# Searches for Astroparticle Physics beyond the Standard Model

- Unsolved questions on the astrophysics of ultra-high energy cosmic rays
- Secondary gamma-rays and neutrinos as test meams
- Limits on Lorentz invariance violation and quantum gravity
- Photon mixing with new light states

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Günter Sigl
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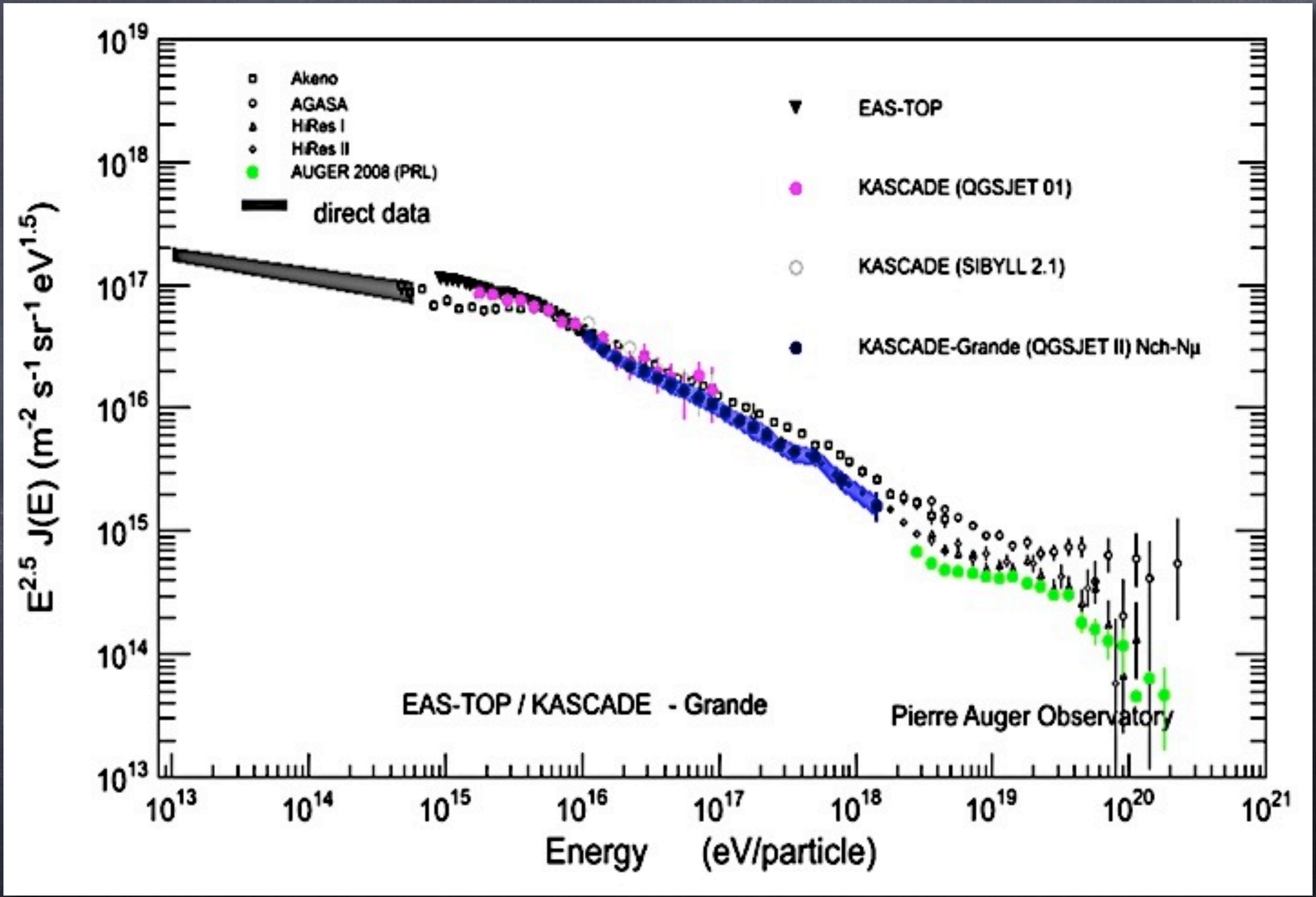
http://www2.iap.fr/users/sigl/homepage.html

# Ultra-High Energy Cosmic Rays



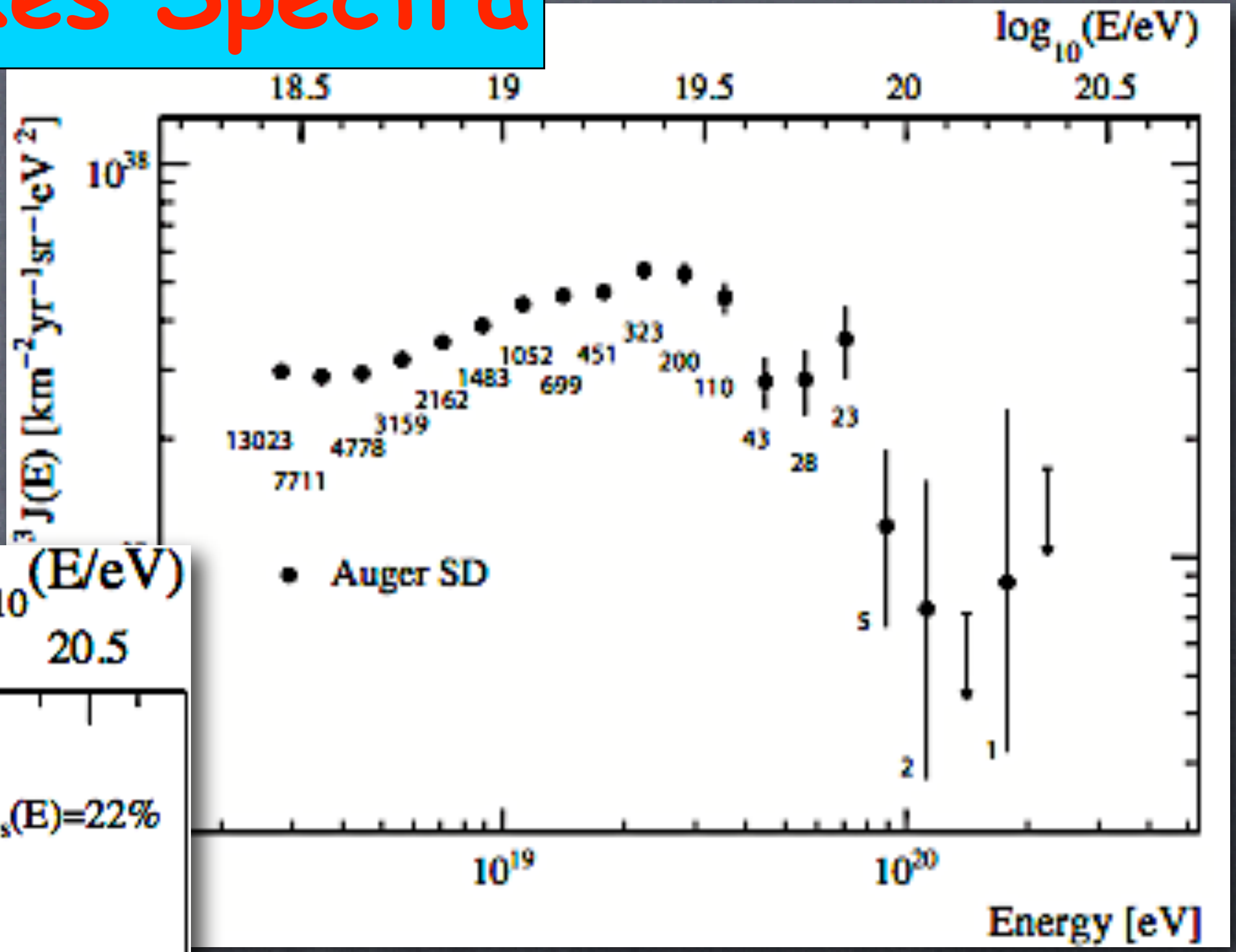

## A View of the All Particle Spectrum

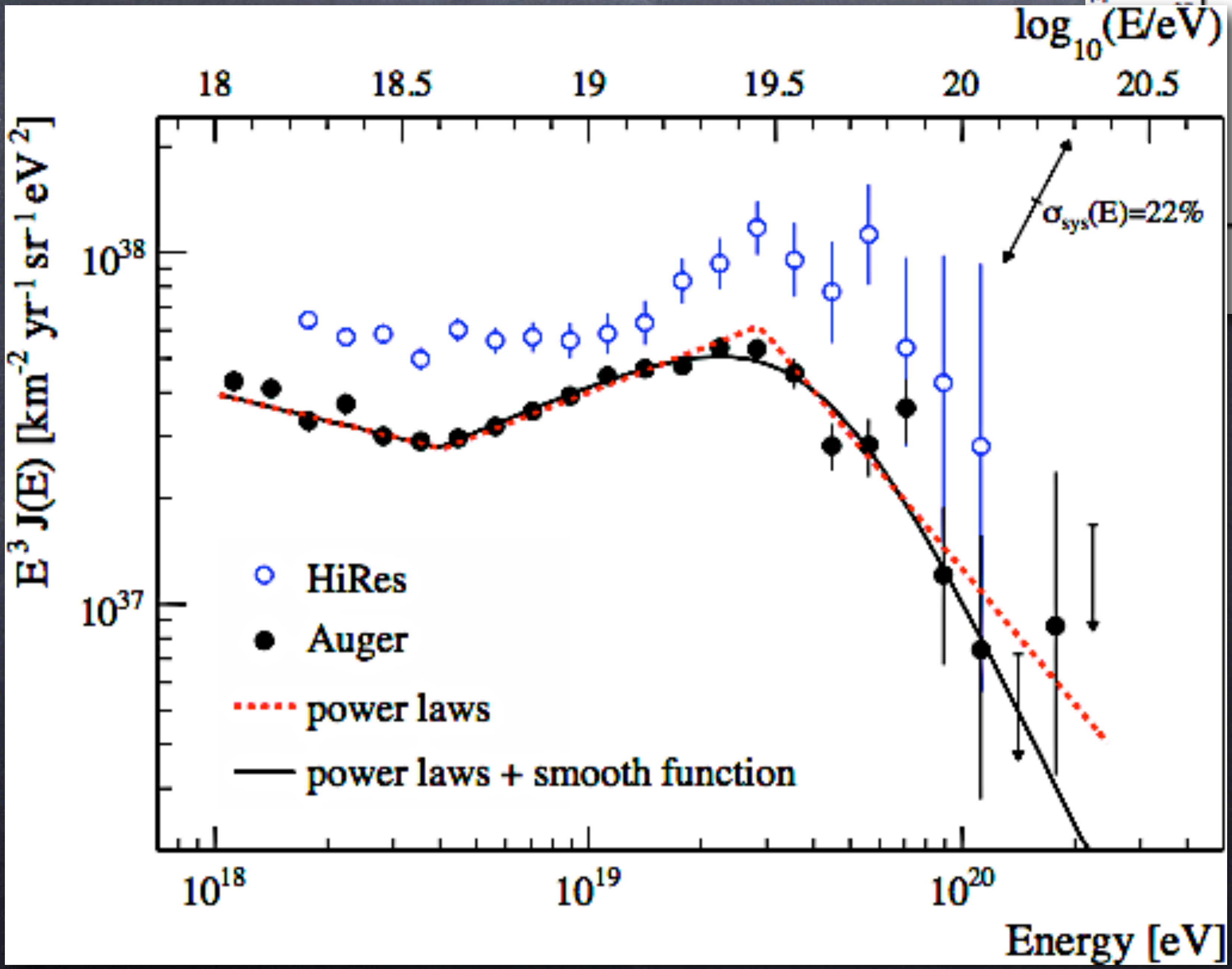
KASCADE-Grande collaboration, arXiv:1009.4716

# Auger and HiRes Spectra

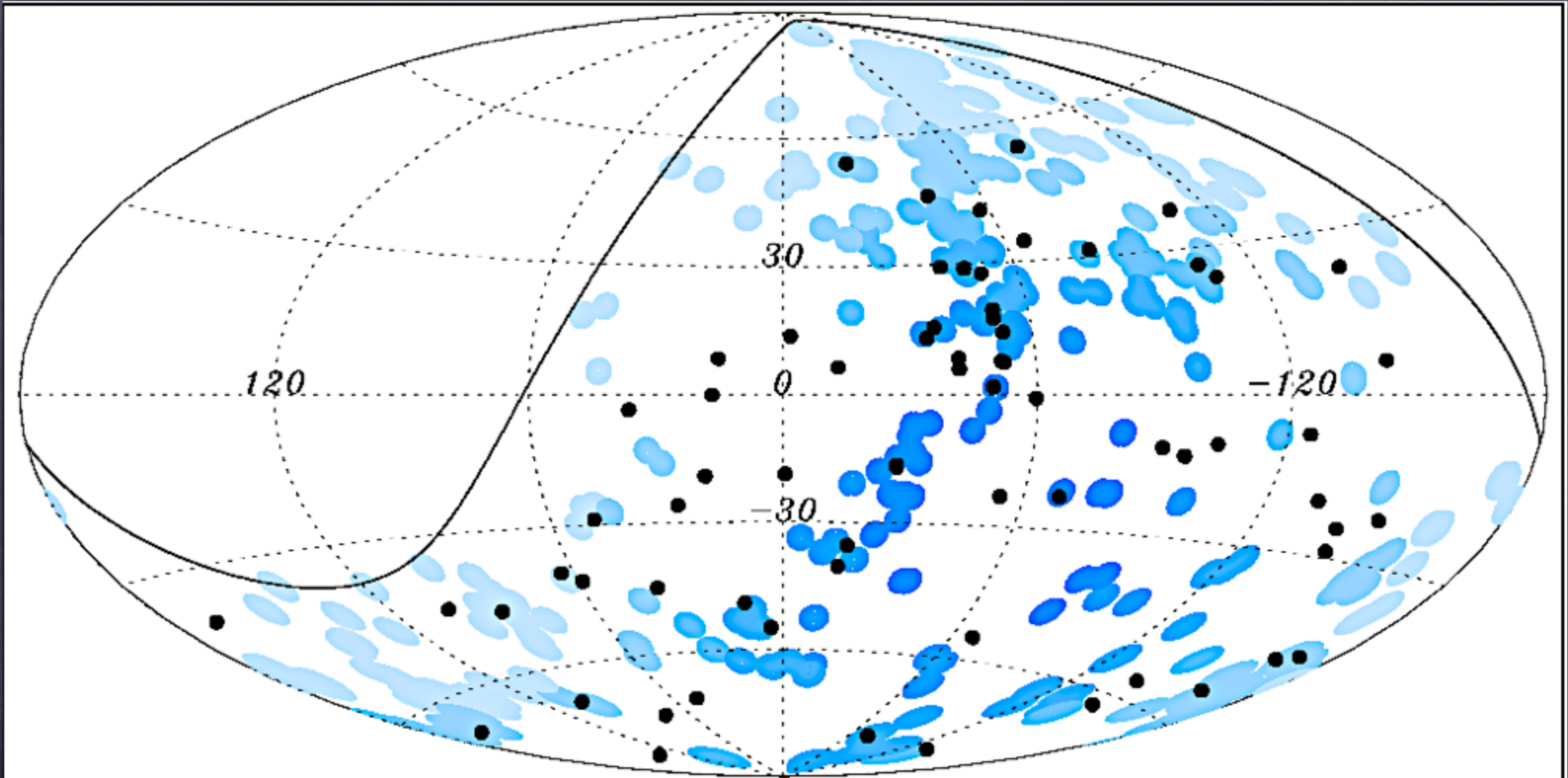
Auger exposure = 12,790 $km^2$ sr yr
up to December 2008

Pierre Auger Collaboration, PRL 101, 061101 (2008)
and Phys.Lett.B 685 (2010) 239



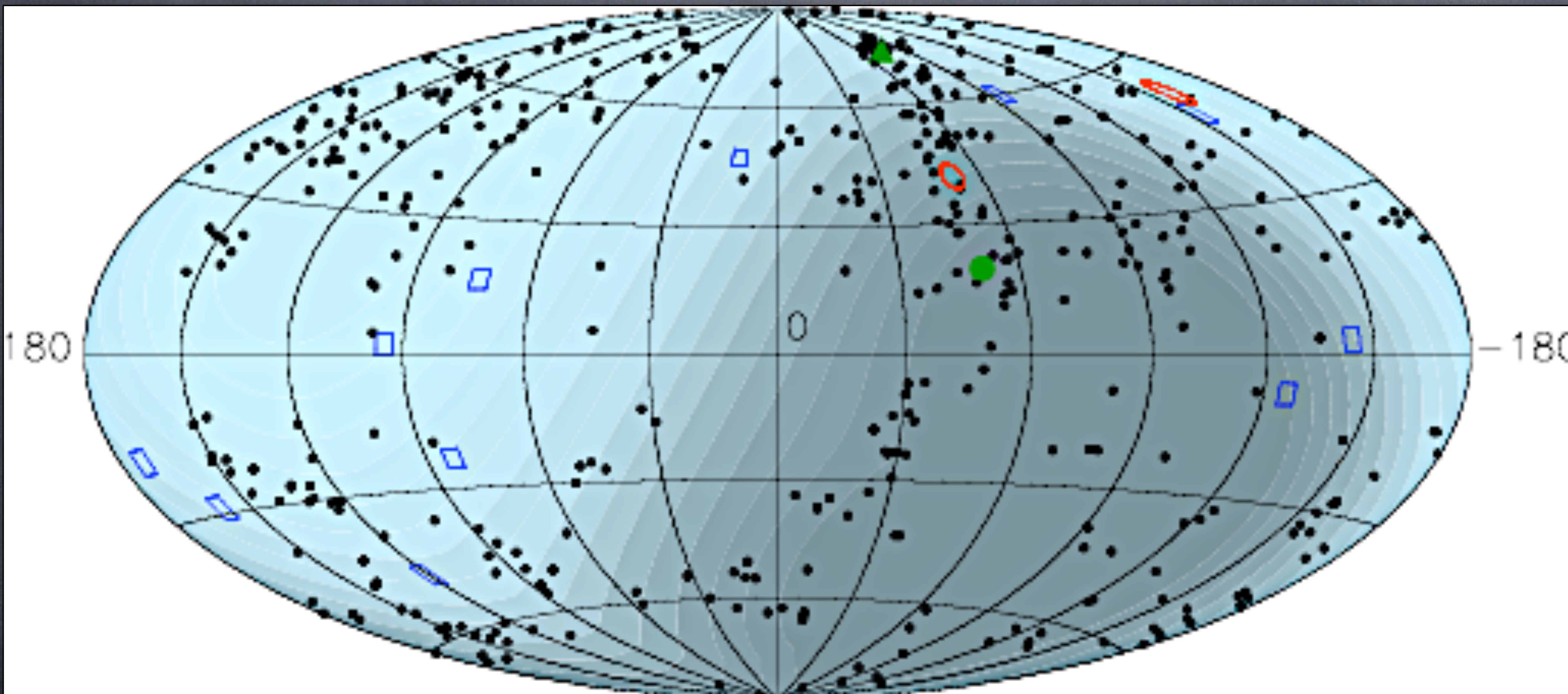
# Auger sees Correlations with AGNs !




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

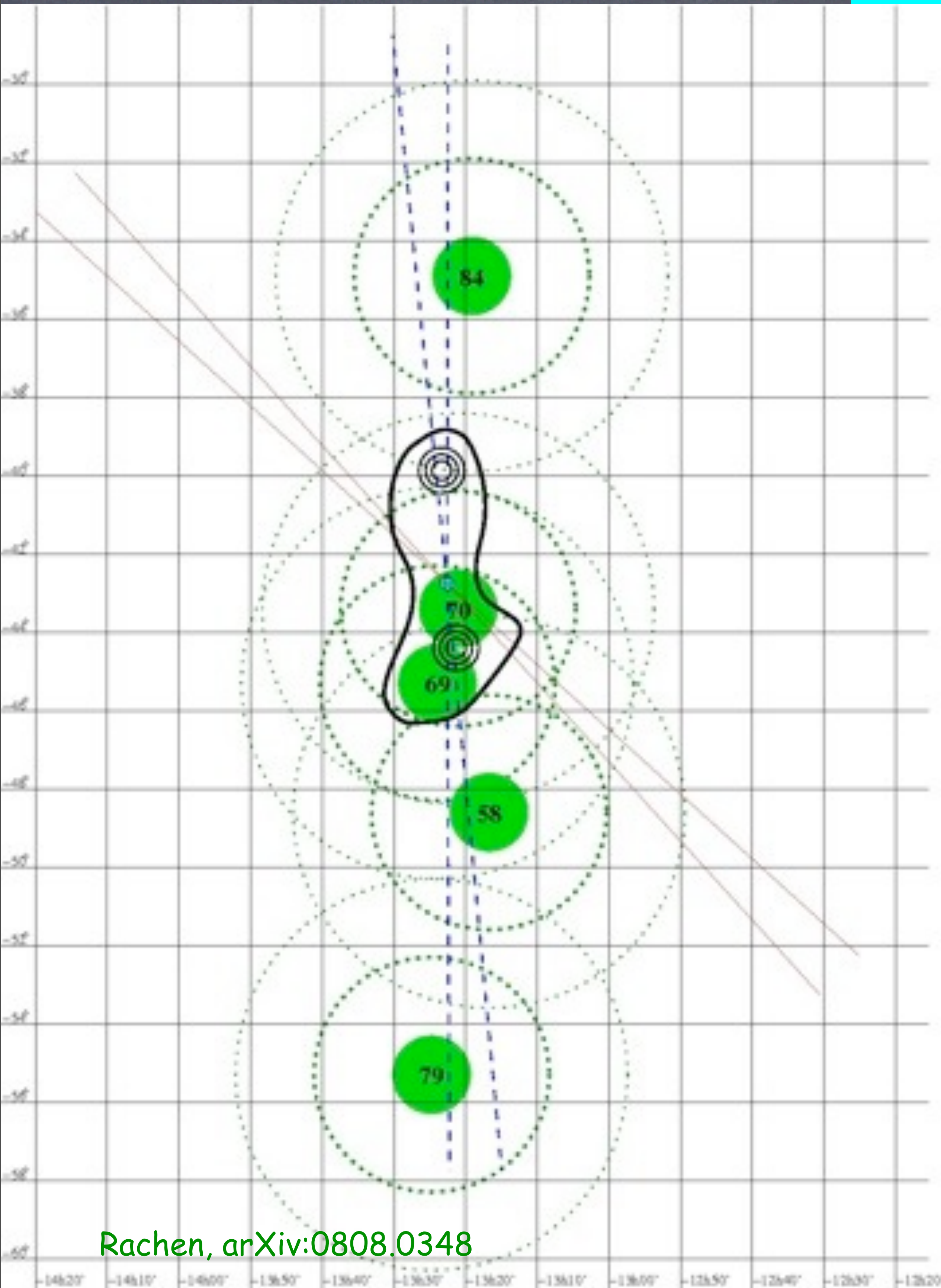
# But HiRes sees no Correlations !

