Search for ultra-high energy neutrinos at the Pierre Auger Observatory

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February 24, 2022

COLORADO SCHOOL OF MINES NSF PIERRE AUGER OBSERVATORY

- **A cosmic ray observatory near the town Malargüe in the Mendoza province of Argentina**
- The location was chosen for:
  - Clear weather and dark nights
  - A flat open Pampa able to accommodate the Observatory's targeted aperture size
- The observatory itself is 3000 km^2 and has accumulated roughly 100,000 km^2 sr yr of exposure
- The hearts of the Observatory are:
  - The SD: 1660 water Cherenkov detectors
  - The FD: 27 fluorescence telescopes

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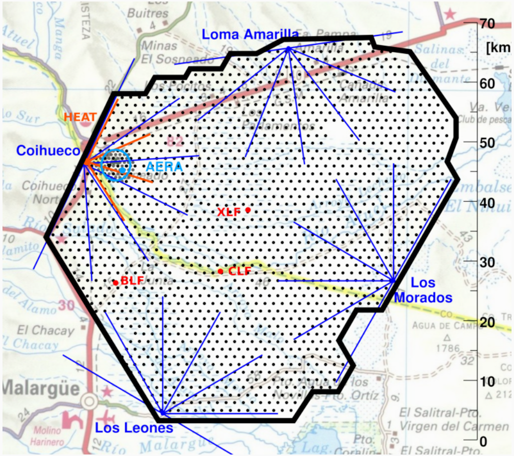

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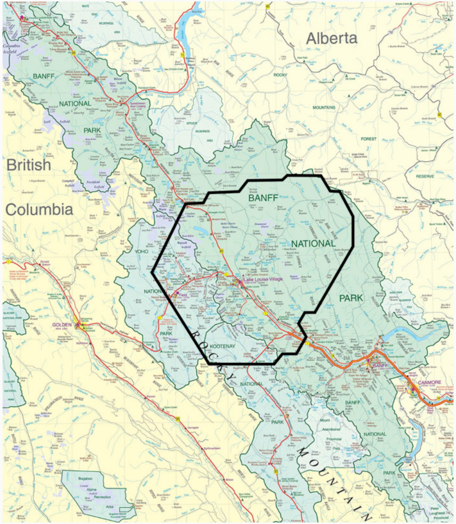

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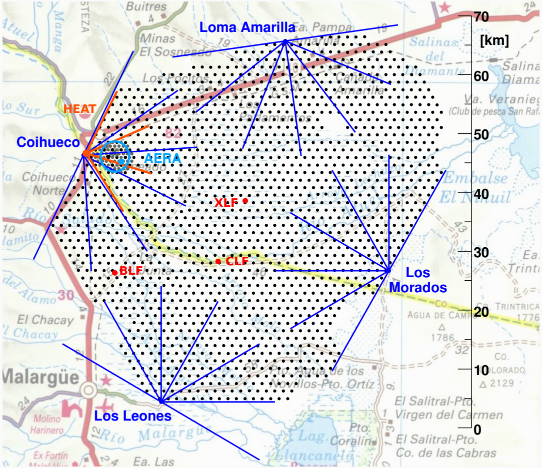

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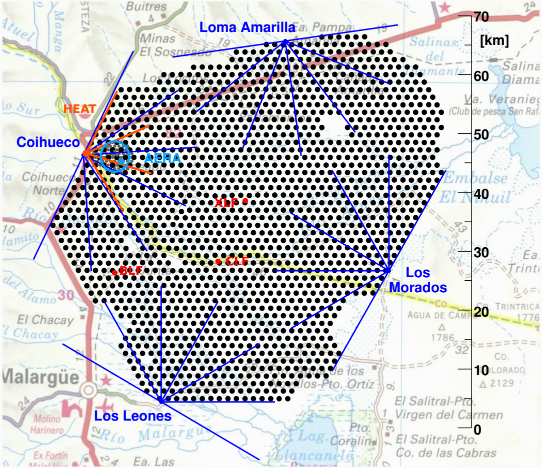

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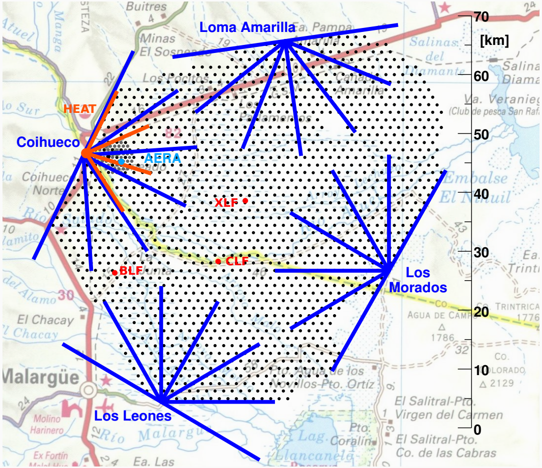
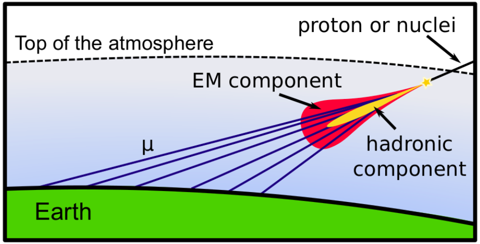


UHE Neutrino search: discrimination method

Leverage the ν cross-section!

