Solar Neutrinos & MSW Effect

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General Seminar Course

Nov. 2012 - IPM

Outline

- Introduction
- Neutrino Oscillation
- Solar Neutrinos
- Solar Neutrino Experiments
- Conclusions
- Summary

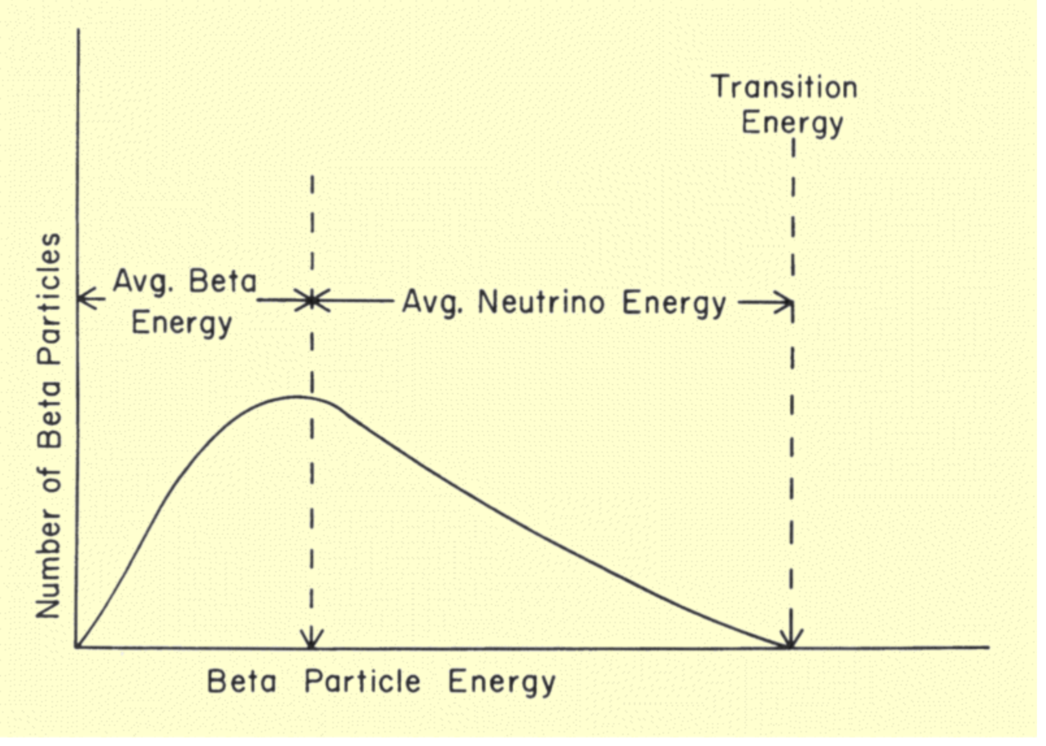
Introduction

Introduction

- History
- Standard Model
- Neutrino Interactions
- Neutrino Sources

History

- 1914, Chadwick, β-spectrum continuous
  α- and γ-rays unique in energy



http://en.wikipedia.org/wiki/Beta_decay

History

- N. Bohr: statistical energy conservation
- 1930, W. Pauli: neutron

I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist shouldever do.
Wolfgang Pauli

History

- N. Bohr: statistical energy conservation
- 1930, W. Pauli: neutron
- 1933, E. Fermi: neutrino, massless
- 1942, Wang Ganchang: proposed detection
- 1956, Reines & Cowan: Detected

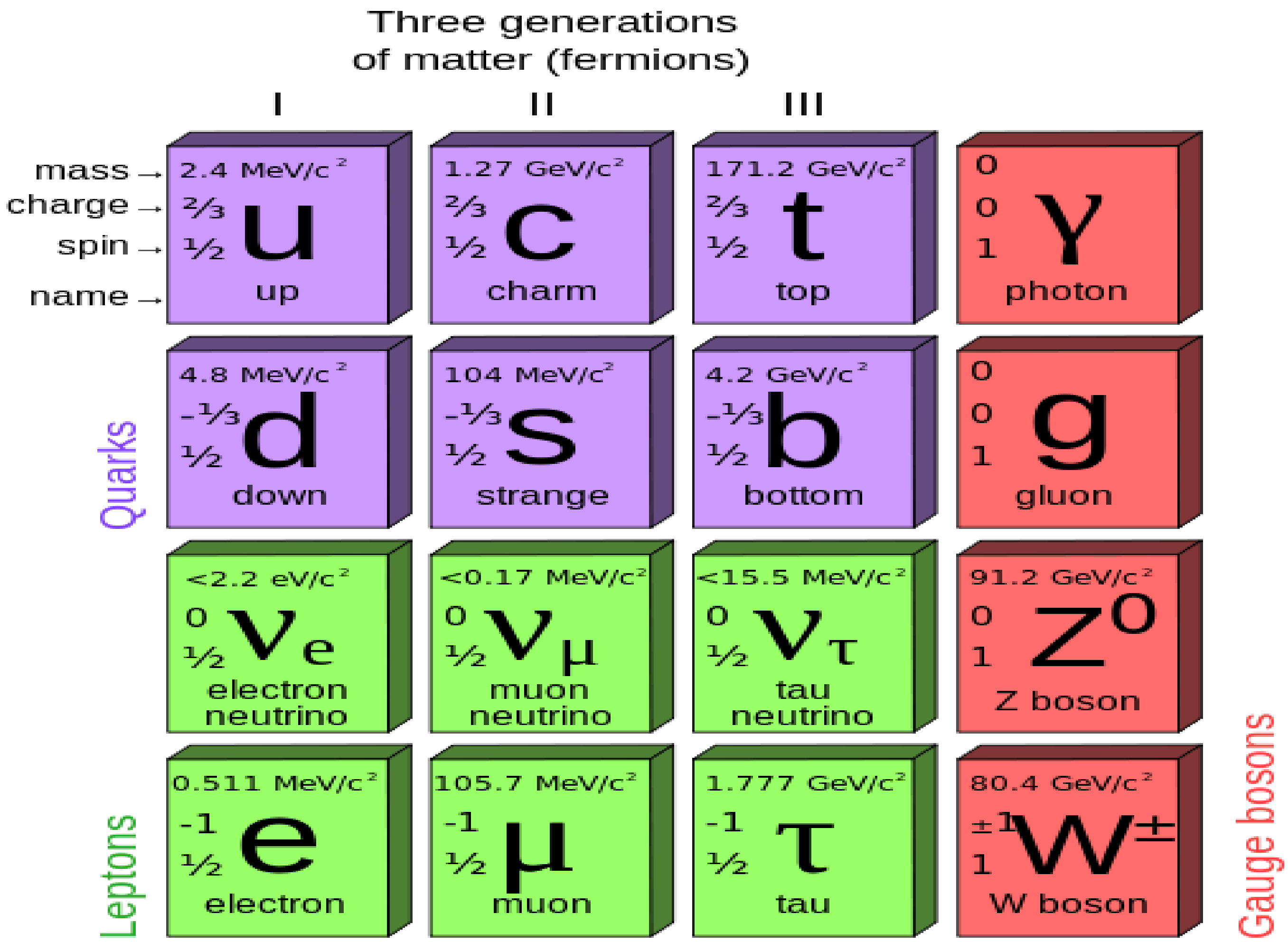
$$\nu_- + p \to n + \beta^+,$$

ON THE DETECTION OF THE FREE NEUTRINO*

F. Reines and C. L. Cowan, Jr.

Los Alsmos Scientific Laboratory

Standard Model



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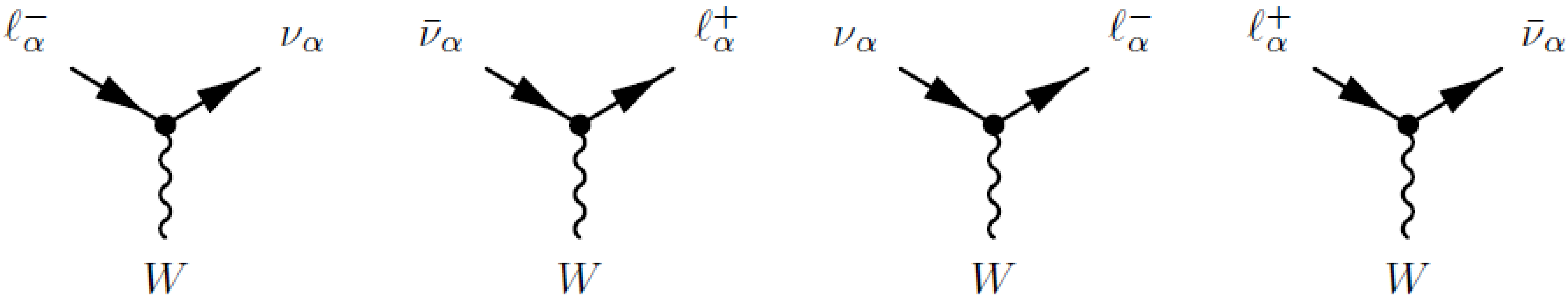
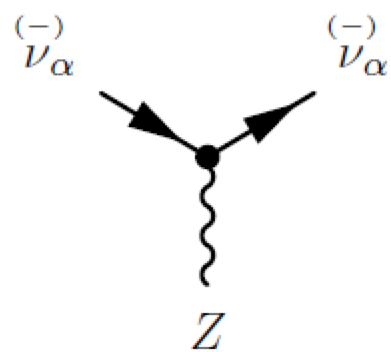
Neutrino Interactions

