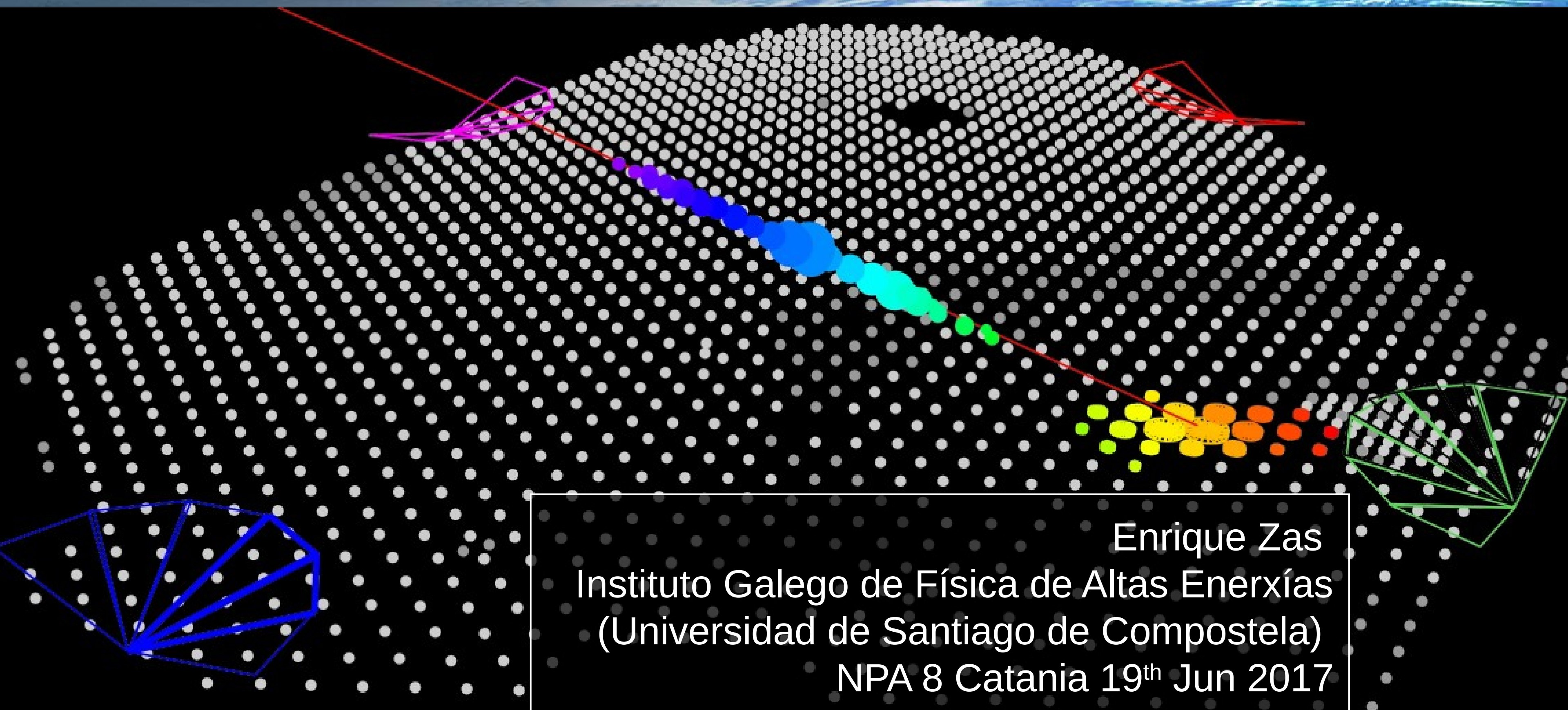
# Recent Ultra High Energy neutrino bounds and multimessenger observations with the Pierre Auger Observatory

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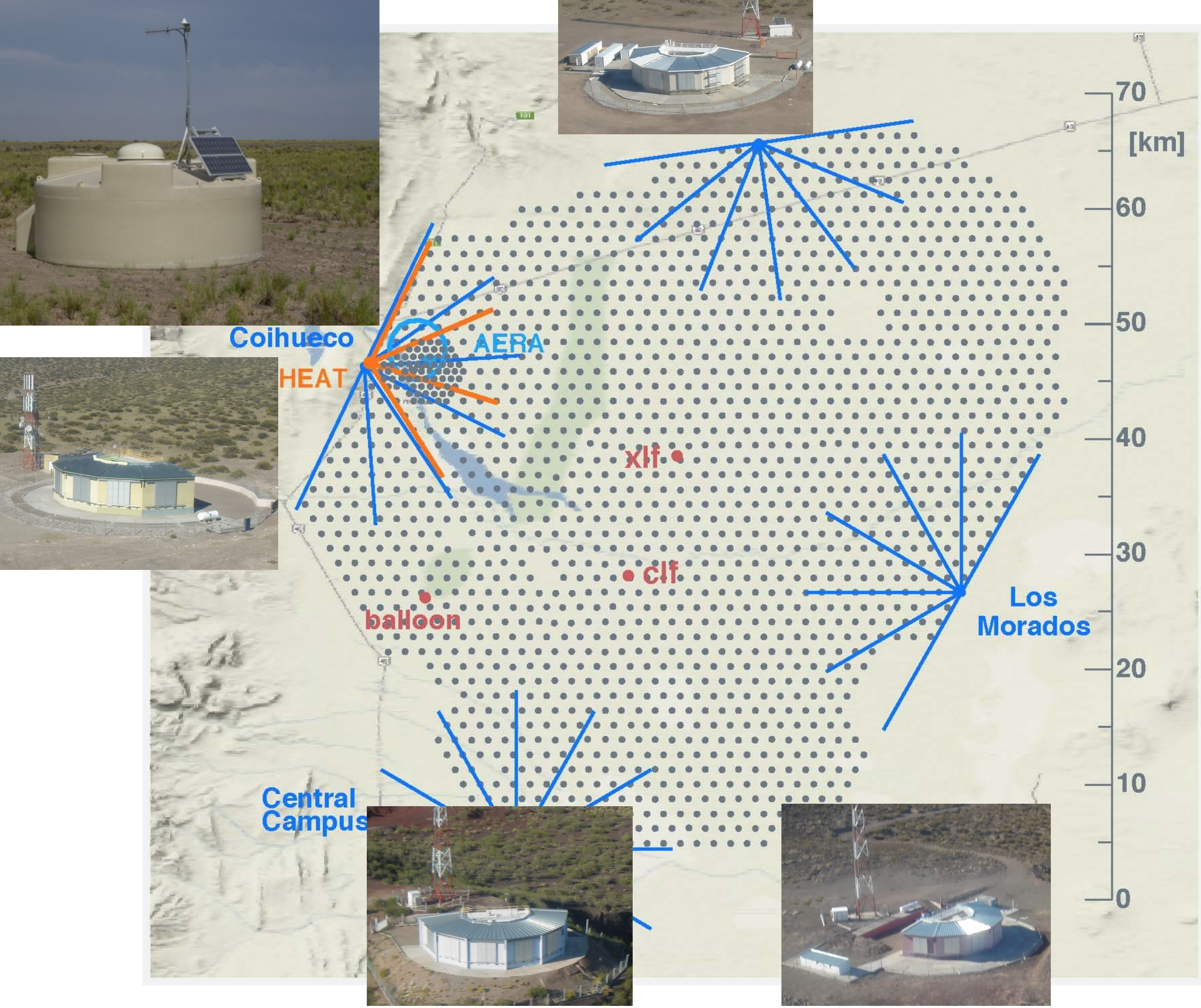
(Universidad de Santiago de Compostela)


NPA 8 Catania 19th Jun 2017


70
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Morados
Central
Campus


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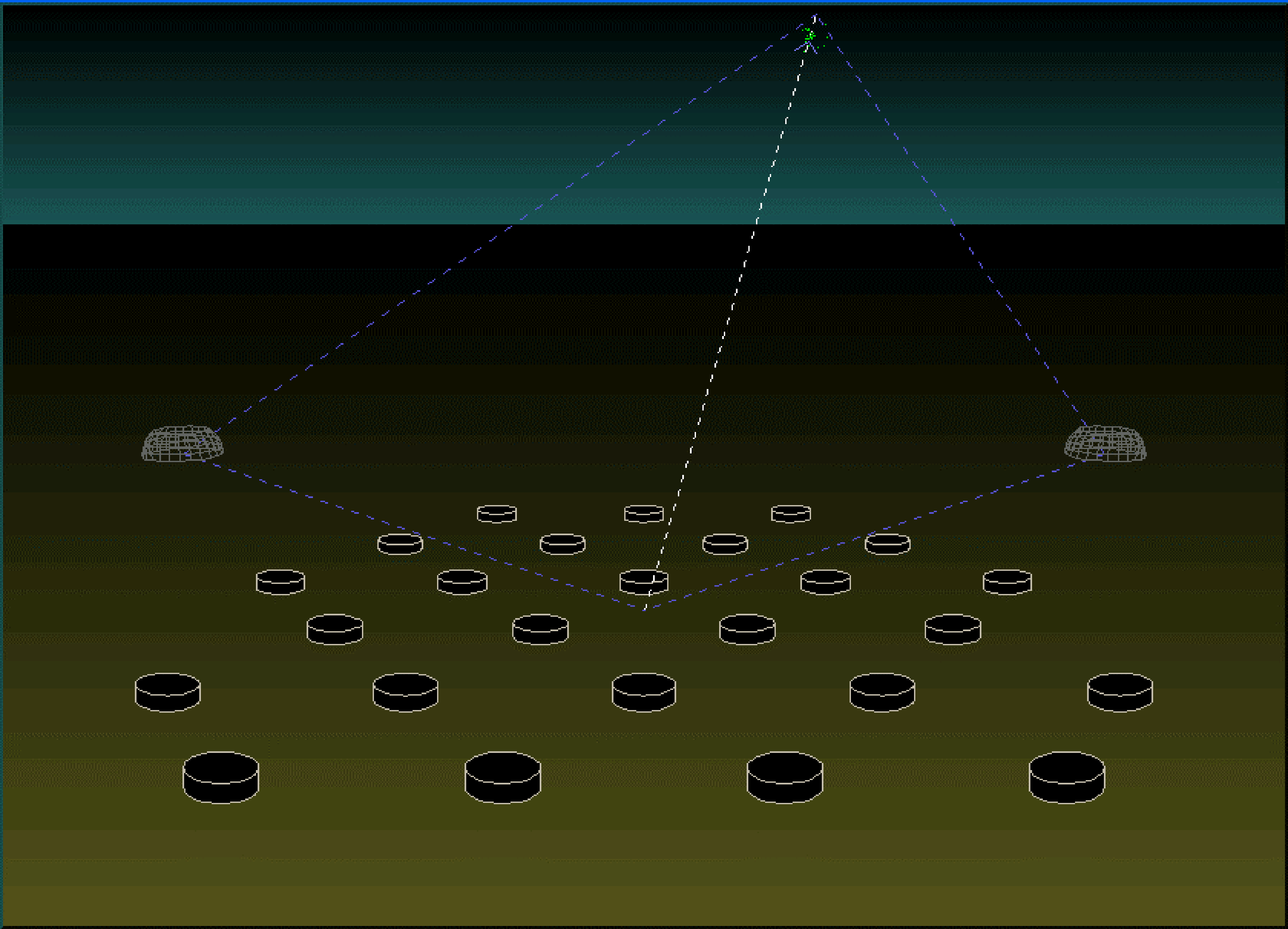
d'Orlando
Patti
Messina
Parco dei
Nebrodi
Taormina
Acireale
Enna
TA

