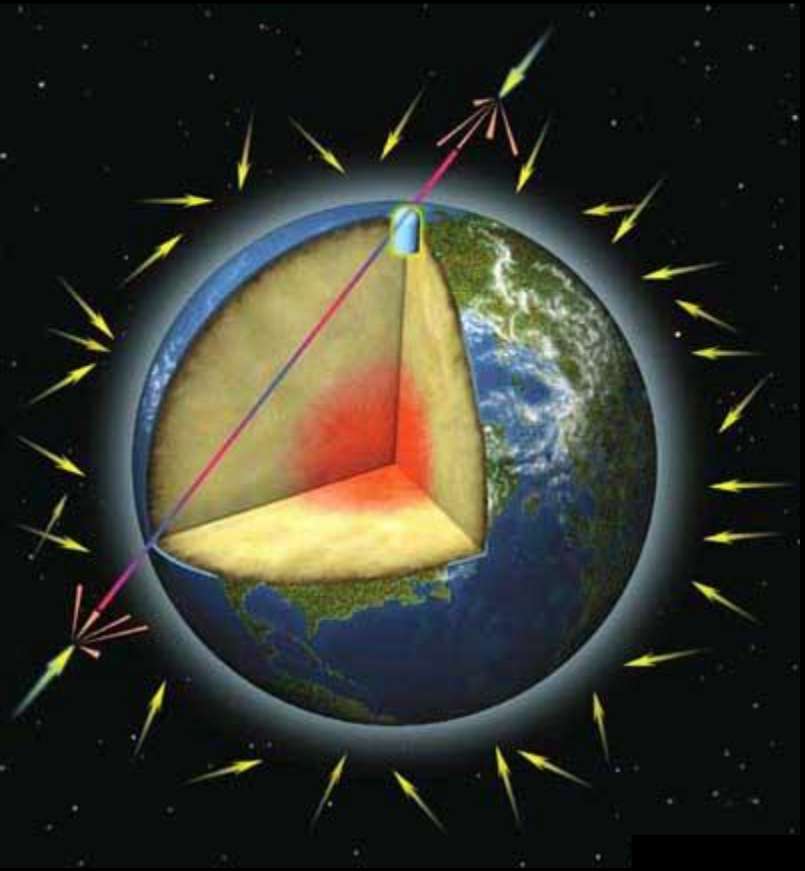


# Solar Neutrinos and Atmospheric Neutrinos

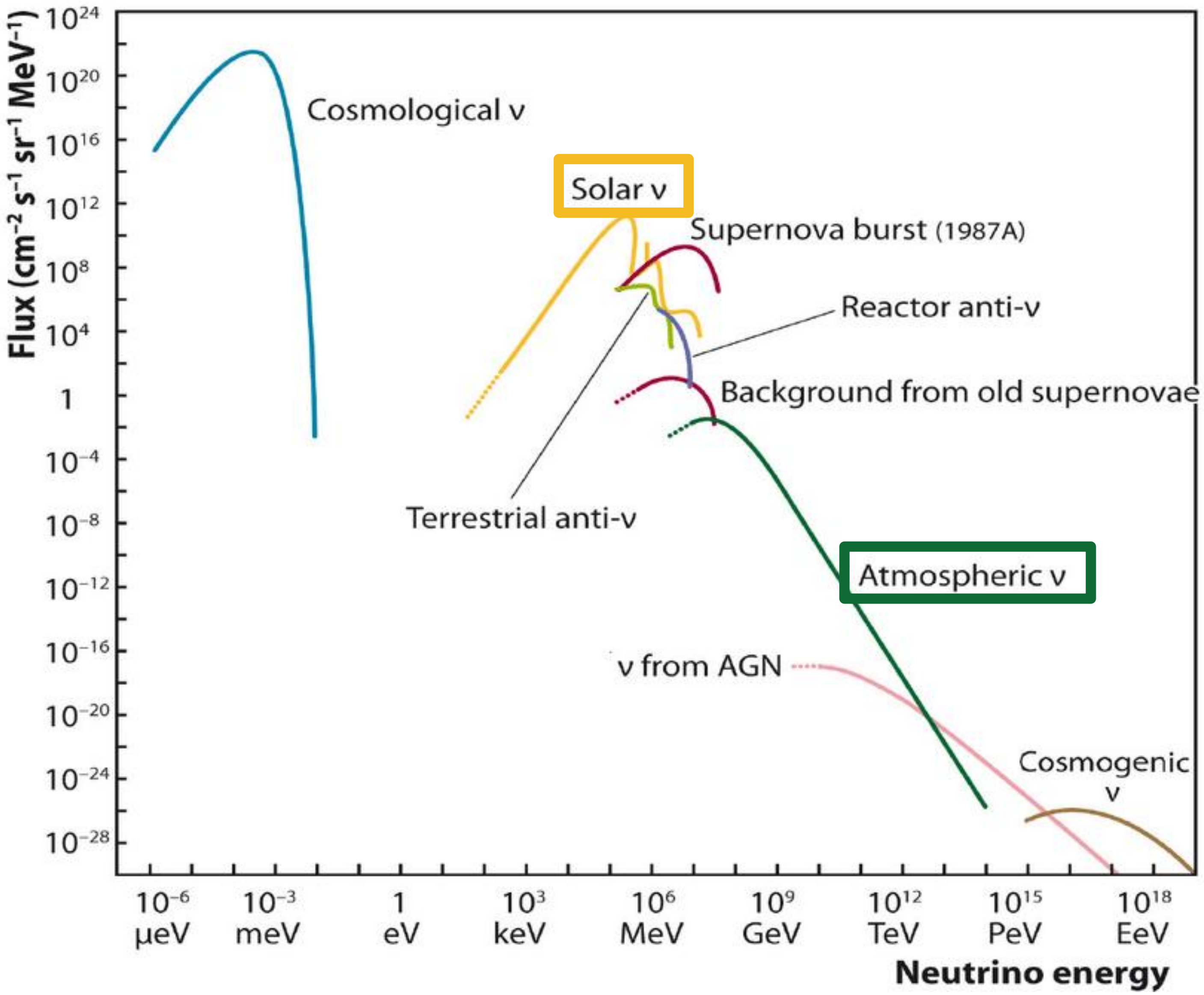
Linyan Wan, Fermilab

July 2, 2025

@Neutrino University

# Neutrino Sources

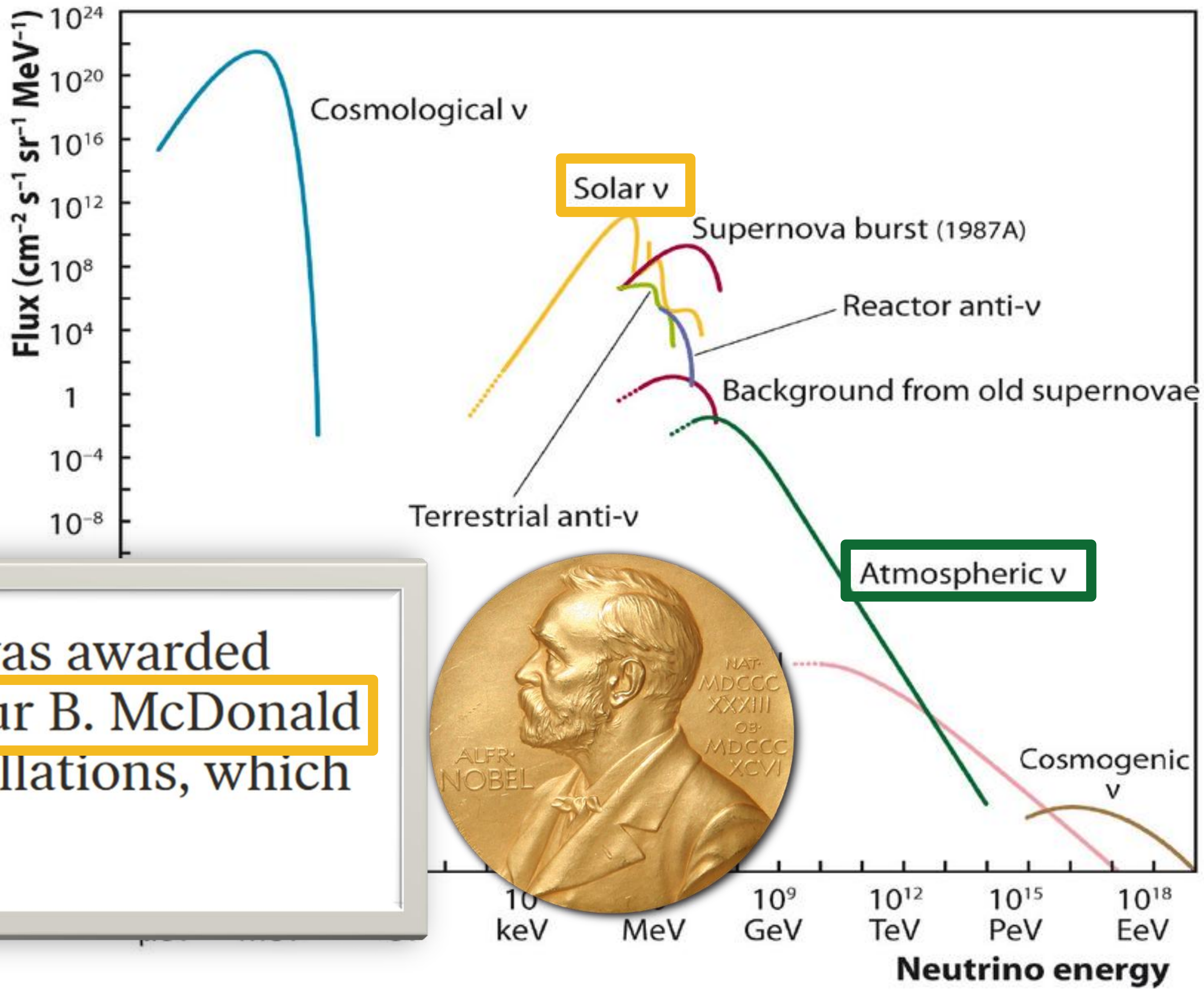
- Solar neutrinos
- Atmospheric neutrinos




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

# Neutrino Sources

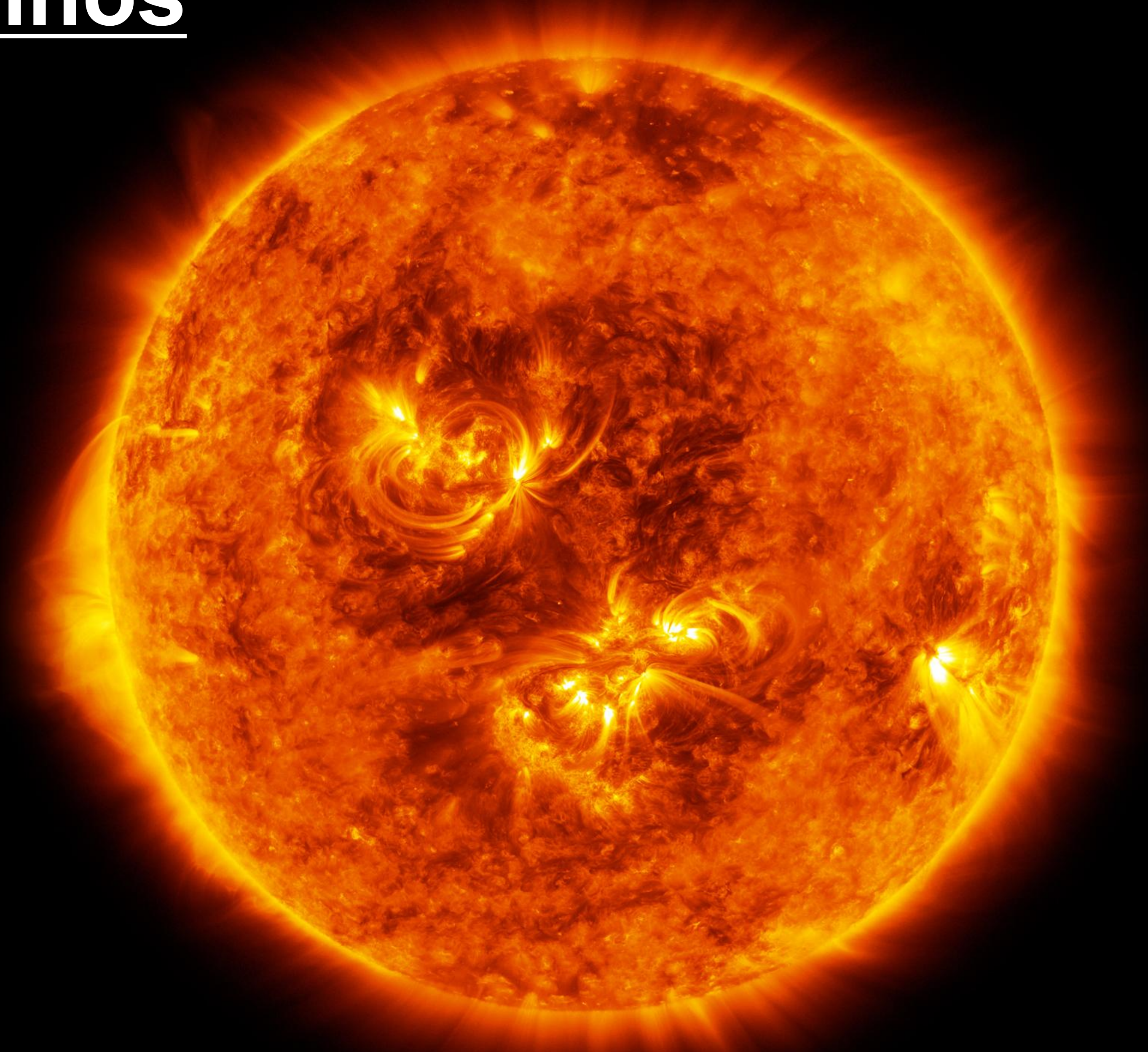
- Solar neutrinos
- Atmospheric neutrinos



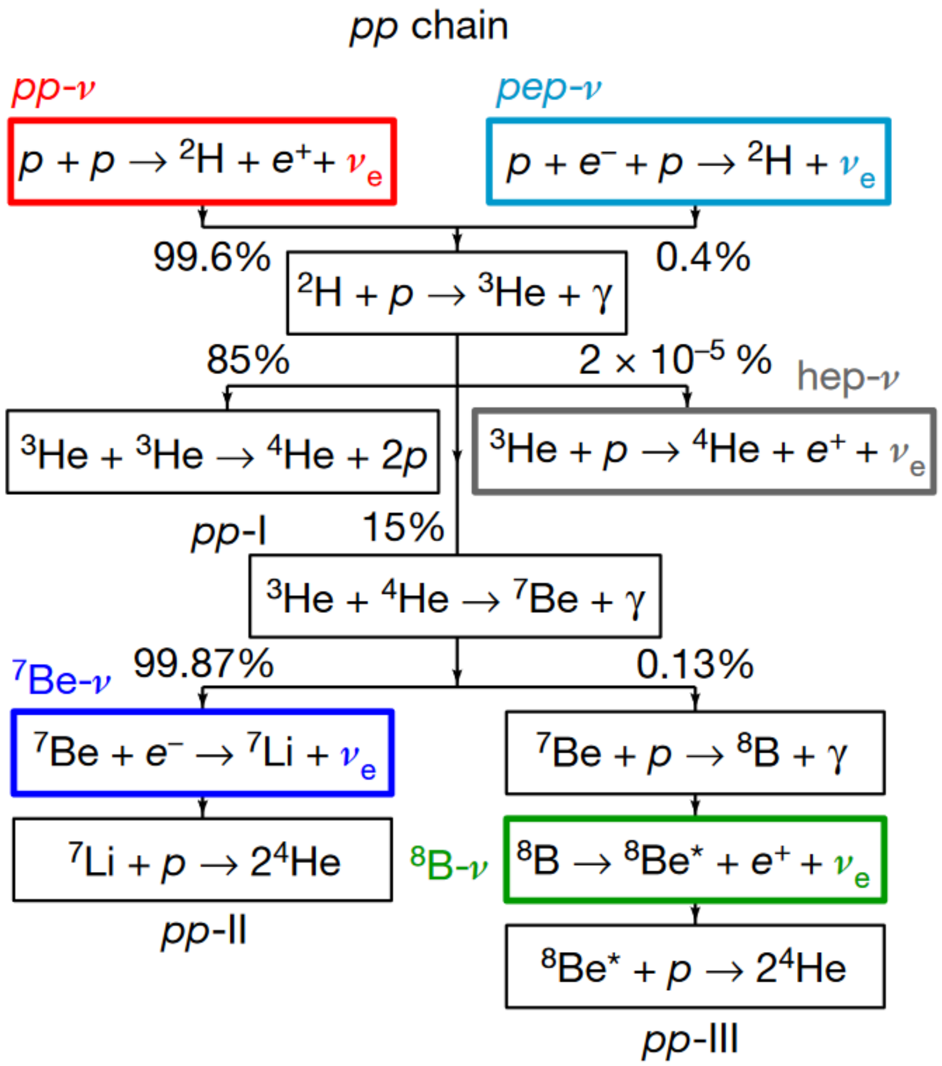

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass"

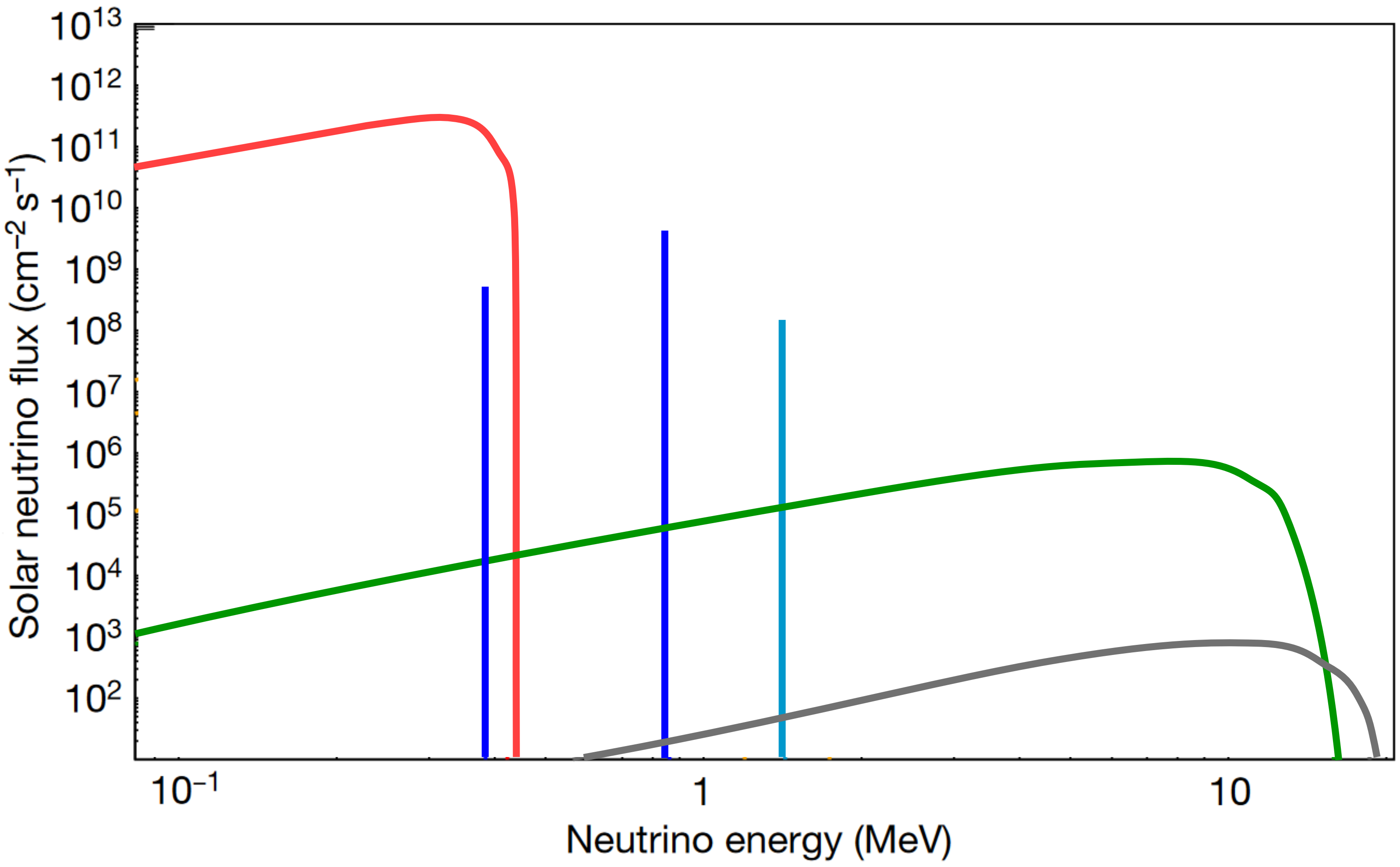
Michel Cribier, *et al.*, La lumière des neutrinos Seuil (1995)

# Solar Neutrinos

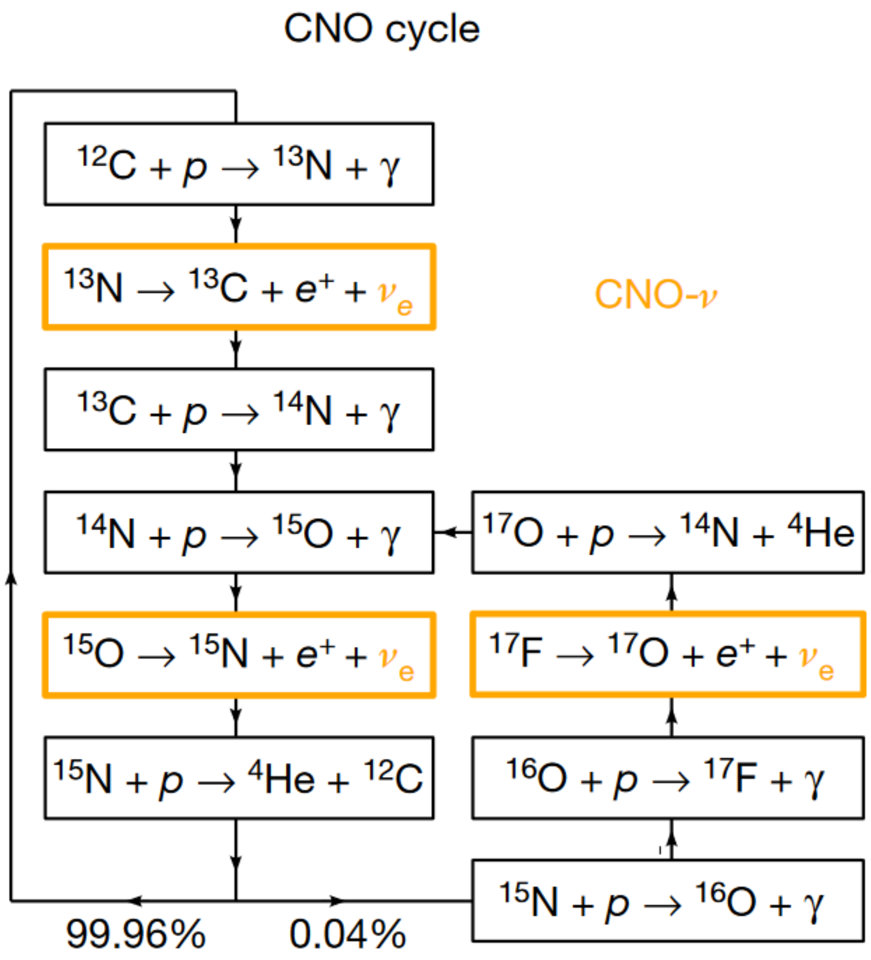


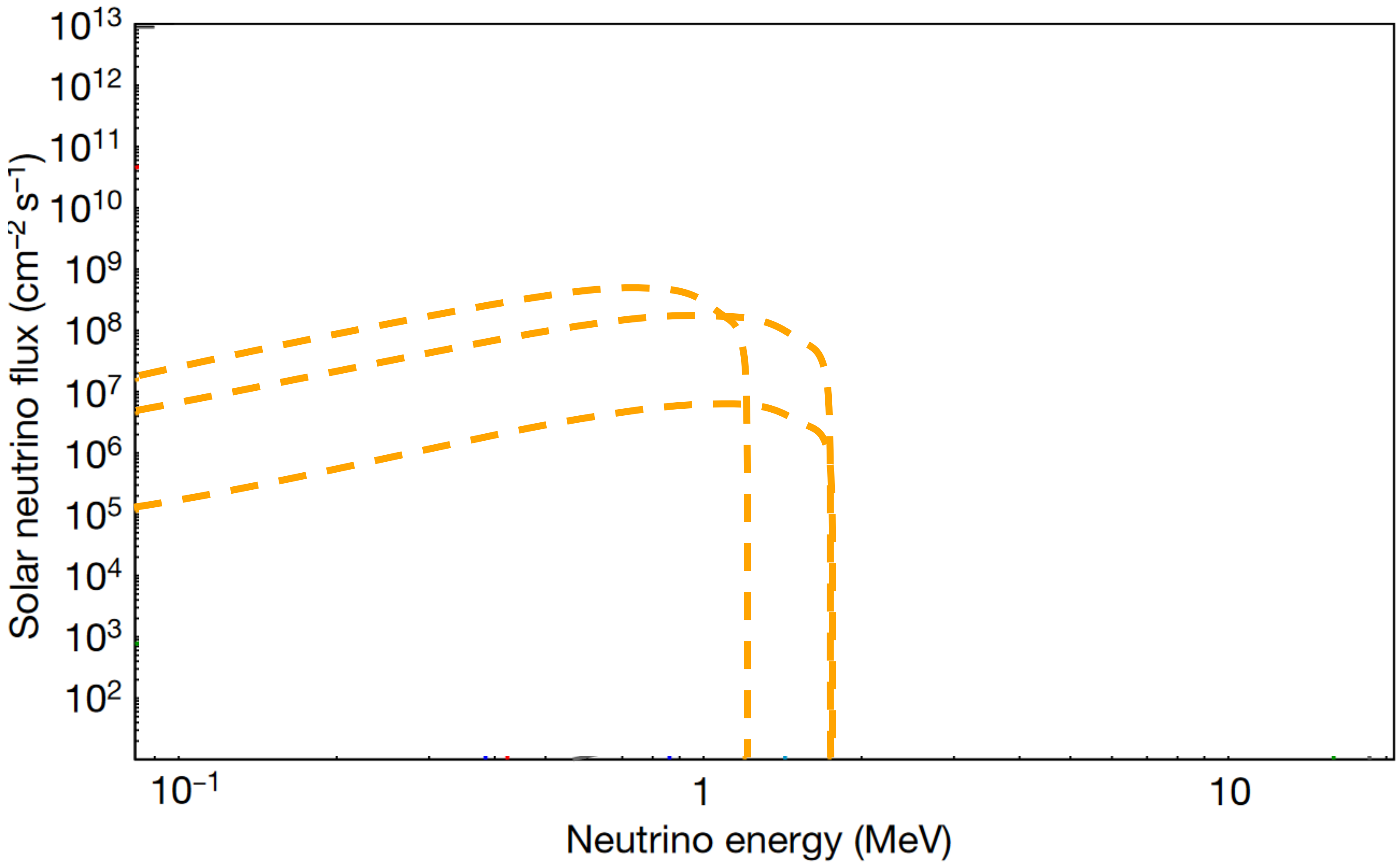
# Production: pp Chain



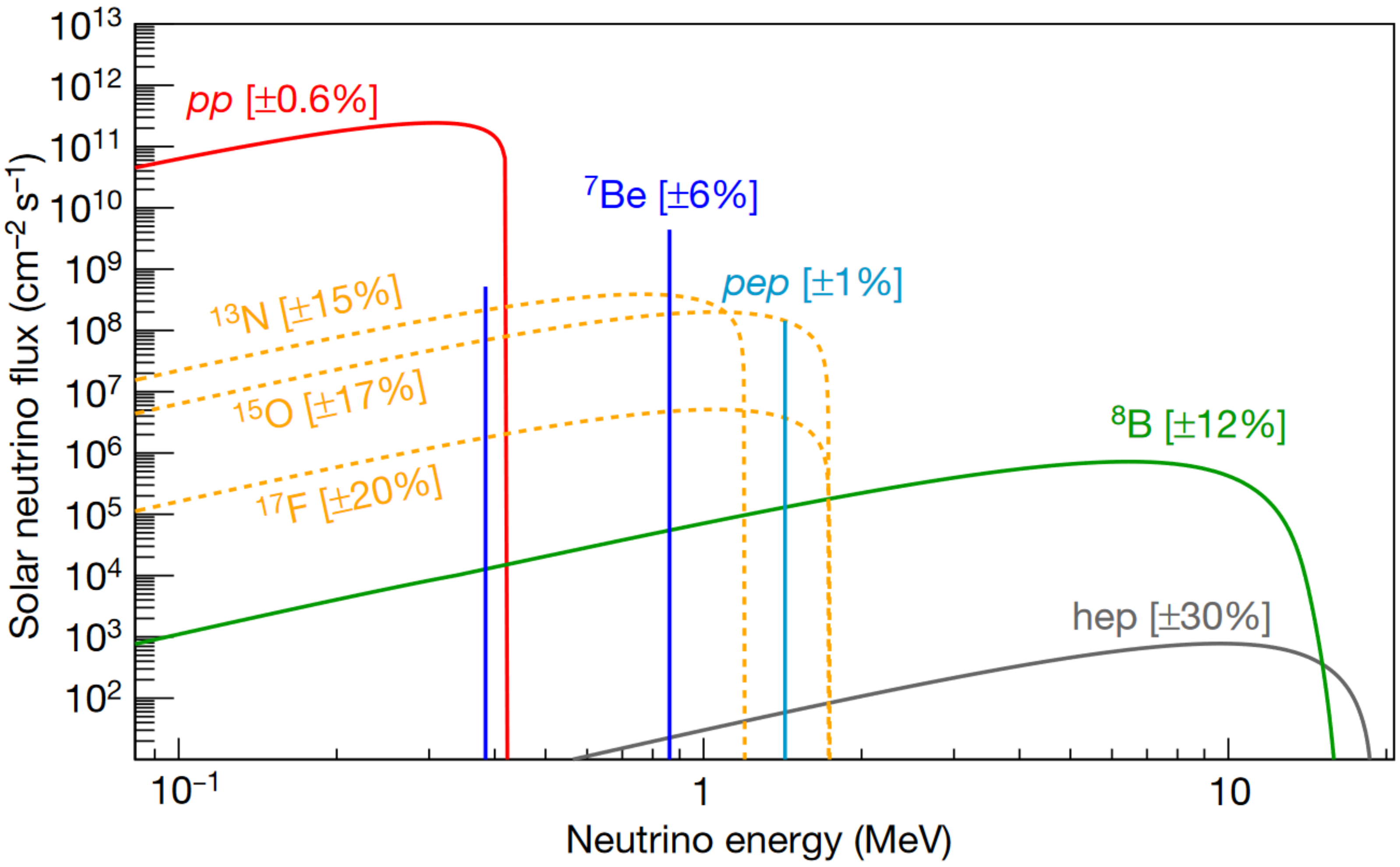
# Production: CNO Cycle



# Solar Neutrino Spectrum at Production

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



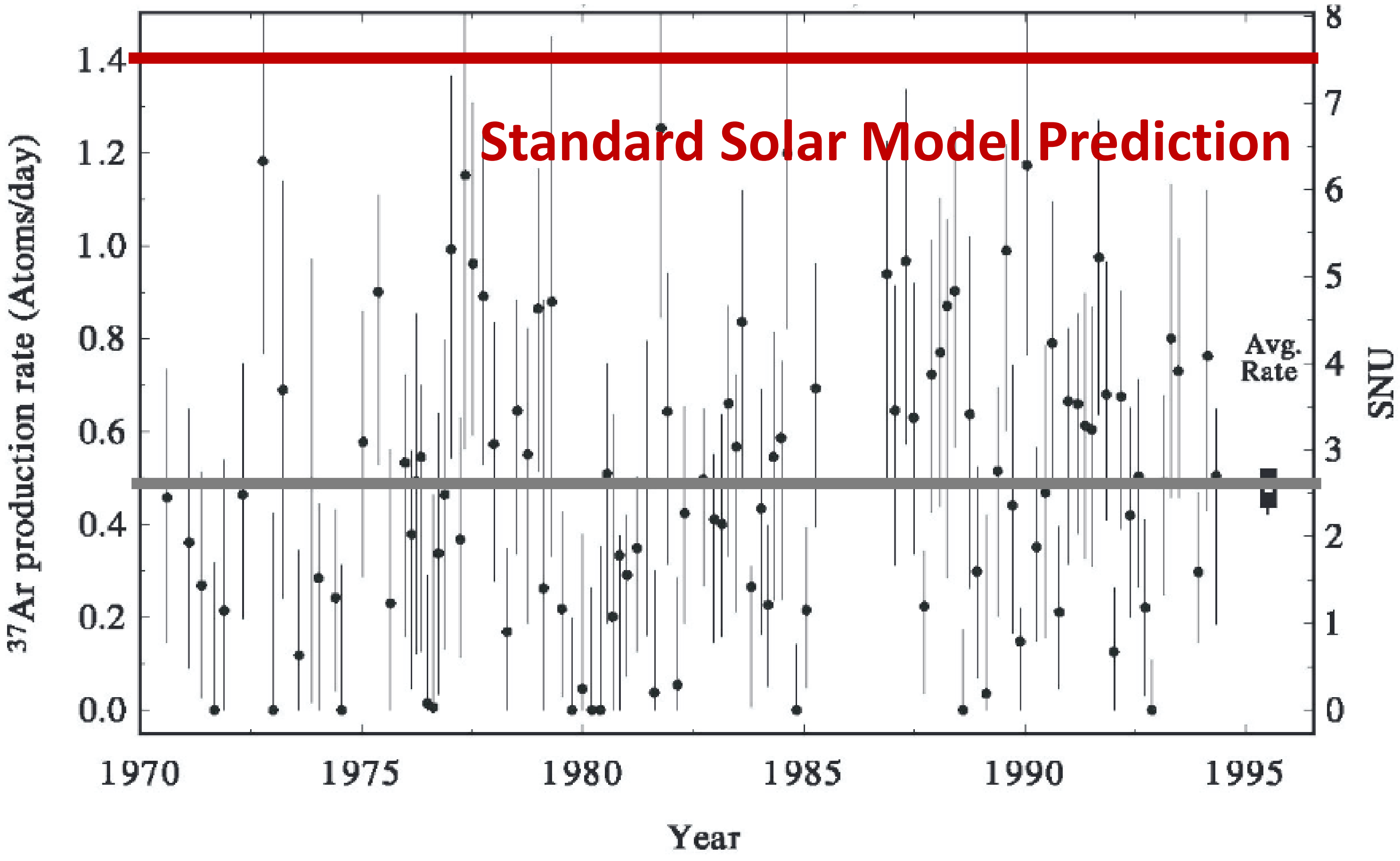

http://www.sns.ias.edu/~jnb/ Vinyoles, N. et al. Astrophys. J. 835,202 (2017). Borexino, *Nature* **562**, 505–510 (2018)

