Very Large Volume Neutrino Telescope

VLVνT workshop

PIERRE AUGER OBSERVATORY

Correlation between the UHECRs measured by the Pierre Auger Observatory and Telescope Array and neutrino candidate events from IceCube

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TELESCOPE ARRAY PROJECT

Multi Messenger Astronomy

$$p + \gamma_{\text{or } p\ldots} \rightarrow \pi^0 + p \rightarrow \gamma + \gamma + p$$
$$\rightarrow \pi^+ + n \rightarrow \mu^+ + \nu_\mu + n \rightarrow e^+ + \bar{\nu}_\mu + \nu_e + \nu_\mu + n$$

Neutrinos

- Gamma Rays

Limited range, ambiguous origins

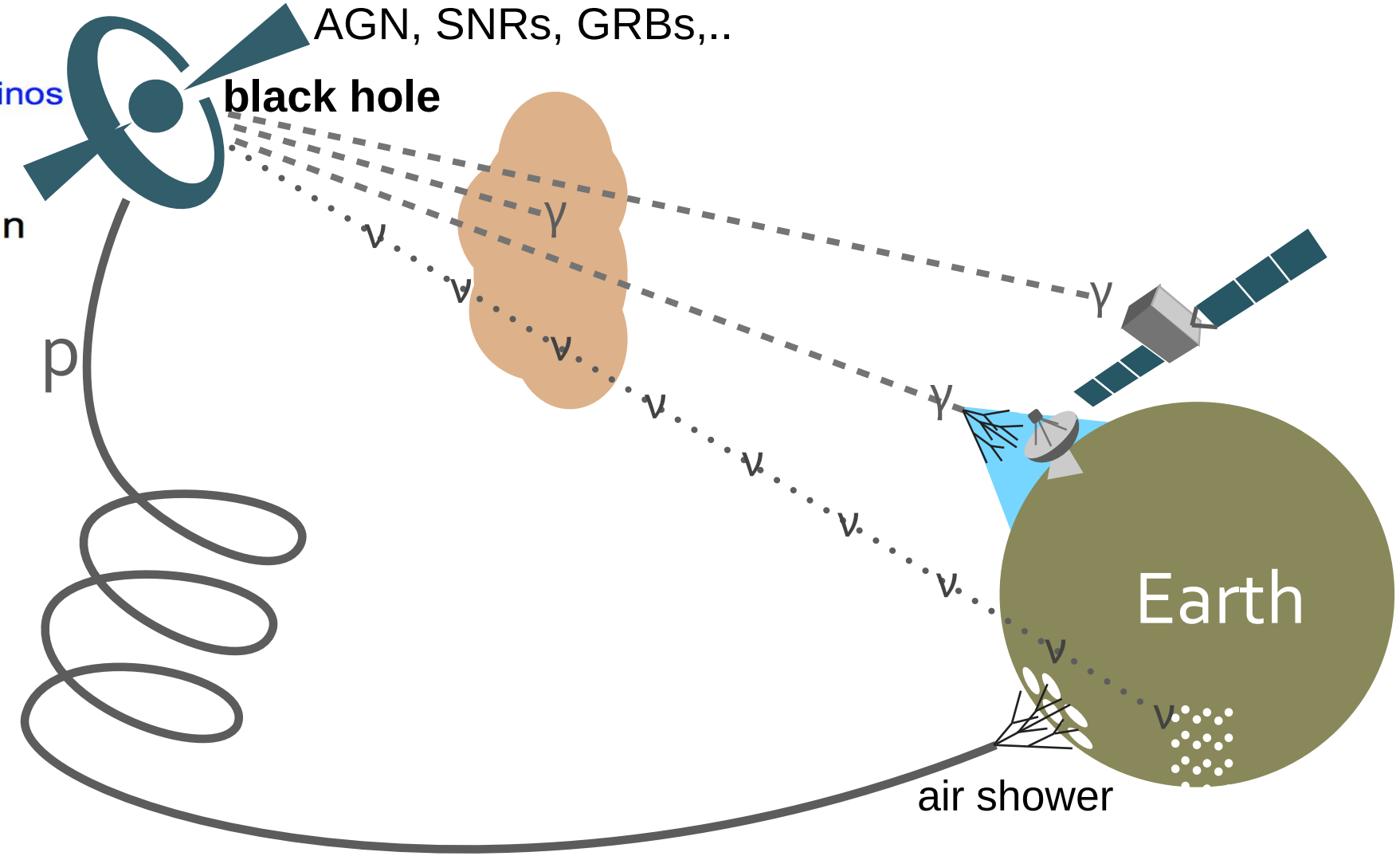
- COSMIC RAYS

Deflected by magnetic fields (E < 10^{19} eV)

- NEUTRINOS

Infinite range

Points back to CR source



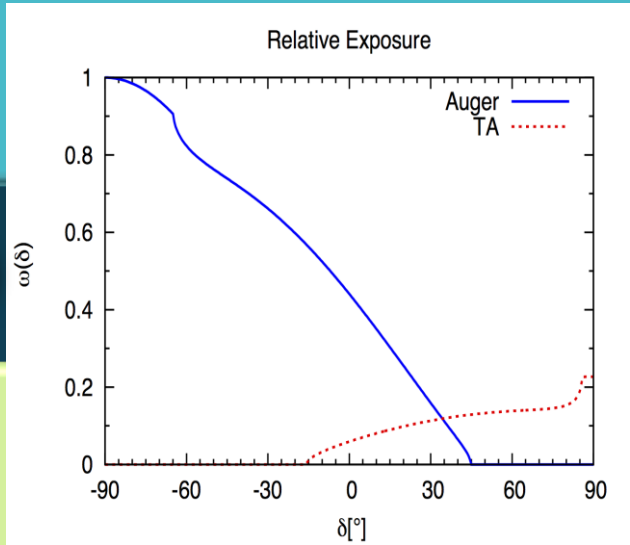
In the era of Auger and TA…

PIERRE AUGER OBSERVATORY

231 events above 52 EeV
between 2004 and 2014
Maximum zenith angle 80°

Angular resolution: 0.9°

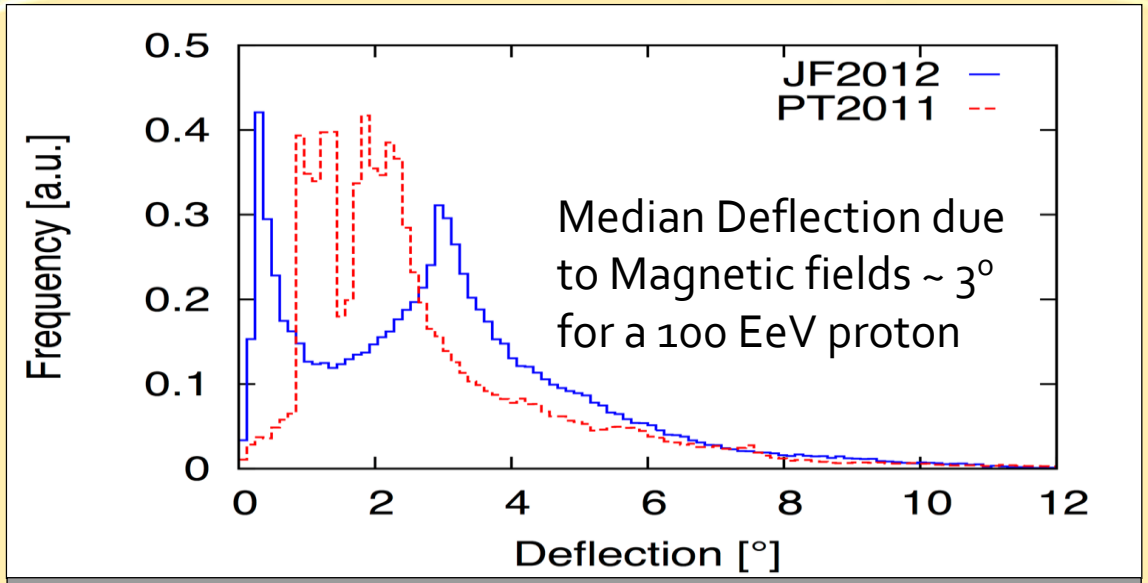
318 Events in Total



TELESCOPE ARRAY PROJECT

87 events above 57 EeV
between 2008 and 2014
Maximum zenith angle 55°

Angular resolution: 1.5°



PT2011: Pshirkov, Tinyakov, Kronberg, Newton-McGee, Astrophys. J. 738 (2011) 192.
JF 2012: Jansson, Farrar, Astrophys. J. 757 (2012) 14.

