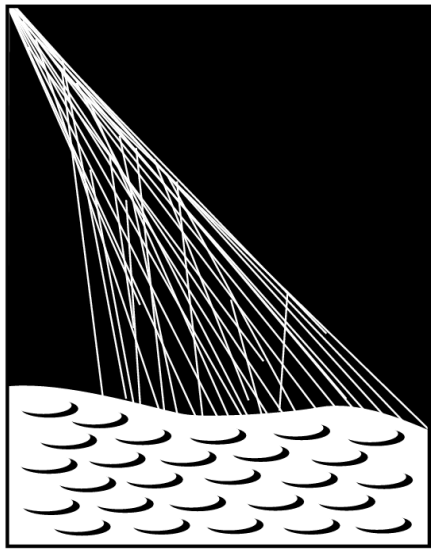

PIERRE AUGER OBSERVATORY

# UHE neutrino follow-up of Gravitational Wave events with the Pierre Auger Observatory

Michael Schimp on behalf of the Pierre Auger Collaboration

September 22, 2016

bmb+f

Großgeräte der physikalischen Grundlagenforschung

BERGISCHE UNIVERSITÄT WUPPERTAL

# LIGO GW Events (GW150914 & GW151226)

- Binary BH mergers @ $d_L \sim 400$ Mpc
- $E_{GW} > M_\odot c^2$ ($\sim 10^{54}$ erg)

# Motivation

LIGO GW Events (GW150914 & GW151226)

- Binary BH mergers @ $d_L$ ~ 400 Mpc
- $E_{GW} > M_\odot c^2$ (~$10^{54}$ erg)

*Kotera and Silk* arXiv:1602.06961
BH merger: possible GRB cause

- Needed: B field + debris
- Could produce the measured UHECR flux up to 100 EeV!

→ Needs ~ 3% efficiency ($E_{UHECR}/E_{GW}$)

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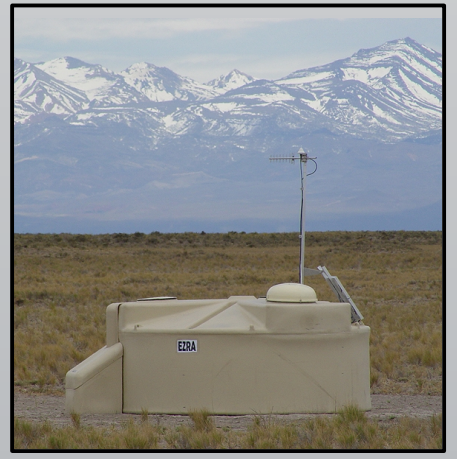
- **Fermi GBM detection 0.4 s** after GW150914, compatible direction
- **No prompt PeV ν** after GW150914 (IceCube, ANTARES)
- UHE (EeV) ν emission predicted (*Vietri, Waxman, Murase*)

# Pierre Auger Observatory surface detector: **Large acceptance**




→Well suited for UHEν search!

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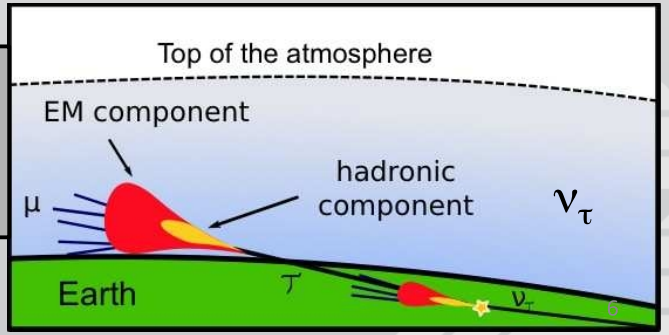
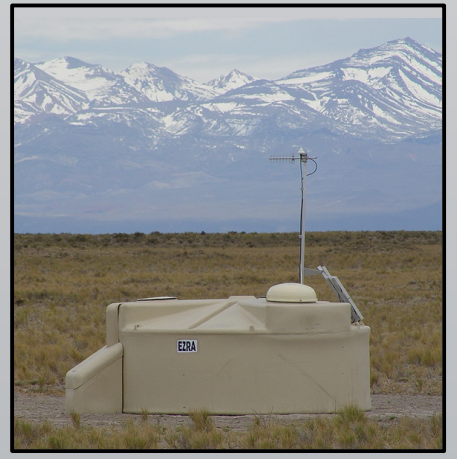
Earth-skimming $\nu_\tau$ ($90° < \theta < 95°$)

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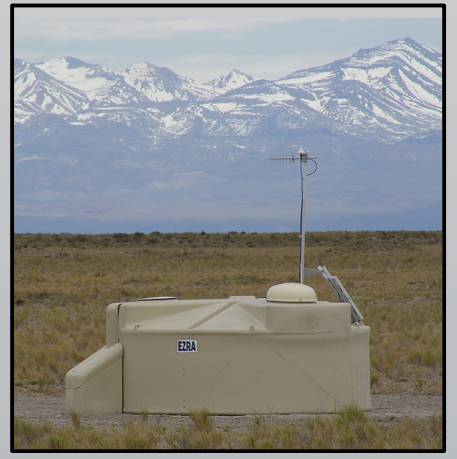


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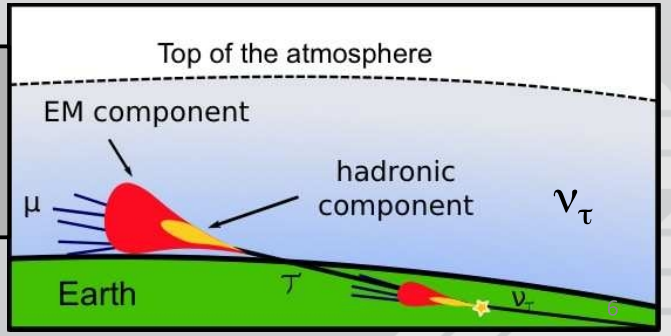
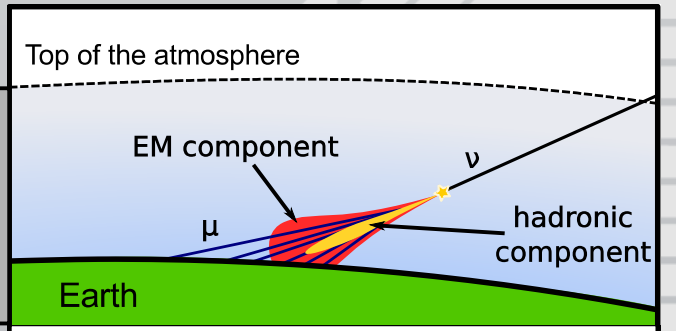
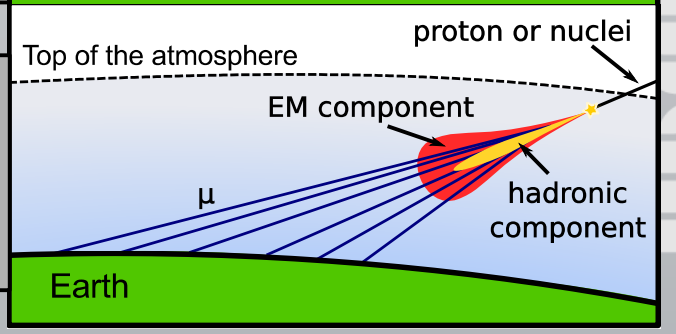



Down-going ν (signal) ($75° < \theta < 90°$)

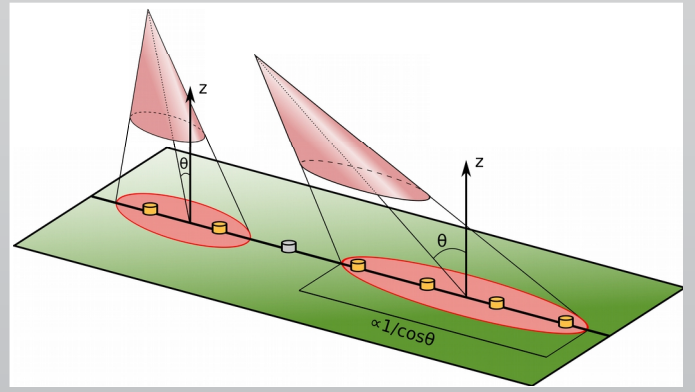



Down-going nuclei (bg) ($75° < \theta < 90°$)

