# Lorentz Symmetry Violation in the Photon Sector

For photons we assume the dispersion relation

$$\omega_\pm^2 = k^2 + \xi_n^\pm k^2 \left(\frac{k}{M_{\rm Pl}}\right)^n \,, n \geq 1 \,,$$

and for electrons

$$E_{e,\pm}^2 = p_e^2 + m_e^2 + \eta_n^{e,\pm} p_e^2 \left(\frac{p_e}{M_{\rm Pl}}\right)^n \,, n \geq 1 \,,$$

with only one term present. Polarizations denoted with ±. For positrons, effective field theory implies $\eta_n^{p,\pm} = (-1)^n \eta_n^{e,\mp}$. Furthermore, $\xi_n^+ = (-1)^n \xi_n^-$, so that the problem depends on three parameters which in the following we denote by

$$\xi_n, \eta_n^+, \eta_n^-$$

for each n.

Consider pair production on a background photon of energy $k_b$ and assume kinematics with ordinary energy-momentum conservation, with $p_e = (1-y)k$, $p_p = yk$. Using $x = 4y(1-y)k/k_{LI}$ with the threshold in absence of Lorentz invariance (LI) violation, $k_{LI}=m_e^2/\omega_b$ , the condition for pair production is then

$$\alpha_n x^{n+2} + x - 1 \geq 0$$

where

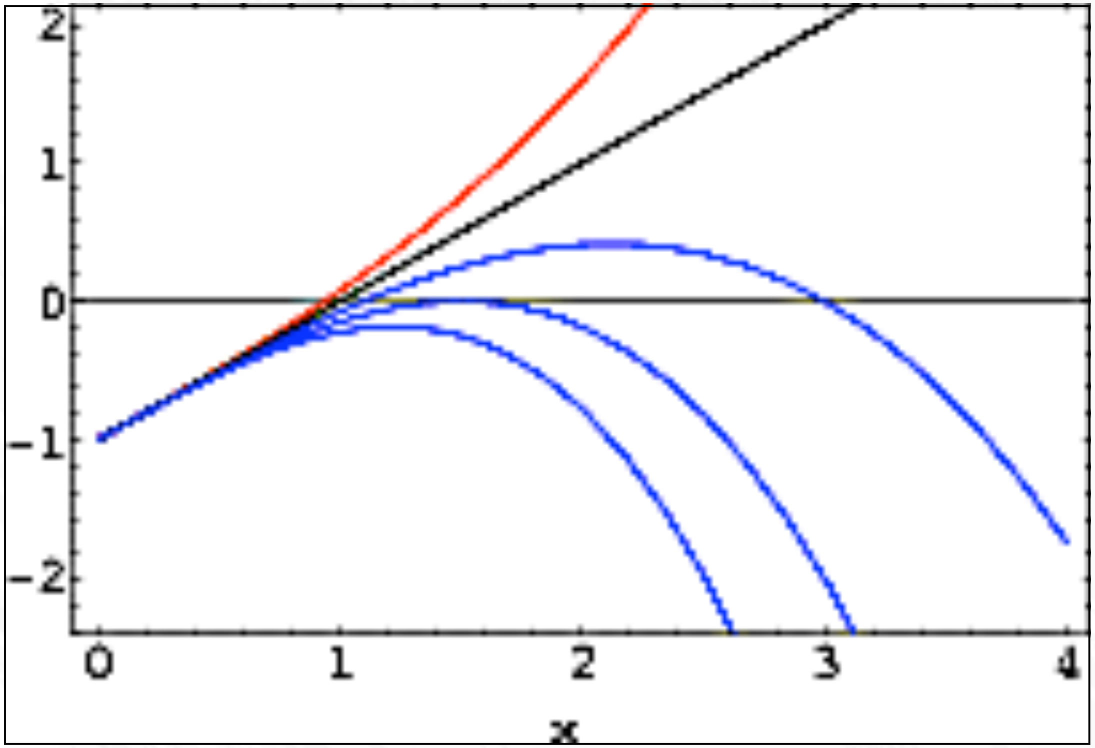
$$\alpha_n = \frac{\xi_n - (-1)^n \eta_n^{\mp} y^{n+1} - \eta_n^{\pm}(1-y)^{n+1}}{2^{2(n+2)} y^{n+1}(1-y)^{n+1}} \frac{m_e^{2(n+1)}}{k_b^{n+2} M_{\mathrm{Pl}}^n} .$$

All combinations of $\xi_n, \eta_n^+, \eta_n^-$ can occur, depending on the partial wave of the pair, governed by total angular momentum conservation. All partial waves are allowed away from the thresholds.

