Neutrino Physics

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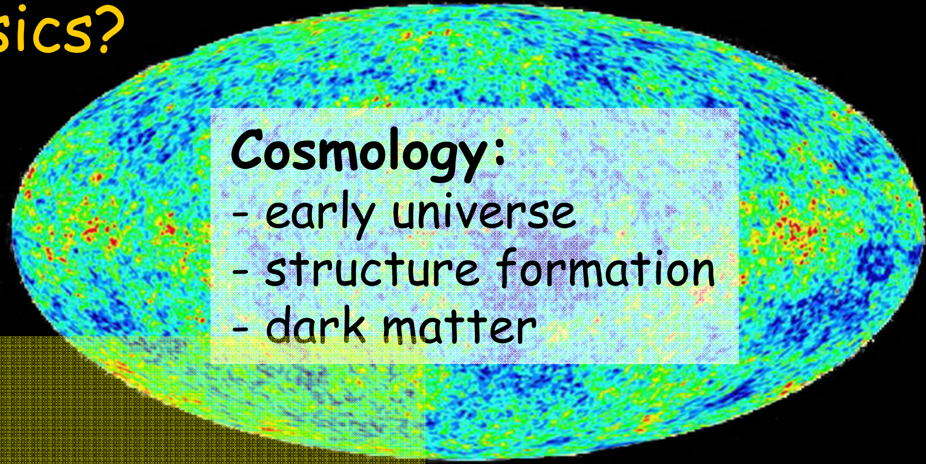
- What are neutrinos?
- Neutrino mass and mixing
- Neutrino oscillations
- Neutrino beams: OPERA
  Oscillation of accelerator neutrinos
- Solar Neutrinos: BOREXINO
- (KamLAND reactor neutrino experiment)
- Summary

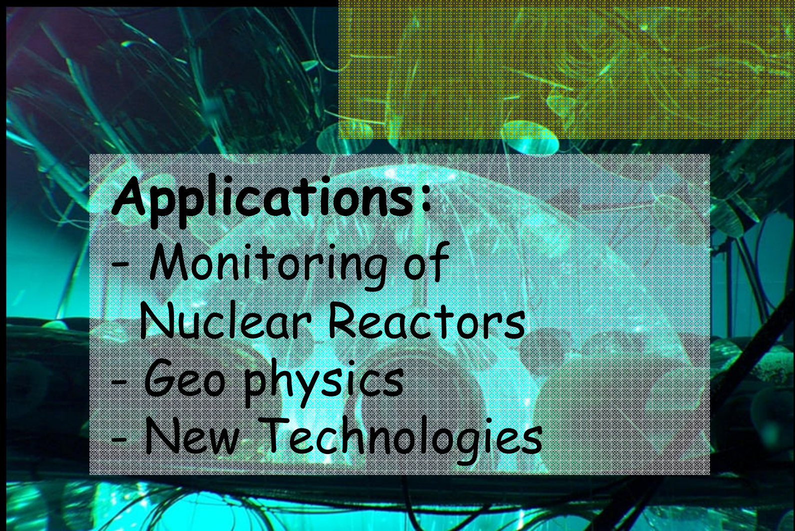
Why are we doing Neutrino Physics?

Elementary Particle Physics:
- Mass?
- Matter – antimatter symmetry
- Physics beyond the Standard Model

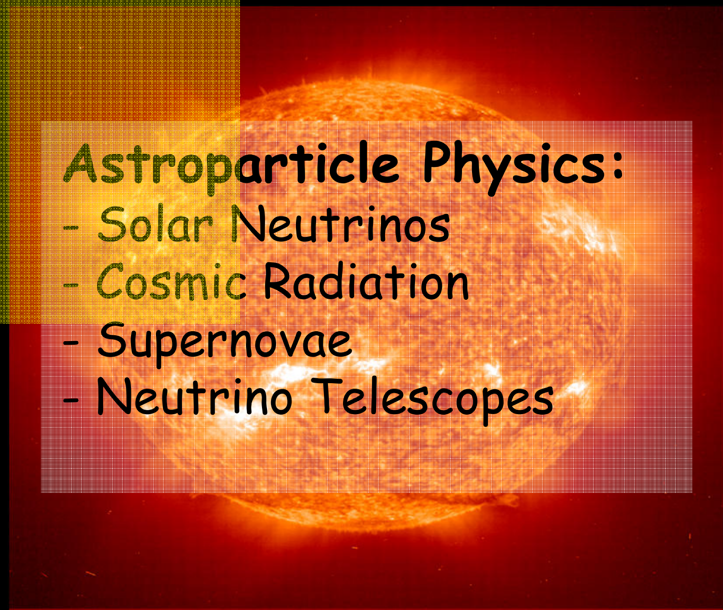


Cosmology:
- early universe
- structure formation
- dark matter

Neutrino Physics



Applications:
- Monitoring of Nuclear Reactors
- Geo physics
- New Technologies



Astroparticle Physics:
- Solar Neutrinos
- Cosmic Radiation
- Supernovae
- Neutrino Telescopes

Fundamental Particles

Quarks:

u	c	t
d	s	b

Leptons:

ν_e	ν_μ	ν_τ
e^-	μ^-	τ^-

Interactions by exchange of bosons:

Graviton, Photon, Gluon, W,Z

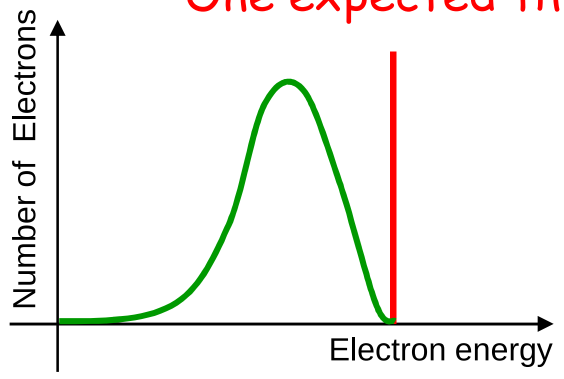
Wolfgang Pauli postulates the Neutrino (1930)

Energy spectrum of electrons from β-decay

$$n \rightarrow p + e^{-}$$

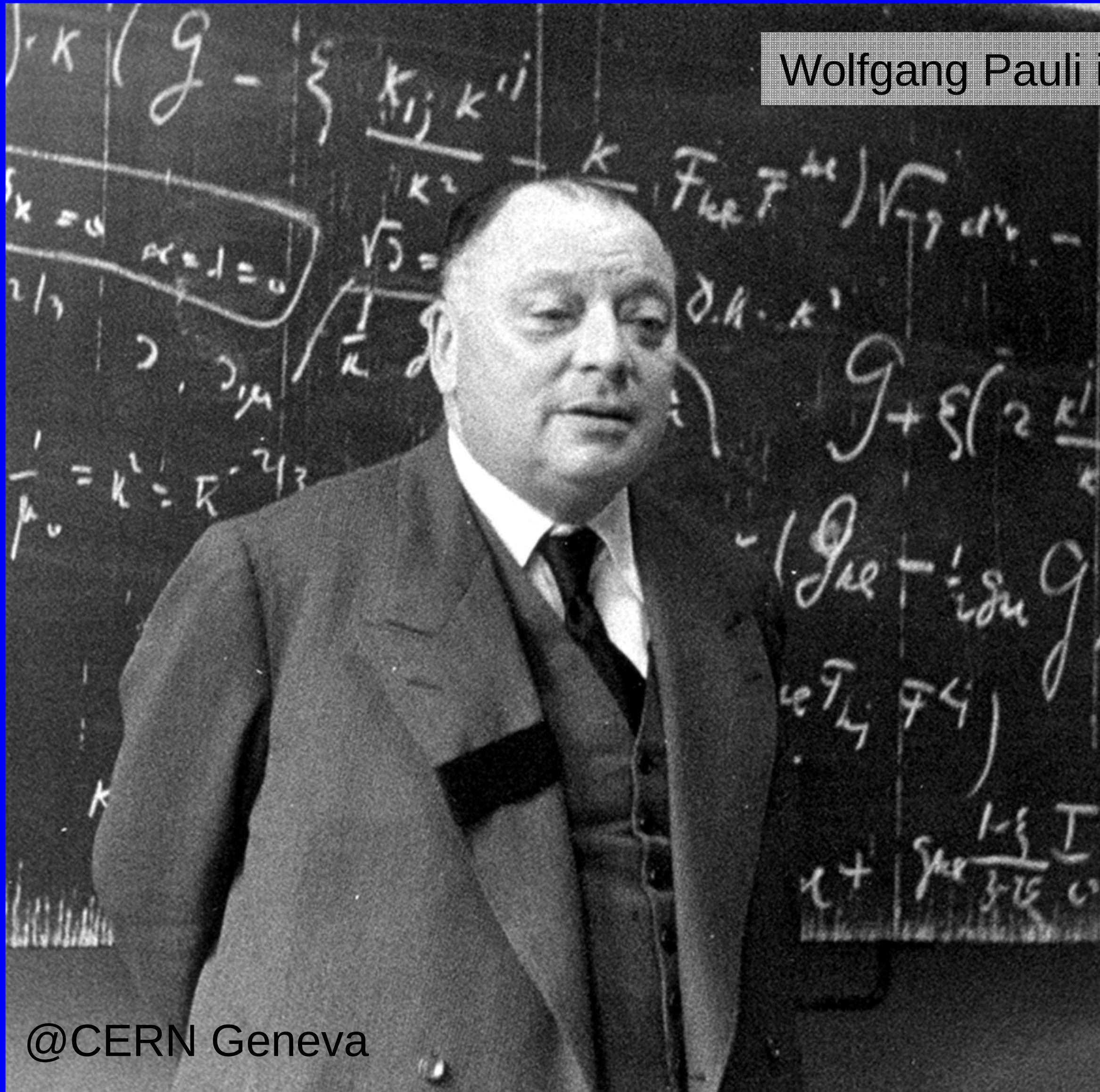
$$E_{electron} = m_n c^2 - m_p c^2$$

One expected this



But this was observed!