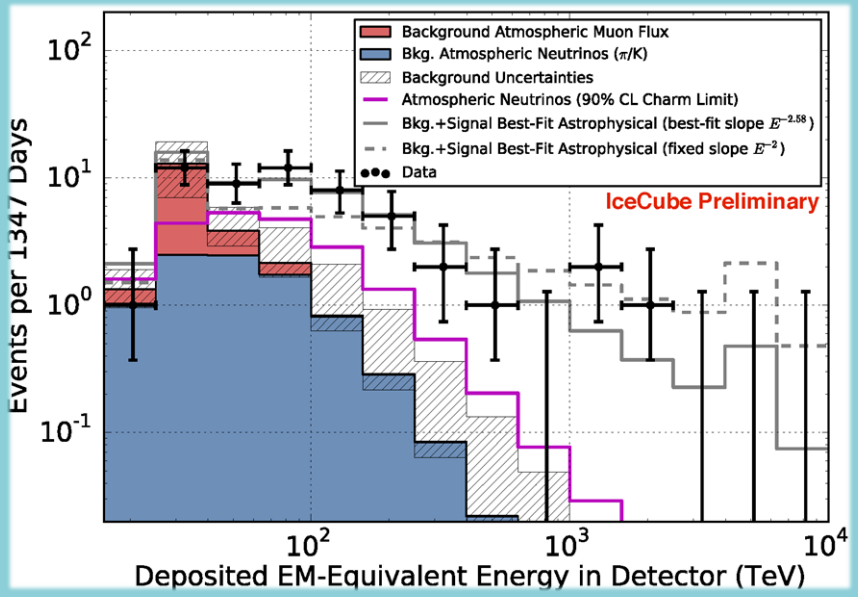
$\sigma_{MD} = D \times 100\ \mathrm{EeV}/E_{CR}$

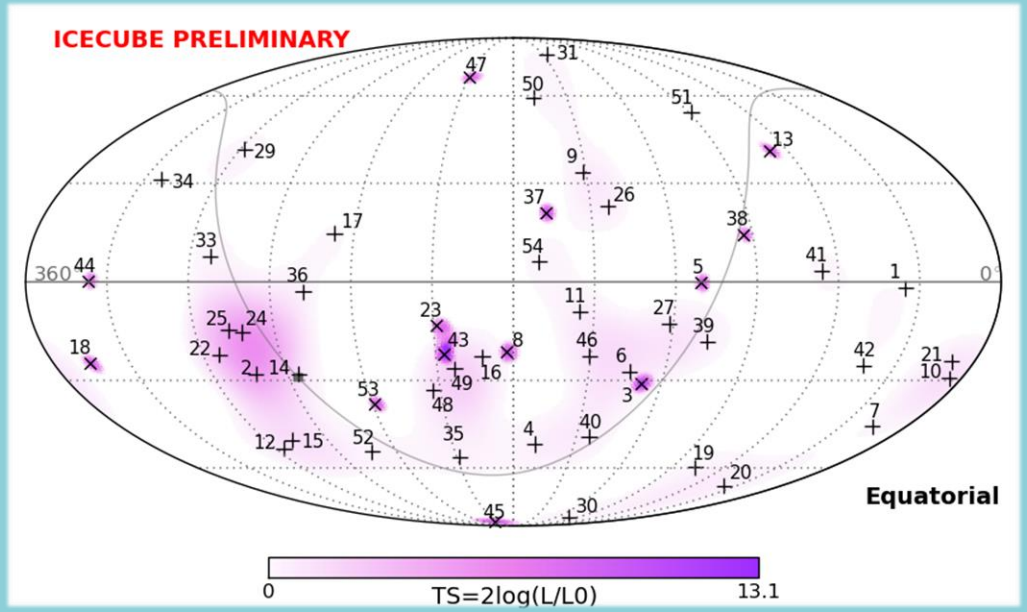
TA Hotspot (RA 146.7°, DEC 43.2°) 3.4σ
ApJ 790 L21 2014

… UHECRs can possibly point back!

The IceCube astrophysical ν flux

Contained All Flavour (HESE)
IC79 + 3xIC86



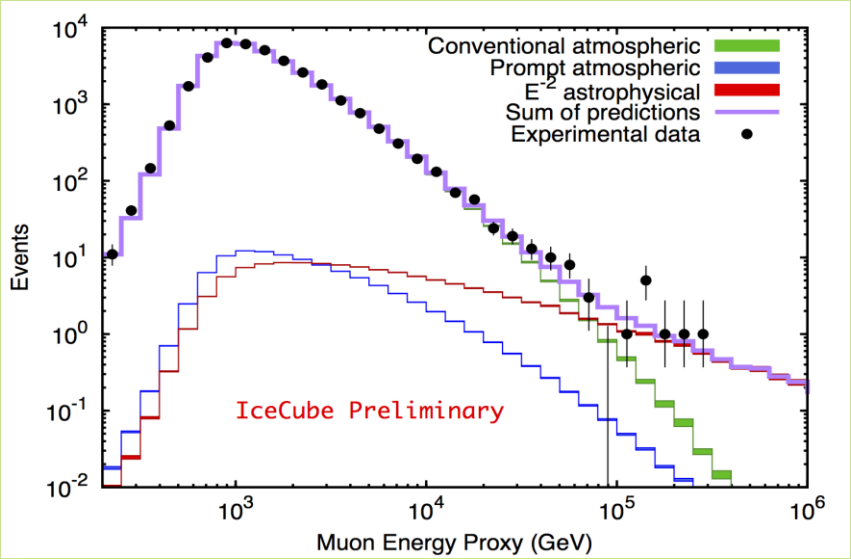


39 Cascades

15 Tracks

(Select 7)

Upgoing Muons
IC79 + IC86



9 Events (tracks) above 100 TeV

39 Cascades

16 Tracks

For this analysis

Global flux level consistent with Waxman Bahcall Limit

So far no statistically significant clustering

Three Analyses

- Are the arrival directions of the UHECRs and neutrinos correlated?

Cross correlation analysis -> Separate for tracks and cascades
- Model independent – no assumption on magnetic deflections

- Do the neutrinos point back to the sources of the UHECRs?

Likelihood stacking -> Separate for tracks and cascades
- Targets specific magnetic deflection hypotheses

UHECR x High Energy Tracks and Cascades

- Are there neutrino point sources in the arrival directions of the highest energy UHECRs?

