Astrophysical Inputs to Atmospheric Neutrinos

1. cosmic ray spectra and composition
2. uncertainties and their impact on atmospheric neutrino flux
3. Astrophysical neutrinos and outlook

based on Garzelli, Moch, Sigl, JHEP 10 (2015) 115

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Calculation of Atmospheric Lepton Fluxes

$$\frac{d\phi_j}{dX} = -\frac{\phi_j}{\lambda_{j,int}} - \frac{\phi_j}{\lambda_{j,dec}} + \sum_{k\neq j} S_{\rm prod}(k \to j) + \sum_{k\neq j} S_{\rm decay}(k \to j) + S_{\rm reg}(j \to j)\,.$$

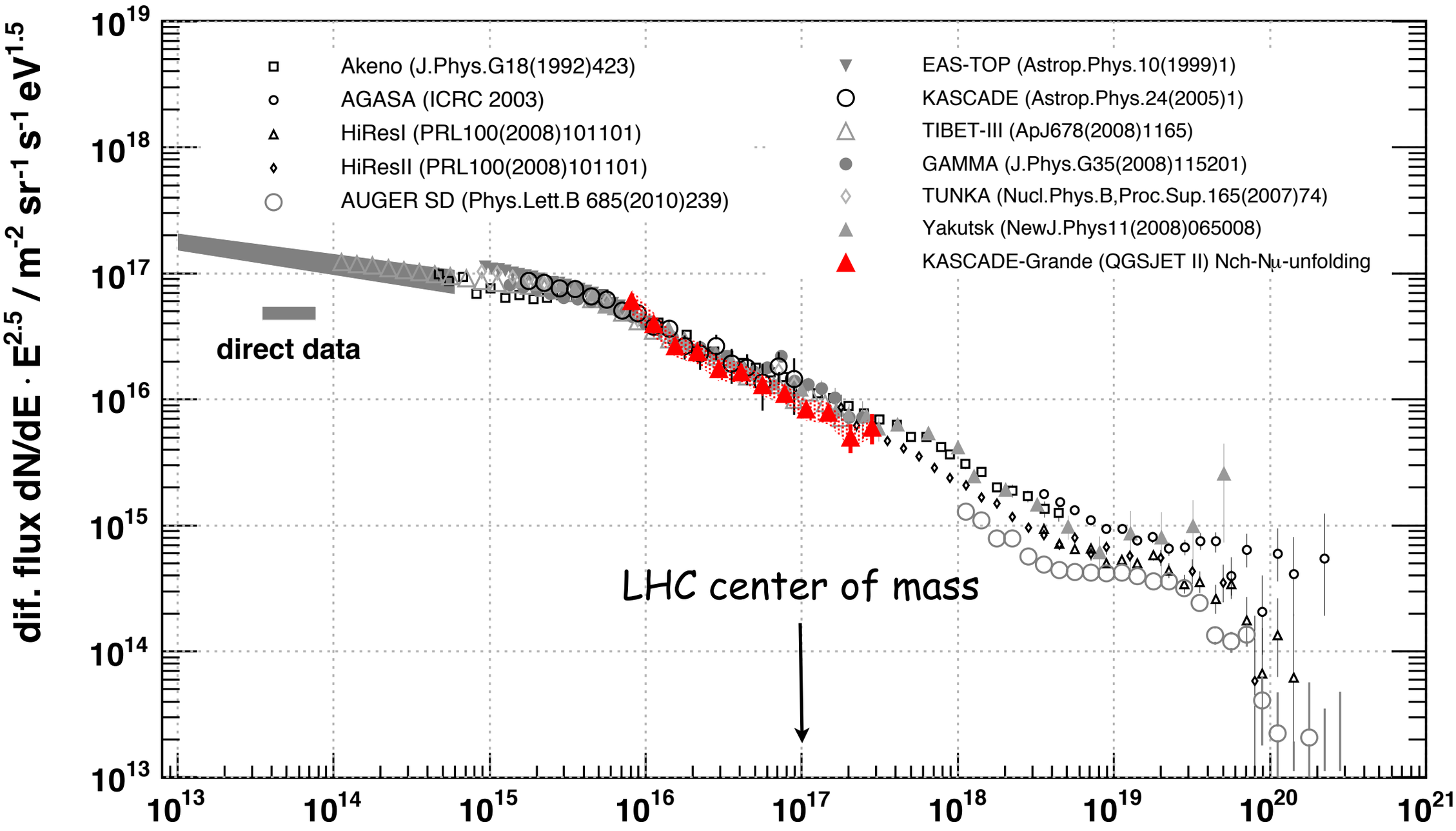
There is a critical energy above which interactions dominate over decay; for charged pions it is about 20 GeV, for charmed mesons it is much higher, ~ 10^7 GeV

$$S_{\rm prod}(k \to j) = \int_{E_j}^{\infty} dE_k \frac{\phi_k(E_k, X)}{\lambda_k(E_k)} \frac{1}{\sigma_k} \frac{d\sigma_{k\to j}(E_k, E_j)}{dE_j} \sim \frac{\phi_k(E_j, X)}{\lambda_k(E_j)} Z_{kj}(E_j)\,,$$

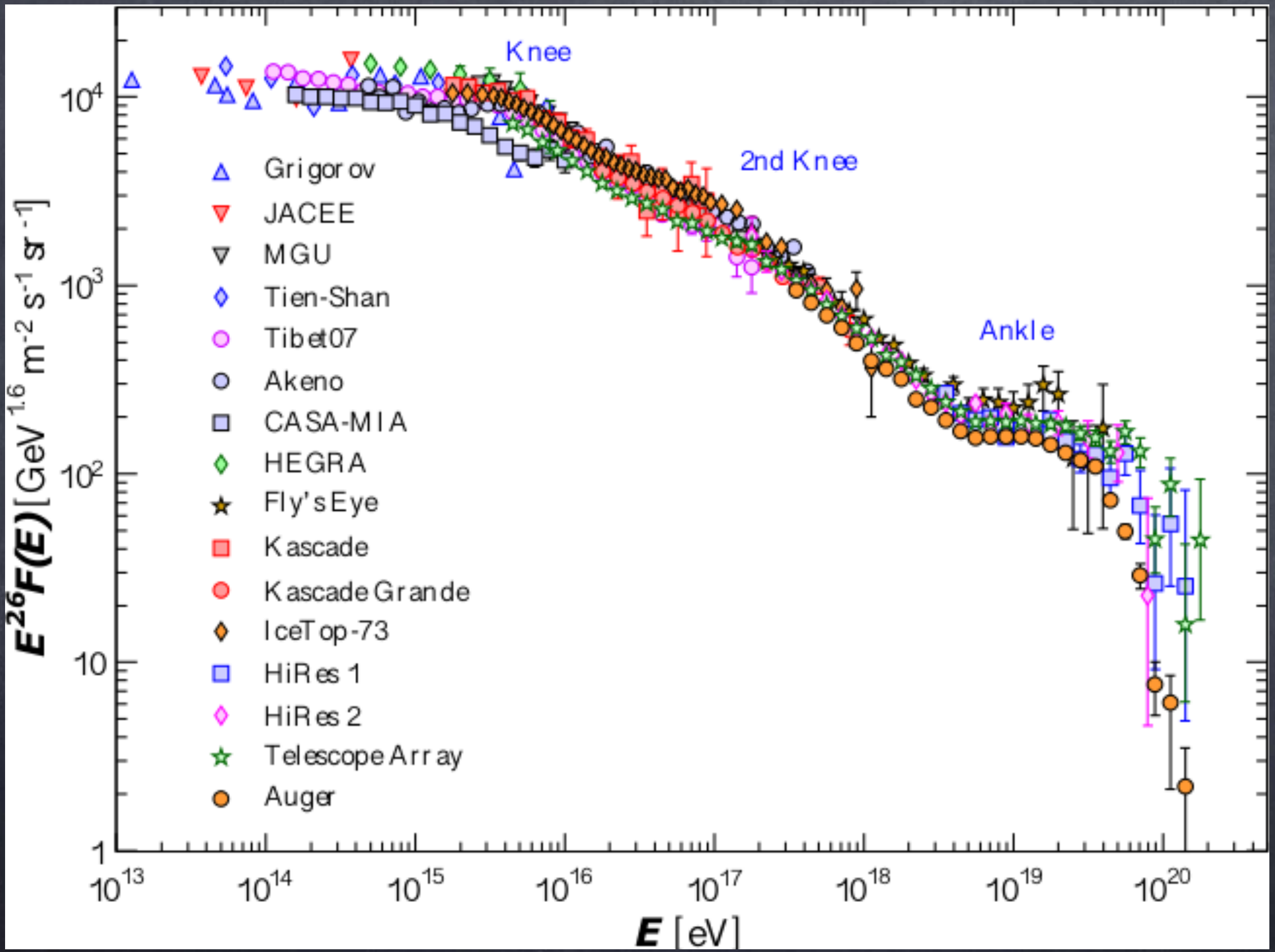
$$S_{\rm decay}(j \to l) = \int_{E_l}^{\infty} dE_j \frac{\phi_j(E_j, X)}{\lambda_j(E_j)} \frac{1}{\Gamma_j} \frac{d\Gamma_{j\to l}(E_j, E_l)}{dE_l} \sim \frac{\phi_j(E_l, X)}{\lambda_j(E_l)} Z_{jl}(E_l)\,.$$

Most relevant for us is the all-nucleon flux which depends both on the all-particle flux and the mass composition

The All Particle Cosmic Ray Spectrum



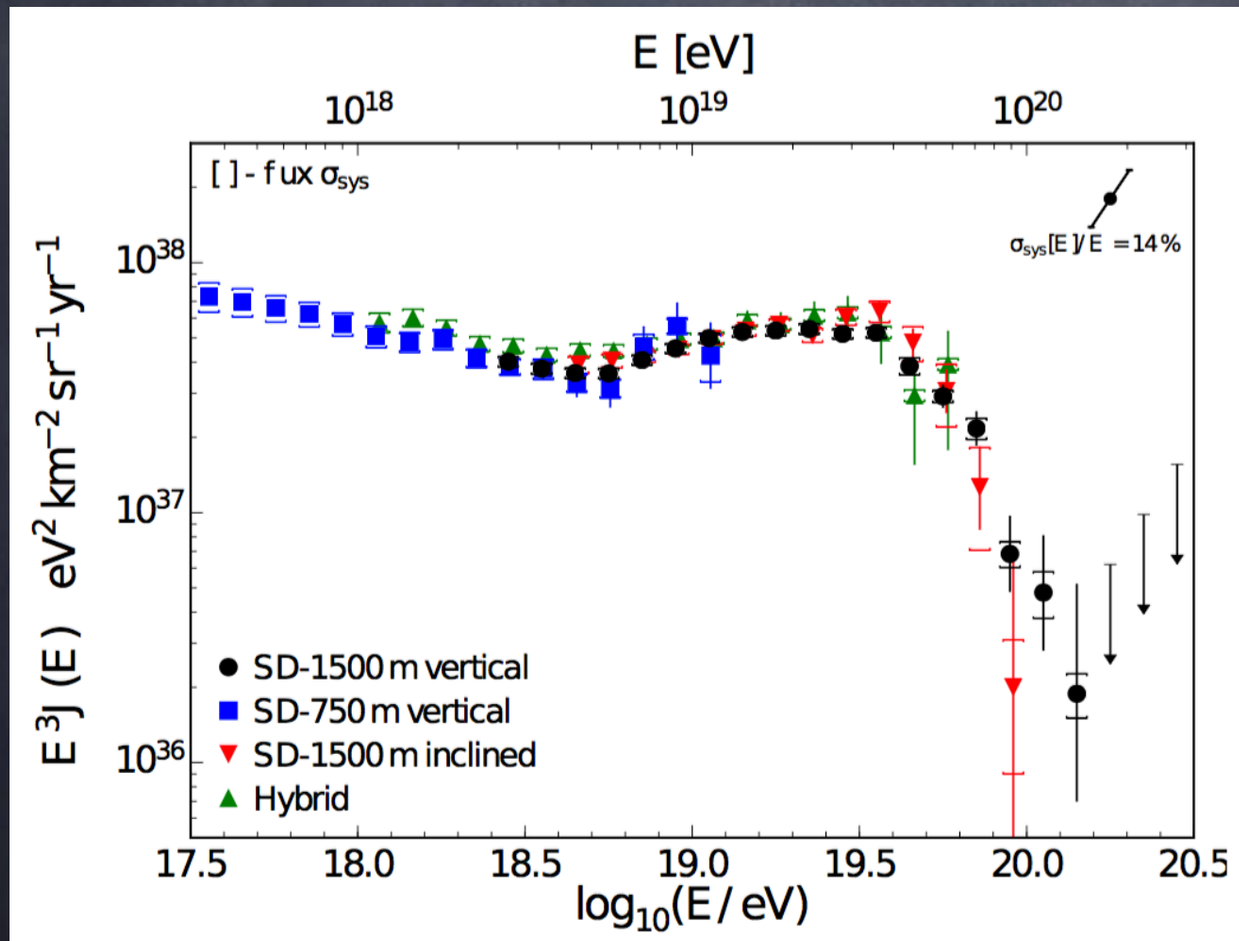
KASCADE-Grande collaboration, arXiv:1111.5436

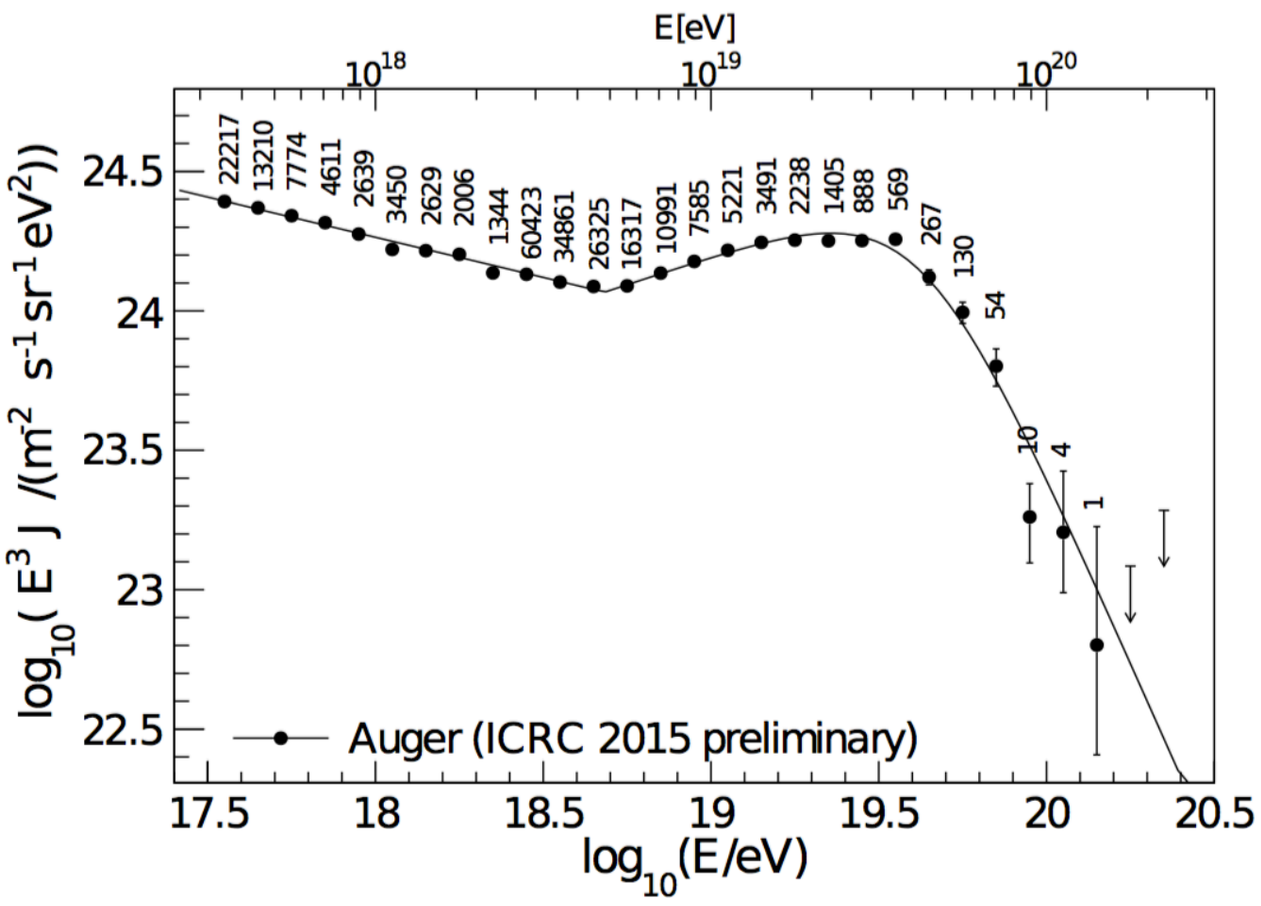

Knee
2nd Knee
Ankle
Grigorov
JACEE
MGU
Tien-Shan
Tibet07
Akeno
CASA-MIA
HEGRA
Fly's Eye
Kascade
Kascade Grande
IceTop-73
HiRes 1
HiRes 2
Telescope Array
Auger
$E^{2.6}F(E)$ [GeV$^{1.6}$ m^{-2} s^{-1} sr^{-1}]
E [eV]
10^4
10^3
10^2
10
1
10^{13}
10^{14}
10^{15}
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

Pierre Auger Spectra

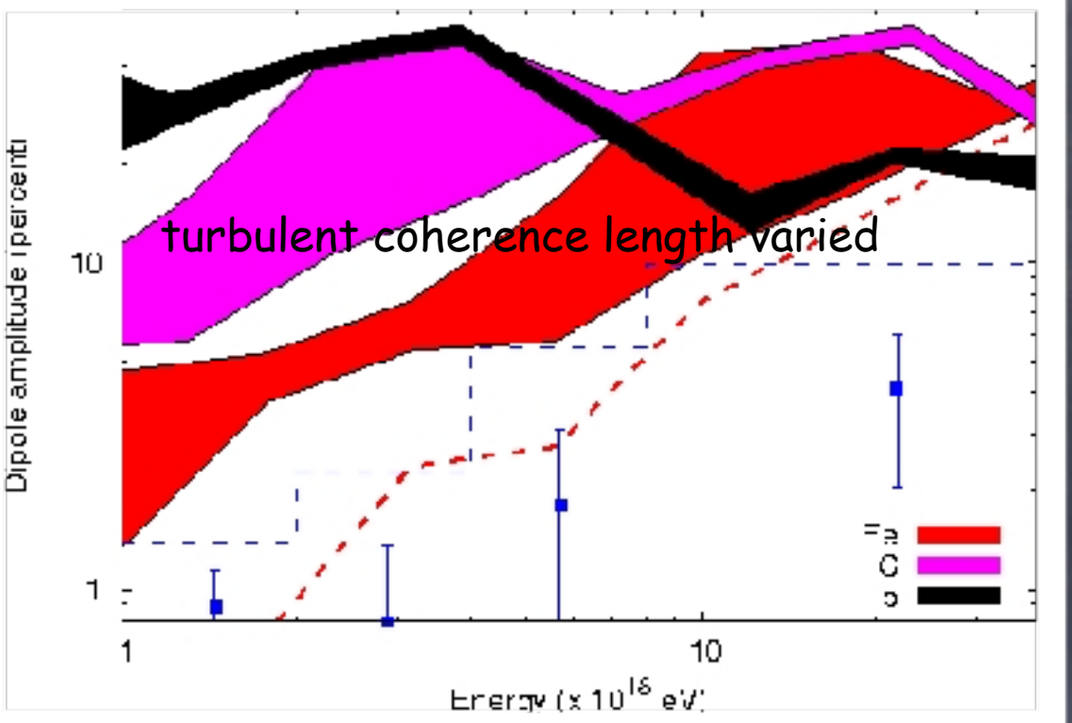
Auger exposure = 50000 km^2 sr yr, 102901 events above 3x10^{18} eV until end 2014

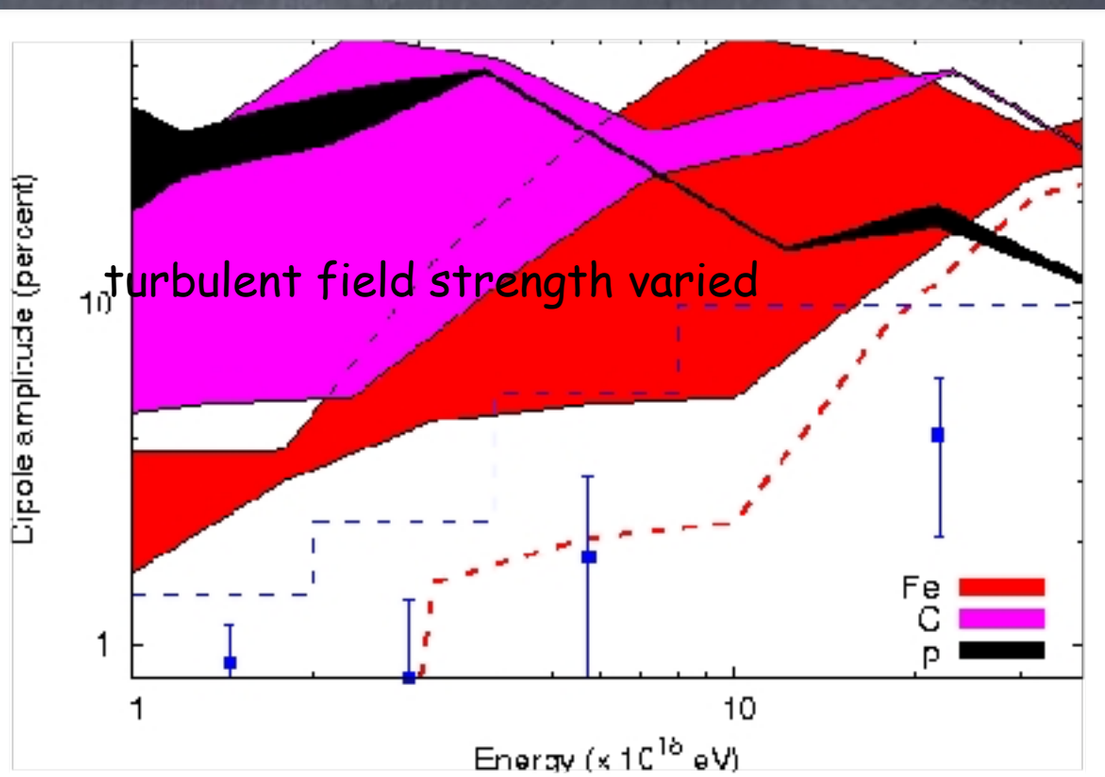
Pierre Auger Collaboration, PRL 101, 061101 (2008)
and Phys.Lett.B 685 (2010) 239
ICRC 2015, arXiv:1509.03732



