# Astrophysics and Fundamental Physics with High Energy Photons

- astrophysics with photons from TeV to EeV energies
- high energy photon mixing with new light states
- limits on Lorentz invariance violation and quantum gravity

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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# Ultra-High Energy Cosmic Rays and the Connection to Diffuse γ-ray and Neutrino Fluxes

accelerated nuclei interact:

$$^{A}_{Z} + N, \gamma \rightarrow X + \begin{cases} \pi^{+} \rightarrow \text{neutrinos} \\ \pi^{0} \rightarrow \gamma - \text{rays} \end{cases}$$

during propagation (“cosmogenic”)
or in sources (AGN, GRB, ...)

=> energy fluences in $\gamma$-rays and neutrinos are comparable due to isospin symmetry.

Universe acts as a calorimeter for total injected electromagnetic energy above the pair threshold.
=> neutrino flux constraints.

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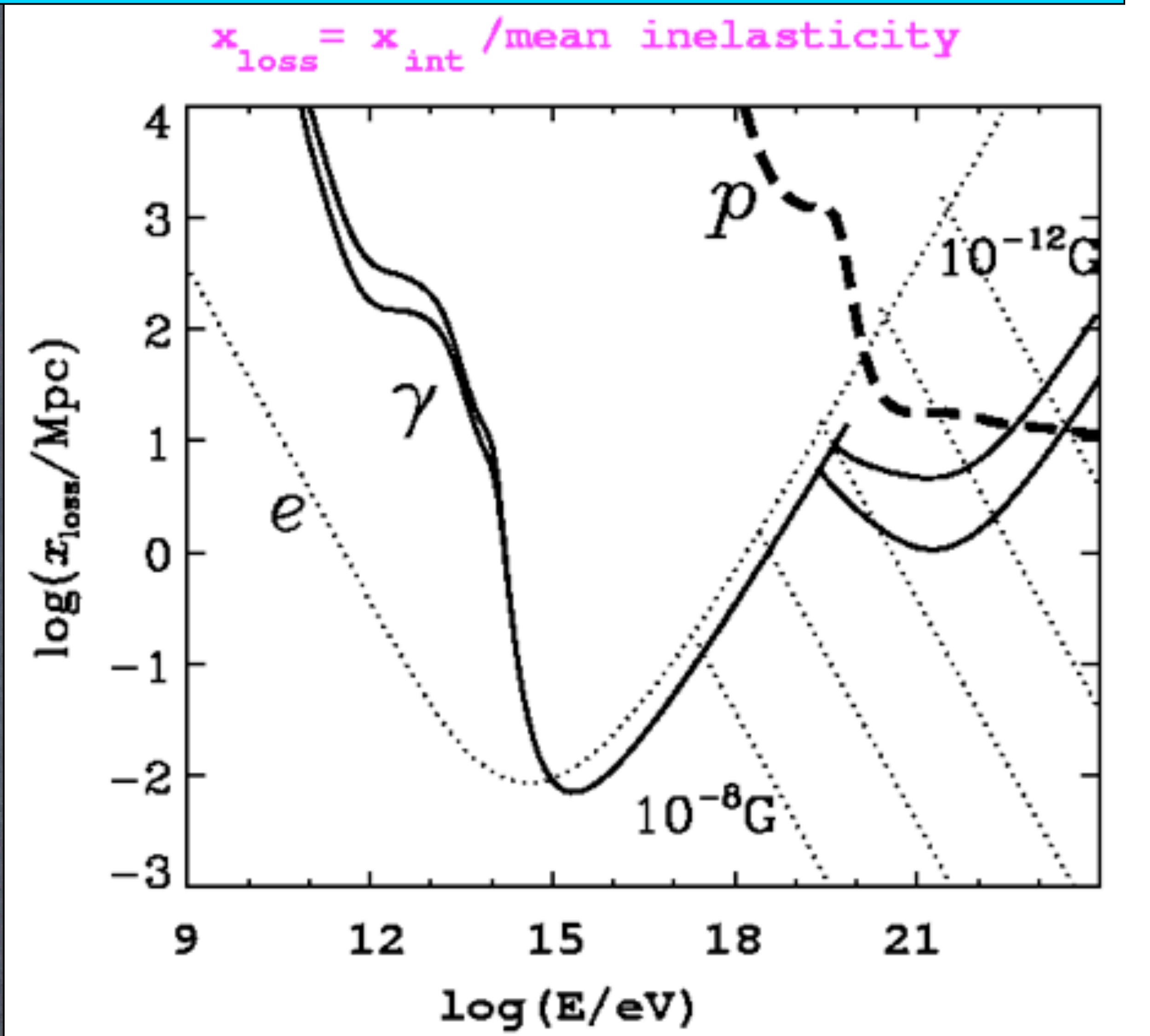


Included processes:

Electrons: inverse Compton; synchrotron rad (for fields from pG to 10 nG)

Gammas: pair-production through IR, CMB, and radio backgrounds

Protons: Bethe-Heitler pair production, pion photoproduction

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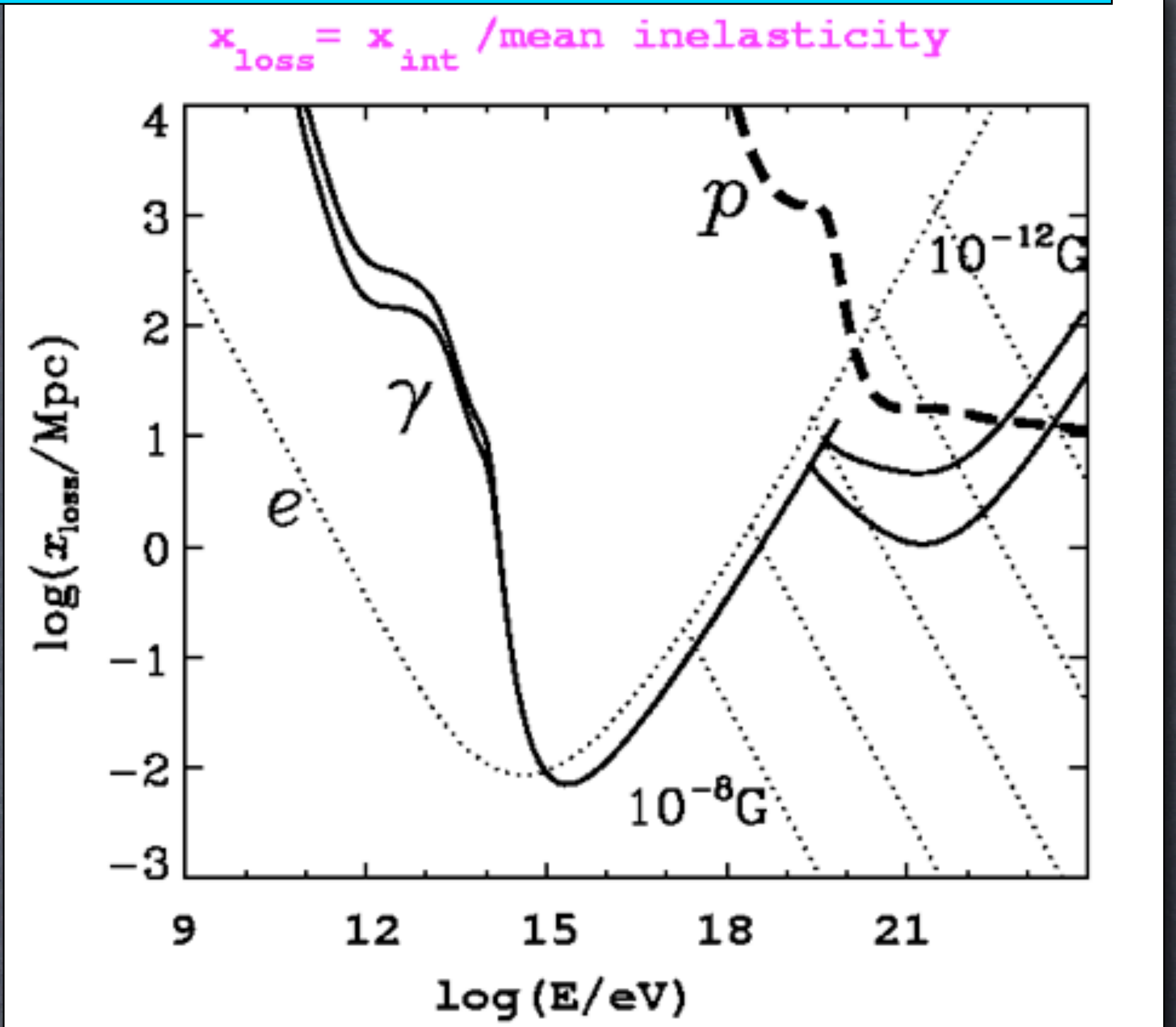
=> energy fluences in γ-rays and neutrinos are comparable due to isospin symmetry.

Neutrino spectrum is unmodified, γ-rays pile up below pair production threshold (on CMB at a few $10^{14}$ eV)

Universe acts as a calorimeter for total injected electromagnetic energy above the pair threshold.
=> neutrino flux constraints.