- Charged Current



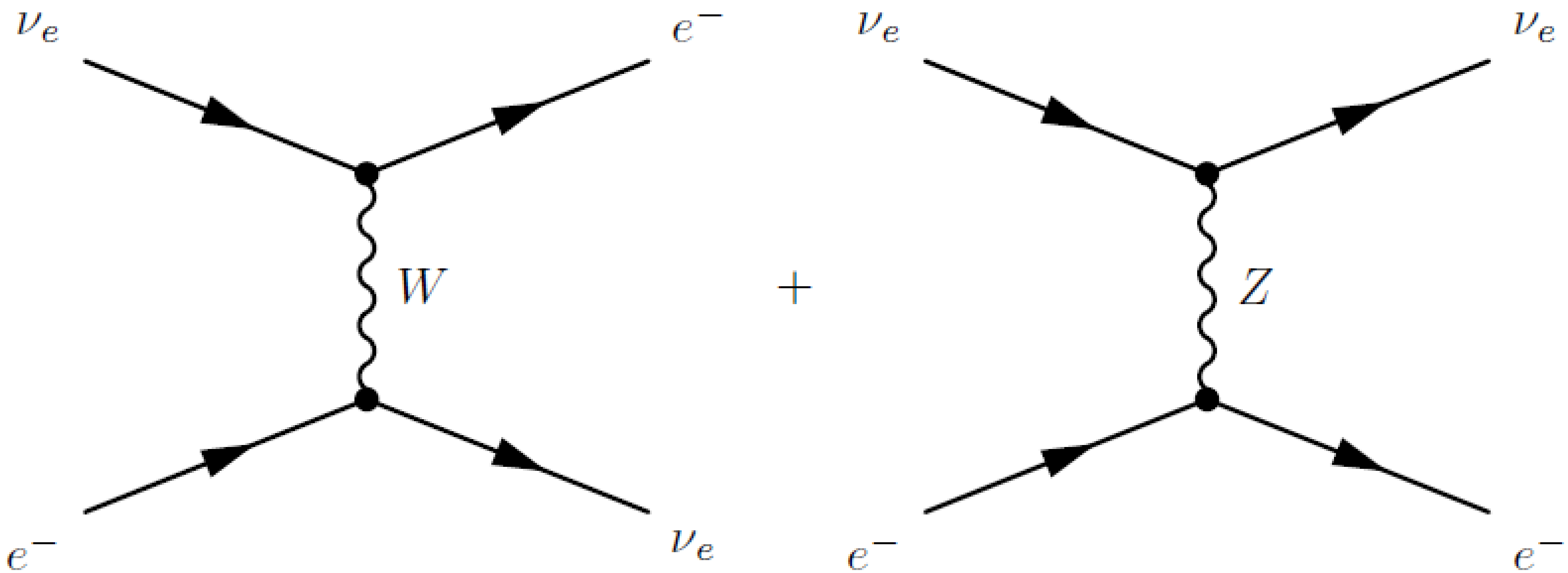
- Neutral Current



Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

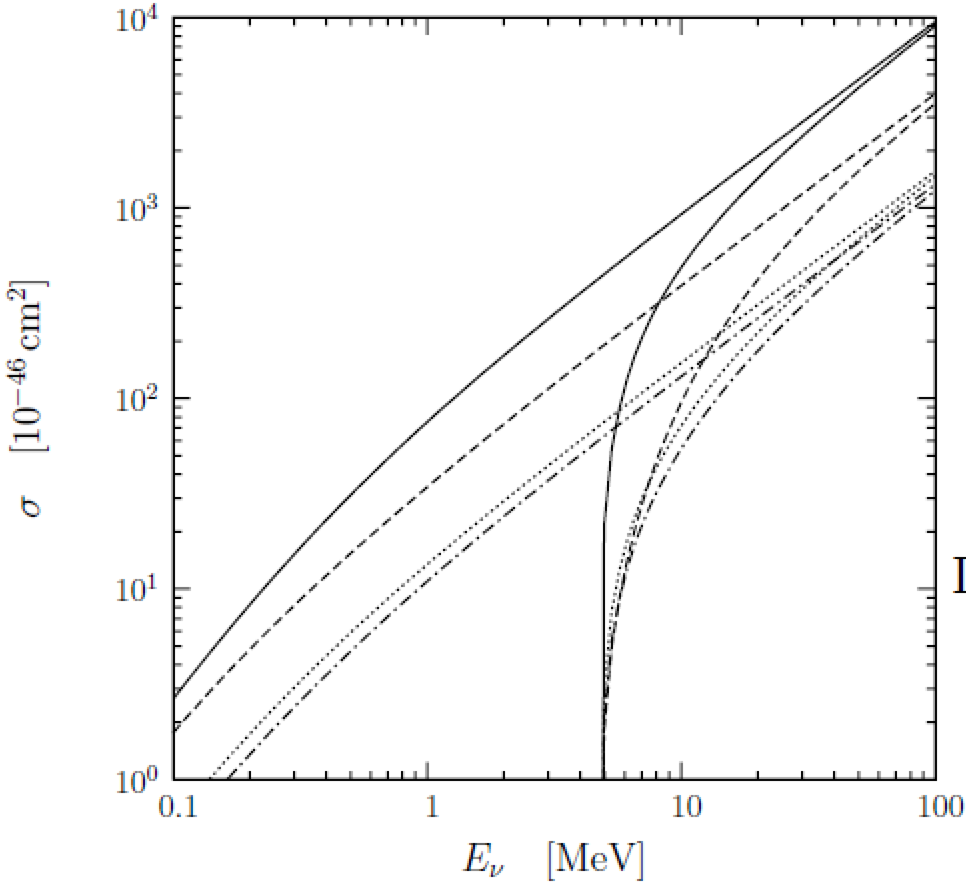
Neutrino Interactions

- Electron + electron neutrino elastic scattering



Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

Neutrino Interactions



Solid line: $\nu_e + e^- \rightarrow \nu_e + e^-$

Dashed line: $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$

Dotted line: $\nu_{\mu,\tau} + e^- \rightarrow \nu_{\mu,\tau} + e^-$

Dash-dotted line: $\bar{\nu}_{\mu,\tau} + e^- \rightarrow \bar{\nu}_{\mu,\tau} + e^-$

Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

Neutrino Sources

- Artificial
- Atmospheric
- Supernova
- Solar
- Big bang
- Geologic
- & ...

Neutrino Oscillation

Neutrino Oscillation

- Mixing
- Neutrino Oscillations in vacuum
- Neutrino Oscillations in matter
- MSW effect

Mixing

- Flavour states & mass eigenstates

$$v_l = U_{li} v_i \quad l = e, \mu, \tau \quad \& \quad i = 1,2,3$$

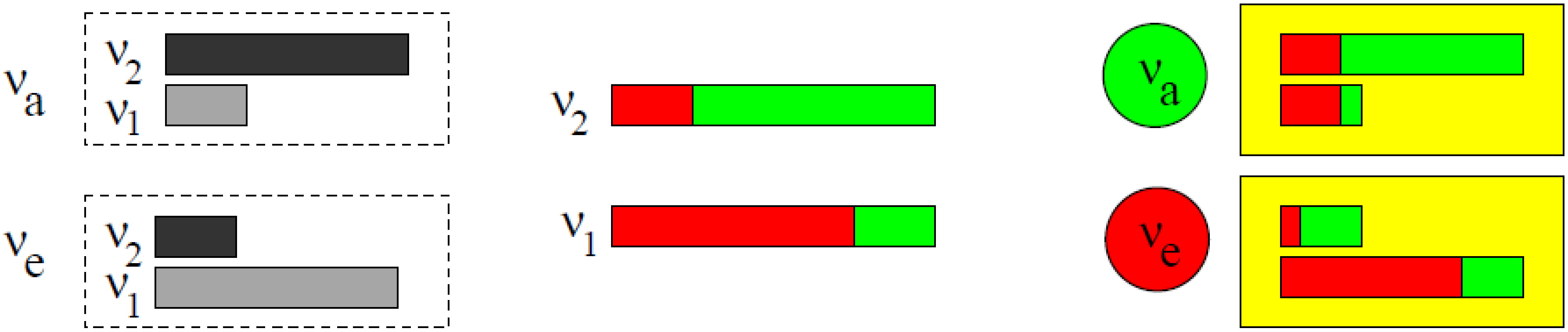
- PMNS mixing matrix
- Two neutrino mixing

$$v_l = \cos\theta\, v_1 + \sin\theta\, v_2 \qquad v_1 = \cos\theta\, v_e - \sin\theta\, v_a$$

$$v_l = \cos\theta\, v_2 - \sin\theta\, v_1 \qquad v_2 = \cos\theta\, v_a + \sin\theta\, v_e$$

Mixing

- Portrait of electron neutrino



The MSW effect and Solar Neutrinos, A. Yu. Smirnov, arXiv:hep-ph/0305106

Neutrino Oscillations in vacuum

$$\mathscr{H} |\nu_k\rangle = E_k |\nu_k\rangle$$

$$E_k = \sqrt{\vec{p}^2 + m_k^2}$$

$$i \frac{\mathrm{d}}{\mathrm{d}t} |\nu_k(t)\rangle = \mathscr{H} \, |\nu_k(t)\rangle$$

$$|\nu_k(t)\rangle = e^{-iE_k t} \, |\nu_k\rangle$$

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k}^* \, |\nu_k\rangle \qquad (\alpha = e, \mu, \tau)$$

Neutrino Oscillations in vacuum

$$|\nu_\alpha(t)\rangle = \sum_k U^*_{\alpha k}\, e^{-iE_k t}\, |\nu_k\rangle$$

$$|\nu_k\rangle = \sum_\alpha U_{\alpha k}\, |\nu_\alpha\rangle$$

$$|\nu_\alpha(t)\rangle = \sum_{\beta=e,\mu,\tau} \left(\sum_k U^*_{\alpha k}\, e^{-iE_k t}\, U_{\beta k} \right) |\nu_\beta\rangle$$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sum_{k,j} U^*_{\alpha k}\, U_{\beta k}\, U_{\alpha j}\, U^*_{\beta j}\, \exp\left(-i\, \frac{\Delta m^2_{kj} L}{2E} \right)$$

