Neutrino results from the Pierre Auger Observatory

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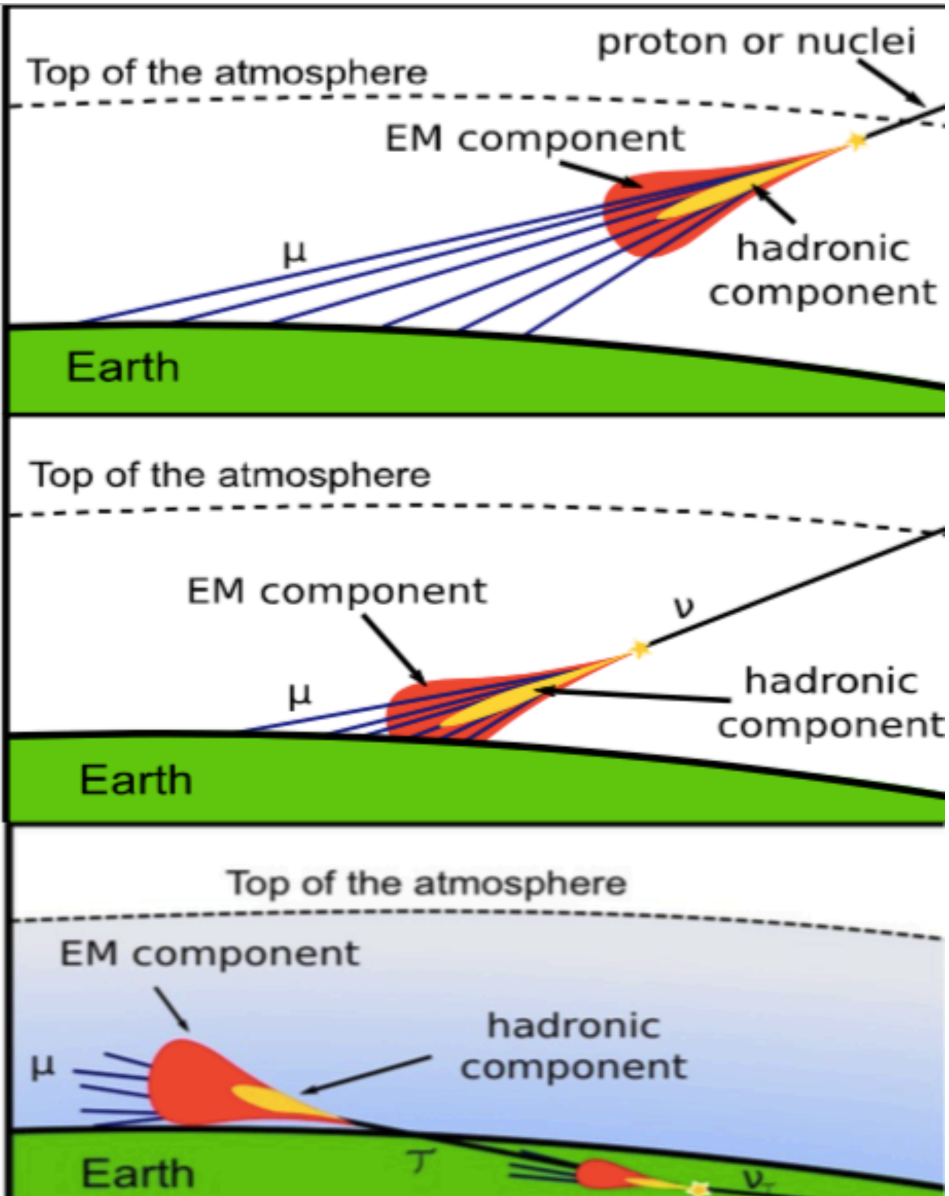
Workshop on Perspectives on the Extragalactic Frontier: from Astrophysics to Fundamental in ICTP, Italy

Outline

- Searching for UHE neutrinos in Auger
- Limits to point-like sources and Gamma-Ray-Bursts (GRB) of UHEν
- Search for UHE neutrinos in coincidence with GW150914
- Summary

Identification of neutrinos



Protons & nuclei initiate inclined showers high in the atmosphere.

✓ Shower front at ground:

electromagnetic component absorbed in atmosphere.

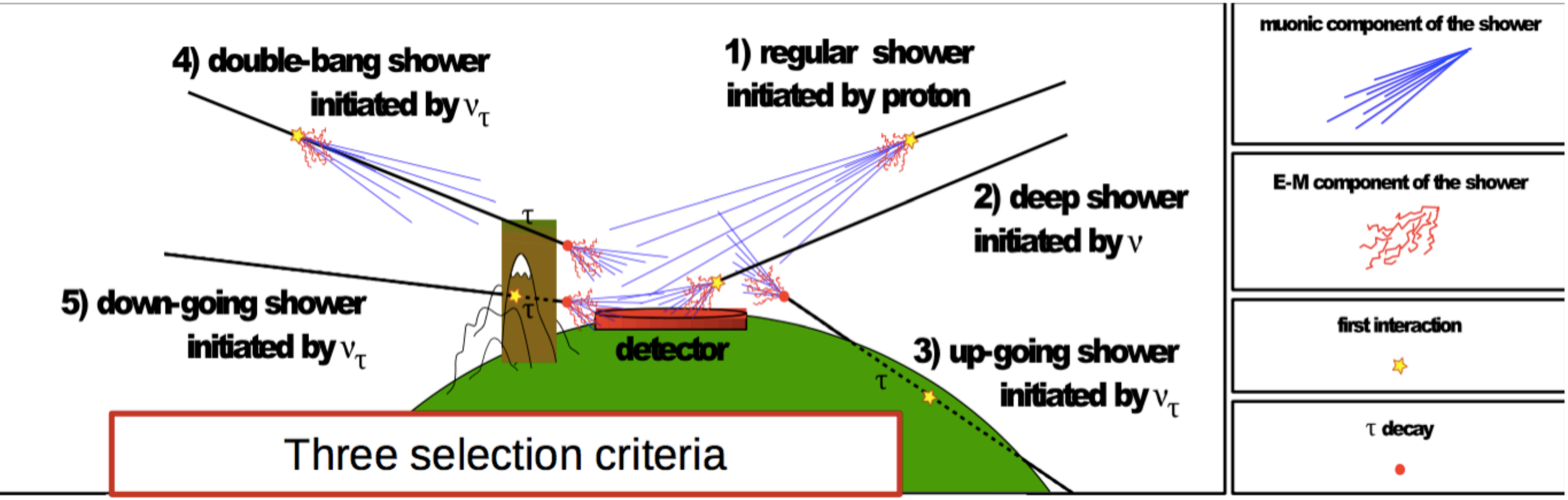
✓ mainly muons remaining

Neutrinos can initiate deep showers close to ground.

✓ Shower front at ground:

electromagnetic + muonic components

Sensitivity to all flavours and channels



Down-going low angle (2 and 4) DGL 60° -- 75°
Down-going high angle (2, 4 and 5) DGH 75° -- 90°

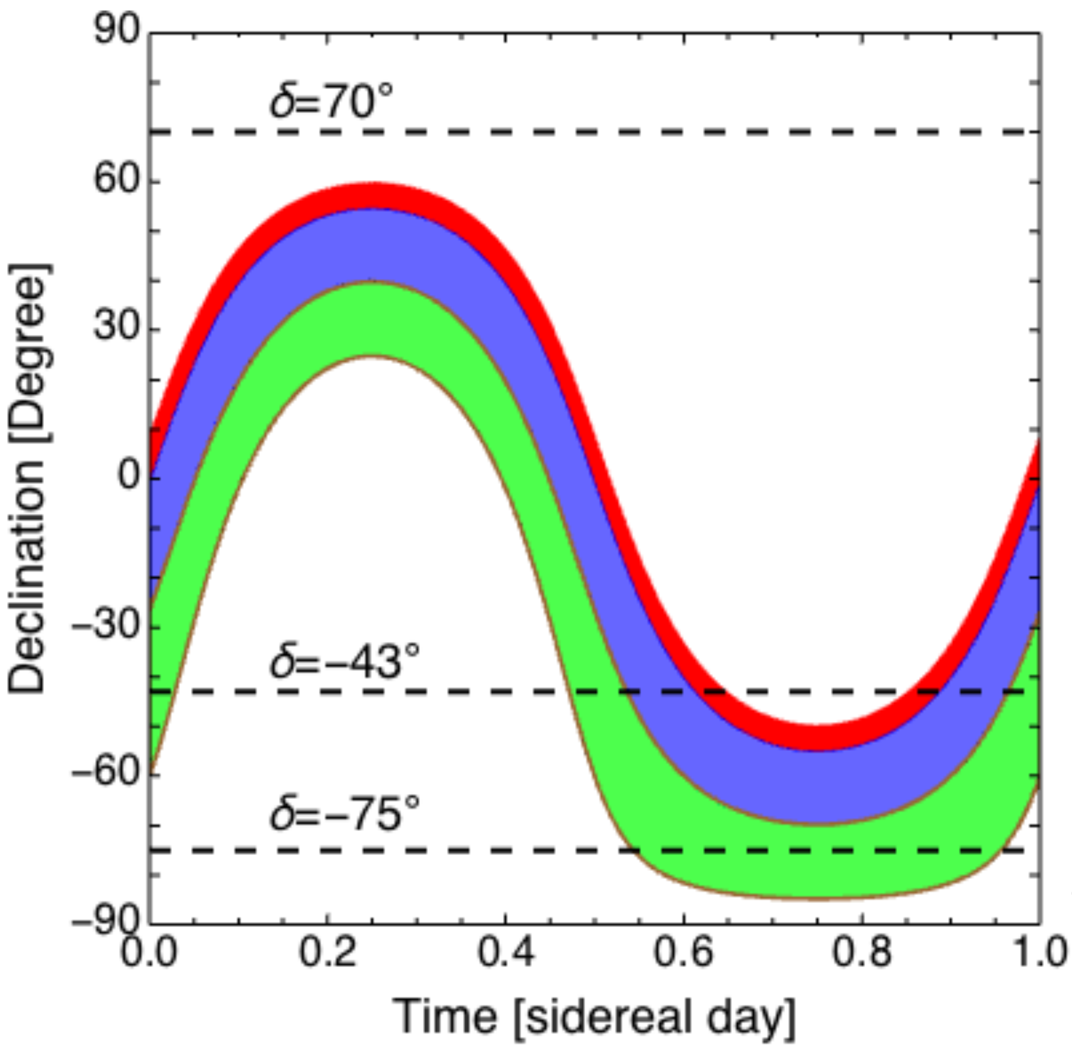
Earth-skimming (3) ES 90° -- 95°

Identification criteria applied "blindly" to the search data set
=> No candidates found in Earth Skimming or Downward-going

Limits to flux of UHEν from point sources

Find times in 1 sidereal day a source at given declination is seen at Auger with zenith angle q.

Pierre Auger Collab. ApJ Lett **755**, L4 (2012)



A point source moves across the sky in 1 sidereal day.

Source zenith angle q with respect to the SD array changes.

