Neutrino Astrophysics

part one

Francesco Vissani
INFN, Laboratori Nazionali del Gran Sasso

This lecture replaces the one of my colleague and friend Cecilia Lunardini, who unfortunately could not join.

It is based on a series of lectures I gave at GGI one year ago

Event at Galileo Galilei Institute

GGI Lectures on the Theory of Fundamental Interactions 2023

Jan 09, 2023 - Jan 27, 2023

neutrinos: lecture plan

1) **Main properties of neutrinos, Majorana formalism**
2) **Neutrino transformations (oscillations)**
3) **Natural neutrino sources and their observations**
4) **Artificial sources, introduction to data analysis**
5) **Theoretical aspects**

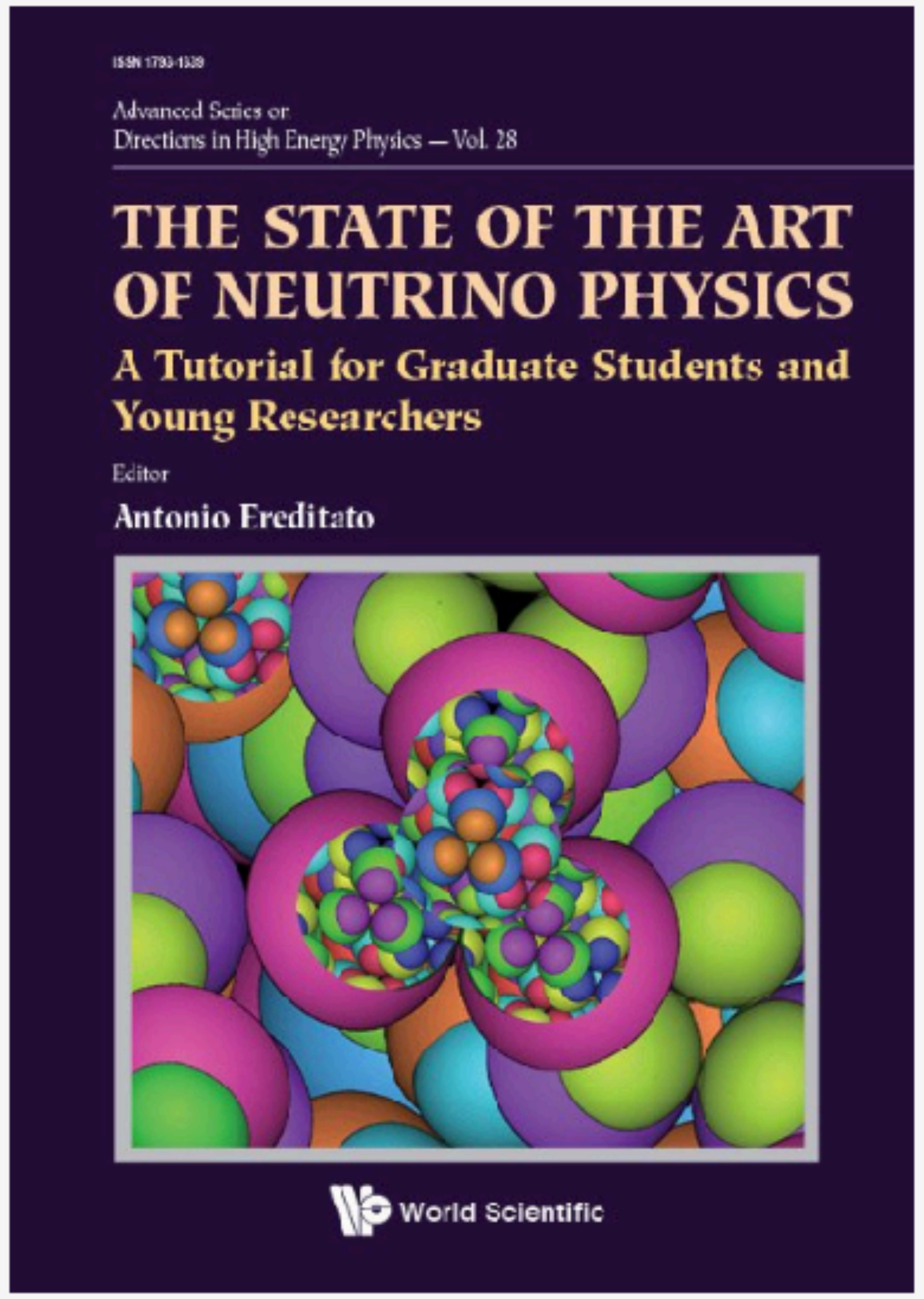
We introduce the features of neutrinos, of foundational relevance for the standard model but also for revealing its limits; moreover we discuss the main observations, concerning these intriguing particles. We examine some technical aspects of particular importance and propose a few exercises to trigger discussion.

main references I used

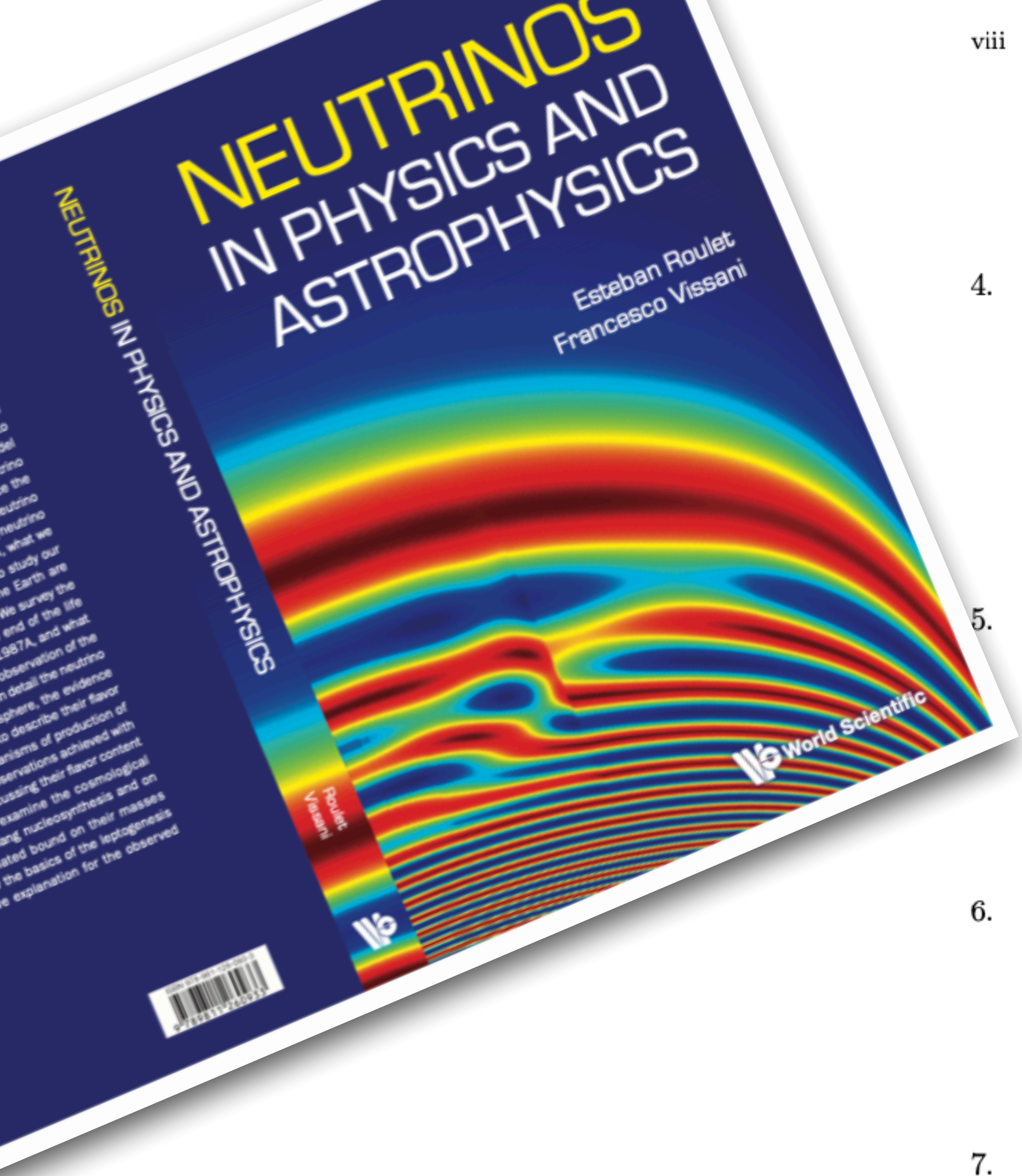
Advanced Series on Directions in High Energy Physics
| The State of the Art of Neutrino Physics, pp. 37-119 (2018)

Chapter 2: Introduction to the Formalism of Neutrino Oscillations

G. Fantini, A. Gallo Rosso, V. Zema and F. Vissani



also
https://arxiv.org/pdf/1802.05781.pdf



Neutrinos in Physics and Astrophysics

https://doi.org/10.1142/12982 | October 2022
Pages: 250

By (author): Esteban Roulet (*CONICET, Argentina*) and Francesco Vissani (*INFN, Italy*)

ISBN: 978-981-126-093-3 (hardcover)

Neutrinos - 2

ultra-relativistic neutrino “oscillations”

Francesco VISSANI - Laboratori Nazionali del Gran Sasso - Jan 24, 2023

EXERCISES

- check that the matter term has dimensions of energy (as it should be)
- reinsert the factors **ħ** and **c** and check the following numerical formulae

$$V = \sqrt{2}\, G_{\rm F} n_{\rm e} = \frac{3.868 \times 10^{-7}}{\rm m} \times \frac{n_{\rm e}}{\rm mol/cm^3}$$

$$k = \frac{\Delta m^2}{2E} = \frac{2.533}{\rm m} \times \frac{\Delta m^2}{\rm eV^2} \times \frac{\rm MeV}{E}$$

- compare the size of the matter term with the vacuum term and discuss when the two are similar

neutrino transformation (oscillations)

an essential reminder of the relevant theoretical ingredients

the neutrinos produced in weak interactions are superposition of mass eigenstates

$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$

this is not a stationary state, $|\nu_e, t\rangle \neq |\nu_e\rangle$, due to the phases of propagation $|\nu_i\rangle \to \exp\left(-i\frac{E_i t}{\hbar}\right)|\nu_i\rangle$ with $E_i = \sqrt{(pc)^2 + (m_i c^2)^2}$; thus, the probability $P_{\nu_e\to\nu_e} = \left|\langle\nu_e, t|\nu_e\rangle\right|^2$ deviates from unity

furthermore, the state $|\nu_e\rangle$ receives another special phase (=Mikheyev-Smirnov-Wolfenstein effect) when it propagates in matter rich of electrons, due to weak interactions. The effect on oscillations depends upon the ratio

$$\varepsilon_\odot = \frac{\sqrt{2}G_F N_e^\odot}{\Delta m^2/(2E_\nu)} \approx 1.04 \left(\frac{N_e^\odot}{100\ \text{mol}}\right)\left(\frac{7.37\times 10^{-5}\ \text{eV}^2}{\Delta m^2}\right)\left(\frac{E_\nu}{5\ \text{MeV}}\right)$$

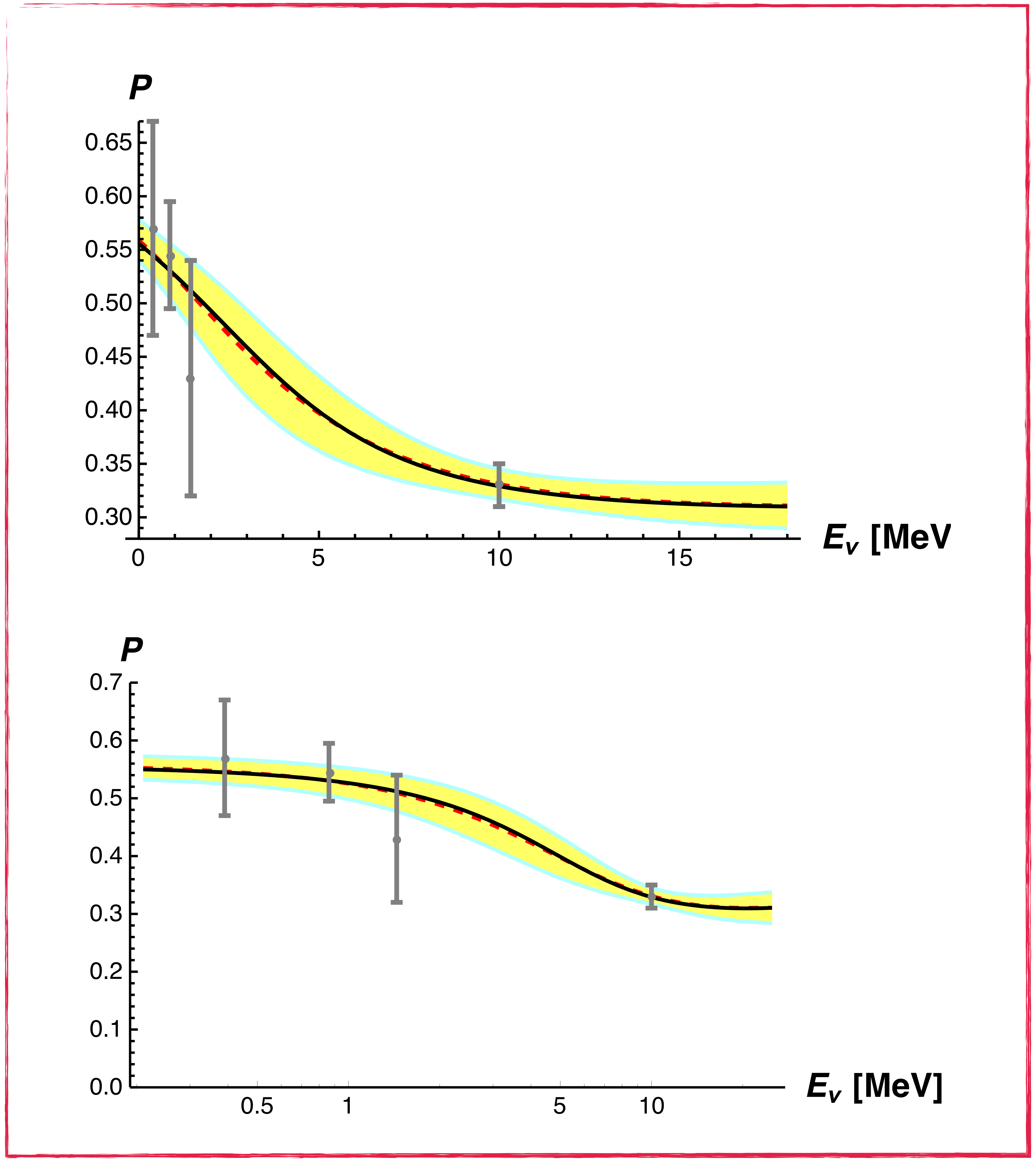
survival probability

of the electron neutrinos in the Sun

- the probabilities differ from 1
- something around 5 MeV

this is a success of MSW theory

these two graphs are based on SNO and Borexino measurements. Recently SK revised day/night and slope now better



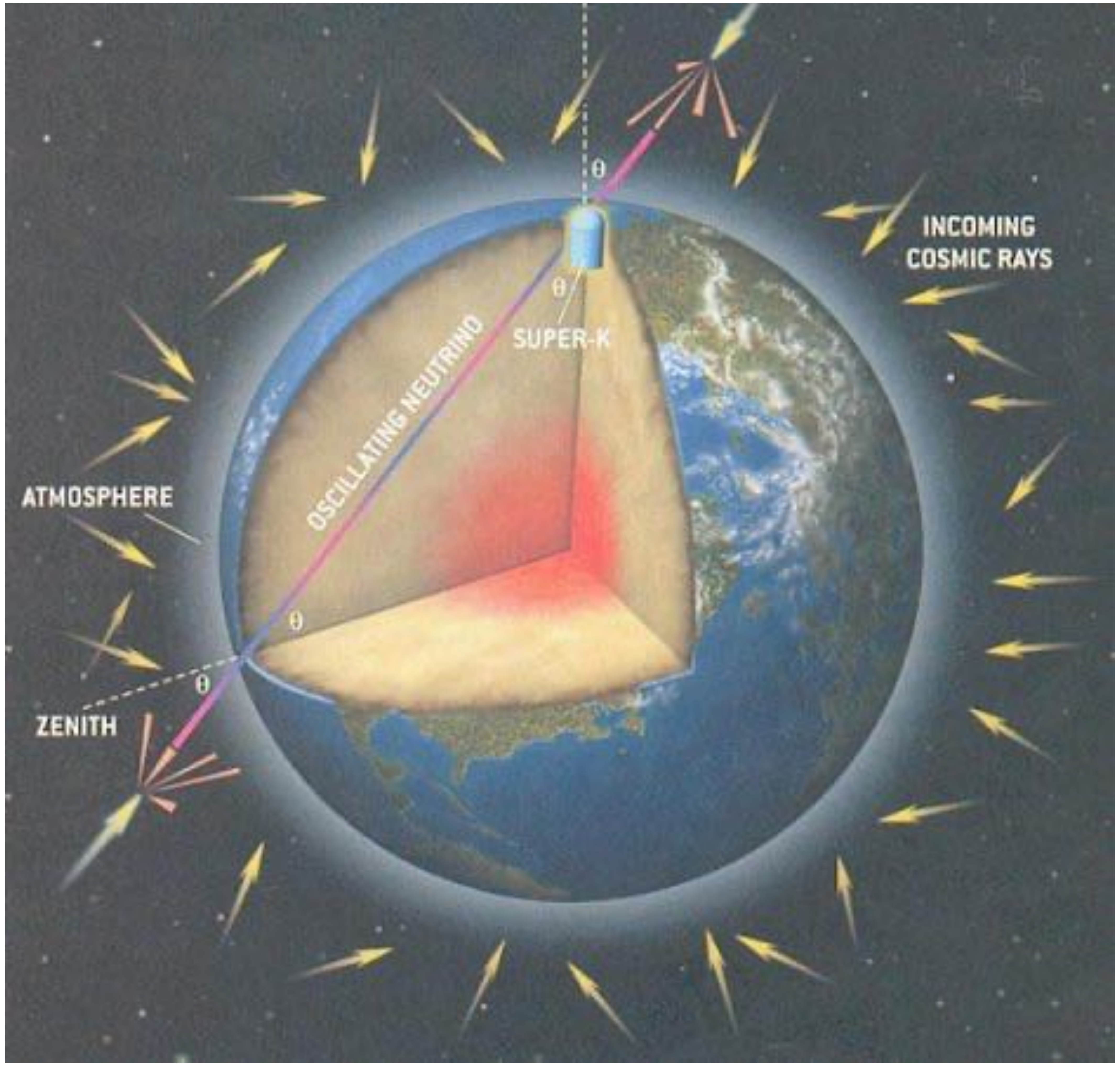
atmospheric neutrinos

and neutrino oscillations

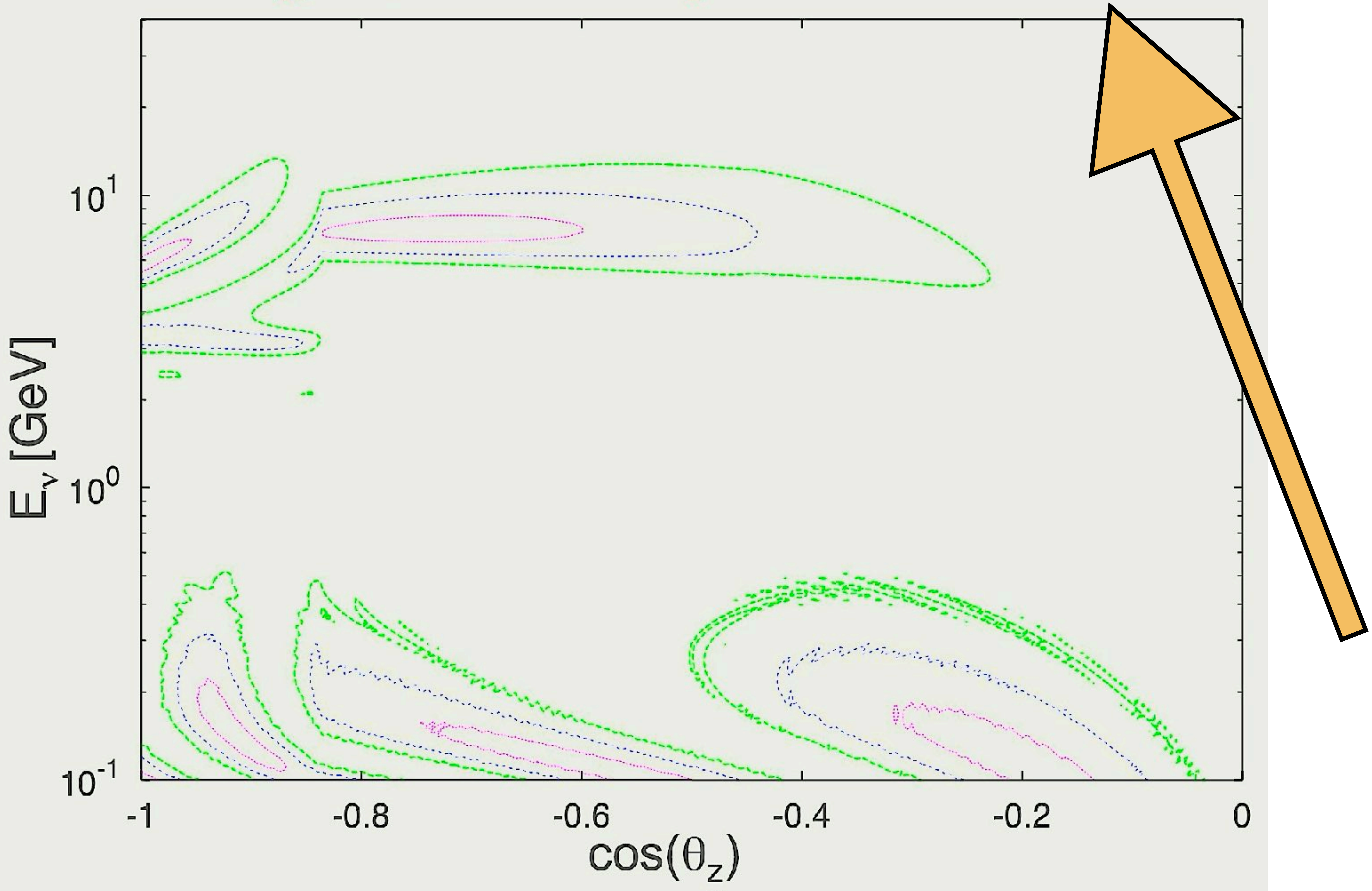
two predictions concerning atmospheric neutrinos show evidence of oscillations at $E_\nu \sim$ GeV energies, as a function of θ_{zenith}

1. the **muon-to-electron ratio**, which goes from 2 to 1
2. the **up-down symmetry** which is not obeyed for muon neutrinos

MSW effect expected at $E_\nu \sim 5$ GeV



P_{ee}=0.7, 0.5, 0.3 through the Earth (La Thuile 2003)



oscillations of high energy neutrinos is simple

Gribov-Pontecorvo = classical regime does apply

ordering	P_0	P_1	P_2
NO	0.113 ± 0.006	$0.0345^{+0.010}_{-0.012}$	$0.0075^{+0.0045}_{-0.0038}$
IO		$0.0285^{+0.010}_{-0.057}$	$0.008^{+0.005}_{-0.006}$

Table 4. The natural parameters obtained from Monte Carlo sampling the oscillation parameters from [30] according to their distribution.

A Neutrino oscillation/survival probabilities and their distributions

In order to account for neutrino oscillations, we followed the methodology of [43], which i based on the observation that the oscillation matrix $P_{\ell\ell'}$ is symmetric under $\ell \leftrightarrow \ell'$:

$$P_{\ell\ell'} = \sum_{i=1}^{3} |U_{\ell i}^2||U_{\ell' i}^2| \qquad \ell, \ell' = e, \mu, \tau$$

and thus they worked out a "natural" parametrization with just three independent param eters, named P_0, P_1 and P_2. $P_{\ell\ell'}$ is then parametrized as follows:

$$P_{\ell\ell'} = \begin{pmatrix} 1/3 + 2P_0 & 1/3 - P_0 + P_1 & 1/3 - P_0 - P_1 \\ & 1/3 + P_0/2 - P_1 + P_2 & 1/3 + P_0/2 - P_2 \\ & & 1/3 + P_0/2 + P_1 + P_2 \end{pmatrix}$$

EXERCISES

- Convince yourself that oscillations are unavoidable for high energy cosmic neutrinos - assume E_ν >1 TeV

- How a tau neutrino could be possibly seen?
  (This would be a "space OPERA" experiment).

- Is it possible that very high energy cosmic neutrinos produce a real W boson decaying into two jets?