Solution:
The Neutrino

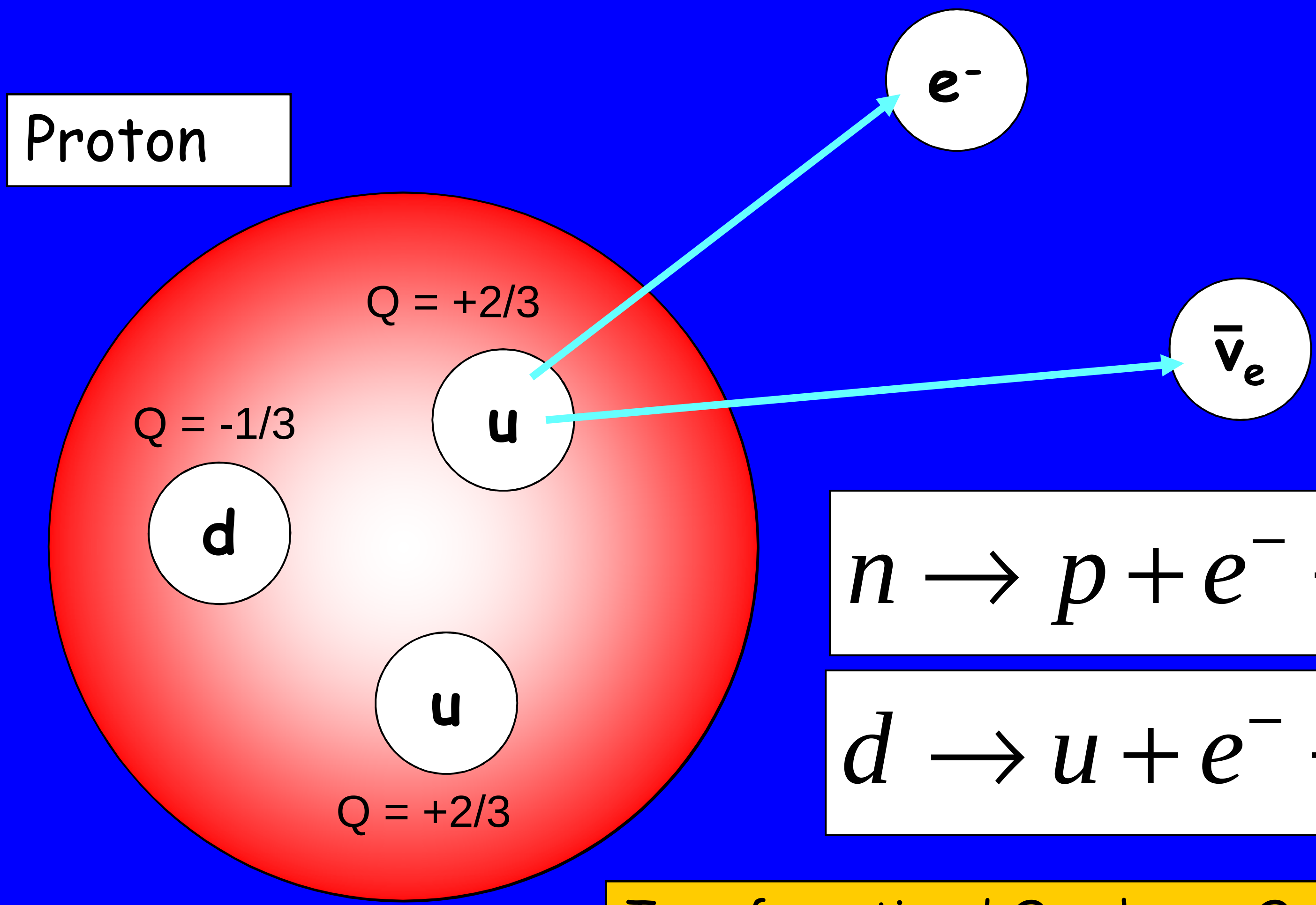


Wolfgang Pauli in Hamburg (1955)

1925 Kopenhagen

1922 Assistant at Universität Hamburg
1924 Habilitation in Hamburg (Discovery of the Exclusion Principle)

Decay of the Neutron - Birth of a Neutrino



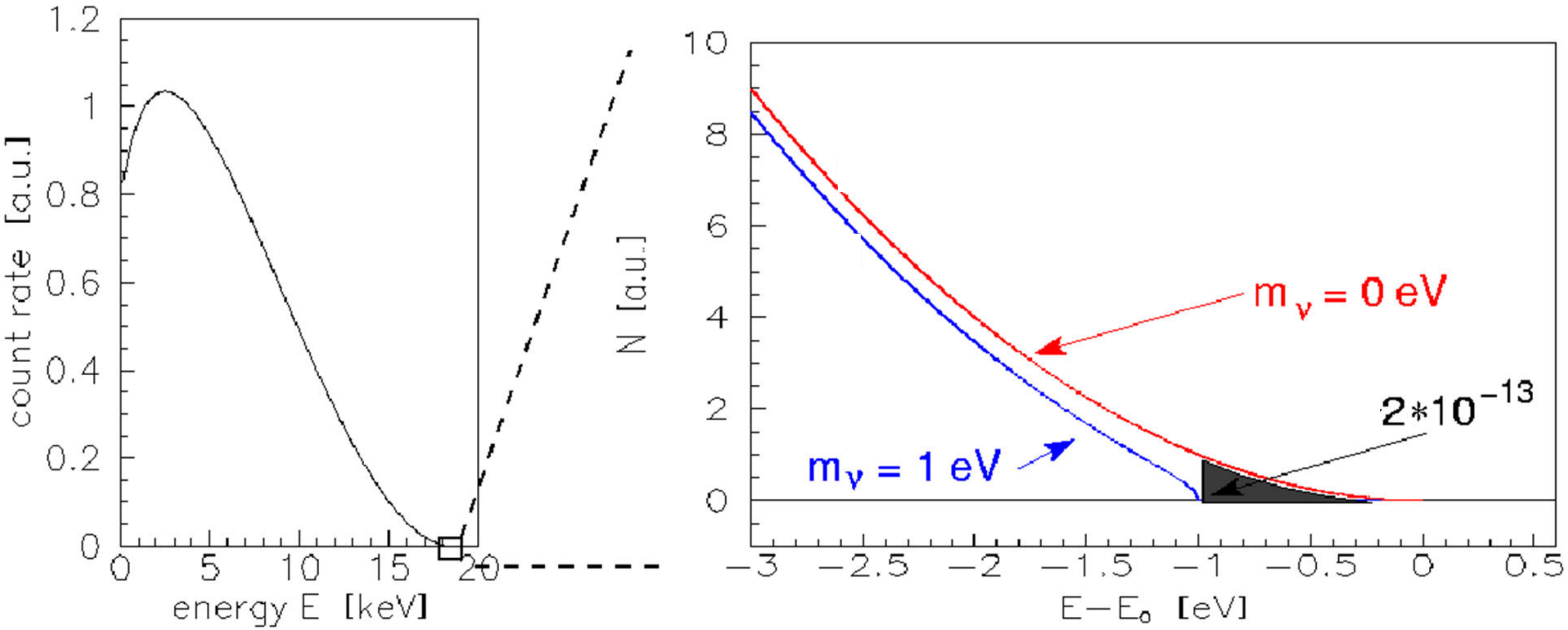
$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$d \rightarrow u + e^- + \bar{\nu}_e$$

Transformation d-Quark → u-Quark:
Electroweak Interaction!

Tritium β-Decay: Mainz/Troitsk

$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + \mathrm{e}^- + \overline{\nu}_e$$ E_0 = 18.6 keV



Mainz Data (1998,1999,2001)

$$\left\langle m^2 \right\rangle_\beta = -1.2 \pm 2.2 \pm 2.1 \ \mathrm{eV}^2 \quad \Rightarrow \ \left\langle m \right\rangle_\beta < 2.2\mathrm{eV} \ (95\%\mathrm{CL})$$

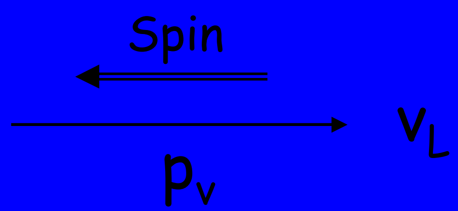
KATRIN: delivery of vacuum vessel (2008)

Goal:

$$\langle m \rangle_\beta < 0.20\ \mathrm{eV}$$

Neutrino Properties

- Neutral
- Fermions with Spin ½
- In the Standard Model:
  massless, stable, always left handed!

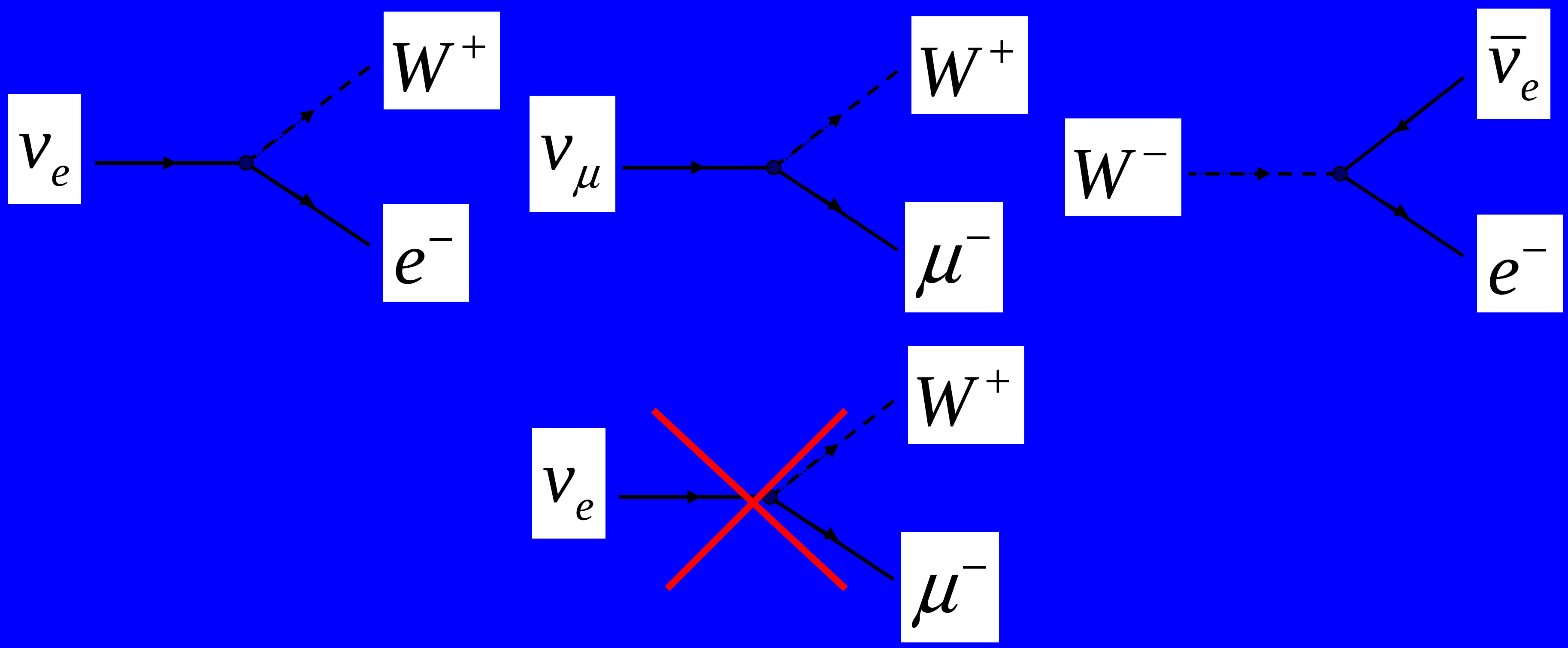


- **BUT:** Today we know that neutrinos have mass
  $0.05\ eV < m_\nu < 2\ eV$
  Standard Model must be extended!