- **CR showers must start high in atmosphere;**
  $\rightarrow$ only muons survive to ground at high zenith angles
- ν induced showers can start much deeper:
  $\rightarrow$ will maintain a high E/M component to ground
- ν_τ can interact in the earth and cause a particle shower from τ-lepton decay in atmosphere
  $\rightarrow$ look for showers below limb $\rightarrow$ **lowest background**



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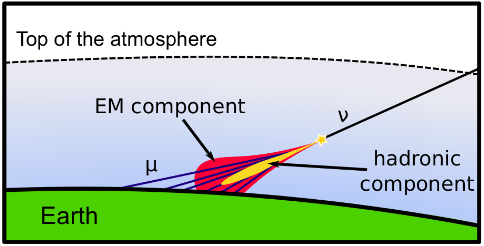

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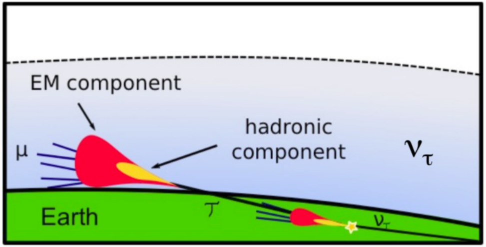

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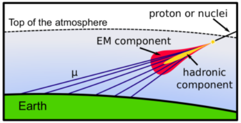
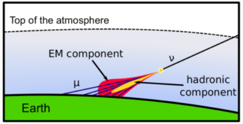
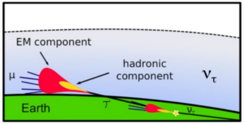
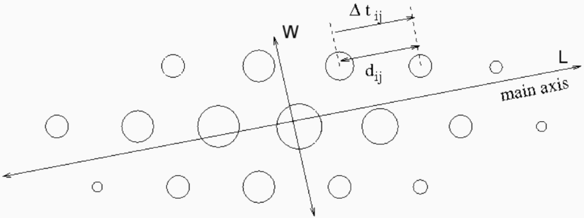


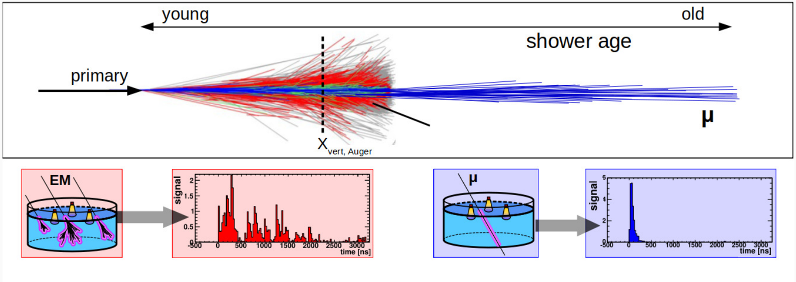




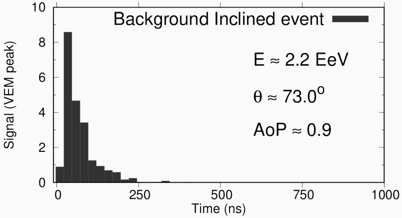
Highly inclined events, with long, E/M rich signals

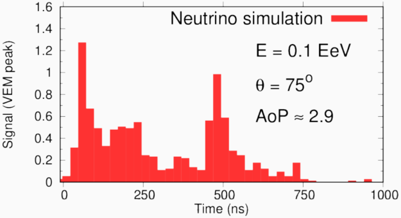


UHE Neutrino search: SD signatures



Highly inclined events, **with long, E&M rich signals**





UHE Neutrino search: Area over Peak (AoP)

Use the Area over Peak (AoP) to distinguish CR from ν

$$\text{AoP} = \frac{\text{Area of signal trace}}{\text{Peak trace value}}$$

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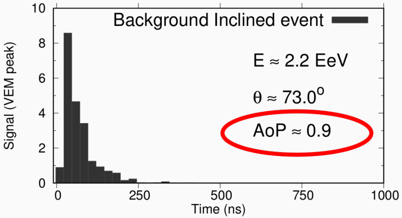
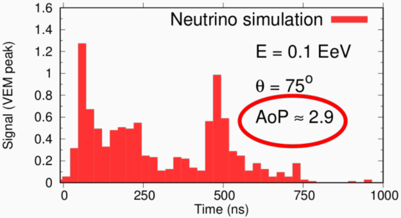
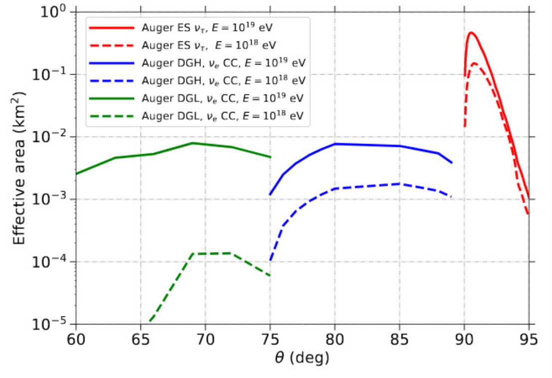
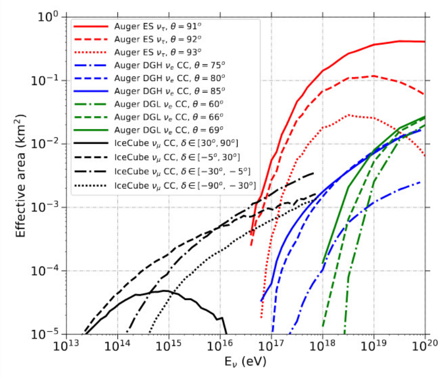




The Auger SD analysis is split into 3 channels:

Down **G**oing **L**ow: $\theta \in [60^\circ, 75^\circ)$ **D**own **G**oing **H**igh: $\theta \in [75^\circ, 90^\circ)$ **E**arth **S**kimming: $\theta \in [90^\circ, 95^\circ]$

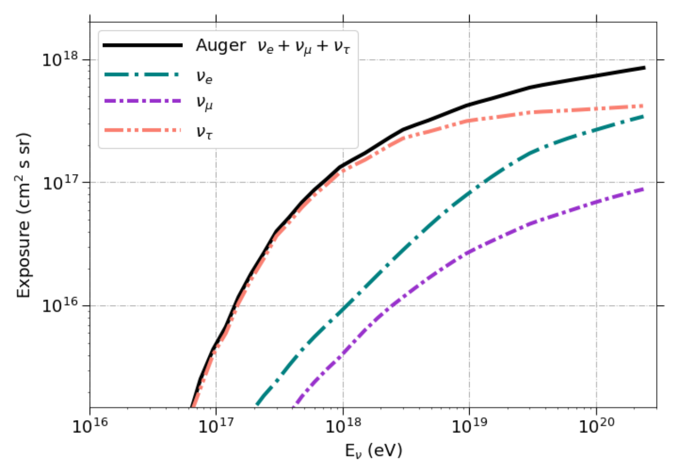




Due to low background, Auger sensitivity dominated by Earth skimming channel

Diffuse Neutrino search results: exposure by flavor

JCAP10 (2019) 022 • 1906.07422[astro-ph]

