University of Granada

Solar Atmospheric Neutrinos Searches with the ANTARES Neutrino Telescope

ANTARES-KM3NeT

Dark Ghost-2022

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On behalf of the ANTARES collaboration

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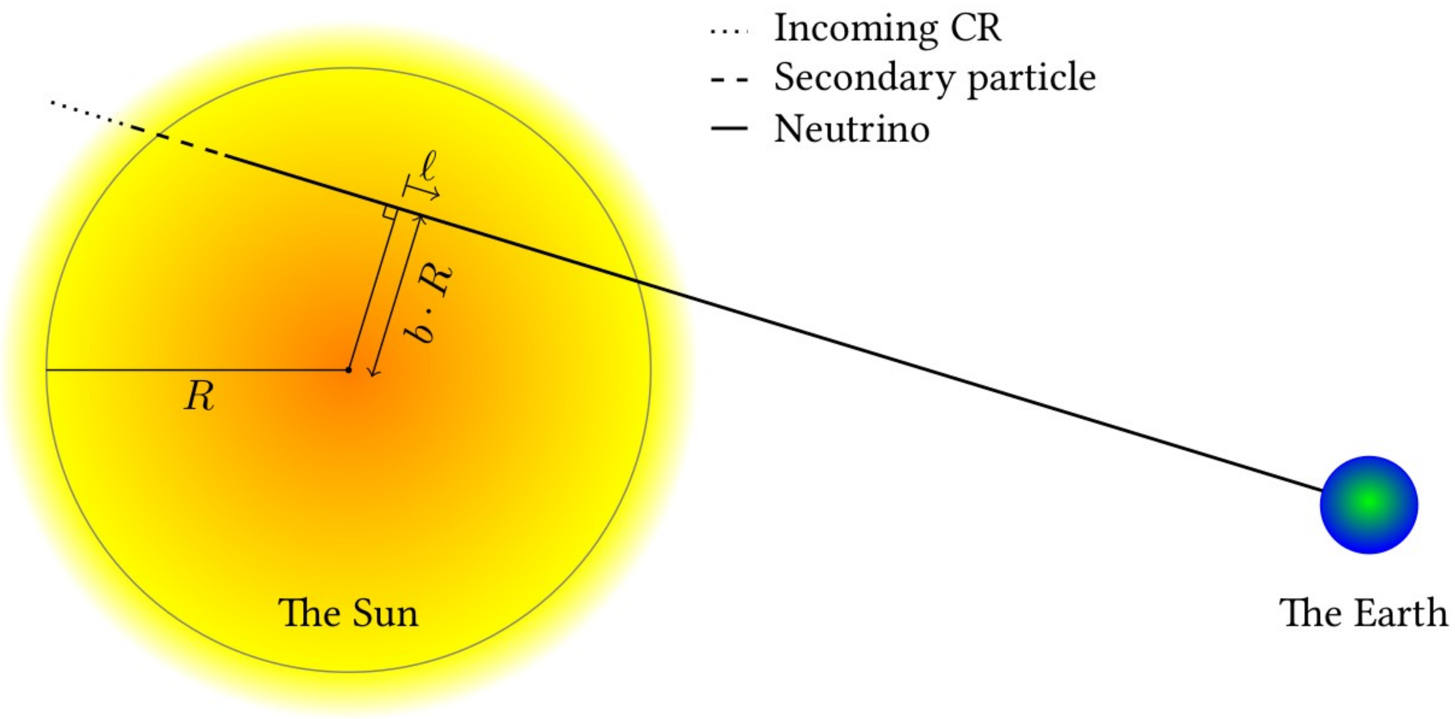
Search for solar atmospheric neutrinos with the ANTARES neutrino telescope [arXiv:2201.11642]

Solar Atmospheric Neutrinos

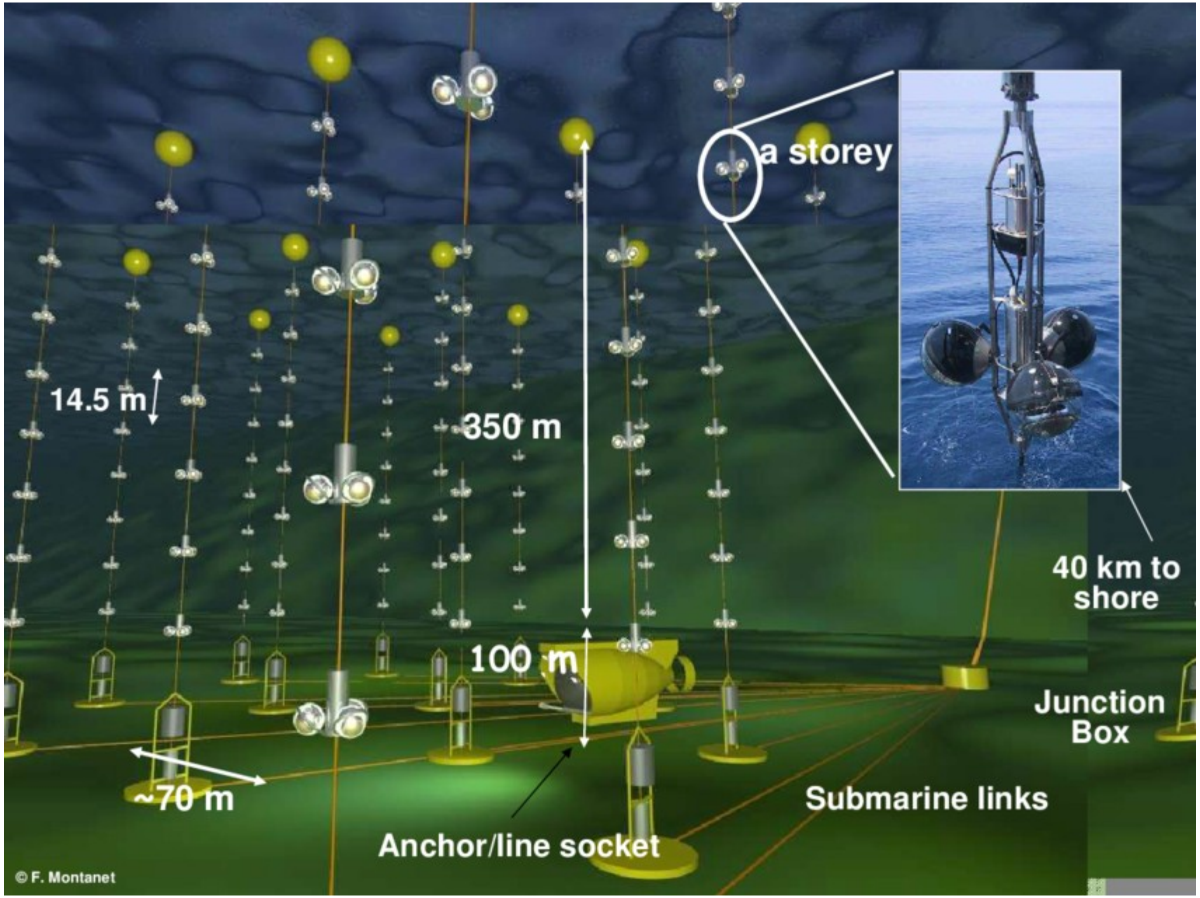
- CRs blocked by the Sun yield ν as final state particles.
- The majority of the neutrinos are absorbed in the inner part.
- ν produced at the solar corona can escape and reach the Earth.
- Important for understanding the solar composition as well as the background for indirect solar DM searches.