A fraction of time per day the source is seen with:

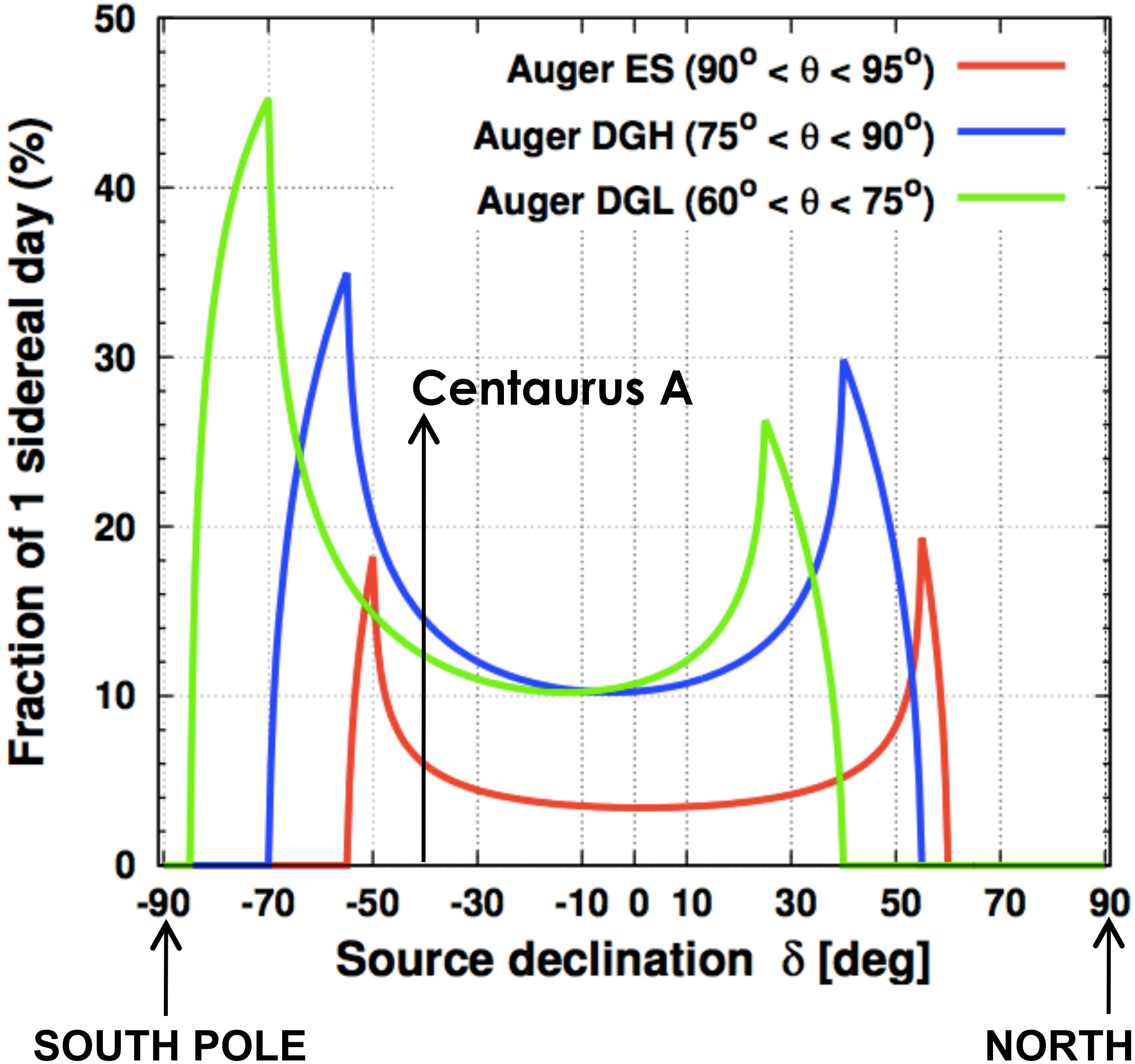
90º < θ < 95º (**ES**)
75º < θ < 90º (**DGH**)
60º < θ < 75º (**DGL**)

$$\cos\theta = \sin l \sin\delta + \cos l \cos\delta \sin(2\pi\, t + \varphi)$$

l ~ -35.2 latitude of Auger Obs.

Fraction of time source visible vs declination

Integrate in time only when the source is visible.



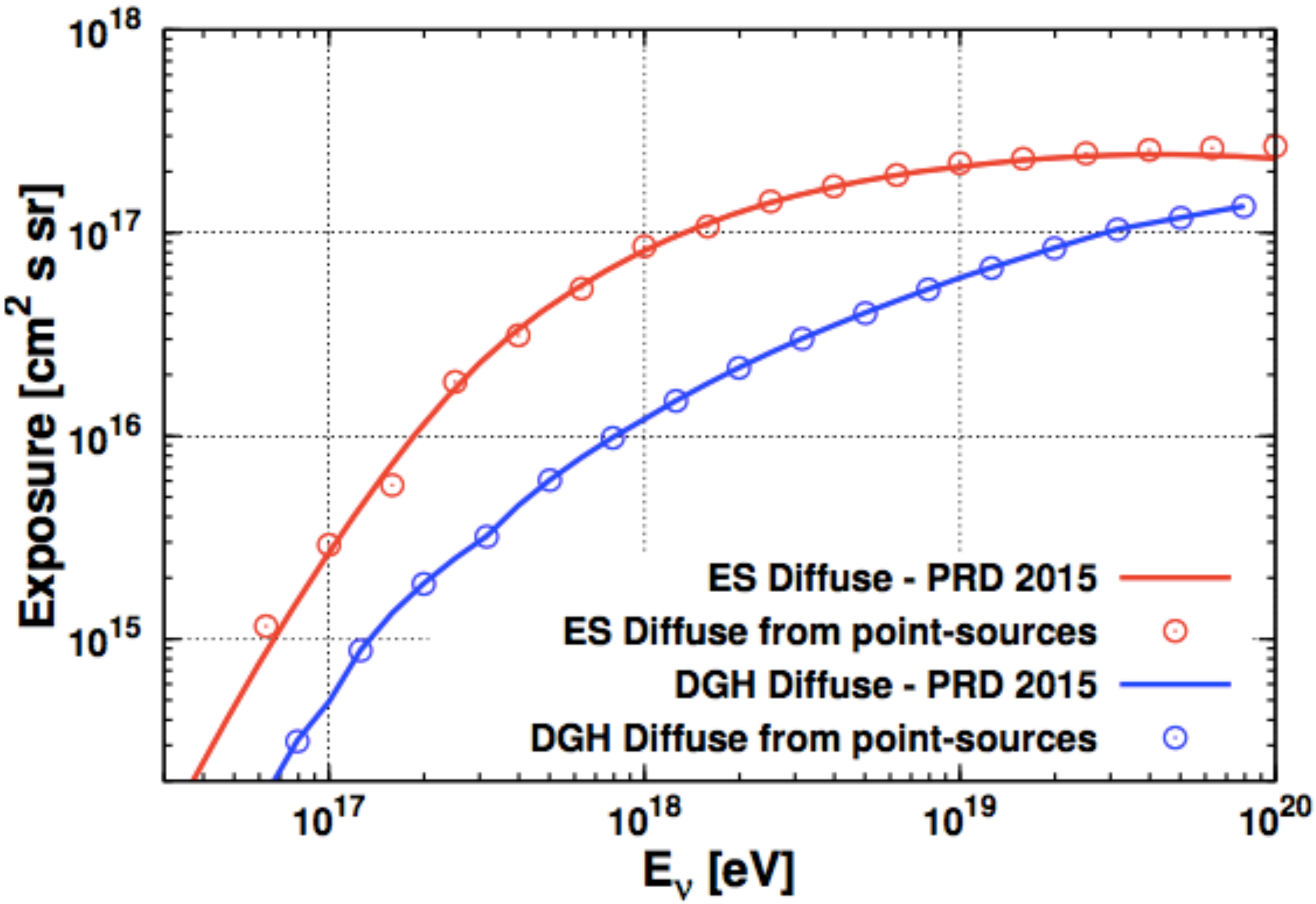
Fraction of 1 sidereal day a source is seen in ES, DGH, DGL as a function of declination.

Source declinations visible:

ES	$-52^o < \delta < 60^o$
DGH	$-70^o < \delta < 55^o$
DGL	$-90^o < \delta < 40^o$

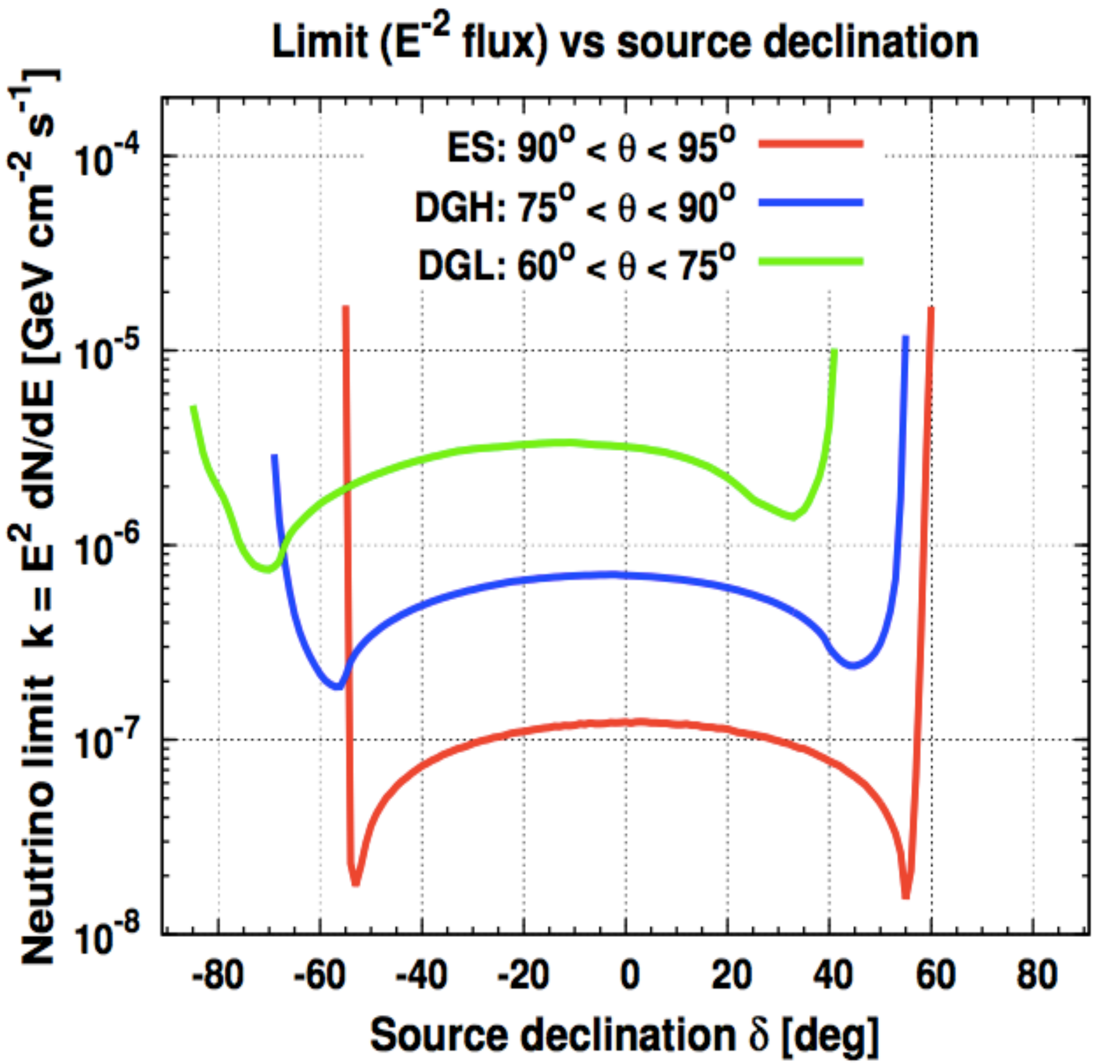
Example:
Visibility of Centaurus A
($\delta \sim 42.97^o$)
~ 7% with $\theta \in (90^o, 95^o)$
~ 16% with $\theta \in (75^o, 90^o)$
~ 13% with $\theta \in (60^o, 75^o)$

Calculated Exposure



Weight with effective detection area cosq A_{eff}(t,q) and probabilities of tau production & decay (ES only)

Limits to ν flux vs source declination



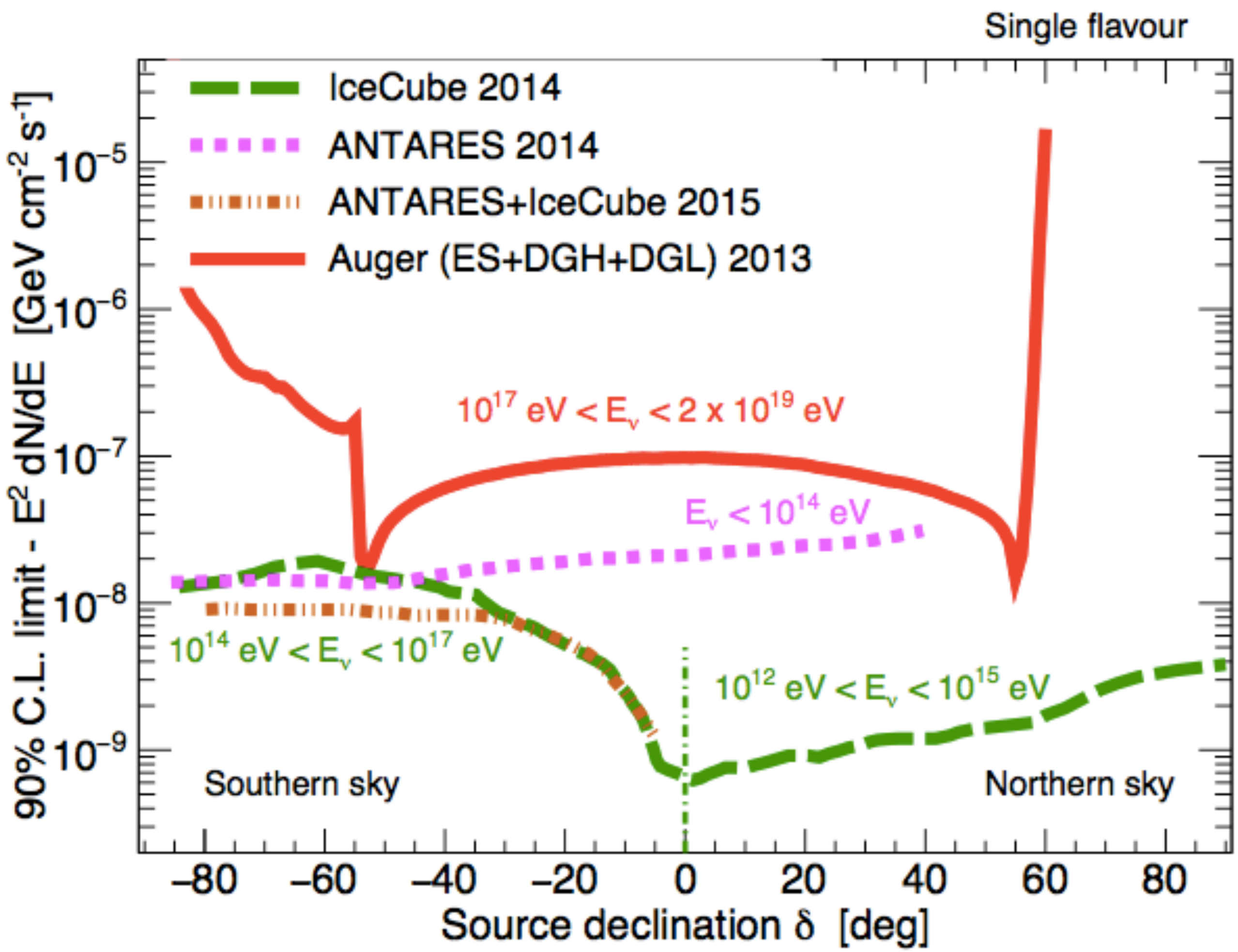
Assuming neutrino flux:
dN/dE = k E^{-2}
(GeV^{-1}cm^{-2} s^{-1})

$$k^{PS}(\delta) = \frac{2.44}{\int_{E_\nu} E_\nu^{-2}\, \mathcal{E}_{PS}(E_\nu, \delta)\, dE_\nu}$$

