Searches for Neutrinos and Cosmic-Ray Sources at Ultra-High Energies

Olivier Deligny, IPN Orsay,
CNRS/IN2P3 & Université Paris Sud

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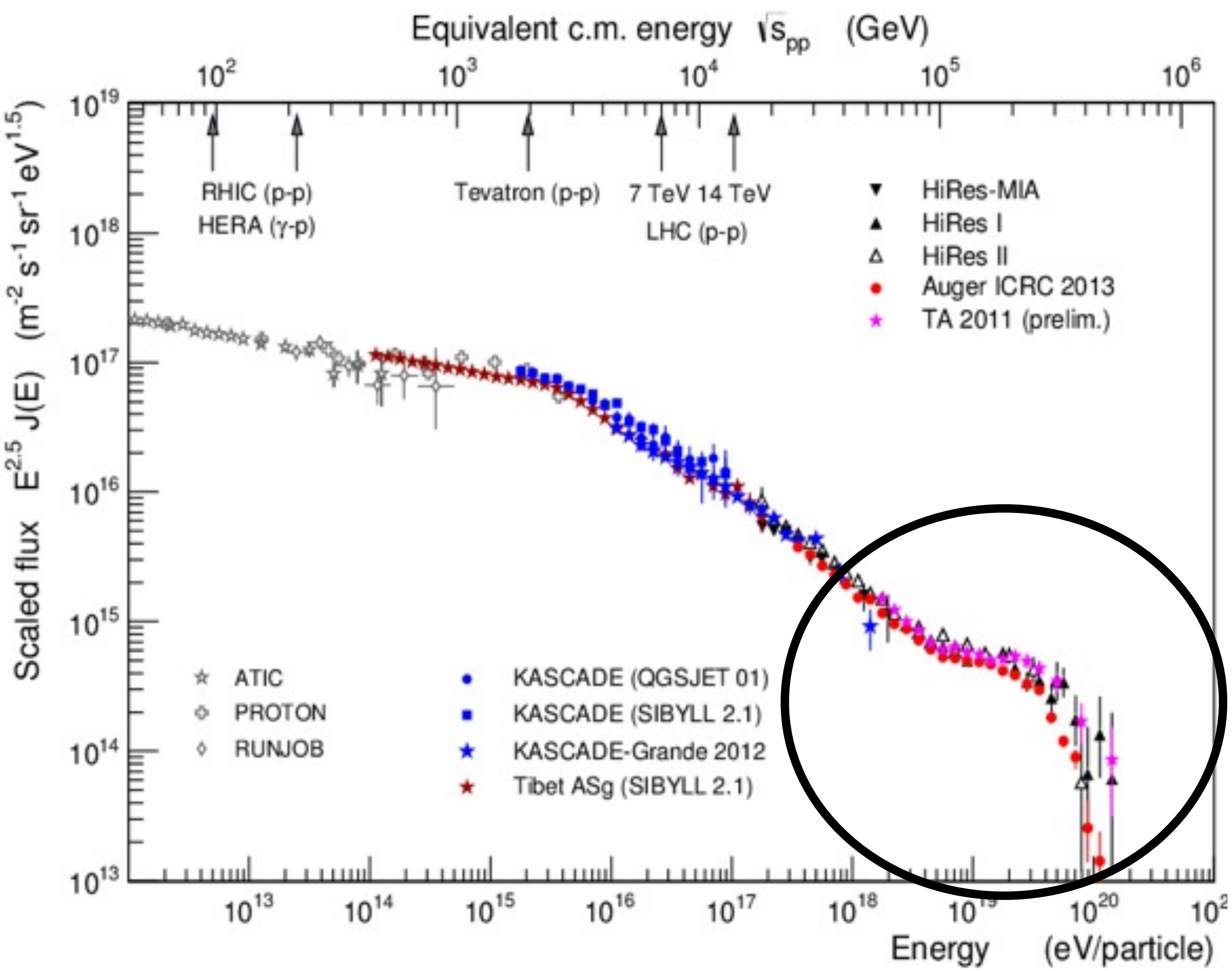
Ultra-High Energy Cosmic Rays



Contemporary questions:

- Gal/Xgal transition ?
- Origin of the ankle ?
- Origin of the UHE suppression ?
- Composition at UHE ?
- Sources ?

➡ UHECRs + CMB ⇒ cosmogenic neutrinos

➡ Implications for CRs from a «multi-messenger approach» ?

Cosmogenic Neutrinos

- <Ep>~1.6 10^{20} eV/(Eγ/10^{-3} eV) with <Eγ>~7 10^{-4} eV for CMB photons at z=0

➡ Production through decay of pions:

$$p + \gamma_{2.7K} \rightarrow \Delta(1232) \rightarrow n + \pi^+ \nearrow \mu^+ + \nu_\mu \searrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\searrow p + \pi^0 \searrow \gamma + \gamma$$

➡ 3ν, Eν~5% Ep

➡ 2γ, Eγ~10% Ep

➡ Production through decay of neutrons:

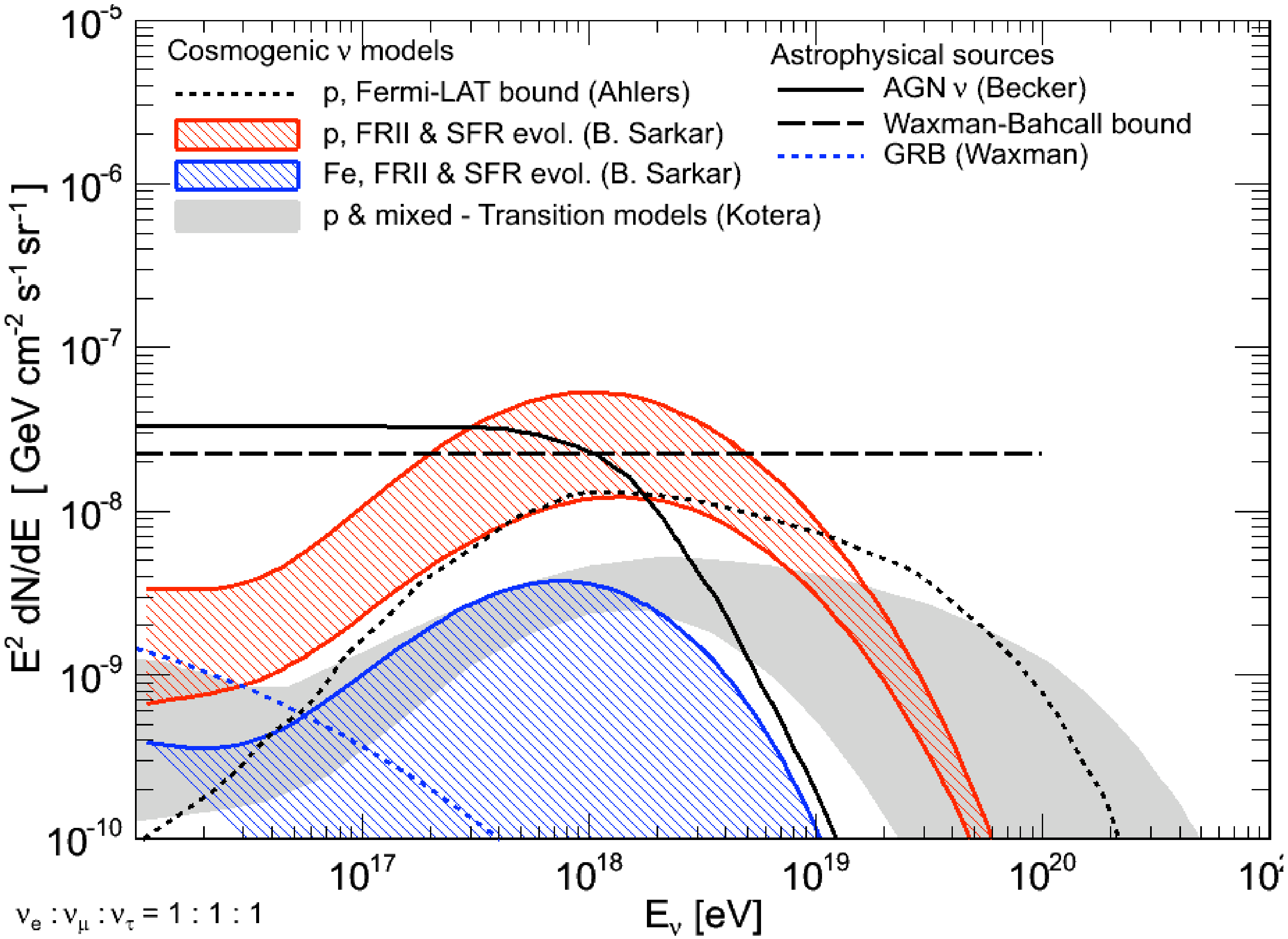
$$n \rightarrow p e \bar{\nu}_e$$ ➡ Eν~0,03% Ep

- Cosmological evolutions
  - ➡ Wide peak through pion decay around 1 EeV
  - ➡ Wide peak through neutron decay around few PeV

- Relationship between the two fluxes:

$$\left[E_\nu^2 \frac{\mathrm{d}\Phi_{\bar{\nu}_e}}{\mathrm{d}E}\right]^{n-dec,CMB}_{(E_{\bar{\nu}_e}=6\times10^{15}\ \mathrm{eV})} \simeq 6\times10^{-3}\left[E_\nu^2 \frac{\mathrm{d}\Phi_{\nu_\mu}}{\mathrm{d}E}\right]^{\pi-dec,CMB}_{(E_{\nu_\mu}=10^{18}\ \mathrm{eV})}$$
$$\simeq 2\times10^{-3}\left[E_\nu^2 \frac{\mathrm{d}\Phi_{\mathrm{all}\ \nu}}{\mathrm{d}E}\right]_{(E_\nu=10^{18}\ \mathrm{eV})}.$$

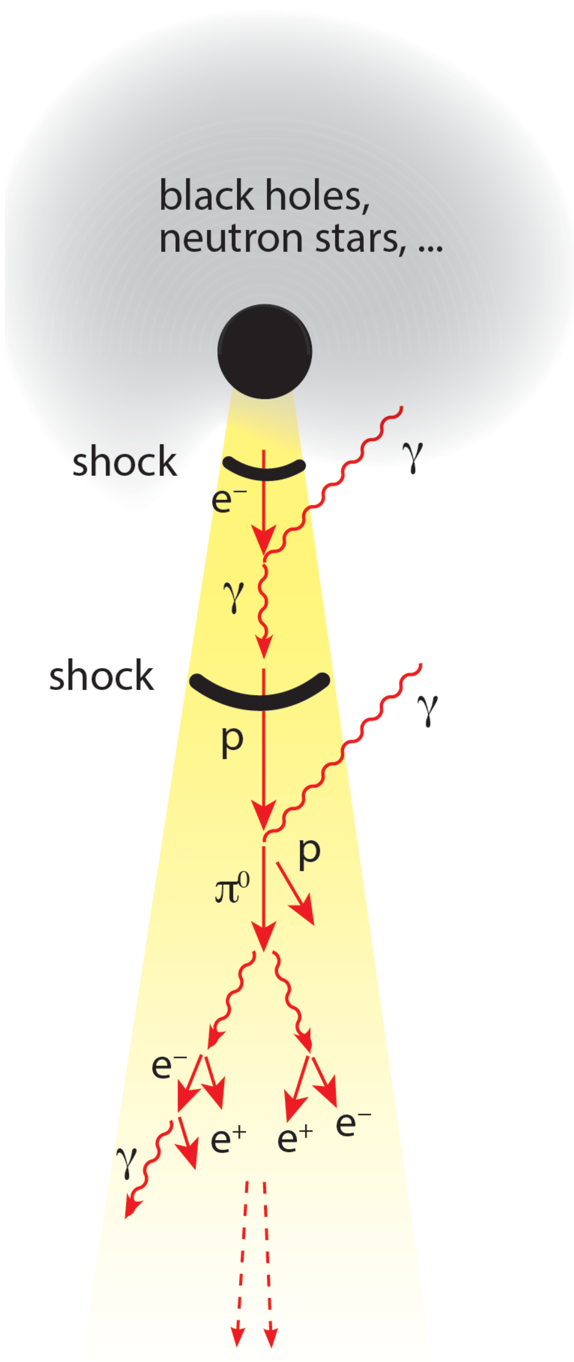
EeV-Cosmogenic Neutrinos



BUT Many «parameters»...

