CSIC
Consejo Superior de Investigaciones Científicas

IFIC
Institut de Física Corpuscular

Vniversitat de València

ANTARES

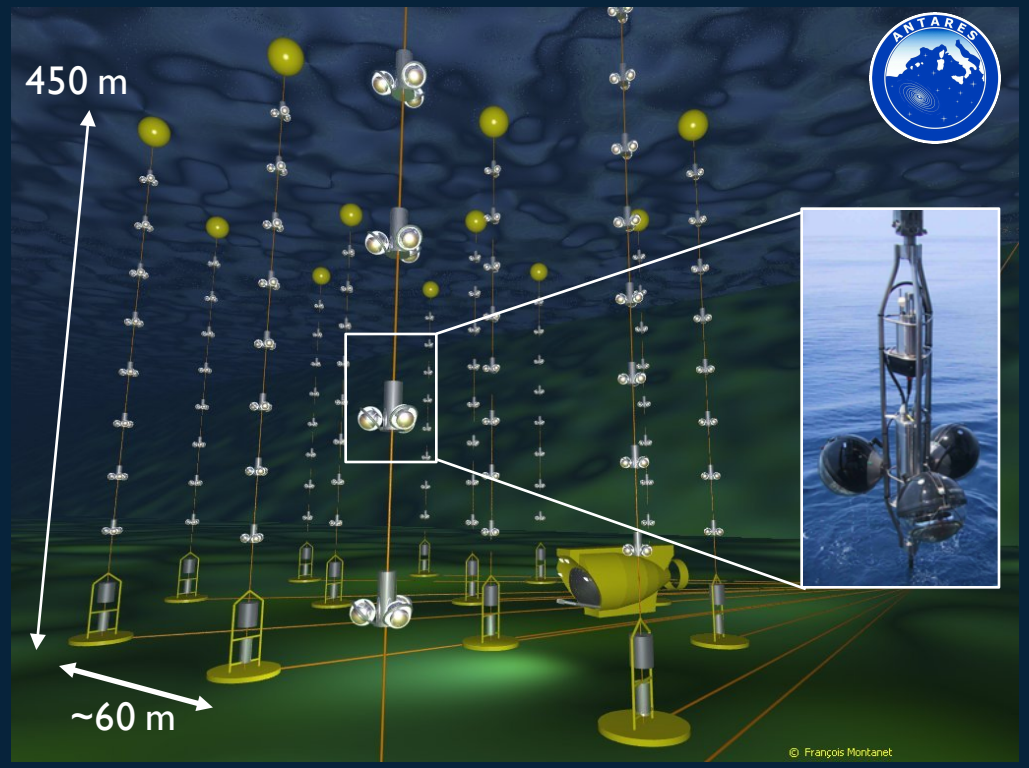
IceCube
South Pole Neutrino Observatory

# ANTARES and IceCube Combined Search for Neutrino Point-like and Extended Sources in the Southern Hemisphere

Giulia Illuminati on behalf of the ANTARES and IceCube Collaborations

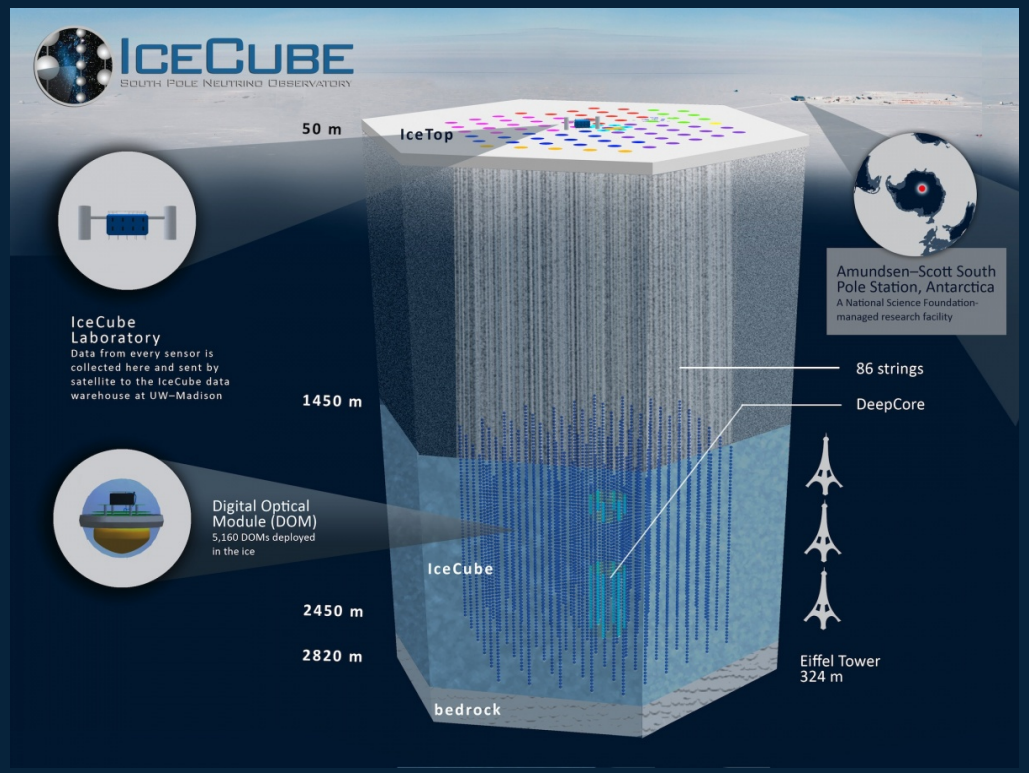
ICRC2019 - 27/07/2019 – Madison

# The ANTARES and IceCube detectors




Mediterranean Sea
Northern Hemisphere
between 2010 and 2470 m deep
12 lines, 885 PMTs
~0.01 km$^3$

Good visibility of the Southern sky for energies < 100 TeV




Antarctic Ice
South Pole
between 1450 and 2450 m deep
86 lines, over 5000 PMTs
~1 km$^3$