Figure from:
J. Edsjö et al JCAP06(2017)033



The ANTARES Detector

- First undersea Neutrino Telescope.
- Located in the Mediterranean Sea, near Toulon, at 2500 m depth.
- Construction 2006-2008.
- Continuously taking data.
- Switched off on February 2022. Dismantling forseen by summer 2022.
- 12 lines (885 PMTs)
- 25 storeys/line
- 3 PMTs/storey



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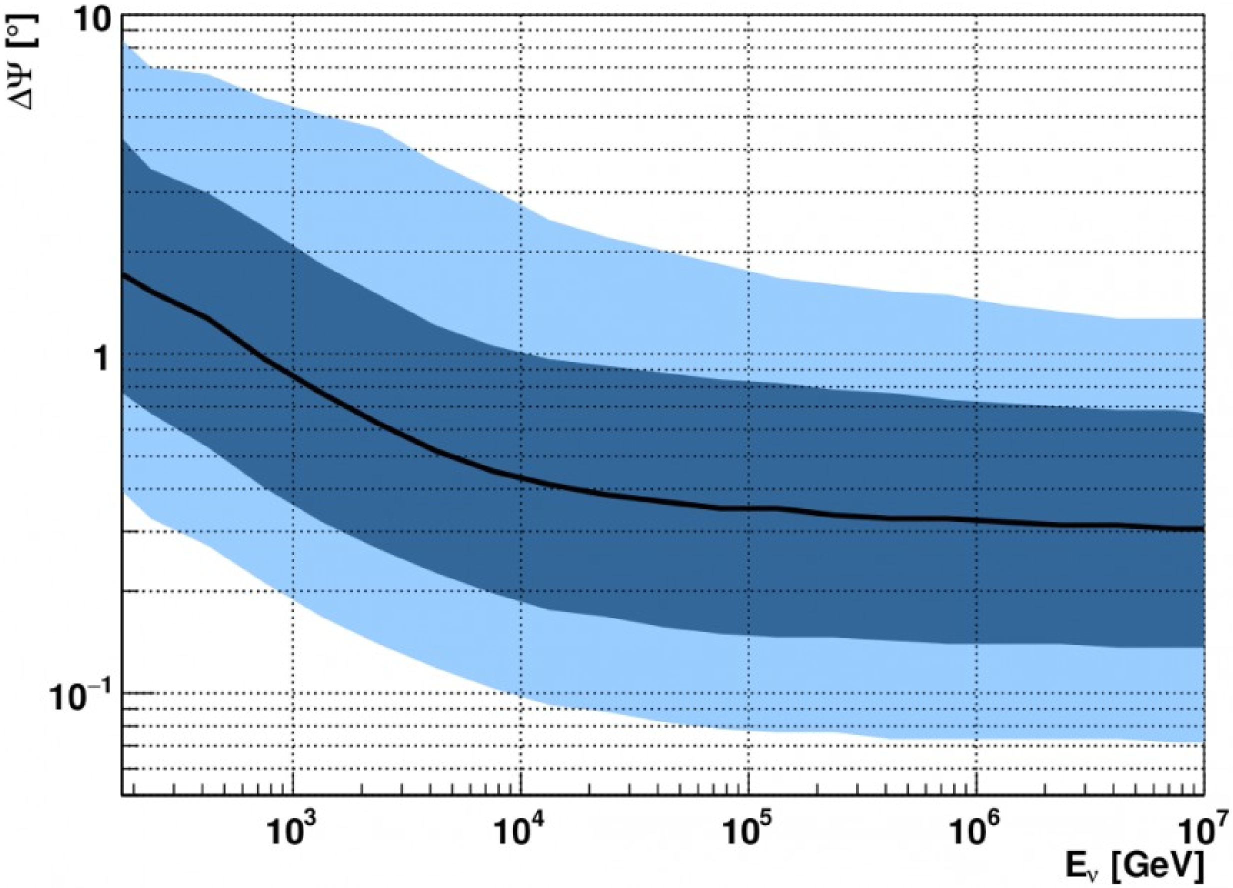
The ANTARES Detector

- 2 main topologies
  - Track like → From ν_μ and ν_τ CC.
  - Shower like→ From all-flavours NC and ν_e and ν_τ CC.
- Angular resolution < 0.4° for E_ν > 10 TeV).

Median angular resolution, track channel.



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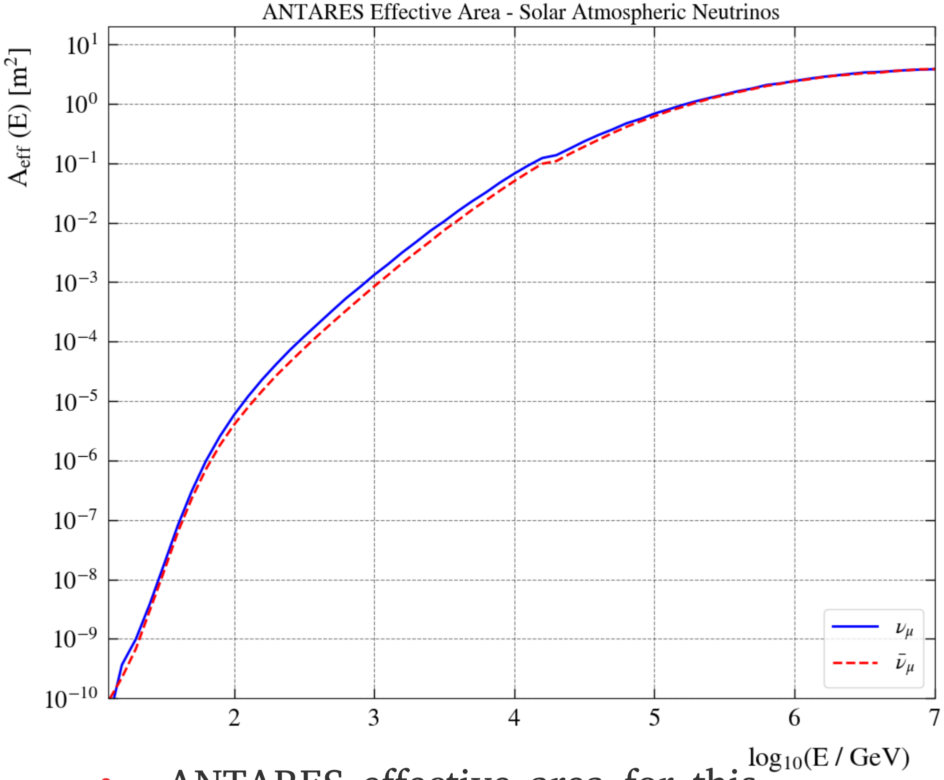
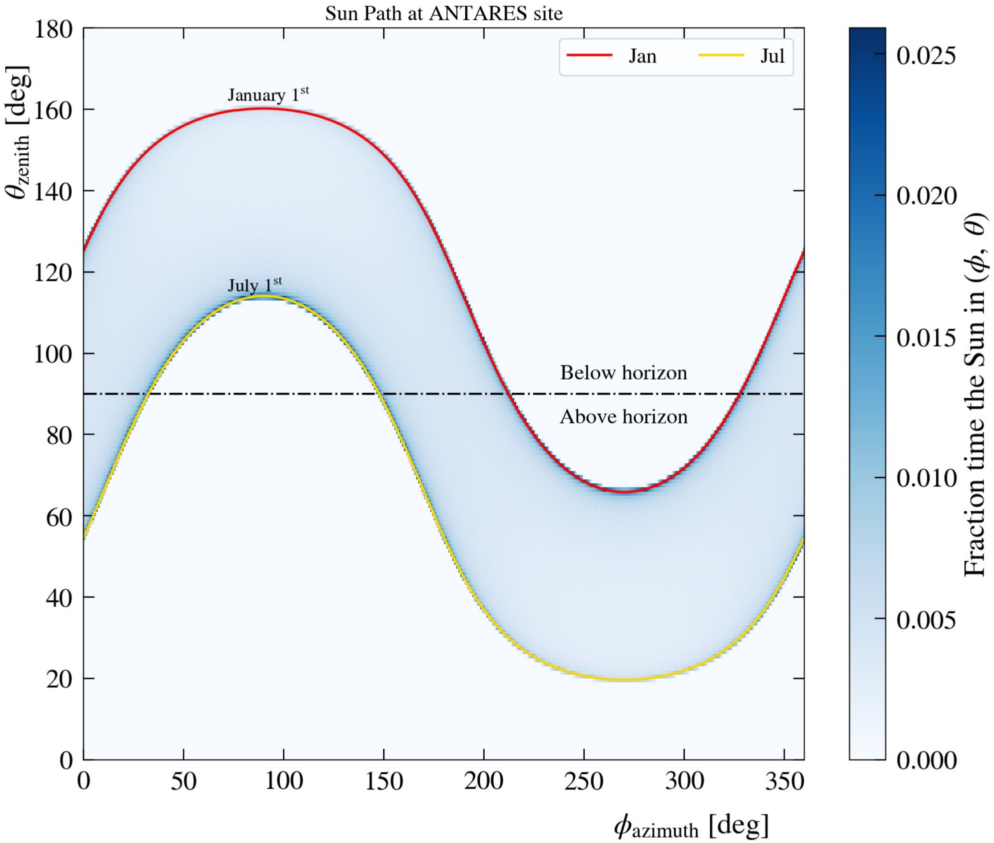
The ANTARES Detector