- Total emissivity in UHECRs
- Average acceleration spectrum
- Chemical composition of UHECRs
- Average maximum acceleration energy
- Cosmological evolution of UHECR sources

Astrophysical Sources of Neutrinos



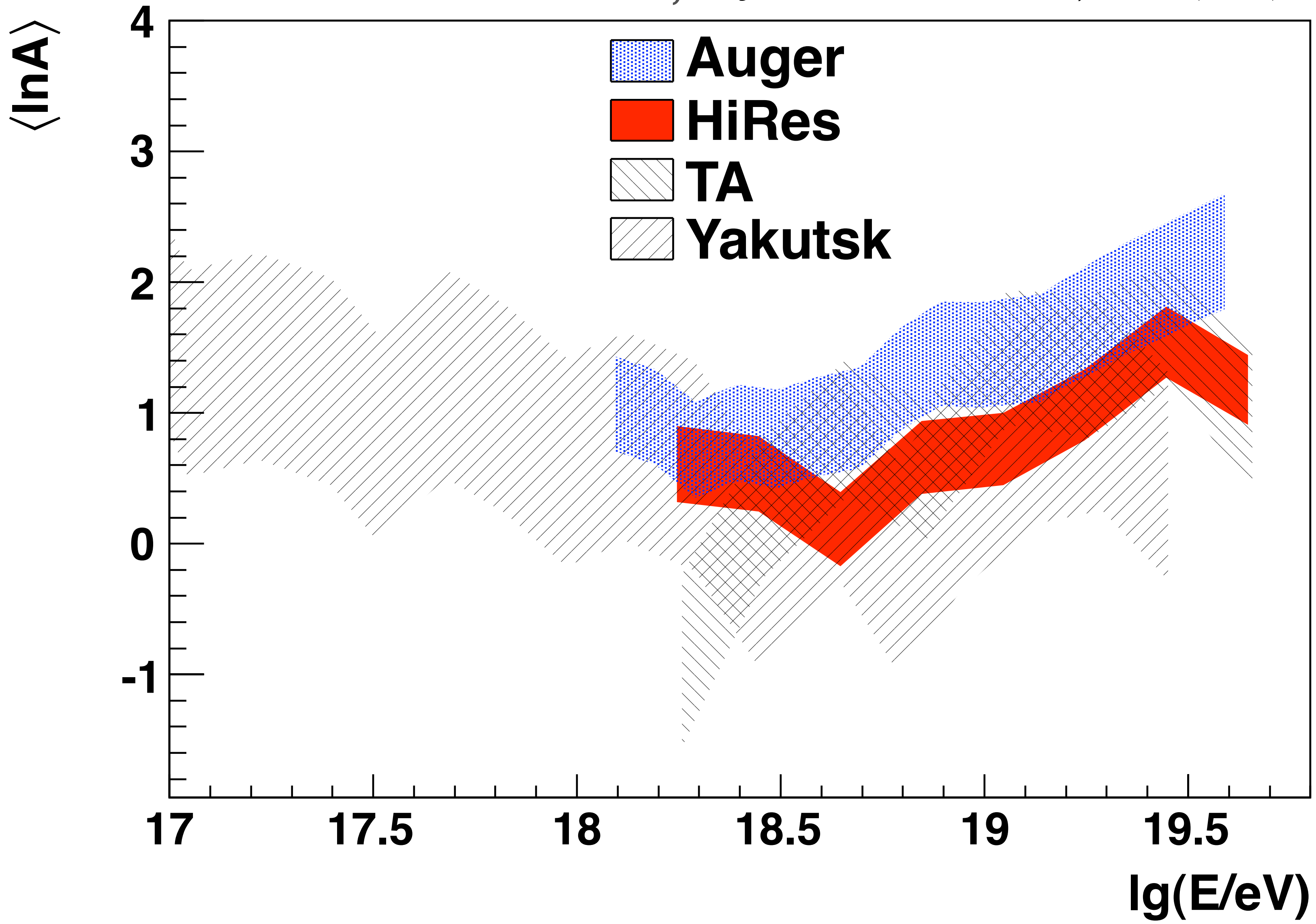
- Photons get attenuated > 100 TeV
- Charged CRs deflected in magnetic fields
- Neutrons decay

➡ ν: the ideal multi-messenger

- Travel unimpeded through the Universe
- Point back to Xgal sources
- Very distant sources
- Deep into opaque sources
- Detection of EeV neutrinos as indirect information on UHECR nature (p vs Fe)

UHECR Composition ?

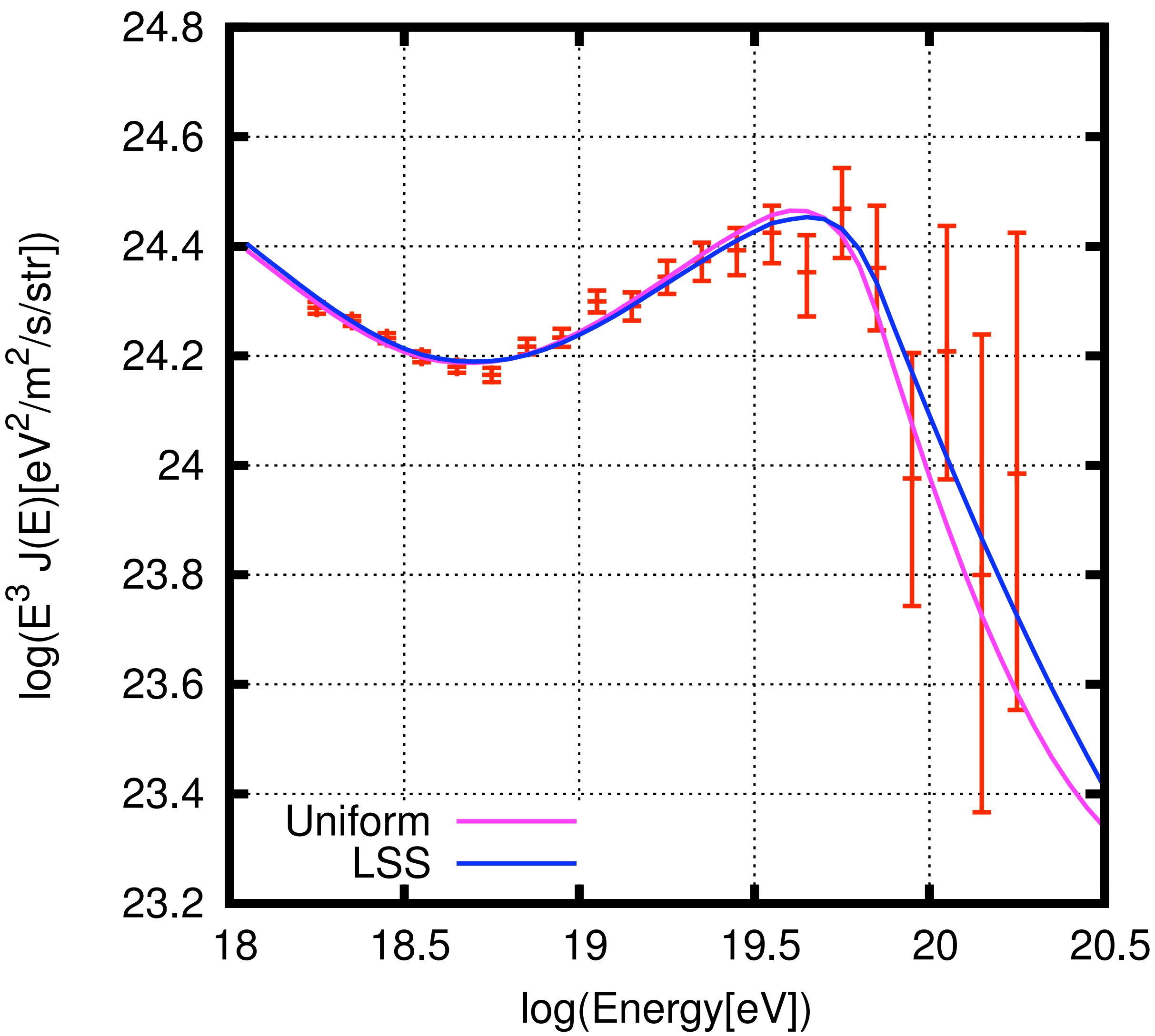
➡ Barcikowski et al., EPJ Web of Conferences 53, 01006 (2013)