How Neutrinos interact

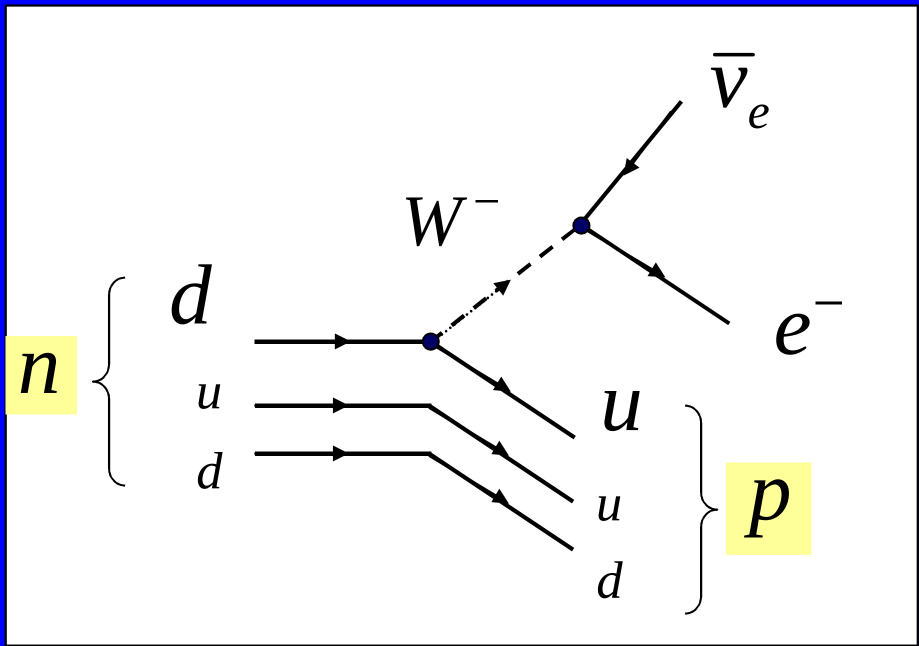
- The weak interaction

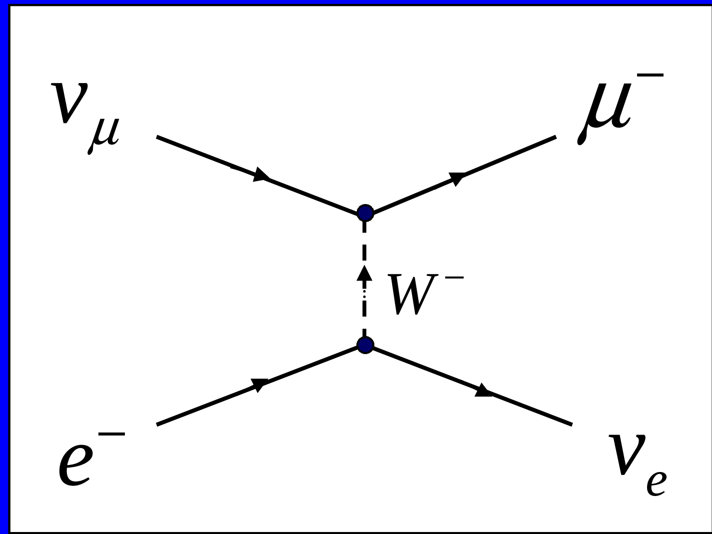
$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

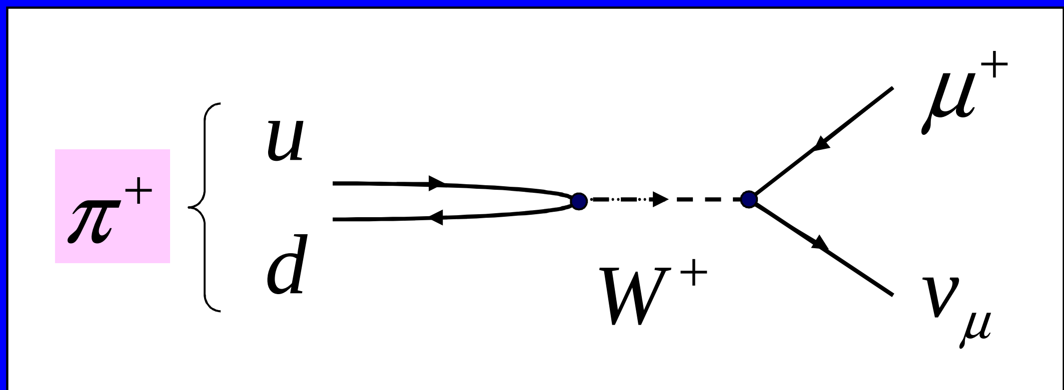


Charged Current

- Exchange of a W Boson:

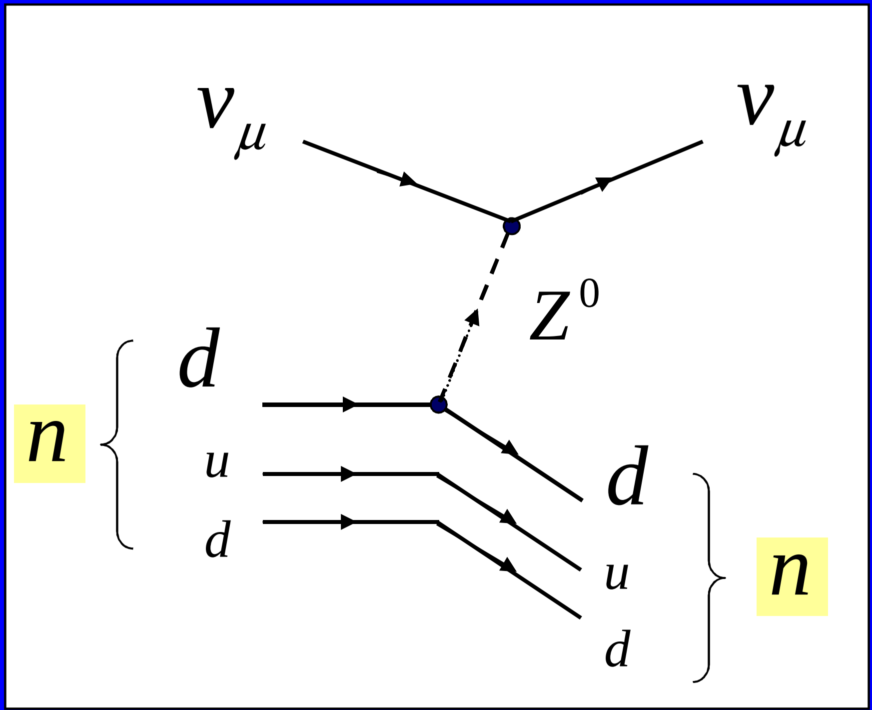


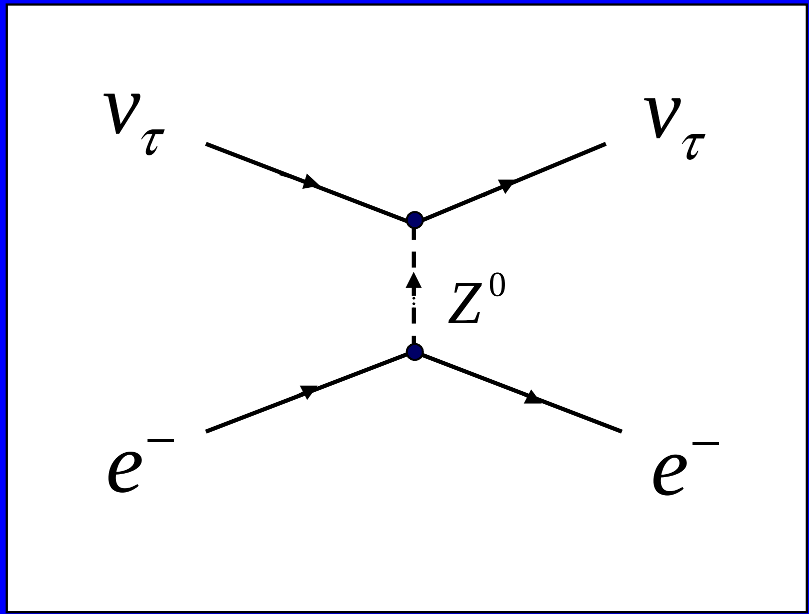




Neutral Current

- Exchange of a Z^0 Boson:





Neutrino mass and mixing

3 massive neutrinos: ν_1, ν_2, ν_3 with masses: m_1, m_2, m_3

Flavor-Eigenstates ν_e, ν_μ, ν_τ ≠ Mass-Eigenstates

Neutrino mixing!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

Parametrisation of Neutrino Mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

- 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- 1 Dirac-phase (CP violating): δ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{atm} | θ_{13}, δ | θ_{sol}

Θ_{23}: 34° - 58°

θ_{13}<13°, δ ?

