

# *Neutrinos with a mass of $0.4 \text{ eV}/c^2$ Columbus' egg ?*

*Richard WIGMANS (TTU)*

**EUCAPT Astroneutrino workshop, Prague, September 2021**

## *Outline :*

- Relic neutrinos in an expanding Universe
  - Current properties
  - Consequences of the Pauli principle
    - *Large scale structure*
    - *Accelerated expansion*
  - Intriguing features of the cosmic ray spectrum
    - *Dark matter*
  - Conclusions
- Part 1 (9/27)*
- Part 2 (9/29)*

## Summary Monday

- Relic (Big Bang) neutrinos are the most abundant particles in the Universe  
There are  $\sim 5$  billion of them for every baryon
- They are *non-relativistic*. Some fraction (depending on their mass) have velocities compatible with the escape velocity of galaxies
- Relic neutrinos form a *degenerate* Fermi-Dirac gas.  
(Almost) all available quantum states are occupied.
- Gravitationally decelerated neutrinos may violate the *Pauli principle* in the low-field region *near the center-of-gravity of galaxy clusters*
- To avoid this, a *local expansion of space* is needed in this region.  
Such an expansion could lead to the observed *Large-Scale Structure*
- This mechanism could also explain the *high-z Supernova data* without the need for *"dark energy"*
- *However, the neutrino mass has to be larger than  $0.2 - 0.3 \text{ eV}/c^2$  for this to be at all possible*

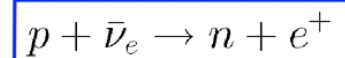
## Part 2

### *Intriguing features of the cosmic ray spectrum*

## How to detect Relic Neutrinos?

- Until now, **no mechanism has been found** (How to detect weak interactions at  $10^{-4}$  eV?)

- *Proposal:* high-energy particle scattering off relic neutrino target



If  $m_\nu \gg 10^{-4}$  eV:  $E_{\text{cm}} = \sqrt{m_p^2 + m_\nu^2 + 2E_p m_\nu} \approx \sqrt{m_p^2 + 2E_p m_\nu}$

Substitute  $m_p = 938.272$  MeV,  $E_{\text{cm}} > 940.077$  MeV ( $m_n + m_e$ )  $\Rightarrow E_p m_\nu > 1.7 \cdot 10^{15} (\text{eV})^2$

Threshold for this process:

$$E_p(\text{eV}) = \frac{1.7 \cdot 10^{15}}{m_\nu(\text{eV})}$$

If  $m_\nu = 1$  eV  $\rightarrow$  threshold  $E_p = 1.7$  PeV

if  $m_\nu = 0.1$  eV  $\rightarrow$  threshold  $E_p = 17$  PeV, *etc.*

- Use entire **Universe** as a **target**

High energy protons (cosmic rays) might induce this reaction.