- Light elements around EeV energies
- No consensus at UHE

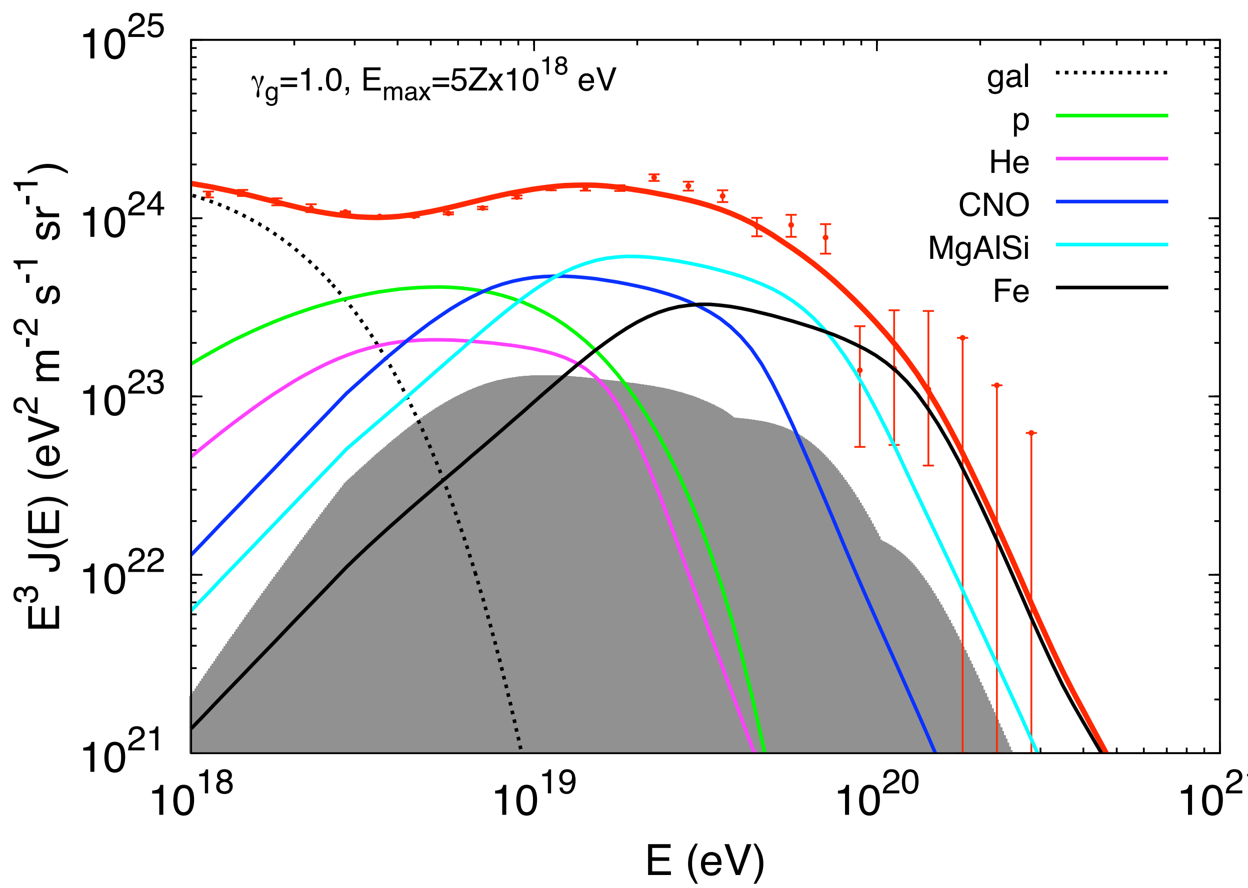
UHECR Composition, Implications

➡ Kido & Kalashev for TA 2013, ICRC 2013



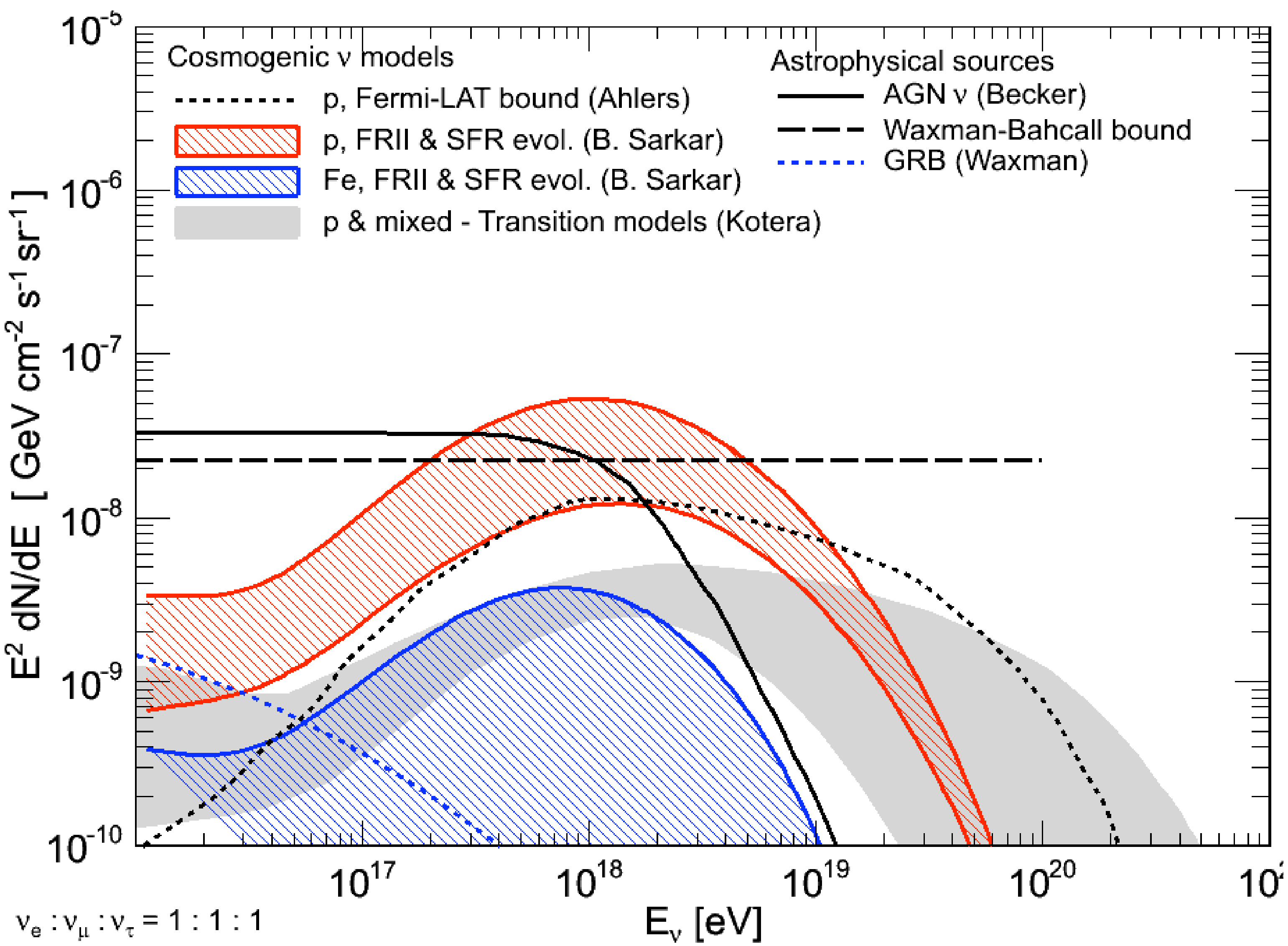
TA data, dip model

➡ Aloisio, Berezinsky & Blasi, arXiv:1312.7459



Auger data, rigidity-dependent maximum acceleration energy at the sources

UHECR Composition and UHE Neutrinos



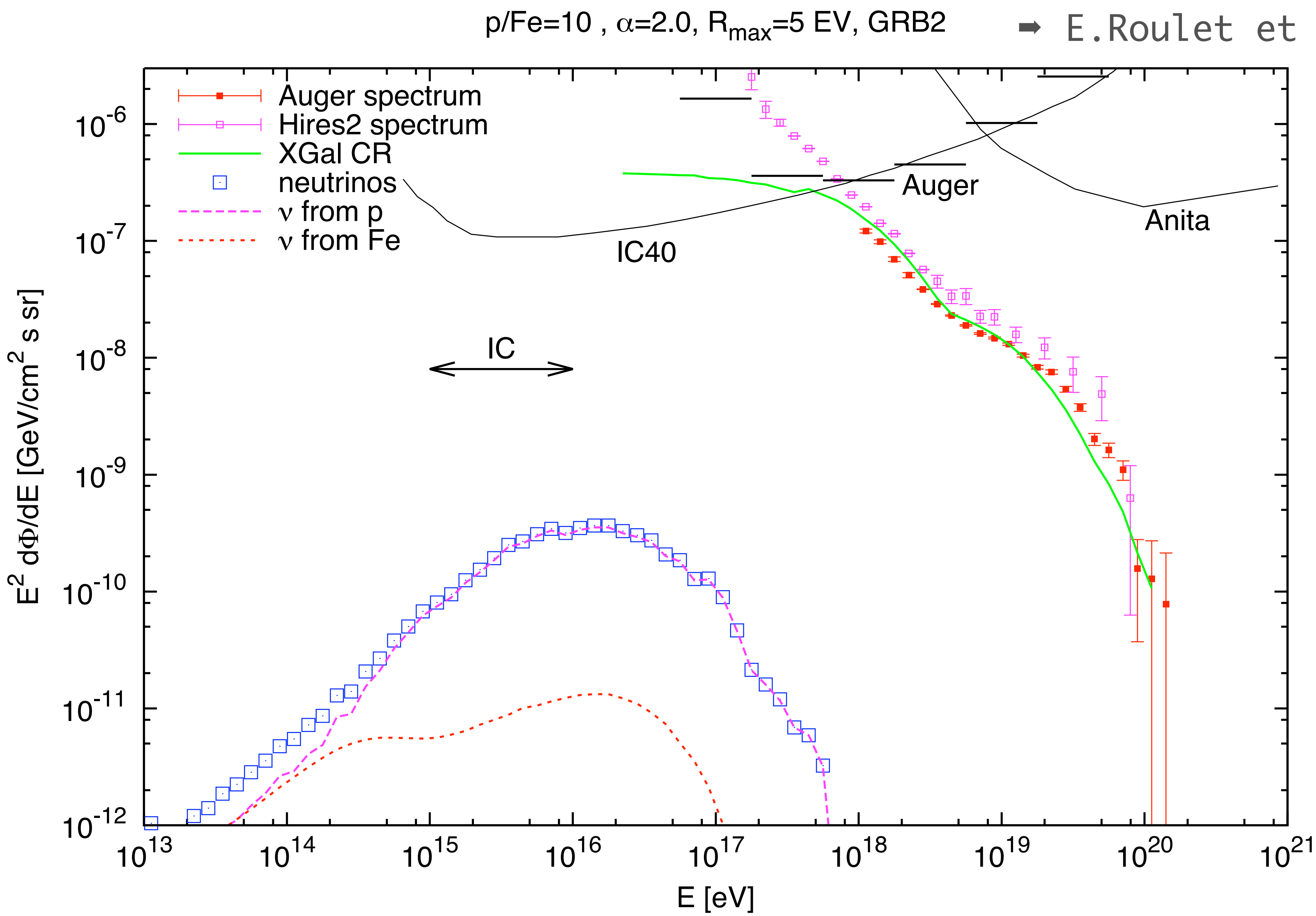
- Strong dependence of the EeV-cosmogenic flux with the CR composition at UHE
- Observation or non-observation of EeV-neutrinos would be an indirect tool to understand the CR composition at UHE

PeV-Cosmogenic Neutrinos

- <Ep>~1.6 10^{17} eV/(Eγ/eV) with UV/optical/IR photons

➡ Cosmogenic neutrinos from pion decay peaking around 8 10^{15} eV/(1+z)/(Eγ/eV)

➡ E.Roulet et al, JCAP 01(2013)028



➡ IC events interpretation in terms of cosmogenic neutrinos <u>unlikely</u>

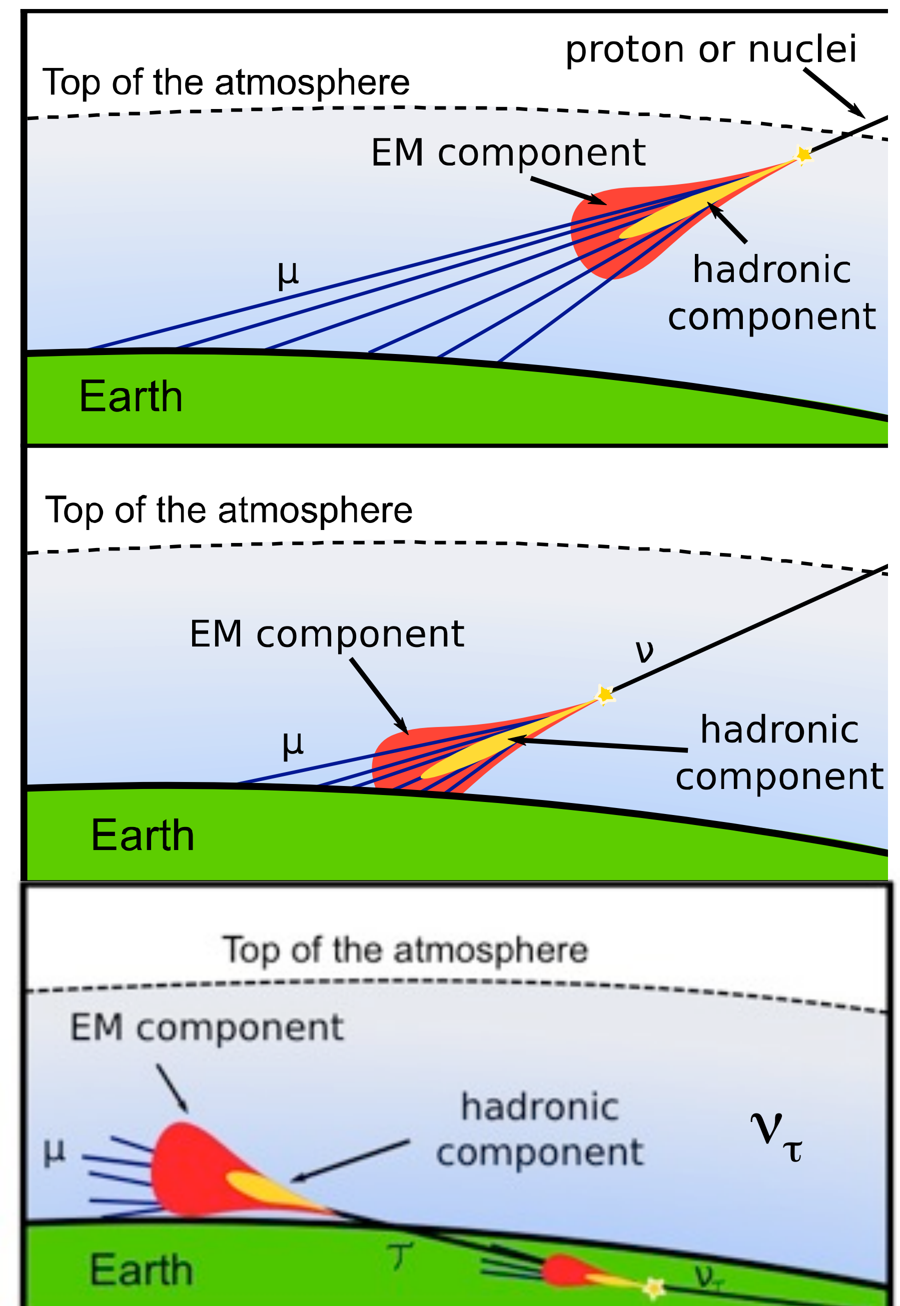
UHE Neutrinos: Current Searches with Ground Array of Particle Detectors

➡ Horizontal Air Showers

- CRs initiate showers high in the atmosphere
  - ➡ e.m. component absorbed in the atmosphere
  - ➡ Shower front composed mainly of muons
- Neutrinos can initiate <u>deep</u> showers
  - ➡ Shower front composed of μ+e.m. components

