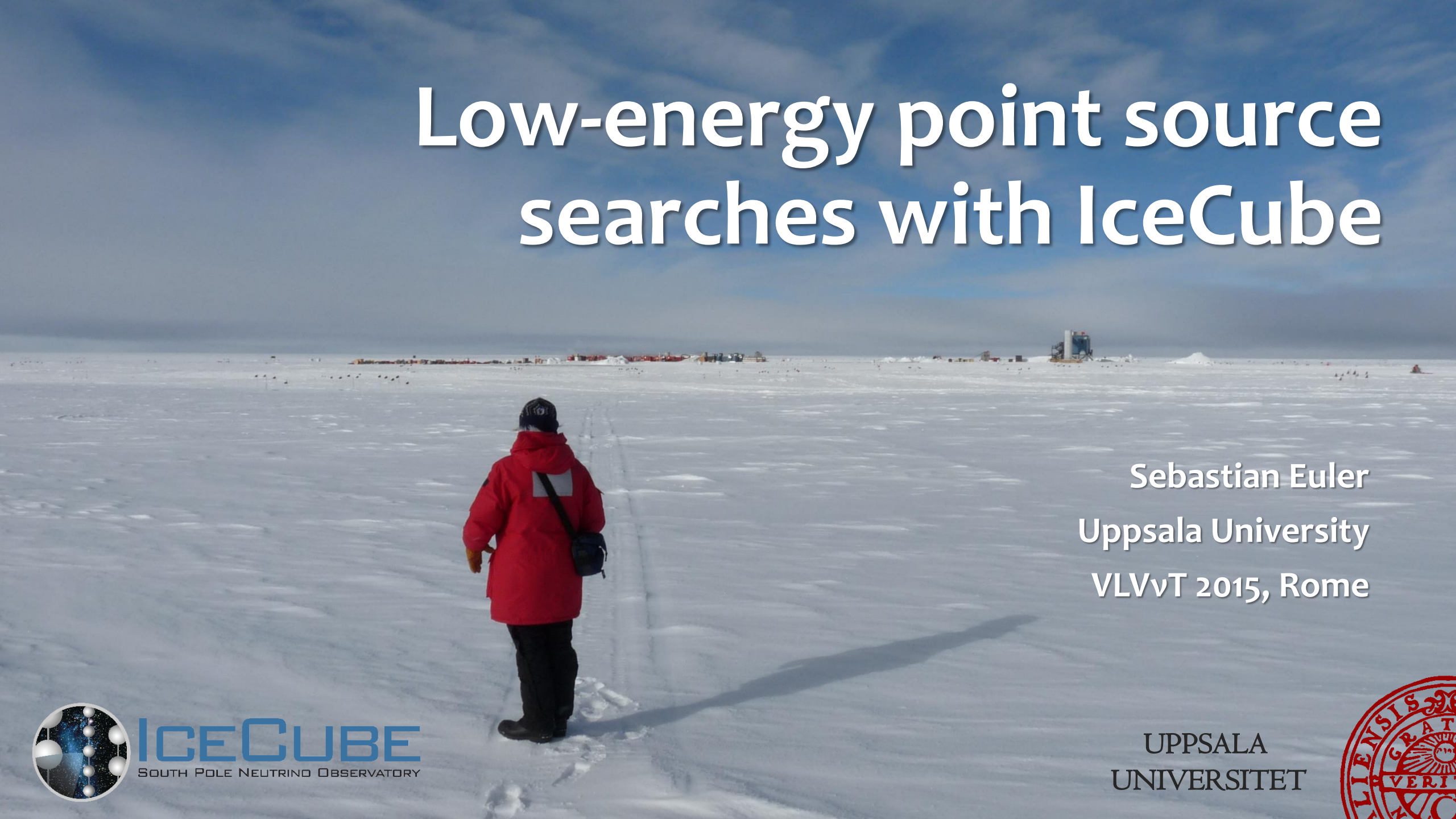
Low-energy point source searches with IceCube



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VLVνT 2015, Rome

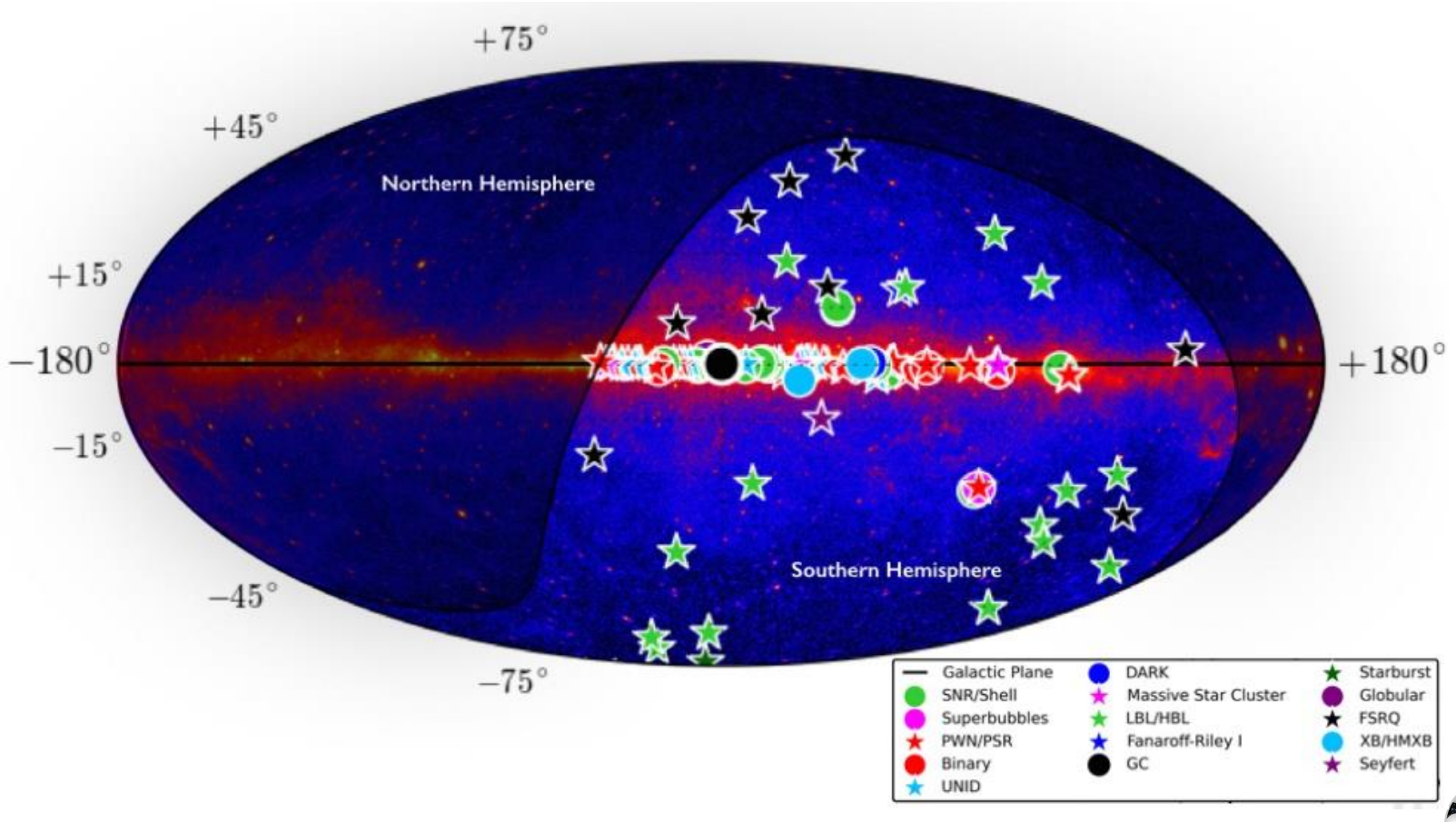
IceCube
South Pole Neutrino Observatory

UPPSALA
UNIVERSITET

Point source searches in IceCube

- standard search sensitive mainly in Northern Hemisphere
- some down-going sensitivity at higher energies (>100 TeV)

- many interesting sources in the Southern Hemisphere:
  - most Galactic sources
  - Galactic center



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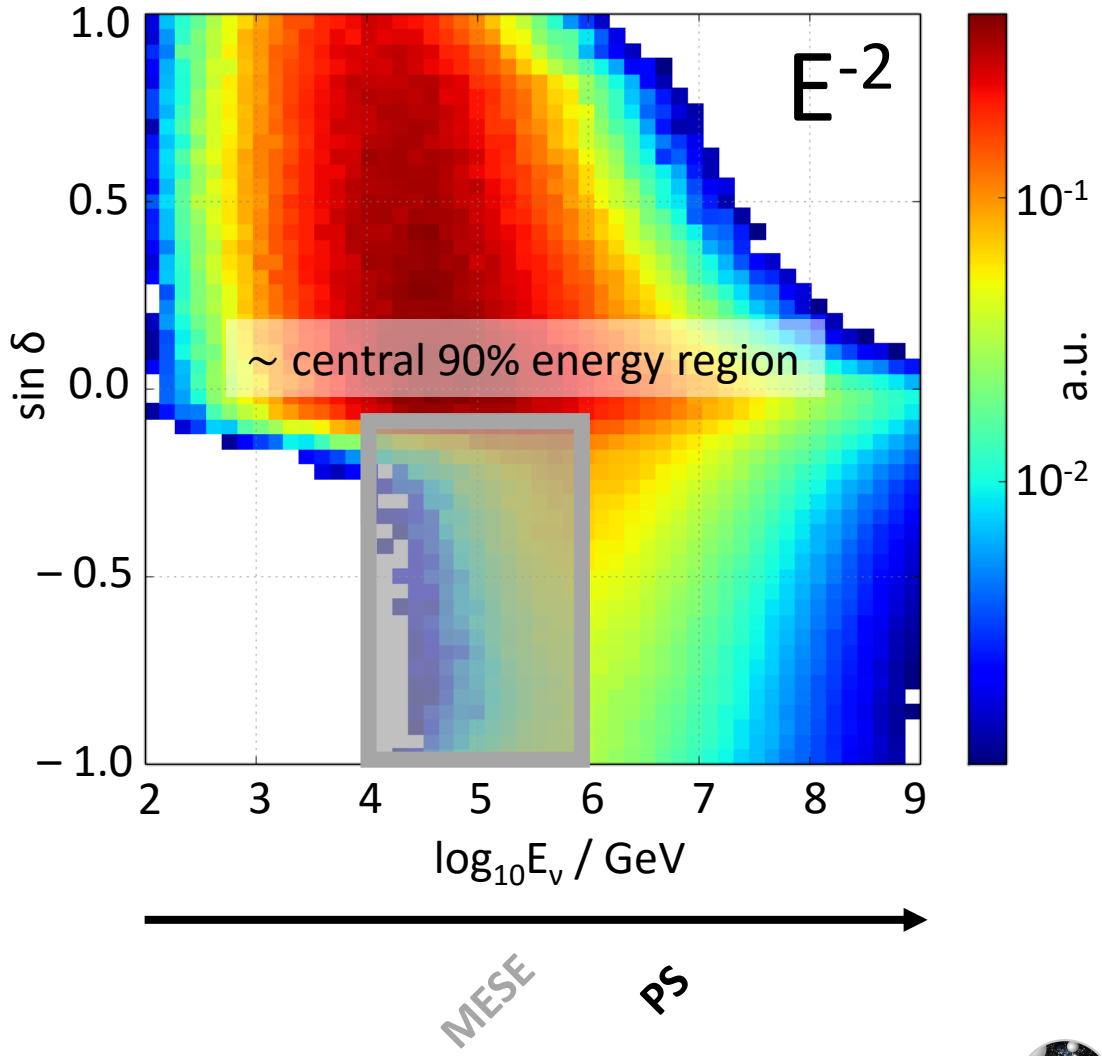
  - MESE: 10 TeV – 1 PeV



