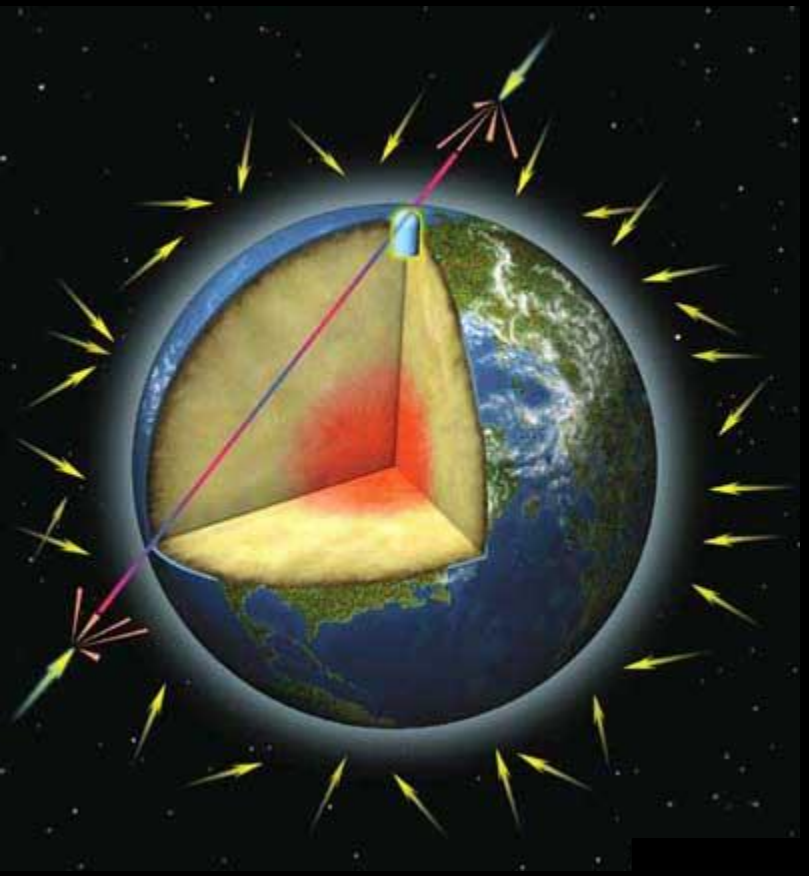


Solar Neutrinos and Atmospheric Neutrinos

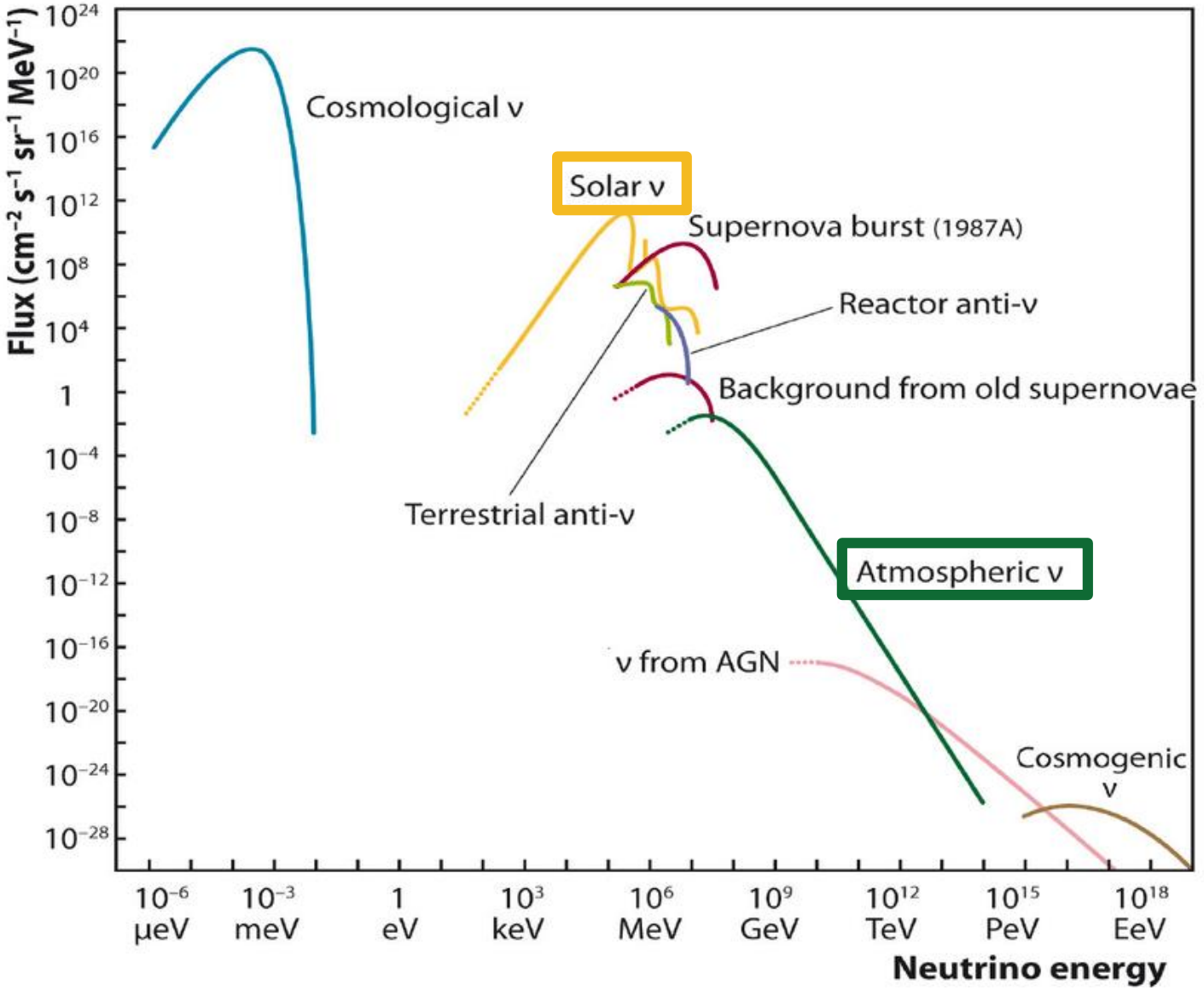
Linyan Wan, Fermilab

August 9, 2023

@Neutrino University

Neutrino Sources

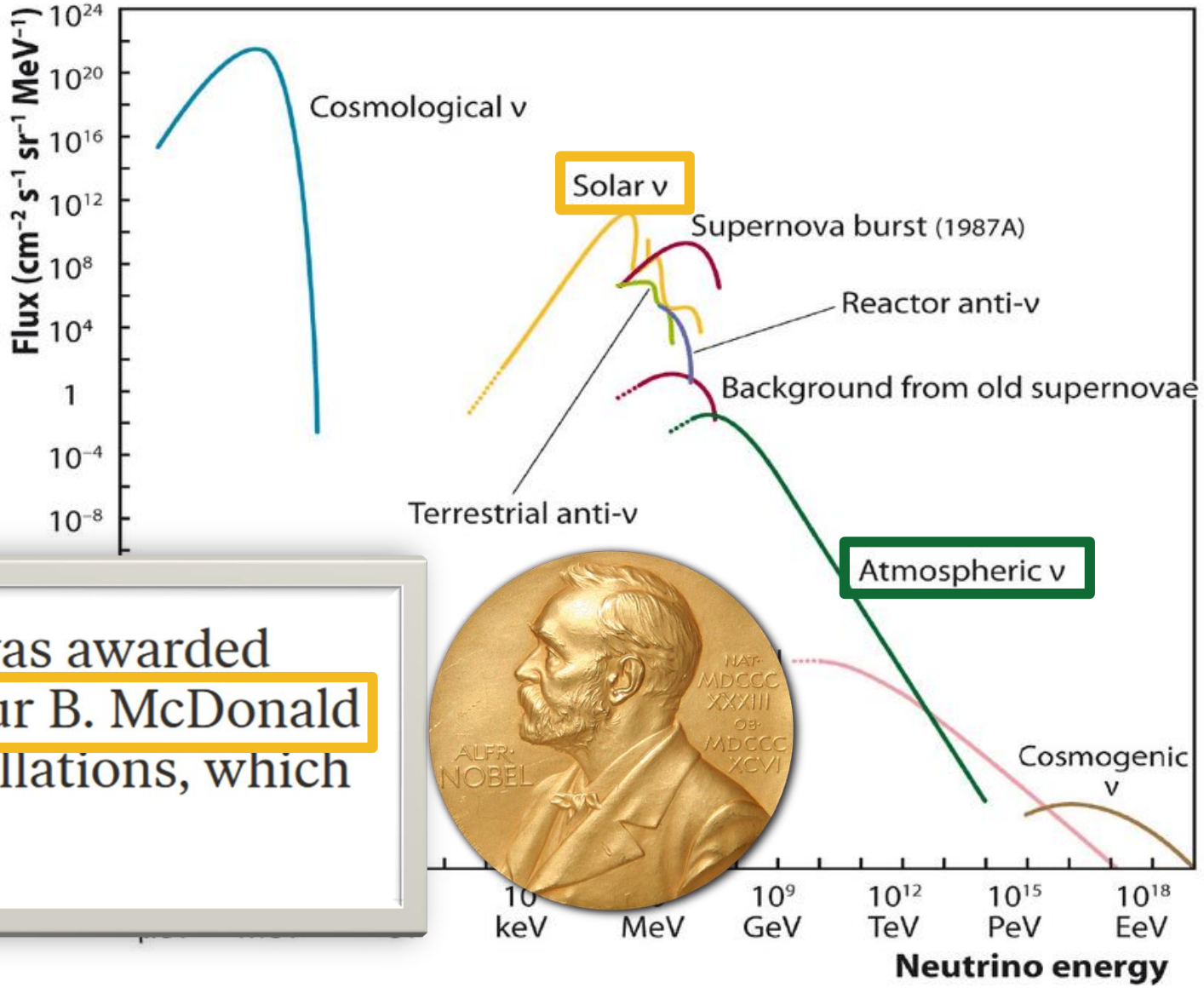
- **Solar neutrinos**
- **Atmospheric neutrinos**



Michel Cribier, *et al.*, La lumière des neutrinos Seuil (1995)

Neutrino Sources

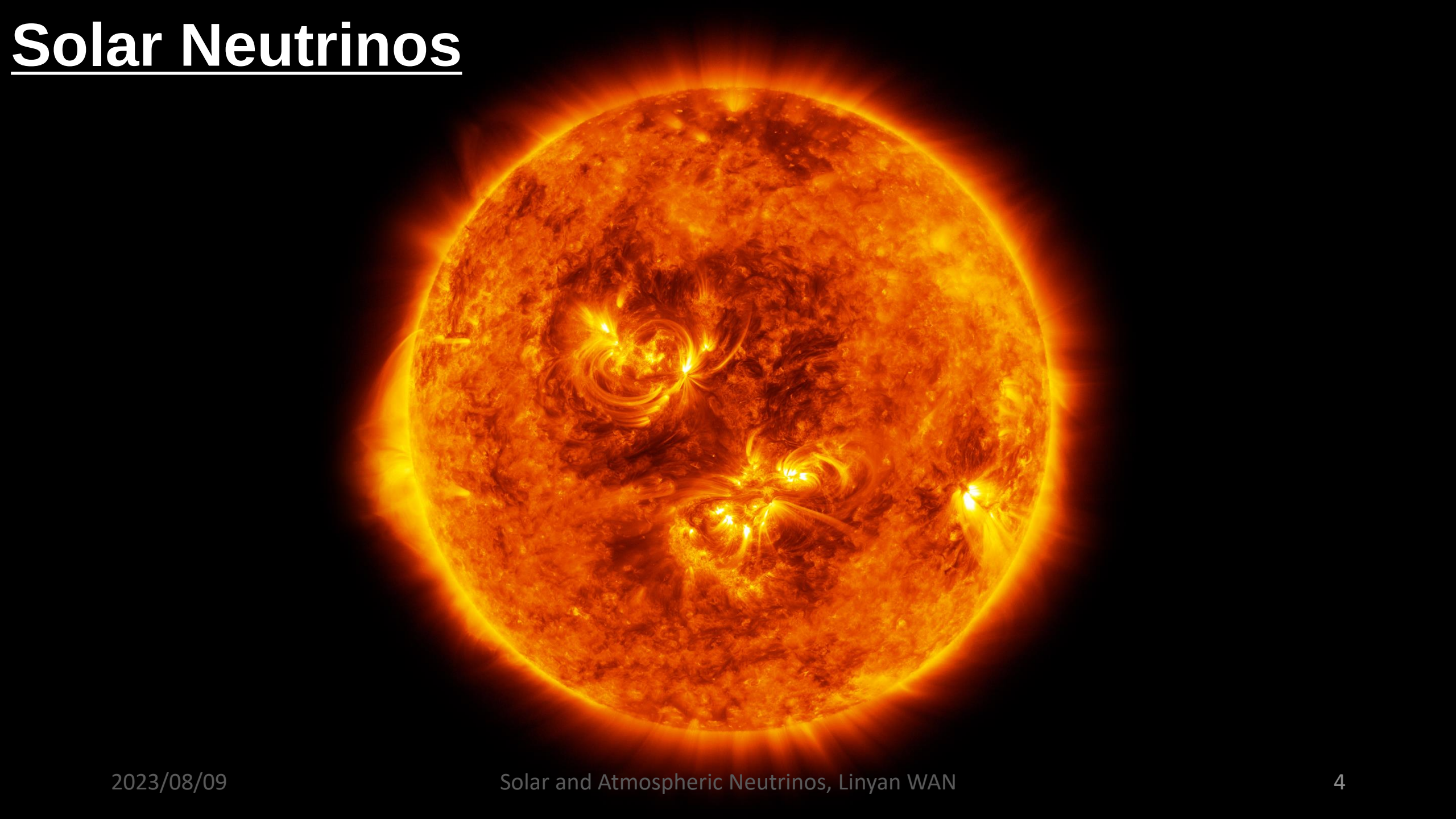
- **Solar neutrinos**
- **Atmospheric neutrinos**



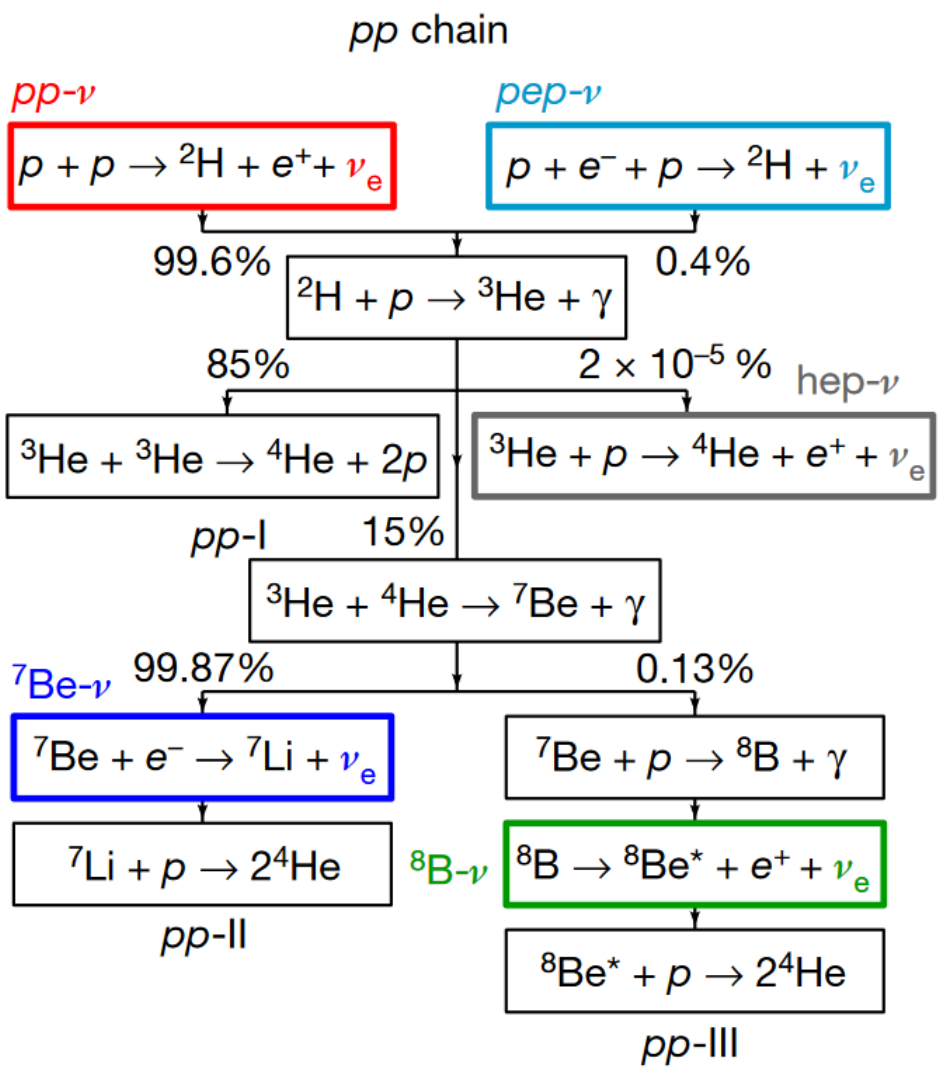
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

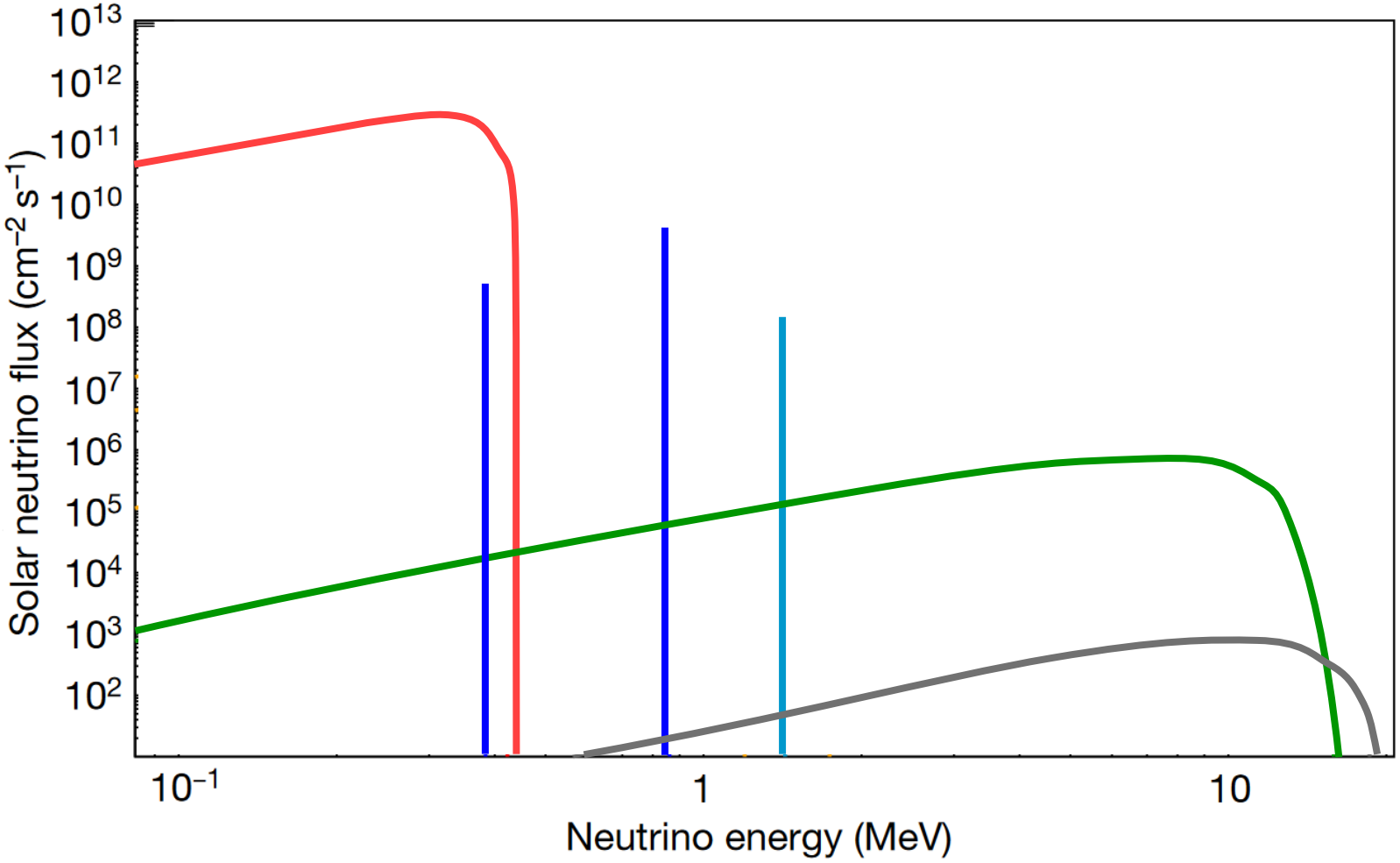
Michel Cribier, *et al.*, La lumière des neutrinos Seuil (1995)

Solar Neutrinos

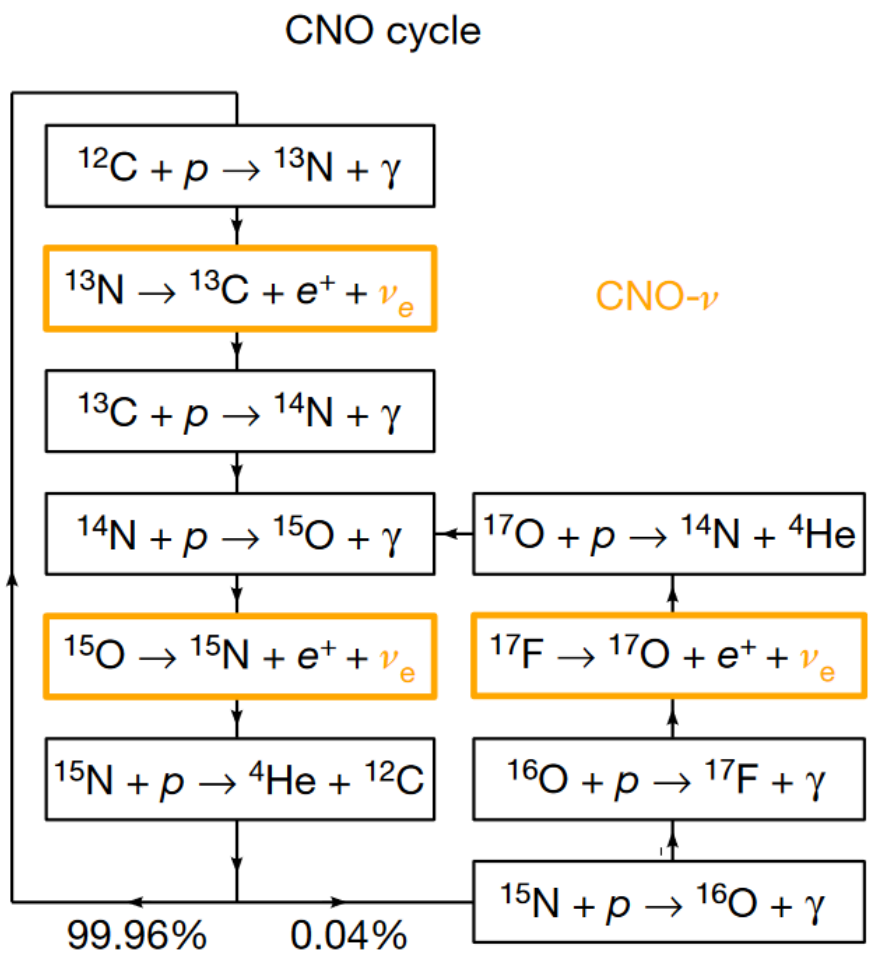


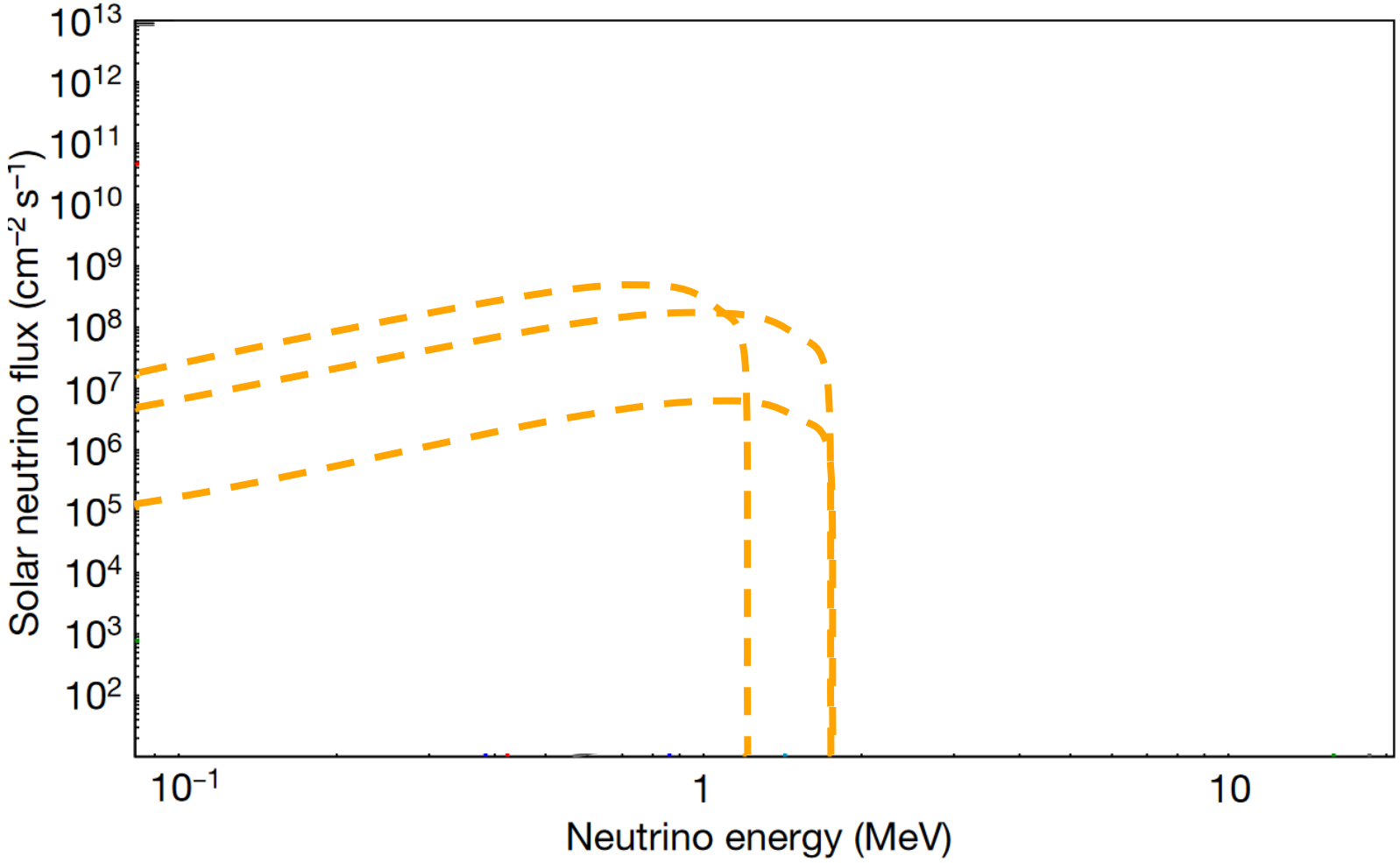
Production: pp Chain





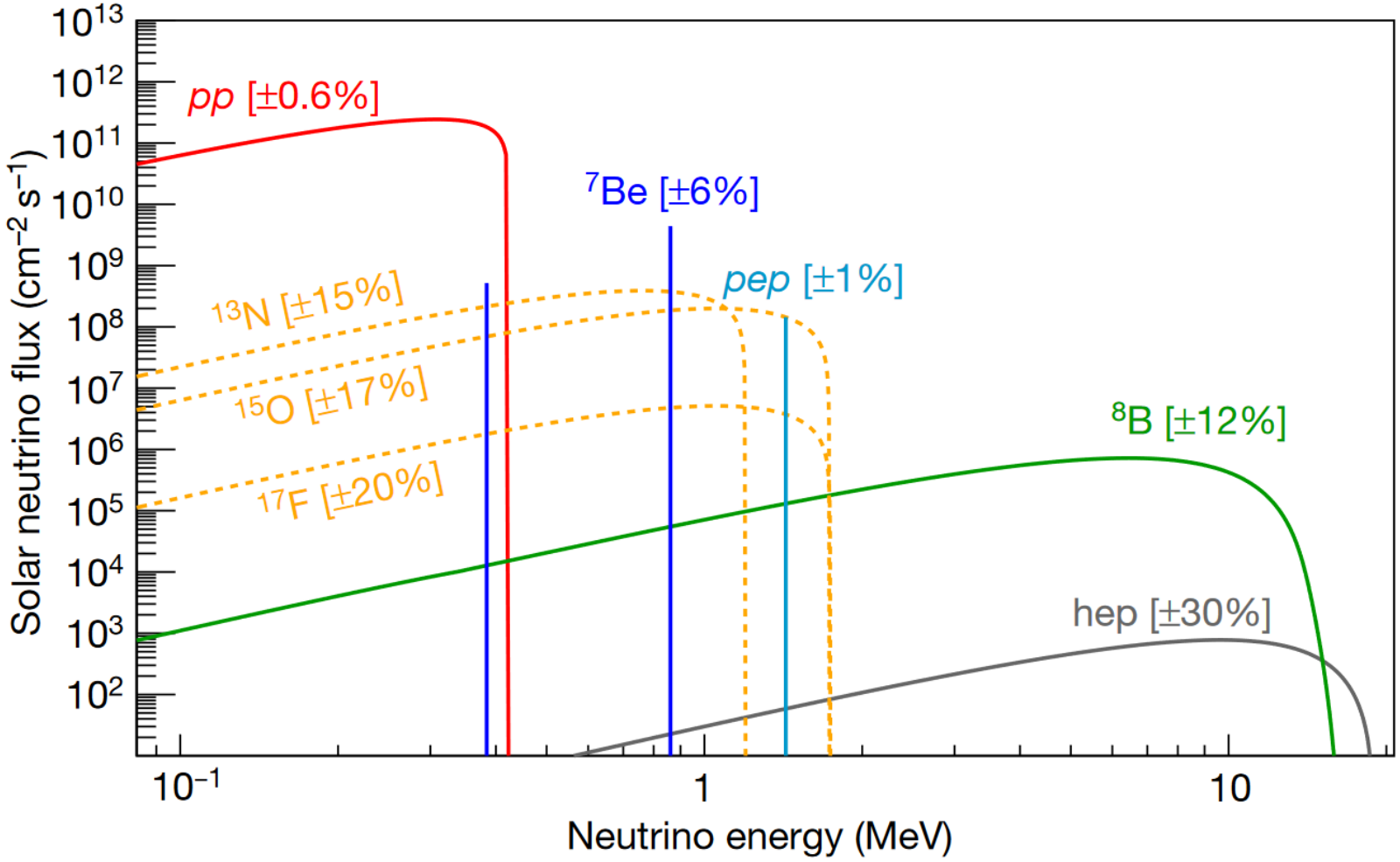
Production: CNO Cycle





Solar Neutrino Spectrum at Production

- All solar neutrinos are ν_e's
- Flux is predicted by the **Standard Solar Model**