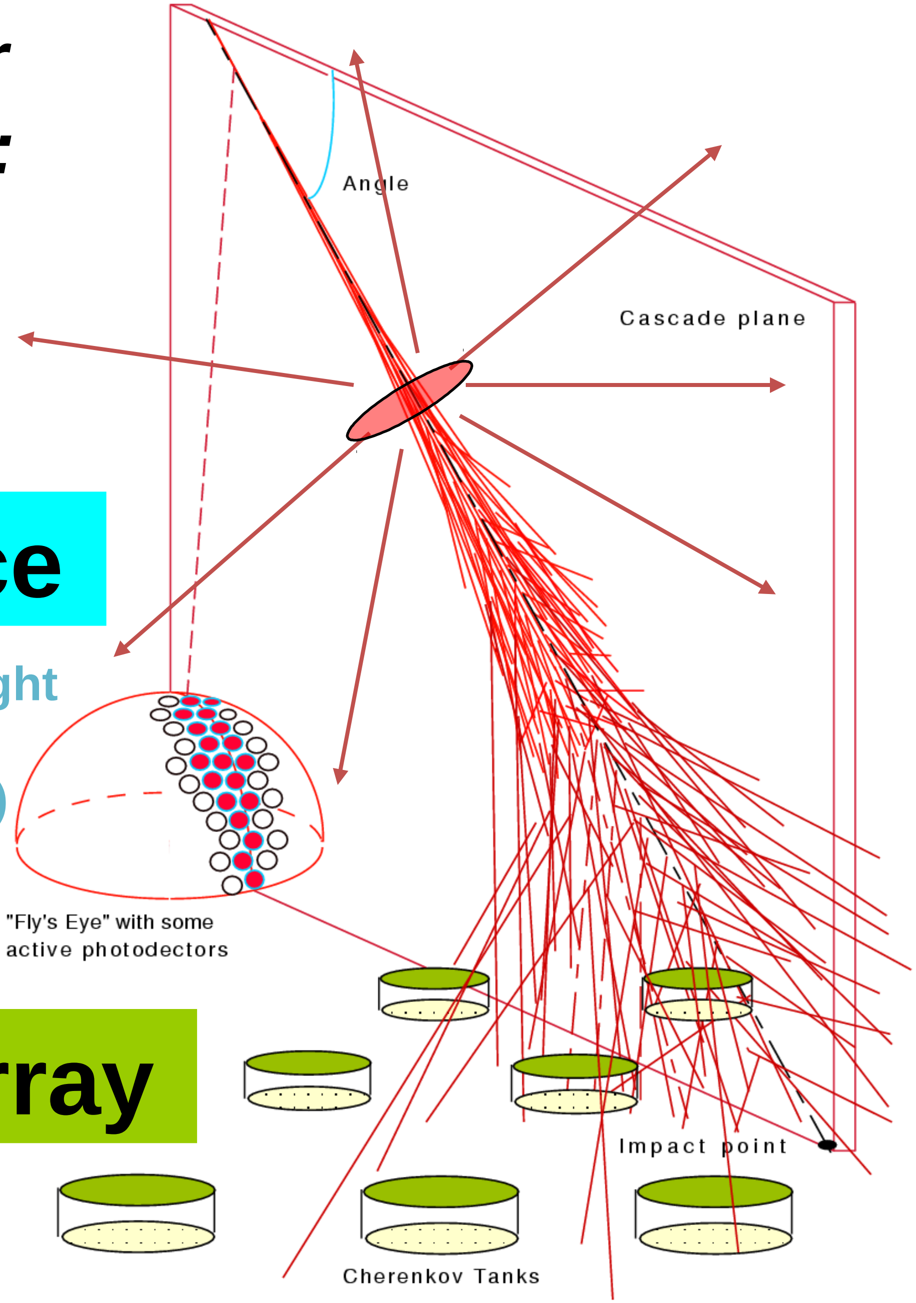


# *TA and the Pierre Auger Observatory are Hybrid: Combine the two succesful techniques*

## Fluorescence

**Isotropic Fluorescence light from nitrogen (~4 γ per meter of track)**

## Particle array



Designed to find the sources of UHECRs

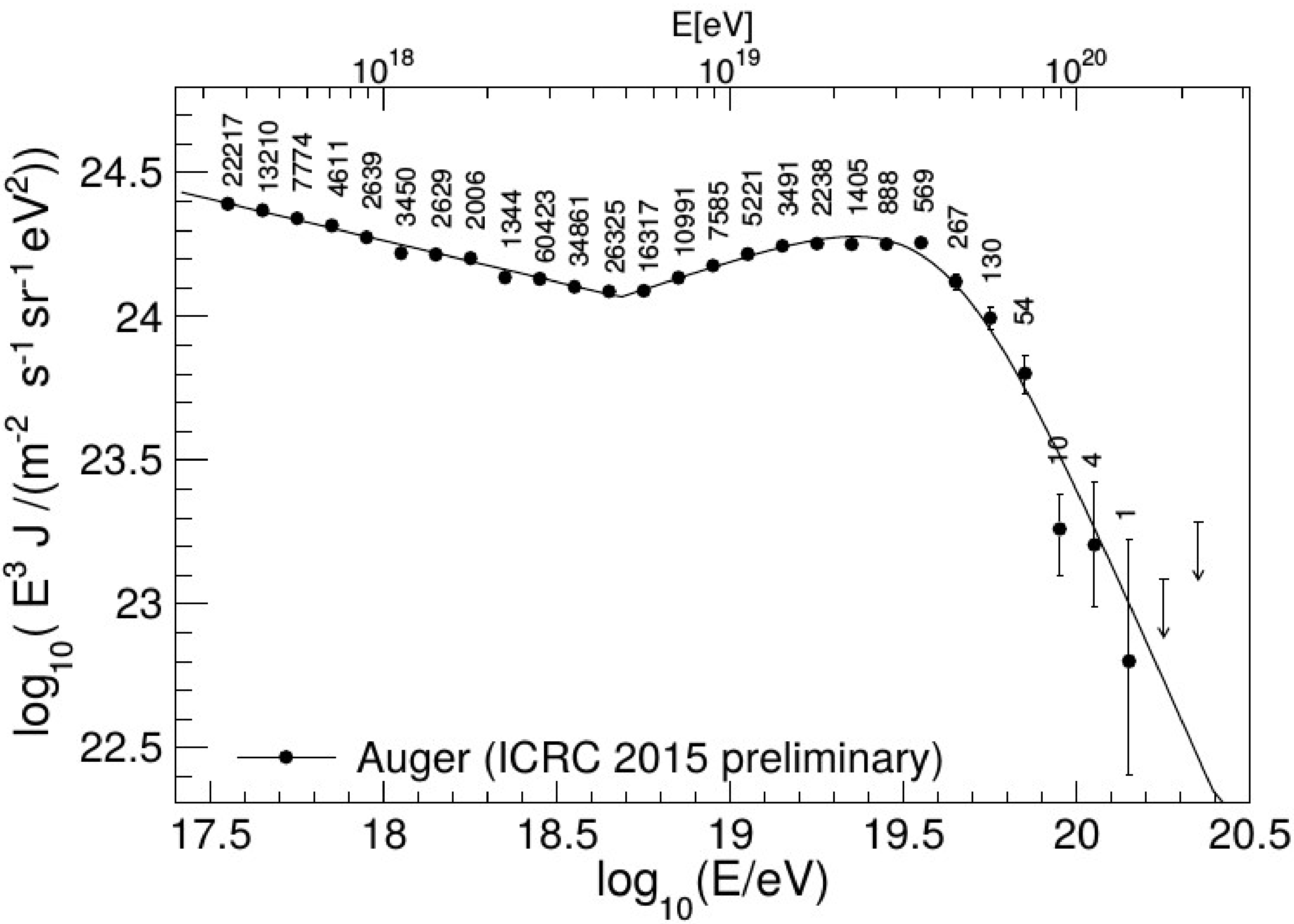
Measuring spectrum
Arrival directions
Composition

with unprecedented precision

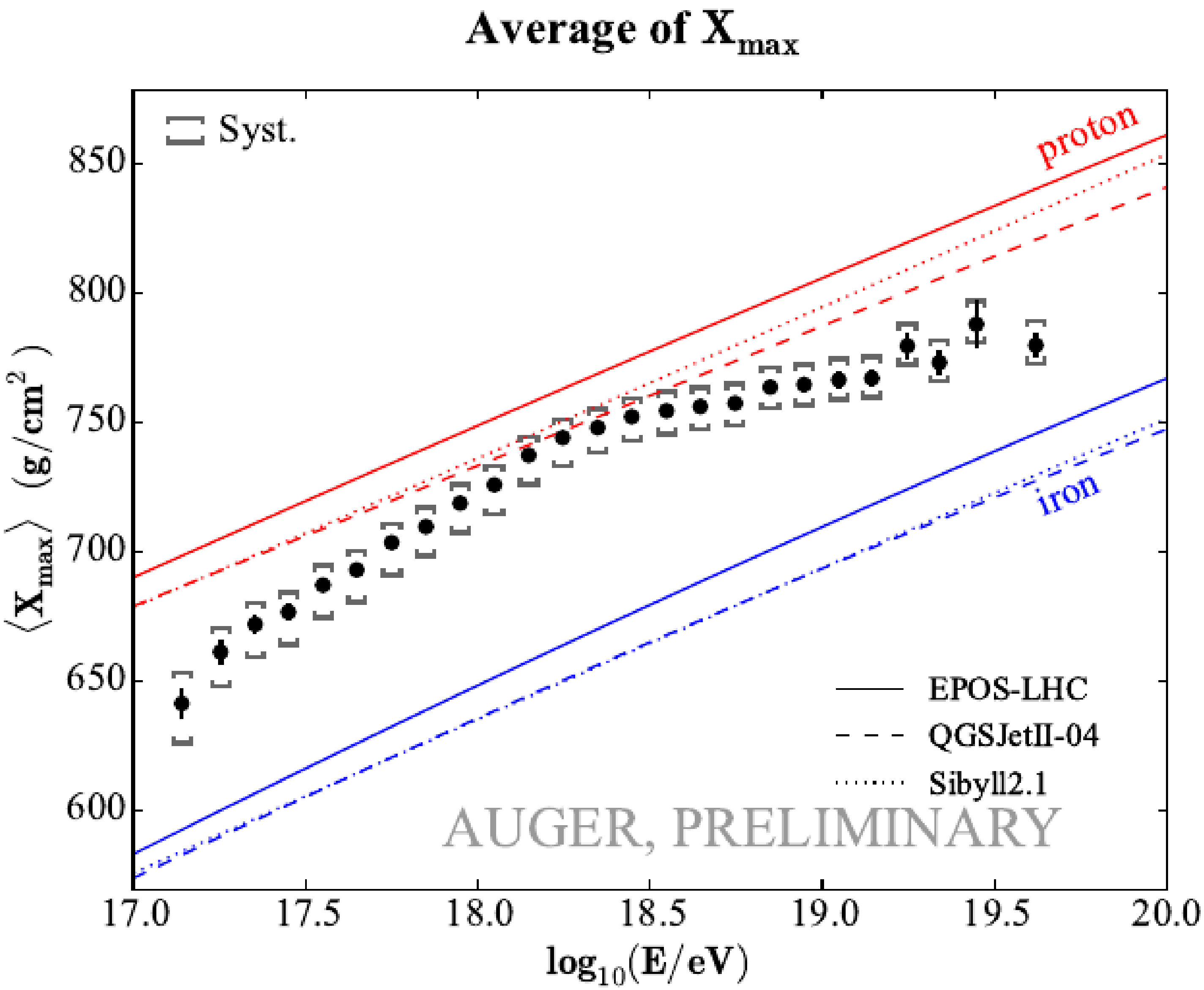
In addition we showed that it was good to search for UHE $\nu$s