90% C.L. limit on **"k"** vs source declination
(old vs new limits)

Broad declination range with good sensitivity to UHEν

Directional limits



Assuming neutrino flux: **dN/dE= k E^{-2}** ⟶ 90% C.L. limit on **k** vs declination

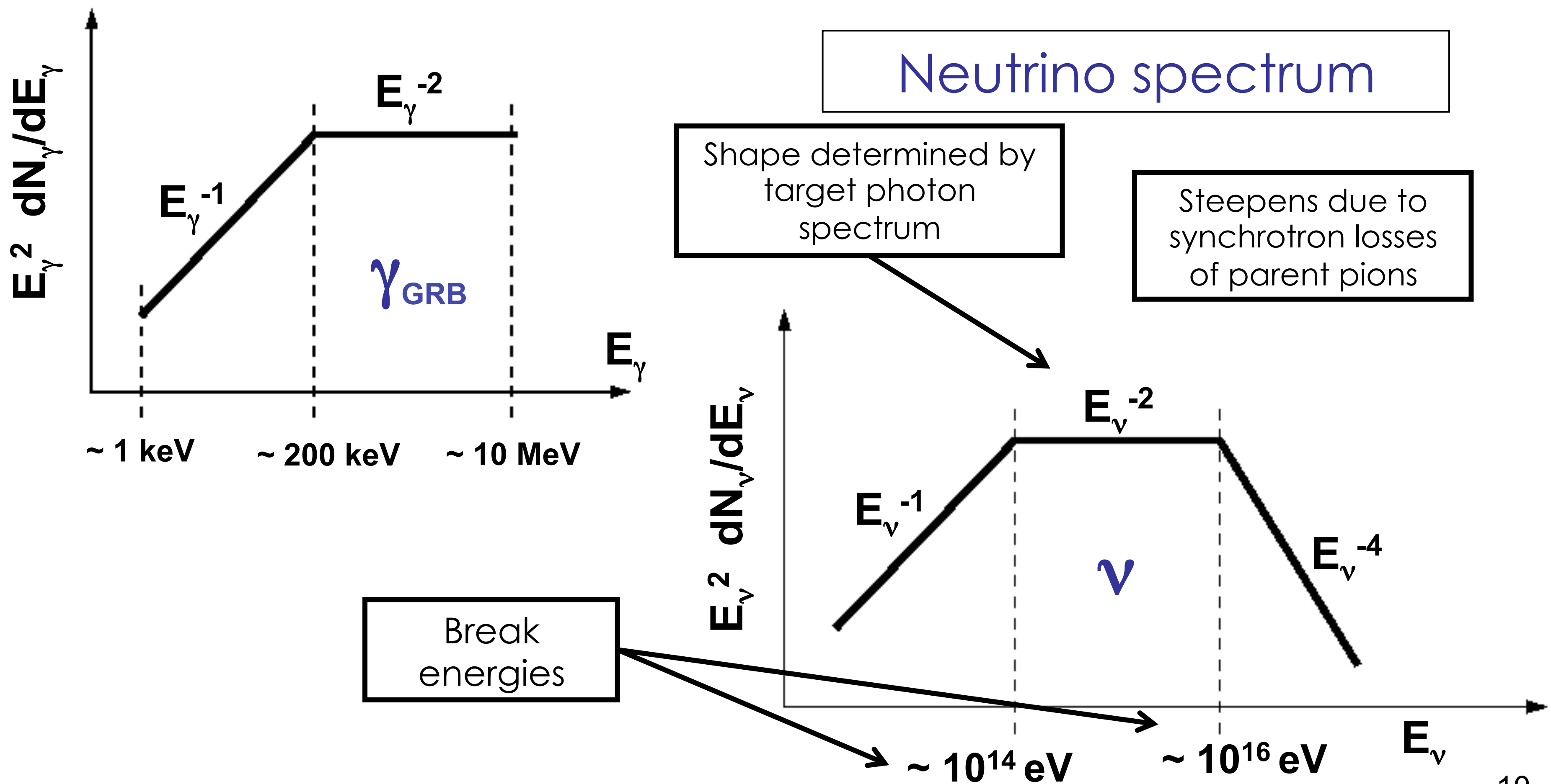
Note different energy ranges of experiments

Limits to flux of UHEν from GRB

$$p\,\gamma_{GRB} \rightarrow n\,\pi^{+} \rightarrow \nu\text{'s}$$

Projectile proton spectrum: E_p^{-2} (assumed)

Target photon spectrum: double power-law (measured)



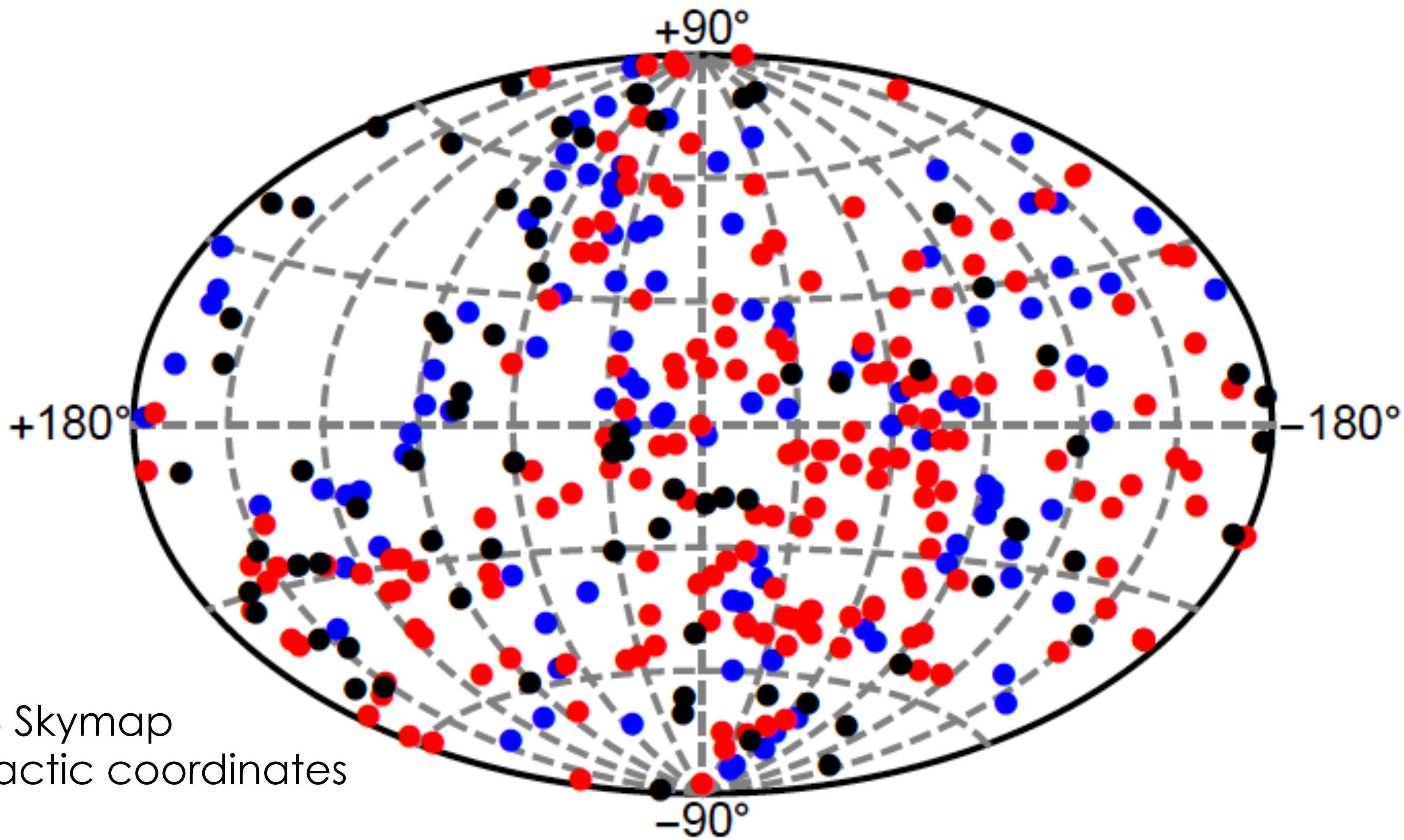
Pierre Auger Collab. ApJ Lett **755**, L4 (2012) & GAPs, 2011-055, 2013-013, 2013-100

The GRB sample

- Based on Fermi, Swift and GBM catalogs
  - Equatorial coordinates measured => θ_{GRB} known
  - Time duration T90 & GRB fluence,… provided.
  - Redshift z only measured for a few GRBs
  - Lorentz boost factor Γ not measured
- Selected GRB:
  - visible from Auger in inclined directions when array is active:
    - Exclude GRBs during the dead-time
    - ES with $\theta \in [90^o, 95^o]$ DGH with $\theta \in [75^o, 90^o]$ DGL with $\theta \in [60^o, 75^o]$
- Model neutrino production in GRB sample:
  - Typical redshift z=2, Lorentz factor $\Gamma = 300$ (not measured)
  - This implies "break energy" > 10^{17} eV => $dN/dE \sim E^{-4}$ in Auger
  - Zenith angle of GRB does not change during T_{90}

GRB visible in Auger in ES, DGH or DGL

90° < θ < 95° (Earth-Skimming - **ES**) – 79 GRB
75° < θ < 90° (Downward-Going High-angle - **DGH**) – 149 GRB
60° < θ < 75° (Downward-Going Low-angle - **DGL**) – 183 GRB



