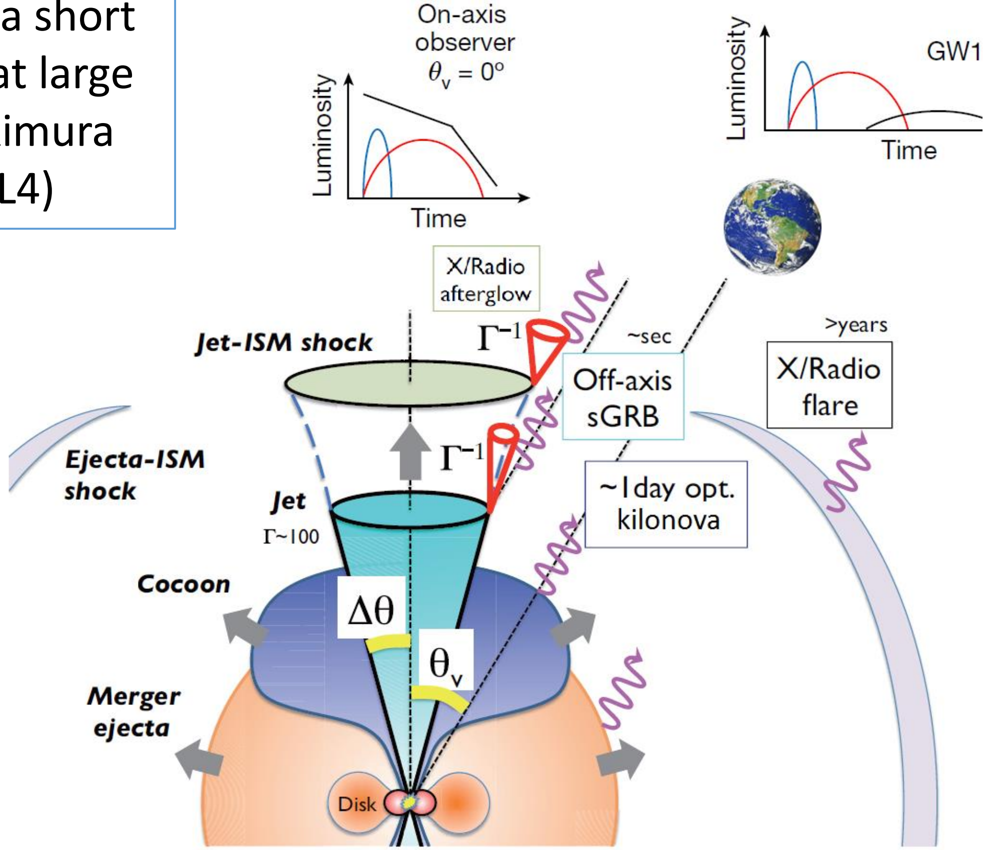
Neutrino Follow-up of GW170817

📖 ANTARES, IceCube, Pierre Auger, LIGO/Virgo. ApJL 850 L35 (2017)

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



Non-detection: consistent with a short GRB observed at large off-axis angle (Kimura et al. ApJL 848, L4)



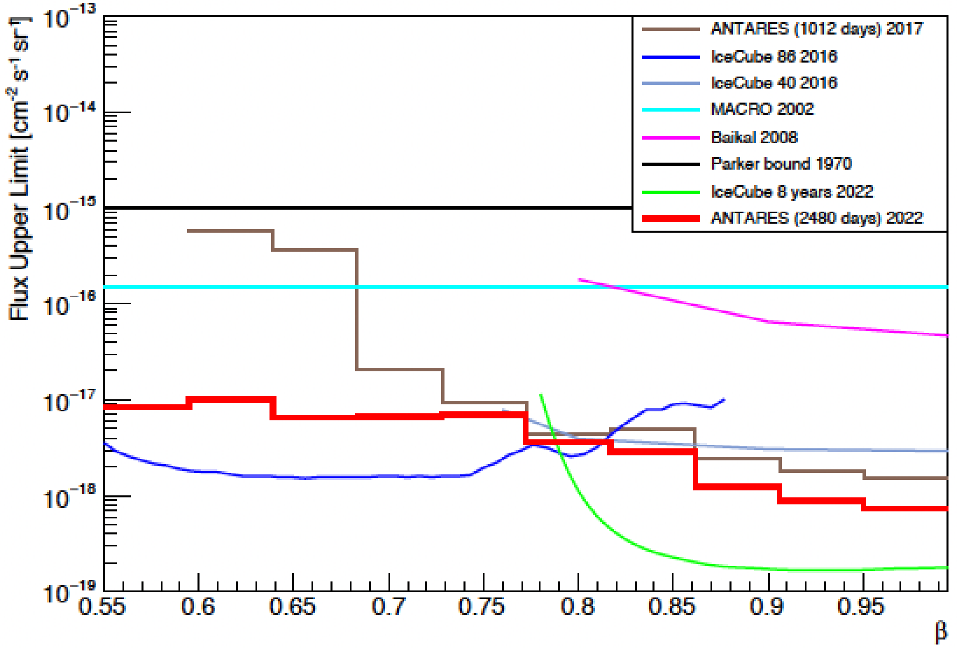
No detection during extended time period of 14 days after the GRB (Fang& Metzger, arXiv:1707.04263)

Search for New Physics

📖 JHEAp, Volume 34, 2022, Pages 1-8 (monopoles)
📖 Paper submitted: arXiv:2208.