Available online at www.sciencedirect.com
SCIENCE DIRECT
Nuclear Physics B 708 (2005) 215–267
NUCLEAR PHYSICS B

Probing oscillations into sterile neutrinos with cosmology, astrophysics and experiments

M. Cirelli [a], G. Marandella [b], A. Strumia [c], F. Vissani [d]

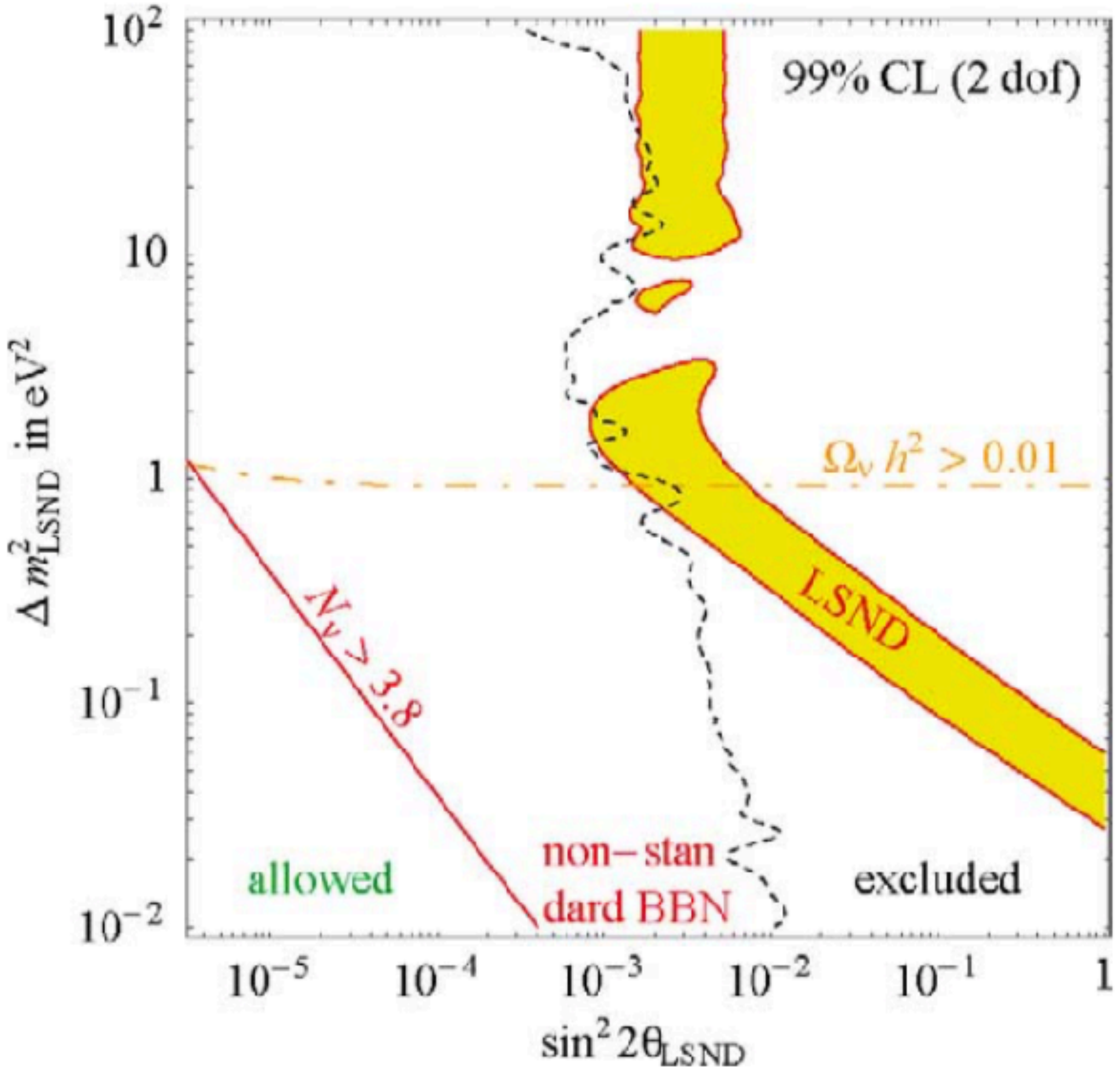
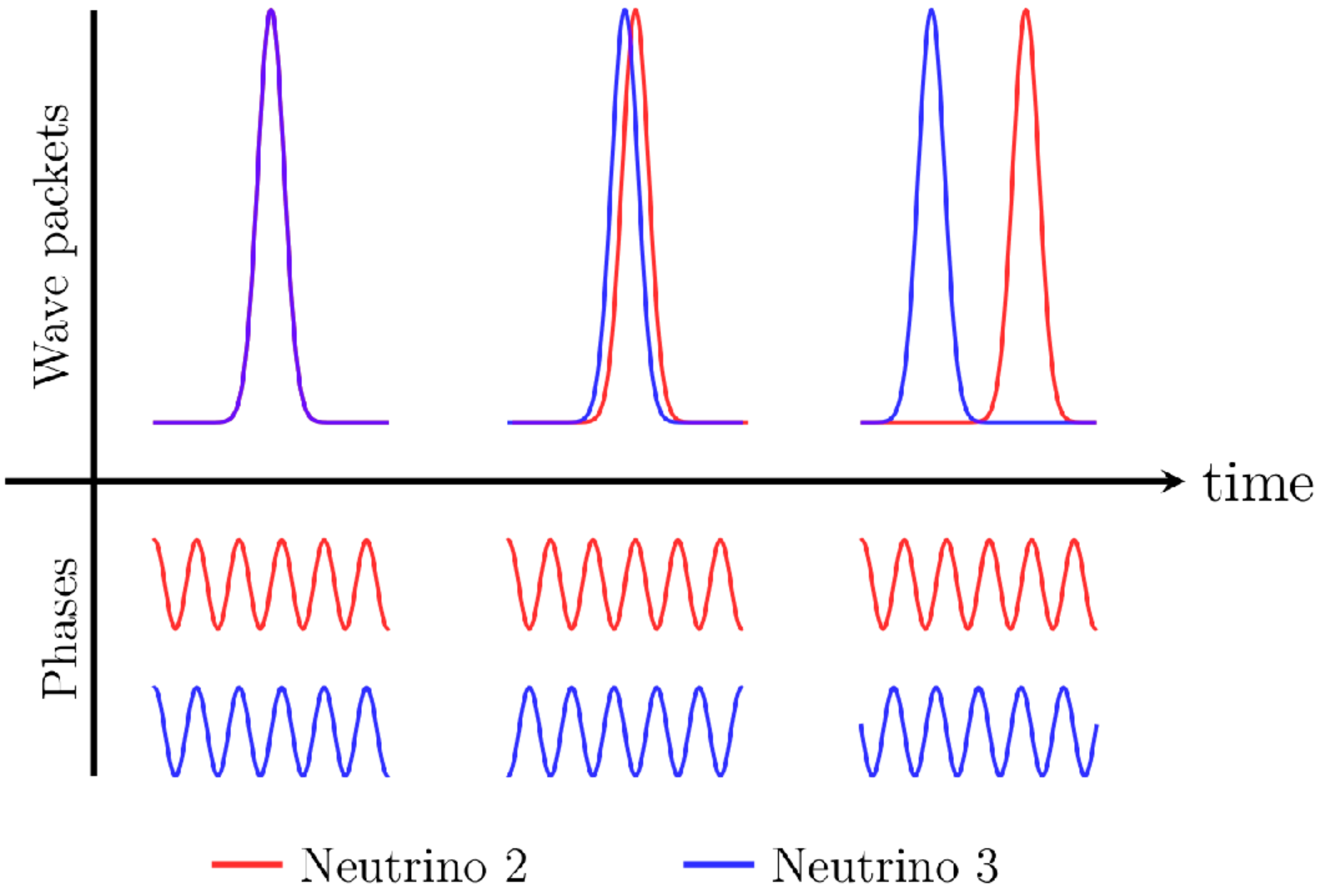


Fig. 13. The LSND anomaly interpreted as oscillations of 3 + 1 neutrinos. Shaded region: suggested at 99% C.L. by LSND. Black dotted line: 99% C.L. global constraint from other neutrino experiments (mainly Karmen, Bugey, SK, CDHS). Continuos red line: $N_\nu = 3.8$ thermalized neutrinos. Dot-dashed orange line: $\Omega_\nu h^2 = 0.01$.

the picture inclusive of wavepackets



wavepacket of a flavor state

$$[\Psi^\ell(t)]_{\ell'} = U_{\ell' j} e^{i(pz - E_j t)} \mathcal{G}(z - v_j t) U^*_{\ell j}$$

for a wavepacket with $\delta E\, \delta t \sim \hbar$

time for `un-packeting'	time for `de-phasing'
$v_1 t - v_2 t \sim c\ \delta t$ →	$E_2 t' - E_1 t' \sim \hbar$ →
$t \sim \dfrac{2E^2/c^4}{m_2^2 - m_1^2} \times \delta t$	$t' \sim t \times \dfrac{\delta E}{E}$

EXERCISE: prove it using c=1, $v_i = p/E_i$ and $E_i^2 = p^2 + m_i^2$

Neutrinos - 3

main natural sources, detectors, characteristics and properties, a few open issues

Francesco VISSANI - Laboratori Nazionali del Gran Sasso - Jan 25, 2023

this lecture

selected topics in astroparticle neutrinos physics

- solar neutrinos
- geoneutrinos
- ((supernova neutrinos))
- atmospheric neutrinos
- HE astroph. neutrinos

Solar neutrinos

(is not only matter of oscillations)

The Nobel Prize in Physics 2002

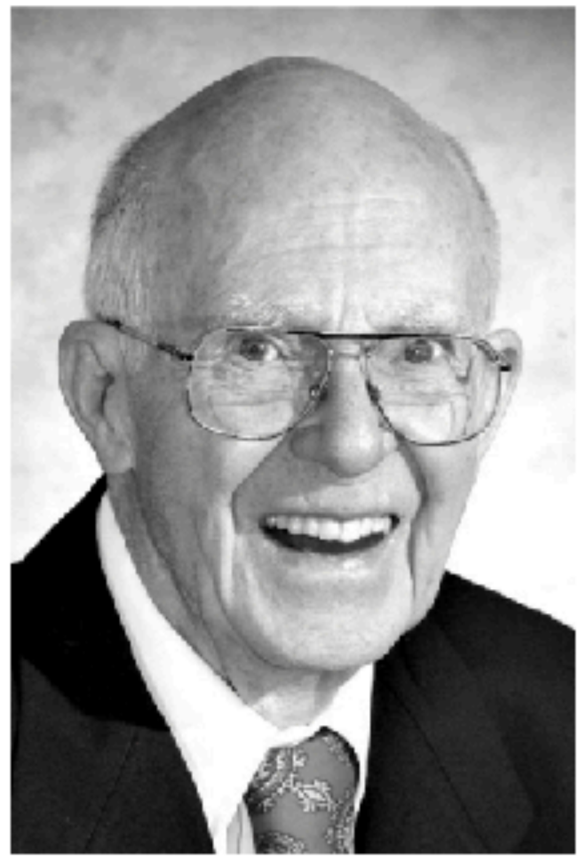


Photo from the Nobel Foundation archive.
Raymond Davis Jr.
Prize share: 1/4


Photo from the Nobel Foundation archive.
Masatoshi Koshiba
Prize share: 1/4


Photo from the Nobel Foundation archive.
Riccardo Giacconi
Prize share: 1/2

The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba "for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos" and the other half to Riccardo Giacconi "for pioneering contributions to

Davis: first **observation of solar neutrinos**
Koshiba: observation of **solar** and supernova neutrinos

The Nobel Prize in Physics 2015


© Nobel Media AB. Photo: A. Mahmoud
Takaaki Kajita
Prize share: 1/2


© Nobel Media AB. Photo: A. Mahmoud
Arthur B. McDonald
Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."

Kajita: experimental proof of oscillation with atmospheric neutrinos
McDonald: experimental proof of oscillation with **solar neutrinos**

also Sakata (1911-1970), Pontecorvo (1913-1993), Bahcall (1934-2005) had much merit for neutrino science

Direct Approach to Resolve the Solar-Neutrino Problem

Herbert H. Chen
Department of Physics, University of California, Irvine, California 92717
(Received 27 June 1985)

A direct approach to resolve the solar-neutrino problem would be to observe neutrinos by use of both neutral-current and charged-current reactions. Then, the total neutrino flux and the electron-neutrino flux would be separately determined to provide independent tests of the neutrino-oscillation hypothesis and the standard solar model. A large heavy-water Cherenkov detector, sensitive to neutrinos from ^8B decay via the neutral-curent reaction $\nu + d \to \nu + p + n$ and the charged-current reaction $\nu_e + d \to e^- + p + p$, is suggested for this purpose.

PACS numbers: 96.60.Kx, 14.60.Gh

The solar-neutrino problem, i.e., fewer neutrinos are assigned to the sun in the chlorine-argon radiochemical experiment of Davis and co-workers[1] than predicted by the standard solar model,[2] has prompted a variety of possible solutions ranging from neutrino oscillations[3] to a very large number of nonstandard solar models.[4]

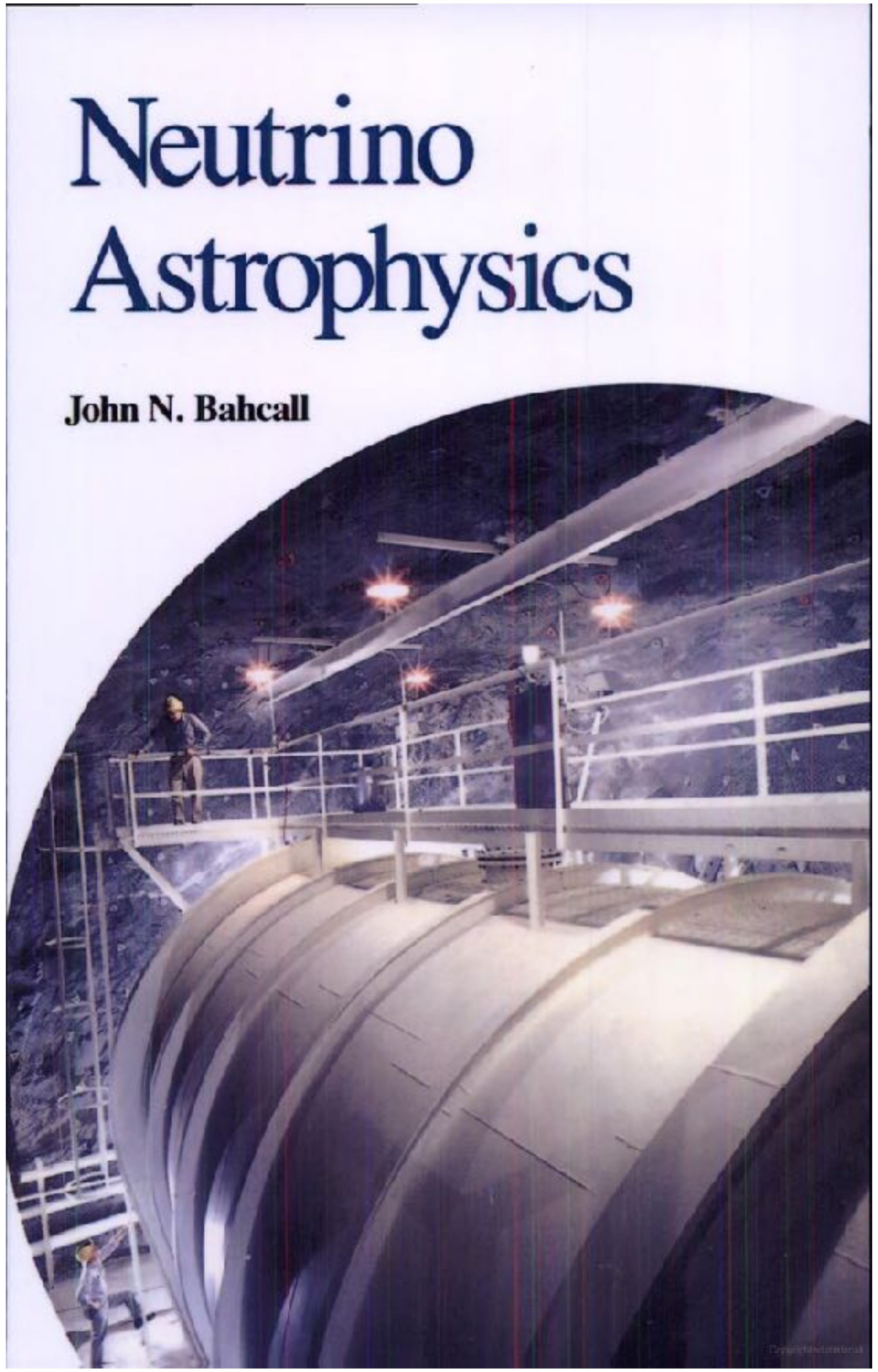
[1] R. Davis, Jr., D. S. Harmer, and K. C. Hoffman, Phys. Rev. Lett. **20**, 1205 (1968); J. N. Bahcall and R. Davis, Jr., Science **191**, 264 (1976); J. K. Rowley, B. T. Cleveland, and R. Davis, Jr., in *Solar Neutrinos and Neutrino Astronomy (Homestake, 1984)*, edited by N. L. Cherry, W. P. Fowler, and K. Lande, AIP Conference Proceedings No. 126 (American Insitute of Physics, New York, 1985), p. 1.

[2] J. N. Bahcall, W. F. Huebner, S. H. Lubow, P. D. Parker, and R. K. Ulrich, Rev. Mod. Phys. **54**, 767 (1982).

[3] B. Pontecorvo, Zh. Eksp. Teor. Fiz. **53**, 1717 (1967) [Sov. Phys. JETP **26**, 984 (1968)]; V. Gribov and B. Pontecorvo, Phys. Lett. **28B**, 495 (1969); S. M. Bilenky and B. Pontecorvo, Phys. Rep. **41**, 226 (1978).

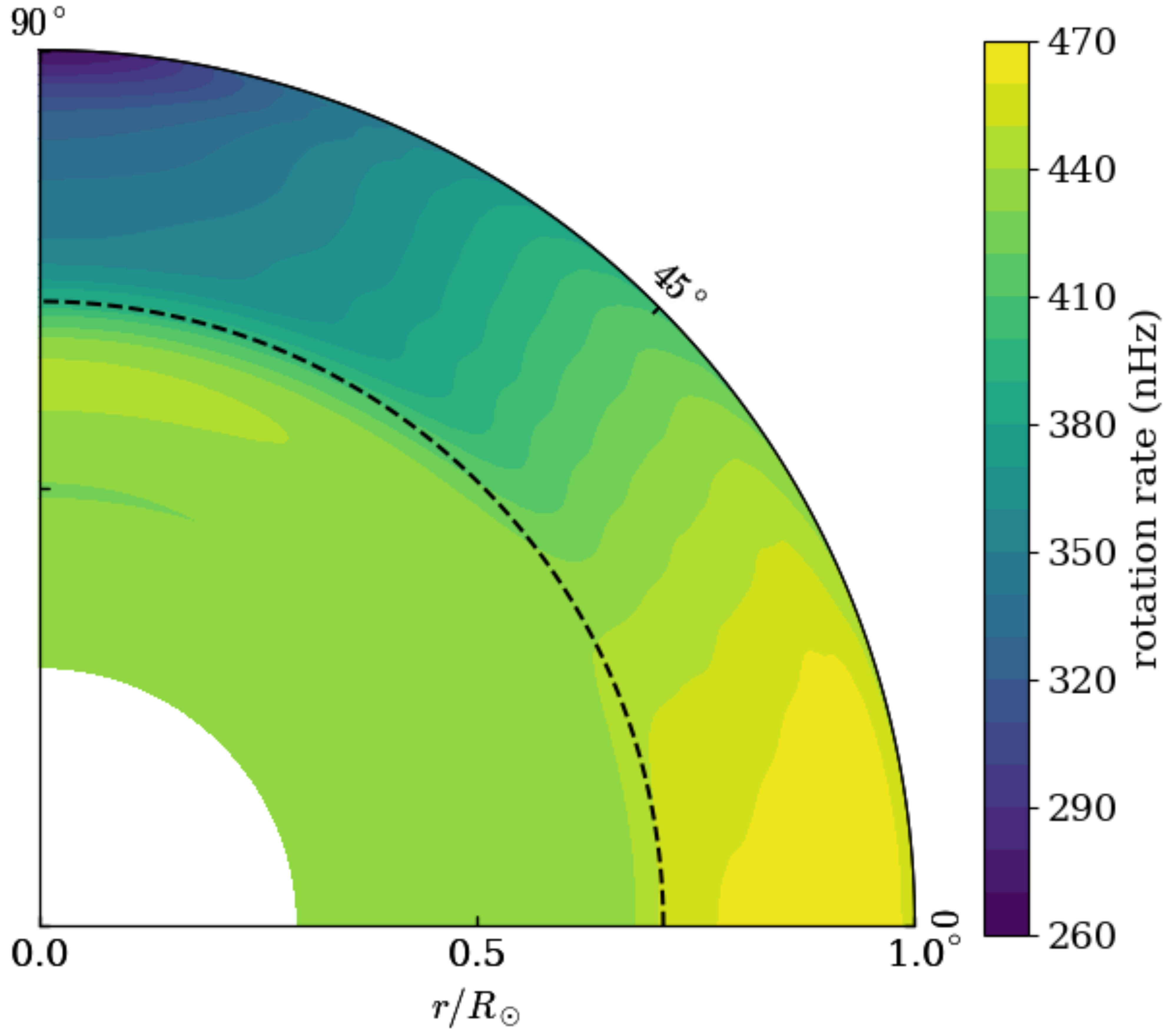
Bahcall 1989

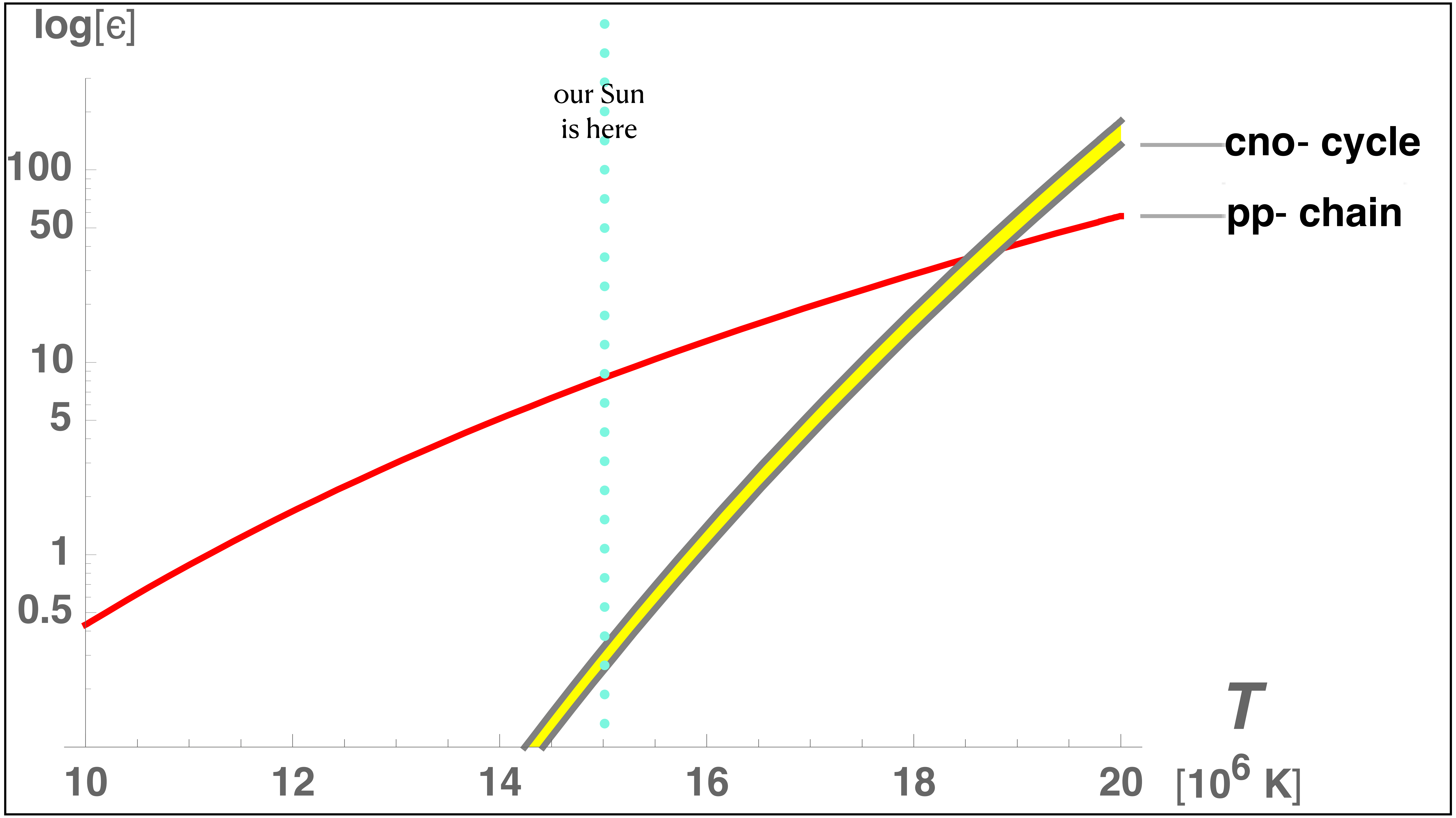
is still an excellent source of information especially on solar neutrinos



