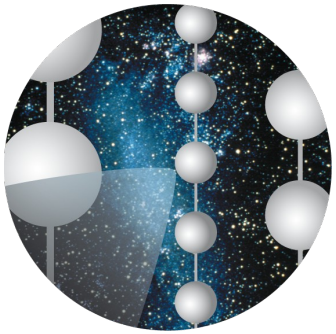
Directional correlations between UHECRs and neutrinos observed with IceCube

22nd European Cosmic Ray Symposium

Turku

August 3rd 2010



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Outline

Introduction - UHECRs and neutrinos

IceCube - Neutrino astronomy

Correlation - Binned method and first results

Outlook - Improved methods and new data samples

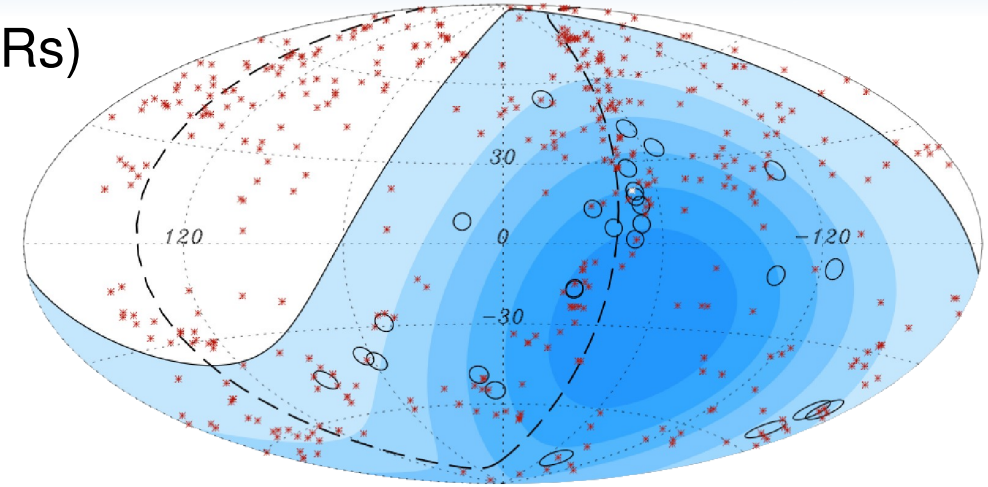
Introduction

Ultra-high energy cosmic rays (UHECRs) charged particles **above a few 10 EeV**:

Low influence of magnetic fields

⇒ arrival directions of allow to identify **source regions with hadronic acceleration**

⇒ possibly **neutrinos from p-p or p-γ**



Abraham et al. (PAO), Science, 2007

Idea: **Correlation between neutrinos (direct path) and UHECR (clear signal) to boost combined significance**

Search objectives:

- Efficient neutrino production in the sources?
- Limited number of strong UHECR accelerators?
- Estimation of interstellar magnetic field deflection possible?

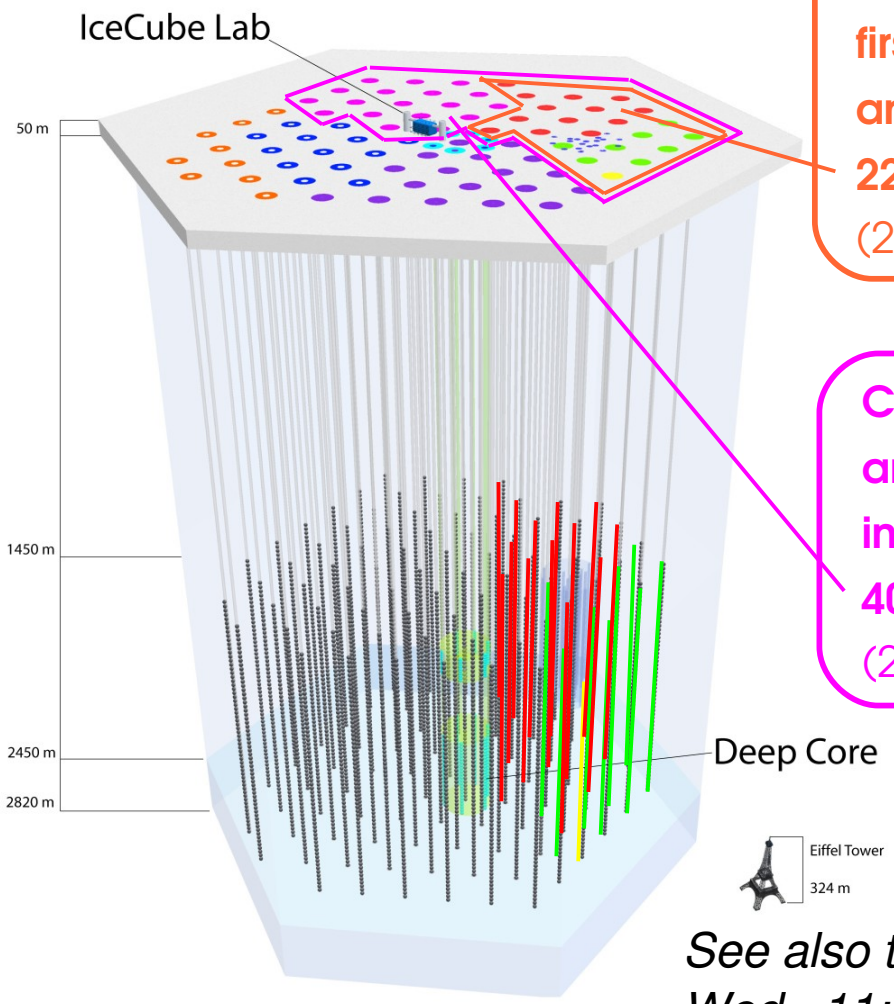
IceCube Observatory

At the surface:

IceTop - Air-shower array
73 stations, 2 tanks each
(2011: 80 stations)

Below the surface: (1.5-2.5 km)

- **79 strings** deployed
  (2011: 86)
- **4740 photomultipliers**
  (2011: 5160)
- incl. 6 **DeepCore** strings



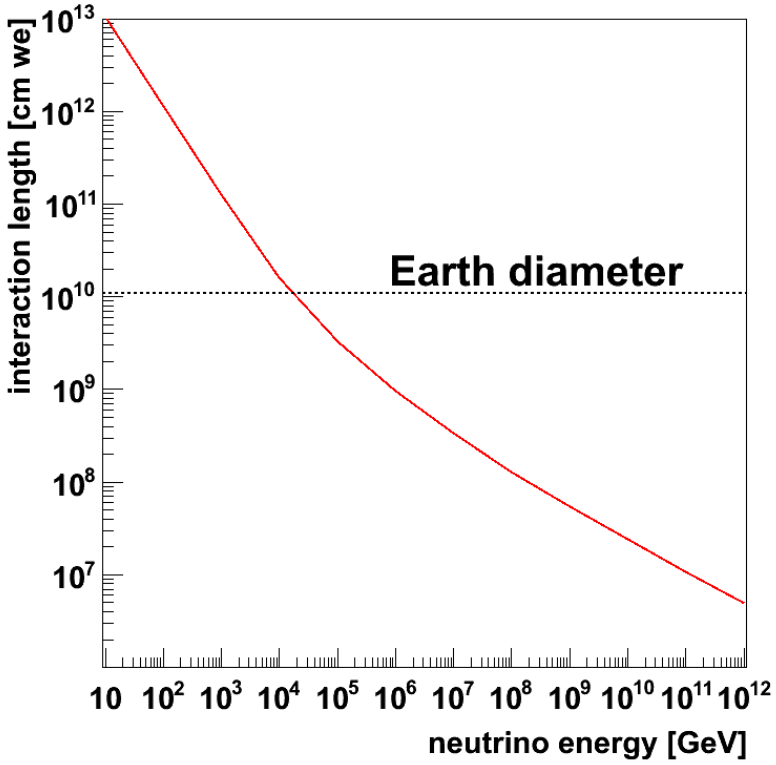
Used for the first correlation analysis: 22 strings (2007-2008)