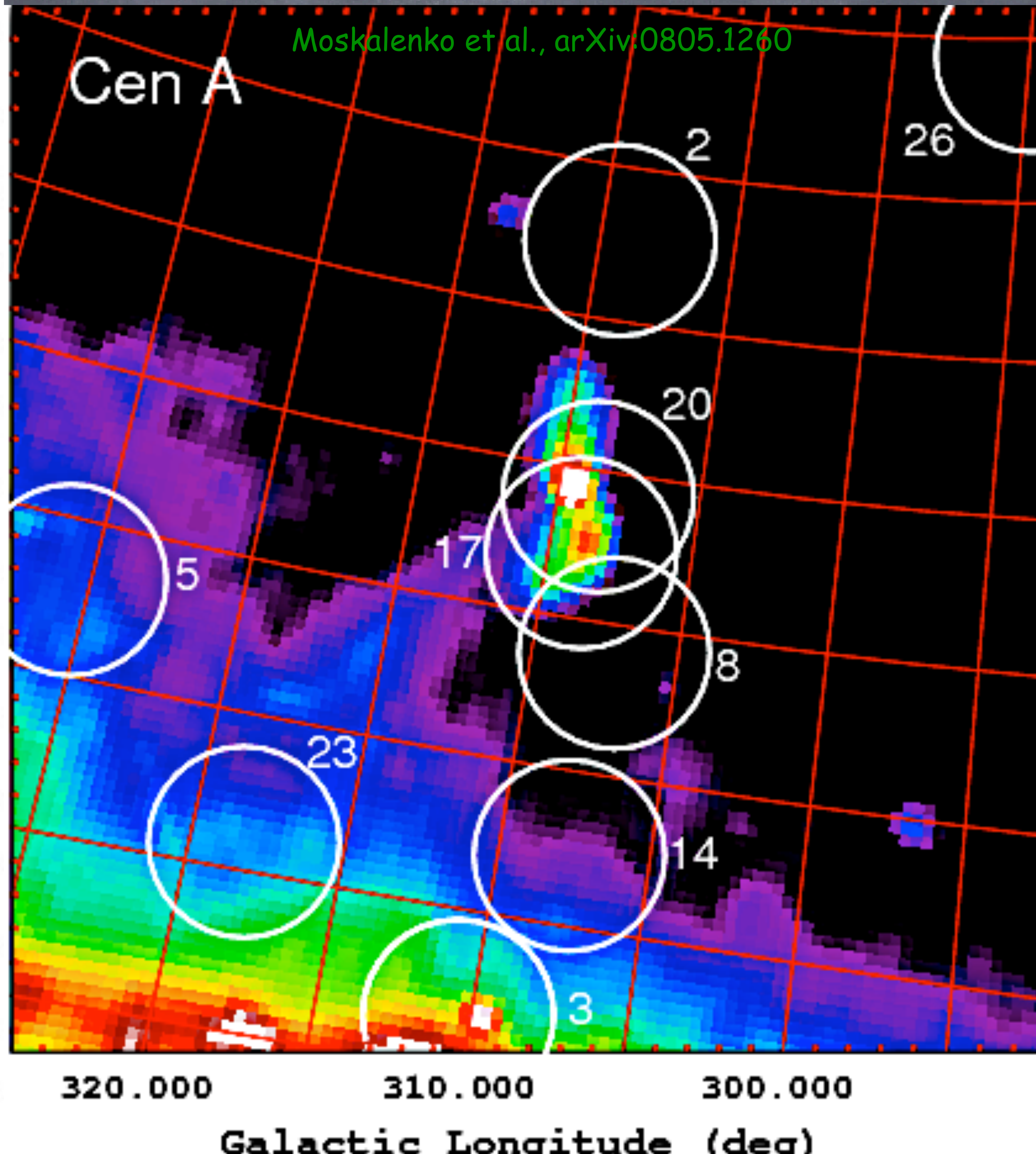


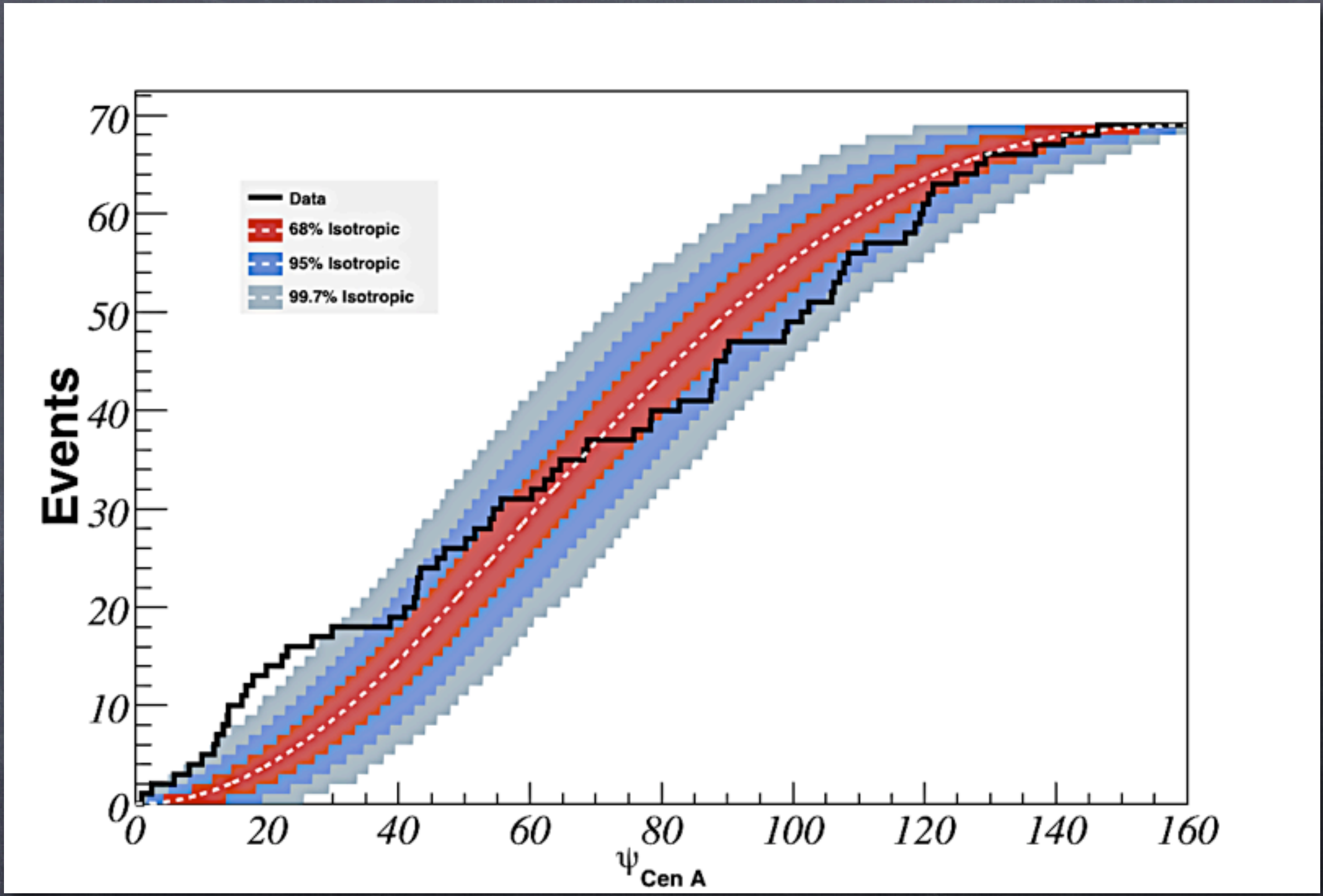

Black dots = 457 AGNs + 14 QSOs from the Veron Cetty catalogue for z < 0.018
red circles = 2 correlated events above 56 EeV within 3.1°,
blue squares = 11 uncorrelated events

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

# Centaurus A


84
70
69
58
79
Rachen, arXiv:0808.0348


Moskalenko et al., arXiv:0805.1260
Cen A
2
26
20
17
5
8
23
14
3
320.000
310.000
300.000
Galactic Longitude (deg)

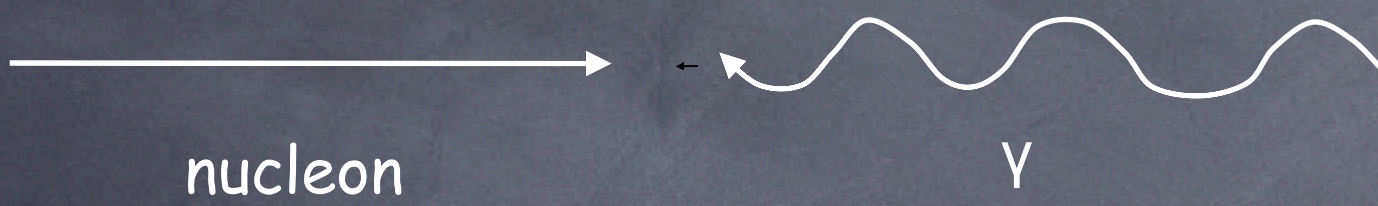



Pierre Auger sees a clear excess in the direction of Centaurus A.

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

# The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background

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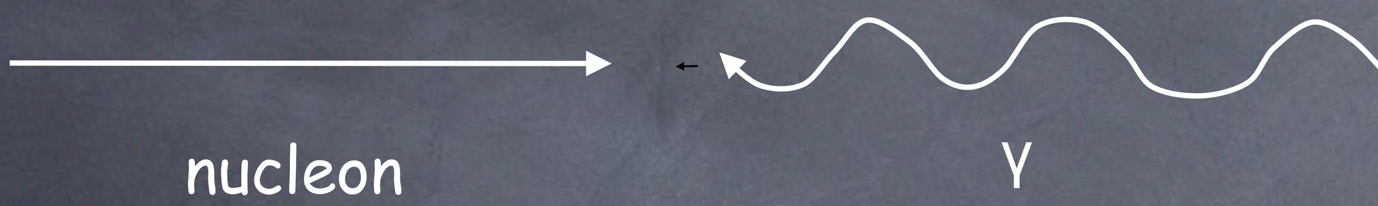


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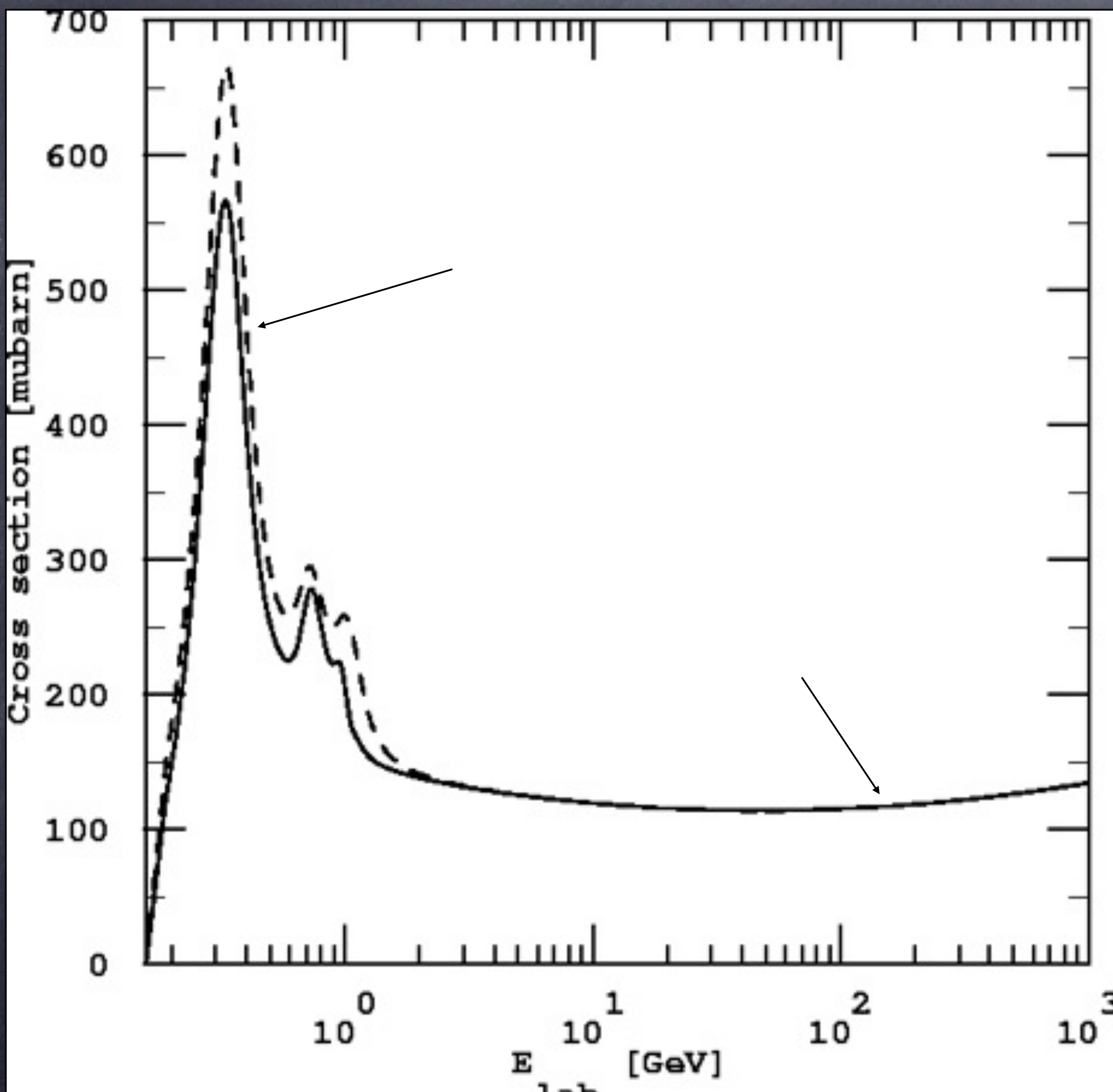

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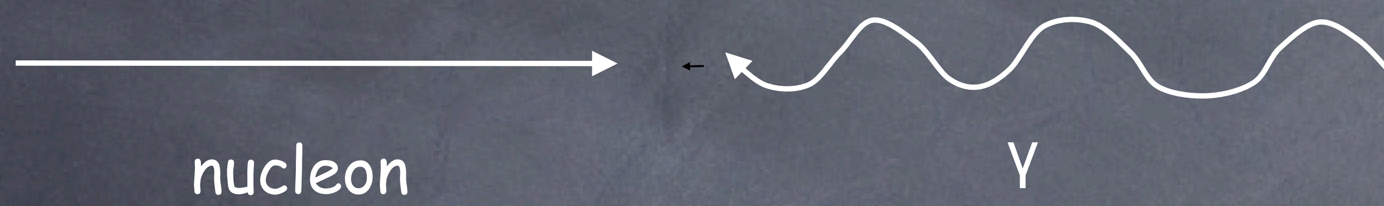


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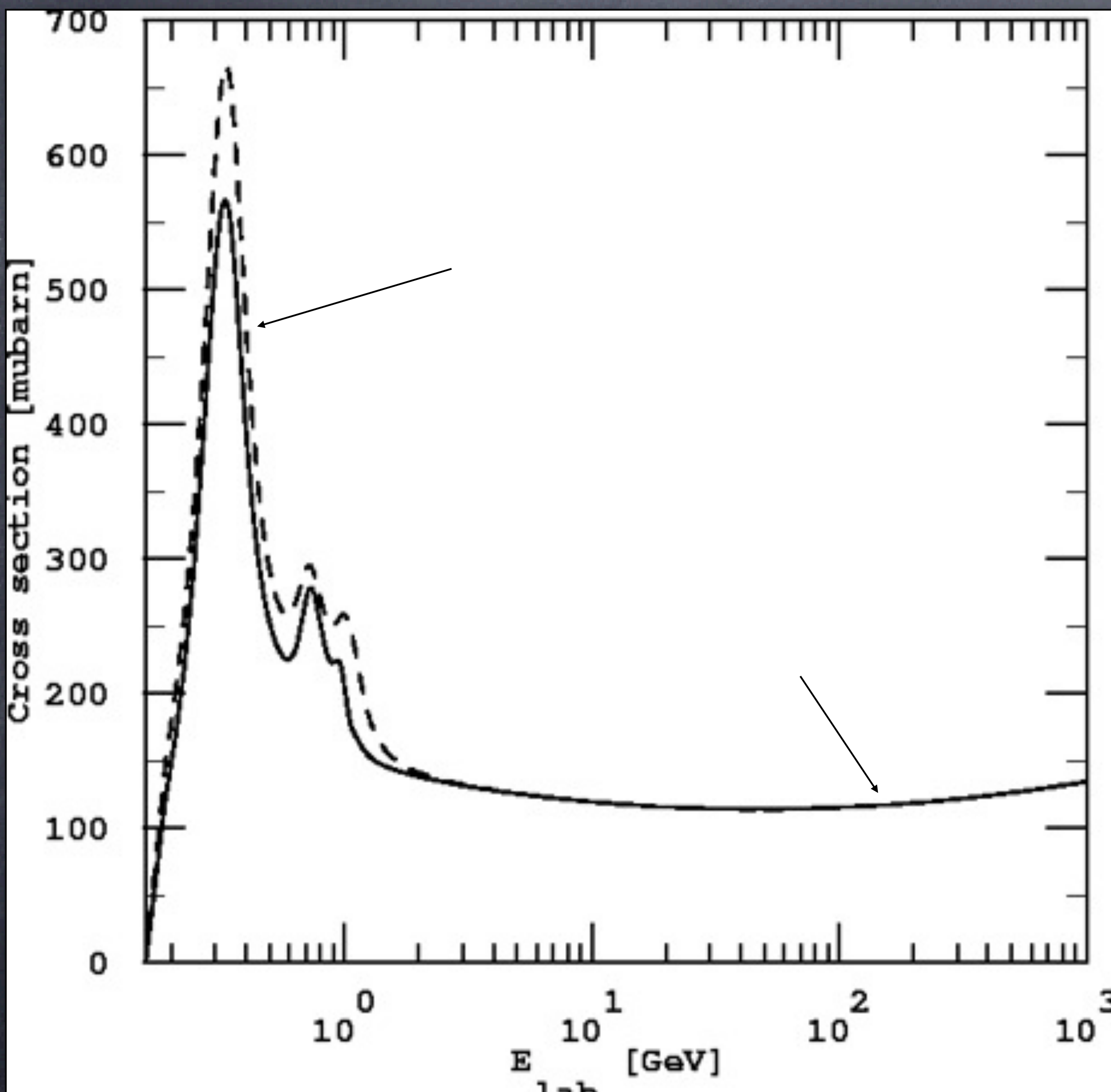


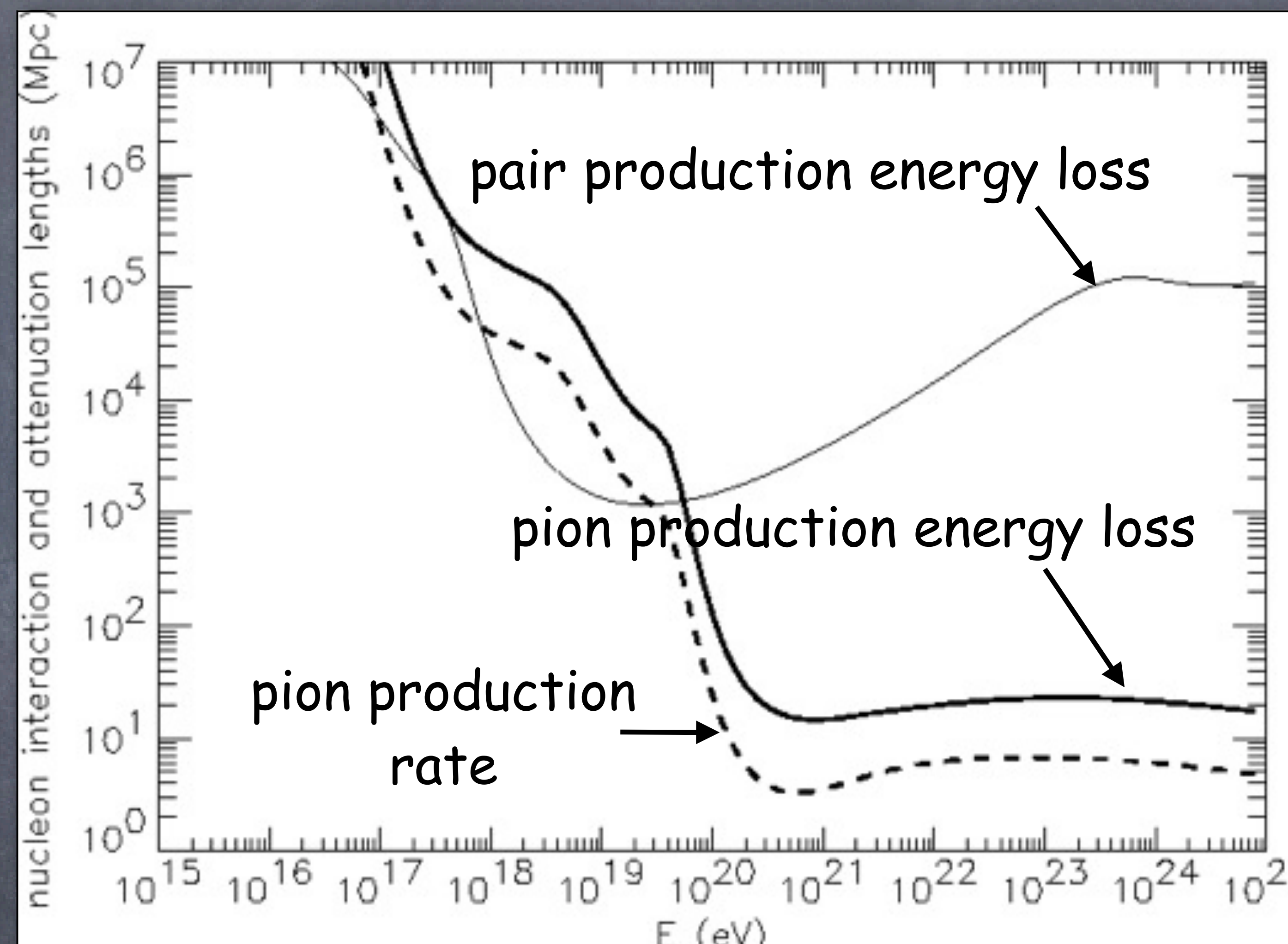

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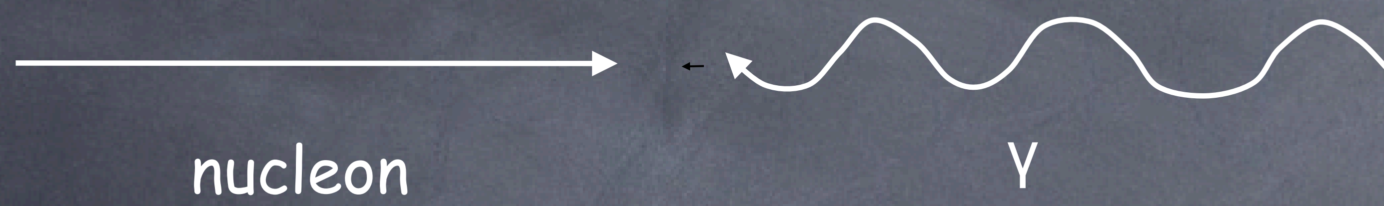