*Is there any evidence for this?*

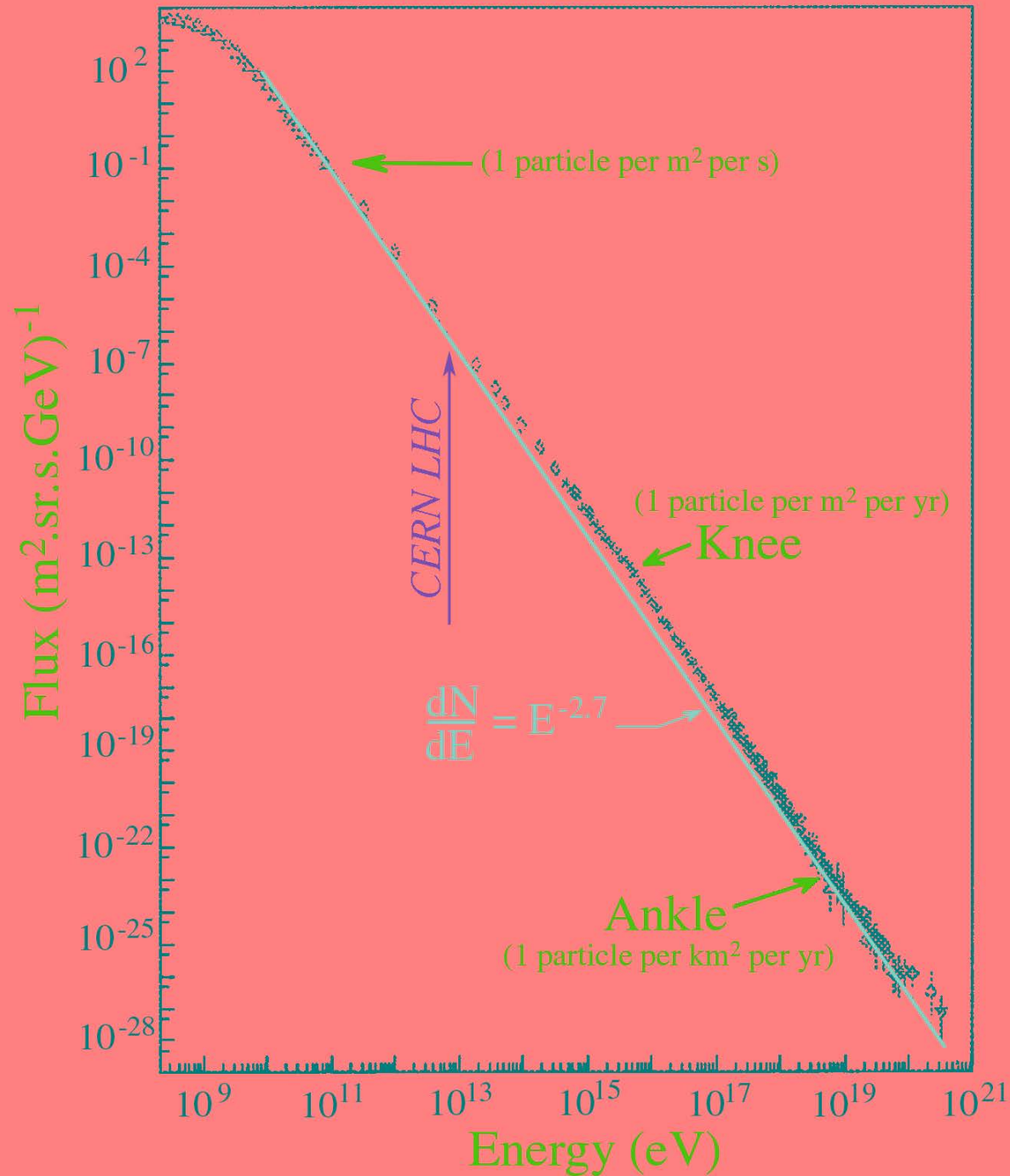
# The Spectrum of Cosmic Rays

- Spectrum falls off according to a *power law*

$$\frac{dN}{dE} \sim E^{-n}, \quad \text{with } n \approx 2.7$$



# Charged-particle cosmic ray spectrum



# The Spectrum of Cosmic Rays

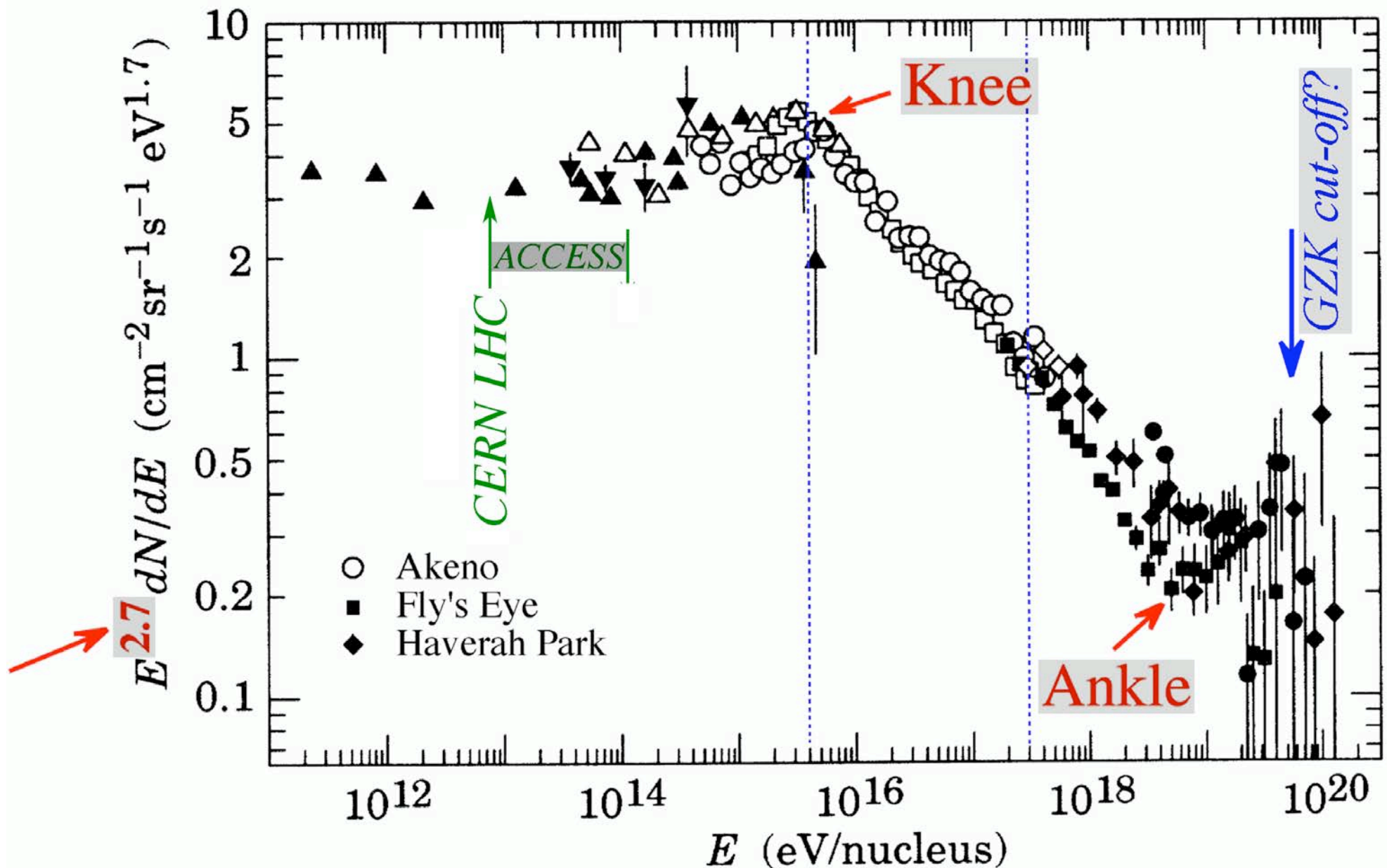
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- “Hot” topics in cosmic ray physics:
  - The *knee* at 3 - 4 PeV ( $n$  changes abruptly to 3.0)
  - The *GZK* cutoff:  $p + \gamma(2.7^\circ\text{K}) \rightarrow \pi + X$  above  $\sim 5 \cdot 10^{19}$  eV
  - *Acceleration mechanisms* of high-energy cosmic rays

