PeV Neutrinos from Ultra-High Energy Cosmic Rays

Rencontres de Moriond, EW session, 2014

- Overview
- Main Processes
- Flux Predictions

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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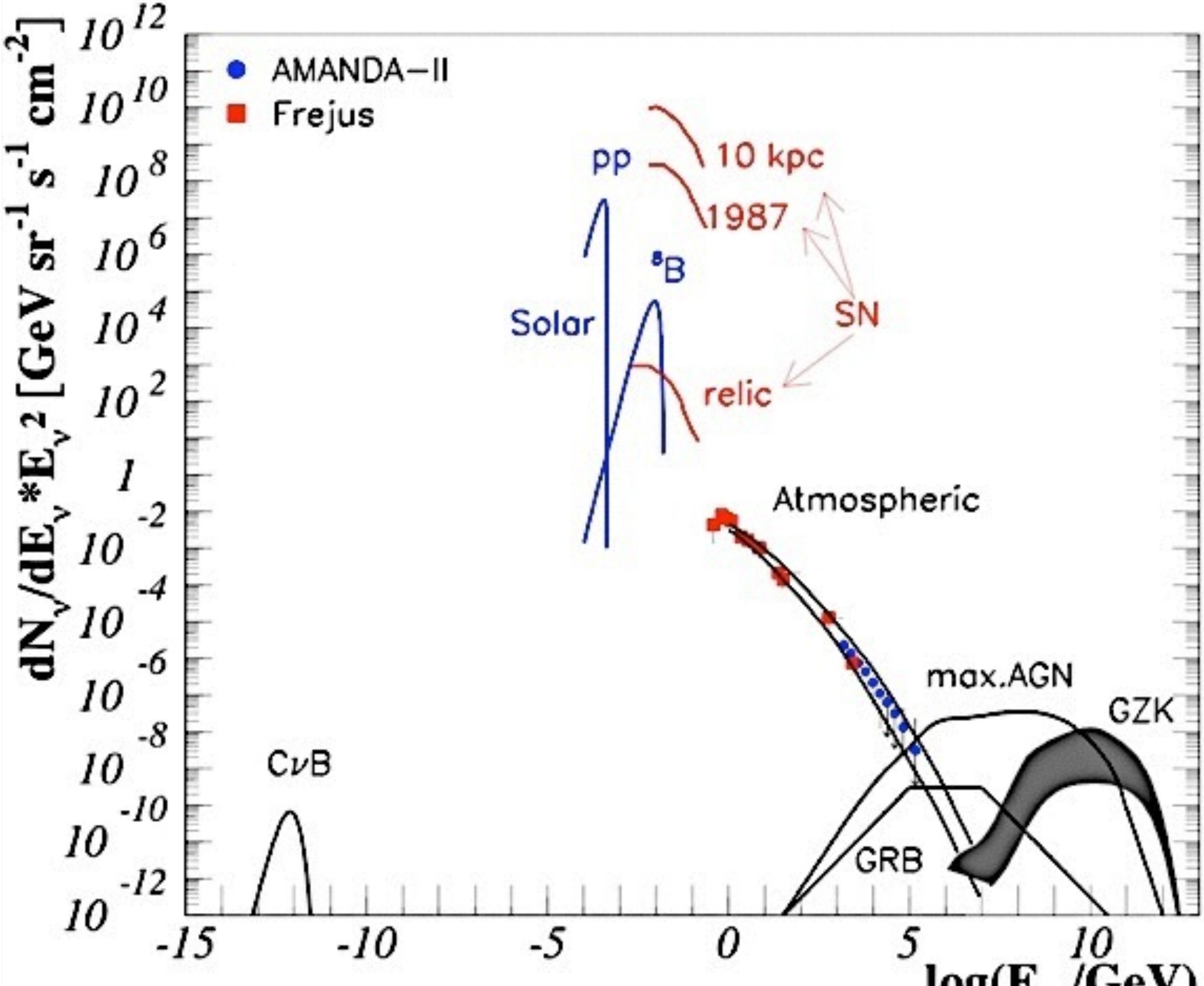
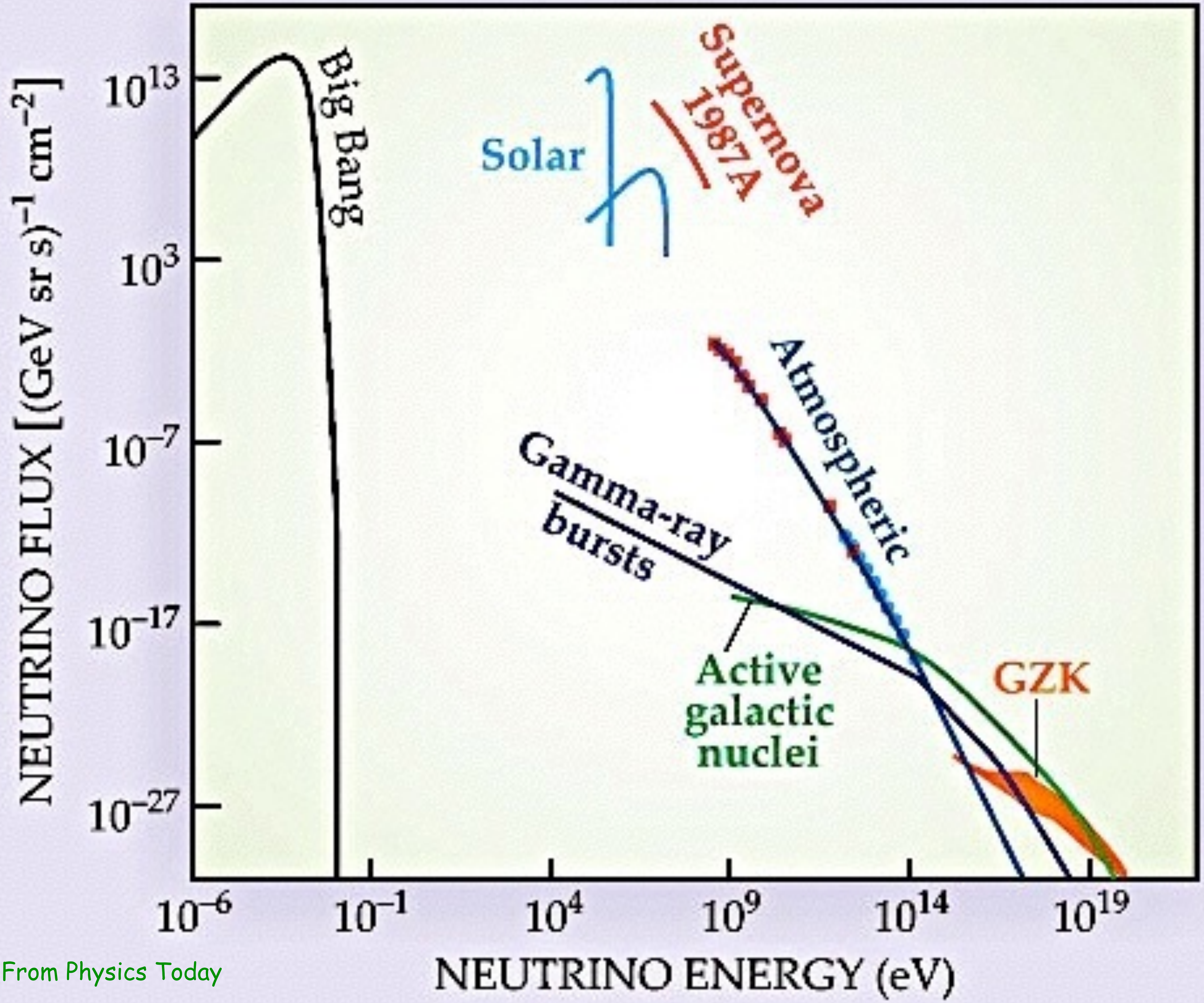
The „grand unified" neutrino energy flux spectrum