GRB Skymap
Galactic coordinates

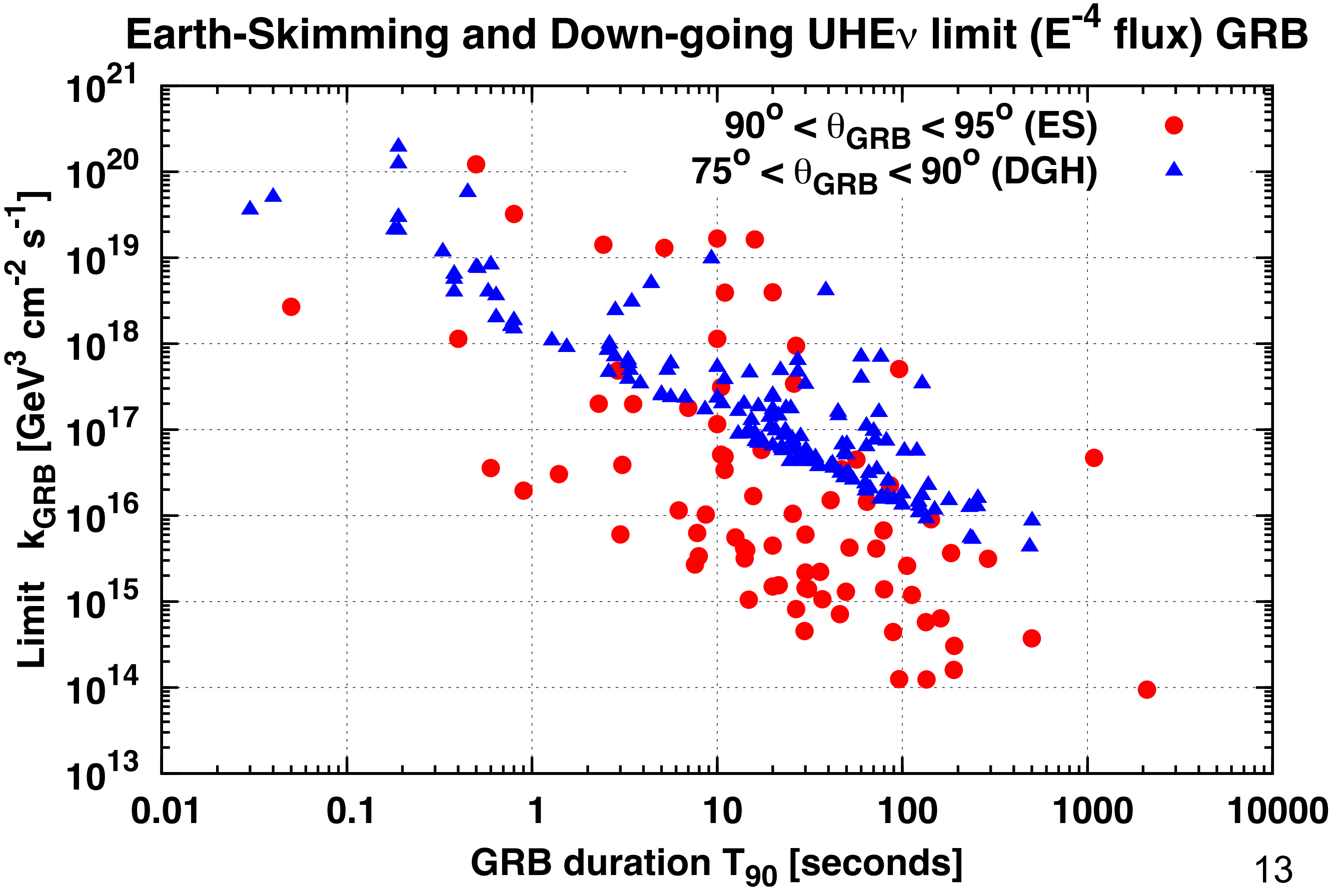
Limits to ν flux from GRB

Assuming neutrino flux: $\mathbf{dN/dE = k_{GRB}\, E^{-4}}$ (GeV^{-1} cm^{-2} s^{-1}) we show:

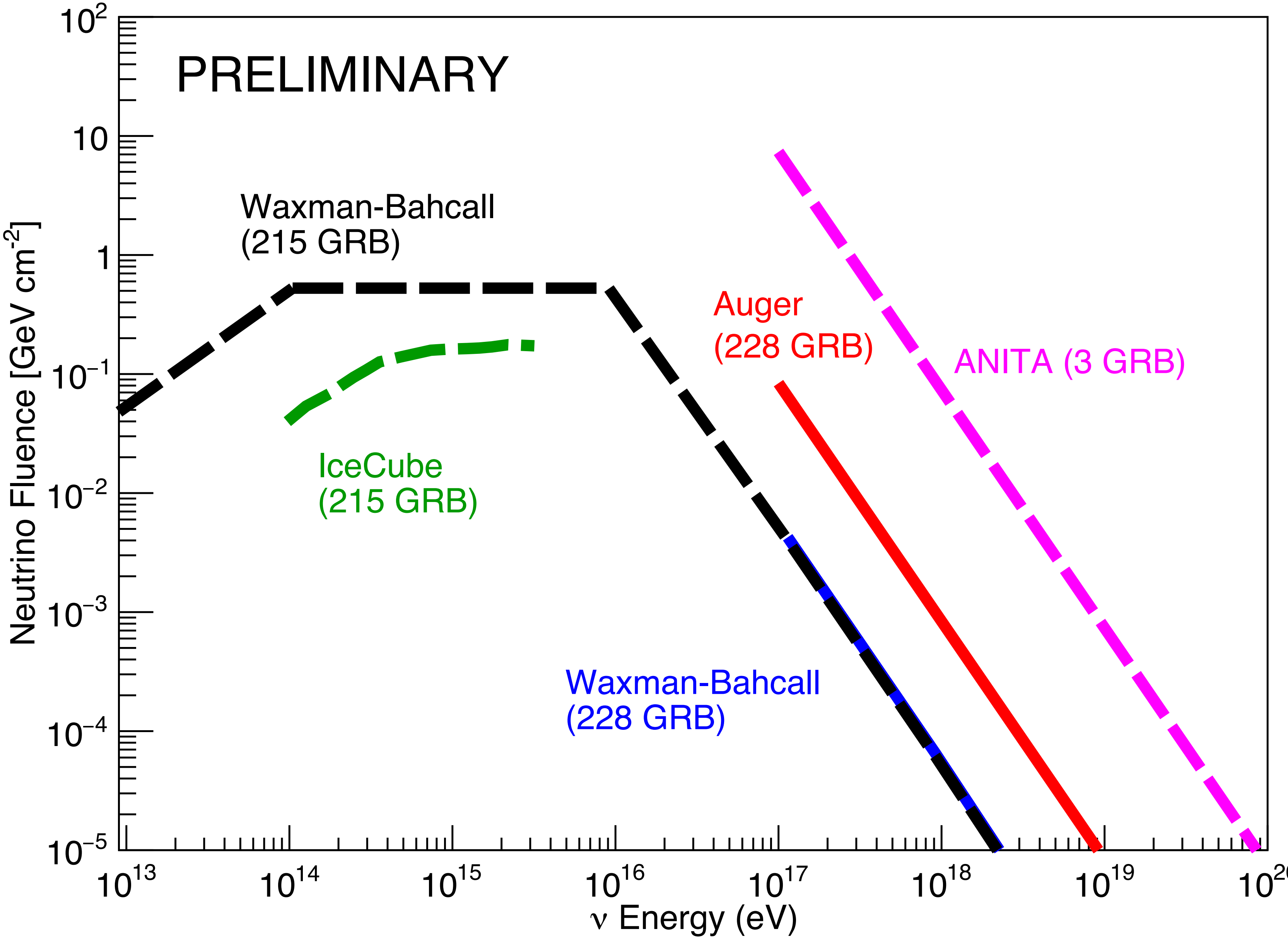
90% C.L. limit on "$\mathbf{k_{GRB}}$" vs GRB time duration $\mathbf{T_{90}}$

- **Better limits for ES than for DGH**
- **Better limits for longer GRB**

NOTE: Limits to DGL not yet obtained – small contribution



Aggregate limits to ν fluence from GRB

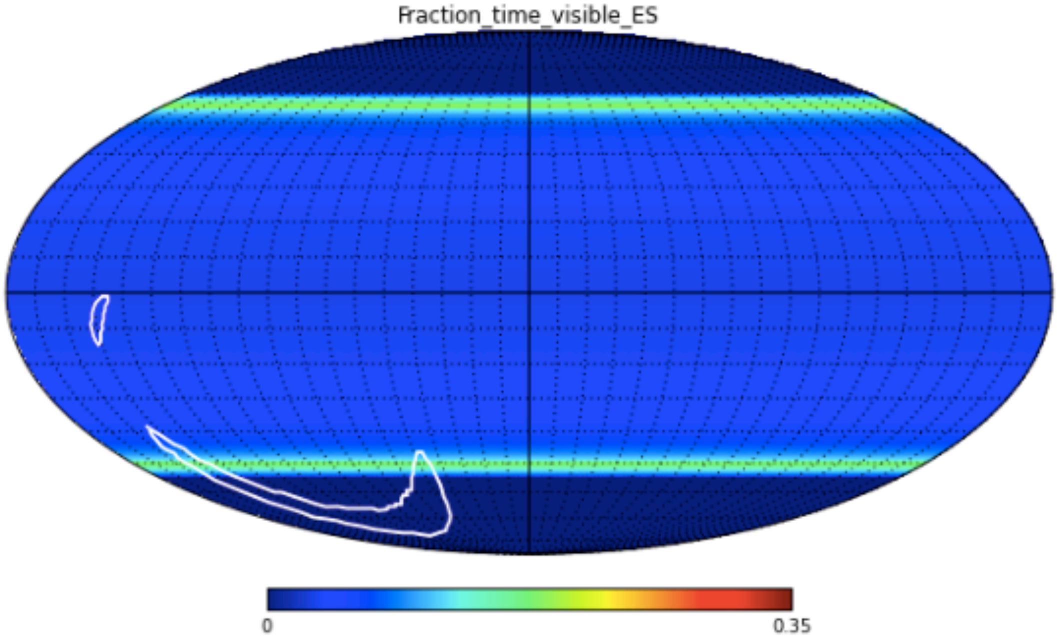


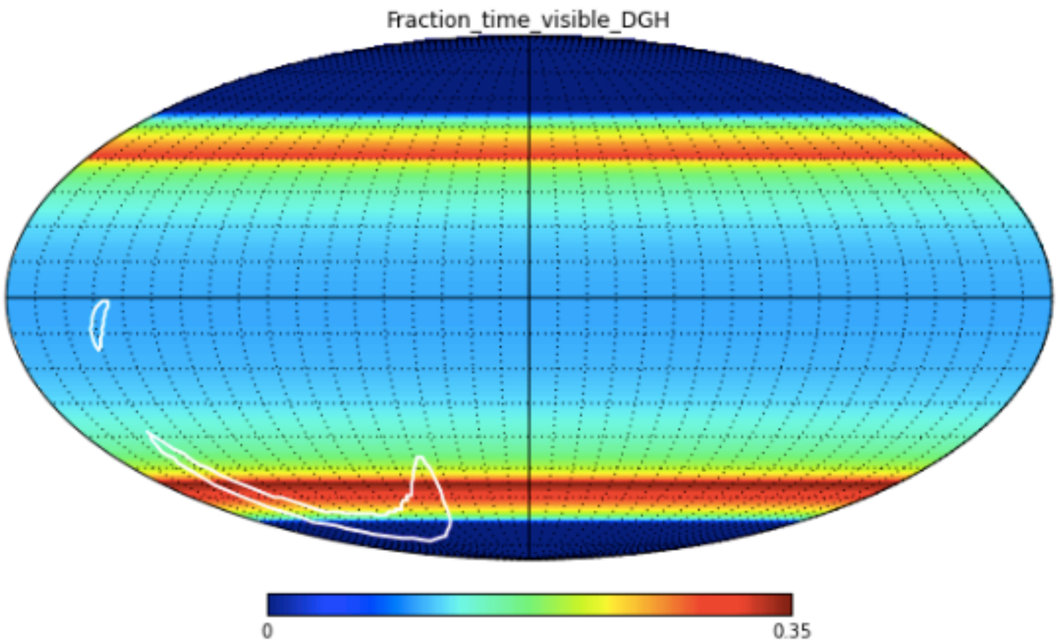
Neutrino Search for GW150914

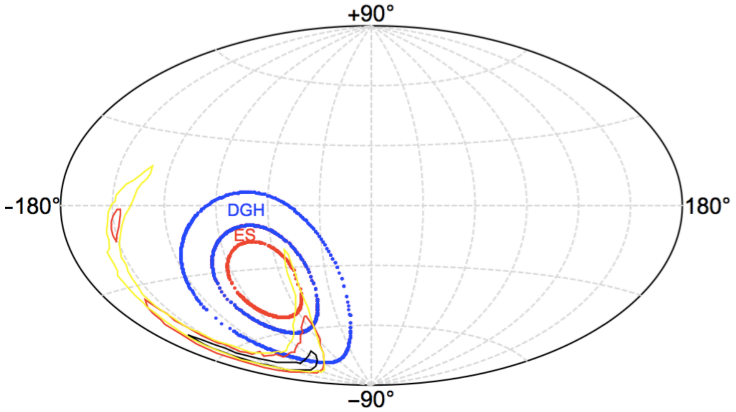
No neutrino candidates found
in any of the data periods unblinded

- Data **+/- 500 s** around GW150914 (09:50:45 UTC):
  – No inclined events found in ES selection
  – No inclined events found in DGH (75° -- 90°) selection

- Data **1 day after** GW150914:
  – 12 inclined events found in ES selection, none passed young shower selection => no candidates
  – 24 inclined events found in DGH (75° - 90°), none passed young shower selection => no candidates