# 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

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

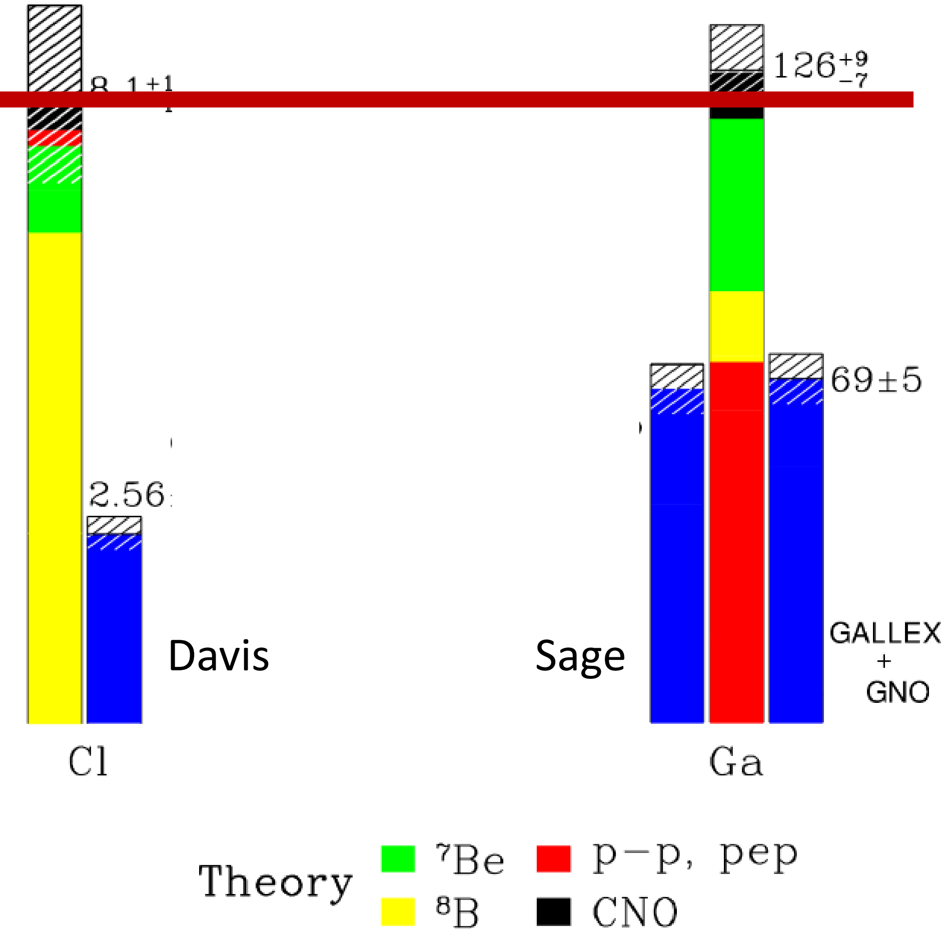
GALLEX experiment

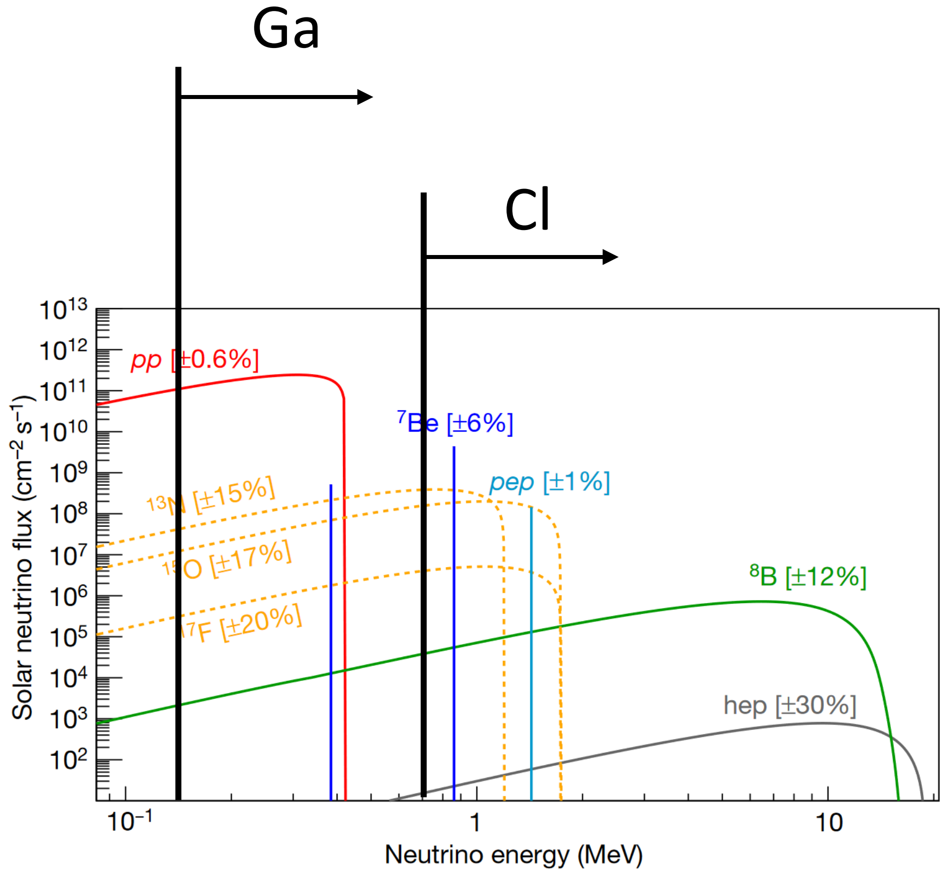

Sage experiment

# The Deficit

**Standard Solar Model Prediction**

**Experimental results**

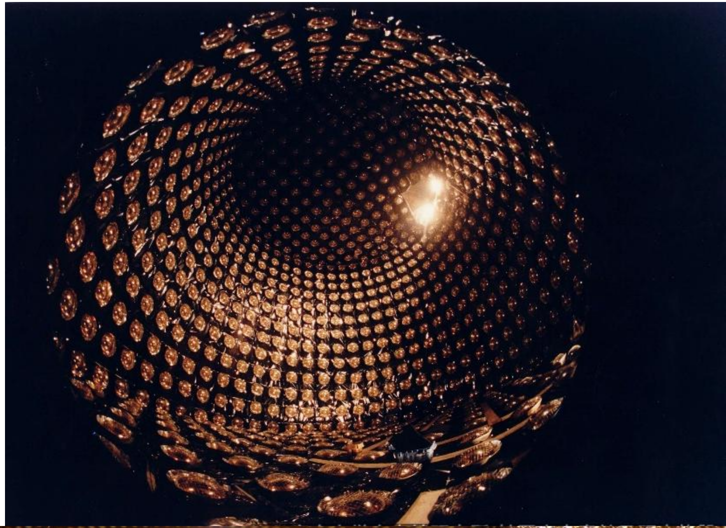


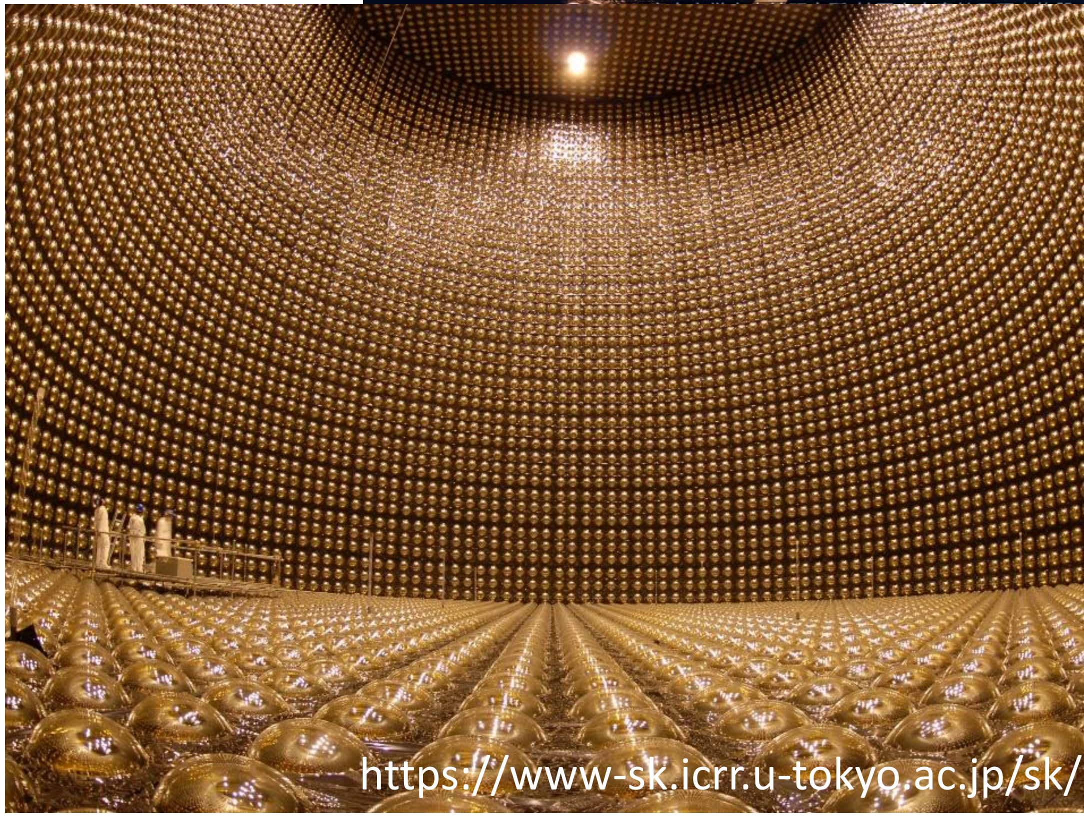



# Detection at Kamioka

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

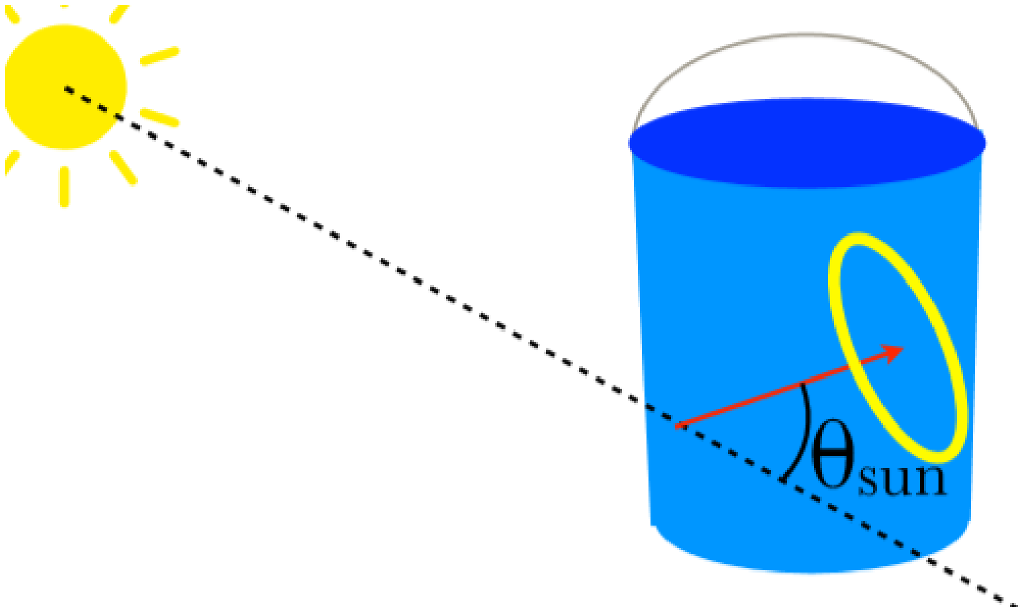
Kamiokande-II
(1985-1990)
↓
Super-Kamiokande
(1996-now)



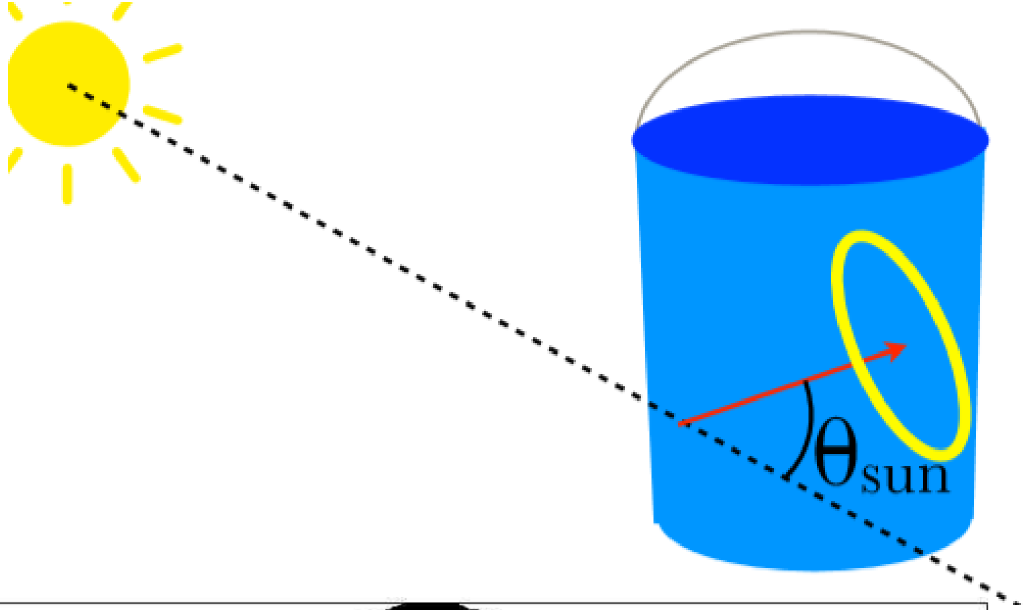


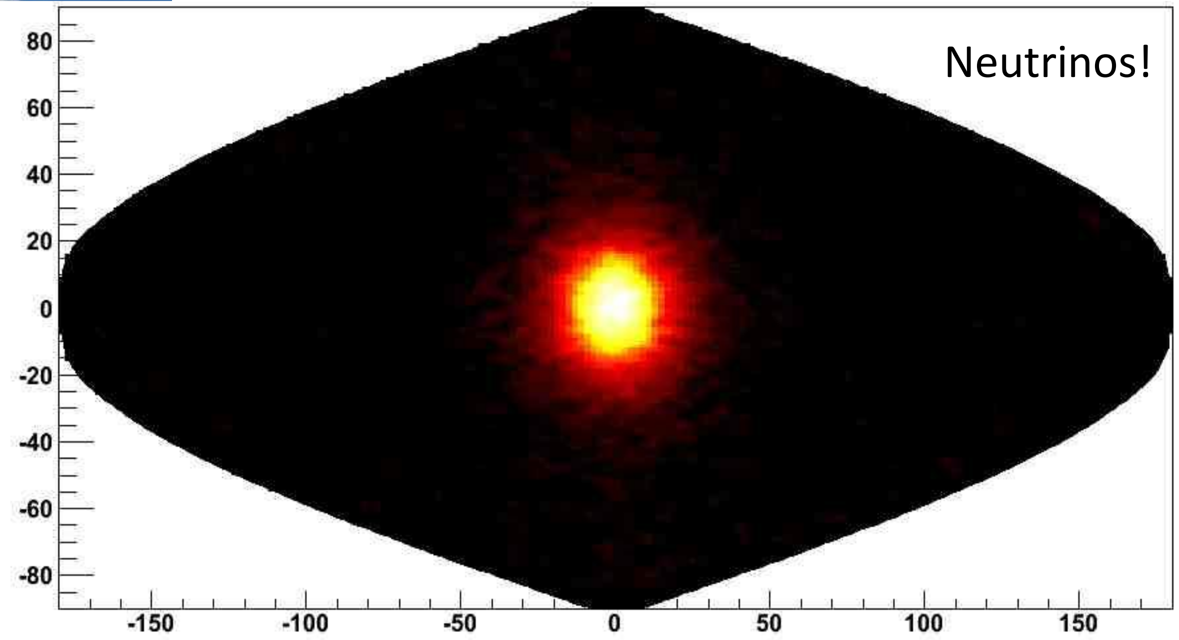
# Cherenkov Detectors

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



# An Image of the Sun


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

# Cherenkov Detectors

| | Kamiokande-II, Super-Kamiokande |
|---|---|
| Target | H2O |
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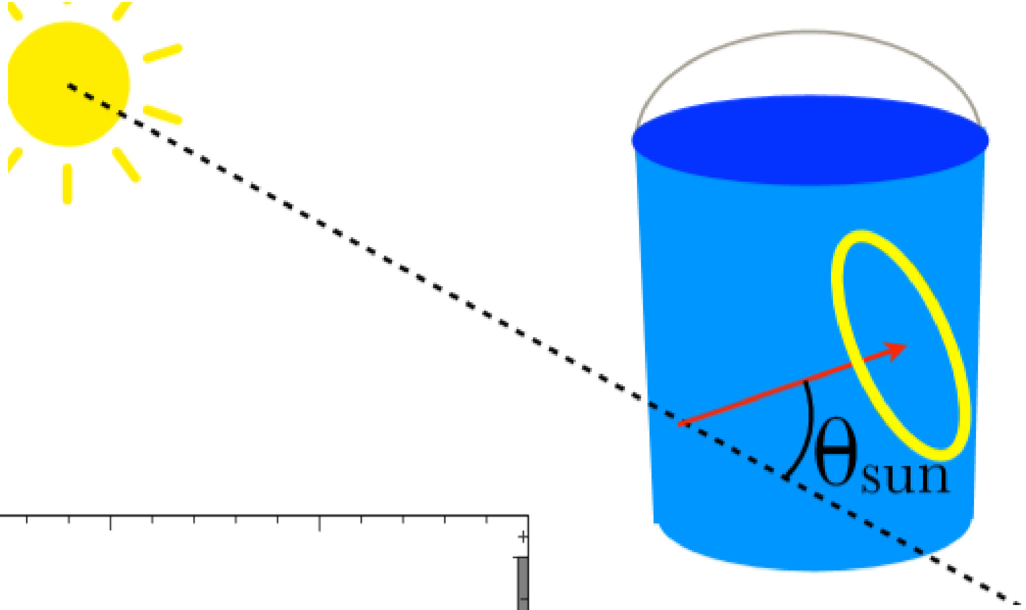
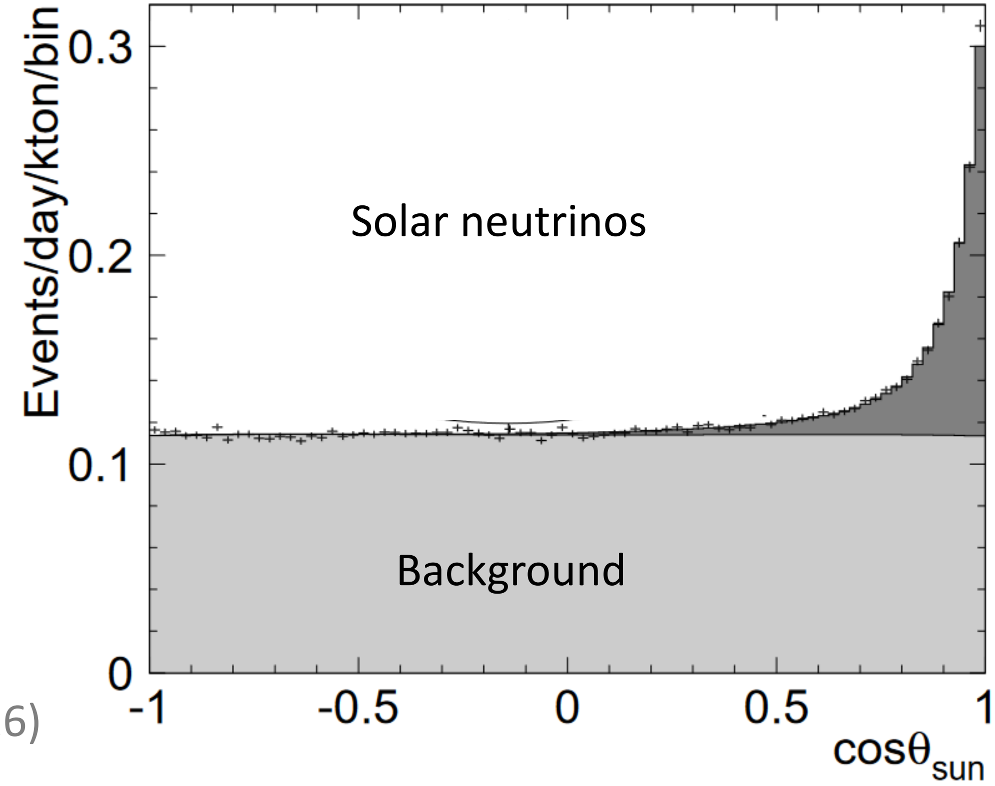


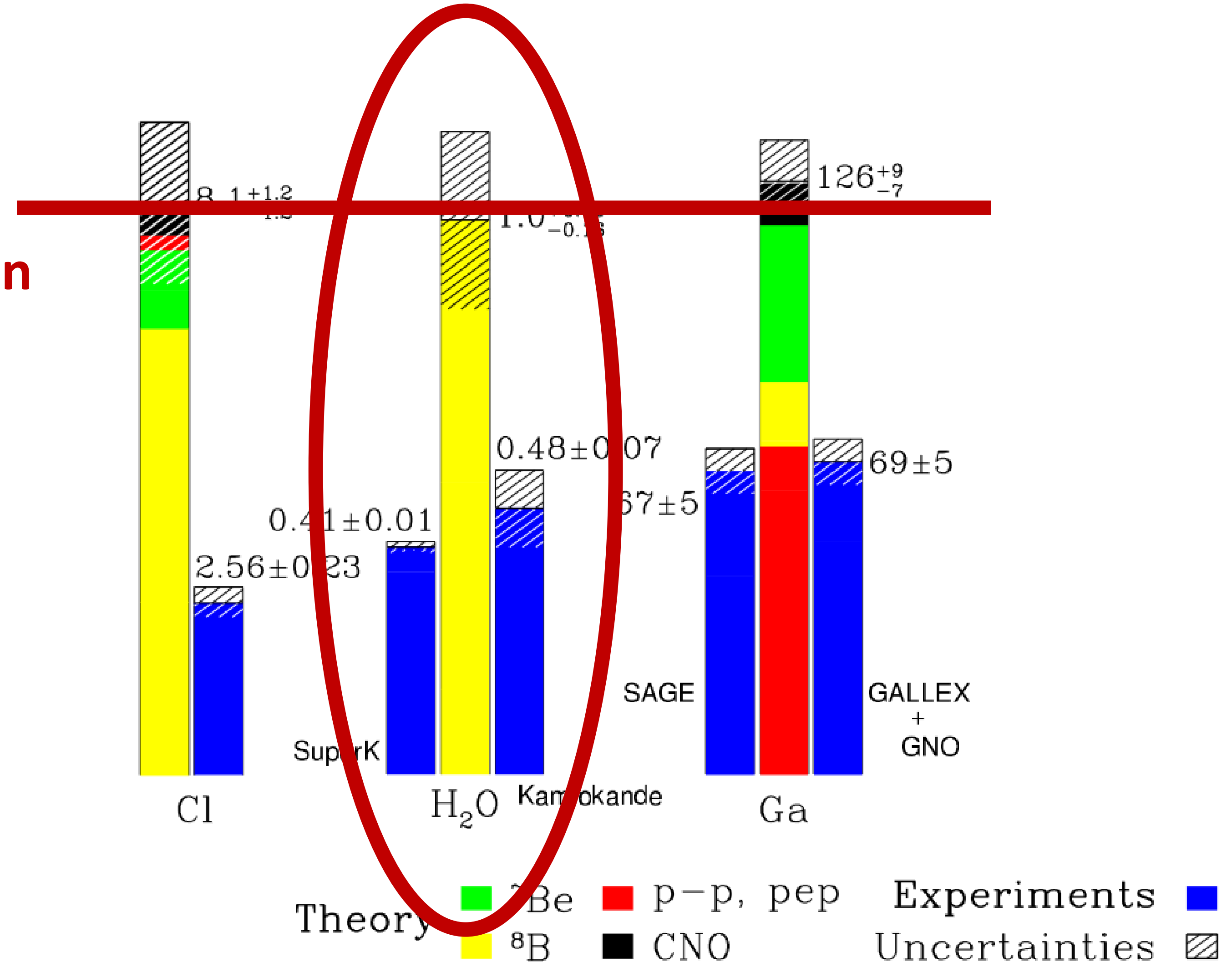




Super-Kamiokande, Phys. Rev. D 94, 052010 (2016)

# The Solar Neutrino Problem

**Standard Solar Model Prediction**

**Experimental results**



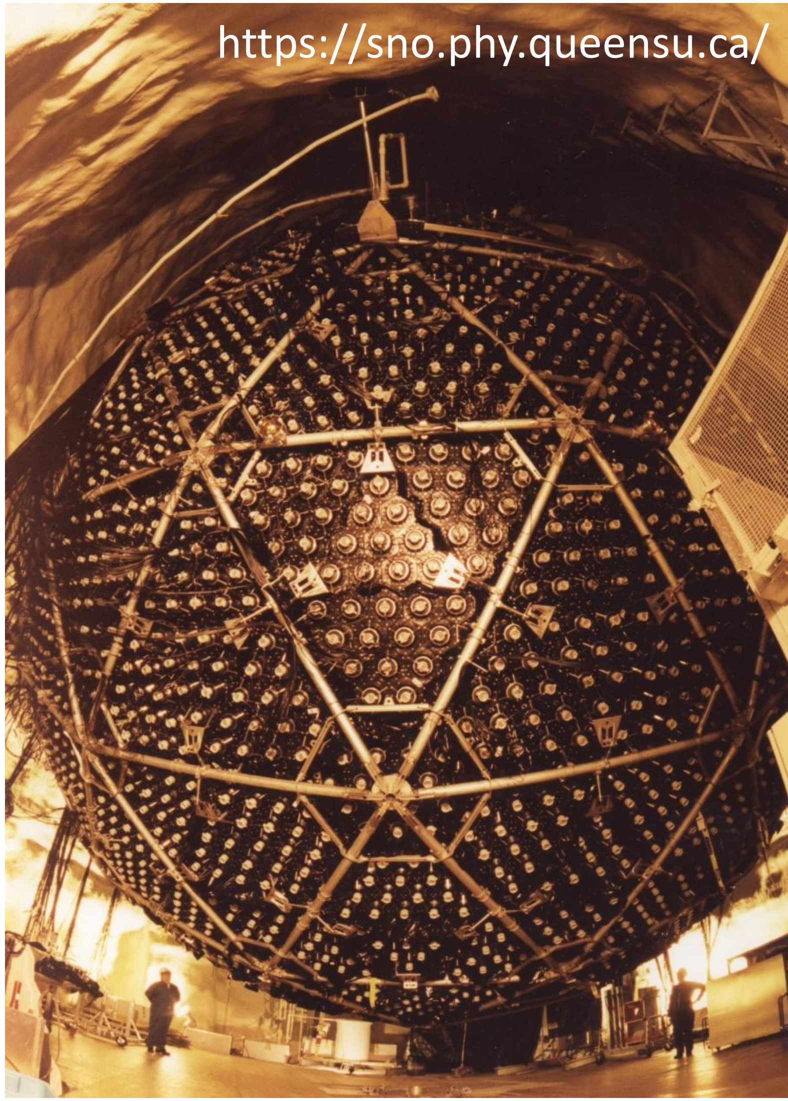

http://www.sns.ias.edu/~jnb/

# SNO: A Special Cherenkov Detector

SNO (1999-2006)

| | 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: A Special Cherenkov Detector

