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

accelerated nuclei interact:

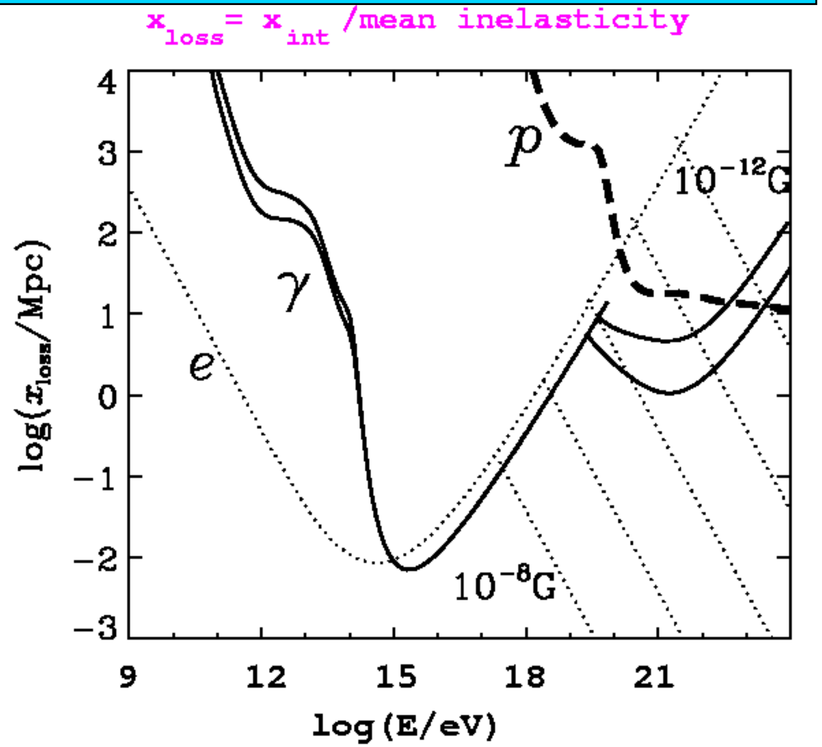
$$ {}^{A}_{Z} + N,\gamma \to X + \begin{cases} \pi^{+} & \to \text{neutrinos} \\ \pi^{0} & \to \gamma - \text{rays} \end{cases} $$

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

=> 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.



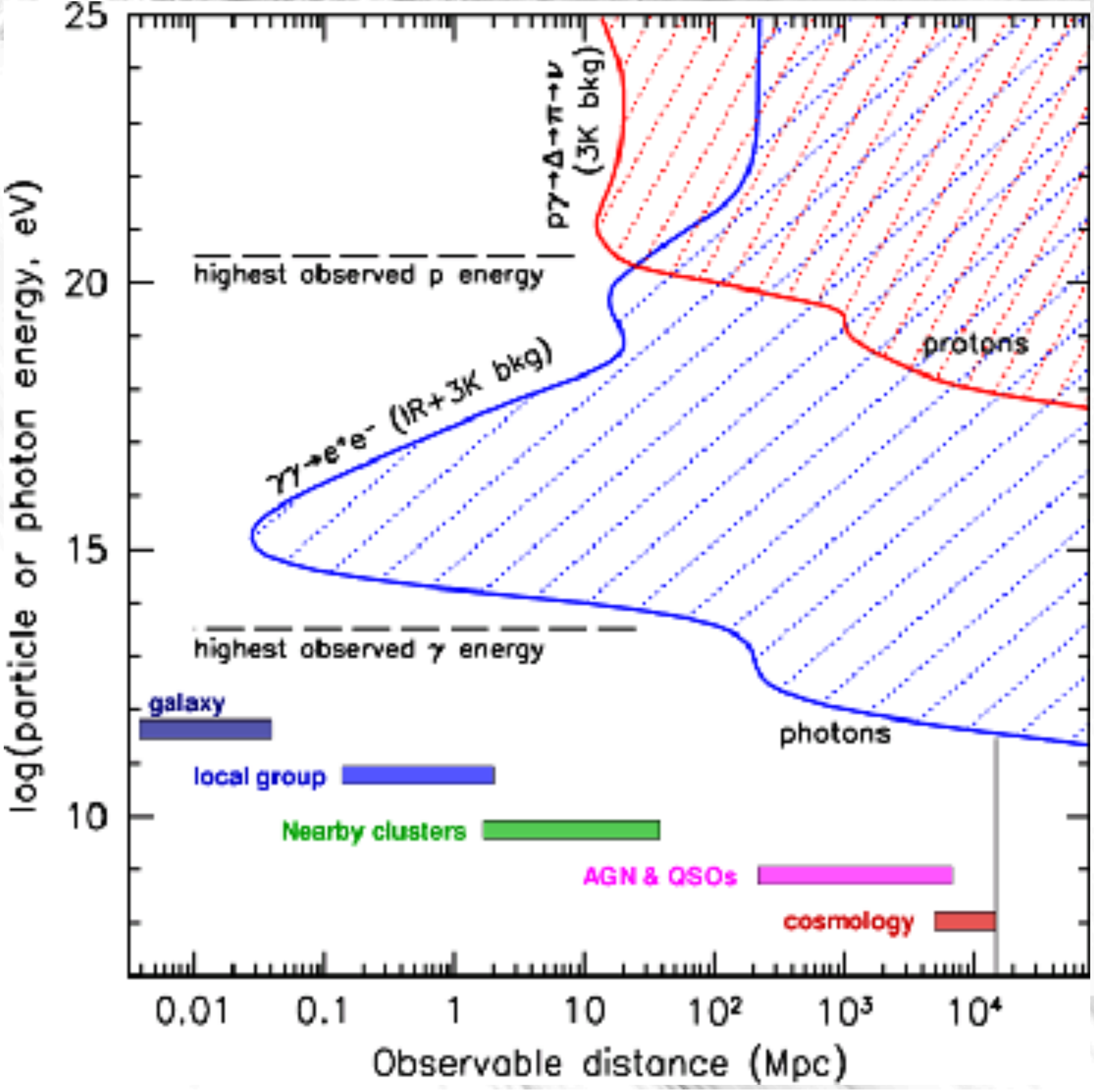
Included processes:

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

Interaction Horizons



Propagation of nucleons, photons, electrons, and neutrinos

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

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

where:

$\Phi_i(E)$ =injection spectrum,

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

μ = cos(angle between background and in-particle),

β =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 ~ 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

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

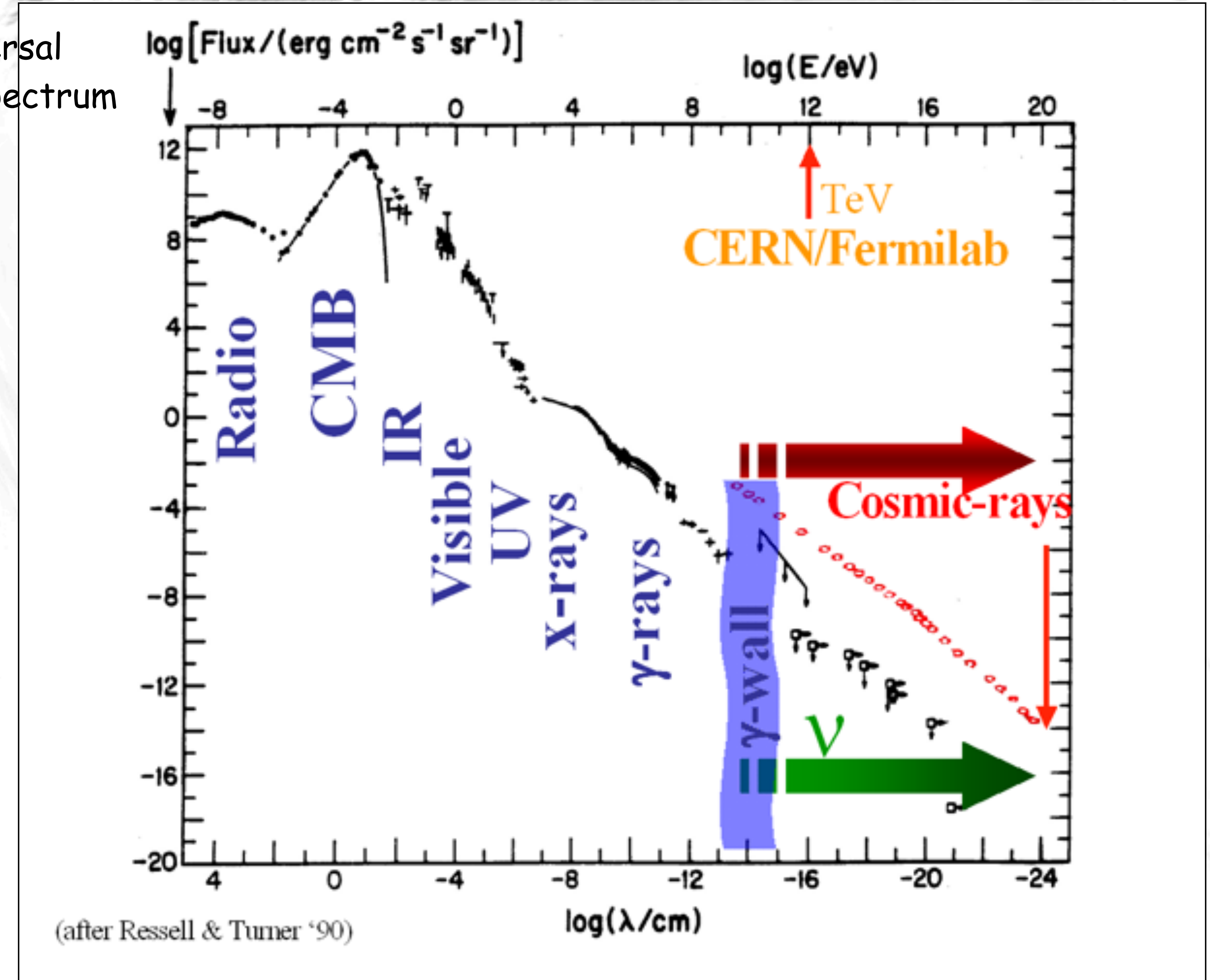
  with fractional energy loss η of leading e

