Neutrinos - first lecture

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

Francesco VISSANI - Laboratori Nazionali del Gran Sasso - July 20, 2022

Gianni Fiorentini

(1948-2022)

in dedication to the memory of an excellent colleague and friend

this lecture

selected topics in astroparticle neutrinos physics

- solar neutrinos
- geoneutrinos
- supernova neutrinos
- atmospheric neutrinos
- high-energy astrophysical neutrinos

Solar neutrinos

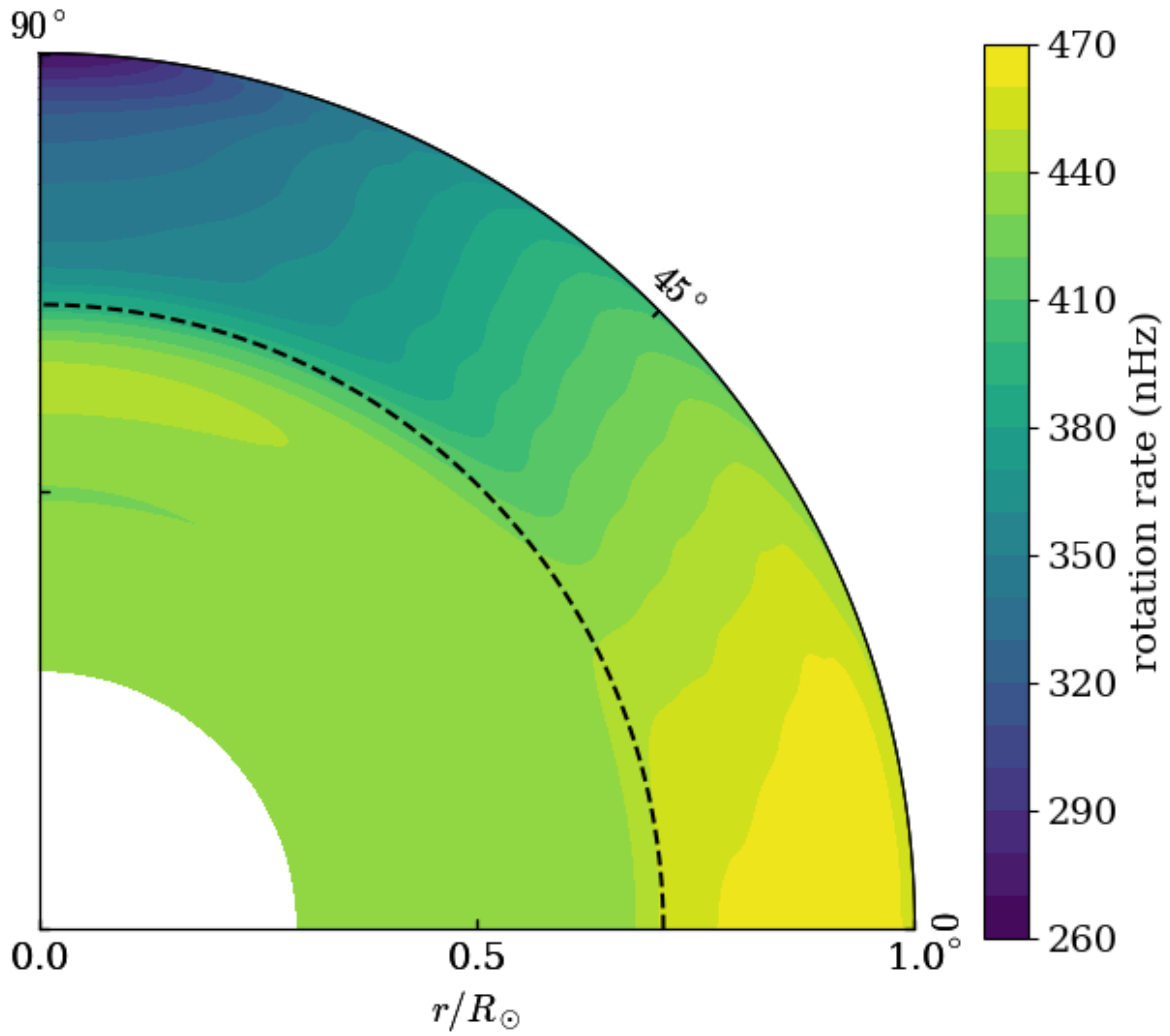
introduction

on solar neutrinos

- Reliable models of the sun have existed since the 1960s. Many tests conducted.
- Neutrino studies provided 1st evidence of f*lavour oscillations,* and for the past 10 years, have probed solar core and verified the functioning of its nuclear engine.
- Many detectors have been involved - see later. Observations obtained by scattering on particular nuclei and $\nu + e \rightarrow \nu + e$ (=elastic scattering)

Generalities on the Sun

- The sun radiates a prodigious amount of energy, $L_\odot = 3.282 \times 10^{33}\,\dfrac{\text{erg}}{\text{s}}$
- 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

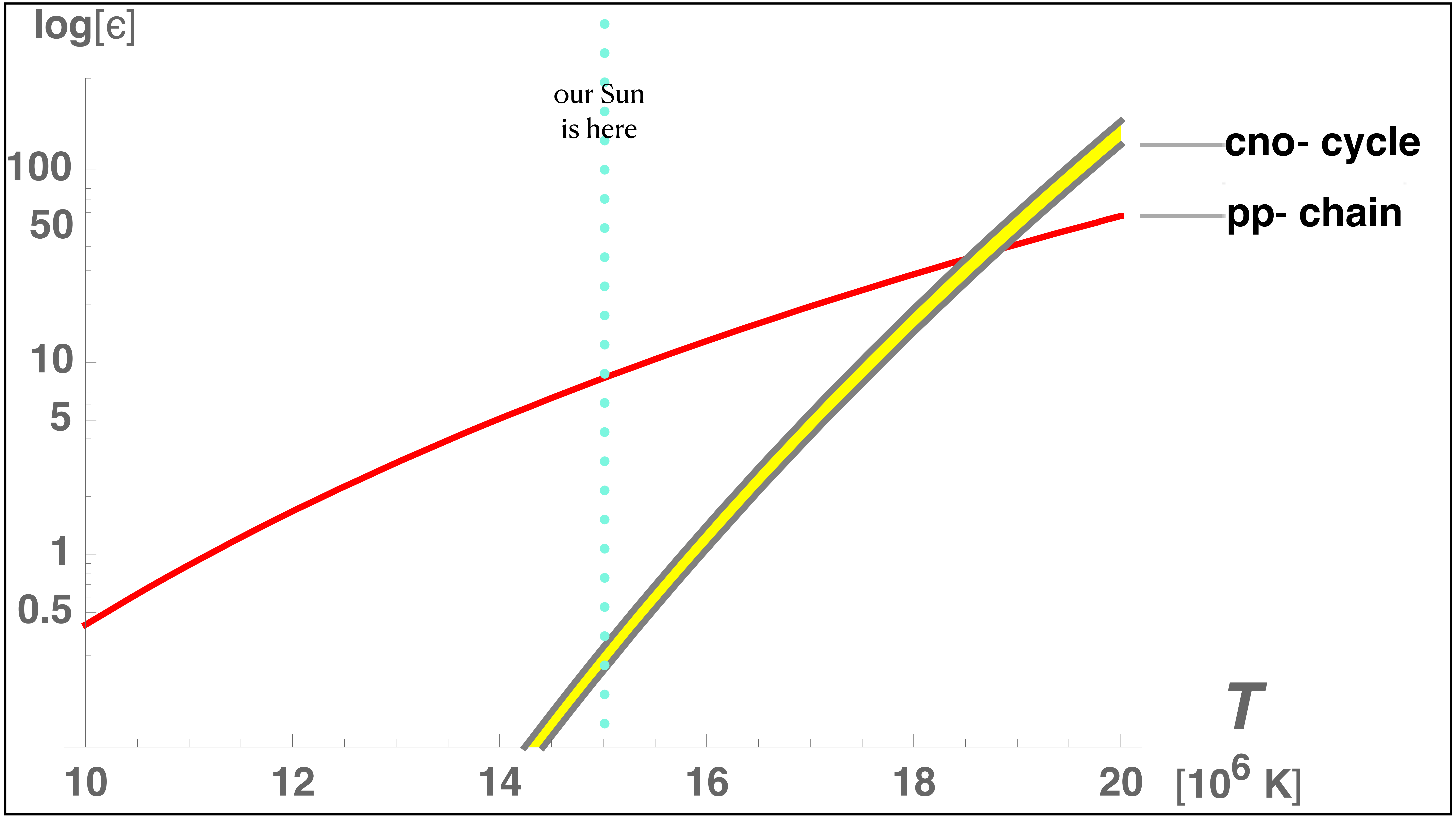


History

- Sun as a **fusion reactor**: first imagined about 100 yr ago in the discussion of nuclei, model elaborated before WWII *(von Weizsäcker & Bethe)*, last details worked out mid fifties *(Fowler)*
- End of WWII, *Bruno Pontecorvo* proposed to **observe solar neutrinos**

History

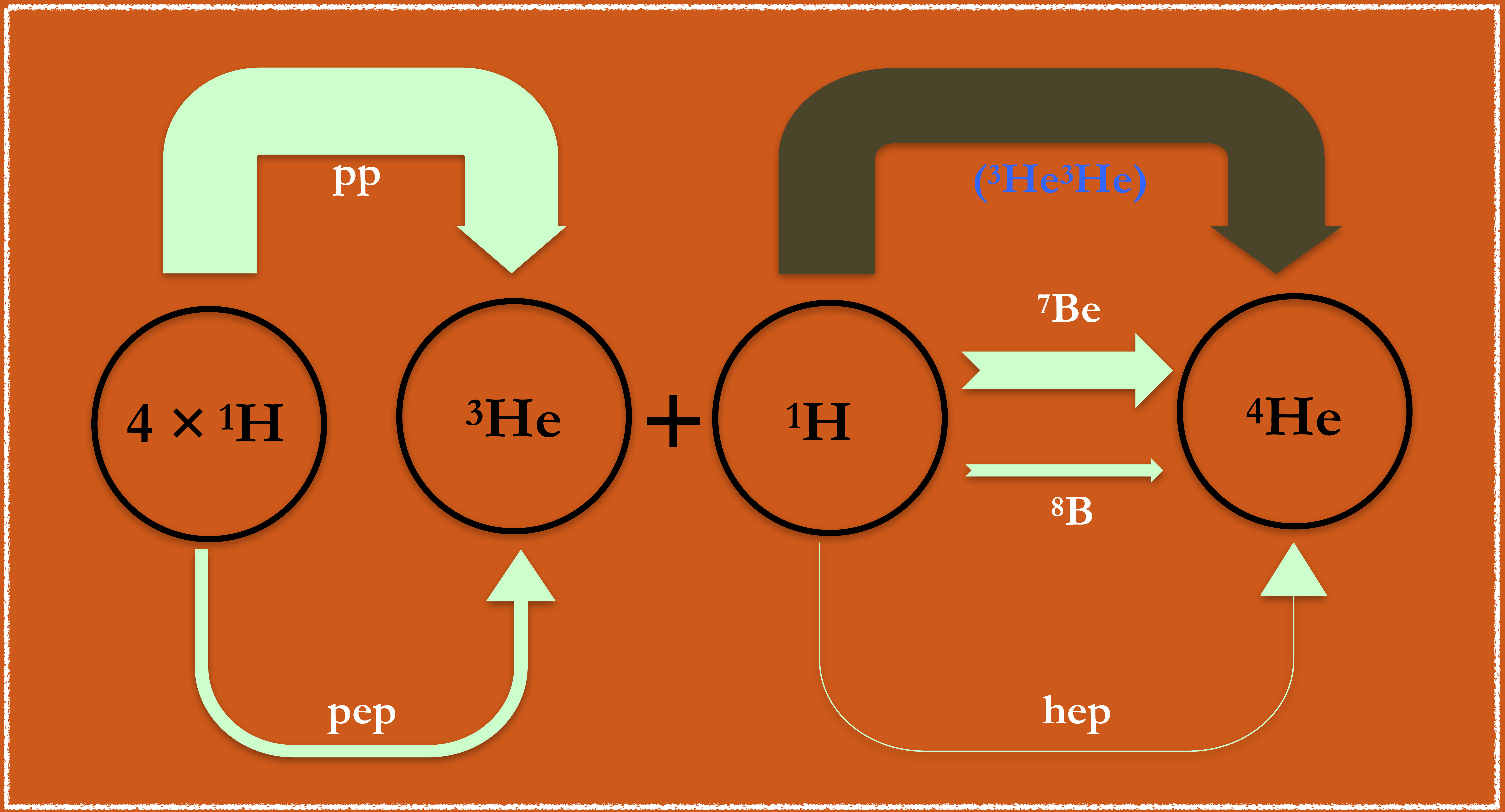
- Sun as a **fusion reactor**: first imagined about 100 yr ago in the discussion of nuclei, model elaborated before WWII *(von Weizsäcker & Bethe)*, last details worked out mid fifties *(Fowler)*
- End of WWII, *Bruno Pontecorvo* proposed to **observe solar neutrinos**
- Key theoretical astrophysics tool: the **standard solar model**. We owe its first realisation in mid sixties to *John Bahcall*
- Again *Pontecorvo* elaborated the idea of **flavor oscillations** (1957-1967)



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

We begin the discussion from the pp-chain.

pp-chain and nuclear transformations



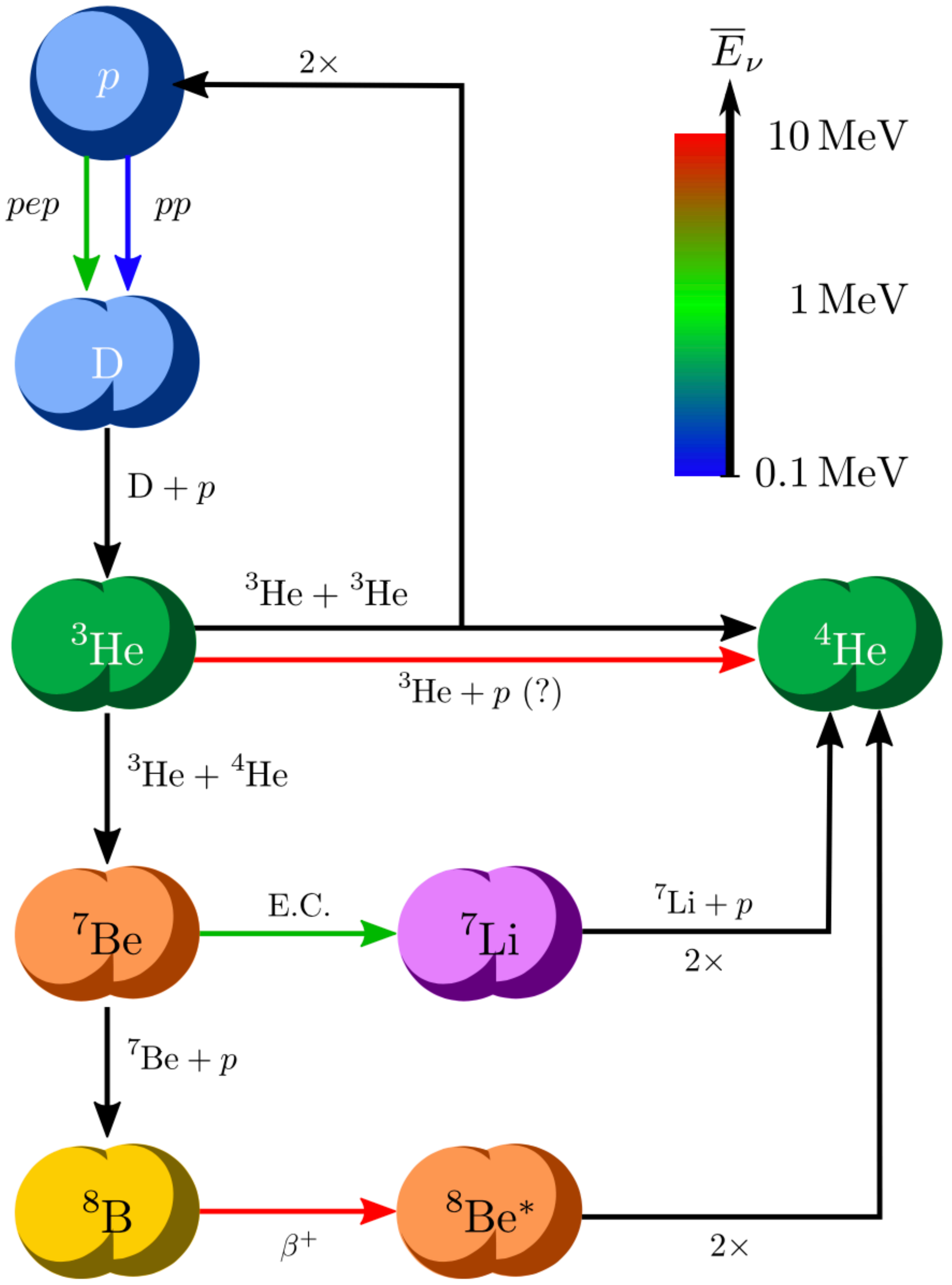
production of ^{3}H fully tagged by pp + pep neutrinos

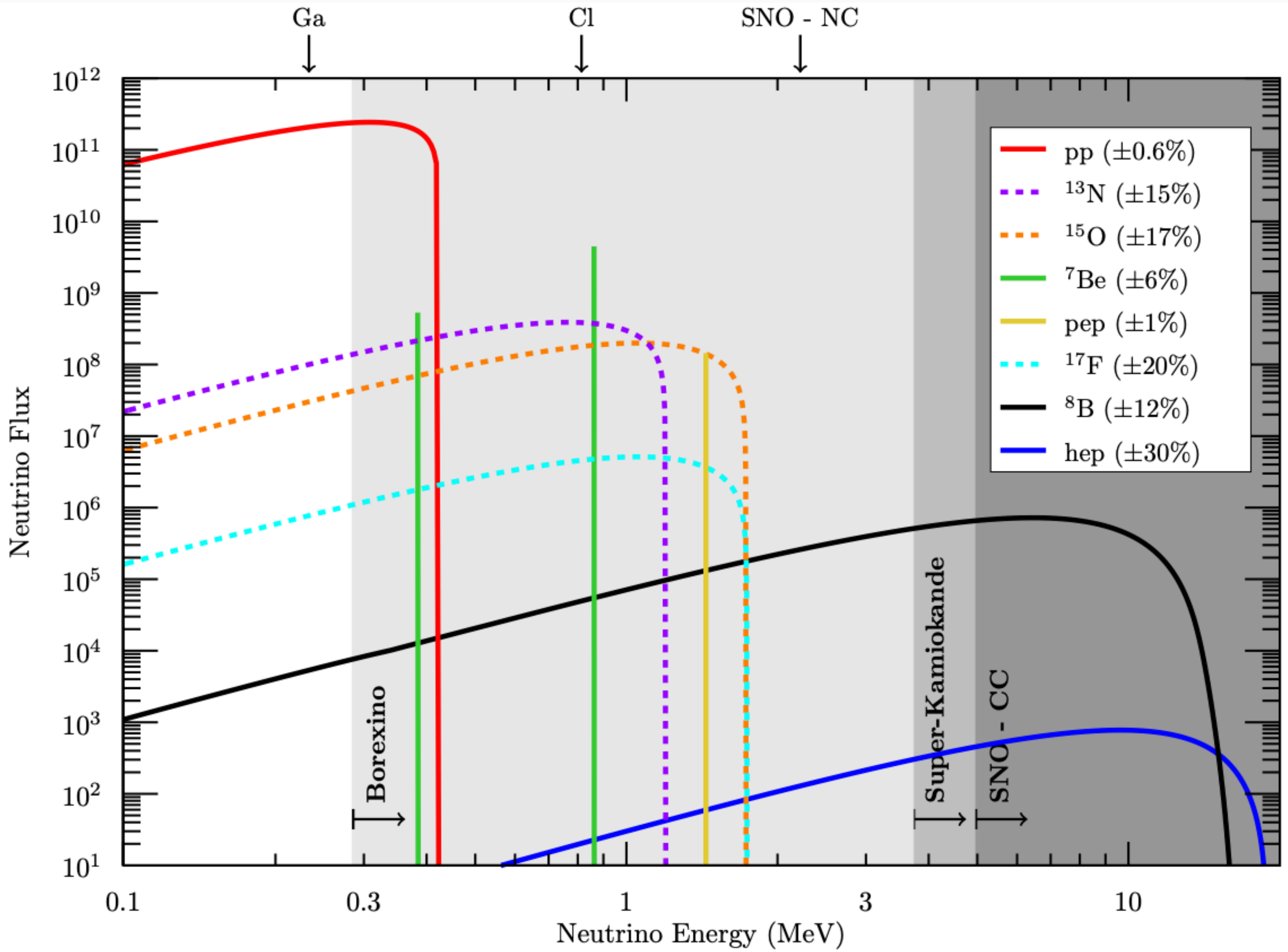
consumption of ^{3}H = (^{3}H^{3}H) + 7Be + 8B + hep neutrinos

again on the pp-chain

the color code in the arrows (see inset) indicates the energies of the corresponding neutrinos

Carlo Mascaretti, PhD thesis, 2020



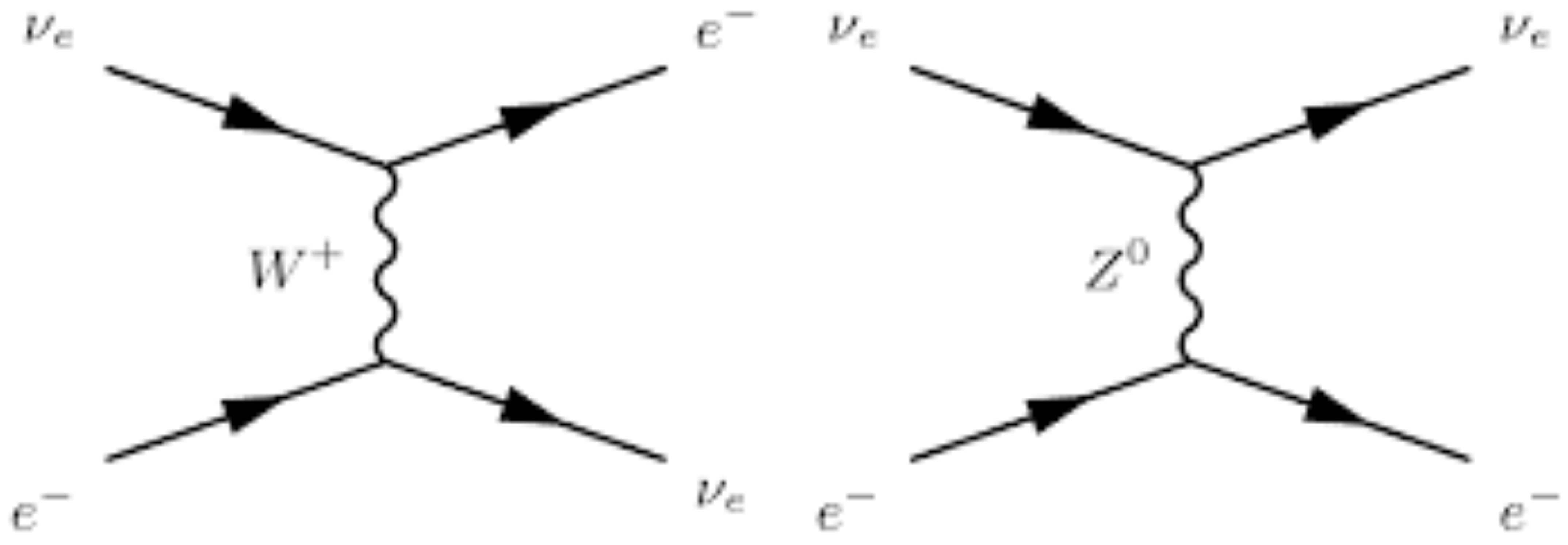


Carlo Mascaretti, PhD thesis, 2020

elastic scattering

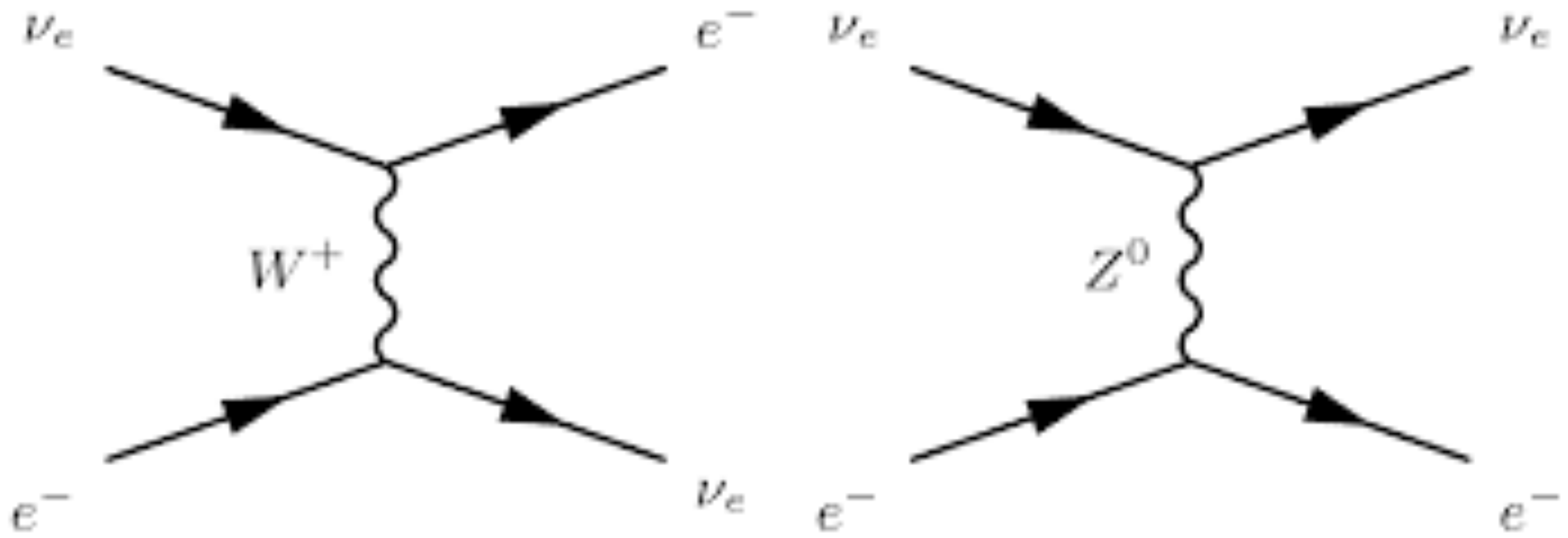
of neutrinos on electrons

- a basic process of the standard model
- (radiative corrections known)
- theoretically very clean



elastic scattering

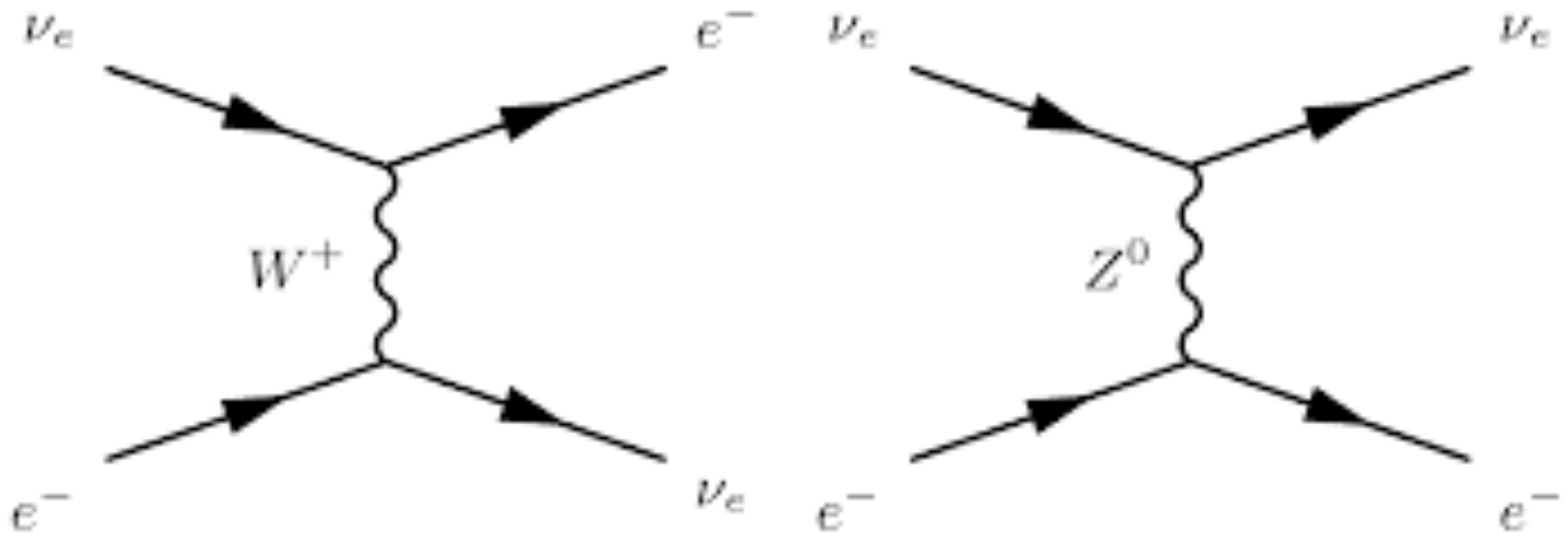
of neutrinos on electrons



- a basic process of the standard model
- (radiative corrections known)
- theoretically very clean
- mass of the electron is less than the energies of boron neutrinos: in water Cherenkov detectors, direction can be reconstructed (—> Kamiokande, SK)

elastic scattering

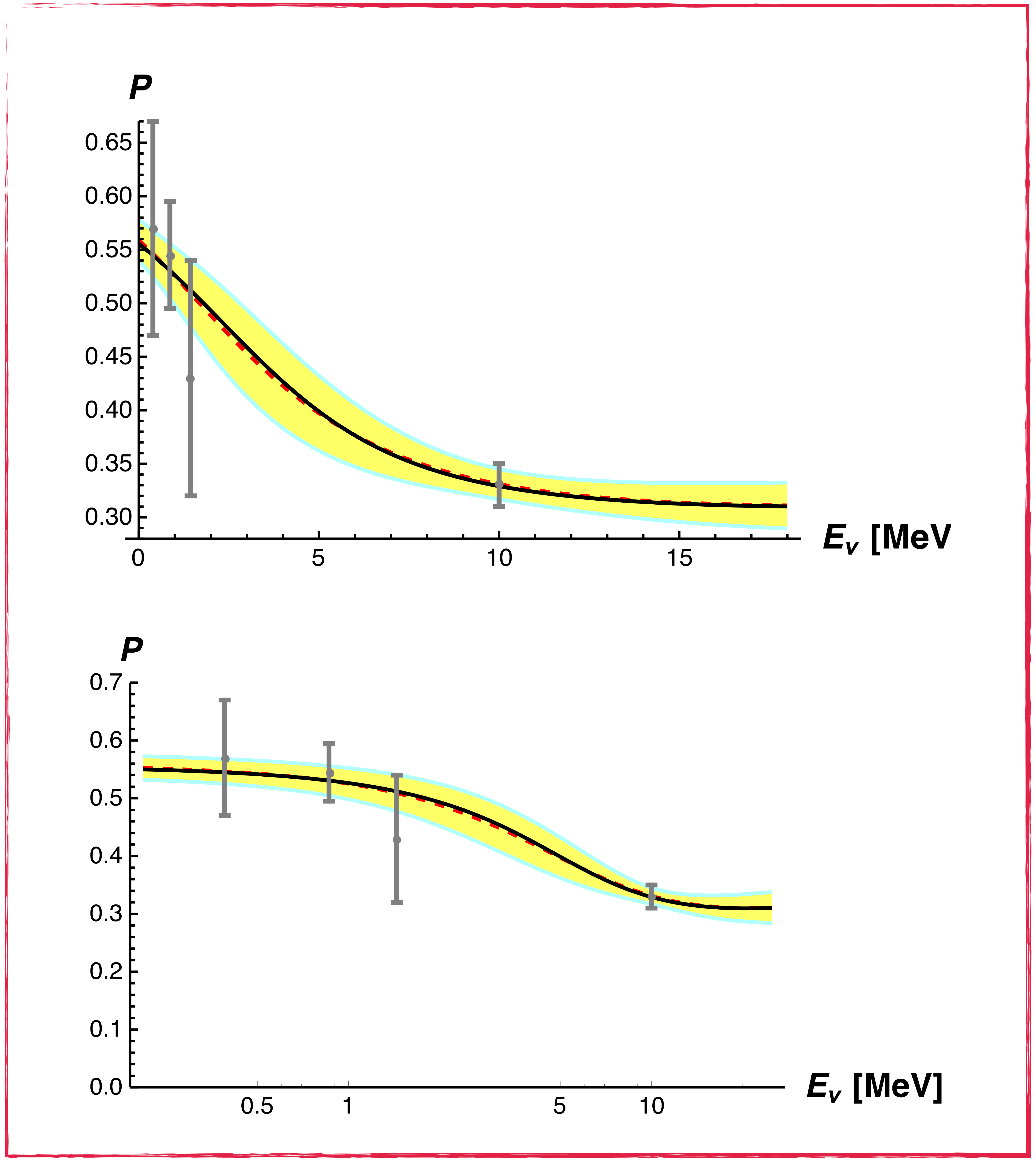
of neutrinos on electrons



- a basic process of the standard model
- (radiative corrections known)
- theoretically very clean
- mass of the electron is less than the energies of boron neutrinos: in water Cherenkov detectors, direction can be reconstructed (—> Kamiokande, SK)
- the different components of the neutrino energy spectrum can be identified and scintillator detectors allow to cover them all (—> Borexino)