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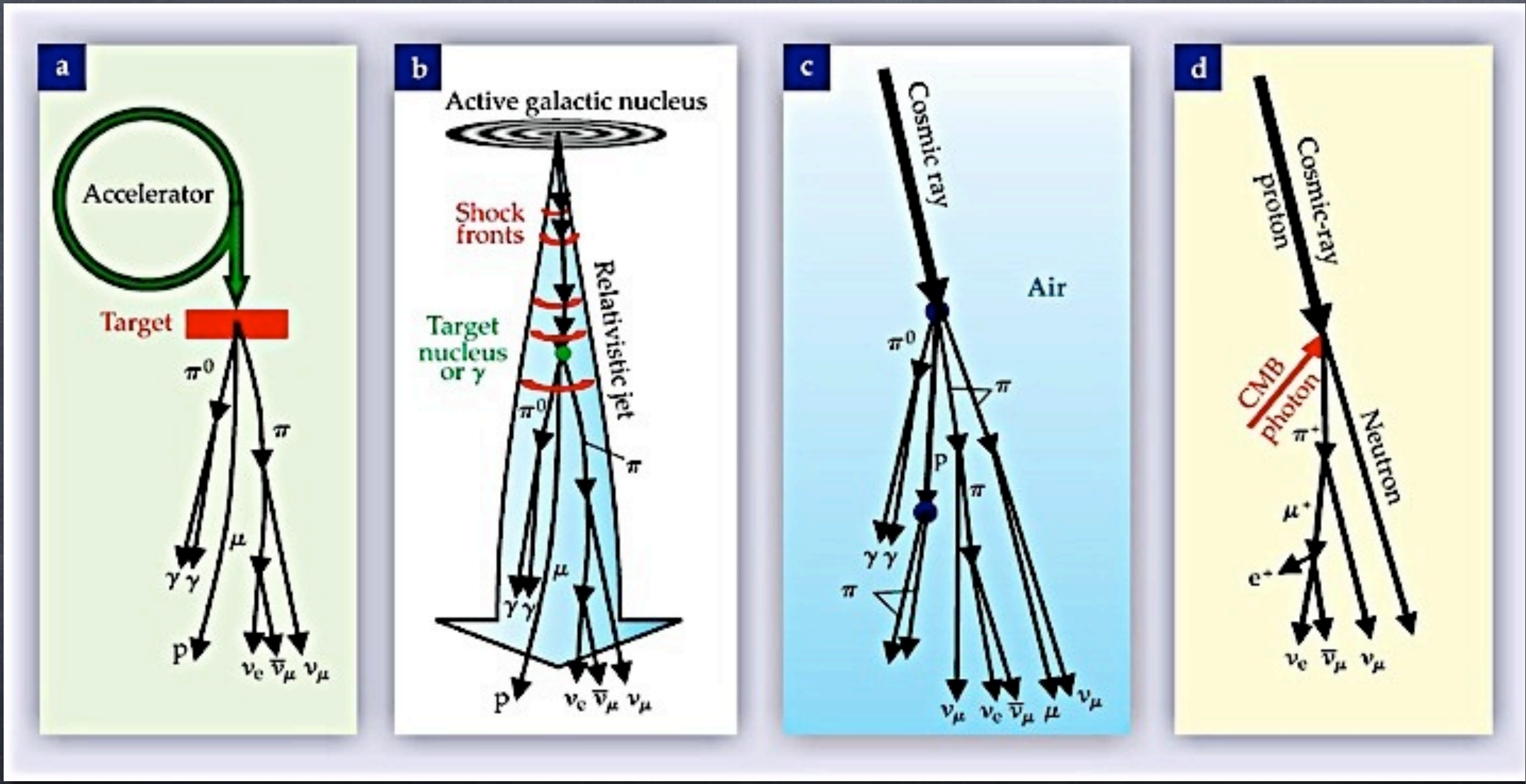
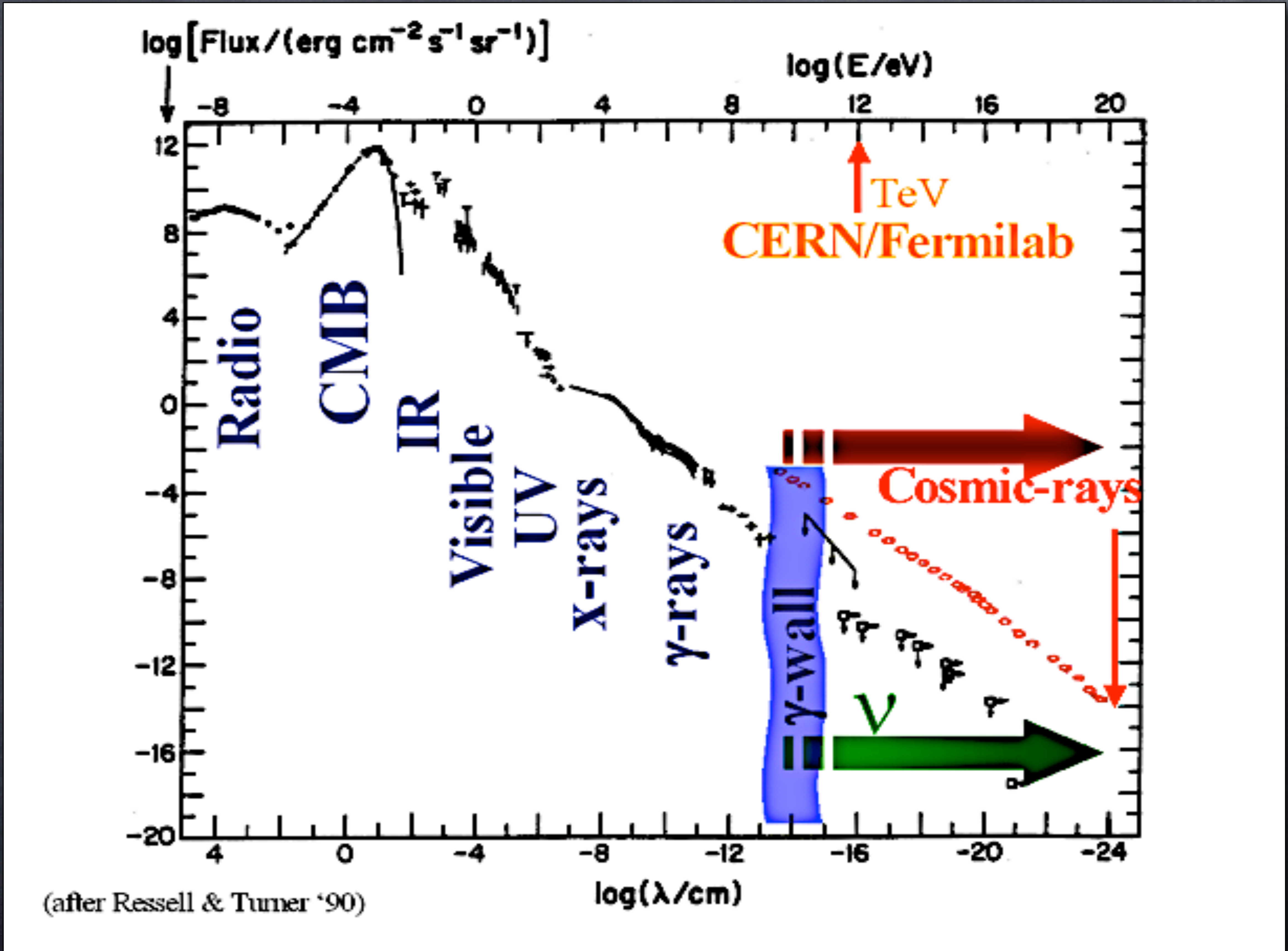
## Summary of hadronic neutrino and photon production modes

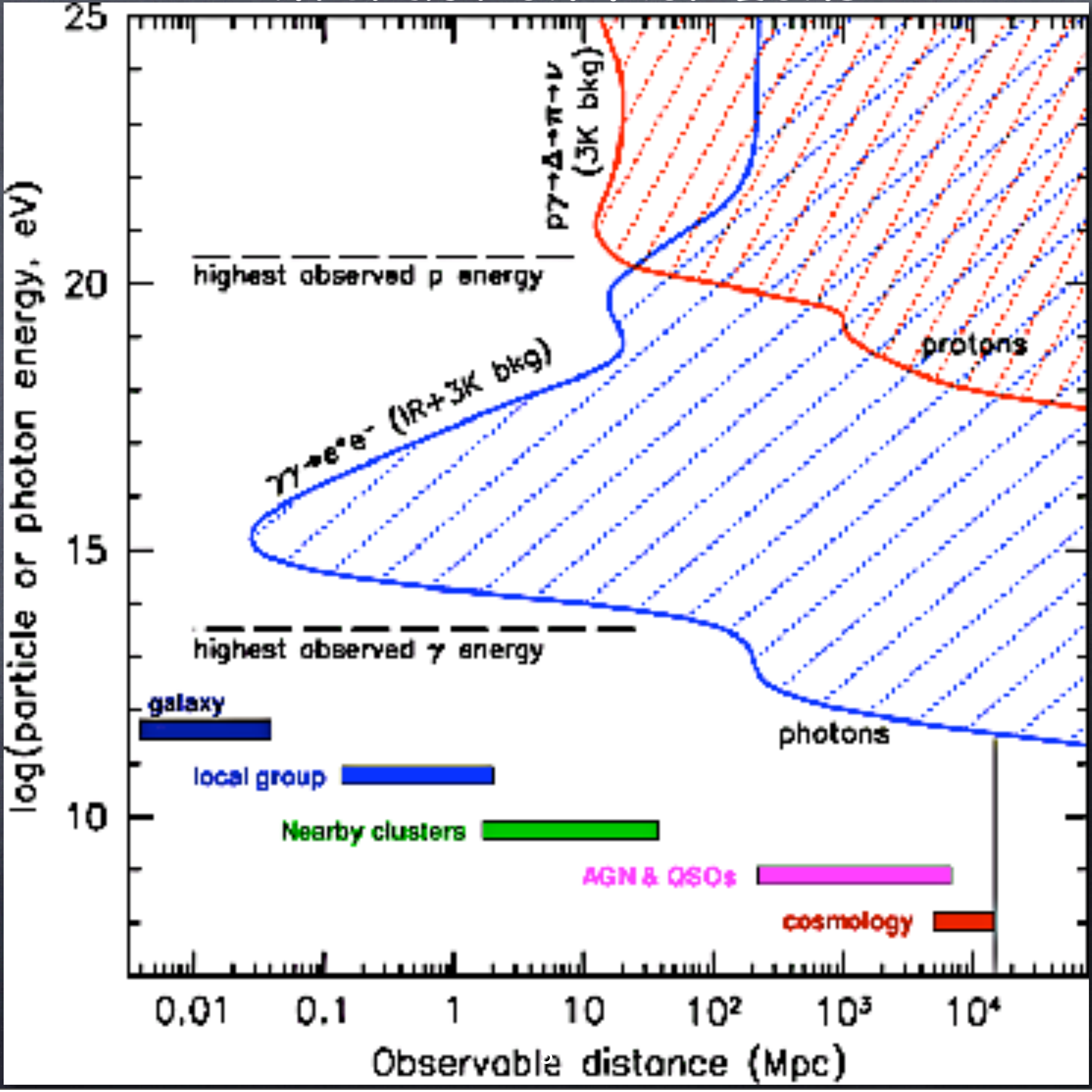



From Physics Today

# The universal photon spectrum



# Interaction Horizons



# Propagation of nucleons, photons, electrons, and neutrinos

In one dimension propagation is governed by Boltzmann equations for differential spectrum of species $i$, $n_i(E)$:

$$\frac{\partial n_i(E)}{\partial t} = \Phi_i(E) - n_i(E) \int d\varepsilon n_b(\varepsilon) \int_{-1}^{+1} d\mu \frac{1-\mu\beta_b\beta_i}{2} \sum_j \sigma_{i\to j}\big|_{s=\varepsilon E(1-\mu\beta_b\beta_i)}$$
$$+ \int dE' \int d\varepsilon n_b(\varepsilon) \int_{-1}^{+1} d\mu \sum_j \frac{1-\mu\beta_b\beta_j'}{2} n_j(E') \left.\frac{d\sigma_{j\to i}(s,E)}{dE}\right|_{s=\varepsilon E'(1-\mu\beta_b\beta_j)},$$

where:

$\Phi_i(E)$ =injection spectrum,

$n_b(\varepsilon)$ =diffuse background neutrino or photon density at energy $\varepsilon$,

$\mu$ = cos(angle between background and in-particle),

$\beta$ =particle velocities,

$\sigma_{i\to j}$ = cross sections for processes $i \to j$,

$s$ =center of mass energy.

Background spectrum between $\sim 10^{-8}$ eV and $\sim 10$ eV
propagated particles between 100 MeV and $10^{16}$ GeV (GUT scale)
transport equations (including cosmology, i.e. redshift-distance relation) solved by implicit methods.

# Processes taken into account

**Nucleons:**

- (multiple) pion production: $N\gamma_b \to N(n\pi)$ with subsequent pion decays: leads to "GZK-effect".
- pair production by protons: $p\gamma_b \to pe^+e^-$: relevant below GZK threshold (similar to triplet pair production below)
- Neutron decay: $n \to pe^-\bar{\nu}_e$

**Electromagnetic channel:**

- pair production and inverse Compton scattering: $\gamma\gamma_b \to e^+e^-$ and $e\gamma_b \to e\gamma$: leading order processes with

$$\sigma_{\rm PP} \simeq 2\sigma_{\rm ICS} \simeq \frac{3}{2}\sigma_T\frac{m_e^2}{s}\ln\frac{s}{2m_e^2} \quad (s \gg m_e^2)\,.$$

- double pair production: $\gamma\gamma_b \to e^+e^-e^+e^-$: dominates at highest energies with

$$\sigma_{\rm DPP} \simeq \frac{43\alpha^2}{24\pi^2}\sigma_T \quad (s \gg m_e^2)\,.$$

- triplet pair production: $e\gamma_b \to ee^+e^-$: dominant at highest energies with

$$\sigma_{\rm TPP} \simeq \frac{3\alpha}{8\pi}\sigma_T\left(\frac{28}{9}\ln\frac{s}{m_e^2} - \frac{218}{27}\right) \quad (s \gg m_e^2)\,,$$

