Neutrino oscillation experiments

Joachim Kopp, CERN

July 2021

Outline

1. Neutrino sources
2. Neutrino detector technologies
3. Measuring neutrino oscillations

Natural neutrino sources

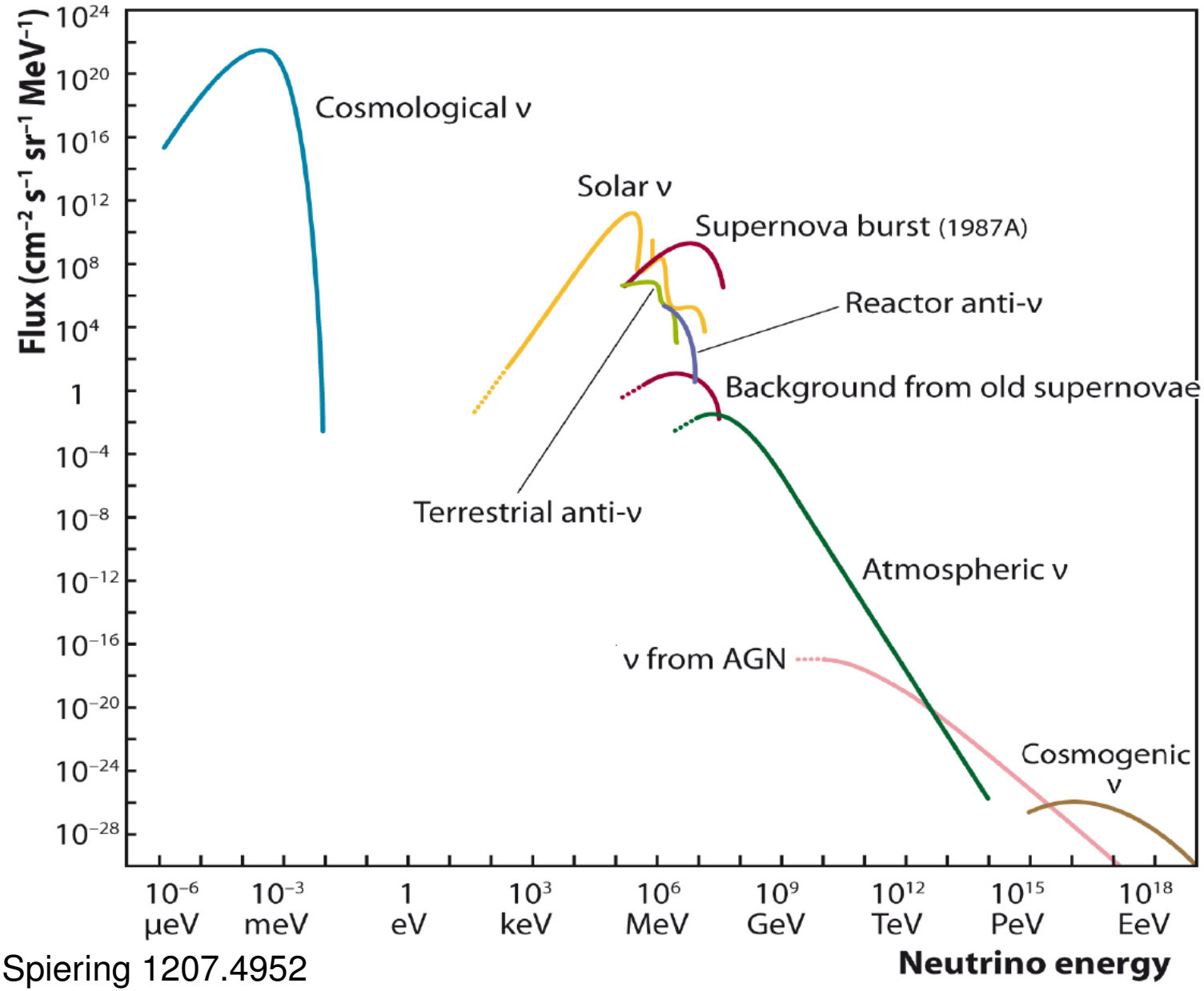
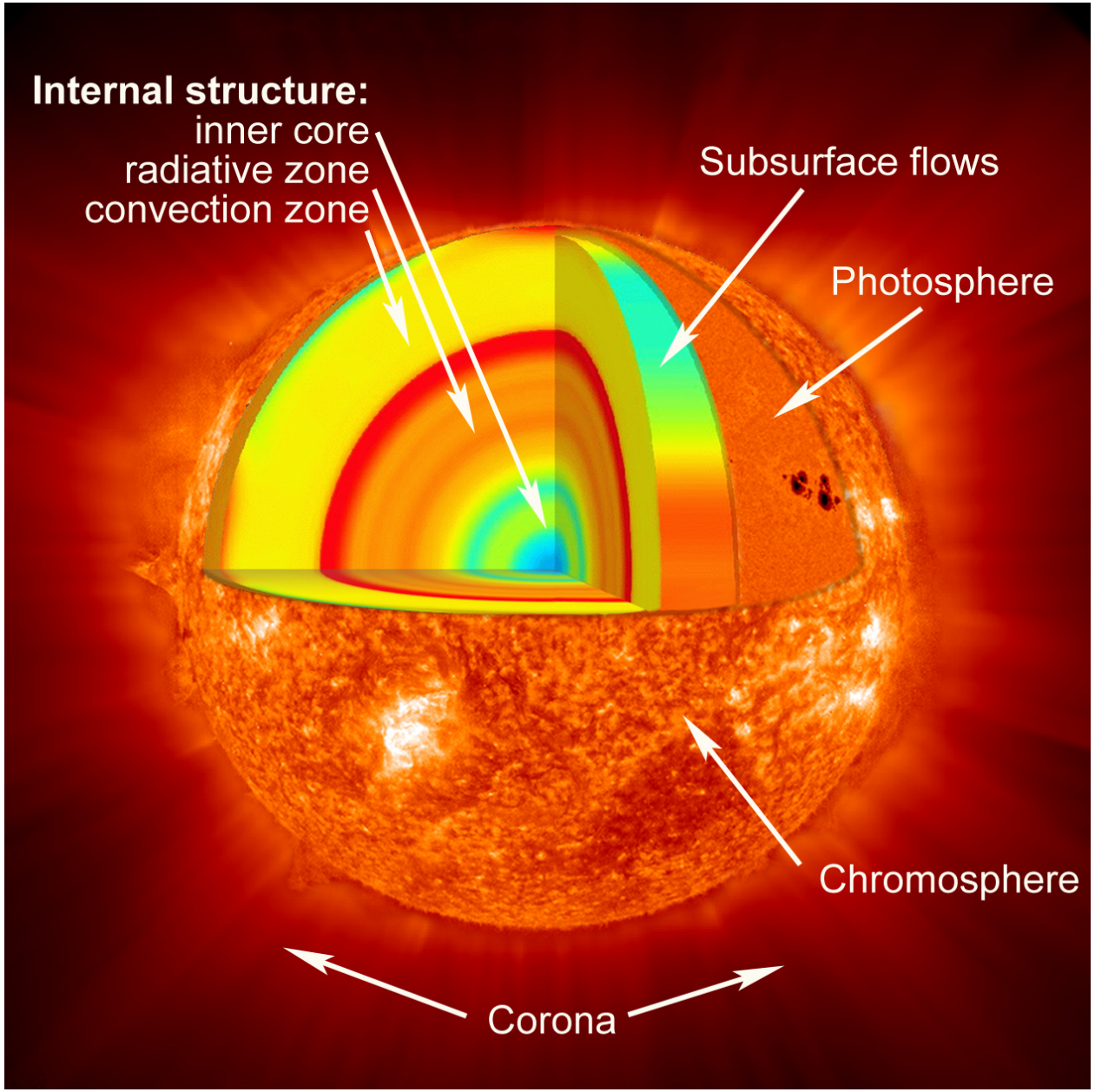


Image: C. Spiering 1207.4952

Solar neutrino production



Solar neutrino production

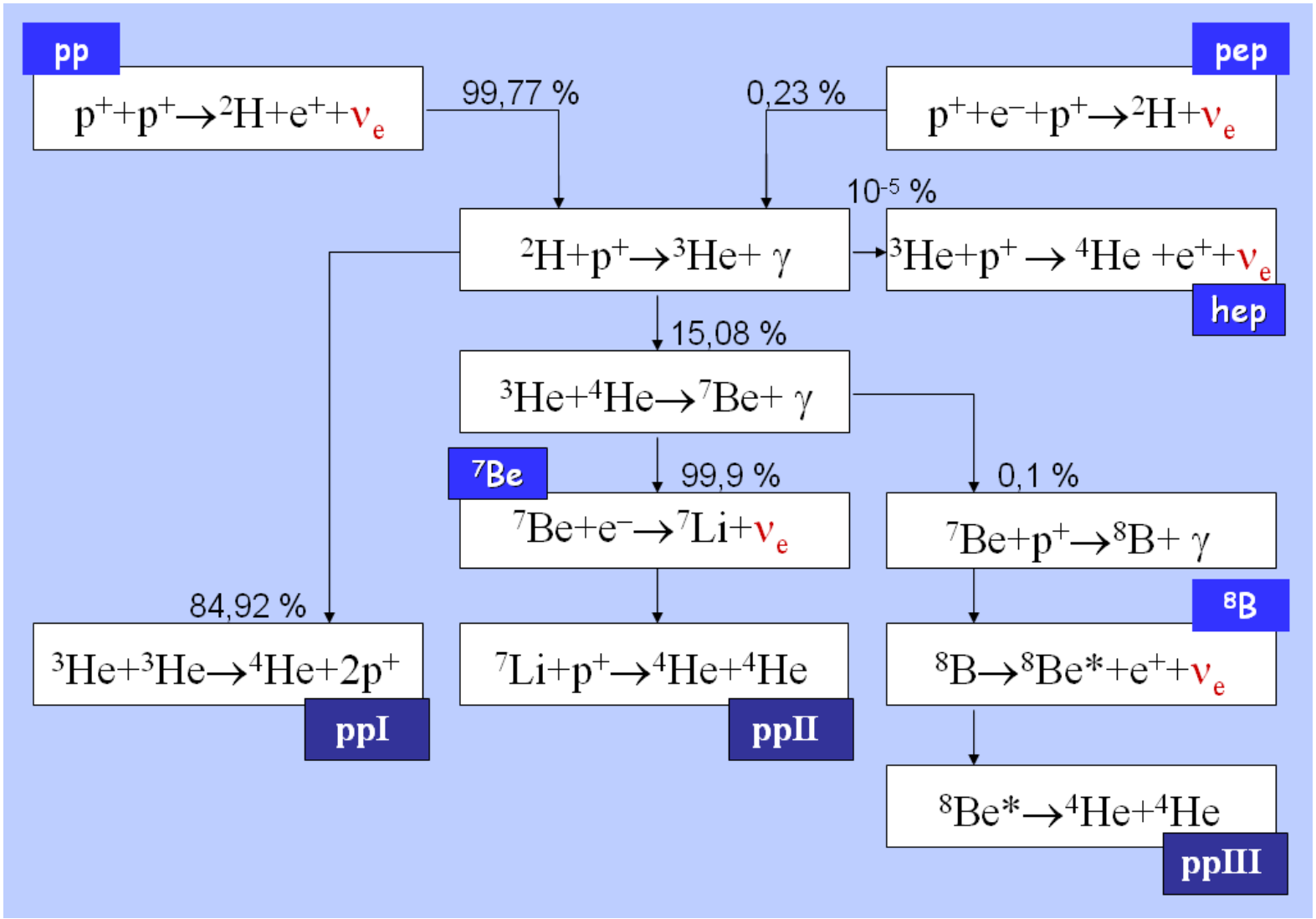


Image: Wikimedia Commons

Solar neutrino properties

- Pure ν_e flux (before oscillations)
- Flux on Earth: $\sim 10^{11}$ cm^{-2}s^{-1}
- Energy $\lesssim 10$ MeV

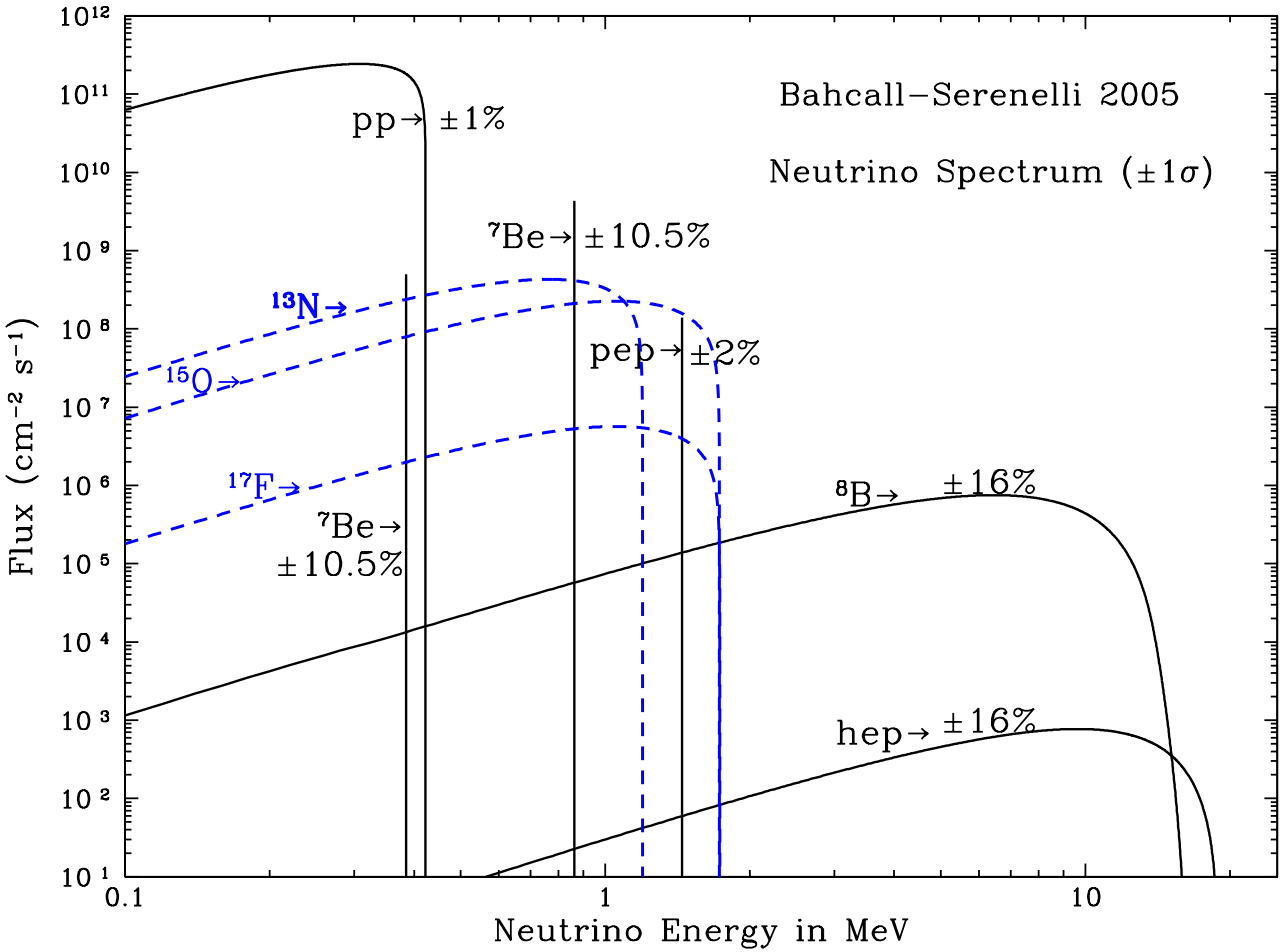
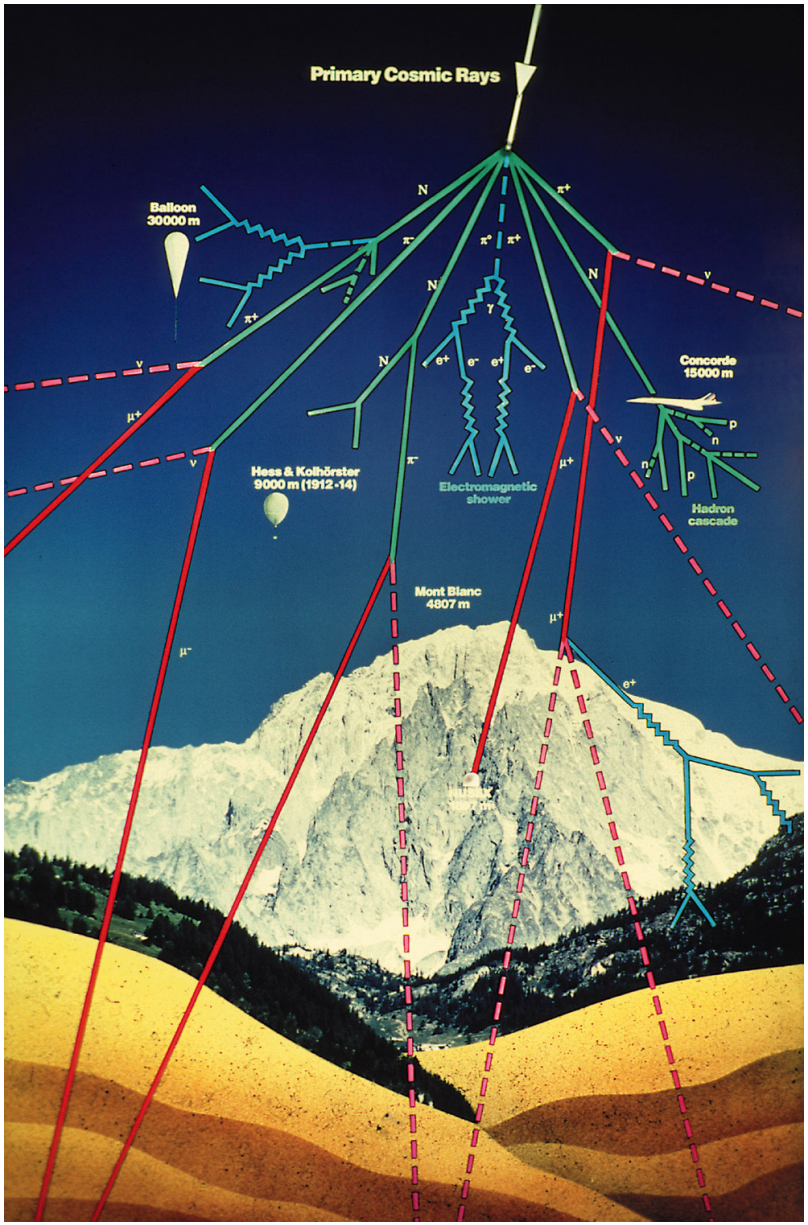
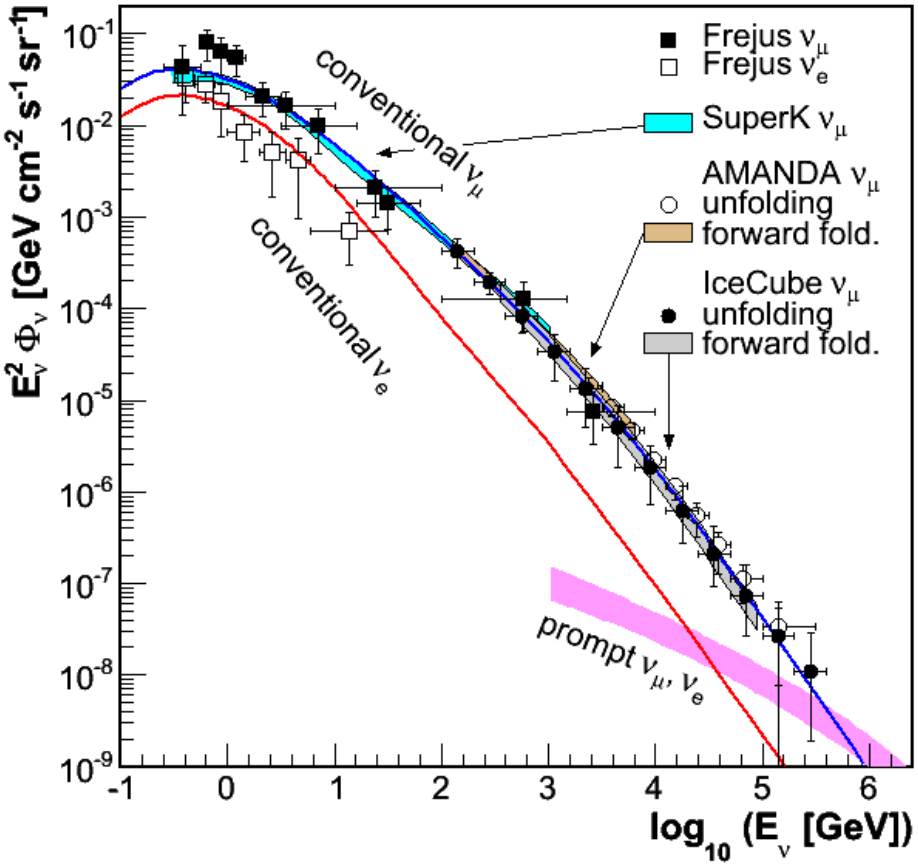