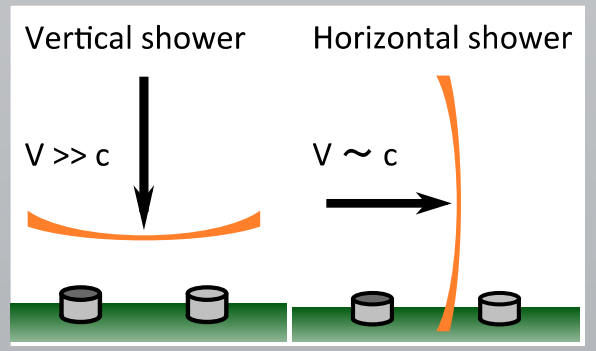


Inclination: θ > 75°

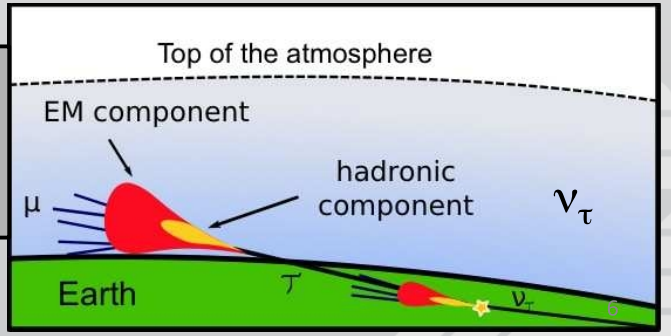
- Elongated footprint




- "Ground signal speed" ~ c/cos(θ)




Earth-skimming $\nu_\tau$ (90° < θ < 95°)

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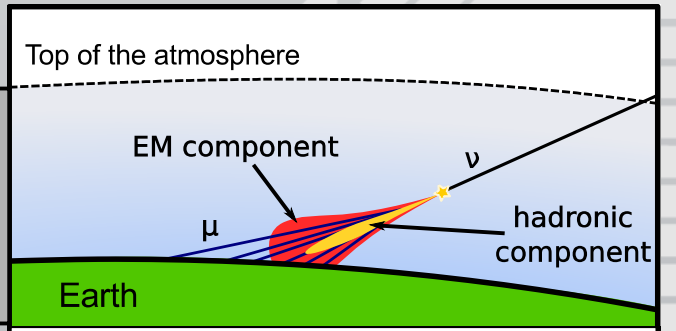


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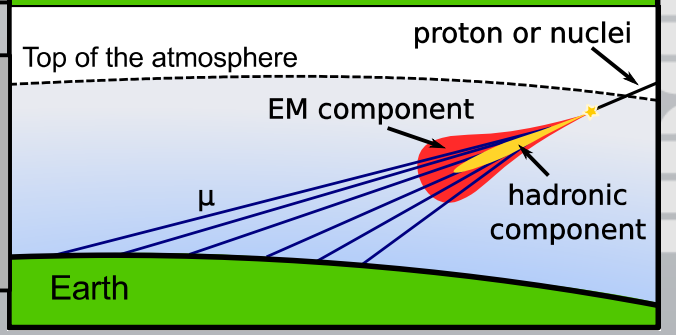
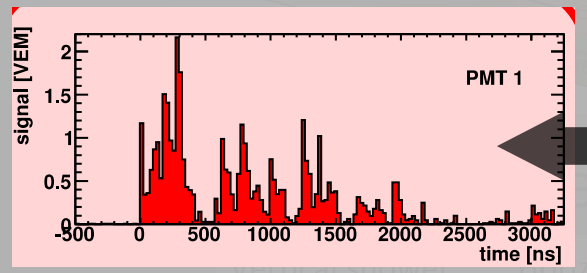
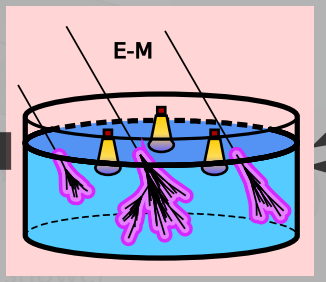
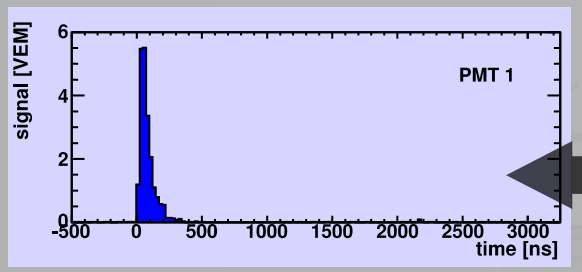


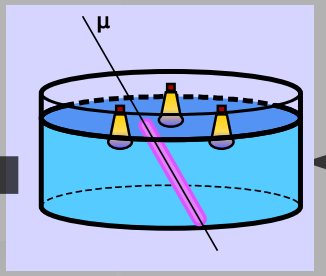
Reject “muonic” events:

- Select events dominated by wide PMT signals
- Compare to simulation
  → ν identification

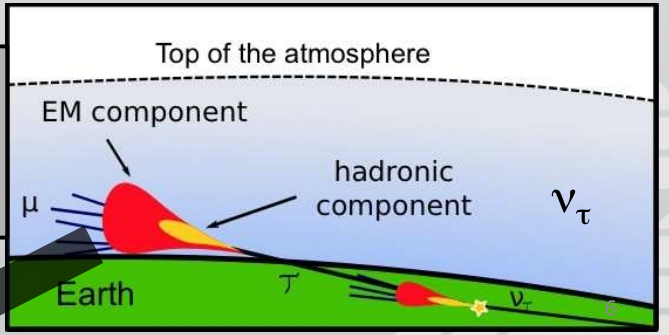



Earth-skimming $\nu_\tau$ ($90° < \theta < 95°$)

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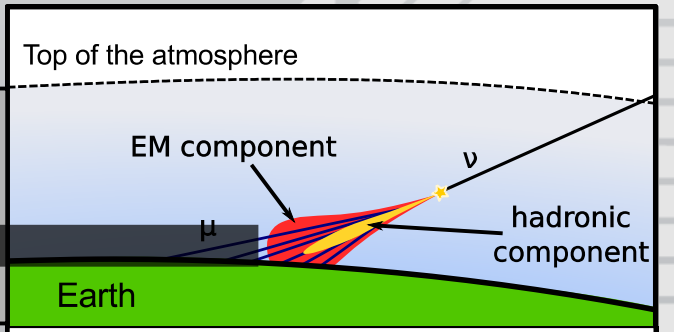


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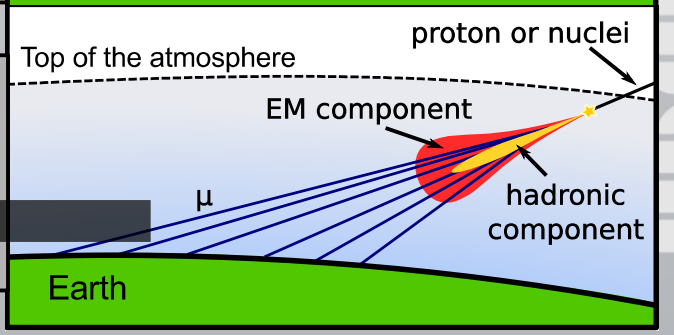


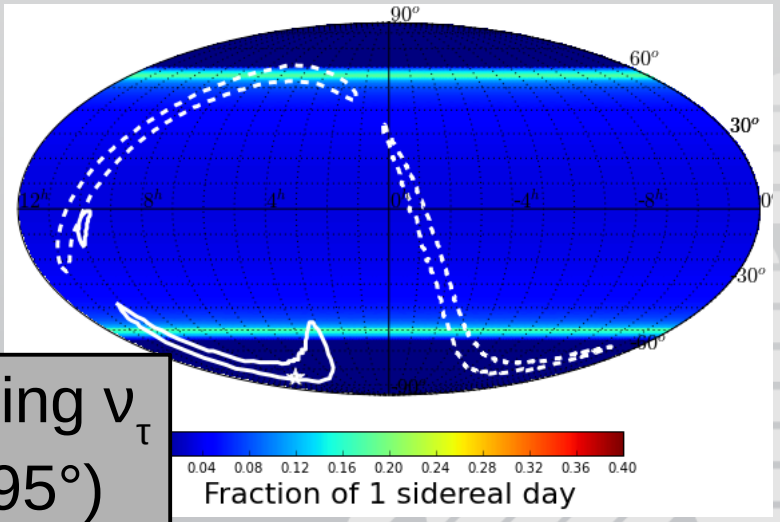
**No candidate** in [–500 s, 1 day]
around GW events