θ_{12}: 29° - 39°

Neutrino Mixing for 2 Flavors

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

$$|\nu_\mu\rangle = \cos\theta_{23} |\nu_2\rangle + \sin\theta_{23} |\nu_3\rangle$$

The probability that ν_μ has mass m_2 is $\cos^2\theta_{23}$

mixing angle → probability to have a certain mass

Today we know that $\theta_{23} \approx 45°$:

$$|\nu_\mu\rangle = \tfrac{1}{2}\left(|\nu_2\rangle + |\nu_3\rangle\right) \qquad |\nu_\tau\rangle = \tfrac{1}{2}\left(-|\nu_2\rangle + |\nu_3\rangle\right)$$

e.g. probability that ν_μ has mass m_2: 50%

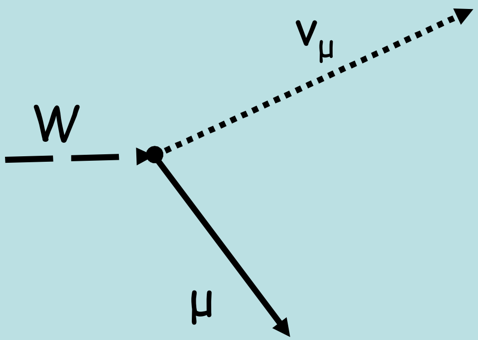
Neutrino Oscillations

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta_{23} & \sin\theta_{23} \\ -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

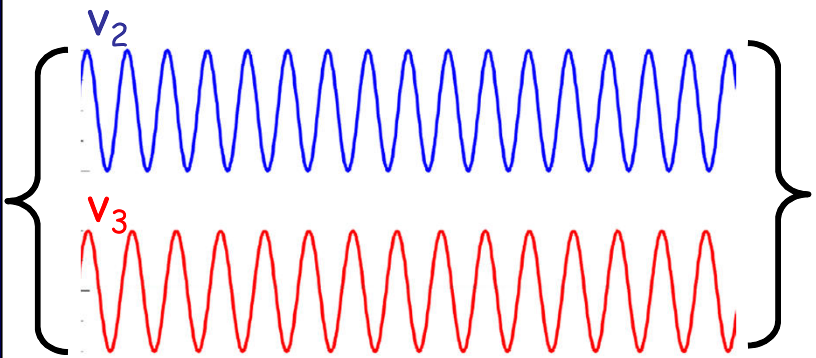
Flavor eigenstates ν_μ, ν_τ

Mass eigenstates ν_2,ν_3
with m_2, m_3

source creates
flavor-eigenstates



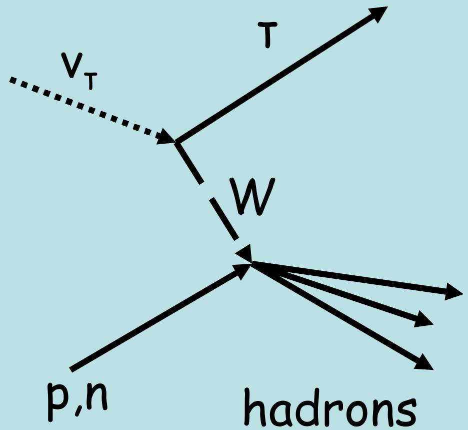
propagation determined by
mass-eigenstates



$$\omega_{2,3} = E_{2,3} = \sqrt{p^2 + m_{2,3}^2}$$

slightly different frequencies
→ phase difference changes

detector sees
flavor-eigenstates



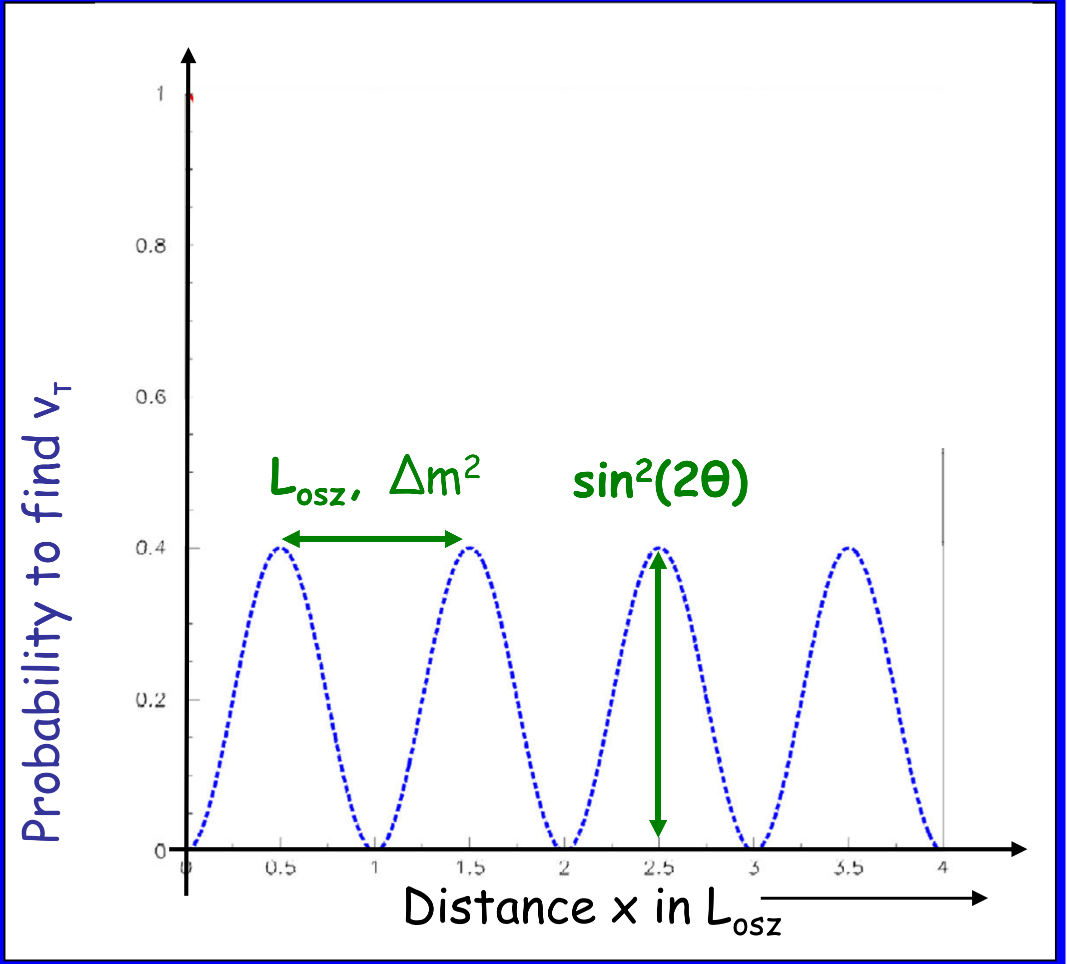
2 Flavor Neutrino Oscillations

<u>Oscillation probability</u>

$$P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta_{23}) \cdot \sin^2\left(\pi \frac{x}{L_{osz}}\right)$$

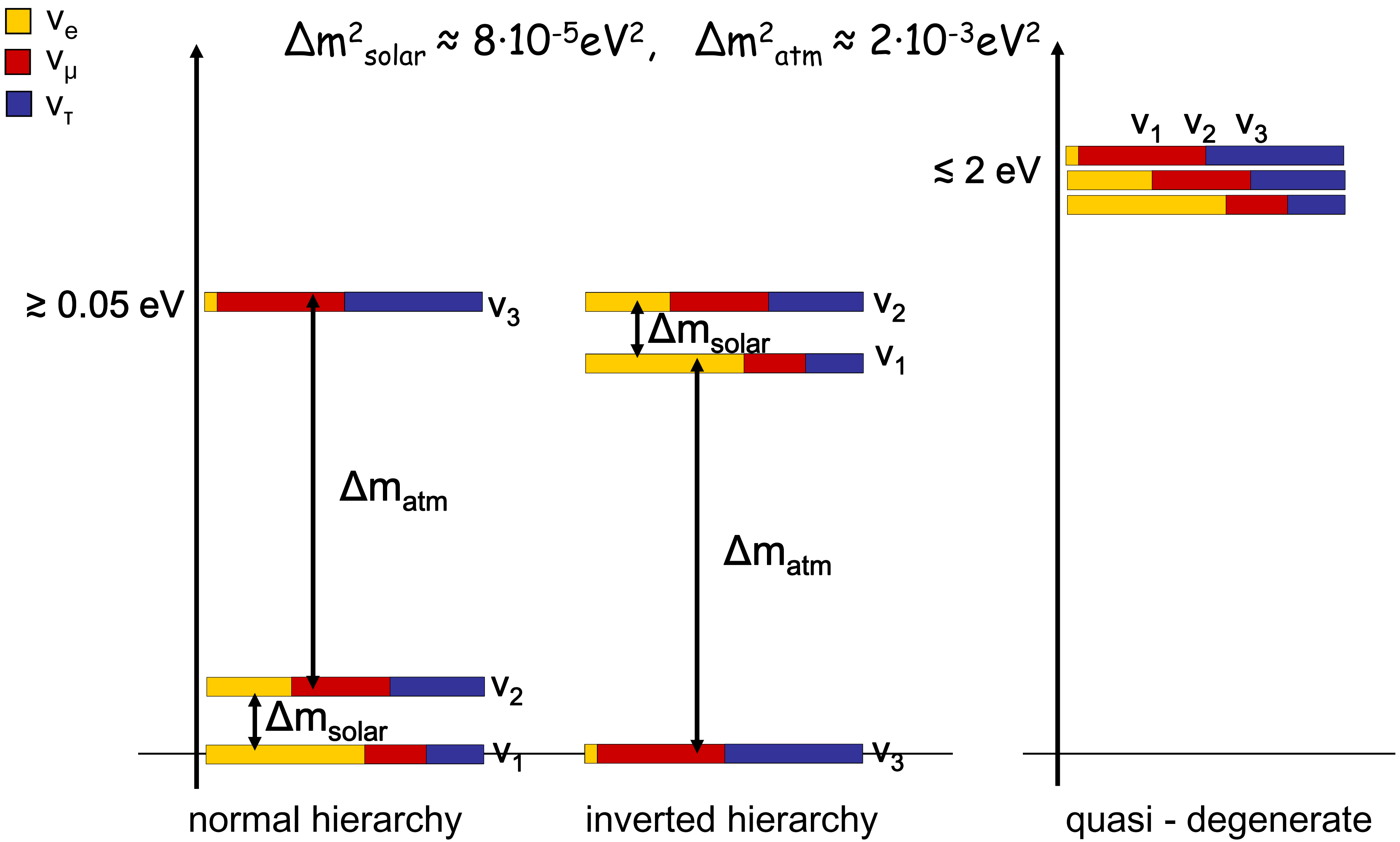
$$L_{osz}(\text{in km}) = \frac{2.48 \cdot E(\text{in GeV})}{\Delta m^2(\text{in eV}^2)}$$