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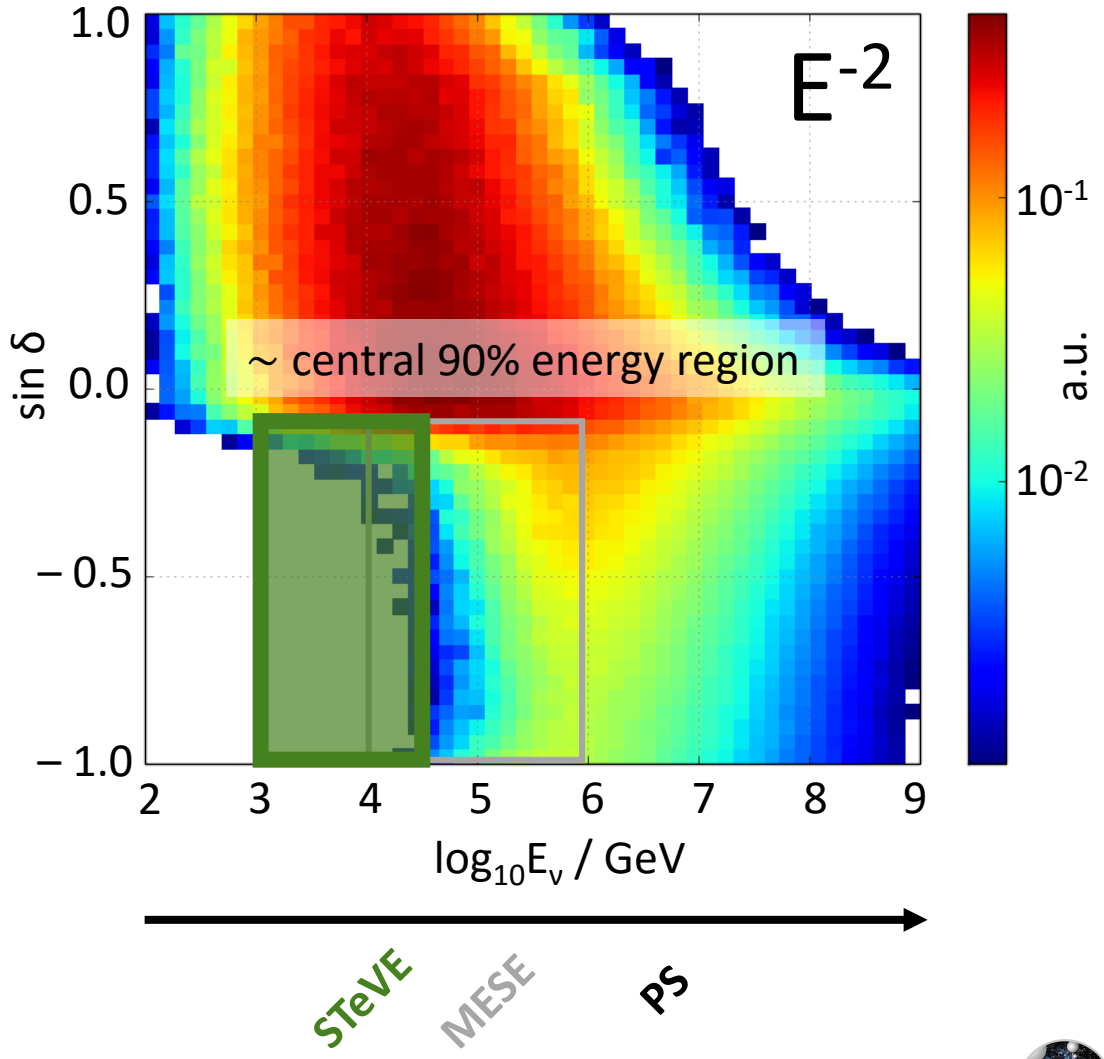

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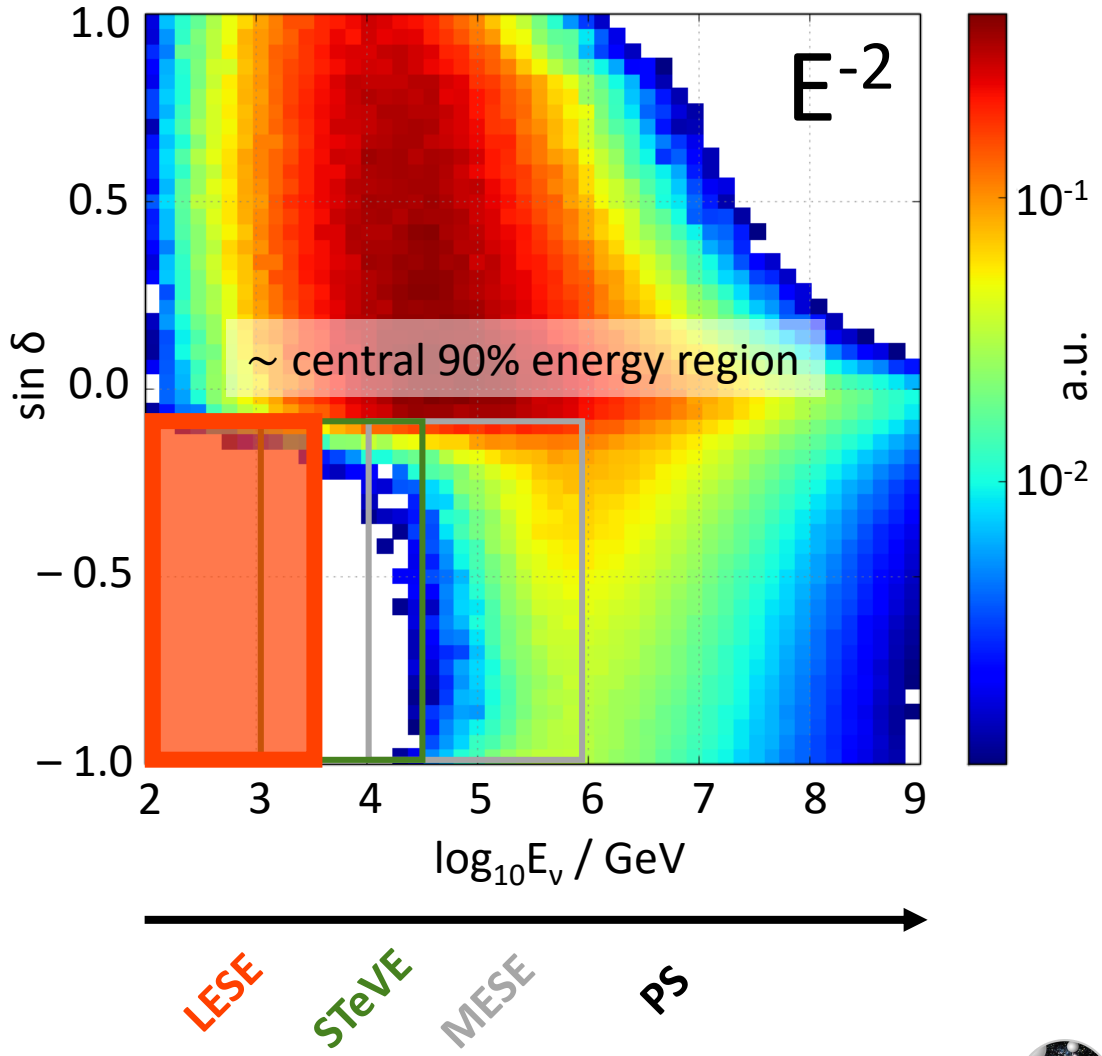

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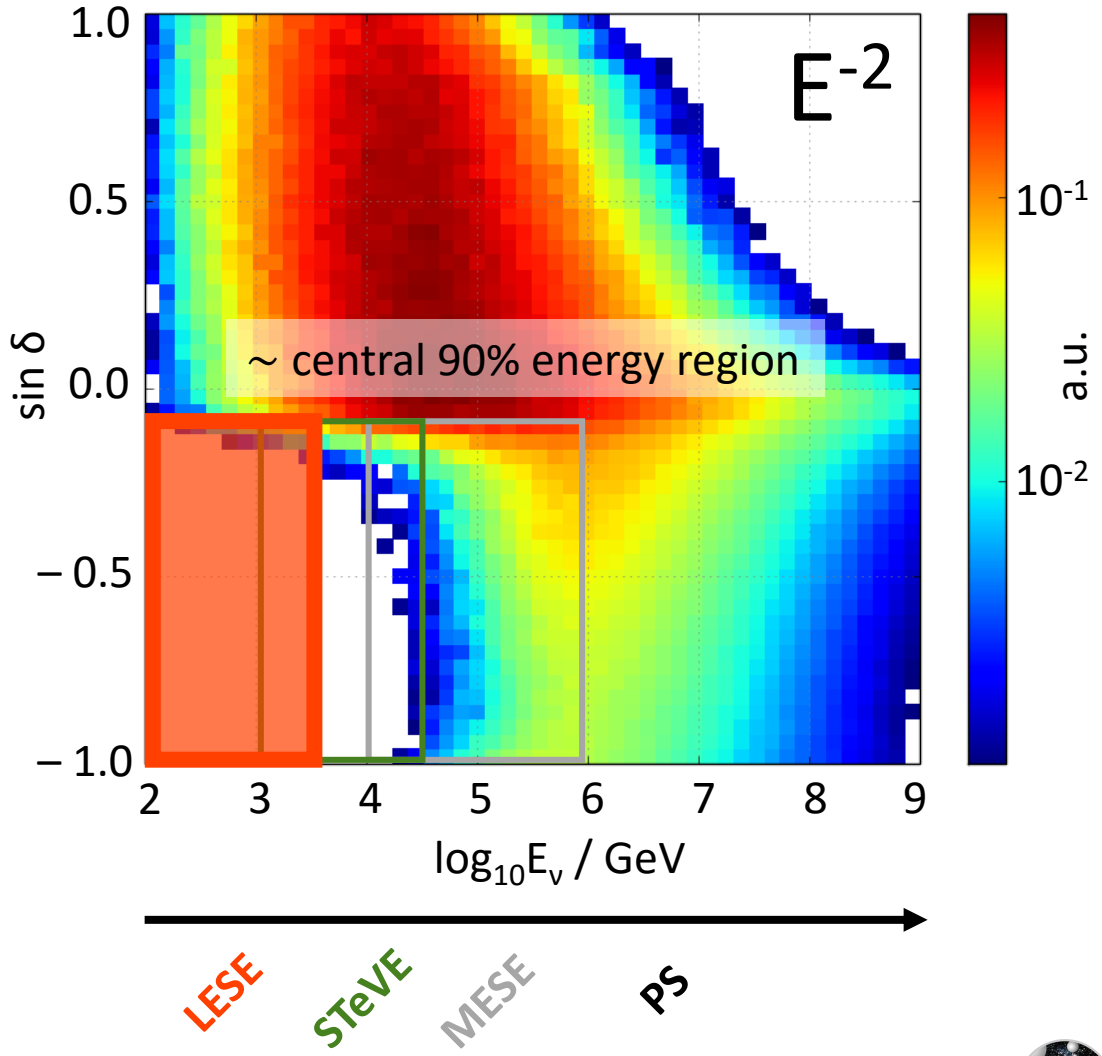
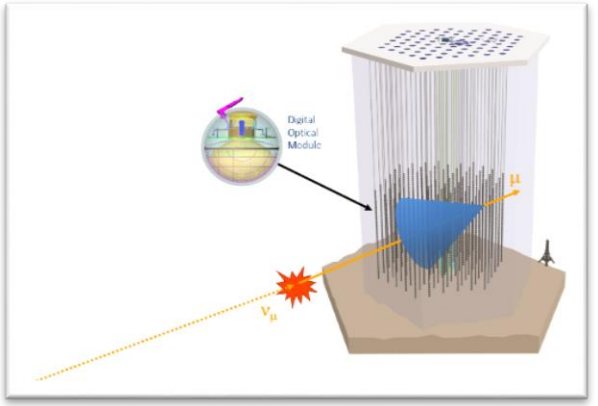
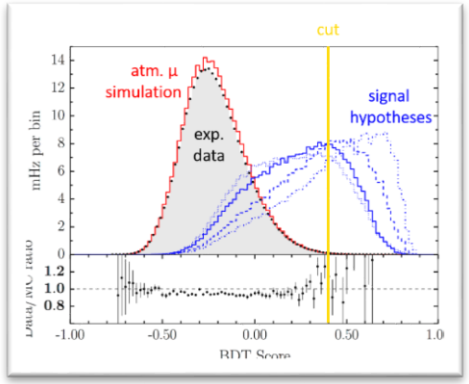
I will be talking mostly about this one

