The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2246-17

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Cosmogenic neutrino backgrounds: present status and future prospects

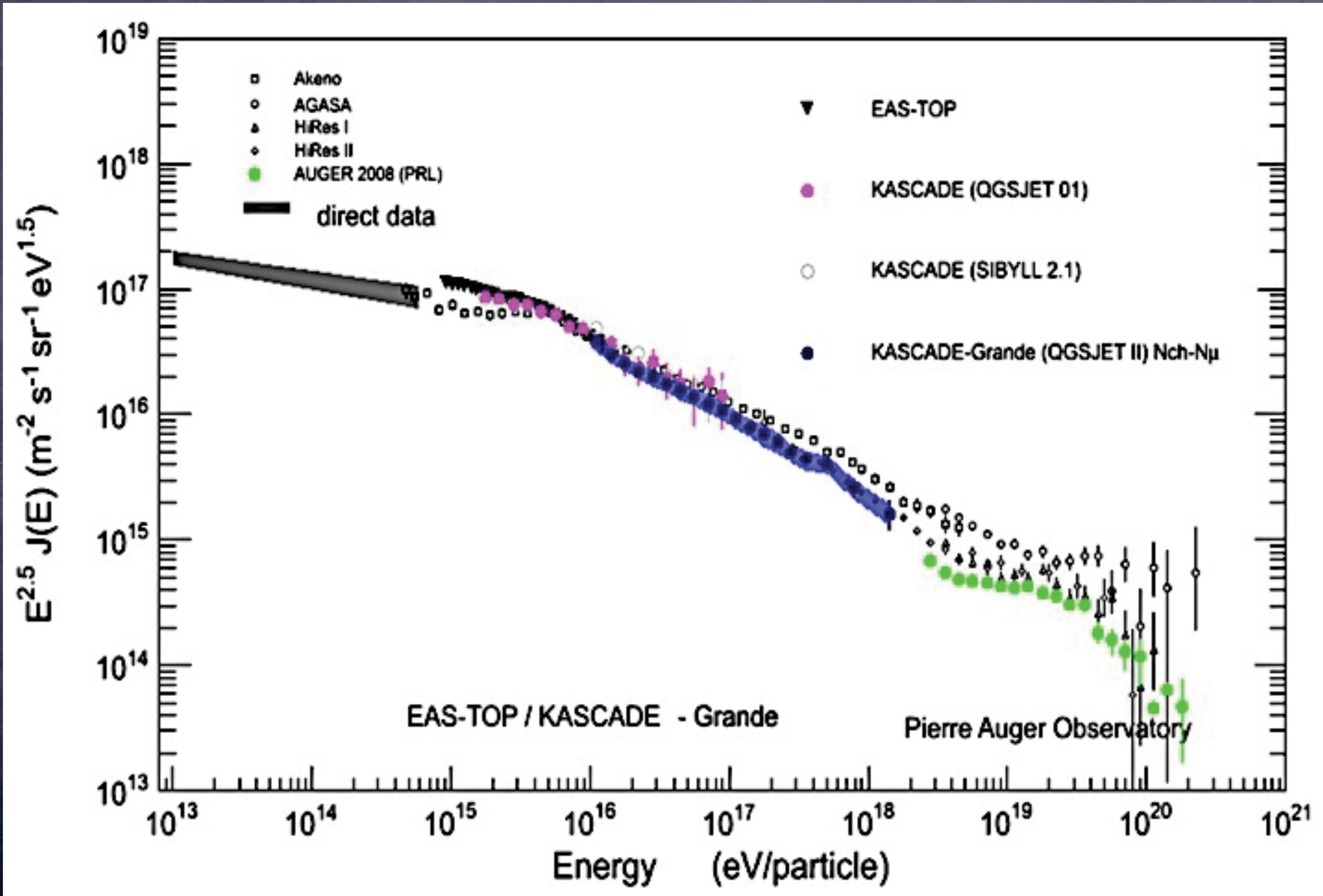
Luca MACCIONE
DESY, Hamburg
Germany

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

Ultra High Energy neutrinos: status and future prospects

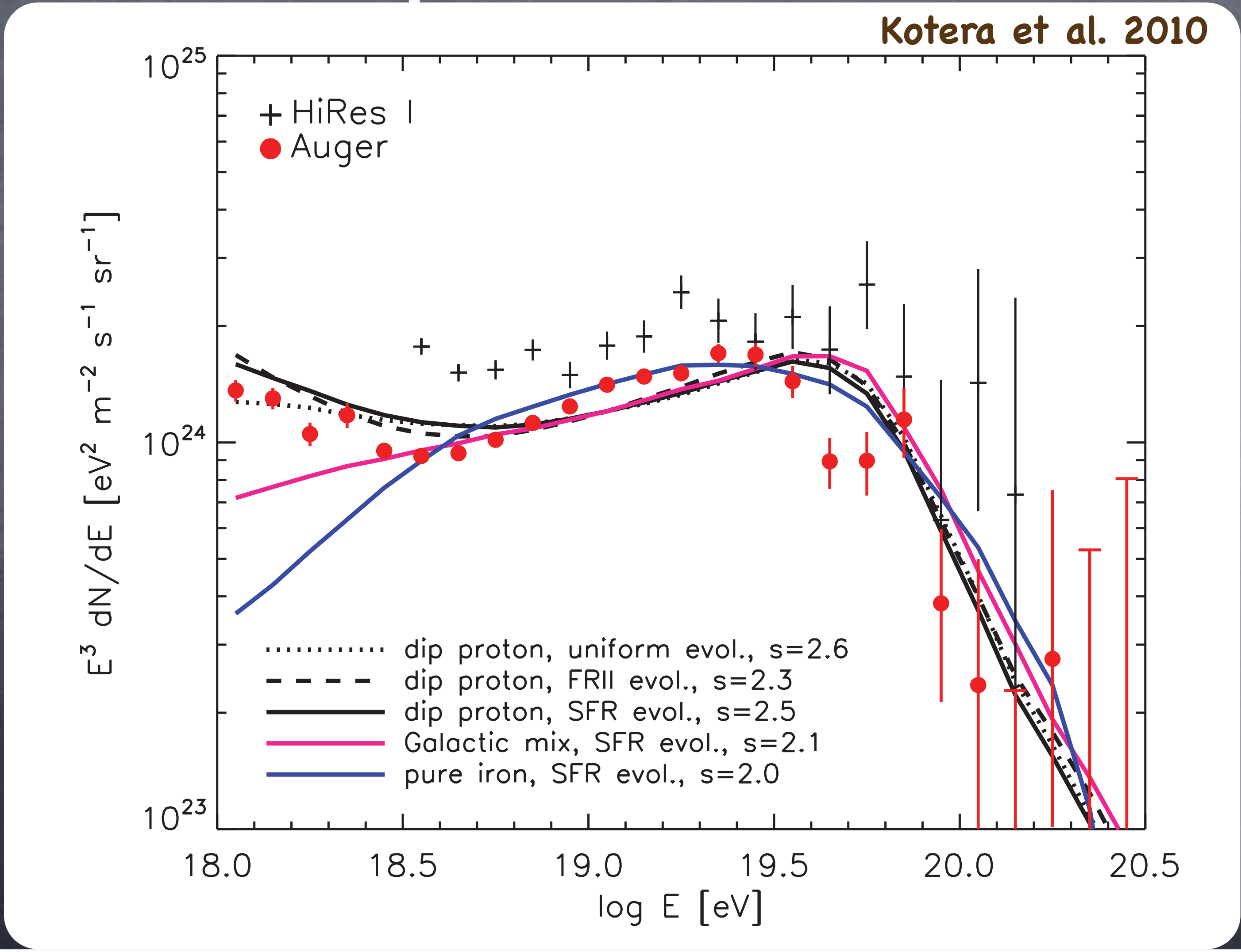
Luca Maccione (on behalf of G. Sigl)
NUSKY - ICTP - 22.06.2011

CR Spectrum

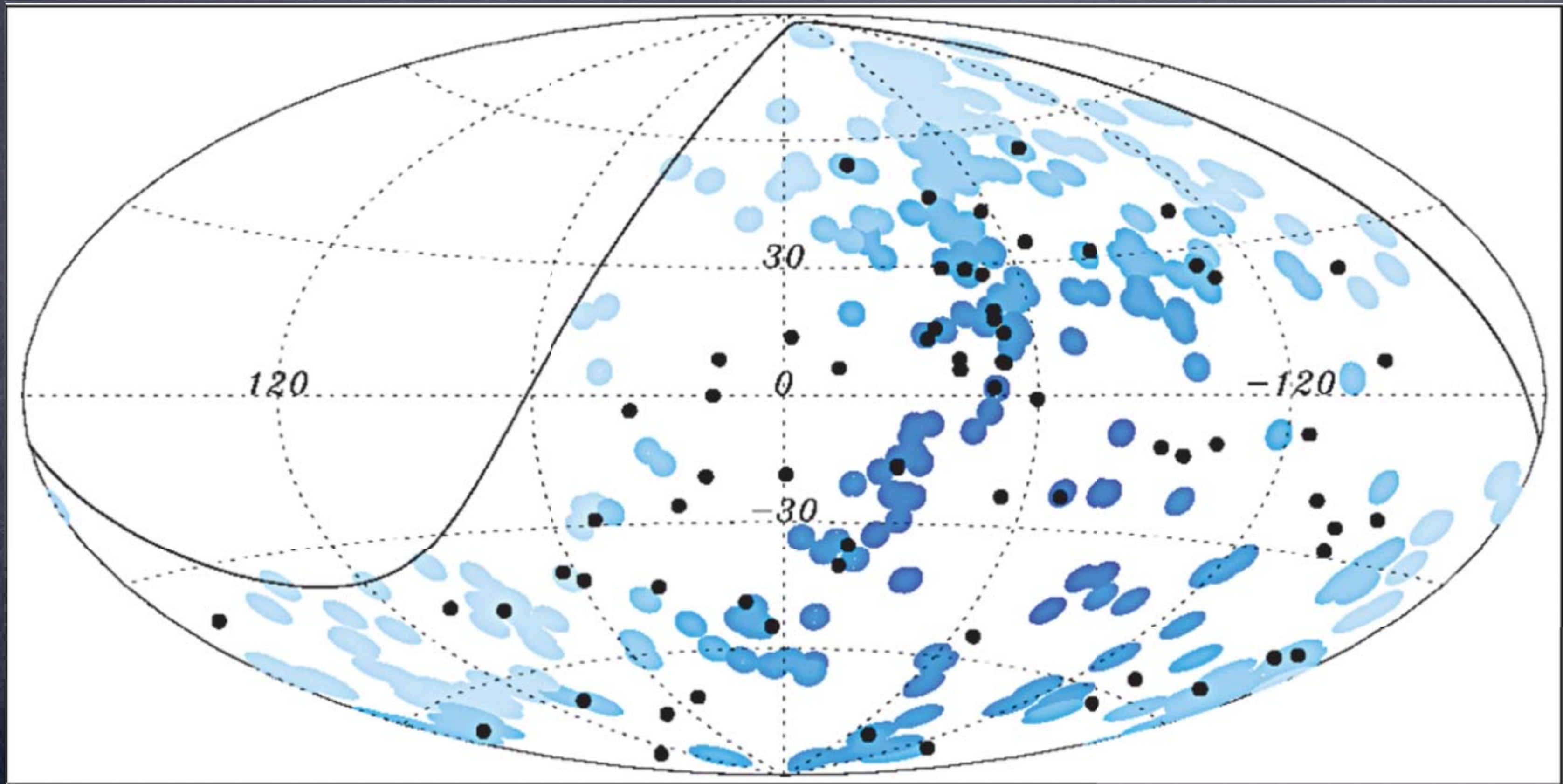


KASKADE-Grande collaboration arXiv:1009.4716

AUGER and HiRes spectra



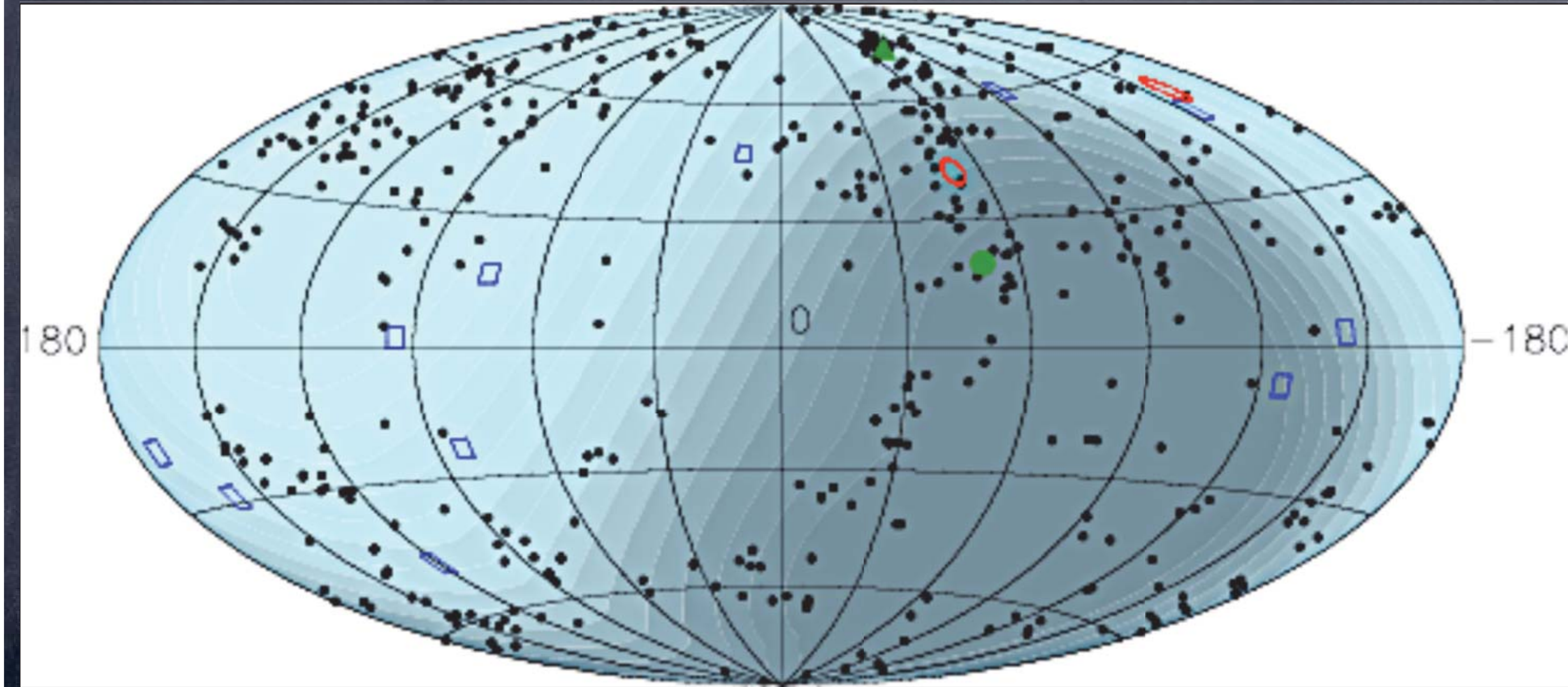
Anisotropy ?



Blue 3.1 deg. circles = 318 AGNs from the Veron Cetty catalogue within 75 Mpc (exposure weighted color); black dots = 69 events above 55 EeV.
29 events correlated within 3.1°, 14.5 expected for isotropy

Pierre Auger Collaboration, Astropart.Phys. 34 (2010) 314

Anisotropy ?

