Search for correlations of high-energy neutrinos and ultra-high energy cosmic rays

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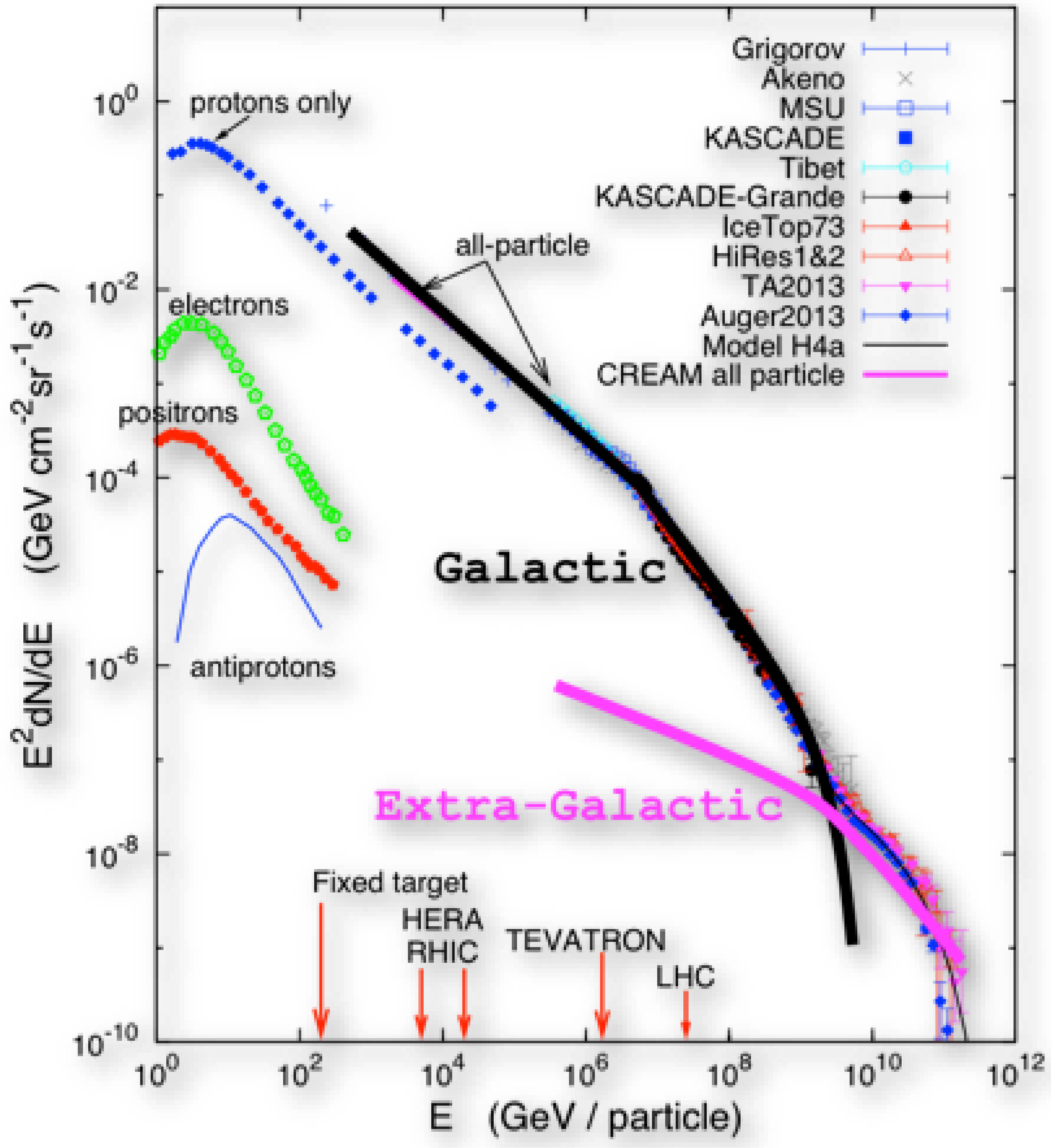
Outline

- Neutrinos as a probe of UHECR origin
- Detectors and data samples
- Strategy and results of three UHECR-neutrino correlation analyses
    - **UHECR-neutrino cross-correlation analysis**
    - **Neutrino-stacking correlation analysis with UHECRs**
    - **UHECR-stacking correlation analysis with neutrinos**
- Summary and conclusions

Neutrinos as a probe of UHECR origin

- **Galactic accelerators** (as SNRs) most likely sources for **cosmic rays (CRs) below 10^{15} eV** [1]
- **Sources of UHECRs (E > 10^{18} eV)** most probably of **extra-galactic origin**



Neutrinos as a probe of UHECR origin

[1] Int. J. Mod. Phys. D23 (2014) 1430013
[2] Science 357 (2017) 1266–1270

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  - AGNs, γ-ray bursts, magnetized and fast-spinning neutron stars among most promising sources
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- Inelastic collisions of **UHECRs** with radiation or gas **produce gamma-rays and neutrinos**, e.g.:

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

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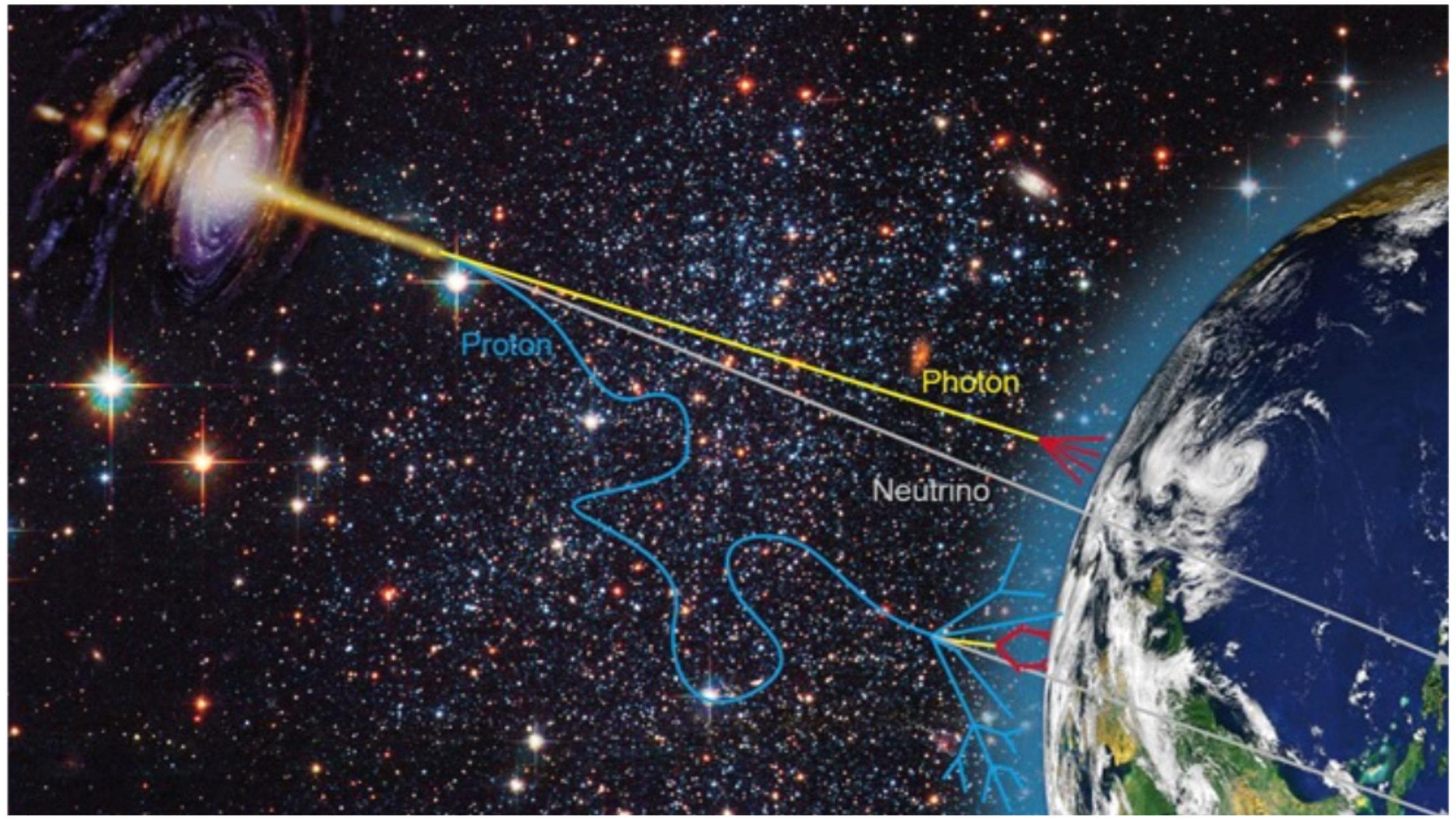
- **Neutrinos** are **excellent probes** to investigate the **origin of UHECRs** and acceleration mechanisms due to:
  - **tiny** interaction cross section
  - **insensitivity** to (inter-)galactic **magnetic fields**



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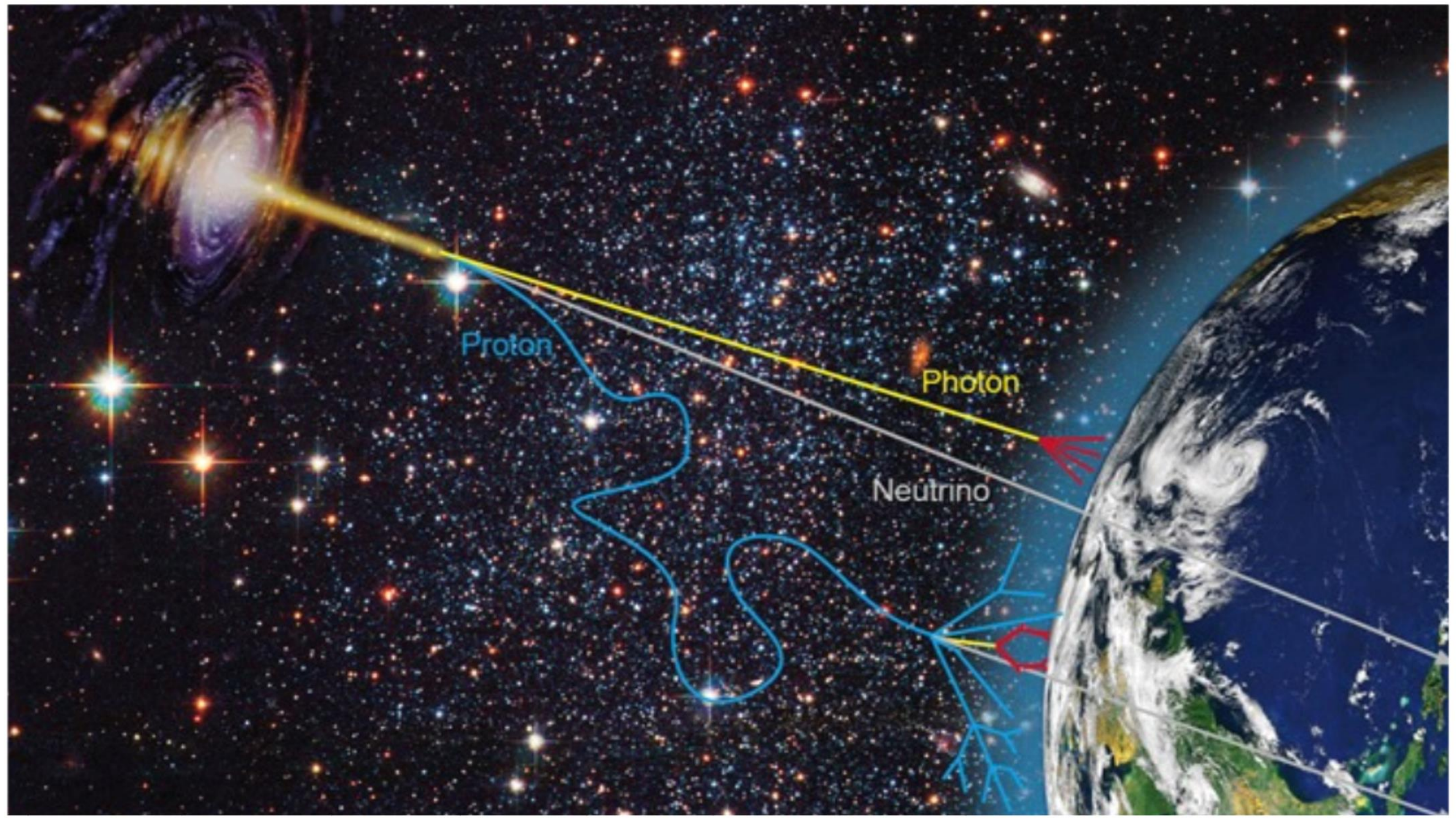
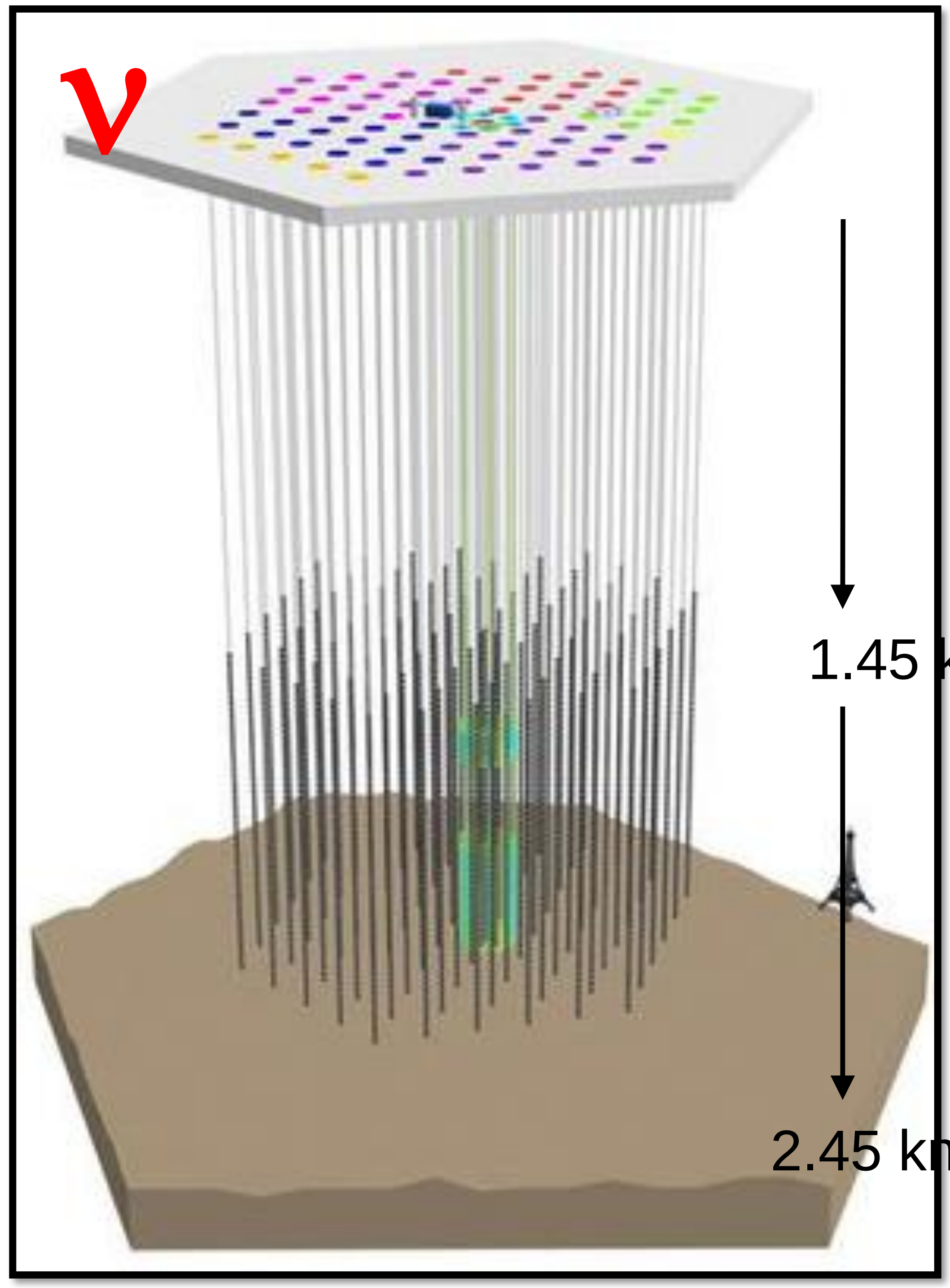
- **Neutrinos** are **excellent probes** to investigate the **origin of UHECRs** and acceleration mechanisms due to:
  - **tiny** interaction cross section
  - **insensitivity** to (inter-)galactic **magnetic fields**
- **Three analyses** searching for a **common origin of UHECRs and high-energy neutrinos** will be presented
- Joint analyses by the IceCube, ANTARES, Pierre Auger and Telescope Array (TA) Collaborations