# The all-particle spectrum of cosmic rays

(PDG 1998)





# The Spectrum of Cosmic Rays

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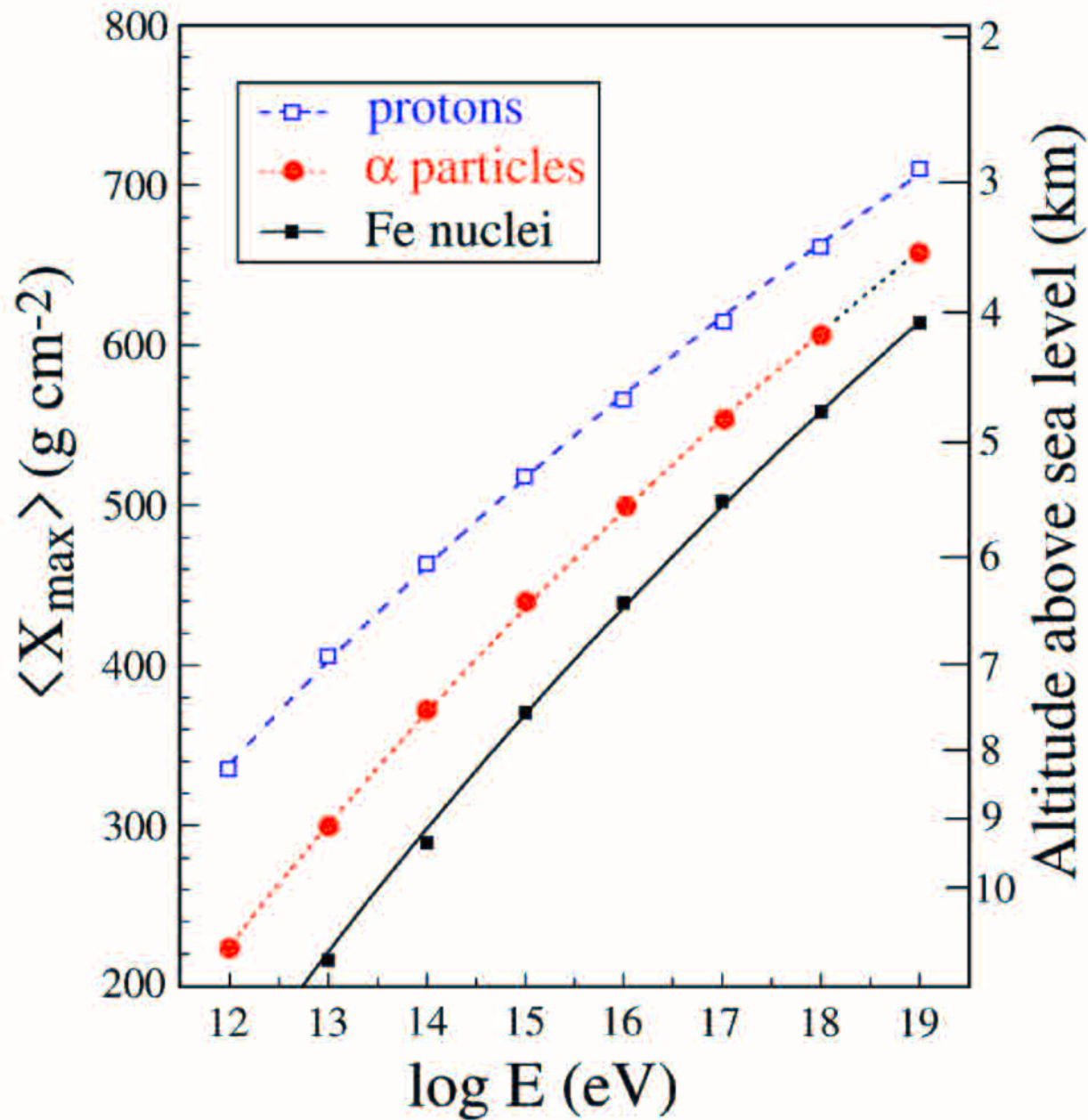
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  - *Acceleration mechanisms* of high-energy cosmic rays
- “Standard Model” of cosmic ray physics:
  - High-energy cosmic rays produced in *shockwaves* generated by *supernova* explosions
  - Model predicts power law spectrum
  - One SN every 30 years in our galaxy needed to explain the energy
  - Model predicts *maximum energy,  $\propto Z$* : Protons:  $E_{\text{max}} \approx 10^{14}$  eV,  $^{56}\text{Fe}$ :  $E_{\text{max}} \approx 3 \cdot 10^{15}$  eV  
dramatic changes in chemical composition between 0.1 and 3 PeV, *no protons at  $E \gtrsim 0.1$  PeV*
- Experimental data supporting this model are extremely *scarce*  
More and more experimental data seem to *contradict* this model (second knee,  $X_{\text{max}}$ )
- *Important:* Almost all cosmic rays up to  $\sim 10^{18}$  eV *originate in our own galaxy*

## Chemical Composition of Cosmic Rays

- *Direct* measurements (up to 10 TeV):
  - 50% protons
  - 30% He nuclei
  - 20% C,O,.....Fe nuclei
- In PeV regime, only *indirect* measurements available.
  - All available data comes from extensive air shower experiments
  - Earth's atmosphere is calorimeter with  $11\lambda$  thickness.
  - Depth of shower maximum* ( $X_{\text{max}}$ ) provides *statistical* information on Z