- ANTARES effective area for this analysis.
- Sun tracking taken into account.

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Analysis Outlook

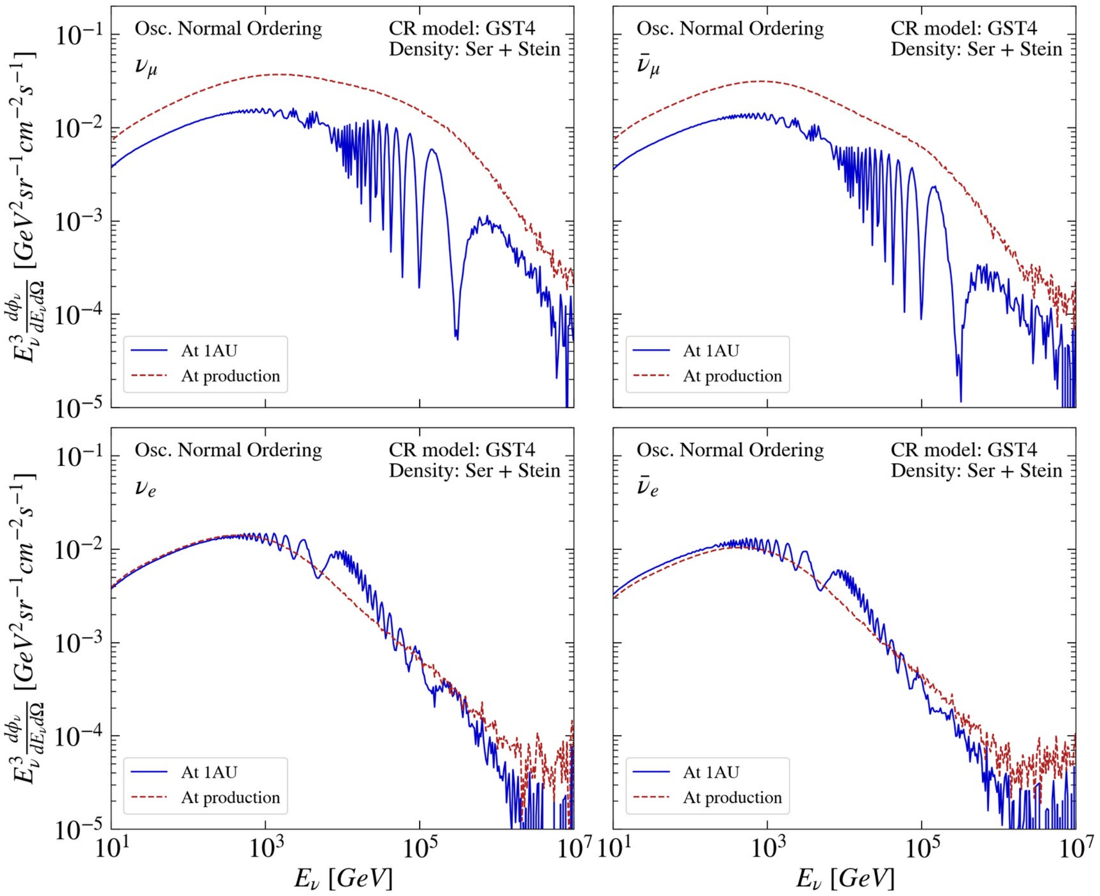
- Only track channel considered (ν_μ CC).
- Data taking period from 2008 to 2018 (both included) → lifetime of 3022 days.
- Main background → Atmospheric μ and atmospheric ν.
- Selection quality cuts to optimize SAν Sensitivity and reject background.
  - $\Lambda > -5.2$, reconstruction fit parameter
  - $\beta < 1°$, error estimate in the reconstructed angle
  - $\cos\theta > 0$ → upward-going events.
- Unbinned likelihood search.

Analysis

- Solar Atmospheric Neutrino flux from WimpSim 5.0
  From: J. Edsjö et al JCAP06(2017)033
  - 2 Cosmic Ray (CR) models (H3a and GST4).
  - 2 Solar composition models. (Ser+Stein and Ser+GS98).
  - Oscillation and Normal Ordering parameters. From global-best fit: JHEP 01 (2017) 087
  - Solar Magnetic Field Effect is neglected.

$$\theta_{12} = 33.56^\circ \qquad \delta = 261^\circ$$
$$\theta_{13} = 8.46^\circ \qquad \Delta m^2_{21} = 7.5 \cdot 10^{-5}\mathrm{eV}^2$$
$$\theta_{23} = 41.6^\circ \qquad \Delta m^2_{31} = 2.524 \cdot 10^{-3}\mathrm{eV}^2$$

- Sun as a point source, filled disk and ring shape.