Neutrino Oscillations in vacuum

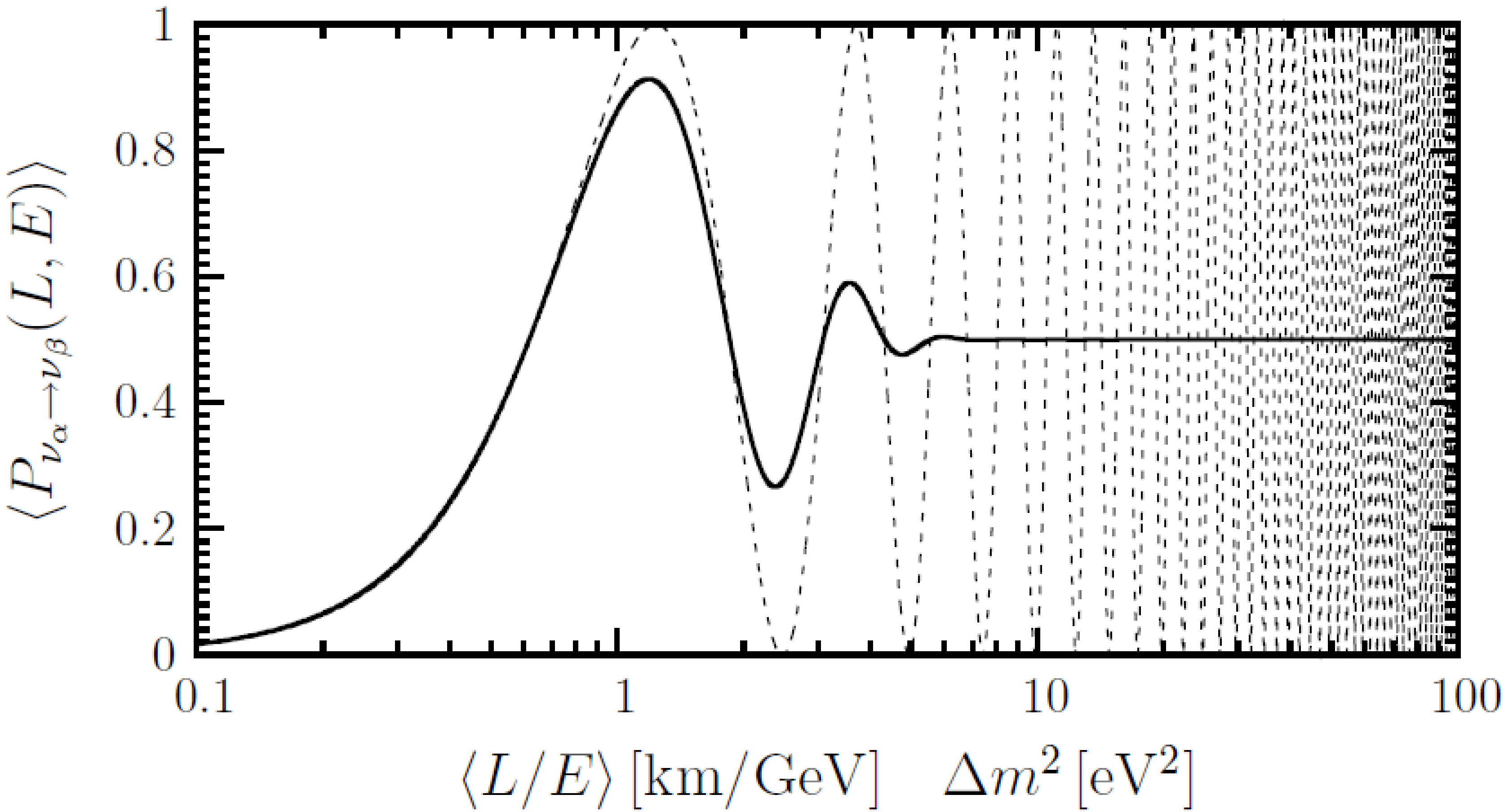
- Two neutrinos

$$U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix}$$

$$P_{\nu_\alpha \to \nu_\beta}(L,E) = \sin^2 2\vartheta \, \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \qquad (\alpha \neq \beta)$$

$$\langle P_{\nu_\alpha \to \nu_\beta}(L,E) \rangle = \frac{1}{2} \sin^2 2\vartheta \left[1 - \left\langle \cos\left(\frac{\Delta m^2 L}{2E}\right) \right\rangle \right]$$

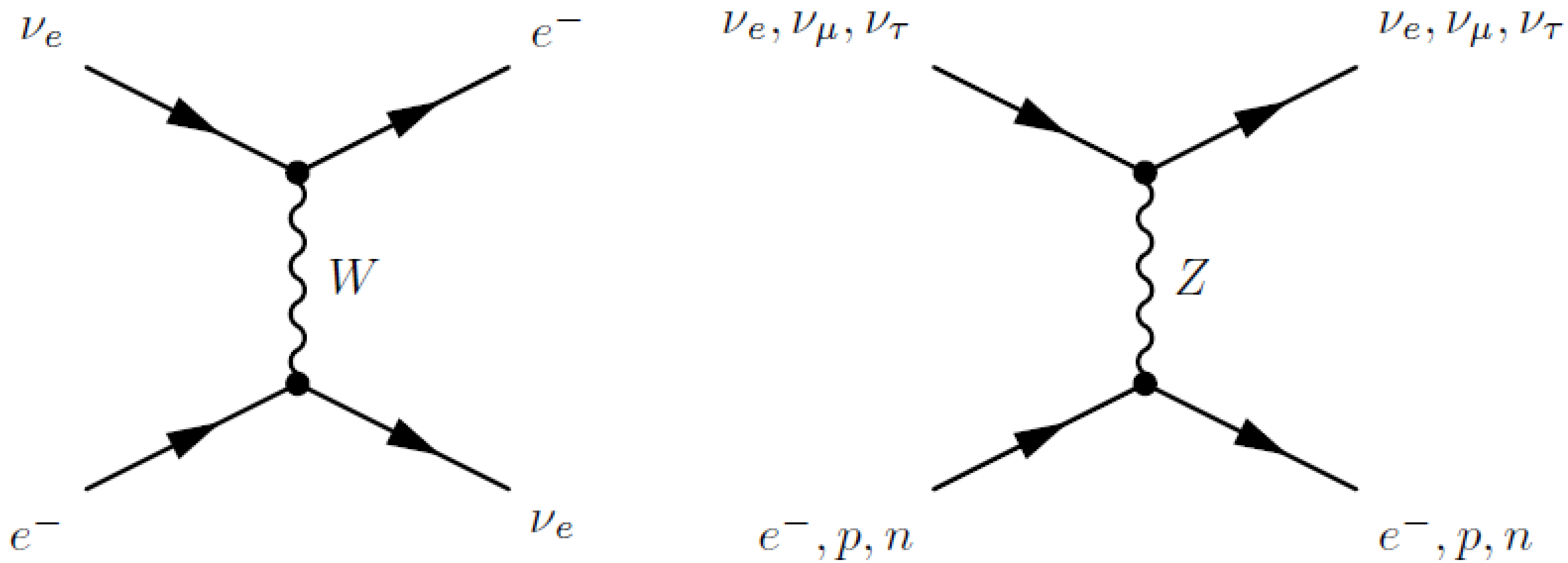
Neutrino Oscillations in vacuum



Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

Neutrino Oscillations in matter

- Coherent forward elastic scattering



Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

Neutrino Oscillations in matter

$$\mathscr{H} = \mathscr{H}_0 + \mathscr{H}_I$$

$$\mathscr{H}_I \left|\nu_\alpha\right\rangle = V_\alpha \left|\nu_\alpha\right\rangle$$

$$V_\alpha = V_{\mathrm{CC}}\,\delta_{\alpha e} + V_{\mathrm{NC}} = \sqrt{2}\,G_{\mathrm{F}}\left(N_e\,\delta_{\alpha e} - \frac{1}{2}\,N_n\right)$$

$$U_{\mathrm{M}} = \begin{pmatrix} \cos\vartheta_{\mathrm{M}} & \sin\vartheta_{\mathrm{M}} \\ -\sin\vartheta_{\mathrm{M}} & \cos\vartheta_{\mathrm{M}} \end{pmatrix}$$

$$\Delta m^2_{\mathrm{M}} = \sqrt{\left(\Delta m^2 \cos 2\vartheta - A_{\mathrm{CC}}\right)^2 + \left(\Delta m^2 \sin 2\vartheta\right)^2}$$

MSW effect

$$A_{\mathrm{CC}} \equiv 2\,E\,V_{\mathrm{CC}} = 2\,\sqrt{2}\,E\,G_{\mathrm{F}}\,N_e$$