probability of “survival”

of the electron neutrinos in the Sun



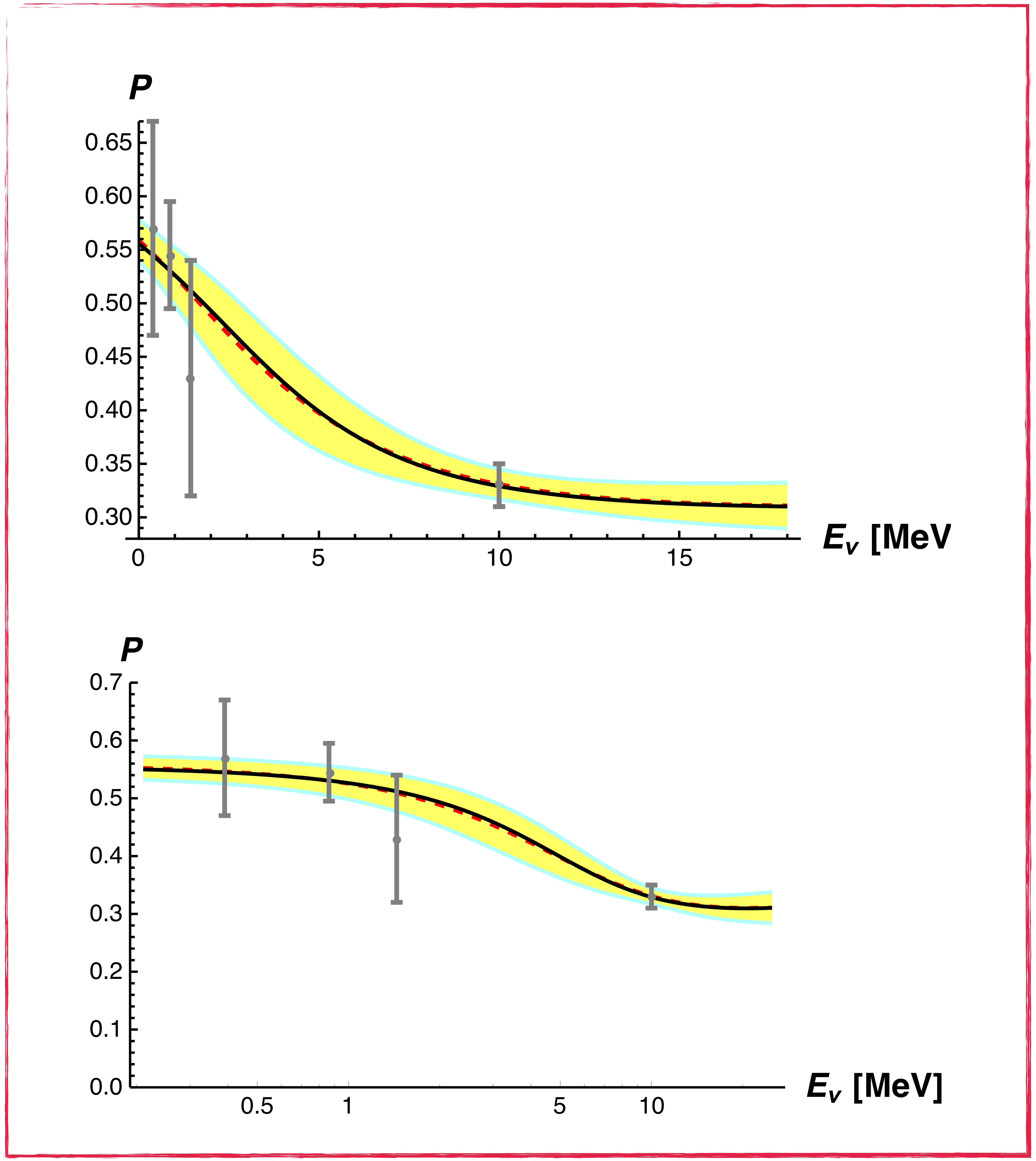
probability of “survival”

of the electron neutrinos in the Sun

- the probabilities differ from 1

- something around 5 MeV

Let us recall just how these characteristics arise in the theory



neutrino transformation (oscillations)

an essential reminder of the relevant theoretical ingredients

the neutrinos produced in weak interactions are superposition of mass eigenstates

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

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

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

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

The Nobel Prize in Physics 2002

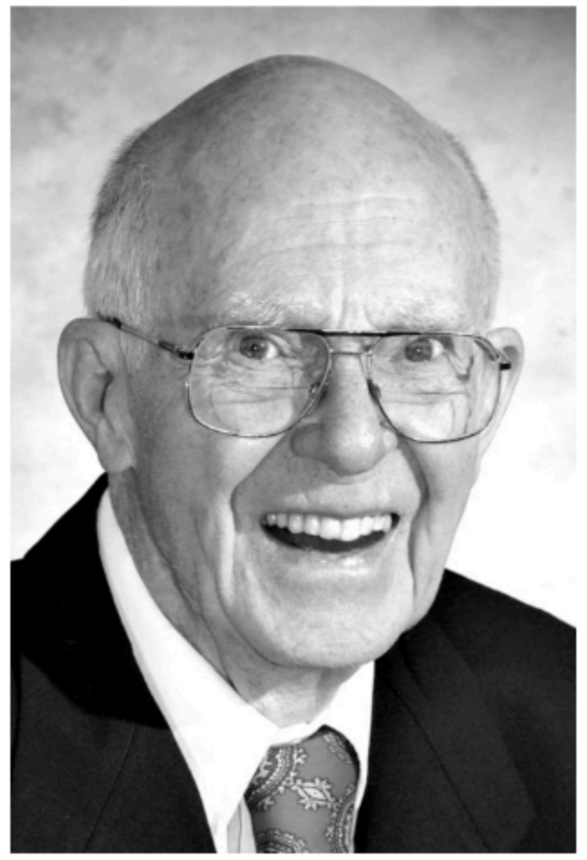


Photo from the Nobel Foundation archive.

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."

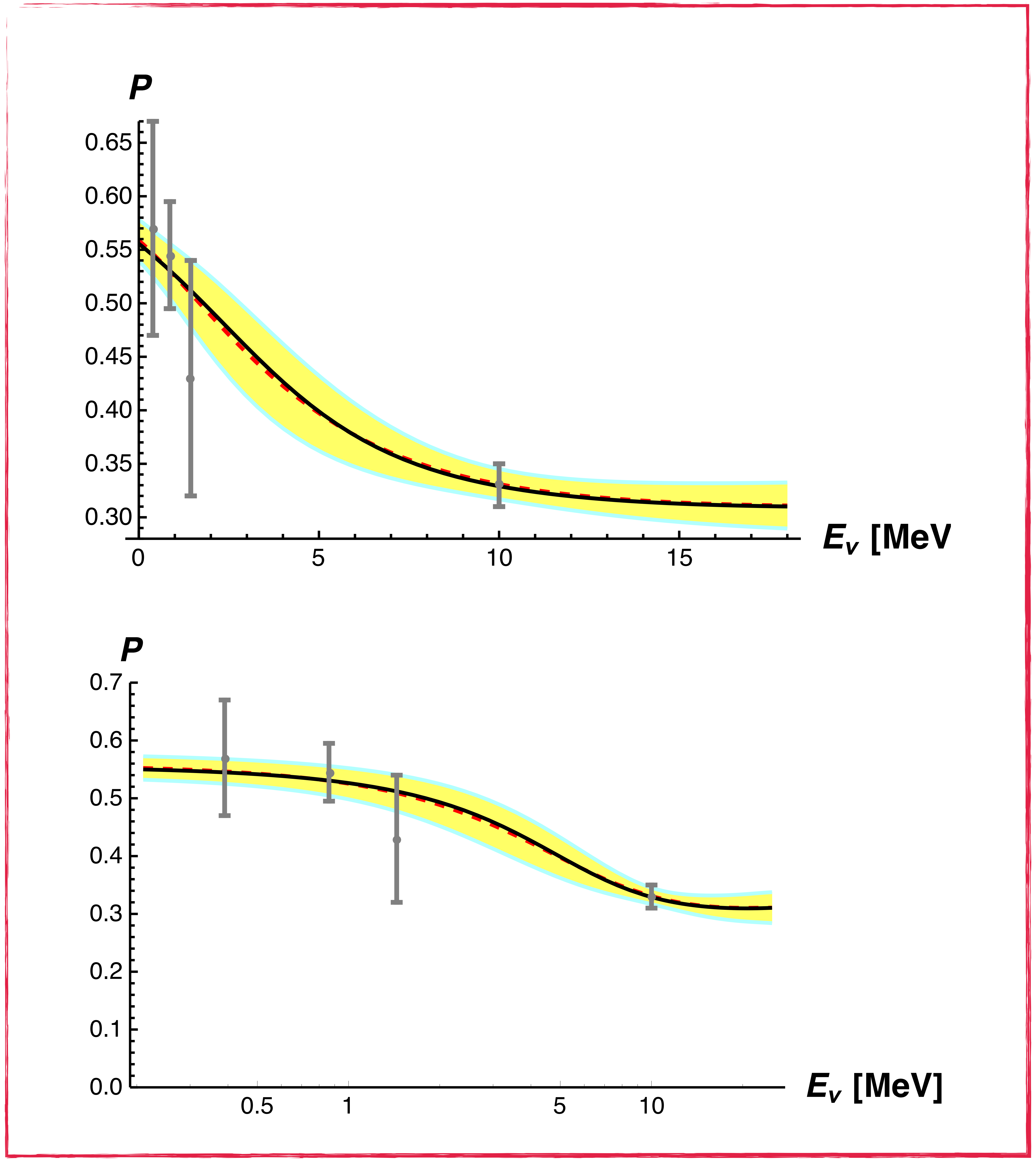
Kajita: experimental proof of oscillation with atmospheric neutrinos
McDonald: experimental proof of oscillation with **solar neutrinos**

probability of "survival"

of the electron neutrinos in the Sun

- the probabilities differ from 1
- something around 5 MeV

these two graphs are based on SNO and Borexino measurements - grey bars



Borexino's exploration of the centre of the Sun

nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄ Subscribe

nature > articles > article

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

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

nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄

nature > articles > article

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

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*)

summary and discussion

on solar neutrinos

- Recognition of solar neutrino oscillations has changed the field and impacted on particle physics (more discussion tomorrow)
- The SSM remains a key tool and can be still improved
- Borexino played a big role and opened new avenues for the experimental research

Geoneutrinos

introduction

on geoneutrinos

- Relevant probe of radioactive elements in the Earth's interior. Natural links with geophysics, but also planetology
- Two detectors: KamLAND and Borexino
- Detection reaction $\bar{\nu}_e + p \to e^+ + n$ (=inverse beta decay)

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

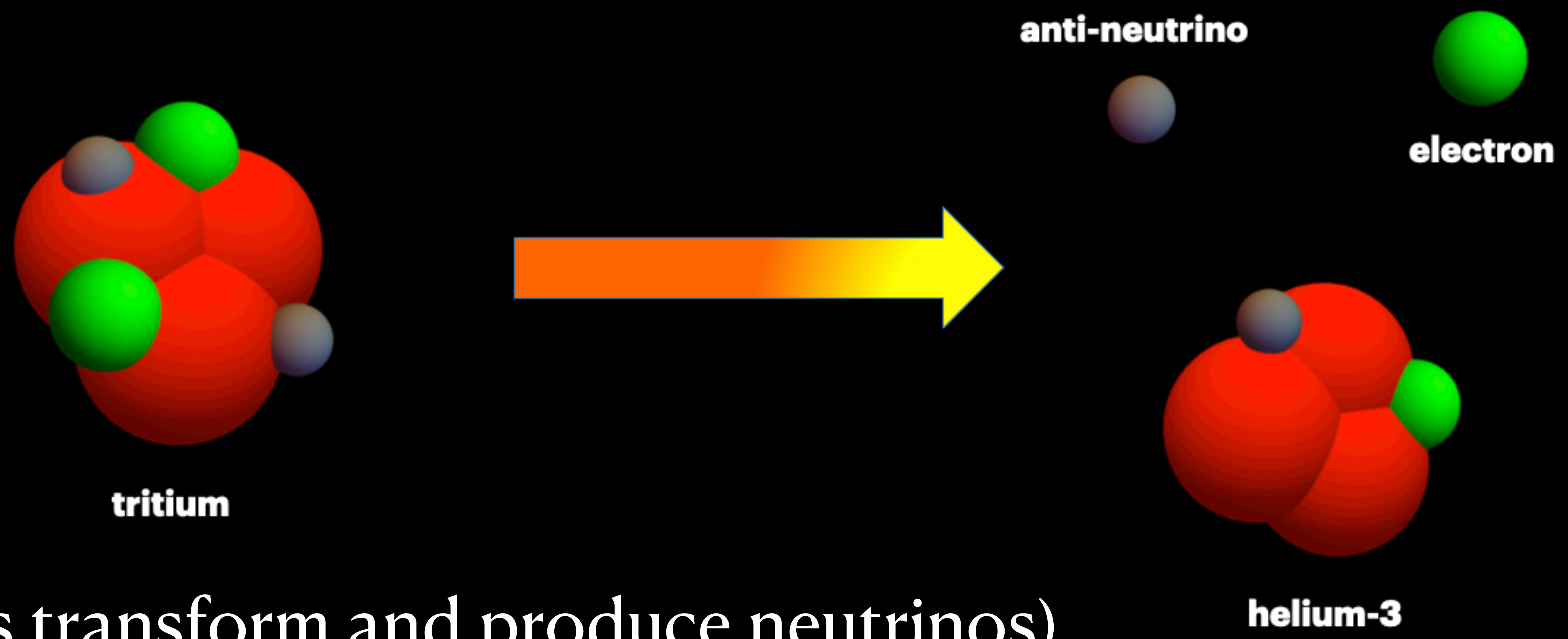
- The Earth is (almost) as old as the Sun
- It is formed by various stratified structures. The main ones: **crust; mantle; core**

- 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 ~10^{7} years scale
- They were wrong because of **incorrect modeling**
- Furthermore, **radioactivity**, which contributes to Earth' internal heath, was unknown

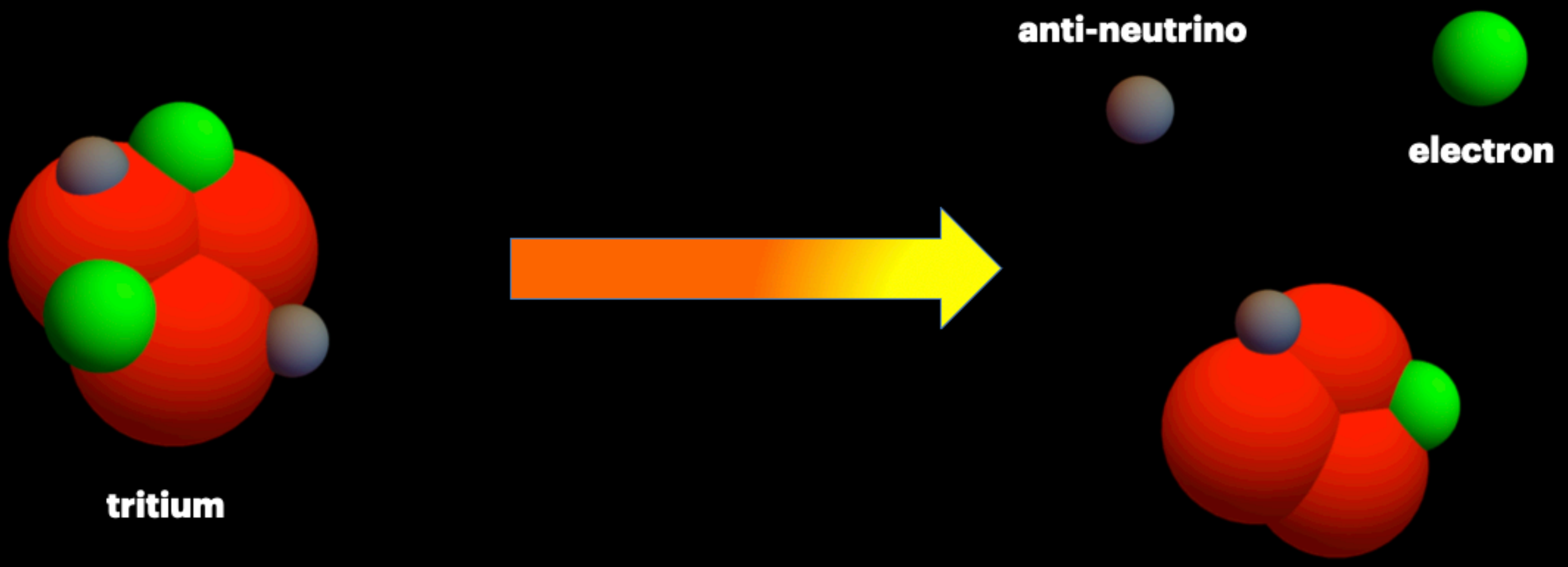
nature of geoneutrinos

* beta decay of neutron rich elements leading to antineutrinos
* (to be contrasted with solar neutrinos where proton rich elements transform and produce neutrinos)



nature of geoneutrinos

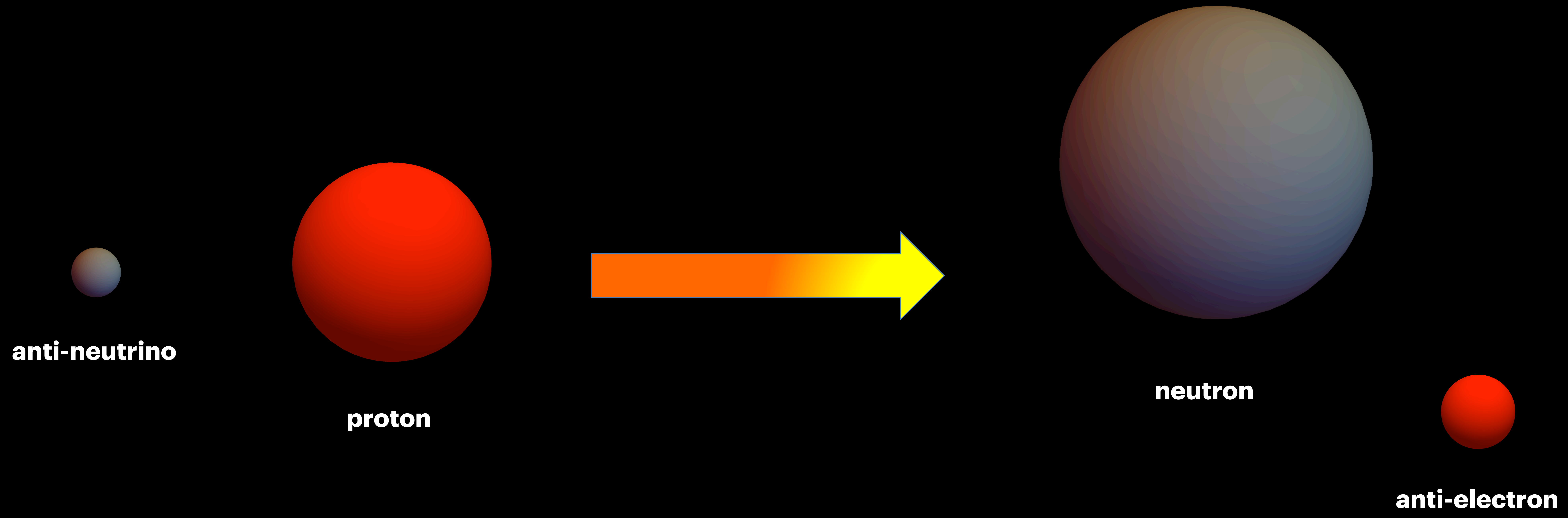
* beta decay of neutron rich elements leading to antineutrinos



* (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)



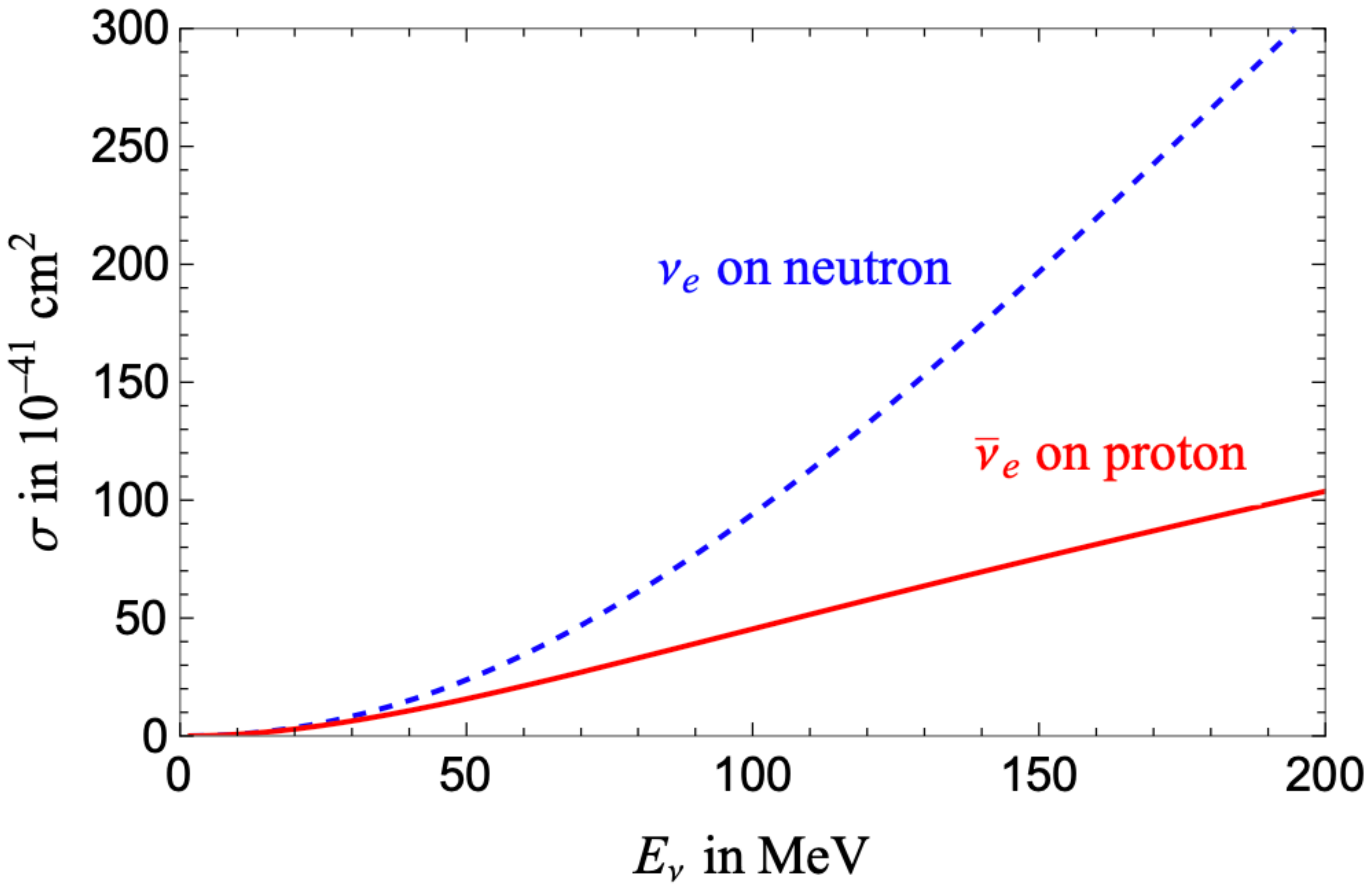
proton targets are available in water or hydrocarbon
(this reaction used to detect for the 1st time a signal)

an updated calculation

arXiv:2206.05567v1

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

$$\mathcal{M} = \bar{v}_\nu \gamma^a (1-\gamma_5) v_e \cdot$$
$$\bar{u}_n\left(f_1\gamma_a + g_1\gamma_a\gamma_5 + if_2\sigma_{ab}\frac{q^b}{2M} + g_2\frac{q_a}{M}\gamma_5 + f_3\frac{q_a}{M} + ig_3\sigma_{ab}\frac{q^b}{2M}\gamma_5\right)u_p$$

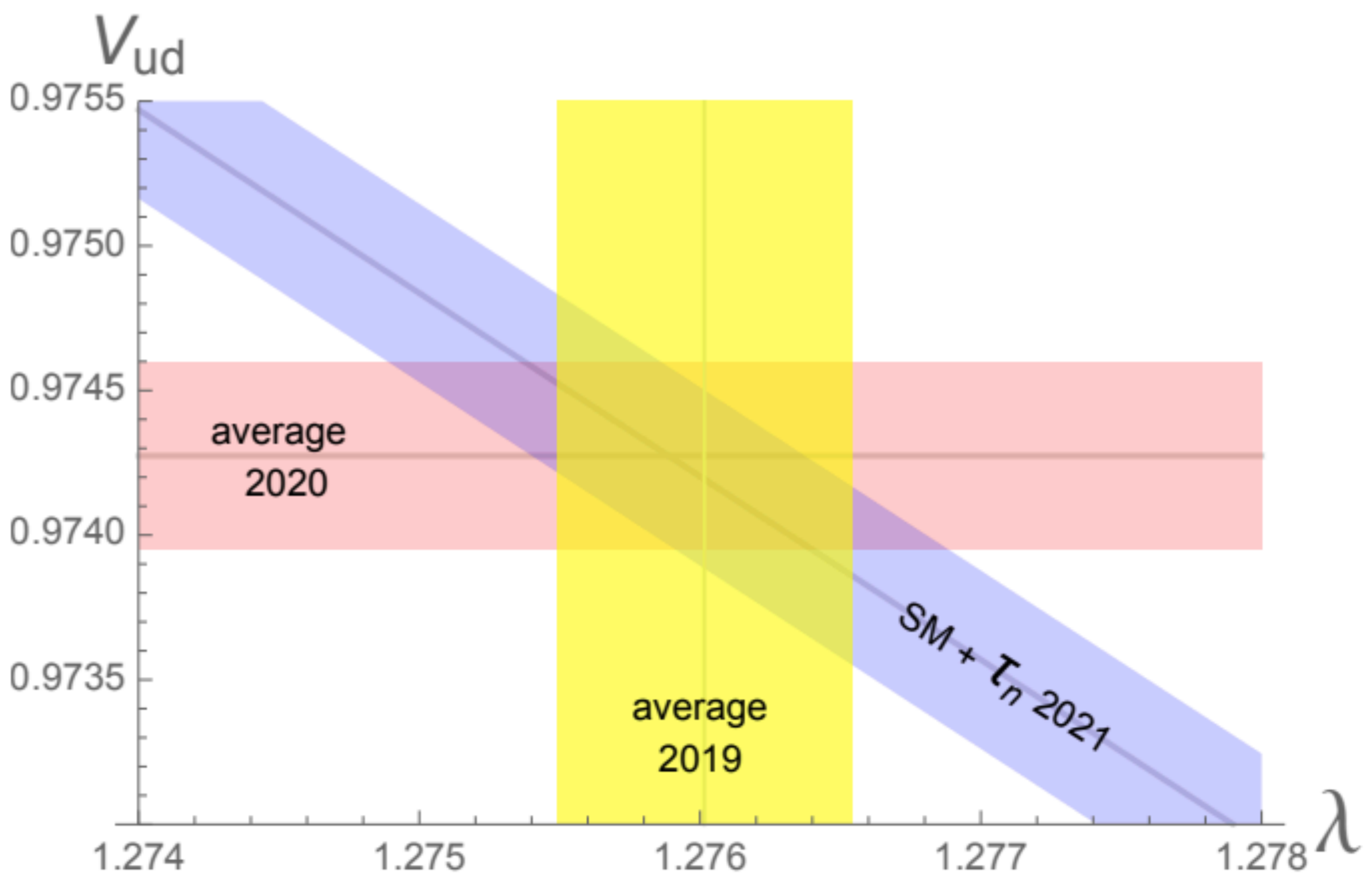


an updated calculation

arXiv:2206.05567v1

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

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



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

antineutrino spectra

expectations

There are three components:

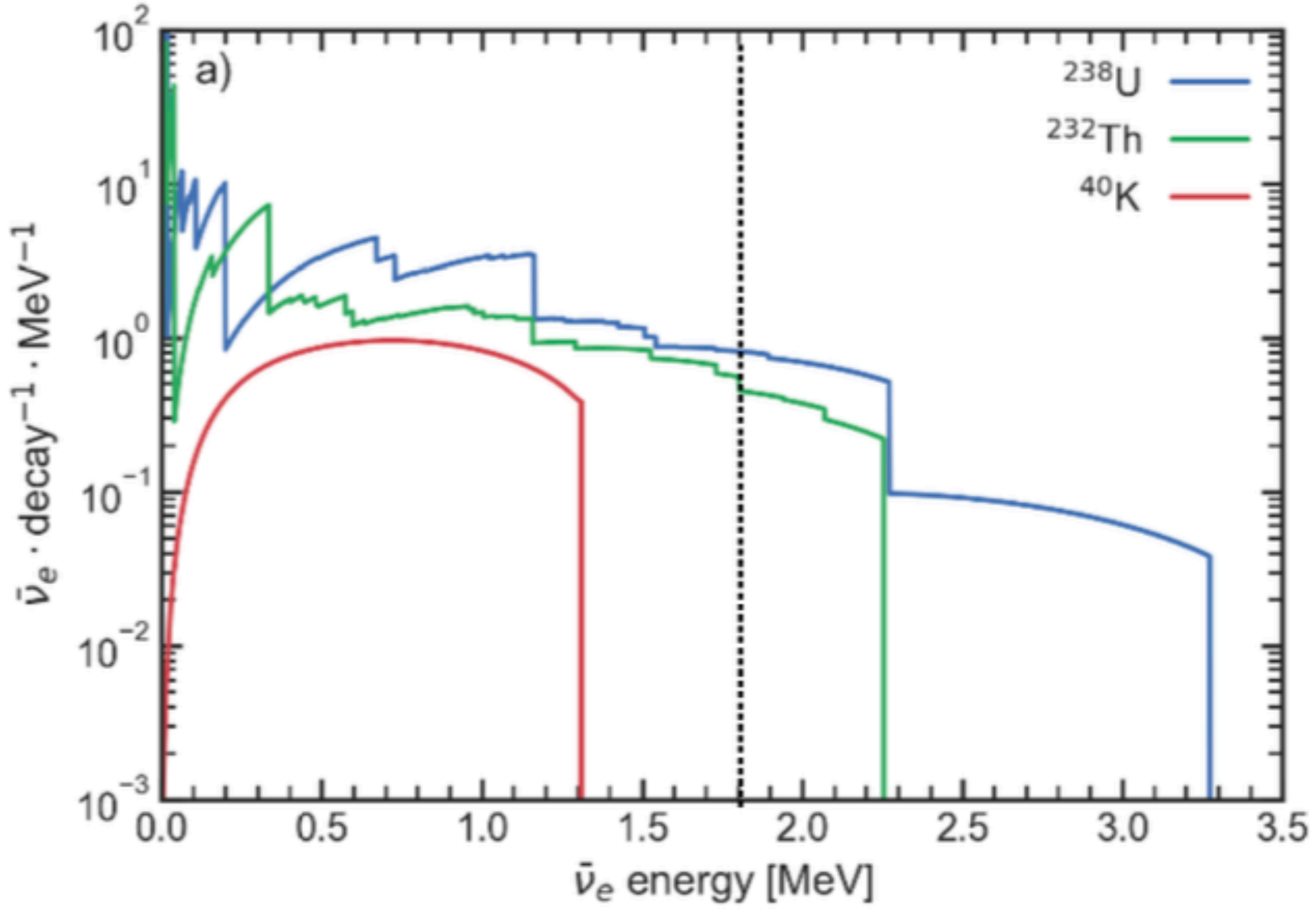
$$^{238}\mathrm{U} \to {}^{206}\mathrm{Pb} + 8\alpha + 6e + 6\bar{\nu}_e + 51.7\,\mathrm{MeV}.$$