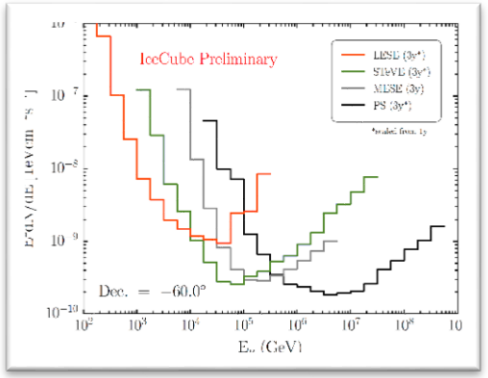


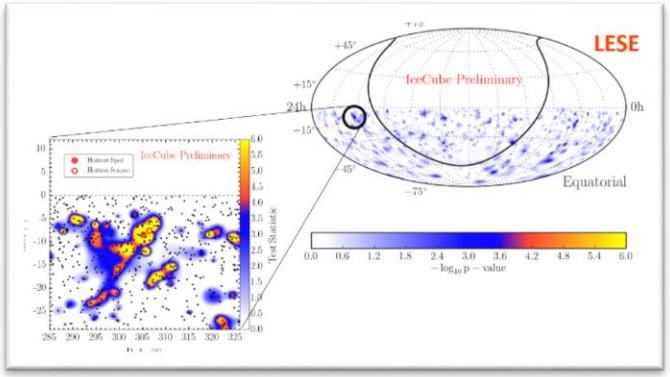
Contents

- The IceCube Neutrino Observatory
- Event selection (**LESE**)
- Analysis method & sensitivity (**LESE** & **STeVE**)
- Results (**LESE** & **STeVE**)



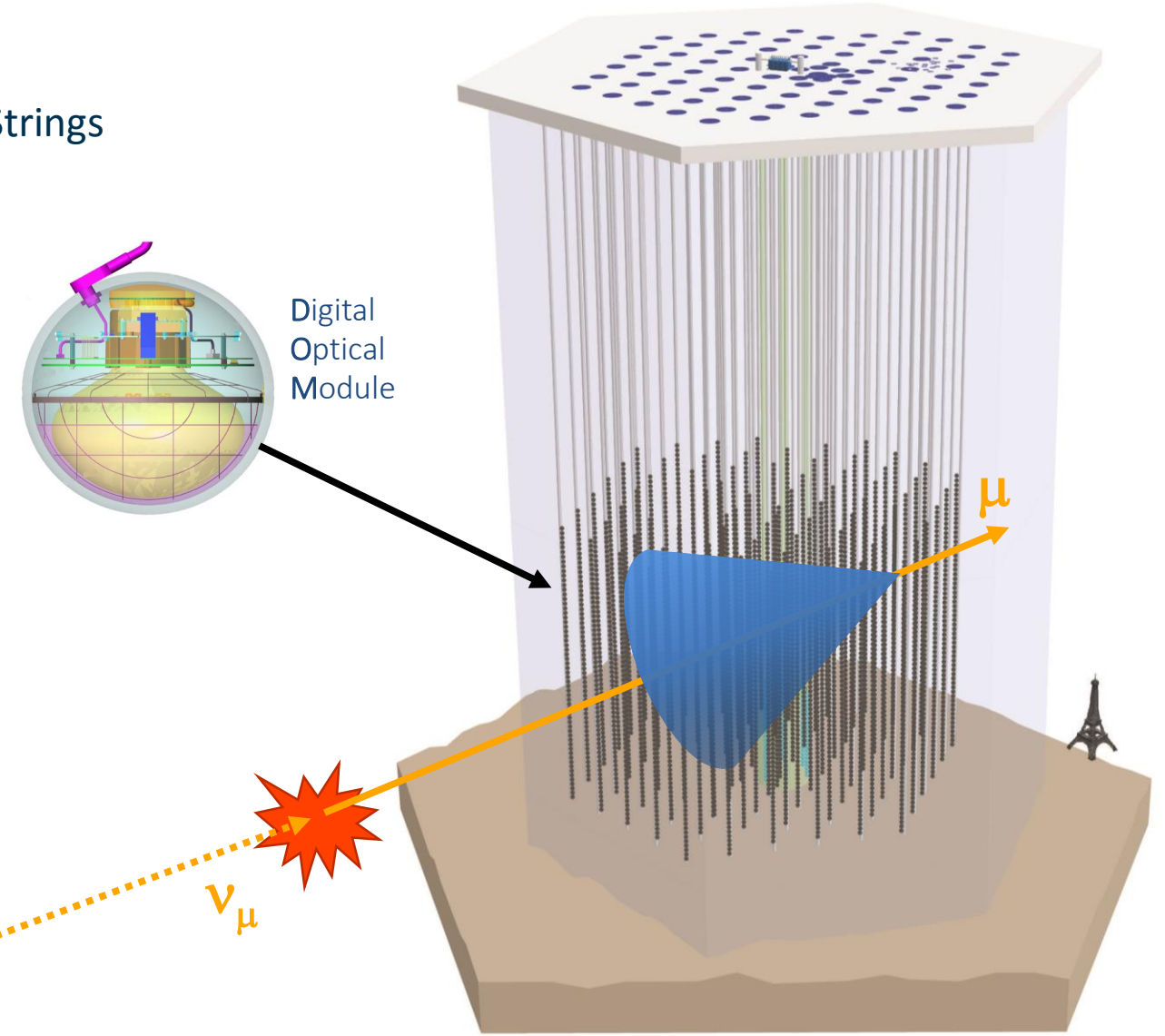






The IceCube Neutrino Observatory

- 5160 Digital Optical Modules (DOMs) on 60 Strings
- in depths of 1450 m – 2450 m
- 1km^3 instrumented volume
- neutrinos interact in the ice
- detect Cherenkov light from secondary particles (here: μ)



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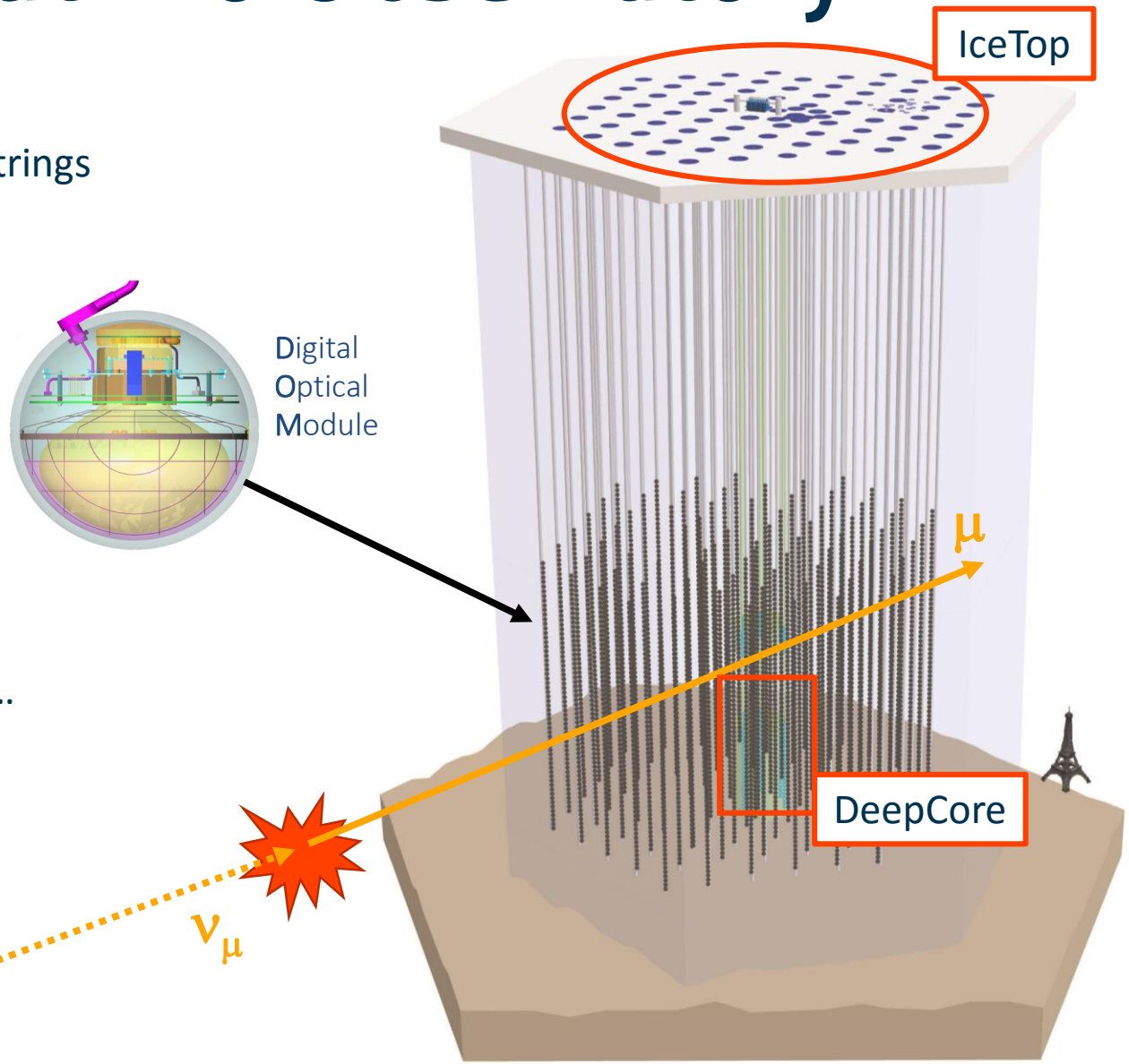
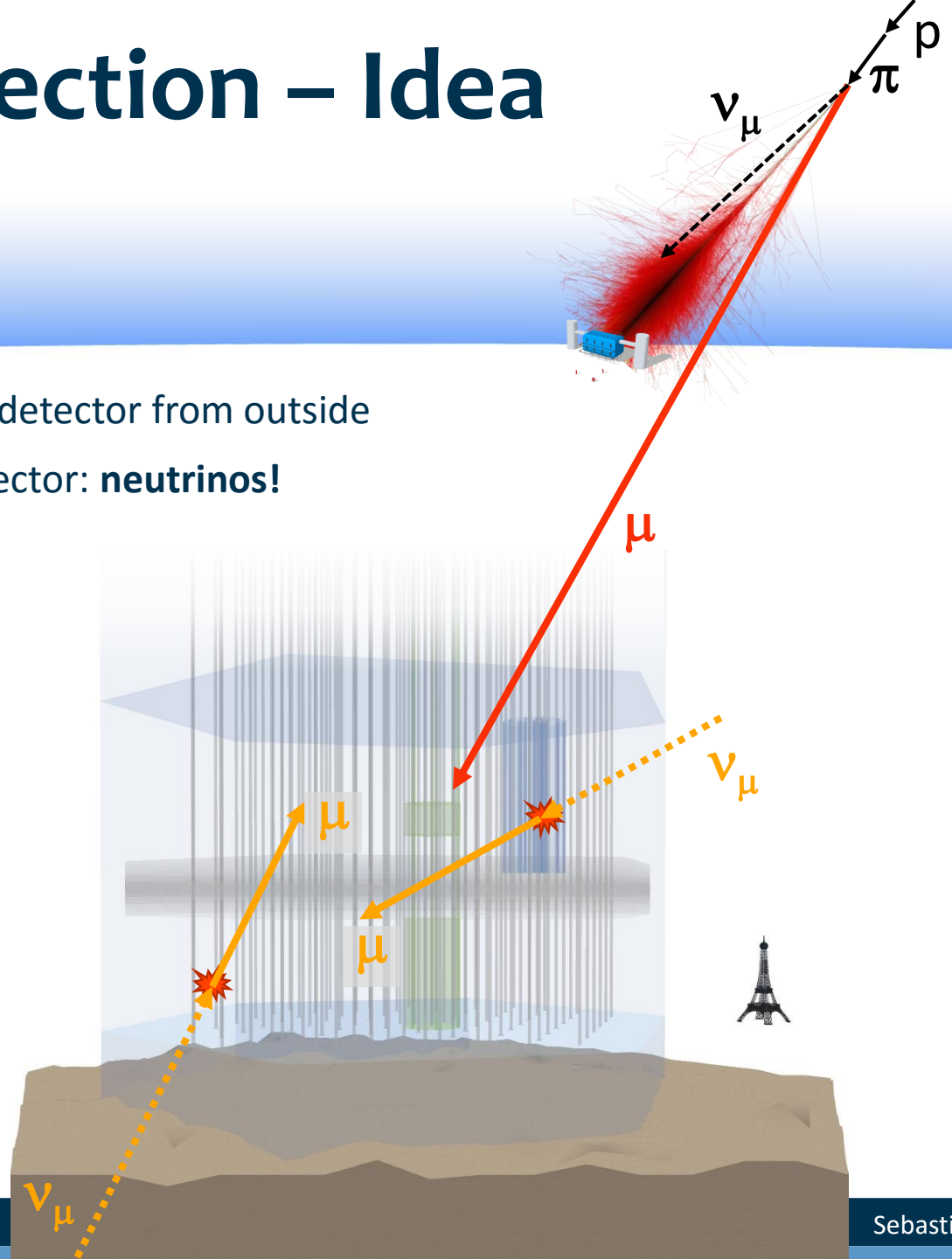
- DeepCore: low-energy core (E_ν > 10 GeV)
  - included in the analyses presented here…
  - … but they use full IceCube
- IceTop: surface array of tanks
  - used as cosmic ray veto



