

# Search for point-like neutrino sources over the Southern Hemisphere with the ANTARES and IceCube neutrino telescopes

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for the ANTARES and IceCube Collaborations

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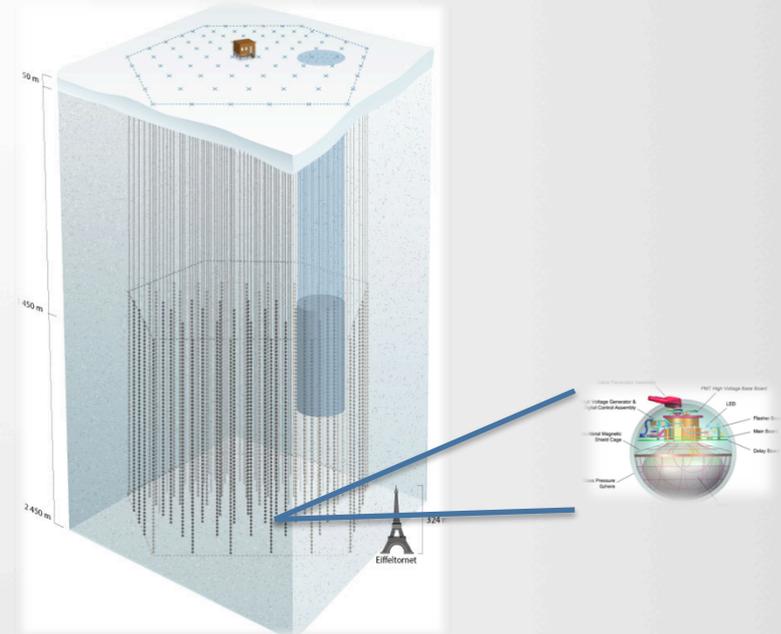
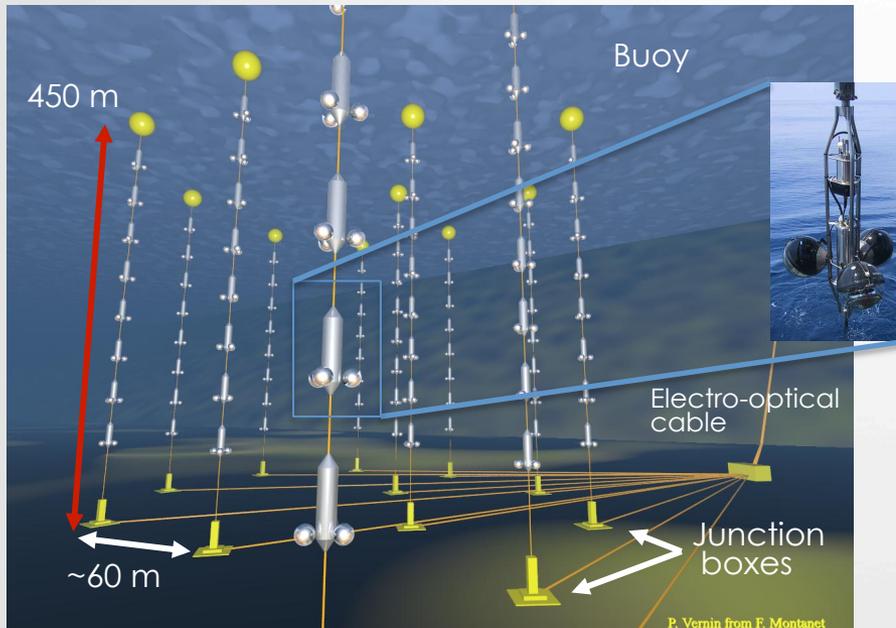
(3<sup>rd</sup> August, 2015)





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# The ANTARES and IceCube detectors



- Largest neutrino telescope in the Northern Hemisphere
- 12 lines with 25 storeys (3 OMs each)
- 2500 m deep in the Mediterranean Sea

- Largest neutrino telescope (1 km<sup>3</sup>)
- ~2500 m deep in Antarctica
- 86 strings with 60 DOMs
- 17 m between Oms
- 125 m between strings

Complementarity for the **Southern Sky**:

- ANTARES has better sensitivity for  $E_\nu < 100$  TeV
- IceCube has a better sensitivity for high energy events



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# Data samples

- Combined point source analysis for the **Southern Sky**.
- Samples used:
  - **IC 40 strings:** 375 days, 22796 events
  - **IC 59 strings:** 348 days, 64240 events
  - **IC 79 strings:** 316 days, 59009 events
  - **ANTARES 2007-2012:** 1338 days, 4136 events
- All these samples have already been used for point-source analysis in their respective collaborations.