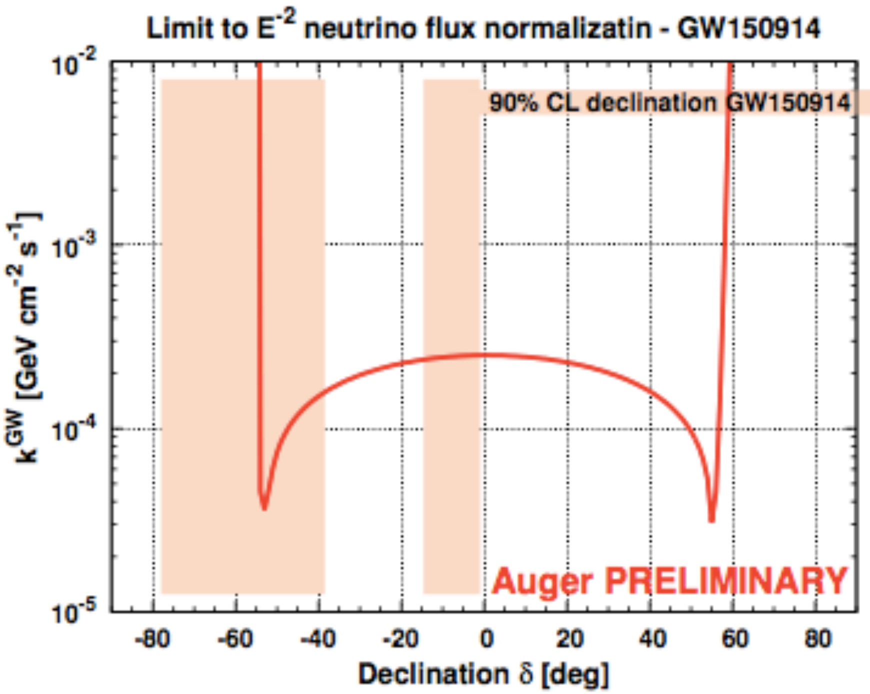


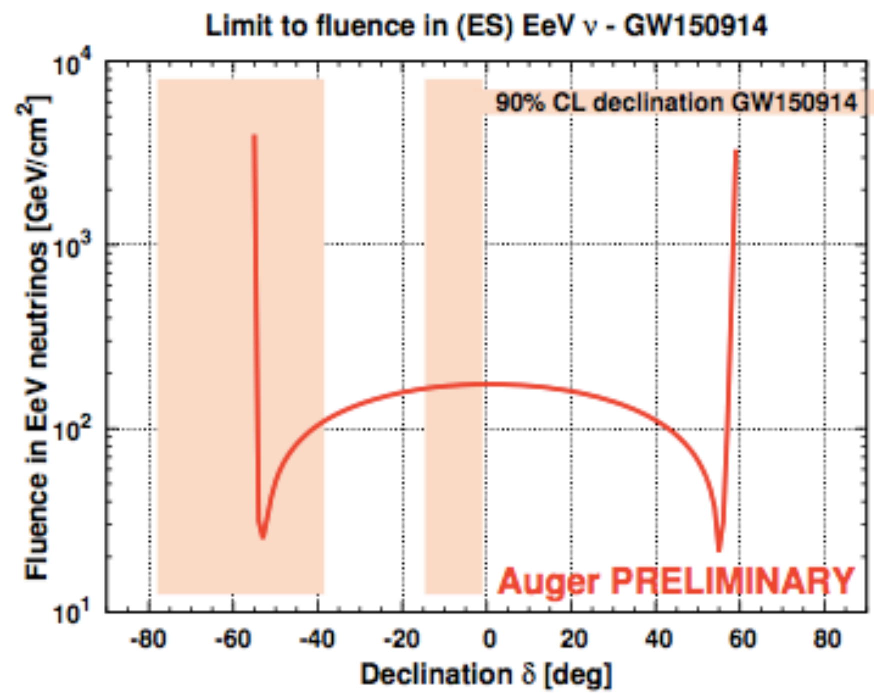




Both 90% CL declination ranges overlap with the field of view of the ES and DGH channels for fractions of 1 sidereal day that can reach up to ~ 17% and ~ 35% respectively.

Limit to fluence





Values above the red line are excluded at 90% CL from the non-observation of neutrino events in Auger.

Declination bands of the 90% CL position of the GW150914 are shown as shaded rectangles.

$$\mathcal{F}_\nu(\delta) = \left[\int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{dN_\nu^{\mathrm{GW}}}{dE_\nu}\, dE_\nu\right] \times \Delta t = \left[\int_{E_\nu^{\min}}^{E_\nu^{\max}} E_\nu \frac{k^{\mathrm{GW}}(\delta)}{E_\nu^2}\, dE_\nu\right] \times \Delta t$$

Summary

- Updated limits to point-like sources of UHE neutrinos:
  - Sensitivity to large fraction of sky
  - Best limits to n flux at EeV in particular to CenA

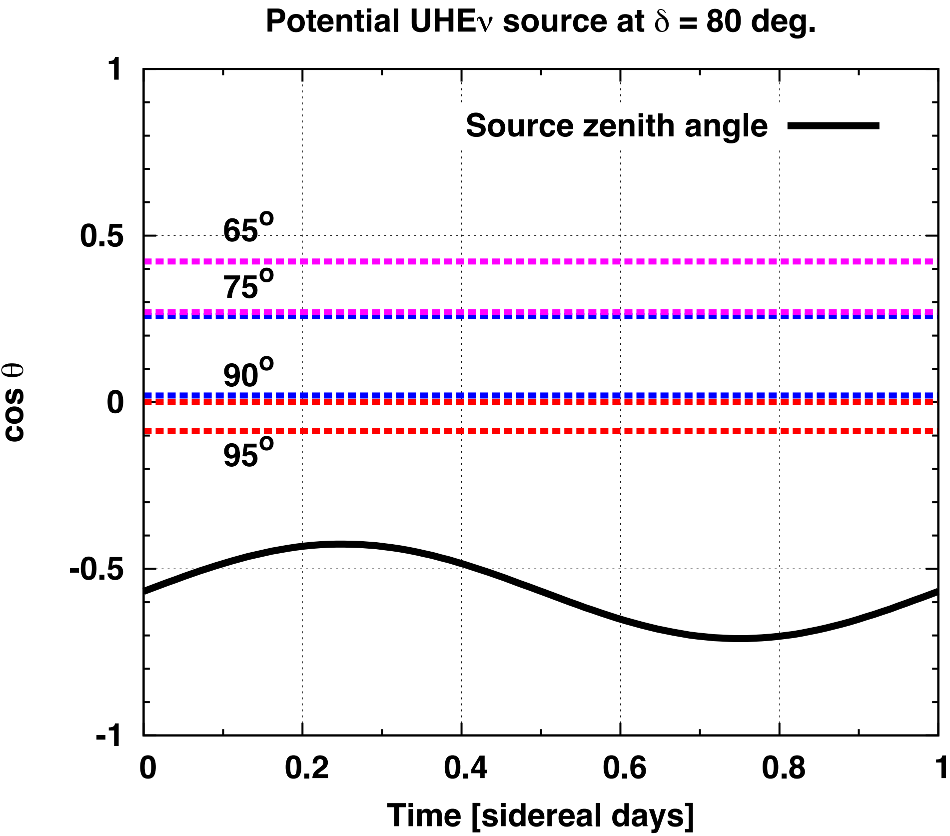
- Preliminary limits to GRB neutrino fluence:
  - Best limits to GRB fluence in the EeV range although still far from Waxman-Bahcall expectations.
  - Astrophysical implications on GRB to be explored

- No candidates observed within +/- 500 s and 1 day after GW150914 in Auger data. Observation of UHE neutrinos in coincidence with any future LIGO event would be a breakthrough !

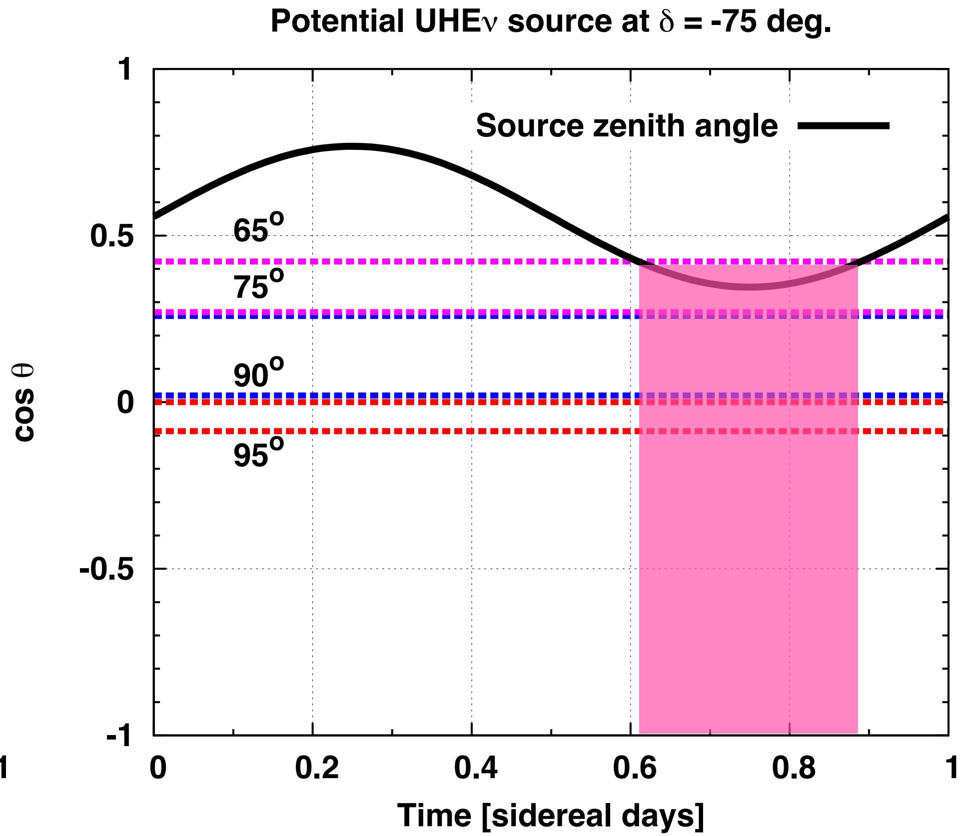
Back Up

Some sources NOT seen in ES or DGH or DGL

Source too close to the North Pole (NOT seen in ES, DGH or DGL)



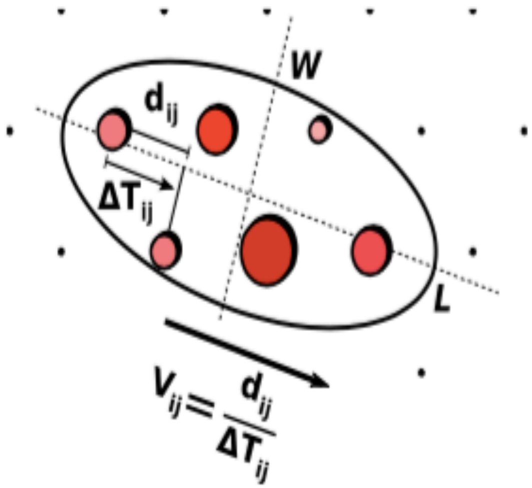
Source too close to the South Pole (only seen in DGL)



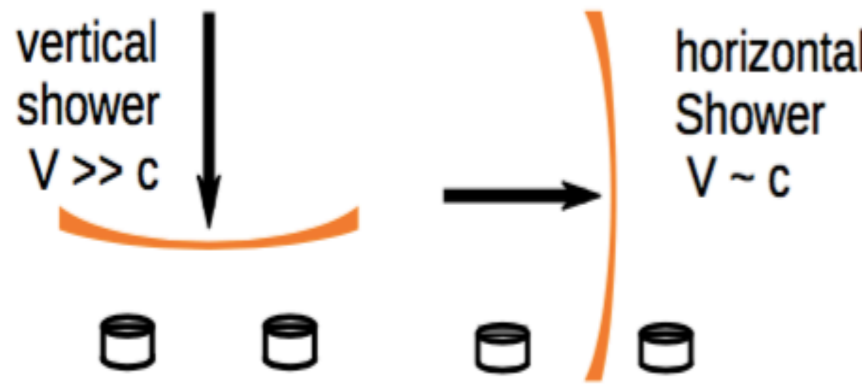
$$\cos\theta = \sin l \sin\delta + \cos l \cos\delta \sin(2\pi\,\mathrm{t} + \varphi)$$