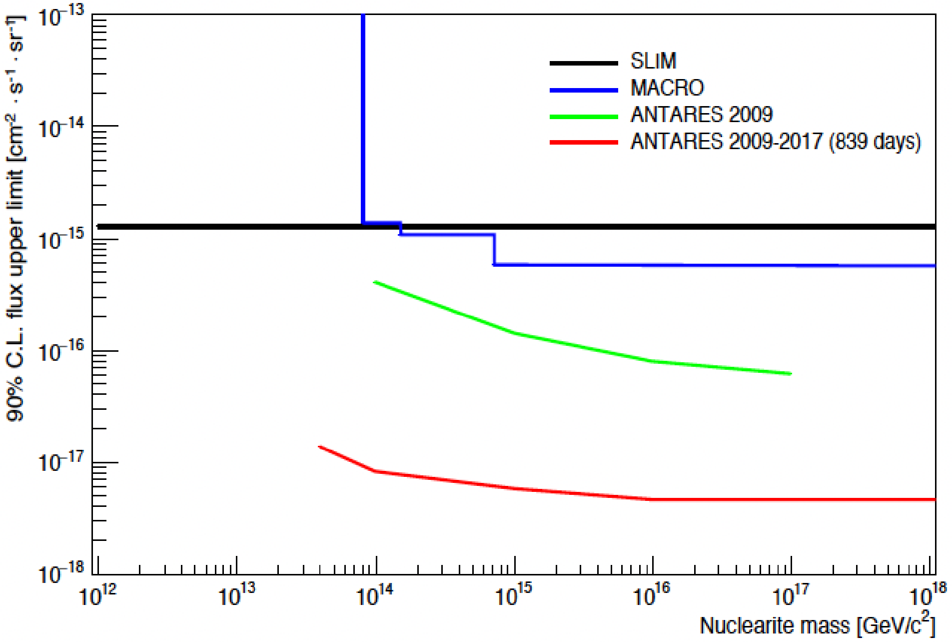
Magnetic Monopoles

- Limits for fast MM with Dirac magnetic charge and velocity >0.55 c
- Kasama, Yang and Goldhaber interaction cross section (secondary particles produce the ligth)

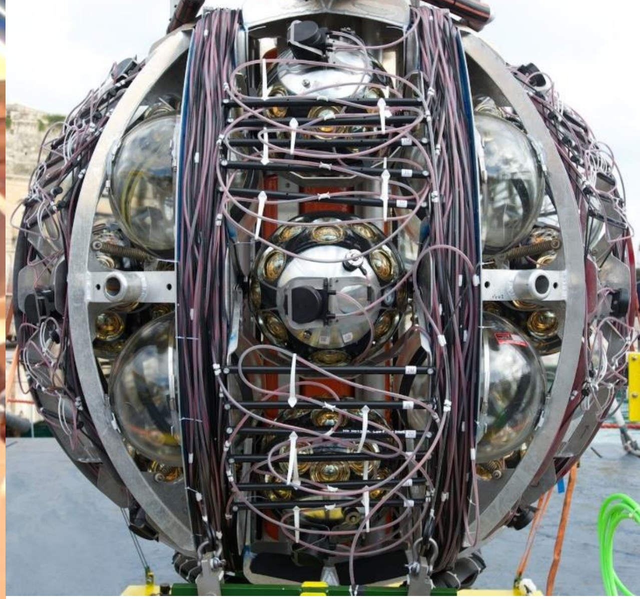


Nuclearites

- Nuclearites made of strange quark matter
- Down going flux with Galactic velocities (v/c=10^{-3})
- dE/dx according to de Rujula & Glashow model
- Limits as a function of the nuclearite mass



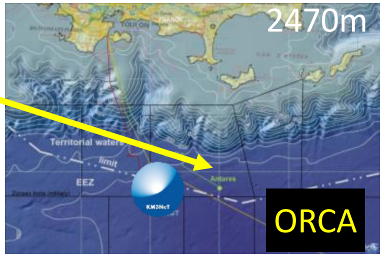
ANTARES → KM3NeT



- ANTARES was the first and largest NT in the Sea.
- First line deployed 2006, construction completed 2008, decommissioned May-June 2022
- Although smaller than 1 km^3 scale, it has provided competitive physics results & intriguing hints
- Constraints on the sources of neutrino observed by IceCube.
- Extensive multi-messenger program and joint studies with several partners (electromagnetic+ GWs + Cosmic Rays + Neutrinos).
- About 100 papers published & 100 PhD.
- A multi disciplinary observatory (associated sciences)
- Public sample (with increasing details in the future) available on the website.