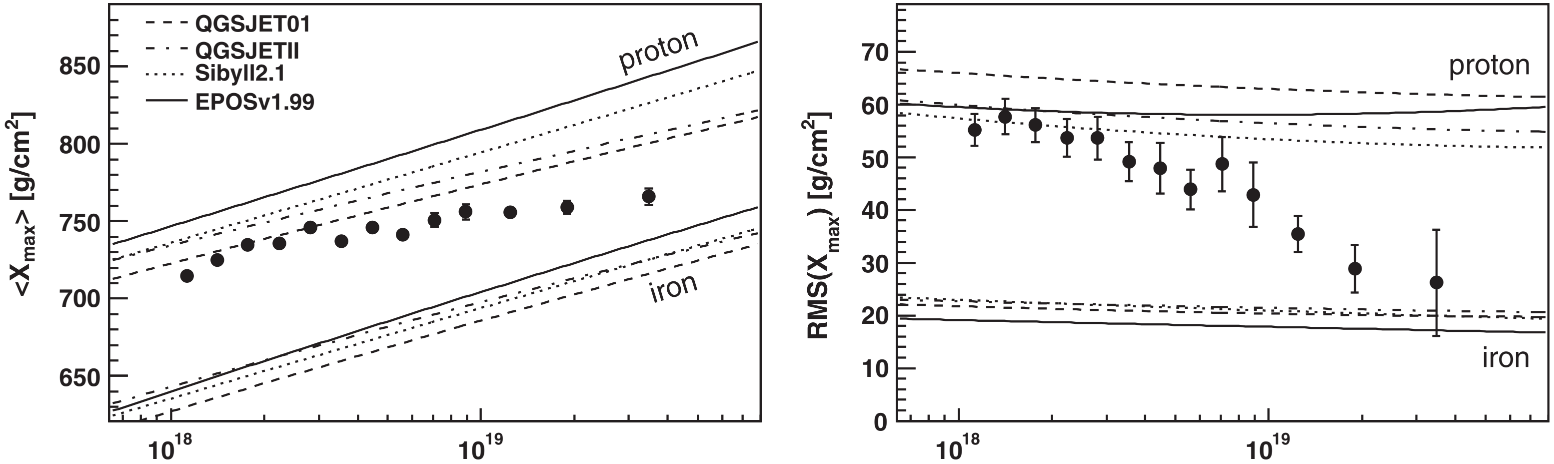


Black dots = 457 AGNs + 14 QSOs from the Veron Cetty catalogue for z < 0.018
red circles = 2 correlated events above 56 EeV within 3.1°,
blue squares = 11 uncorrelated events

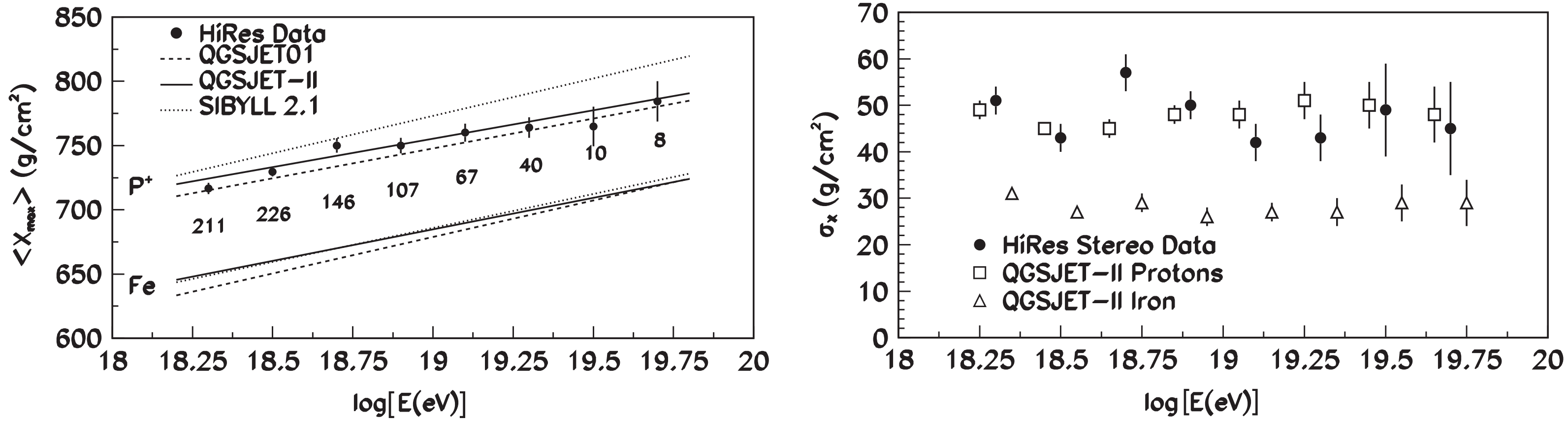
HiRes Collaboration, Astropart.Phys. 30 (2008) 175

Also nuclei?

PAO Coll, PRL 104 (2010)



HiReS Coll, PRL 104 (2010)

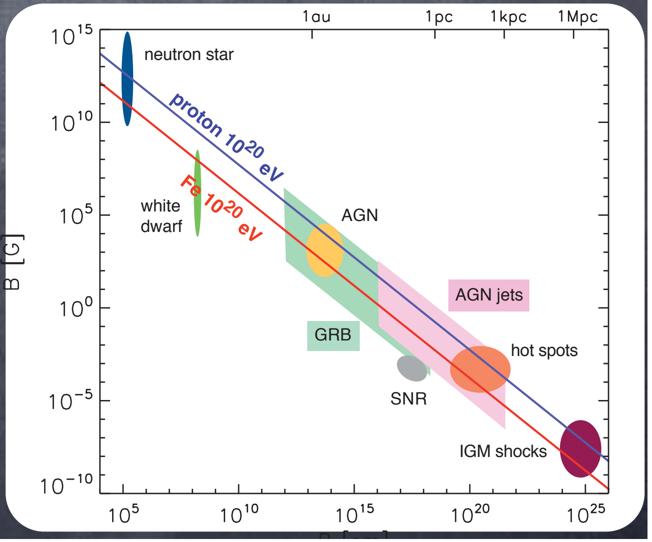


A tension?

IF deflection is small and IF sources follow LSS

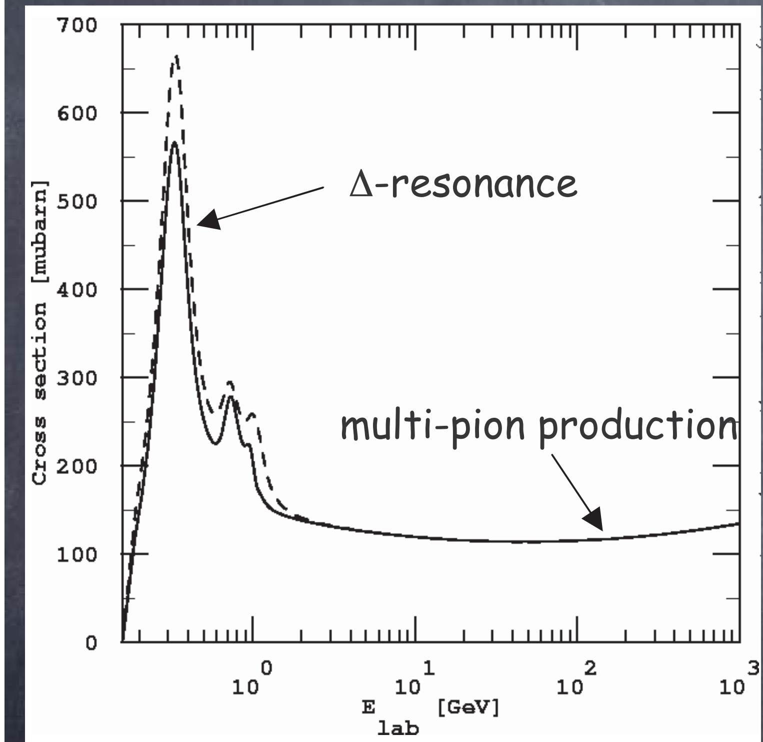
THEN
primaries should be protons (small deflections in galactic field)

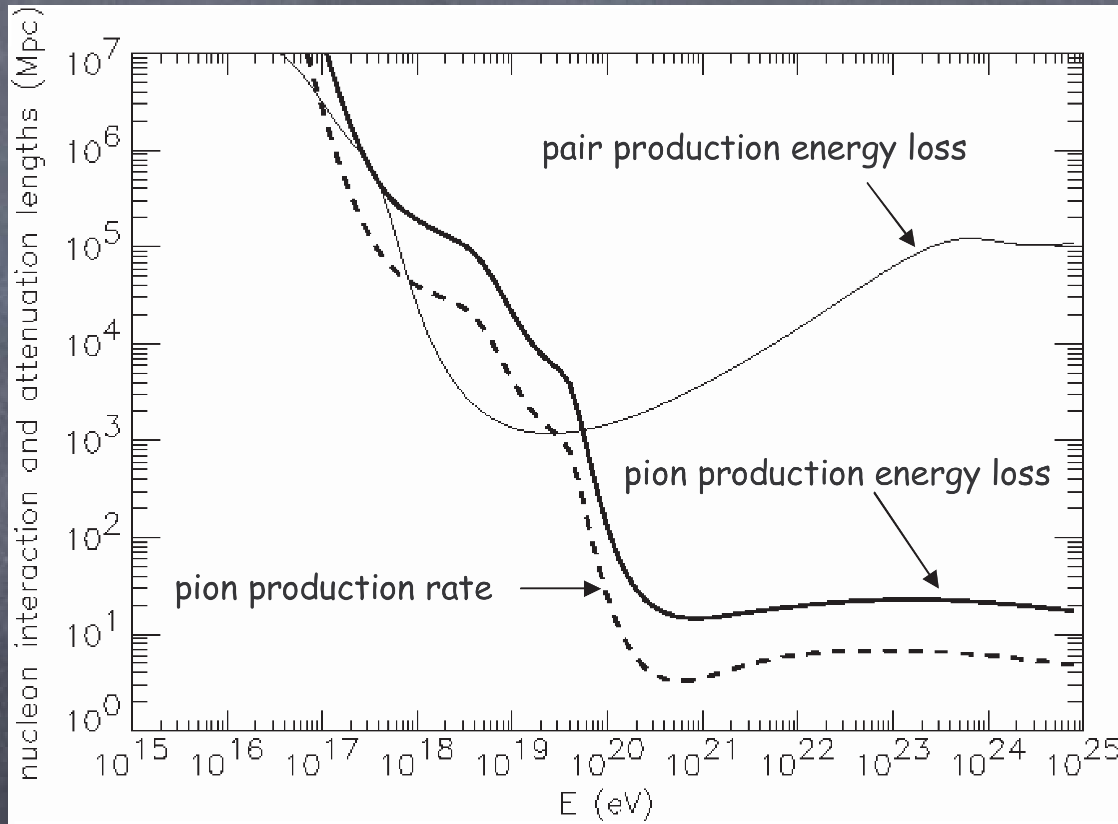
BUT
air shower measurements by PAO
(but not by HiRes) favor mixed/heavy
composition



The Greisen-Zatsepin-Kuzmin effect

$p + \gamma \to N + \pi$ $\quad E_{\rm th} = \dfrac{2 m_p m_\pi + m_\pi^2}{4\epsilon} \sim 4 \cdot 10^{19}\ {\rm eV}$ on CMB





UHECRs at $E > 10^{20}$ eV must be produced within 100 Mpc from us.

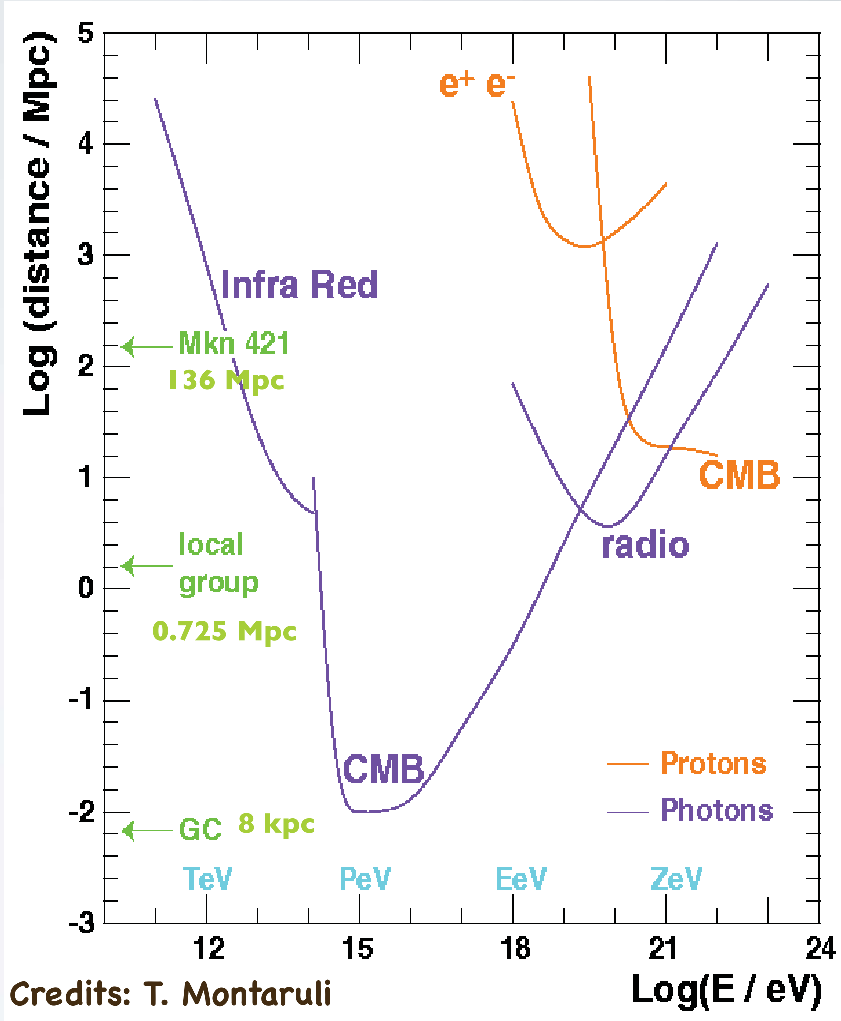
OR there is violation of Lorentz symmetry for boosts > 10^{11}.