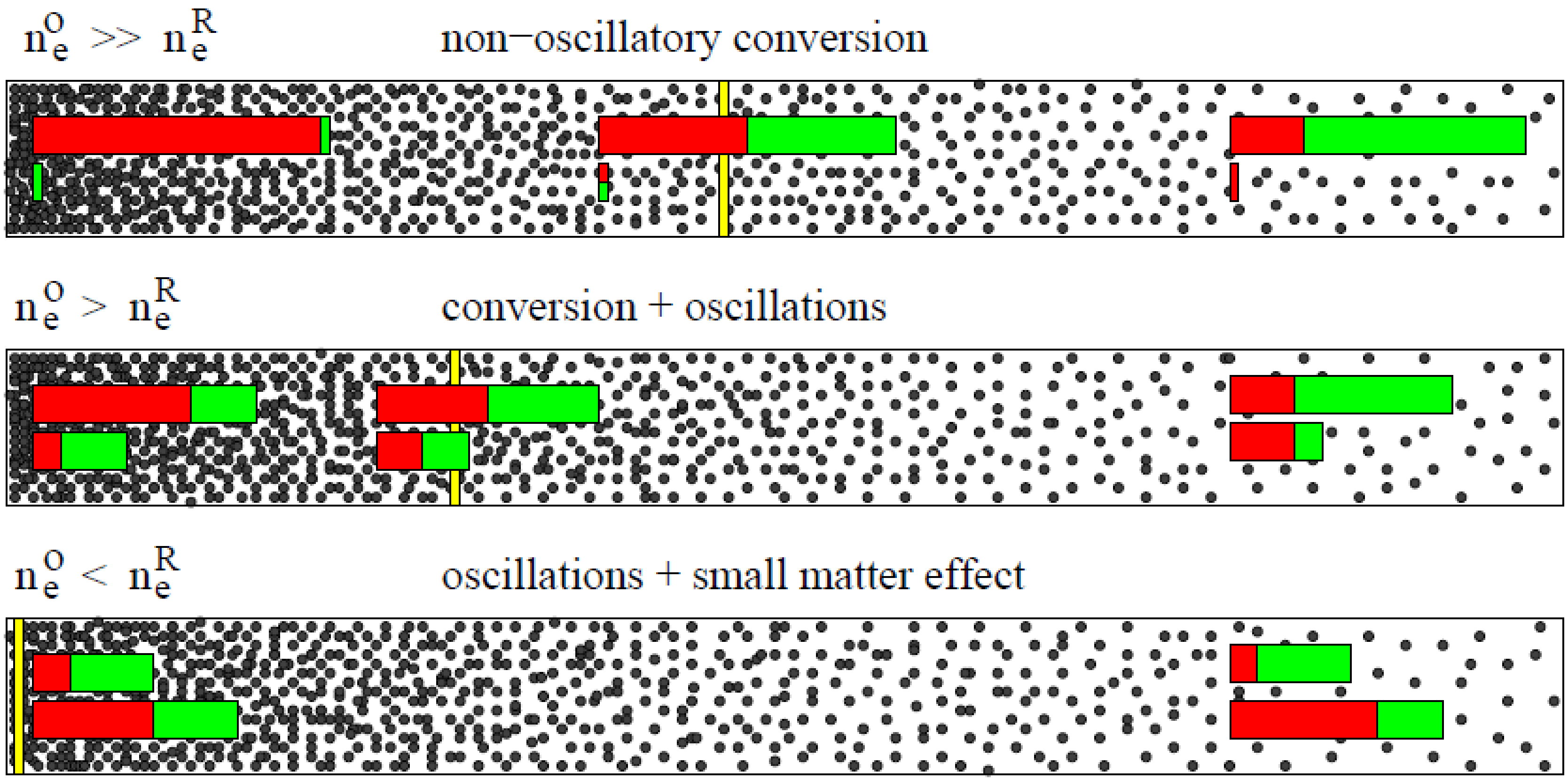
$$\tan 2\vartheta_{\mathrm{M}} = \frac{\tan 2\vartheta}{1 - \dfrac{A_{\mathrm{CC}}}{\Delta m^2 \cos 2\vartheta}}$$

$$A_{\mathrm{CC}}^{\mathrm{R}} = \Delta m^2 \cos 2\vartheta$$

$$N_e^{\mathrm{R}} = \frac{\Delta m^2 \cos 2\vartheta}{2\sqrt{2} E G_{\mathrm{F}}}$$

$$\Delta m^2_{\mathrm{M}}\big|_{\mathrm{R}} = \Delta m^2 \sin 2\vartheta$$

MSW effect



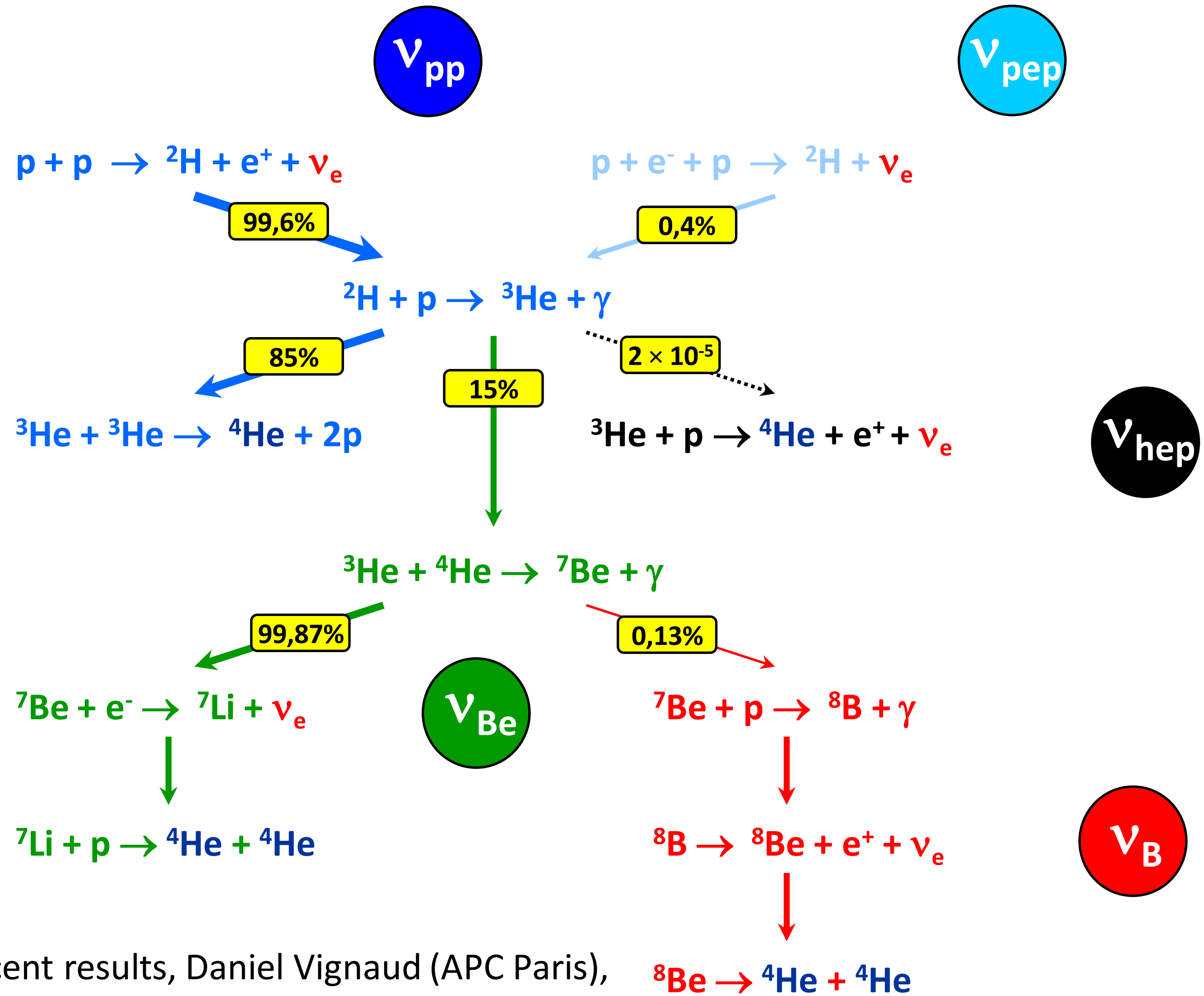
The MSW effect and Solar Neutrinos, A. Yu. Smirnov, arXiv:hep-ph/0305106

Solar Neutrinos

Solar Neutrinos

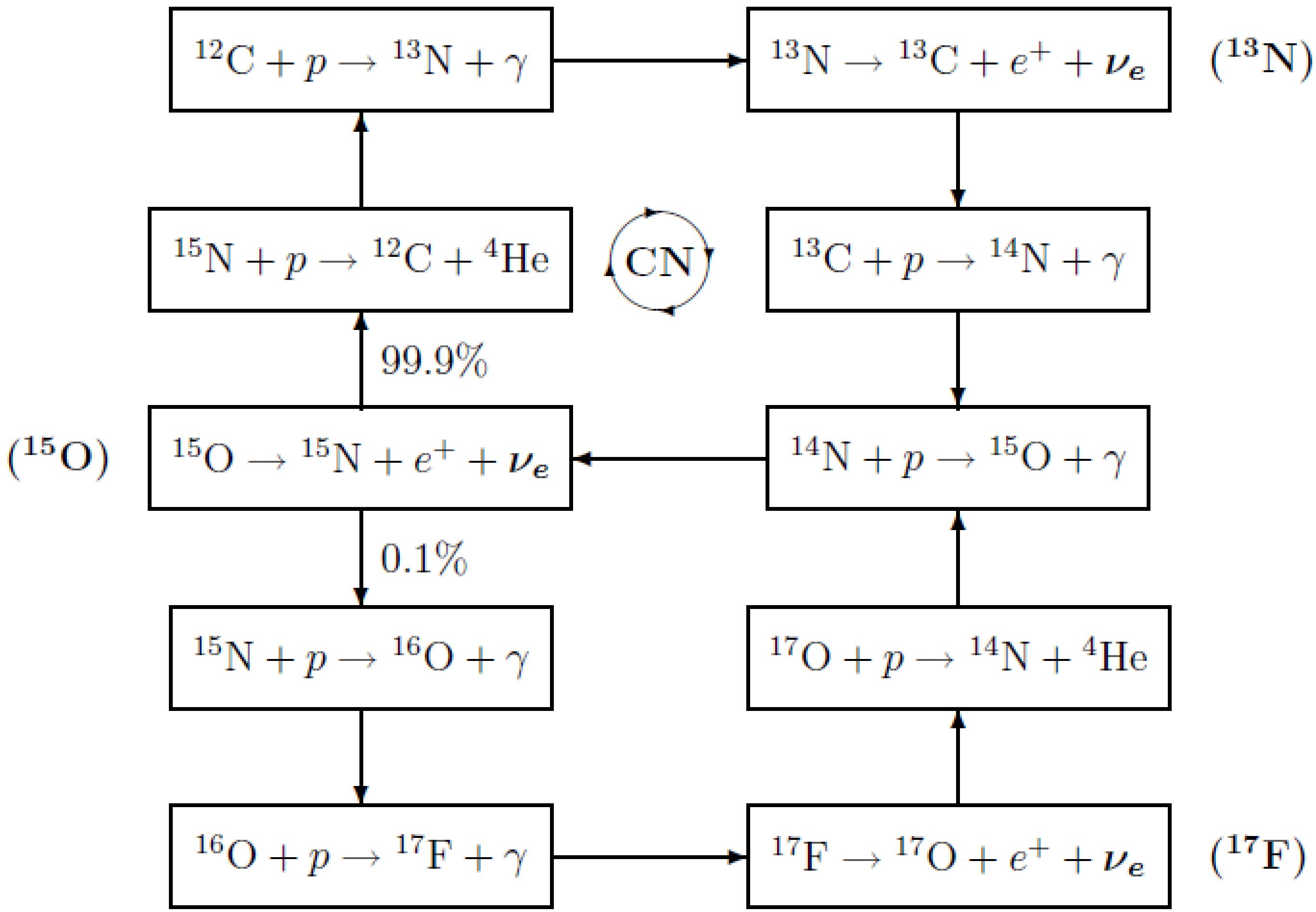
- Two type of thermonuclear reactions
  - pp chain
  - CNO cycle
- Standard Solar Model (SSM) Neutrinos

