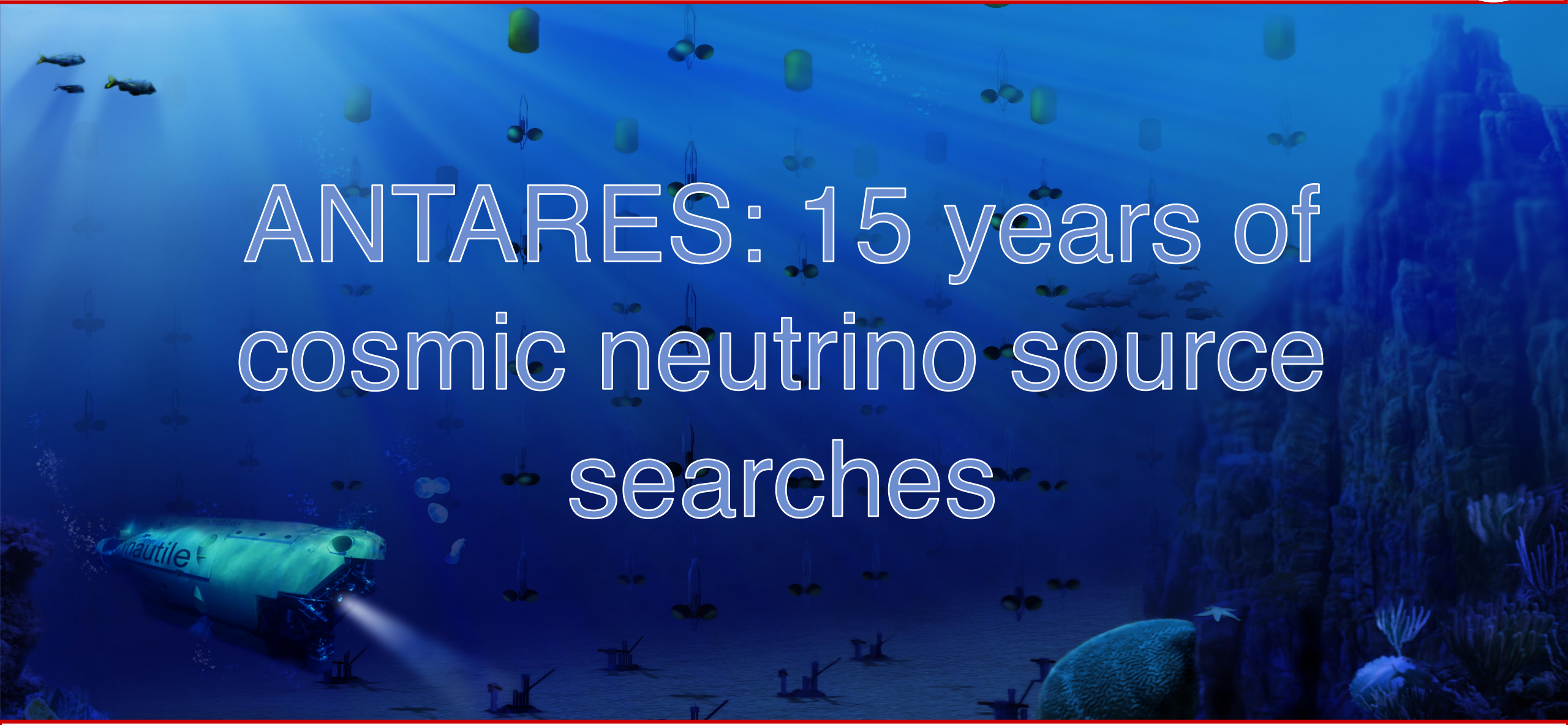
ANTARES: 15 years of cosmic neutrino source searches

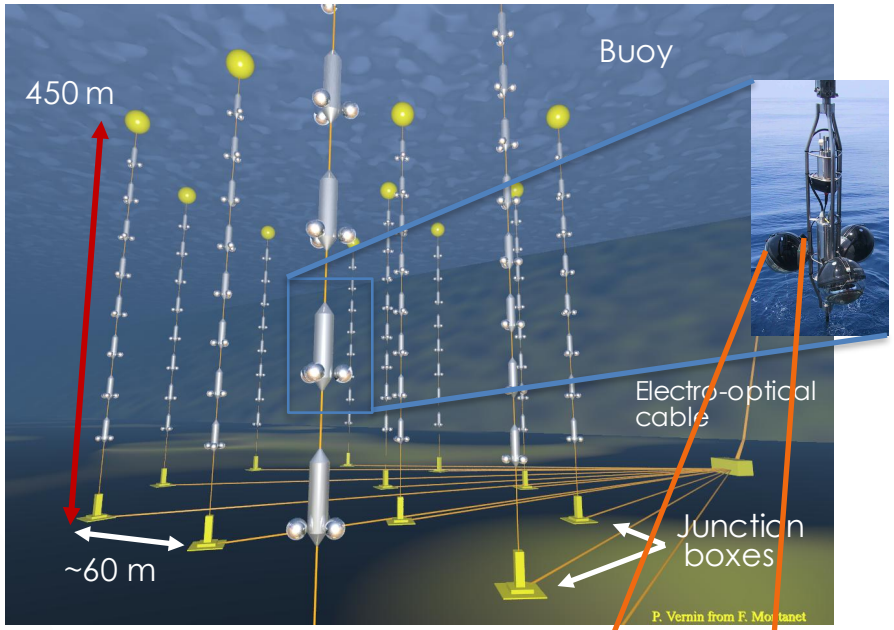


Giulia Illuminati on behalf of the **ANTARES** Collaboration

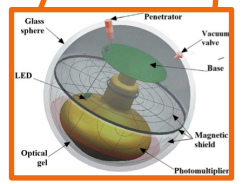
Marcel Grossmann Meeting, Pescara, 2024

ANTARES telescope

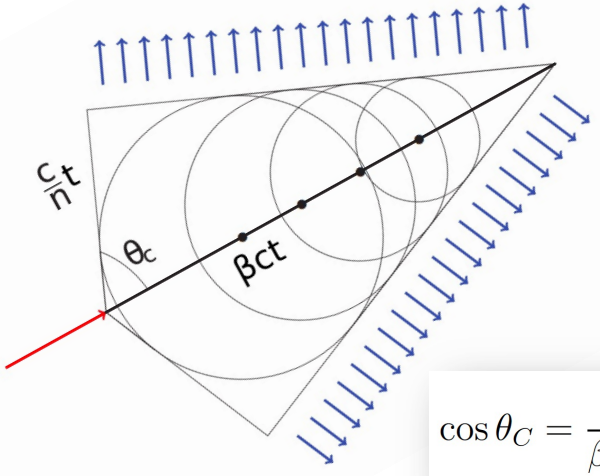
- Designed to detect ν **with E > few GeV**
- First detection line installed in early 2006
- **Completed in 2008, decommissioned in 2022**
- **2475 m depth** in the Mediterranean Sea
- 40 km offshore from Toulon



- Matrix of **885 PMTs**
- **12 vertical lines**, 25 storeys



Cherenkov radiation detected by PMTs



$$\cos\theta_C = \frac{1}{\beta n}$$

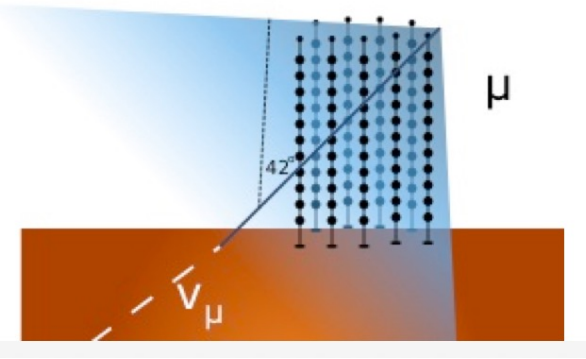
Position, time and charge used to reconstruct **direction and energy of the parent ν**

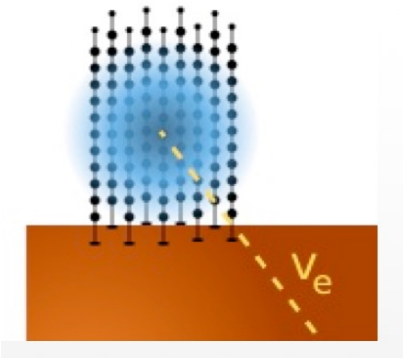
Either **CC** or **NC interaction** with a nucleon N of a nucleus

CC: $\nu_l + N \rightarrow l + X$

NC: $\nu_l + N \rightarrow \nu_l + X$

ANTARES telescope





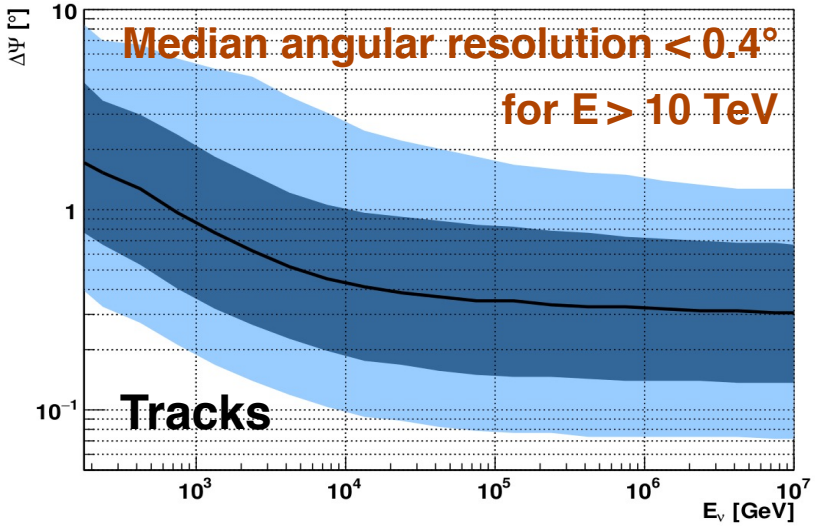
Track-like events:

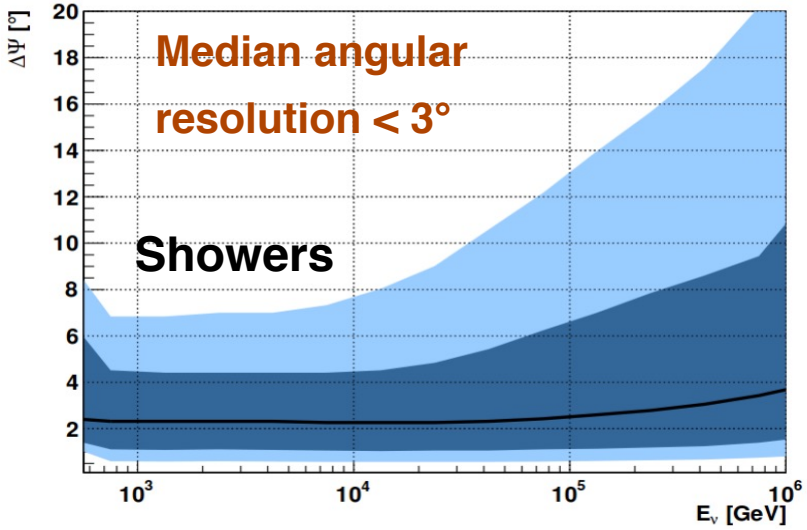
$\nu_\mu(\nu_\tau)$ neutrino
CC interaction near the detector

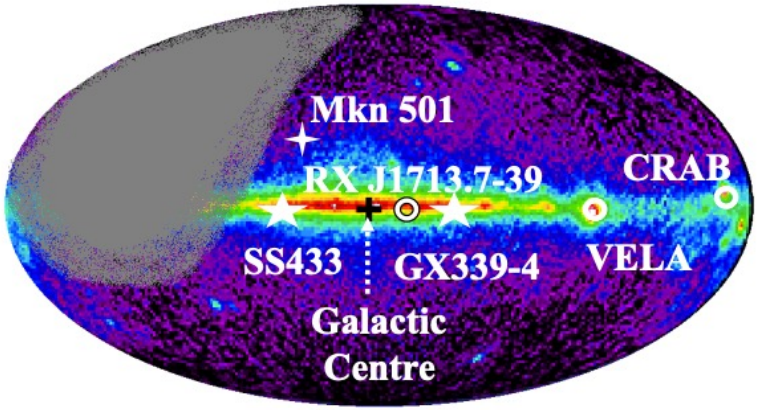
Shower-like events:

all neutrinos NC, ν_e, ν_τ CC interaction
inside or very close to the detector

Earth used as shield against up-going atmospheric muons







Visibility for up-going events: ¾ of the sky, most of the Galactic plane
~95% duty cycle

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Search method: unbinned likelihood

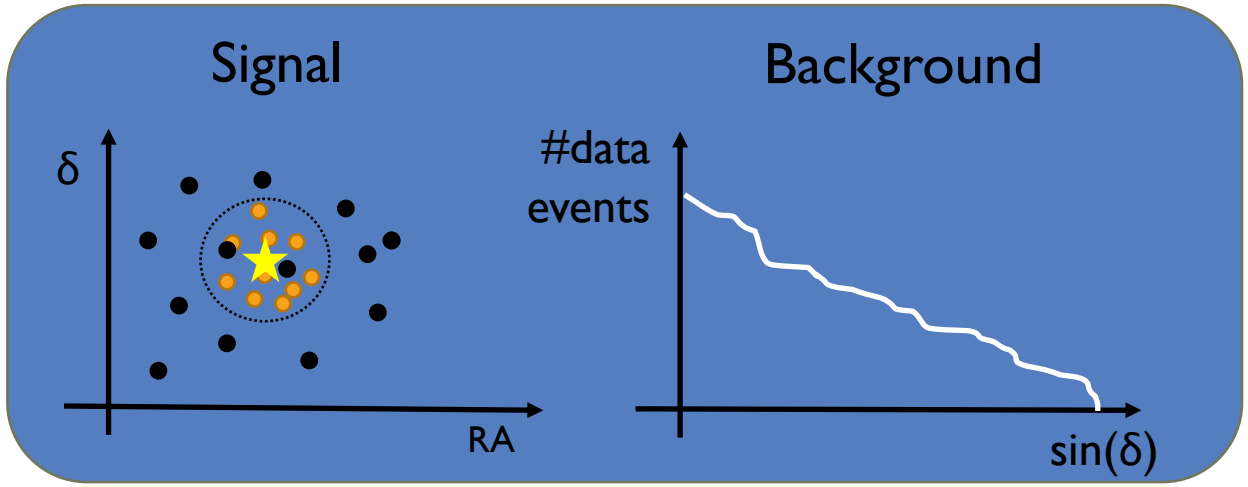
$$L(n_s, \Theta) = \prod_{j=1}^{N_{samples}} \prod_{i=1}^{N_{events}^{j}} \left[\frac{n_s^j}{N_{events}^j} S_i^j(\Theta) + \left(1 - \frac{n_s^j}{N_{events}^j}\right) B_i^j \right]$$

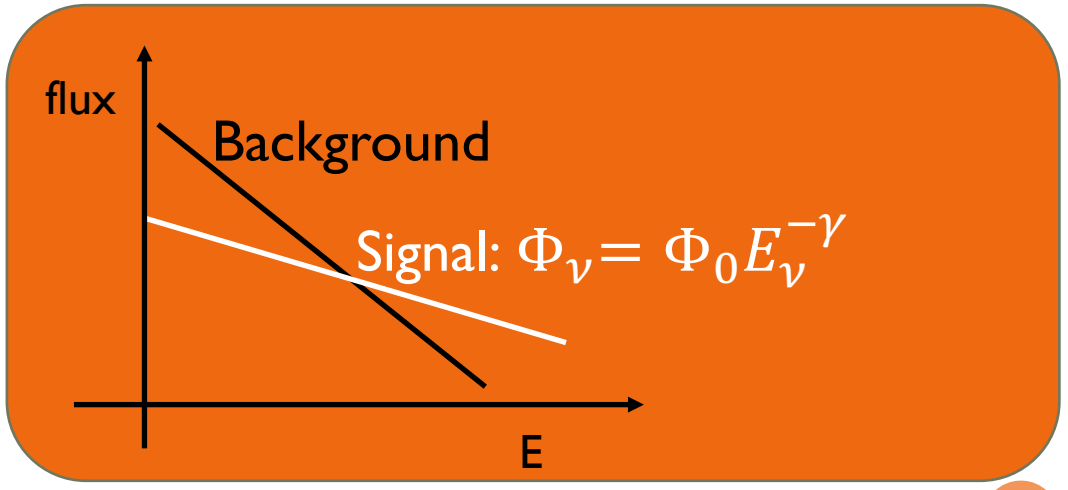
Signal PDFs

Background PDFs

$$S_i = S^{space} \cdot S^{energy}$$

$$B_i = B^{space} \cdot B^{energy}$$





Search method: unbinned likelihood

$$L(\underbrace{n_s, \Theta}) = \prod_{j=1}^{N_{samples}} \prod_{i=1}^{N_{events}^{j}} \left[\frac{n_s^j}{N_{events}^j} S_i^j(\Theta) + \left(1 - \frac{n_s^j}{N_{events}^j}\right) B_i^j \right]$$

free parameters

n_s: number of detected signal events

Θ: set of model parameters

Likelihood maximization → $\hat{n}_s, \hat{\Theta}$ best estimation of n_s, Θ

- H_0: the data consist solely of background
- H_S: the data contain also astrophysical neutrino events (n_s) coming from a source with some given features (Θ)

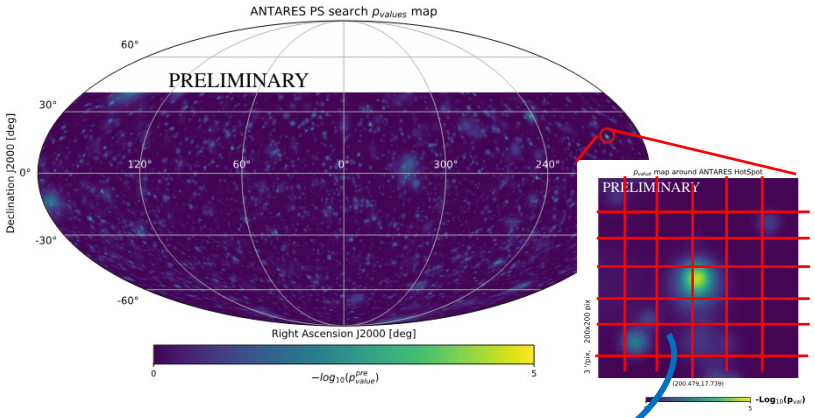
signal spectral index, source extension, source coordinates …

test statistic

$$TS = \log \frac{L(\hat{n}_s, \hat{\Theta})}{L(n_s = 0)}$$

Search method: different approaches

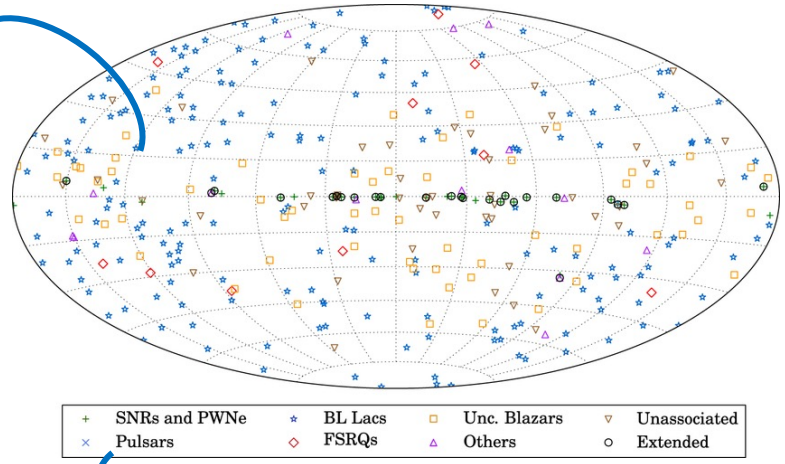
All-sky search



- Sky divided into a fine grid
- Likelihood evaluated in each pixel
- **Disadvantage**: large trial factor
- **Advantage**: unbiased by EM observations