Generalities on the Sun

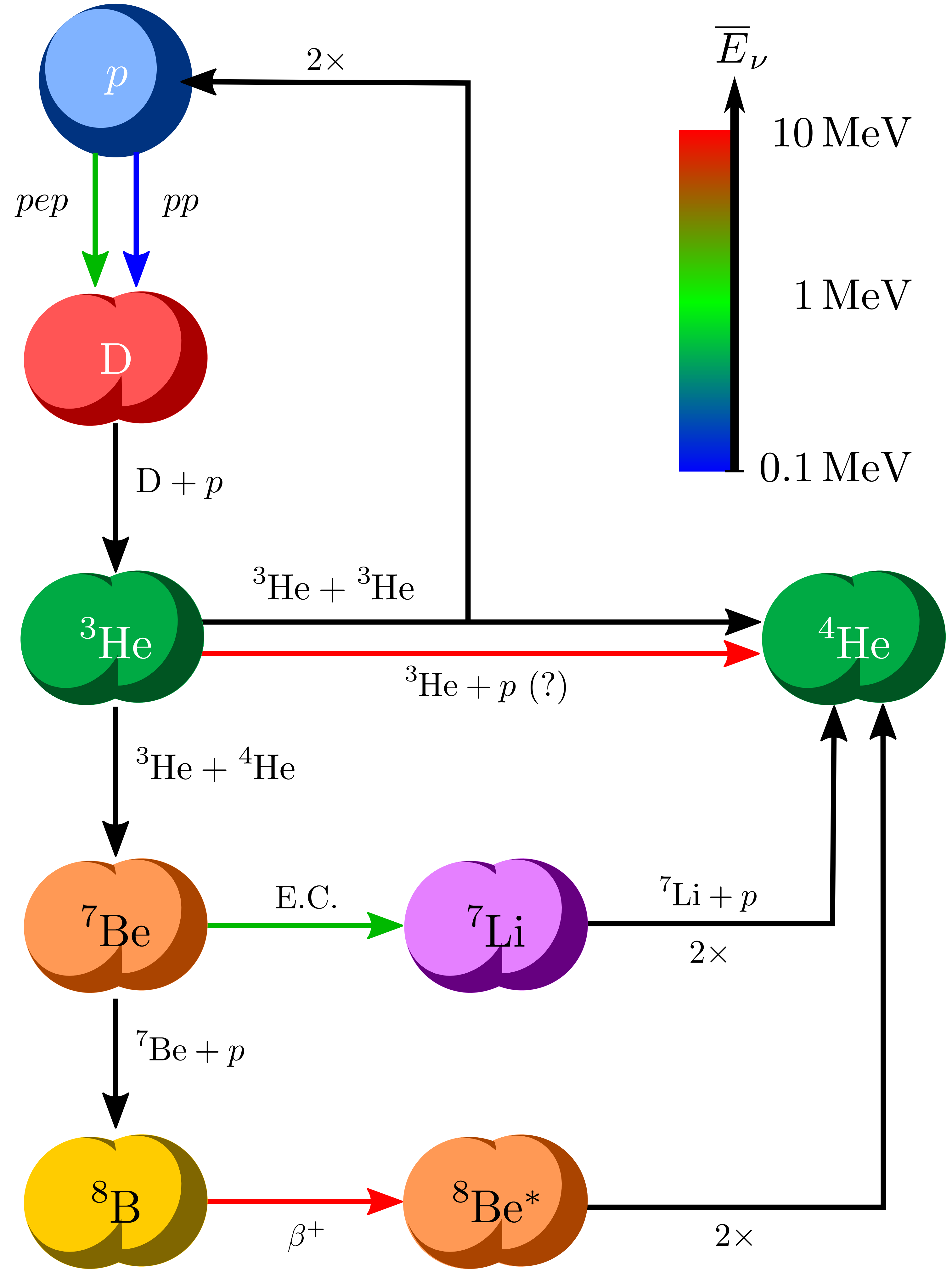
- The sun radiates a prodigious amount of energy, $L_\odot = 3.828 \times 10^{33}\,\frac{\text{erg}}{\text{s}}$
- Elemental abundances at its surface, roughly summarized by *X,Y,Z*
- Helioseismology allows to measure the velocity of the sound and the depth of the convective zone

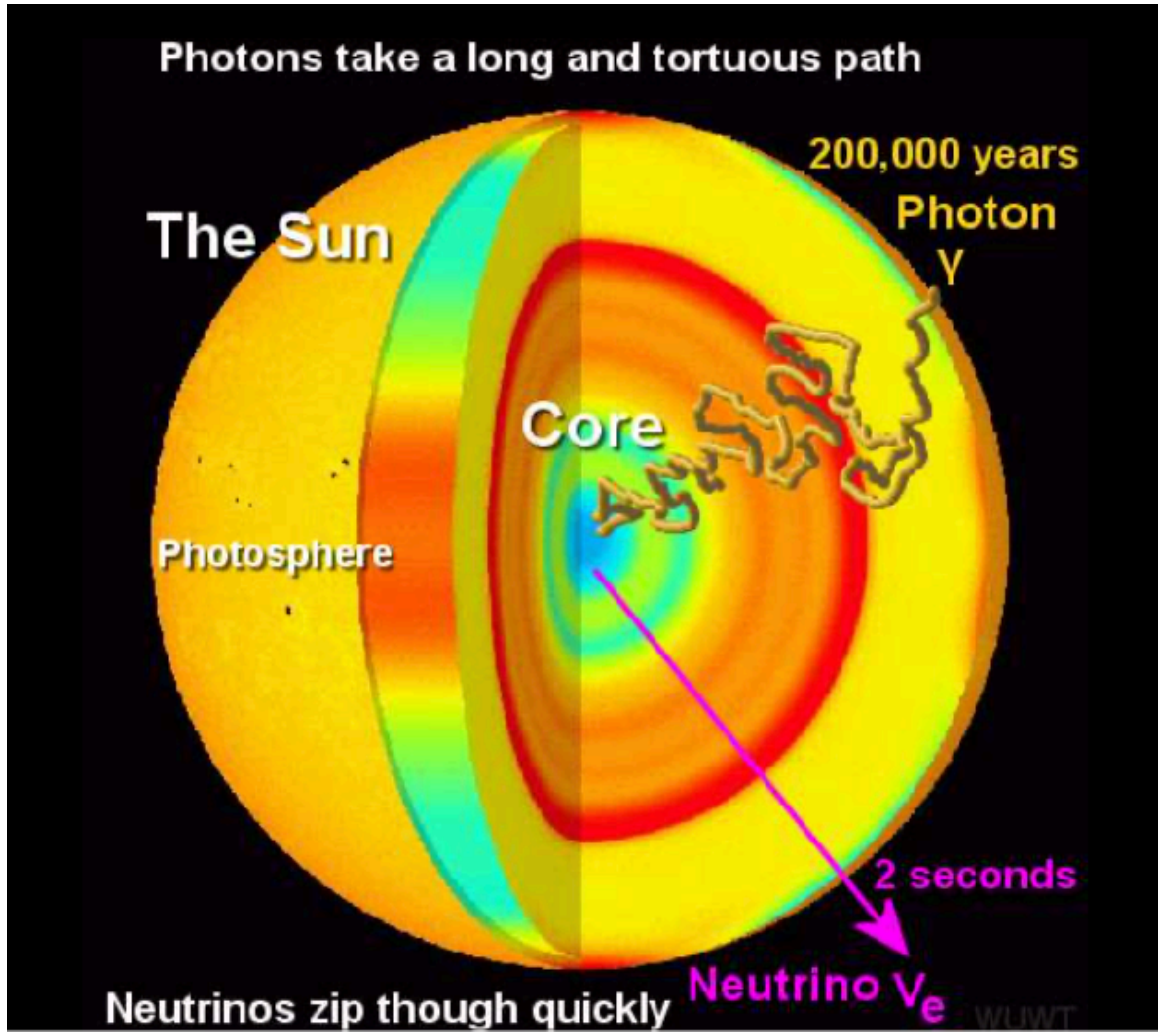


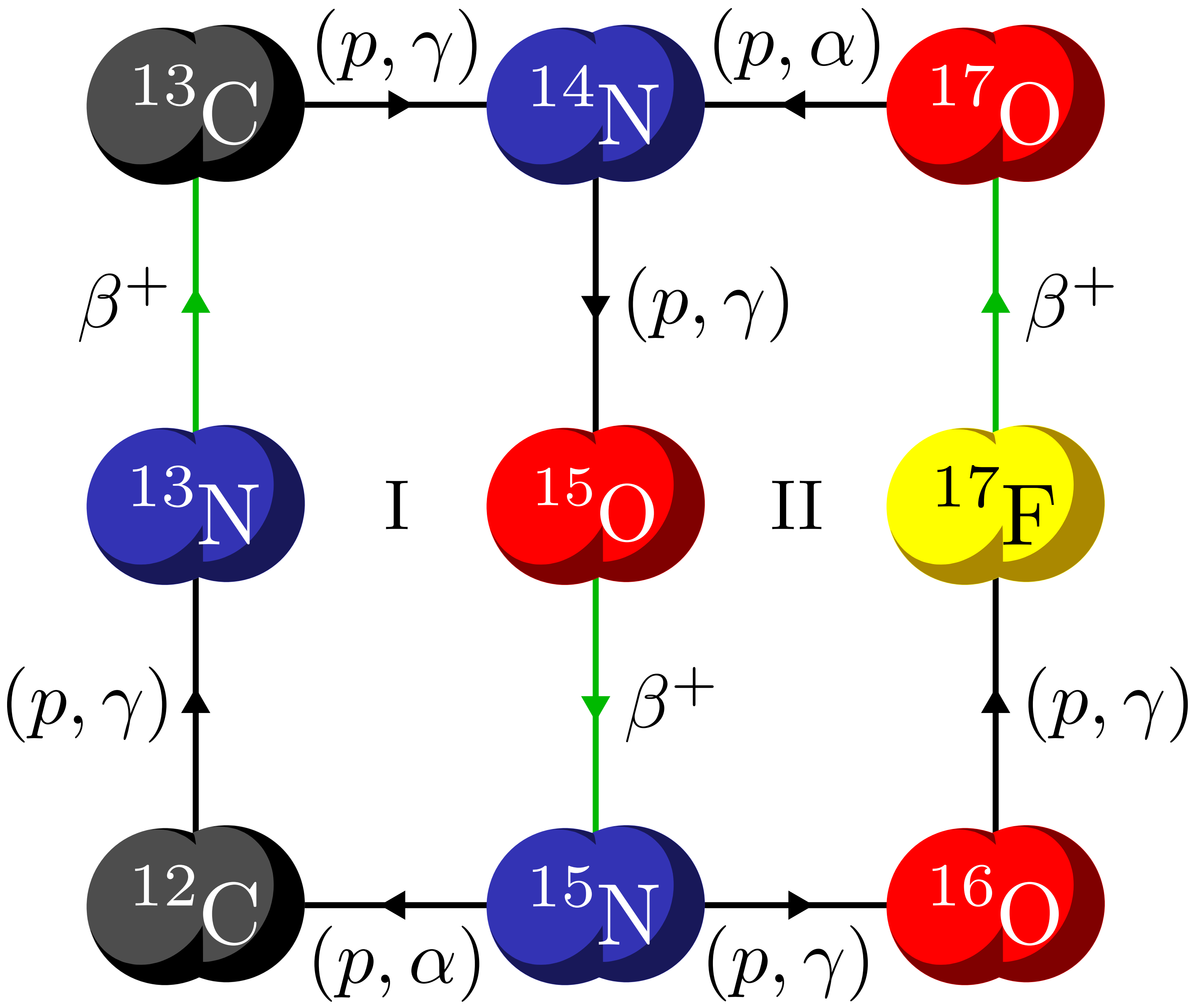


Effectiveness of the energy production processes in a star alike the Sun, depending upon its central temperature.

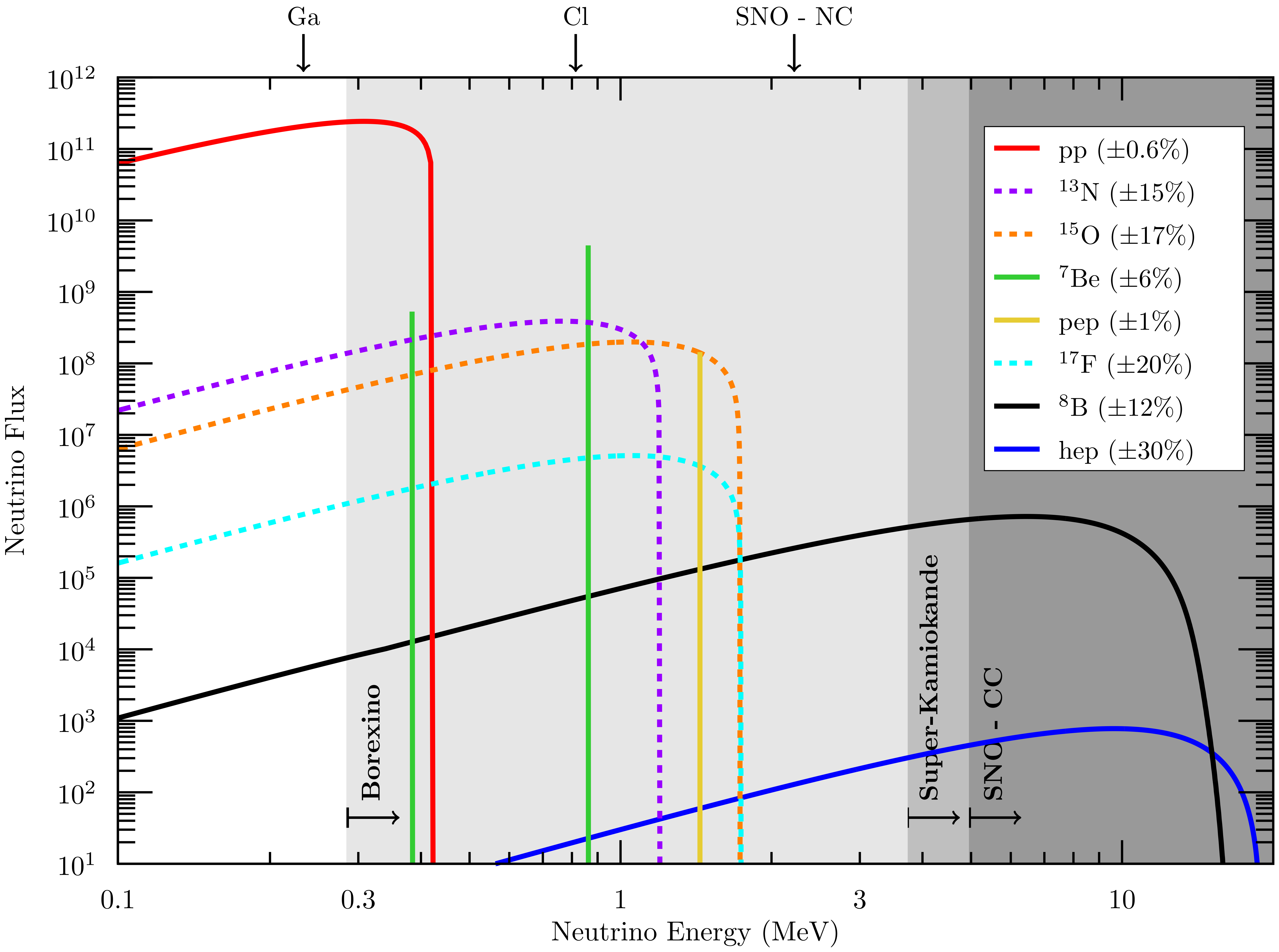
the sun emits light & neutrinos





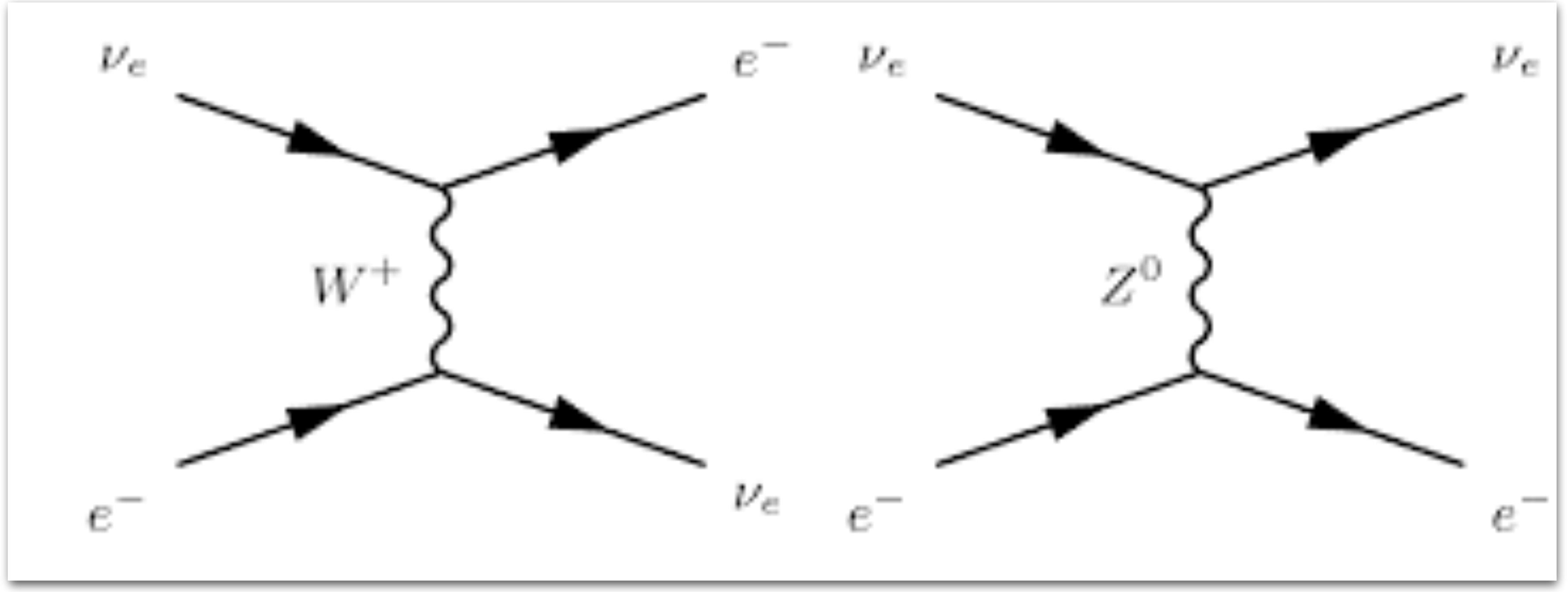


only few experiments can cover all relevant reactions



advantages of detecting neutrinos with elastic scattering on electrons

- ☑ a basic process of the standard model



- ☑ theoretically very clean, radiative corrections are known
- ☑ $m_e c^2 \ll E_\nu$ for boron neutrinos: thus, in water Cherenkov detectors, direction can be reconstructed (—> Kamiokande, SK)
- ☑ scintillator detectors allow to cover all the other components (—> Borexino)

Borexino's explored pp and CNO almost entirely

nature

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Published: 27 August 2014

Neutrinos from the primary proton–proton fusion process in the Sun

Borexino Collaboration

Nature **512**, 383–386 (2014) | Cite this article

15k Accesses | **211** Citations | **399** Altmetric | Metrics

Abstract

In the core of the Sun, energy is released through sequences of nuclear reactions that convert hydrogen into helium. The primary reaction is thought to be the fusion of two protons with

2014

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Article | Published: 25 November 2020

Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun

The Borexino Collaboration

Nature **587**, 577–582 (2020) | Cite this article

12k Accesses | **63** Citations | **902** Altmetric | Metrics

Abstract

For most of their existence, stars are fuelled by the fusion of hydrogen into helium. Fusion proceeds via two processes that are well understood theoretically: the proton–proton (*pp*)

2020

summary and discussion

on solar neutrinos

- Wide recognition of solar neutrino oscillations has changed the field of solar neutrinos and impacted on particle physics
- The SSM remains a key tool and can be still improved
- Borexino played a big role and opened new avenues for the more research
- New exp.s will improve and probe several possble unexpected physics

the original idea of "NSI"

Rapid Communication

Mikheyev-Smirnov-Wolfenstein effect with flavor-changing neutrino interactions

Esteban Roulet

Phys. Rev. D **44**, R935(R) – Published 15 August 1991

Article | References | Citing Articles (155) | PDF | Export Citation

ABSTRACT

We consider the effect that flavor-nondiagonal neutrino interactions with matter have on the resonant ν oscillations. It is shown that, even in the absence of ν mixing in a vacuum, an efficient conversion of the electron neutrinos from the Sun to another ν flavor can result if the strength of this interaction is $\sim 10^{-2} G_F$. We show how this can be implemented in the minimal supersymmetric standard model with R-parity breaking. Here, the L-violating couplings induce neutrino masses, mixings, and the flavor-nondiagonal neutrino interactions that can provide a Mikheyev-Smirnov-Wolfenstein-like solution to the solar-neutrino problem even for negligible vacuum mixings.

Received 18 January 1991

Mirror World

and sterile states

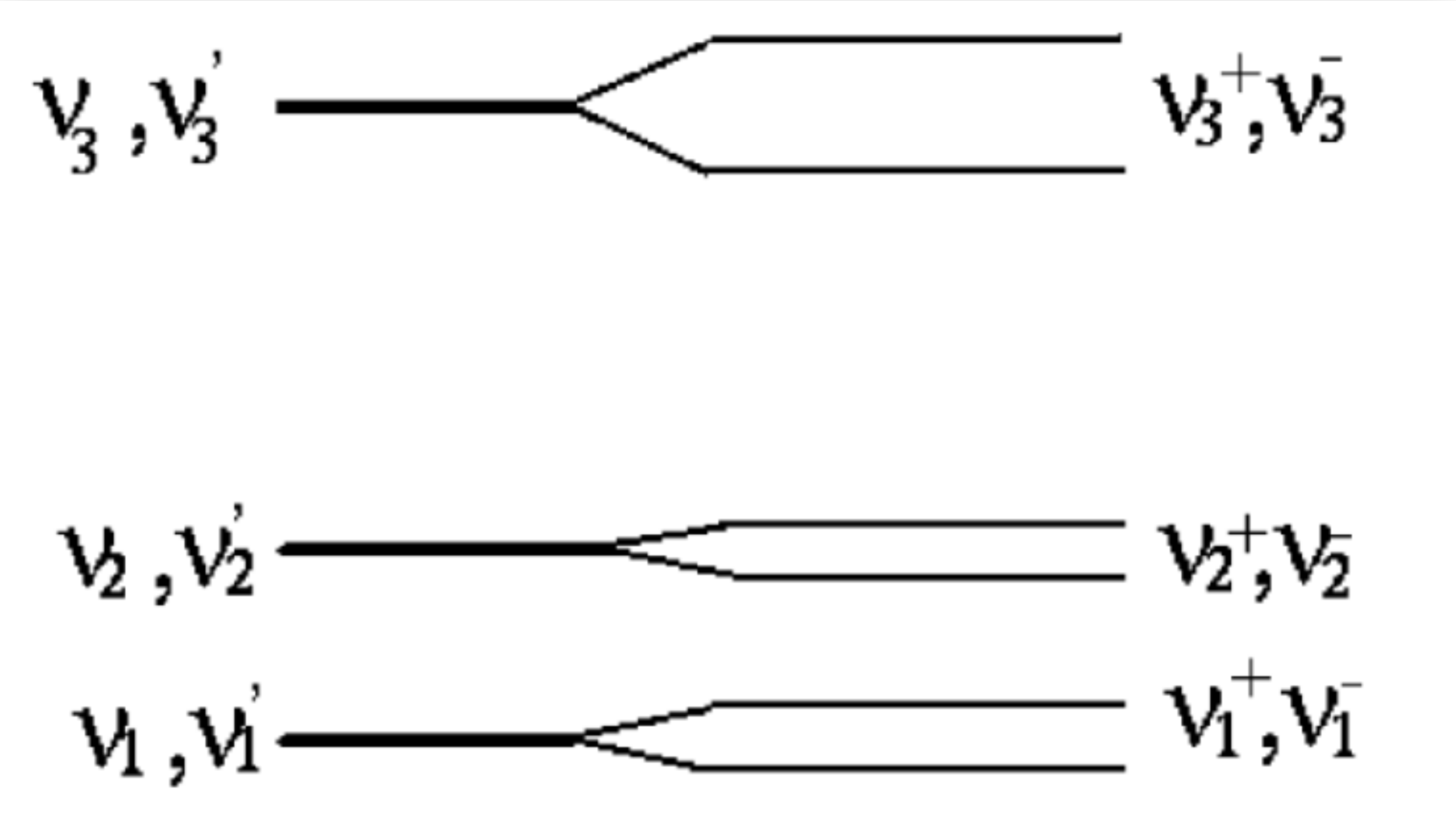
Mirror models is a motivated extension of standard model