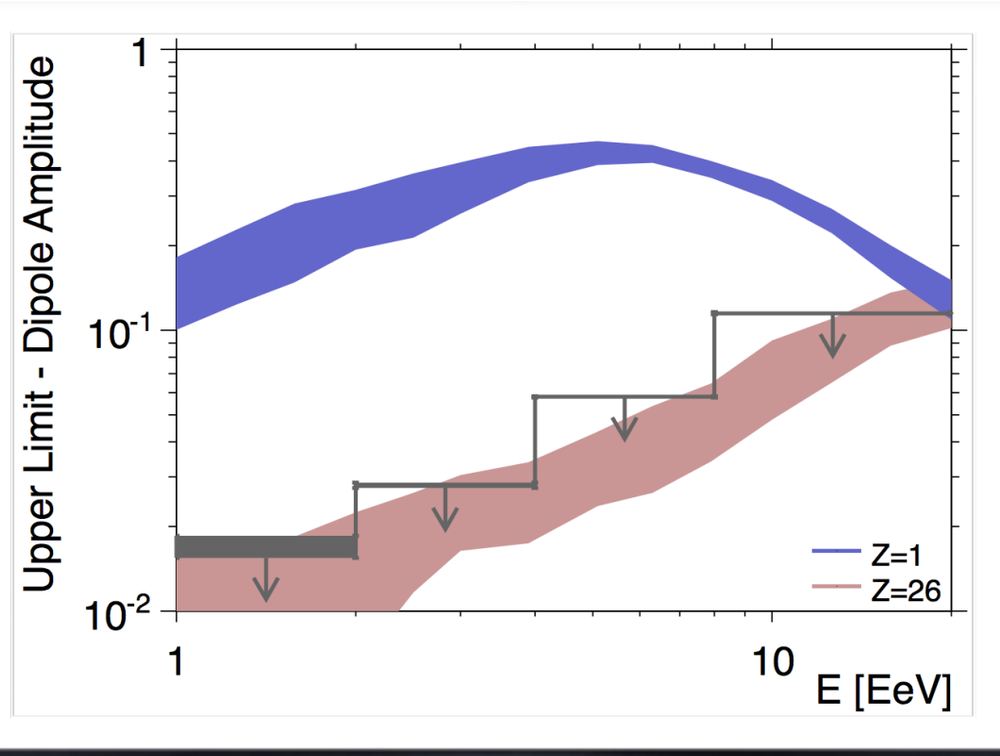


Composition and the Transition Galactic/Extragalactic Cosmic Rays





Giacinti, Kachelriess, Semikoz, Sigl,
JCAP 07 (2012) 031
and Pierre Auger Collaboration, Astrophys.J. 762 (2012) L13



KASCADE data suggest a heavy composition below ~10^{18} eV possibly becoming lighter around 10^{18} eV

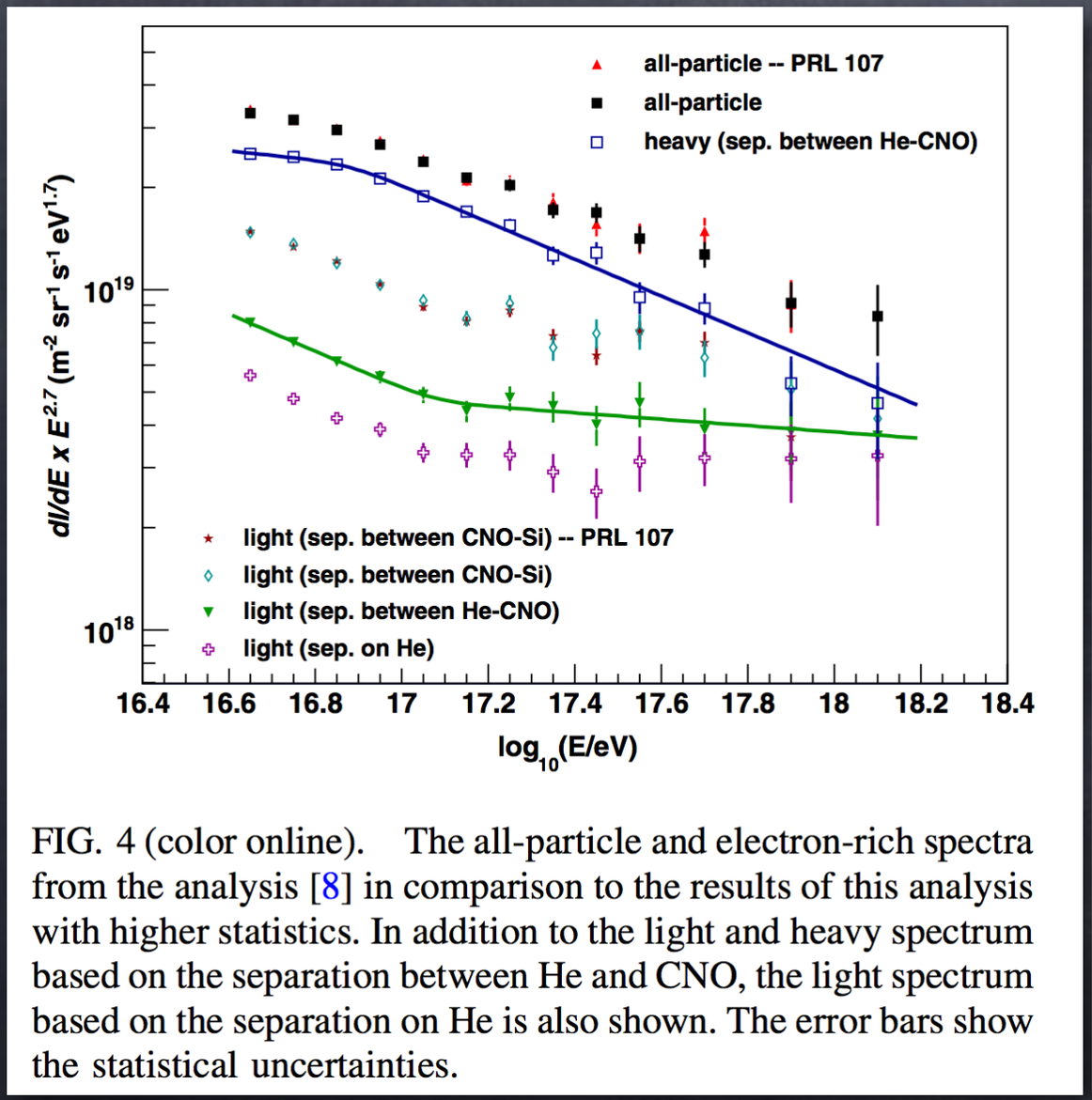
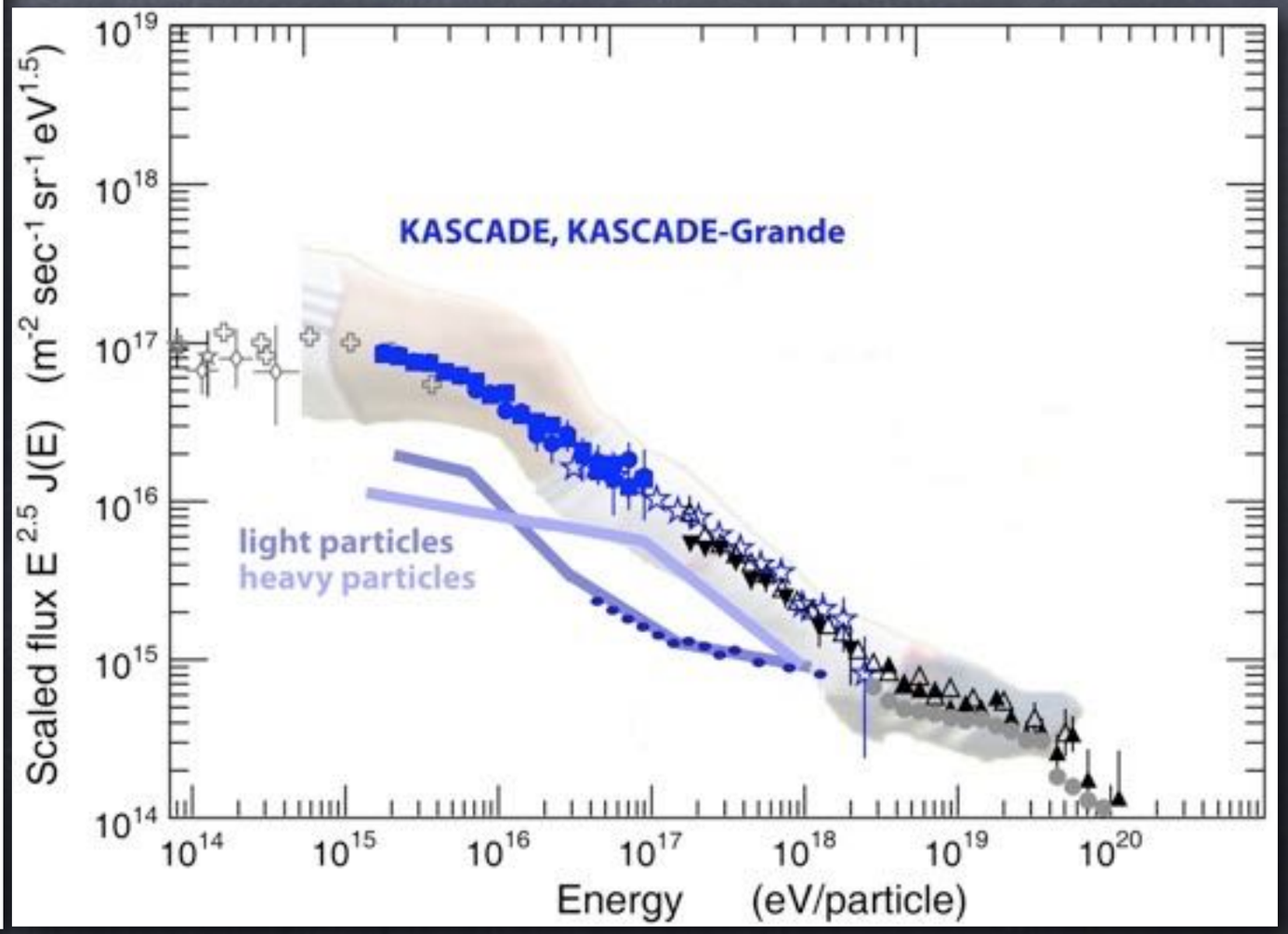
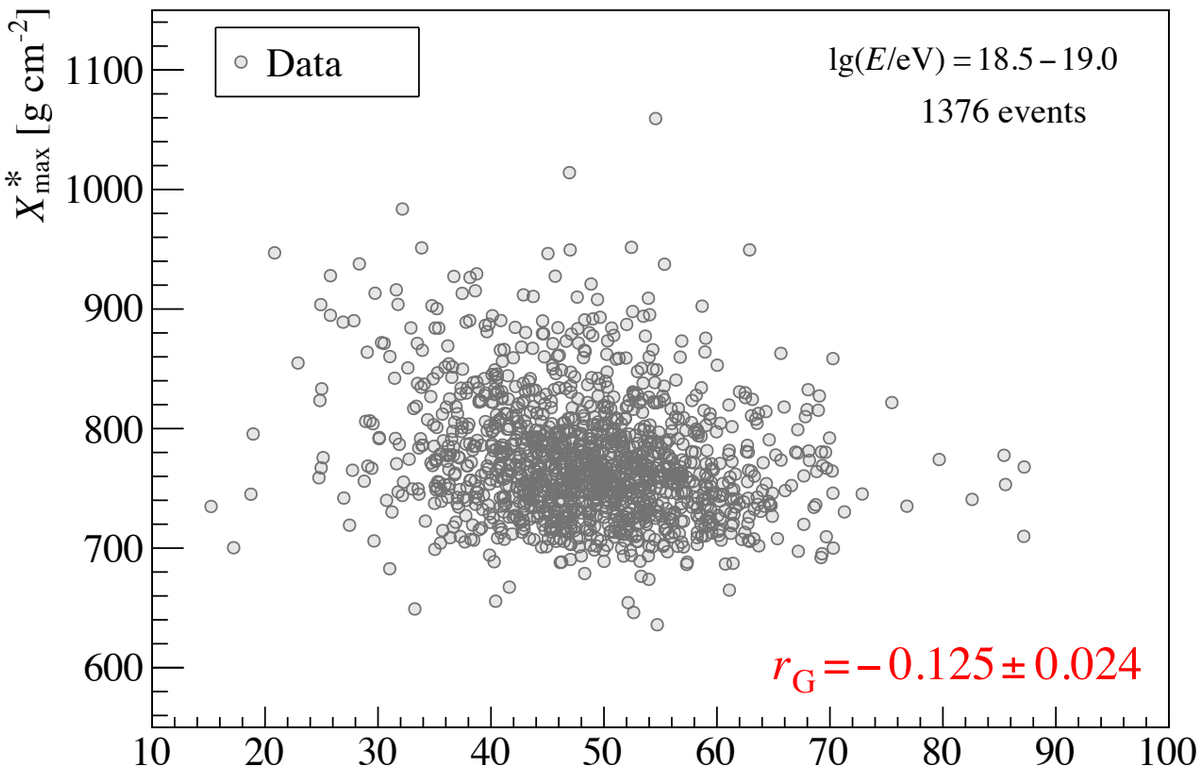


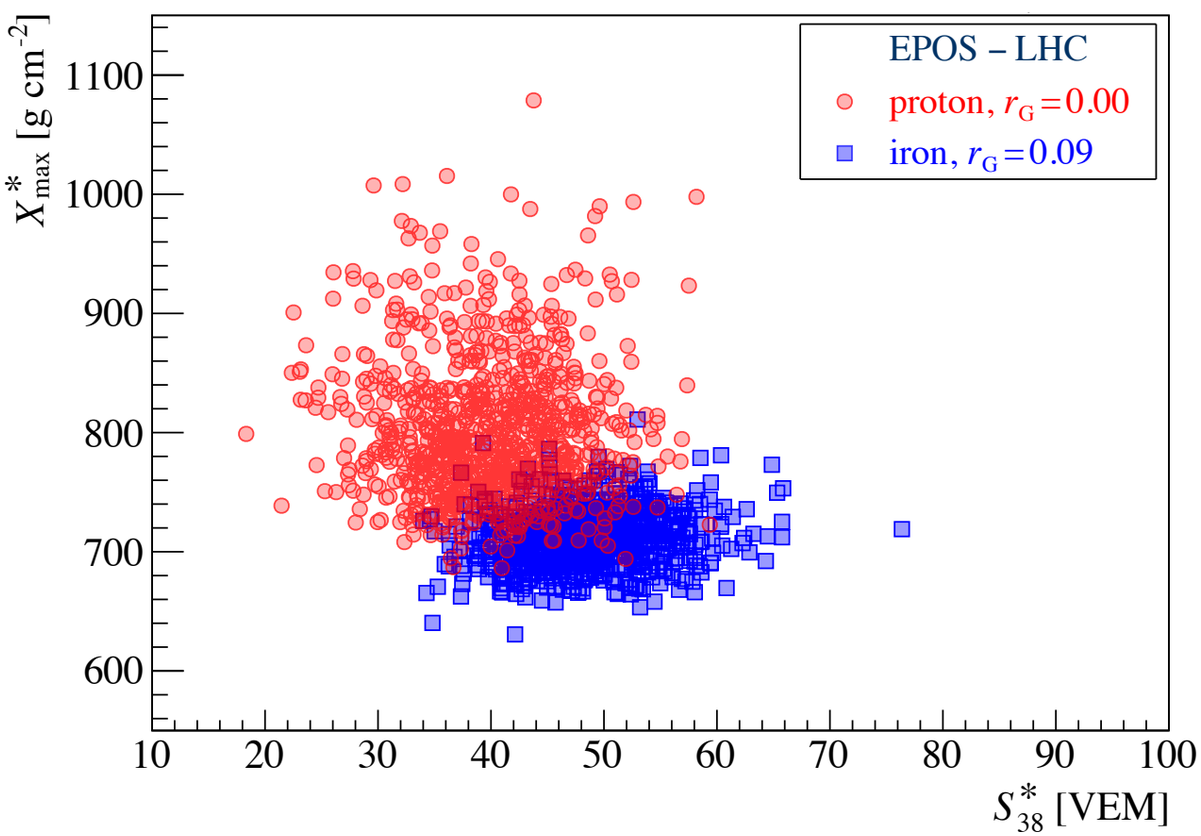
FIG. 4 (color online). The all-particle and electron-rich spectra from the analysis [8] in comparison to the results of this analysis with higher statistics. In addition to the light and heavy spectrum based on the separation between He and CNO, the light spectrum based on the separation on He is also shown. The error bars show the statistical uncertainties.

KASCADE Collaboration, Phys.Rev. D87 (2013) 081101,



Latest Pierre Auger results suggest mixed composition around the Ankle



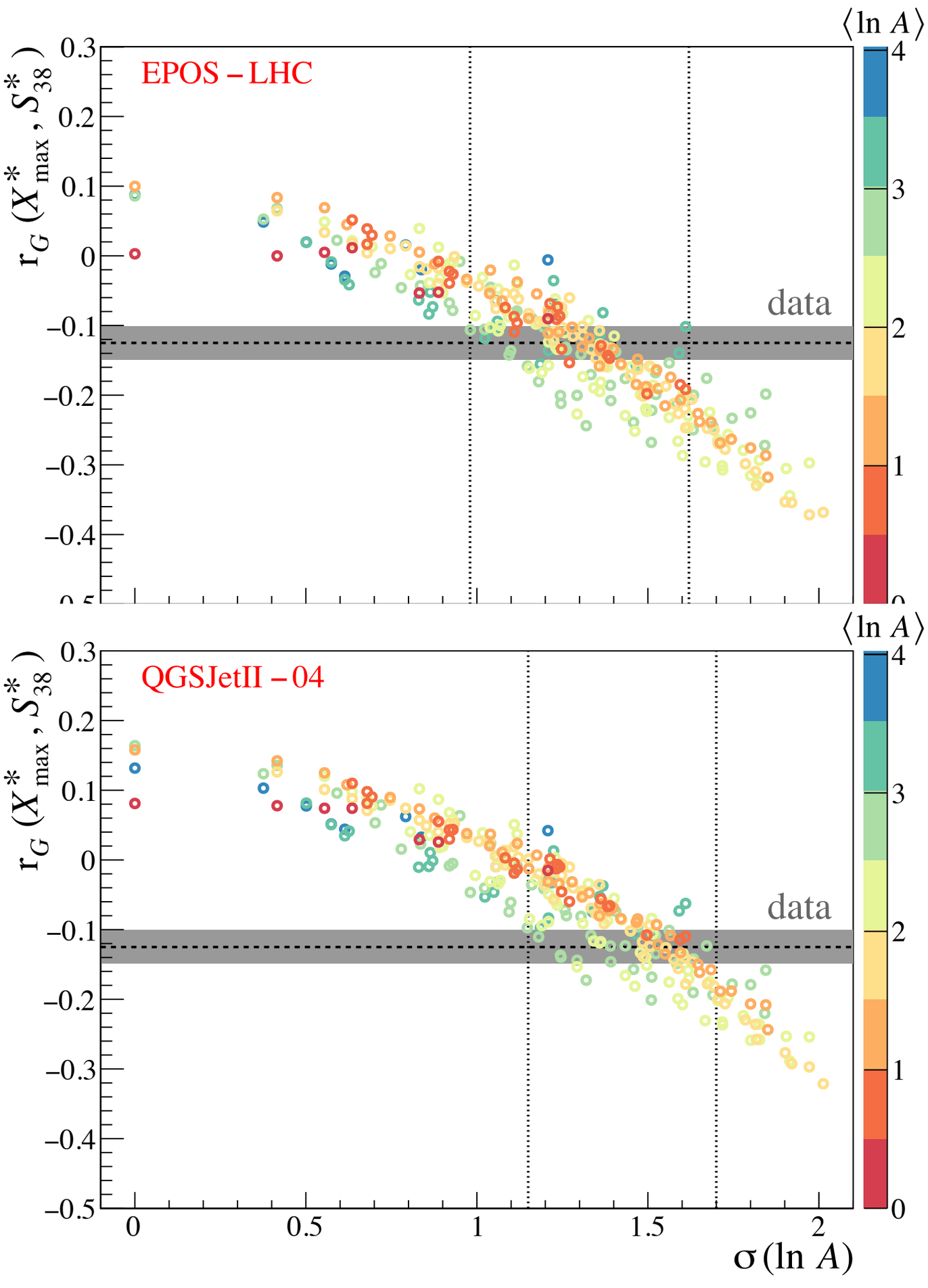


correlation between shower depth (measured by fluorescence detector) and particle density at 1km from shower core (measured by ground array) which is proxy for muon number is relatively insensitive to hadronic interaction models

Energy and zenith angle dependencies are projected out by scaling to 10 EeV and zenith angle 38 degrees.

Pure composition: zero or positive correlation mixed composition: negative correlation because large X_{max} correlates with light nuclei and small muon abundance

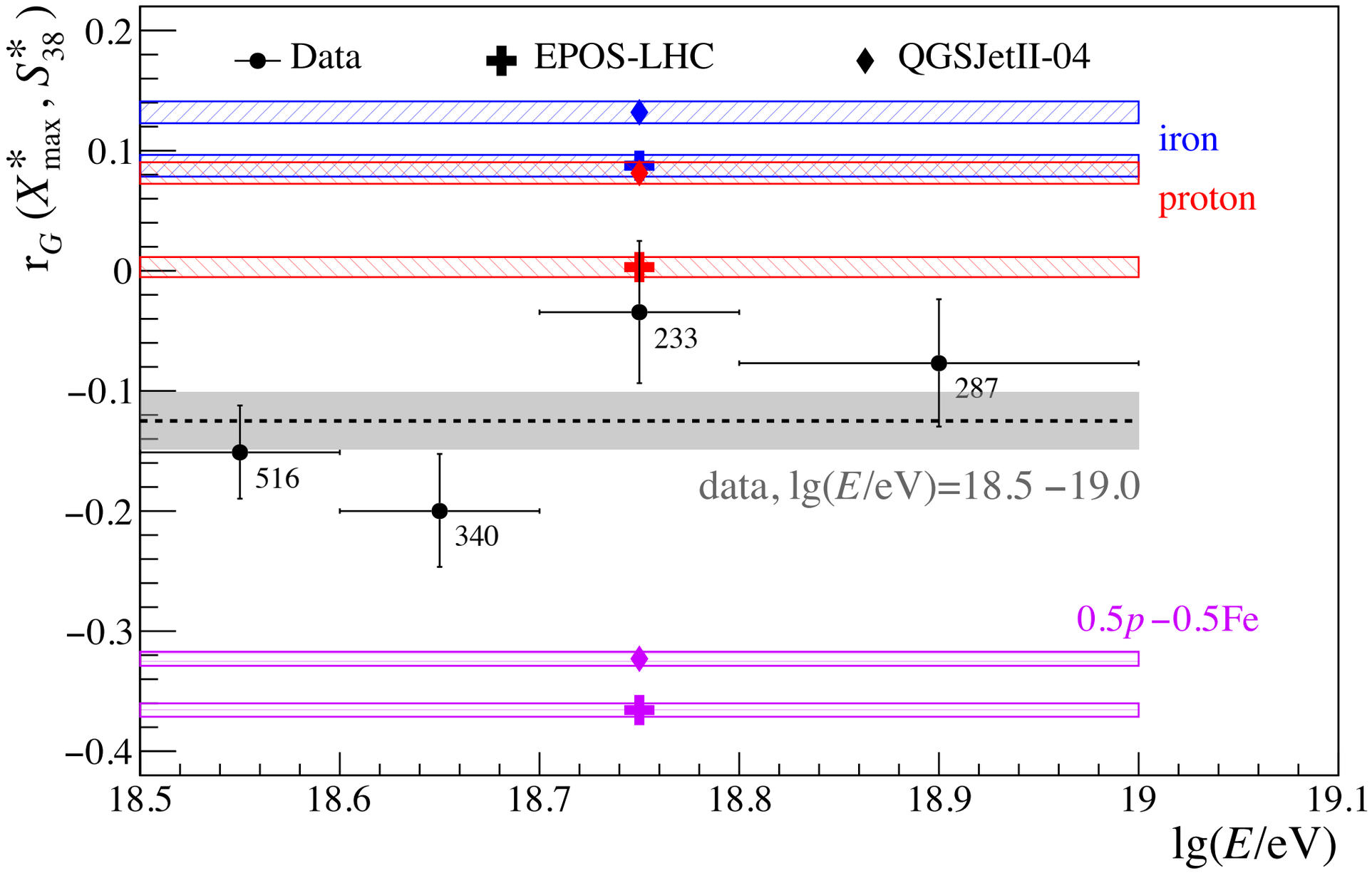
Pierre Auger collaboration, Phys. Lett. B 762, 288 (2016) [arXiv:1609.08567]



correlation coefficient versus measure of width of mass distribution:
larger spread of masses leads to smaller correlation coefficients