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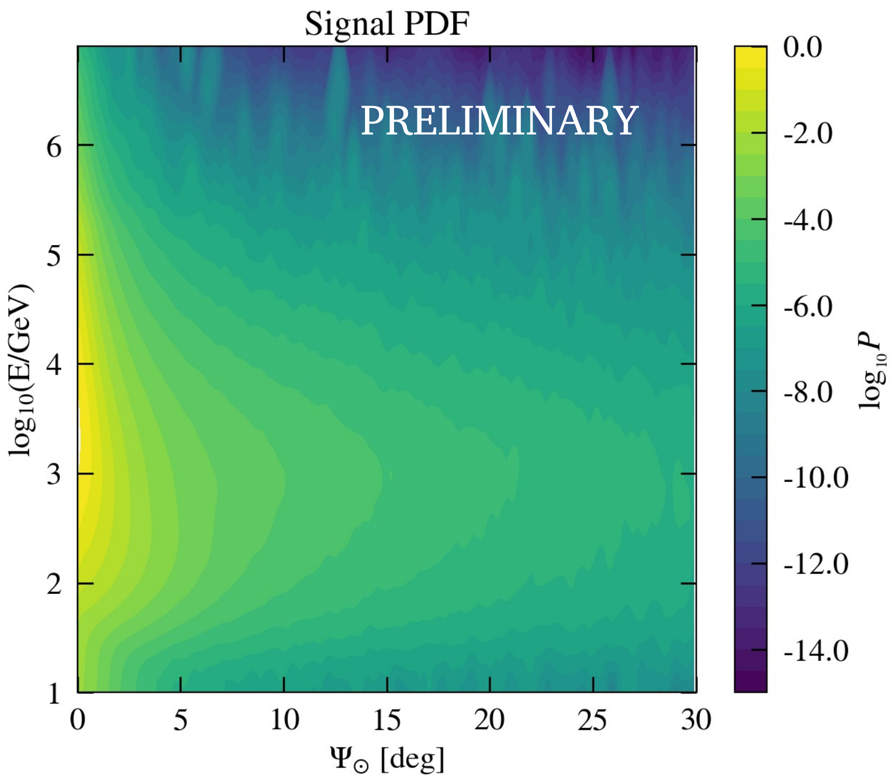
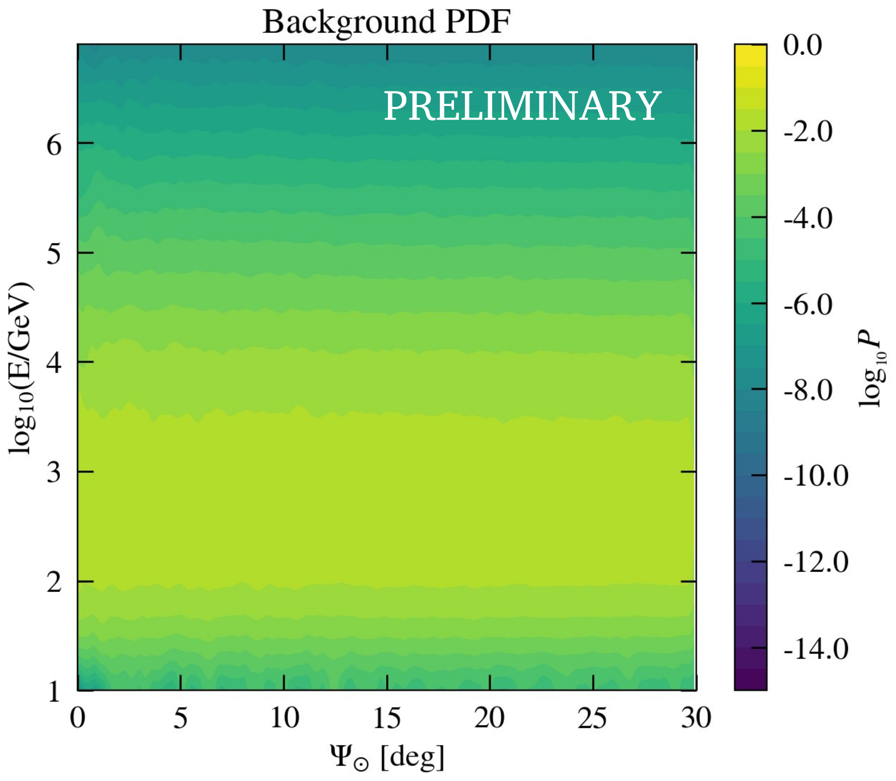
Analysis

- Unbinned Likelihood search. $\mathcal{L}(n_{\text{sig}}) = e^{-(n_{\text{sig}}+n_{\text{bkg}})} \prod_{i}^{N} \left[n_{\text{sig}} \cdot \mathcal{S}(\Psi_{\odot,i}, \beta_i, E_i) + n_{\text{bkg}} \cdot \mathcal{B}(\Psi_{\odot,i}, \beta_i, E_i) \right]$
- Signal and Background PDFs from MC weighted events and scrambled data respectively.





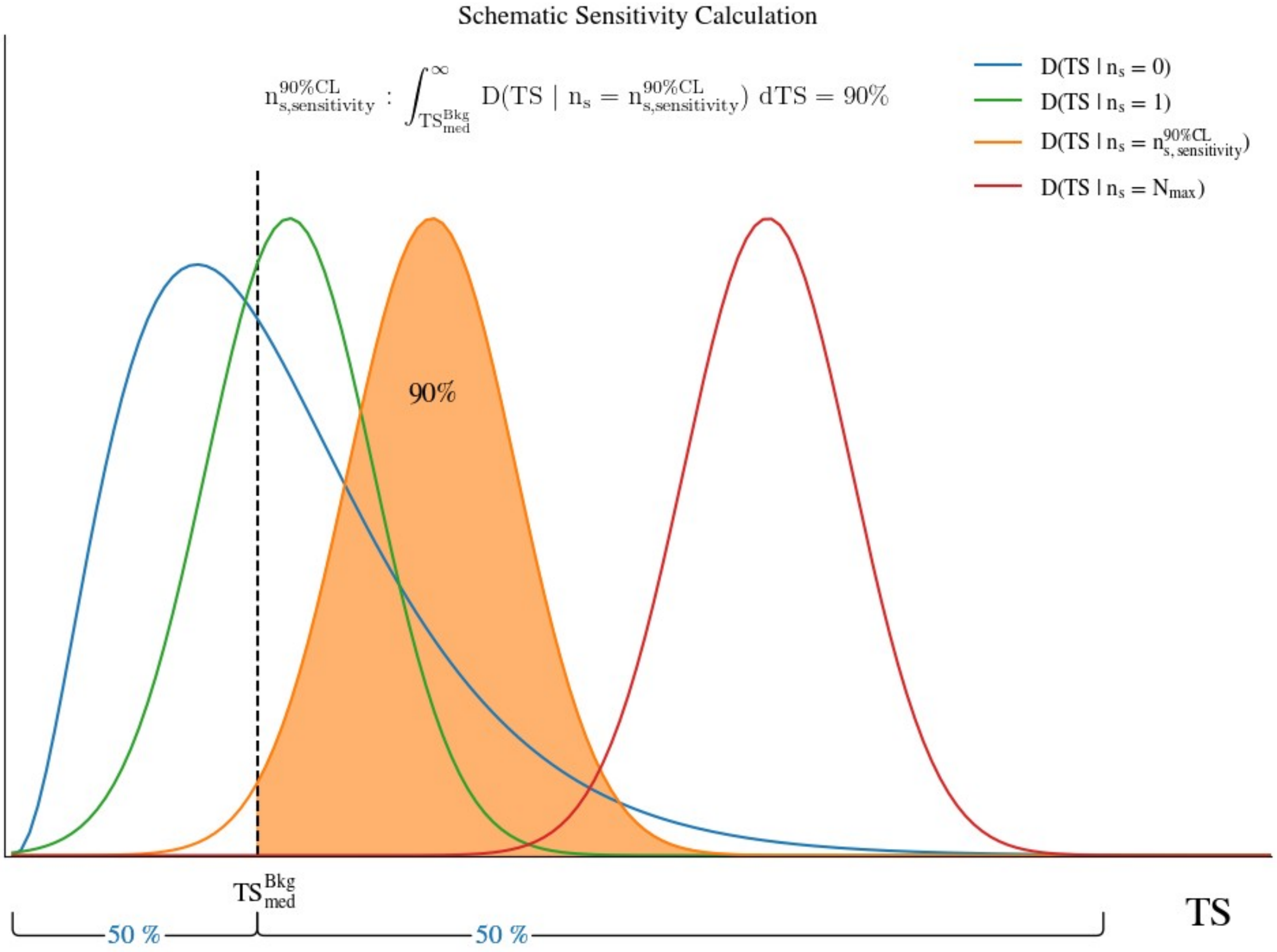
Analysis

$$\mathcal{L}(n_{\text{sig}}) = e^{-(n_{\text{sig}}+n_{\text{bkg}})} \prod_{i}^{N} \left[n_{\text{sig}} \cdot \mathcal{S}(\Psi_{\odot,i}, \beta_i, E_i) + n_{\text{bkg}} \cdot \mathcal{B}(\Psi_{\odot,i}, \beta_i, E_i) \right]$$

- Likelihood ratio test.

$$\text{TS} = \log_{10}\left(\frac{\mathcal{L}(\hat{n}_{\text{sig}})}{\mathcal{L}(0)}\right)$$

- Natural statistical fluctuations and 15% uncertainty in the number of detected events are included.
- Sensitivity computation.
- 90% CL upper limit computation.