pp chain



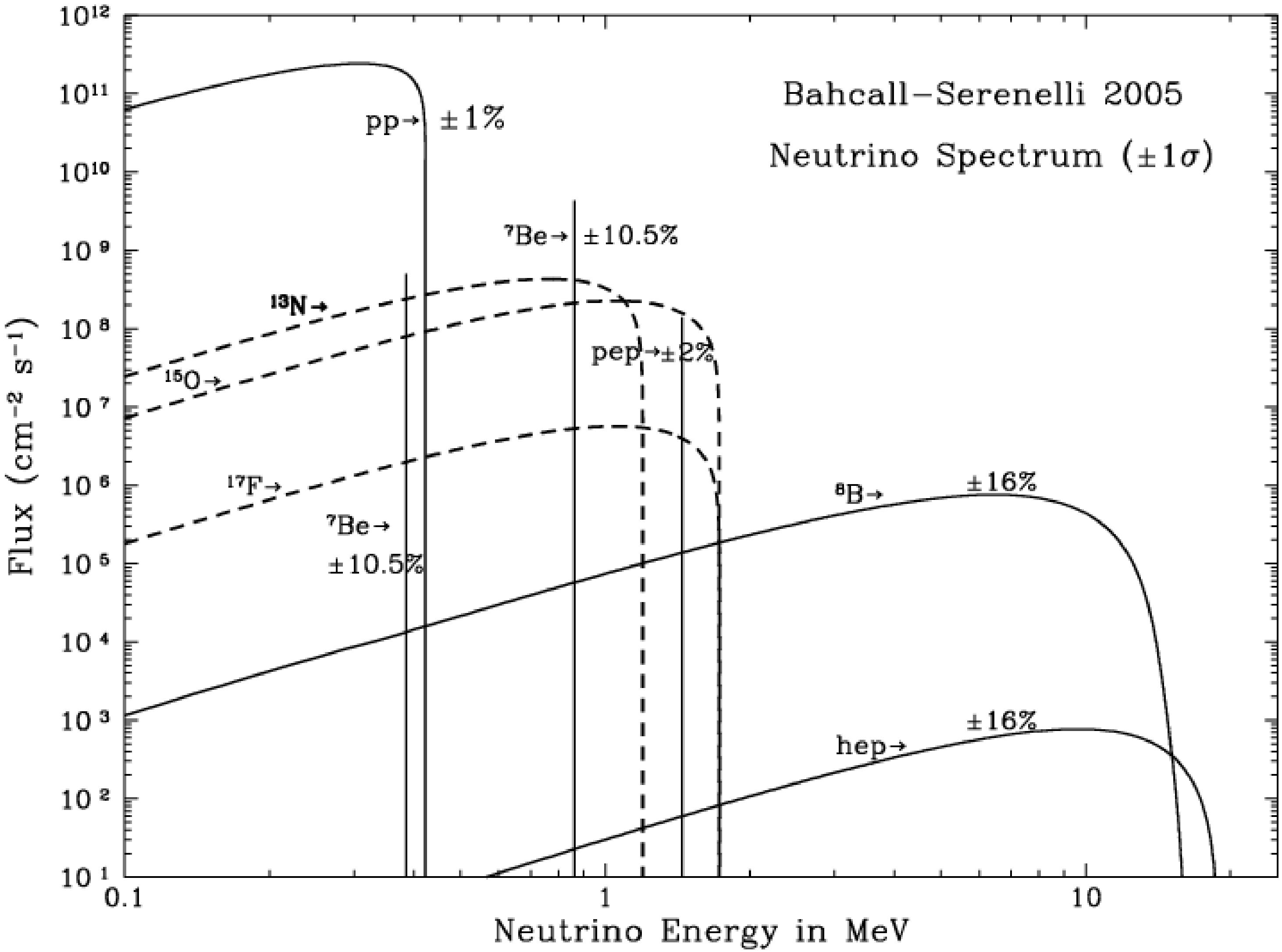
Solar neutrinos Recent results, Daniel Vignaud (APC Paris), 23 October 2012

CNO cycle

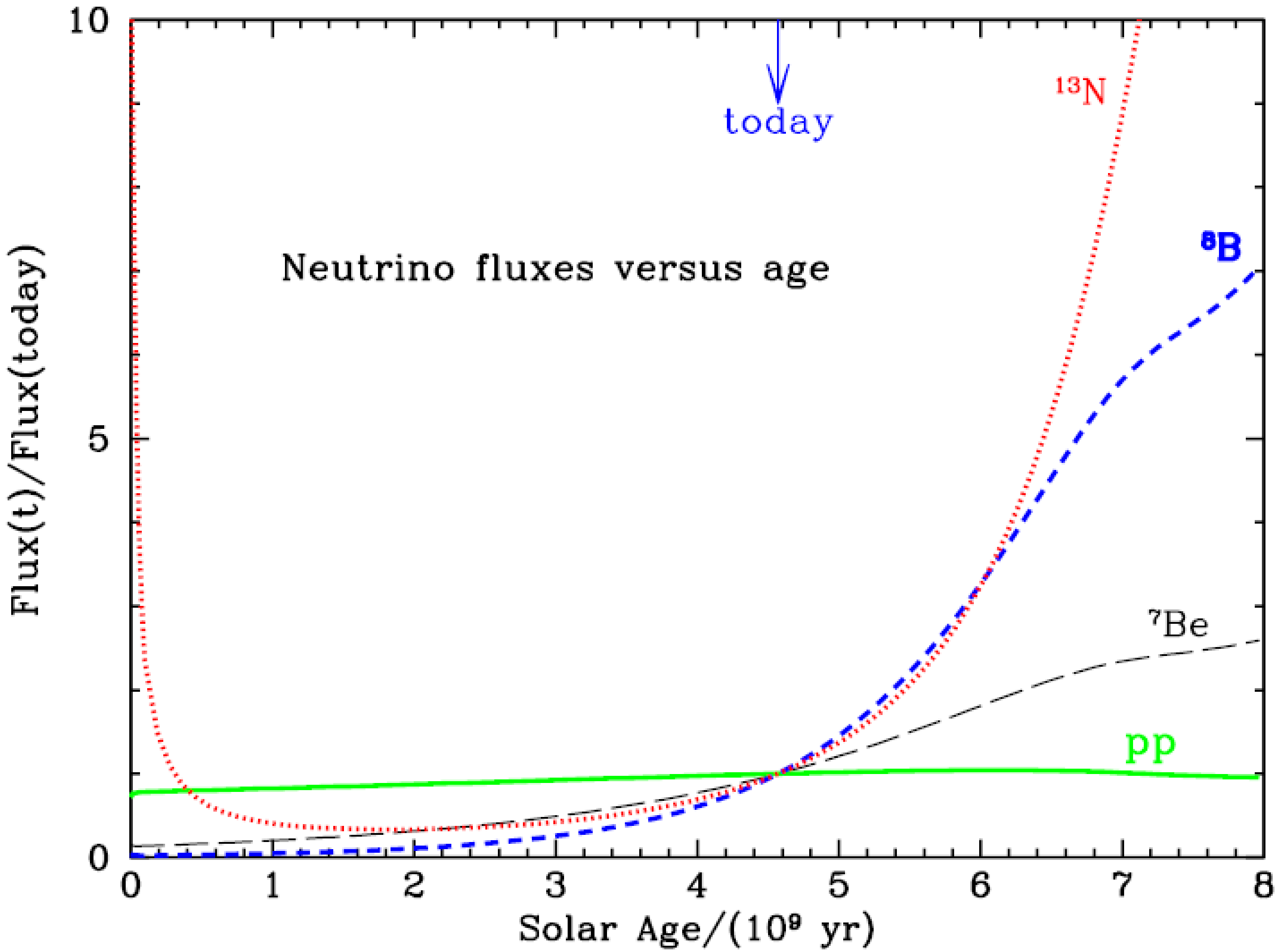


Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

SSM Neutrinos



SSM Neutrinos



Solar Models: current epoch and time dependences, neutrinos, and helioseismological properties, John N. Bahcall, M. H. Pinsonneault, Sarbani Basu, arXiv:astro-ph/0010346v2