# Depth of shower maximum in Earth's atmosphere

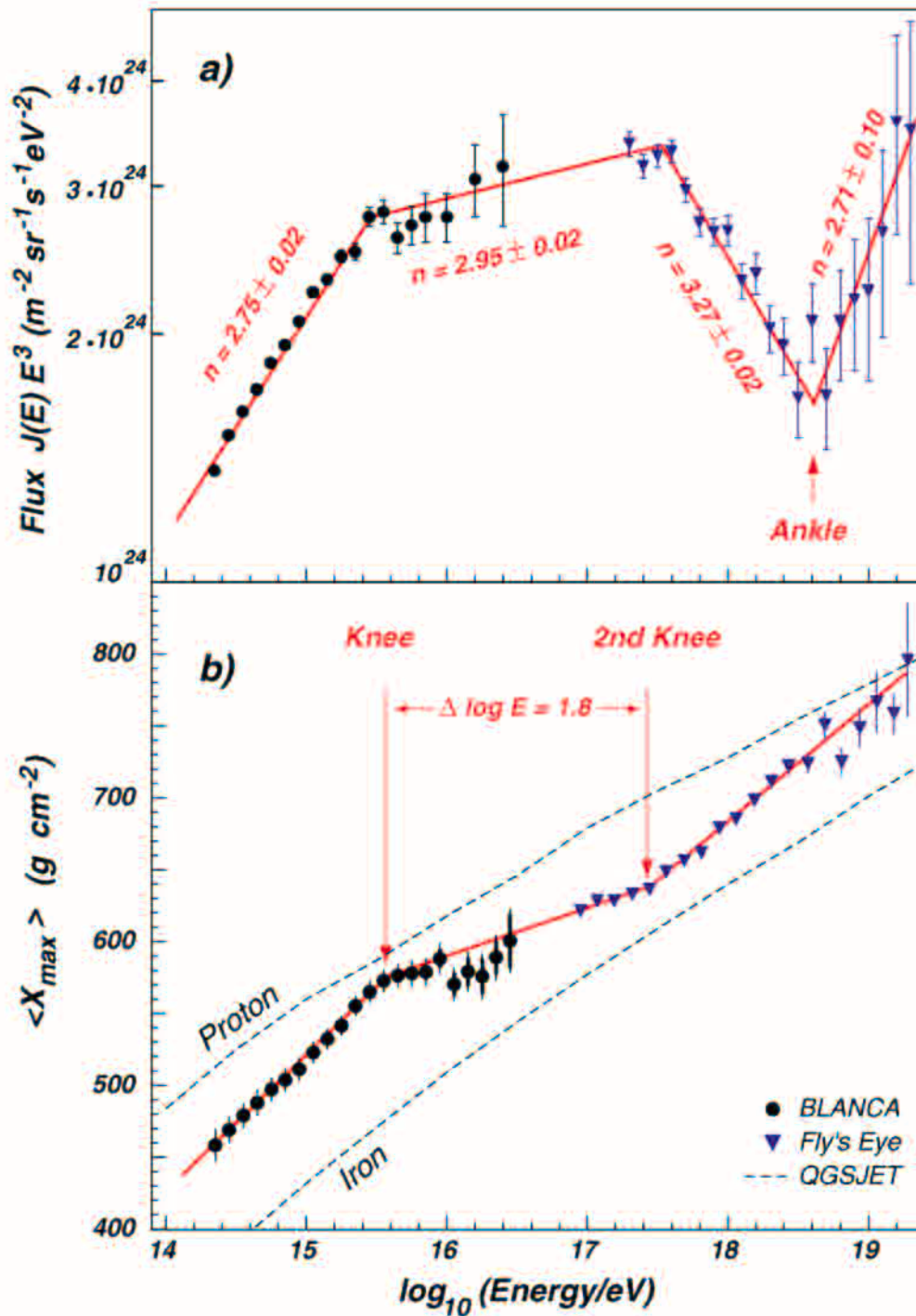


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Earth's atmosphere is calorimeter with  $11\lambda$  thickness.  
*Depth of shower maximum* ( $X_{\max}$ ) provides *statistical* information on Z
- As Z increases  
the first nuclear encounter occurs *at higher altitude*, and  
the *multiplicity of secondaries is larger*  
  
→  $X_{\max}$  is reached earlier, i.e. at higher altitude

Experimental data  
on

Spectral index  $n$



$X_{\max}$   
(depth shower max.)



# A Model to Explain ALL Features of the PeV Cosmic Rays

- The neutrino ( $\nu_e$ ) mass is  $0.4 \text{ eV}/c^2$   
( $0.5 \pm 0.2 \text{ eV}/c^2$  when taking a variety of measurements into account)

The *knee* at 3 - 4 PeV corresponds to the *threshold* for the reaction  $p + \bar{\nu}_e \rightarrow n + e^+$

Beyond the threshold, the spectrum is gradually depleted of protons.