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

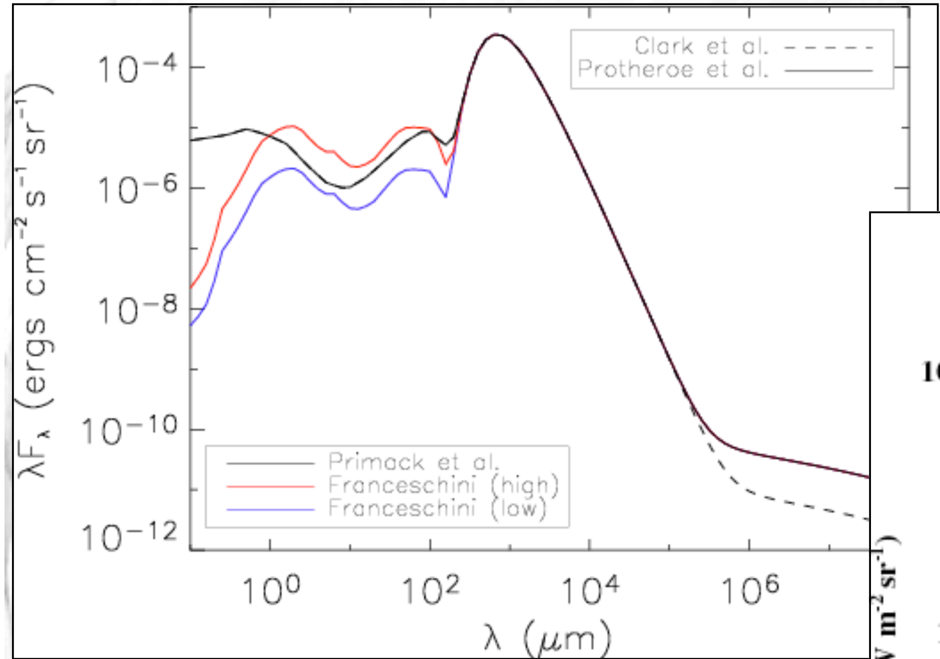
- synchrotron loss of electrons and positrons in cosmic magnetic fields: $eB \to e\gamma$. Energy loss given by

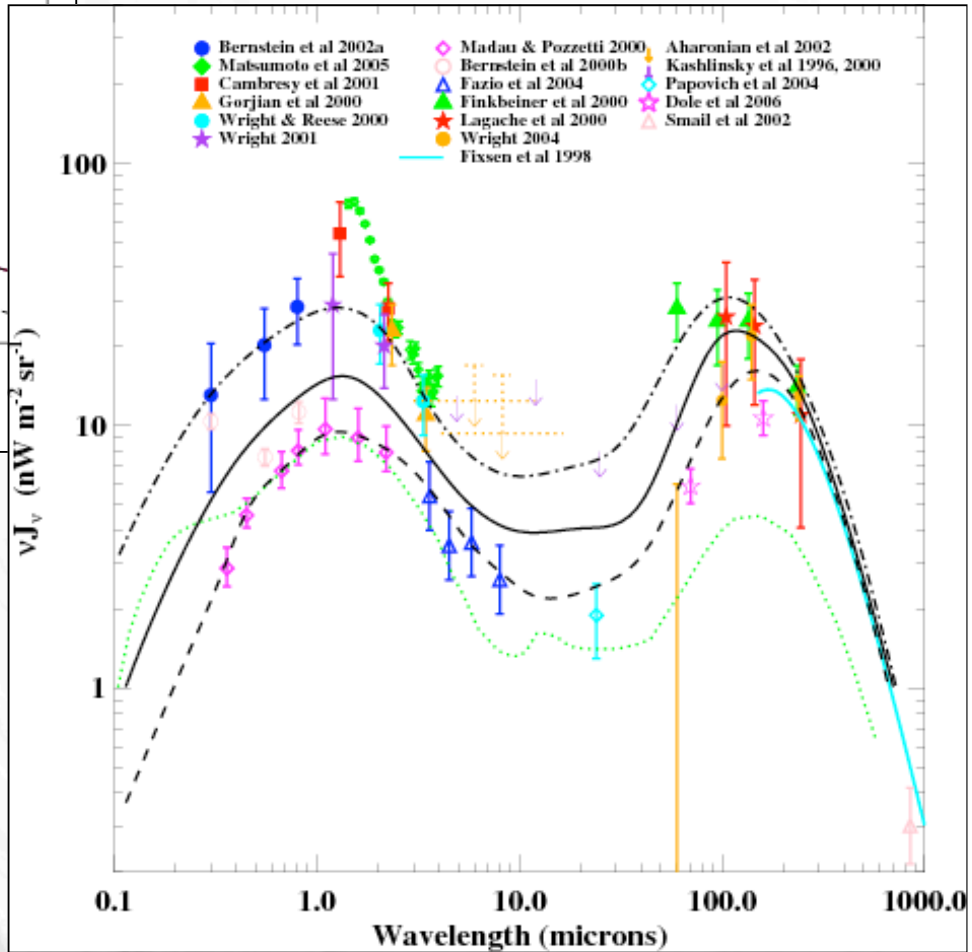
$$\frac{dE}{dt} = -\frac{4}{3}\sigma_T\frac{B^2}{8\pi}\left(\frac{Zm_e}{m}\right)^4\left(\frac{E}{m_e}\right)^2\,.$$