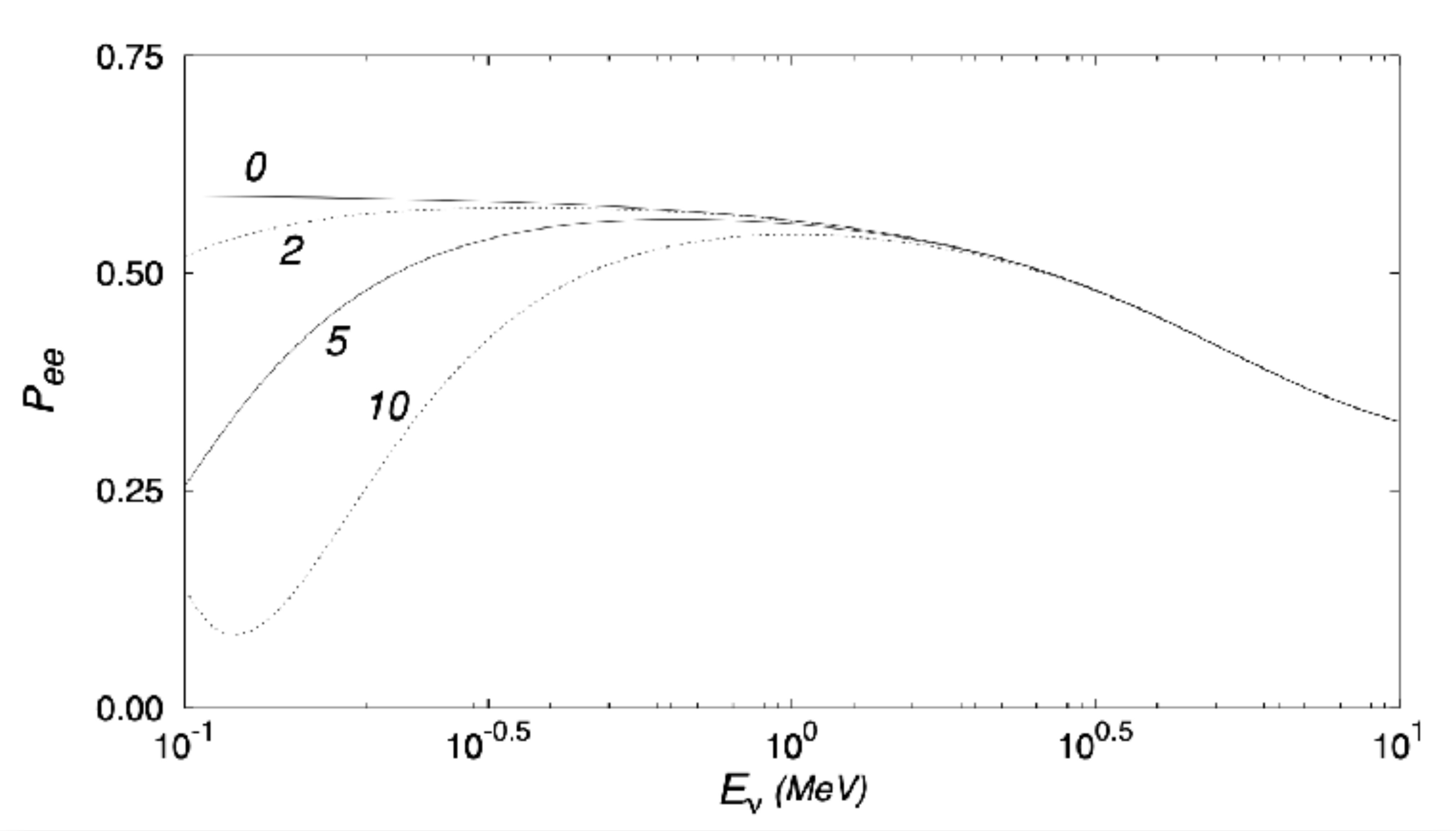
Mirror baryons are candidates for dark matter

Ordinary neutrinos and mirror neutrinos mix at $\propto \dfrac{\langle H \rangle^2}{M_{\text{Planck}}}$

Many possible manifestations: solar, supernovae and HE neutrinos

see NPB 658 (2003) 254





Gabriela.Barenboim@uv.es
Re: (Fwd) Re: CERN Theory Institute "Neutrinos: the quest f
To: Francesco Vissani

Dear Francesco,

This is indeed what we want. Nobody will cover solar neutrinos in the workshop. So, the question to address is precesiely whether this a finished subject and whether there is anything at all that we hope to learn for from solar neutrinos.

The way you are focusing it is exactly what we have in mind.

Yours,

Gabriela.

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ЯДЕРНА ФІЗИКА

УДК 523.9, 539.1 https://doi.org/10.15407/jnpae2017.01.005

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SOLAR NEUTRINO PHYSICS ON THE BEGINNING OF 2017

This writeup is a review of current hot topics on solar neutrinos. It is based on a talk at the conference "Neutrinos: the quest for a new physics scale", held at the CERN on March 2017, where the Organizers entrusted me with a discussion of the provocative question "whether solar neutrino physics is over". Rather than providing a straight (negative) answer, in view of an audience consisting mostly of colleagues working in theoretical particle physics, I deemed it more useful providing a description of what is the current activity of the physicists working in solar neutrinos, leaving the listener free of forming his/her own opinion apropos.

Ф. Віссані

Національний інститут ядерної фізики,
Національна лабораторія Гран Сассо та Науковий інститут Гран Сассо, Аквіла, Італія

ФІЗИКА СОНЯЧНИХ НЕЙТРИНО НА ПОЧАТКУ 2017 Р.

Представлено огляд сучасних «гарячих» питань в області сонячних нейтрино. Огляд базується на доповіді на конференції «Нейтрино: пошуки нової фізичної шкали», що відбулася в ЦЕРНі в березні 2017 р., де організатори довірили мені обговорення провокаційного питання «чи закінчилась фізика сонячних нейтрино». Замість того, щоб дати прямолінійну (негативну) відповідь, зважаючи на аудиторію, яка складалася головним чином із колег, які працюють у галузі теоретичної фізики частинок, я вважав більш корисним дати сучасний опис діяльності фізиків, які працюють над сонячними нейтрино, дозволяючи слухачам сформувати власну думку.

Ключові слова: сонячні нейтрино, нейтринні осциляції, ядерна астрофізика, *pp* цикл, CNO цикл.

Ф. Виссани

Национальный институт ядерной физики,
Национальная лаборатория Гран Сассо и Научный институт Гран Сассо, Аквила, Италия

ФИЗИКА СОЛНЕЧНЫХ НЕЙТРИНО В НАЧАЛЕ 2017 Г.

Представлен обзор современных «горячих» вопросов в области солнечных нейтрино. Обзор основан на докладе на конференции «Нейтрино: поиски новой физической шкалы», которая состоялась в ЦЕРНе в марте 2017 г., где организаторы доверили мне обсуждение провокационного вопроса «закончилась ли физика солнечных нейтрино». Вместо того, чтобы дать прямолинейный (негативный) ответ, принимая во внимание аудиторию, которая состояла в основном из коллег, работающих в области теоретической физики частиц, я счел более полезным дать современный обзор деятельности физиков, работающих над солнечными нейтрино, позволяя слушателям сформировать собственное мнение.

Ключевые слова: солнечные нейтрино, нейтринные осцилляции, ядерная астрофизика, *pp* цикл, CNO цикл.

Geoneutrinos

(is a new geophysical probe)

the Earth

and radioactive decays

- The Earth is (almost) as old as the Sun
- It is formed by various stratified structures. The main ones: **crust; mantle; core**

the Earth

and radioactive decays

- The Earth is (almost) as old as the Sun
- It is formed by various stratified structures. The main ones: **crust; mantle; core**

- It has been cooling since the beginning and it radiates **47 TW.**
- (the innermost part has a temperature of about 7500 ^{o}C)

the Earth

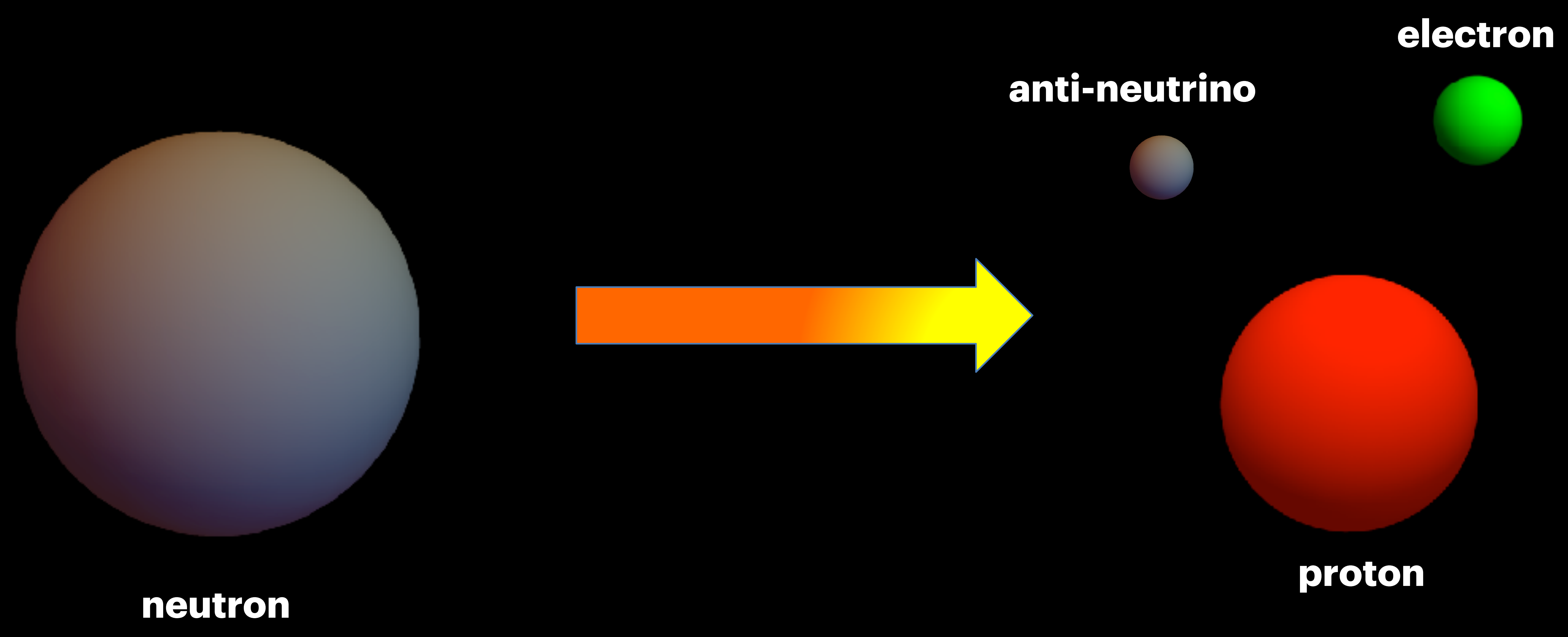
and radioactive decays

- The Earth is (almost) as old as the Sun
- It is formed by various stratified structures. The main ones: **crust; mantle; core**

- It has been cooling since the beginning and it radiates **47 TW.**
- (the innermost part has a temperature of about 7500 ^{o}C)

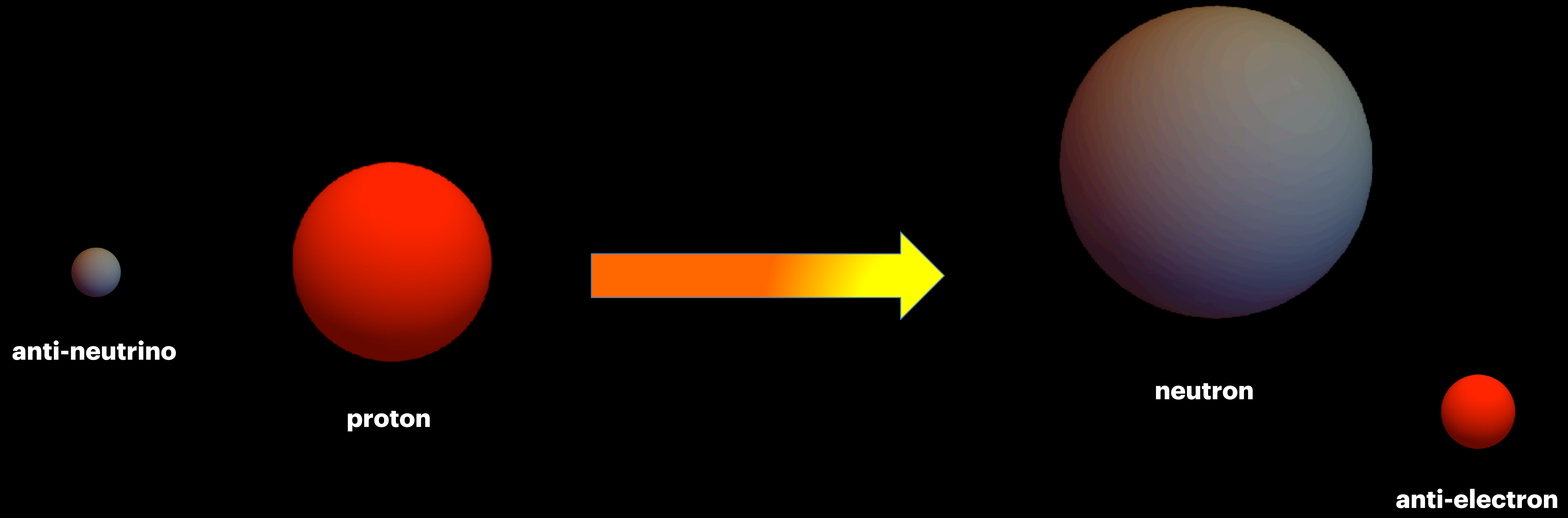
- Kelvin' early estimations of the heating rate led to an age in $\sim 10^7$ years scale
- They were wrong because of **incorrect modeling**
- Furthermore, **radioactivity**, which contributes to Earth' internal heath, was unknown then

nature of geoneutrinos



- beta decay of neutron-rich elements leading to antineutrinos
- (to be contrasted with solar neutrinos where proton rich elements transform and produce neutrinos)
- in that, this more closely resembles the physical situation realised in artificial fission reactors, which actually act as a background for geo-neutrinos

“inverse beta decay” (Bethe & Peierls)



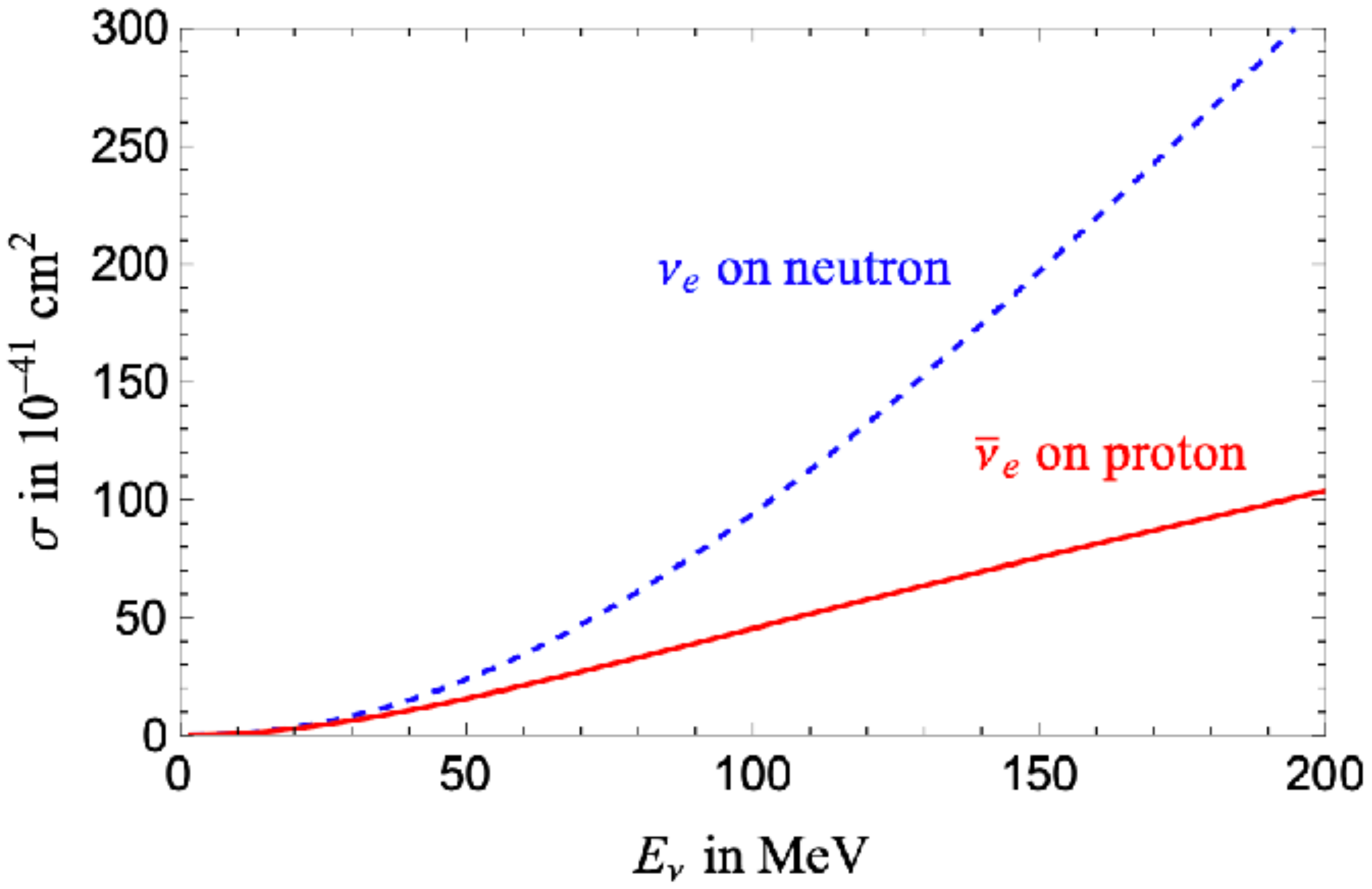
proton targets are available in water or hydrocarbon
(this reaction used to detect for the 1st time a signal)

an updated calculation

arXiv:2206.05567v1

$$\frac{d\sigma}{dt} = \frac{G_F^2 \cos^2\theta_C}{64\pi(s-m_p^2)^2}\overline{|\mathcal{M}^2|}$$

$$\mathcal{M} = \bar{v}_\nu \gamma^a (1-\gamma_5) v_e \cdot$$
$$\bar{u}_n \left(f_1\gamma_a + g_1\gamma_a\gamma_5 + i f_2 \sigma_{ab}\frac{q^b}{2M} + g_2 \frac{q_a}{M}\gamma_5 + f_3\frac{q_a}{M} + i g_3 \sigma_{ab}\frac{q^b}{2M}\gamma_5 \right) u_p$$



an updated calculation

arXiv:2206.05567v1

$$\frac{d\sigma}{dt} = \frac{G_F^2 \cos^2\theta_C}{64\pi(s-m_p^2)^2}\overline{|\mathcal{M}^2|}$$

$$\mathcal{M} = \bar{v}_\nu \gamma^a (1-\gamma_5) v_e \cdot$$
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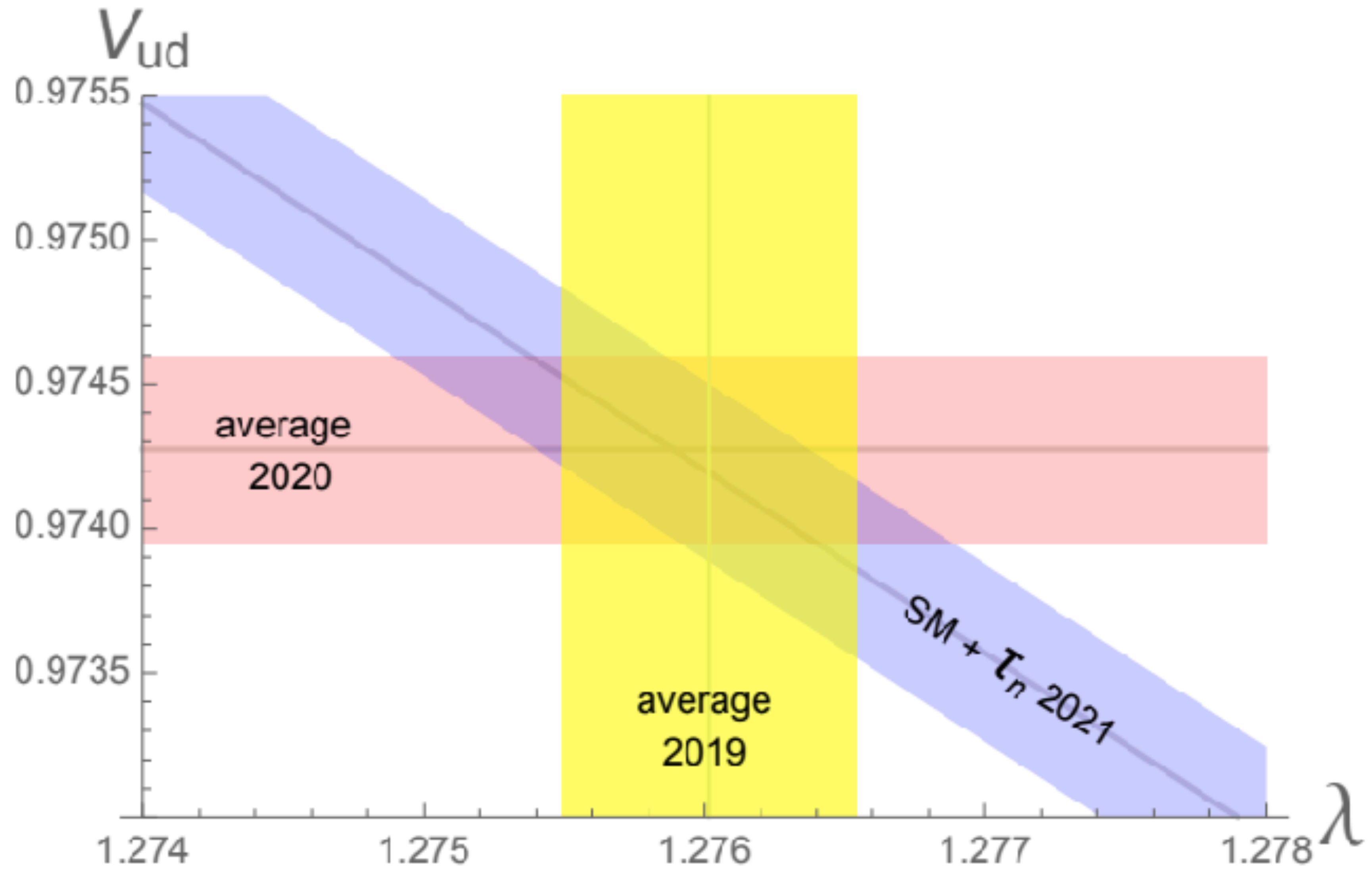


$$\delta\sigma(V_{ud}) = 0.66\,‰ \quad \delta\sigma(\lambda) = 0.68\,‰ \quad \delta\sigma = 0.94\,‰$$

antineutrino spectra

expectations

There are three components:

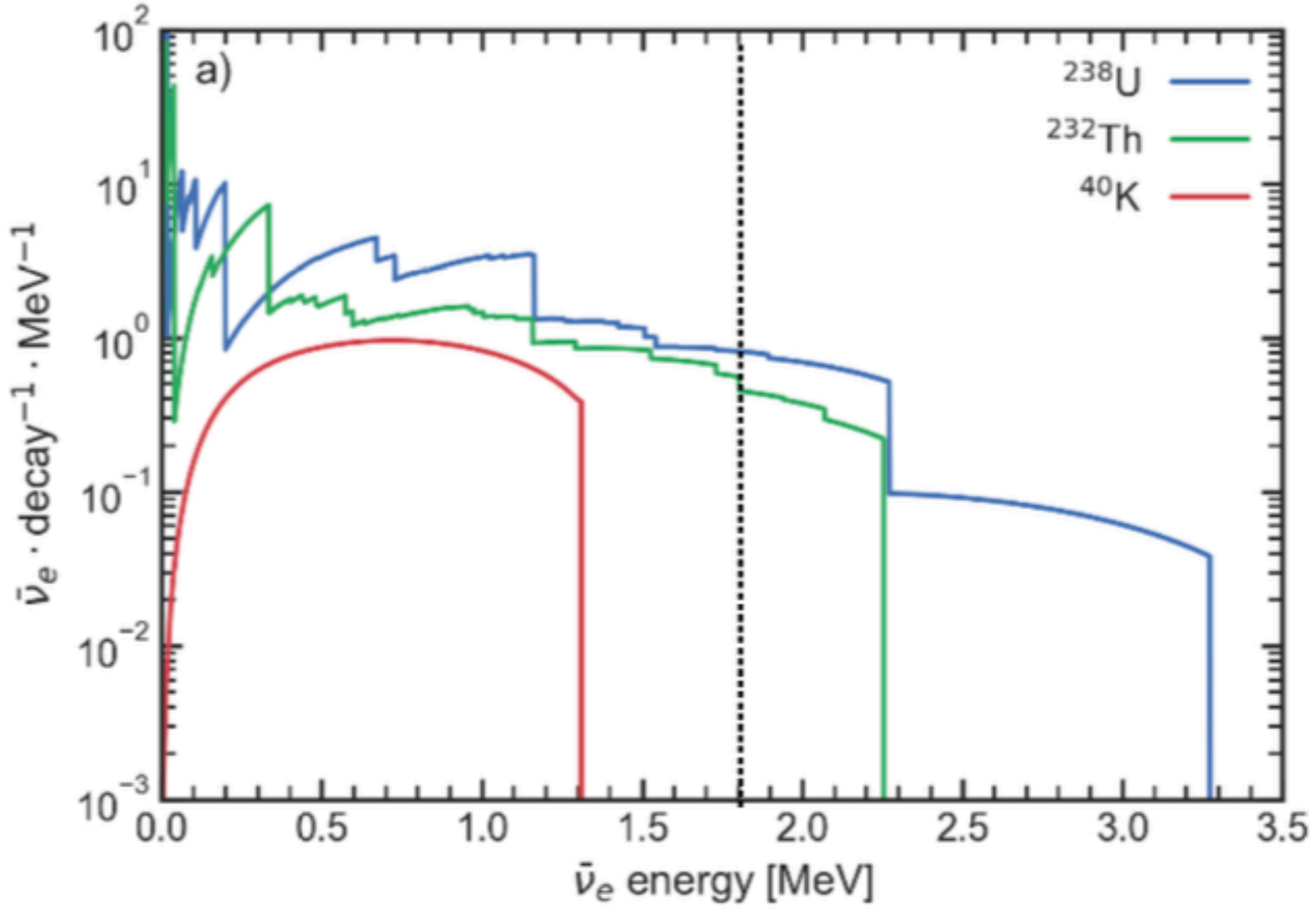
$$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\alpha + 6e + 6\bar{\nu}_e + 51.7\,\mathrm{MeV}.$$

$$^{232}\mathrm{Th} \to {}^{208}\mathrm{Pb} + 6\alpha + 4e + 4\bar{\nu}_e + 42.7\,\mathrm{MeV}.$$

$$^{40}\mathrm{K} \to {}^{40}\mathrm{Ca} + e + \bar{\nu}_e + 1.31\,\mathrm{MeV}.$$

The first 2 can be seen with IBD.