The observed correlations indicate a mixed composition including nuclei heavier than helium, $A > 4$ with mass spread $\sigma(\ln A)=1.35\pm0.35$

Summary of correlation coefficient: no significant energy trend



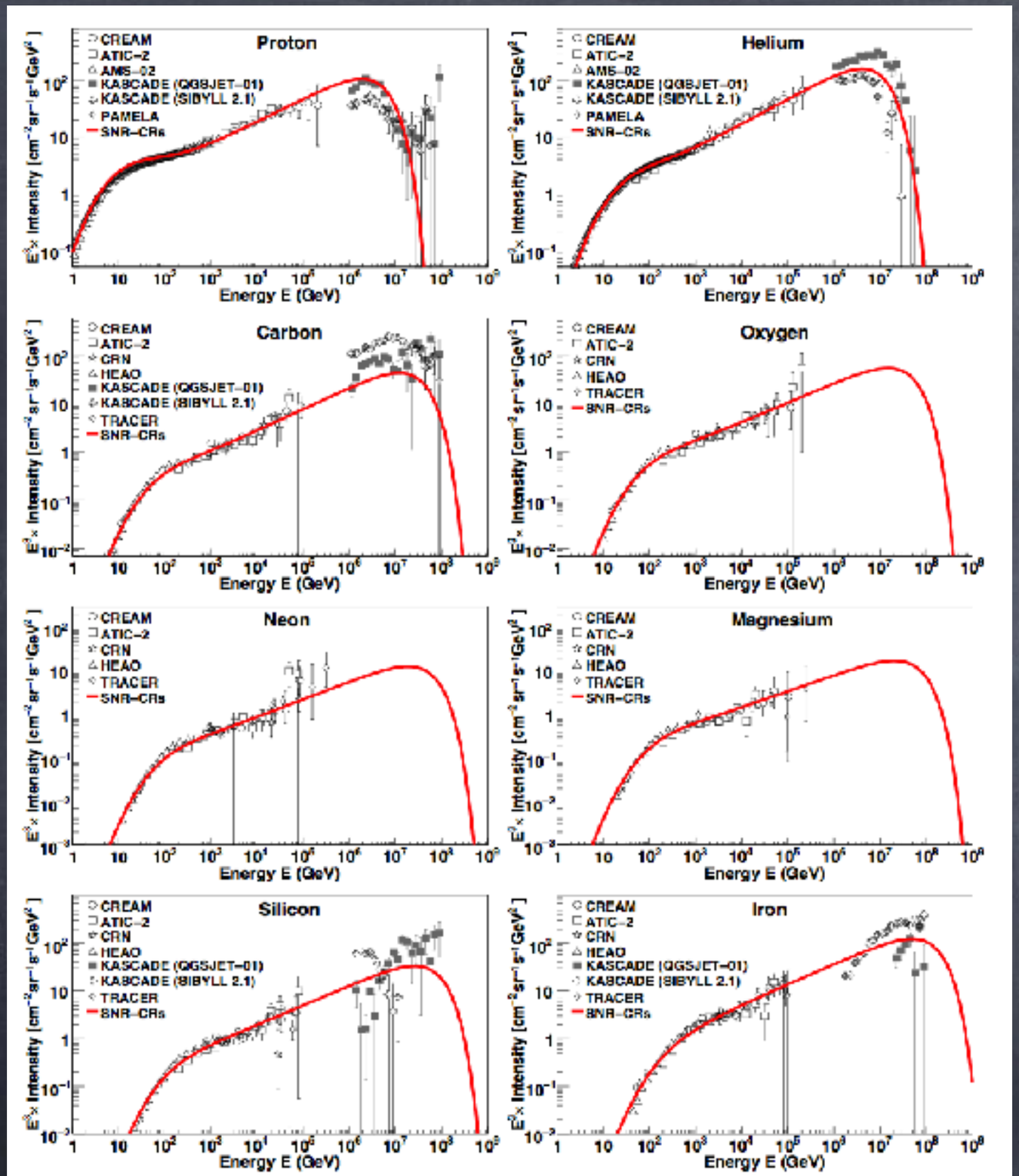


Fig. 1. Energy spectra for different cosmic ray elements. *Solid line*: Model prediction for the SNR CRs. *Data*: CREAM (Ahn et al. 2009; Yoon et al. 2011), ATIC 2 (Panov et al. 2007), AMS 02 (Aguilar et al. 2015a,b), PAMELA (Adriani et al. 2011), CRN (Müller et al. 1991; Swordy et al. 1990), HEAO (Engelmann et al. 1990), TRACER (Obermeier et al. 2011), and KASCADE (Antoni et al. 2005). Cosmic-ray source parameters (g, f) used in the calculation are given in Table 1. for the other model parameters (D_0, a, η, s), see text for details.

recent compilation of individual element spectra

S. Thoudam et al., arXiv:1605.03111

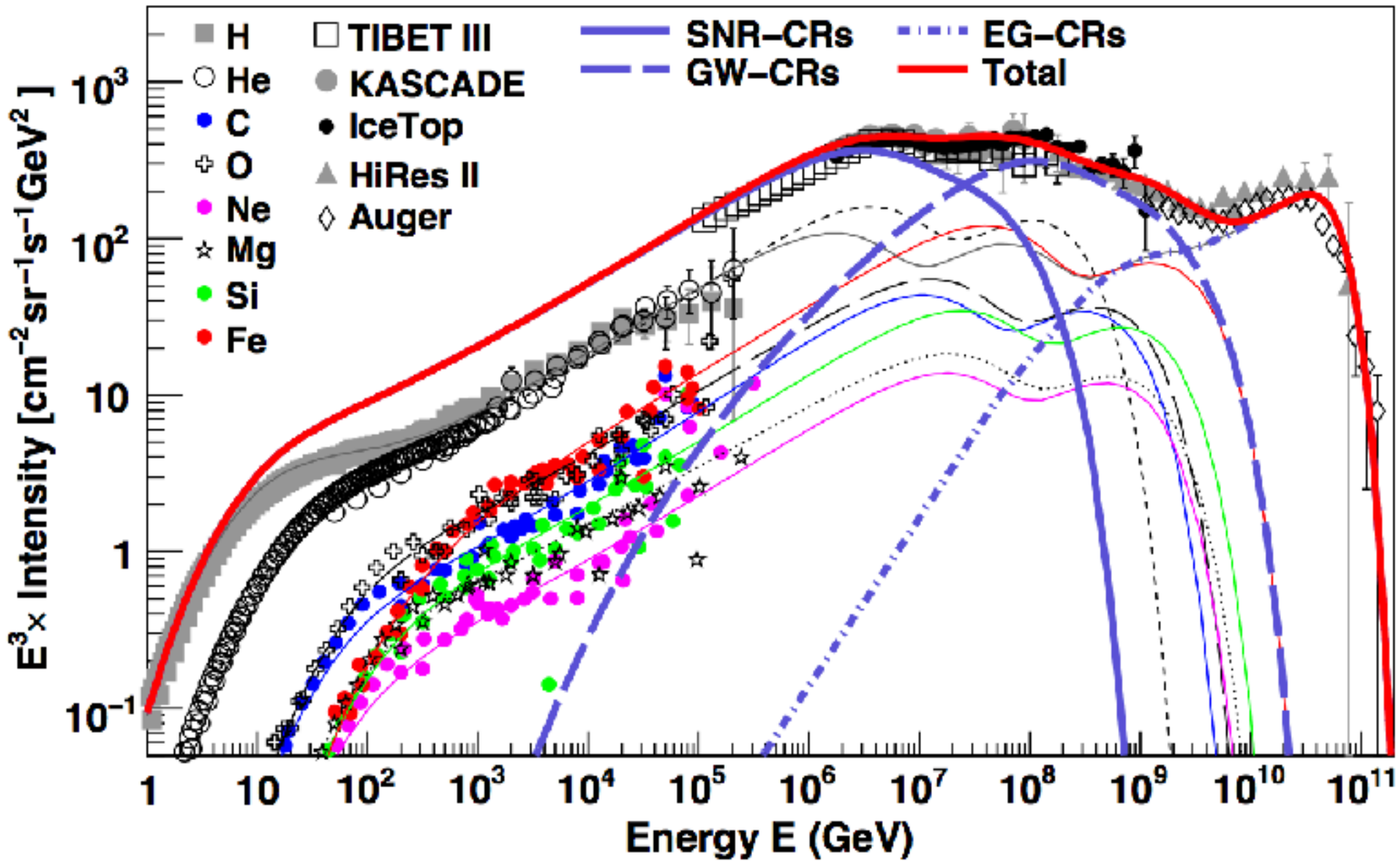


Fig. 5. Model prediction for the all-particle spectrum using the Galactic wind re-acceleration model. The thick solid blue line represents the total SNR-CRs, the thick dashed line represents GW-CRs, the thick dotted-dashed line represents EG-CRs, and the thick solid red line represents the total all-particle spectrum. The thin lines represent total spectra for the individual elements. For the SNR-CRs, an exponential energy cut-off for protons at $E_c = 3 \times 10^6$ GeV is assumed. See text for the other model parameters. Data are the same as in Figure 2.

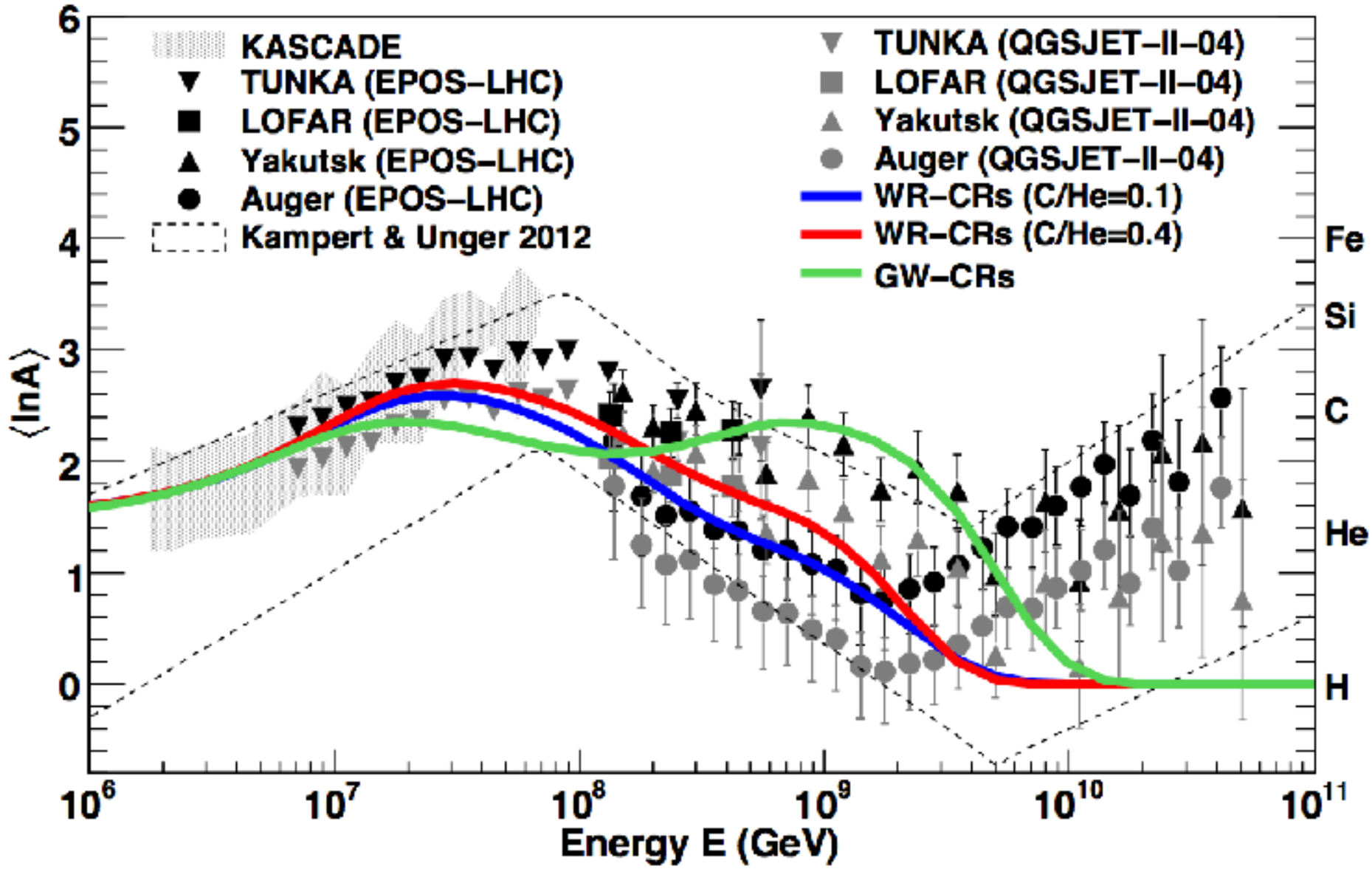


Fig. 8. Mean logarithmic mass, ⟨lnA⟩, of cosmic rays predicted using the three different models of the additional Galactic component: WR-CRs (C/He = 0.1), WR-CRs (C/He = 0.4), and GW-CRs. *Data*: KASCADE (Antoni et al. 2005), TUNKA (Berezhnev et al. 2013), LOFAR (Buitink et al. 2016), Yakutsk (Knurenko & Sabourov 2010), the Pierre Auger Observatory (Porcelli et al. 2015), and the different optical measurements compiled in Kampert & Unger (2012). The two sets of data points correspond to two different hadronic interaction models (EPOS-LHC and QGSJET-II-04) used to convert $X_{\max}$ values to ⟨lnA⟩.

Global Picture on Mass Composition

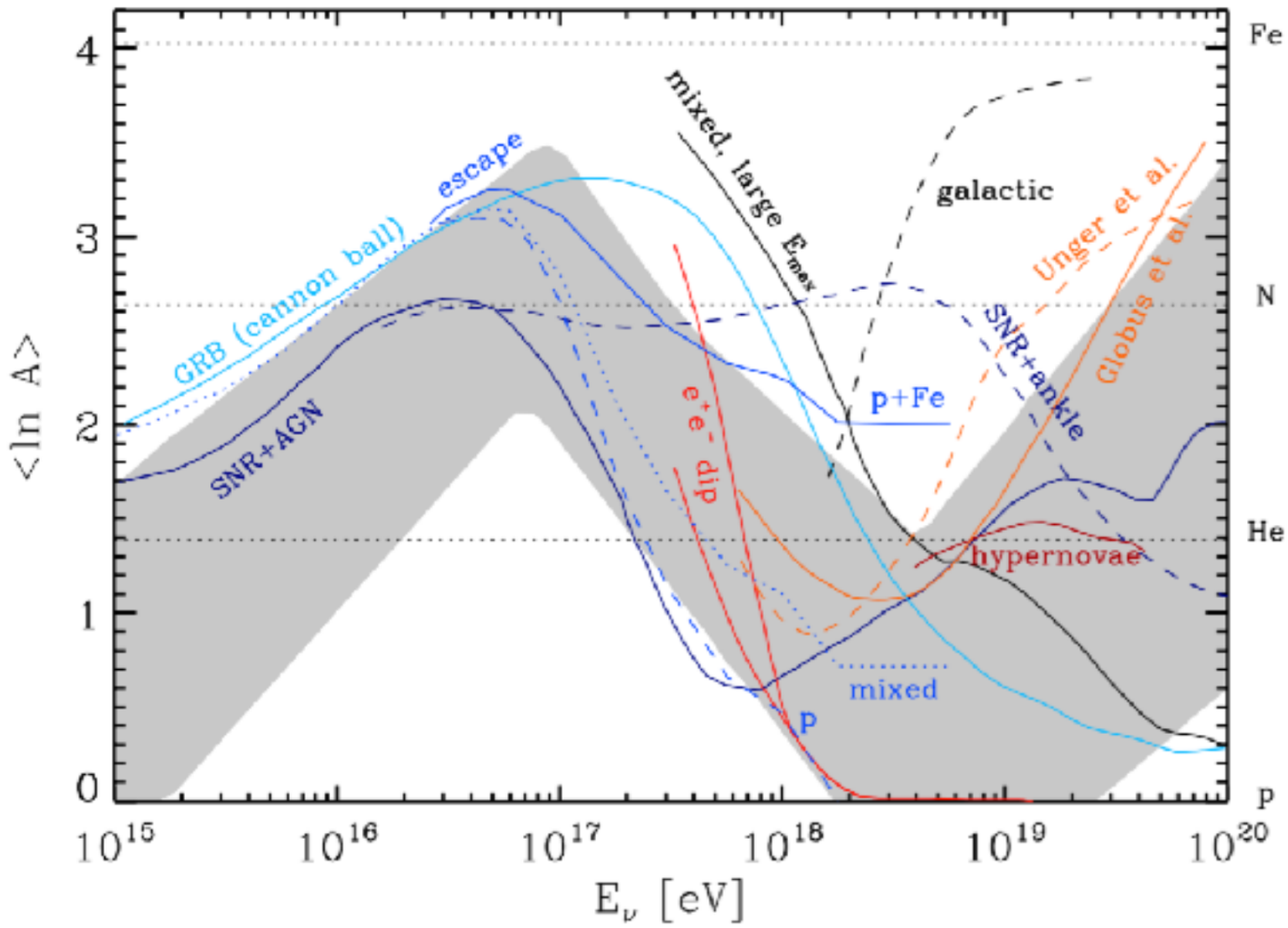


Fig. 5.8 The energy dependence of the average logarithmic mass predicetd by various models, as indicated and explained in more details in the text. The grey band represents the combined uncertainties resulting from systematic experimental errors and hadronic model uncertainties, based on data such as the ones shown in Fig. 5.7. The first minimum in $\langle \ln A \rangle$ at $\simeq 3 \times 10^{15}$ eV corresponds to the CR knee and the first maximum in $\langle \ln A \rangle$ at $\simeq 10^{17}$ eV corresponds to the *second knee*. Both the knee and the second knee could signify a rigidity dependent Peters cycle either due to the maximal rigidity reached at acceleration in supernova remnants or due to a transition to a propagation regime leading to faster CR leakage from the Galaxy. Finally, the second minimum in $\langle \ln A \rangle$ at $\simeq 5 \times 10^{18}$ eV signifies the *ankle*. Compare the CR spectrum shown in Fig. 5.6. Inspired by Ref. [231].

Indications of "Peters cycles" for galactic and extragalactic sources whose maximal energies are proportional to the charge Z and extend up to ~ 10^{17} and 10^{20} eV, respectively

G. Sigl, book to appear

see also K.-H.Kampert and M.Unger, Astropart.Phys. 35 (2012) 660

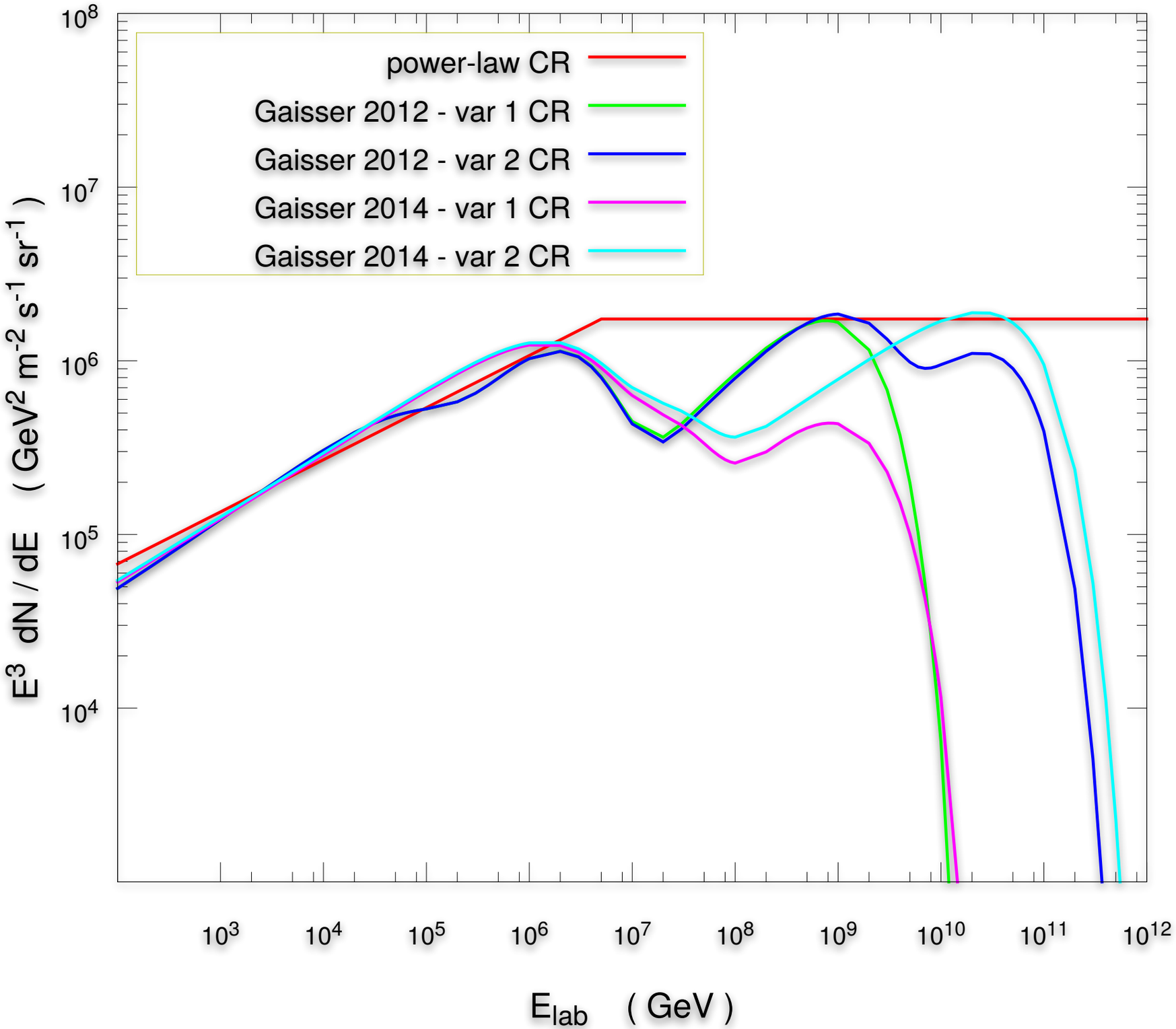
Light Galactic Nuclei produce too much anisotropy above $\simeq 10^{18}$ eV. This implies:

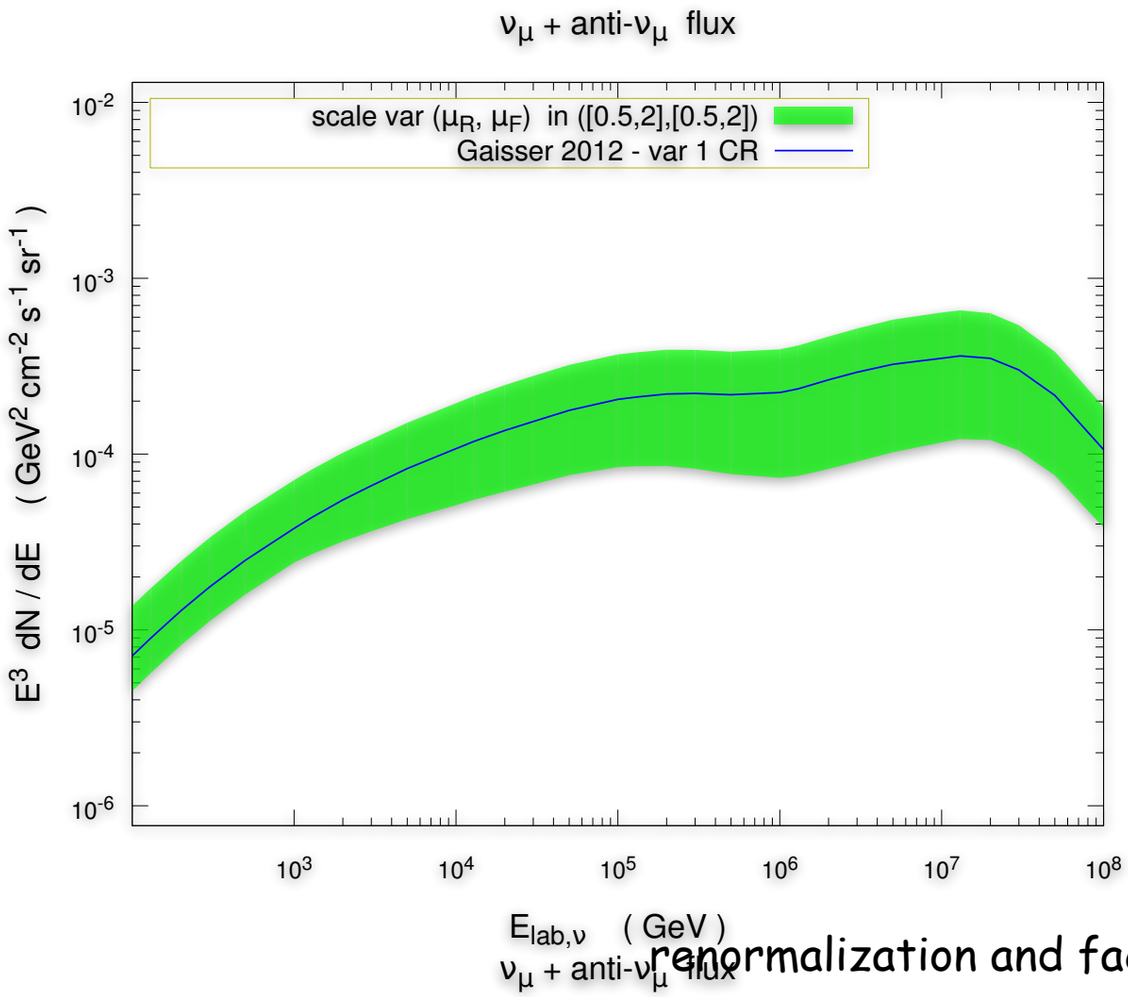
1.) if composition around 10^{18} eV is light => probably extragalactic and ankle may be due to pair production by protons, but this scenario is now strongly disfavoured by Pierre Auger finding mixed composition at the ankle

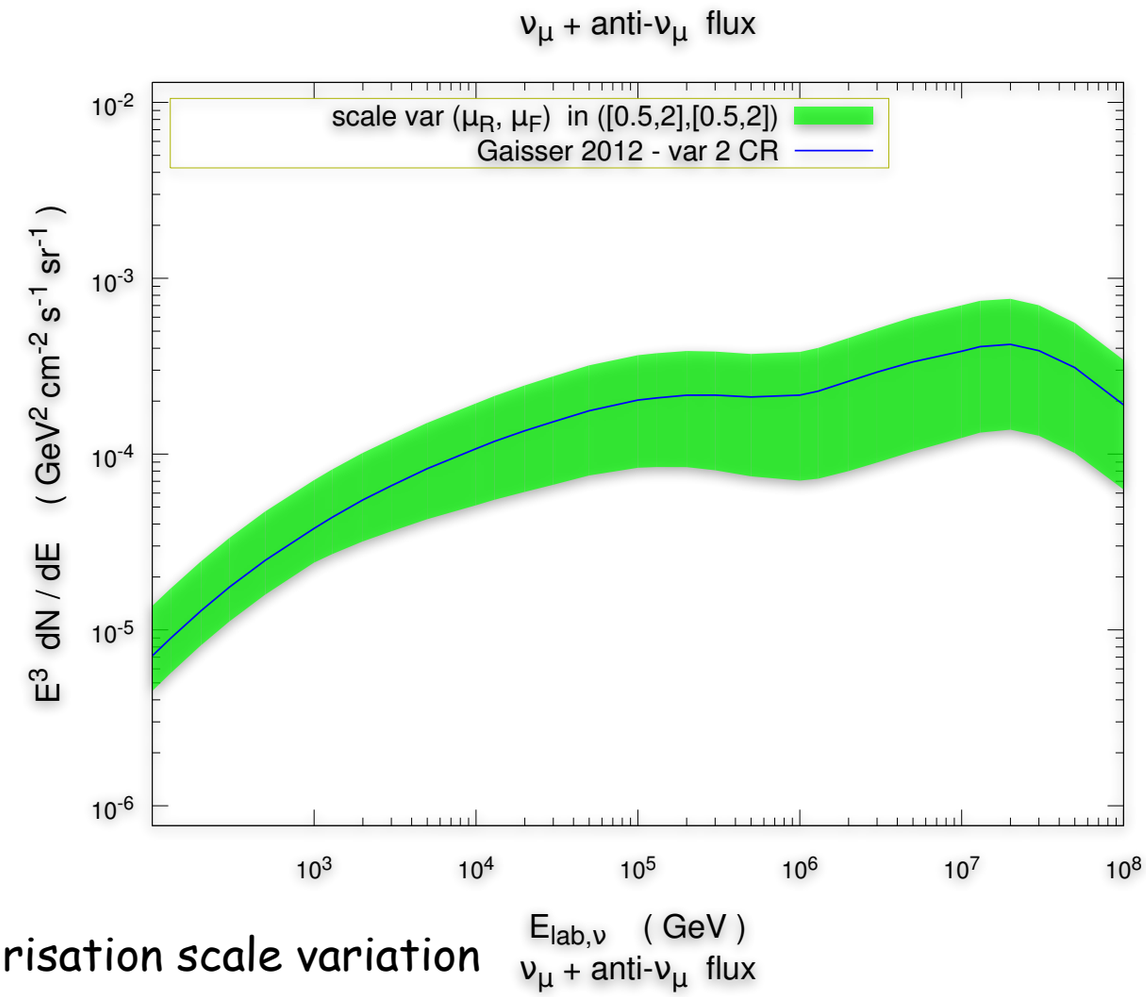
2.) if composition around 10^{18} eV is heavy => transition could be at the ankle if Galactic nuclei are produced by sufficiently frequent transients, e.g. magnetars

Flux models used in this work

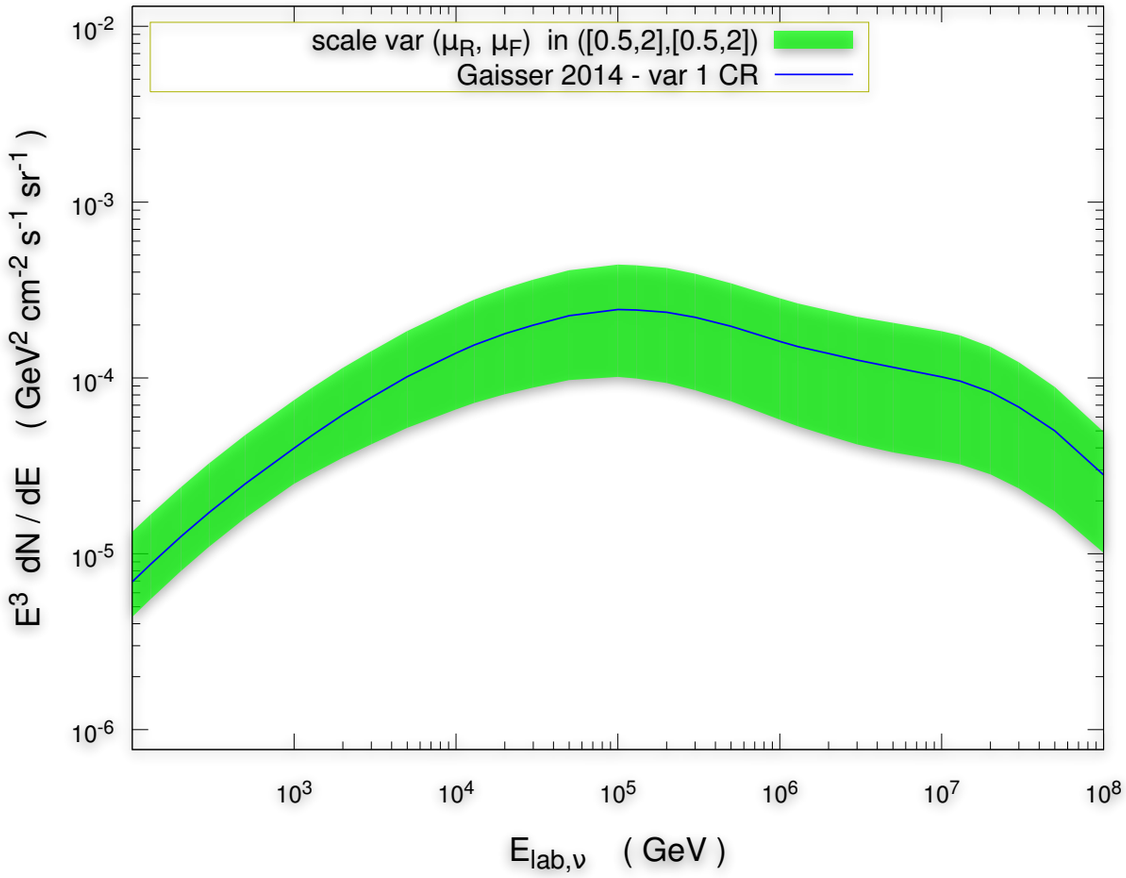
Cosmic Ray primary all-nucleon flux

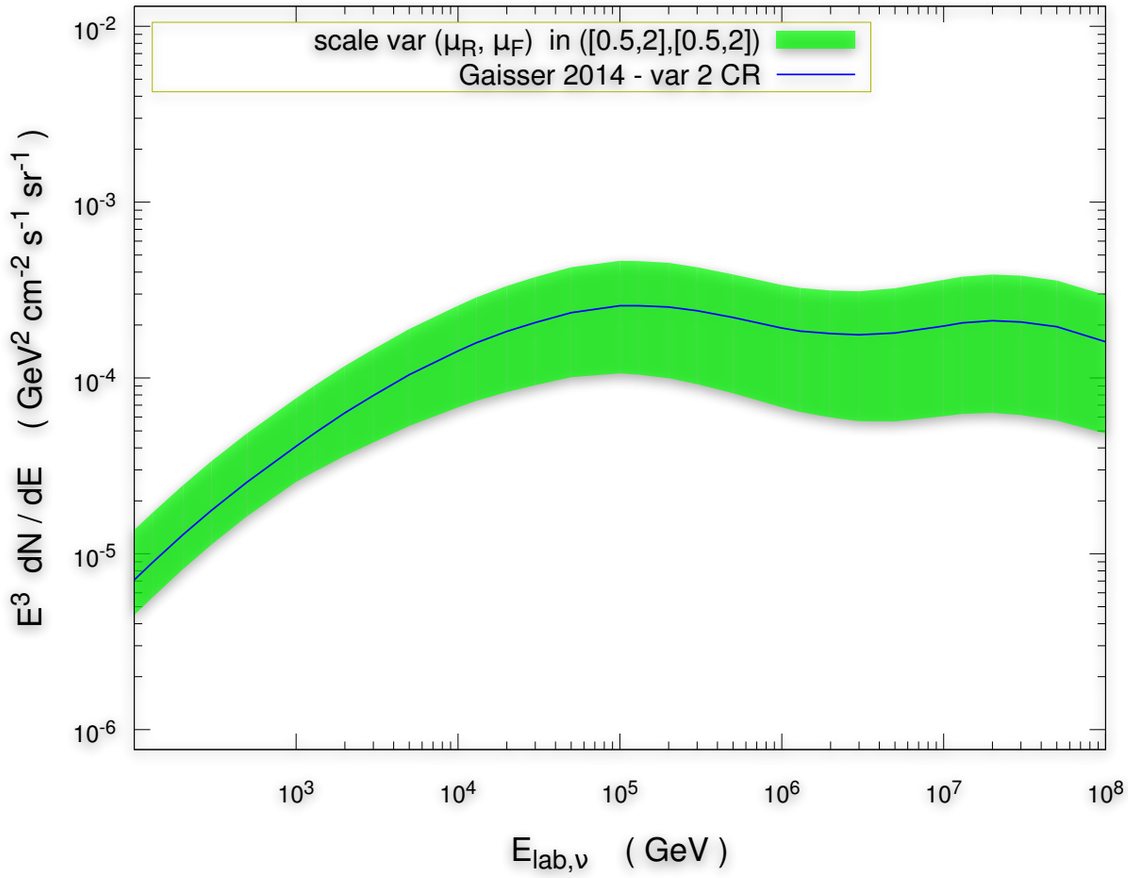


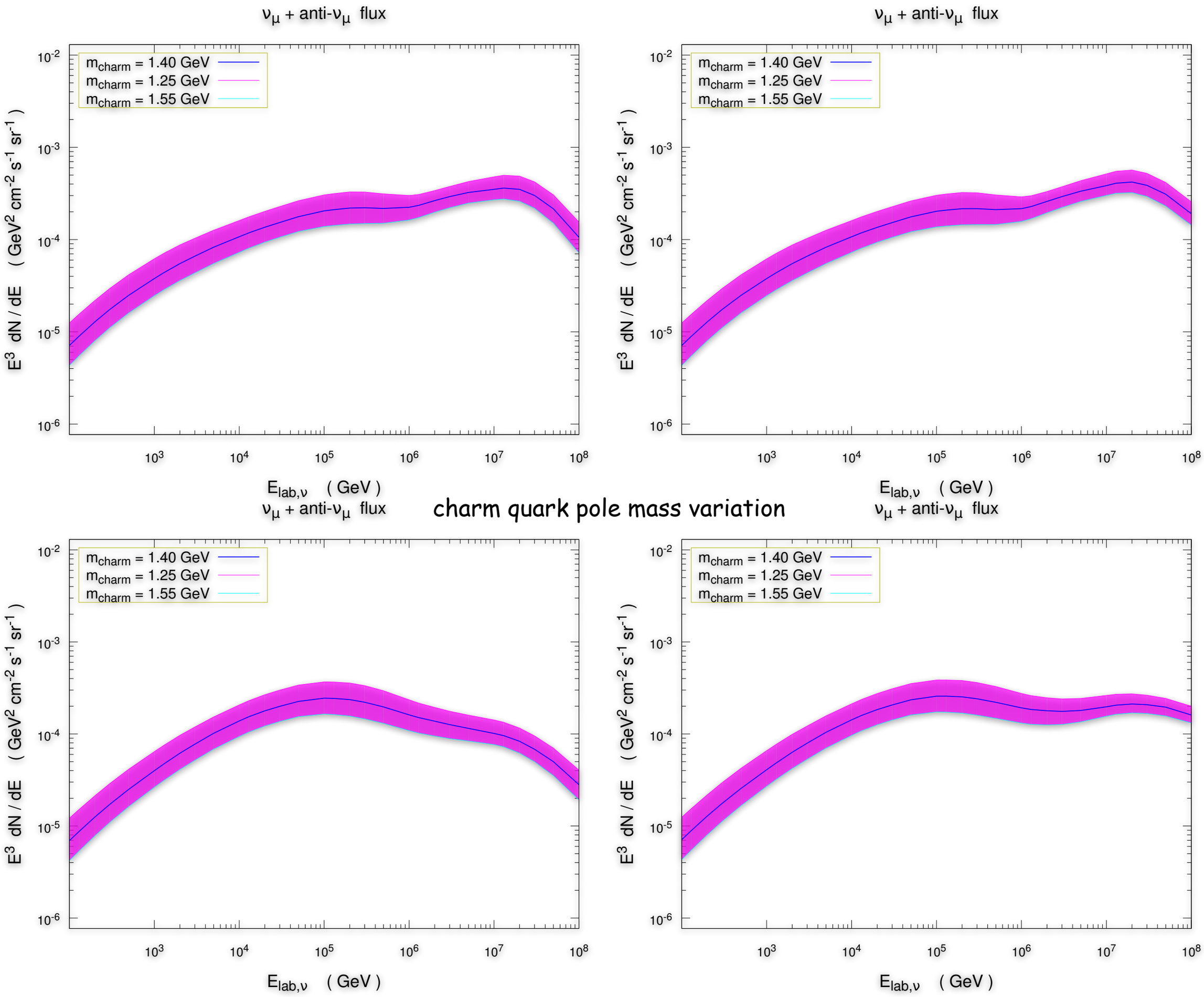


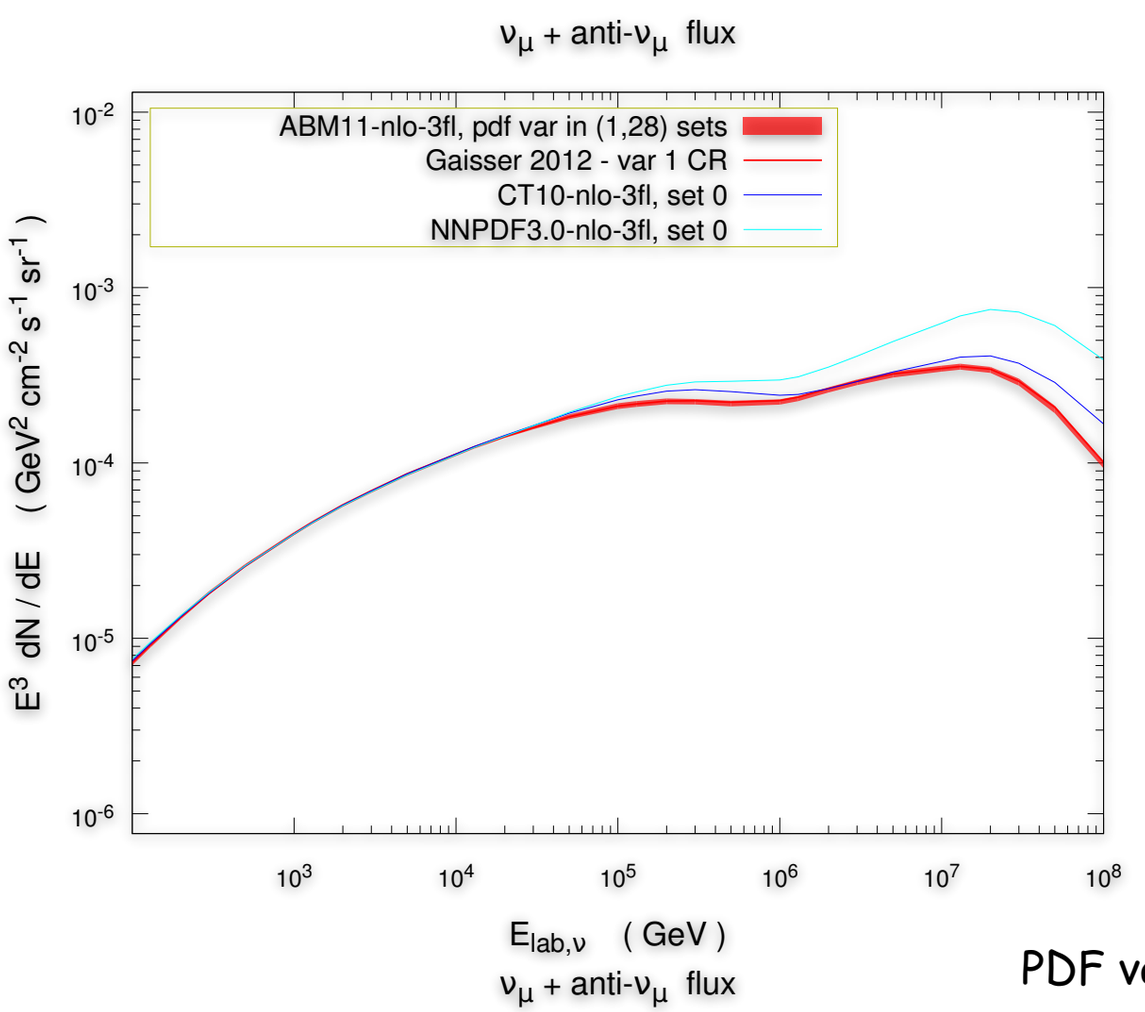


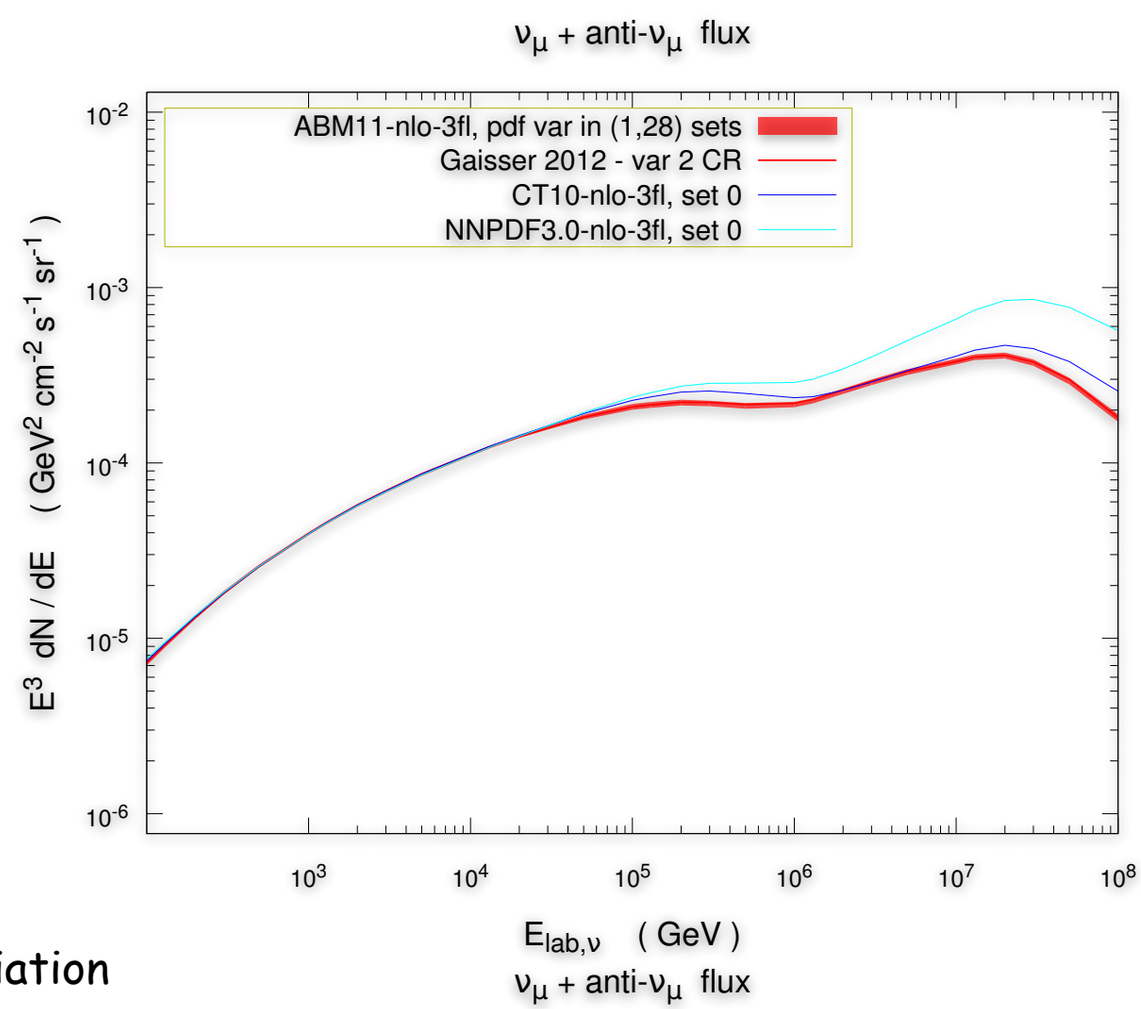
renormalization and factorisation scale variation