High statistics

Complementarity for the Southern sky

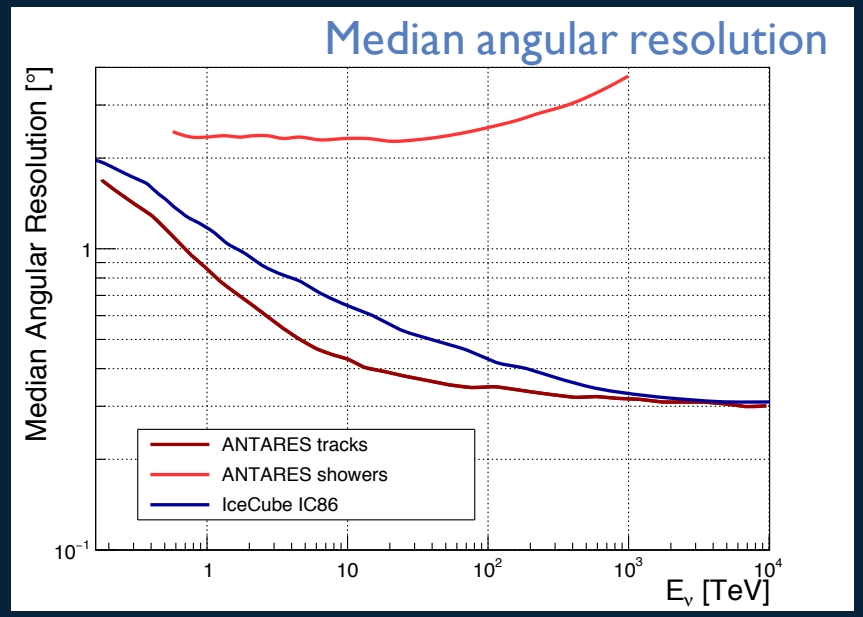
# Data samples

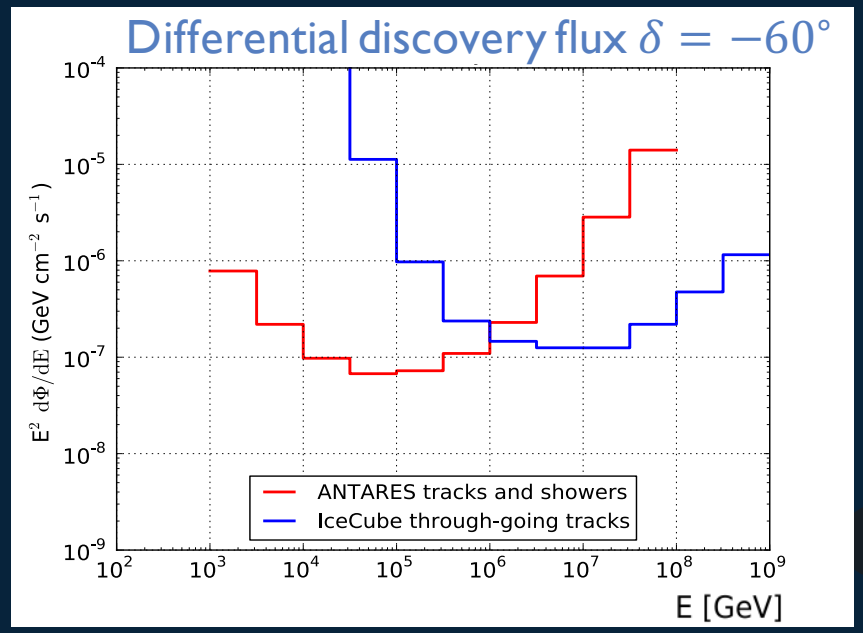
## ANTARES 9 years: tracks and shower

| Sample | Livetime (days) | # of events |
|---|---|---|
| tracks | 2415 | 5807 |
| showers | 2415 | 102 |

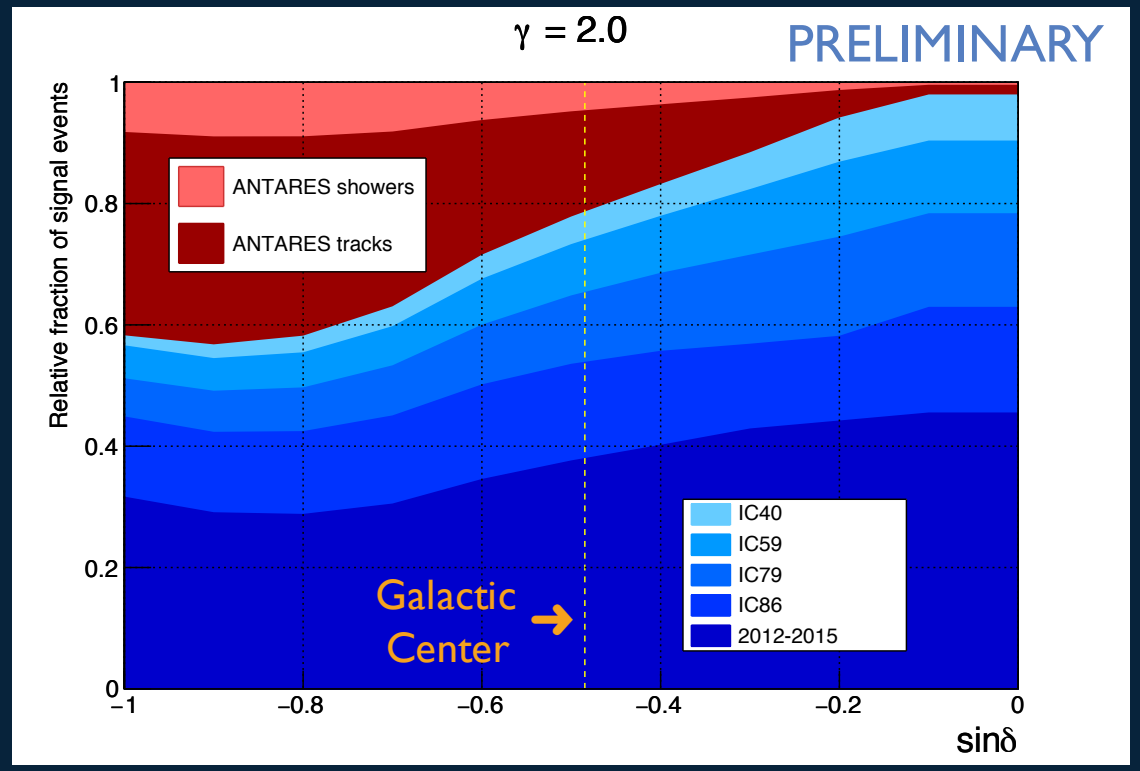
## IceCube 7 years: through-going tracks