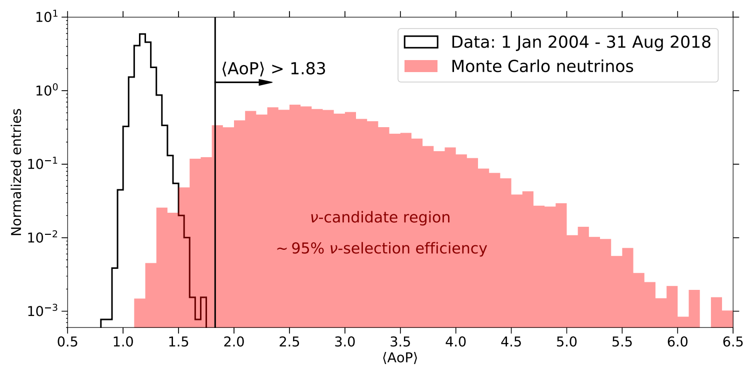


Channel	Relative contribution
DG (H+L) $\nu_e + \nu_\mu + \nu_\tau$	0.21
ES ν_τ only	0.89

Flavor	Relative contribution
ν_e	0.10
ν_μ	0.04
ν_τ	0.86

Auger sensitivity dominated by τ

JCAP10 (2019) 022 • 1906.07422[astro-ph]



No neutrino events found in candidate region

Skimming channel:
ν candidate if $\langle$AoP$\rangle > 1.83$
Set with 20% burn sample

$\langle$AoP$\rangle$ is the mean AoP of all stations in event

Data date range:
01.2004 - 08.2018

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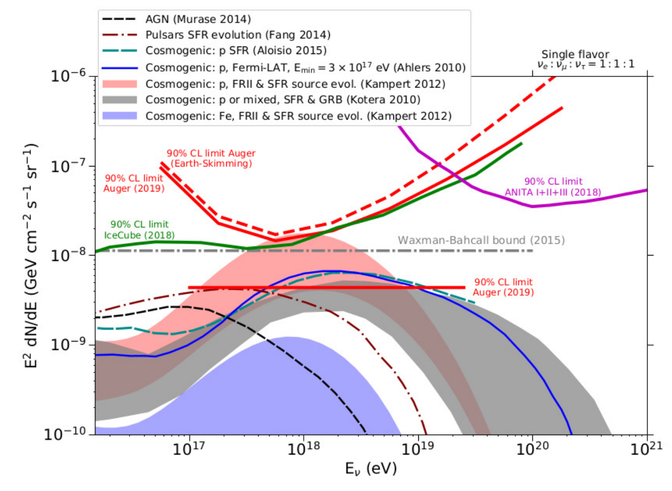

Expected ν events:

Red band: 1.4 – 5.9

Gray band: 0.8 – 2.0

Blue band: 0.4

Auger integrated limit

Assume $dN/dE = \alpha E^{-2}$

$\alpha \sim 4.4 \times 10^{-9}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$

Data date range:

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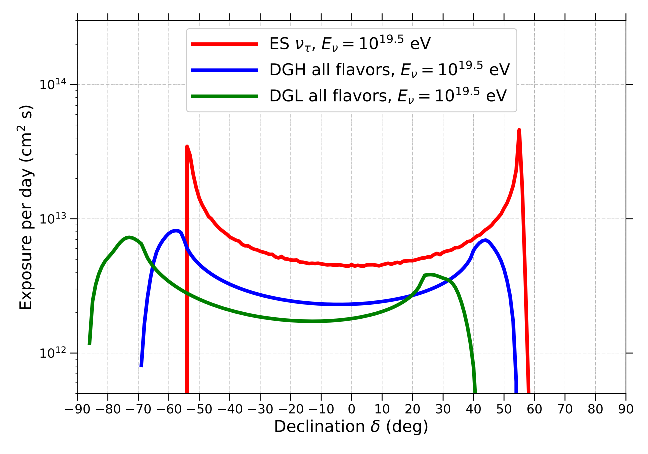
JCAP11 (2019) 004 • 1906.07419[astro-ph]



Good sensitivity at EeV energies in a broad range of declinations

The best sensitivity at $-53°$ and $55°$ where sources spend more time in the field of view of Earth-skimming

Higher upper limits than: IceCube and ANTARES, but strongest over 100 PeV

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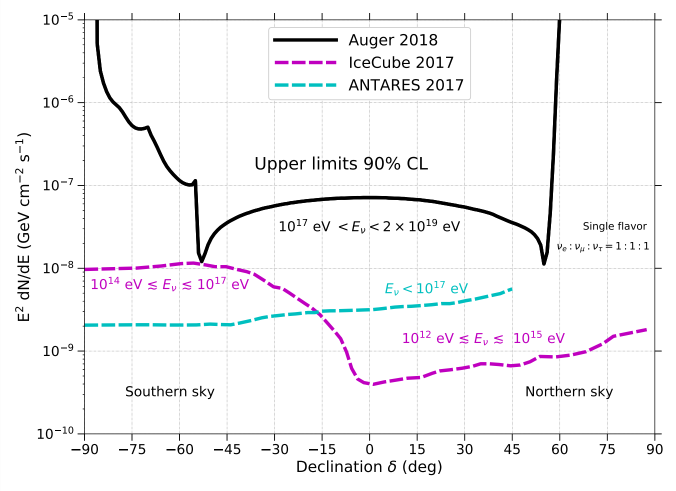

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SD exposure to transients: example GW151012

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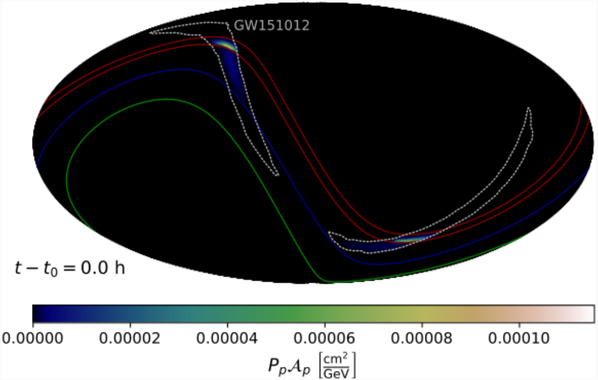