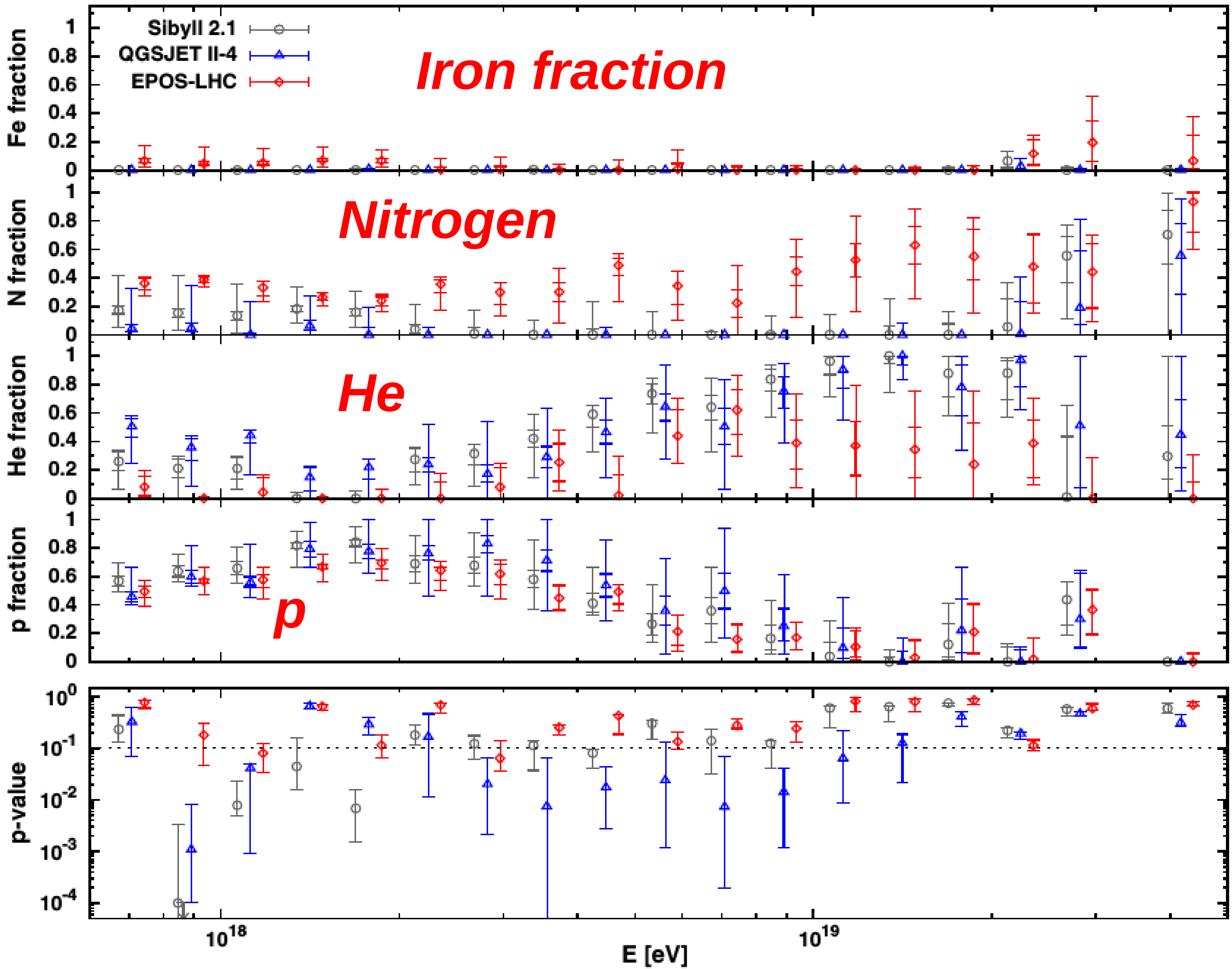
The predjudice was proton composition but Observatory measurements disfavor it

# The energy spectrum of UHECR



# Mean $X_{max}$ measurements



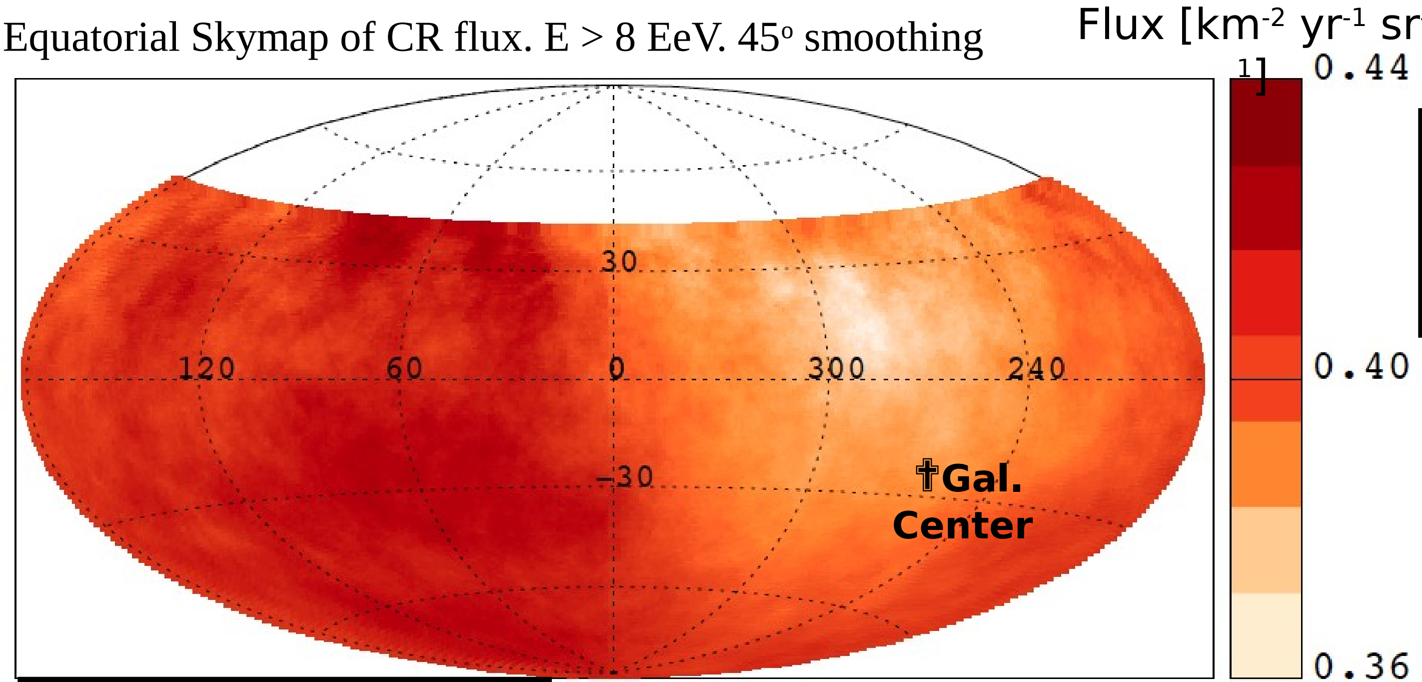


Sibyll 2.1
QGSJET II-4
EPOS-LHC
Iron fraction
Nitrogen
He
p
Fe fraction
N fraction
He fraction
p fraction
p-value
E [eV]

# Arrival directions of UHECR

- **Small angular scale anisotropy** of CRs, E > 40 EeV (602 events):
  - Some hints but **no significant excesses**
- **Large angular scale anisotropy**:
  - Indications of a dipole for E > 8 EeV: (7.3% ± 1.5%)

Equatorial Skymap of CR flux. E > 8 EeV. 45° smoothing



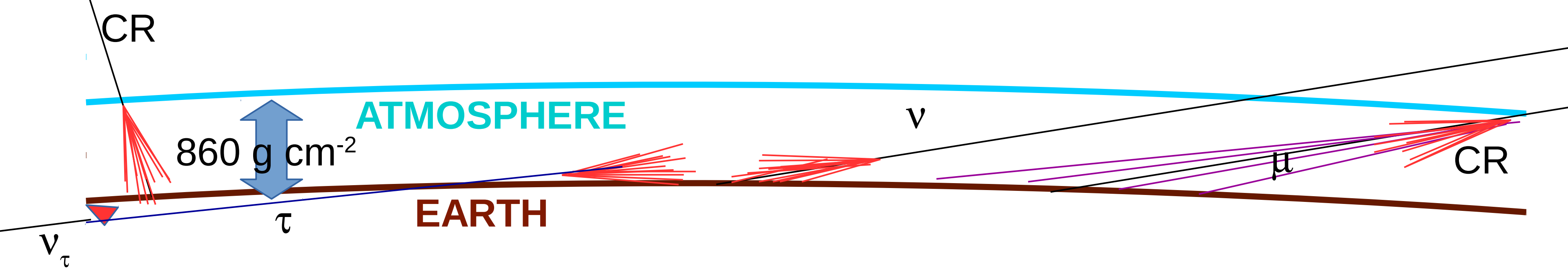

Dipole pointing to
RA = 95° ± 13°
$\delta$ = -39° ± 13°
**> 4 $\sigma$**

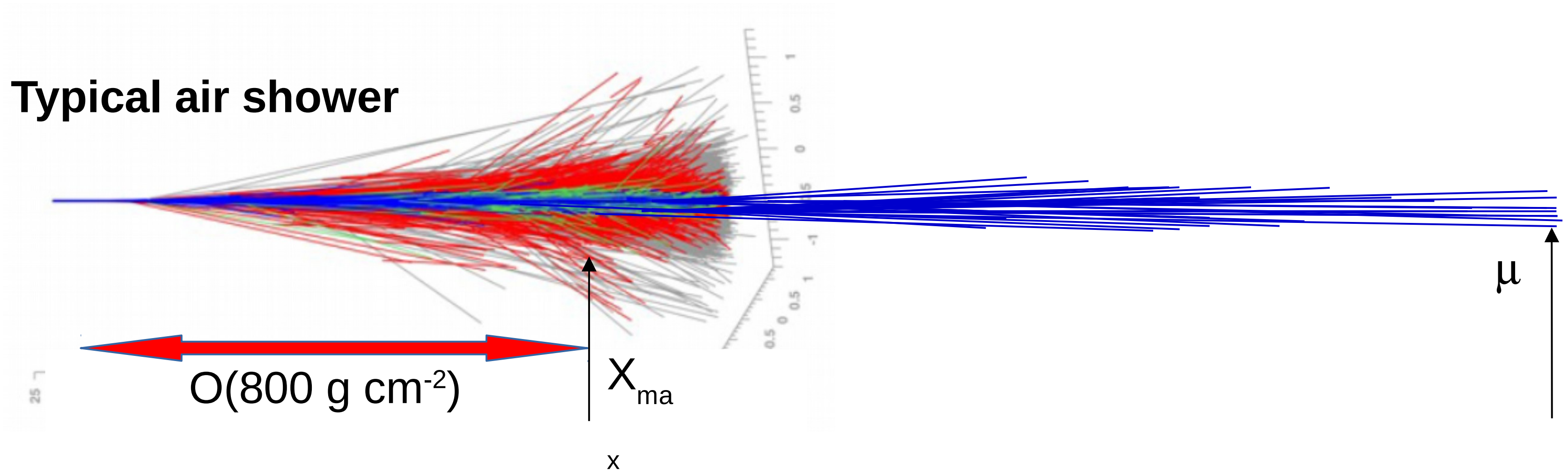
Jan. 2004 to Dec. 2013

*Ap. J* ***802****, 111 (2015)*

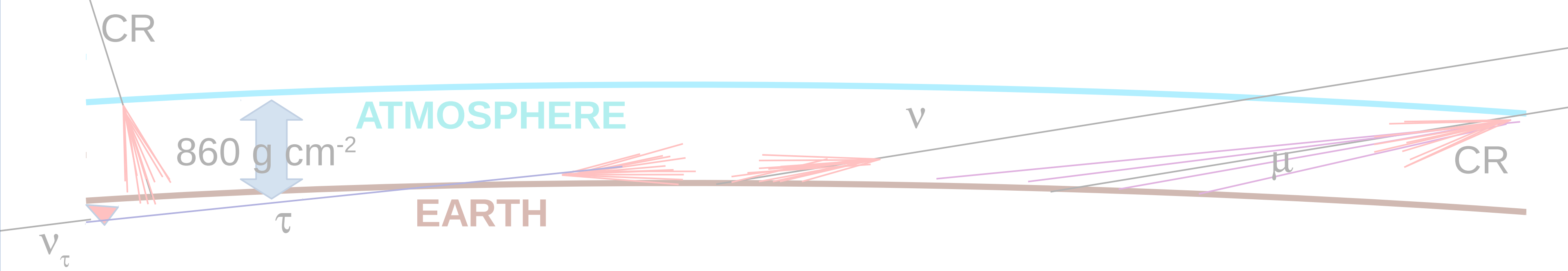
**Wait for exciting updates over the next couple of months**