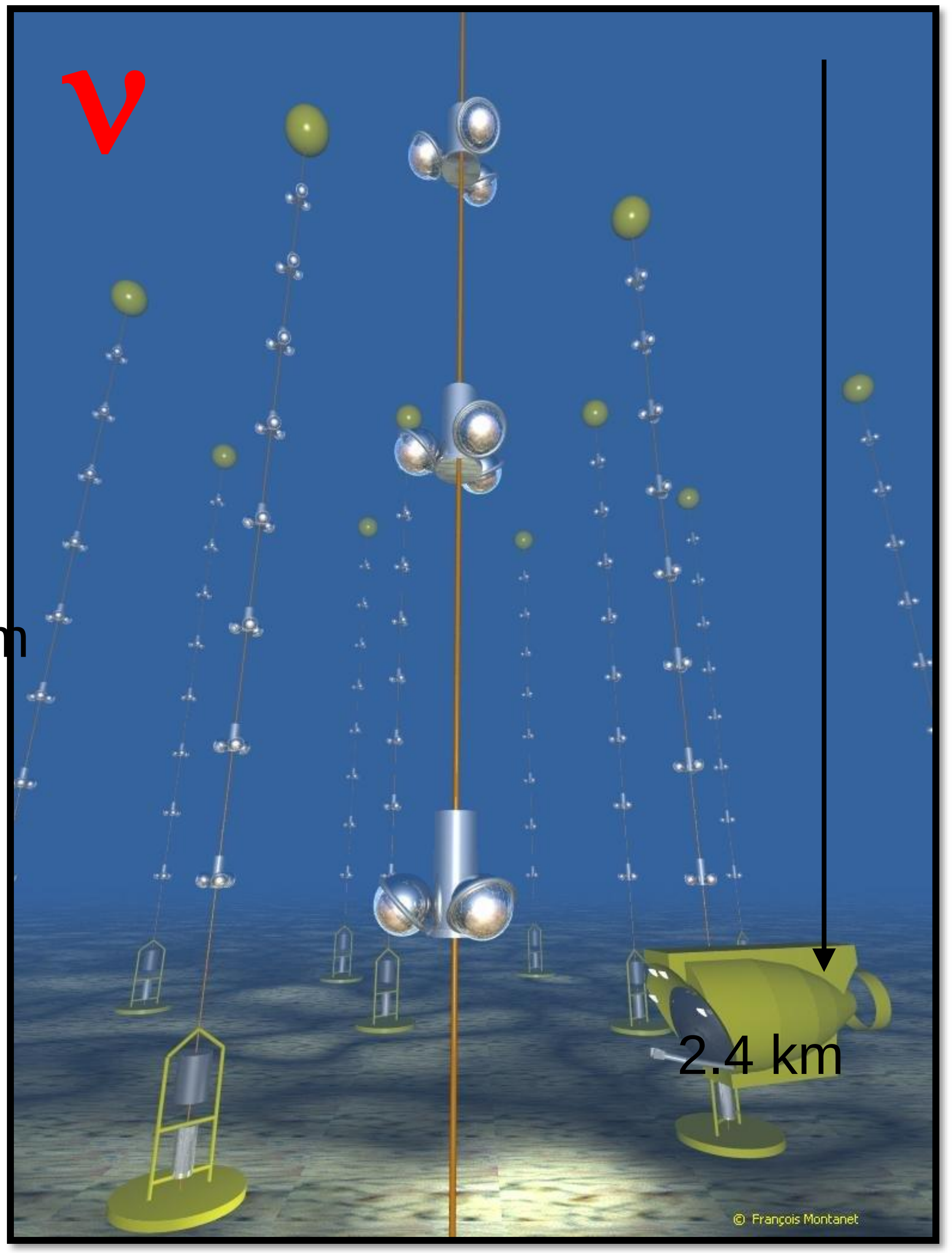
Detectors

IceCube



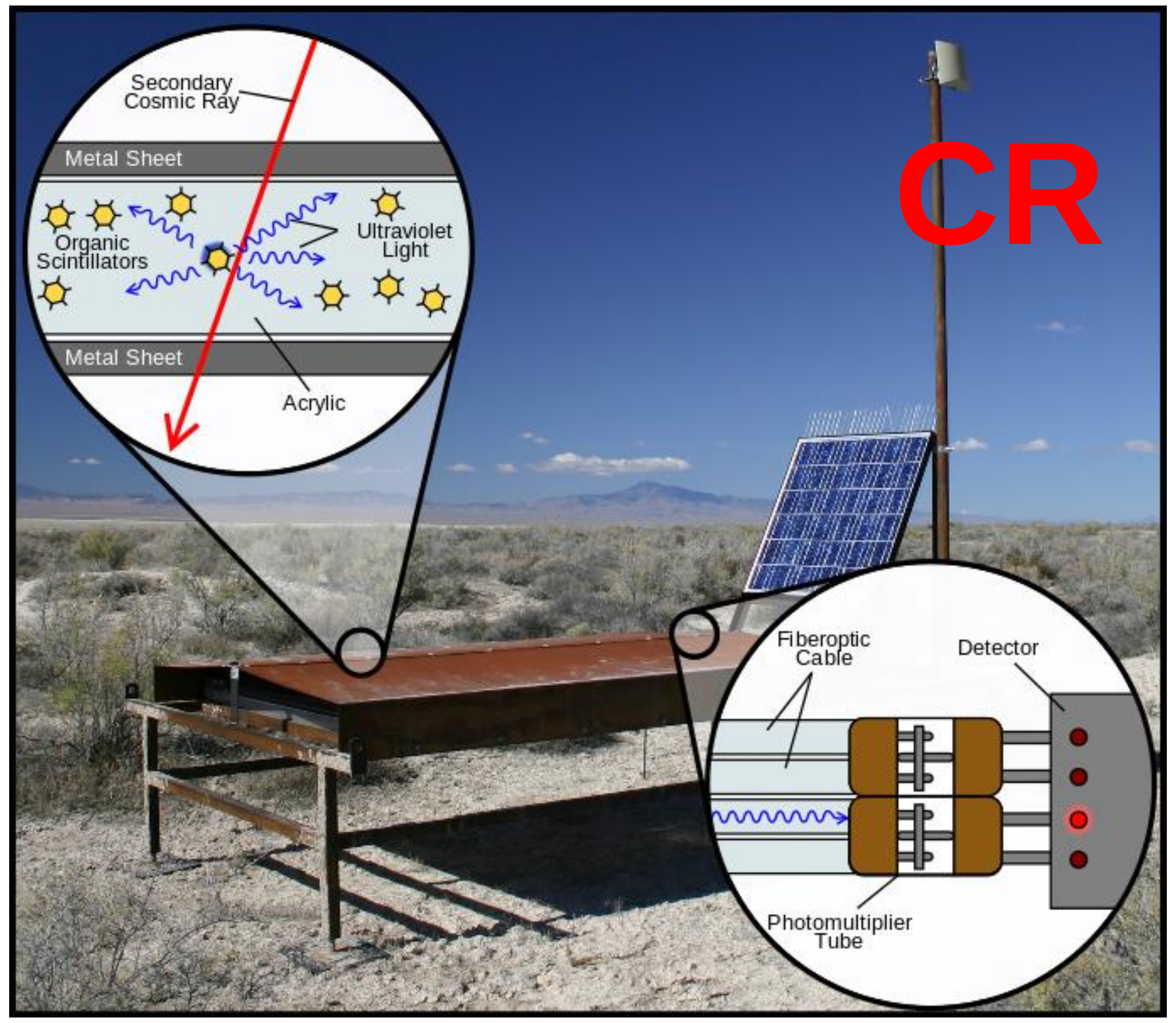
- Location: South Pole
- 86 string with 60 Digital Optical Modules each

ANTARES



- Location: Mediterranean Sea
- 12 strings anchored at sea floor
- 885 optical modules

Telescope Array



- Location: Utah desert
- Surface detector array (SD, 507 scintillator detectors)
- 3 fluorescence detector stations (FD, equipped with telescopes)
- Exposure: Northern hemisphere up to -15°

Pierre Auger

- Location: Argentina
- SD (1660 water-Cherenkov detectors) and FD arrays (27 telescopes at five peripheral buildings)
- Exposure: from -90° to +45° in declination

Data samples

UHECRs:

- TA: **143 events** (E > 57 EeV, zenith angle ≤ 80°), from May 2008 to May 2017 [1]
- Auger: **324 events** (E > 52 EeV, zenith angle ≤ 80°), recorded with the SD from Jan. 2004 to Apr. 2017 [2]
- Rescaling applied to event energies to match TA and Auger fluxes (-14% and 14% respectively) [3]

Neutrinos:

(Cross-correlation and Neutrino-Stacking Analyses)

- IceCube:

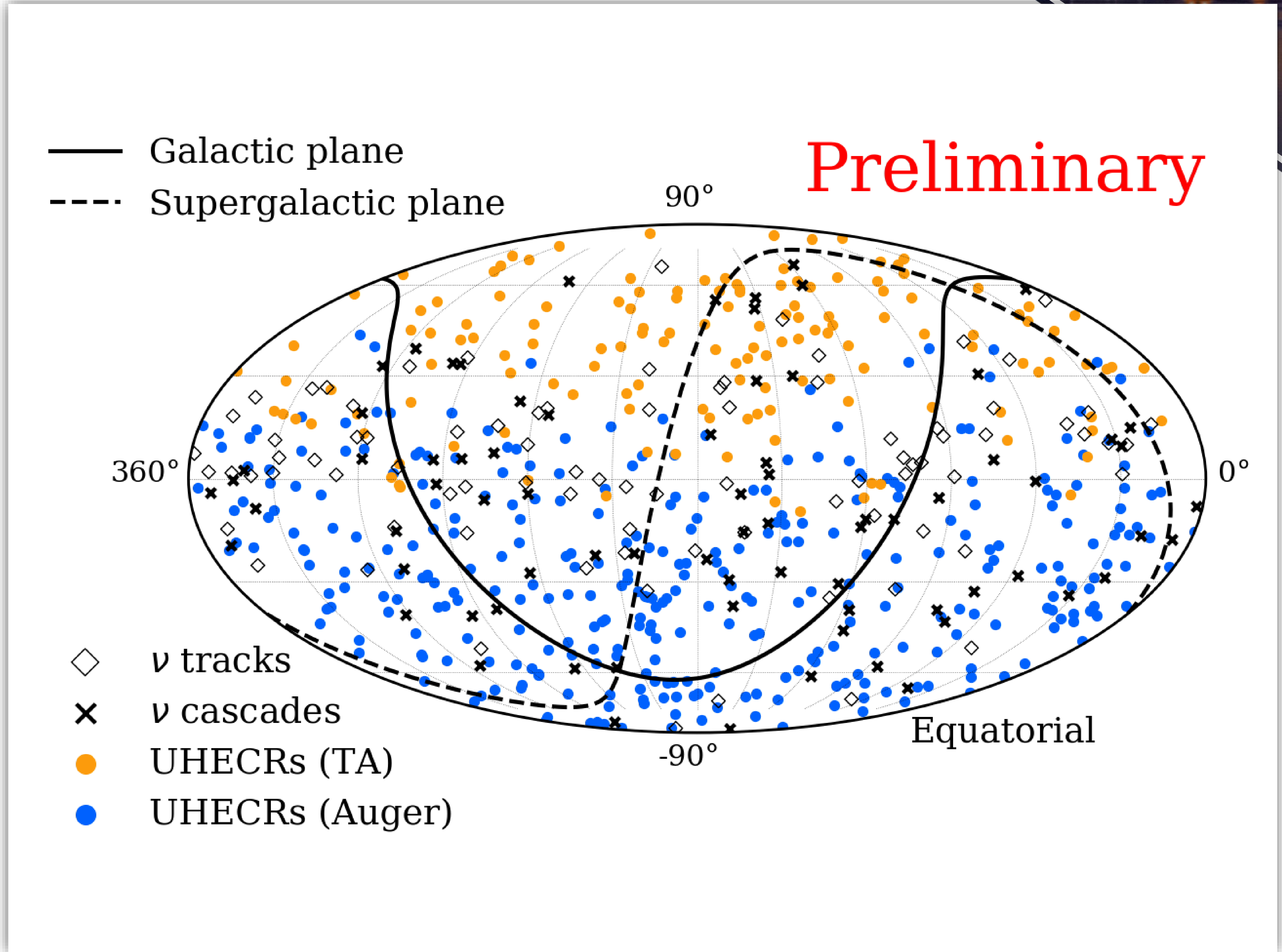
(i) 7.5-year preliminary sample (6 years new reco, last 1.5 years old reco) of High-Energy Starting Events (tracks and cascades) [4]

(ii) 9-year sample of Extremely High-Energy event alerts (tracks) [5]

(iii) 7-year sample of through-going muons induced by charged-current interactions of ν_μ candidates from the Northern sky (tracks) [6]

→ **81 tracks and 76 cascades in total**

- ANTARES: 9-year point-source sample (→ **3 tracks**) [7]



[1] Astrophys. J. Letters 768 (May, 2013) L1
[2] Astrophys.J. 804 (2015) no.1, 15
[3] EPJ Web Conf.210(2019) 01005
[4] N. Wandkowsky, Neutrino 2018
[5] Phys. Rev. D98 (2018) 062003
[6] PoS(ICRC2017)1005 (2018)
[7] Phys. Rev. D96 (2017) 082001

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Neutrinos:

(UHECR-Stacking Analyses)

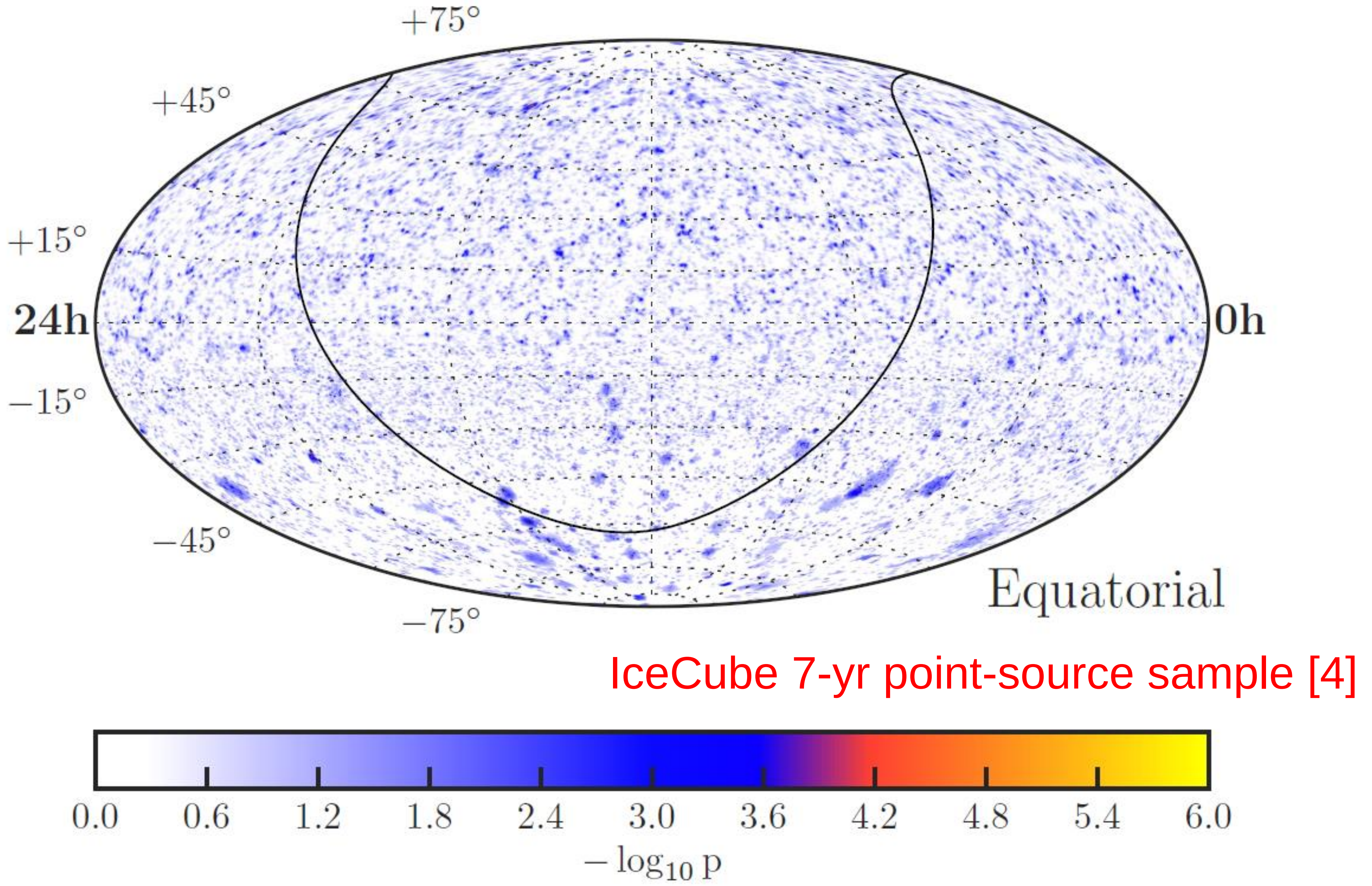
- **IceCube:**

(i) 7-year neutrino point-source sample [4]

(ii) latest 3.5 years of the gamma-ray follow-up sample [5]

→ **1.4M events in total**, between 2008 and 2018

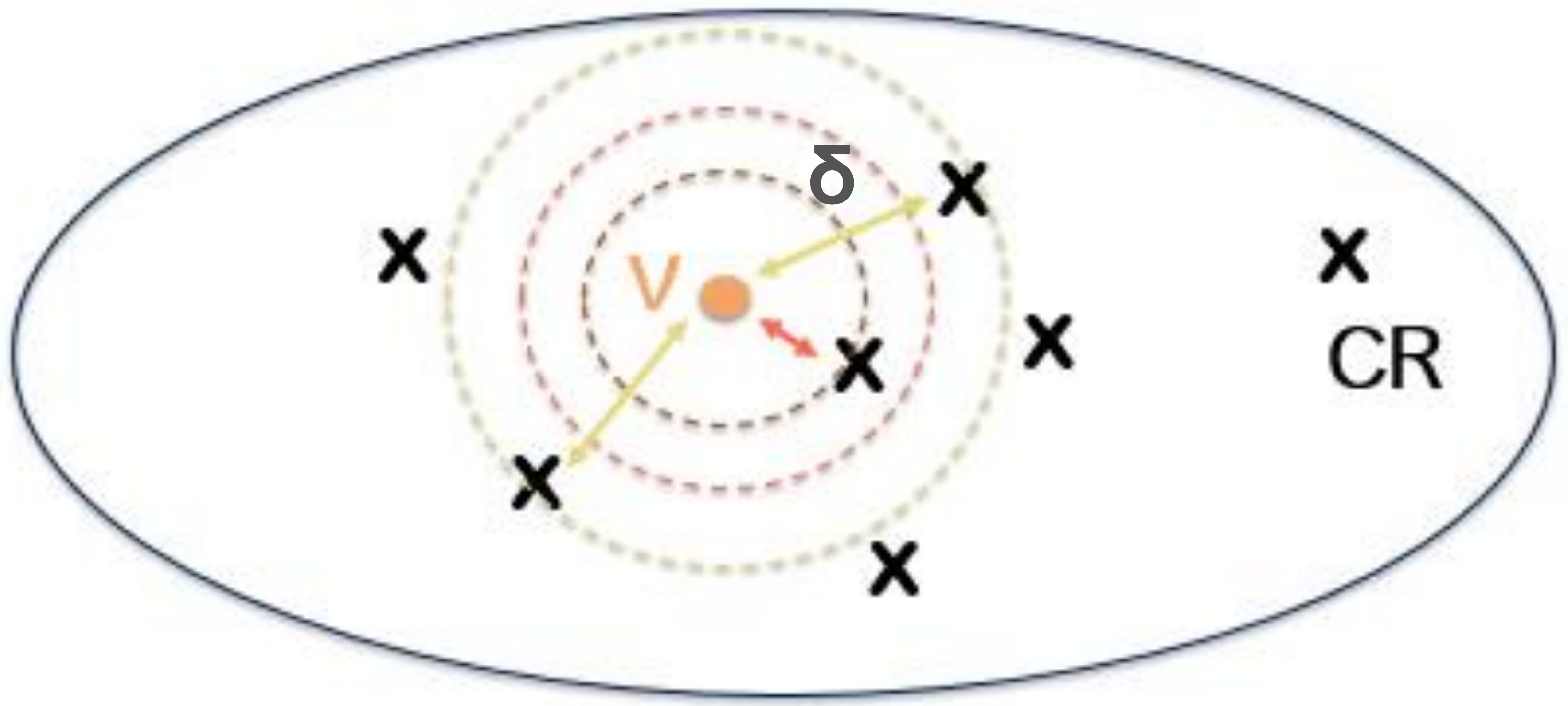
- **ANTARES:** 11-year point-source sample including events until 2017 [6]



IceCube 7-yr point-source sample [4]

[1] Astrophys. J. Letters 768 (May, 2013) L1
[2] Astrophys.J. 804 (2015) no.1, 15
[3] EPJ Web Conf.210(2019) 01005
[4] Astrophys. J. 835 (2017) 151
[5] Science 361 (2018) 147–151
[6] Astrophys. J. 863 (2018) L30

