Review of underground physics

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Lecture n 1

IDPASC

Otranto School

Outline

- Motivations
- Rare event physics
- Underground laboratories

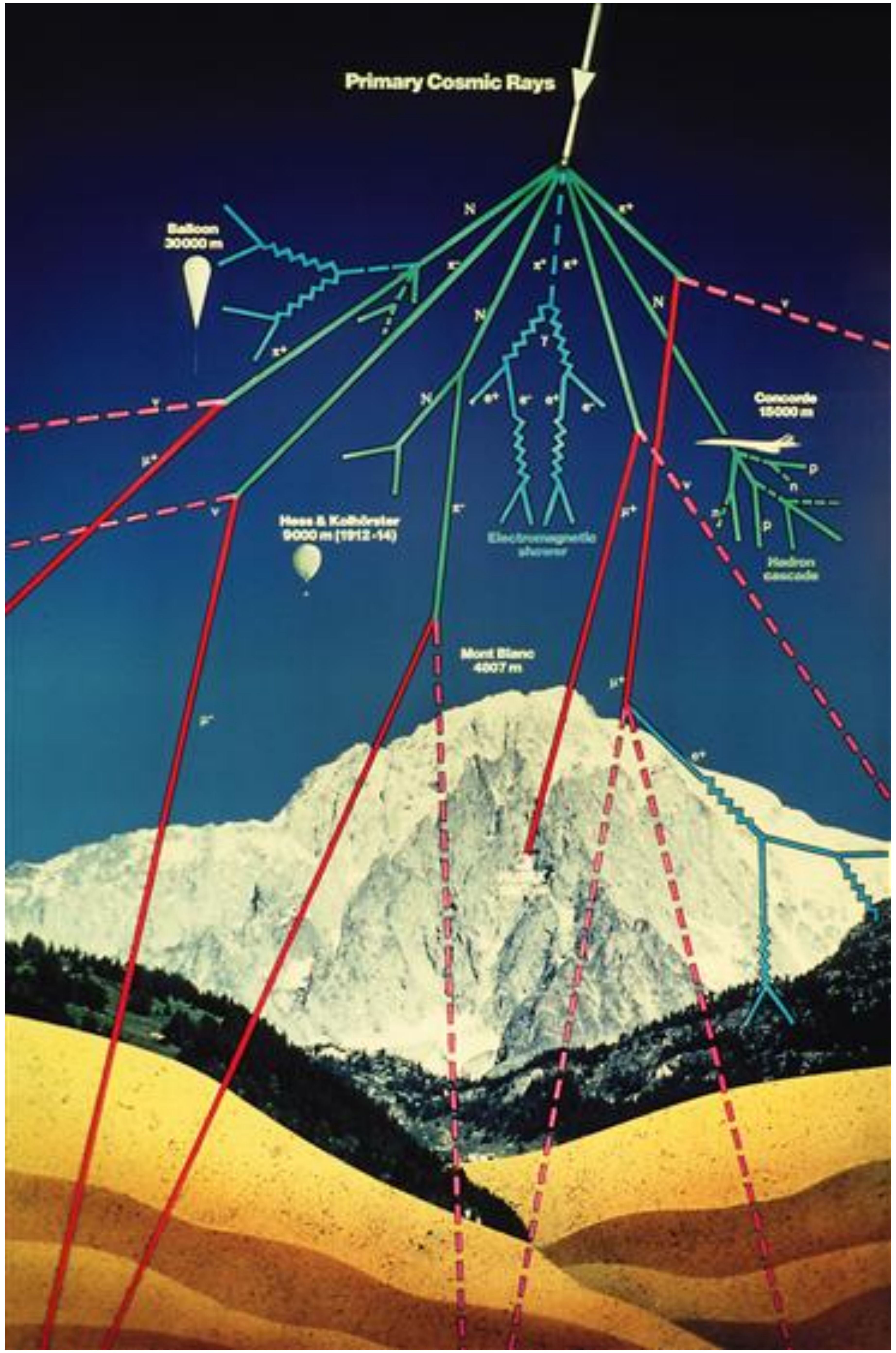
Astro-particle:
- Neutrino physics
- Rare Nuclear decays
- Dark matter
- …

Other:
- Nuclear reactions
- Gravitational waves
- Fundamental physics
- Technology
- Biology
- …

No mention to:
- Under-water
- Under-ice

Cosmic rays

- high-energy radiation (mainly from outside the Solar System)
- impacting with the Earth's atmosphere produce showers of secondary particles
  - ➡ production of many secondaries
- composition: mainly high-energy protons and atomic nuclei
- spectrum: span several orders of magnitude in energy
  - ➡ highest available energy radiation (research)
- **nuisance for particle physics experiments (in particular rare event searches)**



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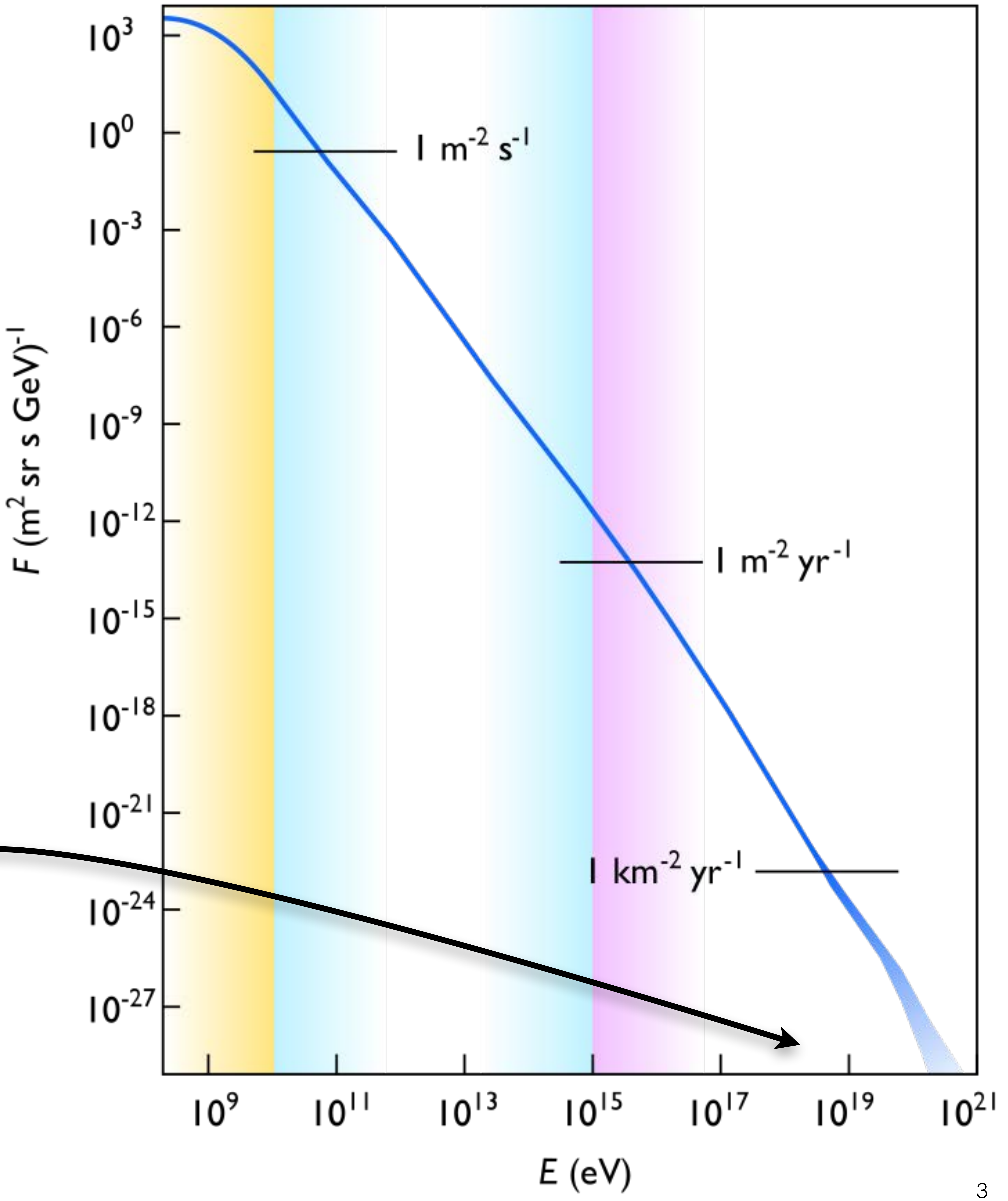


Underground laboratories:

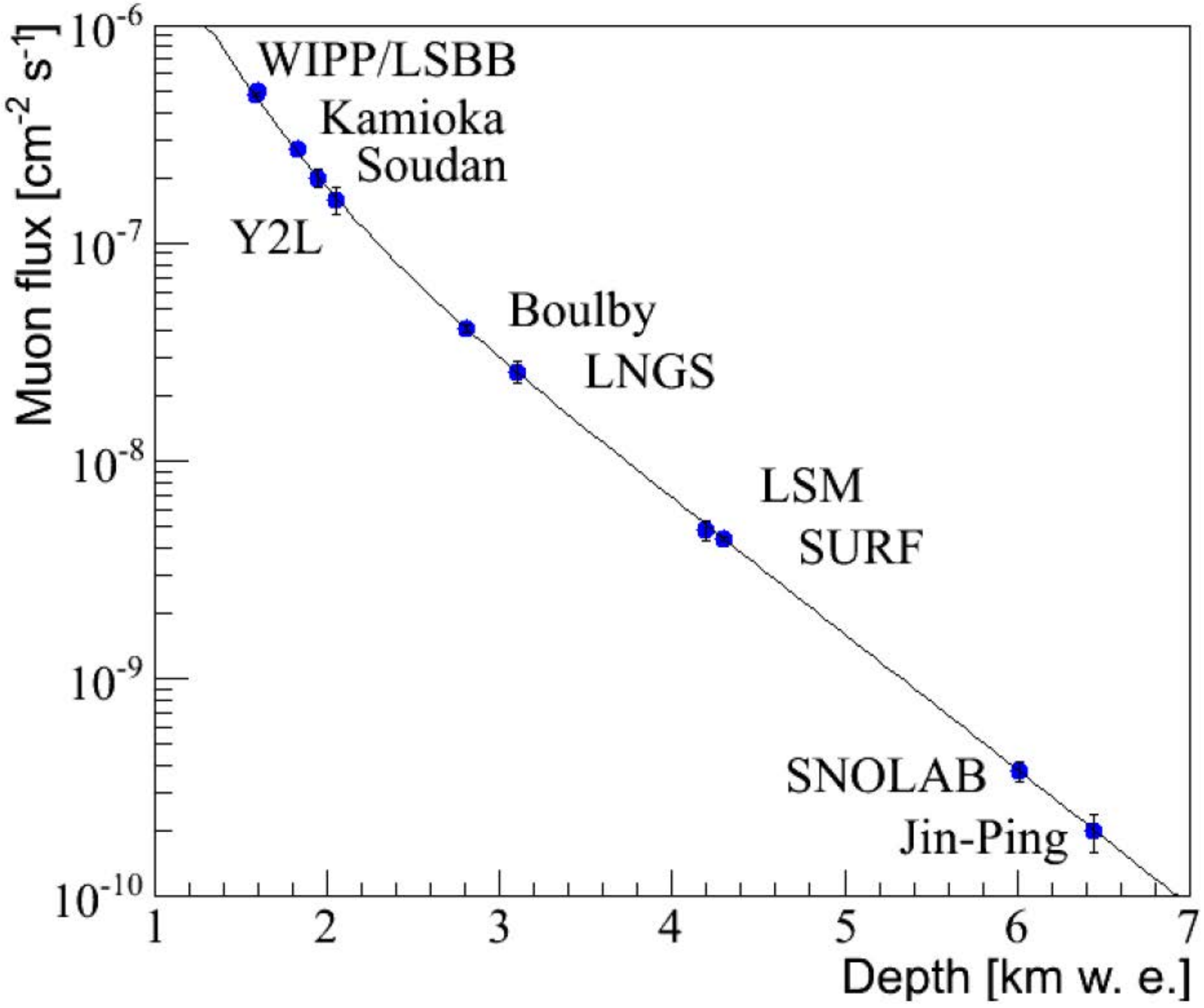
- Offer a natural and (relatively) cheap shield from cosmic radiation
- Provide the low radioactive background environment necessary to explore the highest energy scales
  - Search for very rare phenomena
    - ➡ Challenge: background control and reduction.

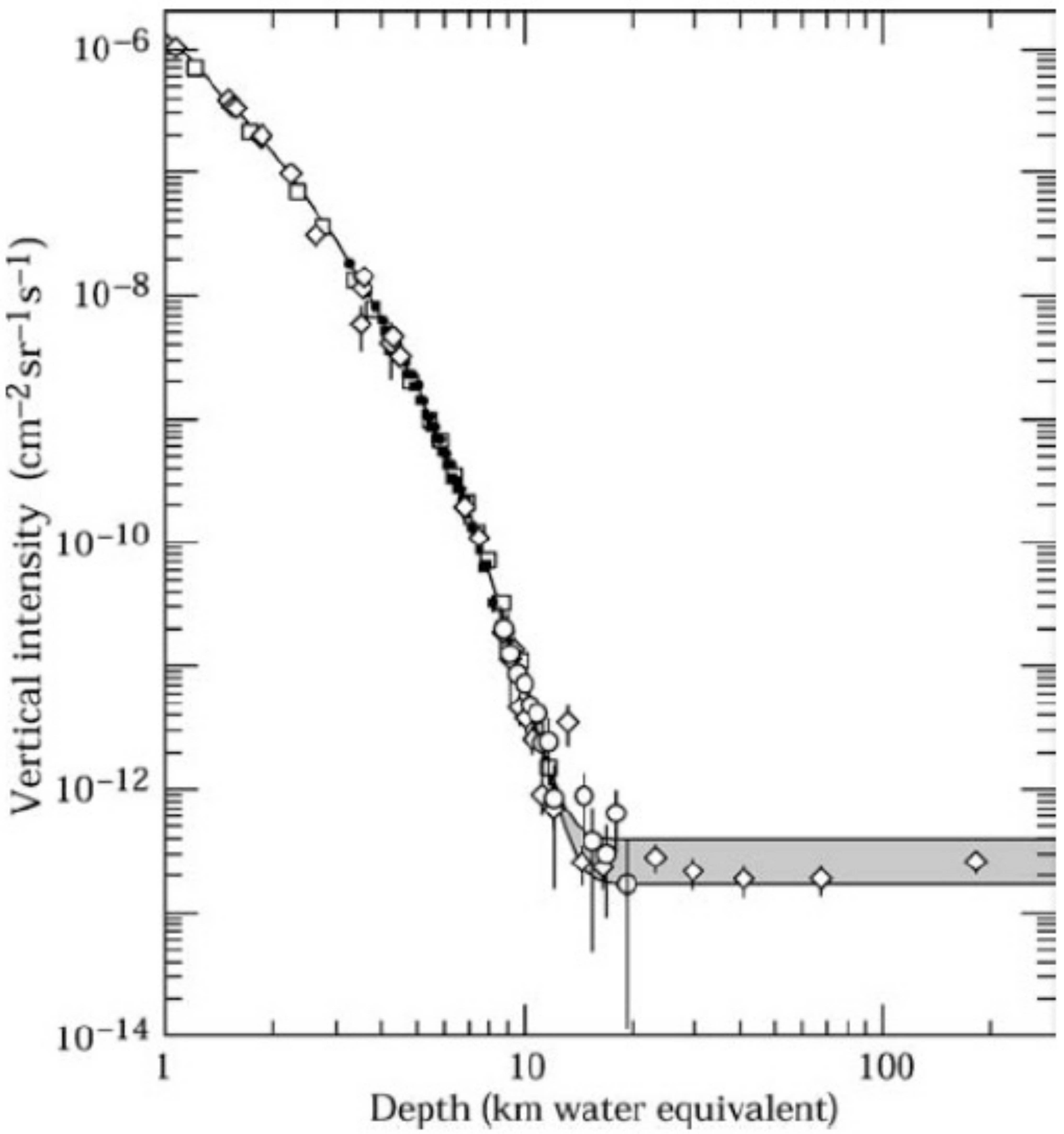
- Underground experiments provide an indirect reach to the **highest energy scales**.
  - m_ν ~ 50 meV corresponds (see-saw mechanism) to 10^{16} GeV
- The higher the energy the more rare are the corresponding phenomena.
  - extremely low backgrounds.

- There are important physical and practical differences between the existing facilities.
  - These range from fully developed laboratories to simple underground sites.
- The muon flux decreases with the thickness of the rock overburden, roughly, but not exactly, exponentially. However depth is not the only relevant parameter

CUPP
Boulby
SOUDAN
SNOLab
SURF
LSM
LSC
LNGS
BNO
Kamioka
WIPP
CUNPA
CJPL
INO
ANDES
Tau Tona
Stawell

An effective natural shield



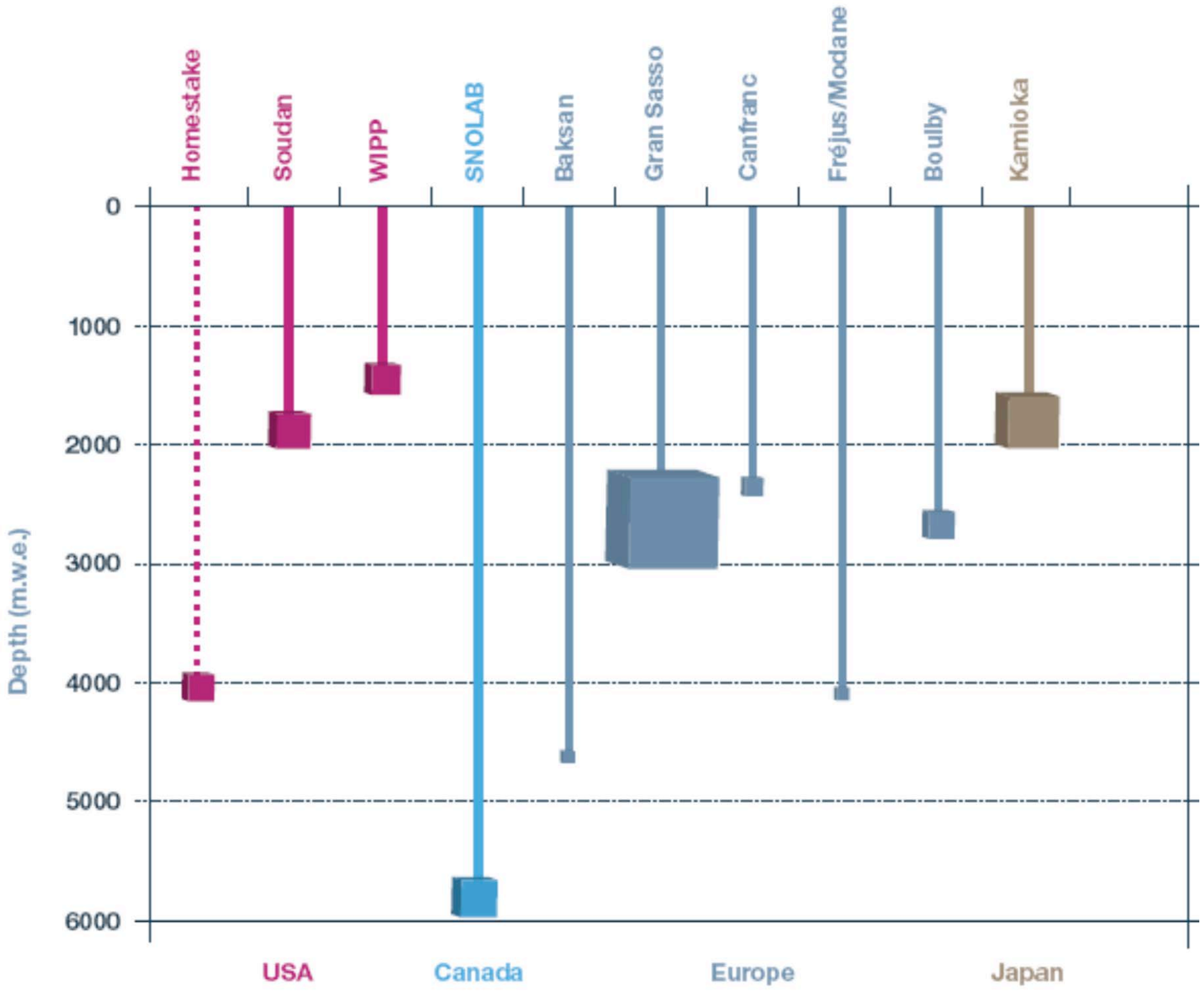


Factors to consider (1/2)

A simple underground cavity is NOT a laboratory

➡ Important differences

- Depth (μ flux, spallation n flux)
  - Important but “the deeper is not the better” statement.
  - Optimum depth depends on physics
  - Determines only a fraction of the background sources
  - Maximum cavity size decreases with increasing depth, costs increase
- Dimensions
  - Diameter & height of the halls may limit the thickness of the shields
  - Depend on rock quality and depth
- Accessibility (vertical vs horizontal)
  - May limit detector size
  - Costs increase
  - May affect safety



Factors to consider (2/2)

- Distance from accelerator (>1000 km for sign(Δm^2))
- Support infrastructures (facilities), personnel (quantity and quality)
- Underground area allocation policy, turnover of experiments
- Laboratory vs. observatory
- Scientific Committee: international vs. local (or national)
- Degree of internationality of the community
- Outreach and education
- Safety and security policy
- Environment
  - Affects temperature and noise
  - Environmental radioactivity
- Other science (geology, biology, engineering, etc.)

Existing underground labs characteristics

	SNOLab	LNGS	LSC	Boulby	LSM	Callio Lab	Baksan	SURF	CJPL-I/II	Kamioka	Y2L
Date of creation	2003 (1991)	1987	2010	1989	1982	1995	1967	2007 (1967)	2009/ 2014	1983	2003 A6 2014 A5
Personnel	100	106	12	6	12	13	227	125	20	94	4
Surface U/S [m^2]	5350/ 3100	17000/ 95000	1600/ 2550	1700/ 400	400	220	1600/ 10000	1900/ 190	8000	15000/ 3000	300/ 60
Volume [m^3]	30000	**180000**	10000	7200	3500	1000*	23000	7160	4000/ **300000**	150000	5000
Depth [m]	2070	1400	850	1100	1700	1440	1700	1500	2400	1000	700
Access [V or H]	V	H	H	V	H	V / drive in	H	H	H	H	Drive in
Makeup Air [m^3/h]	12000	35000-60000	20000	300	5500	3600	1440	510000	–	6000	3300
Air change/day	10	5-8	48	24	38	7	–	144 (LUX)	–	6	15
Muon flux [m/m^2/s]	$3.1\ 10^{-6}$	$3\ 10^{-4}$	$3\ 10^{-3}$	$4\ 10^{-4}$	$4.6\ 10^{-5}$	$1\ 10^{-4}$	$3\ 10^{-5}$	$5.3\ 10^{-5}$	$2\ 10^{-6}$	10^{-3}	$4\ 10^{-3}$
Radon [Bq/m^3]	130	80	100	**<3**	15	70	40	300	40	80	40
Cleanliness	2000 or better	Only in sector	Only in sector	10000	ISO9	Only in sector	Only in sectors	3000	Only in sectors	Only in sectors	Only in sectors

Upcoming facilities characteristics

	SUPL	ARF	ANDES
Expected to be in operation	end of 2018	mid-end of 2019	2027
Personnel	3	20	–
Access	Drive in	V / drive in	H
Volume [m^3]	3025	47000	70000
Surface [m^2]	350	2000	2800
Outside surface [m^2]	100	1000	Foreseen building
Depth [m]	1025	1100	1750
Muon Flux [$\mu/m^2/s$]	$3.7\ 10^{-4}$	$\sim 10^{-3}$	$\sim 5\ 10^{-5}$
Makeup air [m^3/h]	From the mine through Rn purification	7840	-
Air change/day	96	6	-
Cleanliness requirement	Yes (SNOLab style)	Only in sectors	–

Backgrounds

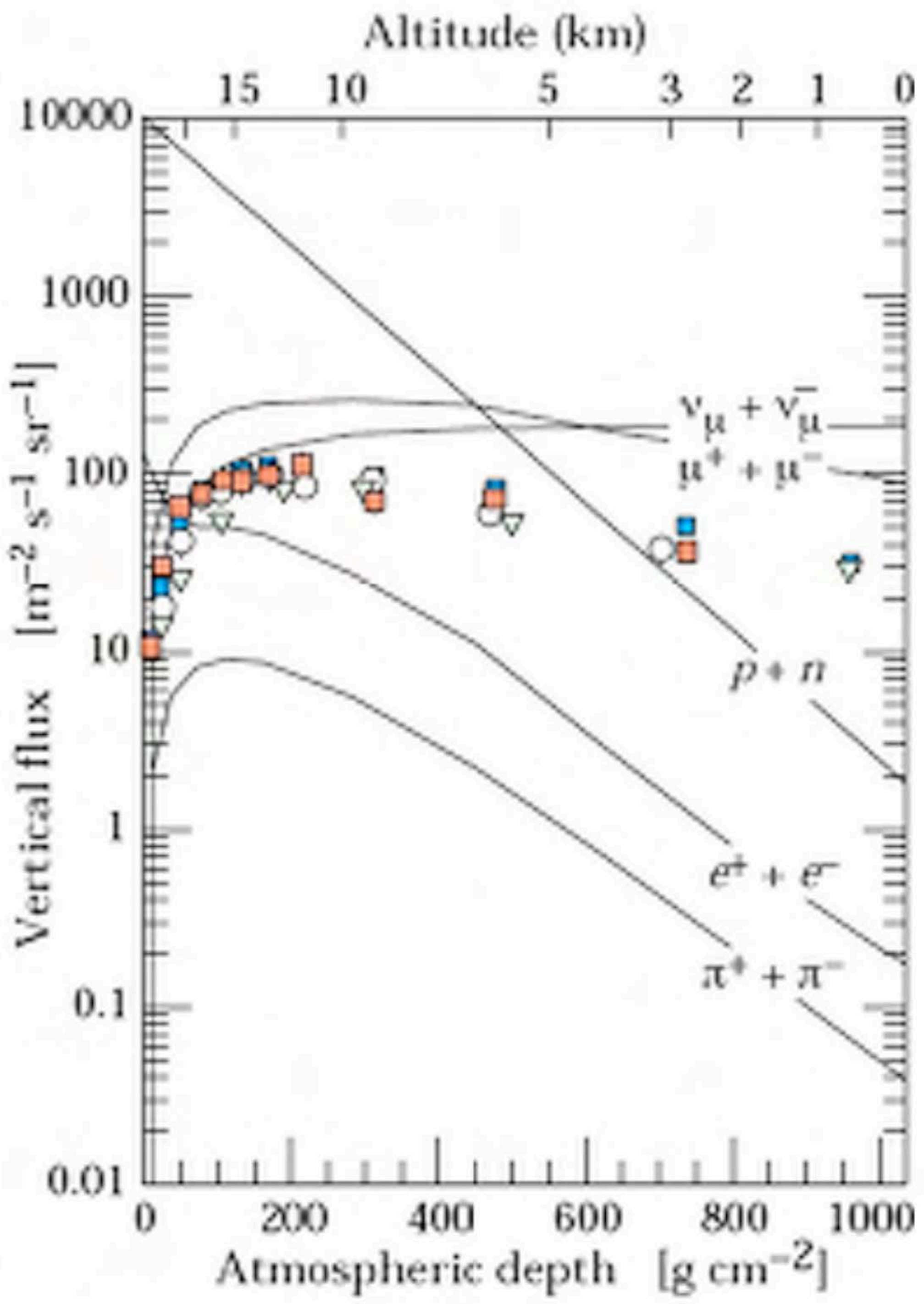
- In general, every interaction of a particle with the detector risks to contribute some background:

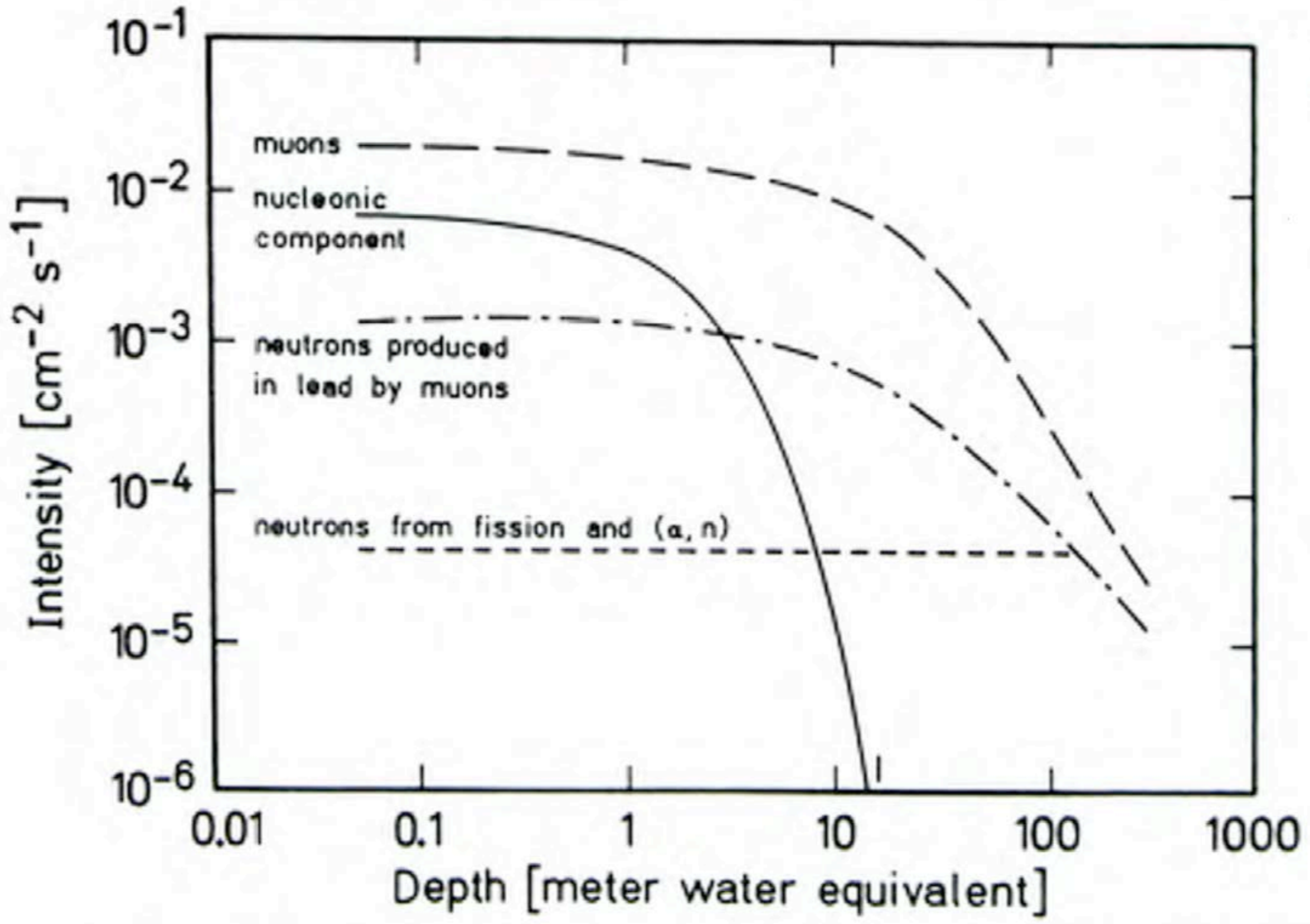
Muons
- Direct energy deposition in detector
  - Sometimes extremely high
  - Continuous: can deposit any amount of energy
  - Neutrons, radioisotopes

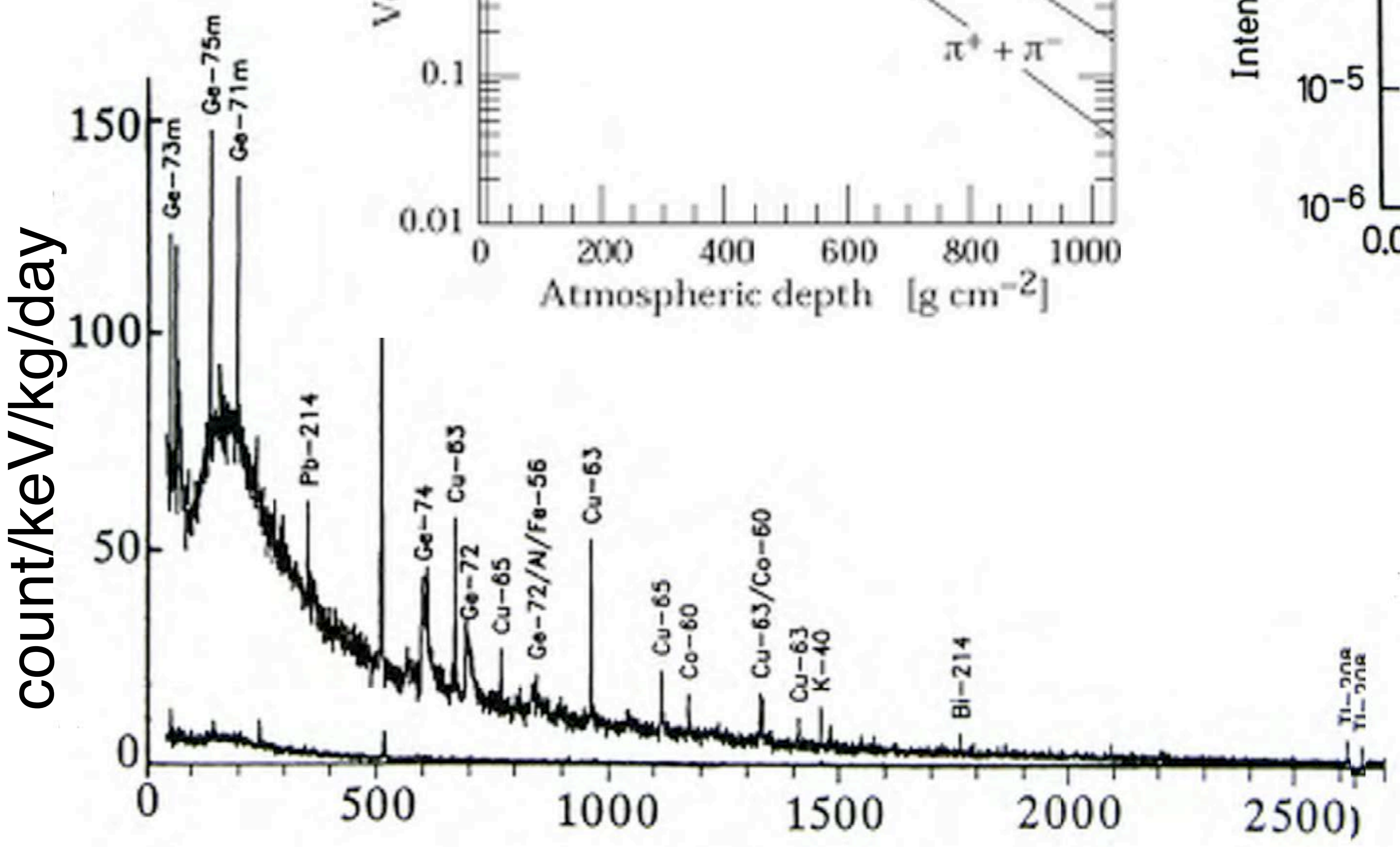
Neutrons
- Direct nuclear collisions: continuous spectra
  - Create radioisotopes with various signals: discrete
  - Beta-neutron sources: 8He, 9Li, for example
  - Beta-only: 9C, 12B, 12N, for example
  - Gammas: 60Co, for example
  - Q-values of decays could be in right range to mimic energy deposition of signal