- QUITE AN ADVENTURE ! But only the beginning …

ANTARES



Oscillation **R**esearch with **C**osmics **I**n the **A**byss

KM3NeT

Astroparticle **R**esearch with **C**osmics in the **A**byss

KM3NeT started!

Next generation neutrino telescope in the Mediterranean Sea

- Under construction: currently running with 19 DUs (ARCA) and 10 DUs (ORCA)
- ARCA reached a comparable sensitivity to cosmic neutrinos as ANTARES
- Better median angular resolution (~0.1° @1 PeV) and x100 ANTARES instrumented volume (ARCA)
- Will allow multi-flavour neutrino detection in real-time over an extended energy range (ARCA+ORCA)
- Real-time framework in preparation, enter the multi-messenger game soon!
- ARCA detector: burst in 2022 from the Italian PNRR (Insfrastrutture di ricerca)

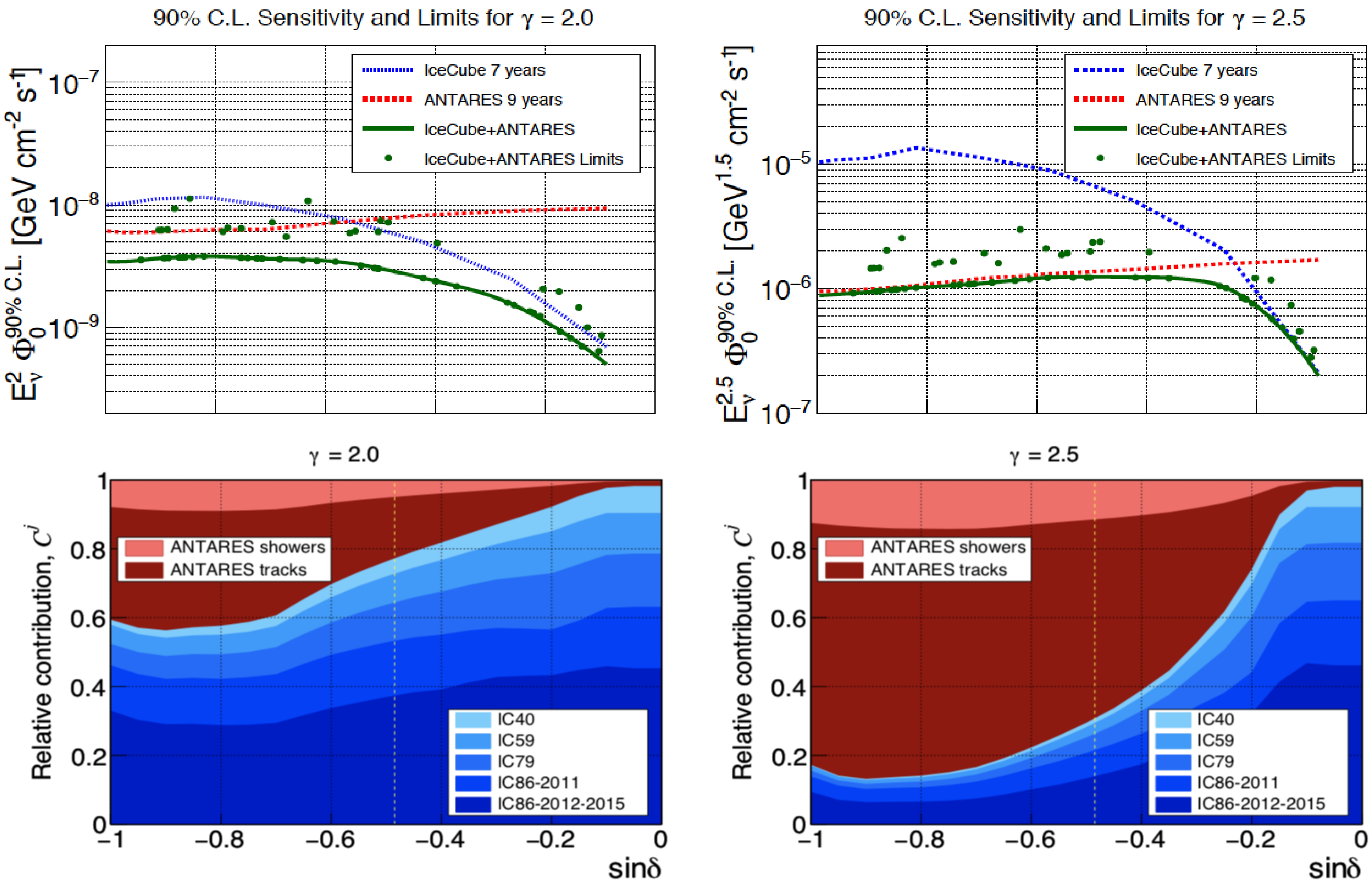
Spares →

Search for cosmic sources: ANTARES+IceCube

📖 ApJ892 (2020) 2

- ANTARES data= 9 year (2007 to 2015)
- Cosmic source= excess of events from one direction