# Search method: Likelihood

- Likelihood for the analysis:

$$L(n_s) = \prod_j L^j(n_s^j) = \prod_j \prod_{i \in j} \left[ \frac{n_s^j}{N^j} S_i^j + \left(1 - \frac{n_s^j}{N^j}\right) B_i^j \right]$$

$n_s^j$  related to each sample with the relative contribution of each experiment:

$$n_s^j = C^j(\delta) n_s$$

IceCube signal PDF

$$S_i^{IC} = \frac{1}{2\pi\sigma_i^2} e^{-\frac{|x_s - x_i|^2}{2\sigma_i^2}} P_s(E_i, \sigma_i | \delta_i)$$

IceCube background PDF

$$B_i^{IC} = B^j(\delta_i) P_b(E_i, \sigma_i | \delta_i)$$

ANTARES signal PDF

$$S_i^{ANT} = \frac{1}{2\pi\beta_i^2} e^{-\frac{|x_s - x_i|^2}{2\beta_i^2}} P_s(E_i, \beta_i)$$

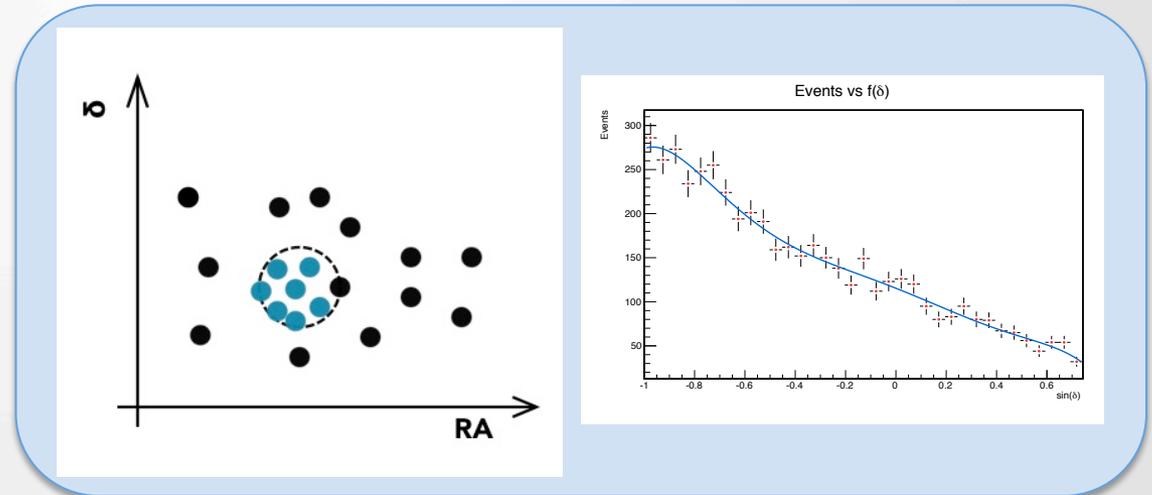
ANTARES background PDF

$$B_i^{ANT} = B(\delta_i) P_b(E_i, \beta_i)$$

# Search method: Likelihood

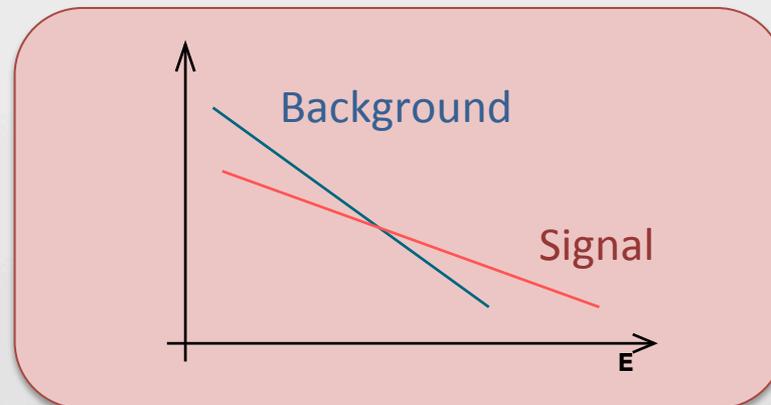
Signal PDF:

$$S_i = \frac{1}{2\pi\beta_i^2} e^{-\frac{|x_s - x_i|^2}{2\beta_i^2}} P_s(E_i, \beta_i)$$