# Suitable for EeV ν search

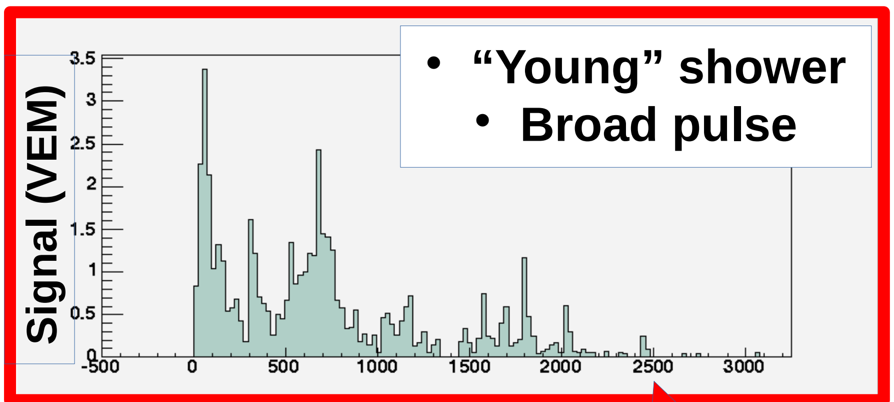


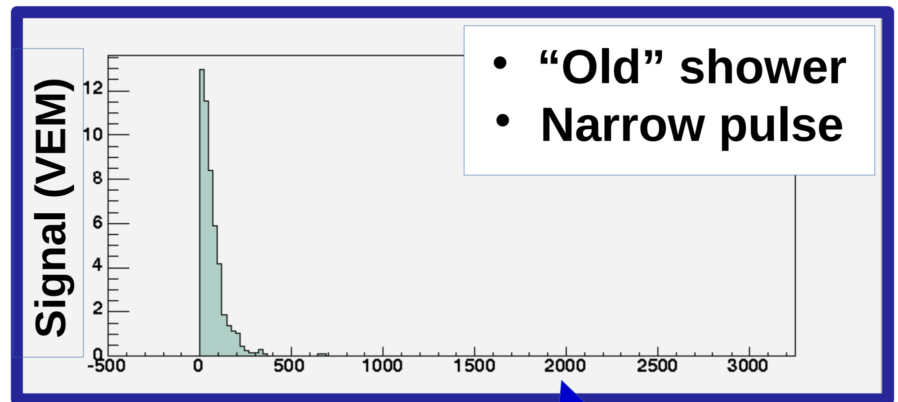



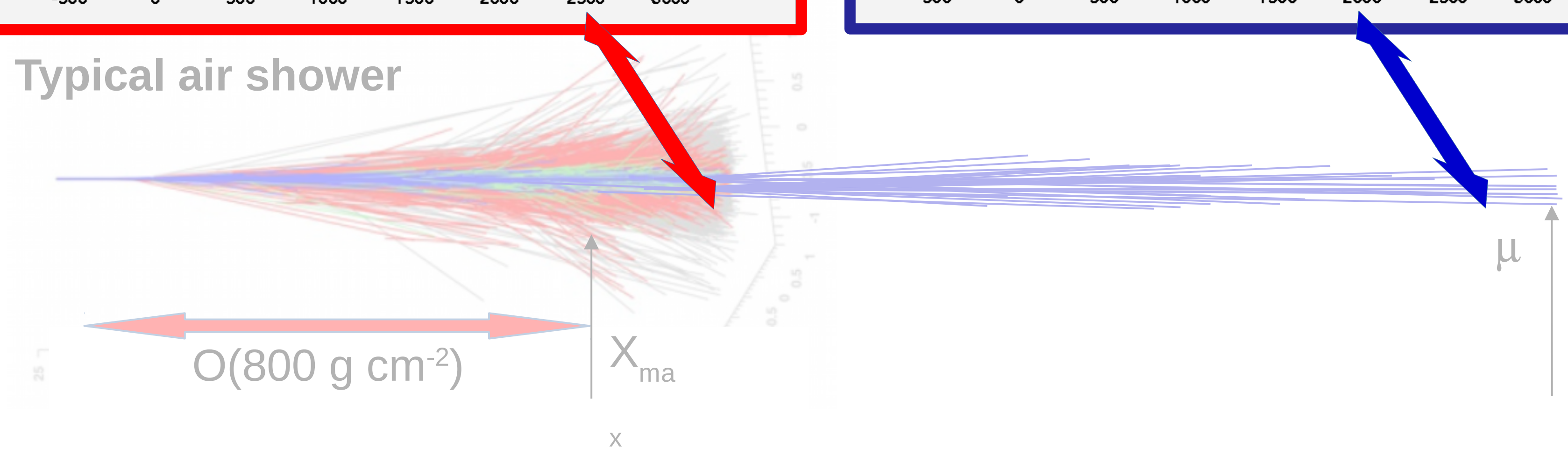
# Suitable for EeV ν search




**Neutrino: Inclined air shower with broad component**



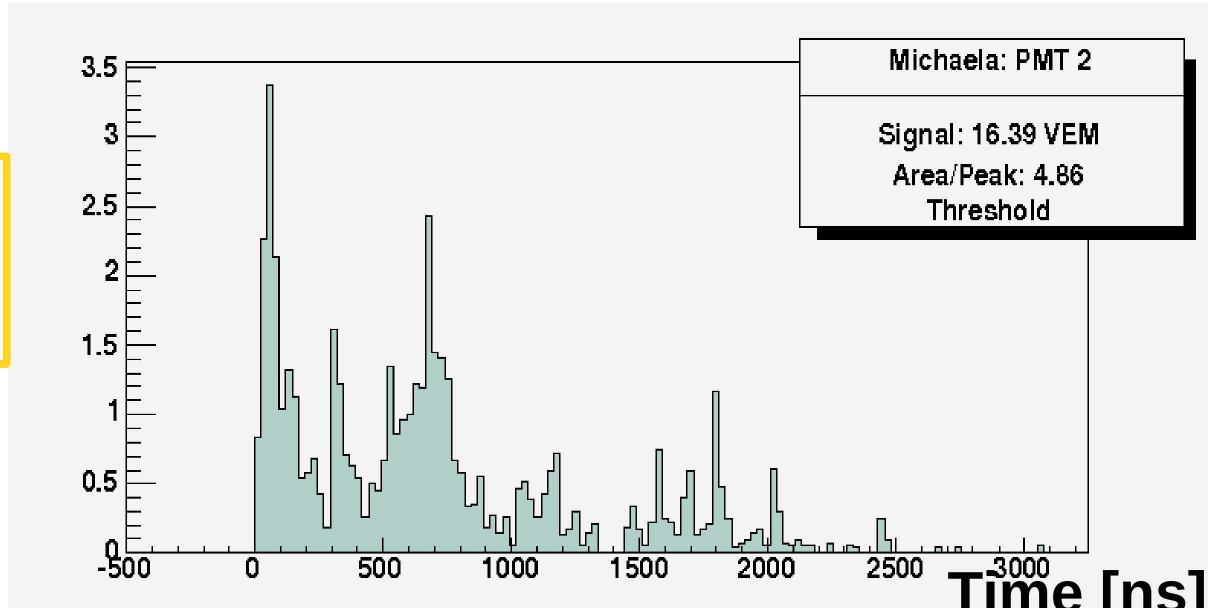



# The SD

Nuclear Instruments & Methods in Physics Research A **798** (2015) 172–213

Low signal triggers:
SD: “ToT” 13 bins in 2 PMTs
Event: 3 ToT stations

or
Area over Peak (AoP)




**FADC Traces**
**25 ns digitising**

**25 ns bin sampling => Measure shower “thickness”**

# Neutrino channels

Two types of events **ES / DG**

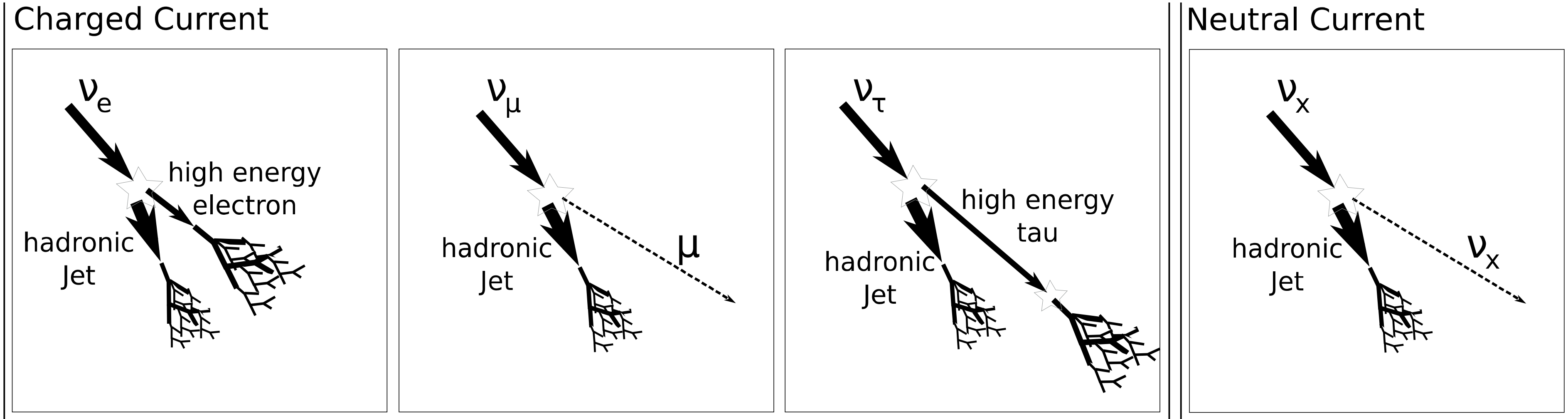
**3** search categories (**different flavor sensitivities**):

- **Earth skimming tau neutrinos (1) ES**
  - Between $90^0$ and $95^0$ (upcoming)
  - Decay early

  *To trigger SD array*

- **Atmospheric interactions** ($\theta > 60^0$ $X_{atm} > 1700$ g cm$^{-2}$)
  - + **$60^0 < \theta < 75^0$ (2) DGL**
  - + **$75^0 < \theta < 90^0$ (3) DGH**

| | |
|---|---|
| ***All $\nu$ NC & $\nu_\mu$ CC*** | ***20% transfer*** |
| ***$\nu_e$CC*** | ***100% transfer*** |
| ***$\nu_\tau$CC*** | ***20% in first 65% in $\tau$ decay*** |

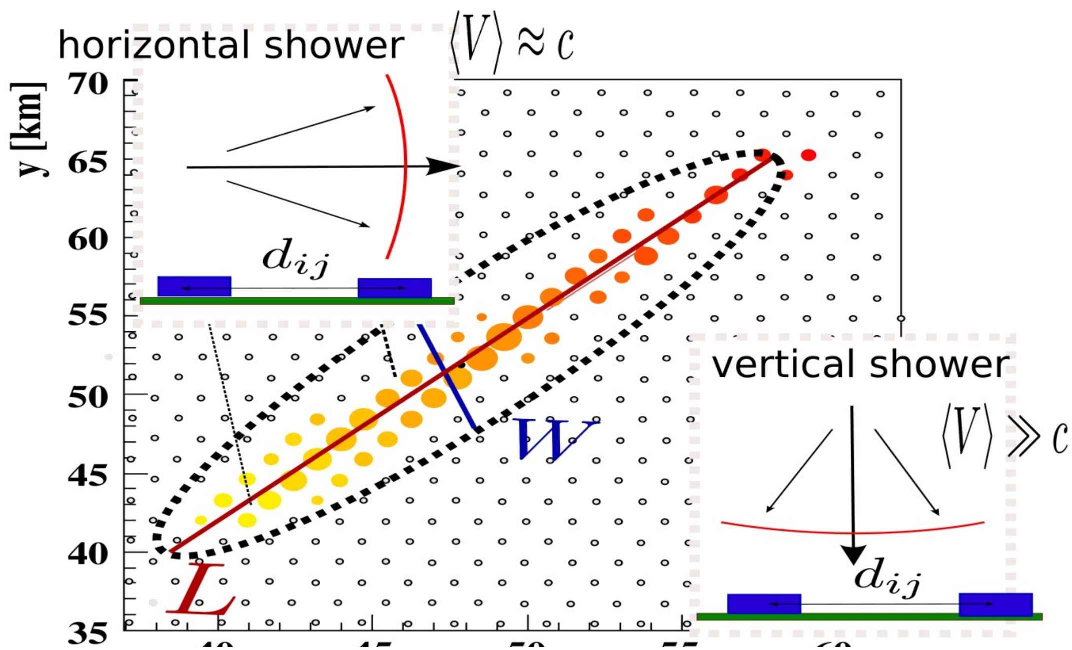


# Selecting ν in data

## *(1) Inclined selection:*

### ***Angular selection (3 triggers for ES / 4 for DG):***

- **Elongated pattern (large Length over Width)** (ES & $75^0$-$90^0$)
- **Apparent speed of signal along Length** (mean c + rms) (ES & $75^0$-$90^0$)
- **Angular reconstruction** (plane fit $60^0$-$75^0$ & $75^0$-$90^0$)