Selection of inclined events

(1) Elongated footprint



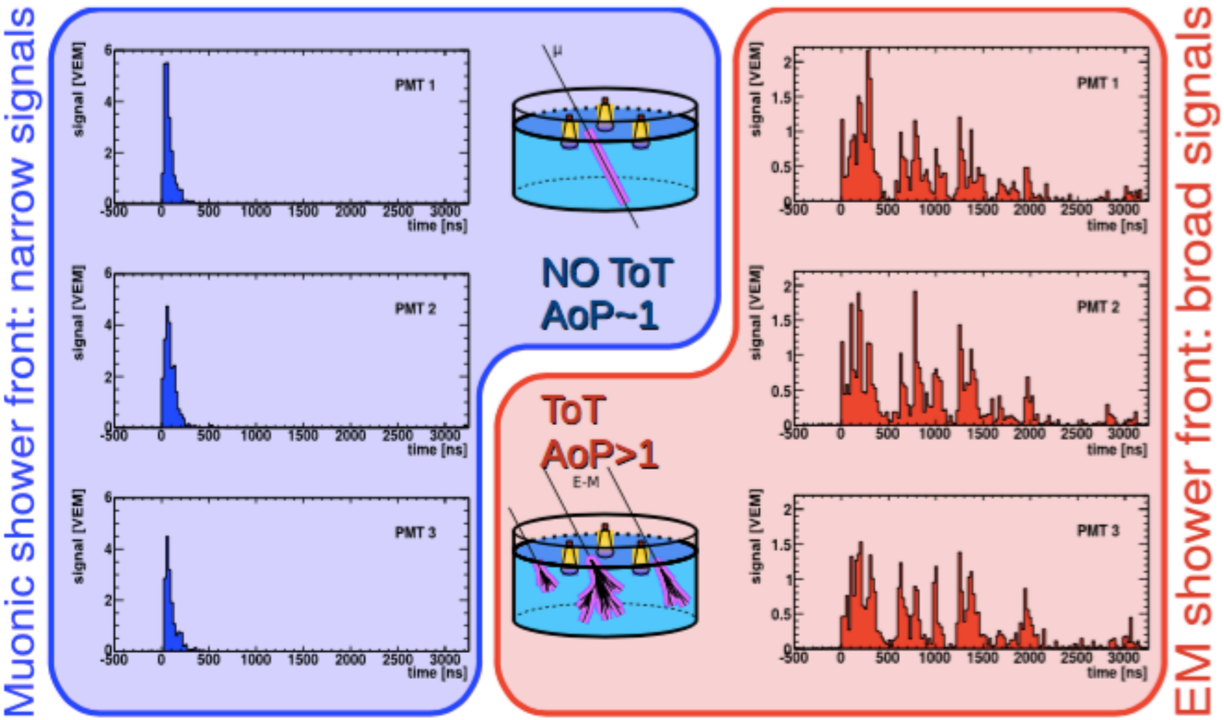
(2) Apparent velocity V of propagation of the shower front along major axis L

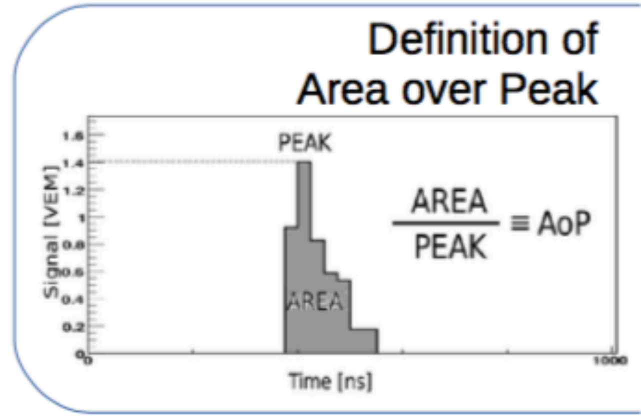


(3) Reconstructed zenith angle

	Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$	Down-going Low $(65°, 75°)$
(1)	$L/W > 5$	$L/W > 3$	–
(2)	$\langle V \rangle \in (0.29,\ 0.31)$ m ns^{-1}	$\langle V \rangle < 0.313$ m ns^{-1}	–
	$\mathrm{RMS}(V) < 0.08$ m ns^{-1}	$\mathrm{RMS}(V)/\langle V \rangle < 0.08$	–
(3)	–	$\theta_{\mathrm{rec}} > 75°$	$\theta_{\mathrm{rec}} \in (58.5°,\ 76.5°)$

Identifying electromagnetic shower fronts





Select stations with:

- Time-over-Threshold (ToT) trigger

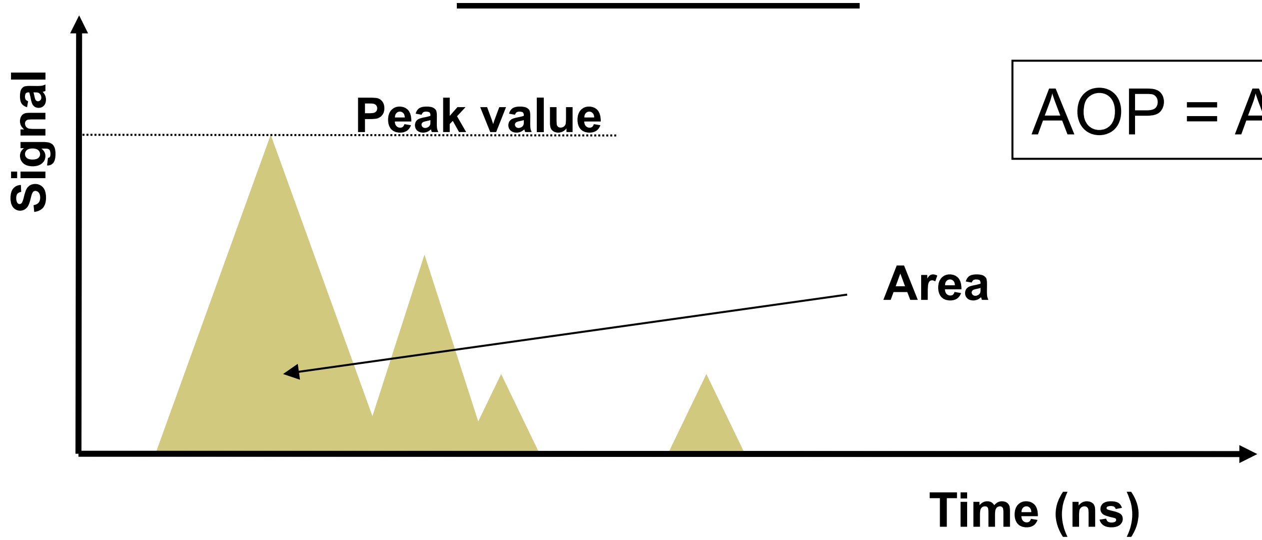
AND/OR

- Large Area-over-Peak (AoP)

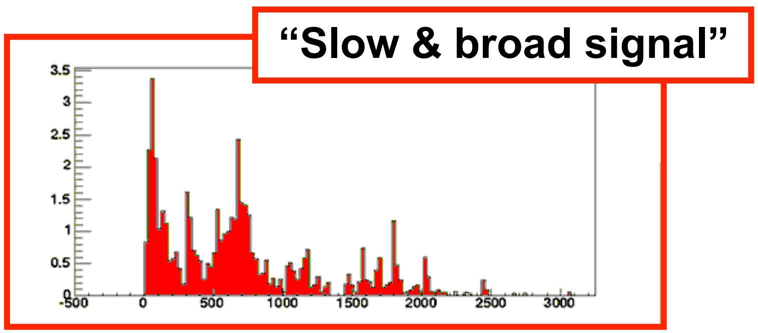
Using the time structure of signals in WCDs, search for signals extended in time. 7

Looking for broad signals: Area Over Peak (AOP)

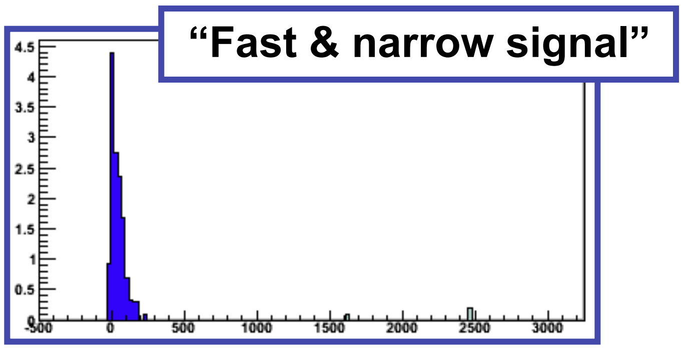
FADC trace



AOP = Area/Peak

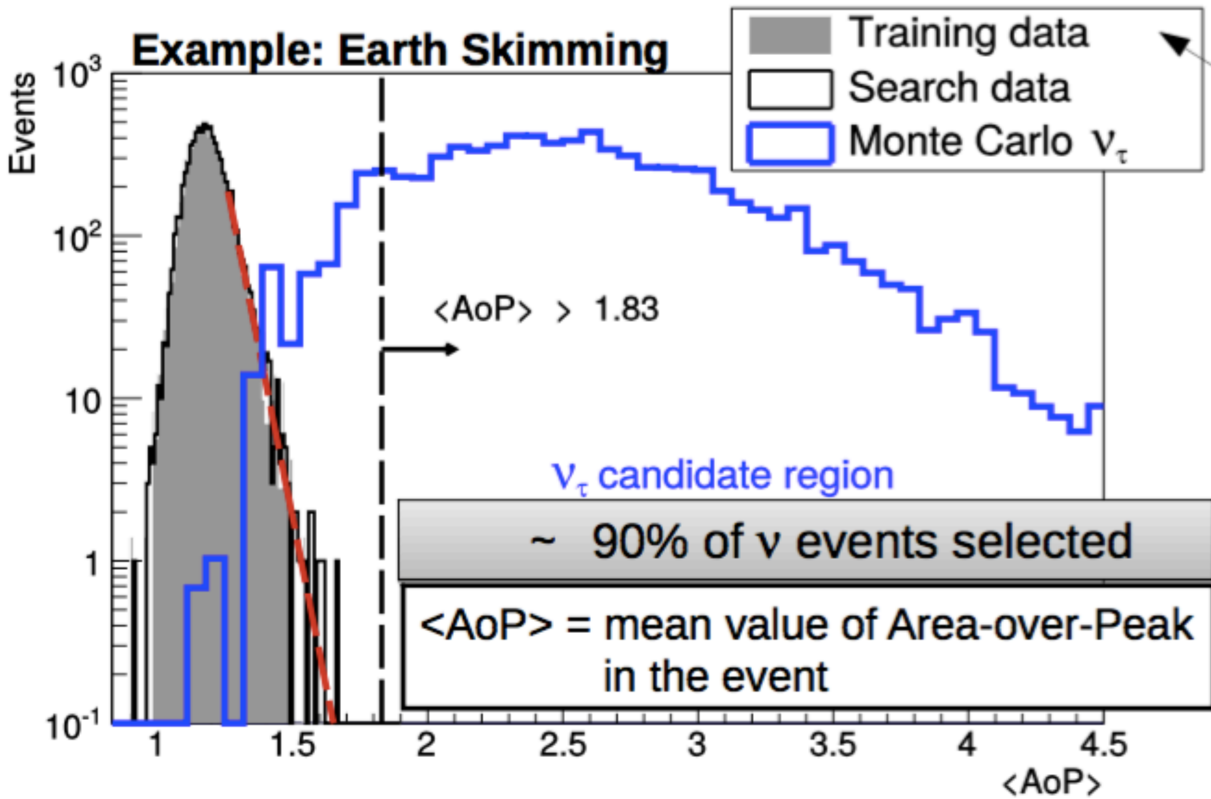


Large AOP (> 3)



Small AOP (~ 1)