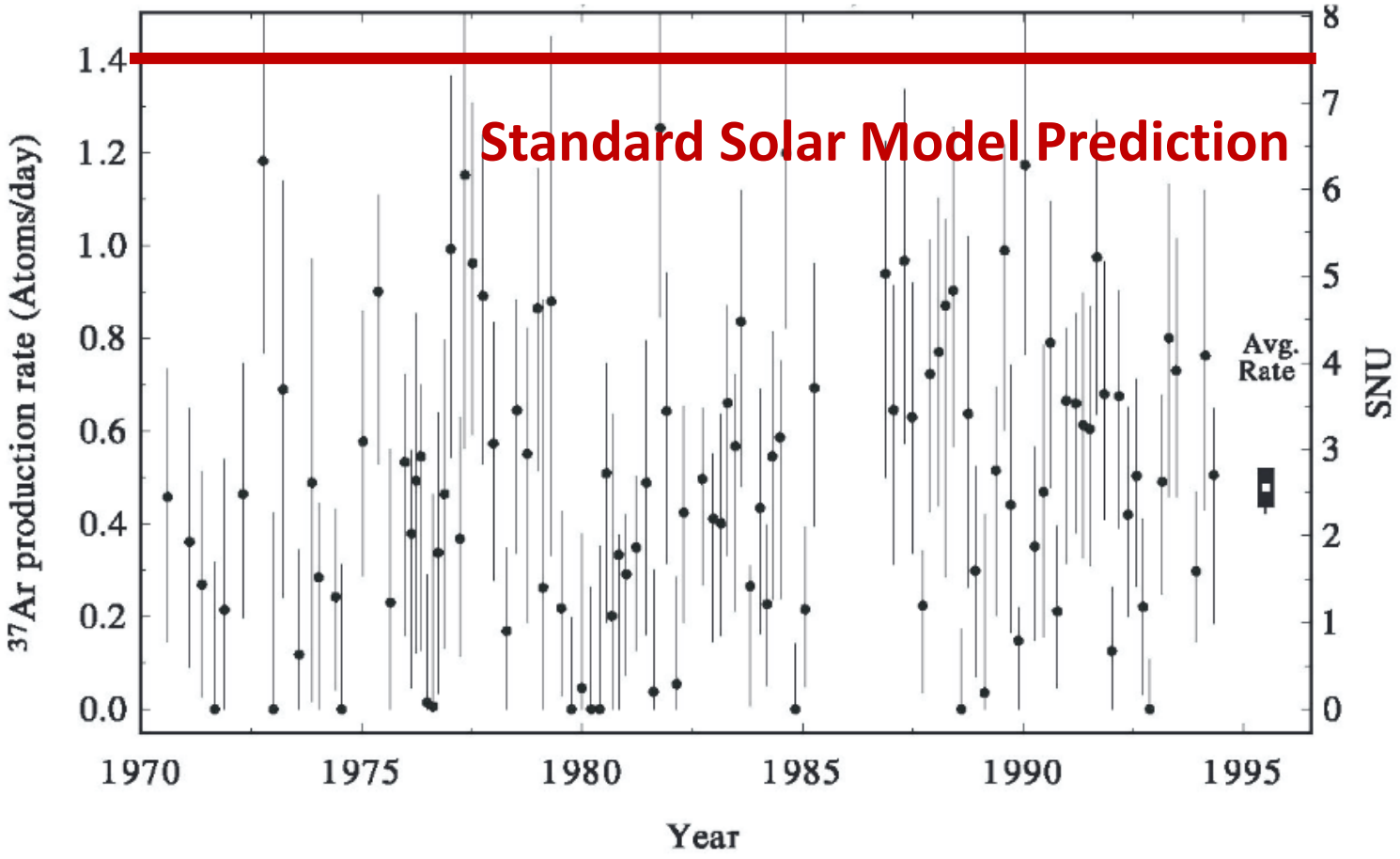
http://www.sns.ias.edu/~jnb/ Vinyoles, N. et al. Astrophys. J. 835,202 (2017). Borexino, *Nature* **562**, 505–510 (2018)

First Detection

The Davis experiment,
or the Homestake experiment

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

Solar Neutrino Deficit at Davis



B.T. Cleveland et al., Astrophys. J. 496, 505 (1998)

The Davis experiment,
or the Homestake experiment

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

Radiochemical Detection

	Homestake, SAGE, GALLEX…
Target	Ga or Cl
Interaction	$\nu_e + N \rightarrow e^- + N'$
Detection	Radioactivity from the product nucleus

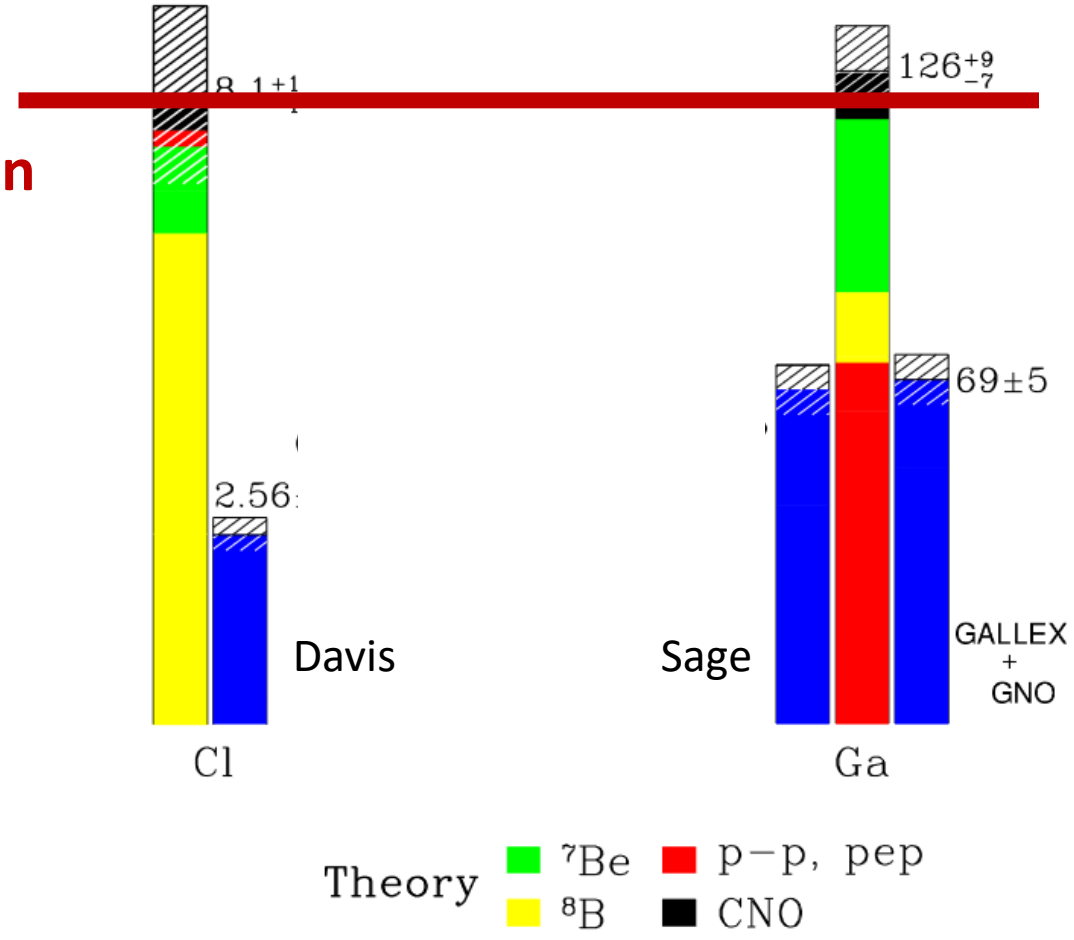
The Davis experiment,
or the Homestake experiment

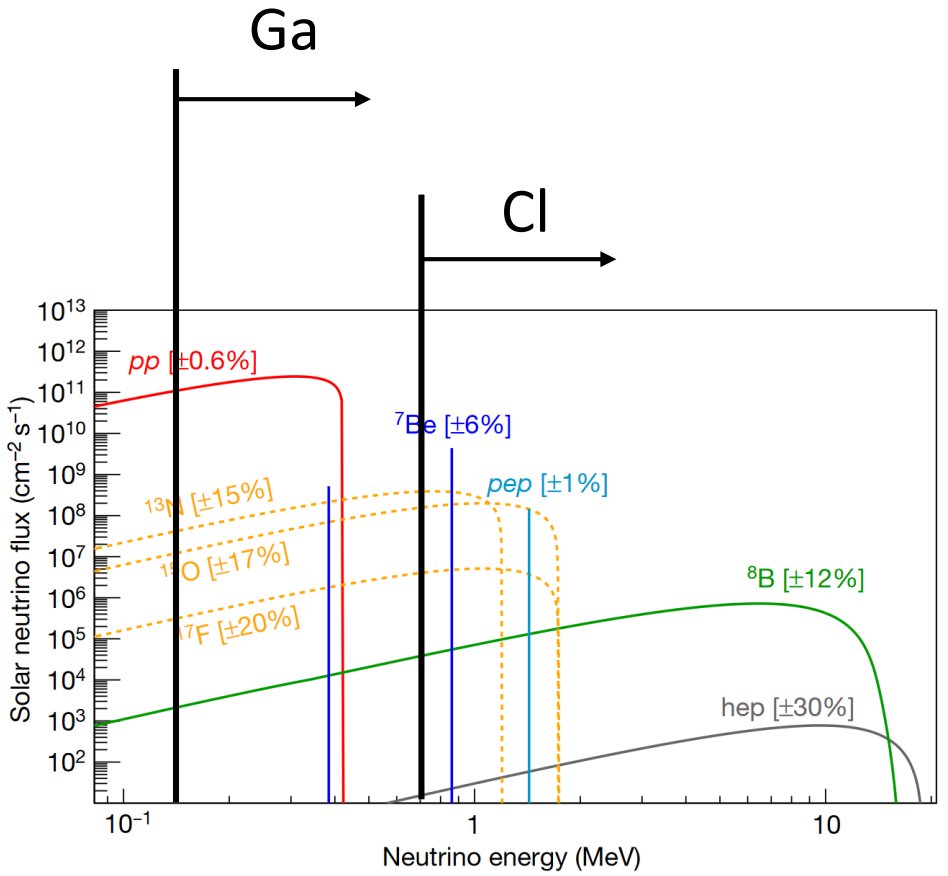
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}^+$$

The Deficit

Standard Solar Model Prediction

Experimental results

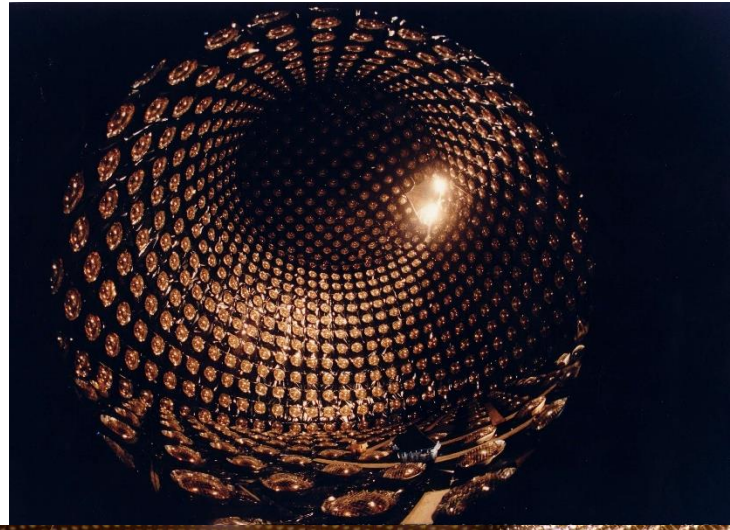


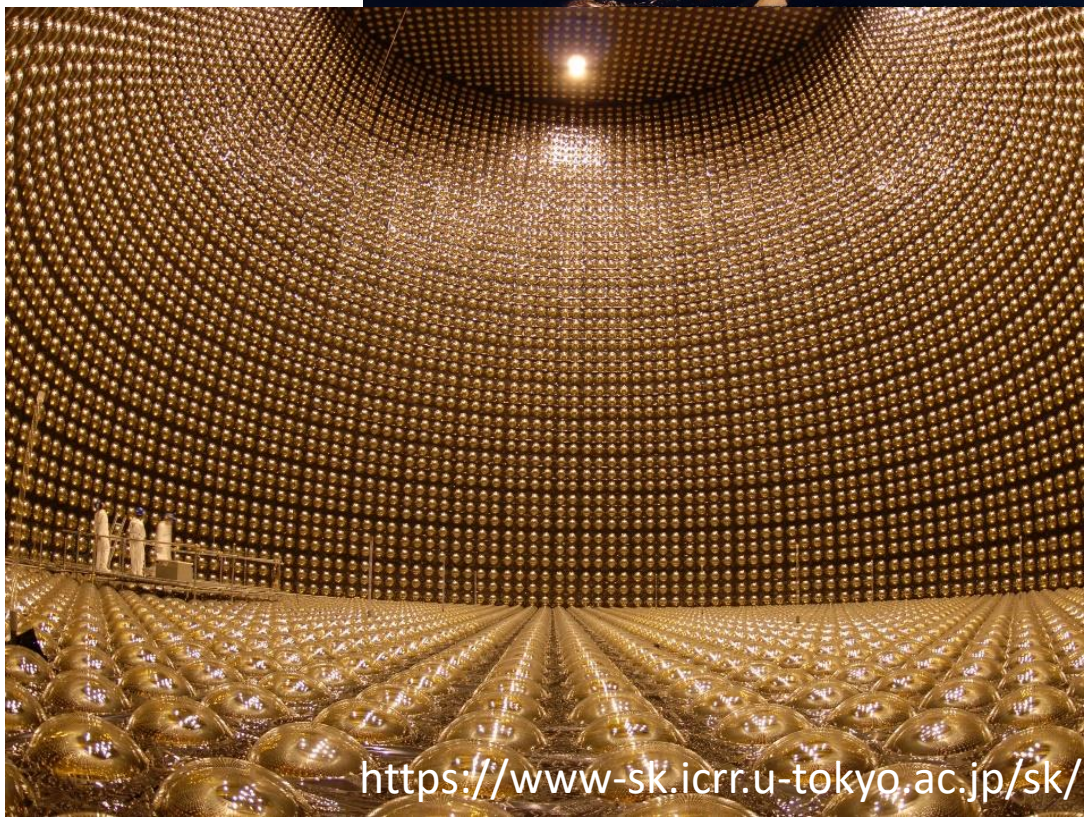


Detection at Kamioka

	Kamiokande-II, Super-Kamiokande
Target	H2O
Interaction	$\nu + e^- \rightarrow \nu + e^-$
Detection	Cherenkov

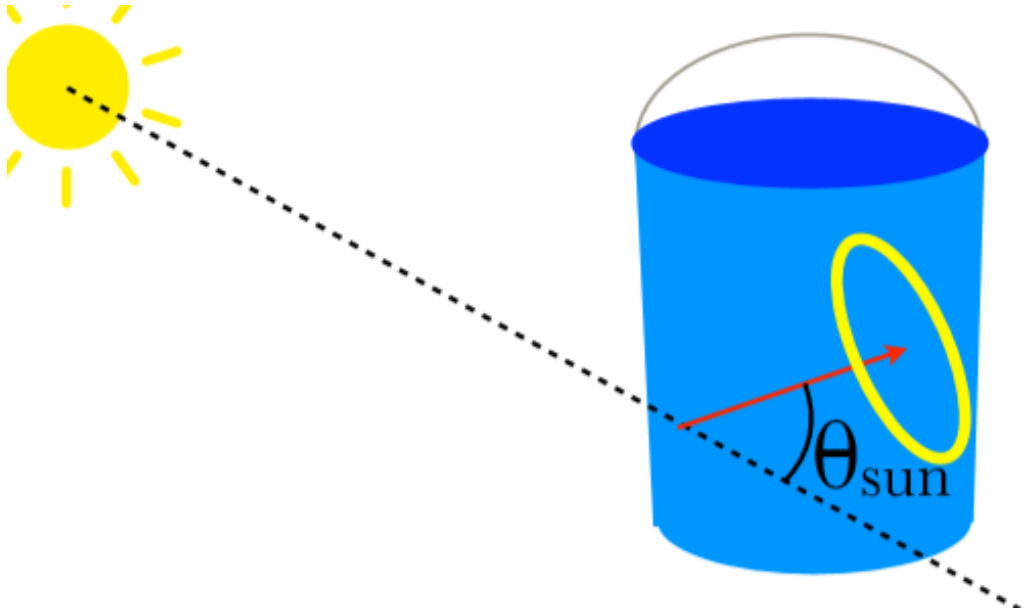
Kamiokande-II
(1985-1990)
↓
Super-Kamiokande
(1996-now)





Cherenkov Detectors

	Kamiokande-II, Super-Kamiokande
Target	H2O
Interaction	$\nu + e^- \rightarrow \nu + e^-$
Detection	Cherenkov



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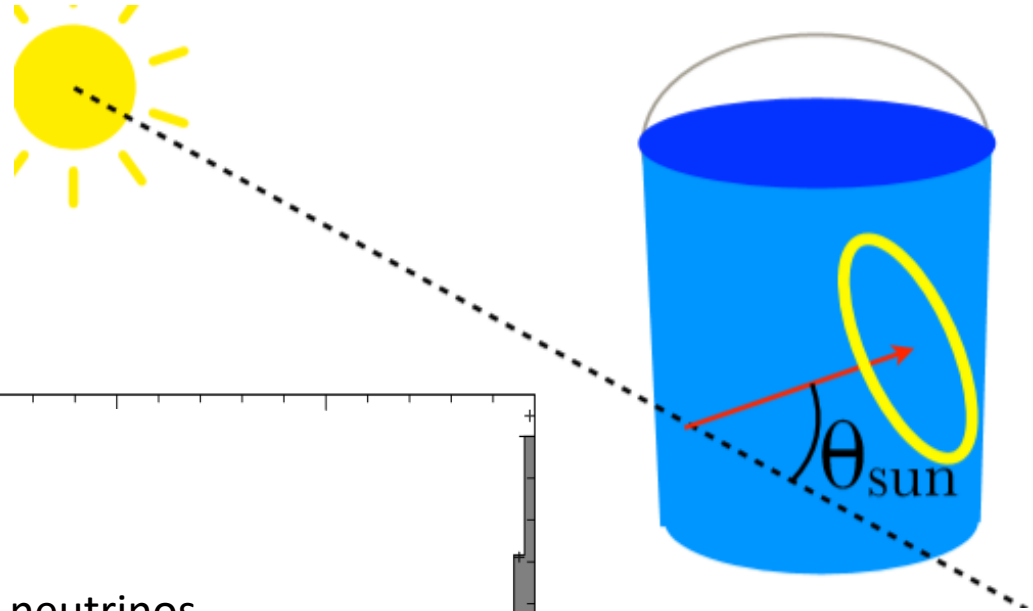
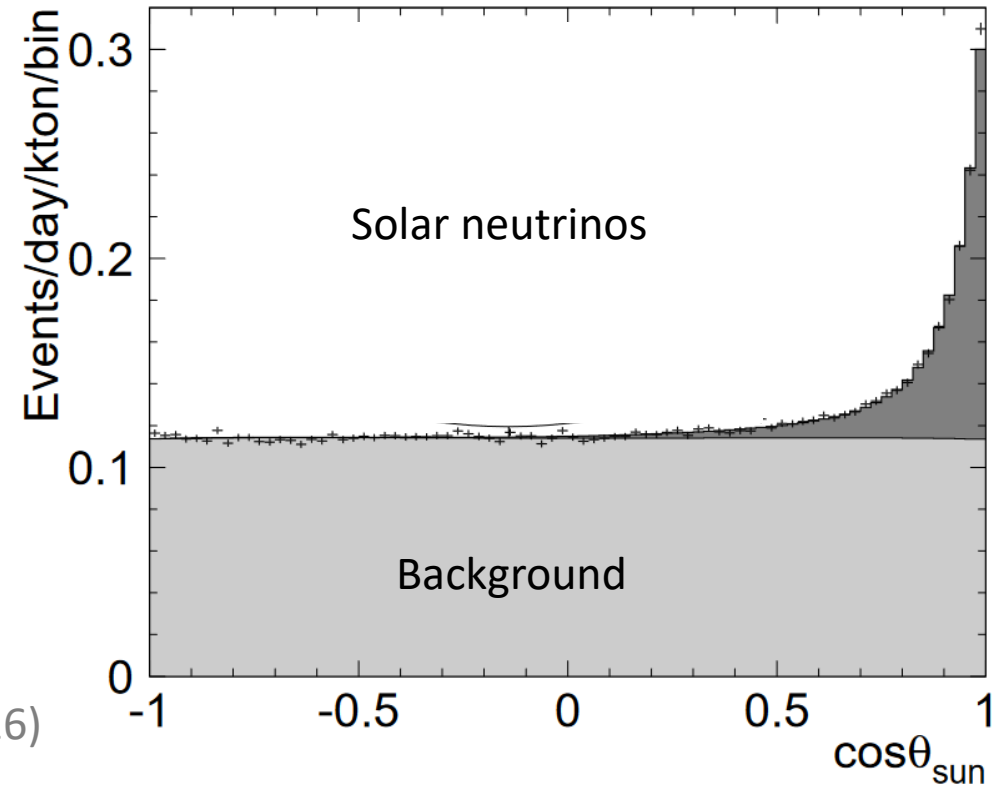
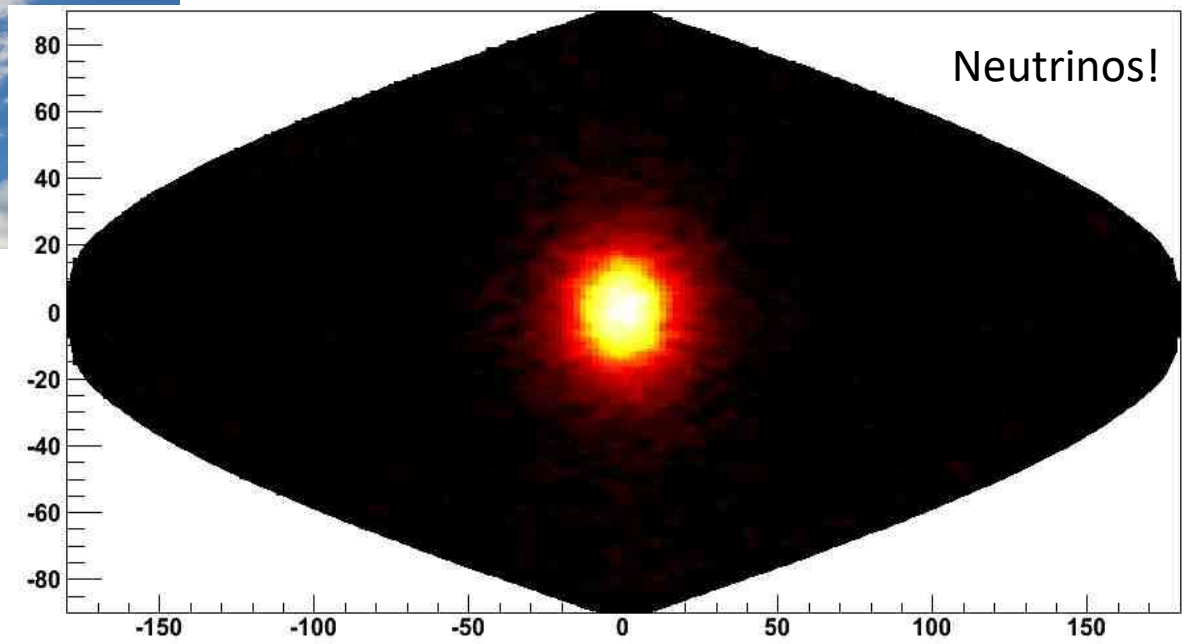




Super-Kamiokande, Phys. Rev. D 94, 052010 (2016)

An Image of the Sun

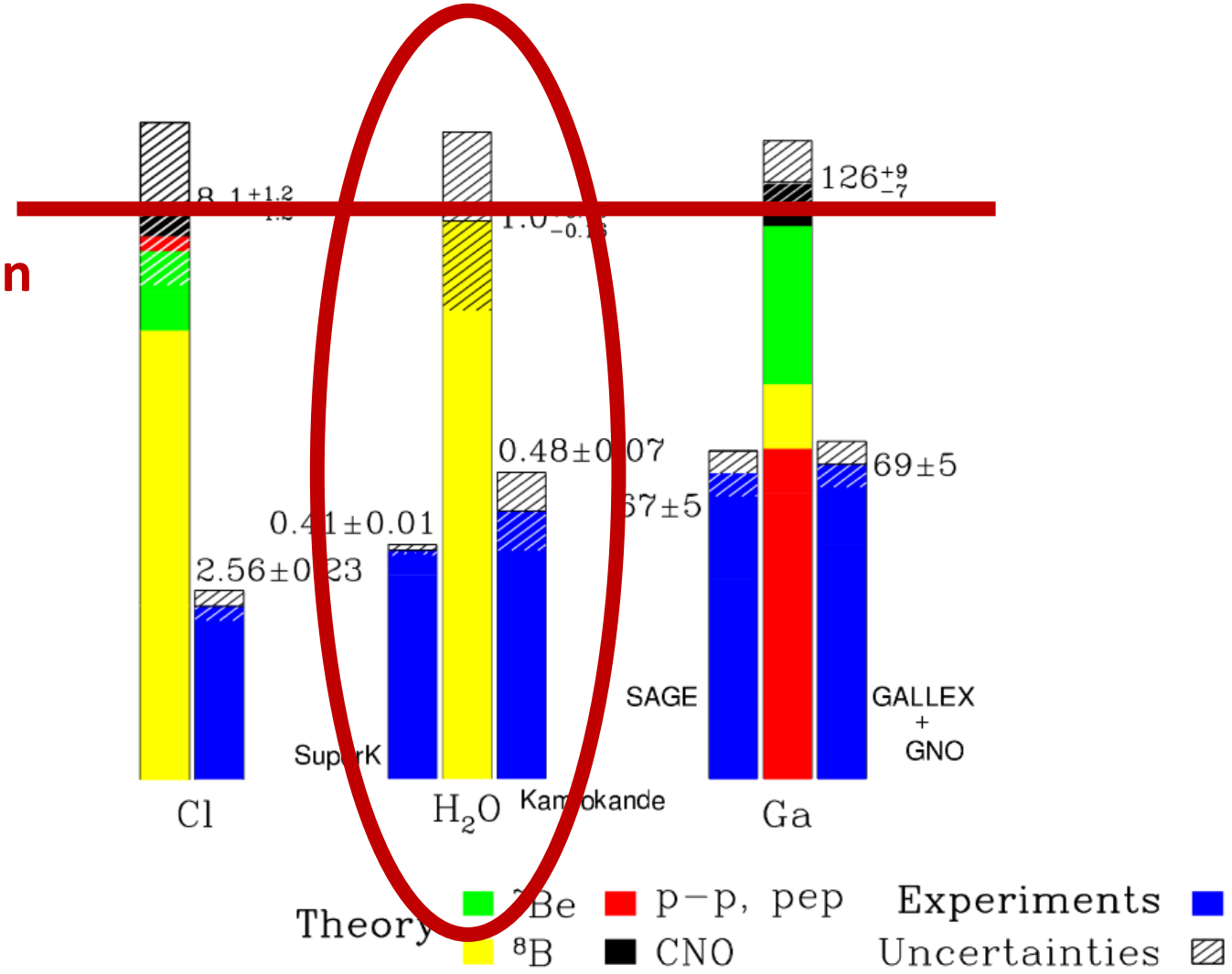


https://www-sk.icrr.u-tokyo.ac.jp/sk/

The Solar Neutrino Problem

Standard Solar Model Prediction

Experimental results



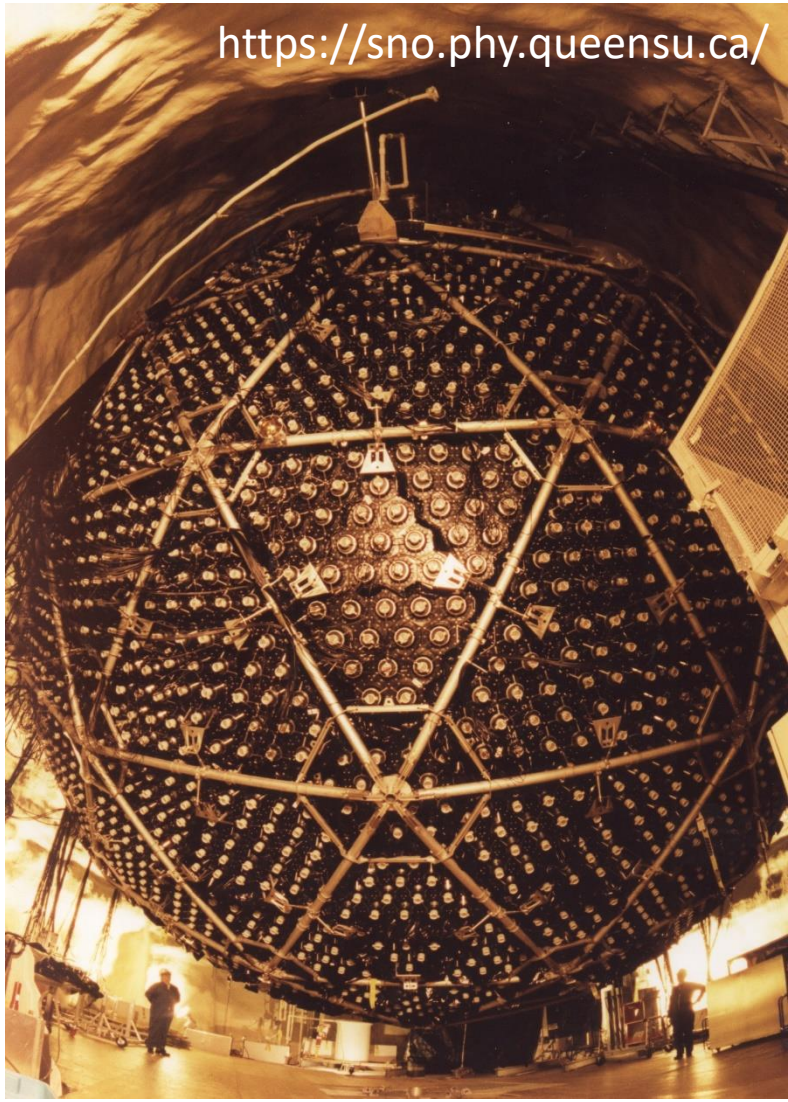
http://www.sns.ias.edu/~jnb/

SNO: A Special Cherenkov Detector

	Kamiokande-II, Super-Kamiokande	SNO
Target	H2O	D2O
Interaction	$\nu + e^- \rightarrow \nu + e^-$	ES + CC + NC
Detection	Cherenkov	Cherenkov