UHECR-neutrino cross-correlation analysis



1° < δ < 30°, in 1° steps

U. Giaccari, G. Golup

Observable: $n_{obs} / \langle n_{exp} \rangle - 1$

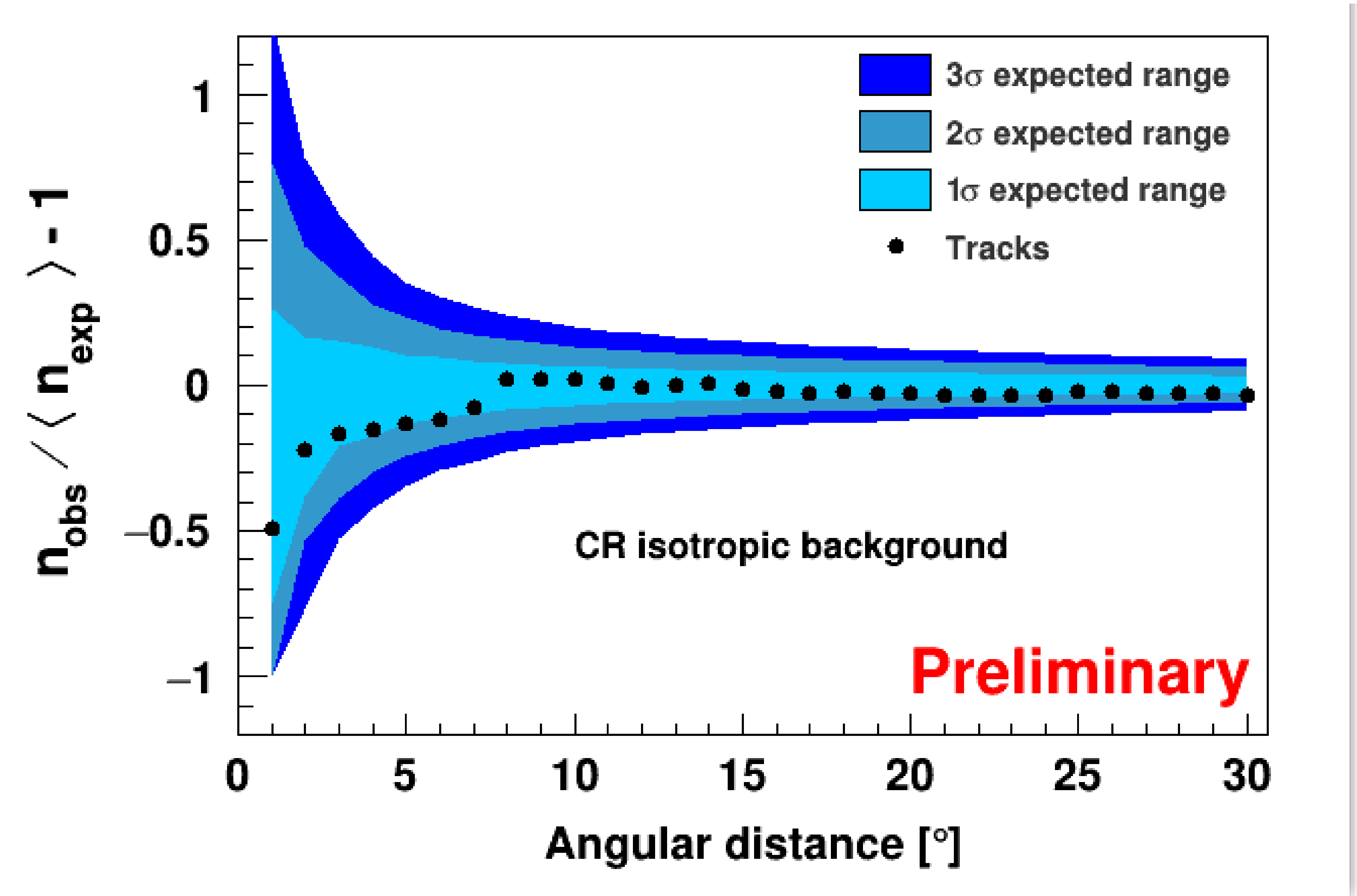
- n_{obs} = number of UHECR-neutrino pairs within angular distance δ
- n_{exp} = number of UHECR-neutrino pairs within same distance, expected in the null-hypothesis scenario

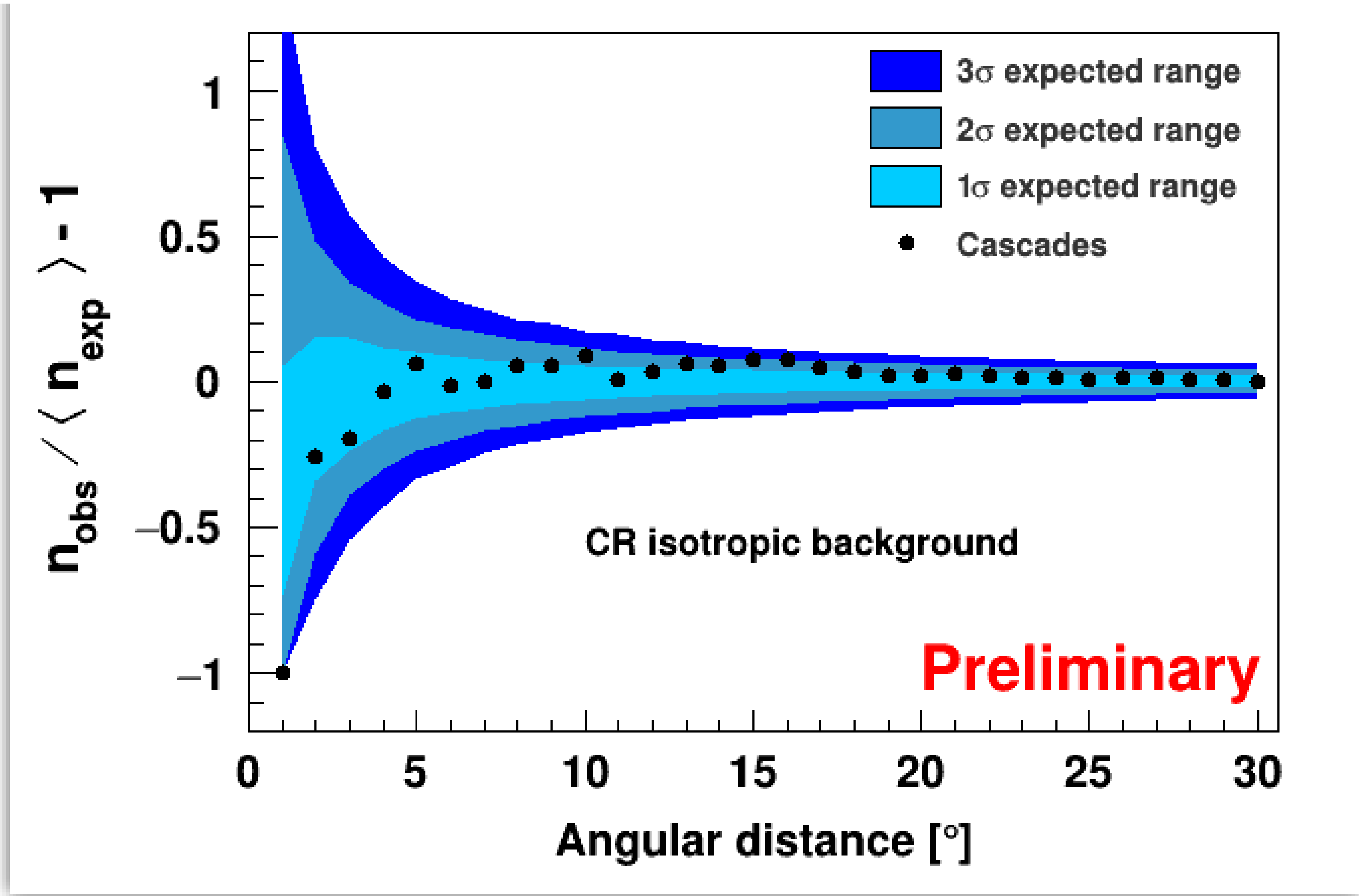
- Two null-hypotheses investigated:
  - i. isotropic distribution of UHECRs
  - ii. isotropic distribution of neutrinos
- Angle that maximizes n_{obs} / n_{exp} provides local p-value
- Final global p-value obtained by trial correcting local p-value for the number of scanned angles
- Track- and shower-like events analyzed separately

  → 4 p-values reported

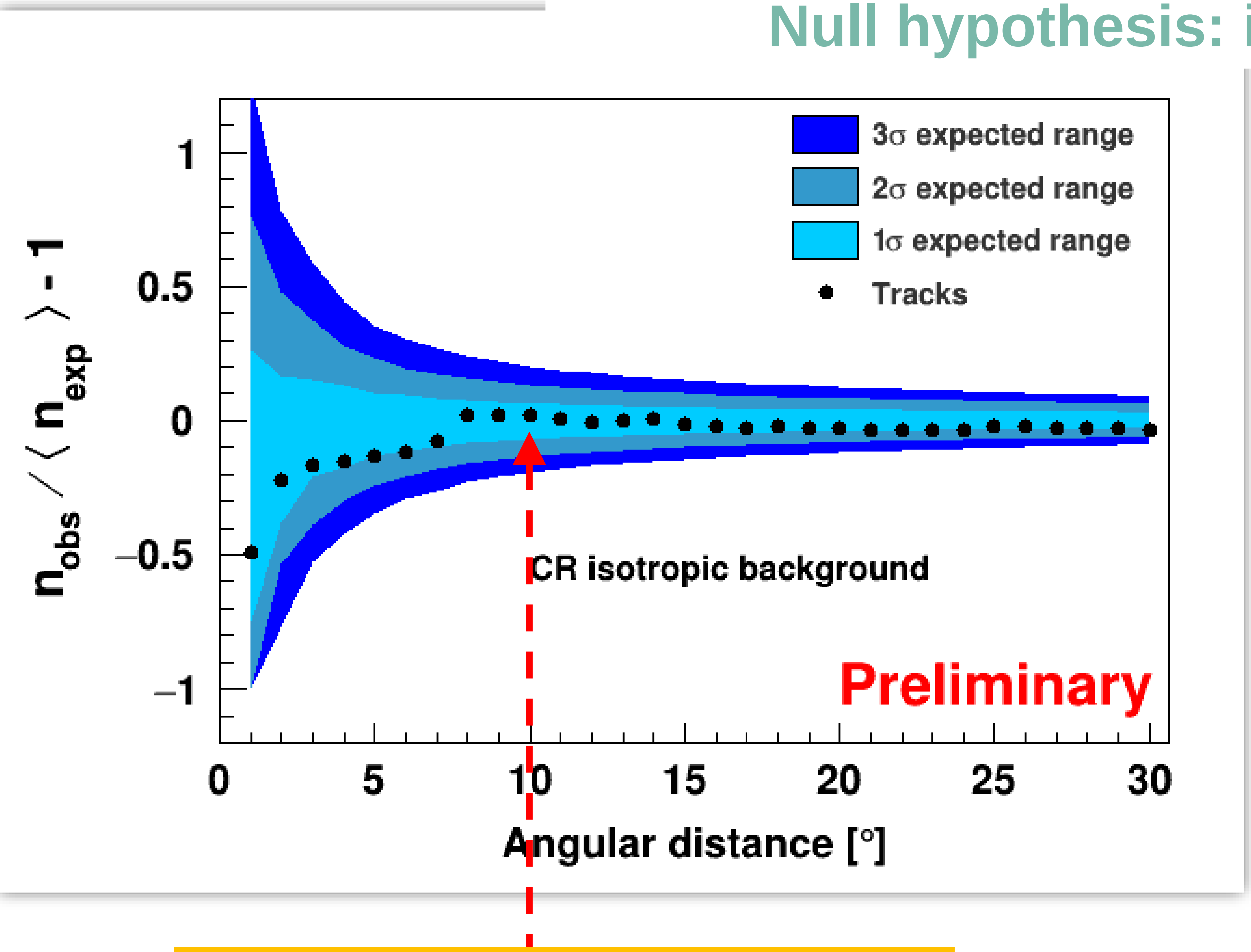
Results: UHECR-neutrino cross-correlation analysis

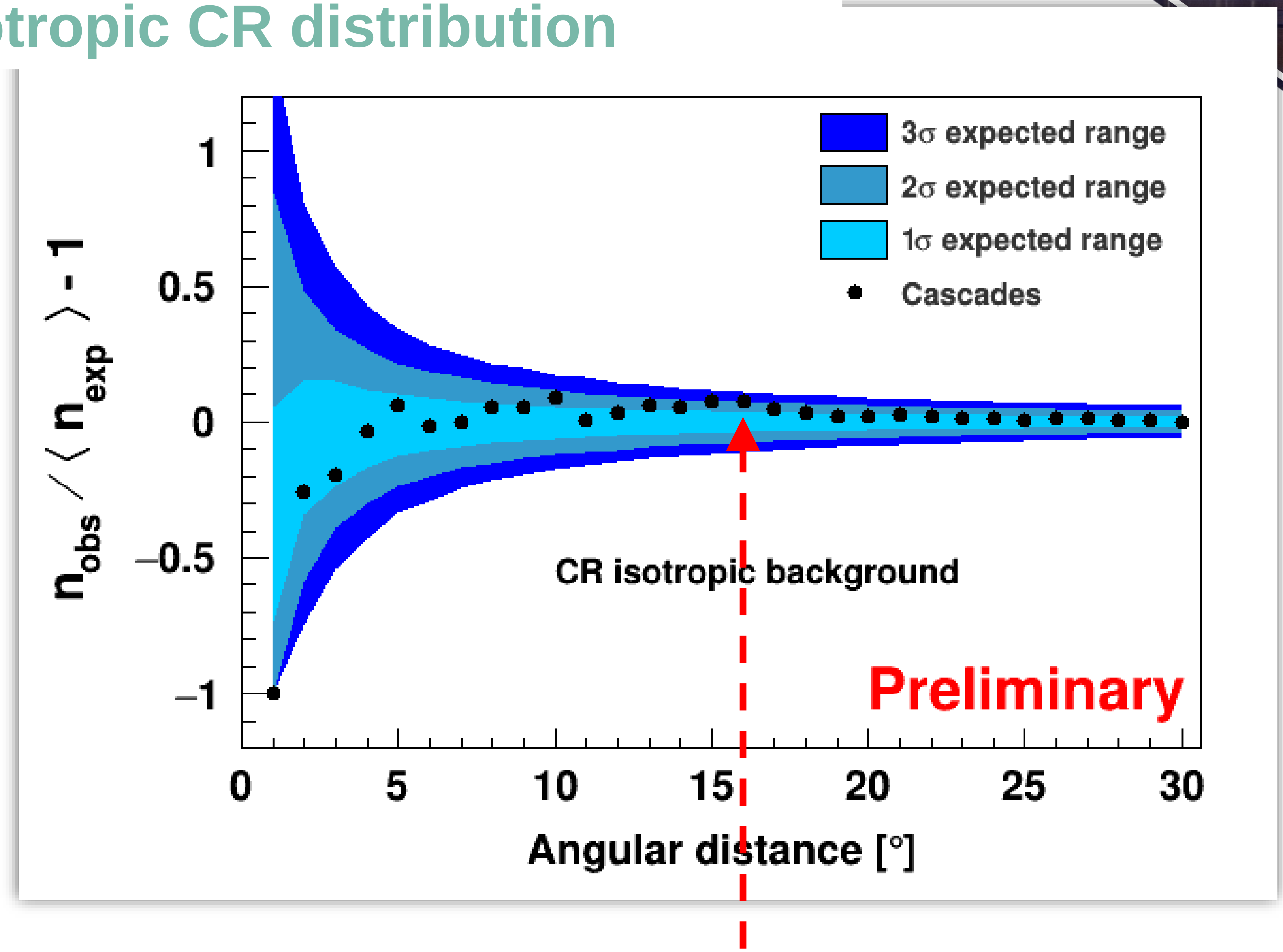
Null hypothesis: isotropic CR distribution