Image: John Bahcall

Atmospheric neutrinos

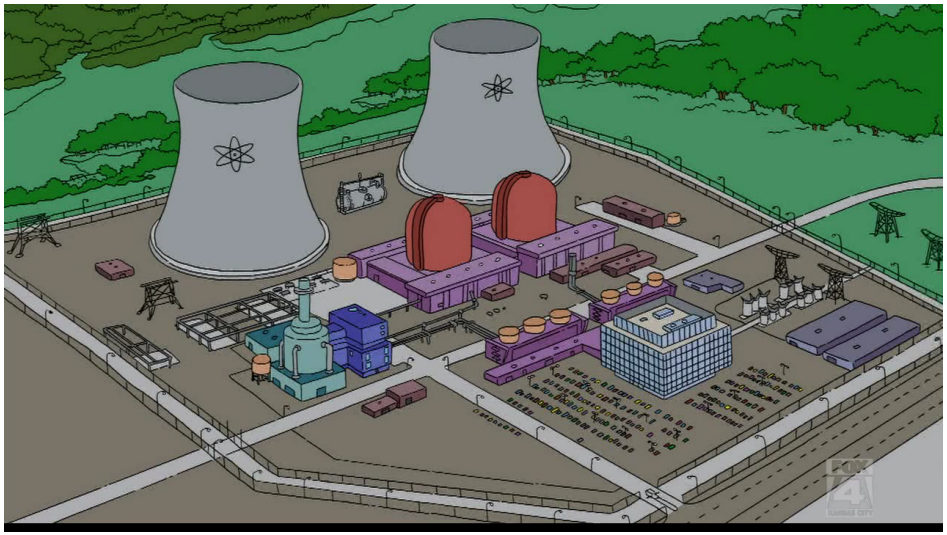


- Energy spectrum:



- Observable at $E \gtrsim$ few $\times$ 100 MeV
  (below: cross sections too low)
- Flavor composition
  $\overset{(-)}{\nu}_e : \overset{(-)}{\nu}_\mu : \overset{(-)}{\nu}_\tau \sim 1 : 2 : 0$

Nuclear reactors



- Intense source of $\bar{\nu}_e$ from

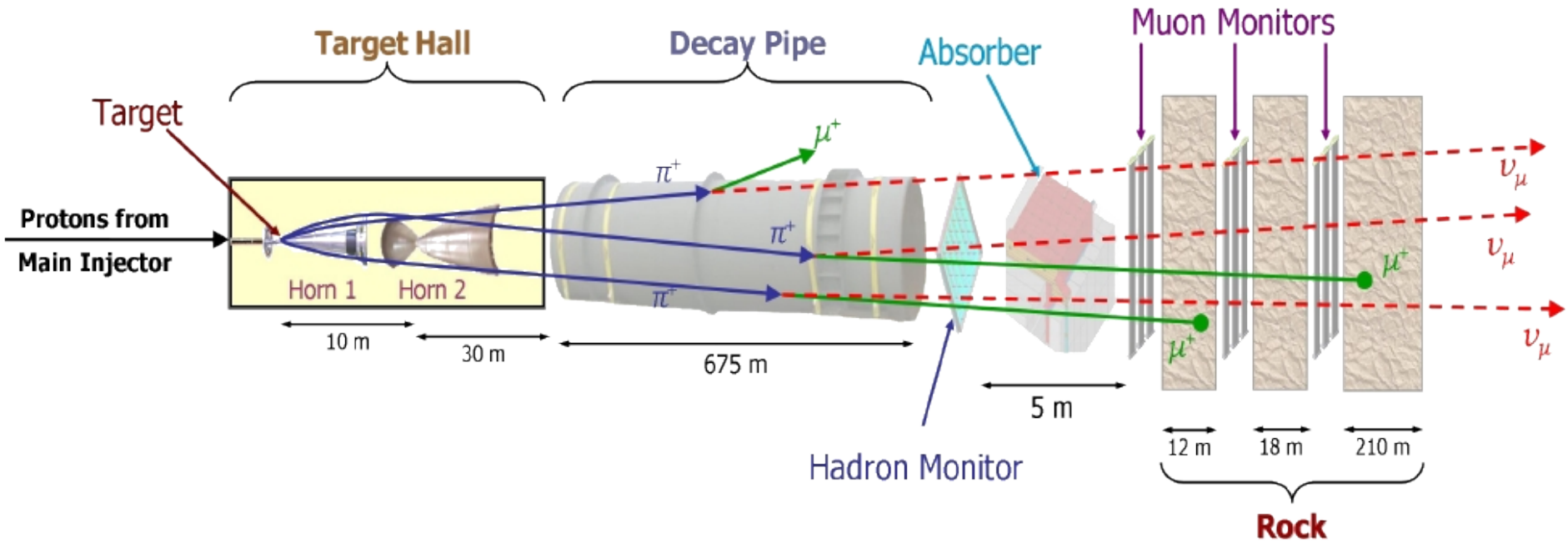
$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$

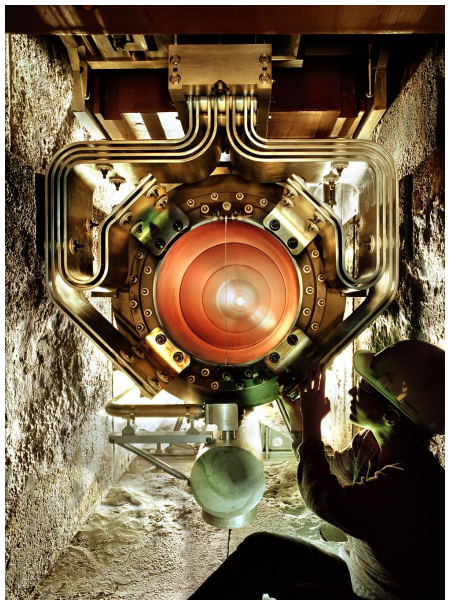
- Typical flux @ 100 m:

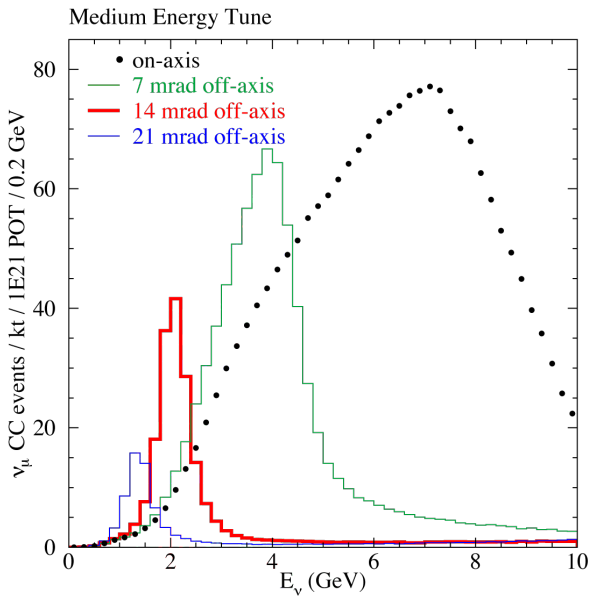
$$10^{15}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1} = 1\,\mathrm{kW\,m}^{-2}$$

- Neutrino energy: $\lesssim 10$ MeV
- First-ever detection of neutrinos (Reines & Cowan, 1956)

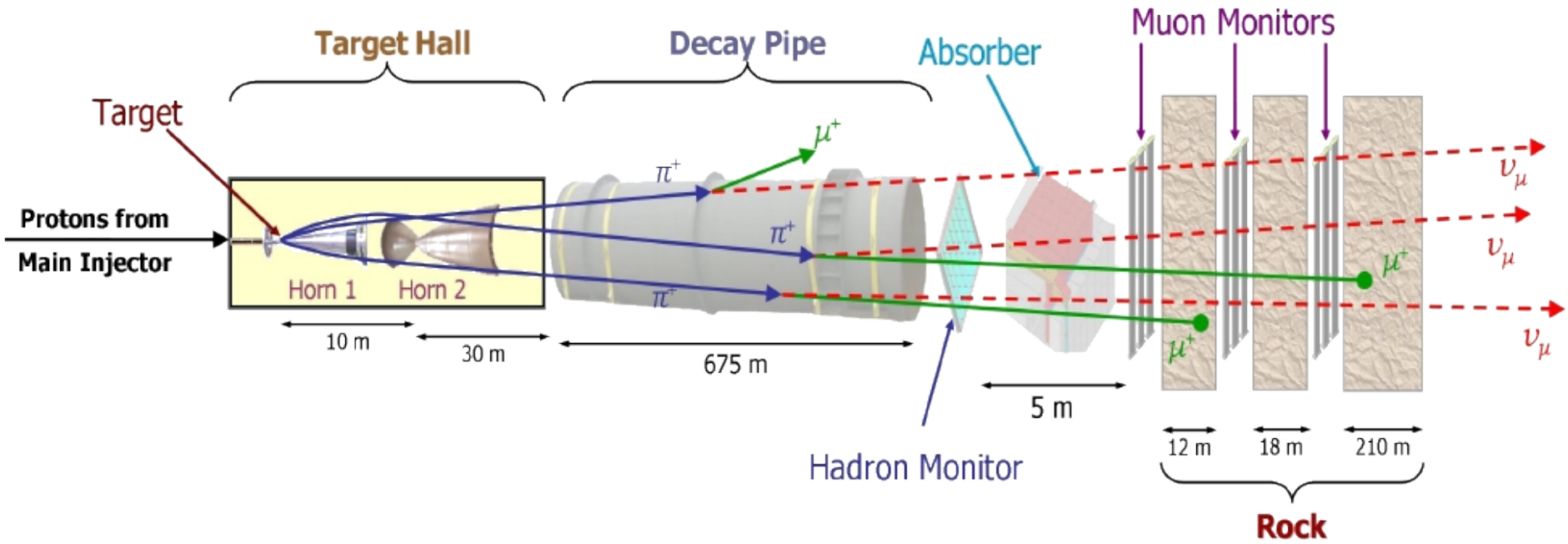
Accelerator neutrinos





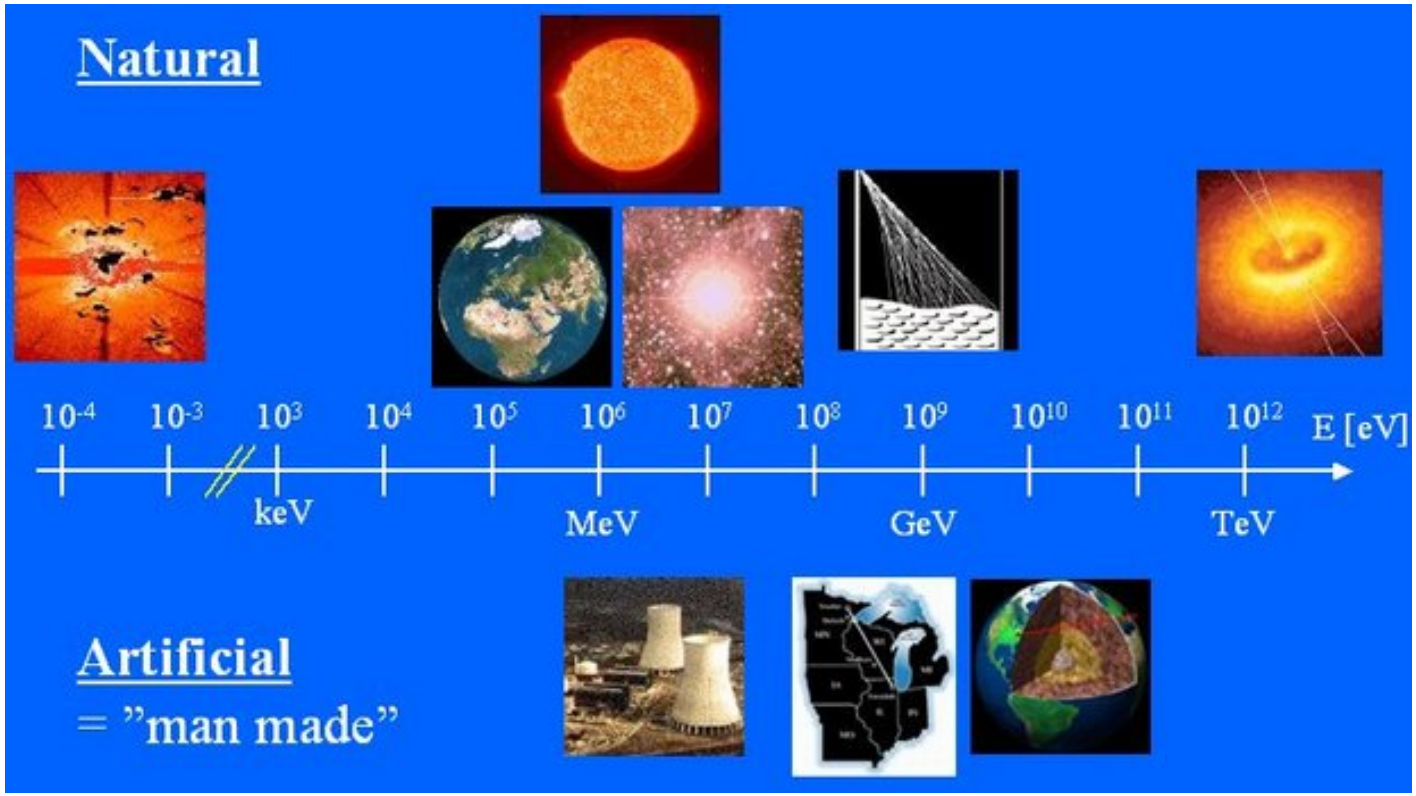


Accelerator neutrinos



- Energy: few 100 MeV – few 100 GeV
- Flavor composition (depending on horn polarity)
  - ν_μ (with contamination from $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$)
  - $\bar{\nu}_\mu$ (with contamination from ν_μ, ν_e, $\bar{\nu}_e$)