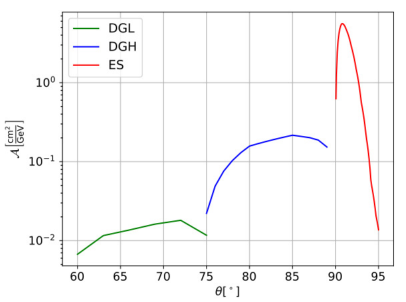

Exposure can be very large or very small depending on luck

Complex exposure means sensitivity to sources depends on source location and event timing

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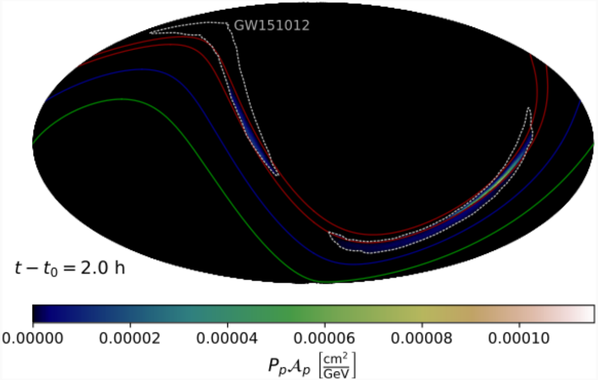

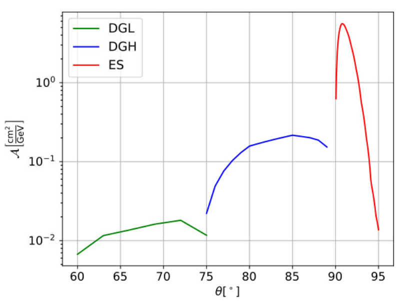

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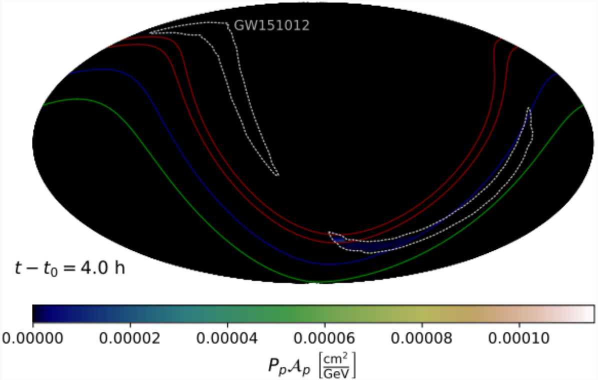

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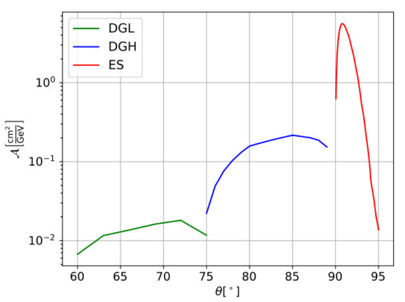

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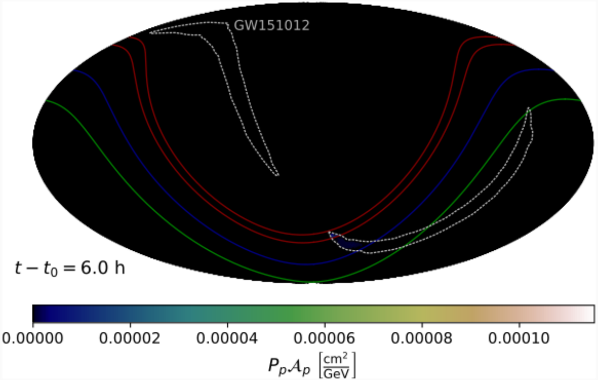

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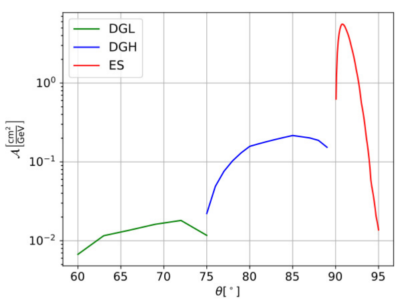

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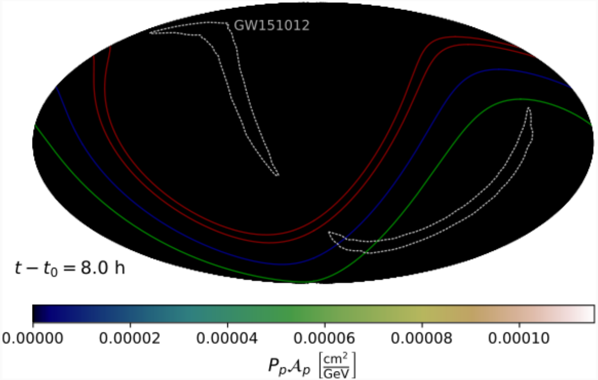

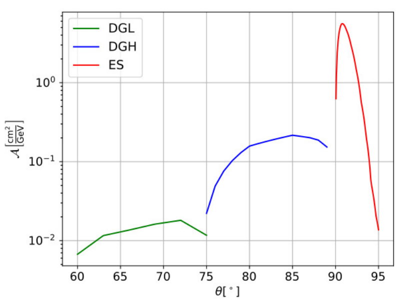

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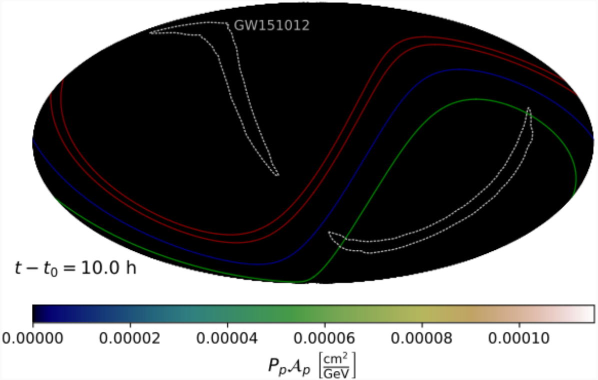