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|---|---|---|
| Target | H2O | D2O |
| Interaction | $\nu + e^- \rightarrow \nu + e^-$ | ES + CC + NC |
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- Elastic scattering: $\nu + e^- \rightarrow \nu + \boldsymbol{e}^-$
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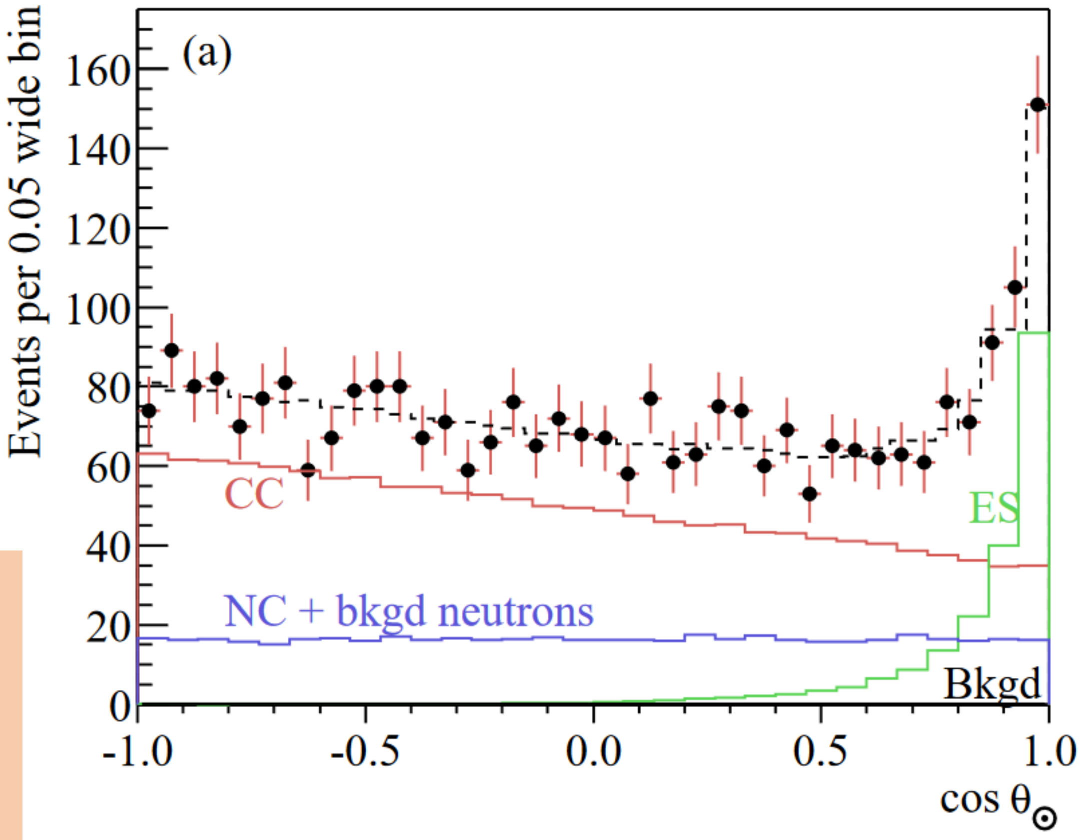
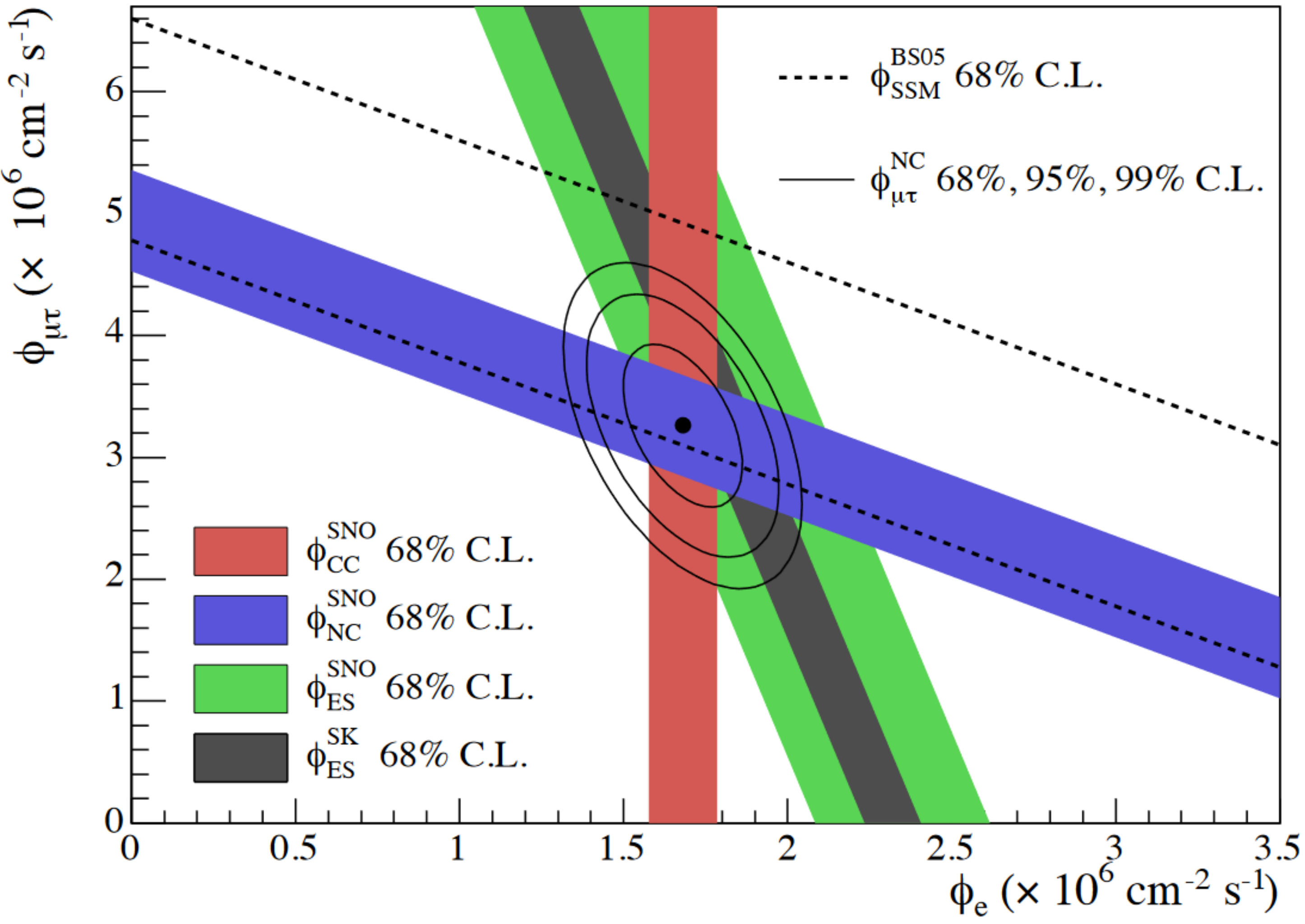
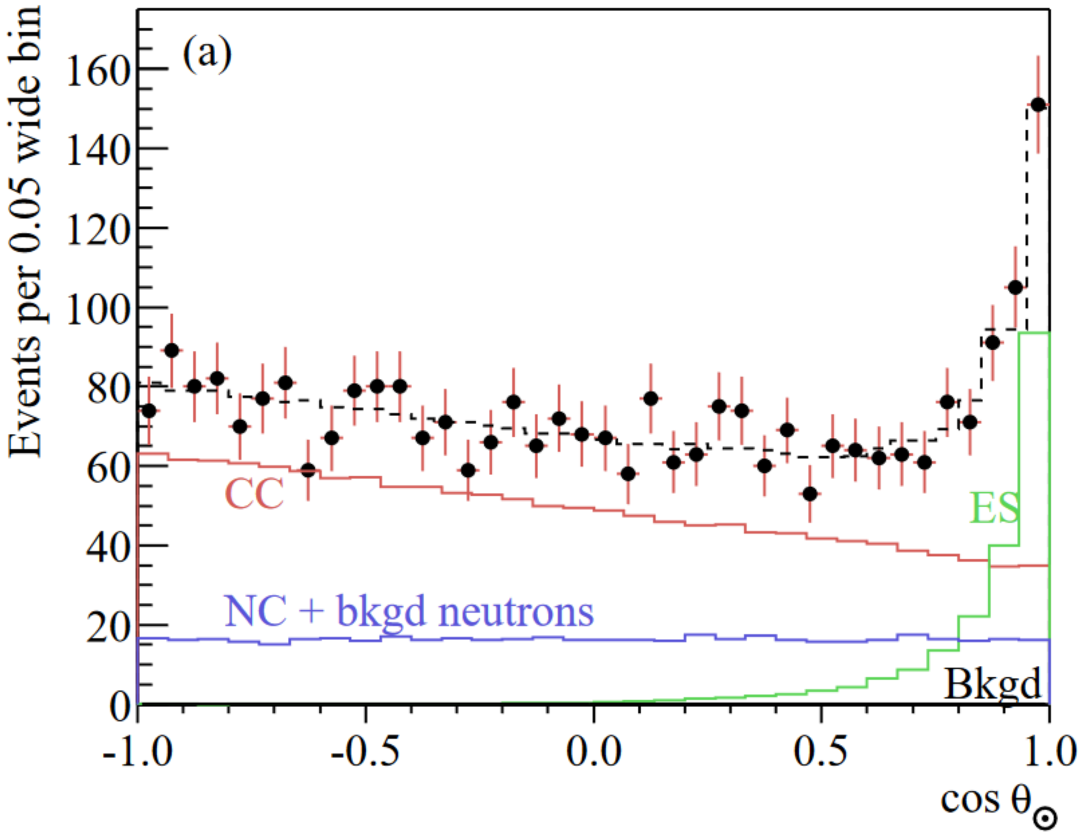



SNO, Phys.Rev.Lett.89:011301 (2002)

# SNO: Flavor Measurement



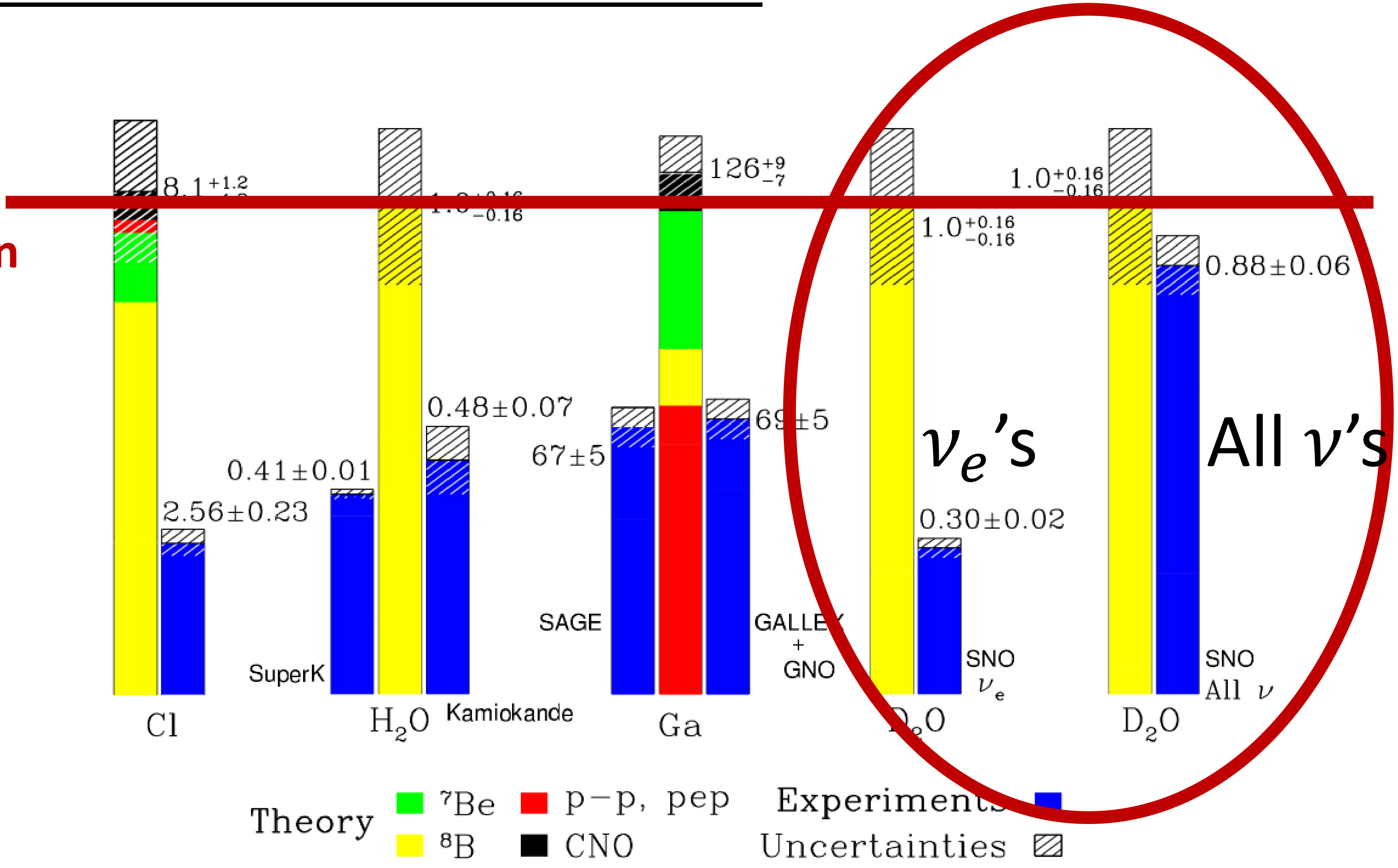




SNO, Phys.Rev.Lett.89:011301 (2002)

# The Solar Neutrino Problem

**Standard Solar Model Prediction**

**Experimental results**




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

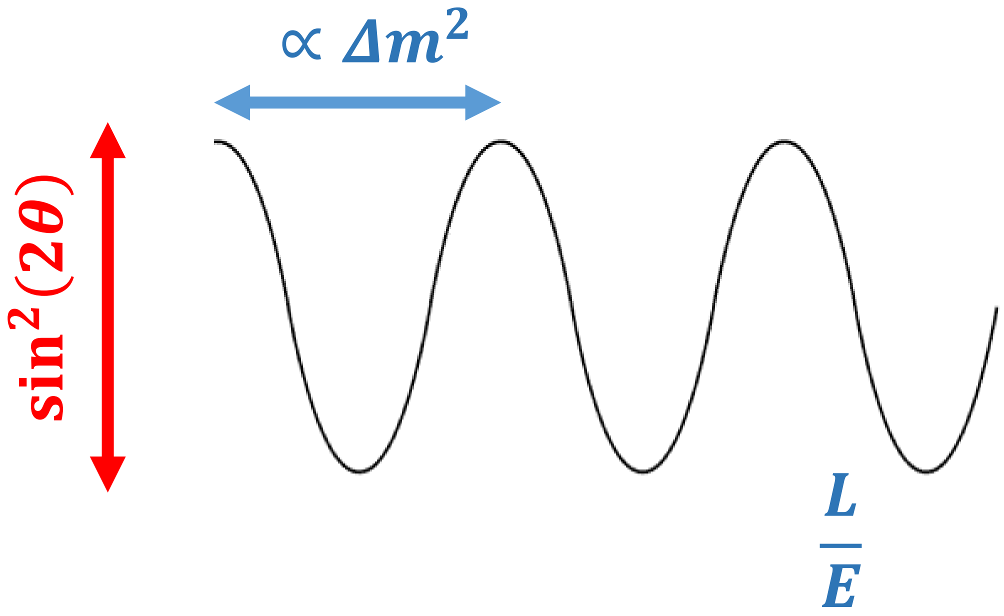
# Neutrino Oscillation: Simplified 2-Flavor Model

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

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

$\Delta m^2_{21}$

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

$\Delta m^2_{32}$

Flavor eigenstate

Mass eigenstate

# Neutrino Oscillation

Pontecorvo–Maki–Nakagawa–Sakata matrix

$\Delta m^2_{21}$

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

$\Delta m^2_{32}$

Flavor eigenstate

Mass eigenstate

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

# Neutrino Oscillation

Pontecorvo–Maki–Nakagawa–Sakata matrix

$\Delta m^2_{21}$

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

$\Delta m^2_{32}$

Flavor eigenstate

Mass eigenstate

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

# Neutrino Oscillation

Pontecorvo–Maki–Nakagawa–Sakata matrix

$\Delta m_{21}^2$

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

$\Delta m_{32}^2$

Flavor eigenstate

Solar

Mass eigenstate

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

$$\cancel{- \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2}{4\bar{p}} L\right)}$$

$$\cancel{- \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{32}^2}{4\bar{p}} L\right)}$$

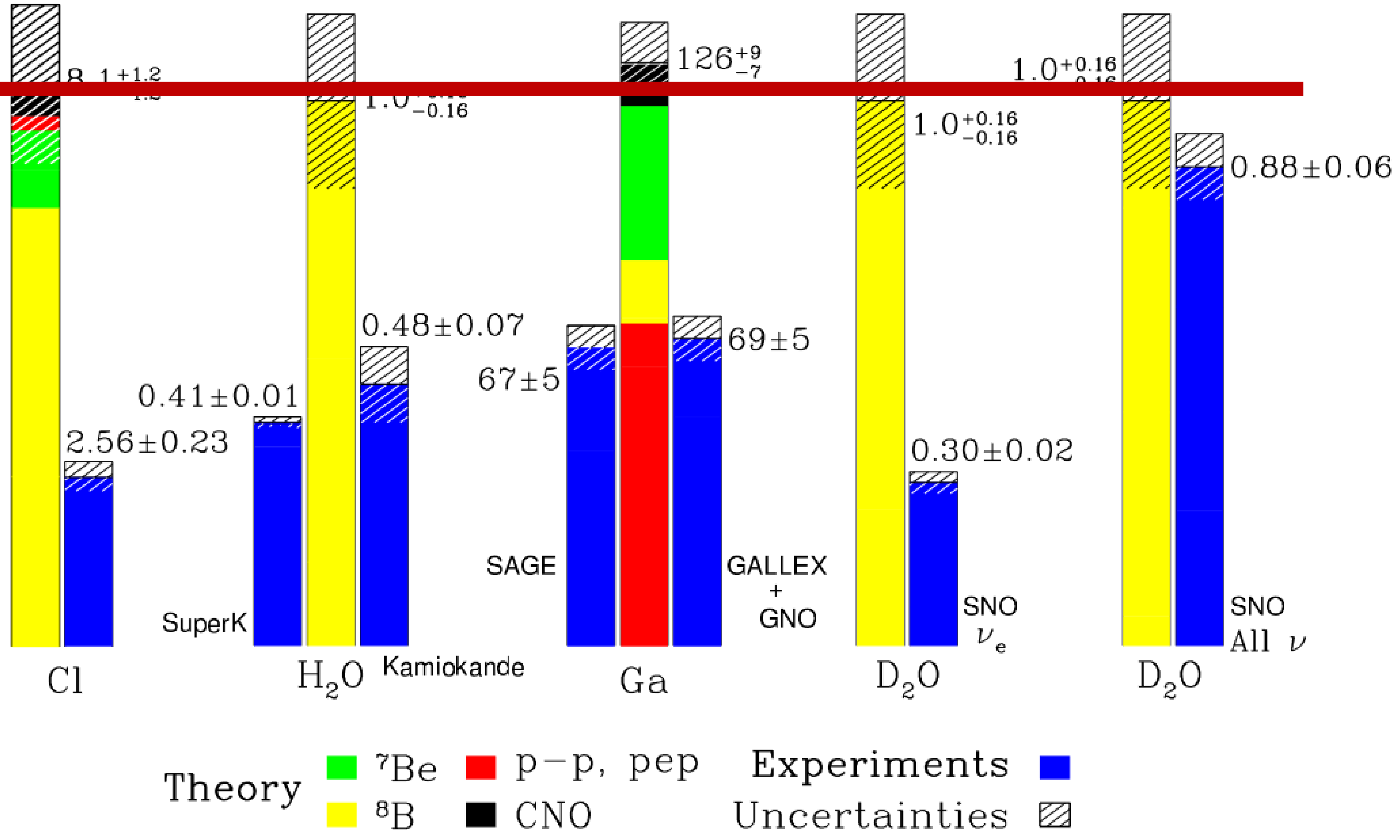
$$\approx 1 - \frac{1}{2}\sin^2(2\theta_{12})$$

# The Solar Neutrino Problem

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

**Standard Solar Model Prediction**

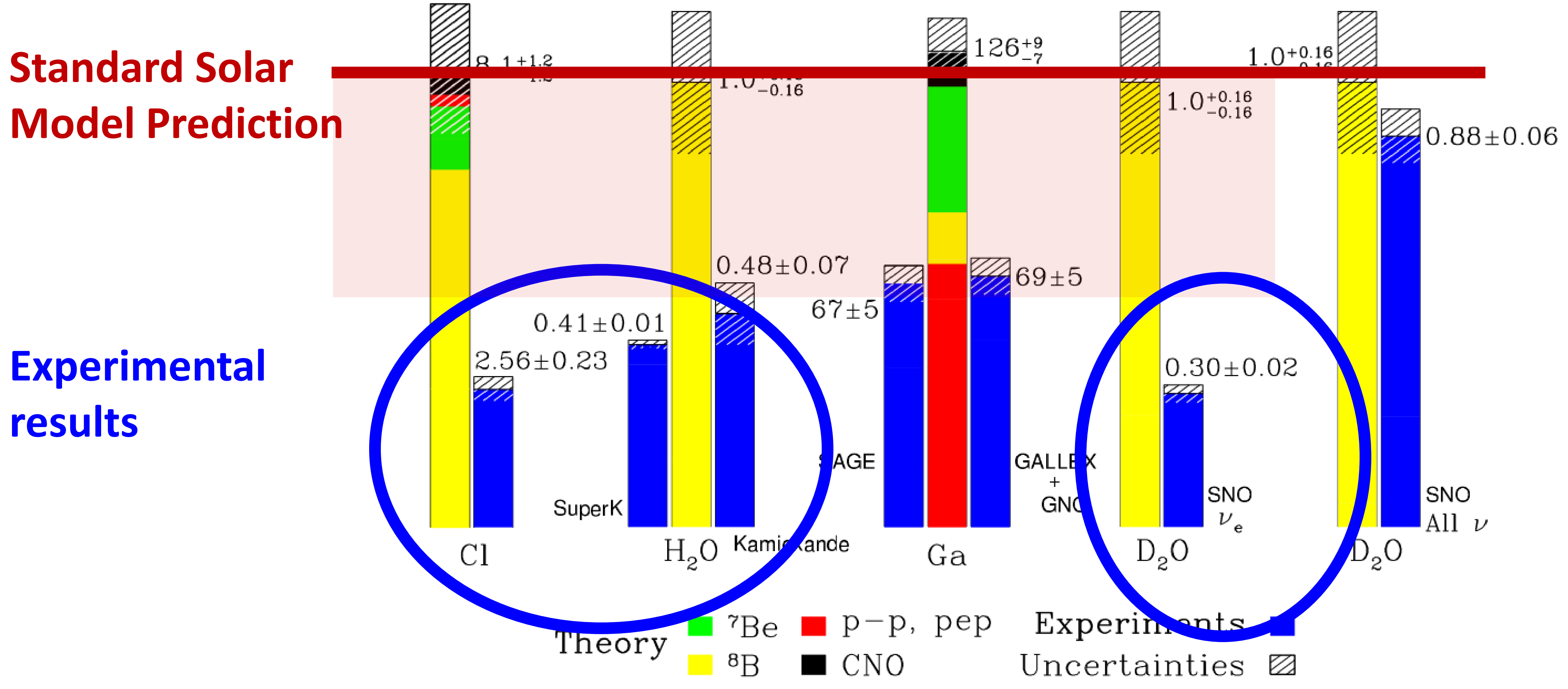
**Experimental results**




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

# The Solar Neutrino Problem

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




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

# Matter Effect

$$H_V = \frac{1}{4E}\begin{pmatrix} -\Delta m^2 \cos^2 2\theta & \Delta m^2 \sin^2 2\theta \\ \Delta m^2 \sin^2 2\theta & \Delta m^2 \cos^2 2\theta \end{pmatrix},$$

# Matter Effect

$$H_V = \frac{1}{4E}\begin{pmatrix} -\Delta m^2 \cos^2 2\theta & \Delta m^2 \sin^2 2\theta \\ \Delta m^2 \sin^2 2\theta & \Delta m^2 \cos^2 2\theta \end{pmatrix},$$

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

# Matter Effect

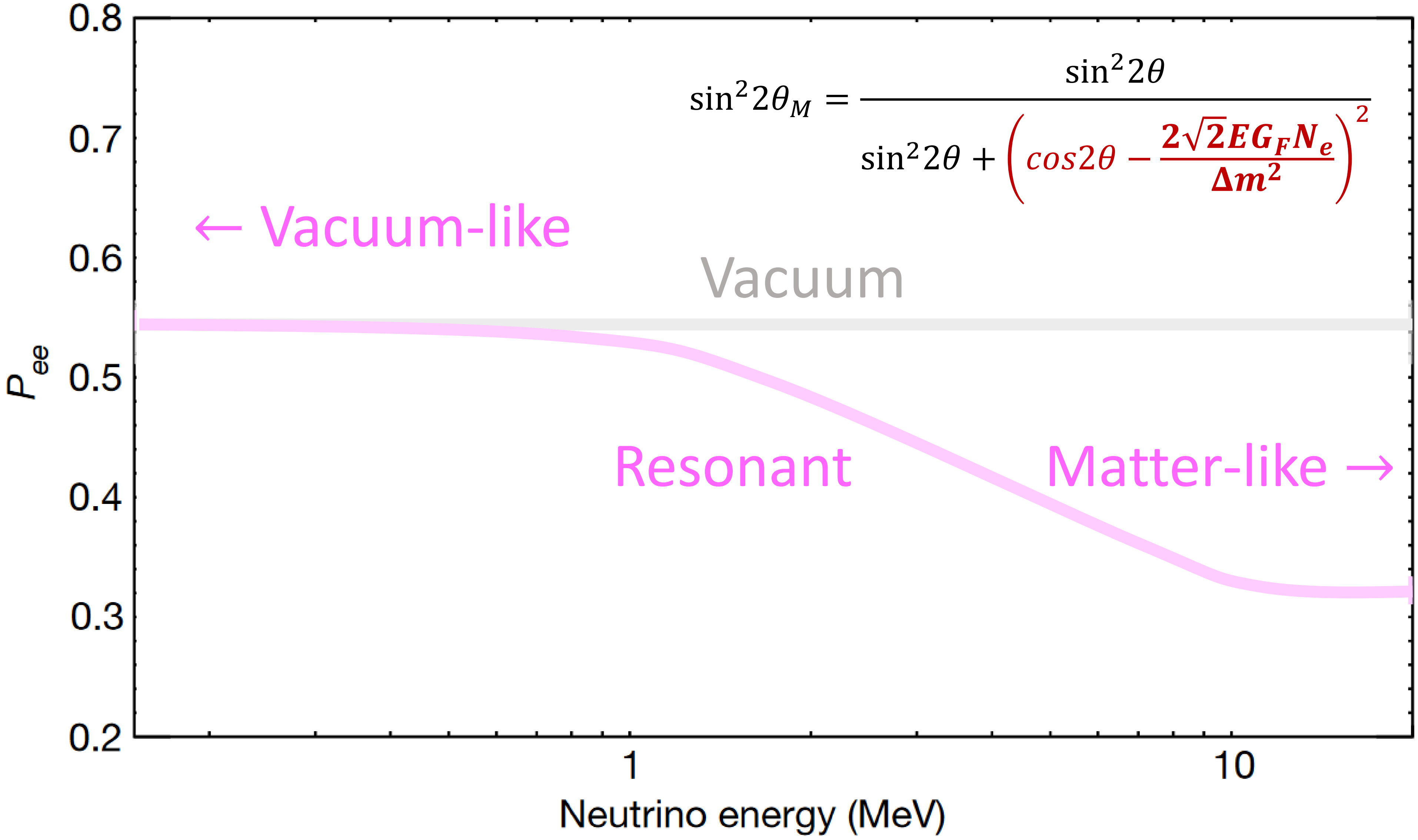
$$H_V = \frac{1}{4E}\begin{pmatrix} -\Delta m^2 \cos^2 2\theta & \Delta m^2 \sin^2 2\theta \\ \Delta m^2 \sin^2 2\theta & \Delta m^2 \cos^2 2\theta \end{pmatrix},$$

*Effective mixing parameters*

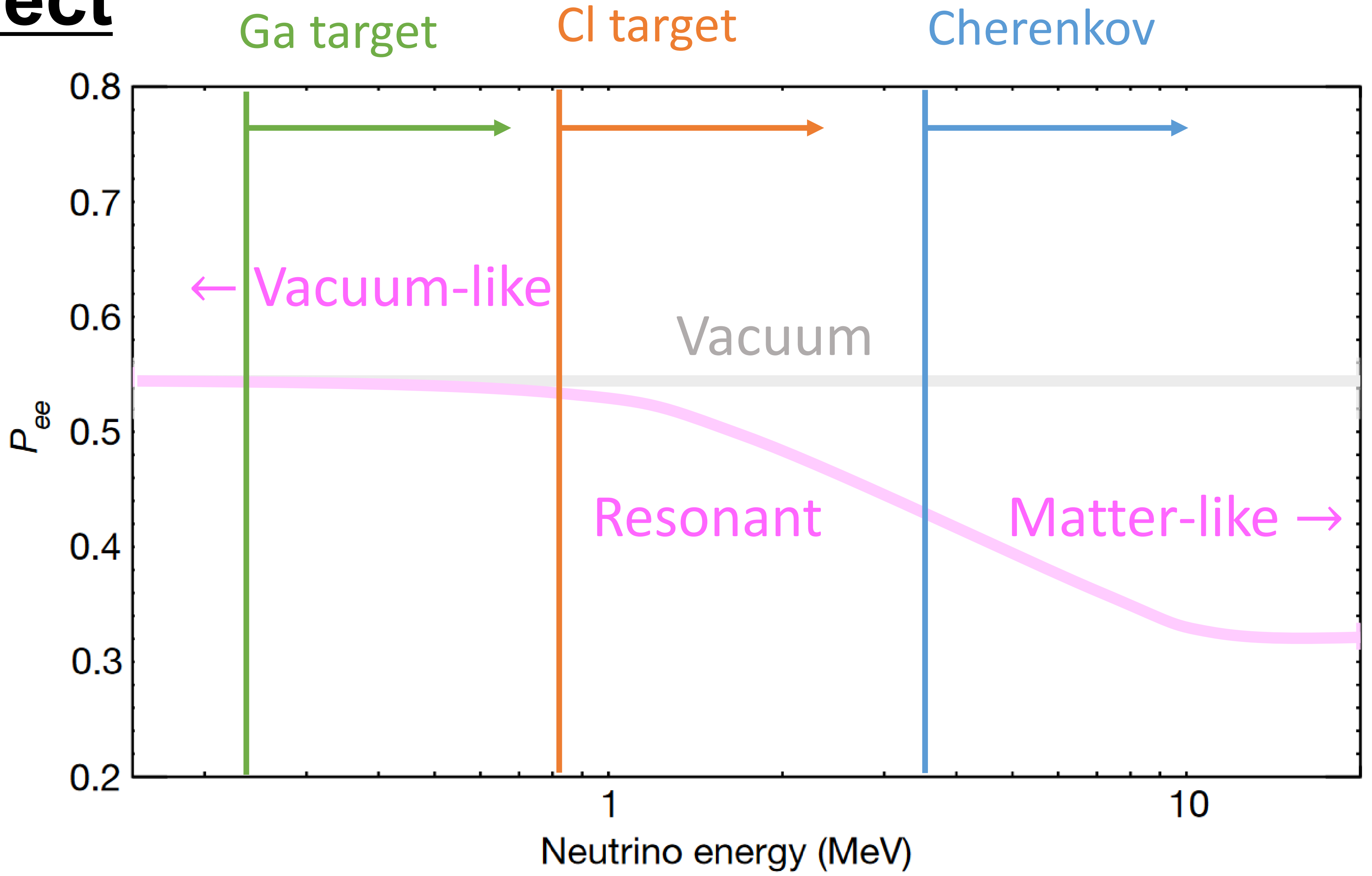
$$H_M = H_V + \begin{pmatrix} \frac{\sqrt{2}}{2} G_F N_e & \\ & 0 \end{pmatrix} \Rightarrow \begin{cases} \Delta m_M^2 = \sqrt{\left(\Delta m^2 \cos 2\theta - \mathbf{2\sqrt{2}EG_FN_e}\right)^2 + (\Delta m^2 \sin 2\theta)^2} \\ \sin^2 2\theta_M = \dfrac{\sin^2 2\theta}{\sin^2 2\theta + \left(\cos 2\theta - \dfrac{\mathbf{2\sqrt{2}EG_FN_e}}{\mathbf{\Delta m^2}}\right)^2} \end{cases}$$