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

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

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

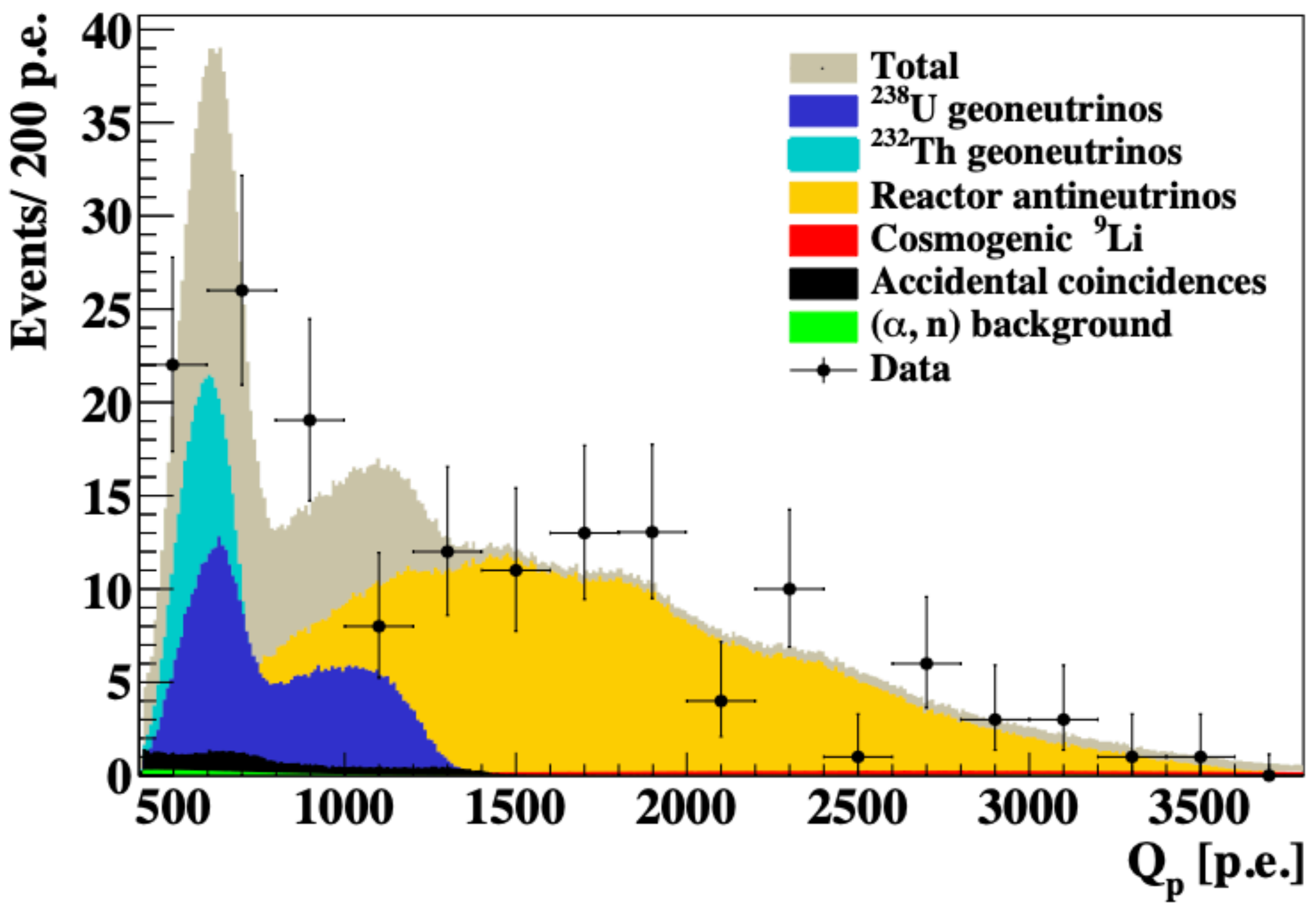
- discovering geo-neutrinos (seeing something)
- observe site dependencies
- testing geophysical models
- quantify the mantle component
- distinguish uranium and thorium contributions

measurements

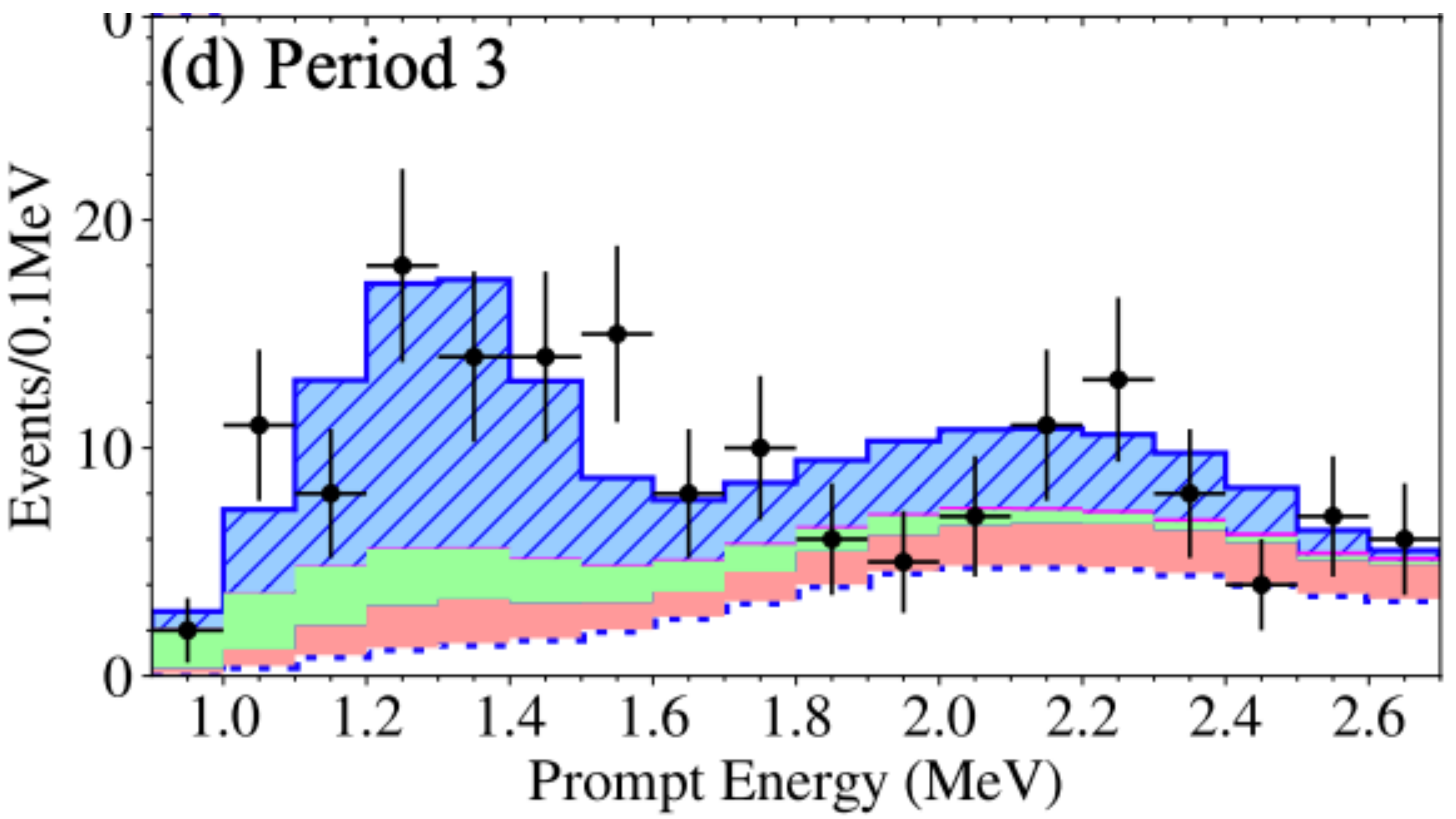
In the spectra of Borexino 2020 and KamLAND 2022, geoneutrino signal is visible and not only.

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

introduction

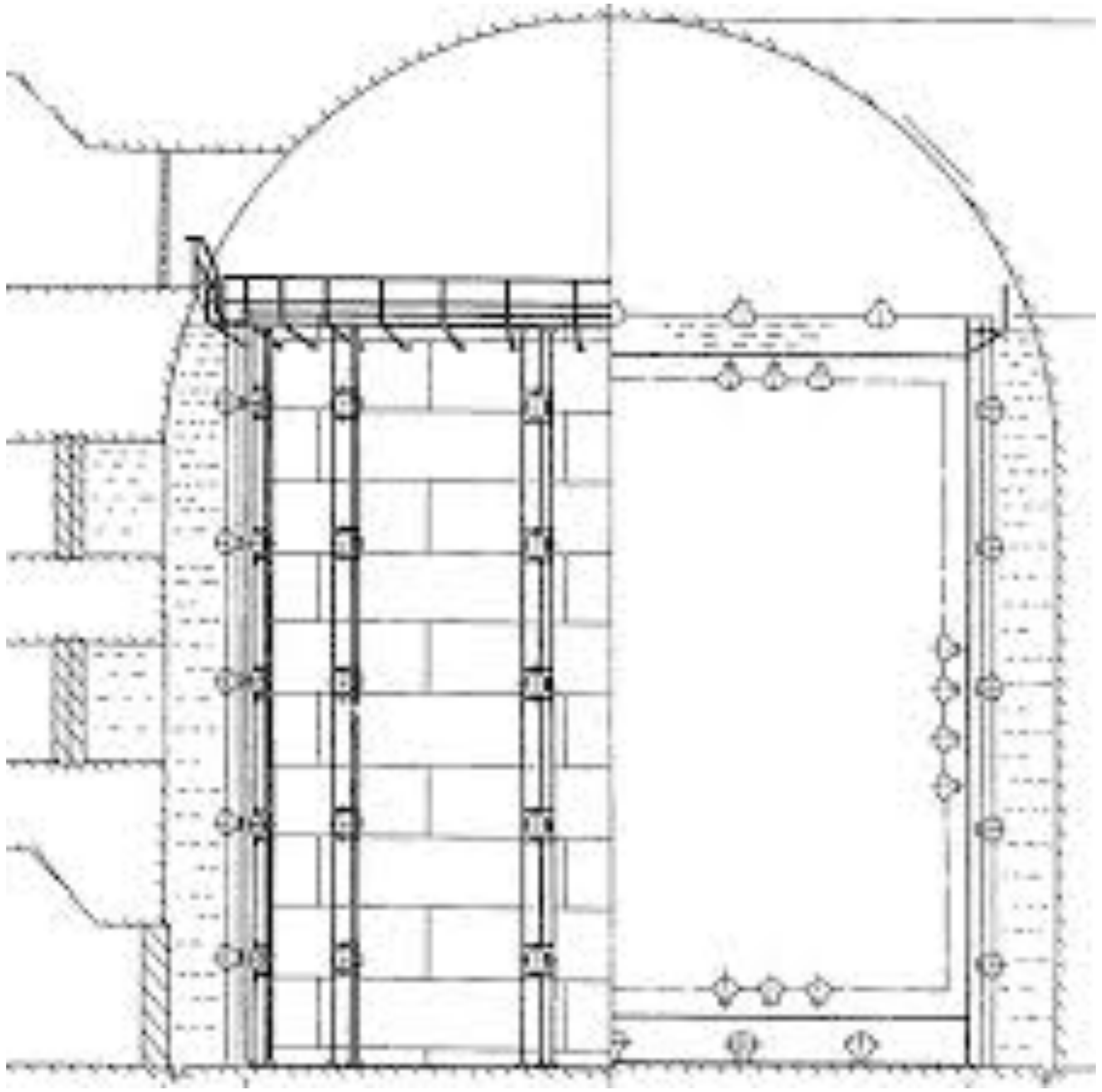
on supernova neutrinos

- Supernovae are one of the most important events in astronomy, although those in the Milky Way are rare on the human time scale.
- Several useful reactions for detections, including those previously discussed.
- The role of neutrino oscillations is unclear.
- A historical detection was made in 1987. Its discussion offers us several occasions to discuss certain relevant issues.

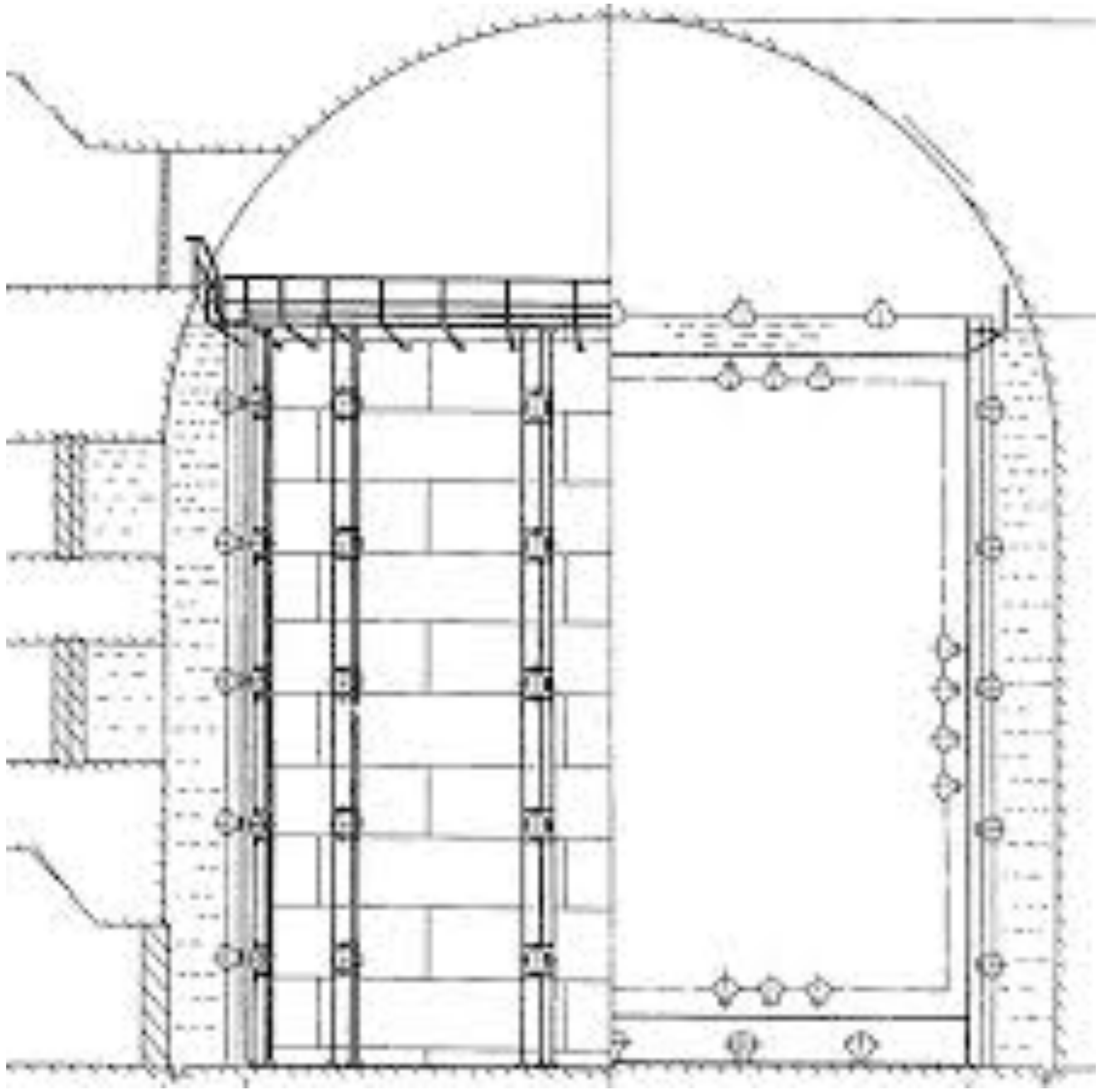
A bit of history

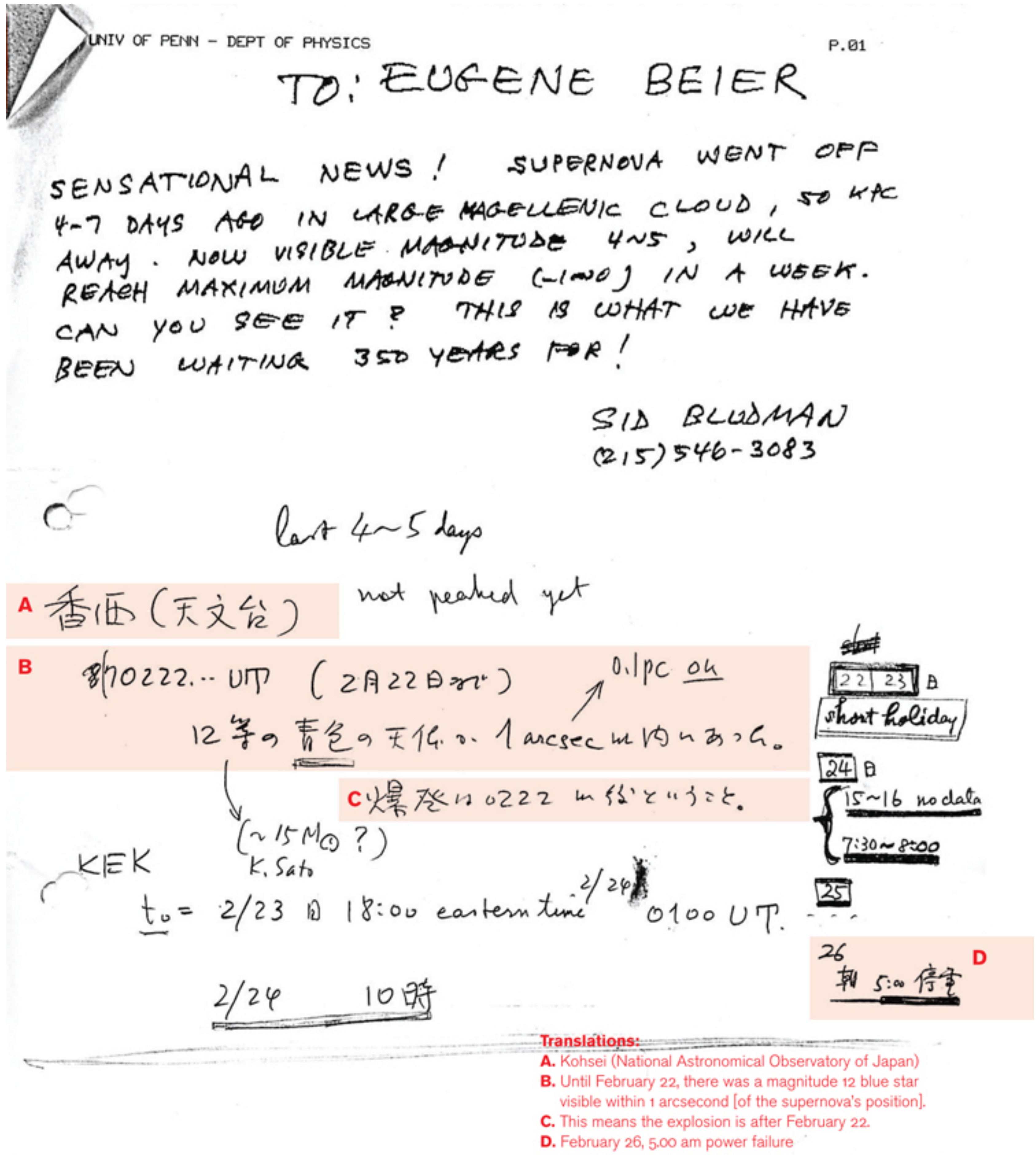
- ❑ Ian Shelton and Oscar Duhalde observed SN1987A on Feb 24, 1987
- ❑ a neutrino signal was seen in Kamiokande, IMB, Baksan ~5h earlier
- ❑ maybe there was a signal in LSD/Mont Blanc before that

Kamiokande-II and SN1987A



Kamiokande-II and SN1987A





UNIV OF PENN - DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4½, WILL REACH MAXIMUM MAGNITUDE (-1 or 0) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083

last 4~5 days

A 香西(天文台) not peaked yet

B 約0222... UT (2月22日まで)
12等の青色の天体が1 arcsec以内にあった。 0.1pc ok

C 爆発は0222以後ということ。

(~15M☉?)
K. Sato

KEK

t_0 = 2/23 日 18:00 eastern time 2/24 0100 UT.

2/24 10時

~~short~~
22 23 日
short holiday

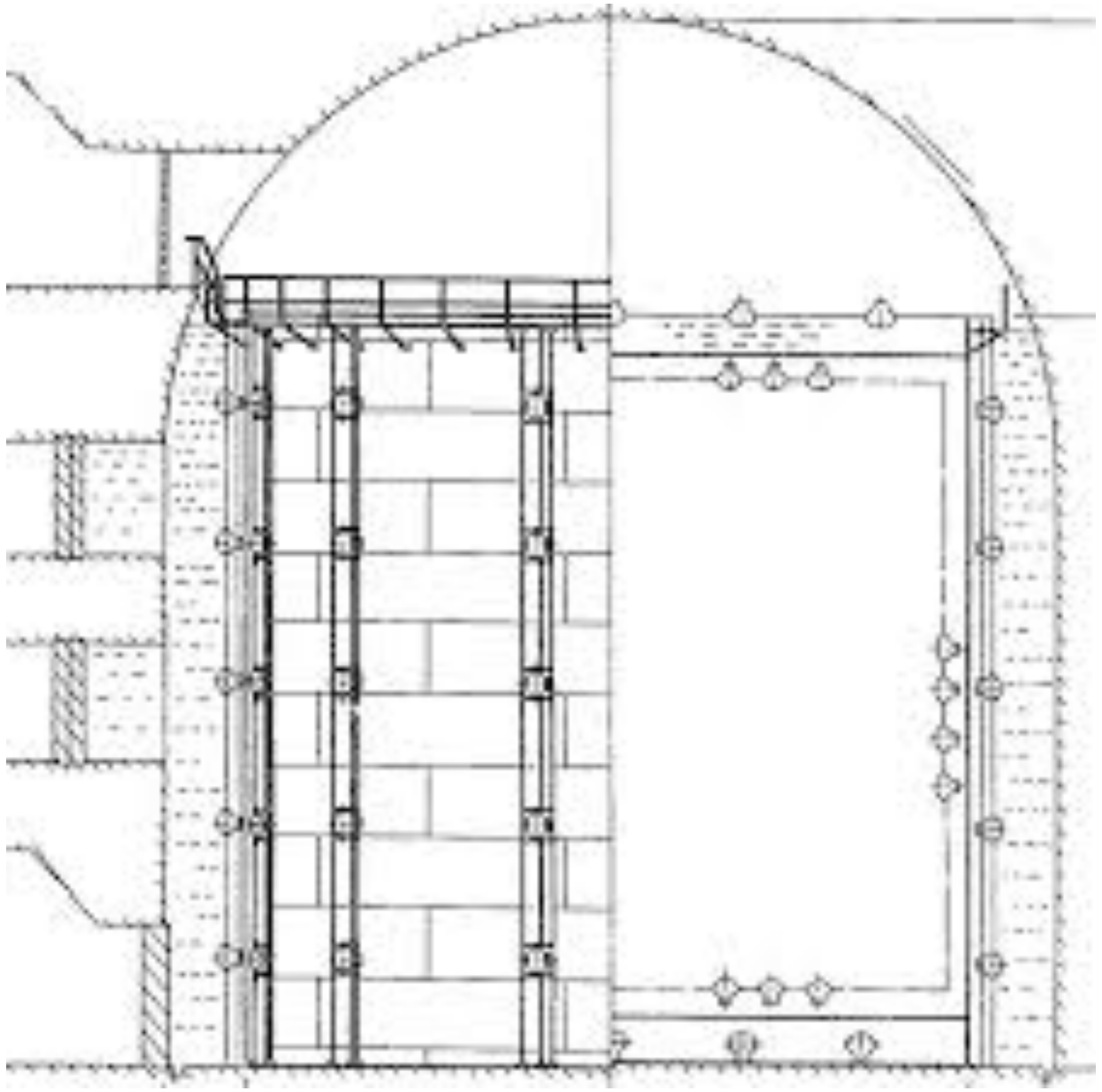
24 日
15~16 no data
7:30~8:00

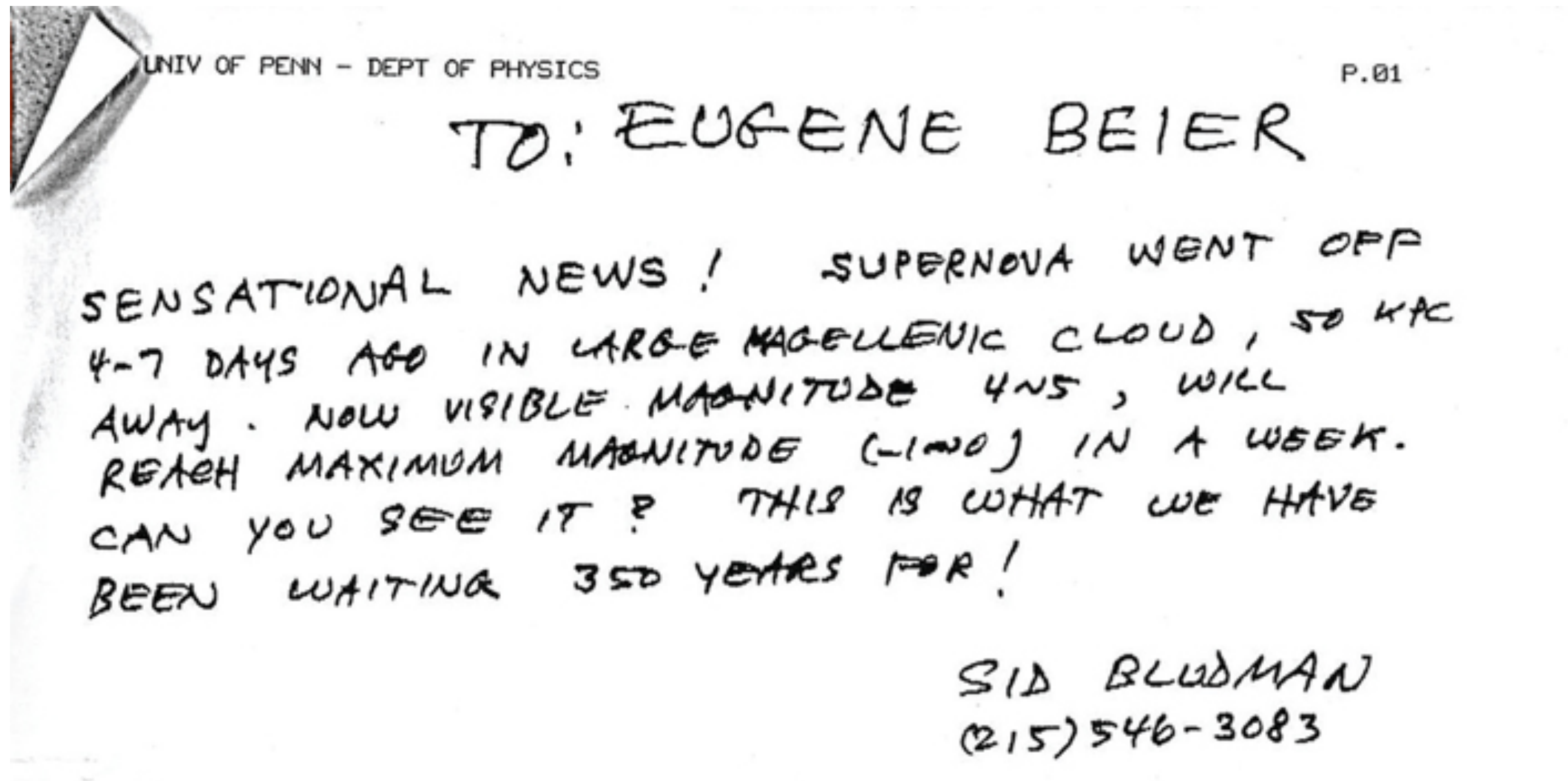
25

D 26 朝 5:00 停電

Translations:
A. Kohsei (National Astronomical Observatory of Japan)
B. Until February 22, there was a magnitude 12 blue star visible within 1 arcsecond [of the supernova's position].
C. This means the explosion is after February 22.
D. February 26, 5.00 am power failure

Kamiokande-II and SN1987A

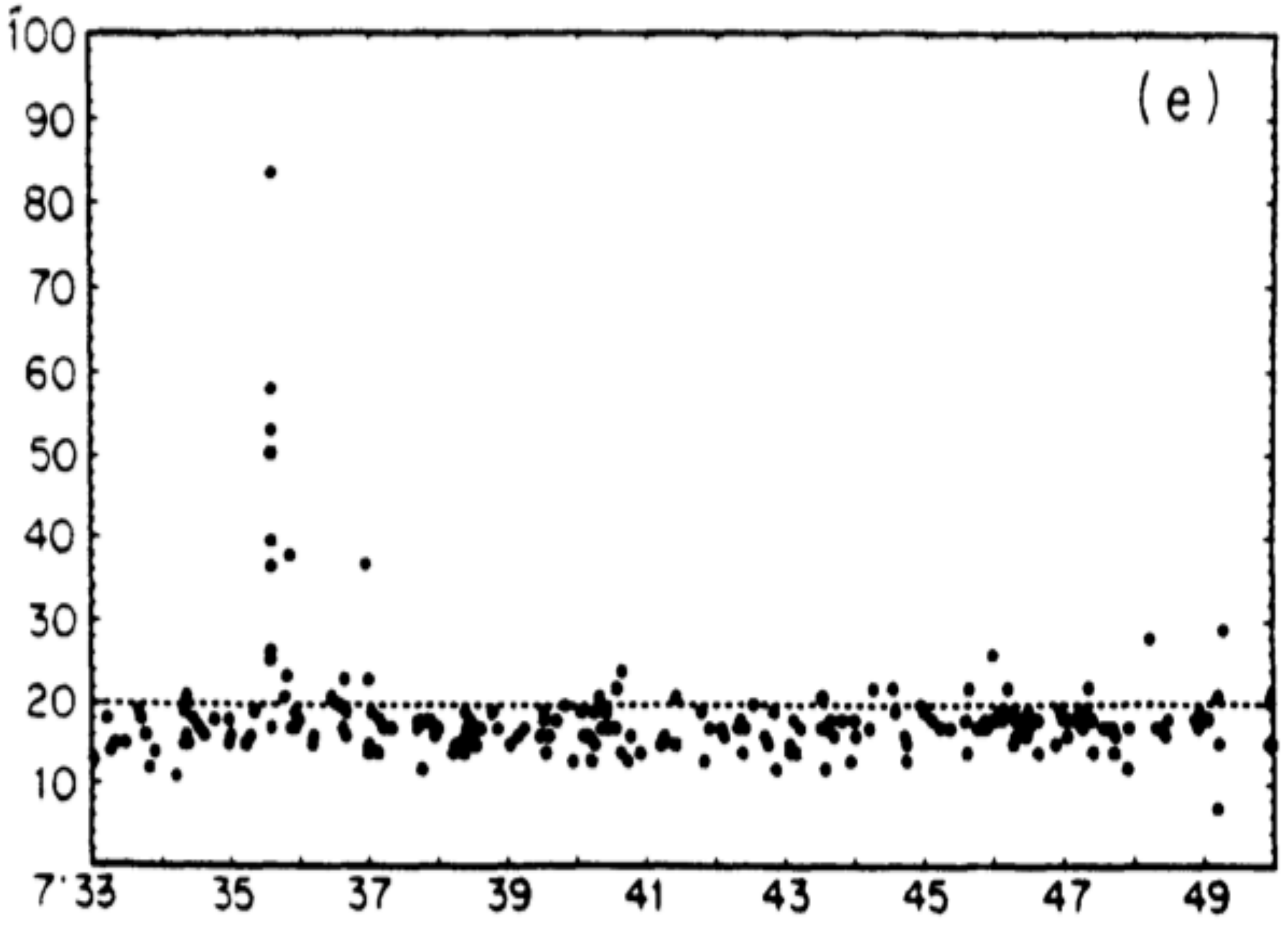



UNIV OF PENN - DEPT OF PHYSICS P.01

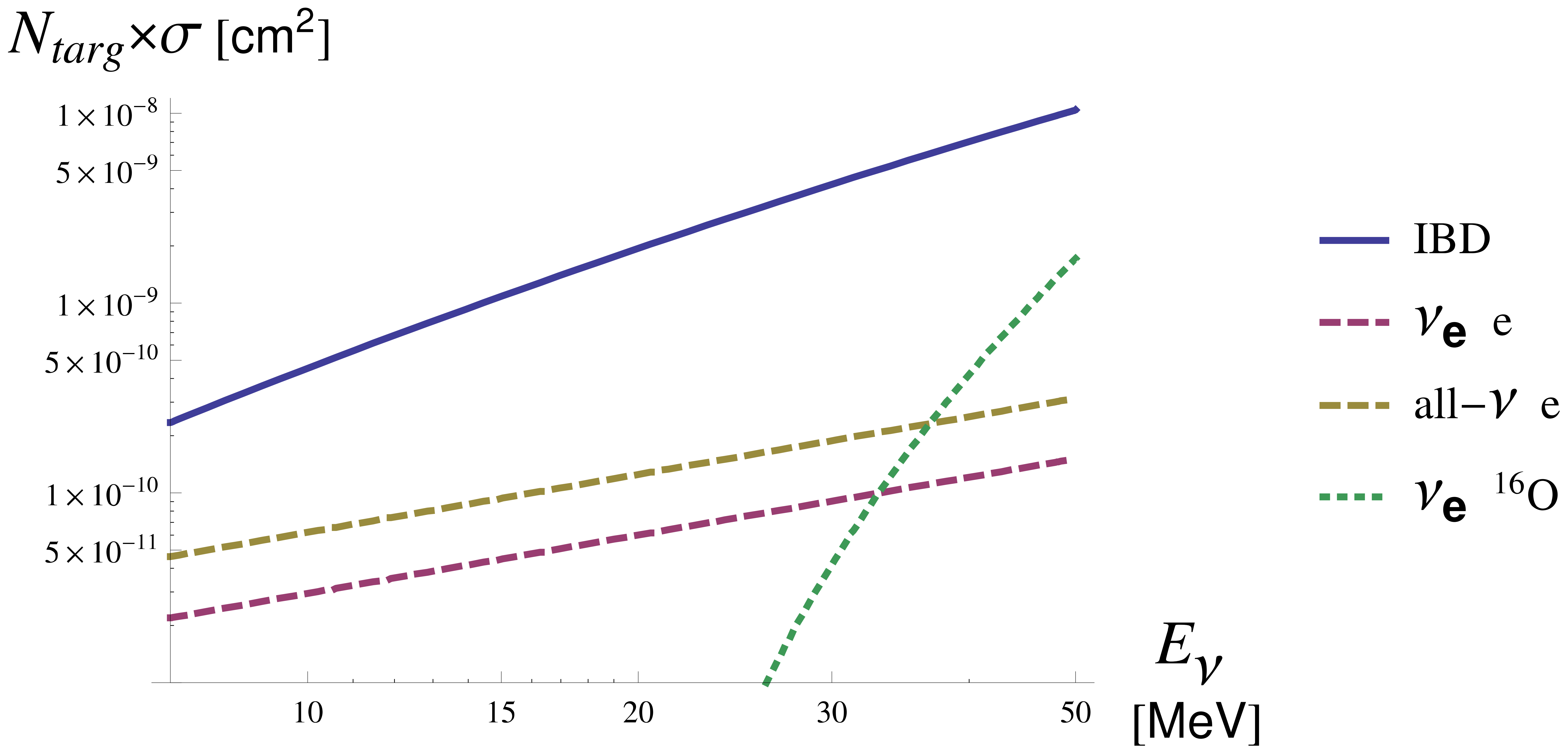
TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF
4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC
AWAY. NOW VISIBLE MAGNITUDE 4~5, WILL
REACH MAXIMUM MAGNITUDE (-1~0) IN A WEEK.
CAN YOU SEE IT? THIS IS WHAT WE HAVE
BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083



cross sections in 1 kton of water



modeling SN emission

the simplest model

the concept of neutrino sphere

The surface of proto-neutron star is a black body radiator

Each neutrino has its own temperature: one for ν_e; one for anti-ν_e; one for the other 4, grouped

the simplest model

the concept of neutrino sphere

The surface of proto-neutron star is a black body radiator

Each neutrino has its own temperature: one for ν_e; one for anti-ν_e; one for the other 4, grouped