Source list search

- Only location of selected EM sources investigated
- Likelihood evaluated for each source
- **Disadvantage**: might be biased
- **Advantage**: reduced trial factor

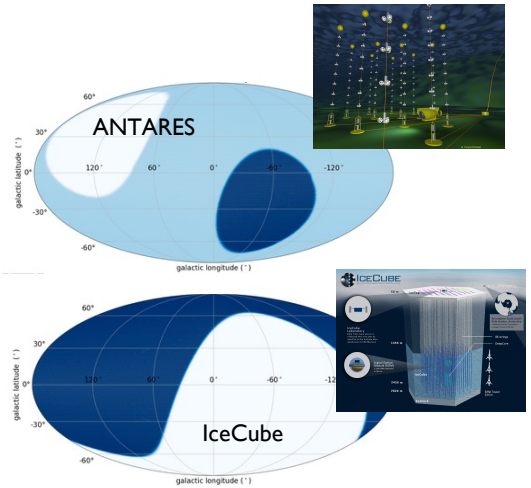


Stacking search

- Search for cumulative excess from catalogs of sources
- Cumulative likelihood evaluated for each catalog
- **Further advantage**: sensitive to individually weak sources

Combining detectors

- **Advantage**: exploit complementarity to gain in sensitivity



Time-dependent searches

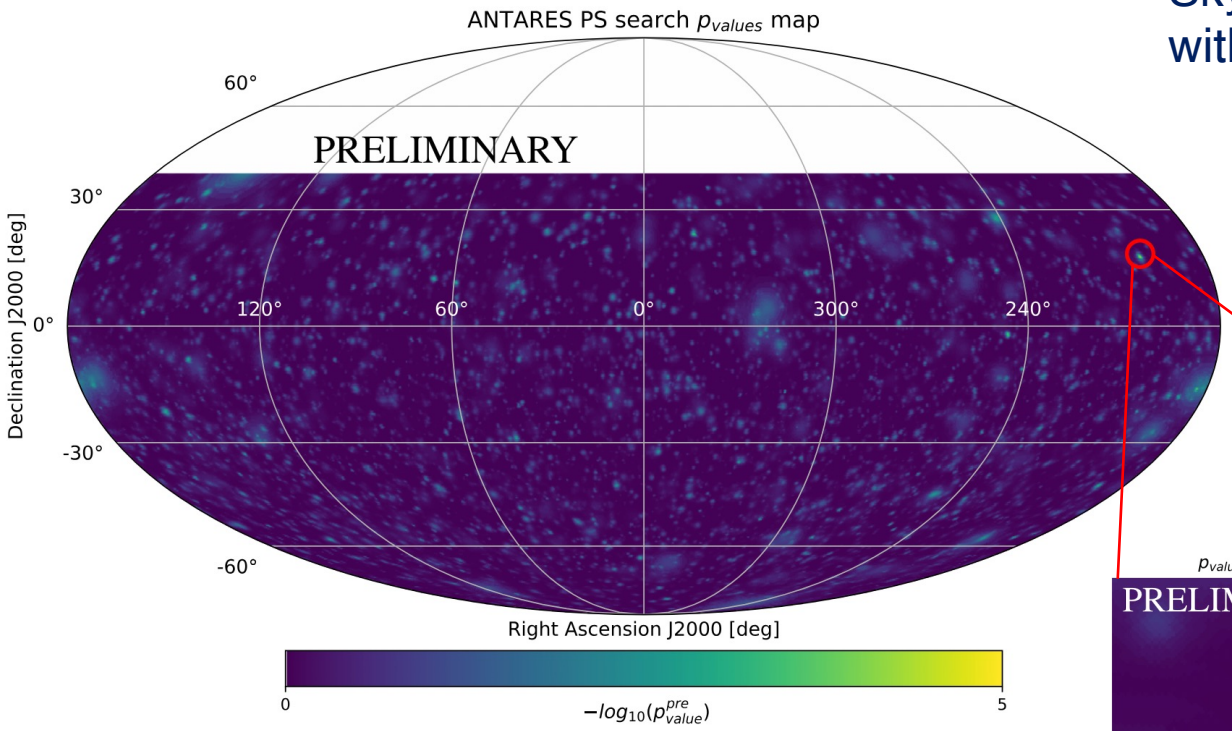
- **Advantage**: reduce background contamination in short time window

(COVERED IN NEXT TALK)

All-sky search

PoS(ICRC2023)1128

Sky divided in **~0.11°×0.11° pixels** using a **HEALPix** grid with NSIDE=512. Each pixel direction is investigated



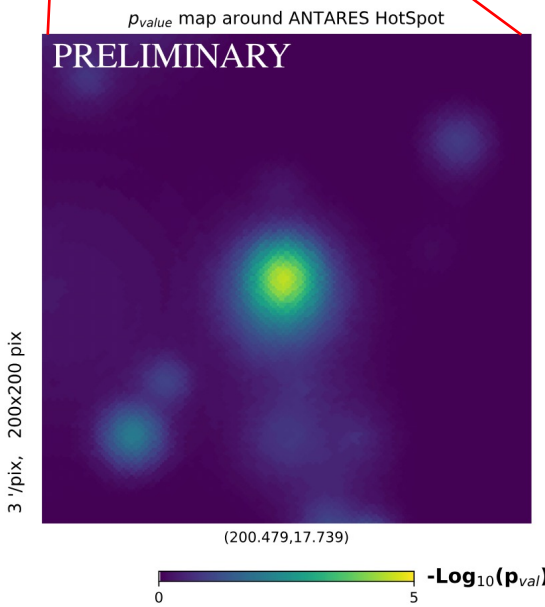
Highest excess

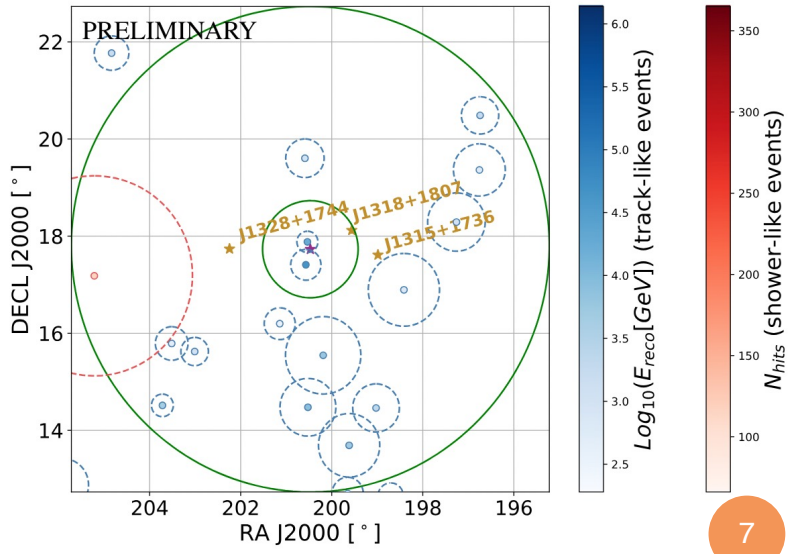
$(\hat{\alpha}, \hat{\delta})$ = (200.5°, 17.7°)