*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)

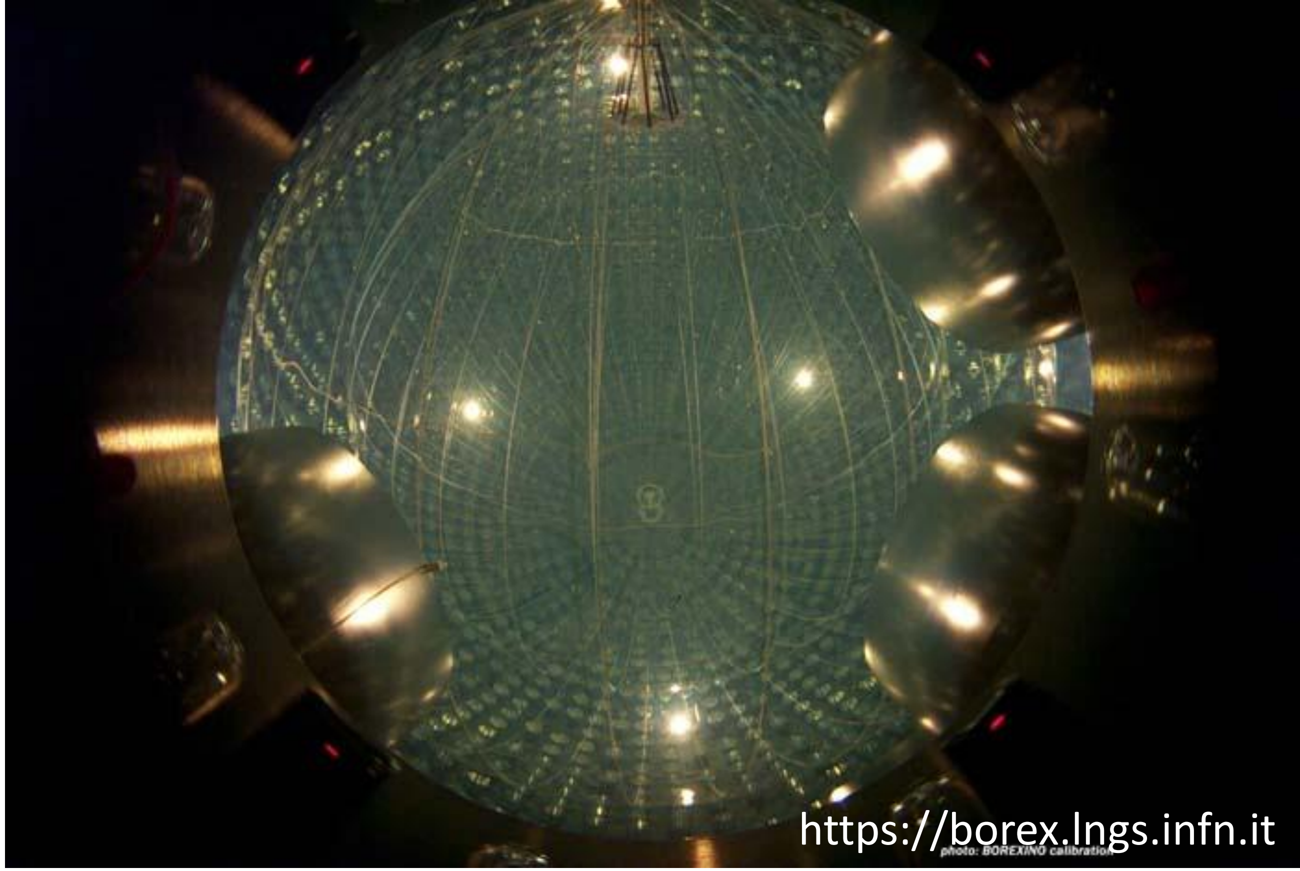
# MSW Effect


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

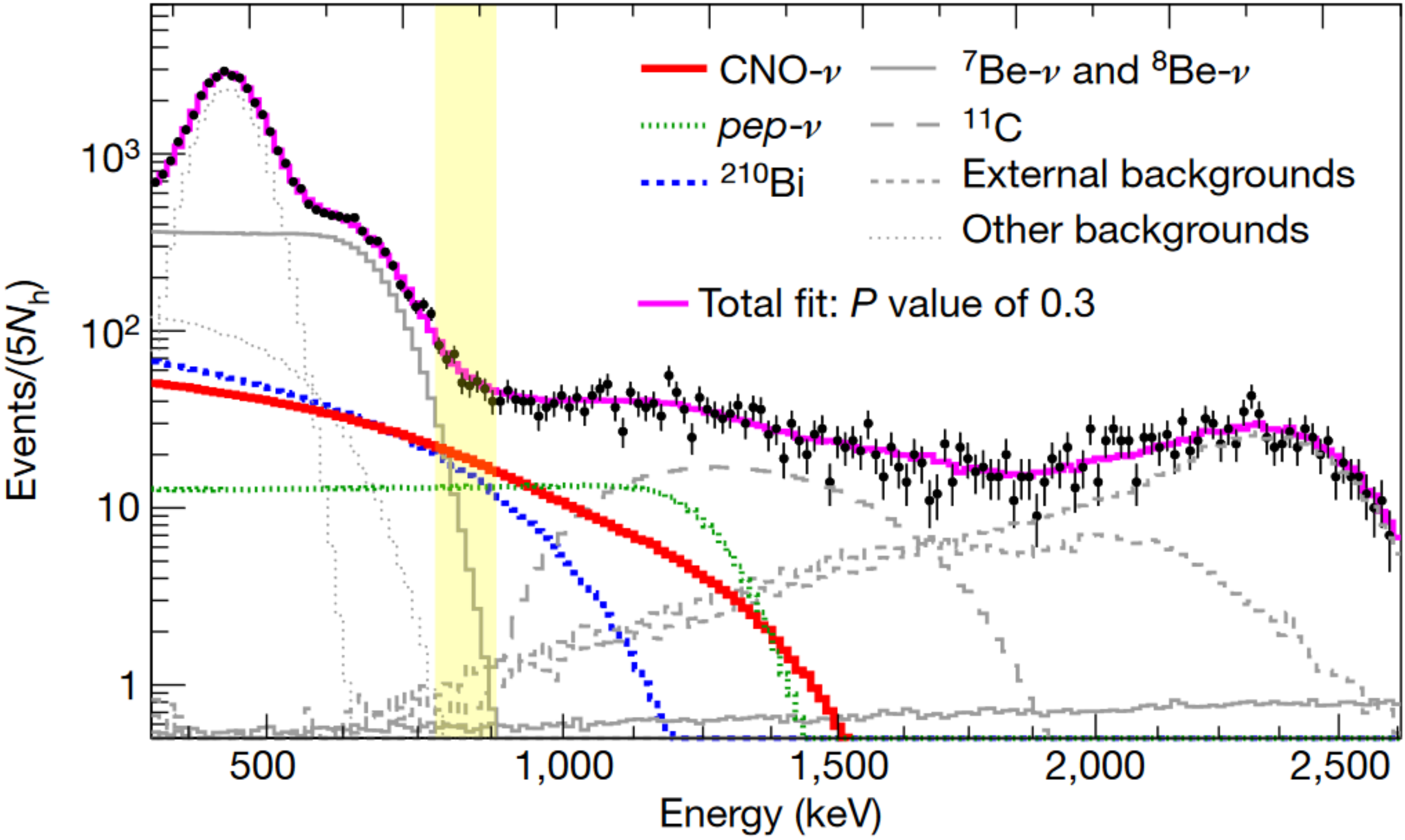
| | KamLAND, Borexino… |
|---|---|
| Target | Liquid scintillator |
| Interaction | $\nu + e^- \rightarrow \nu + e^-$ |
| Detection | Scintillation |


KamLAND (2002-)




Borexino (2007-2021)

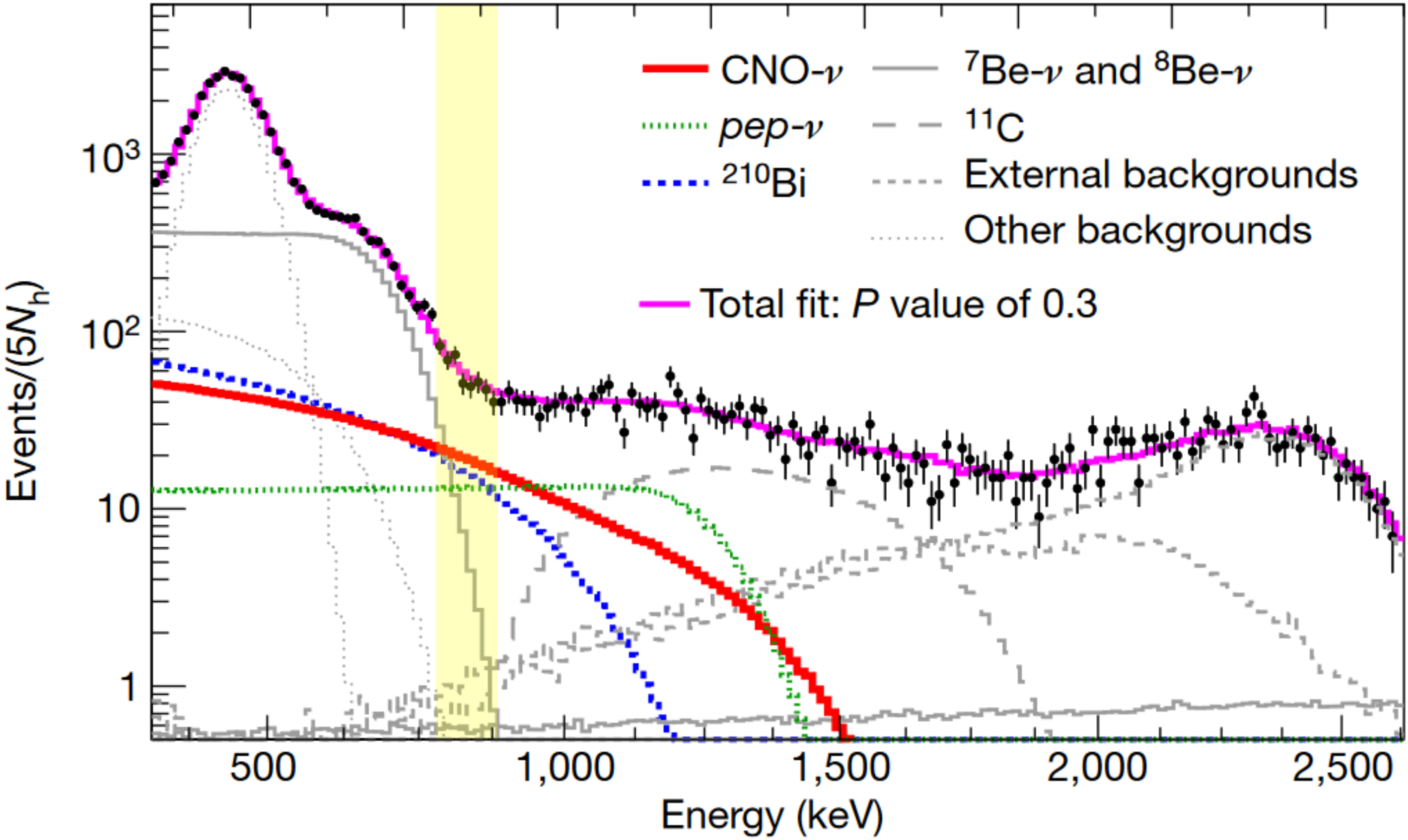
# Borexino Results




Borexino, Nature 587, 577–582 (2020)

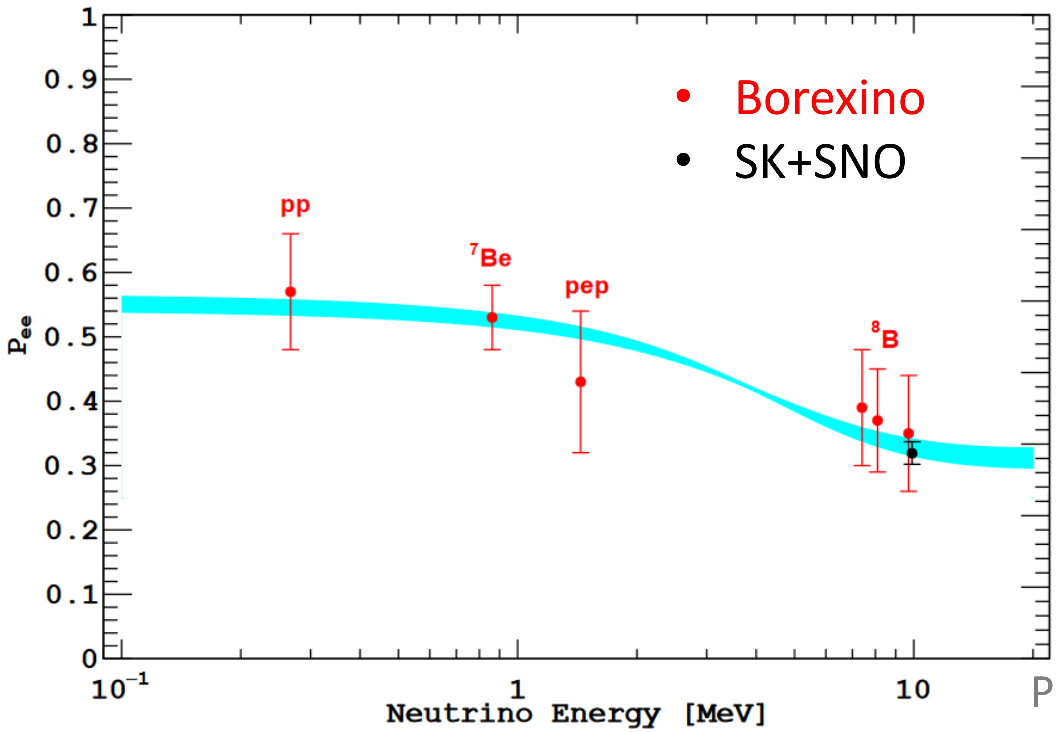
- Discovery of CNO neutrinos in 2020

# Borexino Results




Borexino, Nature 587, 577–582 (2020)

- Discovery of CNO neutrinos in 2020




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

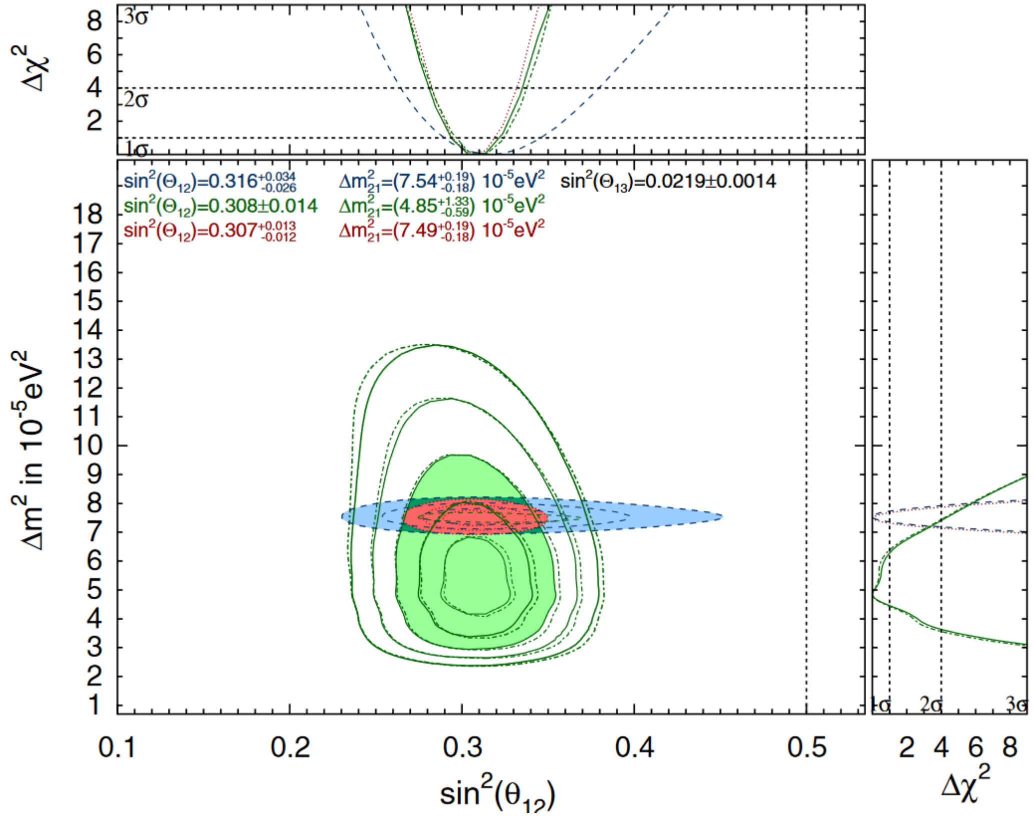
# Looking Forward

- Neutrino oscillation
- Probing the Sun
- …

# Looking Forward

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

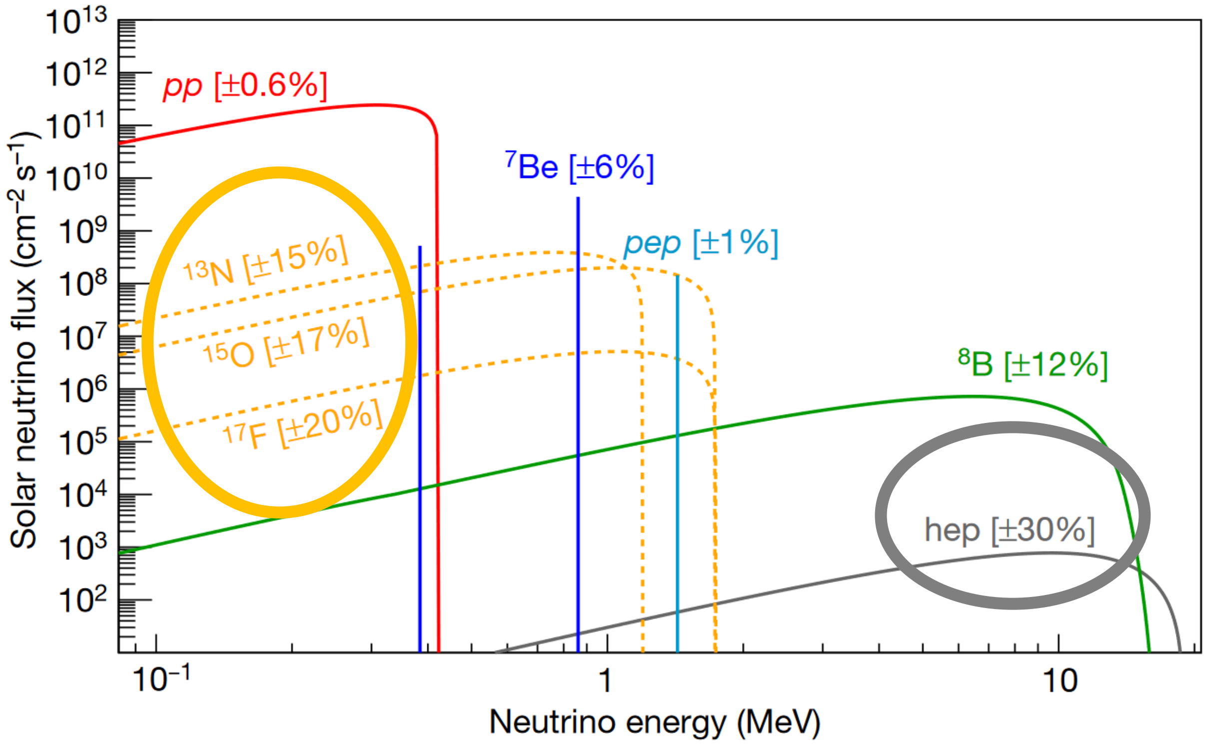
Solar neutrinos (SNO+SK)