The condition for photon decay is

$$\alpha_n x^{n+2} - 1 \geq 0$$

There are at most two real solutions $0 \leq x_n^l \leq x_n^r$ for pair production (lower and upper thresholds):

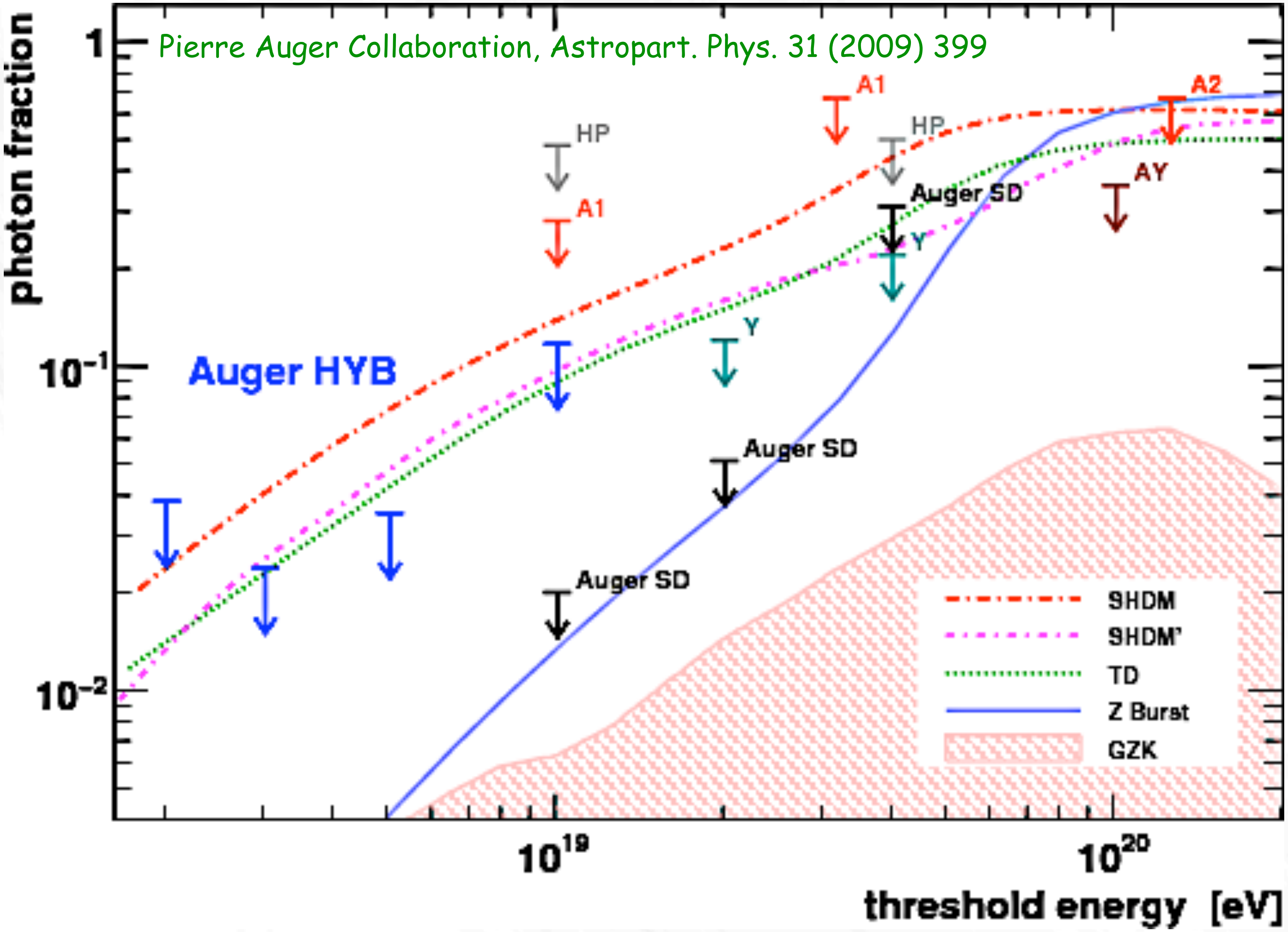


Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

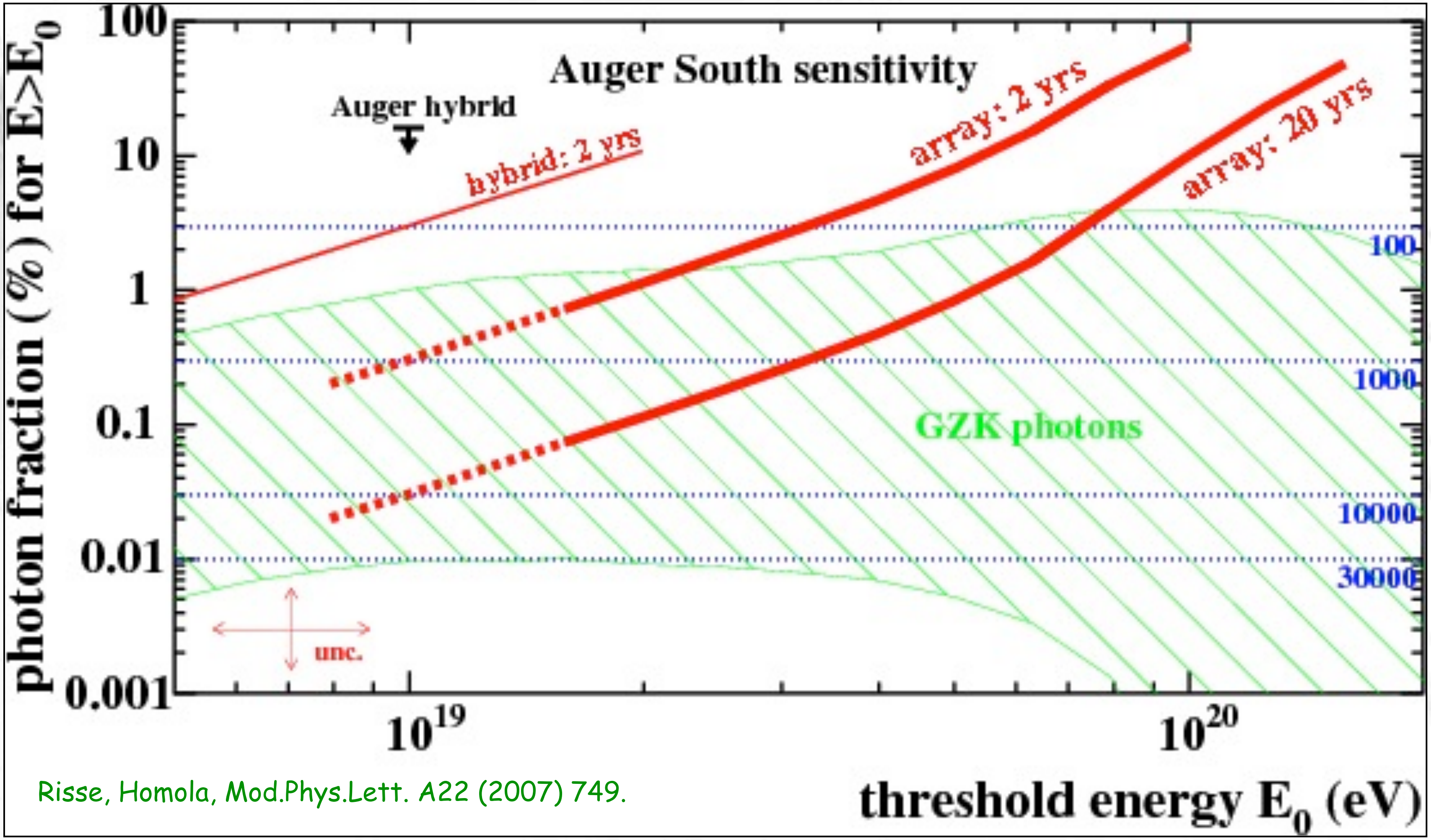
For photon decay there is at most one positive real threshold.