Neutrino source — Summary



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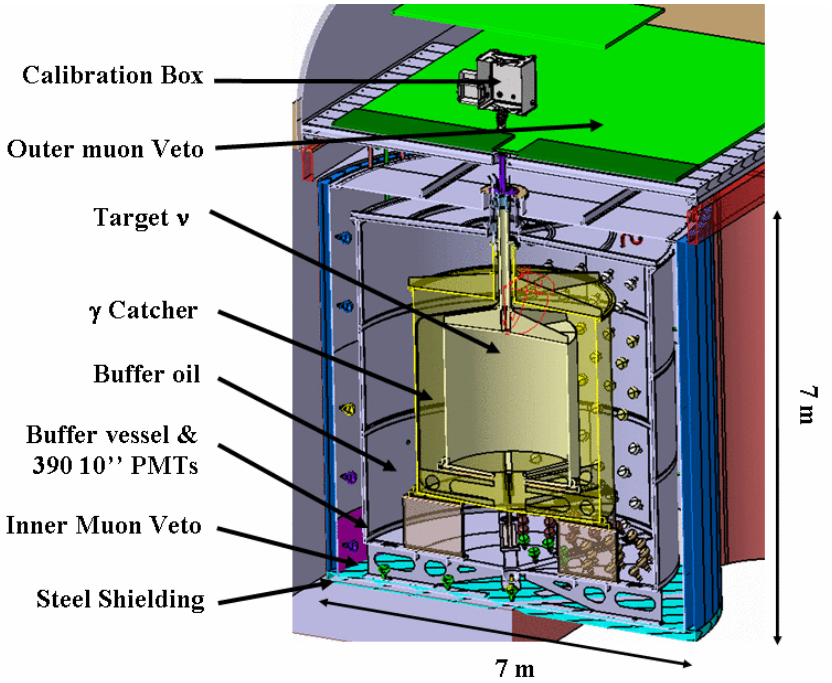
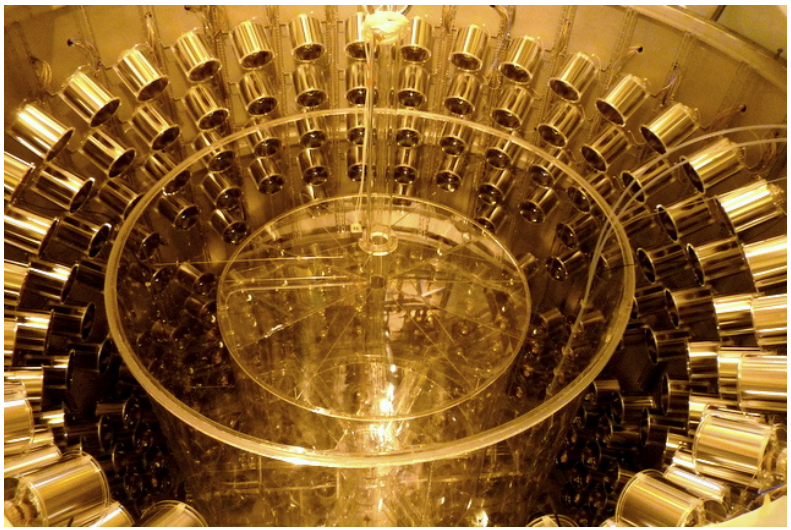
2. Neutrino detector technologies
3. Measuring neutrino oscillations

Liquid scintillator detectors





Example: Double Chooz

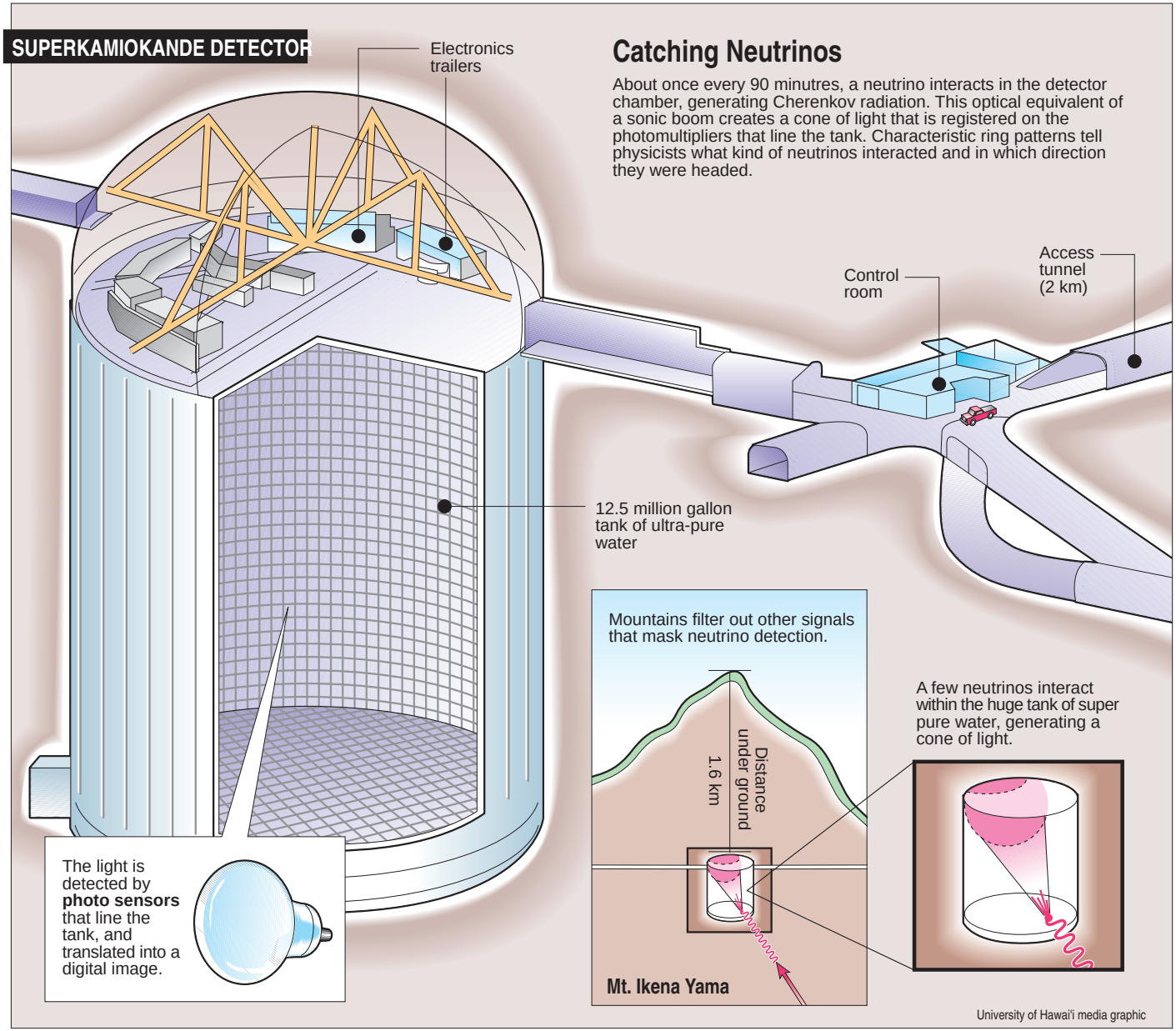
- Scintillating mineral oil
- Doped with gadolinium (large neutron capture cross section) to tag

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

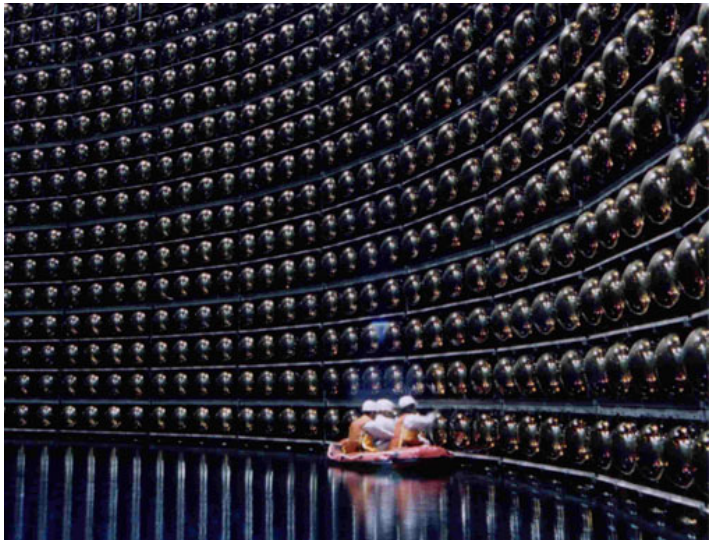
via coincidence of prompt e^+ and delayed n capture

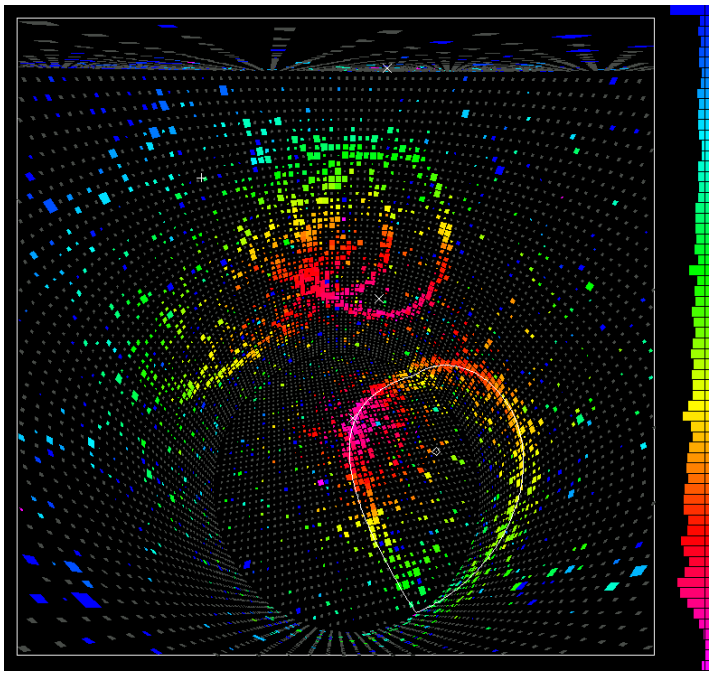
- Challenges:
  - Radiopurity
    - ★ Careful material selection
    - ★ Multiple layers of shielding
  - Suppression of cosmic ray BG
    - ★ Underground
    - ★ Active veto
  - ...
- Sensitive to low-E (MeV) neutrinos

Water Čerenkov detectors



Super-Kamiokande





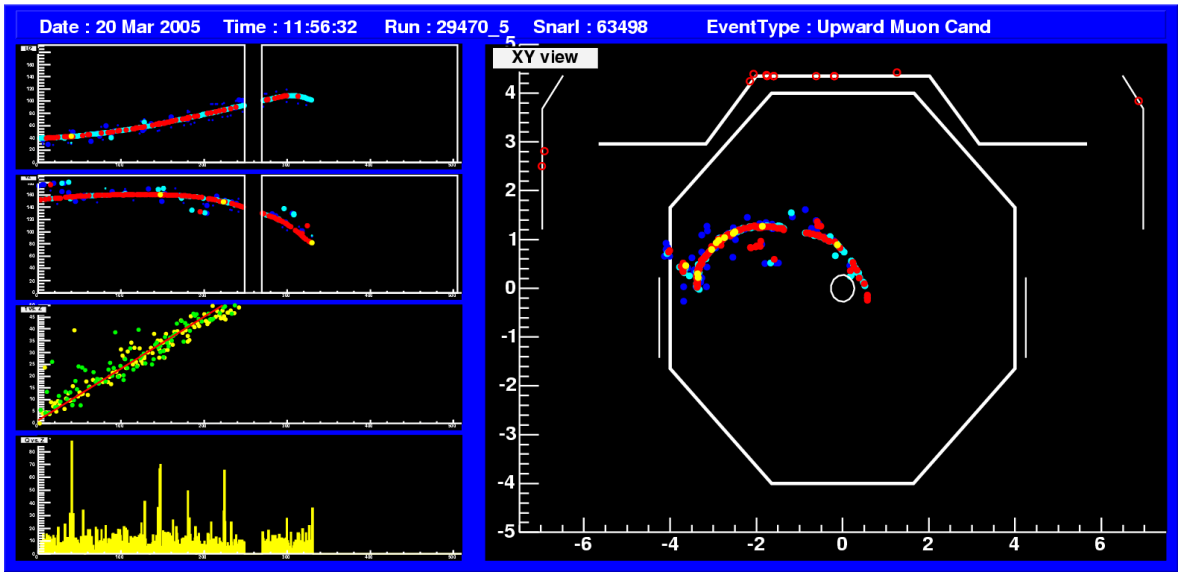
- Detection principle:
  - Observe Čerenkov light from high-E secondary particles in

$$\nu + N \to N' + \ell$$

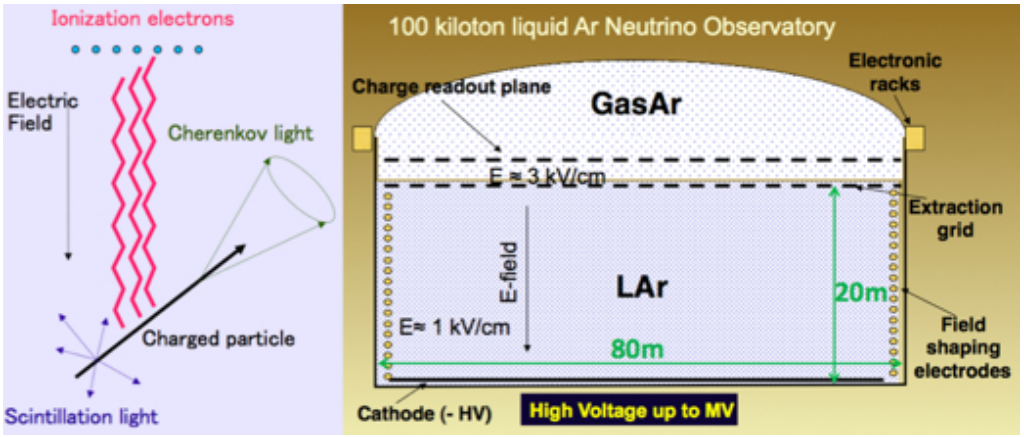
- Sensitive to $E_\nu \gtrsim$ few10 MeV
- Huge targets feasible
  (Super-K: 22.5 kt)
- Only particles above Čerenkov threshold visible
  - Event reconstruction more challenging