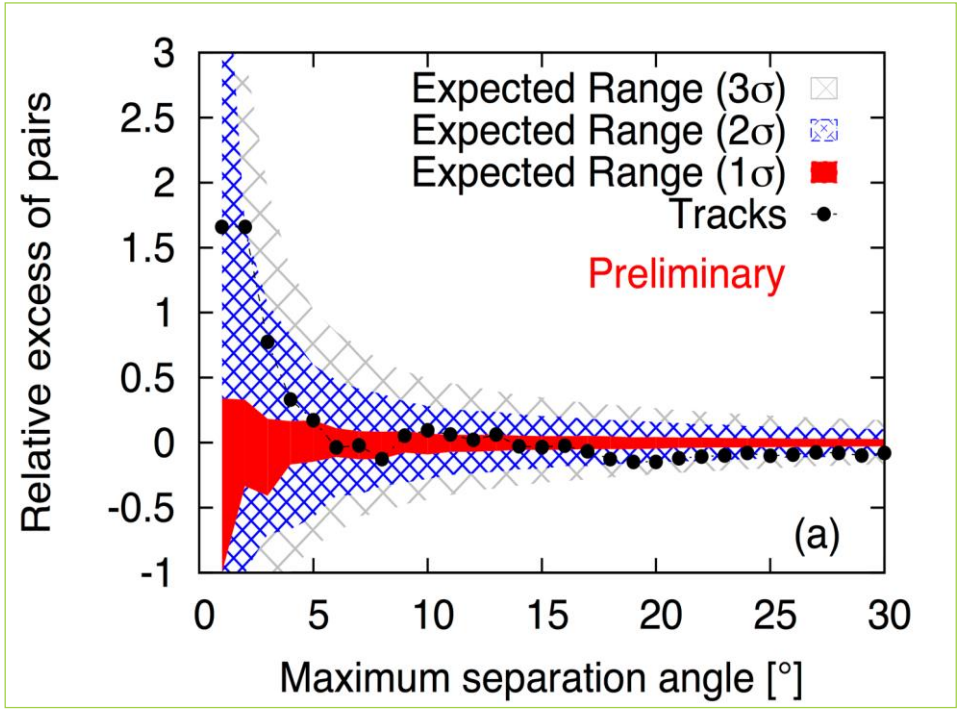
Likelihood stacking of the UHECRs on the IceCube Point Source Sample
- Looks for excesses in TeV neutrinos

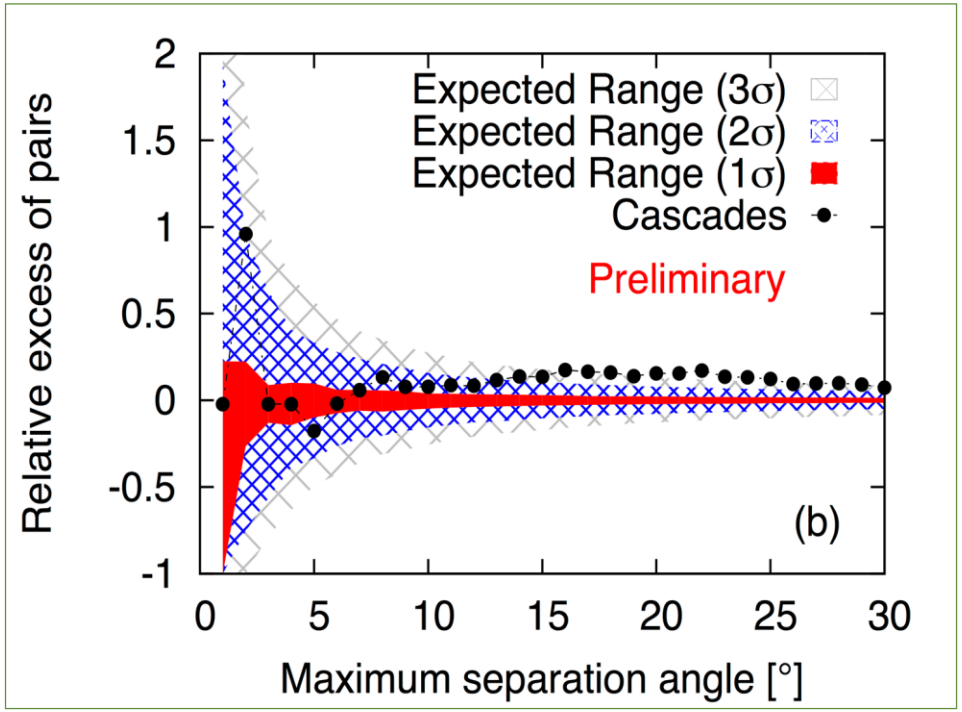
UHECR x Point Source Sample

Cross Correlation Analysis

Compute the number of UHECR-neutrino pairs as a function of the angular separation in the data and compare it with expectations from an isotropic distribution of UHECRs.

Relative excess of pairs: $[n_p(\alpha)/\langle n_p^{iso}(\alpha)\rangle] - 1$





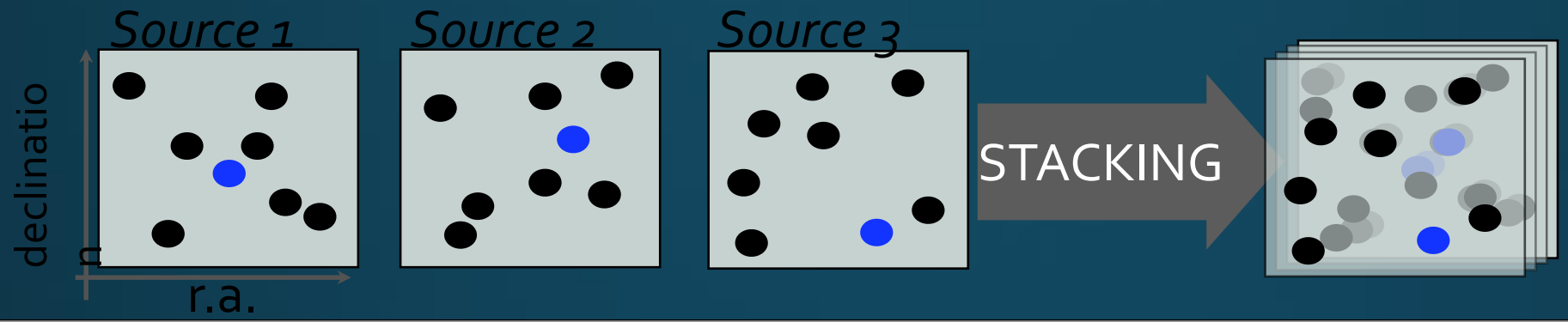
Tracks

minimum at 2^0, n_p=4, $\langle n_p^{iso}\rangle$= 1.5,
post-trial p-value=0.34
with respect to an isotropic flux of CRs.

Cascades

minimum at 22^0, n_p=575, $\langle n_p^{iso}\rangle$= 490.3,
post-trial p-value=5 x 10^{-4} (3.3 σ)
with respect to an isotropic flux of CRs.