The universal photon spectrum

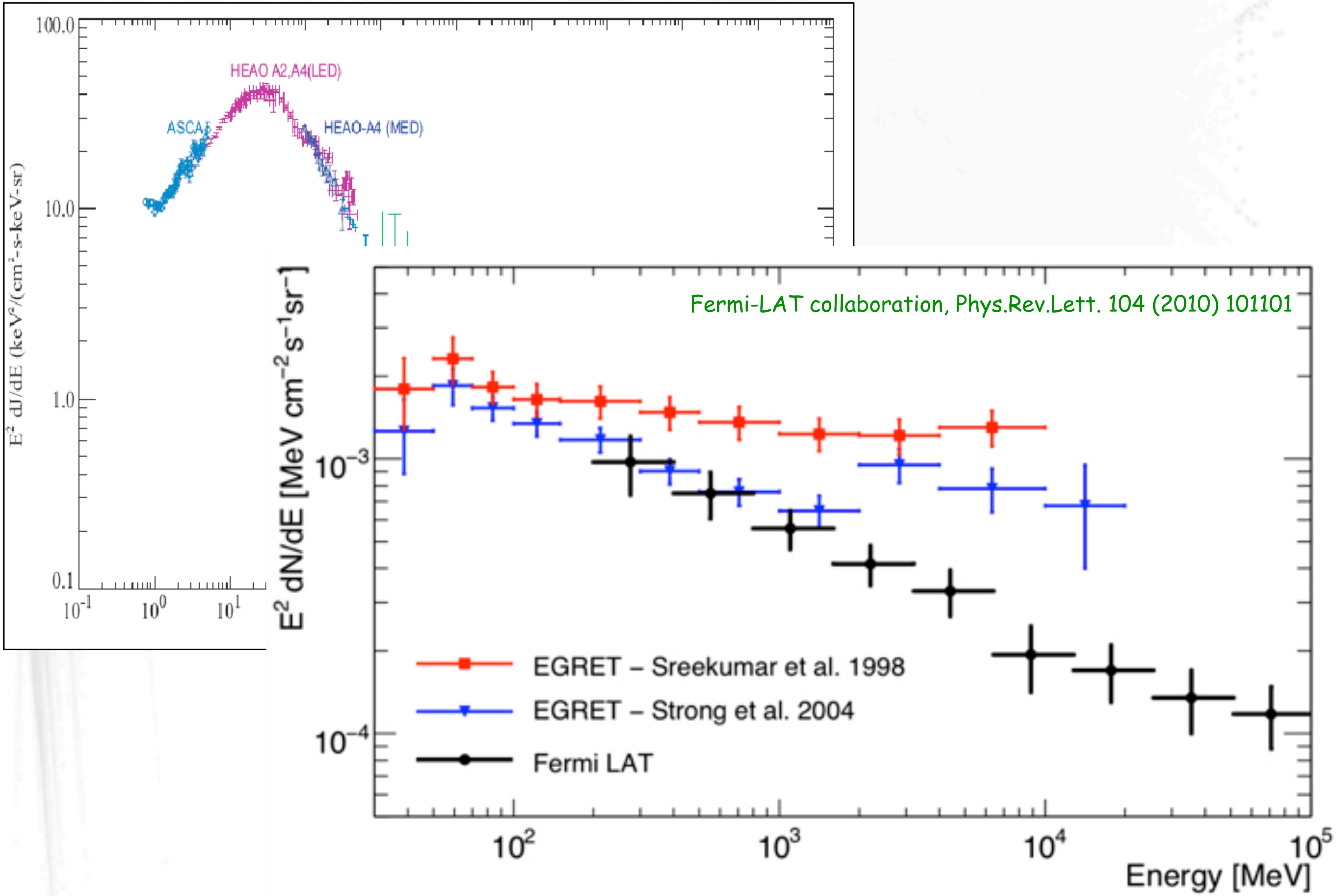


Low energy photon target: Diffuse fluxes

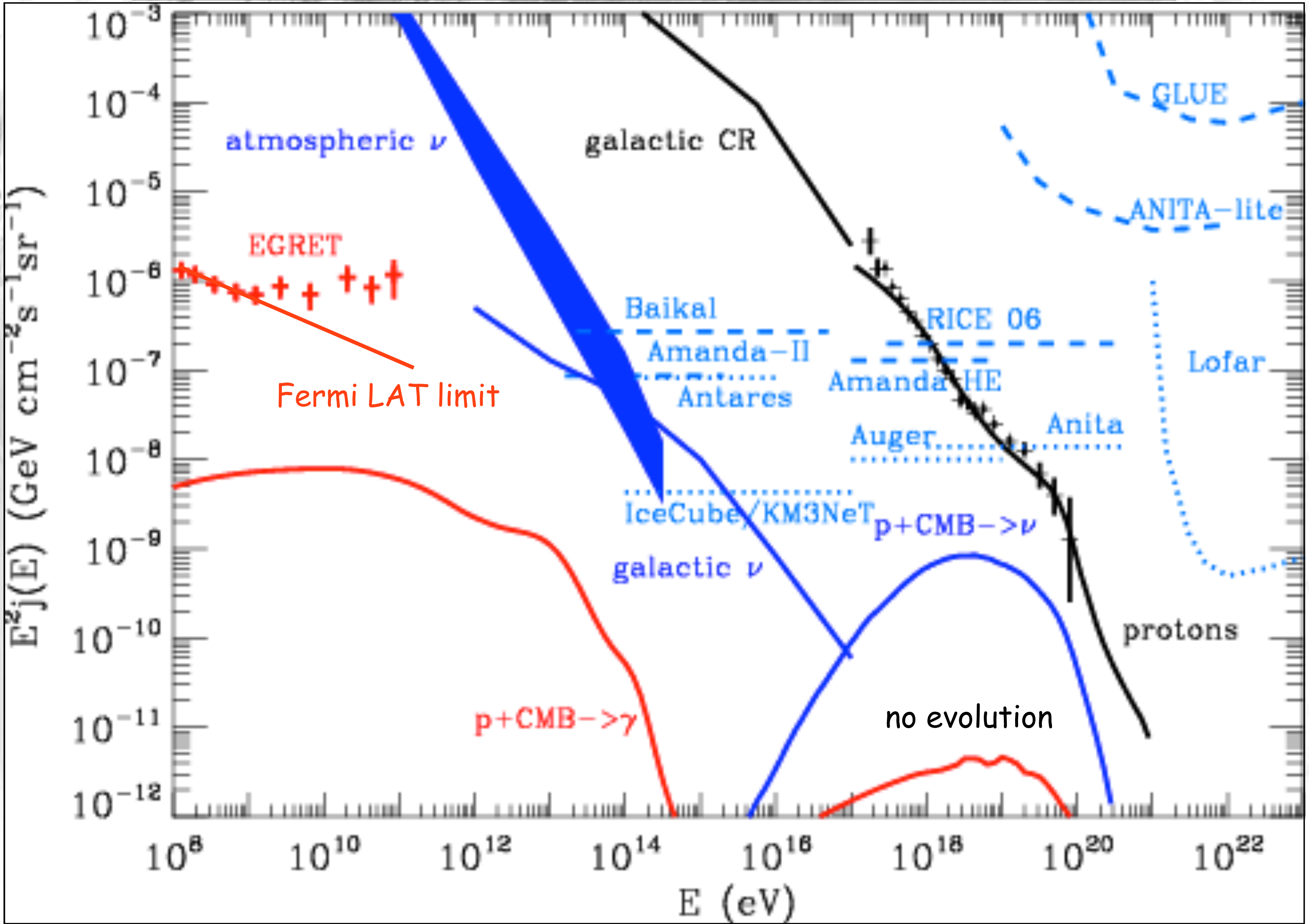