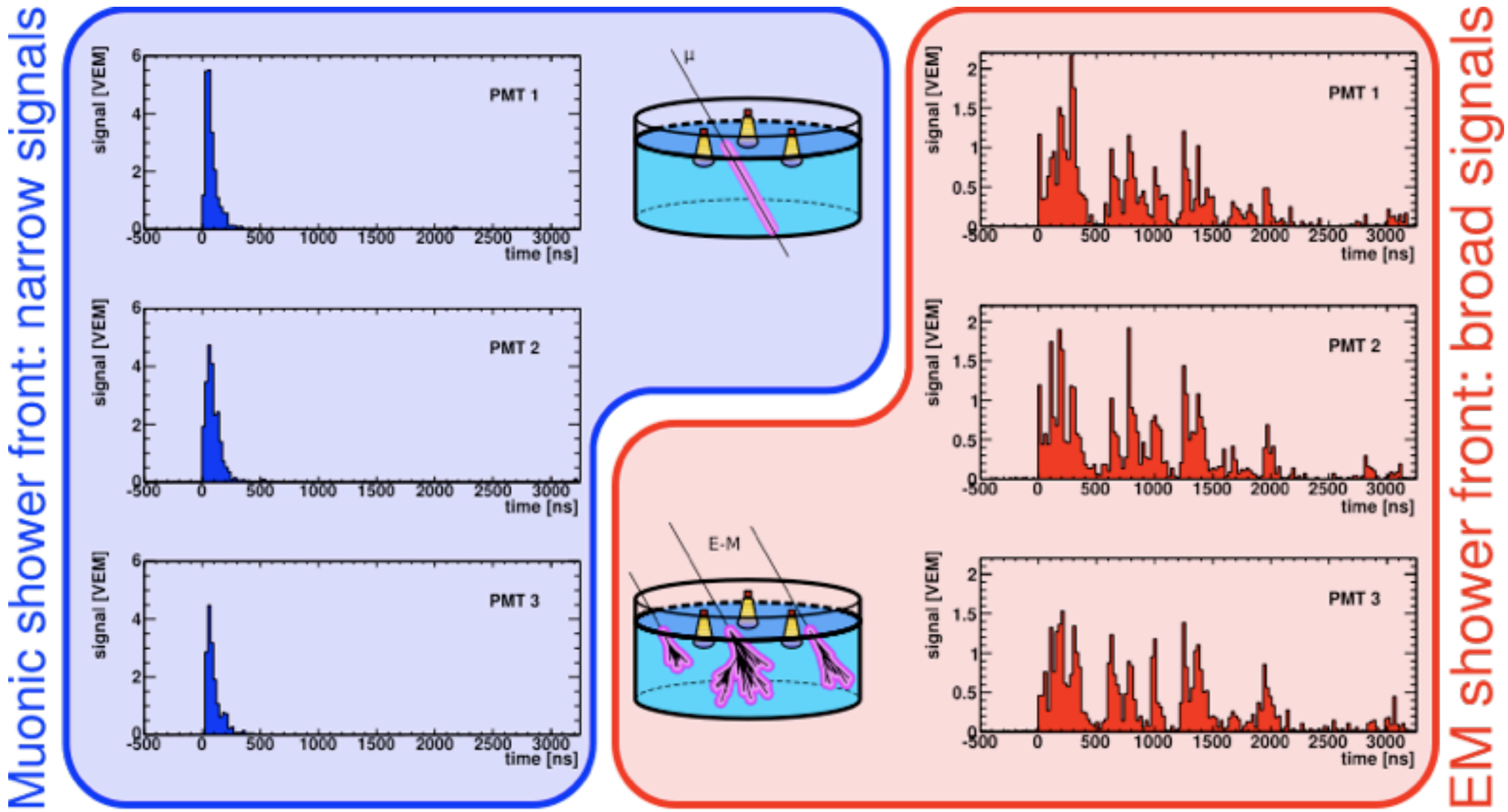
Searching for neutrinos ⇒

searching for inclined showers
with electromagnetic component



Water Cherenkov Detectors : Auger

➡ Distinguishing muonic from e.m. shower front from the time structure of the WCD signals



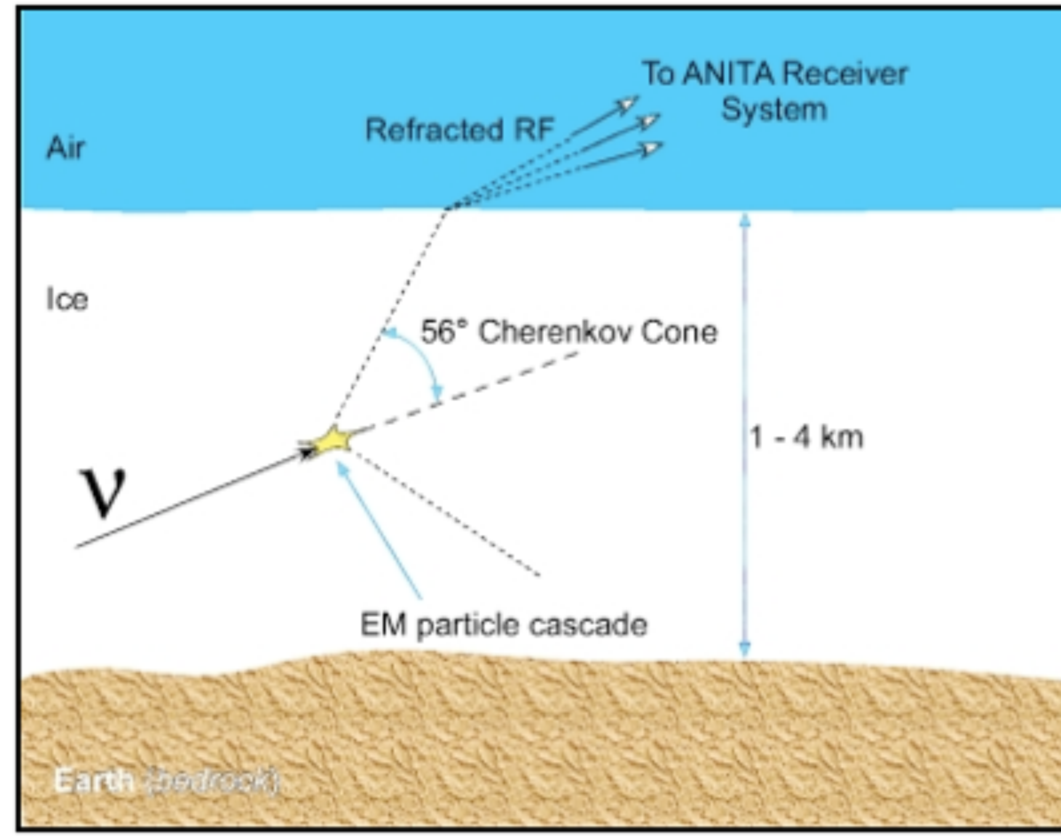
Radio-Detection: the Askaryan Effect

- e.m. cascade : Compton scattering of photons on atomic electrons induce negative charge excess of ~20%
- Negative charge radiates coherently at MHz-GHz => $P \sim E^2$
- Askaryan effect observed on ice at SLAC with 12-tons of ice + ANITA
- Ice is good for radio-detection of neutrinos: long radio attenuation lengths (1km for RF vs ~100m for optical signals used by IceCube)
- ANITA, TREND, ARIANNA, ARA, Greenland Neutrino Observatory, EVA

ANITA-I & ANITA-II

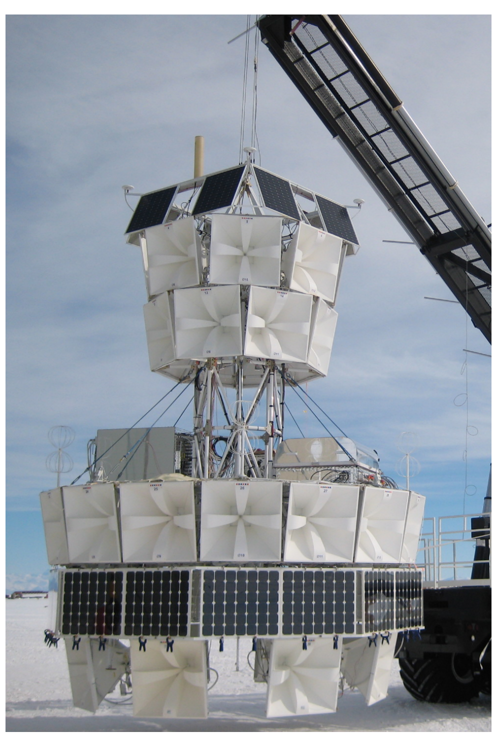
NASA long duration balloon
launched from Antarctica

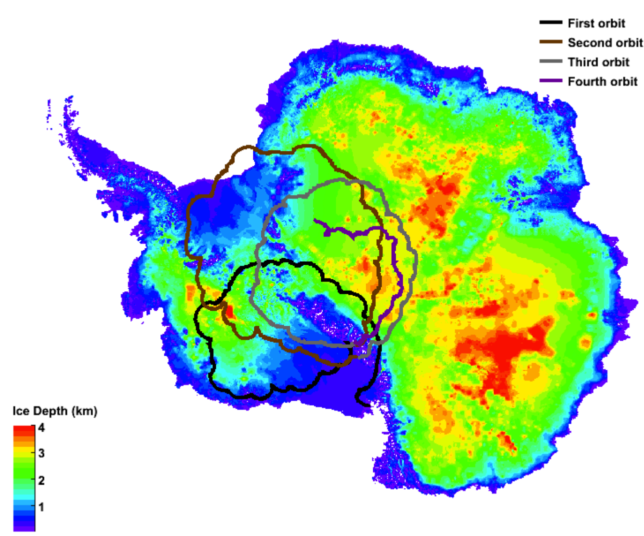
ANITA-I: 35 day flight 2006-07
ANITA-I: 30 day flight 2008-09



Instrument Overview:

- 40 horn antennas, 200-1200 MHz
- Direction calculated from timing delay between antennas
- In-flight calibration from ground
- Threshold limited by thermal noise



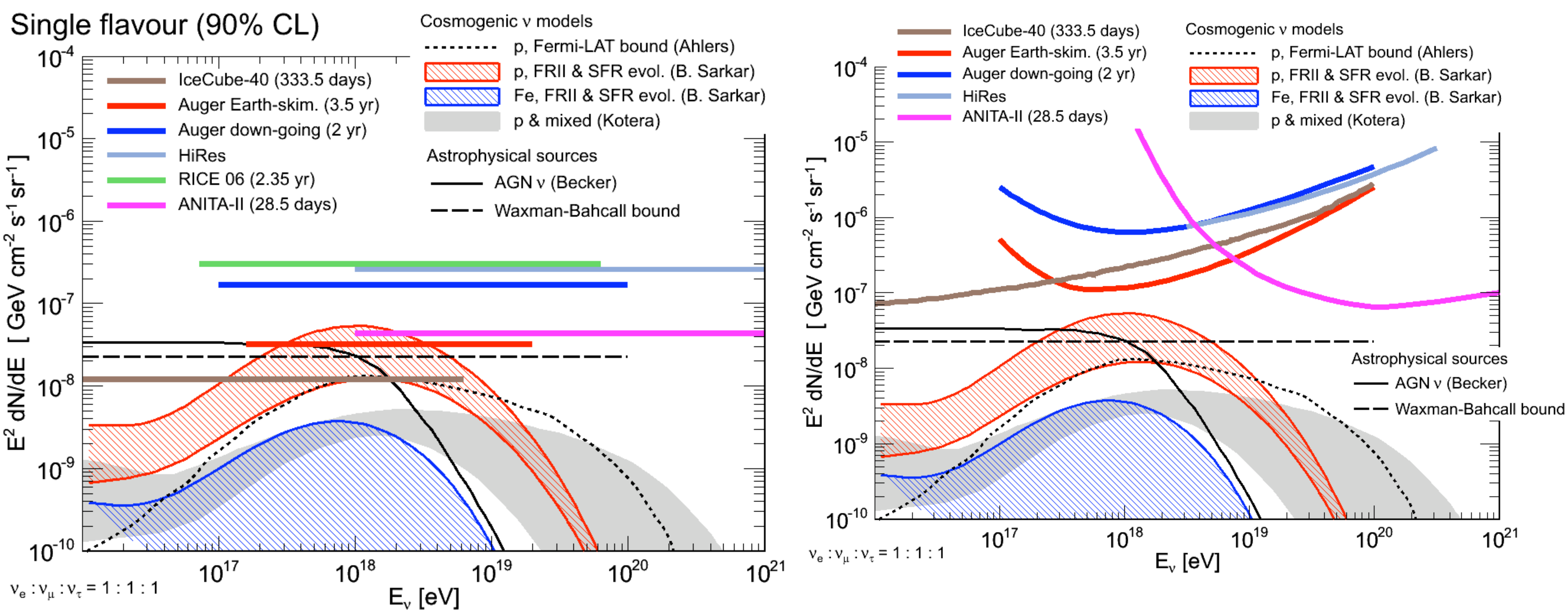


UHE Neutrino Search Results:

	ANITA-I	ANITA-II
Neutrino Candidate Events	1	1
Expected Background	1.1	0.97 +/- 0.42

ANITA-III: factor of 5 improvement expected in sensitivity

Current Limits



integral limits: assume E^{-2} ν flux & find normalization needed to detect ~ 2.4 events