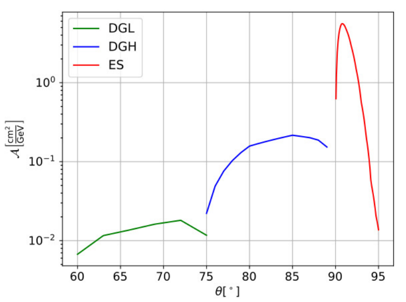

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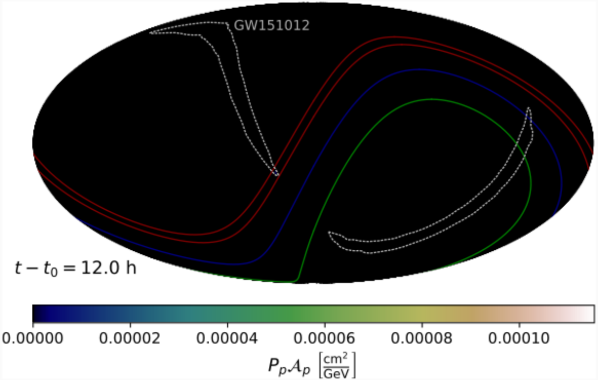

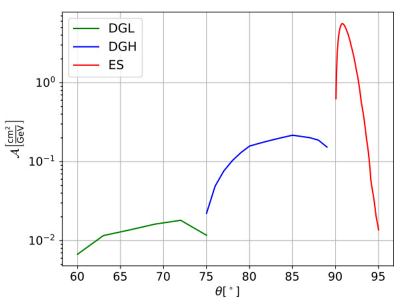

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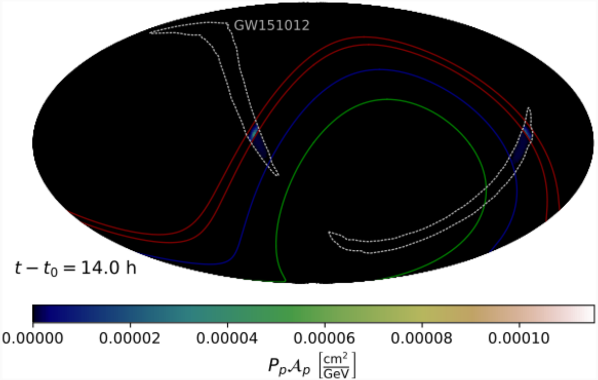

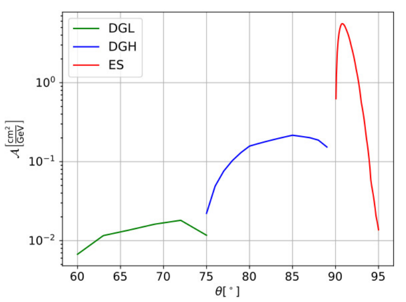

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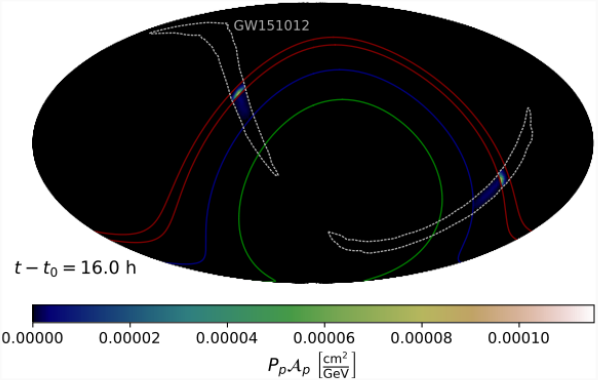

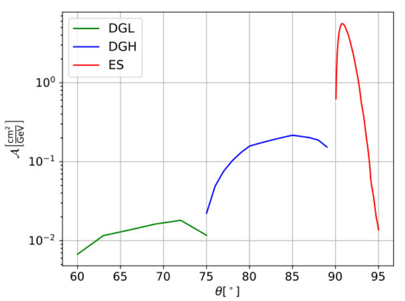

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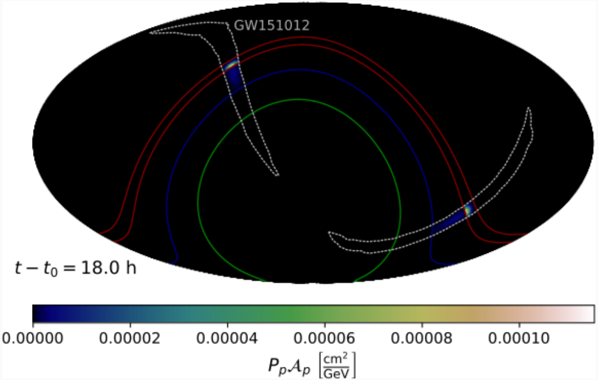

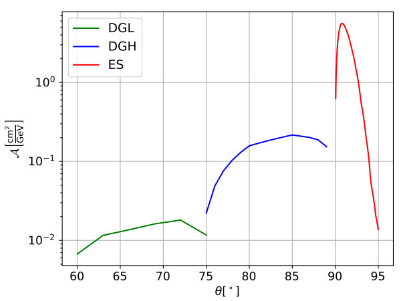

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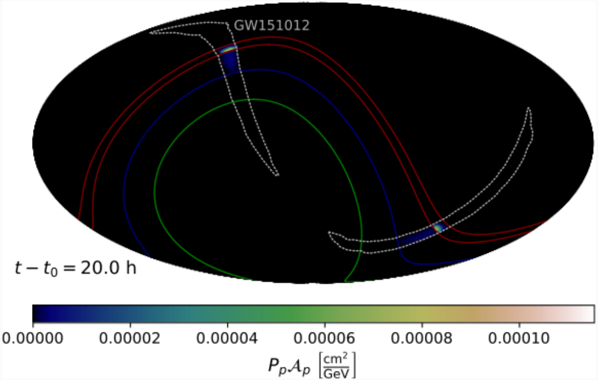