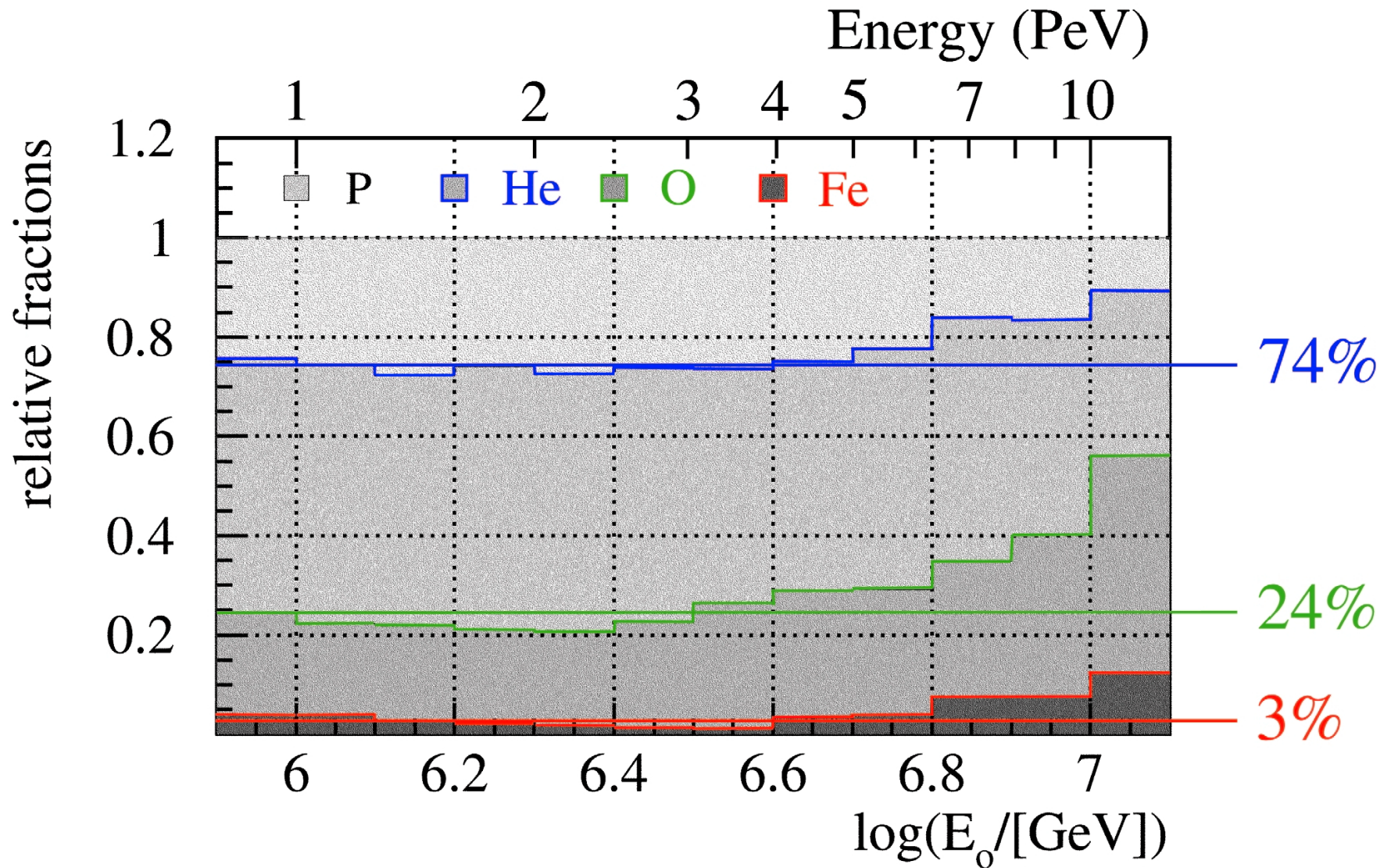
→ Experimentally verifiable predictions of this model:

- 1) The knee is a feature for protons and *protons alone*
- 2) *Abrupt change in chemical composition* at  $E > 4 \text{ PeV}$  ( $p$  disappear)

These predictions have been *experimentally confirmed* (KASKADE, BLANCA)

But there is (much) more!

# KASKADE results



Nucl. Phys. B (Proc. Suppl.) 85 (2000) 311

# Additional Predictions of the Alternative Model

- If cosmic protons interact with relic neutrinos, so do the  $\alpha$  particles:

$$\begin{array}{ll} \alpha + \nu_e \rightarrow 3p + n + e^- & Q = 27.5 \text{ MeV} \\ \alpha + \bar{\nu}_e \rightarrow p + 3n + e^+ & Q = 30.1 \text{ MeV} \end{array}$$

$$E_{\text{cm}} = m_\alpha + Q \approx \sqrt{m_\alpha^2 + 2E_\alpha m_\nu}, \quad \text{substitute } m_\alpha = 3727.40 \text{ MeV}$$

$$\rightarrow E_{\text{thresh}}(\alpha\nu_e) \approx 61 E_{\text{thresh}}(p\bar{\nu}_e), \quad E_{\text{thresh}}(\alpha\bar{\nu}_e) \approx 66 E_{\text{thresh}}(p\bar{\nu}_e)$$

$$\rightarrow E_{\text{th}}(\alpha\nu_e)/E_{\text{th}}(p\bar{\nu}_e) = 63.6 \pm 3.0, \text{ or } \Delta \log E_{\text{th}} = 1.80 \pm 0.03$$

→ Expect second kink in cosmic ray spectrum!