Gammas
- Direct energy deposition in detector
  - Natural radioactivity lines
  - Continuous up to 2.6 MeV

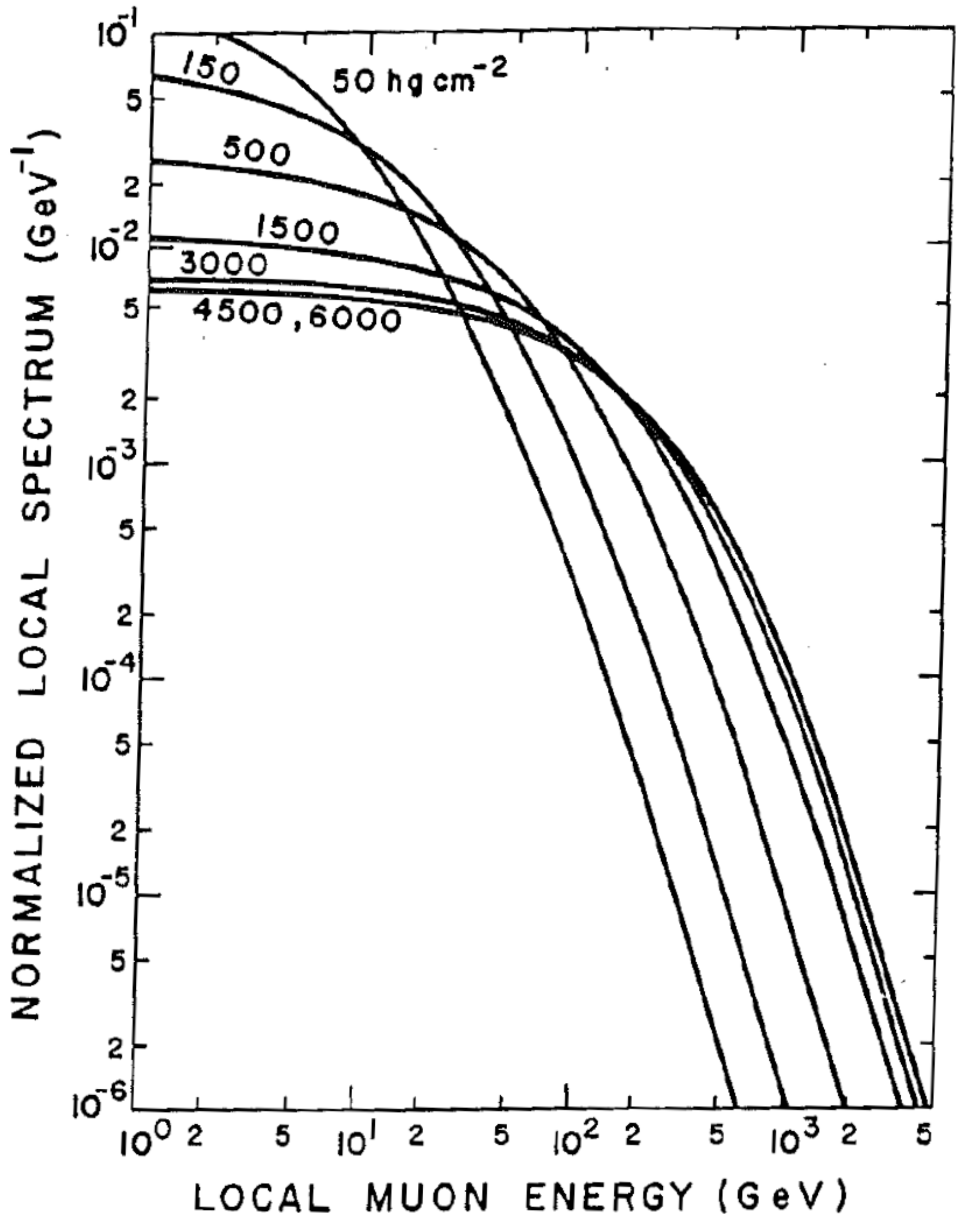
- Underground labs provide an essential protection ….







Muons



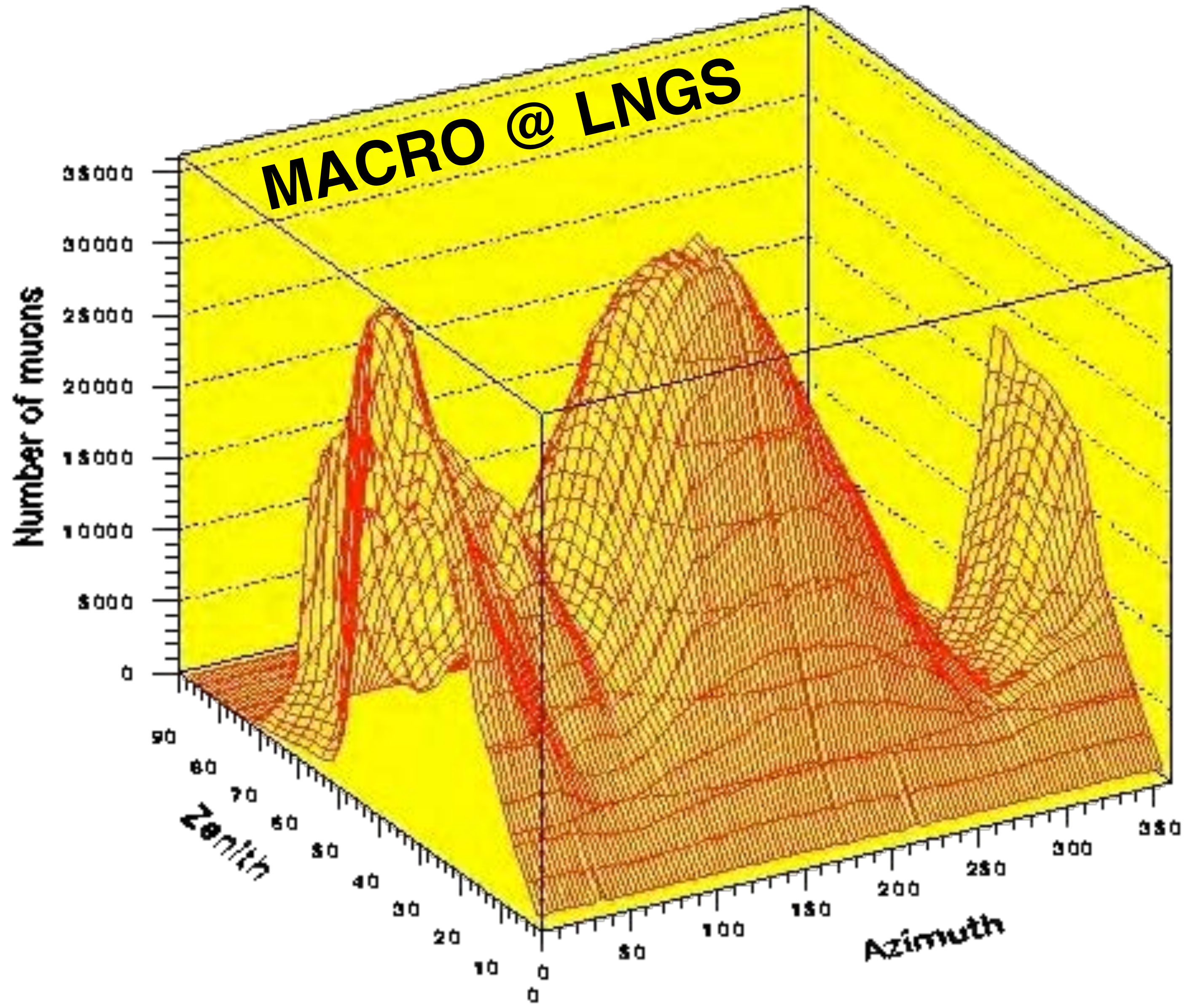
Created by decays of cosmic koans and pions

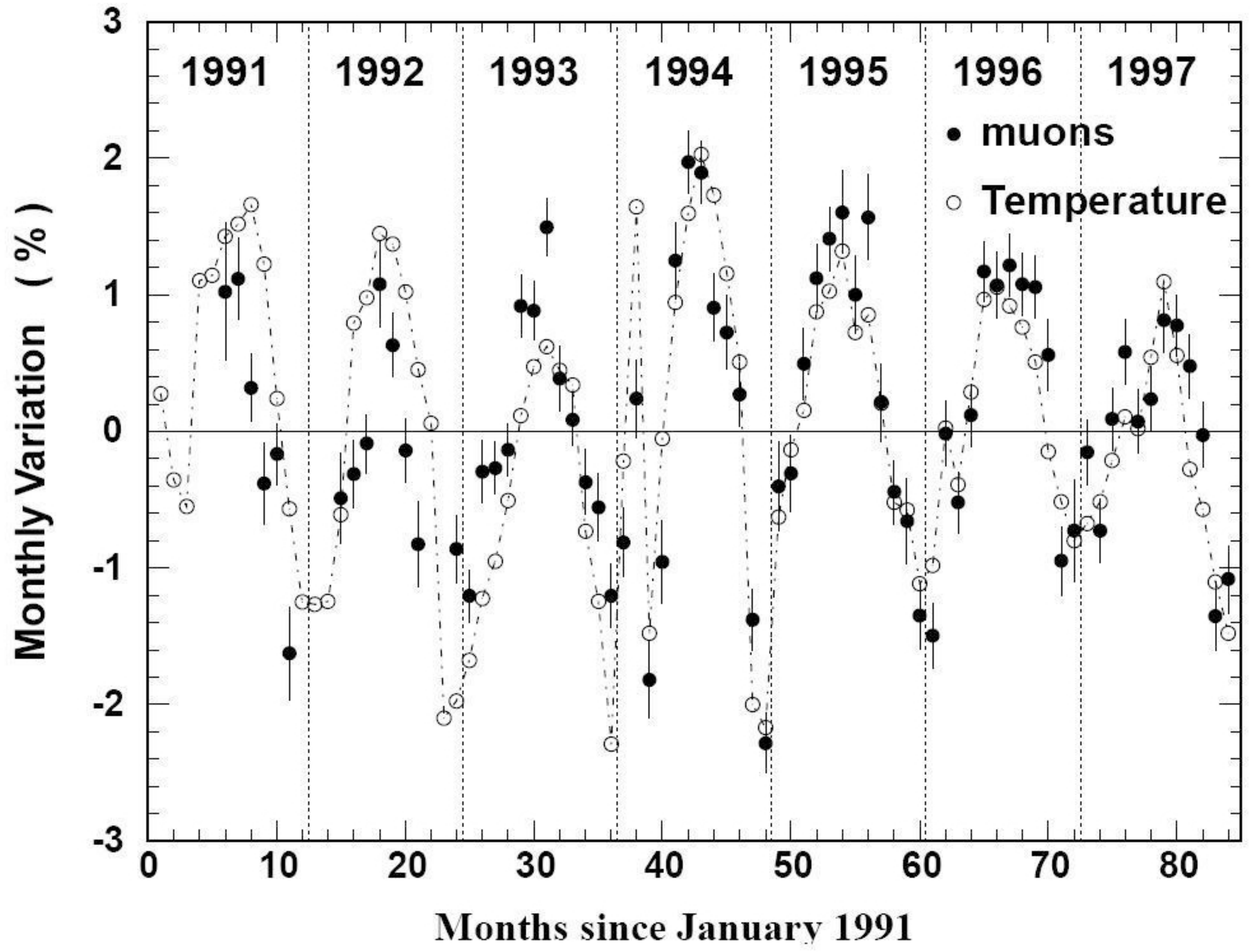
- Interactions with matter underground:
  - Ionization energy loss: more or less constant
  - Loss from bremsstralung, nuclear interactions, EM showers (proportional to E)
- General solution for energy: $\langle E(X)\rangle = (E_0 + \epsilon)e^{-X/\xi} - \epsilon$
- Only high-energy muons go deep

Location	Depth (km.w.e.)	$E_0^{\min}$ (TeV)
KGF	≤ 7 (many levels)	10 (deepest level)
Homestake	4.4	2.4
Mont Blanc	~ 5	~ 3
Frejus	~ 4.5	~ 2.5
Gran Sasso	~ 4	~ 2
IMB	1.57	0.44
Kamiokande	2.7	~ 1
Soudan	1.8	0.53

Experimental sites must be characterized

- angular dependence of the μ flux d(θ,ϕ)
- seasonal variations of the μ flux
- energy dependence of n flux
- seasonal variations of the n flux
- γ flux
- Rn activity continuous monitoring





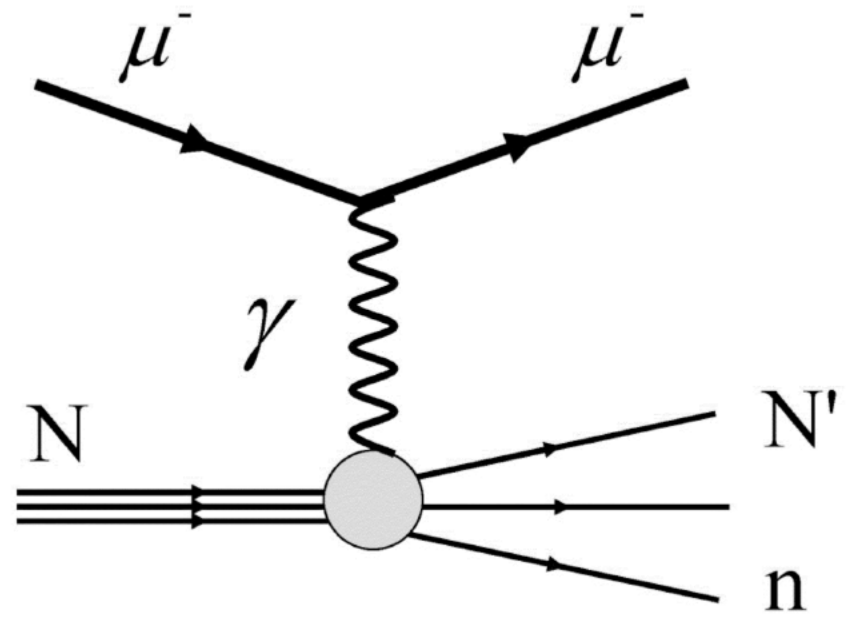
Neutrons

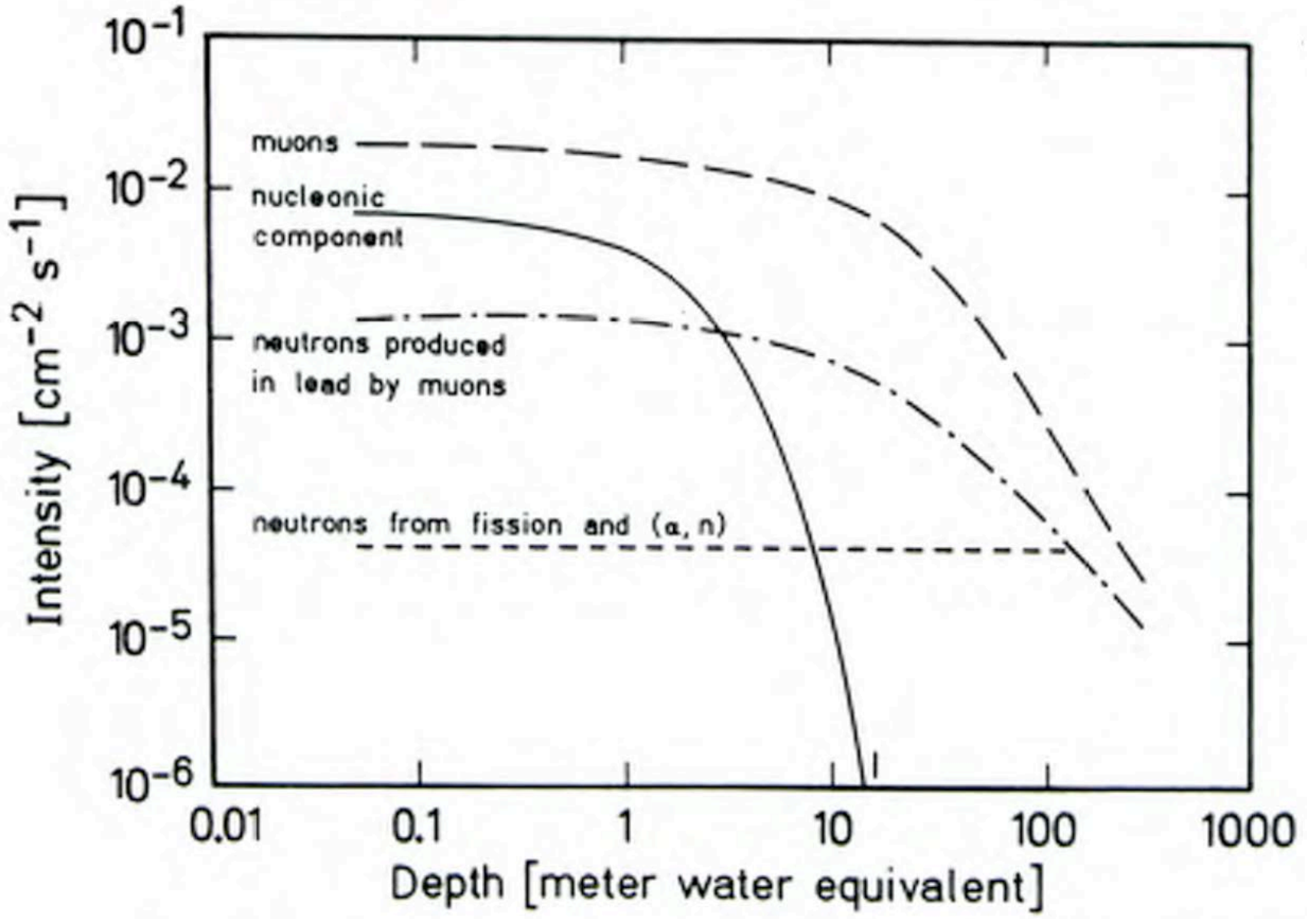
- From (α,n) reactions and fission (mainly U/Th) in the rocks at lower energies (typical < 8 MeV)
  - not difficult to shield
  - depend on geology; however, in practice pretty similar fluxes: few 10^{-2} $m^{-2}s^{-1}$
  - independent of depth for d > 200 m
- Interactions of μ's in the rocks
  - higher neutron energies (several GeV)
  - thicker shields needed
  - flux depends on geology and depth
  - flux 3-4 orders of magnitude smaller than thermal
- Interactions of μ's in the shields/detector
  - cannot be shielded
  - decrease with increasing depth
- induced fast background can be reduced by anticoincidence
  - BOREXINO: 4 orders of magnitude
- metastable nuclides more difficult, can be reduced by depth
  - experiment dependent, more severe for high-Z materials

- Muon capture: goes as Z^4
- Electromagnetic showers: goes as Z^2
- Spallation via virtual photon exchange

➡ Secondary neutrons

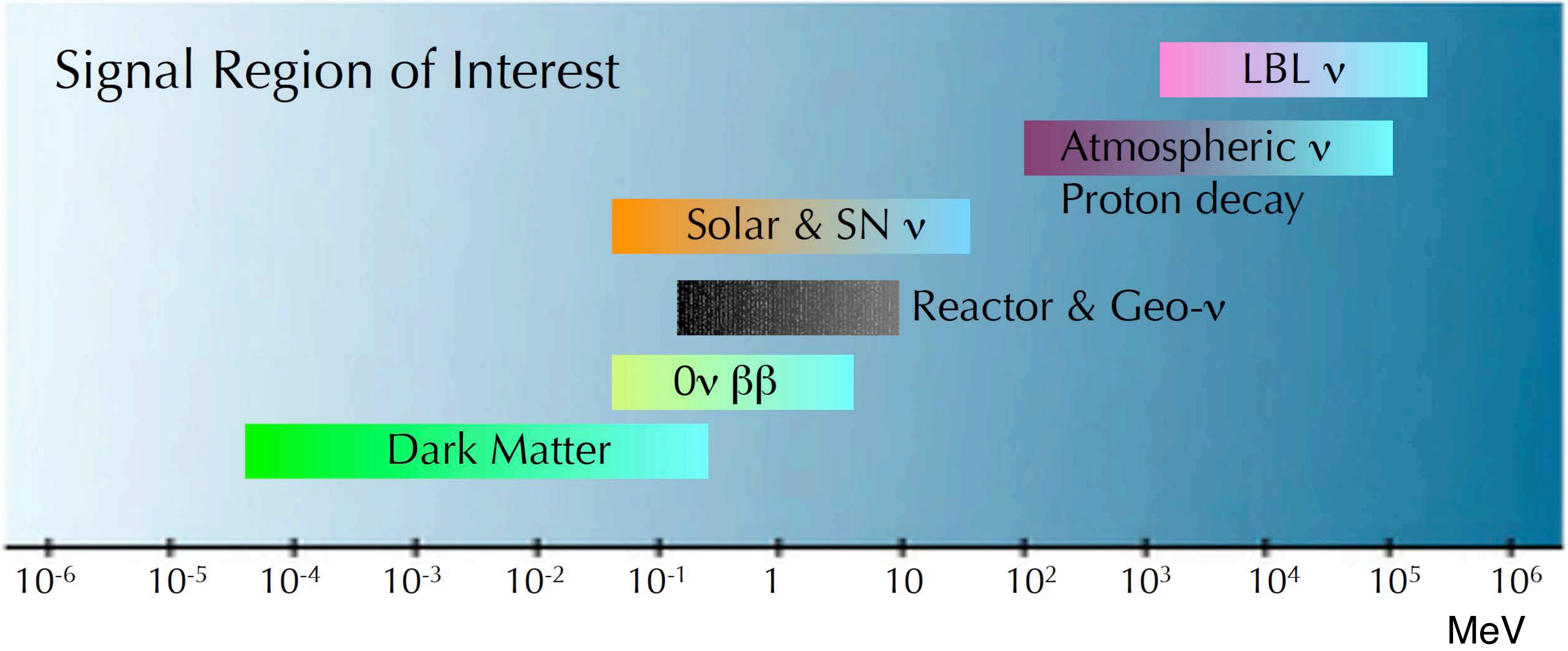
$$\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N+1)$$





Backgrounds

The most general conclusion is that **main backgrounds are determined by the energy scale of the experiment**



Underground physics (1/2)

- Deep underground laboratories are the ideal locations to explore the highest energy scales with/without accelerators and search for extremely rare phenomena
- Background control and reduction are the main obstacles to advance the effective-high-energy frontier

- Astro-particle physics is the main subject:
  - neutrino properties
  - dark matter search
  - proton decay
  - gravitational waves
- but multi-disciplinary extensions are possible and have been already devised
  - fundamental physics
  - geology and seismology
  - biology

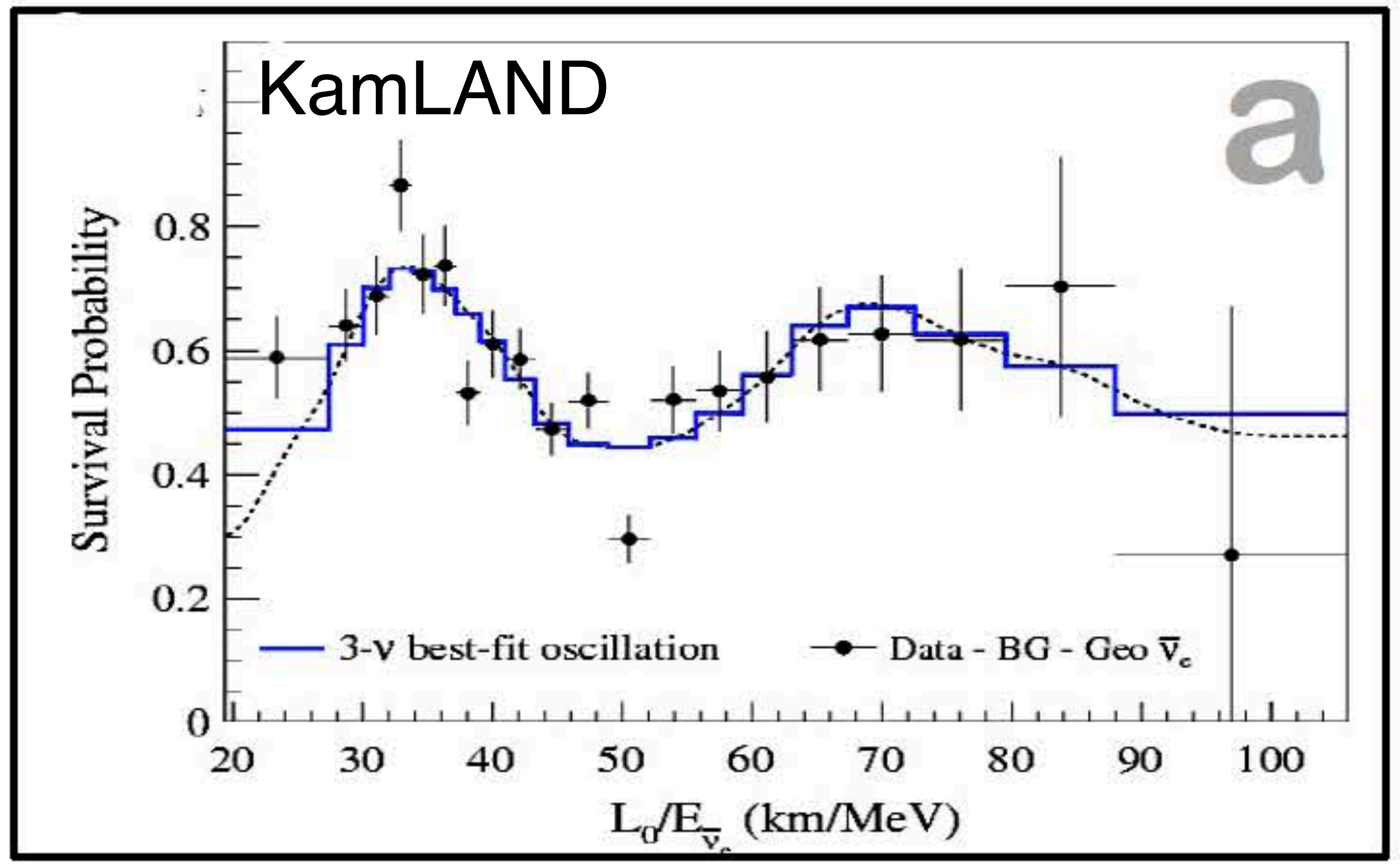
Neutrinos

History in brief

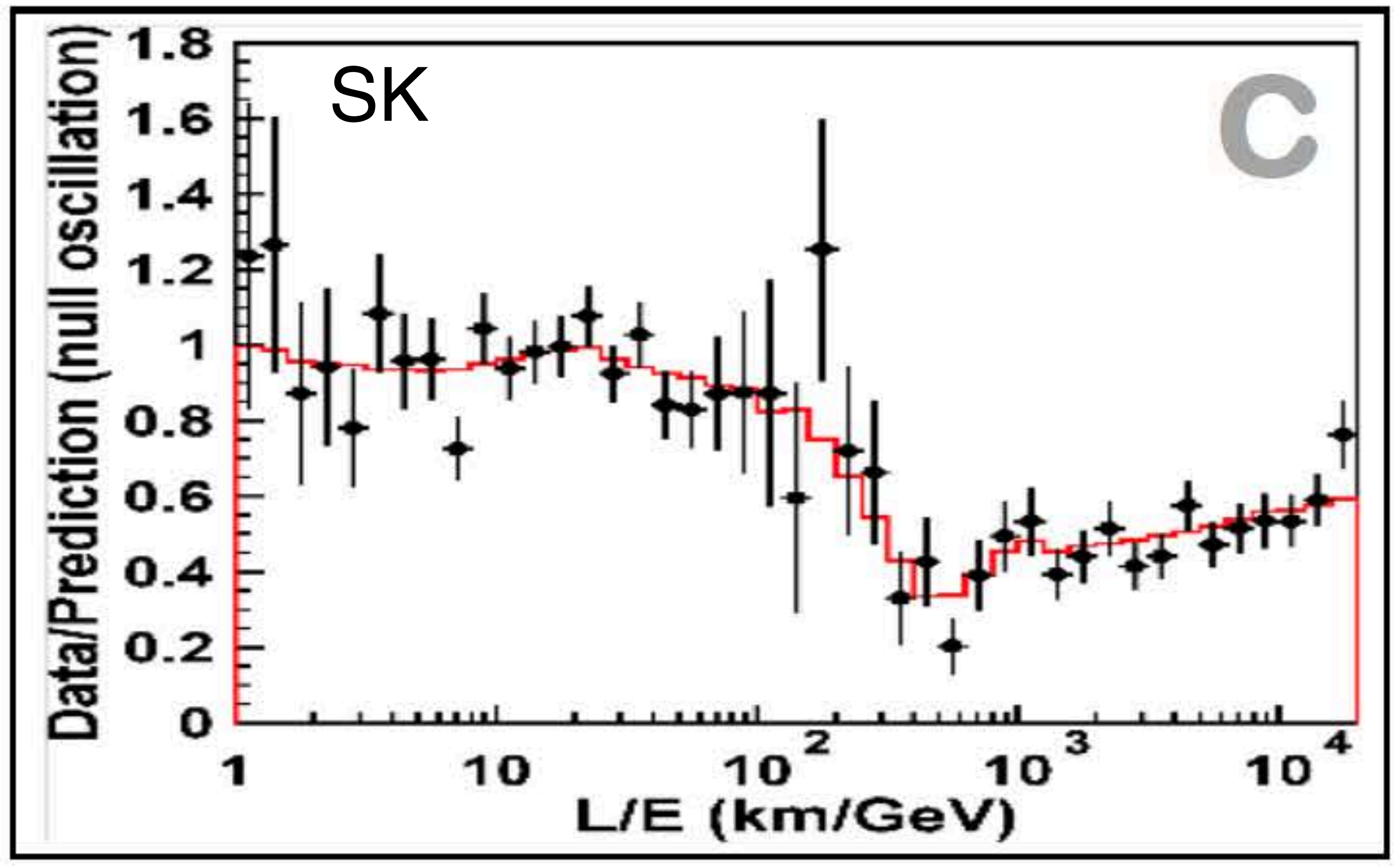
- In the 60s, Ray Davis builds the first experiment (Homestake mine) to study solar neutrinos and test the solar models of his friend John Bachall.
- At the end of the 70s the Grand Unified Theories (GUT) developments trigger a lot of interest for the experimental investigation on nucleon stability
  - A number of experiments (hosted in underground "labs") are funded and start operation: IMB, SOUDAN-2 ((USA), Kolar Gold Field (India), NUSEX (Italy), Kamiokande (Japan), Frejus (France)
  - At that time, (atmospheric) neutrinos are the "irreducible background" for these experiments
  - Physicists grasp the nettle and first studies on atmospheric neutrinos are published
- The visionary mind of (the Nobel laureate) Masatoshi Koshiba brings the potential of his detector (Kamiokande) from the GeV scale to a handful of MeV. A second hera for solar neutrino physics is born (direct measurements).
- In 1987 these same experiments observe neutrinos from SN 1987a
- In 1998 the Super-Kamiokande collaboration announces the discovery of neutrino oscillations observed as a deficit of muon neutrinos in the atmospheric neutrinos. The result is confirmed by the MACRO experiment results
- In the 2000s antropogenic neutrino beams (reactor and accelerator) are used for precision tests of this discovery
- … (to be continued)