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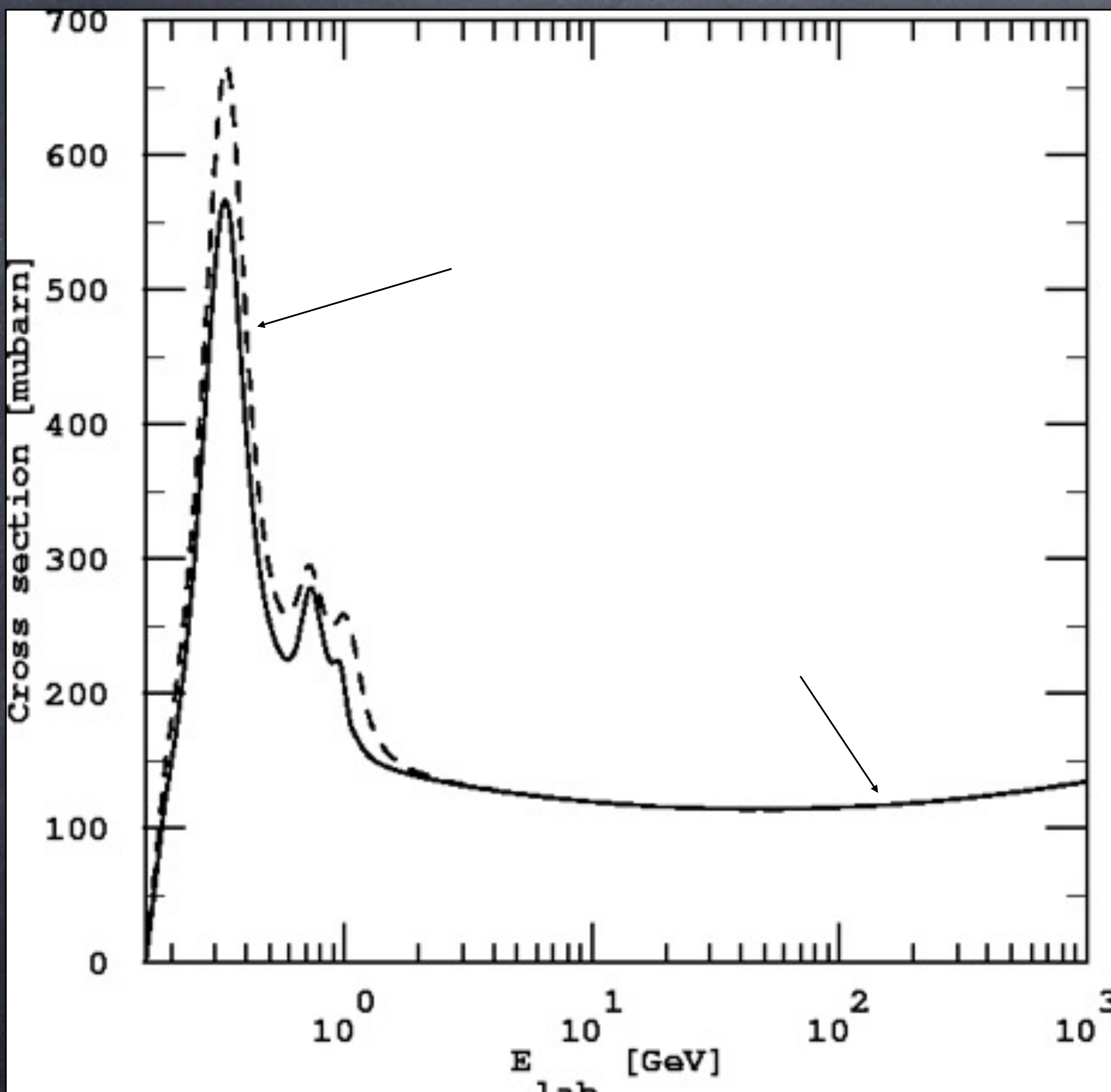
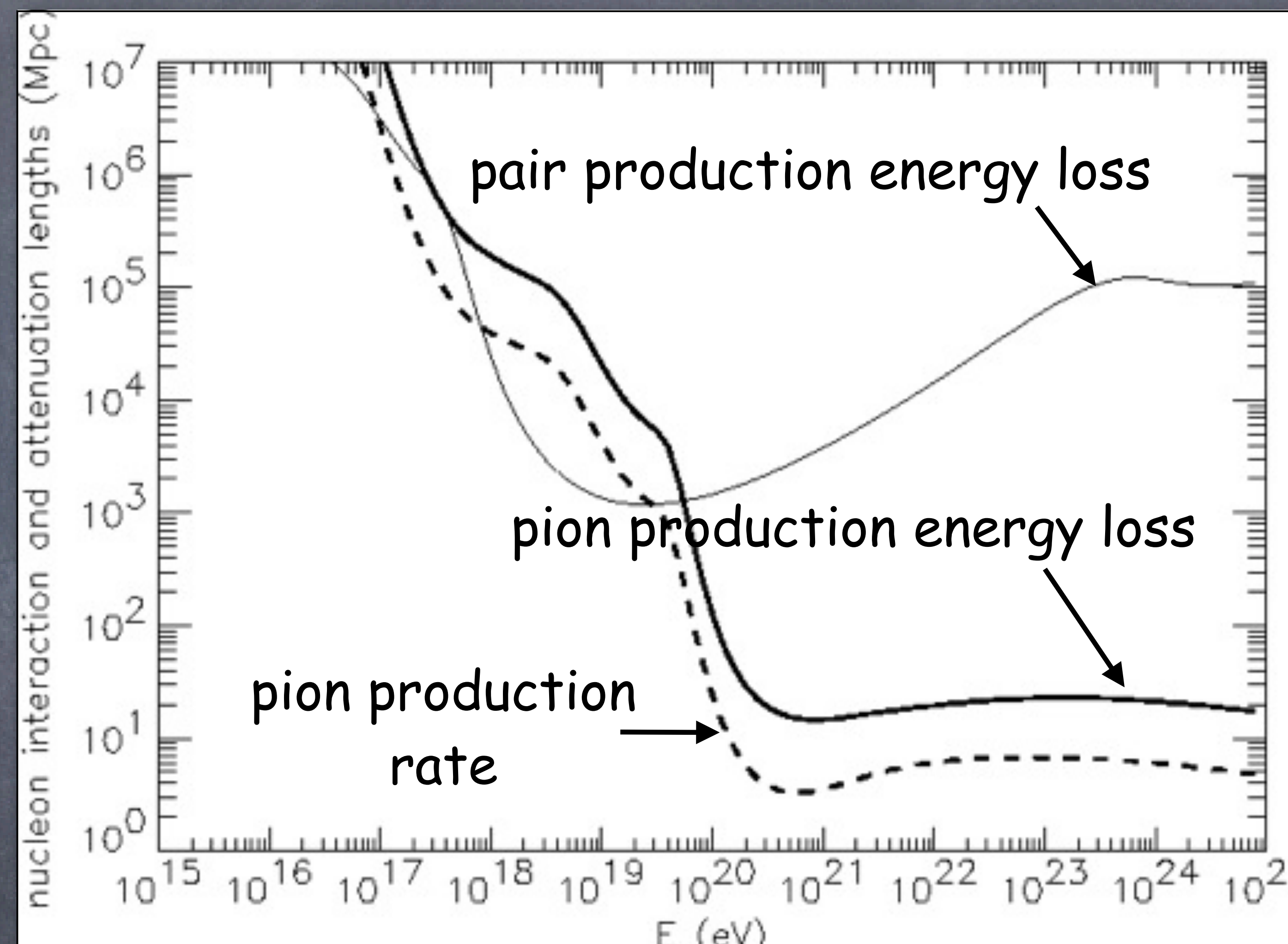
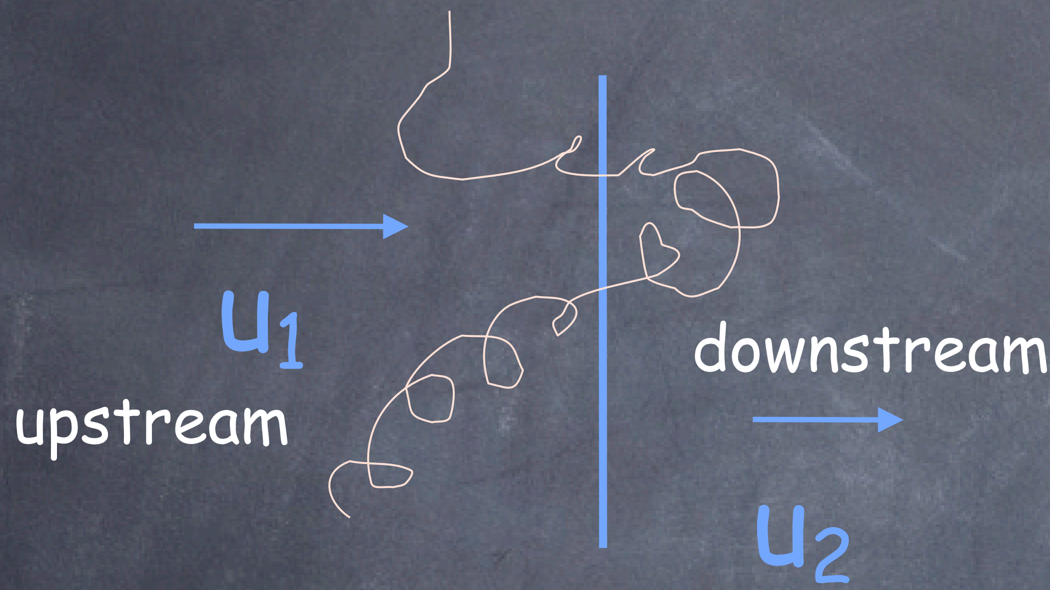



sources must be in cosmological backyard
Only Lorentz symmetry breaking at $\Gamma > 10^{11}$
could avoid this conclusion.

# $1^{st}$ Order Fermi Shock Acceleration

The most widely accepted scenario of cosmic ray acceleration




Fractional energy gain per shock crossing proportional to $u_1 - u_2$ on a time scale $r_L/u_2$.

Together with downstream losses this leads to a spectrum $E^{-q}$ with $q > 2$ typically.

When the gyro-radius $r_L$ becomes comparable to the shock size L, the spectrum cuts off.

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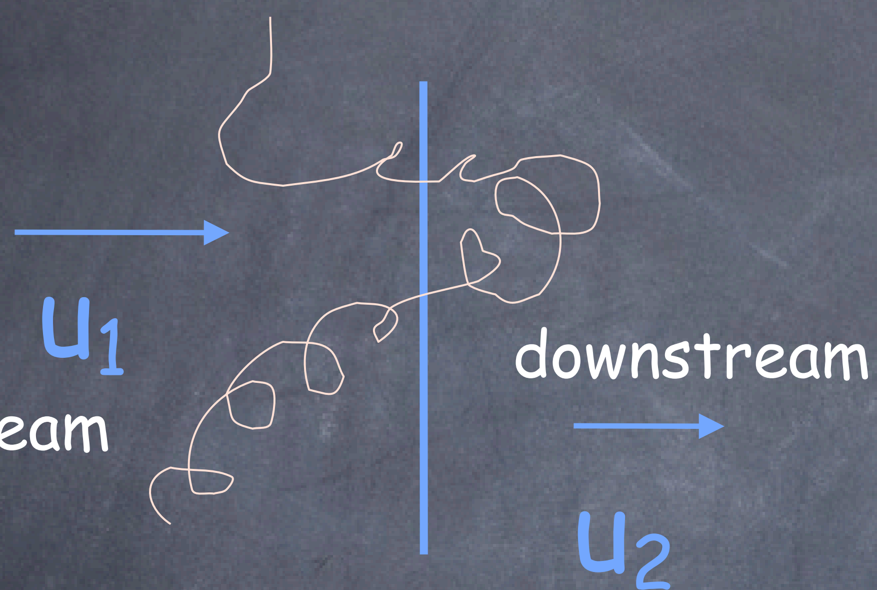


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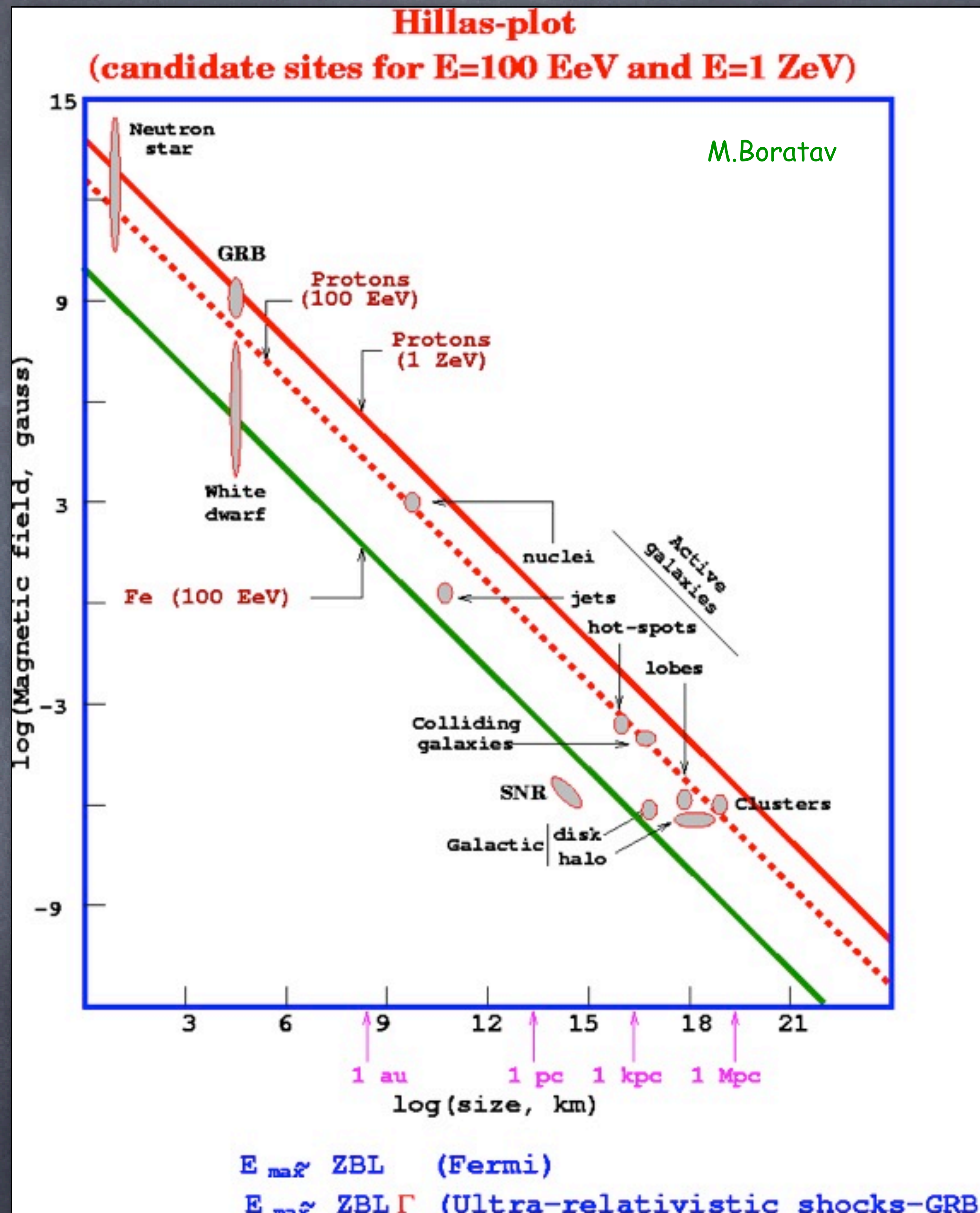
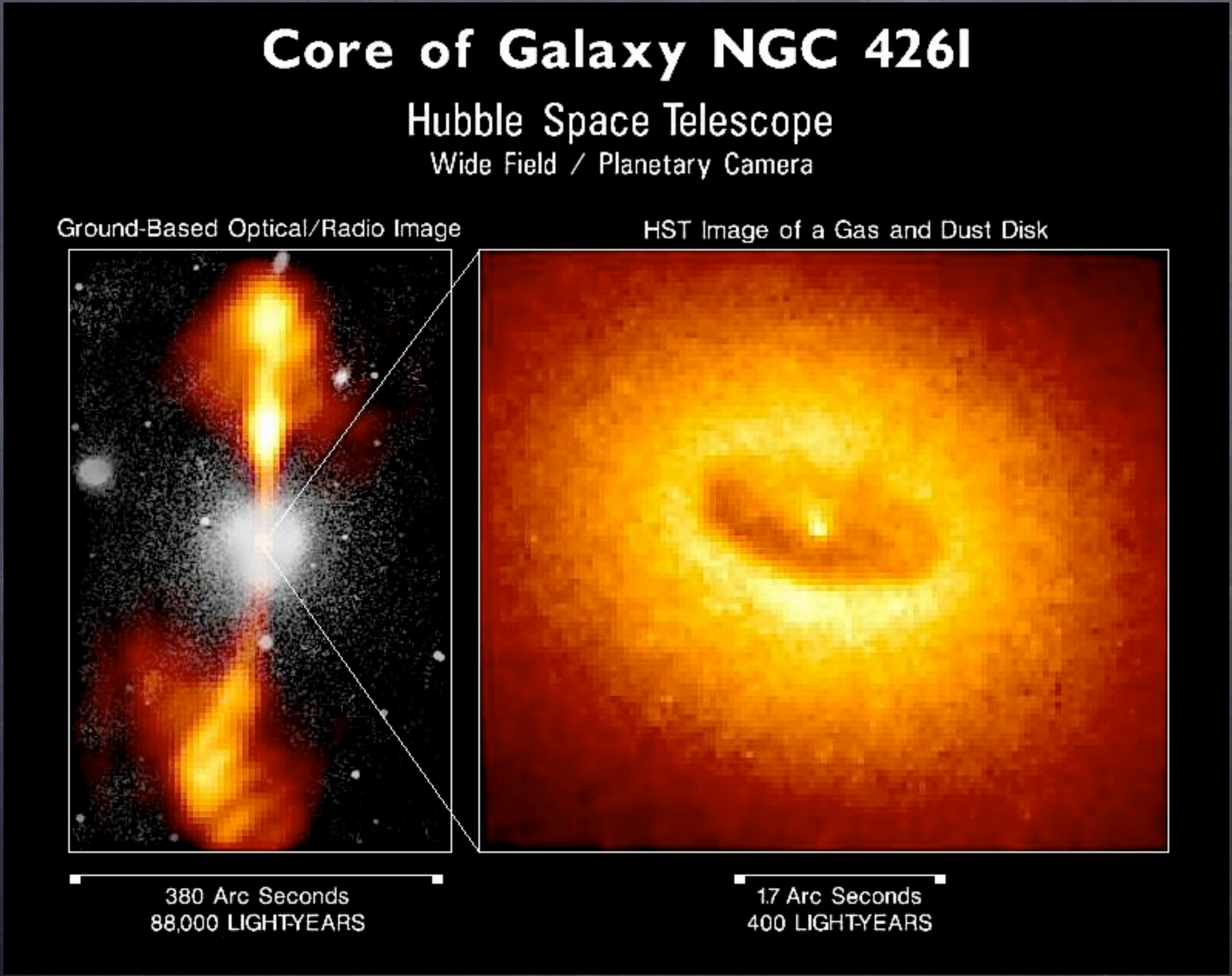
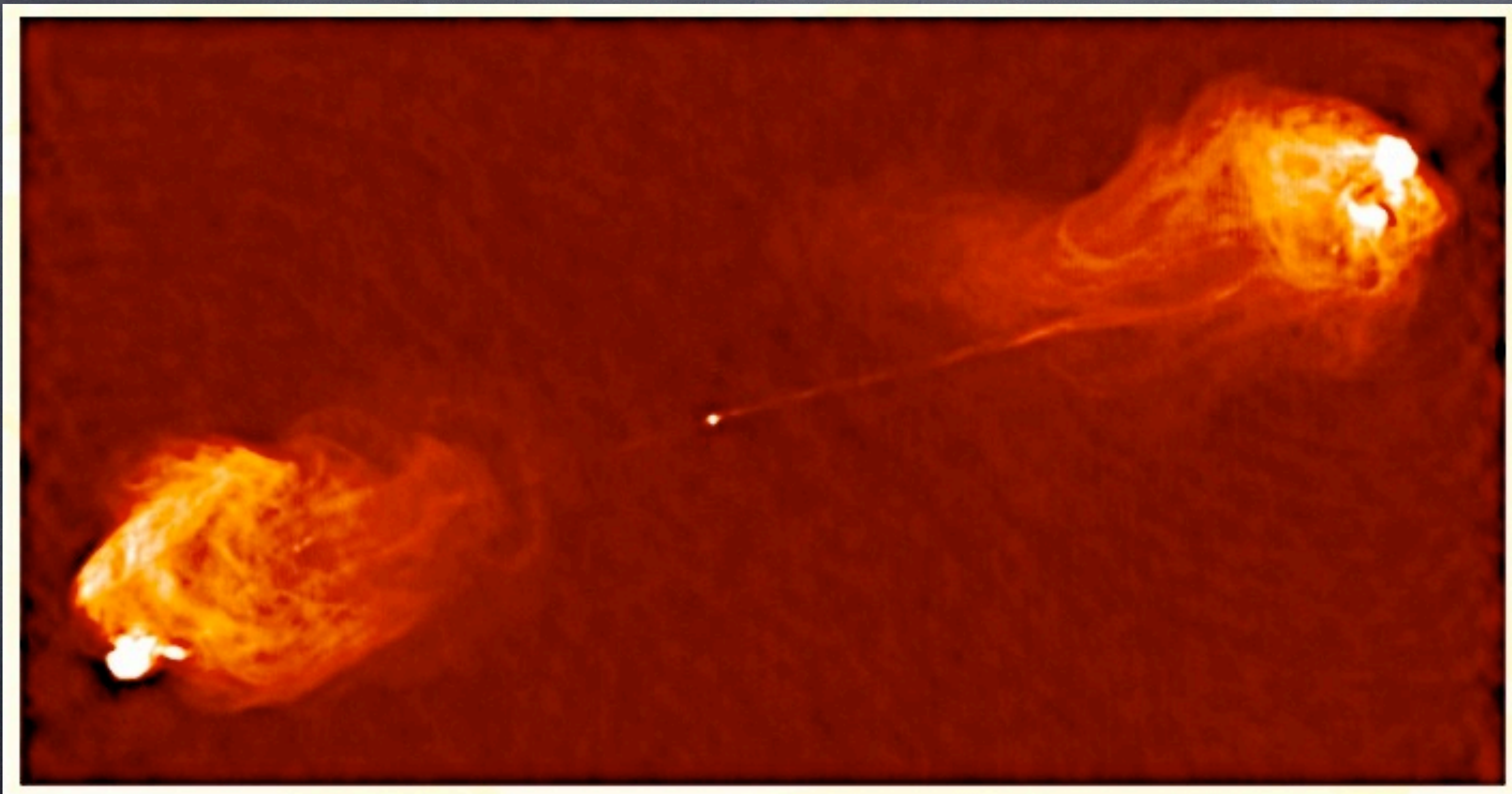


# A possible acceleration site associated with shocks in hot spots of active galaxies



# Or Cygnus A



“Conundrum”:

If deflection is small and sources follow the local large scale structure then

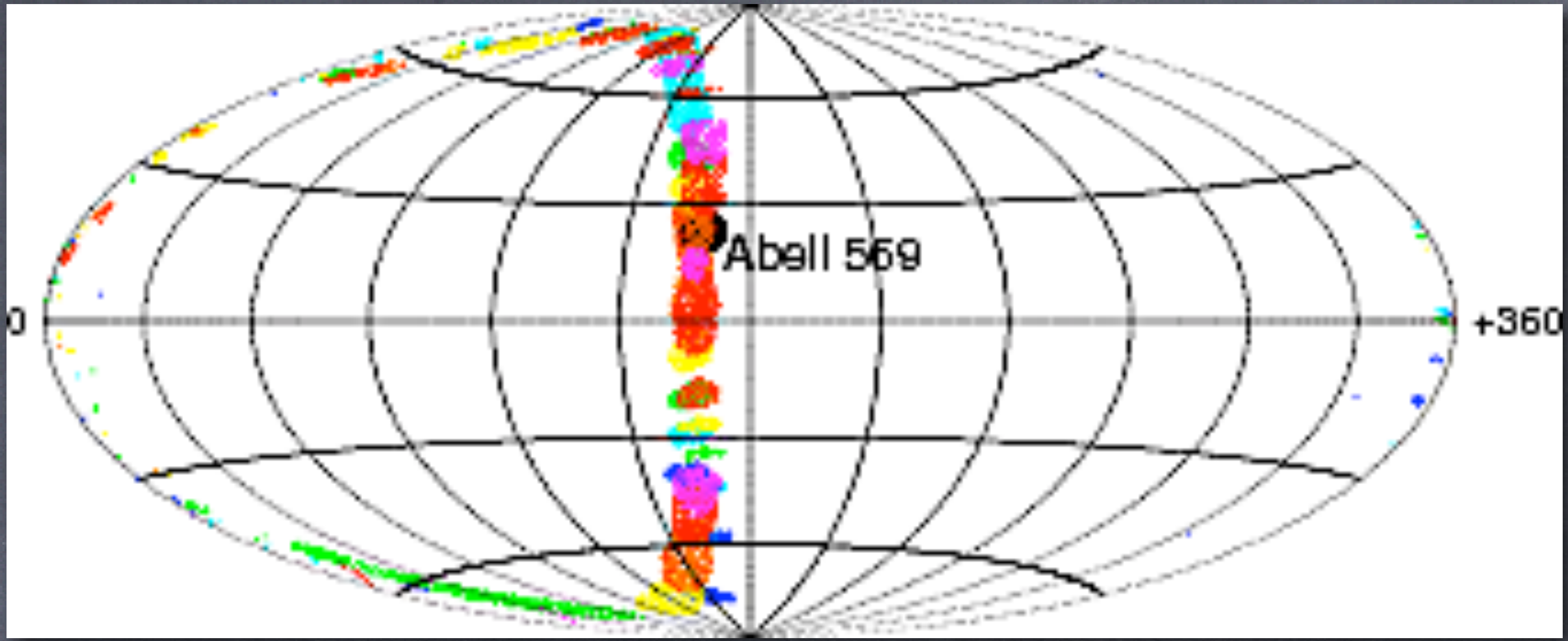
a) primaries should be protons to avoid too much deflection in galactic field

b) but air shower measurements by Pierre Auger (but not HiRes) indicate mixed or heavy composition