Background PDF:

$$B_i = B(\delta_i) P_{bg}(E_i, \beta_i)$$



# Relative fraction of signal events

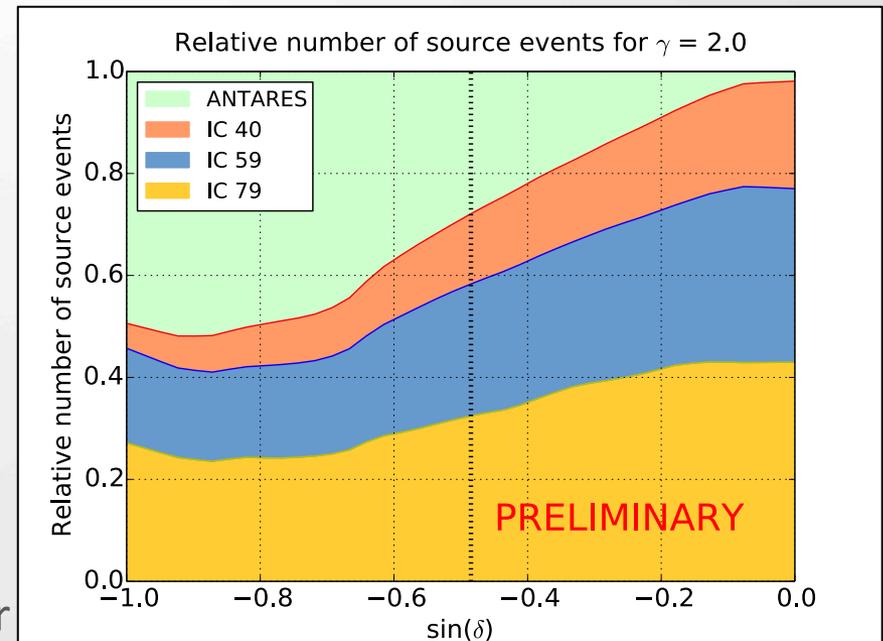
- Fraction of expected source events:

$$C^j \left( \delta, \frac{d\Phi}{dE_\nu} \right) = \frac{N^j \left( \delta, d\Phi / dE_\nu \right)}{\sum_i N^i \left( \delta, d\Phi / dE_\nu \right)}$$

where:

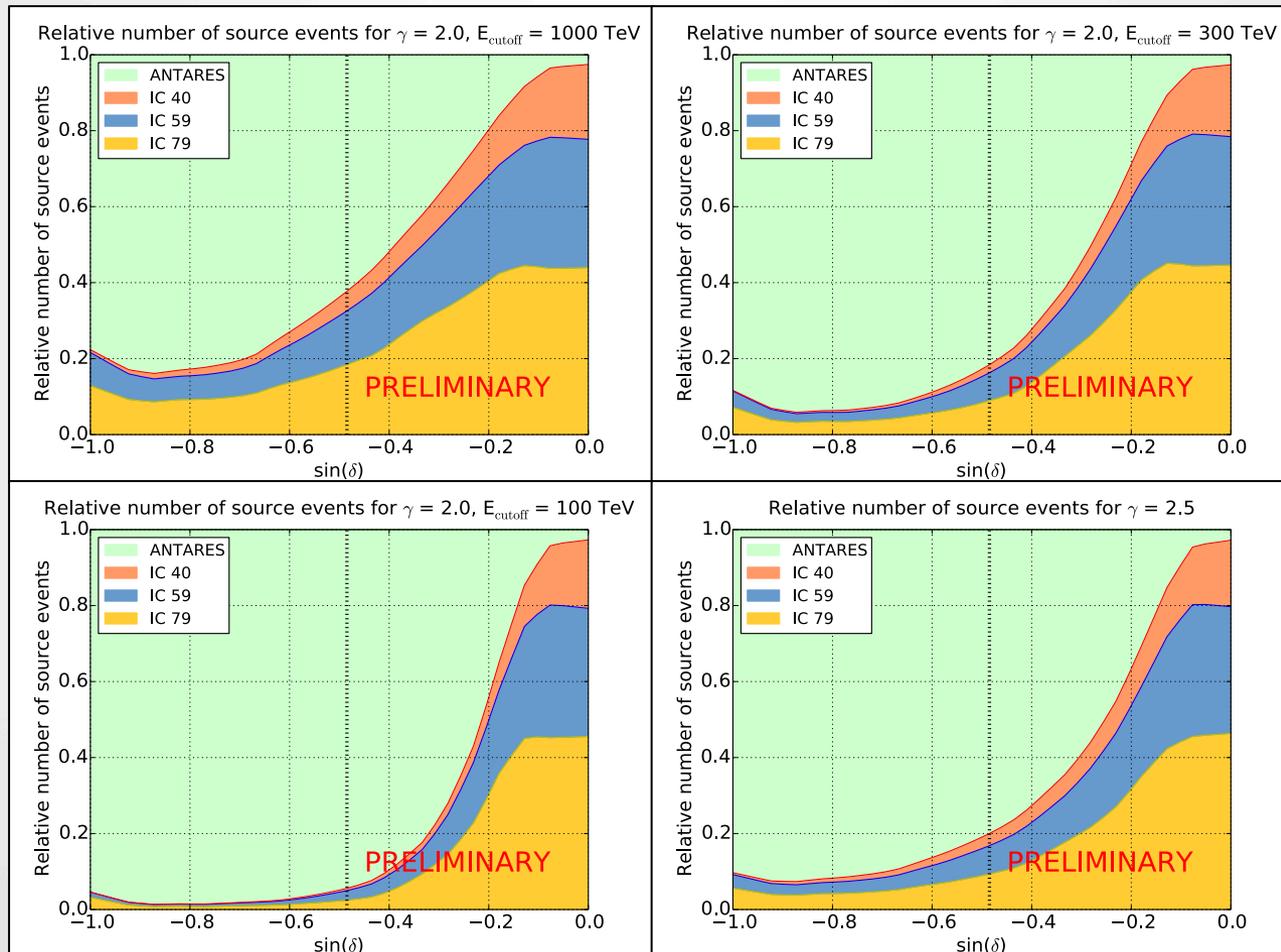
$$N(\delta) = \iint dE dt A_{\text{eff}}(E, \delta) \frac{d\Phi}{dE}$$

- Indicates the performance of detector at a given signal.
- Different flux assumptions:
  - Different energy spectra ( $E^{-2}$ ,  $E^{-2.5}$ )
  - Energy cutoffs (100 TeV, 300 TeV, 1 PeV).



Relative fraction of source events for an  $E^{-2}$  energy spectrum.

# Relative fraction of signal events



Relative fraction of signal events for different energy source spectra. Exponential square-root energy cutoffs of 1 PeV (top-left), 300 TeV (top-right) and 100 TeV (bottom left), and  $E^{-2.5}$  (bottom right).

# Search method: Likelihood

- Likelihood for the analysis:

$$L(n_s) = \prod_j L^j(n_s^j) = \prod_j \prod_{i \in j} \left[ \frac{n_s^j}{N^j} S_i^j + \left( 1 - \frac{n_s^j}{N^j} \right) B_i^j \right]$$

$n_s^j$  related to each sample with the relative contribution of each experiment:

$$n_s^j = C^j(\delta) n_s$$

- From this likelihood, we define the following test statistic:

$$TS = \log L^{\max}(n_s) - \log L(n_s = 0)$$



# Search method: Strategies

## Full Southern Sky search

- Evaluation of the TS in squares of  $1^\circ \times 1^\circ$  over the Southern Sky
- Free parameters:  $n_s$ ,  $\delta_s$ ,  $\alpha_s$