GZK effect and secondary production

GZK interactions lead to

$$\pi^0 \to \gamma\gamma$$
$$\pi^\pm \to \mu\nu_\mu \to e\,\nu_\mu\bar{\nu}_\mu\nu_e$$

- Due to isospin symmetry we have a roughly equal amount of energy in photons and neutrinos
- Neutrinos do not interact further: their spectrum on Earth is the production one
- Photons experience pair production! They pile up below the pair production spectrum on CMB at 10^{14} eV.
- The Universe acts as a calorimeter for the total energy injected in electromagnetic flux above the pair production threshold.
- This constrains the neutrino flux

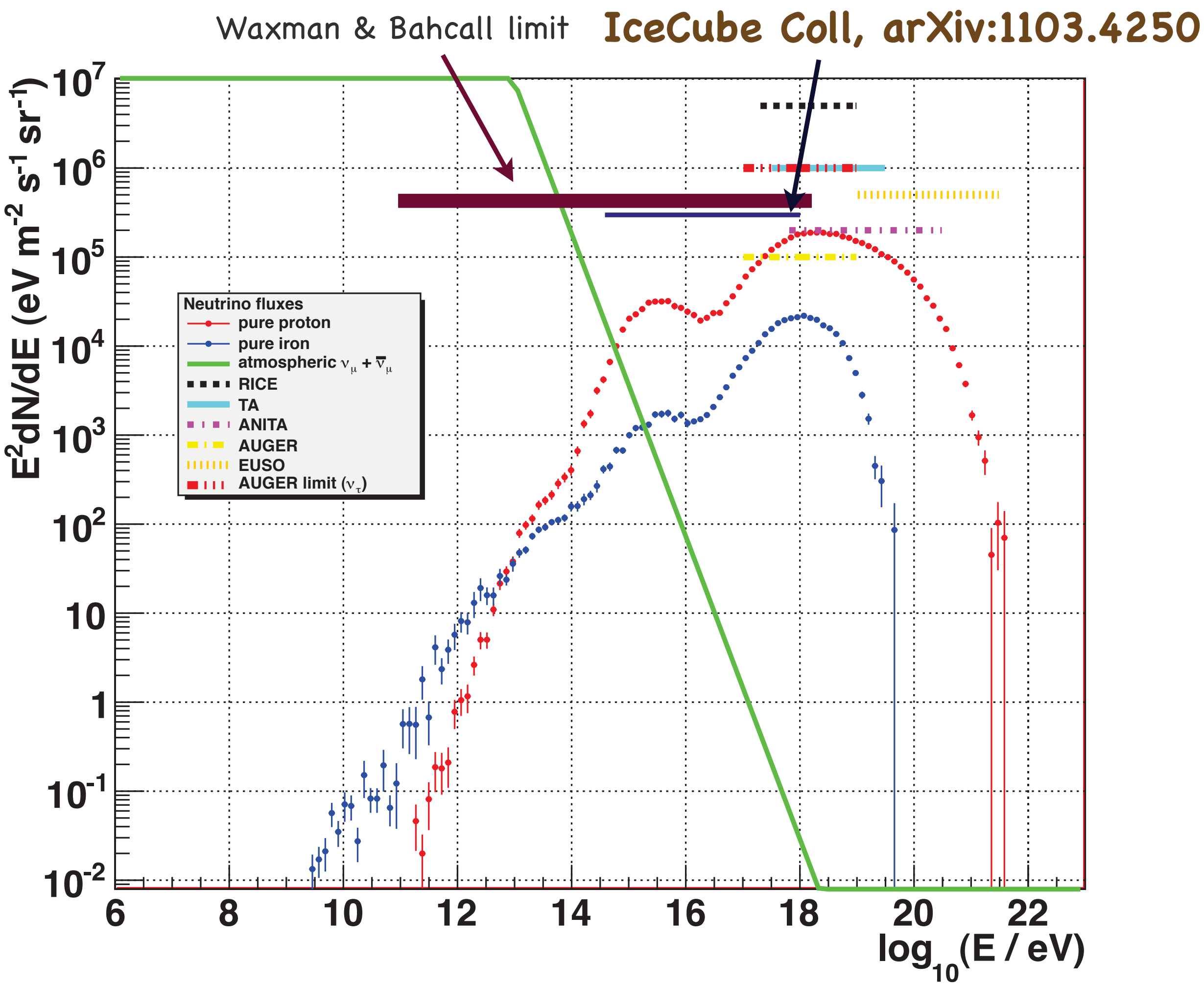


Secondary neutrinos

$$p + \gamma \rightarrow \pi^{\pm,0} \rightarrow \nu, \gamma, e^{\pm}$$

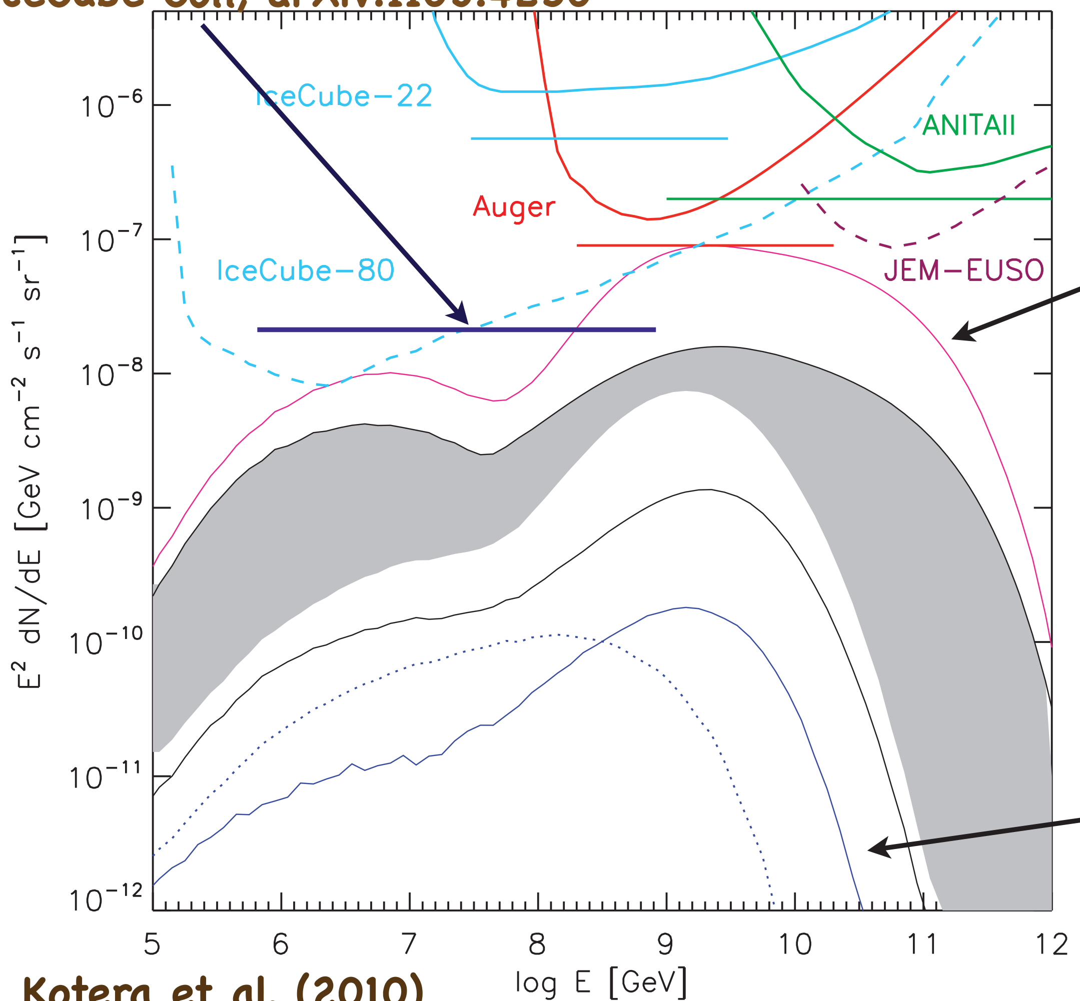
Pure proton composition leads to larger fluxes. Depending on the scenario, such fluxes might be detected at PeV energies

obtained with CRPropa 2.0 to be released soon!!



Overview of neutrino fluxes

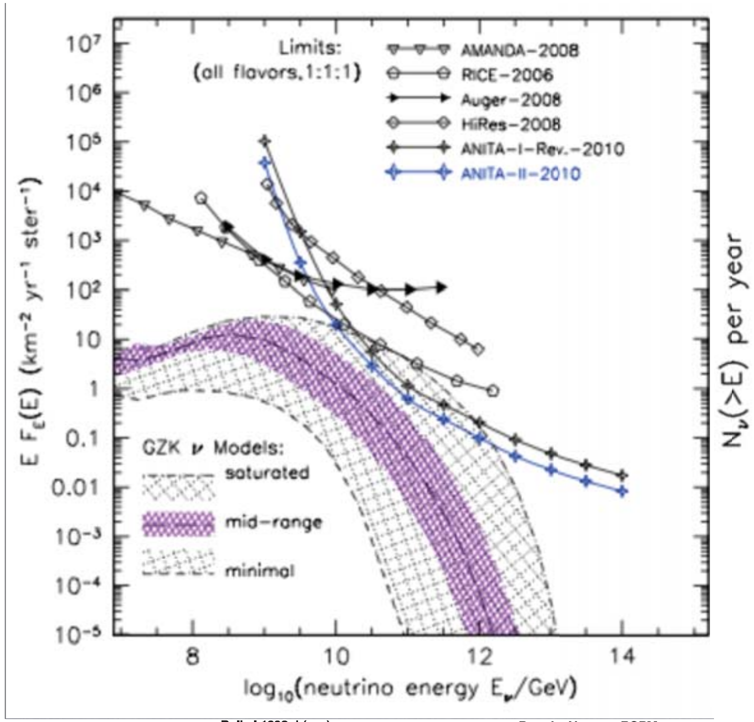
IceCube Coll, arXiv:1103.4250



Kotera et al. (2010)

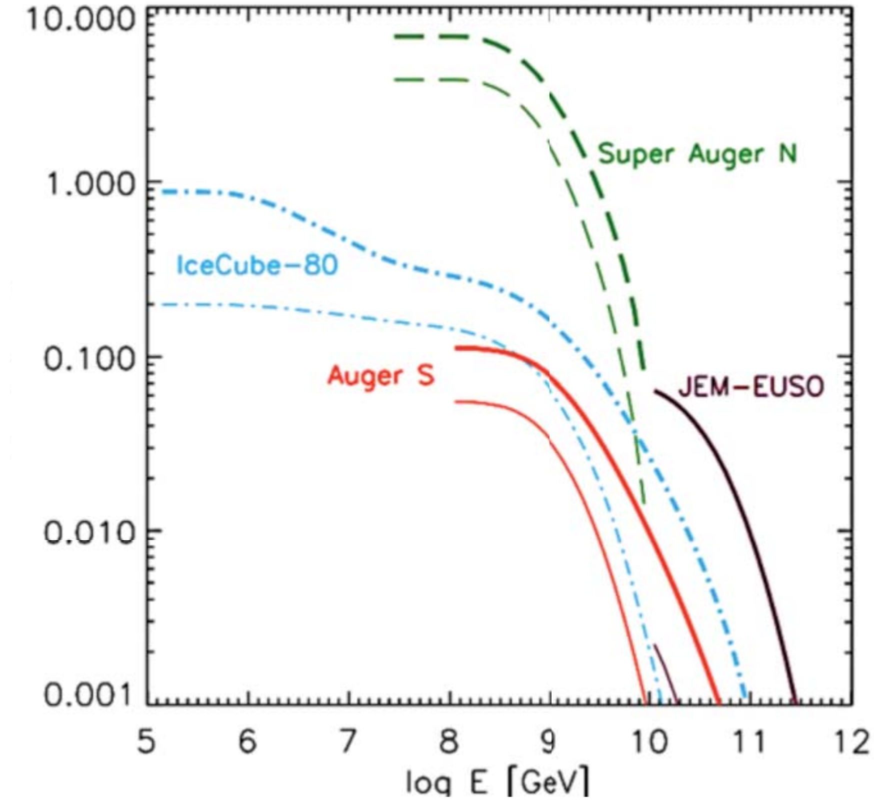
pure proton, strong evolution, E_{max} = 3000 EeV

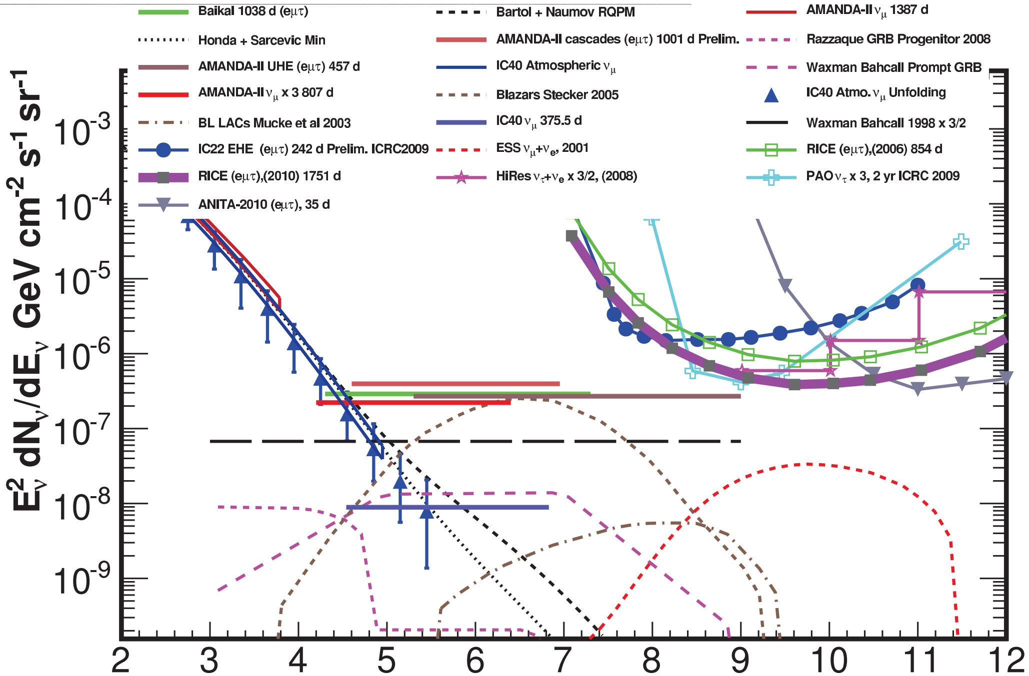
pure Fe, uniform evolution, E_{max} = Z x 100 EeV



Gorham et al, PRD 82 (2010)

Kotera et al, JCAP 1010 (2010)