Any type of neutrinos or antineutrino carries away 1/6 of the total energy, a hypothesis called "equipartition"

$L \sim R^2 \times T^4 \sim 10^{52}$ erg/s for R=15 km and T=5 MeV

the simplest model

the concept of neutrino sphere

The surface of proto-neutron star is a black body radiator

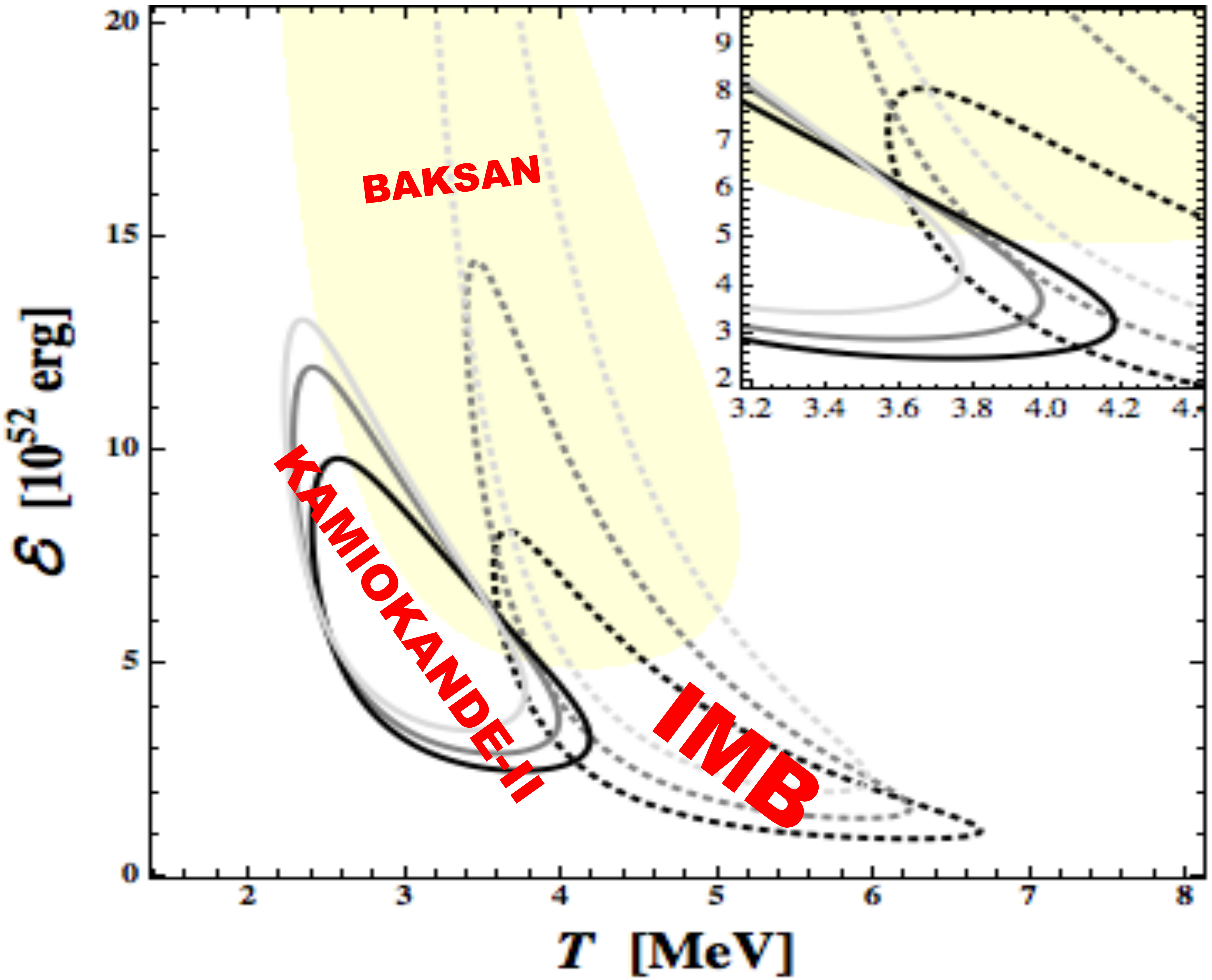
Each neutrino has its own temperature: one for ν_e; one for anti-ν_e; one for the other 4, grouped

Any type of neutrinos or antineutrino carries away 1/6 of the total energy, a hypothesis called "equipartition"

$L \sim R^2 \times T^4 \sim 10^{52}$ erg/s for R=15 km and T=5 MeV

Emission time = Energy/$(6L) \sim 10$ s

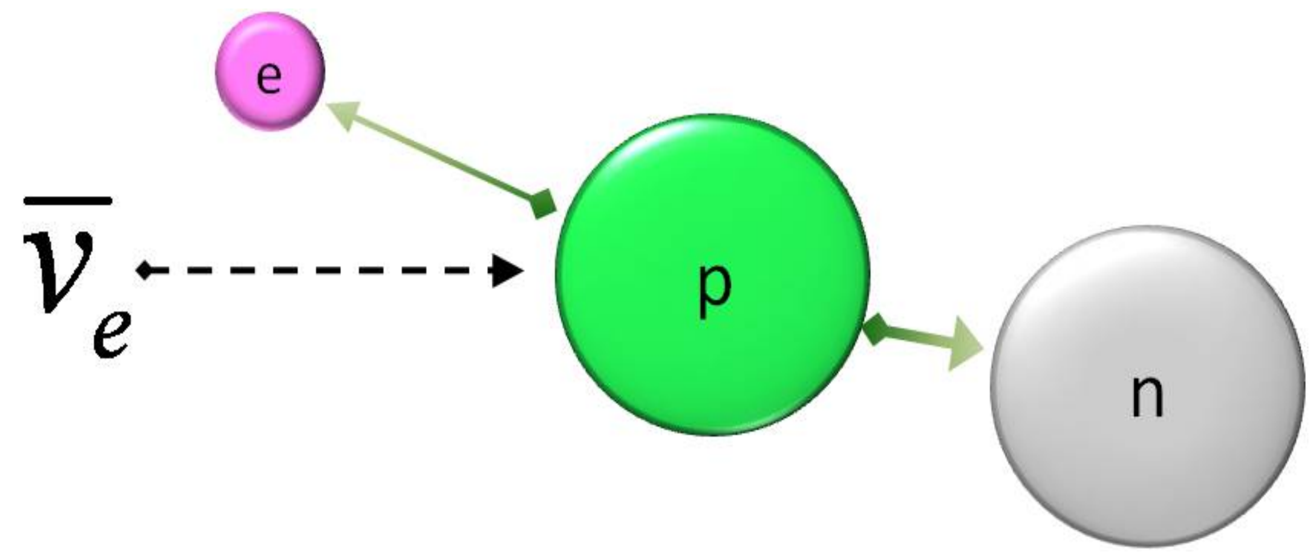
comparison with the data

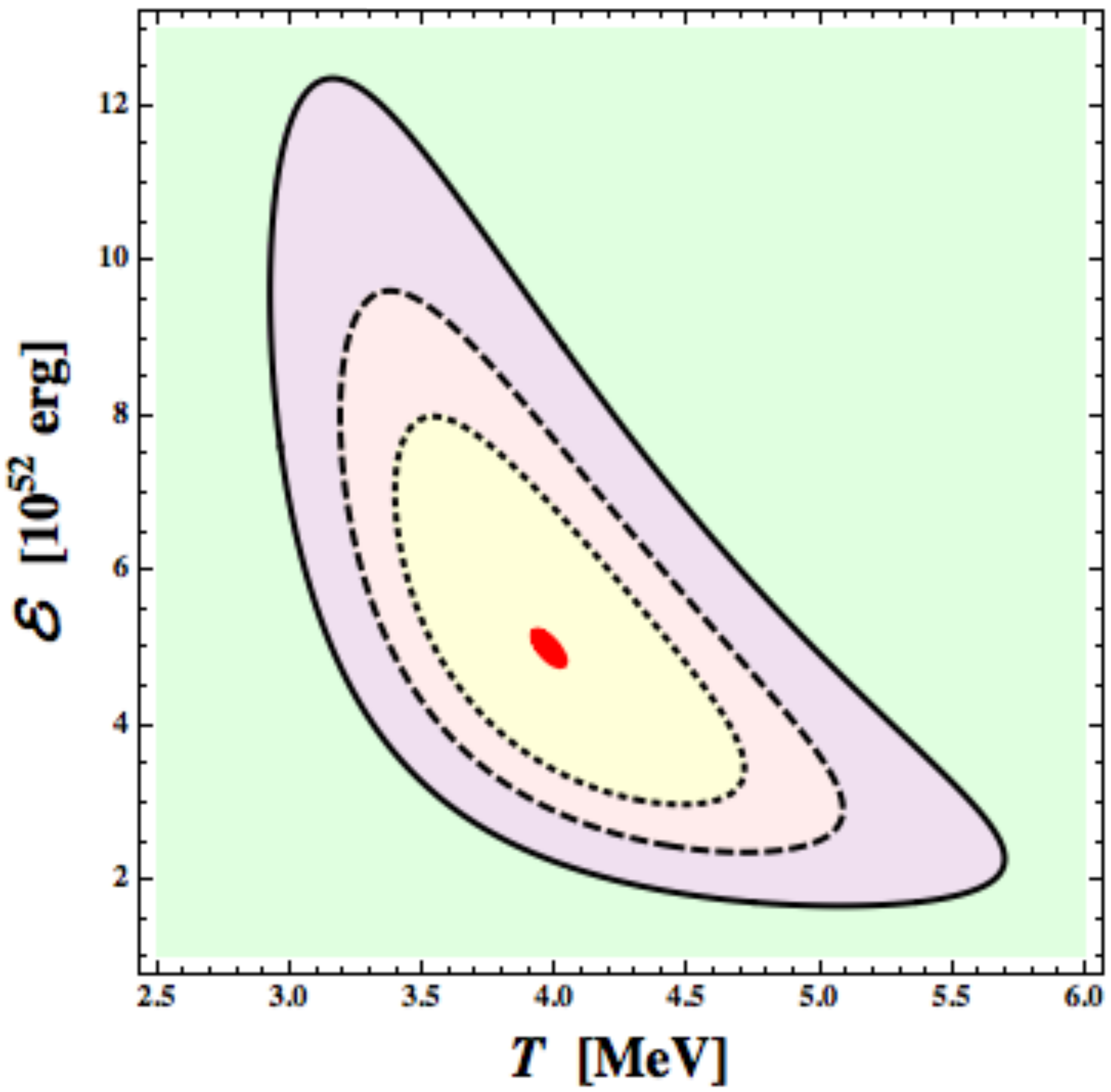


extends Jegerlehner et al 96

combined fit

Fitting IMB, Kamiokande-II above 4.5 MeV and Baksan by a Maxwell-Boltzmann and assuming I.B.D. reactions





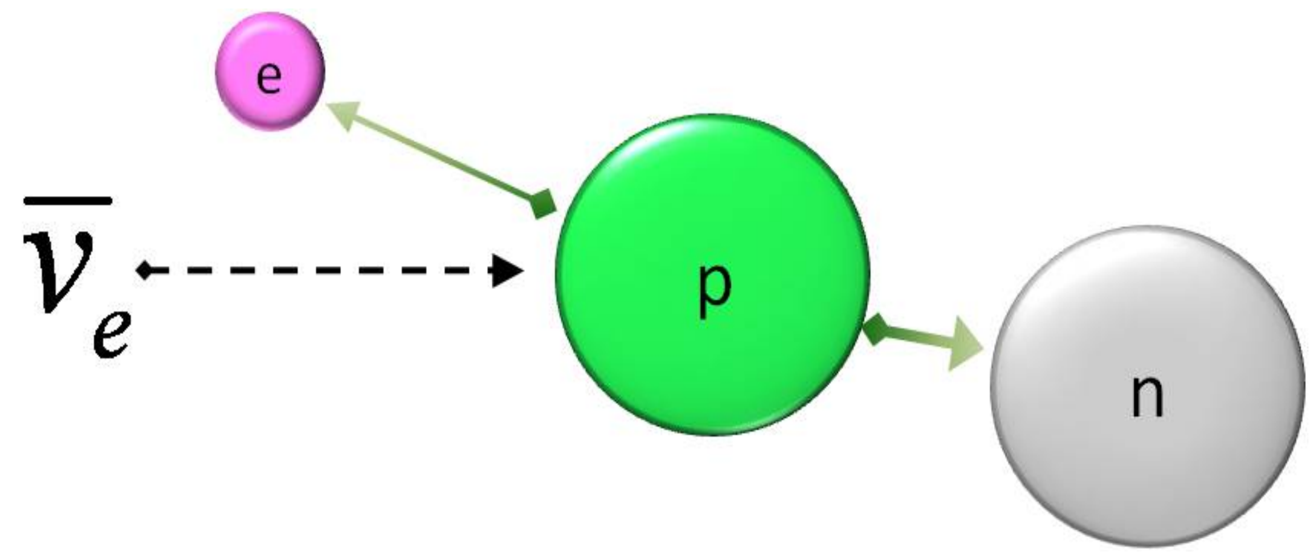
we find the allowed region to the r.h.s. with best fit values:

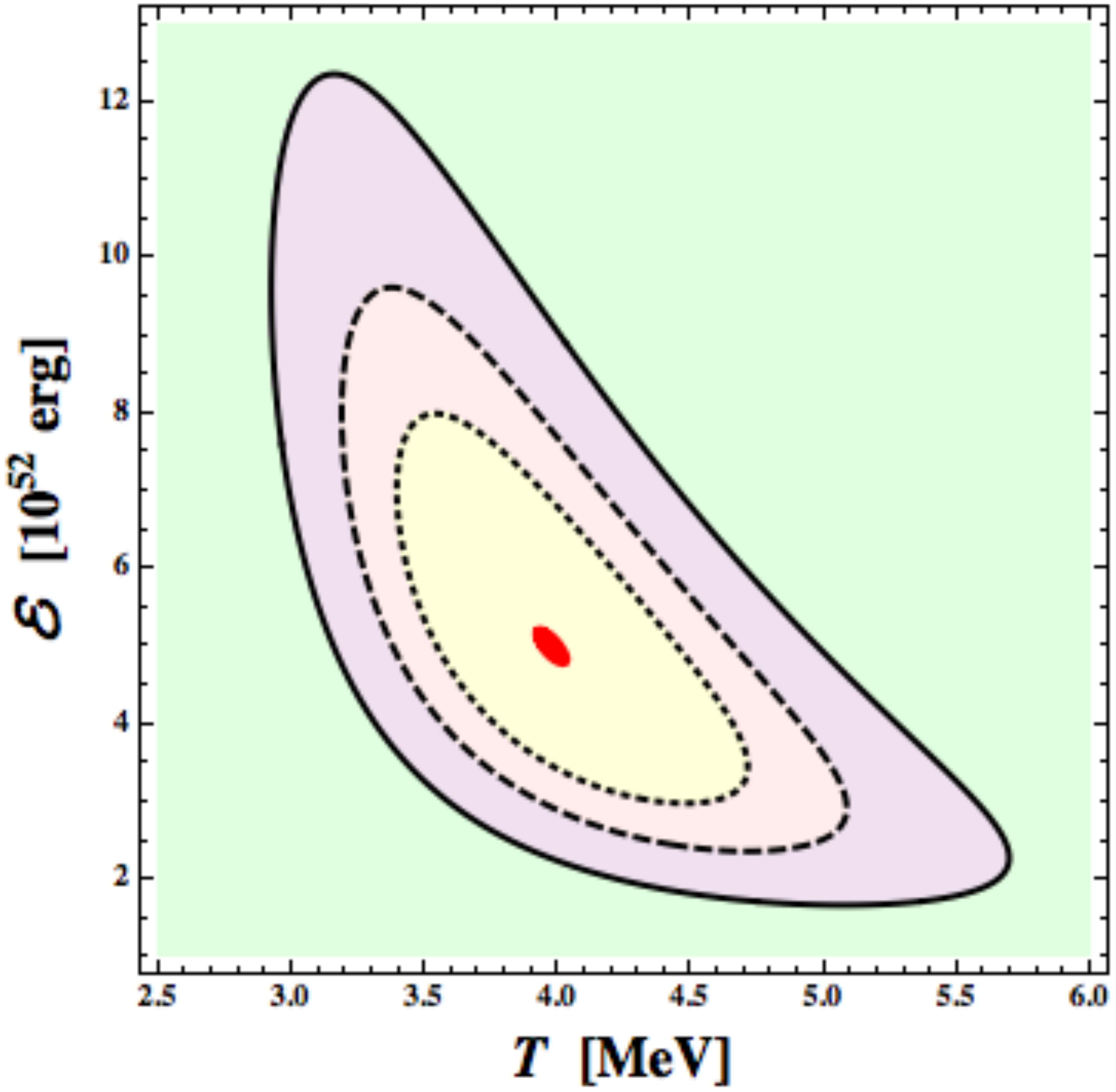
Temperature = 4 MeV

Radiated energy = 5 10^{52} erg

combined fit

Fitting IMB, Kamiokande-II above 4.5 MeV and Baksan by a Maxwell-Boltzmann and assuming I.B.D. reactions

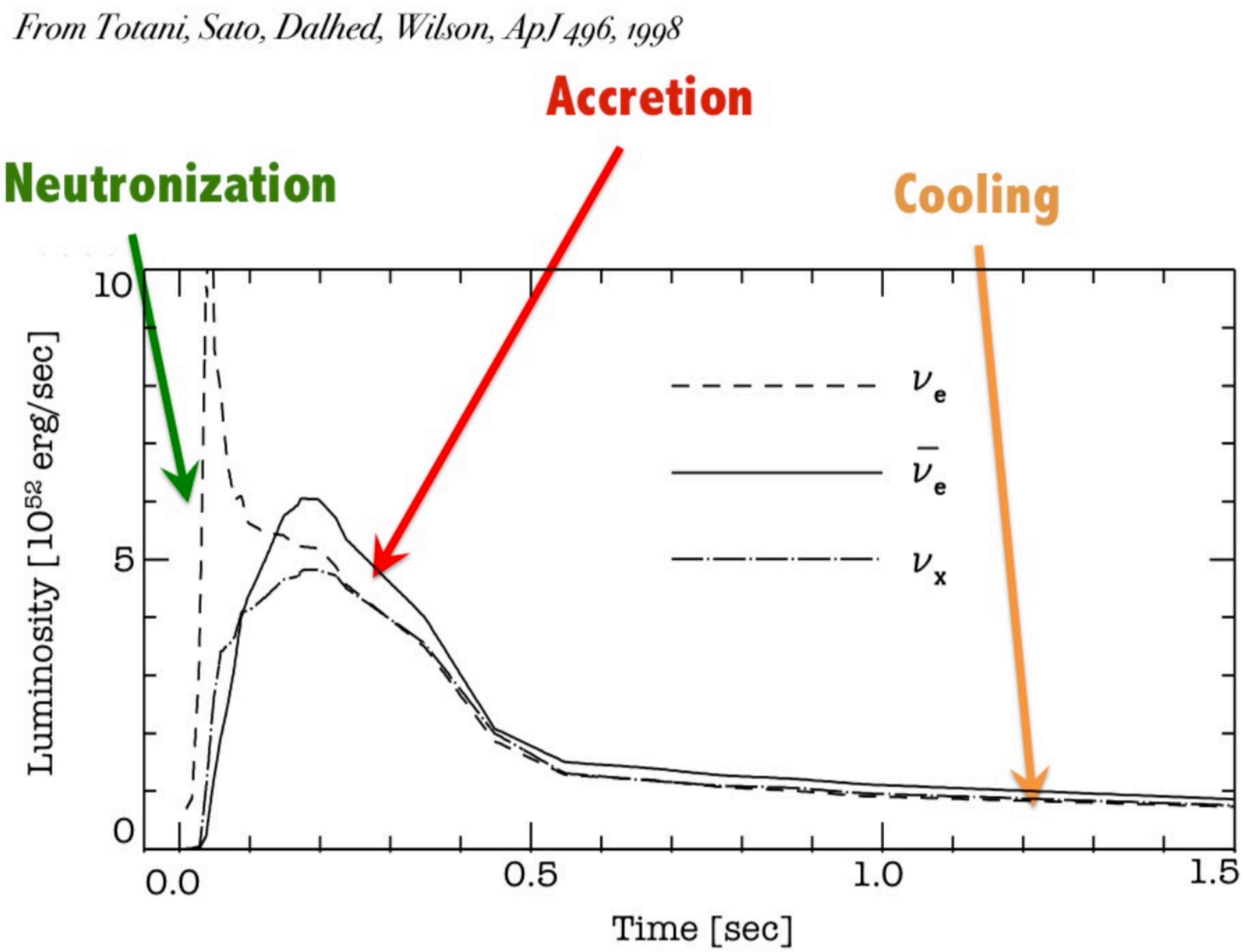




we find the allowed region to the r.h.s. with best fit values:
Temperature = 4 MeV
Radiated energy = 5 10^{52} erg

Expectations: $T = \langle E_\nu \rangle = 4$ MeV, $\mathscr{E} = \mathscr{E}_{\text{tot}}/6 \sim 5 \times 10^{52}$ erg (!)

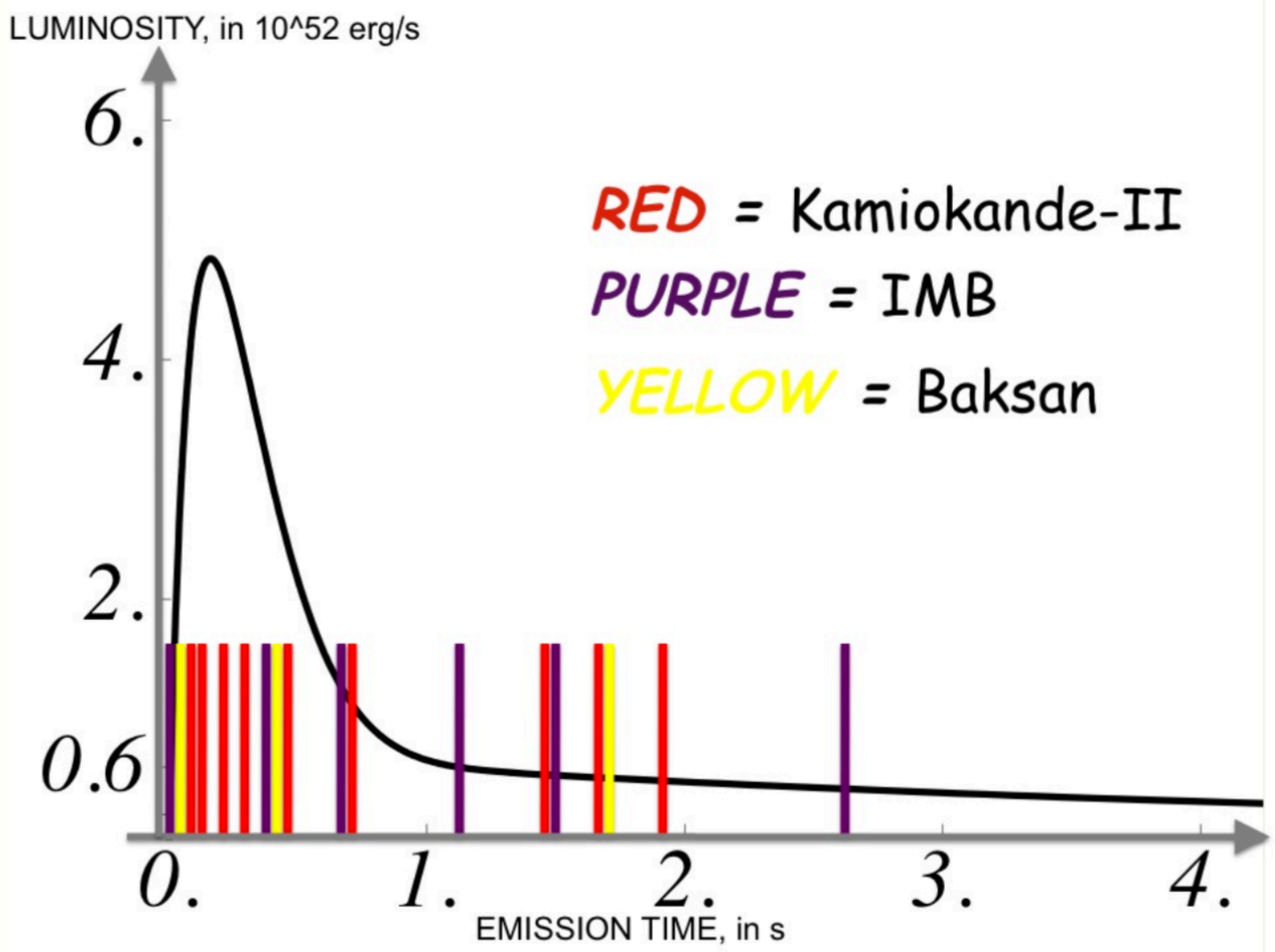
more refined modelling



Nadyozhin 78, Wilson 81, Wilson and Bethe 86... argued that the emission is different than thought by Zatsepin. It consists of 3 main phases: neutronization, accretion, cooling. In Super-Kamiokande, a supernova at $D = 10$ kpc yields

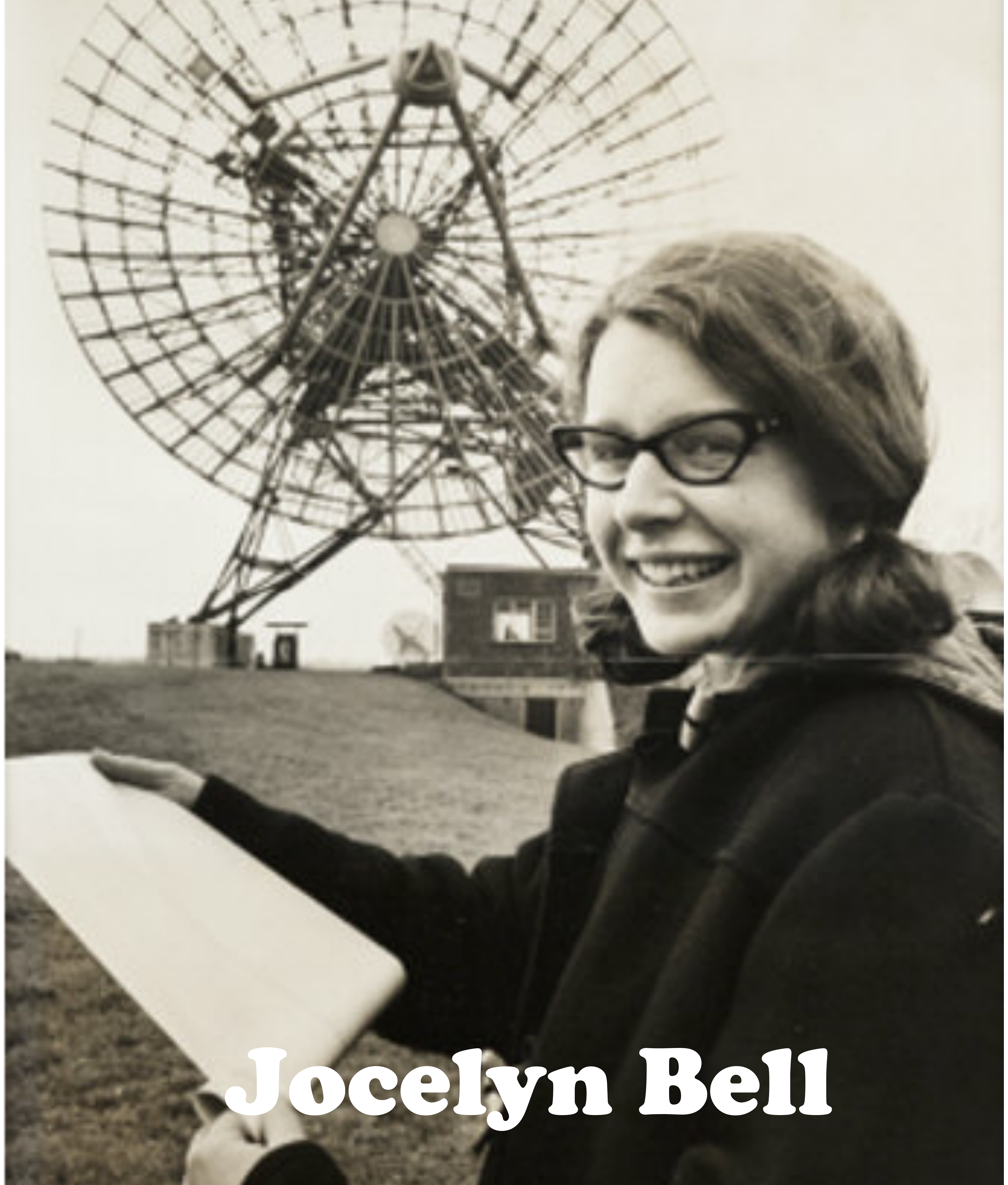
Events	Energy	Duration
1 (ES)	2 foe	3 ms
1K (IBD)	50 foe	0.5 s
3K (IBD)	200 foe	10 s

data and initial peak



REF.: T. Loredo, D.Q. Lamb, "Bayesian analysis of neutrinos observed from supernova SN1987A," PRD **65** (2002) 063002.
REF.: G.Pagliaroli, FV, M.L.Costantini, A.Ianni, "Improved analysis of SN1987A antineutrino events," Astropart. Ph. **31** (2009) 163.