## *(2) Select EM component*

**1 variable** (using AoP of selected stations))

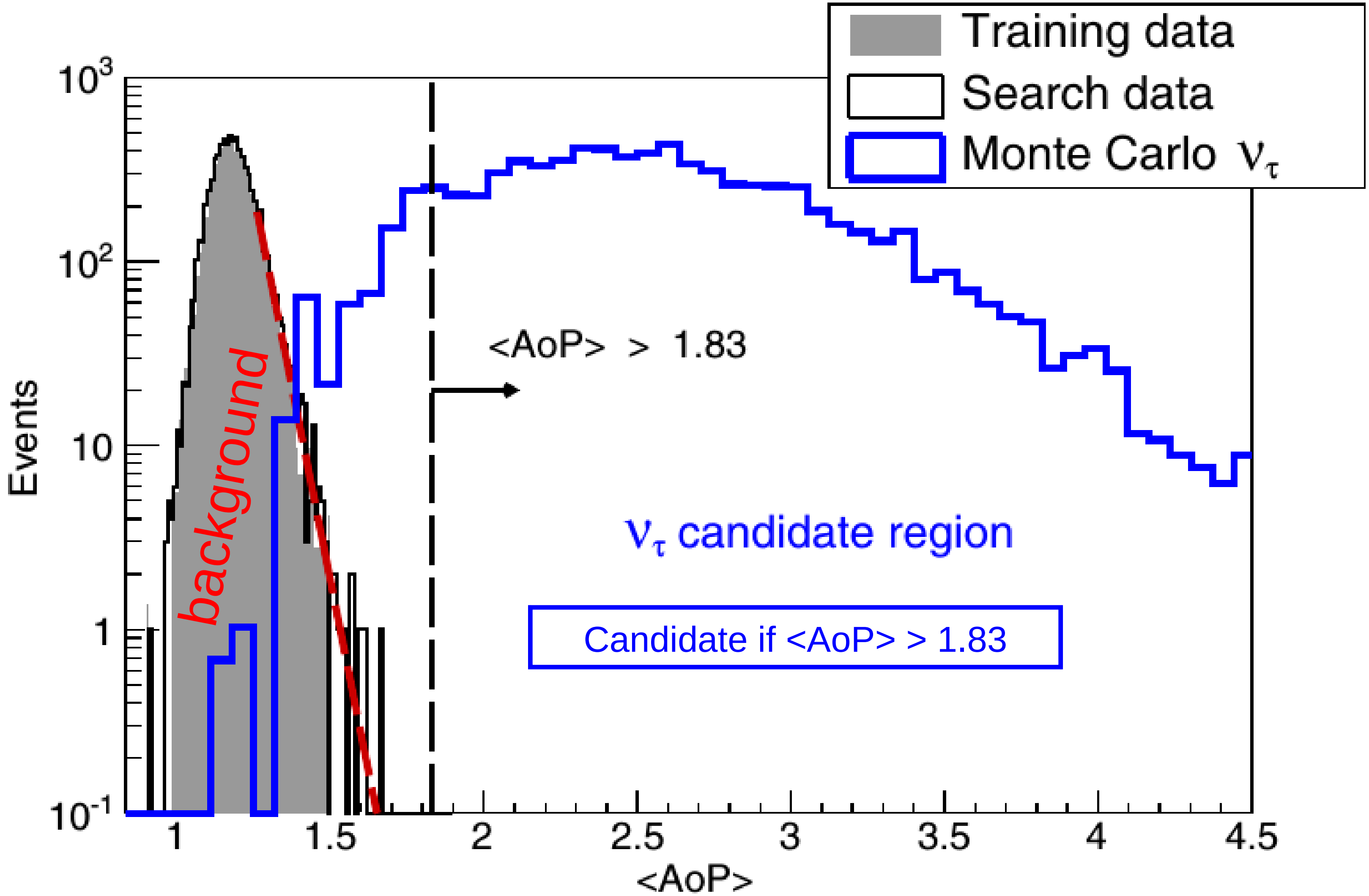
ES: <AoP> > 1.83
(AoP > 1.4 if only 3 SD)
(60% ToT up to Jun-10)

$60^0$-$75^0$: AoP of 4/5 central SD
Fisher discriminant 8/10 var
AoP, $AoP^2$ (& 75% ToT)

$75^0$-$90^0$: AoP of 4 early SD
Fisher discriminant 10 var:
AoP, $AoP^2$, product &

# $\nu$ search: Earth-Skimming

No $\nu$ candidate events found in any of the analyses



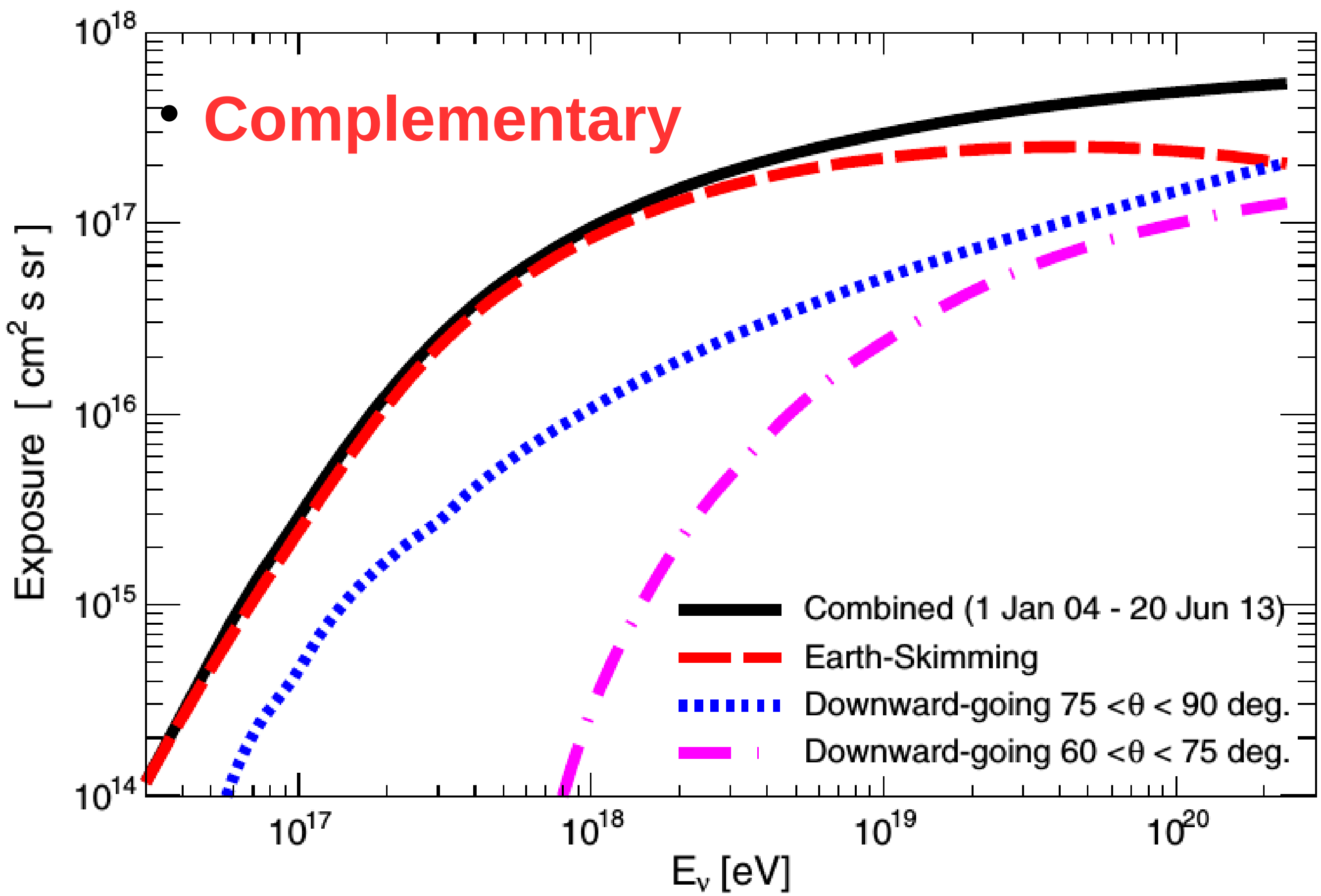

<AoP> = mean value of Area-over-Peak in event

# **Exposure $\mathcal{E}_{tot}(E_\nu)$:** 1 Jan 04 – 30 June 13

$$N_{\rm events} = \int_{E_\nu} \Phi_{\rm single\ flavor}(E_\nu)\ \mathcal{E}_{\rm tot}(E_\nu)\ {\rm d}E_\nu$$

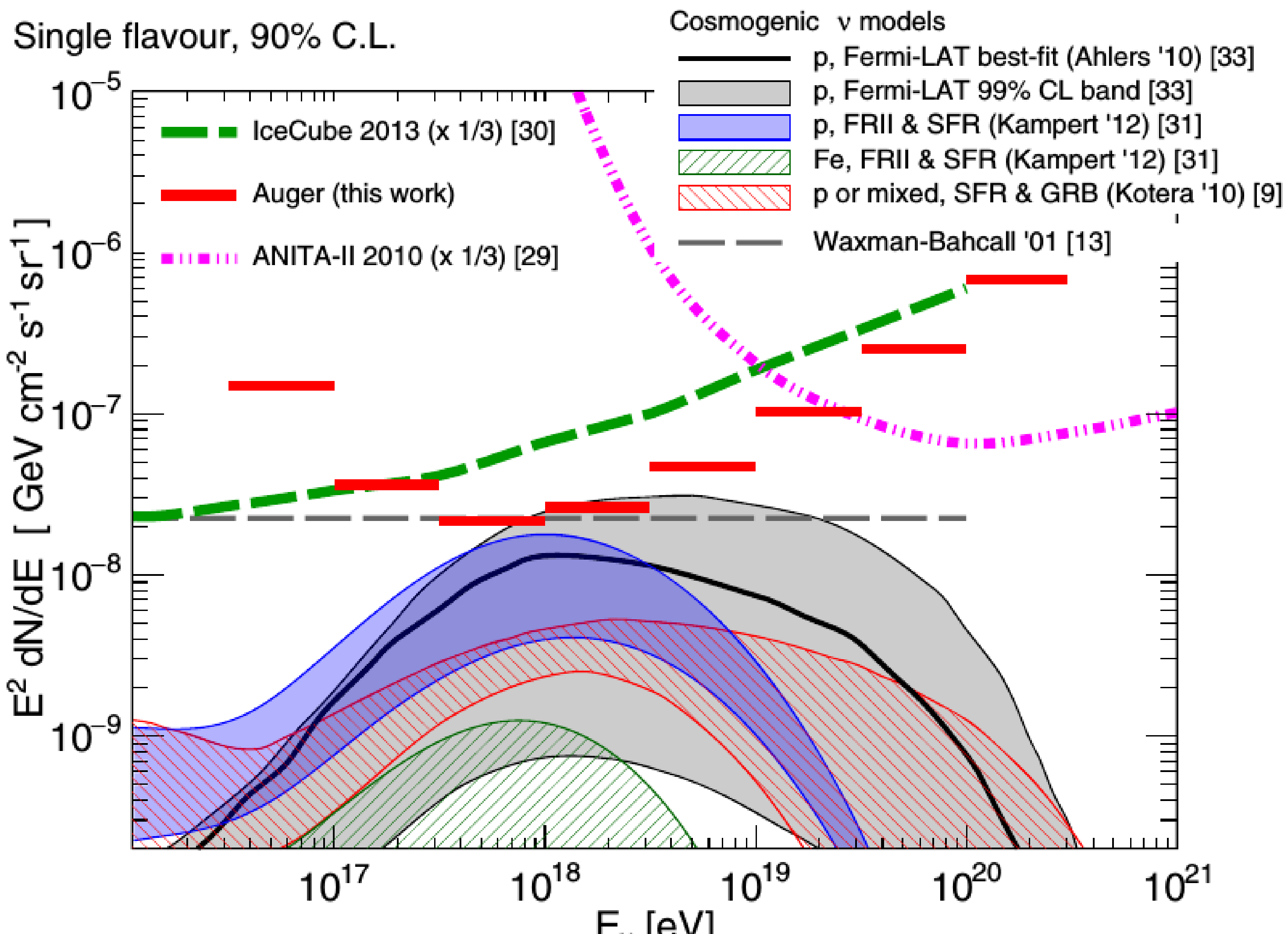
**Assumed flavor ratio (1:1:1)**

| Relative contribution of channels & flavours to event rate ($E^{-2}$ flux) | |
|---|---|
| • **ES** | • 79.4% |
| • **DGH** | • 17.6% |
| • **DGL** | • 3.0% |
| • electr | • 10.1% |
| • **muon** | • 3.8% |
| • **tau** | • 86.1% |