“Prompt” / ”afterglow”

**No candidate** in [–500 s, 1 day] around GW events

→ Calculate **exposure** taking into account

- Time-dependent aperture (area x solid angle)
- ν-nucleon cross section + efficiencies (E,δ)

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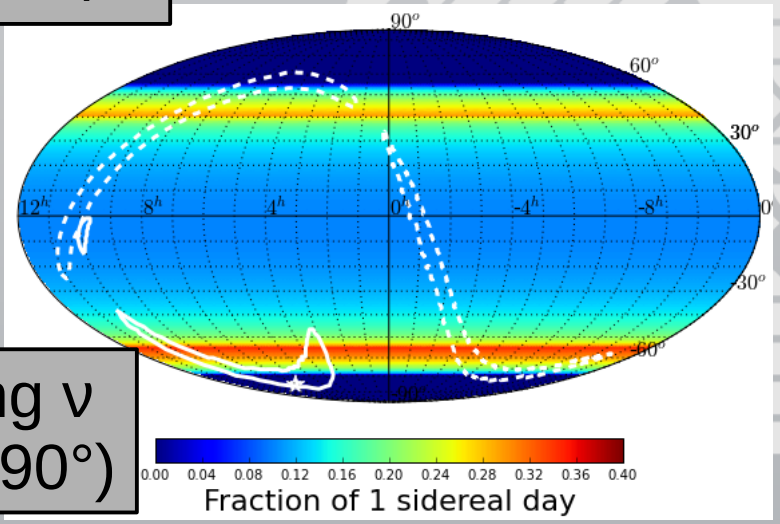


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**No candidate** in [–500 s, 1 day] around GW events

→ Calculate **exposure** taking into account

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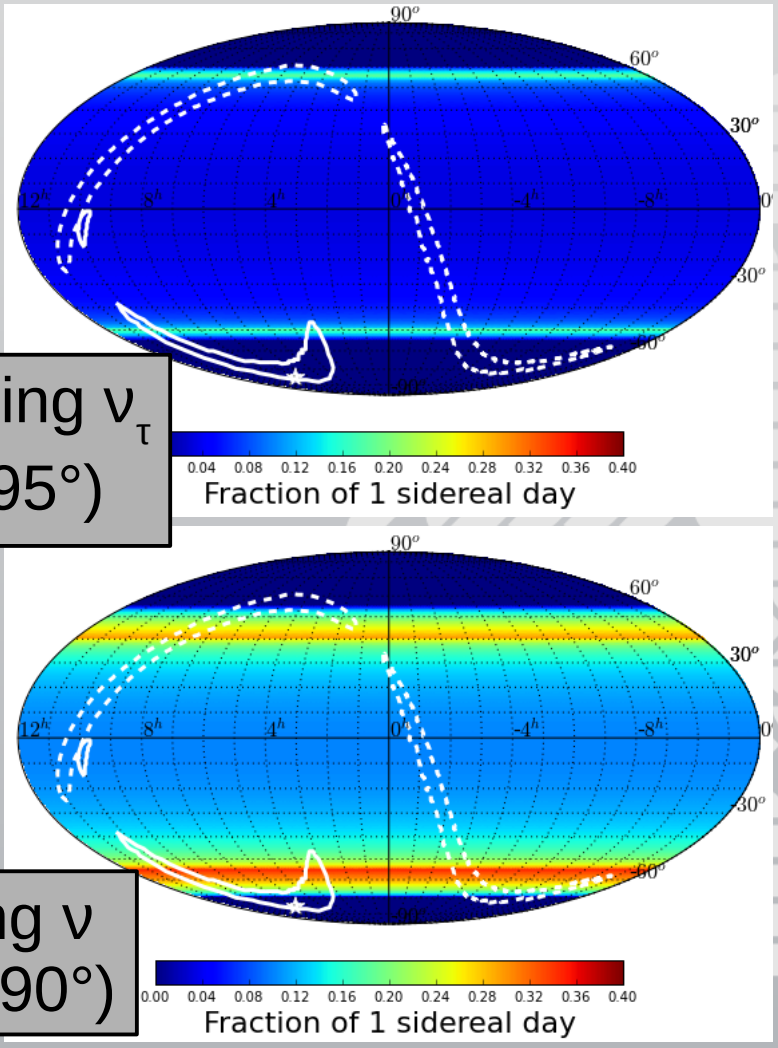
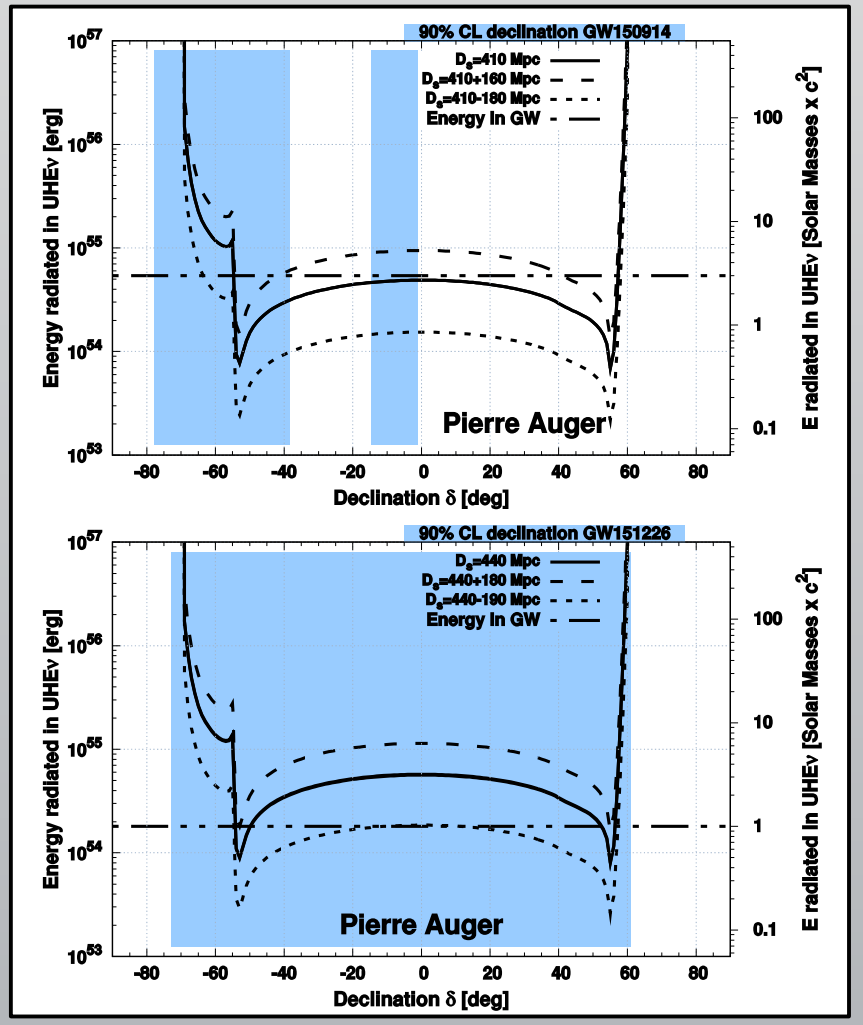
→ Calculate upper limits on **energy radiated in UHEν** (δ) ($E^{-2}$ spectrum)