Neutrino oscillations

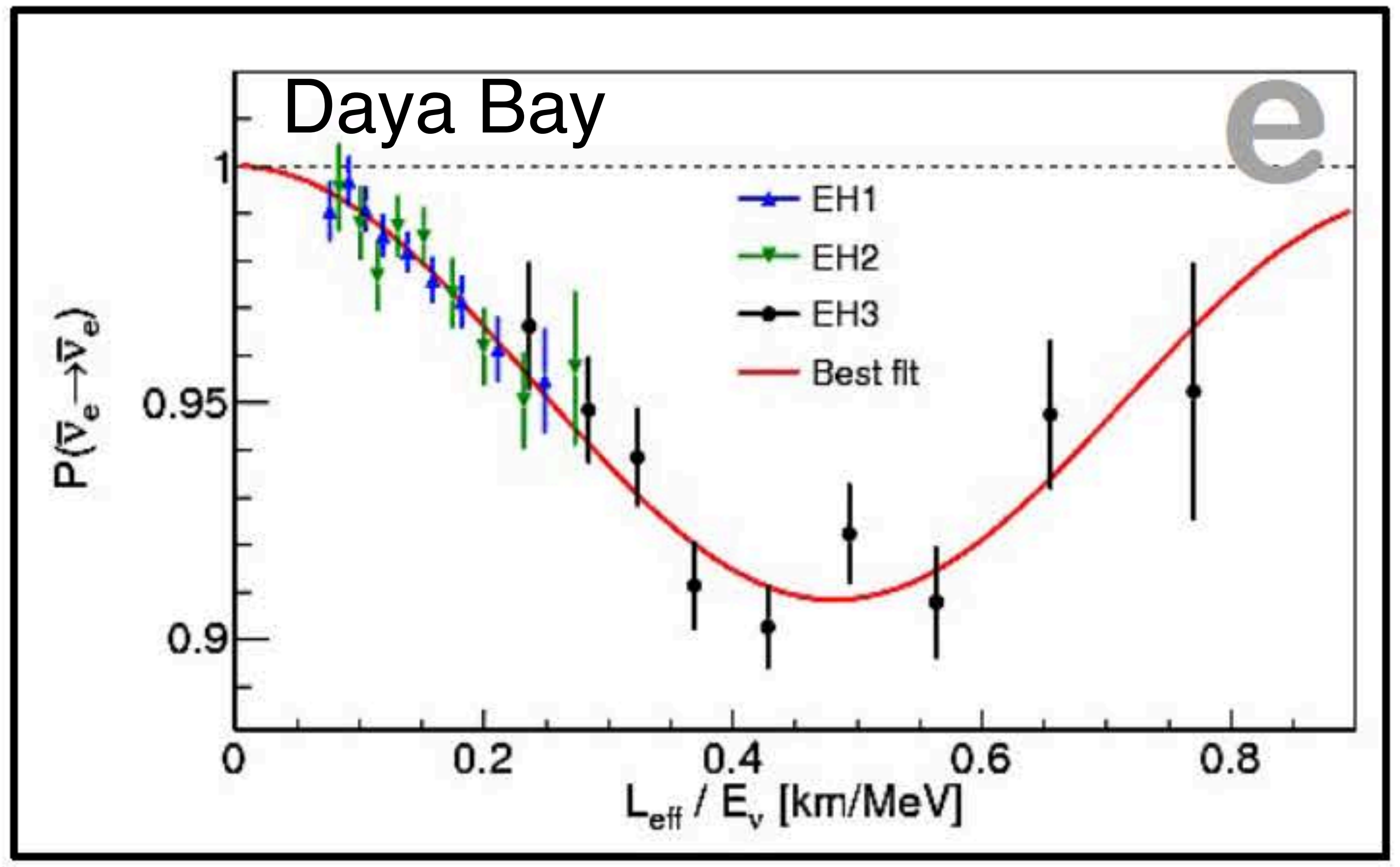
e→e (KamLAND)



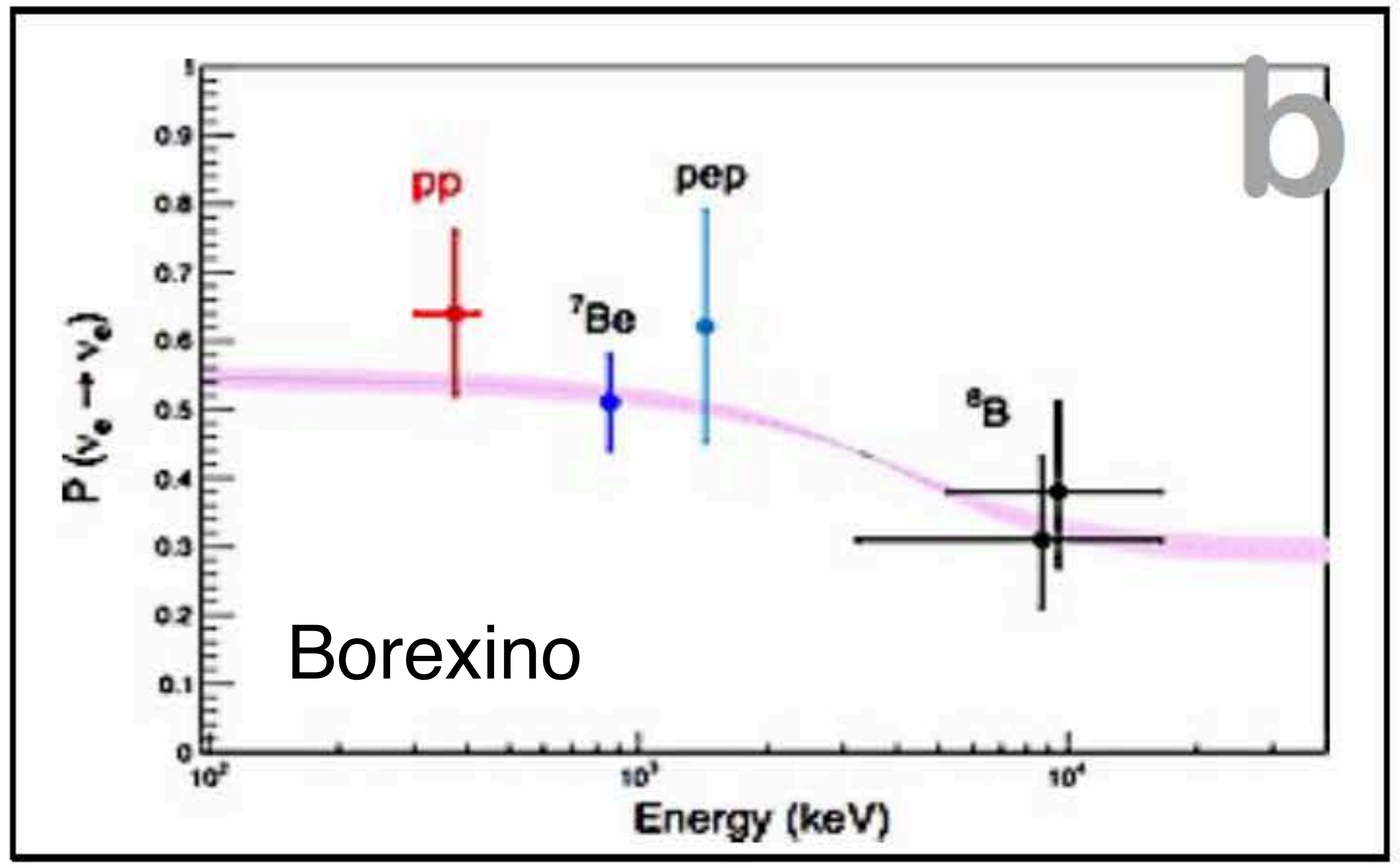
μ→μ (Atmospheric)



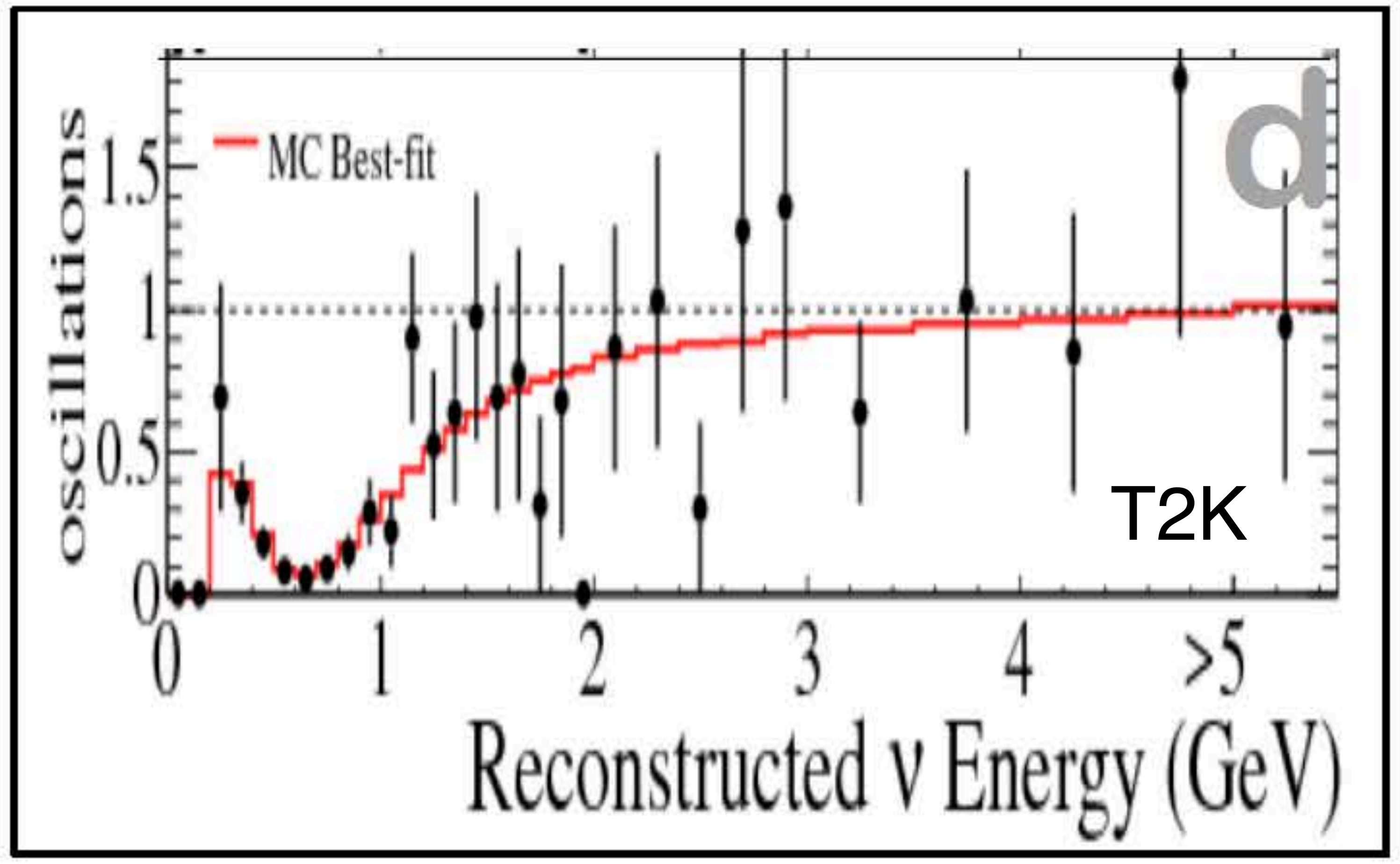
e→e (SBL Reac.)



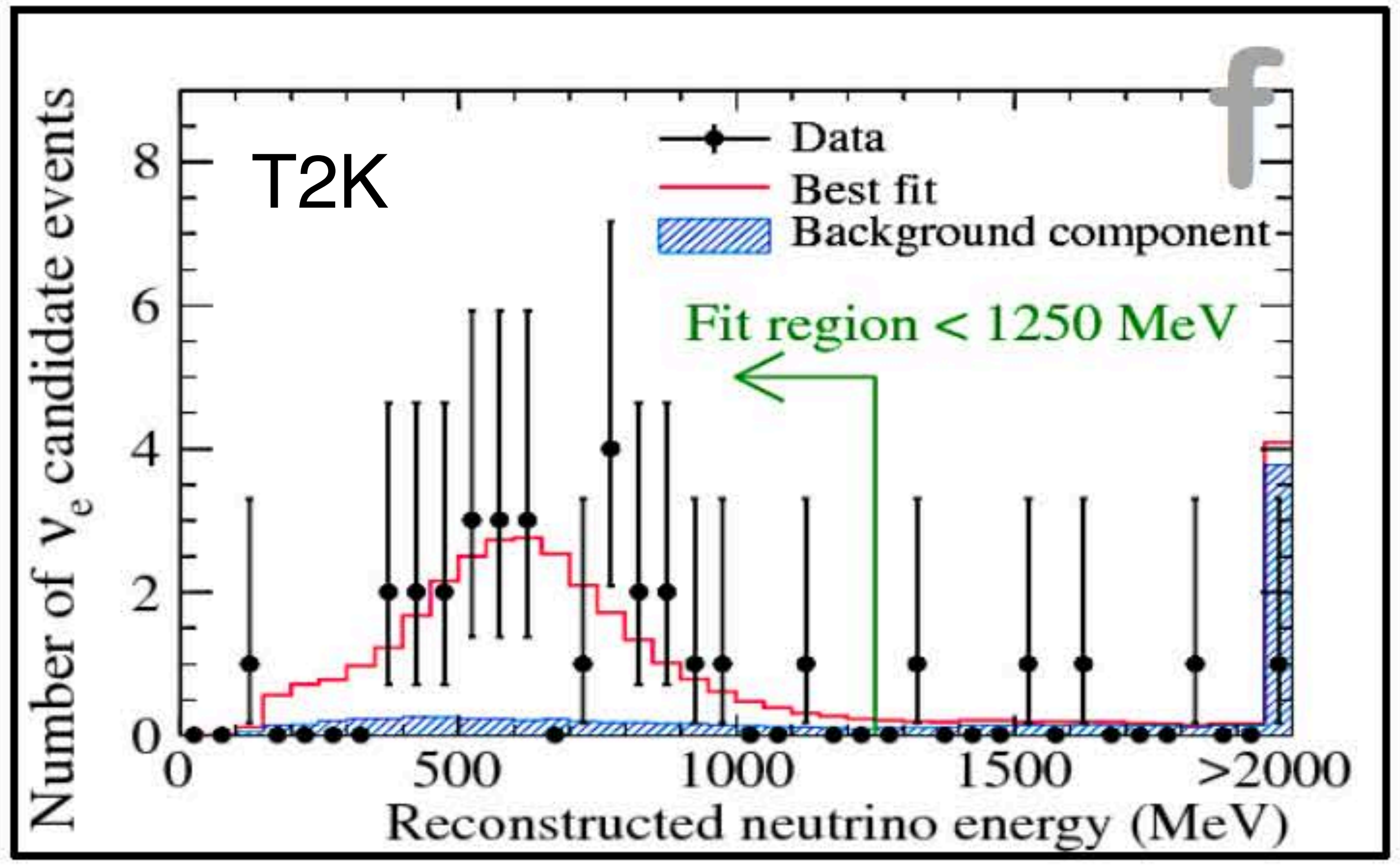
e→e (Solar)



μ→μ (LBL Accel)



μ→e (LBL Accel)



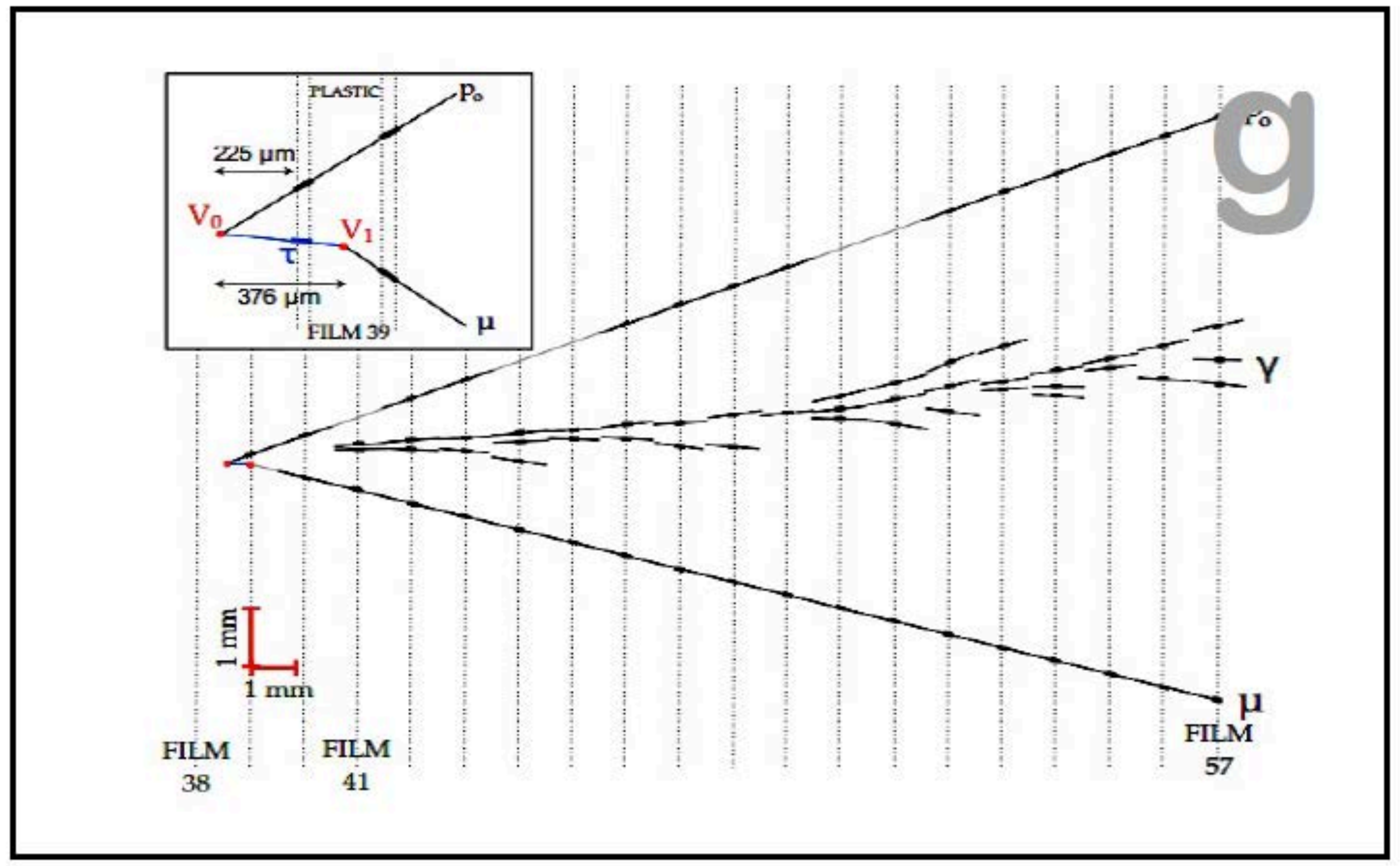
Neutrino oscillations

- Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

- (a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS, NOvA; (g) OPERA [plot], Super-K atmospheric.

- **Irrespective of the chosen neutrino source, the (far) detector is always located underground**

$\mu \to \tau$ (OPERA)



1σ uncertainty

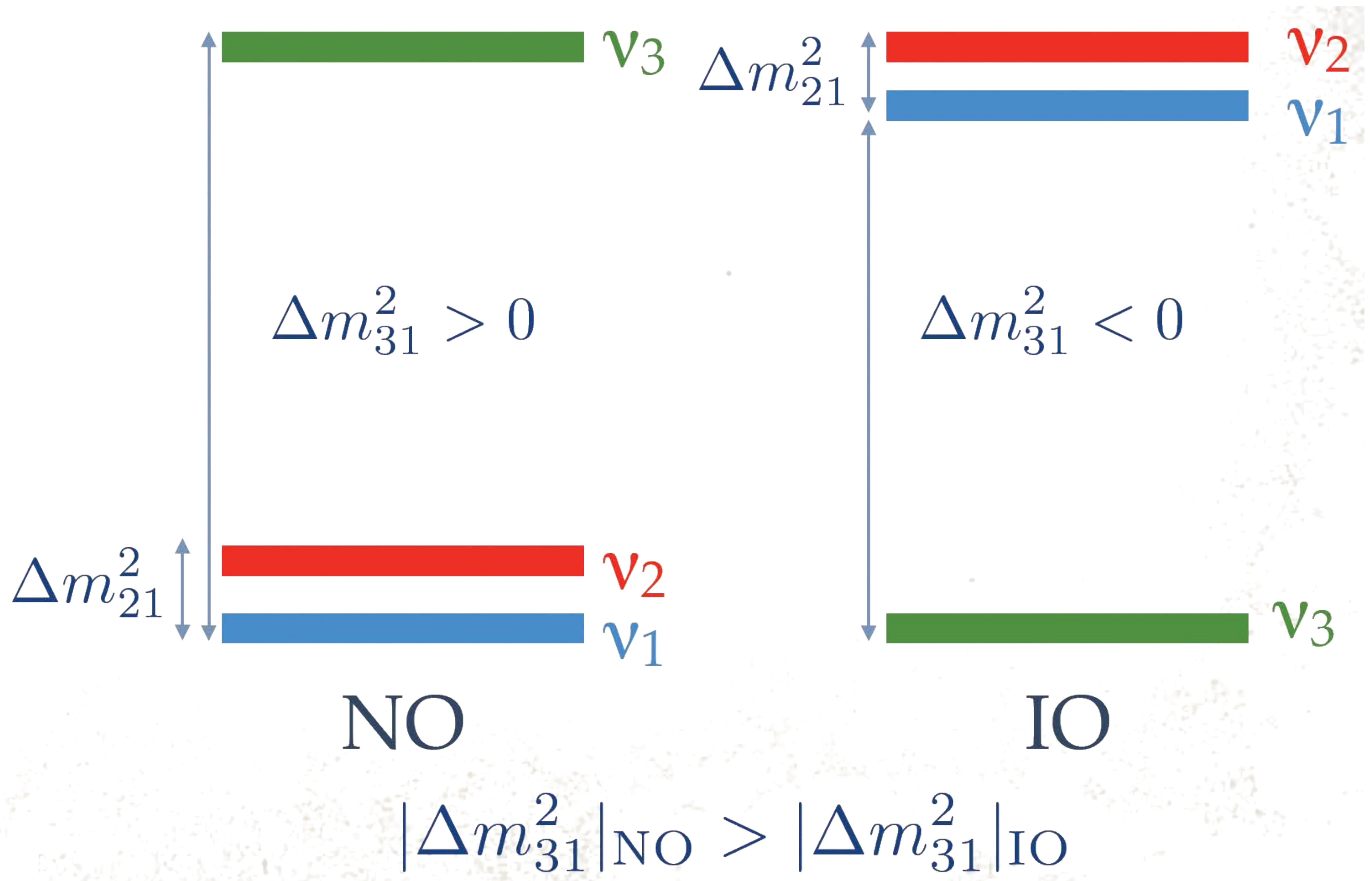
Δm^2	1.4 %
δm^2	2.2 %
$\sin^2\theta_{13}$	3.8 %
$\sin^2\theta_{12}$	4.4 %
$\sin^2\theta_{23}$	~ 5 %

Status of neutrino physics

- Neutrino mixing: $\nu_\alpha = \sum_k U_{\alpha k}\, \nu_k$ (ν_k are mass eigenstates)

$$U_{3\times3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- three mixing angles: θ_{12}, θ_{23}, θ_{13}
- three CP phases: 1 Dirac + 2 Majorana
- three masses: m1, m2, m3
  - absolute neutrino mass: m0
  - two mass splittings: Δm_{21}^2 Δm_{31}^2



Status of neutrino oscillations

parameter	best fit ± 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.50±0.03	2.41–2.60
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

still missing:

- CP violating phase δ
- $m_0 = m_{min}$

a simple case: 2 neutrino (vacuum) oscillations

$$\nu_\alpha = \sum_{k=1,2} U_{\alpha k}\, \nu_k$$

(α = e,μ)

$$E_k = \sqrt{(p^2 + m_k^2)} \simeq p + \frac{m_k^2}{2p}$$

$$P(\nu_\alpha \to \nu_\alpha) = 1 - P(\nu_\alpha \to \nu_\beta)$$

$$P(\nu_\alpha \to \nu_\beta) = 4 \sin^2\theta \cos^2\theta \sin^2(\frac{\Delta m_{ij}^2 L}{4E})$$

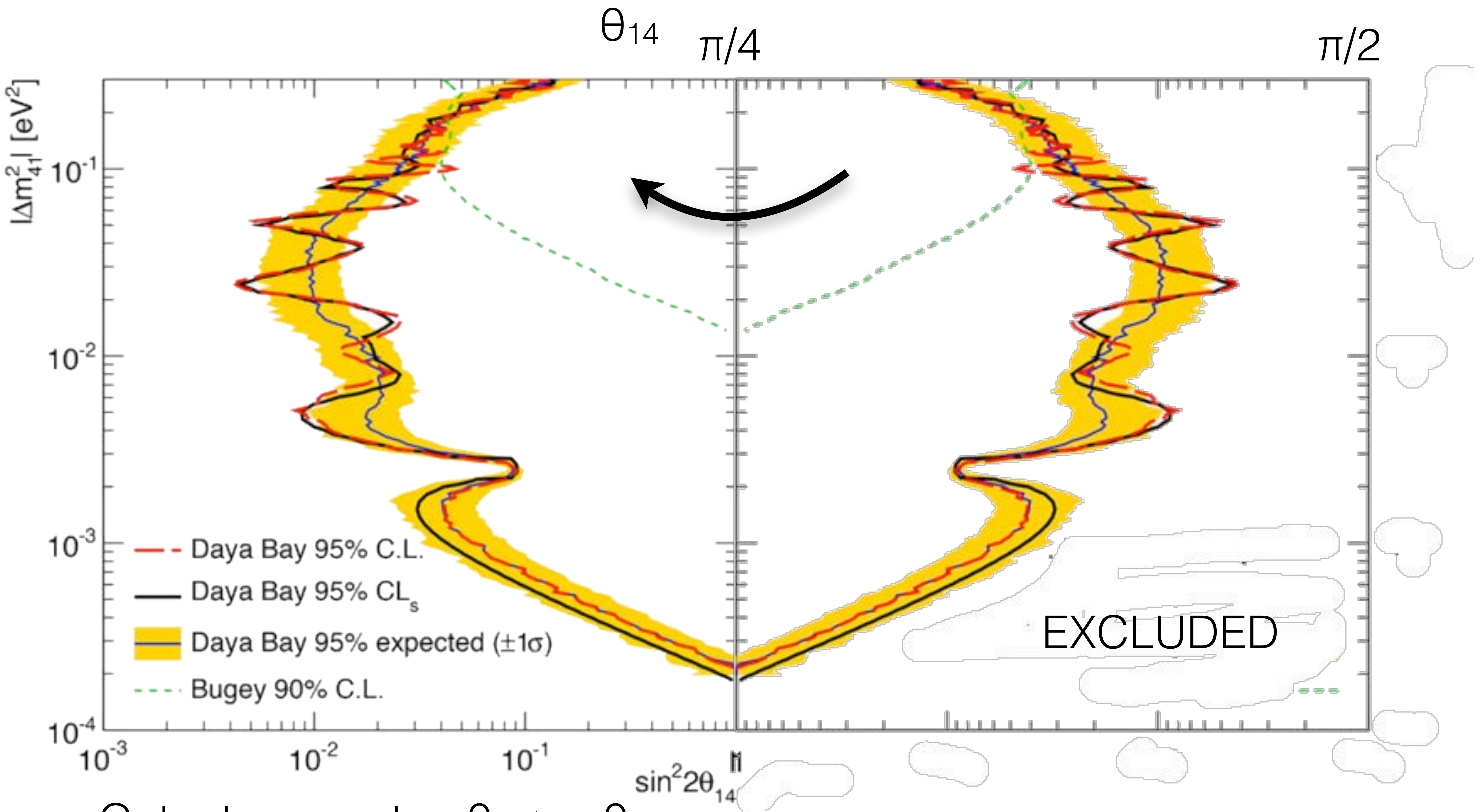
Amplitude: vanishes for θ=0 or π/2, is maximal for θ=π/4)

Oscillation phase: vanishes for degenerate masses or small L/E)

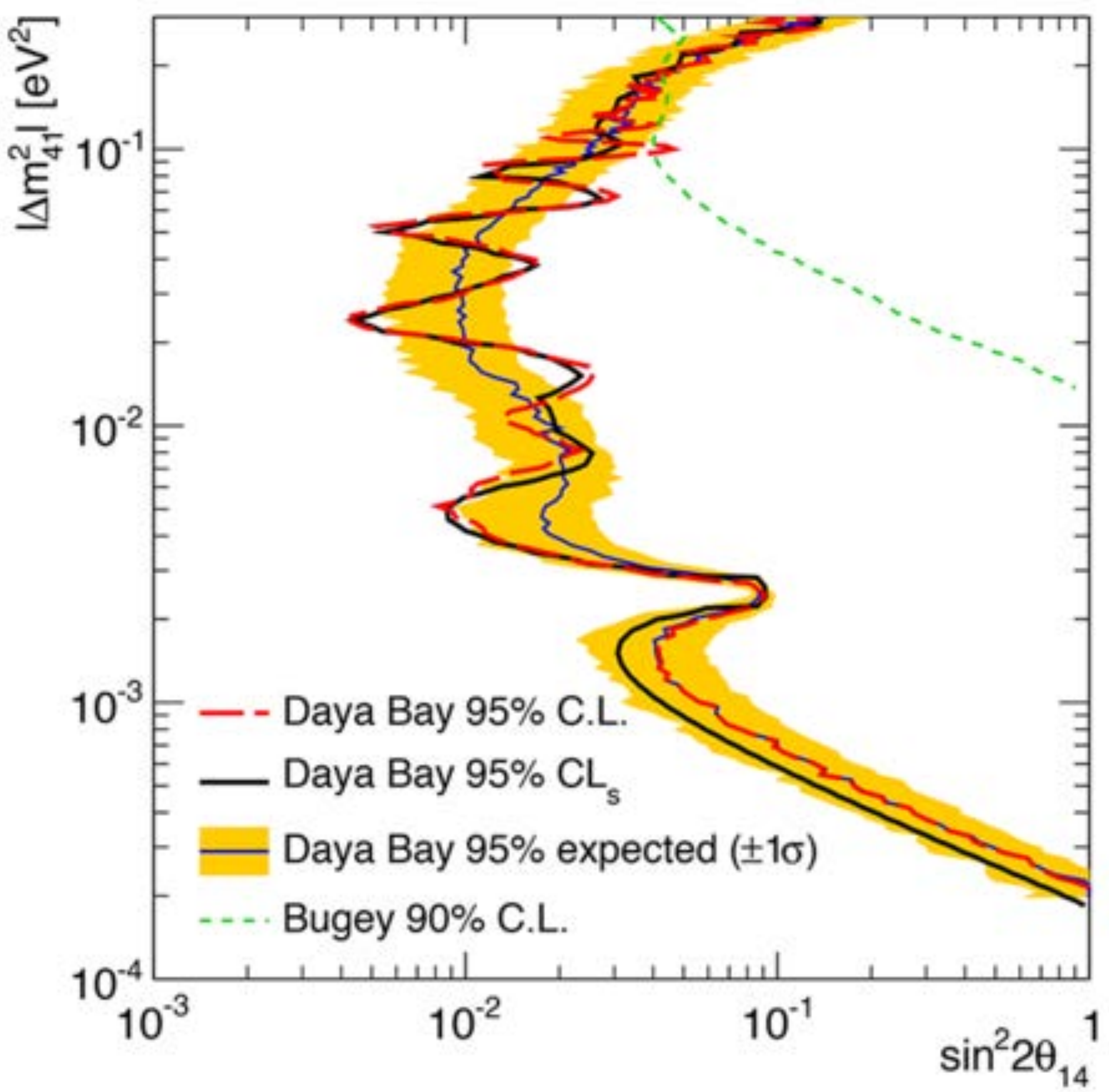
a neutrino created with **flavor** α can develop in vacuum a different **flavor** β with periodical oscillation probability in **L/E**