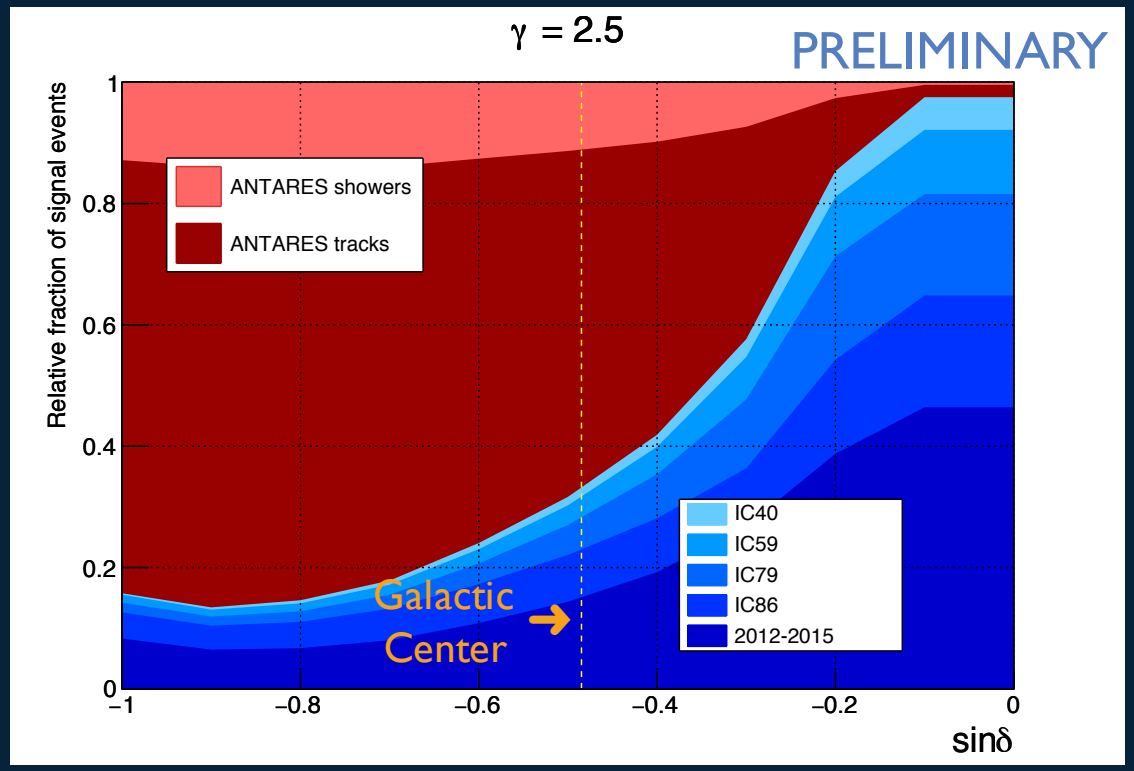
| Sample | Livetime (days) | # of events |
|---|---|---|
| IC40 | 376 | 22779 |
| IC59 | 348 | 64257 |
| IC79 | 316 | 44771 |
| IC86 | 333 | 74931 |
| 2012-2015 | 1058 | 119231 |



# 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

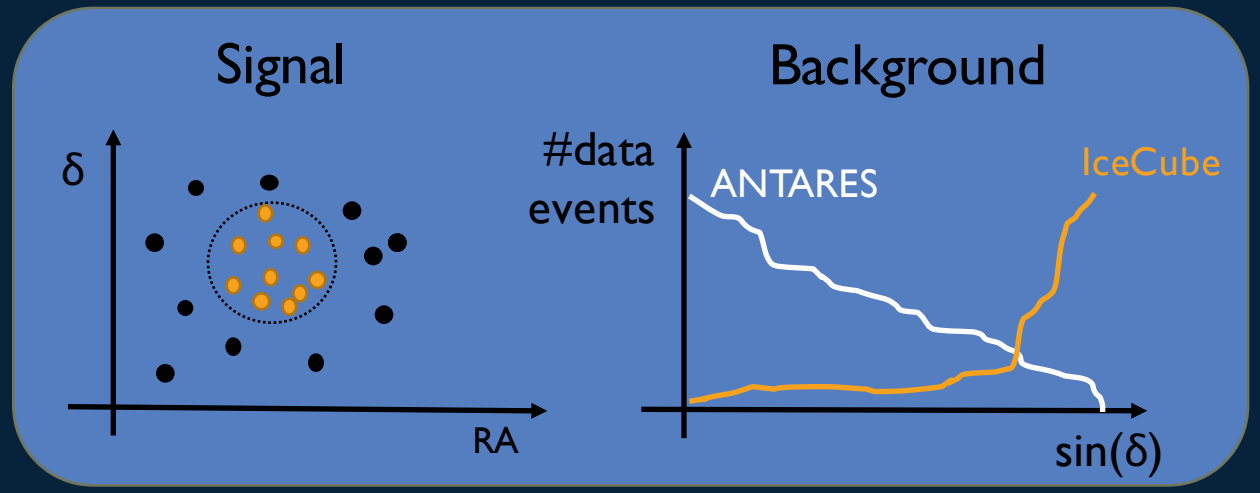
# Search method: Likelihood

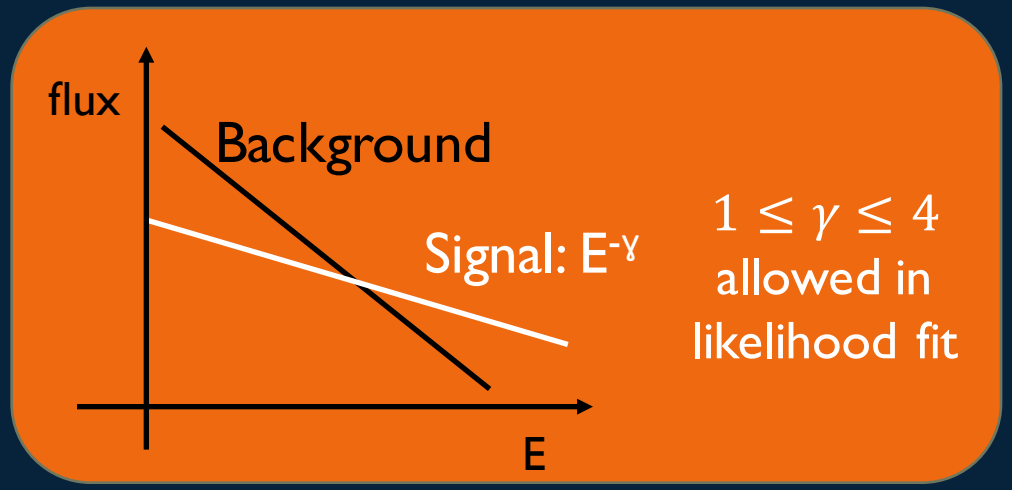
$$L(\underbrace{n_s, \gamma, \delta_s, \alpha_s}_{\text{free parameters}}) = \prod_{j=1}^{7} \prod_{i=1}^{N^j} \left[ \frac{n_s^j}{N^j} S_i^j(\gamma, \delta_s, \alpha_s) + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