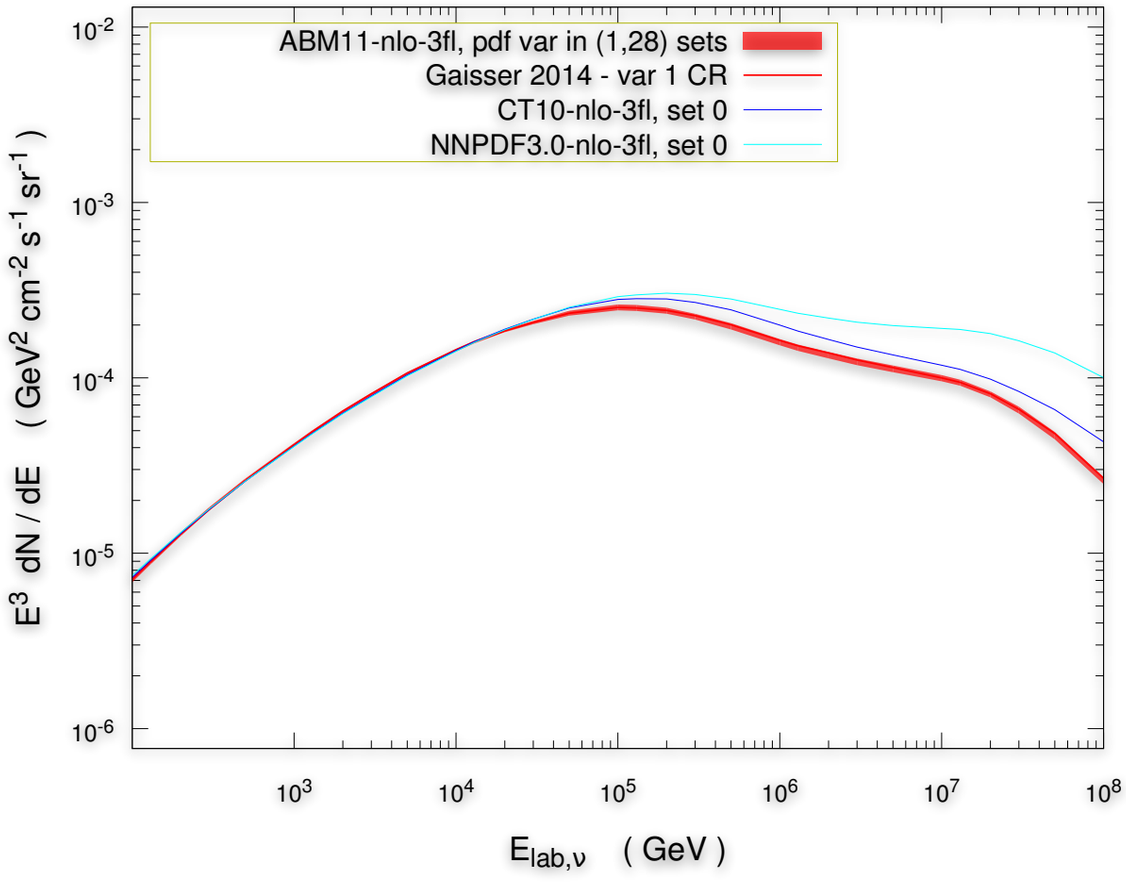


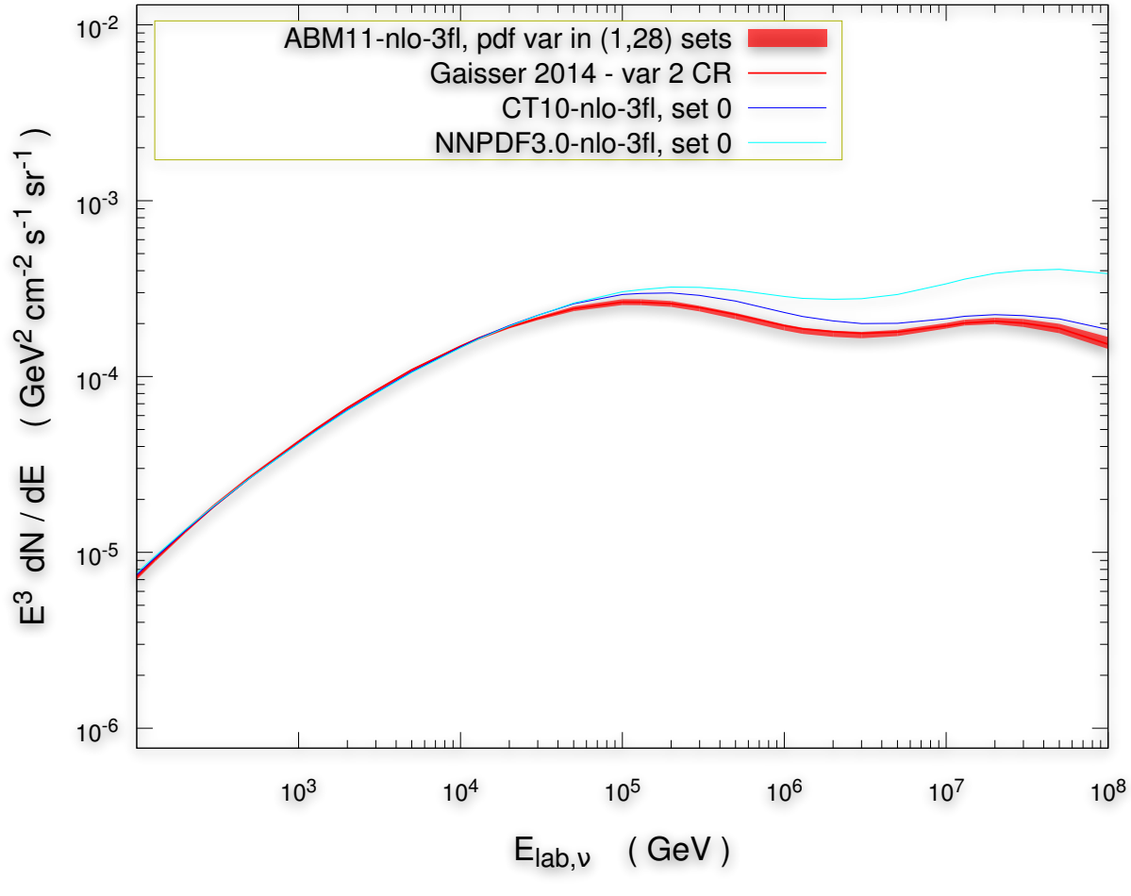

νμ + anti-νμ flux
mcharm = 1.40 GeV
mcharm = 1.25 GeV
mcharm = 1.55 GeV
E3 dN / dE (GeV2 cm-2 s-1 sr-1)
10-2
10-3
10-4
10-5
10-6
10³
10⁴
10⁵
10⁶
10⁷
10⁸
Elab,ν (GeV)
νμ + anti-νμ flux
charm quark pole mass variation
νμ + anti-νμ flux
mcharm = 1.40 GeV
mcharm = 1.25 GeV
mcharm = 1.55 GeV
E3 dN / dE (GeV2 cm-2 s-1 sr-1)
Elab,ν (GeV)
νμ + anti-νμ flux
mcharm = 1.40 GeV
mcharm = 1.25 GeV
mcharm = 1.55 GeV
E3 dN / dE (GeV2 cm-2 s-1 sr-1)
Elab,ν (GeV)
mcharm = 1.40 GeV
mcharm = 1.25 GeV
mcharm = 1.55 GeV
E3 dN / dE (GeV2 cm-2 s-1 sr-1)
Elab,ν (GeV)