- ν_μ golden channel
- ANTARES sensitivity optimized for the Southern Hemisphere
- No significant excess also combining results with IC

ANTARES data set is public : see https://antares.in2p3.fr



ANTARES: a multidisciplinary observatory

🕮 PLoS ONE 8 (7) 2013
Deep-sea bioluminescence blooms after dense water formation at the ocean surface

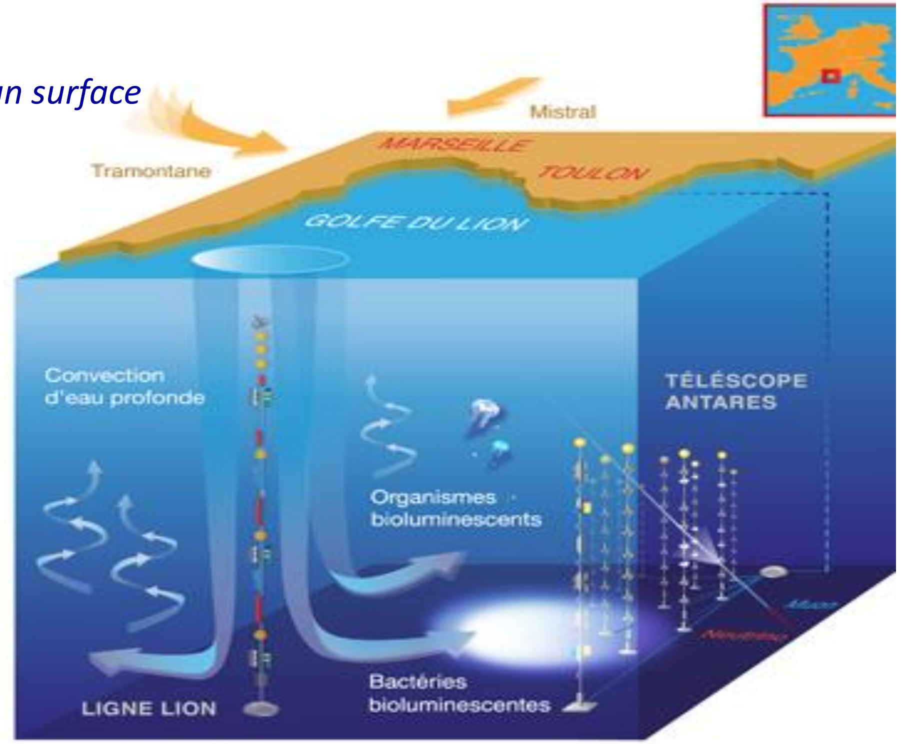
🕮 *Journal of Geophysical Research: Oceans, Vol 122, 3, 2017*
Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection

🕮 Deep-Sea Research I 58 (2011) 875–884
Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean

🕮 *Sci. Rep. 7 (2017) 45517*
Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope

🕮 Ocean Dynamics, April 2014, 64, 4, 507-517
High-frequency internal wave motions at the ANTARES site in the deep Western Mediterranean

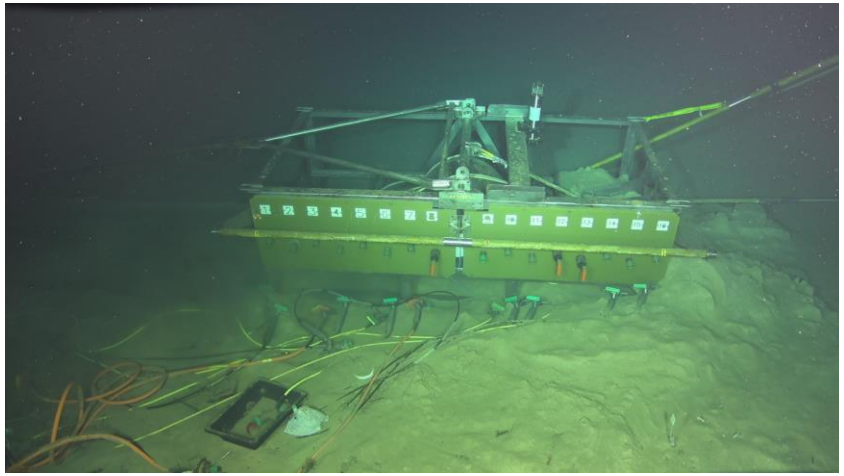
🕮 https://arxiv.org/abs/2107.08063
Studying Bioluminescence Flashes with the ANTARES Deep Sea Neutrino Telescope