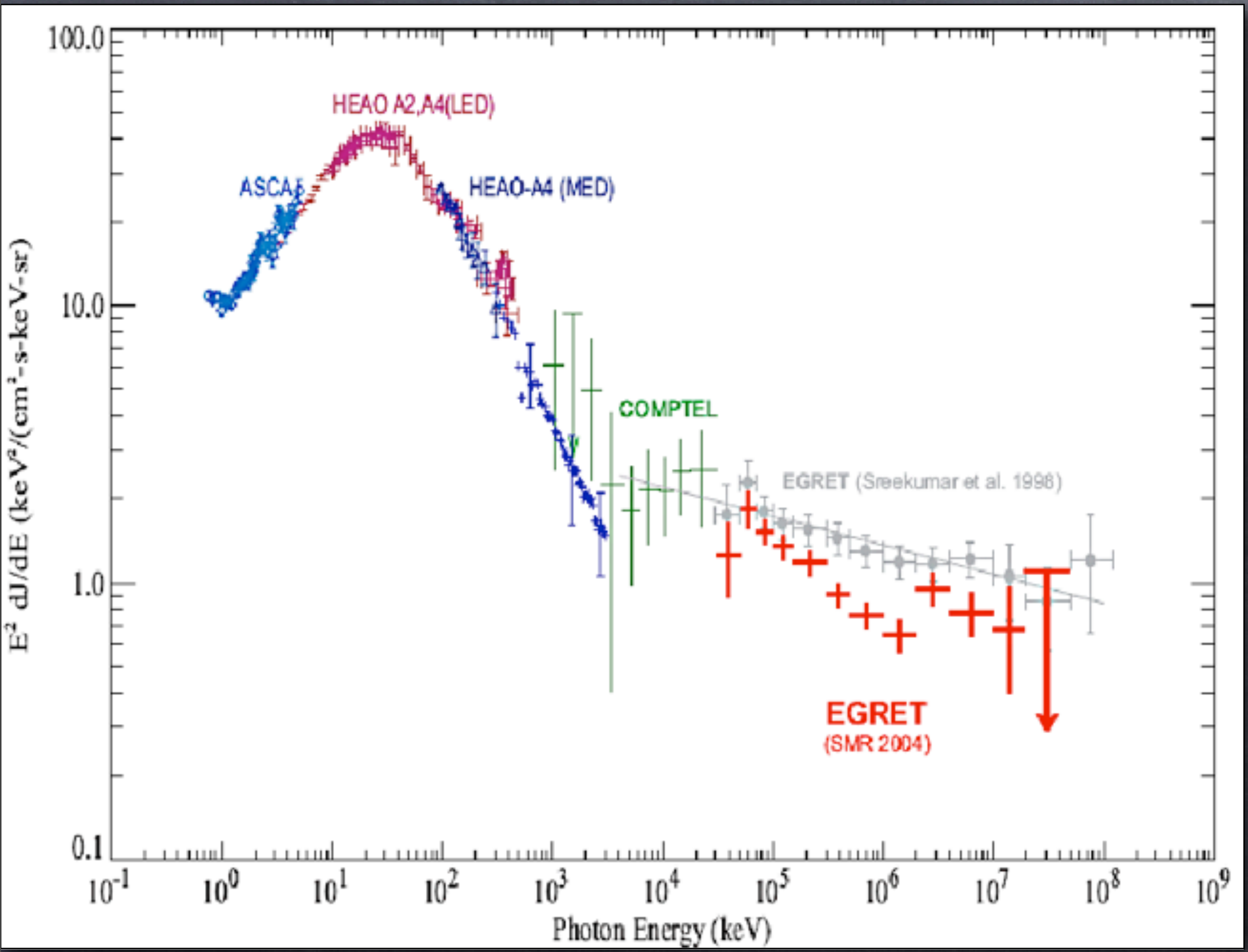
  with fractional energy loss $\eta$ of leading $e$

$$\eta \simeq 1.768\left(\frac{s}{m_e^2}\right)^{-3/4} \quad (s \gg m_e^2)\,.$$

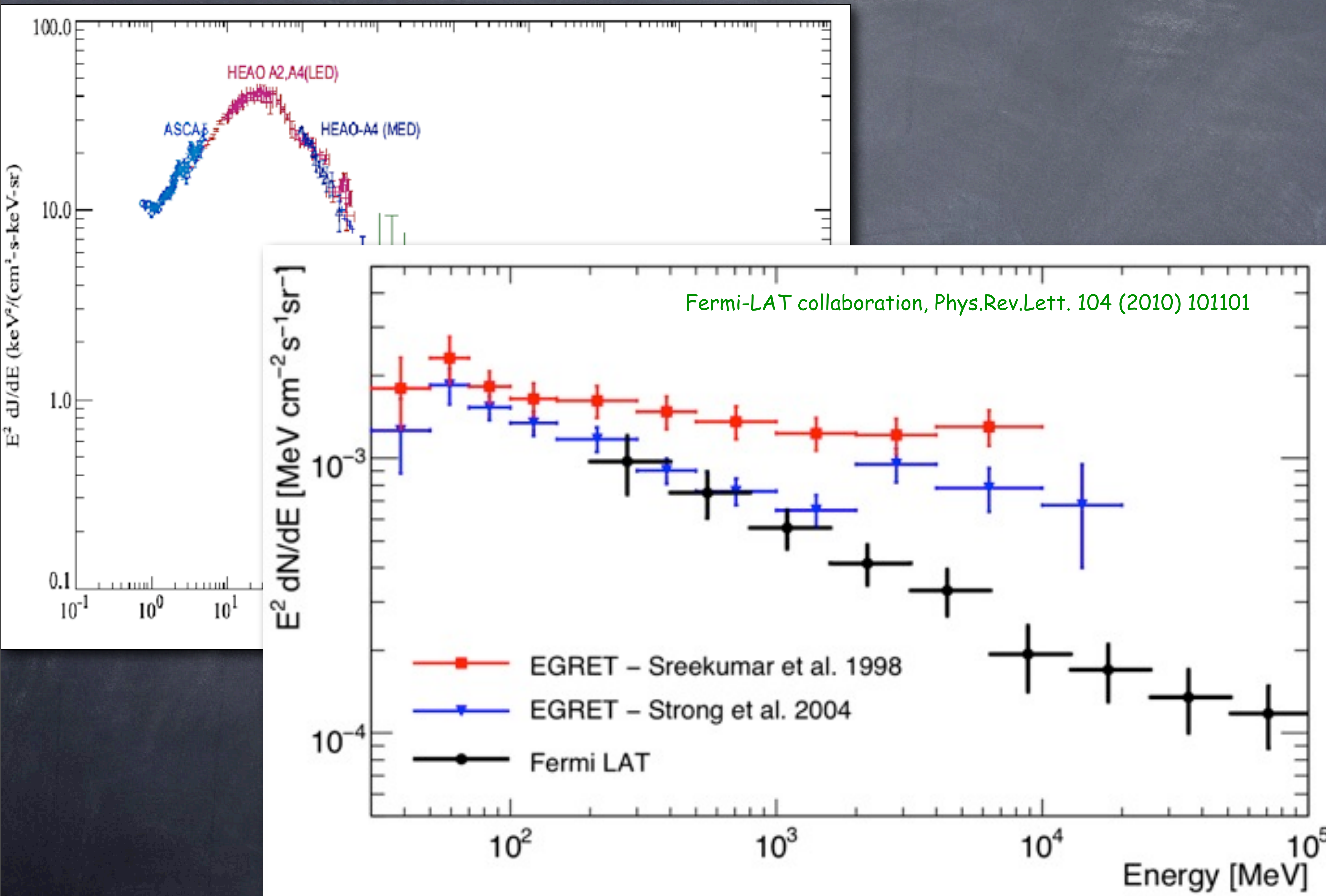
- synchrotron loss of electrons and positrons in cosmic magnetic fields: $eB \to e\gamma$. Energy loss given by

$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T\frac{B^2}{8\pi}\left(\frac{Zm_e}{m}\right)^4\left(\frac{E}{m_e}\right)^2\,.$$

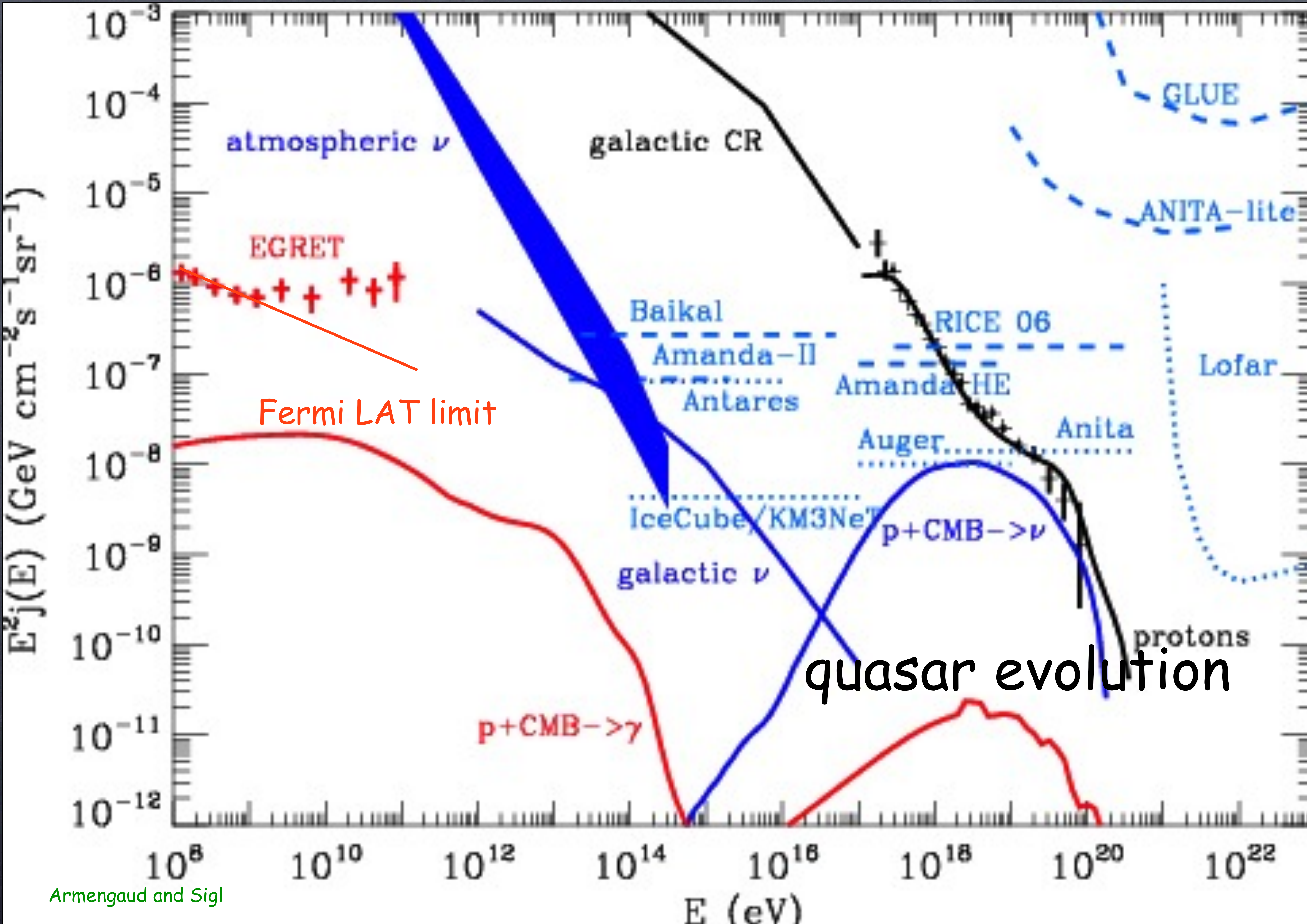
# The diffuse photon background from keV to 100 GeV



