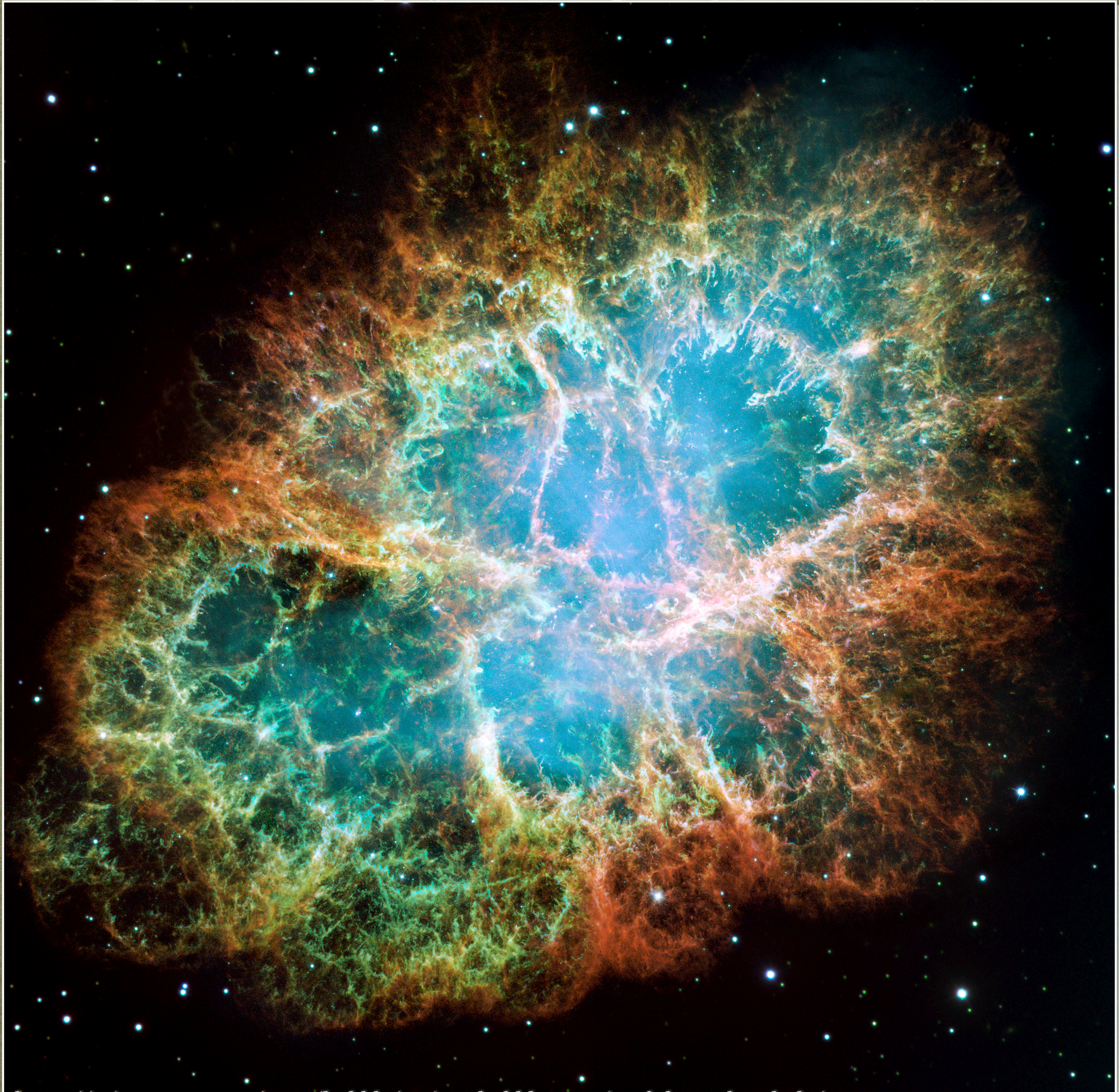

https://science.nasa.gov/asset/hubble/a-giant-hubble-mosaic-of-the-crab-nebula/

NEUTRINO ASTROPHYSICS:
A window to new physics

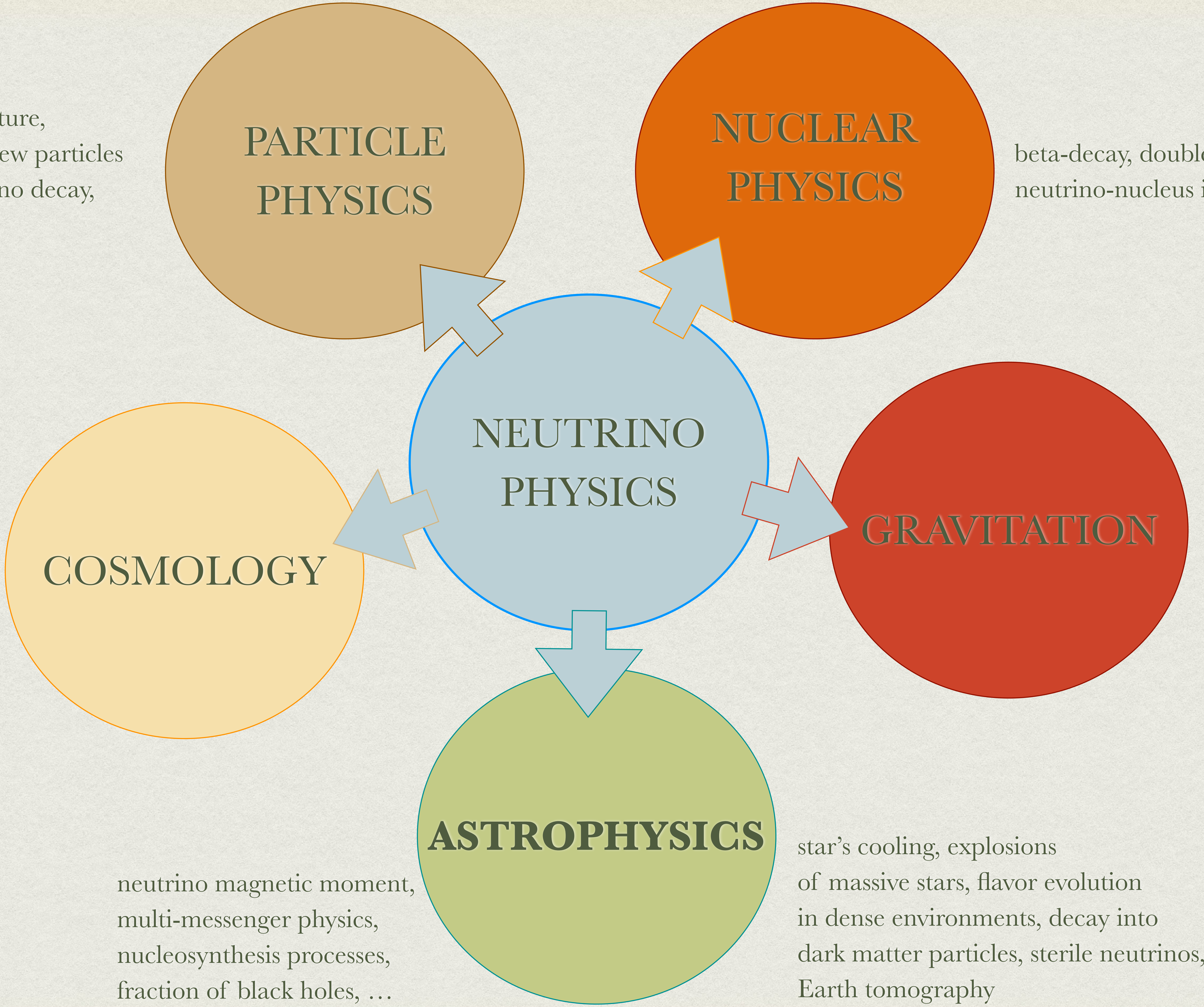
Lecture I

M. Cristina VOLPE

French National Center for Research (CNRS) and Astroparticle and Cosmology (APC) Laboratory,
email: volpe@apc.in2p3.fr

origin of neutrino masse, neutrino nature, beyond the standard model physics, new particles and non-standard interactions, neutrino decay, neutrino magnetic moment…

beta-decay, double-beta decay, neutrino-nucleus interactions,…



neutrinos and primordial nucleosynthesis, neutrino masses, sterile neutrinos, matter-antimatter asymmetry, diffuse cosmological background…

neutrino energy redshift and bending, neutrino decoherence, extended theories of gravity…

neutrino magnetic moment, multi-messenger physics, nucleosynthesis processes, fraction of black holes, …

star's cooling, explosions of massive stars, flavor evolution in dense environments, decay into dark matter particles, sterile neutrinos, Earth tomography

OUTLINE OF THE FIRST LECTURE

General and historical

> The birth of neutrinos
> The solar neutrino problem
> Derivation of the oscillation probabilities

> The discovery of neutrino vacuum oscillations
> The solution of the solar neutrino problem
> The oscillation parameters

> Status and open questions
> Conclusions

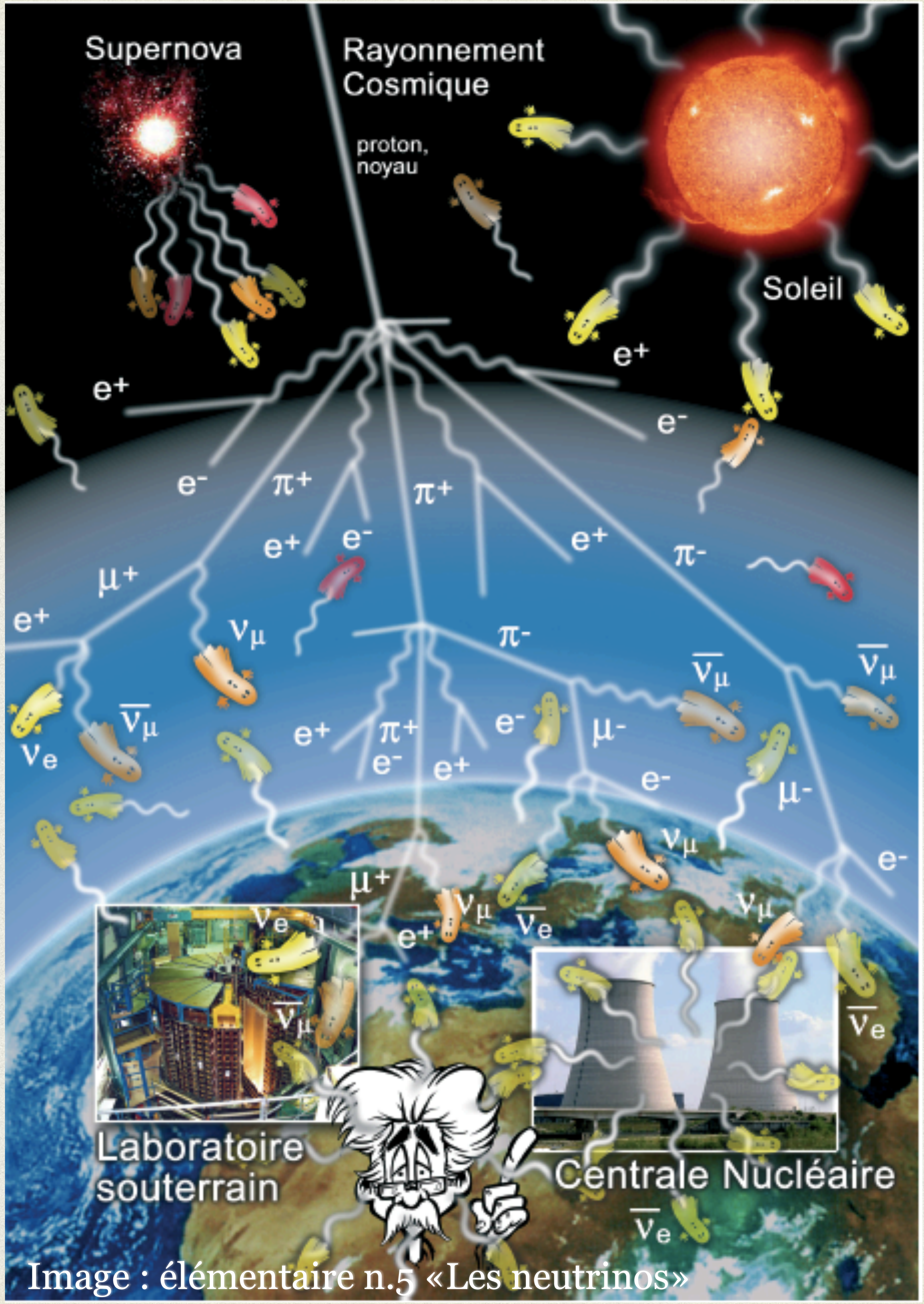


Image : élémentaire n.5 «Les neutrinos»

Neutrinos are everywhere, on the Earth and in the Universe !

NEUTRINO FLUXES on Earth

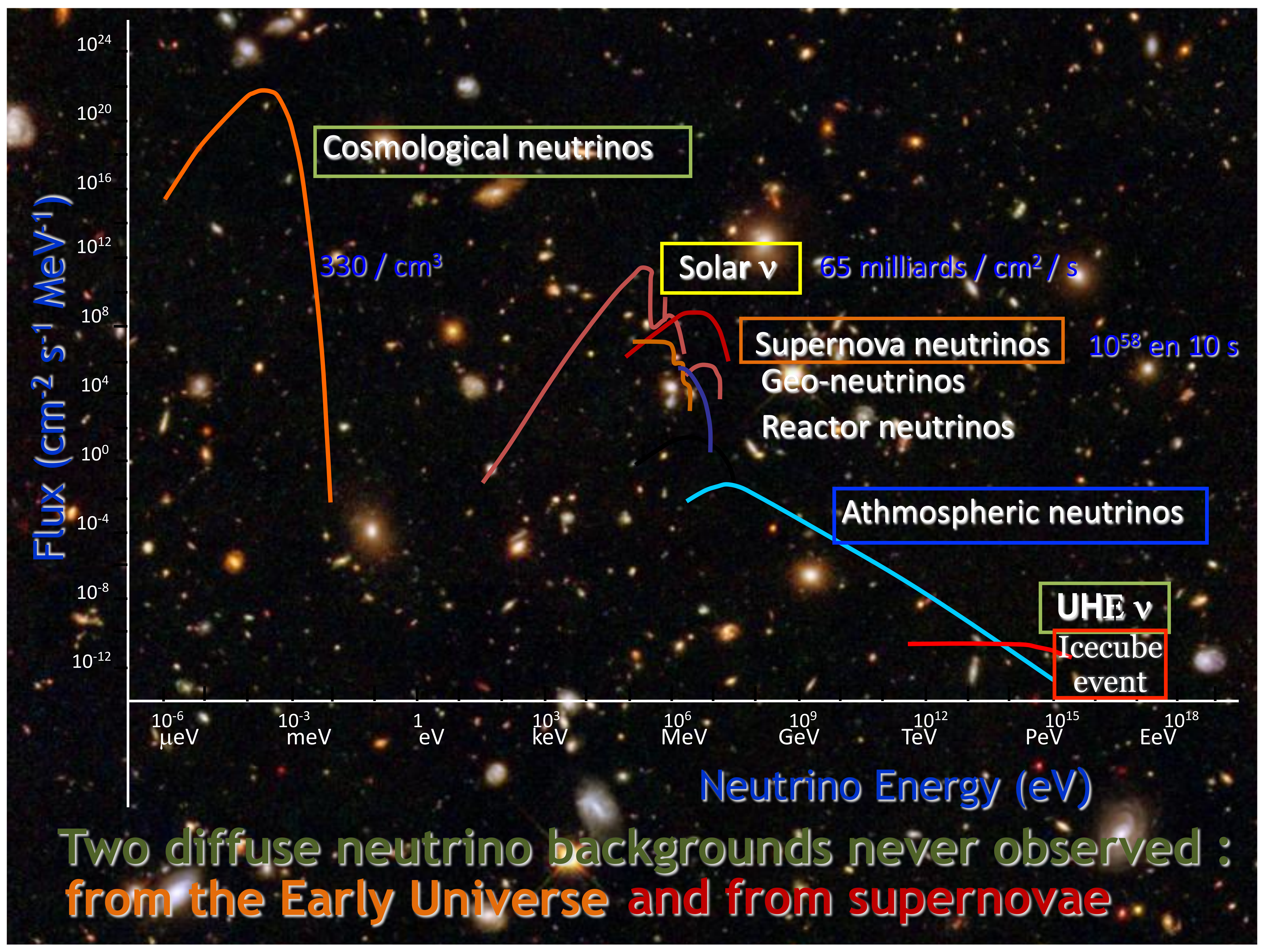
- Variety of natural and man-made sources produce neutrinos of all flavors.

  Fluxes vary over more than 30 orders of magnitudes and go from meV to PeV energies.

- Two diffuse neutrino backgrounds never observed :

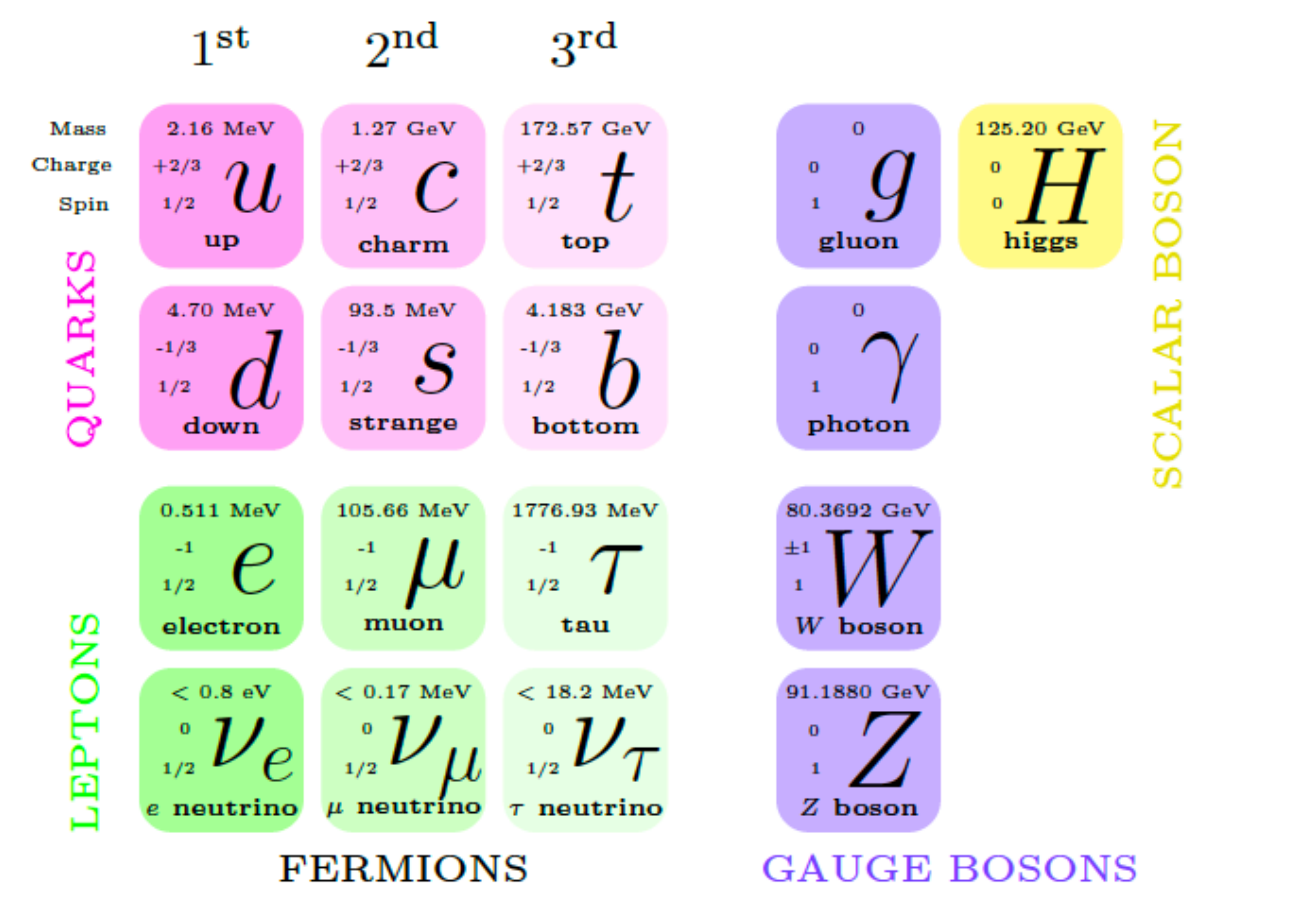
  - cold cosmological one (decoupling at BBN epoch, 1 s after Big-Bang)

  - diffuse supernova neutrino background **(DSNB)** in the tens of MeV energy range



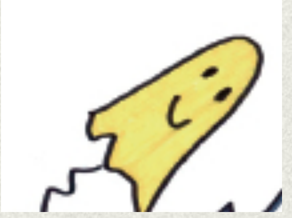
https://science.nasa.gov/mission/hubble/multimedia/hubble-images/

Neutrinos in the Standard Glashow-Weinberg-Salam model
$SU(3) \times SU_L(2) \times U_Y(1)$



THE «NEUTRINO IDENTITY CARD»

- Neutrinos are fermions or spin 1/2.
- In the Standard Model neutrinos are massless. There are no right handed singlets.
- They are neutral particles and only interact weakly. Weak interaction is chiral.



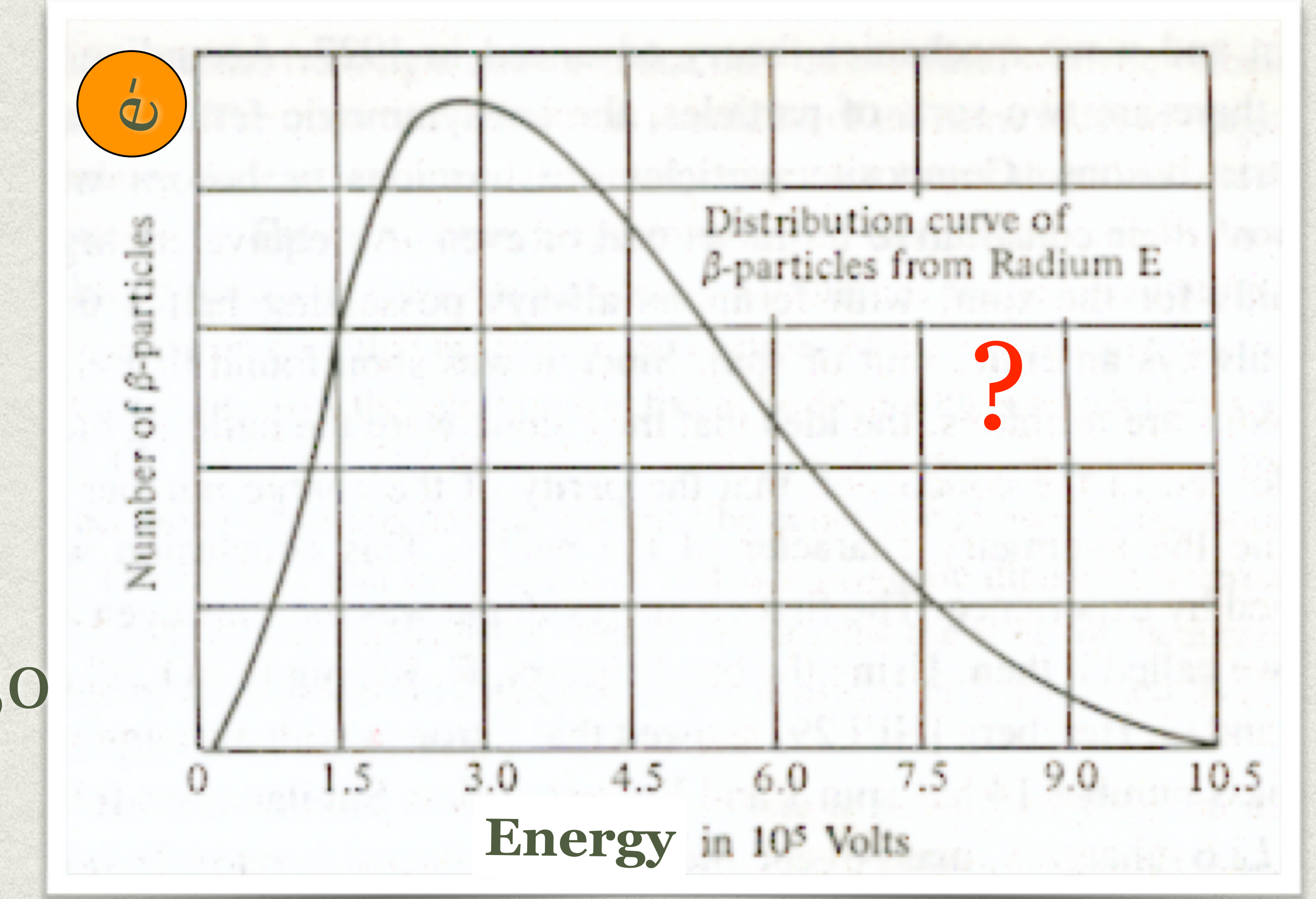
- They are three neutrino families: electron, muon and tau neutrinos (L-lepton doublets).