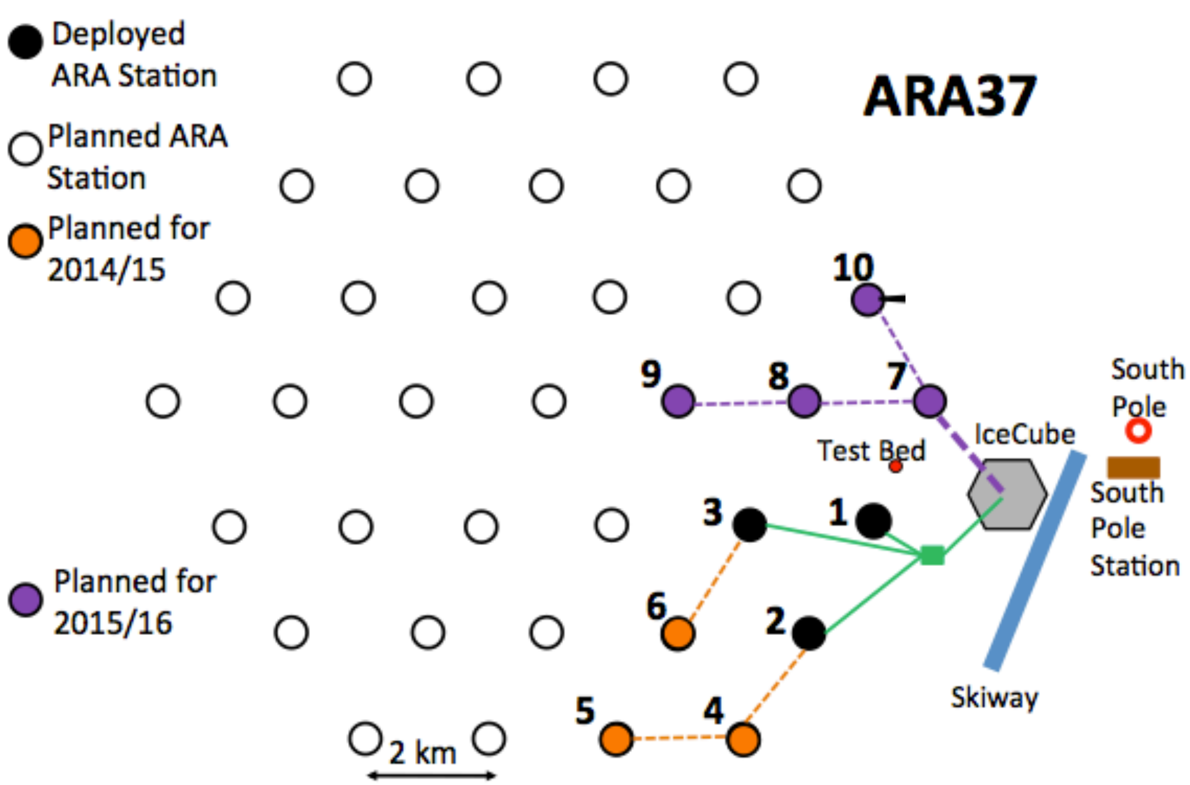
differential limits: assume E^{-2} ν flux in energy bins & find normalization to have 2.4 events in each bin

EAS ground array sensitivity peaks at peak of cosmogenic fluxes (~EeV)

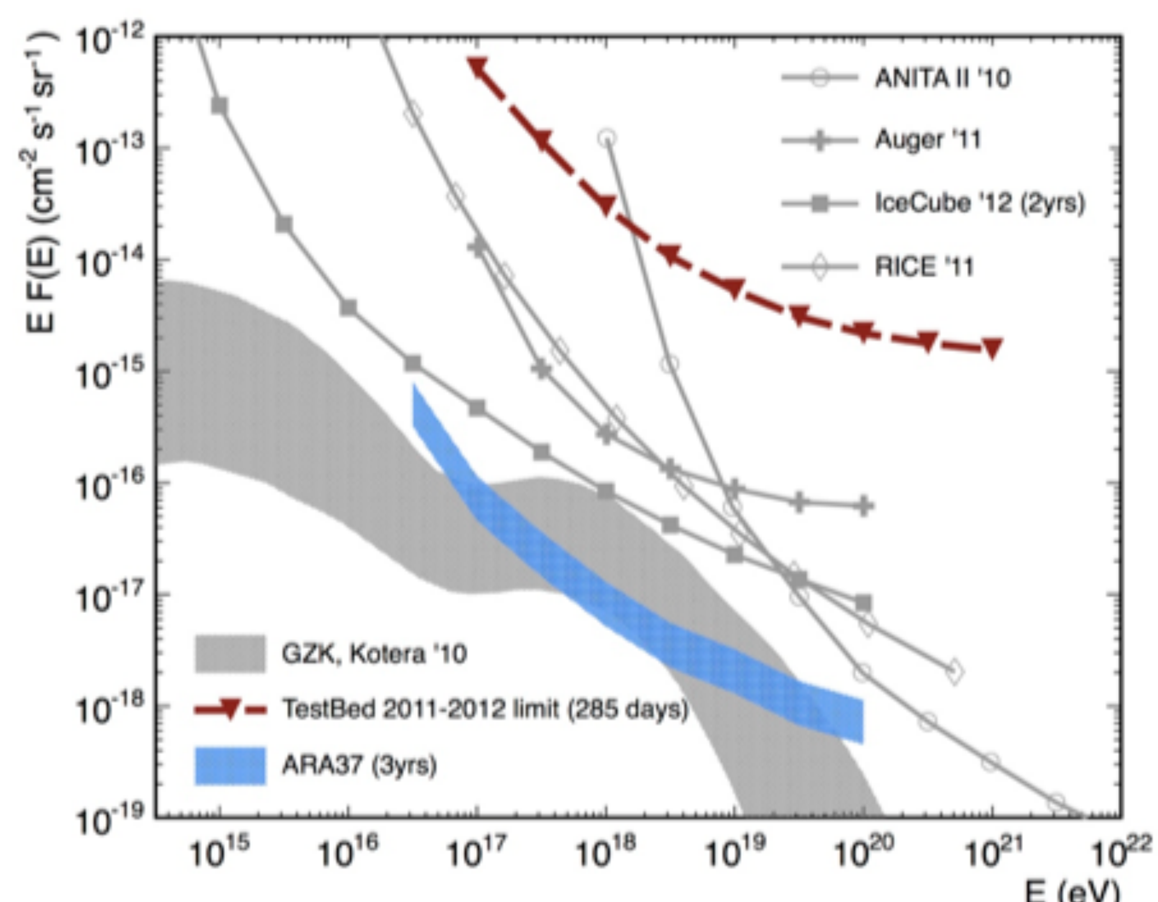
→ **event rates (estimated):**

ν Model	IceCube-40	Auger (Earth-skim.)	
GZK - p, Fermi-LAT (dashed black line)	~ 0.4	~ 0.6	Poorly constrained
GZK - p, FRII evolution (top edge red band)	~ 1.8	~ 2.2	Starts to be constrained
AGN (solid black line)	~ 5.5	~ 1.2	Strongly constrained

Askaryan Radio Array

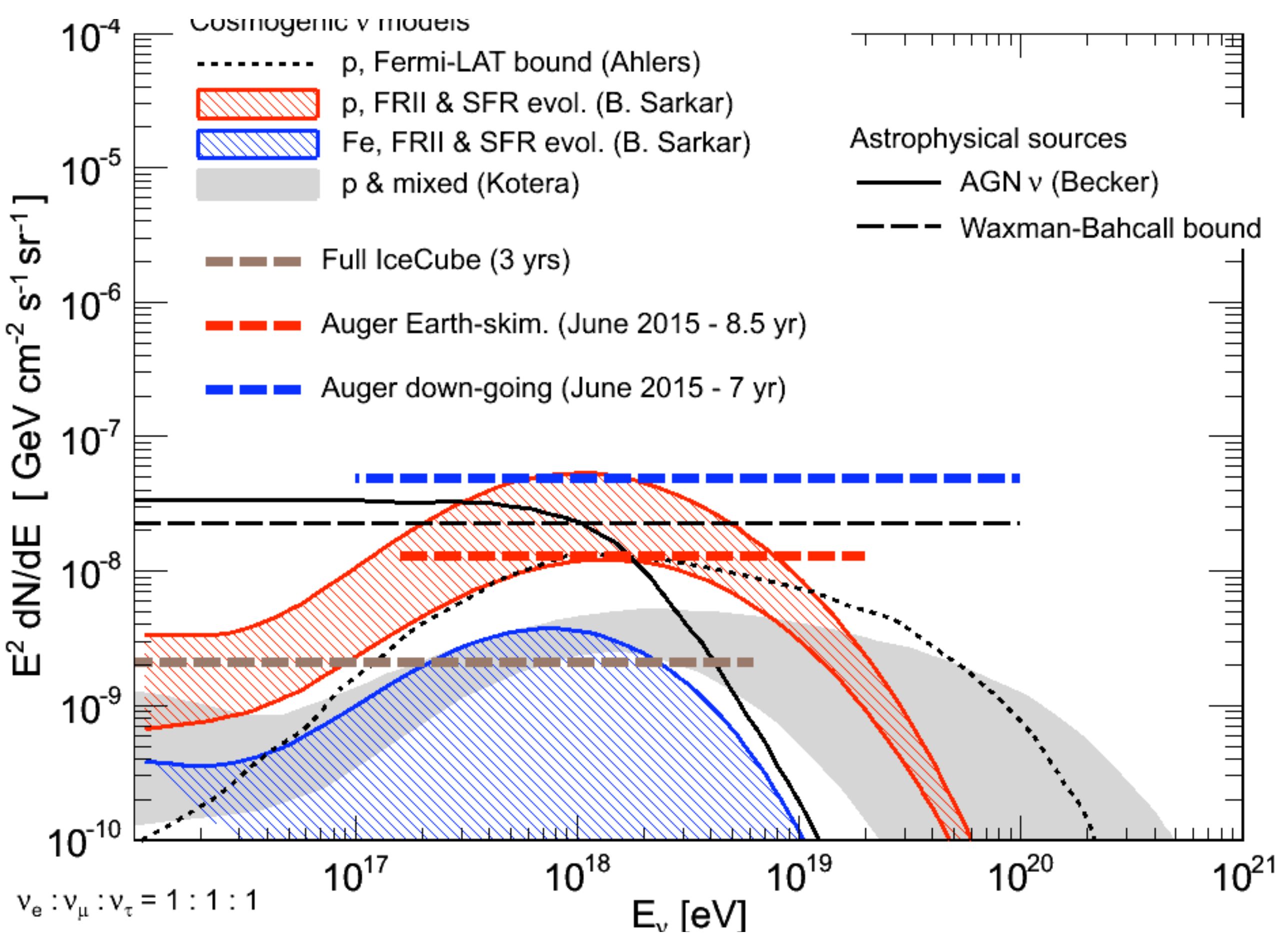


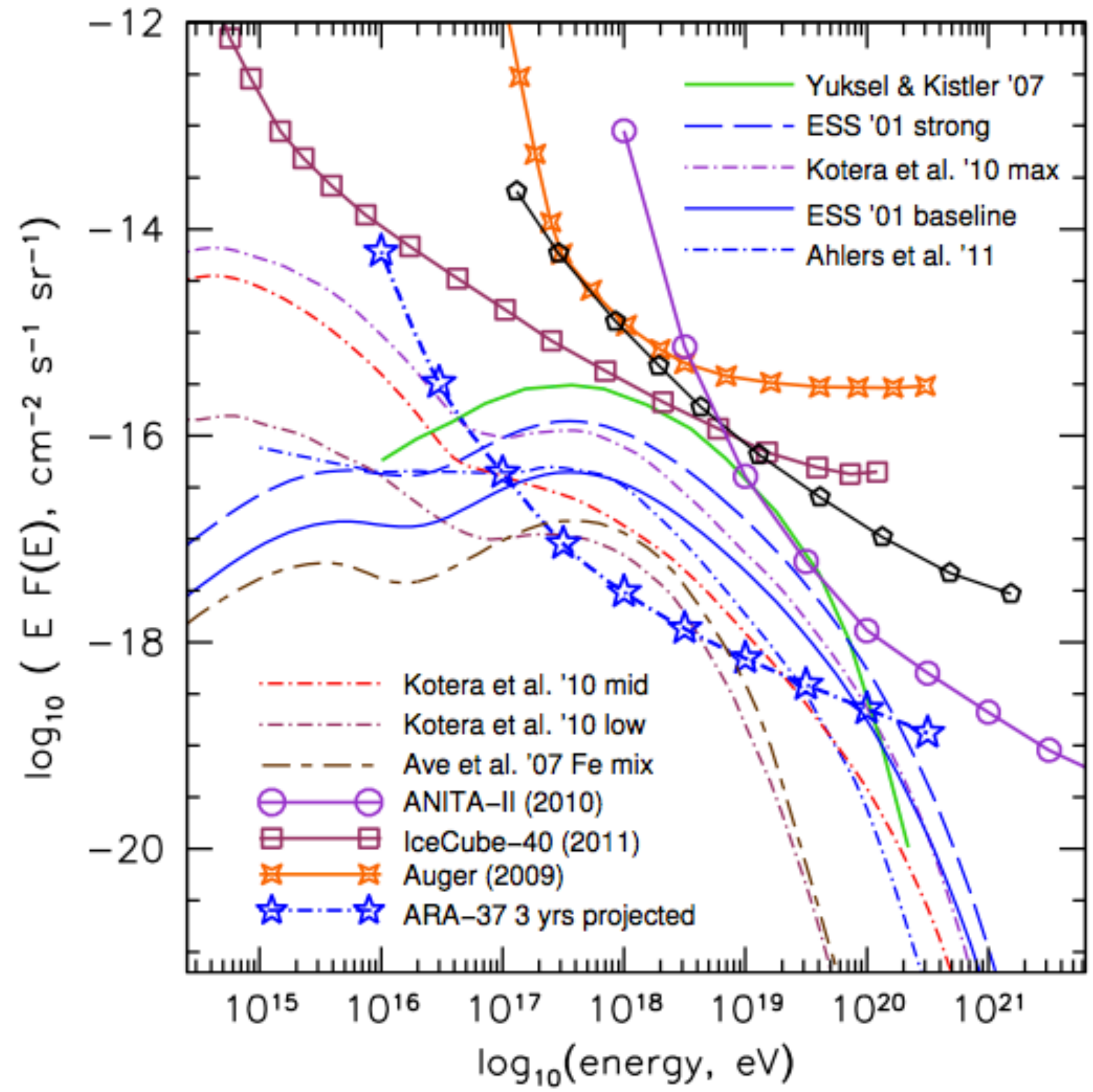
- Plan: 37-station array of antennas buried 200m below the surface at the South Pole
- 3 stations+testbed deployed and working
- Blind analyses of 10% sample of the 2011 and 2012 testbed station data