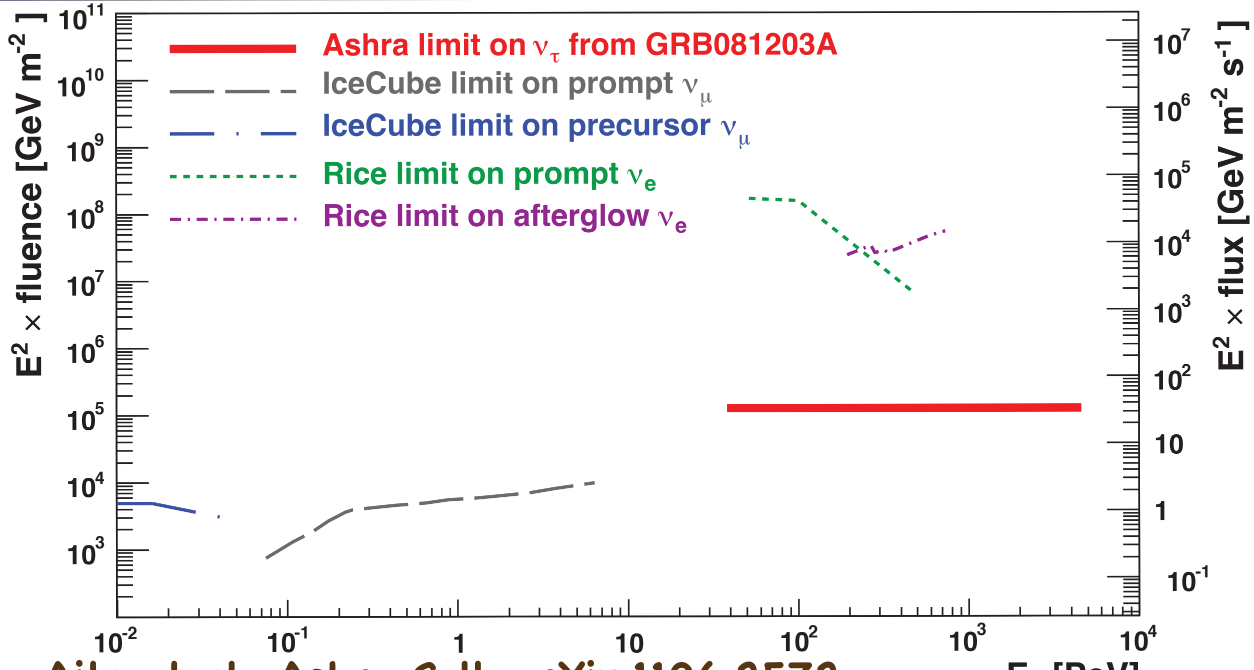




Kravchenko et al, arXiv:1106.1164

Searches from GRBs

Limits on tau neutrinos from GRB081203A using Earth skimming neutrinos

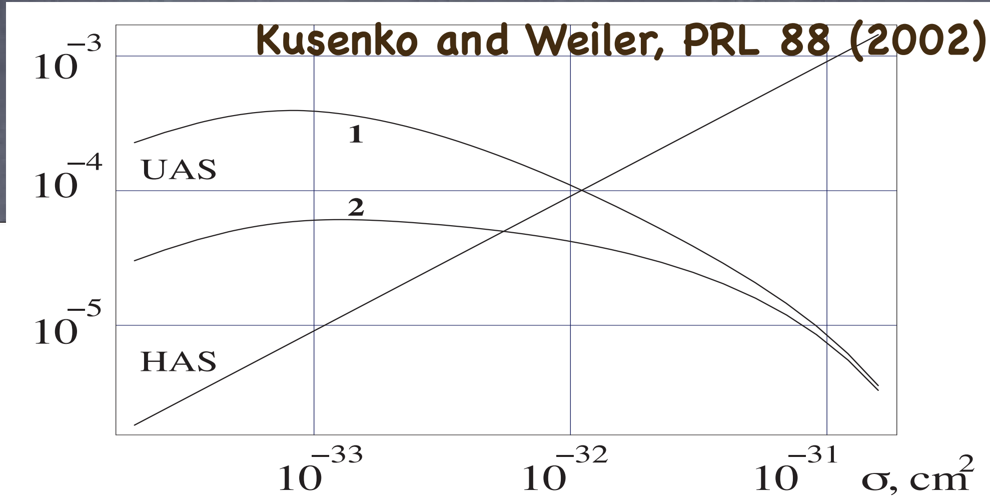


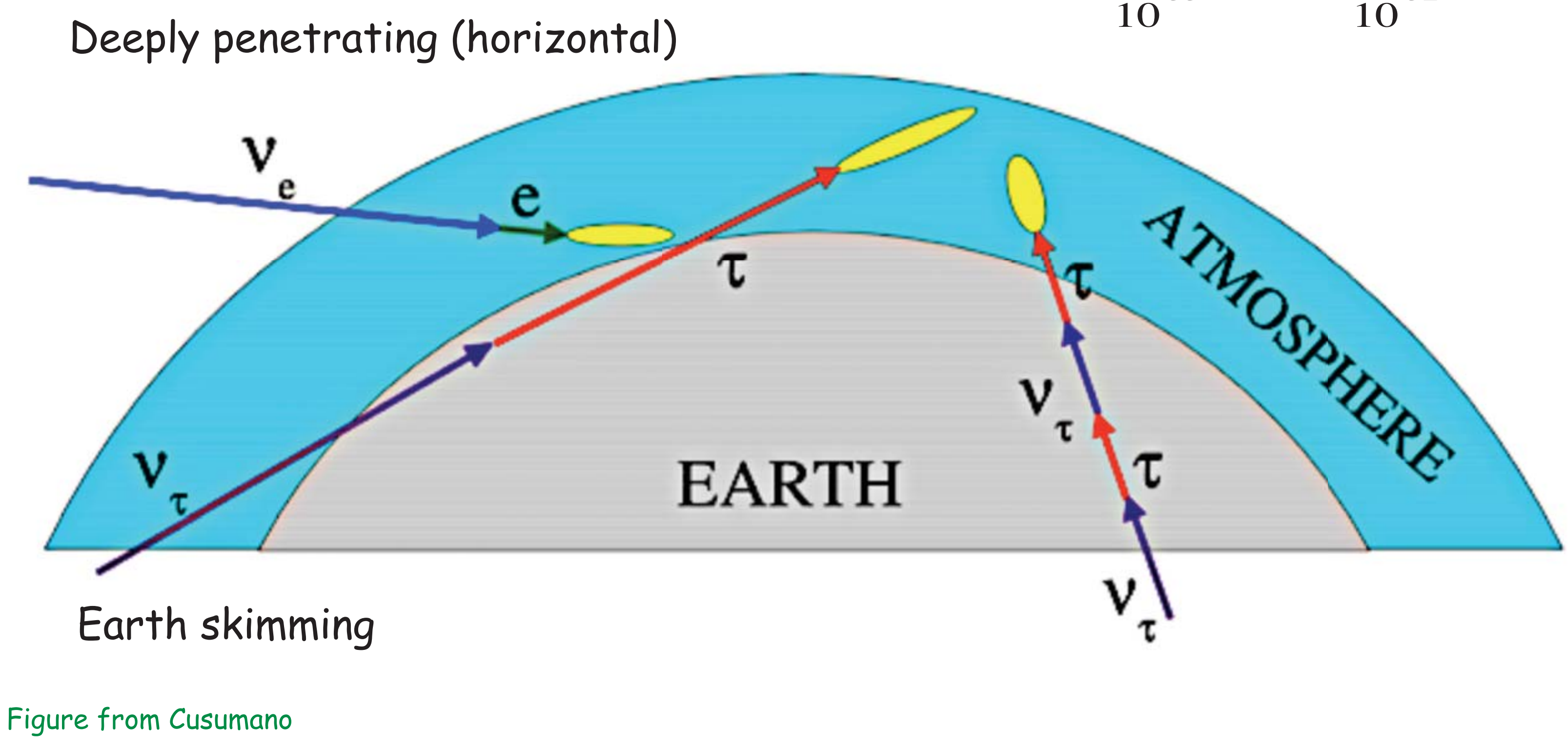
Aita et al., Ashra Coll. arXiv:1106.2572

Cross sections

- For 10^{20} eV neutrinos:
  - production cross section “well known”
  - source function unknown
  - detection cross section needs extrapolation of SM over at least 2 orders of magnitude ---> Not known!!
- How to disentangle source effects from cross section effects upon detection?

Earth skimming neutrinos





Can infer neutrino cross section "directly"

Neutrinos as probes of Planck scale physics

Why LV?

Known theories of gravity rest on Einstein's equivalence principle → local Lorentz invariance

Principle of relativity	Implies the group structure
Isotropy	Implies reciprocity together with Principle of Relativity
Homogeneity	Implies linearity of coordinate transformations
Pre-causality	Implies a notion of past and future

Lorentz invariance

von Ignatowski (1910-1911)

Challenging Lorentz invariance

Lorentz invariance relates, through **homogeneity**, **short to long distances**.

What happens if we have a **minimum length scale?**

$$l_{\mathrm{Pl}} = \sqrt{\hbar G_N / c^3} \sim 1.6 \times 10^{-35}\,\mathrm{m}$$
$$M_{\mathrm{Pl}} = \sqrt{\hbar c / G_N} \sim 1.22 \times 10^{19}\,\mathrm{GeV}$$

Homogeneity likely to be broken

↓

Boost invariance likely to be broken

Modified dispersion relations

Many QG models have led to modified dispersion relations

From a purely phenomenological point of view, the general form of Lorentz invariance violation (LIV) is encoded into the dispersion relations

$$E^2 = p^2 + m^2 + \Delta(p, M)$$

$M \equiv$ spacetime structure scale, generally assumed $\approx M_{\text{Planck}} = 10^{19}$ GeV

Assuming rotation invariance
we can expand this as

$$E^2 = p^2 + m^2 + M\eta^{(1)}|p| + \eta^{(2)}p^2 + \eta^{(3)}|p|^3/M \quad \ldots$$

Exotic physics and UHECRs

- UHECRs can be probes of Lorentz symmetry violation, e.g. induced by Quantum Gravity

- Lorentz violation is expressed through modified dispersion relations

$$E^2 = c^2 p^2 \left(1 + \frac{m^2 c^2}{p^2} + \sum_n \eta^{(n)} \frac{p^{n-2}}{M_{\rm Pl}^{n-2}}\right)$$

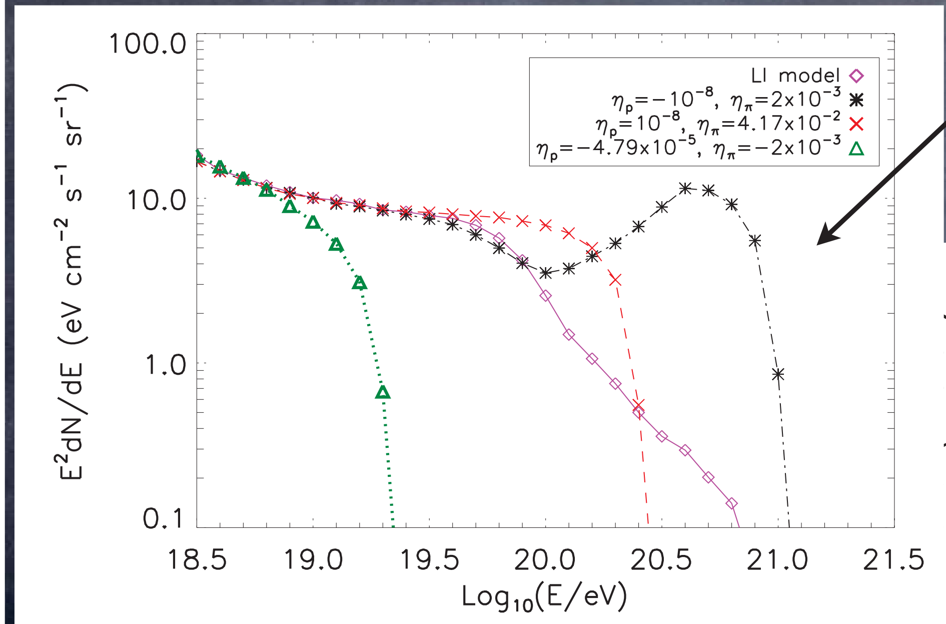
- An estimate of the critical momentum at which LV effects are important is

$$\frac{m^2}{p^2} \approx \frac{p^{n-2}}{M^{n-2}} \Rightarrow p_{crit} \approx \sqrt[n]{m^2 M^{n-2}}$$

n	p_{crit} for ν_e	p_{crit} for e^-	p_{crit} for p^+
2	$p \approx m_\nu \sim 1$ eV	$p \approx m_e = 0.5$ MeV	$p \approx m_p = 0.938$ GeV
3	~1 GeV	~10 TeV	~1 PeV
4	~100 TeV	~100 PeV	~3 EeV

Lorentz invariance violations

Propagated (simulated) LIV spectra

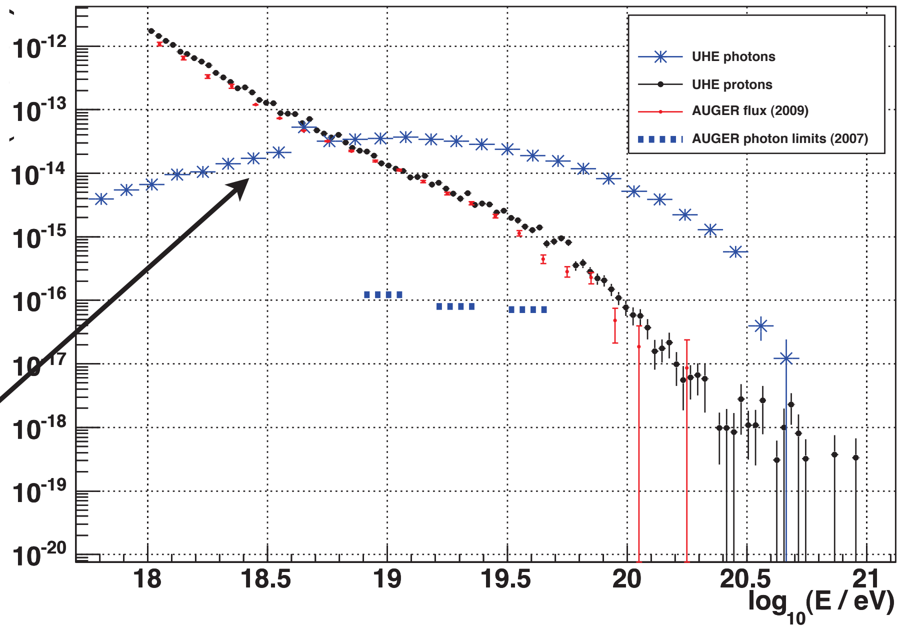


LM, Taylor, Mattingly, Liberati, JCAP 0904 (2009)

modified GZK effect

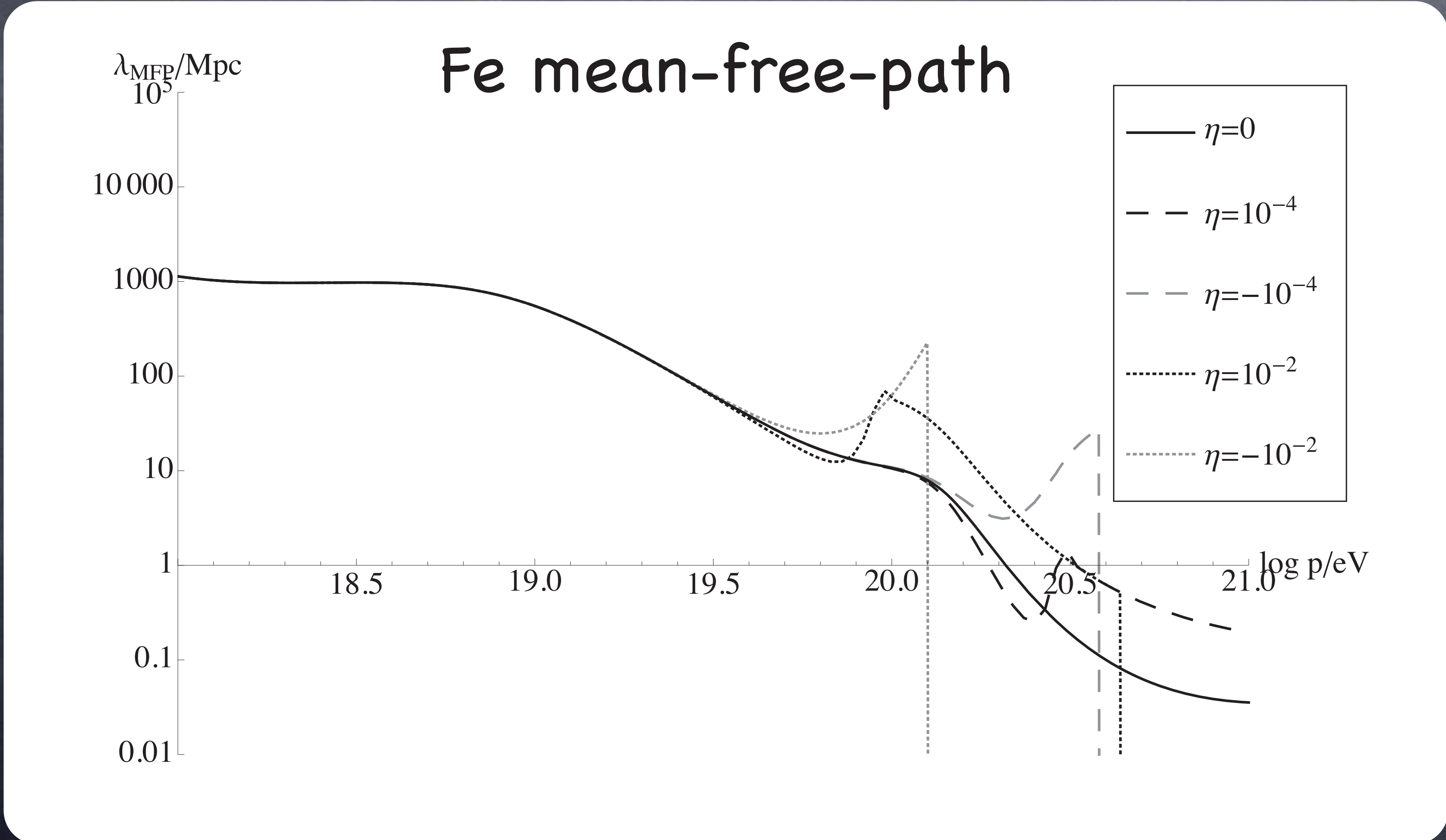
absence of pair production

LM, Liberati, Sigl, PRL 105 (2010)



Lorentz invariance violations

A. Saveliev, LM, G. Sigl, JCAP 2011



LV in the neutrino sector

Effects on oscillations

$$E_{cr} \approx M_{\rm Pl} \left(\frac{\Delta m^2}{M_{\rm Pl}^2 \eta_\nu^n} \right)^{1/n}$$

0.2 GeV (n=3)
20 TeV (n=4)

Strong constraints already from neutrino experiments!

