Search for common sources of cosmic neutrinos and ultra-high-energy cosmic rays

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Overview

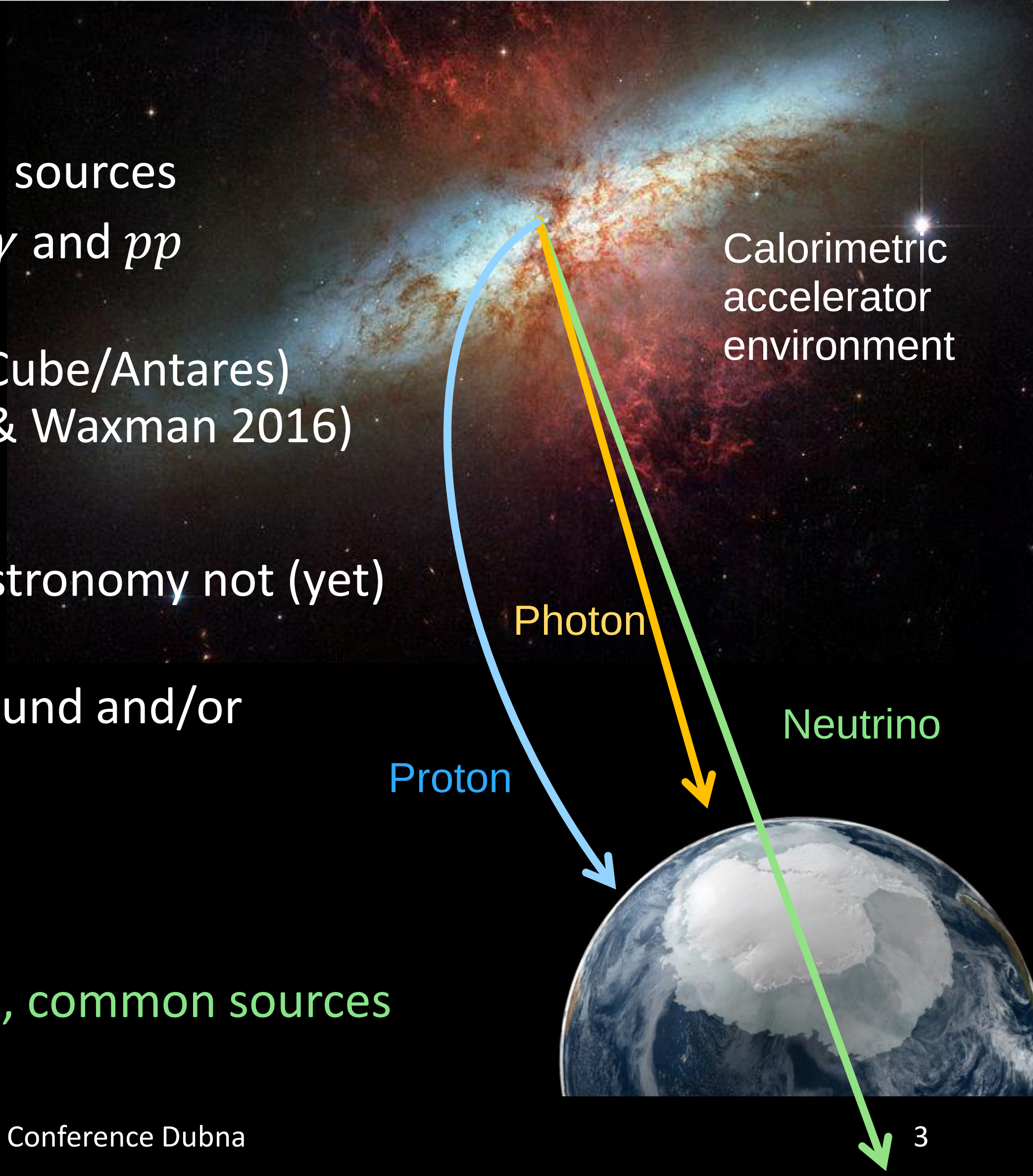
- Multimessenger motivation
- Analysis approach:
  Combining UHECR + neutrino + deflection information
- Analysis performance estimate
- Summary and Outlook

Multimessenger: Generic source models

- <u>Theory:</u>
  - UHE cosmic rays accelerated in yet unknown, local sources
  - Lower energy, confined CRs produce γ and ν via $p\gamma$ and pp interactions
  - Escaping UHECRs (Auger/TA), γ (Fermi) and ν (IceCube/Antares) fluxes explained in “calorimetric” model (Murase & Waxman 2016)
- Difficulties in finding hadronic sources:
  - CRs deflected by magnetic fields, UHECR proton astronomy not (yet) in reach
  - Astrophysical neutrino samples limited by background and/or statistics
  - Photons may originate from leptonic processes

➢ Neutrinos “smoking gun” of hadronic processes of CRs

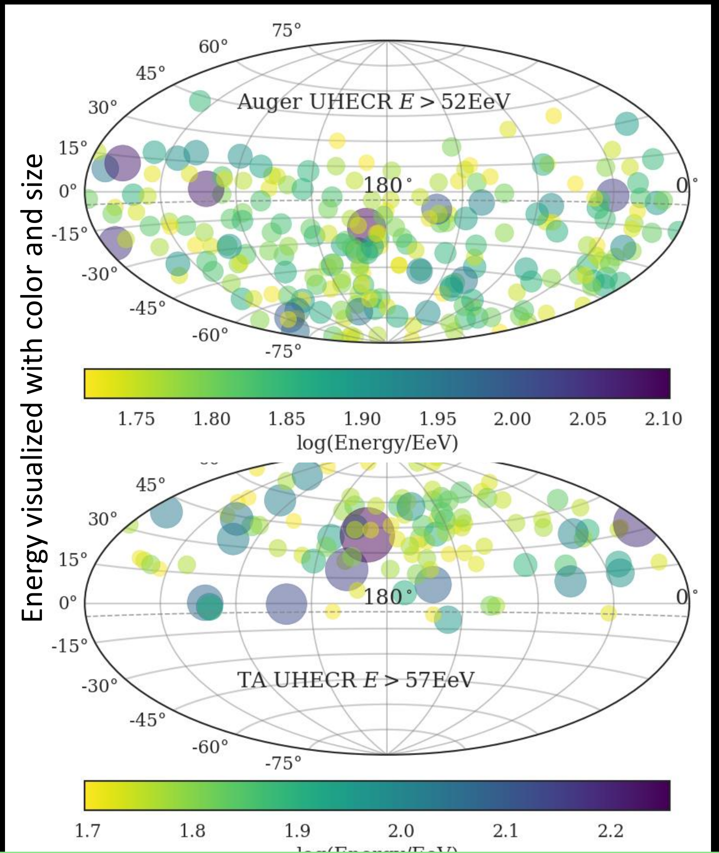
➢ Combine UHECR and neutrino information to find local, common sources