Signal PDFs

Background PDFs

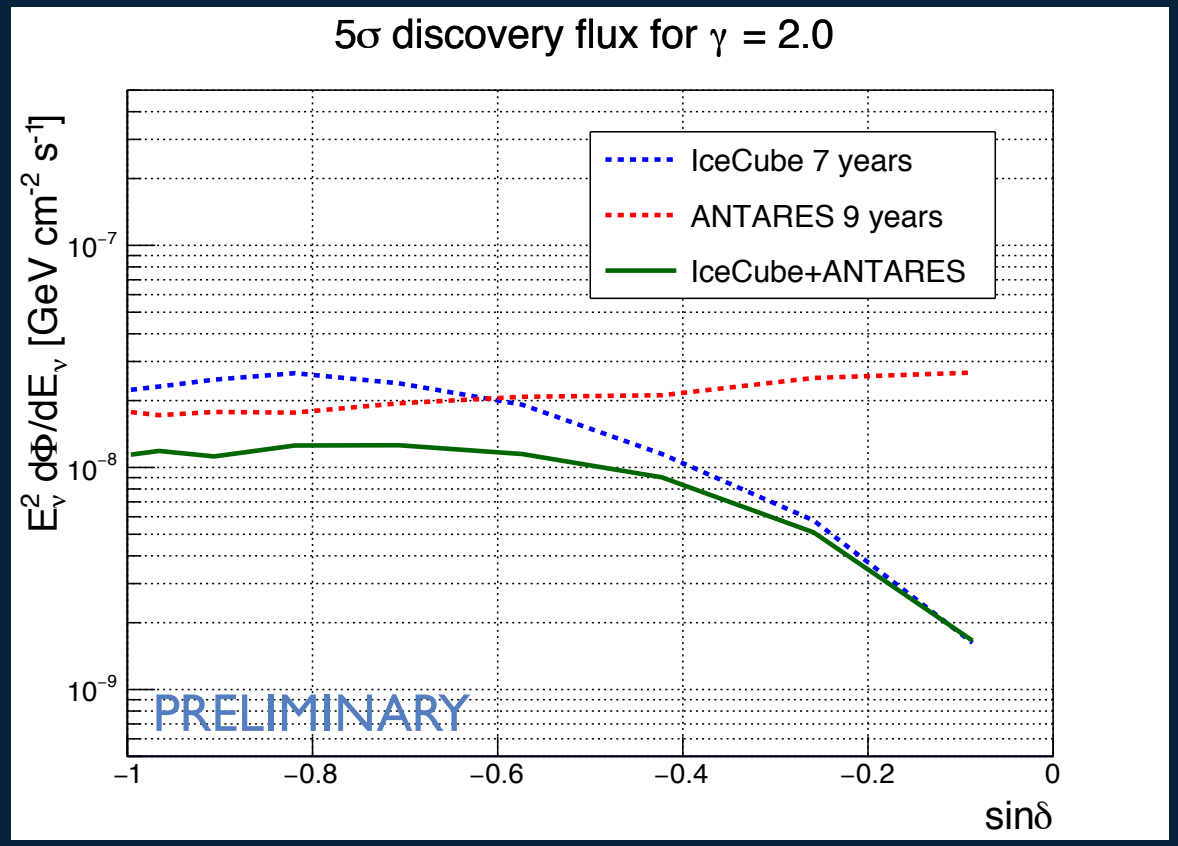
$$S_i = S^{space} \cdot S^{energy} \qquad B_i = B^{space} \cdot B^{energy}$$