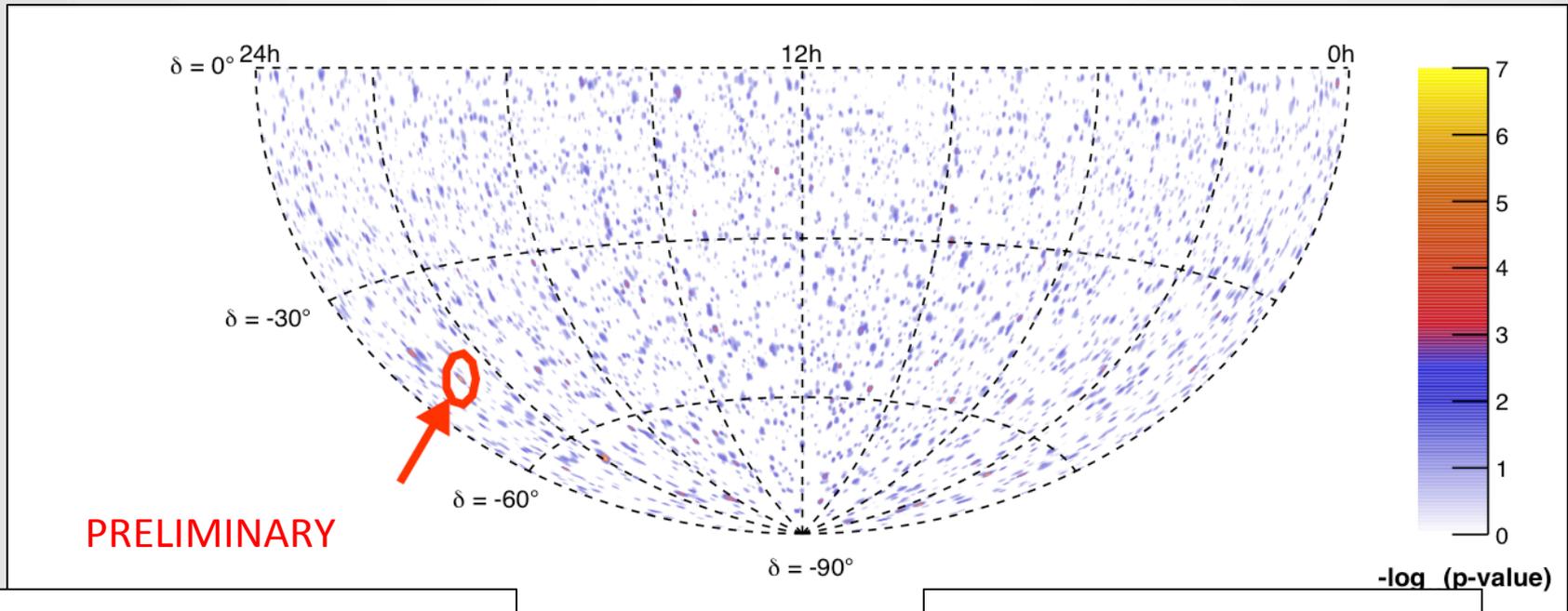
## Candidate list search

- List of 40 known sources which are neutrino source candidates.
- SNRs, AGNs, ...
- Free parameter:  $n_s$

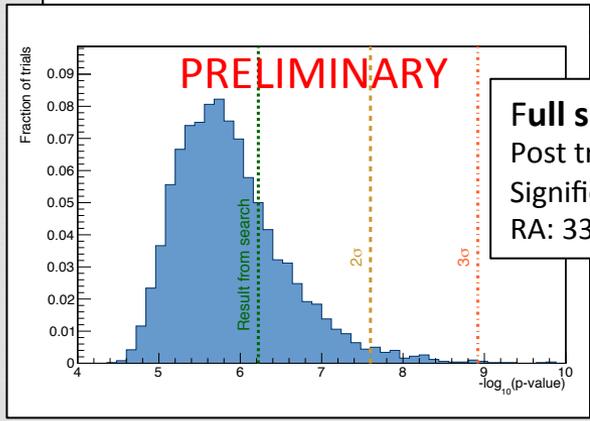
## Calculation of p-value:

- TS distributions of only background calculated in steps of  $1^\circ$  in declination
- TS obtained for a given source is compared to the corresponding TS distribution.