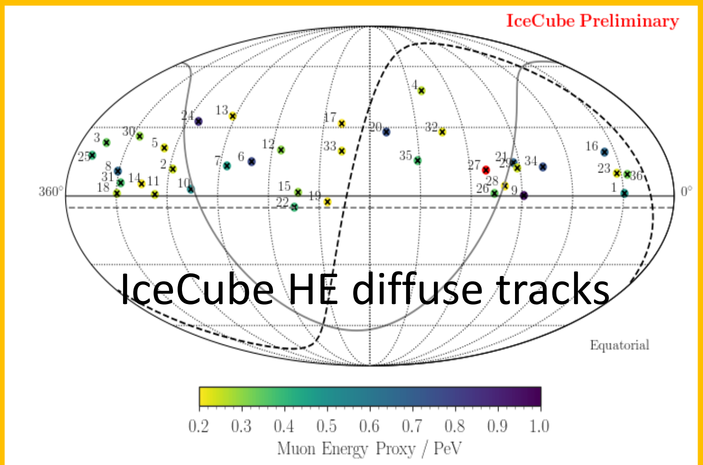
http://www.spacetelescope.org/images/heic0604a/
http://www.livescience.com/images/i/000/066/035/original/NSIDCimages__SPclouds.2158.jpg

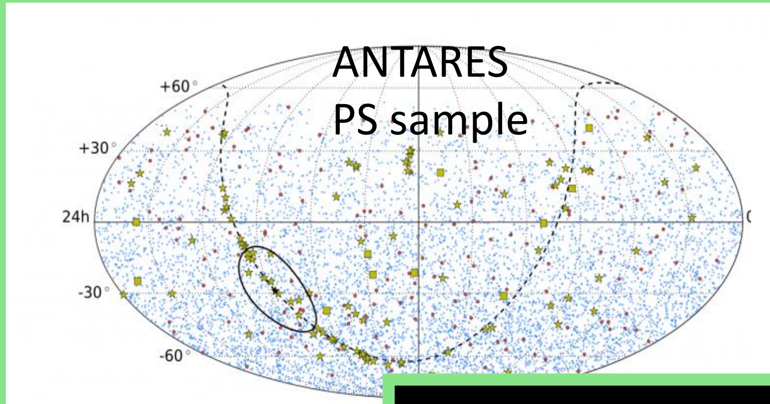
Data sets

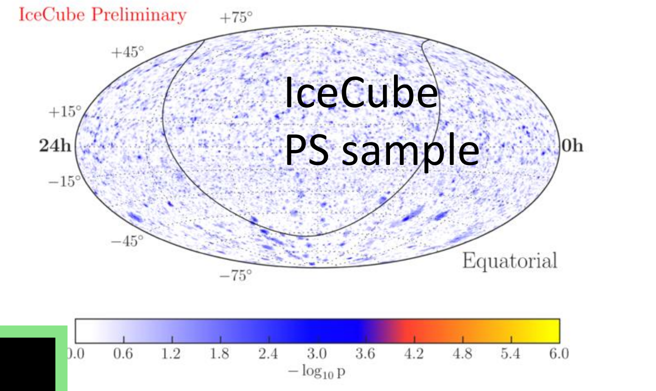
- Auger: 231 UHECRs (2004-2014), E>52EeV
- Telescope Array: 109 UHECRs (2008-2015), E>57EeV
- ANTARES:
  - 8k events in muon-track sample (9yr)
  - 3 HE muon-tracks with P(astro)>40%
- IceCube:
  - >1M events in muon-track samples ("Point-source sample"+GFU)
  - 35 HE-through-going muon tracks >200TeV (ν_{atm}, ν_{astro}, P(astro)>50%)
  - 58+15 HE-starting-events cascades and tracks