Event Selection – Idea

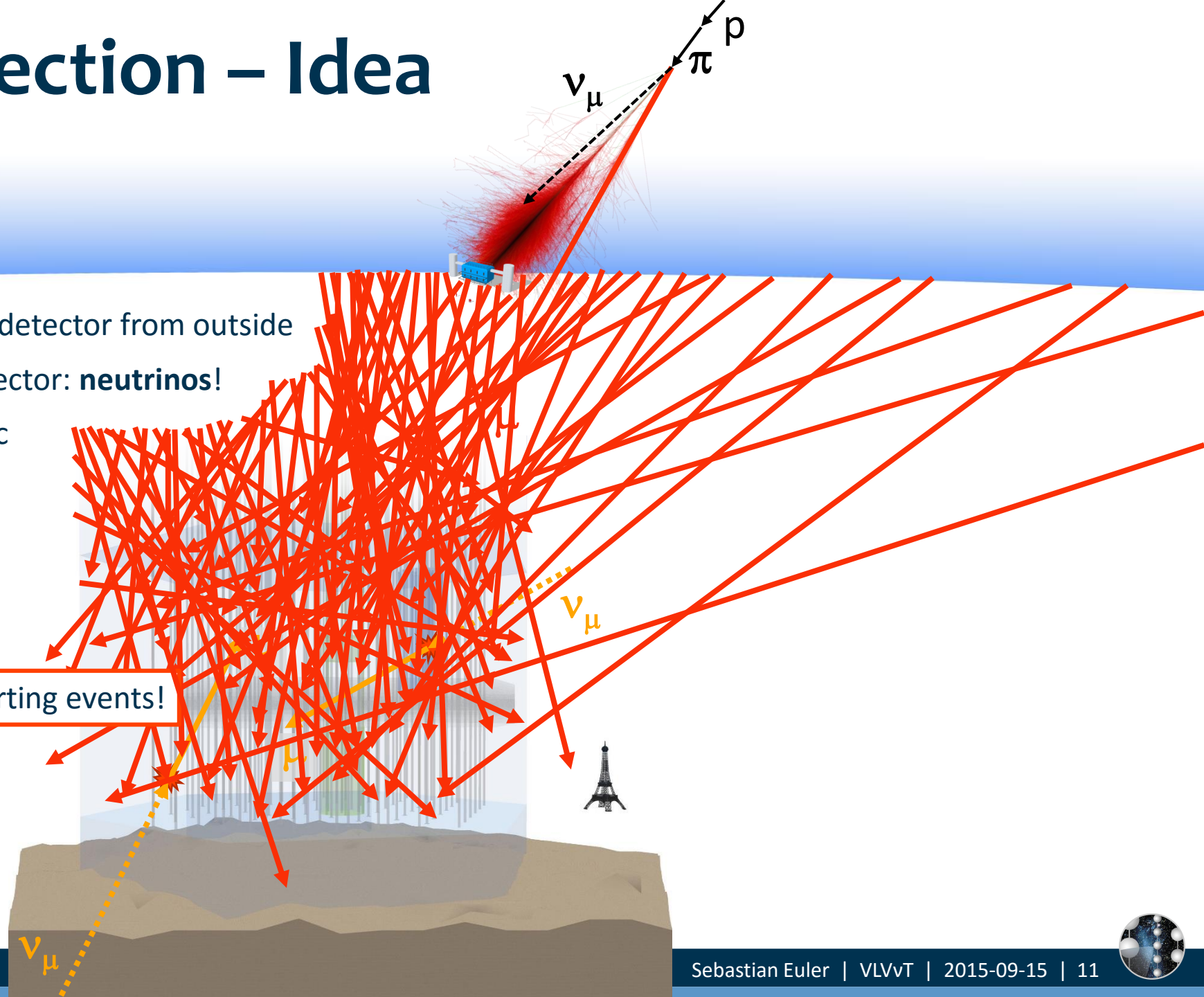
- atmospheric muons entering detector from outside
- events starting inside the detector: **neutrinos!**



Event Selection – Idea

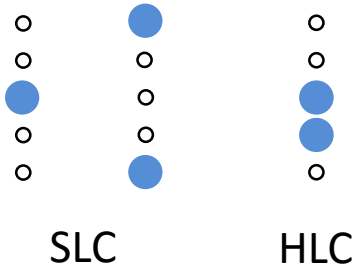
- atmospheric muons entering detector from outside
- events starting inside the detector: **neutrinos**!
- background from atmospheric muons overwhelmingly large at low energies

➡ use veto methods to find starting events!

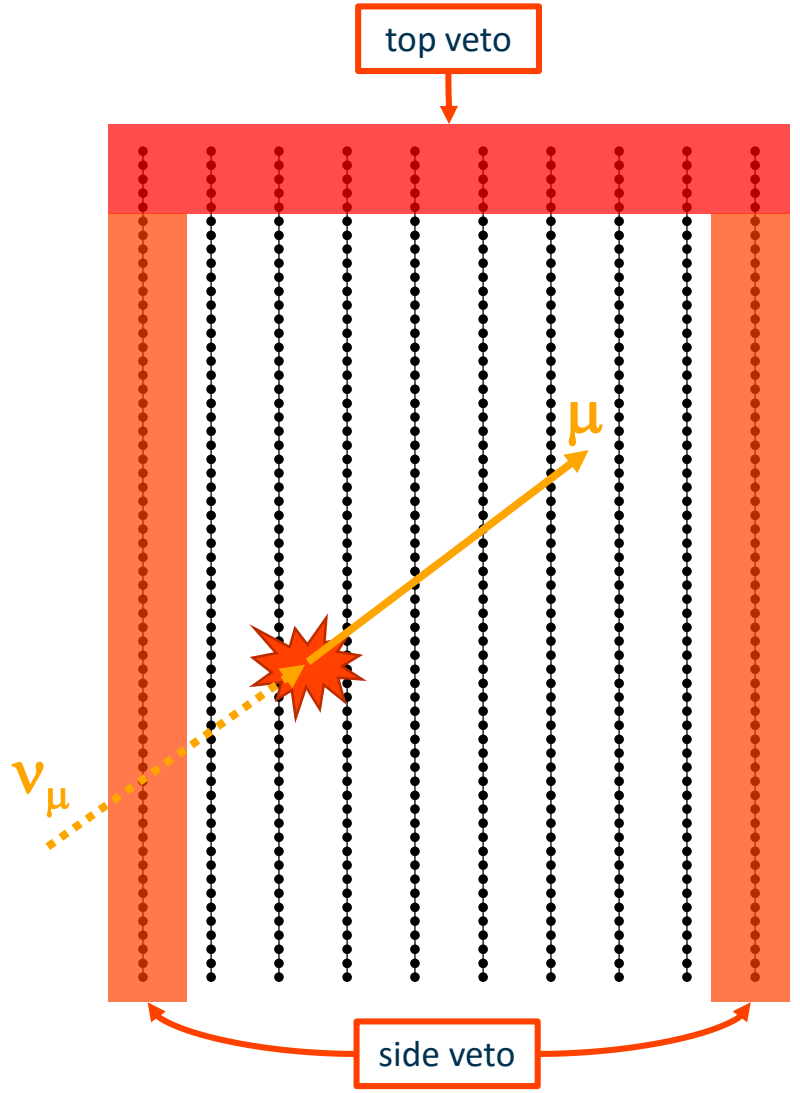


Event Selection – Online Filter

- not all IceCube data is immediately transferred to the North
- filters select „interesting events“, which are then transmitted via satellite
- dedicated filter for low-energy starting events:
  - reject events with HLC hits on the top 5 DOMs
  - reject events with the first HLC hit on an outer string
  - cuts on first guess of reconstructed interaction vertex