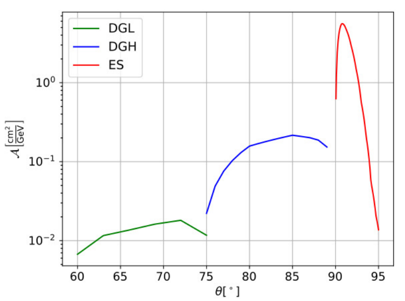

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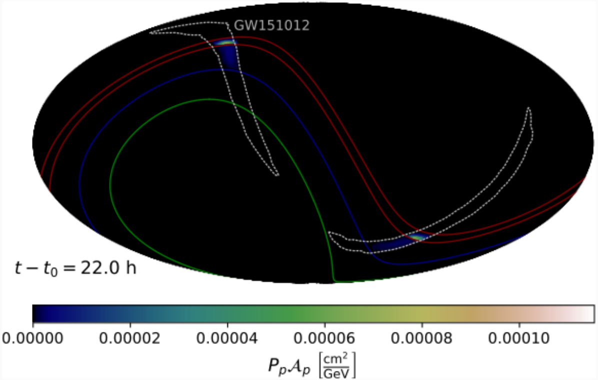

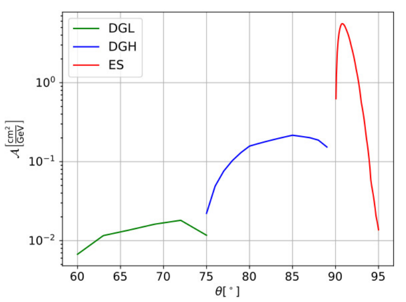

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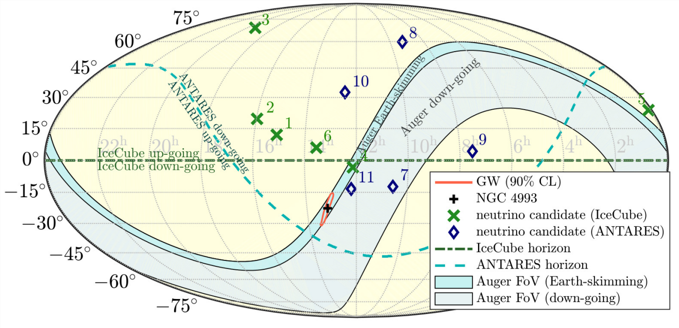
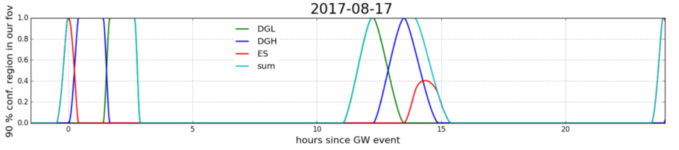
ApJL850 (2017) 2,L35 • 1710.05839 [astro-ph]





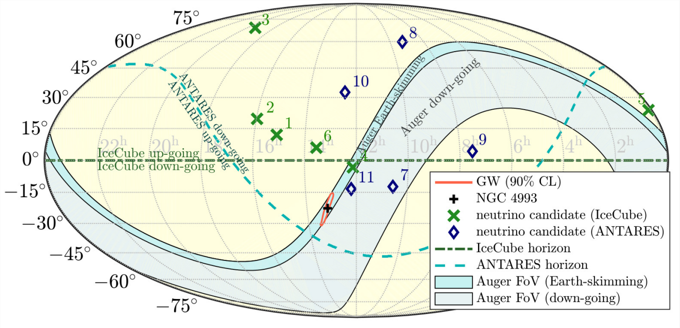
Entirety of 90% CL GW event location in FoV of ES channel

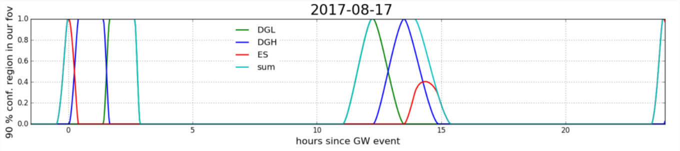
Leads to very high prompt neutrino fluence limits

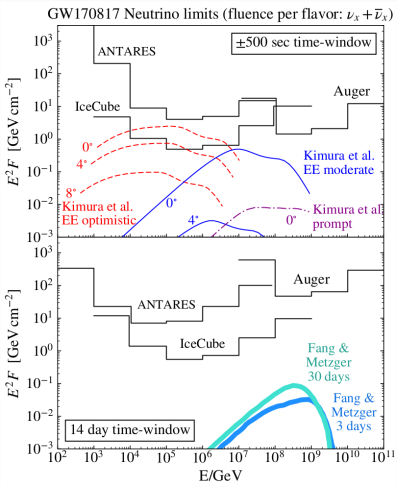
Time dependent exposure leads to substantially lower 14-day neutrino fluence limits

A lucky catch: NS-NS merger event GW170817

ApJL850 (2017) 2,L35 • 1710.05839 [astro-ph]







PIERRE AUGER OBSERVATORY

PoS(ICRC2021)968 • FAL Paper in prep

Fast LVC alert follow-up infrastructure in place
No UHE-neutrino events found for 62 O1-3a events

Non-observation leads to an all sources stacked luminosity upper limit calculated as

$$L_{up,i} = \frac{N_{up,i}}{T}\left(\sum_{s}\sum_{p\in\Omega_{90}(s)} P_{p,s}A_{p,s,i}\int_0^\infty \frac{\Pi_{p,s}(r)}{r^2}dr\right)^{-1}$$

Where:

s, i, and p are source, time-bin and sky pixel respectively

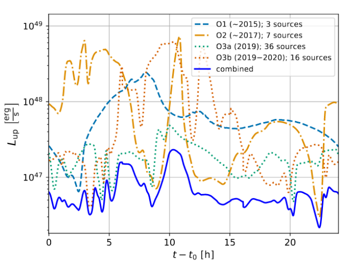
r is a luminosity parameter

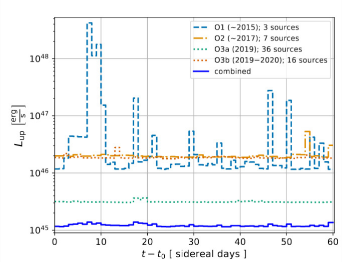
$N_{up} = 2.44$, the 90 % CI FC non-observation limit