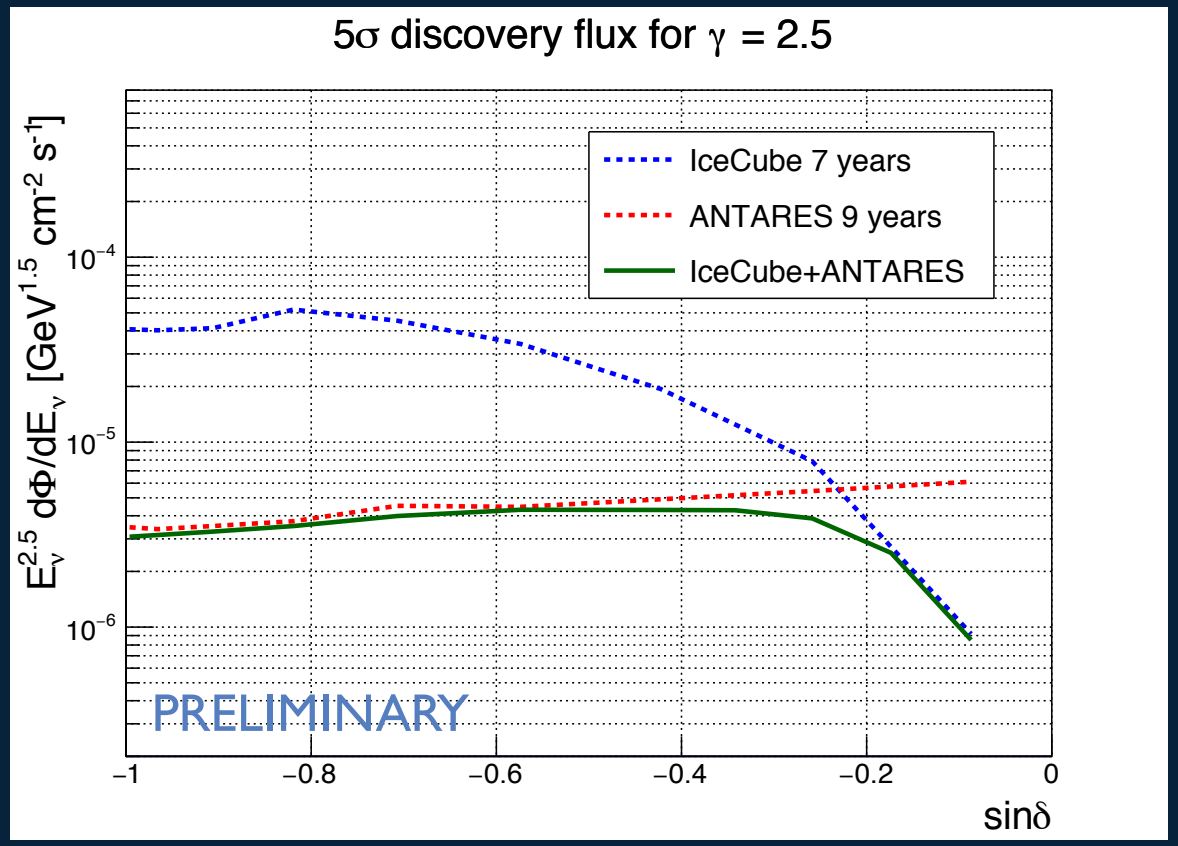



test statistic: $Q = \log L(\hat{n}_s, \hat{\gamma}, \hat{\delta}_s, \hat{\alpha}_s) - \log L(n_s = 0)$

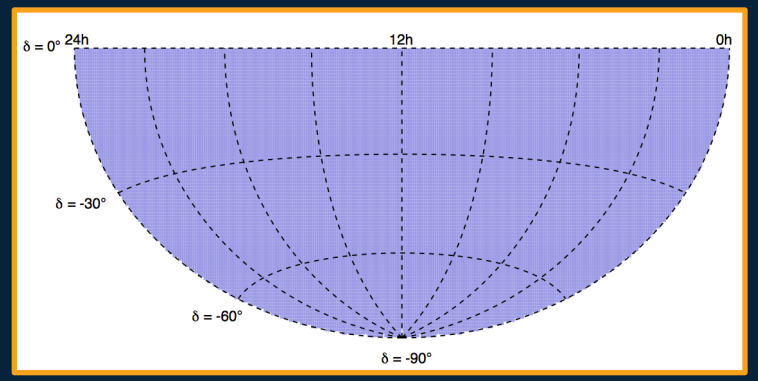
# Combined 5σ discovery flux



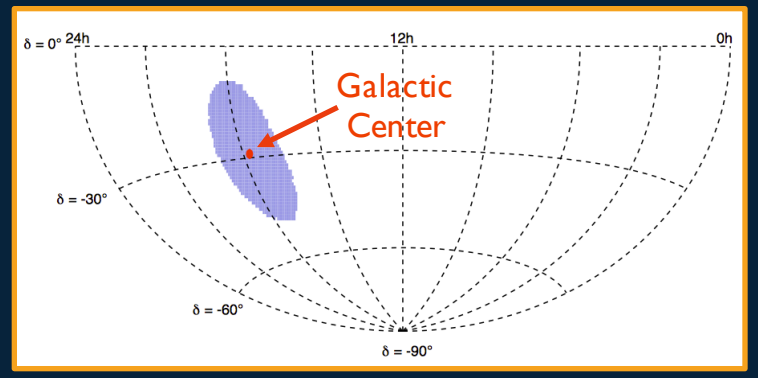

Improvement of a factor ~2 in different regions of the Southern sky, depending on the energy spectrum of the source, compared to individual analyses

# Search method: Stategies



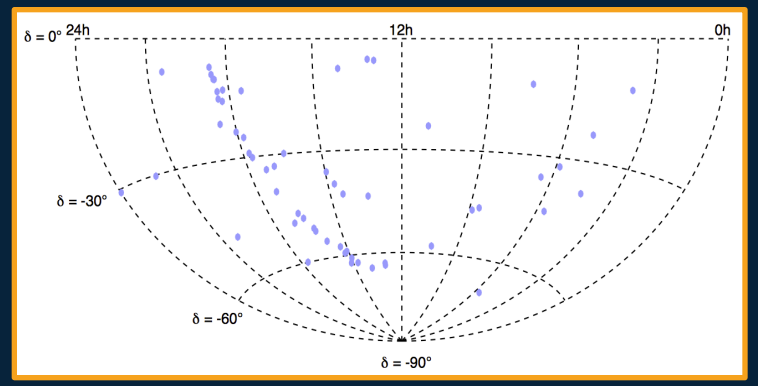

## Southern-sky search

- Investigated region: Southern sky
- TS evaluated in squares of 1°x1°
- Free parameters: $n_s, \gamma, \delta_s, \alpha_s$
- Search for point-like and extended sources ($\sigma_s$ = 0.5°, 1.0°, 2.0°)




## Galactic Center Region search

- Investigated region: ellipse, centred in the GC,
  15° semi-axis in galactic latitude, 20° semi-axis in galactic longitude
- Same method as in the Southern-sky search
- Search for point-like and extended sources ($\sigma_s$ = 0.5°, 1.0°, 2.0°)




## Candidate List search

- Investigated directions: 57 pre-selected source candidates
- All Southern sky candidates considered in the individual ANTARES and IceCube point-source analyses
- Galactic and extra-Galactic sources from TeVCat
- Free parameters: $n_s, \gamma$