few last points


Jocelyn Bell


Marco Miceli


Salvatore
Orlando

ELSEVIER

New Astronomy
Volume 83, February 2021, 101498

On the rate of core collapse supernovae in the milky way

Karolina Rozwadowska [a, b], Francesco Vissani [a, b], Enrico Cappellaro [c]

the best value for the rate

$$R = 1.63 \pm 0.46 \frac{SN}{100\ \mathrm{yr}}$$

which corresponds to a time of occurrence

$$T = 63^{+23}_{-14}\ \mathrm{yr}$$

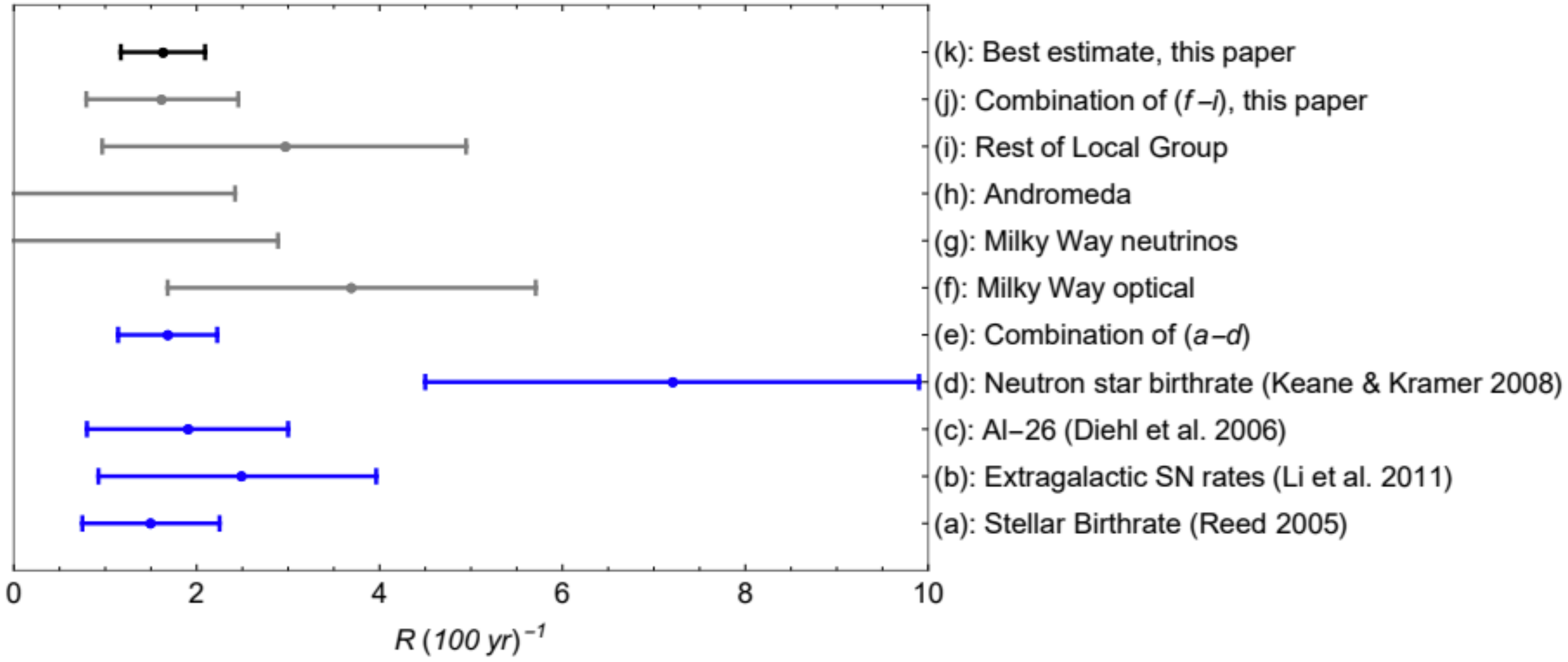


Figure 1: *CCSN rate R in the Milky Way: from the existing literature (blue), computed from direct information from the Local Group (gray) and full result (black) of Eq. (17).*

the difficulties with neutrino oscillations

- We are sure that 3-flavor neutrino oscillations occur
- We have reliable formulae for matter effect on electrons (MSW)
  (Dighe & Smirnov PRD 2000)
- Neutrino-neutrino refraction makes the problem non-linear
  (Pantaleone PLB 1992 ...)
- Many discussions, but still inconclusive

summary and discussion

on supernova neutrinos

- ⭐ The experience of SN1987A suggests that there are large margins for experimental progresses: closer (galactic) event and larger detector mass.

- ⭐ A galactic core collapse supernova is a dream for particle- nuclear- and astro-physicists.

- ⭐ We all hope that the experience accumulated by theoretical astrophysicists should meet observations sooner or later.

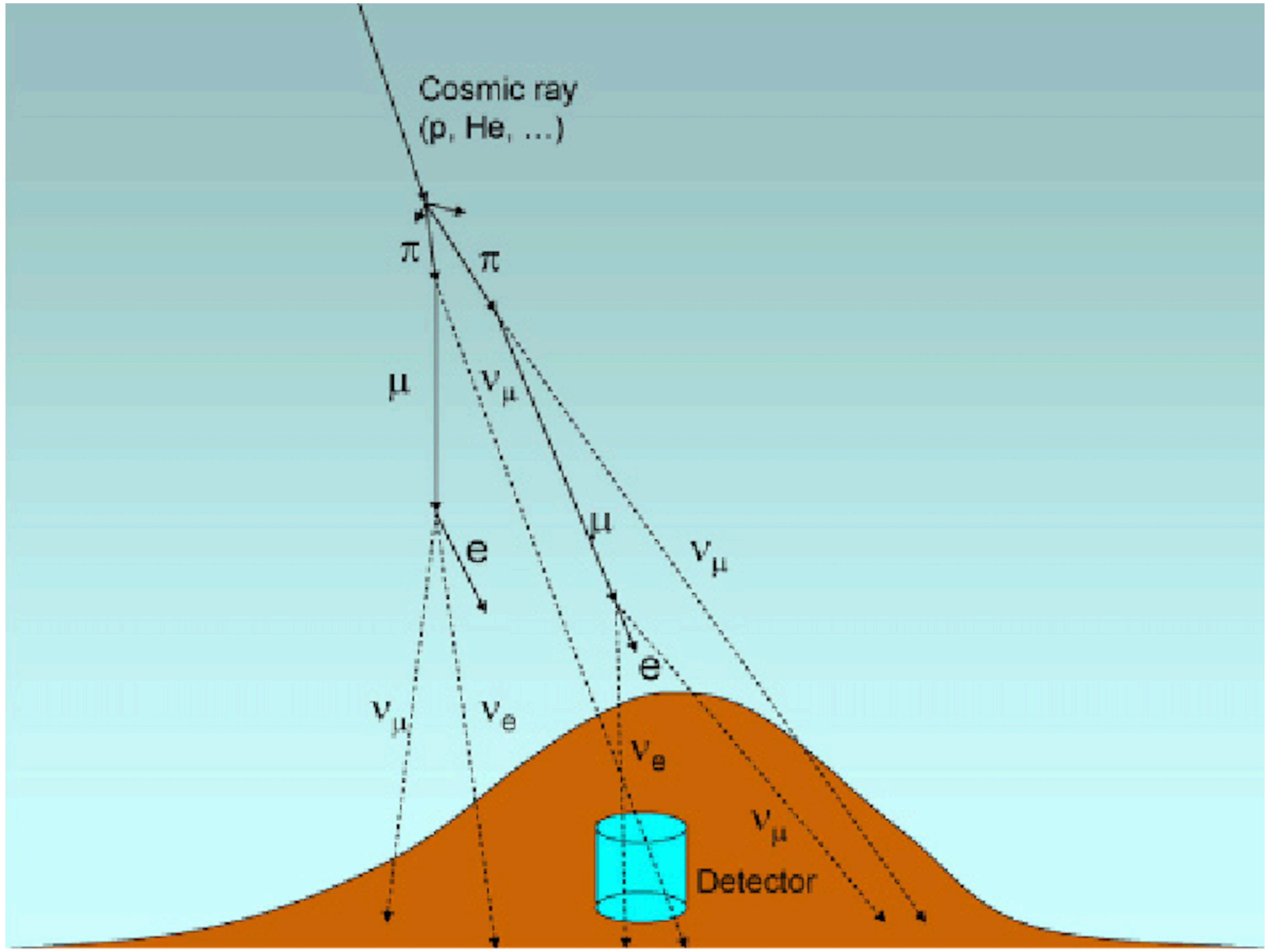
Atmospheric neutrinos

(only few urgent remarks)

atmospheric neutrinos

as secondary particles

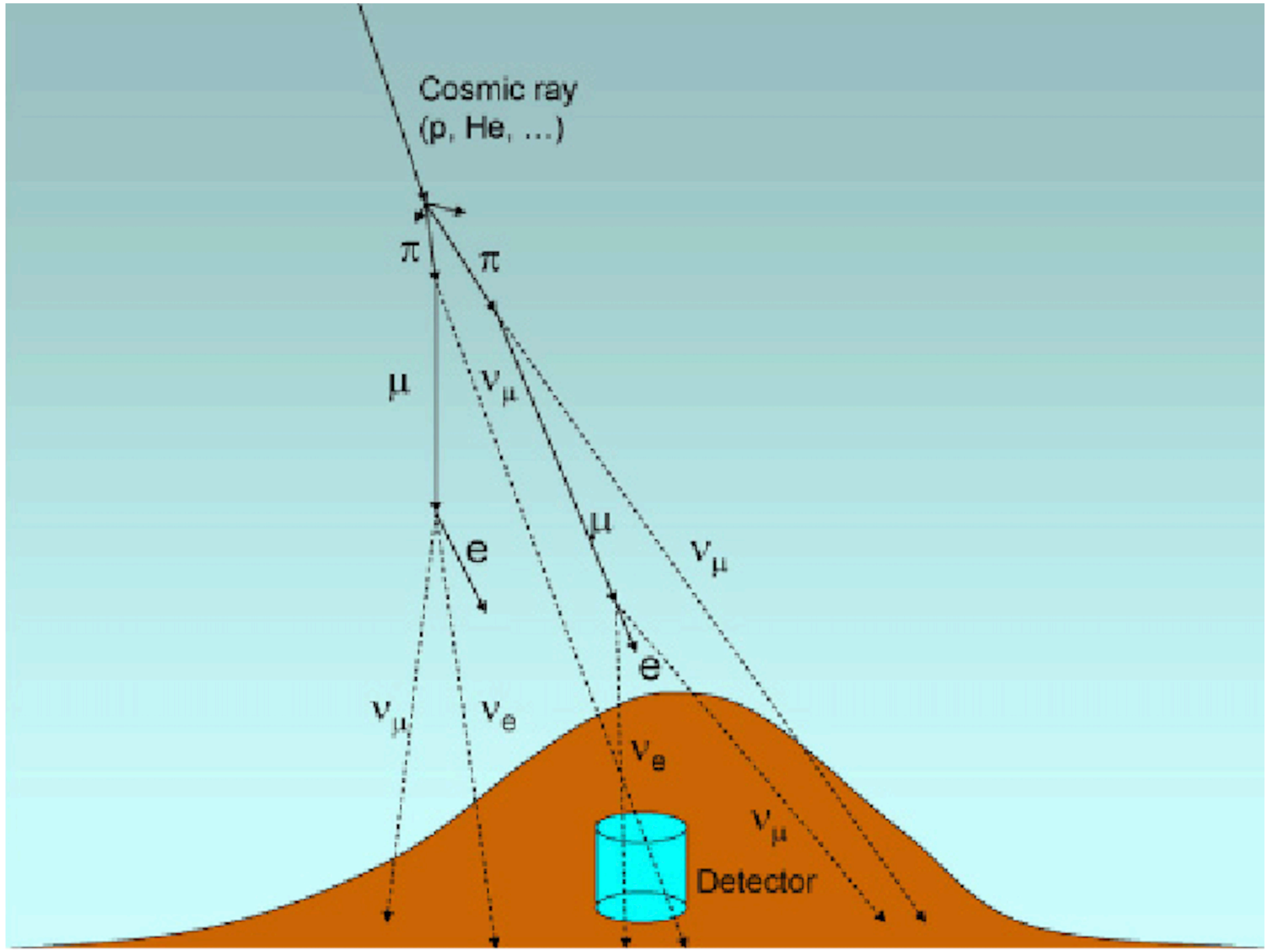
- the collisions of primary particles produce secondary mesons, in part. $\pi^{\pm}$



atmospheric neutrinos

as secondary particles

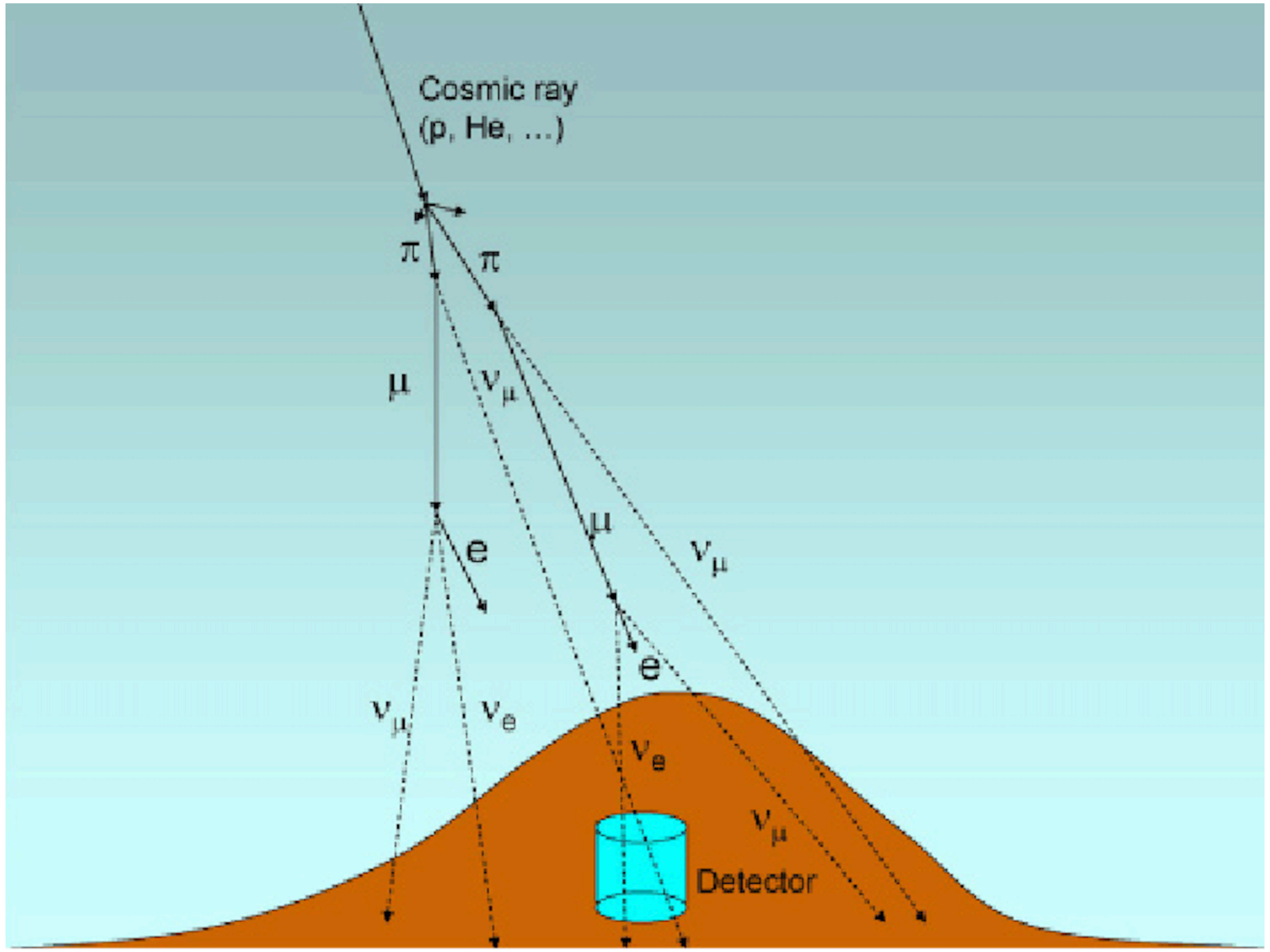
- the collisions of primary particles produce secondary mesons, in part. $\pi^{\pm}$
- when $\pi^{\pm}$ decay, it produces $\mu^{\pm}$ and $\nu_\mu/\bar{\nu}_\mu$
- when the $\mu^{\pm}$ decay, it produces $e^{\pm}$and $\nu_e, \bar{\nu}_\mu$ or $\bar{\nu}_e, \nu_\mu$



atmospheric neutrinos

as secondary particles

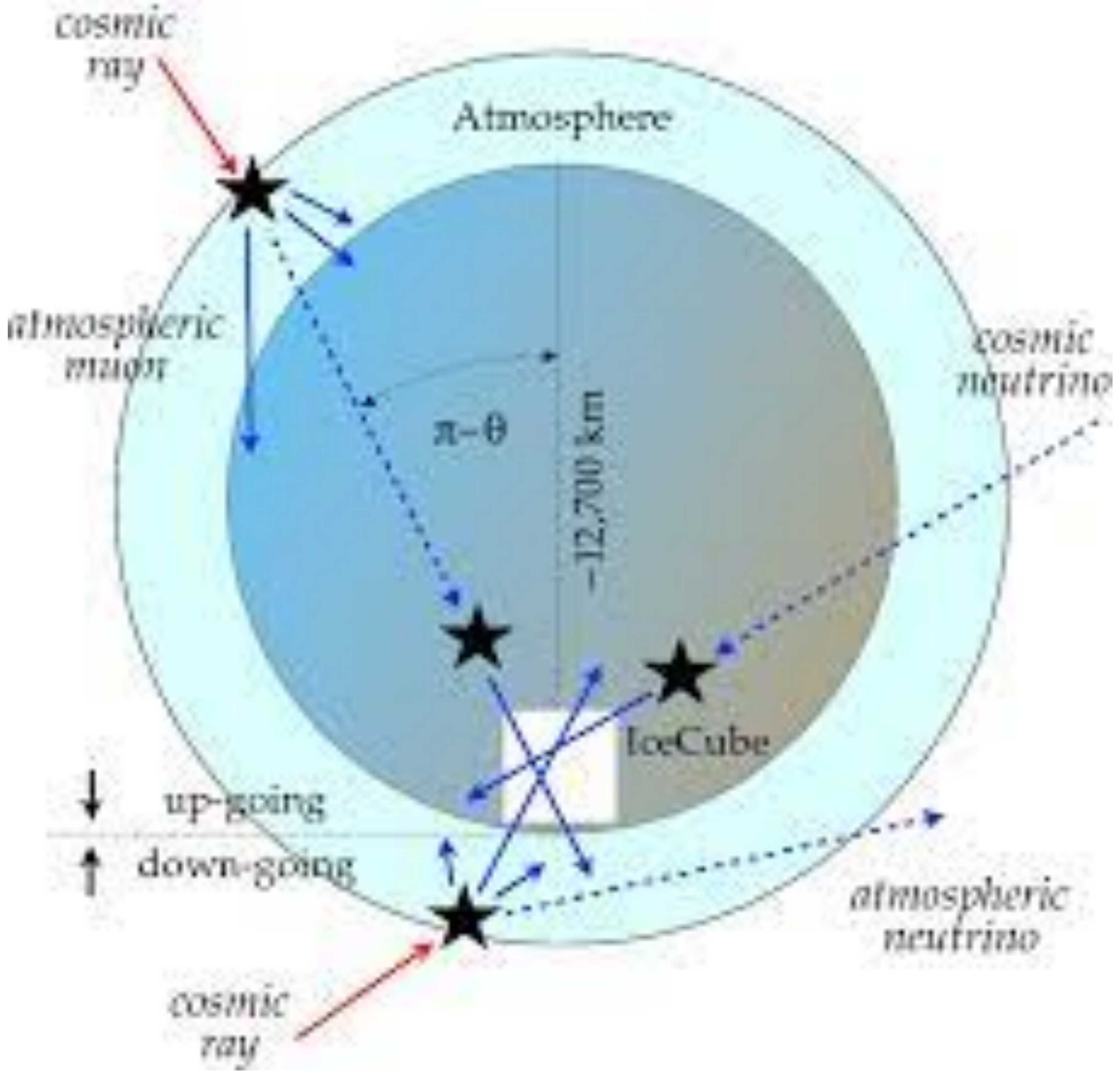
- the collisions of primary particles produce secondary mesons, in part. $\pi^{\pm}$
- when $\pi^{\pm}$ decay, it produces $\mu^{\pm}$ and $\nu_{\mu}/\bar{\nu}_{\mu}$
- when the $\mu^{\pm}$ decay, it produces $e^{\pm}$and $\nu_e, \bar{\nu}_{\mu}$ or $\bar{\nu}_e, \nu_{\mu}$
- at higher energies, muon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



atmospheric neutrinos

and the induced muons

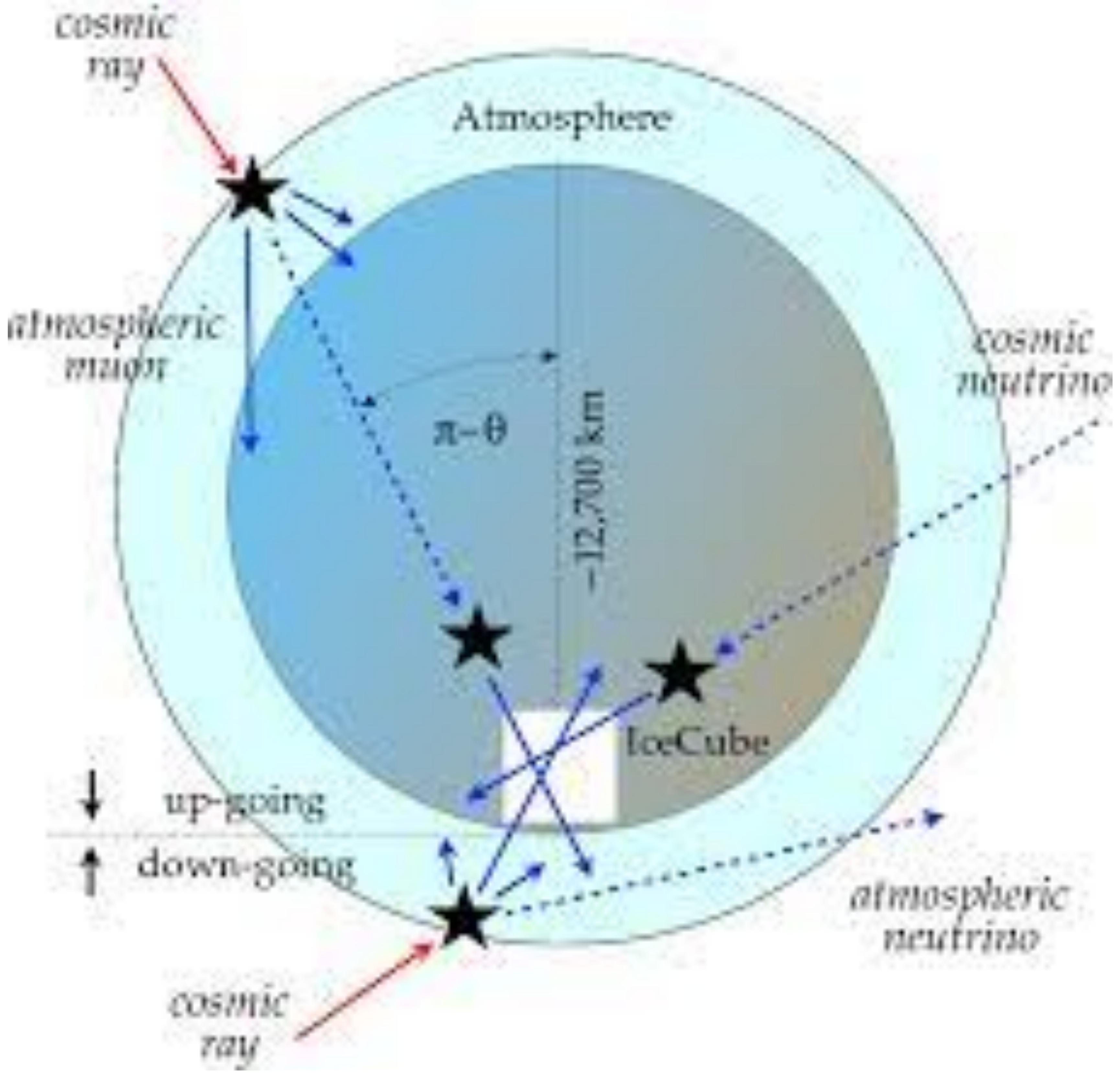
- the muons are very penetrating particles and a big annoyance for underground neutrino detectors



atmospheric neutrinos

and the induced muons

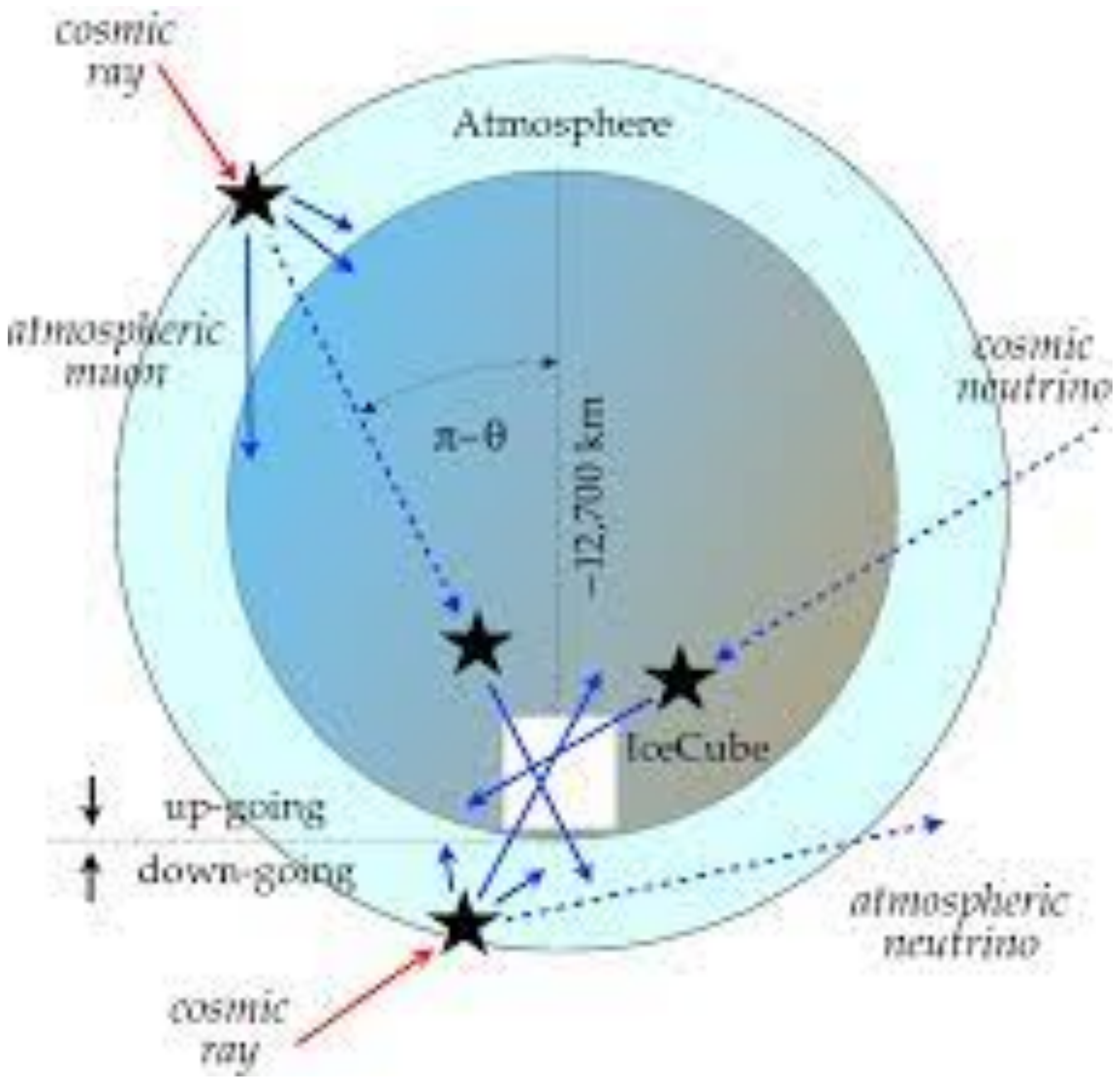
- the muons are very penetrating particles and a big annoyance for underground neutrino detectors
- when the direction of the particles are observed, one can search for up-going muons
- these are unmistakably to be attributed to muon (anti)neutrinos interacting around the detector



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!



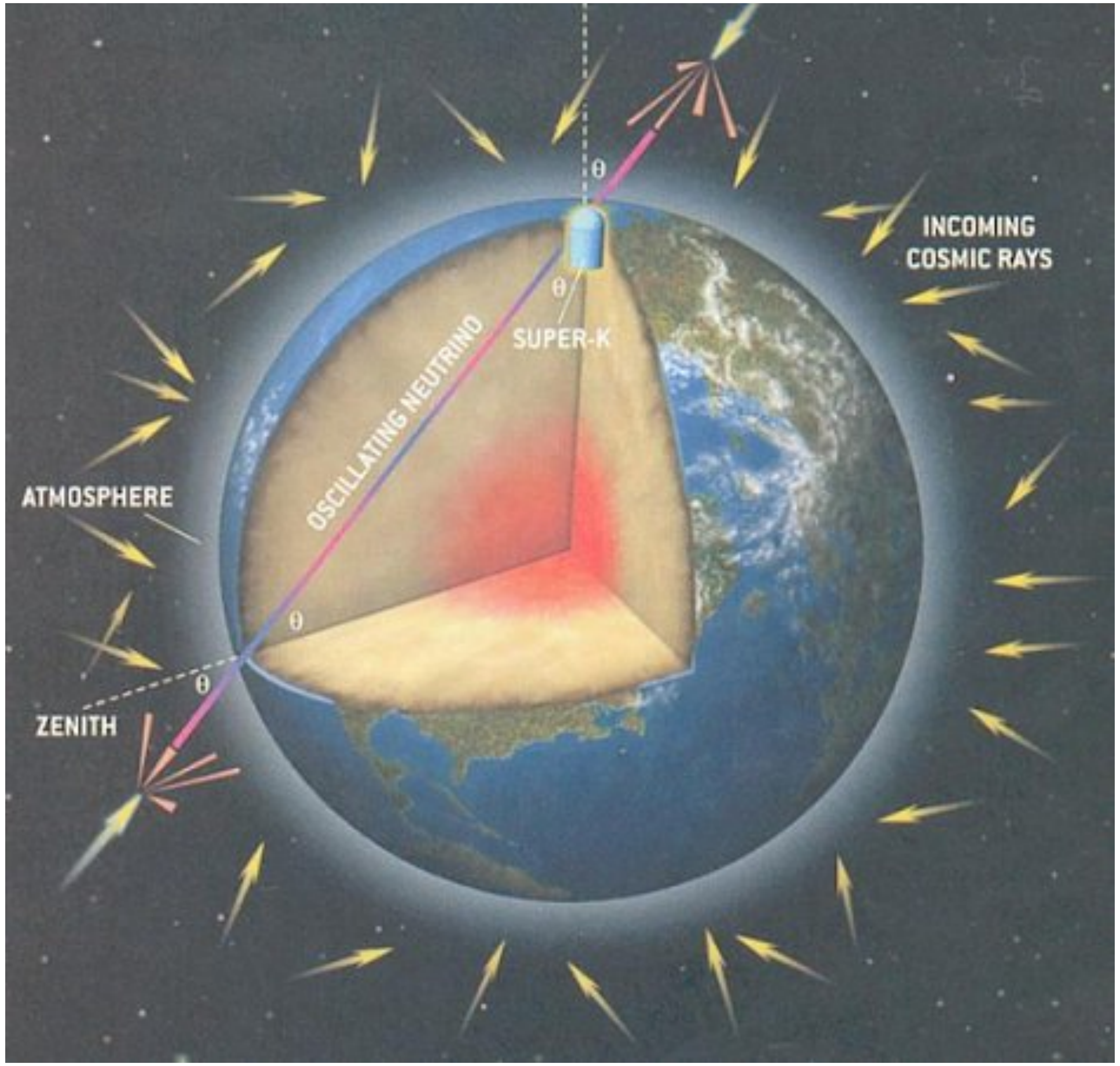
atmospheric neutrinos

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.