→ Expect abrupt change in chemical composition at this second kink

Below 300 PeV,  $\alpha$ 's dominate the cosmic spectrum,

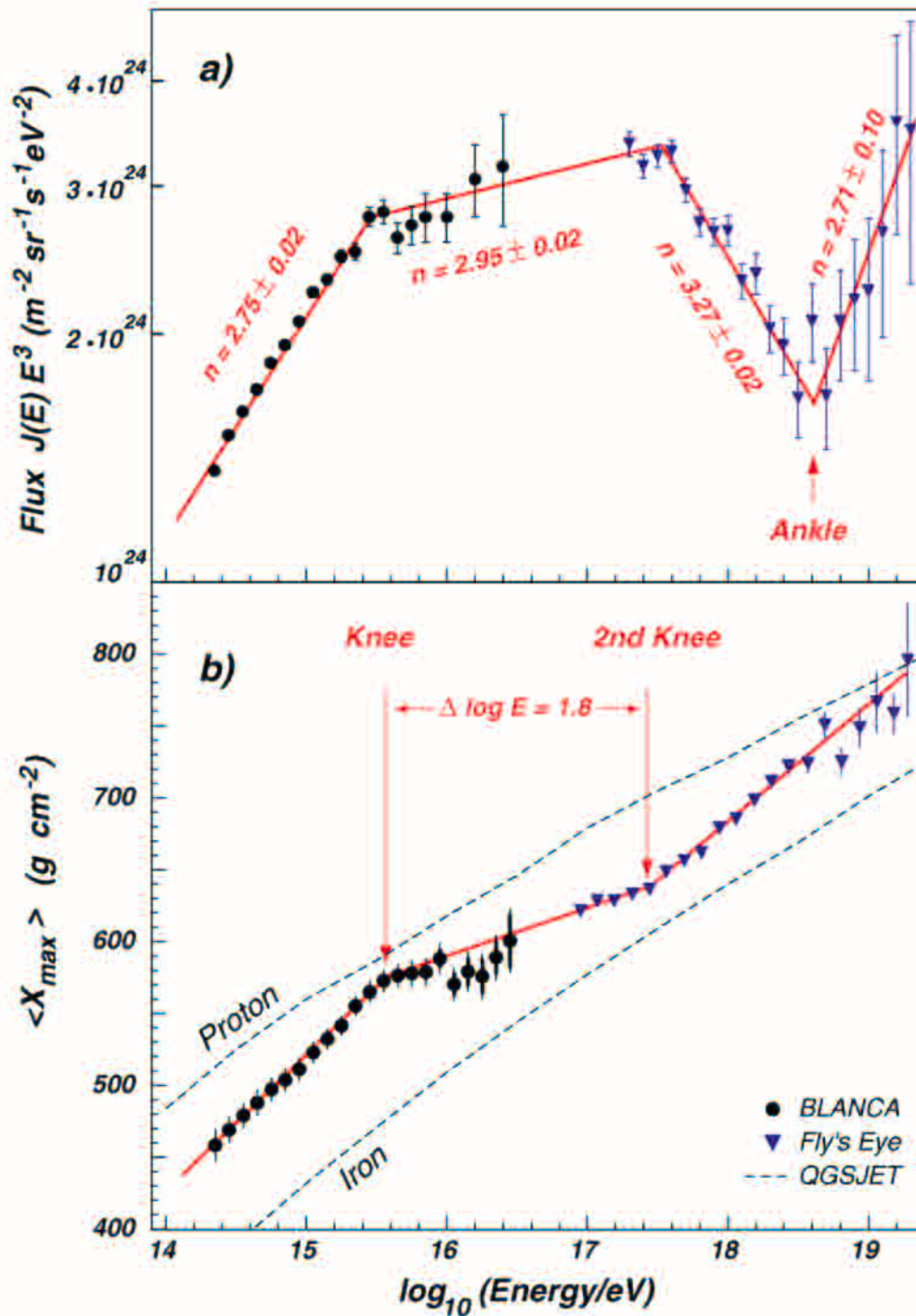
above 300 PeV,  $\alpha$ 's disappear, protons (reaction products) reappear

- These predictions are *confirmed in great detail* by extensive air-shower experiments Fly's Eye, CASA BLANCA, Haverah Park: See measurements of  $n$ ,  $X_{\text{max}}$



Experimental data  
on

Spectral index  $n$



$X_{\max}$   
(depth shower max.)