Results: UHECR-neutrino cross-correlation analysis



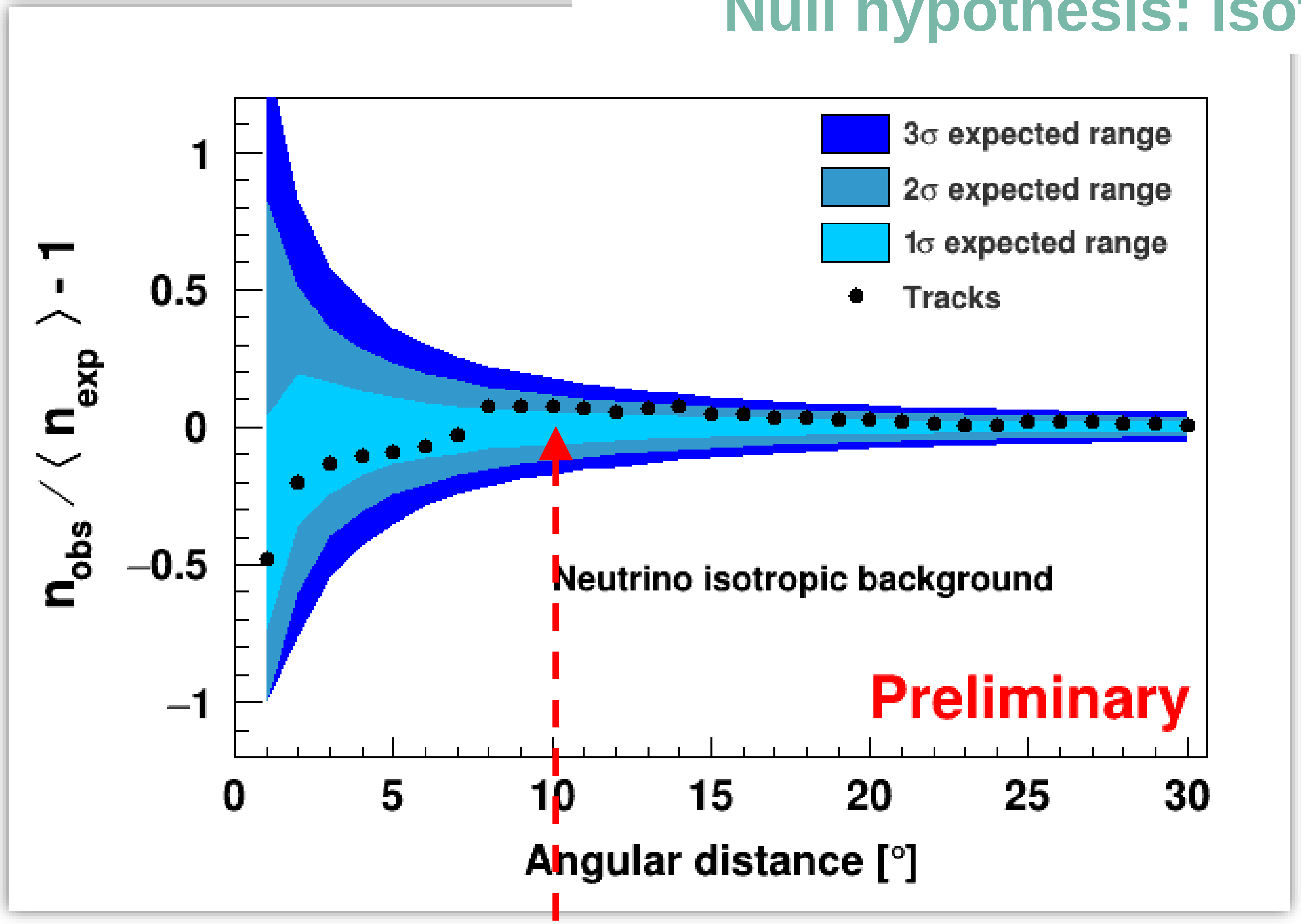


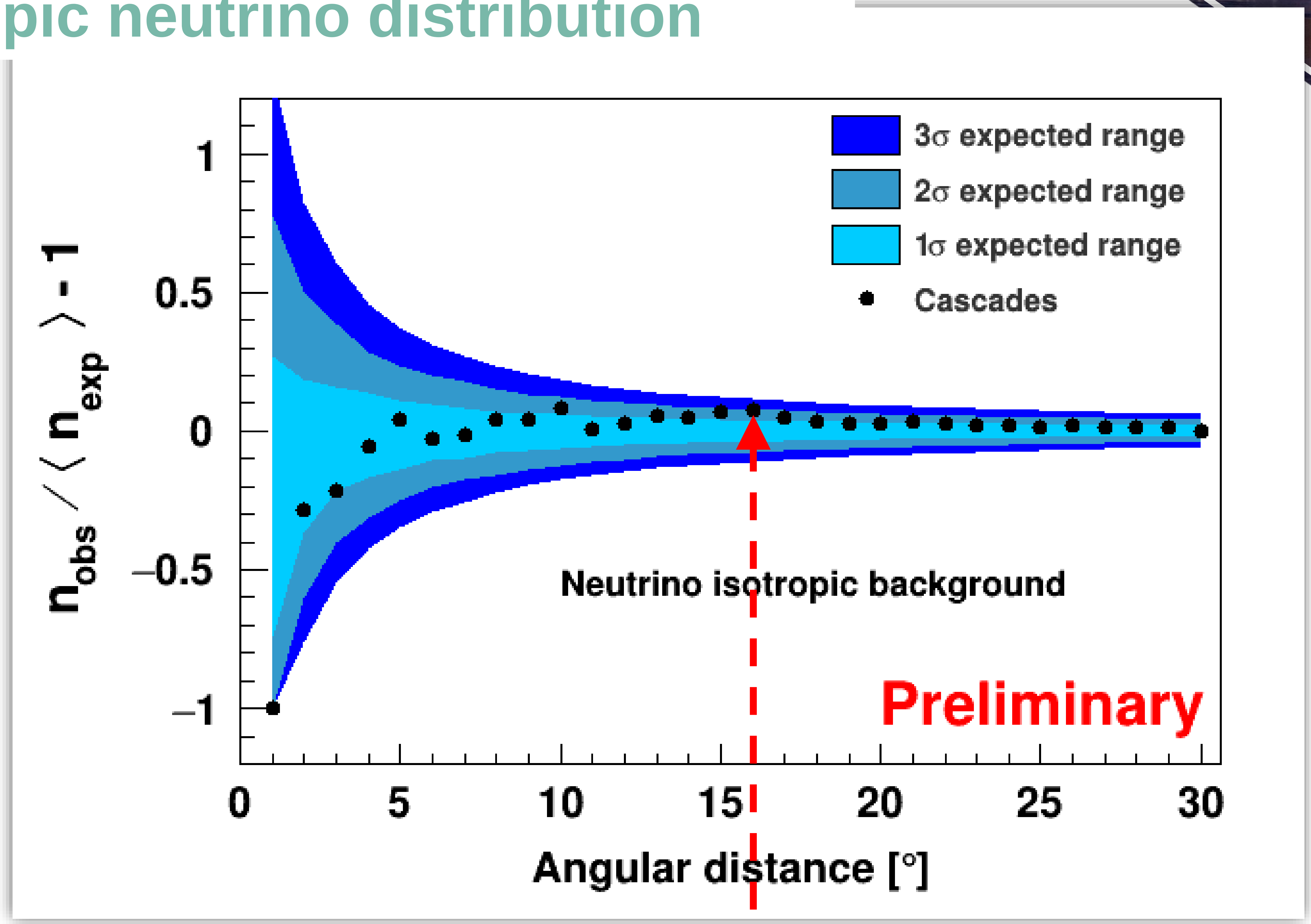
- 303 pairs observed at 10°
- Post-trial p-value = 0.84

- 763 pairs observed at 16°
- Post-trial p-value = 0.18

Results: UHECR-neutrino cross-correlation analysis

Null hypothesis: isotropic neutrino distribution



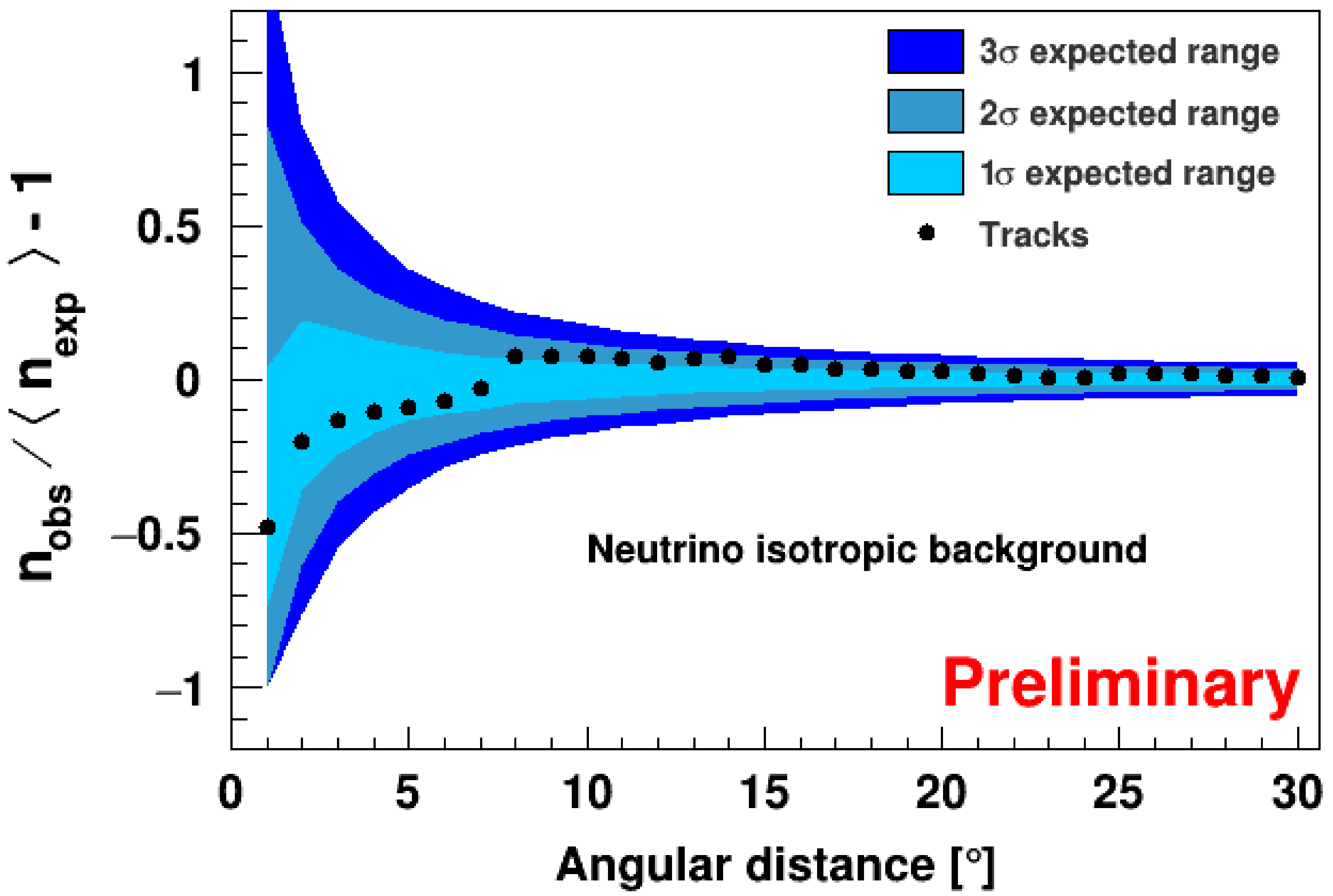


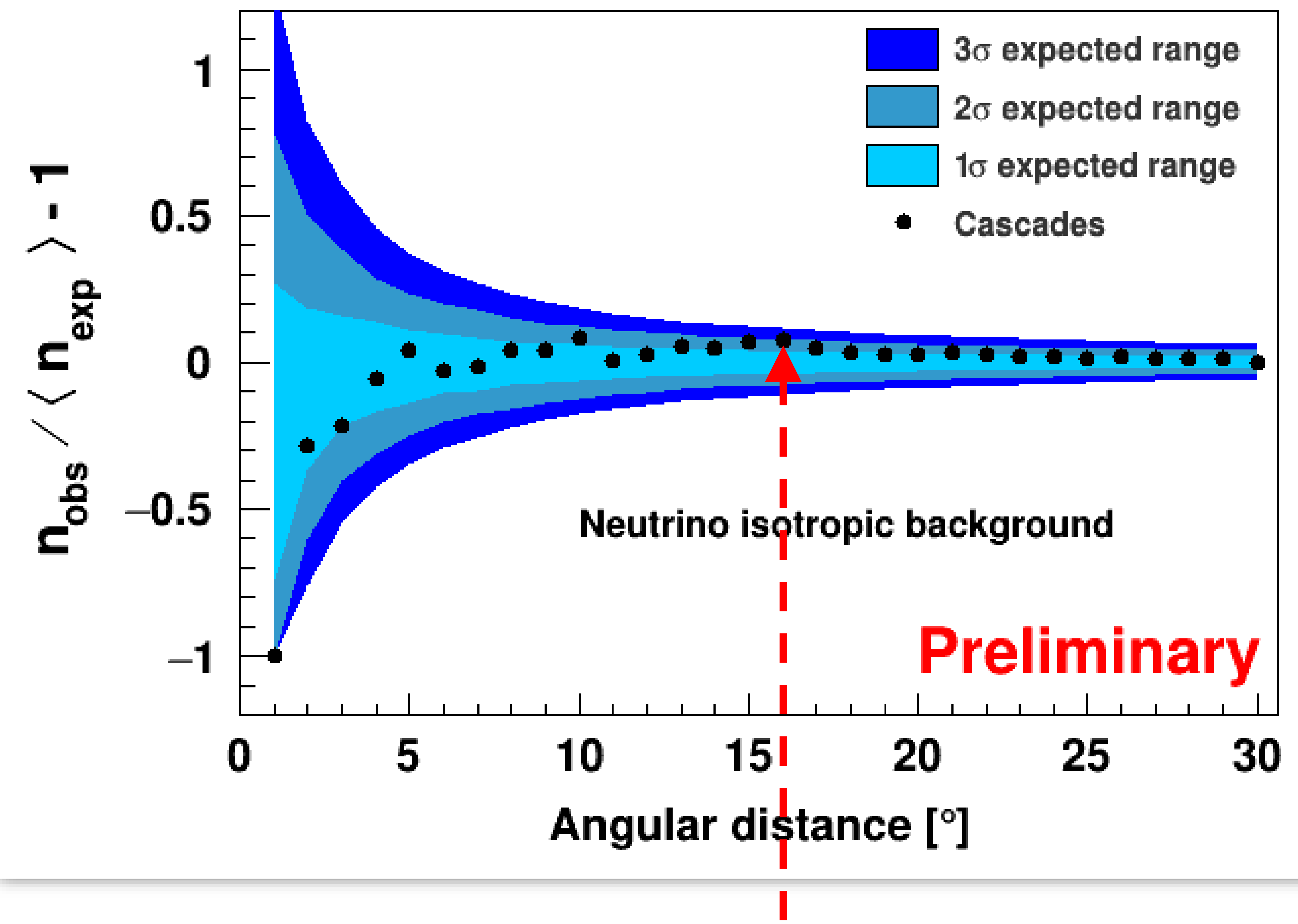
- 582 pairs observed at 14°
- Post-trial p-value = 0.23

- 763 pairs observed at 16°
- Post-trial p-value = 0.15

Results: UHECR-neutrino cross-correlation analysis

Null hypothesis: isotropic neutrino distribution





- Result compatible with background
- Most significant result from previous publications [1]: post-trial p-value at 22° for cascades: 5.0×10^{-4} (isotropic CR background)

- 763 pairs observed at 16°
- Post-trial p-value = 0.15

[1] JCAP 1601 (2016) 01 037

Neutrino-stacking correlation analysis with UHECRs

- Method: stacked unbinned likelihood:

C. Alispach, A. Barbano, T. Montaruli

$$\ln \mathscr{L}(n_s) = \sum_{i=1}^{N_{\text{Auger}}} \ln\left(\frac{n_s}{N_{\text{CR}}} S^i_{\text{Auger}} + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B^i_{\text{Auger}}\right) + \sum_{i=1}^{N_{\text{TA}}} \ln\left(\frac{n_s}{N_{\text{CR}}} S^i_{\text{TA}} + \frac{N_{\text{CR}} - n_s}{N_{\text{CR}}} B^i_{\text{TA}}\right),$$

n_s = number of UHECR signal event (free parameter)
N_{CR} = total number of CR events

$S^i_{\text{CR experiment}}$ = signal PDF
$B^i_{\text{CR experiment}}$ = background PDF

- Signal PDF:

$$S^i_{\text{CR observatory}}(\vec{r}_i, E_i) = \boxed{R_{\text{CR observatory}}(\delta_i)} \sum_{j=1}^{\boxed{N_{\text{src}}}} \boxed{S_j(\vec{r}_i, \sigma(E_i))}$$

Relative exposure at given event declination

N_{src}: number of stacked sources

value of the normalized directional likelihood map for the j-th source (i.e. neutrino) taken at r_i and smeared with a Gaussian with standard deviation $\sigma(E_i)$

- σ accounts for angular resolution of the CR observatory and magnetic deflection
- Background PDF: normalized exposure of the CR observatory

Neutrino-stacking correlation analysis with UHECRs

C. Alispach, A. Barbano, T. Montaruli

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n_s = number of UHECR signal event (free parameter)
N_{CR} = total number of CR events

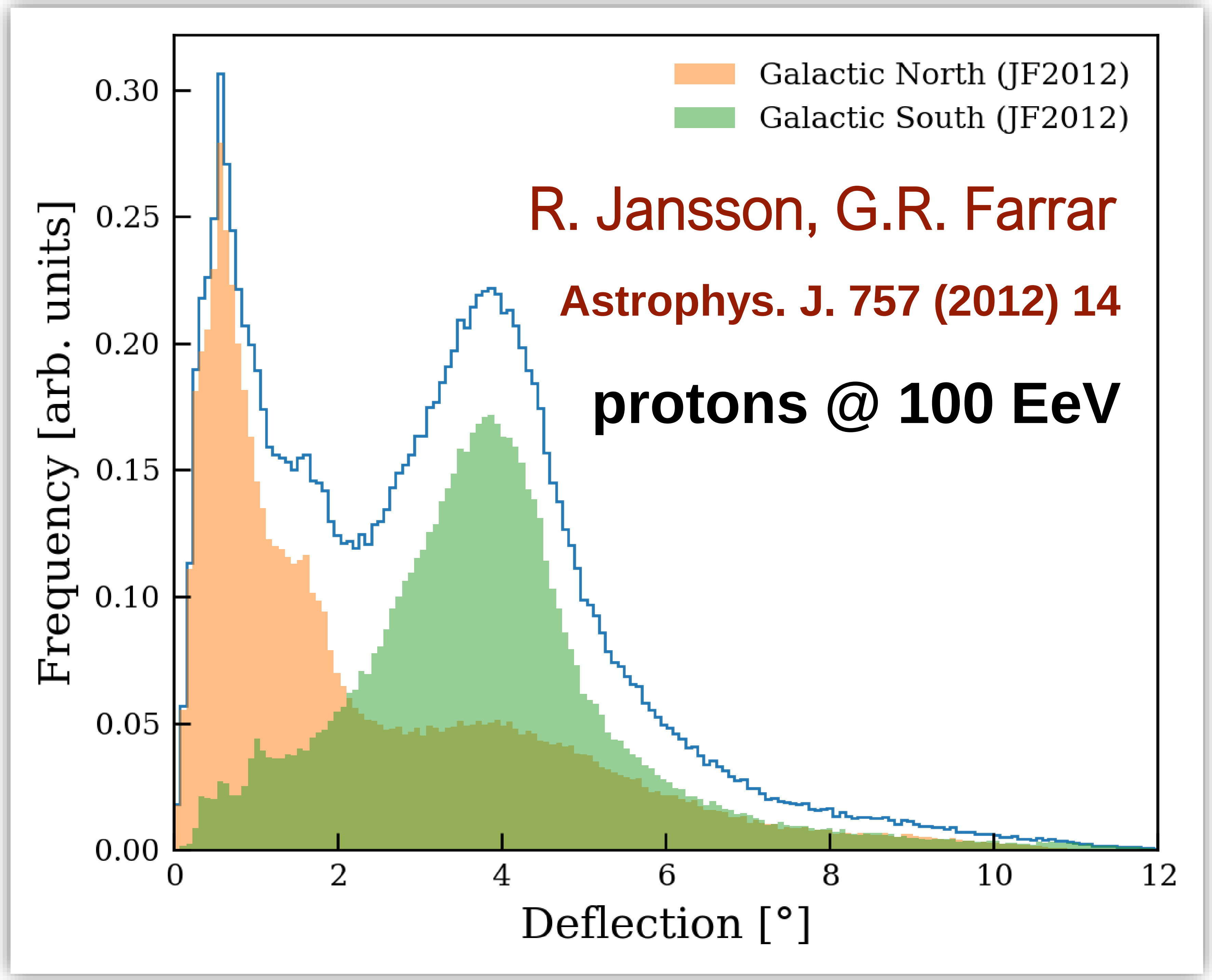
$S^i_{\text{CR experiment}}$ = signal PDF
$B^i_{\text{CR experiment}}$ = background PDF