Astrophysical purity







Statistics

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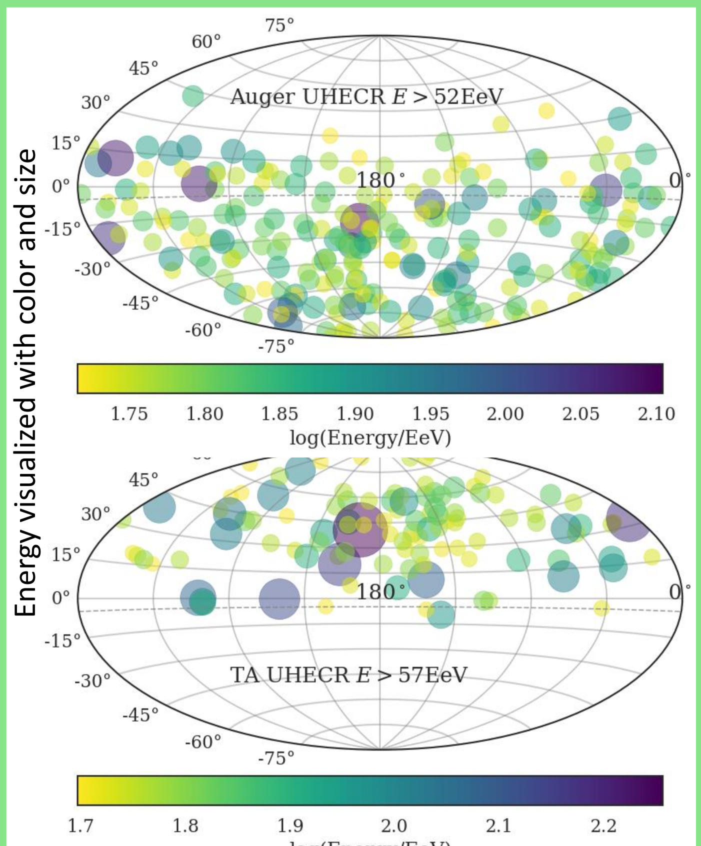
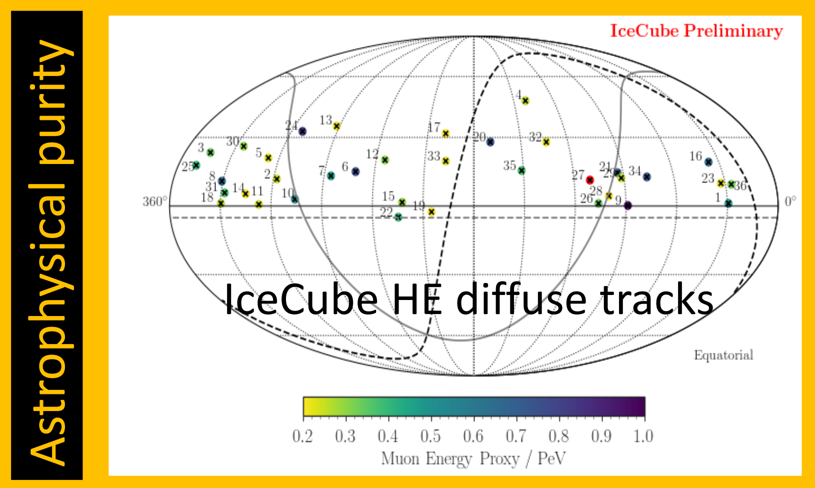
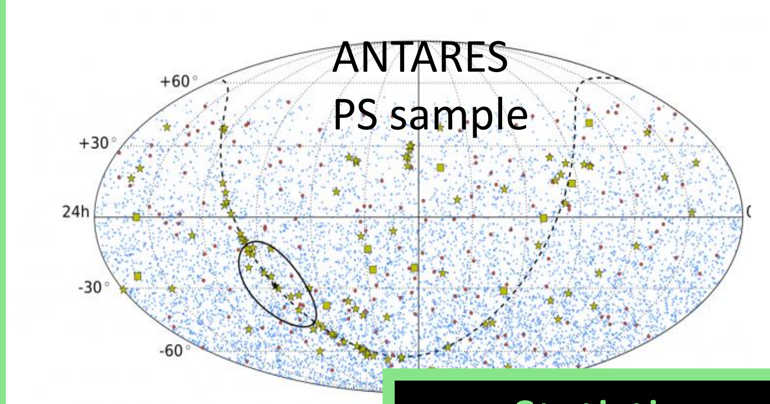
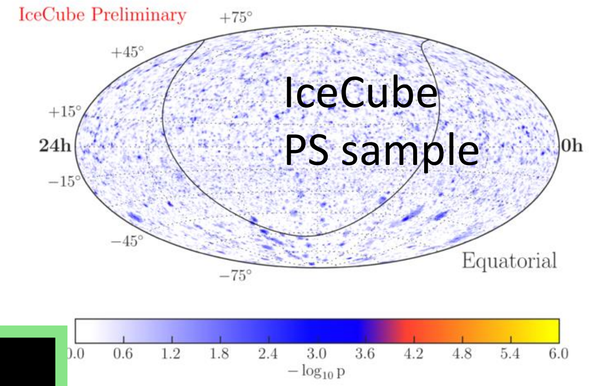
Used in this analysis

Used in other analyses









Overview: UHECR & neutrino correlation analyses

2015 publication: arXiv:1511.09408; ICRC 2017 https://pos.sissa.it/301/961/

Using „astrophysical purity" neutrino samples

- a) Cross-correlation, latest result: Decreased significances $5.4 \cdot 10^{-3}$ / $1.0 \cdot 10^{-2}$ with respect to an isotropic flux of CRs / neutrinos (2017, cascades)
- b) Neutrino-source stacking, latest result: Decreased significances $2.2 \cdot 10^{-2}$/ $1.7 \cdot 10^{-2}$ with respect to an isotropic flux of CRs/neutrinos (2017, cascades)

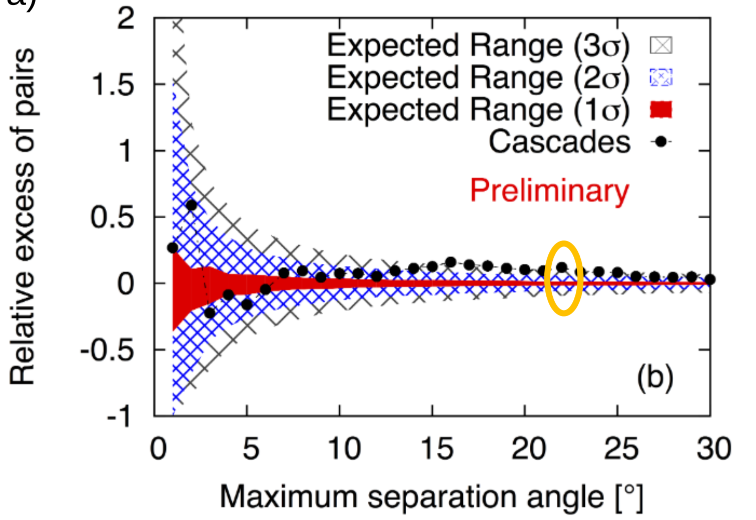
Used „statistics" neutrino samples

- c) UHECR-extended-source stacking: Smallest p-value: 0.25 w.r.t an isotropic flux of neutrinos (2015), no update for ICRC2017

➢ Continue monitoring, with new data from all experiments, and including HE- and PS-samples from ANTARES

➢ There will be brand-new results of analysis a) with 30% more UHECR data and HE-tracks by ANTARES at UHECR2018

a)



b)

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

Next chapter:

Search for correlations using full-sky neutrino „point-source“ samples with a more sensitive ansatz