$A_{p,s,i}$ is each source's Auger exposure

$P_{p,s}$ and $\Pi_{p,s}(r)$ are the source localization and distance PDFs

$\Omega_{90}(s)$ is the 90 % CI contour for $P_{p,s}$ and $\Pi_{p,s}$





UHE neutrino fluence limits from BH-BH mergers

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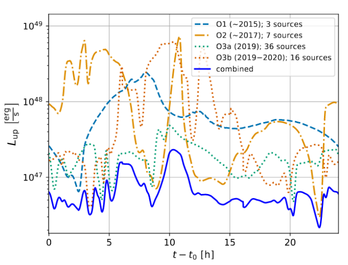
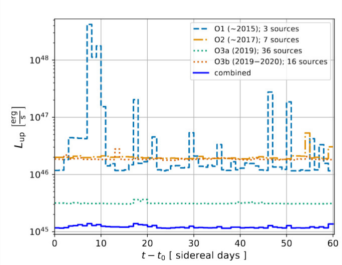
Integrated isotropic neutrino fluence limits per merger:

2.2×10^{46} erg s^{-1} instantaneous
6.0×10^{51} erg over 24-hours
6.3×10^{51} erg over 60-days

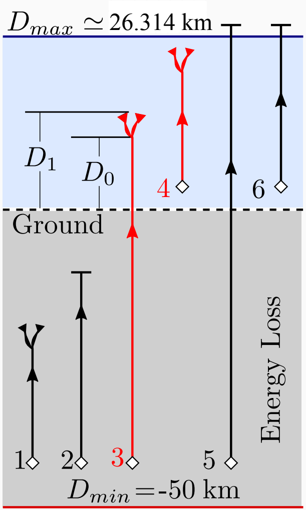




PoS(ICRC2021)1140 • FAL Paper in prep
PoS(ICRC2021)1145 • FAL Paper in prep

ANITA flight 1 and 3 saw two steeply up-going showers:
$E \sim 2 \times 10^{17}$ eV $\beta_1 = 27^\circ$ and $\beta_2 = 35^\circ$
No SD sensitivity. Large FD sensitivity

- **Basic methodology: search for steeply up-going shower-like event signatures in FD data ($\theta > 110^\circ$)**
- FD acts like a tracking calorimeter
  → monitored atm is $> 8\,\mathrm{km}^3$ of water equivalent
  → ~ 2 yr exposure after accounting for duty cycle
- Aperture and detector volume are energy dependent
- Known background of laser and atmospheric events
  → required extensive cleaning using 10 % burn sample
- Difficult to remove background of geometrically degenerate reconstuctions



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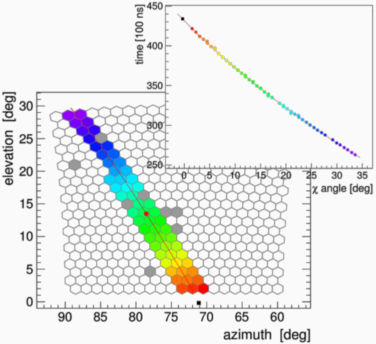

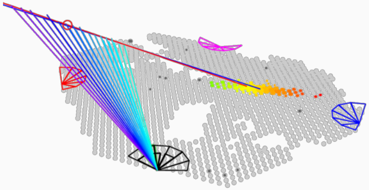

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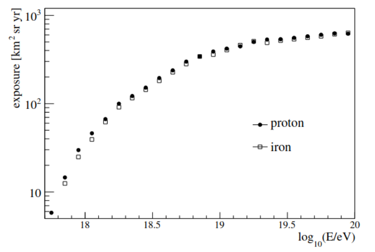

Search for steeply up-going showers and ANITA events follow-up

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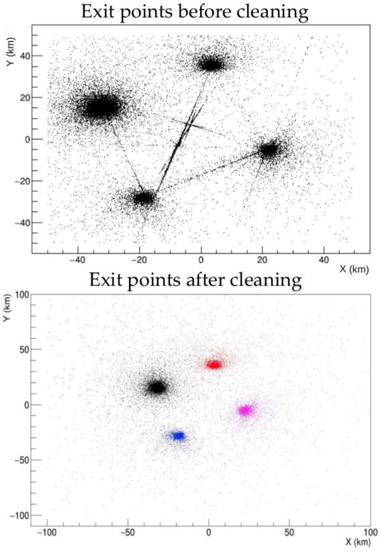

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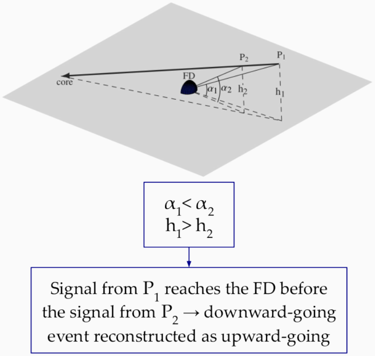


Up-going search: Background discrimination and candidate selection

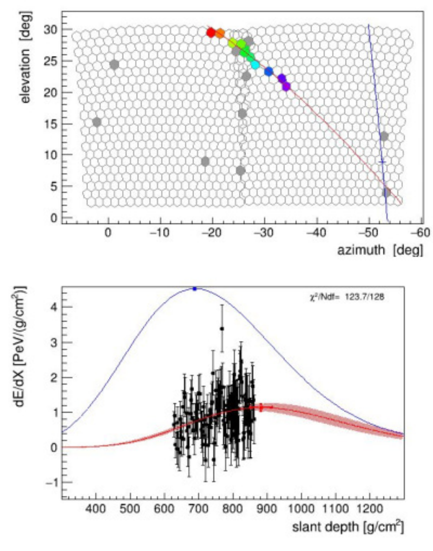
PoS(ICRC2021)1140 • FAL Paper in prep

PoS(ICRC2021)1145 • FAL Paper in prep

- **Reconstruct geometry and profile simultaneously to reduce degeneracy**
- Reconstruct in both upward and downward geometries
- Compare fit likelihoods to select candidates

$$l = \frac{\arctan(-2\log(\frac{L_{down}}{max(L_{up},L_{down})})/50)}{\pi/2}$$

- Use down-going CR background simulations to model background
- Optimize candidate selection cut to maximise efficiency and purity