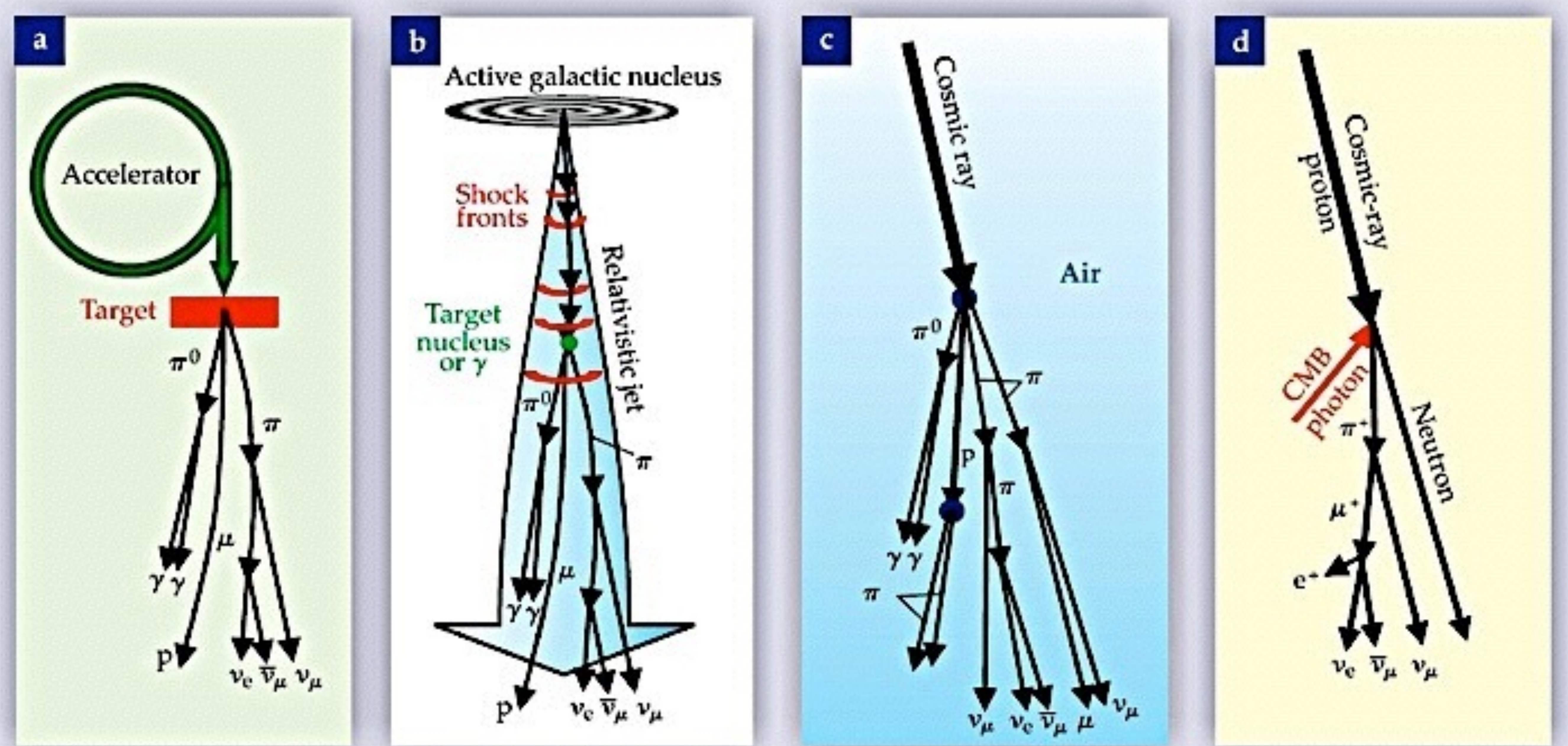
From the European ASPERA roadmap

The „grand unified“ differential neutrino number spectrum



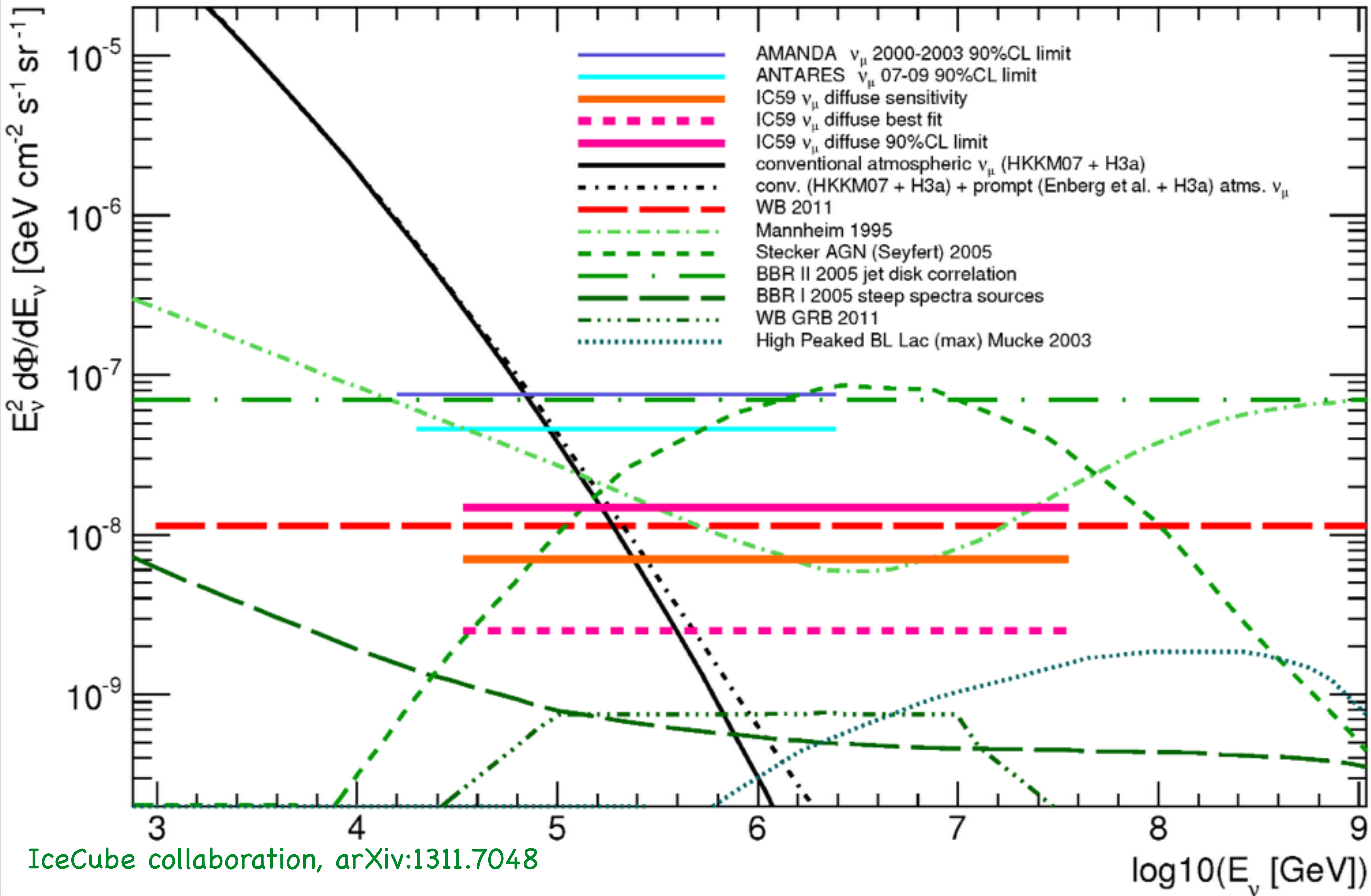
From Physics Today

Summary of neutrino production modes

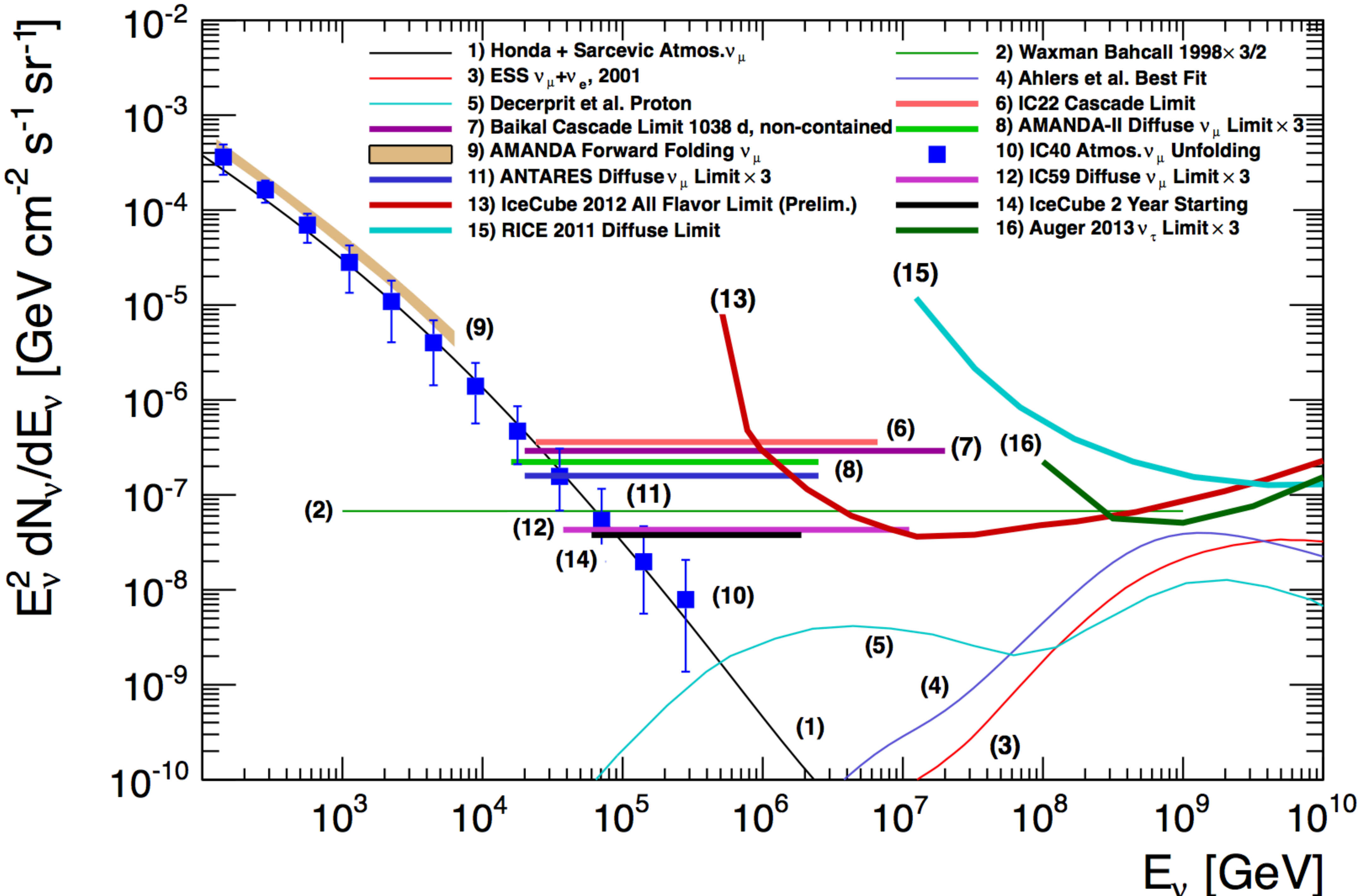


From Physics Today

Current Upper Limits at TeV-EeV energies



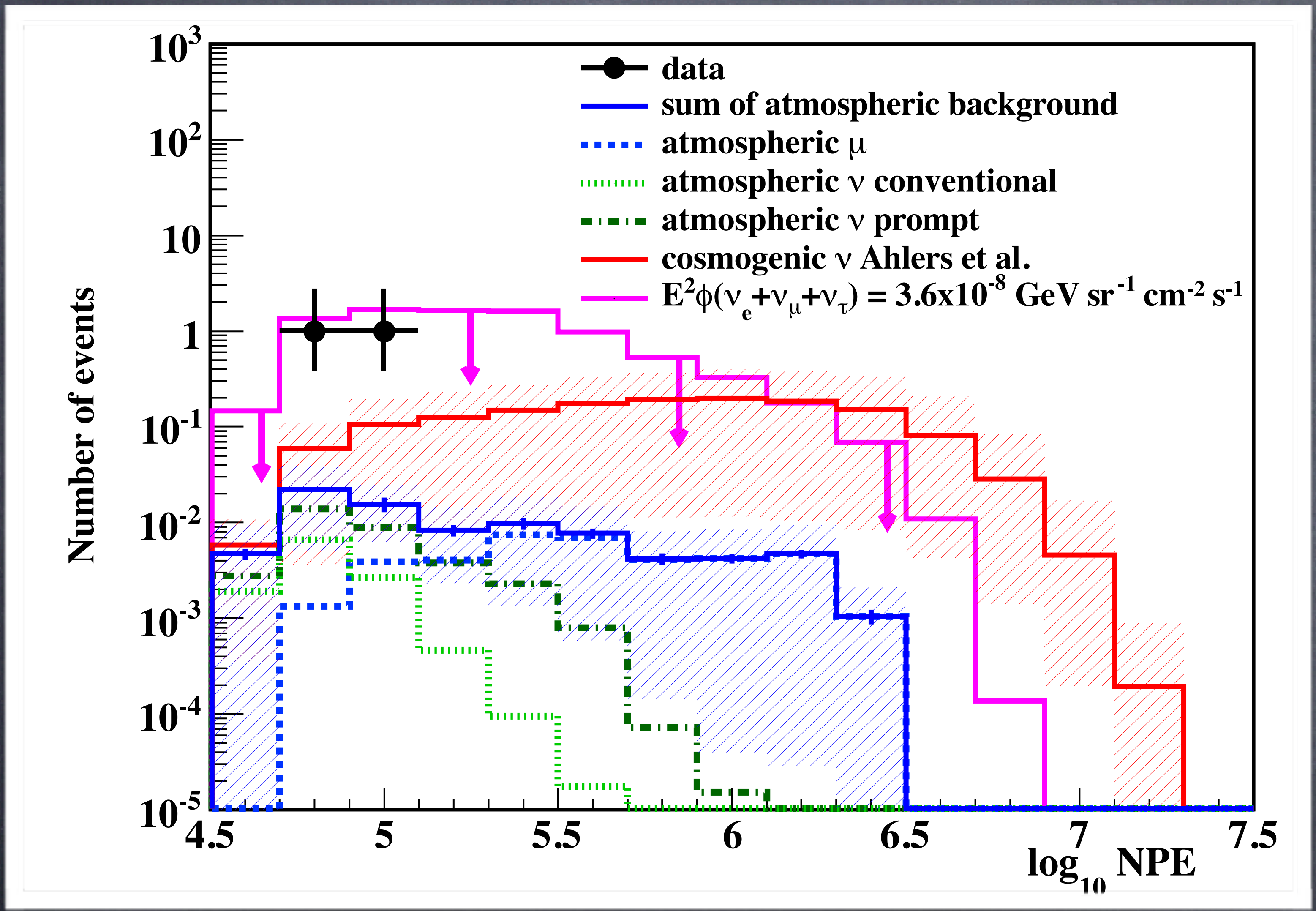
IceCube collaboration, arXiv:1311.7048

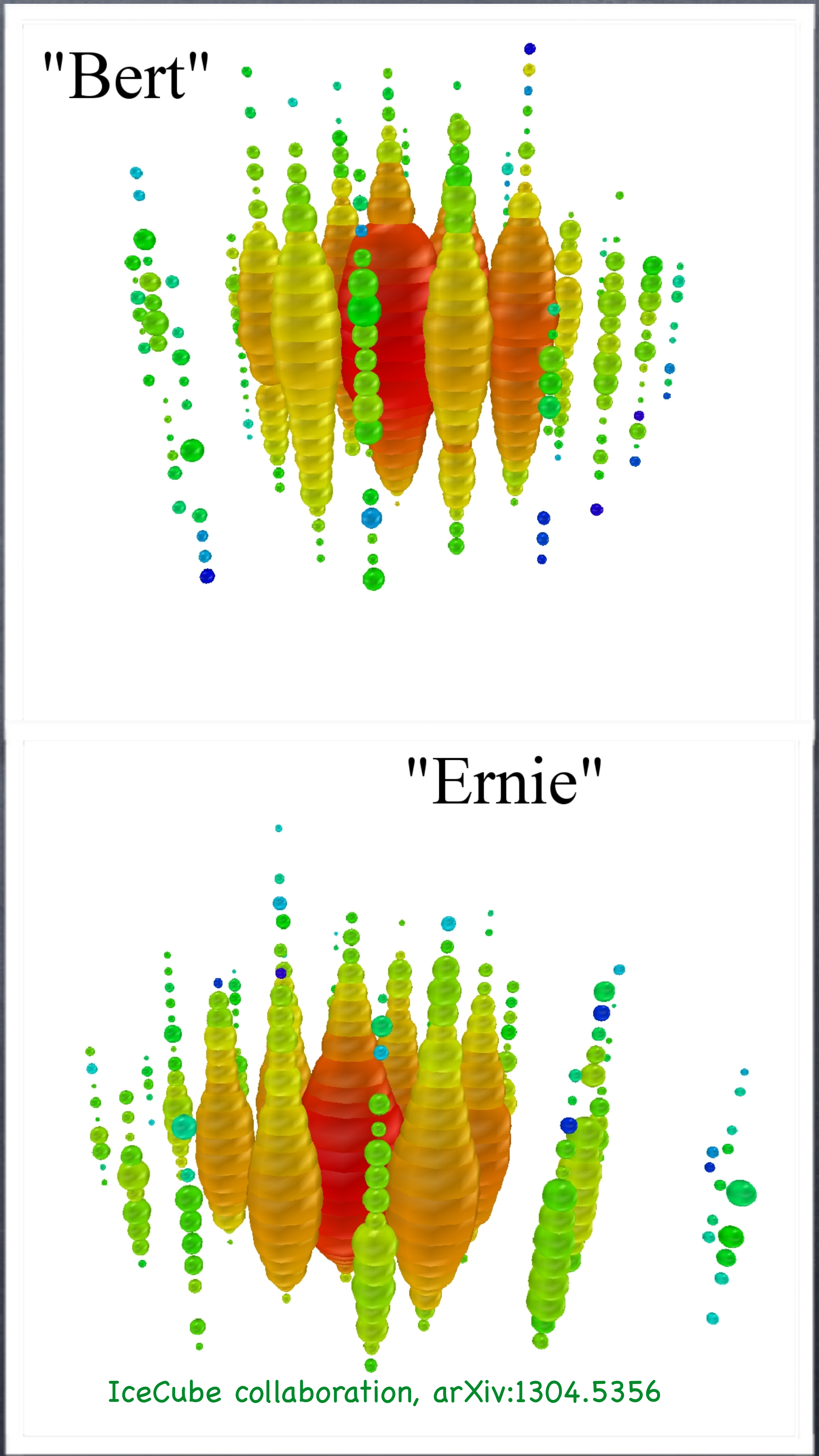