- Elastic scattering: $\nu + e^- \rightarrow \nu + \boldsymbol{e^-}$
- Charge current: $\nu_e + d \rightarrow \boldsymbol{e^-} + p + p$
- Neutral current: $\nu + d \rightarrow \nu + p + \boldsymbol{n}$

SNO (1999-2006)



SNO: A Special Cherenkov Detector

	Kamiokande-II, Super-Kamiokande	SNO
Target	H2O	D2O
Interaction	$\nu + e^- \rightarrow \nu + e^-$	ES + CC + NC
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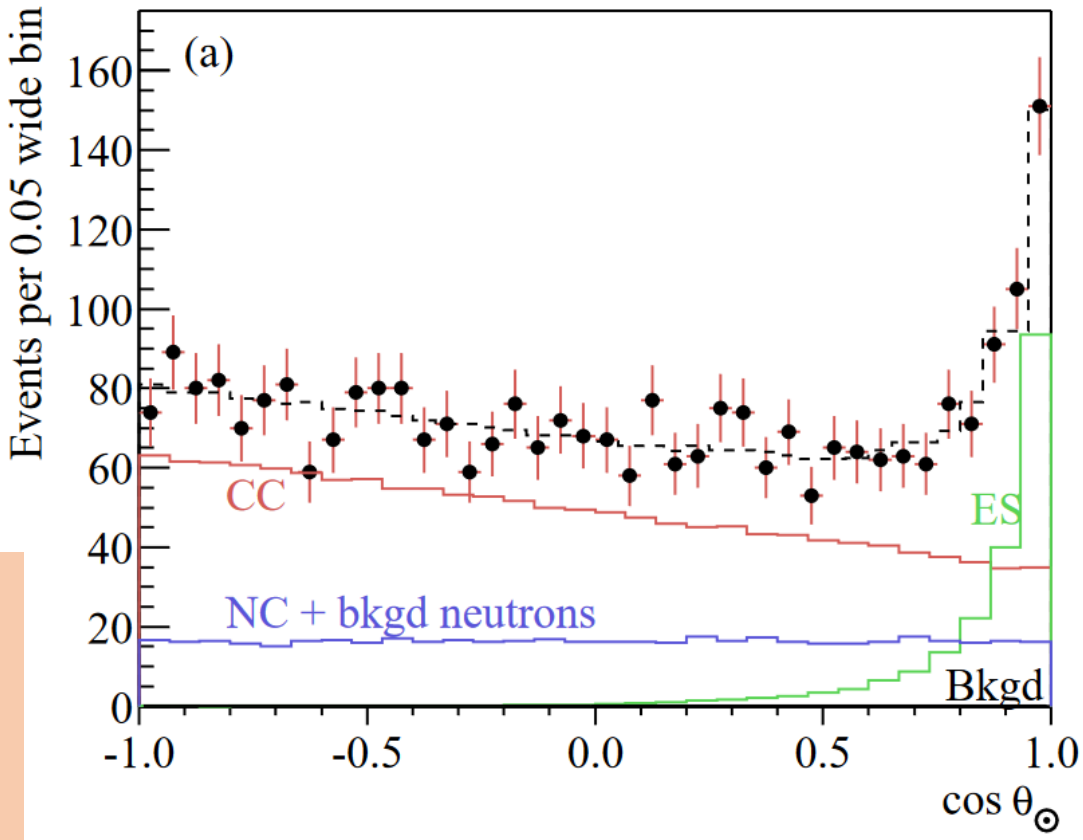
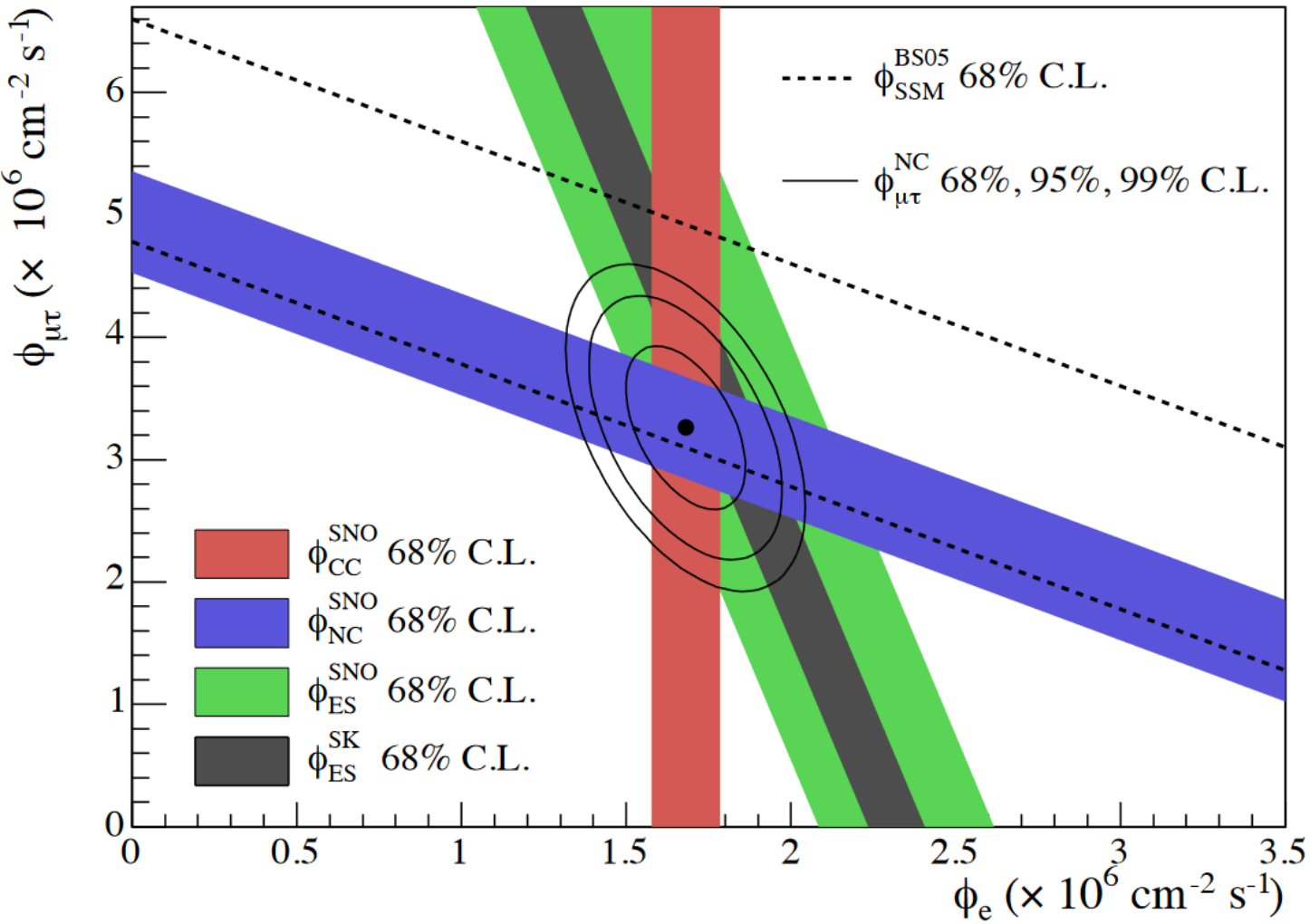
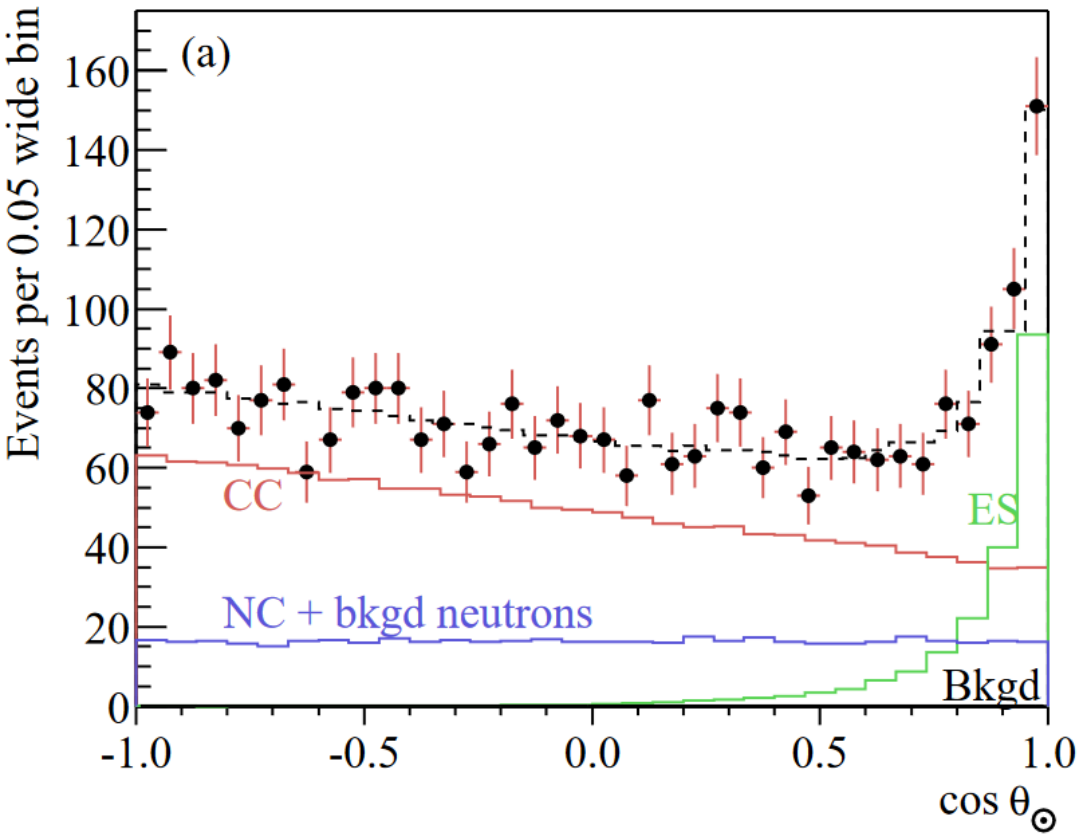


SNO, Phys.Rev.Lett.89:011301 (2002)

SNO: Flavor Measurement



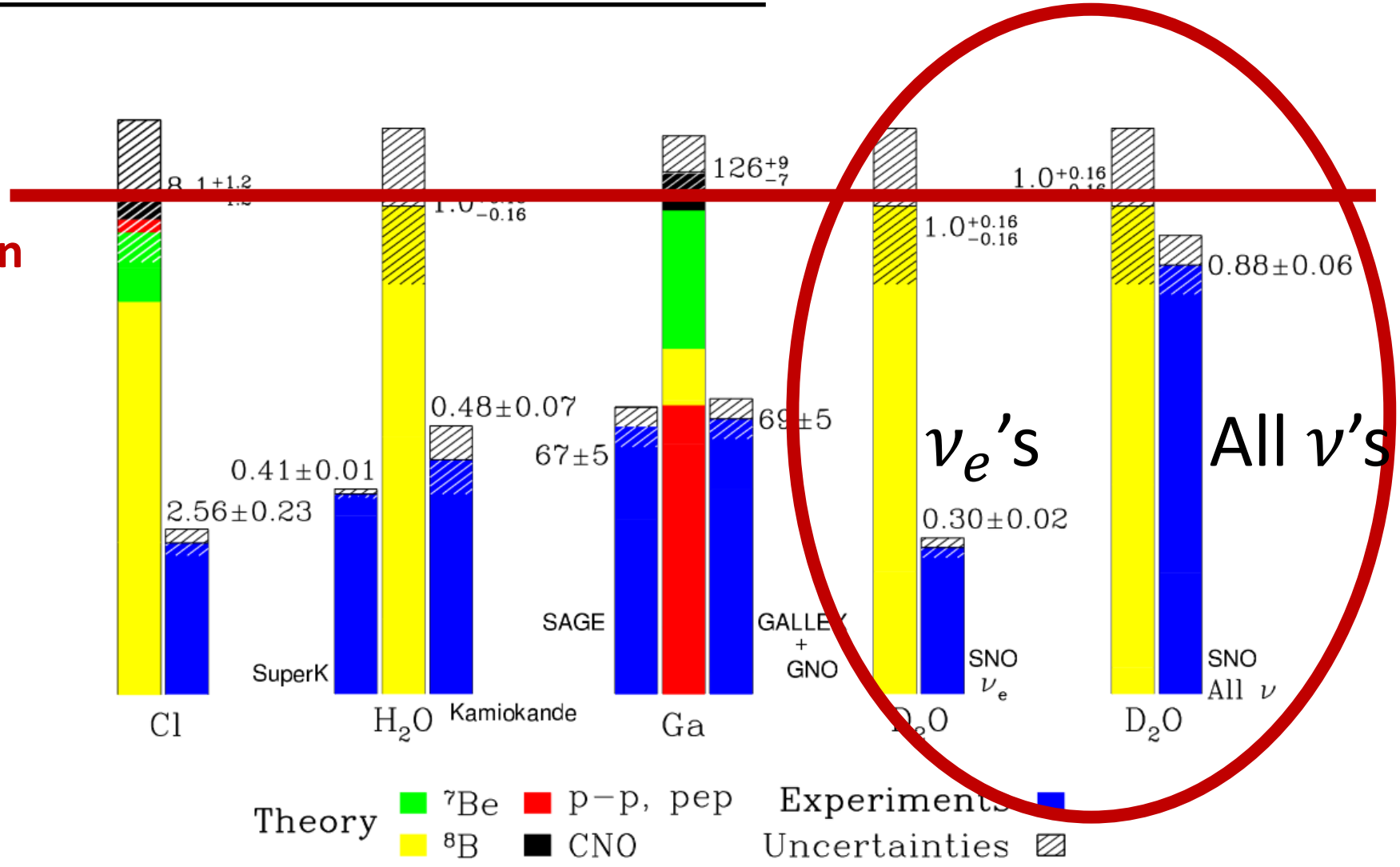


SNO, Phys.Rev.Lett.89:011301 (2002)

The Solar Neutrino Problem

Standard Solar Model Prediction

Experimental results



http://www.sns.ias.edu/~jnb/

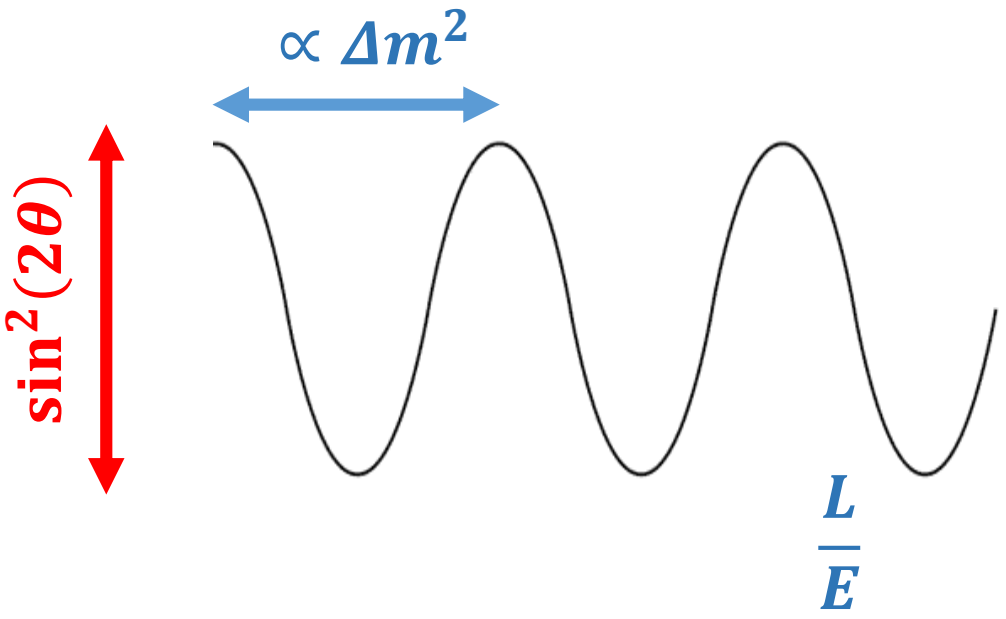
Neutrino Oscillation: Simplified 2-Flavor Model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Flavor eigenstate

Mass eigenstate

$$P_{\nu_e \to \nu_e} = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



Neutrino Mixing

Pontecorvo–Maki–Nakagawa–Sakata matrix

Δm^2_{21}

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

Δm^2_{32}

Flavor eigenstate

Mass eigenstate

Neutrino Oscillation

Pontecorvo–Maki–Nakagawa–Sakata matrix

Δm^2_{21}

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

Δm^2_{32}

Flavor eigenstate

Mass eigenstate

$$P_{ee} = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4\overline{p}}L\right) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}}{4\overline{p}}L\right) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}}{4\overline{p}}L\right)$$

Neutrino Oscillation

Pontecorvo–Maki–Nakagawa–Sakata matrix

Δm^2_{21}

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

Δm^2_{32}

Flavor eigenstate

Mass eigenstate

$$P_{ee} = 1 - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21}}{4\bar{p}} L\right)$$
$$- \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31}}{4\bar{p}} L\right)$$
$$- \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{32}}{4\bar{p}} L\right)$$

Neutrino Oscillation

Pontecorvo–Maki–Nakagawa–Sakata matrix

Δm^2_{21}

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

Δm^2_{32}

Flavor eigenstate

Solar

Mass eigenstate

$$P_{ee} = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4\bar{p}}L\right) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}}{4\bar{p}}L\right) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}}{4\bar{p}}L\right)$$

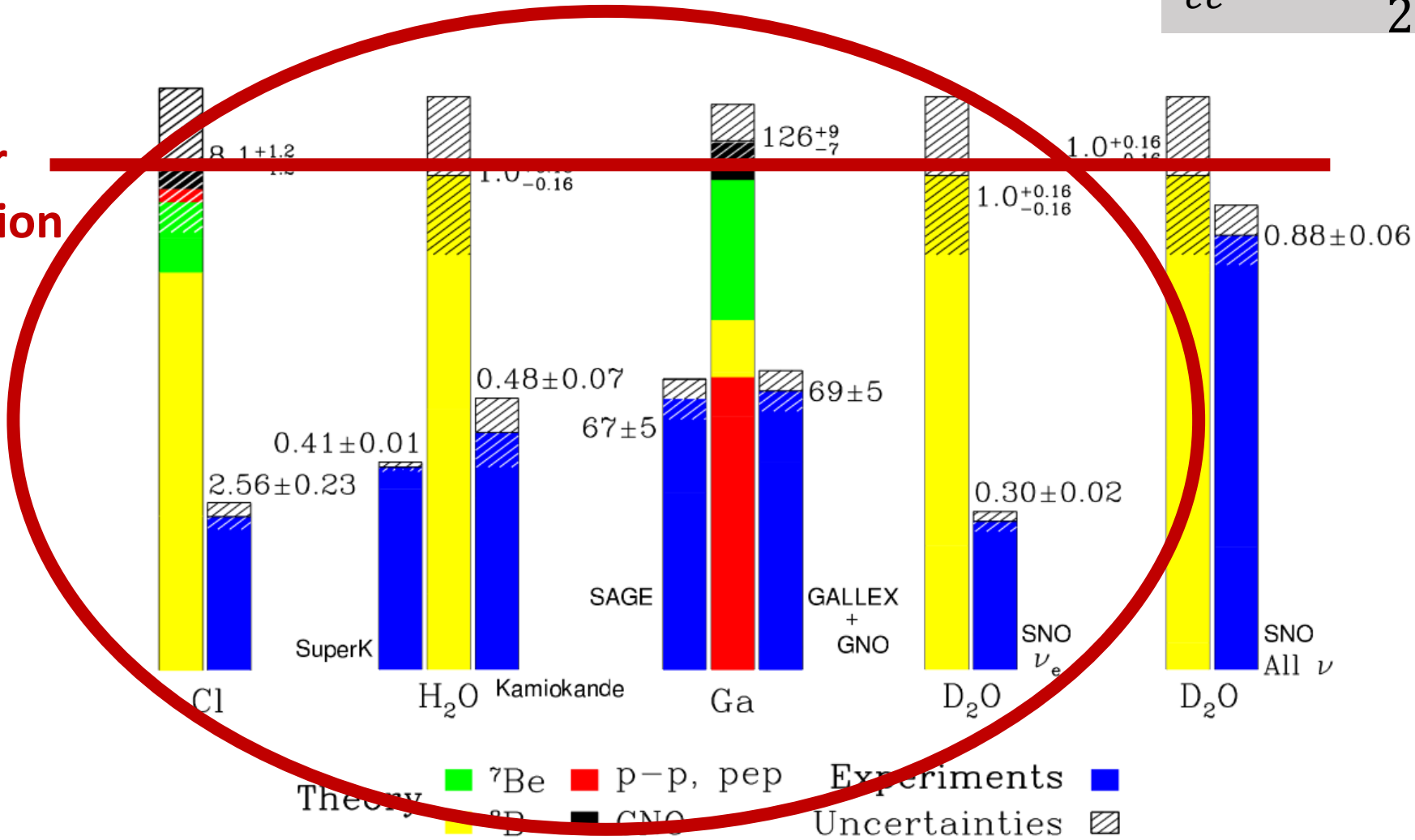
$$\approx 1 - \frac{1}{2}\sin^2(2\theta_{12})$$

The Solar Neutrino Problem

$$P_{ee} \approx 1 - \frac{1}{2}\sin^2(2\theta_{12})$$

Standard Solar Model Prediction

Experimental results



http://www.sns.ias.edu/~jnb/

Matter Effect

$$H_V = \begin{pmatrix} \frac{m_1^2}{2E} & \\ & \frac{m_2^2}{2E} \end{pmatrix},$$

Matter Effect

$$H_V = \begin{pmatrix} \frac{m_1^2}{2E} & \\ & \frac{m_2^2}{2E} \end{pmatrix},$$

$$H_M = H_V + U^{\dagger} \begin{pmatrix} \sqrt{2} G_F N_e & \\ & 0 \end{pmatrix} U$$

Matter Effect

$$H_V = \begin{pmatrix} \frac{m_1^2}{2E} & \\ & \frac{m_2^2}{2E} \end{pmatrix},$$

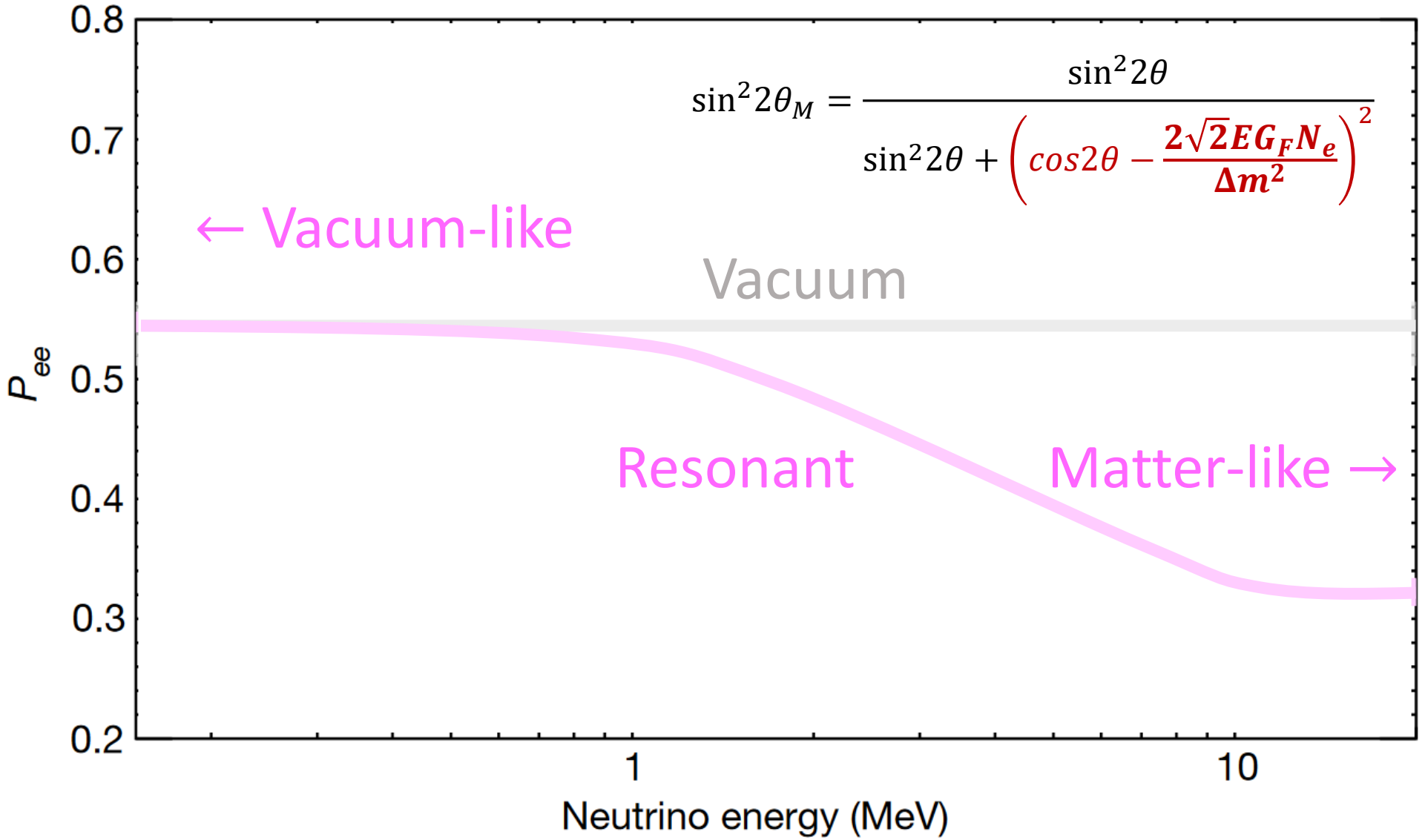
$$H_M = H_V + U^{\dagger} \begin{pmatrix} \sqrt{2} G_F N_e & \\ & 0 \end{pmatrix} U$$

Effective mixing parameters

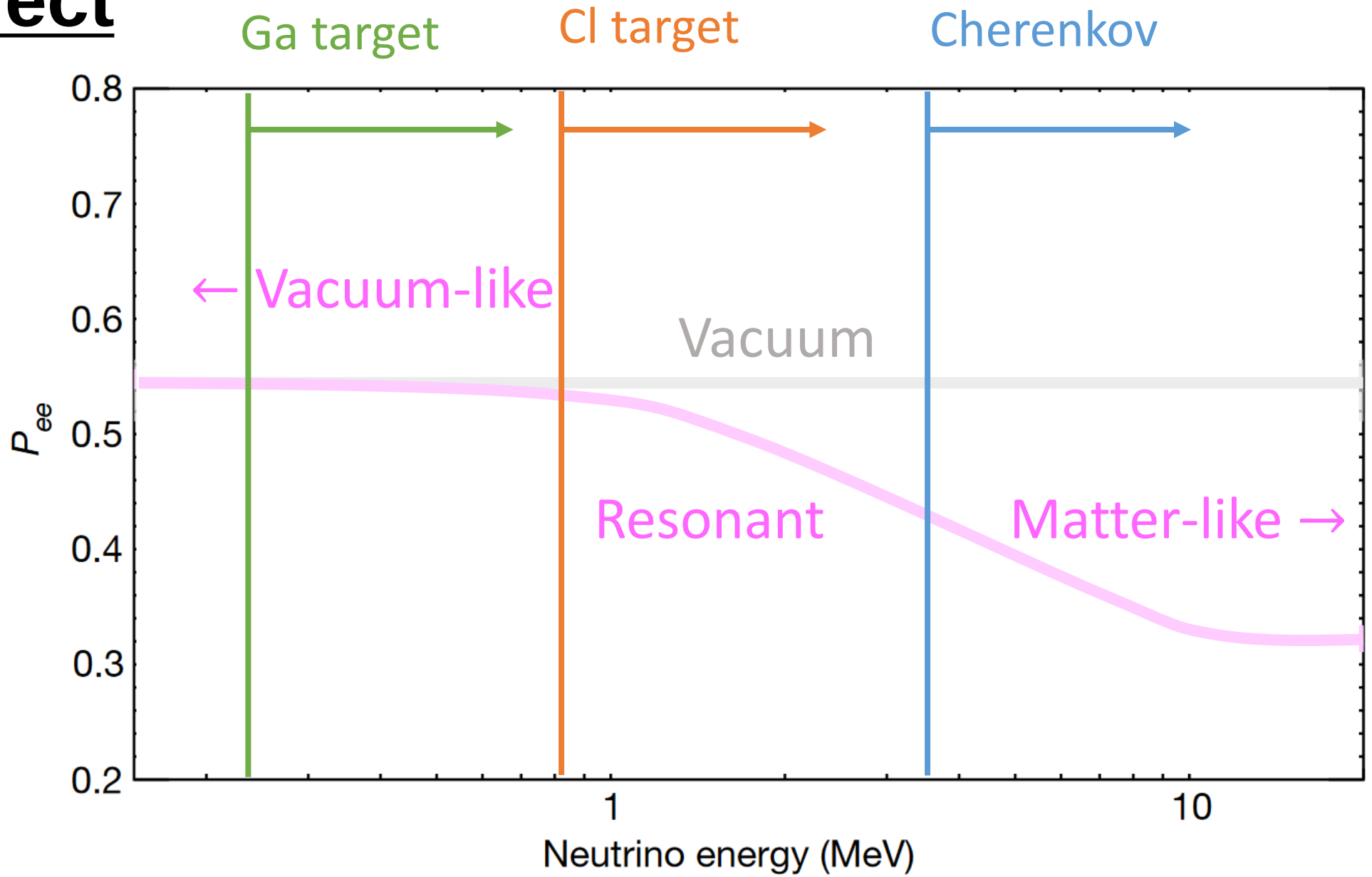
$$\begin{cases} \Delta m_M^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - 2\sqrt{2} E G_F N_e\right)^2 + (\Delta m^2 \sin 2\theta)^2} \\ \sin^2 2\theta_M = \dfrac{\sin^2 2\theta}{\sin^2 2\theta + \left(cos2\theta - \dfrac{\mathbf{2\sqrt{2} E G_F N_e}}{\mathbf{\Delta m^2}}\right)^2} \end{cases}$$

Energy dependent mixing!