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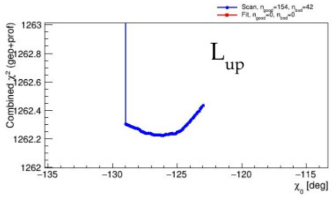
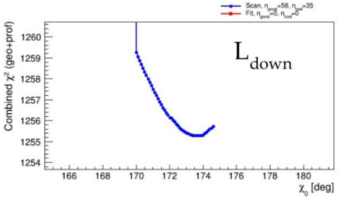
likelihood from the reconstruction in upward mode



likelihood from the reconstruction in downward mode



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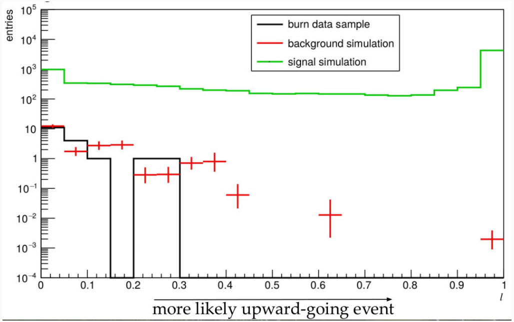

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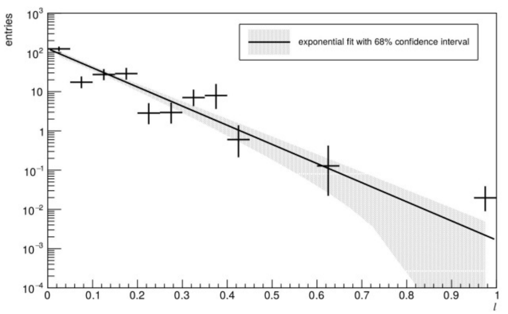

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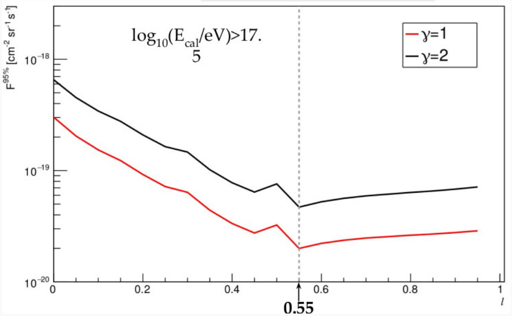

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Background expectation 0.45 ± 0.18 **events**

After unblinding 1 up-going candidate event found

Consistent with background expectation

Candidate undergoing further testing

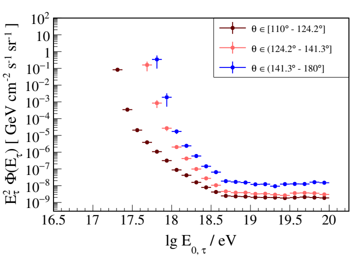
Rolke the integral upper limit with $N_{bkg} = 0.45$ and $N_{obs} = 1$, for steeply up-going showers:

Limit for E^{-1} **spectrum:** 3.6×10^{-20} $\mathbf{cm^{-2}\,sr^{-1}\,s^{-1}}$

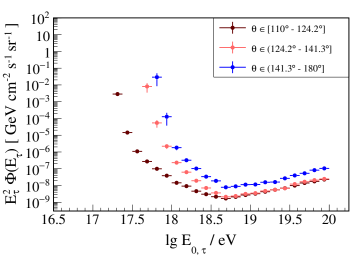
Limit for E^{-2} **spectrum:** 8.5×10^{-20} $\mathbf{cm^{-2}\,sr^{-1}\,s^{-1}}$

Recast to a τ-lepton production within 50 km of surface for different zenith ranges using nuTauSim

E^{-1} Spectrum



E^{-2} Spectrum

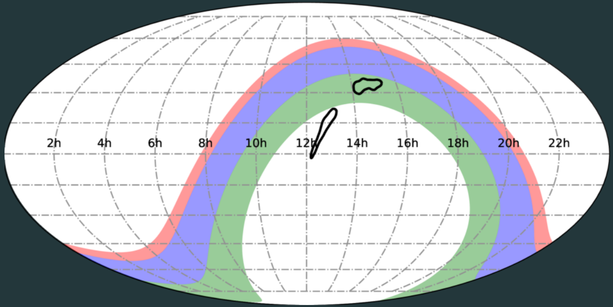


Conclusion

- **Very restrictive limits to the diffuse flux of UHE neutrinos for energies at and above 10^{18} eV.**
- **Outstanding sensitivity to transient sources if located in the FoV of the Earth-skimming channel.**
- **Highly constraining direct follow-up of ANITA anomalous events.**
- **Pierre Auger Observatory is a key detector in multi-messenger astronomy at EeV energies.**

Thanks for you interest!

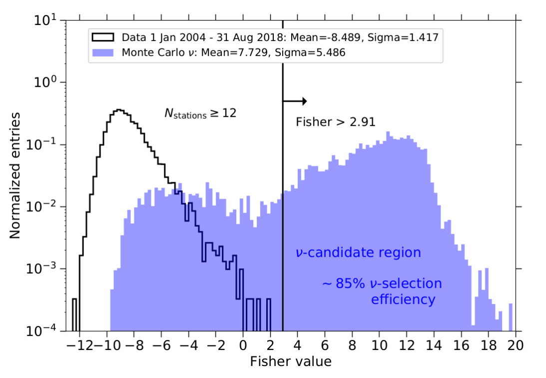
Questions?



Backup

Backup slides

JCAP10 (2019) 022 • 1906.07422[astro-ph]



No neutrino events found in candidate region

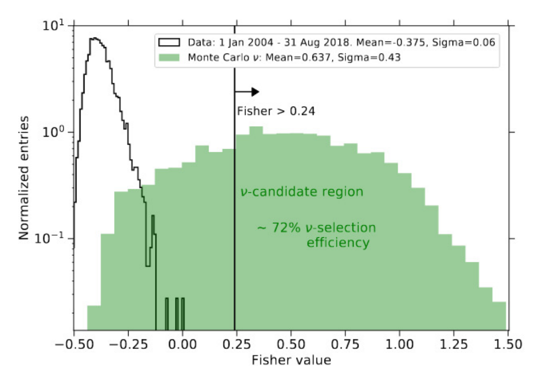
DGH channel:
ν **candidate if** $\langle$**Fisher**$\rangle > \mathbf{2.91}$

Fisher Discriminate is a combo of 10 sensitive variables

Data date range: 01.2004 - 08.2018

Neutrino search results: all sky diffuse down-going low

JCAP10 (2019) 022 • 1906.07422[astro-ph]



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DGL channel: ν **candidate if** $\langle$**Fisher**$\rangle > \mathbf{0.24}$

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