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

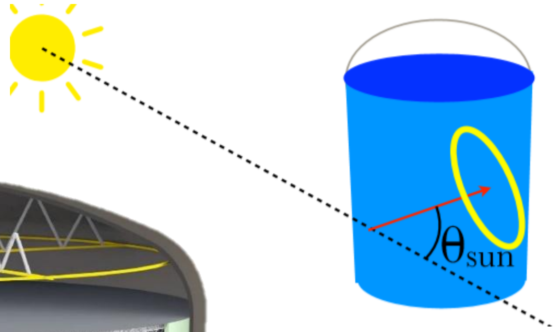
# Looking Forward

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



# Future Detectors

Directional

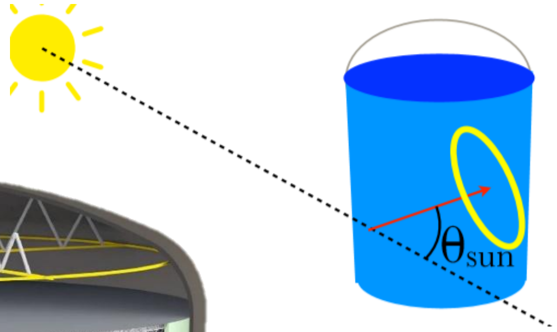


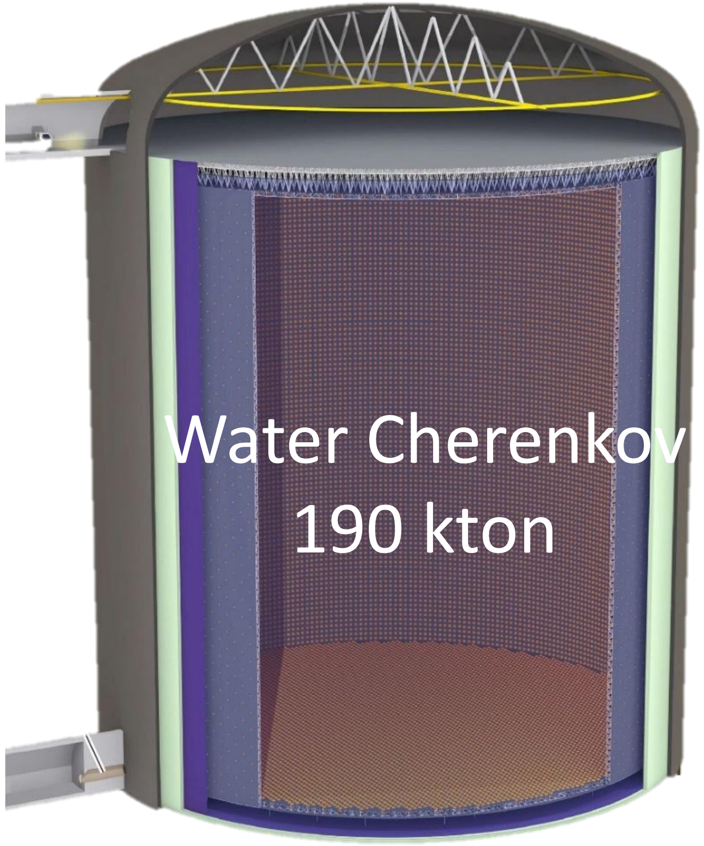


Hyper-Kamiokande

# Future Detectors

Directional



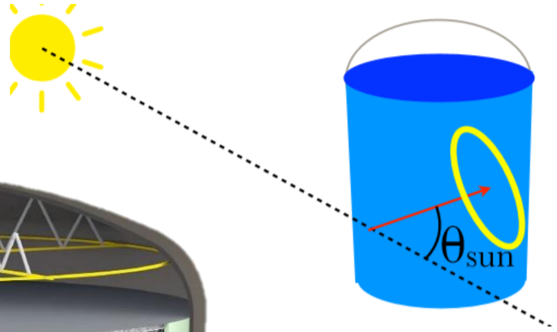



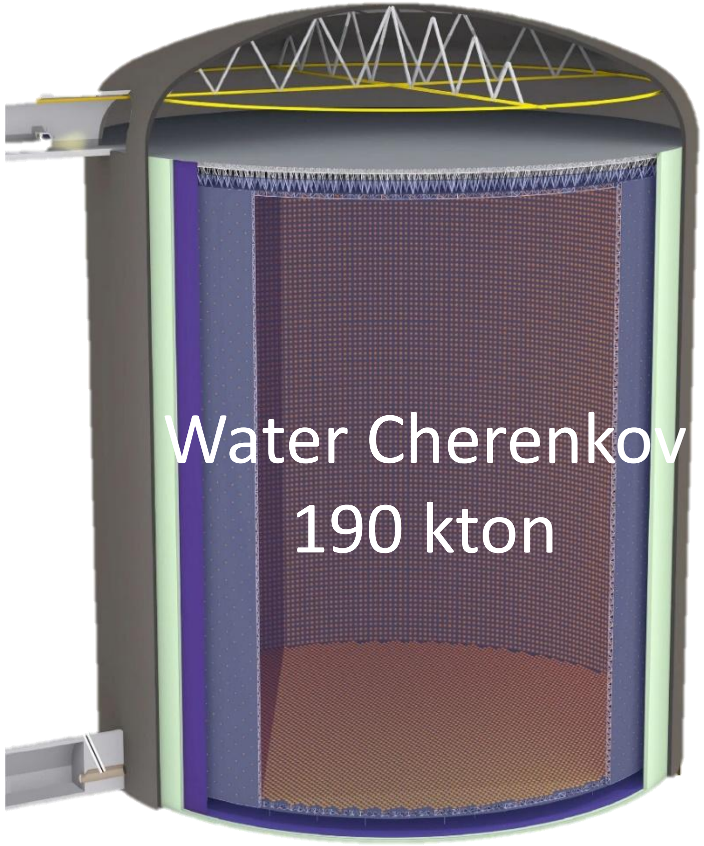

Hyper-Kamiokande

Energy resolution ~3%

# Future Detectors

Directional




Hyper-Kamiokande

THEIA
WbLS

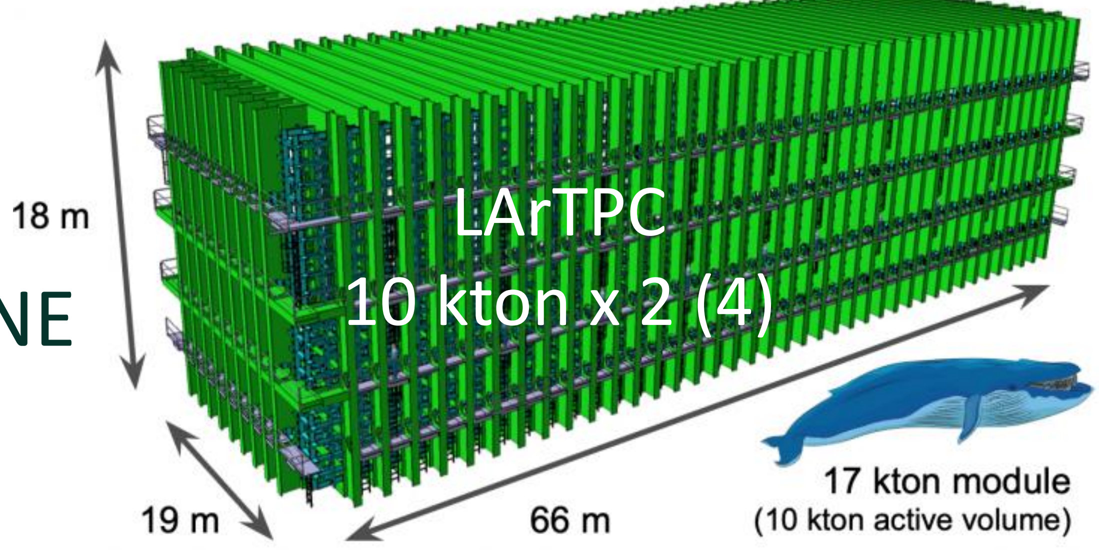
JINPING
NEUTRINO
EXPERIMENT

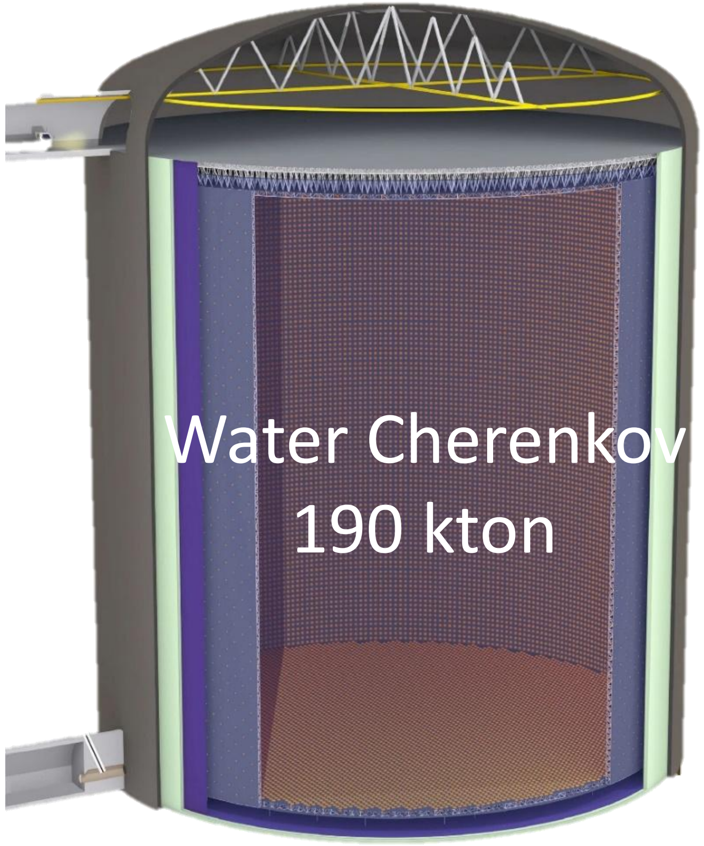
Energy resolution ~3%

# Future Detectors

Charged current
+
Elastic scattering

DUNE



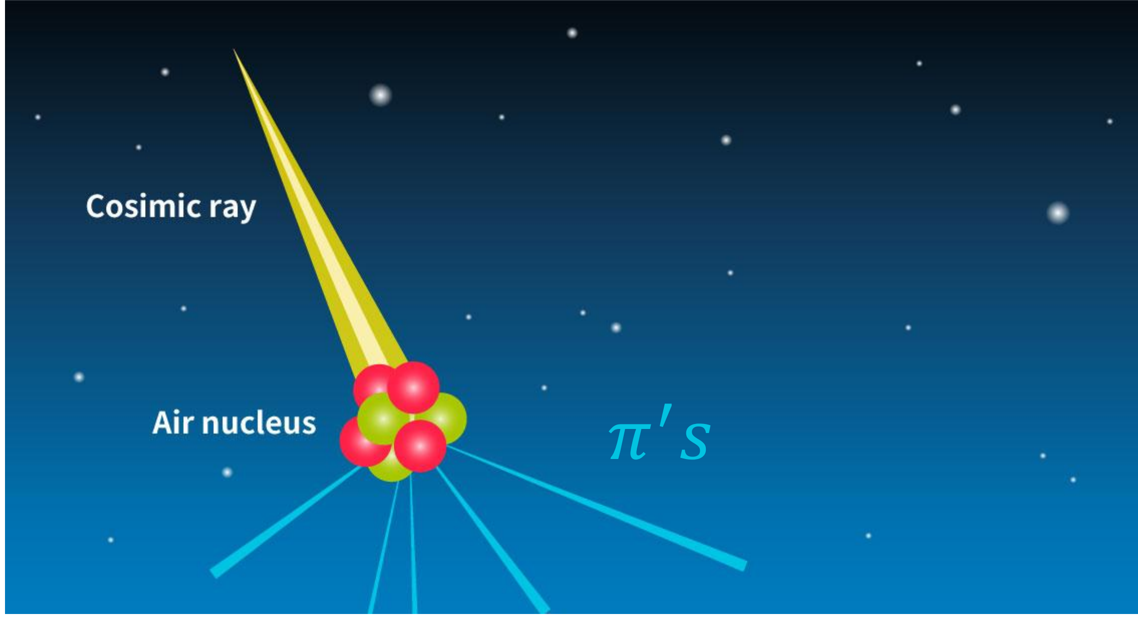

Hyper-Kamiokande

THEIA
WbLS

JINPING
NEUTRINO
EXPERIMENT

# Atmospheric Neutrinos

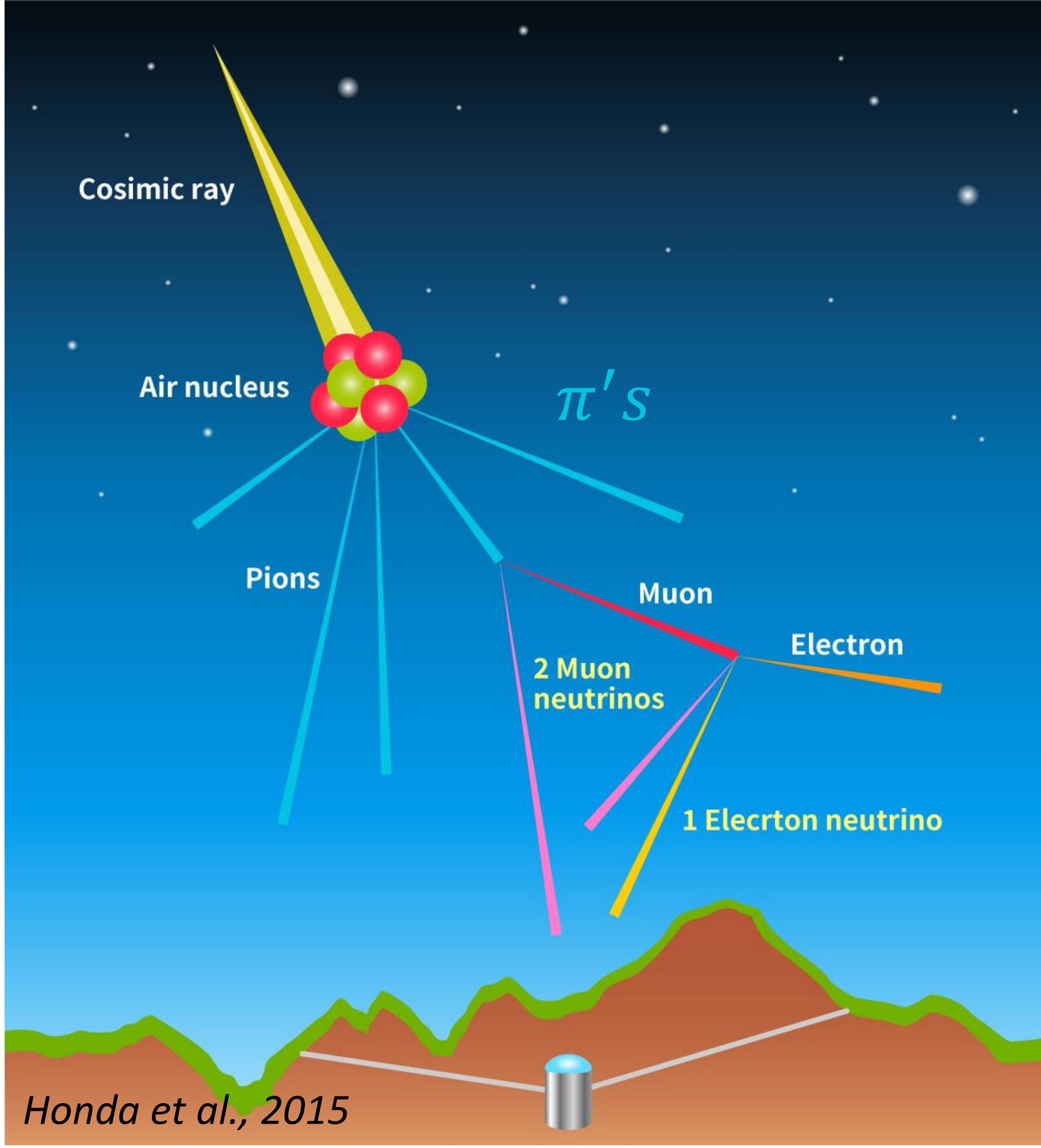
# Atmospheric Neutrinos



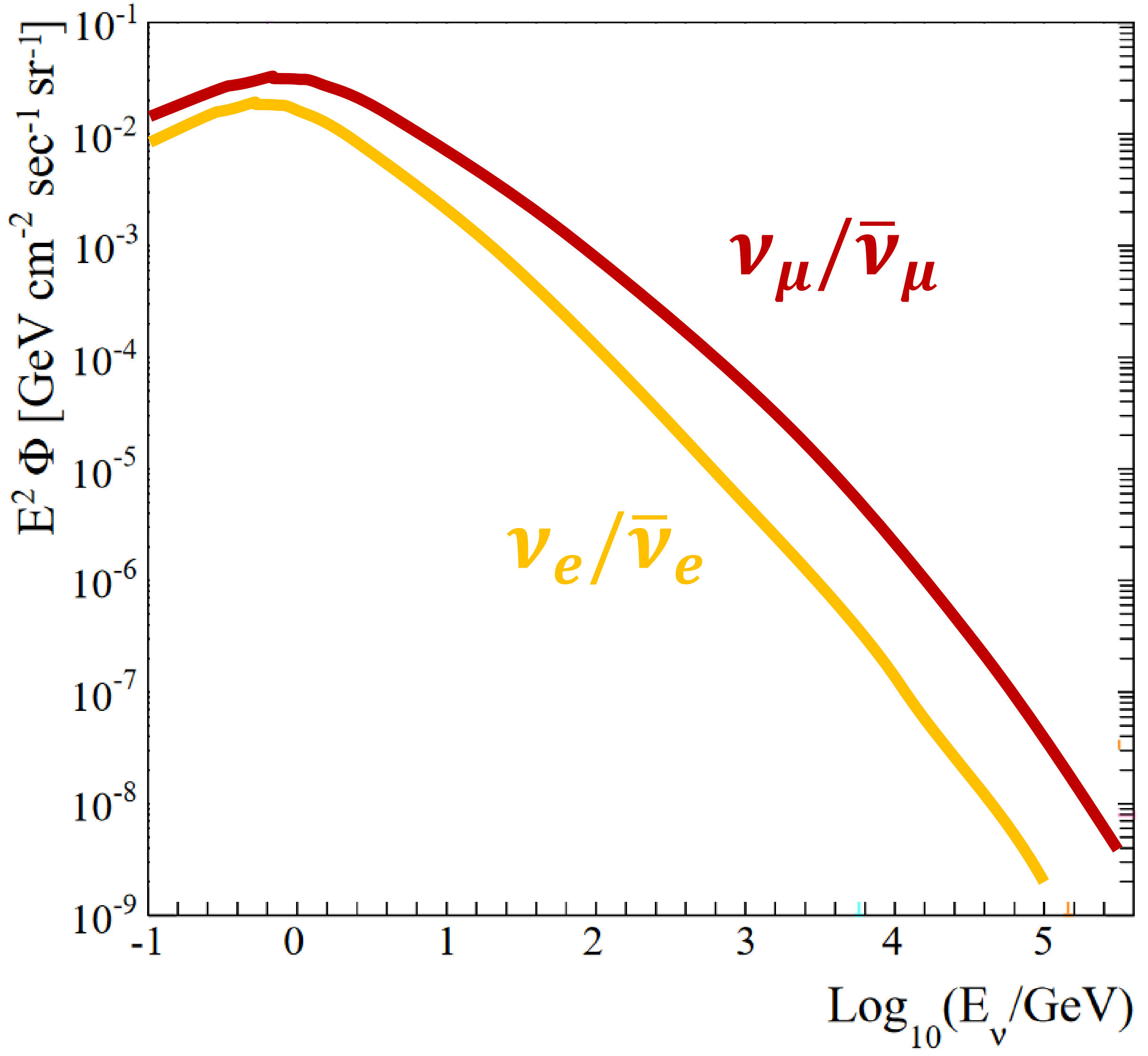
# Atmospheric Neutrinos

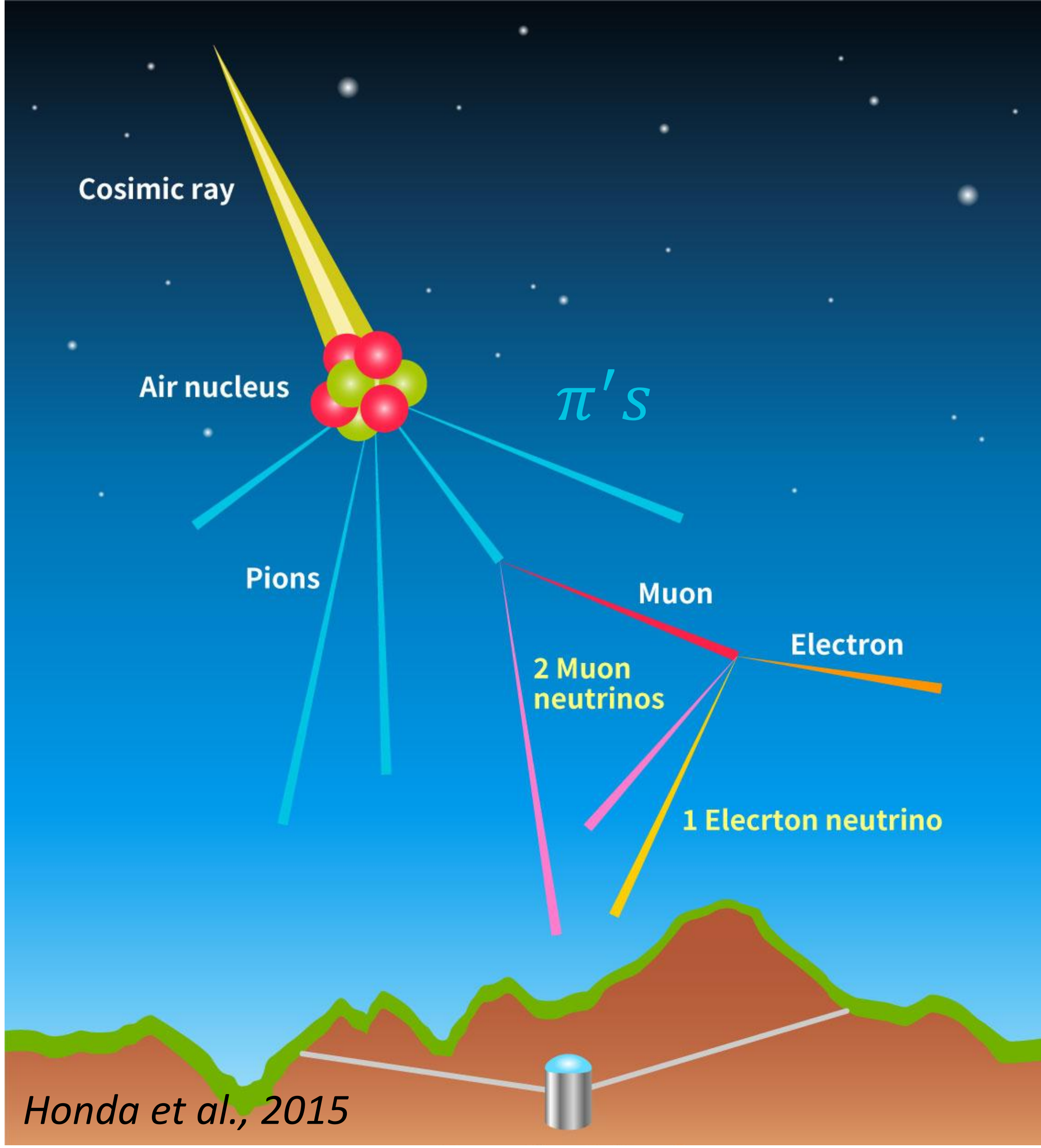
- $\pi^- \rightarrow \bar{\nu}_\mu + \mu^-$
- $\mu^- \rightarrow \nu_\mu + \bar{\nu}_e + e^-$

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

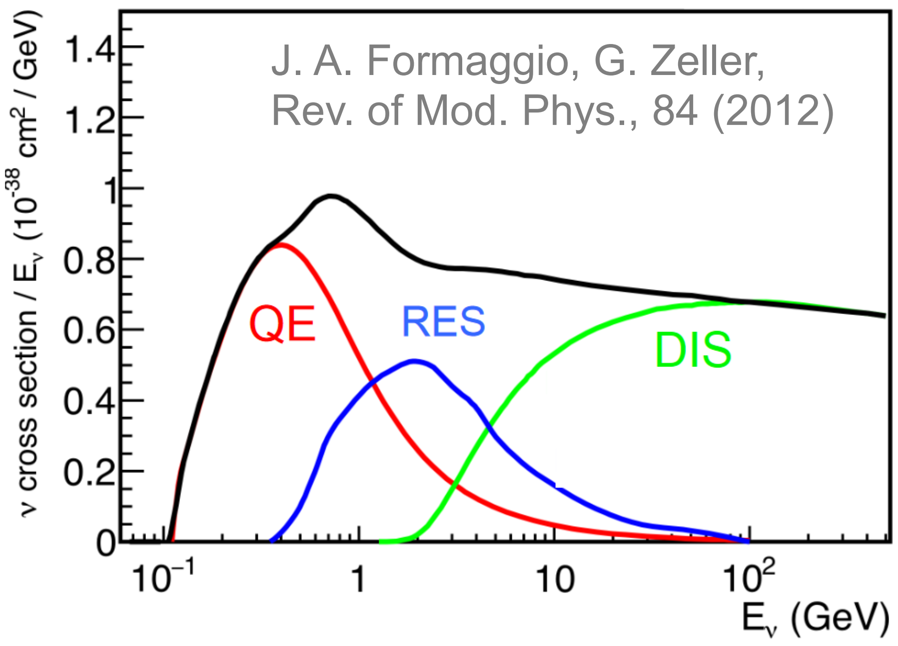


# Atmospheric Neutrinos



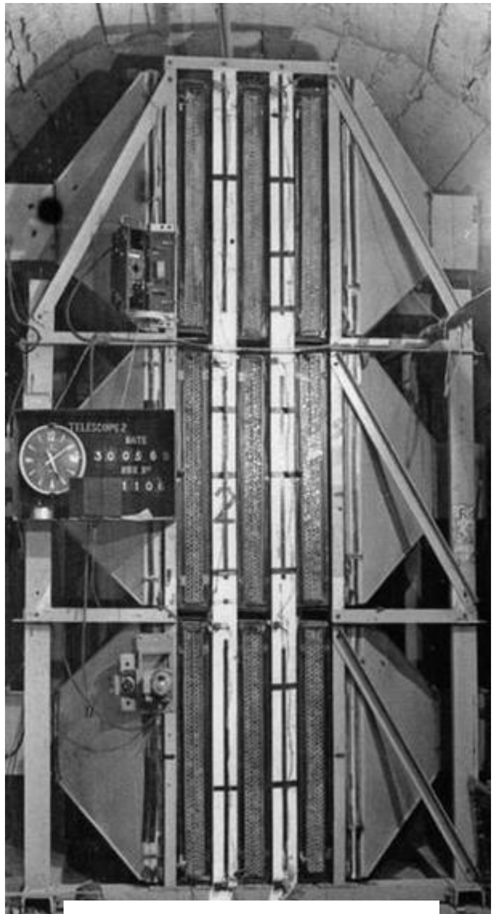



# Neutrino Interaction at GeV



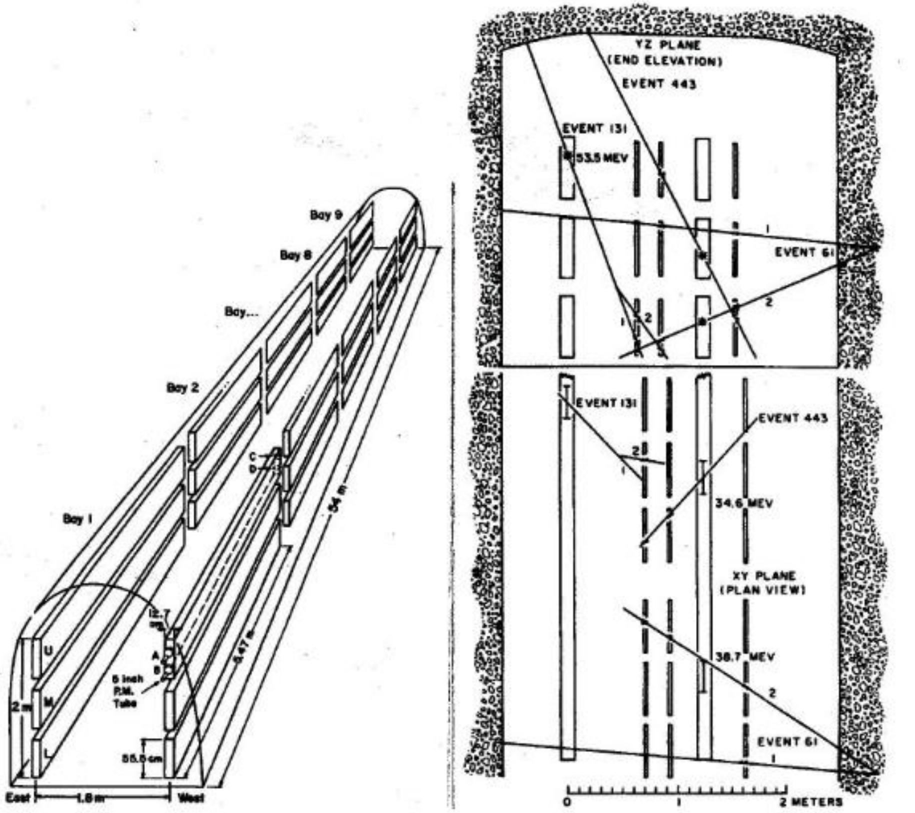

- Main interactions:
  - (Quasi-)Elastic scattering
    - $\nu_l + n \rightarrow l^- + p$ charged current
    - $\bar{\nu}_l + p \rightarrow l^+ + n$ charged current
    - $\nu + p \rightarrow \nu + p$ neutral current
  - Resonant Meson Production
  - Deep inelastic scattering

# First Observations



Kolar Gold Fields

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

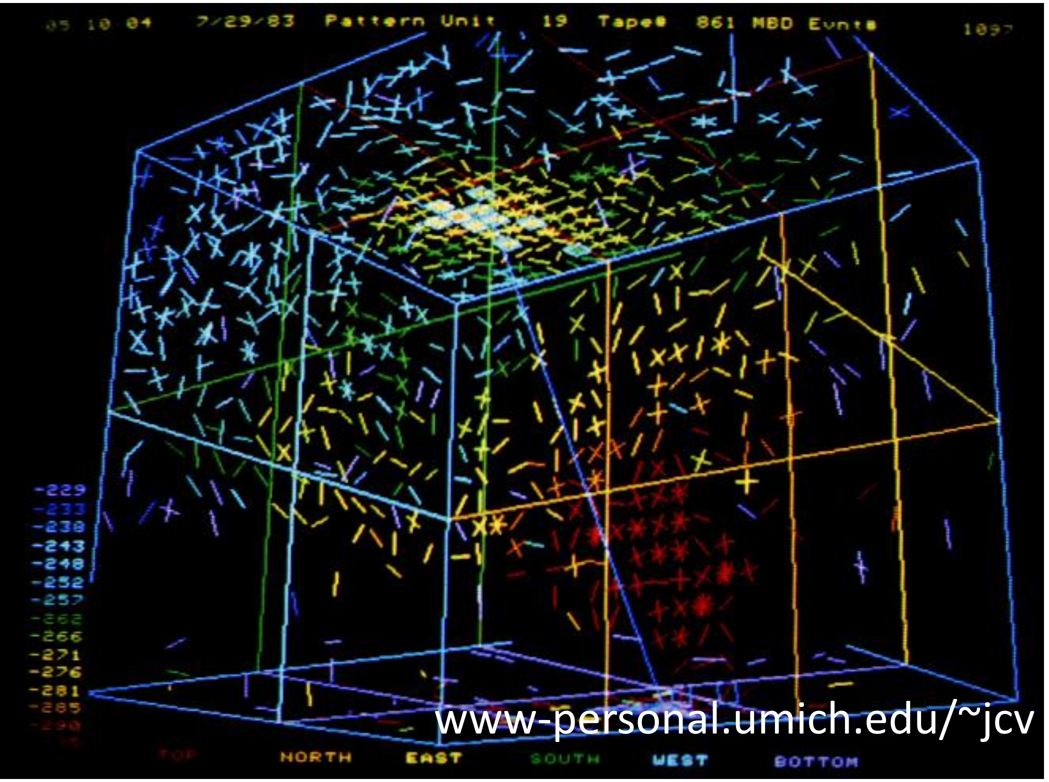



**East Rand Proprietary Mines**

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

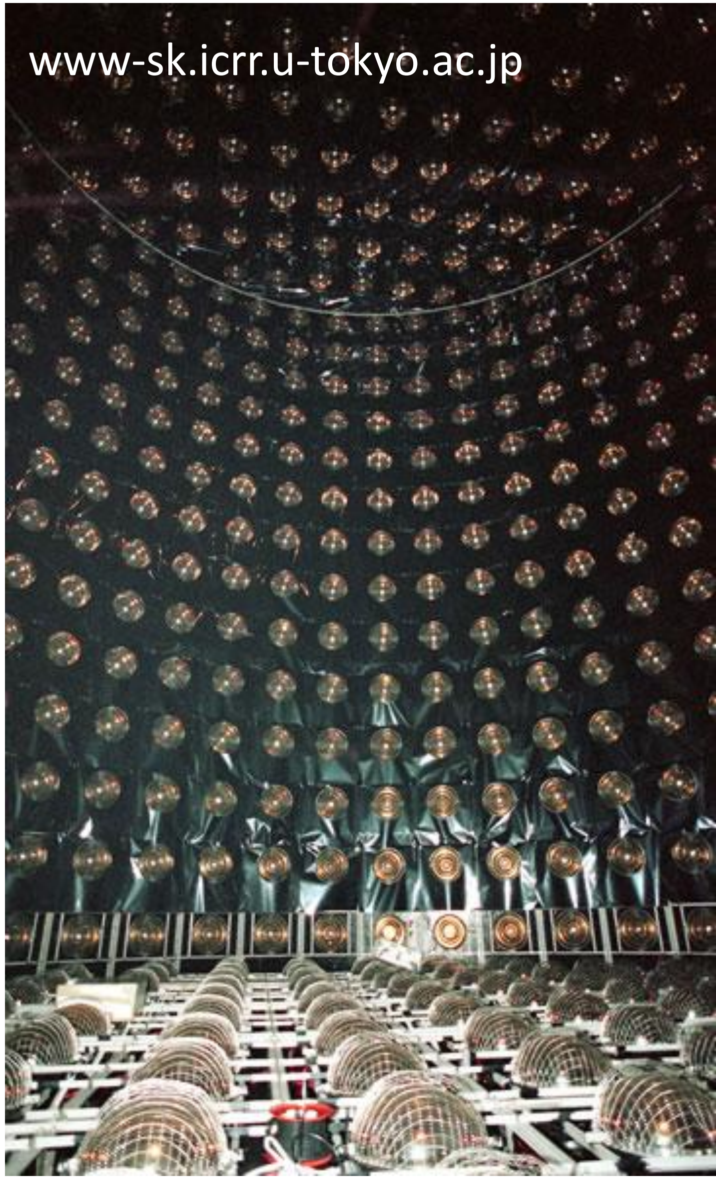
# Detection in Water Cherenkov Detectors




IMB

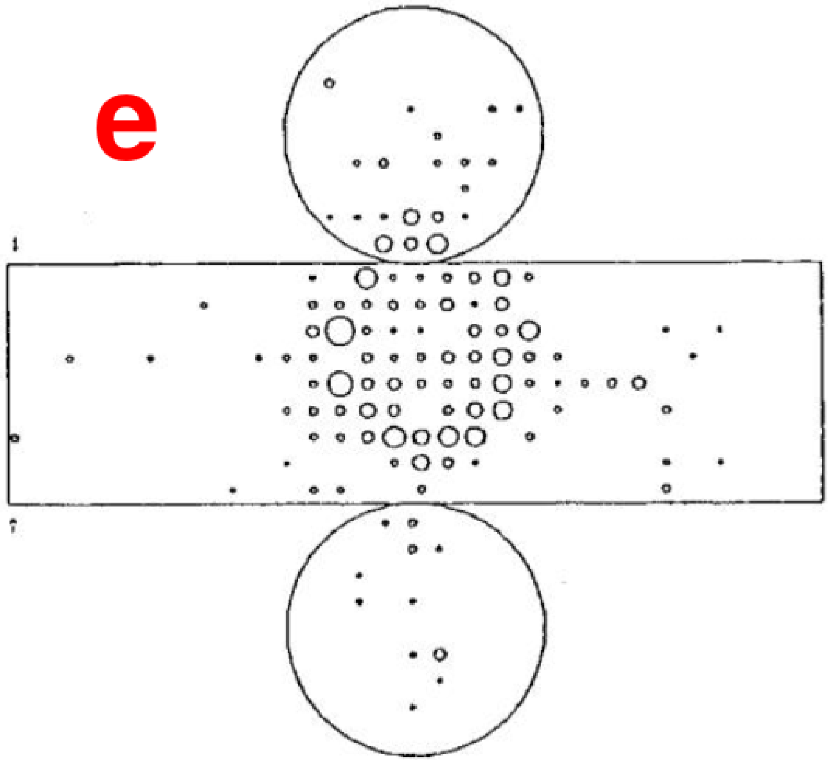
An event display of an upward-going $\nu_\mu$