$$\Delta m^2 = m_2^2 - m_3^2$$



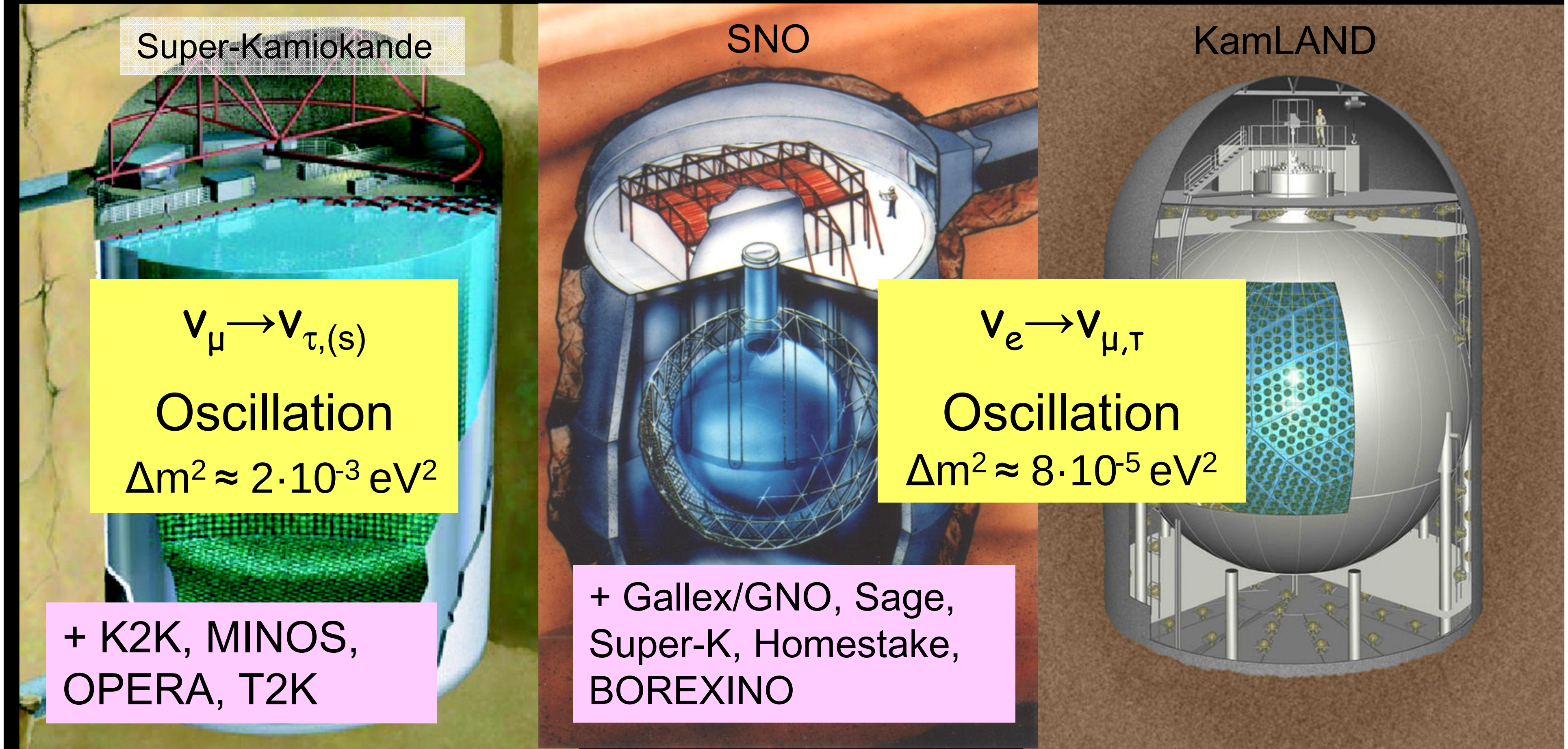
What do we know about neutrino masses?

$\Delta m^2_{solar} \approx 8 \cdot 10^{-5} eV^2, \quad \Delta m^2_{atm} \approx 2 \cdot 10^{-3} eV^2$



Neutrino Oscillations were observed
→ Neutrinos have mass!

JAPAN | CANADA | JAPAN



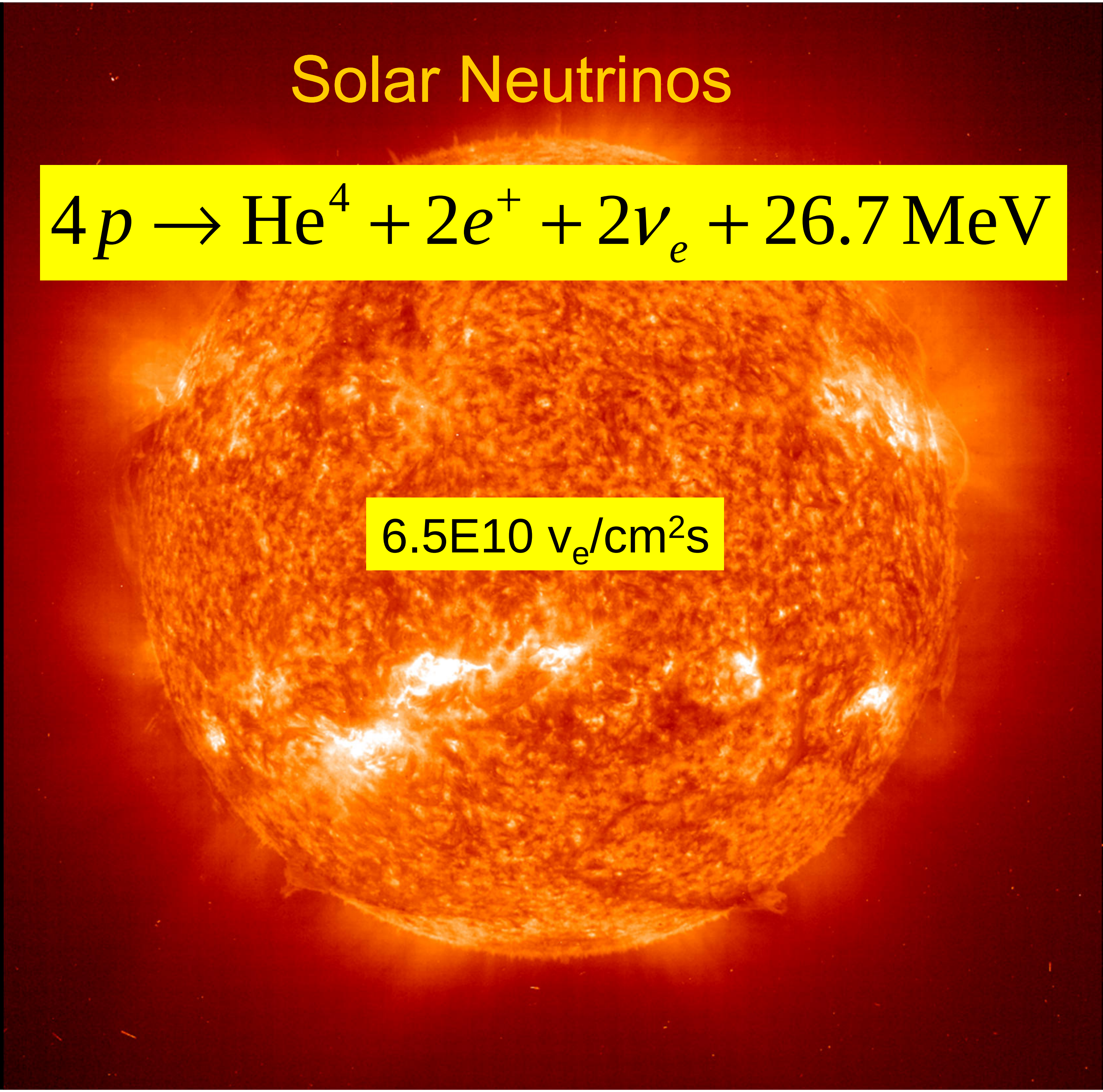
atmospheric neutrinos
accelerator neutrinos