Minimize/maximize these wrt. y

Current upper limits on the photon fraction are of order 2% above $10^{19}$ eV from latest results of the Pierre Auger experiments (ICRC) and order 30% above $10^{20}$ eV.

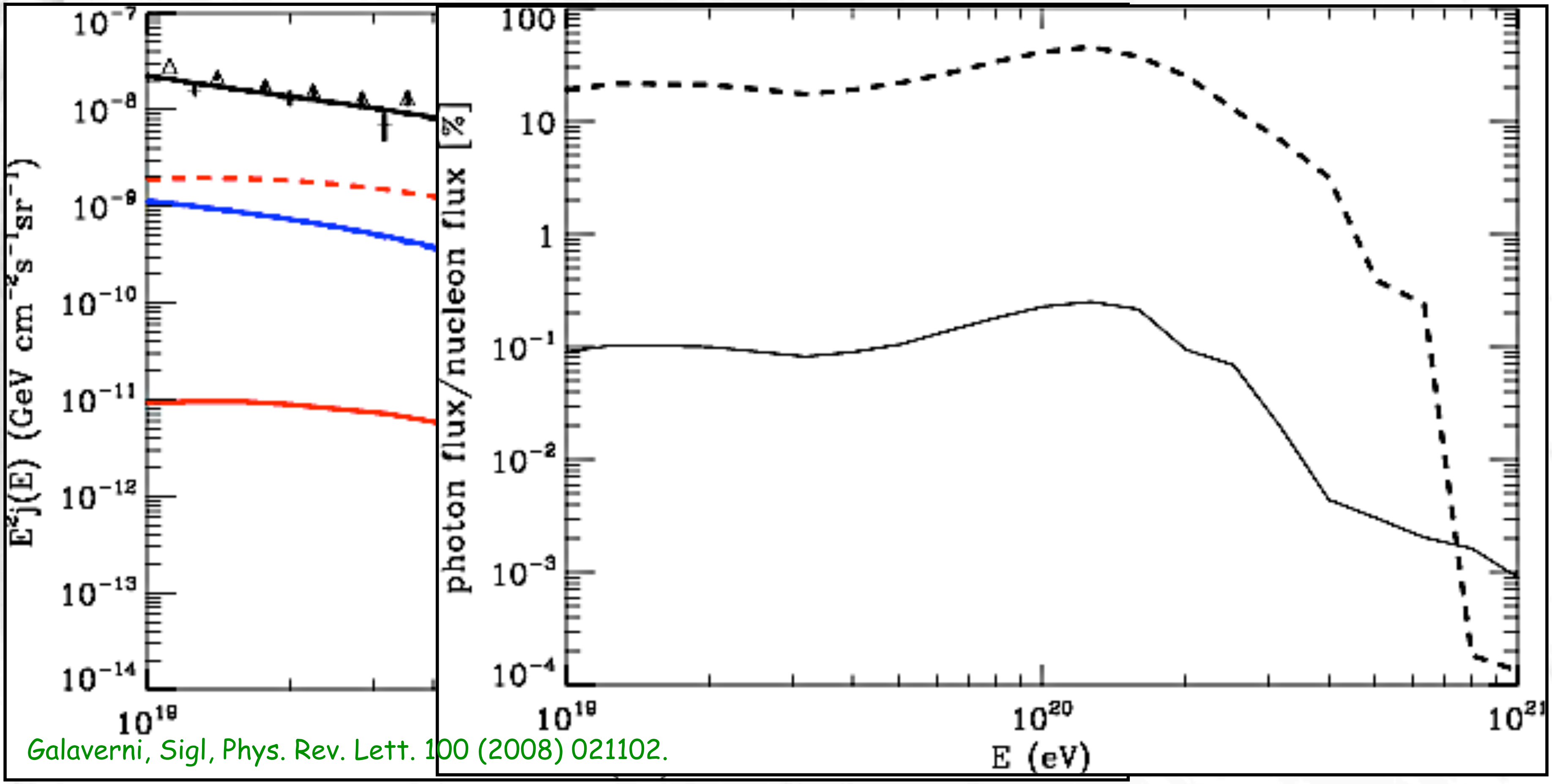

Pierre Auger Collaboration, Astropart. Phys. 31 (2009) 399

Future data will allow to probe smaller photon fractions and the GZK photons



Risse, Homola, Mod.Phys.Lett. A22 (2007) 749.

In absence of pair production for $10^{19}$ eV < ω < $10^{20}$ eV the photon fraction would be ~20% and would thus violate experimental bounds:



Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

A given combination $\xi_n, \eta_n^+, \eta_n^-$ is ruled out if, for $10^{19}$ eV < ω < $10^{20}$ eV, at least one photon polarization state is stable against decay and does not pair produce for any helicity configuration of the final pair.

In the absence of LIV in pairs for n=1, this yields:

$$\xi_1 \leq 2.4 \times 10^{-15}$$

and for n=2:

$$\xi_2 \geq -2.4 \times 10^{-7}$$

If a UHE photon were detected, any LIV parameter combination for which photon decay is allowed for at least one helicity configuration of the final pair, for both photon polarizations, would be ruled out.

For n = 1, all parameters of absolute value < $10^{-14}$ ruled out

For n = 2, if absolute value of both the photon and one of the electron parameters is < $10^{-6}$, the second electron parameter can be arbitrarily large even once a UHE photon is seen.

**Such strong limits may indicate that Lorentz invariance violations are completely absent !**

# Conclusions1

1.) The origin of very high energy cosmic rays is still one of the fundamental unsolved questions of astroparticle physics.
This is especially true at the highest energies, but even the origin of Galactic cosmic rays is not resolved beyond doubt.

2.) Above 60 EeV, arrival directions are anisotropic at 99% CL and seem to correlate with the local cosmic large scale structure.