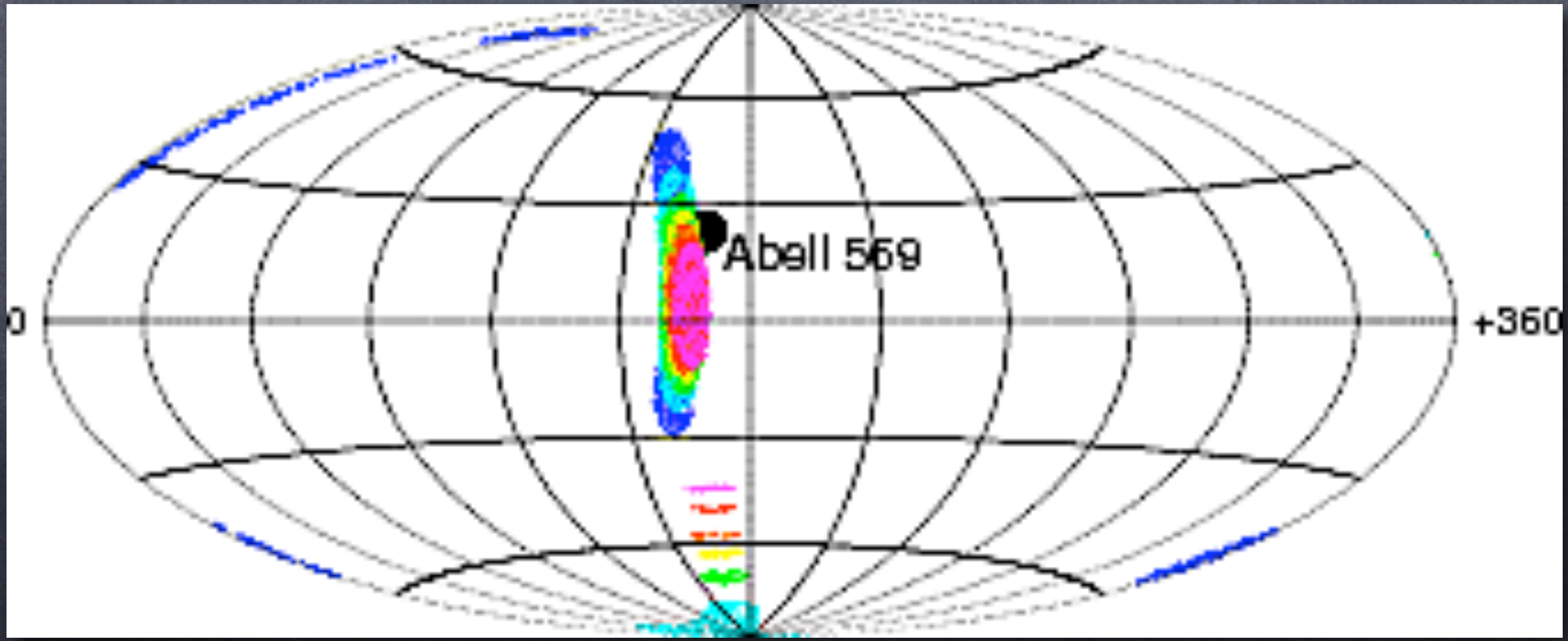
c) Theory of AGN acceleration seem to necessitate heavier nuclei to reach observed energy

# "Iron Image" of galaxy cluster Abell0569 in two galactic field models

Iron image of Abell 569 at energies from 60 to 140 EeV



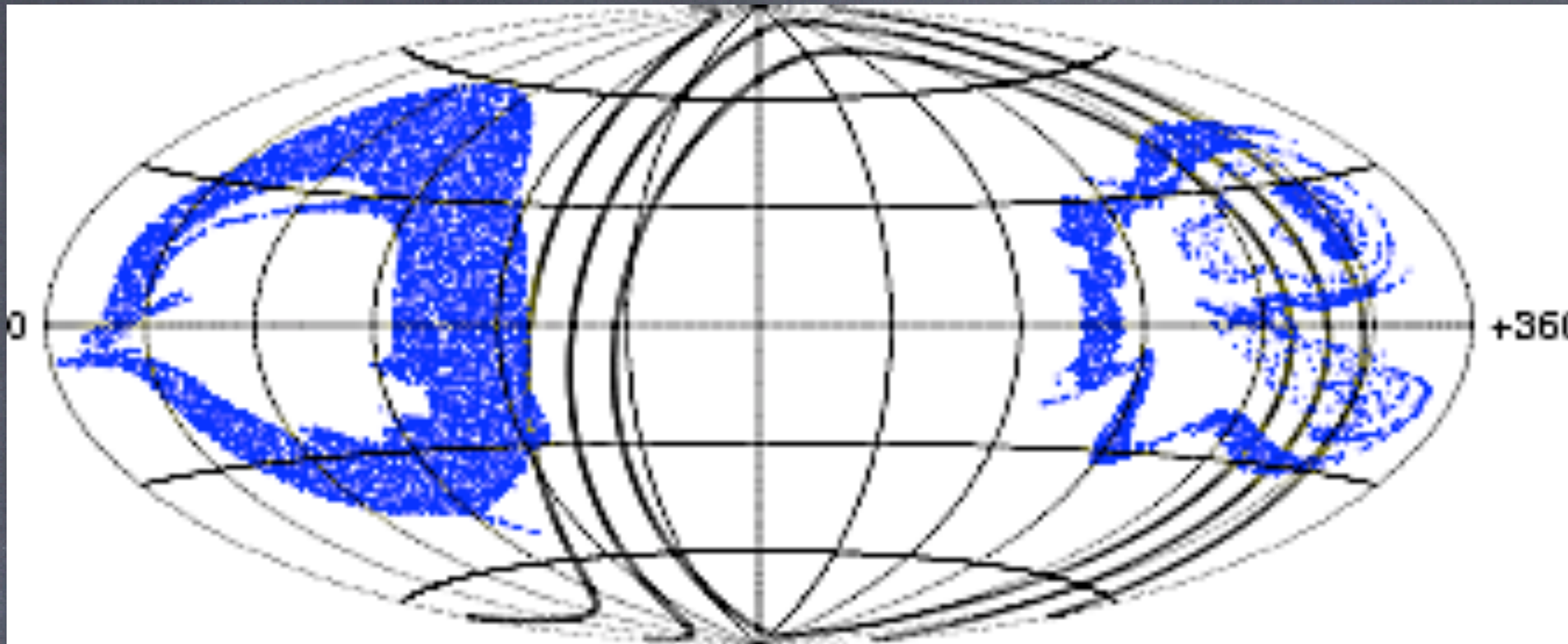

Sun08 model



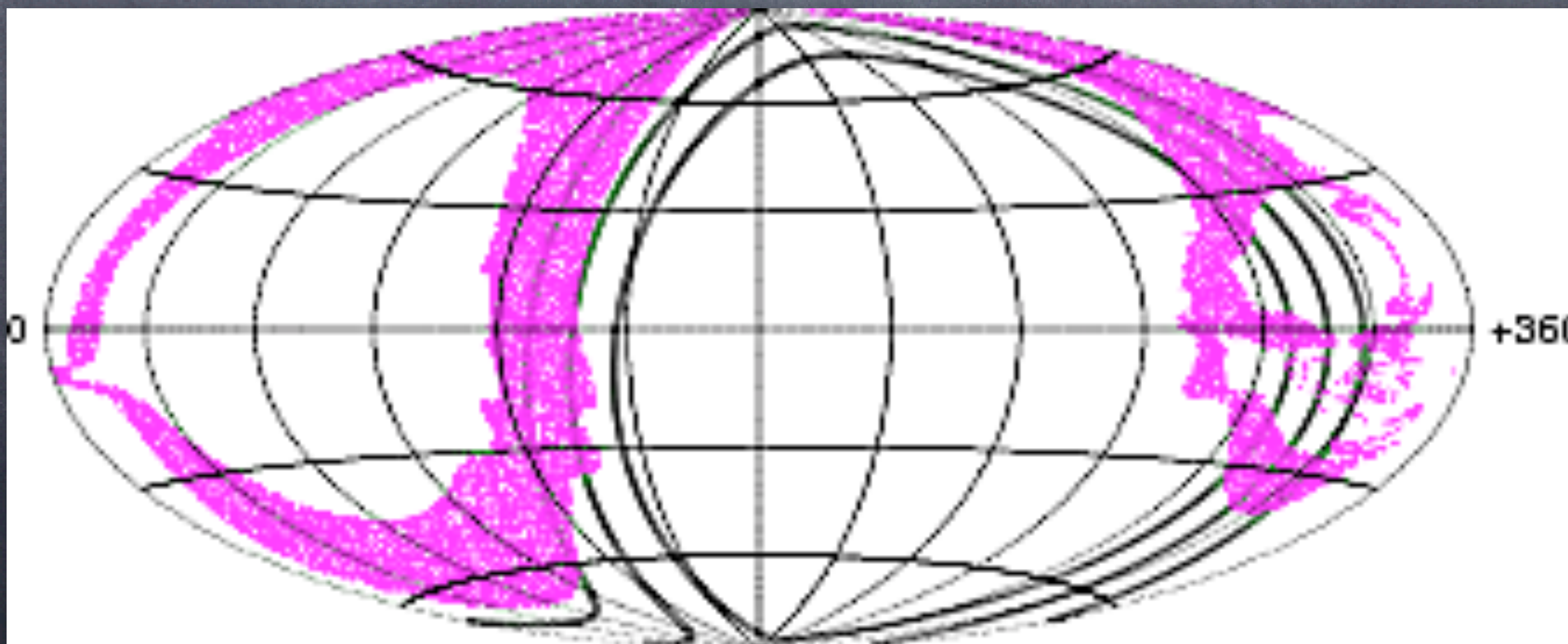

Sun08 modified halo model

Giacinti, Kachelriess, Semikoz, Sigl, JCAP 1008 (2010) 036

## “Iron image” of supergalactic plane in galactic magnetic field model of Prouza&Smida




E=60 EeV




E=140 EeV

Giacinti, Kachelriess, Semikoz, Sigl, JCAP 1008 (2010) 036

# 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.
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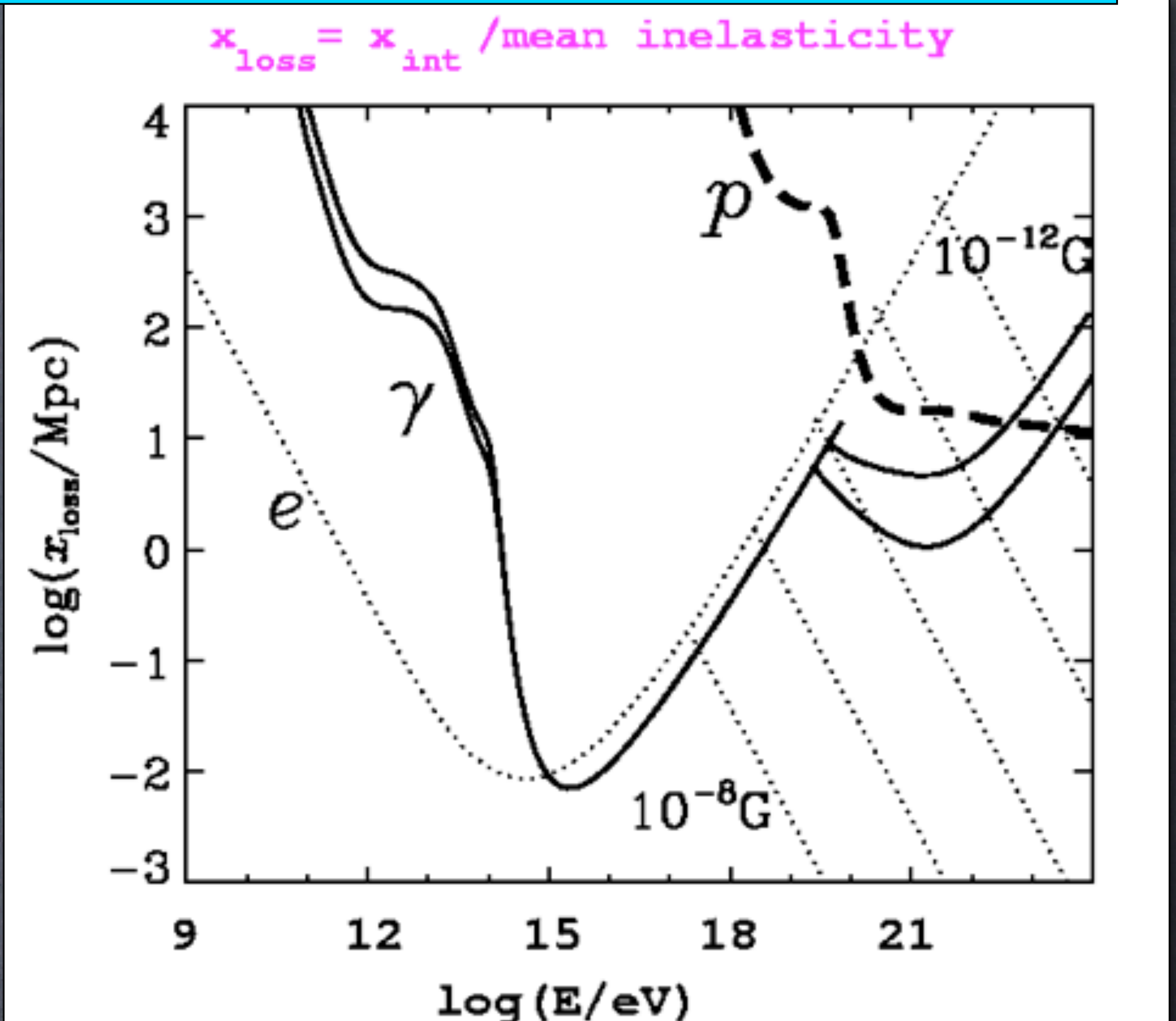


**Included processes:**

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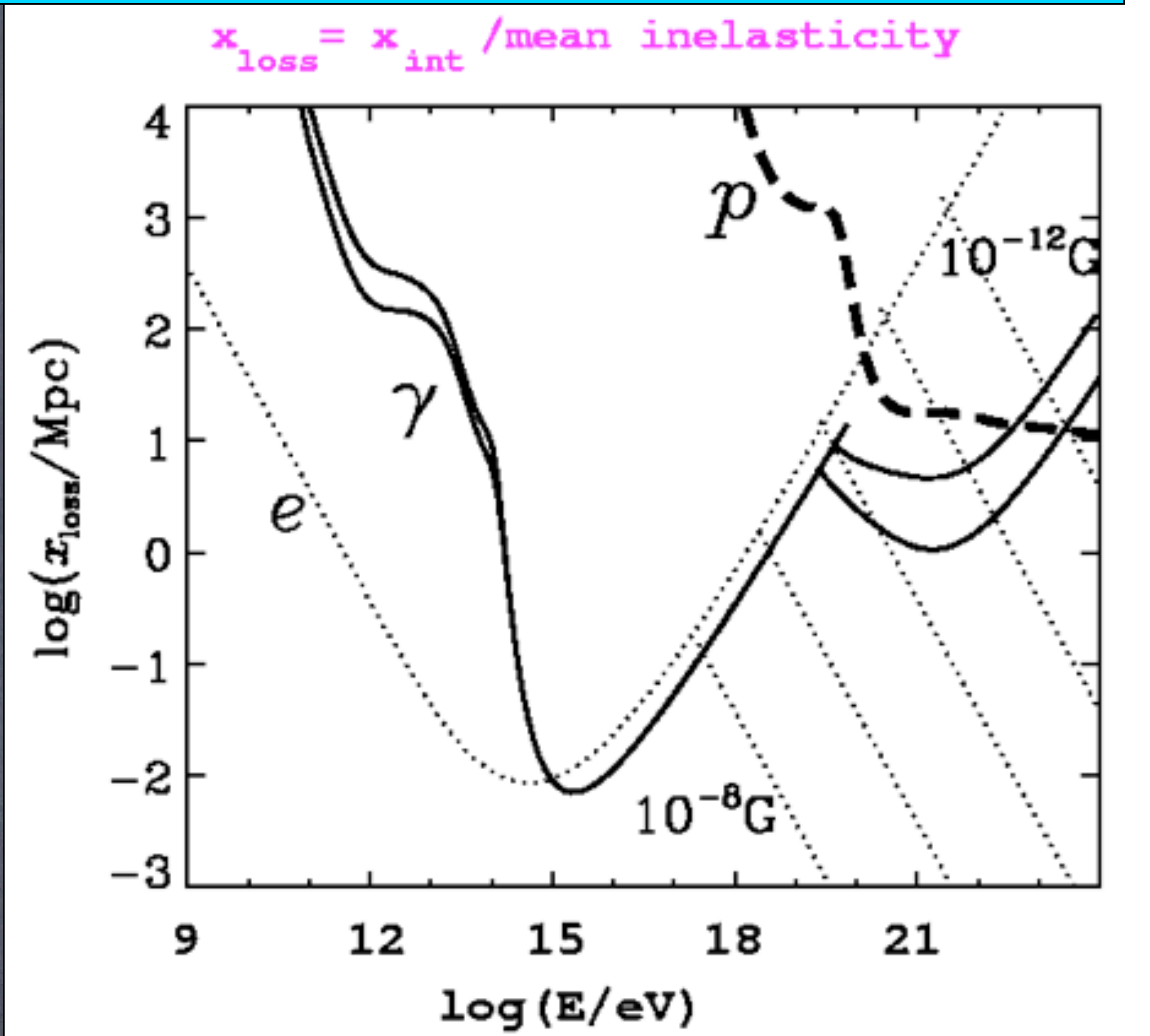
Neutrino spectrum is unmodified, γ-rays pile up below pair production threshold (on CMB at a few $10^{14}$ eV)

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

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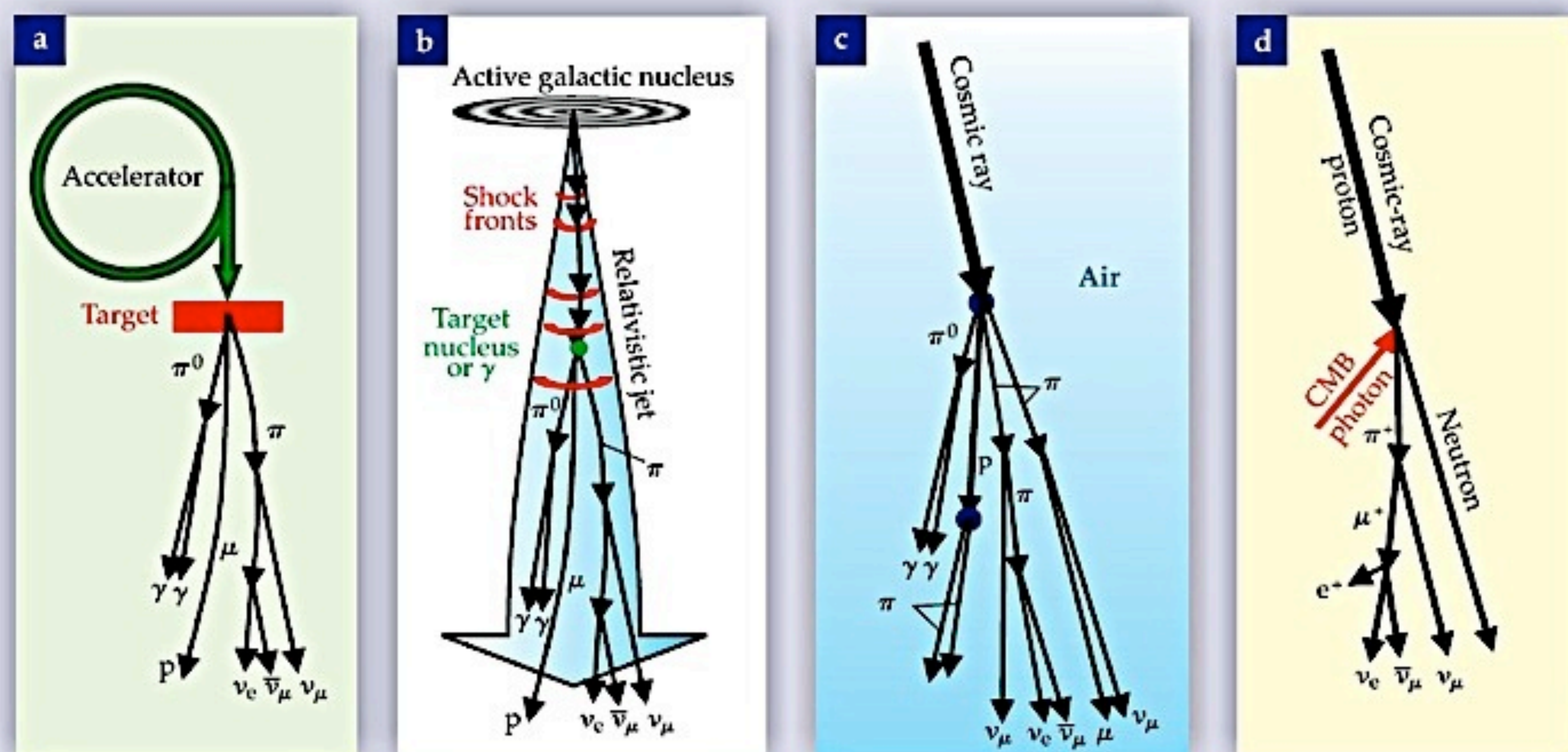
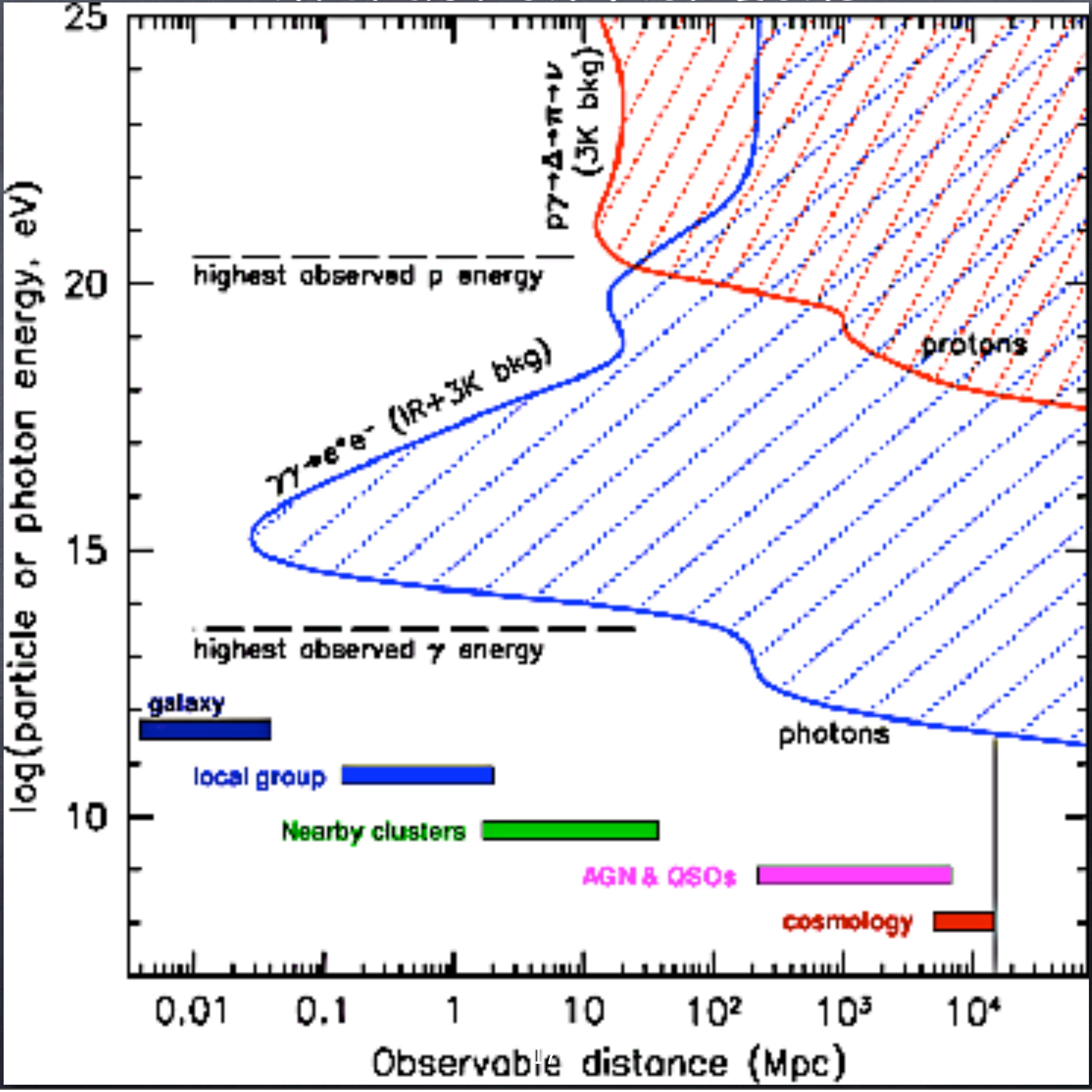
# Summary of hadronic neutrino and photon production modes