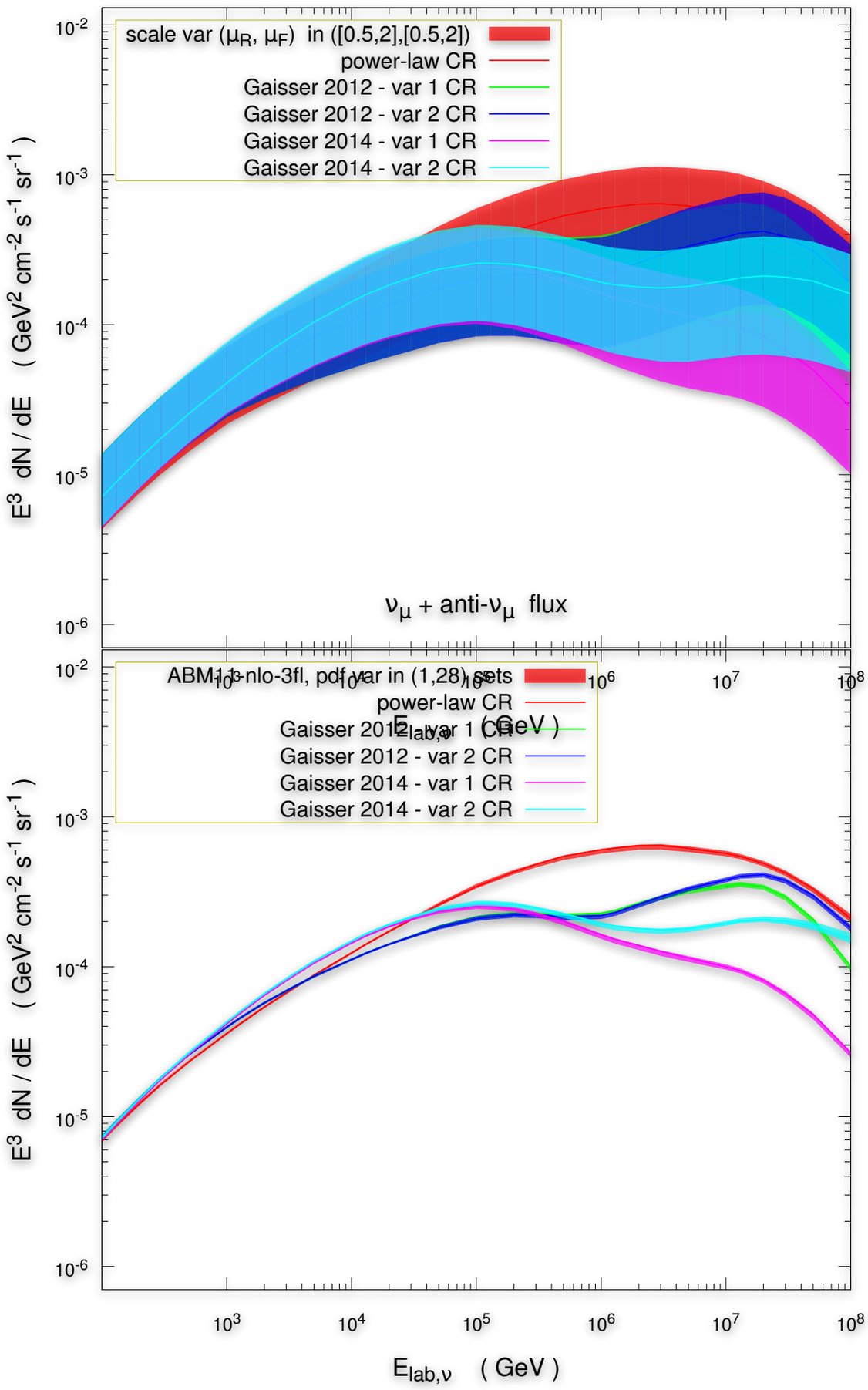


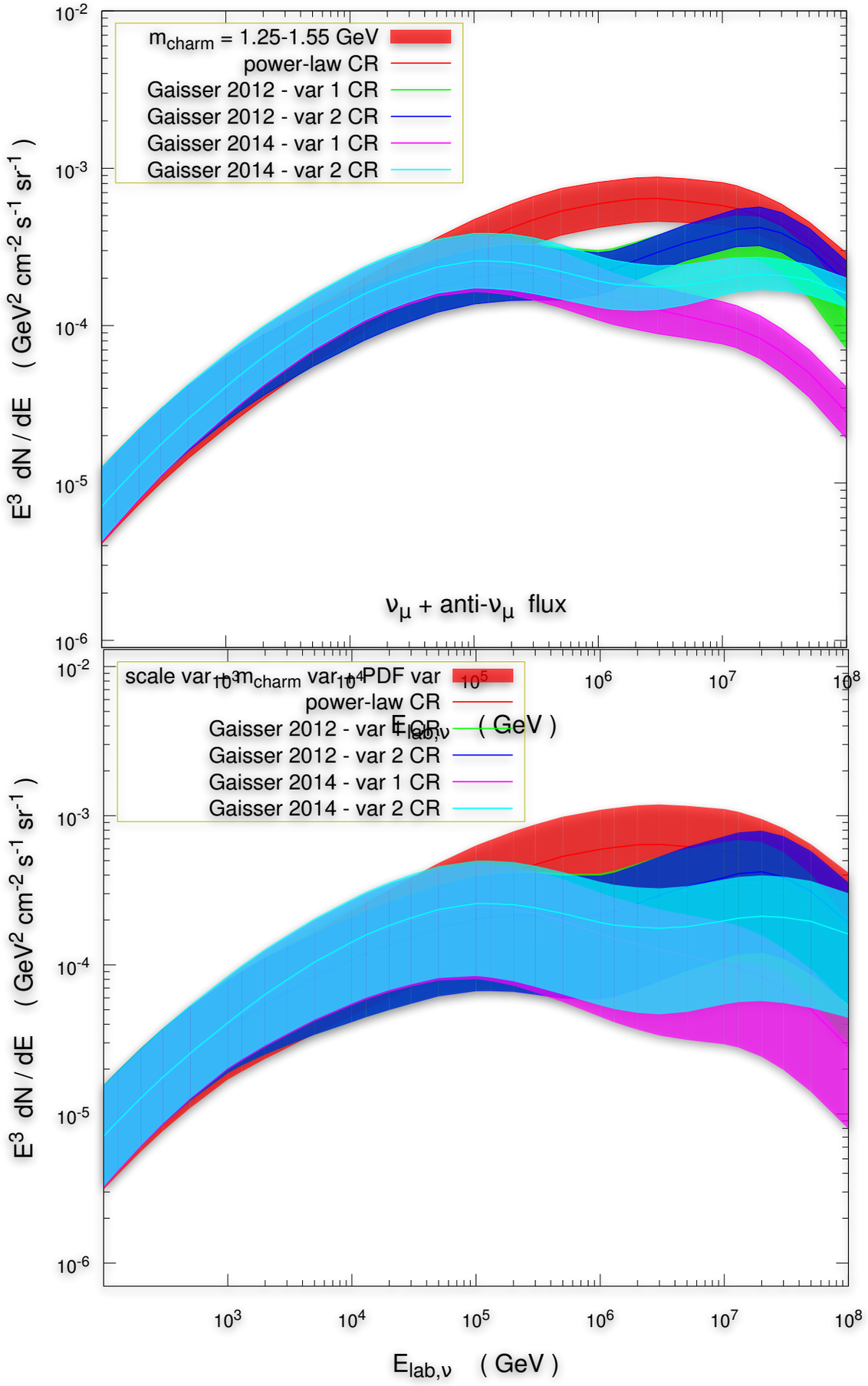
PDF variation

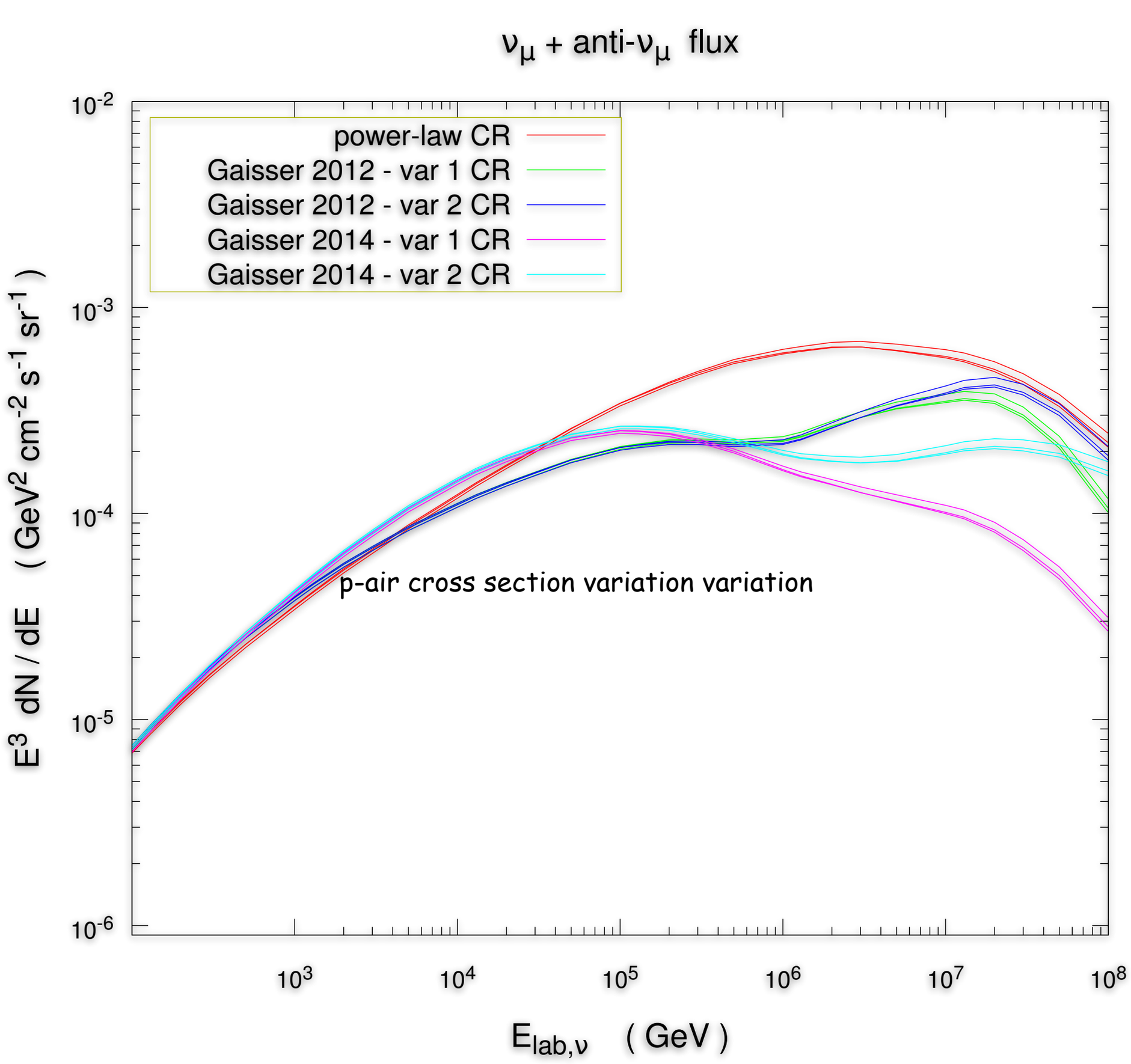


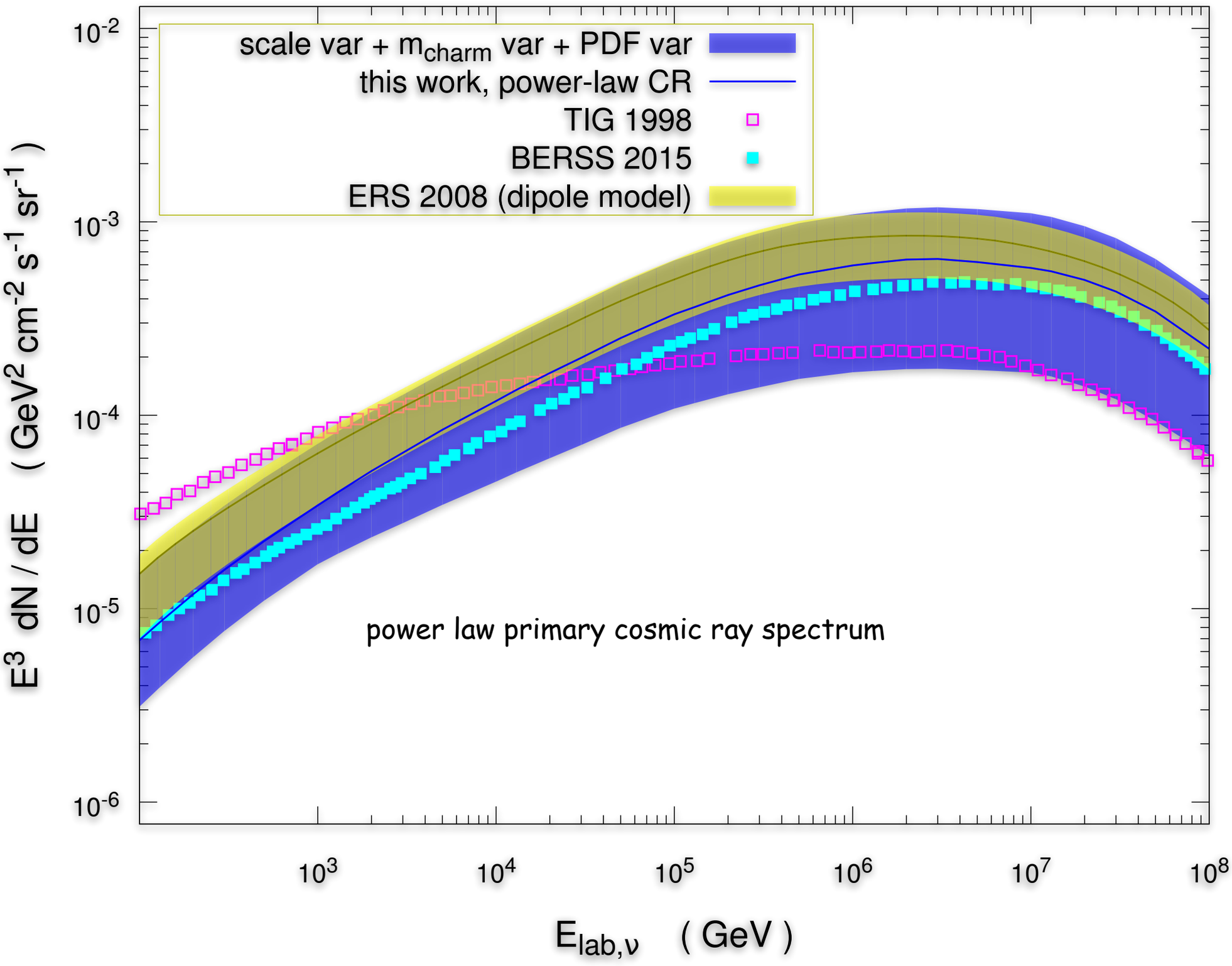


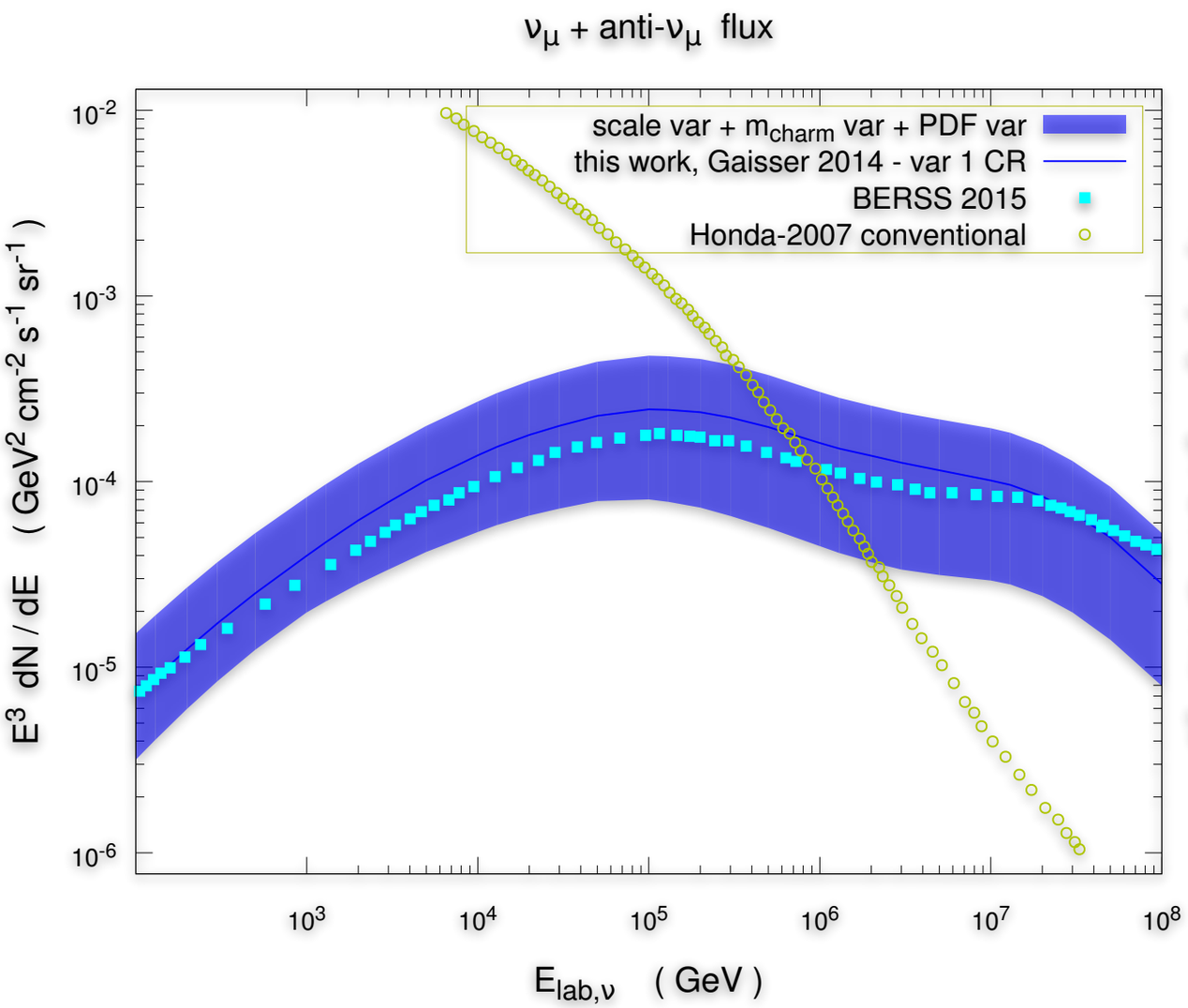
Summary of variations

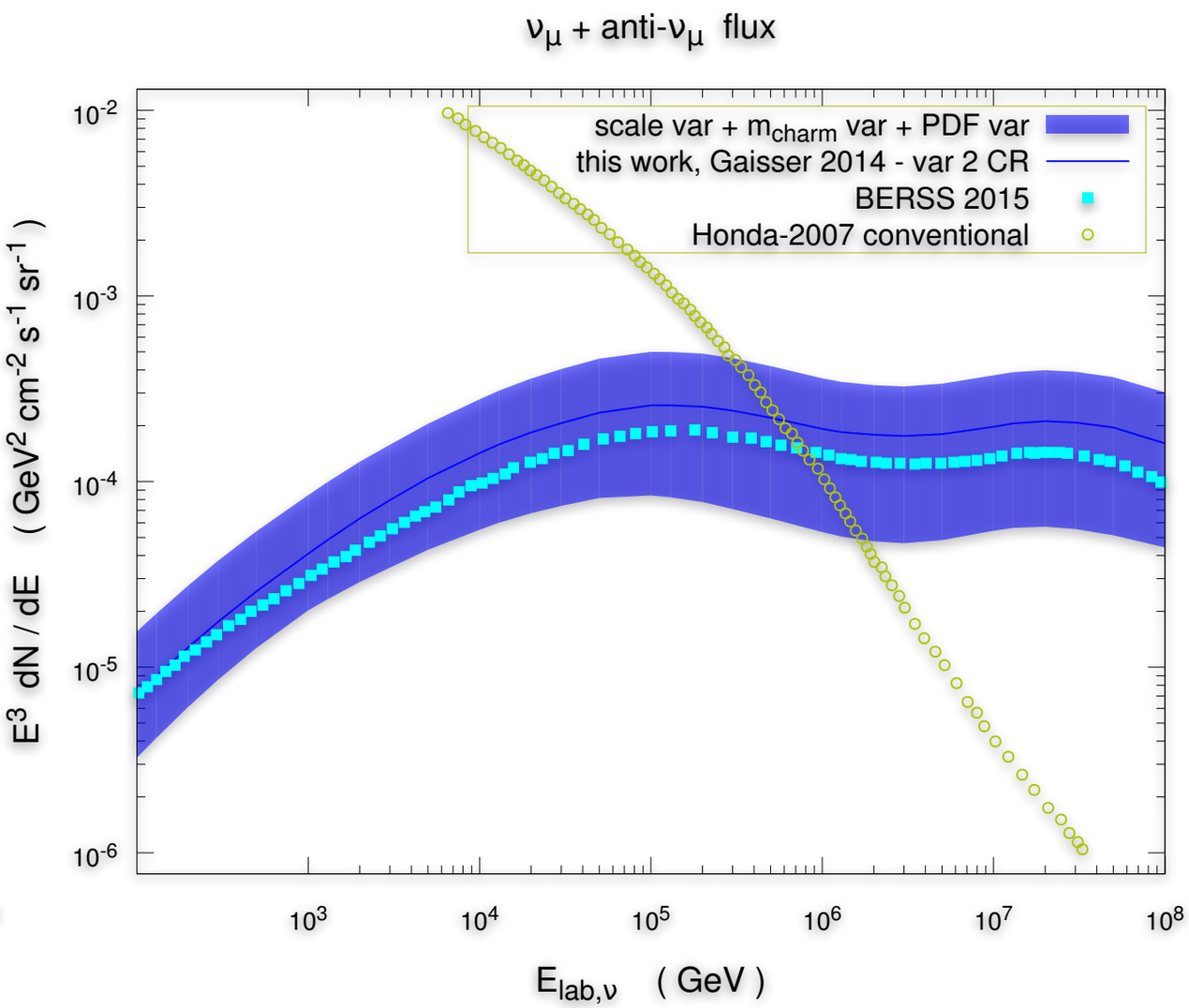





ν_μ + anti-ν_μ flux
power-law CR
Gaisser 2012 - var 1 CR
Gaisser 2012 - var 2 CR
Gaisser 2014 - var 1 CR
Gaisser 2014 - var 2 CR
p-air cross section variation variation
E^3 dN / dE (GeV^2 cm^{-2} s^{-1} sr^{-1})
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^3
10^4
10^5
10^6
10^7
10^8
$E_{lab,\nu}$ (GeV)


ν_μ + anti-ν_μ flux
scale var + m_{charm} var + PDF var
this work, power-law CR
TIG 1998
BERSS 2015
ERS 2008 (dipole model)
power law primary cosmic ray spectrum
E^3 dN / dE
(GeV^2 cm^{-2} s^{-1} sr^{-1})
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^3
10^4
10^5
10^6
10^7
10^8
$E_{lab,\nu}$ (GeV)

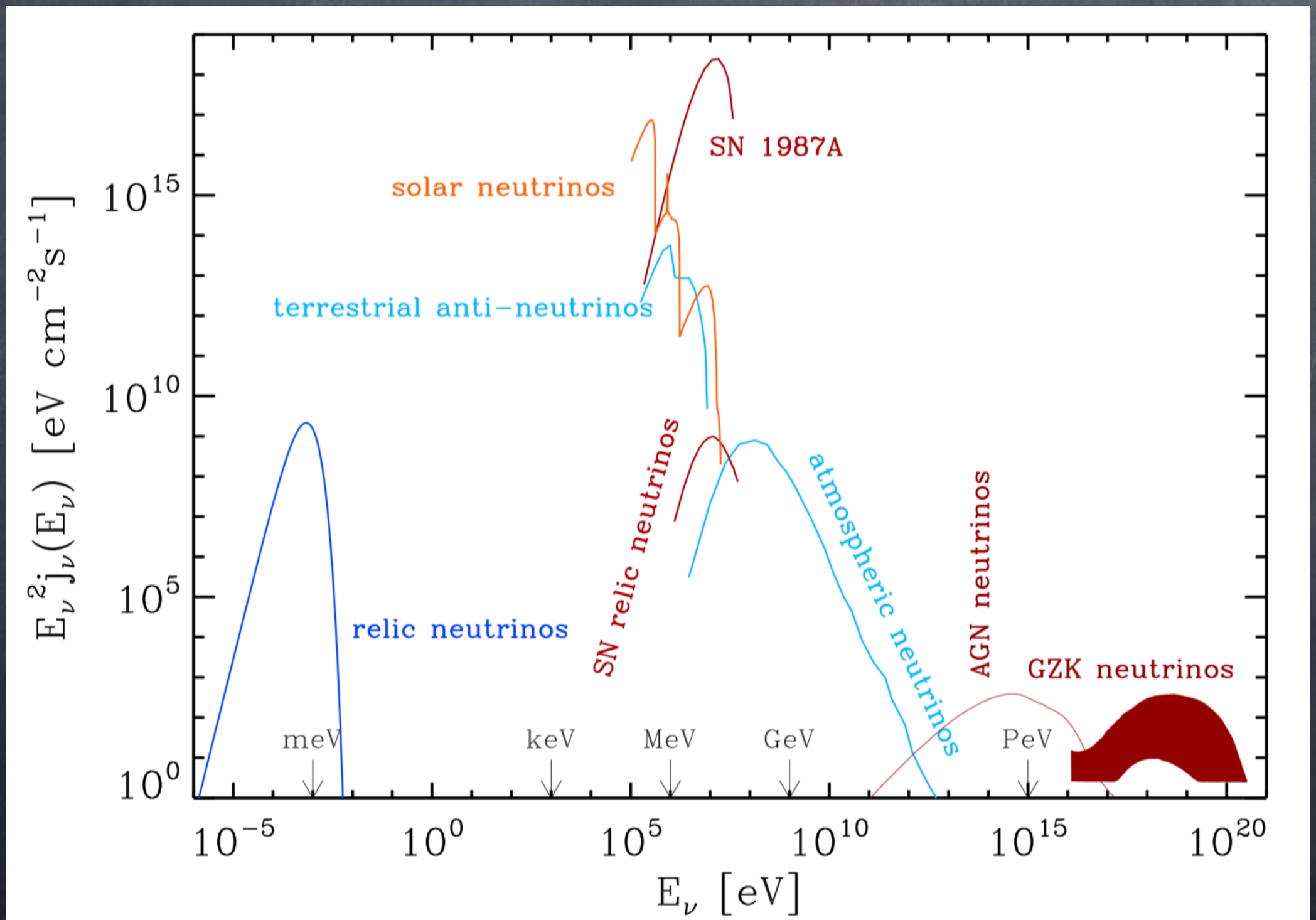




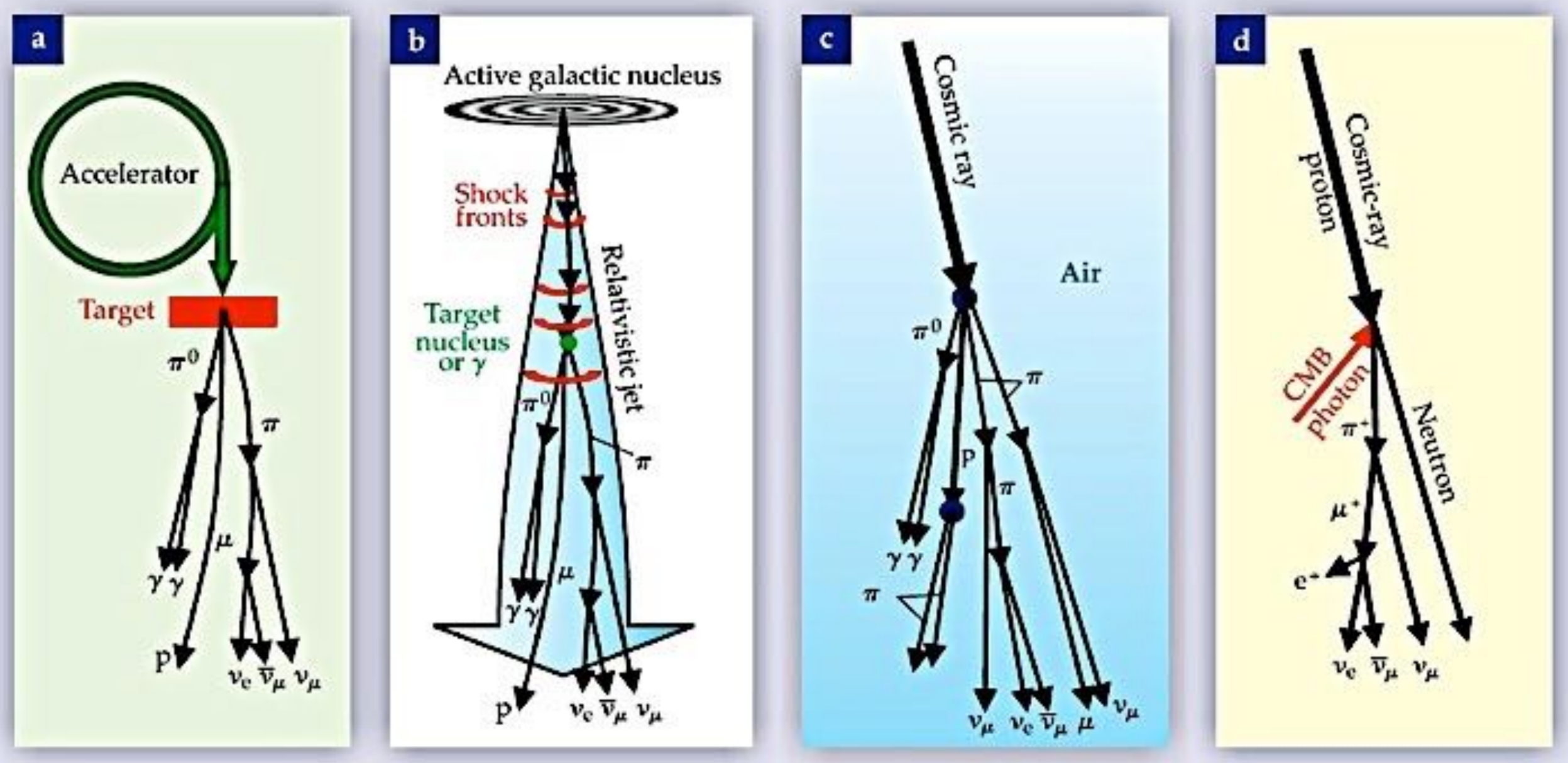
extragalactic mixed (left panel) versus pure proton (right panel) composition, Gaisser 2014