Likelihood stacking the high-energy cascades and tracks



The neutrino positions are the “stacked sources”, and the results are compared to those from an isotropic distribution of CRs.

$$\ln \mathcal{L} = \sum_{i=1}^{N_{\mathrm{Auger}}} \ln \left(\frac{n_{sCR}}{N_{\mathrm{tot}}} S_i^{\mathrm{Auger}} + \frac{N_{\mathrm{tot}} - n_{sCR}}{N_{\mathrm{tot}}} B_i^{\mathrm{Auger}} \right) + \sum_{i=1}^{N_{\mathrm{TA}}} \ln \left(\frac{n_{sCR}}{N_{\mathrm{tot}}} S_i^{\mathrm{TA}} + \frac{N_{\mathrm{tot}} - n_{sCR}}{N_{\mathrm{tot}}} B_i^{\mathrm{TA}} \right)$$

Signal PDF: the magnetic deflection and the neutrino spatial PDFs have to be accounted for:

Background PDF: geometric exposure

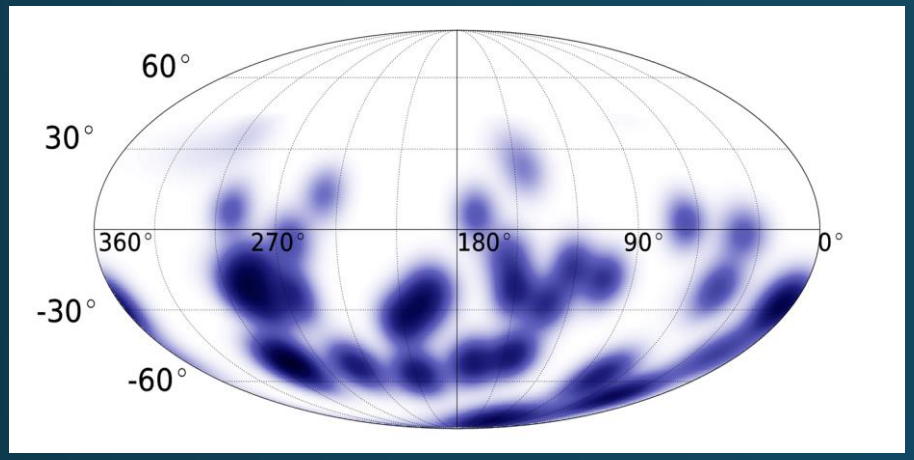
$$N_{\mathrm{tot}} = N_{\mathrm{Auger}} + N_{\mathrm{TA}}$$

$$S_i = \sum_{j=1}^{N_\nu} \omega(\delta_i) S_i^j(ra_i, \delta_i, \sigma_{MD}(E_i))$$

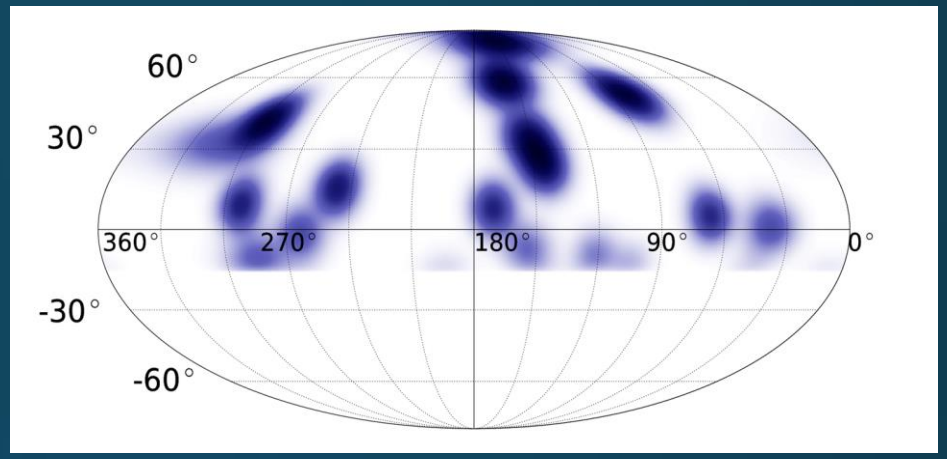
A PDF for a single CR and a single neutrino: takes into account the neutrino map and the magnetic deflection

Neutrino maps

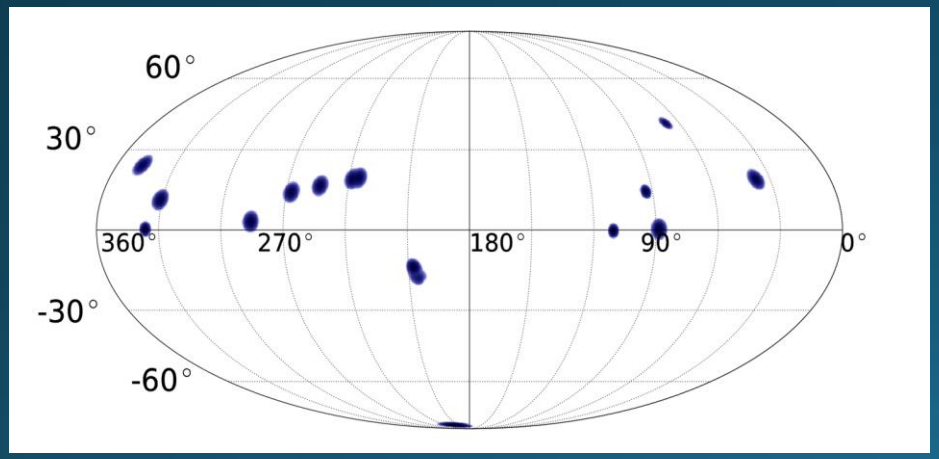
Auger exposure, high-energy cascades



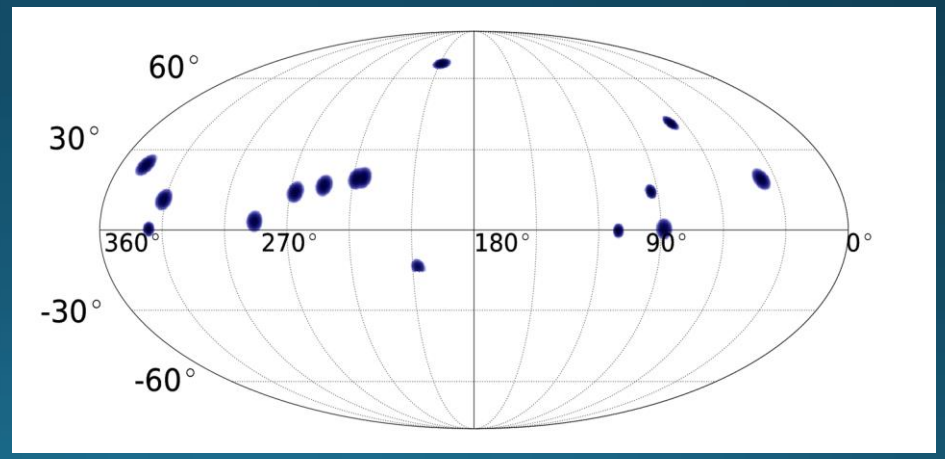
TA exposure, high-energy cascades



Auger exposure, high-energy tracks



TA exposure, high-energy tracks



Signal PDFs taking into account the exposure of the CR observatories, in equatorial coordinates.

Likelihood stacking the high-energy cascades and tracks - Results

D	Tracks		Cascades	
	$n_{s_{CR}}$	pre-trial p-value	$n_{s_{CR}}$	pre-trial p-value
3°	4.3	0.22	53.7	2.1×10^{-3}
6°	0.5	0.48	85.7	2.7×10^{-4}
9°	-	under-fluctuation	106.1	3.8×10^{-4}

Cascades, D=6°:

post-trial p-value = 8×10^{-4} (3.2 σ)
with respect to an isotropic flux of CRs.

This is consistent with the results of the cross-correlation analysis.