The diffuse photon background from keV to 100 GeV



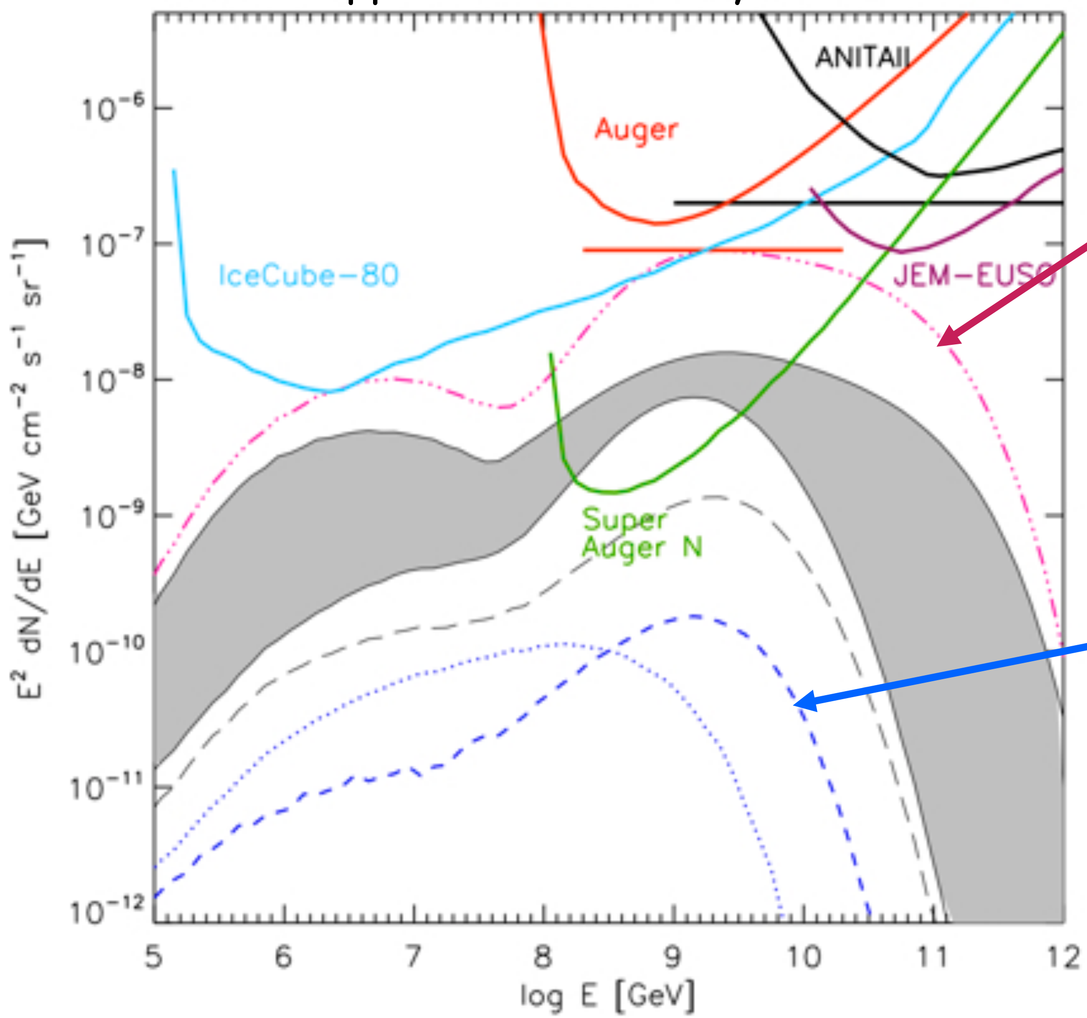
Theoretical Limits, Sensitivities, and "Realistic" Fluxes: A Summary