Note that uranium-238 extends at higher energies



G. Bellini et al., Riv. Nuovo Cimento 45 (2022) 1

interesting questions

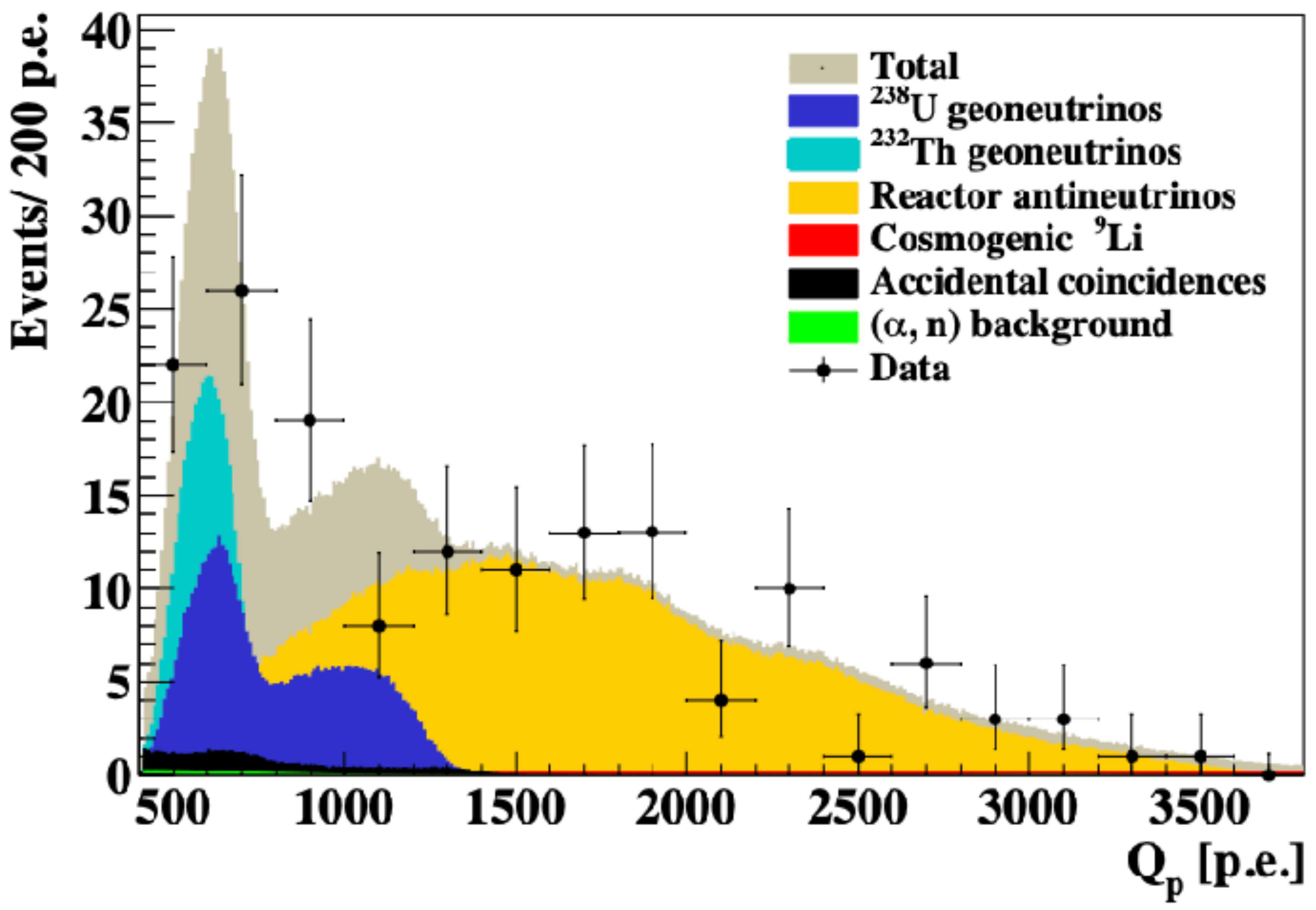
- discovering geo-neutrinos (seeing something)
- observe site dependencies
- testing geophysical models
- quantify the mantle component
- distinguish uranium and thorium contributions

measurements

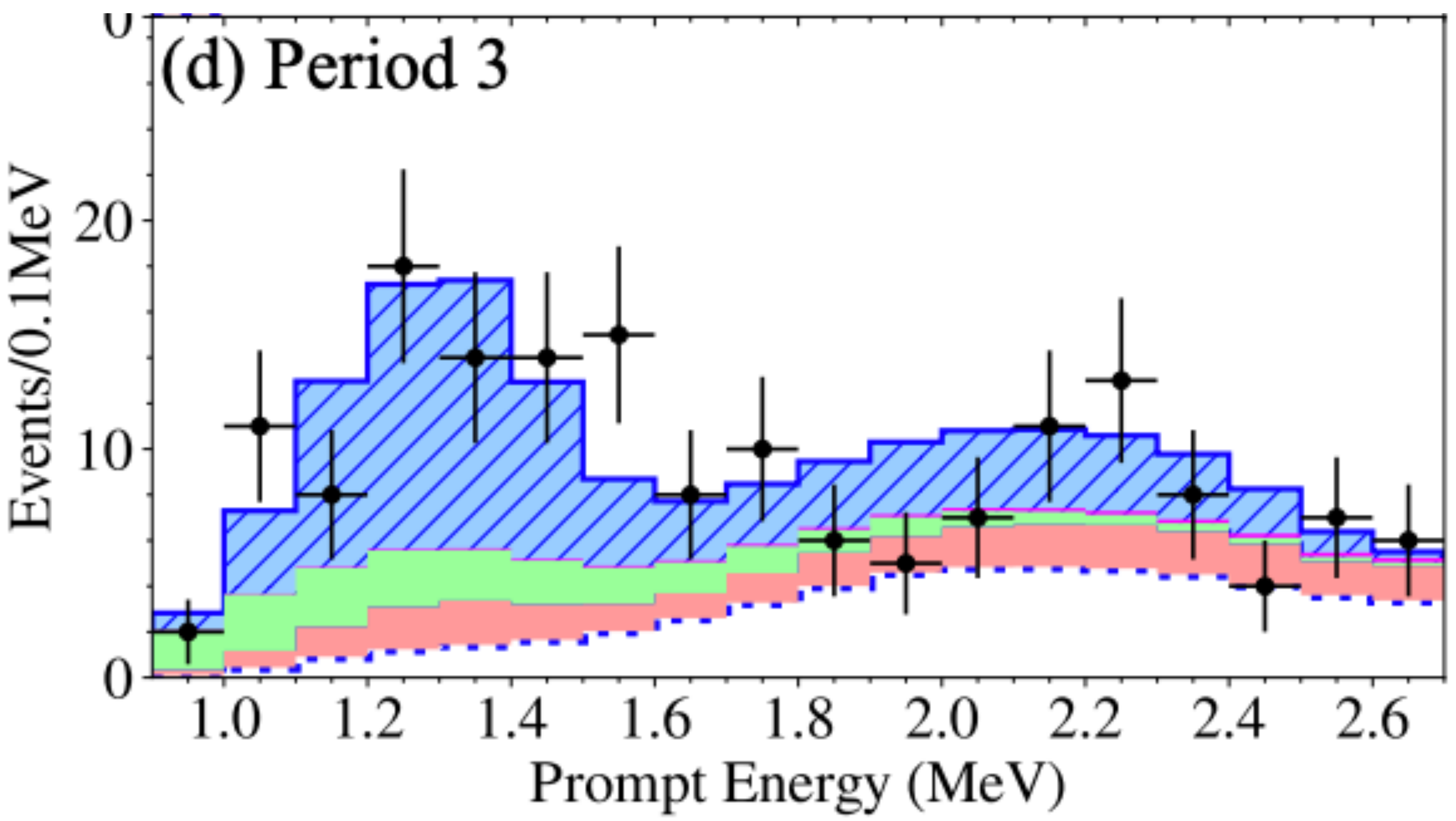
In the spectra of Borexino 2020 and KamLAND 2022, geoneutrino signal is visible and not only.

There is also an indication of both its components, i.e.:

- thorium-232 and
- uranium-238, the latter extending at higher energies



BOREXINO



KAMLAND

summary and discussion

on geoneutrinos

- ⭐ The discovery of geoneutrinos (KamLAND + Borexino) is fairly recent
- ⭐ Geoneutrinos will allow interesting questions to be addressed, and no major problems should be an obstruction to proceed further
- ⭐ Significant scope for progress, especially with larger detectors (JUNO)

Supernova neutrinos

(will be covered by Cristina Volpe tomorrow)

a race of neutrinos and photons

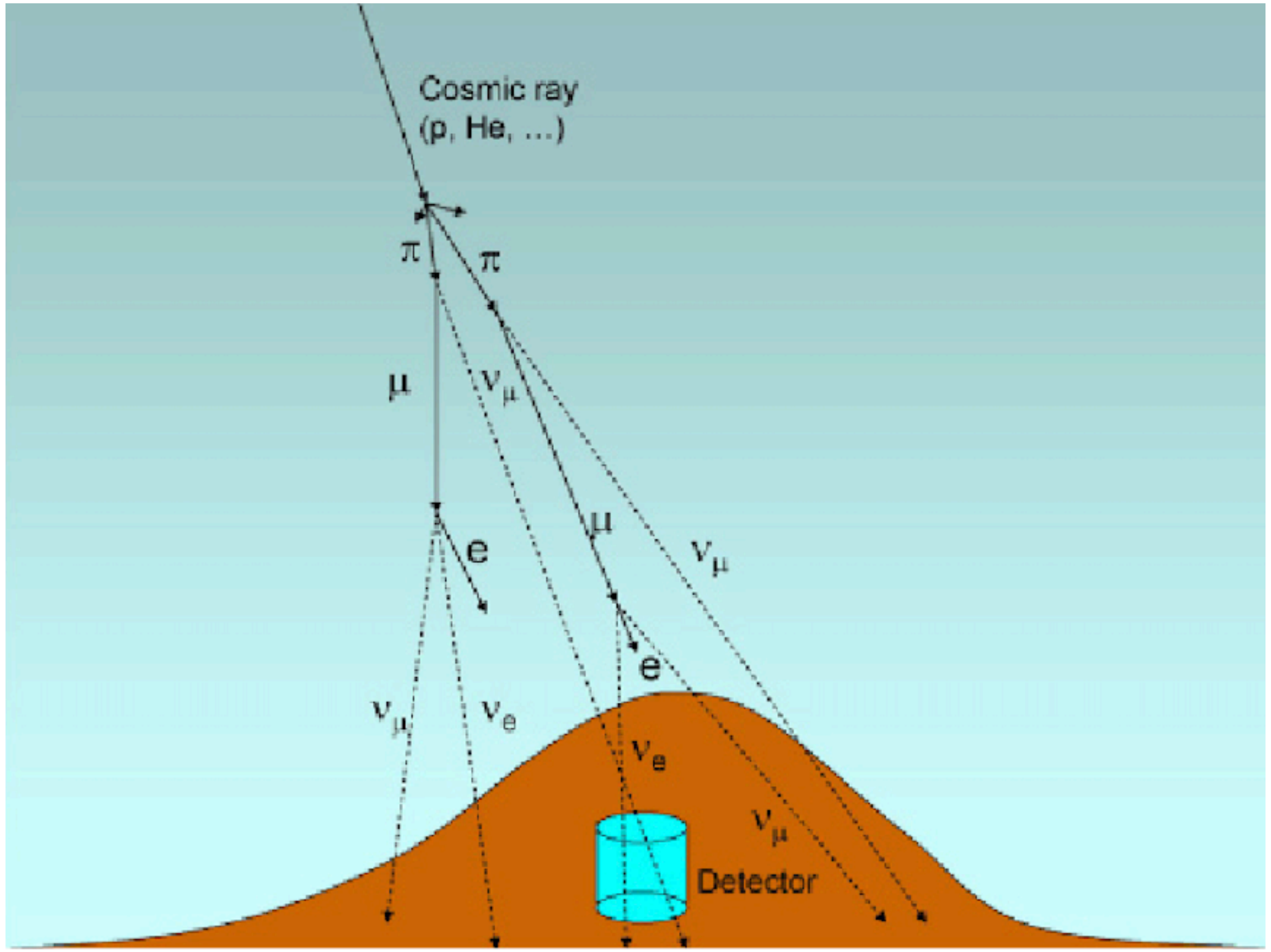
Atmospheric neutrinos

(just few urgent remarks)

atmospheric neutrinos

as secondary particles

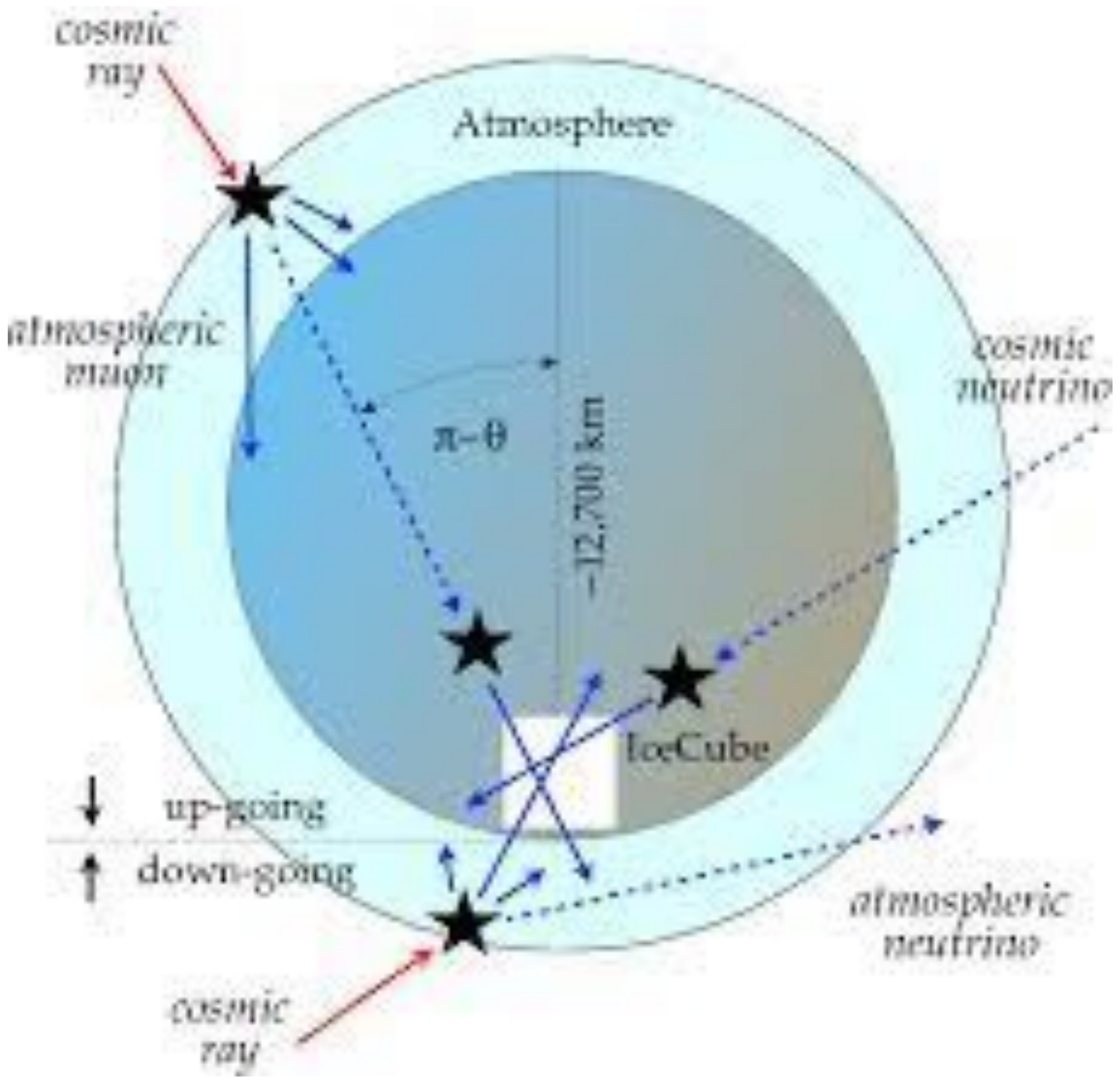
- the collisions of primary particles produce secondary mesons, in part. $\pi^{\pm}$
- when $\pi^{\pm}$ decay, it produces $\mu^{\pm}$ and $\nu_{\mu}/\bar{\nu}_{\mu}$
- when the $\mu^{\pm}$ decay, it produces $e^{\pm}$and $\nu_e, \bar{\nu}_{\mu}$ or $\bar{\nu}_e, \nu_{\mu}$
- at higher energies, muon reach the ground before decaying and pions are damped by interactions



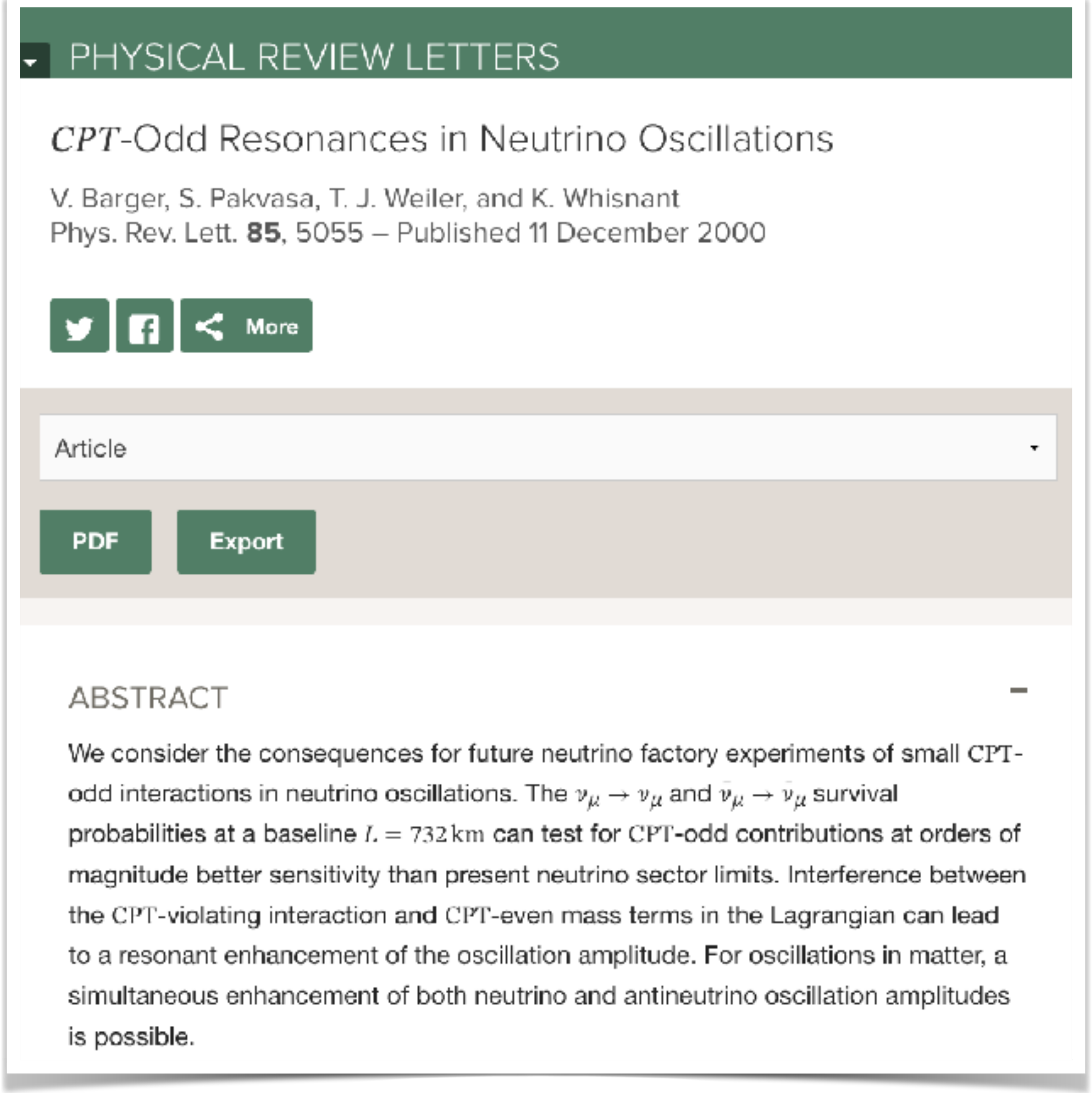
atmospheric neutrinos

and the induced muons

- the muons are very penetrating particles and a big annoyance for underground neutrino detectors
- when the direction of the particles are observed, one can search for up-going muons
- these are unmistakably to be attributed to muon (anti)neutrinos interacting around the detector
- seen already in sixties (CWI & KGF)!



CPT and its tests with neutrinos



PHYSICAL REVIEW LETTERS

CPT-Odd Resonances in Neutrino Oscillations

V. Barger, S. Pakvasa, T. J. Weiler, and K. Whisnant

Phys. Rev. Lett. **85**, 5055 – Published 11 December 2000

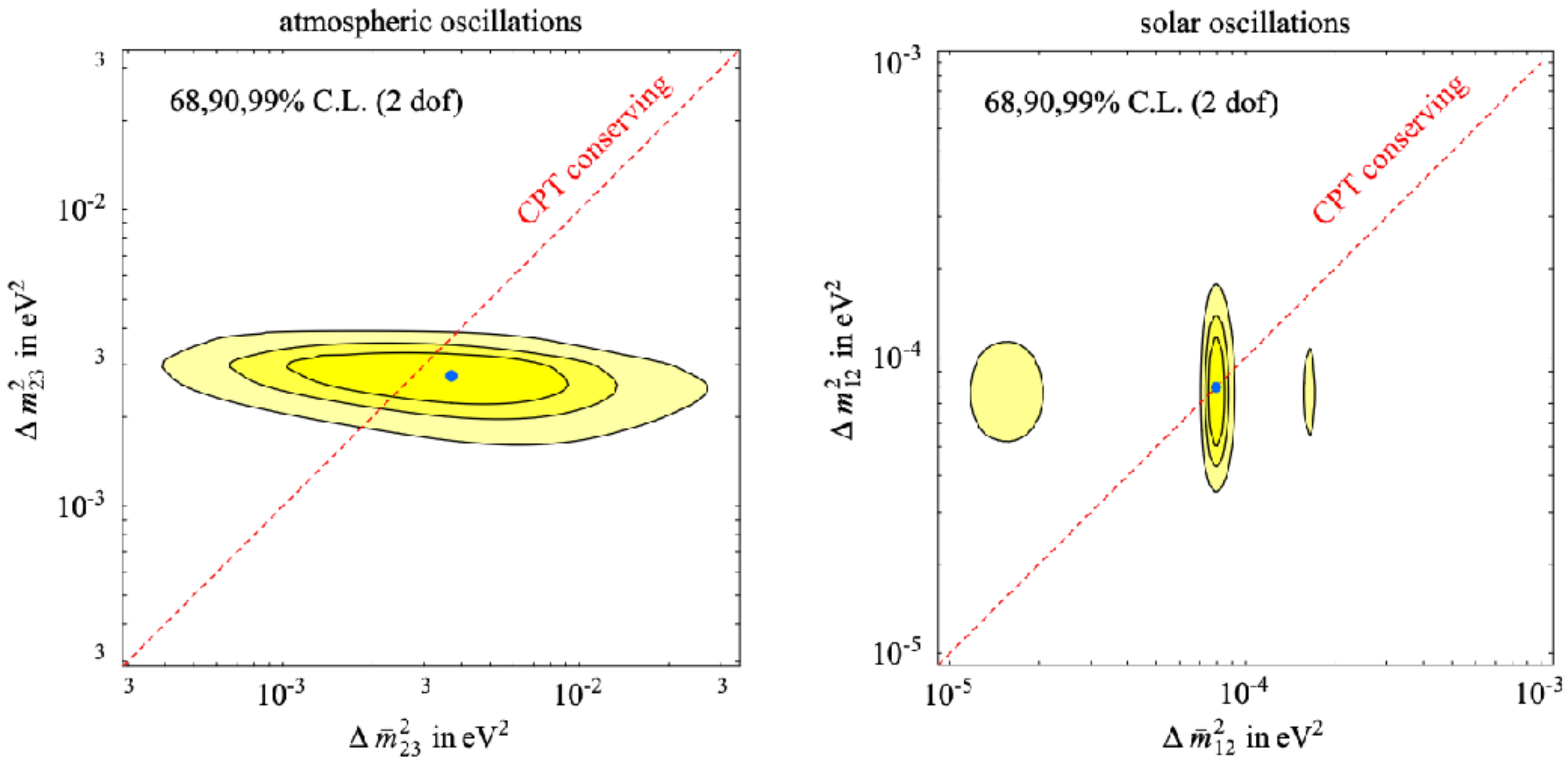
More

Article

PDF Export

ABSTRACT

We consider the consequences for future neutrino factory experiments of small CPT-odd interactions in neutrino oscillations. The $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ survival probabilities at a baseline $L = 732\,\mathrm{km}$ can test for CPT-odd contributions at orders of magnitude better sensitivity than present neutrino sector limits. Interference between the CPT-violating interaction and CPT-even mass terms in the Lagrangian can lead to a resonant enhancement of the oscillation amplitude. For oscillations in matter, a simultaneous enhancement of both neutrino and antineutrino oscillation amplitudes is possible.