Magnetized iron detectors

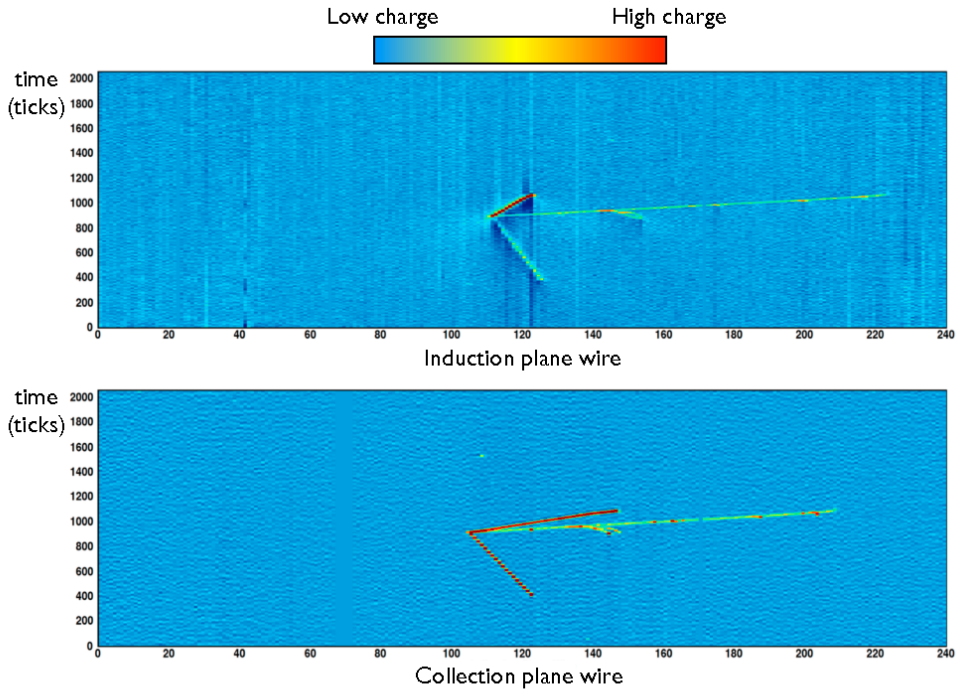
- Interleaved layers of iron (neutrino target) and plastic scintillator (tracking)
- Magnetizeable $\rightarrow$ distinguish ν and $\bar{\nu}$
- Sensitive to $E_\nu \gtrsim$ GeV
- Limited event reconstruction:
  - Hadrons, electrons: Localized shower
  - Muons: Long track



Liquid Argon Detectors



- Very good event reconstruction capabilities
- Low threshold $\sim$ 10 MeV
- Works at the 600 ton level (ICARUS), scalability to bigger sizes not proven



Outline

1 Neutrino sources

2 Neutrino detector technologies

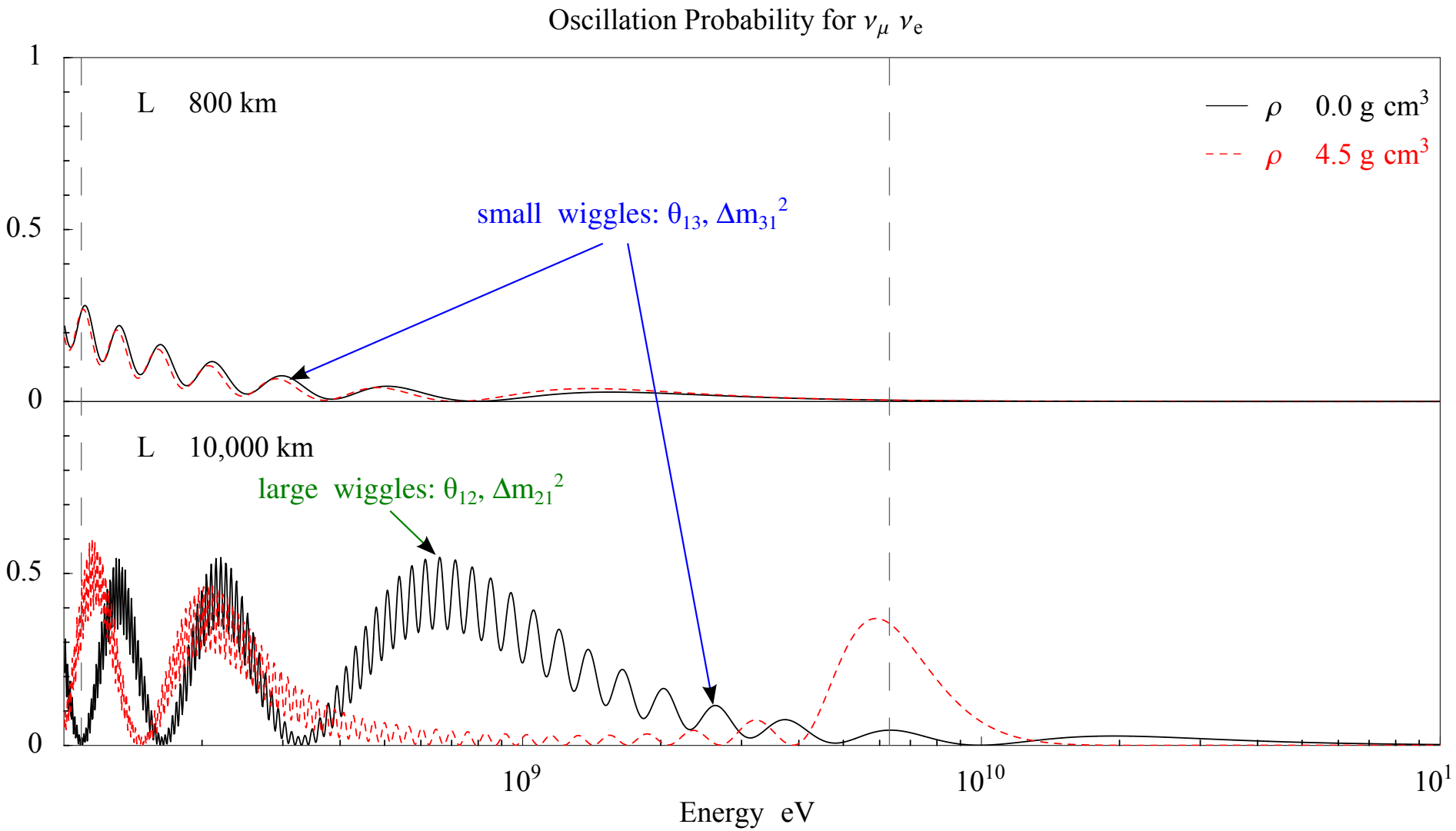
3 Measuring neutrino oscillations

The challenge

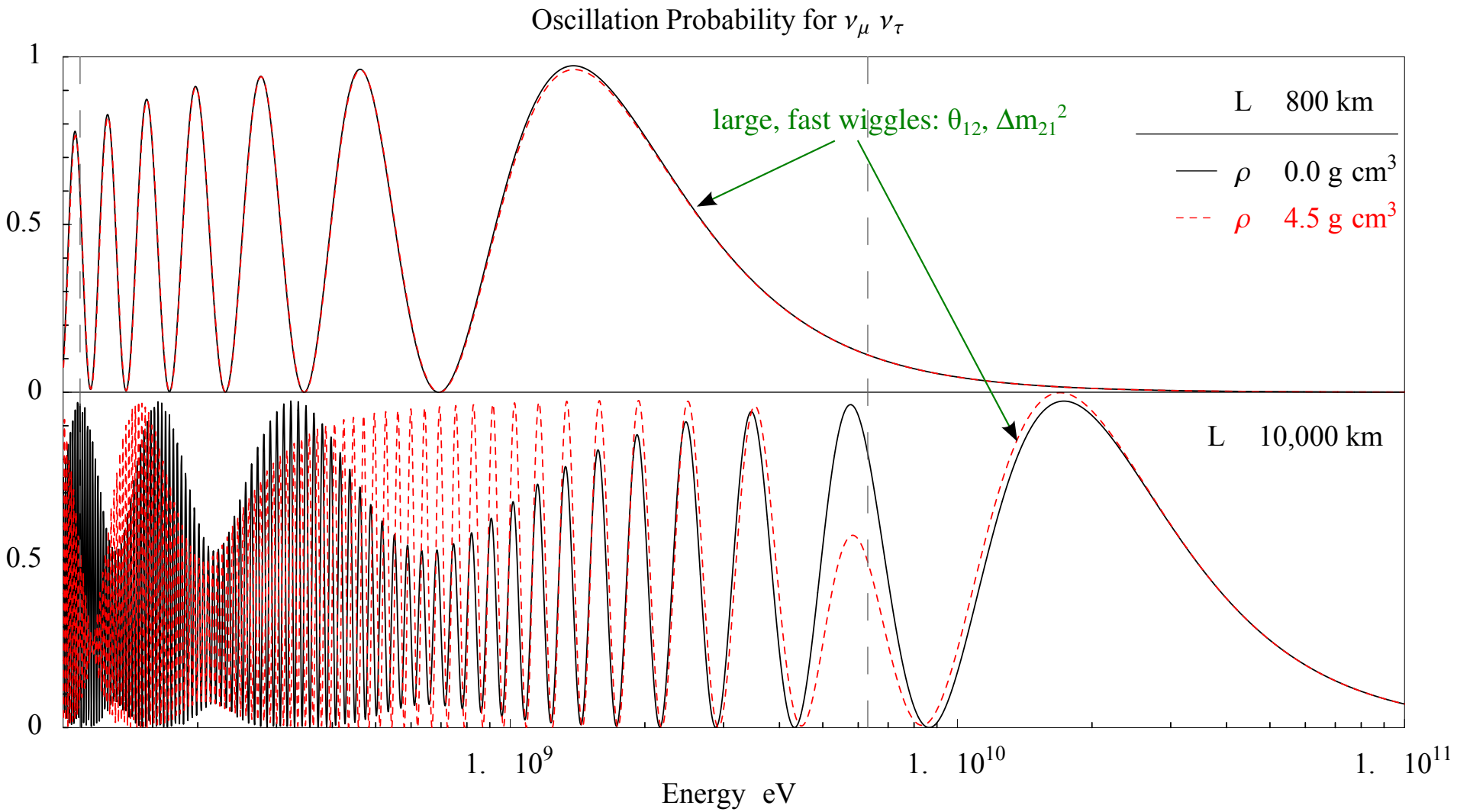
Six parameters to measure:

θ_{23}, Δm^2_{31},
θ_{12}, Δm^2_{21},
θ_{13},
δ_{CP}

Oscillation probability $P_{\mu \to e}$



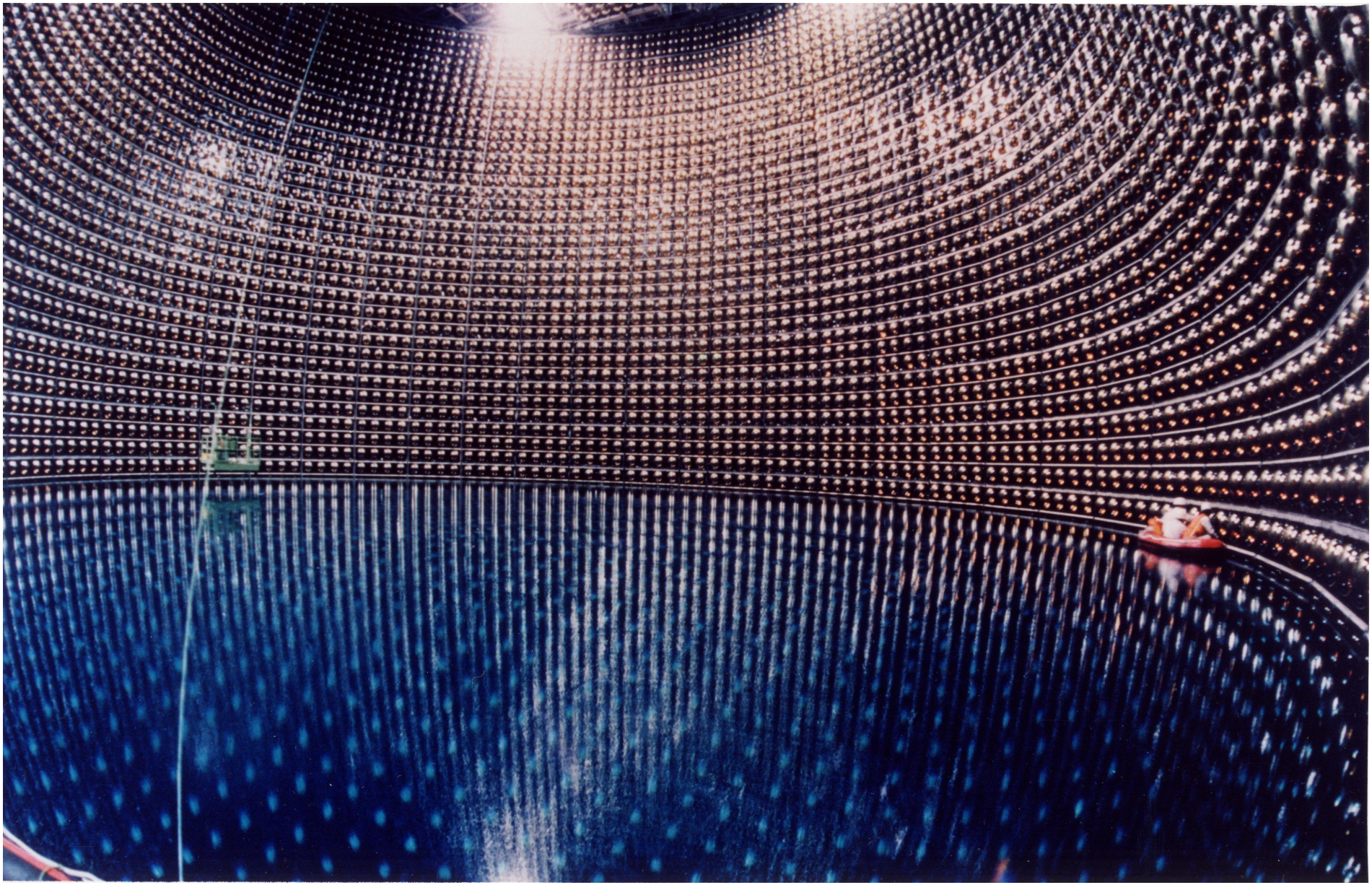
Oscillation probability $P_{\mu\to\tau}$



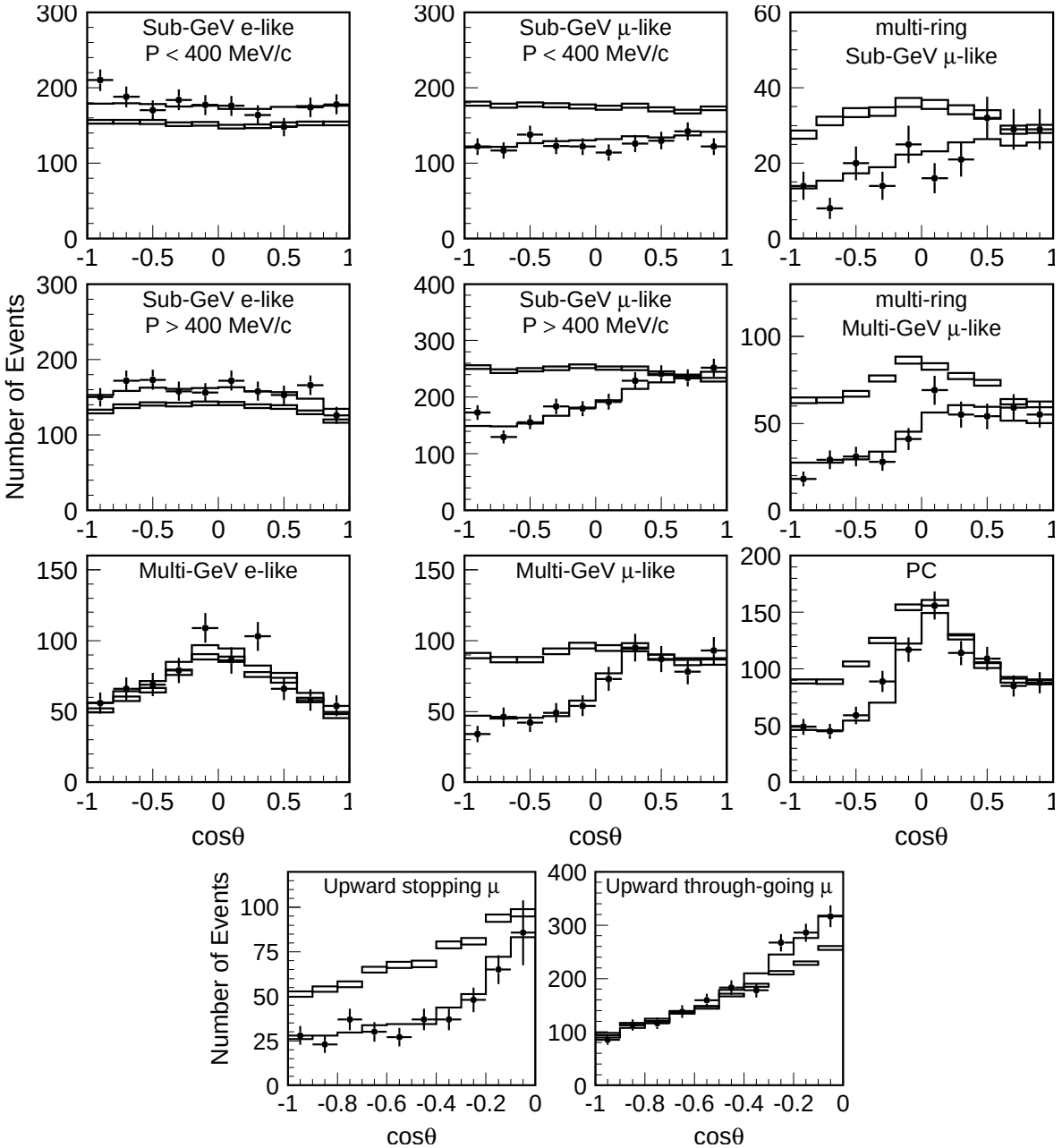
Strategy

- θ_{23}, Δm^2_{31}
  - $\overset{(-)}{\nu}_\mu$ disappearance (into $\overset{(-)}{\nu}_\tau$) at $L/E \sim 500$ km/GeV
- θ_{12}, Δm^2_{21}
  - $\overset{(-)}{\nu}_e$ disappearance (into $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_\tau$) at $L/E \sim 15\,000$ km/GeV
- θ_{13}
  - $\overset{(-)}{\nu}_e$ disappearance (into $\overset{(-)}{\nu}_\mu$ and $\overset{(-)}{\nu}_\tau$) at $L/E \sim 500$ km/GeV