UHECRs and ν information gathering

IceCube's Standard Point Source Search, currently implemented in *SkyLab*

- Neutrinos:
  - (Extragalactic) neutrino sources appear point-like (0.5°) compared to isotropically distributed background events
  - Energy spectrum of astrophysical neutrinos $\gamma_S \approx 2.19^*$ vs atm. neutrinos $\gamma_{atm} \approx 3.7$
- UHECRs:
  - Originate from unknown hadronic sources in the „local" universe (<200 Mpc)
  - Energy spectrum well-known, good event-by-event calorimetric reconstruction
  - No conclusive information on rigidity E>50 EeV, esp. not on event-by-event basis
- Magnetic fields:
  - Deflect UHECRs depending on their rigidity
  - IGMF+turbulent GMF not well known
  - Average deflection per energy assuming low masses can be roughly estimated

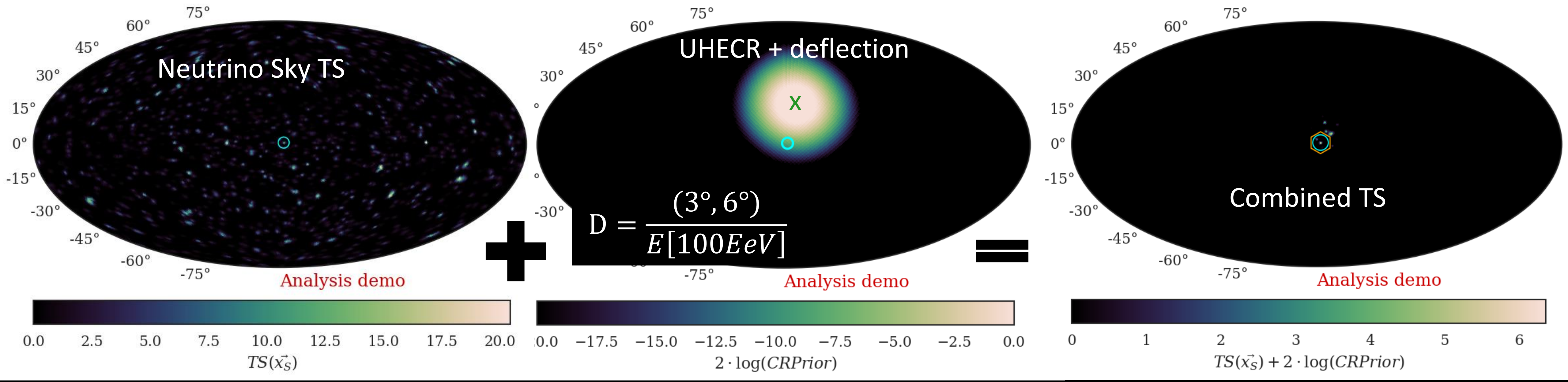
* best-fit of spectral index with up-going muon neutrino tracks in IceCube

➢ Use UHECR arrival direction and estimate their average deflection to construct „prior windows" in which to search for point-like neutrino hotspots

New combined approach!

Fit one neutrino source with CR information

1. Fit neutrino signal parameters (n_S, γ_S) on grid positions $\overrightarrow{x_S}$ → Test Statistic skymap (PS standard)
2. Add the 2*log(CRprior) to the TS map → selecting interesting region with prior window
3. Find hottest neutrino source “S” as counterpart for one particular CR → $TS\,(\widehat{x_S})$ (markers)



$$TS\,(\overrightarrow{x_S}) = 2\log\frac{\mathcal{L}(\widehat{n_S}, \widehat{\gamma_S}|\overrightarrow{x_S})}{\mathcal{L}(n_S = 0|\overrightarrow{x_S})}$$

Single gaussian prior window scaled by estimated deflection D

Single hotspot $TS\,(\widehat{x_S}, \widehat{n_S}, \widehat{\gamma_S})$

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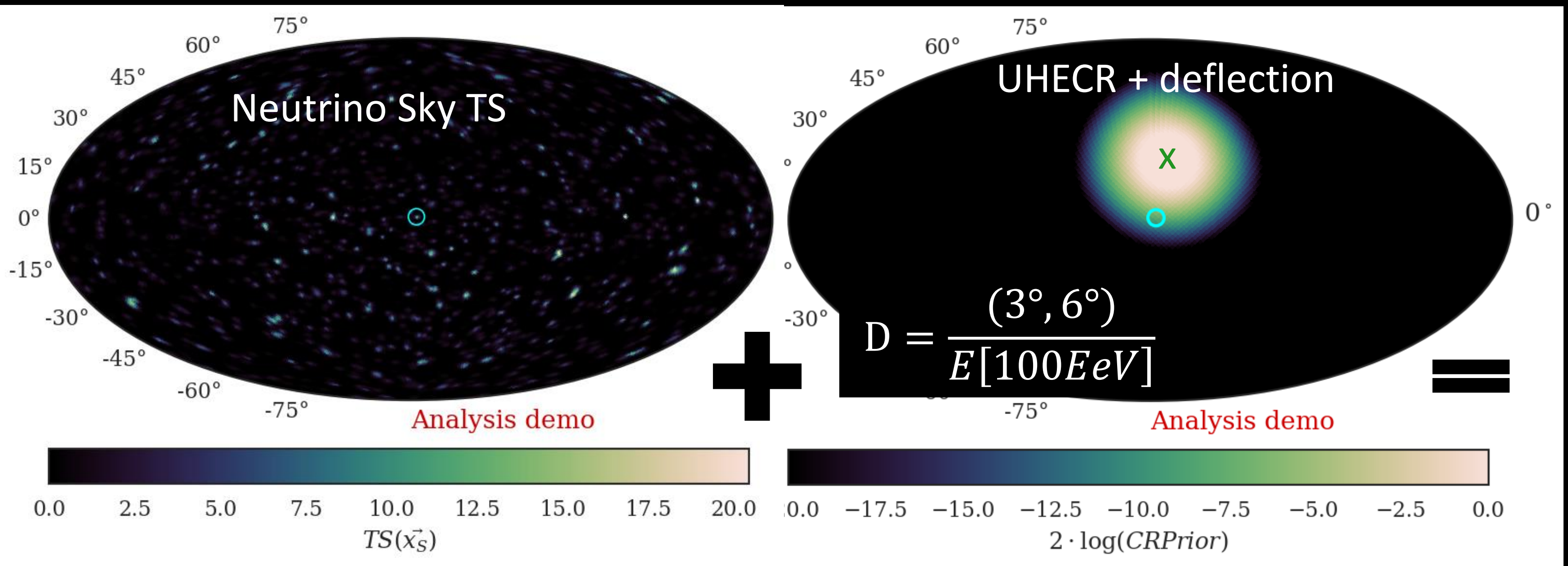