A.Karle, IceCube collaboration, arXiv:1401.4496

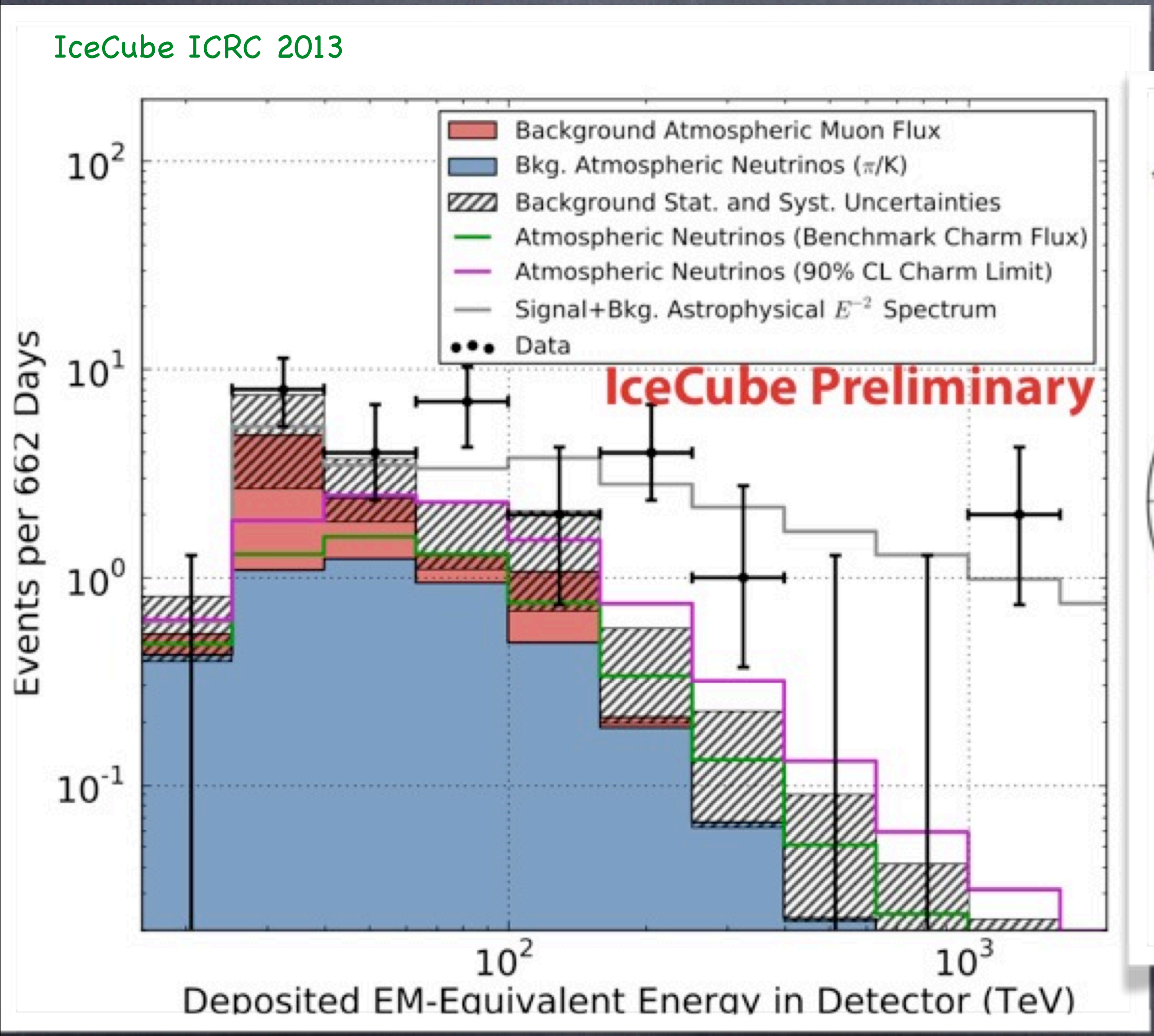
Figure 7: An overview is presented of observed atmospheric neutrino fluxes, upper limits to diffuse fluxes and models. The IceCube 2012 differential upper limit (11) turn up sharply at 1PeV because of observed PeV events. The best fit diffuse flux using starting events in IceCube (12) forms evidence for a diffuse astrophysical flux up to PeV energies above the atmospheric neutrino spectrum extending to a few 100 TeV.