Analysis

$$\mathcal{L}(n_{\rm sig}) = e^{-(n_{\rm sig}+n_{\rm bkg})} \prod_i^N \left[n_{\rm sig} \cdot \mathcal{S}(\Psi_{\odot,i}, \beta_i, E_i) + n_{\rm bkg} \cdot \mathcal{B}(\Psi_{\odot,i}, \beta_i, E_i)\right]$$

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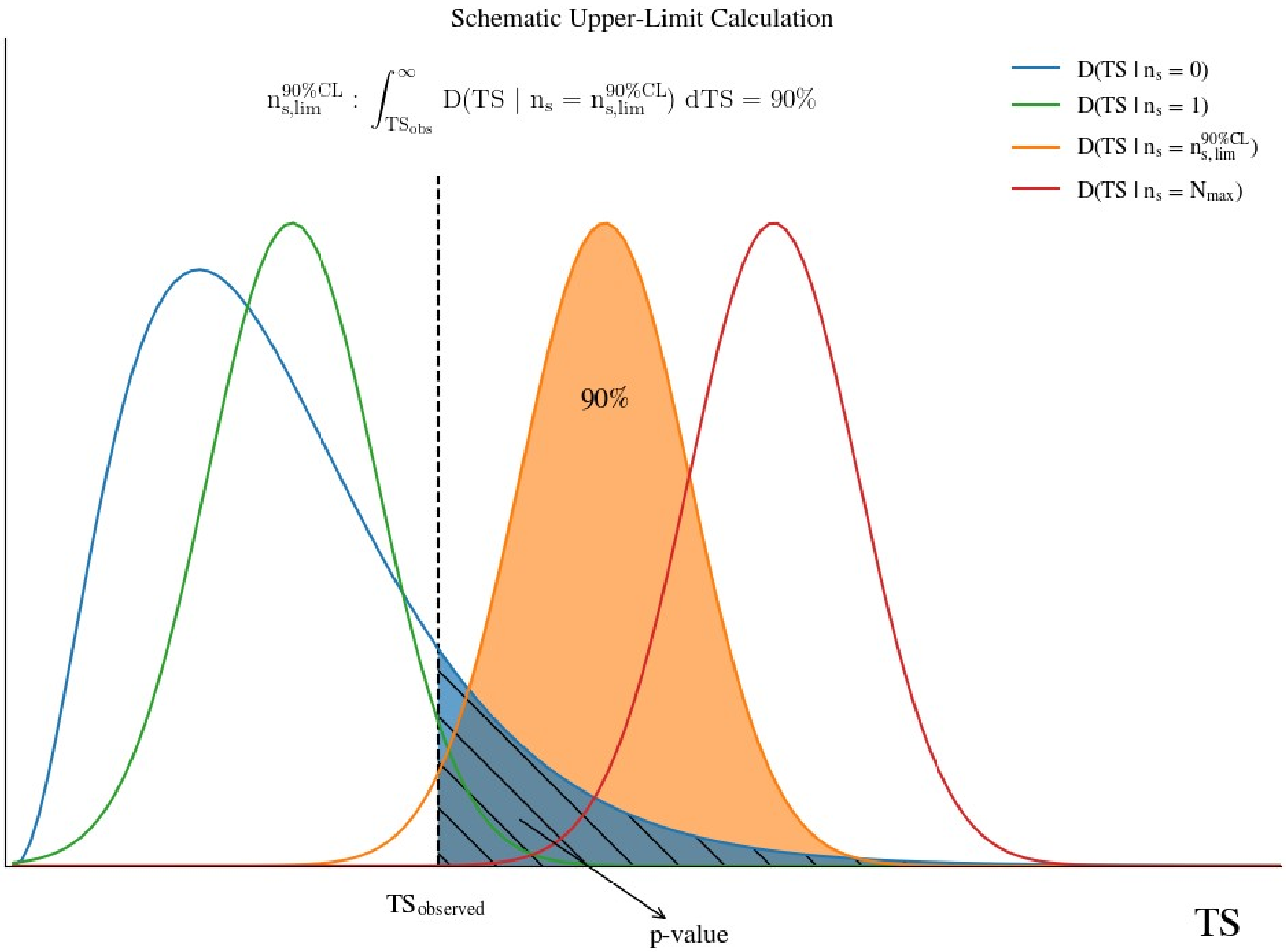
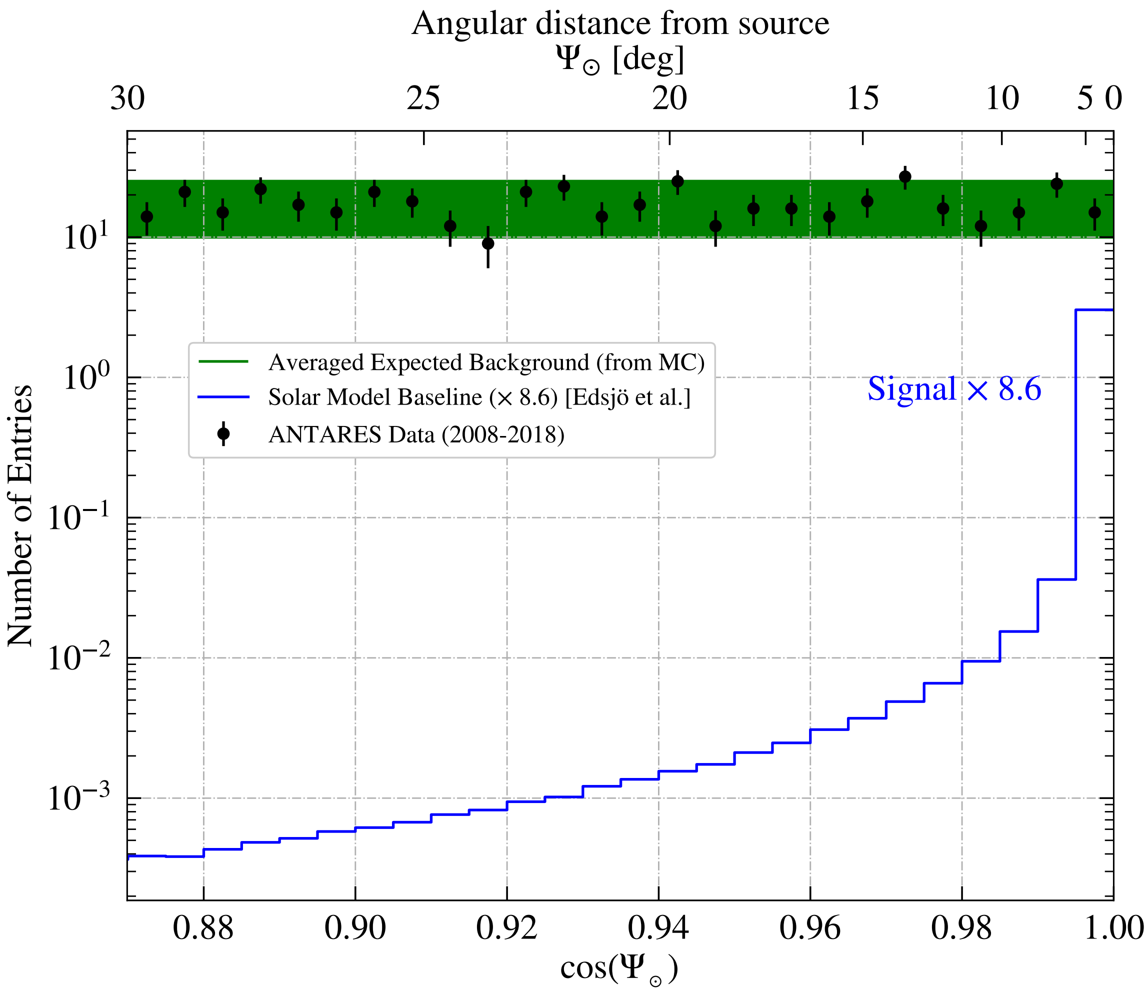


Results



- Event distribution as a function of the angular distance around the source.
- Expected signal magnified for comparison (blue histogram).
- Expected background (green).
- Data (black points).