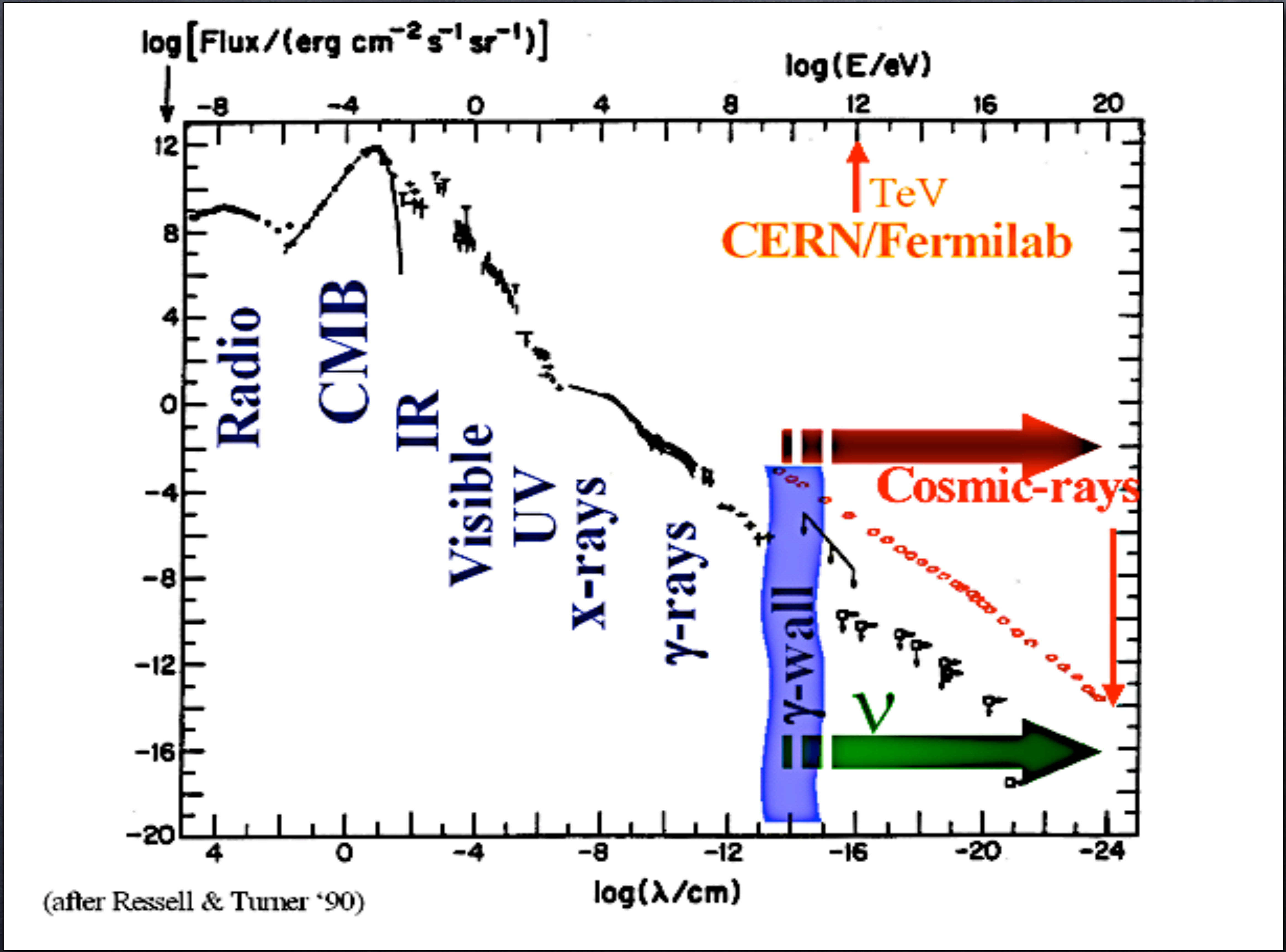



From Physics Today

# Interaction Horizons



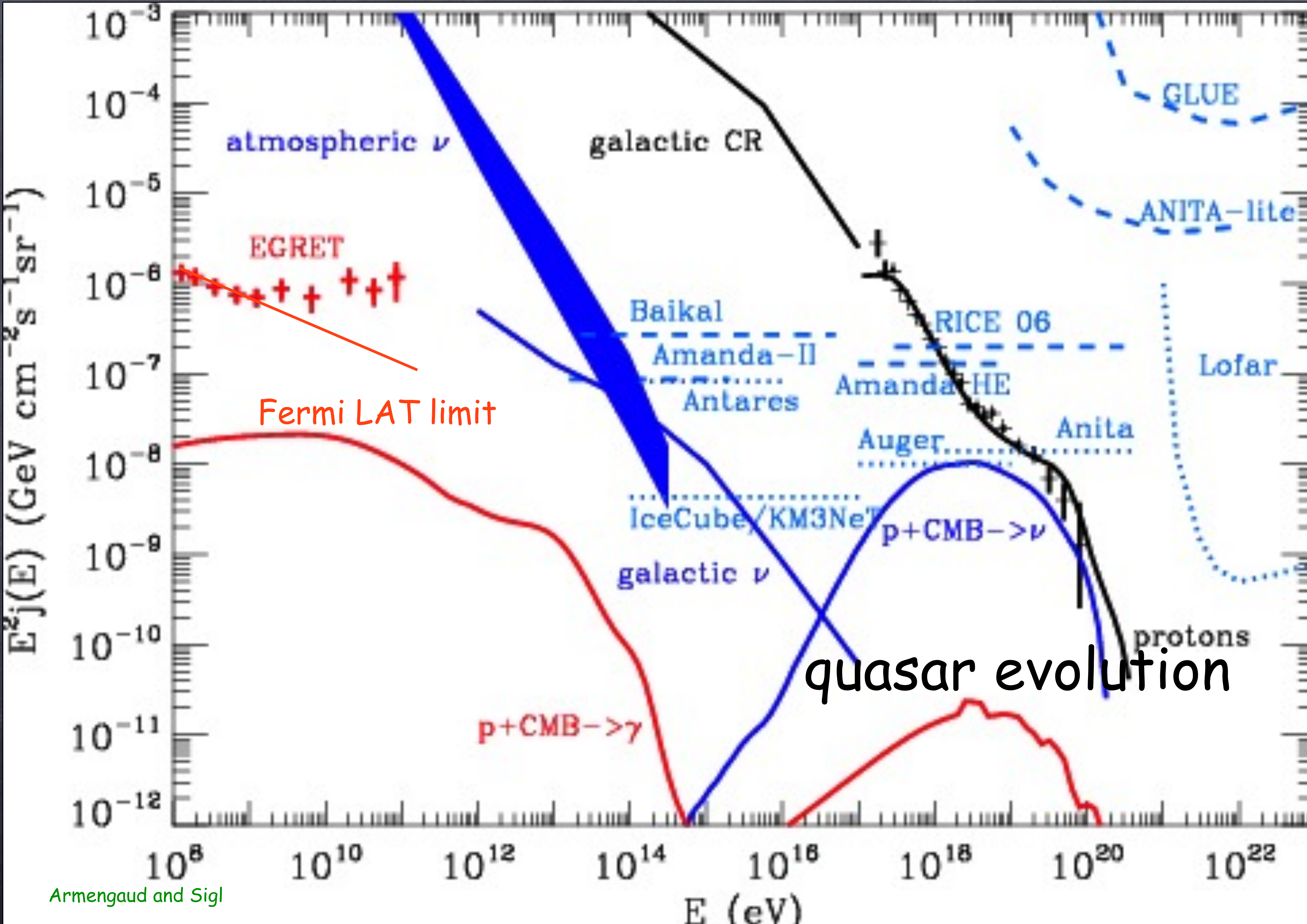
# The universal photon spectrum

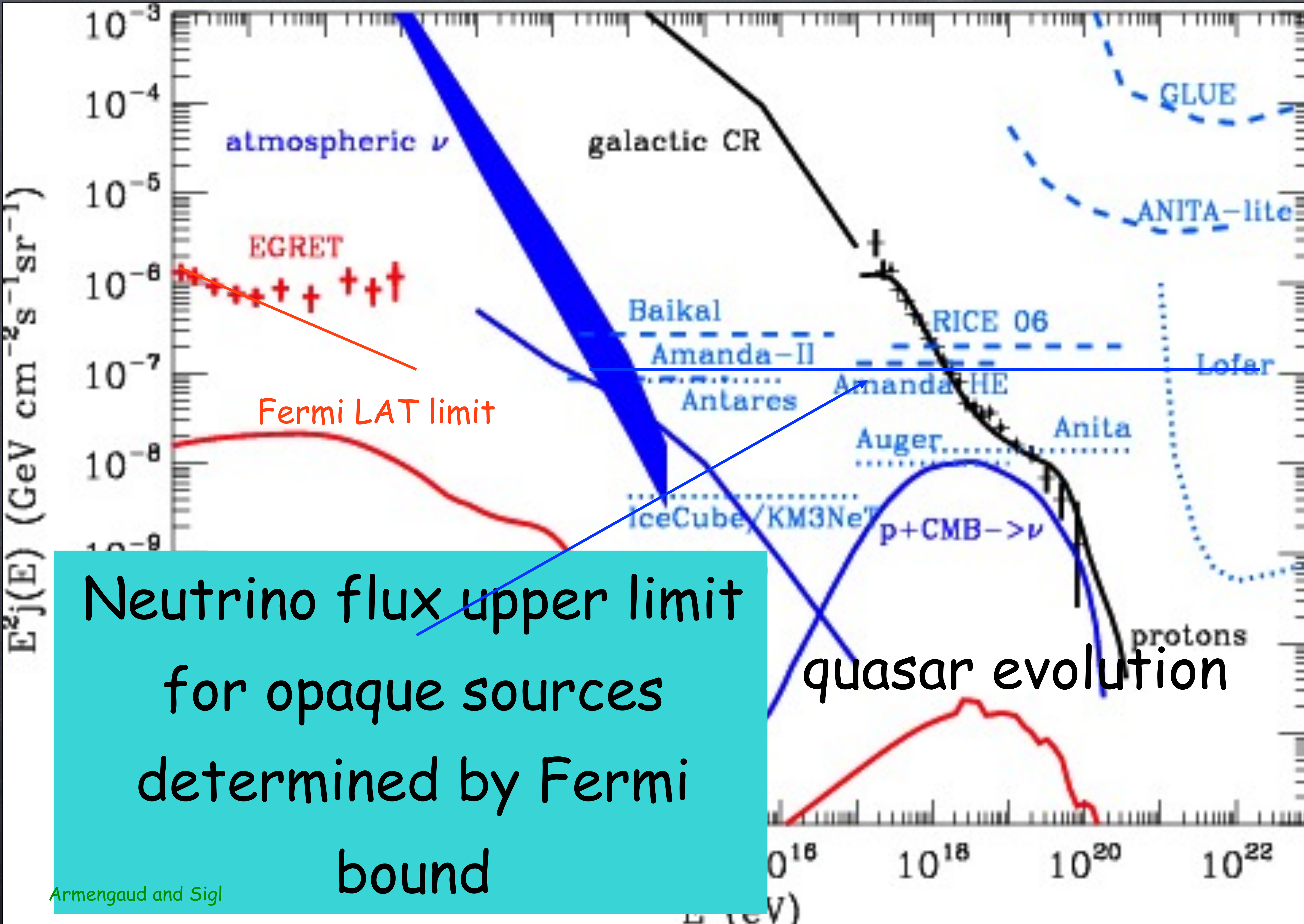





Freitag, 3. Juni 2011

# Cascade γ-rays and UHE neutrinos: An Overview






Neutrino flux upper limit for opaque sources determined by Fermi bound

Armengaud and Sigl

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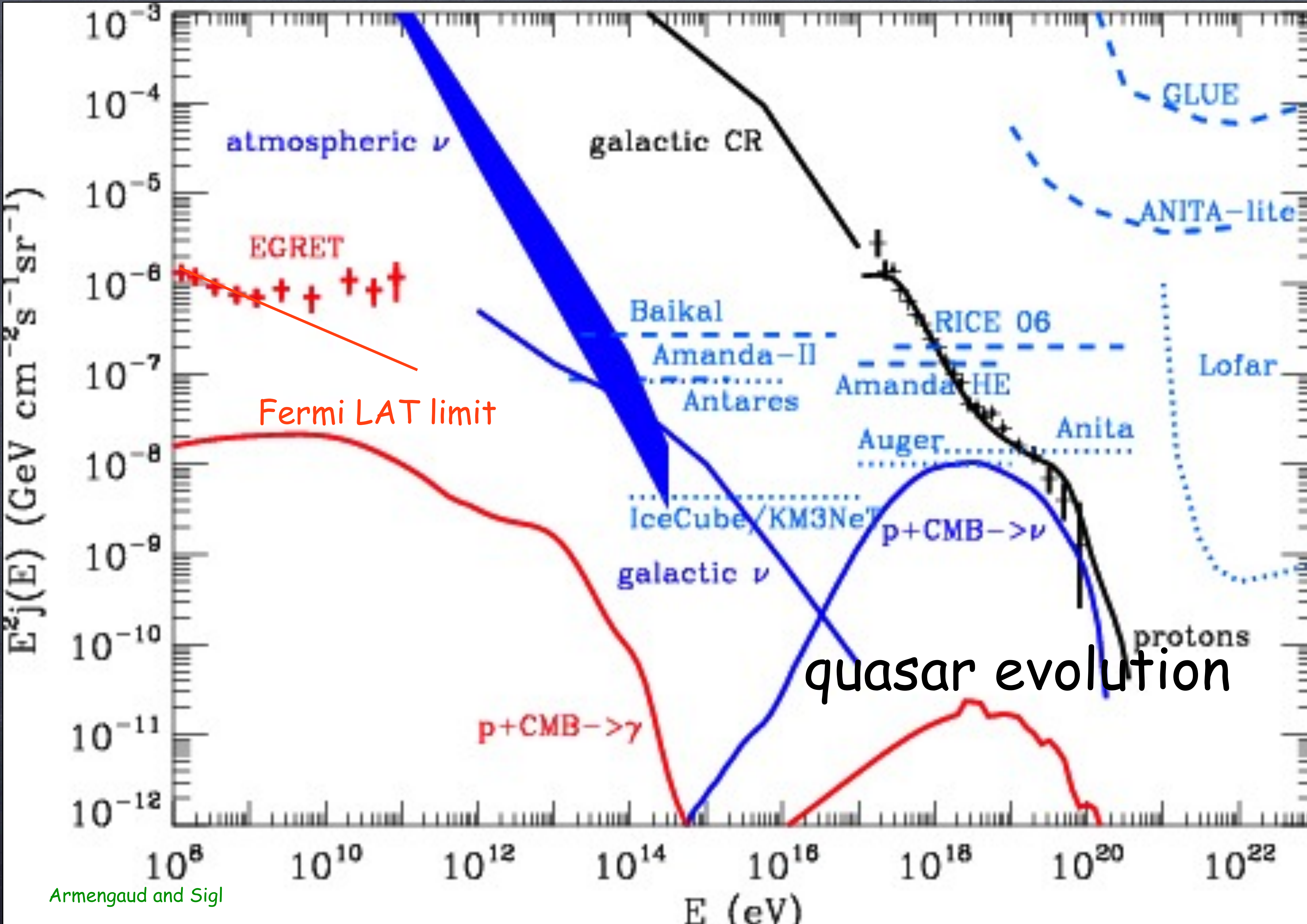
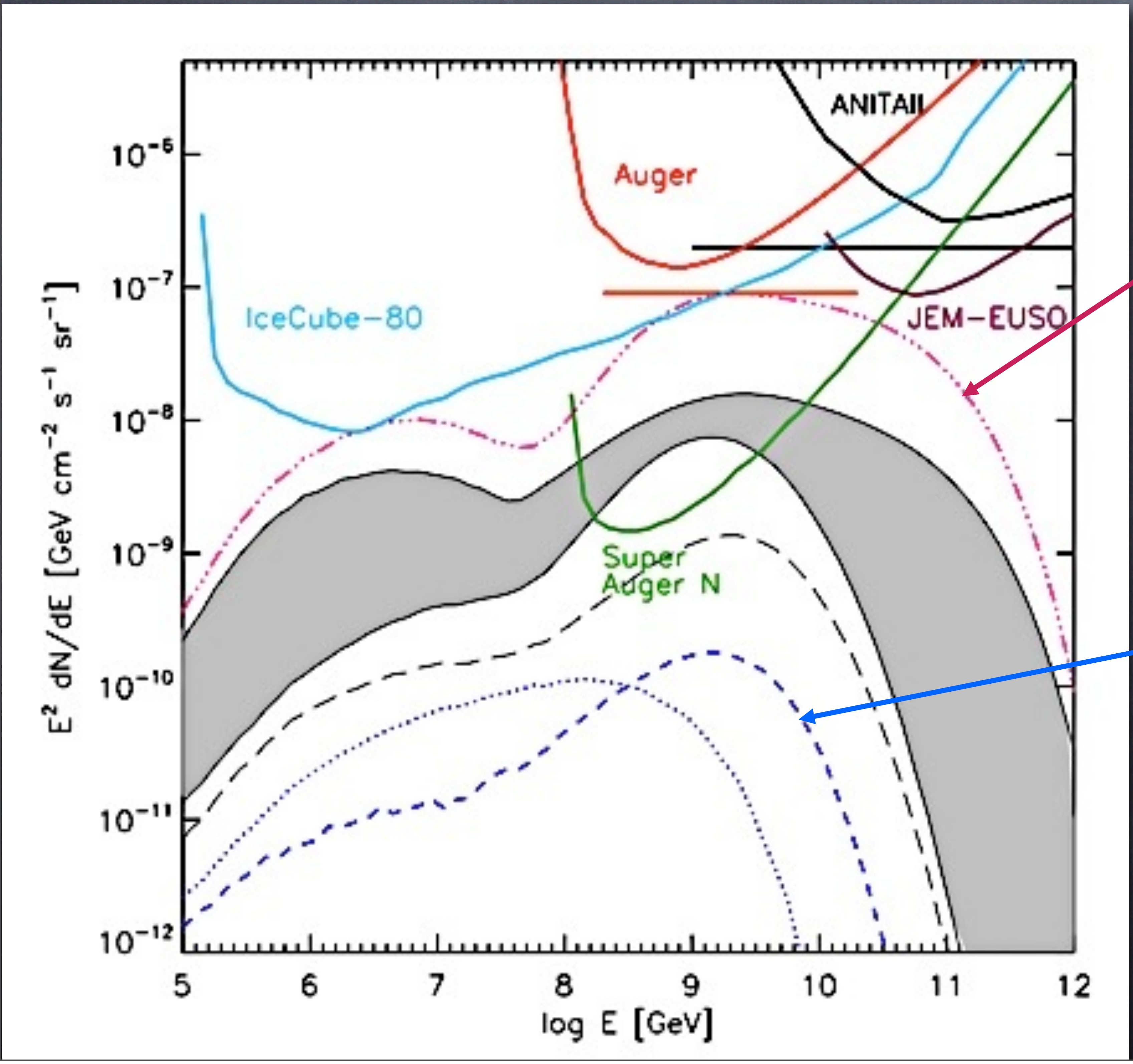



Armengaud and Sigl

# Physics with Diffuse Cosmogenic Neutrino Fluxes

Cosmogenic neutrino fluxes depend on number of nucleons produced above GZK threshold which is proportional to $E_{max}/A$