# The diffuse photon background from keV to 100 GeV



# Cascade γ-rays and UHE neutrinos: An Overview



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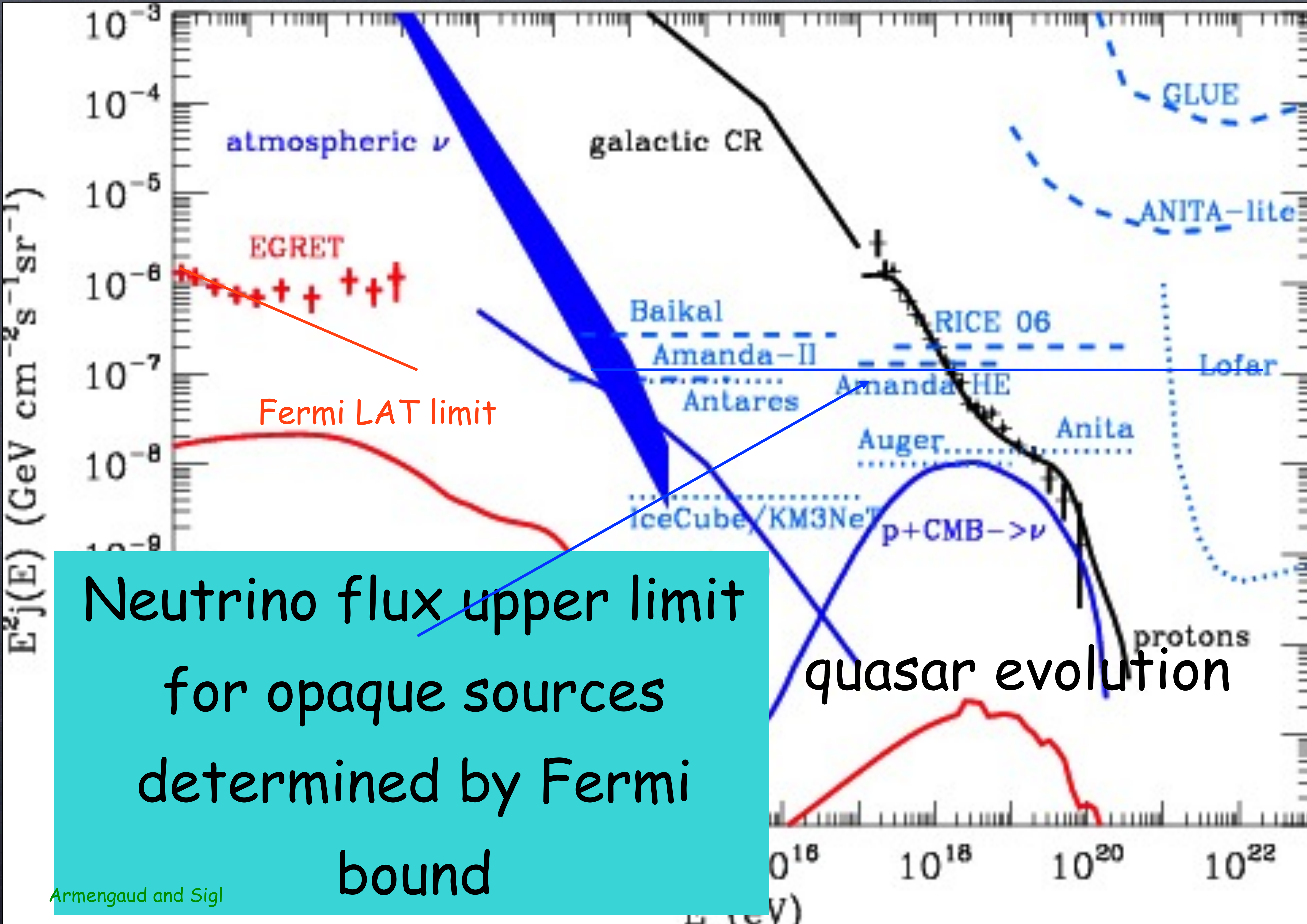


Neutrino flux upper limit for opaque sources determined by Fermi bound

Armengaud and Sigl

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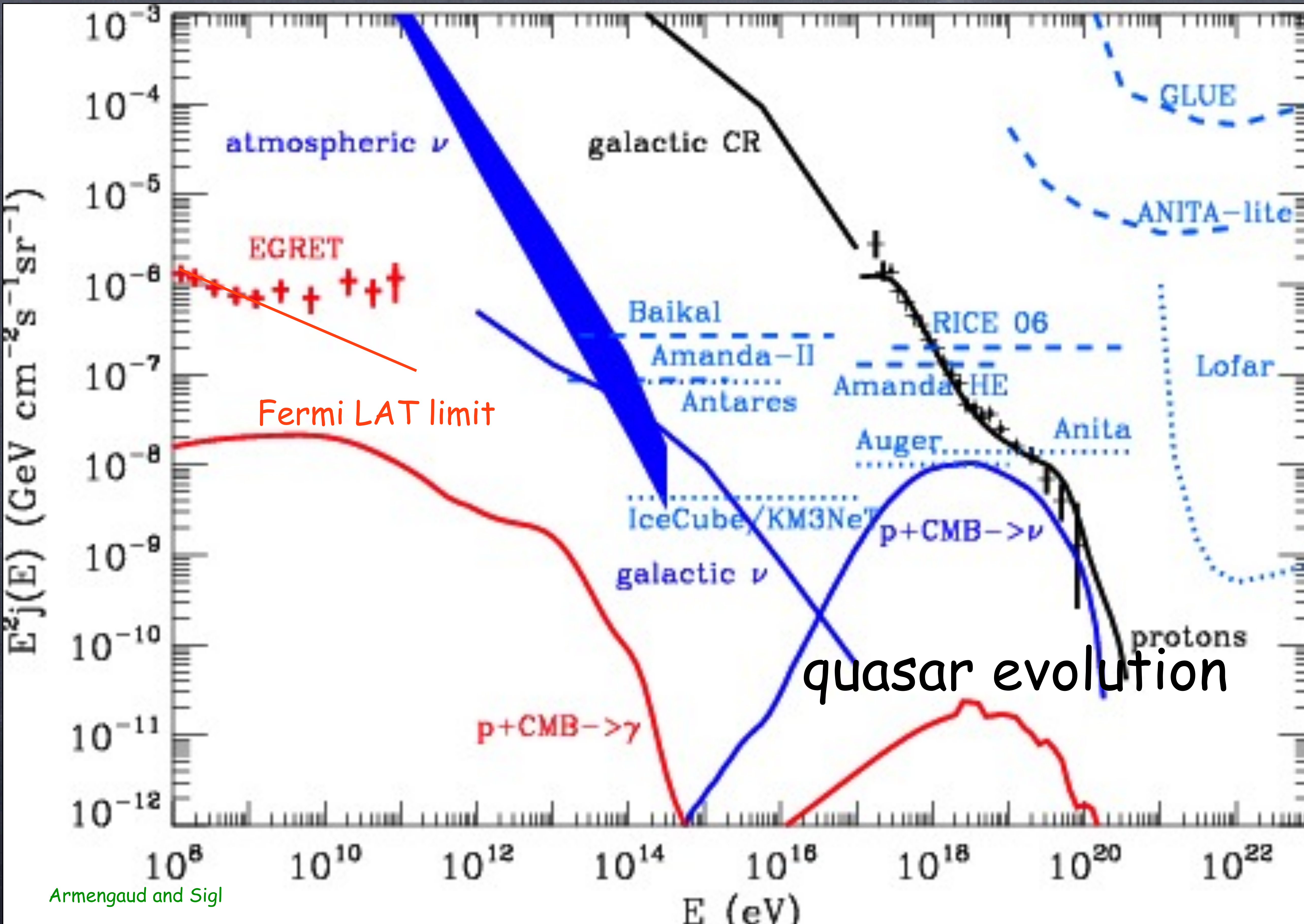
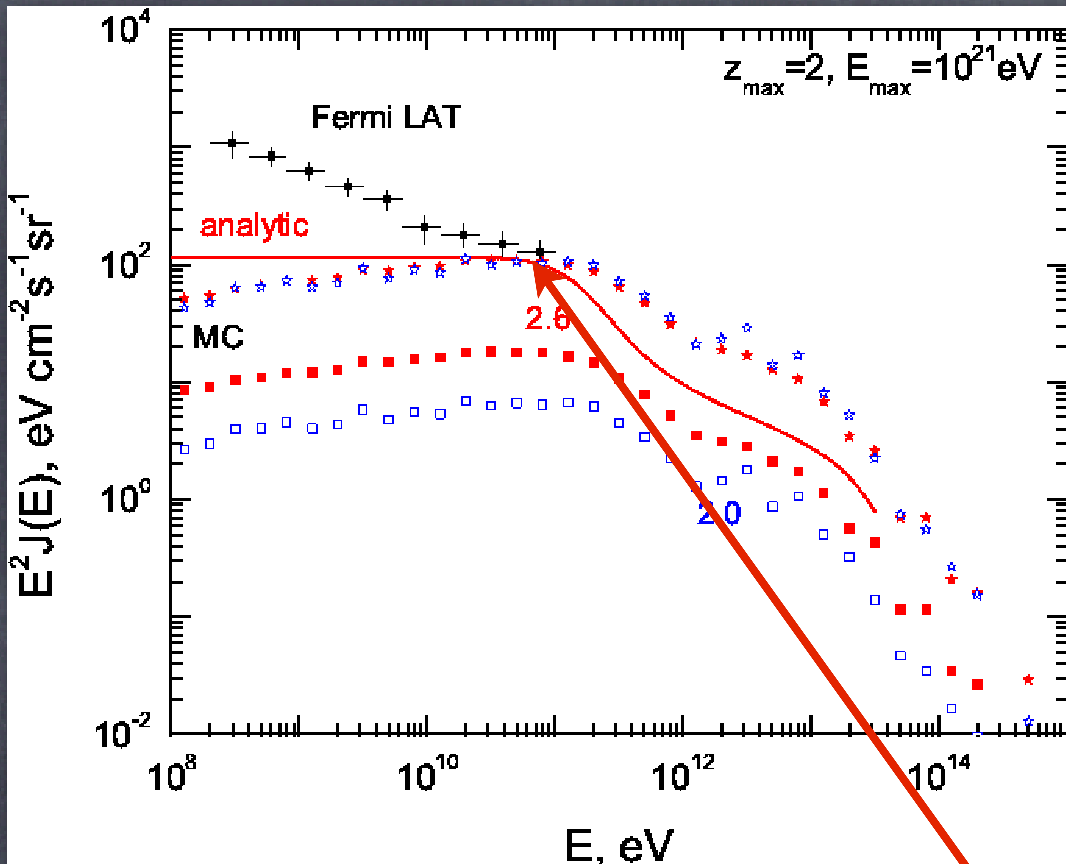
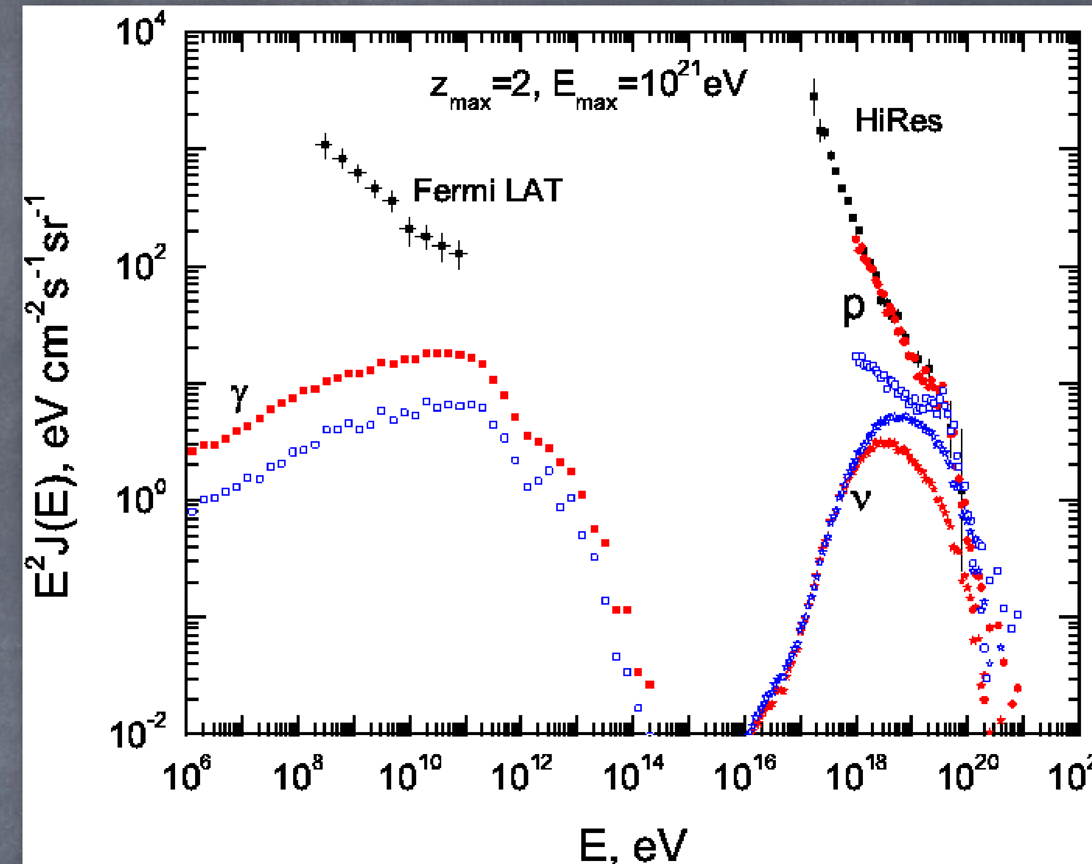
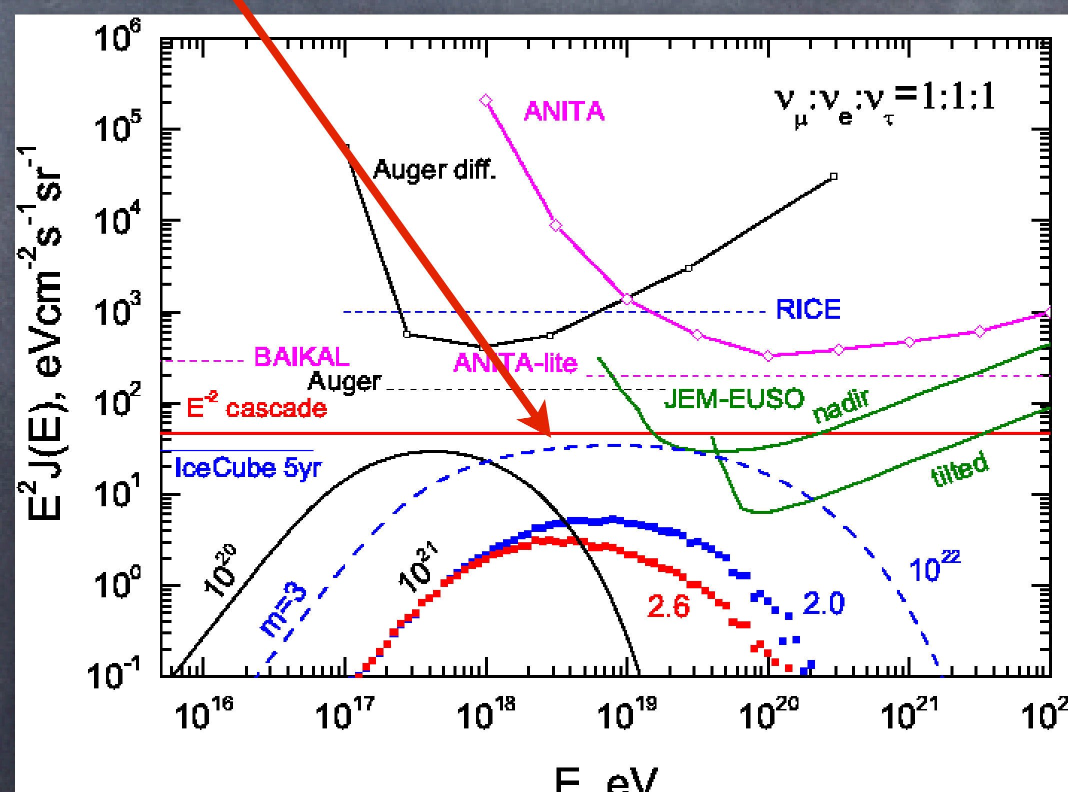