Kamiokande-II

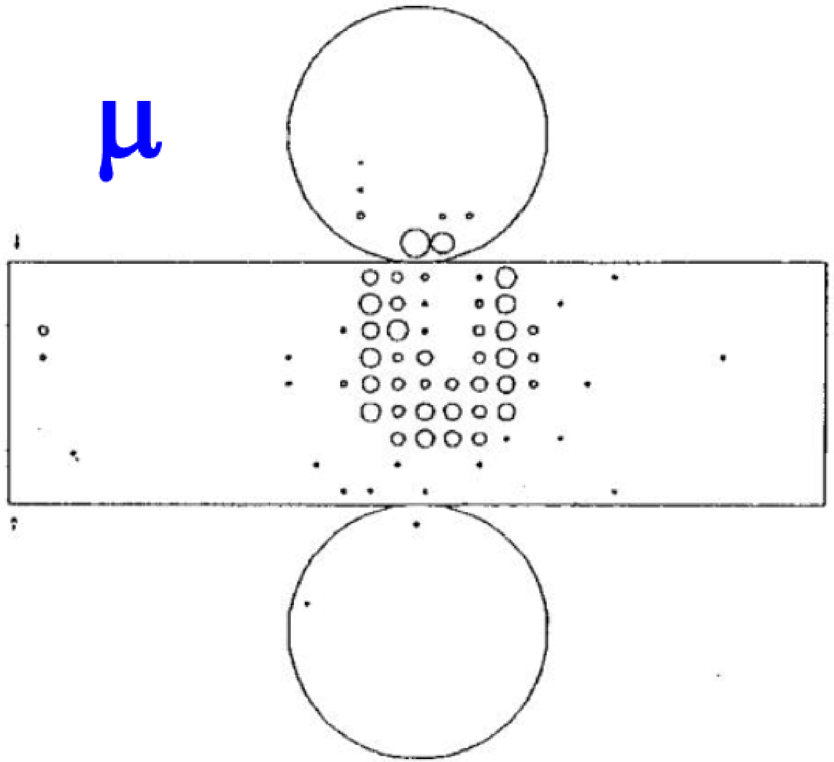


# Particle Identification for $e/\mu$

e



μ



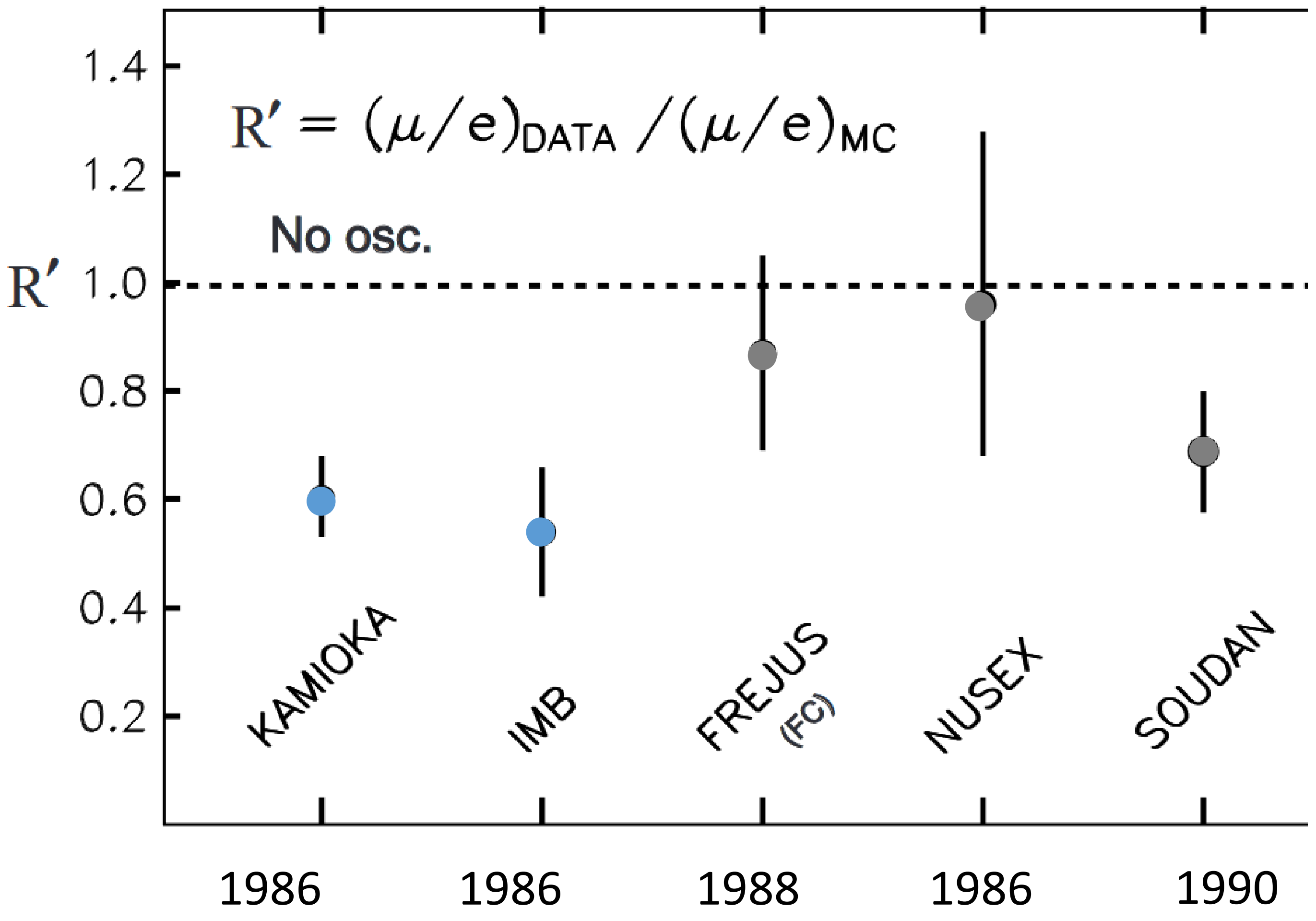
Event display
in KamiokaNDE

Y. Oyama XIV ICFA School On Instrumentation (2017)

Fuzzy ring

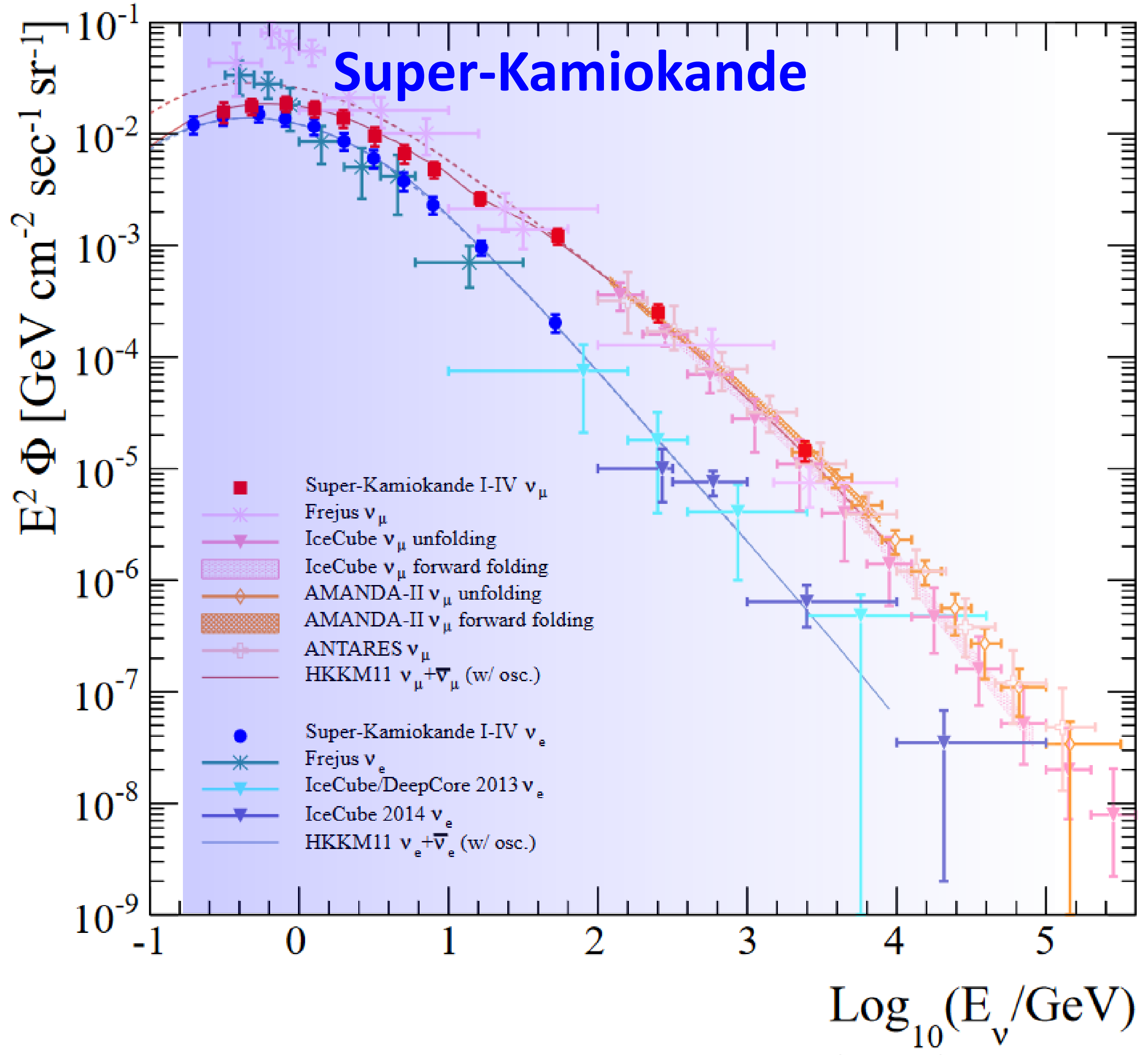
Sharp ring

# Atmospheric Neutrino Anomaly

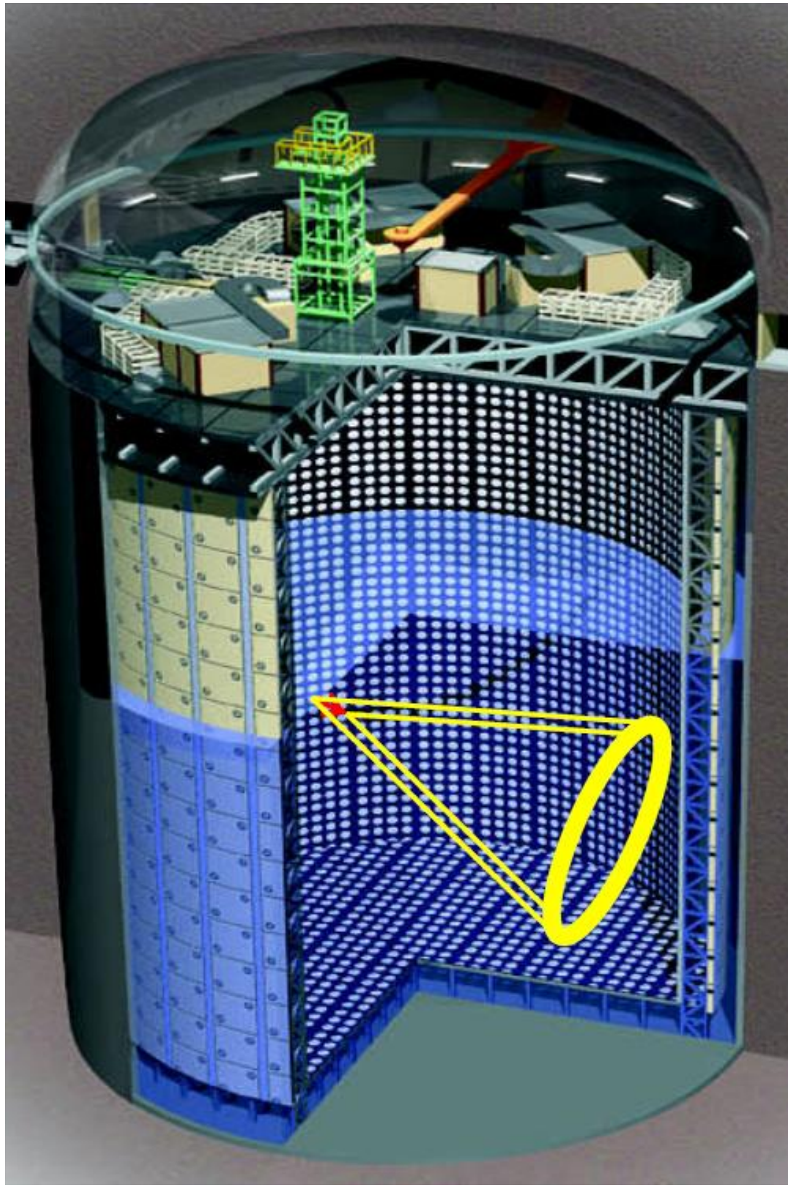



Int.J.Mod.Phys.A 15S1 (2000) 229-256, eConf C990809 (2000) 229-256

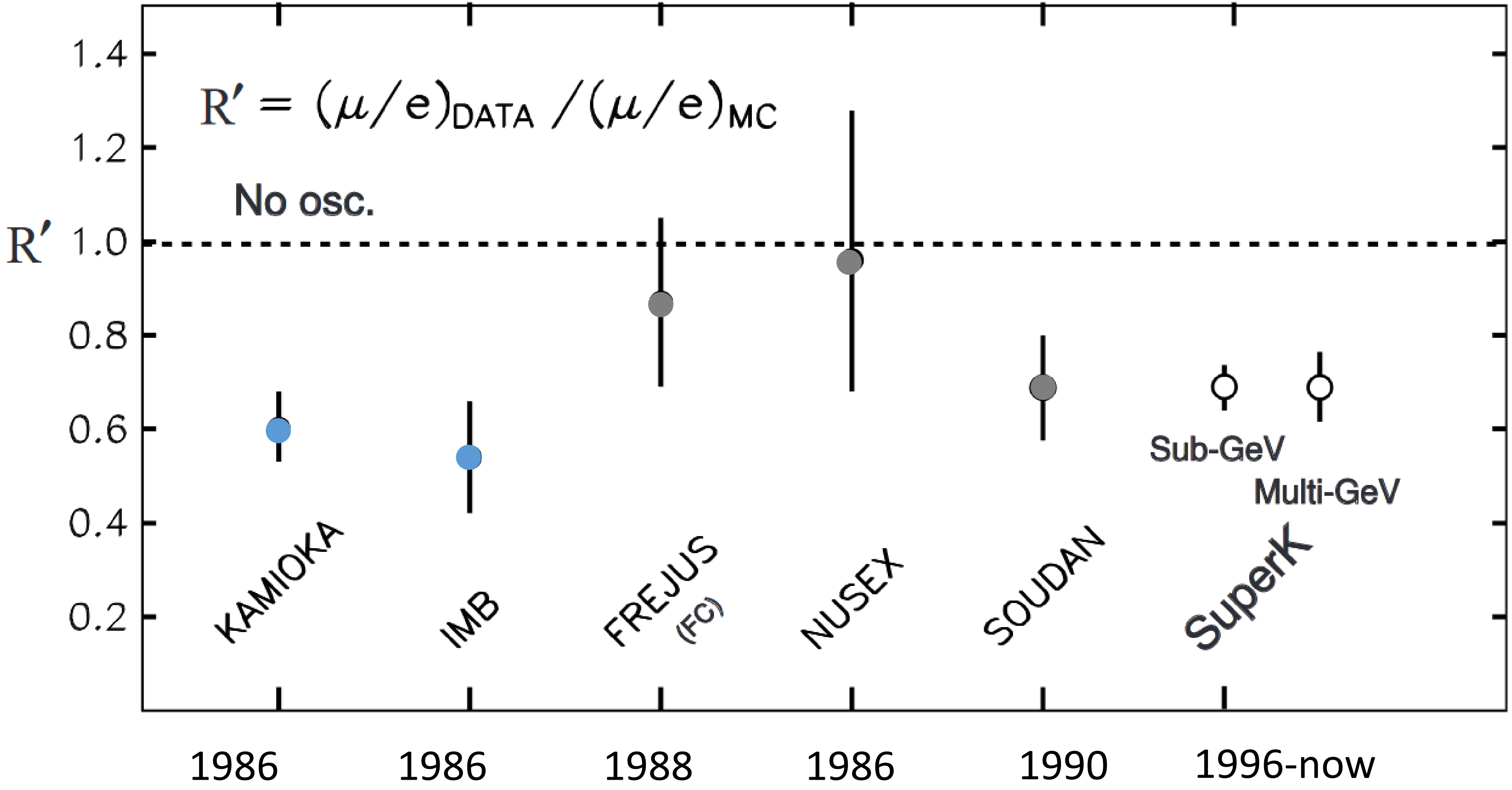
# Detection at Super-Kamiokande




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



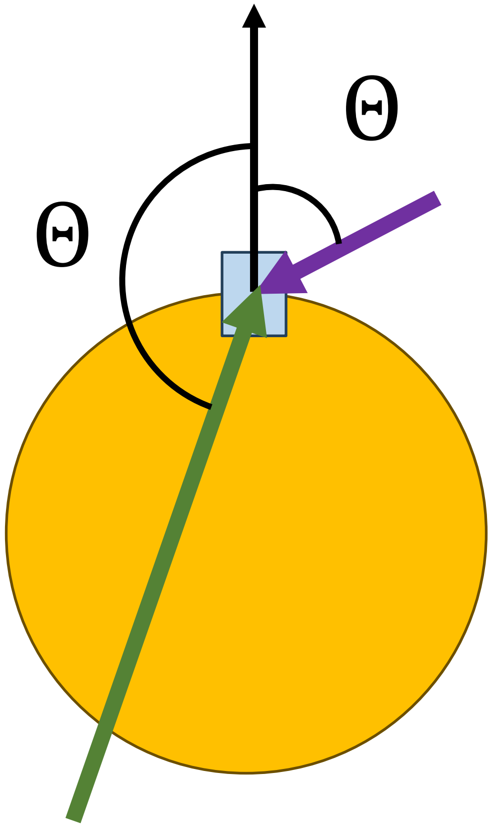
# Atmospheric Neutrino Anomaly with SK

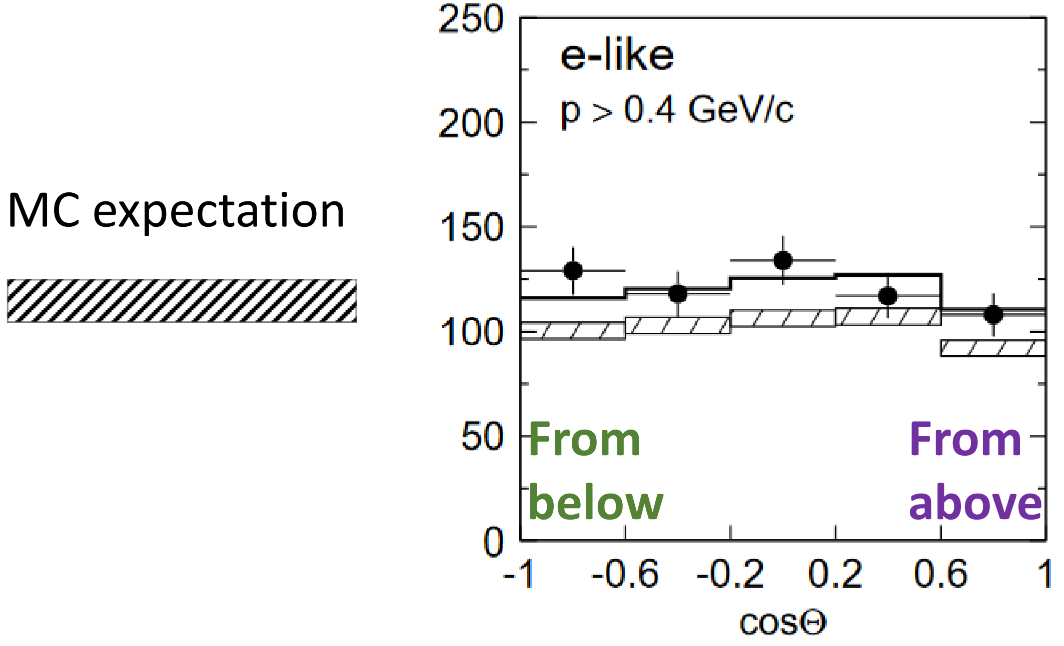



**Deficit in $\nu_\mu/\nu_e$ ratio**

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

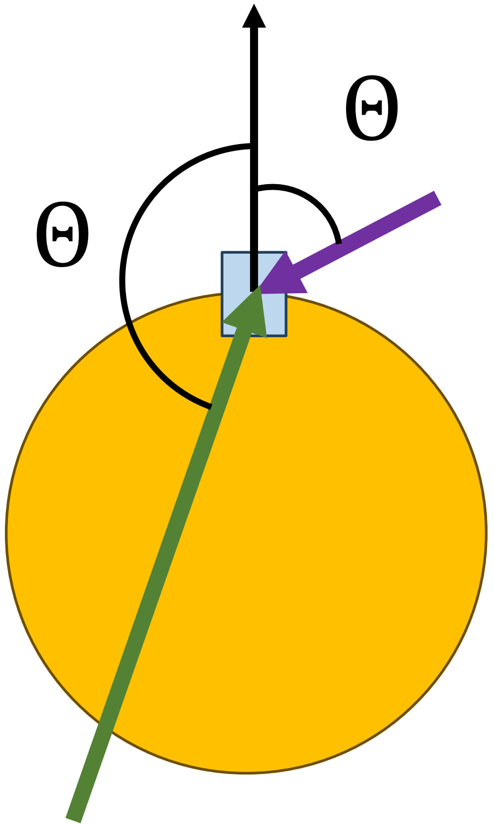
# Zenith Angle Distribution



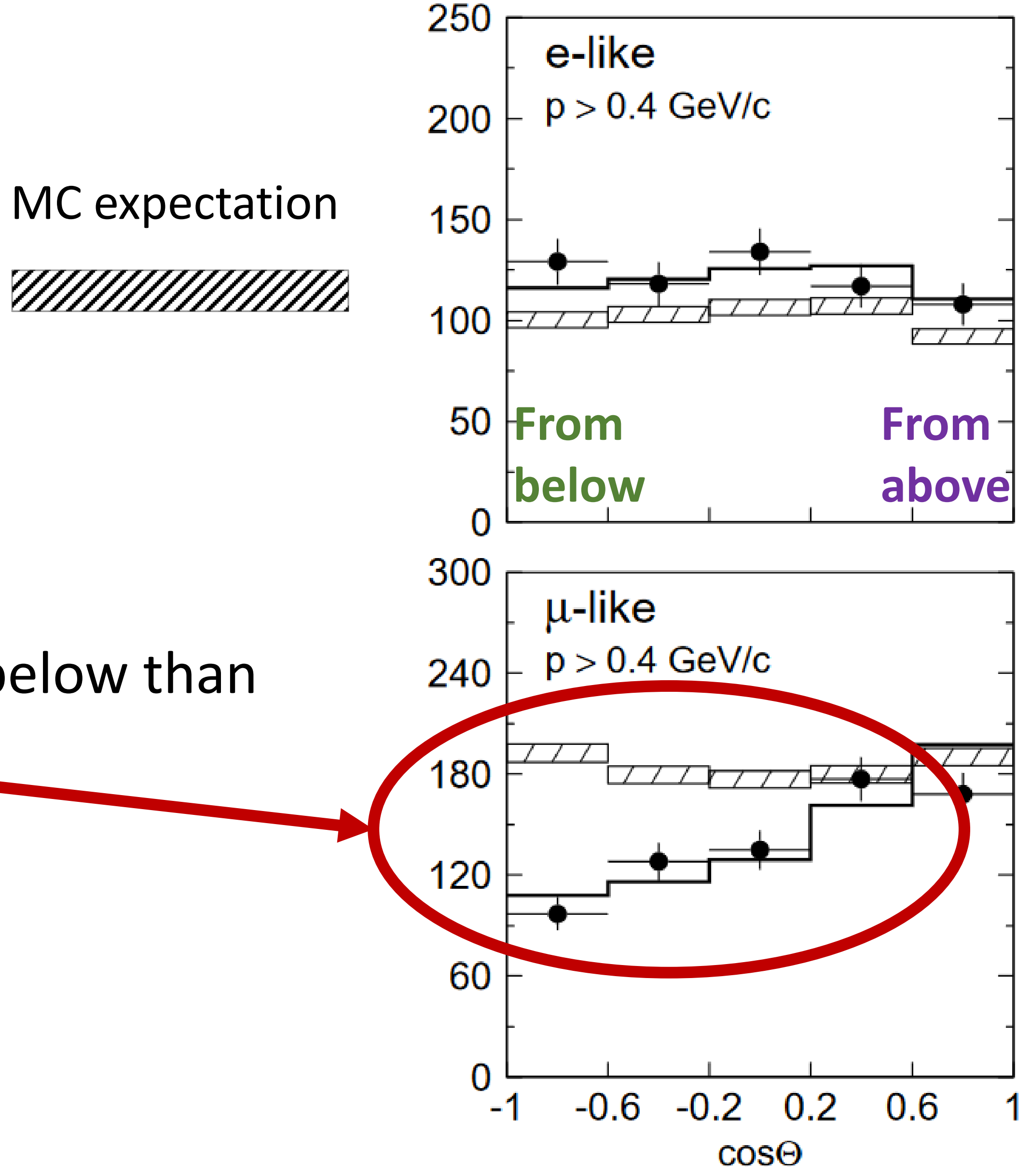




Super-Kamiokande, Phys.Rev.Lett.81:1562-1567 (1998)

# Zenith Angle Distribution



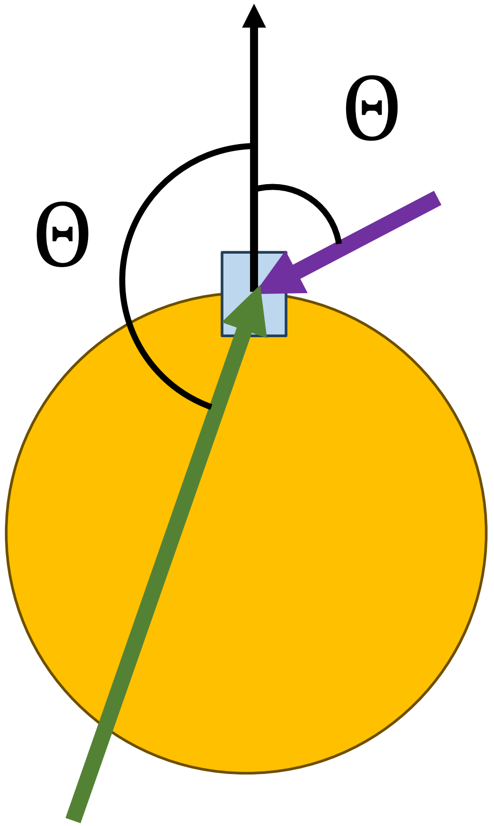

MC expectation




- Fewer $\nu_\mu$ from below than from above

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

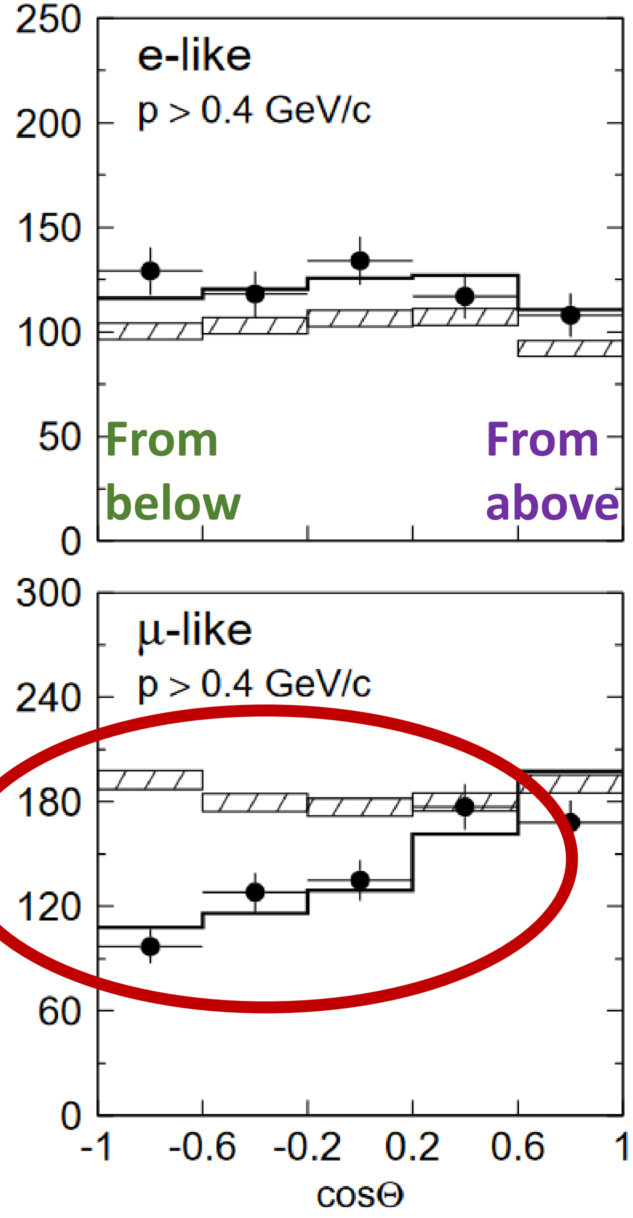
# Zenith Angle Distribution




MC expectation

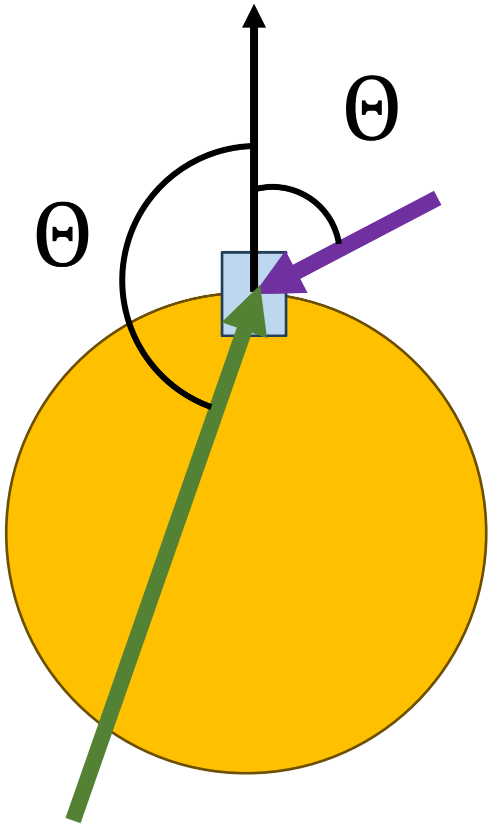
- Fewer $\nu_\mu$ from below than from above

oscillation




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

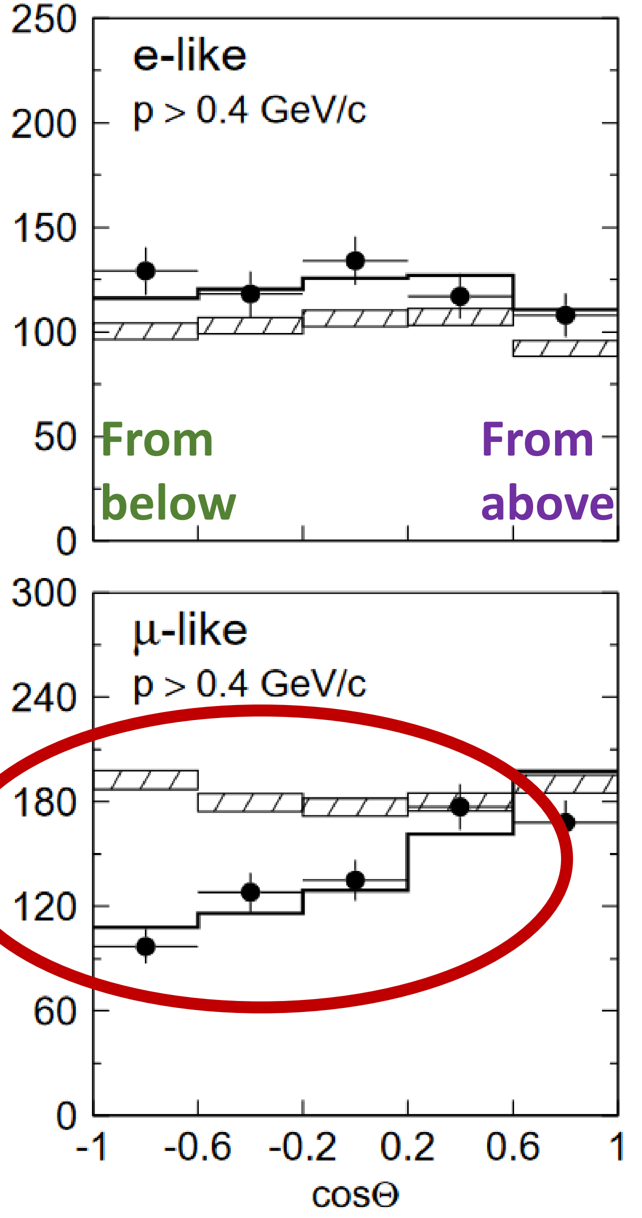
# Zenith Angle Distribution




- Same $\nu_e$ from below as from above

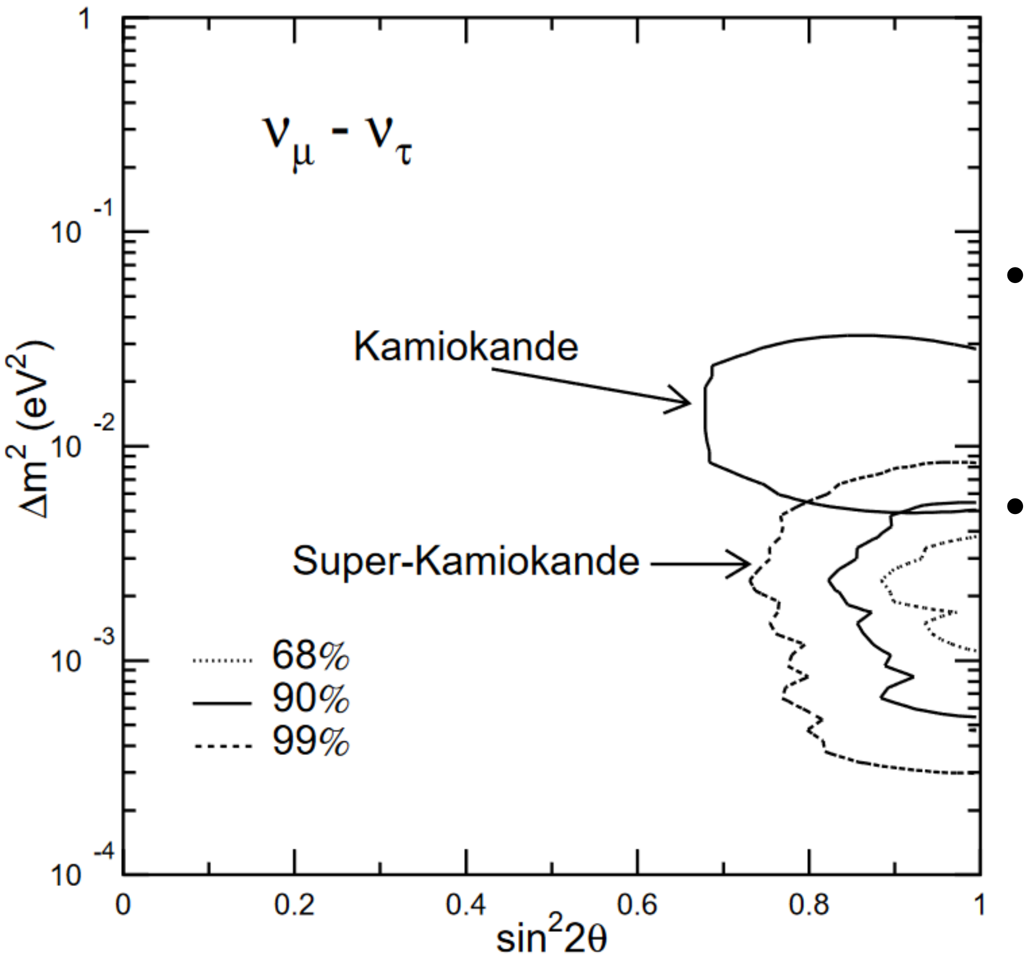
- Fewer $\nu_\mu$ from below than from above