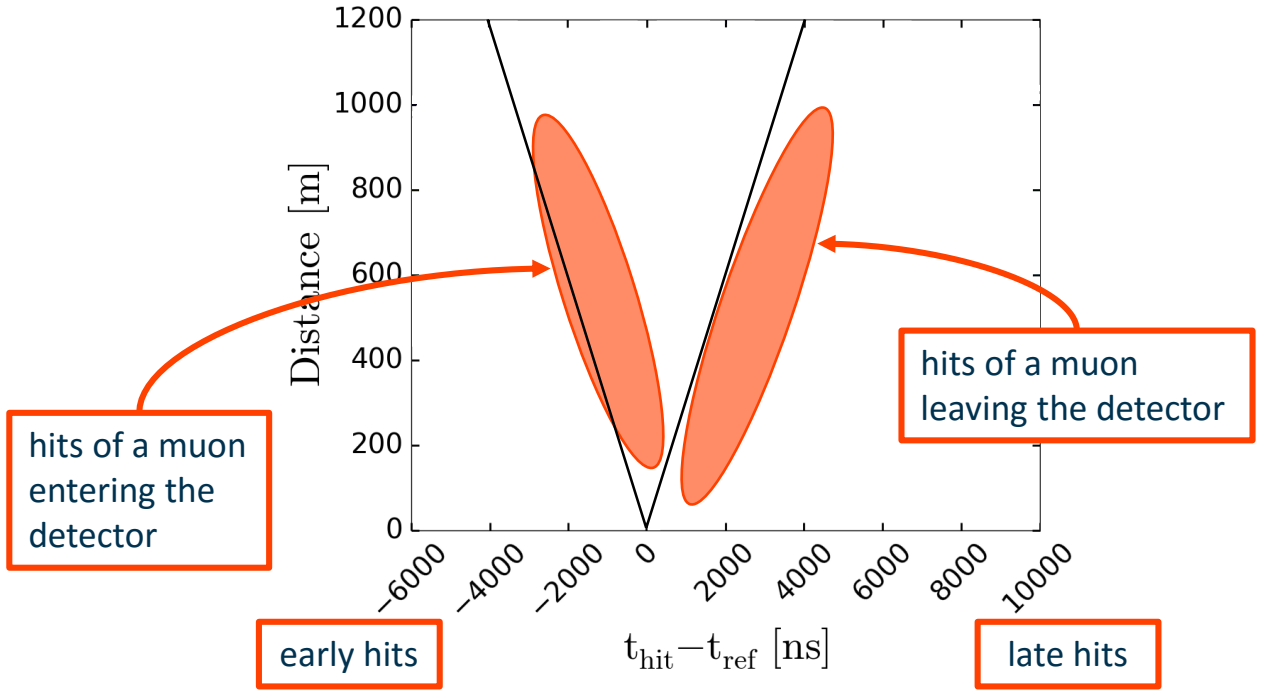


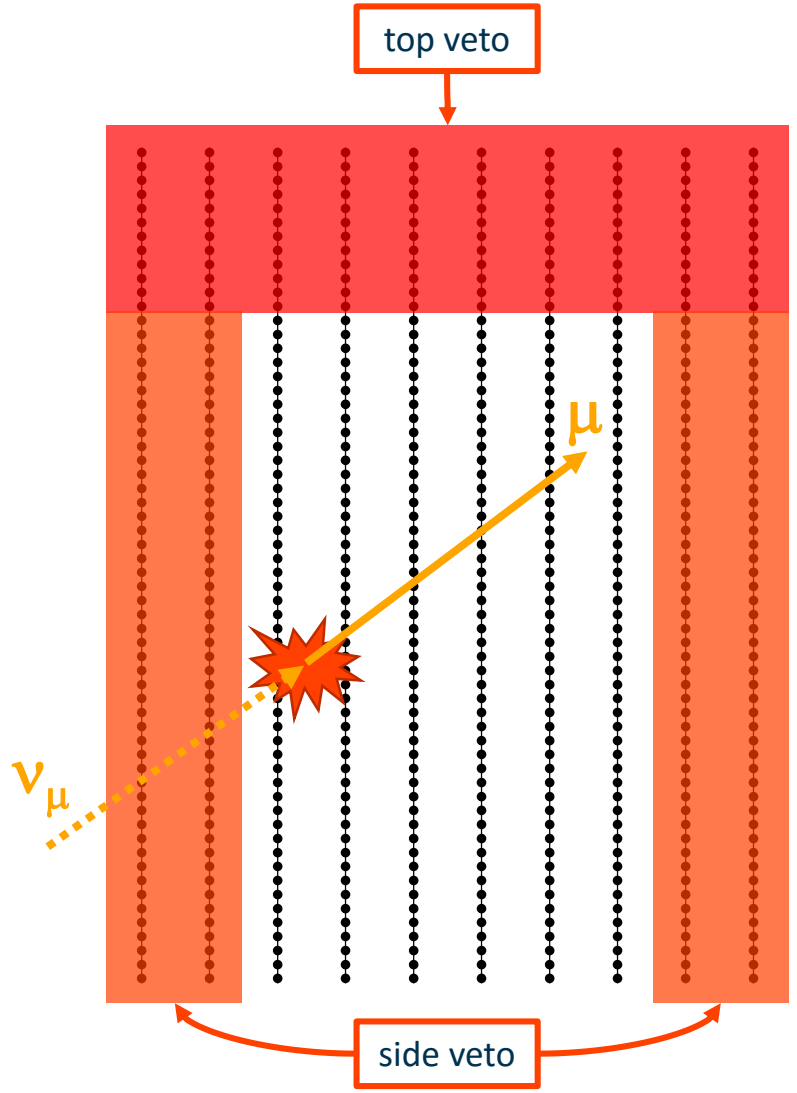
HLC (Hard Local Coincidence) hit: two (next-to-)neighbouring DOMs both over threshold within 1 µs



Event Selection – Causality Veto

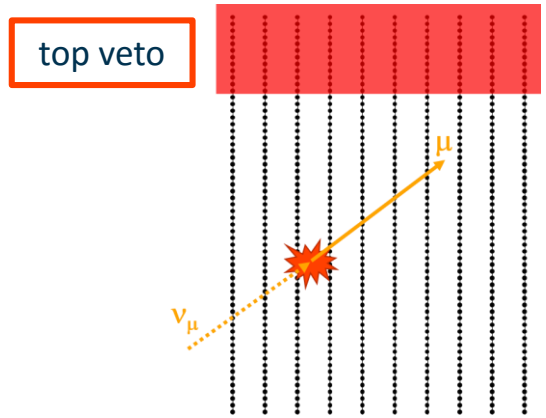
- look for hits consistent with particle travelling with speed of light through the detector
- plot distance vs. time of all hits relative to **reference hit** (first HLC hit inside fiducial volume)
- separately for top and side veto



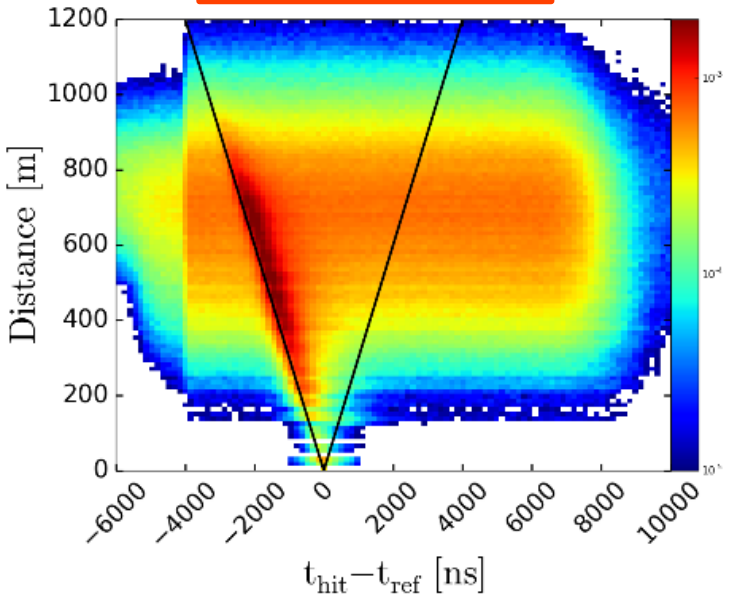


Event Selection – Causality Veto

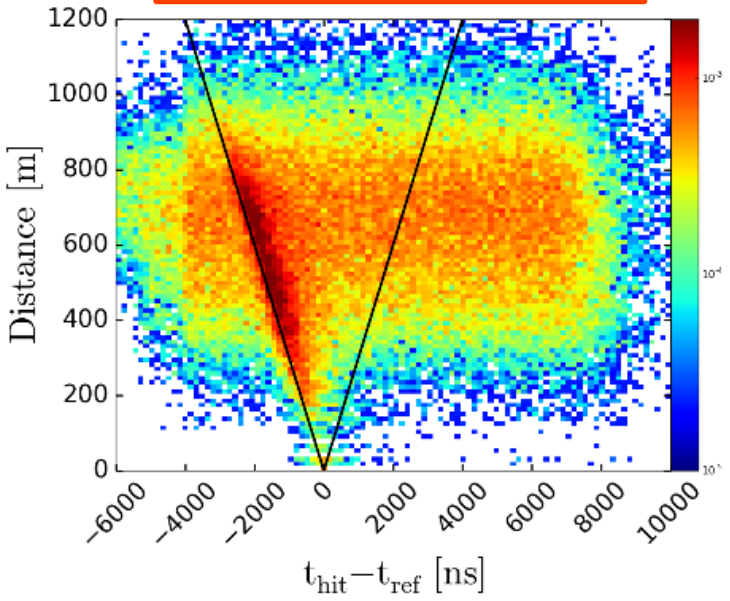
- plot distance vs. time of all hits relative to **reference hit** (first HLC hit inside fiducial volume)
- here: top veto
- use distributions as PDF
- calculate LLH value



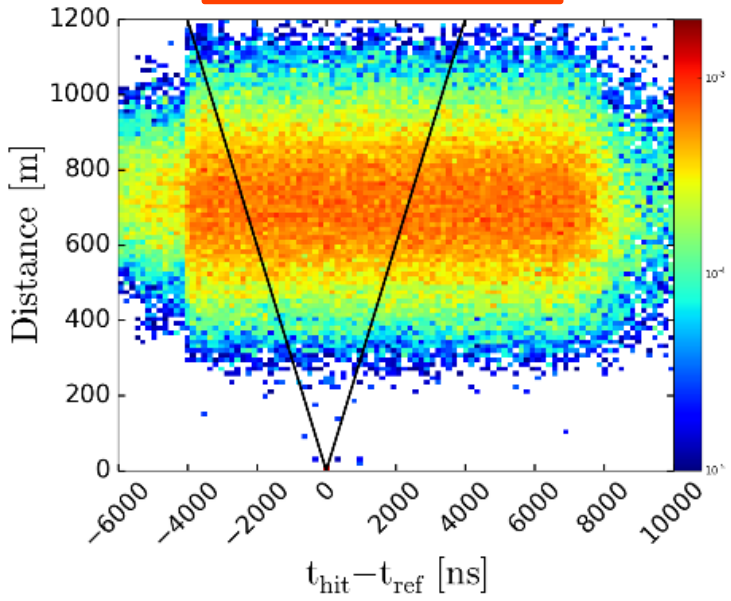
experimental data



atm. μ background (CORSIKA)



signal simulation



Event Selection – Causality Veto

- plot distance vs. time of all hits relative to **reference hit** (first HLC hit inside fiducial volume)
- here: side veto
- use distributions as PDF
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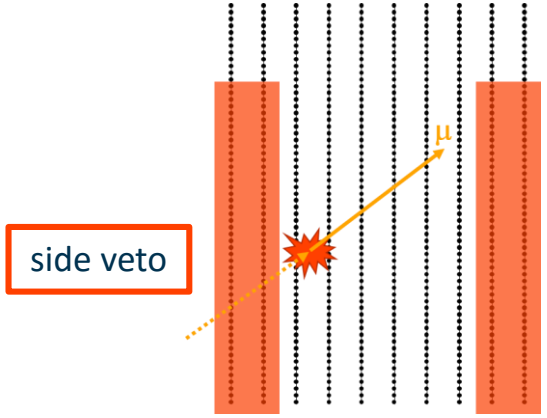

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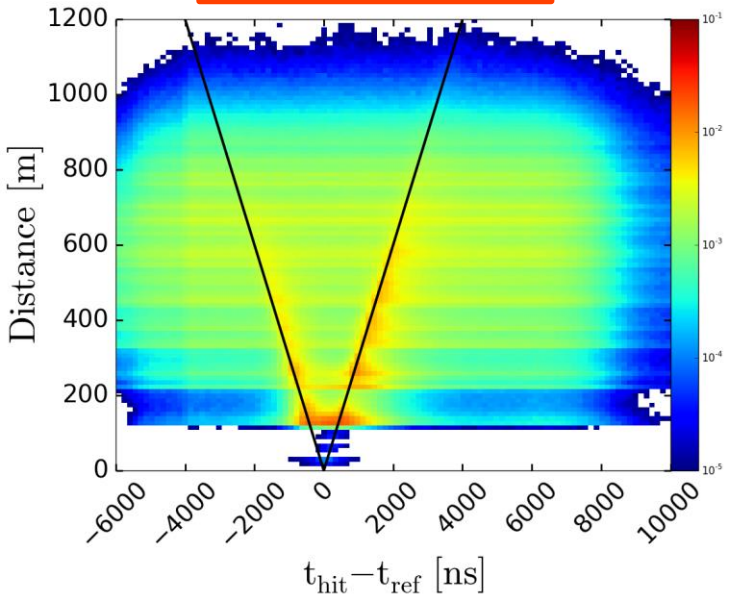

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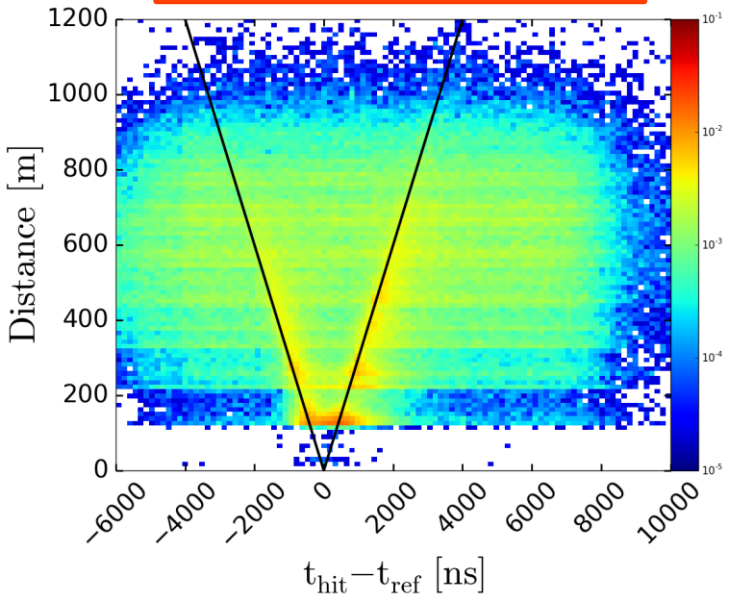