# TeV γ-ray fluxes also constrain cosmogenic neutrino fluxes



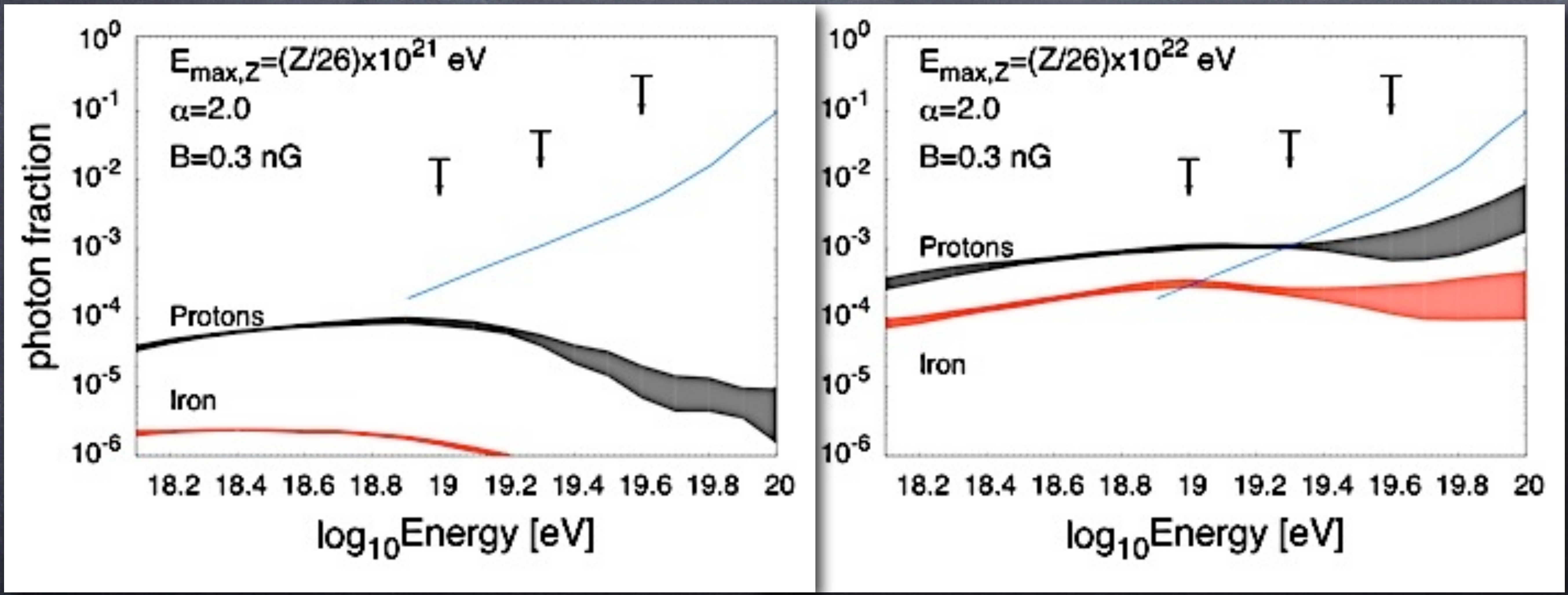




Berezinsky et al., Phys. Lett. B 695 (2011) 13

# Physics with EeV Secondary Gamma-Ray Fluxes

UHE gamma-ray fluxes depend on number of nucleons locally produced above GZK threshold which is proportional to $E_{max}/A$

Further suppressed for heavy nuclei due to increased pair production




Hooper, Taylor, Sarkar, Astropart.Phys. 34 (2011) 340

# Photon-WISP Conversion in Astrophysics and Cosmology

WISP= Weakly Interacting Sub-eV Particle

The structure of the coupling of axion-like particles (ALPs) a to photons is,

$$\mathcal{L}_{a\gamma} = -\frac{g_{\gamma a}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}m_a^2 a^2 = g_{\gamma a} a \mathbf{E}\cdot\mathbf{B} + \frac{1}{2}m_a^2 a^2$$

with $g_{a\gamma}$ the coupling energy-scale, $m_a$ the ALP mass. Thus, the presence of magnetic fields induces mixing (Primakoff-process) which also depends on photon plasma mass

Axions were originally motivated by the strong QCD problem for which

$m_a = (3.8\times10^{10}\ \mathrm{GeV} * g_{a\gamma})$ meV

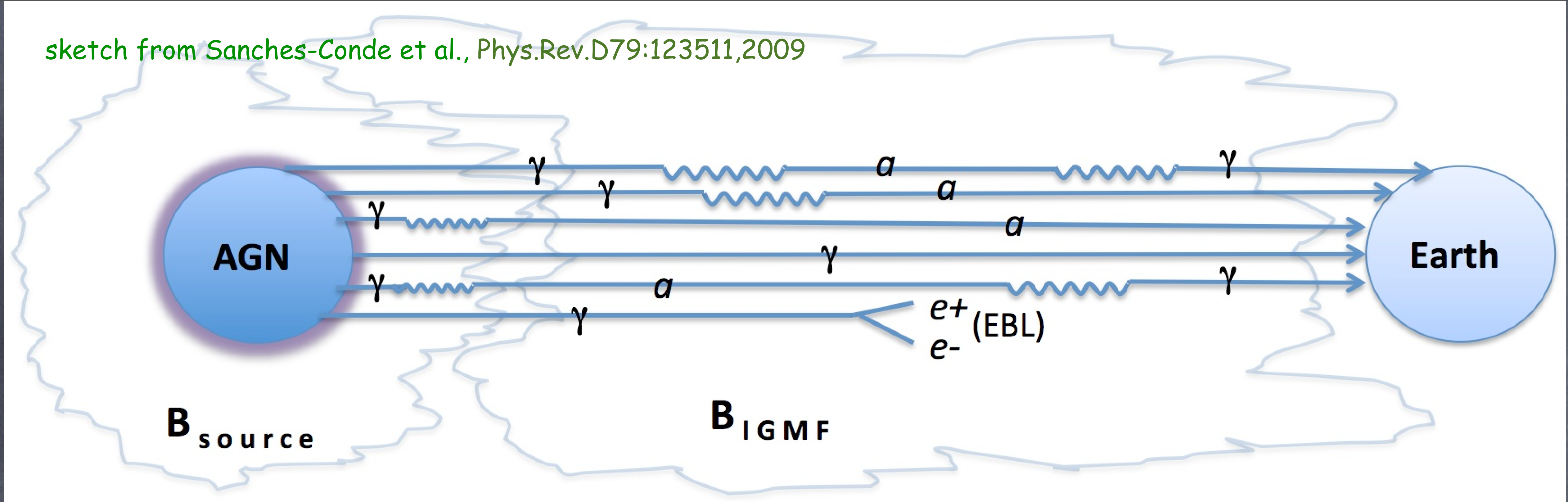
but model-dependent axions can also be motivated by hidden sectors in string theory

This is different for mixing with a hidden-photon field $X_\mu$, for which

$$\mathcal{L}_{X\gamma} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{\sin\chi}{2}X_{\mu\nu}F^{\mu\nu} + \frac{\cos^2\chi}{2}m_{\gamma'}^2 X_\mu X^\mu + j^\mu_{\rm em}A_\mu$$

which only depends on (constant) kinetic mixing and photon plasma mass and can have interesting effects, e.g., on CMB distortions.

In the following restrict to axions.