ANTARES: before and after the sea

First complete detector line - 2006

Junction Box 2022, after 20 y in seawater

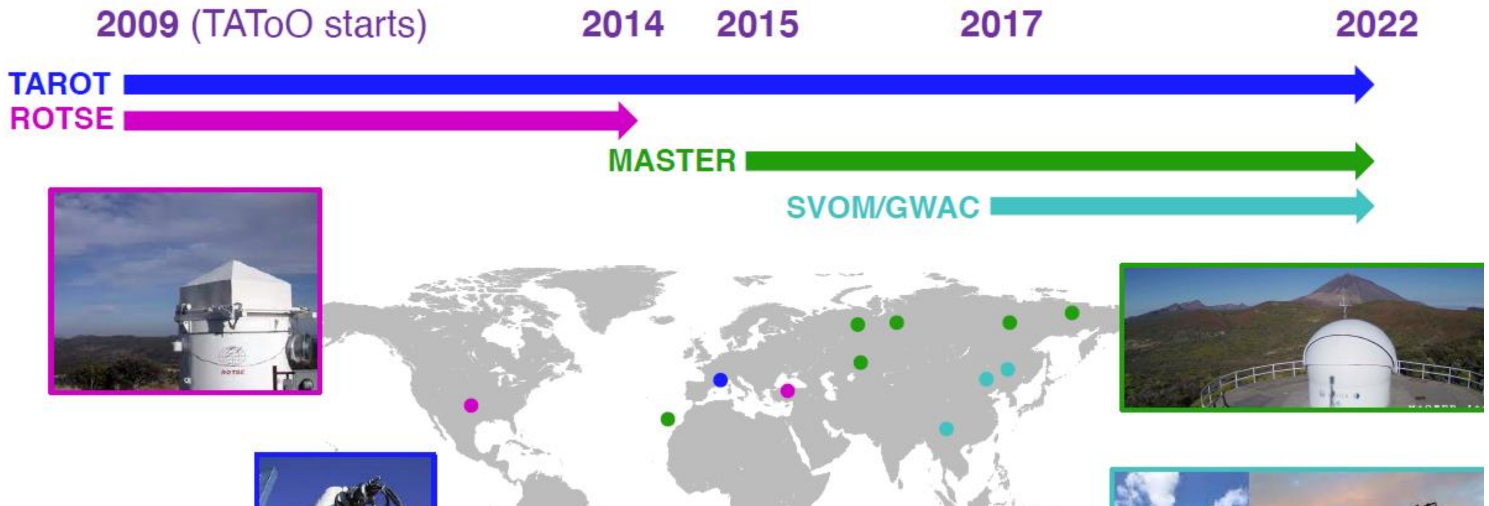


Recovery line - 2022

OMs (PMTs) after 16 y in water - 2022

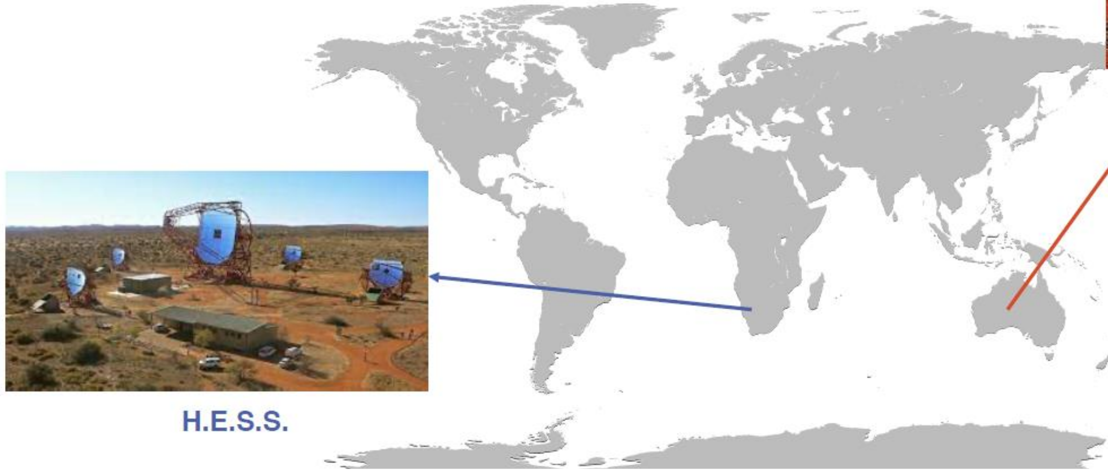
ANTARES partner followers

📖 APP 35 (2012) 530–536
📖Results: Paper in preparation

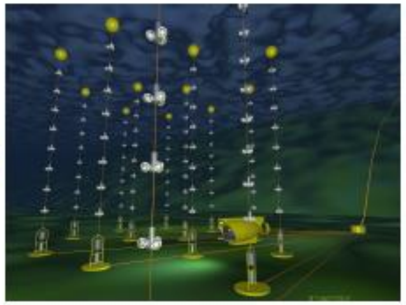


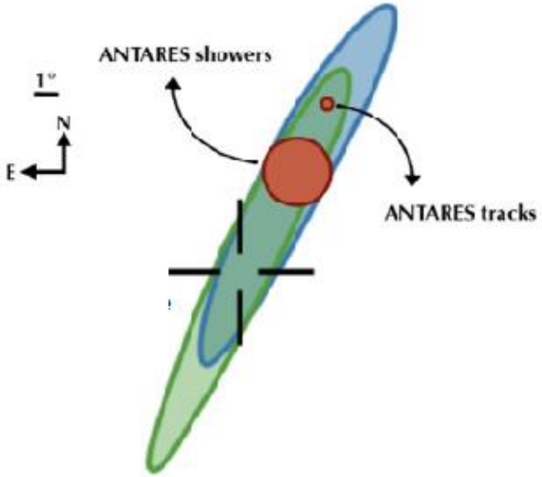
Optical telescopes

Radio, x-ray and gamma-ray telescopes

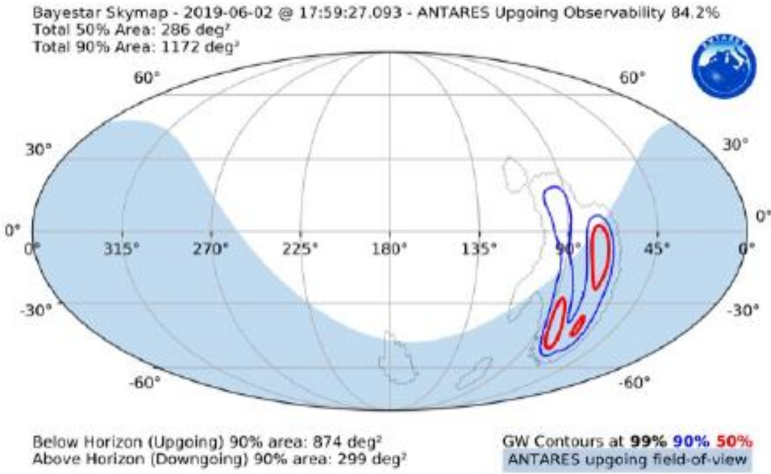


Follow-up of LIGO/Virgo GWs



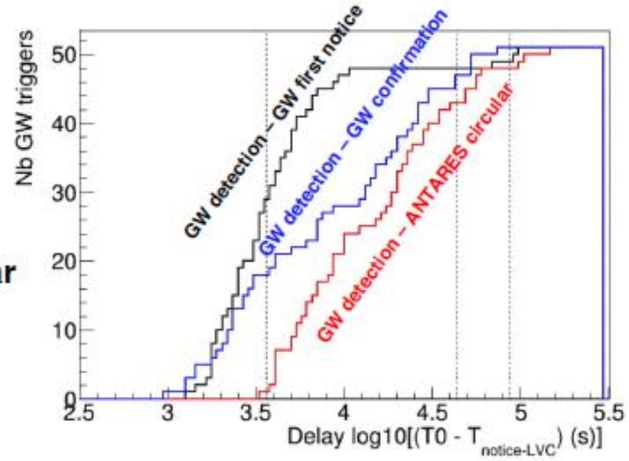


- RunO1 (2015): **3 GW events** detected, all followed **offline** **(online analysis not ready)**
- RunO2 (2016-2017): **15 GW alerts**, all followed **online** **(manually)**
- RunO3 (2019-2020): **78 GW alerts** (22 retracted, 3 terrestrial noise, 2 non visible) → **51 followed online** **(fully automatised)**



Search in
Spatial overlap between 90% GW contour and ANTARES visibility region
±500 s and **±1 hour**

- **No** time&space **coincidence found**
- Results communicated through **GCN circular**
- **~4.5h from GW detection**
- **< 2h from GW signal confirmation**



Refined offline analyses:
→ Phys.Rev. D93 (2016) no.12, 122010, → Phys.Rev. D96 (2017) no.2, 022005
→ Eur.Phys.J. C77 (2017) no.12, 911, → Astrophys.J. 850 (2017) no.2, L35