ARA Collaboration: arXiv:1404.5285

Future Sensitivity Estimates



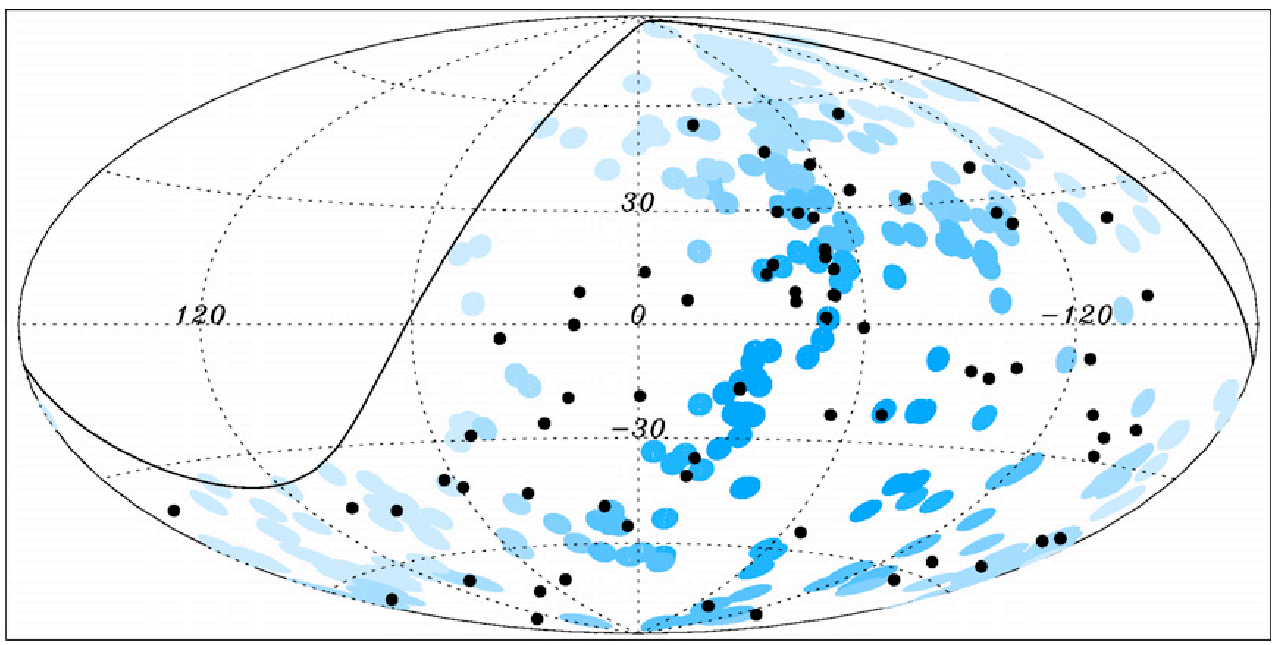


ARA Coll. arXiv:1105.2854

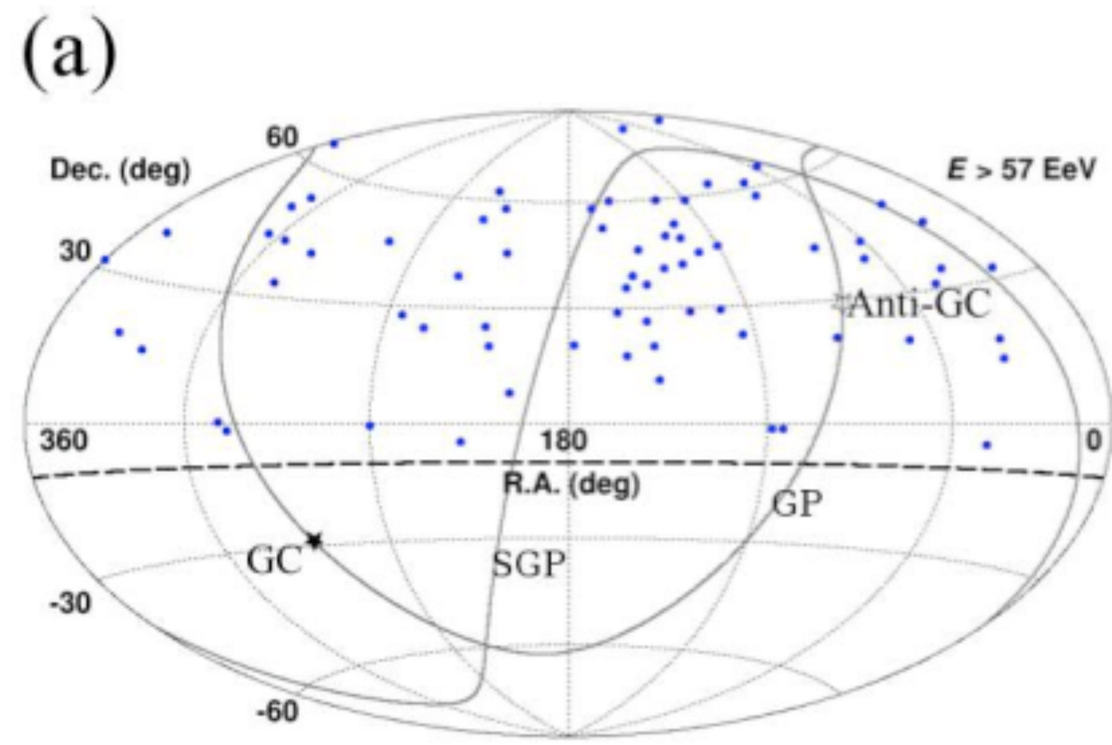
➡ In 5-10 years, hope to have UHEν observatories

UHECR Sources ?

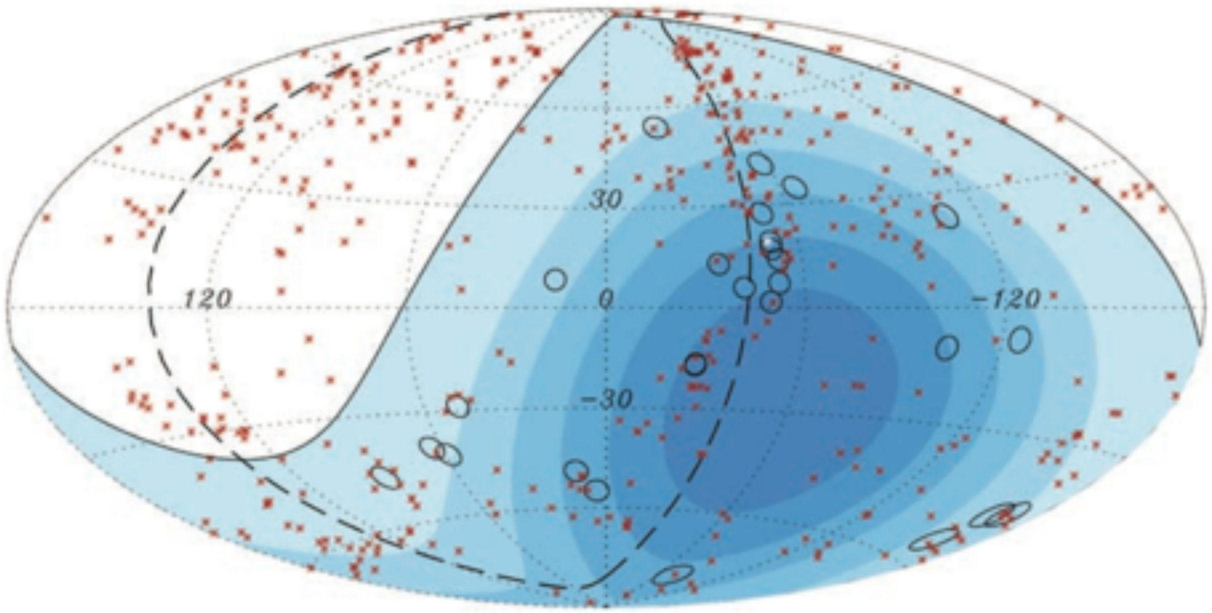
➡ Auger Collaboration, APP 34 314 (2010)