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

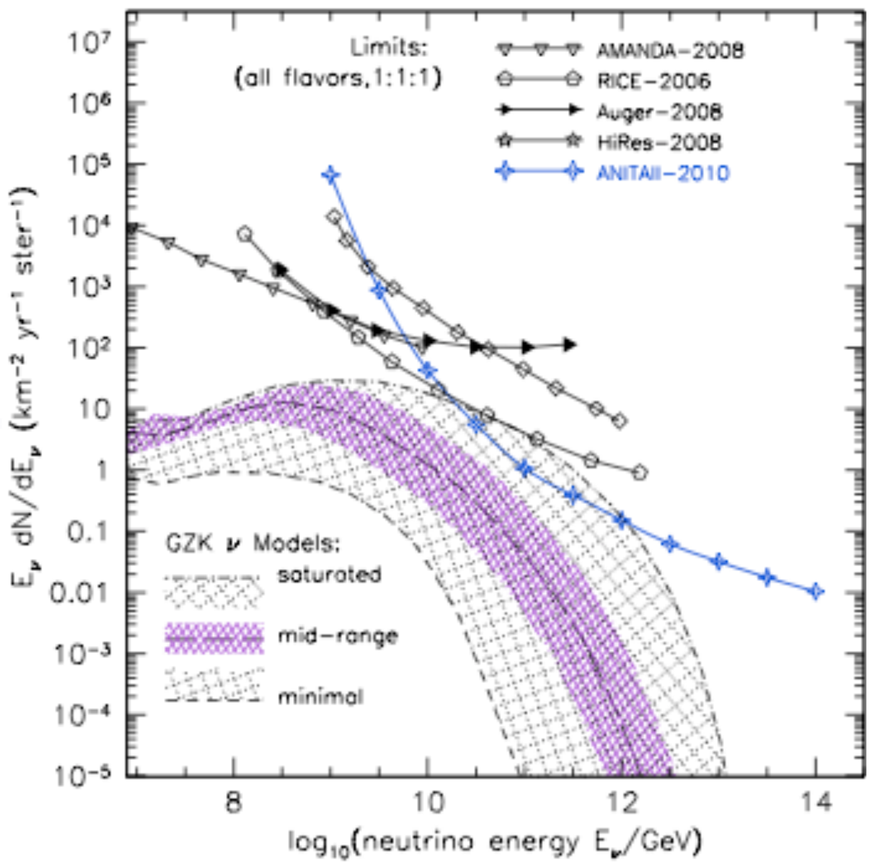


Pure protons, E_{max}=3 10^{21} eV, strong evolution

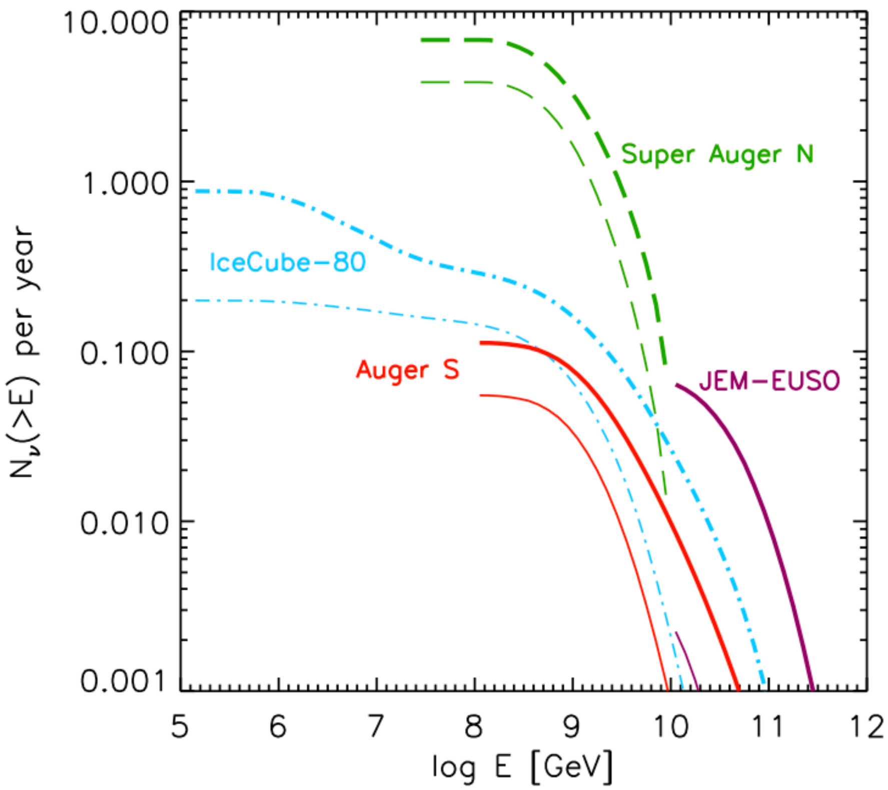
Pure iron, E_{max}= 10^{20}/26 eV, no evolution