2.

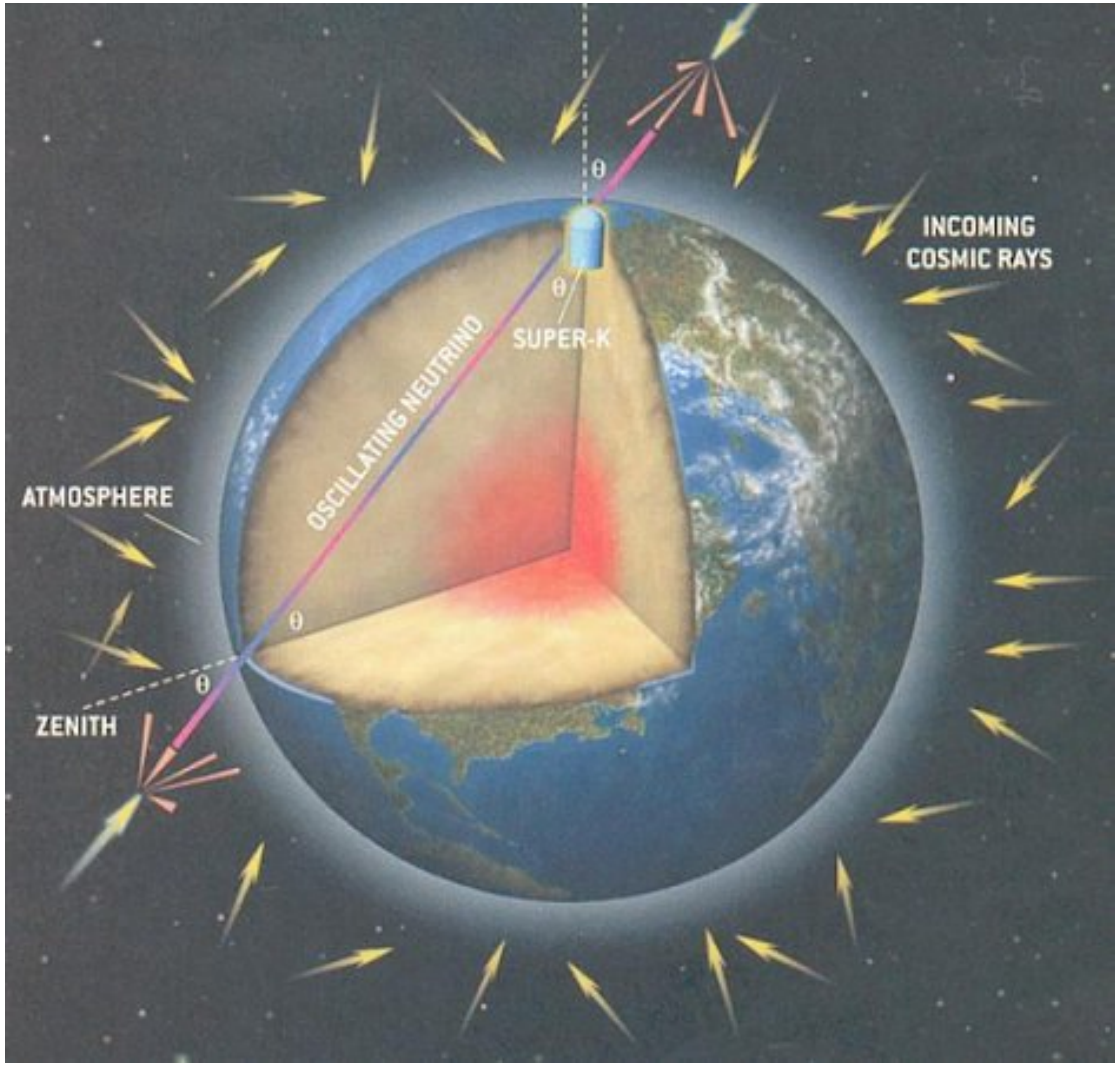


atmospheric neutrinos

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



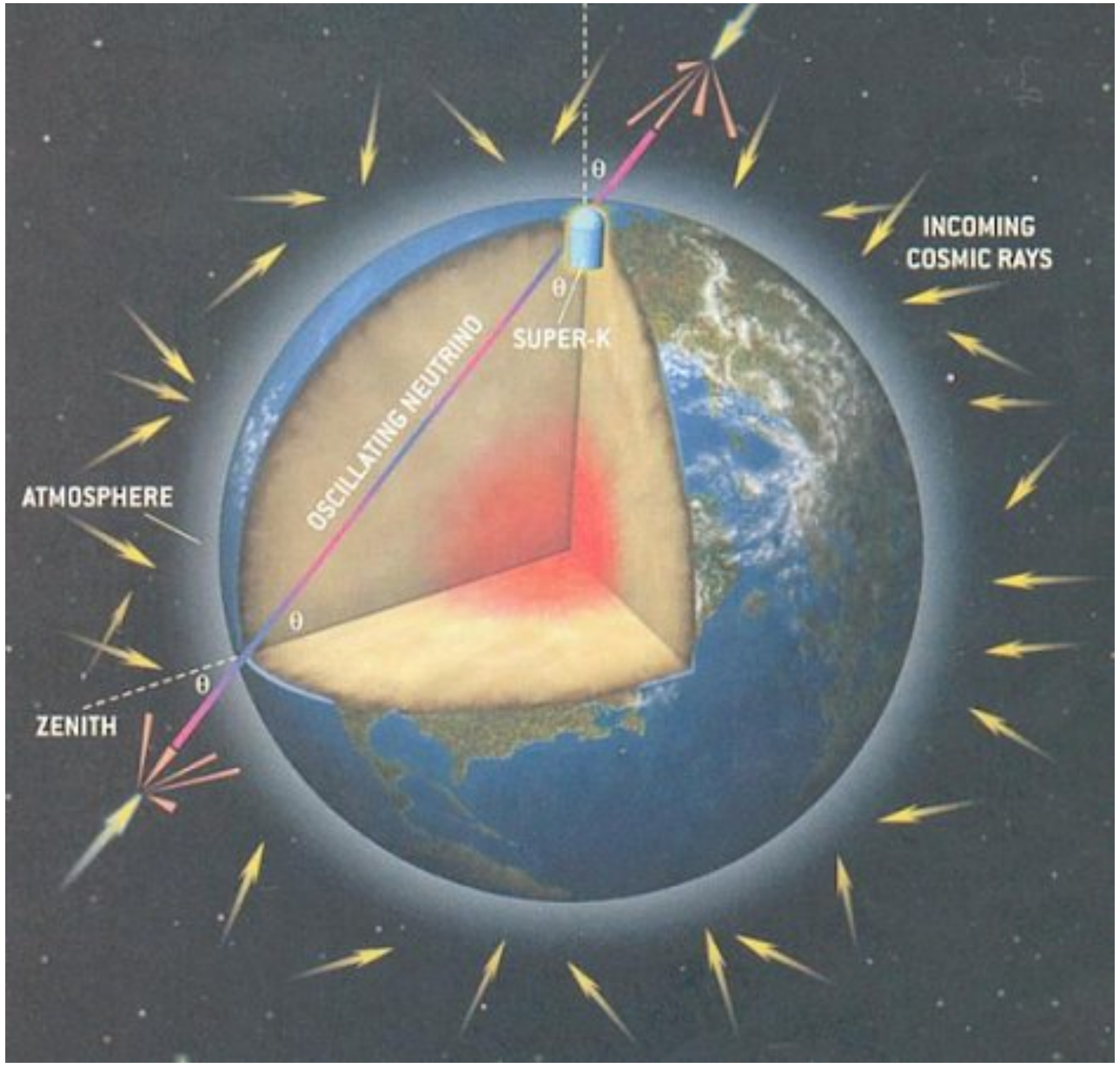
atmospheric neutrinos

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



summary and discussion

on atmospheric neutrinos

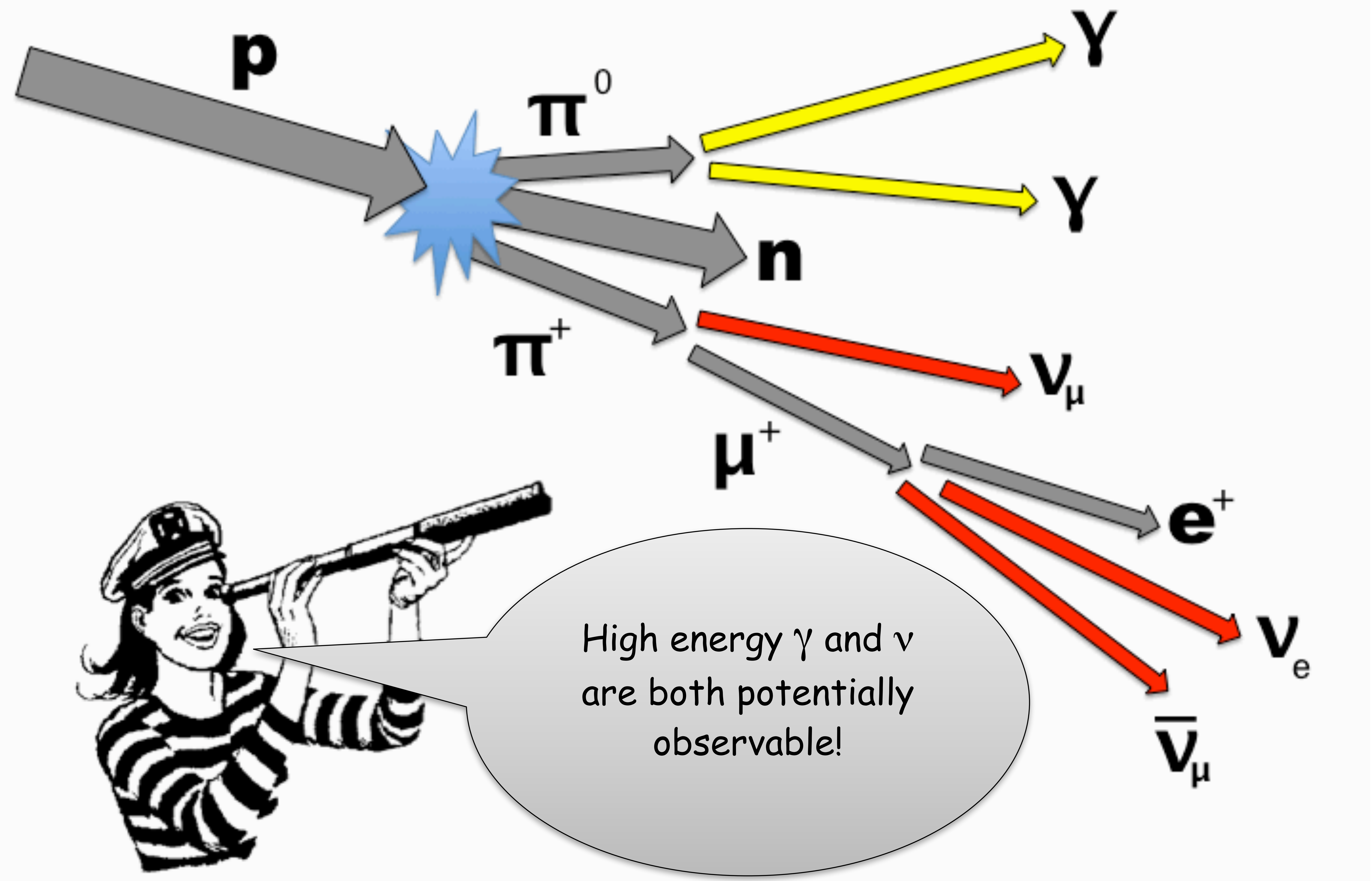
- For neutrino physics, atmospheric neutrinos have played an enormous historical role.
- Interestingly, in current **oscillation studies** and in the few-few ten GeV region, they still play a prominent role.
- Their distribution above 10-100 TeV is not well known. Note that we expect them to include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

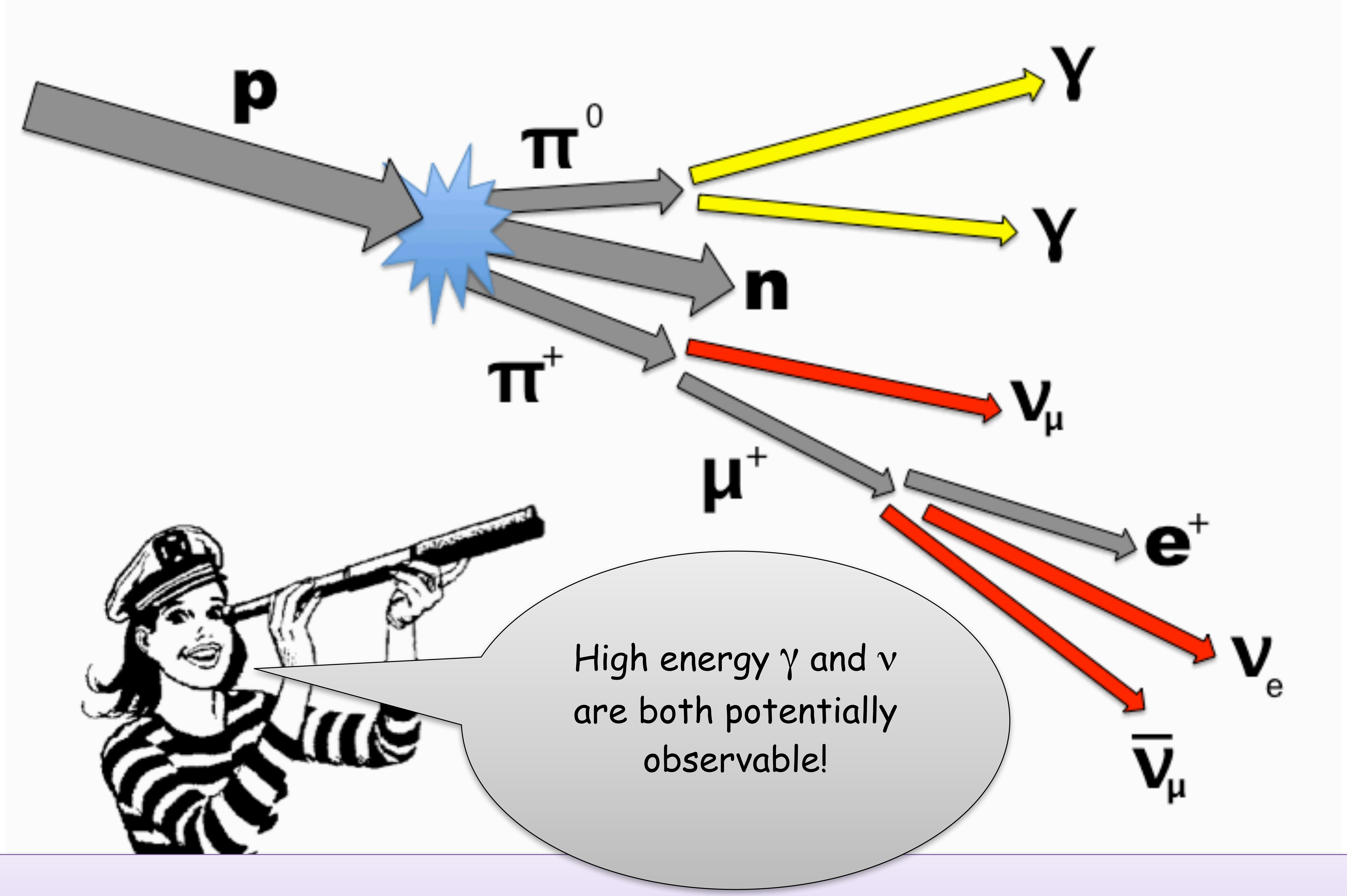
H.E. astrophysical neutrinos

introduction

on high-energy astrophysical neutrinos

- We are in a merry moment: after a long phase of preparation, in the last 10yr the field begun observational phase, thanks to IceCube experiment.
- Here, we introduce the matter and examine the main motivations.

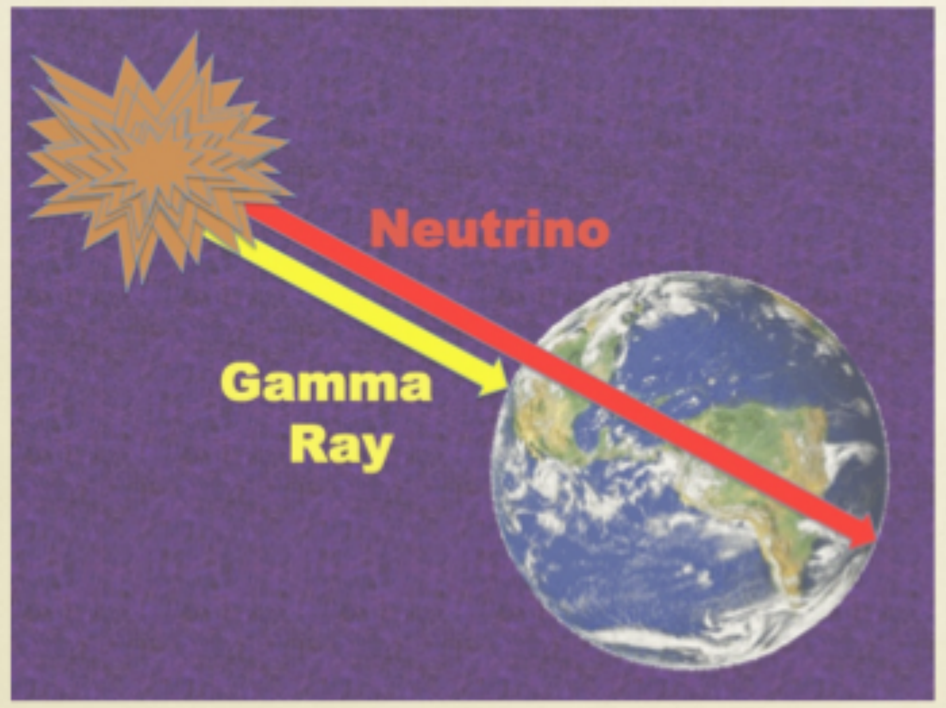

p
π0
π+
n
γ
γ
νμ
μ+
e+
νe
ν̄μ
High energy γ and ν
are both potentially
observable!



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

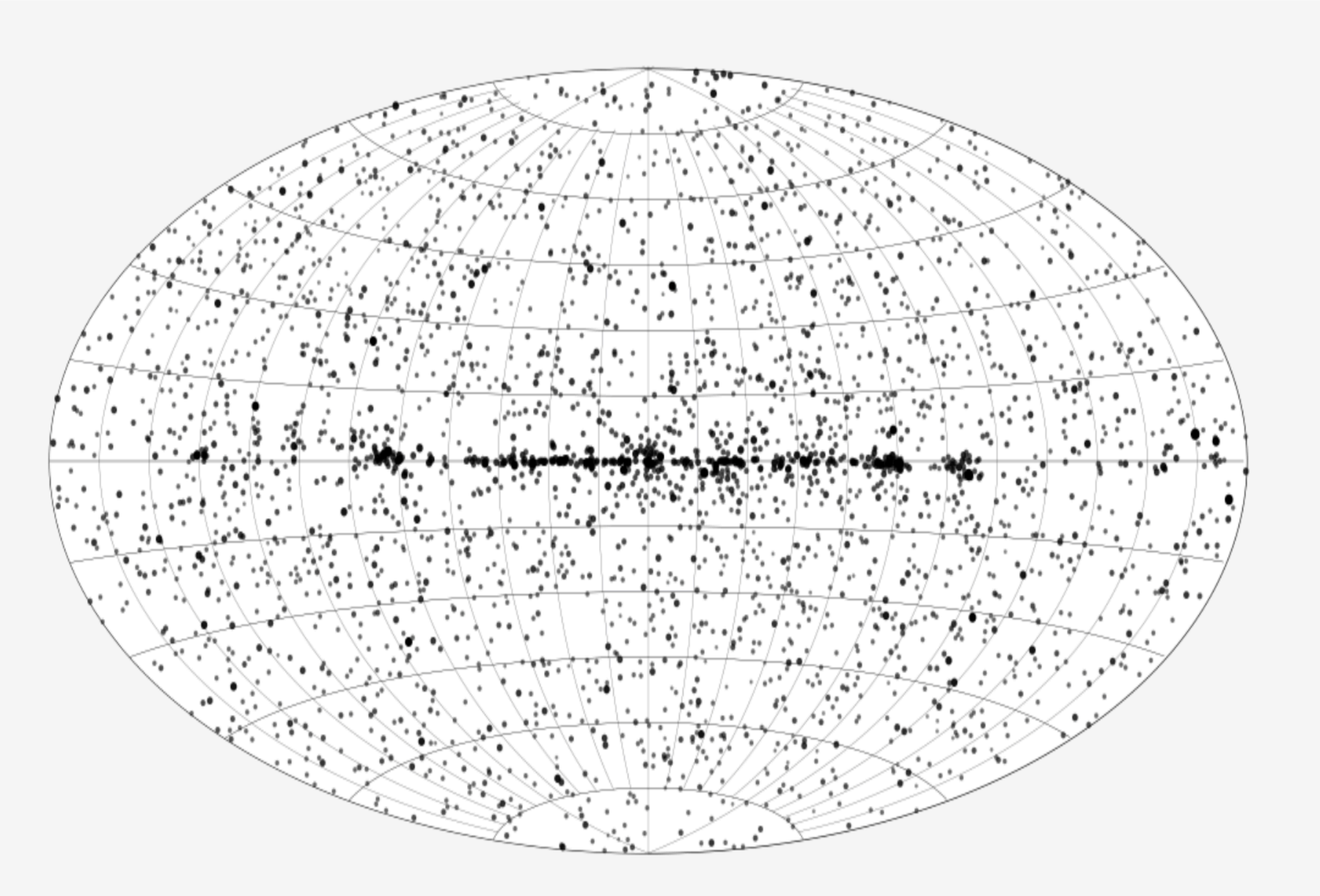
Cosmic neutrinos: how & why

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.

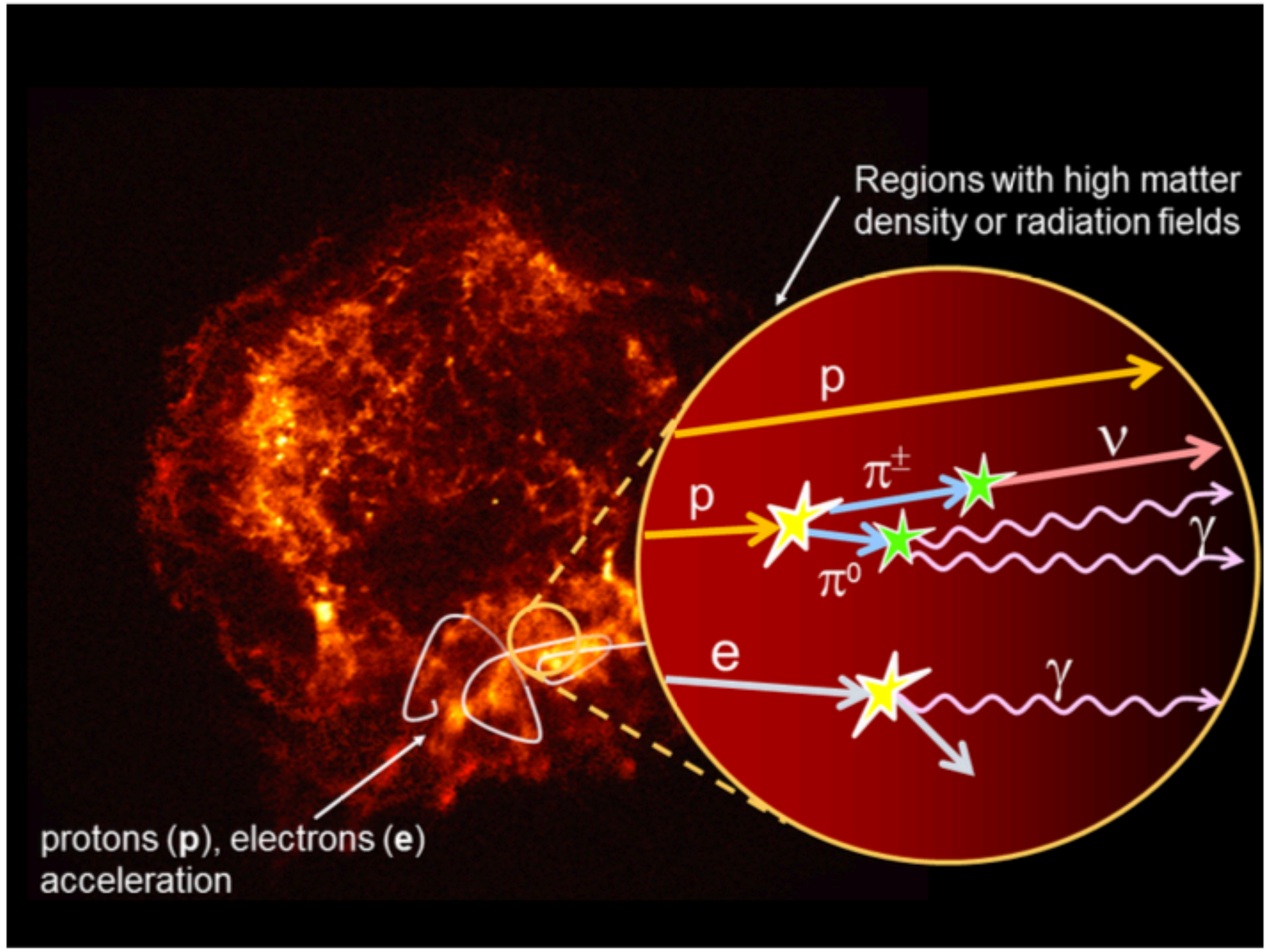


- *"γ quanta of 1 TeV favor existence of cosmic high-energy neutrinos"*
- *"worth searching especially if HE γ beyond atmosphere were found"*
- *from new star's shell as Crab "the flux could equal the atmospheric one"*
- *from old CR population as GC "could be large if attenuation is essential"*

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



what is the target for CR collisions?

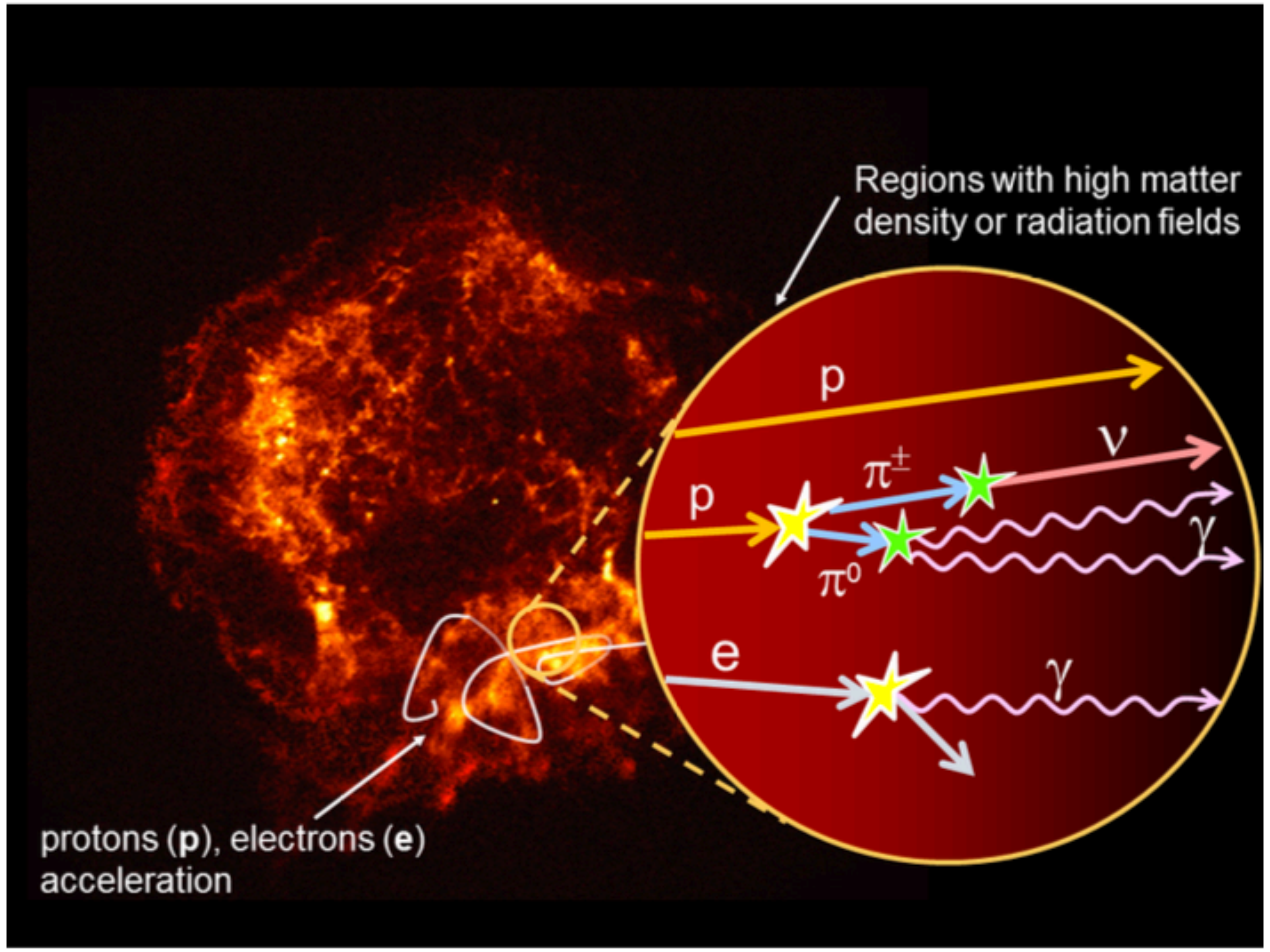


If the target is due to hadrons

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

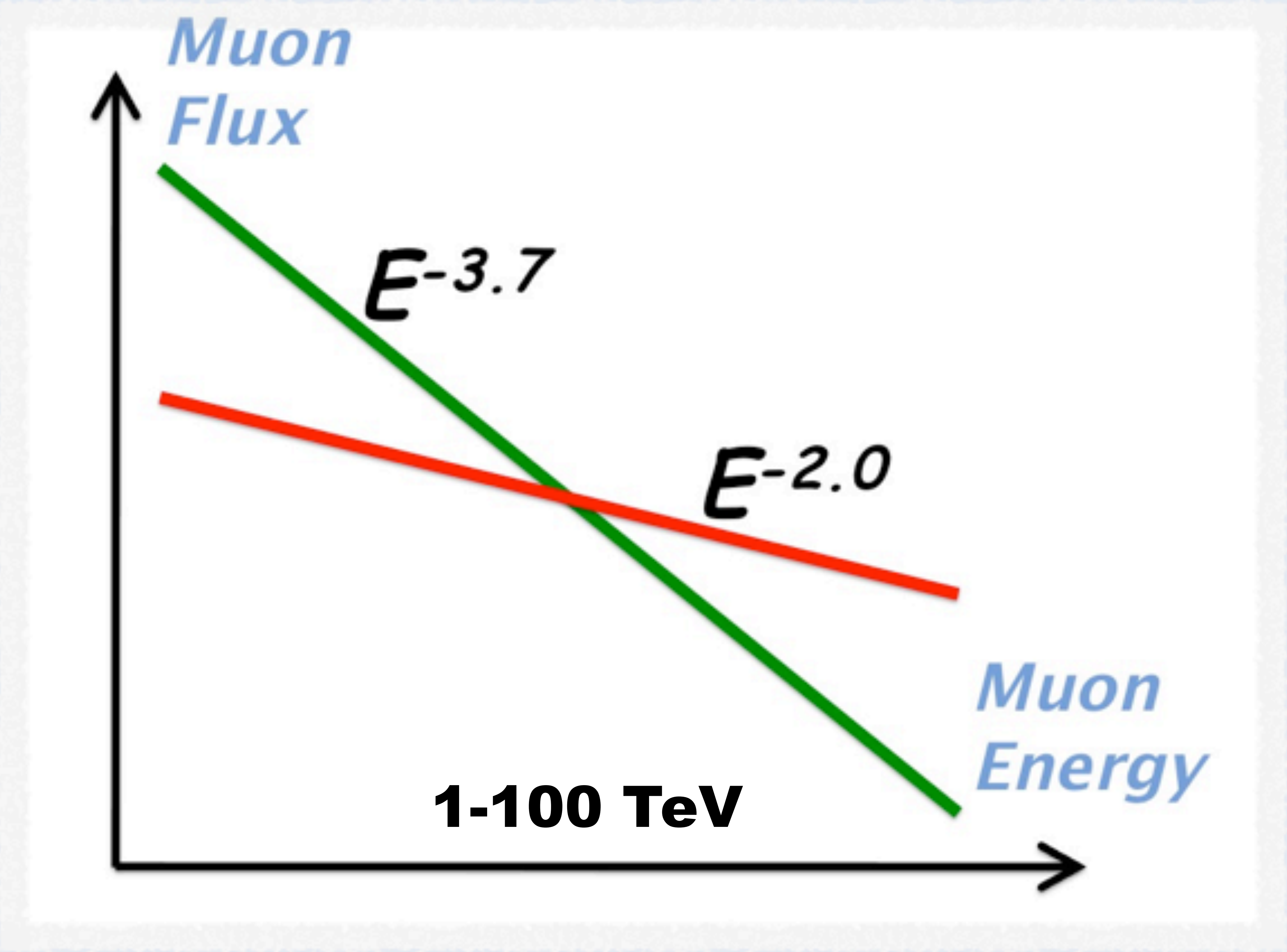
PP-mechanism:

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

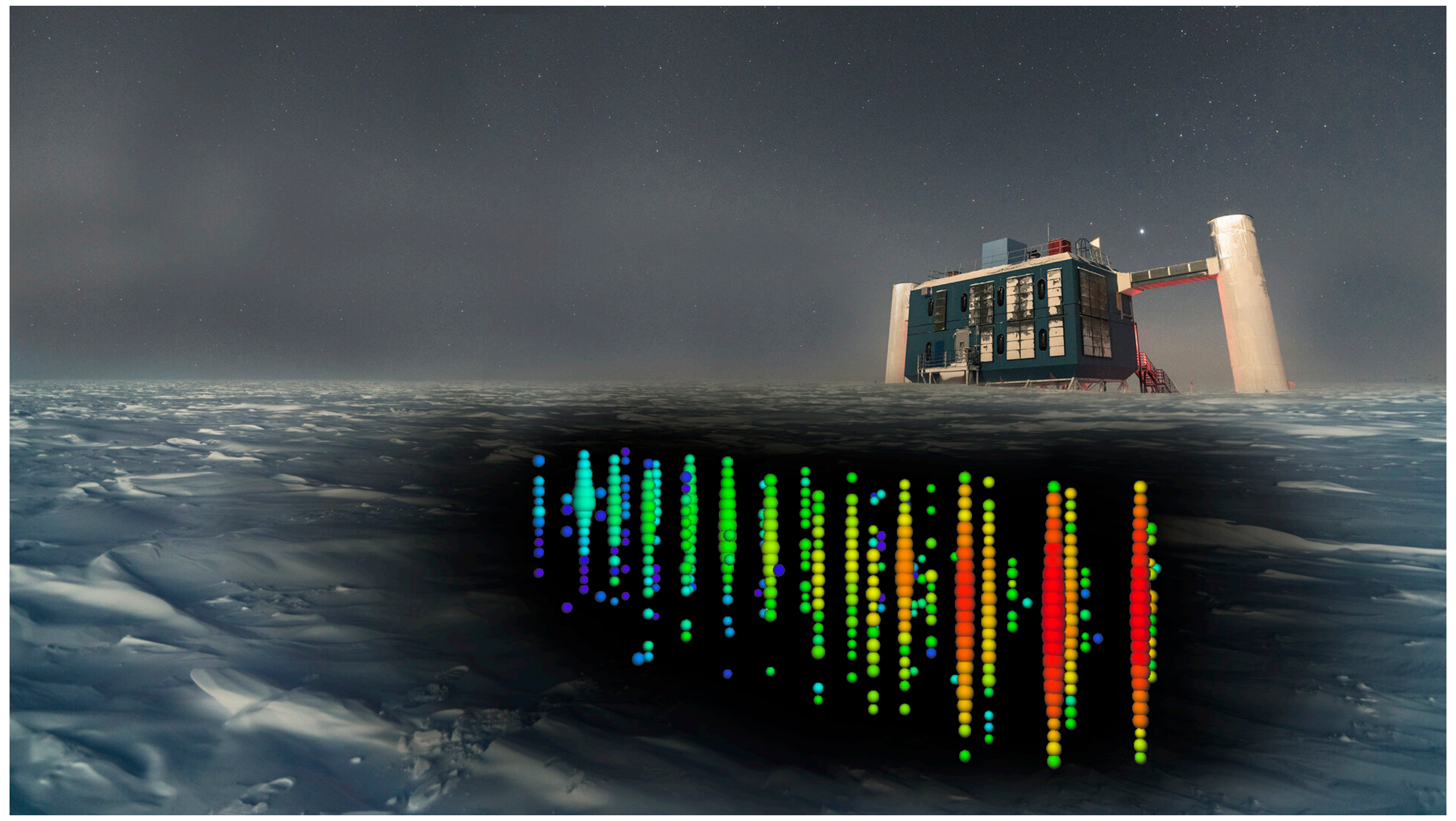
- astronomical goals: see some bright **point source**, steady or possibly sporadic, over the atmospheric neutrino background; gamma rays studies offer us hints and guidance

- 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

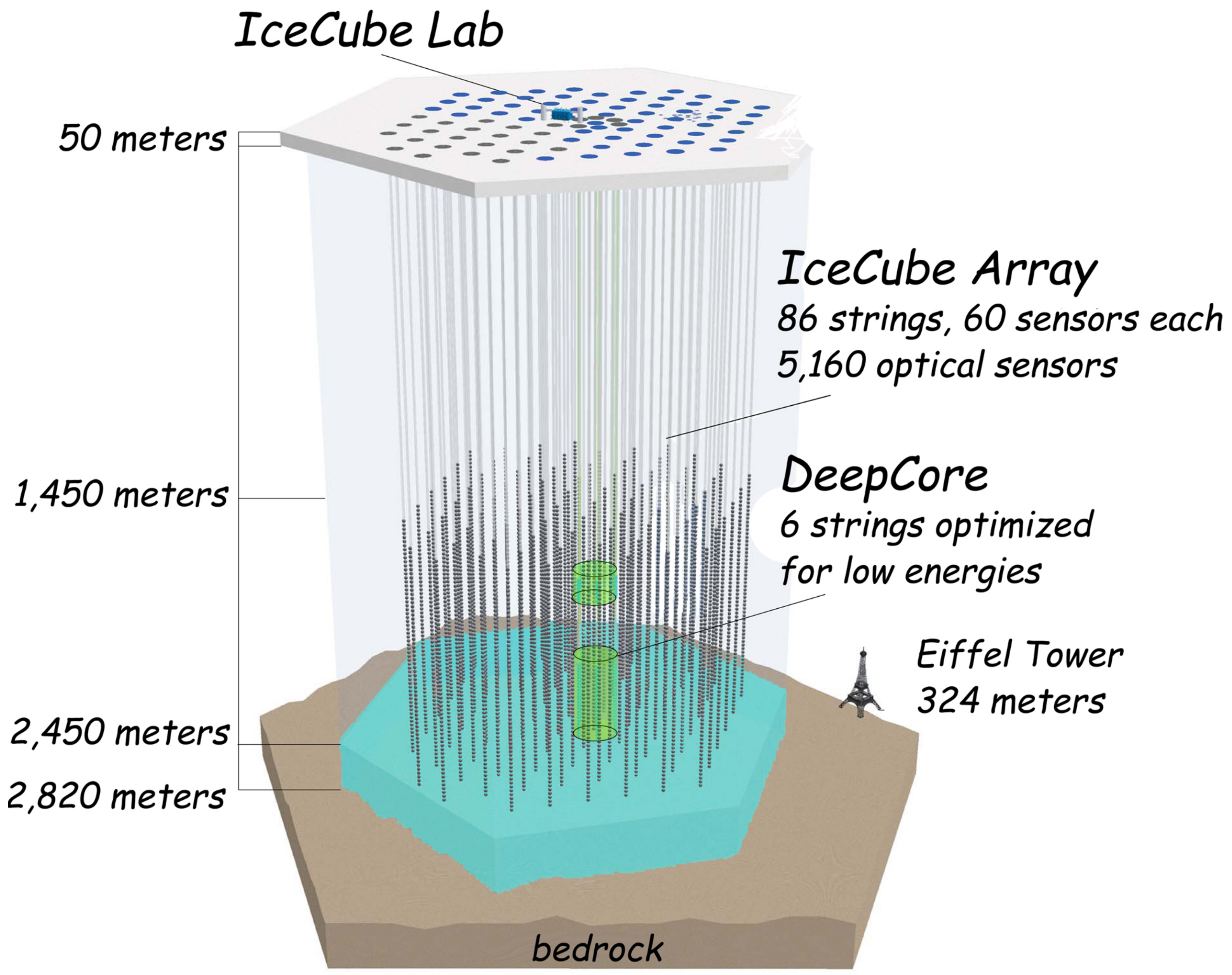


IceCube is a detector installed in the ice of the South Pole.

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.

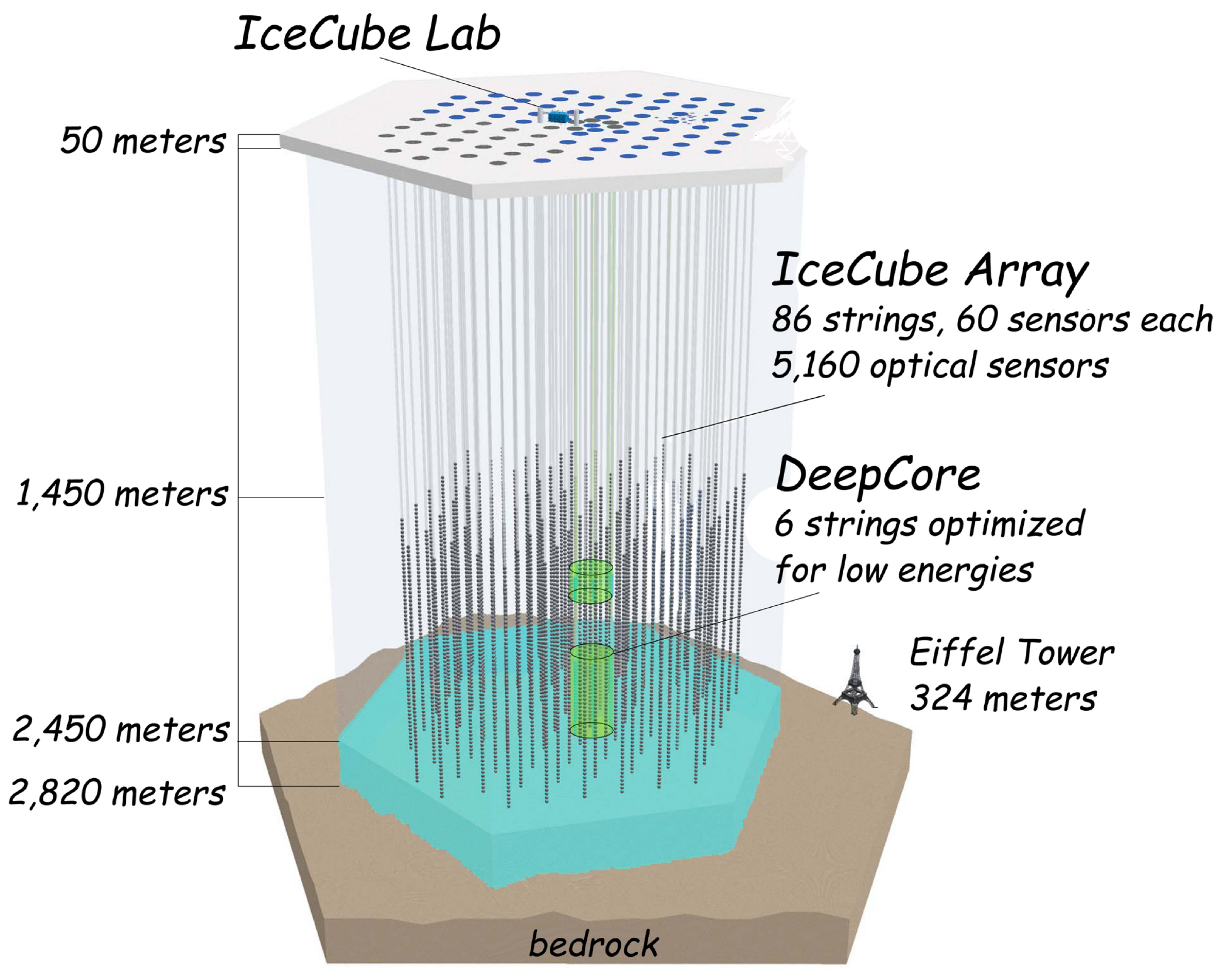


IceCube

highlights

new population seen as

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



IceCube

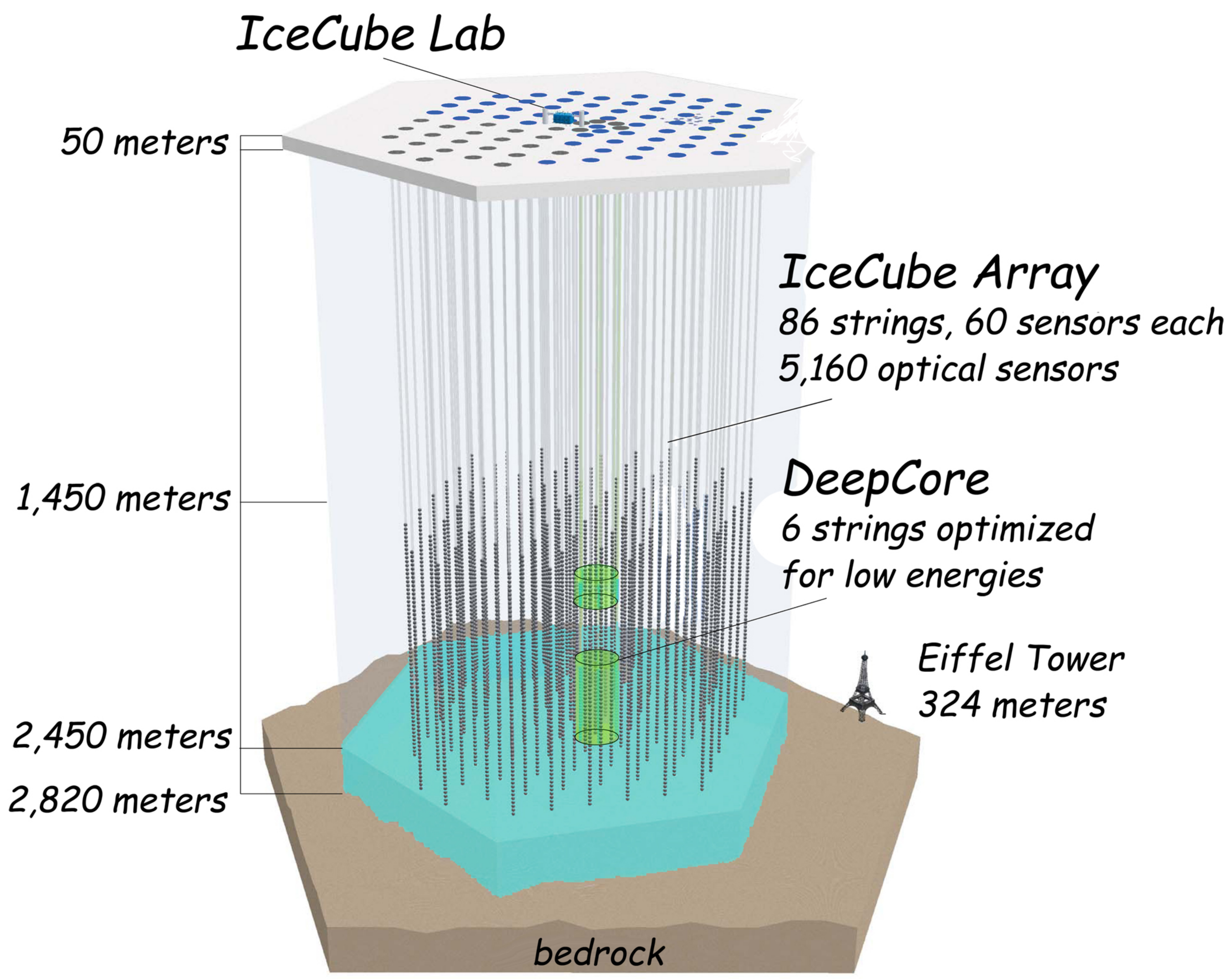
highlights

new population seen as

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

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

angular distribution almost isotropic, as expected from extragalactic population



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.

end of the
first lecture

Journal of Physics G: Nuclear and Particle Physics

PAPER

The luminosity constraint in the era of precision solar physics

Diego Vescovi[6,1,2,3], Carlo Mascaretti[5,1], Francesco Vissani[1,4], Luciano Piersanti[2,3] and Oscar Straniero[3,4]

Published 17 November 2020 •

Journal of Physics G: Nuclear and Particle Physics, Volume 48, Number 1

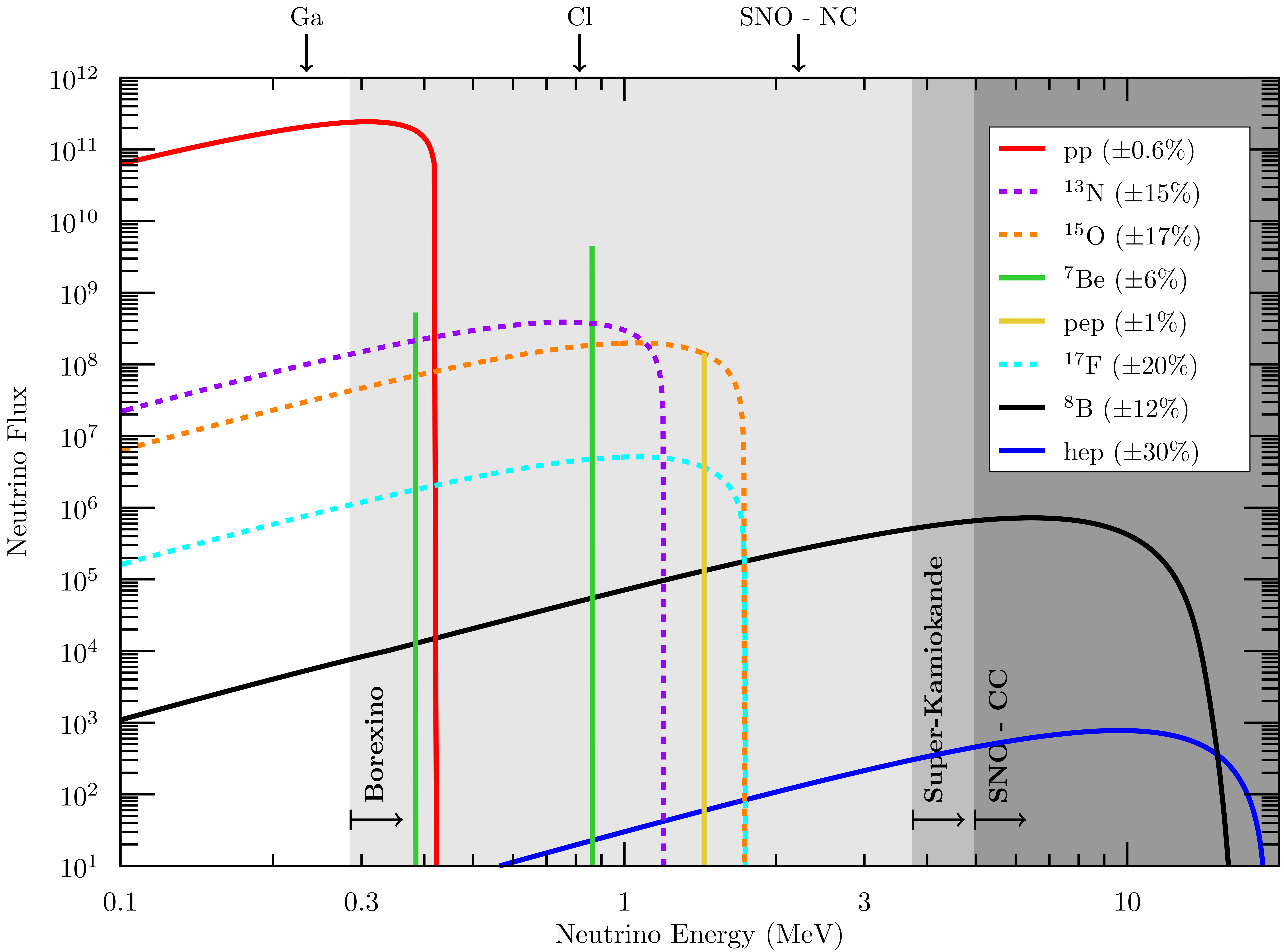
Citation Diego Vescovi *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* **48** 015201

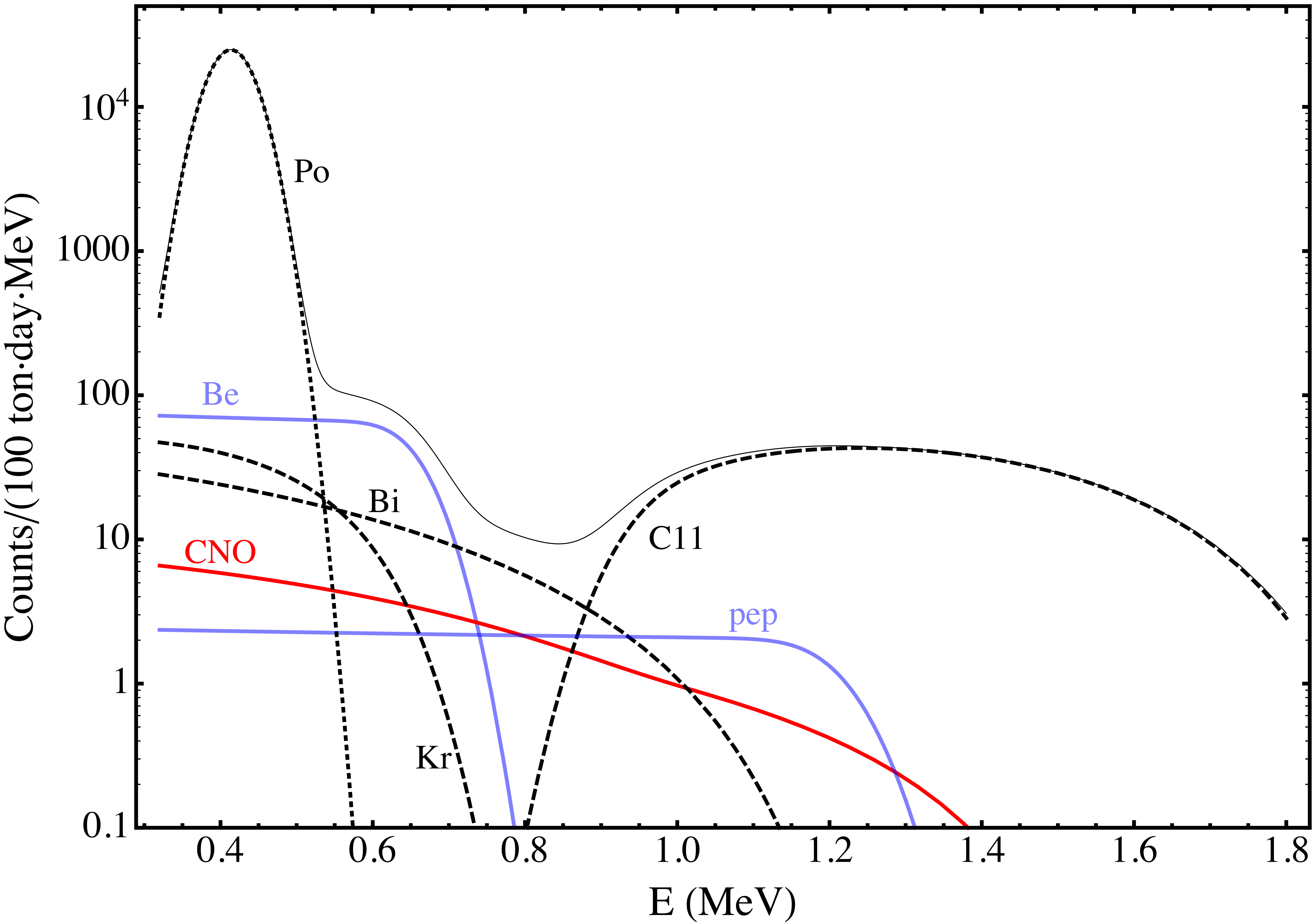
+Article information

Abstract

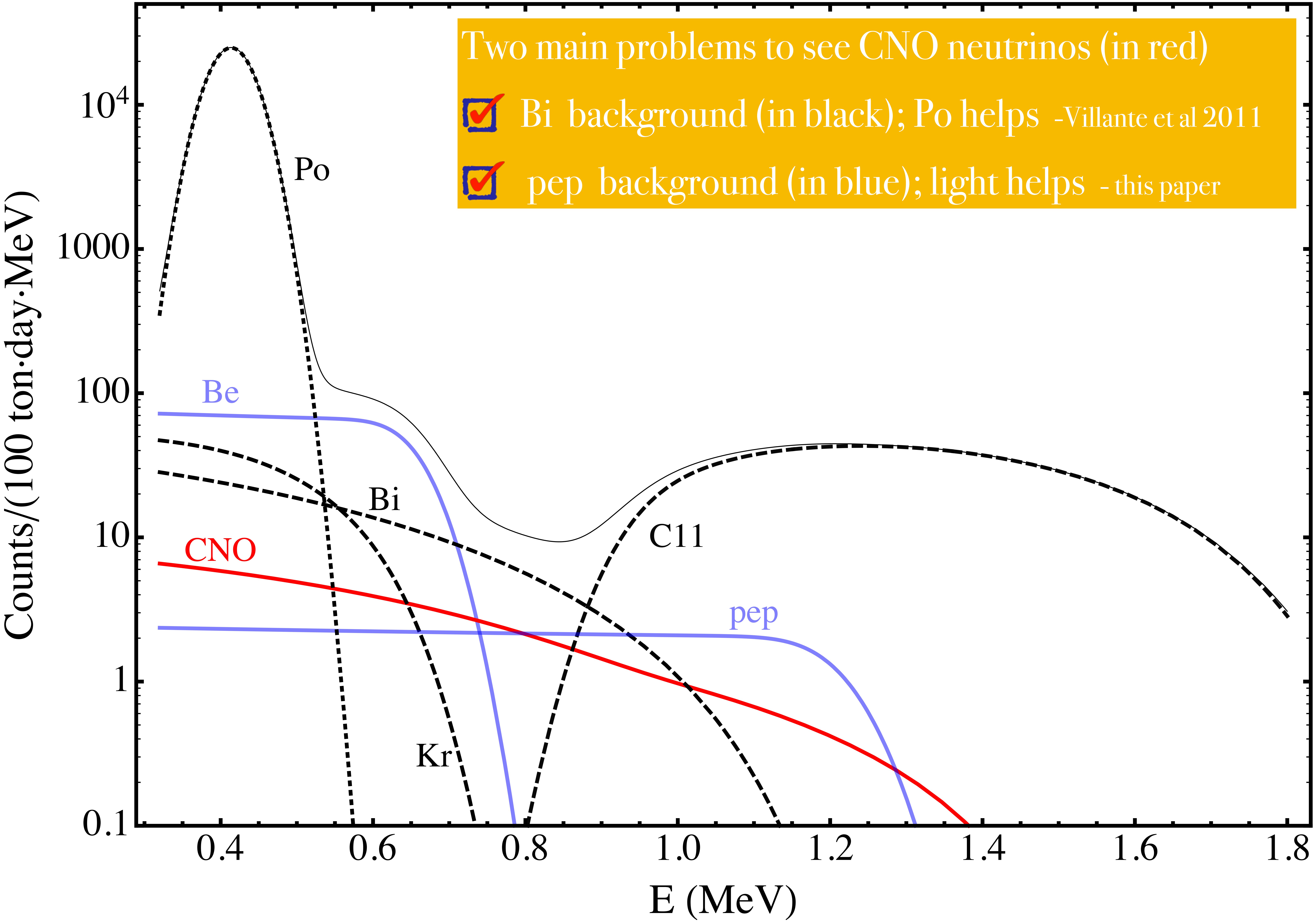
The *luminosity constraint* is a very precise relationship linking the power released by the Sun as photons and the solar neutrino fluxes. Such a relation, which is a direct consequence of the physical processes controlling the production and the transport of energy in the solar interior, is of great importance for the studies of solar neutrinos and has a special role for the search of neutrinos from the CNO cycle, whose first detection with a 5σ significance has been recently announced by the Borexino collaboration. Here we revise the luminosity constraint, discussing and validating its underlying hypotheses, in the light of latest solar neutrino and luminosity