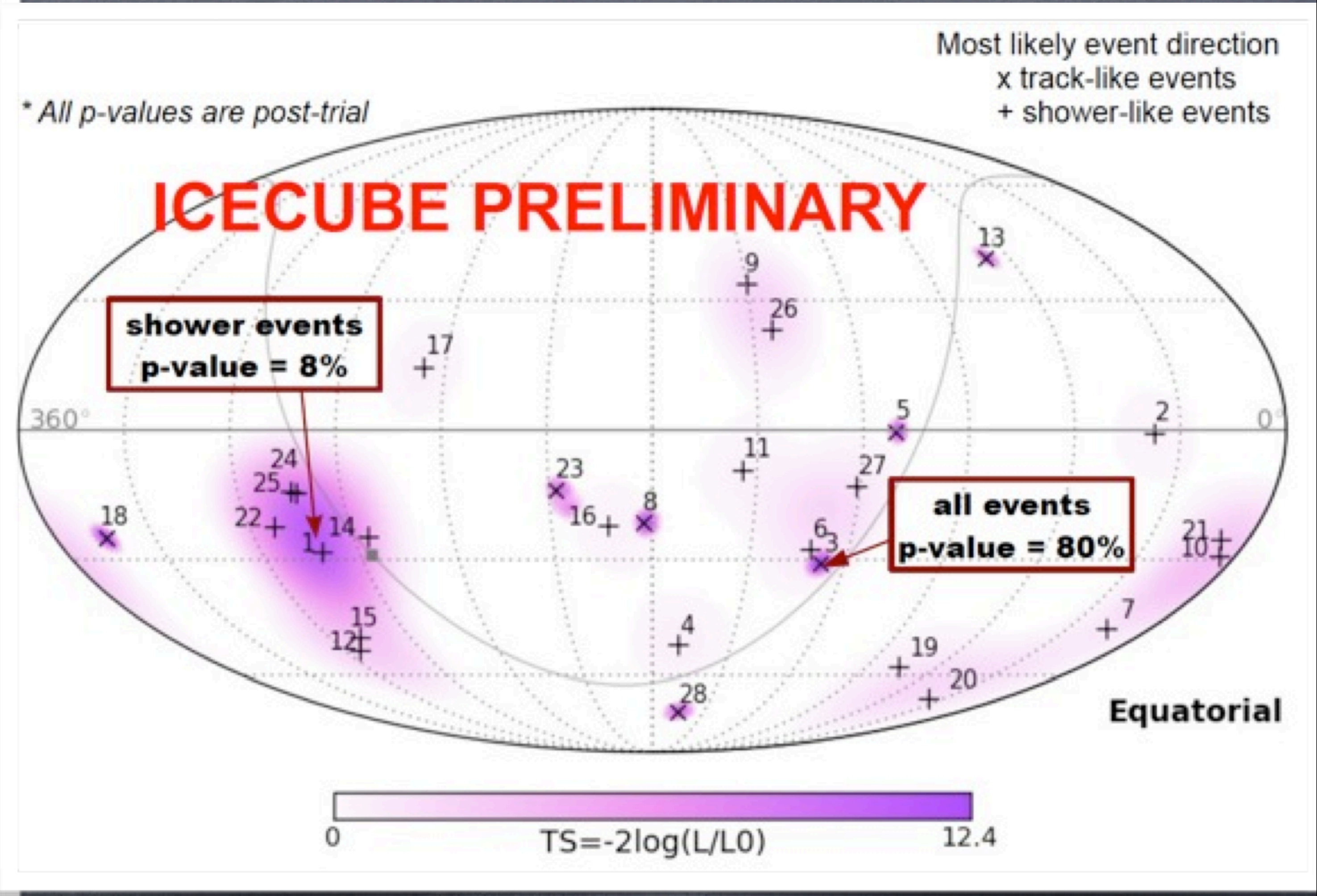
But now two PeV energy candidate neutrinos observed by IceCube





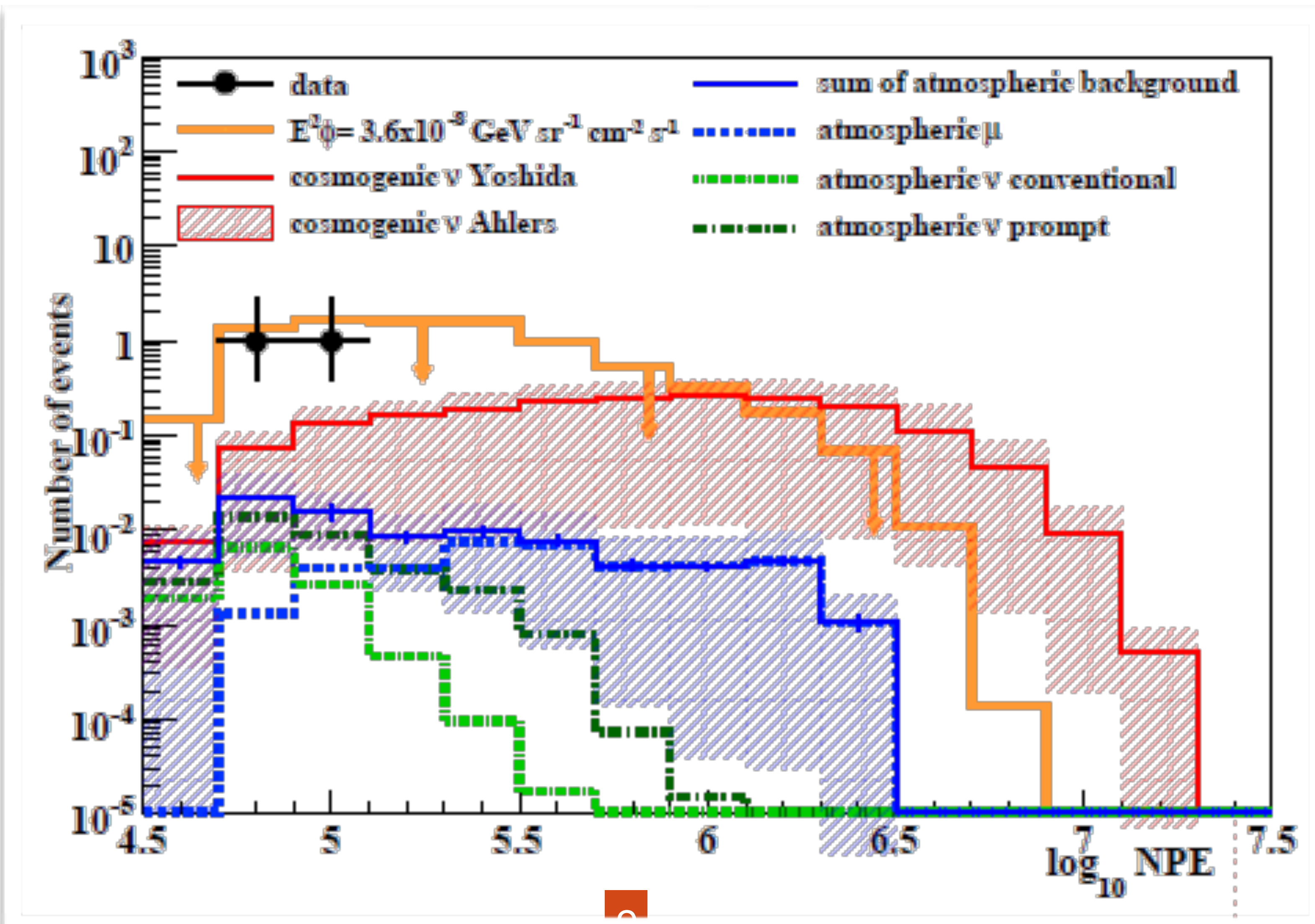
and even more events at few 100 TeV:





Possible sources of PeV neutrinos

- Atmospheric interactions of UHECRs
- Astrophysical neutrino sources such as GRBs or AGNs
- <u>Here: Extragalactic UHECRs interacting with radiation backgrounds</u>



Main Interactions

- Photopion production ("GZK effect")

$$p+\gamma \rightarrow \Delta^{+} \rightarrow p+\pi^{0} \rightarrow p+\gamma\gamma$$
$$\rightarrow n+\pi^{+}$$

$$n \rightarrow p+e^{-}+\bar{\nu}_{e}$$
$$\pi^{+} \rightarrow \mu^{+}+\nu_{\mu} \rightarrow e^{+}+\nu_{e}+\bar{\nu}_{\mu}+\nu_{\mu}$$

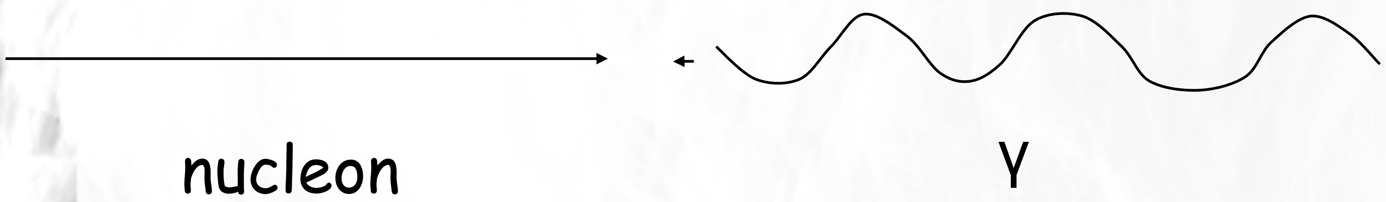
- Photodisintegration and Decay

$$N+\gamma \rightarrow N'+X(n,p,...)$$

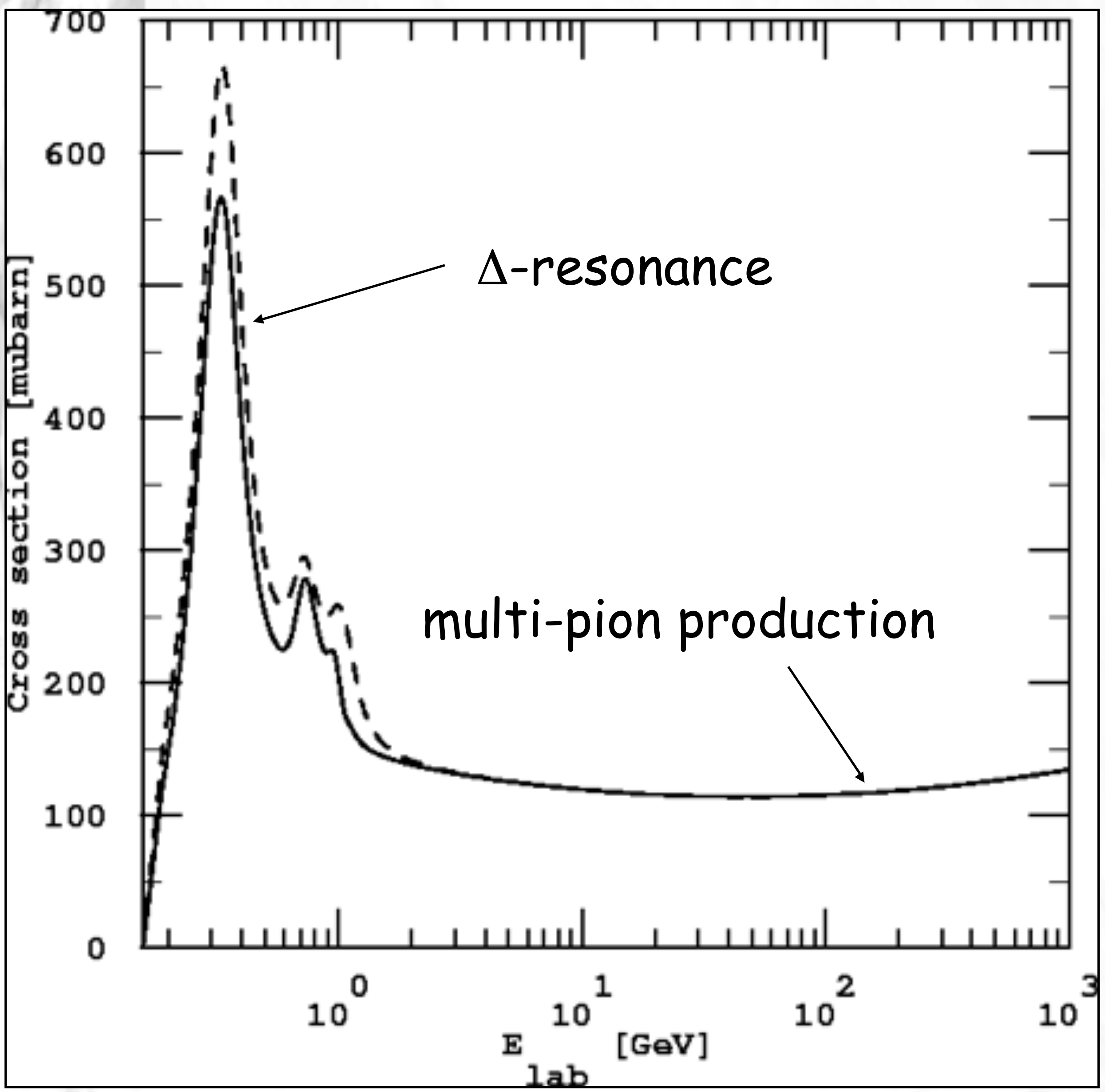
- Photon backgrounds:
  - Cosmic Microwave Background (CMB)
  - UV/optical/IR backgrounds (IRB)