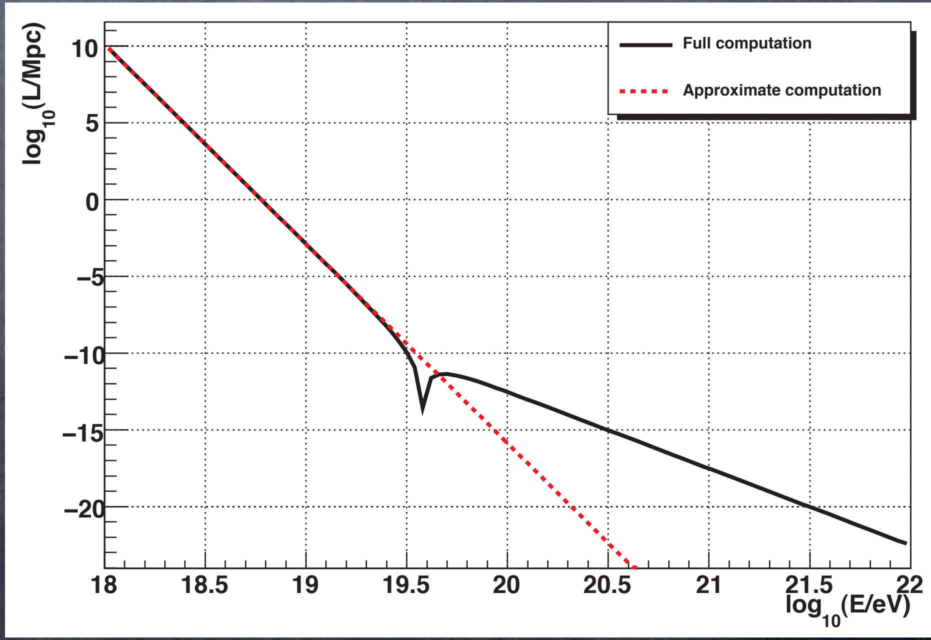
Oscillations: $\delta c / c \lesssim 10^{-27}$

Also quantum decoherence effects alter oscillation patterns

LIV: prospects for the UHE neutrino sector

Mattingly, LM, Galaverni, Liberati, Sigl, JCAP 1002:007,2010

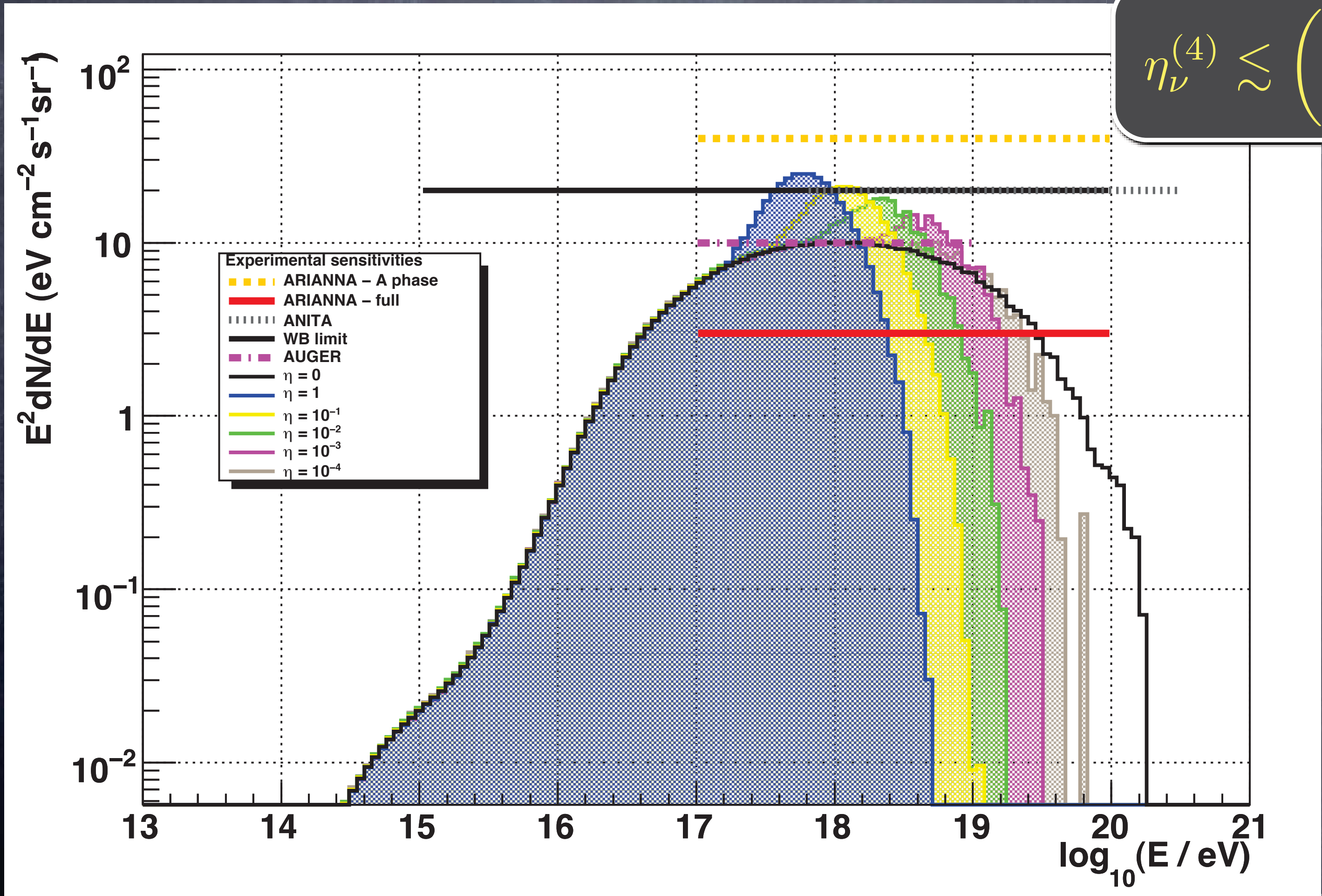
- Neutrino Cherenkov emission $\nu \to \nu\gamma(\nu g)$
  very low rate, irrelevant on Hubble scales
- Neutrino splitting $\nu \to \nu\nu\bar{\nu}$
  very fast rate above 10^{19} eV
- Neutrino decay $\nu \to \nu q\bar{q}$
  can mimic a Z-burst effect
  --> effect at only 5% on the UHECR spectrum, not visible yet



LIV: prospects for the UHE neutrino sector

Mattingly, LM, Galaverni, Liberati, Sigl, JCAP 1002:007,2010

$$\eta_\nu^{(4)} \lesssim \left(\frac{E_{\rm obs}}{6\times 10^{18}\ {\rm eV}}\right)^{-13/4}$$



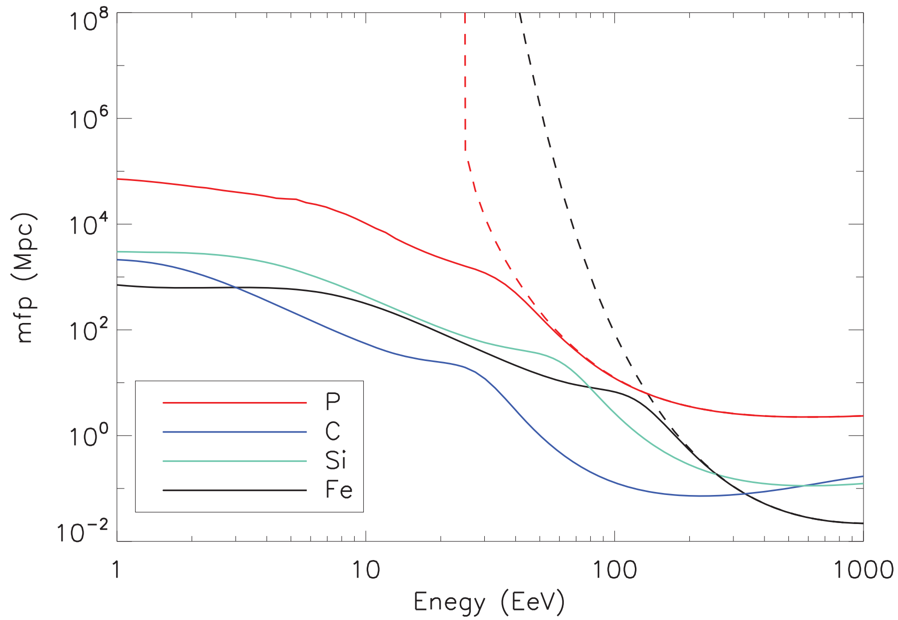
Conclusions

- UHE neutrinos can provide relevant information on UHECRs (compositions, interactions)
- UHE neutrinos can also allow to access new physics beyond SM
- UHE neutrino fluxes already constrained at some level from gamma-ray observations. More careful estimates in the presence of large deflections are ongoing (CRPropa 2.0, https://crpropa.desy.de/)
- Experimentally hard to detect. Experimental sensitivity still to be improved to expect detection. Interesting prospects for IceCube at PeV

The “future”: CRPropa 2.0 nuclei interactions

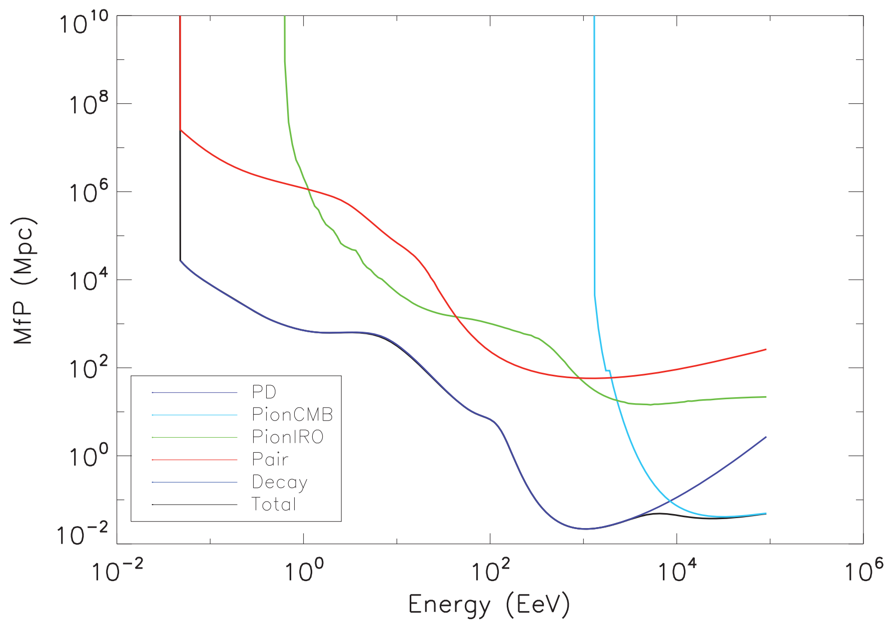
- Pion production (baryon resonance of the constituent nucleons)
- Photodisintegration (fragmentation/giant dipole resonance)
- pair production (continuous energy loss)
- nuclear decay (decay tables + Lorentz boost)
- More info under https://crpropa.desy.de/