A posteriori tests

Cross Correlation Analyses - Cascades

- P – value w.r.t. different null hypothesis : Isotropic neutrinos (scramble cascades in R.A.) – preserves the TA hotspot in each scrambled trial: 8.5×10^{-3} (post trial) (2.4 σ)

- separating the data of Auger and TA
  - TA: p-value of 9.3×10^{-4} @ 22^0 (post-trial) w.r.t the Isotropic CR hypothesis
  - Auger: p-value of 4.1×10^{-4} @ 22^0 (post-trial) w.r.t the Isotropic CR hypothesis

  Hence, both results reinforce each other when considering the entire UHECR data set.

Likelihood Stacking - Cascades

- P – value w.r.t. different null hypothesis : Isotropic neutrinos (scramble cascades in R.A.) – preserves the TA hotspot in each scrambled trial: 1.3×10^{-3} (post trial) (3.0 σ)

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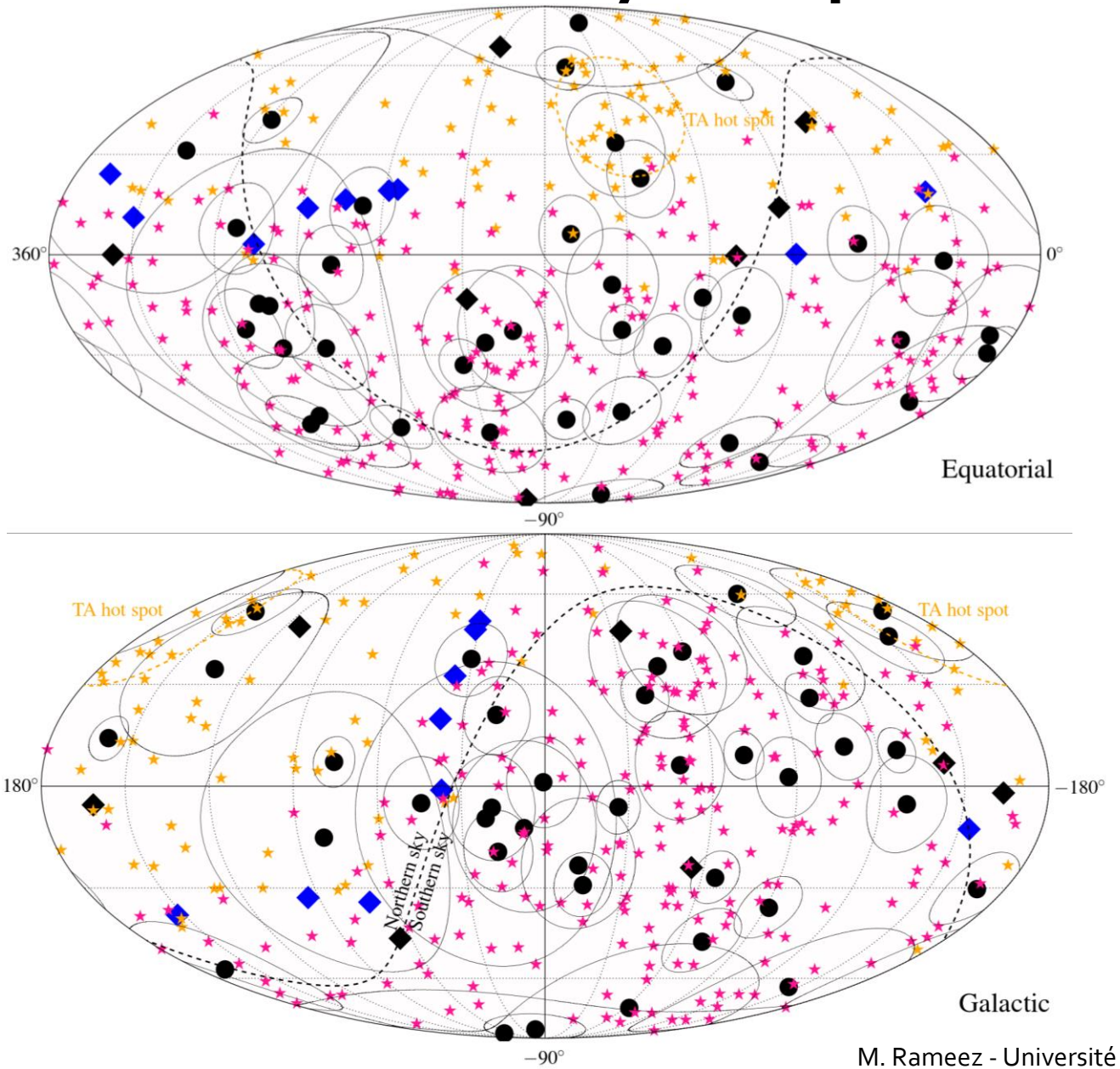
Skymaps of the Events



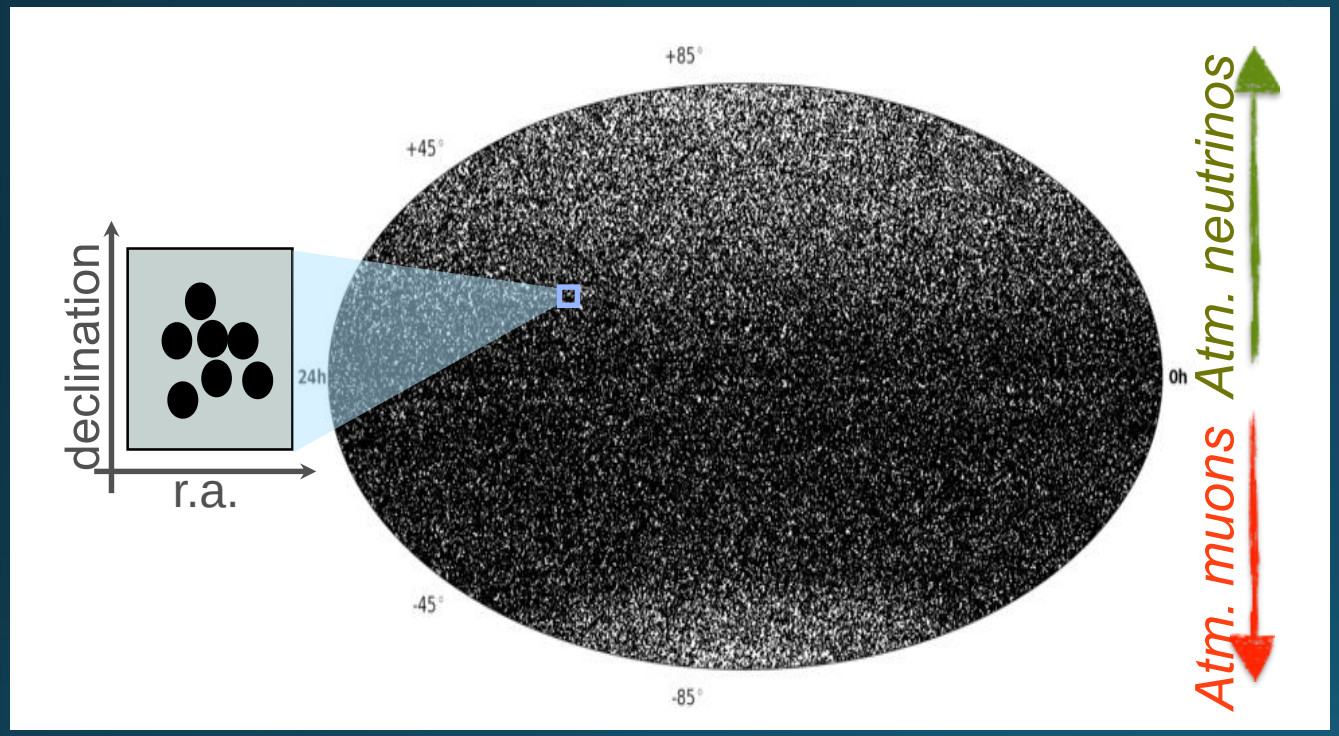
Orange stars: TA UHECR
Magenta stars: Auger UHECR