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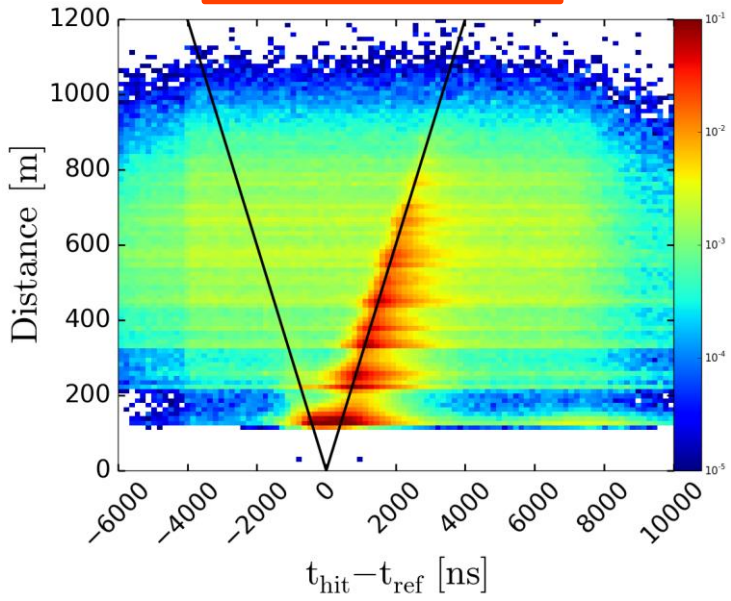
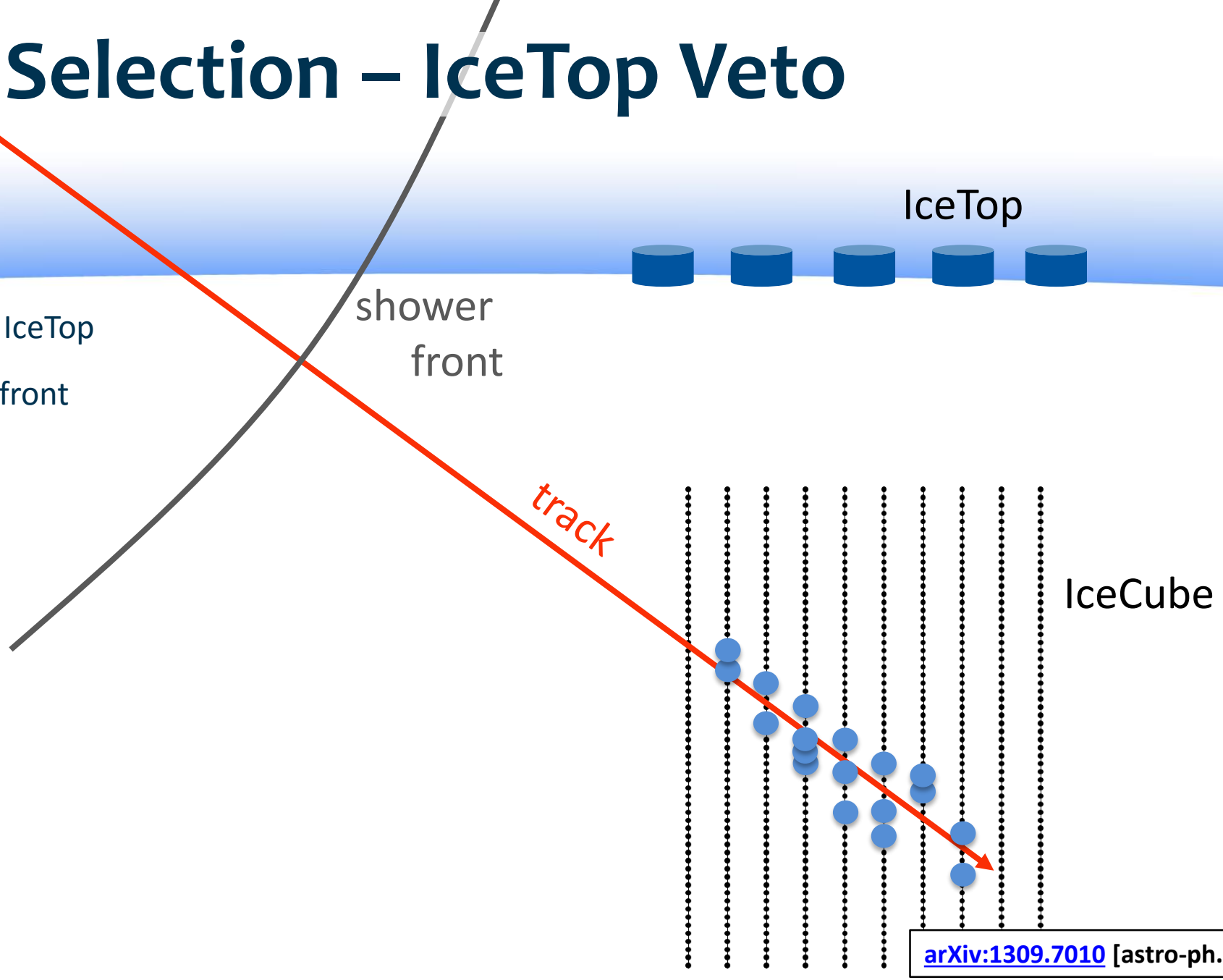


Event Selection – IceTop Veto

- **Idea**: search for hits in IceTop coinciding with the reconstructed shower front



arXiv:1309.7010 [astro-ph.HE]

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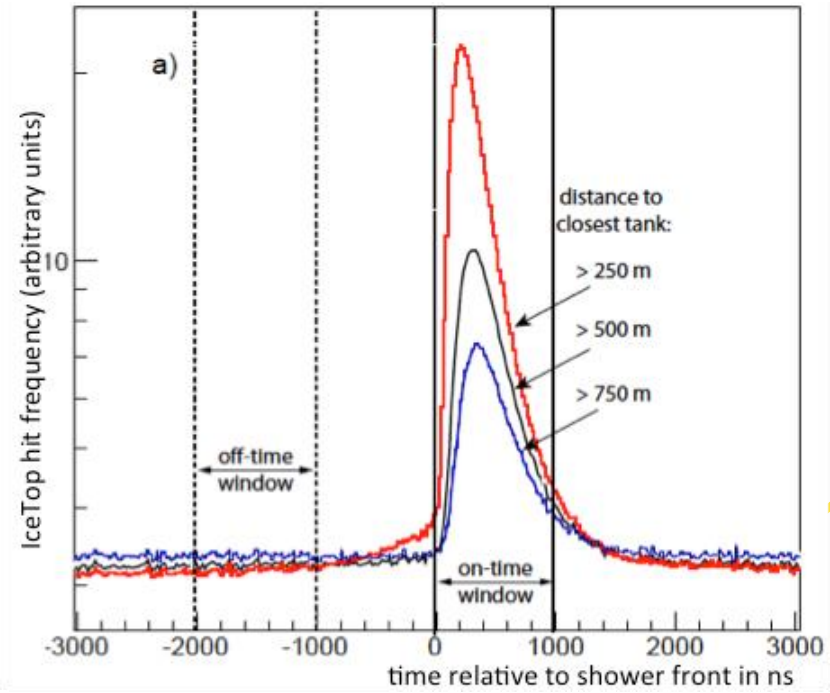
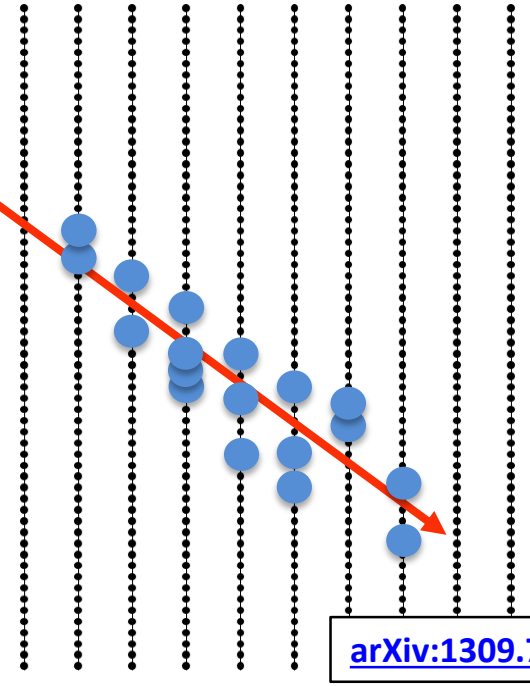


shower front

coincidence



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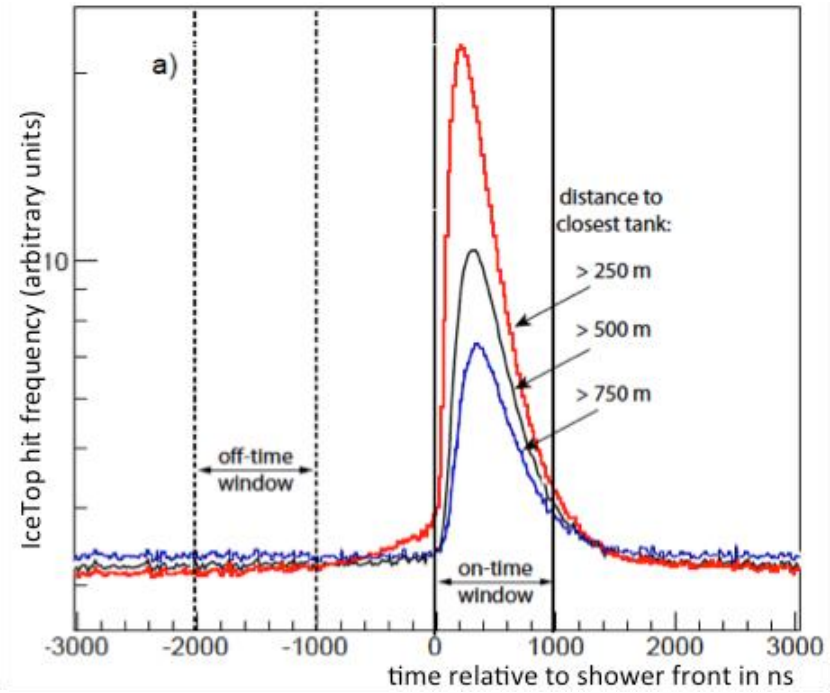