Solar Neutrino Experiments

Solar Neutrino Experiments

- Homestake experiment
- Gallium experiments
- KamiokaNDE
- Super-KamiokaNDE (SK)
- The Sudbury Neutrino Observatory (SNO)

Homestake experiment

- Proposed in 1964

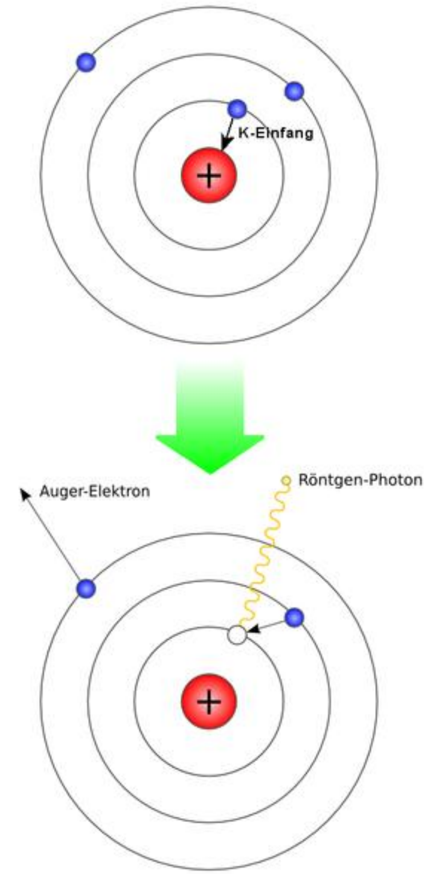
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

$$E_\nu^{\mathrm{th}} = 0.814\,\mathrm{MeV}$$

- Electron capture

$$e^- + {}^{37}\mathrm{Ar} \rightarrow {}^{37}\mathrm{Cl} + \nu_e$$

- Auger electron



wikipedia.org

Homestake experiment

- Located 1478 m below the surface
- volume of 6×10^5 litters
- steel tank 6.1 m in diameter and 14.6 m long
- containing 2.16×10^{30} atoms of ^{37}Cl(133 ton)
- 615 ton of tetrachloroethylene C_2Cl_4

Homestake experiment

- first data indicated in 1968
- 108 extraction from March 1970 to February 1994
- Solar Neutrino Problem (SNP)
- Changes to the Solar Model

Gallium experiments

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$
$$E_\nu^{\mathrm{th}} = 0.233\,\mathrm{MeV}$$

- GALLium EXperiment (GALLEX)
- Gallium Neutrino Observatory (GNO)
- The Soviet–American Gallium Experiment (SAGE)

KamiokaNDE

- Kamioka Nucleon Decay Experiment
- Kamioka Neutrino Detection Experiment
- Water Cherenkov detector
- 1000 m underground
- Kamiokande-I , II, III
- E_{th} = 9.0 , 7.2 , 6.7MeV

Kamiokande

- 3 kton water, 1000 PMTs
- Elastic scattering

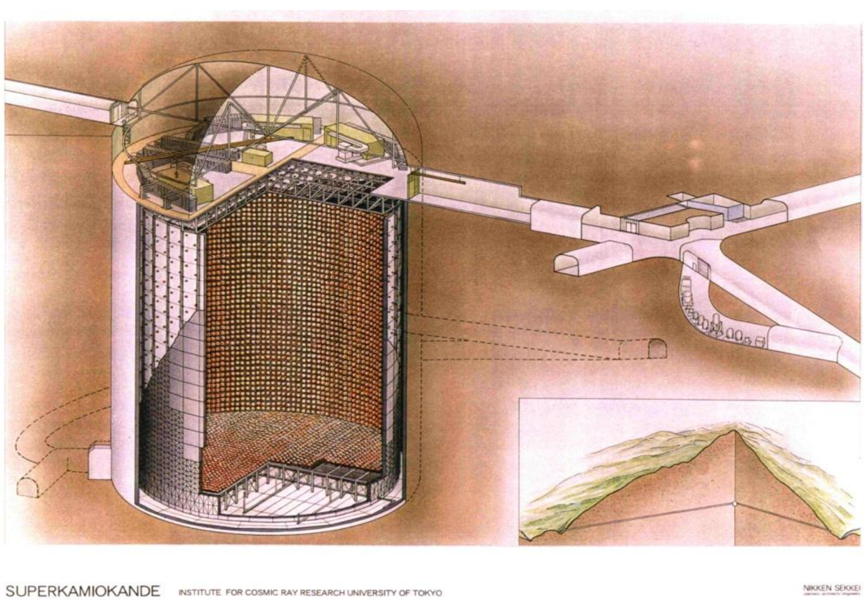
$$\nu_\alpha + e^- \rightarrow \nu_\alpha + e^-$$

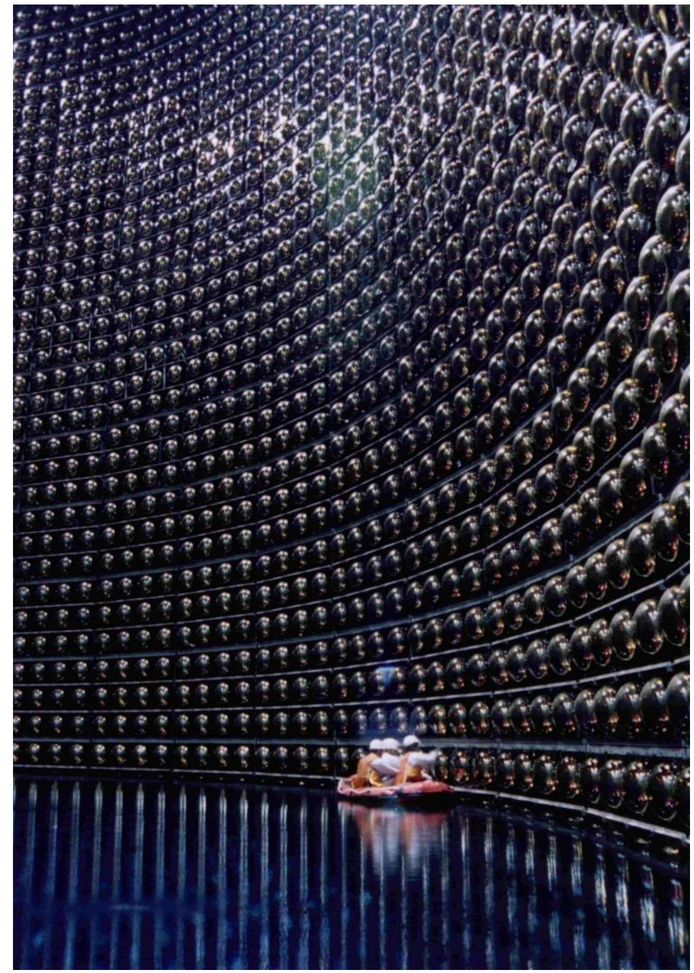
- Sensitive to electron
- ^8B solar ν_e's measured by Kamiokande is about half of the SSM flux