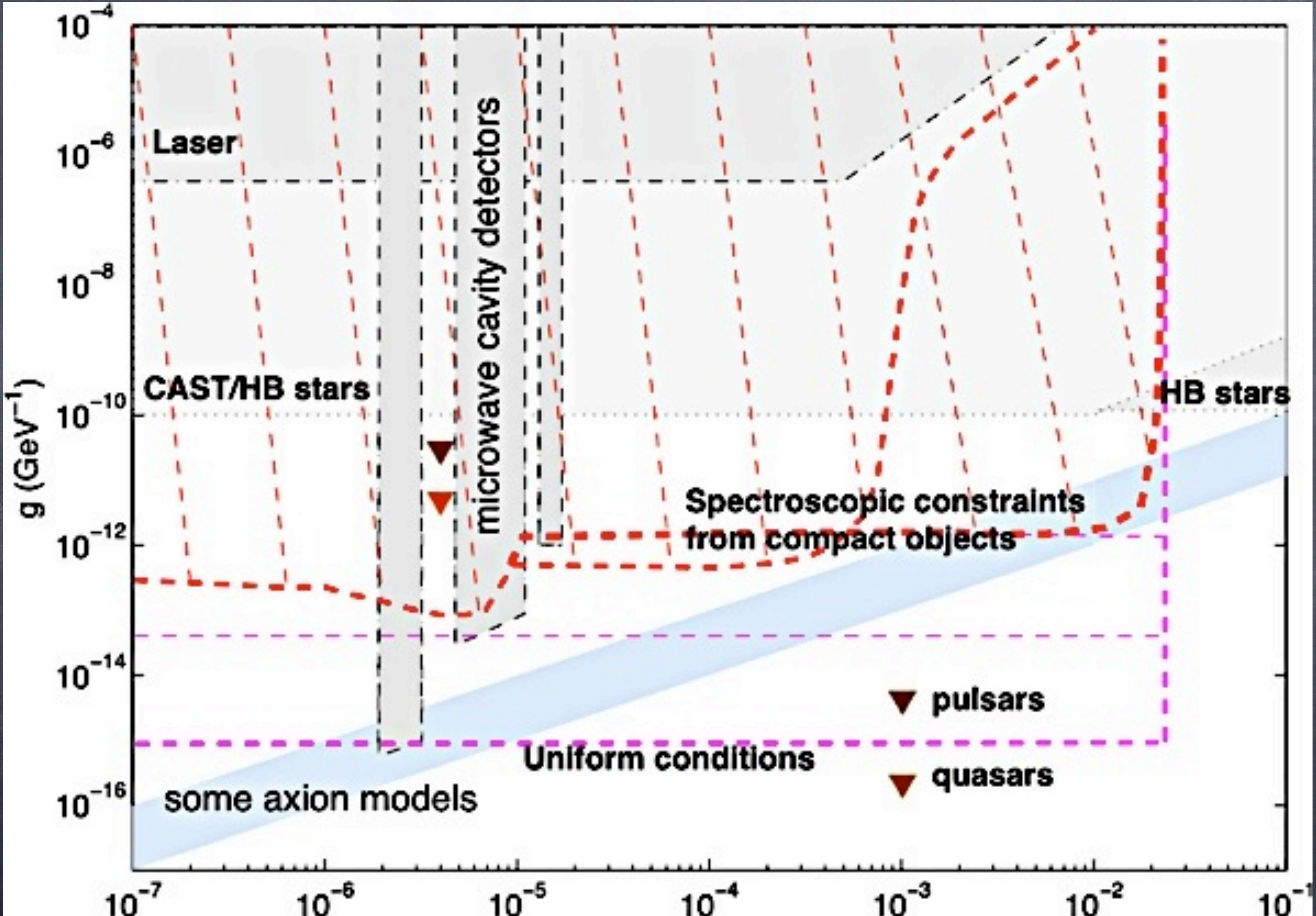

In absence of polarization effects the mixing equation reads:

$$\left[ E - \mathrm{i}\partial_z - \begin{pmatrix} \Delta_{\rm pl}(z) + \Delta_{\rm CM}(z) & \Delta_B(z) \\ \Delta_B(z) & \Delta_a \end{pmatrix} \right] \begin{pmatrix} A \\ a \end{pmatrix} = 0$$

with the frequencies

$$\begin{aligned}
\Delta_a &= \frac{m_a^2}{2E} \simeq 2.5 \times 10^{-20}\, m_{\mu\rm eV}^2 \left(\frac{\rm TeV}{E}\right) \mathrm{cm}^{-1}, \\
\Delta_{\rm pl} &= \frac{\omega_{\rm pl}^2}{2E} \simeq 3.5 \times 10^{-26} \left(\frac{n_e}{10^3\,\mathrm{cm}^{-3}}\right) \left(\frac{\rm TeV}{E}\right) \mathrm{cm}^{-1}, \\
\text{Cotton-Mouton term} \quad \Delta_{\rm CM} &\simeq -\frac{\alpha}{45\pi} \left(\frac{B_{\rm t}}{B_{\rm cr}}\right)^2 E \simeq -1.3 \times 10^{-21}\, B_{\rm mG}^2 \left(\frac{E}{\rm TeV}\right) \mathrm{cm}^{-1}, \\
\Delta_B &= \frac{g_{\gamma a} B_{\rm t}}{2} \simeq 1.7 \times 10^{-21}\, g_{11}\, B_{\rm mG}\, \mathrm{cm}^{-1}
\end{aligned}$$

# Comparison of Experimental and Astrophysical Sensitivities

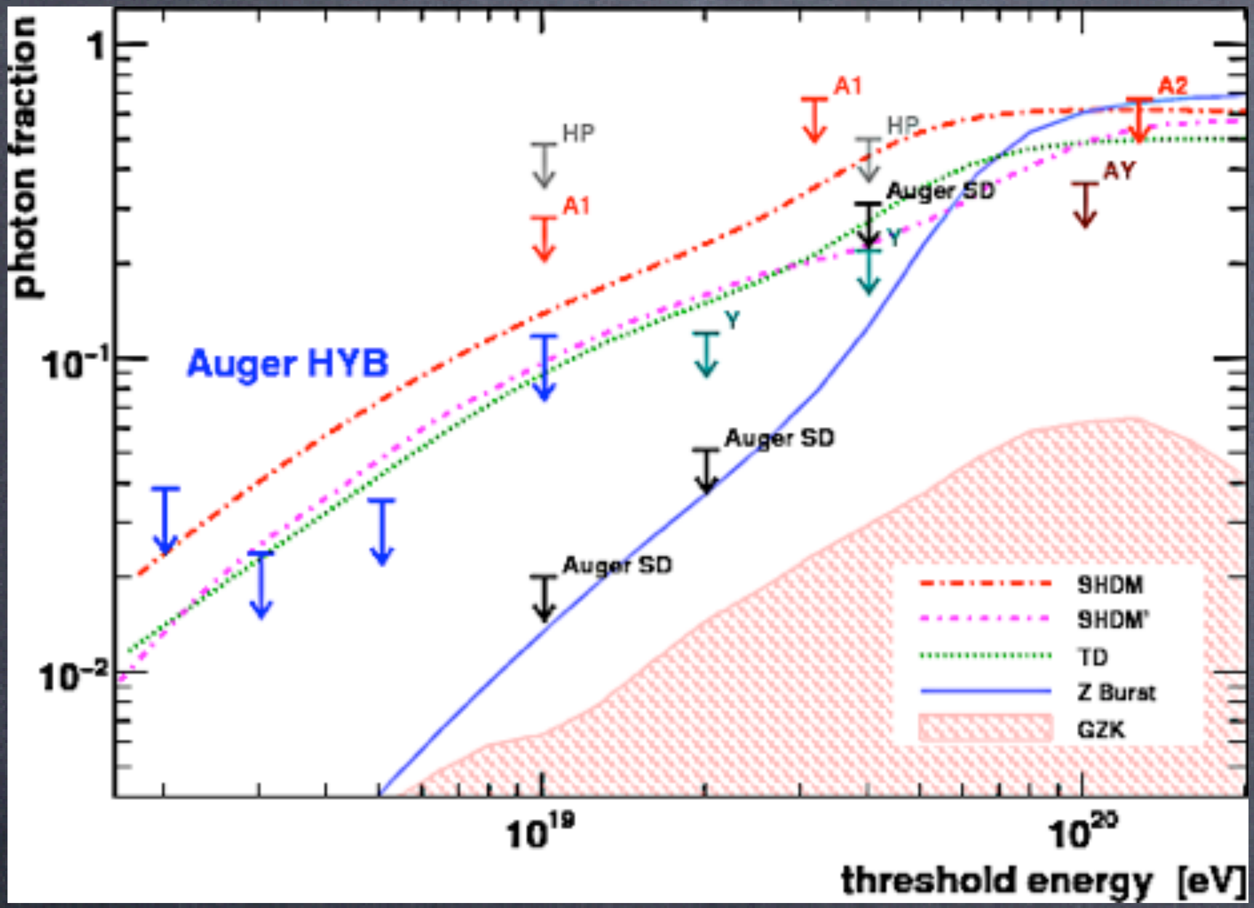



Chelouche et al., Astrophys.J.Suppl. 180 (2009) 1

# Lorentz Symmetry Violation in the Electromagnetic Sector

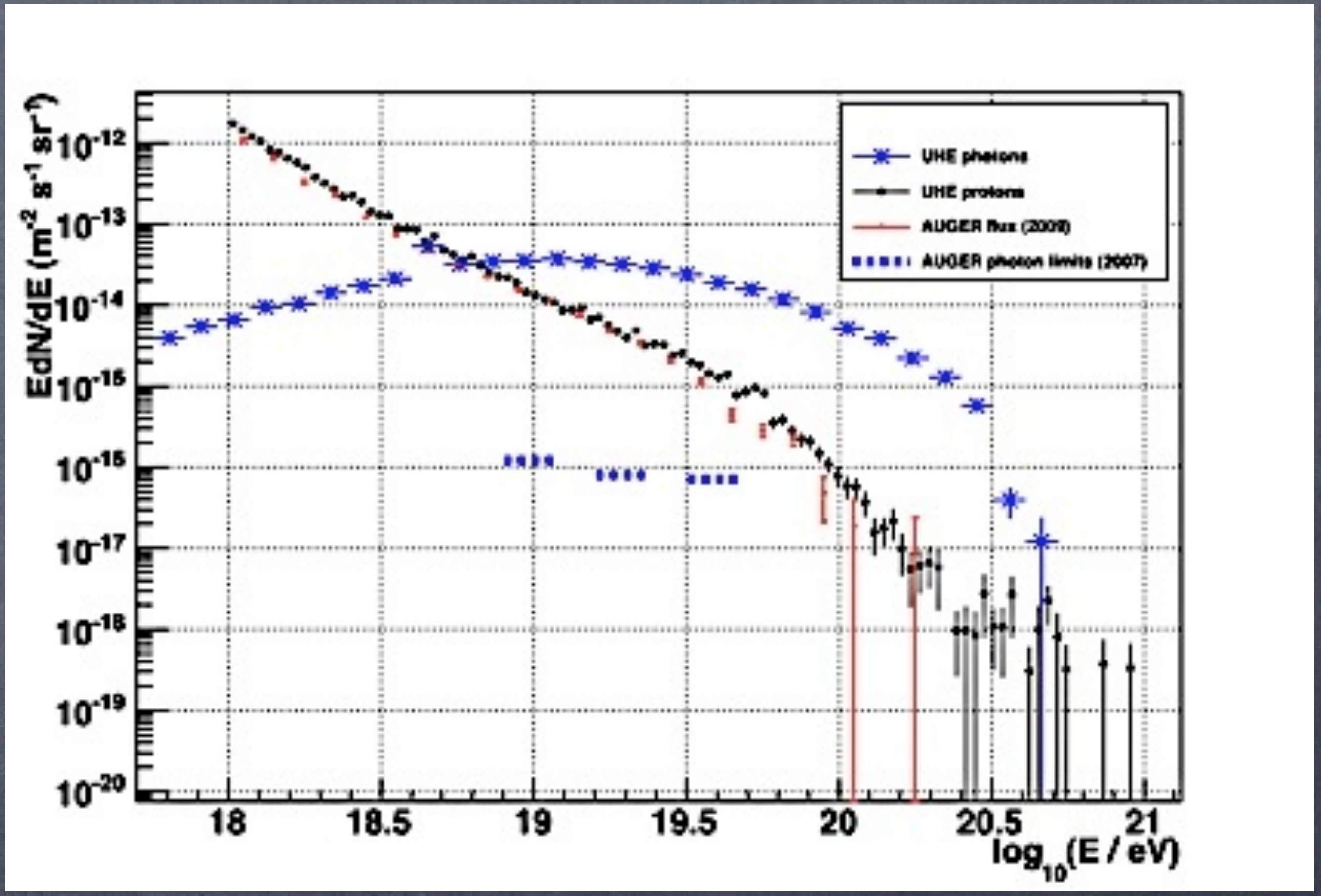
## The idea:

Experimental upper limits on UHE photon fraction




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

Contradict predictions if pair production is absent




Maccione, Liberati, Sigl, PRL 105 (2010) 021101

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 $\eta_n^{p,\pm} = (-1)^n \eta_n^{e,\pm}$ . 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