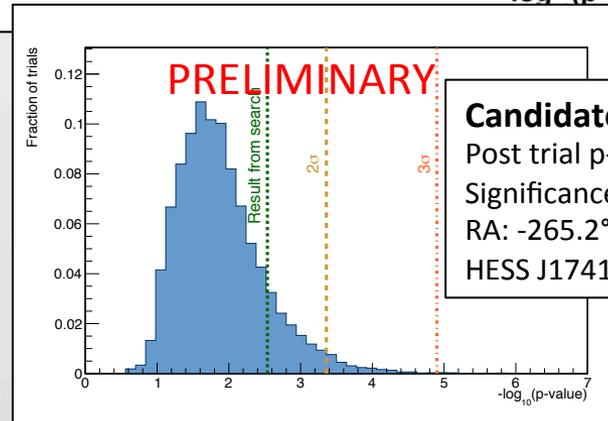
# Results



**PRELIMINARY**



**Full sky search:**  
 Post trial p-value: 0.24  
 Significance:  $0.7\sigma$   
 RA:  $332.8^\circ$       DEC:  $-46.1^\circ$

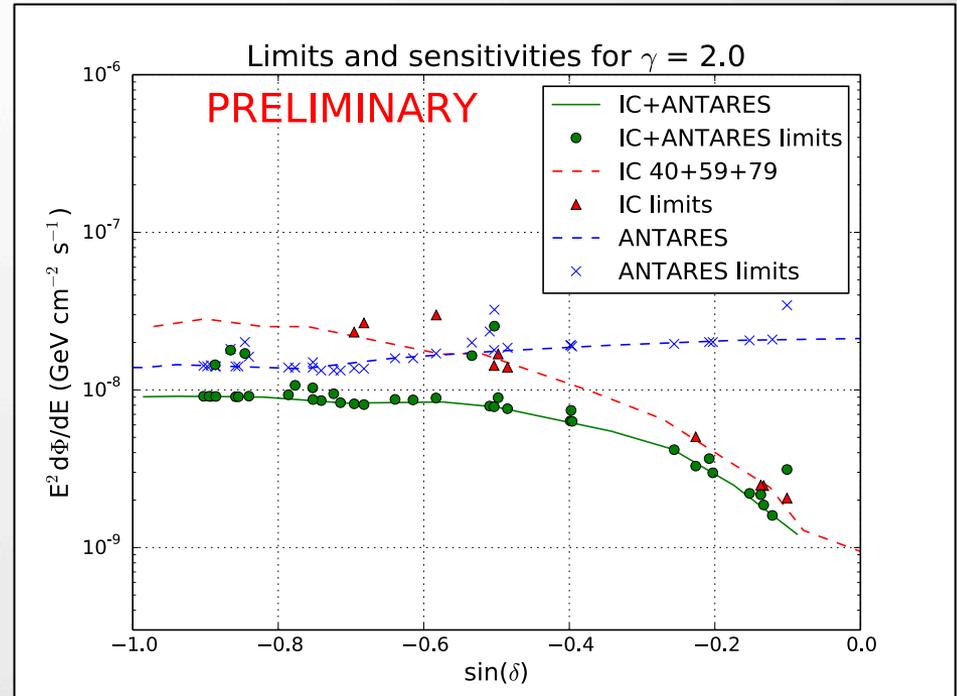


**Candidate list:**  
 Post trial p-value: 0.11  
 Significance:  $1.2\sigma$   
 RA:  $-265.2^\circ$       DEC:  $-30.2^\circ$   
 HESS J1741-302

# Results: Limits

Source name	$\sin(\delta)$	$n_s$	Pre-trial p-value	Flux limit*
HESSJ1741-302	-0.50	1.6	0.003	2.5
3C279	-0.10	1.1	0.05	0.3
PKS0548-322	-0.53	0.9	0.07	1.6
ESO139-G12	-0.87	0.8	0.07	1.8
HESSJ1023-575	-0.85	0.8	0.08	1.7
RCW86	-0.88	0.2	0.11	1.4