# Results & Conclusions

# GW Follow-Up Results



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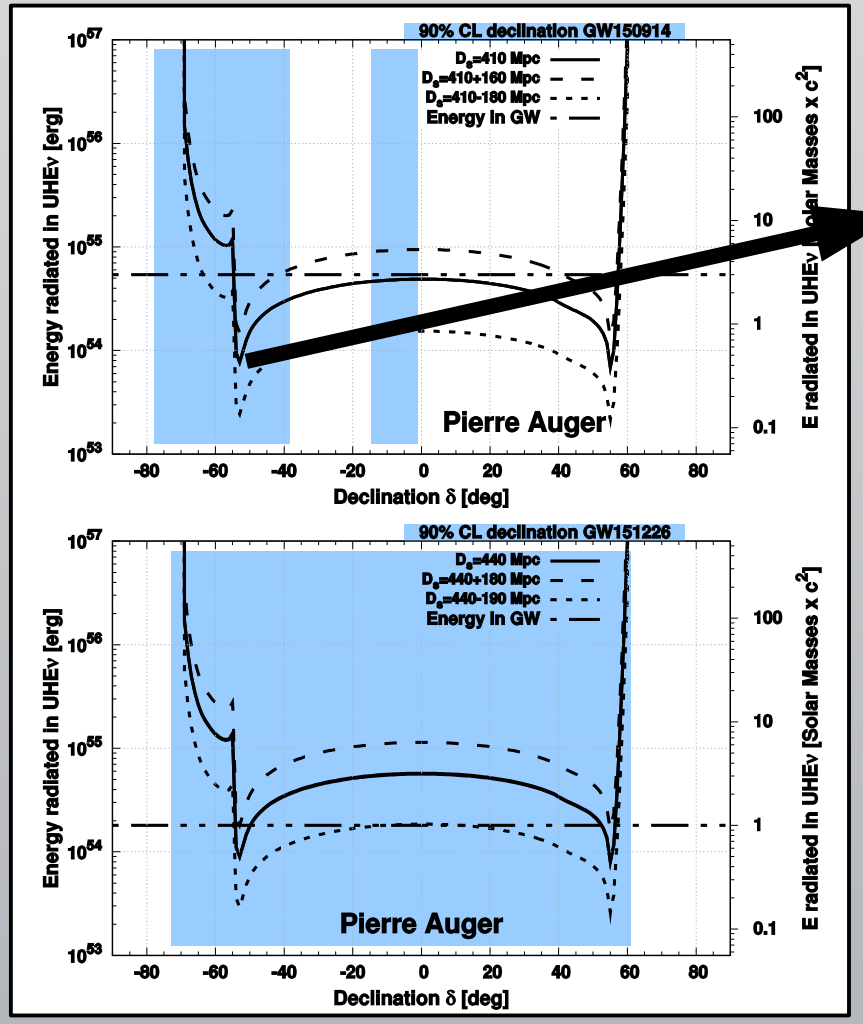


Most stringent:
15% of GW energy into UHEν

→ *Kotera, Silk:* 3% of GW energy needed for UHECR to explain their flux

- If 3% of GW energy into UHEν
  → ~ 1 event in our search ($E^{-2}$)

→ We need
- More powerful GW events
- More precise distance measure
- More sensitivity to UHEν

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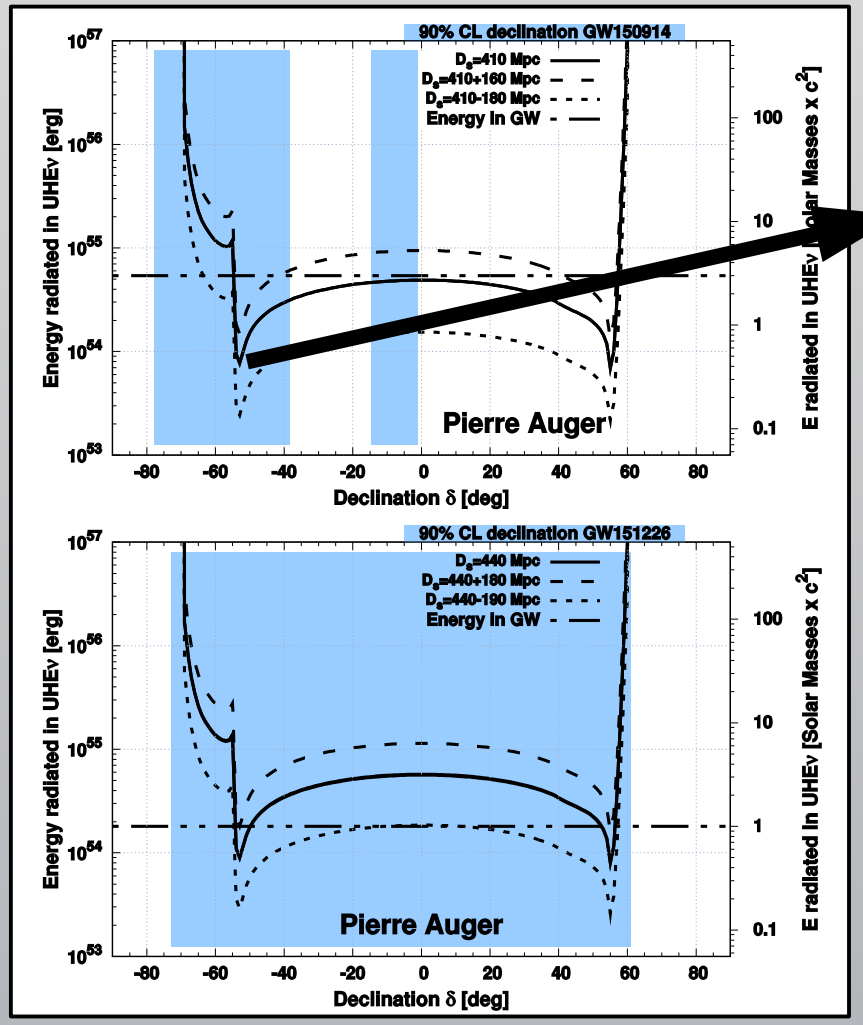


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# Auger Constraints On Diffuse Flux

Also *Kotera, Silk:*

Prediction of **diffuse** UHEν flux from inferred BH merger **population** with 3% UHECR production efficiency:

- $E^2\ dN/dE \sim 8.3 \times 10^{-8}\ GeV\ cm^{-2}\ s^{-1}\ sr^{-1} \times f_\nu \times f_z$
- Auger data up to 2013:
  $E^2\ dN/dE < 6.4 \times 10^{-9}\ GeV\ cm^{-2}\ s^{-1}\ sr^{-1}$

$f_\nu$: ν optical depth

$f_z$: Redshift loss / source evolution

At least 1 is true

- UHECR production efficiency < 3%
- Inefficient charged pion (→ neutrino) production, $f_\nu < 1$
- Unfavorable source evolution

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Extrapolation based
→ We need more GW events!

~~The End~~

—Questions?