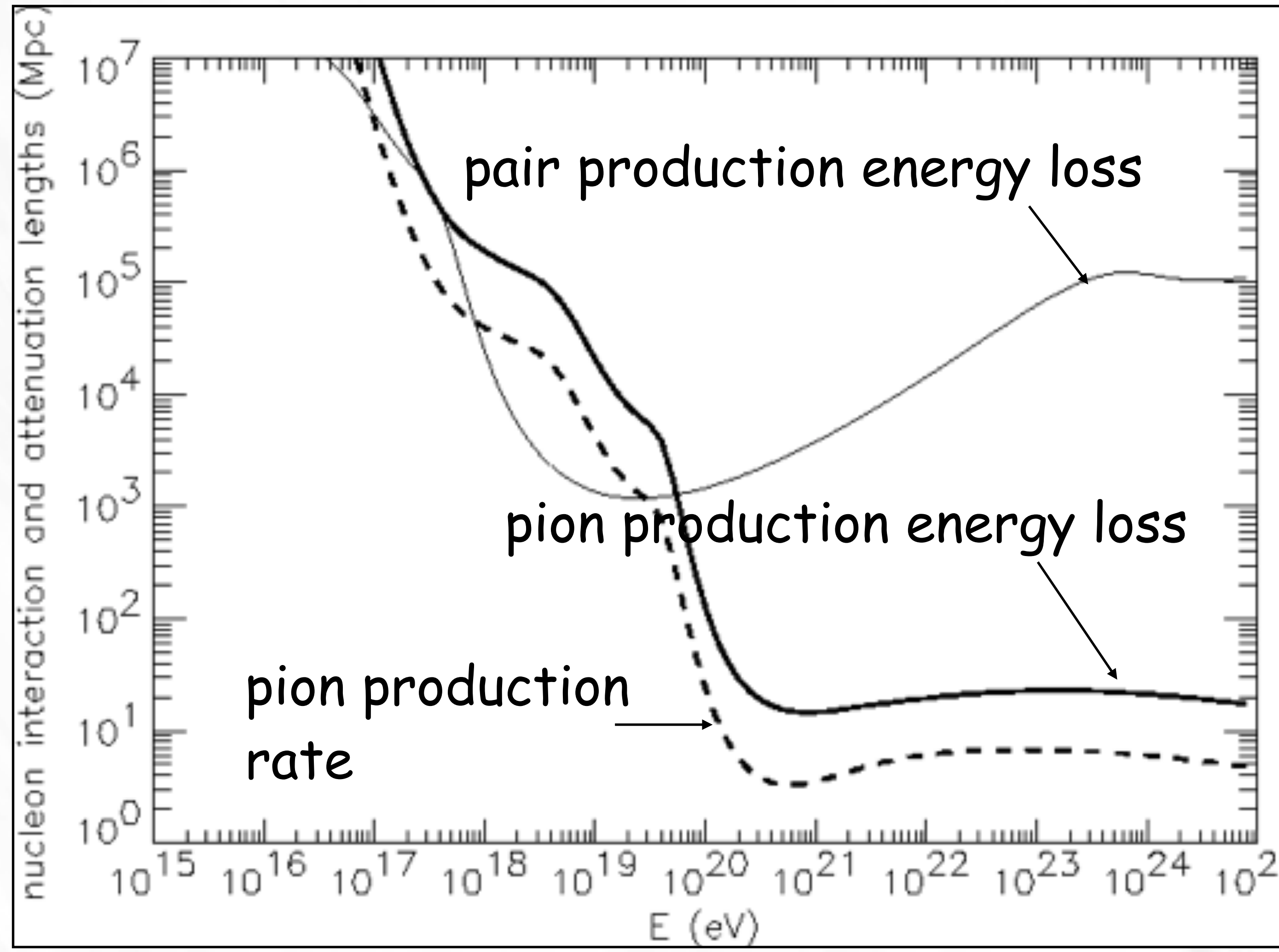
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



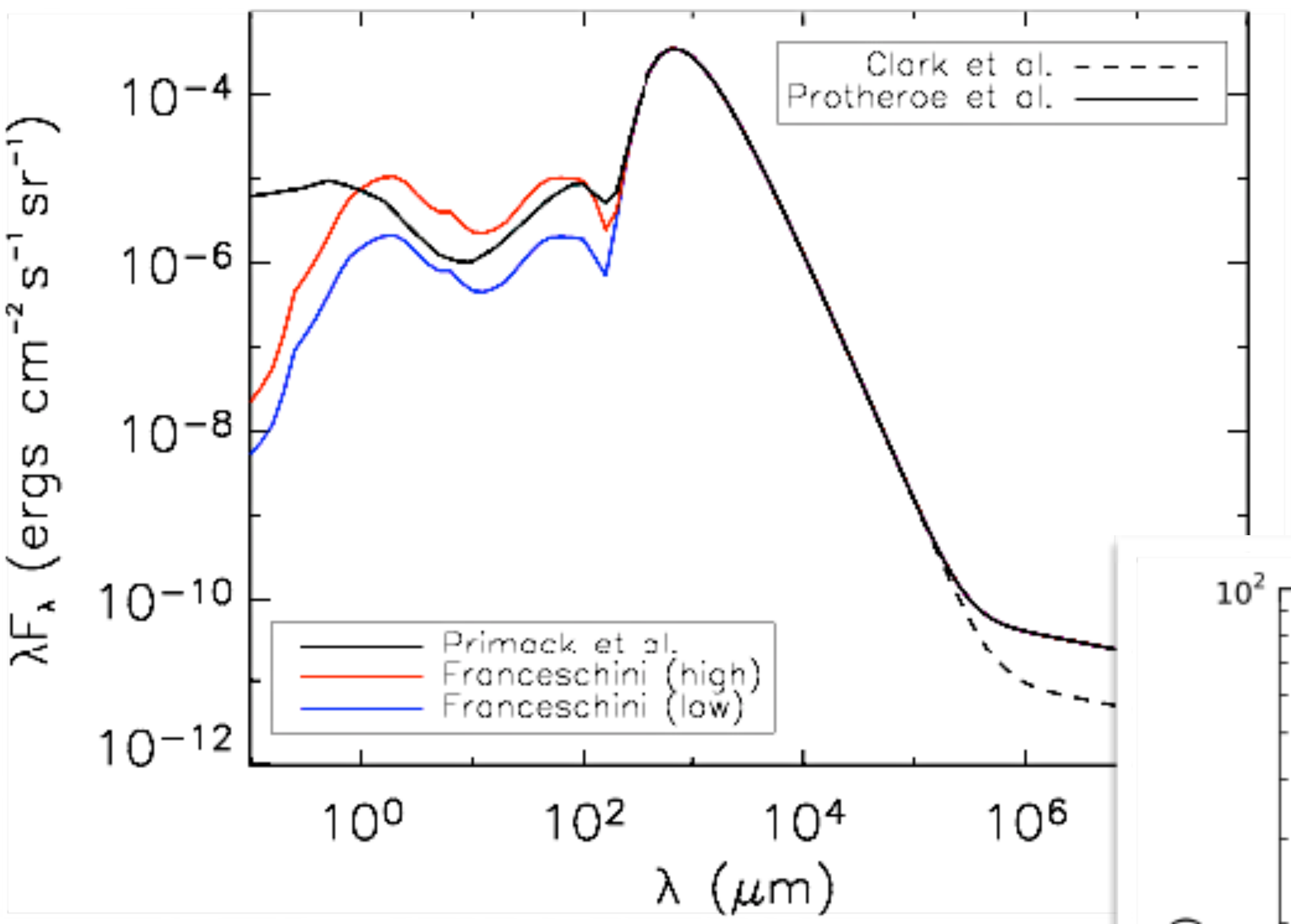
$$E_{\mathrm{th}} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \simeq 4 \times 10^{19}\,\mathrm{eV}$$