$$D = \frac{(3°, 6°)}{E[100EeV]}$$

Blue: true neutrino source position

Orange: fit neutrino source position

Combined TS

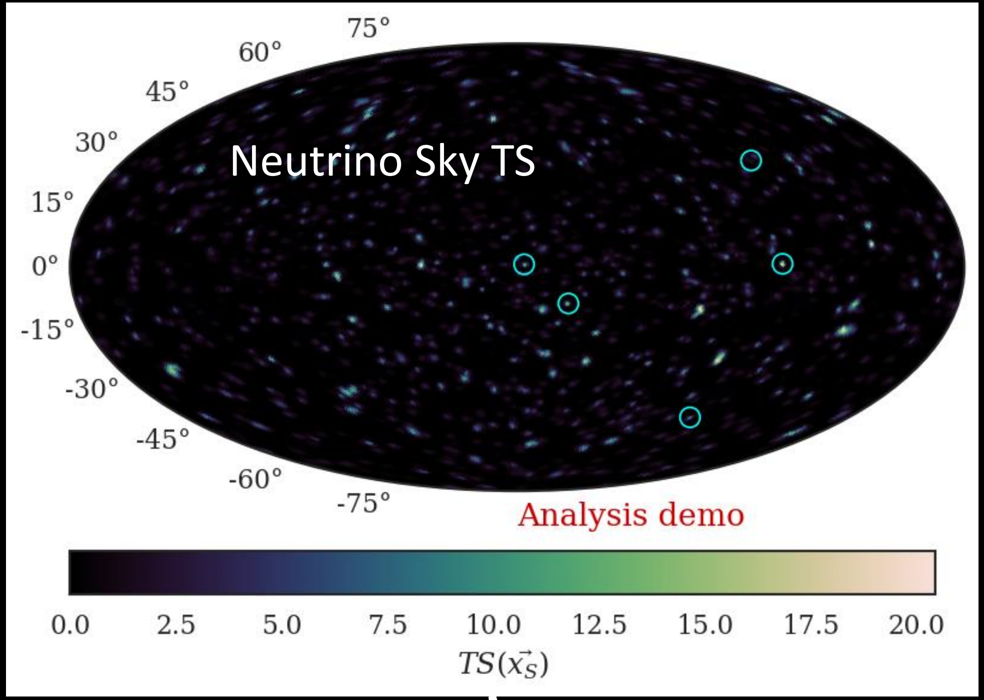
$$TS\,(\overrightarrow{x_S}) = 2\log\frac{\mathcal{L}(\widehat{n_S}, \widehat{\gamma_S} | \overrightarrow{x_S})}{\mathcal{L}(n_S = 0 | \overrightarrow{x_S})}$$

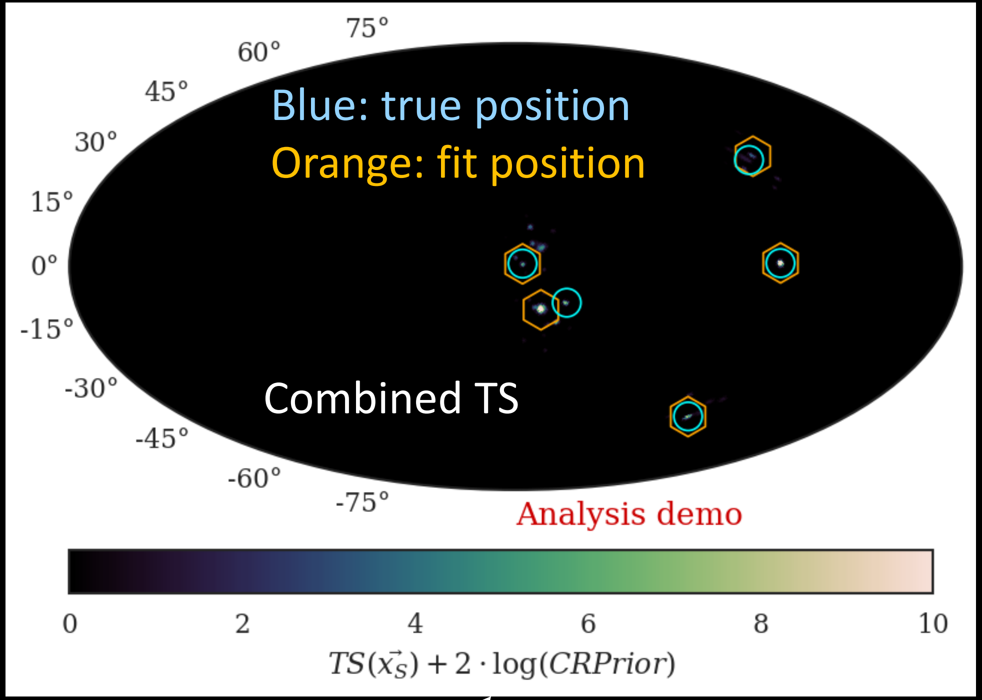
Single gaussian prior window scaled by estimated deflection D

Single hotspot $TS\,(\widehat{x_S}, \widehat{n_S}, \widehat{\gamma_S})$

Fit multiple neutrino sources with CR information

- Start with same all-sky neutrino $TS\,(\vec{x_S})$ map
- Repeat neutrino source fit for all UHECR priors individually $TS\,(\widehat{\vec{x_S}}) \rightarrow TS_i(\widehat{\vec{x_{S,i}}})$
- Individual TS_i values of all neutrino hotspots are summed up yielding final value $\mathrm{TS} = \sum_i TS_i$