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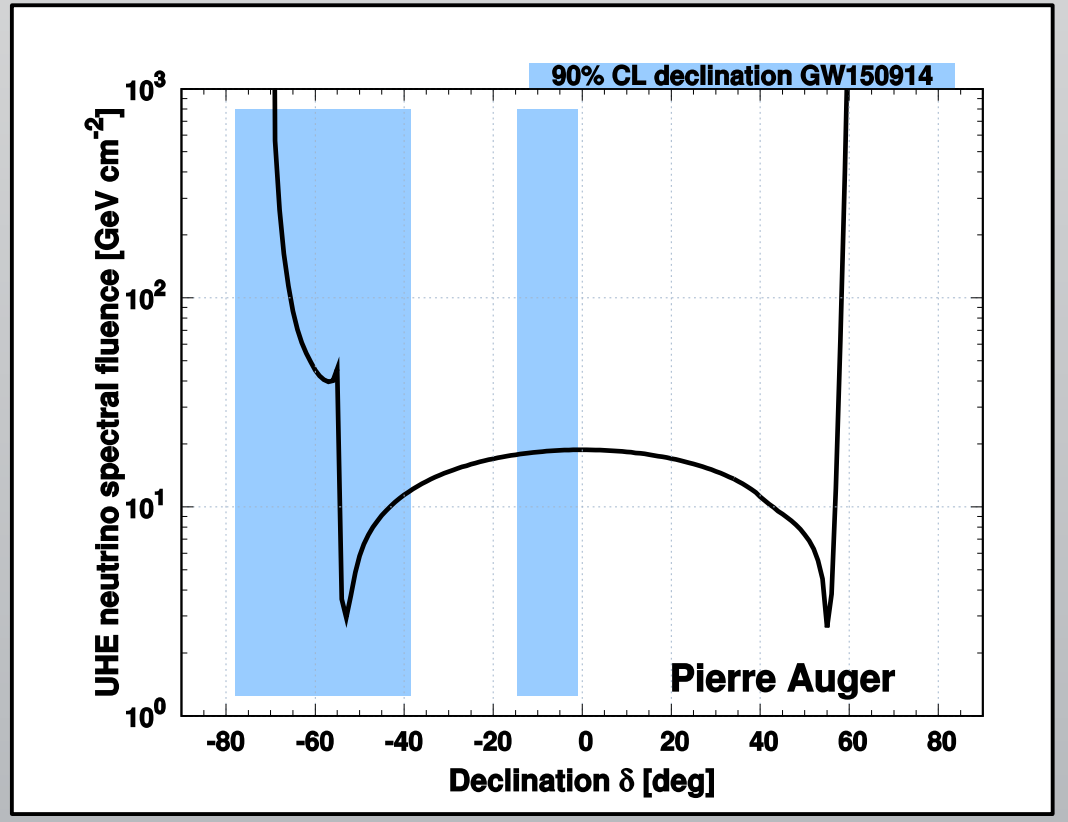
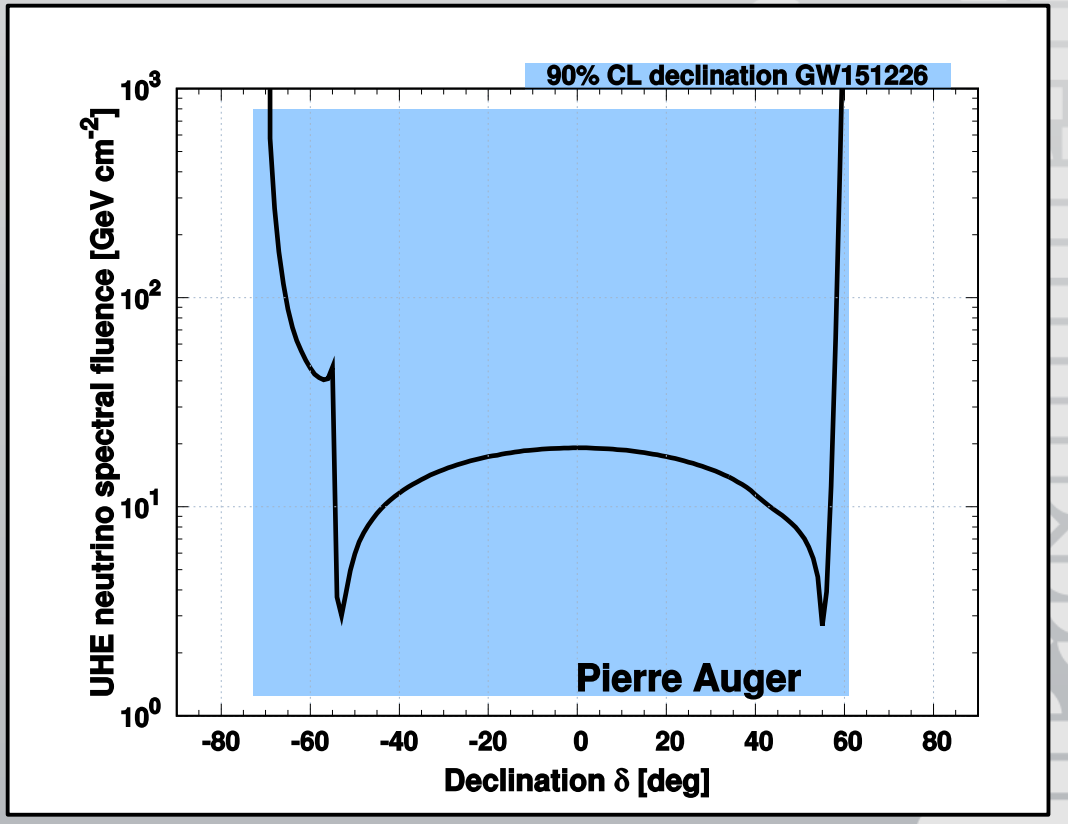
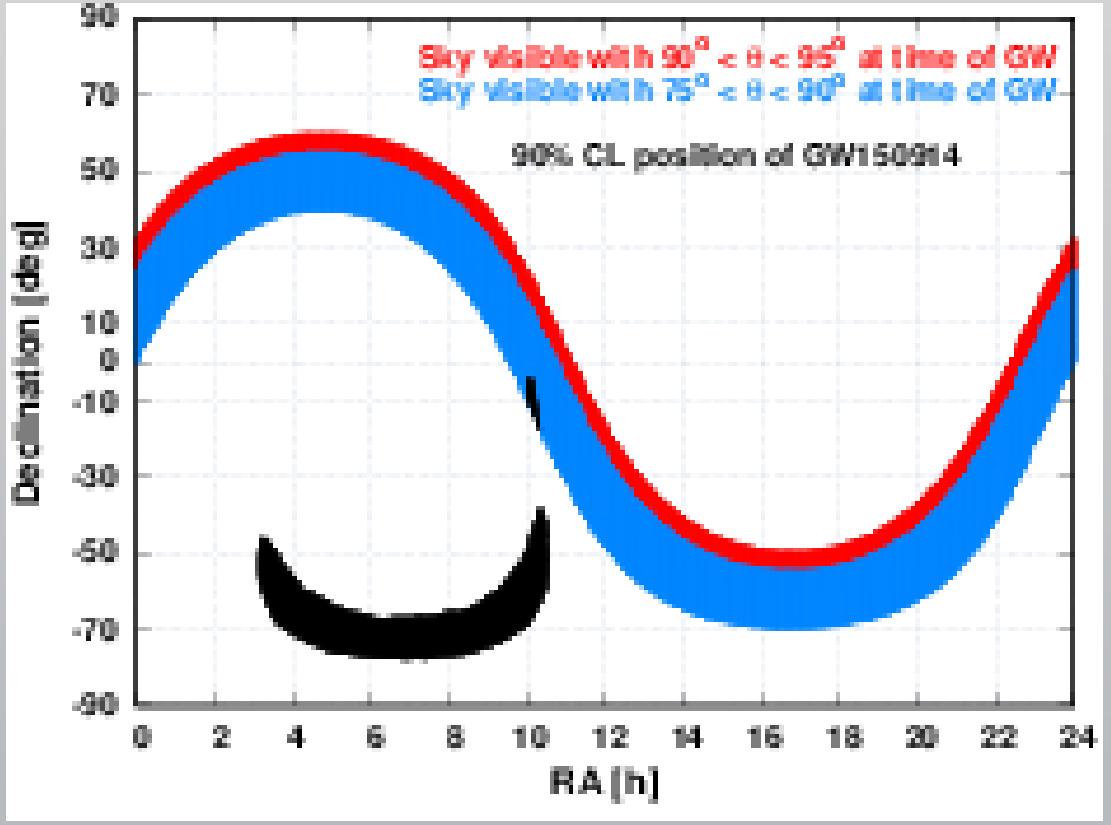
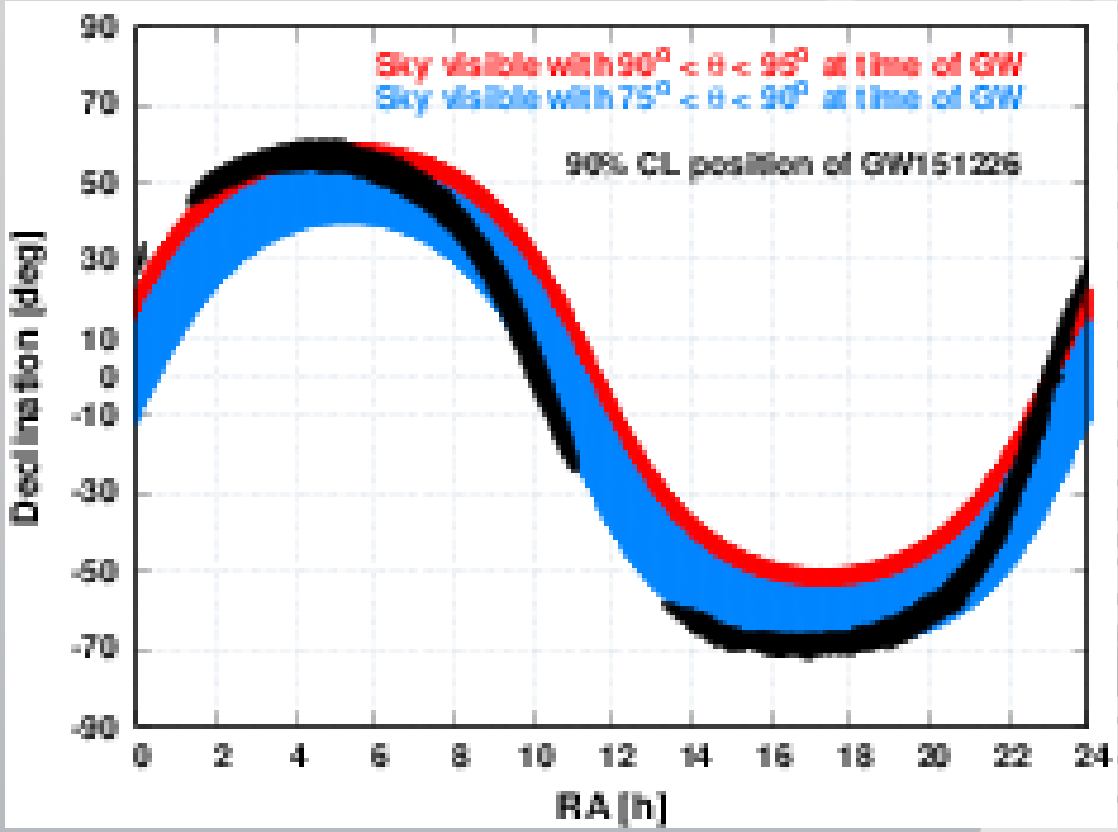
# Fluence Upper Limits