- $P_{\alpha\beta}$ is is the flavor "appearance" probability. The "disappearance" probability is the complement to 1.
- The oscillation effect depends on the difference of (squared) masses, not on the absolute masses themselves

exclusion plots



Octant symmetry: $\theta \to \pi-\theta$



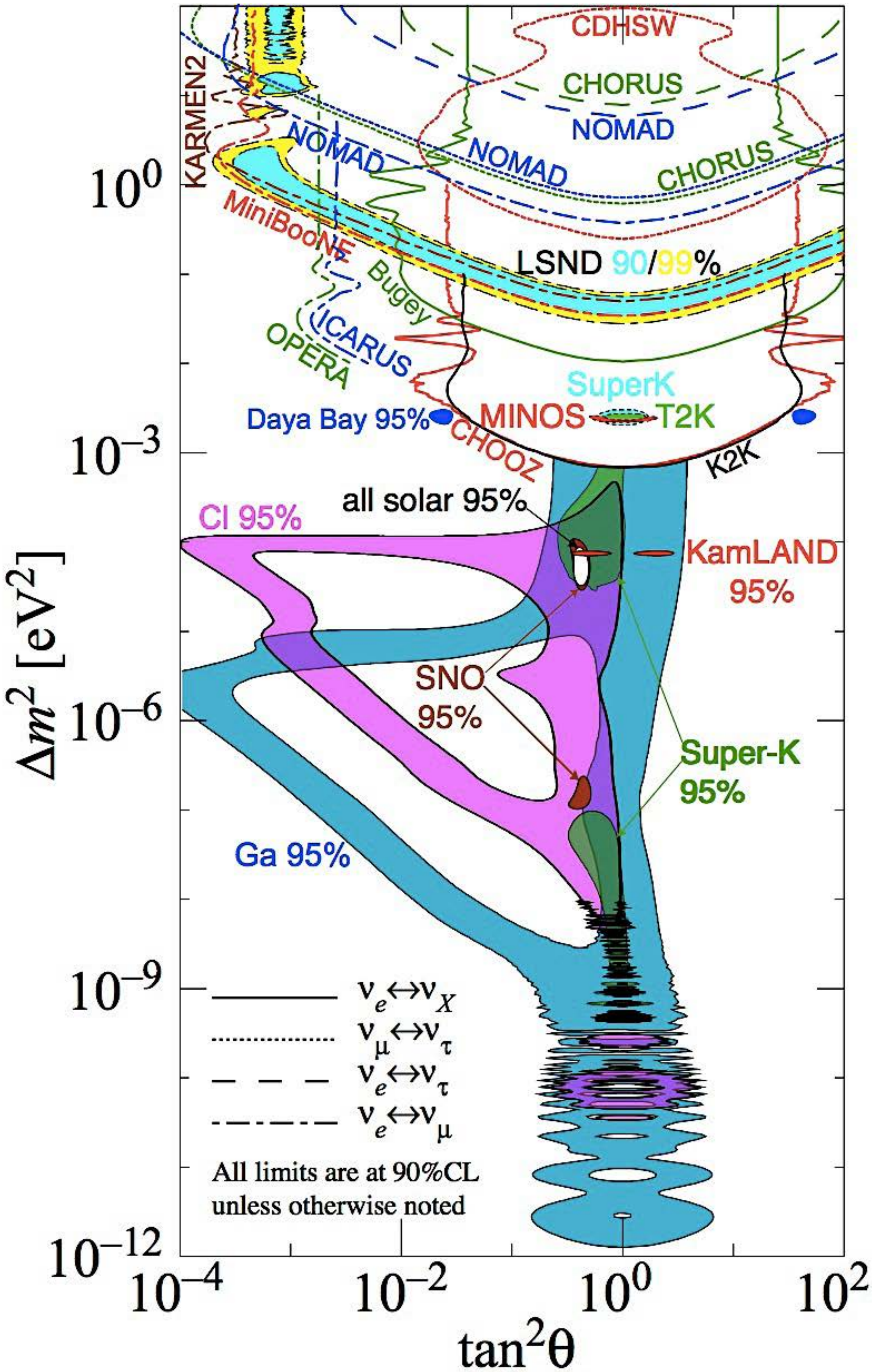
Basically obsolete

- 2ν octant symmetry broken by 3ν and/or maUer effects
- better to use log $\tan^2\theta$ or $\sin\theta$

exclusion plots

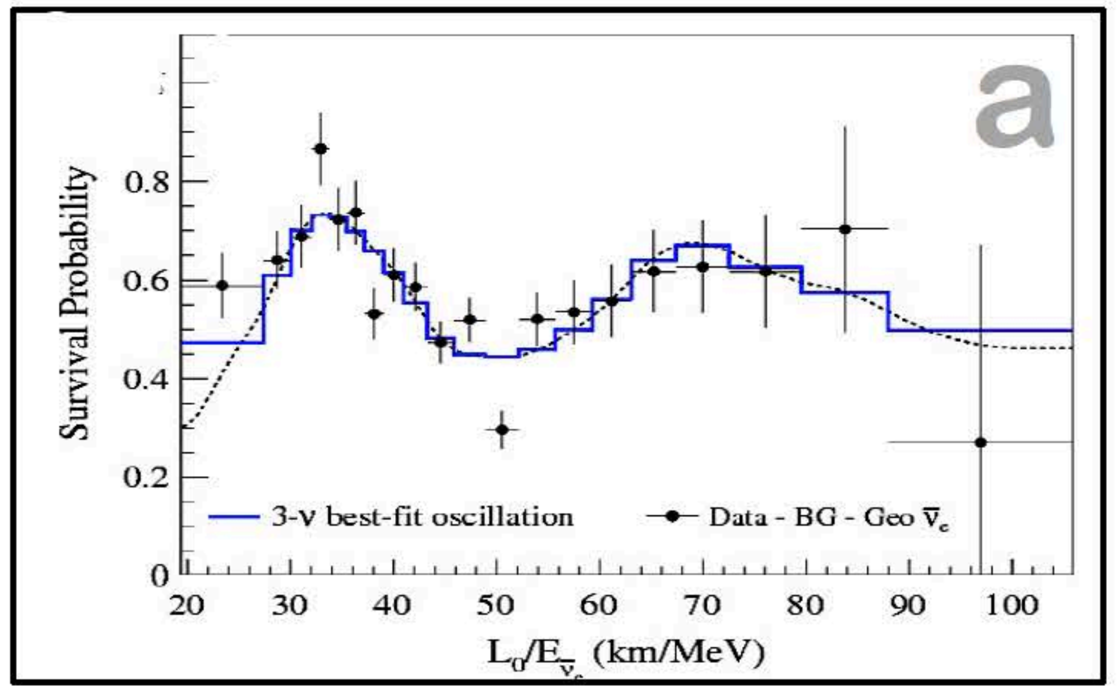
Octant (a)symmetric 2ν contours from PDG Review

- but... patching 2ν approximations in different oscillation channels, in order to get a full 3ν picture, is no longer a useful approach.
- btter to go the other way around, from the full 3ν case to 2ν limits

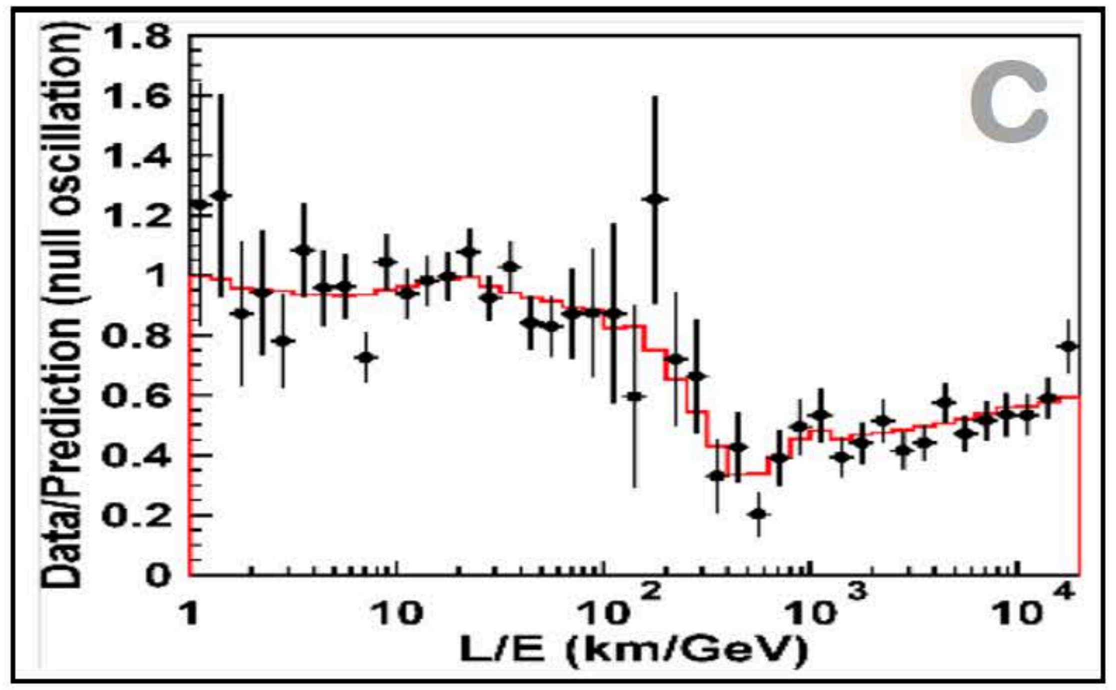


standard 3ν oscillations: results revisited

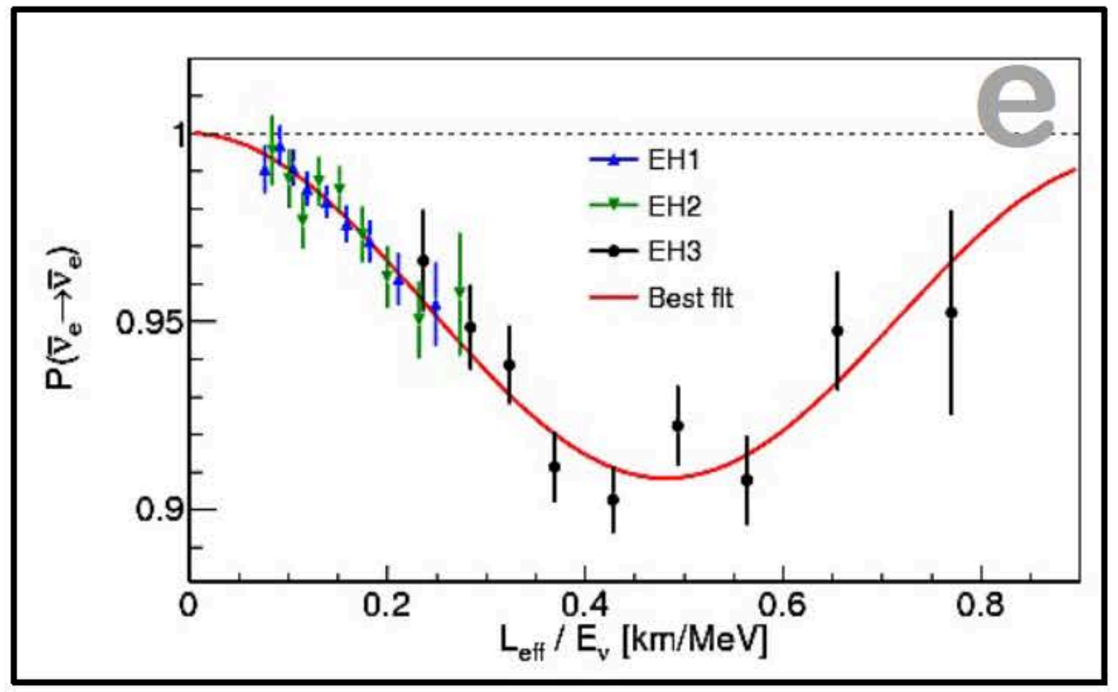
e→e (KamLAND)



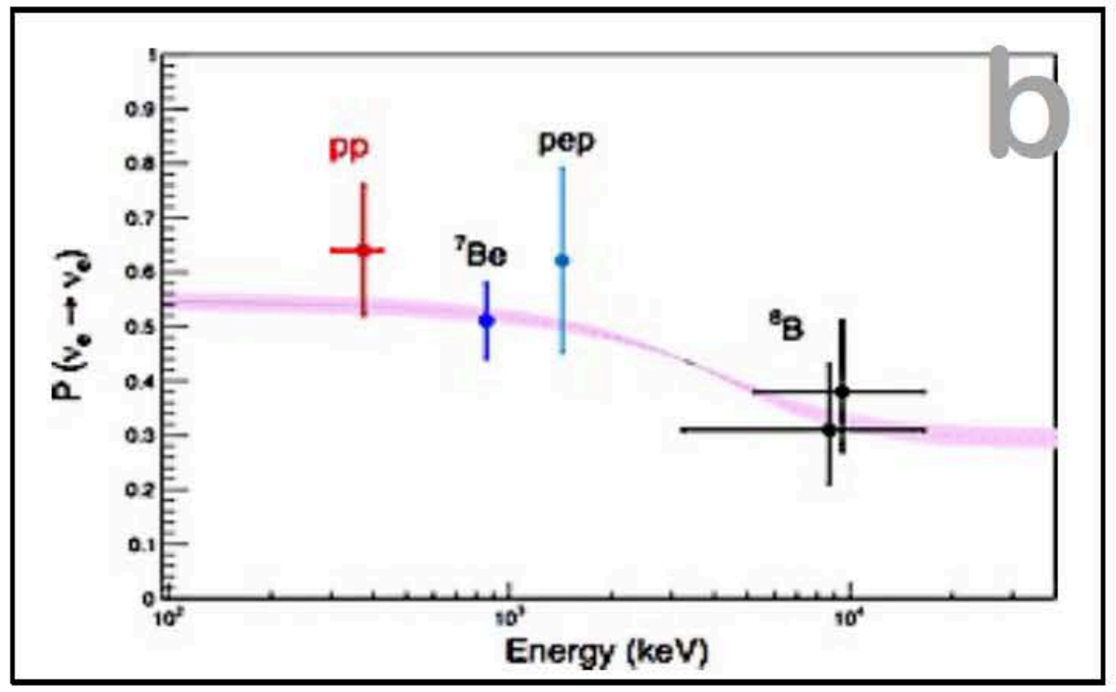
μ→μ (Atmospheric)



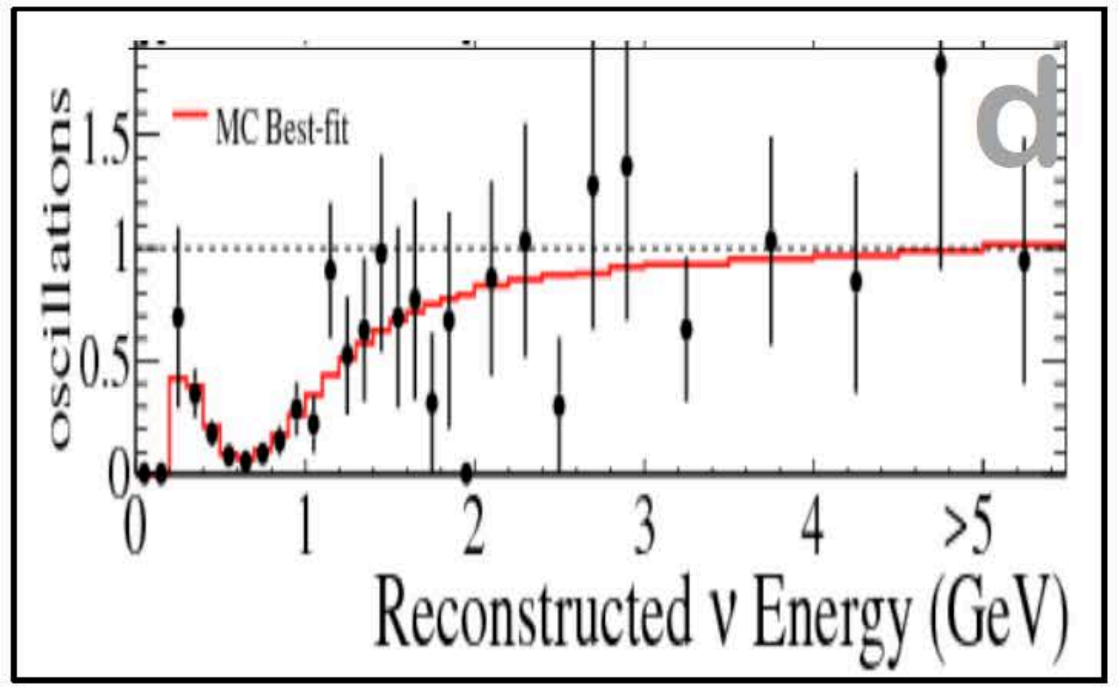
e→e (SBL Reac.)



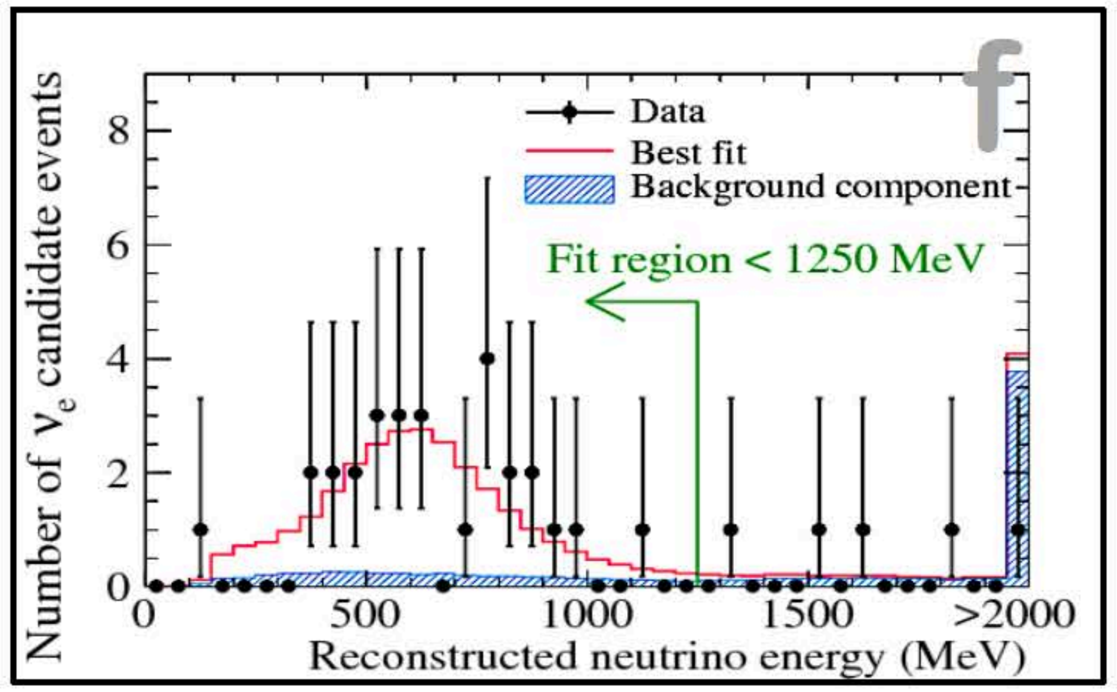
e→e (Solar)



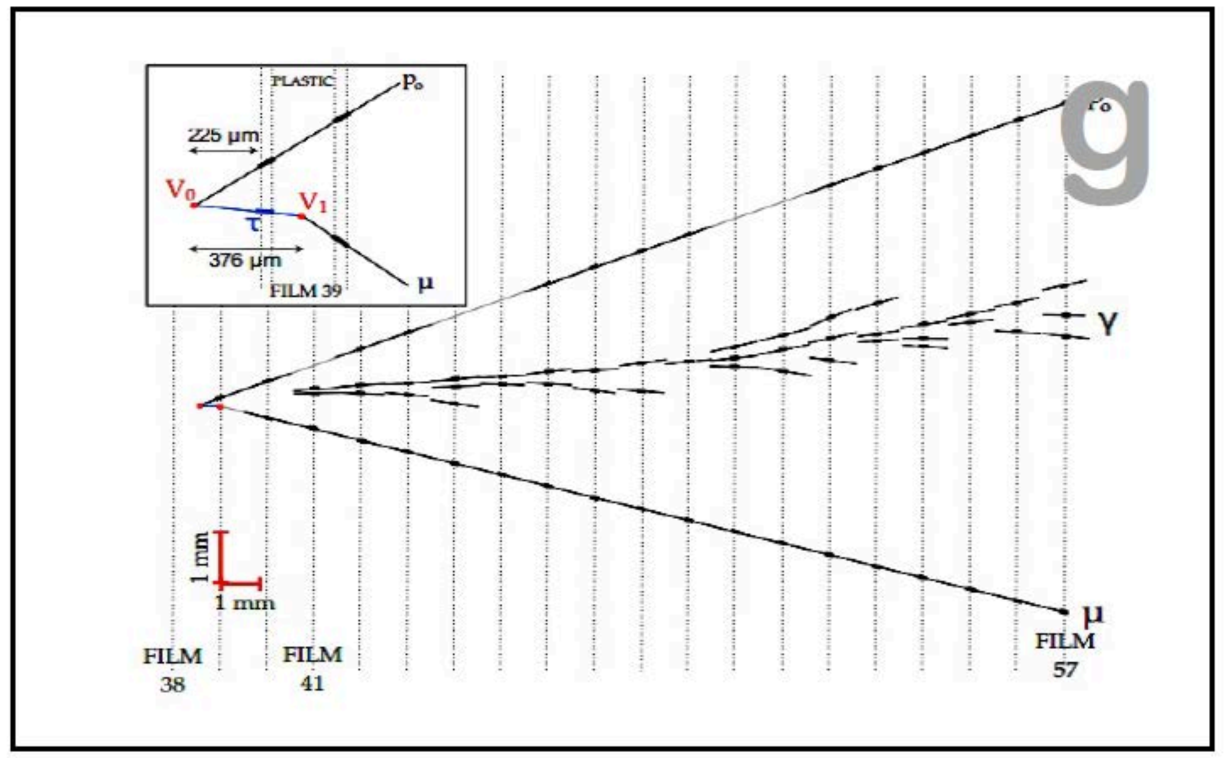
μ→μ (LBL Accel)



μ→e (LBL Accel)

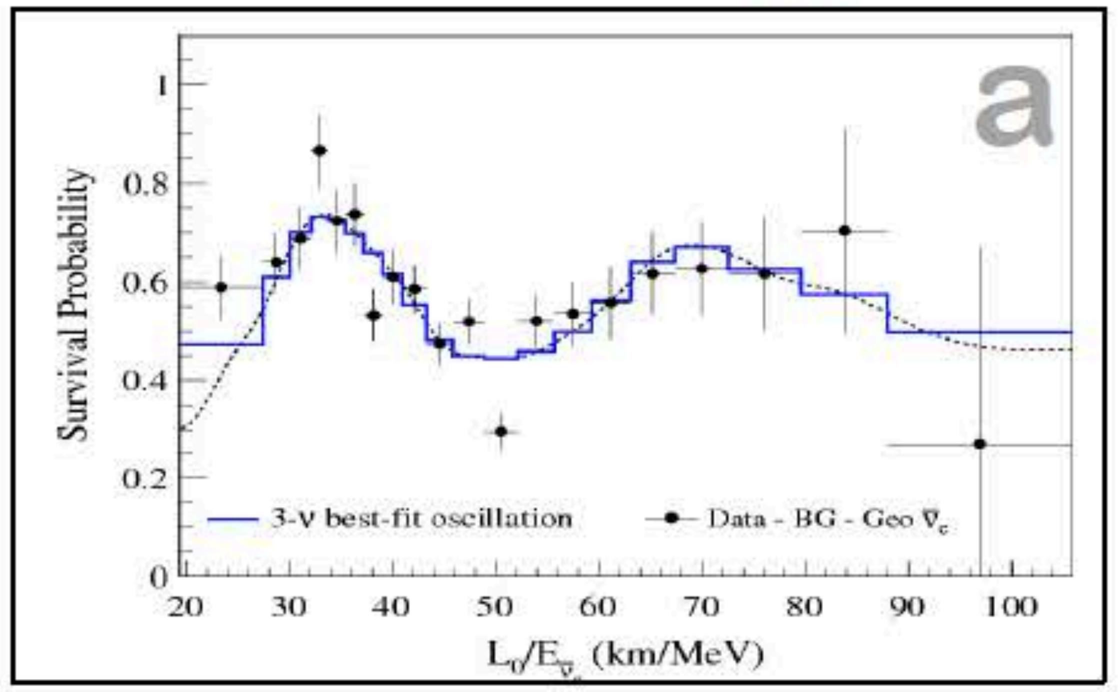


μ→τ (OPERA)

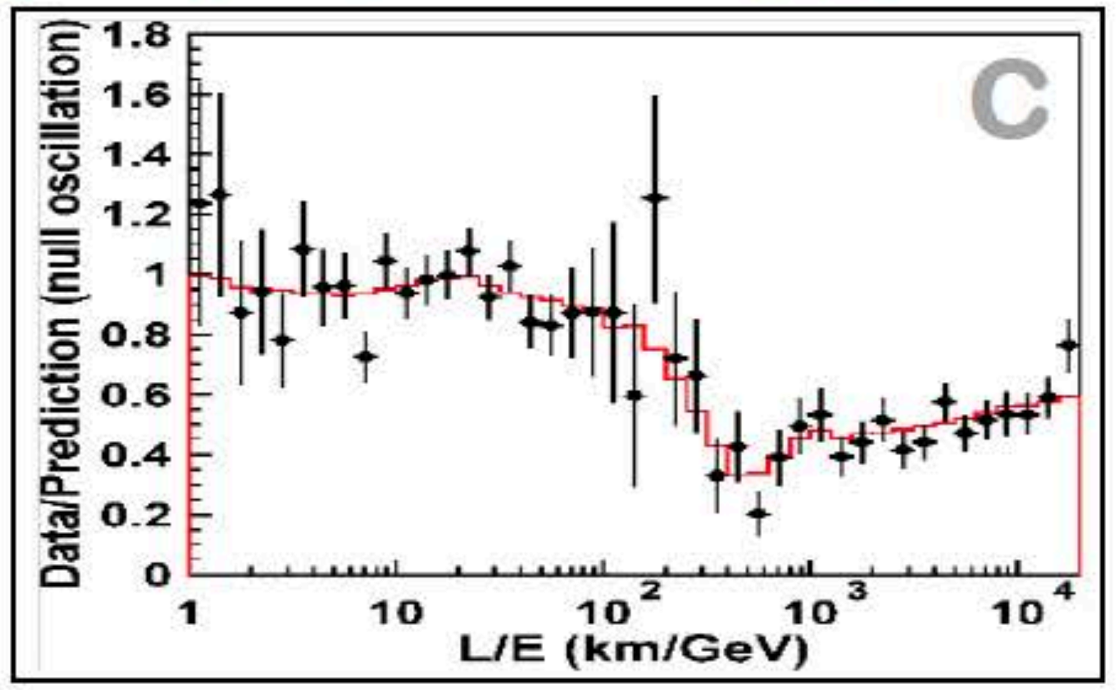


standard 3ν oscillations: results revisited

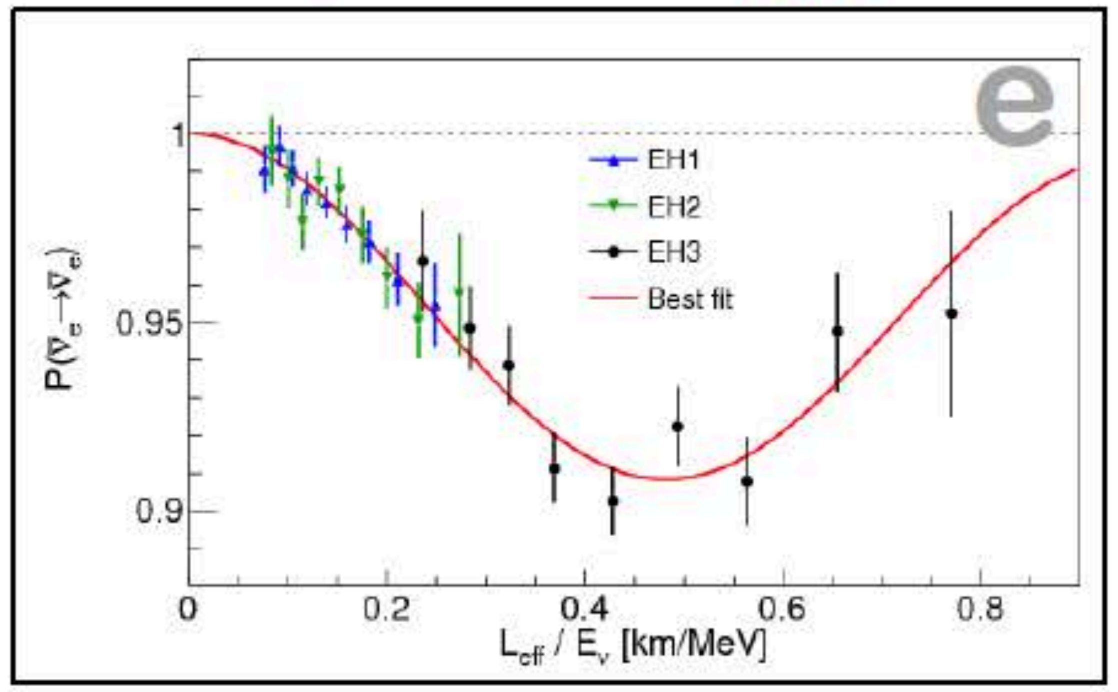
e→e (δm^2 , θ_{12})



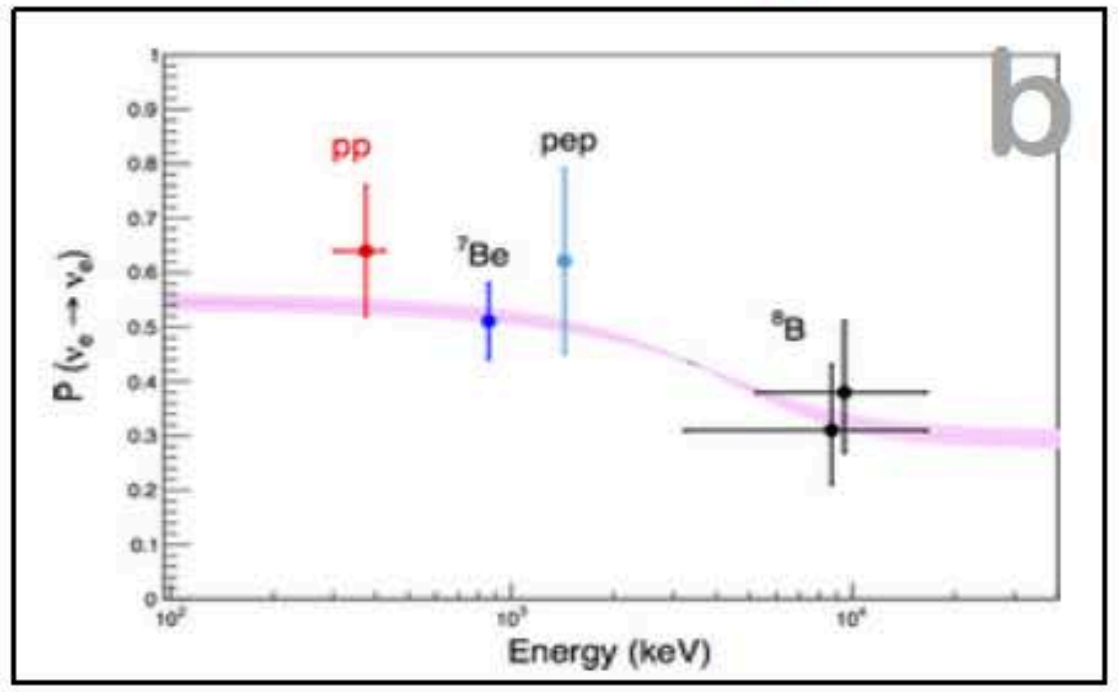
μ→μ (Δm^2 , θ_{23})



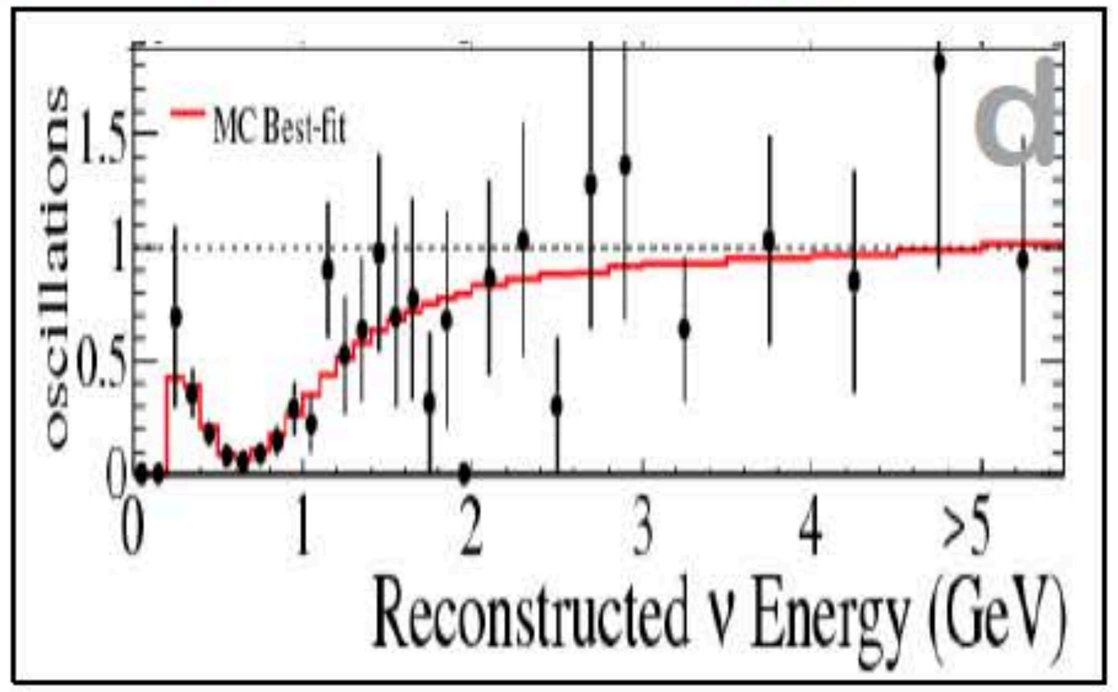
e→e (Δm^2 , θ_{13})



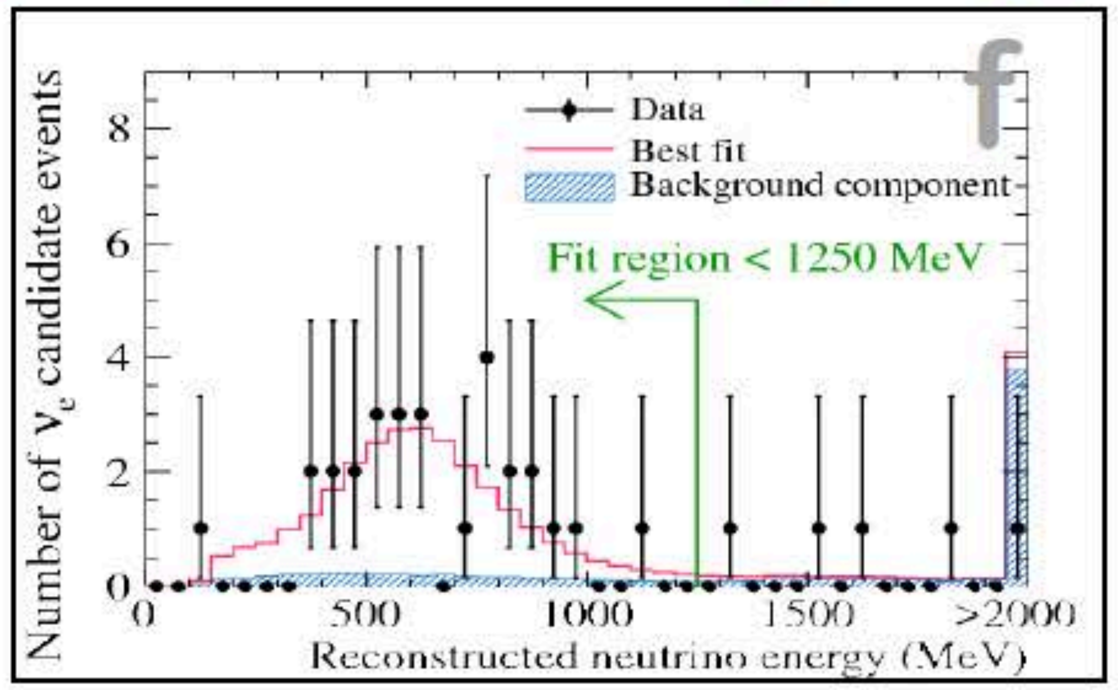
e→e (δm^2 , θ_{12})



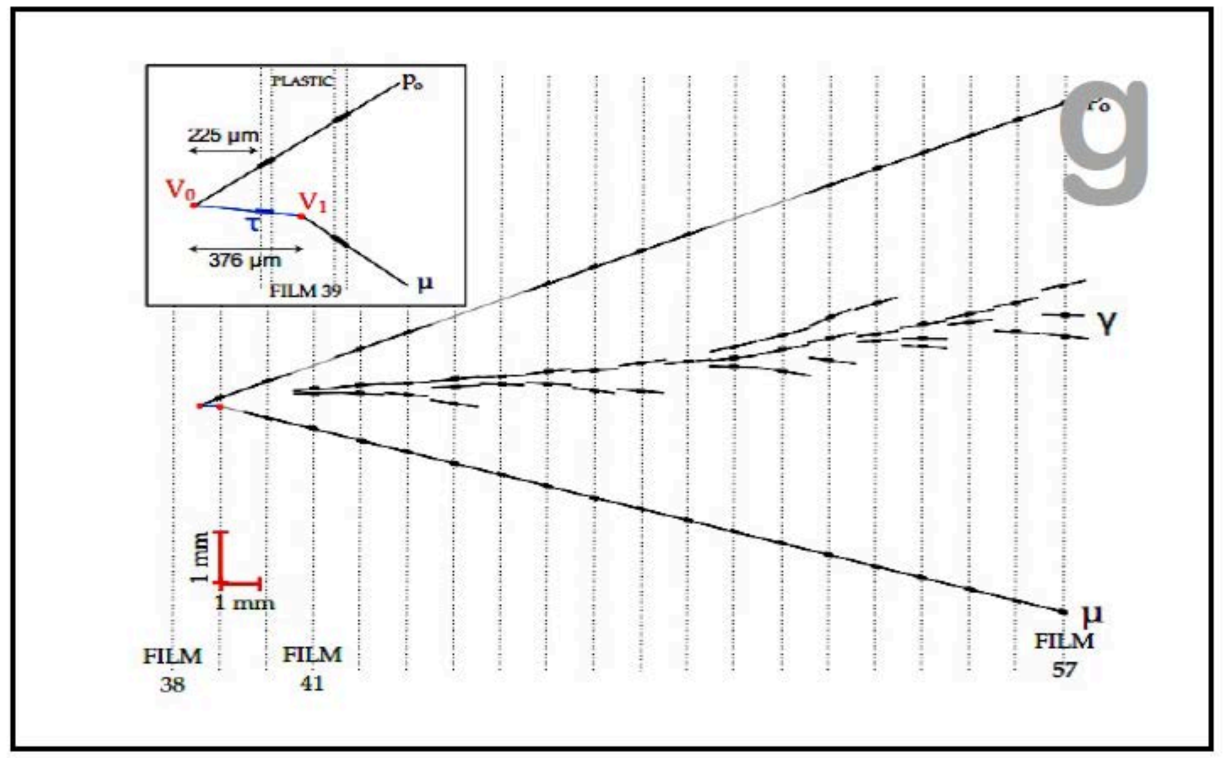
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



So far established for θ_{12}, θ_{13}, θ_{23} ,Δm^2 and δm^2

standard 3ν oscillations

- There are three mass states ν1, ν2, ν3 with masses m1, m2, m3
- For ultrarelativistic ν in vacuum: $E=(p^2+m_k^2)^{1/2} \simeq p+m_k^2/2p$
- Neutrino oscillations probe the differences $\Delta E \sim \Delta m_{ij}^2 \equiv m_i^2 - m_j^2$
- 3 neutrinos means two independent Δm_{ij}^2, (Δm^2, δm^2)
- Experimentally, very different scales: $\Delta m^2 / \delta m^2 \sim 30$
  - ➡ Difficult to observe both! Current expts sensitive to a dominant one.