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




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

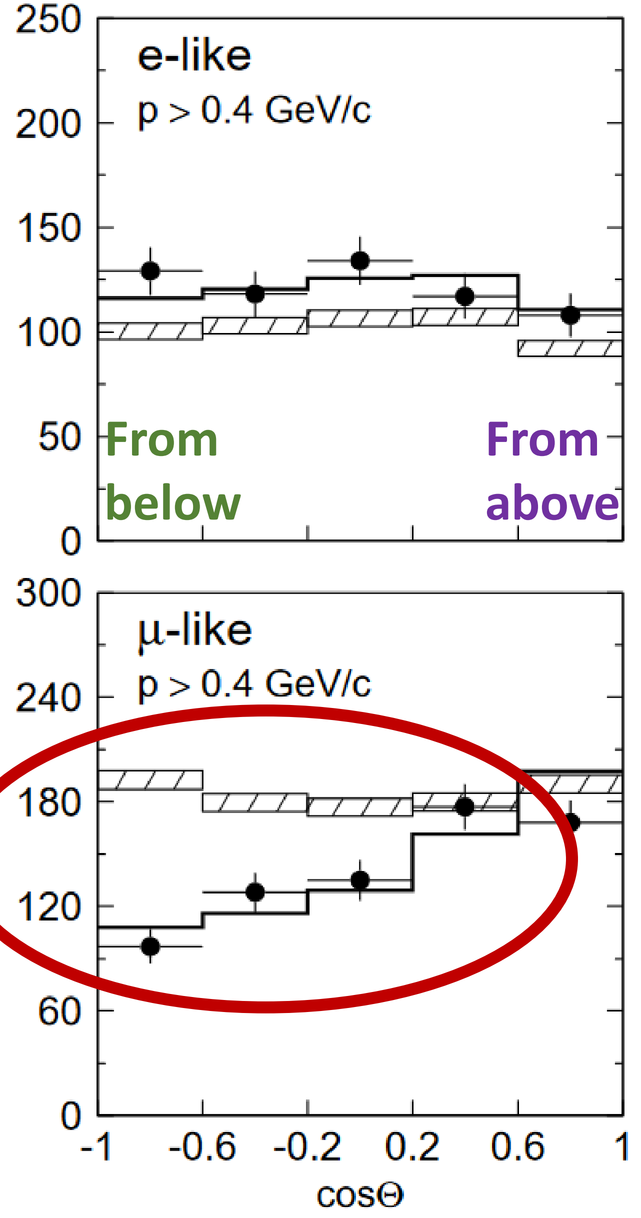
# Atmospheric Mixing Parameters




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

- Same $\nu_e$ from below as from above
- Fewer $\nu_\mu$ from below than from above

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




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

# Neutrino Mixing

Pontecorvo–Maki–Nakagawa–Sakata matrix

$\Delta m^2_{21}$

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

Flavor eigenstate

Atmospheric √ Interference √ Solar √

$\Delta m^2_{32}$

Mass eigenstate

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

# Missing Pieces in Neutrino Mixing

Pontecorvo–Maki–Nakagawa–Sakata matrix

**CP violation**

$\Delta m^2_{21}$

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

$\Delta m^2_{32}$

Flavor eigenstate

Atmospheric √

Interference √

Solar √

Mass eigenstate

**Mass Ordering**

# Mass Ordering

Pontecorvo–Maki–Nakagawa–Sakata matrix

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

$\Delta m^2_{21}$

$\Delta m^2_{32}$

Flavor eigenstate

Atmospheric √

Interference √

Solar √

Mass eigenstate

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

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

Mass Ordering

# Mass Ordering

Pontecorvo–Maki–Nakagawa–Sakata matrix

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

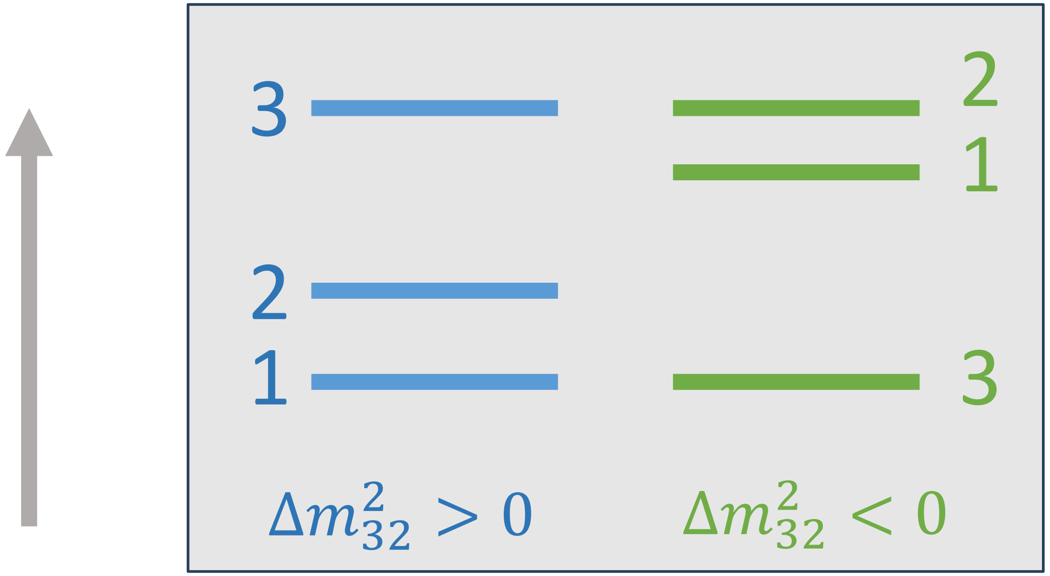
$\Delta m^2_{21}$

$\Delta m^2_{32}$

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

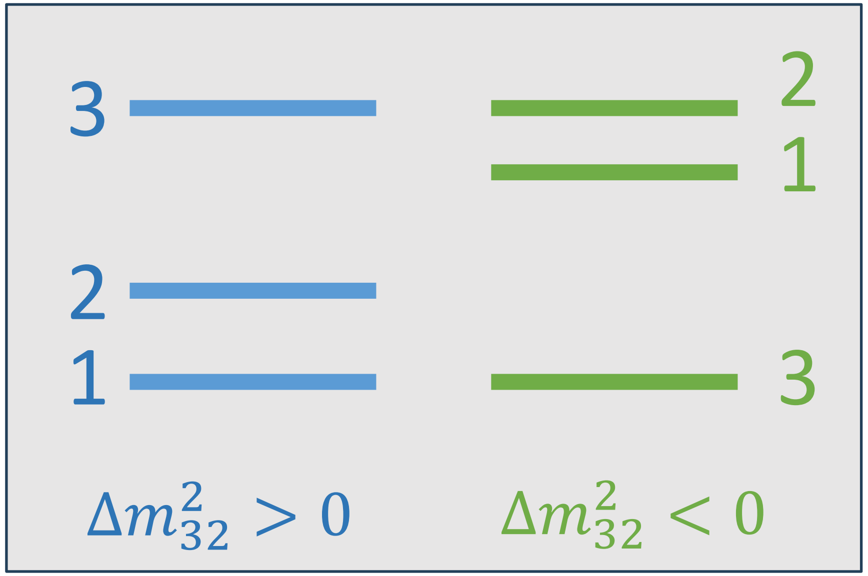
Atmospheric

$\Delta m^2_{21}$

$\Delta m^2_{32}$

Mass eigenstate

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



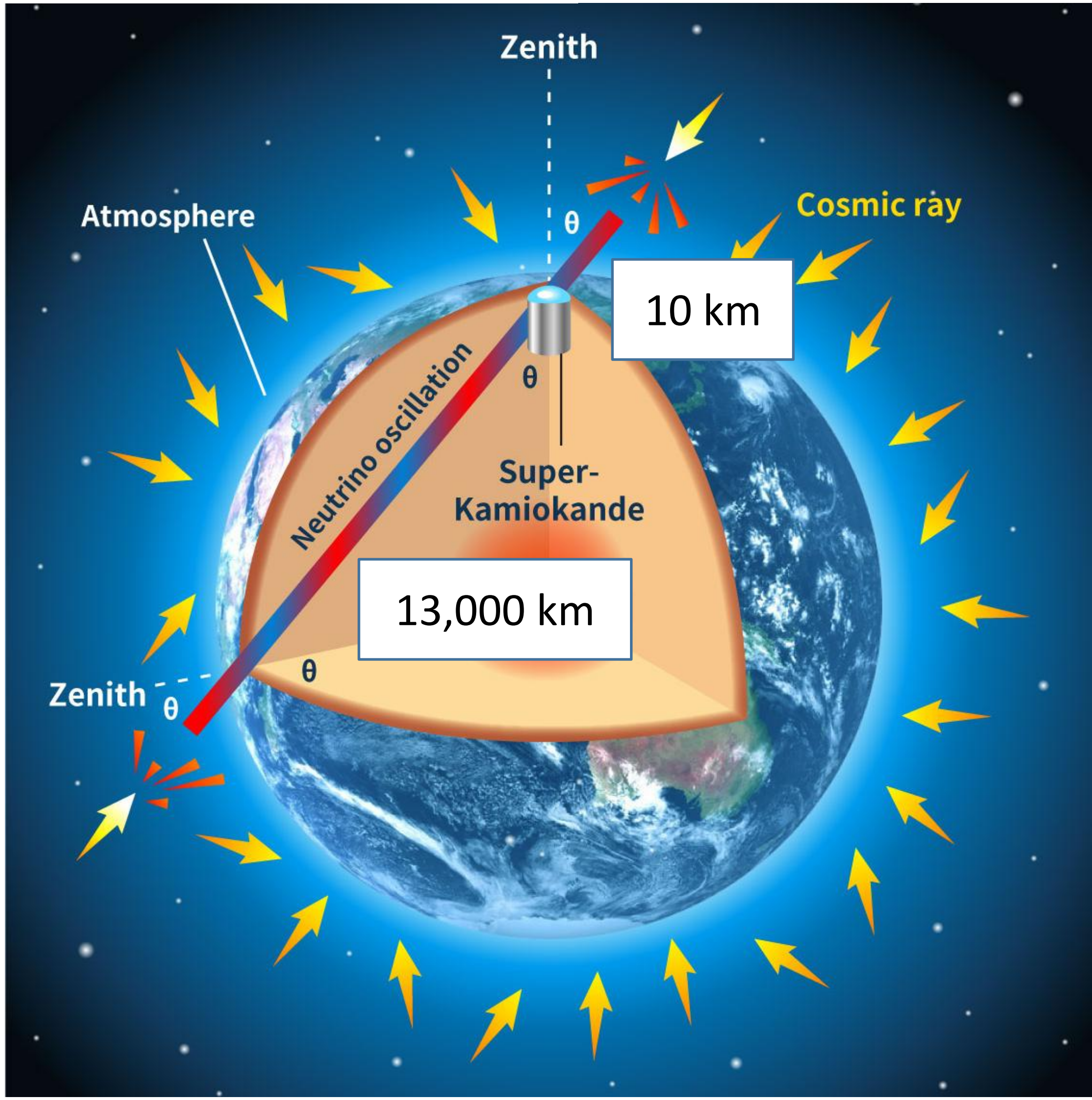

Normal Inverted

**Mass Ordering**

# Atmospheric Neutrino Propagation

$H_V$

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

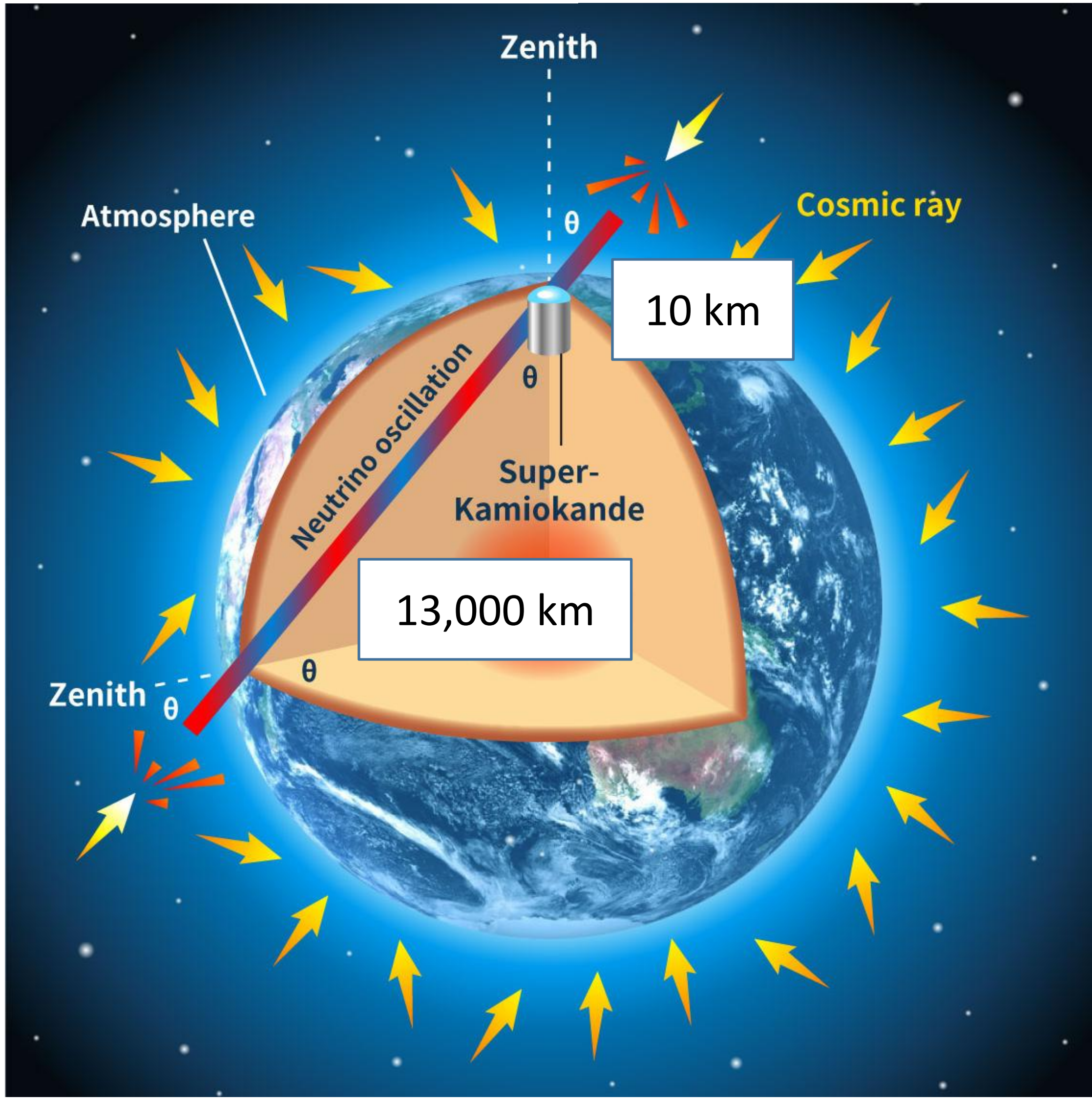


# Atmospheric Neutrino Propagation

$H_V$

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

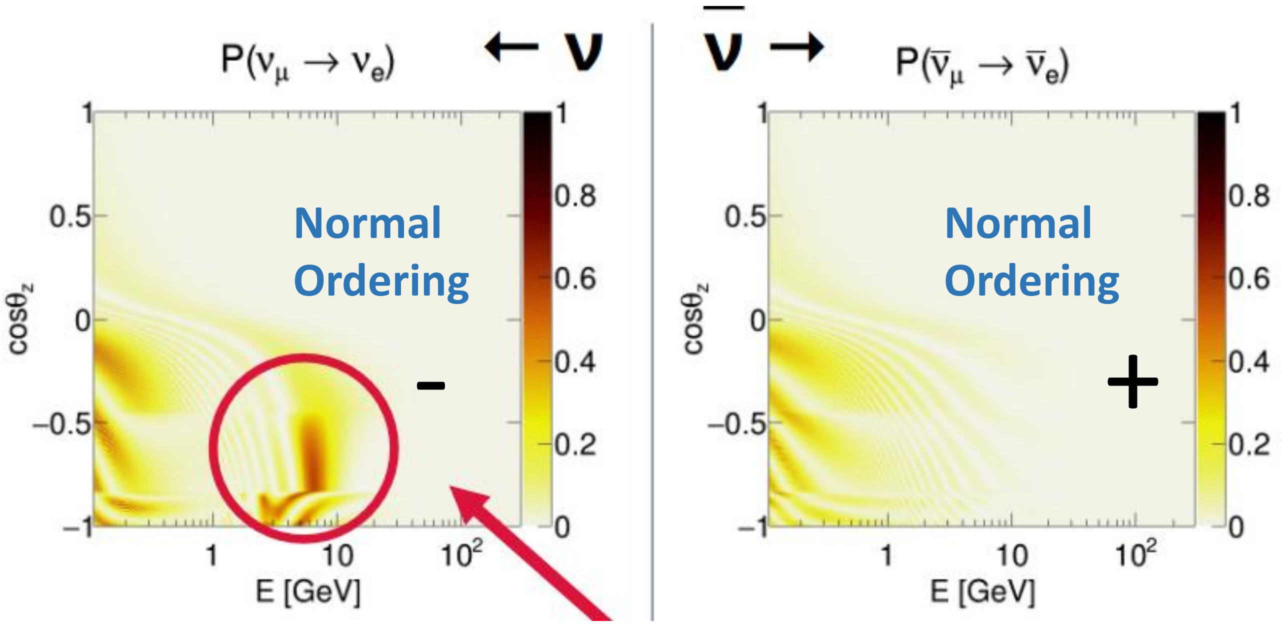
$$H_M = H_V + U^\dagger \begin{pmatrix} \sqrt{2} G_F N_e & \\ & 0 \end{pmatrix} U$$