Multiple gaussian prior windows

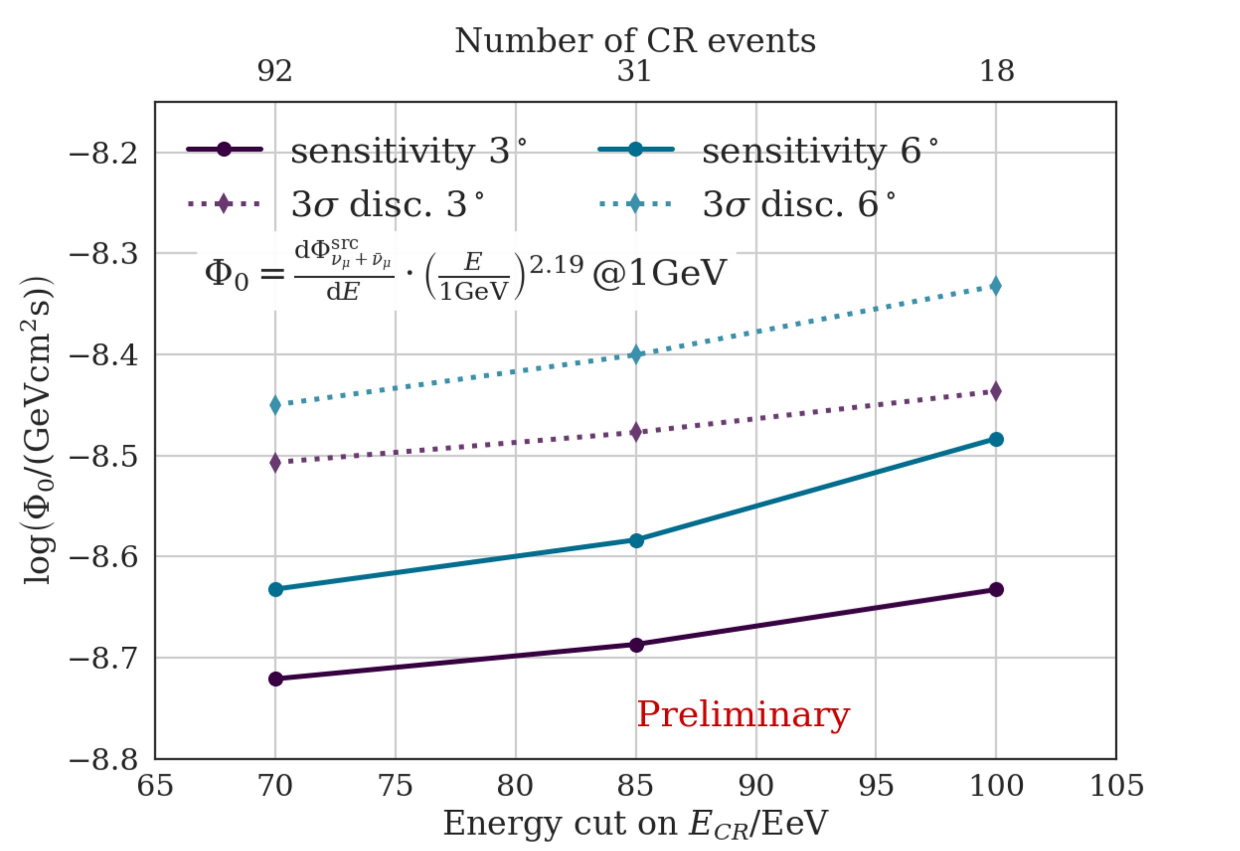
Analysis performance – Benchmark signal model

- Benchmark signal: one neutrino source for each UHECR, same spectral index (2.19) and same flux on Earth
  - ➢ Three UHECR energy cuts: 70, 85, 100 EeV
  - ➢ Two magnetic deflection scalings:

$$D = \frac{(3°, 6°)}{E[100EeV]}$$

  - ➢ All 6 models tested, since none is intrinsically better than the others if we don‘t know the underlying true model