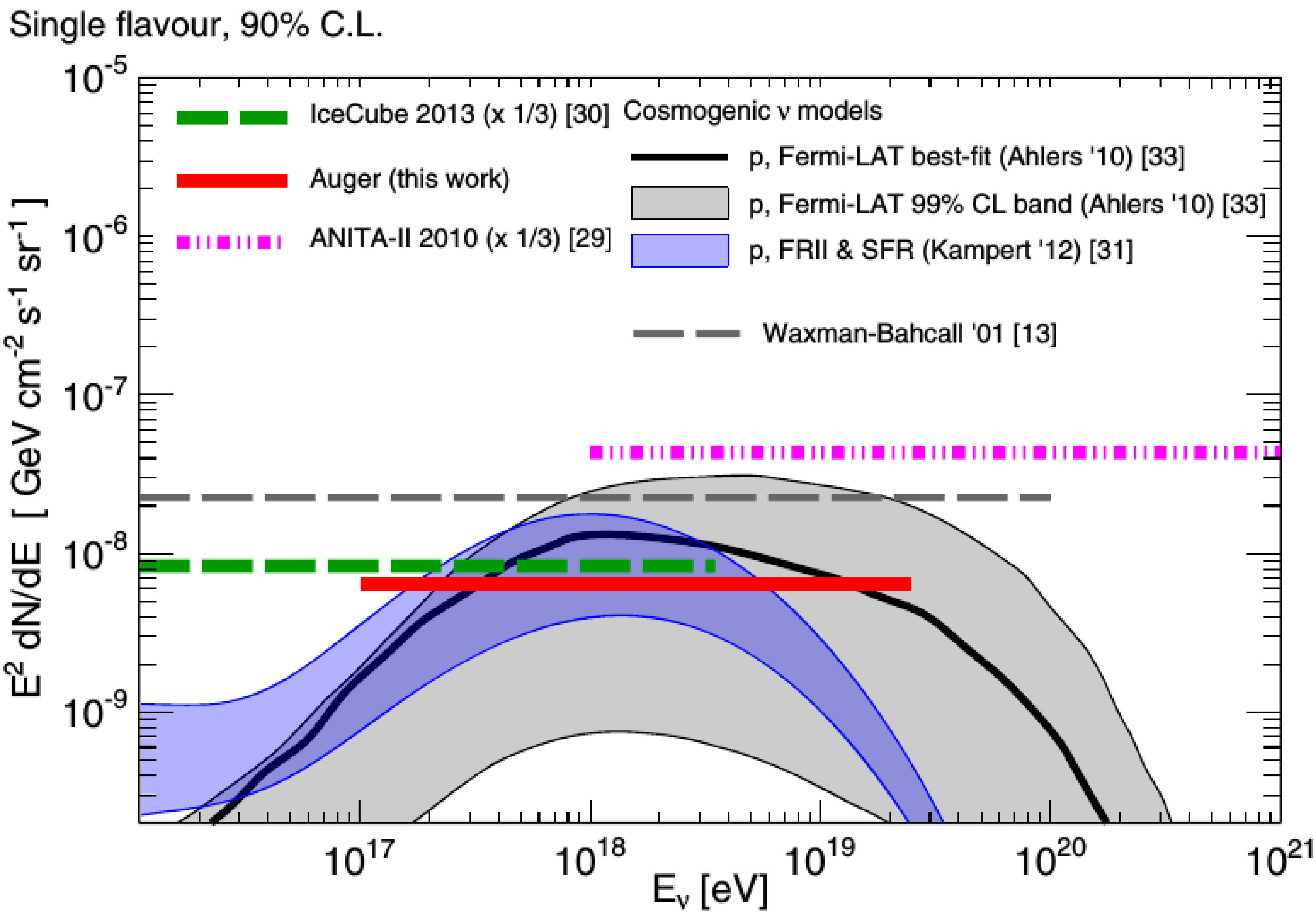
# Diffuse limit ("differential")

## integrate in $\log_{10}E$=0.5 bins



# Diffuse limit (“integral”)

## Integrate $E^{-2}$ flux: range as indicated



# Source models: p with large z evolution: very disfavoured (to be updated)

***PR D 91, 092008 (2015)***

| Diffuse flux Neutrino model | Expected number of events (1 January 2004–20 June 2013) | Probability of observing 0 |
|---|---|---|
| Cosmogenic—proton, FRII [33] | ~4.0 | $\sim 1.8 \times 10^{-2}$ |
| Cosmogenic—proton, SFR [33] | ~0.9 | ~0.4 |
| Cosmogenic—proton, Fermi-LAT, $E_{\mathrm{min}} = 10^{19}$ eV [34] | ~3.2 | $\sim 4 \times 10^{-2}$ |
| Cosmogenic—proton, Fermi-LAT, $E_{\mathrm{min}} = 10^{17.5}$ eV [34] | ~1.6 | ~0.2 |
| Cosmogenic—proton or mixed, SFR & GRB [9] | ~0.5–1.4 | ~0.6–0.2 |
| Cosmogenic—iron, FRII [33] | ~0.3 | ~0.7 |
| Astrophysical $\nu$ (AGN) [35] | ~7.2 | $\sim 7 \times 10^{-4}$ |
| Exotic [36] | ~31.5 | $\sim 2 \times 10^{-14}$ |