Further suppressed for heavy nuclei due to increased pair production

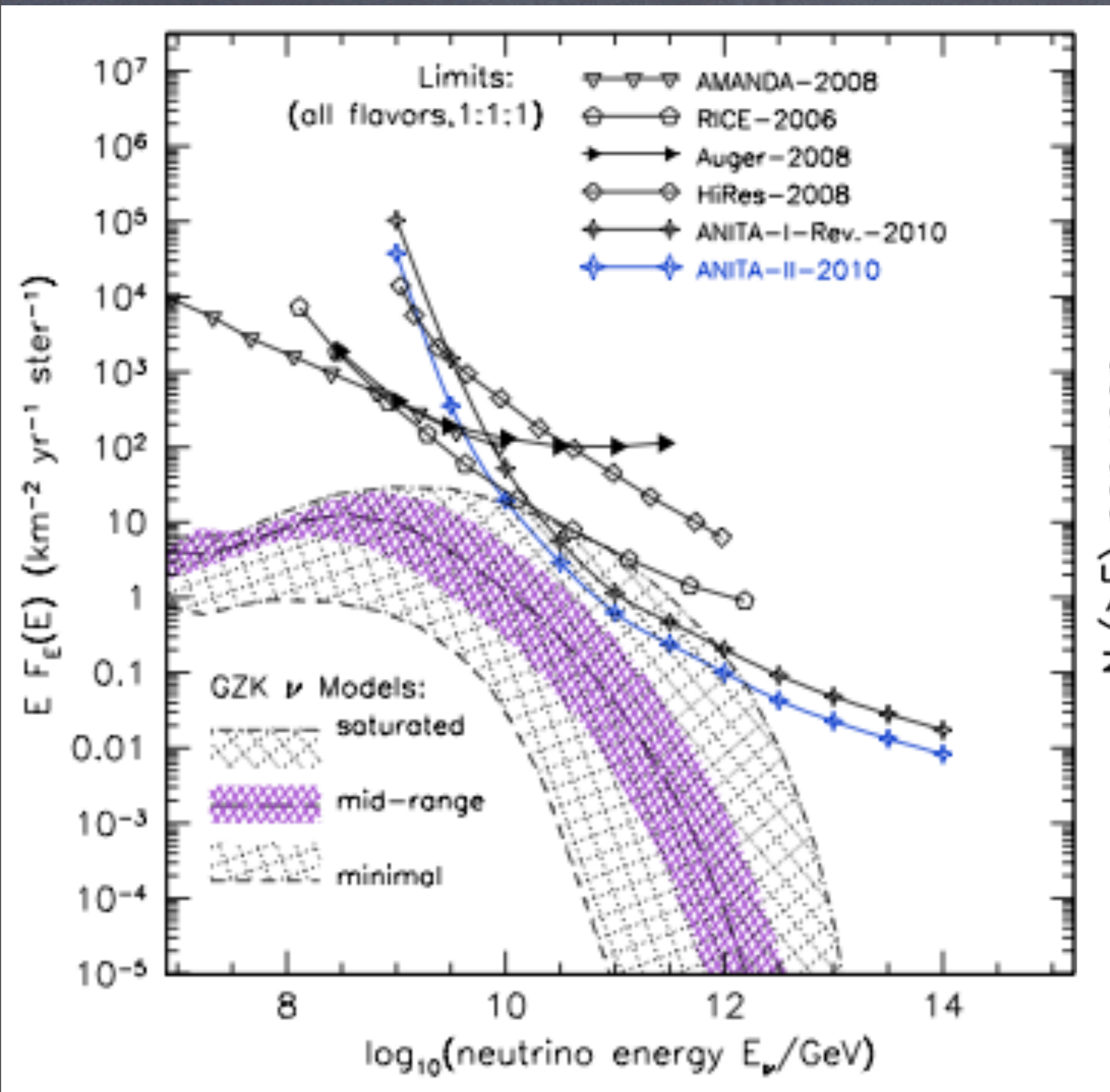


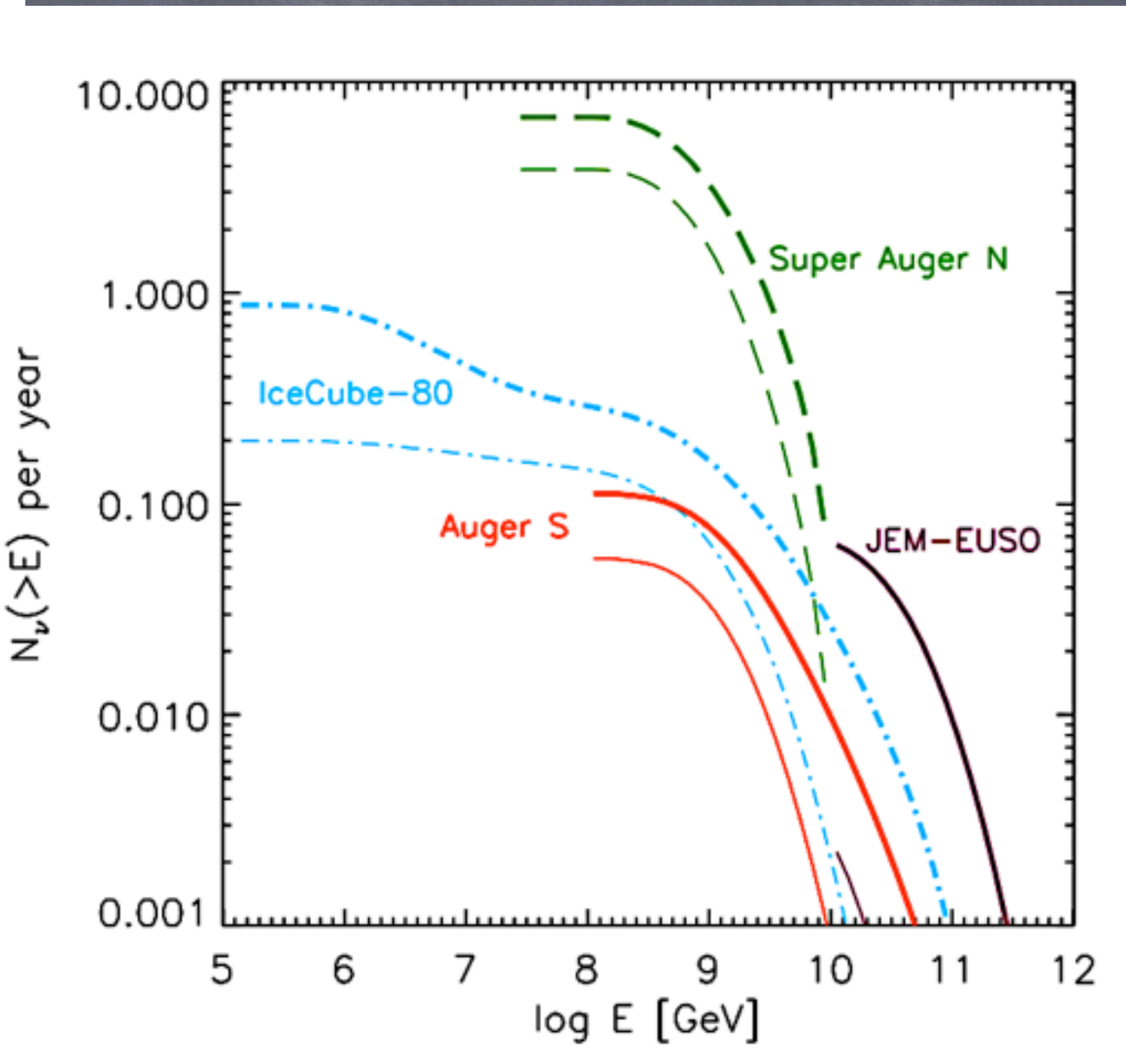

Pure protons, $E_{max}$=3 $10^{21}$ eV, strong evolution

Pure iron, $E_{max}$= $10^{20}$/26 eV, no evolution

Kotera, Allard, Olinto, JCAP 1010 (2010) 013

# Expected Sensitivities to/Rates of UHE neutrino fluxes



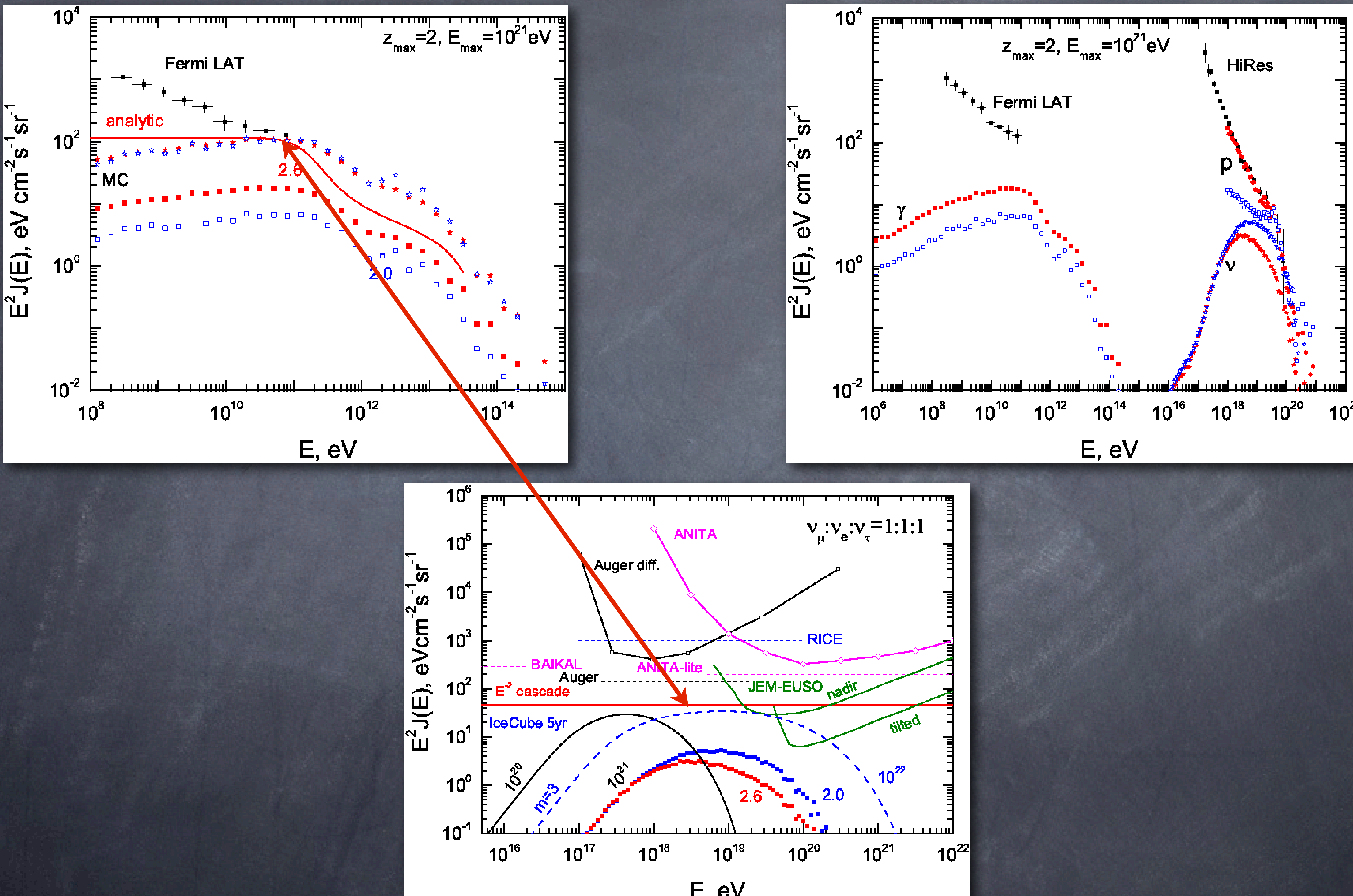




Rates for intermediate fluxes

P. Gorham et al, arXiv:1011.5004, Phys.Rev. D82 (2010) 022004

Kotera, Allard, Olinto, JCAP 1010 (2010) 013

# TeV γ-ray fluxes also constrain cosmogenic neutrino fluxes




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

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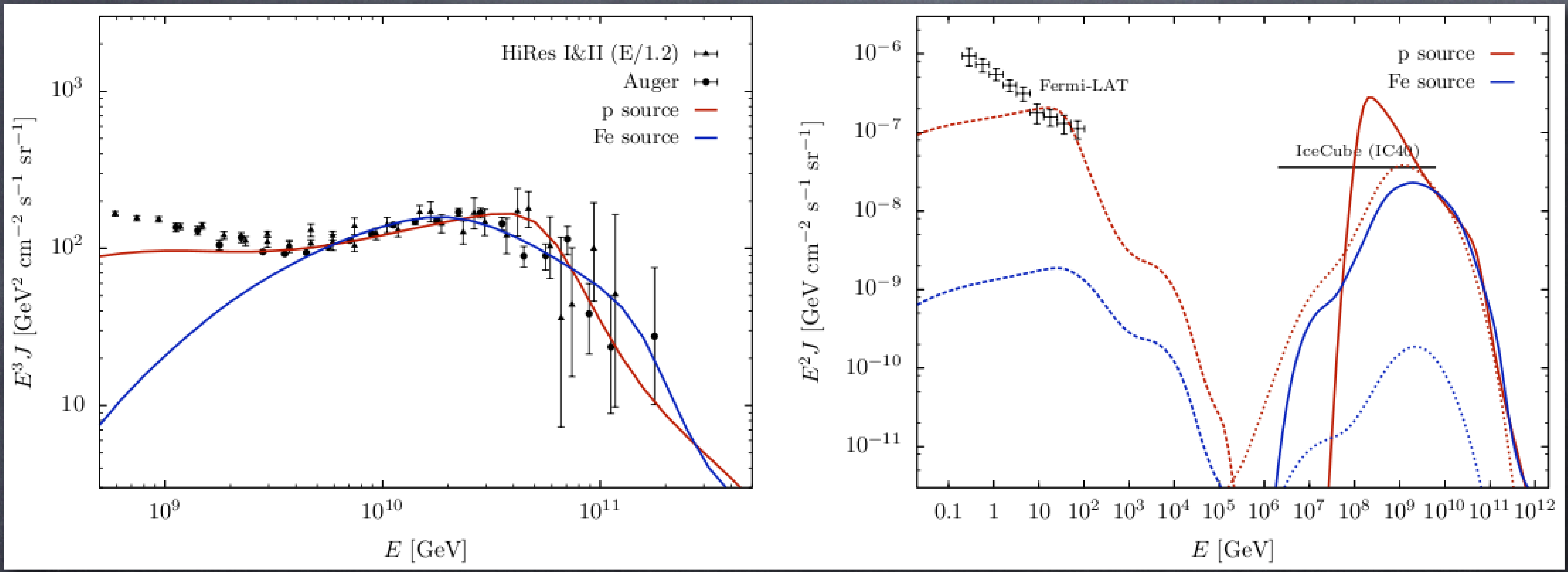


$$j_p(E) \propto \Theta(2-z)\,(1+z)^5\,E^{-2.3}\,\Theta\left(10^{20.5}\,\mathrm{eV}-E\right)\,,$$

$$j_{\mathrm{Fe}}(E) \propto E^{-2.3}\,\Theta\left(26\times 10^{20.5}\,\mathrm{eV}-E\right)\,.$$

Ahlers and Salvado, arXiv:1105.5113

# Physics with EeV Secondary Gamma-Ray Fluxes

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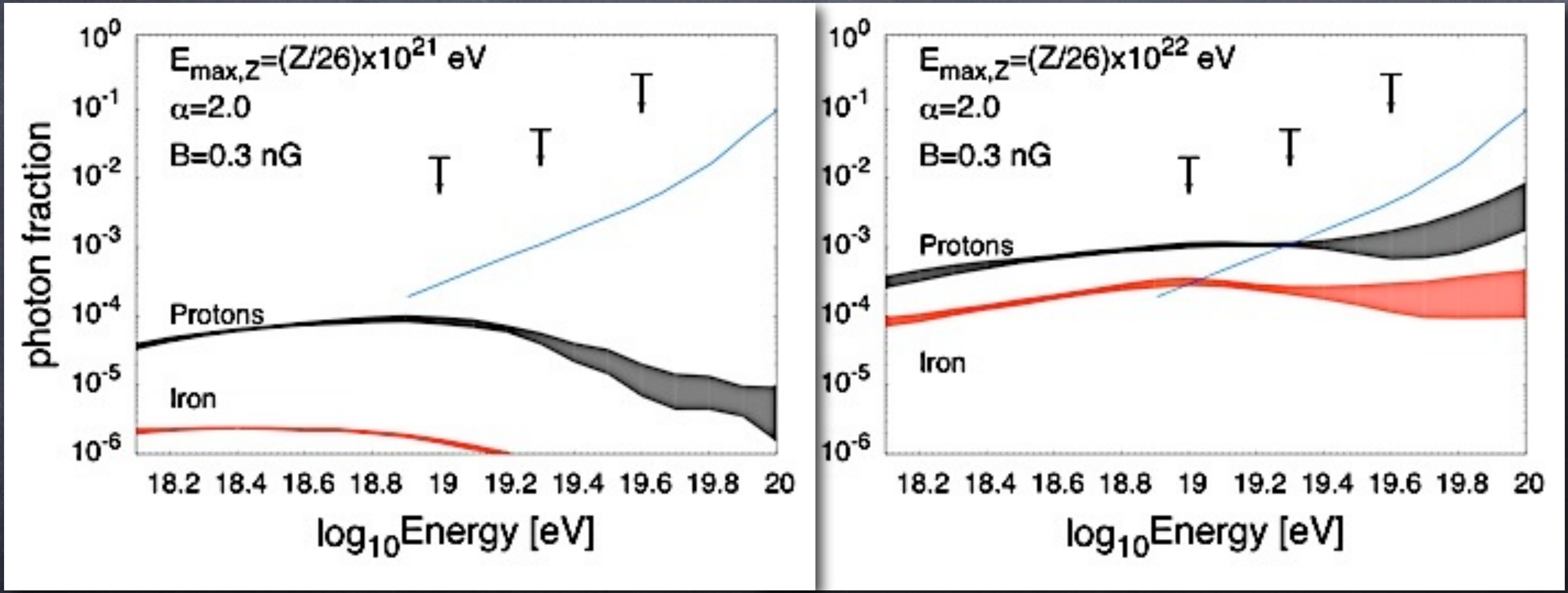


Hooper, Taylor, Sarkar, Astropart.Phys. 34 (2011) 340

# Probes of Neutrino Interactions beyond the Standard Model

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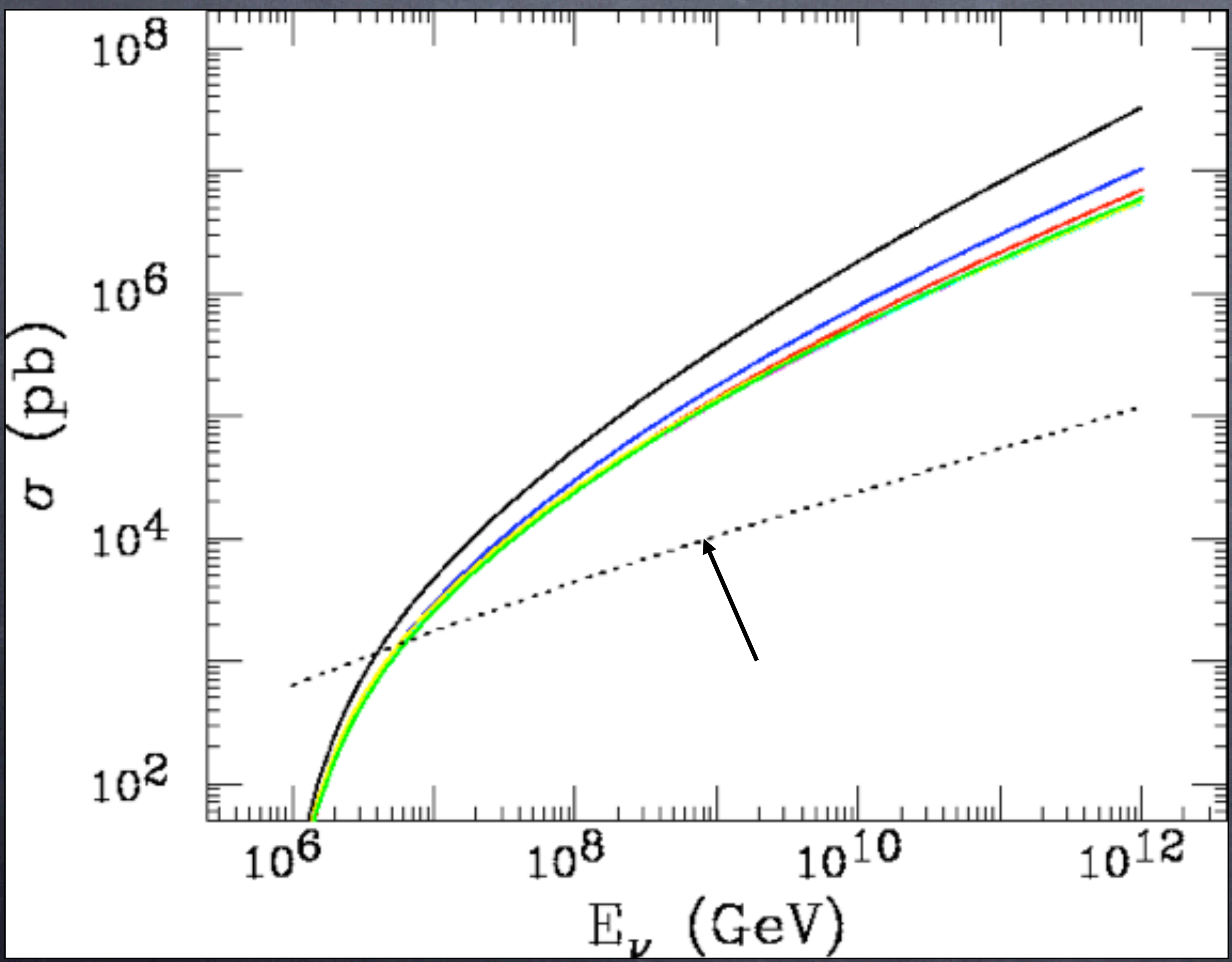
Example: microscopic black hole production in scenarios with a TeV string scale:




Feng, Shapere, PRL 88 (2002) 021303

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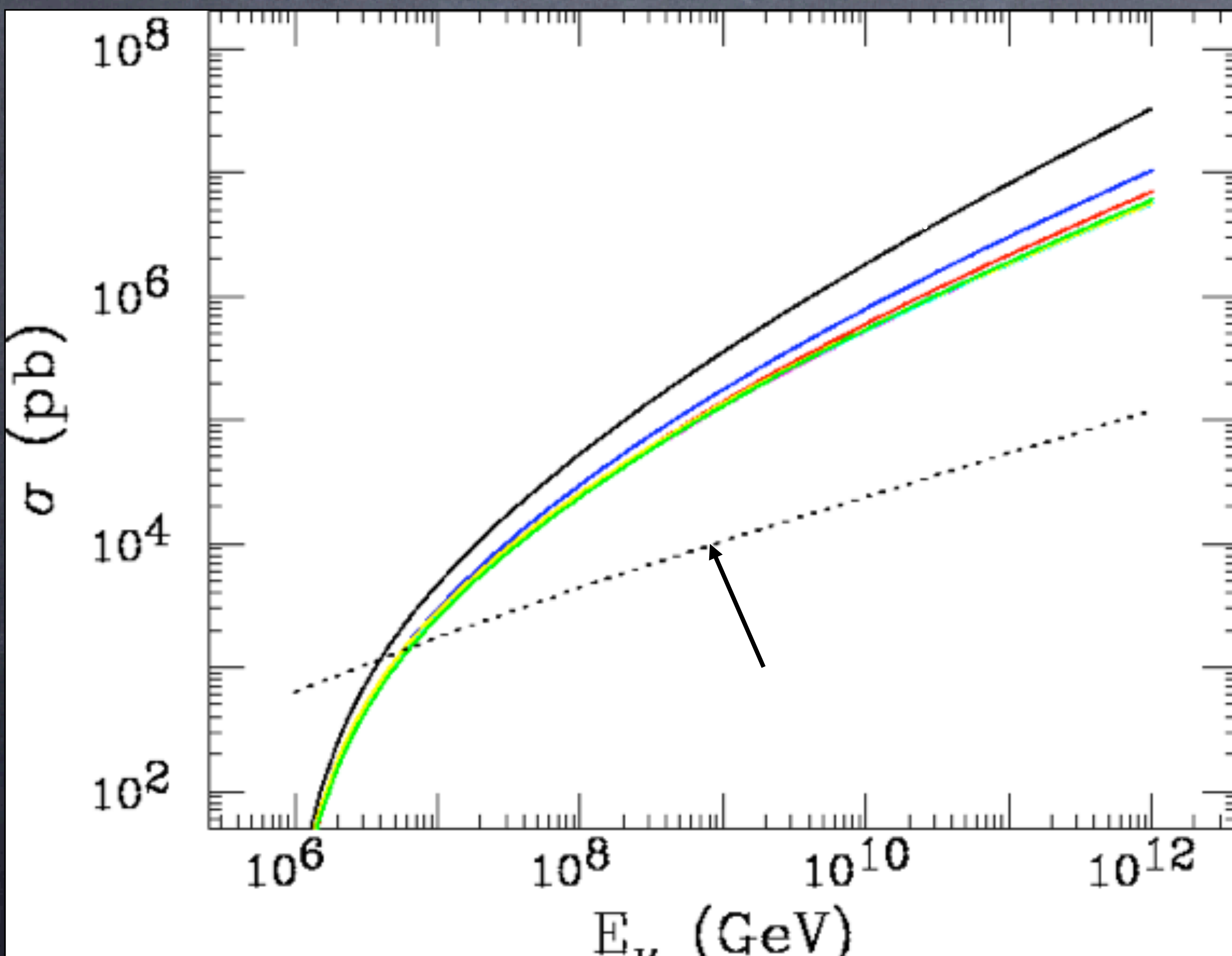



Feng, Shapere, PRL 88 (2002) 021303

This increase is not sufficient to explain the highest energy cosmic rays, but can be probed with deeply penetrating showers.