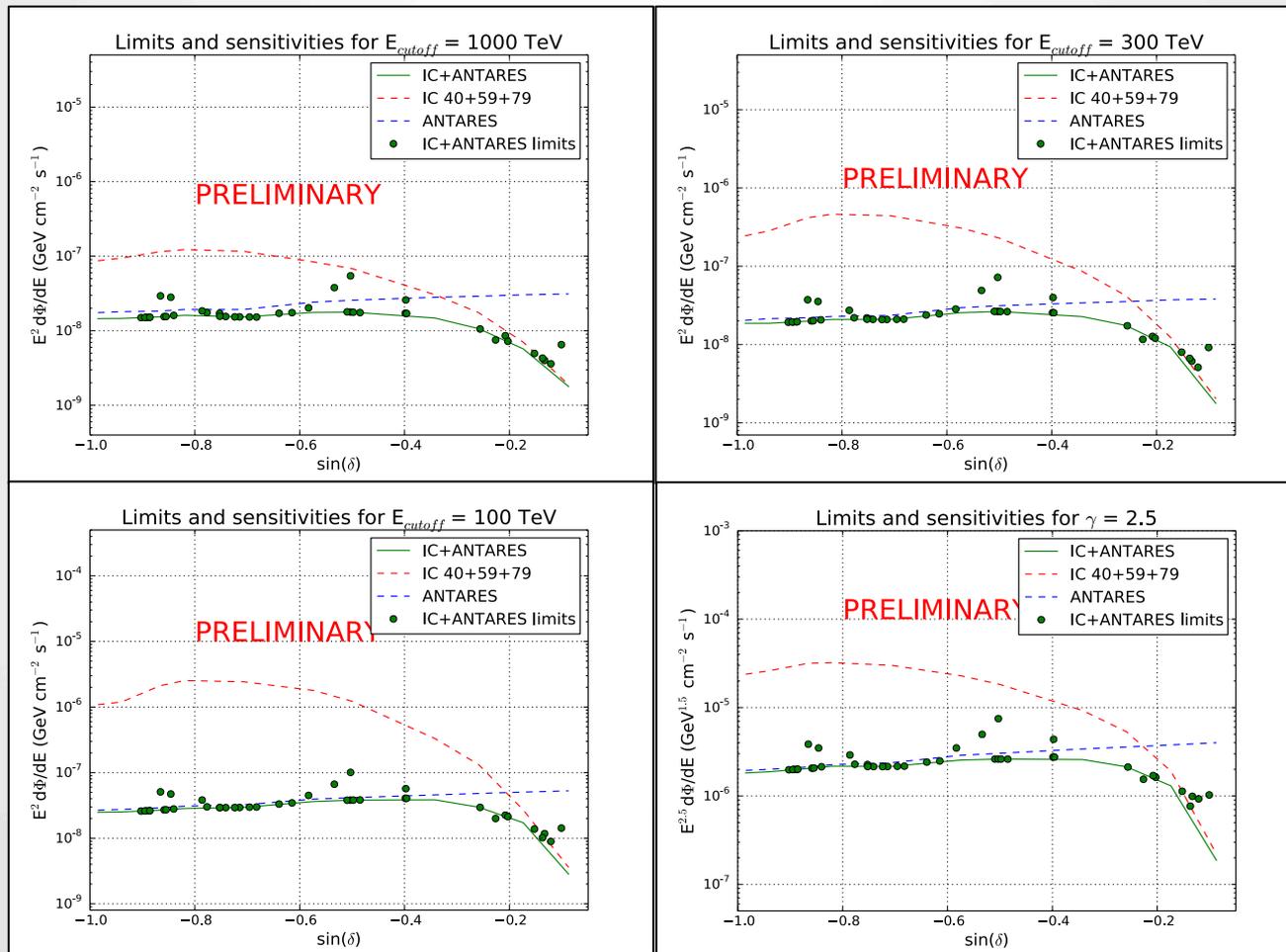
\*Flux limit in units of  $10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1}$



90% CL sensitivities and limits for an E-2 source spectrum using the Neyman method.



# Results: Limits





# Conclusions

- First combined search over the Southern Hemisphere with the ANTARES and IceCube neutrino telescopes.
- Sensitivity for point sources up to factor 2 improvement
  - Improvement varies depending on the source declination and assumed source spectra
- No significant clusters have been found.
- Full sky search: Largest excess with  $0.7\sigma$  significance (post-trial) at  $(\alpha, \delta) = (332.8, -46.1)$
- Candidate list: Largest excess found for HESS J1741-302 with  $1.2\sigma$  significance.