# Mass Ordering

- Assume $\Delta m^2 > 0$

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



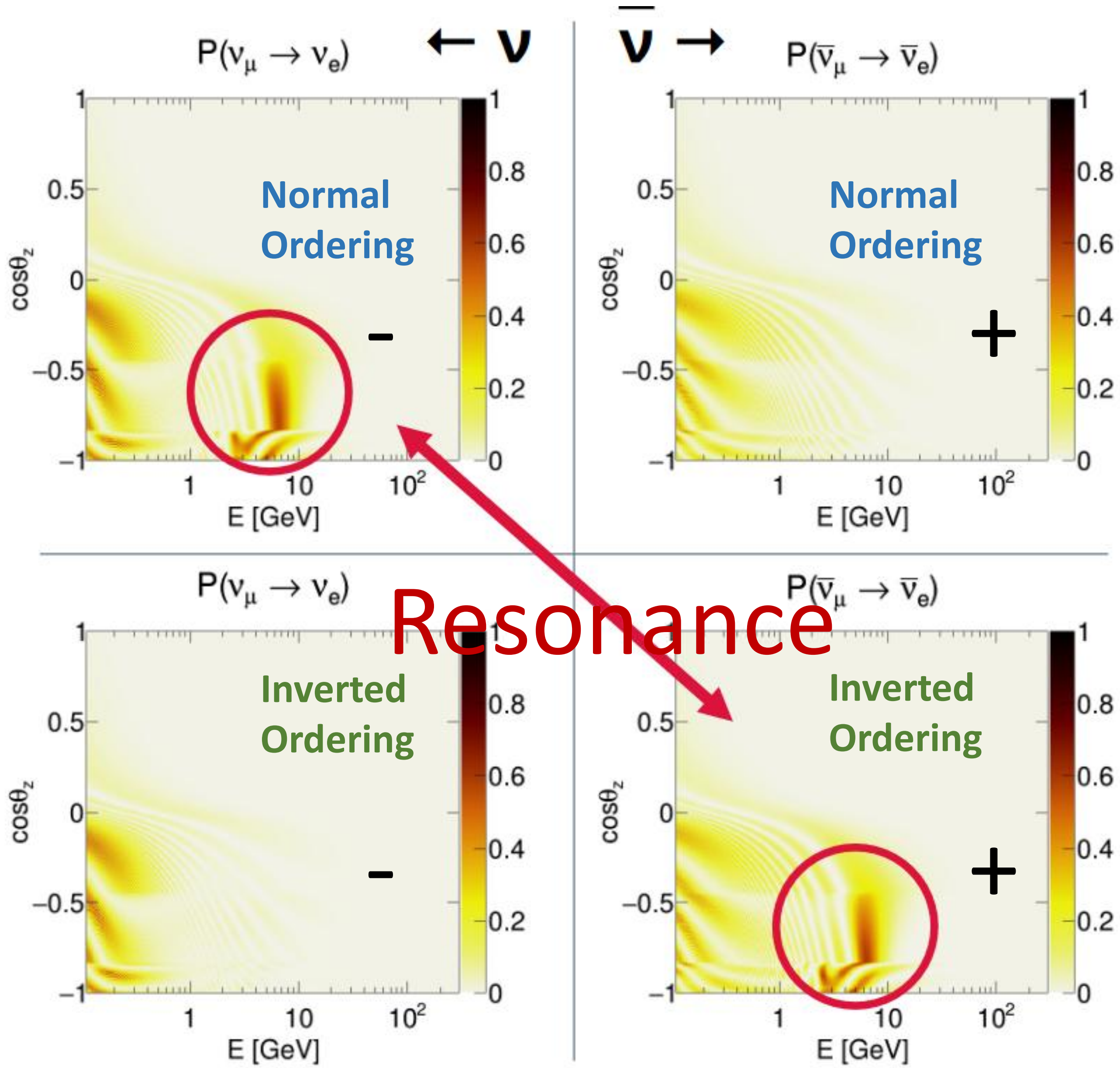

Resonance

# Mass Ordering

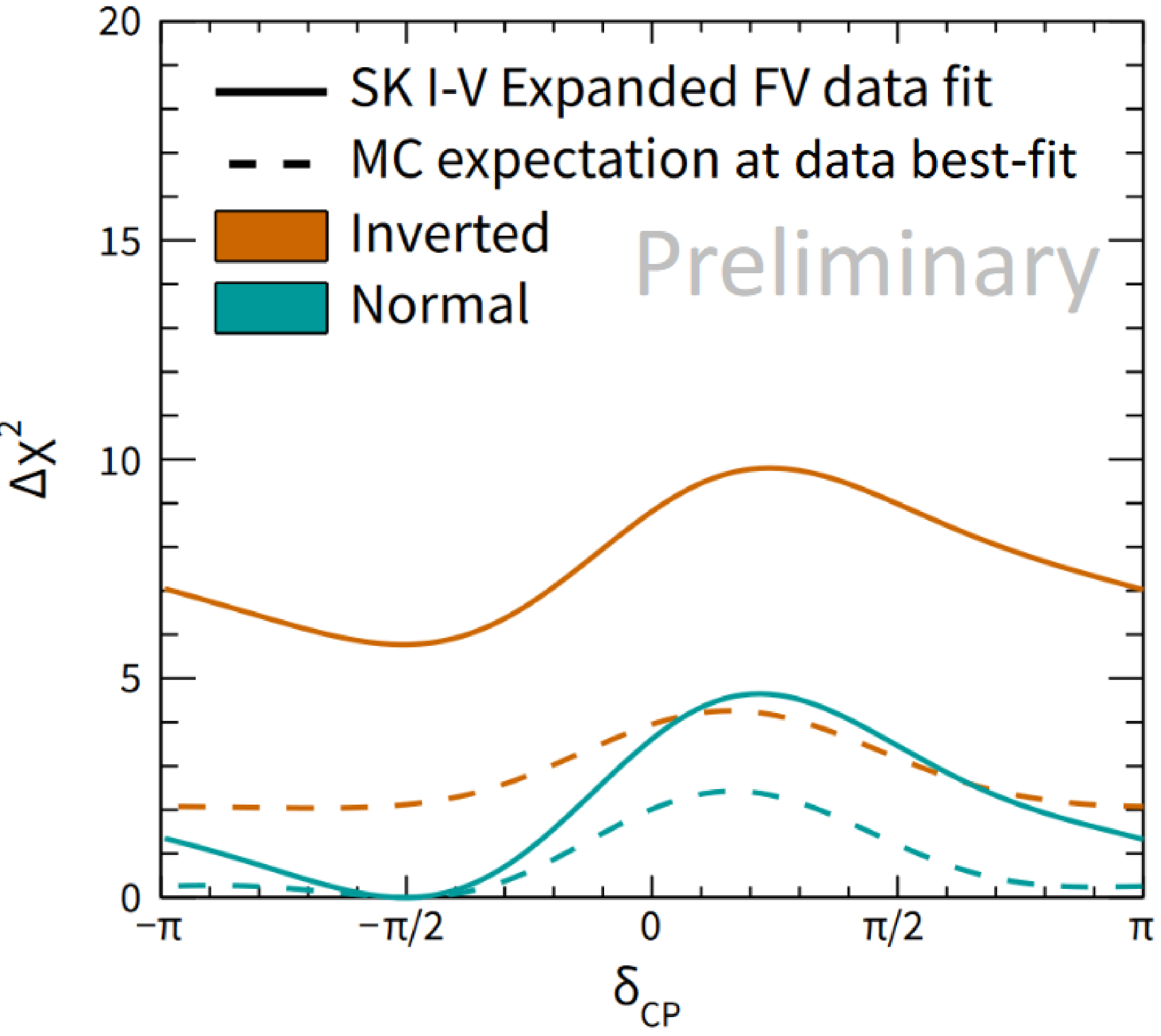
- Assume $\Delta m^2 > 0$

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

- Assume $\Delta m^2 < 0$



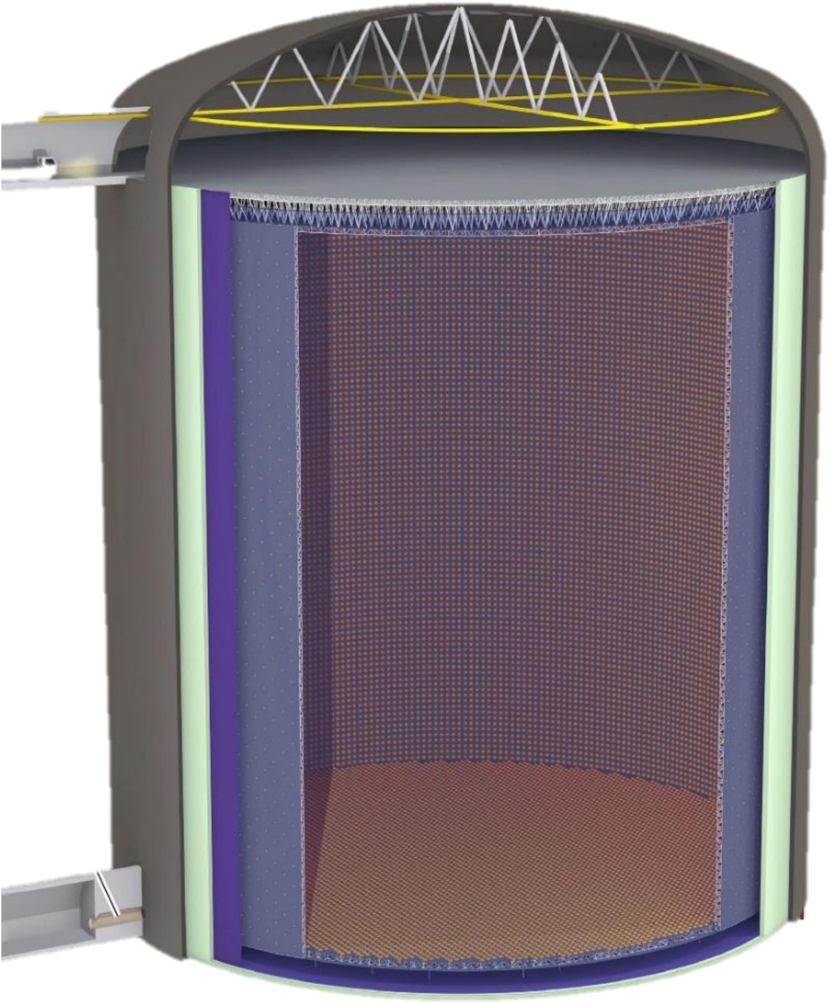
# Mass Ordering Measurement




Super-Kamiokande, Neutrino 2022

- Not yet conclusive
- Statistically constrained

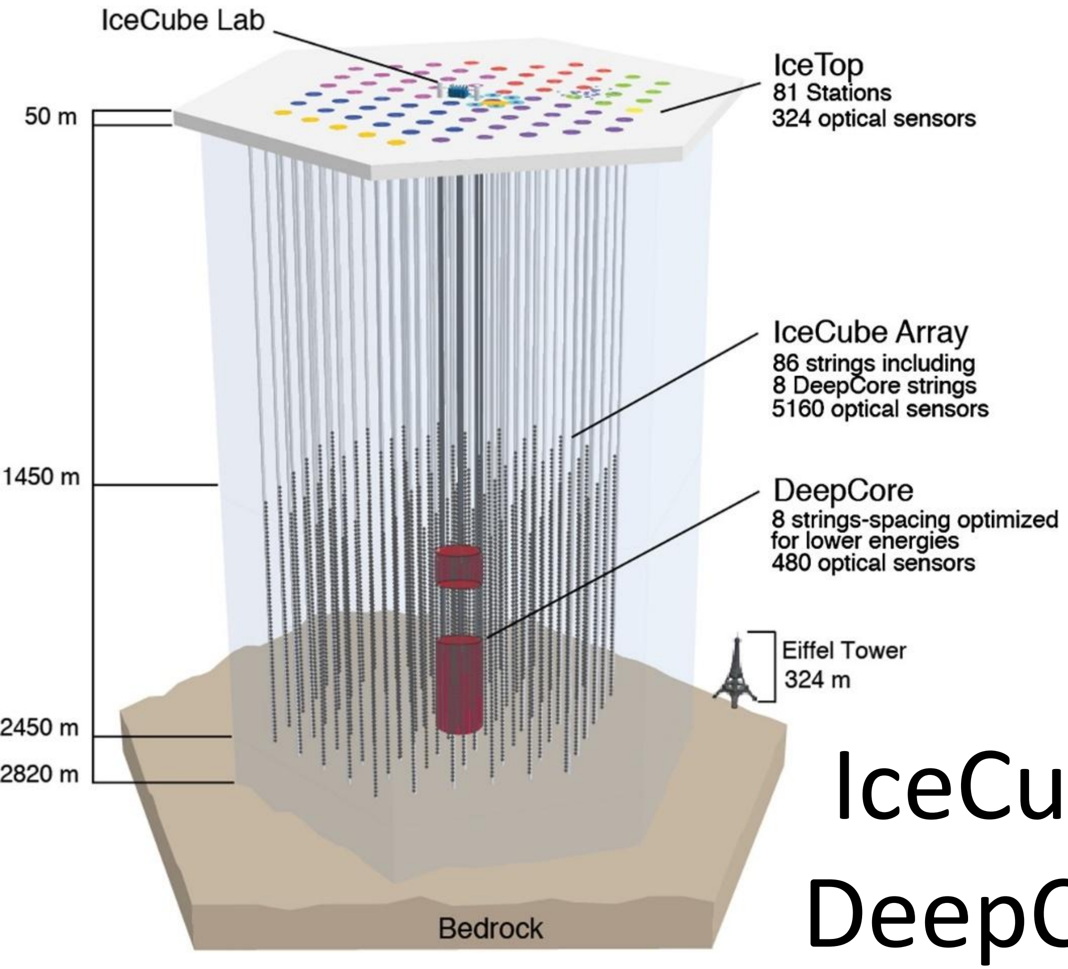
# Future Upgrade: Hyper-Kamiokande



- ~~Statistically constrained~~

Water Cherenkov
190 kton

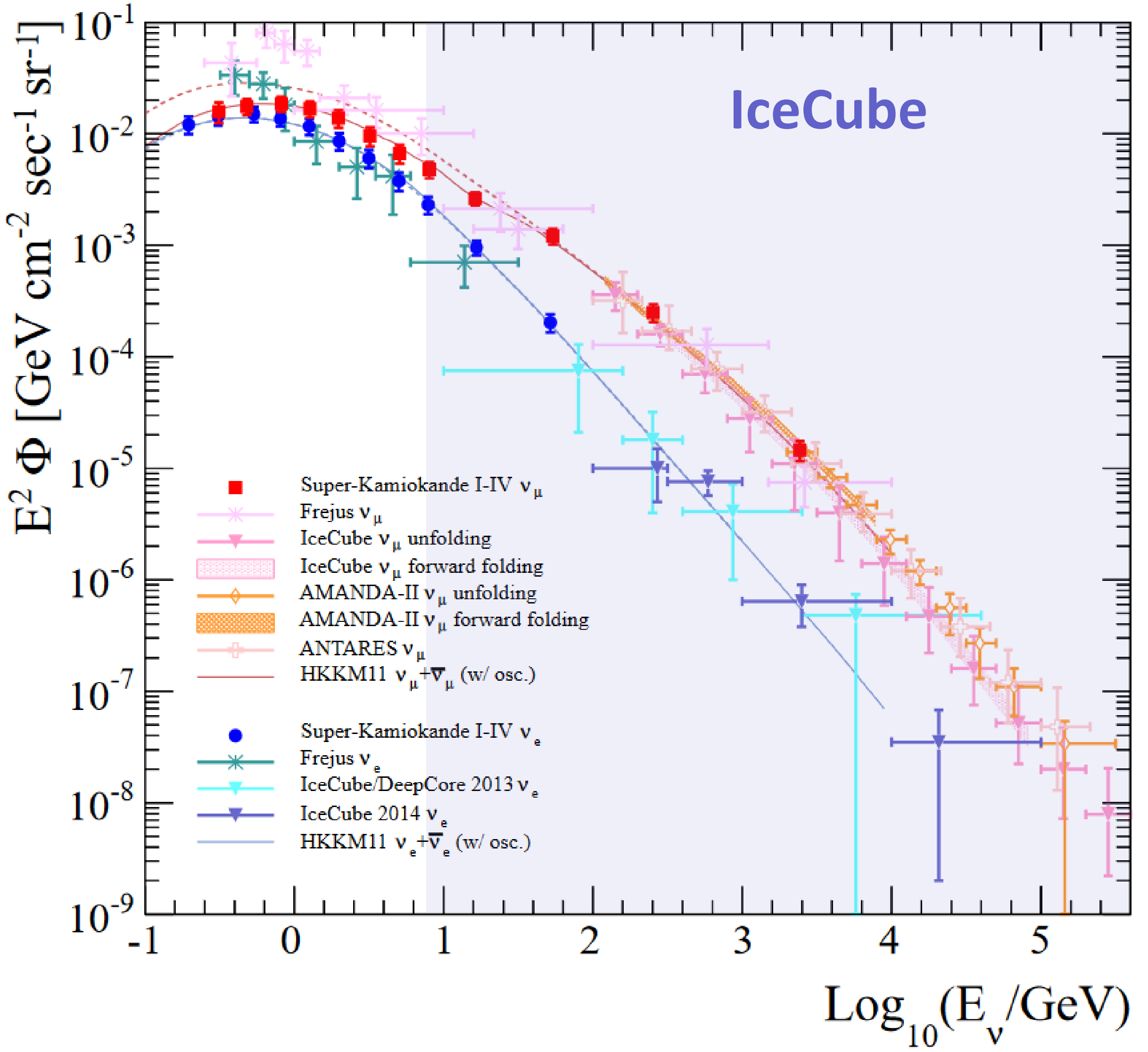
# IceCube




IceCube

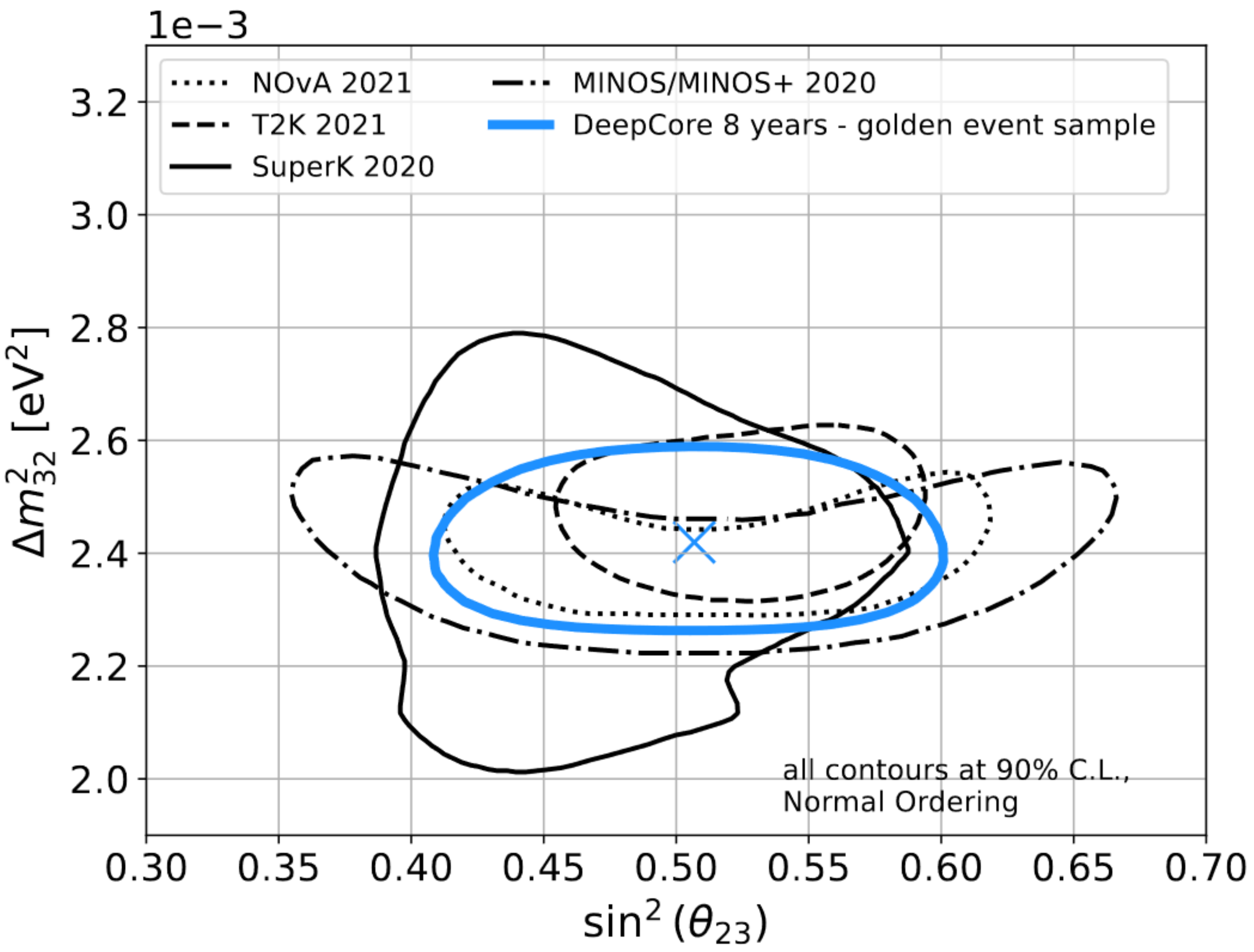
DeepCore

$E_{thr}$: 6 GeV




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

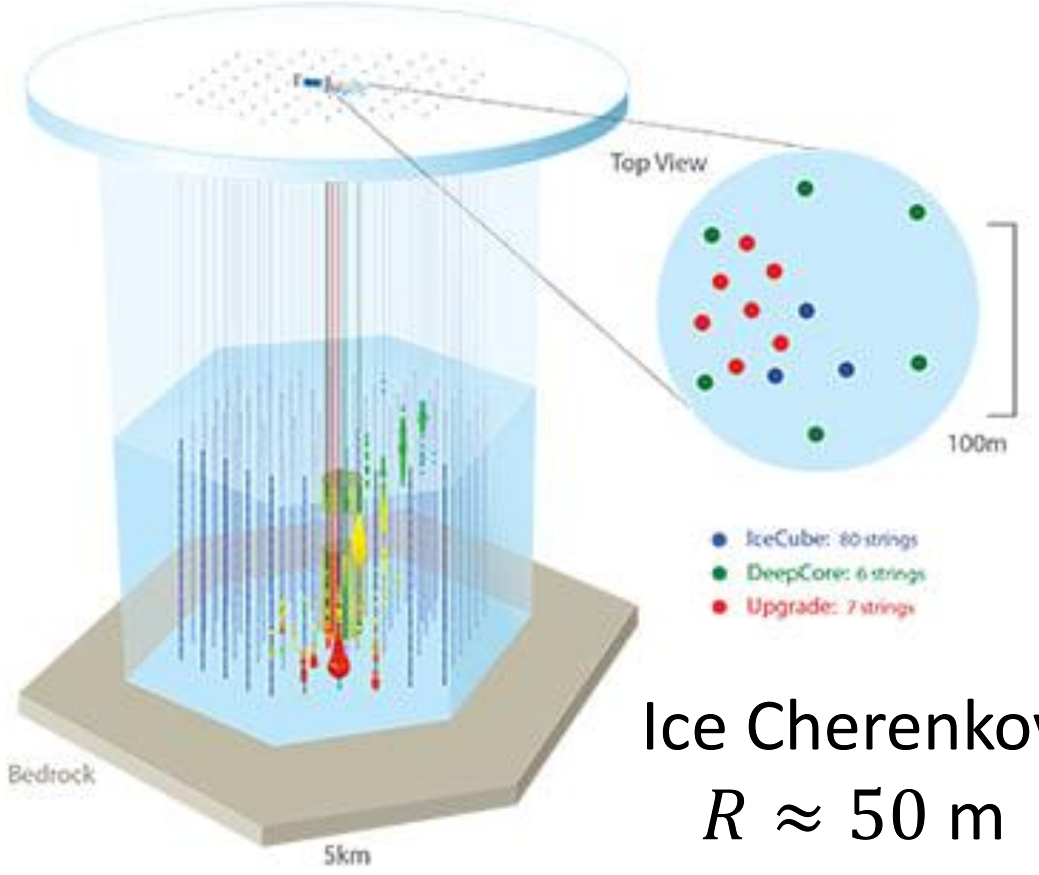
# IceCube Results




arXiv: 2304.12236

# Future Detectors

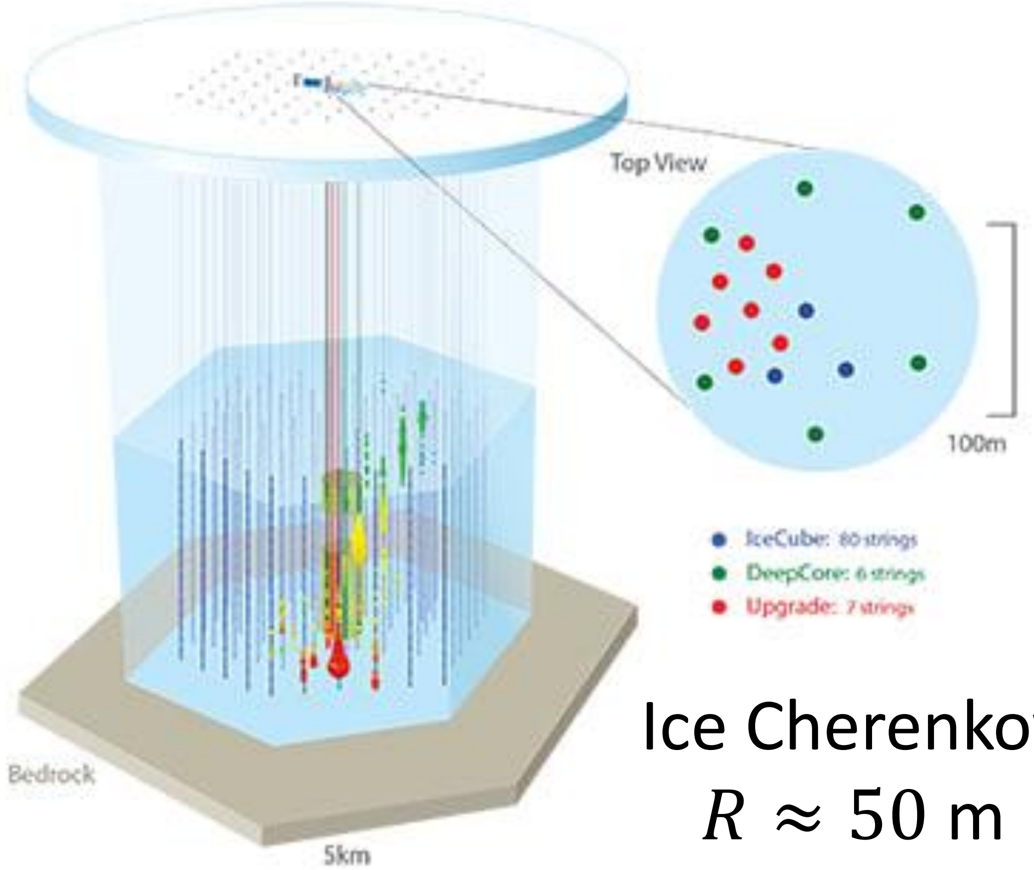
IceCube-Upgrade




Ice Cherenkov
$R \approx 50$ m

# Future Detectors

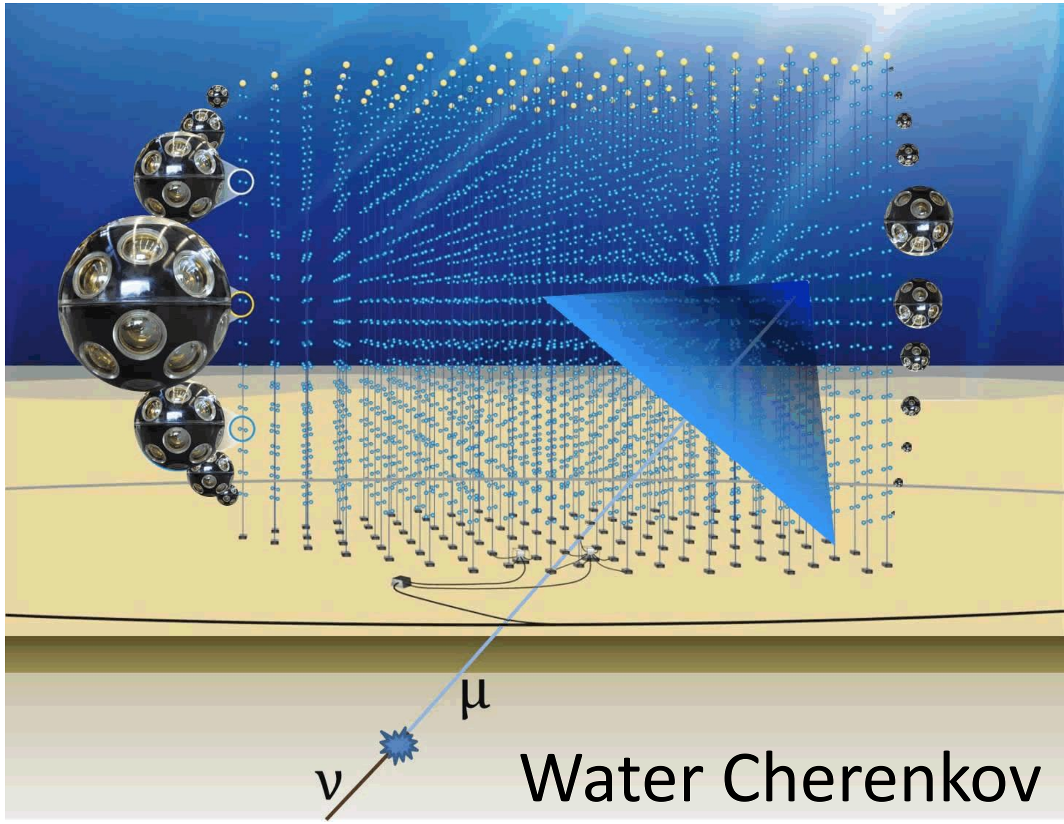
IceCube-Upgrade




Ice Cherenkov

$R \approx 50$ m

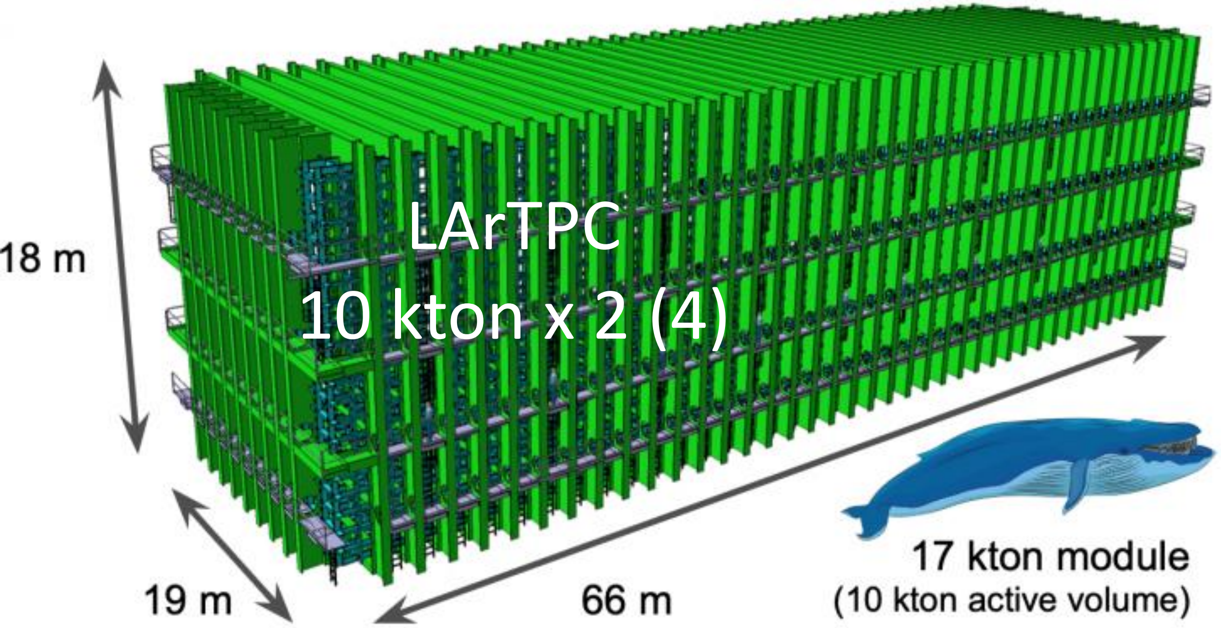
KM3NeT-ORCA




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

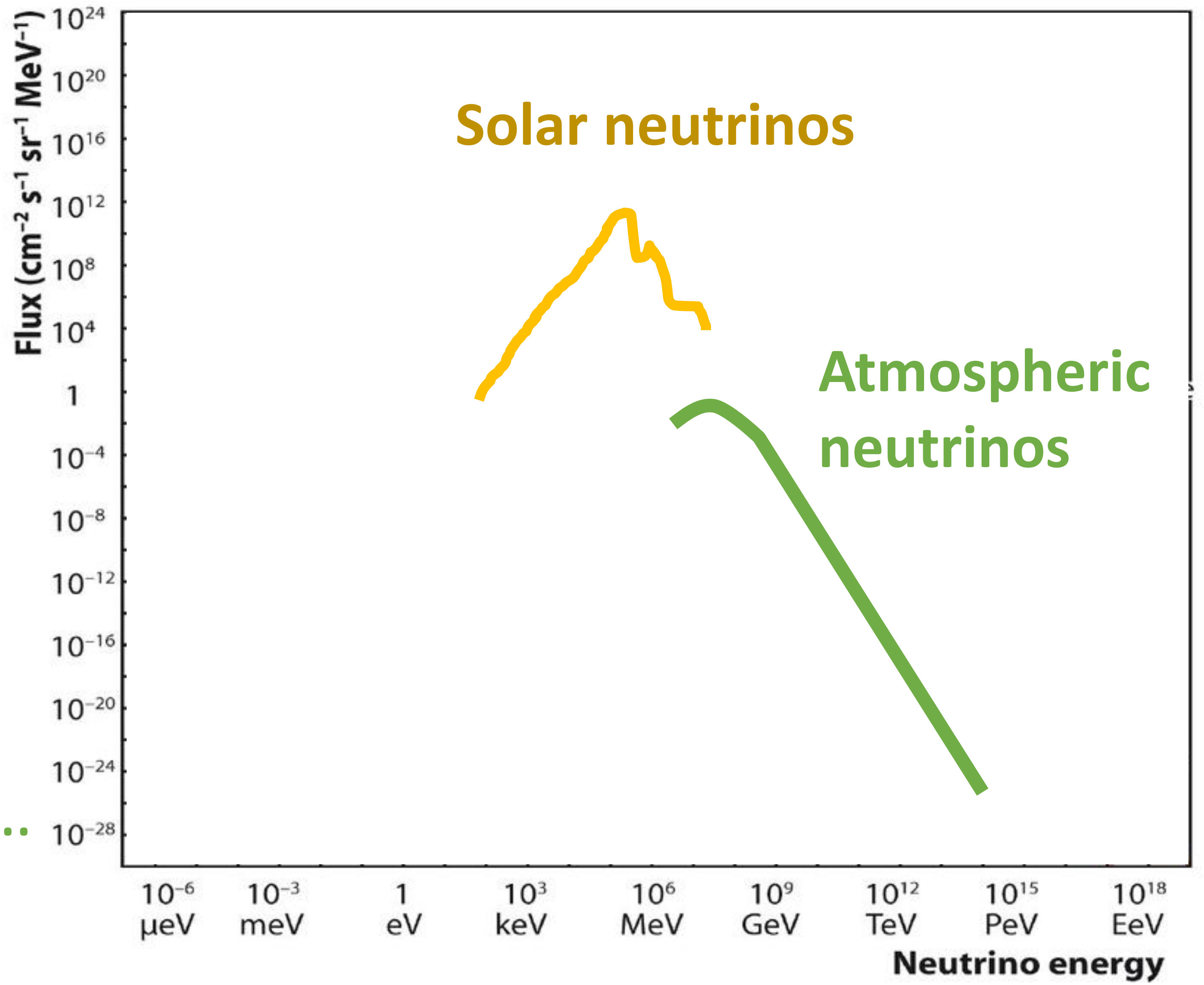
# Take-away Messages

Solar neutrinos

- Pure $\nu_e$'s
- Measure 1-2 mixing;
- Solar metallicity and more…

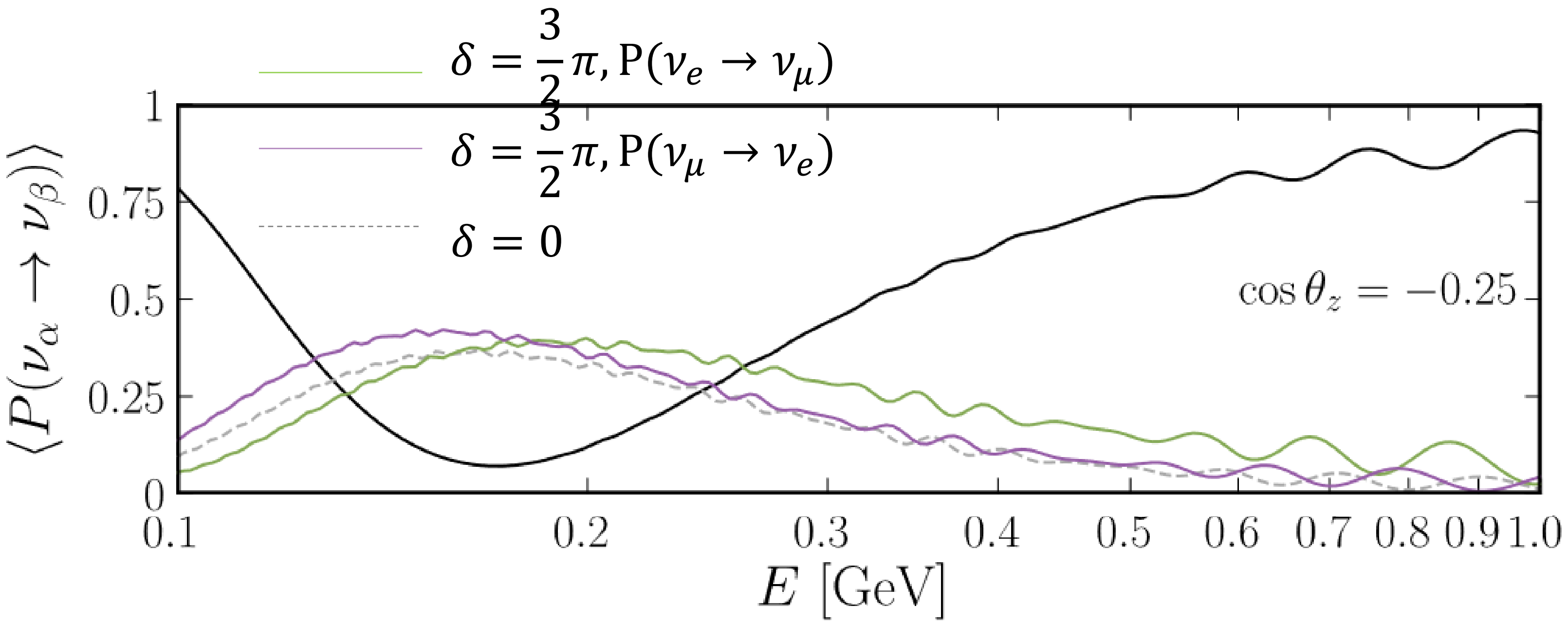
Atmospheric neutrinos

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



# Thank you!

# CP Violation

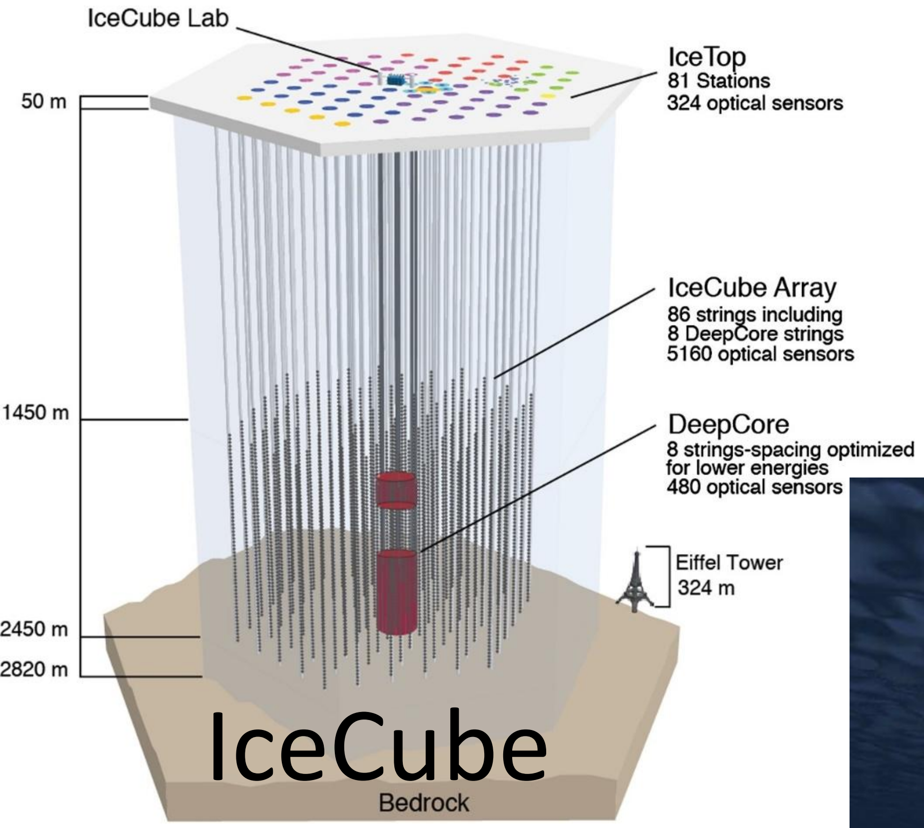



Kevin J. Kelly et al. PhysRevLett.123.081801

Signature at sub-GeV

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

# Other Atmospheric Neutrino Observatories




IceCube

DeepCore

$E_{thr}$: 6 GeV

ANTARES

$E_{thr}$: 20 GeV