Very High High Energy Neutrinos

The „grand unified" differential neutrino energy spectrum

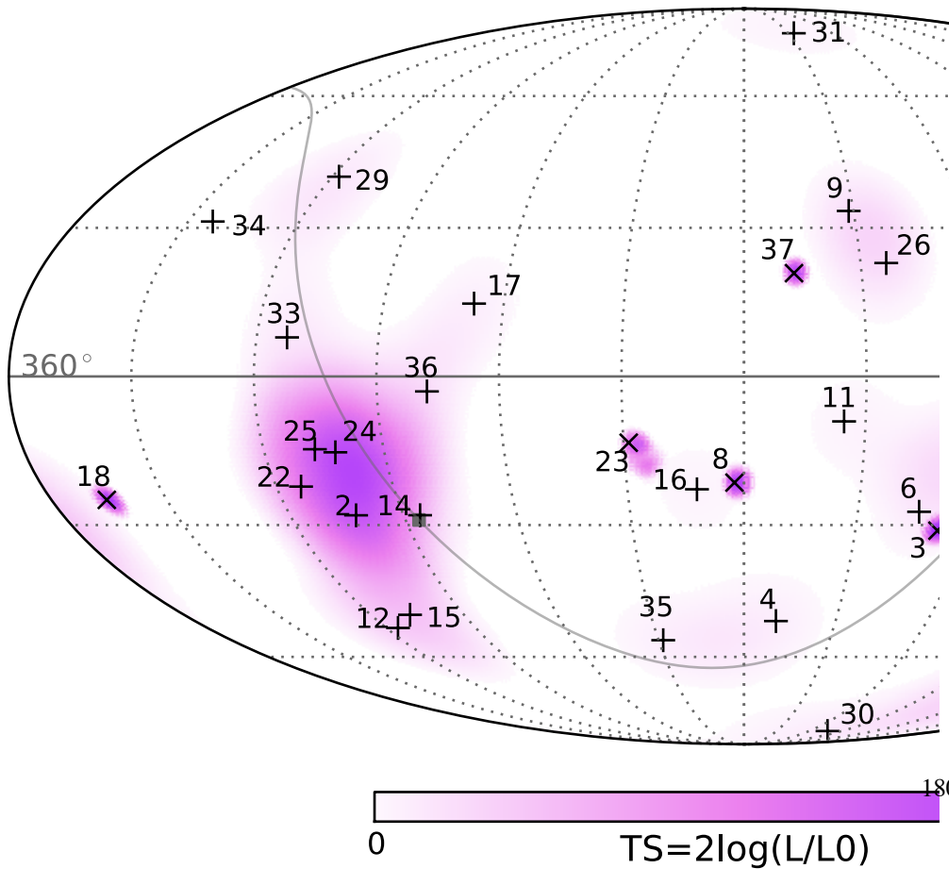


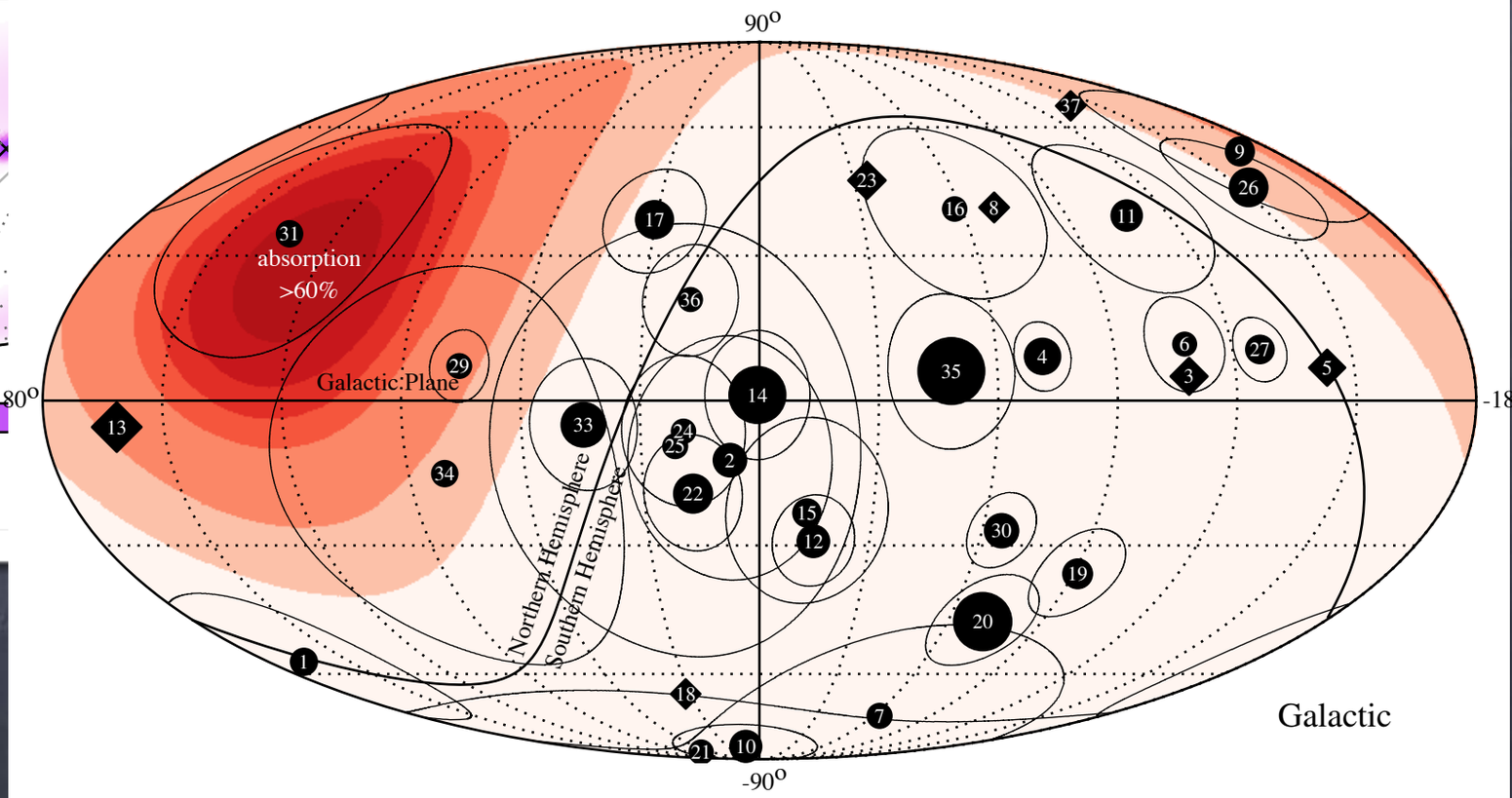
Summary of neutrino production modes



From Physics Today

Neutrino sky distribution

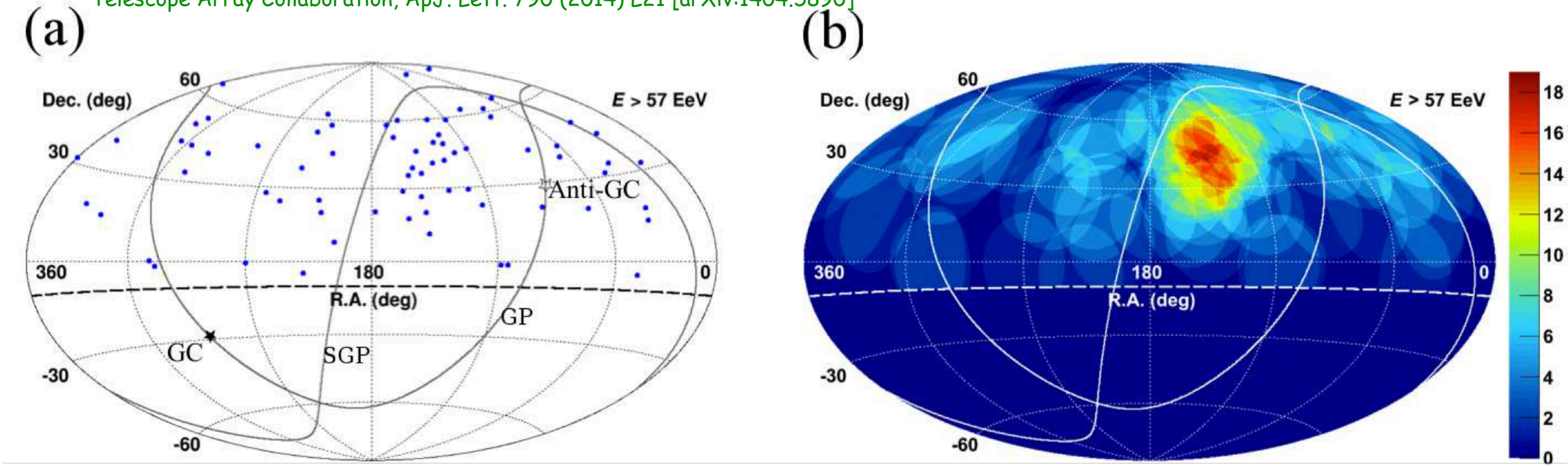




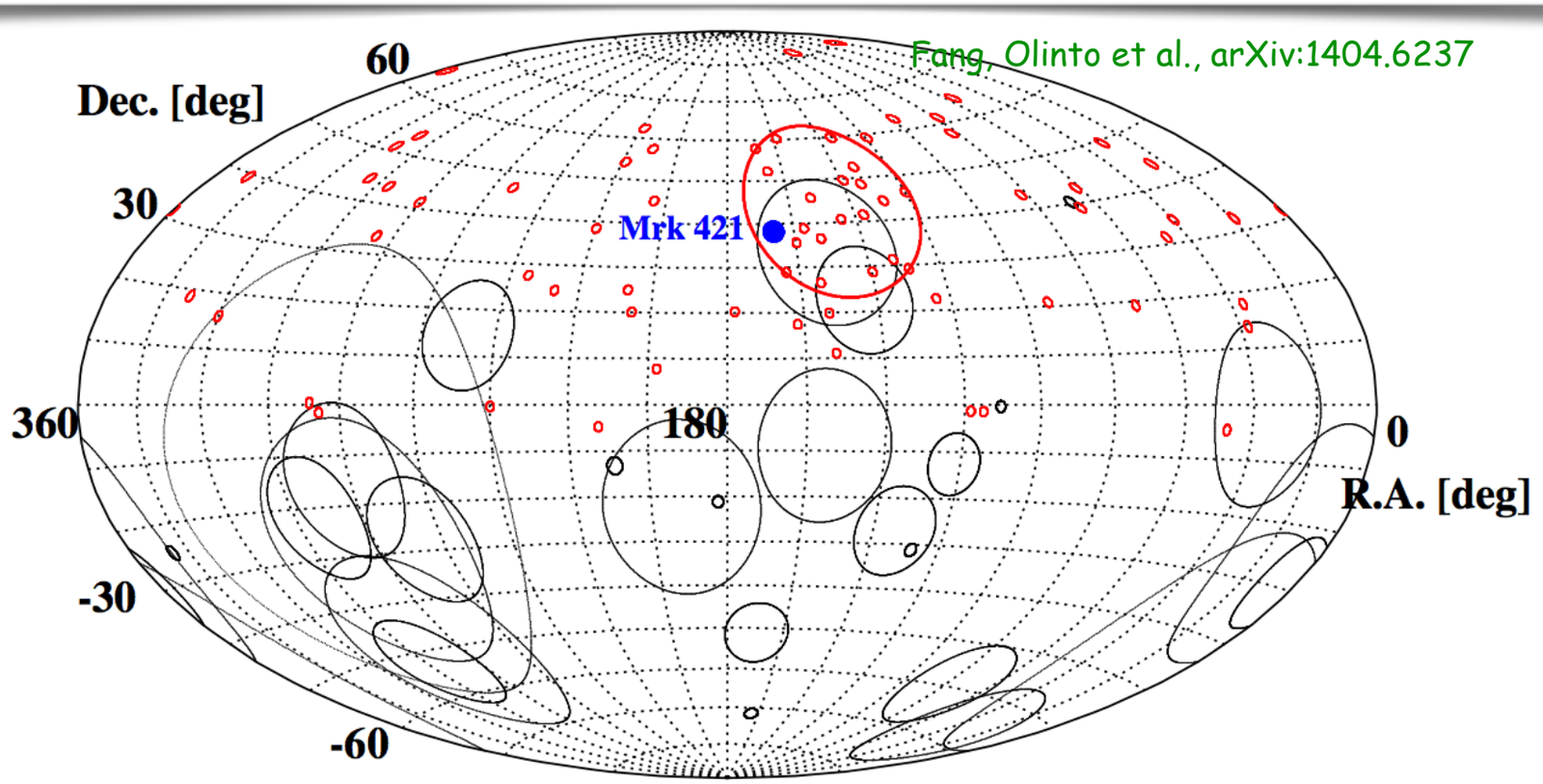
IceCube collaboration, Phys.Rev. Lett. 113 (2014) 101101 [arXiv:1405.5303]

A possible Correlation of IceCube Neutrinos with the Cosmic Ray Excess seen by Telescope Array ?

Telescope Array Collaboration, ApJ. Lett. 790 (2014) L21 [arXiv:1404.5890]

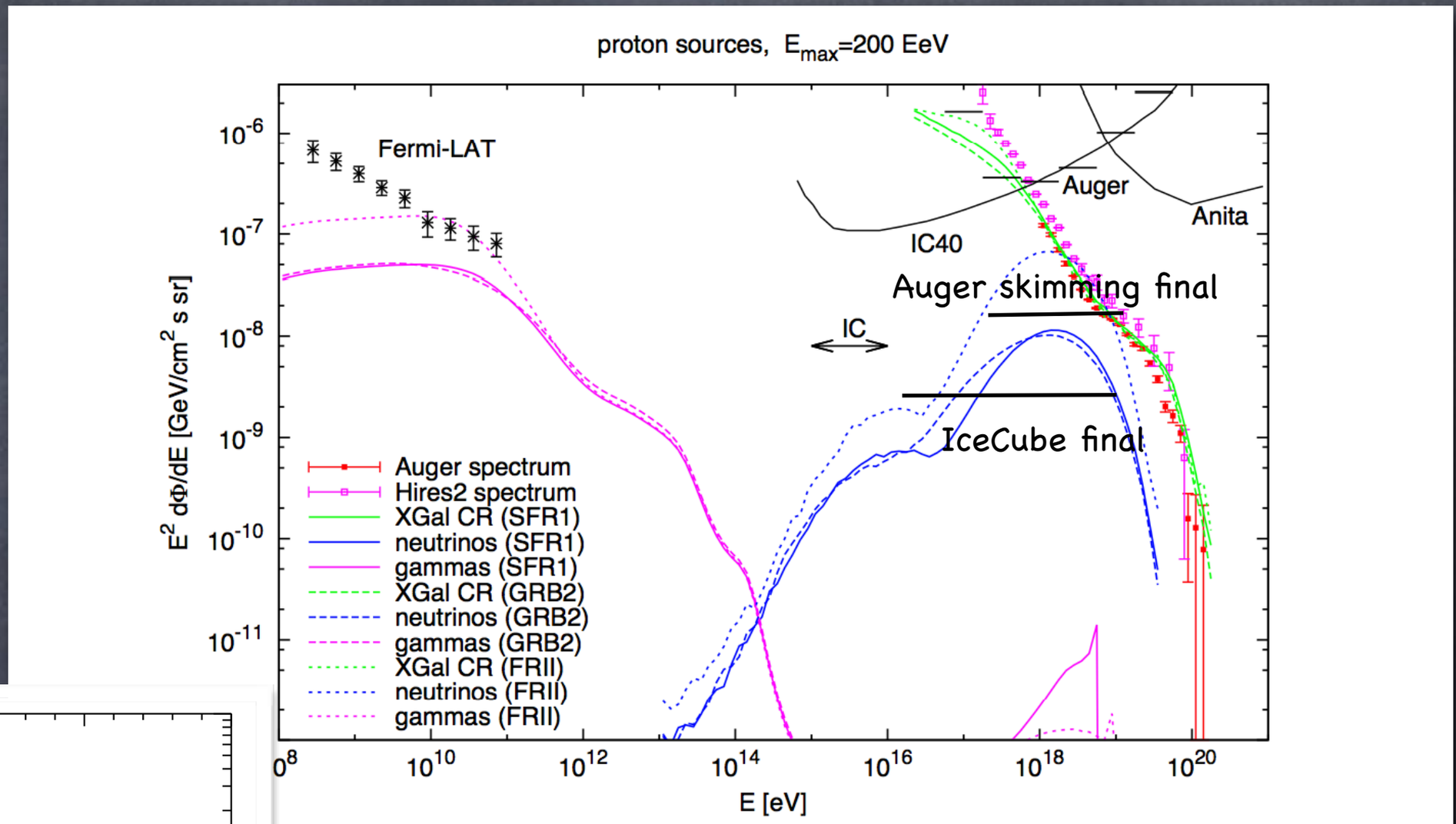


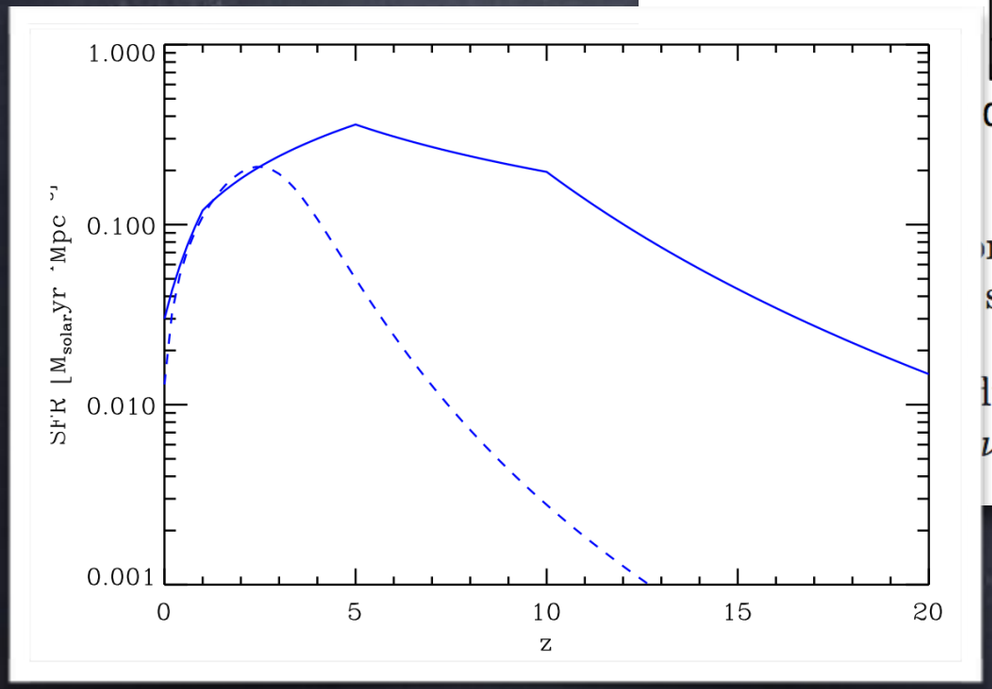
Fang, Olinto et al., arXiv:1404.6237



Cosmogenic Neutrinos: Maximal Fluxes for Pure Proton Injection insufficient to explain IceCube neutrinos

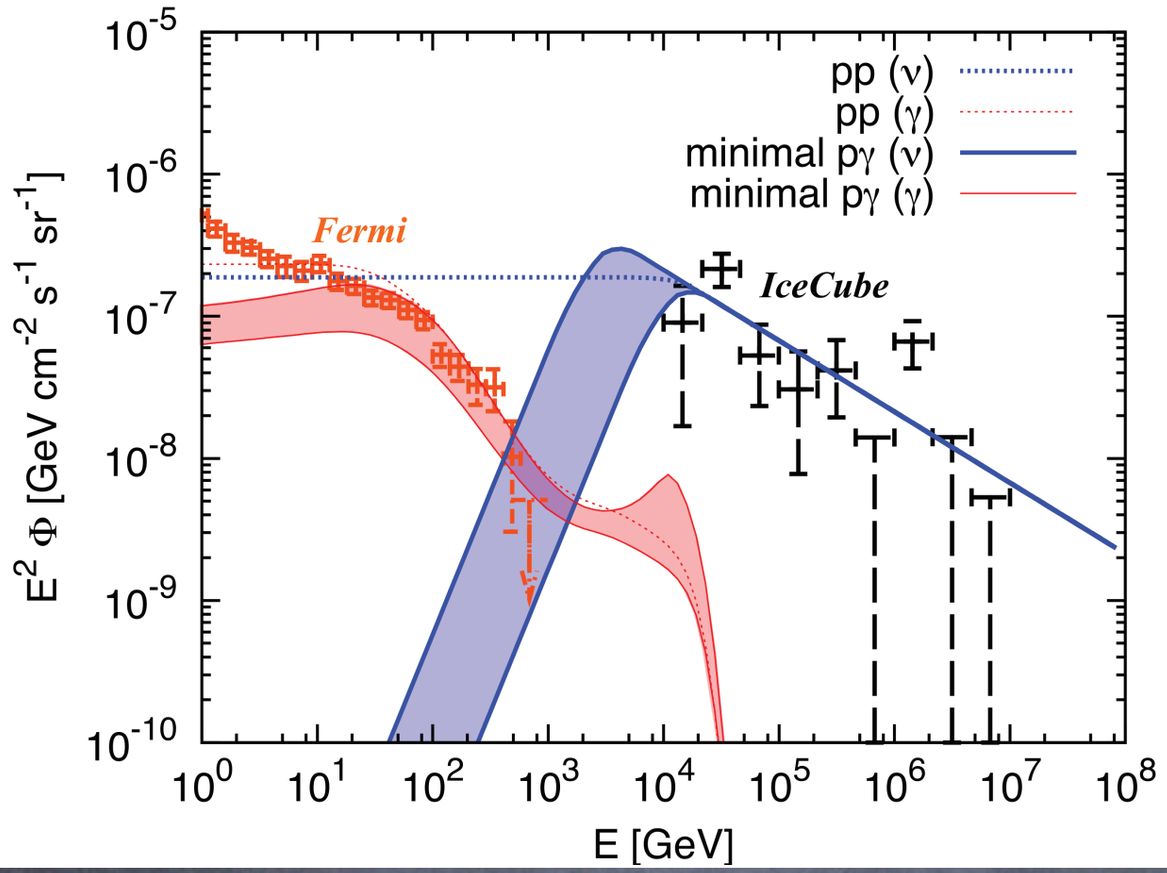
- Including secondary photons
- strong source evolution is here constrained by Fermi-LAT results

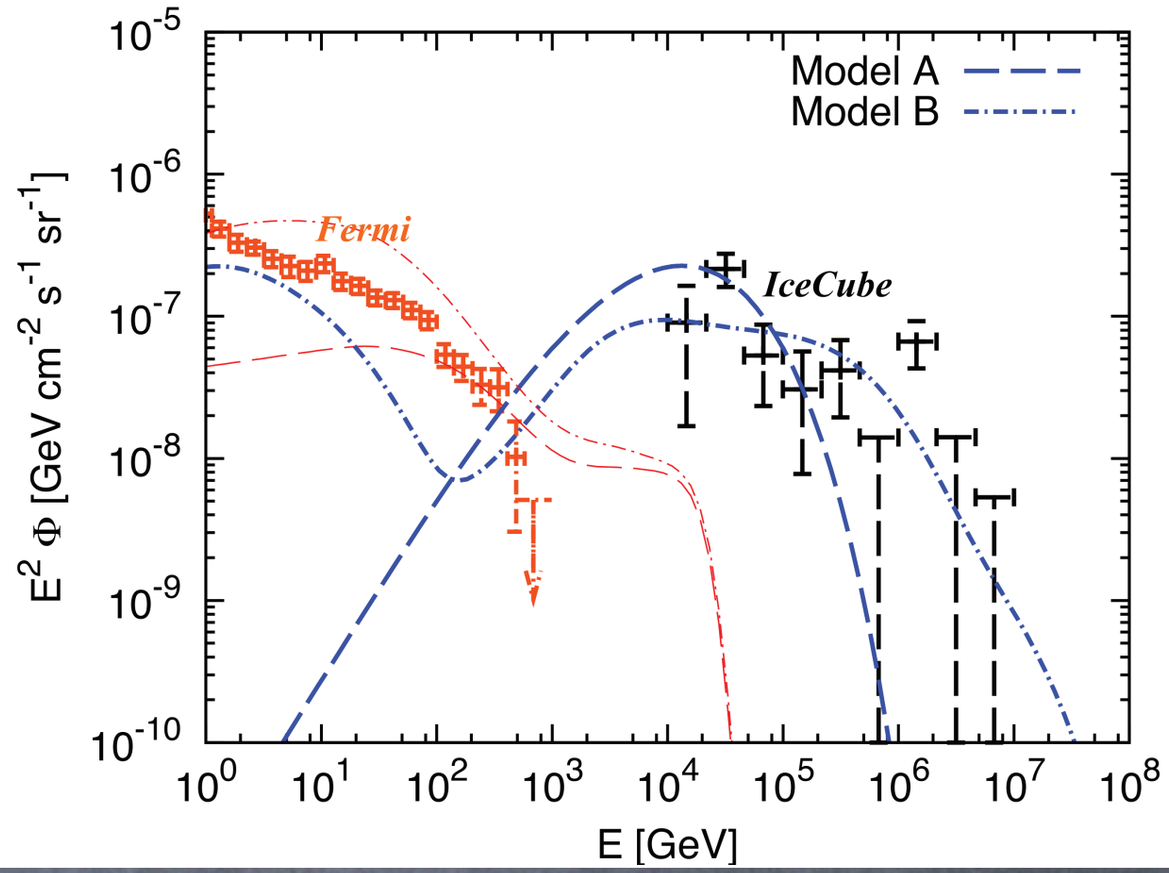




n scenario with $E_{\max} = 200\,\mathrm{EeV}$ for different source evolution models (SFR1, GRB2 source spectral index is $\alpha = 2.4$ for the SFR1 and GRB2 models, while $\alpha = 2.2$ for Indicated are the propagated proton spectrum, the resulting (all flavor) neutrino luxes. The photon background measured by Fermi-LAT [10] is indicated, besides the ν bounds included in figure 1.

Roulet, Sigl, van Vliet, Mollerach, JCAP 1301, 028

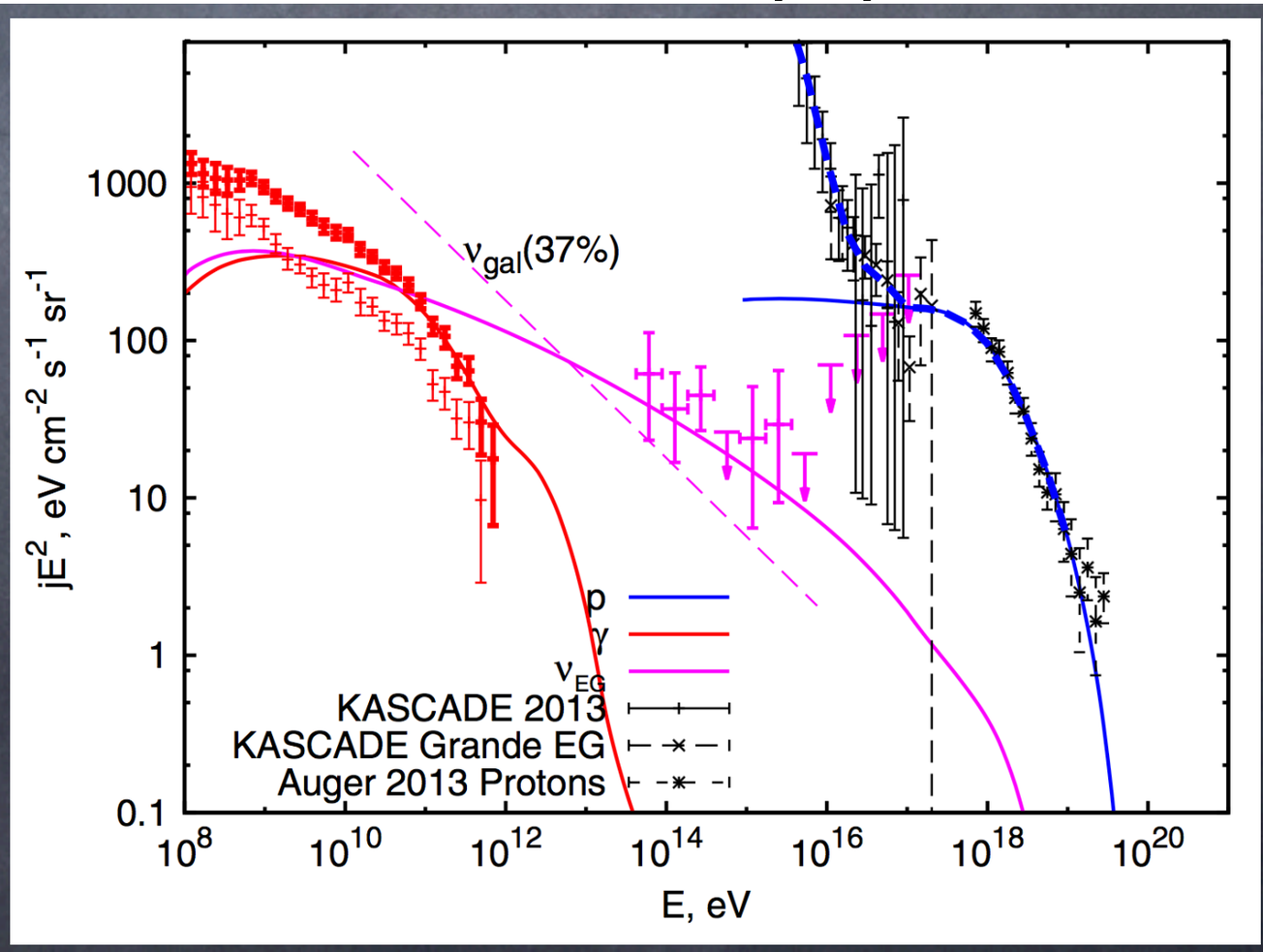




Murase, Guetta, Ahlers, PRL 116}, 071101 (2016)

Sources may have to be "hidden" in gamma-rays and primary cosmic rays to be consistent with other data

Giacinti, Kachelrieß, Kalashev, Neronov, Semikoz, PRD 92}, 083016 (2015)