NPB 2005, Strumia et al

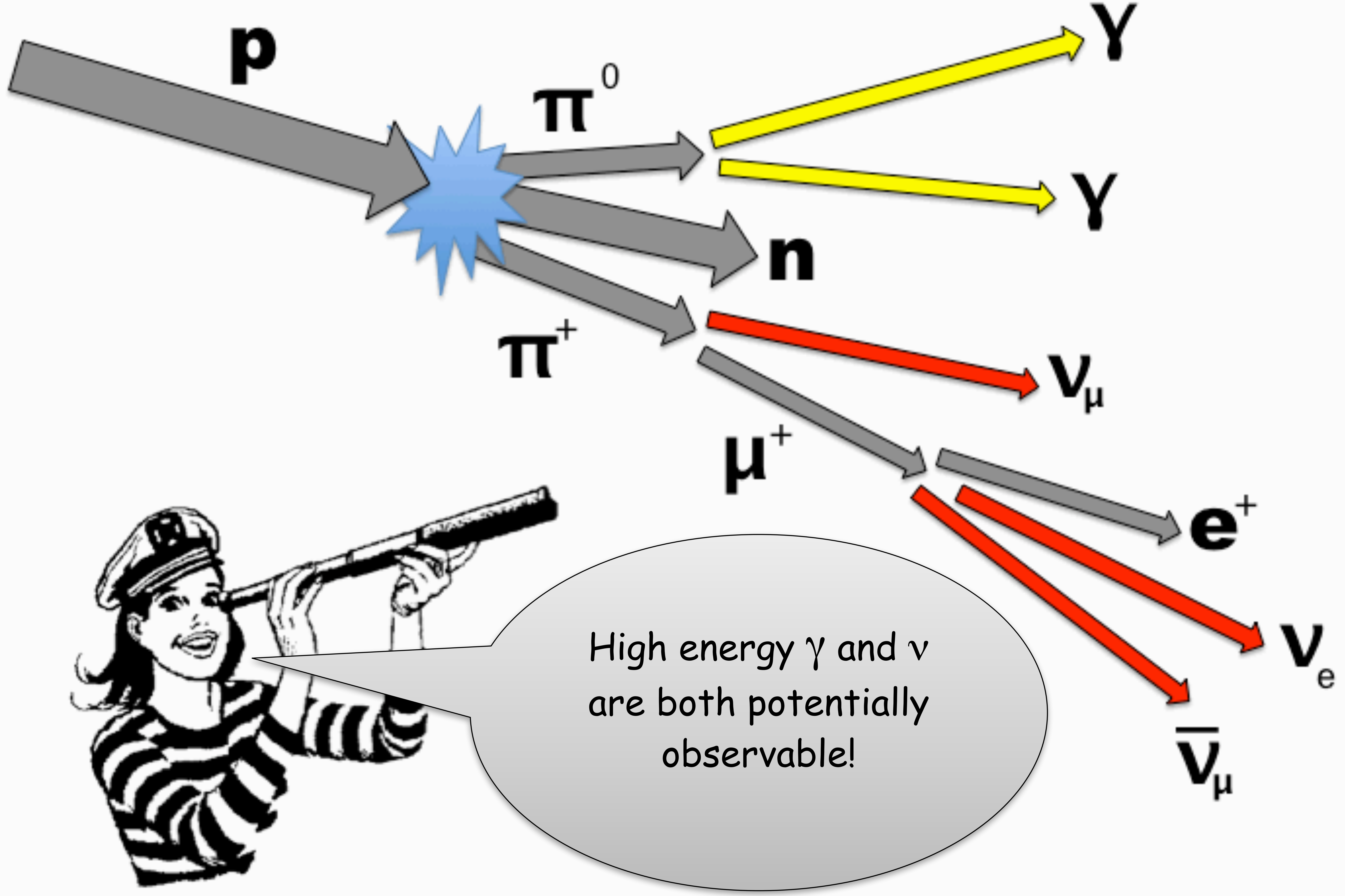
summary and discussion

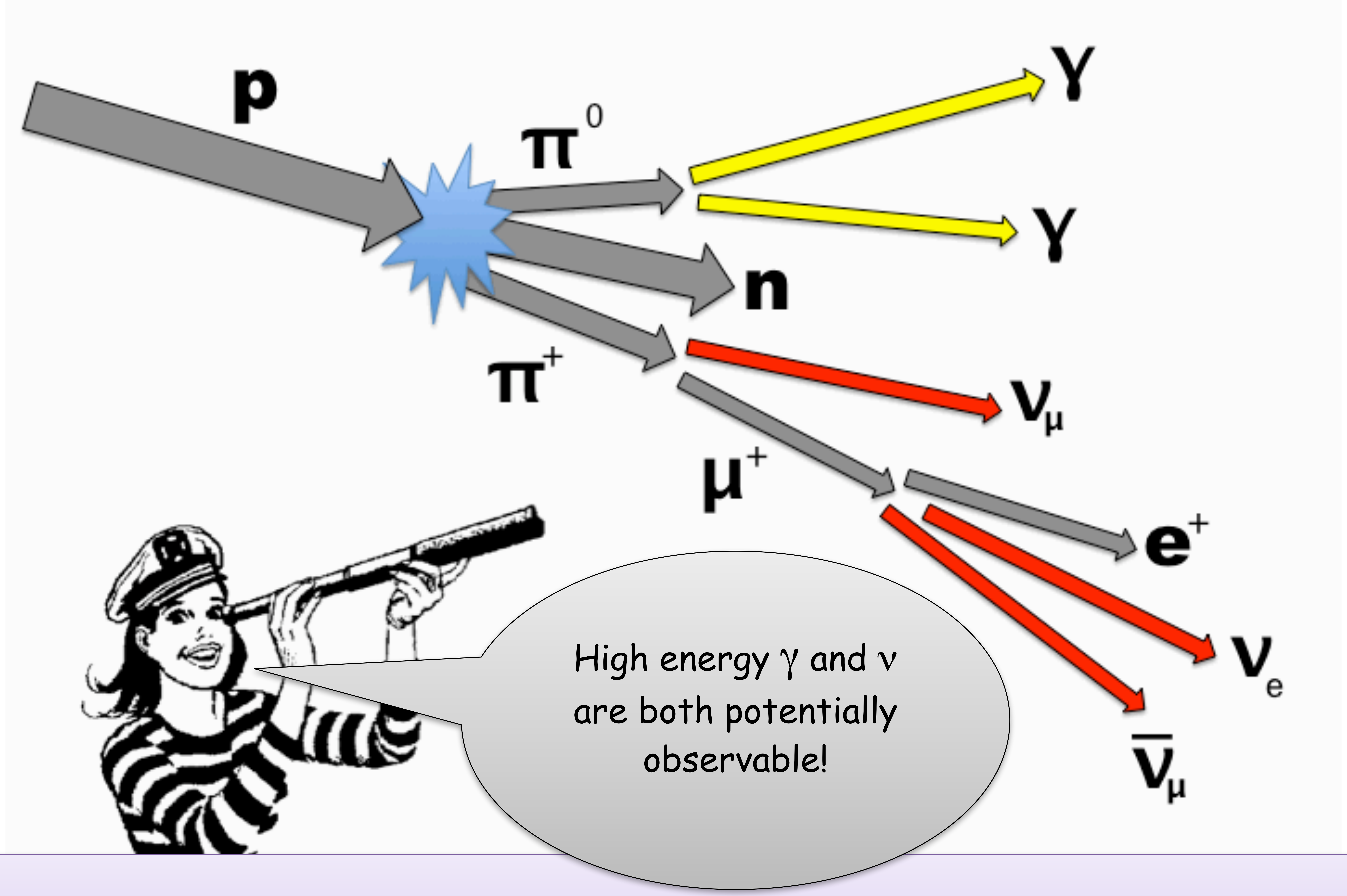
on atmospheric neutrinos

- For neutrino physics, atmospheric neutrinos have played an enormous historical role.
- Interestingly, in current **oscillation studies** and in the few GeV region, they still play a prominent role.
- Their distribution above 10-100 TeV is not well known. Note that we expect them to include a component of **prompt neutrinos** - from charm decay - that has not yet been observed.

H.E. astrophysical neutrinos

(an introduction)

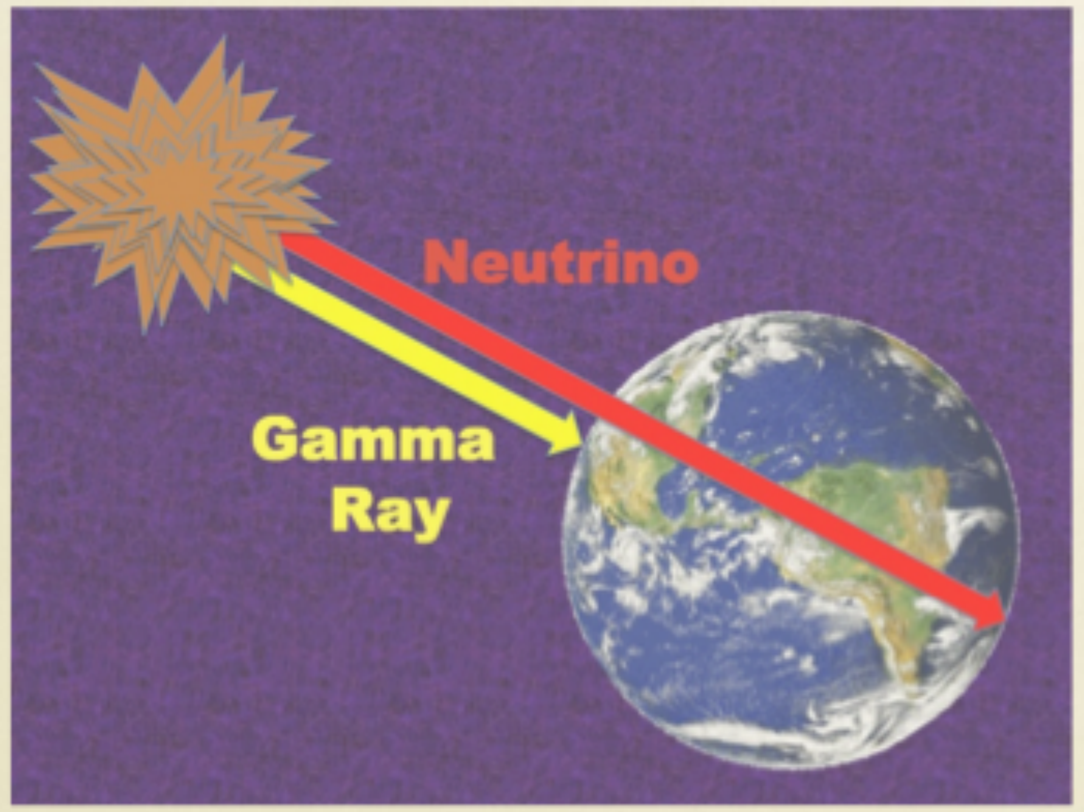

p
π0
γ
γ
n
π+
νμ
μ+
e+
νe
ν̄μ
High energy γ and ν are both potentially observable!



useful thumb rules: $E_\pi = E_p/5, E_\gamma = E_\pi/2$ **and** $E_\nu = E_\pi/4$

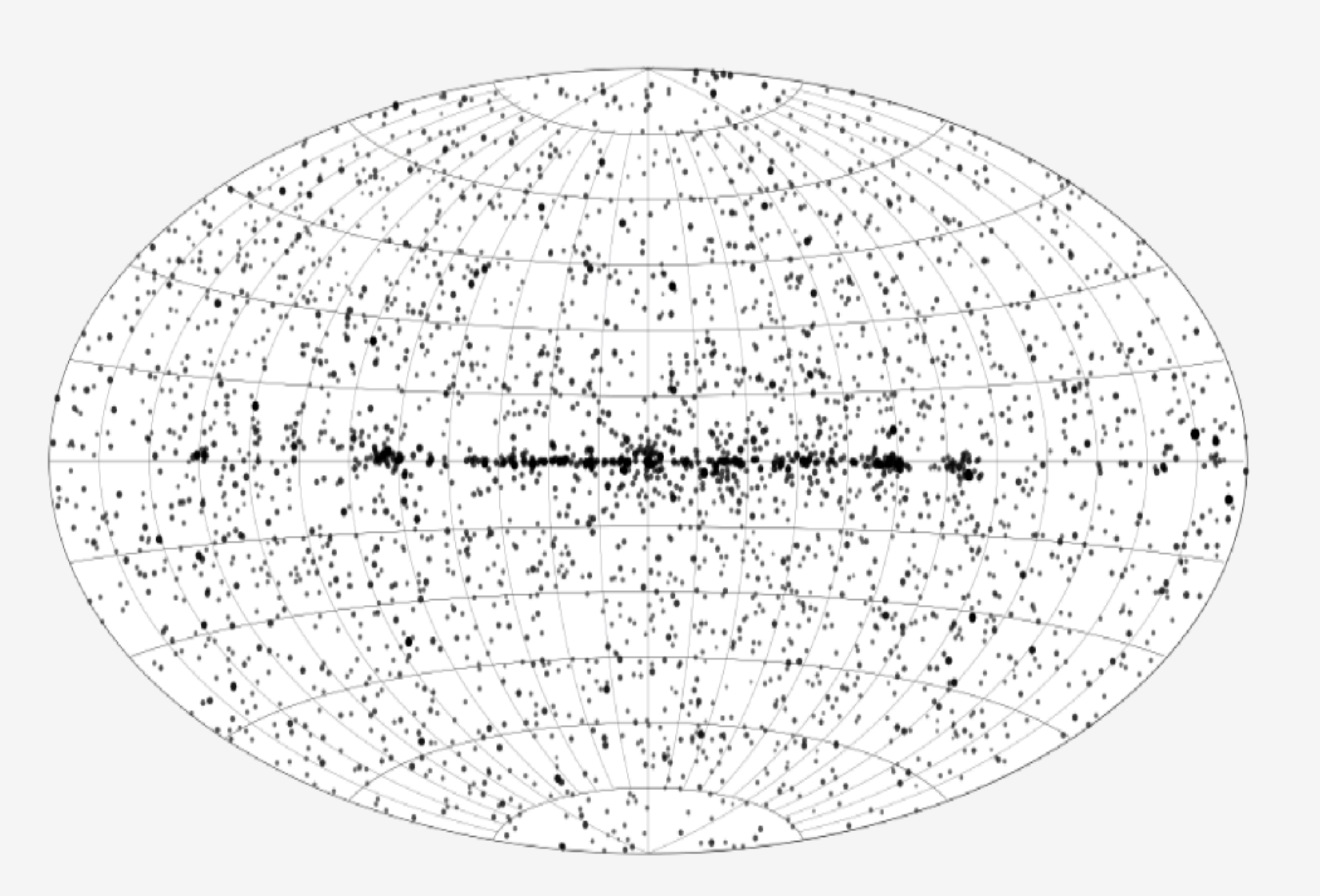
Cosmic neutrinos: how & why

In the master thesis of one student of Markov, Zheleznykh (1958), the key **technique** to observe the high-energy neutrinos was proposed for the 1st time.

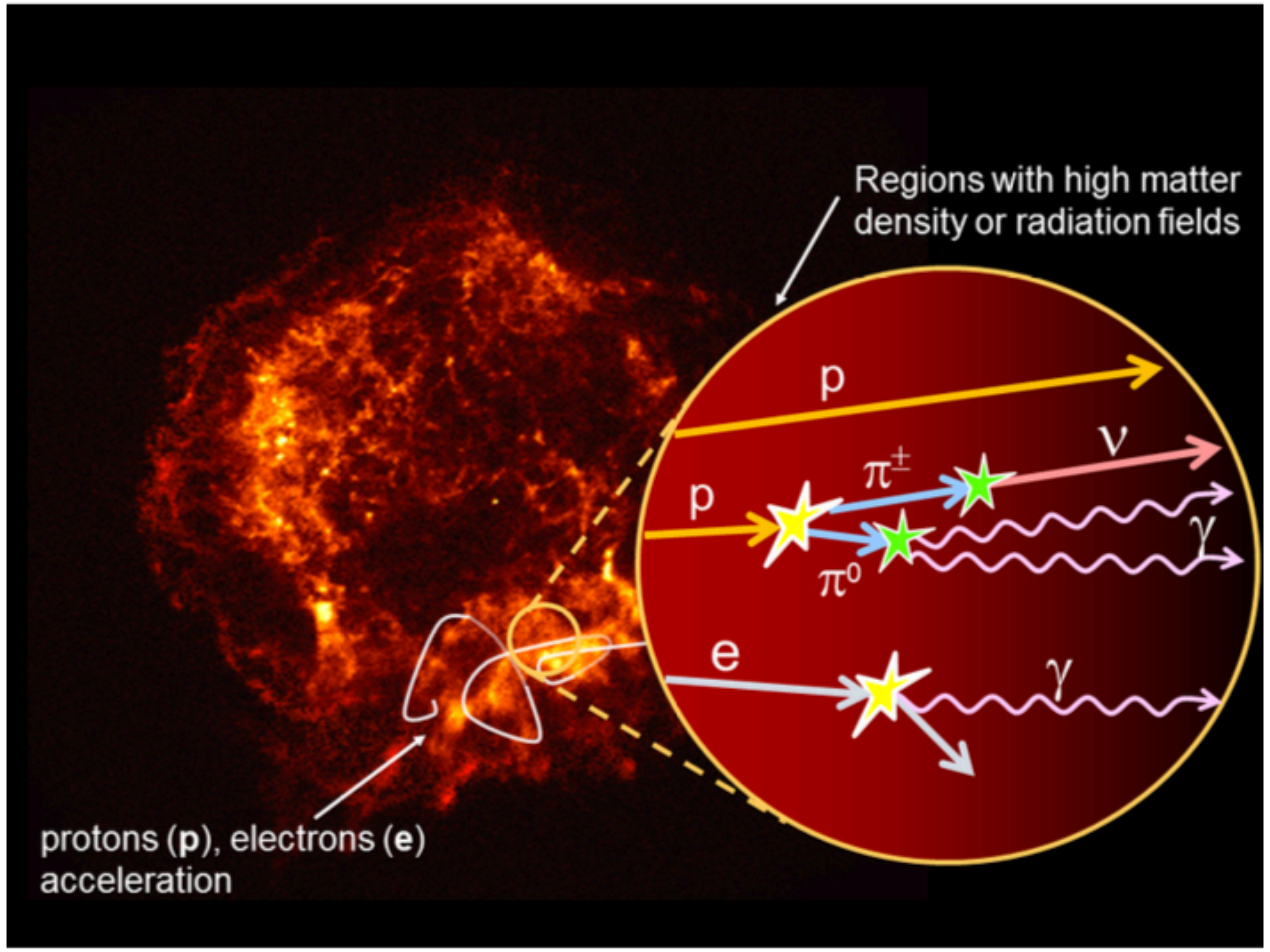


- *"γ quanta of 1 TeV favor existence of cosmic high-energy neutrinos"*
- *"worth searching especially if HE γ beyond atmosphere were found"*
- *from new star's shell as Crab "the flux could equal the atmospheric one"*
- *from old CR population as GC "could be large if attenuation is essential"*

Gamma rays in 1-100 GeV energy region: 3rd catalogue of Fermi-LAT



what is the target for CR collisions?

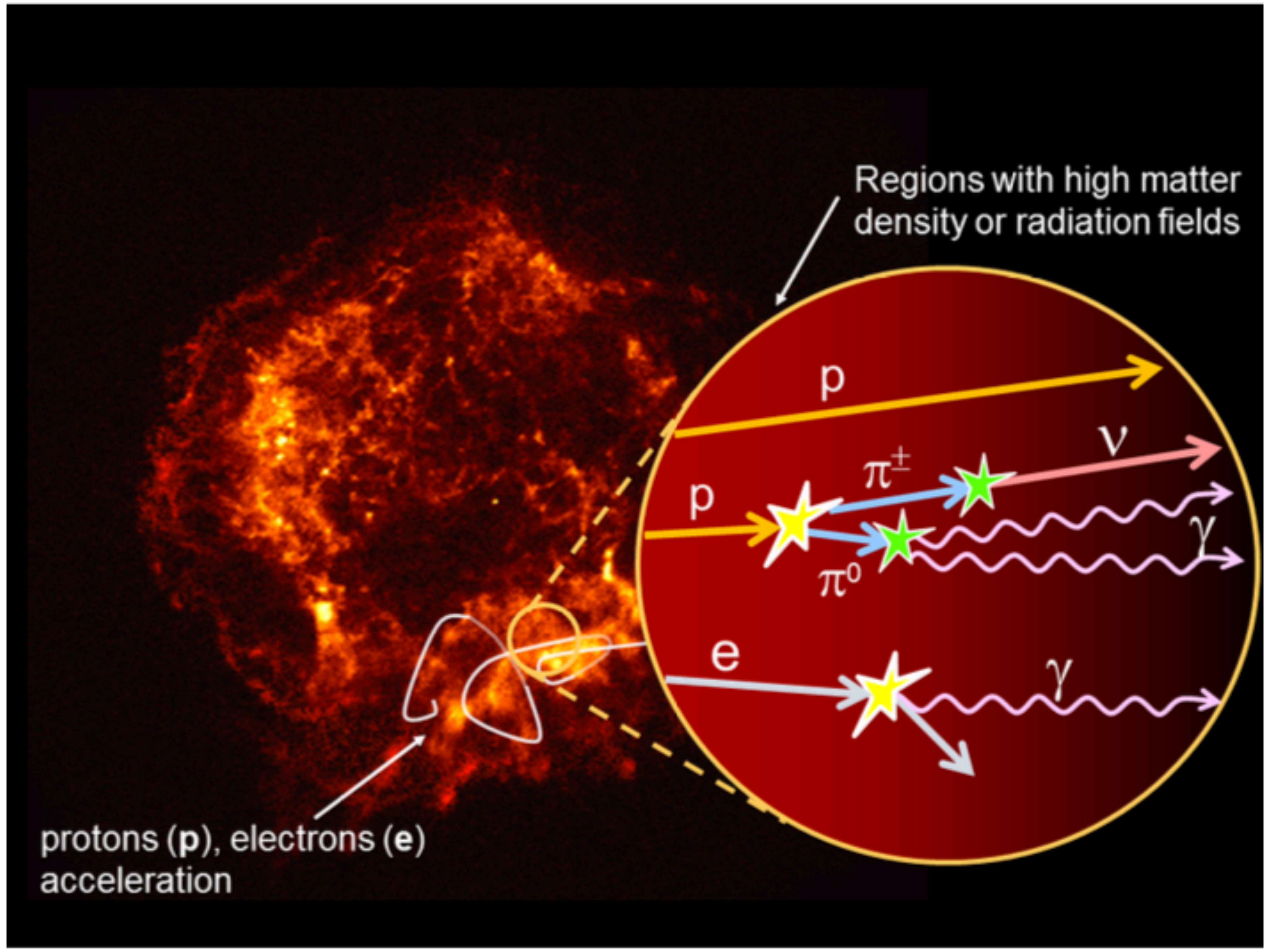


If the target is due to hadrons

PP-mechanism:

The spectrum of neutrino reflects the spectrum of the CR, and it is plausibly power-law like, $E^{-\alpha}$

what is the target for CR collisions?