MSW Effect


$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(cos2\theta - \frac{2\sqrt{2}EG_F N_e}{\Delta m^2}\right)^2}$
← Vacuum-like
Vacuum
Resonant
Matter-like →
P_{ee}
0.8
0.7
0.6
0.5
0.4
0.3
0.2
1
10
Neutrino energy (MeV)

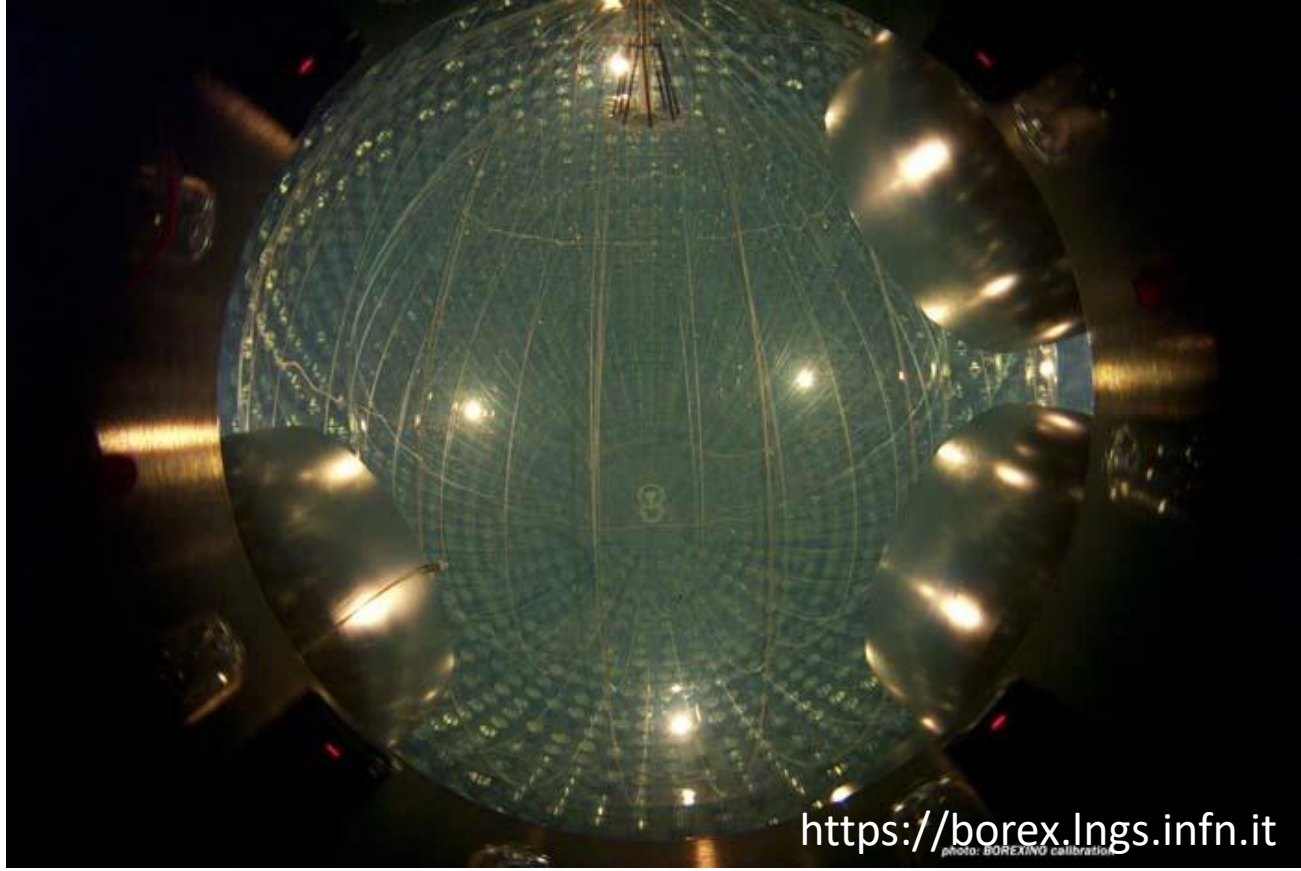
MSW Effect


Ga target
Cl target
Cherenkov
0.8
0.7
0.6
0.5
0.4
0.3
0.2
P_{ee}
← Vacuum-like
Vacuum
Resonant
Matter-like →
1
10
Neutrino energy (MeV)

Scintillation Detection

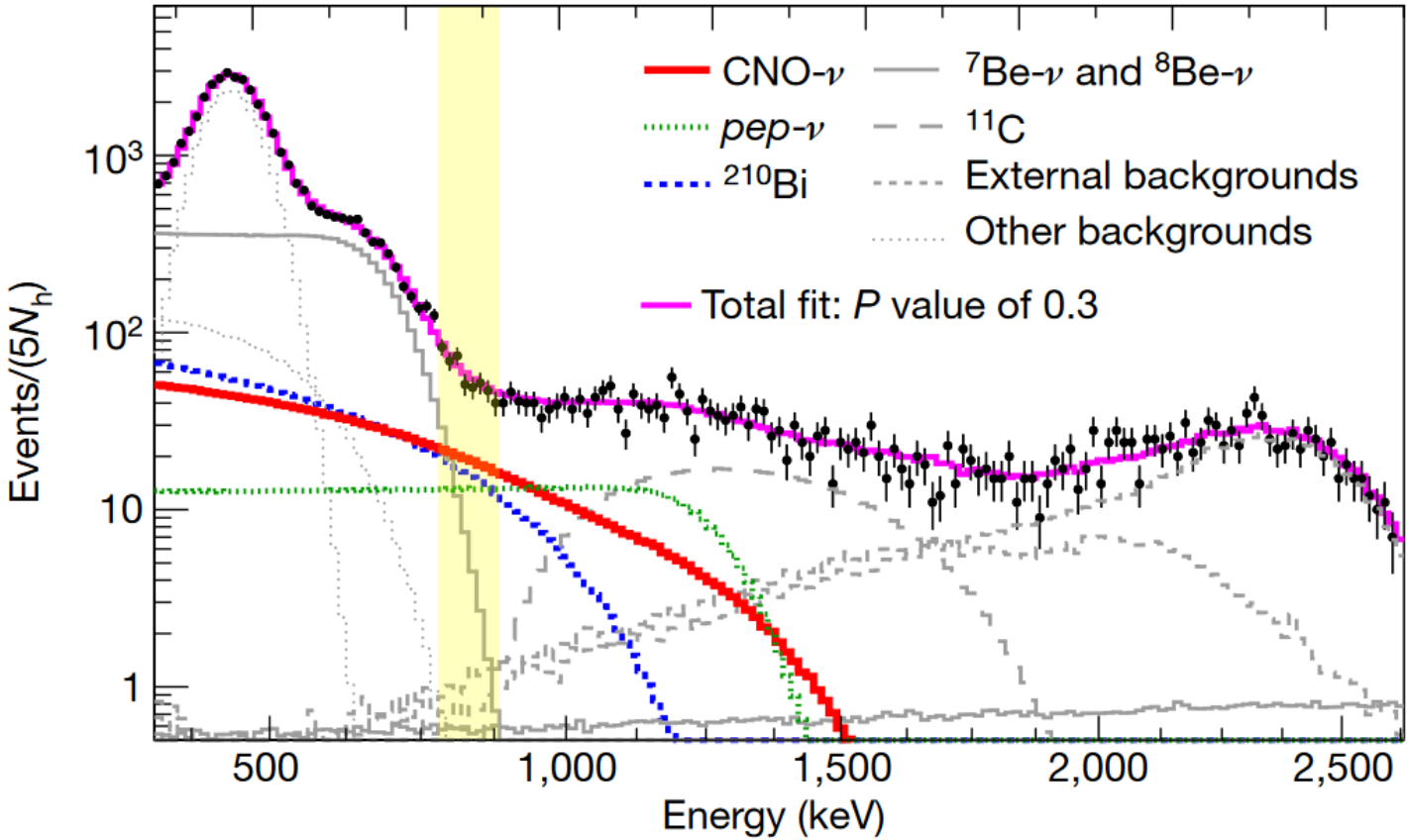
	KamLAND, Borexino…
Target	Liquid scintillator
Interaction	$\nu + e^- \rightarrow \nu + e^-$
Detection	Scintillation

KamLAND (2002-)



Borexino (2007-2021)

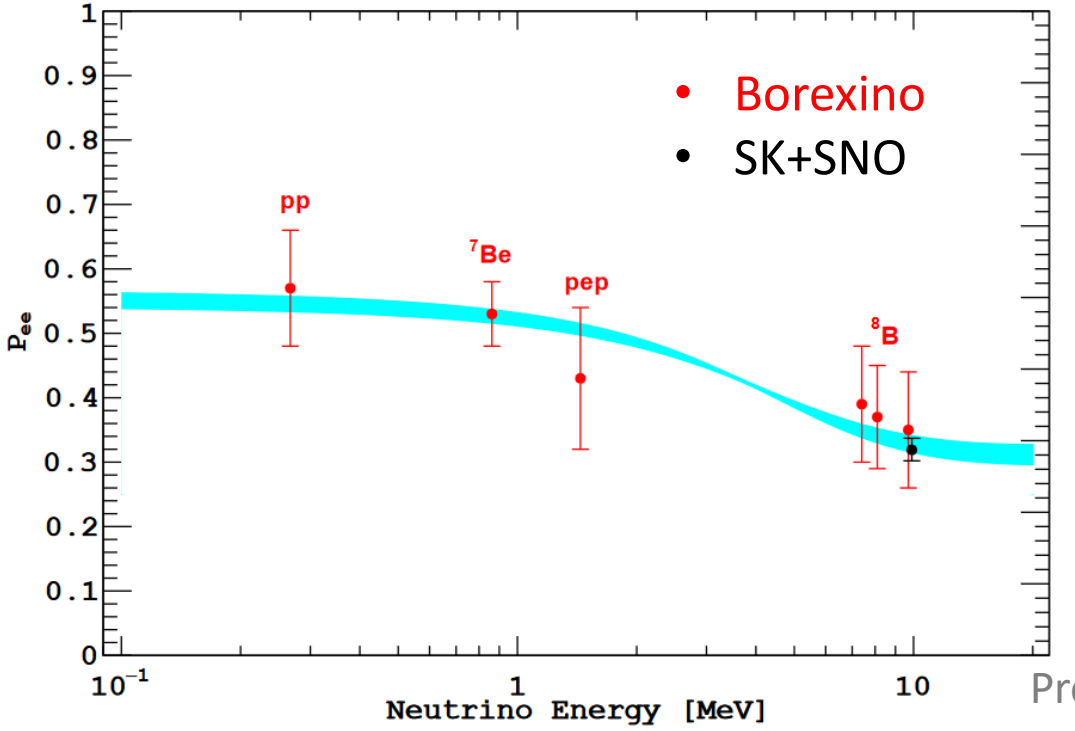
Borexino Results



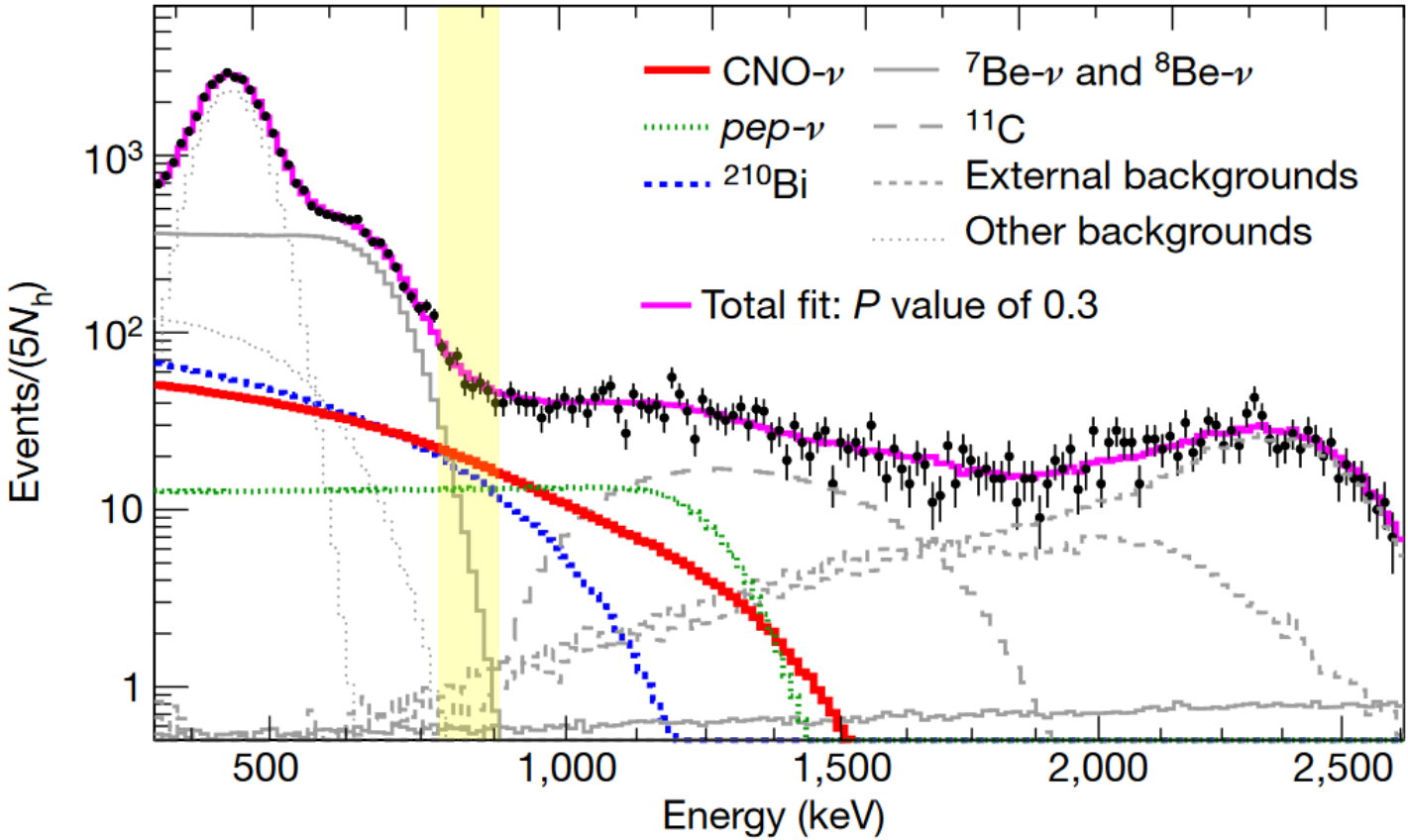
Borexino, Nature 587, 577–582 (2020)

- Discovery of CNO neutrinos in 2020

Borexino Results



Prog. Theor. Exp. Phys. 2022, 083C01 (2022)



Borexino, Nature 587, 577–582 (2020)

- Discovery of CNO neutrinos in 2020

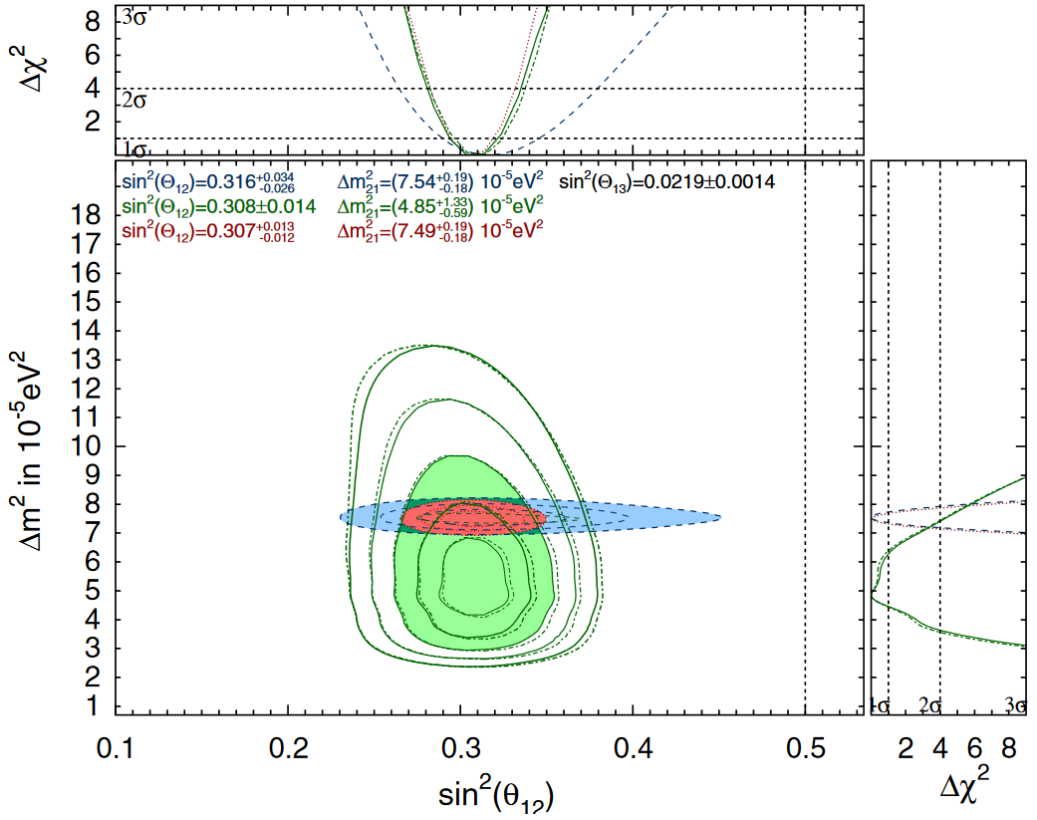
Looking Forward

- Neutrino oscillation
- Probing the Sun
- …

Looking Forward

- Neutrino oscillation
  - Precise measurement of $\sin^2\theta_{12}$ and Δm^2_{21}

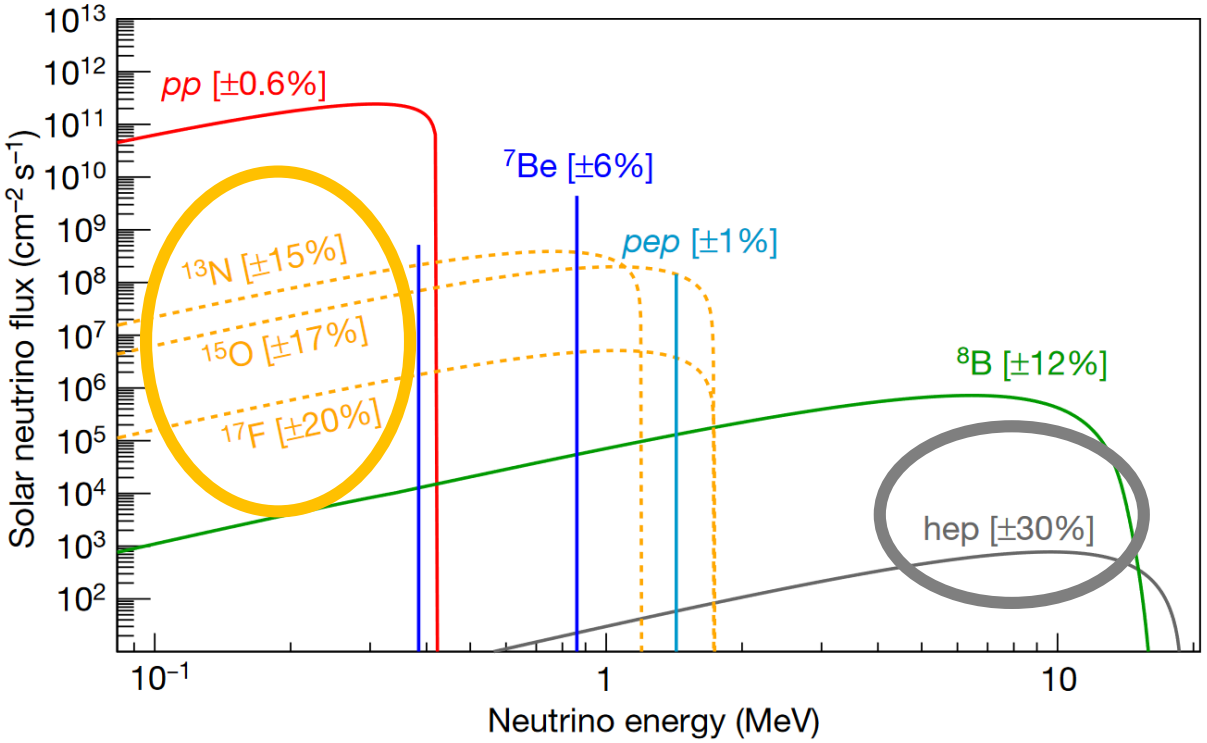
Solar neutrinos (SNO+SK)



Super-Kamiokande, Phys. Rev. D 94, 052010 (2016)

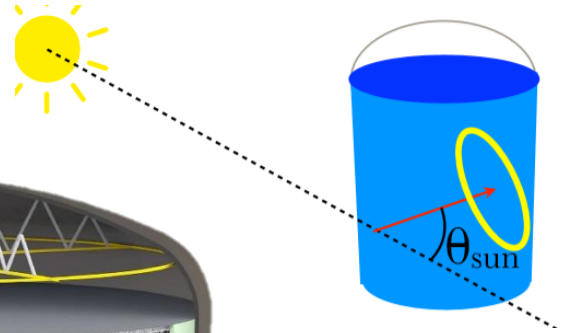
Looking Forward

- Neutrino oscillation
  - Precise measurement of $\sin^2\theta_{12}$ and Δm^2_{21}
- Probing the Sun
  - Metallicity
  - Discover hep neutrinos
- …