➡ **$\delta m^2 \simeq 7.5 \cdot 10^{-5}$** - “small” or “solar” splitting

➡ **$\Delta m^2 \simeq 2.5 \cdot 10^{-3}$** - “large” or “atmospheric” splitting

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

$UU^\dagger = 1$
$U \to U^*$ for $\nu \to \bar{\nu}$
$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

3 ν oscillations: general formalism

- Let's consider a 3 ν mixing general scheme

$$\nu_\alpha = \sum_{k=1,3} U_{\alpha k}\nu_k \qquad \nu_k = \sum_{k=1,3} U^\dagger_{\alpha k}\nu_\alpha$$

- If the ν is characterised by a momentum p_ν its time evolution will be described by

$$\nu_\alpha(x,t) = \sum_{k=1,3} U_{\alpha k}\nu_k e^{ip_\nu x - iE_k t} \qquad \nu_\alpha^{(0)} \equiv \nu_\alpha(x, t=0) \equiv \nu_\alpha = \sum_{k=1,3} U_{\alpha k}\nu_k e^{ip_\nu x}$$

where, assuming $m_k \ll p_\nu$

$$E_k = E(\nu_k) = \sqrt{p_\nu^2 + m_k^2} \quad \rightarrow \quad E_k \simeq p_\nu + \frac{m_k^2}{2p_\nu}$$

- If $m_k \ll p_\nu$, the ν will travel approximately at the light speed, so that x≃t and

$$\nu_\alpha(x,x) \simeq \sum_k U_{\alpha k}\nu_k e^{-i(m_k^2/2p_\nu)x}$$

3 ν oscillations: general formalism

- Replacing now ν_k in terms of the flavour eigenstates

$$\nu_\alpha(x,x) \simeq \sum_\beta [\sum_k U_{\alpha k} e^{-i(m_k^2/2p_\nu)x} U^*_{\beta k}]\nu_\beta$$

- After a time t, the original pure flavour state is a superposition of all the flavours
- We can now easily derive the flavour transition probability

$$P(\alpha \to \beta, x) = [\sum_j U^*_{\alpha j} e^{im_j^2 x/2p_\nu} U_{\beta j}][\sum_k U^*_{\alpha k} e^{im_k^2 x/2p_\nu} U_{\beta k}]$$

$$= \sum_k |U_{\alpha k}|^2 |U_{\beta k}|^2$$

$$+ \sum_{j\neq k} \Re(U_{\alpha k} U^*_{\alpha j} U_{\beta j} U^*_{\beta k}) \cos(\frac{m_k^2 - m_j^2}{2p_\nu} x) + \sum_{j\neq k} \Im(U_{\alpha k} U^*_{\alpha j} U_{\beta j} U^*_{\beta k}) \sin(\frac{m_k^2 - m_j^2}{2p_\nu} x)$$

- If CP is conserved U is real (orthogonal) and

$$P(\alpha \to \beta, x) = \sum_k U^2_{\alpha k} U^2_{\beta k} + \sum_{j\neq k} U_{\alpha k} U_{\alpha j} U_{\beta j} U_{\beta k} \cos(2\pi \frac{x}{L_{kj}}) \qquad L_{kj} = 2\pi \frac{2p_\nu}{m_k^2 - m_j^2} \equiv 2\pi \frac{2p_\nu}{\delta m^2_{kj}}$$

3 ν oscillations: general formalism

- The transition probability shows a clear oscillatory pattern as a function of the distance.
- L_{kj} is called oscillation length between mass eigenstates k and j
- A mass eigenstate ν_k does not oscillate to different eigenstates
- If $x \ll L_{kj}$, ν stays in its original flavor
- If $x \gg L_{kj}$ the oscillation pattern will be washed out.
- Indeed, given the unavoidable Δp spread of any real beam, any component p_ν will cancel out with a component having $p'_\nu = p_\nu + \Delta p_\nu/2$ corresponding to a phase shift ~π.
- Let's evaluate the corresponding distance X. If L'_{kj} is the oscillation length corresponding to p'_ν, our condition is:

$$2\pi \frac{X}{L'_{kj}} = 2\pi \frac{X}{L_{kj}} - \pi \quad \rightarrow \quad L'_{kj} \simeq L_{kj}\left(1 + \frac{\Delta p_\nu}{2p_\nu}\right) \quad \rightarrow \quad X \sim \frac{p_\nu}{\Delta p_\nu} L_{kj}$$

- For x>X the oscillation disappears and

$$P(\alpha \rightarrow \beta, x > X) = \sum_k U^2_{\alpha k} U^2_{\beta k} \neq 0$$

Oscillation experiments

Two categories:

- ➡ disappearance: measure $P_{\alpha\alpha}$
- ➡ appearance: measure $P_{\alpha\beta}$

NB: $P_{\alpha\alpha}$ is never actually observable

$$\mathbf{R}_\beta \sim \int \mathbf{\Phi}_\alpha \otimes \mathbf{P}_{\alpha\beta} \otimes \boldsymbol{\sigma}_\beta \otimes \epsilon_\beta$$

Observable event rate | Source flux (production) | Propagation (flavor change) | Interaction | Detection

- need to take into account detailed phenomenology
- specific issues for each of these ingredients, in all subfields of neutrino physics.

Vacuum oscillations formula: summary

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \Re J^{ij}_{\alpha\beta} \sin^2(\frac{\Delta m^2_{ij} x}{4E})$$
$$-2\sum_{i<j} \Im J^{ij}_{\alpha\beta} \sin(\frac{\Delta m^2_{ij} x}{2E})$$

where

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

$$J^{ij}_{\alpha\beta} = U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}$$

$$\frac{\Delta m^2_{ij}}{4E} = 1.267(\frac{\Delta m^2_{ij}}{\mathrm{eV}^2})(\frac{x}{\mathrm{m}})(\mathrm{MeV}(E))$$

2 neutrino oscillations revisited

- let's consider P_{ee} in the conditions where $\delta m^2 = m_2^2 - m_1^2 \simeq 0$ (which essentially means that **$\Delta m^2 x/E \sim O(1)$** and **$\delta m^2 x/E \simeq 0$**
- this means that the only non zero terms are multiplied by $J_{ee}^{13} = U_{e1}^* U_{e3} U_{e3}^* U_{e1} = |U_{e1}|^2 |U_{e3}|^2$ and $J_{ee}^{23} = U_{e2}^* U_{e3} U_{e3}^* U_{e2} = |U_{e2}|^2 |U_{e3}|^2$
- this also means $Im(J_{ee}^{13}) = Im(J_{ee}^{23}) = 0$

$$
\begin{aligned}
P(\nu_e \to \nu_e) &= 1 - 4(|U_{e1}|^2 |U_{e3}|^2 + |U_{e2}|^2 |U_{e3}|^2)\sin^2(\frac{\Delta m^2 L}{4E}) \\
&= 1 - 4|U_{e3}|^2 (1 - |U_{e3}|^2)\sin^2(\frac{\Delta m^2 L}{4E}) \\
&= 1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2 L}{4E})
\end{aligned}
$$

- δ is not observable (as well as sign($\pm\Delta m^2$)) and $P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e)$

- intuitively: U = (23) (13) (12)
  - (23) mixes unobservable flavours (ν_μ, ν_τ)
  - (12) mixes degenerate states (ν_1, ν_2)

2 neutrino oscillations revisited

- in the present approximation we are essentially probing Δm_{13}^2 and the mixing matrix elements $|U_{\alpha 3}|^2$.

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

- the relevant probabilities are

$$P(\nu_e \to \nu_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

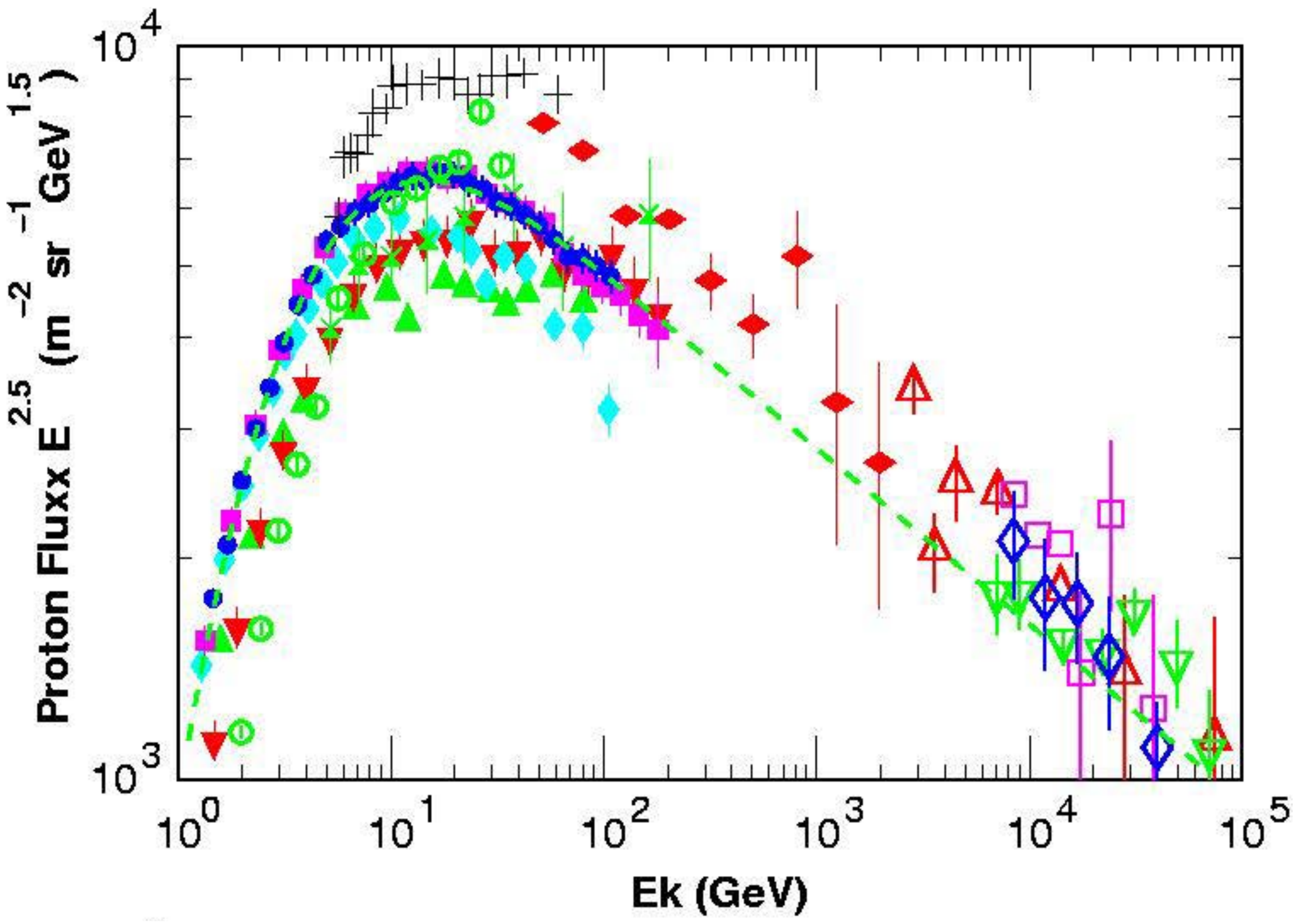
$$P(\nu_\mu \to \nu_e) \simeq s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

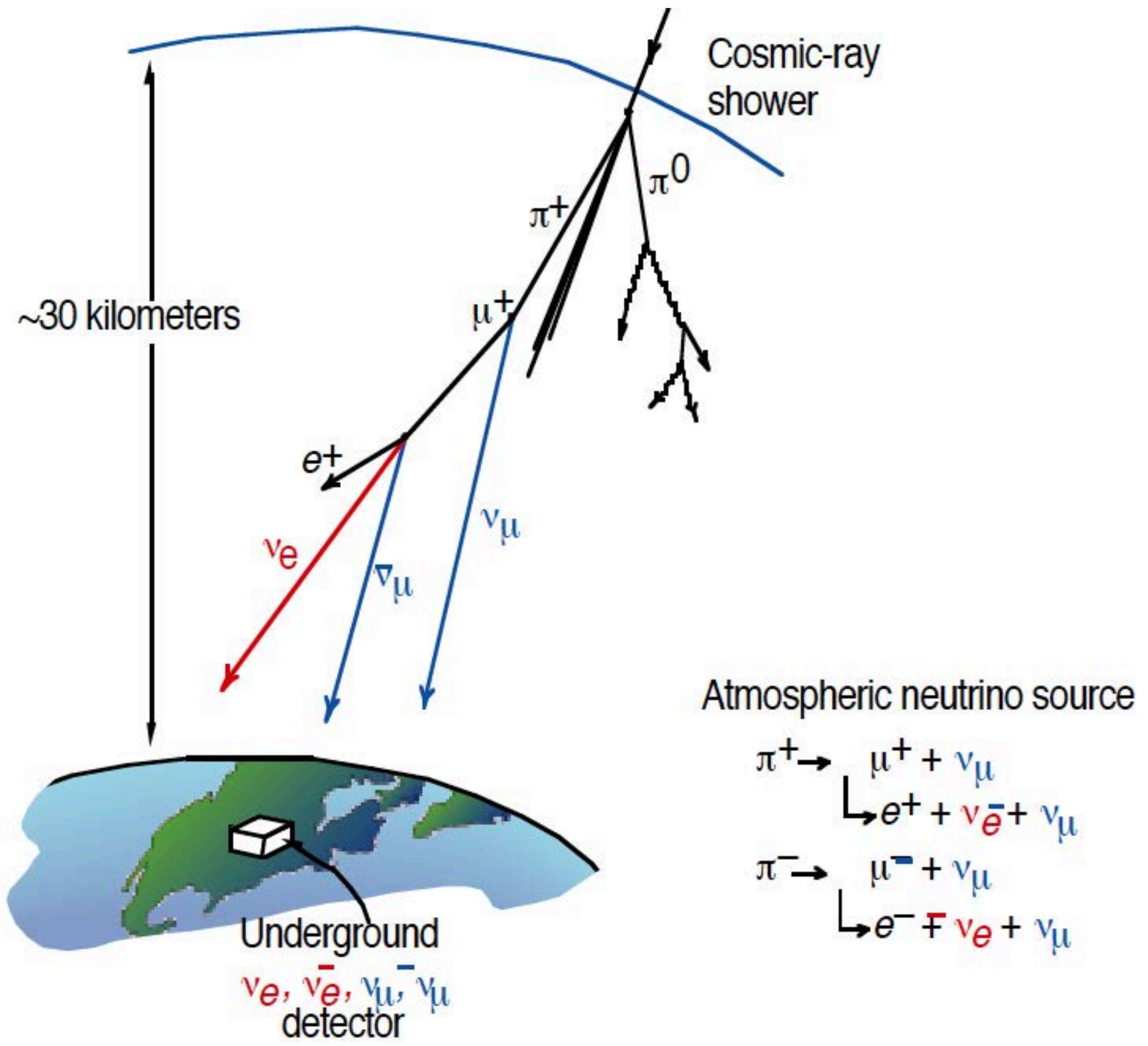
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4c_{13}^2 s_{23}^2 (1 - c_{13}^2 s_{23}^2) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P(\nu_\mu \to \nu_\tau) \simeq c_{13}^4 \sin^2 2\theta_{23} \left(\frac{\Delta m^2 L}{4E}\right)$$

atmospheric neutrinos

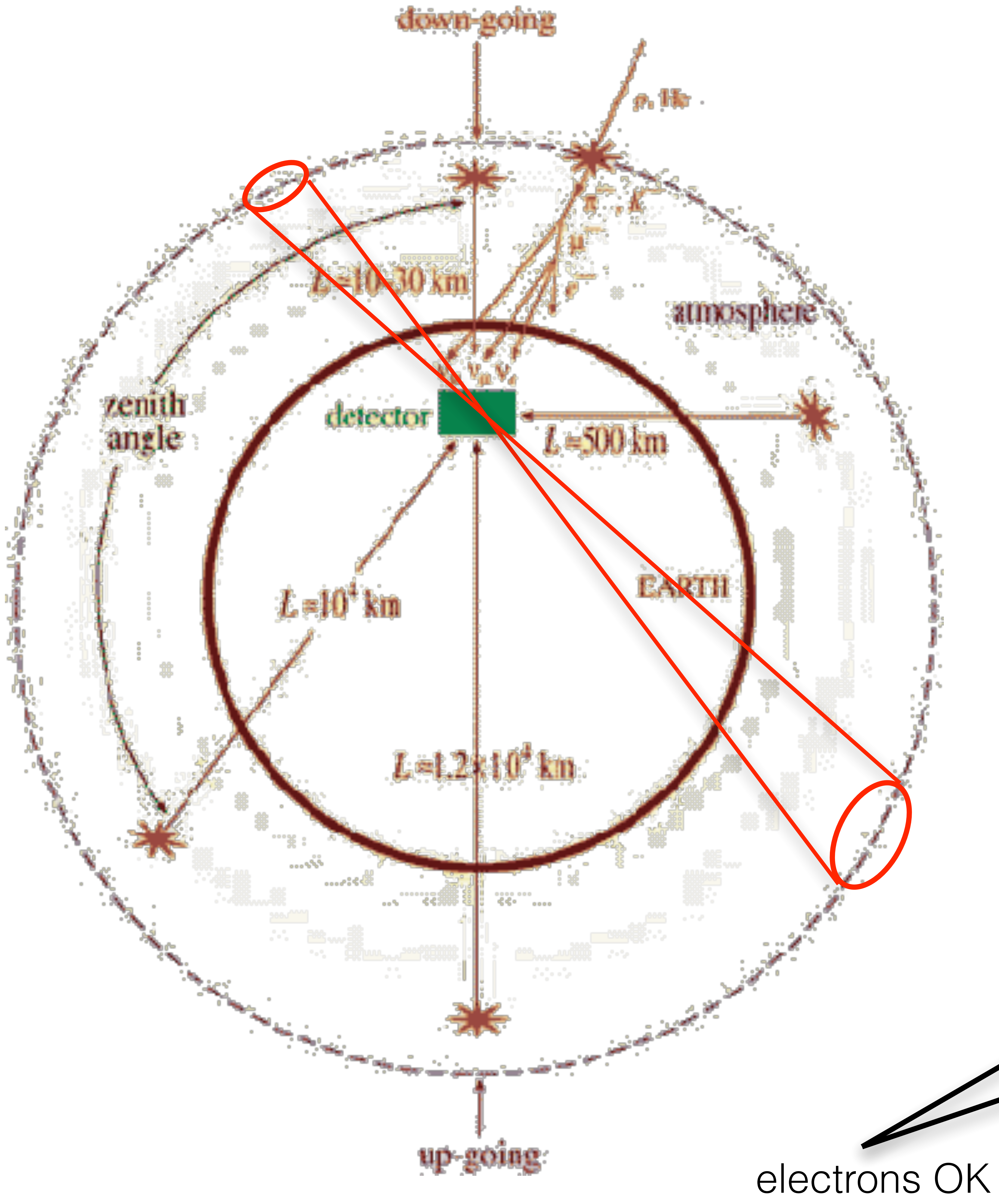
- Cosmic rays hittng the atmosphere can generate secondary (anti)neutrinos with electron and muon flavor via meson decays





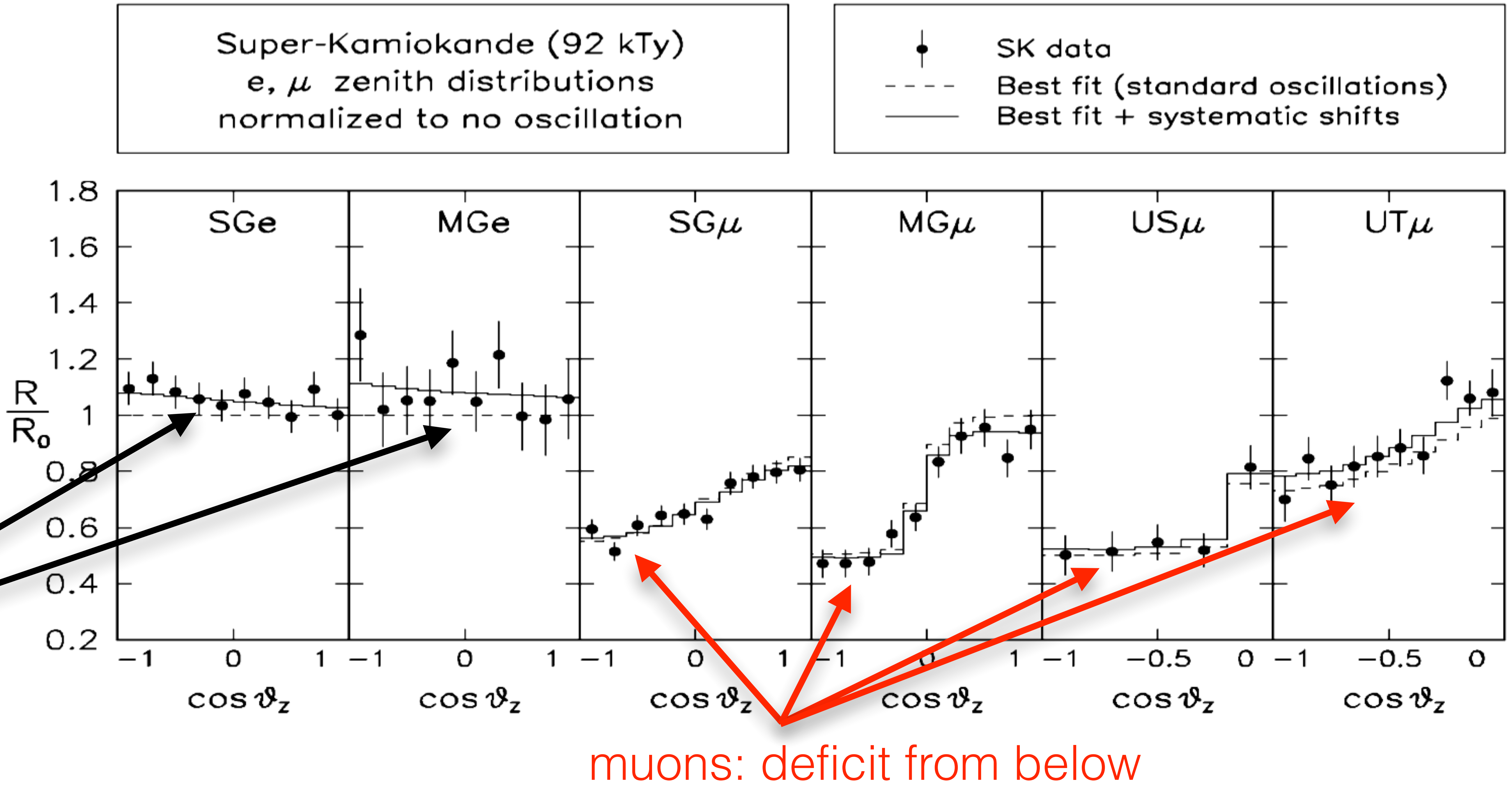
- primary flux affected by large normaliza<on uncertain<es…
- … but (an<)neutrino flavor ra'o (μ/e ~ 2) robust within few %

atmospheric neutrinos

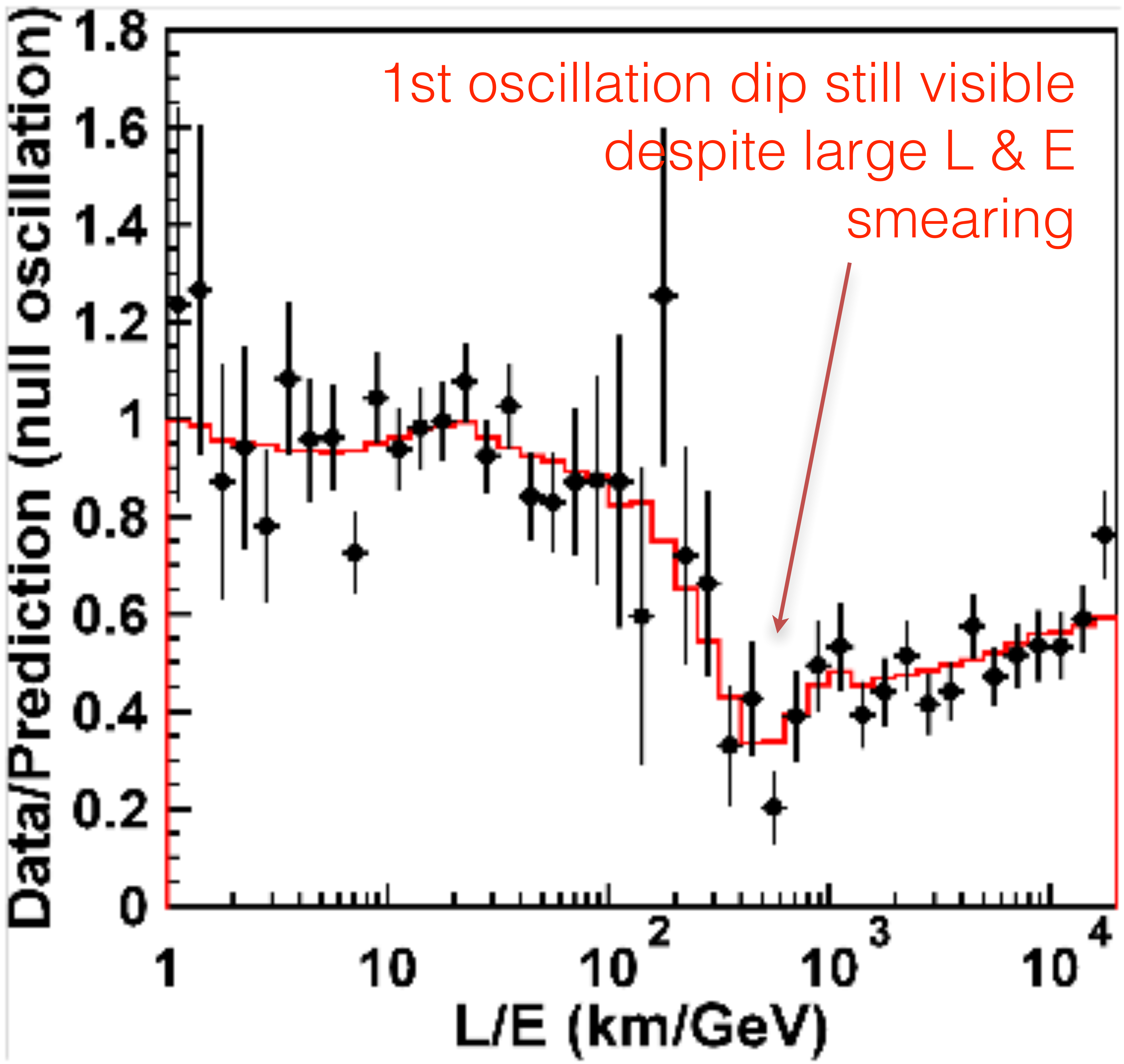


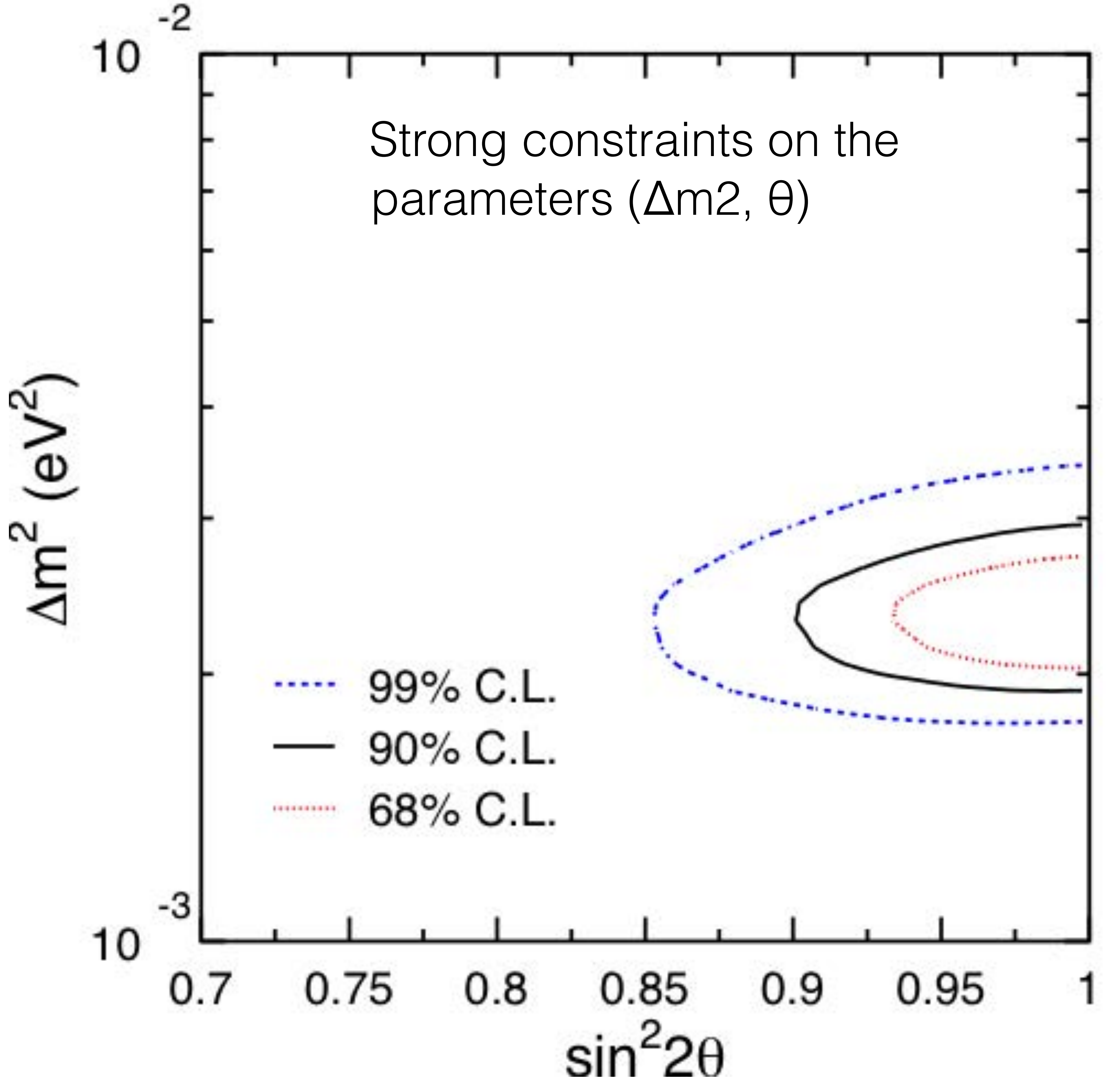
- **Observatons over several decades in L/E:**
  - Same ν flux from opposite solid angles (up-down symmetry)
  - Flux dilution (~1/r^2) is compensated by larger production surface (~r^2)
  - Should be reflected in symmetry of event zenith spectra, if energy & angle can be reconstructed well enough
- **One-mass-scale approximation (for θ$_{13}$~0):**

$$P_{\mu\tau} \sim \sin^2(2\theta_{13})\sin^2(\frac{\Delta m^2 L}{4E})$$



Super Kamiokande (S-K)