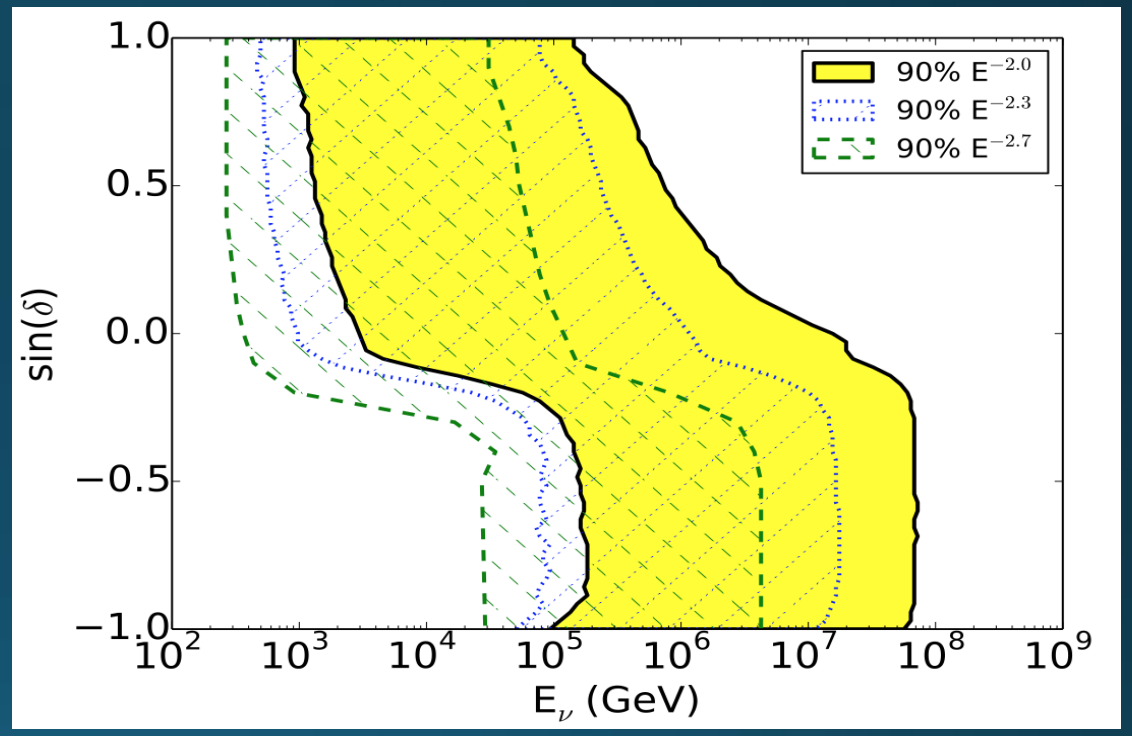
Black dot and circle around it:
HESE Cascades
- Circle size ~ Angular uncertainty

Diamonds:
High Energy Tracks
- Black →selected HESE tracks
- Blue → Throughgoing tracks
- Angular uncertainty < 1°

4 year Point Source Sample - Stacking

4 yr sample of well reconstructed, through-going muons that could be associated with charged-current muon neutrino interactions (394,000 events)





$$S_i = \sum_{j=1}^{N_{CR}} R_{\mathrm{IC}}(\delta_j, \gamma) S_i^j \Big/ \sum_{j=1}^{N_{CR}} R_{\mathrm{IC}}(\delta_j, \gamma)$$

$$S_i^j = \frac{1}{2\pi(\sigma_i^2 + \sigma_j^2)} e^{-r_{ij}^2/2(\sigma_i^2+\sigma_j^2)} P(E_i|\gamma)$$

Deal with magnetic deflections as source extensions :

$$\sigma_j = \sqrt{\sigma_{\mathrm{MD}}^2 + \sigma_{\mathrm{exp}}^2}$$

Results : Stacking 27 UHECRs (> 85 EeV)

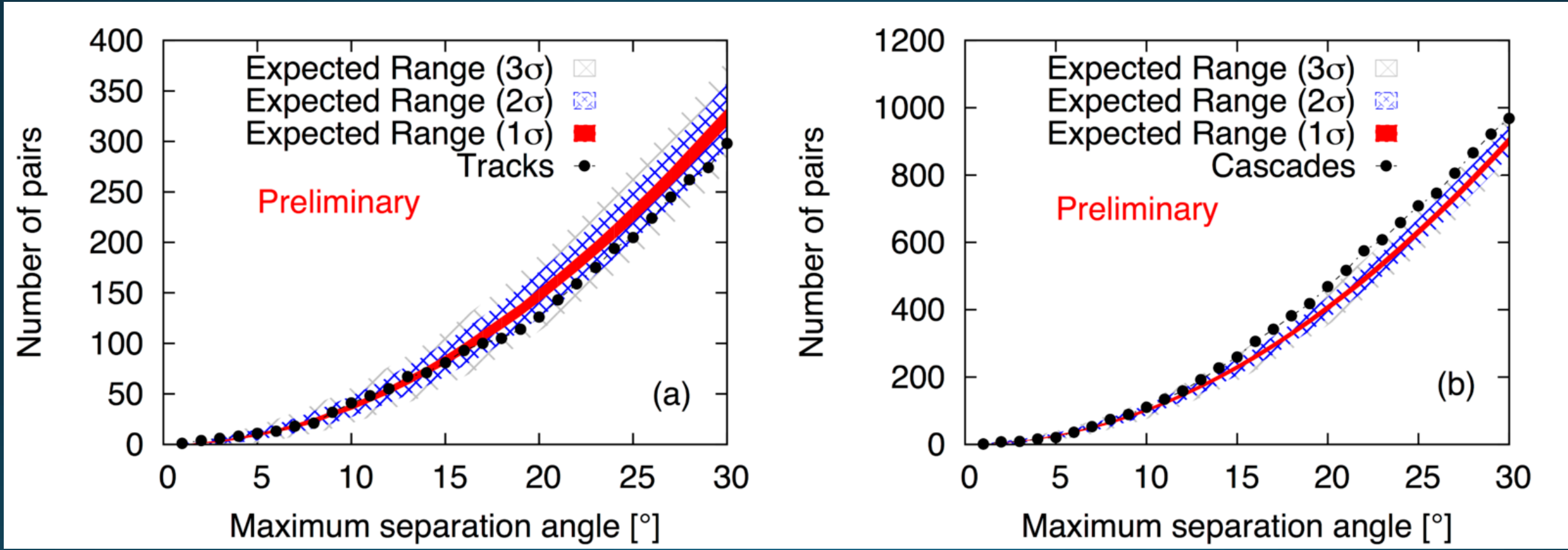
D	Fitted $n_{s\nu}$	Fitted γ	pre-trial p-value
3°	123.3	3.24	17.1%
6°	$\sim$0	-	$>$ 50%