3.) It is currently not clear what the sources are within these structures. Potential sources closest to the arrival directions require heavier nuclei to attain observed energies. Air shower characteristics also seem to imply a mixed composition.

4.) This is surprising because larger deflections would be expected for nuclei already in the Galactic magnetic field.

5.) A possible solution could be considerable deflection only within the large scale structure; but this would be a coincidence for galactic deflection

# Conclusions2

6.) Pion-production establishes a very important link between the physics of high energy cosmic rays on the one hand, and γ-ray and neutrino astrophysics on the other hand. All three of these fields should be considered together.

7.) There are many potential high energy neutrino sources including speculative ones. But the only guaranteed ones are due to pion production of primary cosmic rays known to exist: Galactic neutrinos from hadronic interactions up to $\sim 10^{16}$ eV and "cosmogenic" neutrinos around $10^{19}$ eV from photopion production. Flux uncertainties stem from uncertainties in cosmic ray source distribution and evolution.

8.) Both diffuse cosmogenic neutrino and photon fluxes depend on chemical composition (and maximal acceleration energy)

9.) Multi-messenger modeling sources including gamma-rays and neutrinos start to constrain the source and acceleration mechanisms

# Conclusions3

10.) At energies above ~$10^{18}$ eV, the center-of mass energies are above a TeV and thus beyond the reach of accelerator experiments. Especially in the neutrino sector, where Standard Model cross sections are small, this probes potentially new physics beyond the electroweak scale, including possible quantum gravity effects.

11.) The large Lorentz factors involved in cosmic radiation at energies above ~ $10^{19}$ eV provides a magnifier into possible Lorentz invariance violations (LIV).

12.) Many new interesting ideas on a modest cost scale for low precision, high statistics ultra-high energy cosmic ray and neutrino detection (radio, acoustic, space based...) are currently under discussion.