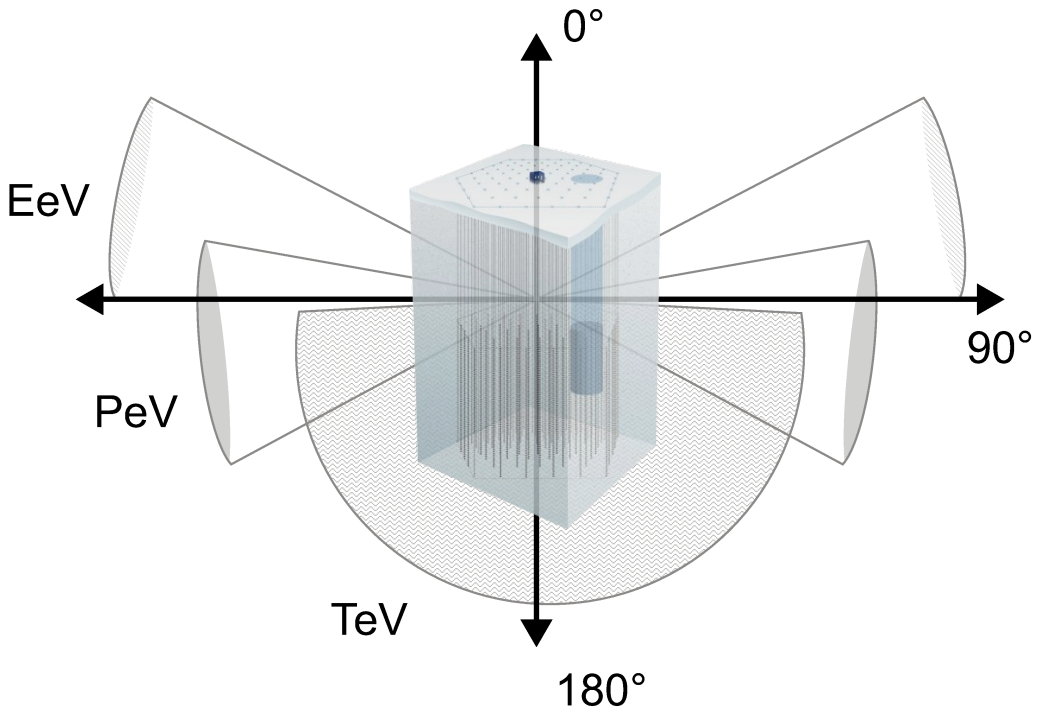
Correlation analysis being prepared: 40 strings (2008-2009)

See also talk by T.Karg: Wed., 11:00 (2A_Pa2)

IceCube – above the horizon

Zenith cut at the horizon **disfavours** neutrinos with **energies above a few PeV!**

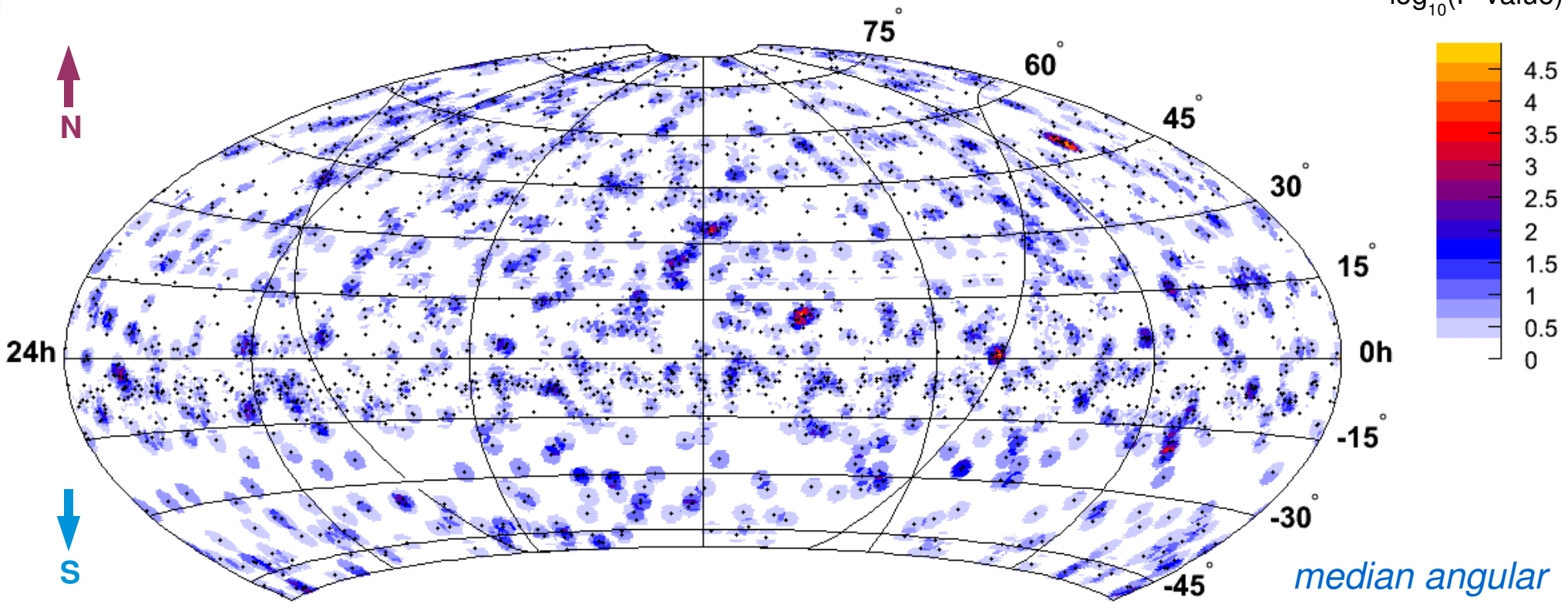




Including events from above the horizon opens the **PeV to EeV energy range!**

IceCube 22 strings standalone search

Published in: *Abbasi et al. (IceCube), Phys. Rev. Lett. 103, 2009*



*median angular resolution: **1.3°***

Max. excess: Dec. 1.00°, RA 103.5°

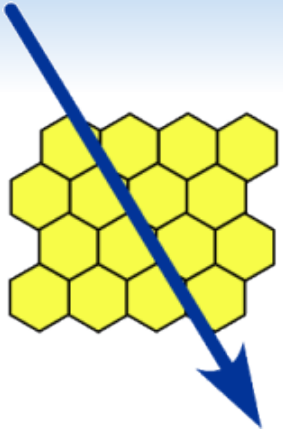
P-value: **$2.9*10^{-5}$** (pre-trial prob.)

Bin content: **8 events with 1.2 expected** (109 in dec. band)

Not significant - Trial-corrected probability** for a random excess of this magnitude is **37 %.