If the target is due to hadrons

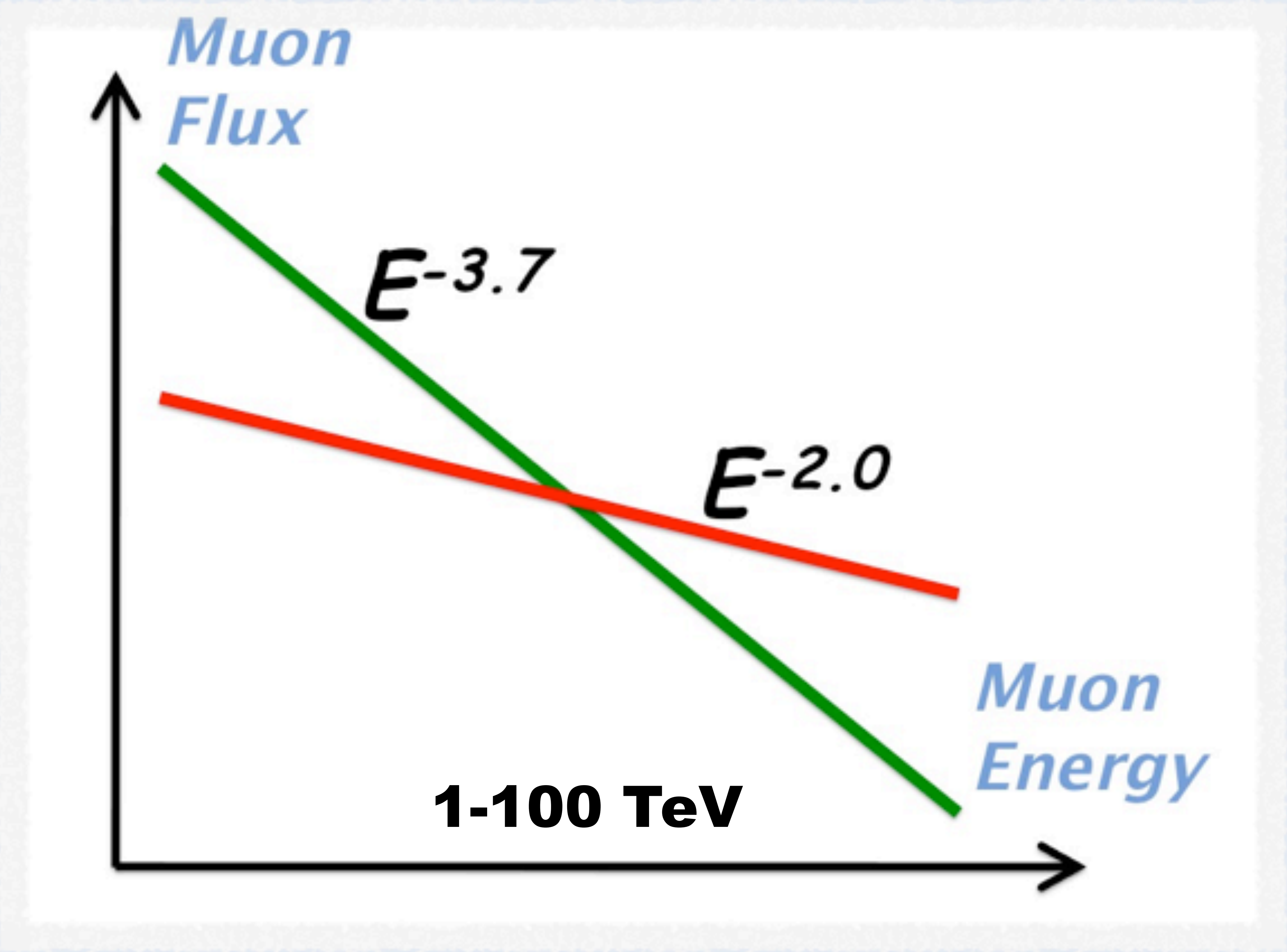
PP-mechanism:

The spectrum of neutrino reflects the spectrum of the CR, and it is plausibly power-law like, $E^{-\alpha}$

If the target is due to photons

Pγ-mechanism:

There is threshold for the CR and thus for neutrinos. The spectrum changes with photon distribution



one can search a new component of the high energy neutrino spectrum, possibly reflecting the production spectrum of cosmic rays at their sources

summary of the main goals of high-energy neutrino science

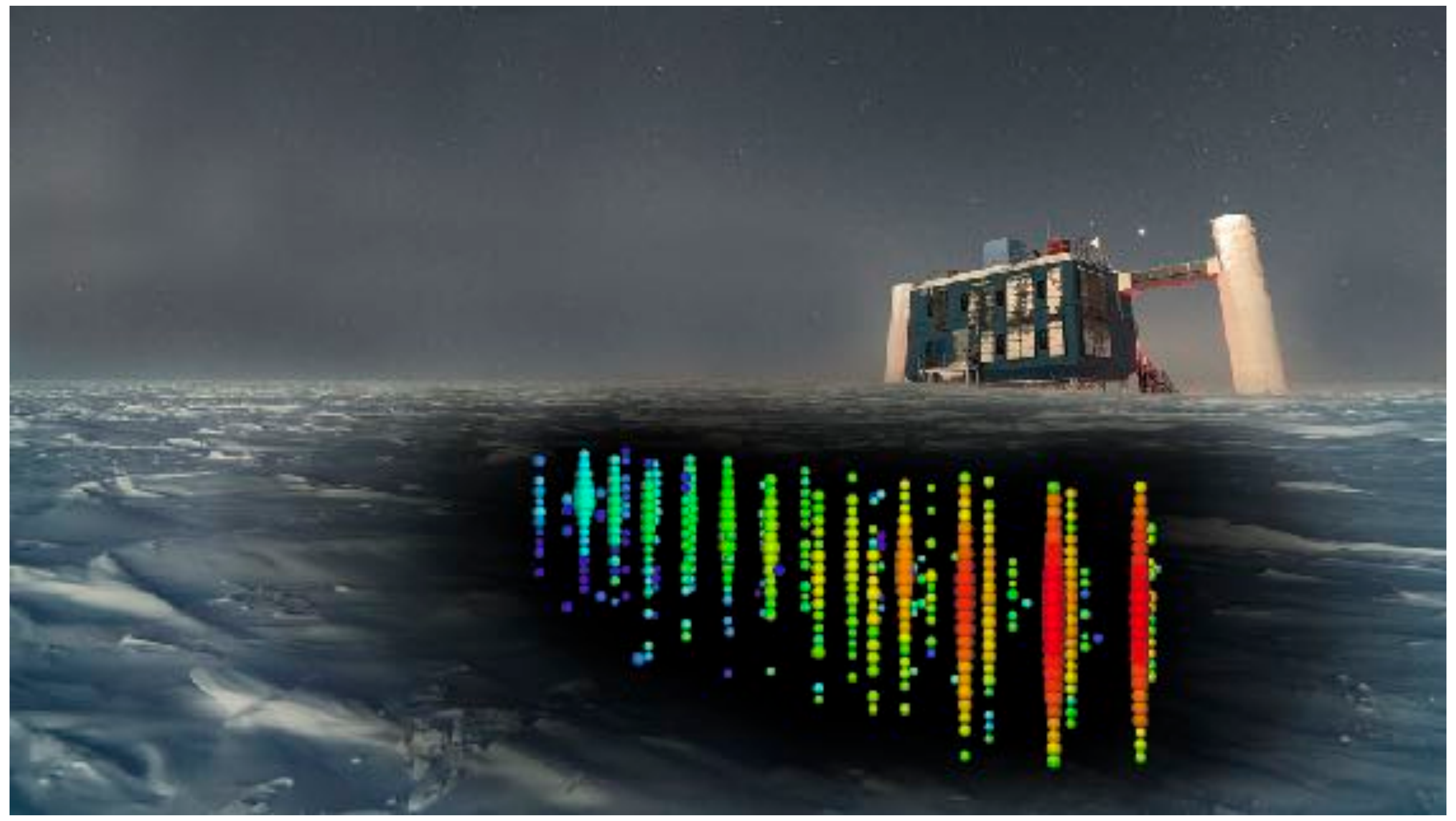
- astronomical goals: see some bright **point source**, steady or possibly sporadic, over the atmospheric neutrino background; gamma rays studies offer us hints and guidance

- other observational approach: search for a new components of **high-energy spectrum**

- astrophysical goals: the hopes is that this help **identify the sources** of cosmic rays

- particle physics goals: assess the chances of **exotic** origin / propagation

IceCube

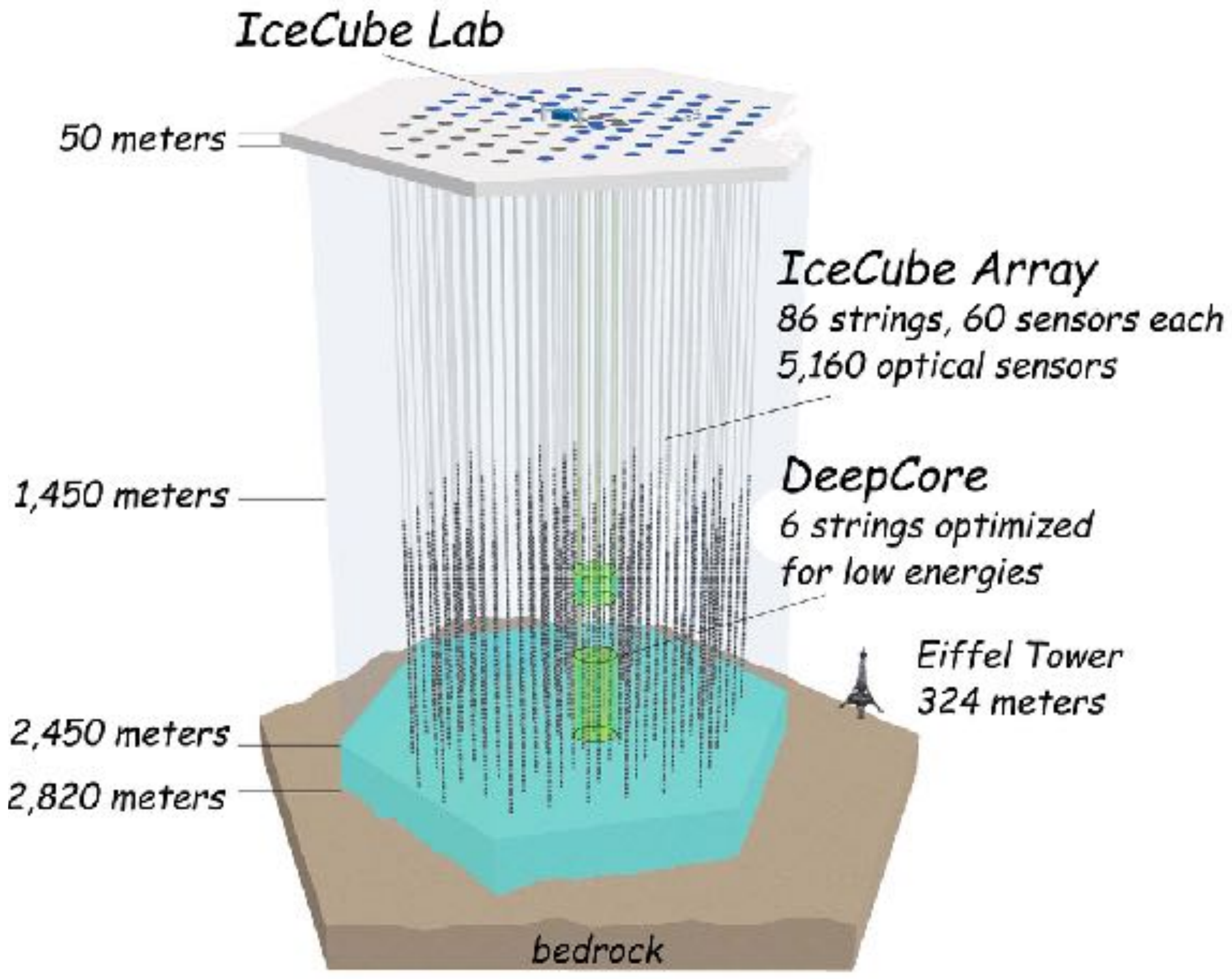


IceCube is a detector installed in the ice of the South Pole.

Charged particles emit Cherenkov light as they propagate through the ice. There are strings of 60 optical modules each.

From the detected light, the detector reconstructs the direction of arrival and the energy of the charged particles.

Since 2013, the detector has revealed that, in addition to particles produced in the Earth's atmosphere, there is a new population of neutrinos with energies up to about 10 PeV.

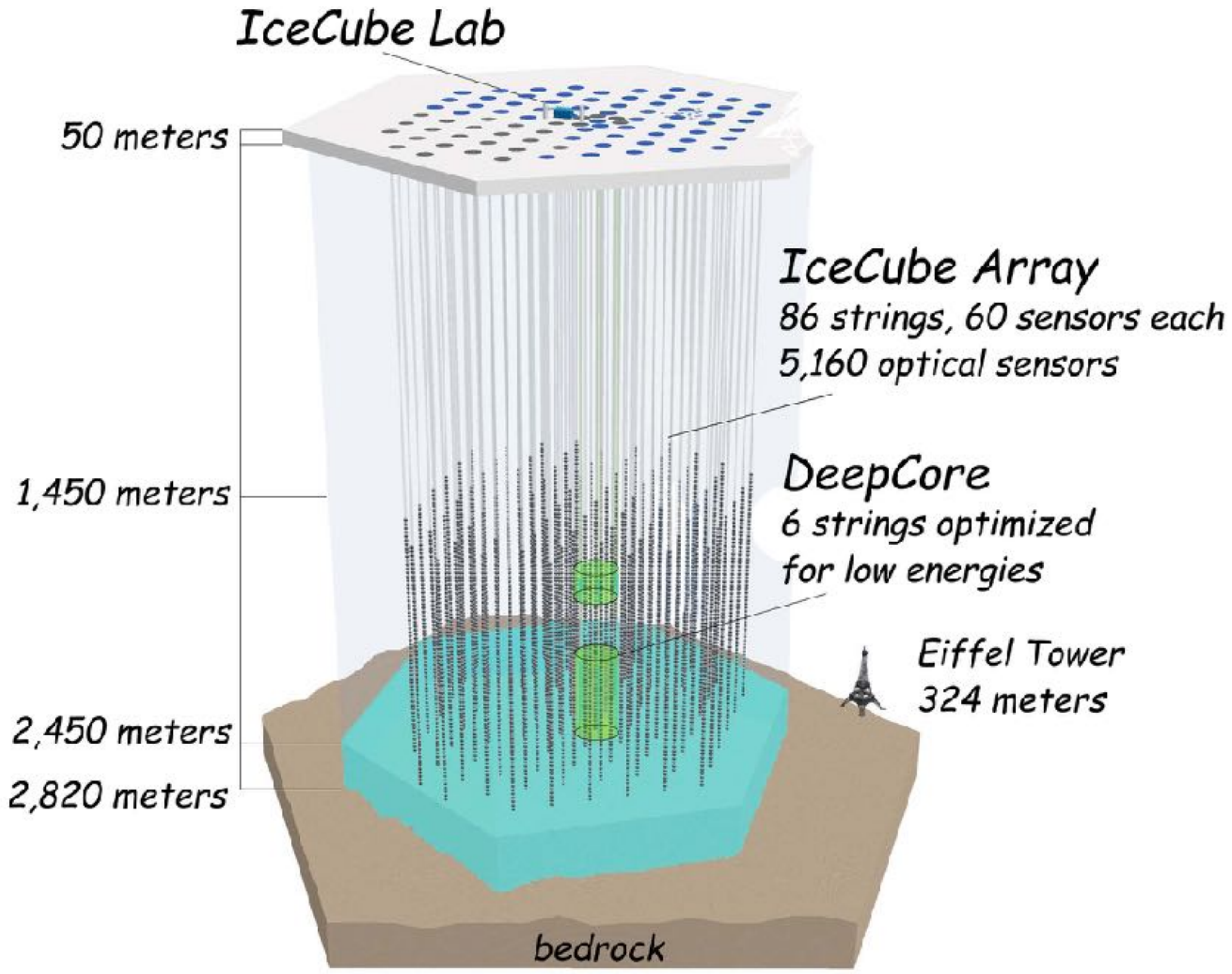


IceCube

highlights

new population seen as

1. neutrino induced muons from surrounding ice/rock
2. neutrino entering the detector
3. special events: taus, Glashow



IceCube

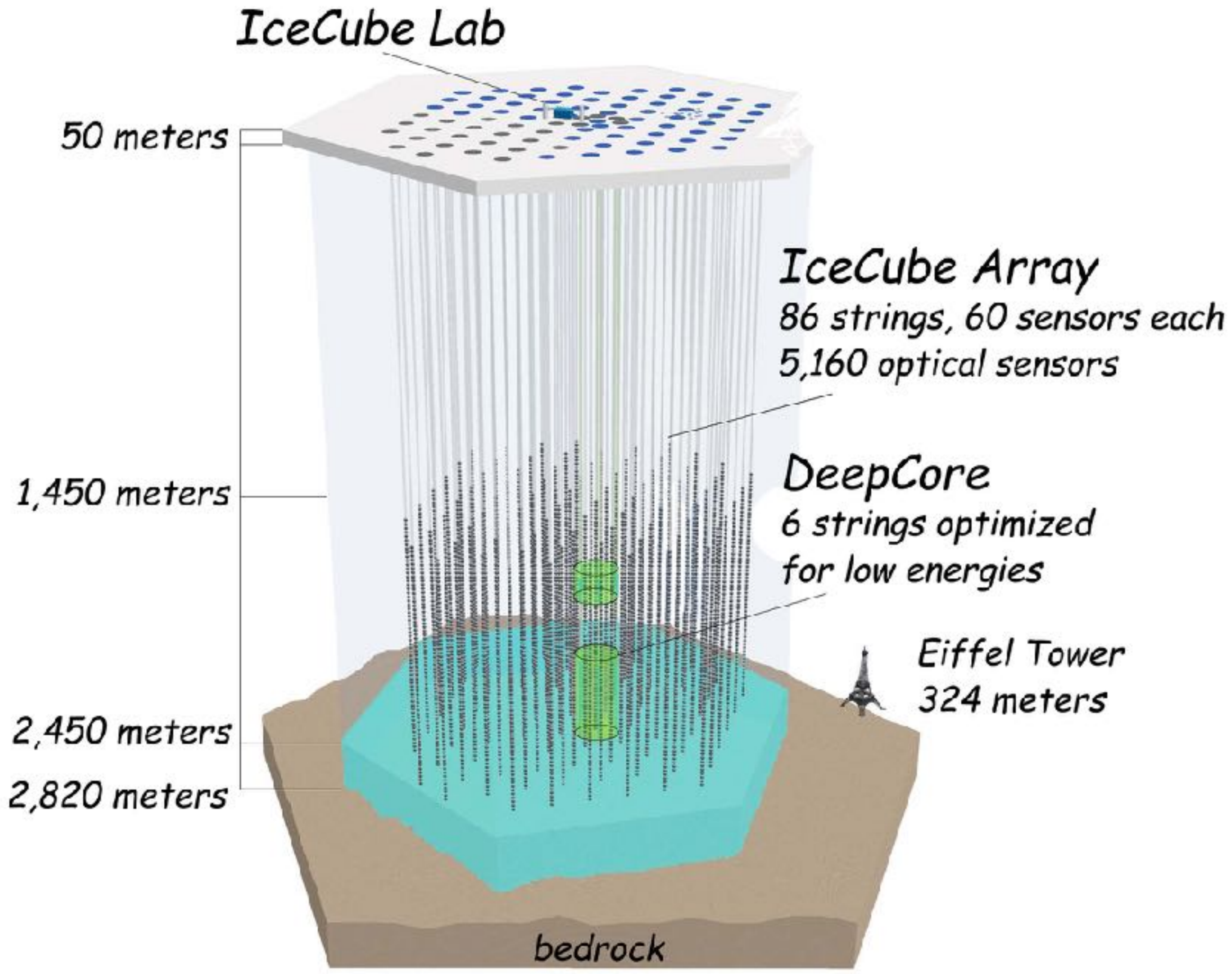
highlights

new population seen as

1. neutrino induced muons from surrounding ice/rock
2. neutrino entering the detector
3. special events: taus, Glashow

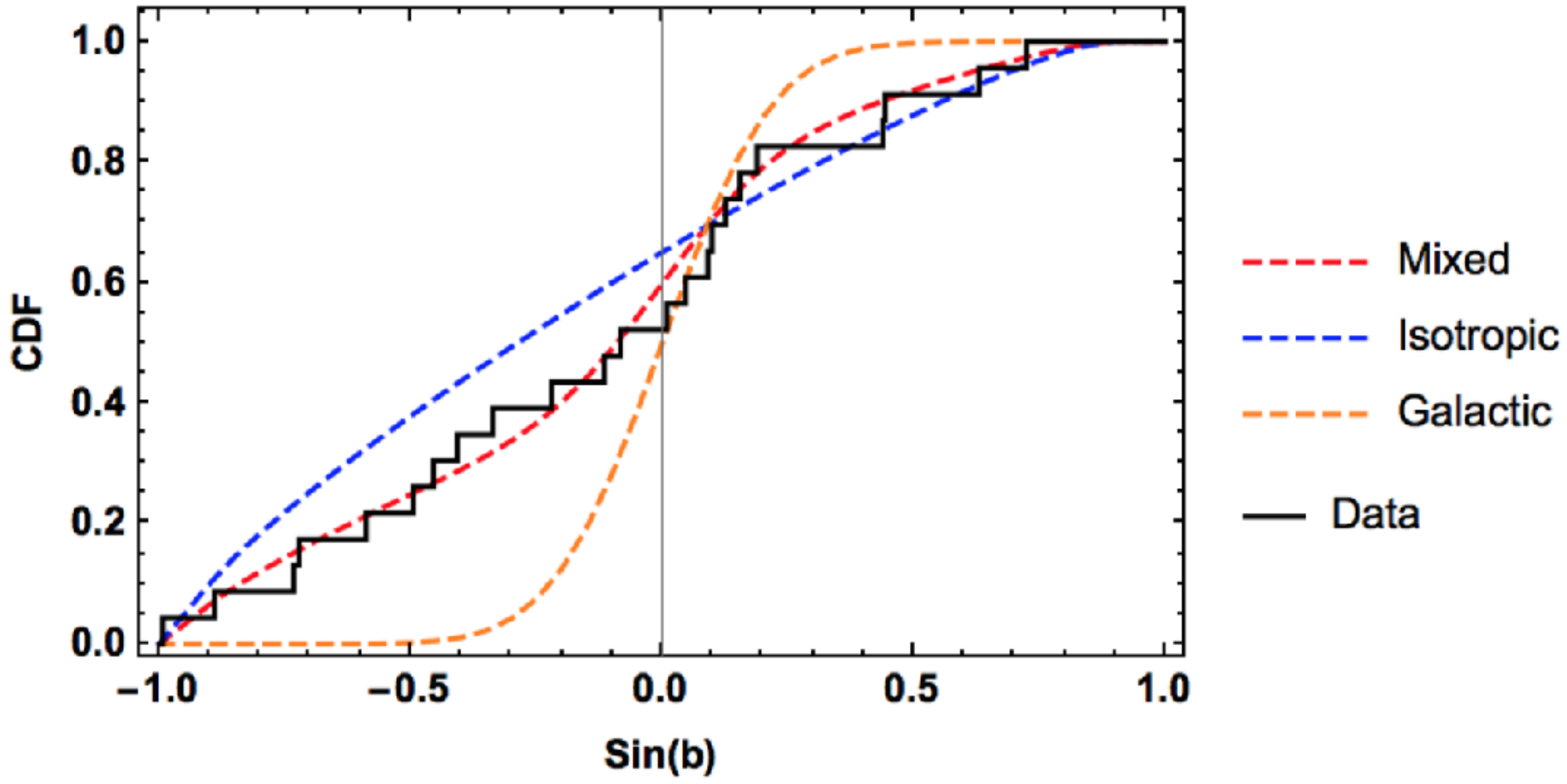
consist of "quasi-power law spectra $E^{-\alpha}$ with moderate compatibility among datasets

angular distribution almost isotropic, as expected from extragalactic population



deviations from isotropy

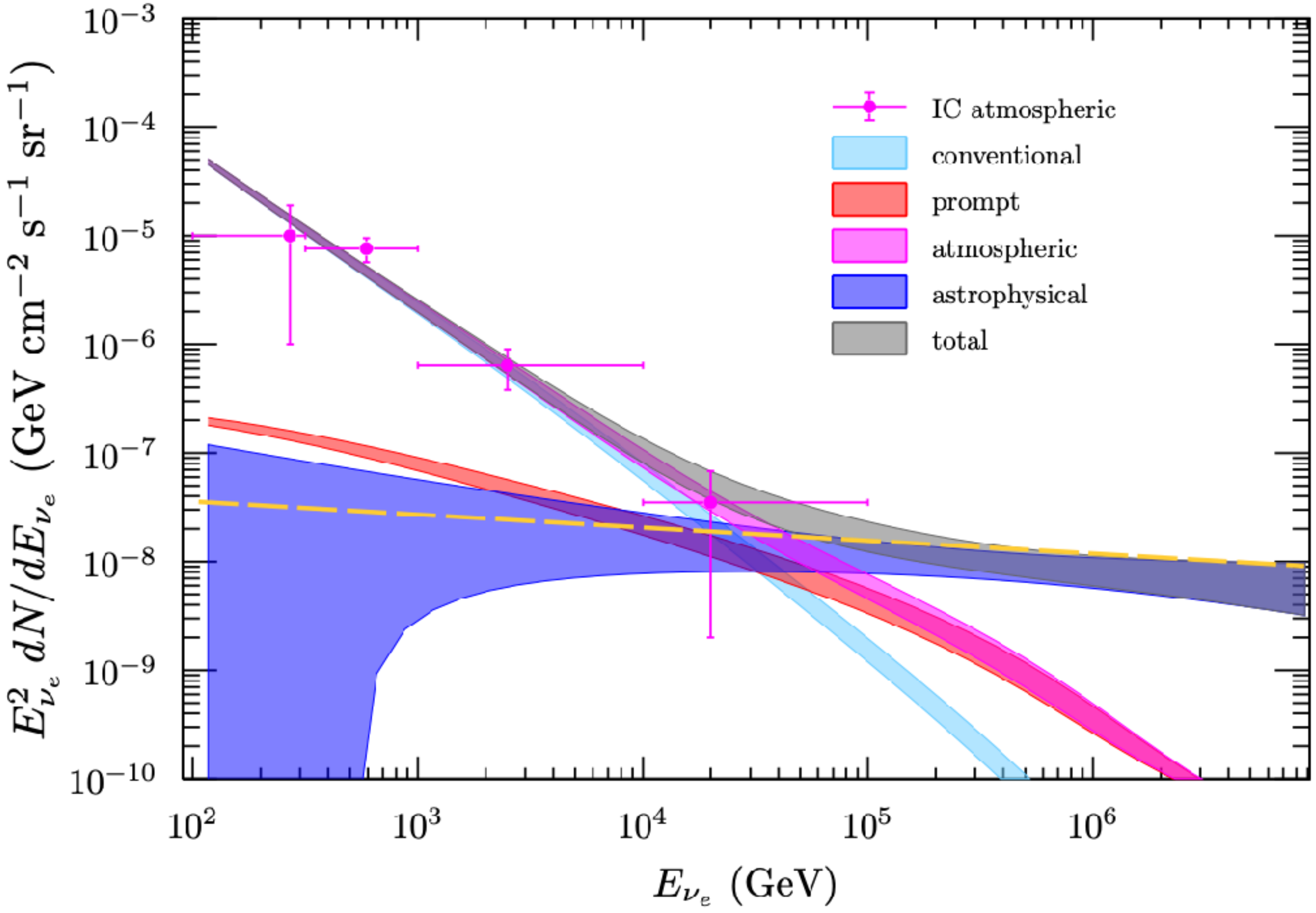
- Spurio claimed already in 2014 that IceCube data had hint of a galactic component
- Several arguments in favor of this hypothesis collected in the course of the years (e.g., Palladino et al ApJ 2016, figure at the right)
- In 2023 IceCube claimed a 4.5 σ hint with the help of a "template"