solar neutrinos

reactor neutrinos

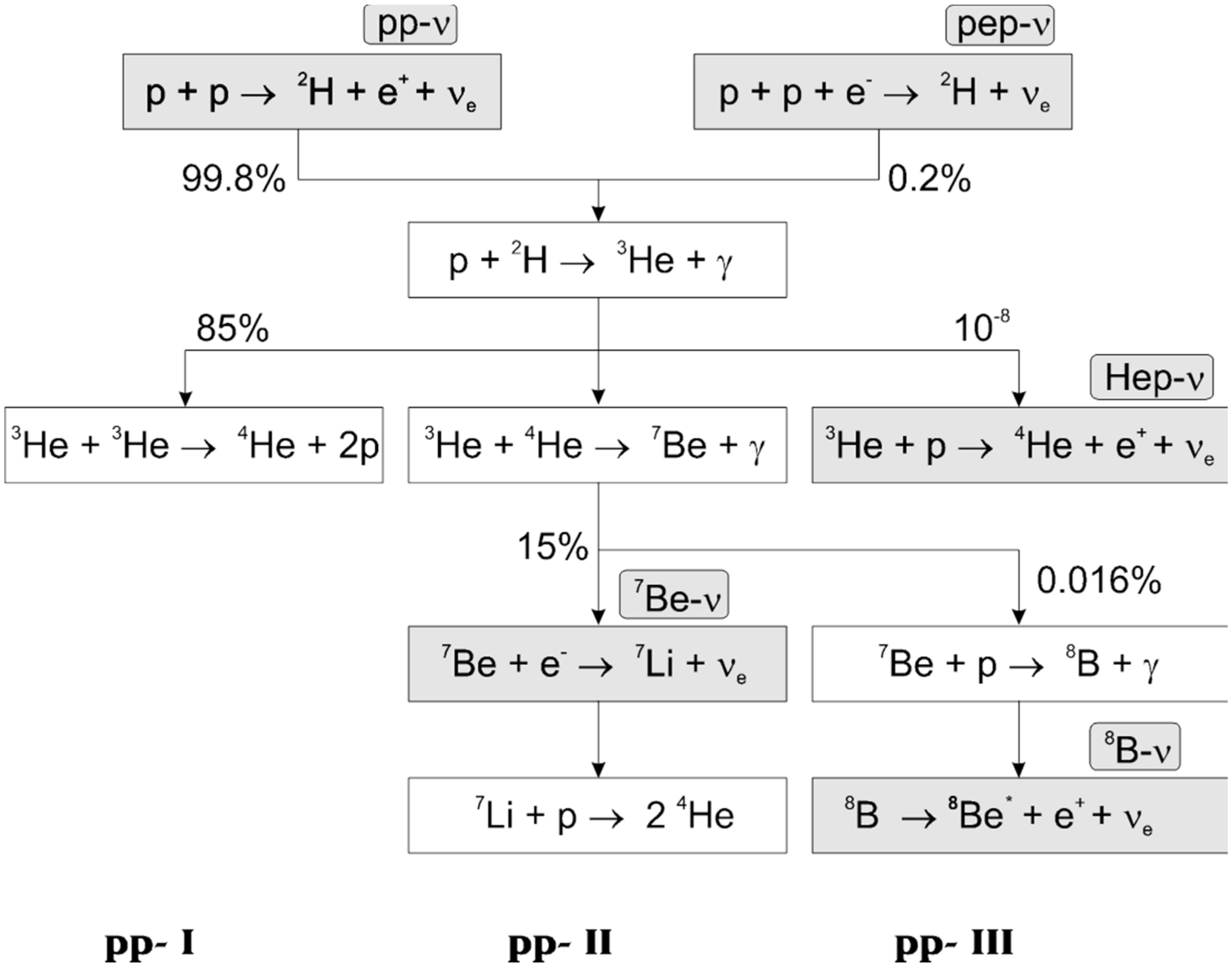
Solar Neutrinos

$$4p \rightarrow \mathrm{He}^4 + 2e^+ + 2\nu_e + 26.7\,\mathrm{MeV}$$

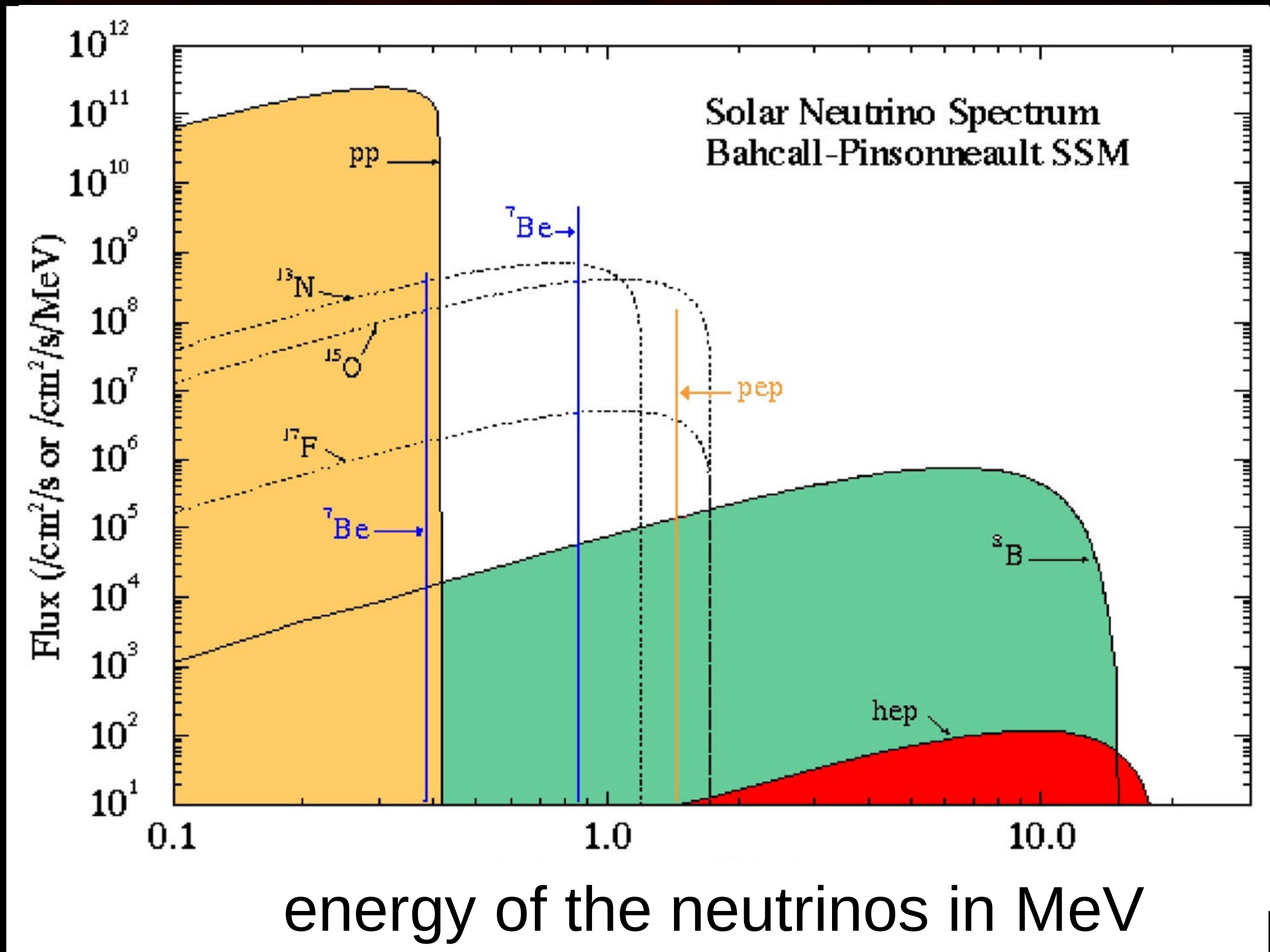


6.5E10 v_e/cm^2s

Neutrino Production in the Sun: The pp Cycle



Solar Neutrinos ($E_\nu \approx$ MeV)

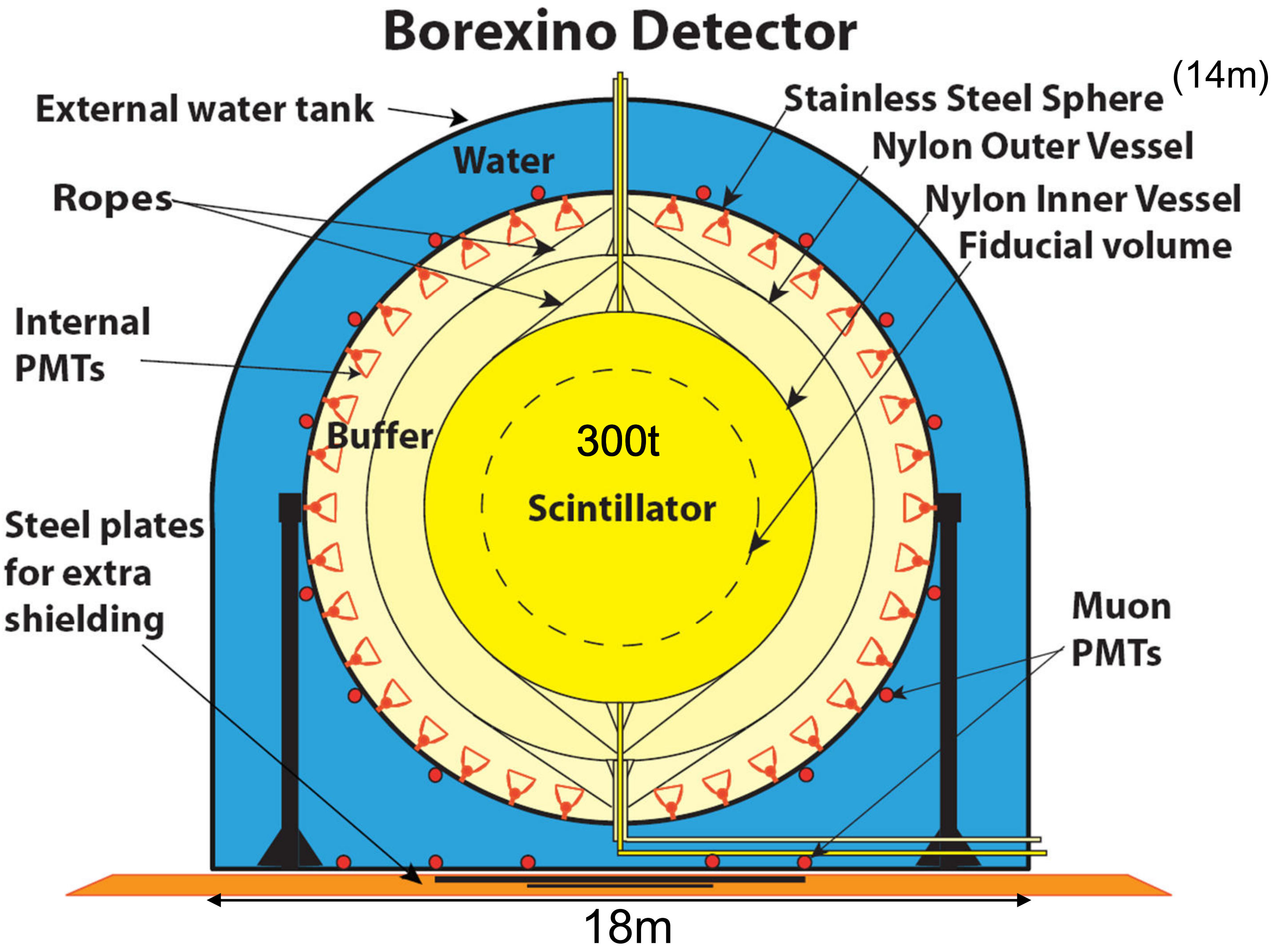


The Sun in Neutrino Light (Super-Kamiokande)