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Results

- The flux limit is computed as:

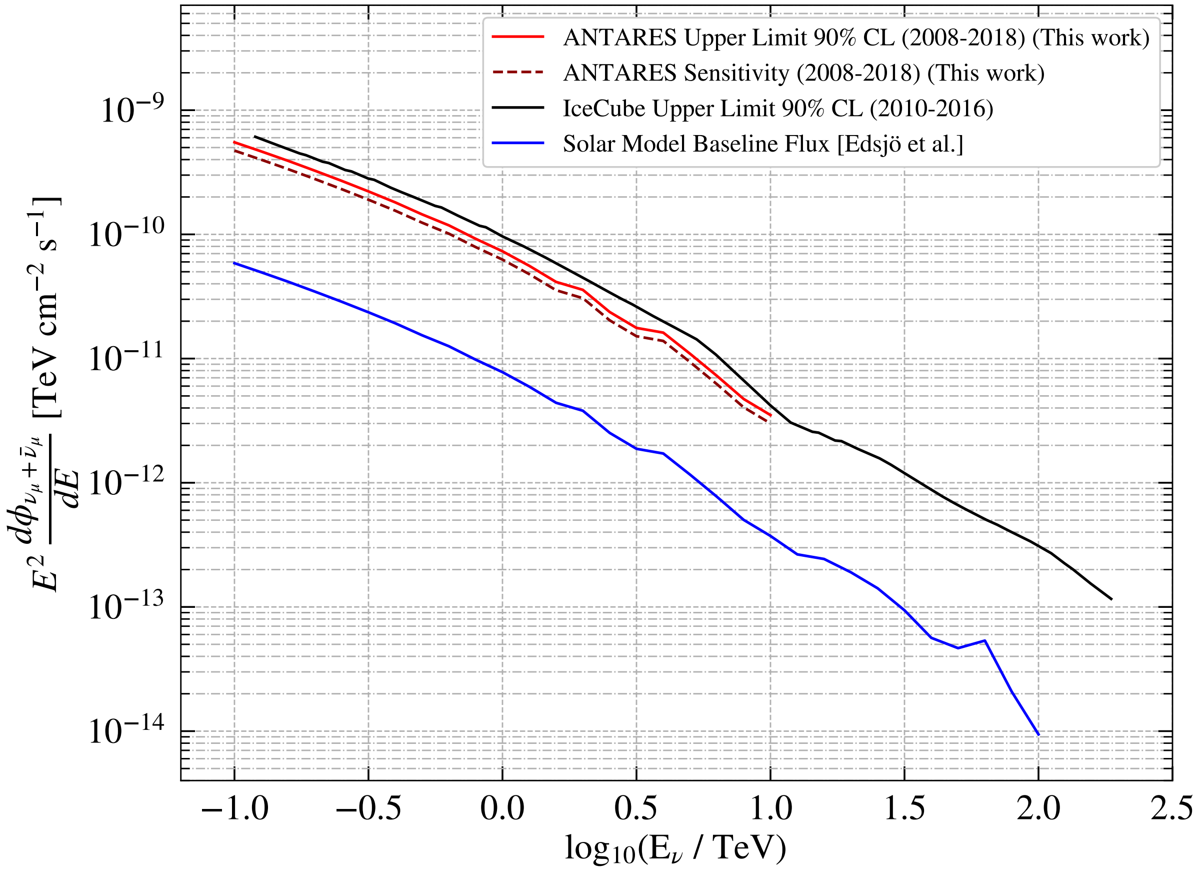
$$\frac{d\phi^{90\%CL}_{\nu_\mu+\bar{\nu}_\mu}(E)}{dE} = \frac{\bar{\mu}^{90\%CL}_{sg}}{n^{\text{theor}}_{sg}} \cdot \frac{d\phi^{\text{theor}}_{\nu_\mu+\bar{\nu}_\mu}(E)}{dE}$$

Where:

$$n^{\text{theor}}_{sg} = T_{\text{live}} \int \sum_{l \in \nu_\mu, \bar{\nu}_\mu} \left(\frac{d\phi^{\text{theor}}_l(E')}{dE} A^l_{\text{eff}}(E') \right) dE'$$

- Is the expected number of signal events for the considered lifetime (3022 days).
  - $n^{\text{theor}}_{\text{sig}} = 0.36$
- Unblinded results:
  - $\mu_{90} = 3.15 \rightarrow C_{90} \approx 8.6$
  - p-value = 0.41

- Base line:
  - H3a + Ser-Stein
  - Sun as a Point Source



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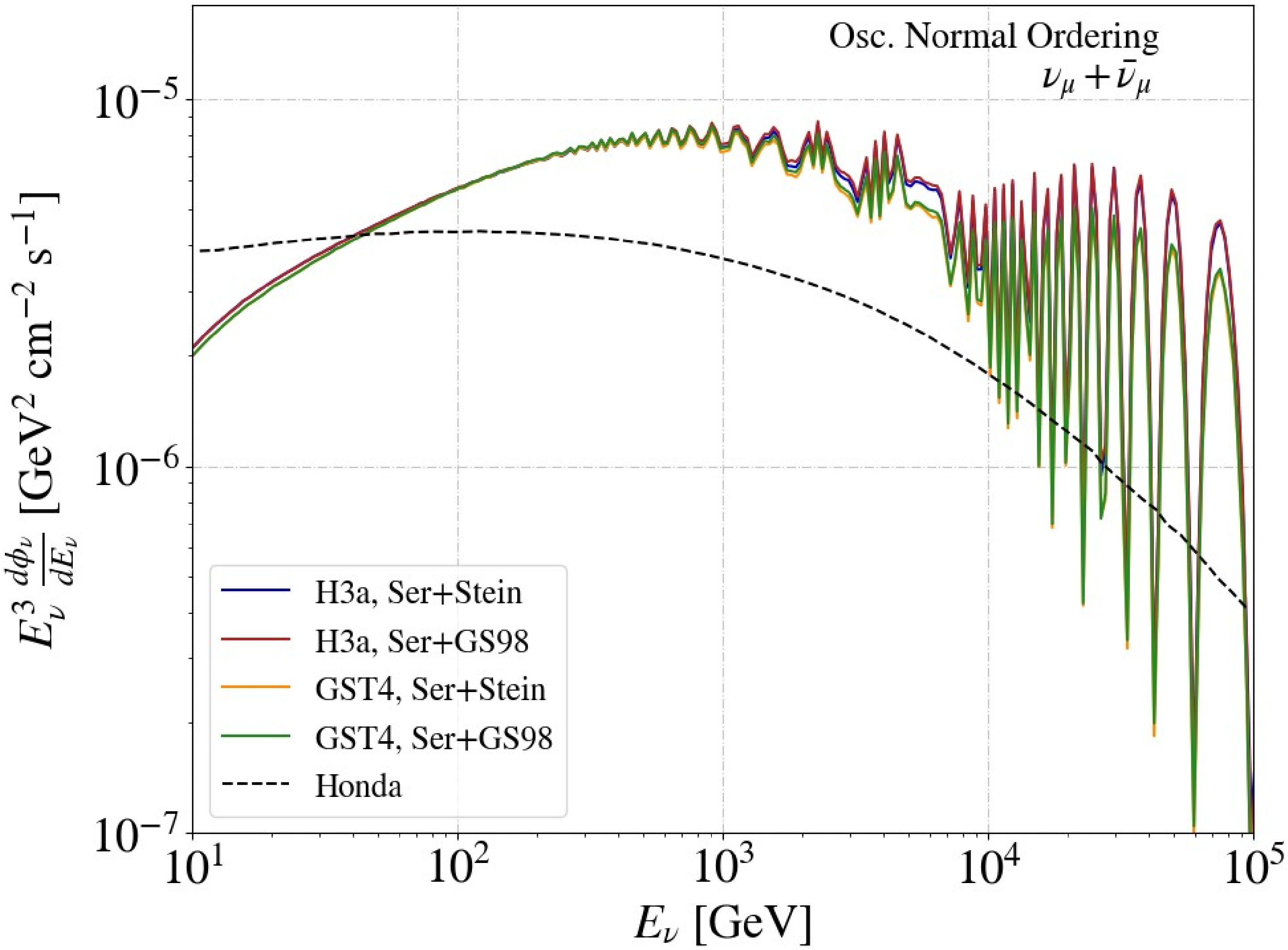
Summary