Future Detectors

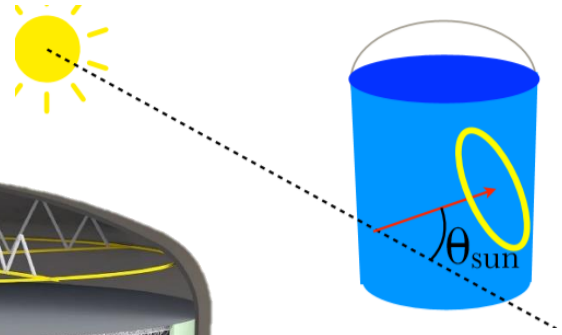
Directional



Hyper-Kamiokande

Future Detectors

Directional

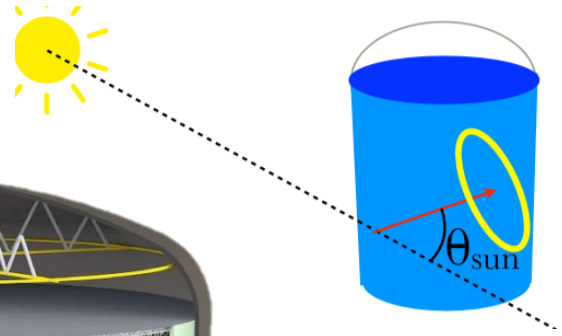


Hyper-Kamiokande

Energy resolution ~3%

Future Detectors

Directional



Hyper-Kamiokande

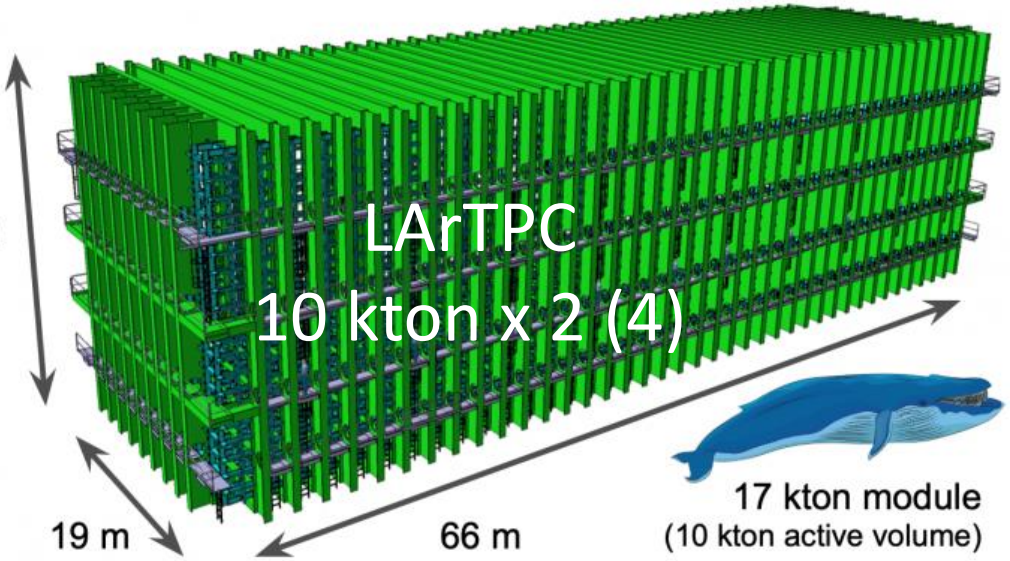
THEIA
WbLS

JINPING NEUTRINO EXPERIMENT

Energy resolution ~3%

Future Detectors

Charged current
+
Elastic scattering



DUNE

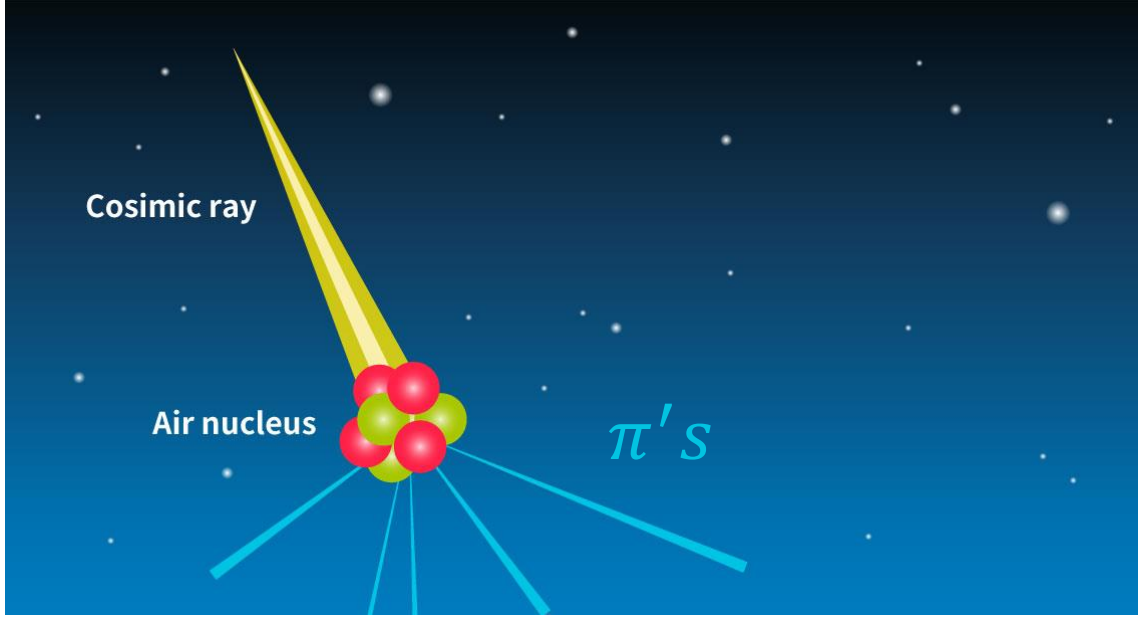
Hyper-Kamiokande

THEIA
WbLS

JINPING NEUTRINO EXPERIMENT

Atmospheric Neutrinos

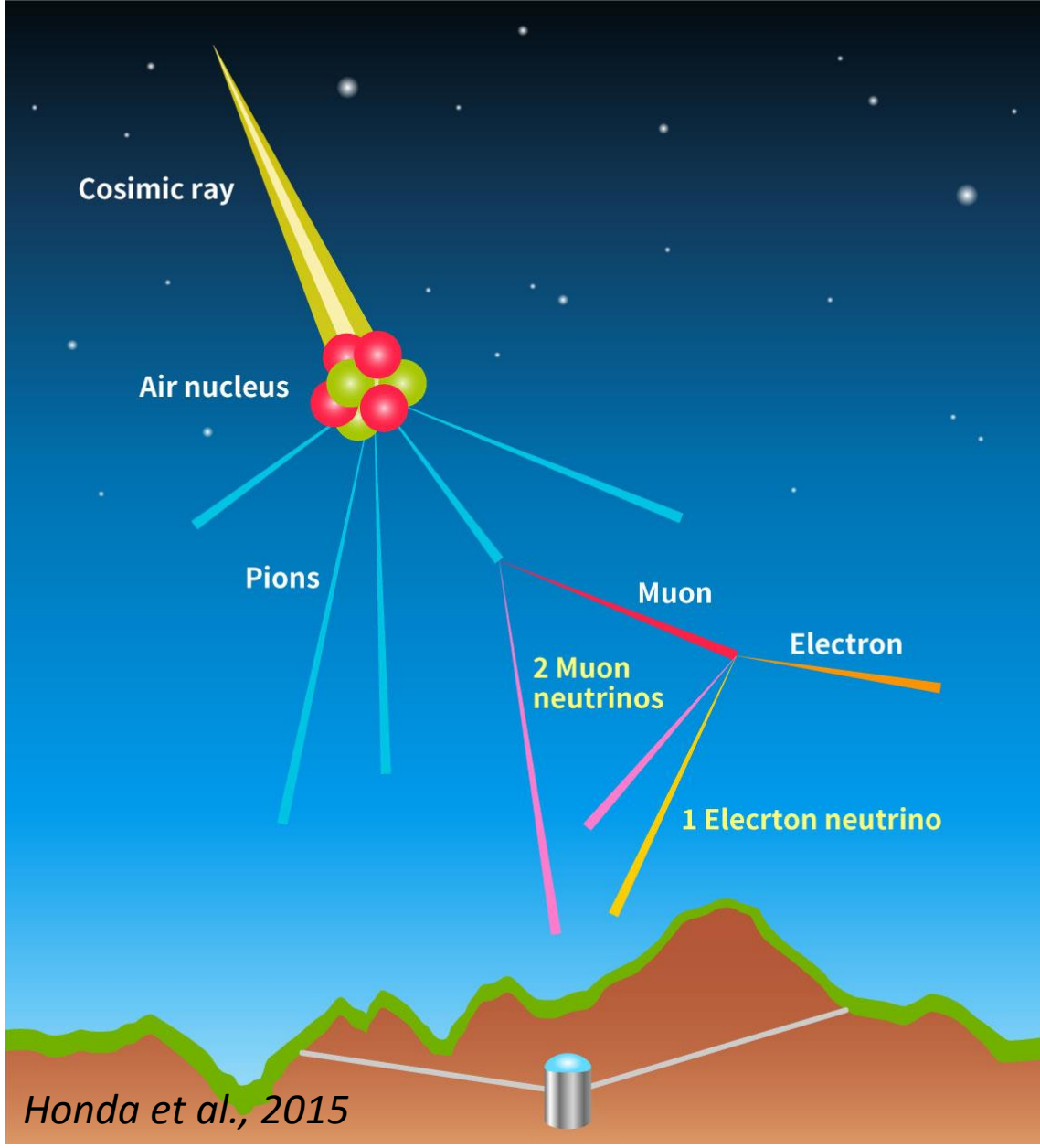
Atmospheric Neutrinos



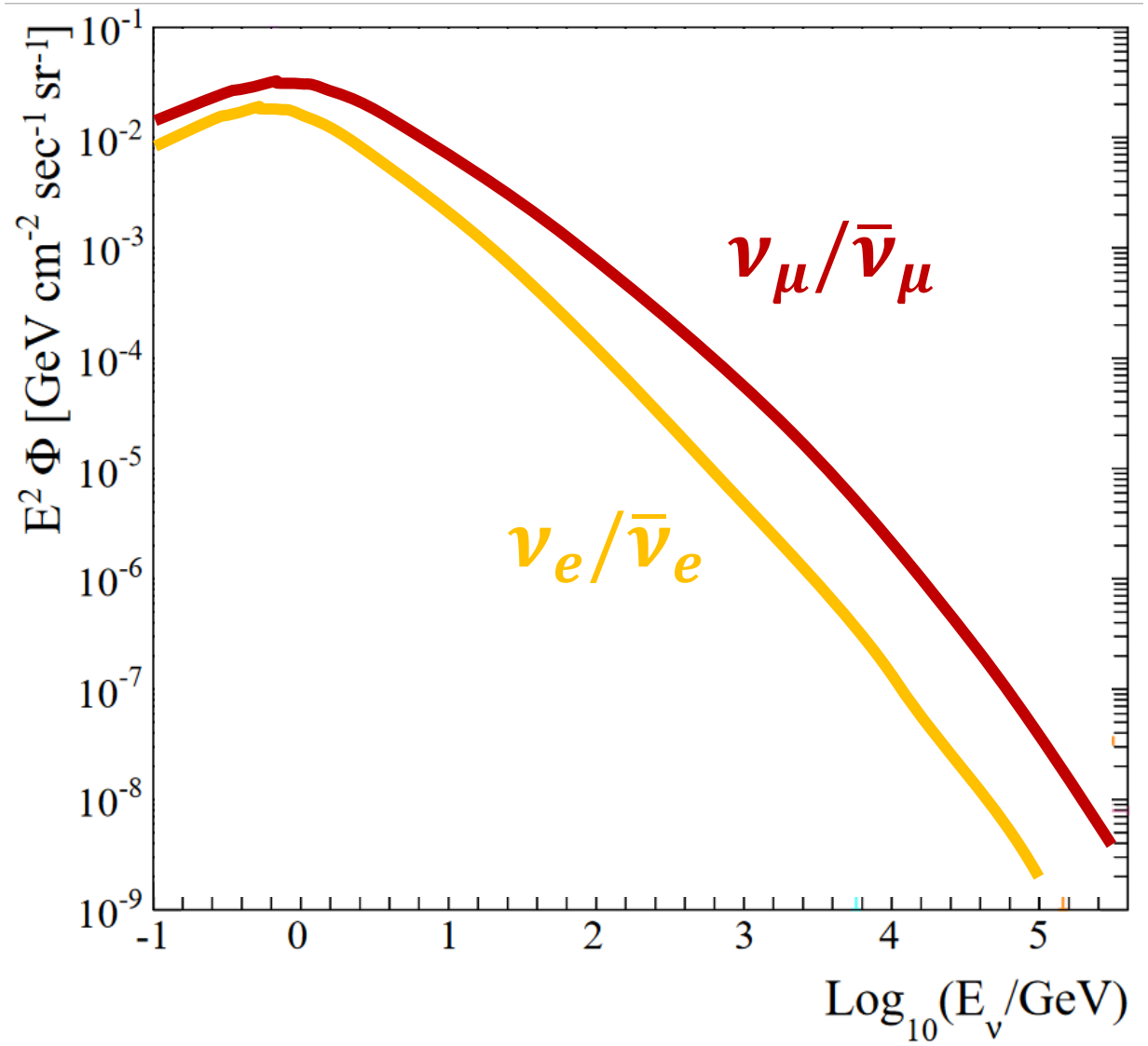
Atmospheric Neutrinos

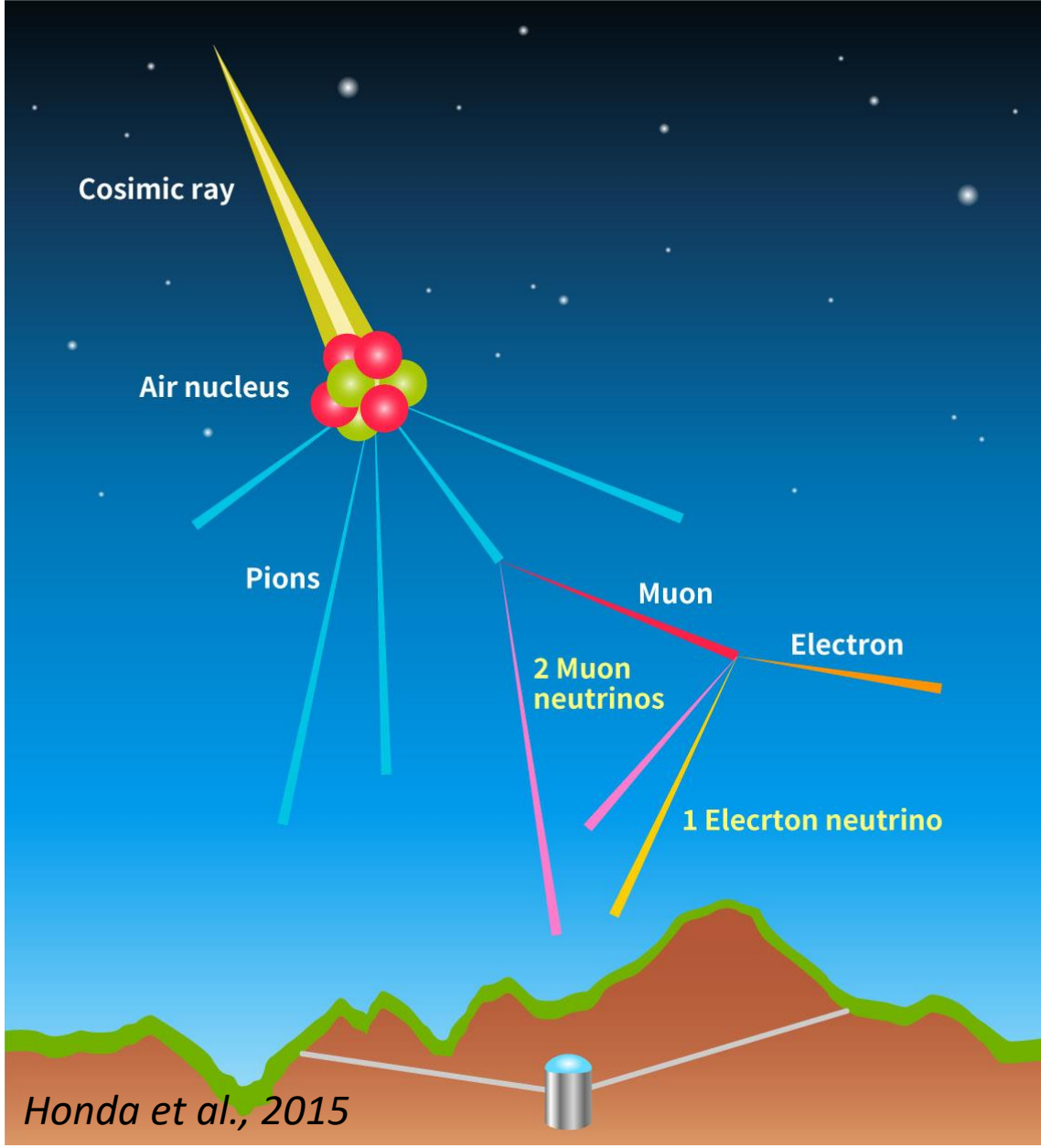
- $\pi^- \rightarrow \bar{\nu}_\mu + \mu^-$
- $\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$

- $\pi^+ \rightarrow \nu_\mu + \mu^+$
- $\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$

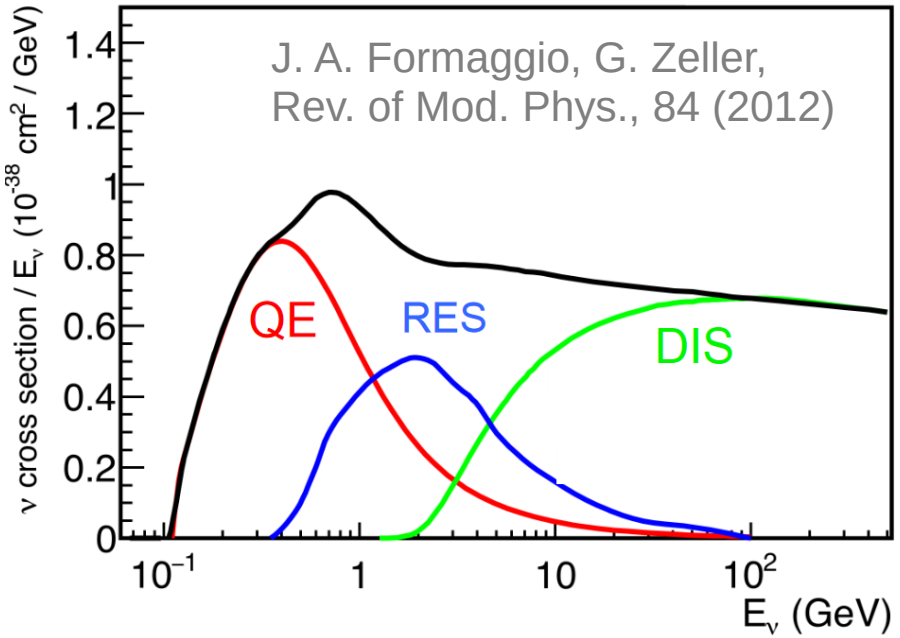


Atmospheric Neutrinos



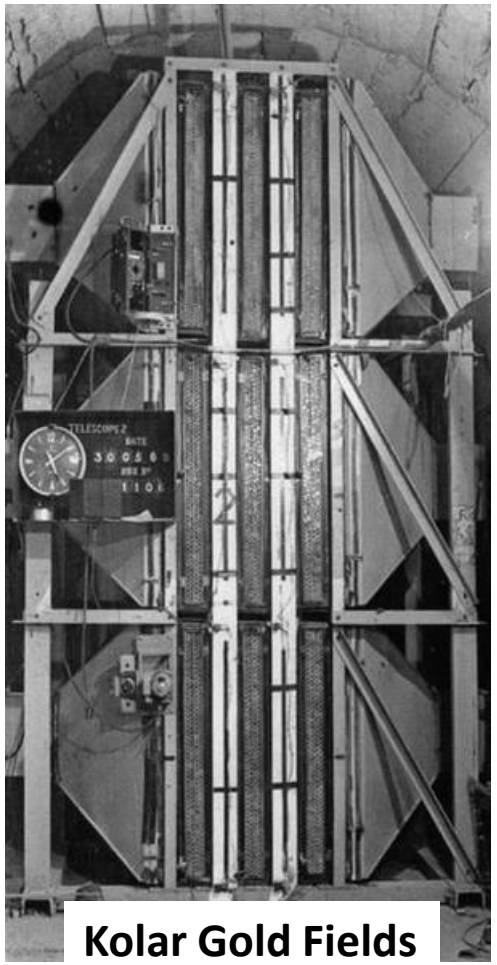


Neutrino Interaction at GeV



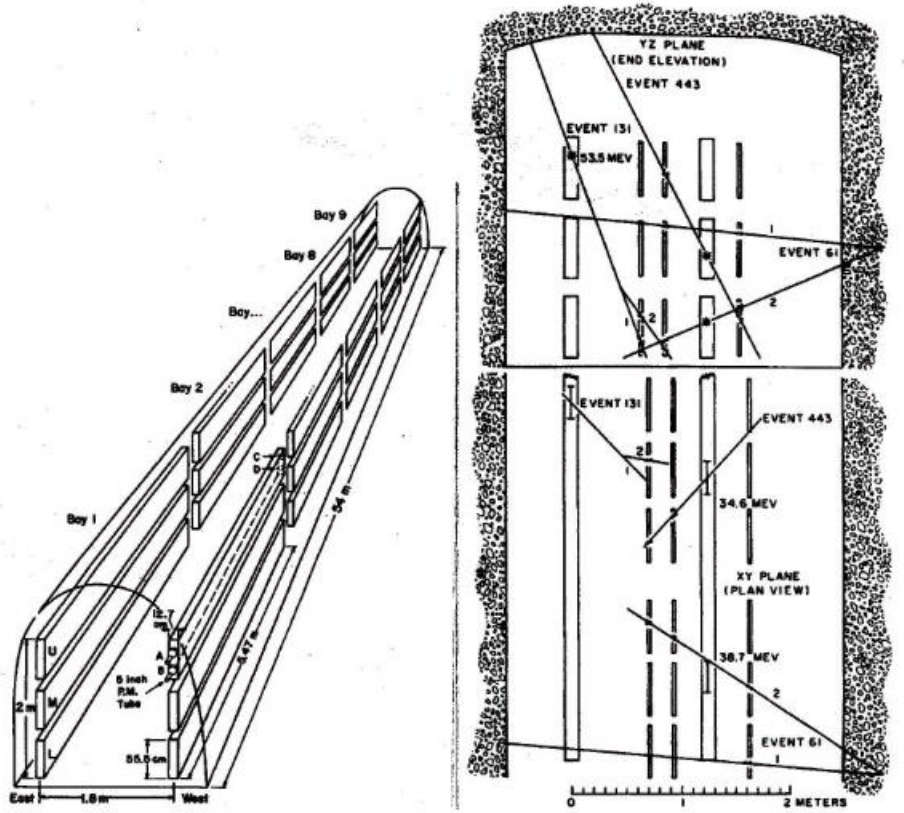
- Main interactions:
  - (Quasi-)Elastic scattering
    - $\nu_l + n \rightarrow l^- + p$ charged current
    - $\bar{\nu}_l + p \rightarrow l^+ + n$ charged current
    - $\nu + p \rightarrow \nu + p$ neutral current
  - Resonant Meson Production
  - Deep inelastic scattering

First Observations



Kolar Gold Fields

1965, in India
Bombay-Osaka-Durham experiment
Plastic scintillator counter

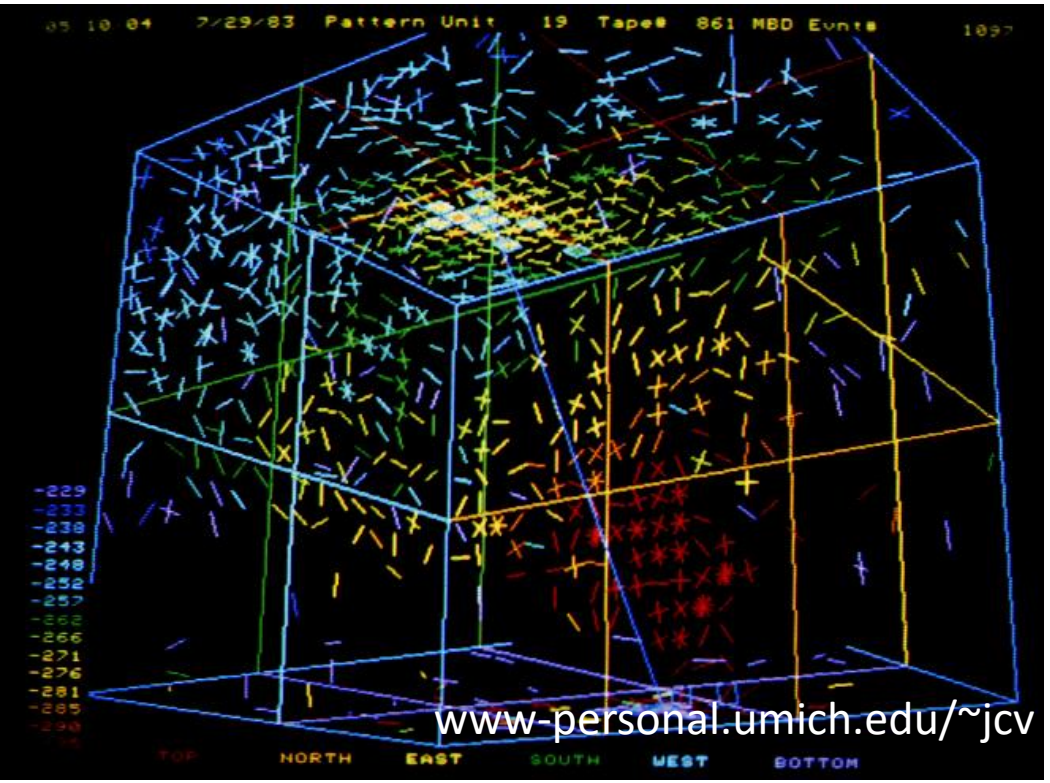


East Rand Proprietary Mines

1965, in South Africa
Case-Witwatersrand-Irvine experiment
Liquid scintillator paddles

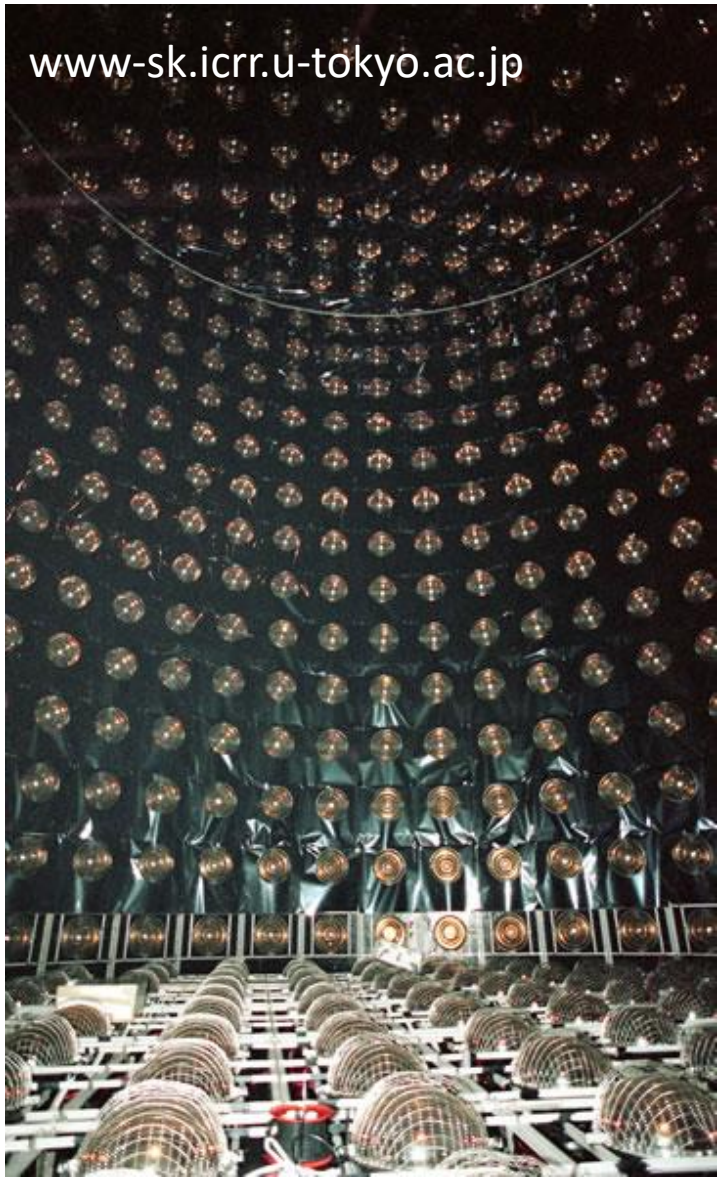
Proc Indian Natn Sci Acad, 70, A, No.1, January 2004, pp.11–25