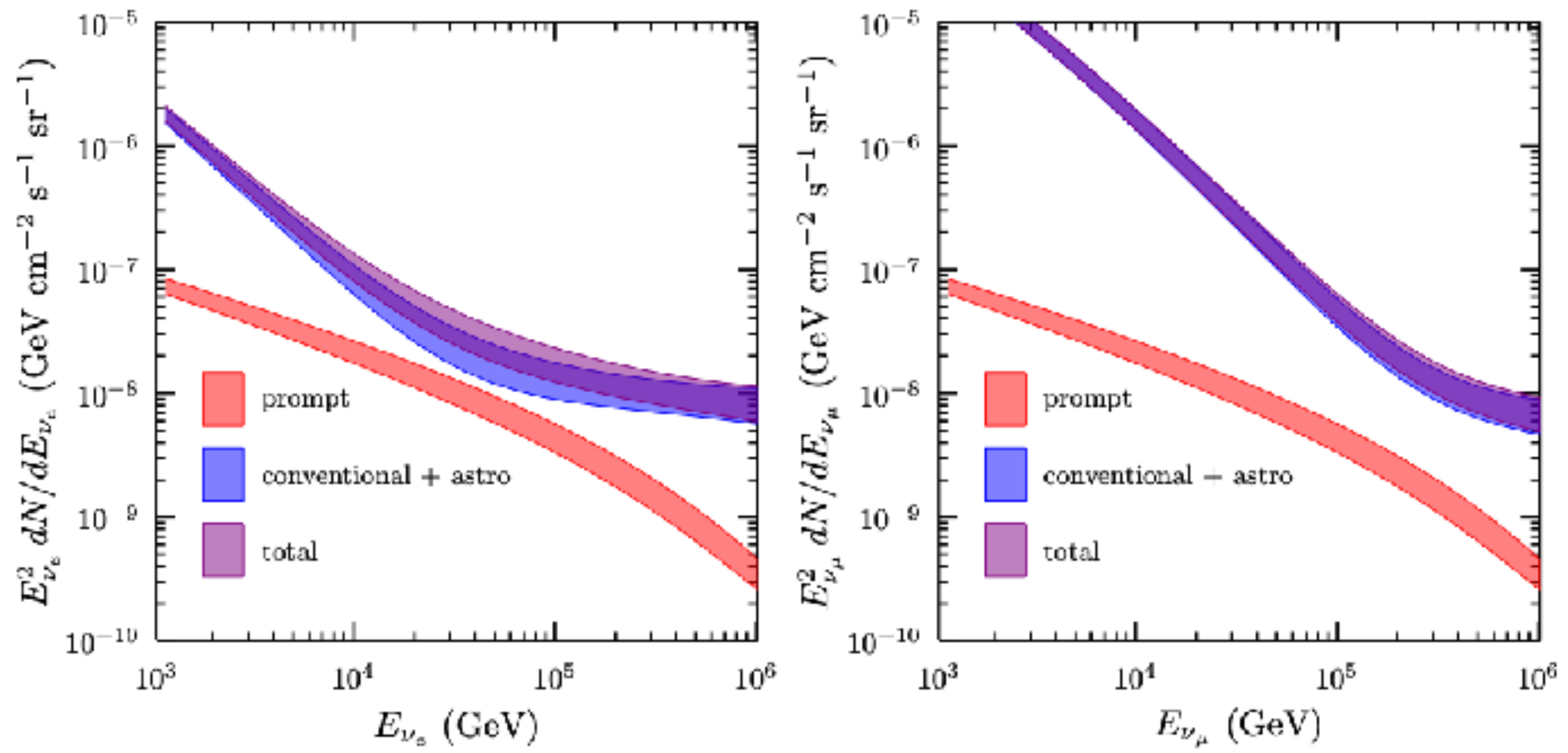


model expectations

Mascaretti & FV, JCAP 2019

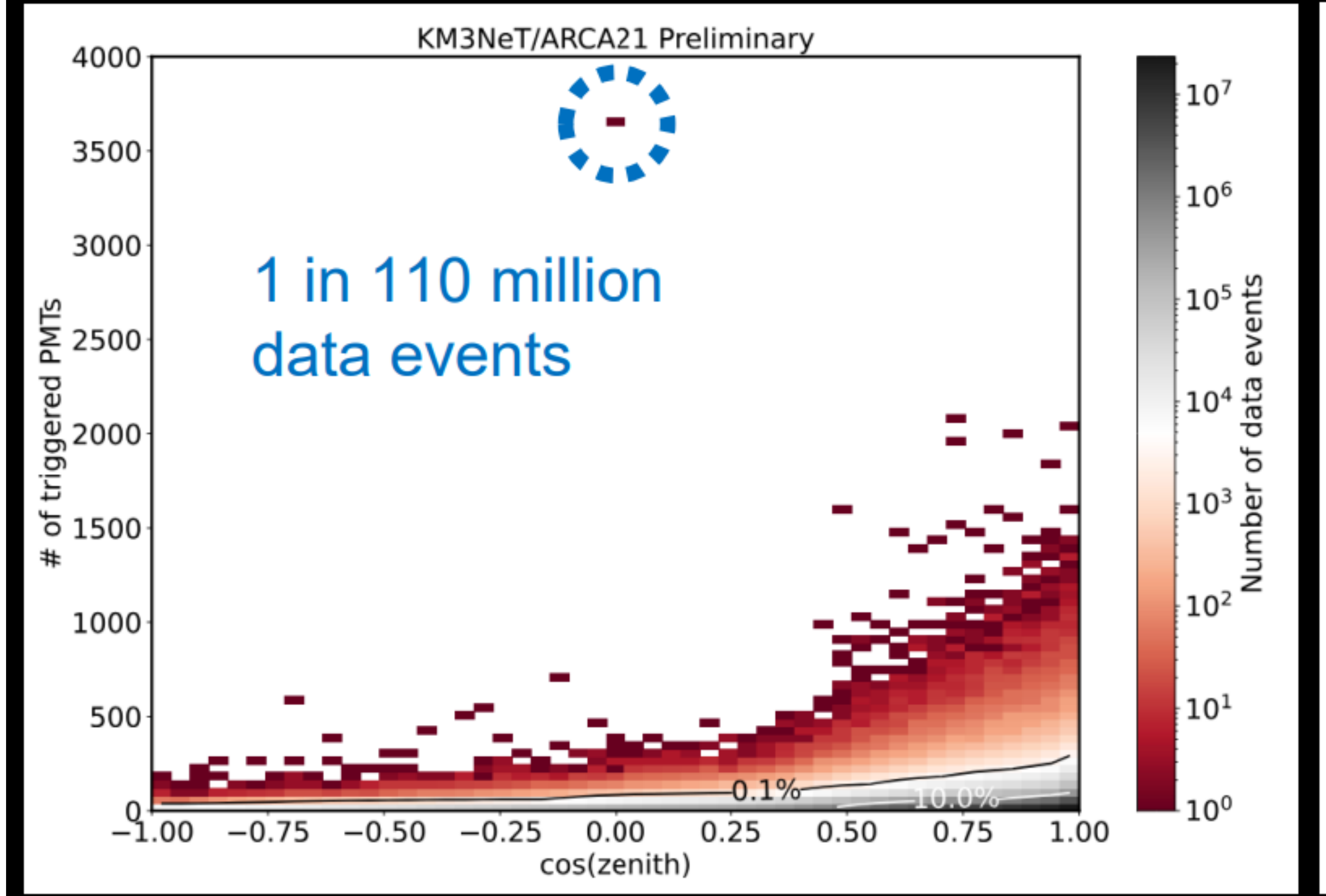
- expected electron neutrino flux from a model for power law "astrophysical" component that does not disagree with data
- and does not exceed the electromagnetic bounds (yellow)
- (conventional + prompt=purple)
- below, emphasis on the occasion to see the prompt from the data

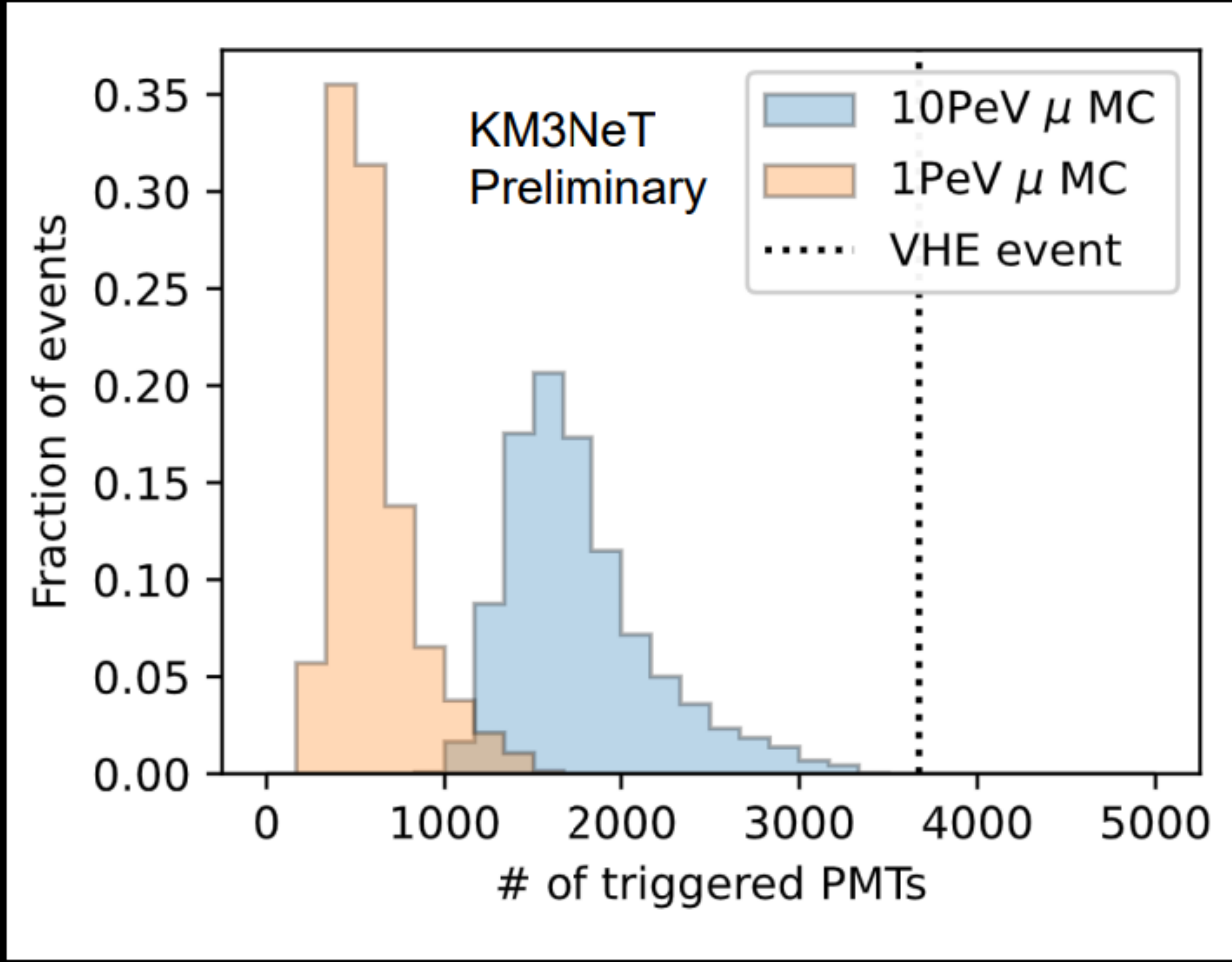




Uncharted Territory

- Significant event observed with huge amount of light
- Horizontal event (1° above horizon) as expected since earth opaque to neutrinos at PeV scale
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light
  - Likely multiple 10's of PeV





summary and discussion

on high-energy astrophysical neutrinos

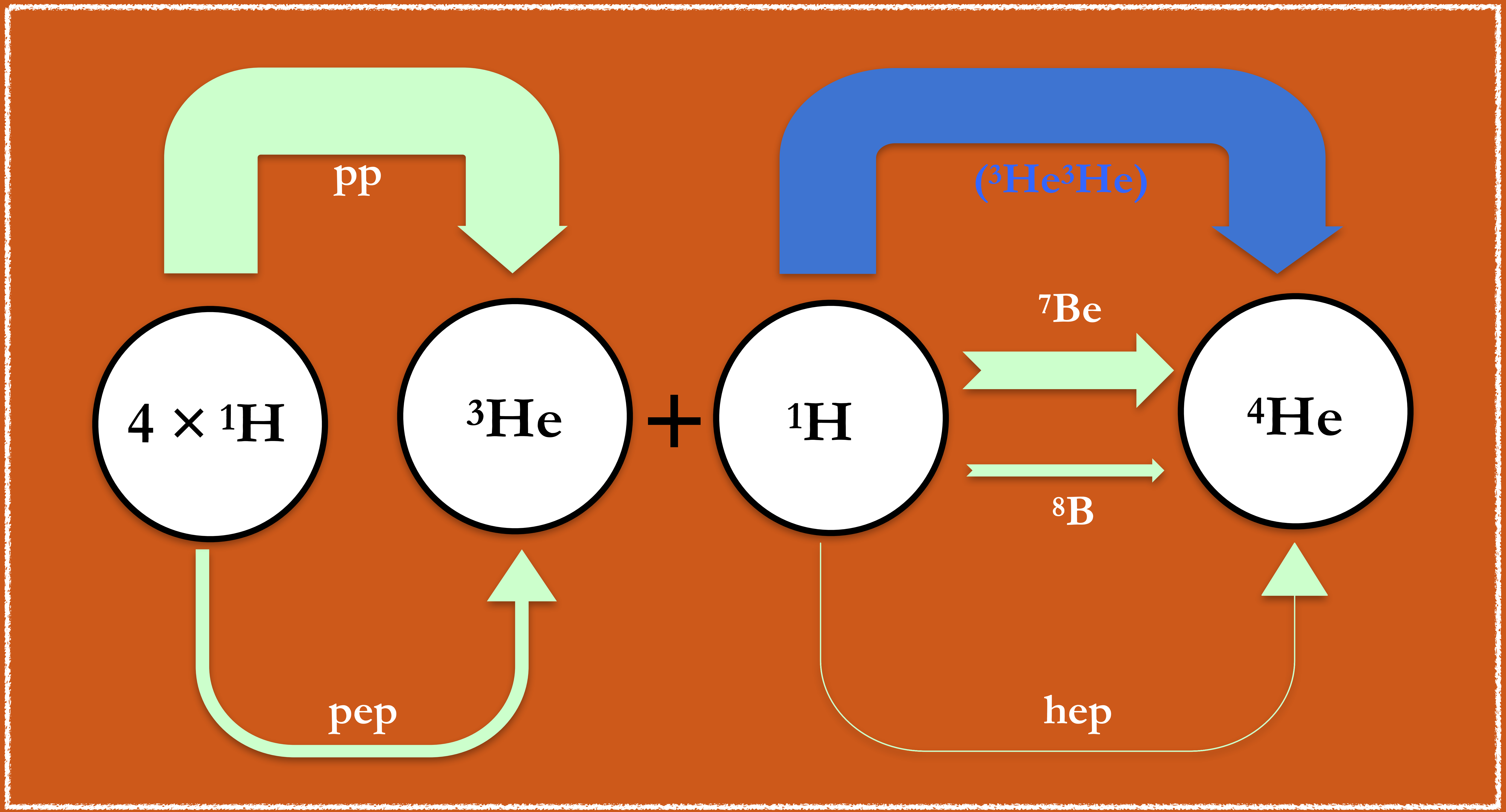
- A discovery of a new component (most likely of cosmic origin) has been made. Now time to understand what we are seeing.
- Next targets: clear point sources; galactic component.
- Oscillations provide very useful constraints.
- At this point, new measurements are warranted. The results will have a big impact on high-energy astrophysics.

spare slides

more on pp neutrinos, an exercise on neutrino propagation, sterile neutrinos 2006, highlights from Neutrino 2024

Francesco VISSANI - Laboratori Nazionali del Gran Sasso

nuclear transformations of the pp-chain



production of ^3H fully tagged by pp + pep neutrinos

consumption of ^3H = $(^3H^3H)$ + 7Be + 8B + hep neutrinos

[neutrinos] differ from photons through the fact that they would not travel at the speed of light. [Pauli, 1930]

exercise

thoughts around a wrong result

A dozen years ago, an experiment measured the velocity of neutrinos over a distance of 730 km, *finding that neutrinos arrive* 60 ns *before light.*

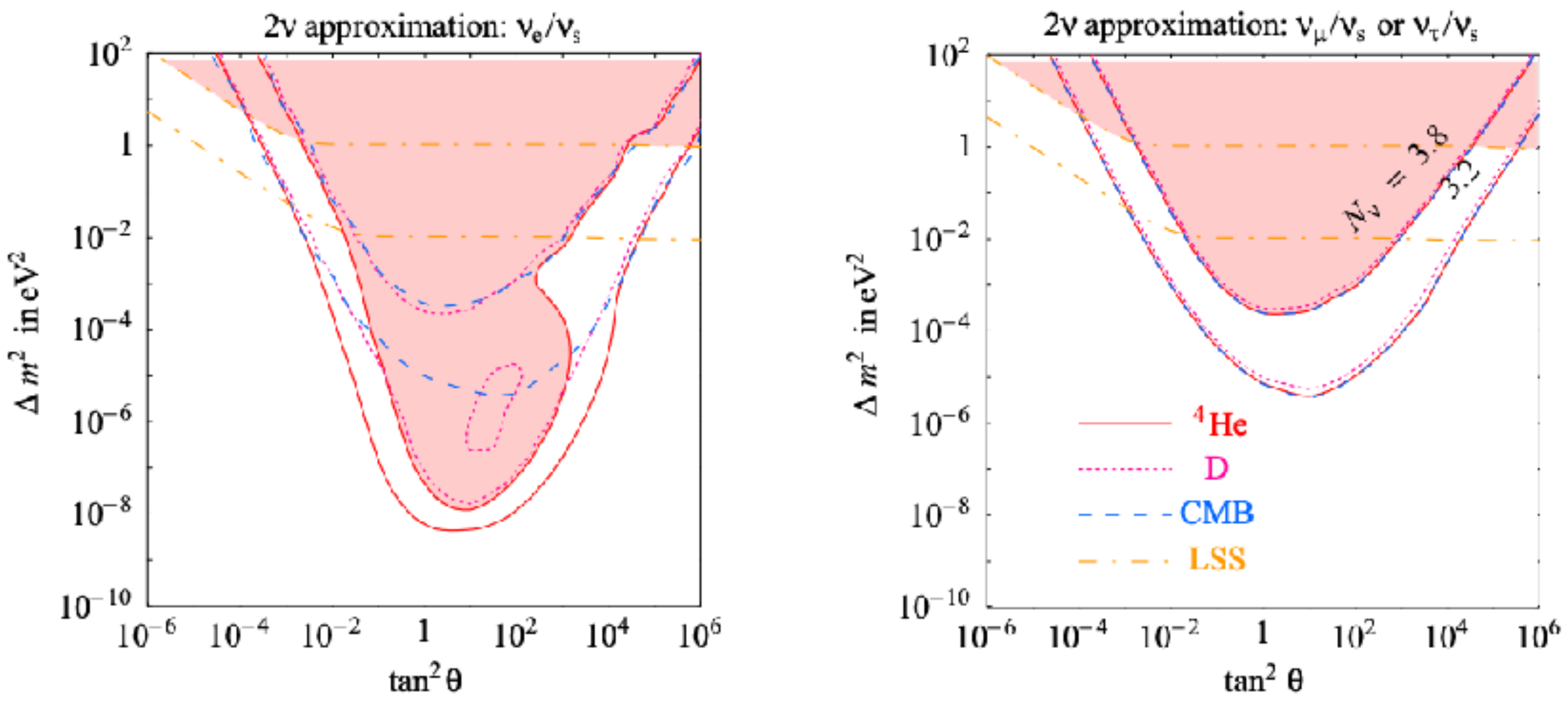
- What would be the fractional excess of neutrino speed $\delta = \dfrac{v_\nu - c}{c}$?
- Neutrinos from a 50 kpc supernova (SN1987A) arrived within 3 hours of the predicted time. Is this result compatible with the previous one?
- The Hamilton-Jacobi relation links the velocity with (energy-momentum) dispersion relation. Can you imagine any consequences of this?

sterile neutrinos 2006 - some details

$$\dot{\rho} = zZH\frac{d\rho}{dz} = i[\mathscr{H},\ \rho] - \{\Gamma, (\rho - \rho^{\rm eq})\}.$$

$$\mathscr{H} = \frac{mm^\dagger}{2E_\nu} - \frac{7\pi^3\,T_\nu\,\alpha_2}{15\,M_W^4}\Big[T_\nu^4\cos^2\theta_{\rm W}\ {\rm diag}\,(\rho_{ee},\rho_{\mu\mu},\rho_{\tau\tau},0) + 2\,T^4\ {\rm diag}\,(1,0,0,0)\Big]$$

$$\dot{r} = zHZ\frac{dr}{dz} = \Gamma_{p\to n}(1-r) - r\Gamma_{n\to p} \qquad r = \frac{n_n}{n_n + n_p}$$



Neutrino 2024

some news

- very strong limit from KATRIN
  $m_{\bar{\nu}_e} < 0.45$ eV
- an impressive high energy event from Km3NET above 10 PeV (see next slide)
- first hint for diffuse supernova neutrino background @ Superkamiokande

I contributed with a talk on history of neutrinos

Latest results from KM3NeT

João Coelho

for the KM3NeT Collaboration

18 June 2024

The genesis of the neutrino concept

19 Jun 2024, 15:00

1h

Aula Martini (U6 building) (University of Milano Bicocca)

Lecture for Students (i...

Speaker

Francesco Vissani (Istituto Nazional...

Description

The first proposal of the neutrino idea is about to turn a century old. In this lecture, we recall the fundamental advances that occurred soon after, in the era of modelling the atomic nucleus. We discuss the subsequent modifications and developments of the neutrino concept, which shaped modern thinking and prepared for observational advances. We retrace a journey through history, organised in six stages, focusing in particular on the initial ones:

1. Early 1930s. Pauli's neutrino and its significance.
2. Fermi 1933-34: The first beta-ray and neutrino theory. Conceptual and formal foundations, implications. Electron capture.
3. Majorana 1937: The modern understanding of fermions. A new concept of neutrino.
4. From muons to families. The numbers of leptons. Nature of weak interactions and the neutrino. The standard model and its failure.
5. Pontecorvo & Sakata's winning approach to neutrino mass.
6. The part that remains to be written: How to observe the absolute mass of the neutrino? What is its nature?