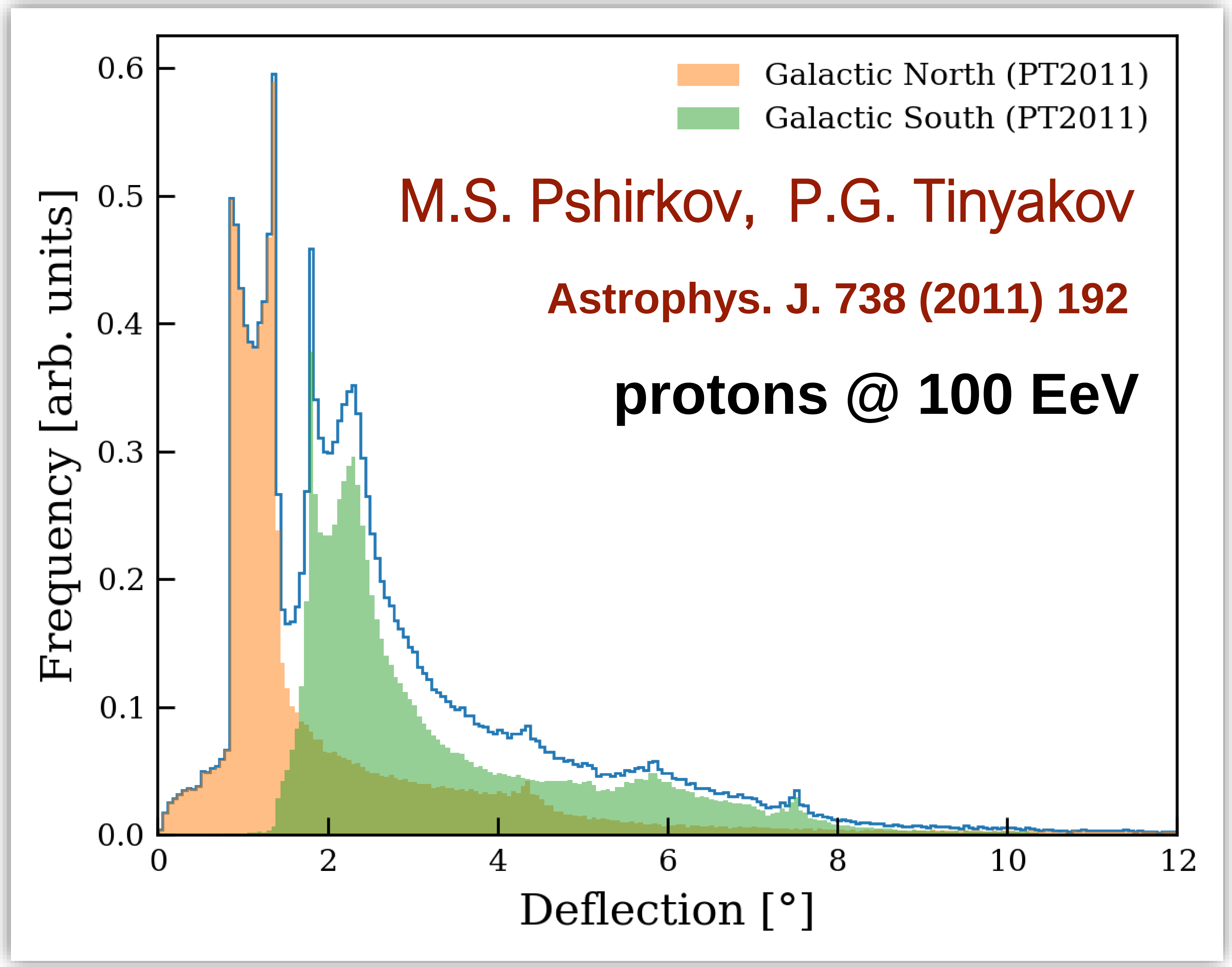
- Test statistic (TS) with one degree of freedom (n_s) is built:

$$\mathrm{TS} = -2\ln\left(\frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(n_s)}\right)$$

- Signal hypothesis: UHECRs events spatially correlated with neutrino events
- Background hypothesis: UHECR events distributed isotropically over the whole sky

Neutrino-stacking correlation analysis with UHECRs





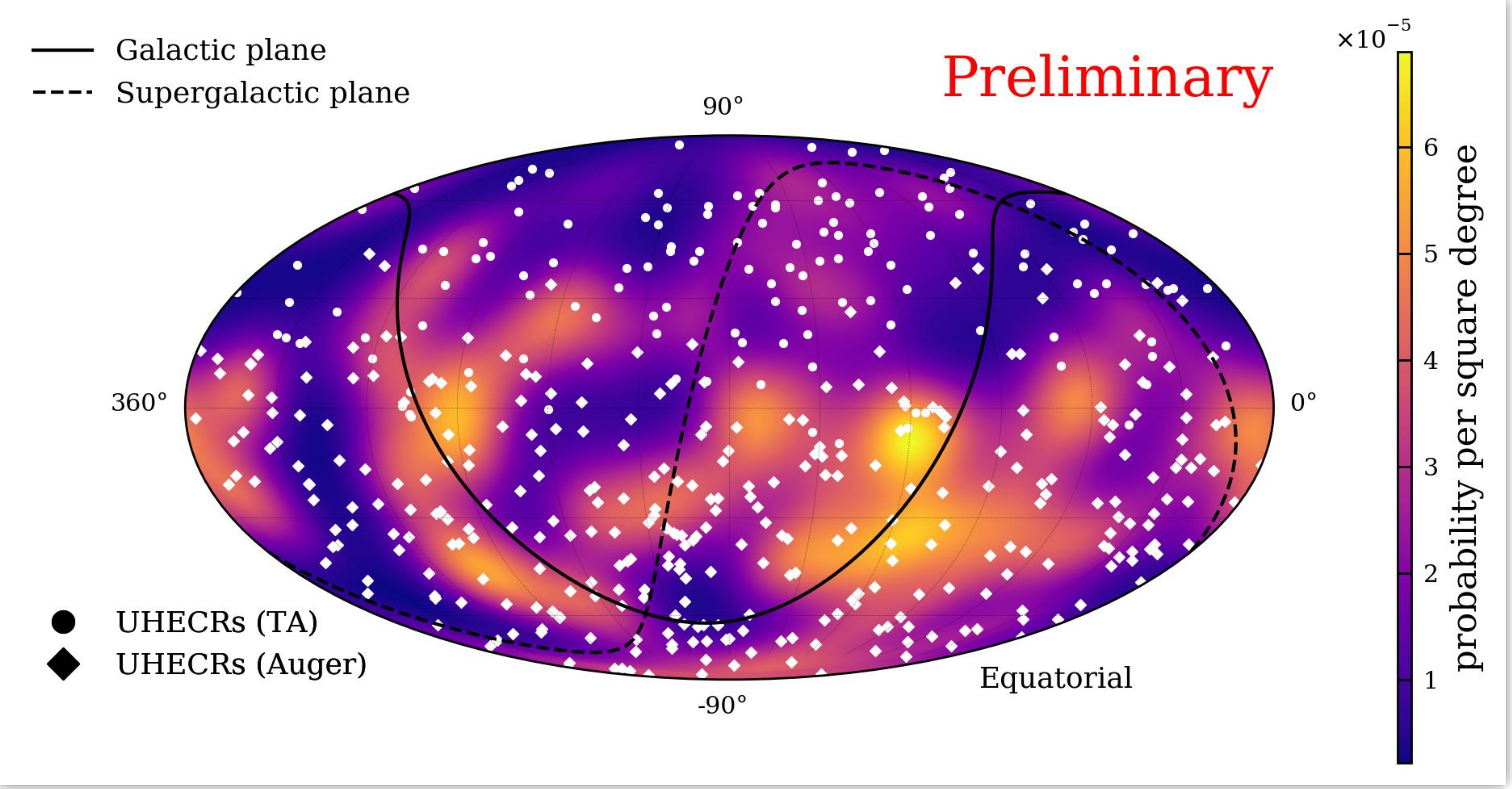
- Different deflection values, for protons @ 100 EeV, in
  (i) Galactic North (b>0°), D_0 = 2.4°
  (ii) Galactic South (b<0°), D_0 = 3.7°
- Rescaled for CR energy and combined in one p-value: $\sigma_{\mathrm{MD}}(E) = D \times 100\,\mathrm{EeV}/E$
- Increased by factor 2 and 3 to account for heavier CR composition and/or larger magnetic fields

Results: Neutrino-stacking correlation analysis with UHECRs

D	(2.4°, 3.7°)	(4.8°,7.4°)	(7.2°,11.1°)
p-values (tracks)	underfluctuation	underfluctuation	underfluctuation
p-values (cascades)	underfluctuation	0.41	0.29

0.90 post-trial

- Result compatible with background
- Most significant result from previous publications [1]: post-trial p-value for cascades with $D = 6°$: 8×10^{-4}
- Right: stacked likelihood map of neutrino shower-like events and UHECR arrival directions



UHECR-stacking correlation analysis with neutrino directions

- Method: stacked unbinned likelihood:

L. Schumacher, C. Wiebusch

$$\ln \mathscr{L} = \underbrace{\sum_{S=1}^{N_{CR}}}_{\substack{\text{stacking,}\\ \text{step 3}}} \left[\underbrace{\left(\sum_{i=1}^{N_\nu} \ln \left(\frac{n_S}{N_\nu} S_i(\gamma_S, \vec{x_S}) + \left(1 - \frac{n_S}{N_\nu}\right) B_i(\vec{x_S}) \right) \right)}_{\substack{\text{neutrino data,}\\ \text{step 1}}} - \underbrace{\frac{(\vec{x_S} - \vec{x_{CR,S}})^2}{2\sigma(E_{CR,S})^2}}_{\substack{\text{UHECR data,}\\ \text{step 2}}} \right]$$

n_s = number of neutrino signal event (free parameter)
N_ν = total number of neutrino events
x_s = position of neutrino source
γ_s = spectrum index of neutrino source (free parameter)

$S^i_{\text{CR experiment}}$ = signal PDF
$B^i_{\text{CR experiment}}$ = background PDF
$x_{CR,s}$, $E_{CR,s}$ = position, energy of the CR source
σ = deflession associated to the CR source

- Signal hypothesis: point-like neutrino sources spatially correlated with UHECR arrival directions
- Background hypothesis: neutrino events are distributed uniformly over the whole sky

UHECR-stacking correlation analysis with neutrino directions

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1. Fit neutrino signal parameters (n_S , γ_S) on grid positions x_S → TS skymap (standard point-source analysis)

n_s = number of neutrino signal event (free parameter)
N_ν = total number of neutrino events
x_s = position of neutrino source
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$S^i_{\text{CR experiment}}$ = signal PDF
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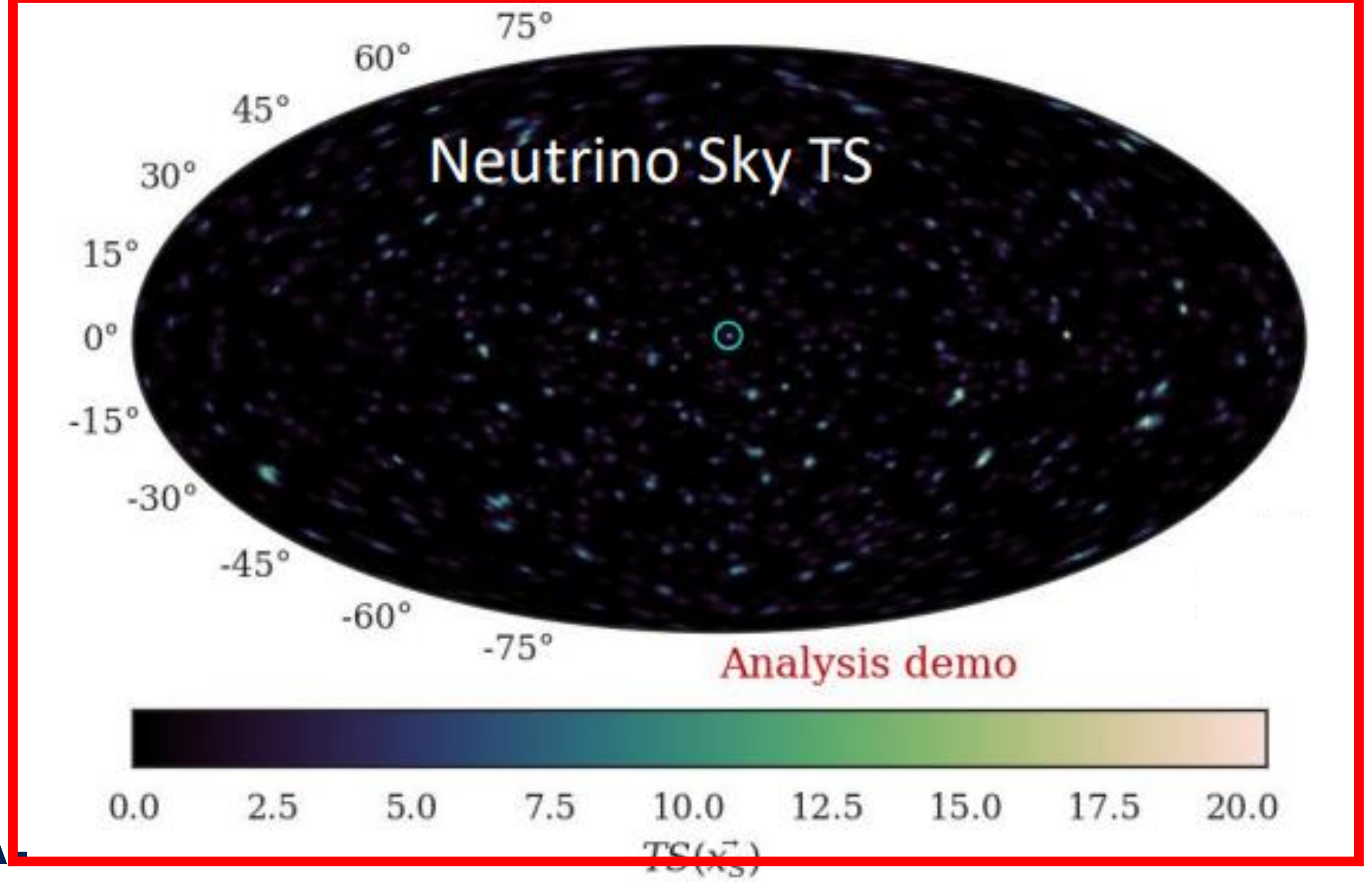

$$\mathrm{TS}(\vec{x_s}) = 2\ln\left(\mathscr{L}_{\text{step 1}}(\hat{n}_s, \hat{\gamma}_s) \,/\, \mathscr{L}_{\text{step 1}}(n_s = 0)\right)$$

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2. Add the 2 x log($CR_{\text{space prior}}$) to the TS map → selecting interesting region with prior window

n_s = number of neutrino signal event (free parameter)
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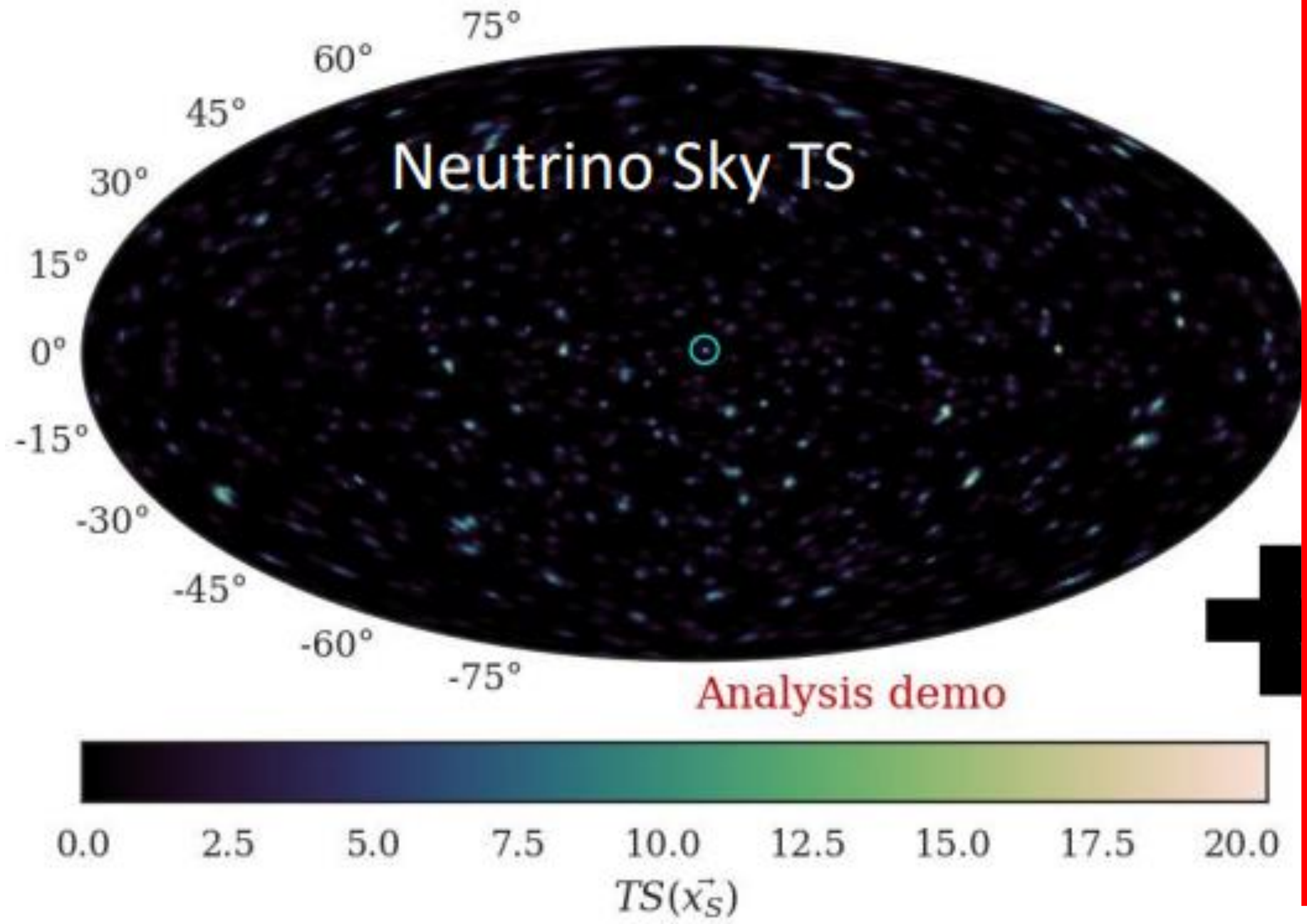

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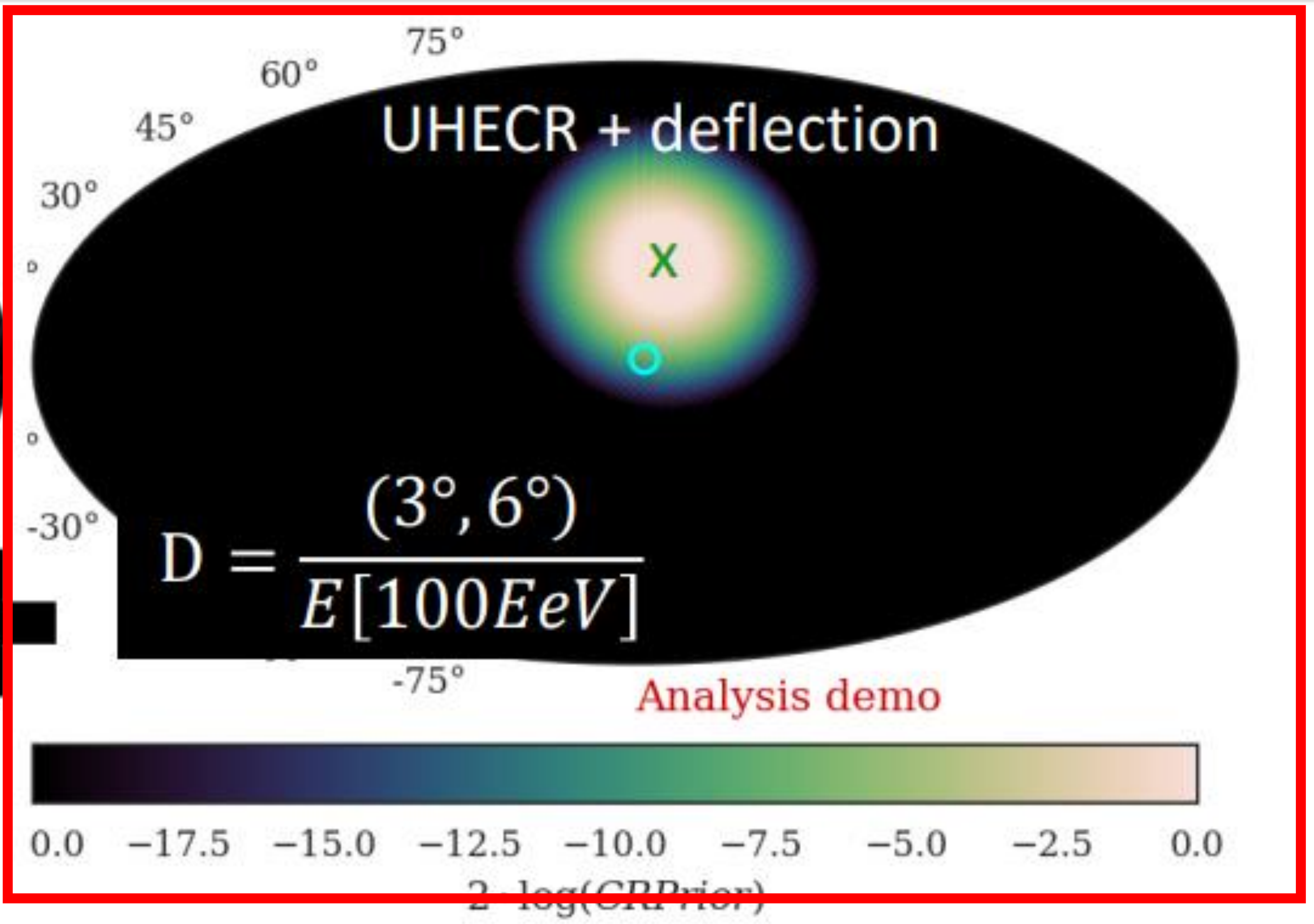

A.