Detection in Water Cherenkov Detectors



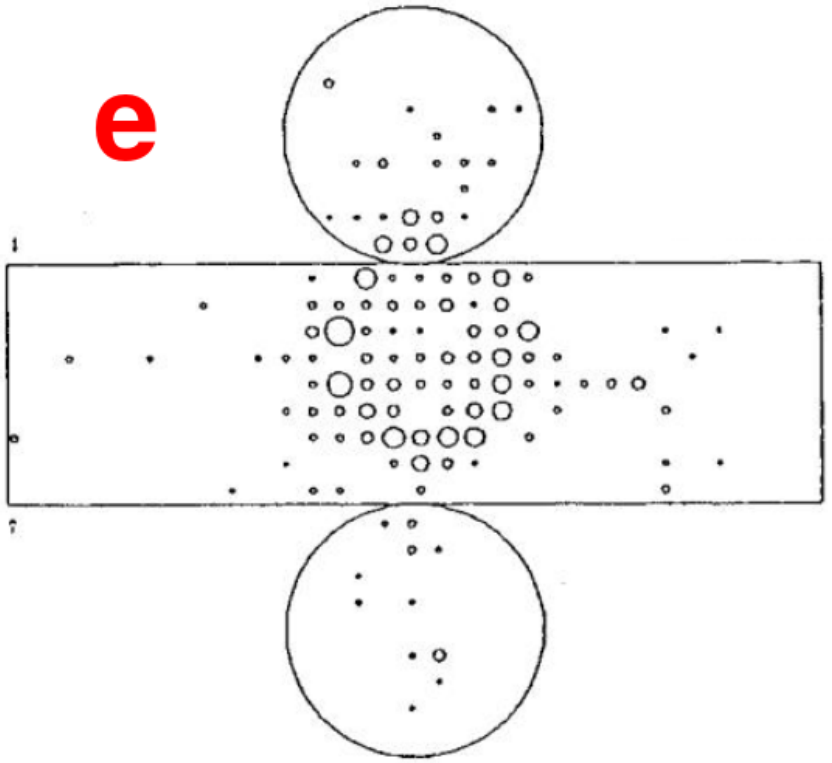
IMB

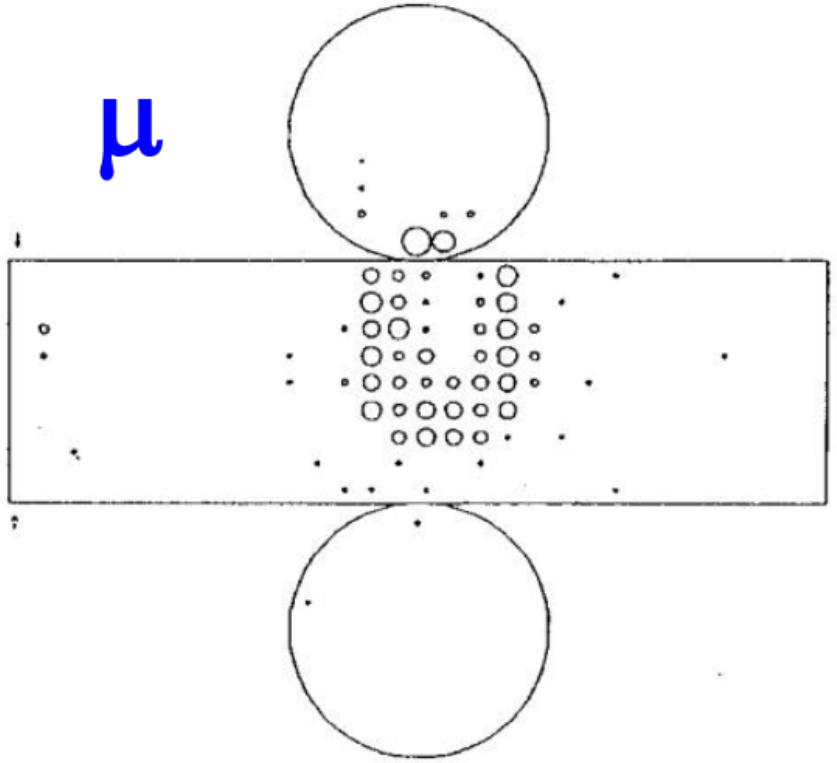
An event display of a upward-going ν_μ



Kamiokande-II

Particle Identification for e/μ





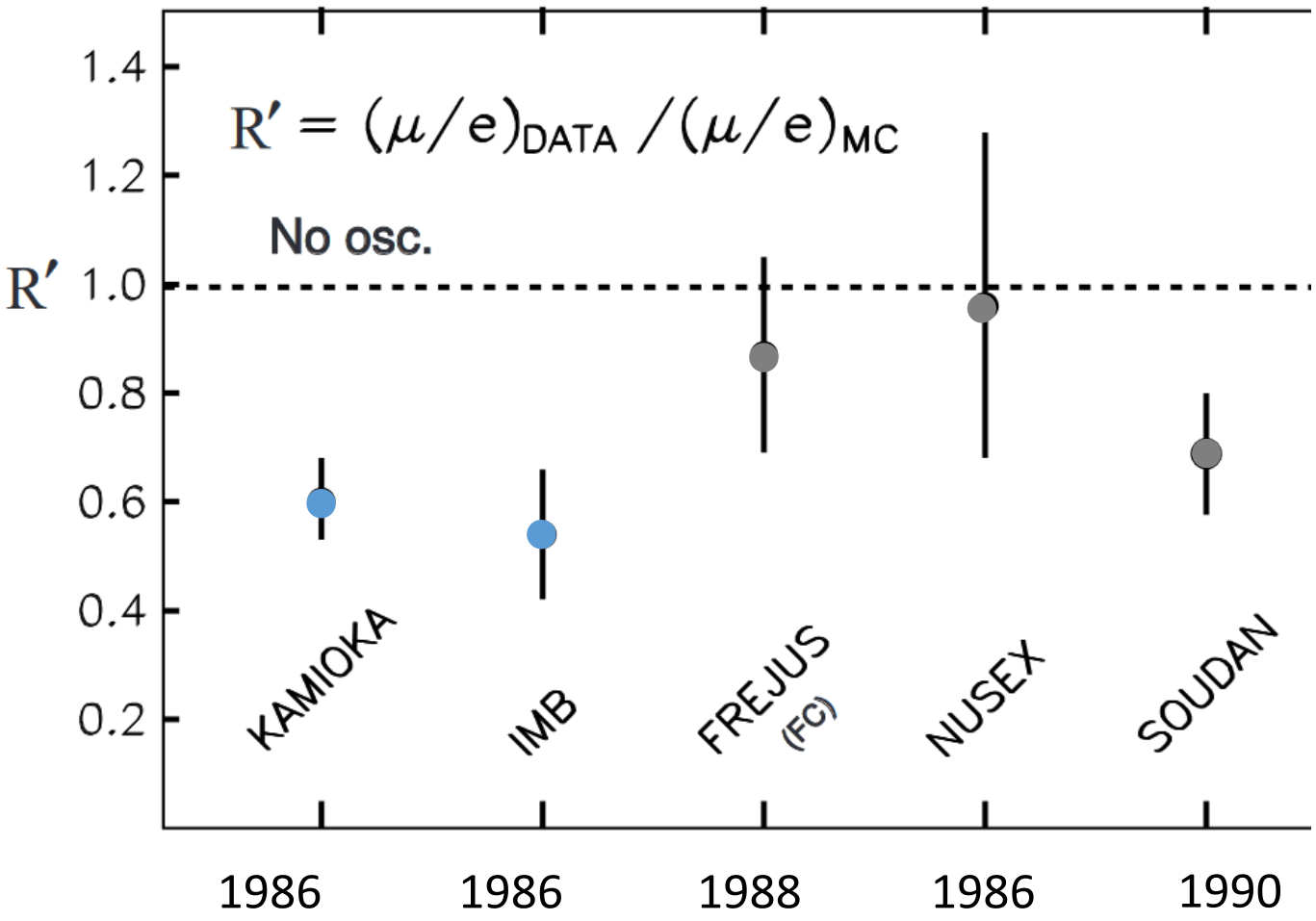
Event display
in KamiokaNDE

Y. Oyama XIV ICFA School On Instrumentation (2017)

Fuzzy ring

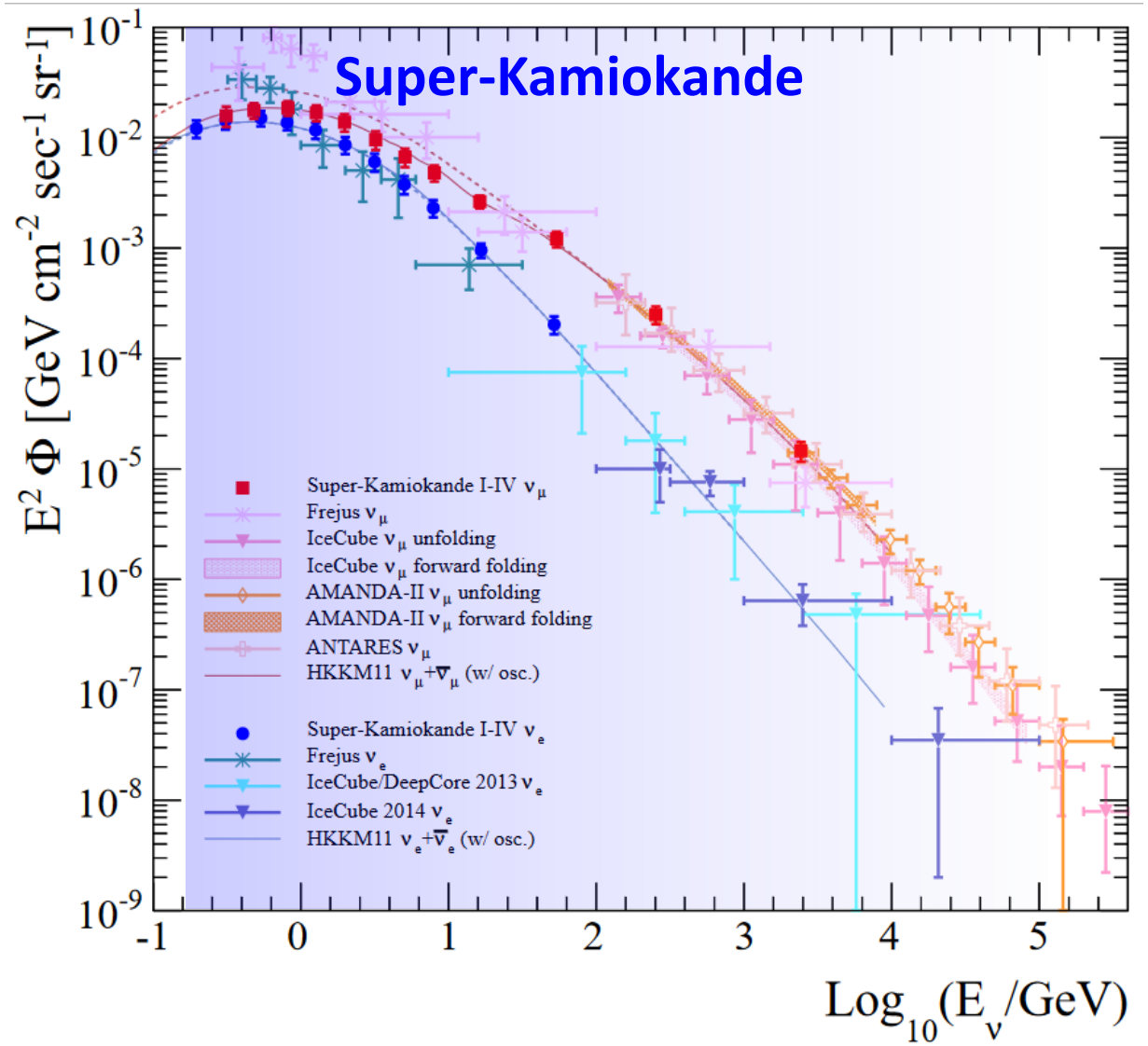
Sharp ring

Atmospheric Neutrino Anomaly

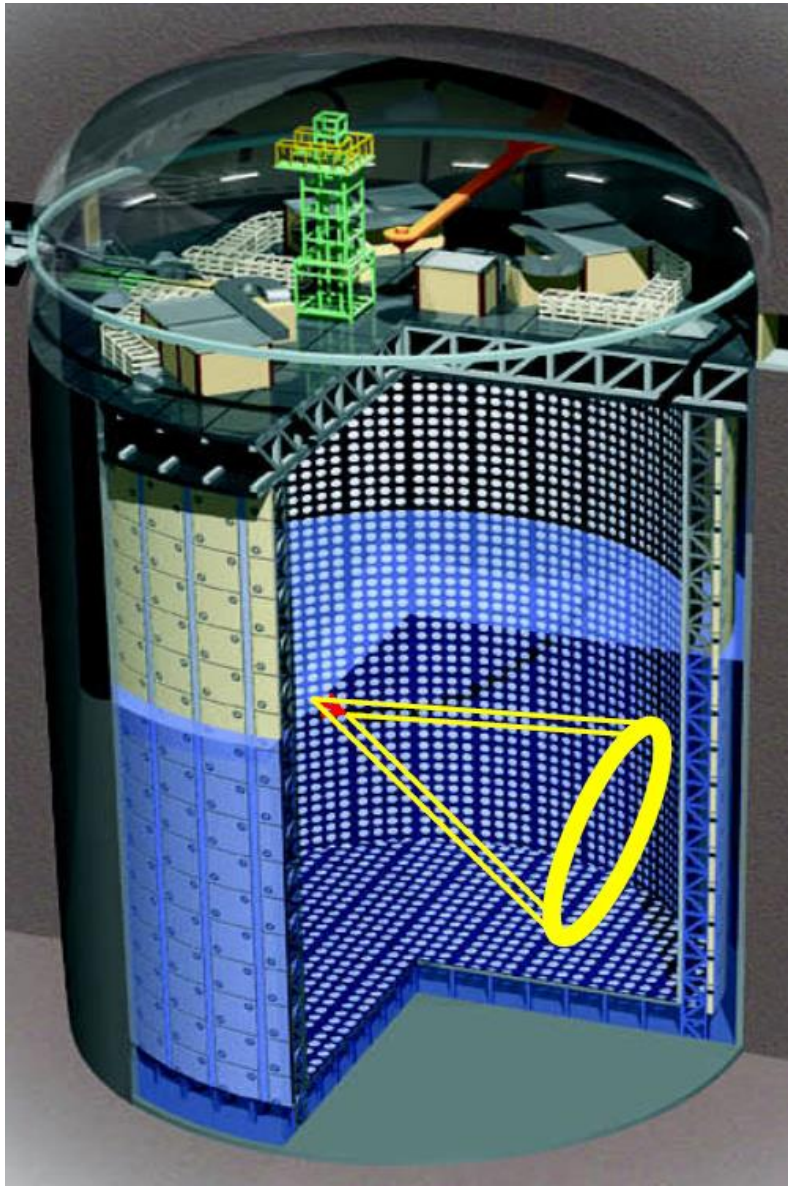


Int.J.Mod.Phys.A 15S1 (2000) 229-256, eConf C990809 (2000) 229-256

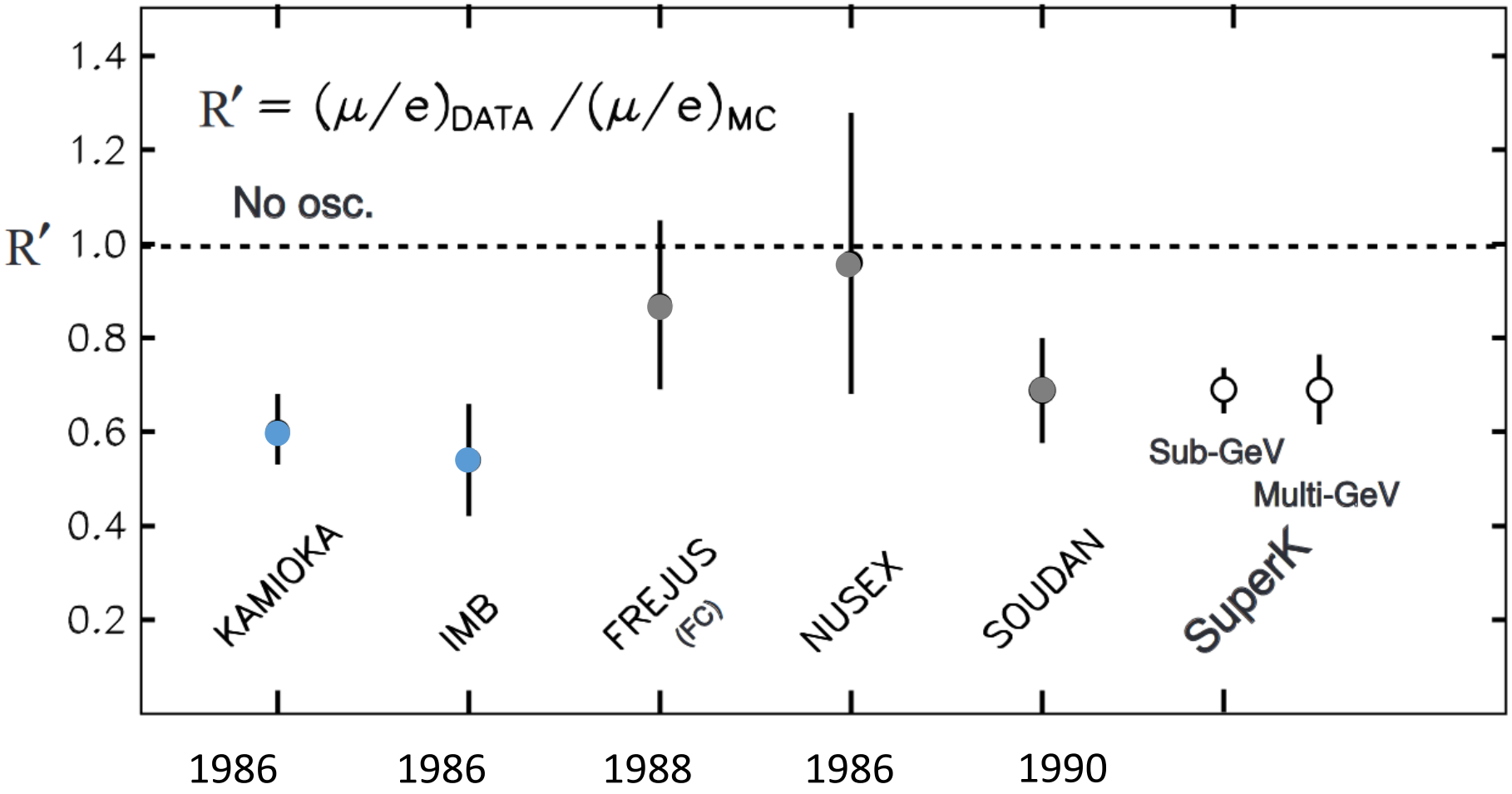
Detection at Super-Kamiokande



Super-Kamiokande, Phys. Rev. D 94, 052001 (2016)



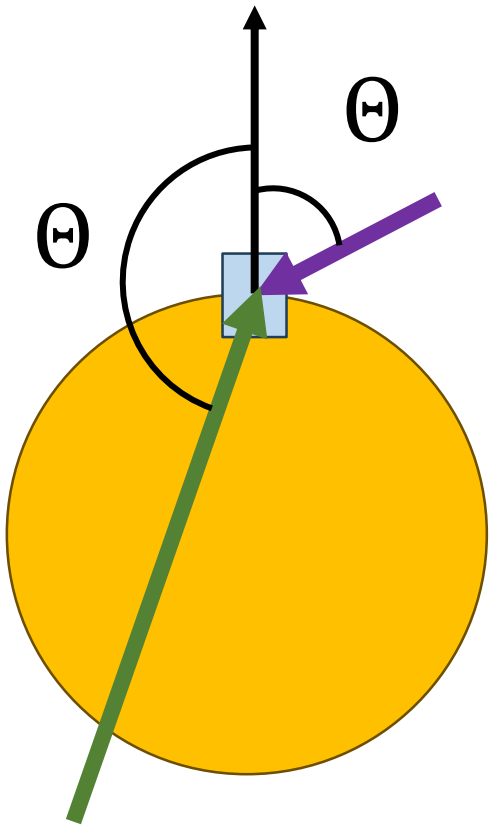
Atmospheric Neutrino Anomaly with SK



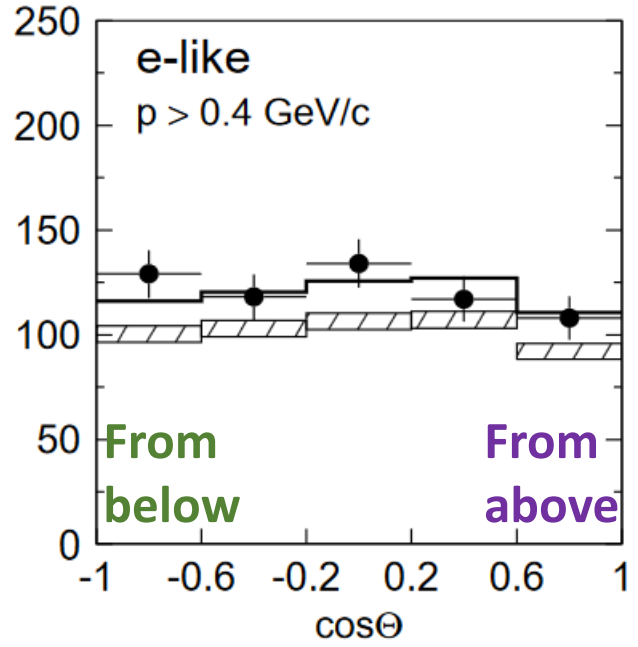
Deficit in ν_μ/ν_e ratio

Int.J.Mod.Phys.A 15S1 (2000) 229-256, eConf C990809 (2000) 229-256

Zenith Angle Distribution

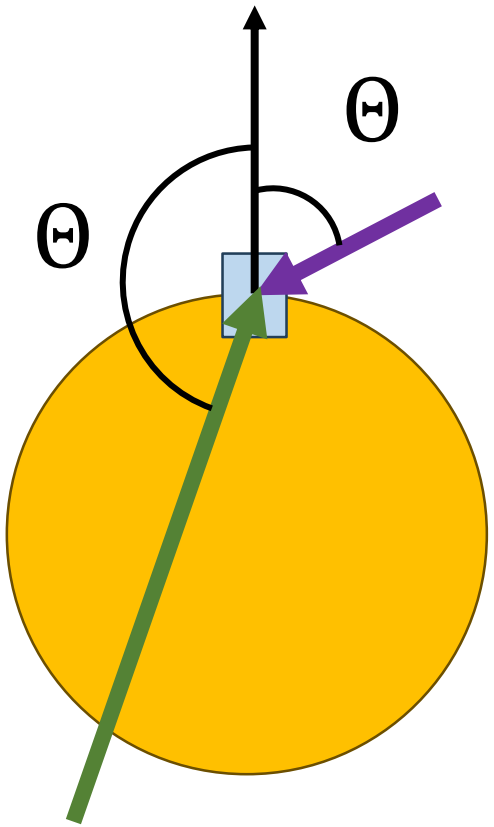


MC expectation

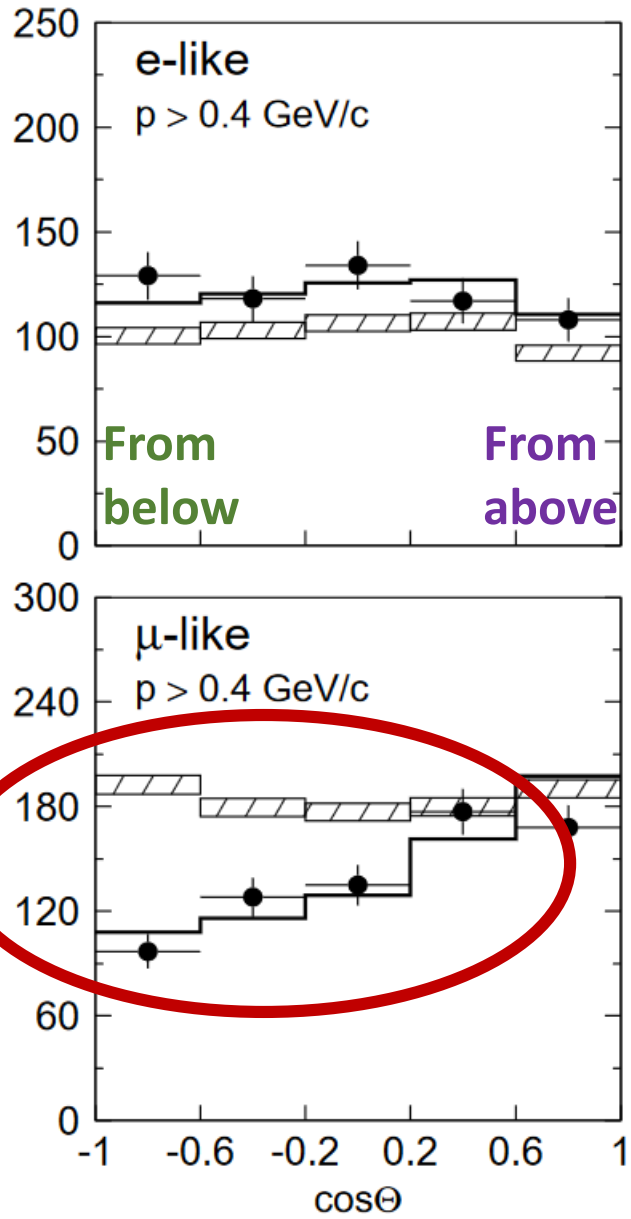


Super-Kamiokande,
Phys.Rev.Lett.81:1562-1567 (1998)

Zenith Angle Distribution



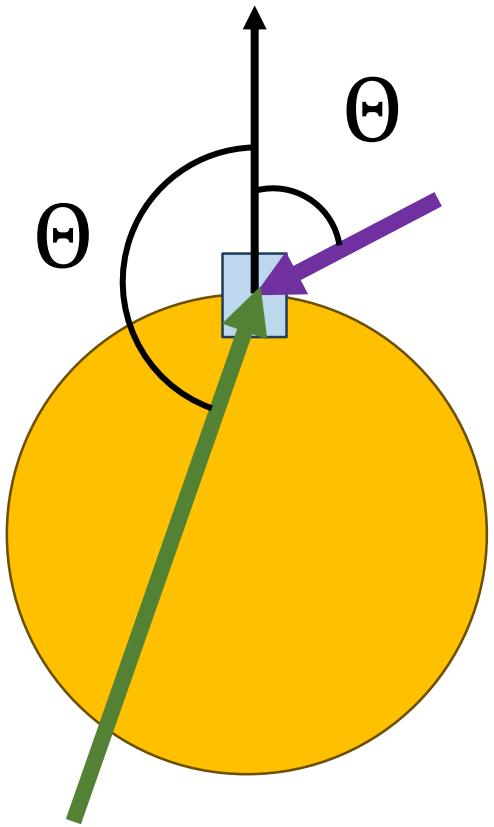
MC expectation



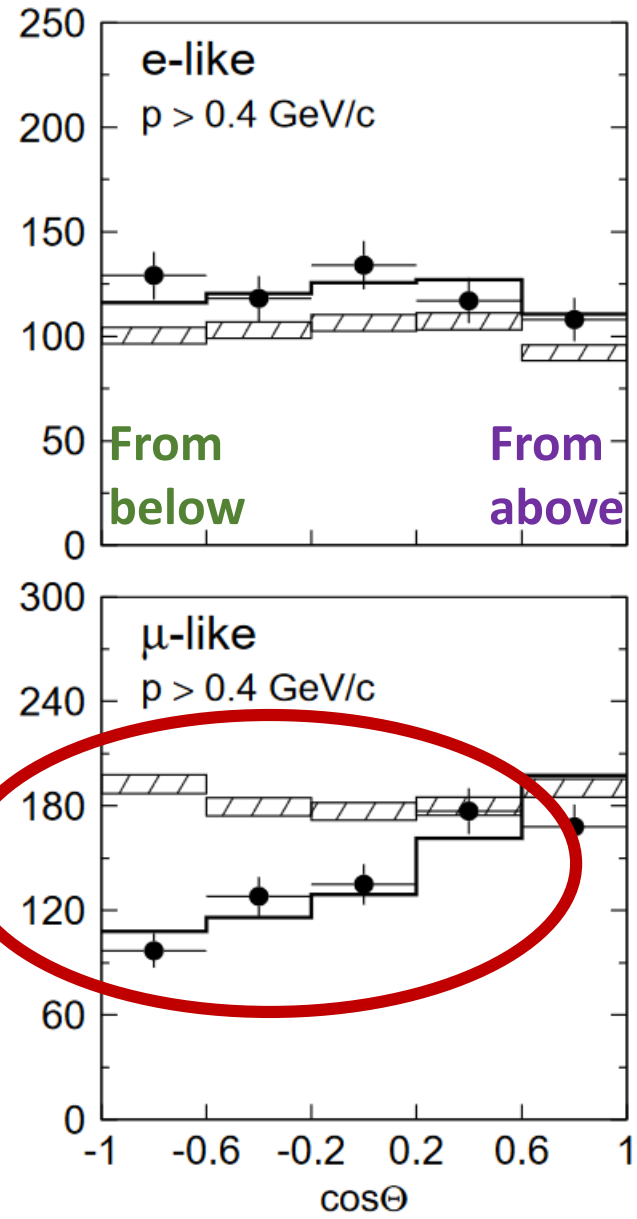
- Fewer ν_μ from below than from above

Super-Kamiokande, Phys.Rev.Lett.81:1562-1567 (1998)

Zenith Angle Distribution



No-oscillation
MC expectation

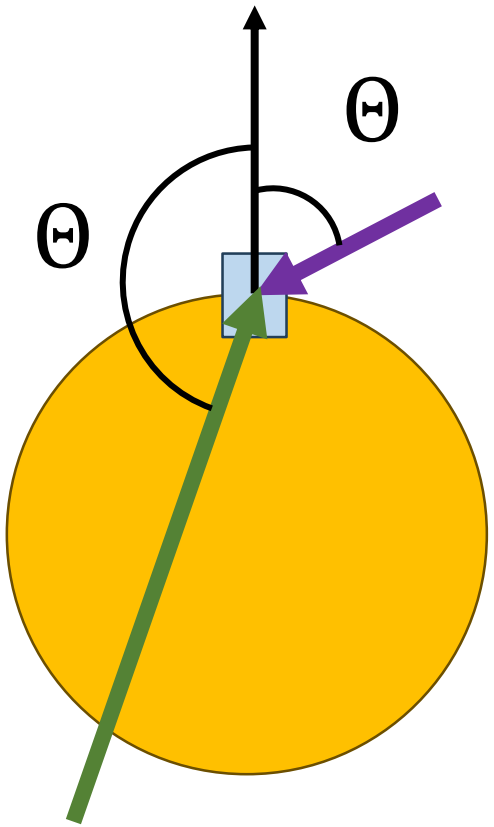


- Fewer ν_μ from below than from above

oscillation

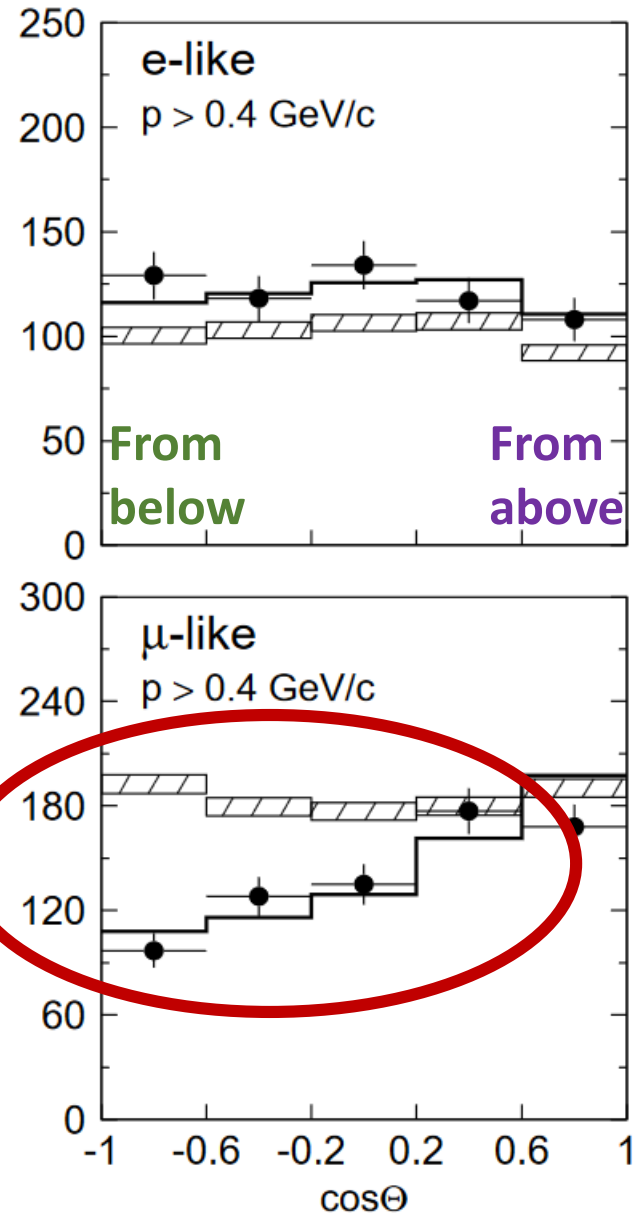
Super-Kamiokande,
Phys.Rev.Lett.81:1562-1567 (1998)

Zenith Angle Distribution



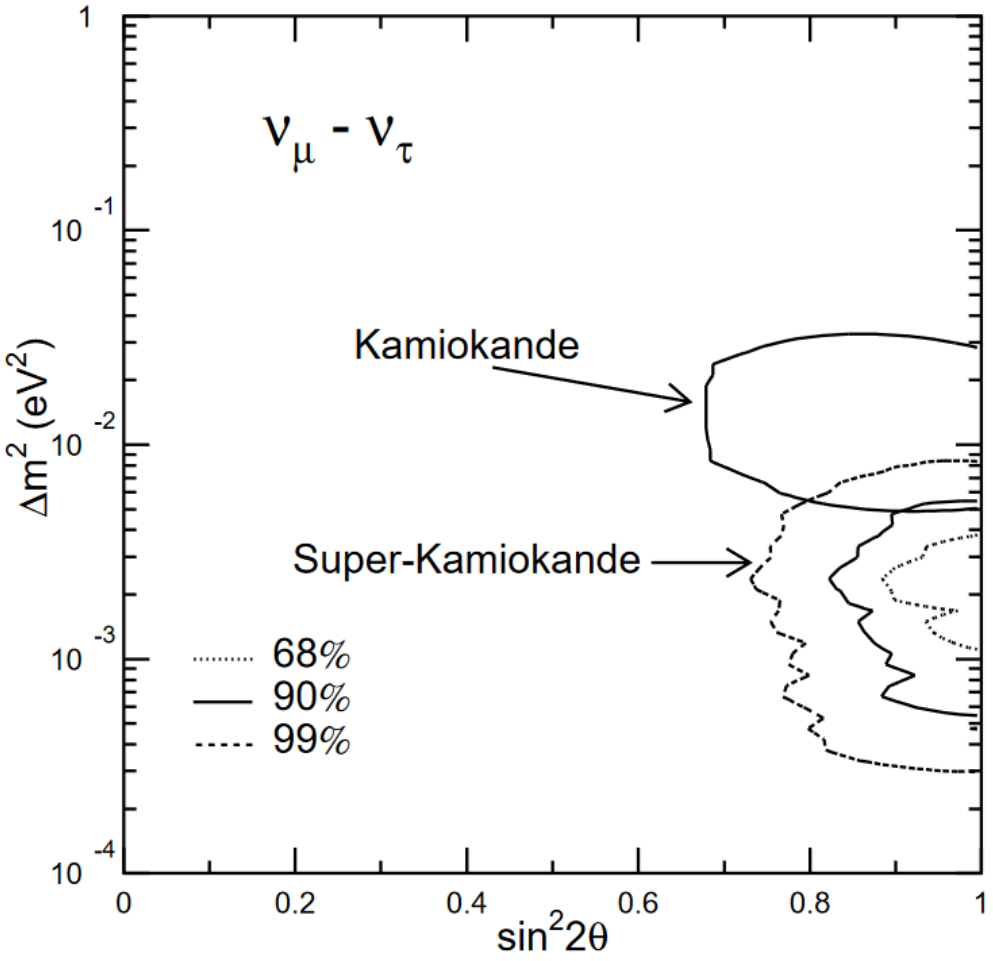
- Same ν_e from below as from above
- Fewer ν_μ from below than from above

$$\boldsymbol{\nu_\mu \rightarrow \nu_\tau}\ \text{oscillation}$$



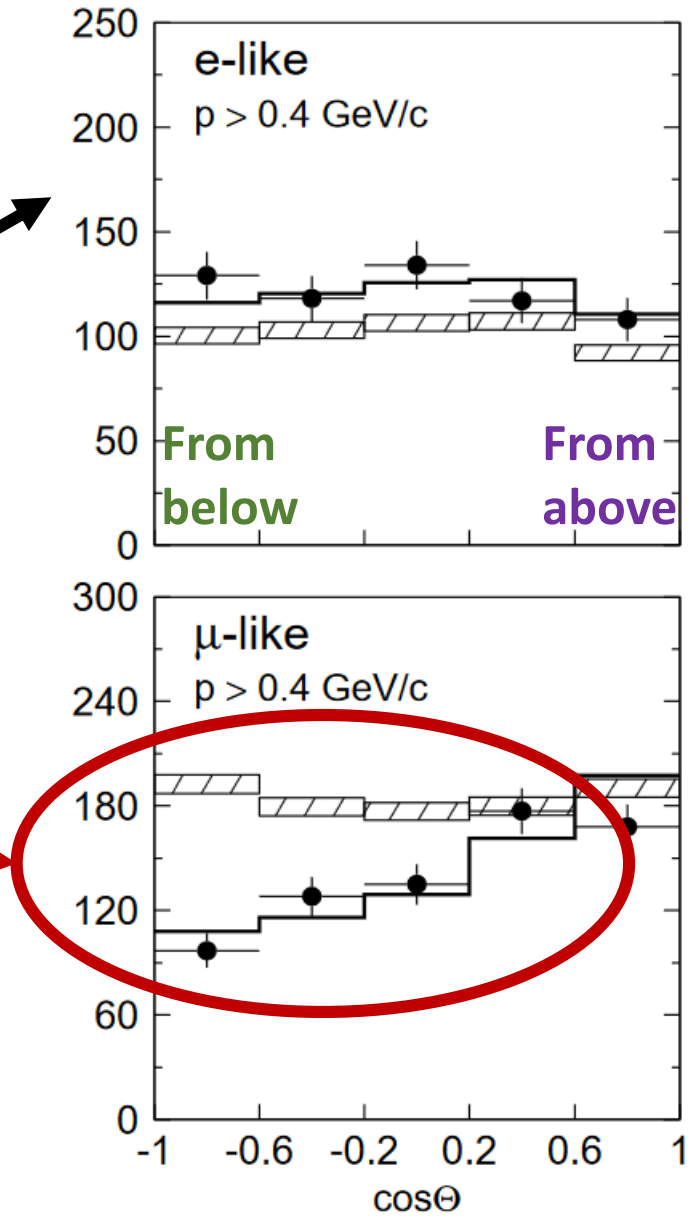
Super-Kamiokande, Phys.Rev.Lett.81:1562-1567 (1998)