Effective Penetration Depth of Electromagnetic Cascades

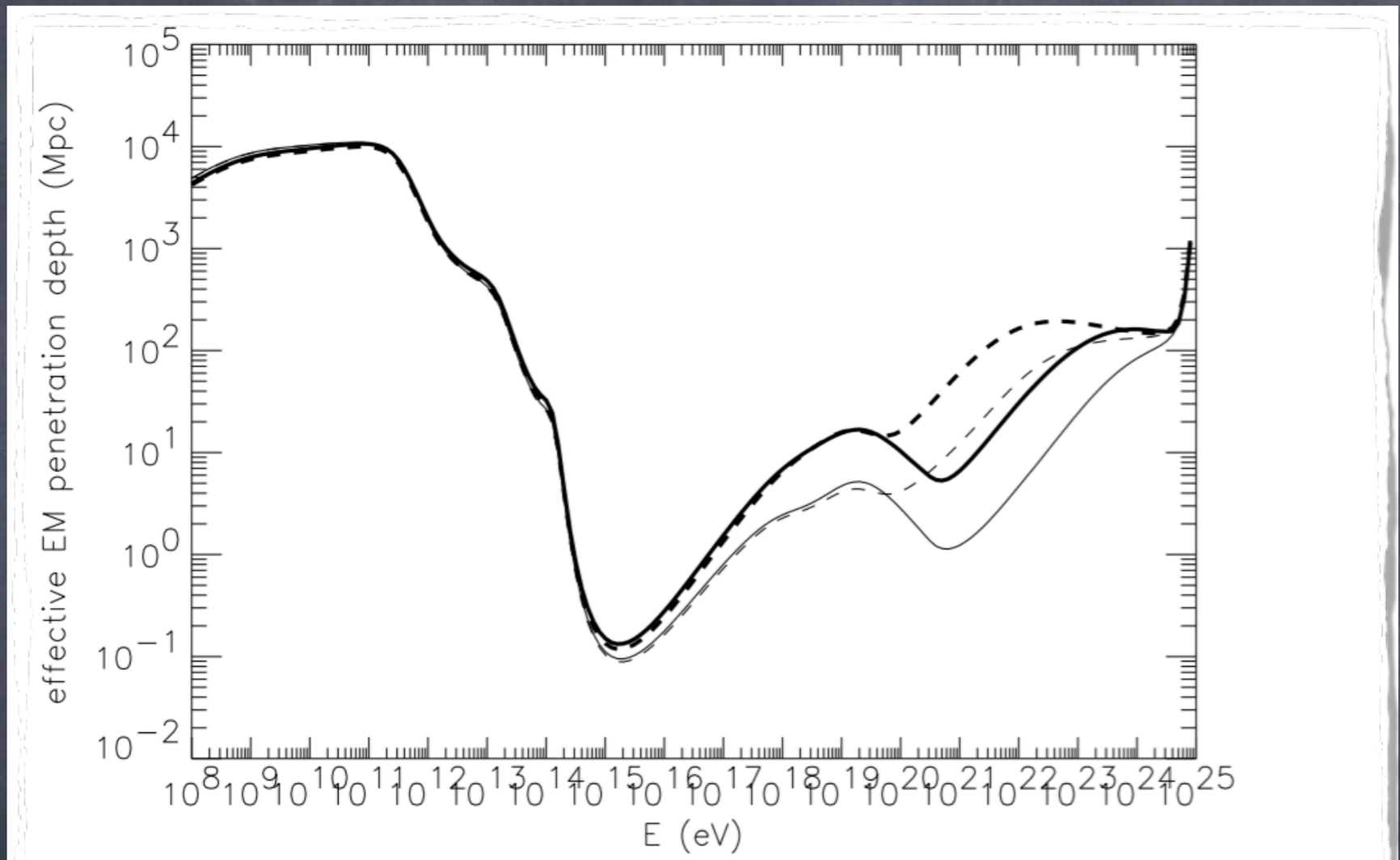
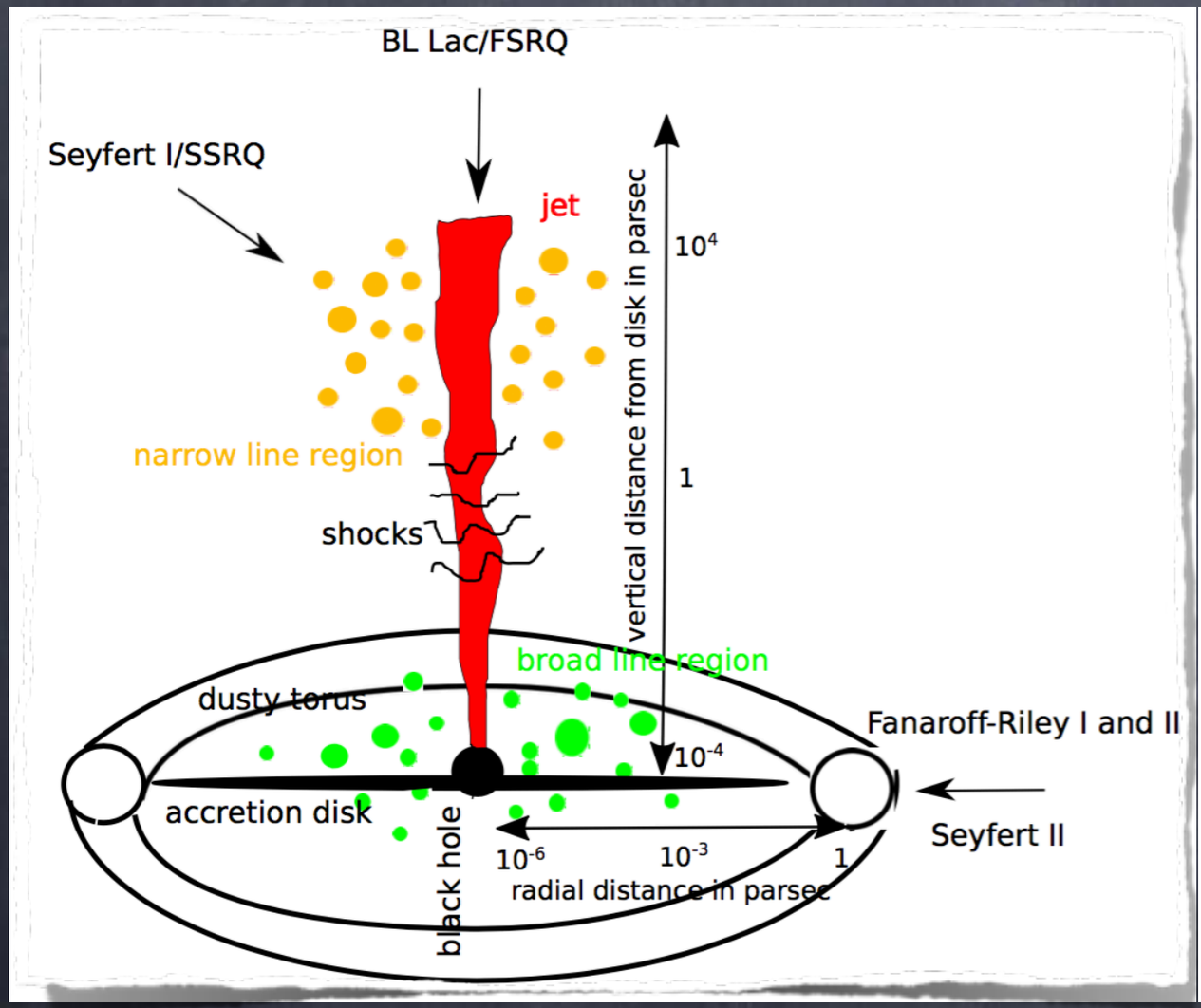


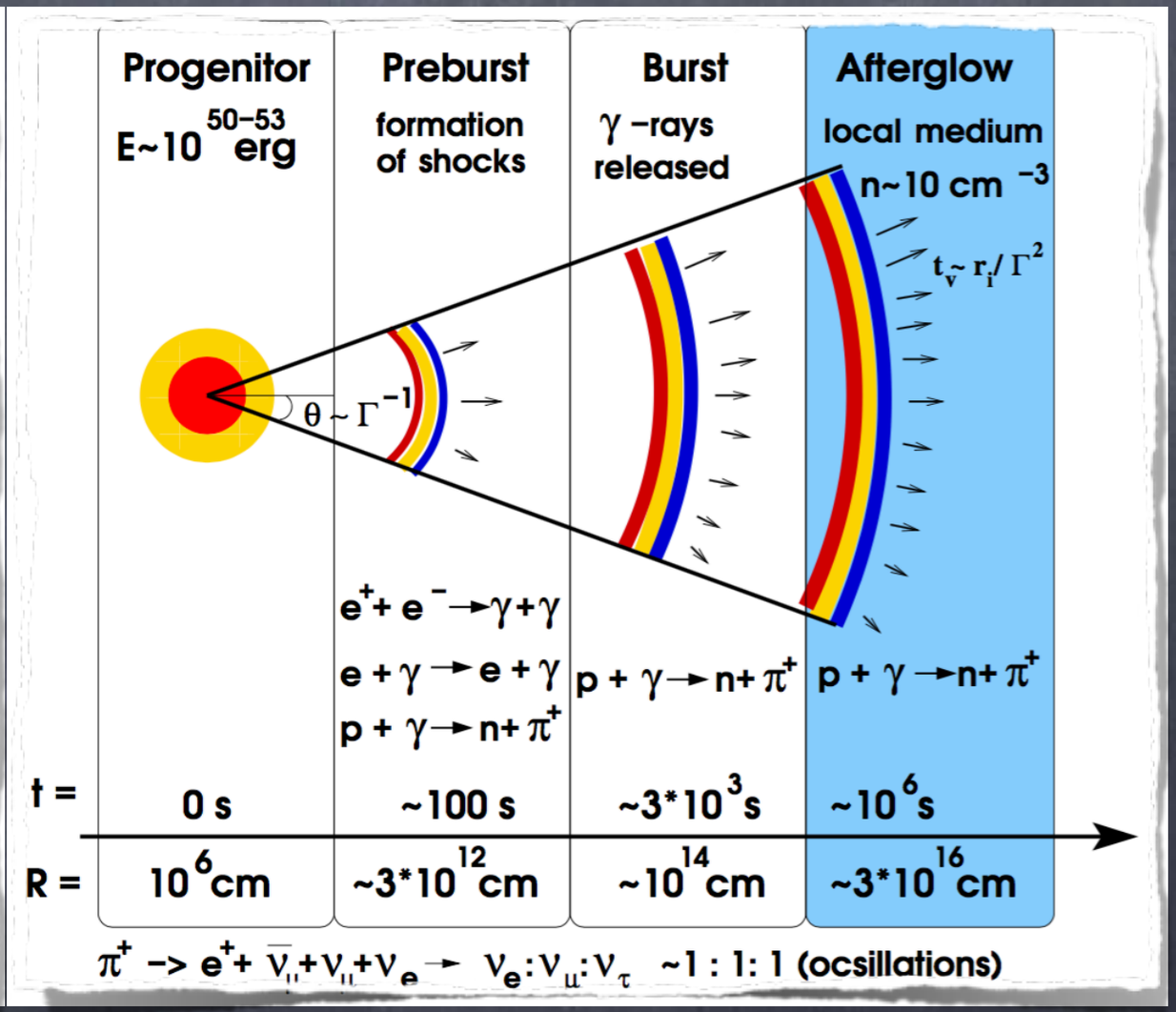
Fig. 8.6 Effective penetration depth of EM cascades, as defined in the text and its dependence on uncertainties of the universal radio background, see the red band at low energies in Fig. 5.16, and the EGMF. Solid lines are for a strong universal radio background estimate, dashed lines for a lower estimate for this background, and thick lines correspond to an EGMF $\ll 10^{-11}$ G whereas thin lines are for 10^{-9} G, respectively. Reprinted figure from Ref. [157], P. Bhattacharjee and G. Sigl, Phys. Rept. **327**, 109 (2000), http://dx.doi.org/doi:10.1016/S0370-1573(99)00101-5, with permission from Elsevier.

Discrete Extragalactic High Energy Neutrino Sources

IceCube neutrinos should be produced mostly within sources, not during propagation



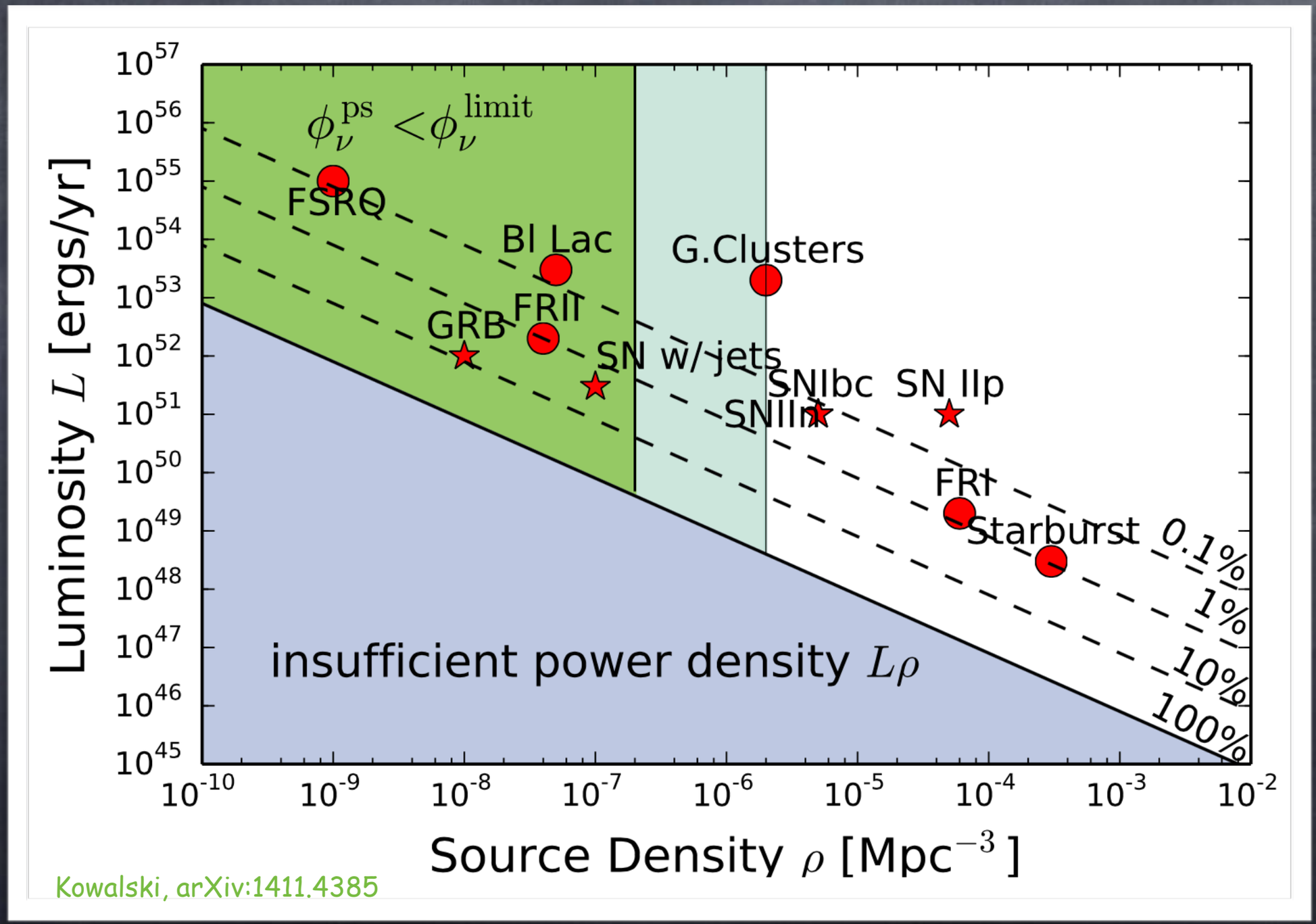
active galaxies



gamma ray bursts

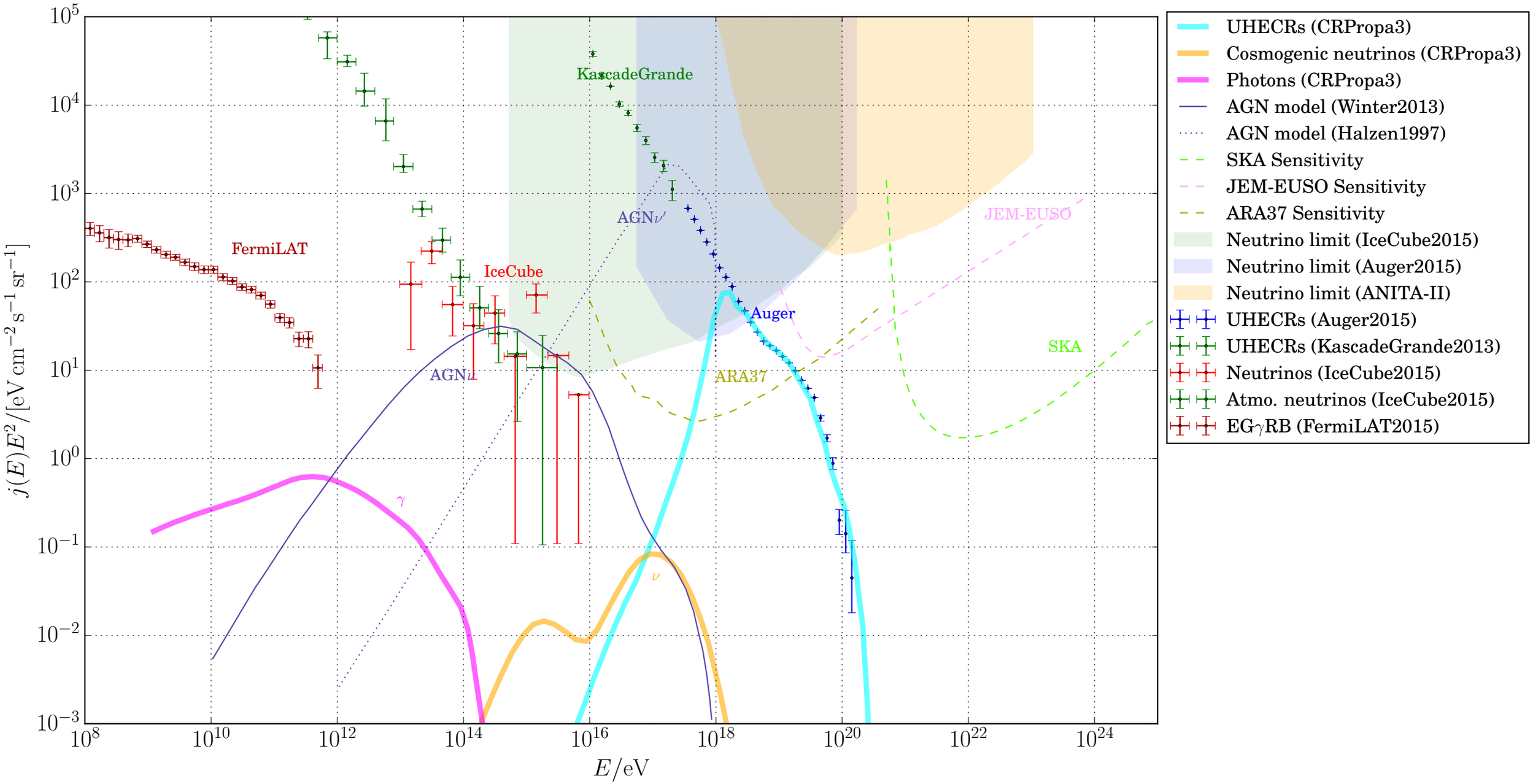
Figures adapted from J. Becker-Tjus, Phys.Rep. 458 (2008) 173

But a combination of the measured diffuse flux with upper limits on individual sources constrains source type



Kowalski, arXiv:1411.4385

Multi-Messengers: The Big Picture

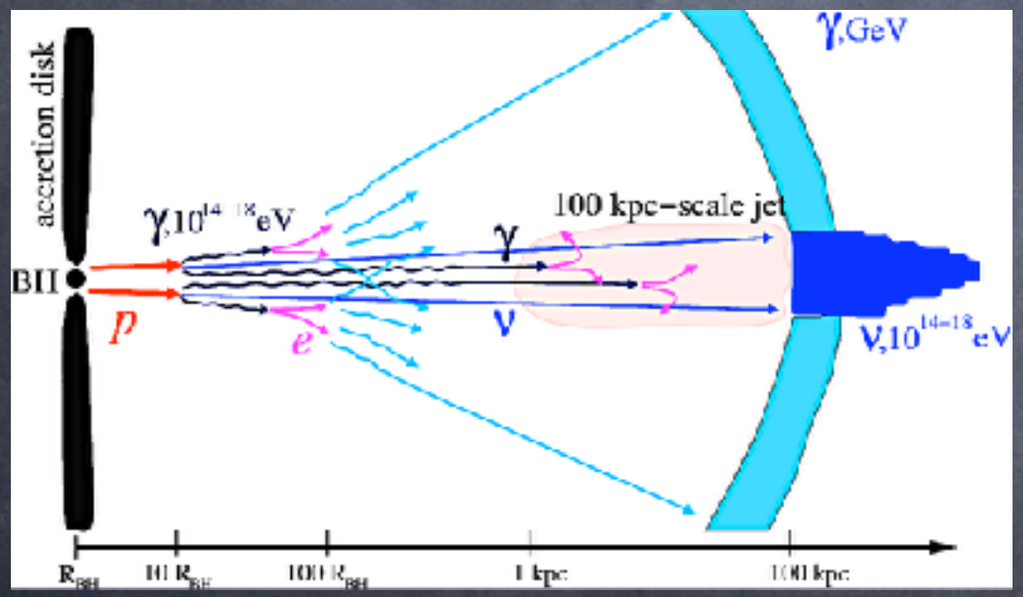


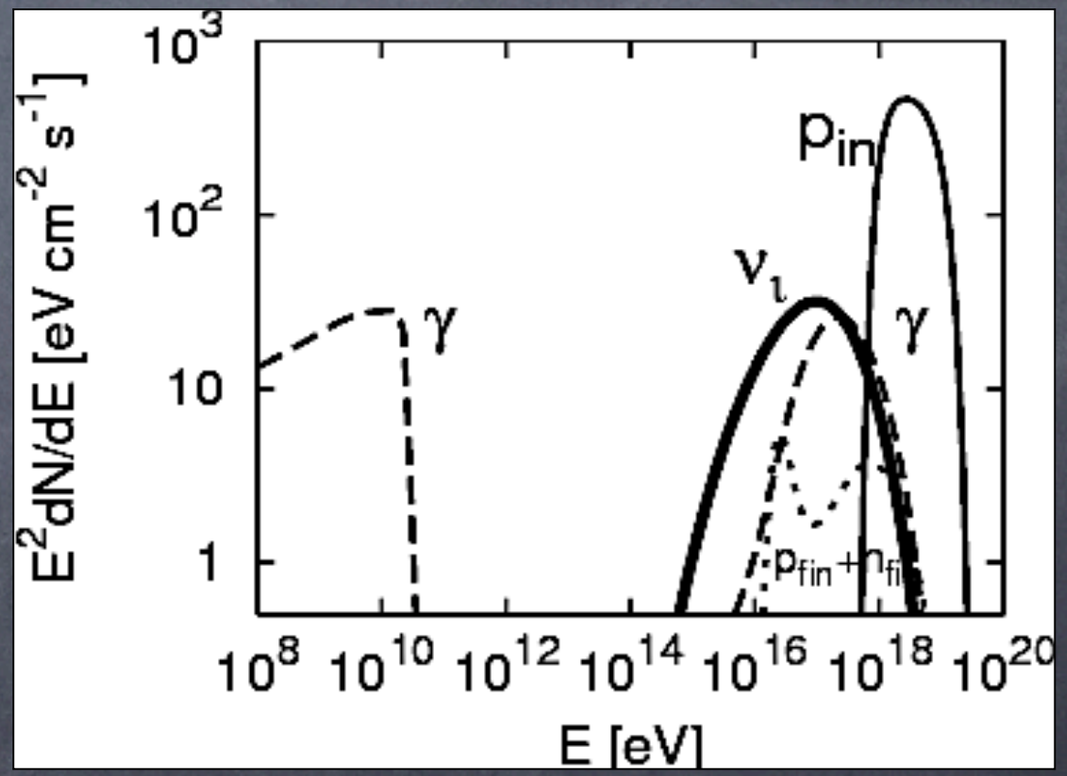
A. Dundovic, G. Sigl

General Multi-Messenger Aspects

Blazars emitting significant neutrino sources should be loud in GeV γ-rays, but NOT in γ-rays above TeV.

This is because such γ-rays pair produce with "blue bump" photons of ~10 eV energy with a cross section ~σ_{Th} ~ 1 b about a factor 10^4 larger than the pγ cross section that produces the neutrinos => If loud in > TeV γ-rays, optical depth for neutrino production would be very small.





Neronov and Semikoz, Phys.Rev.D66 (2002) 123003

Conclusions

1.) Our atmospheric charm component of muon neutron flux is about 40% higher than previous calculations

2.) more importantly, uncertainties are relatively large, up to a factor ten; dominated by QCD up to ~ 10^5 GeV and by cosmic ray total nucleon flux at higher energies
influence of composition (and flux) uncertainties should be updated and projected as a band

3.) Atmospheric neutrinos are an important background for astrophysical neutrinos for which model and constraint building is now in full gear