- 11 years of ANTARES data.
- Unbinned Likelihood Method is used.
- No signal evidence is observed.
- A flux upper limit is established to be 7 x 10^{-11} [TeV^{-1} cm^{-2} s^{-1}] at 1 TeV neutrino Energy.
- Pre-print: arXiv:2201.11642

BACKUP



Fluxes Integrated over the solar solid angle

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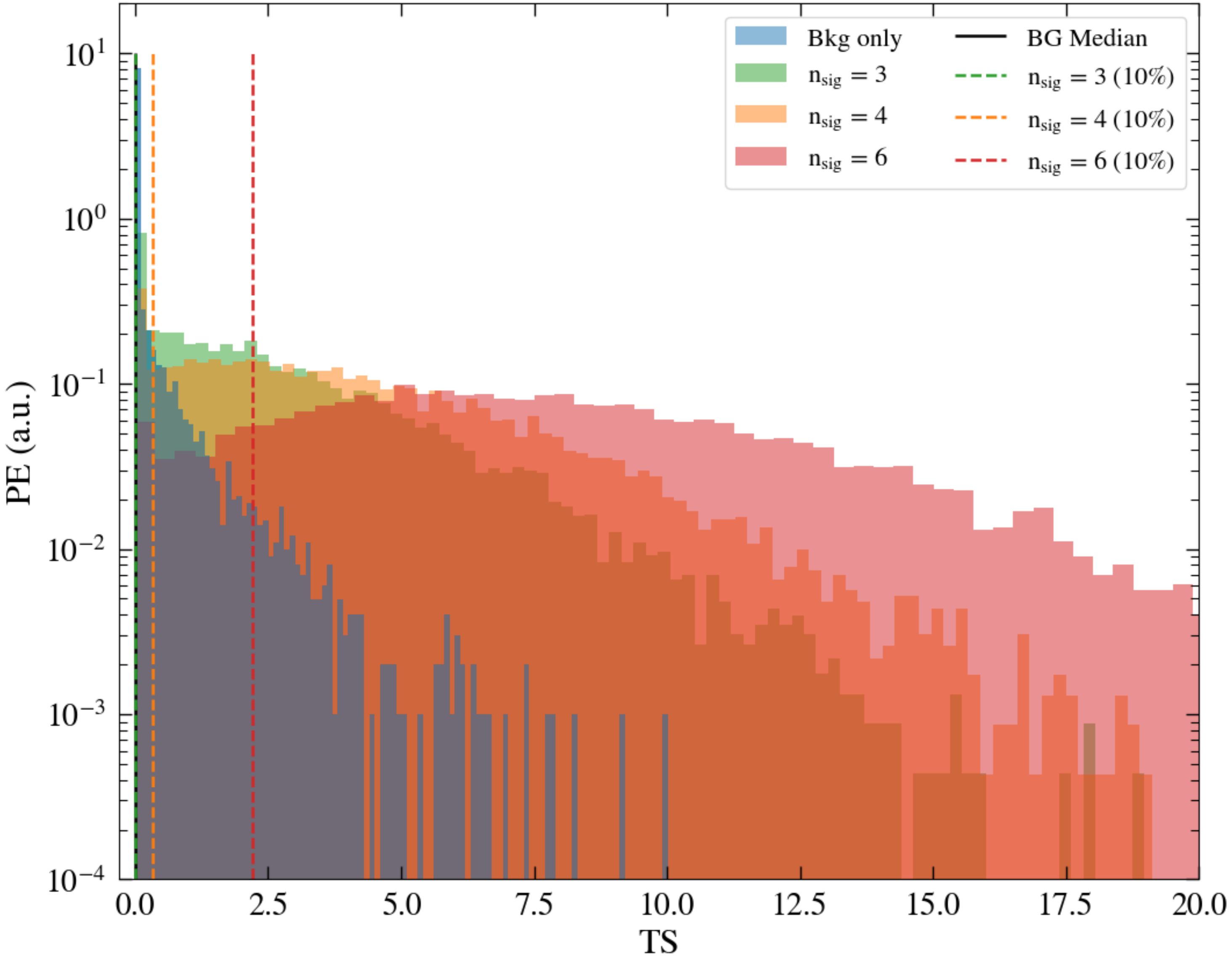

Bkg only
$n_{sig} = 3$
$n_{sig} = 4$
$n_{sig} = 6$
BG Median
$n_{sig} = 3$ (10%)
$n_{sig} = 4$ (10%)
$n_{sig} = 6$ (10%)
PE (a.u.)
TS
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