Atmospheric Mixing Parameters



- Same ν_e from below as from above
- Fewer ν_μ from below than from above

$\boldsymbol{\nu_\mu \rightarrow \nu_\tau}$ oscillation



Super-Kamiokande, Phys.Rev.Lett.81:1562-1567 (1998)

Super-Kamiokande, Phys.Rev.Lett.81:1562-1567 (1998)

Neutrino Mixing

Pontecorvo–Maki–Nakagawa–Sakata matrix

Δm^2_{21}

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

Δm^2_{32}

Flavor eigenstate

Atmospheric $\sqrt{}$

Interference $\sqrt{}$

Solar $\sqrt{}$

Mass eigenstate

With reactor neutrinos
See Bryce Littlejohn's lecture

$$\Delta m^2_{32} = m^2_3 - m^2_2$$

Missing Pieces in Neutrino Mixing

Pontecorvo–Maki–Nakagawa–Sakata matrix

CP violation

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

Δm^2_{21}

Δm^2_{32}

Flavor eigenstate

Atmospheric $\sqrt{}$

Interference $\sqrt{}$

Solar $\sqrt{}$

Mass eigenstate

Mass Ordering

Mass Ordering

Pontecorvo–Maki–Nakagawa–Sakata matrix

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

Δm^2_{21}

Δm^2_{32}

Flavor eigenstate

Atmospheric √

Interference √

Solar √

Mass eigenstate

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{j>k} \mathcal{R}_e\left\{ U^*_{\alpha j}\, U_{\beta j}\, U_{\alpha k}\, U^*_{\beta k} \right\} \sin^2\left(\frac{\Delta_{jk}m^2\, L}{4E}\right)$$

$$+ 2\sum_{j>k} \mathcal{I}_m\left\{ U^*_{\alpha j}\, U_{\beta j}\, U_{\alpha k}\, U^*_{\beta k} \right\} \sin\left(\frac{\Delta_{jk}m^2\, L}{2E}\right)$$

Mass Ordering

Mass Ordering

Pontecorvo–Maki–Nakagawa–Sakata matrix

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

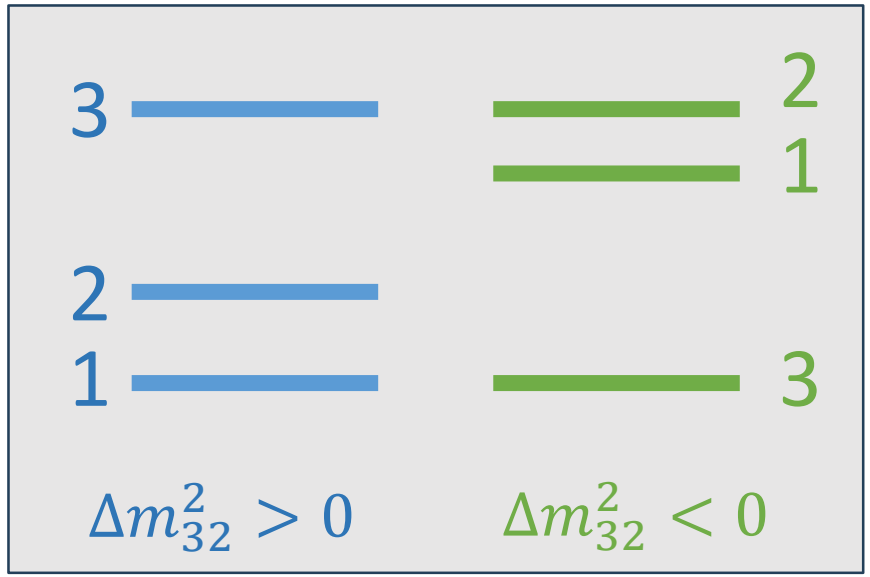
Δm^2_{21}

Δm^2_{32}

Flavor eigenstate

Atmospheric

Mass eigenstate



Normal Inverted

Mass Ordering

Mass Ordering

Pontecorvo–Maki–Nakagawa–Sakata matrix

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

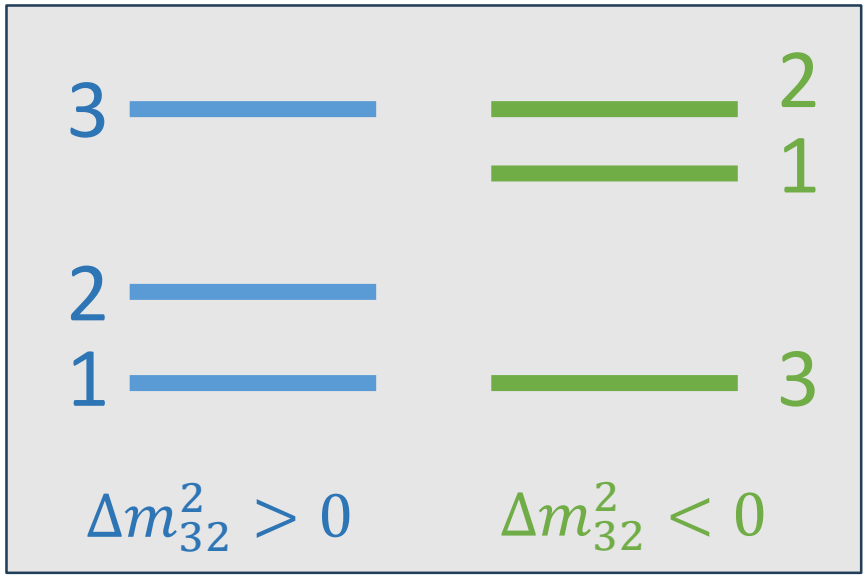
Flavor eigenstate

Atmospheric

Δm^2_{21}

Δm^2_{32}

Mass eigenstate



Normal Inverted

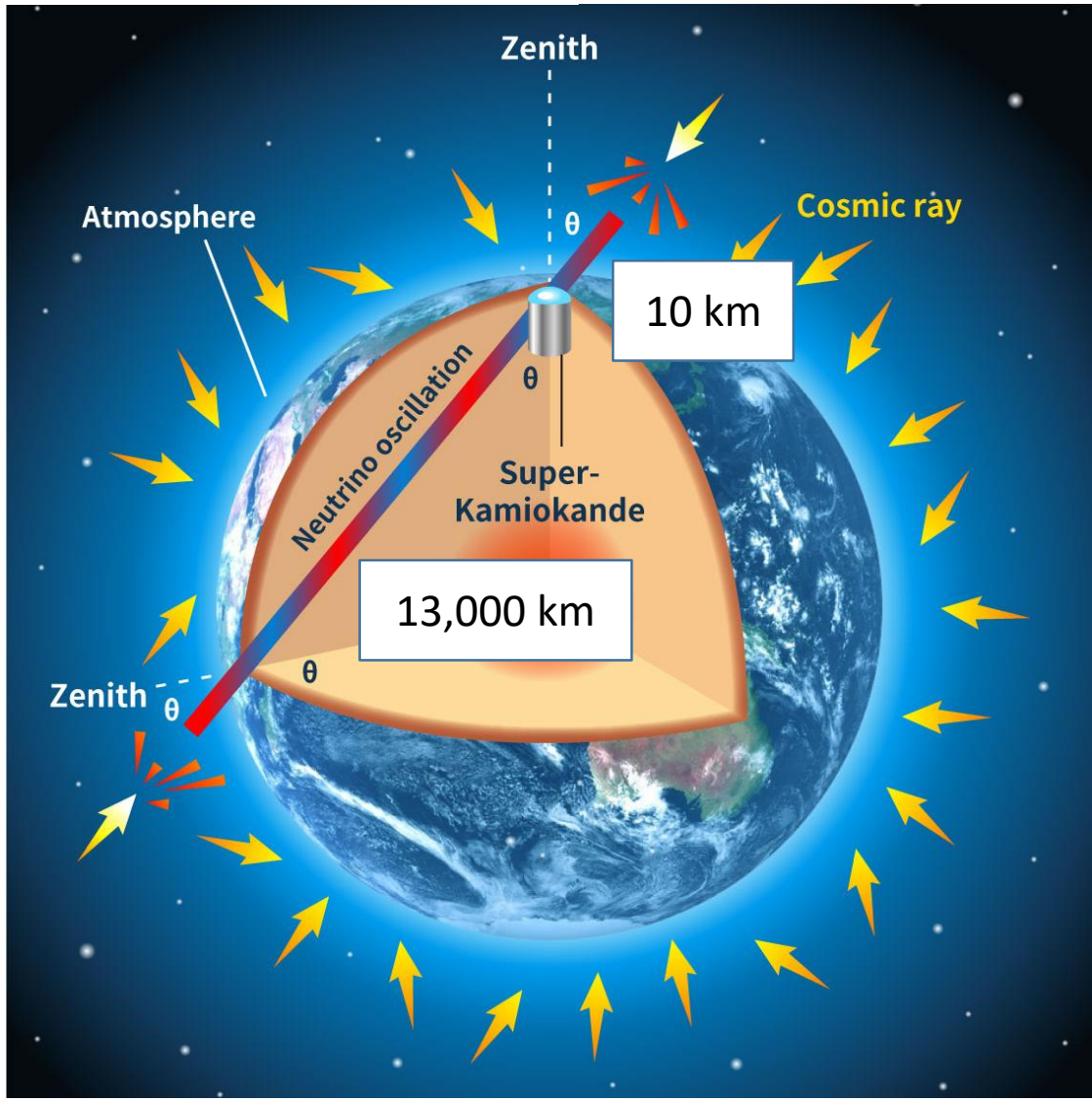
Mass Ordering

Q: How do we know $\Delta m^2_{21} > 0$?

Atmospheric Neutrino Propagation

H_V

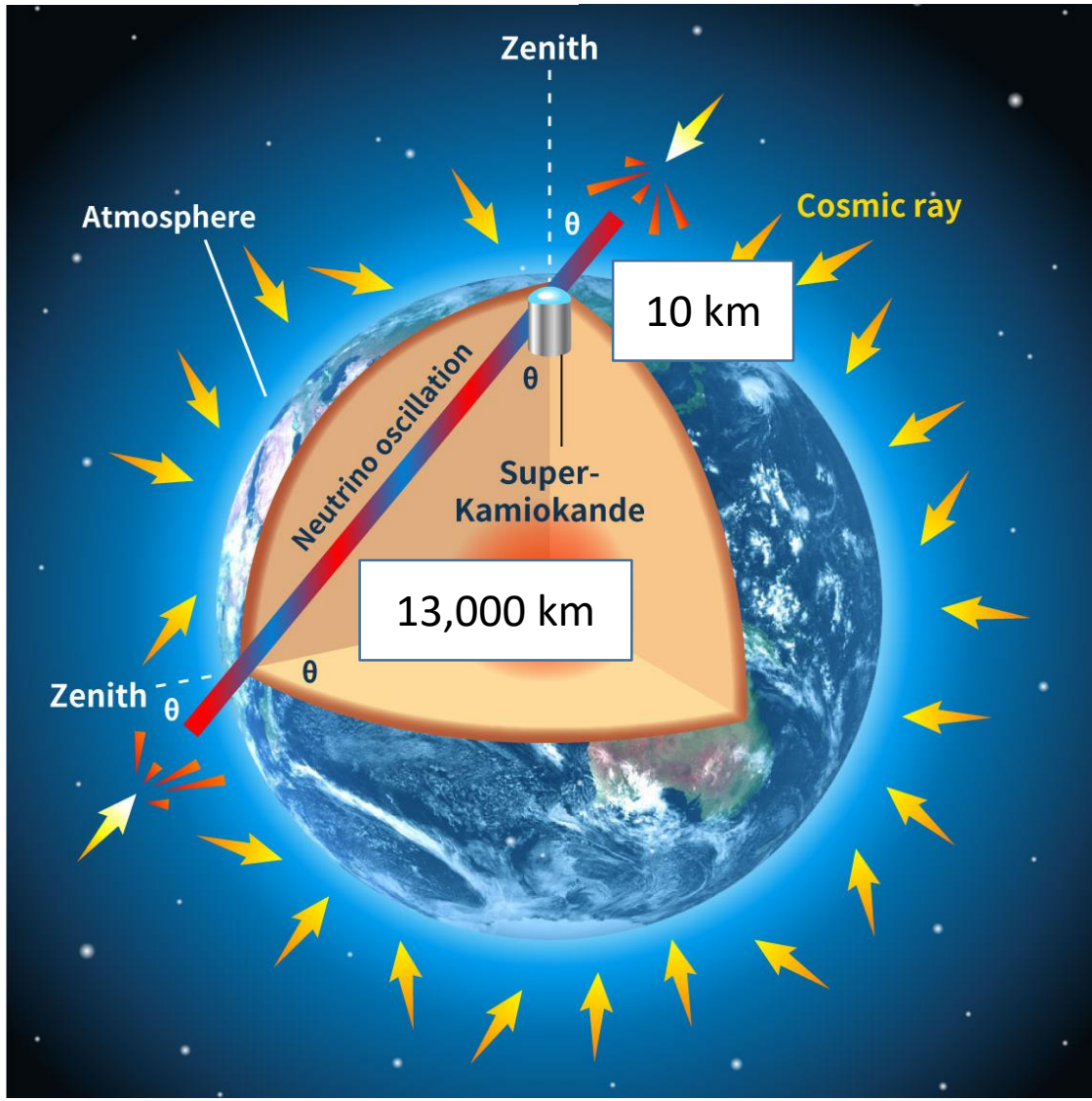
$$H_M = H_V + U^\dagger \begin{pmatrix} \sqrt{2} G_F N_e & & \\ & 0 & \\ & & \end{pmatrix} U$$



Atmospheric Neutrino Propagation

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta \mp \frac{2\sqrt{2} G_F n_e E}{\Delta m^2}\right)^2}$$

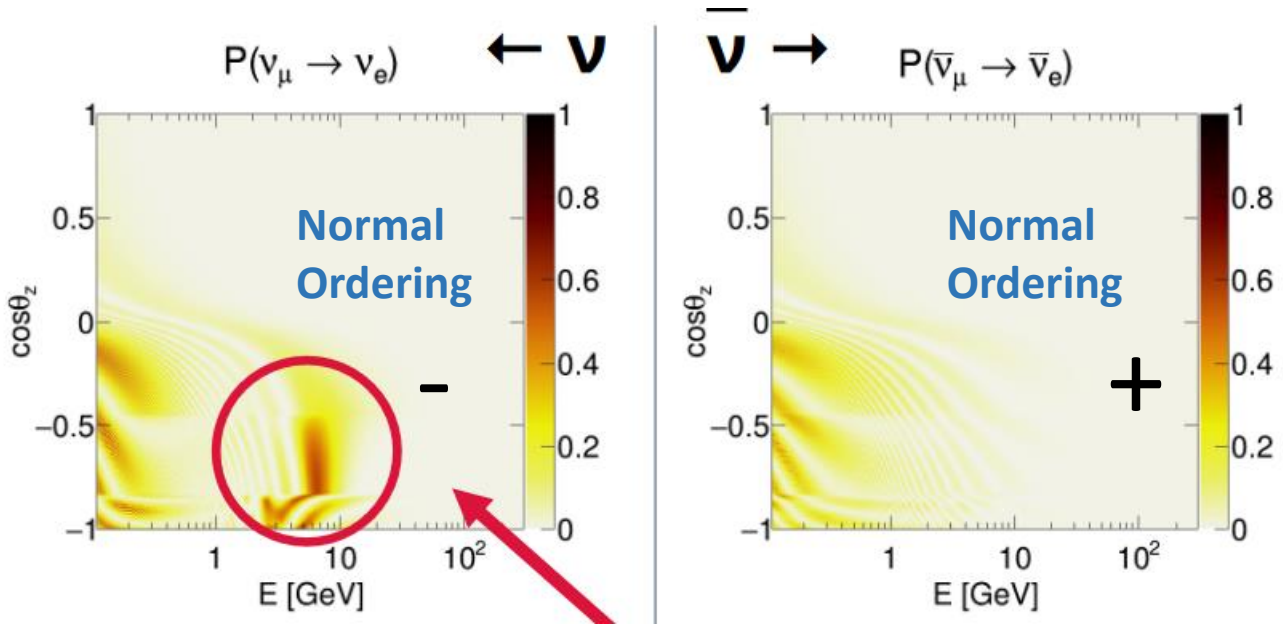
$$H_M = H_V + U^\dagger \begin{pmatrix} \sqrt{2} G_F N_e & \\ & 0 \end{pmatrix} U$$



Mass Ordering

- Assume $\Delta m^2 > 0$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta \mp \frac{2\sqrt{2} G_F n_e E}{\Delta m^2}\right)^2}$$



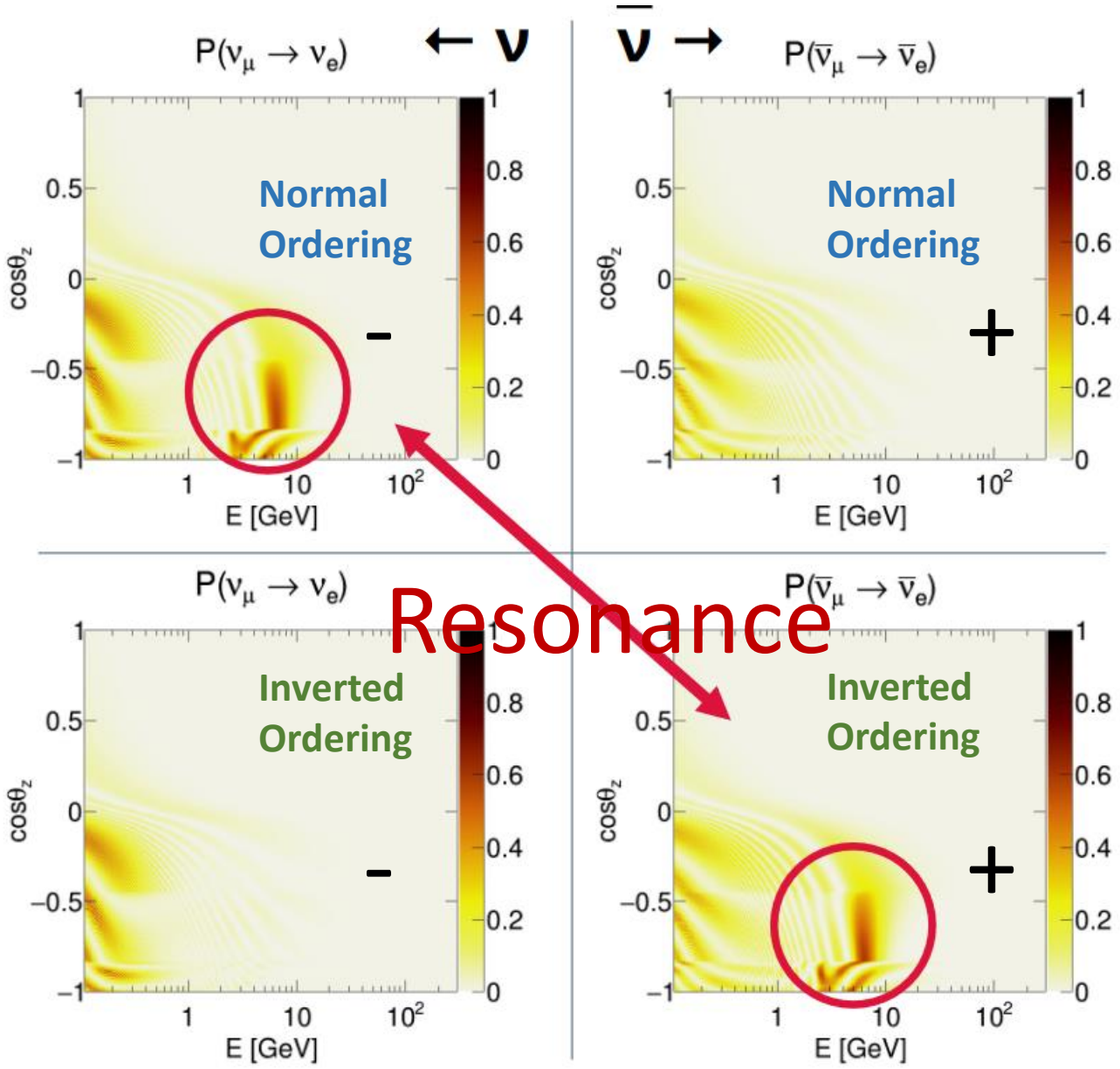
Resonance

Mass Ordering

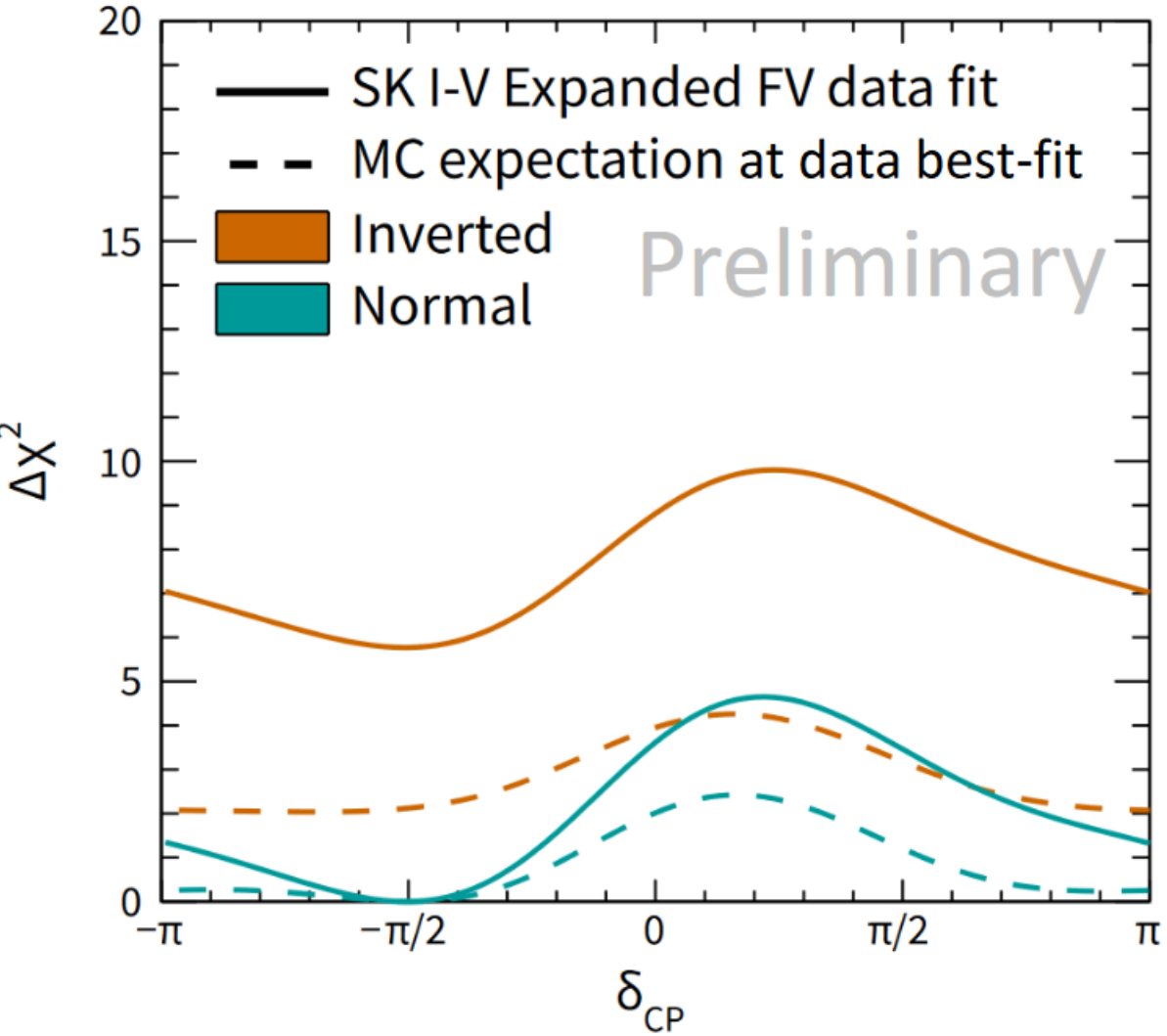
- Assume $\Delta m^2 > 0$

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta \mp \frac{2\sqrt{2} G_F n_e E}{\Delta m^2}\right)^2}$$