## Solution: Compare rates of different types of neutrino-induced showers

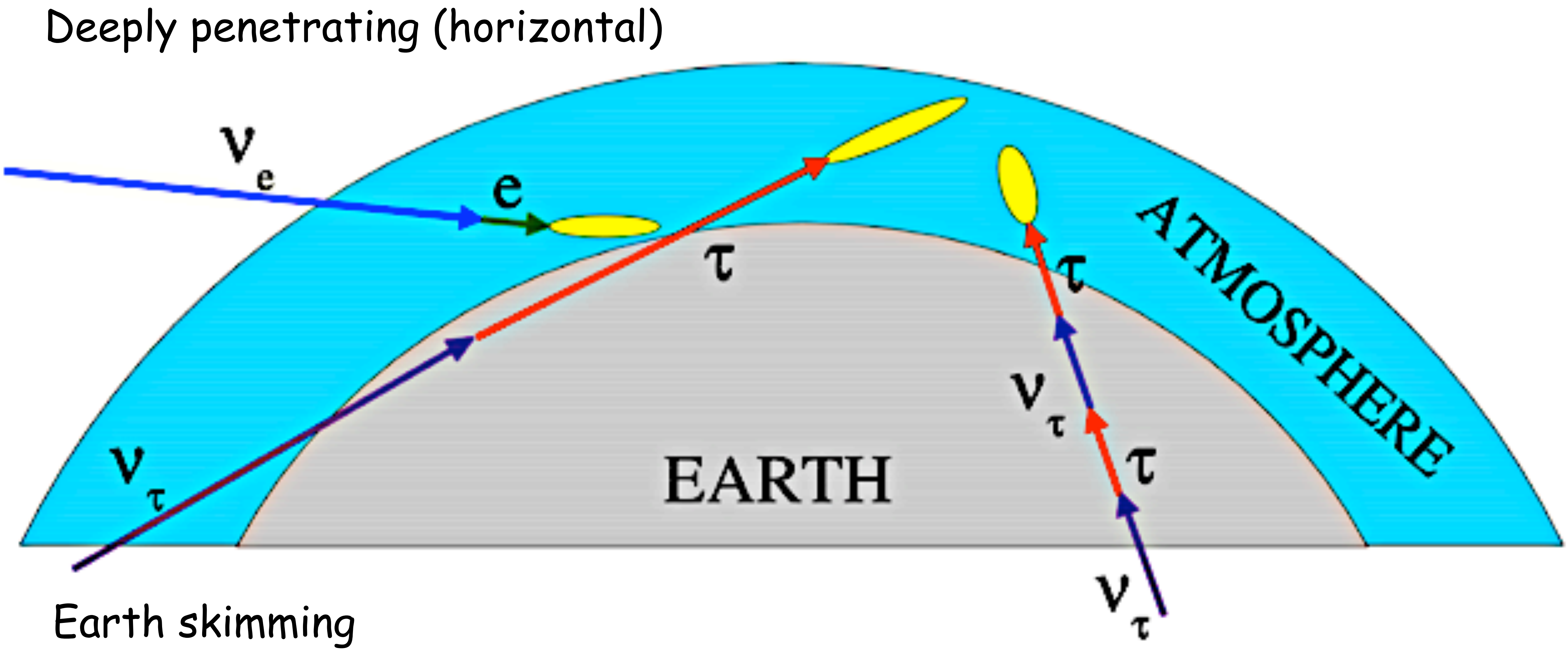
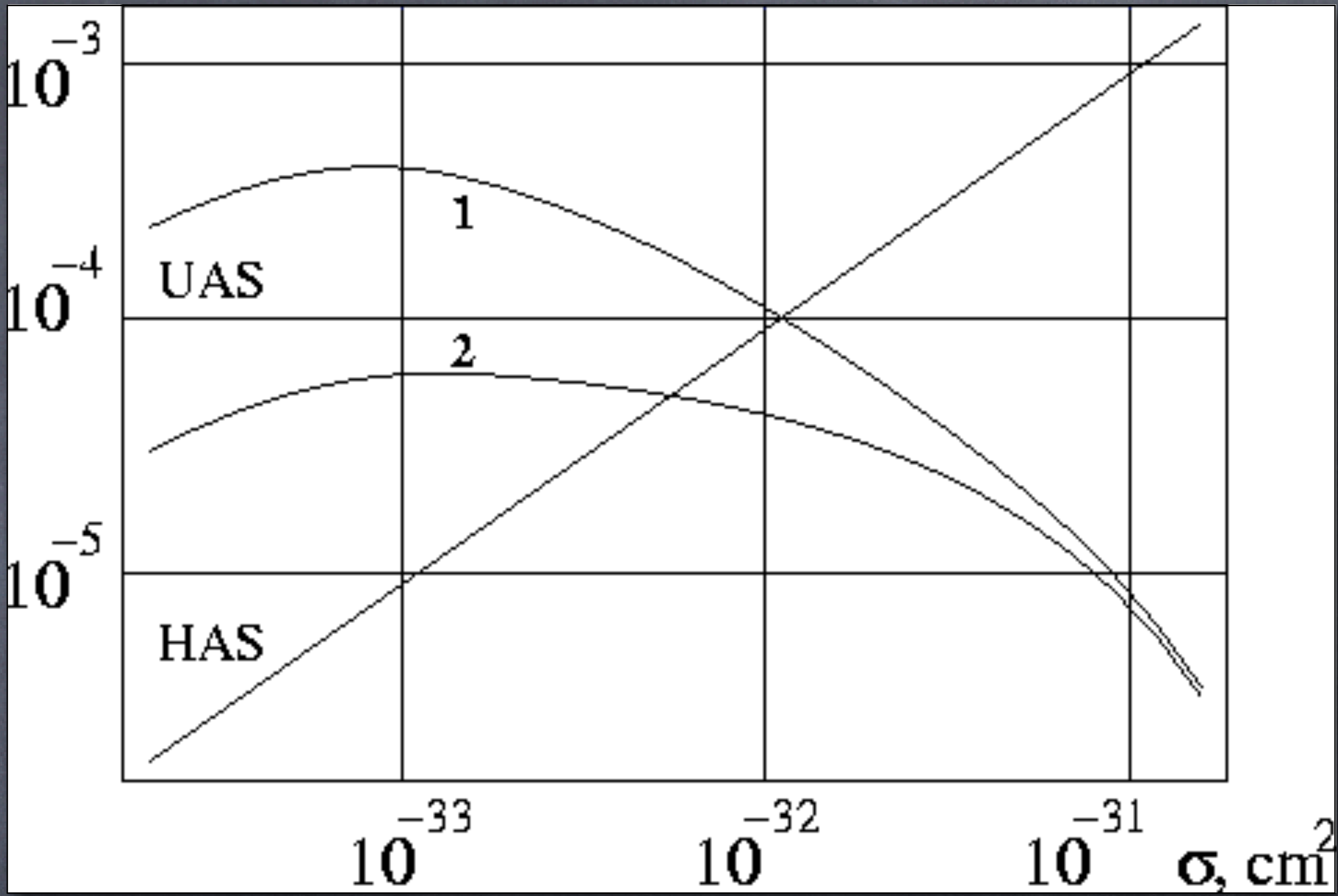



Figure from Cusumano

# Earth-skimming τ-neutrinos




Air-shower probability per τ-neutrino at $10^{20}$ eV for $10^{18}$ eV (1) and $10^{19}$ eV (2) threshold energy for space-based detection.

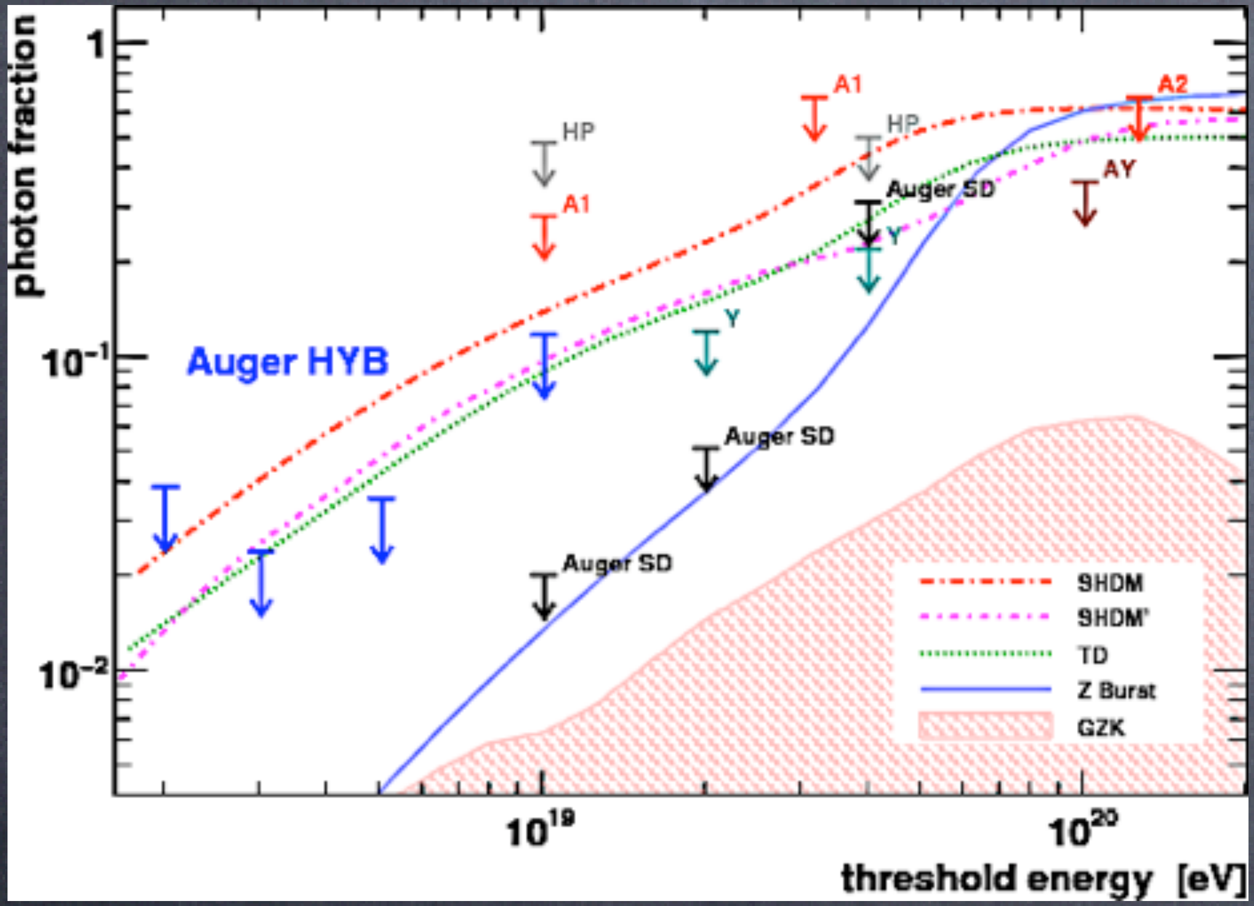
Comparison of earth-skimming and horizontal shower rates allows to measure the neutrino-nucleon cross section in the 100 TeV range.

Kusenko, Weiler, PRL 88 (2002) 121104

# Lorentz Symmetry Violation in the Electromagnetic Sector

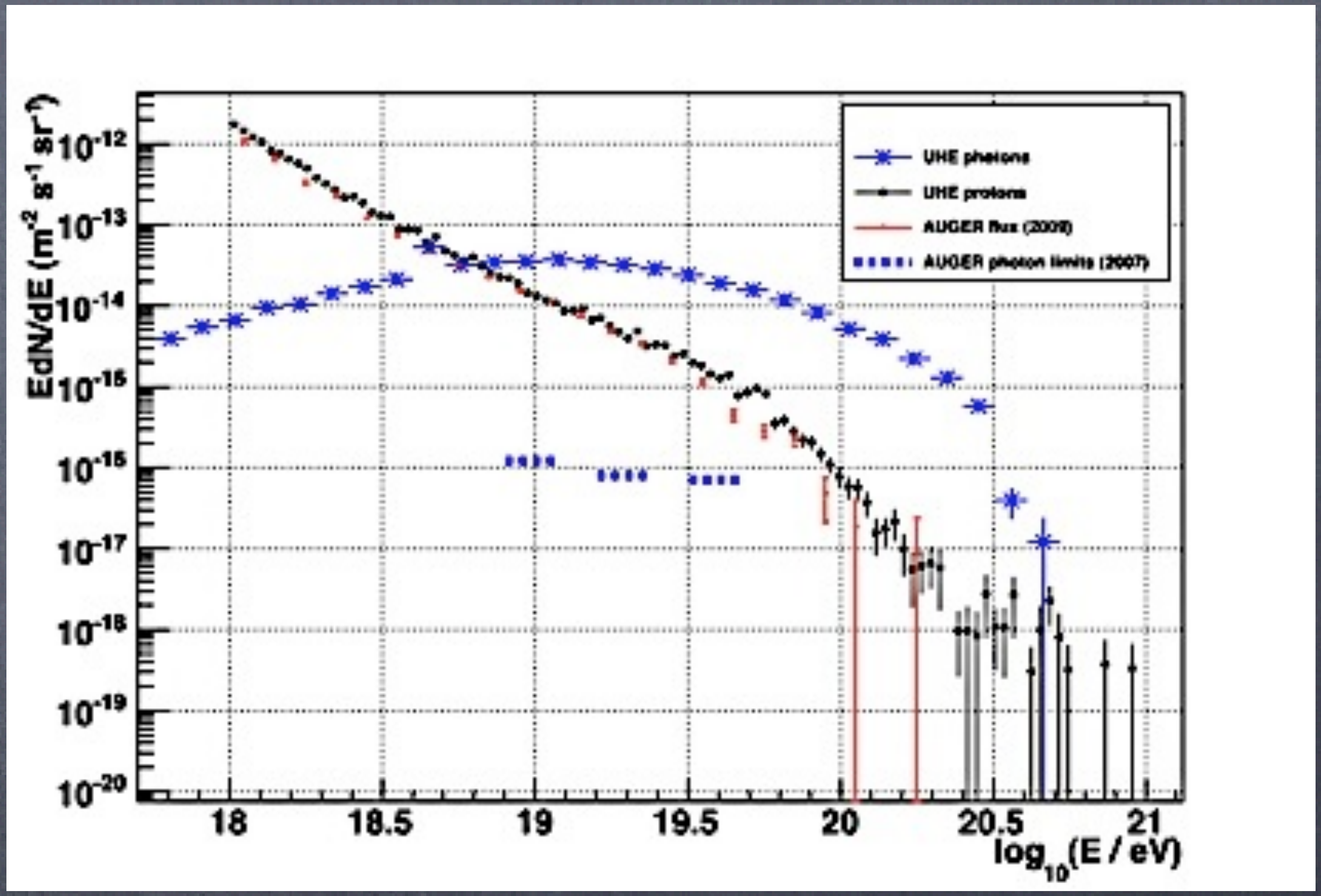
## The idea:

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

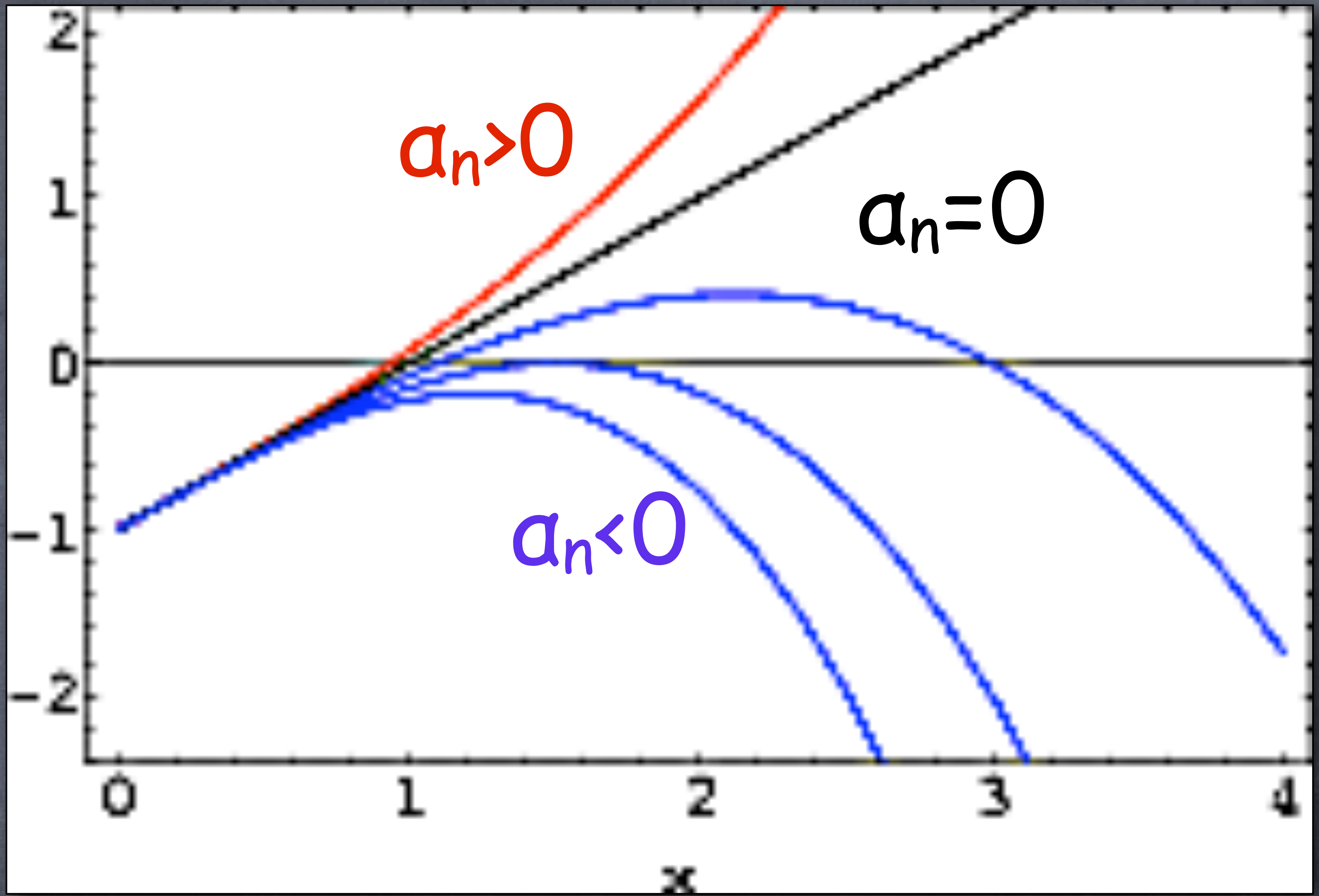
$$\alpha_n = \frac{\xi_n - (-1)^n \eta_n^{\mp} y^{n+1} - \eta_n^{\pm}(1-y)^{n+1}}{2^{2(n+2)} y^{n+1}(1-y)^{n+1}} \frac{m_e^{2(n+1)}}{k_b^{n+2} M_{\rm Pl}^n}.$$

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)

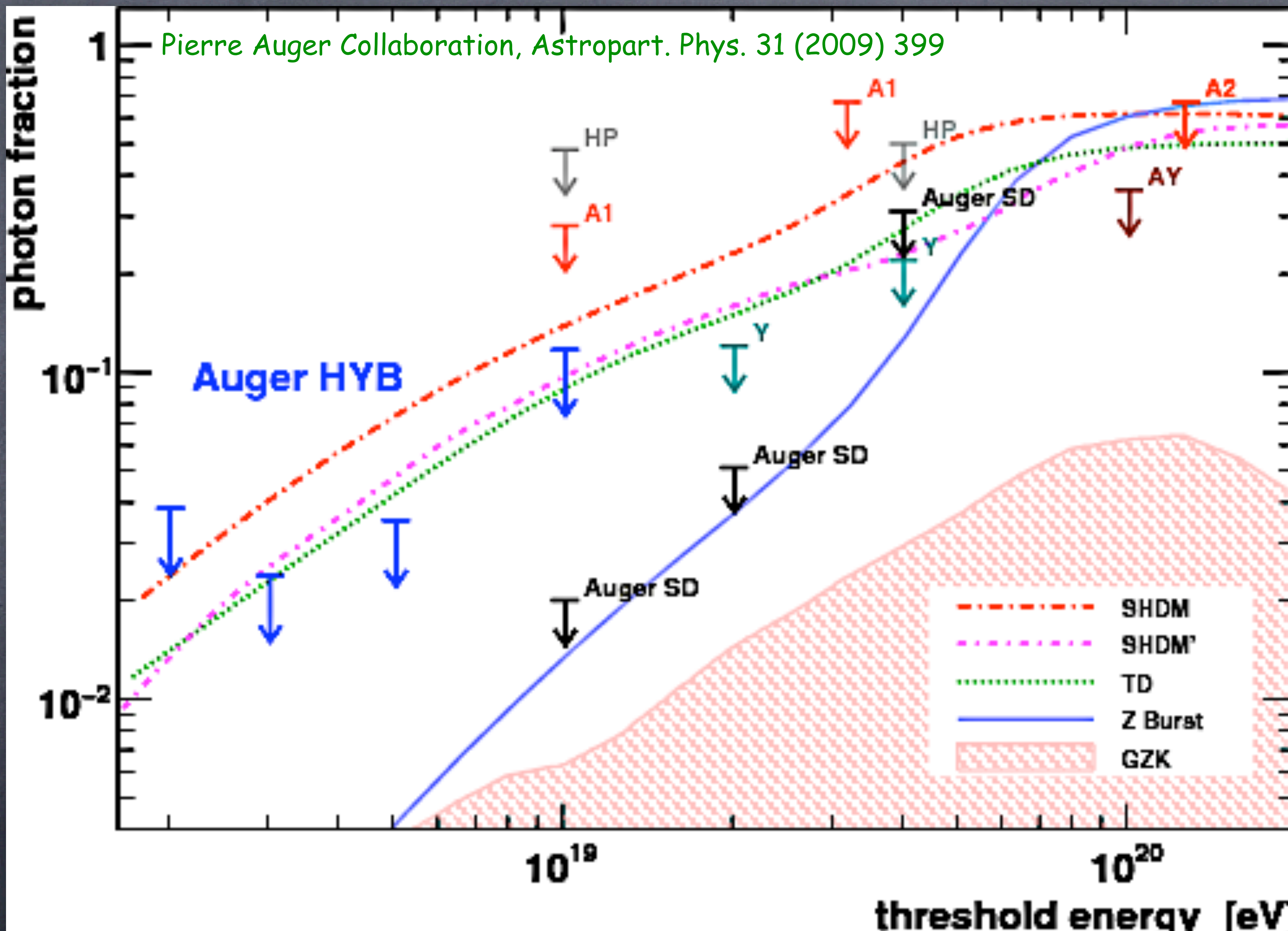



Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

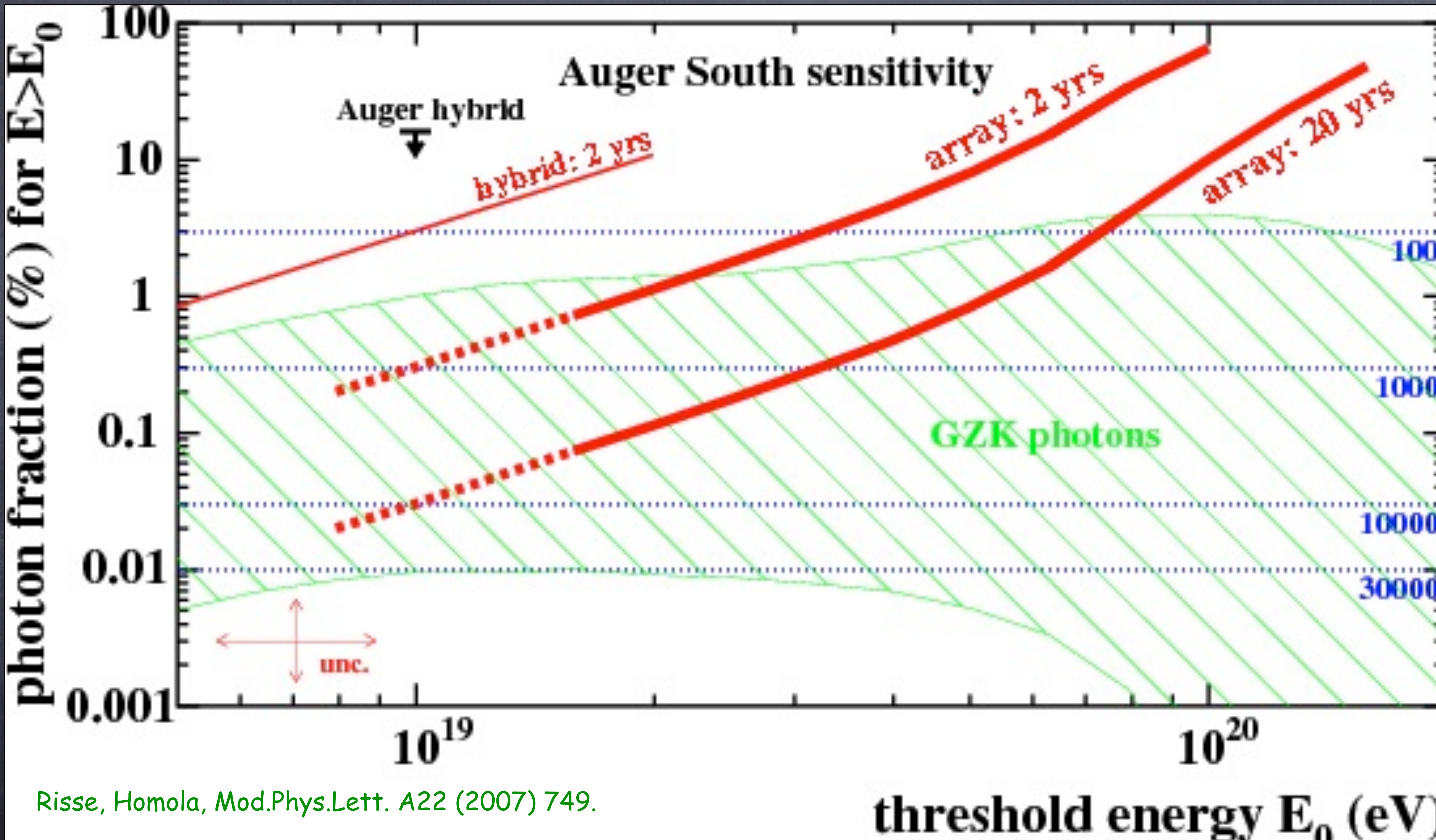
For photon decay there is at most one positive real threshold.