UHECR data

Pierre Auger Observatory



HiRes

Status 2007:

27 events above 57 EeV

- additional events observed after August 2007 were not released for the first search but will be included in next
- Anisotropy observed at 99% CL
- Mostly covering the southern sky
- AGN correlation not regarded here

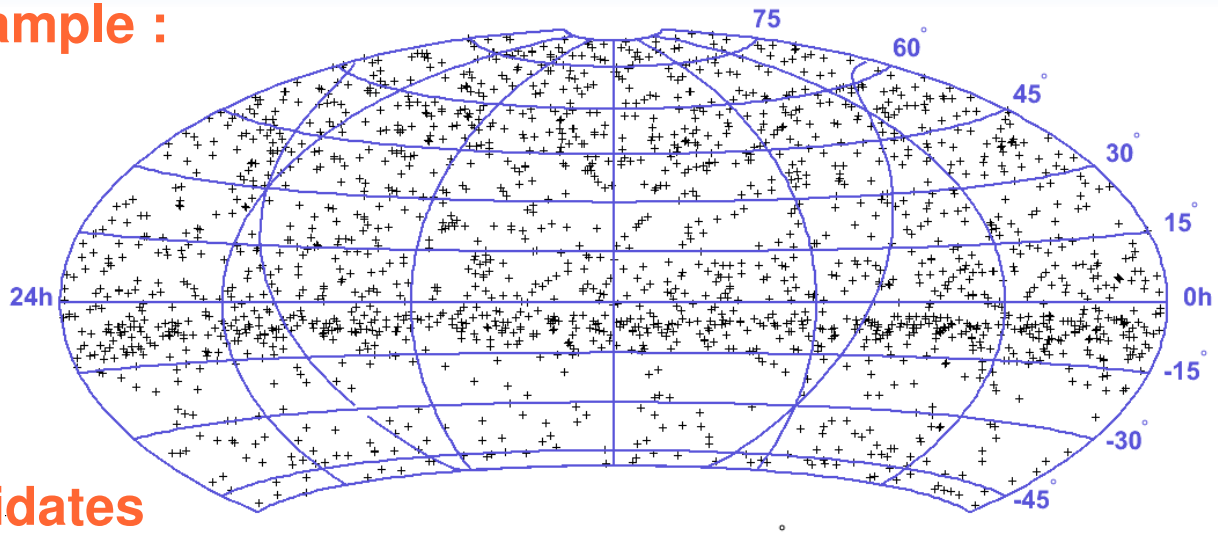
13 (stereo) events above 56 EeV

- energy threshold chosen as in PAO (corrected for calibration offset)
- No anisotropy observed
- Mostly covering the northern sky

Correlation search with 22 strings

IceCube UHE point source sample :

- 1885 events (atm. muons & neutrinos)
- declinations - 50° to + 90°

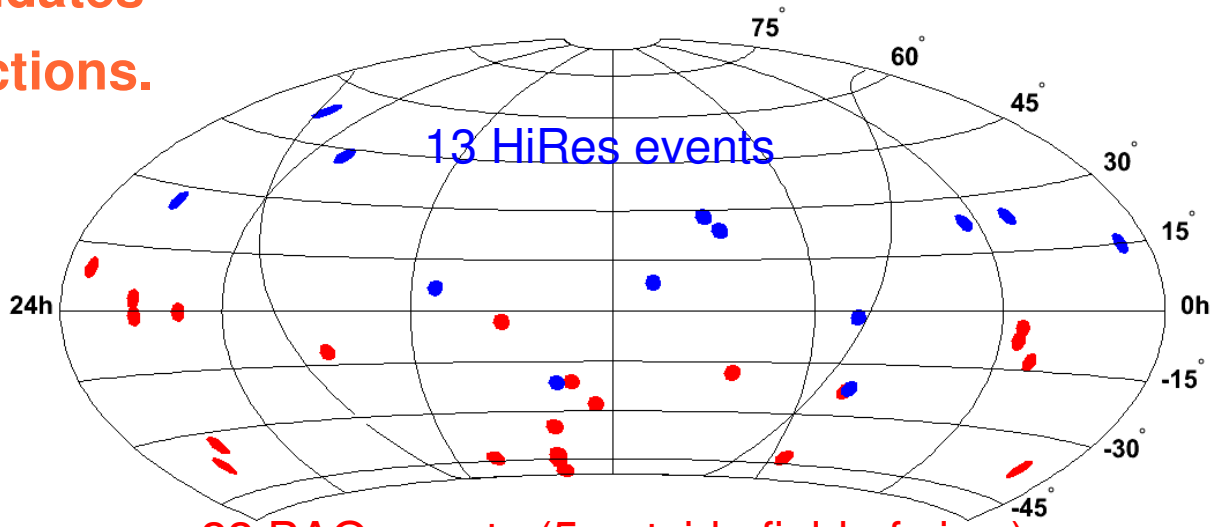


Stacking principle:

Count IceCube **neutrino candidates in bins around UHECRs directions.**

Comparison to randomized maps gives significance of possible excess.

⇒ **Straight-forward result on degree of correlation**



Correlation search with 22 strings

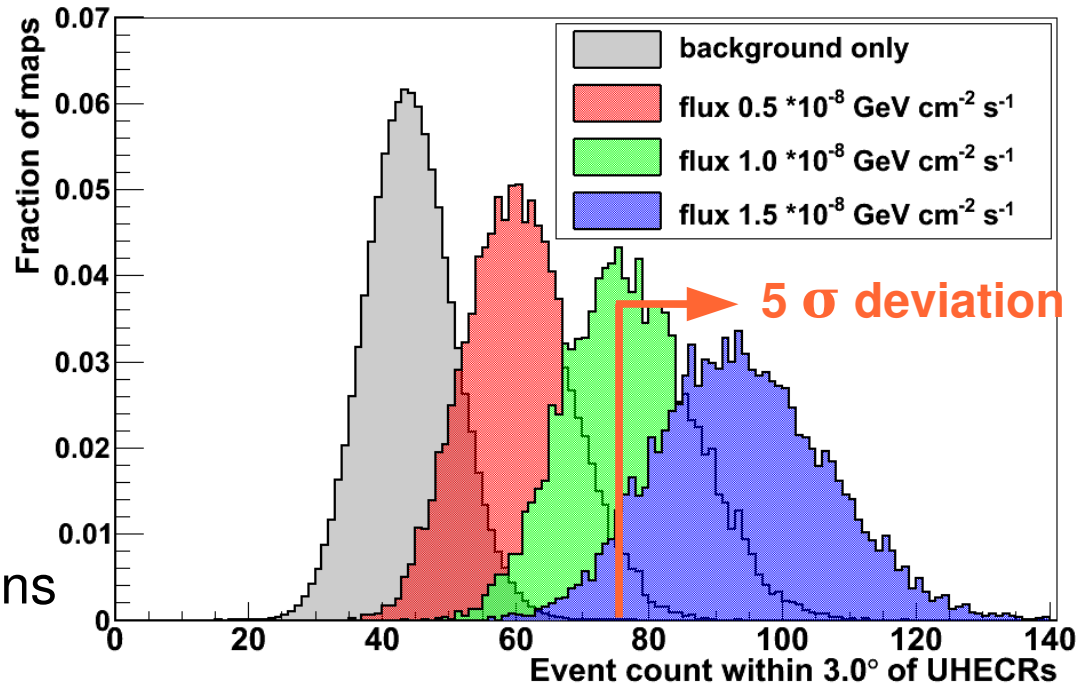
Sensitivity calculation based on **sky maps with added neutrino signals**:

- assuming **equal neutrino fluxes** from all UHECR directions
- accounting for **point spread function and declination dependence** of IceCube

Magnetic deflection of UHECRs:

Position uncertainty implemented as **random shifts of sources** relative to UHECRs

- **gaussian distance profile**
- **width of 3°** for average shift
- effects of weaker/stronger deflections were studied



UHECR correlation results

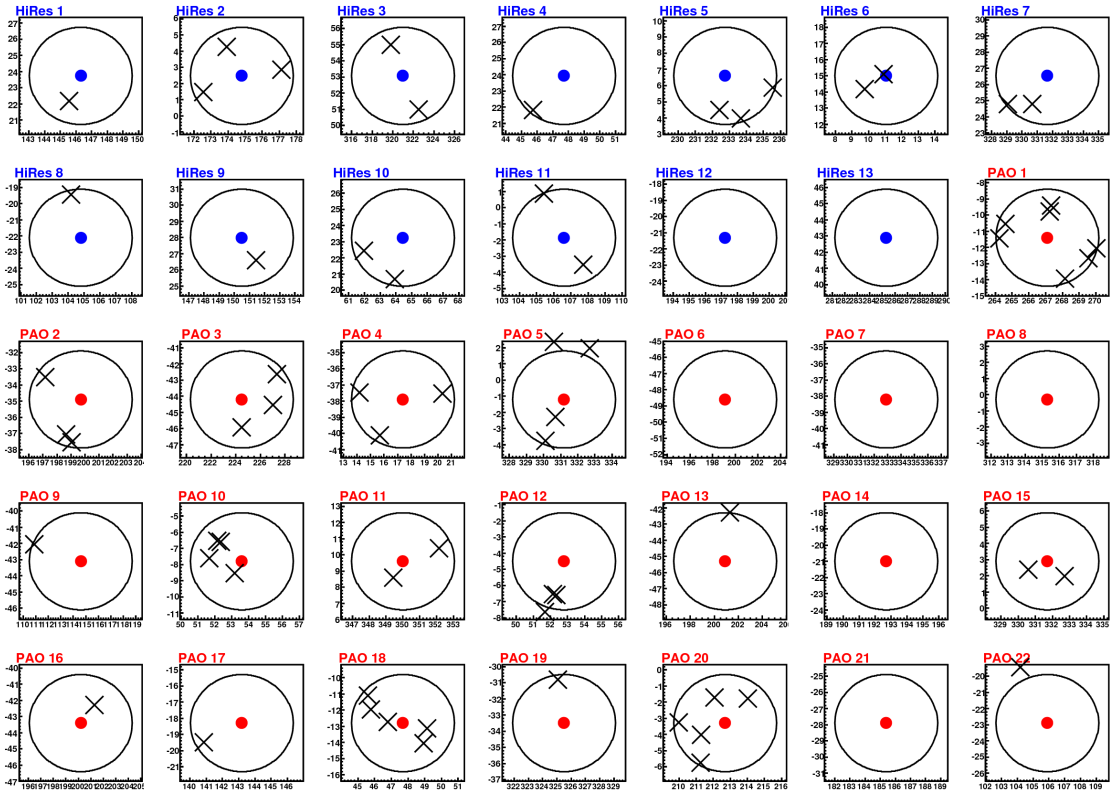
Preliminary

Total IceCube event count
in 35 bins (3° radius): **60**

Mean expectation from scrambled background: 43.7

excess probability: **0.98%** (2.33 σ)

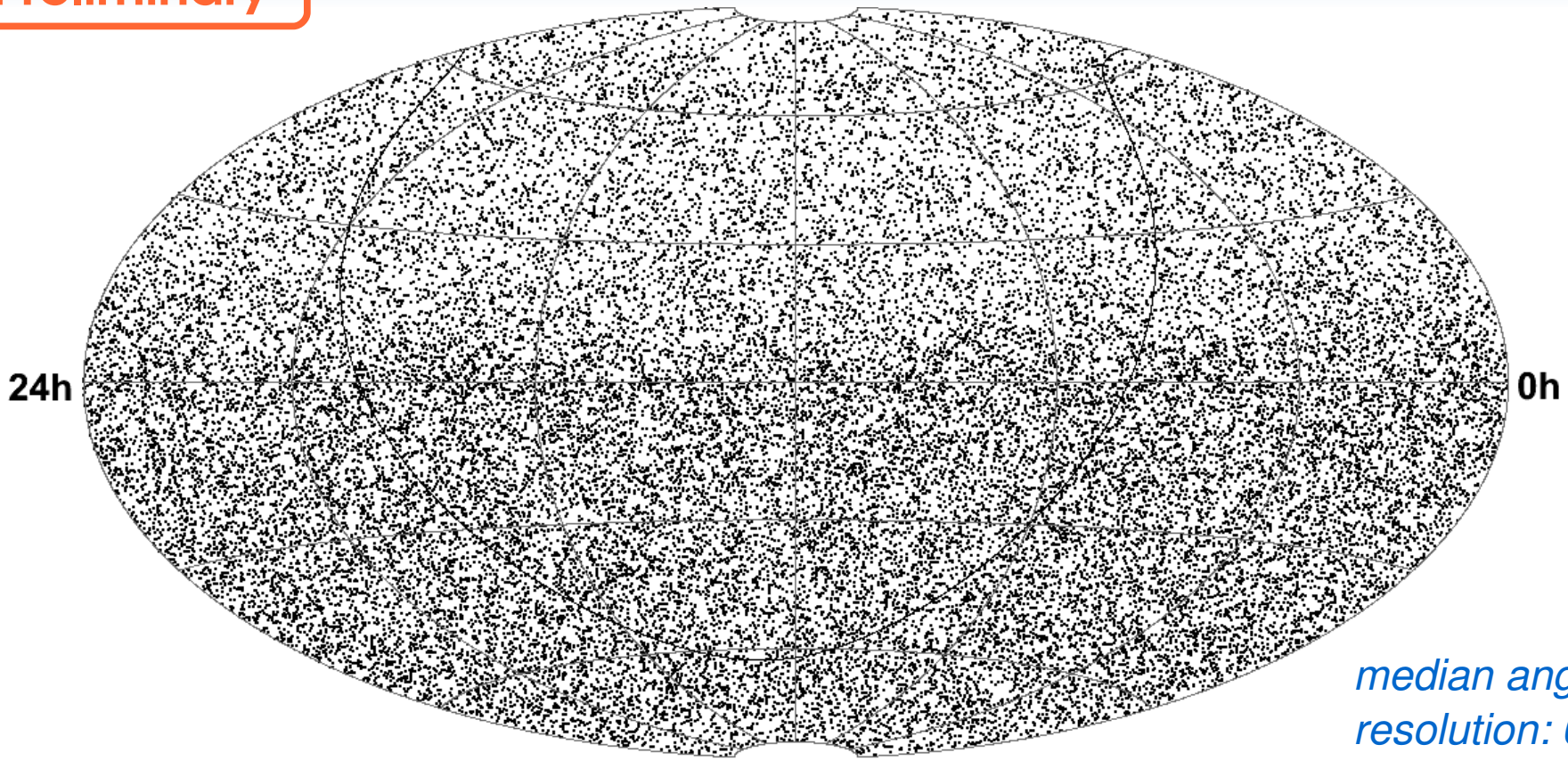
This excess is **compatible with background fluctuations**.