Post-trial p-value=25%

Conclusions

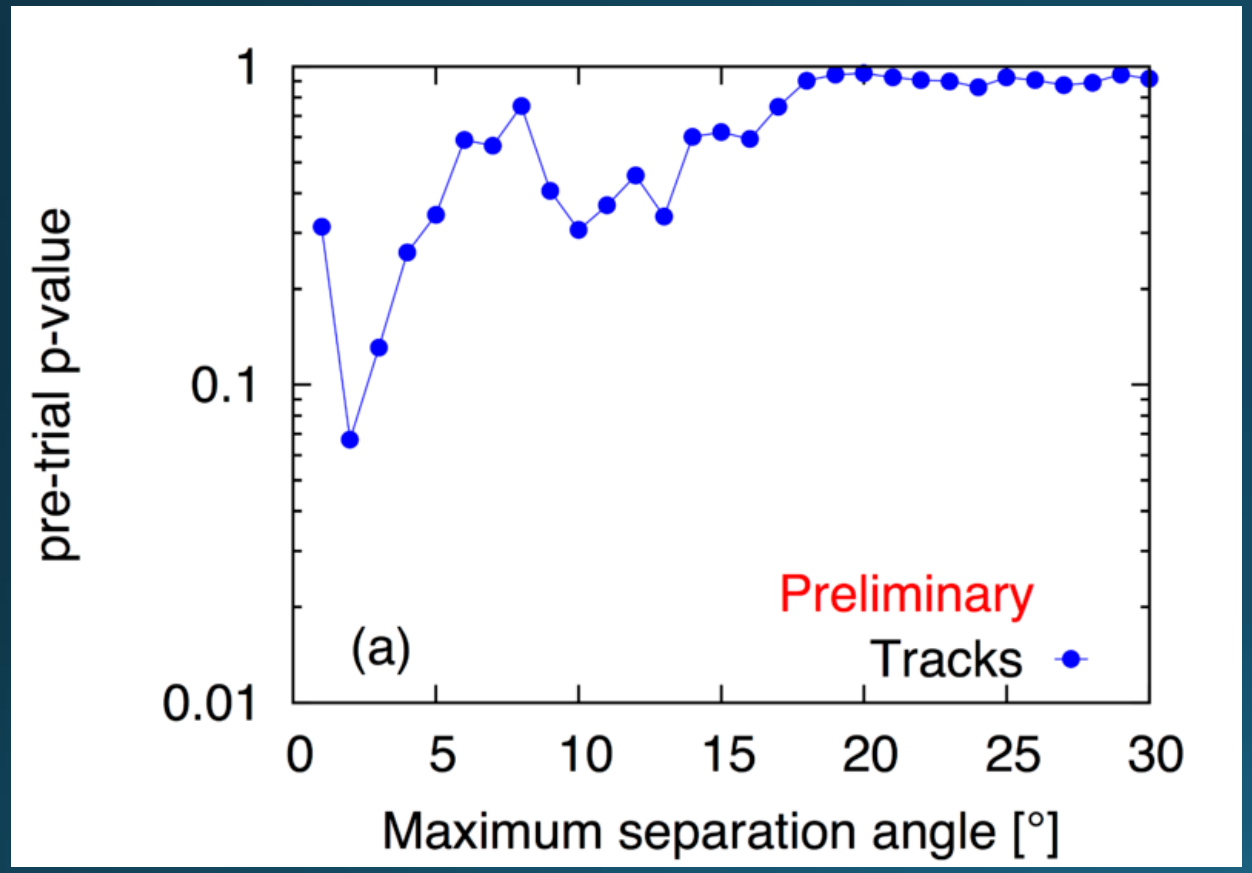
- All correlations found are $< 3.3\ \sigma$ in statistical significance
- Potentially interesting correlation between IceCube High Energy Cascades and UHECRs
  - Disfavours Isotropic CRs hypothesis at $> 3\ \sigma$
  - Disfavours Isotropic ν hypothesis at $\sim 2.4\ \sigma$
- Only more data can confirm if an actual correlation exists.