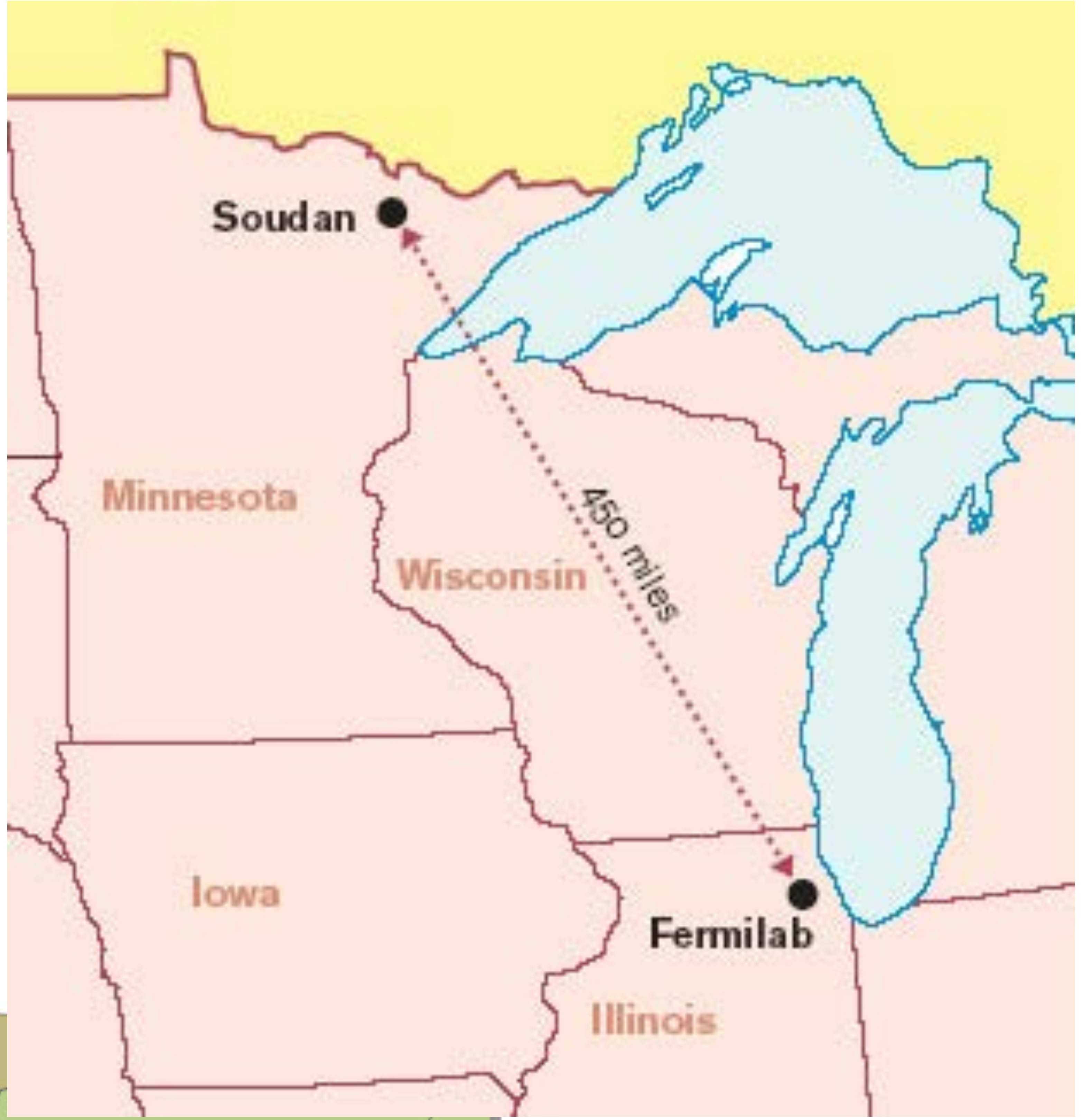


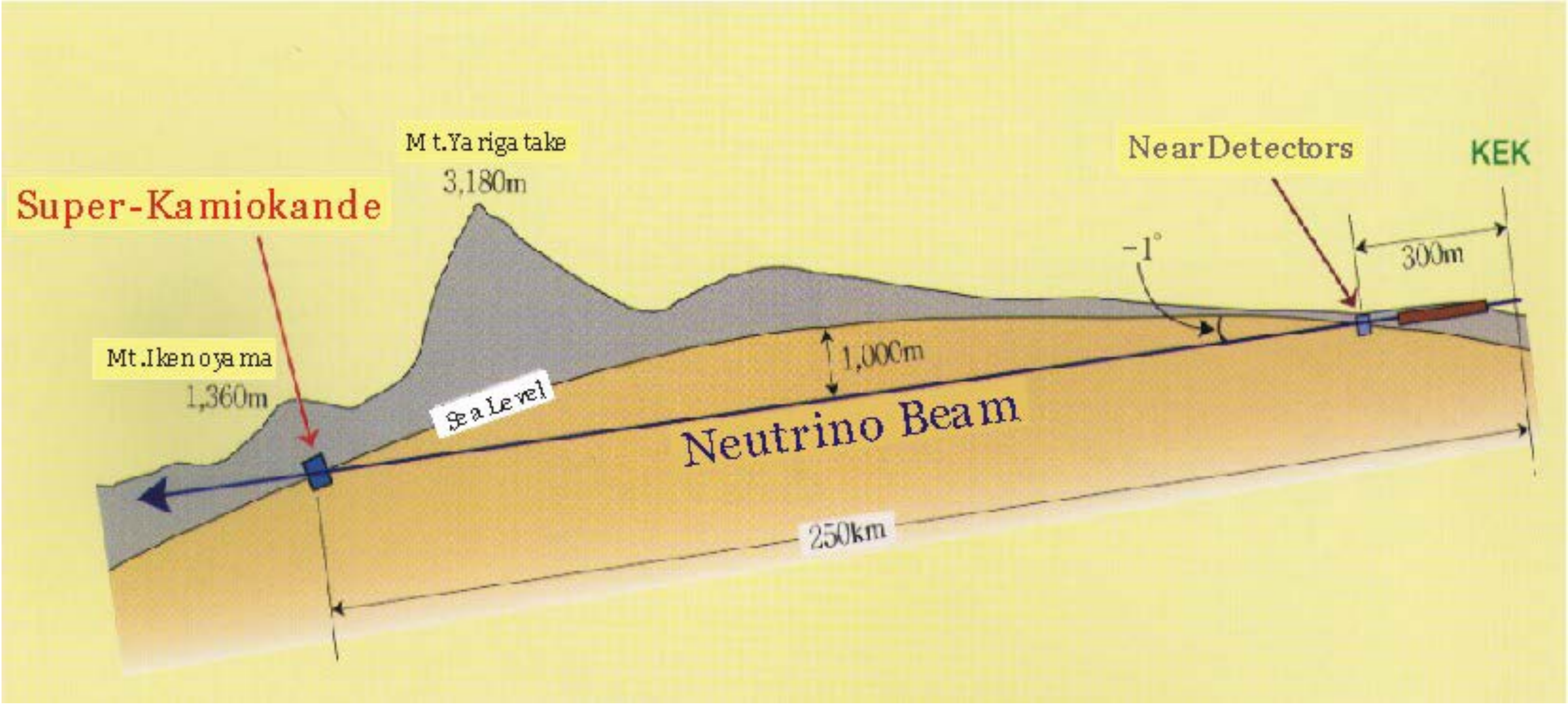


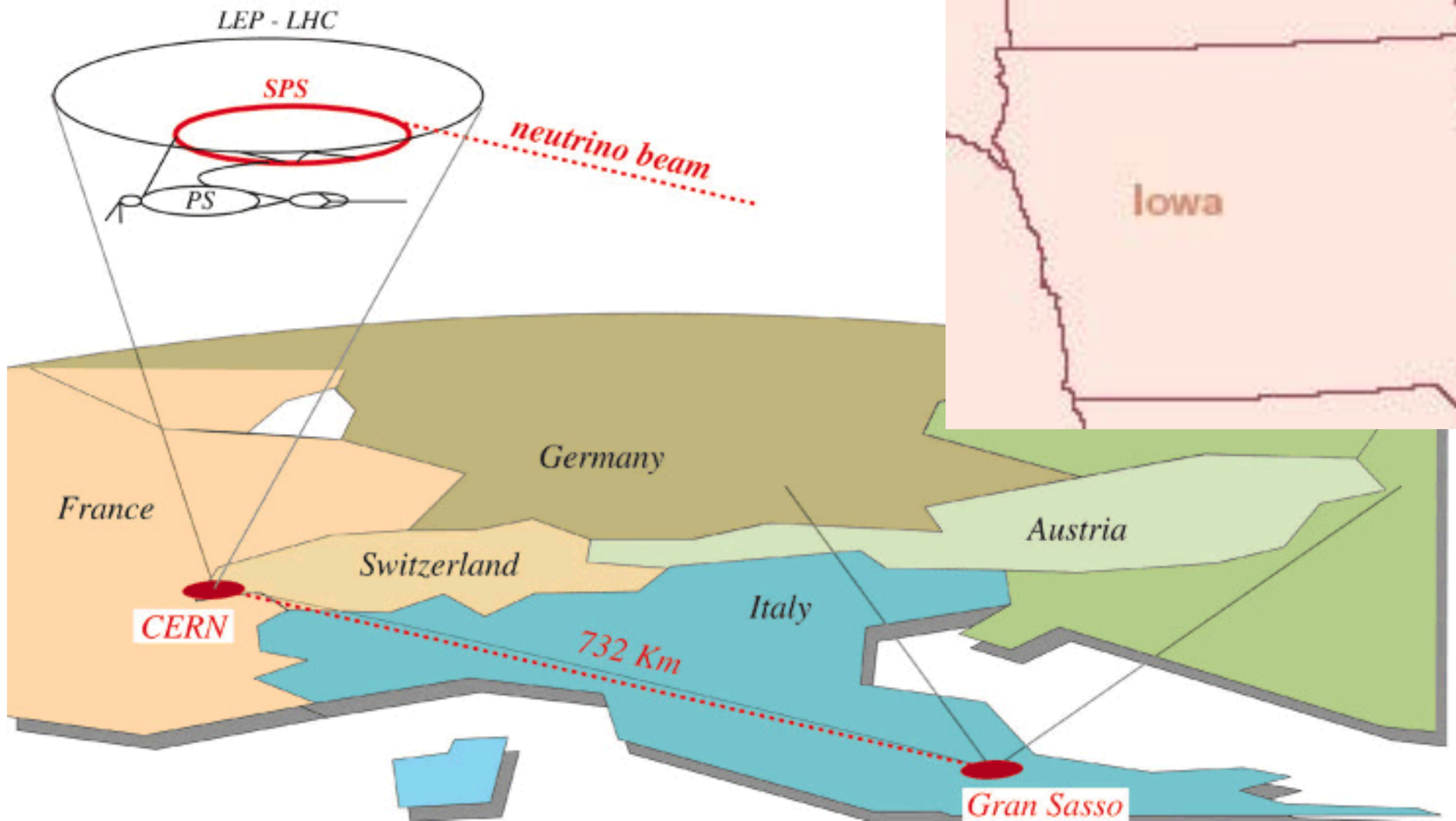
- Latest SK data analyses more refined: include many bins and syst. in order to “squeeze” subleading effects beyond dominant L/E

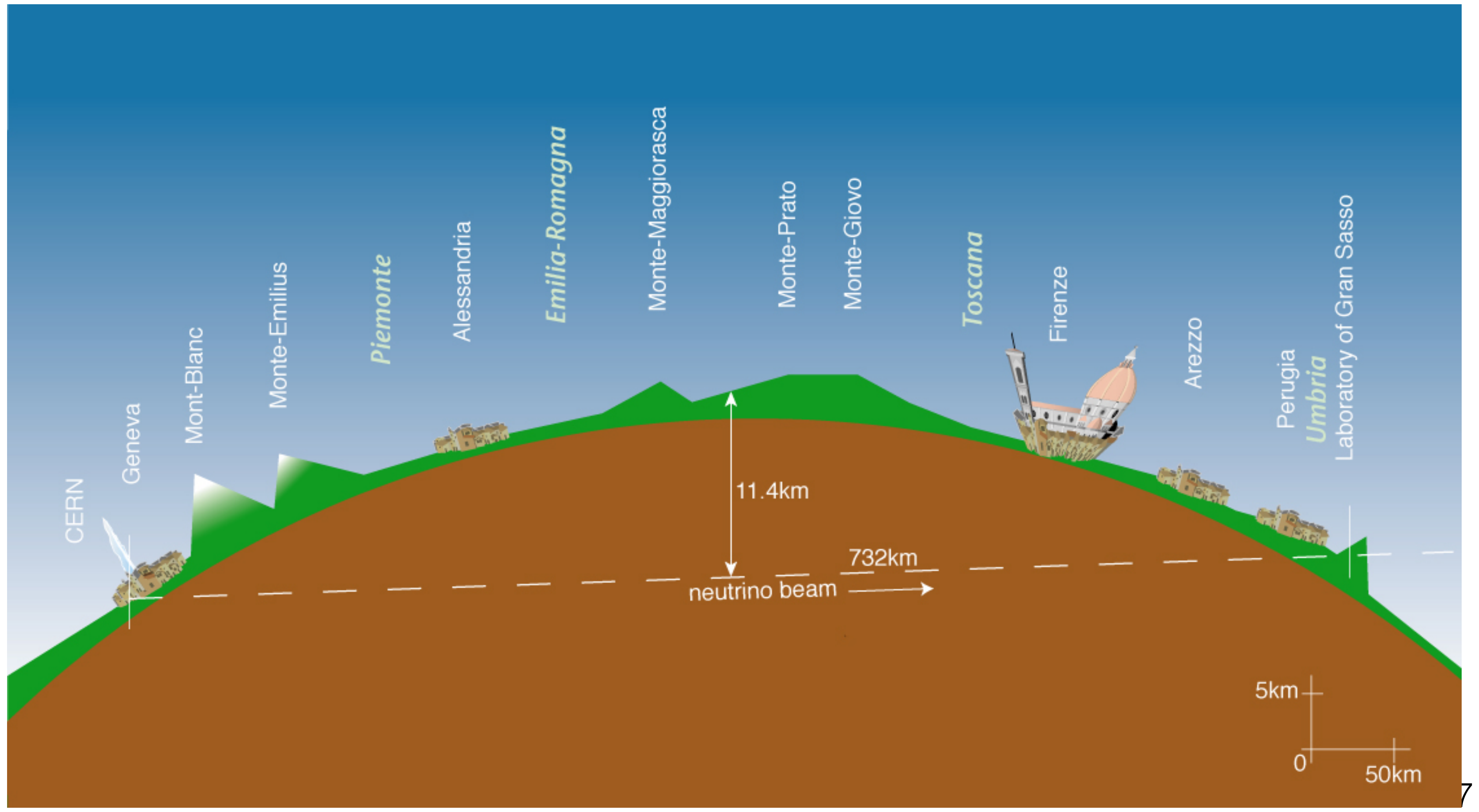
Long BaseLine experiments (LBL)

K2K, T2K (JP), MINOS, NOvA (USA), OPERA (CERN): reproduce atmospheric νμ physics in controlled conditions