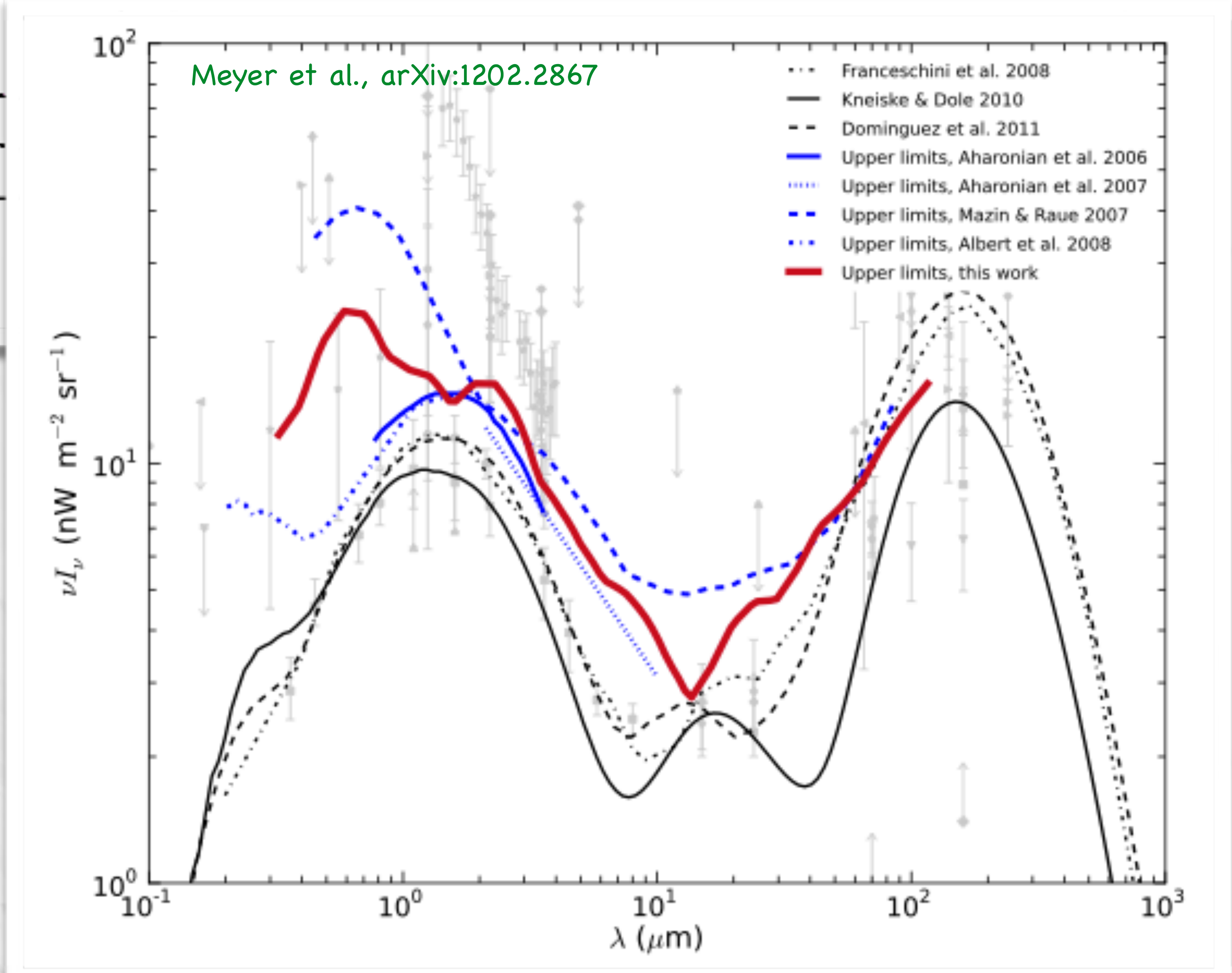




Low energy photon target: Diffuse fluxes

diffuse photon flux from infrared to radio





the infrared part is heavily constrained by source counts (lower limits) and gamma-ray absorption (upper limits)

Interactions with the CMB

- Proton energy at certain redshift:

  $$E_p \approx E_{GZK}/(1+z) \qquad E_{GZK} \approx 10^{20}\ \text{eV}$$

- Resulting average neutrino energy:
  - Neutron decay: $E_\nu \approx 3\times 10^{-4} E_{GZK}/(1+z)^2 \approx 6\times 10^{15}\ \text{eV}$
  - Pion decay chain: $E_\nu \approx E_{GZK}/(20(1+z)^2) \approx 10^{18}\ \text{eV}$
- Wide peaks around these energies
  - Wide Δ resonance
  - Wide thermal spectrum of CMB photons
  - Different redshifts contribute

Interactions with the IRB

- More energetic than CMB photons
- Smaller proton energy required to produce the Δ resonance
- Average neutrino energy
  - Neutron decay: $E_\nu < 10^{14}$ eV
  - Pion decay chain: $E_\nu \approx 8 \times 10^{15}$ eV $/[(1+z)(E_\gamma/\text{eV})]$
- Dominant contribution to the neutrino flux in the PeV range

Neutrino fluxes from UHECR nuclei

- Photodisintegration is the dominant process for nuclei

$$N + \gamma \rightarrow N' + X(n, p, ...)$$

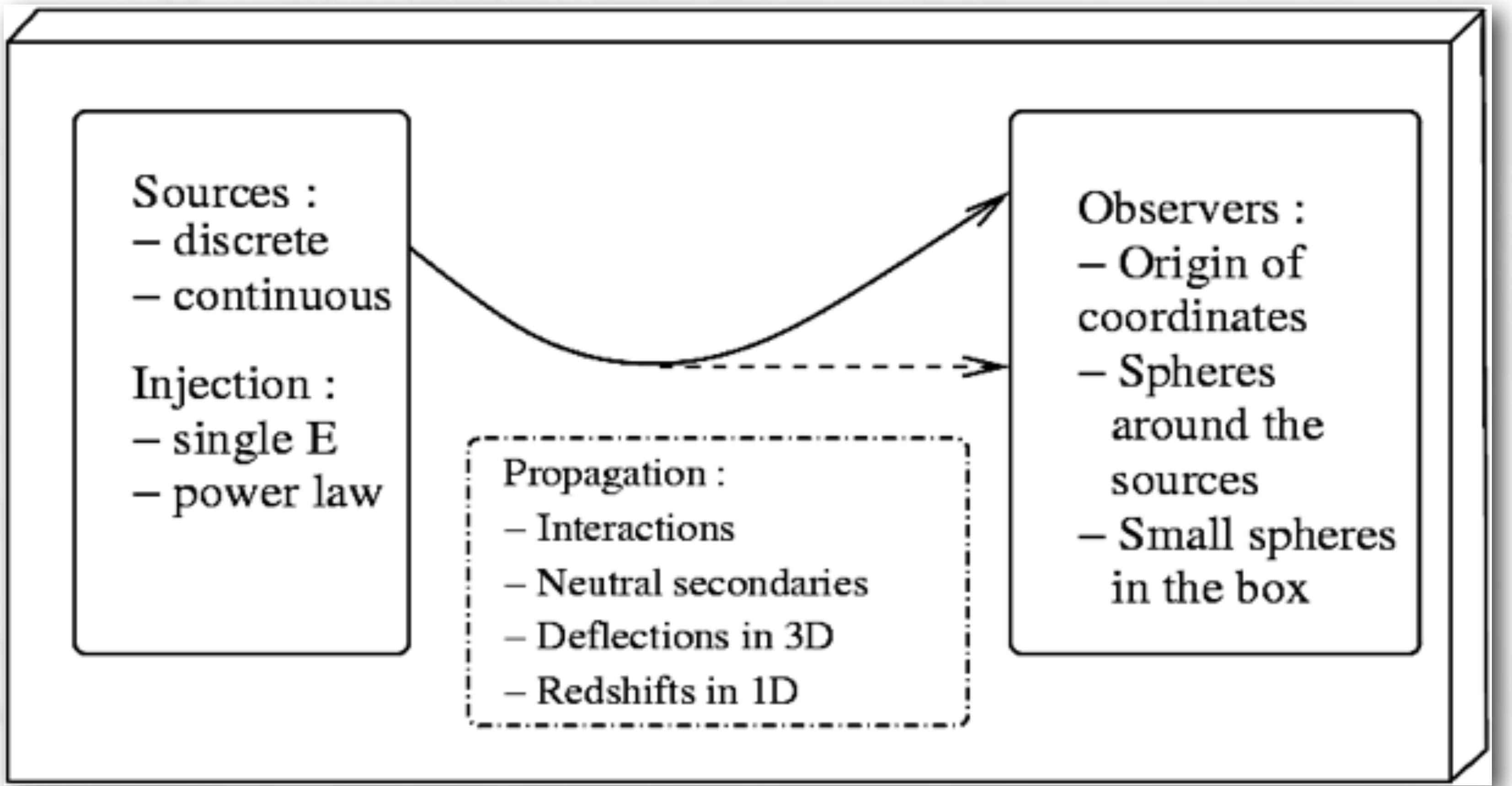
- Neutrinos from neutron decay at around

$$E_\nu \approx 4 \times 10^{-4} (E_{GZK} / A)/(1+z)^2 \approx \text{few } 10^{14} \text{ eV}$$

- Photopion production on IRB
- Nuclei energies of $\approx 20AE_\nu$
- Pion production from bound nucleons suppressed with respect to that from free nucleons
- Expected neutrino flux smaller than in pure proton case

Propagation Tool CRPropa

CRPropa is a public code for UHE cosmic rays, neutrinos and γ-rays being extended to heavy nuclei and hadronic interactions



Version 1.4: Eric Armengaud, Tristan Beau, Günter Sigl, Francesco Miniati, Astropart.Phys.28 (2007) 463.

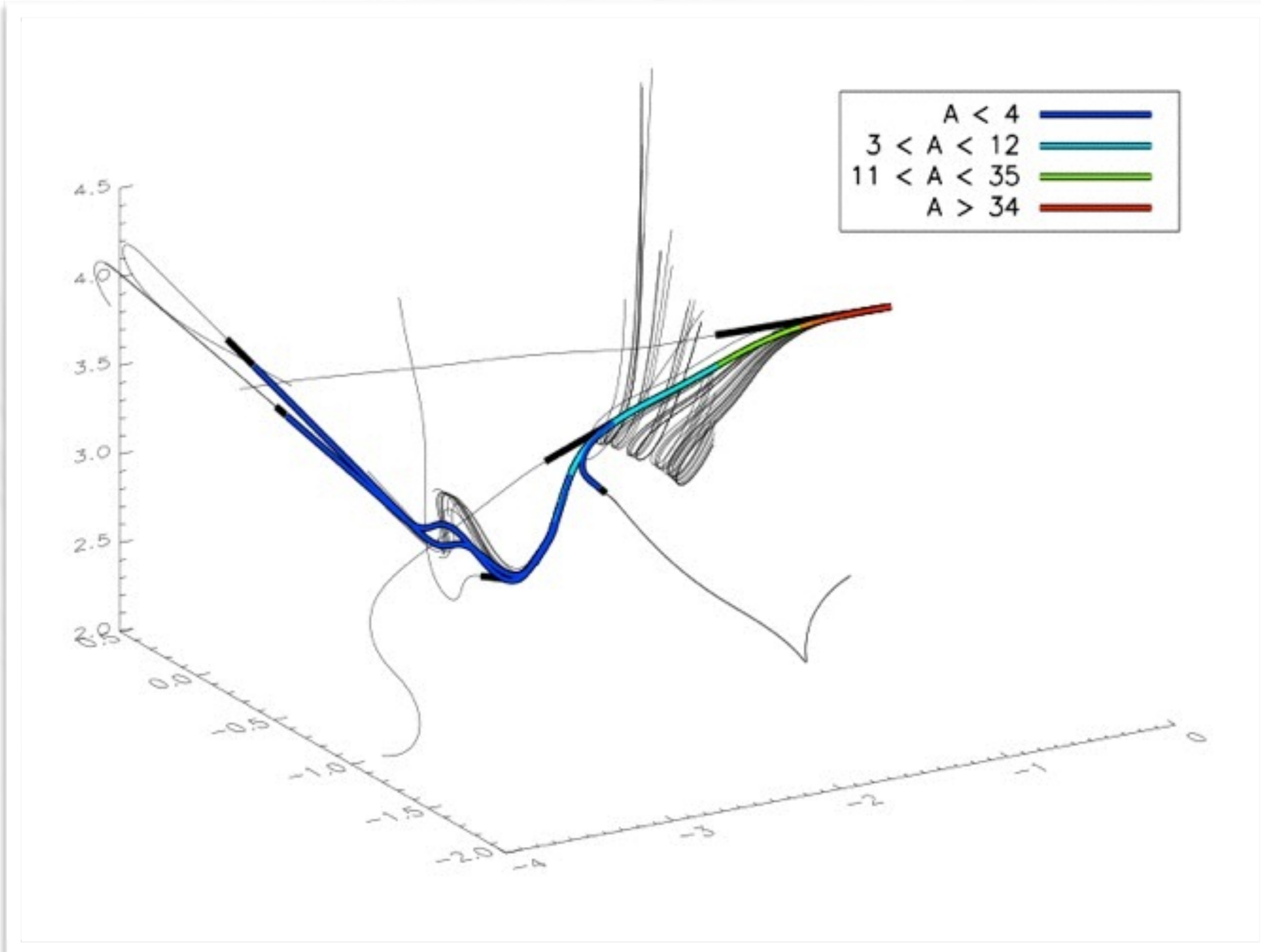
Version 2.0 at https://crpropa.desy.de/Main_Page