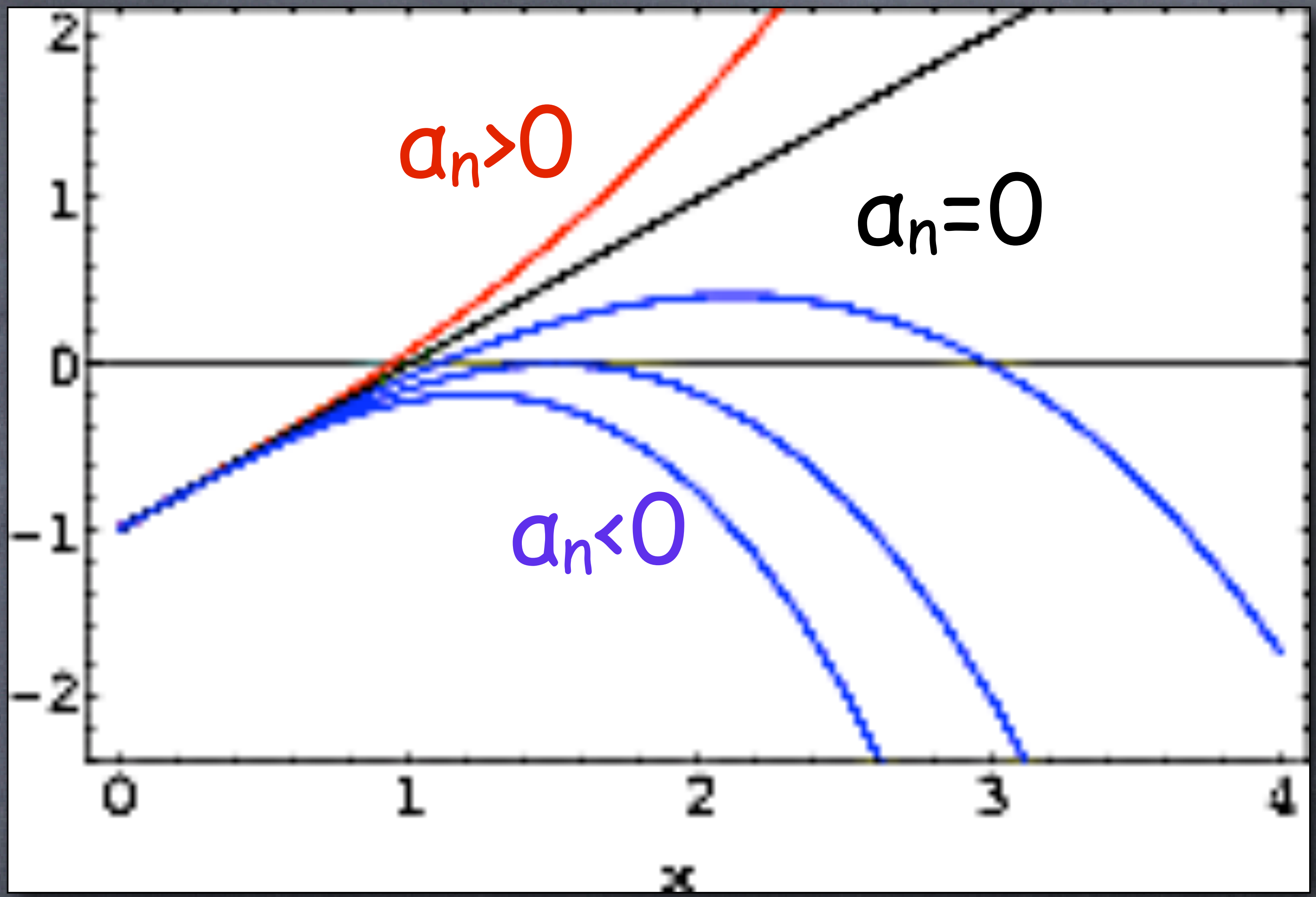
$$\alpha_n = \frac{\xi_n - (-1)^n \eta_n^{\mp} y^{n+1} - \eta_n^{\pm}(1-y)^{n+1}}{2^{2(n+2)} y^{n+1}(1-y)^{n+1}} \frac{m_e^{2(n+1)}}{k_b^{n+2} M_{\rm Pl}^n} .$$

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 least two real solutions $0 \leq x_n^l \leq x_n^r$ for pair production (lower and upper thresholds)

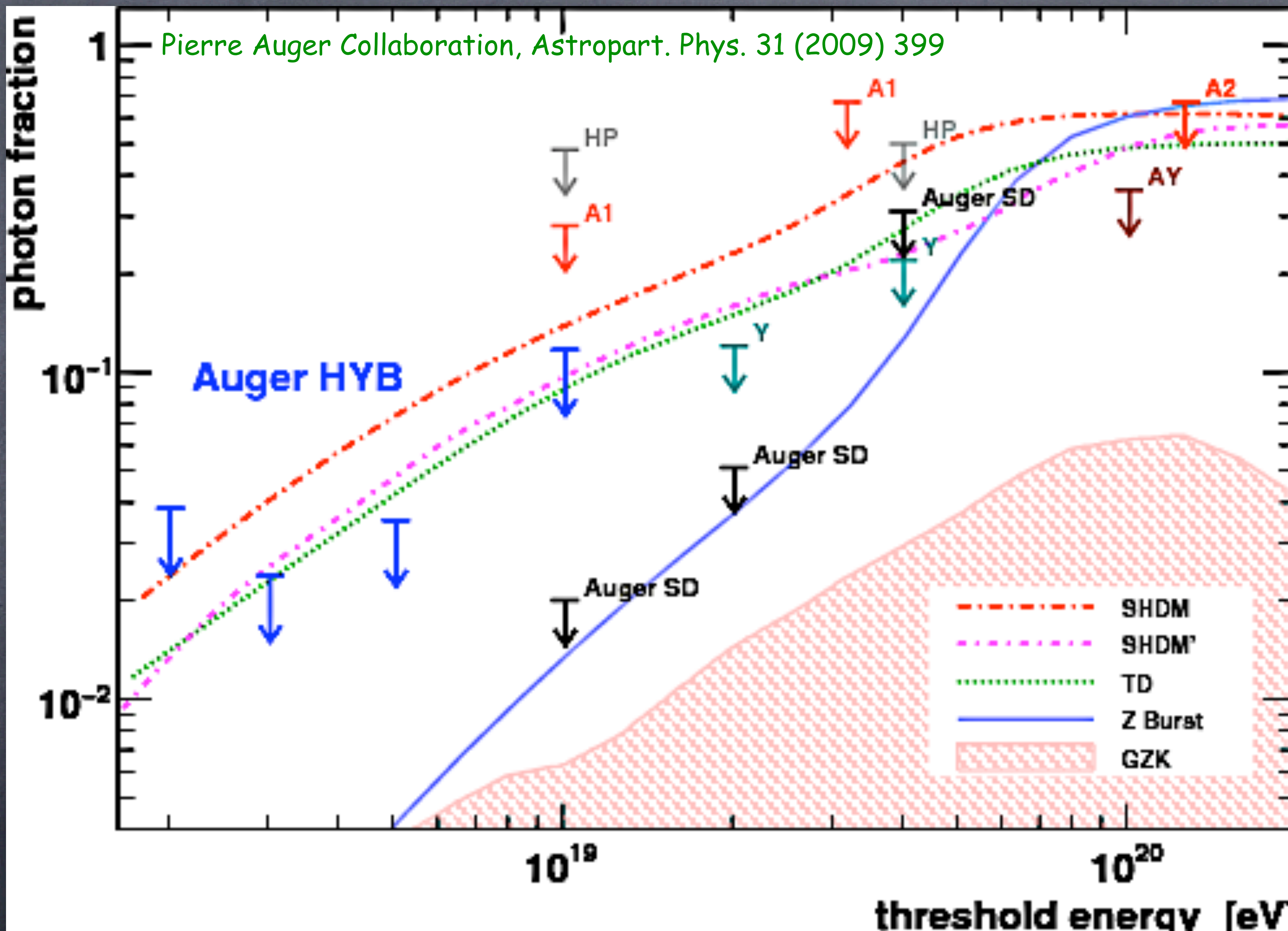



Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

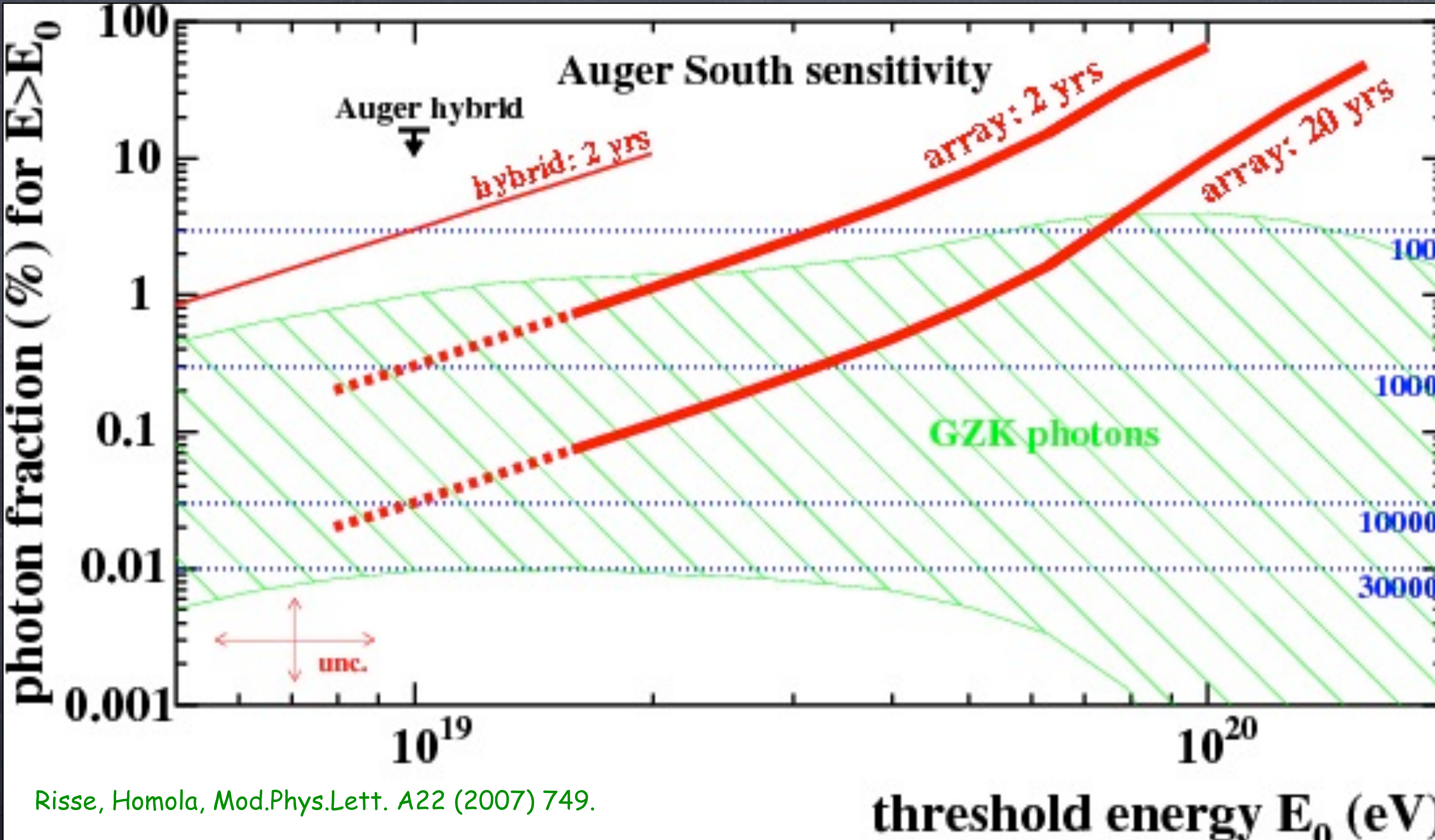
For photon decay there is at most one positive real threshold.

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.