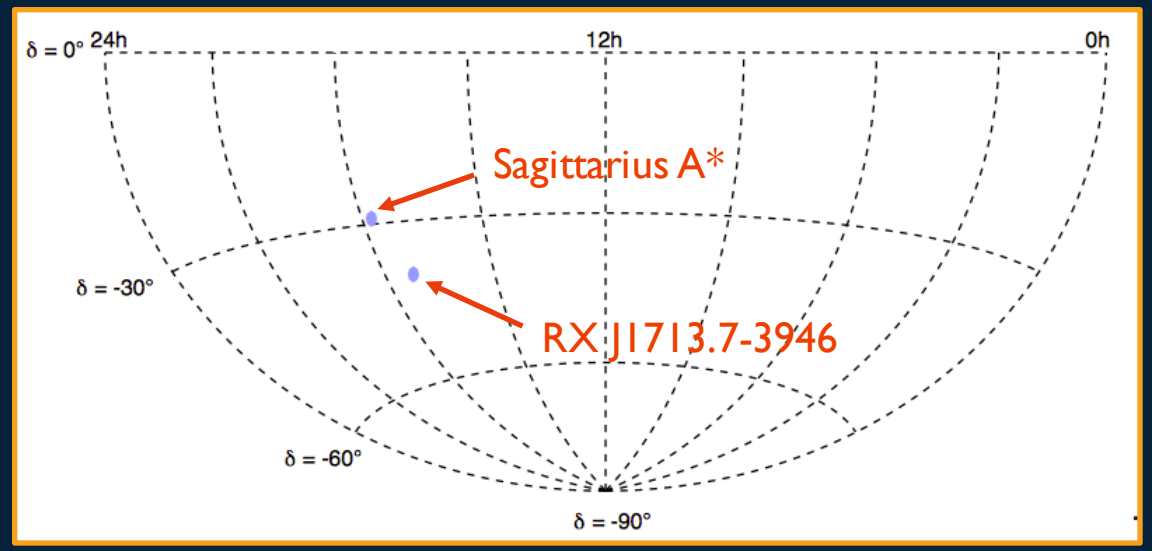
# Search method: Stategies

## Sagittarius A*

- Dedicated search at the location of the SMBH
- Point-like and extended source ($\sigma_s$ = 0.5°, 1.0°, 2.0°) hypotheses tested
- Free parameters: $n_s, \gamma$

## RX J1713.7-3946

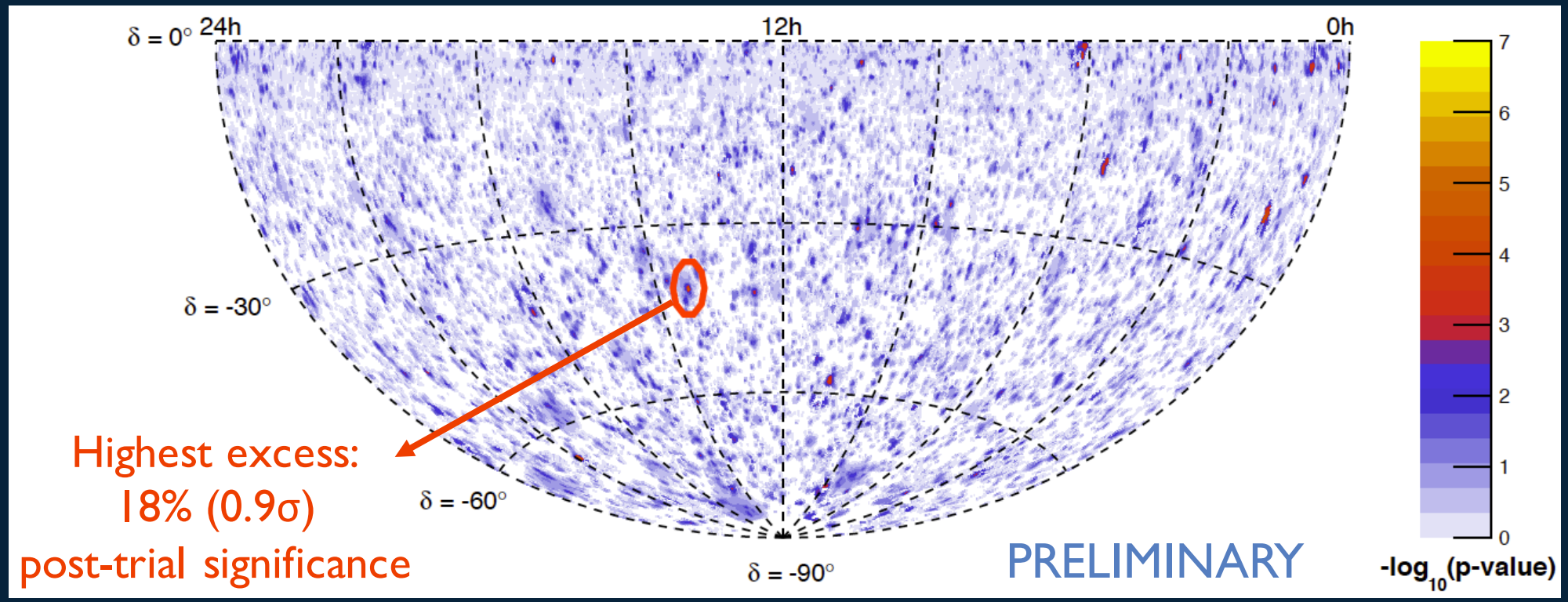
- Dedicated search at the location of the SNR
- Gaussian extension of 0.6° for the emission profile (according to observations by HESS)
- Free parameters: $n_s$
- Two spectrum models:




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

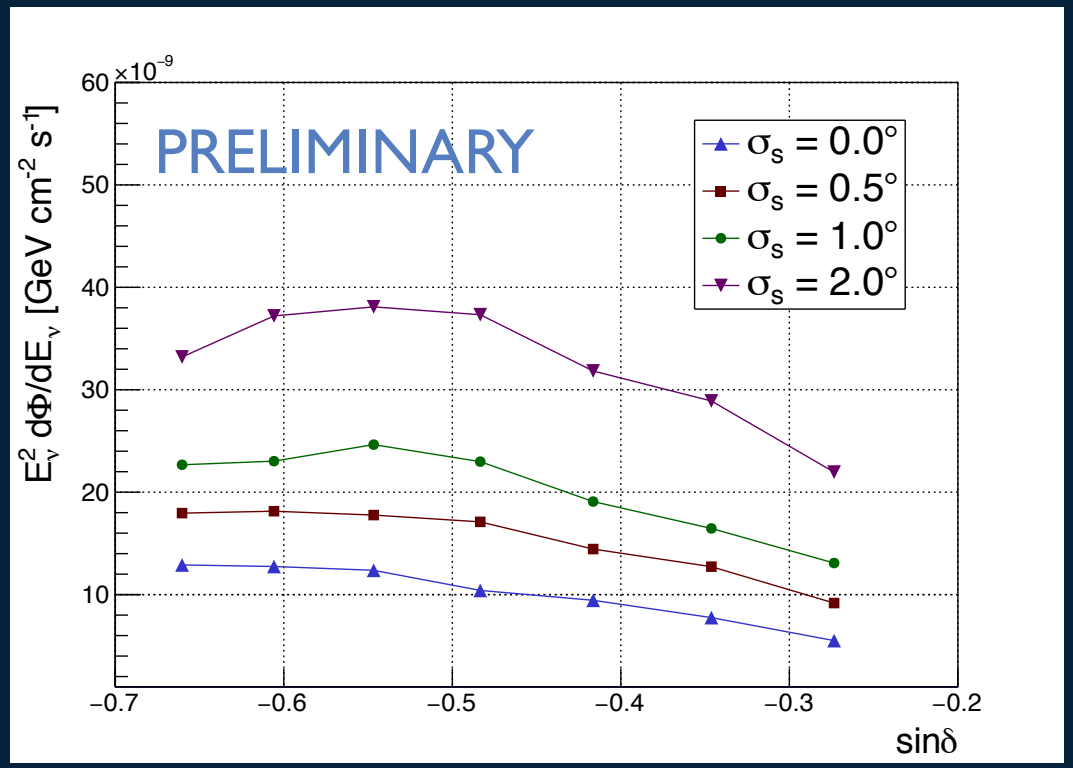
(2) Kappes et al.: $$\frac{dN}{dE_\nu} = 1.55 \times 10^{-11} \left(\frac{E_\nu}{1\ \mathrm{TeV}}\right)^{-1.72} \exp\left(-\sqrt{\frac{E_\nu}{1.35\ \mathrm{TeV}}}\right) \mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