The beginnings: Super-Kamiokande

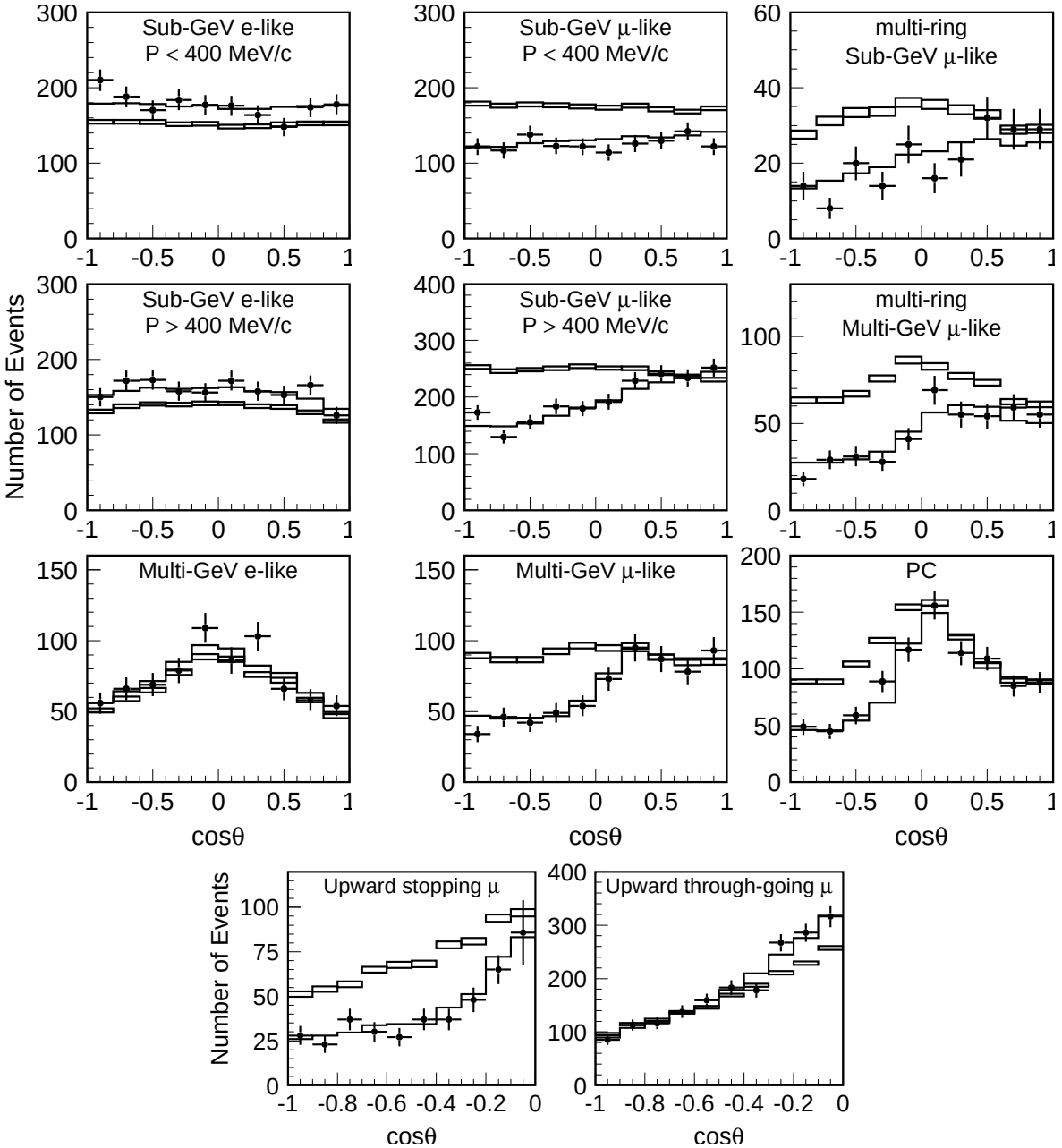


The beginnings: Super-Kamiokande (1998)



- Look for $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$

The beginnings: Super-Kamiokande (1998)



- Look for $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$
- Flavor-ID from shape of Čerenkov ring

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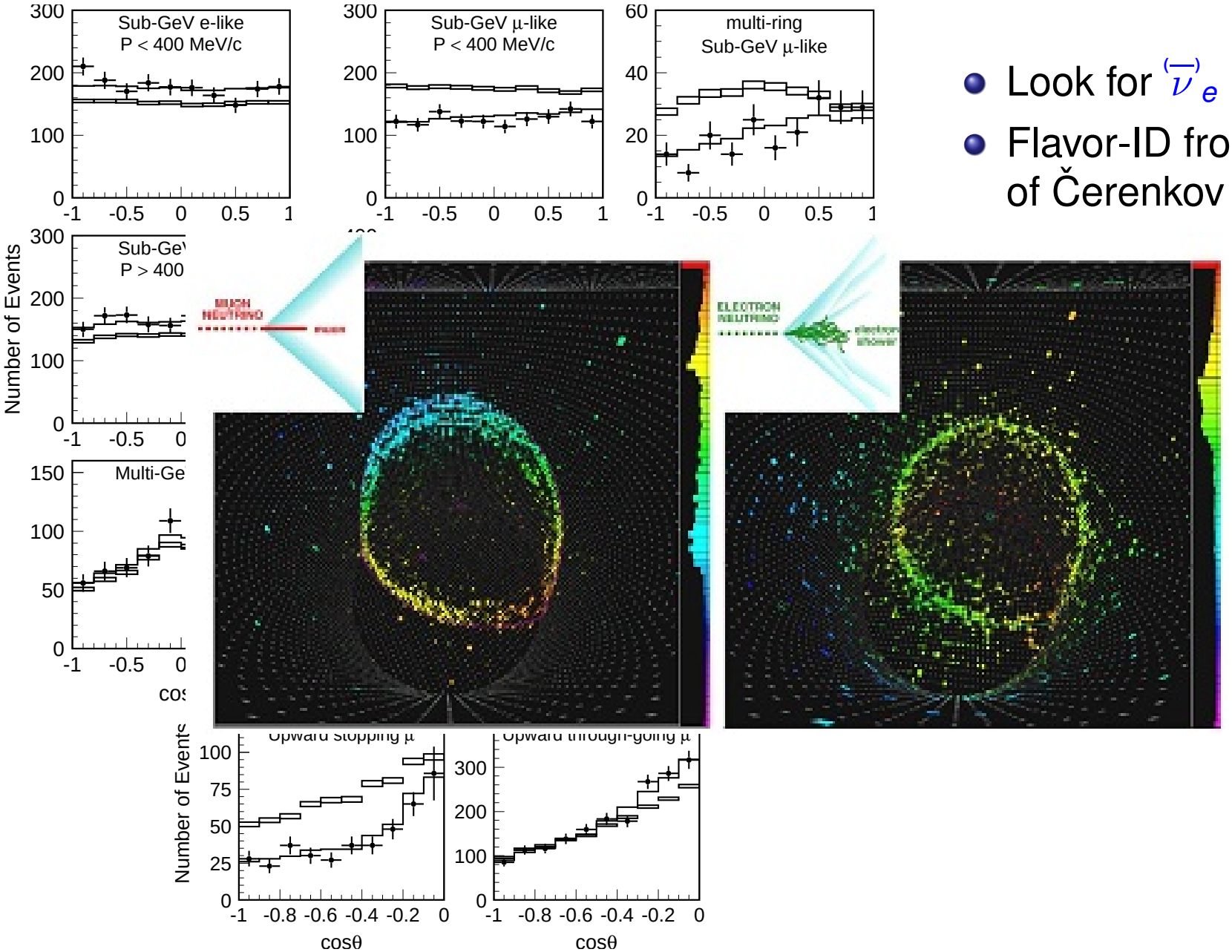

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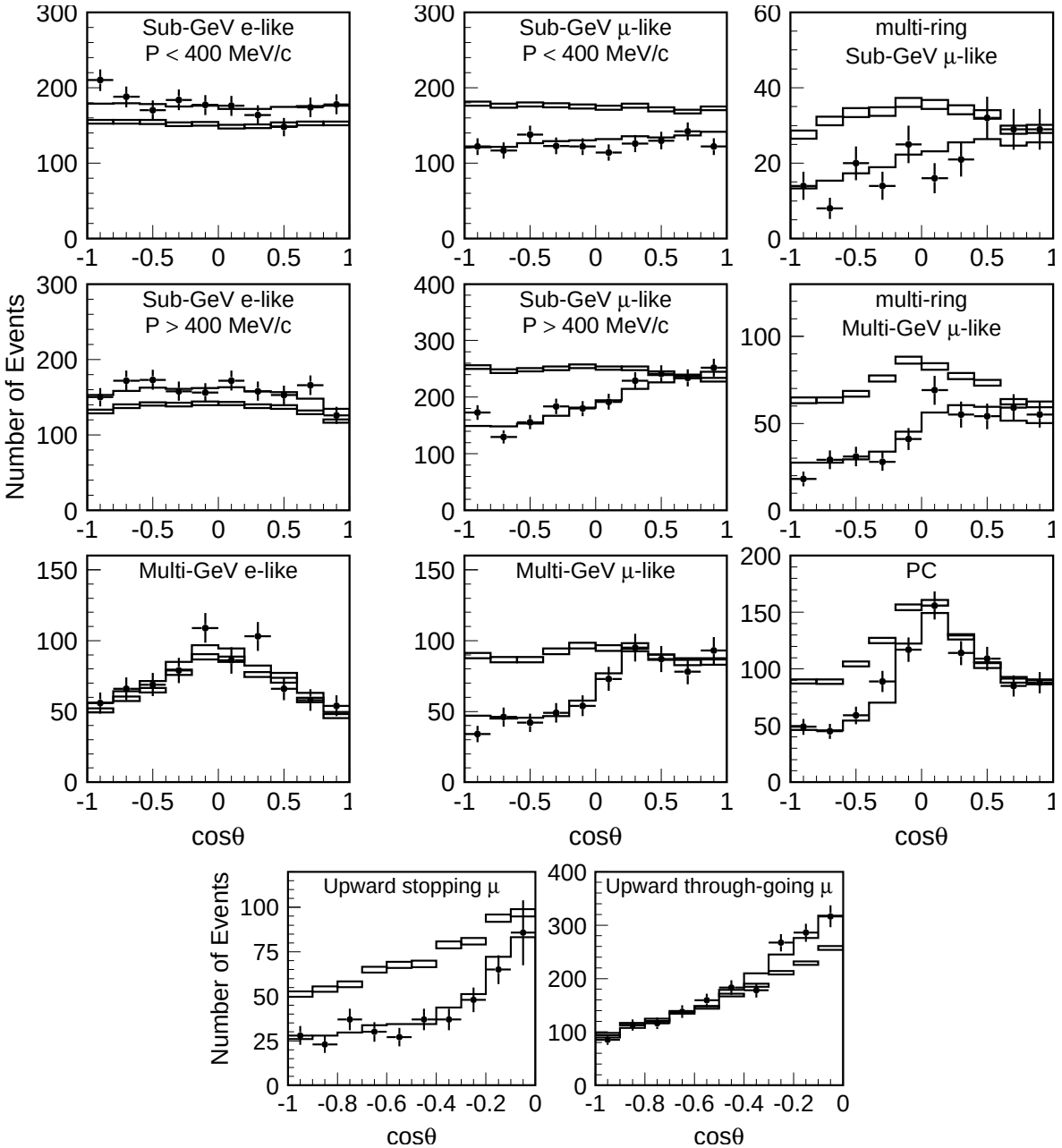
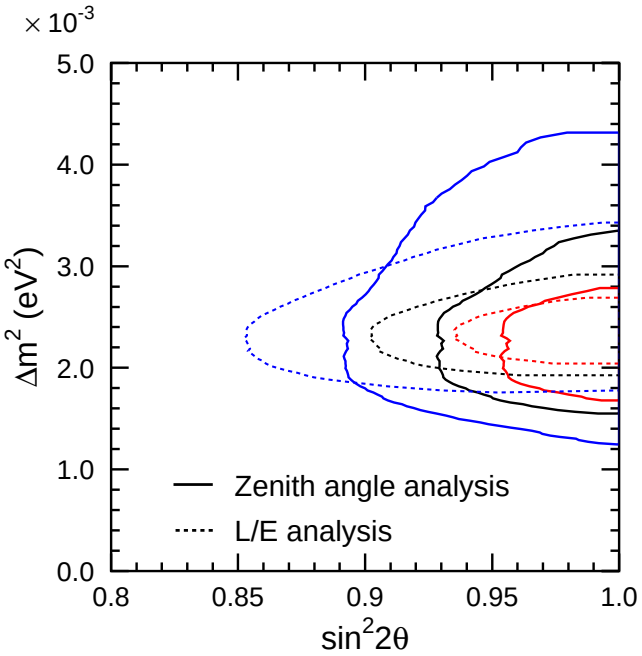


- Look for $\overline{(\nu)}_e$ and $\overline{(\nu)}_\mu$
- Flavor-ID from shape of Čerenkov ring
- Observation
  Lack of upward going $\overline{(\nu)}_\mu$

Super-K two-flavor fit: θ_{23} and $|\Delta m^2_{31}|$



Why does a two-flavor fit work?

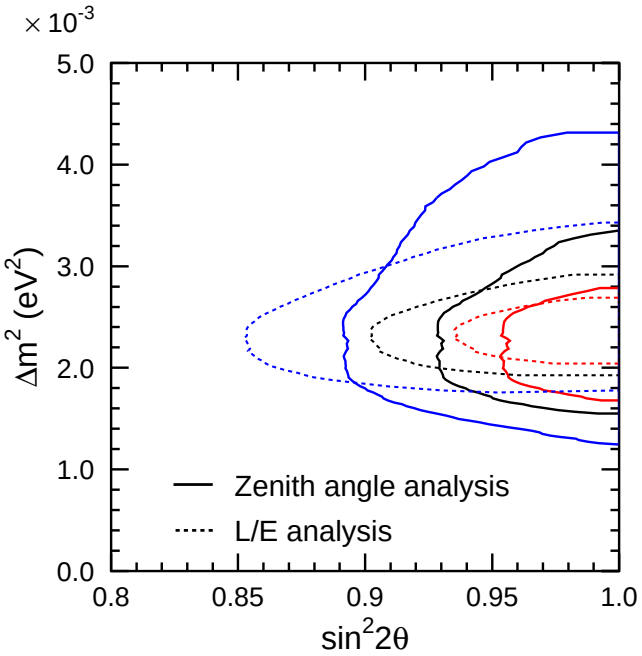
$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & 0 & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

We know today:

- $\sin\theta_{13} \ll 1$
  - Neglect θ_{13}
- $|\Delta m^2_{21}| \ll |\Delta m^2_{31}|$
  - If osc. phase $|\Delta m^2_{21}|L/2E \ll 1$ (relevant at very high E), Δm^2_{21} disappears from the expression for $P_{\alpha\to\beta}$.
  - We can then remove θ_{12} by redefining

$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \to \begin{pmatrix} \nu'_1 \\ \nu'_2 \\ \nu'_3 \end{pmatrix} \equiv \begin{pmatrix} c_{12} & -s_{12} & \\ s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Super-K two-flavor fit: θ_{23} and $|\Delta m^2_{31}|$



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We know today:

- $\sin\theta_{13} \ll 1$
  - Neglect θ_{13}
- $|\Delta m^2_{21}| \ll |\Delta m^2_{31}|$
  - At low E:

$$P_{e\to\mu} \simeq P_{e\to\tau} \simeq \tfrac{1}{2} P_{\mu\to e}$$

and

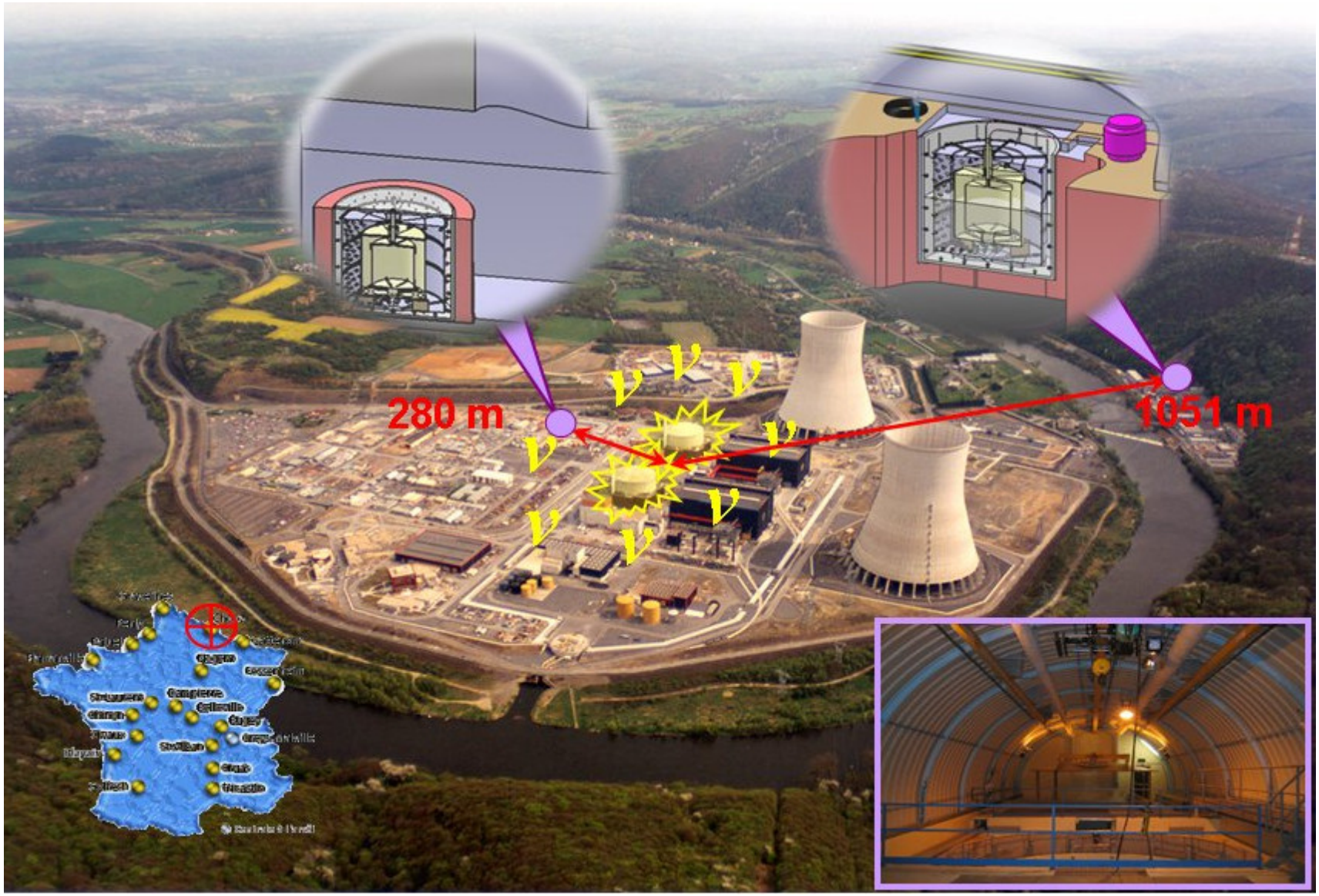
$$\phi(\nu_\mu) \simeq 2\phi(\nu_e)$$

  - $\nu_e \leftrightarrow \nu_\mu,\ \nu_\tau$ oscillations propotional to $\sin^2 2\theta_{12}$ cancel out

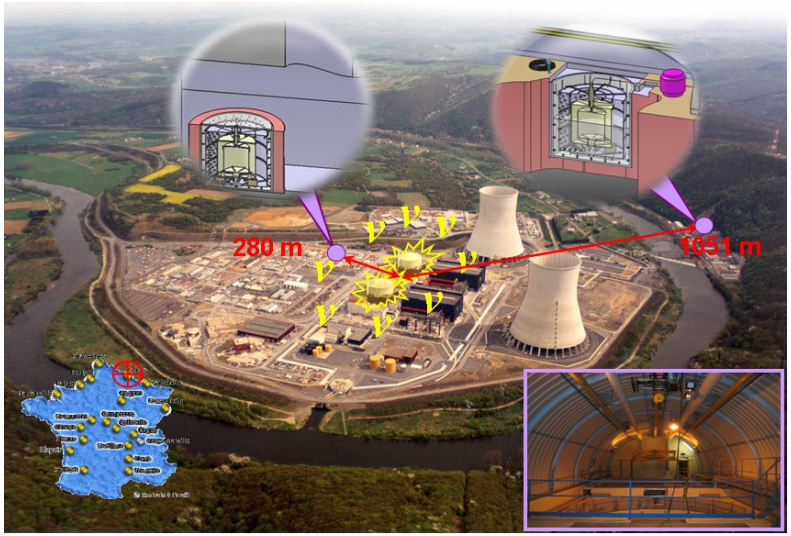
Solar neutrinos: θ_{12} and Δm^2_{21}

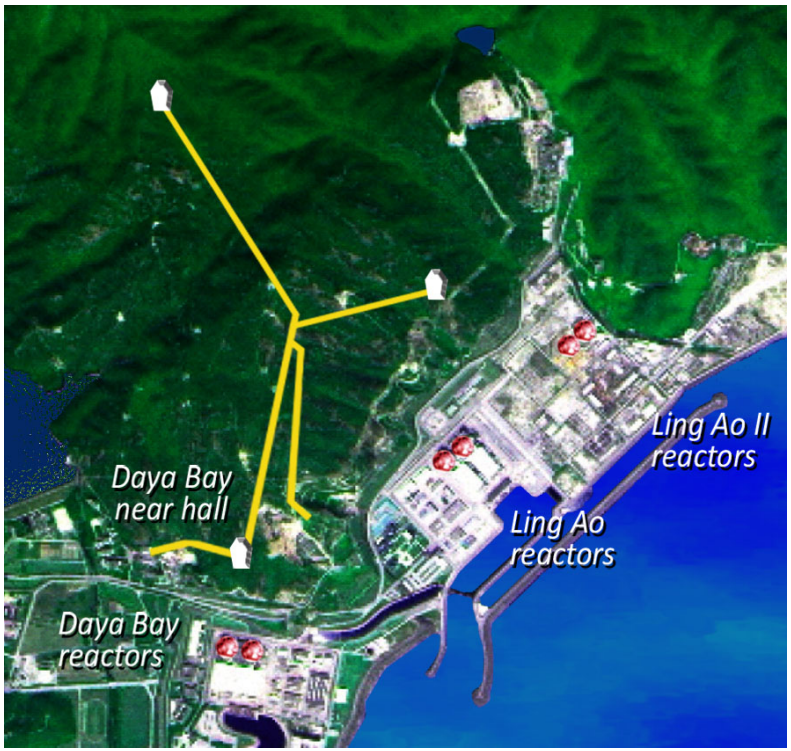
see exercises

Reactor experiments

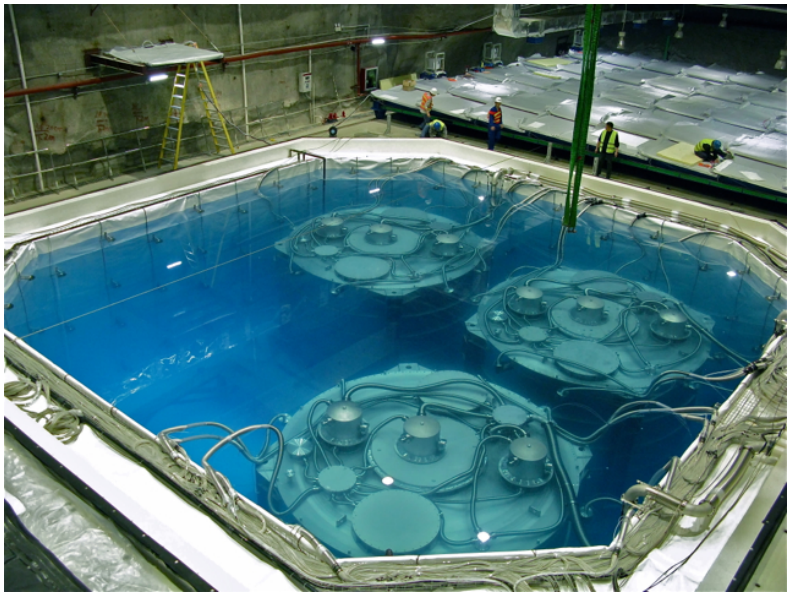


Reactor experiments: θ_{13}

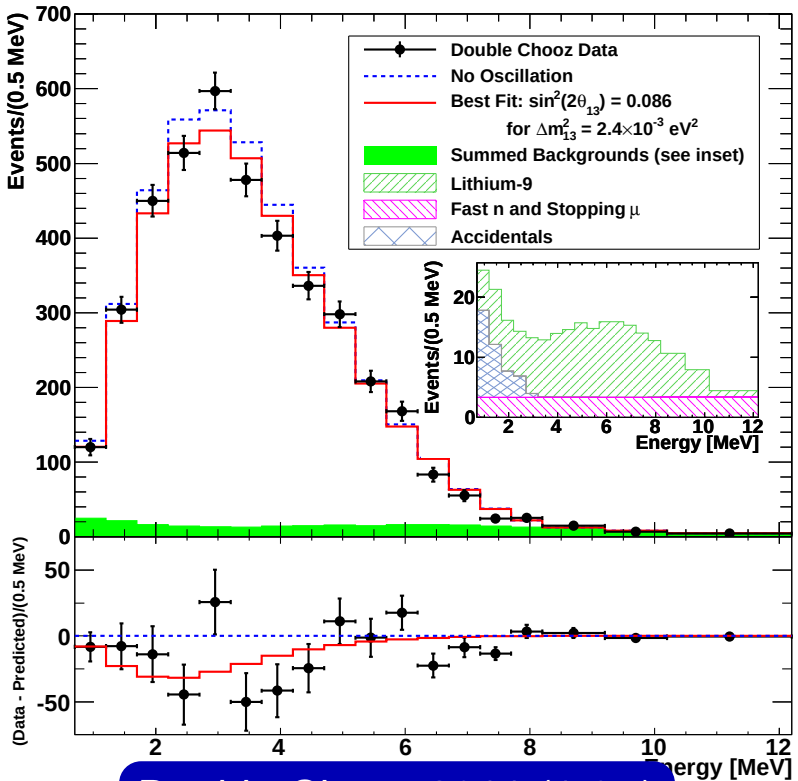




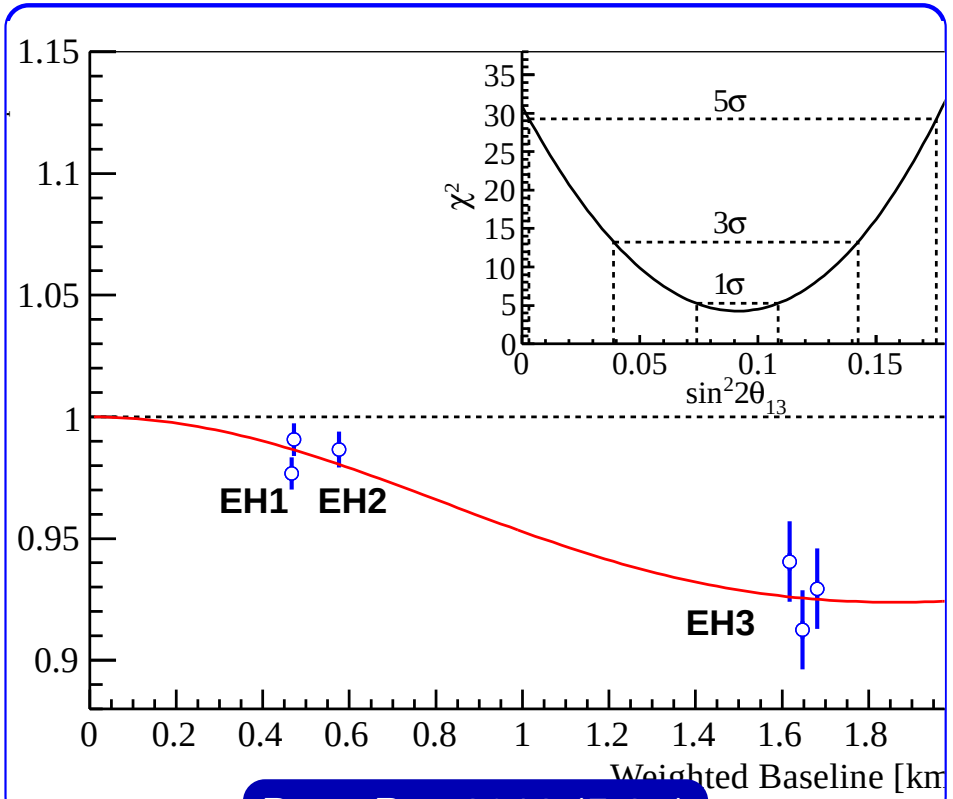
- Use $\bar{\nu}_e$ from nuclear reactor (Peak energy $\sim$ 4 MeV)
- Near detector to measure unoscillated flux and spectrum (reduction of systematic uncertainties)
- Far detector to measure oscillated flux and spectrum



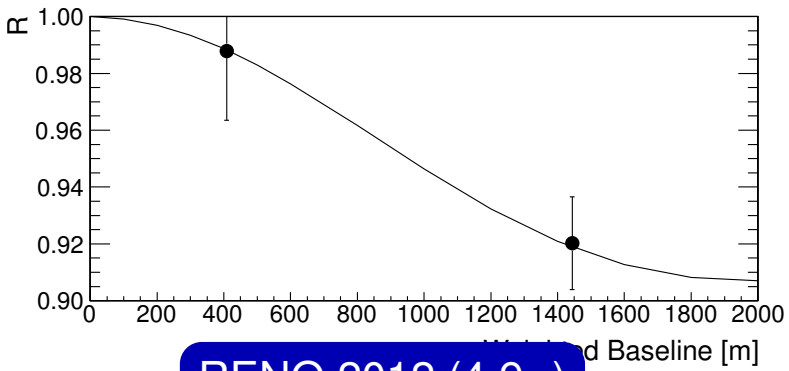
Reactor experiments: θ_{13}



Double Chooz 2011 (1.9σ)



Daya Bay 2012 (5.2σ)



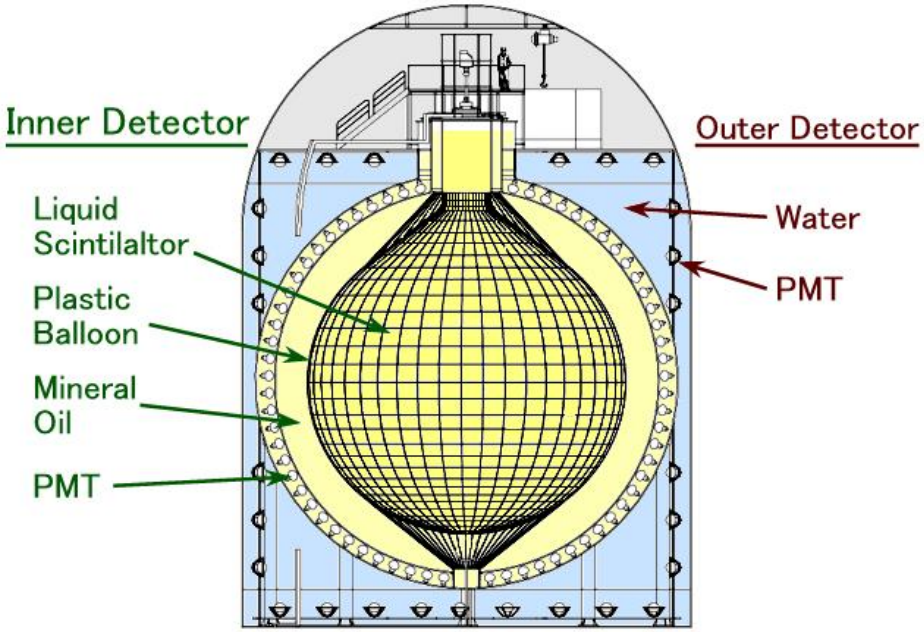
RENO 2012 (4.9σ)