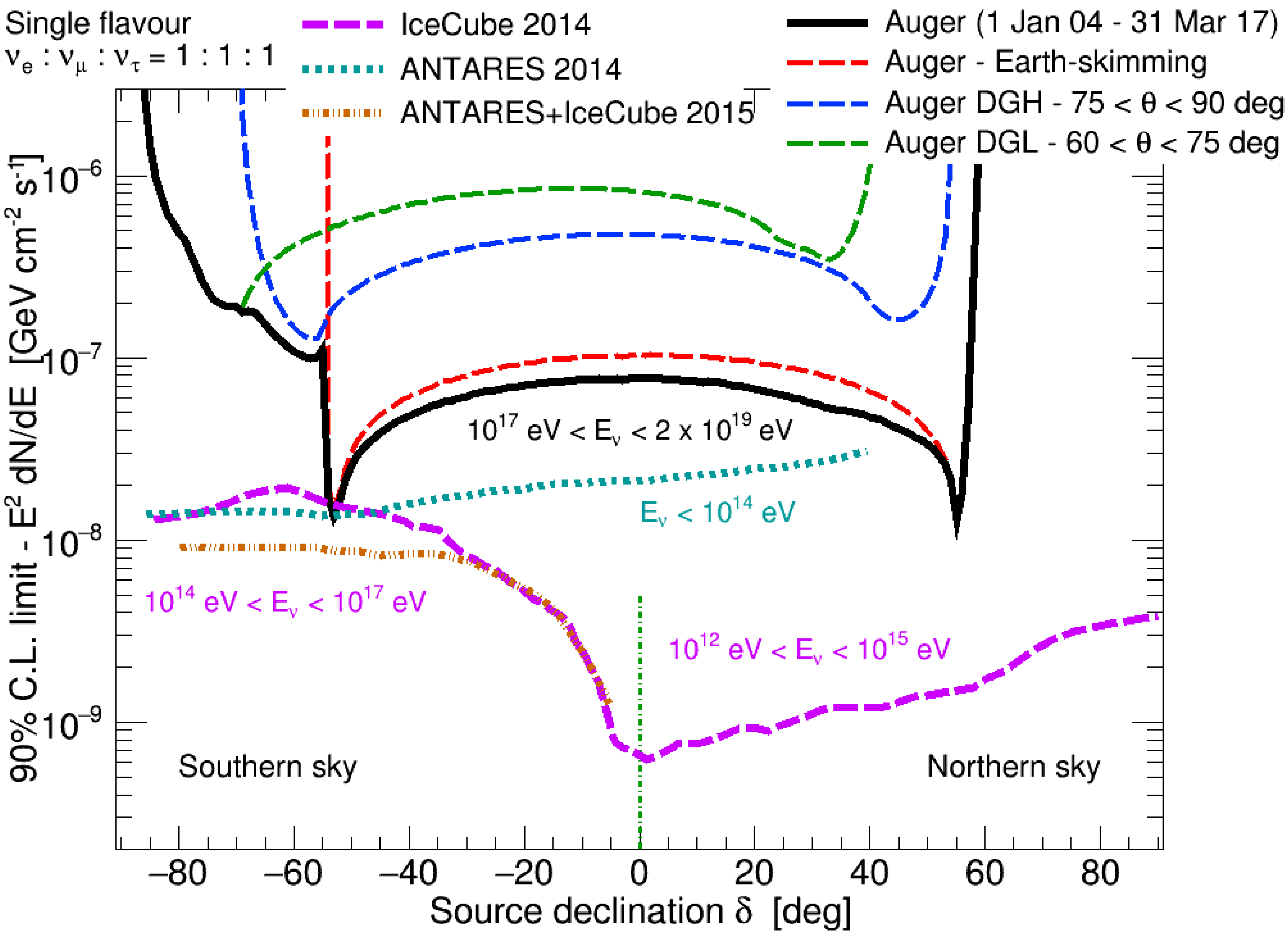
# Multimessenger studies

Point source bounds

Coincidences with GW events

Correlations of UHECR with IceCube

# Limits to point-like sources of UHEν

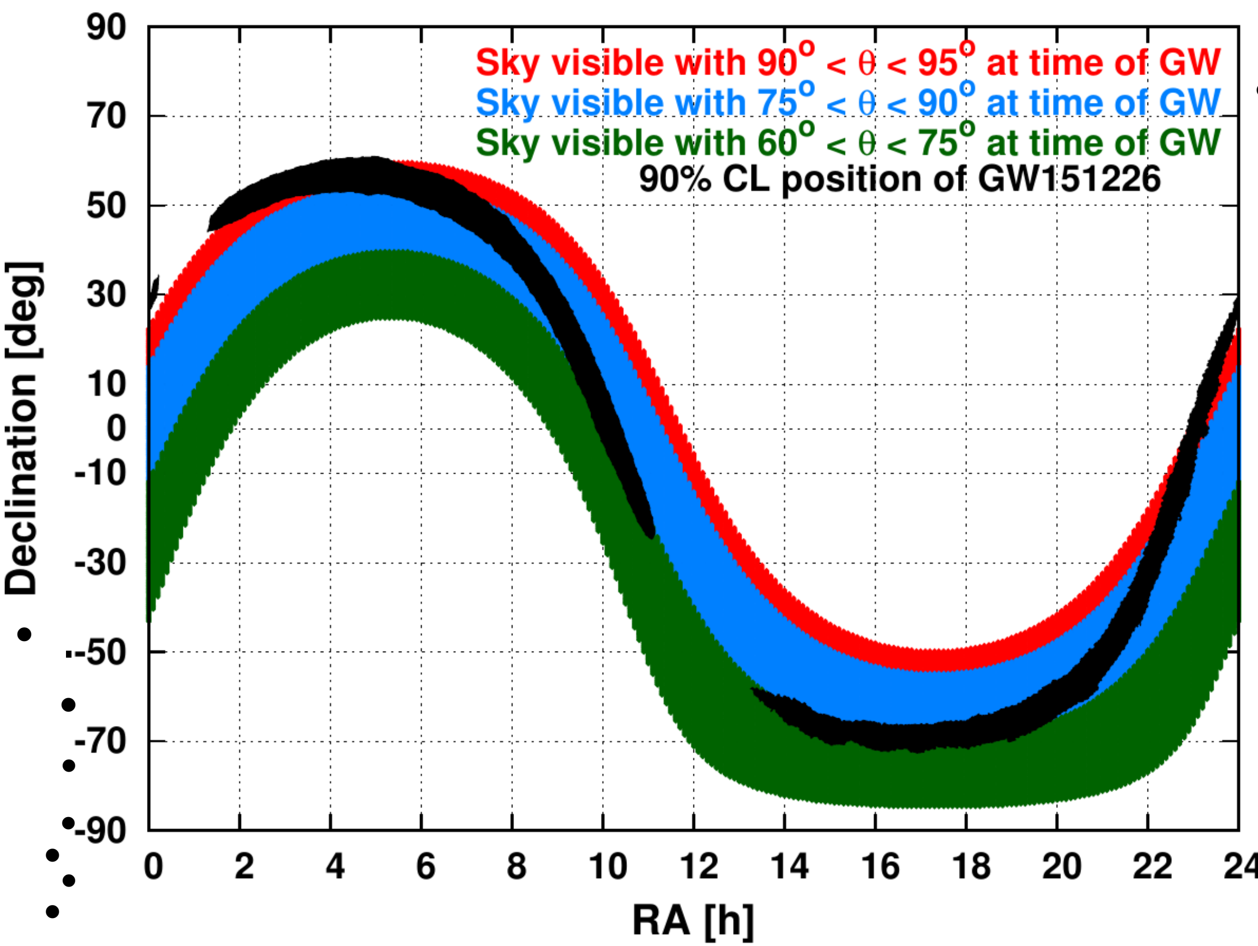



- Note different energy ranges of different experiments

# Searching for νs in coincidence with
## GW150914, GW151226, GW170104 (& LVT151012)

- *Pierre Auger Coll., Phys. Rev. D **94**, 122007 (2016)*

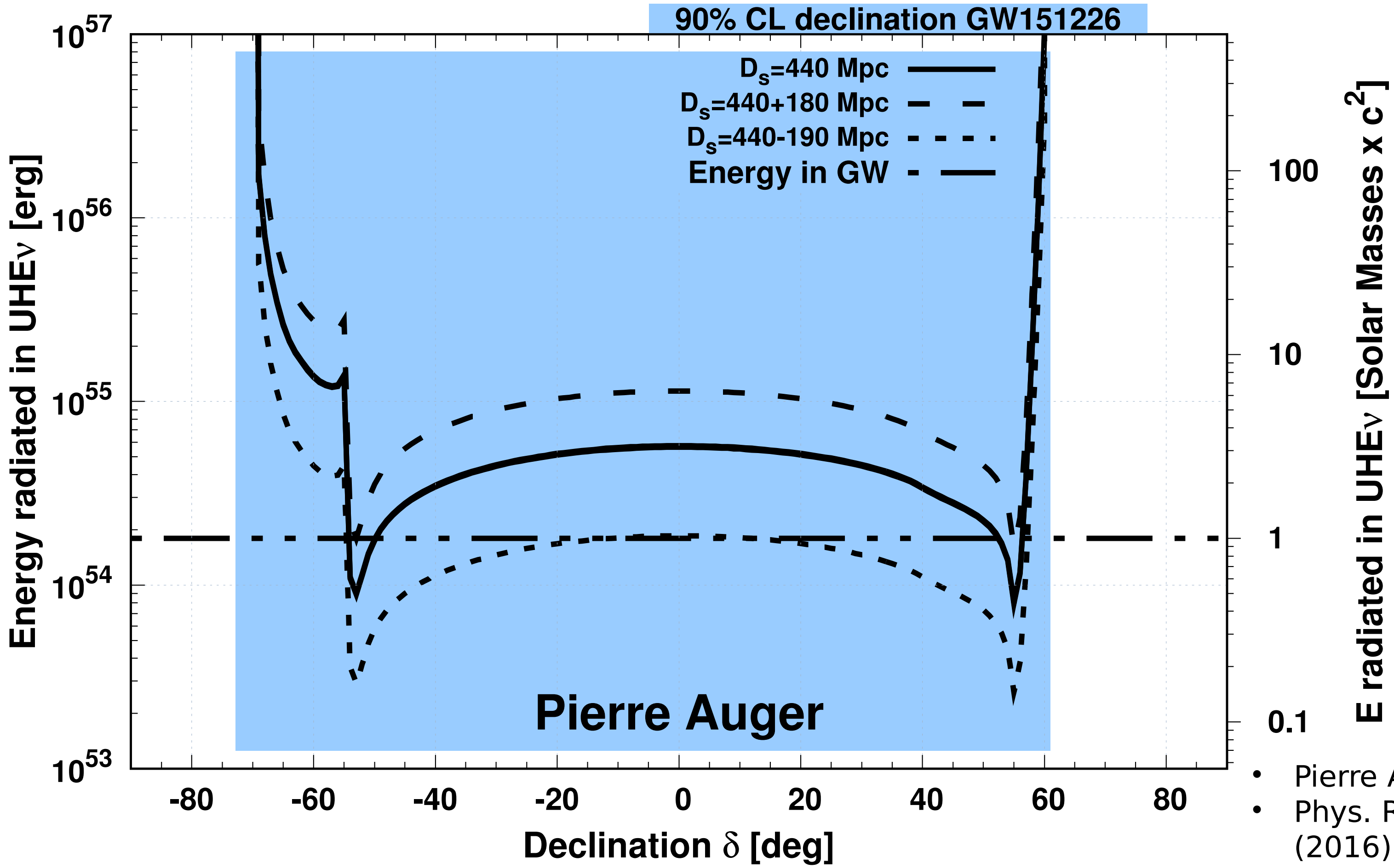
- **Two search windows:**
- **1 day after** each GW events ("GRB afterglow" type) (steady fluxes)
- **+/- 500 s around each GW event (GRB mechanism)**




- Sensitivity limited to large zenith angles =>
- Limited sky coverage at any instant
- Averaged over a sidereal day limits are declination-dependent

- Constraints on energy radiated in UHE$\nu$ ($E_\nu > 10^{17}$ eV):

- **GW151226 (1 day steady)**: less than (0.5, 3) for $-55^0 < \delta < 57^0$




- Pierre Auger Collab.,
- Phys. Rev. D **94**, 122007 (2016)

- **GW150914 and LVT151012**: Similar constraints

- **1000 s only GW151226 and LVT151012**: less than (0.2, 0.75) for optimal $\delta$)

# Correlations between IceCube & Auger+TA

- *Pierre Auger Coll., JCAP **01**, 037 (2016)*

**Data:** **IceCube νs (39 showers +16 tracks)**

**Auger E>52 EeV $\vartheta<80^0$ (231)**

**TA E>57 EeV $\vartheta<55^0$ (87)**

**Methods:**

**1 Cross-correlation**

**N pairs as a function of angle vs isotropy**

**2 Stacking "sources" νs (CR)**

**Unbinned likelihood method**

**Likelihood map for νs smeared with Gaussian**

**Gaussian: angular resolution of CR**

**magnetic deviations: D 100 EeV/E**

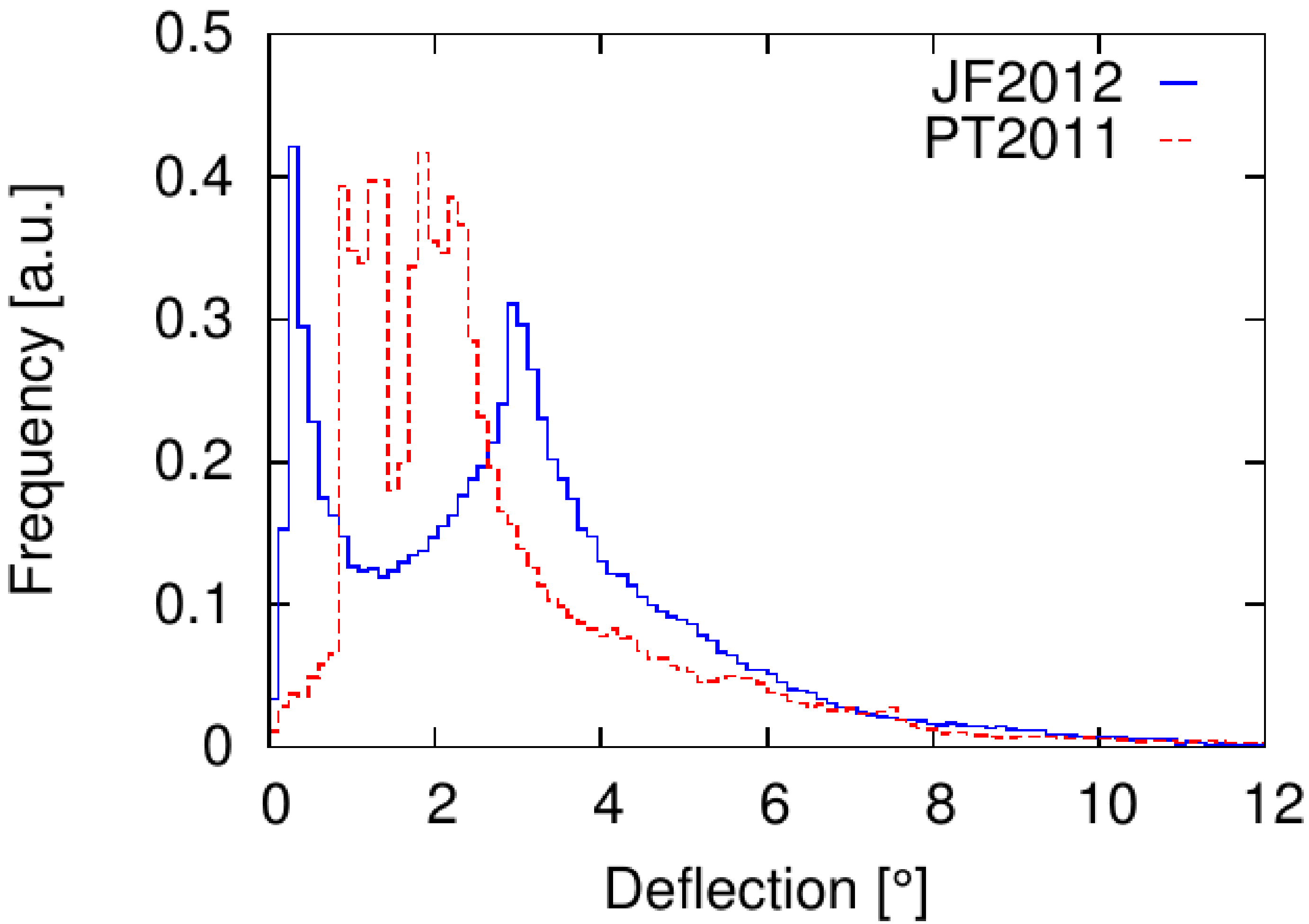
**D=$3^0$, $6^0$, $9^0$ angular deviation (100 EeV p)**