# Results: 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° | $1.3 \times 10^{-5}$ | 0.18 |
| 0.5° | 10.5 | 3.9 | -22.5° | 18.5° | $3.4 \times 10^{-5}$ | 0.31 |
| 1.0° | 11.6 | 3.8 | -21.9° | 18.4° | $8.9 \times 10^{-5}$ | 0.44 |
| 2.0° | 20.3 | 3.0 | -40.1° | 274.1° | $2.2 \times 10^{-4}$ | 0.47 |

# Results: Galactic Center region search

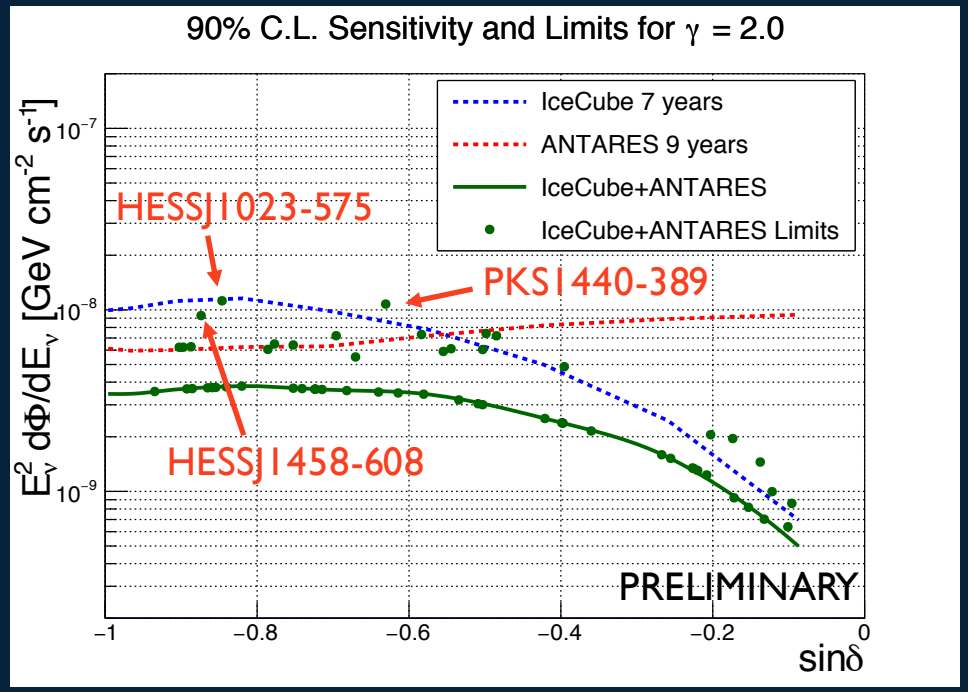


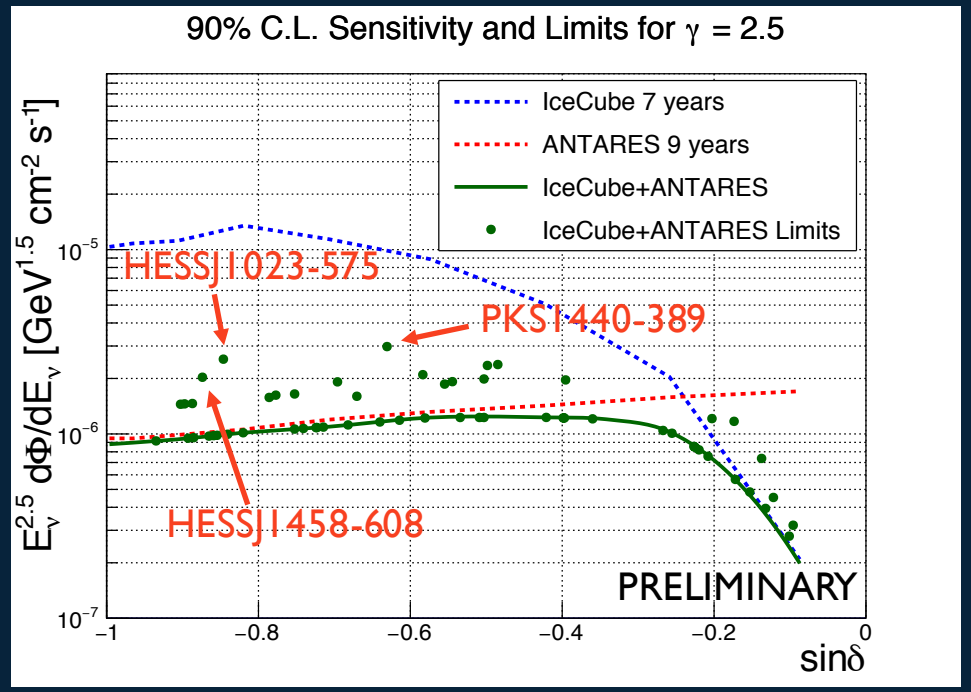

Highest excess: 3% (1.9σ) post-trial significance

| 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° | $7.3 \times 10^{-4}$ | 0.40 |
| 0.5° | 8.4 | 2.8 | -42.0° | 273.1° | $5.2 \times 10^{-4}$ | 0.19 |
| 1.0° | 12.1 | 2.9 | -41.8° | 274.1° | $6.9 \times 10^{-4}$ | 0.15 |
| 2.0° | 20.3 | 3.0 | -40.1° | 274.1° | $2.2 \times 10^{-4}$ | 0.03 |