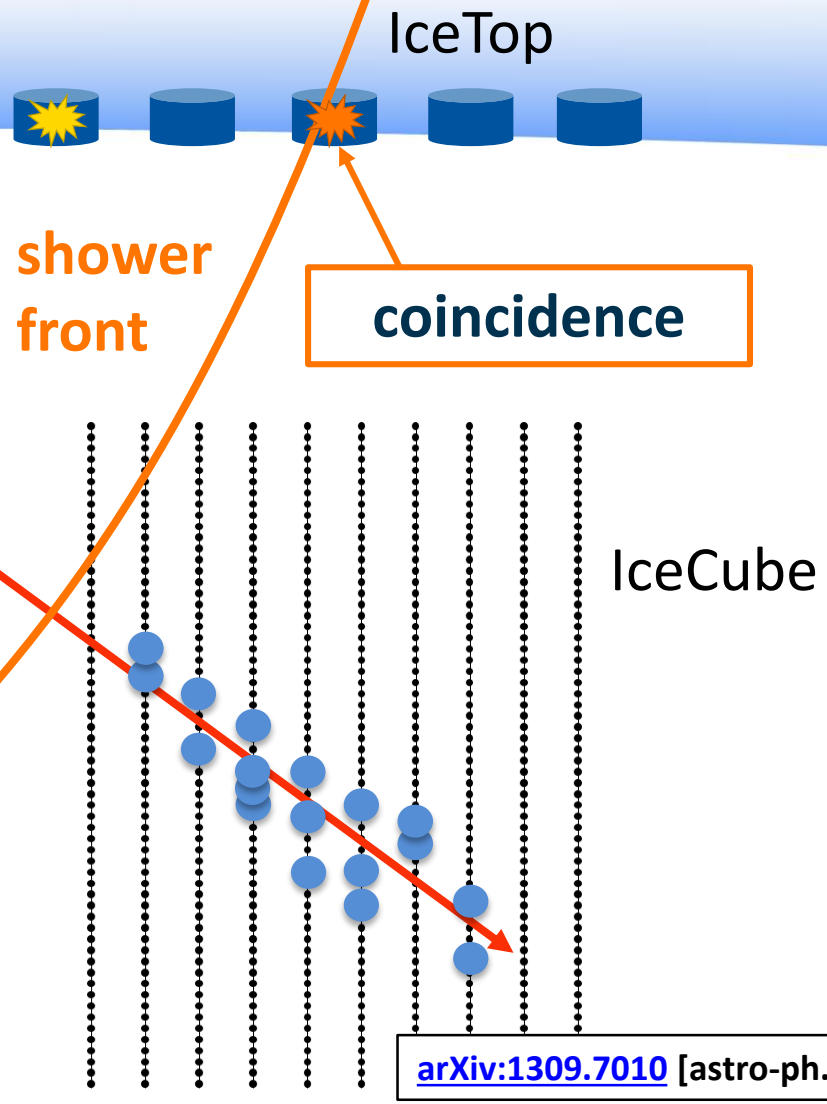

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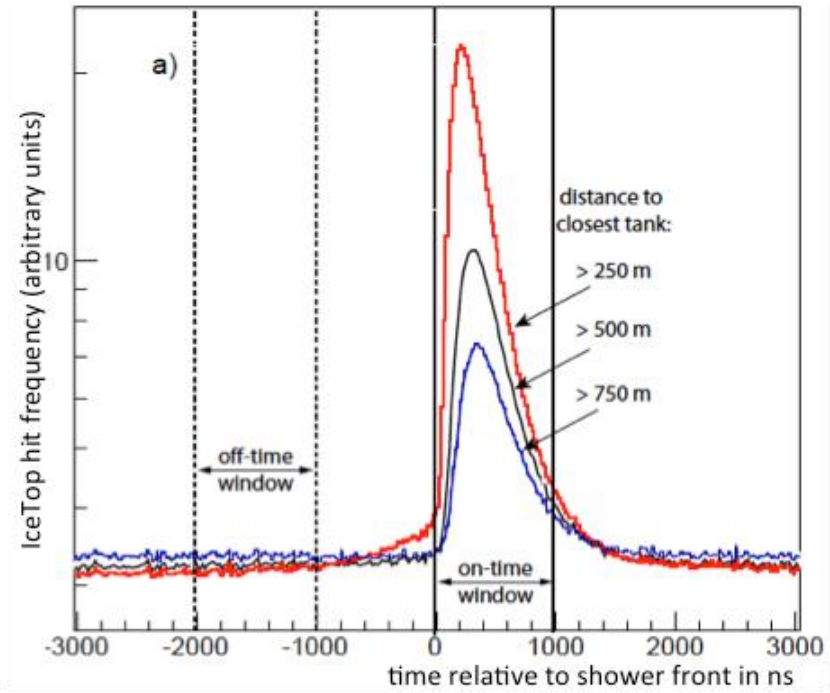

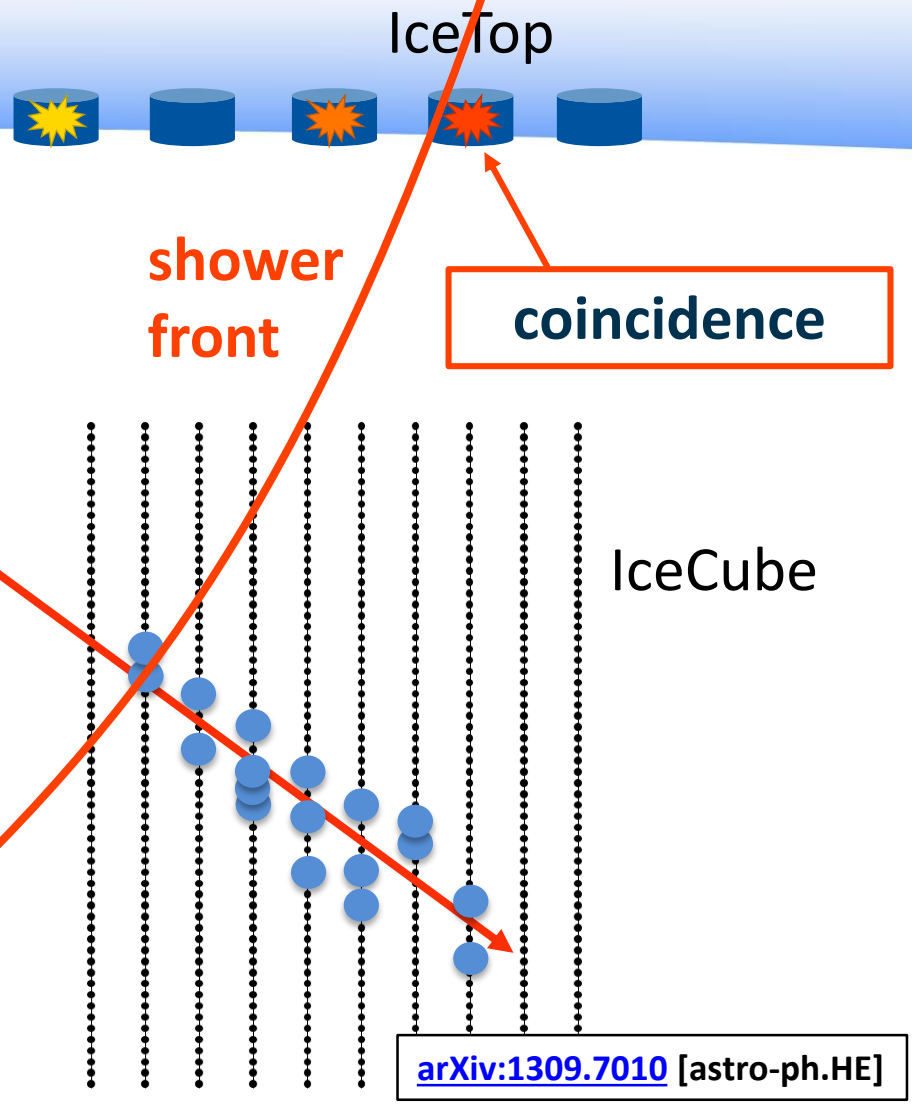

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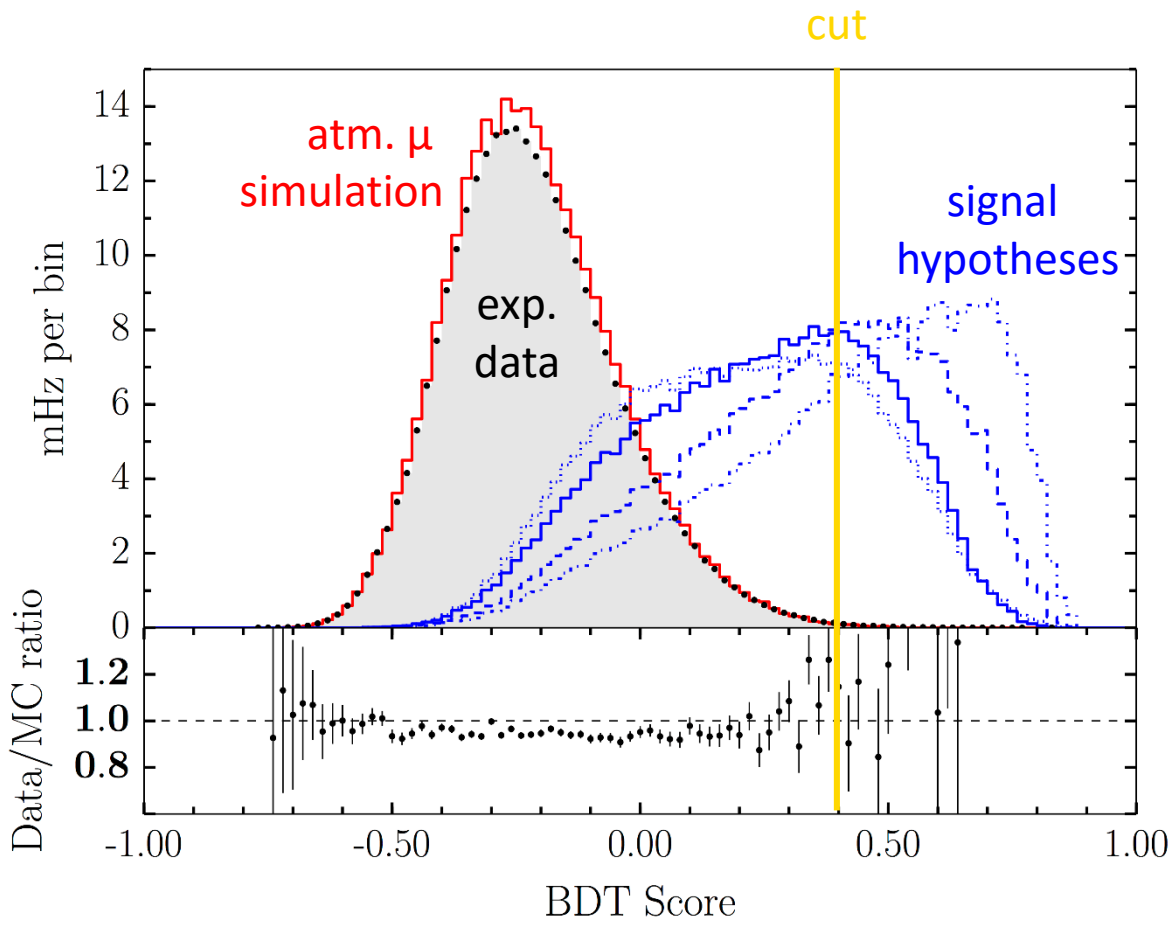
Event Selection – More Cuts

- cuts on more advanced reconstructions of the interaction vertex
- cuts on reconstruction quality
- cut on BDT score

- final sample: 6191 events in 329 days
- median angular resolution: 2°

- similar numbers for **STeVE** analysis



Analysis Method

- use same unbinned likelihood method as standard point source analysis

$$\mathcal{L}(n_s, \gamma) = \prod_i^N \left(\frac{n_s}{N} S_i(\Delta\psi, \sigma, E; \gamma) + \left(1 - \frac{n_s}{N}\right) B_i(\delta, E) \right)$$

Background PDF B_i
depends on
- declination δ
- Energy E

Signal PDF S_i
depends on
- relative position of event and considered location $\Delta\psi$
- angular uncertainty σ
- Energy E
- spectral index γ

- test statistic: likelihood ratio of null hypothesis $(n_s = 0)$ and best fit $(\hat{n}_s, \hat{\gamma})$

$$TS = -2 \log \left(\frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\hat{n}_s, \hat{\gamma})} \right)$$

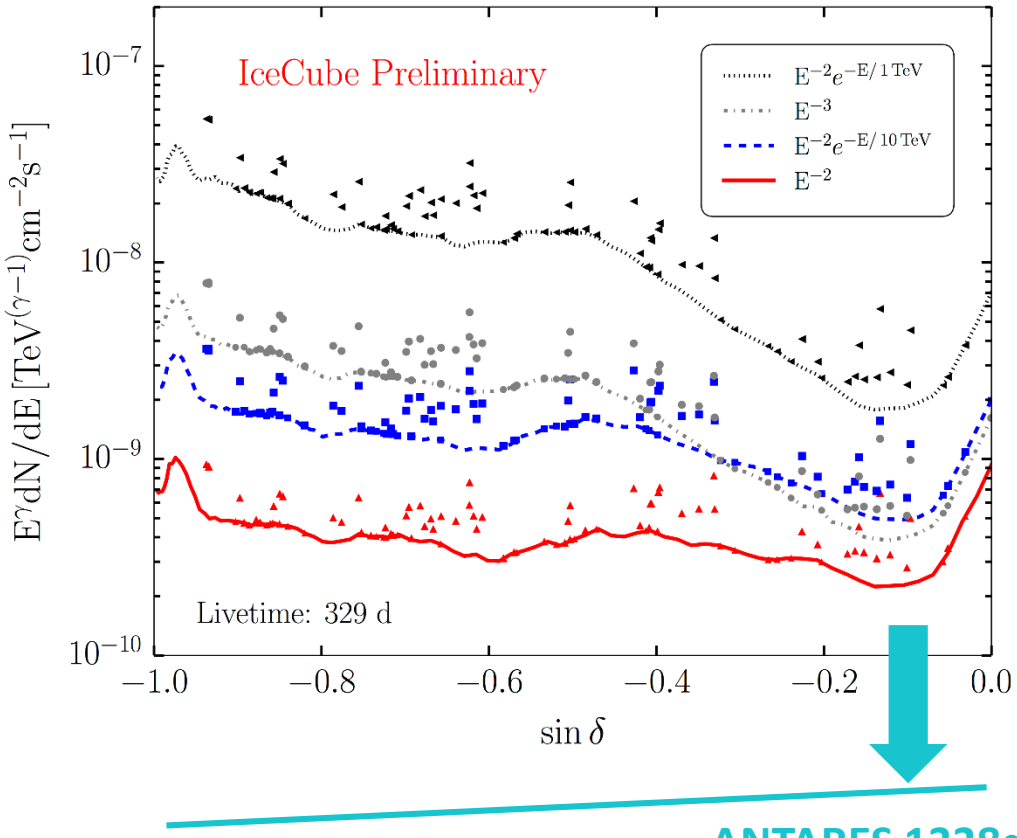
null hypothesis

best-fit likelihood

- true for both **LESE** and **STeVE** (and other analyses, too)