Kotera, Allard, Olinto, arXiv:1009.1382

Expected Sensitivities to/Rates of UHE neutrino fluxes



P. Gorham et al, arXiv:1003.2961



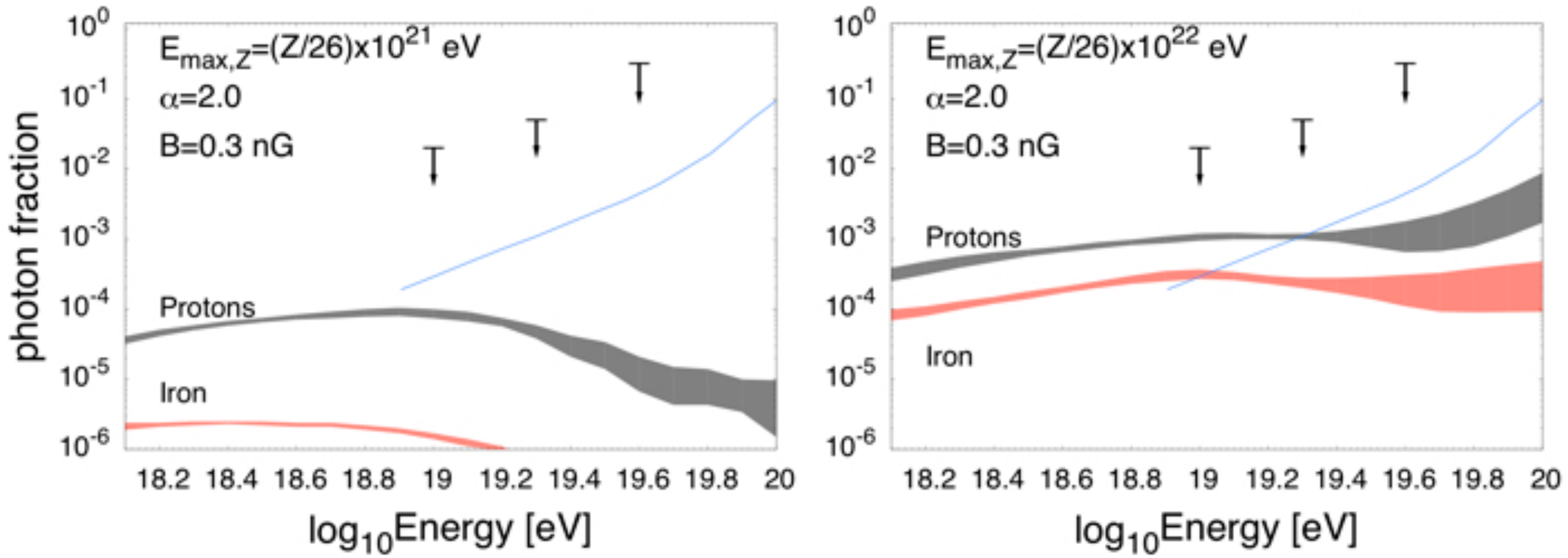
Rates for intermediate fluxes

Kotera, Allard, Olinto, arXiv:1009.1382

Physics with Diffuse Secondary Gamma-Ray Fluxes

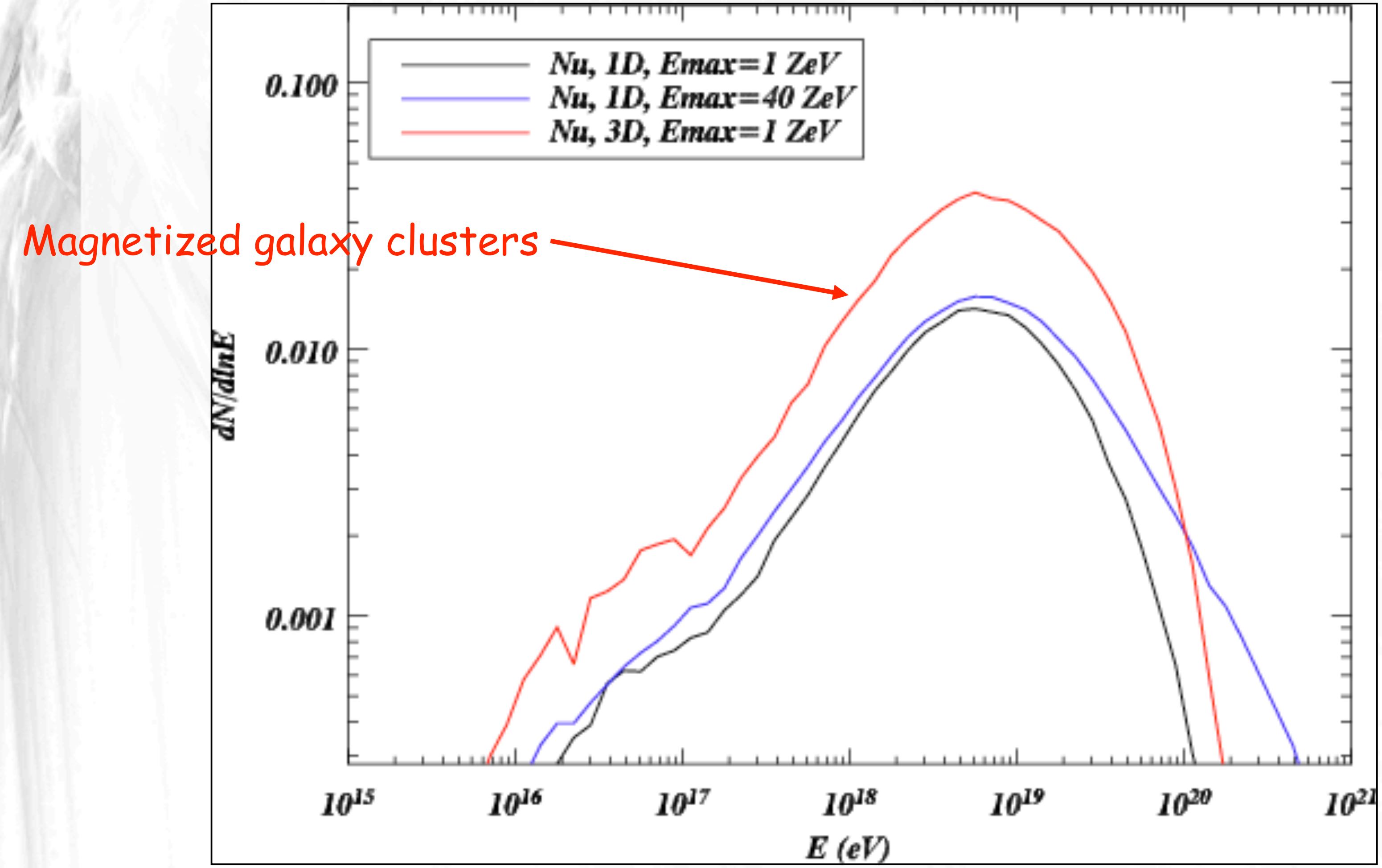
UHE gamma-ray fluxes depend on number of nucleons locally produced above GZK threshold which is proportional to E_{max}/A

Further suppressed for heavy nuclei due to increased pair production



Hooper, Taylor, Sarkar, arXiv:1007.1306

The GZK neutrino flux can also be enhanced by magnetic fields surrounding the sources



Armengaud and Sigl