Neutrino flux per source

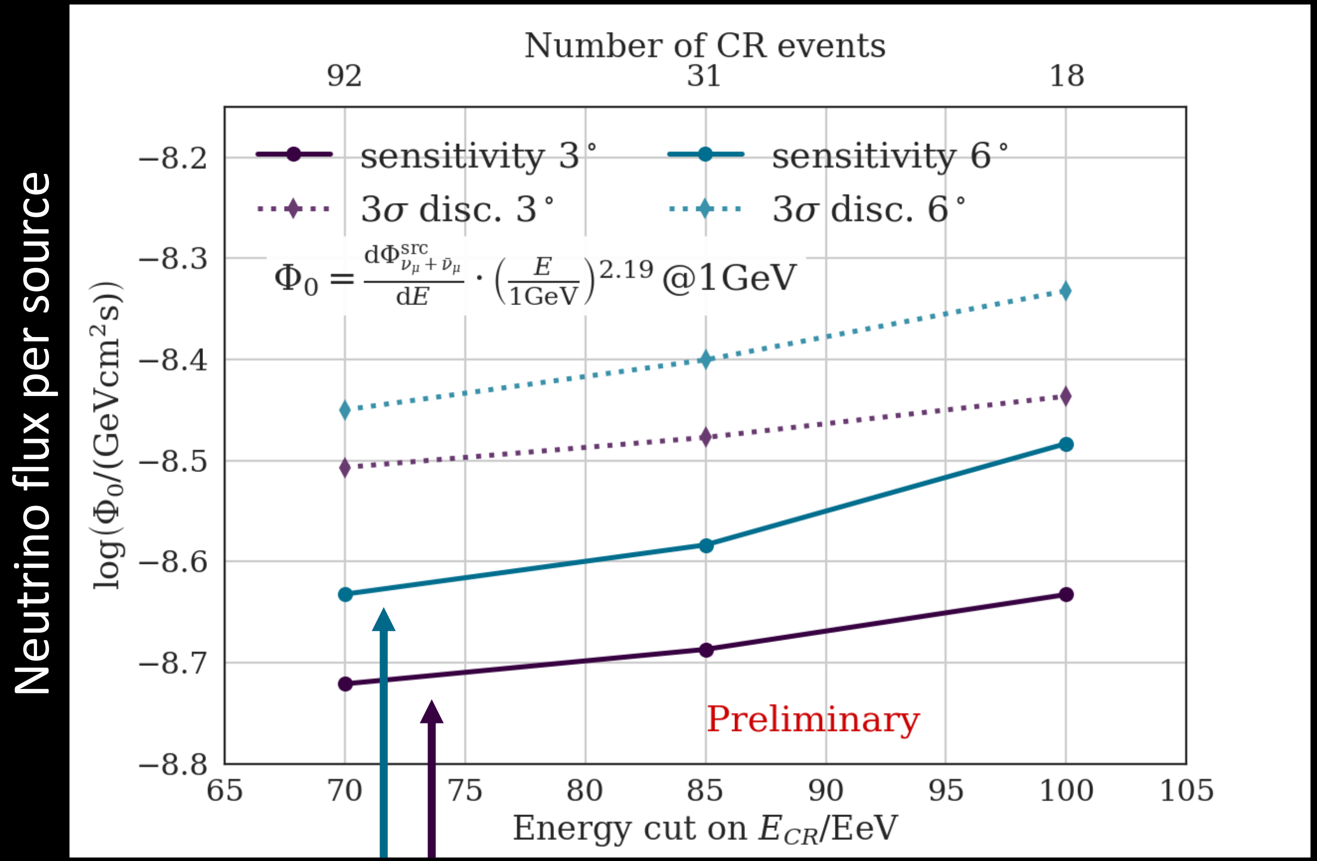


- Analysis performs better for optimistic 3° magnetic deflection hypothesis (IF it is the true underlying signal; purple lines)
- 6° is a more robust approach, especially if composition is not pure proton (blue lines)

The results?

- Very preliminary results are being validated and reviewed within IceCube, and soon also Antares, Auger and TA collaborations
- Stay tuned!

Room for your imagination



In case of a non-detection, the sensitivity corresponds to the 90% U.L.

The possible implications of a non-detection

1. UHECR sources are no sources of astrophysical neutrinos seen with IceCube and ANTARES
2. UHECR sources are burst-like and astrophysical neutrinos are not correlated on the time scale of the contributing experiments
   → There is nothing we can do here
3. If UHECR sources are also sources of astrophysical neutrinos:
   a) The UHECR composition is too heavy, i.e. deflections are too large for neutrino sources to appear spatially correlated
      → Can be solved with knowledge of event-by-event UHECR rigidity information and better knowledge of IGMF and GMF
   b) Given our assumptions about the UHECR composition/magnitude of deflection are true:
      - The neutrino output of these sources is not large enough to be significantly detected
      - Keeping in mind: UHECR-horizon ≈ 200 Mpc vs. Neutrino-horizon ≈ several Gpc
        → Neutrino statistics needs to be largely increased, e.g. with Icecube-Gen2, Baikal-GVD and KM3NET

Pessimistic ↓ Optimistic

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Planning on tweaking the analysis:
- Look into most significant single neutrino hotspot correlations expected from a small percentage of light UHECRs
- Use „light particle“ selection for UHECRs
- Use more specific information from rigidity spectrum (instead of energy spectrum)
- Use asymmetric deflections estimates from GMF models

Pessimistic → Optimistic

Exploring the cosmos, together!

- Analysis Goal: find the most-likely, point-like neutrino source counterparts for each UHECR event
- Presented new method for correlation analysis using UHECR data, deflection estimates and full-sky muon track samples
- Update includes ANTARES‘ 9yr point-source sample to increase sensitivity in the Southern sky

➢ Unblinding neutrino data happend very recently, stay tuned!

➢ Near-future analysis improvements are planned, including 30% more UHECR data as well as detailed single-hotspot analysis

➢ Next steps: optimize analysis technique, refine magnetic deflection estimates, UHECR event selection …

https://www.ntsouthwest.co.uk/wp-content/uploads/2013/11/206-1-Aurora-Borealis-c-Jamie-Cooper.jpg

Thank you!

Likelihood combination of spatially correlated UHECRs and ν

Blue: standard likelihood

Yellow: new combination approach

Fit parameters for each neutrino hotspot:

- Position $\overrightarrow{x_S}$
- #Neutrinos n_S
- Spectral index γ_S

Likelihood product of all single neutrino hotspots after UHECR „prior window“ application

Astrophysical neutrino sources show up as clustering on small scales → neutrino hotspots

Astrophysical energy spectrum $\gamma_S \approx 1.9 \ldots 2.5$

Isotropic background of atmospheric neutrinos and muons inferred from data scrambles

Atmospheric energy spectrum $\gamma_{atm} \approx 3.7$

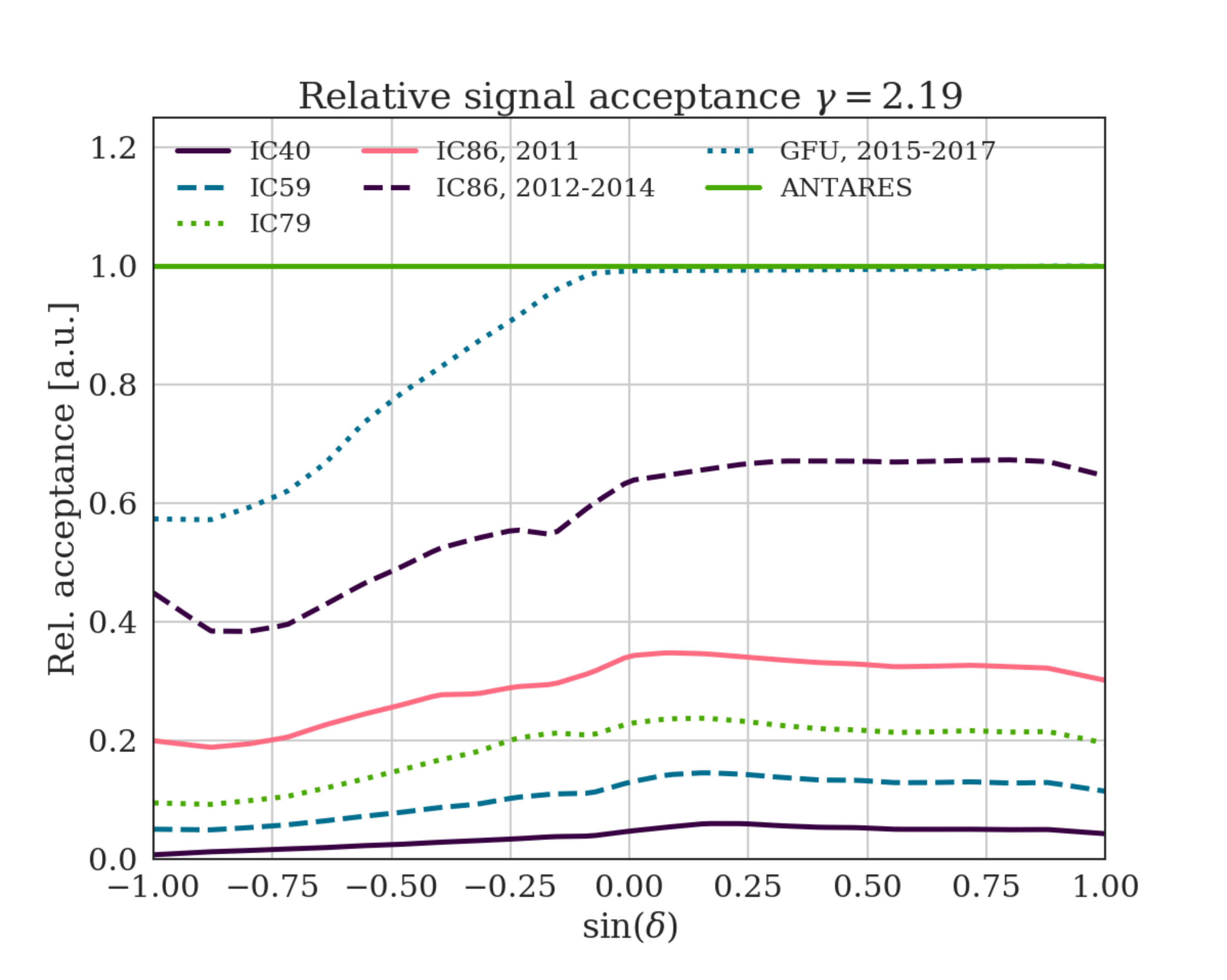
UHECR position/energy well known, composition/rigidity not well known