$\hat{n}_s$ = 2.0

p-value: 3 x 10^{-5} → **4.0σ (pre-trial)**

1.1%→ **1.2σ (post-trial)**





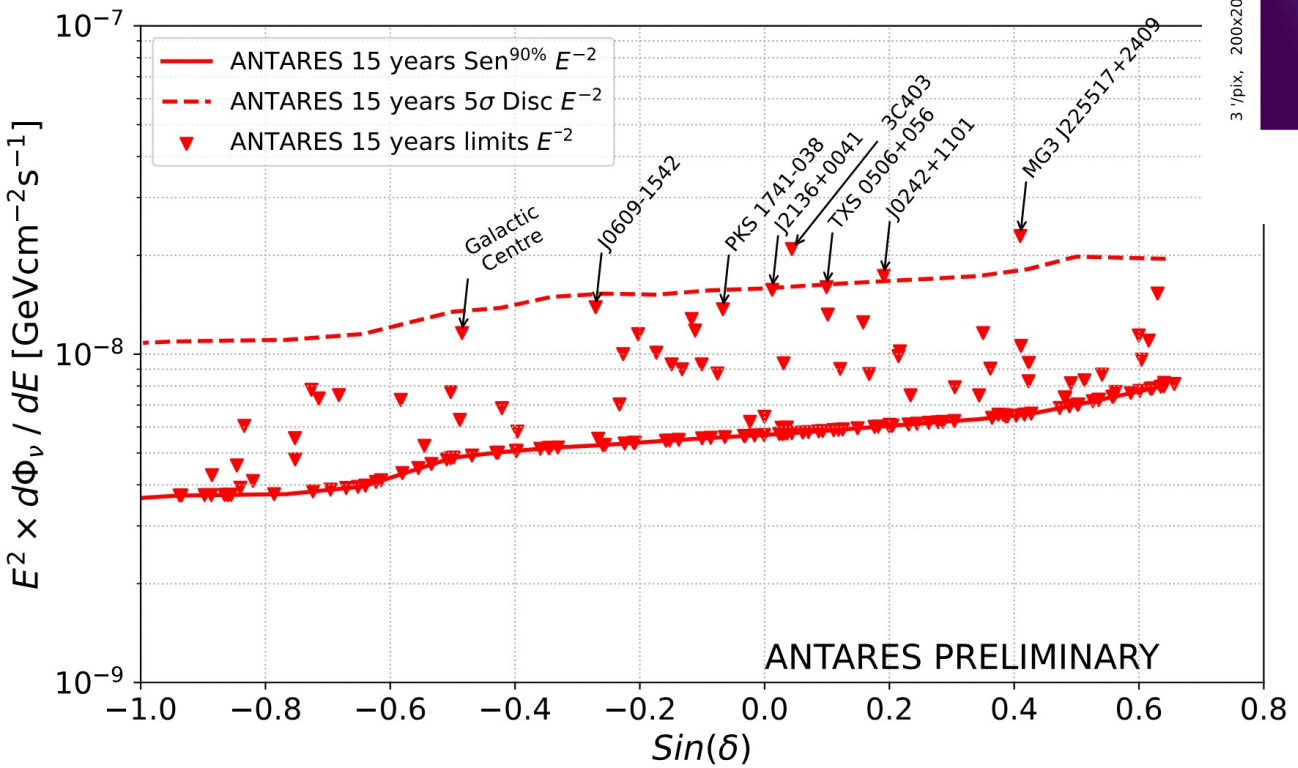
Closest source

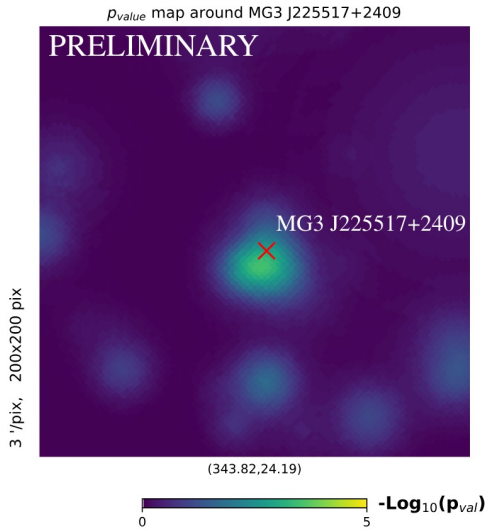
radio source **J1318+1807** (1°distance)

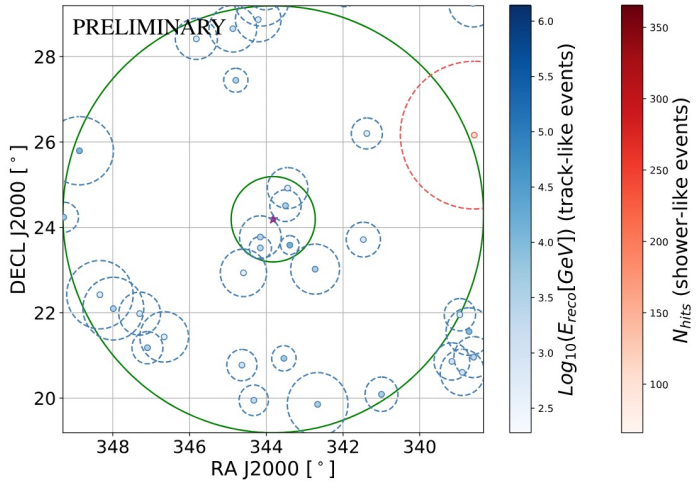
Candidate-list search

PoS(ICRC2023)1128

163 (extra-)Galactic sources investigated, selected from TeVCat, LHAASO, HAWC catalogs, IceCube hotspots







Highest significant source:
blazar MG3 J225517+2409
$\hat{n}_s = 4.4$
3.4σ pre-trial (1.6σ post-trial) significance

Other significant sources (≥2σ):

- 3C403 (3.4σ)
- J0242+1101 (2.6σ)
- J2136+0041 (2.4σ)
- TXS 0506+056 (2.4σ)
- J0609-1542 (2.3σ)
- Galactic Centre (2σ)

Stacking search

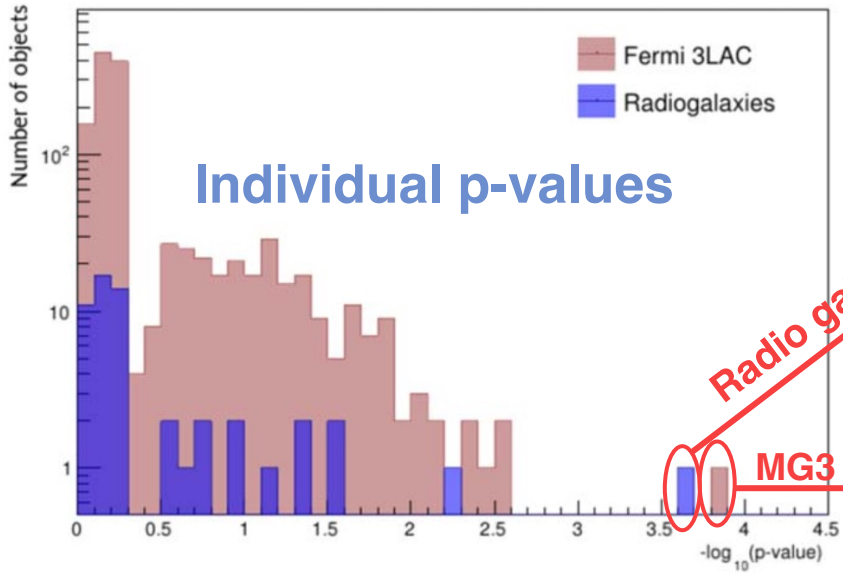
Astrophys.J. 911 (2021) 1, 48

FIVE CATALOGS

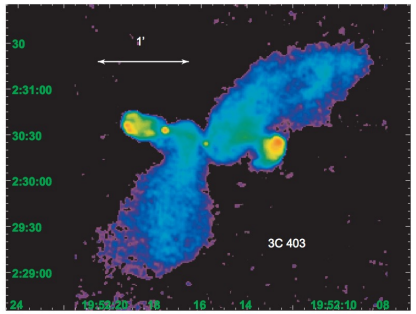
IC HE tracks | Fermi 3LAC Blazars | Radio Galaxies | Star Forming Galaxies | Dust Obscured AGN

Best catalog
2.8σ pre-trial
1.6σ post-trial

Catalog	Equal Weighting				Flux Weighting			
	λ	p	P	$\Phi^{UL}_{90\%}$	λ	p	P	$\Phi^{UL}_{90\%}$
Fermi 3LAC All Blazars	6.1	0.19	0.83	4.3	0.21	0.85	1.0	2.1
Fermi 3LAC FSRQs	0.83	0.57	0.97	2.2	~0	~1	1.0	1.8
Fermi 3LAC BL Lacs	8.3	0.088	0.64	4.8	0.84	0.56	0.96	2.0
Radio Galaxies	3.4	4.8×10^{-3}	0.10	4.2	5.1	6.9×10^{-3}	0.13	4.7
Star-forming Galaxies	0.030	0.37	0.93	2.0	~0	~1	1.0	1.7
Dust-obscured AGNs	1.0×10^{-3}	0.73	0.98	1.5	~0	~1	1.0	1.4
IceCube High-energy Tracks	0.77	0.05	0.49	5.2	…	…	…	…



Radio galaxy 3C403



p-value: 2.3 x 10^{-4} → **3.7σ**
chance probability ($N_{sources}$ = 56) = **1.3%**
→ **2.5σ**

BLLac
MG3 J225517+2409

p-value: 1.4 x 10^{-4} → **3.8σ**
chance probability ($N_{sources}$ = 1255) = **15%**
→ **1.4σ**

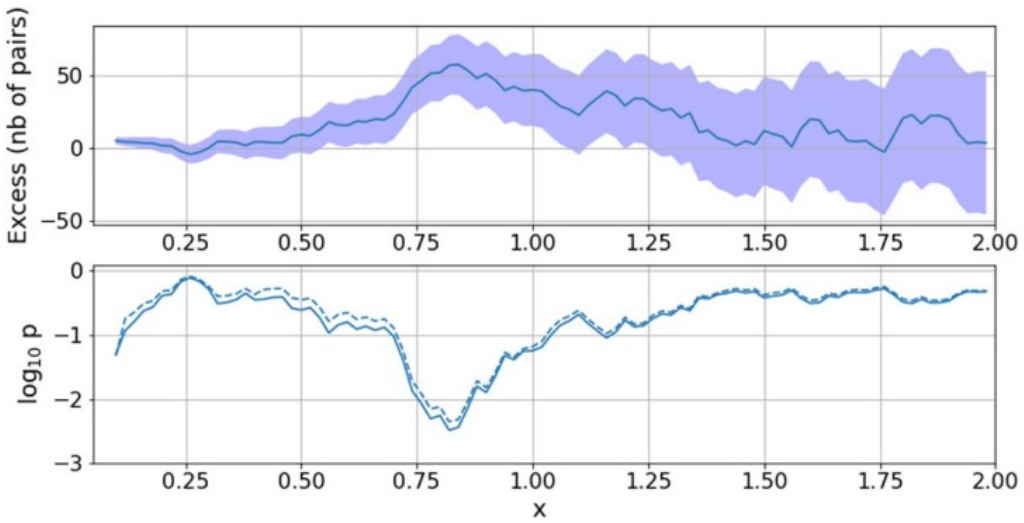
Stacking search: radio-bright blazars

➡️ *Astrophys.J.* 964 (2024) 1, 3

CATALOG: 3051 blazars

- selected on the basis of VLBI **radio flux**
- **showing promising correlation with IceCube events (Plavin et al 2020, 2021, 2023)**