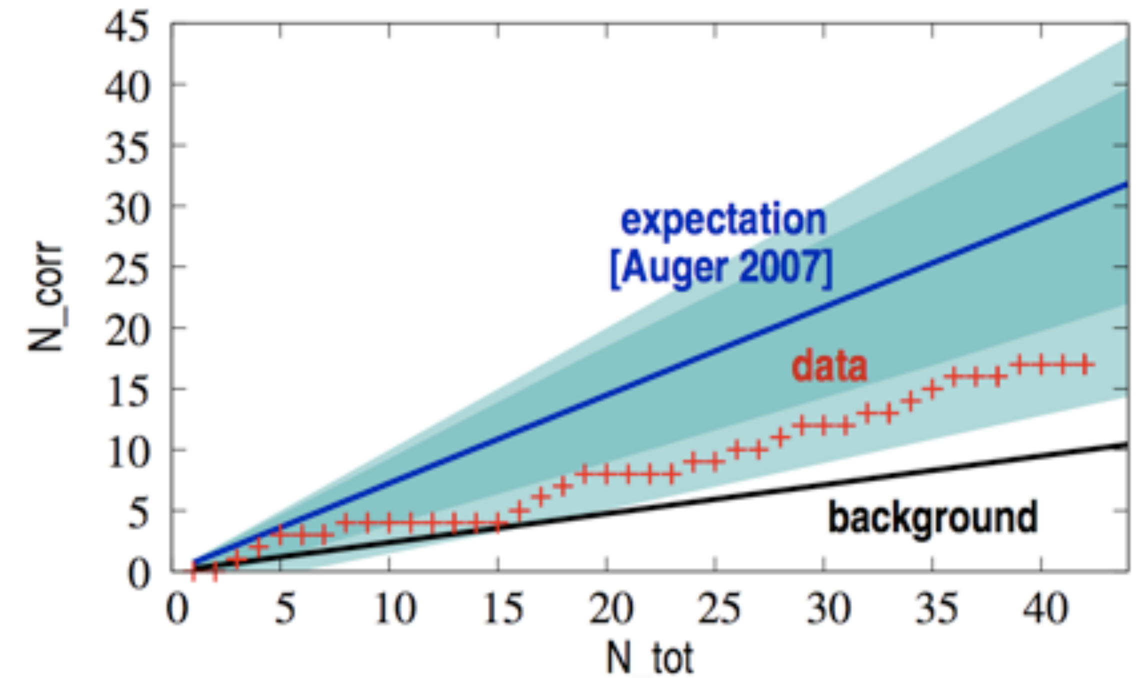


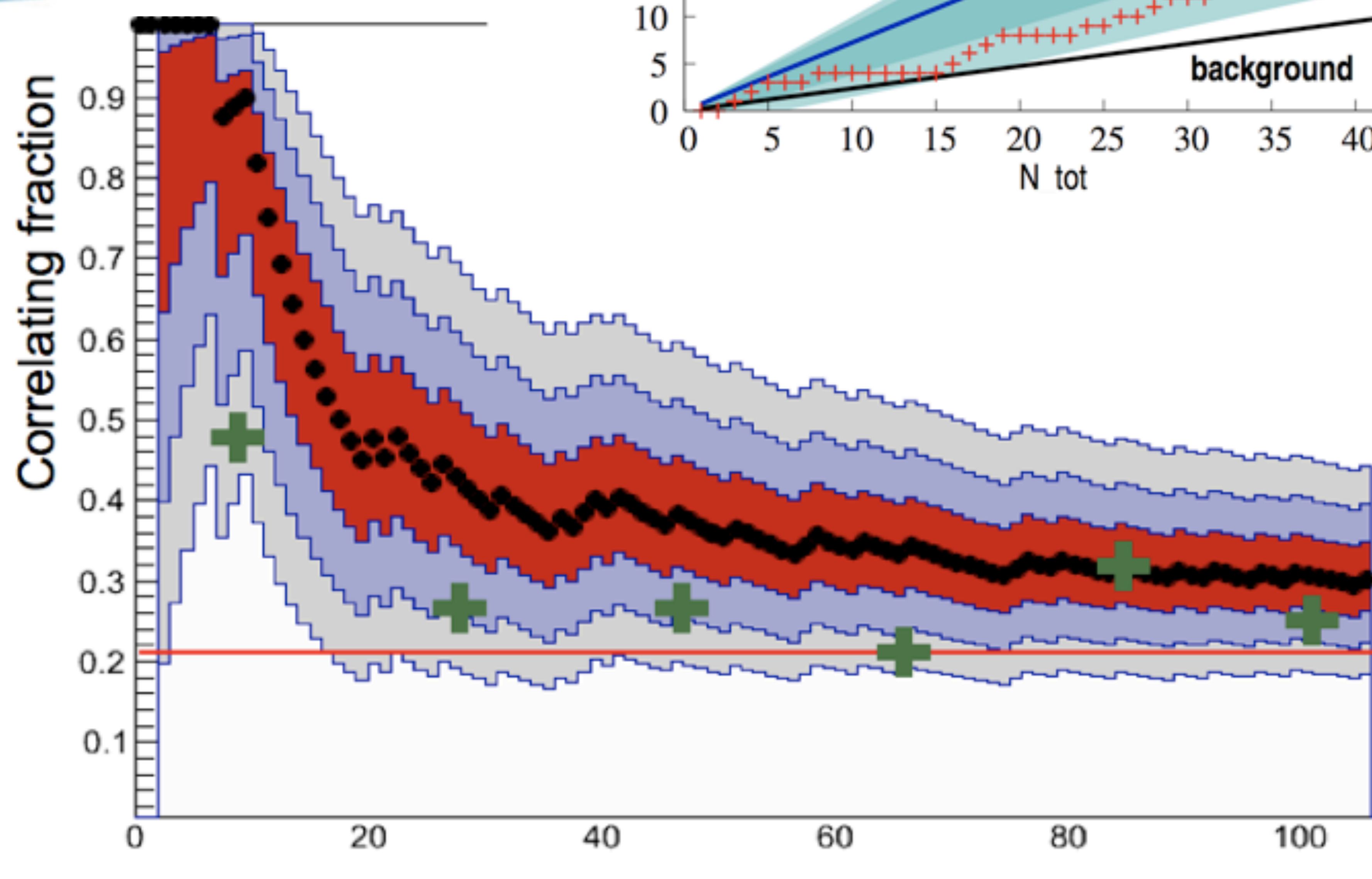
➡ TA Collaboration, arXiv:1404.5890



AGN Correlation

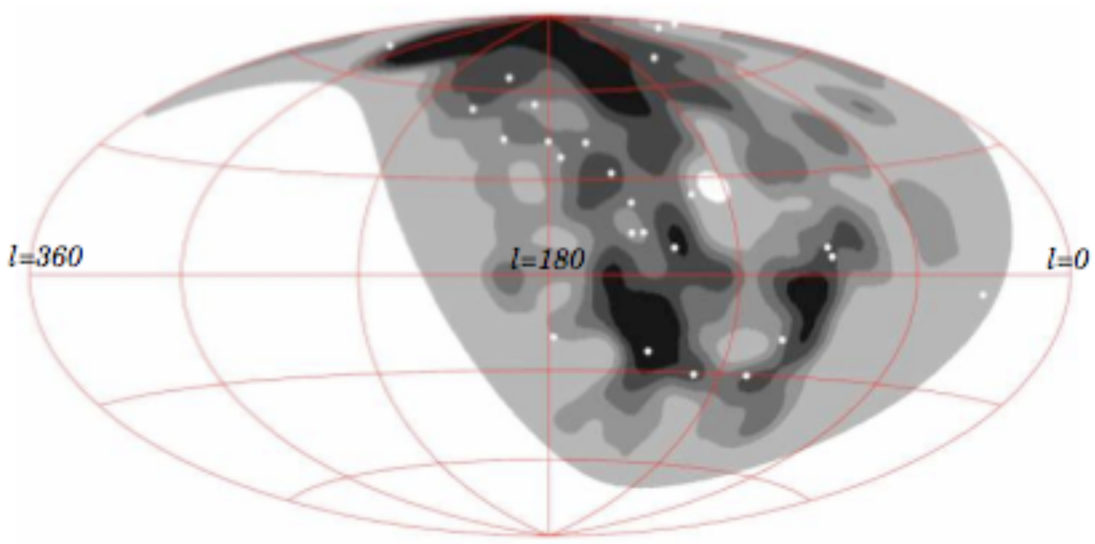






Correlation with Large-Scale Structure

➡ TA Collaboration, ApJ (2012)



➡ Auger Collaboration, APP 34 314 (2010)

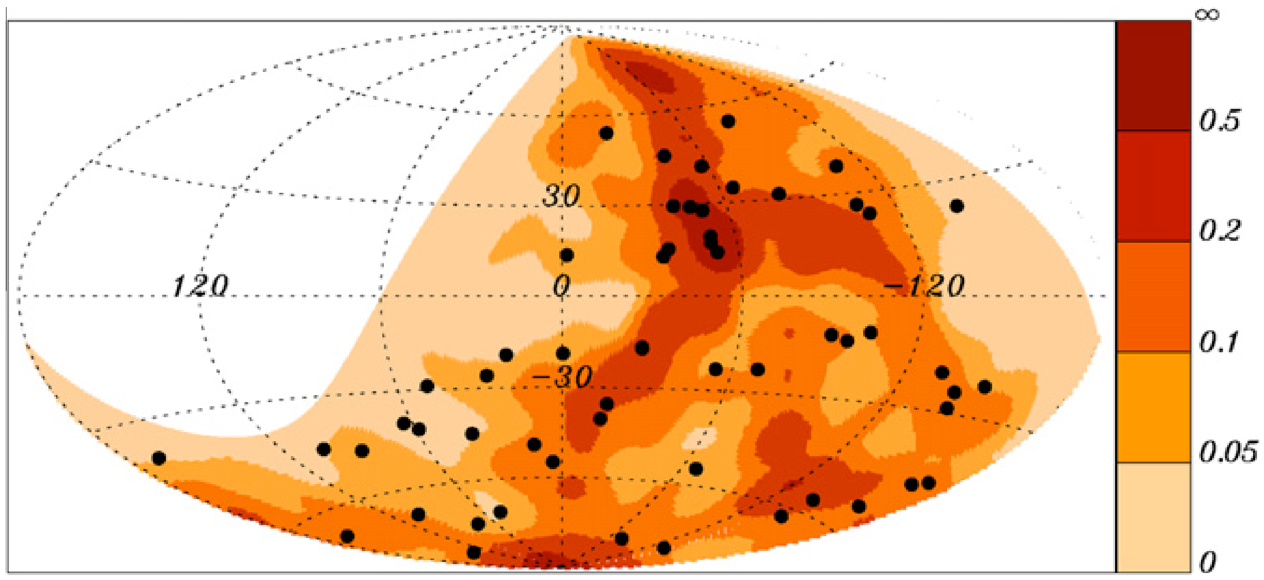
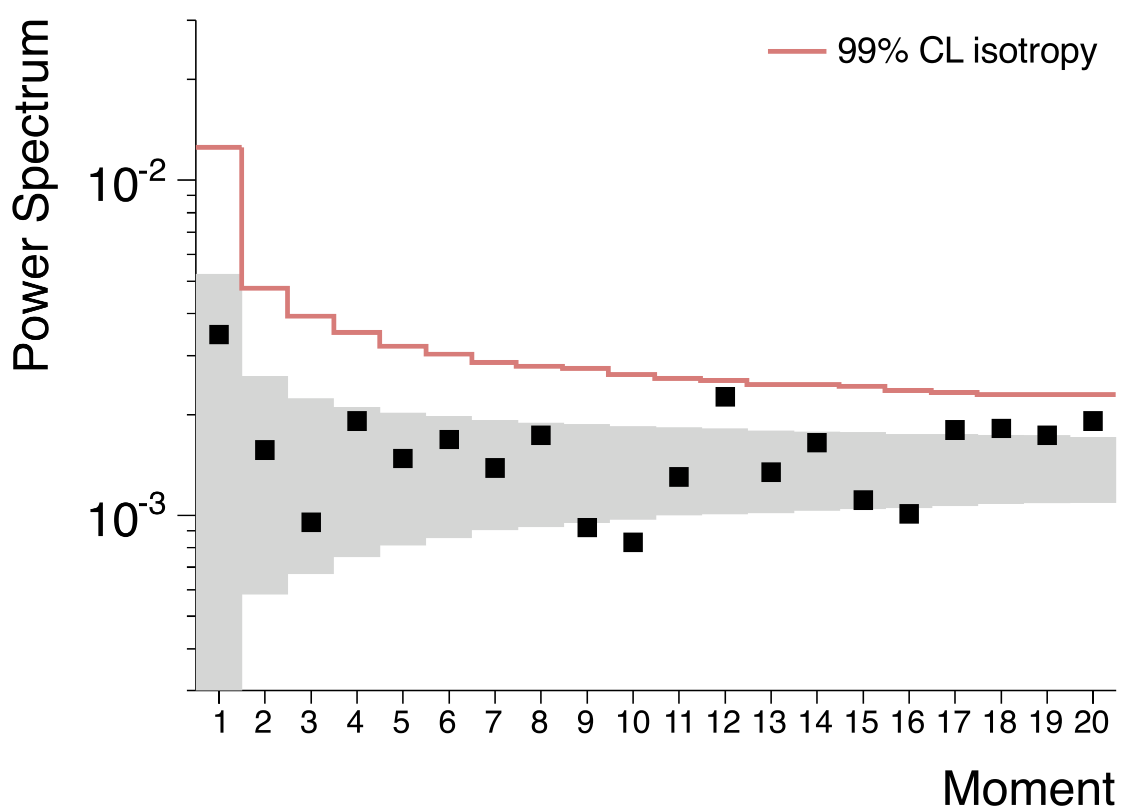


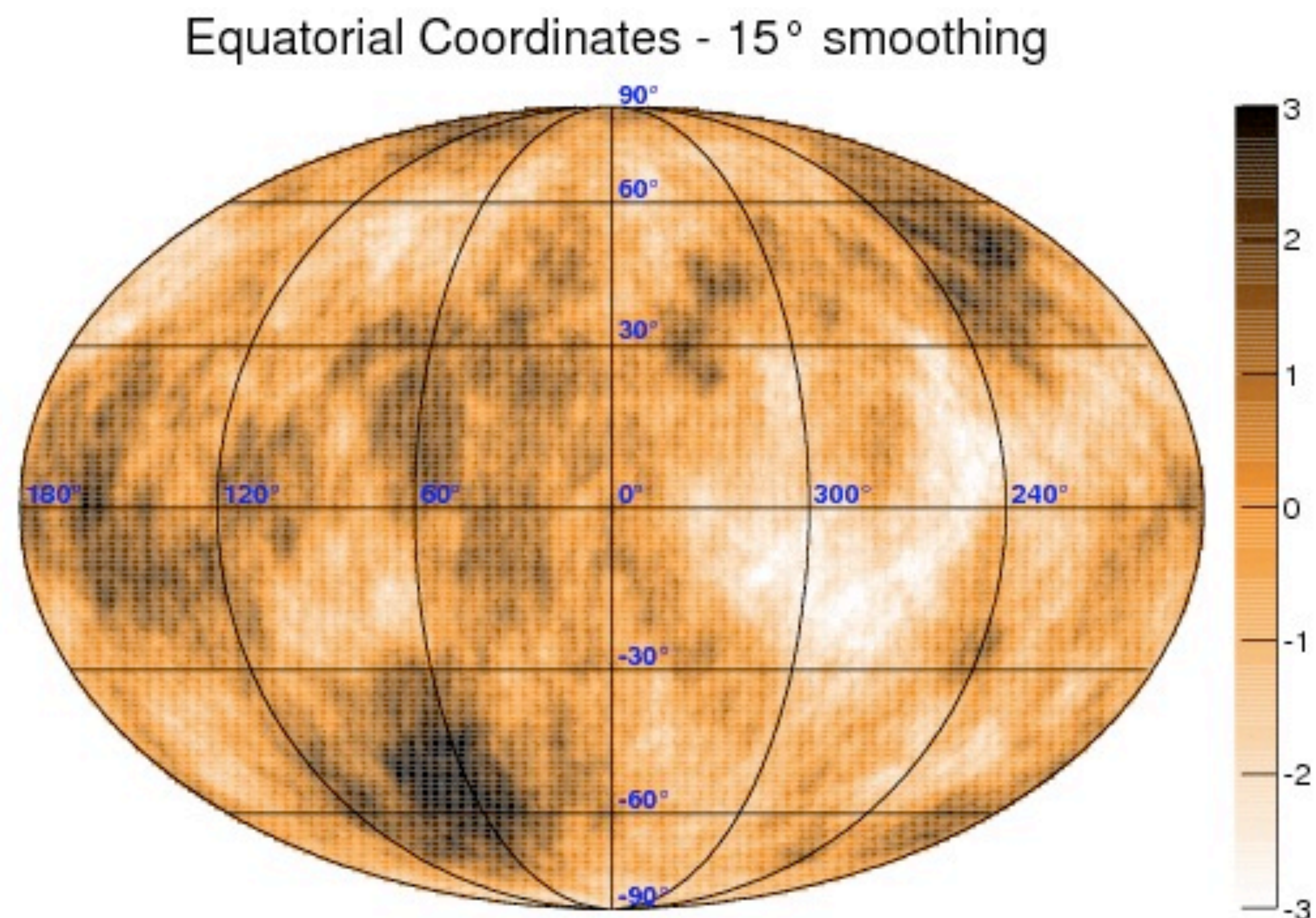
Fig. 5. Cosmic ray density map for the flux-weighted 2MRS galaxies, smoothed with an angular scale $\sigma = 5°$. The black dots are the arrival directions of the CRs with energy $E \geqslant 55$ EeV detected with the Pierre Auger Observatory. Galactic latitudes are restricted to $|b| > 10°$, both for galaxies and CR events.