ANTARES Follow-up of ICECUBE-170922

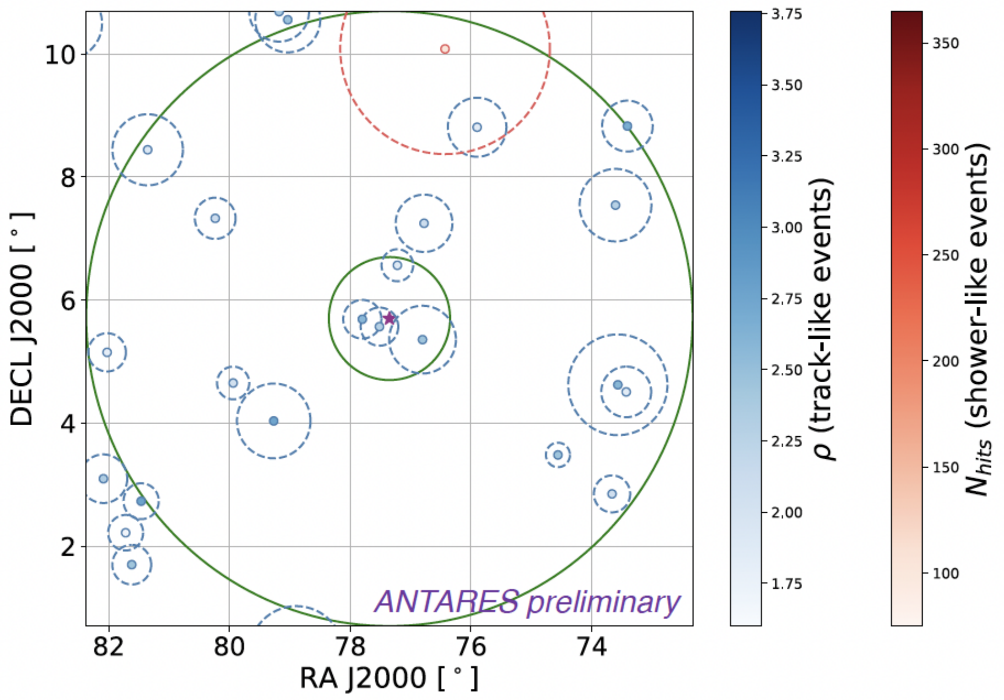
ANTARES Time integrated search

- Same analysis method used for PS study

- Expected background (3136 days) :
  - 0.23/deg^2 for track-like
  - 0.005/deg^2 for shower-like events
- # of events fitted the likelihood signal function for the source: **μ_{sig} = 1.03**
- **Pre-trial p-value of 3.4%** (post-trial 87%)

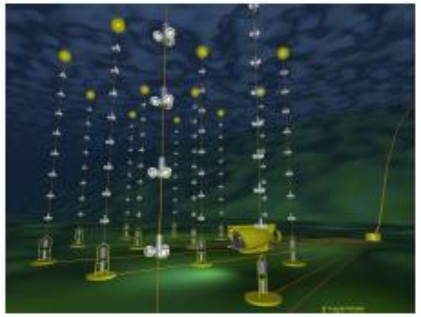
- Updated 2007-2020, recalibrated

- 4 events within 1° μ_{sig} = **2. 9**
- Pre-trial: 2.9σ (1-sided)



📖 ApJL 863, L2 (2018) updated at ICRC 2021

Follow-up of Fermi-GMB and Swift GRBs



Fermi/Swift alert message sent via the **GCN** within a **few tens of seconds** after GRB detection

- **Automatic** analysis of ANTARES online data
- Run for **9 years** (01/2014–02/2022)
- **317** Swift and **230** Fermi-GBM bursts followed
- **No** significant **coincidence** detected

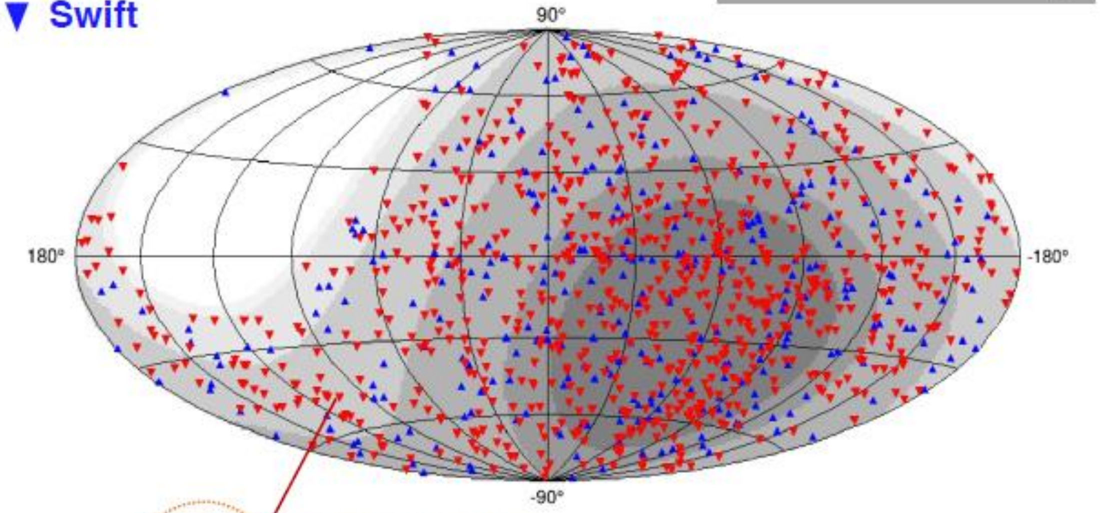
Offline analyses:

→ Eur. Phys. J. C 77.1 (2017)
→ Mon. Not. Roy. Astron. Soc. 469 (2017)
→ MNRAS 500 (2021) 5614

Skymap in Galactic coordinates with the positions of the **GRBs followed by ANTARES**:

▼ Fermi
▼ Swift

ANTARES visibility



Search in

Opening angle:

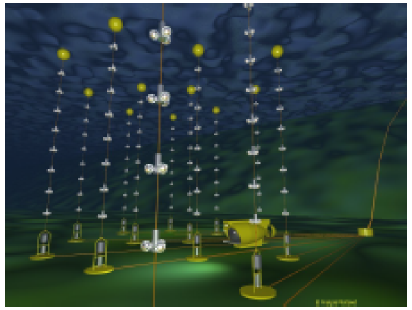
- Fermi trigger: maximum between 2° and size of the GRB error box
- Swift trigger: 2°

Time window:

[–250 s; +750 s] around the GRB time

→ **One coincidence event = p-value of 2-5×10^{-5}**

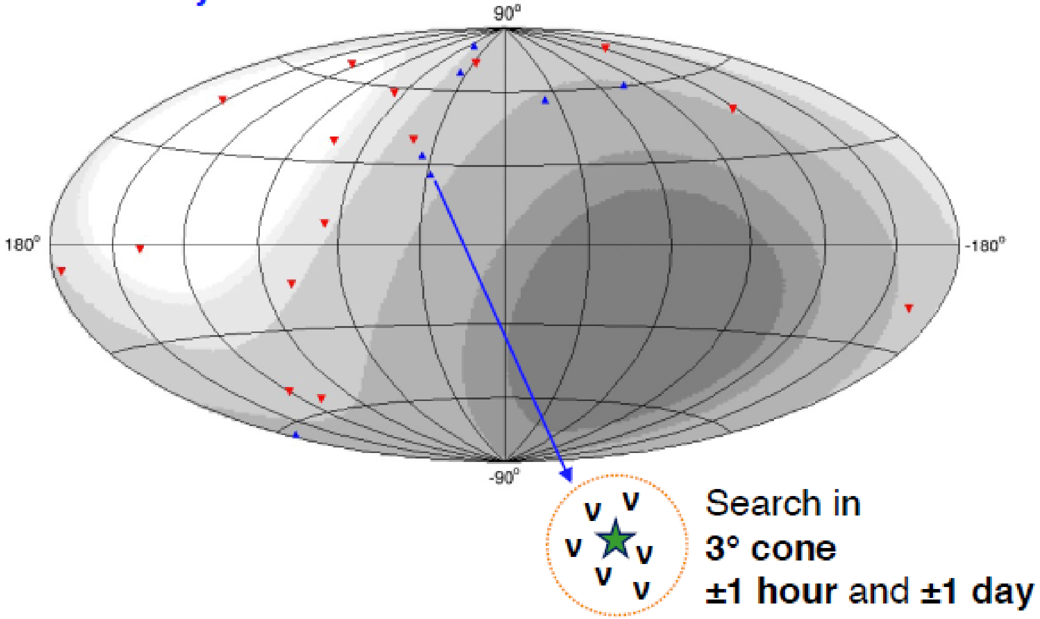
Follow-up of HAWC alerts



Skymap in Galactic coordinates with the positions of the **HAWC alerts**:

▼ Not followed by ANTARES
▼ Followed by ANTARES

ANTARES visibility



- Alerts of **short (0.2 to 100 s) TeV transients** sent by the **HAWC** Collaboration since mid 2019 (→ link to alert list)
- Targeting in particular GRBs
- Alerts channeled via the **AMON** framework and then distributed by the **GCN**
- Up to Feb. 2022, 22 triggers sent, **7 followed by ANTARES (in FoV)**
- No coincidence found

- Additional follow-up of **the IceCube + HAWC coincidences** (NuEM) provided by AMON (→ link to alert list)
- No coincidence found