# Visible Solid Angles At Times Of Events



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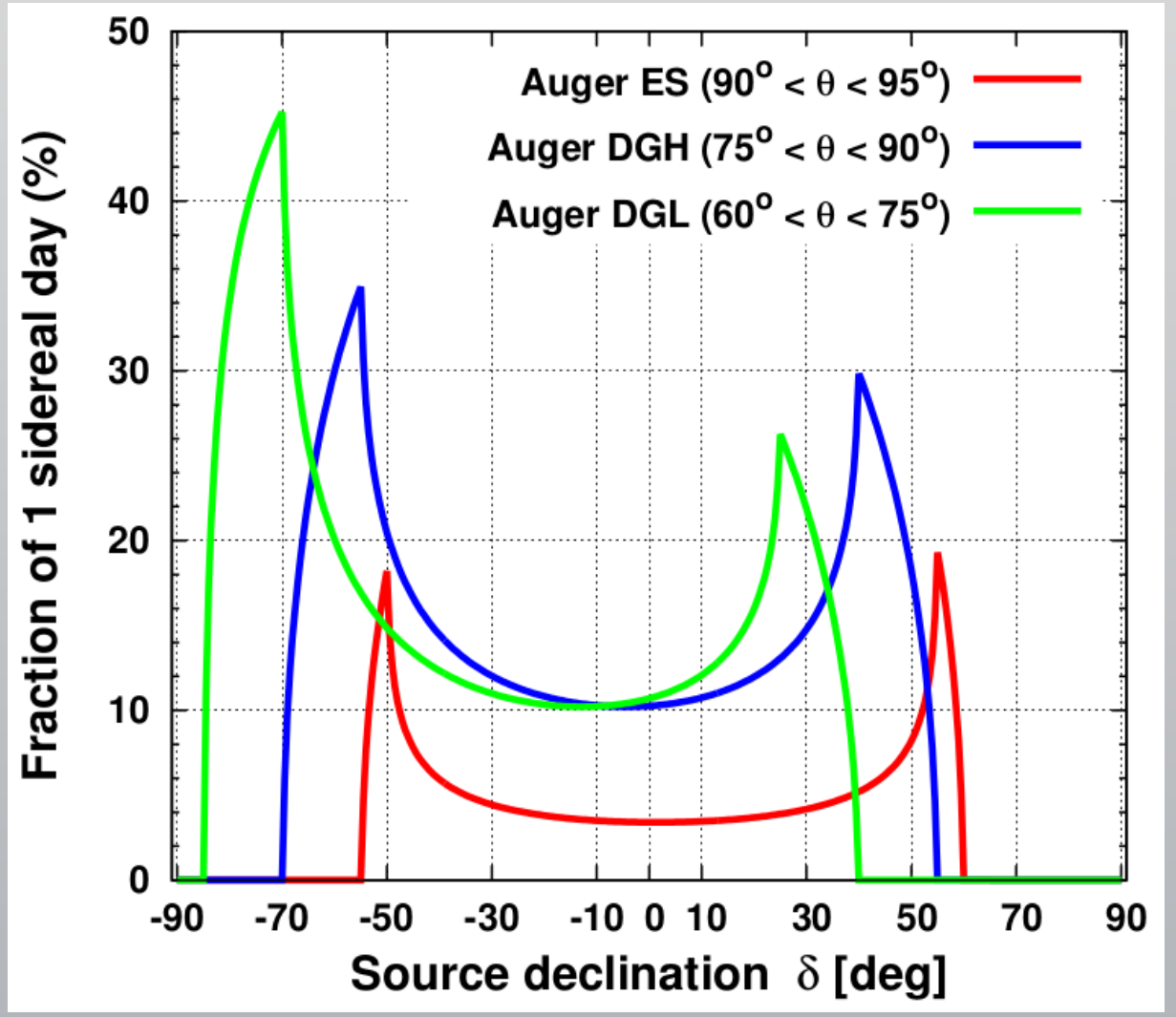
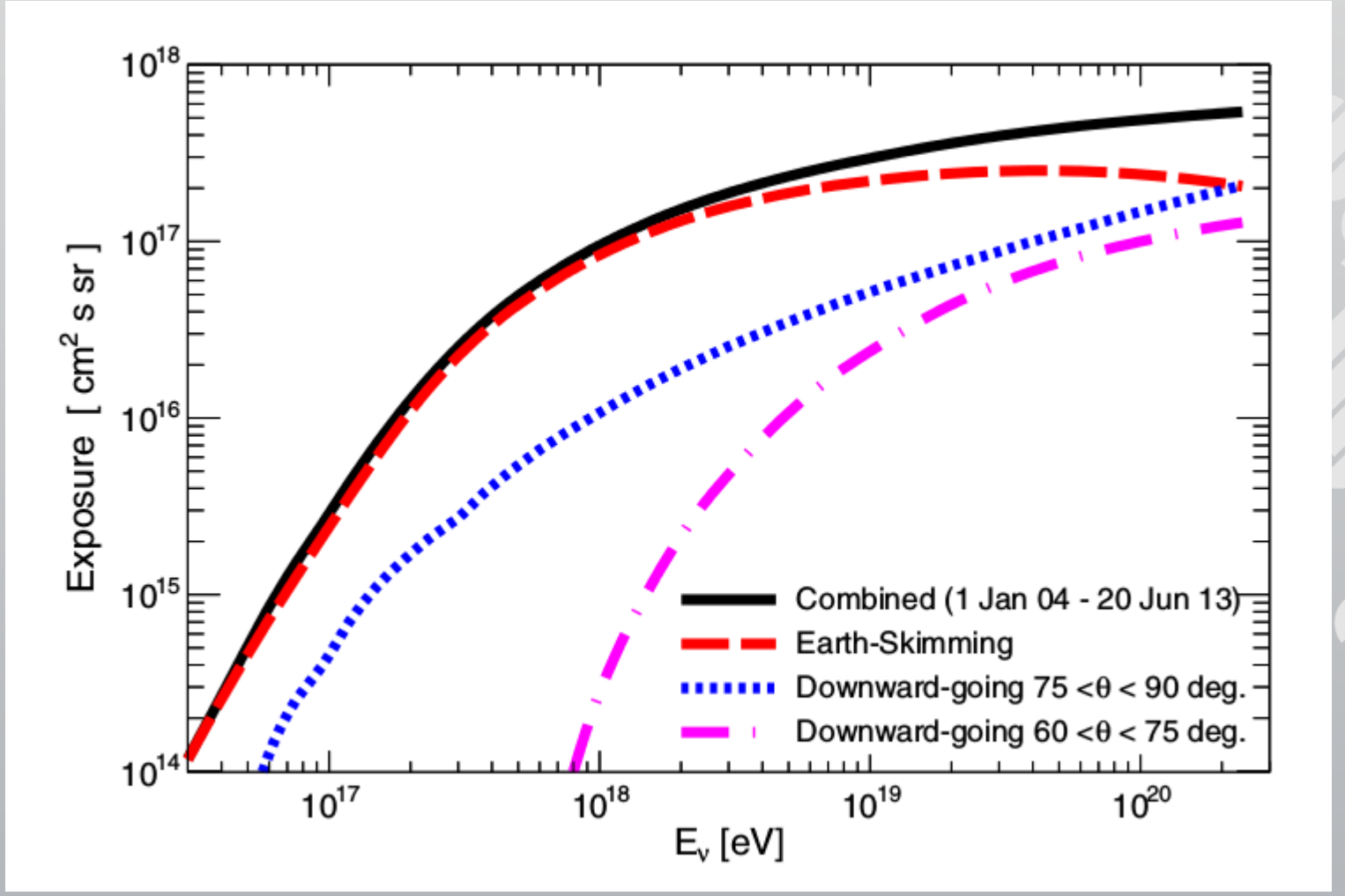
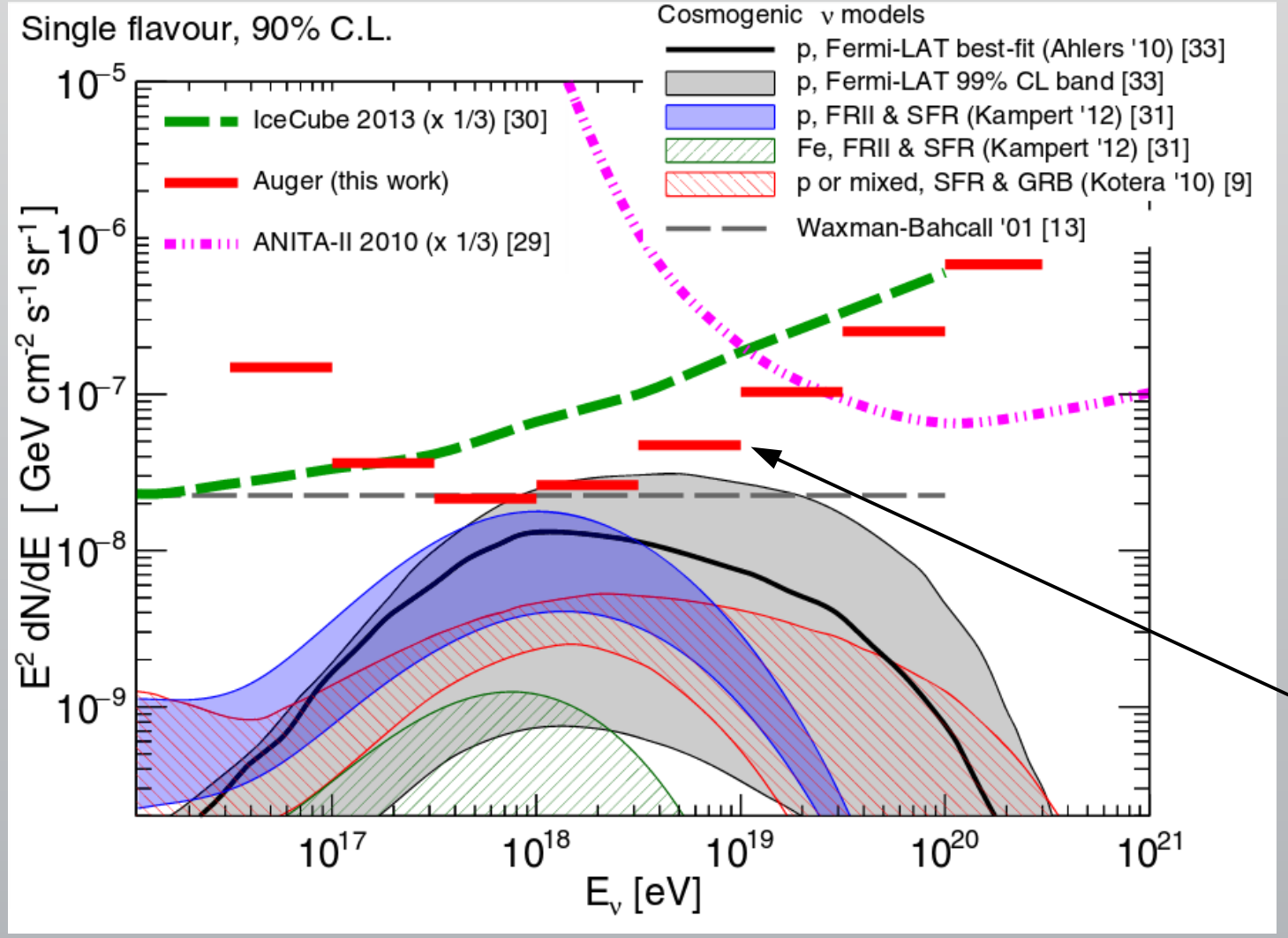