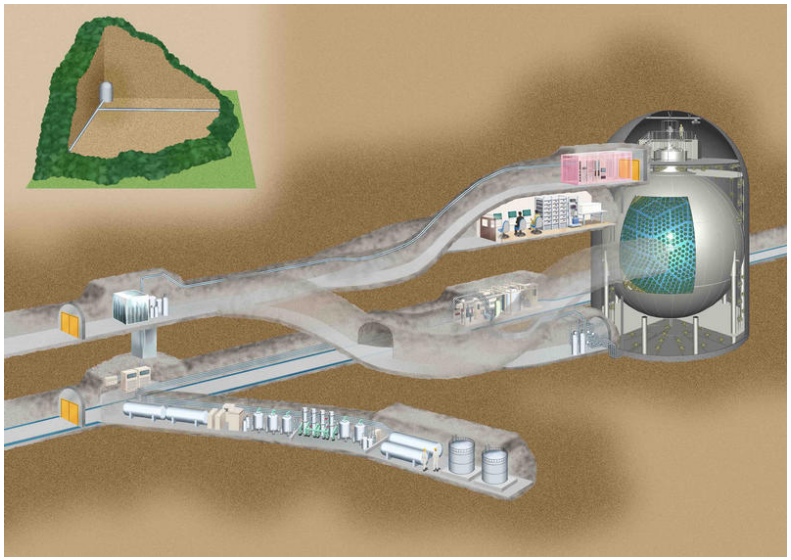
$$\sin^2 2\theta_{13} = 0.0876 \pm 0.0026$$

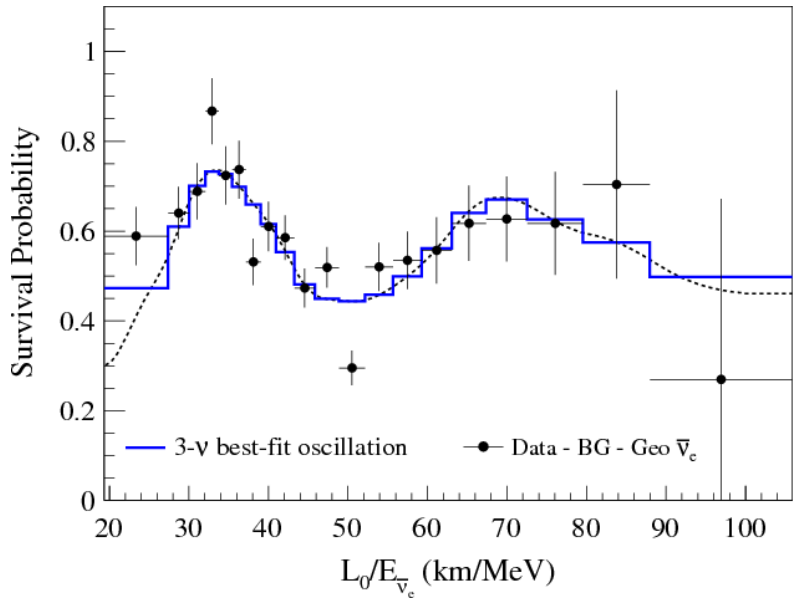
Gonzalez-Garcia et al. 1209.3023

Global best fit 2019 ($\sim 9\sigma$)

KamLAND reactor experiment: θ_{12} and Δm^2_{21}

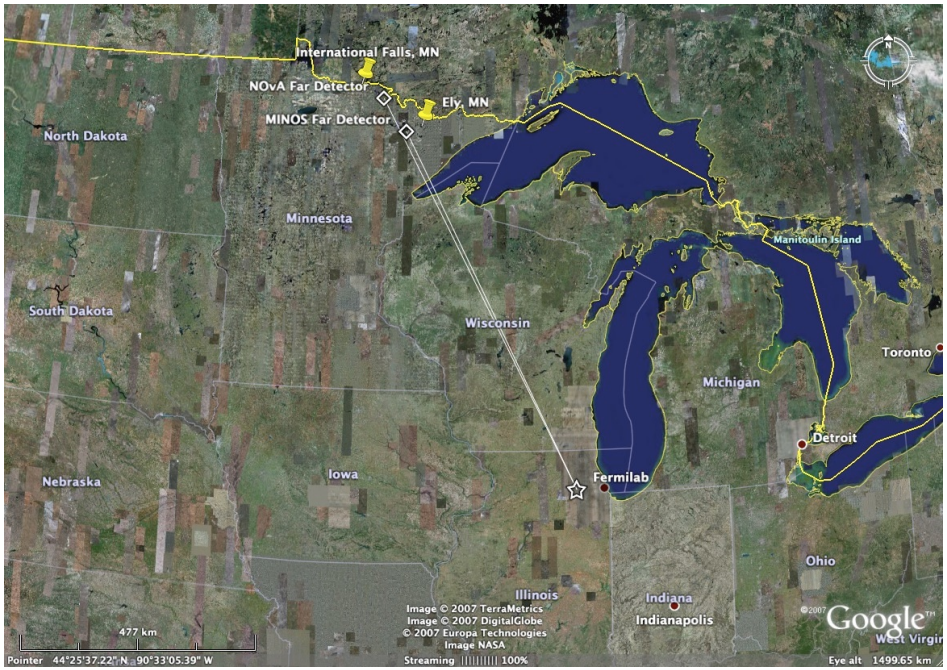


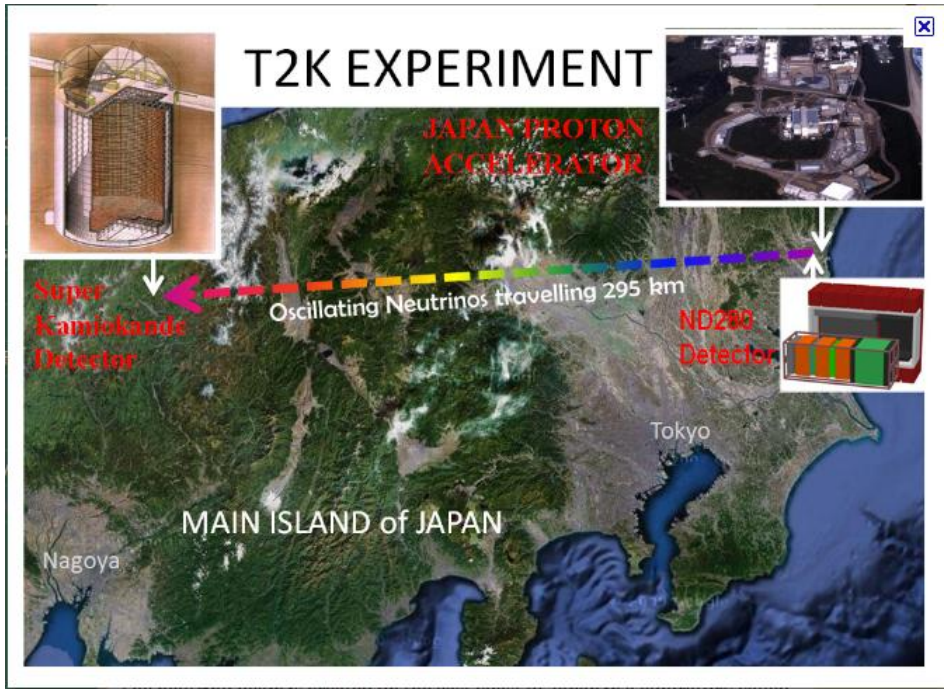




- $\bar{\nu}_e$ from Japanese nuclear reactors
- Average baseline $\sim$ 180 km.

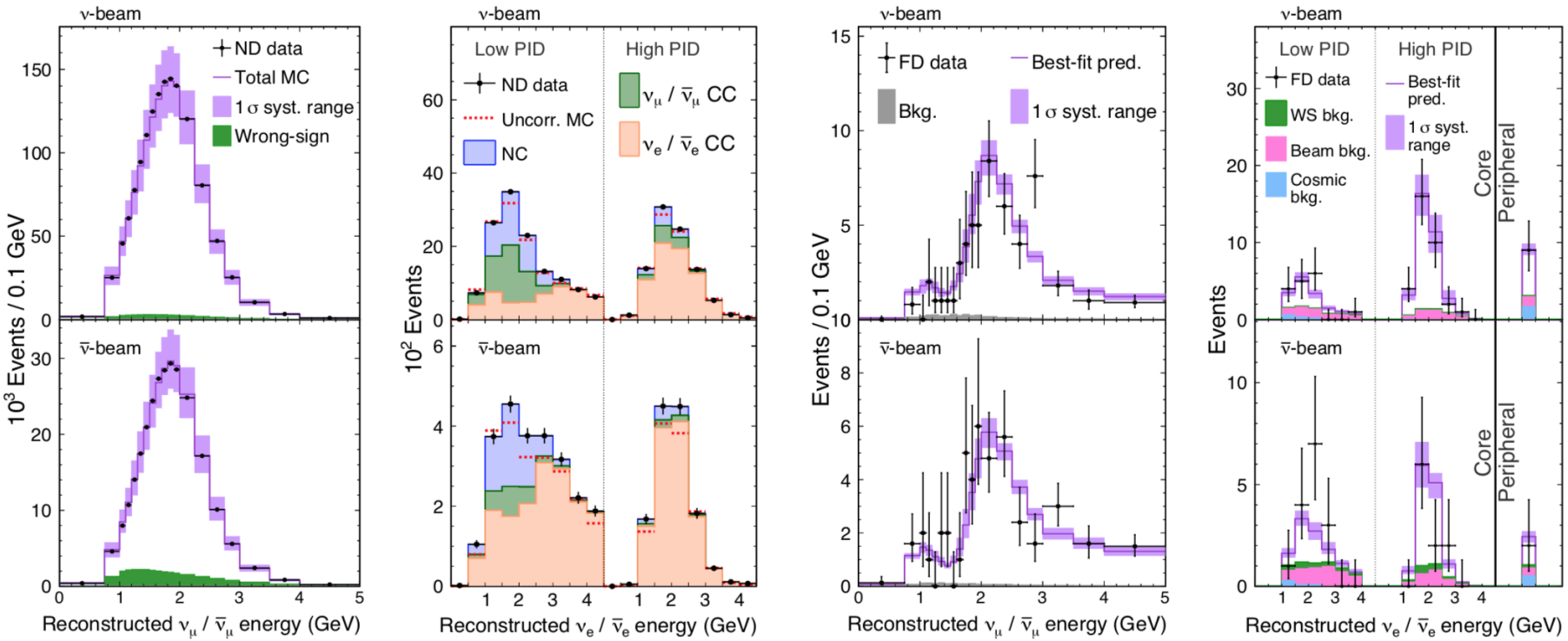
Accelerator experiments





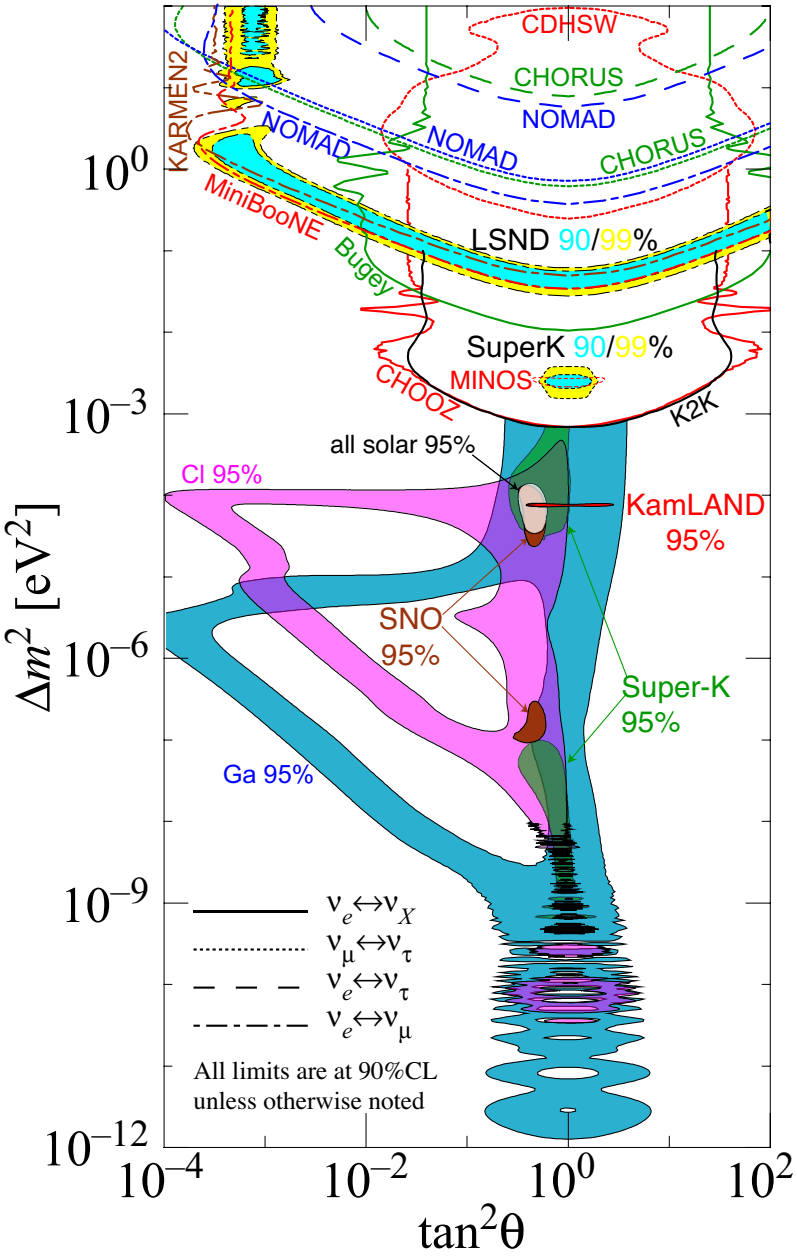
- Measure $\overset{(-)}{\nu}_\mu$ disappearance and $\overset{(-)}{\nu}_e$ appearance in a $\overset{(-)}{\nu}_\mu$ beam