Construct a „prior window“ from UHECR direction and estimated deflection to search for neutrino point sources

$$\mathcal{L}_{tot} = \prod_{S=1}^{N_{CR}} \mathcal{L}_S(n_S, \overrightarrow{x_S}, \gamma_S) = \prod_{S=1}^{N_{CR}} \prod_{i=1}^{N_\nu} \left(\frac{n_S}{N_\nu} \cdot S_i(\overrightarrow{x_S}, \gamma_S | \mathrm{E_i}) + \left(1 - \frac{n_S}{N_\nu}\right) \cdot B_i(\overrightarrow{x_S} | \mathrm{E_i}) \right) \times P(\overrightarrow{x_S} | \overrightarrow{x_{CR,S}}, E_{CR,S})$$

Combining different neutrino samples

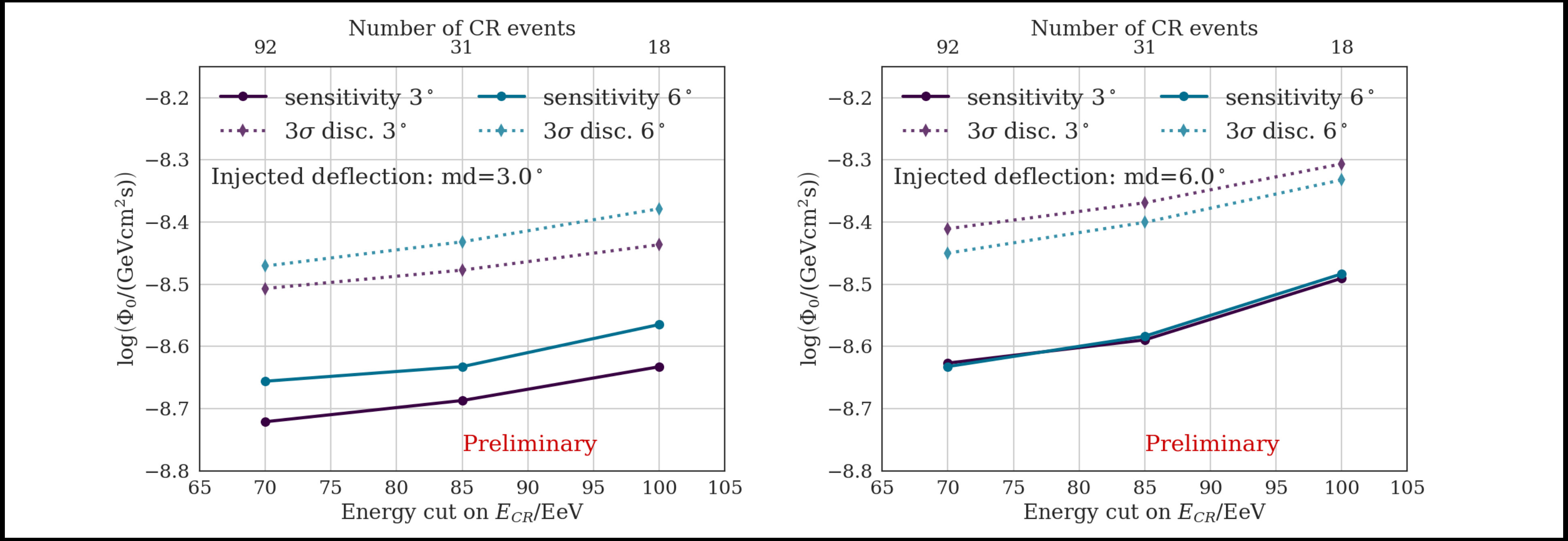
- Exemplarily shown here: relative signal contribution of all data samples, for spectral index = 2.19 calculated from MC
- Combining different samples is a standard procedure in IceCube, since samples with different string configurations and events selections are often used in one analysis
- Relative weight of samples is adjusted during LLH optimization depending on spectral index and declination



Analysis performance – fixed deflection

- Left plot: injected with md=3,
  fit 3° true deflection with 3° prior has best performance, fit 3° with 6° prior performance is worse
- Right plot: injected with md=6,
  fit 6° true deflection with 3° prior affects only discovery potential, sensitivity remains mostly constant as if using 6° deflection + 6° prior
  → may be coincidence, caused by reduced effective trials vs. reduced found sources

➢ Best discovery potential for 3° priors if it‘s the true realization



Analysis performance – fixed energy cut

- From left to right: fixed energy cut for signal injection with [70, 85, 100] EeV
- ➢ Best sensitivity for true ecut=70 EeV, regardless what is used for priors
- ➢ Good discovery potential as long as ecut of priors >= true ecut → such that no signal is lost