Mean free paths



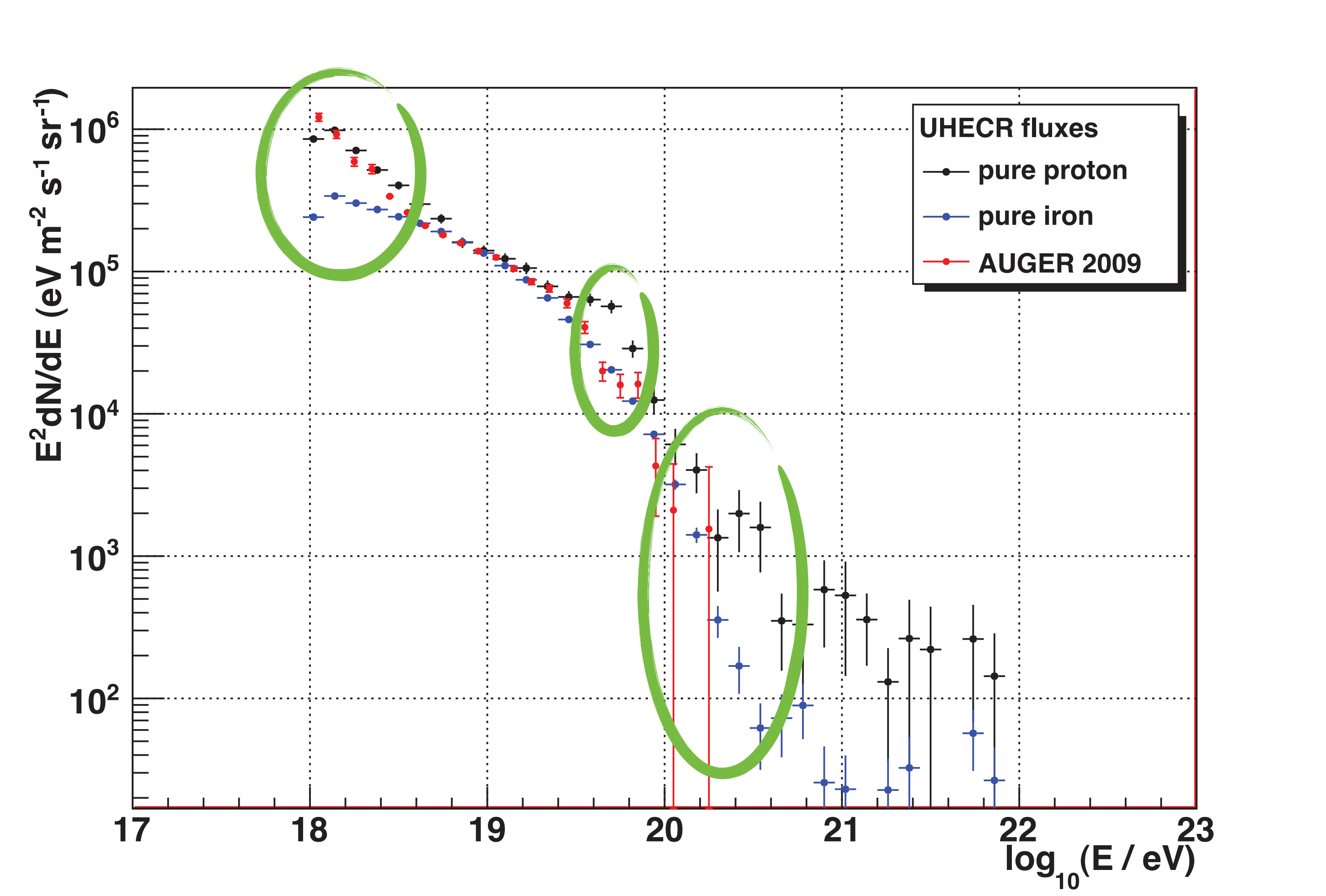
mfp for different nuclear species

Relative contribution of different interactions to the total mfp

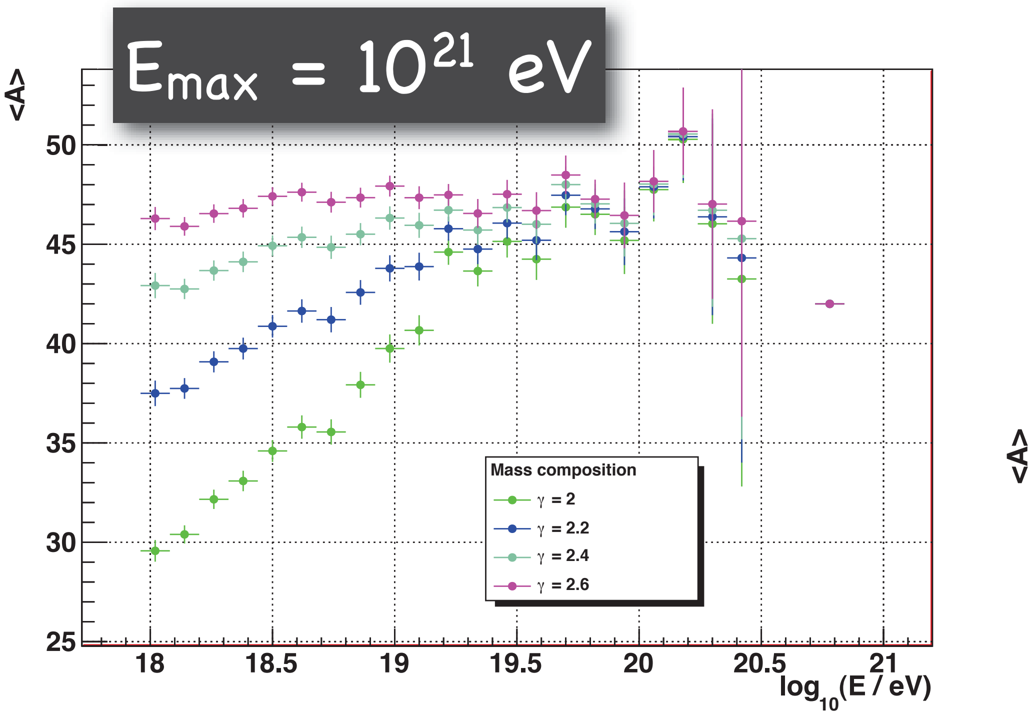


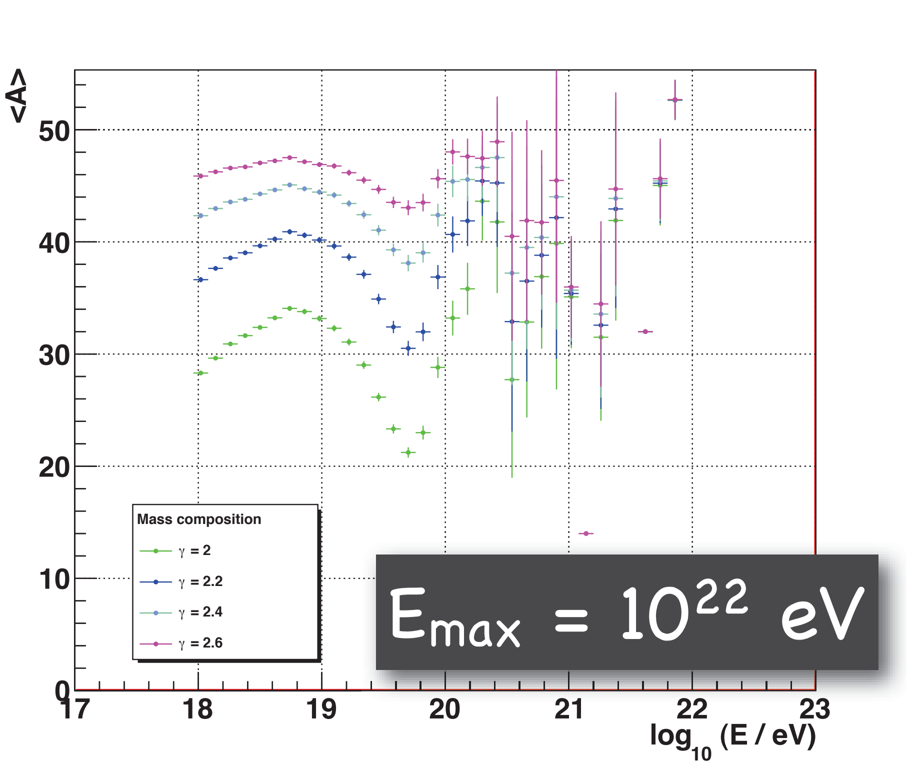
UHECR spectra

Are there distinctive features?

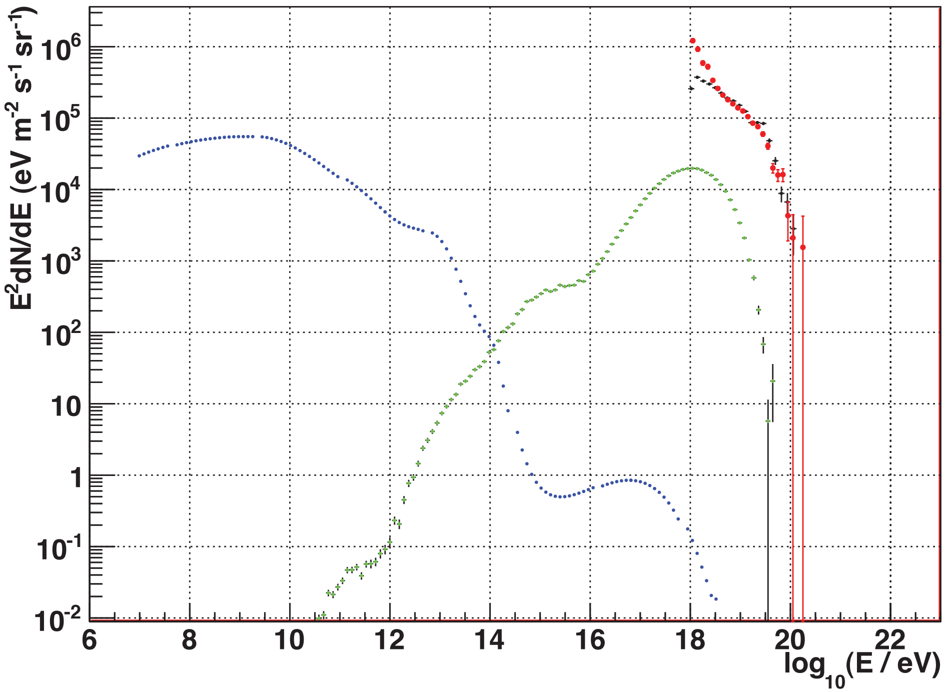


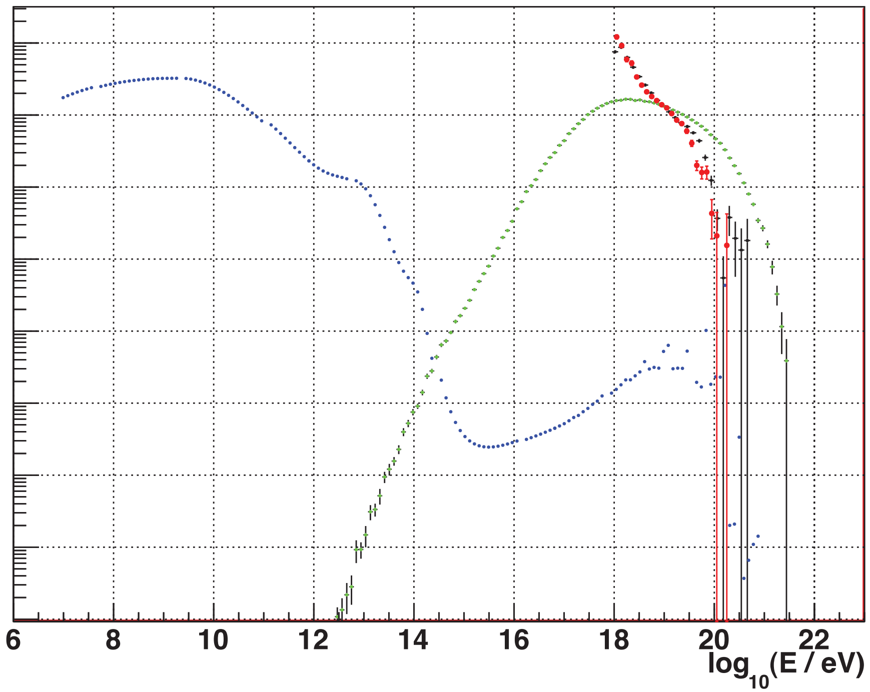
Mass composition





Proton vs Iron ?

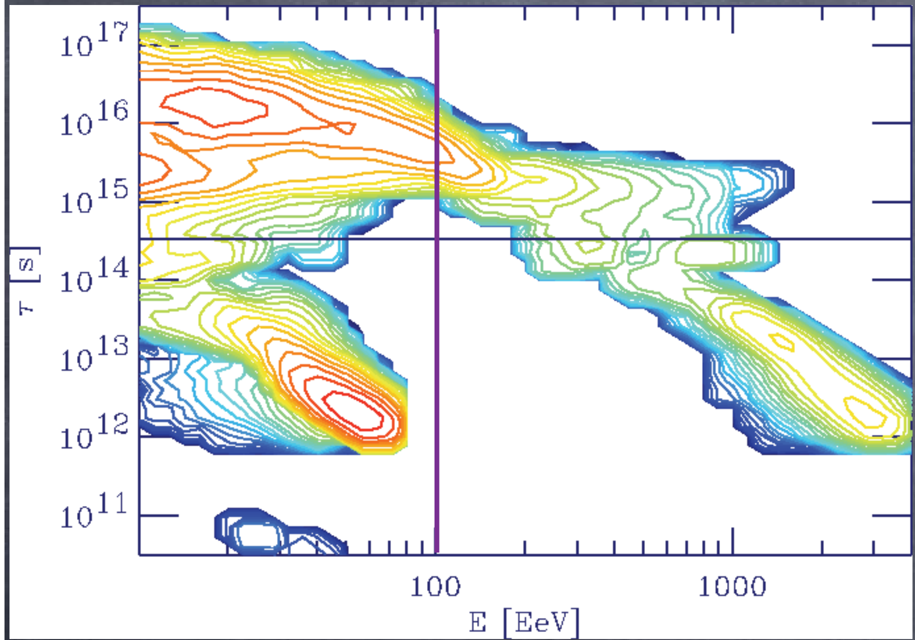


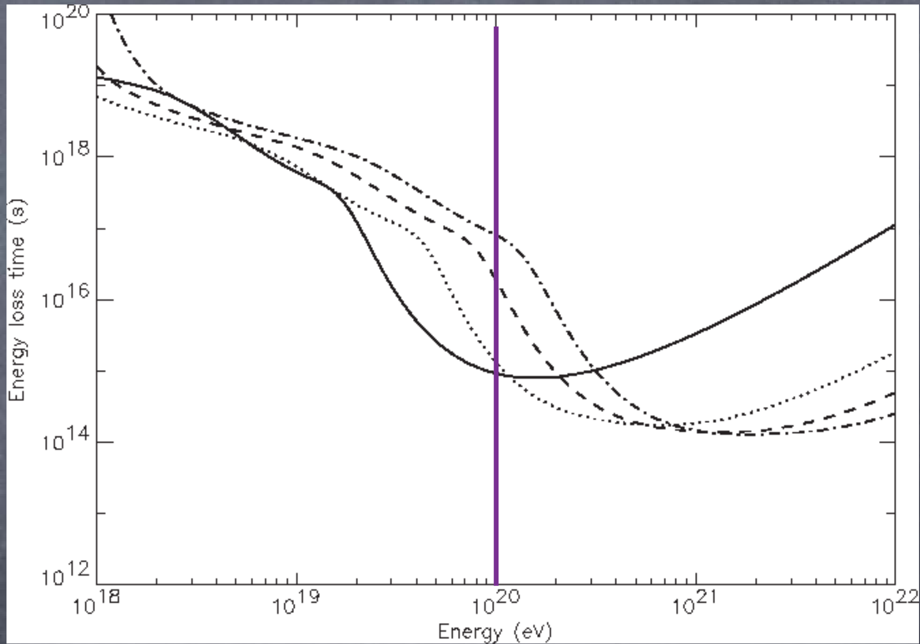


Iron Proton

How relevant are magnetic fields?

Importance of deflections highlighted by comparing propagation time to energy loss time



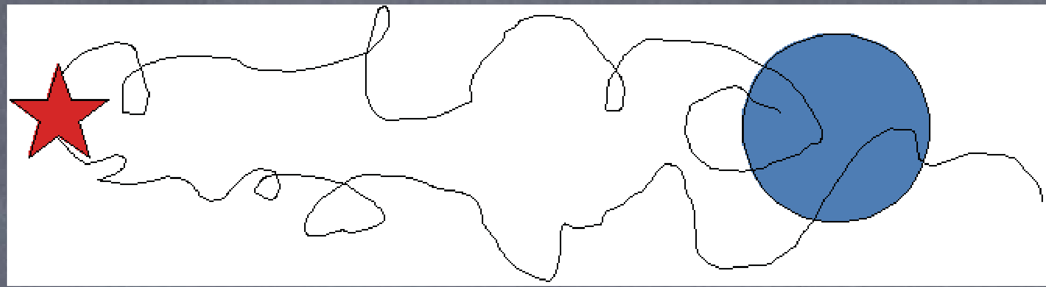


horizontal line=straight line propagation time
low delay-time spike at ~50 EeV due to spallation nucleons produced outside source field.

Energy loss times for helium (solid), carbon (dotted), silicon (dashed), and iron (dash-dotted).