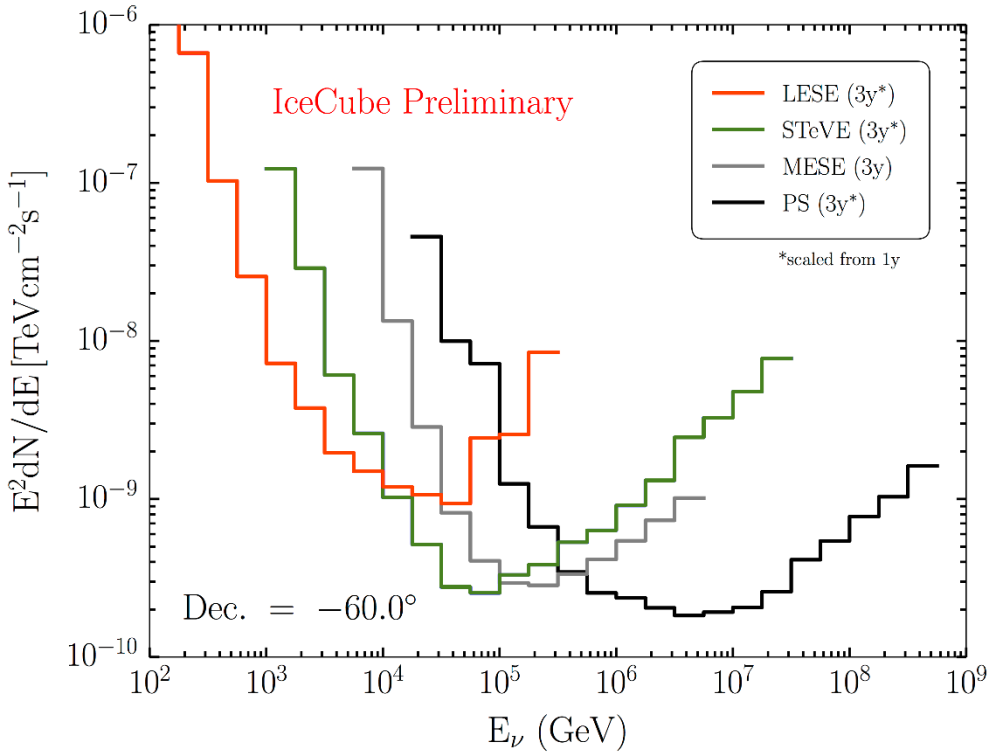
Sensitivity

- median sensitivity as function of declination for different spectra (**LESE**)



ANTARES 1338d

- median sensitivity as function of energy for different analyses



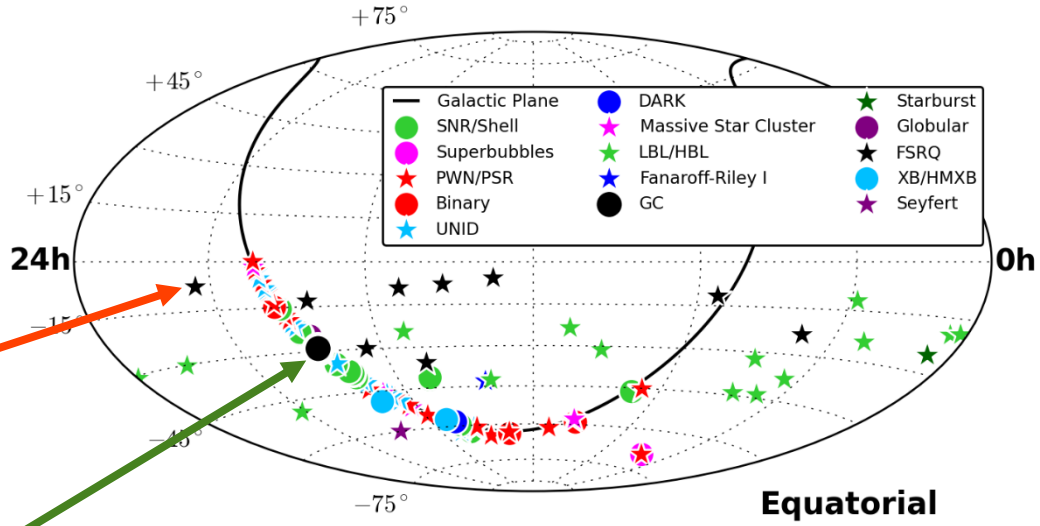
➡ combination covers an unprecedented energy range from 100 GeV to EeV!

Results: Source List

- test 96 pre-defined sources:
  - all 84 TeVCat sources in the Southern Hemisphere
  - 12 sources traditionally tested by IceCube

- most significant source (**LESE**):
  - QSO 2022-077
  - best-fit: $\hat{n}_s = 17.3$, $\hat{\gamma} = 3.5$
  - post-trial p-value: 14.8%

- most significant source (**STeVE**):
  - SNR G000.9+00.1
  - best-fit: $\hat{n}_s = 8.14$, $\hat{\gamma} = 4.0$
  - post-trial p-value: 35.4%



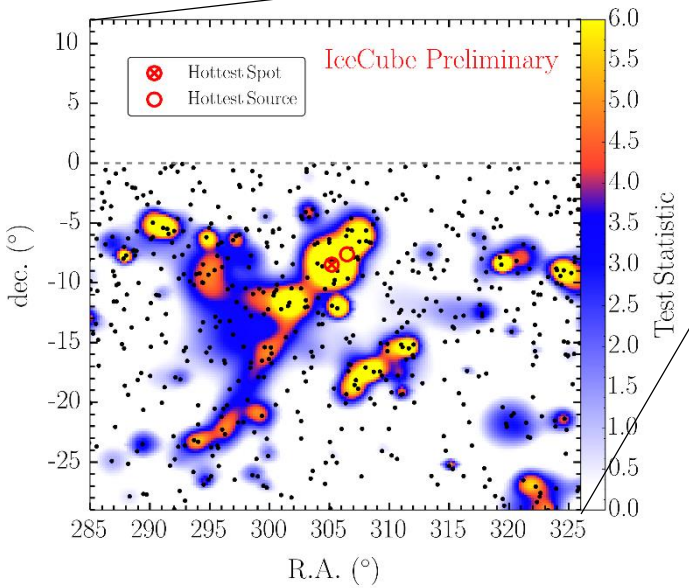
➡ **nothing significant found!**

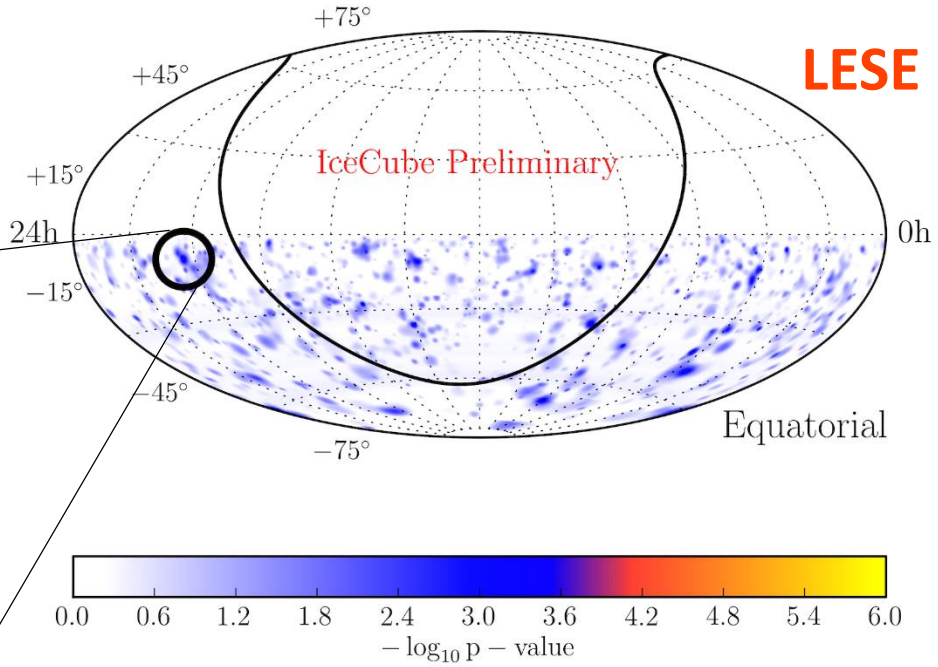
Results: Sky Scan

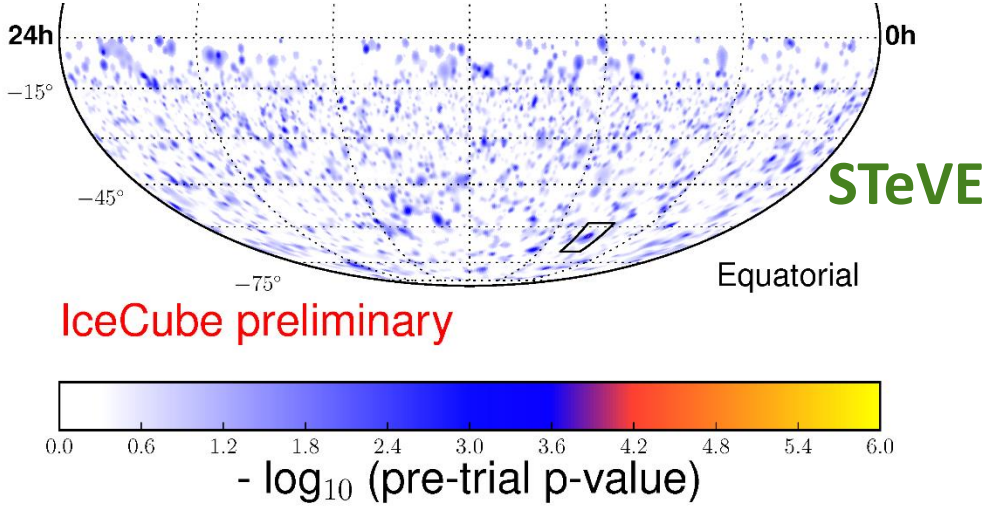
- sky scan on HEALPix map with 0.5° bin size

- hottest spot (**LESE**):
  - RA = 305.2°, δ = -8.5°
  - post-trial p-value: 88.1%
  - close to most significant source

- hottest spot (**STeVE**):
  - RA = 93.1°, δ = -64.3°
  - post-trial p-value: 74.9%







➡ **nothing significant found!**

Summary

- standard point source search is sensitive to the Southern sky only at very high energies (>100 TeV)
- dedicated low-energy searches are able to cover the energy range above 100 GeV
- event selection relies heavily on veto techniques
- no evidence of neutrino emission from point sources was found in one year of data from IC86
  - neither in sky scans nor source list tests
  - neither in **LESE** (100 GeV – 10 TeV) nor in **STeVE** analysis (1 – 30 TeV)
- future plans:
  - 3 more years of data are ready to be incorporated
  - extended source searches
  - Galactic plane searches