# Results: Candidate List search

| Source name | $\delta$ | $\hat{n}_s$ | $\hat{\gamma}$ | pre-trial p-value | $\Phi_{E^{-2.0}}^{90\%C.L.}$ [$10^{-9}$ GeV cm$^{-2}$ s$^{-1}$] | $\Phi_{E^{-2.5}}^{90\%C.L.}$ [$10^{-6}$ GeV$^{1.5}$ cm$^{-2}$ s$^{-1}$] |
|---|---|---|---|---|---|---|
| HESSJ1023-575 | -57.76° | 6.4 | 3.5 | 0.0079 | 11.2 | 2.5 |
| PKS1440-389 | -39.14° | 3.0 | 2.4 | 0.0085 | 10.8 | 3.0 |
| HESSJ1458-608 | -60.88° | 3.7 | 3.6 | 0.036 | 9.3 | 2.0 |

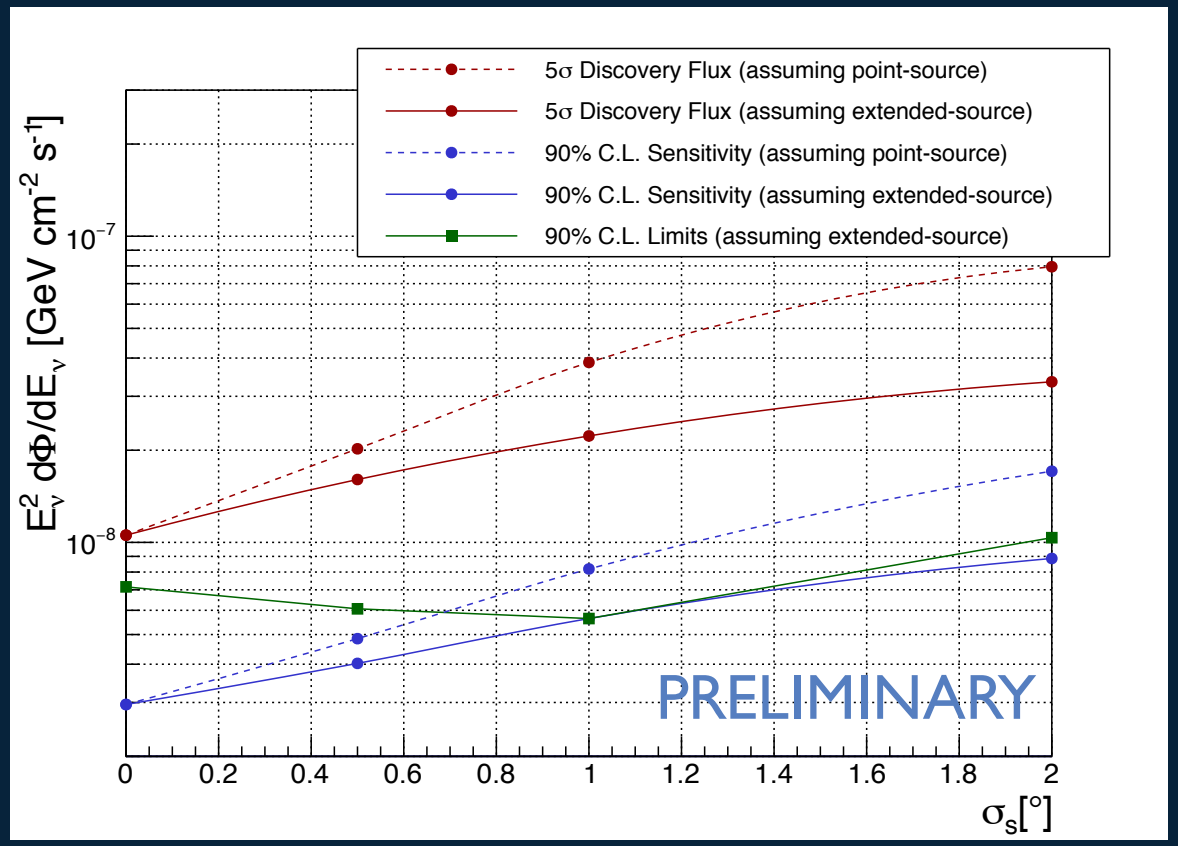



Highest excess:

HESSJ1023-575
0.2σ post-trial significance

# Results: Sagittarius A*




| 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 |

# Results: RXJ 1713.7-3946

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

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

sensitivities and upper limits expressed as ratio with the assumed source flux

| Spectrum | $\hat{n}_s$ | p-value | 90%C.L. Sensitivity $\Phi_S^{90\%C.L}/\Phi_0$ | 90%C.L. Upper limit $\Phi_L^{90\%C.L}/\Phi_0$ |
|---|---|---|---|---|
| RXJ 1713.7-3946 (1) | 0.3 | 0.40 | 10.7 | 13.2 |
| RXJ 1713.7-3946 (2) | 0.3 | 0.41 | 9.7 | 11.7 |

# Summary

- Various combined searches in the Southern sky with ANTARES and IceCube
- No significant point-like nor extended emission found, upper limits set
- Improvement up to a factor 2 achieved in the sensitivity to point sources compared to individual analyses

- Largest excess over the whole Southern sky: $(\alpha, \delta) = (213.2°, -40.8°)$, point-like source, $0.9\sigma$ post-trial
- Largest excess over the GC region: $(\alpha, \delta) = (274.1°, -40.1°)$, 2° source extension, $1.9\sigma$ post-trial
- Most significant source of the 57 investigates candidates: HESSJ1023-575, $0.2\sigma$ post-trial
- Most significant case for SMBH Sagittarius A*: point-like source, 6% p-value
- SNR RXJ 1713.7-3946: sensitivities and upper limits on the neutrino flux for two proposed emission models