Approximate **neutrino flux limit per source: 0.9 x 10^{-8} GeV cm^{-2} s^{-1}**

IceCube 40 strings

Preliminary



median angular resolution: ***0.5°***

IceCube standalone point source search:

Max. excess: Dec. 15.15°, RA 113.75°

Not significant - Trial-corrected probability *for a random excess of this magnitude is* ***18 %.***

Unbinned likelihood method

Unbinned correlation method based on **likelihood maximisation:**

$$L(\{\mathbf{x}_u\},\gamma,n_s)=\prod_i\left(\frac{n_s}{n_{\rm tot}}\sum_{j=1}^{M}R(j,\gamma)S_i^j(\mathbf{x}_i,E_i,\gamma)\Big/\sum_{k=1}^{M}R(k,\gamma)+\left(1-\frac{n_s}{n_{\rm tot}}\right)B(\mathbf{x}_i,E_i)\right)$$

Sum over UHECR directions

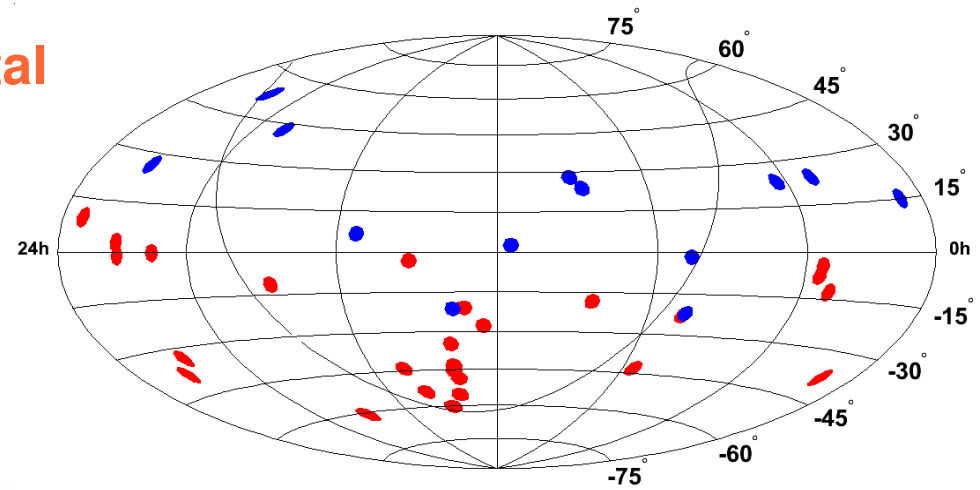
Relative weights due to IceCube declination dependence

Source p.d.f. Depending on position and energy

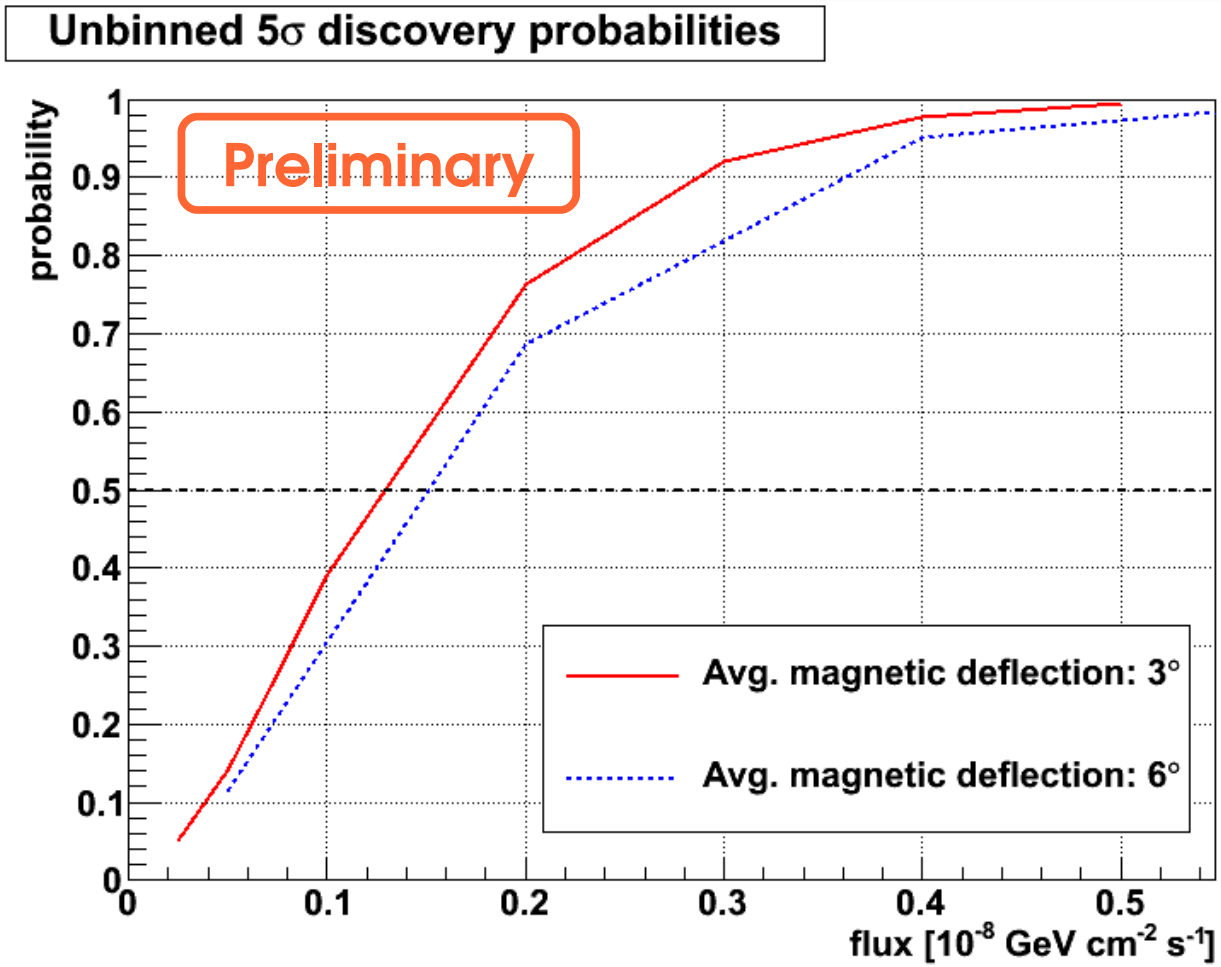
Background p.d.f. obtained from data

Based on the stacking principle, **one total number of signal neutrinos and one common spectral index are fitted.**

IceCube 40 strings covers full sky:
All 40 UHECRs accessible



Discovery potential with 40 strings



Flux per source required for a 50% chance of 5σ:

0.13×10^{-8} GeV cm^{-2} s^{-1}

equivalent to an average of 16.6 neutrinos in total from all 40 sources

Improvement compared to binned IC-22: ~ factor 7

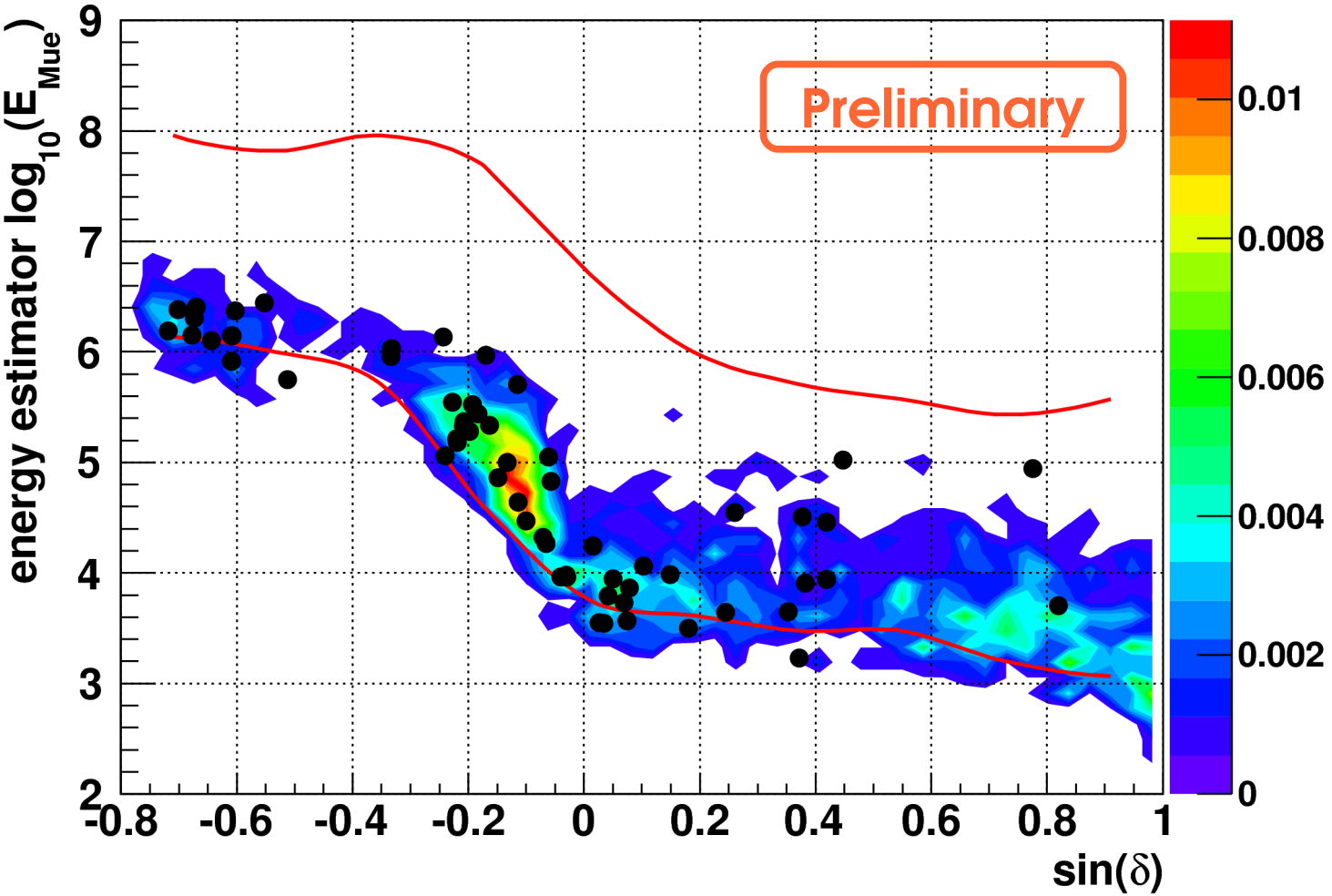
For larger magnetic shifts: Only 15 % worse for avg. deflection twice as large

Summary and outlook

- **The first high statistics all-sky correlation search between ultra-high energy cosmic rays and neutrinos has been performed.**
- **The observed excess of neutrino candidates near cosmic ray directions is not significant.**
- **An extended search based on new IceCube data from 40 strings is in preparation, based on a likelihood approach.**
- **The analysis is being generalized to include the new events expected to be released soon by the Pierre Auger Collaboration.**

Backup Slides

UHECR correlation results

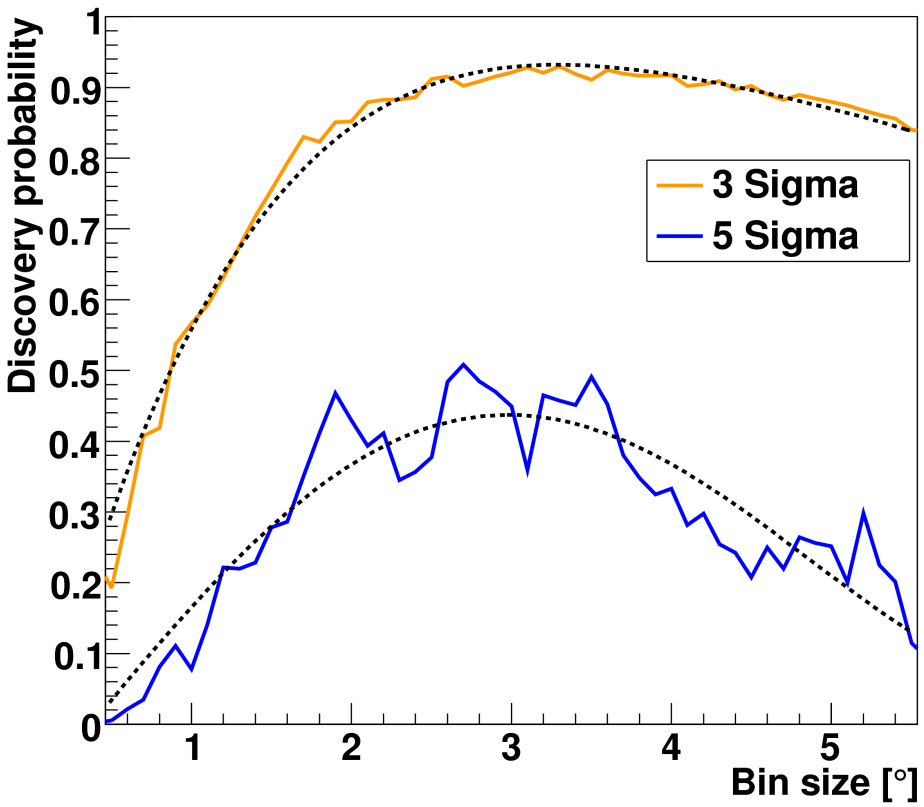


90% containment of simulated E^{-2} neutrino spectrum

Estimated energies over declination for the **60 correlated events**

Colored contour shows distribution of all background events

Bin optimization

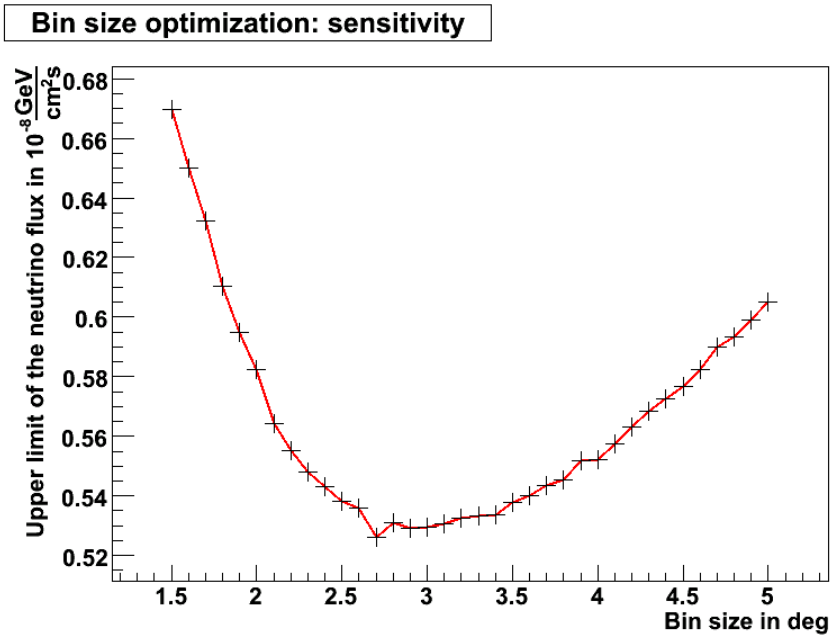


Bin radii optimized for

discovery potential

(fixed flux per source)