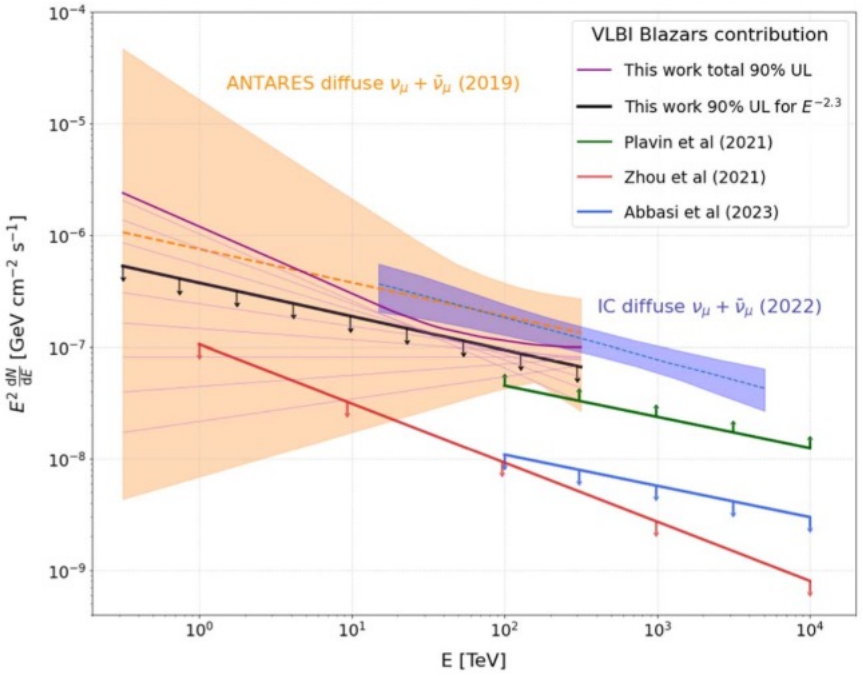
1) Count how many v-blazar pairs are found with a v-blazar angular separation < $x \cdot \beta$



Results ($x = 0.82$):
# of observed (expected) pairs: 469 (410.4)
→ 59 pairs in excess
→ 3σ pre-trial significance
→ 2.2σ post-trial significance

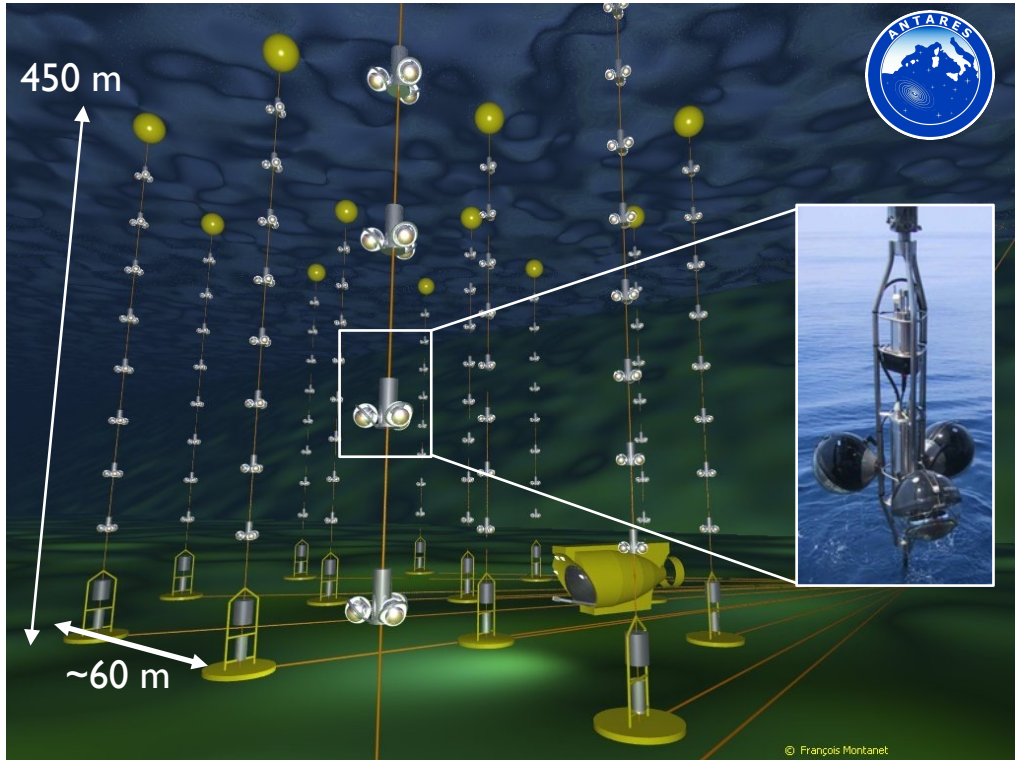
2) Stacking analysis based on maximum likelihood method

Results: highest significance found for $E^{-2.3}$ and with radio-weight hypothesis
→ 2.2σ significance



ANTARES-IceCube combined search

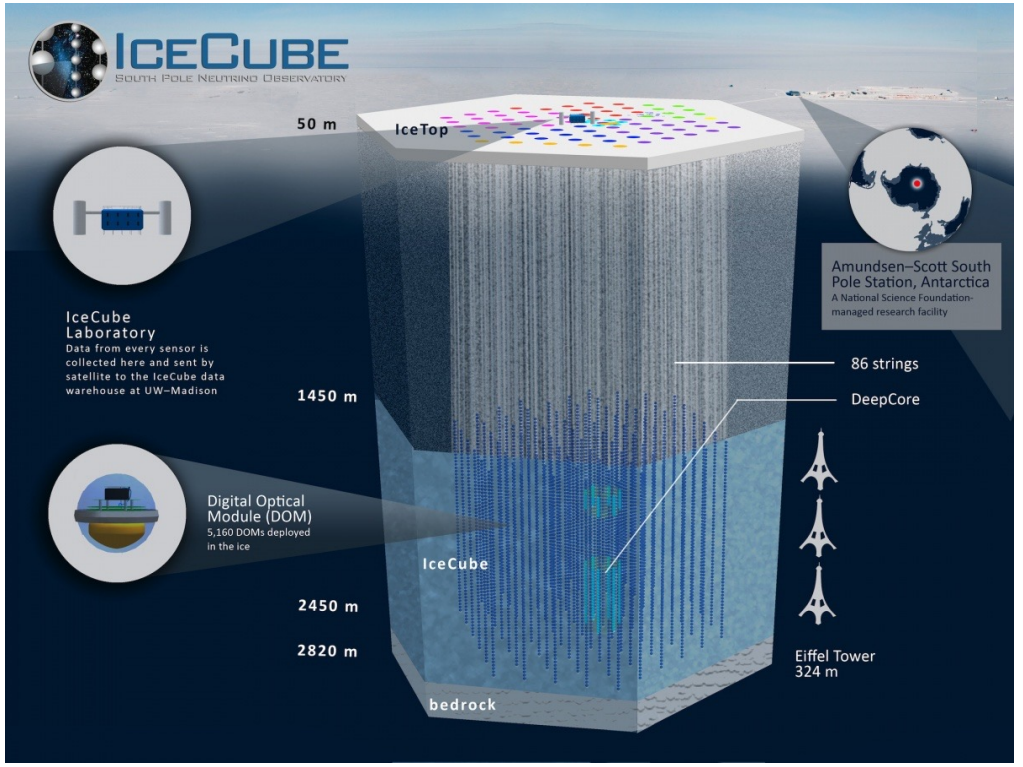
Astrophys.J. 892 (2020) 92



Mediterranean Sea, Northern Hemisphere
~2500 m deep
12 lines, 885 PMTs
~ 0.01 km^3

Clear visibility of the Southern sky for energies < 100 TeV

Complementarity for the Southern sky



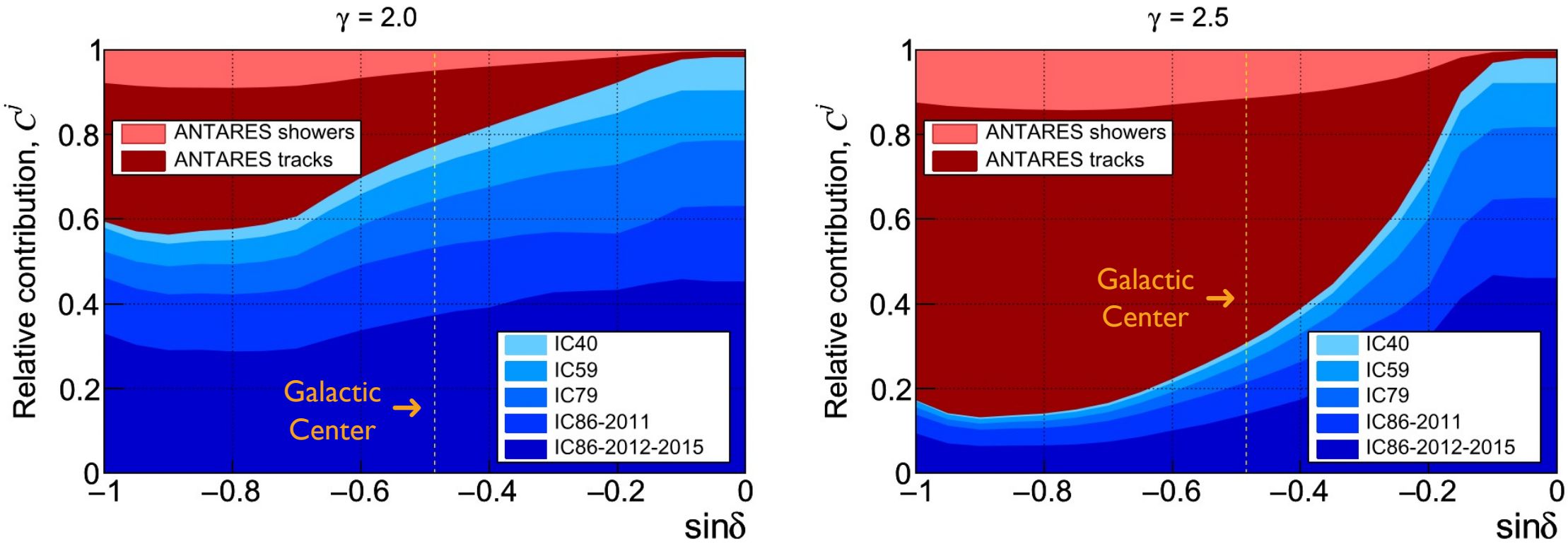
Antarctic Ice, South Pole
~2500 m deep
86 lines, over 5000 PMTs
~ 1 km^3