Ideal messenger from «far away»

Image : https://github.com/mlubej/standard-model/tree/master.

The birth of the neutrino

Wolfgang Pauli, 1930



The problem of the missing energy in nuclear beta-decay

Dear Radioactive Ladies and Gentlemen,

[…] *I have hit upon an undreamed-of remedy* to save the law of energy conservation and the statistics. *It is the possibility that there could exist in nuclei, electrically neutral particles, that I wish to call neutrons, which have spin 1/2* and obey the exclusion principle […]. *The mass of the neutrons should be of the same order of magnitude as the electron mass* and not be larger than 0.01 times the proton mass. The continuous beta spectrum would then become understandable by the assumption that *in beta-decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant…*

… But *only the one who dare can win* and the difficult situation, due to the continuous structure of the beta spectrum, is clarified by a remark of my honoured predecessor, Mr Debye […] : "Oh, It's well better not to think to this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December.

Your humble servant, W Pauli

Letter sent to Lise Meitner, and participants of the Tübingen conference.

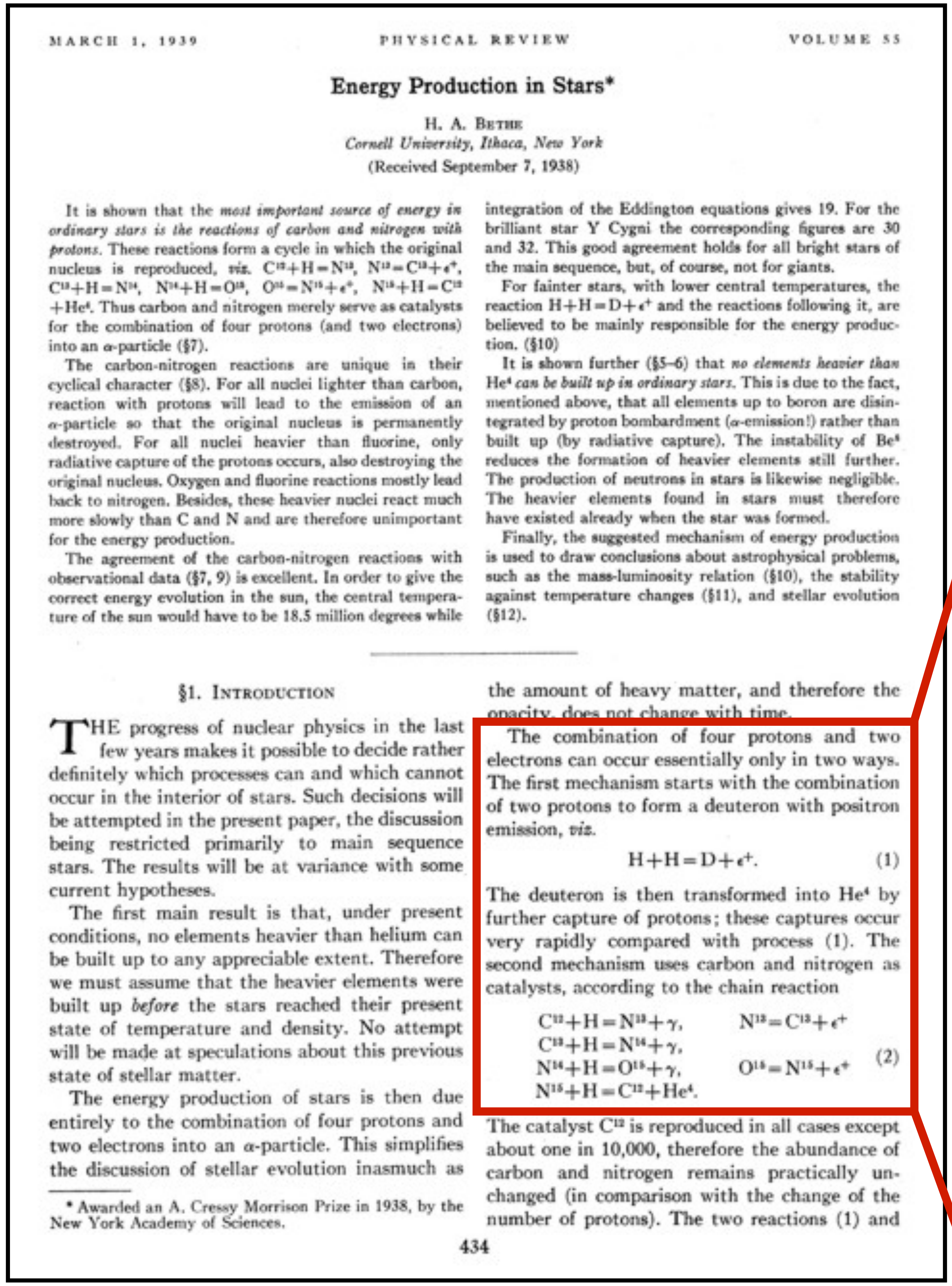
Enrico Fermi

Fermi called it *«neutrino»* after the neutron was discovered in 1932.

Energy production in stars

Hans Bethe

Nobel Prize in Physics 1967
« for his contributions to the theory of nuclear reactions, especially his discoveries concerning the energy production in stars"



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York
(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^{+}$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^{+}$, $N^{15}+H=C^{12}+He^{4}$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^{+}$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than He^4 can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. Introduction

THE progress of nuclear physics in the last few years makes it possible to decide rather definitely which processes can and which cannot occur in the interior of stars. Such decisions will be attempted in the present paper, the discussion being restricted primarily to main sequence stars. The results will be at variance with some current hypotheses.

The first main result is that, under present conditions, no elements heavier than helium can be built up to any appreciable extent. Therefore we must assume that the heavier elements were built up *before* the stars reached their present state of temperature and density. No attempt will be made at speculations about this previous state of stellar matter.

The energy production of stars is then due entirely to the combination of four protons and two electrons into an α-particle. This simplifies the discussion of stellar evolution inasmuch as the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^{+}. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{array}{ll} C^{12}+H=N^{13}+\gamma, & N^{13}=C^{13}+\epsilon^{+} \\ C^{13}+H=N^{14}+\gamma, & \\ N^{14}+H=O^{15}+\gamma, & O^{15}=N^{15}+\epsilon^{+} \\ N^{15}+H=C^{12}+He^{4}. & \end{array} \quad (2)$$

The catalyst C^{12} is reproduced in all cases except about one in 10,000, therefore the abundance of carbon and nitrogen remains practically unchanged (in comparison with the change of the number of protons). The two reactions (1) and

* Awarded an A. Cressy Morrison Prize in 1938, by the New York Academy of Sciences.

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In 1939, H. Bethe predicts that nuclear reactions, in particular coming from he CNO cycle, are responsible for energy production in main sequence stars.

no neutrinos...

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The discovery of the neutrino

Frederick Reines and Clyde Cowan, 1953
(control room of the Hanford nuclear reactor),
repeated at Savannah River, 1956

Nobel Prize in 1995 :
F. Reines (1/2) « for the detection of the neutrino », 1/2 for H. Perl « for the discovery of the tau lepton »

THE EXPERIMENT

antineutrino

antineutrino

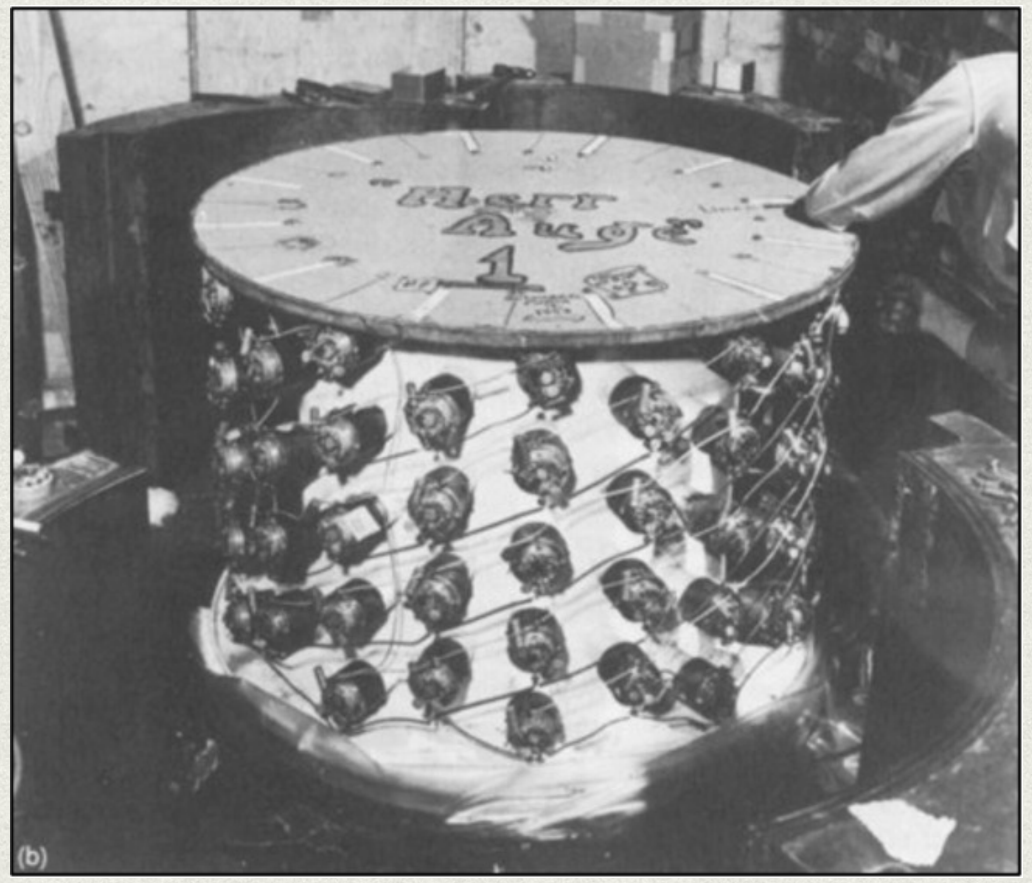
antineutrino

Nuclear reactors are the most powerful man-made (anti)neutrino sources on Earth.

THE SOURCE

Only electron antineutrinos are produced.
Few MeV energies.

$$\phi_{\bar{\nu}_e} = 10^{13} \ \frac{\bar{\nu}_e}{s \ cm^2}$$



THE DETECTOR

Two tanks of 200 liters of water.

THE SIGNAL

$$\bar{\nu}_e + p \rightarrow n + e^+$$

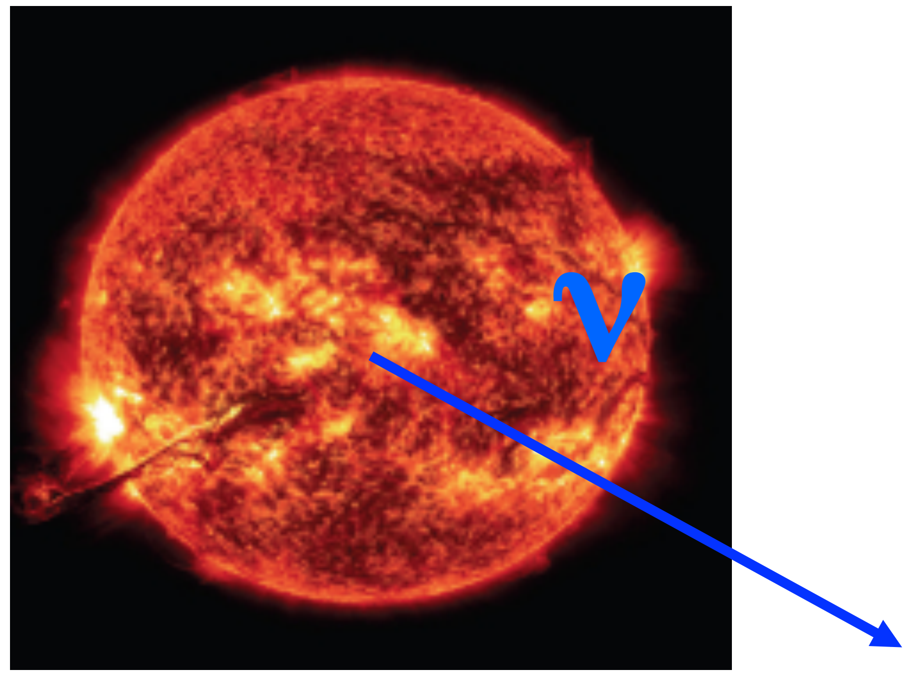
Double coincidence

1-3 events/hour

$$n + Cd \rightarrow Cd' + \gamma$$

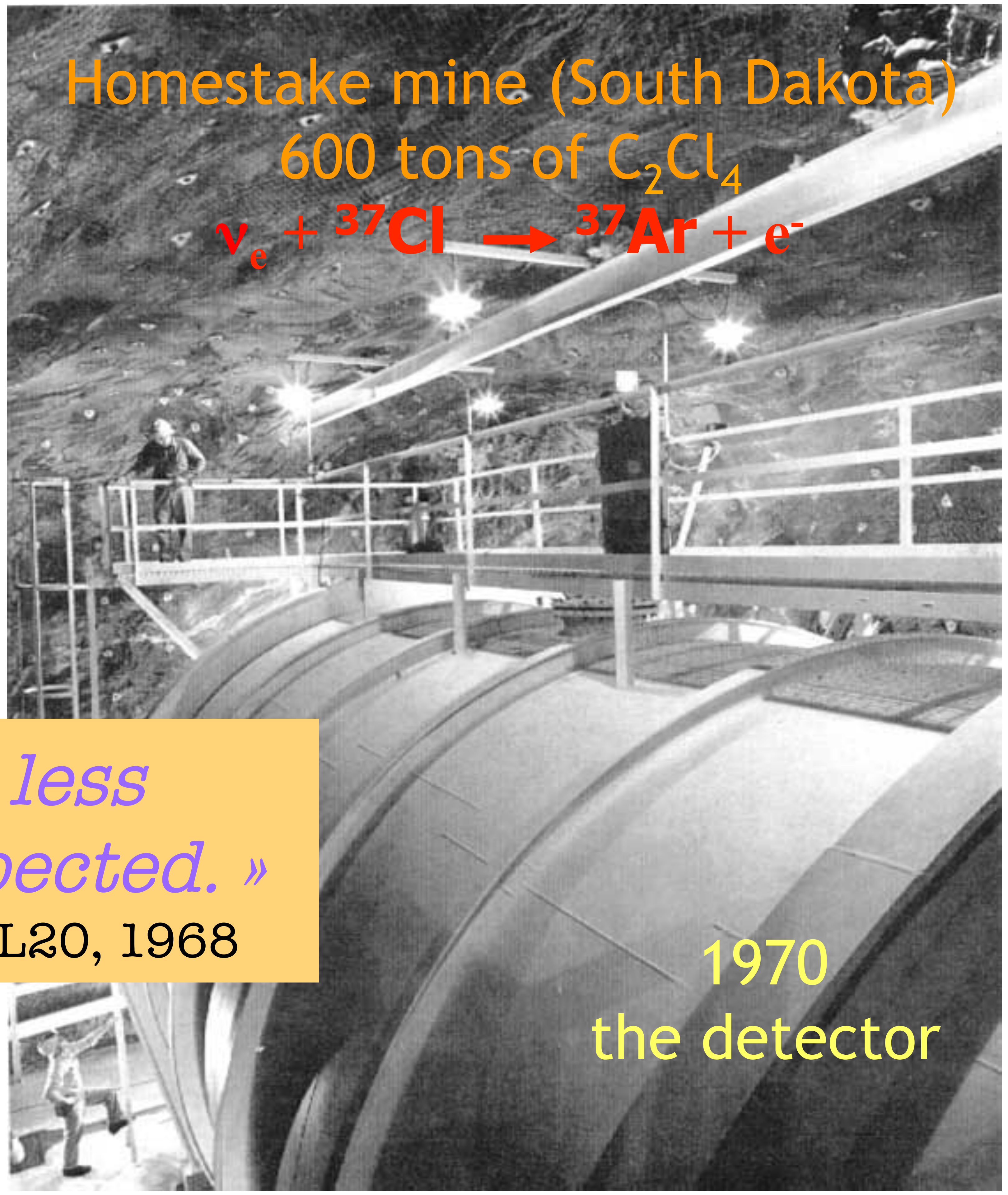
$$e^- + e^+ \rightarrow 2\gamma$$

First observation of solar neutrinos



(metals)

Composition : 73% H, 25% He, 2% other
Central temperature : 15 10^6 degrees K



« We observe much less neutrinos than expected. »
Davis, Harmer, Hoffman, PRL20, 1968

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York

(Received 6 January 1964)

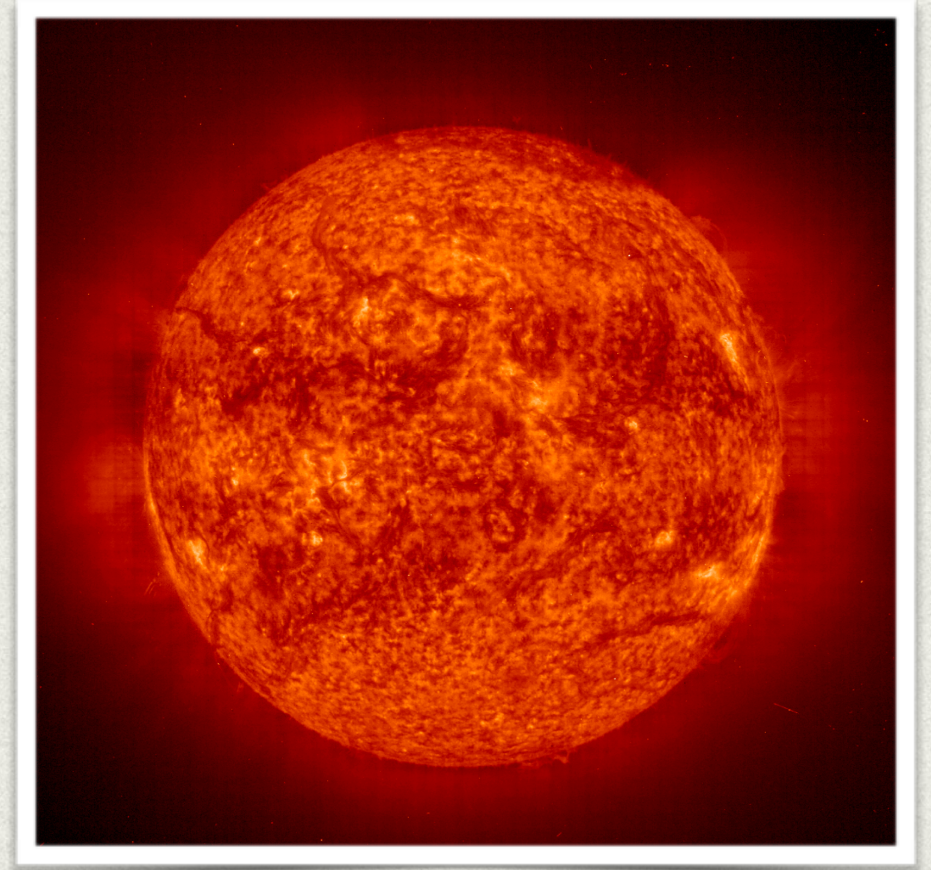
The prospect of observing solar neutrinos by means of the inverse beta process $^{37}Cl(\nu, e^-)^{37}Ar$ induced us to place the apparatus previously de-

3 counts in 18 days is probably entirely due to the background activity. However, if one assumes that this rate corresponds to real events and uses

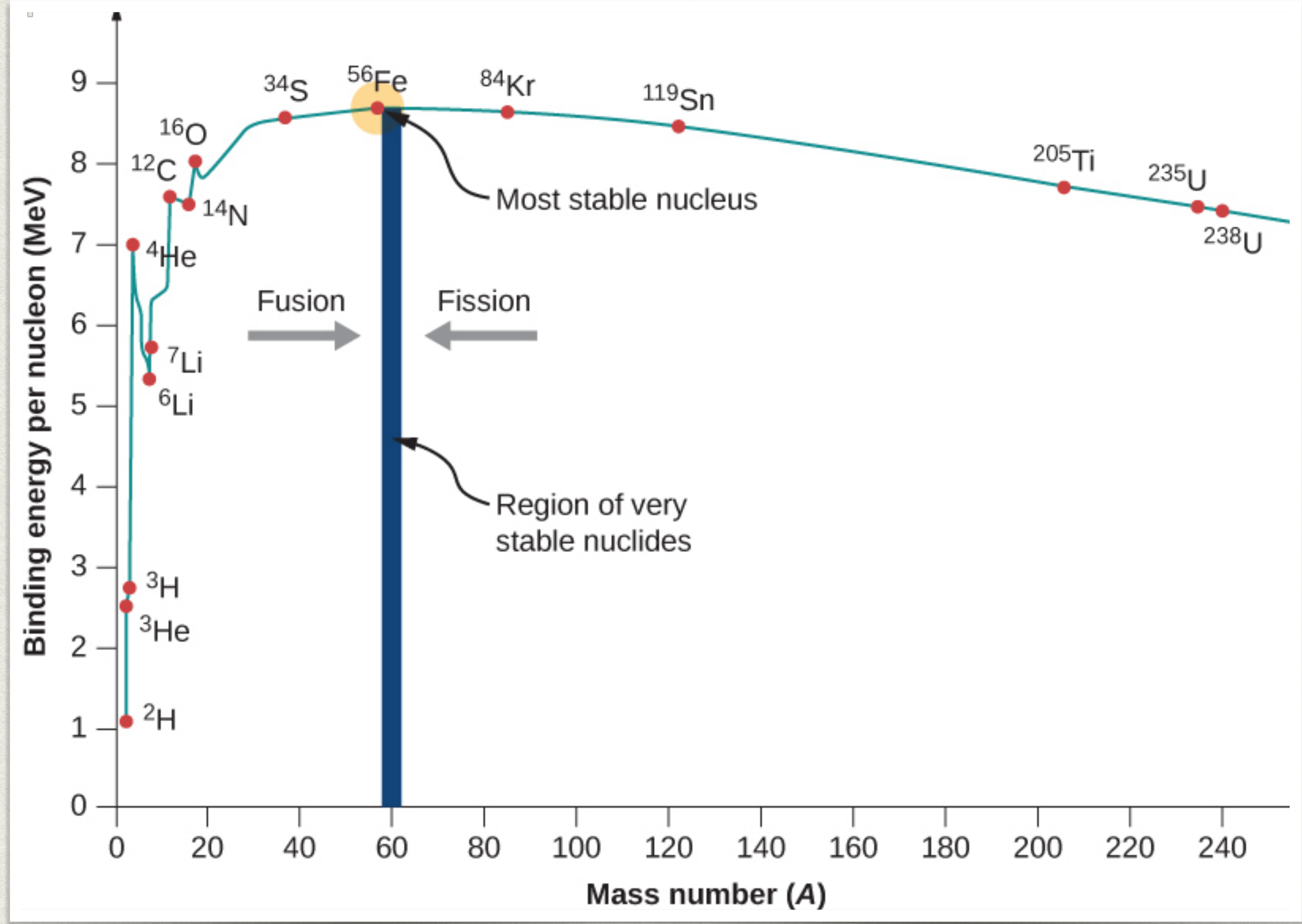
2002 Nobel Prize

A reminder: The nuclear binding energy

A=56 region,
most stable nuclei



Nuclear energy released
by **fusion** reactions - Ex. Stars



Nuclear energy released
by **fission** - ex. Nuclear Reactors

$$M(Z,N) = ZM_H + NM_n - B(Z,N)$$

$m_n = 939.565\ MeV$

$m_p = 938.296\ MeV$

Reference:

Neutrinos from the pp reaction chain

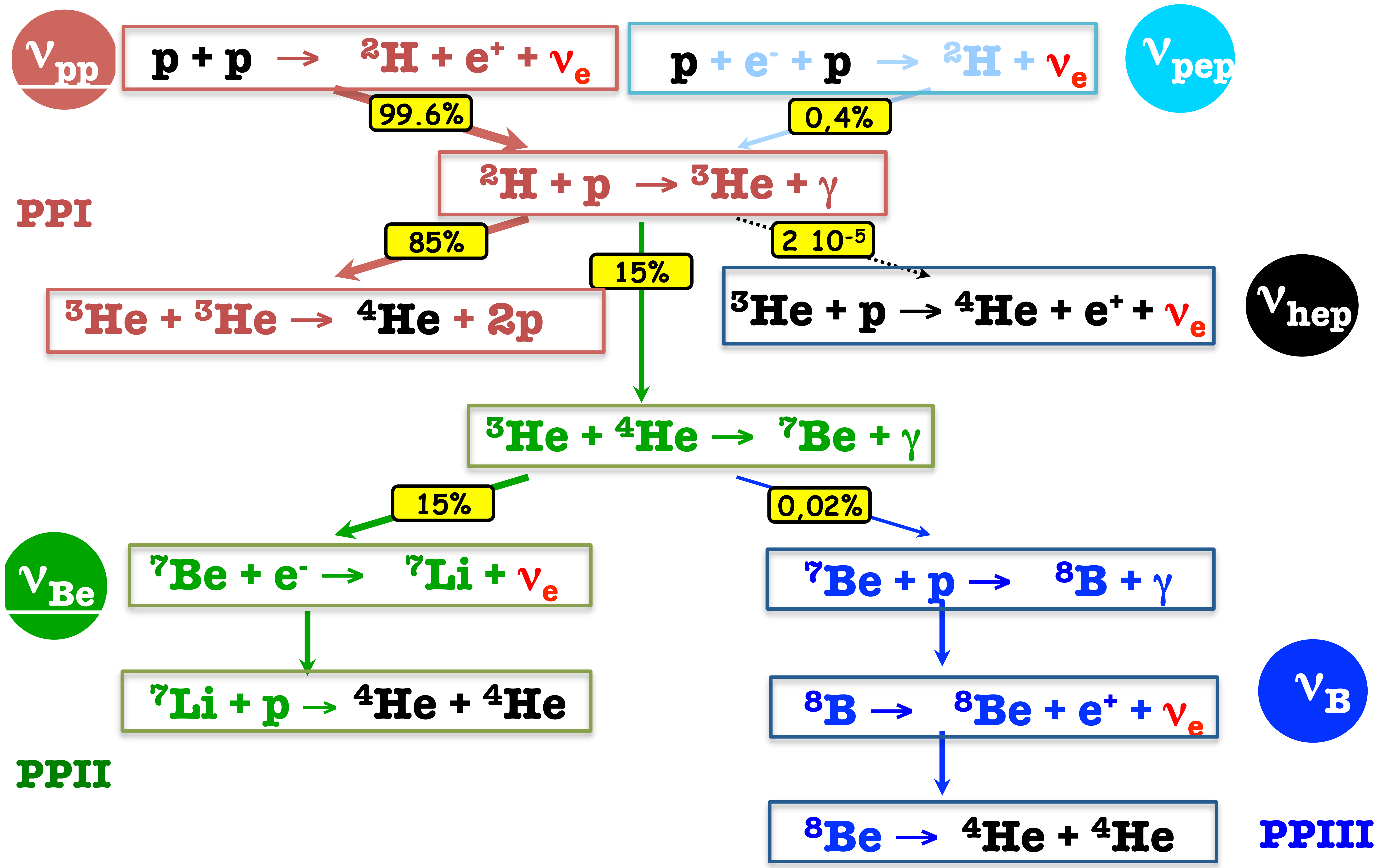
The proton-proton (pp) fusion reaction chain produces 99% of solar energy transforming H into ^4He.

pp I -
83 % energy produced

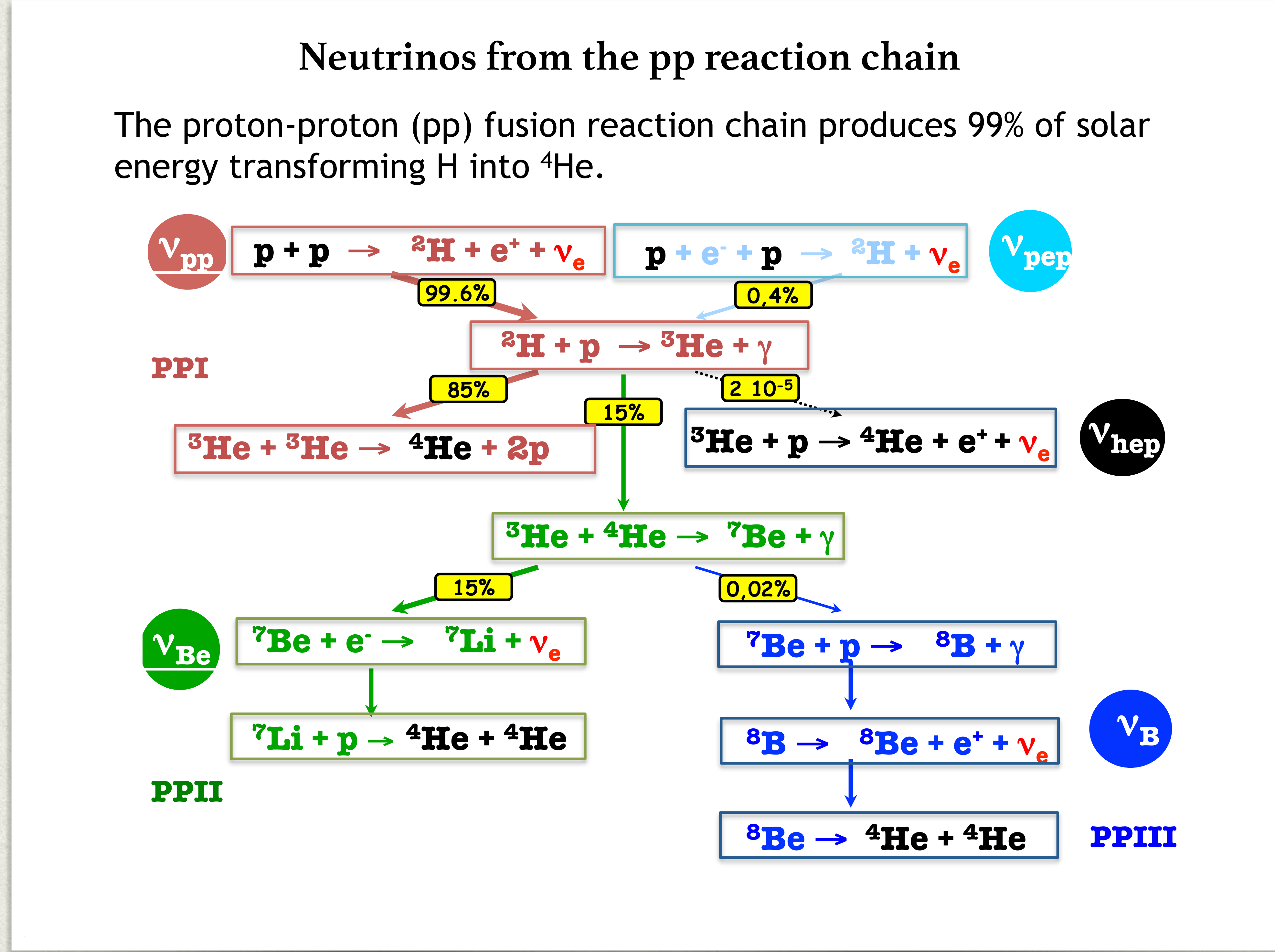
pp II-
16 % energy produced

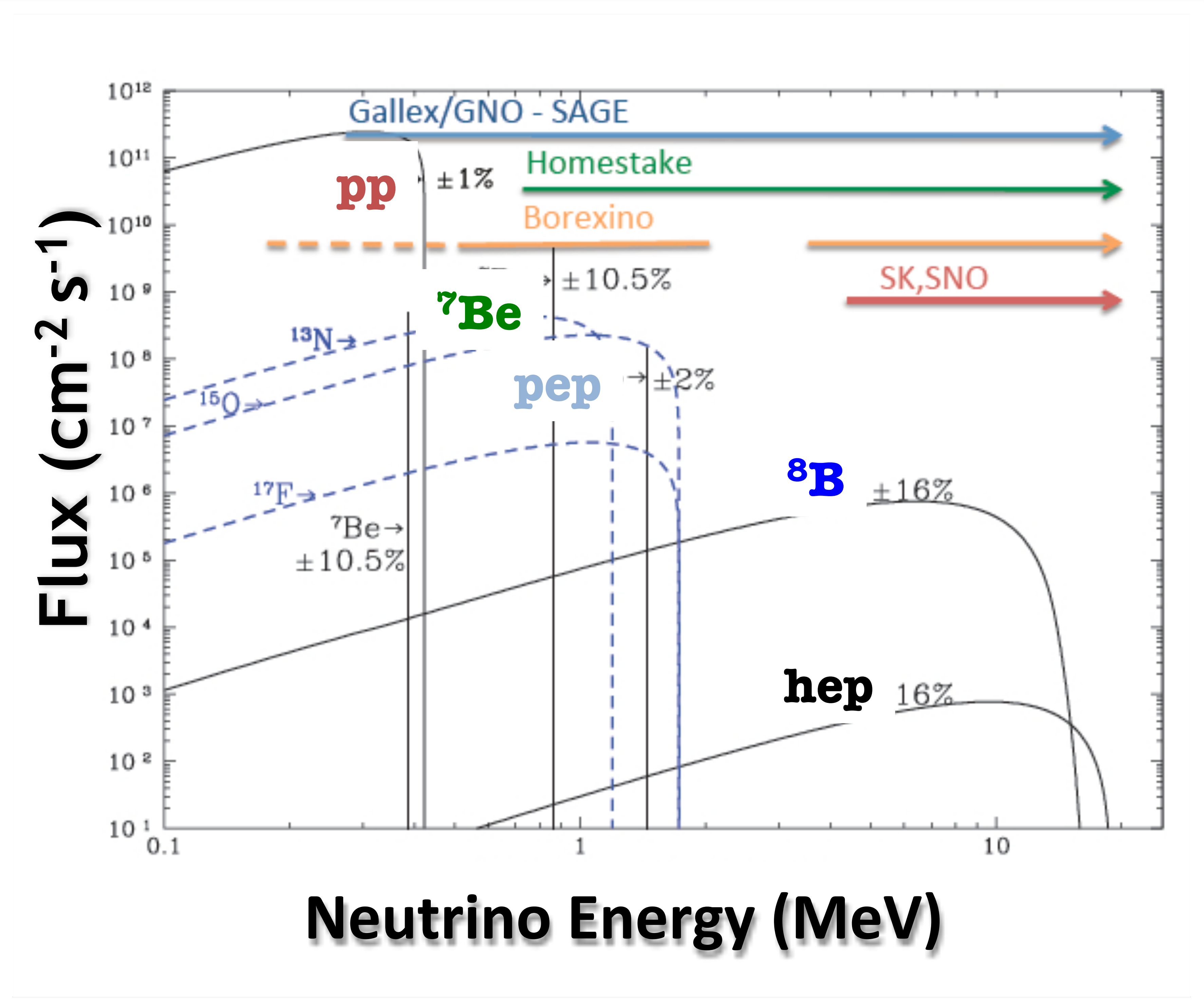
pp IV-
most energetic neutrinos

pp III-
high energy



The solar neutrino fluxes





SOLAR NEUTRINOS

pp - most abundant

pp, **^{7}Be**, **pep** - less than 2 MeV energy

^{8}B - more than 2 MeV energy

hep - not observed so far

SOLAR EXPERIMENTS

Homestake - 600 tons Chlorine (radiochemical)

Kamiokande - water Cherenkov, 240 tons

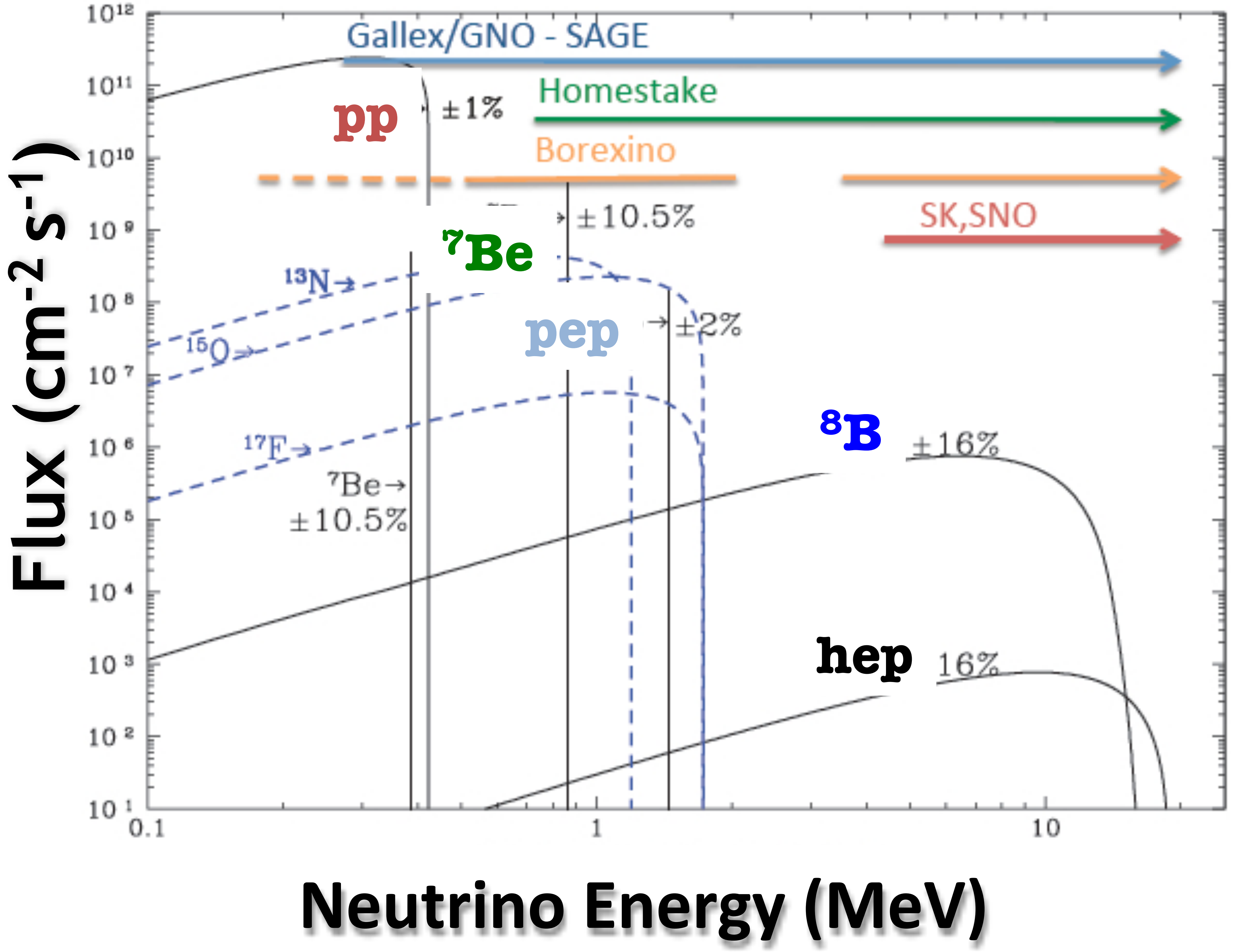
Gallex- 30 tons; **GNO** - up to a 100 tons; **SAGE** - 57 tons of ^{71}Ga

Super-Kamiokande - water Cherenkov, 50 ktons

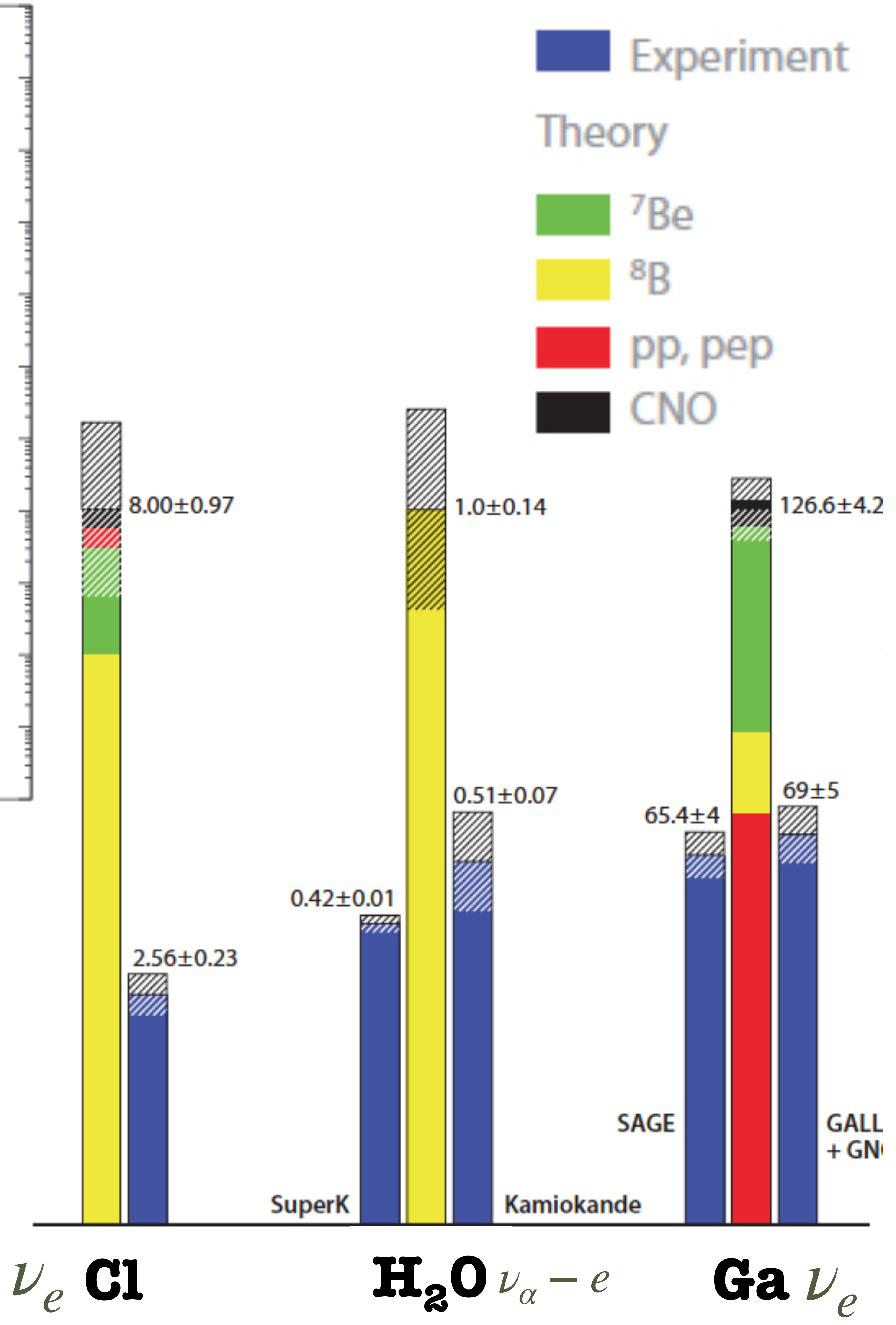
SNO - heavy water (D_2O) Cherenkov, 1 ton

Borexino - liquid scintillator (most recent)

Solar neutrino fluxes and their measurement



SNU=solar neutrino unit (10^{-36} capture/s/atom)



THE SOLAR NEUTRINO PROBLEM is born

Observed deficit energy dependent.

Reference:

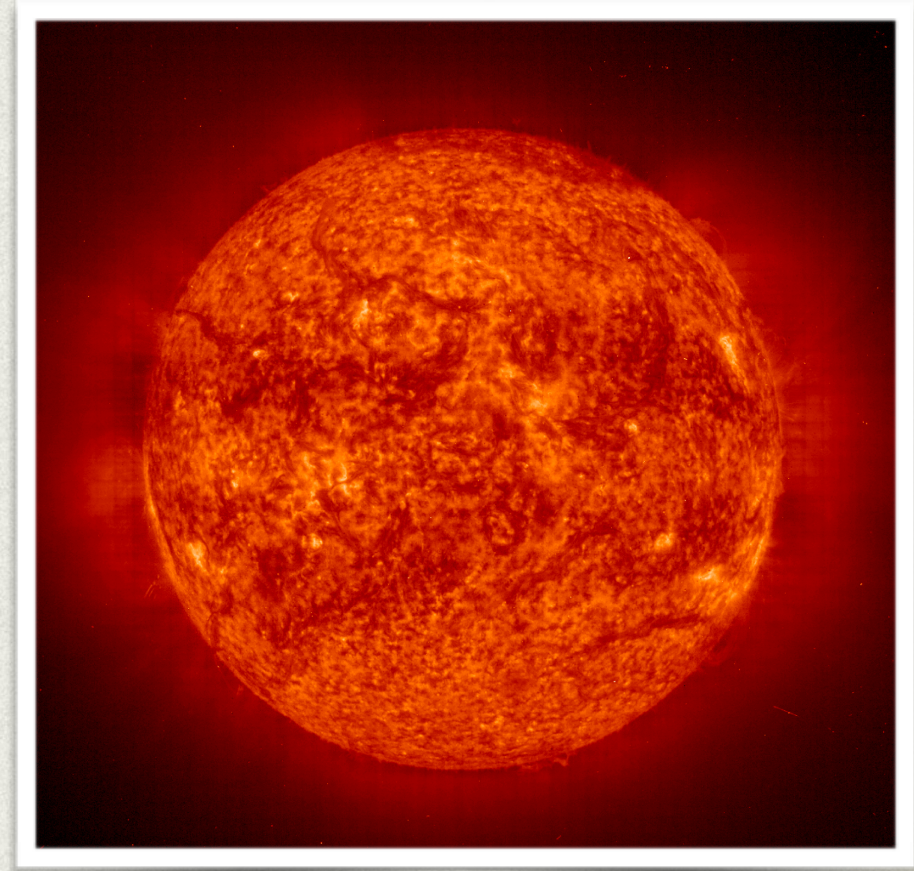
Searching for the solution of the solar neutrino problem

- Two directions were explored:

> the deficit comes uncertainties in the Standard Solar Model

→ **Helioseismology brought an important clue that the Standard Solar Model was right. (surface oscillations, Doppler shifts of the photospheric absorption lines)**

?

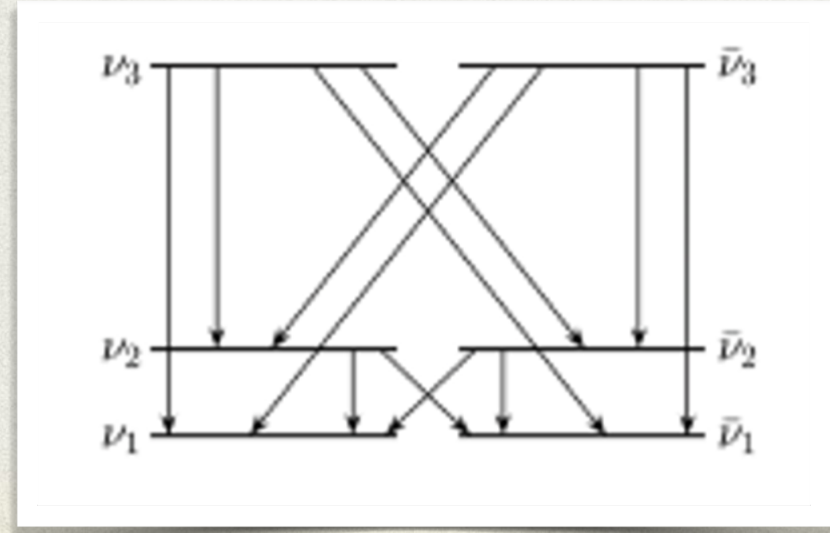


> the deficit is due to unknown neutrino properties:

neutrino decay, the neutrino magnetic moment, neutrino oscillations…

→ **Solar neutrinos were extensively studies - energy dependence, day/night asymmetry, seasonal effects, combined fits, … as well as unknown neutrino properties**

$$\nu_i \rightarrow \nu_j + \phi$$

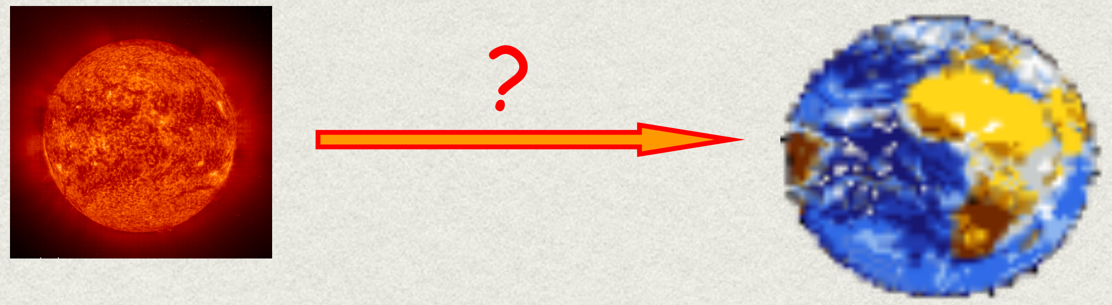


?