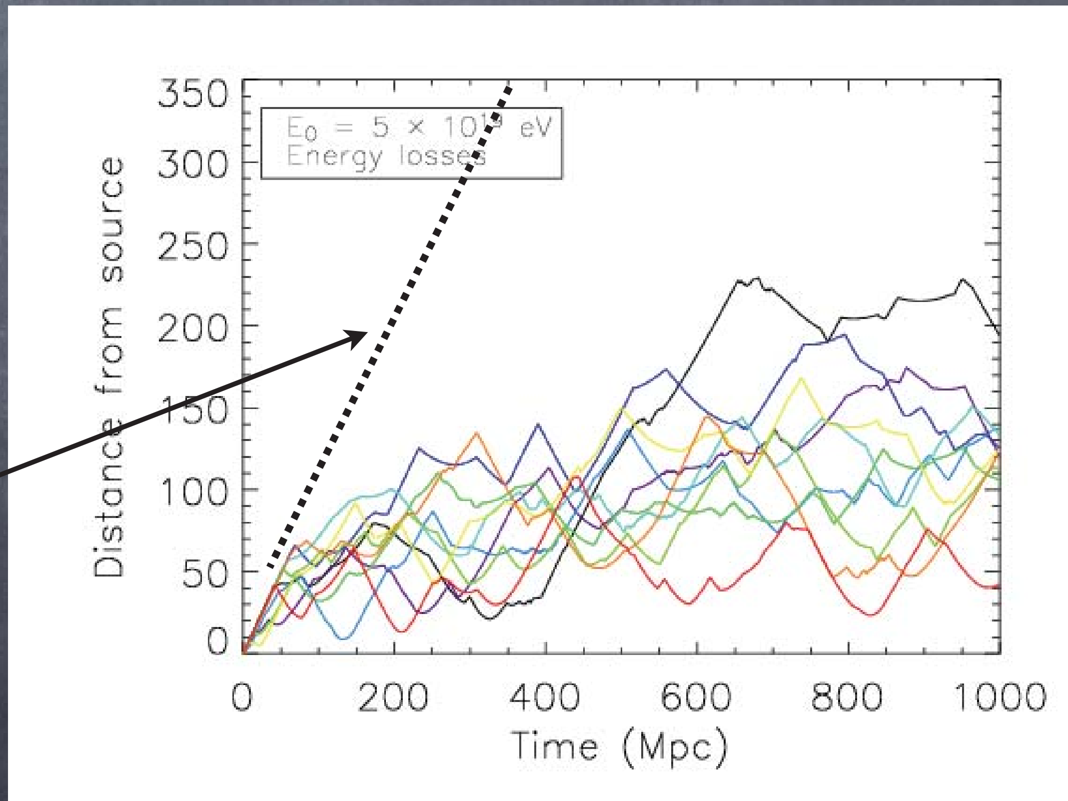
3-D simulations

Many deflections between source and the observer (modeled as a sphere)



Time consuming computation, many trajectories are lost and do not reach the observer

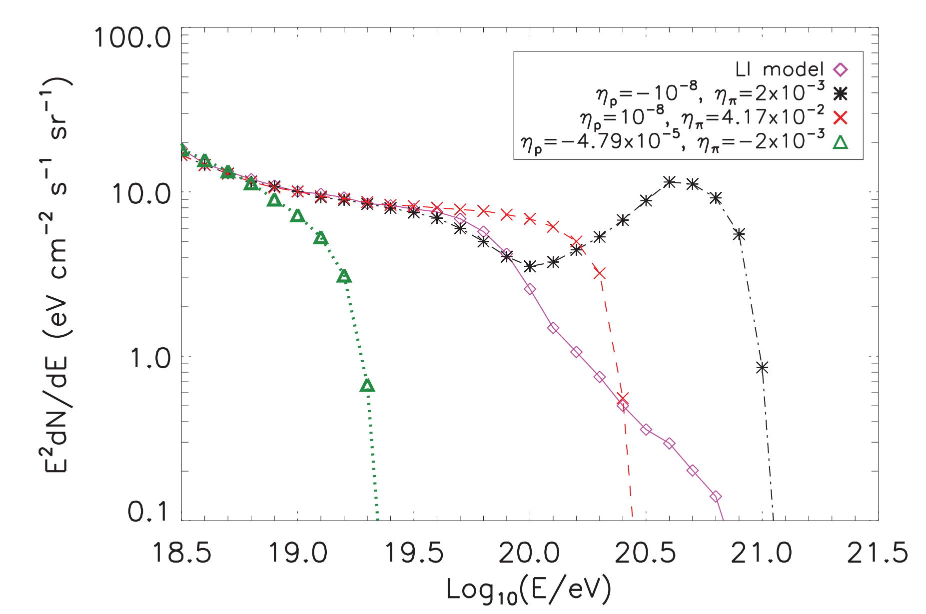
case of ballistic propagation



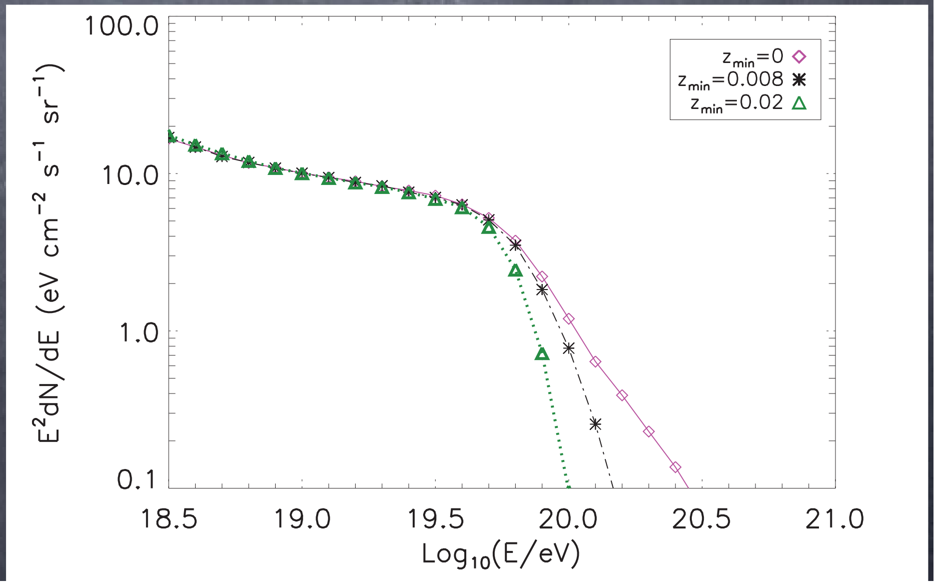
LV in the spectrum

LM, Taylor, Mattingly, Liberati, arXiv:0902.1756

Propagated (simulated) LIV spectra



- Effect of LIV: modify absorption of protons on the CMB (increases/decreases the photon energy needed to interact for η_p < 0/>0)
- Recovery of flux at high energy, due to reduced inelasticity

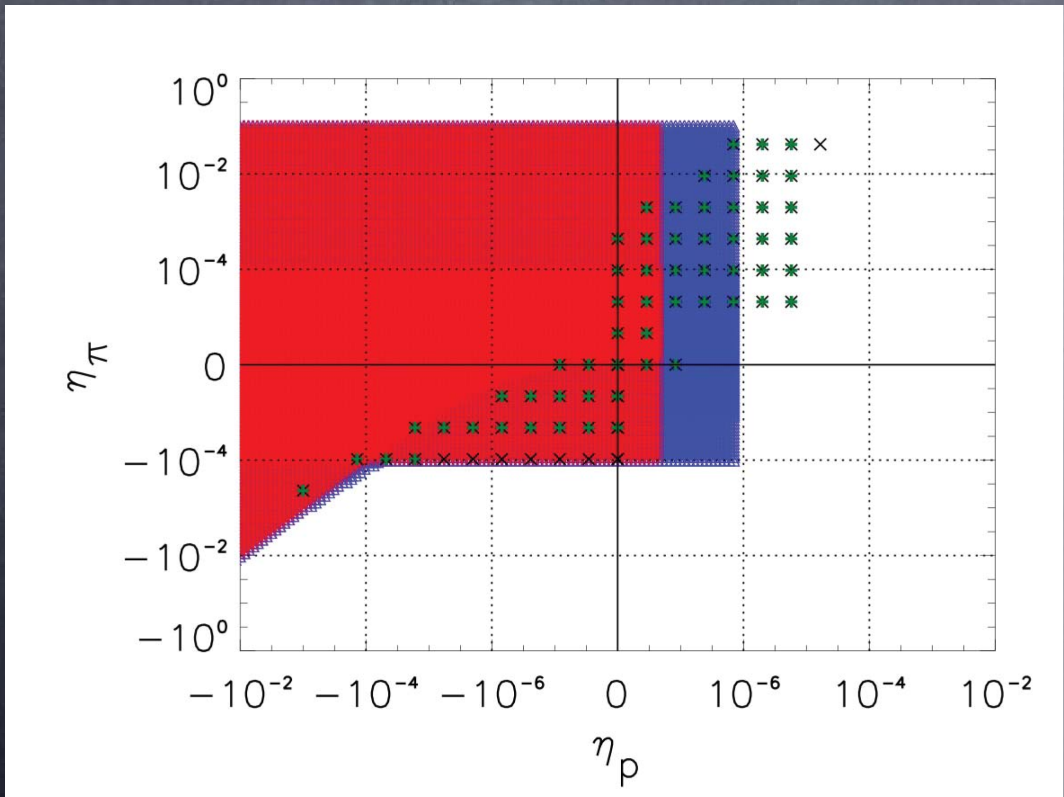


- Effect of sources: where is the closest UHECR source? We don't know, but the effect is different from the one due to LIV

LV in the spectrum

LM, Taylor, Mattingly, Liberati, arXiv:0902.1756

Final constraints in case n=4



red/blue regions:
allowed by absence of VC up to ~10^{20} eV

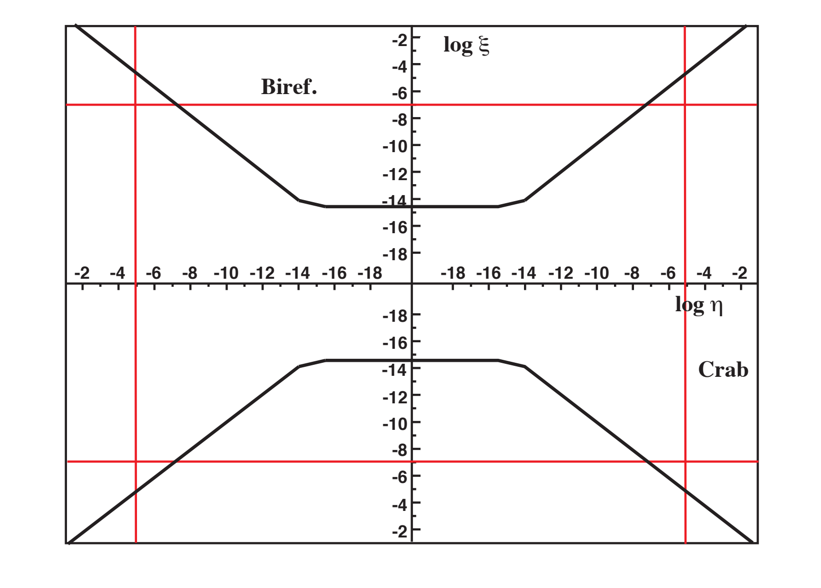
green points/black crosses:
in agreement with observed spectrum within 95% and 99% CL resp.

LV in the photon spectrum

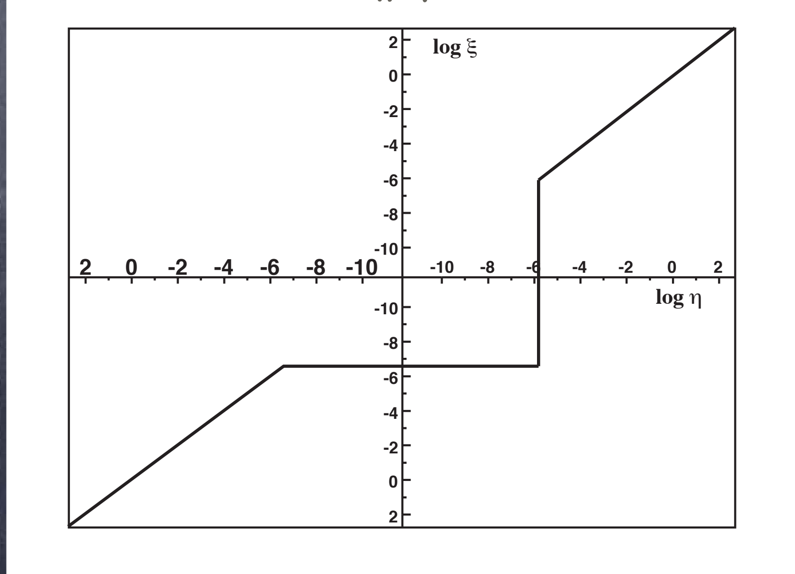
Galaverni, Sigl, PRL 100, 021102 (2008)
LM, S. Liberati, JCAP 0808, 027 (2008)
Galaverni, Sigl, PRD 78, 063003 (2008)

- **GZK photons** are produced by the decay of π^0s due to pion production
- In LI theory they are **attenuated mainly by pair production onto CMB and URB** leading to a theoretically expected photon fraction < 1% at 10^{19} eV and < 10% at 10^{20} eV.
- Present limits on photon fraction: **2.0%, 5.1%, 31%, 36% (95% CL) at 10, 20, 40, 100 EeV**
- **LIV** strongly affects the threshold of this process: **lower and also upper thresholds**.
- **If $k_{up} < 10^{20}$ eV then photon fraction in UHECR much larger than present upper limits**
- LIV also introduces competitive processes: γ**-decay**

n=3



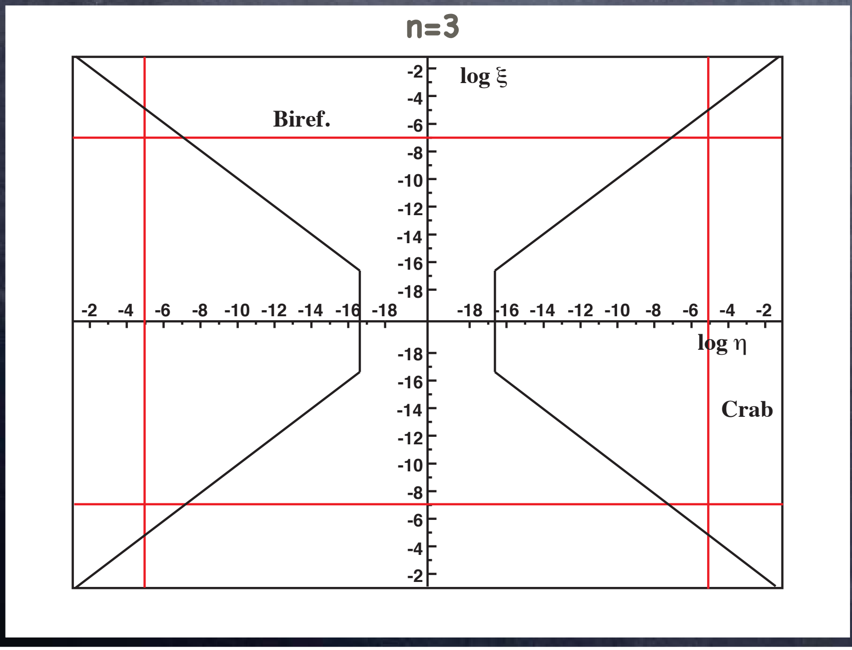
n=4

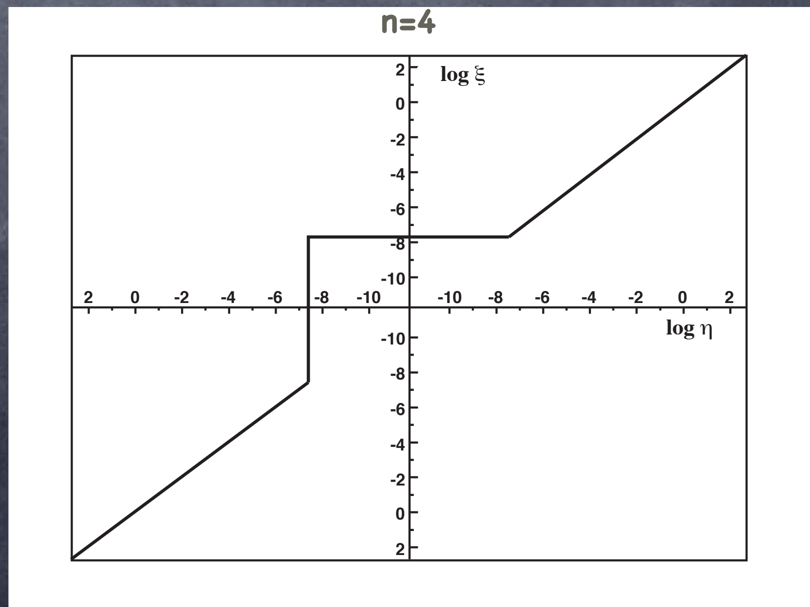


LV in the photon spectrum

Galaverni, Sigl, PRL 100, 021102 (2008)
LM, S. Liberati, JCAP 0808, 027 (2008)
Galaverni, Sigl, PRD 78, 063003 (2008)

- **GZK photons** are produced by the decay of π^0s due to pion production
- In LI theory they are **attenuated mainly by pair production onto CMB and URB** leading to a theoretically expected photon fraction < 1% at 10^{19} eV and < 10% at 10^{20} eV.
- Present limits on photon fraction: **2.0%, 5.1%, 31%, 36% (95% CL) at 10, 20, 40, 100 EeV**
- **LIV** strongly affects the threshold of this process: **lower and also upper thresholds**.
- **If k_{up} < 10^{20} eV then photon fraction in UHECR much larger than present upper limits**
- LIV also introduces competitive processes: γ-**decay**
- **If photons above 10^{19} eV are detected then γ-decay threshold > 10^{19} eV**