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.

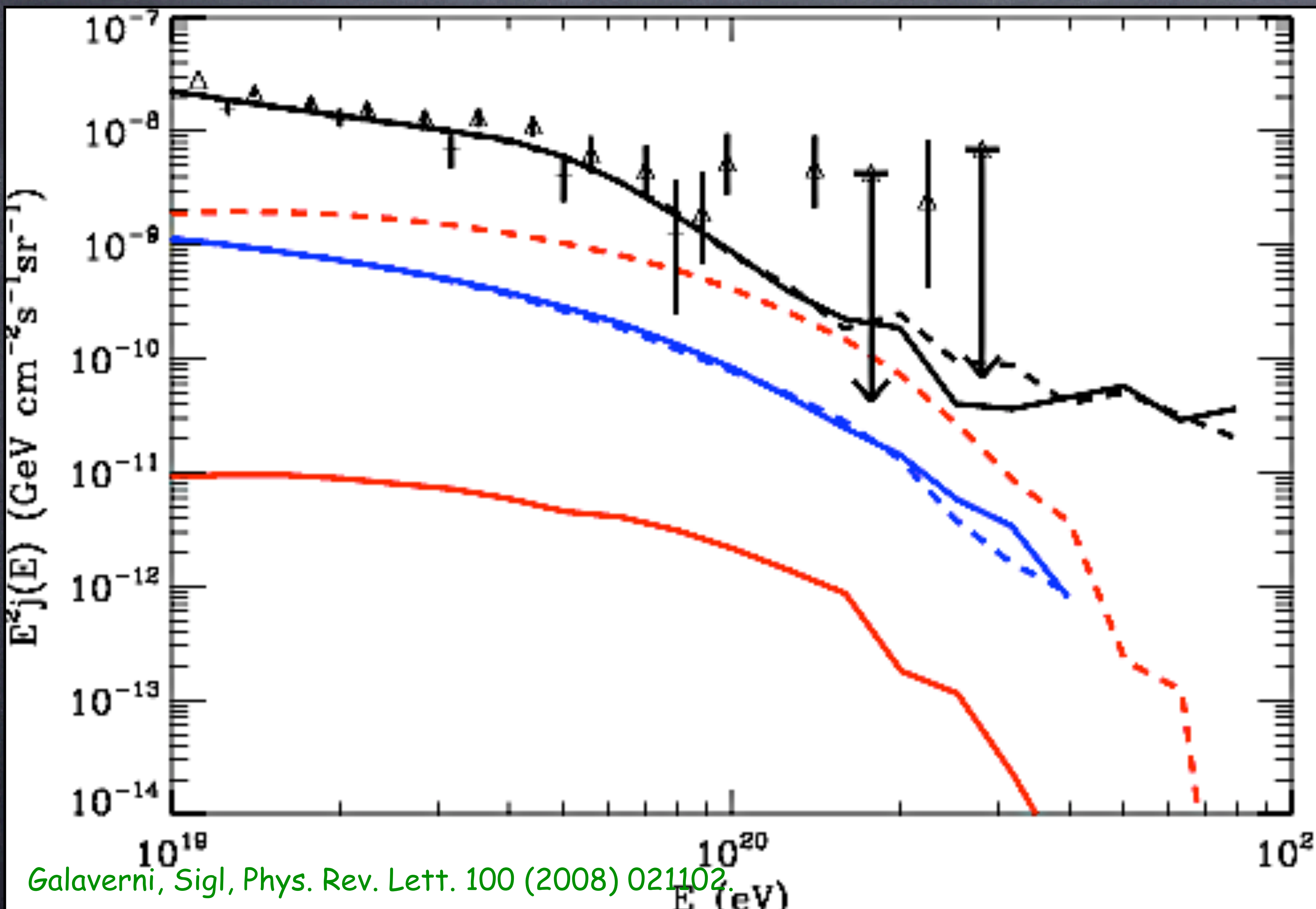


Future data will allow to probe smaller photon fractions and the GZK photons:




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

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

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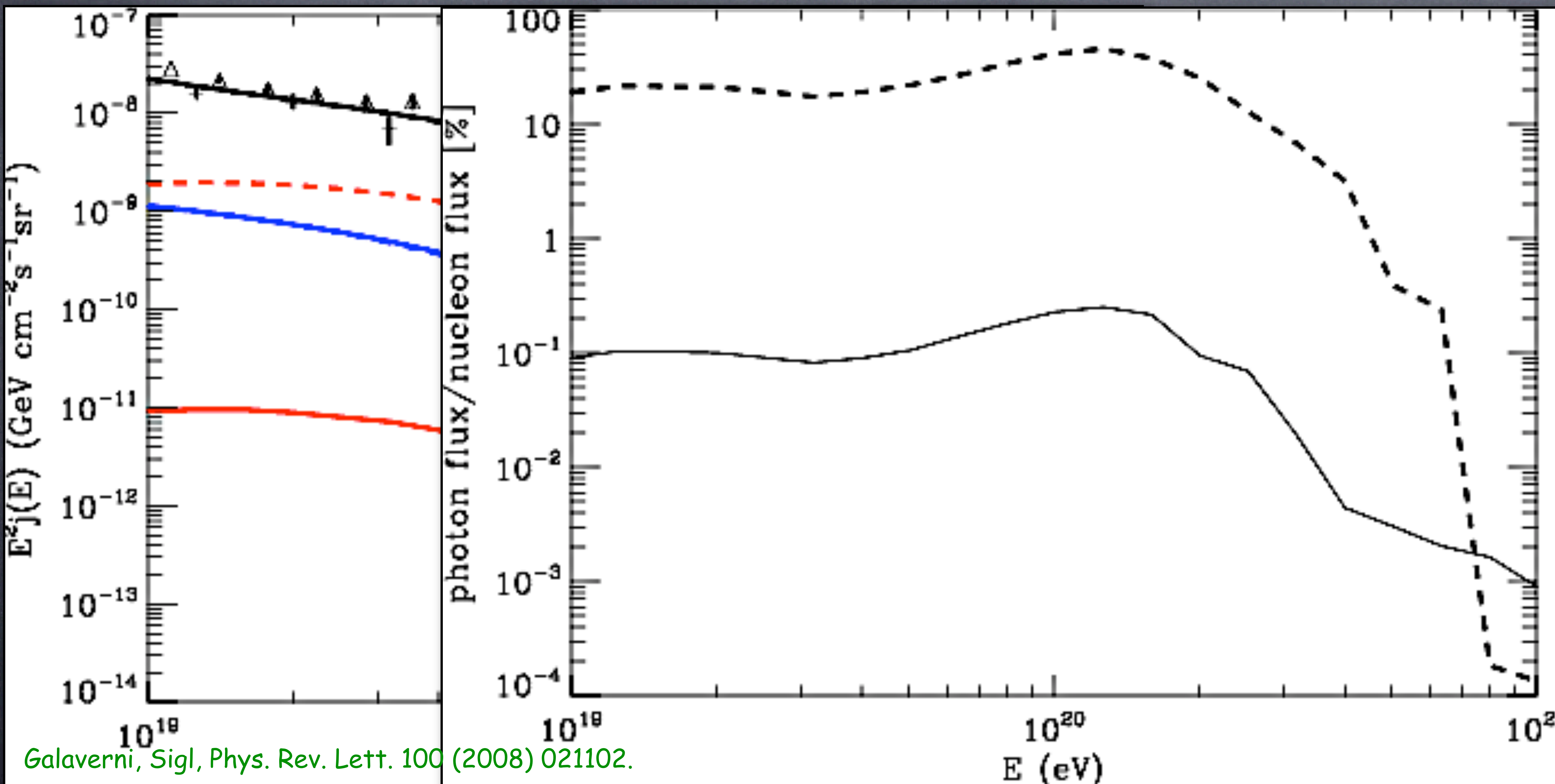



Galaverni, Sigl, Phys. Rev. Lett. 100 (2008) 021102.

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:

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

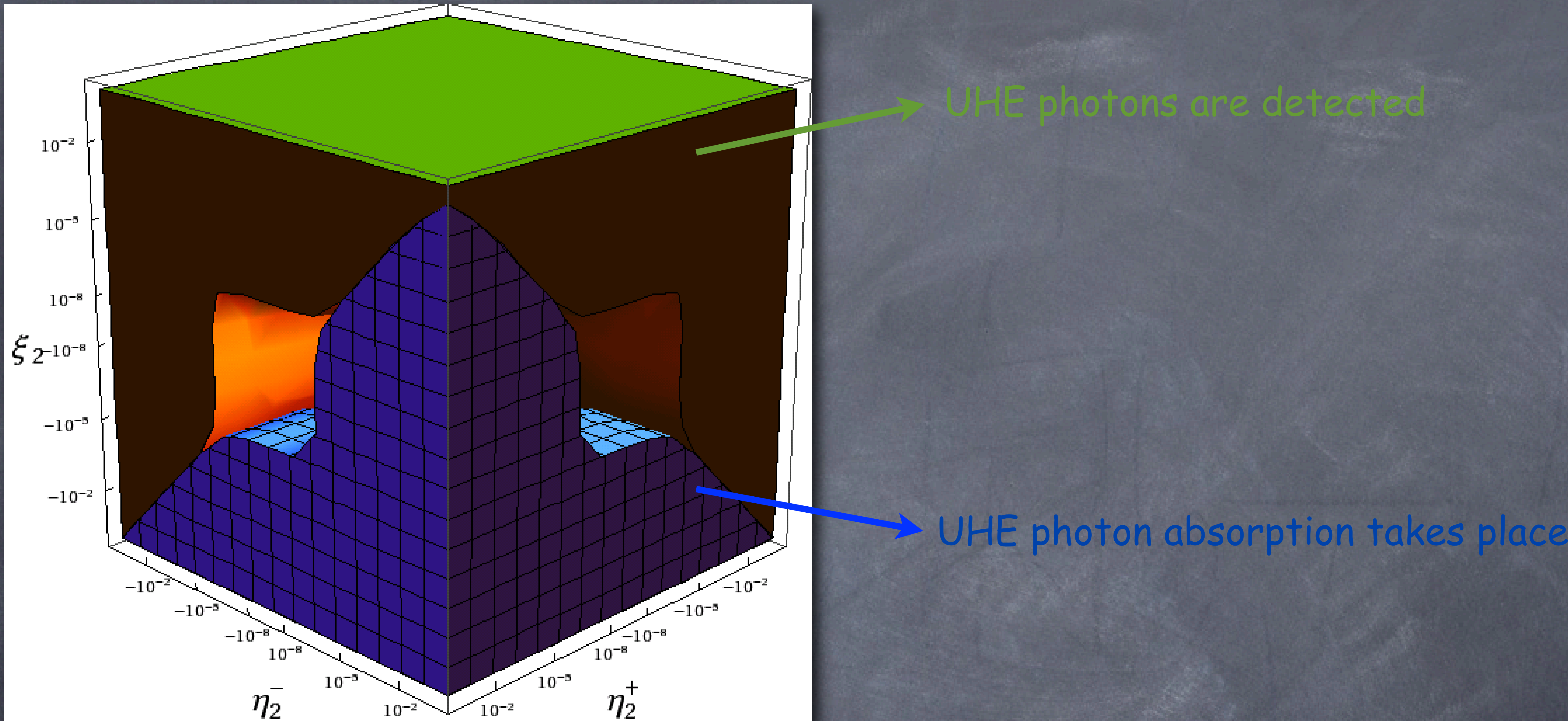
and for n=2:

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

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.




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

The modified dispersion relation also leads to energy dependent group velocity V=∂E/∂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

# 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

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

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

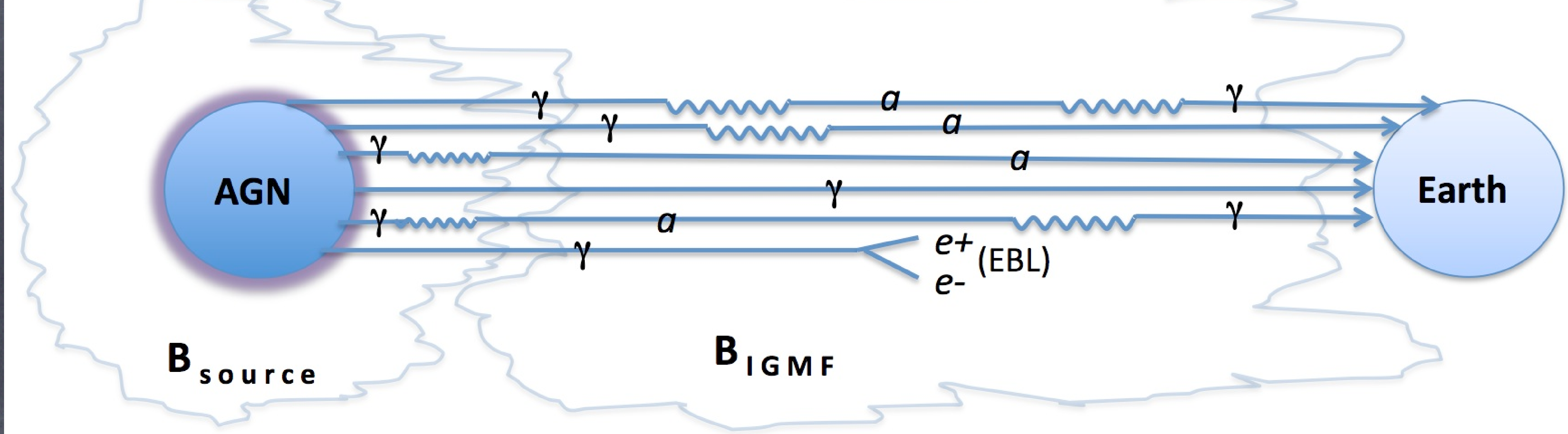
This is different for mixing with a hidden-photon field $X_\mu$, for which

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

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.

sketch from Sanches-Conde et al., Phys.Rev.D79:123511,2009




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

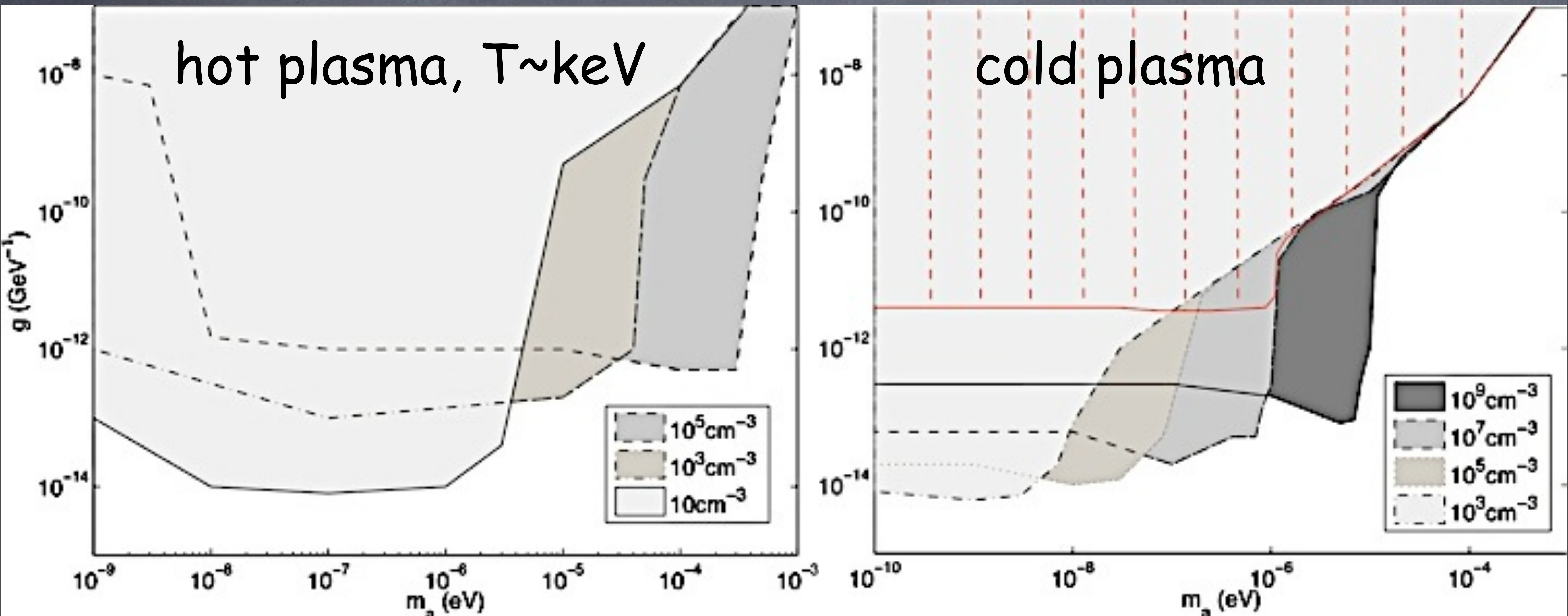
$$\Delta_a = \frac{m_a^2}{2E} \simeq 2.5 \times 10^{-20}\, m_{\mu\rm eV}^2 \left(\frac{\rm TeV}{E}\right) \rm cm^{-1},$$

$$\Delta_{\rm pl} = \frac{\omega_{\rm pl}^2}{2E} \simeq 3.5 \times 10^{-26} \left(\frac{n_e}{10^3\, \rm cm^{-3}}\right) \left(\frac{\rm TeV}{E}\right) \rm cm^{-1},$$

Cotton-Mouton term $$\Delta_{\rm CM} \simeq -\frac{\alpha}{45\pi}\left(\frac{B_{\rm t}}{B_{\rm cr}}\right)^2 E \simeq -1.3 \times 10^{-21}\, B_{\rm mG}^2 \left(\frac{E}{\rm TeV}\right) \rm cm^{-1},$$

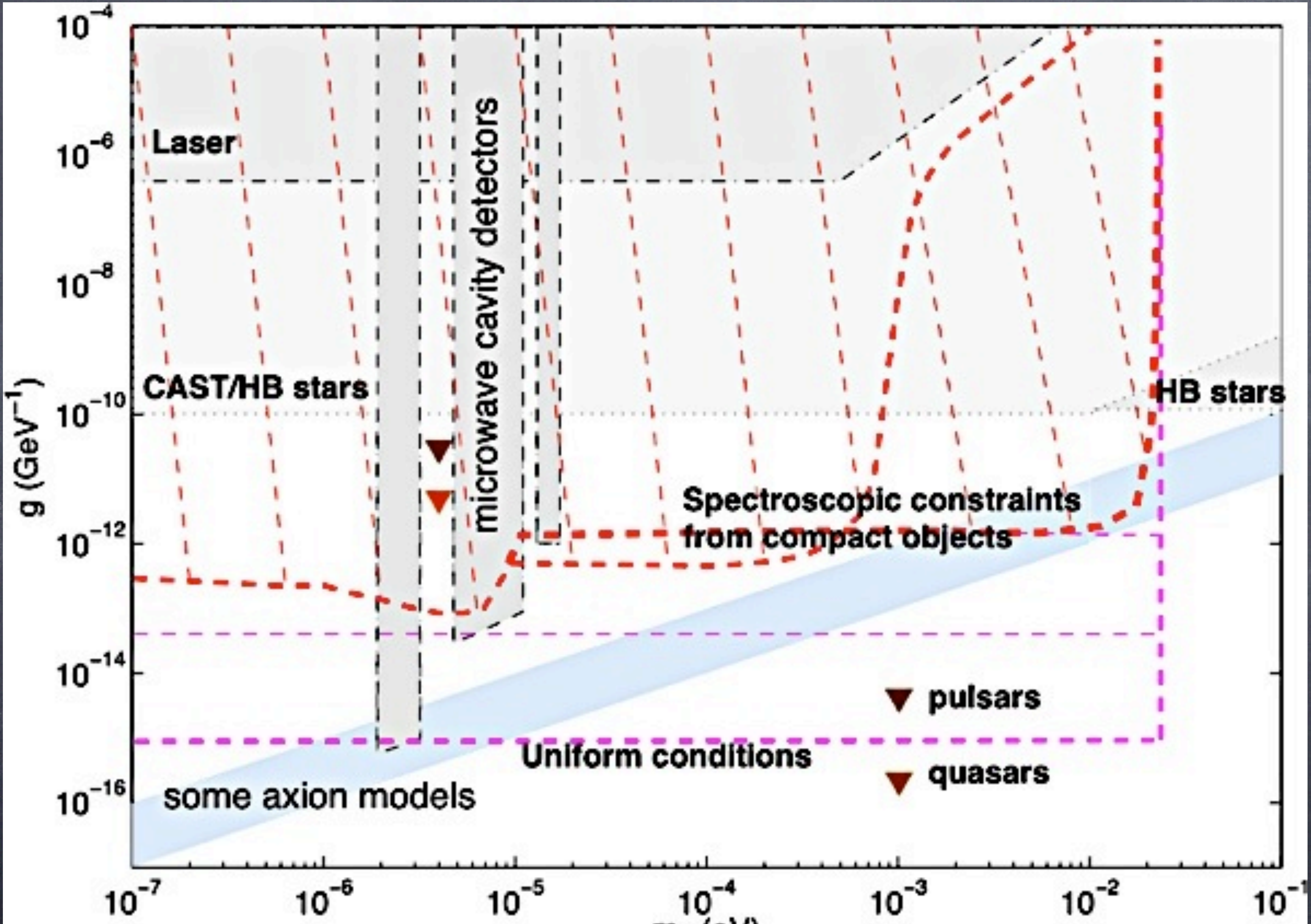
$$\Delta_B = \frac{g_{\gamma a} B_{\rm t}}{2} \simeq 1.7 \times 10^{-21}\, g_{11}\, B_{\rm mG}\, \rm cm^{-1}$$

# Relevant Mass and Coupling Parameter Range for effects in quasars




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

# Comparison of Experimental and Astrophysical Sensitivities




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

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