Knowledge of the Sun and unknown neutrino properties were questioned for more than 30 years…

The conjecture of neutrino oscillations

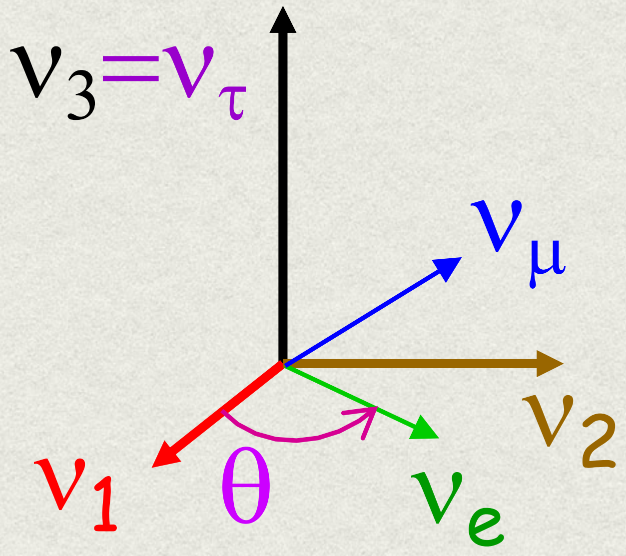
Bruno Pontecorvo



- Pontecorvo (1957) suggested that neutrinos could transform into antineutrinos. Gribov and Pontecorvo (1969) then suggested that neutrinos could change flavor while travelling in analogy with $K_0 - \bar{K}_0$ mesons.

- If one has a source like our Sun, only producing electron neutrinos via the proton-proton reaction chain that burns H to produce ^{4}He, then one can have the appearance of a new neutrino flavor (mu, tau) with a characteristic oscillatory behaviour — <u>vacuum oscillations</u>.

- Vacuum oscillations occur if the mass (propagation) basis and the flavor (interaction) basis do not coincide. They are related by a unitary matrix, in two flavors a rotation matrix.



mixing angle

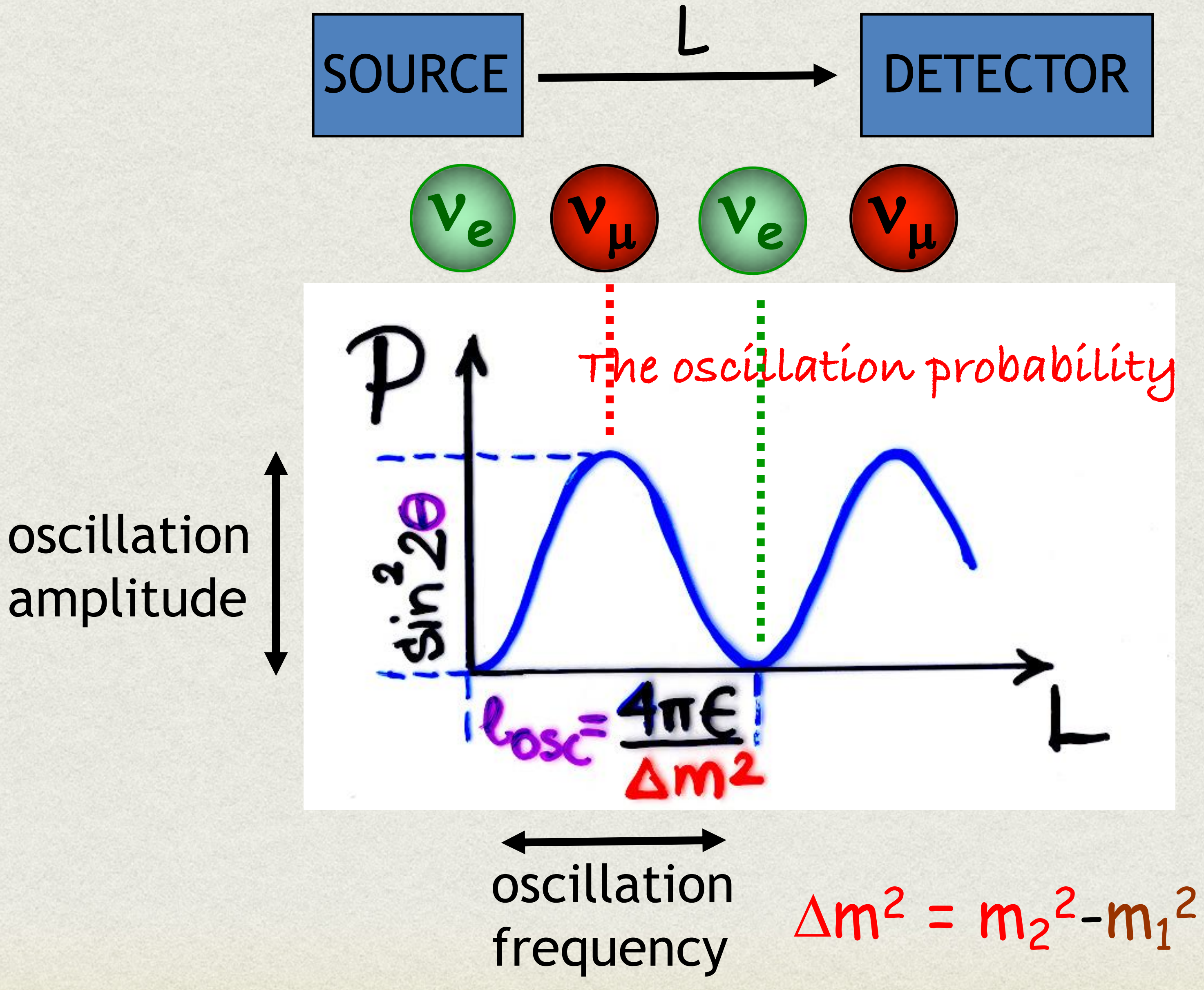
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad \Delta m^2 = m_2^2 - m_1^2$$

flavour basis — mass basis

→

$$P(\nu_e \rightarrow \nu_\mu) = \sin^2 2\theta \, \sin^2\left(\frac{L}{4E}\Delta m^2\right)$$

probability for neutrino oscillations

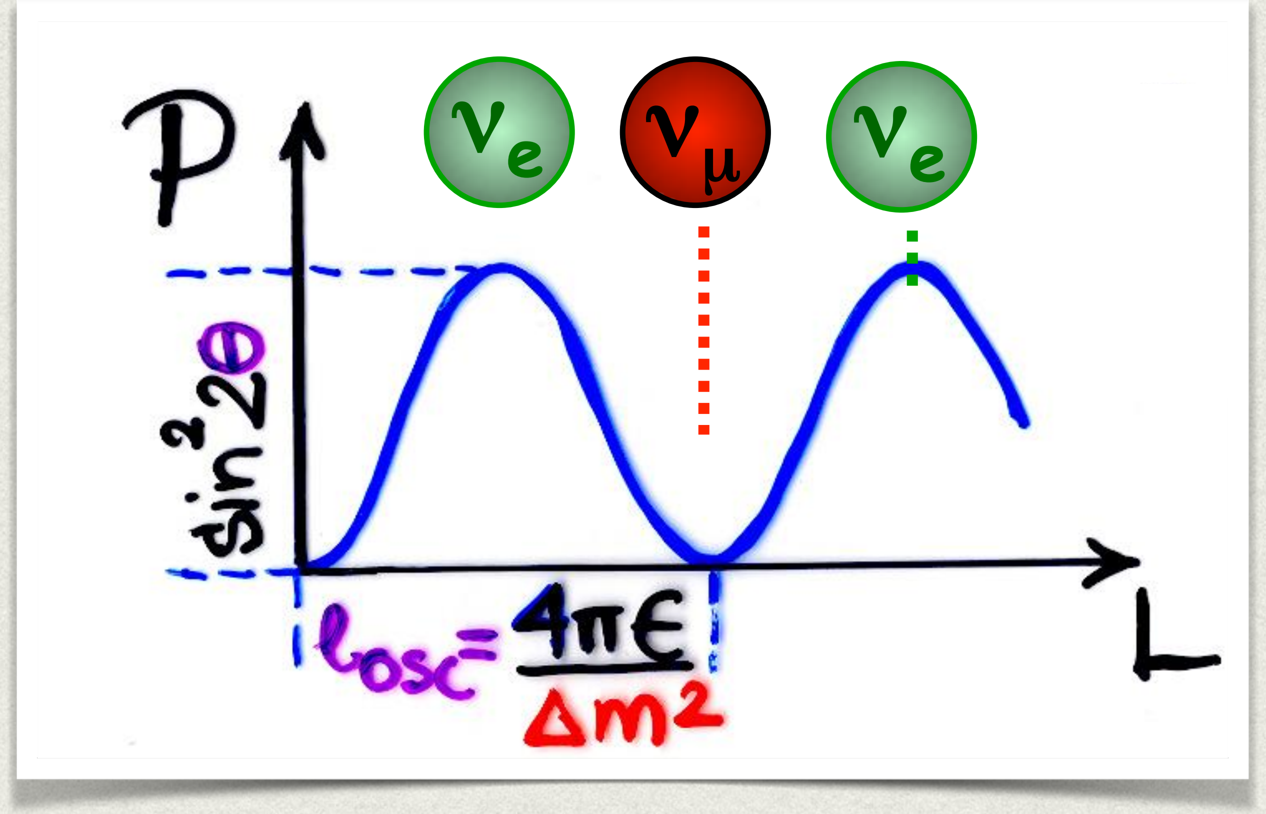


Derivation of the oscillation probabilities

☆ **How do neutrinos change flavor in vacuum?**

How many parameters determine neutrino oscillations in the case of 3 active flavors or more?

How can one search for neutrino oscillations ?



1) The vacuum oscillation formula for two flavors is a special case.

2) Typical neutrino squared-mass differences for the different sources :
Sun, atmosphere, reactors (L = 200 km),
accelerators for short-distance experiments E = 30 MeV, L = 30 m,
accelerators for long-distance experiments E = 500 MeV, L = 700 km

3) Vacuum oscillation probabilities for anti-neutrinos.

$$|\bar{\nu}_\alpha\rangle = U_{\alpha i} |\bar{\nu}_i\rangle \quad i = 1,N$$

4) Determine which term is responsible for CP violation in the neutrino sector.

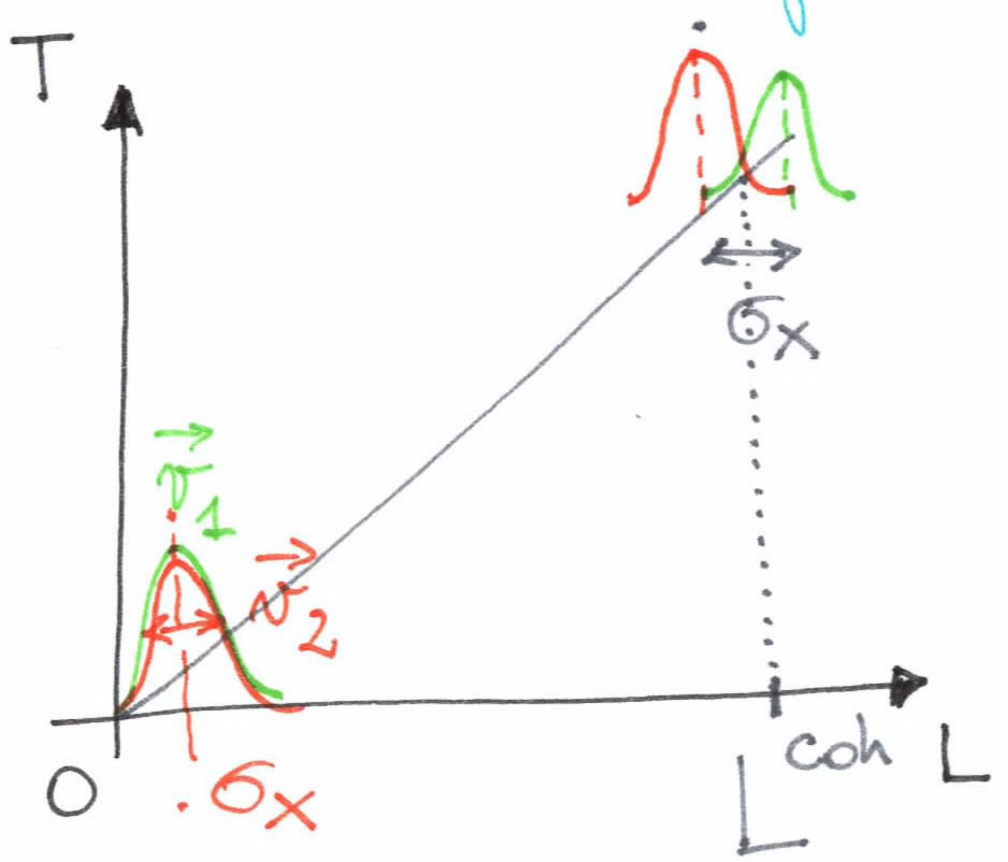
?

VACUUM OSCILLATIONS

The coherence length

Damping suppression due to wave-packet decoherence

- If one takes Gaussian wave-packets the formula gets a correction as follows.



- We define, in general, a coherence length L^{coh} such that when $L \geq L^{coh}$ the wave-packets do not interfere any more

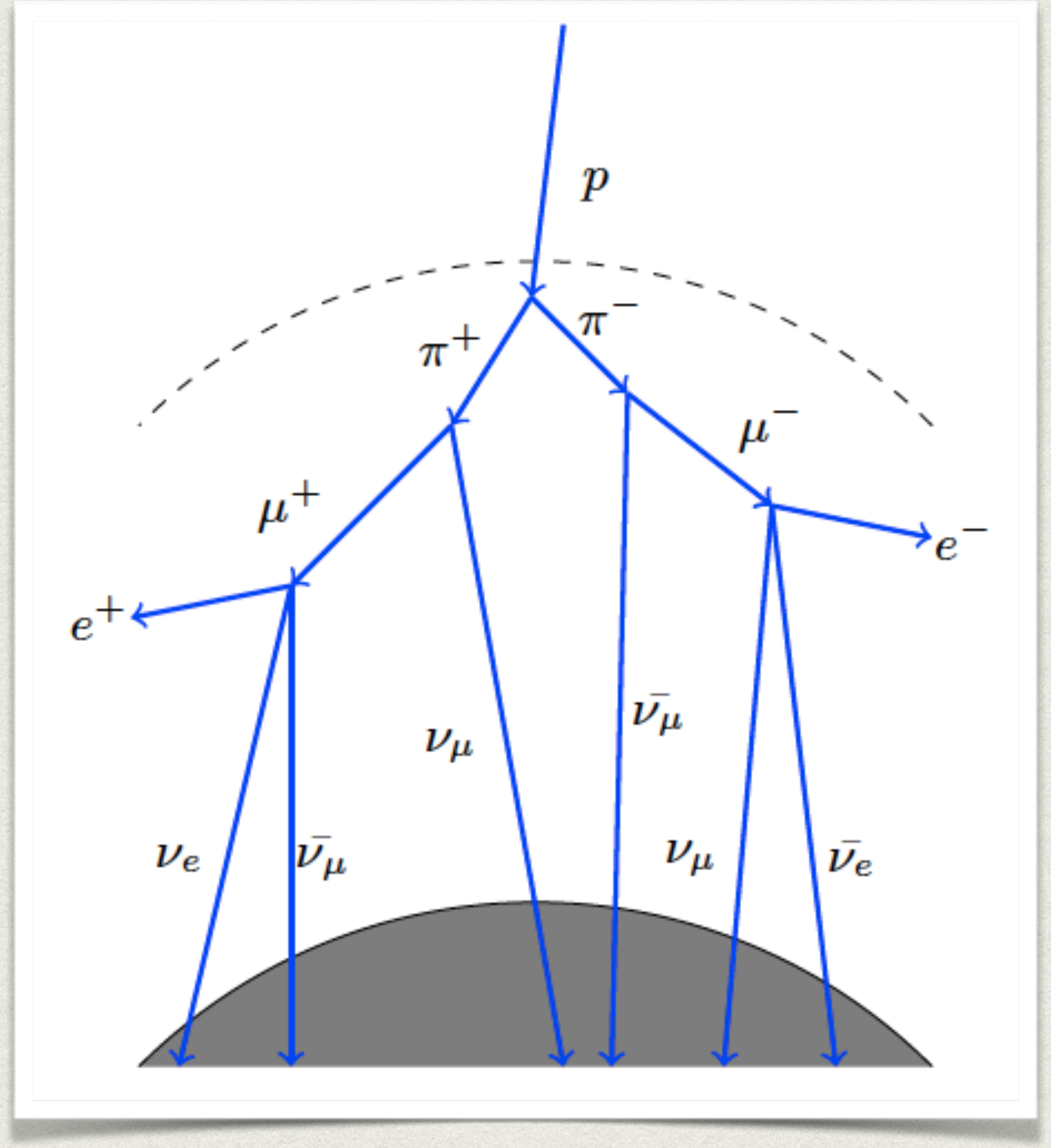
- For Gaussian wave-packets, the correction to the oscillation phase:

$$\underbrace{\Delta\Phi_{WP} = -\left(L/L^{coh}\right)^2}_{\text{WAVE-PACKET CORRECTION}} \quad \text{with} \quad \underbrace{L^{coh} = \frac{4\sqrt{2}\,\epsilon^2}{|\Delta m^2_{KJ}|}\sigma_x}_{\text{COHERENCE LENGTH}}$$

- Neutrino oscillations get exponentially suppressed by WP decoherence. If $L < L^{coh}$, we get the standard formula.

example. If $\sigma_x \sim 4\times10^{-12} - 10^{-11}$ cm, $\epsilon \in [11, 20]$ MeV, $L^{coh} \in [11, 83]$ km.

Atmospheric neutrinos



- **Atmospheric neutrinos** produced by the interaction of cosmic rays (mainly protons) with the Earth atmosphere

- **Main production mechanisms:**

$$p + X \rightarrow Y + \pi$$
$$\pi \rightarrow \mu + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$
$$\dots$$

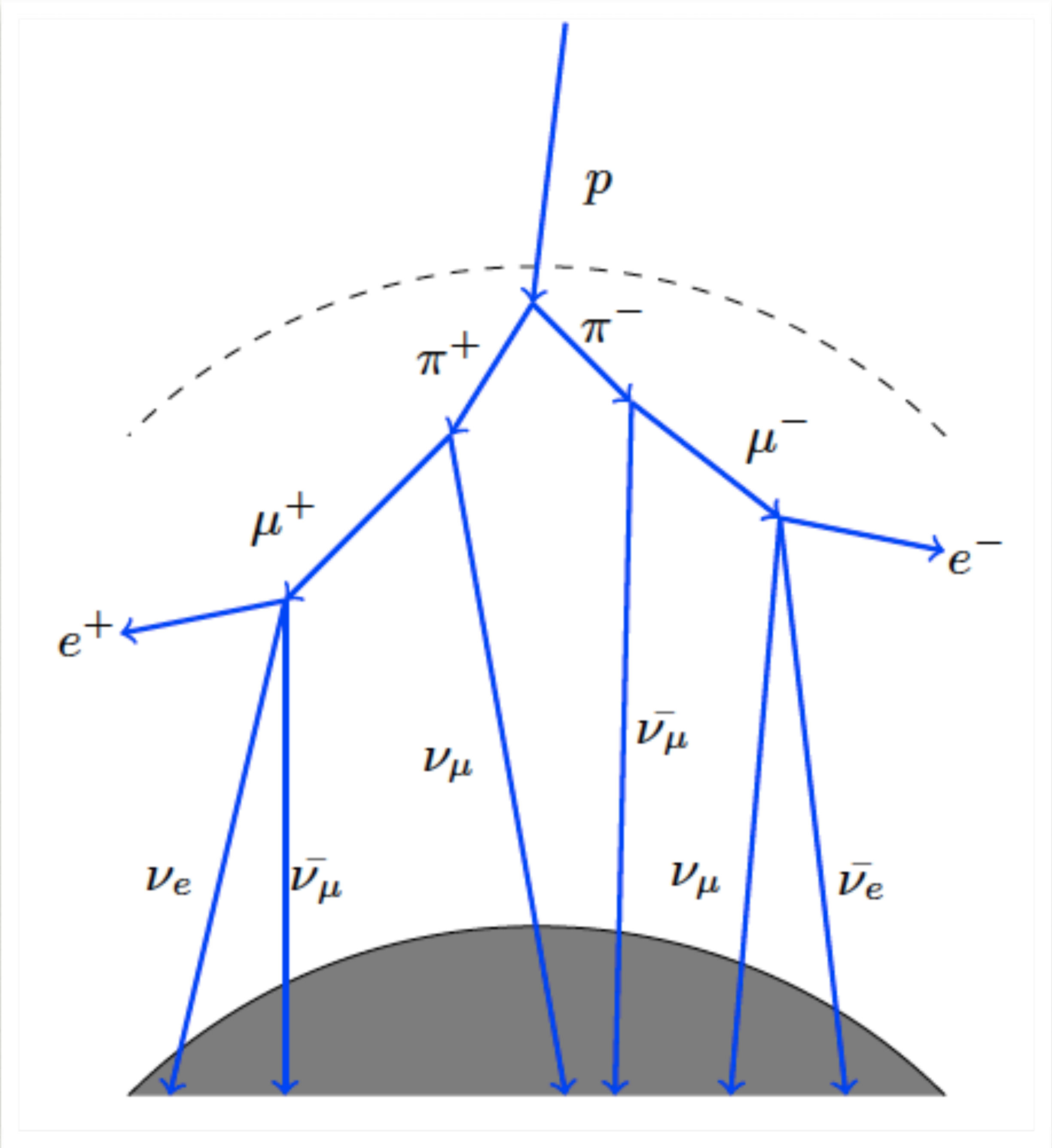
$m_\pi = 106\ MeV$
$m_\pi = 135\ MeV$

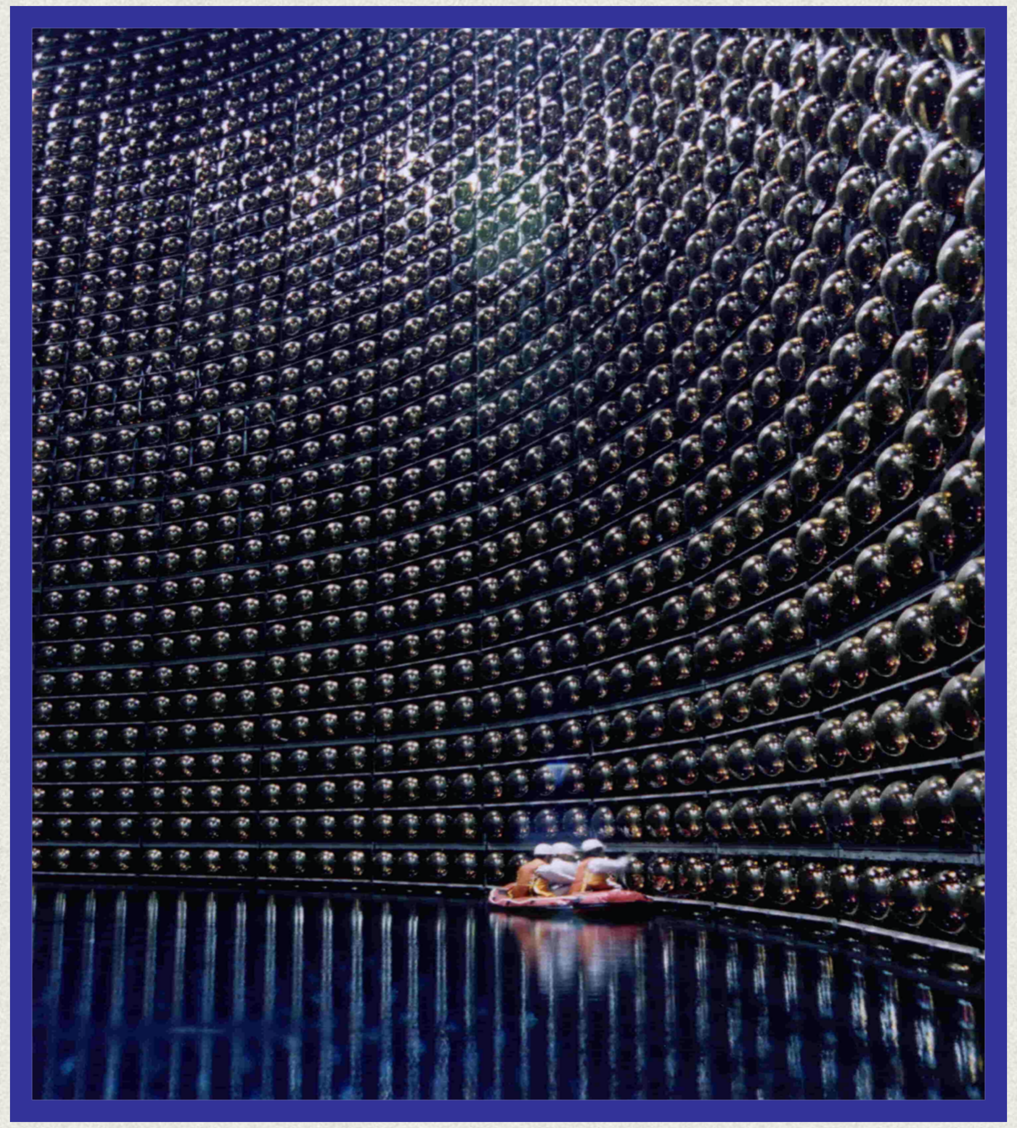
Expect twice more ν_μ than ν_e

- Atmospheric neutrinos were **a background** in experiments searching for proton decay. An anomaly in the ratio of muon/electron neutrinos observed, the *atmospheric neutrino anomaly*.