- Assume $\Delta m^2 < 0$



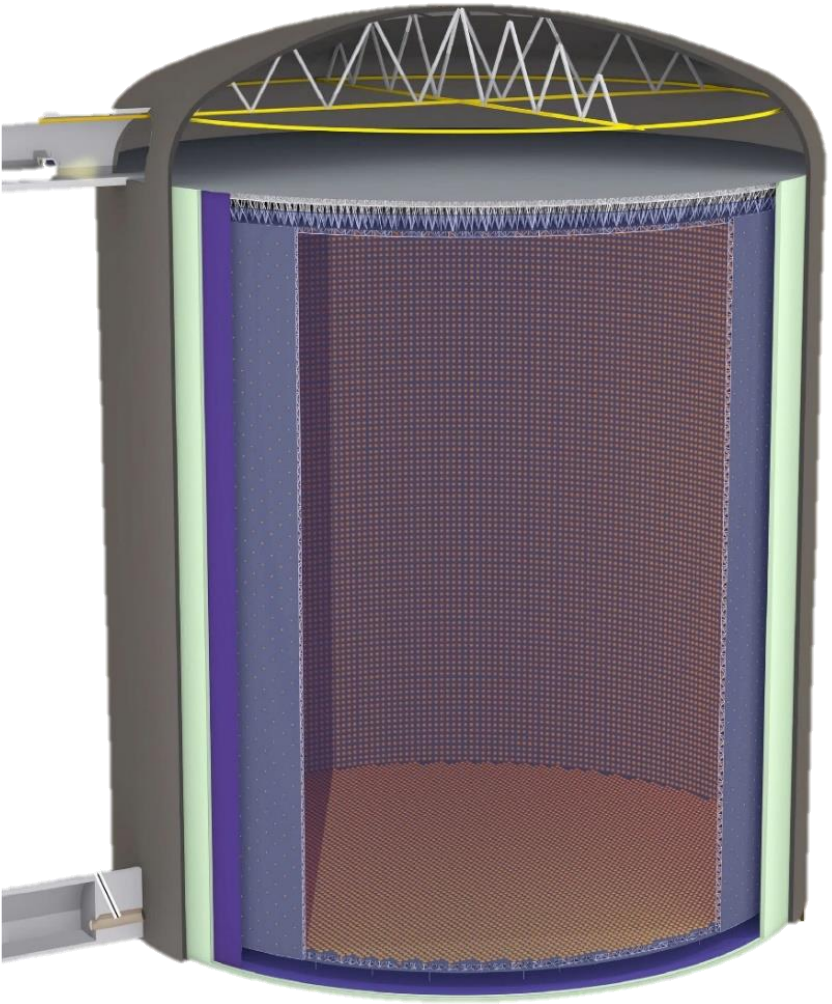
Mass Ordering Measurement



Super-Kamiokande, Neutrino 2022

- Not yet conclusive
- Statistically constrained

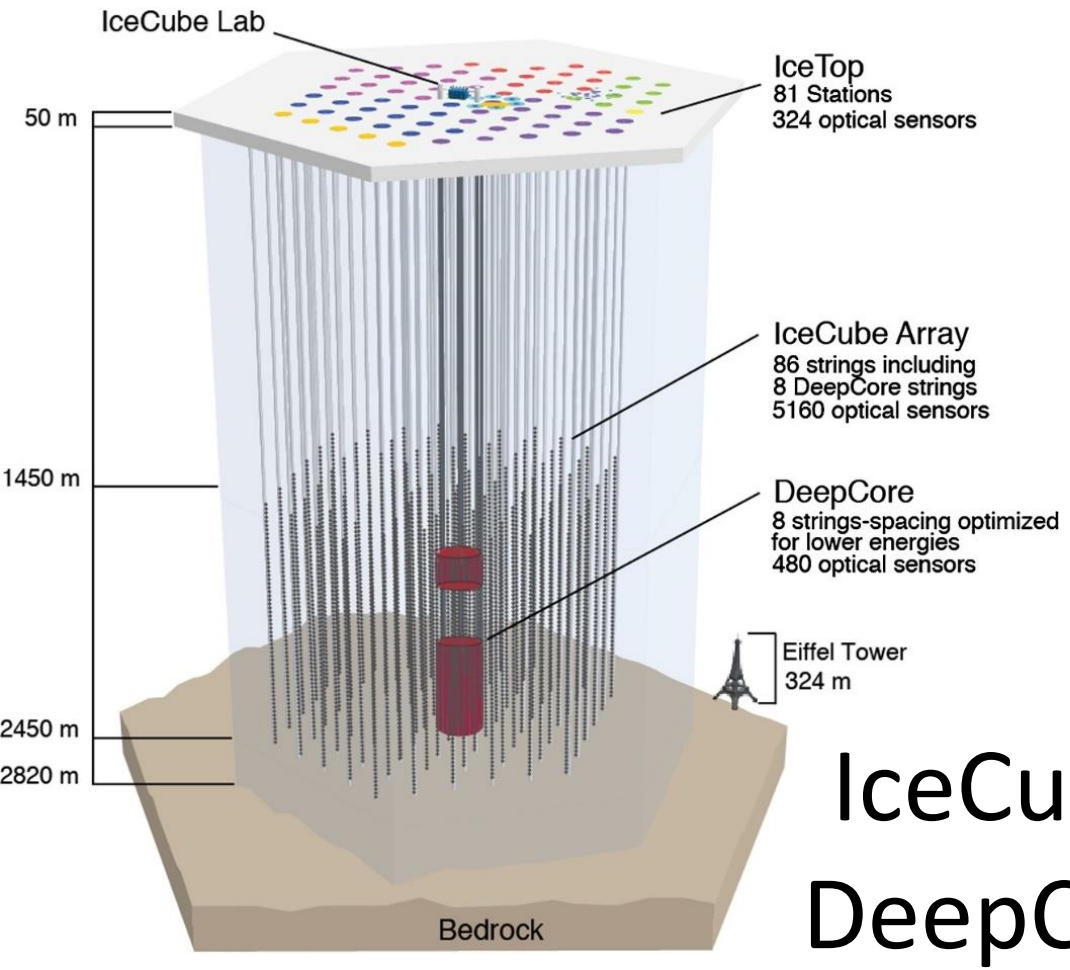
Future Upgrade: Hyper-Kamiokande



- ~~Statistically constrained~~

Water Cherenkov
190 kton

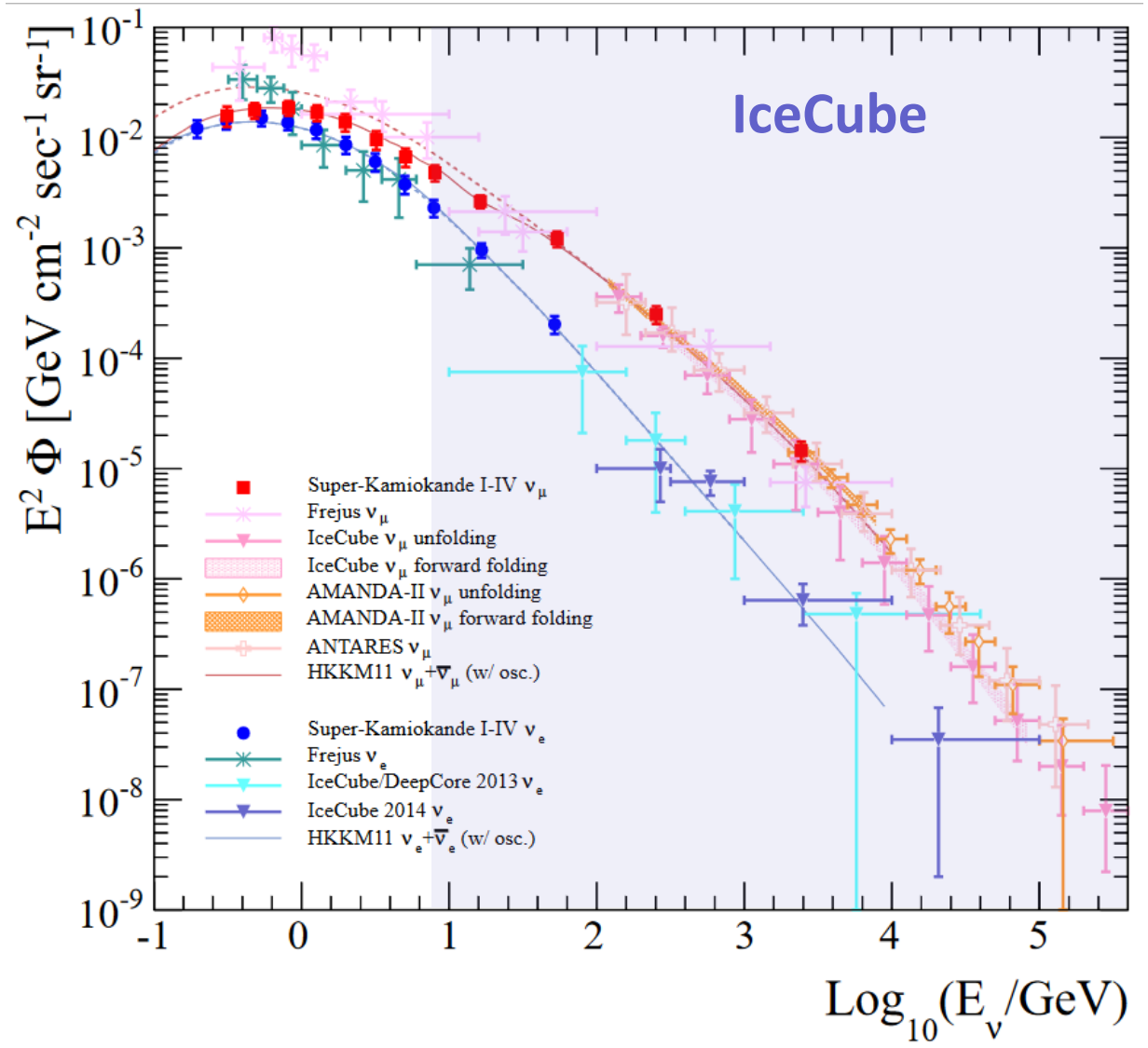
IceCube



IceCube

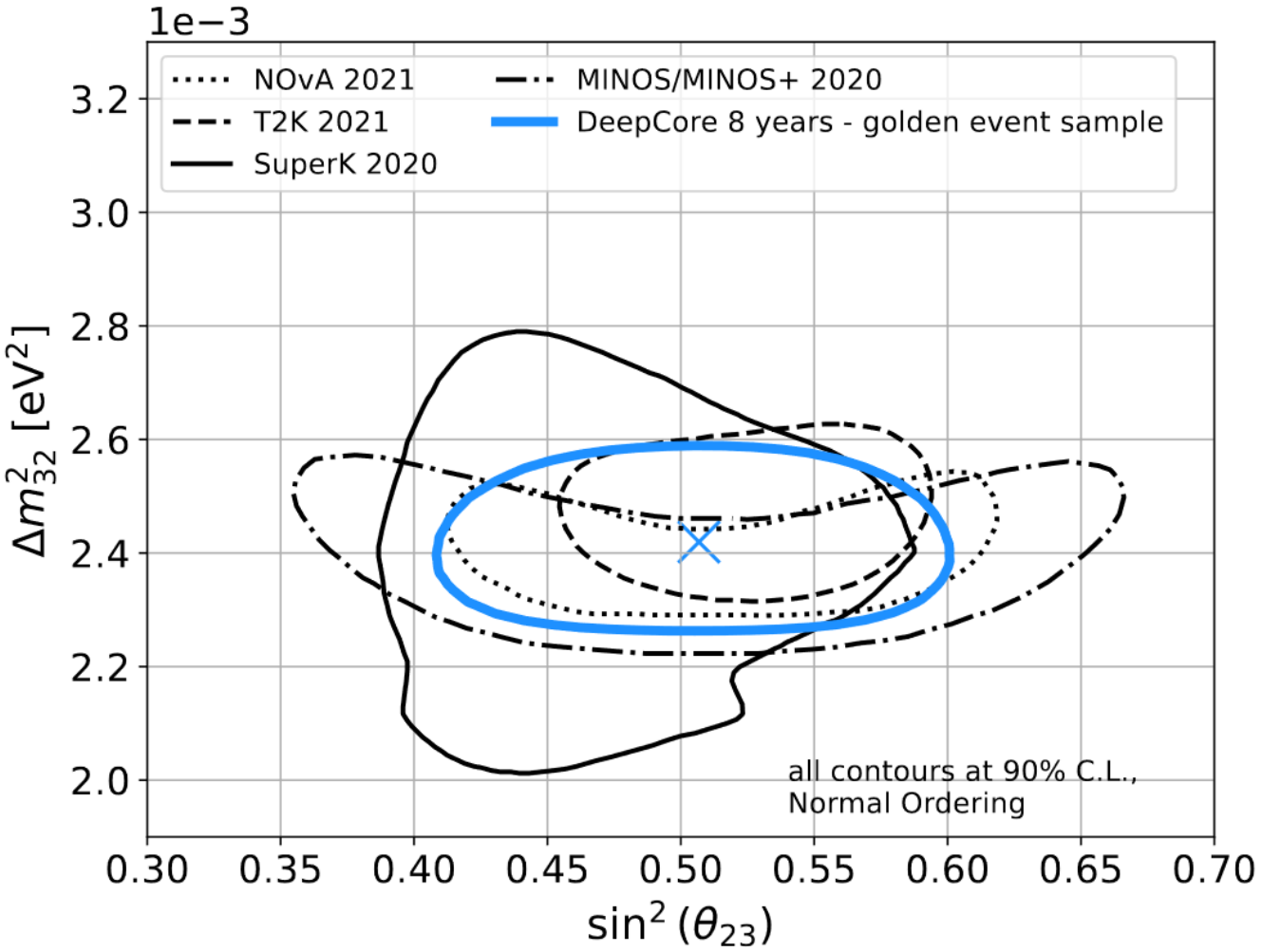
DeepCore

E_{thr}: 6 GeV



Super-Kamiokande, Phys. Rev. D 94, 052001 (2016)

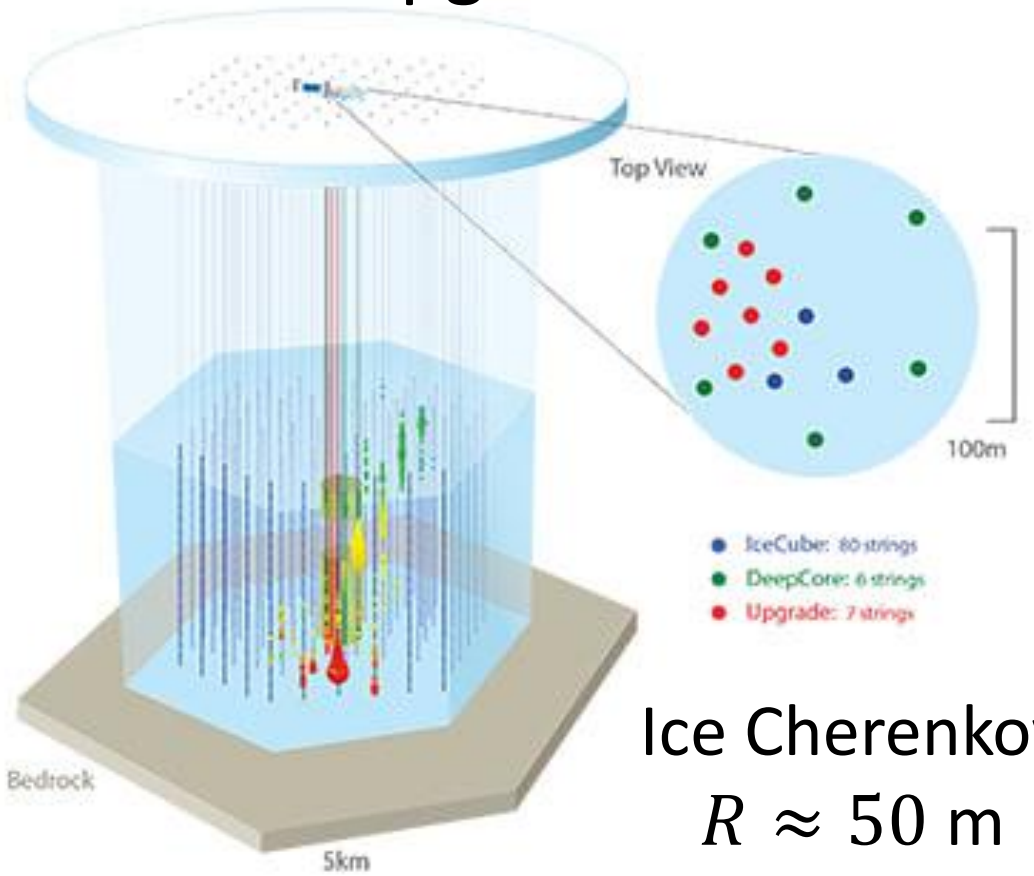
IceCube Results



arXiv: 2304.12236

Future Detectors

IceCube-Upgrade

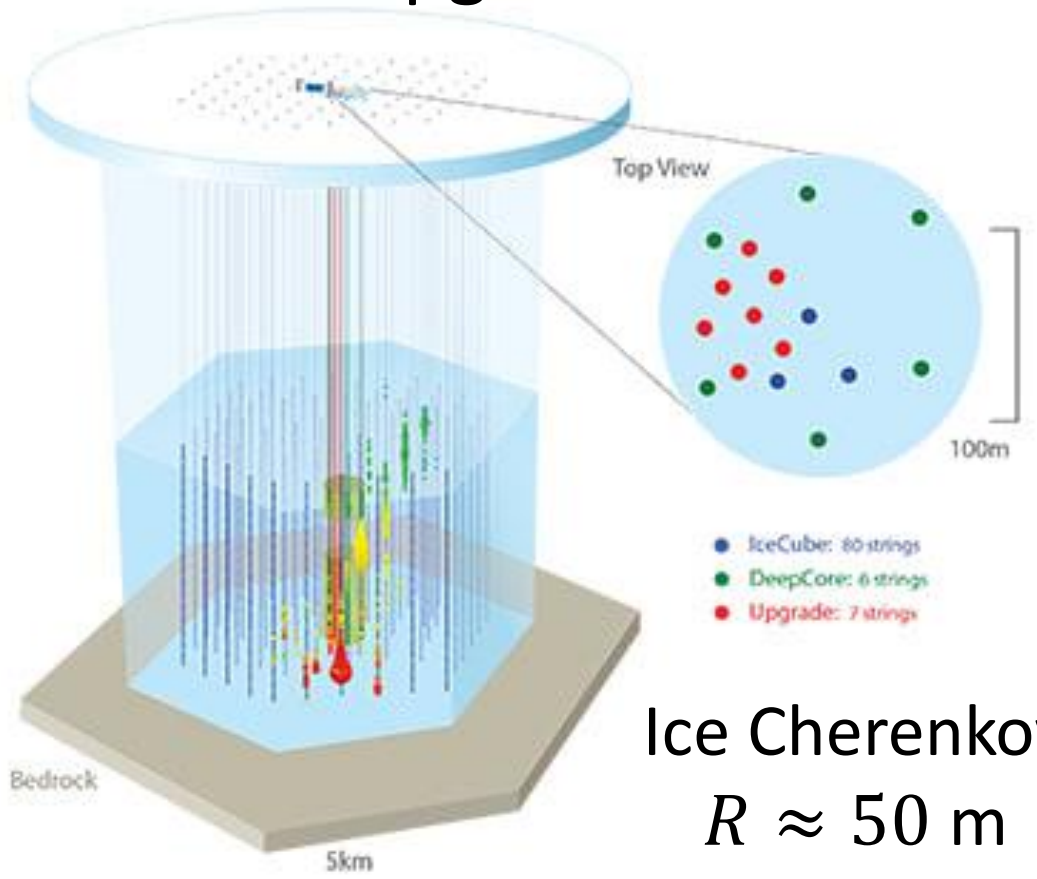


Ice Cherenkov

$R \approx 50$ m

Future Detectors

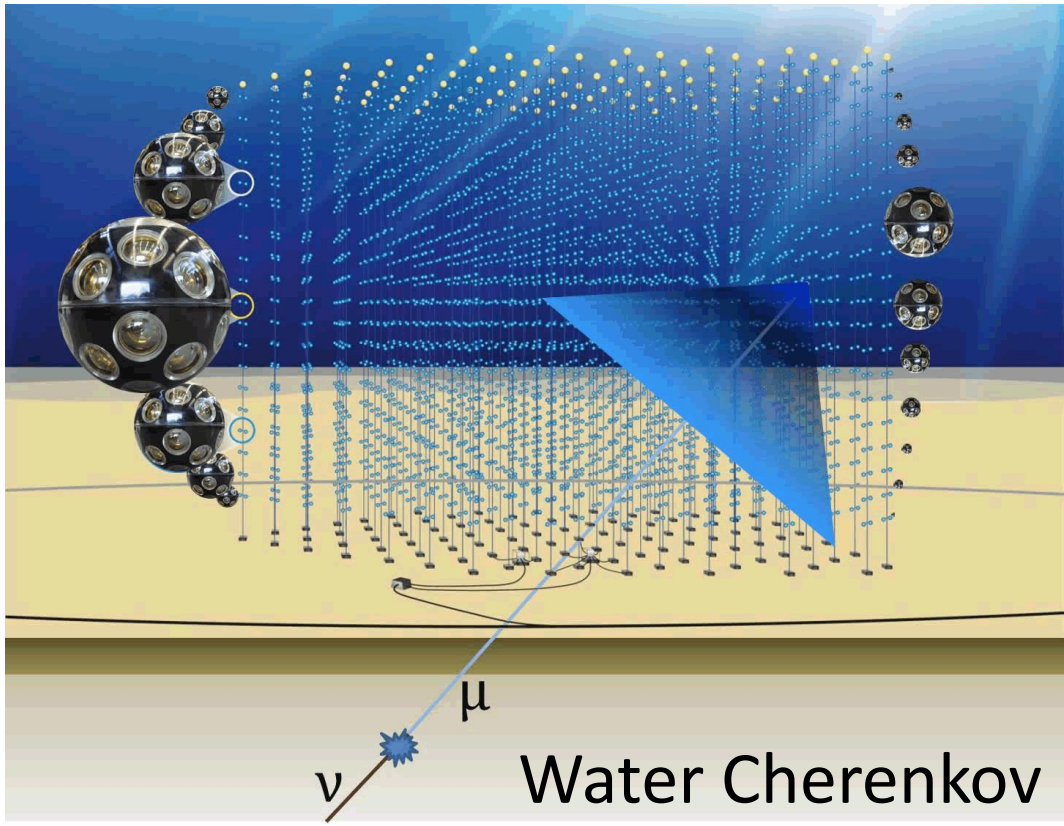
IceCube-Upgrade



Ice Cherenkov

$R \approx 50$ m

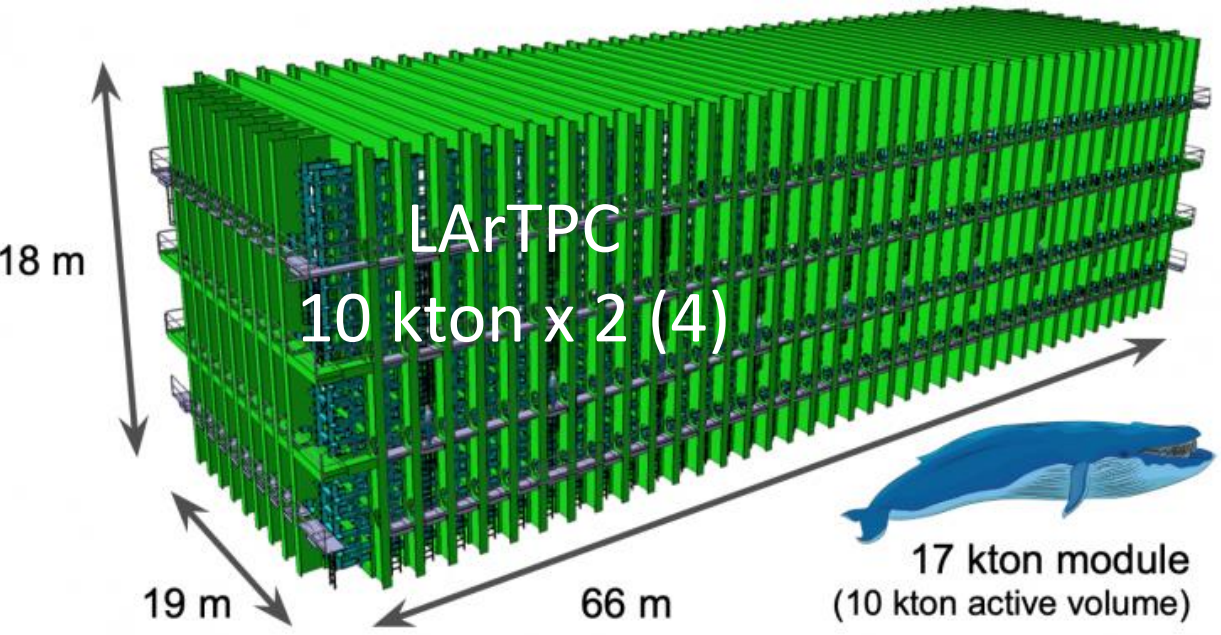
KM3NeT-ORCA



Water Cherenkov

$R \approx 115$ m

Future Detectors: DUNE

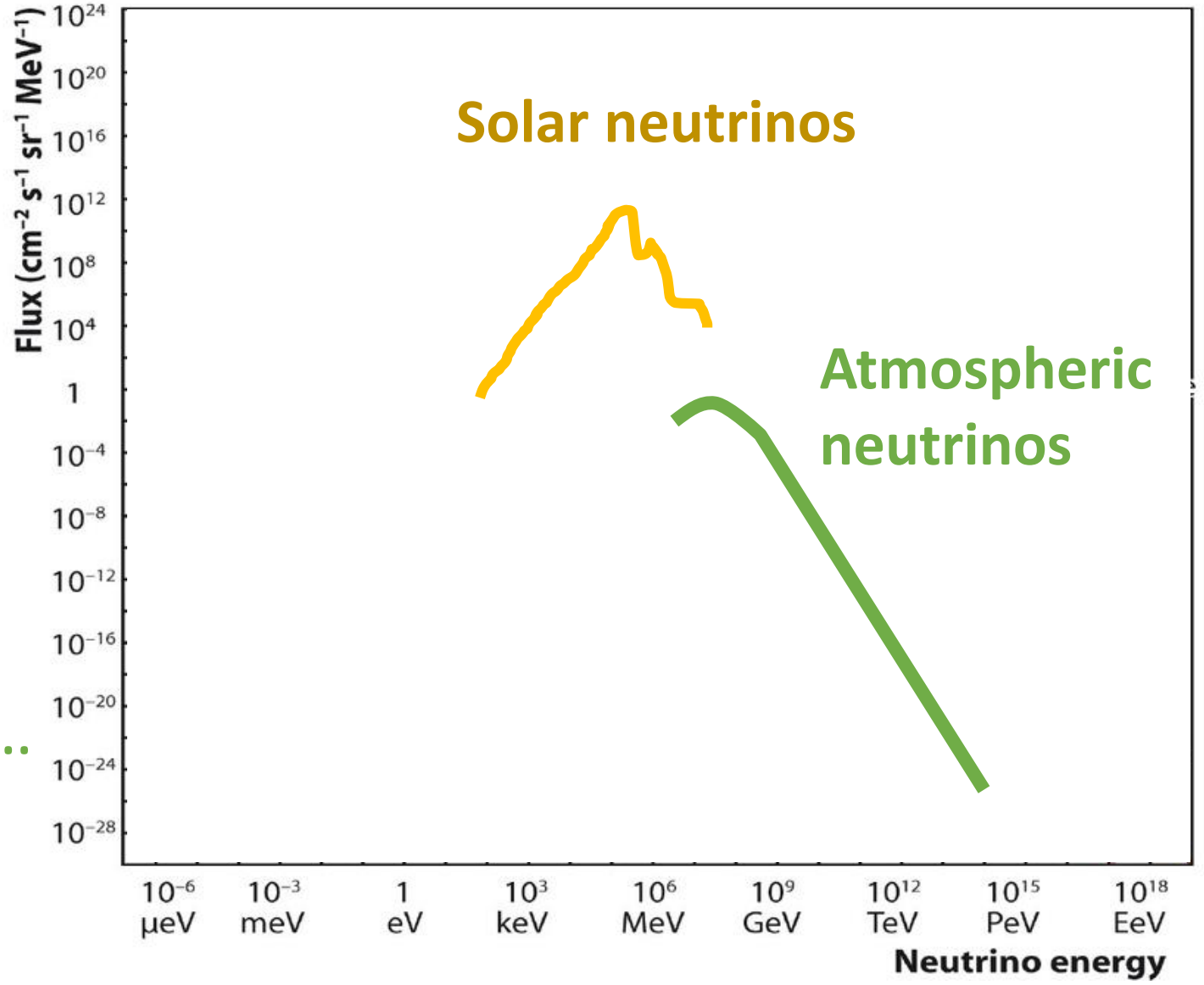


- Low threshold for hadron reconstruction
- $\nu/\bar{\nu}$ separation
- Sensitive to CP violation and mass ordering

Take-away Messages

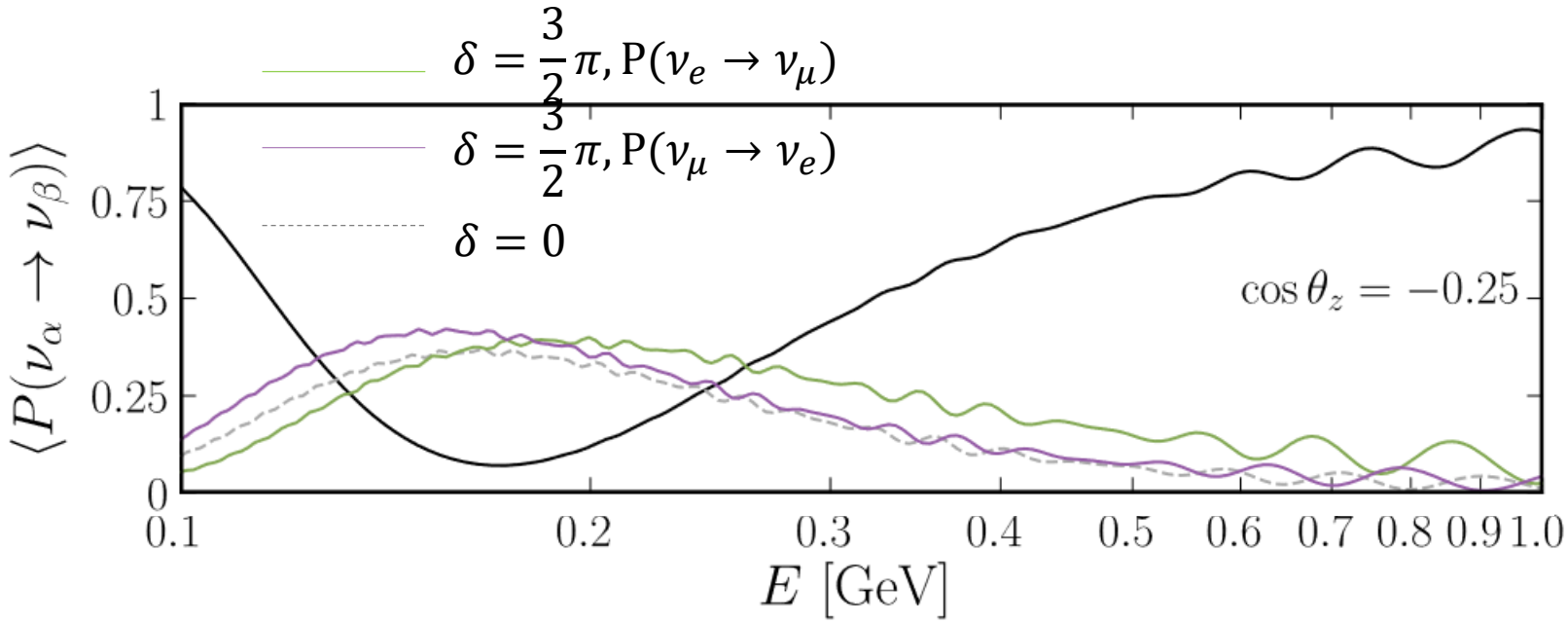
- Pure ν_e's
- Measure 1-2 mixing;
- Solar metallicity and more…

- $\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$
- Measure 2-3 mixing;
- Mass ordering, CP violation, …



Thank you!

CP Violation

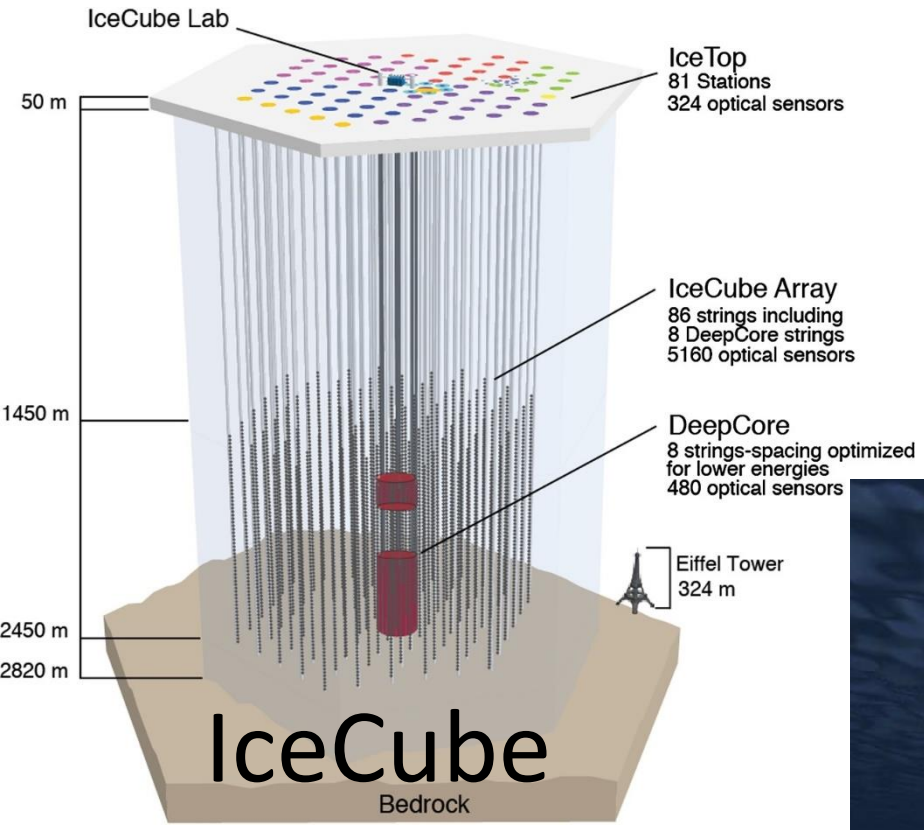


Kevin J. Kelly et al. PhysRevLett.123.081801

Signature at sub-GeV

- Requires precise prediction of neutrino flux and precise reconstruction of neutrino energy

Other Atmospheric Neutrino Observatories



DeepCore

E_{thr}: 6 GeV