# PeV cosmic rays: a window on the leptonic era?

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## Abstract

It is shown that a variety of characteristic features of the high-energy hadronic cosmic-ray spectra, in particular the abrupt changes in the spectral index that occur around 3 and 300 PeV, as well as the corresponding changes in elemental composition that are evident from kinks in the  $\langle X_{\text{max}} \rangle$  distribution, can be explained in great detail from interactions with relic Big Bang antineutrinos, provided that the latter have a rest mass of  $\sim 0.5 \text{ eV}/c^2$ .  
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**Keywords:** Cosmic rays; Knee; Relic neutrinos; Neutrino mass

## 1. Introduction

The energy region between 1 and 10 PeV is an area of intense study in cosmic-ray research. The all-particle cosmic-ray energy spectrum falls extremely steeply with energy. In general, it is well described by a power law

$$\frac{dN}{dE} \sim E^{-n} \quad (1)$$

with  $n \approx 2.7$  for energies below 1 PeV. The steepening that occurs between 1 and 10 PeV, where the spectral index  $n$  changes abruptly from 2.7 to 3.0, is known as the *knee* of the cosmic-ray spectrum.

This phenomenon is generally believed to contain key information about the origin of the cosmic rays and about the acceleration mechanisms that play a role. Especially models in which the

cosmic rays are resulting from particle acceleration in the shock waves produced in Supernova explosions have received much attention in the literature. Such models predict a maximum energy, proportional to the nuclear charge  $Z$  of the particles [1]. In the context of these models, the knee is assumed to be associated with this ( $Z$ -dependent) maximum and the corresponding cutoff phenomena. In the past years, major efforts have been mounted to determine the elemental composition of the cosmic rays in the knee region. These efforts have revealed that the knee coincides with an abrupt change in the elemental composition of the cosmic rays.

We would like to point out that the high-energy cosmic-ray spectra contain several other remarkable features. For example, there is a significant second knee in the energy spectrum at  $\sim 300 \text{ PeV}$ , which coincides with an abrupt change in the elemental composition as well. Even though these features are experimentally well established, they have received little or no attention in the literature.

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## Conclusions, part 2

- The cosmic ray spectrum exhibits a number of intriguing features that can be explained in a coherent manner from interactions between cosmic protons,  $\alpha$ 's and **0.4 eV** relic (anti-)neutrinos:
  - Two *kinks* at  $4 \cdot 10^{15}$  eV and  $3 \cdot 10^{17}$  eV (*thresholds* for  $p\bar{\nu}_e$  and  $\alpha\bar{\nu}_e$ )
  - *Energy separation between kinks* consistent with  $Q$ -values ( $\Delta \log E_{\text{th}} = 1.80 \pm 0.03$ )
  - *Abrupt changes in chemical composition* at both kinks, commensurate with explanation (protons disappear at first kink, reappear at the second one)
- If collisions with relic neutrinos are indeed responsible for these features, *a large concentration* of such neutrinos must be present *in the vicinity of the source* of the high energy cosmic rays. A *massive black hole* in the center of our galaxy is a *plausible candidate*
- If the neutrino mass is indeed  $\sim 0.4$  eV, then the total mass of relic neutrinos in the Universe is compatible with the mass contained in baryons  
*Relic neutrinos are thus a significant component of dark matter*  
(consistent with spherical shape of dark matter halo of galaxies!)

# Summary

- *Relic neutrinos from the Leptonic Era may hold the keys to unraveling some of the great mysteries of the Universe:  
Large scale structure, accelerated expansion, dark matter*
- *Fermion degeneracy effects are usually associated with extremely hot/dense conditions inside White Dwarfs and neutron stars  
They may also play a crucial role in the empty, cold intergalactic space*



*and finally*

*If* this is all true, then

- *Quantum Mechanics drives the expansion of the Universe!!*
- *We are witnessing Quantum Gravity at work*

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Of course, the model proposed in this paper has speculative elements. If the neutrino mass is indeed of the order of  $0.5 \text{ eV}/c^2$ , then violation of the Pauli principle must have been a serious issue when galaxies started to form. Nature might of course have used other ways to prevent such a violation, instead of the one proposed in this paper, although it is unclear what these other ways could be. However, if the model proposed in this paper turned out to be correct, it means that the expansion of the Universe and the observed peculiarities in this process are essentially a consequence of Quantum Mechanics. It would also be the first observation of the effects of gravity at the quantum level. The intimate link between the structure of matter in its smallest details and on its largest imaginable scales is further illustrated by the crucial role played by the value of the neutrino mass in the expansion of the Universe. If our model is correct, this value must be about  $0.5 \text{ eV}/c^2$ , which might make it accessible to direct measurements planned for the near future.

*Note added in proof*

*Recently, the KATRIN Collaboration reported a new result of their measurement of the neutrino mass in tritium decay*

*arXiv 2105.08533 (May 18, 2021)*

$$m_{\nu}^2 = 0.26 \pm 0.34 \text{ (eV/c}^2\text{)}^2$$

*i.e.  $m_{\nu} = 0.5 \pm 0.6 \text{ eV/c}^2$   
error dominated by systematic effects*