Image:. Giunti and C.W Kim, «*Fundamentals of neutrino physics and astrophysics*», Oxford University Press (2007) :

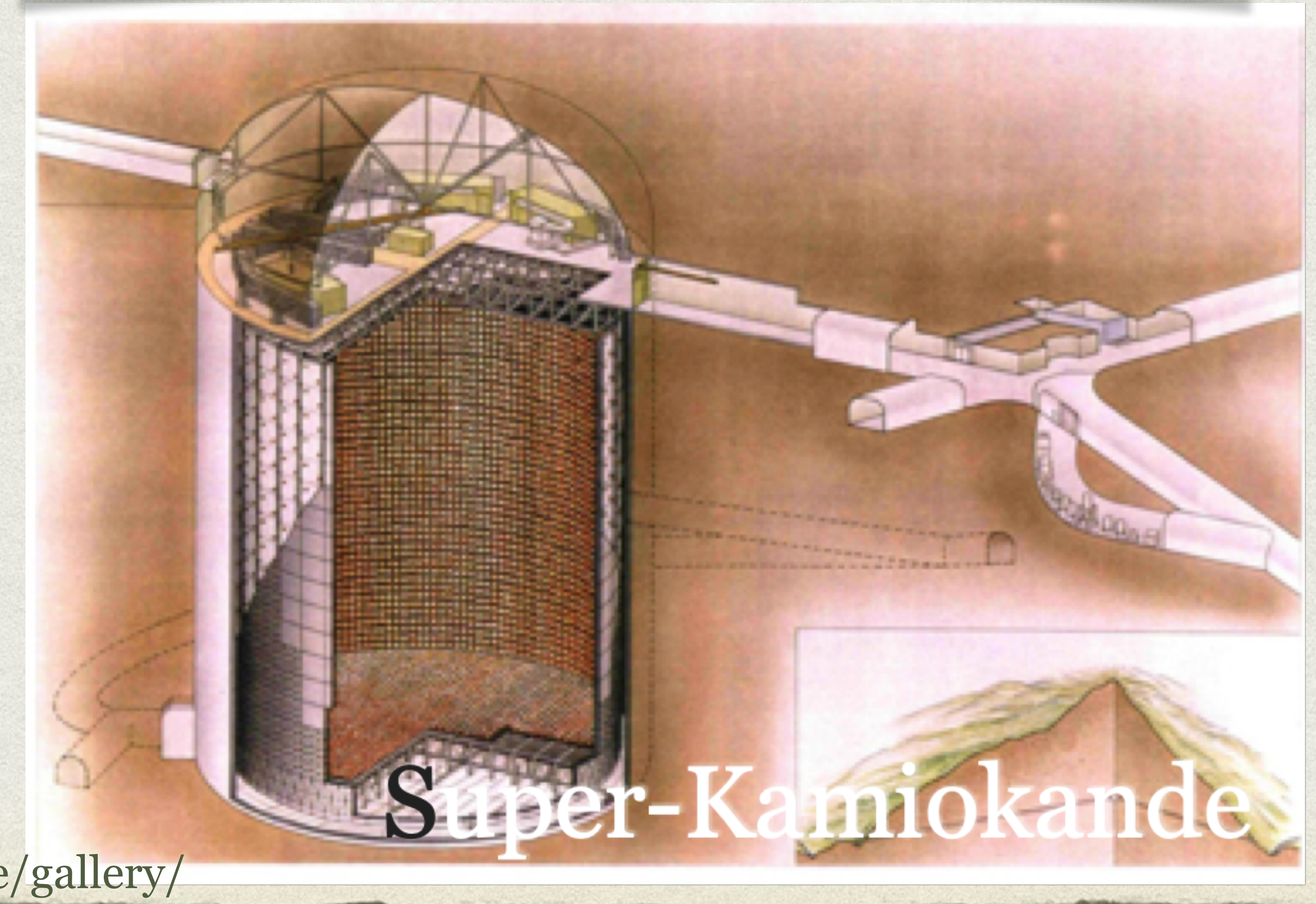
Atmospheric neutrinos and the Super-Kamiokande experiment





Super-Kamiokande experiment (Japan)
water Cherenkov, 50 ktons

SK-I to SK-IV past (20 years)
SK-VI to SK-VIII (since 2020)



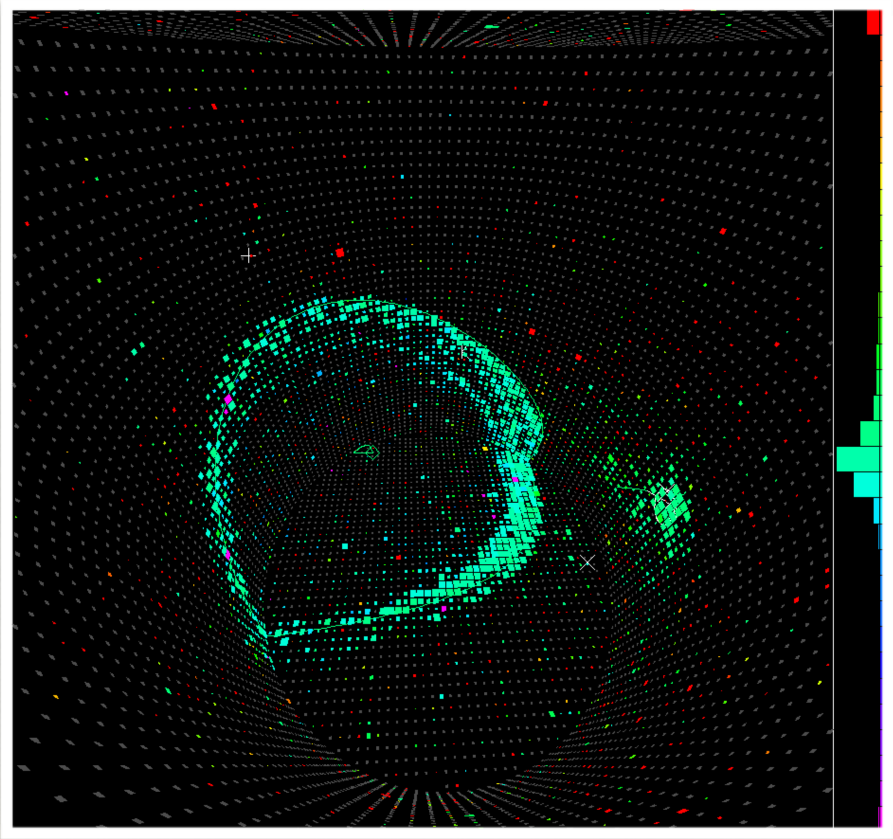
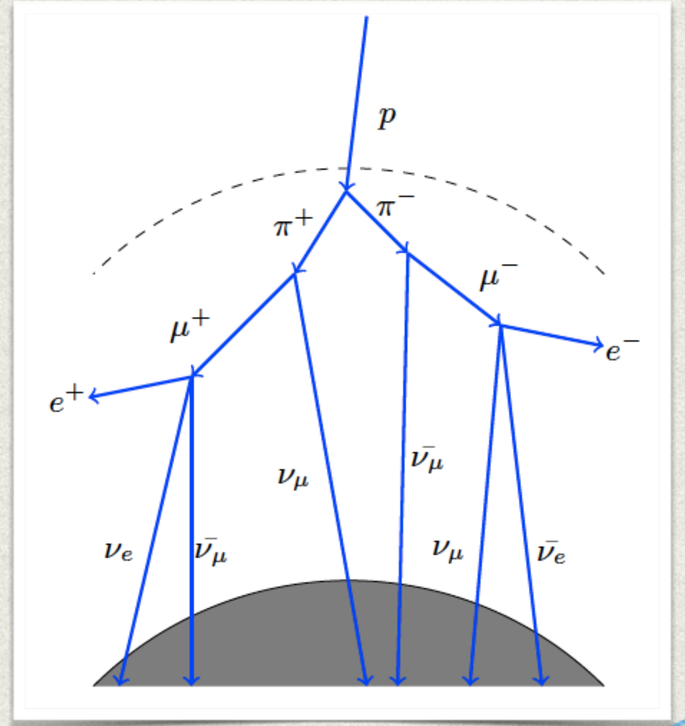


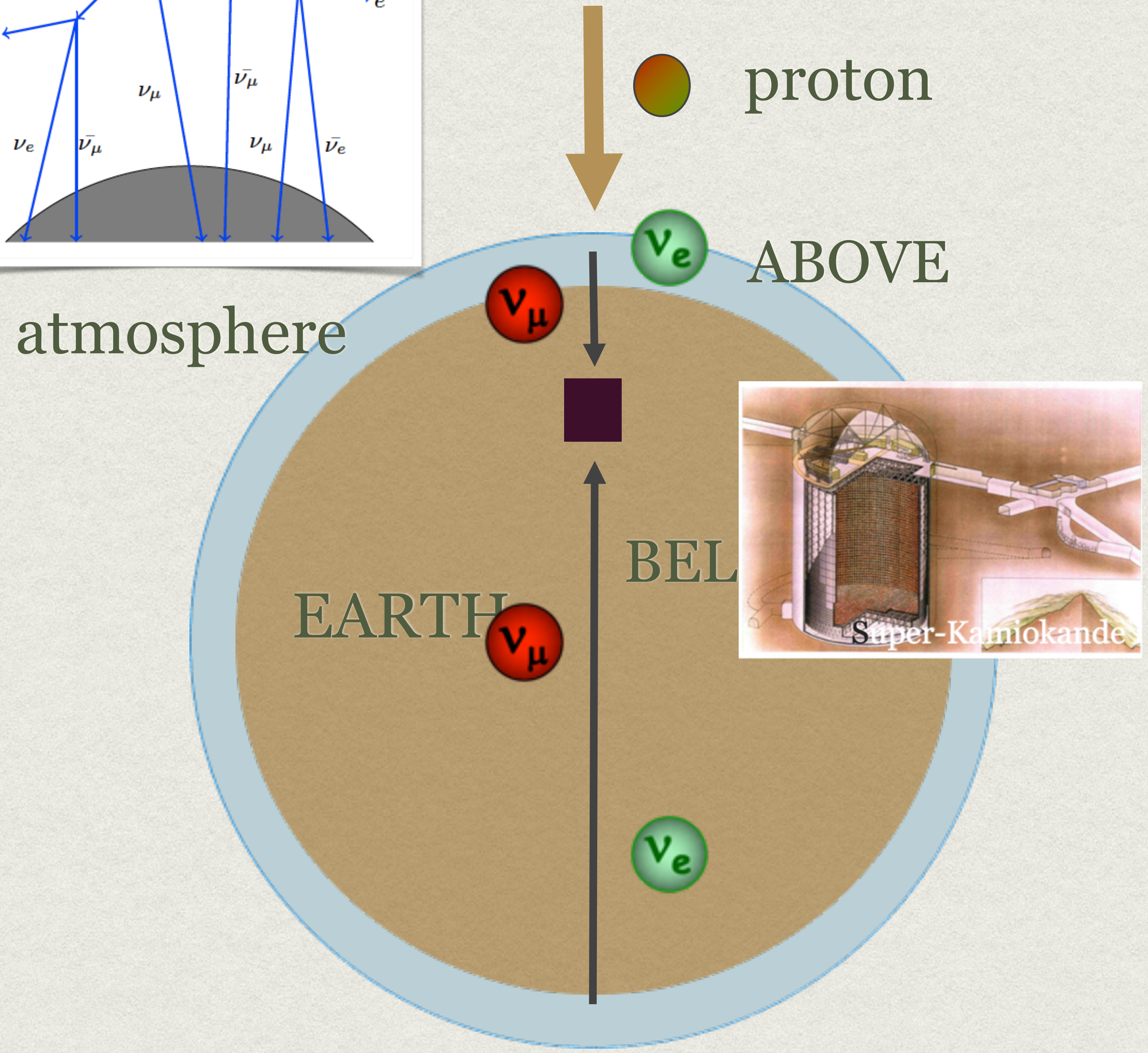
Image of a neutrino
Cherenkov effect

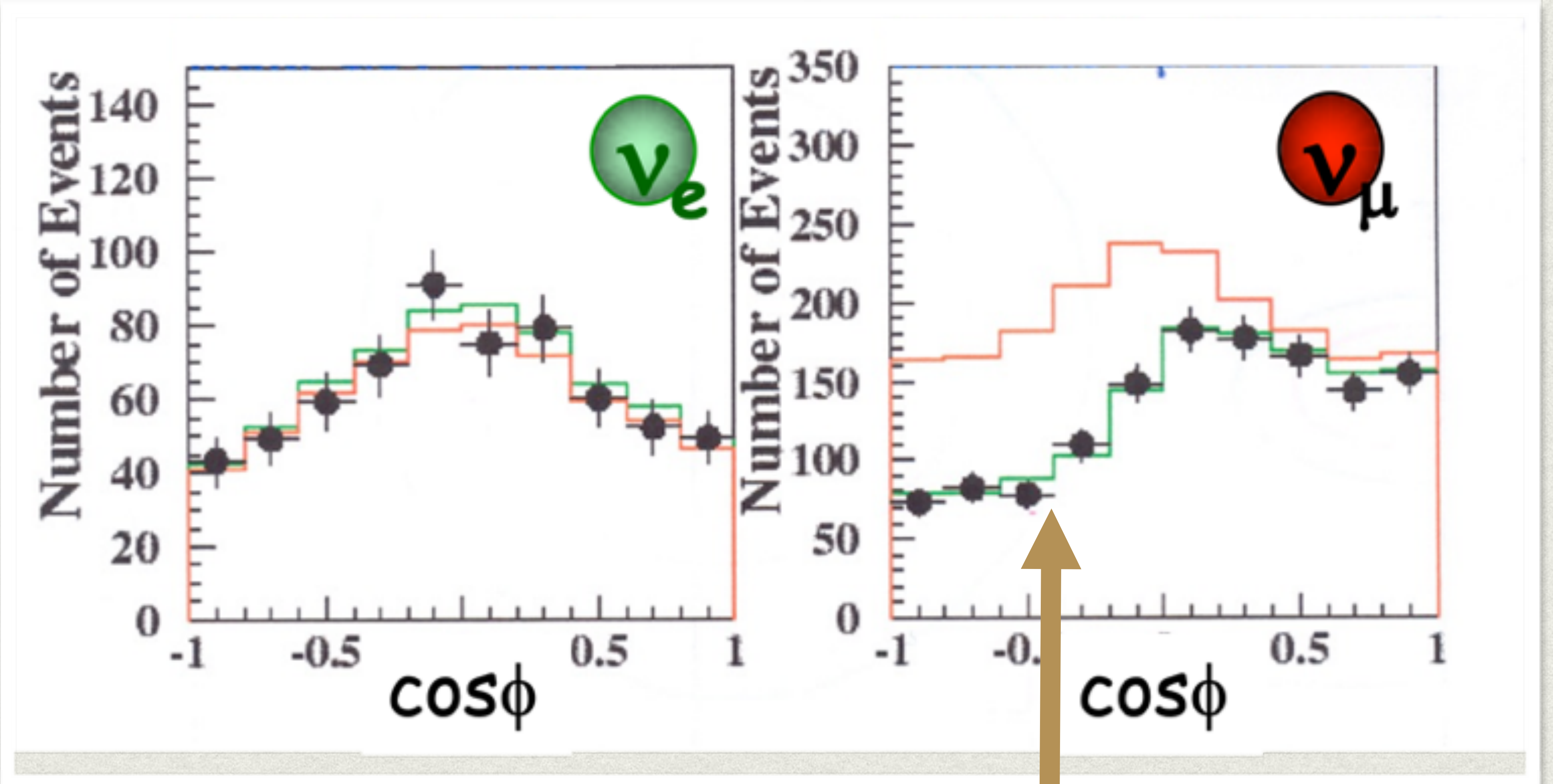
Images:. https://www-sk.icrr.u-tokyo.ac.jp/en/sk/experience/gallery/

The neutrino oscillation discovery

- The Super-Kamiokande Collaboration (1998) discovered that atmospheric neutrinos oscillate while traversing the Earth

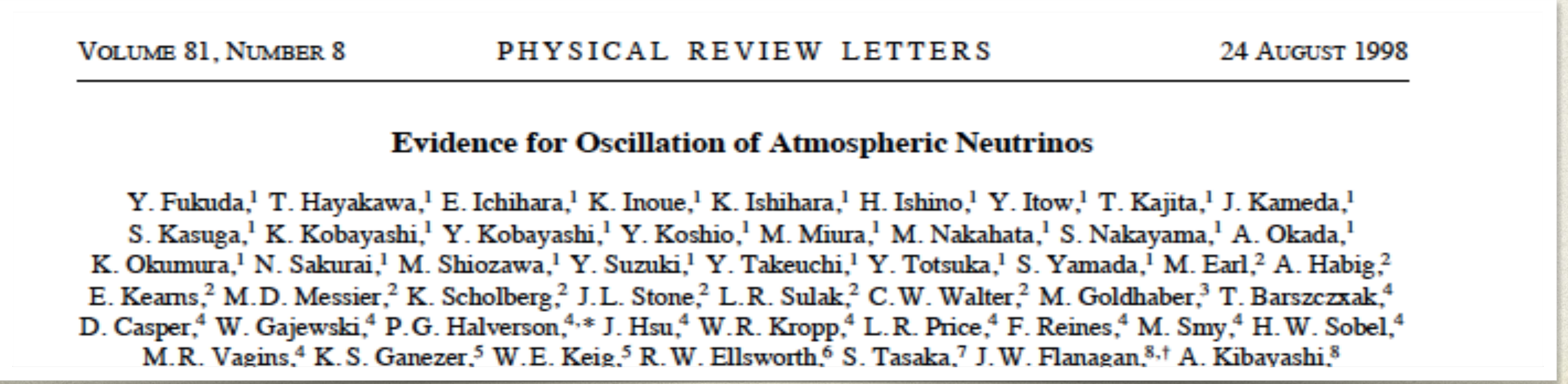






Muon neutrinos oscillate into tau neutrinos

Neutrinos have masses and mixings !


VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

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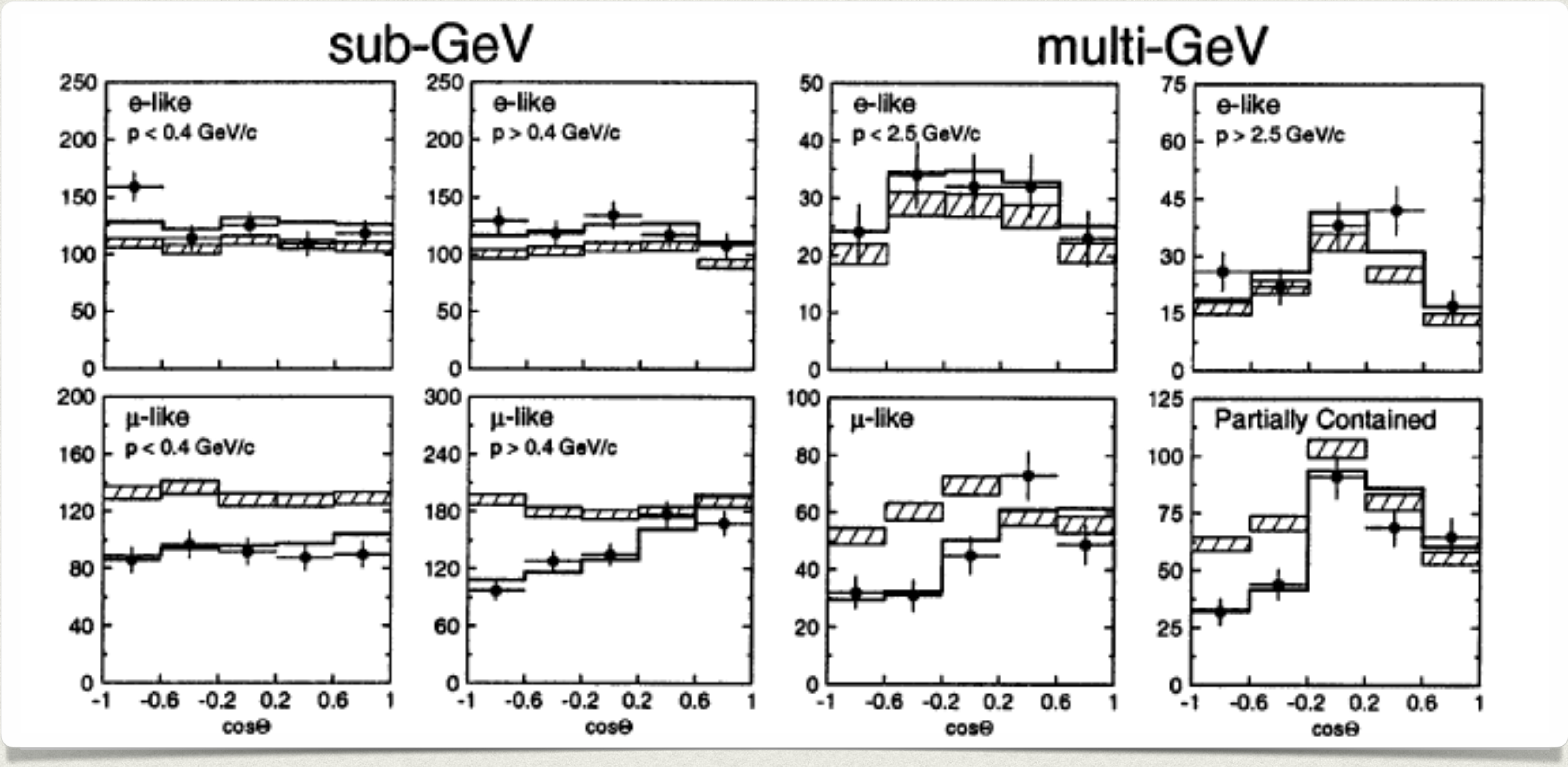
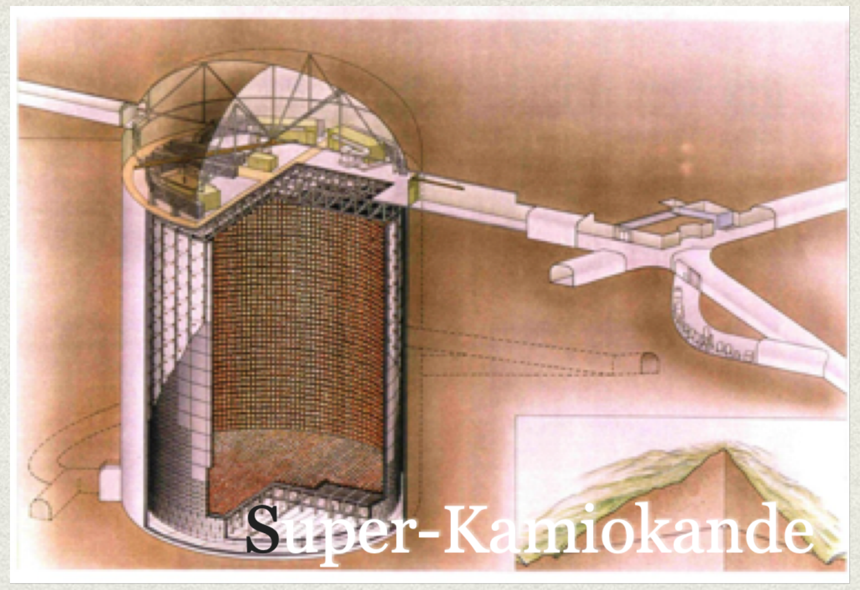
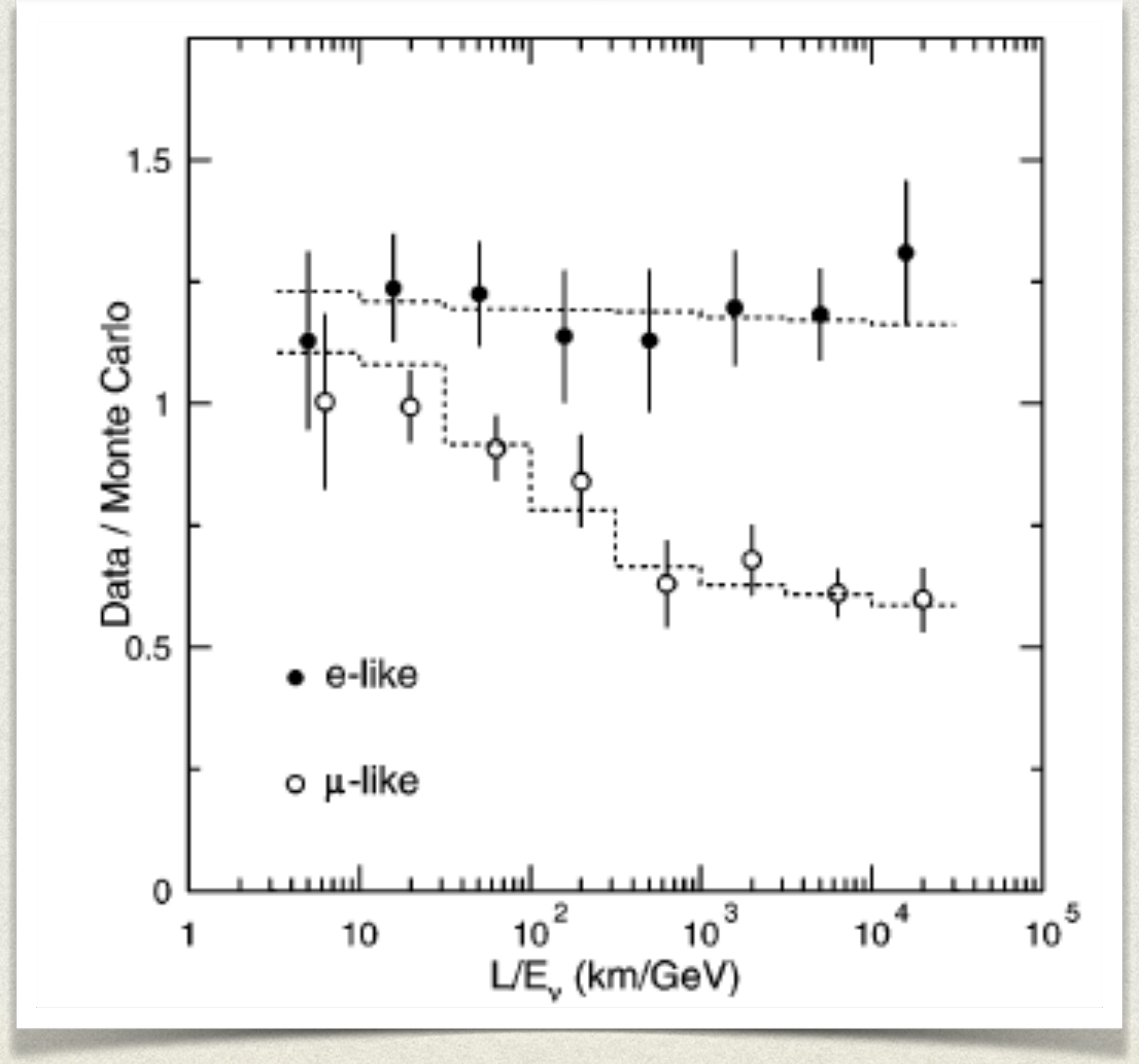
Super-Kamiokande discovery of neutrino oscillations

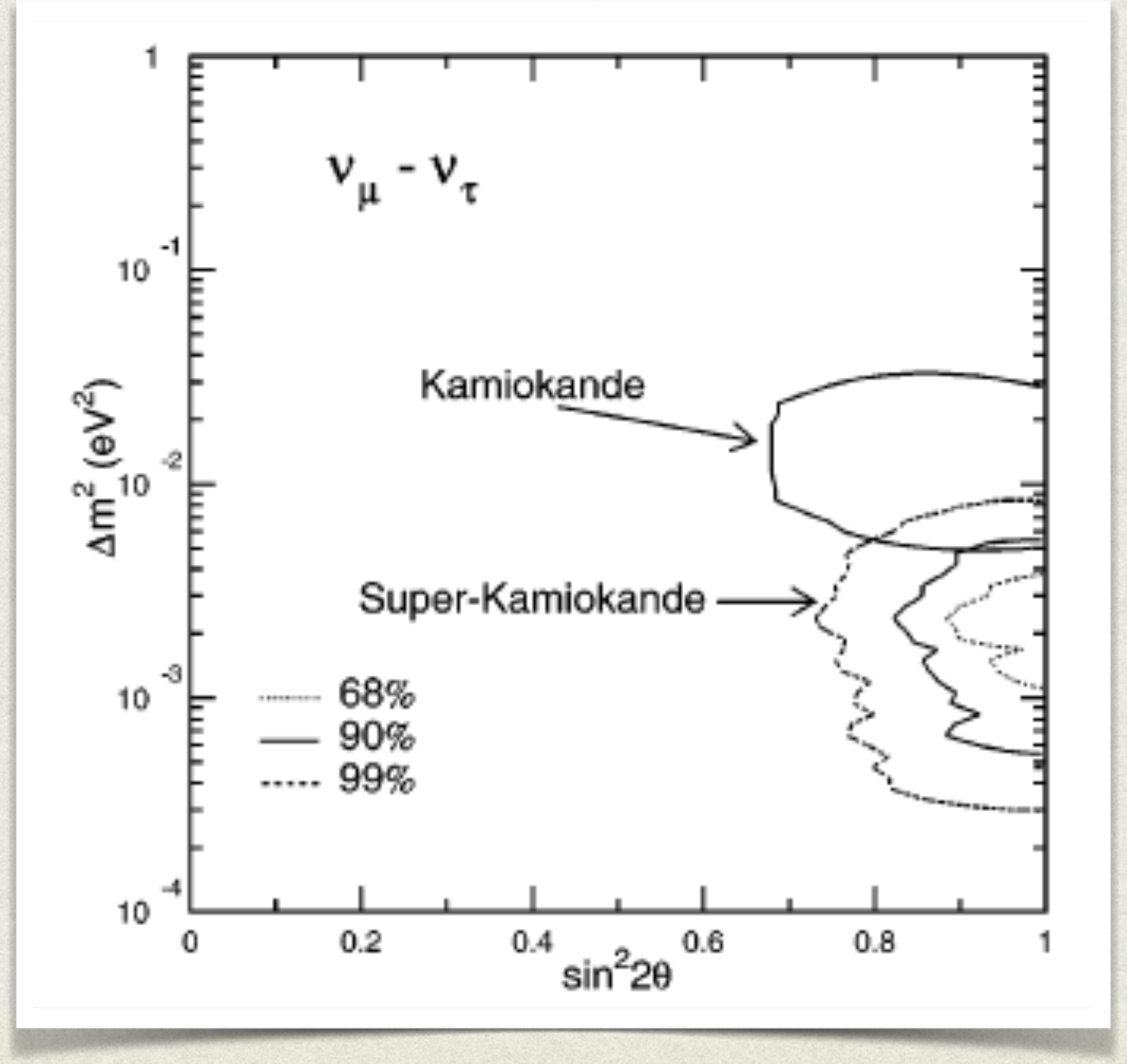


SK, PRL 81 (1998)





The ratio of mu-to-e like events,
the up-down event asymmetry
as function of neutrino momentum,
the zenith angle distributions,
the reconstructed L/E dependence
show evidence for oscillations.



NEUTRINO EVOLUTION EQUATIONS IN VACUUM

- **The phenomenon can be accounted for by a Schrödinger-like equation for the** **neutrino flavor states**, with $\mathcal{H}$ the neutrino Hamiltonian:

$$|\nu_\alpha(0)\rangle = |\nu_\alpha\rangle \qquad i\frac{d}{dt}|\nu_\alpha(t)\rangle = \mathcal{H}^f_{vac}\,|\nu_\alpha(t)\rangle$$

- The Hamiltonian in the mass basis is diagonal and depends on the neutrino energies:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}\,|\nu_i\rangle\,. \qquad \mathcal{H}^f_{\rm vac} = U\mathcal{H}_{\rm vac}U^\dagger. \quad \mathcal{H}_{\rm vac} = {\rm diag}(E_k) \qquad E_k = \sqrt{\mathbf{p}_k^2 + m_k^2}$$

$$\rightarrow \quad i\frac{d}{dt}|\nu_\alpha(t)\rangle = [U\mathcal{H}_{vac}U^\dagger]\,|\nu_\alpha(t)\rangle$$

- **Now, we introduce the** **neutrino flavor amplitudes**, for a neutrino to remain in its flavor, or the amplitude to change into another flavor:

$$\psi_{\alpha\alpha}(t) = \langle\nu_\alpha|\nu_\alpha(t)\rangle \qquad P(\nu_\alpha \rightarrow \nu_\alpha, t) = |\psi_{\nu_{\alpha\alpha}}(t)|^2 \ \text{disappearance probability}$$

$$\psi_{\alpha\beta}(t) = \langle\nu_\beta|\nu_\alpha(t)\rangle \qquad P(\nu_\alpha \rightarrow \nu_\beta, t) = |\psi_{\nu_{\alpha\beta}}(t)|^2 \ \text{appearance probability}$$

$$\psi_{\alpha\beta}(0) = \delta_{\alpha\beta} \qquad \sum_\beta P(\nu_\alpha \rightarrow \nu_\beta)(t) = 1$$

NEUTRINO EVOLUTION EQUATIONS IN VACUUM

- The evolution equations for the neutrino amplitudes can be deduced from the previous equation and read

$$i\frac{d}{dt}\psi_{\alpha\beta}(t) = \sum_{\eta}(\sum_{k} U_{\beta k}E_k U^*_{\eta k})\psi_{\alpha\eta}(t)$$

I add and subtract E_1 (in the parenthesis) on the *r.h.s.* .

- Since neutrinos are relativistic, assuming equal momentum:

$$E_k = \sqrt{\mathbf{p}_k^2 + m_k^2} \qquad E_k \approx |\mathbf{p}| + \frac{m_k^2}{2E} \qquad E = |\mathbf{p}| \qquad k = 1, 2, ...N \qquad p = |\mathbf{p}|$$

$$E_k - E_1 \approx (p + \frac{m_k^2}{2E}) - (p + \frac{m_1^2}{2E}) \approx \frac{(m_k^2 - m_1^2)}{2E} \approx \frac{\Delta m_{k1}^2}{2E}$$

$$i\frac{d}{dt}\psi_{\alpha\beta}(t) = (p + \frac{m_1^2}{2E})\psi_{\alpha\beta}(t) + \sum_{\eta}\sum_{k}(U_{\beta k}\frac{\Delta m_{k1}^2}{2E}U^*_{\eta k})\psi_{\alpha\eta}(t)$$

common phase to all flavors and is irrelevant for oscillations.

NEUTRINOS IN MATTER

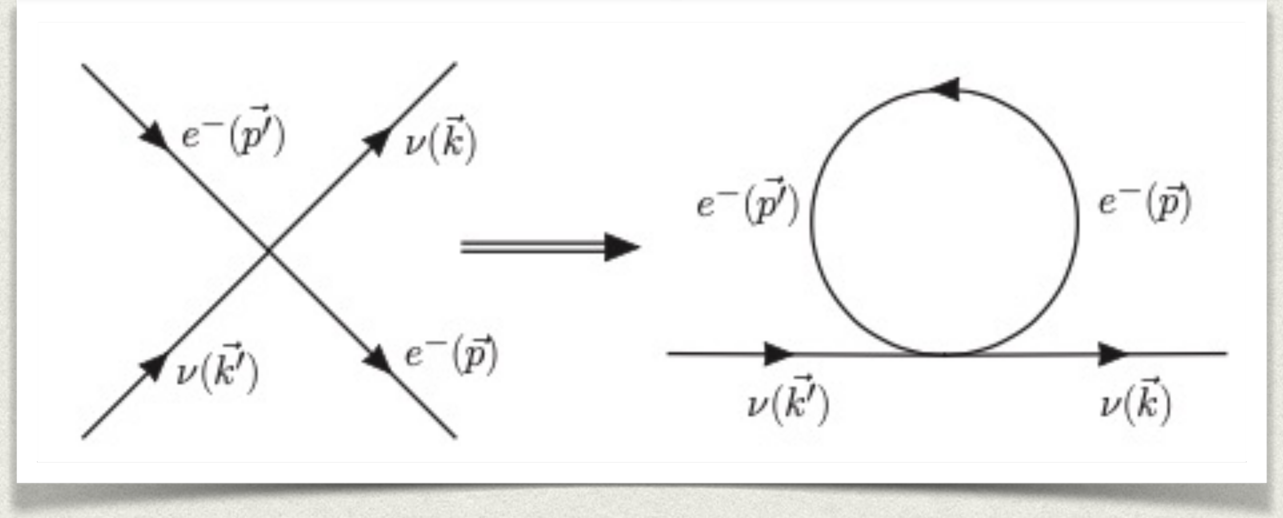
- Wolfenstein (1978) pointed out that neutrinos could change flavor in matter due to coherent forward scattering and a flavor-dependent refractive index.

  Mikheev-Smirnov (1986) suggested that flavor conversion in matter could be resonantly amplified and proposed this as **a solution of the solar neutrino problem**.

- $\nu_e - e$ - scattering in an astrophysical or cosmological environment

  $V_{\rm CC} = \sqrt{2} G_F n_e$ G_F- Fermi coupling constant

→ **MEAN-FIELD approximation**



This is similar to the Hartree or Hartree-Fock approximation in nuclear physics.
Here the interactions are the charged- and neutral-current interaction terms from the GWS SM Lagrangian in the low energy limit (relevant range here is MeV, tens of MeV, 100 MeV).

NEUTRINO EVOLUTION EQUATIONS IN MATTER

- The evolution equations can be generalized to include the contribution from neutrino charged- and neutral-current interactions with matter:

$$i\frac{d}{dt}\psi_{\alpha\beta}(t) = (p + \frac{m_1^2}{2E} + V_{\rm NC})\psi_{\alpha\beta}(t) + \sum_\eta \sum_k (U_{\beta k}\frac{\Delta m_{k1}^2}{2E}U_{\eta k}^* + \delta_{\beta e}\delta_{\eta e}V_{\rm CC})\psi_{\alpha\eta}(t)$$

common phase to all flavors, irrelevant for oscillations.

- In 2 neutrino flavors, the equations with mixings and matter cast in matrix form read:

$$i\frac{d}{dt}\begin{pmatrix}\psi_{ee}\\ \psi_{e\mu}\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}G_{\rm F}n_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\psi_{ee}\\ \psi_{e\mu}\end{pmatrix}$$

beware that here the common term of the Hamiltonian (not shown) is $\mathcal{H}_{\rm com} = p + \frac{m_1^2 + m_2^2}{4}$

That is

$$i\frac{d}{dt}\begin{pmatrix}\psi_{ee}\\ \psi_{e\mu}\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix} + \begin{pmatrix}\sqrt{2}G_{\rm F}n_e & 0 \\ 0 & 0\end{pmatrix}\begin{pmatrix}\psi_{ee}\\ \psi_{e\mu}\end{pmatrix}$$

amplitude that a ν_e stays a ν_e

amplitude that a ν_e becomes a ν_μ

EVOLUTION EQUATIONS FOR 2 nu IN (DILUTE) MATTER

THE Mikheev-Smirnov-Wolfenstein (MSW) EFFECT

Wolfenstein, 1978; Mikheev and Smirnov, 1985

- The total Hamiltonian in 2 neutrino flavors

$$\mathcal{H}^f = \mathcal{H}^f_{\rm vac} + \mathcal{H}^f_{\rm mat} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos^2 2\theta + \sqrt{2}G_{\rm F}n_e & \frac{\Delta m^2}{4E}\sin^2 2\theta \\ \frac{\Delta m^2}{4E}\sin^2 2\theta & \frac{\Delta m^2}{4E}\cos^2 2\theta \end{pmatrix}$$

- It can be made diagonal with the rotation (giving the so called « matter basis ») :

$$\tan 2\tilde{\theta} = \frac{2|H_{12}|}{H_{11} - H_{22}} = \frac{\frac{\Delta m^2}{2E}\sin 2\theta}{\sqrt{2}G_{\rm F}n_e - \frac{\Delta m^2}{2E}\cos 2\theta}$$

MSW resonance condition $\sqrt{2}G_{\rm F}n_e - \frac{\Delta m^2}{2E}\cos 2\theta = 0$

- Parke's formula : $\langle P(\nu_e \to \nu_e)\rangle = \frac{1}{2} + \frac{1}{2}\, cos2\theta\, cos\tilde{\theta}\, (1 - P_{hop})$

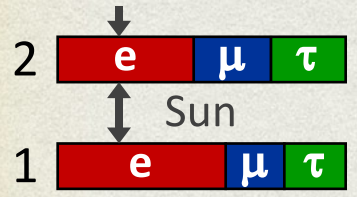
$P_{hop} = 0$ adiabatic case

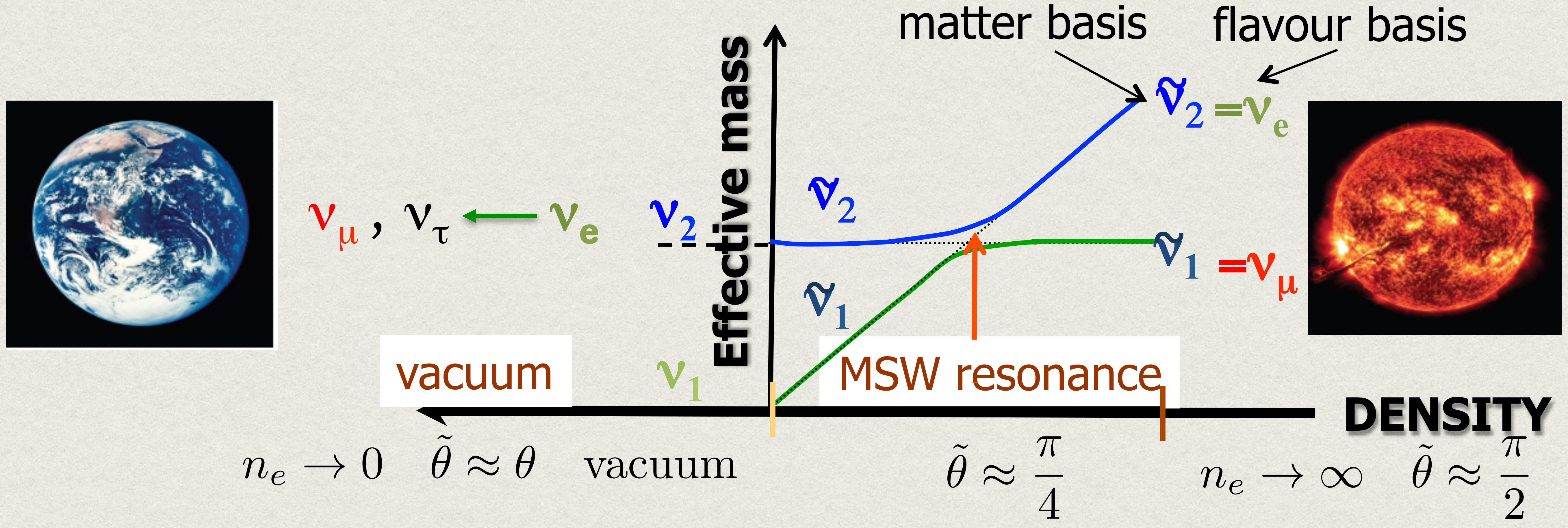
$\langle P(\nu_e \to \nu_e)\rangle = sin^2\theta \approx 0.3 \ (\theta = 33^\circ)$

$P_{hop} = 1$ nonadiabatic case

$\langle P(\nu_e \to \nu_e)\rangle = \frac{1}{2}$

Two-level problem in quantum mechanics





It tells us about the sign of the squared-mass difference.

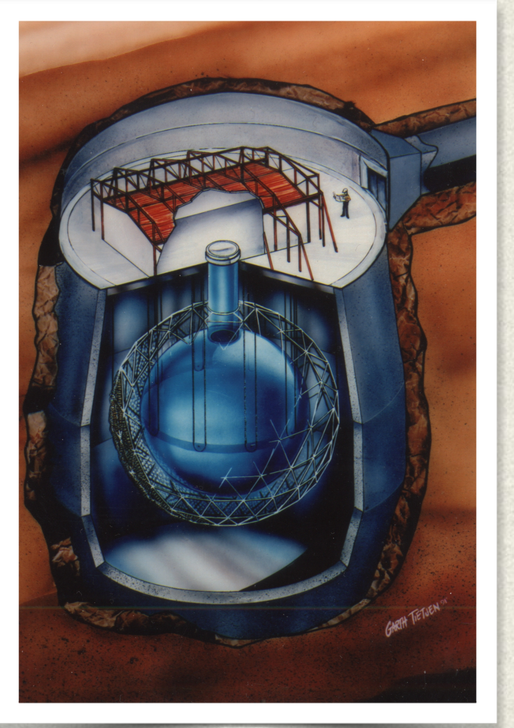
If the MSW resonance is fulfilled, the resonance width is large and the evolution through resonance adiabatic, an electron neutrino will come out as a nu2.