Now including: Luca Maccione, Rafael Alves Batista

Nils Nierstenhoefer, Karl-Heinz Kampert, Peter Schiffer, Arjen van Vliet

Astroparticle Physics 42 (2013) 41

Example: Extragalactic iron propagation produces nuclear cascades in structured magnetic fields:



Initial energy 1.2 x 10^{21} eV, magnetic field range 10^{-15} to 10^{-6} G. Color-coded is the mass number of secondary nuclei

Pure Proton Injection

- Dip or "Berezinsky" scenario
- Cutoff due to the GZK effect

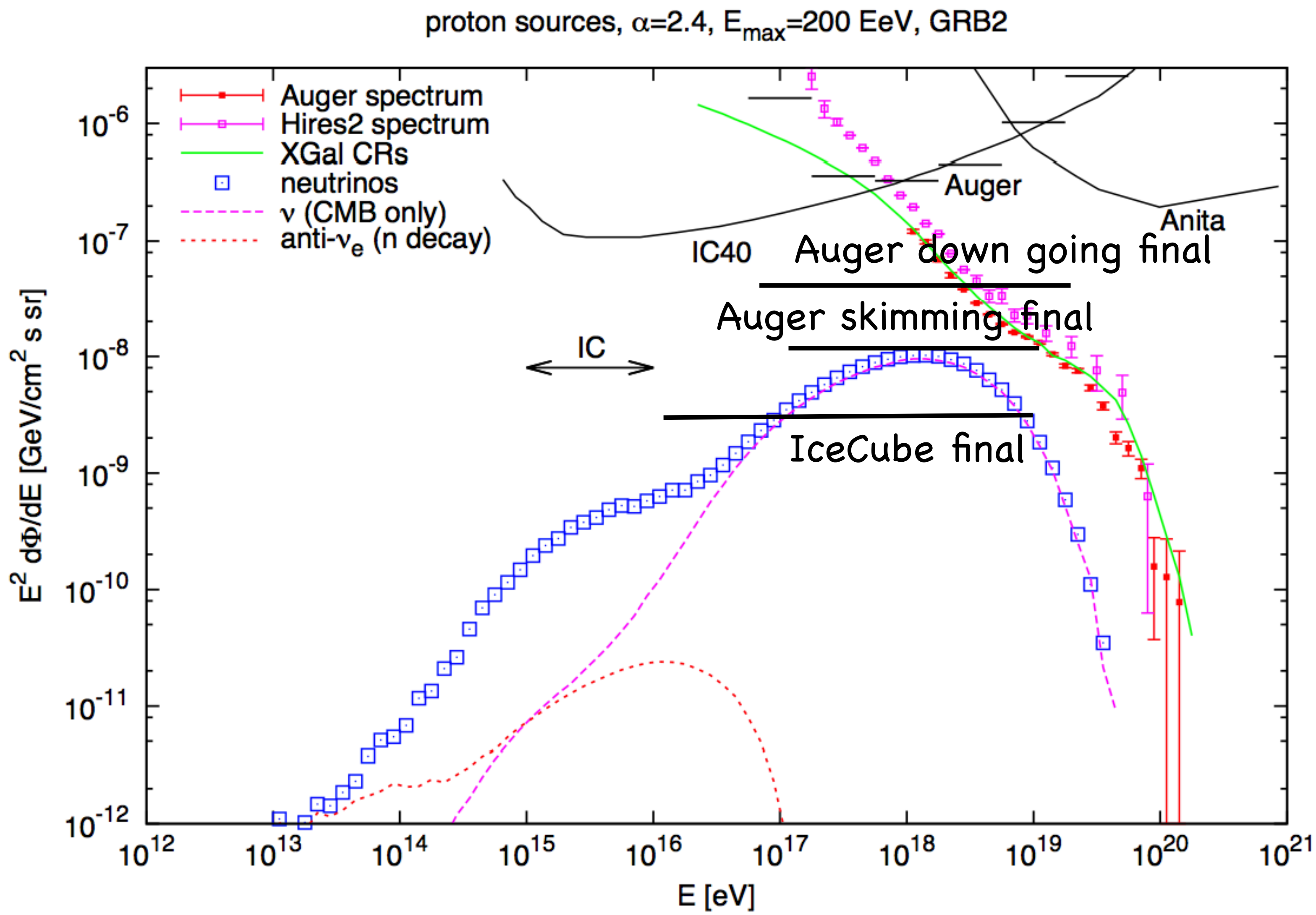
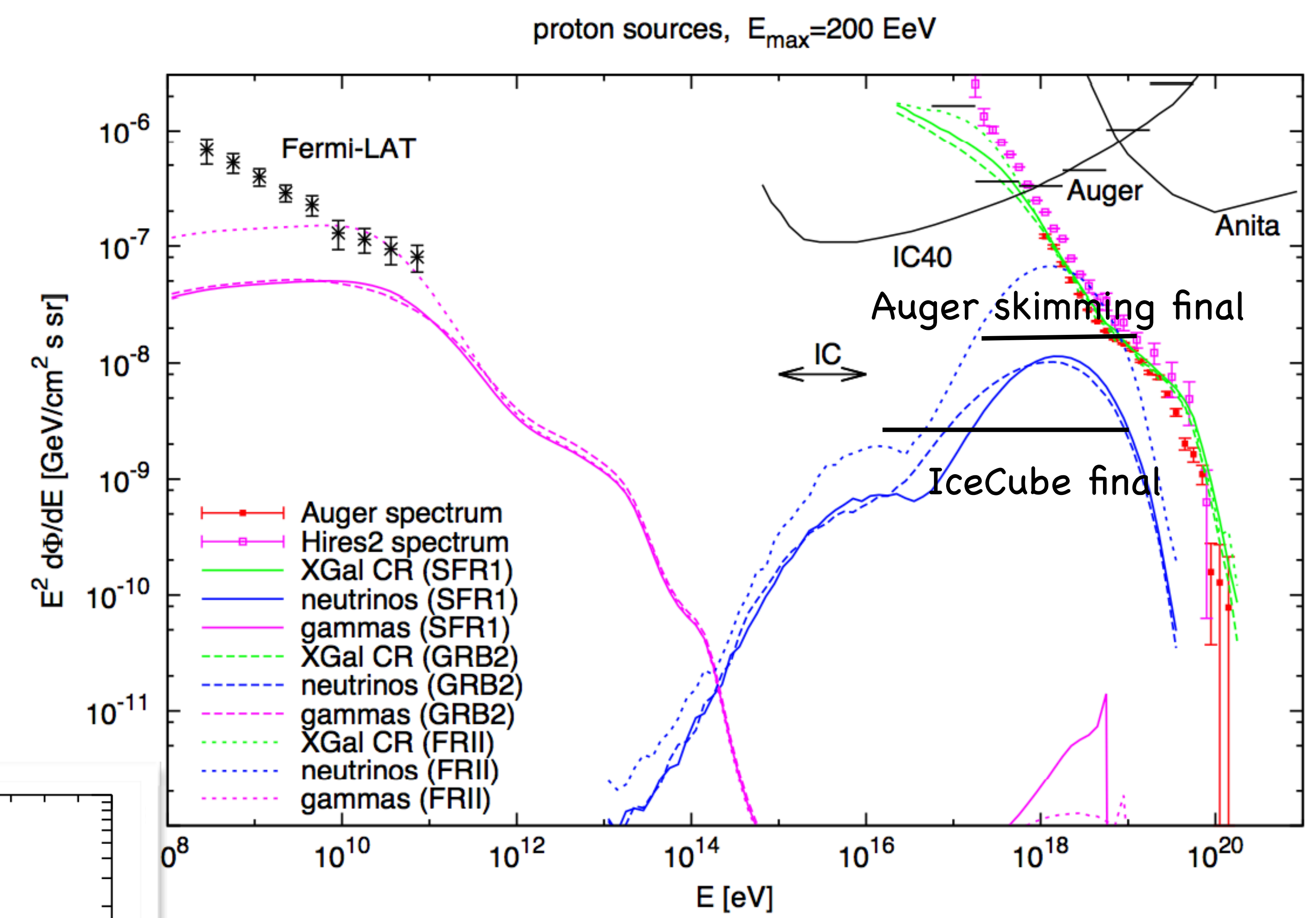


Figure 1. Proton 'dip' scenario with source spectral index $\alpha = 2.4$ and $E_{\mathrm{max}} = 200\,\mathrm{EeV}$. Indicated are the propagated proton spectrum and the resulting all flavor neutrino fluxes (obtained with CR-Propa). We also show separately the neutrino backgrounds due to interactions with CMB alone as well as those resulting from n decays. The CR flux measured by Auger and Hires and the neutrino limits from IceCube, Auger and Anita are displayed. We also indicate the energy range and approximate flux level suggested by the two observed IceCube events.

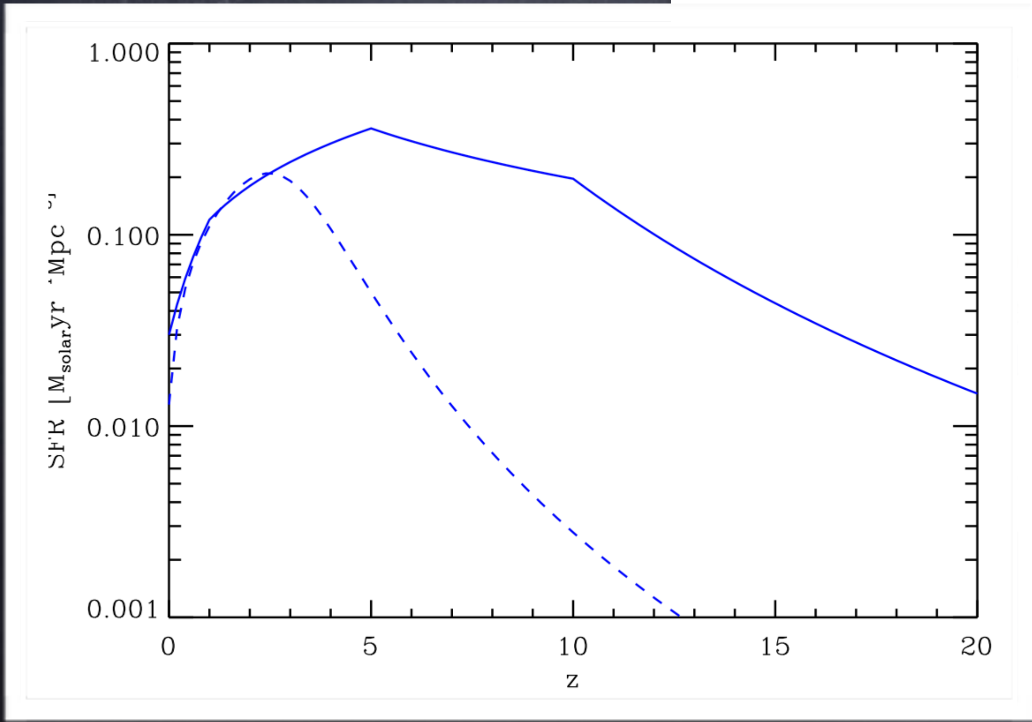
Roulet, Sigl, van Vliet, Mollerach, JCAP 1301, 028

Pure Proton Injection: Dependence on Source Evolution

- 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.