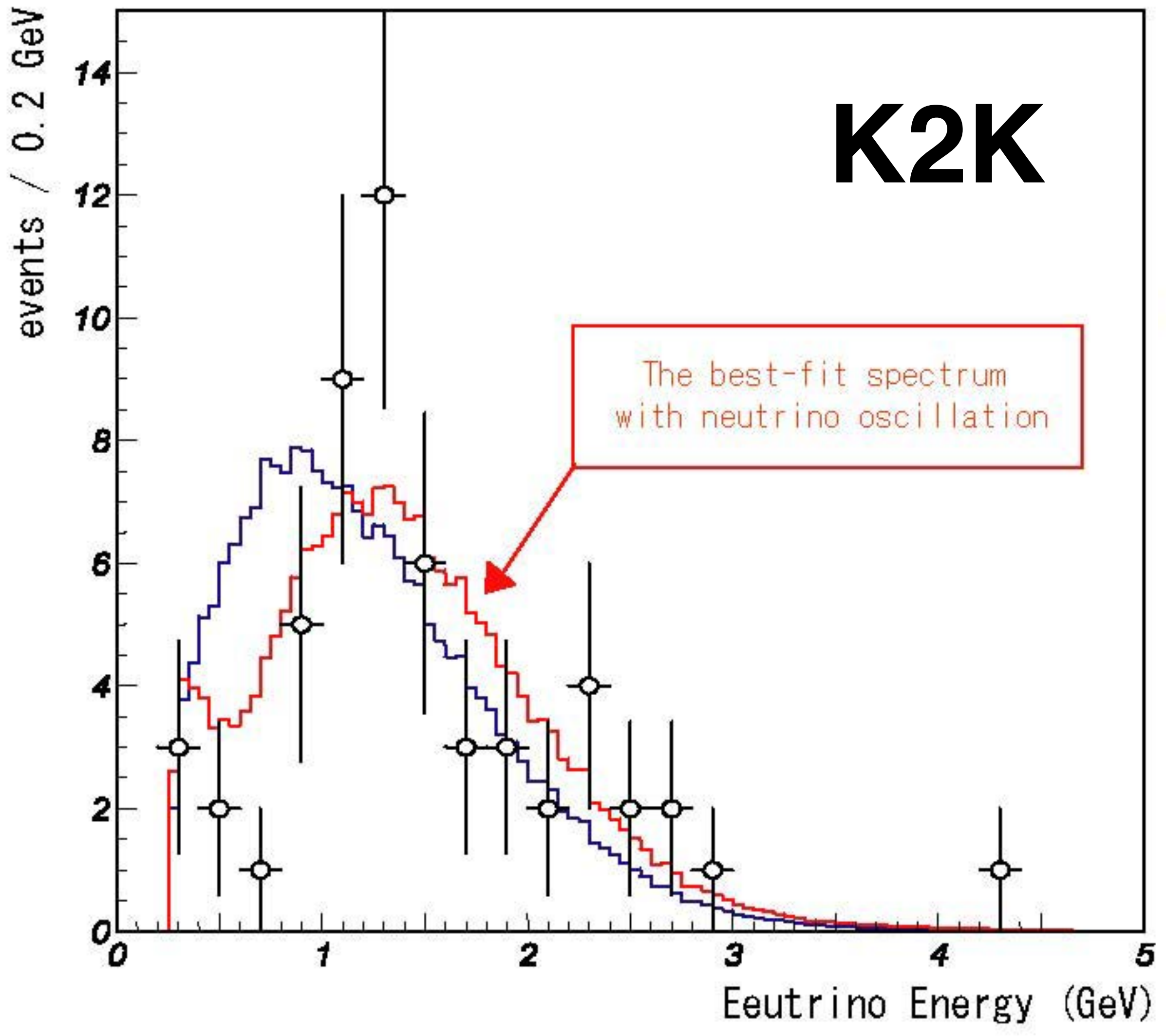


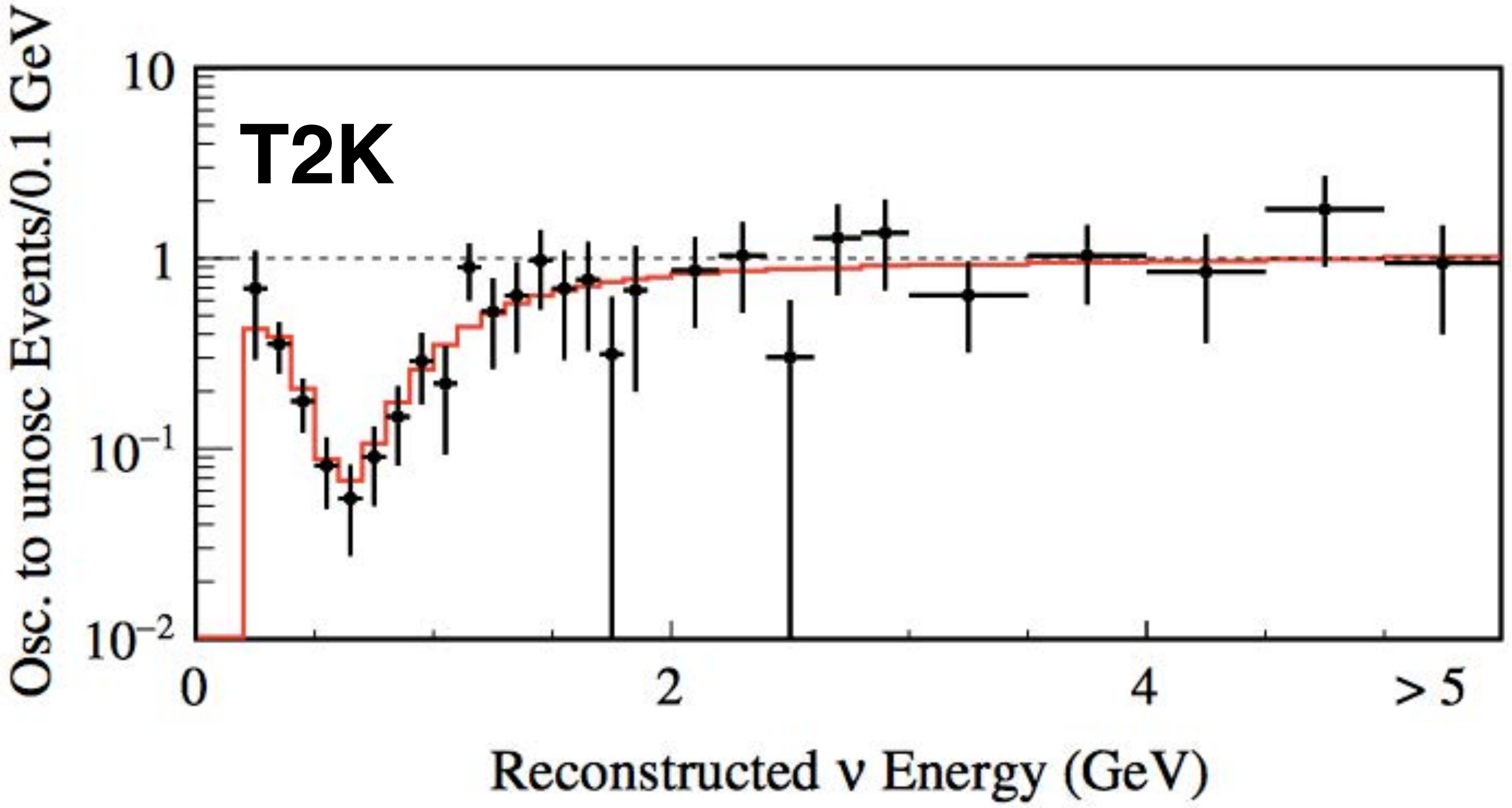


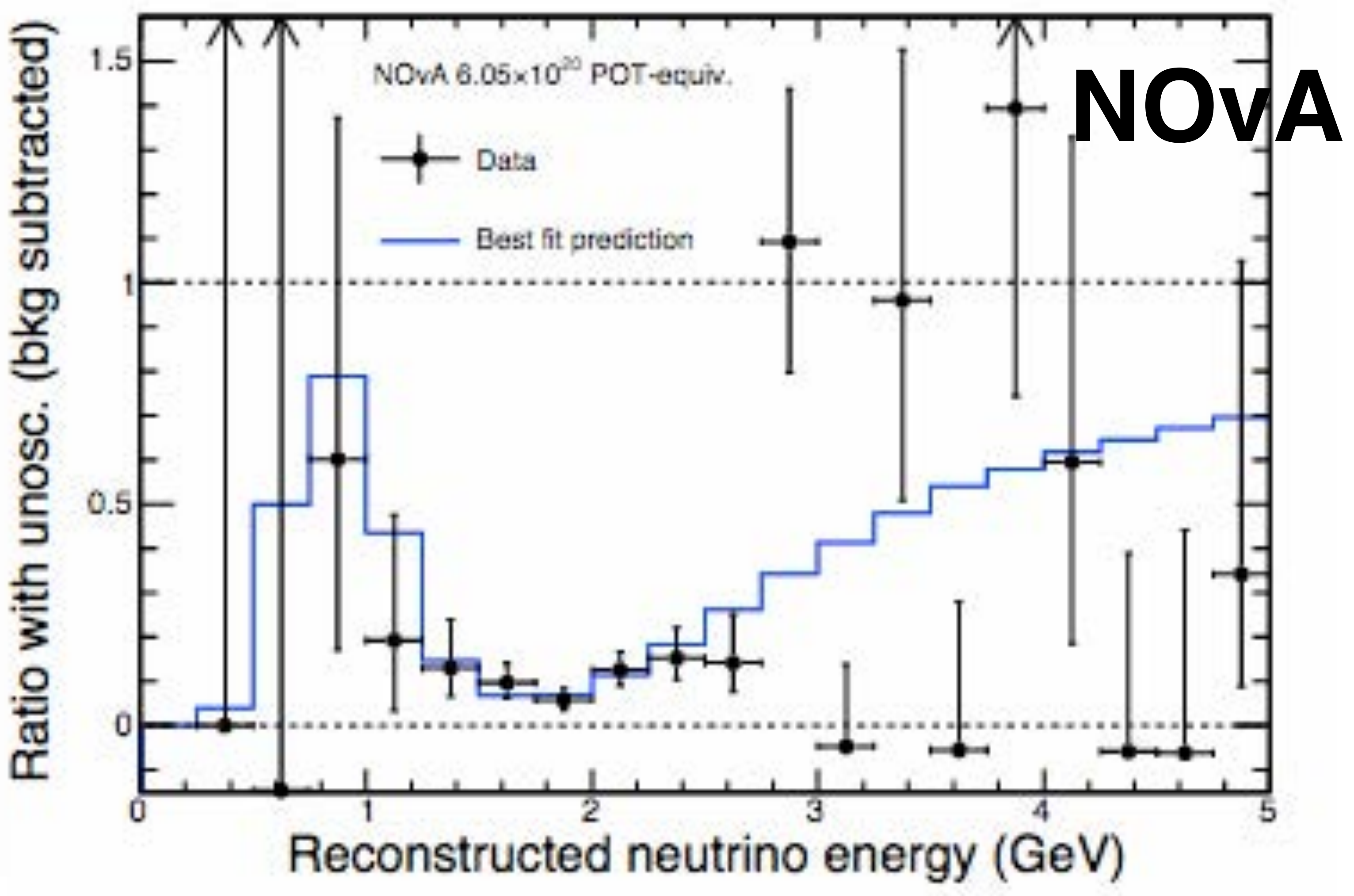


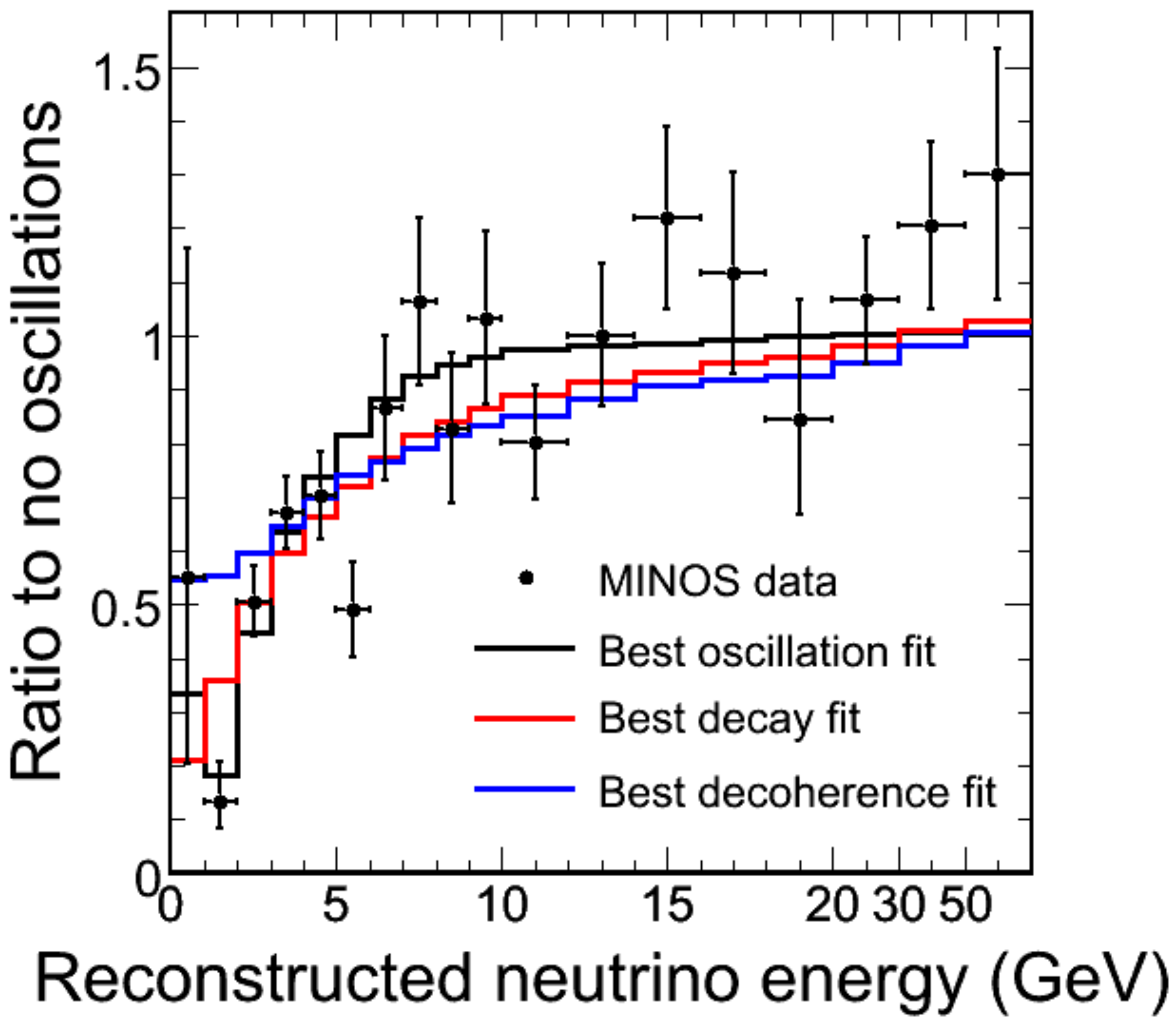
LBL results

- Results in muon neutrino disappearance mode $P_{\mu\mu}$





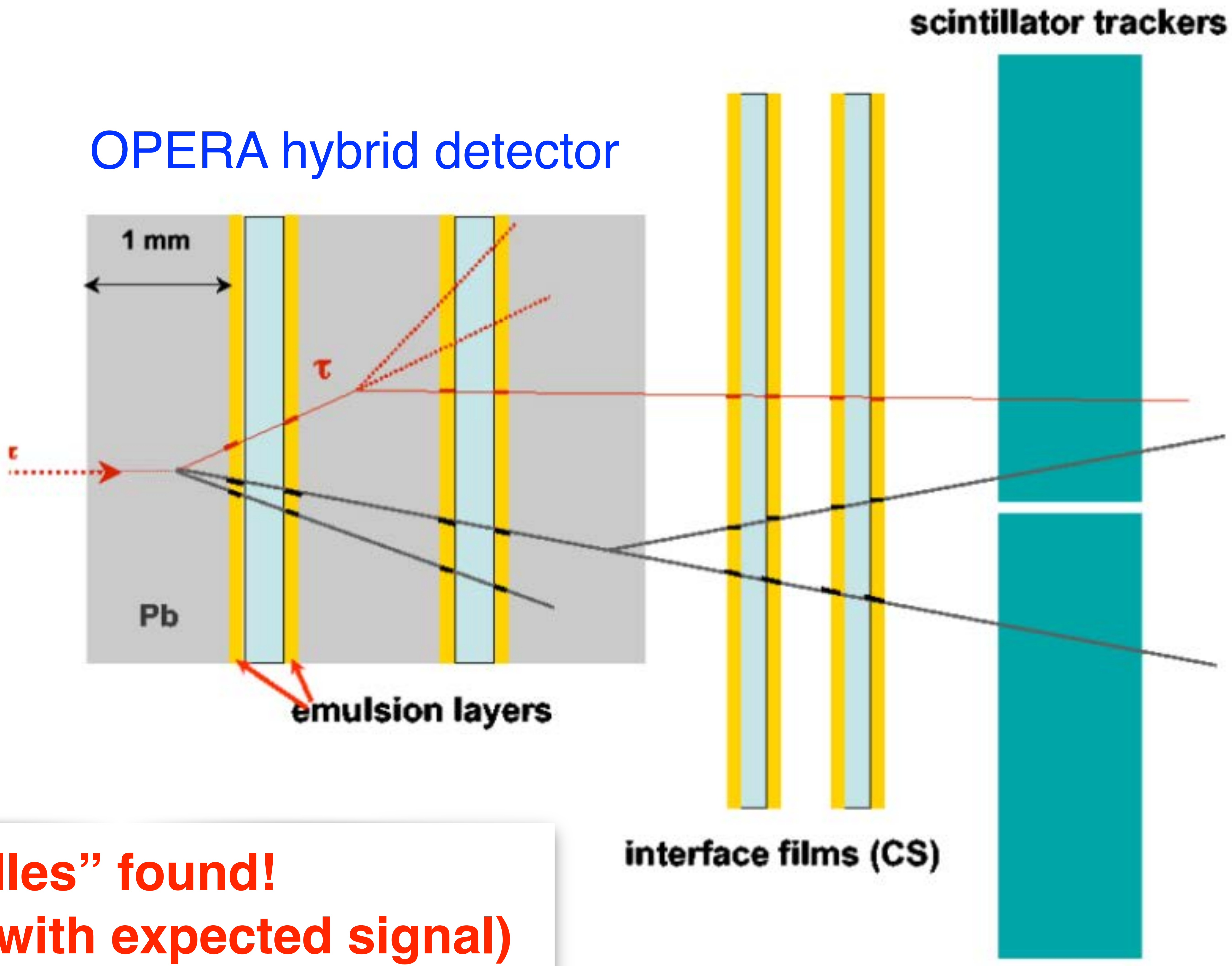


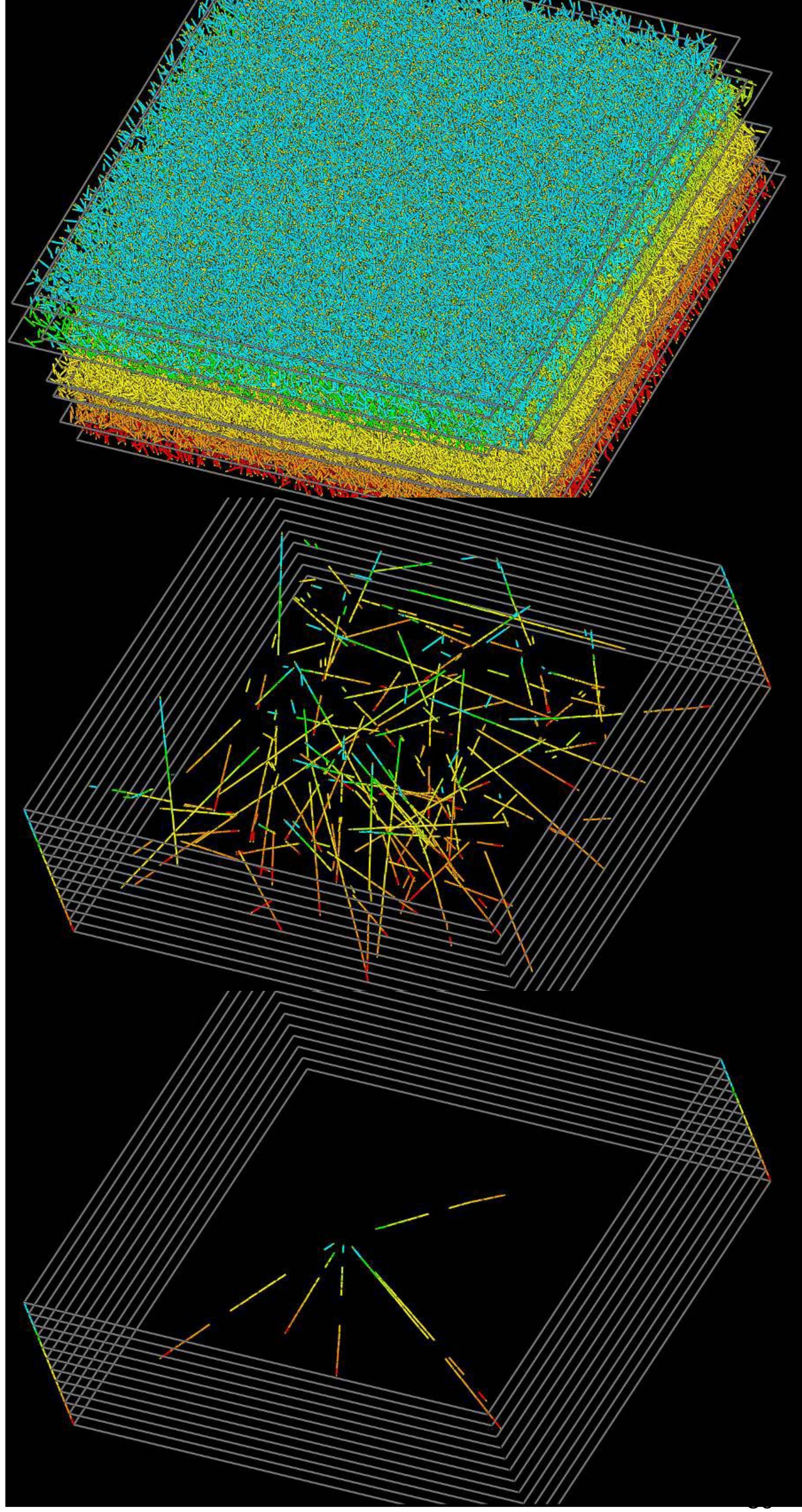


- 1st oscillation dip observed in energy spectrum (equivalent to L/E spectrum since L is fixed).

OPERA

Finding needles in a haystack…



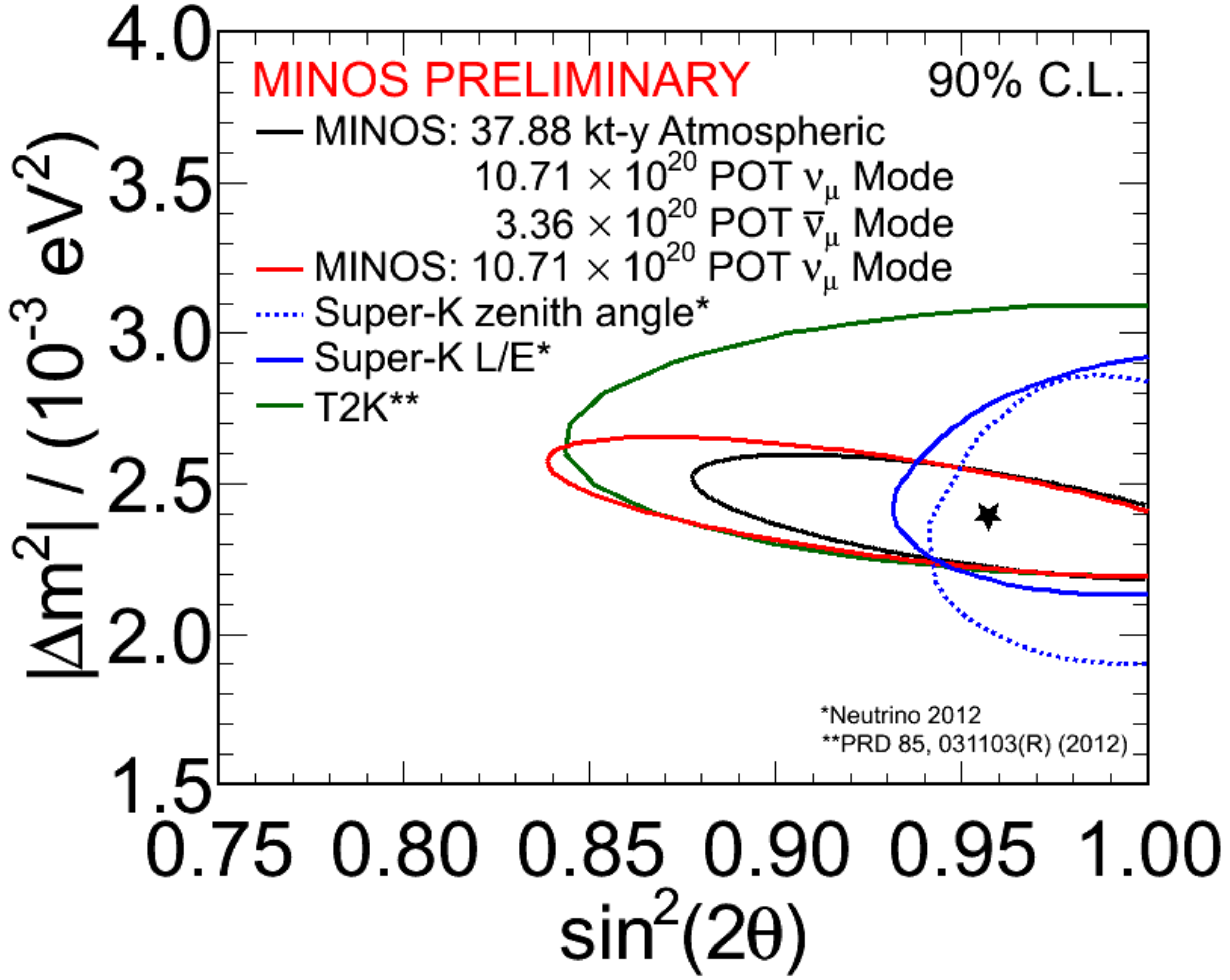


Five "τ needles" found!
(consistent with expected signal)

LBL results

- Dominant $P_{\mu\tau} = \sin^2(2\theta_{23})\sin^2(\frac{\Delta m^2 L}{4E_\nu})$

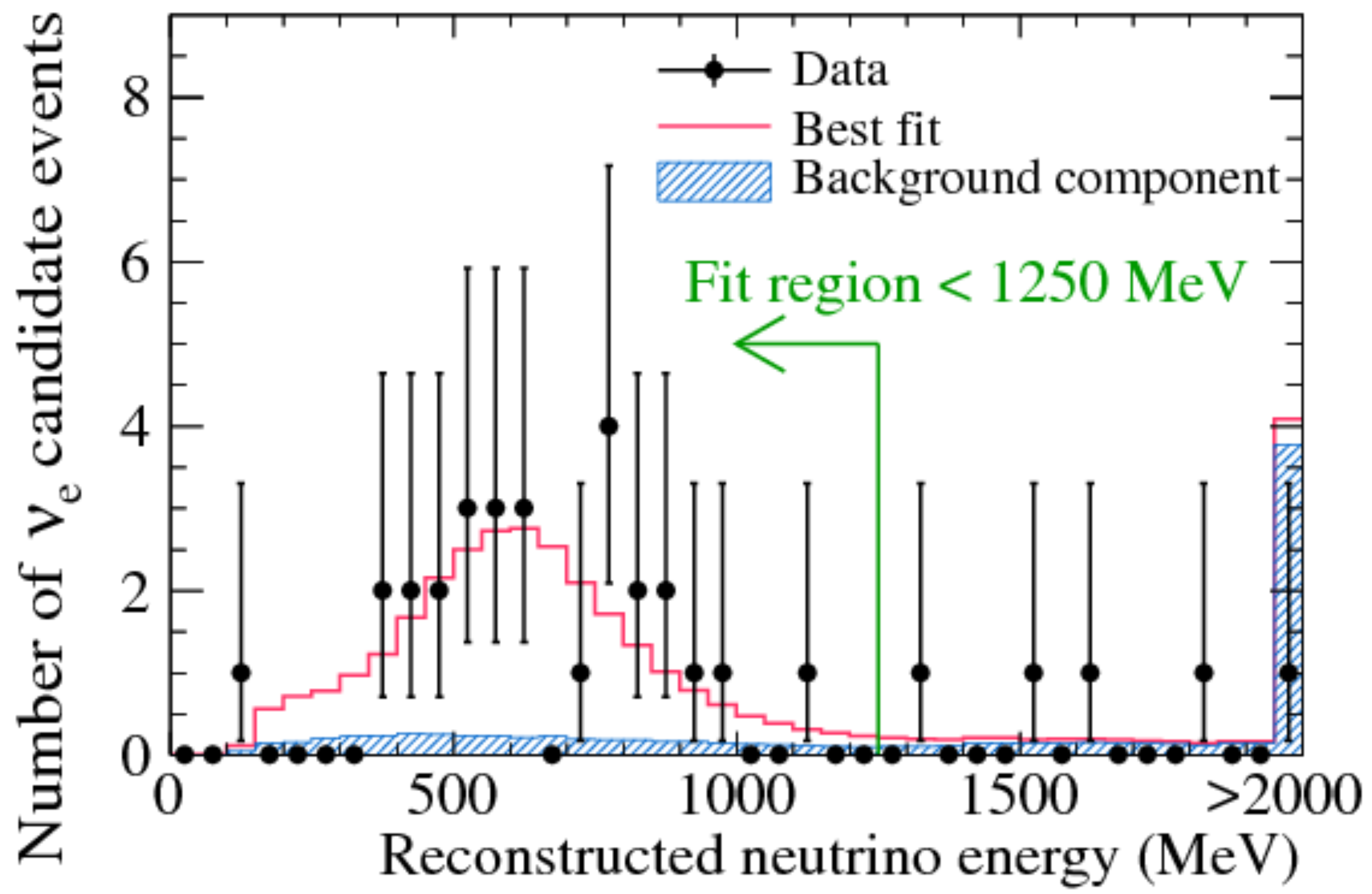
- Dip position and depth determine Δm^2 and θ_{23}
- Osc. parameters consistent among atm and LBL experiments
- Old-fashioned way to present mass--mixing constraints



- Since $\theta_{13}>0$ (SBL reactors) μ→e flavor appearance in LBL experiments is expected
- T2K & NOvA: e-like event rate consistent with reactors θ_{13}

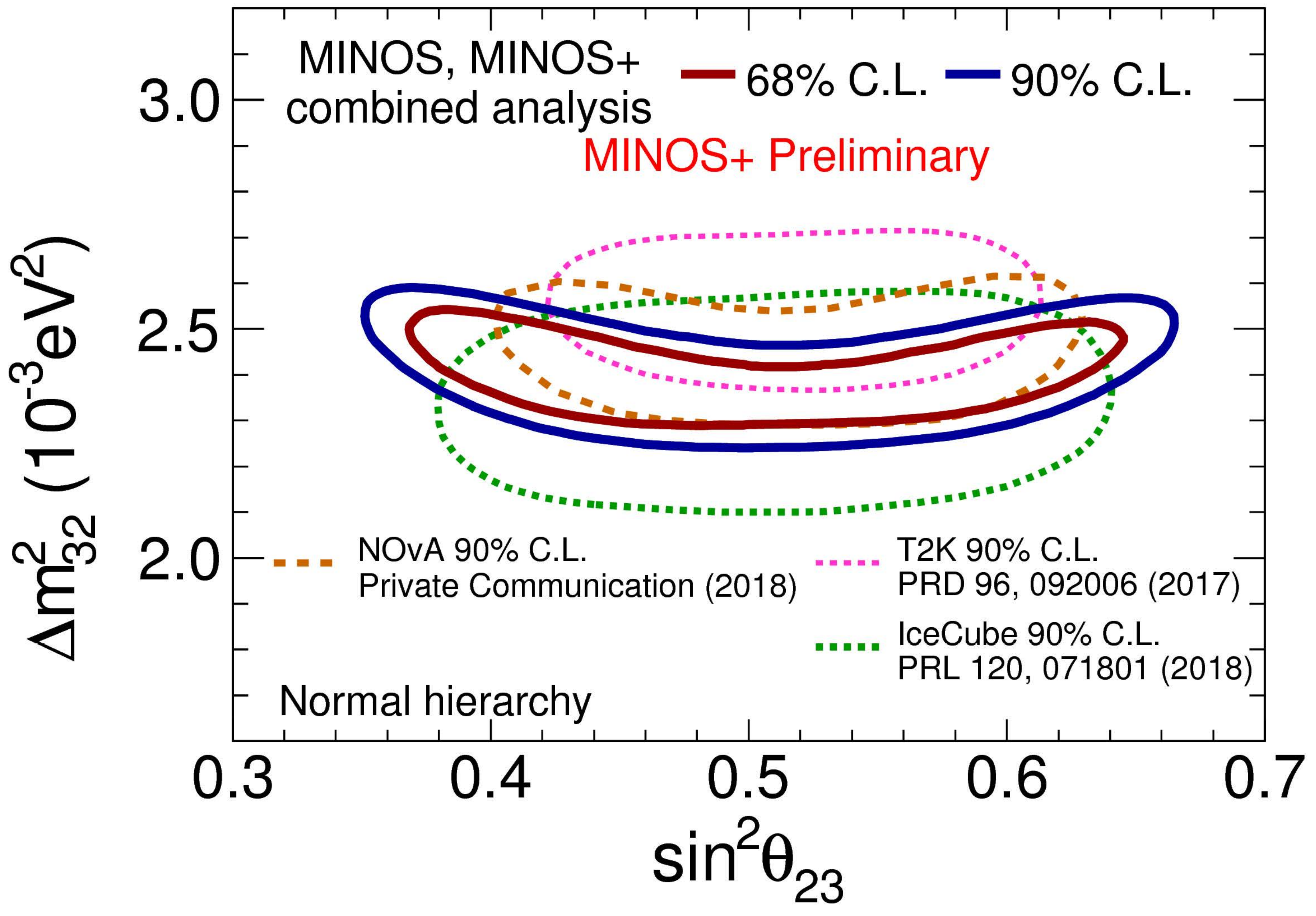
$$P(\nu_\mu \to \nu_e) \simeq s_{23}^2 \sin^2 2\theta_{13} sin^2(\frac{\Delta m^2 L}{4E})$$

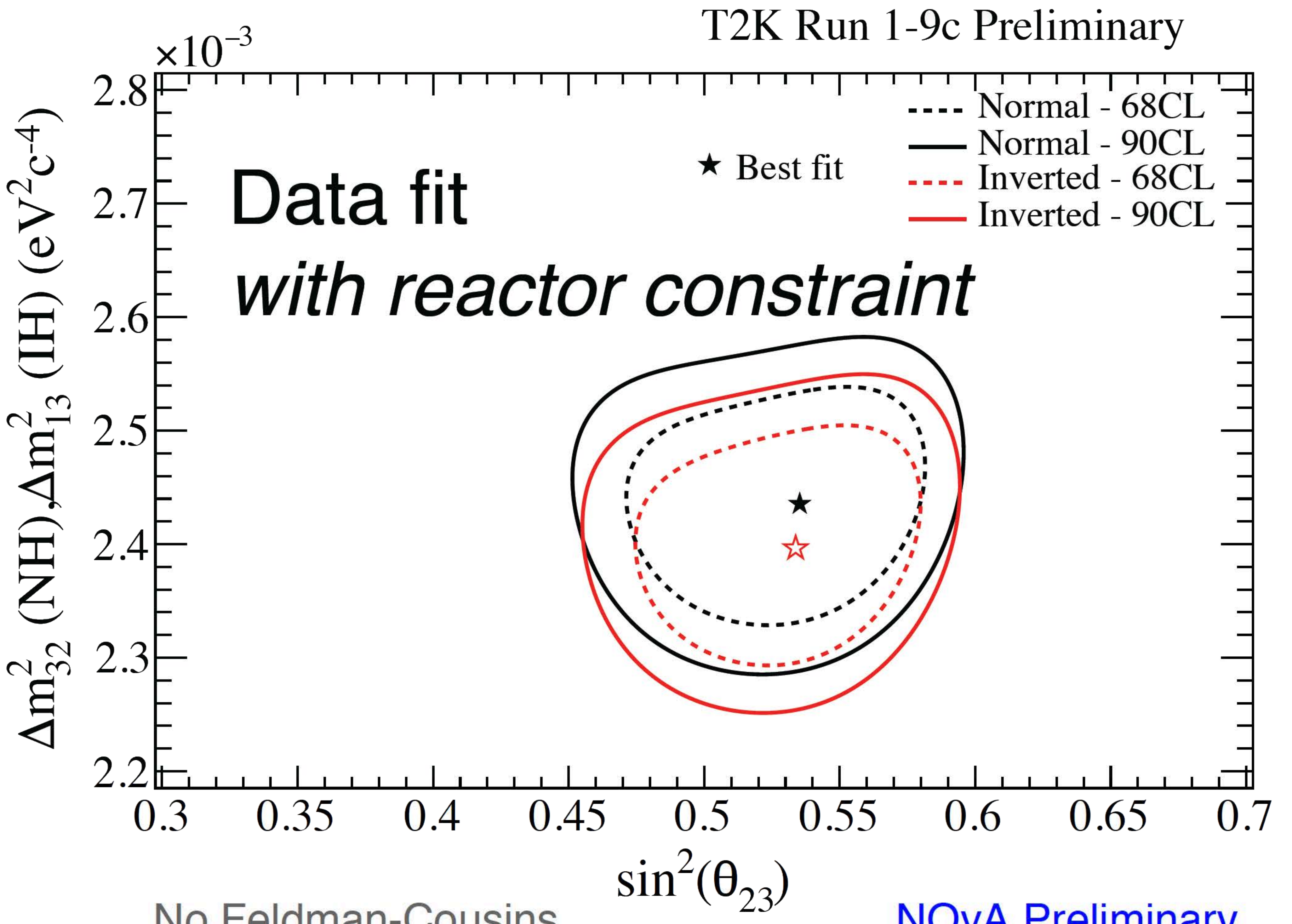
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4c_{13}^2 s_{23}^2 (1 - c_{13}^2 s_{23}^2)\sin^2(\frac{\Delta m^2 L}{4E})$$

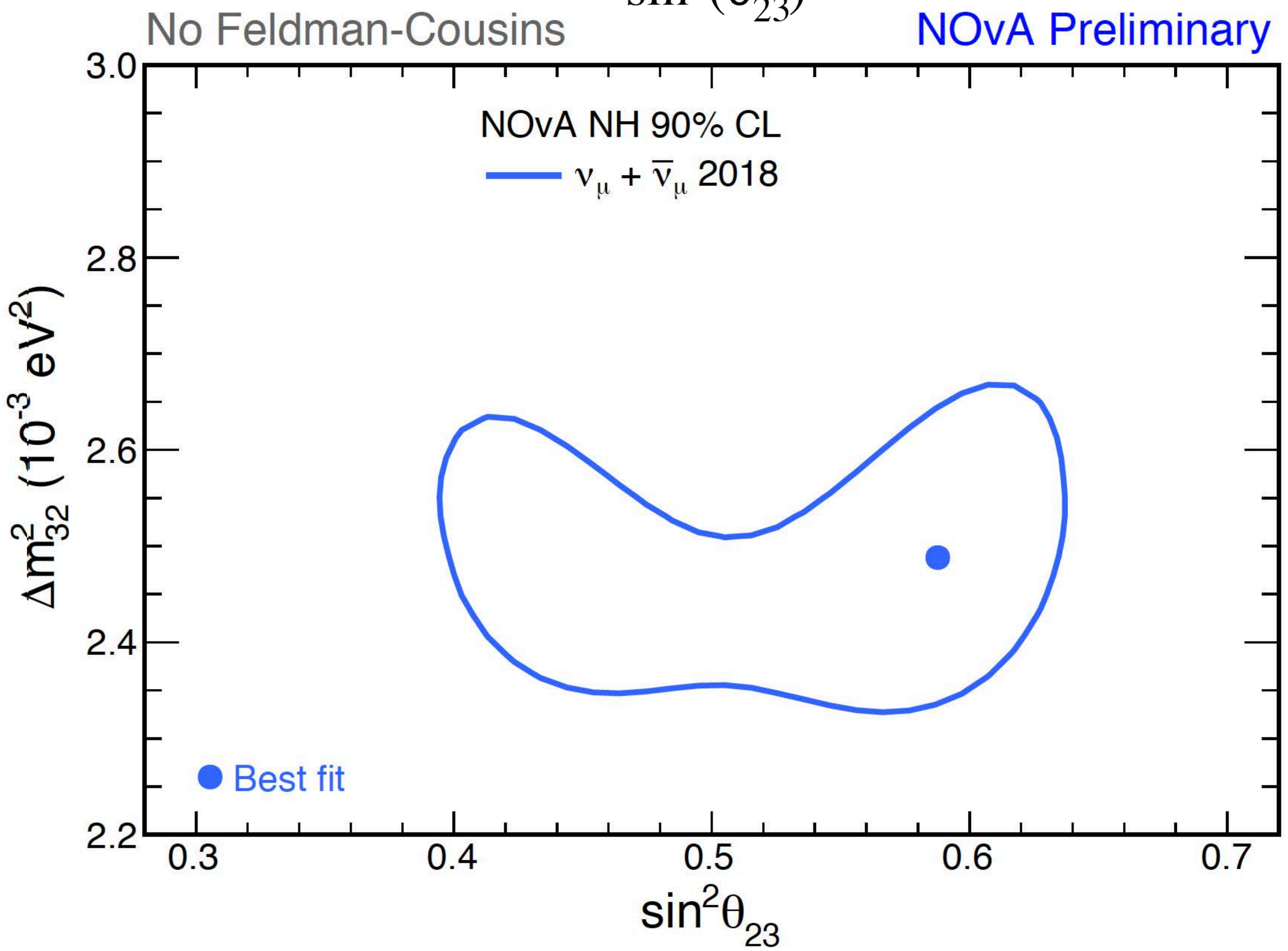


LBL updates

- Not yet established if θ_{23} is maximal.
- If not … first or second octant? ("octant ambiguity)
- Next frontier in LBL/Atmospheric: probe subleading effects related to octant, matter, hierarchy, δCP, δm^2, θ_{12}, …







δm^2 driven oscillations

- Let's analyse the condition $\delta m^2 x/4E \sim O(1)$, $\Delta m^2 x/4E \ll 1$
- LBL reactors with relatively low E and solar neutrinos
- which means …

$$P_{ee} \simeq \cos^4\theta_{13}[1 - \sin^2 2\theta_{12}\sin^2(\frac{\delta m^2 x}{4E})] + sin^4\theta_{13}$$

$$P_{ee}^{3\nu} = c_{13}^4 P_{ee}^{2\nu}(\delta m^2, \theta_{12}) + s_{13}^4$$

- and the probed region is

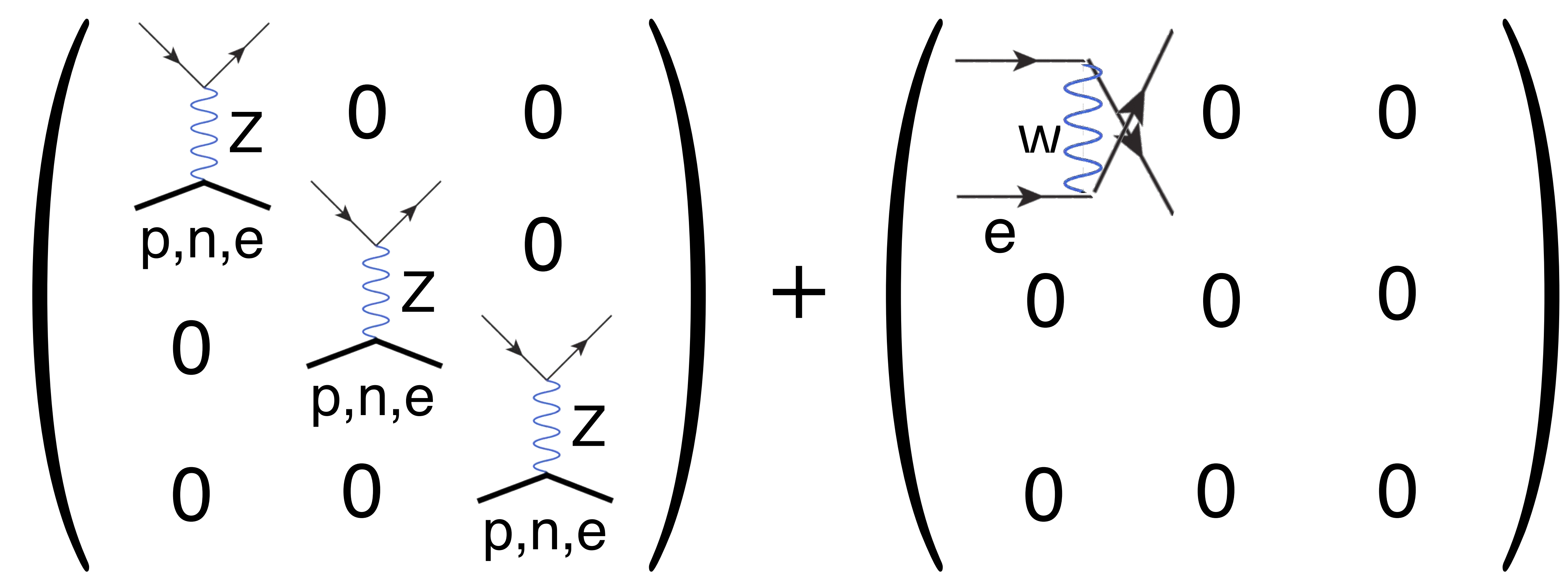
$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{bmatrix}$$

- however oscillations are disturbed by matter effects

$$H_{flavor} = \frac{1}{2E} U \begin{bmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_1^2 \end{bmatrix} U^\dagger + \begin{bmatrix} V_{ee} & V_{e\mu} & V_{e\tau} \\ V_{\mu e} & V_{\mu\mu} & V_{\mu\tau} \\ V_{\tau e} & V_{\tau\mu} & V_{\tau\tau} \end{bmatrix}$$

$V_{\alpha\beta}$ the matter matrix

$V_{\alpha\beta} =$



- Proportional to identity: unobservable
- Observable in ν_e oscillations

- The relevant term is the ν_e-ν_μ difference which is proportional to V_{CC}, the charged current interaction energy: $V_{CC} = \sqrt{2} G_F N_e$ where N_e is the electron number density

- The ν propagation Hamiltonian becomes:

$$H_{flavor} = \frac{1}{2E} U \begin{bmatrix} m_1^2 & & \\ & m_2^2 & \\ & & m_1^2 \end{bmatrix} U^\dagger + \begin{bmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

where $A = 2\sqrt{2} G_F N_e E$

ν oscillations in matter

- ν oscillations in matter depend on the local electron density
- In the 2ν limit (θ_{13}=0) and N_e=const

$$P_{ee}^{2\nu}(\text{mat}) = 1 - \sin^2 2\tilde{\theta}_{12} \sin^2(\frac{\delta\tilde{m}^2 x}{4E})$$

- ν oscillations in constant density matter have a vacuum structure with the simple replacement:

$$\sin^2 2\theta_{12} \to \sin^2 2\tilde{\theta}_{12} = \frac{\sin^2 2\theta_{12}}{\sqrt{(\cos 2\theta_{12} - \frac{A}{\delta m^2})^2 + \sin^2 2\theta_{12}}} \qquad \delta\tilde{m}^2 = \delta m^2 \frac{\sin^2 2\theta_{12}}{\sin^2 2\tilde{\theta}_{12}} \qquad A = \pm\, 2\sqrt{2} G_F N_e$$

where the minus sign in A holds for $\bar{\nu}$

- When $A/\delta m^2$ ~ $\cos 2\theta_{12}$ ν oscillations resonate (nothing changes for $\bar{\nu}$)
- Three limiting cases:

$$A/\delta m^2 \ll 1 : \quad (\delta\tilde{m}^2, \tilde{\theta}) \simeq (\delta m^2, \theta)$$ vacuum-like

$$A/\delta m^2 \simeq \cos 2\theta : \quad (\delta\tilde{m}^2, \tilde{\theta}) \simeq (\delta m^2 \sin 2\theta, \pi/4)$$ resonant

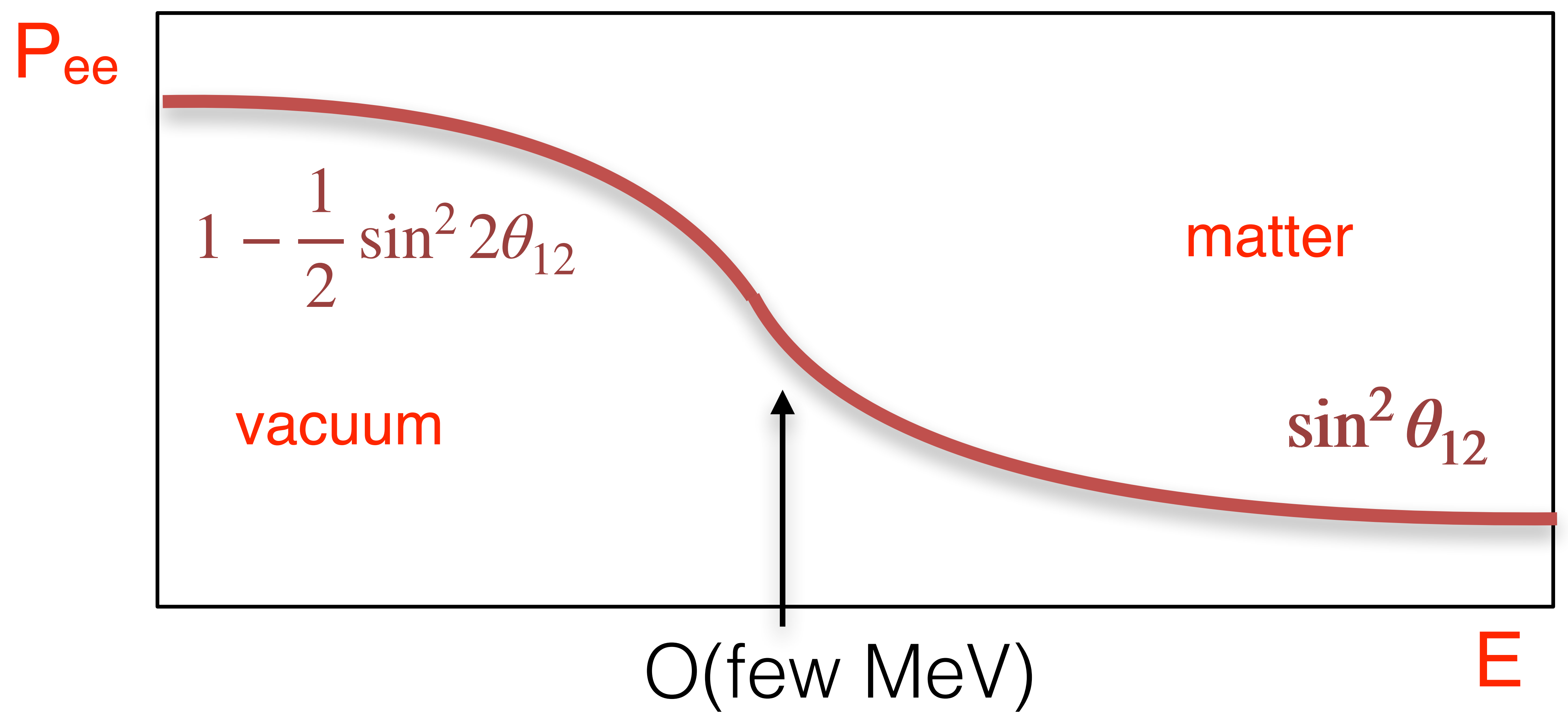
$$A/\delta m^2 \gg 1 : \quad (\delta\tilde{m}^2, \tilde{\theta}) \simeq (A, \pi/2)$$ matter dominance