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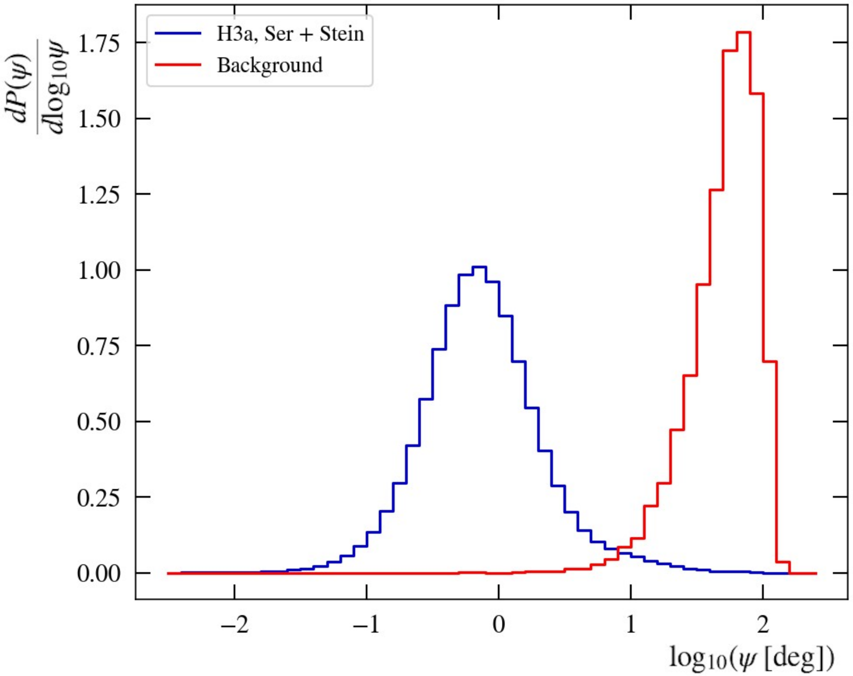
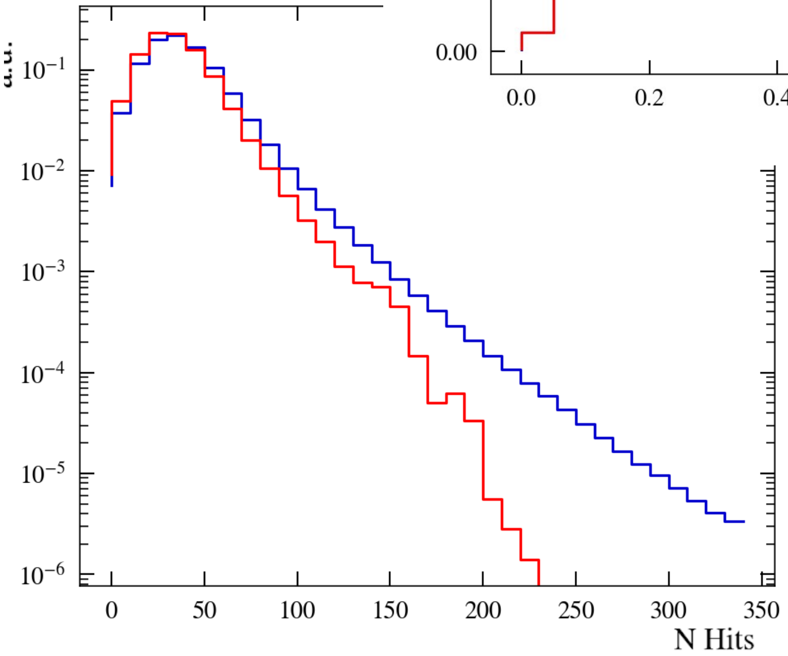
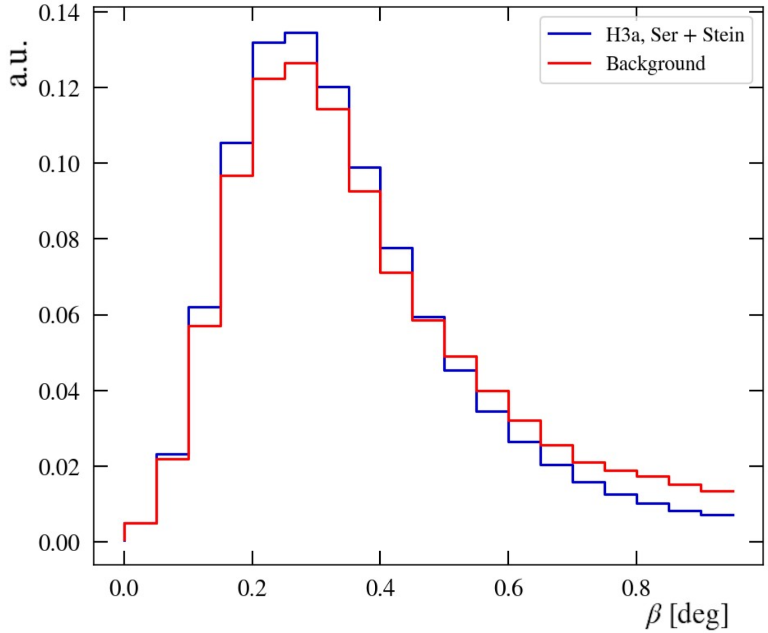
PDFs







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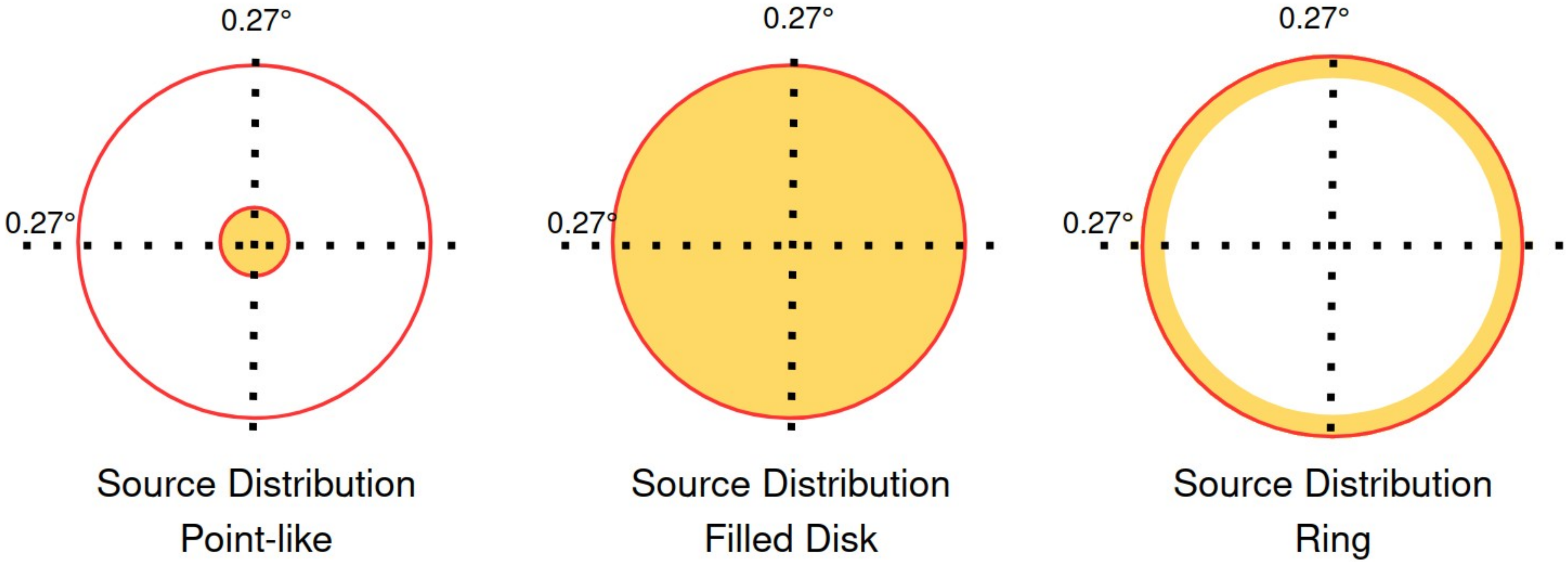
Source shapes



Results in numbers

Λ	β [deg]	θ_{zenith} [deg]	n_{90}^{Point}	n_{90}^{Ring}	n_{90}^{Disk}	$\bar{n}_{\text{sig}}^{\text{theor}}$	$C_{90} = \frac{n_{90}^{\text{Point}}}{\bar{n}_{\text{sig}}^{\text{theor}}}$	Total events
-5.2	1.0	90	2.70	3.45	2.80	0.37	7.4	7071

Table 1. Sensitivity (n_{90}), expected signal from model ($\bar{n}_{\text{sig}}^{\text{theor}}$), scaling factor C_{90} and total number of events for the final cuts. Period from 2008 to 2018 (3022 days of livetime). The percentage of expected signal falling inside the RoI is about 99.6%.

Model	Sun Shape	$n_{\text{sig, sens}}^{90\%\text{ CL}}$	$n_{\text{sig, up-lim}}^{90\%\text{ CL}}$	*p-val*
H3a-Ser+Stein [12, 33]	Point-like	2.70	3.15	0.41
	Filled disk	2.80	3.25	0.43
	Ring-shaped	3.45	3.45	0.50

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