Identification of UHE neutrinos in Auger data

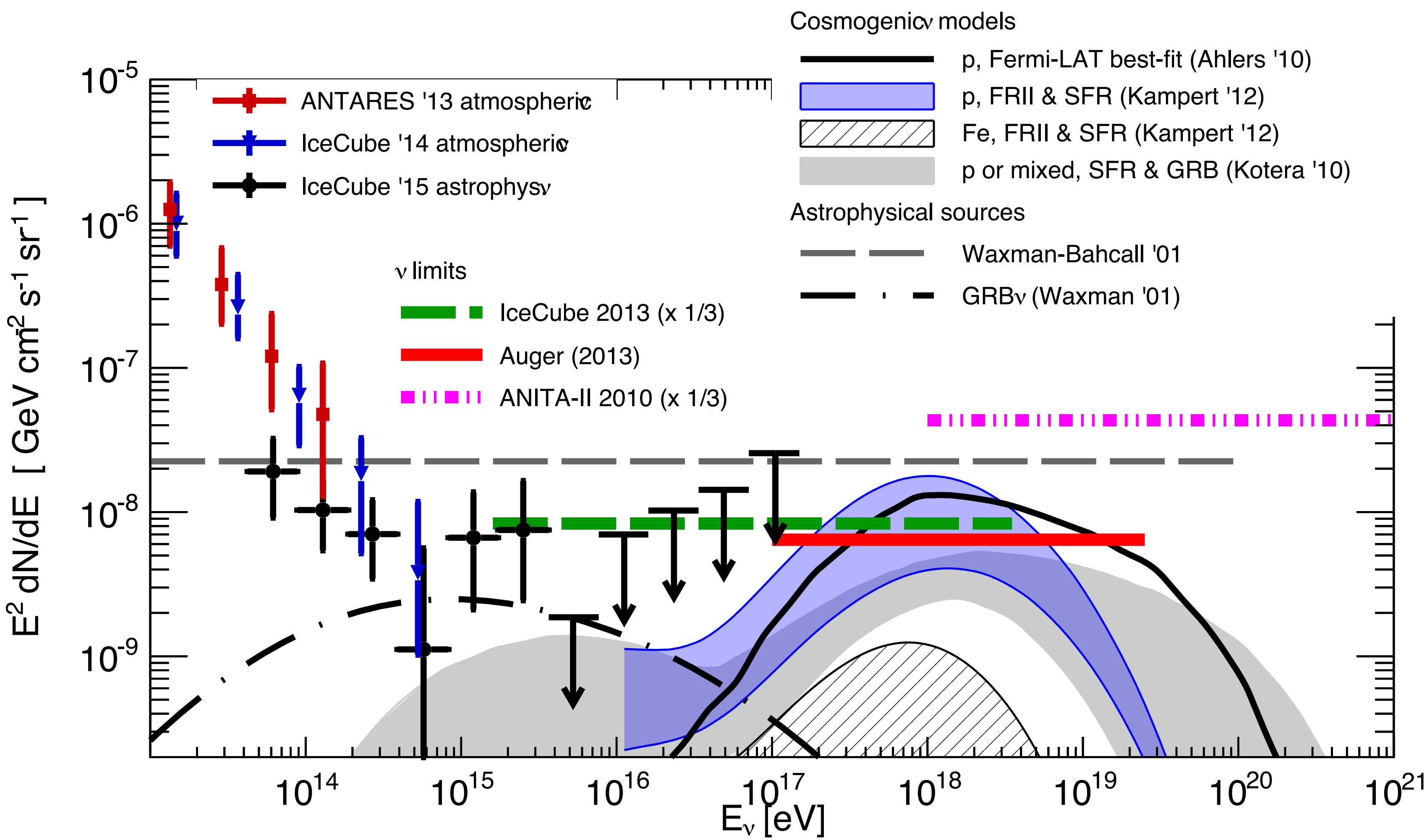


~20% of the data are used to estimate the expected background

Data taking:
01/01/04 – 20/06/13

Identification criteria applied "blindly" to the search data set
=> No candidates found in Earth Skimming or Downward-going

ν fluxes: data, limits & models



Take home message & outlook

- Updated limits to point-like sources of UHE neutrinos:
  - Sensitivity to large fraction of sky
  - Best limits to ν flux at EeV in particular to CenA
  - Limits complementary to those of IceCube

- Preliminary limits to GRB neutrino fluence:
  - Best limits to GRB fluence in the EeV range although still far from Waxman-Bahcall expectations.
  - Astrophysical implications on GRB to be explored

- Paper on point-like sources & GRB planned.

Times in 1 sidereal day a source is seen with large θ

Source too close to the North Pole (NOT seen in ES, DGH or DGL)

Source too close to the South Pole (only seen in DGL)

Weight with effective detection area $\cos\theta\, A_{eff}(t,\theta)$ and probabilities of tau production & decay (ES only)

Integrate in time only when the source is visible.

Assuming a ν flux: $dN/dE = k\, E^{-2}$ $(cm^{-2}\, s^{-1})$

Obtain upper limit on normalization factor “k”

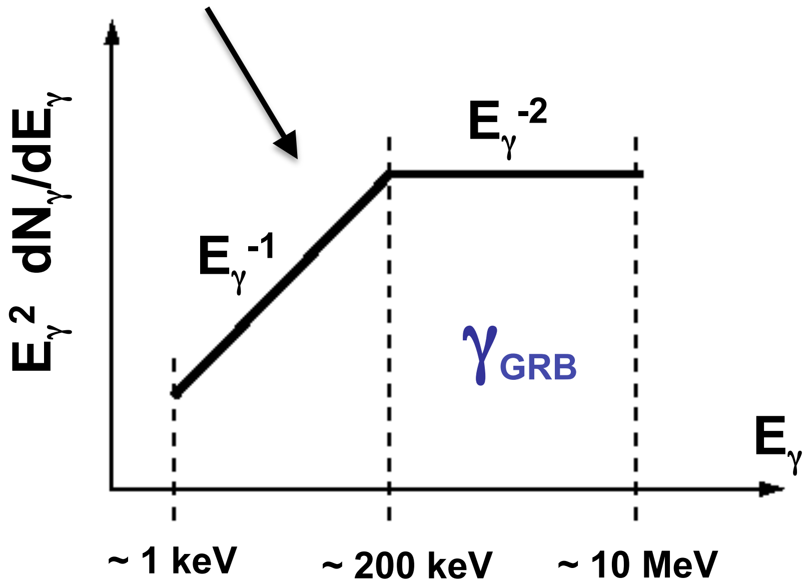
Repeat procedure as a function of declination δ

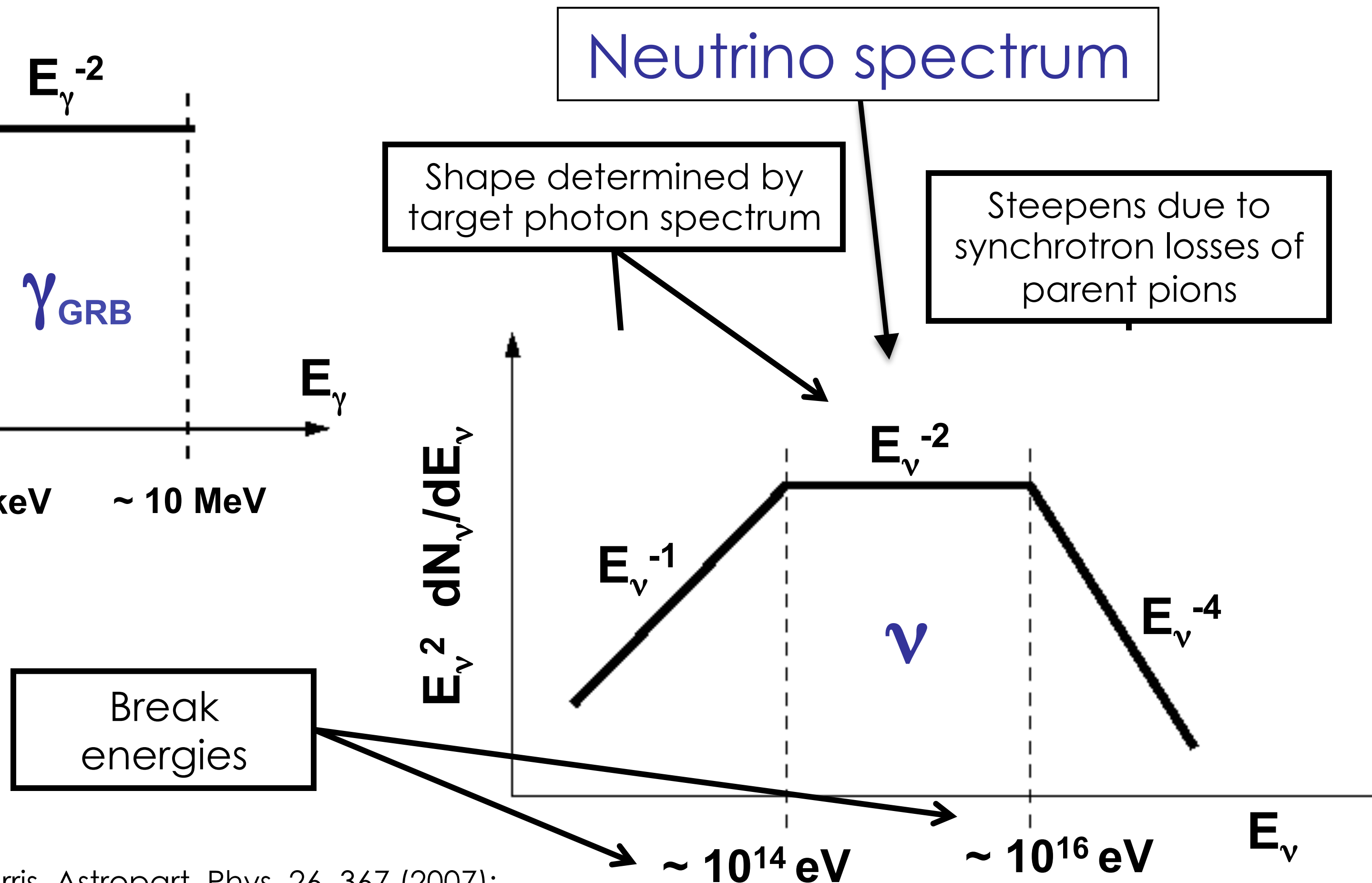
Neutrino spectrum

$p\,\gamma_{GRB} \rightarrow n\,\pi^{+} \rightarrow \nu{'}s$

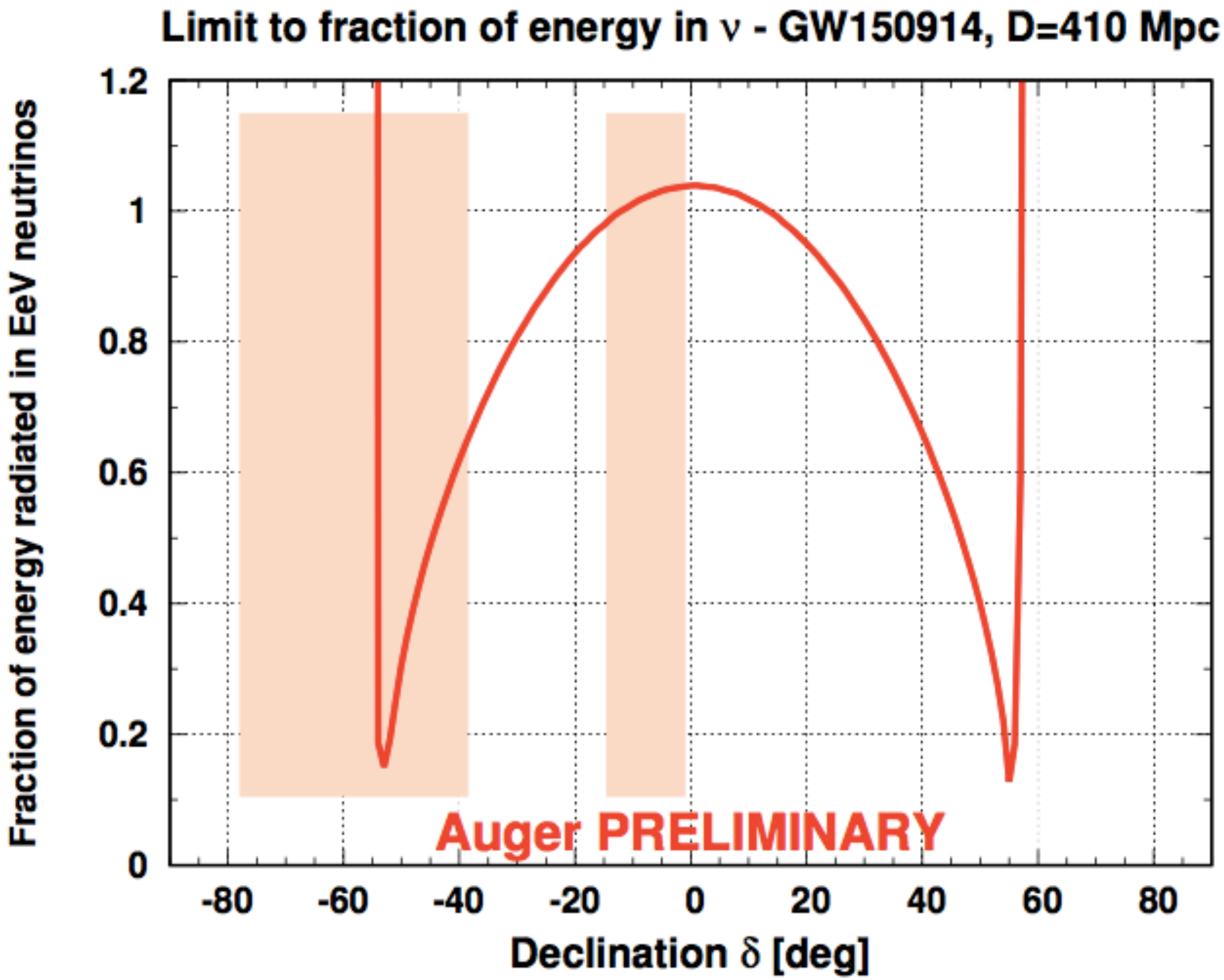
Projectile proton spectrum: E_p^{-2} (assumed)

Target photon spectrum: double power-law (measured)