BOREXINO @ LNGS

Measurement of Flux of ^{7}Be Neutrinos

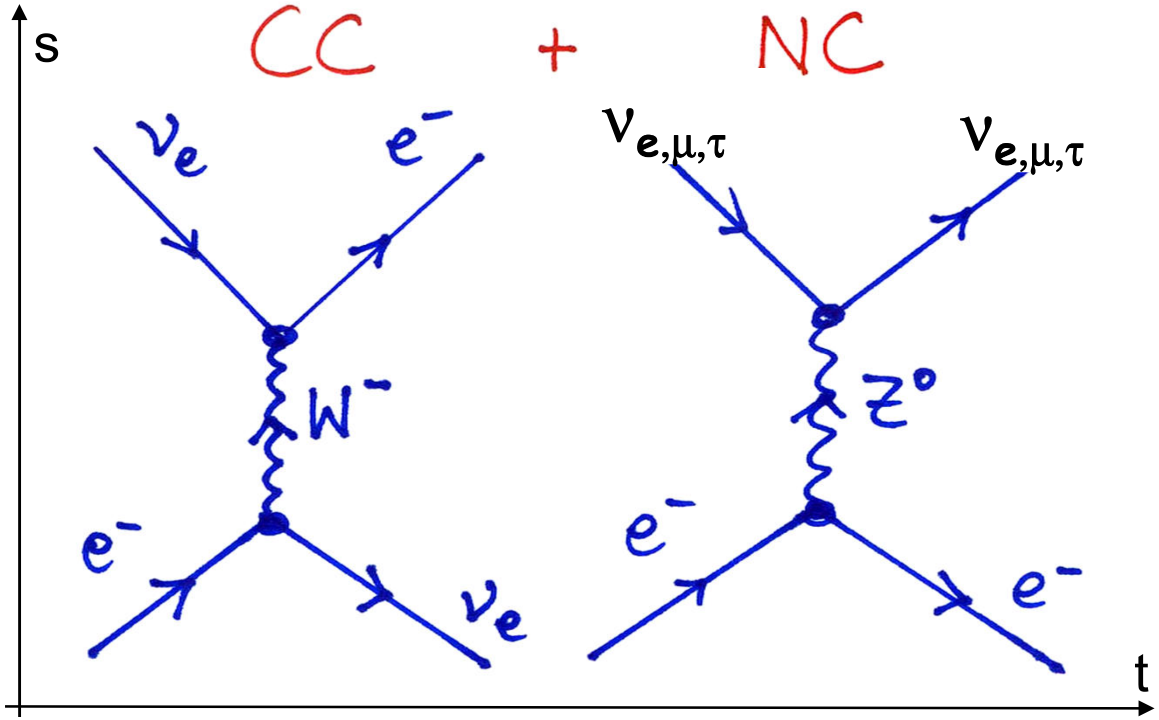
2200



Detection of solar neutrinos in BOREXINO: Elastic neutrino – electron scattering

$$\nu_x + e^- \rightarrow \nu_x + e^-$$ (dominated by ν_e)

(Kinematics like Compton effect)

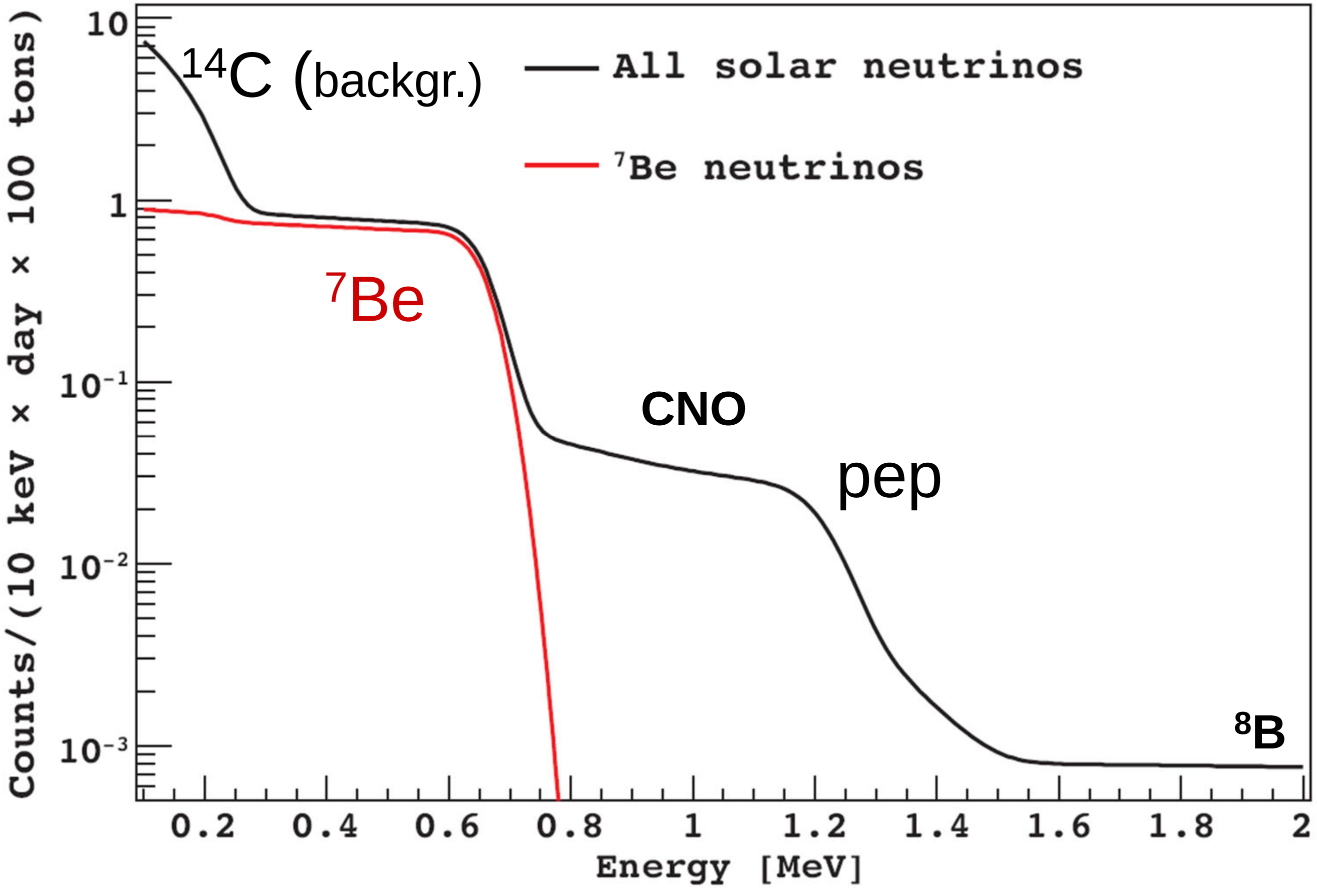


ν_e can interact via CC + NC

ν_μ and ν_τ can only interact via NC!

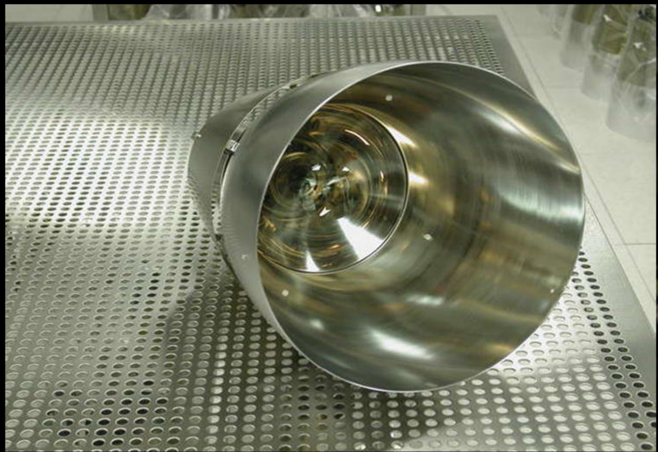
BOREXINO

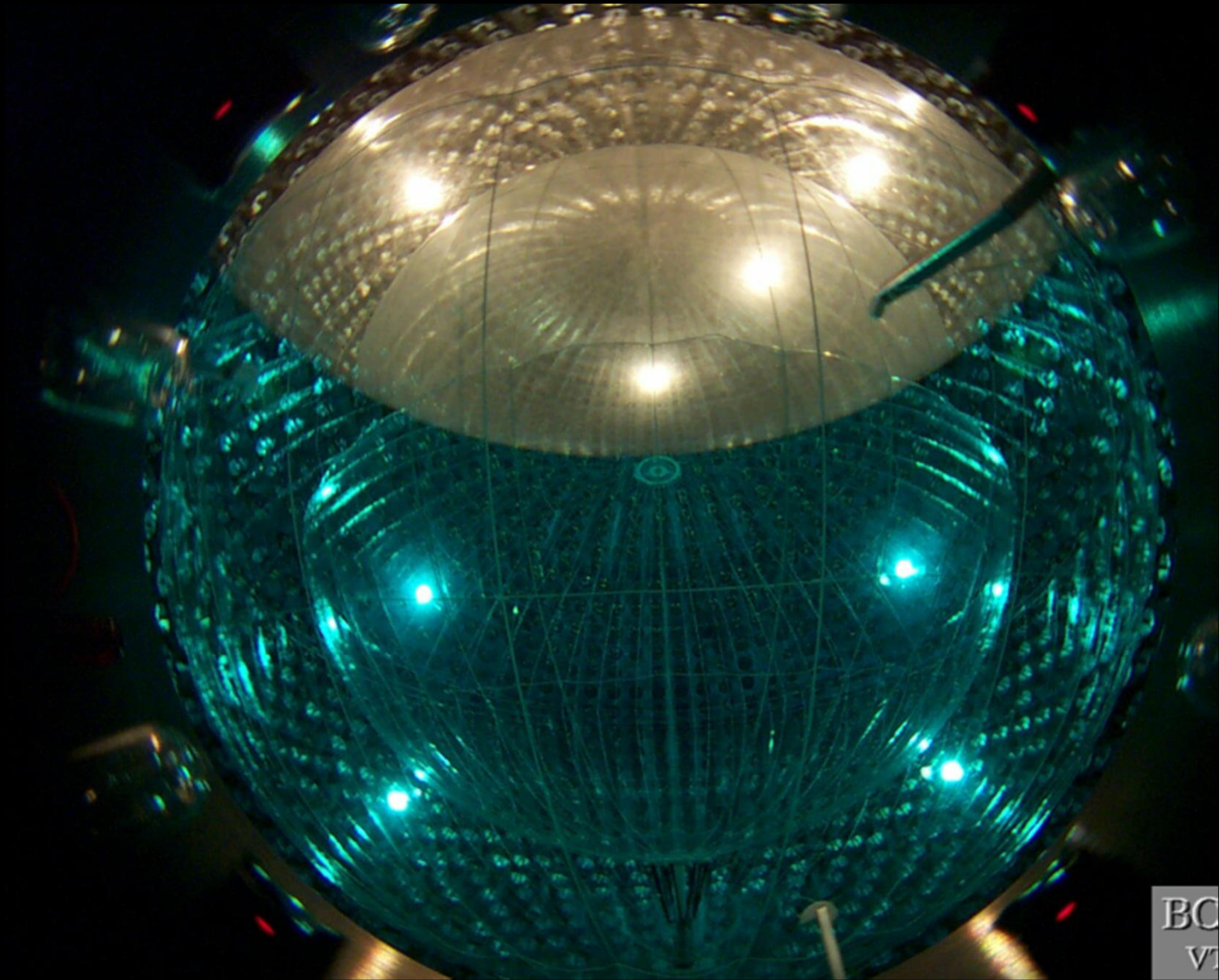
Expected (electron) energy distribution:



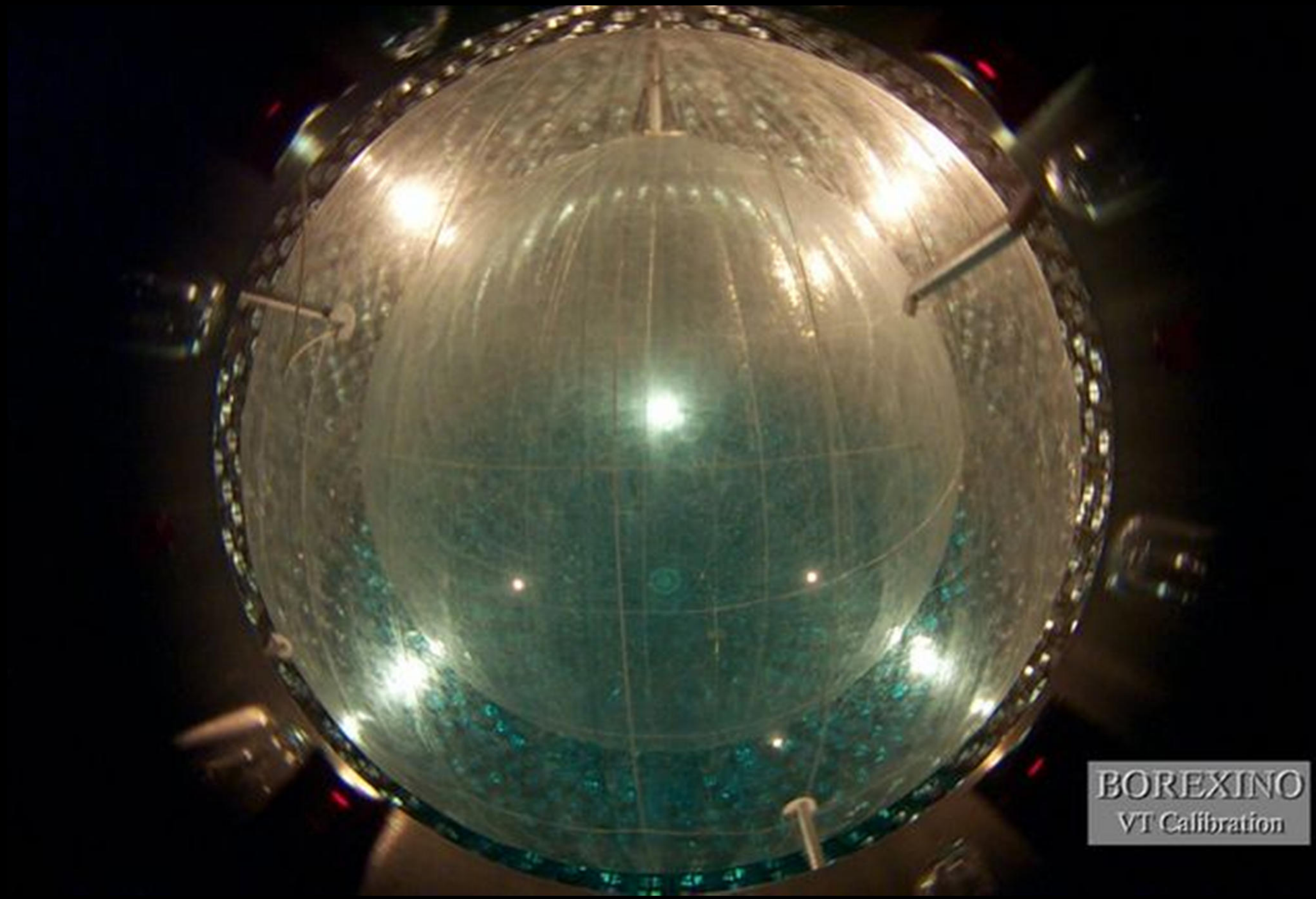
Edge at 665 keV

Photomultipliers and light concentrators in Borexino



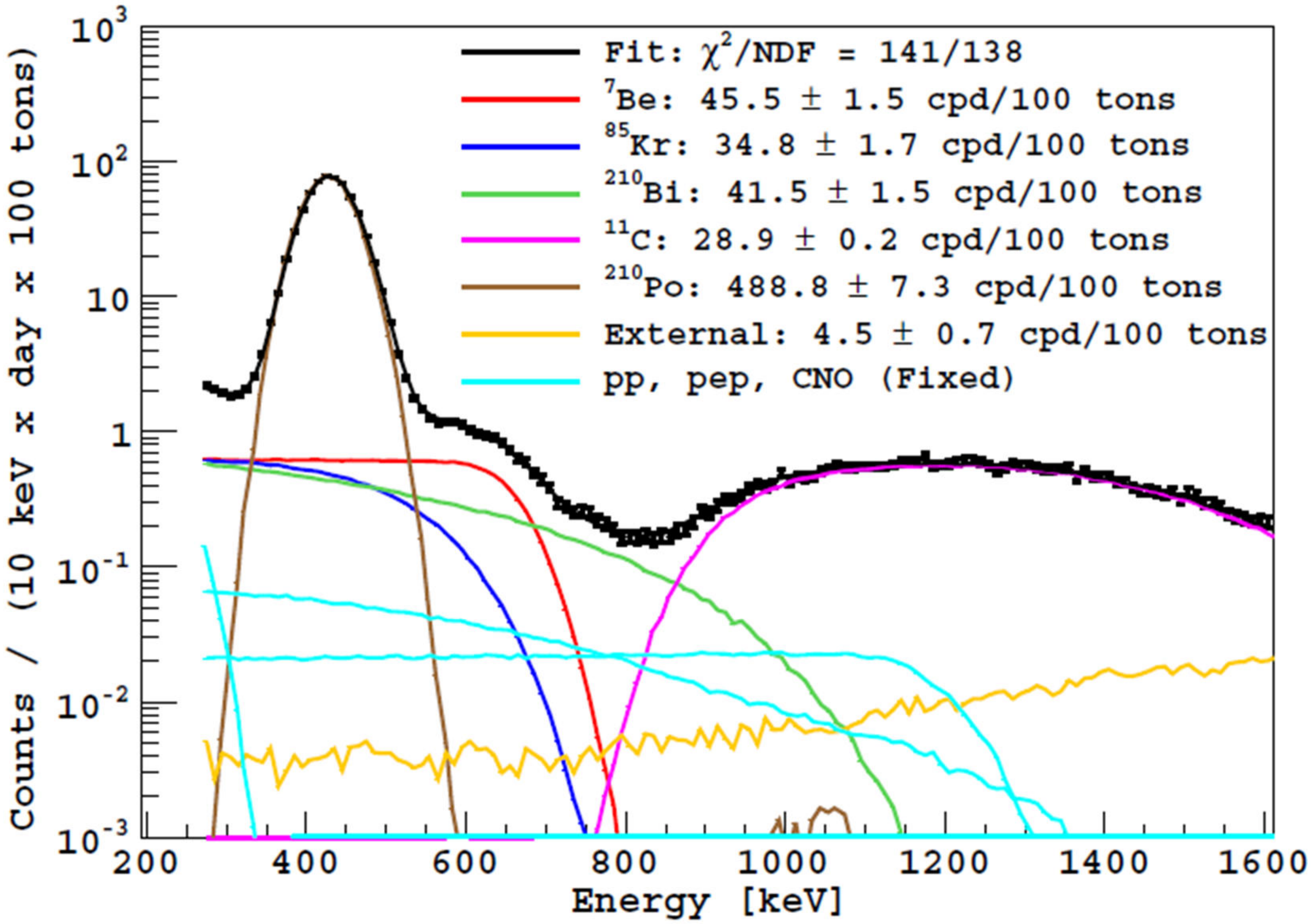


Borexino during filling (on top scintillator, lower part water)



Scintillator filling completed May 15, 2007

Borexino Result:



Borexino Coll. „precision measurement of the 7Be solar neutrino interaction rate in Borexino", arxiv:1104.1816

What can we learn from this?

46 ± 1.5stat ± 1.6sys cpd/100 t

<u>Prediction of standard solar model:</u>

No oscillation	74 ± 5	cpd/100 t
Oscillation (with $\theta_{12} \approx 33^o$):		
„high metalicity Solar Model“	47 ± 3	cpd/100t
„low metalicity Solar Model“	44 ± 4	cpd/100 t

„No-Oscillation“ is excluded from BOREXINO alone with more than 4.9 sigma.

$$\phi(^7\text{Be}) = (4.87 \pm 0.24) \times 10^9\,\text{cm}^{-2}\text{s}^{-1}$$

$$f(^7\text{Be}) = \phi(^7\text{Be}) / \phi_{\text{SSM}} = 0.97 \pm 0.05(\text{stat}) \pm 0.07(\text{syst})$$

$$f(\text{pp}) = 1.013^{+0.003}_{-0.010}$$

$$f_{\text{CNO}} < 1.7\%(95\%\text{CL})$$

Summary of Neutrino Oscillations

- Neutrino Oscillations have been observed with solar, atmospheric, reactor and accelerator neutrinos.
- Neutrinos have mass!
  The absolute neutrino mass has not yet been measured, allowed range: $0.05\ eV < m_\nu < 2\ eV$
- Neutrino mixing exists and is very different from quark mixing. Why?
- Measurements of third mixing angle have been started, hints that $\sin^2(2\theta_{13}) \approx 0.02$ (?).
- Is there CP-violation for neutrinos?
- Is the neutrino a Majorana particle?
  Search for neutrinoless Double-Beta Decay (Evidence?)