UHECR-stacking correlation analysis with neutrino directions

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3. Find hottest neutrino source "S" as counterpart for one particular CR → TS(x_S) and repeat for all CRs

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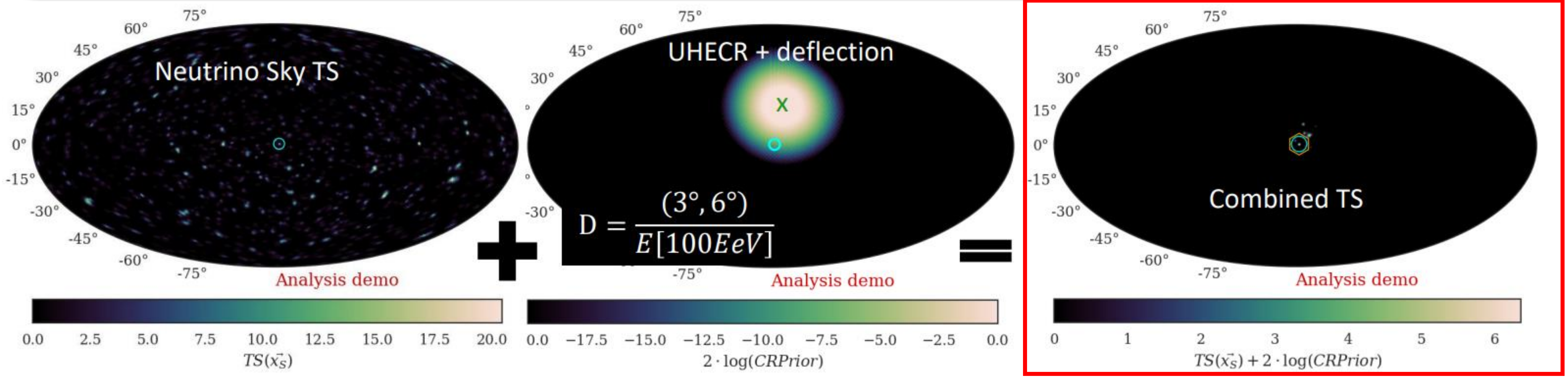

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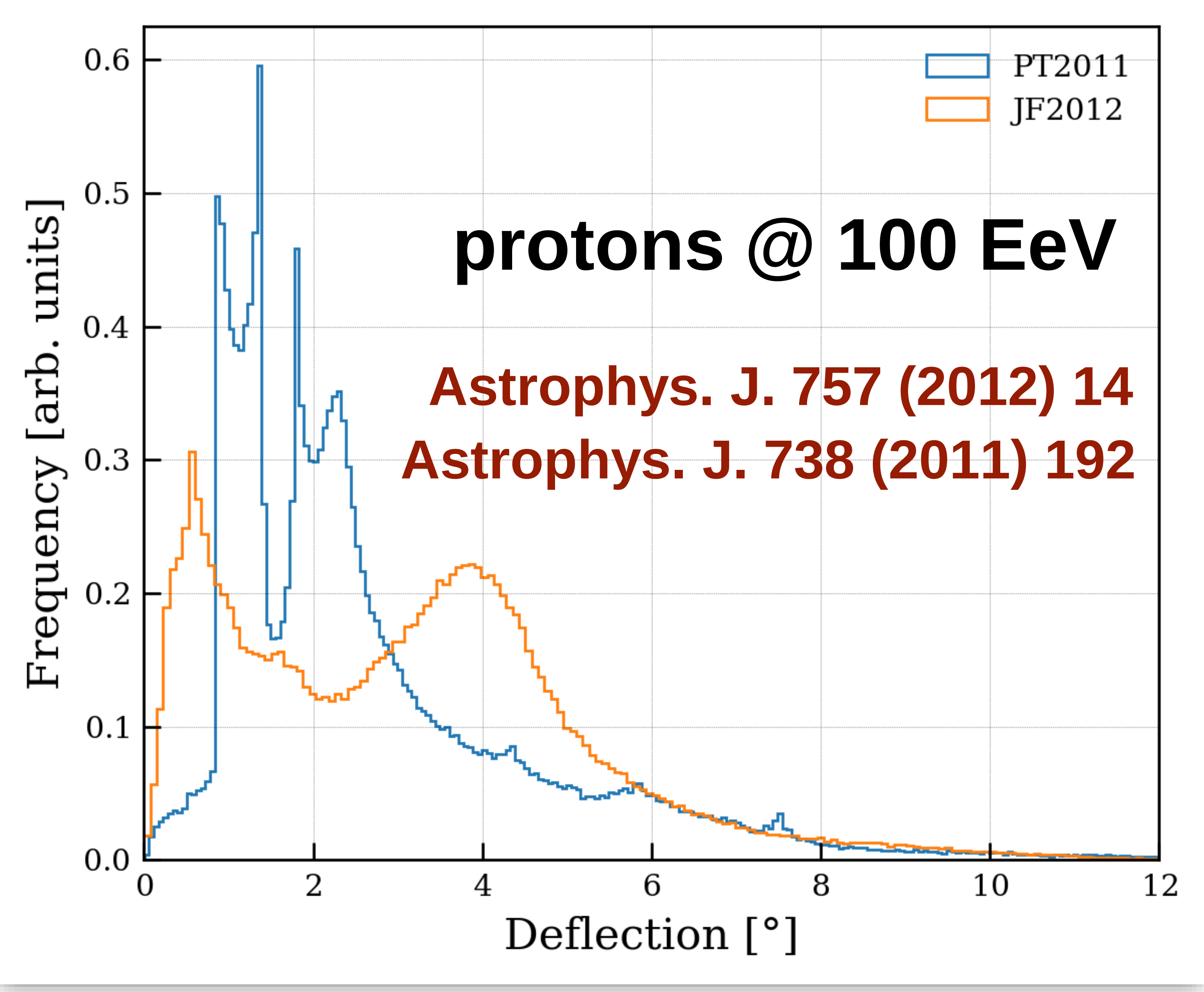
- All-sky uniform magnetic deflection value used:
  - 3° value for pure proton-like sample; also 6° tested to account for heavier composition
  - rescaled by CR energy

$$\sigma_{\rm MD}(E) = D \times 100\,{\rm EeV}/E$$

- Three different CR energy cuts: E_{CR} > 70, 85, 100 EeV

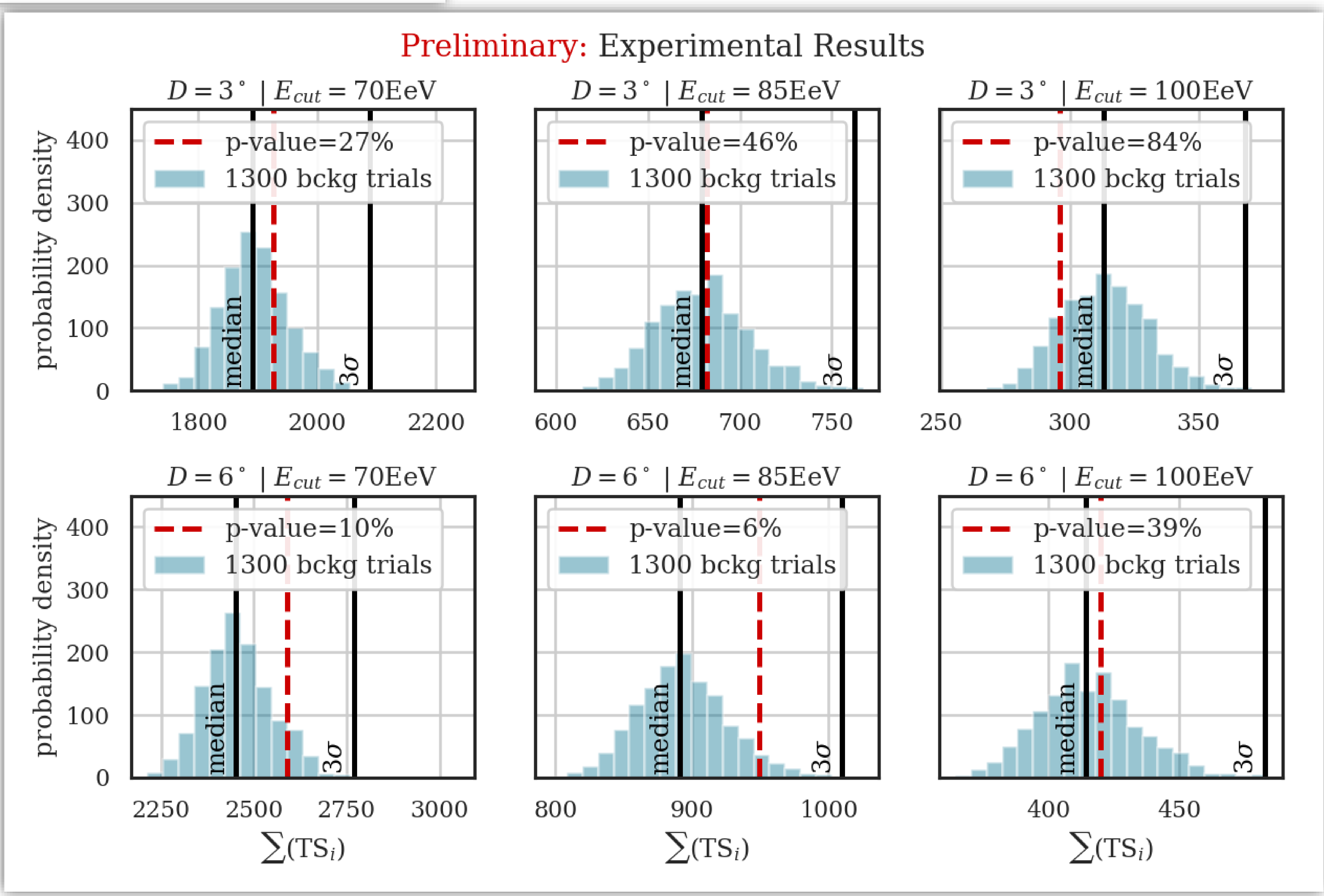


Results: UHECR-stacking correlation analysis with neutrino directions

D [°]	3			6		
E_{CR} [EeV] $\geq$	70	85	100	70	85	100
p-value	0.27	0.46	0.84	0.10	$\boxed{0.06}$	0.39

0.16 post-trial

- Result compatible with background
- Right: background TS from neutrino data randomized in right ascension (UHECR positions fixed) compared to experimental TS result



Summary and conclusions

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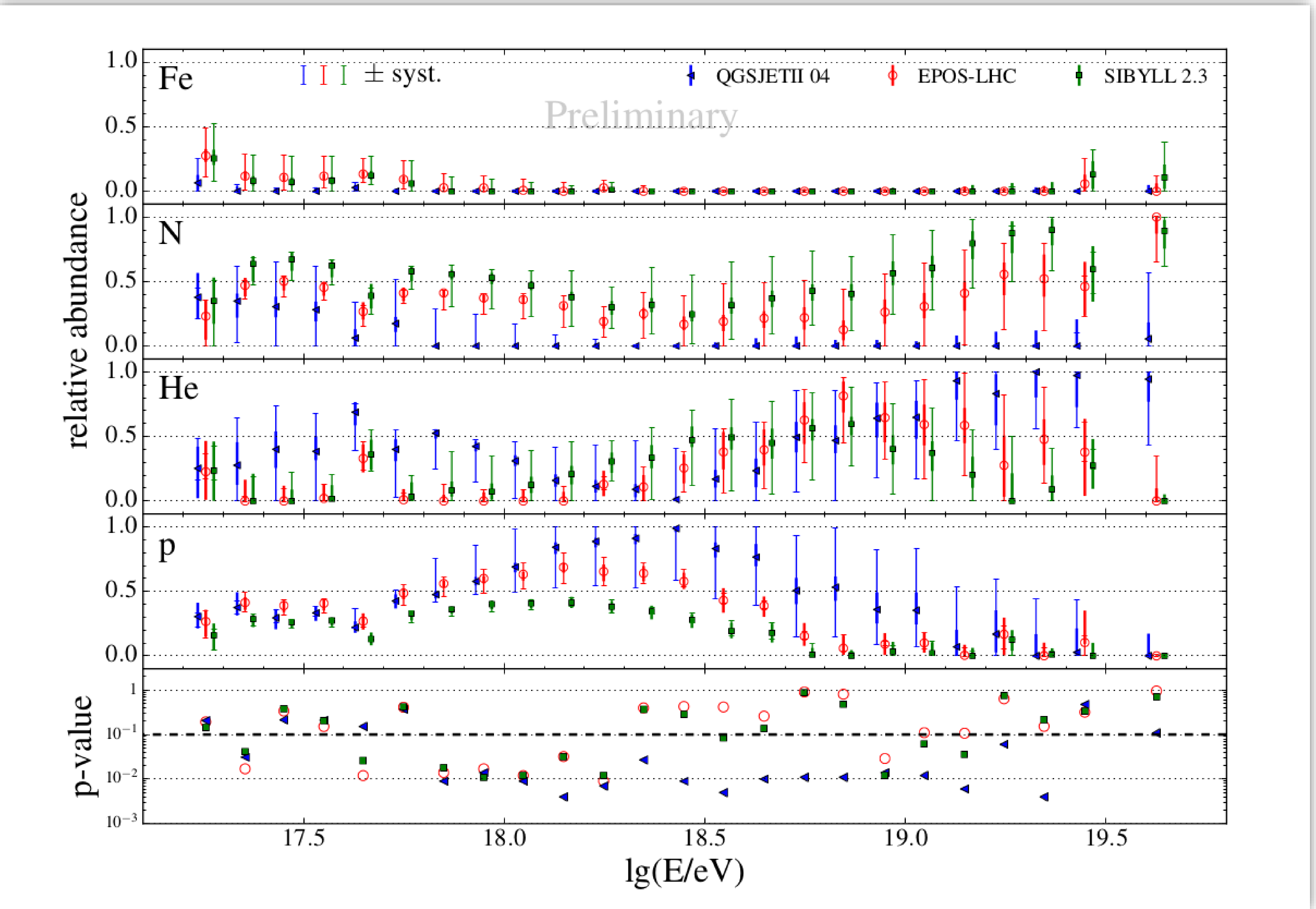
  → **Only few percents of events** in our samples **may constitute** correlated **signal**
- Work ongoing to define physical hypotheses for upper limit calculations
- Paper in preparation

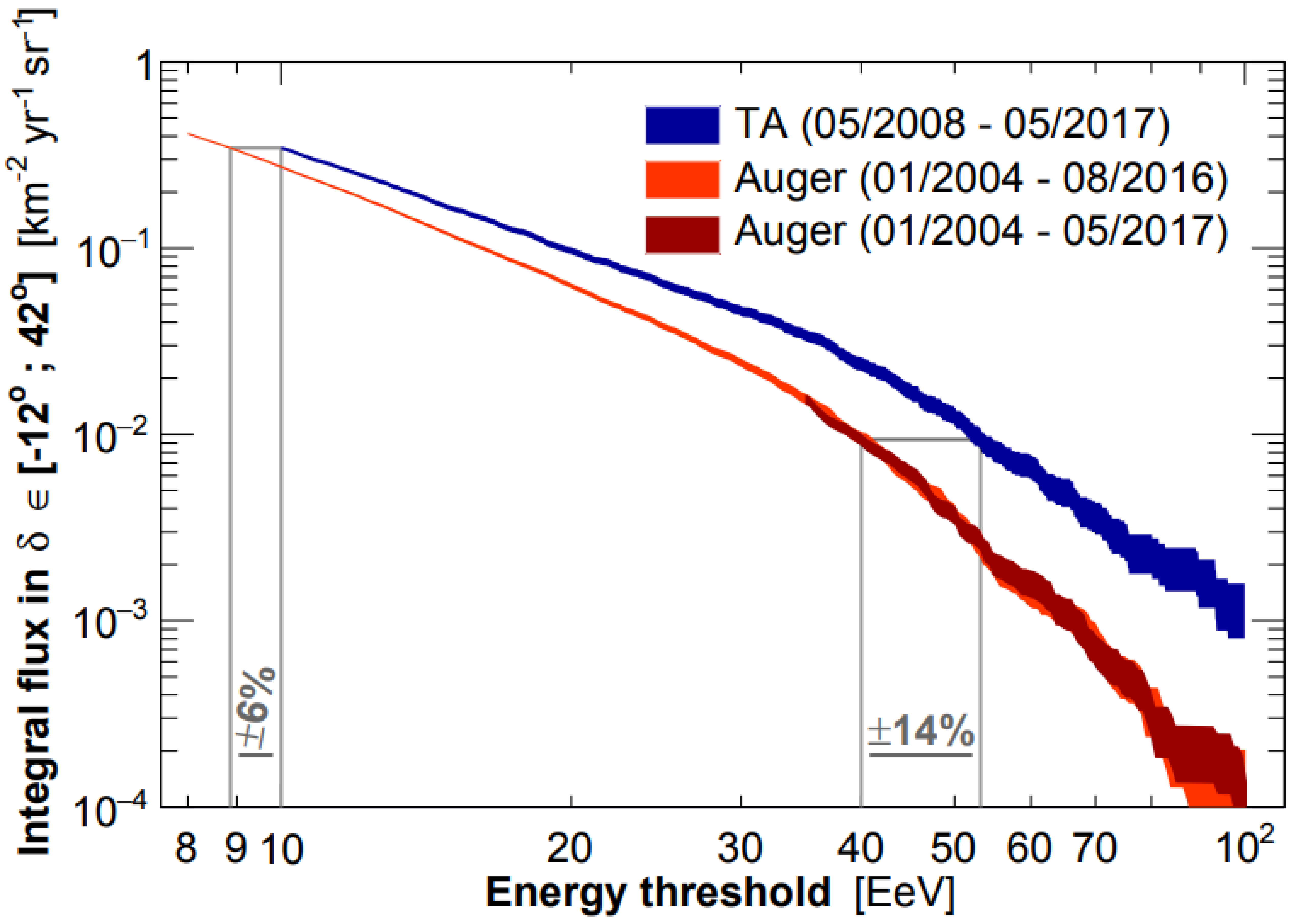
Backup

CR composition above $10^{17.2}$ eV



- Auger mass fraction fits using parameterization of the expected X_{max} distributions with different hadronic interaction models (PoS ICRC2017 (2018) 506)