SNO experiment : Solar neutrinos convert into active neutrinos

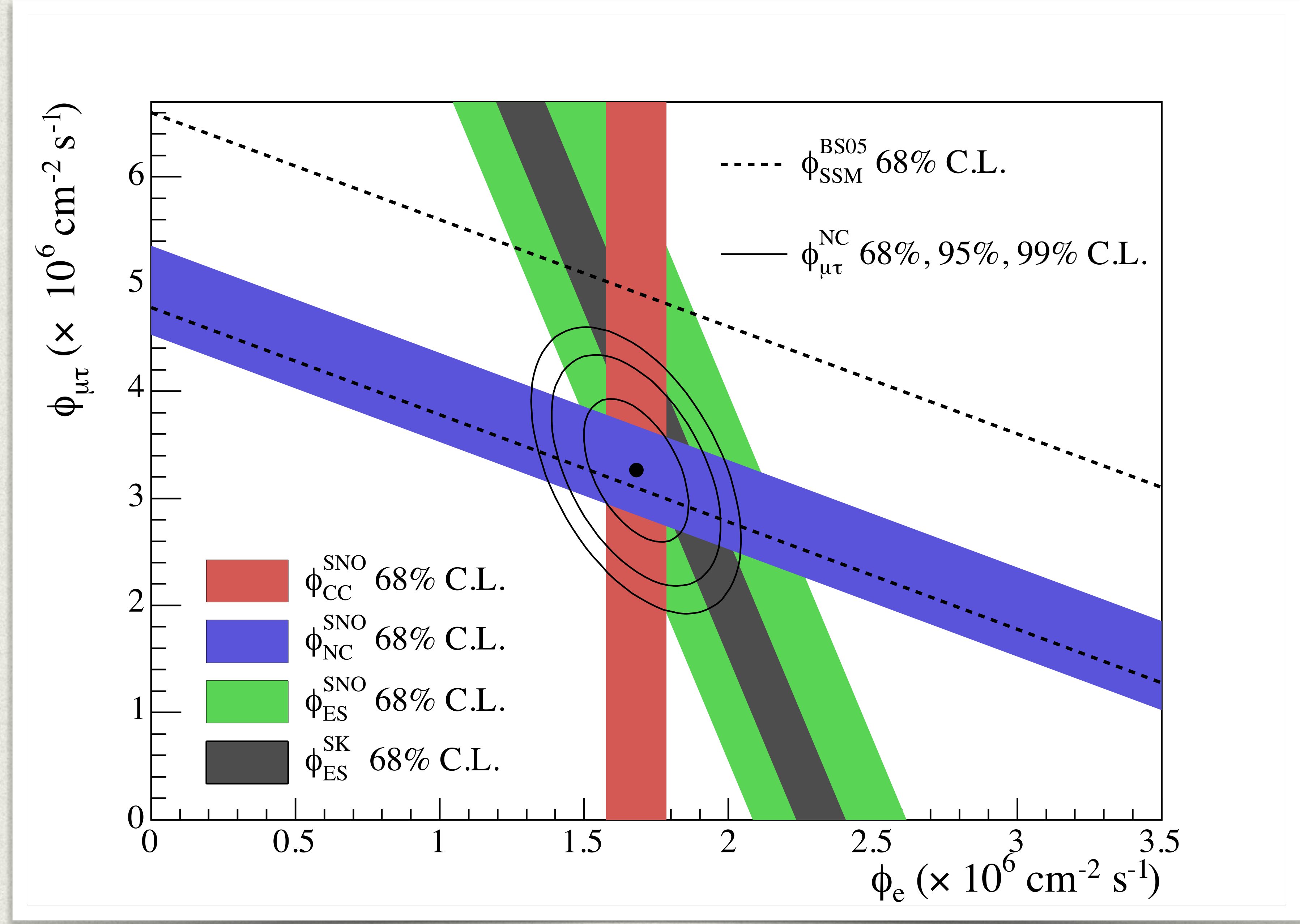
- The SNO Collaboration (2001-2) measured the total solar neutrino flux from the Sun and found it consistent with the Standard Solar Model.

$$\nu_e + D \rightarrow p + p + e^- \text{ (CC)}$$
$$\nu_x + D \rightarrow n + p + \nu_x \text{ (NC)}$$
$$\nu_x + e^- \rightarrow \nu_x + e^- \text{ (ES)}$$

The measurement of the total neutrino flux from the Sun showed a ν_μ, ν_τ flux component (5.3 sigma).

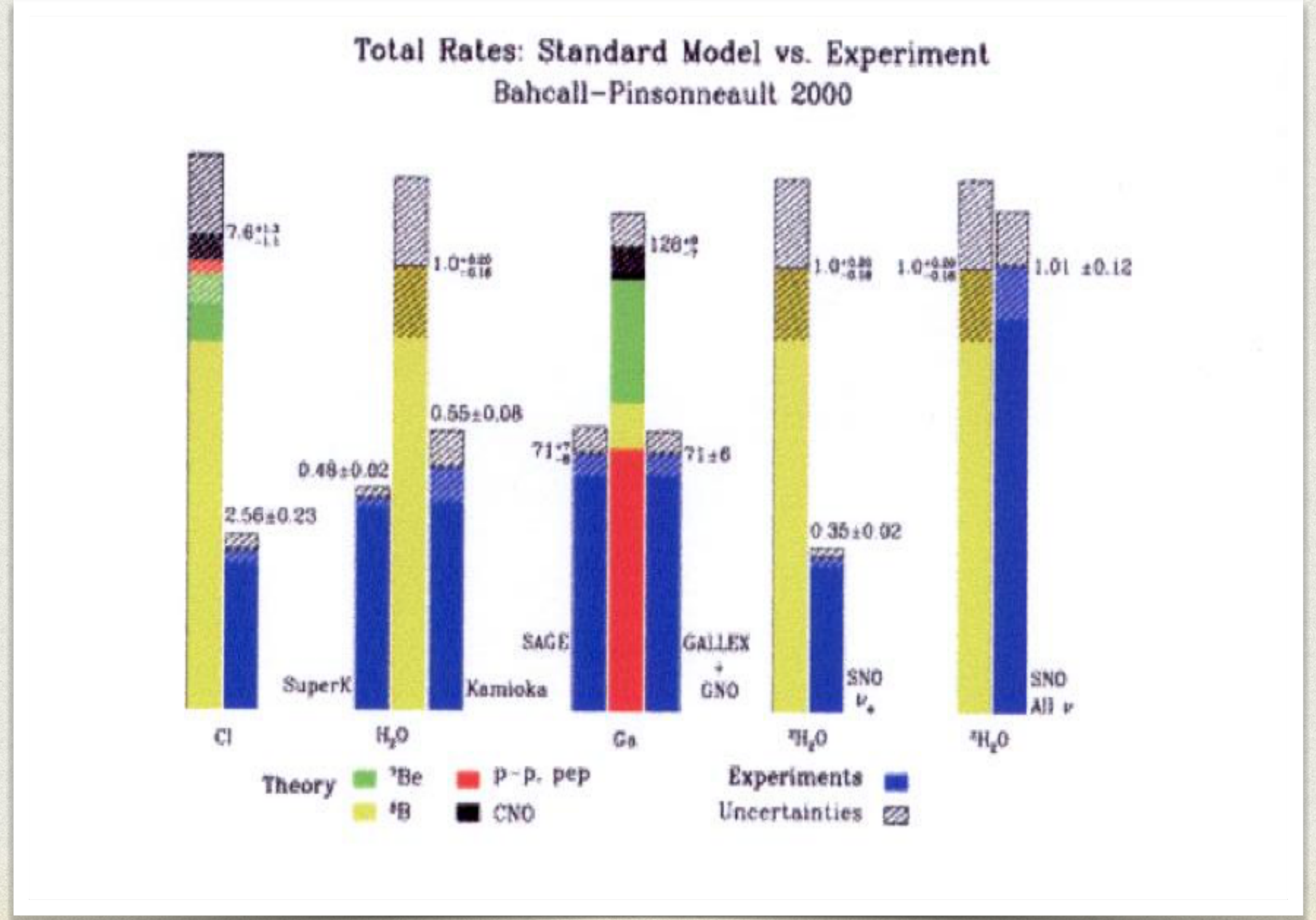


SNO detector
1 kton
heavy water, D_2O



SNO Collaboration, PRL 89 (2002)

$$\phi_e = 1.76^{+0.05}_{-0.05}(\text{stat})^{+0.09}_{-0.09}(\text{syst})$$
$$\phi_{\mu\tau} = 3.41^{+0.45}_{-0.45}(\text{stat})^{+0.48}_{-0.45}(\text{syst})$$



Solar electron neutrinos convert into muon and tau neutrinos (active flavors).

SNO and other observations of the solar neutrinos

SNO, PRL 89 (2002)

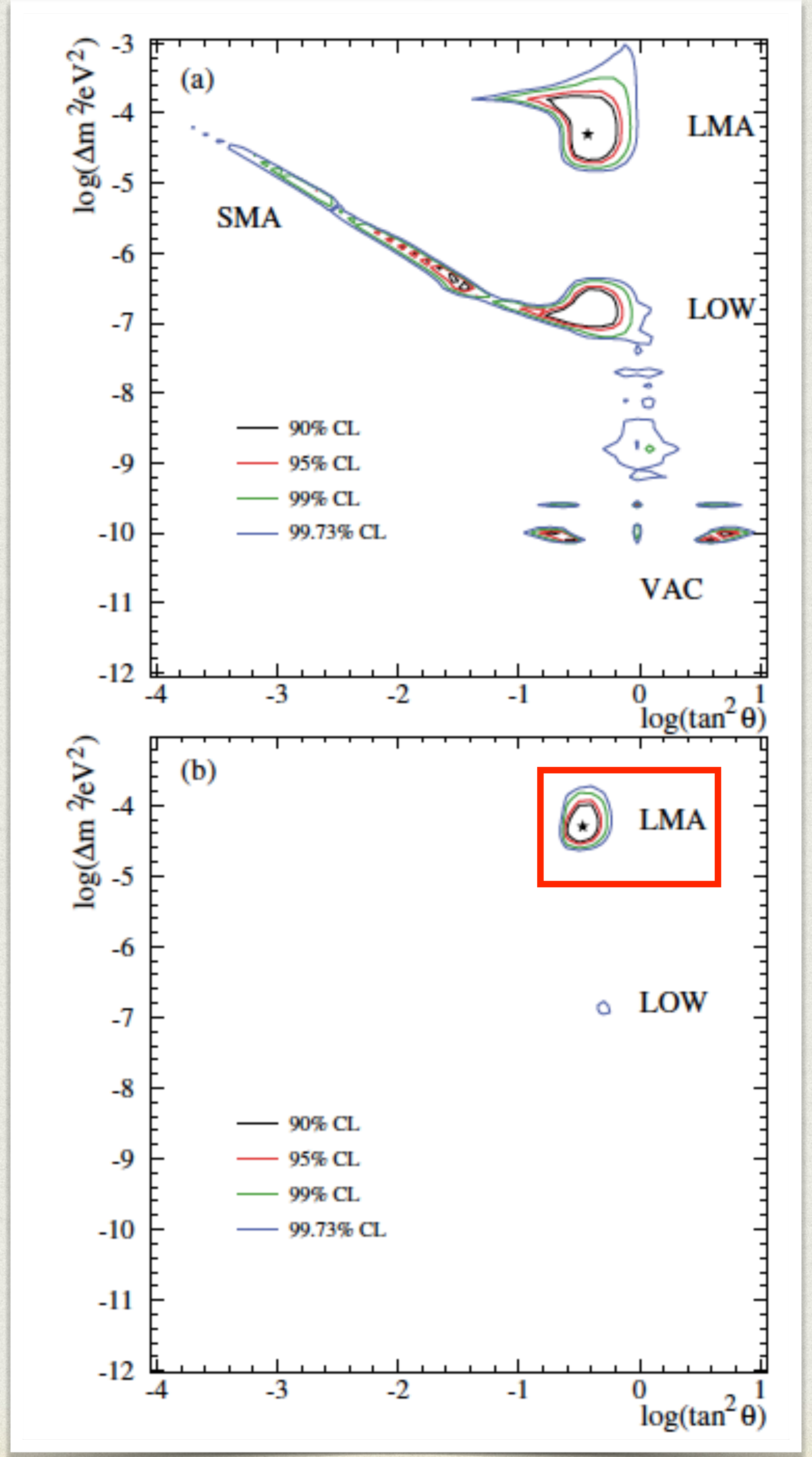
Four possible solutions:

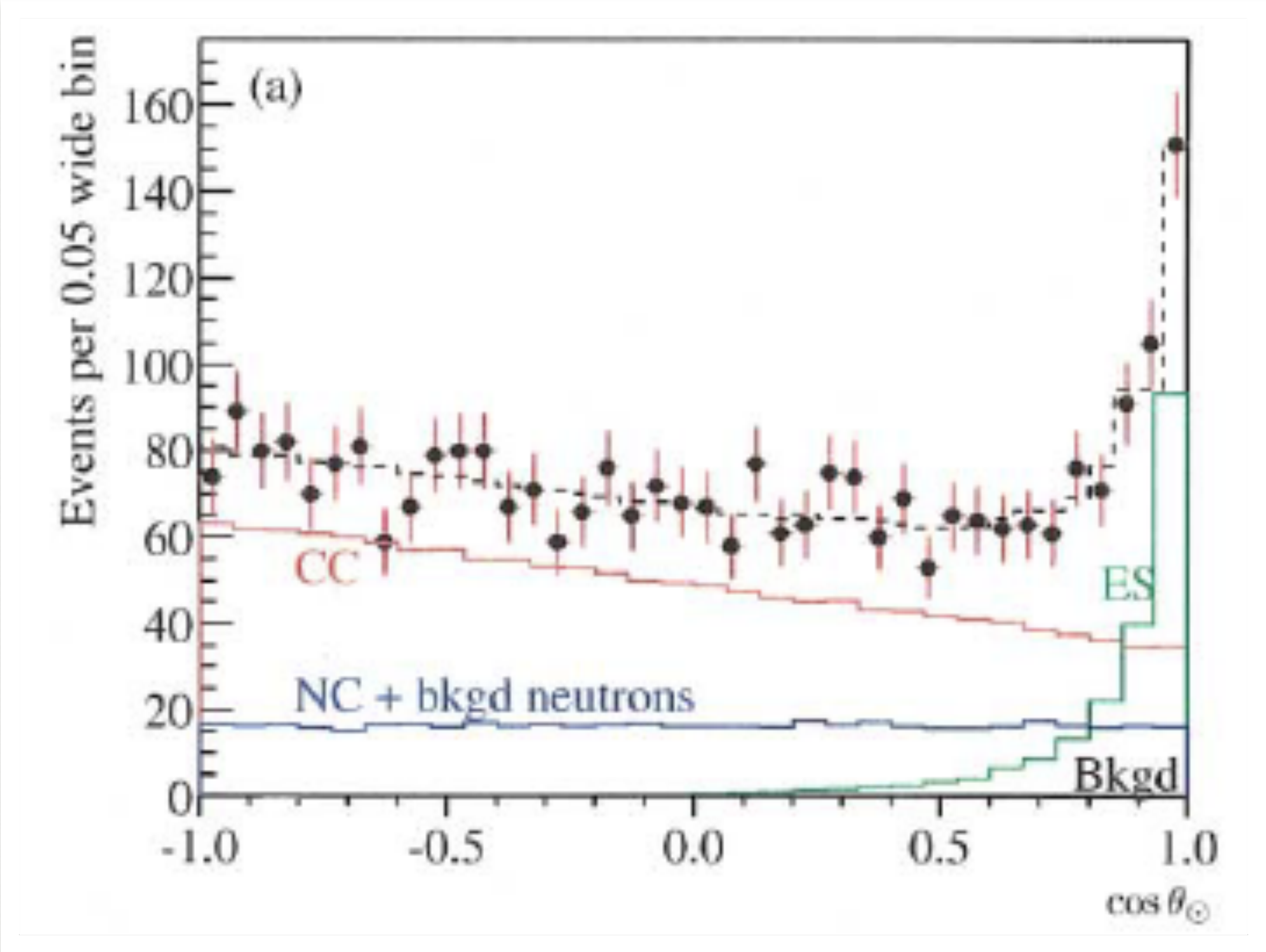
Small Mixing Angle (SMA)

Large Mixing Angle (LMA)

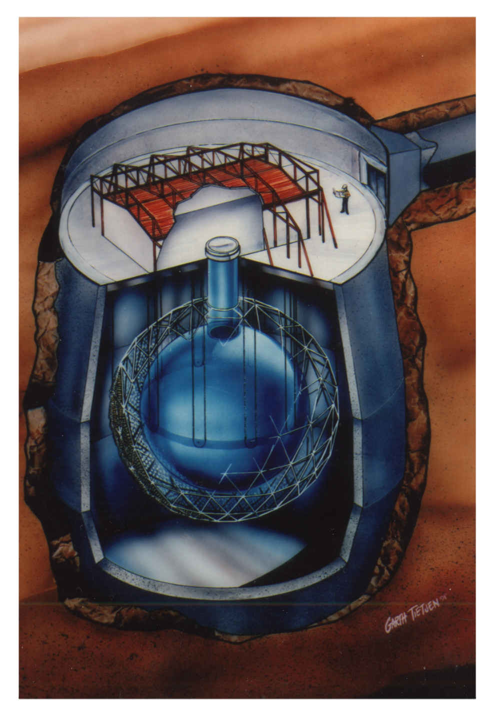
VACuum solution

LOW solution





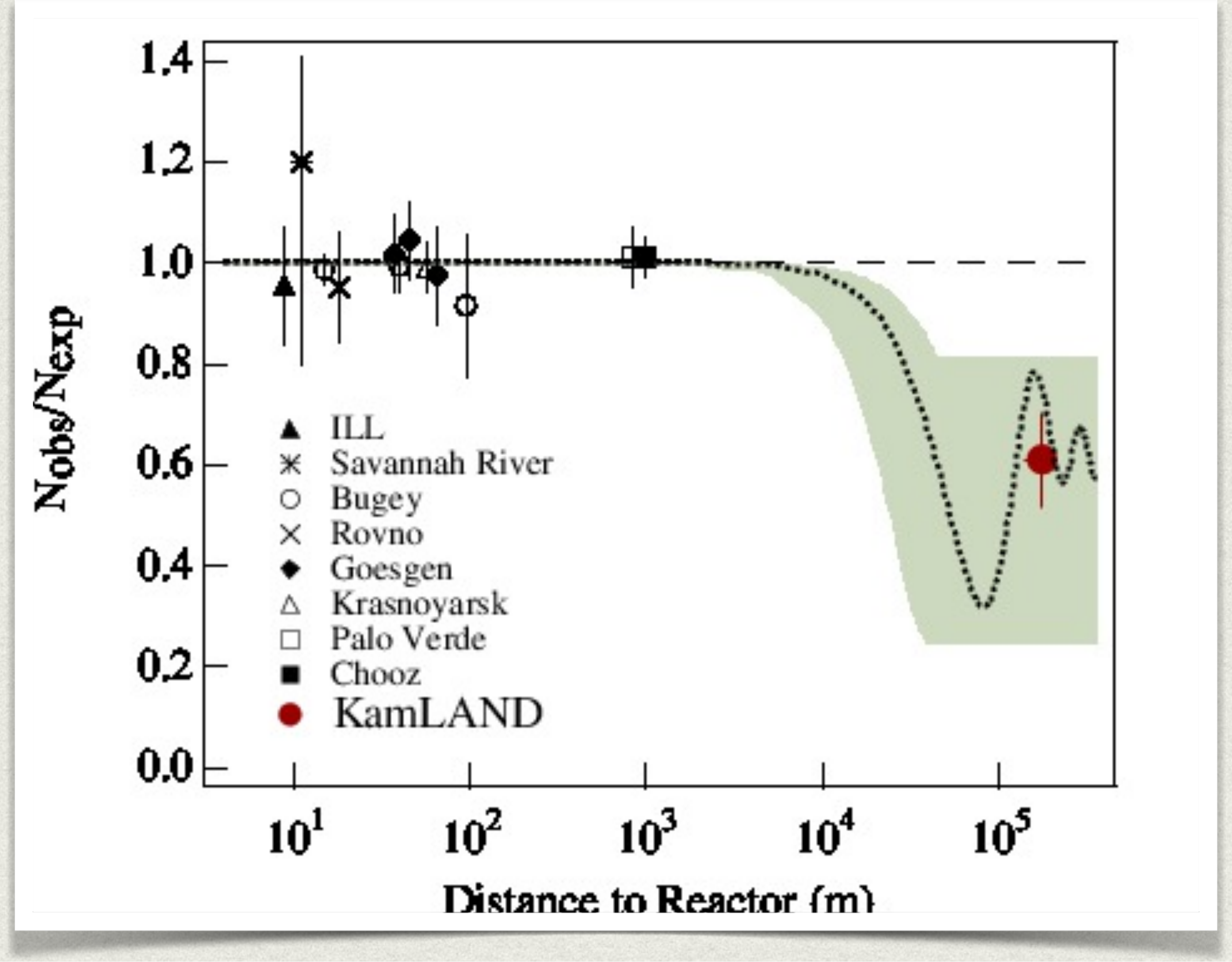
The allowed regions from SNO data alone and with additional information from experimental and solar model data strongly favors the LMA solution.