Borexino has probed all relevant reactions



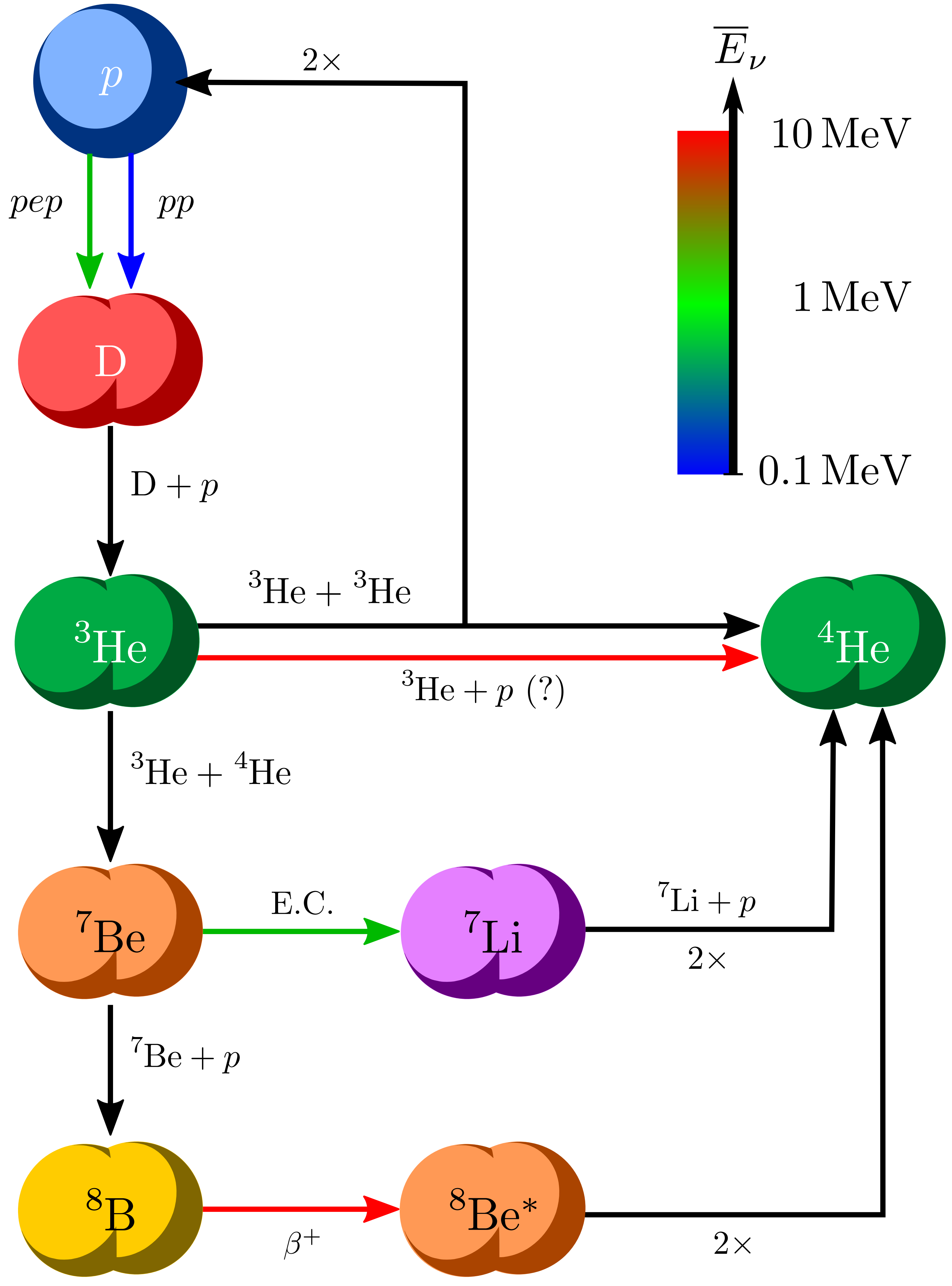


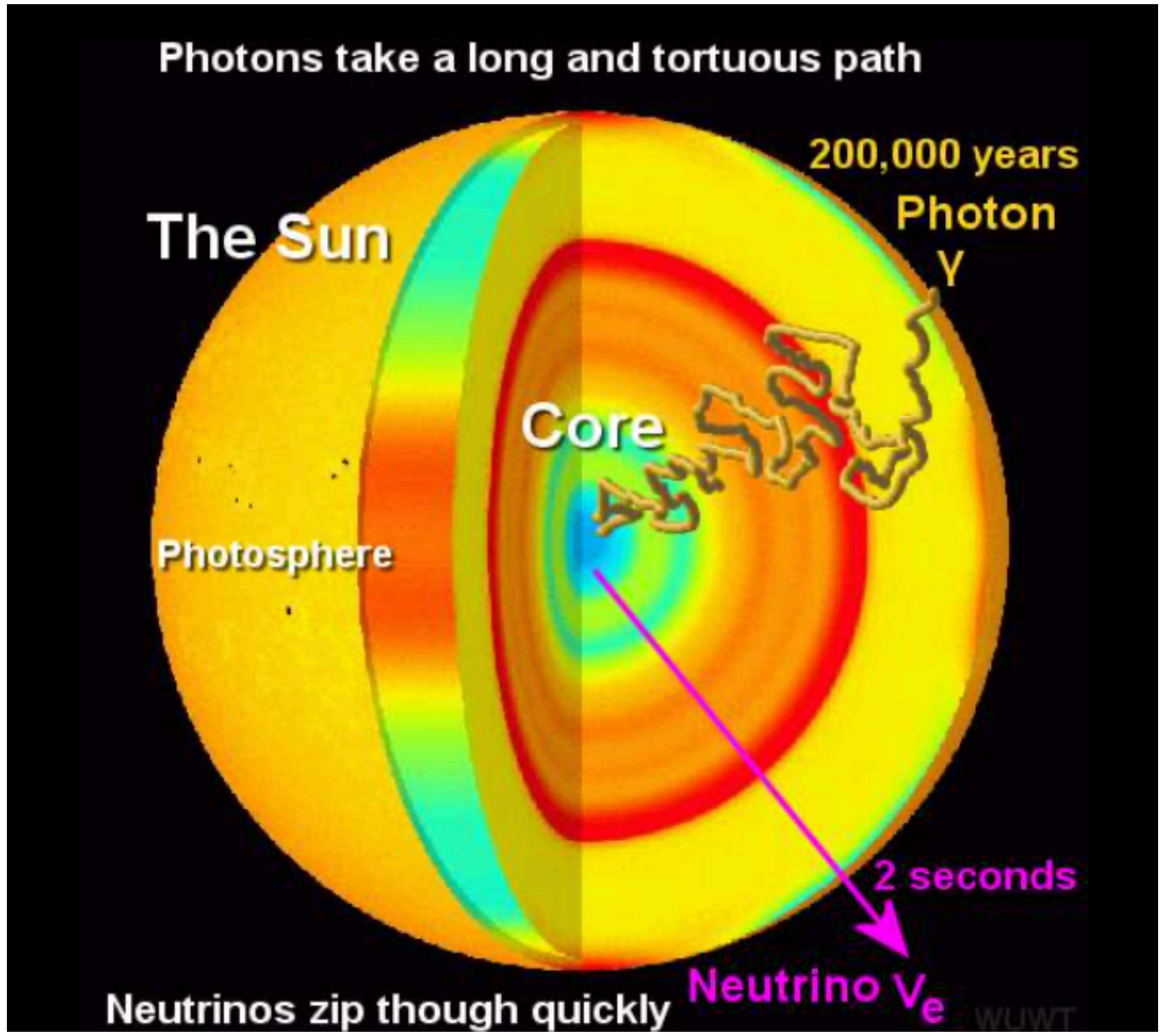
Po
Be
Bi
CNO
C11
pep
Kr
Counts/(100 ton·day·MeV)
E (MeV)
10^4
1000
100
10
1
0.1
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8



Two main problems to see CNO neutrinos (in red)
Bi background (in black); Po helps -Villante et al 2011
pep background (in blue); light helps - this paper
Po
Be
Bi
C11
CNO
pep
Kr
Counts/(100 ton·day·MeV)
E (MeV)
10^4
1000
100
10
1
0.1
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8

light is measured very precisely and is closely related to neutrinos





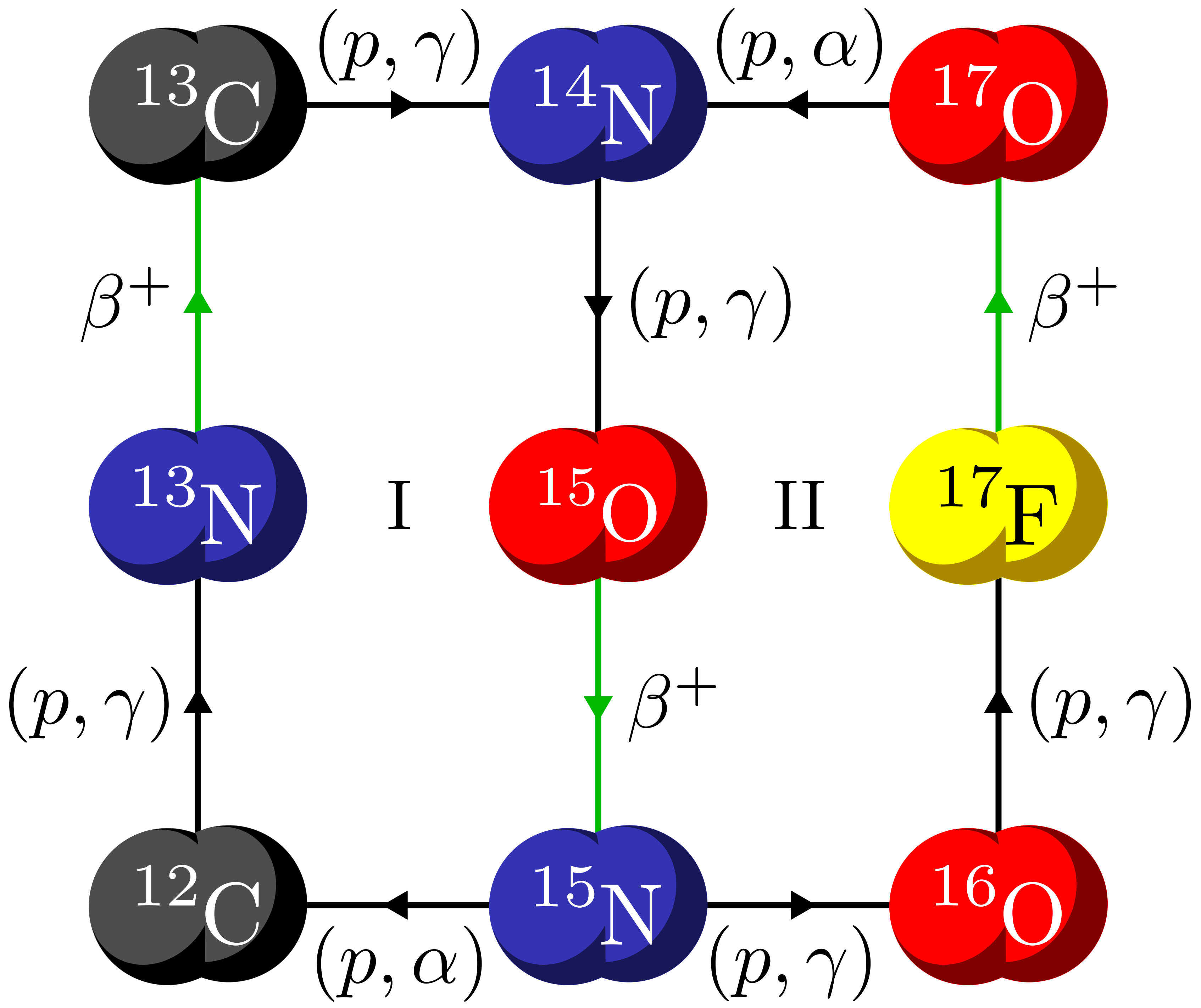
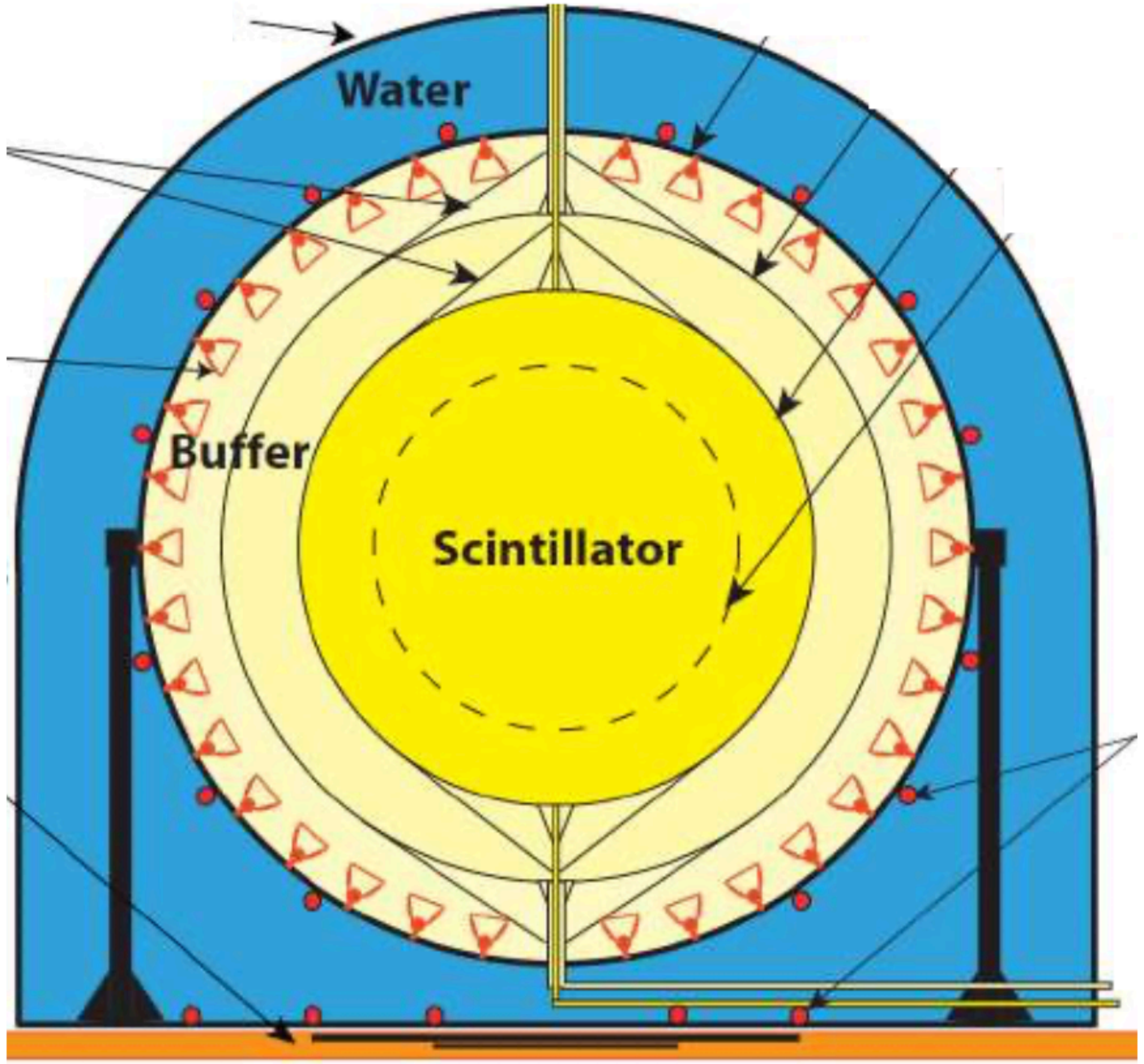


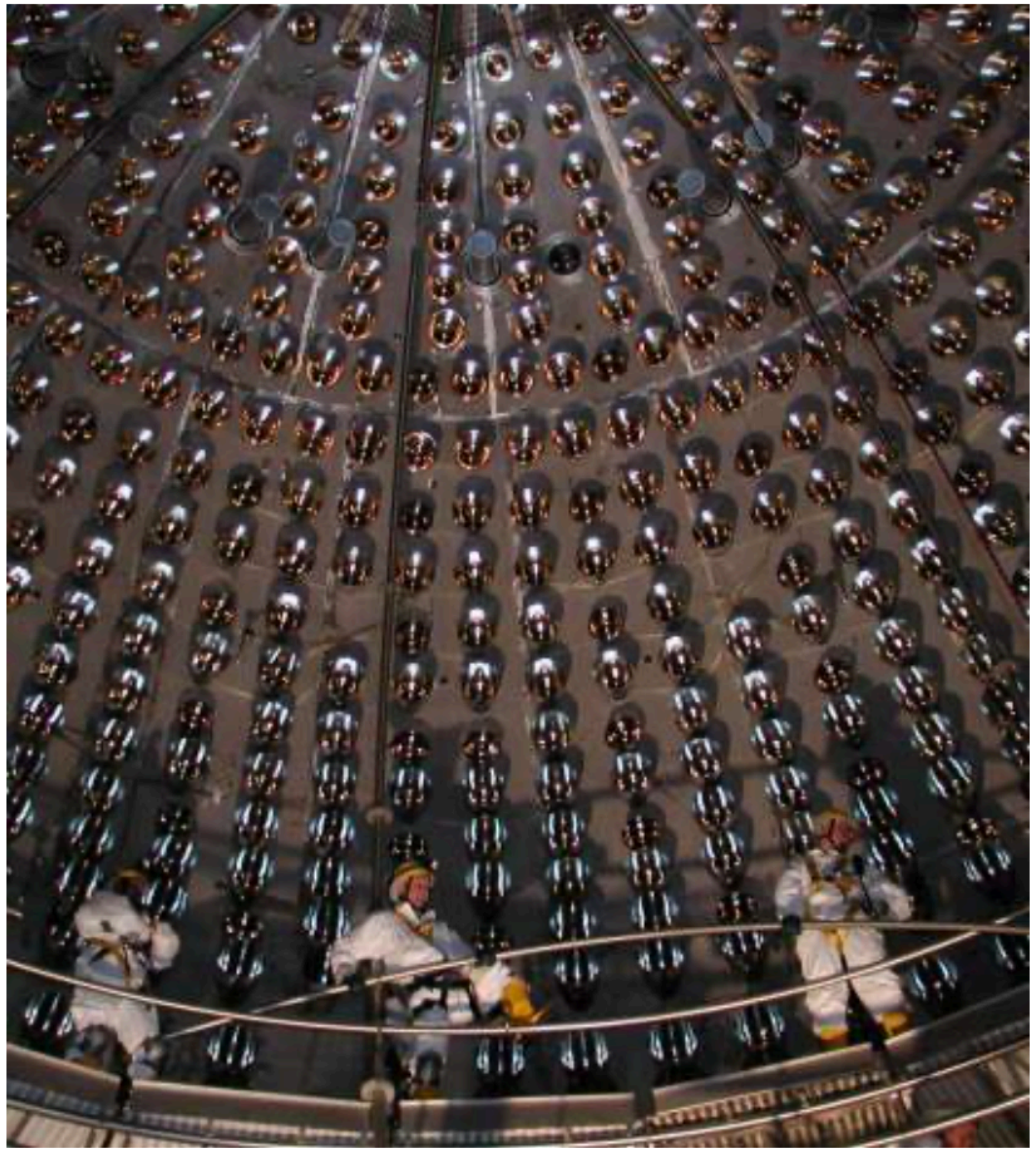
Table 6. The central value, in units of $10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, of the constraint (with 0.2% precision) as described in Eq. (34), including the various refinements of Section 4.

corrective terms	GS98	PLJ14	average
none	5.9937	5.9937	5.9937
$L_{^3\mathrm{He}}$	5.9995	5.9997	5.9996
$L_{^3\mathrm{He}} + L_{^{14}\mathrm{N}}$	6.0004	6.0006	6.0006
$L_{^3\mathrm{He}} + L_{^{14}\mathrm{N}} + L_\mathrm{g}$	6.0031	6.0032	6.0031

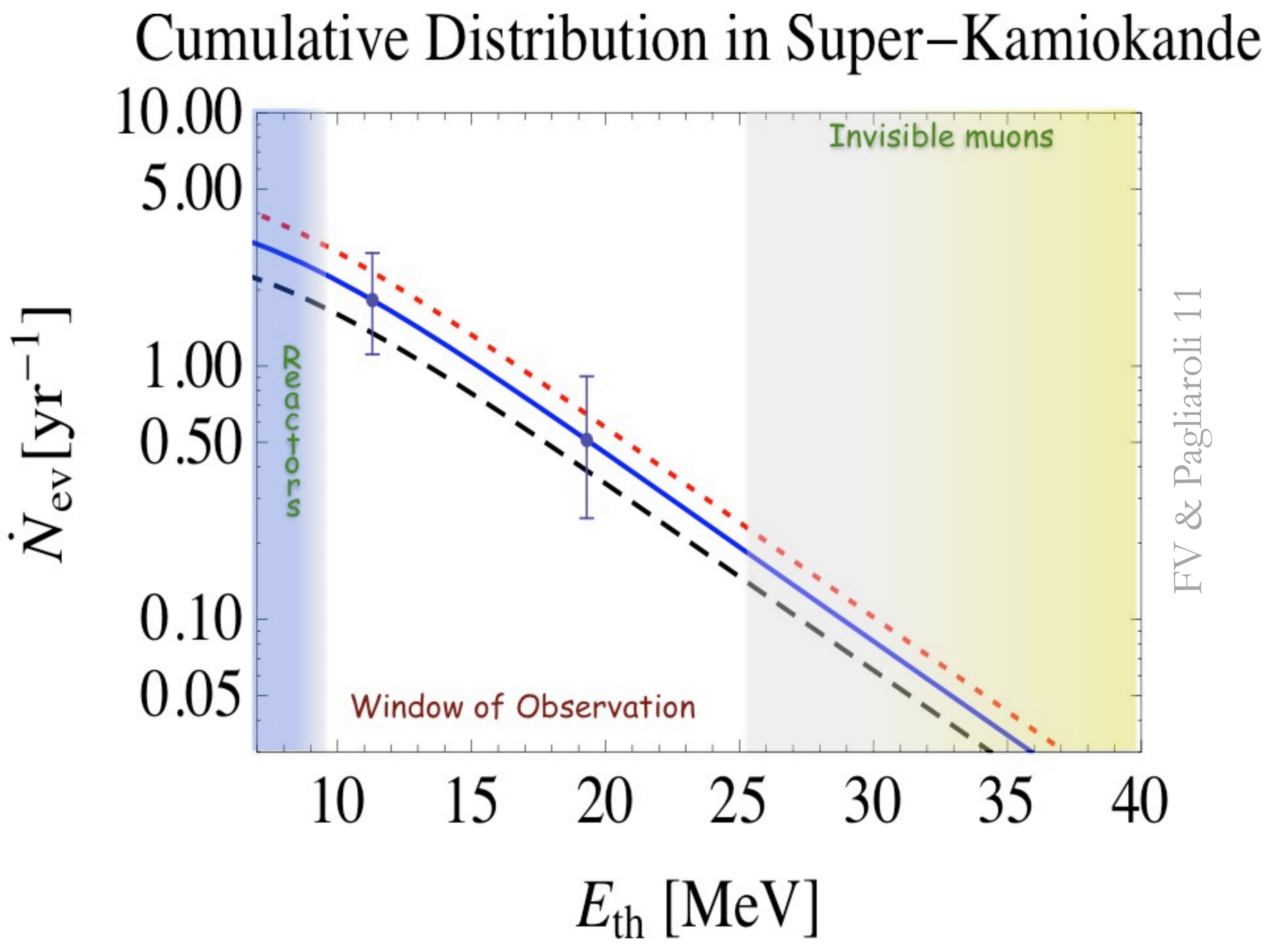
$$\boxed{\Phi_\mathrm{pp} + 0.946\,\Phi_\mathrm{CNO} = 6.003\,(1 \pm 0.2\%) \times 10^{10}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,.}$$

Borexino at the Gran Sasso labs





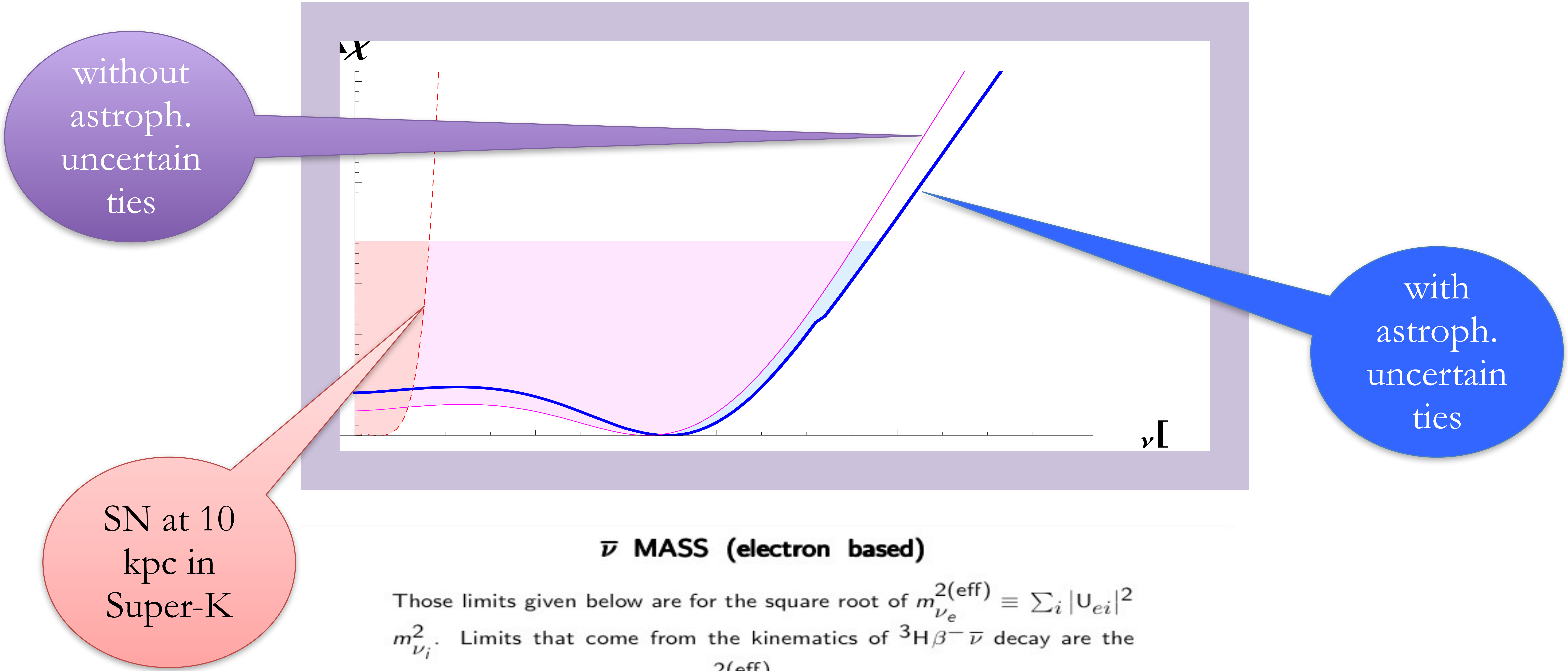
Relic (D.S.N.B.) Neutrinos



FV & Pagliaroli 11

a race of neutrinos and photons

Mass Bound from SN1987A



$\overline{\nu}$ MASS (electron based)

Those limits given below are for the square root of $m^{2(\text{eff})}_{\nu_e} \equiv \sum_i |U_{ei}|^2 m^2_{\nu_i}$. Limits that come from the kinematics of $^3\text{H}\beta^- \overline{\nu}$ decay are the square roots of the limits for $m^{2(\text{eff})}_{\nu_e}$. Obtained from the measurements reported in the Listings for "$\overline{\nu}$ Mass Squared," below.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 2	**OUR EVALUATION**				
< 2.3	95	[1] KRAUS	05	SPEC	^{3}H β decay
< 2.5	95	[2] LOBASHEV	99	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 5.8	95	[3] PAGLIAROLI	10	ASTR	SN1987A
<21.7	90	[4] ARNABOLDI	03A	BOLO	^{187}Re β-decay
< 5.7	95	[5] LOREDO	02	ASTR	SN1987A
< 2.8	95	[6] WEINHEIMER	99	SPEC	^{3}H β decay

ELSEVIER

New Astronomy

Volume 83, February 2021, 101498

On the rate of core collapse supernovae in the milky way

Karolina Rozwadowska [a, b], Francesco Vissani [a, b], Enrico Cappellaro [c]

Show more

Add to Mendeley Share Cite

https://doi.org/10.1016/j.newast.2020.101498

Highlights

- For neutrino astronomy, the knowledge of the rate of core collapse supernovae is of essential importance.
- We use the best available information to update its study and to obtain the state-of-the-art value: $R = 1.63 \pm 0.46$/century.
- We discuss the consistency of the results and point out the critical aspects in this inference.

$$R = 1.63 \pm 0.46 \text{ CCSN per century,}$$

$$\Rightarrow T = 61^{+24}_{-14} \text{ yr}$$

the chances of seeing at least one event are

$$P(>0) = 7.9\%,\ 15.0\%,\ 27.4\% \text{ and } 53.7\%$$

when the time of observation is

$$t = 5, 10, 20 \text{ and } 50 \text{ yr}$$

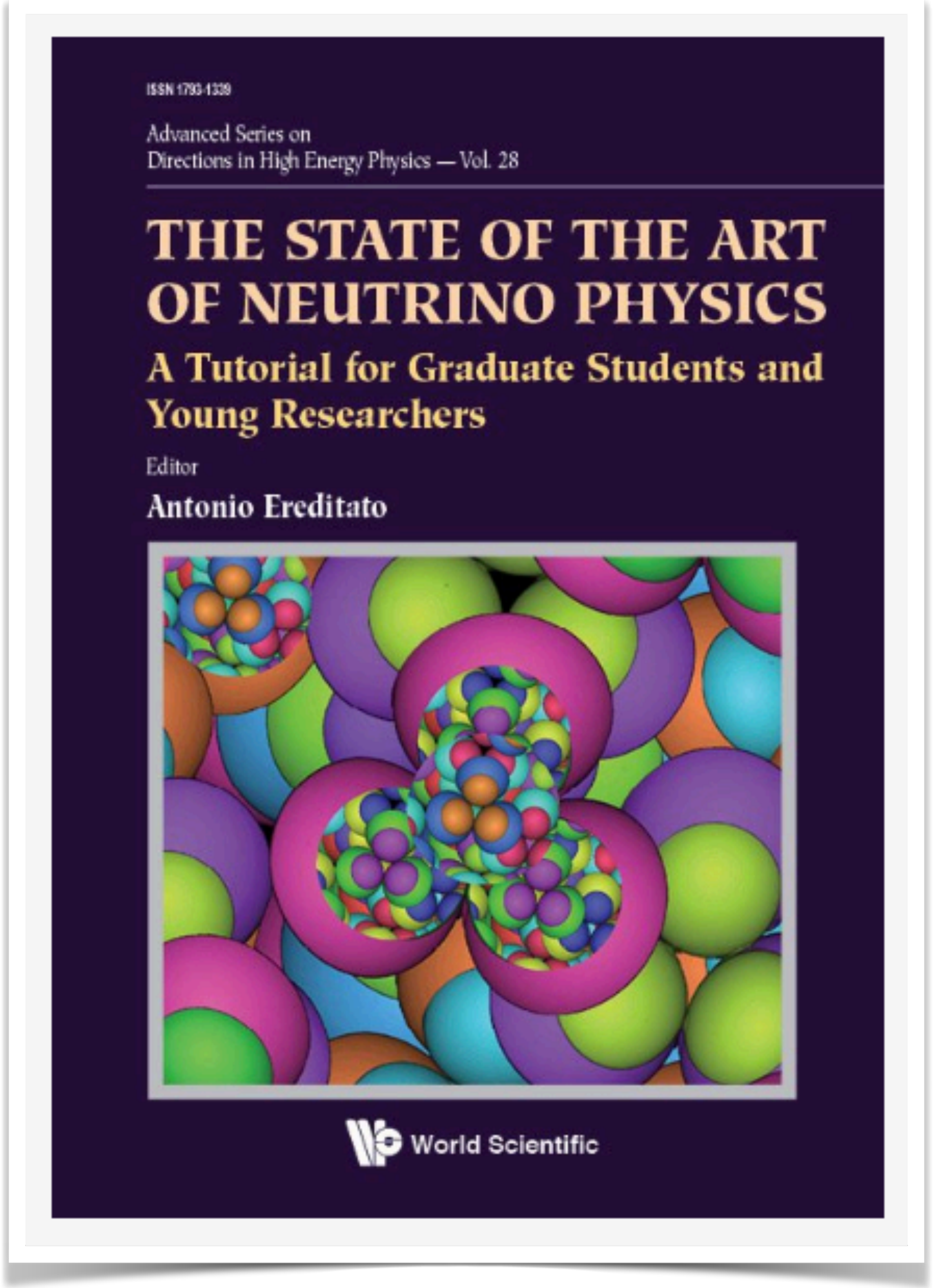

(k): Best estimate, this paper
(j): Combination of (f–i), this paper
(i): Rest of Local Group
(h): Andromeda
(g): Milky Way neutrinos
(f): Milky Way optical
(e): Combination of (a–d)
(d): Neutron star birthrate (Keane & Kramer 2008)
(c): Al–26 (Diehl et al. 2006)
(b): Extragalactic SN rates (Li et al. 2011)
(a): Stellar Birthrate (Reed 2005)
0
2
4
6
8
10
R (100 yr)^-1

references

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

Review | Published: 20 July 2018

Introduction to neutrino astronomy*

A. Gallo Rosso, C. Mascaretti, A. Palladino & F. Vissani

The European Physical Journal Plus **133**, Article number: 267 (2018) | Cite this article

Abstract.

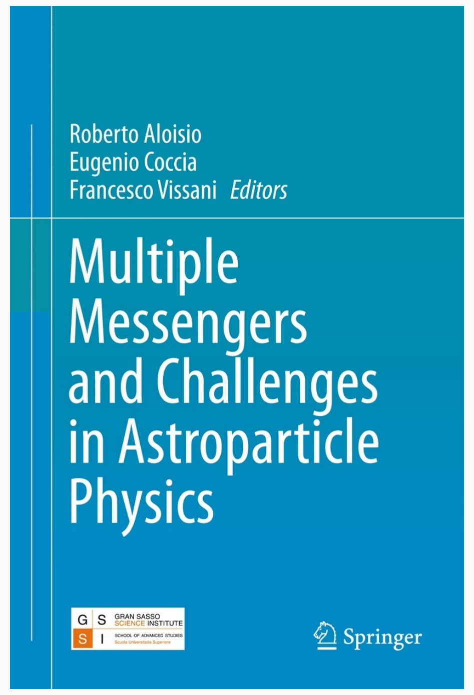
This paper is an introduction to neutrino astronomy, addressed to astronomers and written by astroparticle physicists. While the focus is on achievements and goals of neutrino astronomy, rather than those of particle physics, we will introduce the particle physics concepts needed to appreciate those aspects that depend on the peculiarity of the neutrinos. The material is selected --*i.e.*, not all achievements are reviewed-- and furthermore it is kept to an introductory level, but efforts are made to highlight current research issues.

e-Print: 1806.06339

Neutrino Astronomy

Antonio Capone, Paolo Lipari & Francesco Vissani

Chapter | First Online: 28 February 2018



Abstract

Neutrino astronomy is a lively discipline that has born at the cross road of particle physics, nuclear physics, and astrophysics. Many low-energy neutrino observatories have demonstrated the possibility of investigating the functioning of the Sun, the terrestrial radiactivity and crucial astrophysical phenomena as the gravitational collapse. There are mounting evidences that extraterrestrial high-energy neutrinos are observable. This impacts strongly on our understanding of the high-energy phenomena from the cosmos, and the dataset and the sensitivity continue to improve. In this chapter, the status of the investigations of neutrino radiation is outlined, aiming to provide the reader with a unified description of this discipline that covers its main observational and theoretical aspects. We collect, for a readership at Ph.D. level, the most relevant formulae, expectations, and information concerning neutrino astronomy and astrophysics. Connections with other disciplines and selected applications to particle physics are discussed. Each section begins with an overview of the material included and a brief annotated bibliographical selection to books and review papers, aimed to favor “staged access” into the vast scientific literature.

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)