TA and Auger flux rescaling



EPJ Web Conf.210(2019) 01005

Neutrino-stacking correlation analysis with UHECRs

$$\ln \mathscr{L}(n_s) = \sum_{i=1}^{N_{\mathrm{Auger}}} \ln\left(\frac{n_s}{N_{\mathrm{CR}}} S^i_{\mathrm{Auger}} + \frac{N_{\mathrm{CR}} - n_s}{N_{\mathrm{CR}}} B^i_{\mathrm{Auger}}\right) + \sum_{i=1}^{N_{\mathrm{TA}}} \ln\left(\frac{n_s}{N_{\mathrm{CR}}} S^i_{\mathrm{TA}} + \frac{N_{\mathrm{CR}} - n_s}{N_{\mathrm{CR}}} B^i_{\mathrm{TA}}\right),$$

n_s = number of signal event (free parameter)

N_{CR} = total number of CR events

$S^i_{\text{CR experiment}}$ = signal PDF

$B^i_{\text{CR experiment}}$ = background PDF

Signal PDF:

$$S^i_{\mathrm{CR\ observatory}}(\vec{r}_i, E_i) = R_{\mathrm{CR\ observatory}}(\delta_i) \sum_{j=1}^{N_{\mathrm{src}}} S_j(\vec{r}_i, \sigma(E_i))$$

Relative exposure at given event declination

N_{src}: number of stacked sources

value of the normalized directional likelihood map for the j-th source (i.e. neutrino) taken at r_i and smeared with a Gaussian with standard deviation $\sigma(E_i)$:

$$\sigma(E_i) = \sqrt{\sigma^2_{\mathrm{CR\ observatory}} + \sigma^2_{\mathrm{MD}}}$$

- $\sigma_{CR\ observatory}$: angular resolution of the CR observatory (0.9° for Auger and 1.5° for TA)
- σ_{MD} = D × 100 EeV/E_{CR} (for a pure proton composition with an energy E_{CR} = 100 EeV)

Neutrino-stacking correlation analysis with UHECRs

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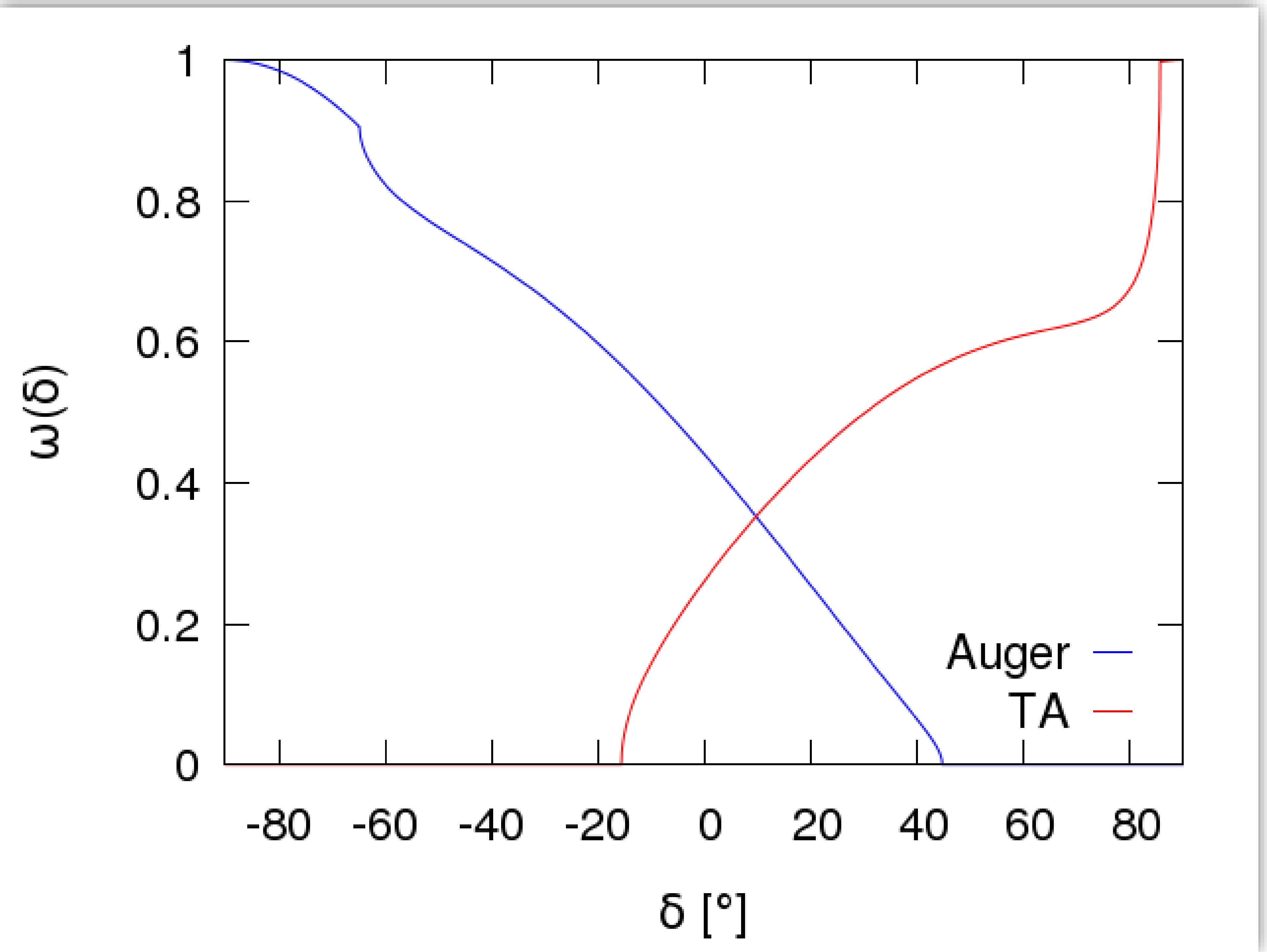
n_s = number of signal event (free parameter)
N_{CR} = total number of CR events

$S^i_{\text{CR experiment}}$ = signal PDF
$B^i_{\text{CR experiment}}$ = sbackground PDF

Background PDF:



the experiments exposures, assuming isotropic cosmic ray flux

IceCube and ANTARES point-source sample combination

Likelihood as a function of the total number of fitted events n_s:

$$\ln \mathcal{L} = \sum_{j=1}^{N_{\rm sample}} \left(\sum_{i=1}^{N_\nu^j} \ln \left(f^j \frac{n_s}{N_\nu^j} S_i + \left(1 - f^j \frac{n_s}{N_\nu^j}\right) B_i \right) \right)$$

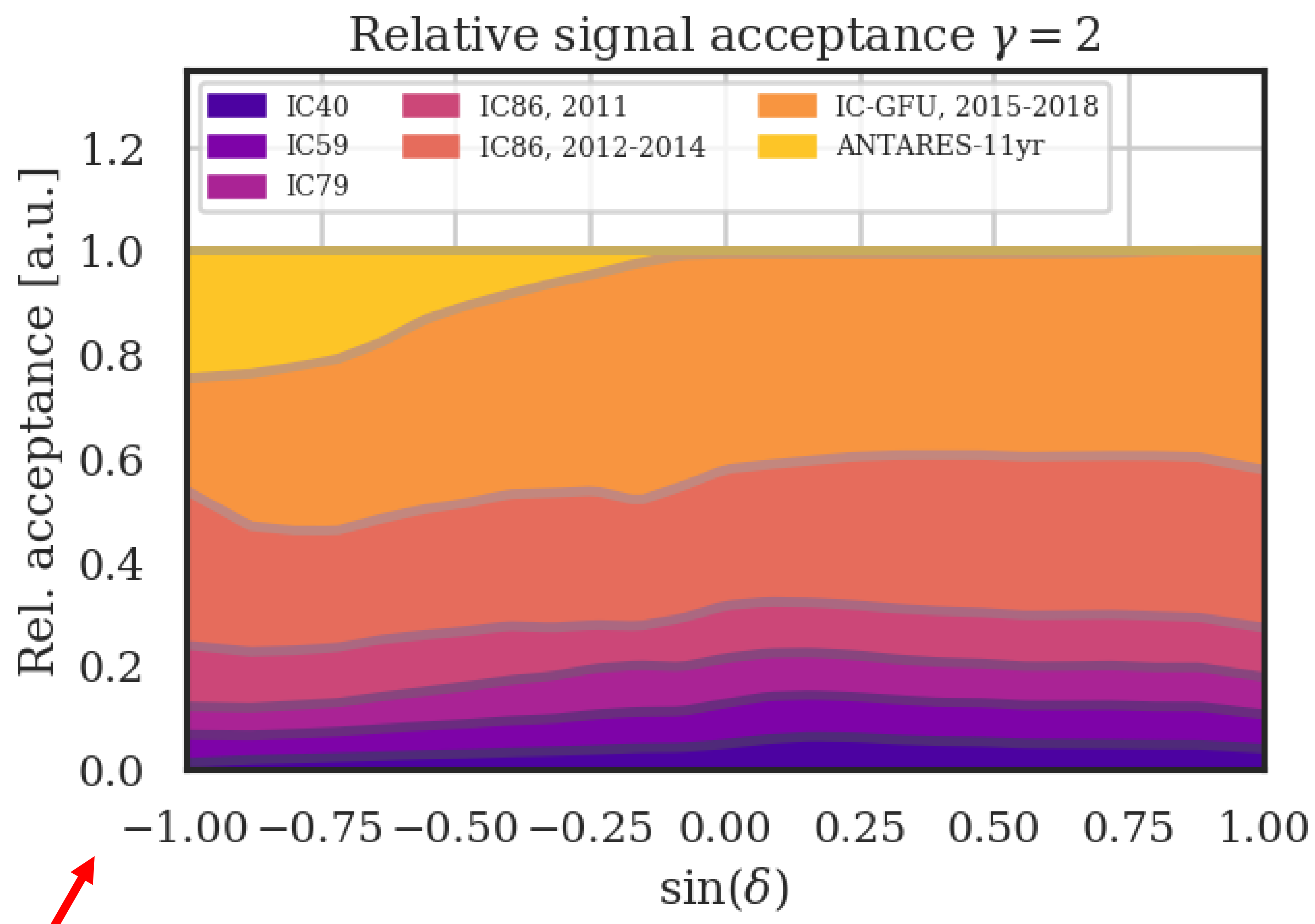
where:

$$n_s^j = n_s \cdot f^j(\delta, \tfrac{d\Phi}{dE})$$

number of signal events in the j$^{\rm th}$ sample

$$f^j(\delta, \tfrac{d\Phi}{dE}) = \frac{N_s^j(\delta, \frac{d\Phi}{dE})}{\sum_j N_s^j(\delta, \frac{d\Phi}{dE})}$$

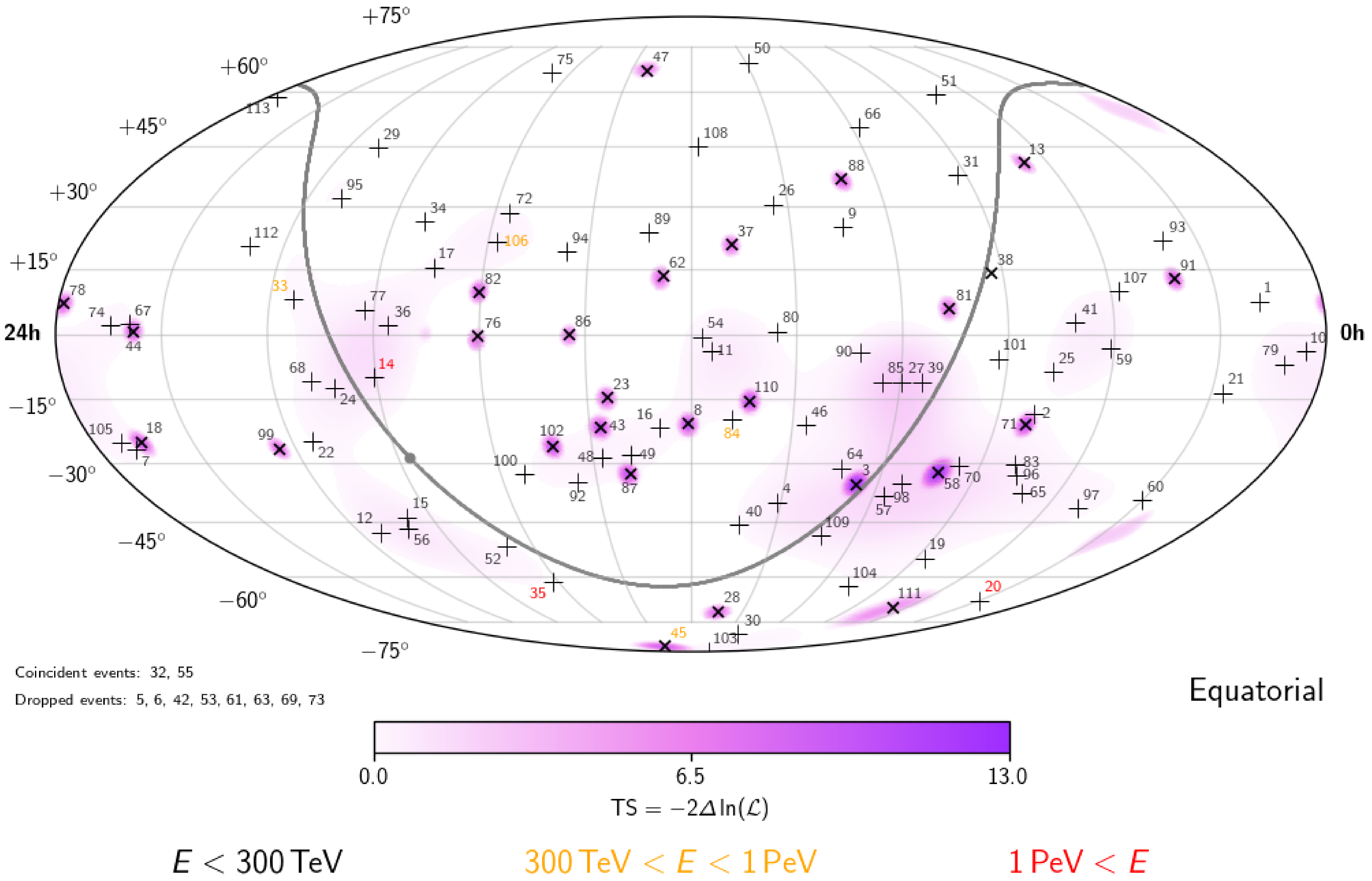
Relative number of expected source events in the j$^{\rm th}$ sample



$$N_s^j(\delta, \tfrac{d\Phi}{dE}) = \int dt\ dE_\nu A_{\rm eff}^j(E_\nu, \delta) \frac{d\Phi}{dE_\nu}$$

Expected source event number for a flux E^{-2}, given the effective area $A_{\rm eff}^j$ of the j$^{\rm th}$ sample