Super-Kamiokande

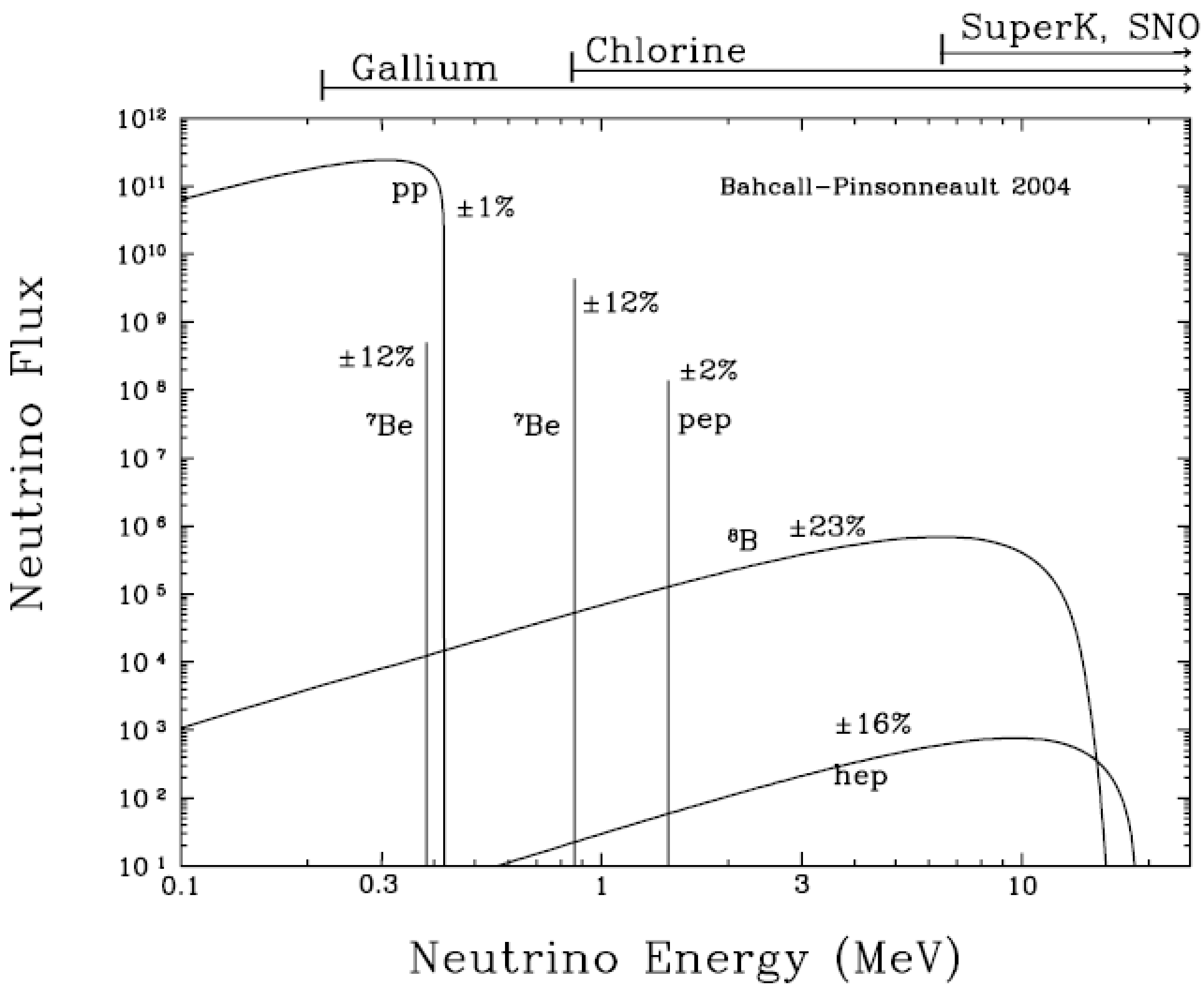
- 50 kton water
- 11146 PMTs

$$E_\nu^{\mathrm{th}} = 4.7\,\mathrm{MeV}$$



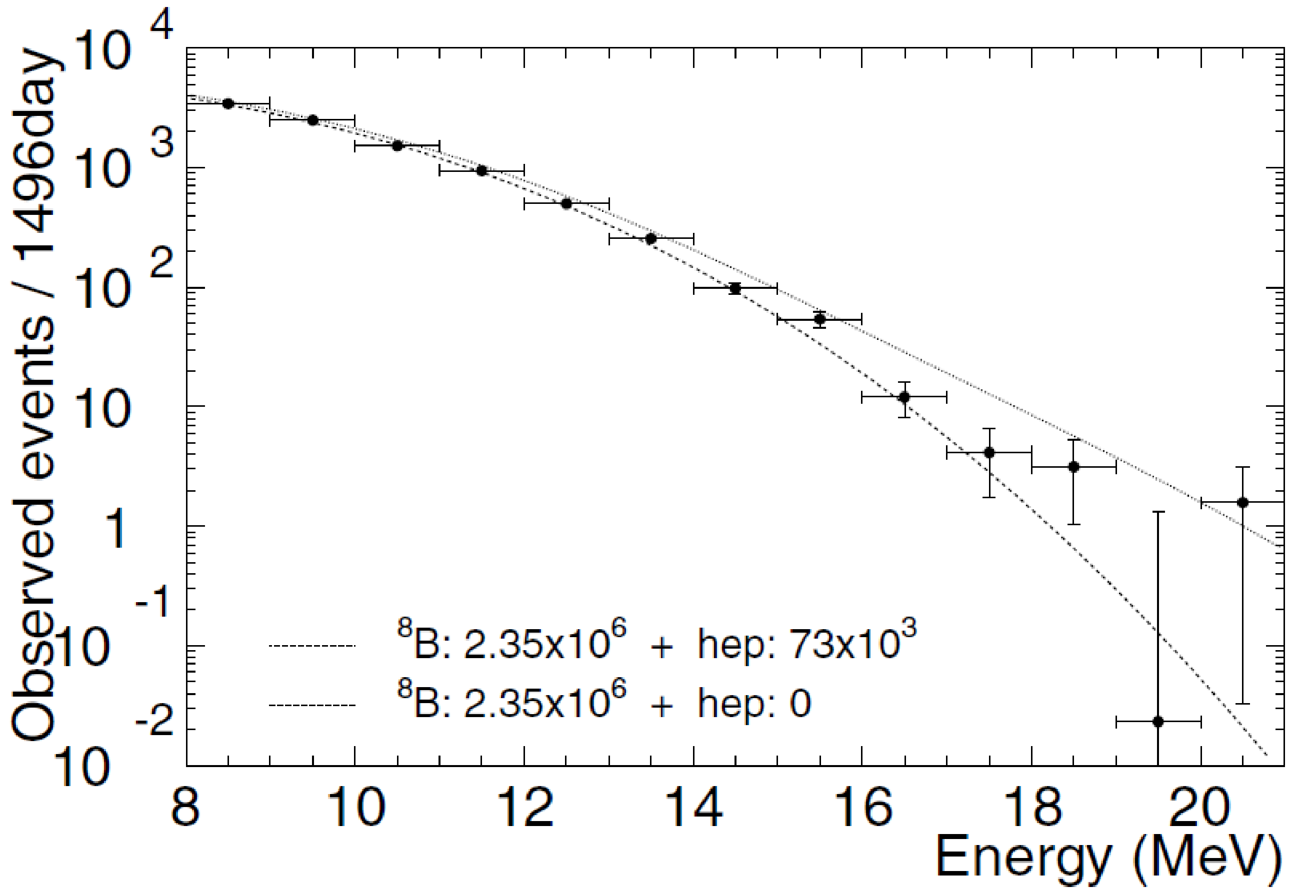


Solar Neutrino Experiments



Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

Super-Kamiokande

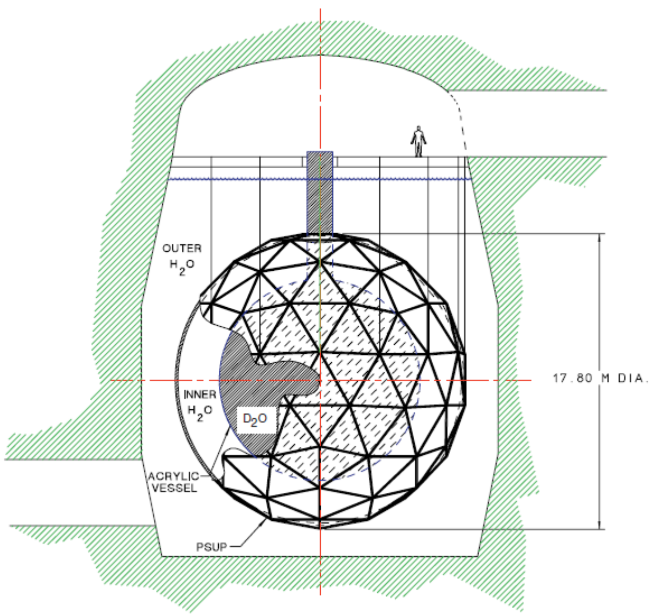


$$\Phi_{hep}{}^{\mathrm{SK}} < 73 \times 10^3\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

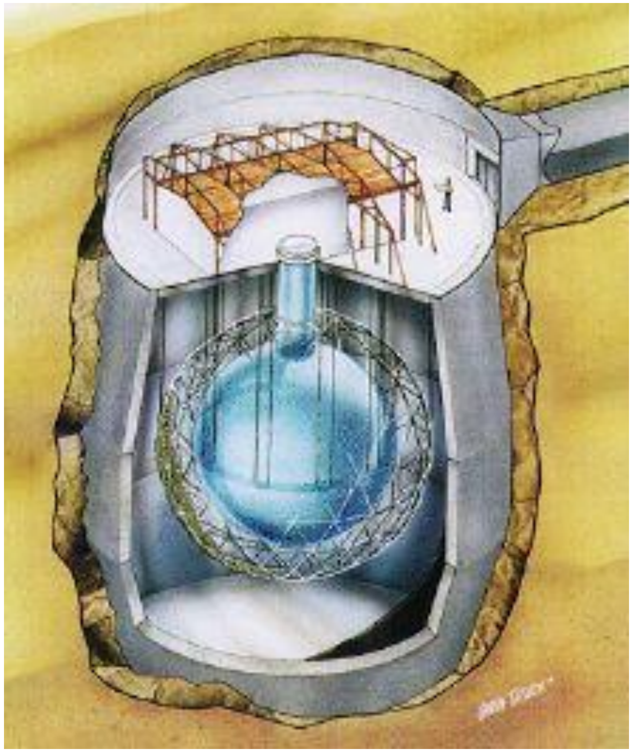
Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

SNO

- one kiloton of 99.92% isotopically pure D_2O
- 9456 PMTs



Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.



Ryan Martin, Queen's University, Kingston, ON, Canada,8th January 2007- EPFL

SNO

- detects through three reactions

$$\text{CC:} \qquad \nu_e + d \to p + p + e^-$$

$$\text{NC:} \qquad \nu_\alpha + d \to p + n + \nu_\alpha$$

$$\text{ES:} \qquad \nu_\alpha + e^- \to \nu_\alpha + e^-$$

- NC reaction on deuterium in important for checking the neutrino oscillation solution of the SNP

SNO

- D_2O Phase

$$n + d \rightarrow {}^3\mathrm{H} + \gamma\,(6.25\,\mathrm{MeV})$$

- NaCl Phase, 2 ton NaCl

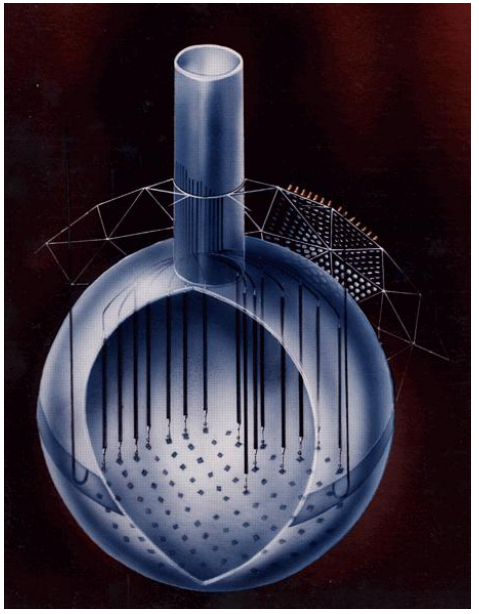
$$n + {}^{35}\mathrm{Cl} \rightarrow {}^{36}\mathrm{Cl} + \gamma\text{'s}\,(8.57\,\mathrm{MeV})$$