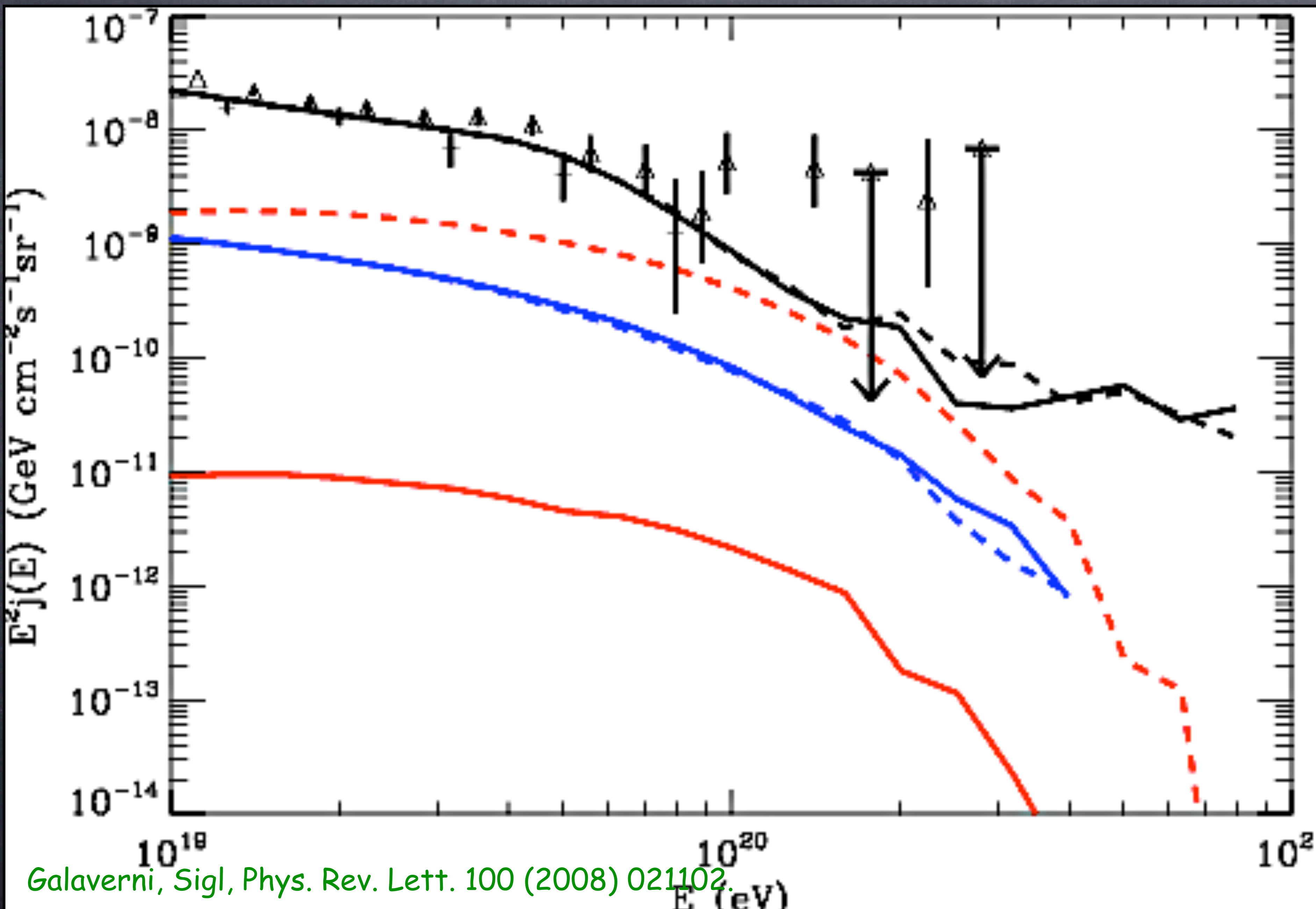


Future data will allow to probe smaller photon fractions and the GZK photons:




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

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

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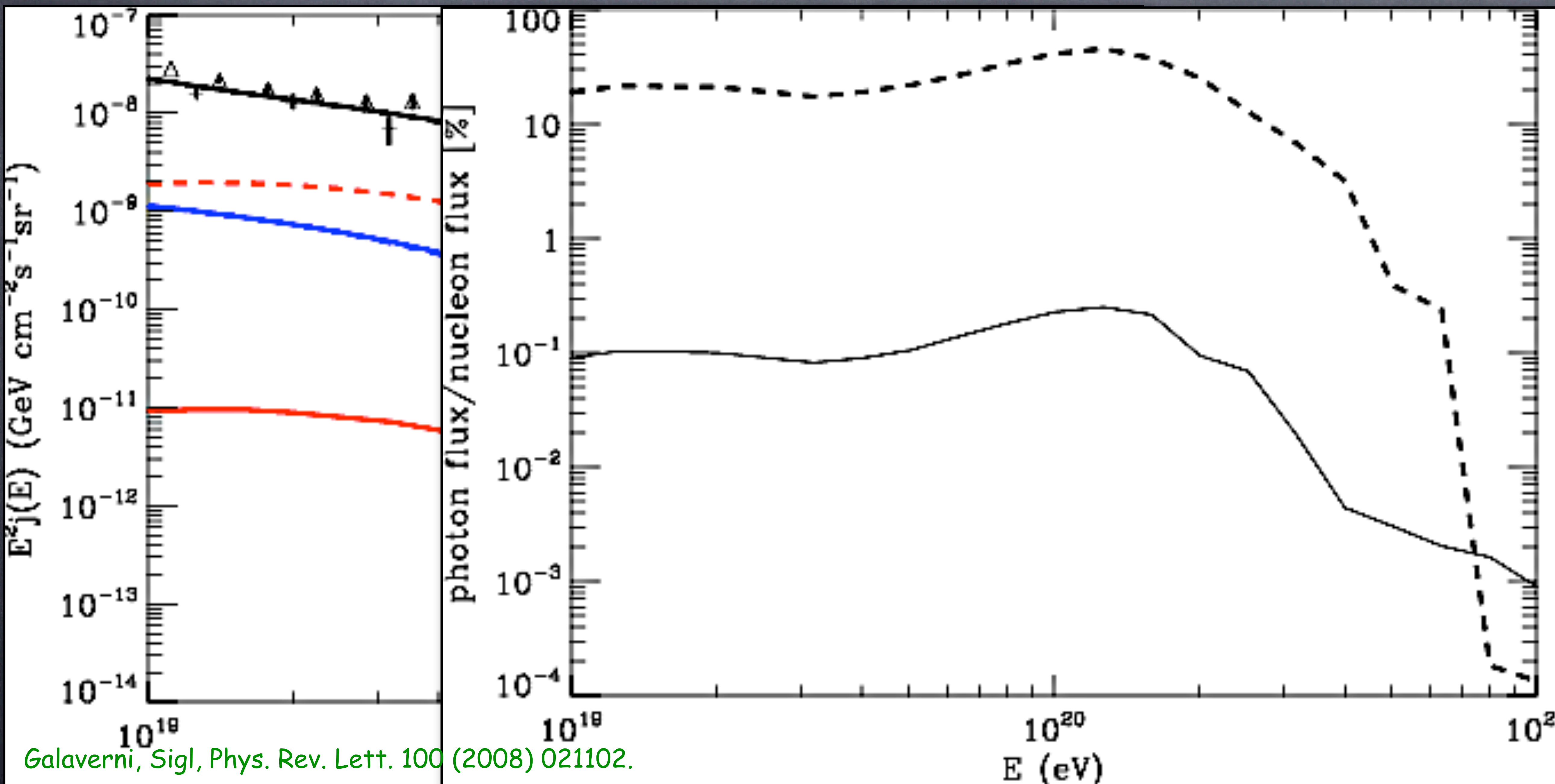



Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

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:

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

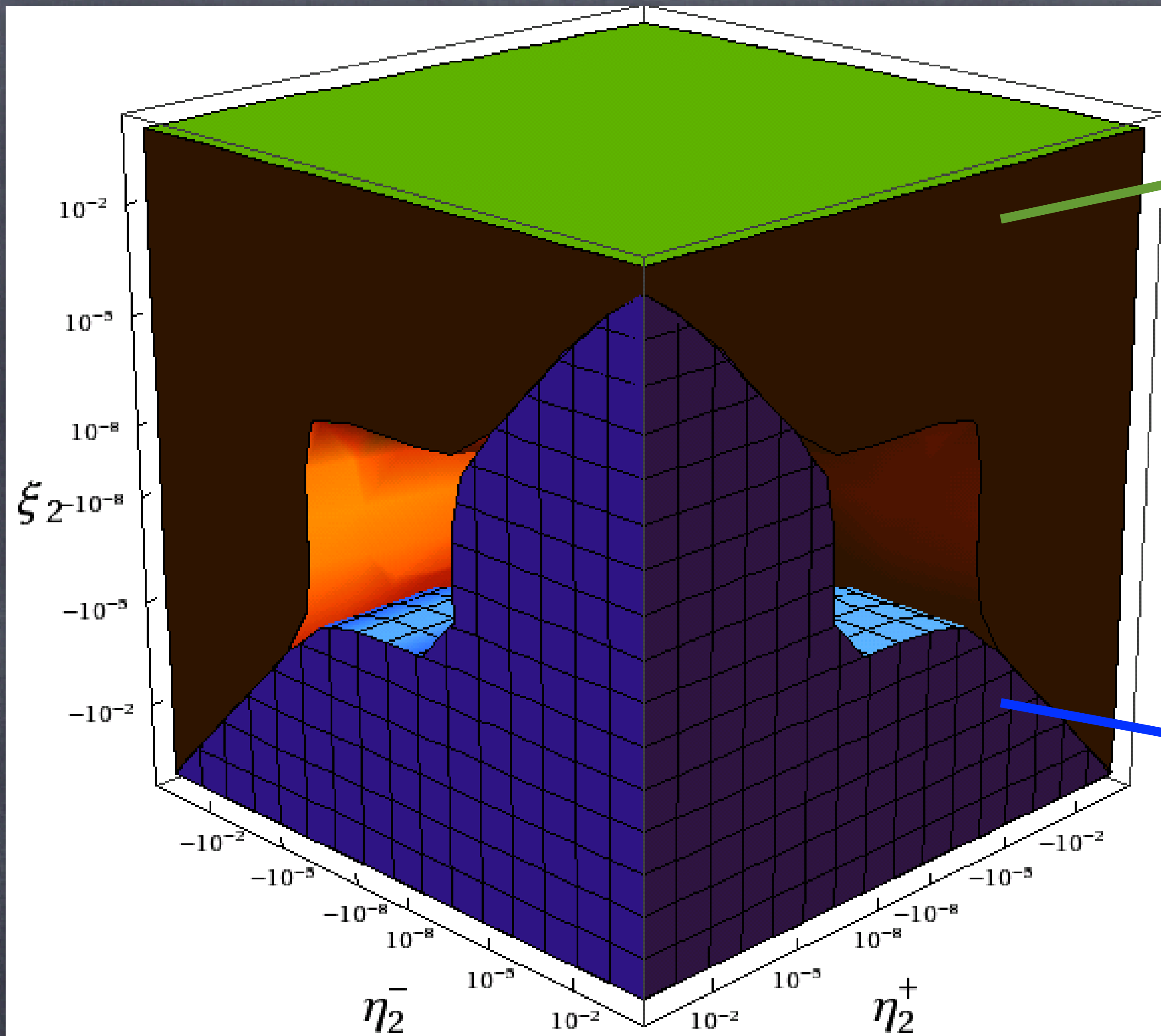
and for n=2:

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

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




UHE photons are detected

UHE photon absorption takes place

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

The modified dispersion relation also leads to energy dependent group velocity $V=\partial E/\partial p$ and thus to an energy-dependent time delay over a distance d:

$$\Delta t = -\xi\, d \frac{E}{M_{\rm Pl}} \simeq -\xi \left(\frac{d}{100\,{\rm Mpc}}\right)\left(\frac{E}{\rm TeV}\right) {\rm sec}$$

for linearly suppressed terms. GRB observations in TeV γ-rays can therefore probe quantum gravity. The current limit is $M_{Pl}/\xi > 8\times10^{15}$ GeV (Ellis et al.).

**But the UHE photon limits are inconsistent with interpretations of time delays of high energy gamma-rays from GRBs within quantum gravity secanrios based on effective field theory**
Maccione, Liberati, Sigl, PRL 105 (2010) 021101

**Possible exception in space-time foam models,**
Ellis, Mavromatos, Nanopoulos, arXiv:1004.4167

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2.) Astrophysics and Cosmology also have sensitivity to photon mixing with possible new light states

3.) The large Lorentz factors involved in cosmic radiation at energies above ~ $10^{19}$ eV provides a magnifier into possible Lorentz invariance violations (LIV) and provides very strong limits on deviations from Lorentz symmetry violations.