**scales with Z**

# Uncertain magnetic deviations

## Distribution of angular deflection for 100 EeV p

## *(Two Models Pshirkov et al. Jansson and Farrar)*



# Likelihood maps for IceCube ν directions

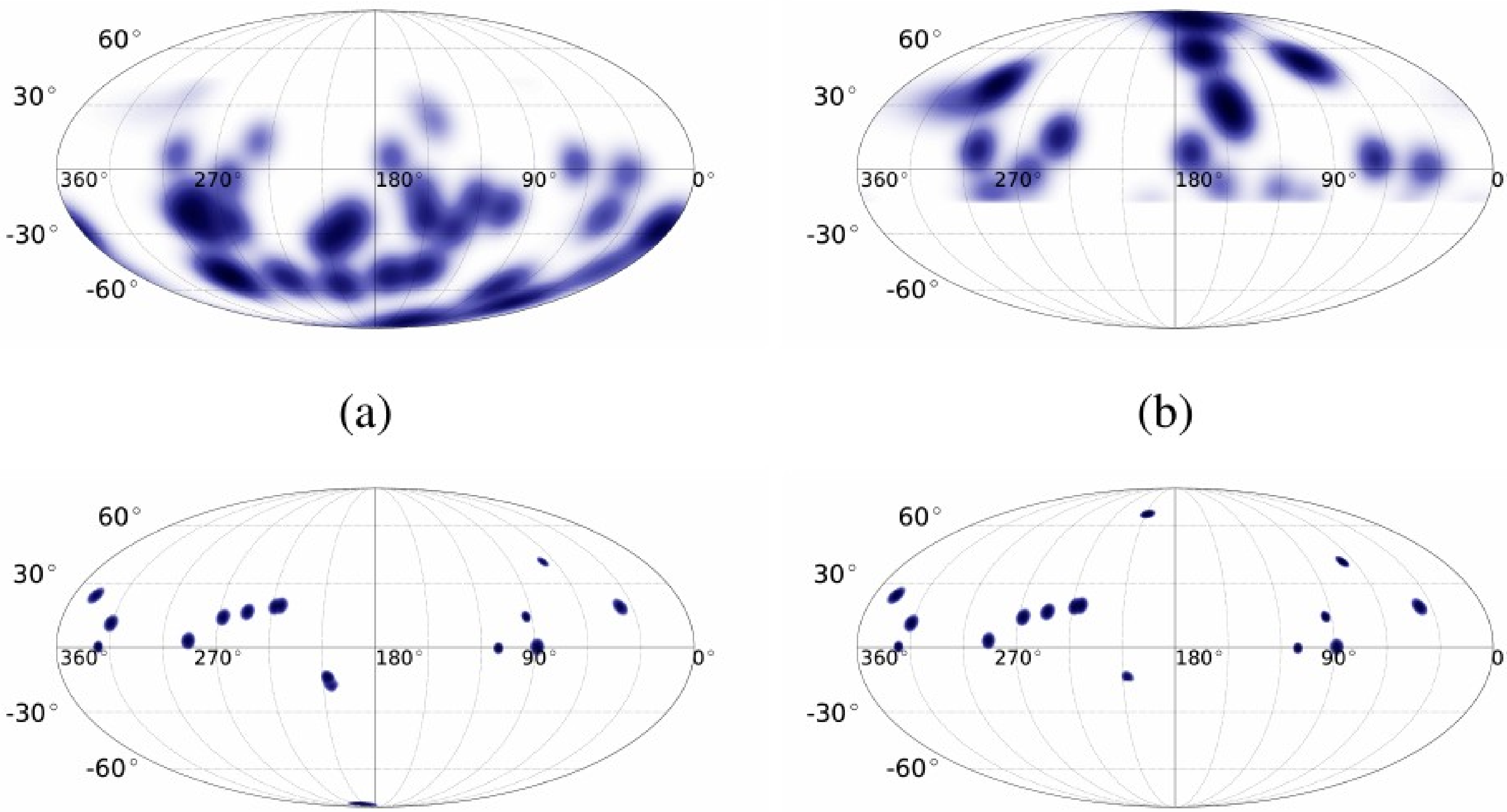
## (Smeared by resolution & deflection and weighted by exposure )

Auger

TA

Showers

Tracks




(a)

(b)

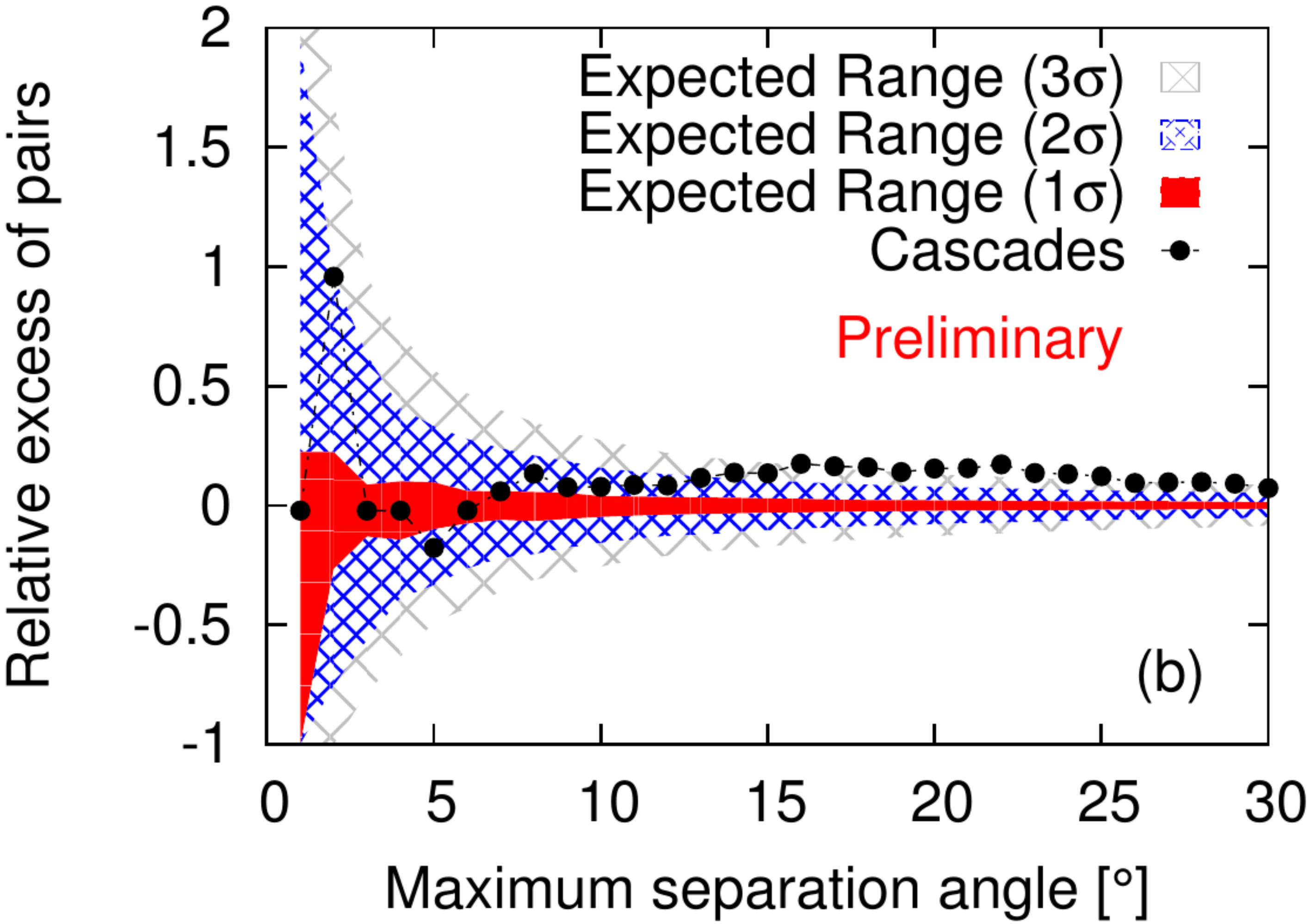
(c)

(d)

# Interesting correlation found (not above 3.3 σ): UHECR with νs (shower events)

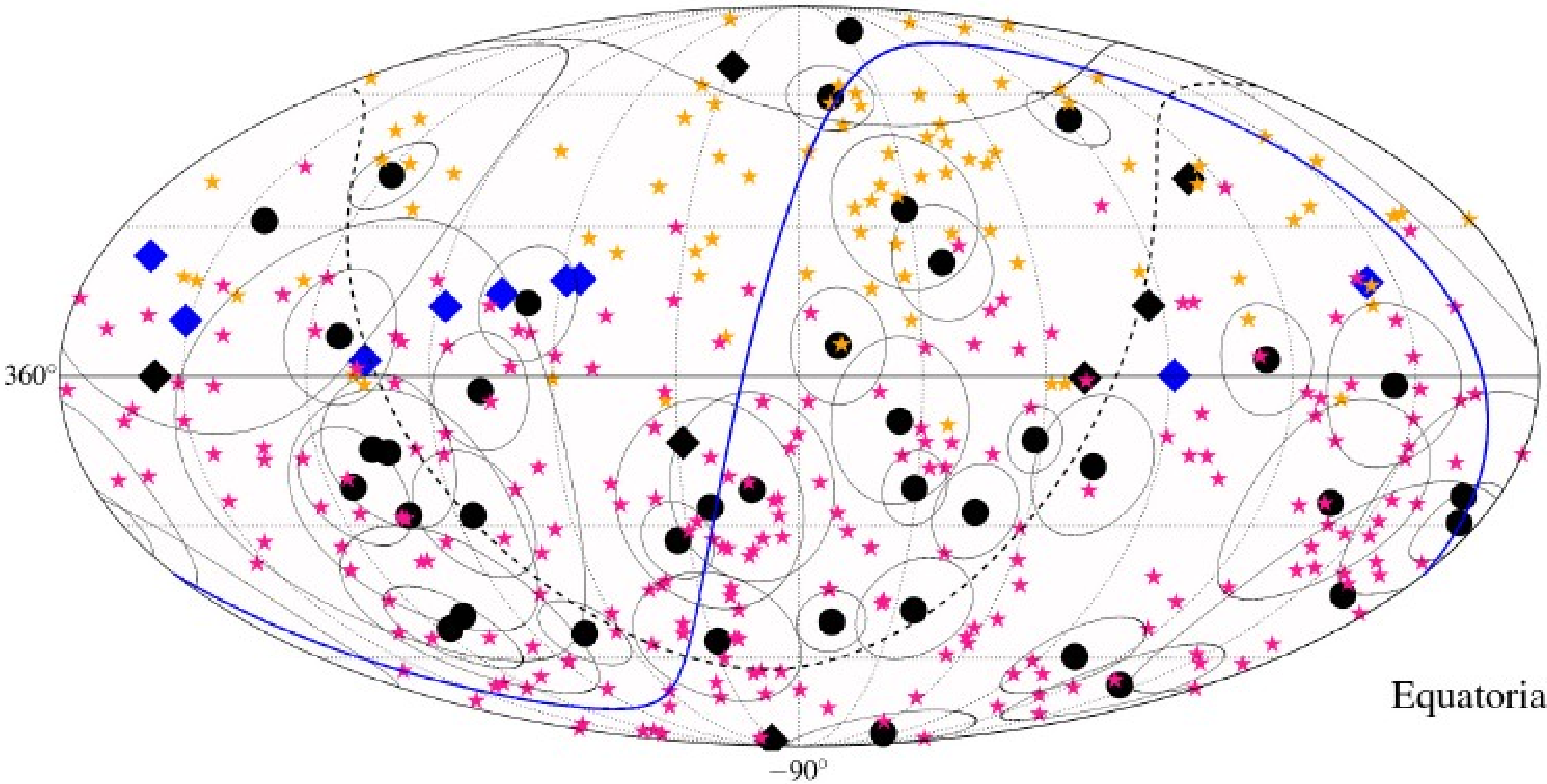
**Post-trial cross correlation p-value = 5 $10^{-4}$**

**stacking p-value = 8 $10^{-4}$**



**HE ν cascades from regions with large densities of UHECR (TA hot spot and supergalactic plane for Auger)**
**To be monitored!**

Auger UHECRs
TA UHECRs
IceCube HESE tracks
IceCube tracks
IceCube cascades
---- Galactic plane
___ Supergalactic Plane



# Summary

## Rich physics program news to come

- **Largest & most precise CR Observatory**

  Spectrum
  Composition
  Anisotropies

  New emerging picture
  Intermediate masses

- **Observatory can search effectively for neutrinos**

  Complementary properties to other ν telescopes

  EeV energies and very efficient for $\nu_\tau$

- **Diffusse bounds constrain Cosmogenic neutrinos:**

- **Multimessenger results:**
  - Point source bounds (declination dependent)
  - Bounds on ν emission coincident with GW events (BH mergers)
  - Correlation IceCube cascade / TA Auger >55 EeV to MONITOR

# Thank you