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Pure Iron Injection

- Cutoff due to Photo-disintegration

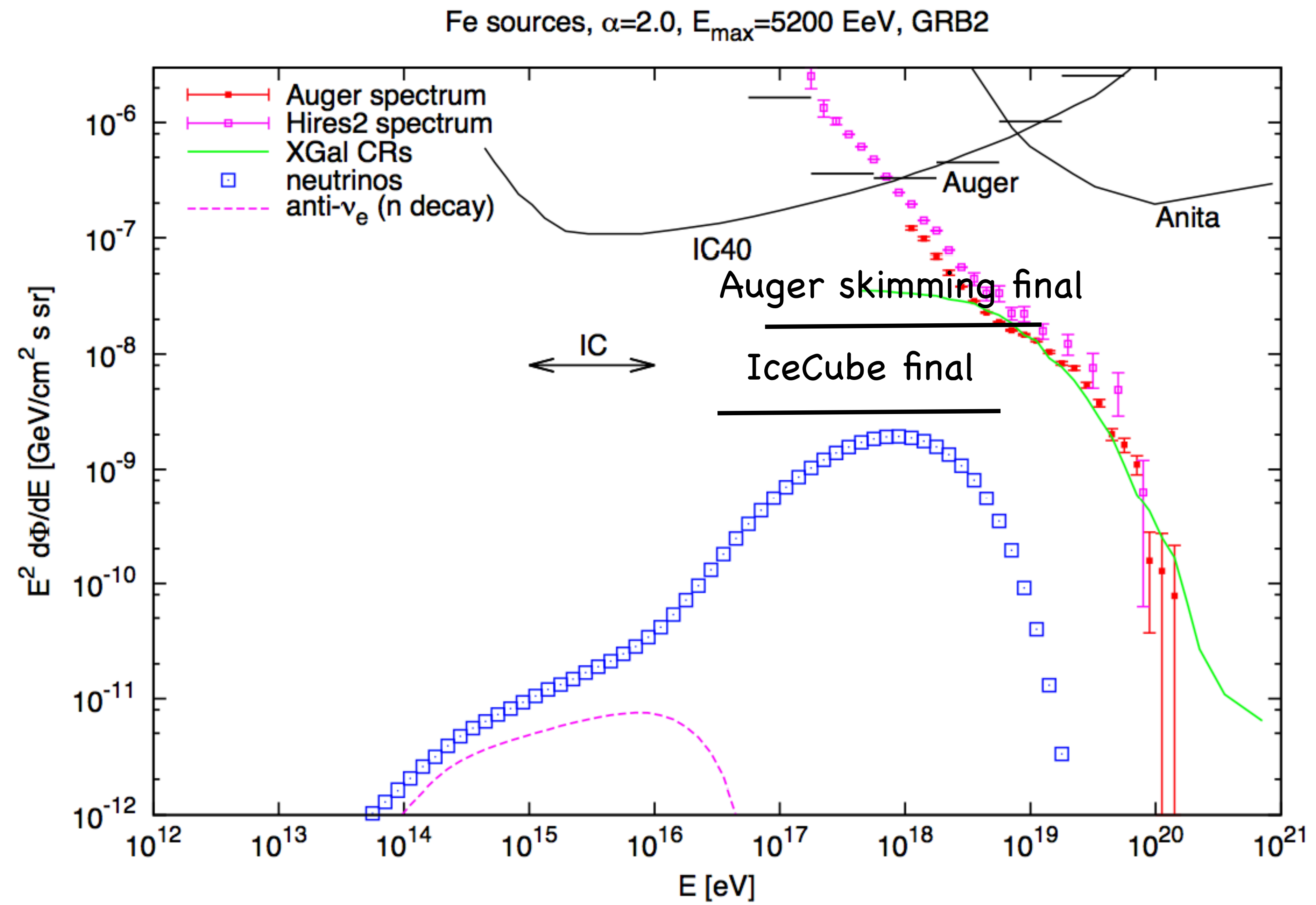

Figure 3. Extragalactic Fe scenario with source spectral index $\alpha = 2.0$ and $E_{max} = 5200$ EeV. Indicated are the propagated CR spectrum and the resulting (all flavor) neutrino fluxes, as well as the neutrino background due to n-decays alone.

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Mixed Composition

- 'Disappointing' model
- Cutoff due to maximal injection energy at the sources

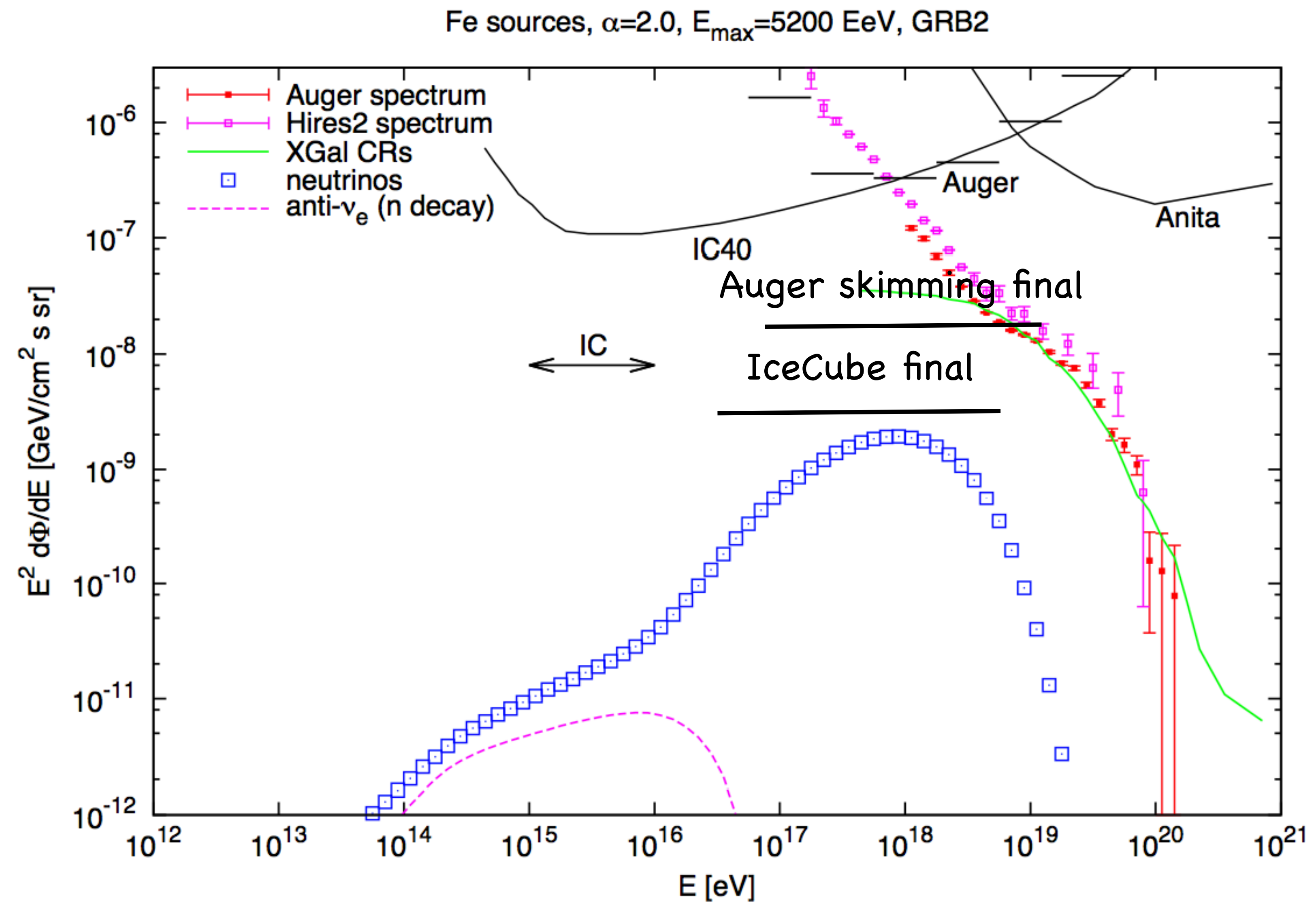

Figure 3. Extragalactic Fe scenario with source spectral index $\alpha = 2.0$ and $E_{\rm max} = 5200\,\mathrm{EeV}$. Indicated are the propagated CR spectrum and the resulting (all flavor) neutrino fluxes, as well as the neutrino background due to n-decays alone.

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Conclusions

- Neutrino spectrum at PeV energies:
  - Negligible contributions from the decays of neutrons produced in photopion production off the CMB or produced in photodisintegration interactions of heavy nuclei
  - Dominant contribution from pion decays produced in photopion interactions with IRB photons, can reach a level of

$$E_\nu^2 \mathrm{d}\Phi_\nu / \mathrm{d}E \approx 10^{-9}\ \mathrm{GeV/cm^2 s\ sr}$$

  - Enhanced in scenarios with strong source redshift evolution
    - Bounded by Fermi-LAT photon measurements
  - maximal cosmogenic neutrino flux prediction about a factor 10 smaller than IceCube PeV neutrino flux

Backup Slides

Source Evolution constrained by diffuse GeV photon fluxes

- Stronger source evolution model
  - Larger neutrino flux
  - Larger gamma ray flux
- Produced in pion production and pair production processes

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow p + \gamma\gamma$$
$$\rightarrow n + \pi^{+}$$
$$p + \gamma \rightarrow p + \gamma + e^{+}e^{-}$$

- Cascade down to lower energies
- Bounded by diffuse photon background measured by Fermi-LAT

Neutrino Fluxes from UHECR protons

- Photopion production on CMB (interaction behind the GZK-cutoff) and IRB

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \rightarrow p + \gamma\gamma$$
$$\rightarrow n + \pi^{+}$$

$$n \rightarrow p + e^{-} + \bar{\nu}_{e}$$
$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \bar{\nu}_{\mu} + \nu_{\mu}$$

- Average neutrino energy
  - Neutron decay: $E_{\nu} \approx 3 \times 10^{-4} E_{p}$
  - Pion decay chain: $E_{\nu} \approx E_{p} / 20$

Berezinsky's "Disappointing" model

- Mixture of proton and iron injected at the source
- Low cutoff E_{max}=4Z EeV
- Cutoff due to sources running out of power, rather than the GZK effect
- Energy too low for photopion production on CMB
- No EeV neutrino peak
- Increased PeV neutrino peak with respect to pure iron case