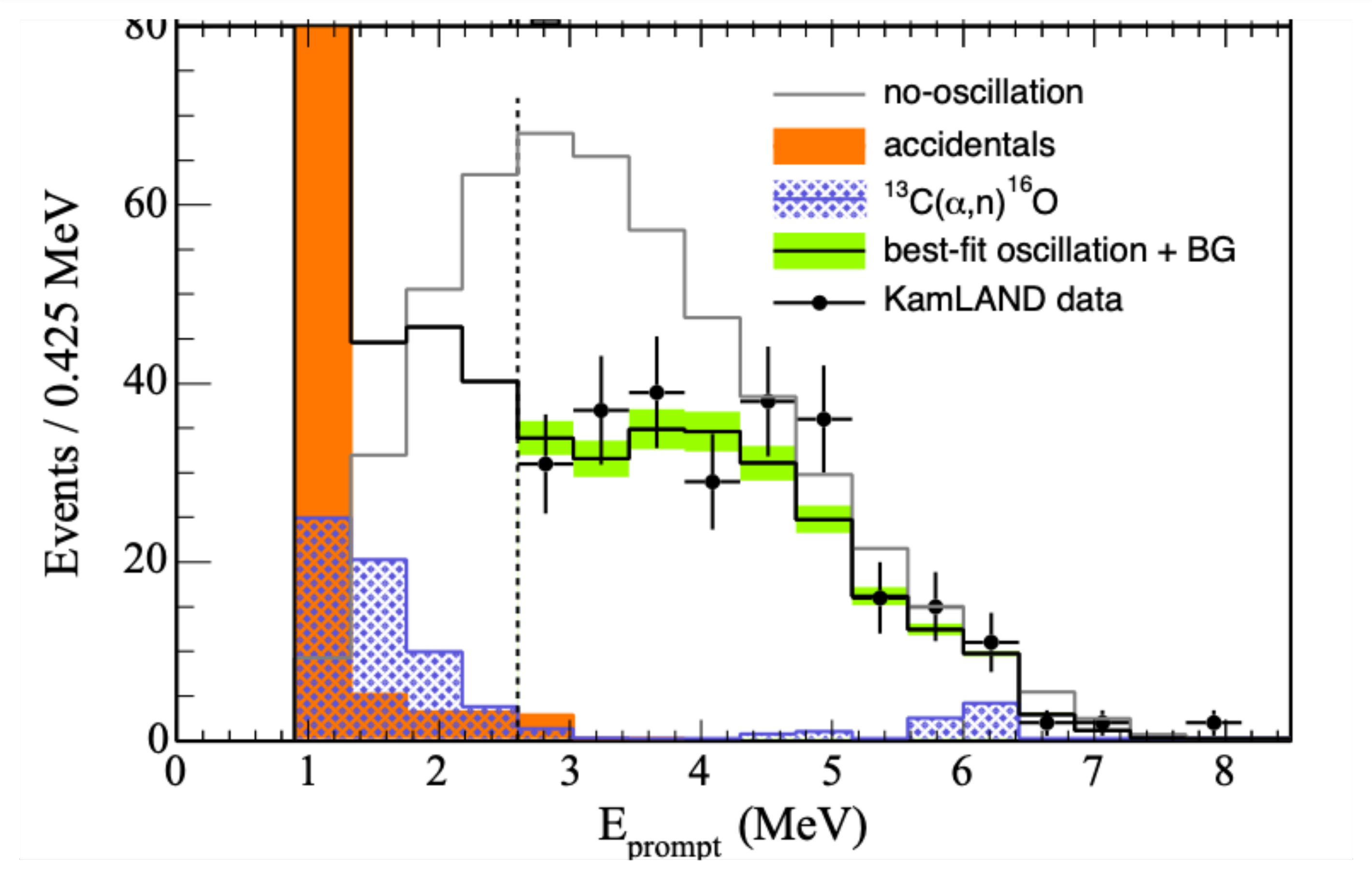


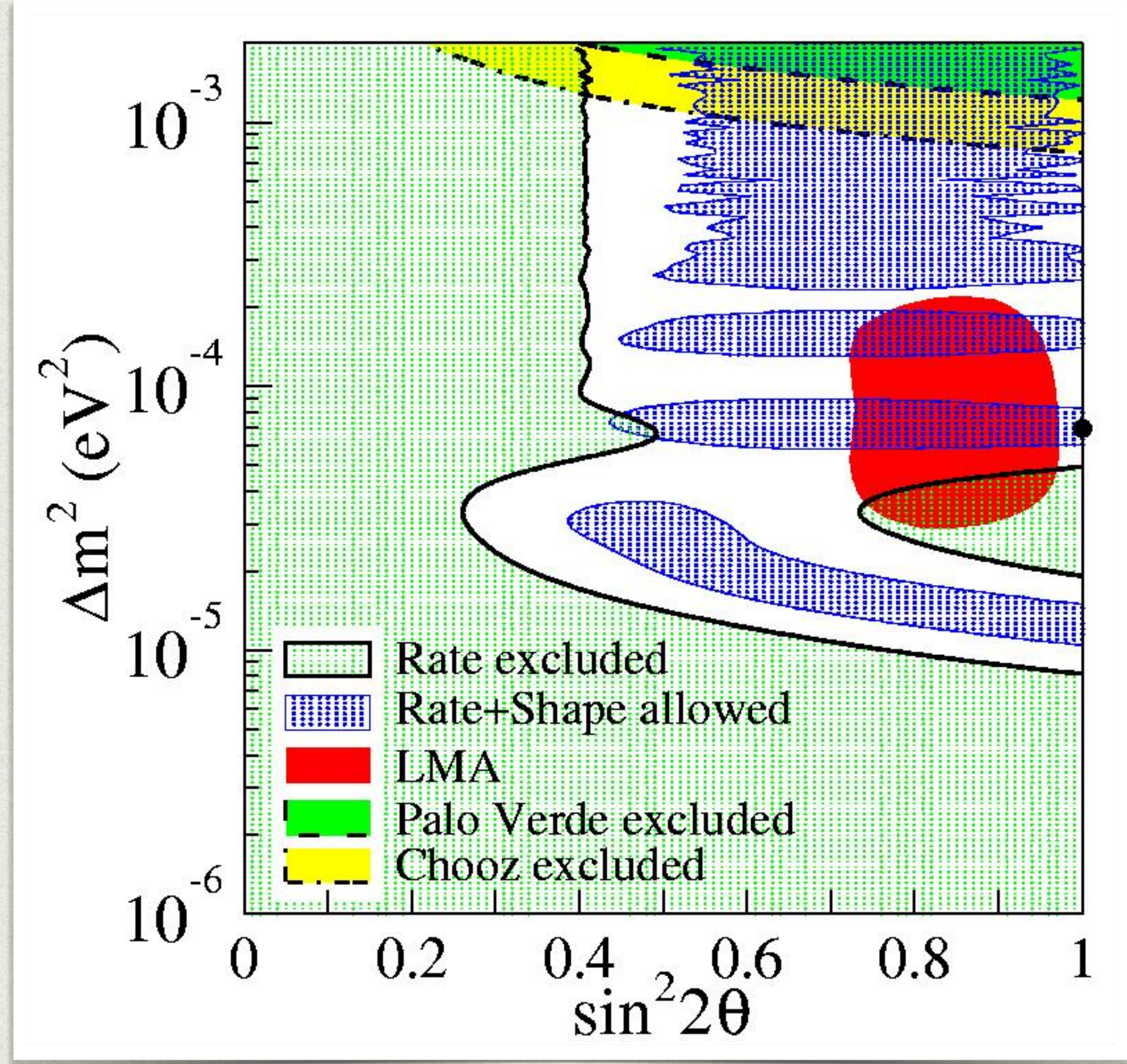
SNO detector
1 kton
heavy water, D_2O

KamLAND: Identifying the Large-Mixing-Angle solution

- KamLAND experiment measured vacuum oscillations using electron anti-neutrinos from all Japanese reactors at an average distance of 200 km.



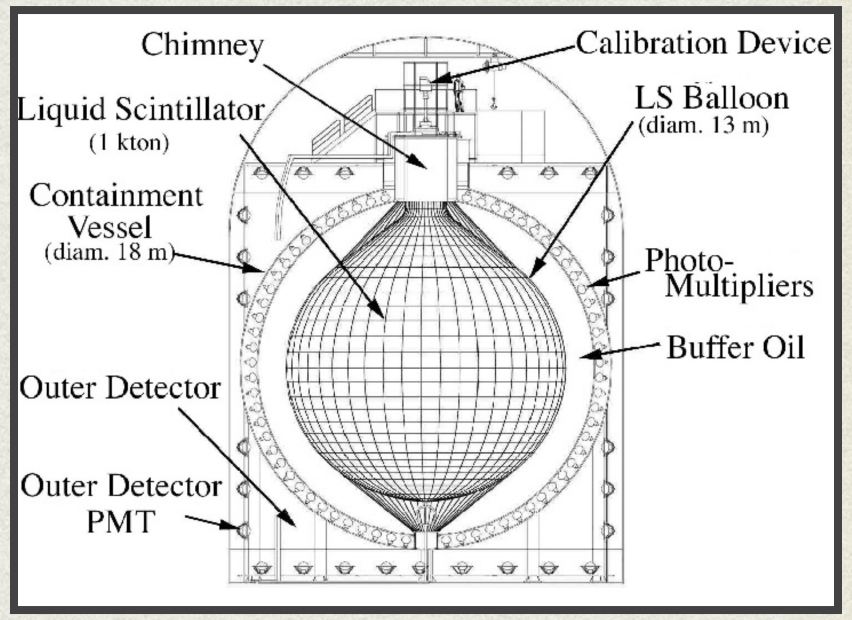




KamLAND Collaboration, PRL 90 (2003)

$$\Delta m^2 \approx 6.9\ 10^{-5}\text{eV}^2 \quad \sin^2 2\theta = 1.0 \quad \text{(best fit)}.$$

Another very clever experiment !



KamLAND detector
1 kton liquid scintillator

2015 NOBEL PRIZE IN PHYSICS

6 October 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

and

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Super-Kamiokande

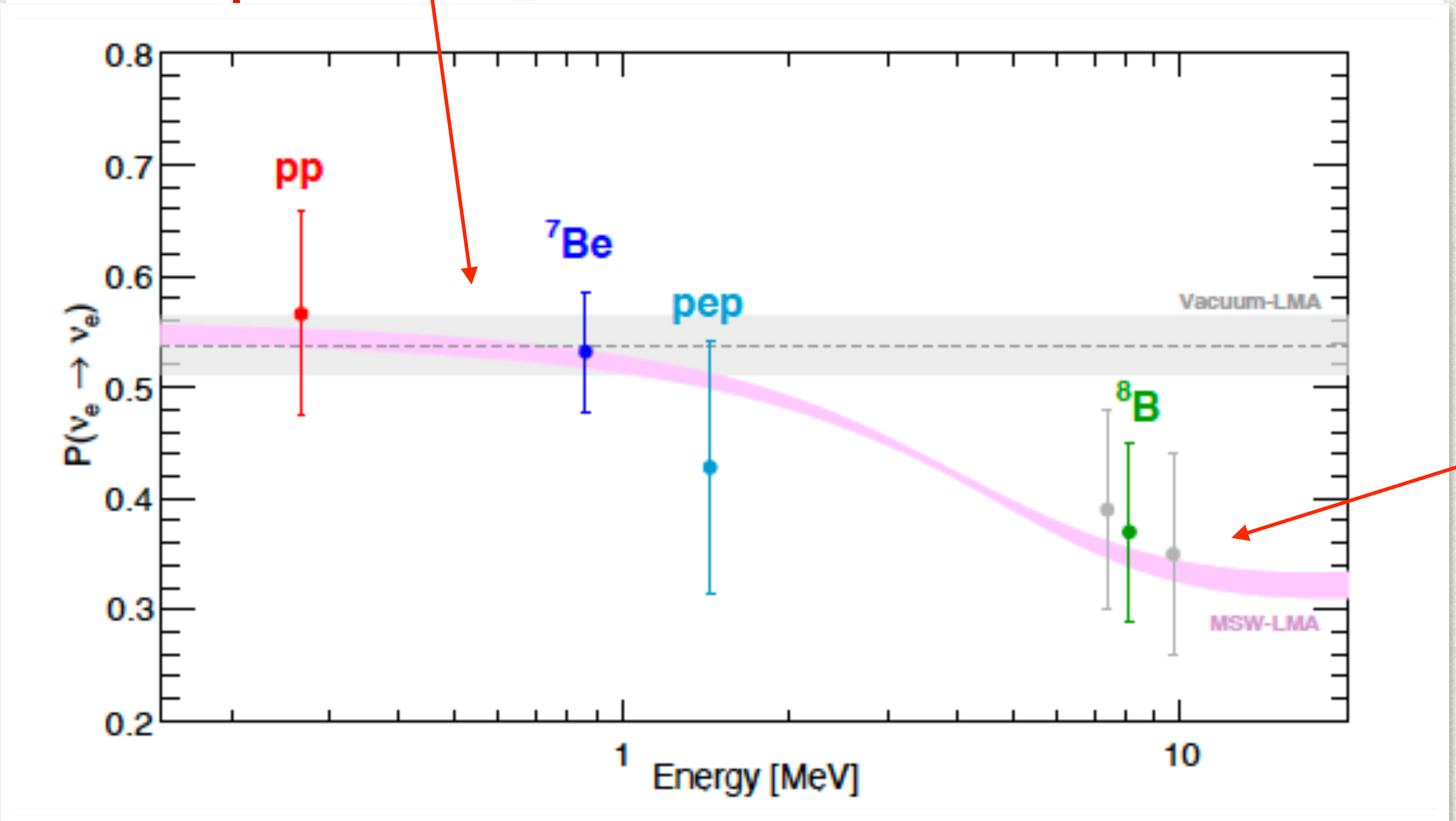
SNO

The solution of the Solar Neutrino Problem

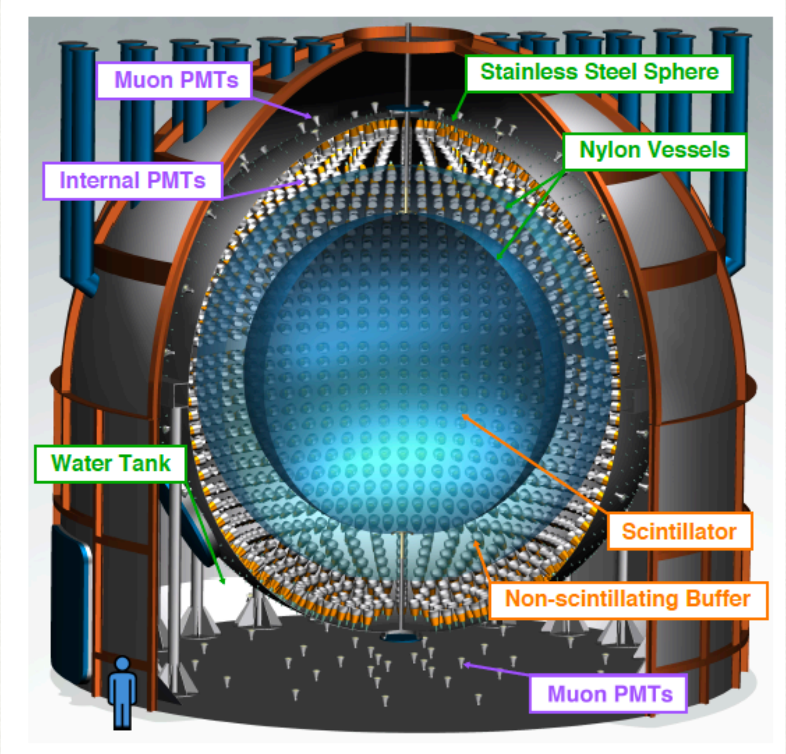
- The low energy pp neutrinos, from the keystone fusion reaction, pep, ^{7}Be measured.

Vacuum averaged oscillations

$$P(\nu_e \to \nu_e) \approx 1 - \frac{1}{2}\sin^2 2\theta_{12} \approx 0.57$$



Borexino Collaboration, arXiv:2105.13858



Borexino detector
280 tons liquid scintillator

$\nu_\alpha + e \to \nu_\alpha + e$

MSW solution

$$P(\nu_e \to \nu_e)^{\text{high density}} \to \sin^2\theta_{12} \approx 0.31$$

thanks for Super-Kamionande discovery of neutrino oscillations in vacuum, SNO measurement of the total solar neutrino flux, KamLAND measurement, but also thirty years of searches and combined data fit and Borexino results for low energy solar neutrinos

CONCLUSIONS

Neutrino astrophysics brought milestones in astrophysics and for fundamental physics.
The solar neutrino problem is solved, with the discovery that neutrinos change flavor in vacuum in an oscillatory way, the measurement of the total flux from the Sun and the identification of the Large-Mixing-Angle (LMA) solution.

Oscillation parameters measured precisely, except Majorana CP violating phases and the Dirac one.
Key open questions include the neutrino nature, the neutrino absolute mass and mass ordering, the origin of the neutrino mass, the neutrino magnetic moment, …

Flavor evolution in vacuum and in the Sun or the Earth well understood
- the Mikheev-Smirnov-Wolfenstein effect.

How neutrinos evolve in dense environments is an open question, where important developments are ongoing.

Helioseismology

Neutrinos and helioseismology probe the Sun's interior.

Neutrinos fluxes are sensitive to the core interior temperature.

Helioseismology studies solar oscillations.

Haxton, Serenelli, Robertson, arXiv:1208.5723

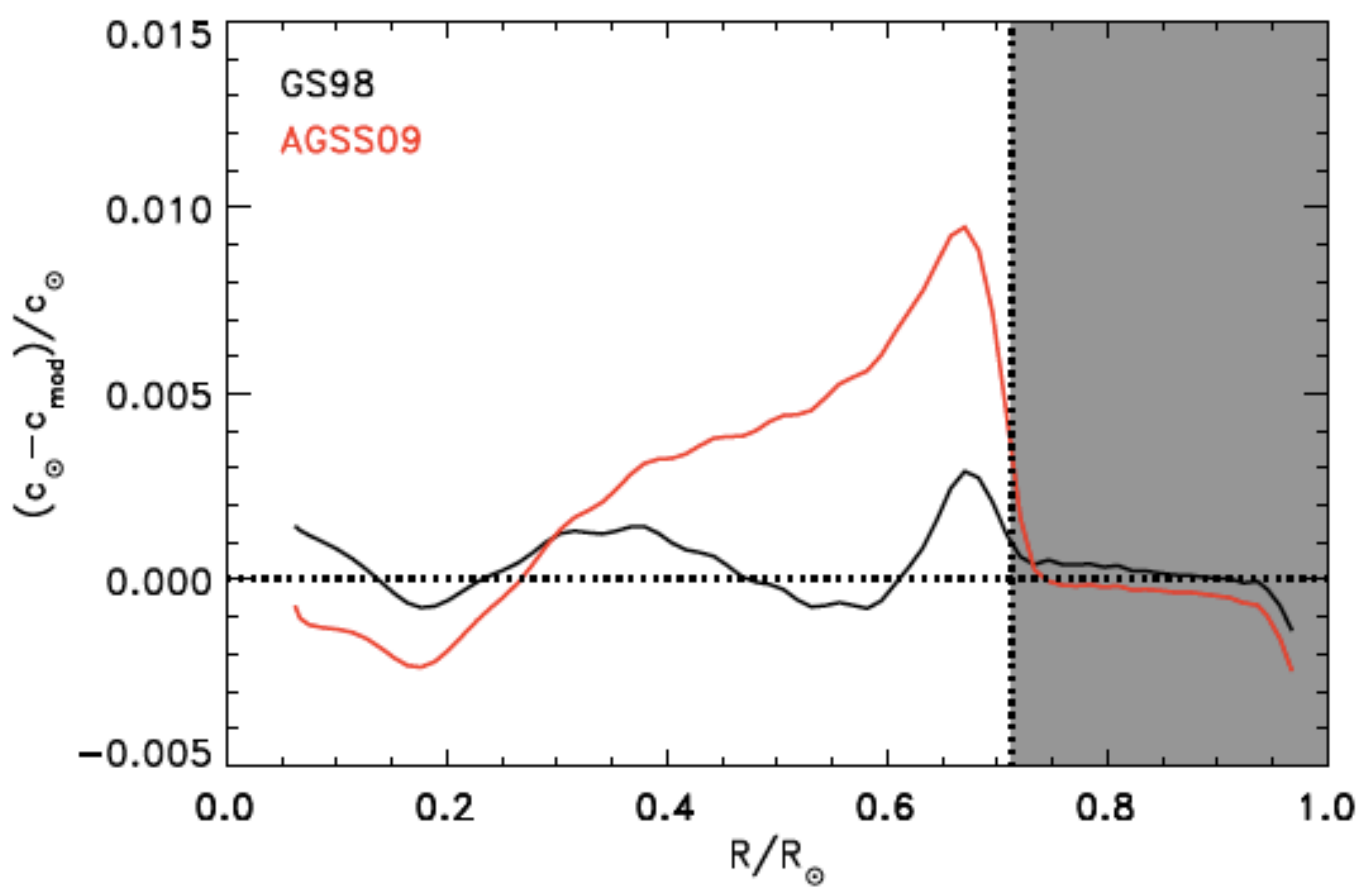


Figure 5: (Color online) The relative sound speed $(c(r)_{\rm solar} - c(r)_{\rm SSM})/c(r)_{\rm SSM}$ where $c(r)_{\rm SSM}$ is the SSM result and $c(r)_{\rm solar}$ the solar profile extracted from BiSON data. The black and red profiles correspond to the high-metallicity GS98-SFII and low-metallicity AGSS09-SFII SSMs, respectively.

Helioseismology

Helioseismology constrains the Sun's density and pressure profiles and determines the boundary between the boundary of the radiative and the convective zones.

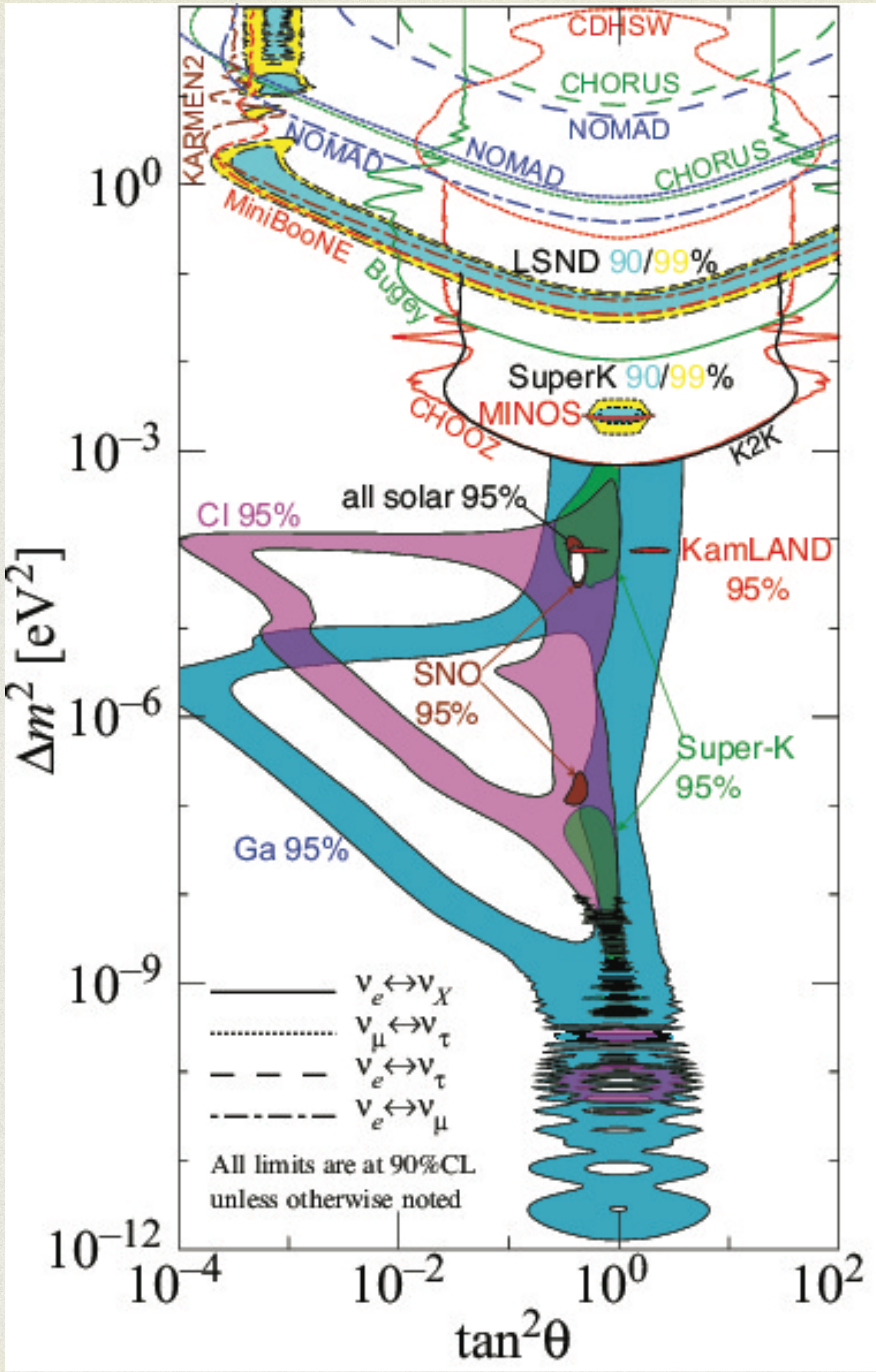
Confirms the Standard Solar Model (SSM) :
GS98 (high metallicity)

Haxton, Serenelli, Robertson, arXiv:1208.5723

Table 1: SSM characteristics are compared to helioseismic values, as determined by Basu & Antia (1997, 2004). X, Y, and Z are the mass fractions in H, He, and metals. The subscripts S, C, and ini denote current photospheric, current core, and zero-age values. R_{CZ} is the radius to the convective zone, and $\langle \delta c/c \rangle$ is the average fractional discrepancy in the sound speed, relative to helioseismic values.

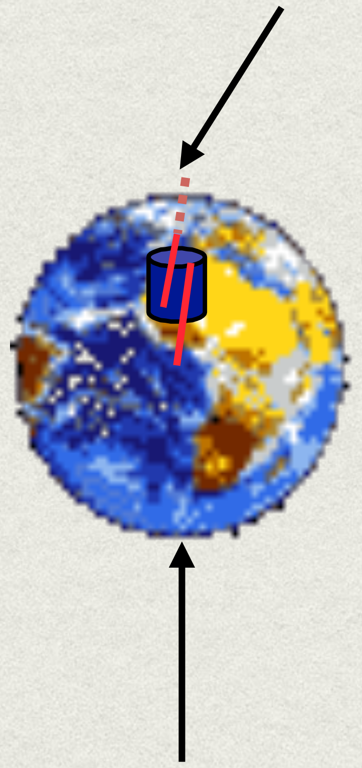
Property	GS98	AGSS09	Solar
$(Z/X)_S$	0.0229	0.0178	–
Z_S	0.0170	0.0134	–
Y_S	0.2429	0.2319	0.2485±0.0035
$R_{CZ}/R_\odot$	0.7124	0.7231	0.713±0.001
$\langle \delta c/c \rangle$	0.0009	0.0037	0.0
Z_C	0.0200	0.0159	–
Y_C	0.6333	0.6222	–
Z_{ini}	0.0187	0.0149	–
Y_{ini}	0.2724	0.2620	–

An example of the exclusion curves and contours in (Δm², theta) from the different experiments



Results from all data (PDG 2012)

The first series of important measurements



- 1998 : Super-Kamiokande discovers neutrino oscillations.
- 2000 : K2K confirms Super-Kamiokande result.
- 2002 : SNO measures the total (ν_e, ν_μ, ν_τ) solar neutrino flux.
- 2003 : KAMLAND determines the solar solution (LMA).
- 2006 : MINOS measures precisely the atmospheric Δm^2.
- 2007 and 2010 : Mini-BOONE does not rule out LSND.
- 2011-2 : T2K, Double-Chooz, Daya-Bay, RENO measure the third mixing angle.