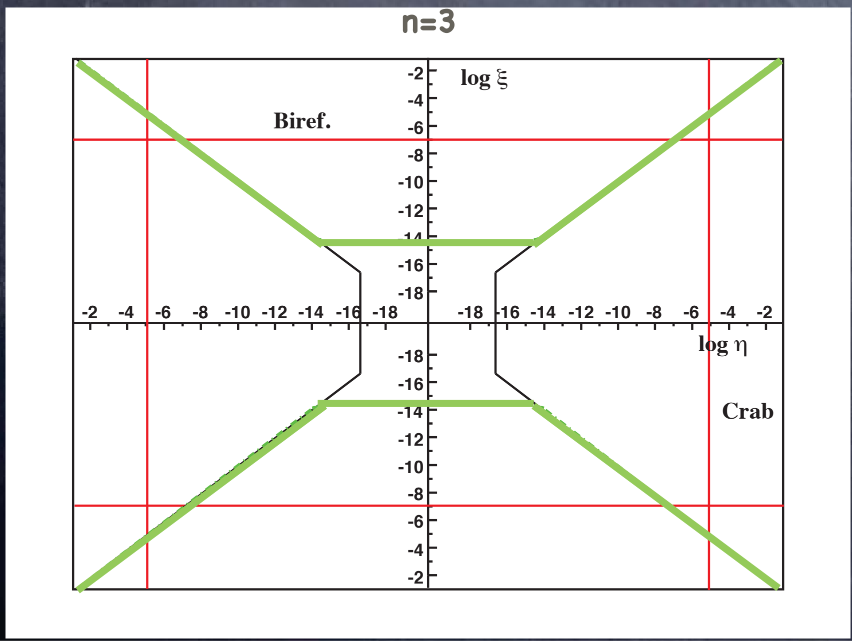


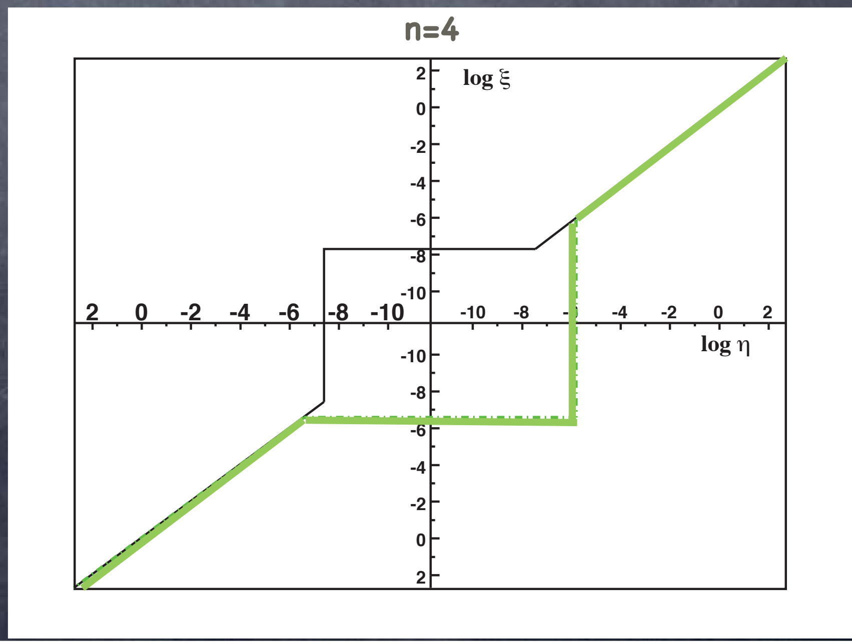


LV in the photon spectrum

Galaverni, Sigl, PRL 100, 021102 (2008)
LM, S. Liberati, JCAP 0808, 027 (2008)
Galaverni, Sigl, PRD 78, 063003 (2008)

- **GZK photons** are produced by the decay of π^0s due to pion production
- In LI theory they are **attenuated mainly by pair production onto CMB and URB** leading to a theoretically expected photon fraction < 1% at 10^{19} eV and < 10% at 10^{20} eV.
- Present limits on photon fraction: **2.0%, 5.1%, 31%, 36% (95% CL) at 10, 20, 40, 100 EeV**
- **LIV** strongly affects the threshold of this process: **lower and also upper thresholds**.
- **If $k_{up} < 10^{20}$ eV then photon fraction in UHECR much larger than present upper limits**
- LIV also introduces competitive processes: **γ-decay**
- **If photons above 10^{19} eV are detected then γ-decay threshold > 10^{19} eV**





Secondary gamma-rays

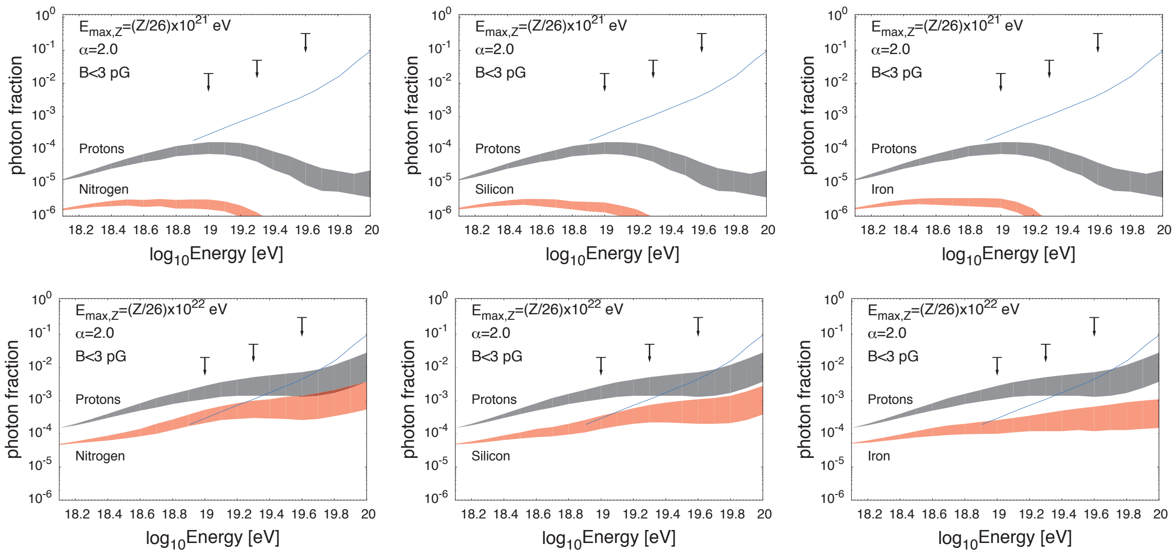


FIG. 1: The fraction of ultra-high energy cosmic rays that are photons as a function of energy for the case of weak extragalactic magnetic fields ($< 3 \times 10^{-12}$ G). Results are shown for two choices of the maximum injected energy and for models in which the cosmic ray sources inject uniquely protons, nitrogen, silicon, or iron nuclei. The bands reflect the range of the extragalactic radio backgrounds considered. Also shown are the upper limits on the photon fraction from the Pierre Auger Observatory [9] and its ultimate projected reach (blue line) [10].

Hooper, Taylor, Sarkar, 2010

Spectra strongly depend on magnetic fields:
- energy losses (electron synchrotron cascades)
- deflections (increased energy losses of primary nuclei)

Evaluation of spectra in full 3D required

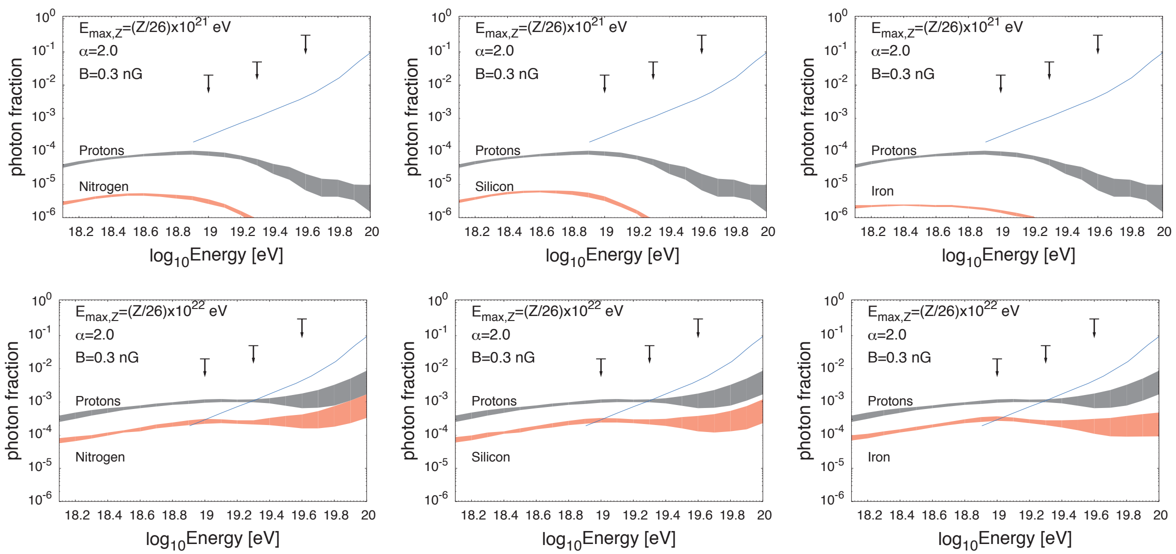
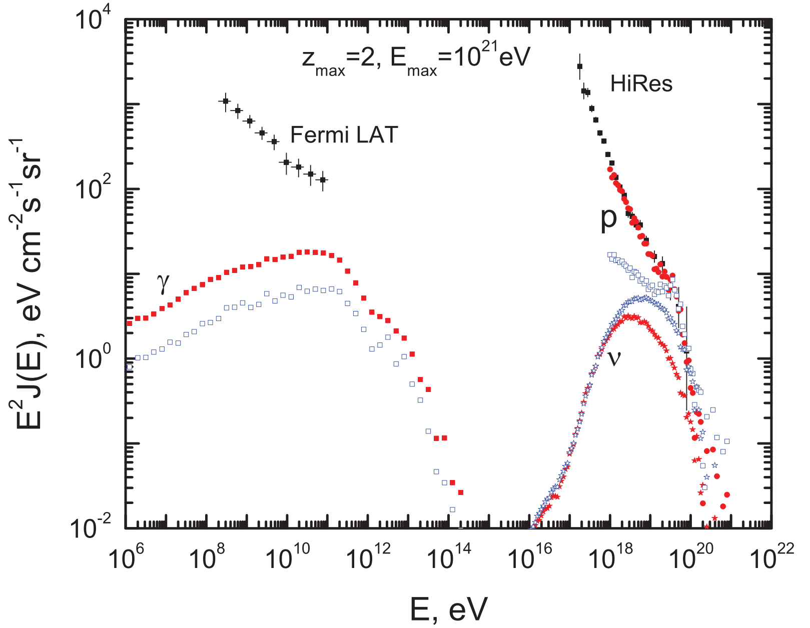


FIG. 2: The same as in Fig. 1, but for the case of 0.3 nG extragalactic magnetic fields.

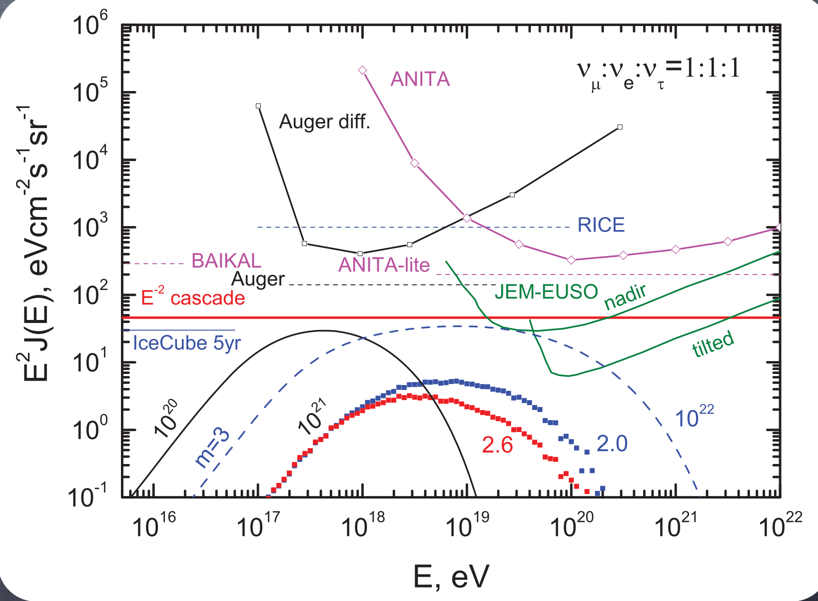
Gamma-ray fluxes constrain neutrino fluxes

Berezinsky et al, 2010
Ahlers et al, 2010



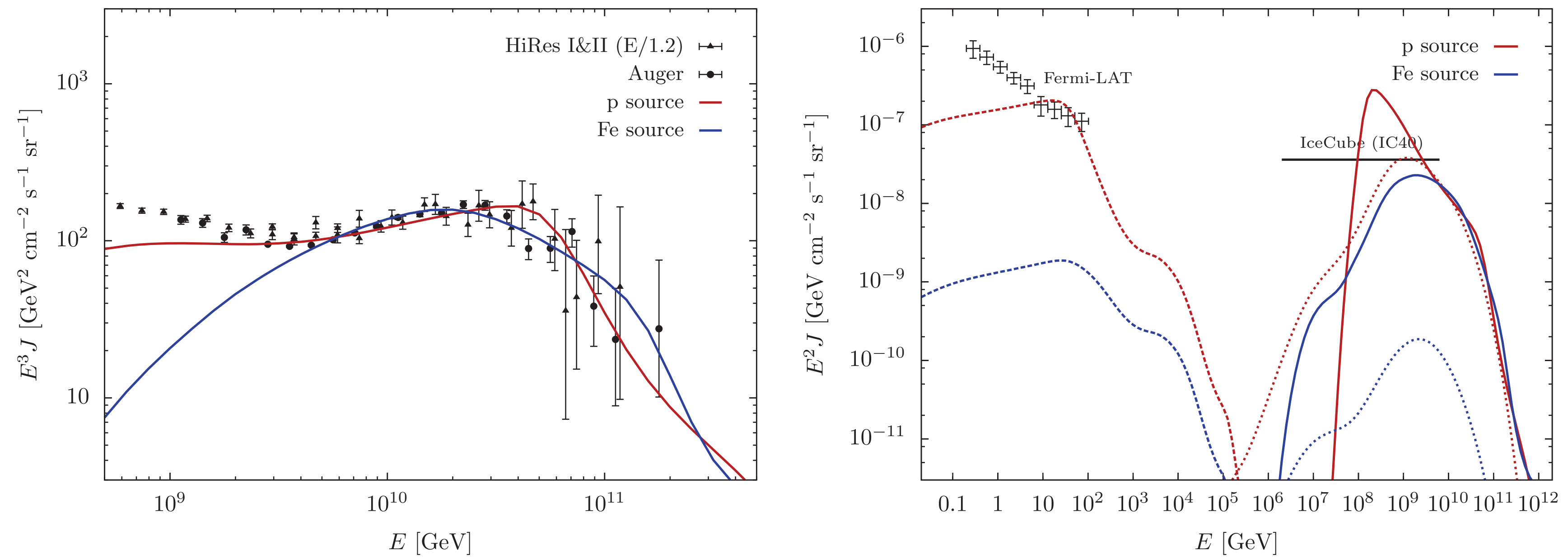
Cosmogenic neutrino flux constrained by FERMI gamma-ray observations

How does the presence of magnetic fields modify these conclusions?
To be investigated with CRPropa 2.0



Gamma-ray fluxes constrain neutrino fluxes

Ahlers and Salvado, arXiv:1105.5113



$$\frac{dN}{dE} \propto (1+z)^5$$

for pure proton injection