High statistics, good visibility of the Southern sky > 100 TeV

ANTARES-IceCube combined search

Astrophys.J. 892 (2020) 92

Samples relative efficiency for detecting events from potential sources



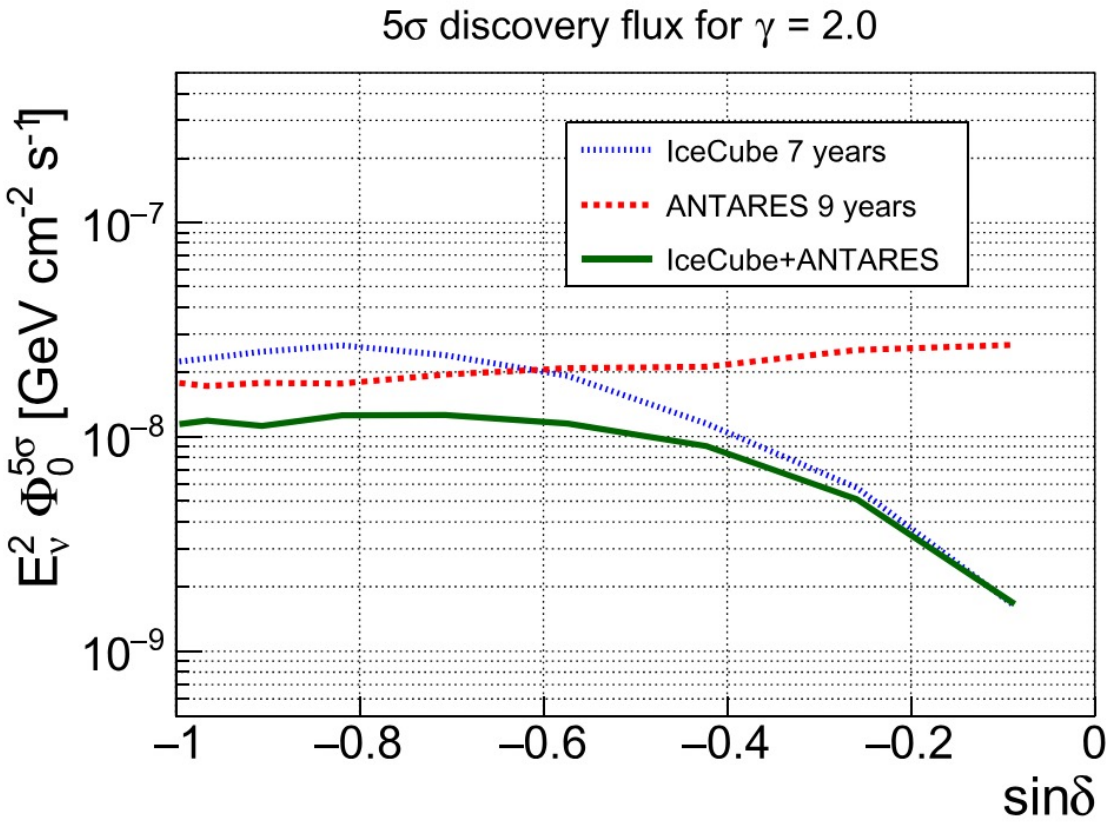
Consequence of the different layouts, locations of the telescopes and selection techniques in the Southern sky

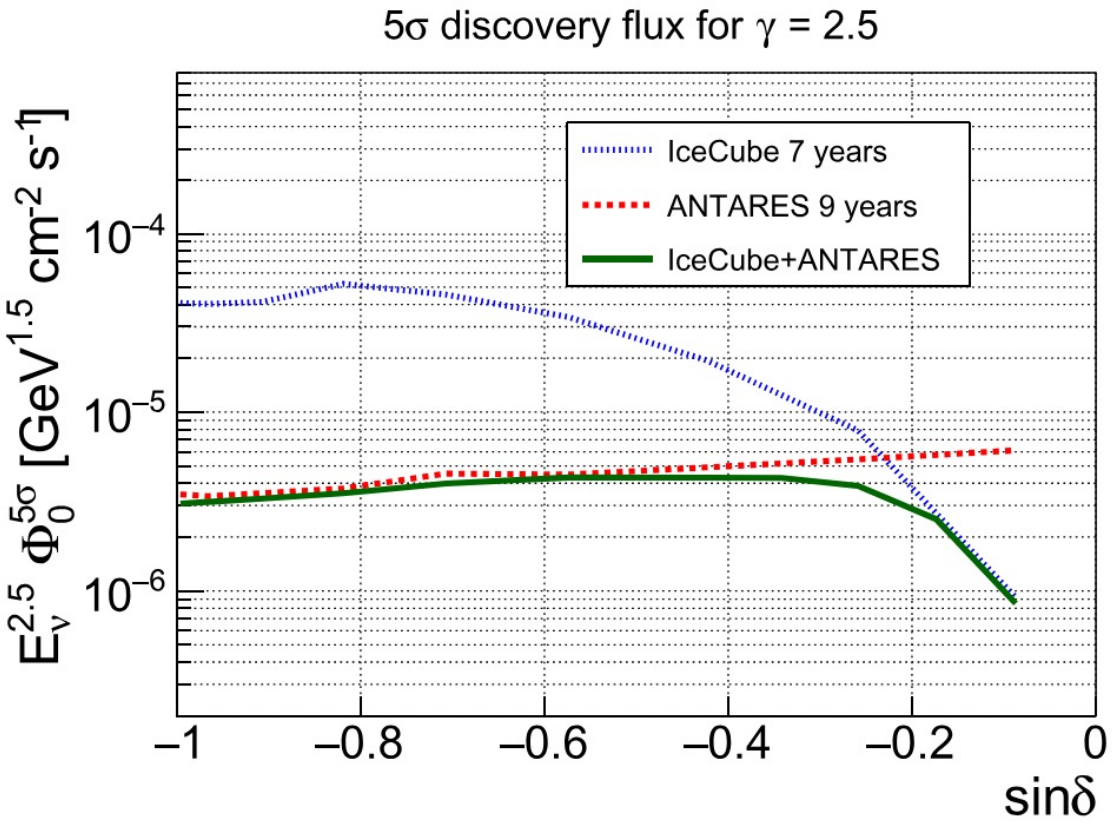
Mainly depends on source spectrum and declination

ANTARES-IceCube combined search

Astrophys.J. 892 (2020) 92

Combined 5σ discovery flux





Improvement of a factor ~2 in different regions of the Southern sky, depending on the energy spectrum of the source, compared to individual analyses

ANTARES-IceCube combined search

➡ *Astrophys.J. 892 (2020) 92*

Southern-sky search

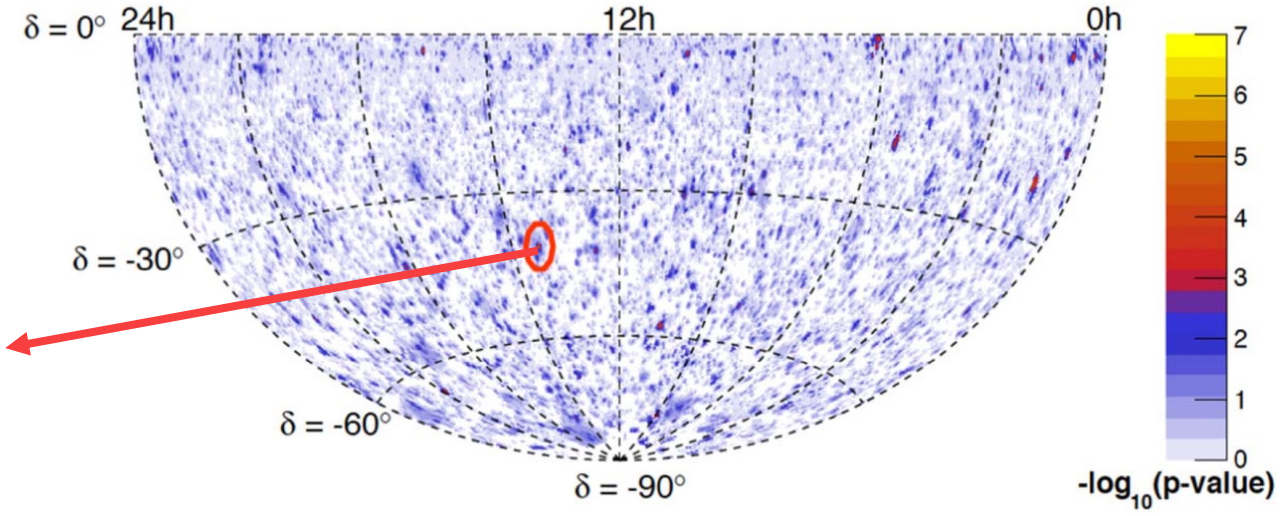
Highest excess

$(\hat{\alpha}, \hat{\delta})$ = (213.2°, -40.8°)