θ_{23}, $|\Delta m^2_{31}|$ and θ_{13} from NOνA

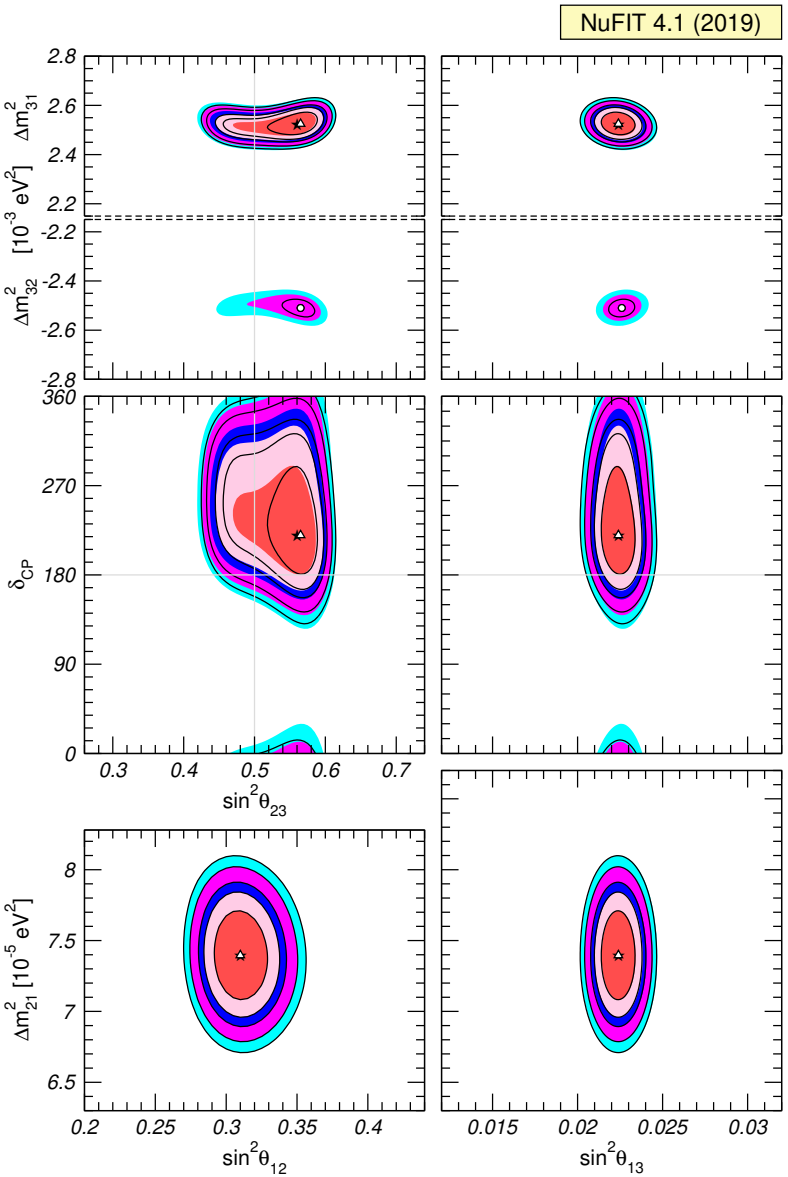


- Clear evidence for ν_e appearance
- Confirms $\theta_{13} \neq 0$

Global status of neutrino oscillations



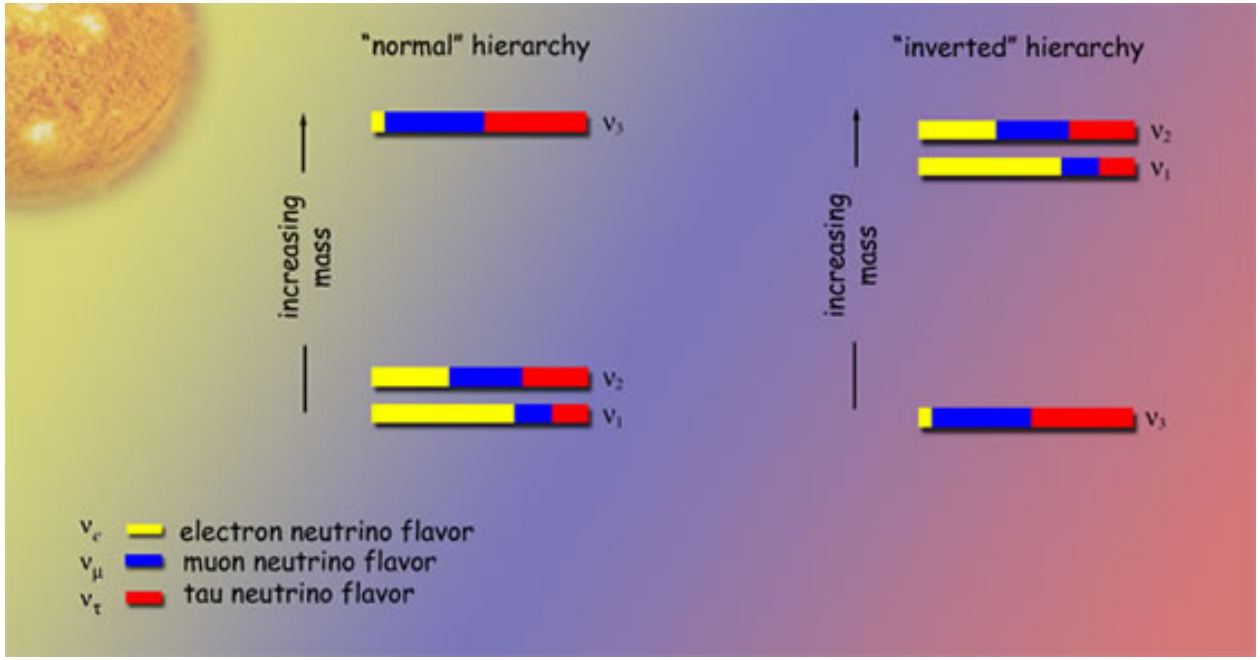
http://hitoshi.berkeley.edu/neutrino



http://www.nu-fit.org

Future accelerator experiments: $\mathrm{sgn}(\Delta m^2_{32})$

Two possible neutrino mass hierarchies:



- Distinsguishable most easily by exploiting matter effects:

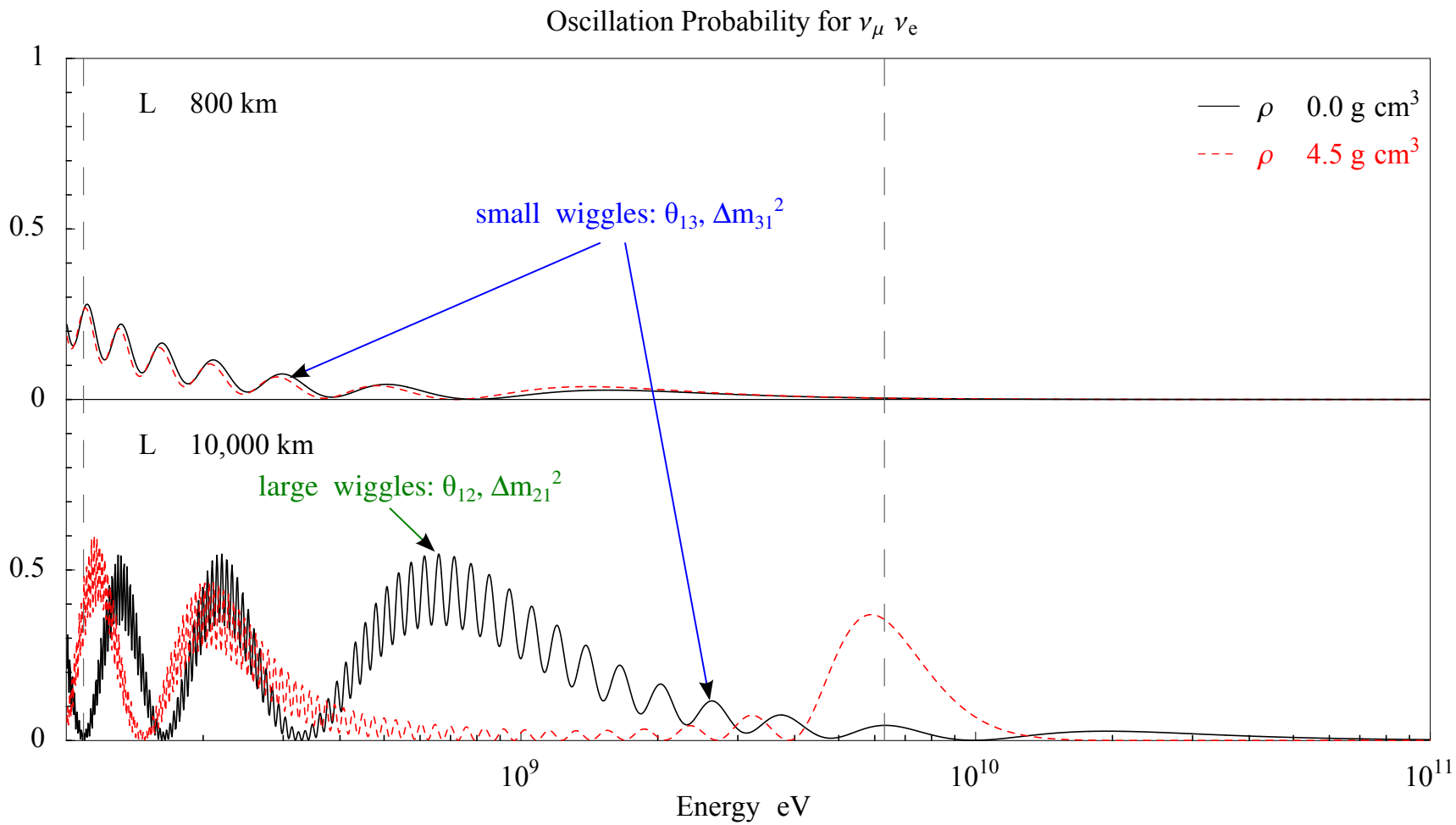
$$\sin 2\theta_{\mathrm{eff}} = \frac{\sin 2\theta}{\sqrt{\sin^2 2\theta + \left(\cos 2\theta - 2EV/\Delta m^2\right)^2}}$$

  $\Delta m^2 > 0$: Resonance for ν; $\Delta m^2 < 0$: Resonance for $\bar{\nu}$
- Note: $\mathrm{sgn}(\Delta m^2_{21})$ known from matter effects in solar neutrino oscillations

Future accelerator experiments: $\mathrm{sgn}(\Delta m^2_{32})$

Idea:

- Accelerator experiment with very long baseline ($\gtrsim 500$ km)
- Look for resonantly enhanced $\nu_\mu \to \nu_e$ oscillations



Future accelerator experiments: $\mathrm{sgn}(\Delta m^2_{32})$

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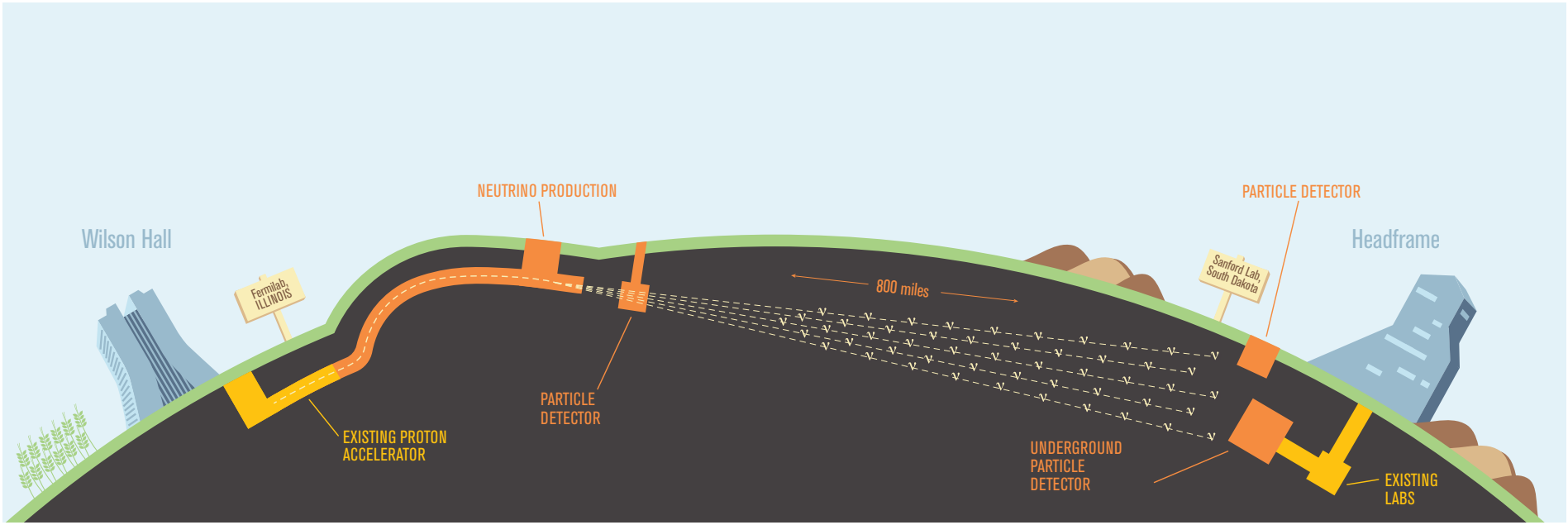


DUNE

CP violation in the neutrino sector

Remember: Leptonic mixing matrix has one complex phase, which flips sign under a *CP*- transformation

$$P_{\mu\to e} \simeq \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1+A)\Delta]}{(1+A)^2}$$

$$- \alpha \sin 2\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin A\Delta}{A} \frac{\sin[(1+A)\Delta]}{1+A}$$

$$+ \alpha \sin 2\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin A\Delta}{A} \frac{\sin[(1+A)\Delta]}{1+A}$$

$$+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 A\Delta}{A^2}$$

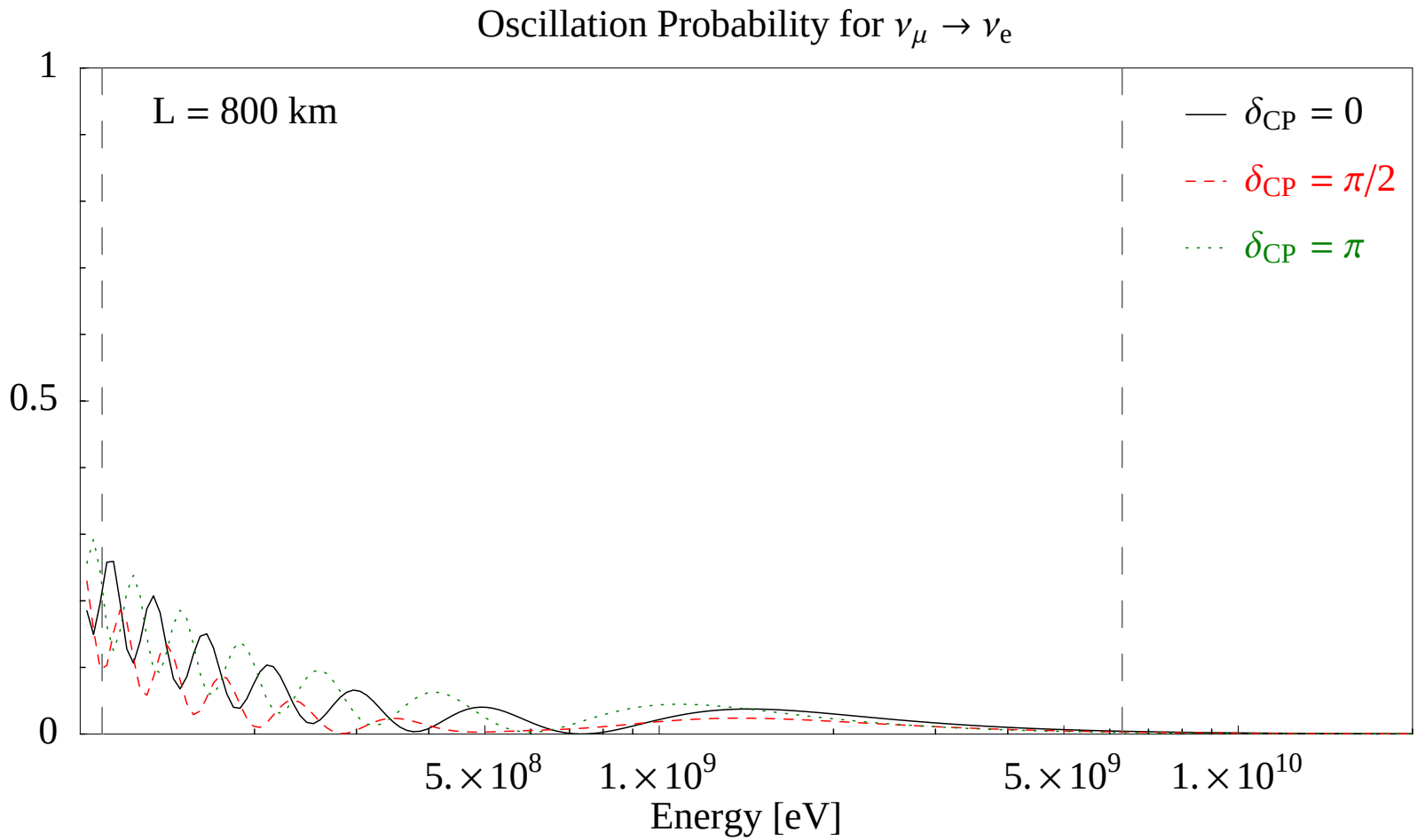
with

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}\,,$$
$$\Delta = \Delta m^2_{31} L/4E\,,$$
$$A = 2\sqrt{2} G_F n_e E/\Delta m^2_{31}$$

Akhmedov et al. hep-ph/0402175

CP violation in the neutrino sector

Remember: Leptonic mixing matrix has one complex phase, which flips sign under a *CP*- transformation



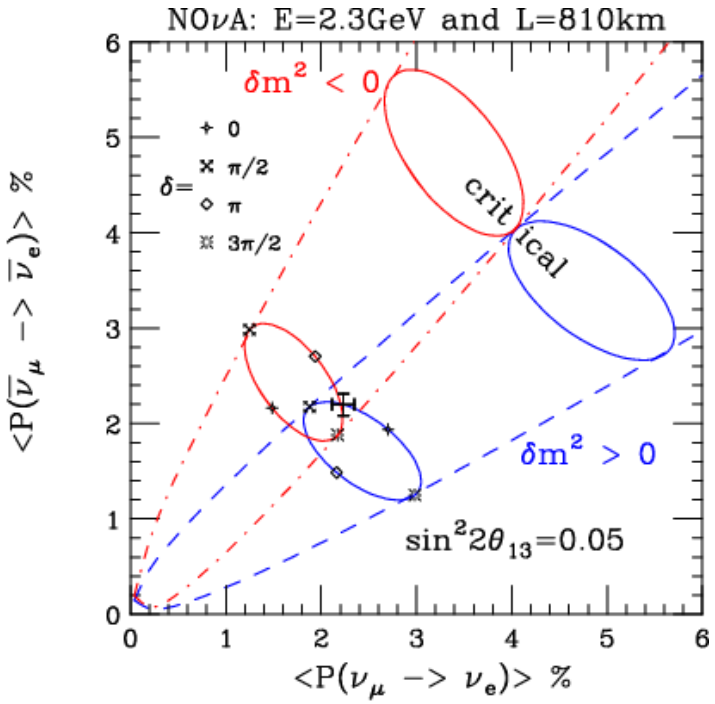
CP violation in the neutrino sector

Remember: Leptonic mixing matrix has one complex phase, which flips sign under a *CP*- transformation

Strategy: Precision measurement of $\nu_\mu \leftrightarrow \nu_e$ oscillations

Main challenge: Disentangling effect of δ_{CP} from

- CP violation due to matter effects
- Uncertainties in other oscillation parameters



Stephen Parke 0807.3311