# Energy Dependence Of Diffuse Exposure (Phys Rev D 91, 092008 (2015))



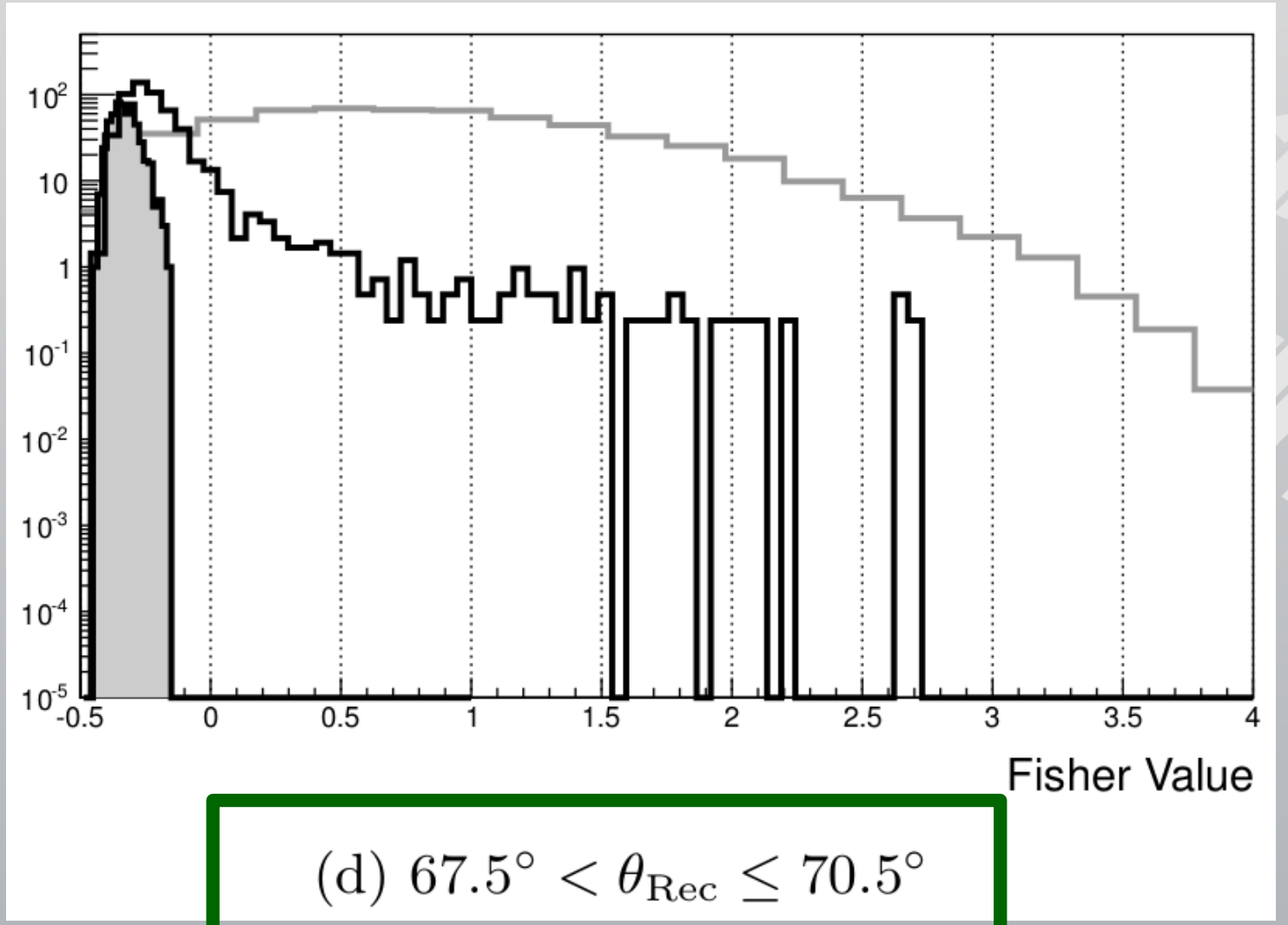
# Binned Diffuse Flux Limits (Phys Rev D 91, 092008 (2015))




$$k = \frac{N_{\mathrm{up}}}{\int_{E_\nu} E_\nu^{-2} \mathcal{E}_{\mathrm{tot}}(E_\nu) dE_\nu}$$