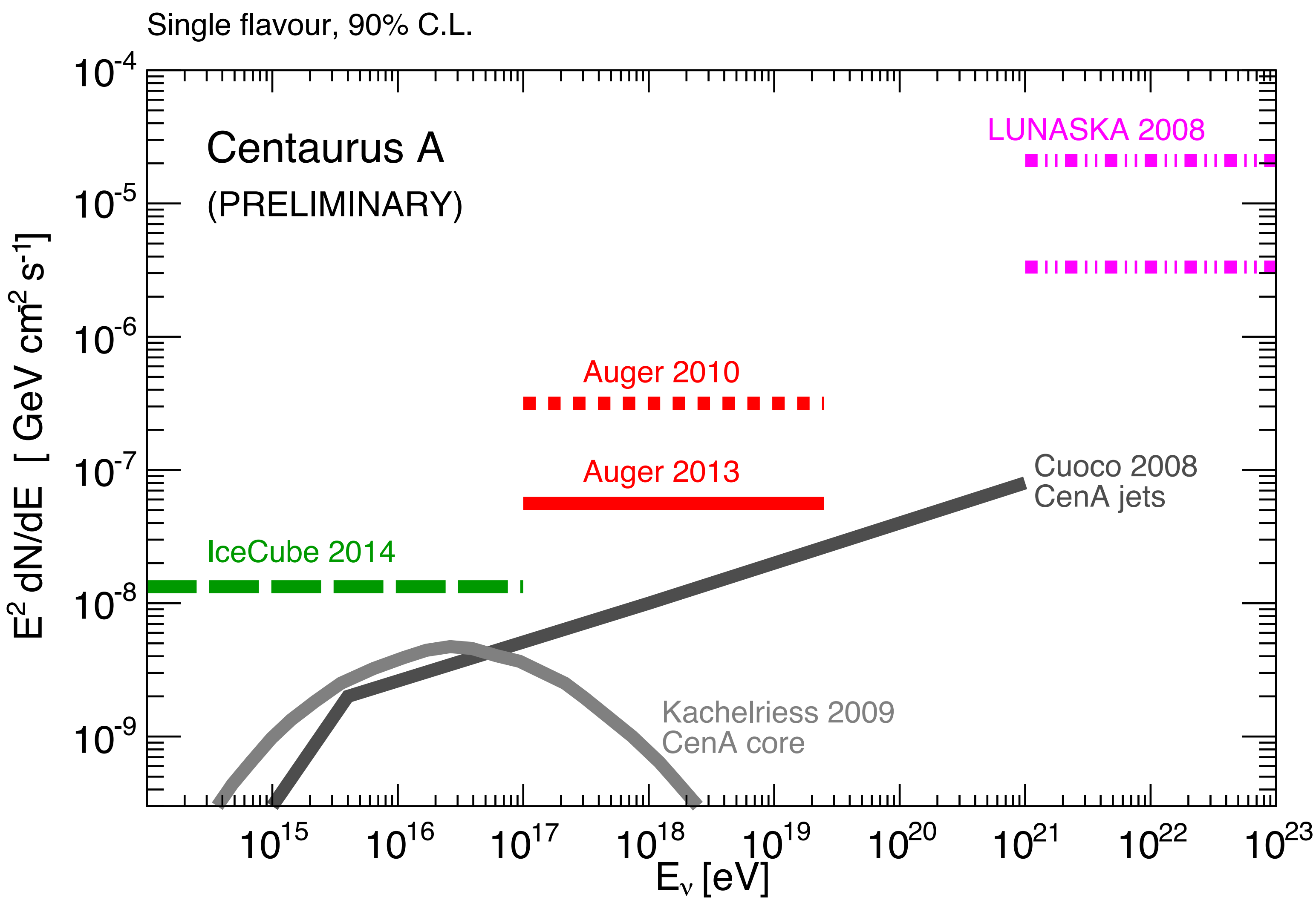


Besson, Razzaque, Adams, Harris, Astropart. Phys. 26, 367 (2007);
Guetta, Alvarez-Muñiz, Hooper, Halzen, Reuveni, Astropart. Phys. 20, 429 (2004)



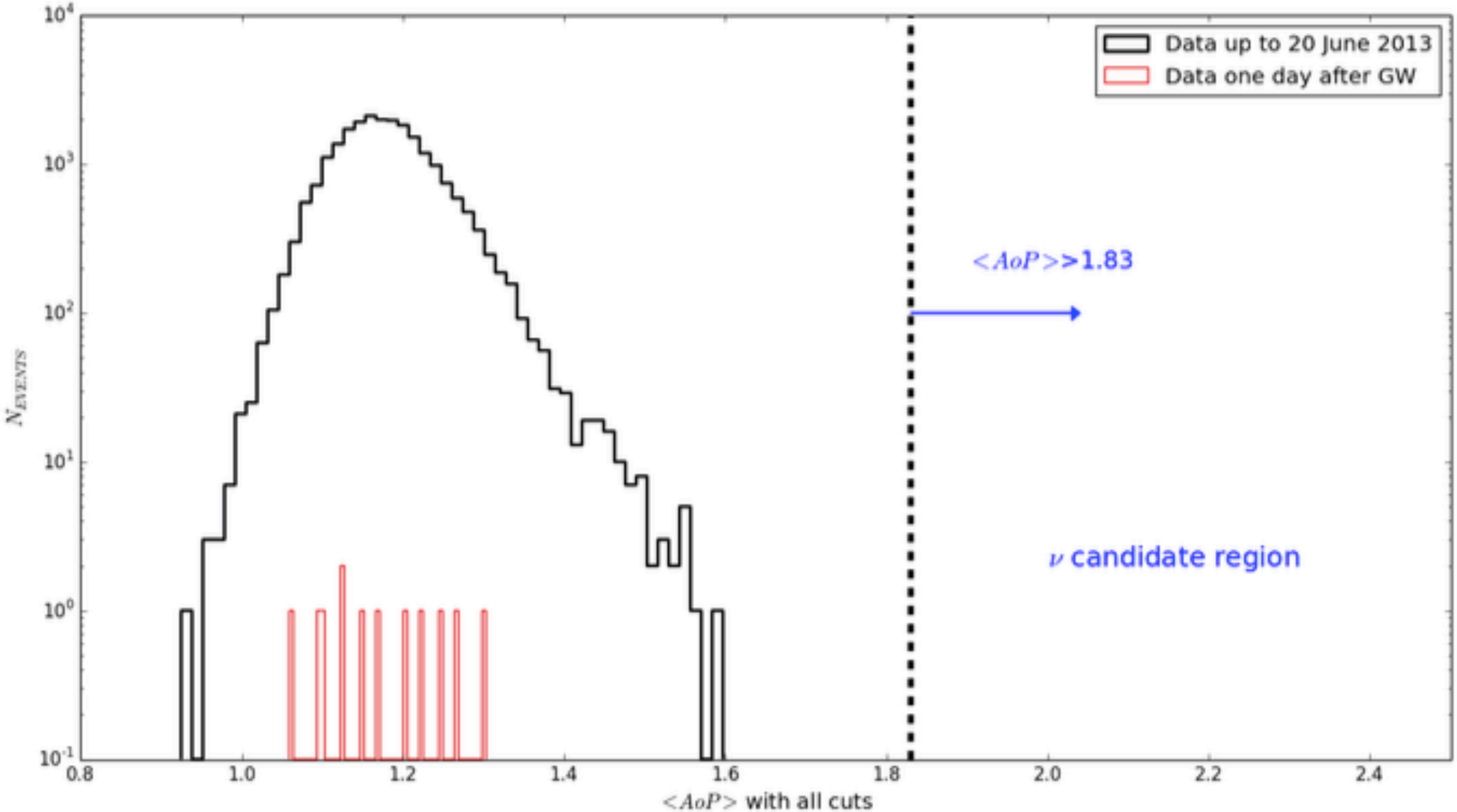
Limit to fraction of energy in ν - GW150914, D=410 Mpc
Fraction of energy radiated in EeV neutrinos
1.2
1
0.8
0.6
0.4
0.2
0
-80
-60
-40
-20
0
20
40
60
80
Declination δ [deg]
Auger PRELIMINARY

Limits to UHEν flux from Centaurus A



- Auger ⟶ best limit in the EeV energy range / complementary to IceCube
- Approaching models of UHEν production in CenA

UHE neutrino follow-up of GW150914



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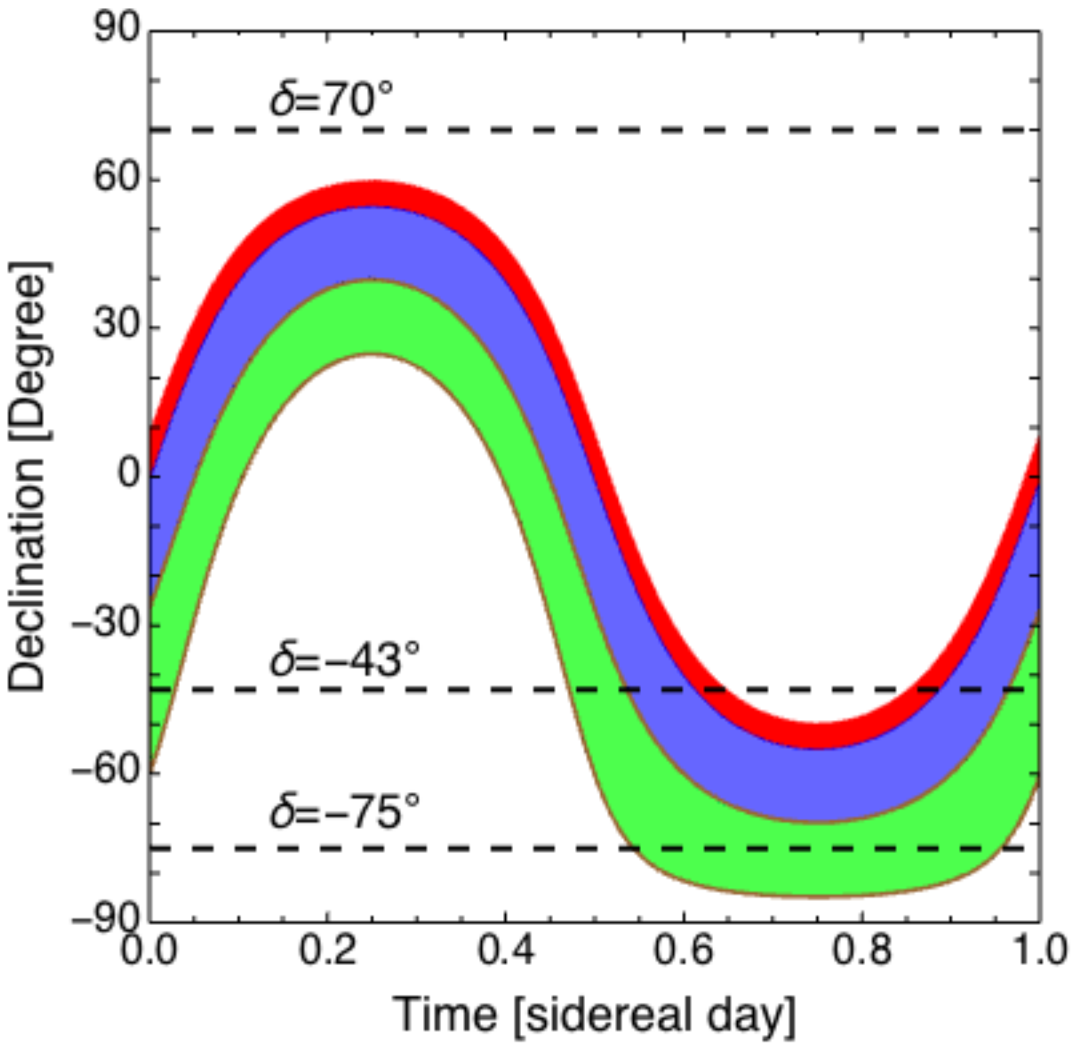

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$$\cos\theta = \sin l \sin\delta + \cos l \cos\delta \sin(2\pi \,\mathrm{t} + \varphi)$$

l ~ -35.2 latitude of Auger Obs.

Limits to flux of UHEν from GRB

- Short (T_{90} ~ 10^{-3} – 10^{3} seconds) flashes of gamma-rays with fluxes of ~ 0.1-100 photons/cm^2/s/keV
  - Long GRBs (T_{90} > 2s): collapse of massive stars to Black Holes
  - Short GRBs (T_{90} < 2 s): merging of binary compact objects

- Most powerful explosions in space:
  - visible across the universe
  - most luminous sources across the electromagnetic spectrum
  - afterglow lasts days.

- Rate ~10^{-7}/yr/galaxy

P. Meszaros, Ann. Rev. Astron. Astrophys. 40, 137 (2002).

$$E_{\nu,\mathrm{tot}}(\delta) = \mathcal{F}_\nu(\delta) \times 4\pi D_s^2.$$

$$E_{\mathrm{GW}} \simeq 3.0^{+0.5}_{-0.5} M_\odot c^2 \simeq 5.4^{+0.9}_{-0.9} \times 10^{54}\,\mathrm{erg},$$