- Third Phase

hundred ^{3}He tubes

$\sigma(\,^{35}\mathrm{Cl}\,) = 44$ b
$\sigma(\,\mathrm{D}\,) = 0.5$ mb

George Ewan, for the SNO Collaboration *Beyond the desert 2003*



SNO

- Salt phase

$$\Phi_{\rm CC}^{\rm SNO} = \left(1.68 \pm 0.06^{+0.08}_{-0.09}\right) \times 10^6\,{\rm cm}^{-2}\,{\rm s}^{-1}$$

$$\Phi_{\rm NC}^{\rm SNO} = \left(4.94 \pm 0.21^{+0.38}_{-0.34}\right) \times 10^6\,{\rm cm}^{-2}\,{\rm s}^{-1}$$

$$\Phi_{\rm ES}^{\rm SNO} = (2.35 \pm 0.22 \pm 0.15) \times 10^6\,{\rm cm}^{-2}\,{\rm s}^{-1}$$

$$\Phi_{\rm CC}^{\rm SNO} = \Phi_{\nu_e}^{\rm SNO}$$

$$\Phi_{\nu_\mu,\nu_\tau}^{\rm SNO,NC} = \left(3.26 \pm 0.25^{+0.40}_{-0.35}\right) \times 10^6\,{\rm cm}^{-2}\,{\rm s}^{-1}$$

$$\Phi_{\nu_\mu,\nu_\tau}^{\rm SNO,ES} = \left(4.36 \pm 1.52^{+0.90}_{-0.87}\right) \times 10^6\,{\rm cm}^{-2}\,{\rm s}^{-1}$$

Conclusions

Conclusions

- Vacuum oscillation disfavored

    no significant seasonal variation

- Resonance flavor transition

  Small Mixing Angle (SMA)

  Large Mixing Angle (LMA)

  Quasi-Vacuum Oscillation (QVO)

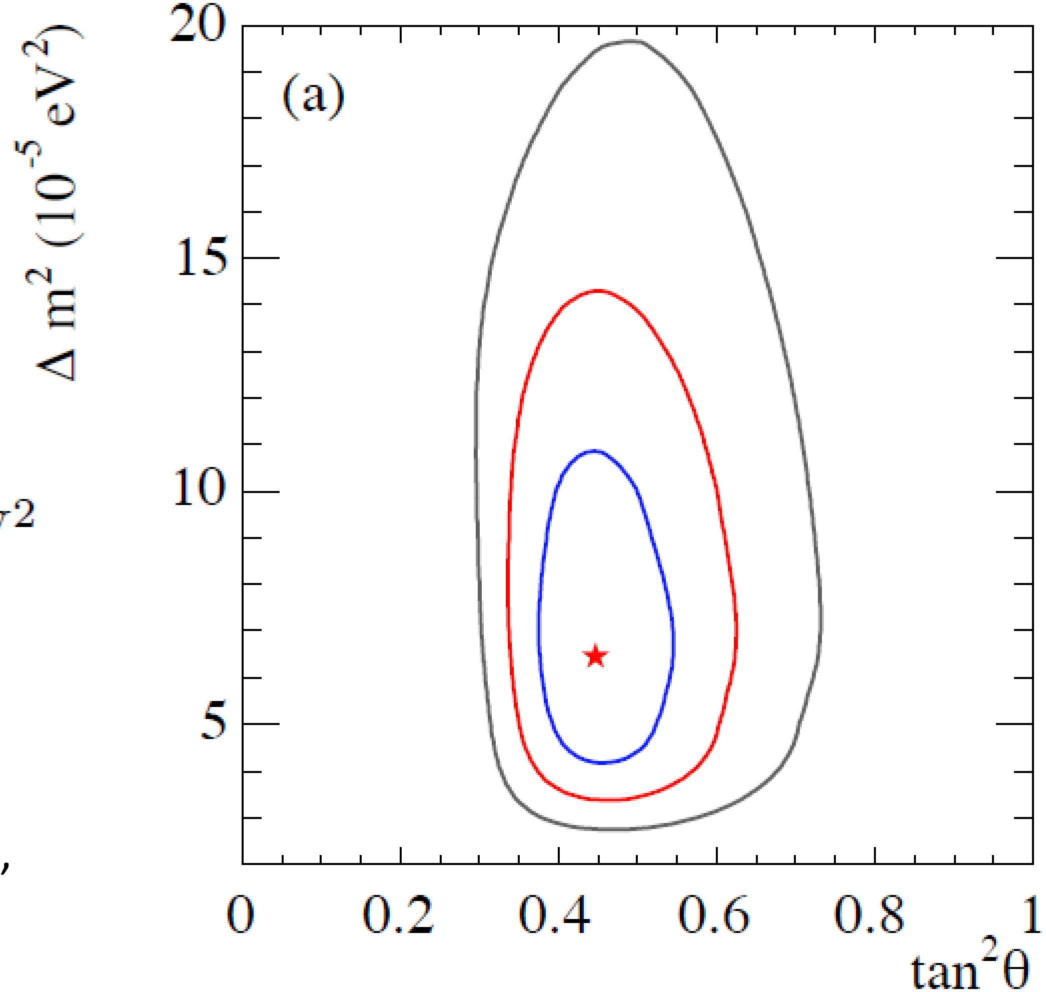
  LOW

Conclusions

Allowed region in the tan2 ϑ-Δm2 plane (LMA) obtained from a global analysis of solar neutrino data

$$\Delta m^2 = \left(6.5^{+4.4}_{-2.3}\right) \times 10^{-5}\,\mathrm{eV}^2$$

$$\tan^2\vartheta = 0.45^{+0.09}_{-0.08}$$



B. Aharmim et al., Phys. Rev., C72, 055502, 2005, nucl-ex/0502021

Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

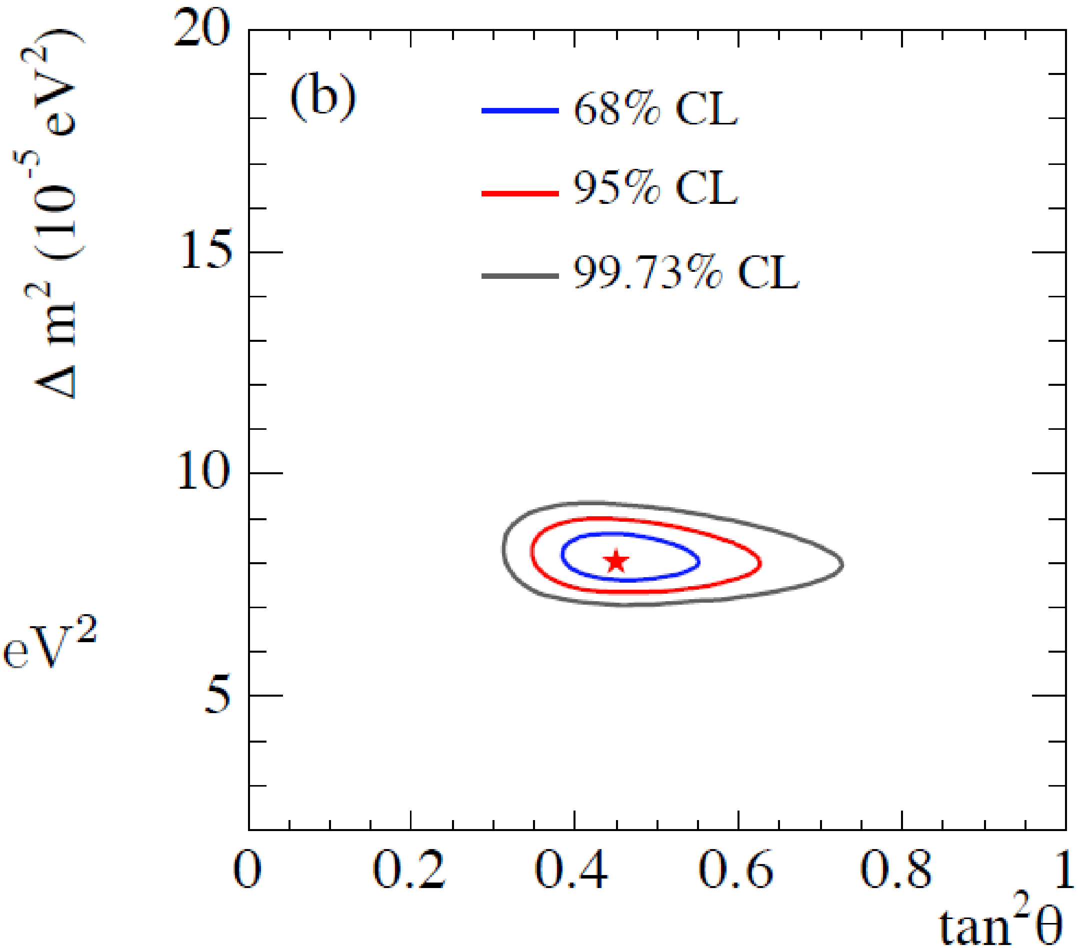
Conclusions

Reactor experiment (KamLAND) + global solar neutrino data

$$\tan^2 \vartheta = 0.45^{+0.09}_{-0.07}$$

$$\Delta m^2 = \left(8.0^{+0.6}_{-0.4}\right) \times 10^{-5}\,\mathrm{eV}^2$$

T. Araki et al., Phys. Rev. Lett., 94, 081801, 2005, hep-ex/0406035



Fundamentals of Neutrino Physics and Astrophysics, Carlo Giunti & Chung W. Kim.

Summary

- Neutrinos
- Neutrino oscillation
- Solar neutrinos
- Solar neutrino experiments & SNP
- Conclusions


Thanks for your attention