➡ Need for a large fraction of isotropic background...

Full-Sky Map > 10 EeV

- Joint analysis Auger/TA
- Submitted to ApJ

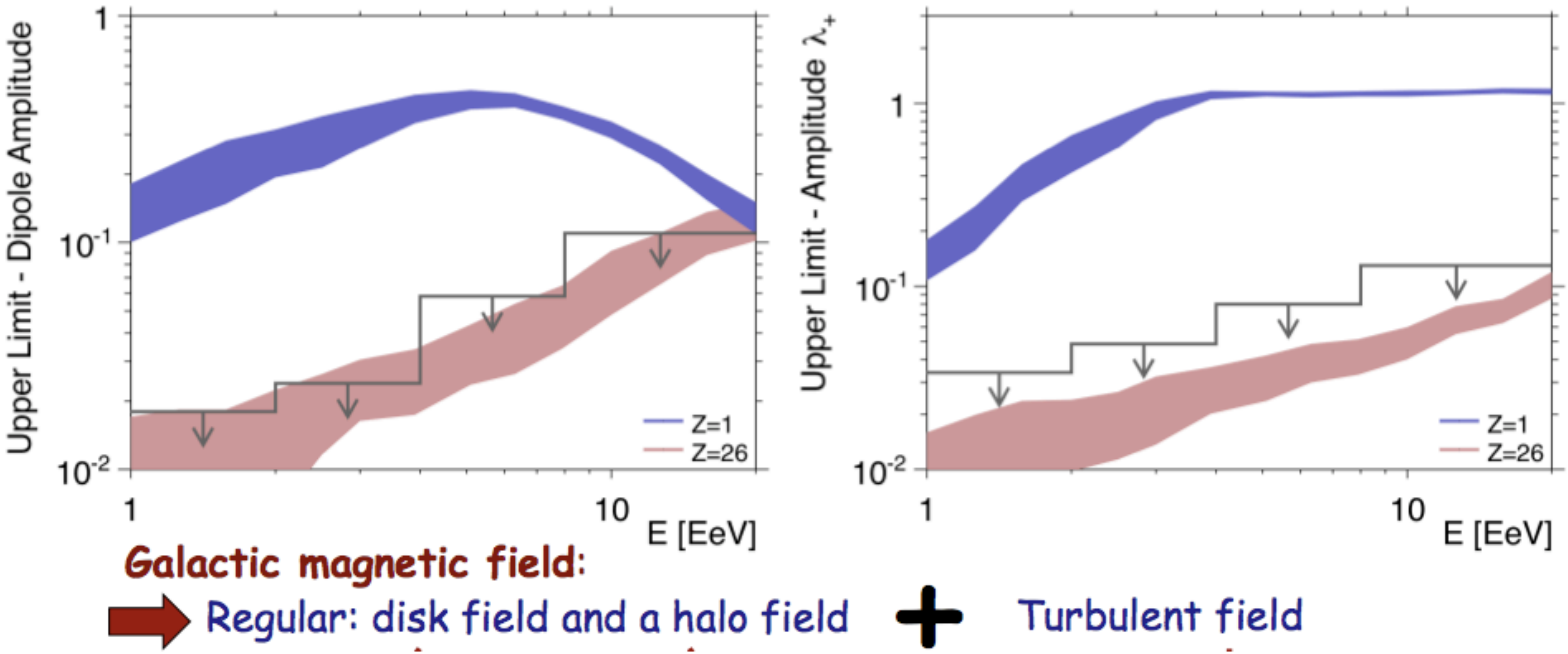




- Upper Limits on dipole ~ 9%

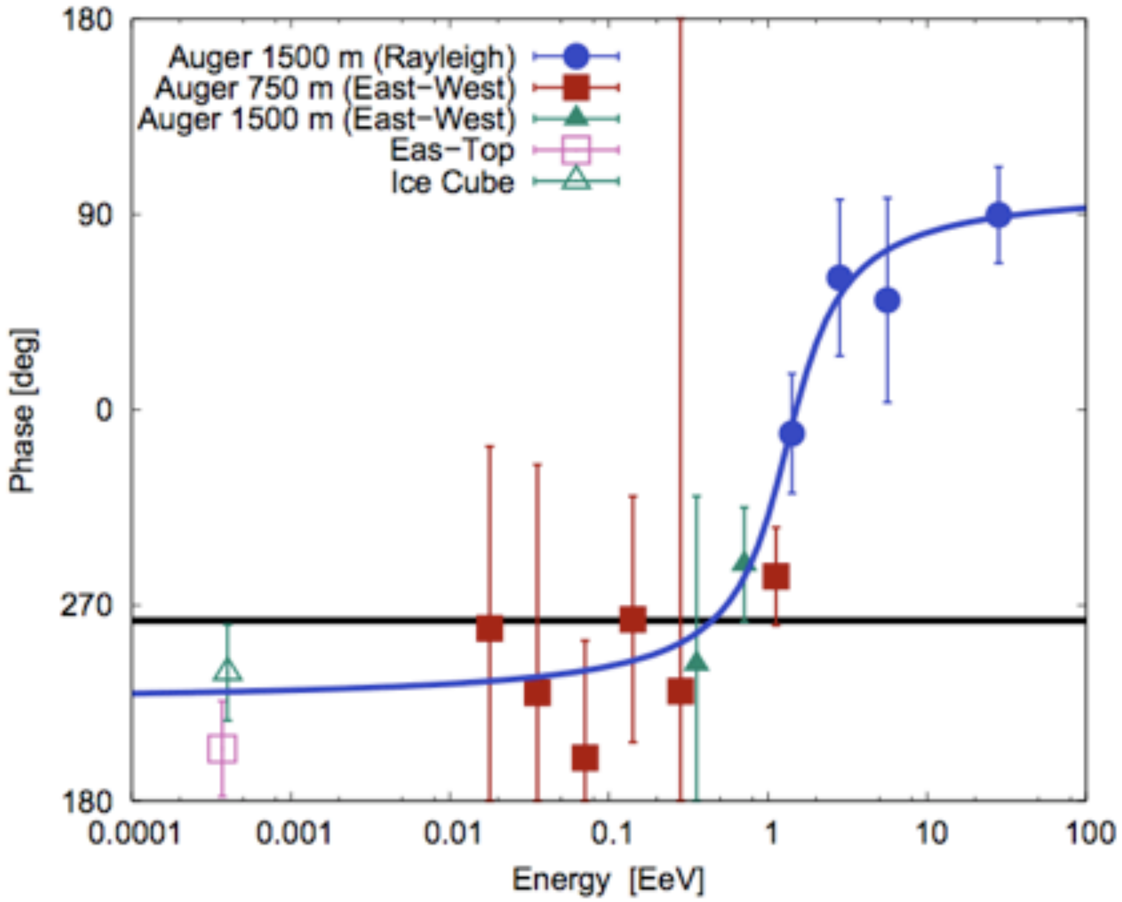
Upper Limits at EeV Energies

➡ The Pierre Auger Collaboration, ApJS 203 34



➡ excludes the hypothesis that the light component of EeV-cosmic rays is of Galactic origin from stationary sources emitting in all directions.

Gal/Xgal Transition ?



Eas-Top: M. Aglietta *et al.* 2009 ApJ **692** L130
IceCube: R. Abbasi *et al.* 2012 ApJ **746** 33

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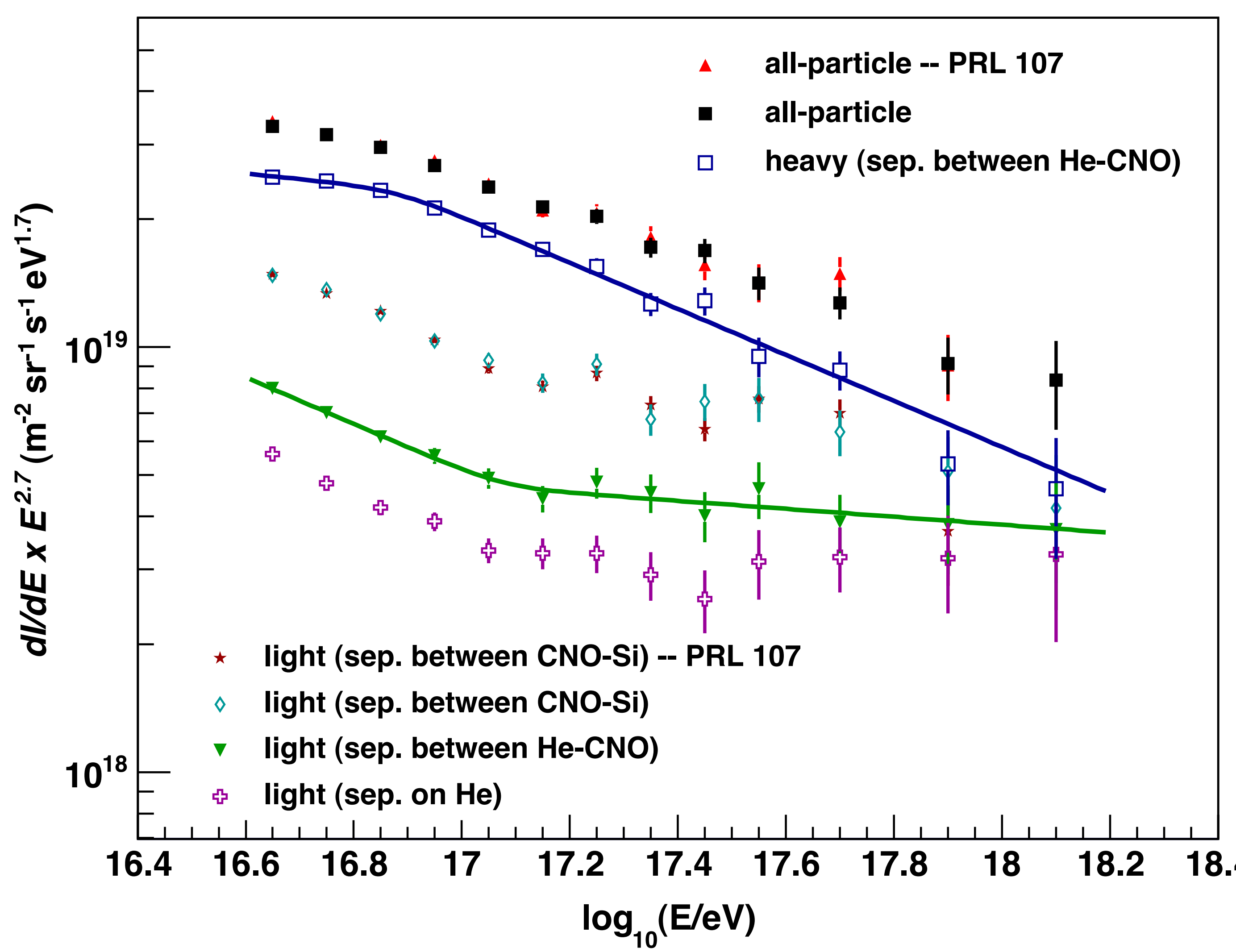

Outlook

- In 5-10 years, sensitivity to detect EeV-neutrinos
- Issue of the light vs heavy composition at UHE
- Absence of correlations at UHE with nearby matter
- Light CR component entering below 1 EeV, most likely protons of extragalactic origin
- Neutrinos and UHECR sources: protons above 10 EeV ?