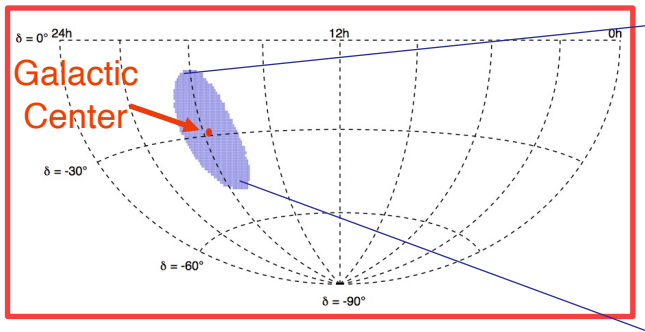
$\hat{n}_s$ = 5.7

p-value: 1.3 x 10^{-5} → **4.2σ (pre-trial)**

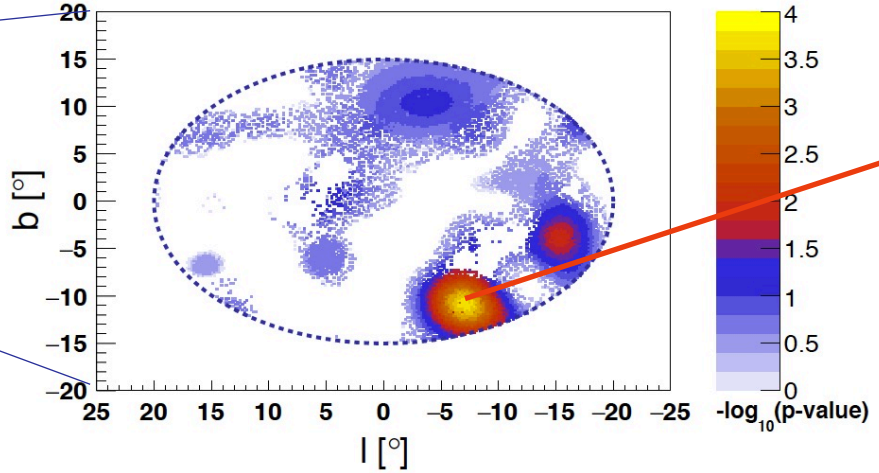
0.18→ **0.9σ (post-trial)**



Search in the Galactic Center region



Result: p-value map



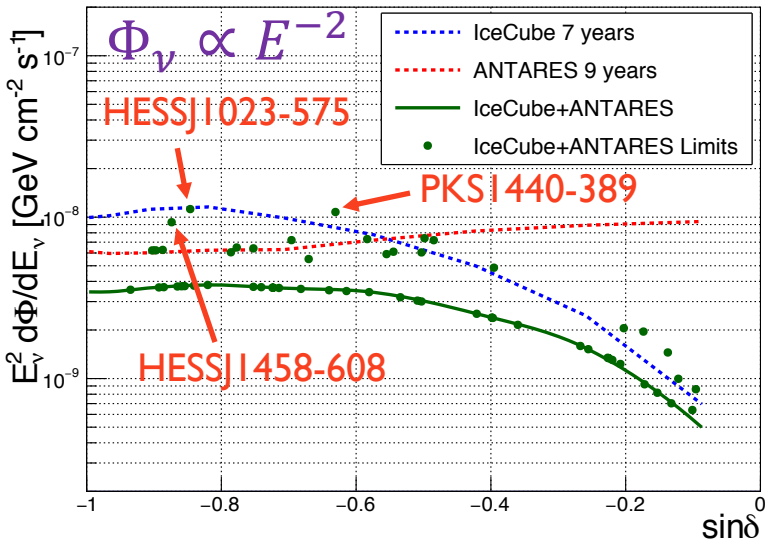
Highest excess

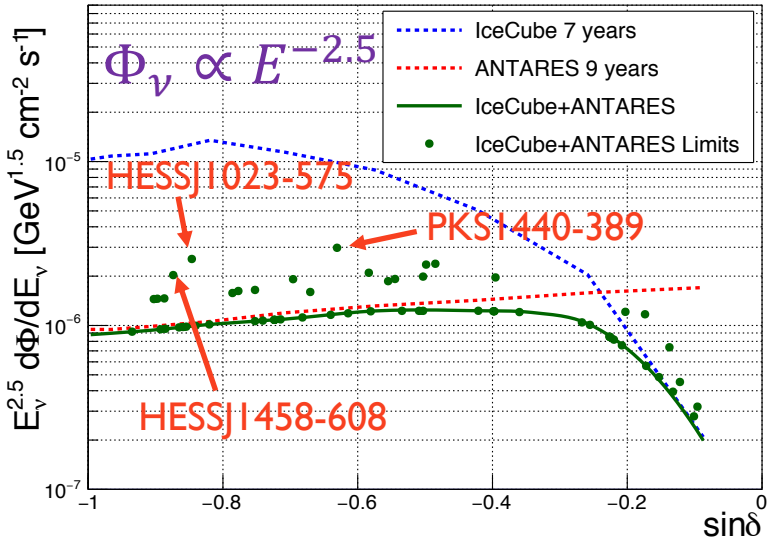
p-value: 2.2 x 10^{-4} → **3.5σ (pre-trial)**

0.03→ **1.9σ (post-trial)**

source extension: 2°

ANTARES-IceCube combined search





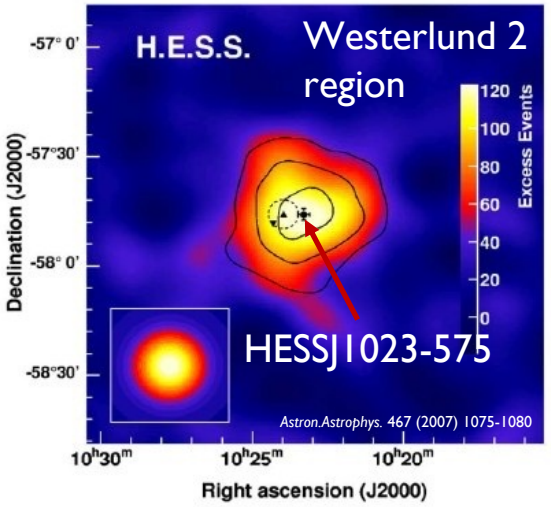
Source-list search:

57 southern-sky Galactic and extra-galactic sources already investigated by ANTARES and IceCube individually

➡ *Astrophys.J. 892 (2020) 92*

Best sources

Source	Type	RA	δ	$\hat{n}_s$	$\hat{\gamma}_s$	#σ pre-trial
HESSJ1023-575	**UNID**	**155.83°**	**-57.76°**	**6.4**	**3.5**	**2.41**
PKS1440-389	BLL	220.99°	-39.14°	3.0	2.4	2.39
HESSJ1458-608	PWN	224.54°	-60.88°	3.7	3.6	1.8



HESSJ1023-575
42% post-trial

TeV γ-ray source coincident with the **young stellar cluster** Westerlund 2

Summary and outlook

❑ ANTARES

- **Fifteen years of continuous data taking with high duty cycle (~95%)**
- Solid results from **various searches** for cosmic neutrino sources and **several methods** explored (all-sky, candidate list, stacking, combination with IceCube)
- **No significant source found, several hotspots to be monitored with future detectors:**
  - **Radio galaxy 3C403**
    - Most significant radio galaxy in stacking search
    - Second most significant source in candidate search
  - **BLLac MG3 J225517+2409**
    - Most significant BLLac in stacking search
    - Most significant source in candidate search
  - **J0242+1101, J2136+0041, J0609-1542, TXS 0506+056, Galactic Centre**
    - ≥2σ significance sources in candidate search
  - **HESSJ1023-575**
    - Most significant source in ANTARES+IceCube candidate search
  - **(α,δ) = (200.5°, 17.7°), (α,δ) = (213.2°, -40.8°)**
    - ANTARES-only and ANTARES+IceCube all-sky hotspots

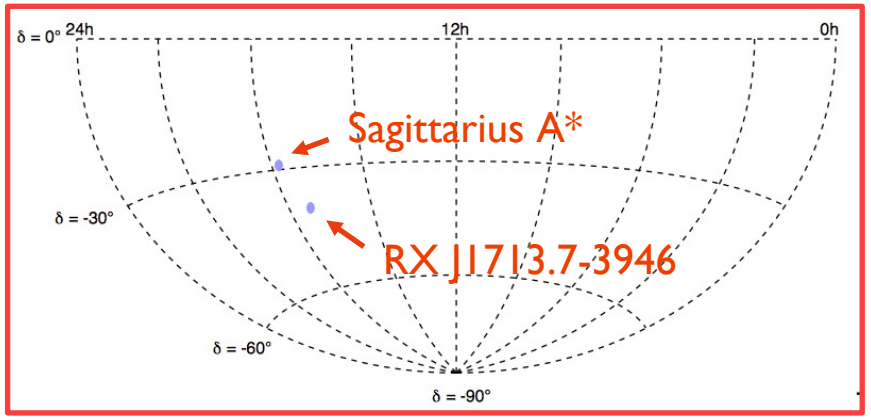
❑ Future: KM3NeT

- Under construction: currently running with 28 DUs (ARCA) and 23 DUs (ORCA)
- Better **median angular resolution and x100 ANTARES instrumented volume** (ARCA), same view of the Galactic Centre as ANTARES, **sensitivity at the level of the expected Galactic neutrino fluxes** reached in few years of operation with full detector
- *More on KM3NeT in this session*

Backup

ANTARES-IceCube combined search

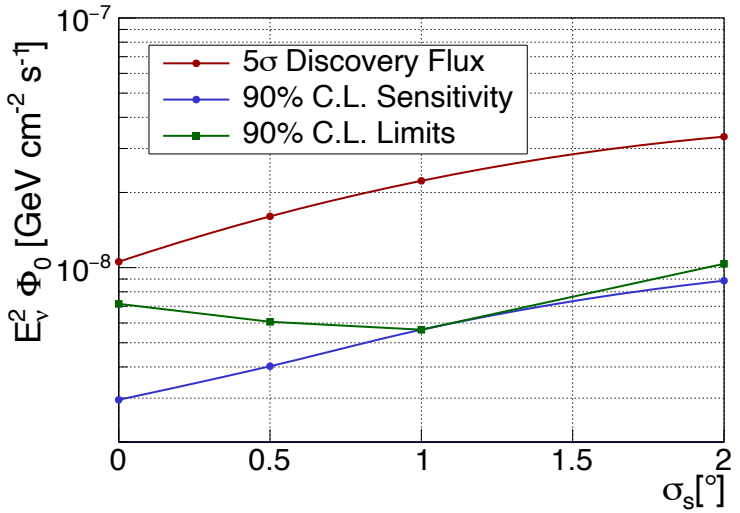
Dedicated searches



Sagittarius A*

Point-like and extended source (σ_s = 0.5°, 1.0°, 2.0°) hypotheses tested

→ **1.6σ significance**



RX J1713.7-3946

- Gaussian extension of 0.6° for the emission profile (according to observations by HESS)
- Two spectrum models derived from observations in γ:

Vissani et al.:

$$\frac{dN}{dE_\nu} = 0.89 \times 10^{-11} \left(\frac{E_\nu}{1\ \text{TeV}}\right)^{-2.06} \exp\left(-\frac{E_\nu}{8.04\ \text{TeV}}\right) \text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$$

Kappes et al.:

$$\frac{dN}{dE_\nu} = 1.55 \times 10^{-11} \left(\frac{E_\nu}{1\ \text{TeV}}\right)^{-1.72} \exp\left(-\sqrt{\frac{E_\nu}{1.35\ \text{TeV}}}\right) \text{TeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$$

RX J1713.7-3946 results

Spectrum	$\hat{n}_s$	p-value	$\Phi_L^{90\%C.L}/\Phi_0$
Vissani	0.3	0.40	13.2
Kappes	0.3	0.41	11.7

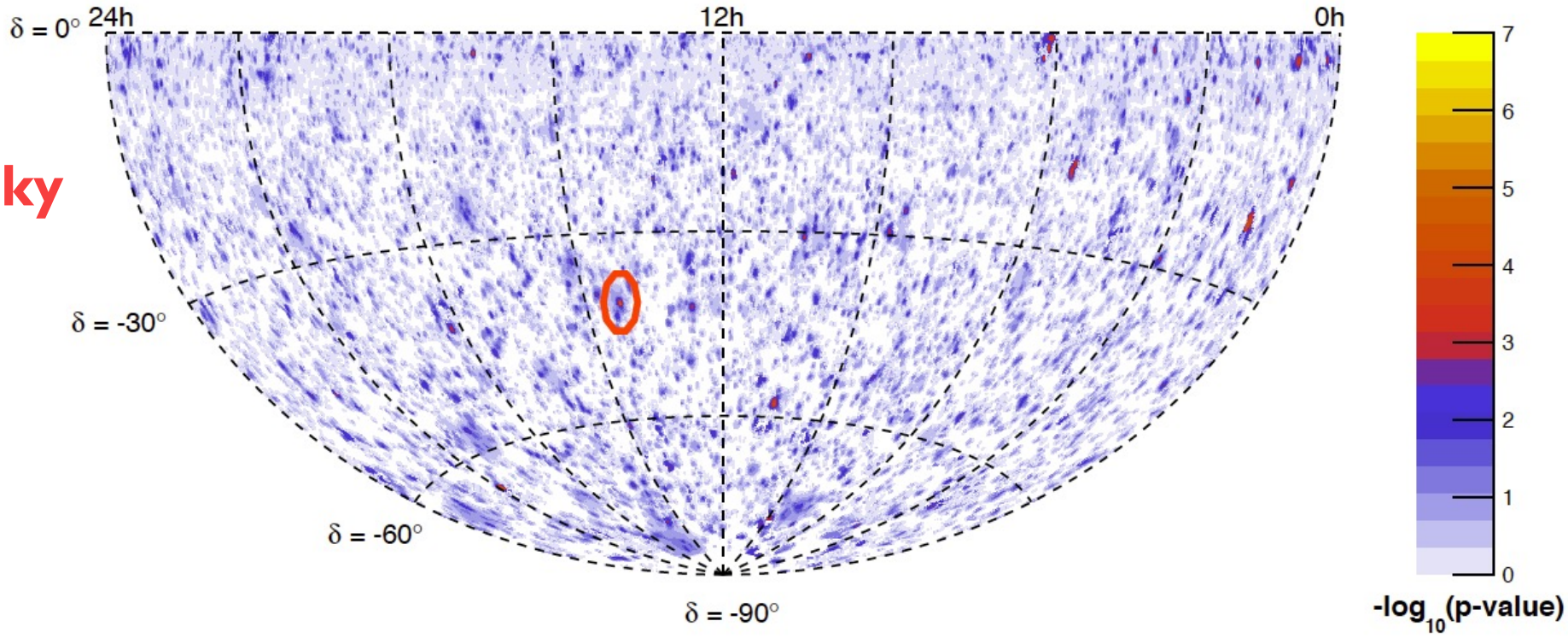
upper limits expressed as ratio with the assumed source flux

Sagittarius A* results

Source extension	$\hat{n}_s$	$\hat{\gamma}$	p-value
0.0°	2.9	2.1	0.06
0.5°	0.6	2.0	0.26
1.0°	--	--	--
2.0°	0.3	3.8	0.40

ANTARES-IceCube combined search

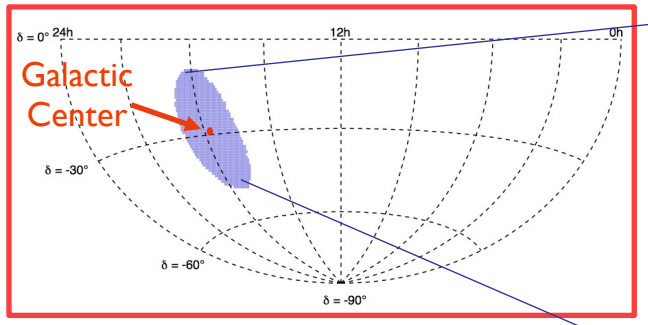
Southern-sky search



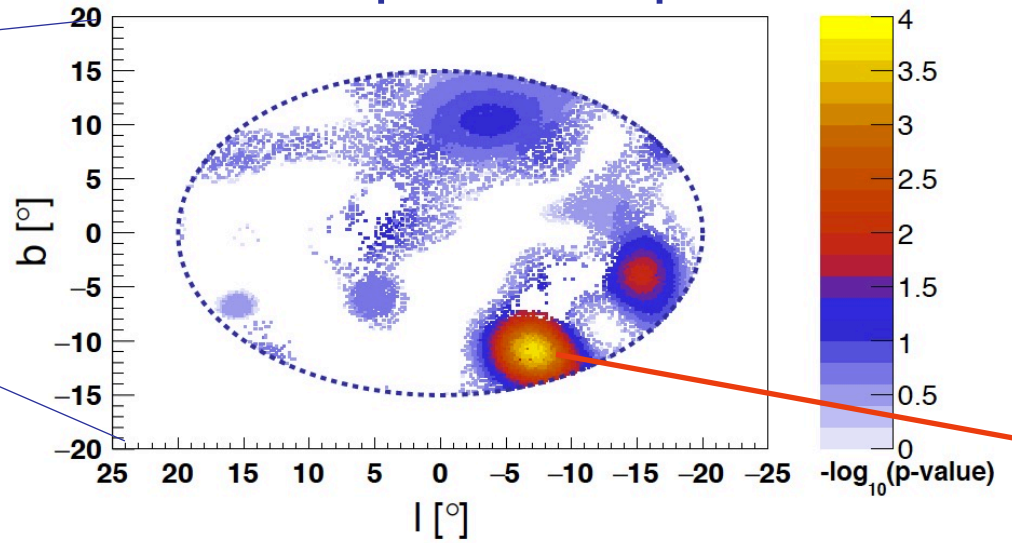
Source extension	$\hat{n}_s$	$\hat{\gamma}$	$\hat{\delta}$	$\hat{\alpha}$	pre-trial p-value	post-trial p-value
0.0°	5.7	2.5	-40.8°	213.2°	1.3×10^{-5}	0.18
0.5°	10.5	3.9	-22.5°	18.5°	3.4×10^{-5}	0.31
1.0°	11.6	3.8	-21.9°	18.4°	8.9×10^{-5}	0.44
2.0°	20.3	3.0	-40.1°	274.1°	2.2×10^{-4}	0.47

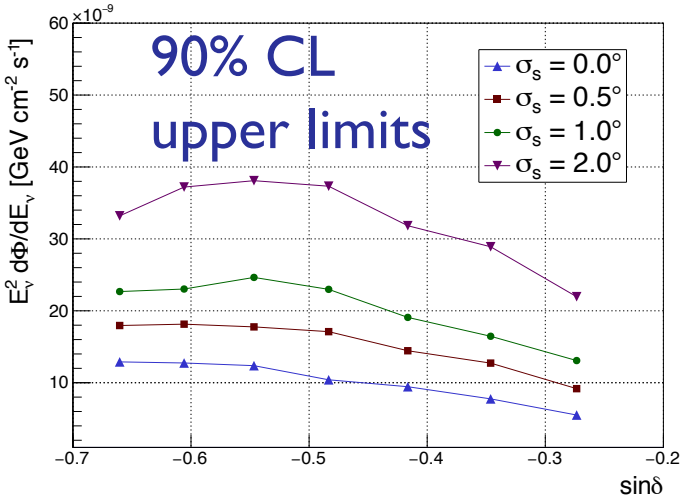
ANTARES-IceCube combined search

Search at the Galactic Center region



Result: p-value map





Highest excess

p-value: 2.2×10^{-4} → **3.5σ (pre-trial)**

0.03 → **1.9σ (post-trial)**

Source extension	$\hat{n}_s$	$\hat{\gamma}$	$\hat{\delta}$	$\hat{\alpha}$	pre-trial p-value	post-trial p-value
0.0°	6.8	2.8	-42.3°	273.0°	7.3×10^{-4}	0.40
0.5°	8.4	2.8	-42.0°	273.1°	5.2×10^{-4}	0.19
1.0°	12.1	2.9	-41.8°	274.1°	6.9×10^{-4}	0.15
2.0°	20.3	3.0	-40.1°	274.1°	2.2×10^{-4}	0.03