⇒ bin radius 3.0°



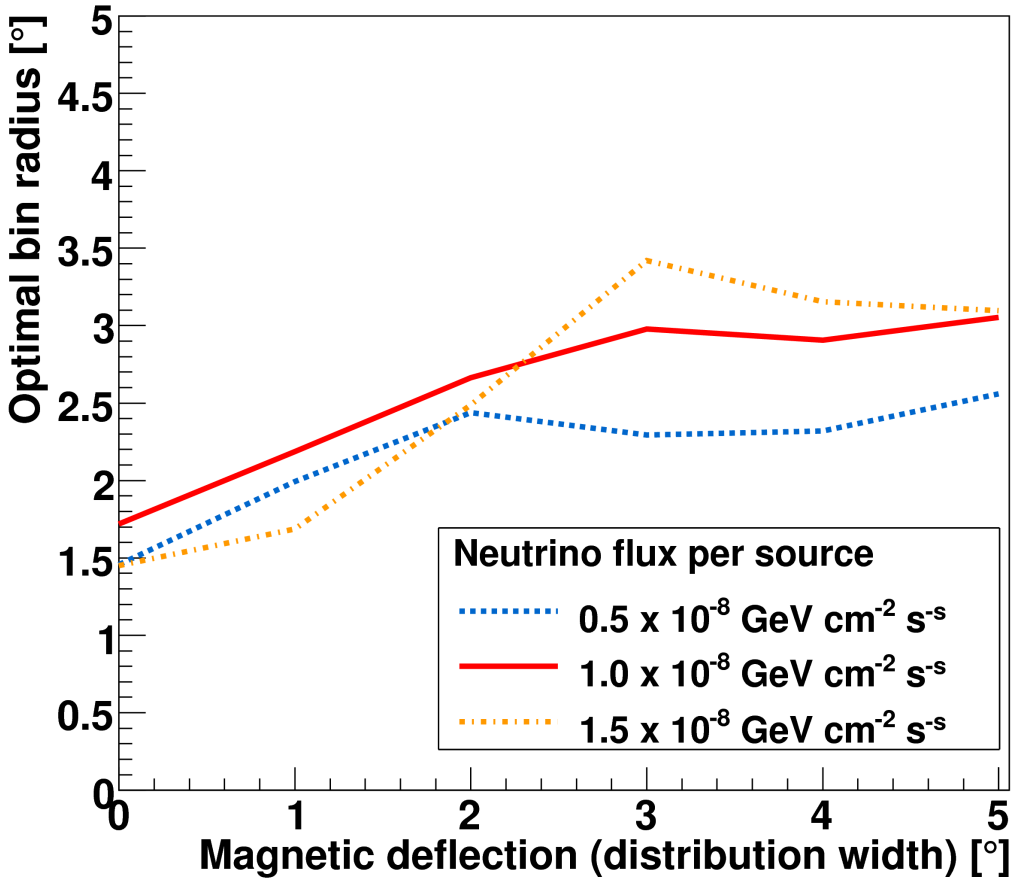
chosen bin size is also close to optimal Sensitivity (90% F&C)

(for equal flux from all sources)

Bin optimization

Varying the simulated deflection

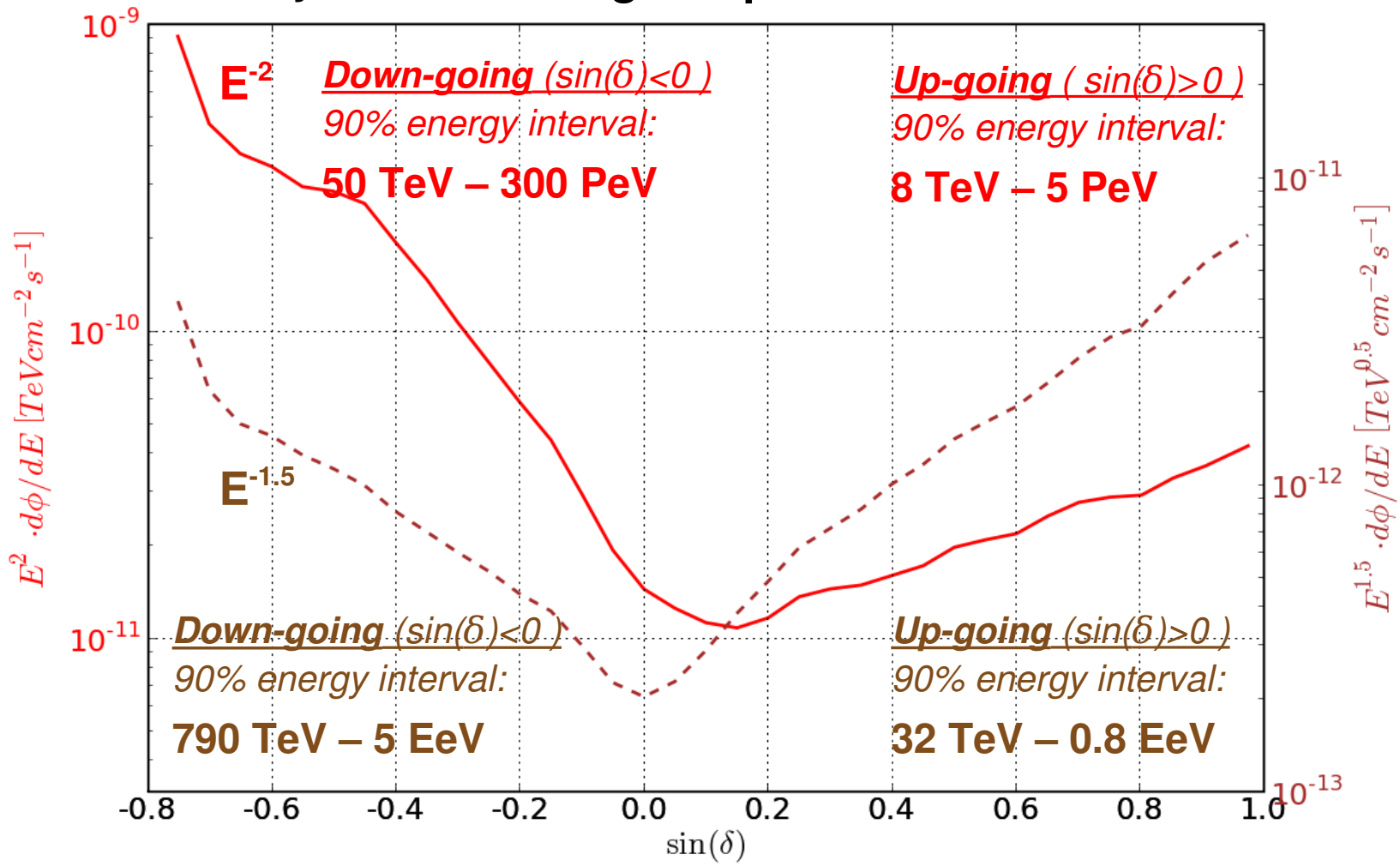
Width of distribution for generation of shifts varied between 0° and 5°