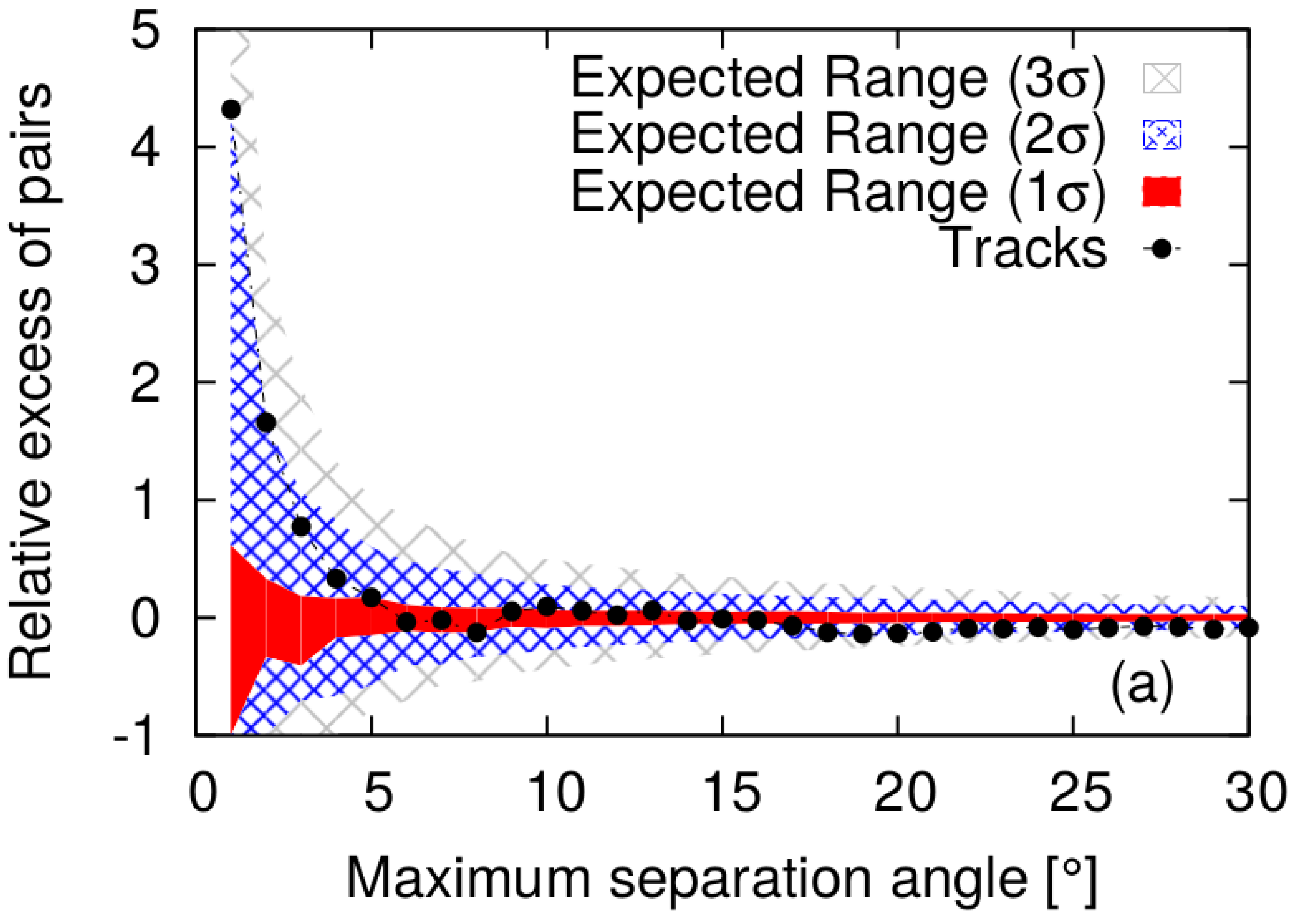
HESE 7.5 yr point-source searches

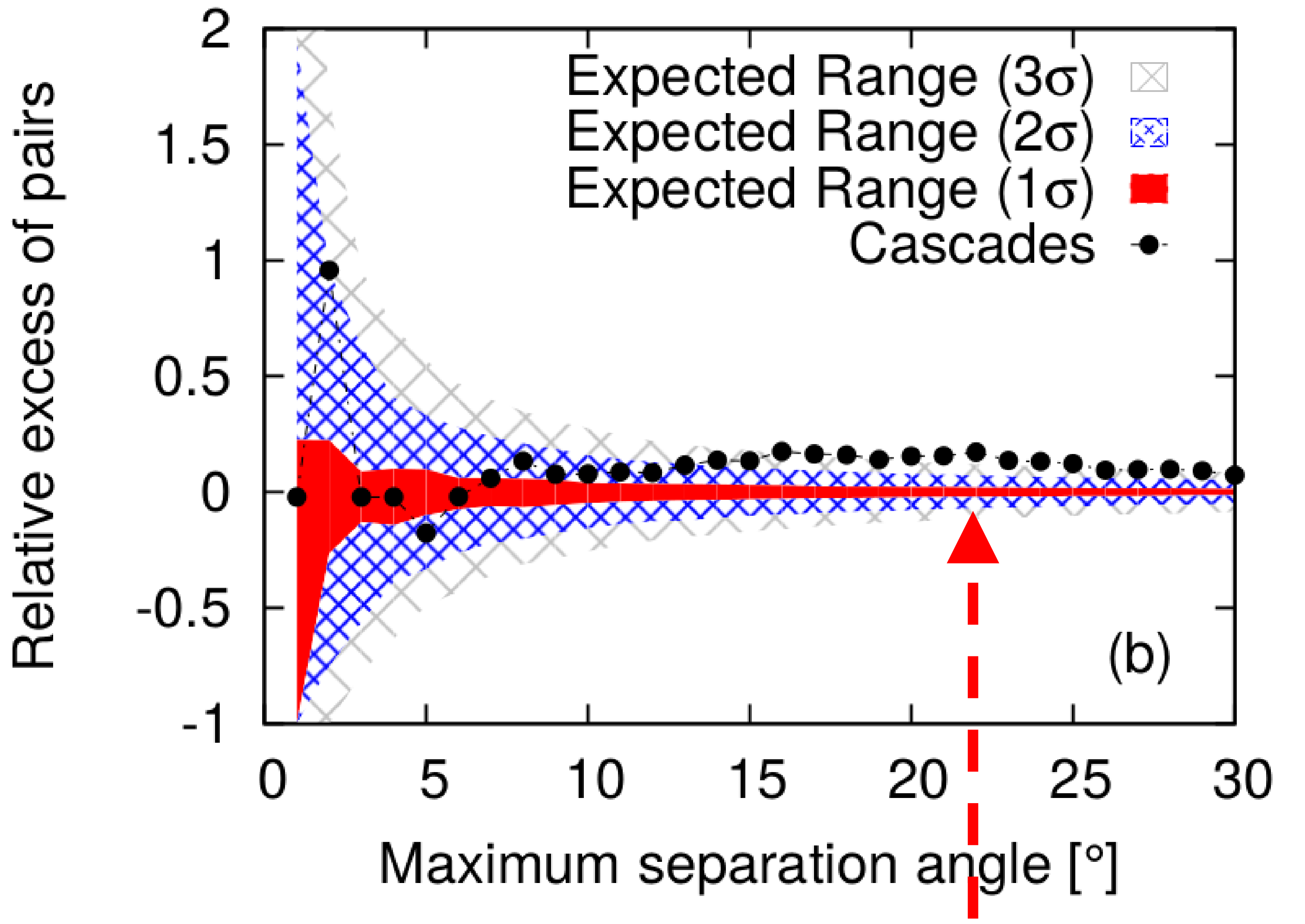


- Maximum observed TS = 12.24 (best-fit number of signal events n_s = 5.1 at (α,δ)=(12.2°, 5.1°).
- Resulting p-value is 0.81.

UHECR-neutrino cross-correlation analysis: published results

[1] JCAP 1601 (2016) 01 037





Post-trial p-value : evolution vs. time	JCAP 2016 [1]	ICRC 2017 [2]	UHECR 2018 [3]
tracks wrt an isotropic flux of UHECR	0.28	0.48	**0.45**
tracks wrt an isotropic flux of neutrinos		0.52	**0.49**
cascades wrt an isotropic flux of UHECR	5×10^{-4}	5.4×10^{-3}	$\mathbf{2.7 \times 10^{-2}}$
cascades wrt an isotropic flux of neutrinos ν	8.5×10^{-3}	1.0×10^{-2}	$\mathbf{2.6 \times 10^{-2}}$

- Isotropic CR background
- Post-trial p-value at 22°: 5.0×10^{-4}

[2] PoS(ICRC2017)961
[3] EPJ Web Conf. 210 (2019) 03003

Neutrino-stacking correlation analysis with UHECRs: published results

	High-energy tracks		High-energy cascades	
D^*	n_s	pre-trial p-value	n_s	pre-trial p-value
3°	4.2	0.22	53.7	$2.1 \cdot 10^{-3}$
6°	0.5	0.48	85.7	$2.7 \cdot 10^{-4}$
9°	-	underfluctuation	106.1	$3.8 \cdot 10^{-4}$

JCAP 1601 (2016) 01 037

* In past analyses, a median all-sky value was used for D

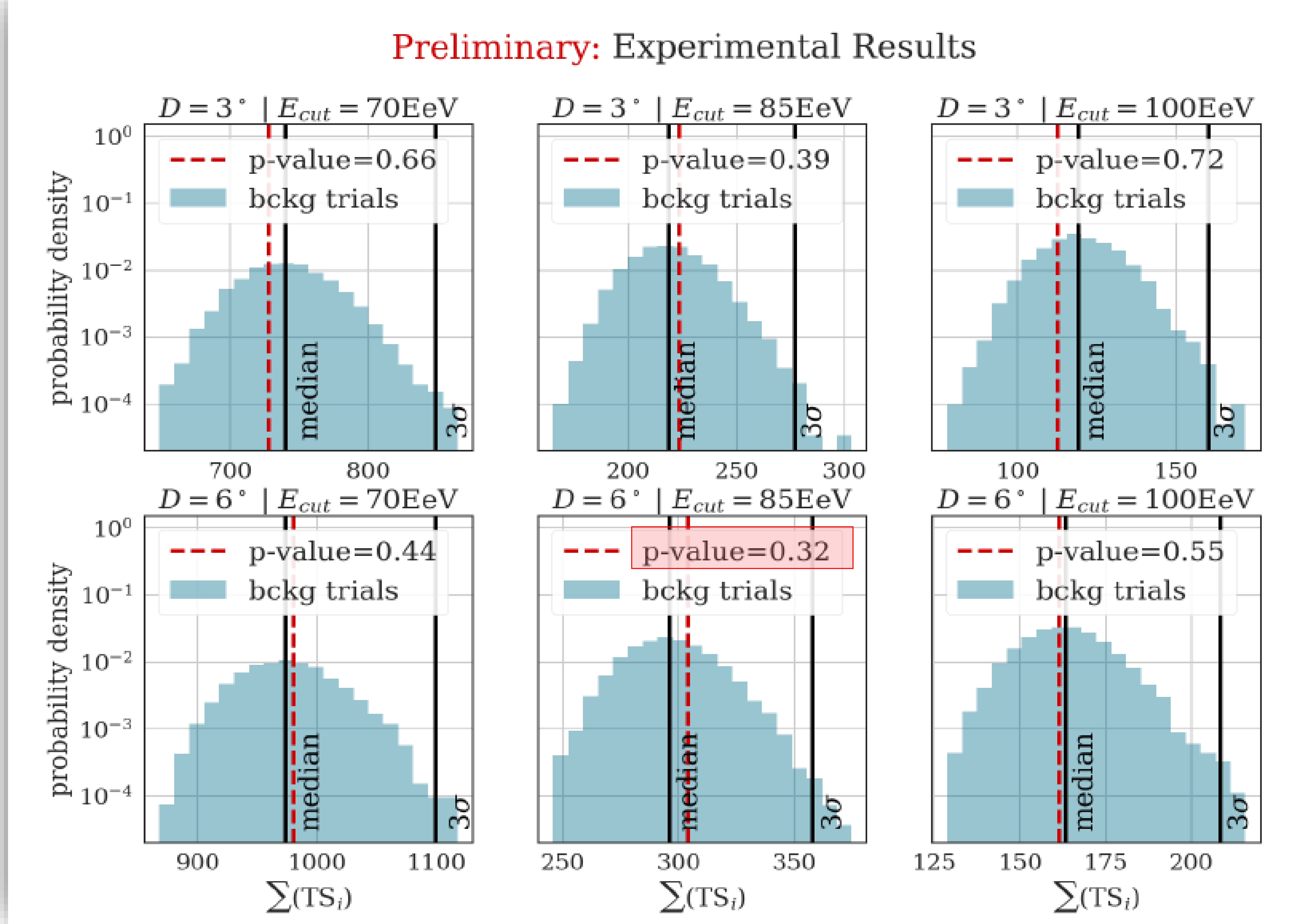
post-trial: 8.0×10^{-4}

	High-energy tracks		High-energy cascades	
D	n_s	pre-trial p-value	n_s	pre-trial p-value
3°	0.9	0.44	45.5	$2.7 \cdot 10^{-2}$
6°	-	underfluctuation	71.5	$1.0 \cdot 10^{-2}$
9°	-	underfluctuation	84.7	$1.5 \cdot 10^{-2}$

PoS(ICRC2017)961

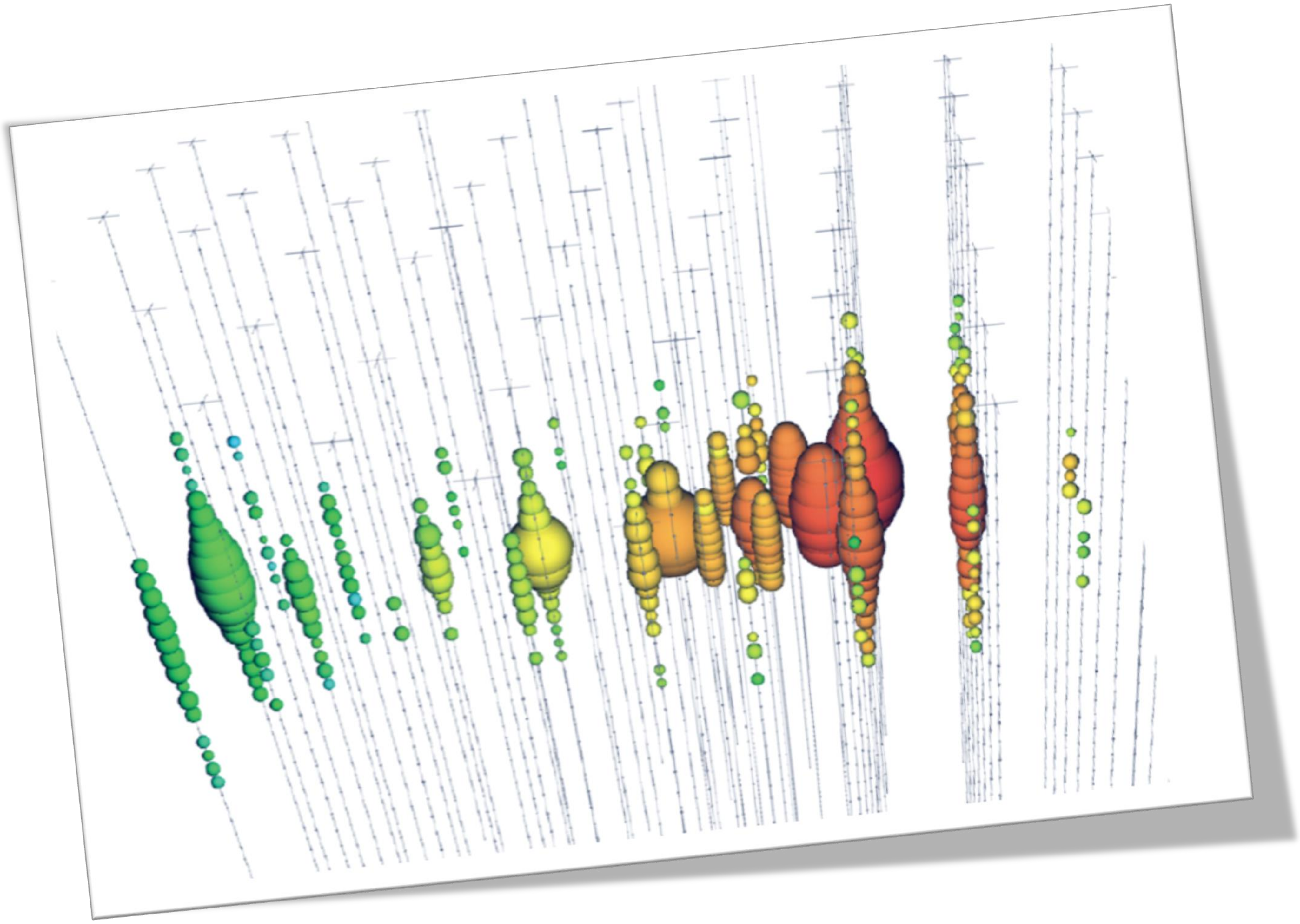
post-trial: 2.2×10^{-2}

UHECR-stacking correlation analysis with neutrino directions: published results



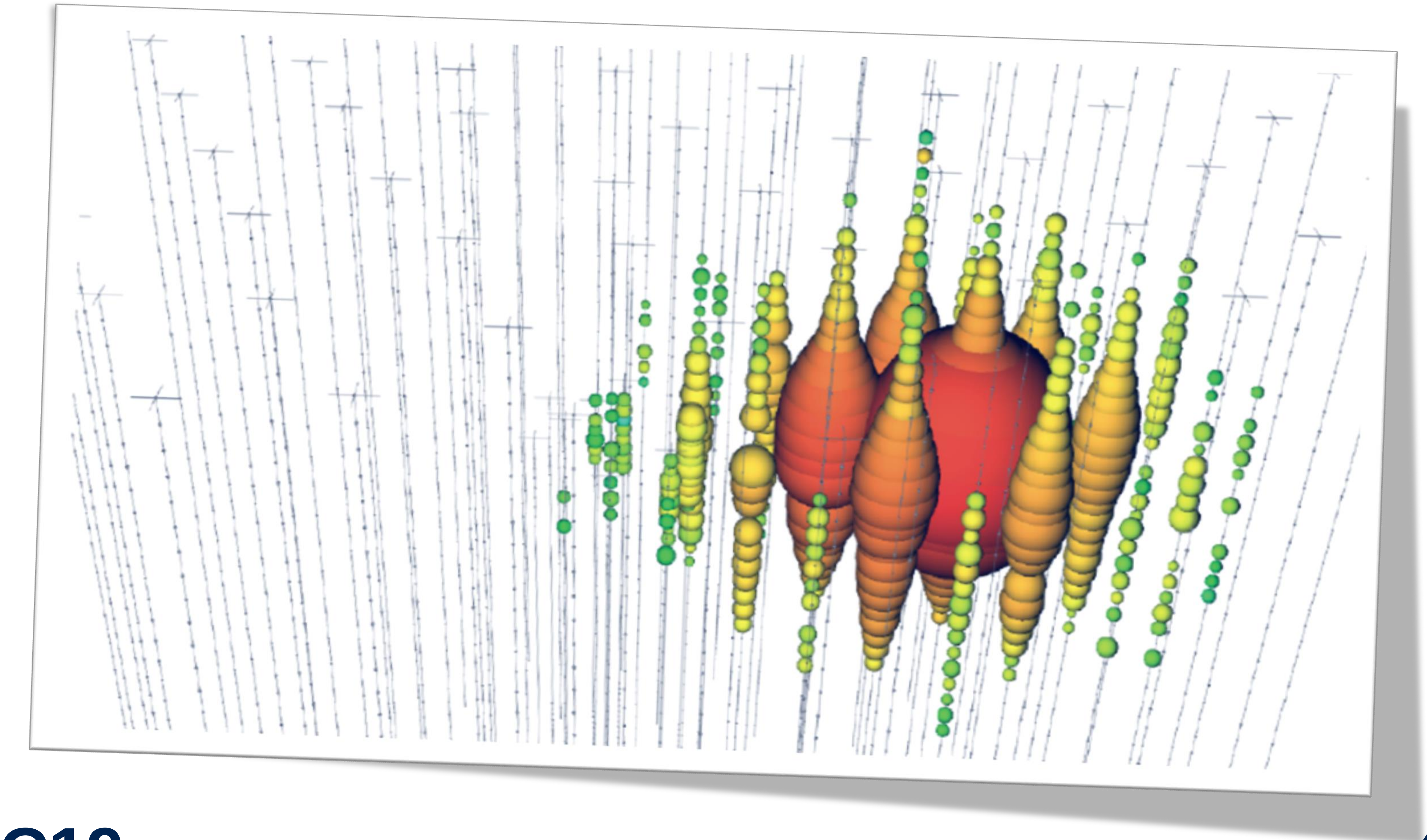
EPJ Web Conf. 207 (2019) 02010

IceCube event signatures



Track-like events:

- Charged-current (CC) interactions of muon neutrinos with nucleons (N): $\nu_\mu + N \rightarrow \mu^- + X$
- Good angular resolution: < 1° above few TeV
- Energy resolution: x2



Cascade-like events:

- neutral current (NC) $\nu_\alpha + N \rightarrow \nu_\alpha + X$
- charged current $N \rightarrow \ell_\alpha^- + X$
- Angular resolution: ~15° above 100 TeV
- Good energy resolution: ~15%