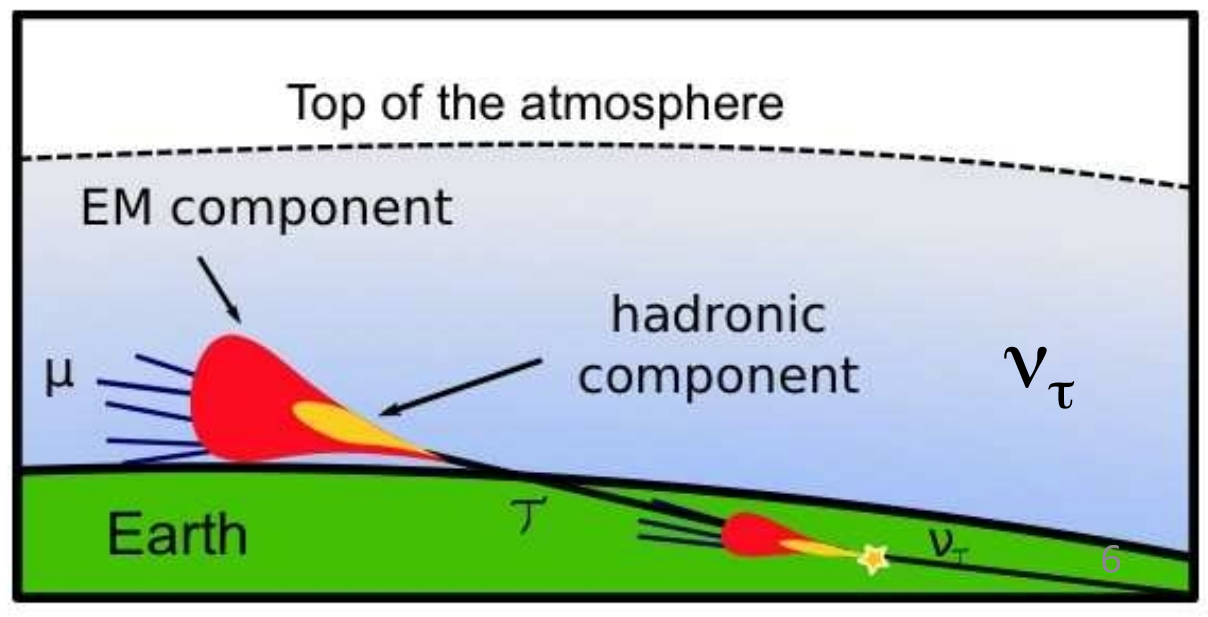
Bin-wise
(0.5 in log E)

# UHE Photon Background




(d) $67.5° < \theta_{\mathrm{Rec}} \leq 70.5°$

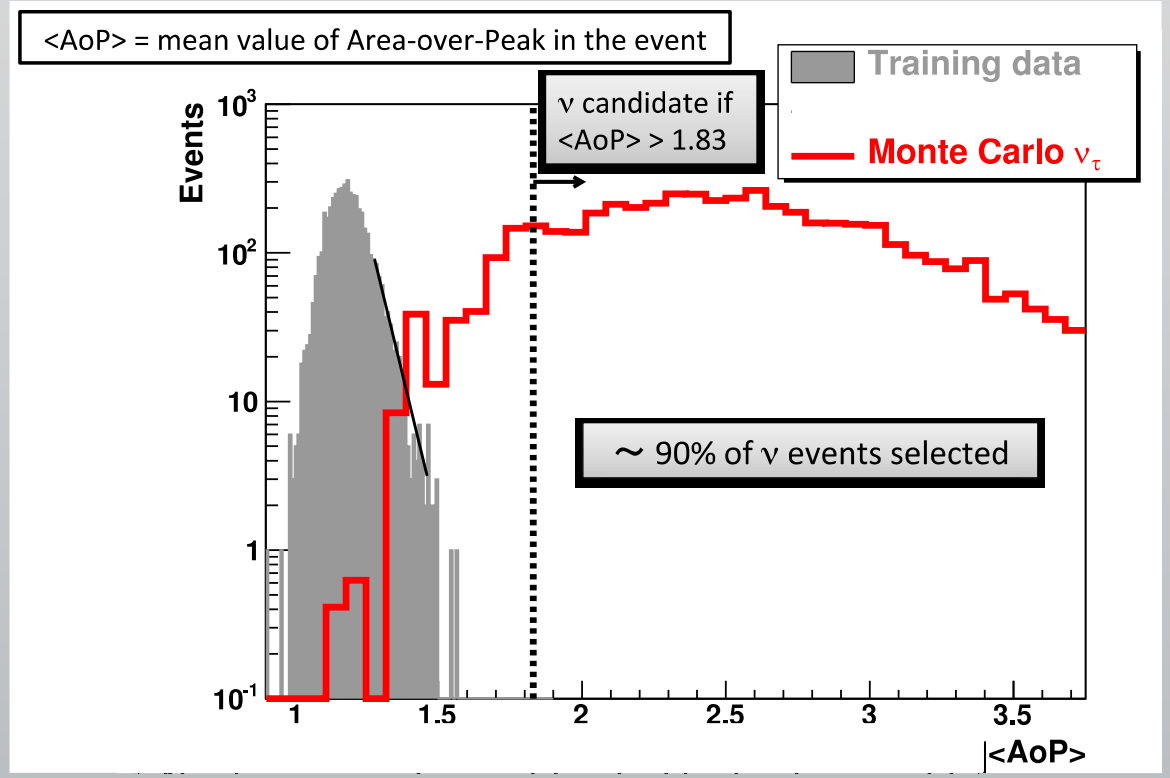
# Earth-Skimming $\nu_\tau$ Search

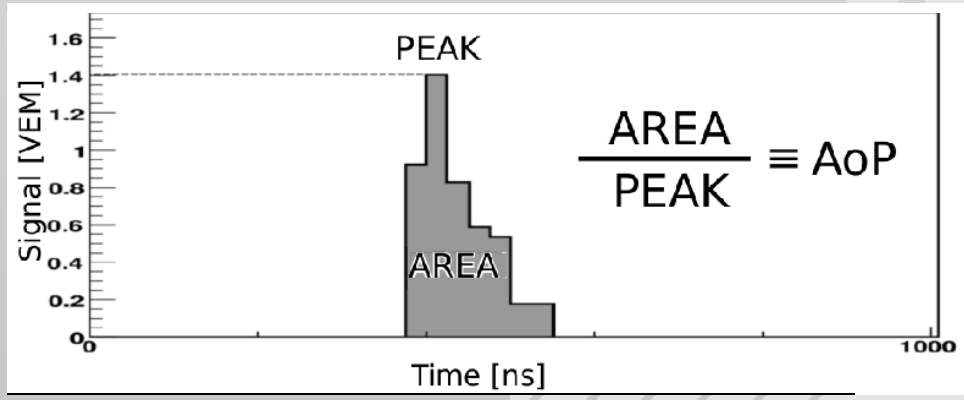



Earth skimming events dominated by $\nu_\tau$

- ν interaction enhanced in Earths crust (producing e, μ, τ, nuclear fragments)
- Only τ can travel long distance through Earth and induce EAS (by decaying after ~ 48 km @ 1 EeV)

# Earth-Skimming $\nu_\tau$ Analysis




No event after <AoP> cut → calculate exposure
→ flux limit ~ event count limit / exposure