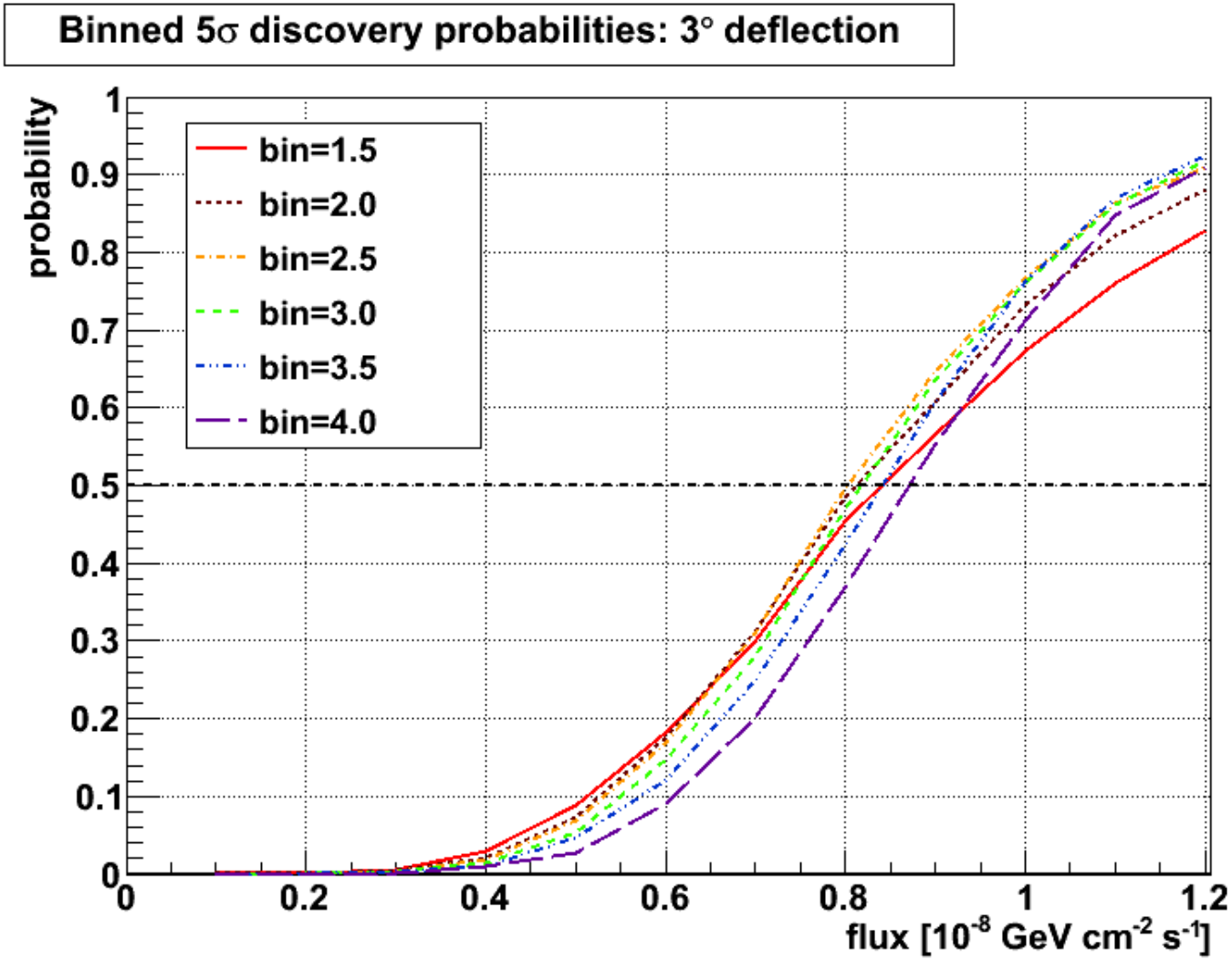
⇒ **Optimal bin size stabilizes for larger deflections**

22 strings point source sensitivity

Sensitivity to neutrino signal spectra:



Binned search with 40 strings



Correlation likelihood – source term

$$S^j_{i,spatial}(|\mathbf{x}_i - \mathbf{x}^j_u|) = \frac{1}{2\pi\sigma_i^2} \int d\mathbf{x_s^j} \; \frac{1}{2\pi\sigma_m^2} \exp\left(-\frac{|\mathbf{x}^j_s - \mathbf{x_u^j}|^2}{2\sigma_m^2}\right) \exp\left(-\frac{|\mathbf{x}_i - \mathbf{x_s^j}|^2}{2\sigma_i^2}\right)$$

Magnetic deflection

IceCube point spread function

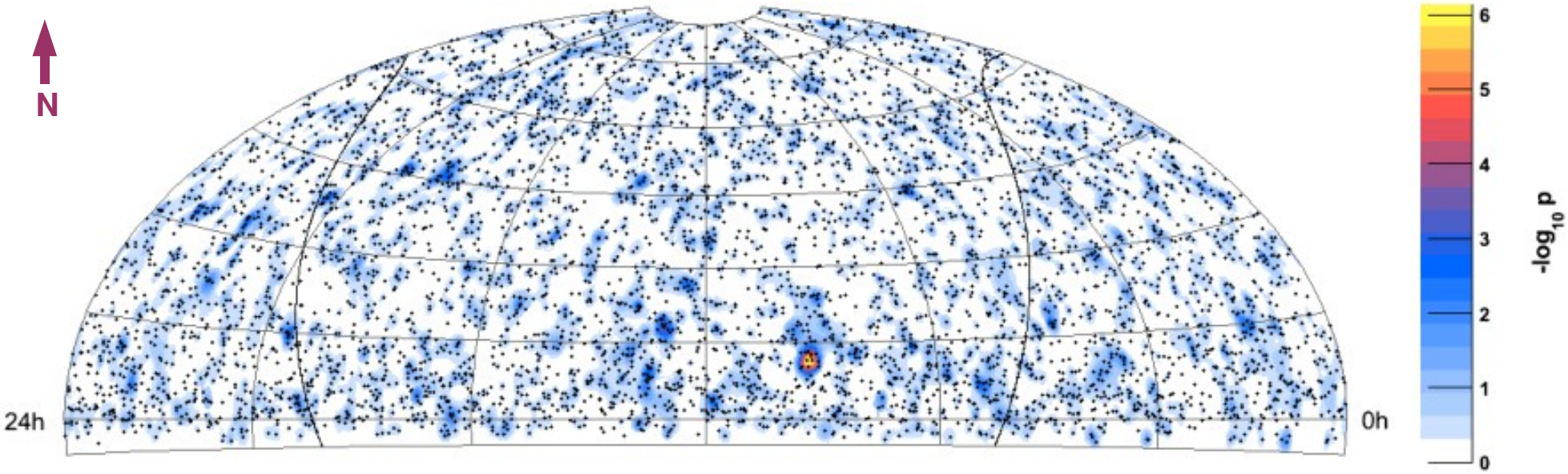
Convolution of two gaussian functions:

$$S^j_{i,spatial}(|\mathbf{x}_i - \mathbf{x}^j_u|) = \frac{1}{2\pi\sigma^2_{conv}} \exp\left(-\frac{|\mathbf{x}_i - \mathbf{x}^j_u|^2}{2\sigma^2_{conv}}\right)$$

$$\sigma^2_{conv} = \sigma^2_m + \sigma^2_i$$

IceCube 22 strings – Northern sky

Published in: *Abbasi et al. (IceCube), Astrophys.J .701, 2009*



Max. excess: Dec. 11.375°, RA 153.375°

P-value: **7.2*10^{-7}** (pre-trial prob.)

Trial-corrected probability for a random excess of this magnitude is 1 %, i.e. not significant.