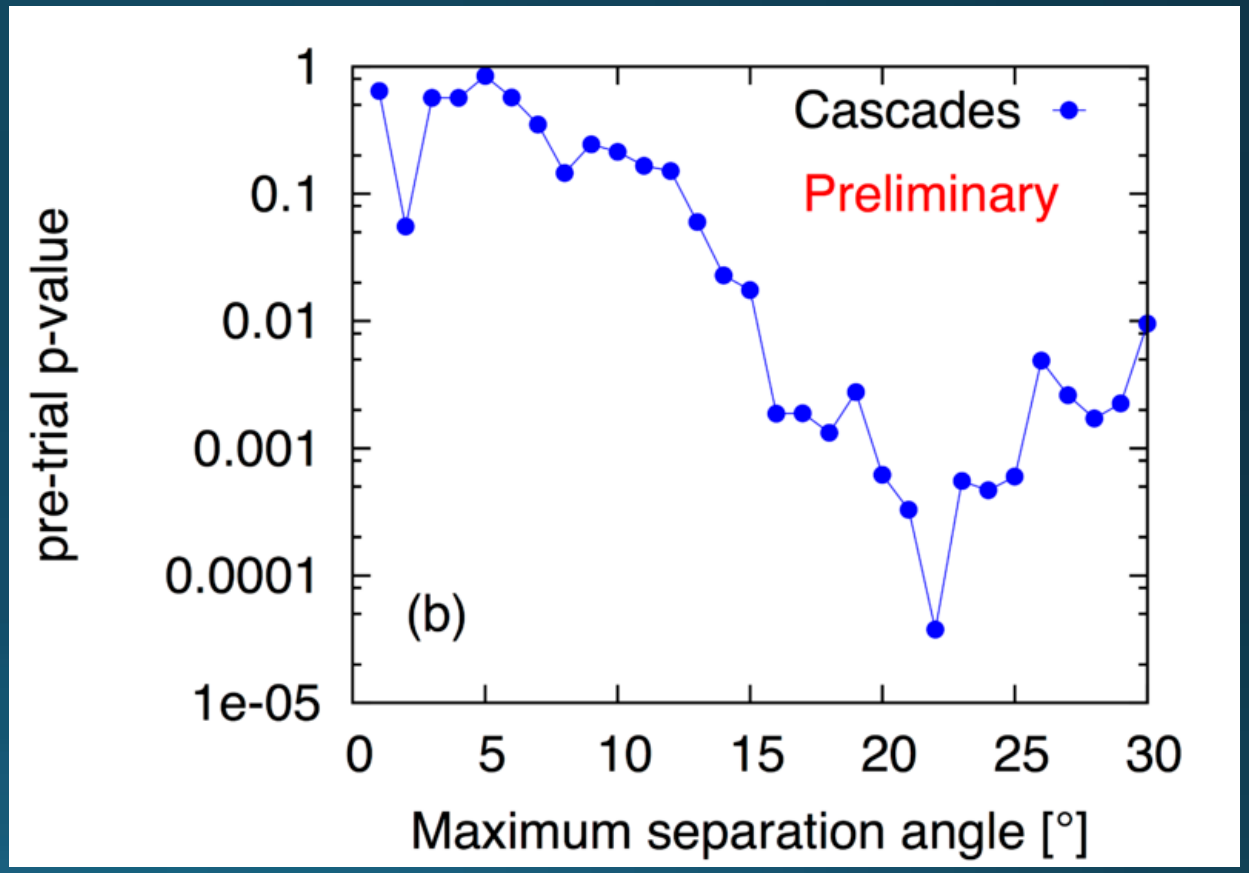
Backup- Cross Correlation Analysis



Absolute Excess of pairs

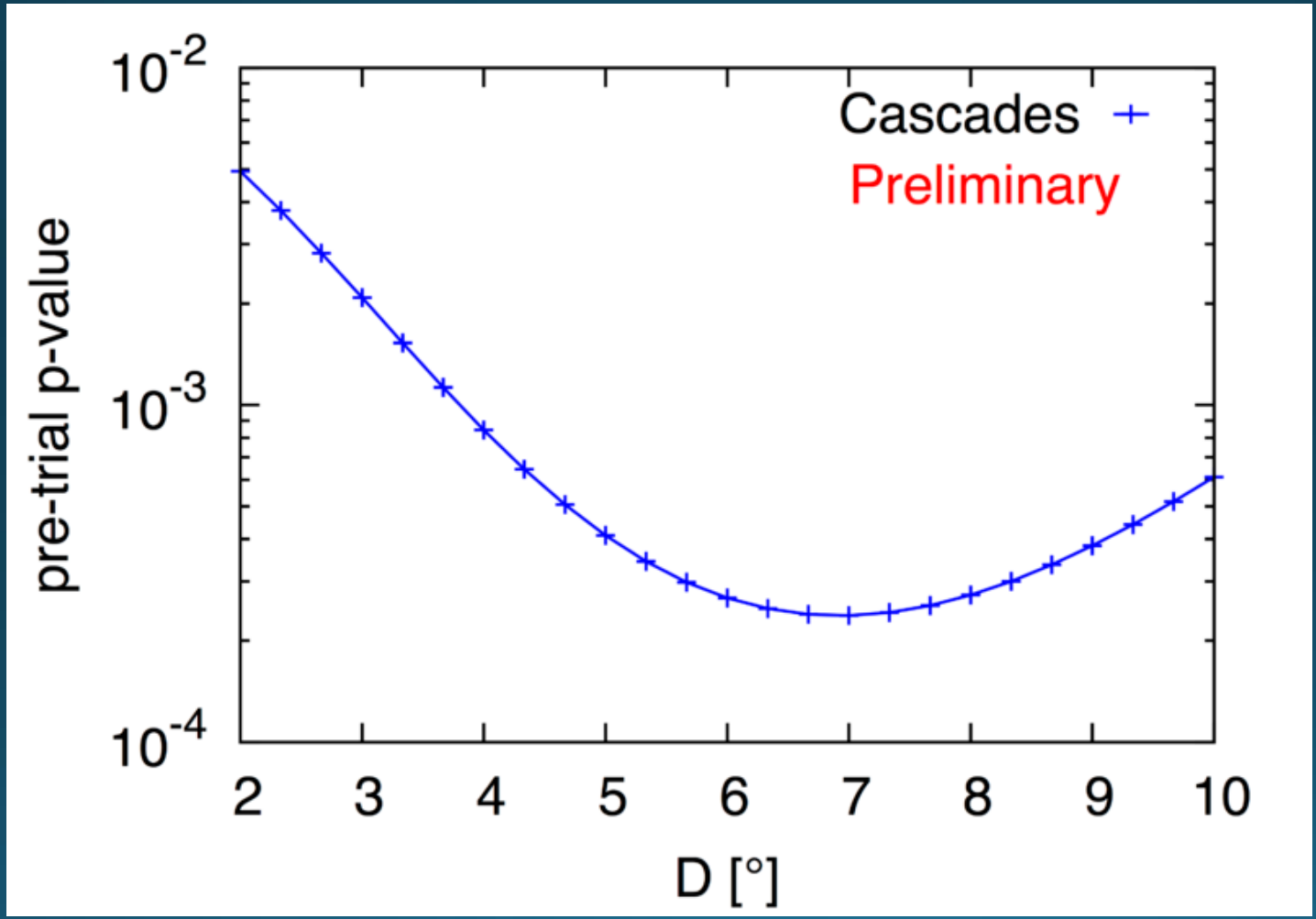
Backup – Cross Correlation Analysis



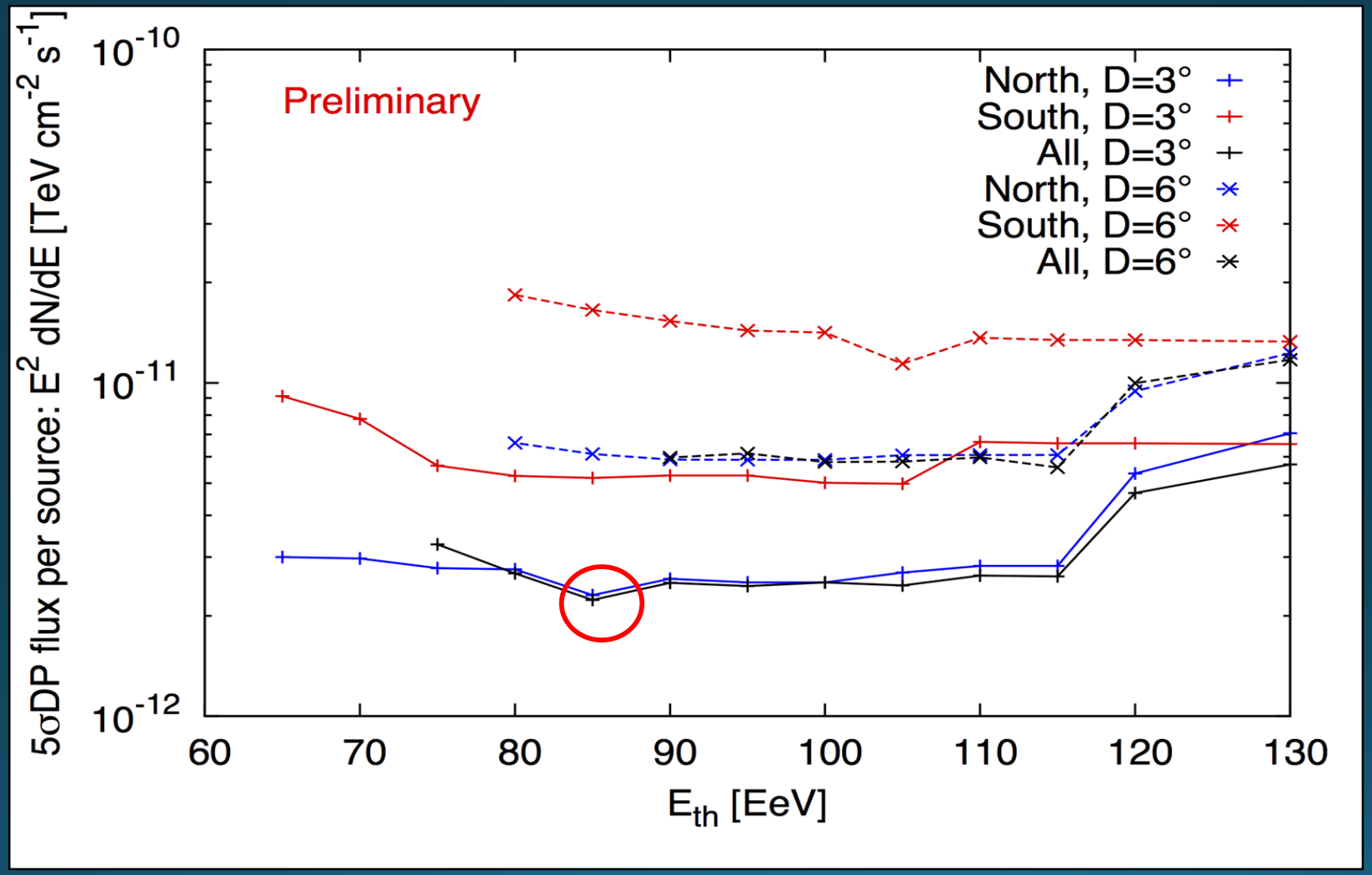


Pre trial p value as a function of maximum angular separation

Backup – UHECR-HESE Cascade Stacking



Backup - Point Source UHECR Stacking



Point Source UHECR Stacking cut optimization