ν oscillations in solar matter

- the adiabatic approximation holds, θ slowly varying from the production point to the vacuum value at the exit from the sun: $\tilde{\theta}_{12}(x) \rightarrow \theta_{12}$
- Two limiting cases:
  - **E ≤ O(few MeV): $A/\delta m^2 \leq 1$ and $\tilde{\theta}_{12}(x) \simeq \theta_{12}$**

    $P_{ee} \simeq c_{12}^4 + s_{12}^4 = 1 - \sin^2 2\theta_{12}/2$ octant symmetric averaged vacuum probability
  - **E ≥ O(few MeV): $A/\delta m^2 \geq 1$ and $\tilde{\theta}_{12}(x) \simeq \pi/2$**

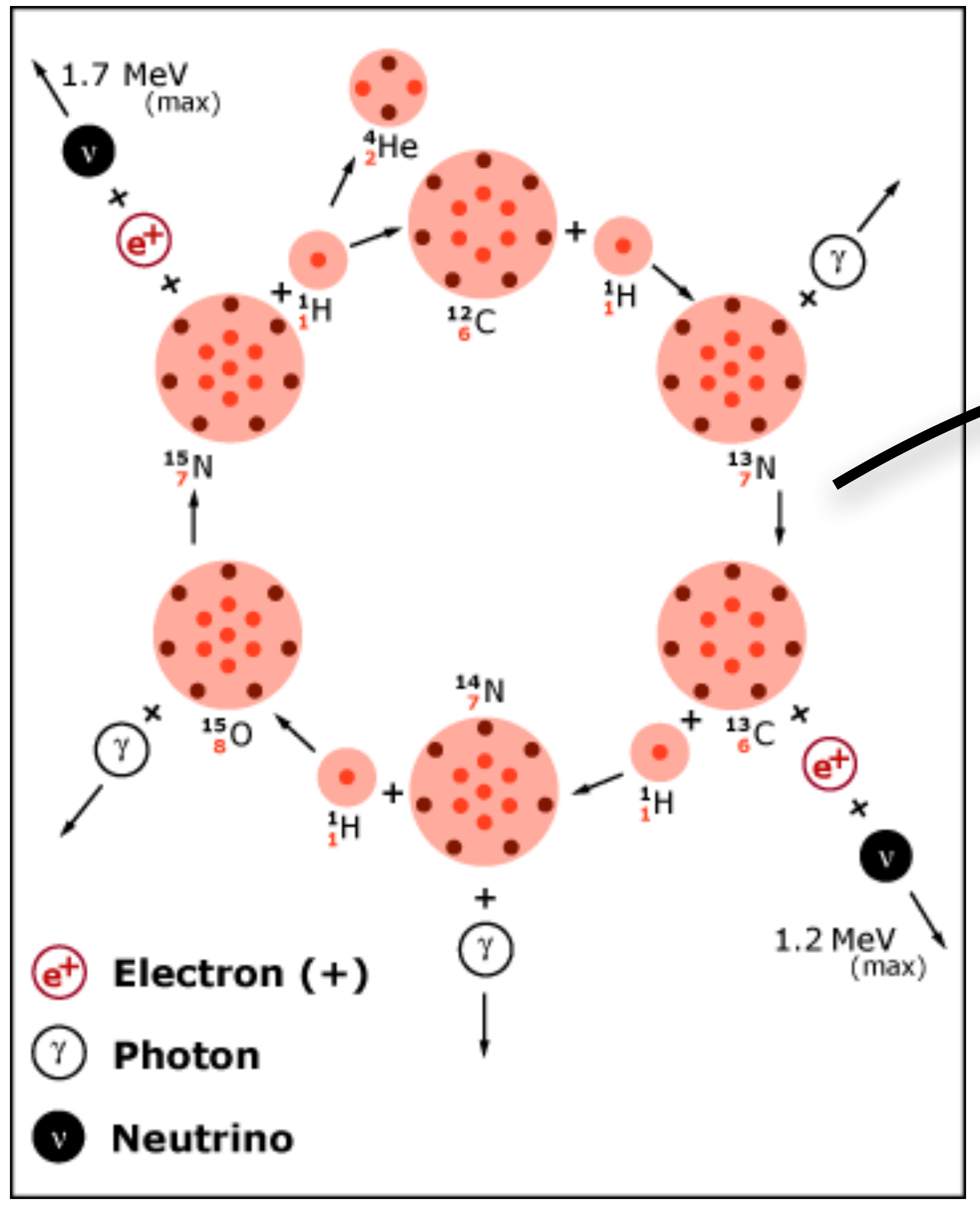
    $P_{ee} \simeq \sin^2\theta_{12}$ octant asymmetric matter dominated probability
-

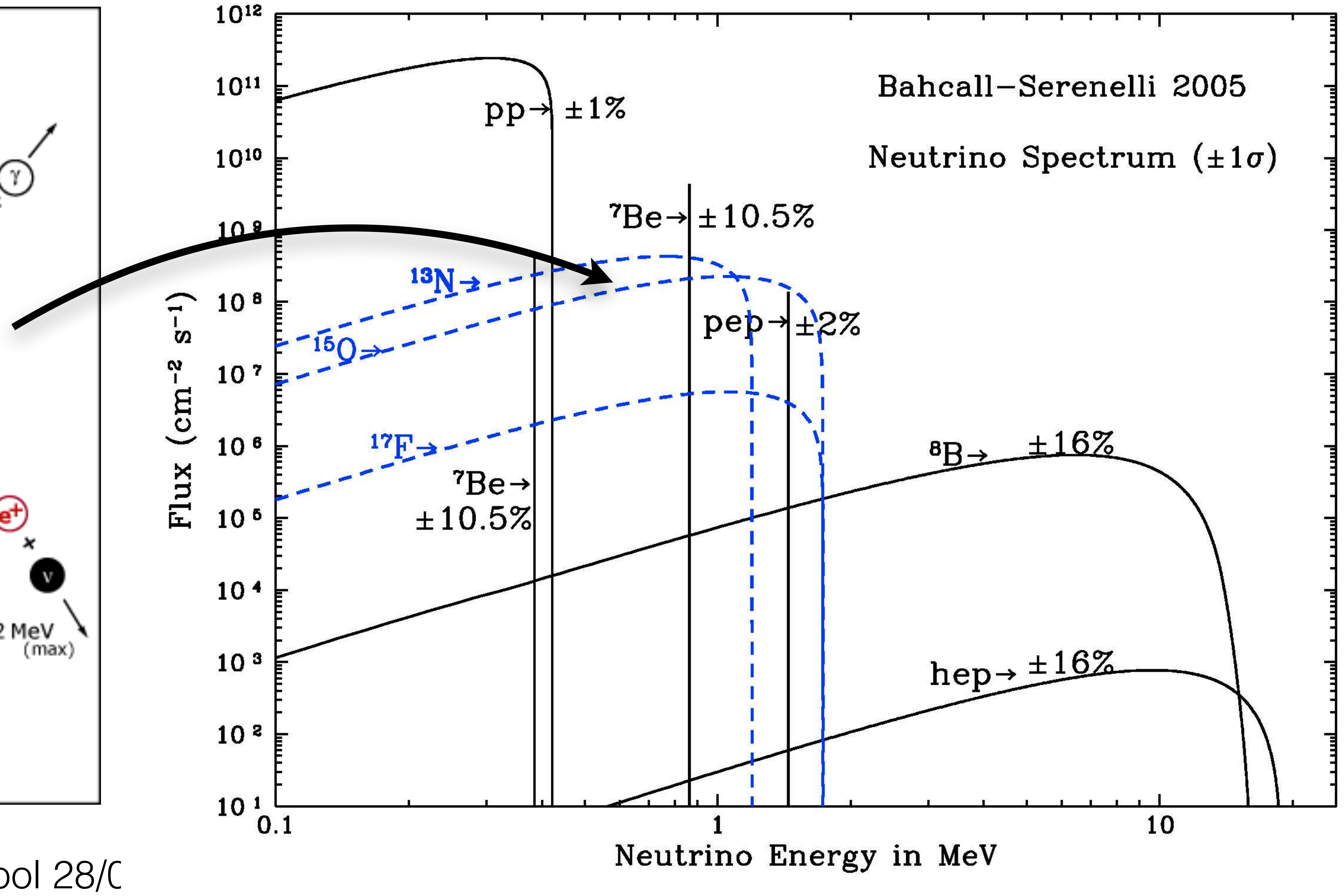


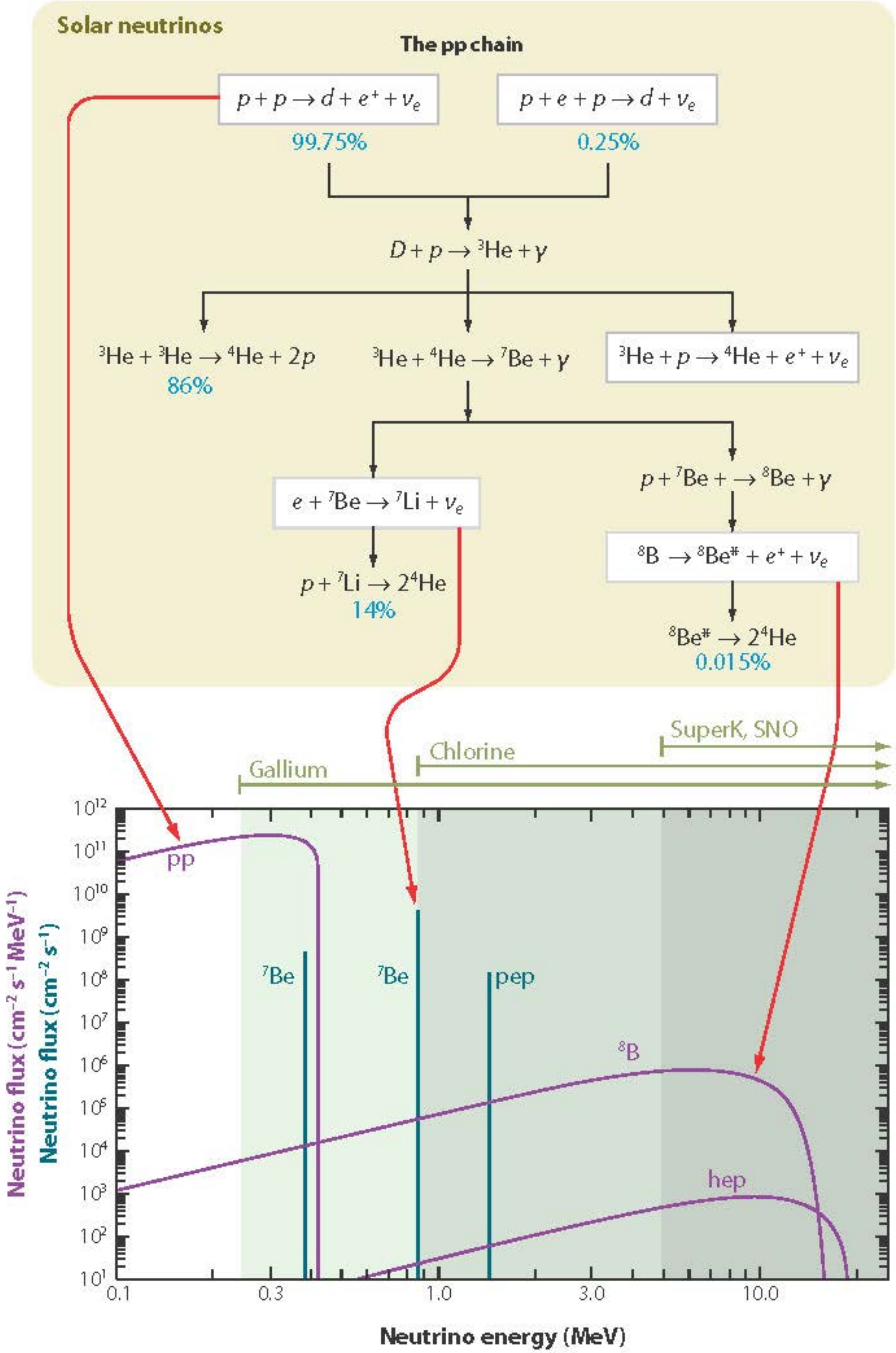
- the P_{ee} transition from "low" to "high" E is a signature of the matter effects in the sun
- it allows to determine the octant the mixing angle θ_{12}

Solar neutrino production

- Sound and important science with reliable roots: (von Weizsäcker, Bethe), Fowler, Bahcall! Oscillations: from Pontecorvo to MSW.
- **pp chain:** Precise measurements of fluxes of B, Be (+NC & shape for B) and pp, pep (initial) - require to check all SSM inputs – nuclear/plasma/atomic/astro-physics
- **CNO cycle:** known since 1937, **still to be probed**. The only flux heavily revised of Bahcall's SSM. Important for metallicity issue. Borexino has a chance; and then?







Solar neutrinos

- **Radiochemical:** count the decays of unstable final state nuclei. Low energy threshold, but energy and time info lost/integrated

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

  $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e$ - GALLEX/GNO, SAGE

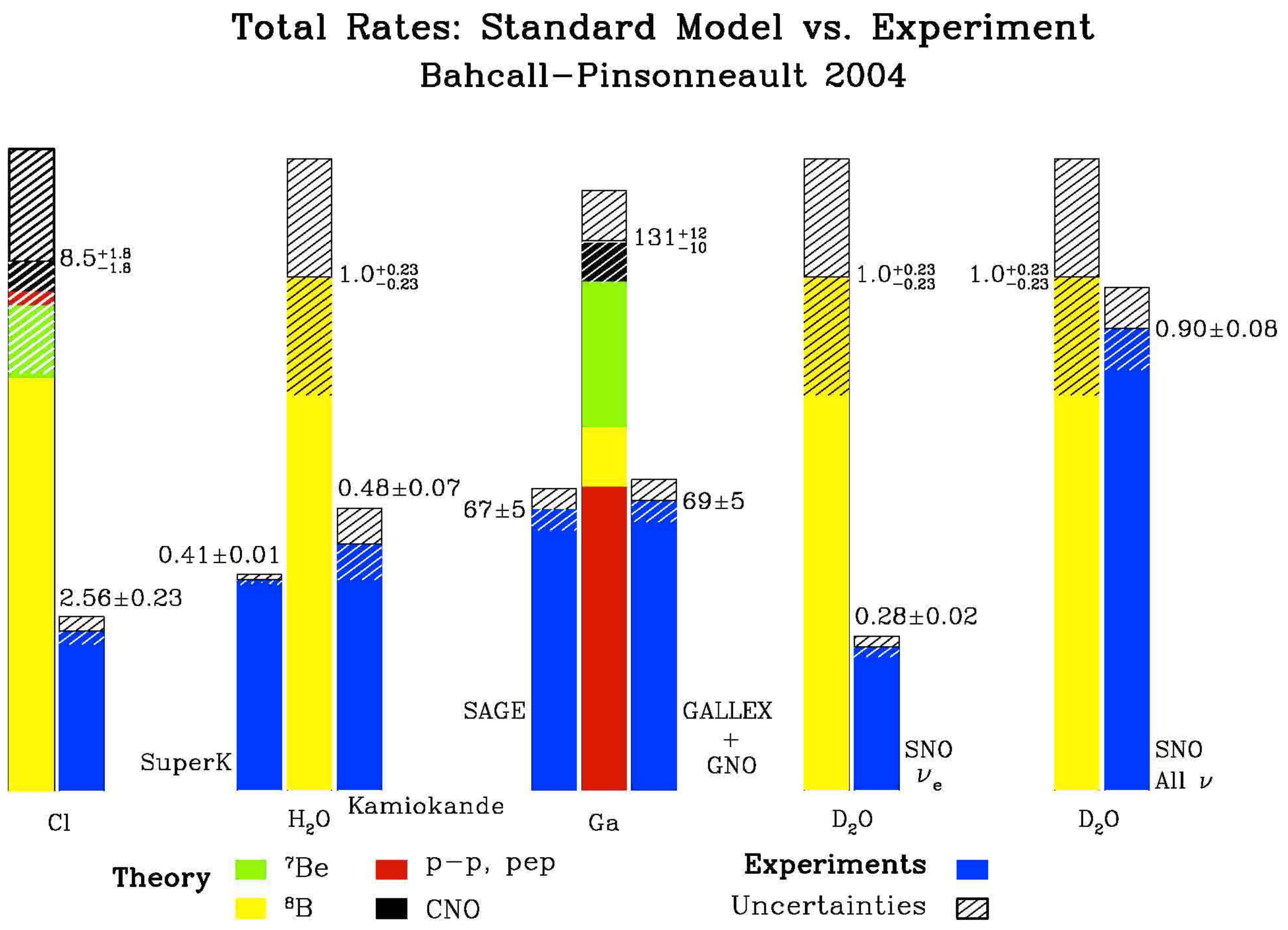
- **Elastic scattering:** events detected in real time with either “high” threshold (Čerenkov, directional) or “low” threshold (Scintillators)

  $\nu_x + e \rightarrow \nu_x + e$ (CC) - SK, SNO, Borexino

- **Interactions on Deuterium:** CC events detected in real time; NC events separated statistically; neutron counters

  $\nu_e + d \rightarrow p + p + e$ (CC) - SNO

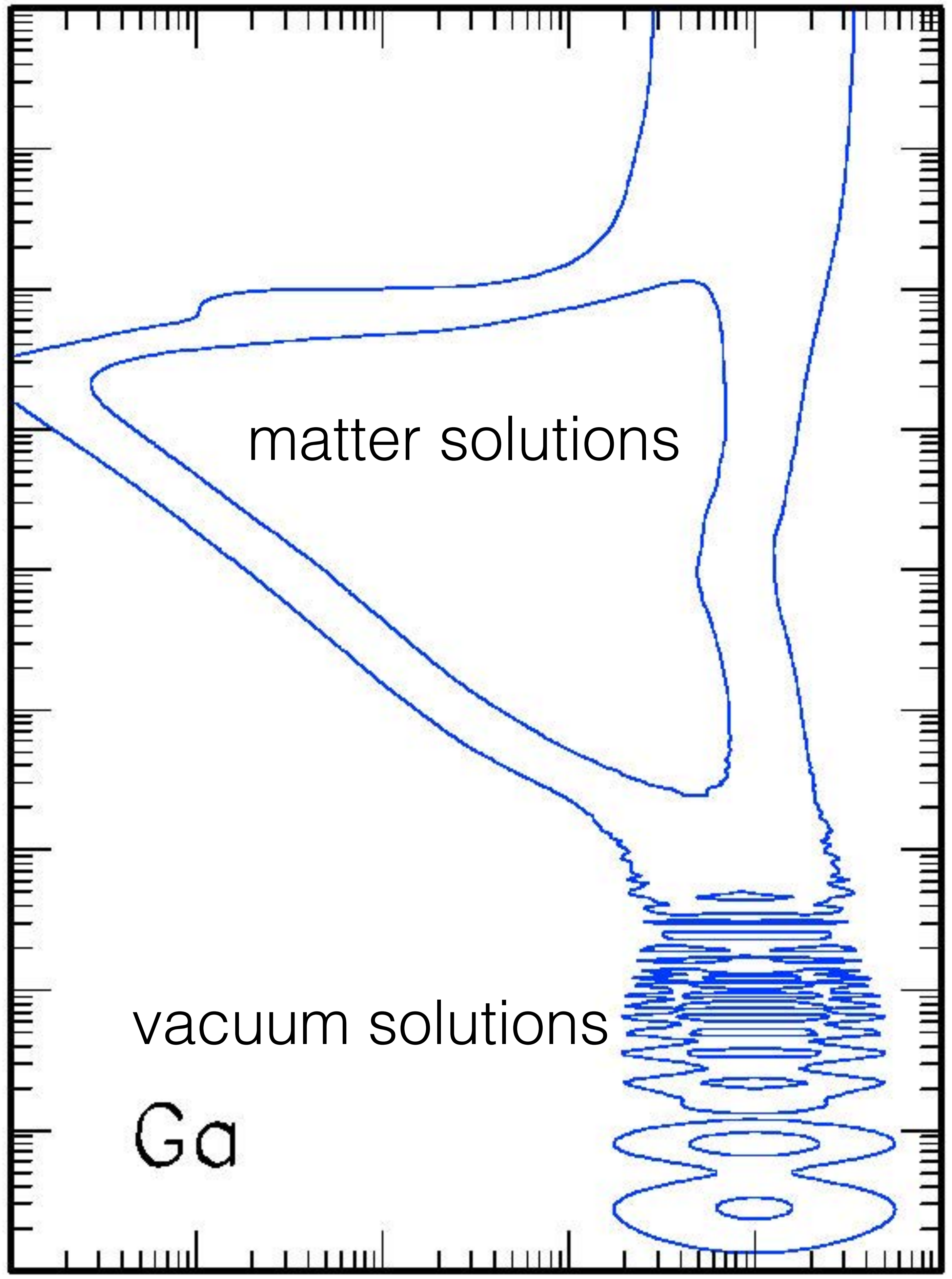
  $\nu_x + d \rightarrow p + n + \nu_x$ (NC)



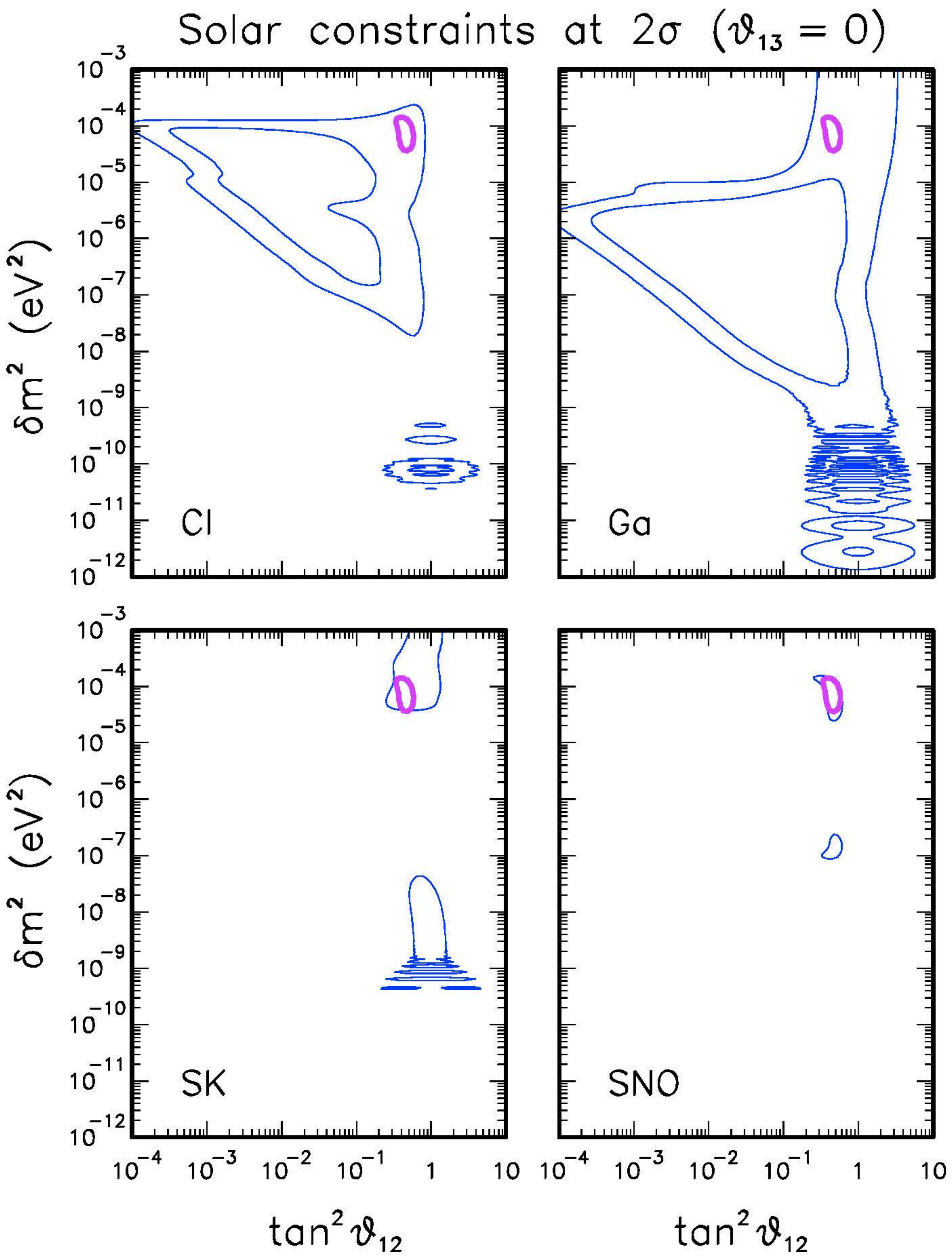
- **All CC-sensitive results indicated a ν_e deficit when compared to solar model expectations**

Solar neutrino results

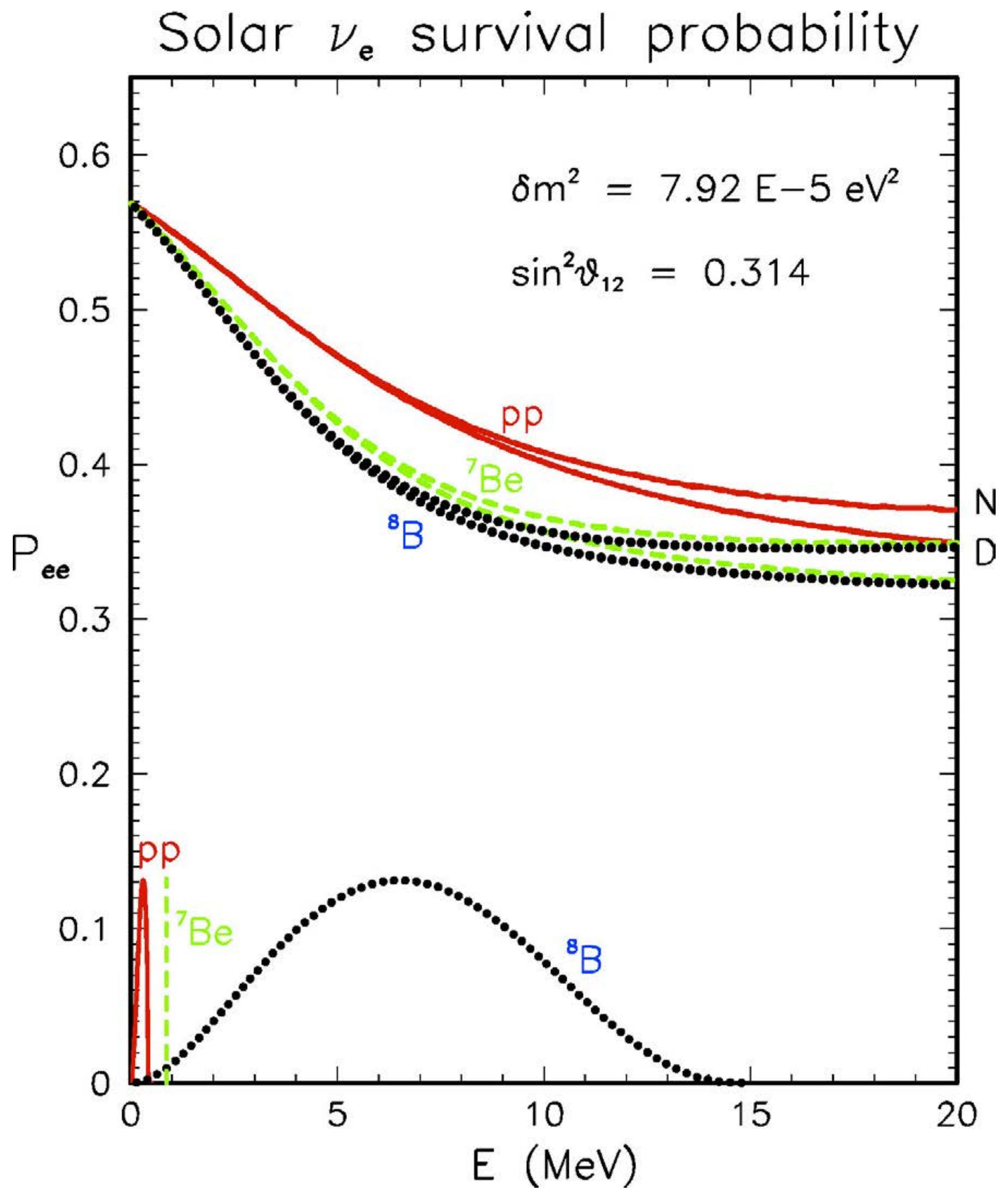
- **Single experiments:**
  - large uncertainties
  - no unmistakable evidence for ν osc



- **2002:** one global solution found by combining all solar data ("large mixing angle" or LMA).

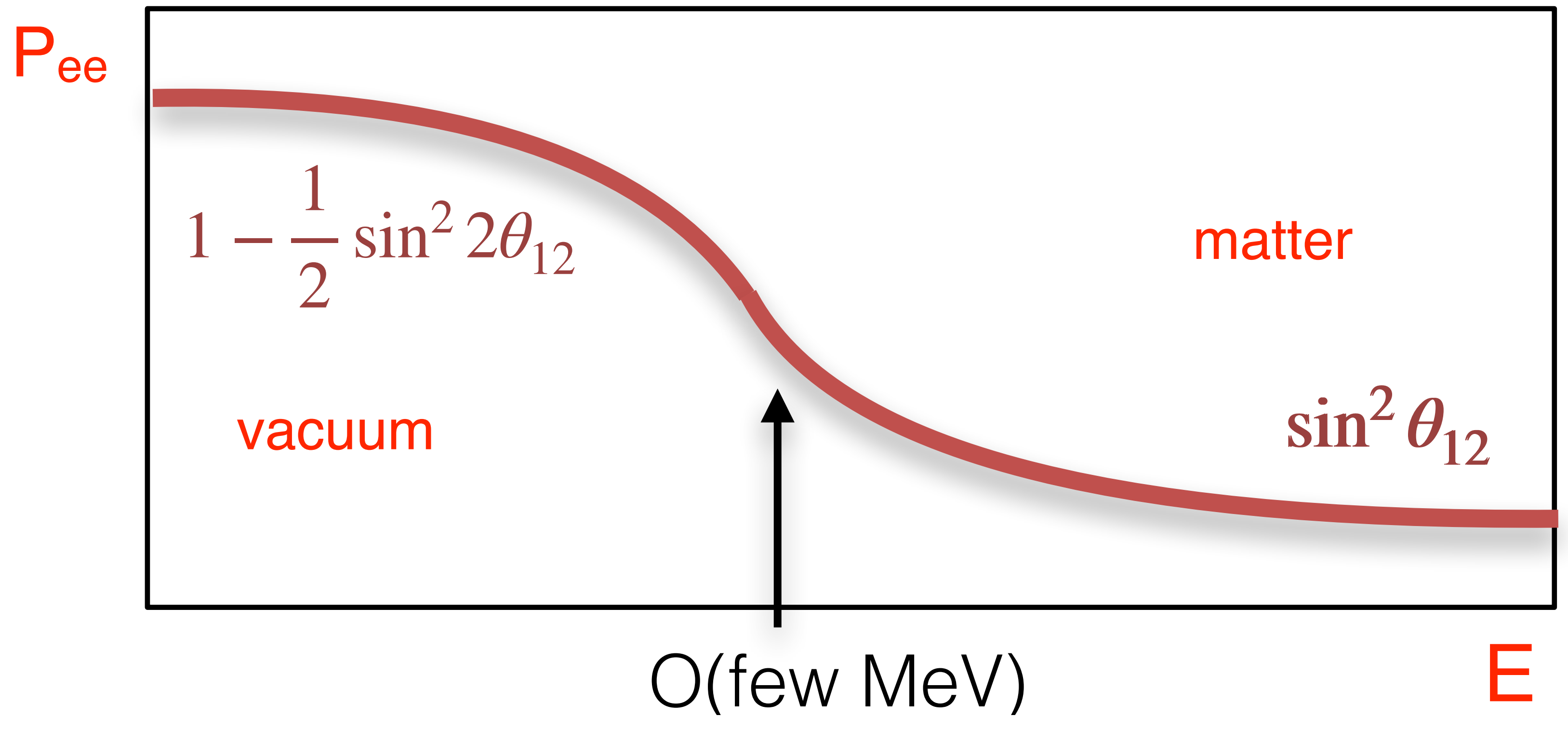


- **LMA:** evolution is adiabatic in solar matter.
- **Earth:** small day/night (D/N) effects, seen at ~3sigma

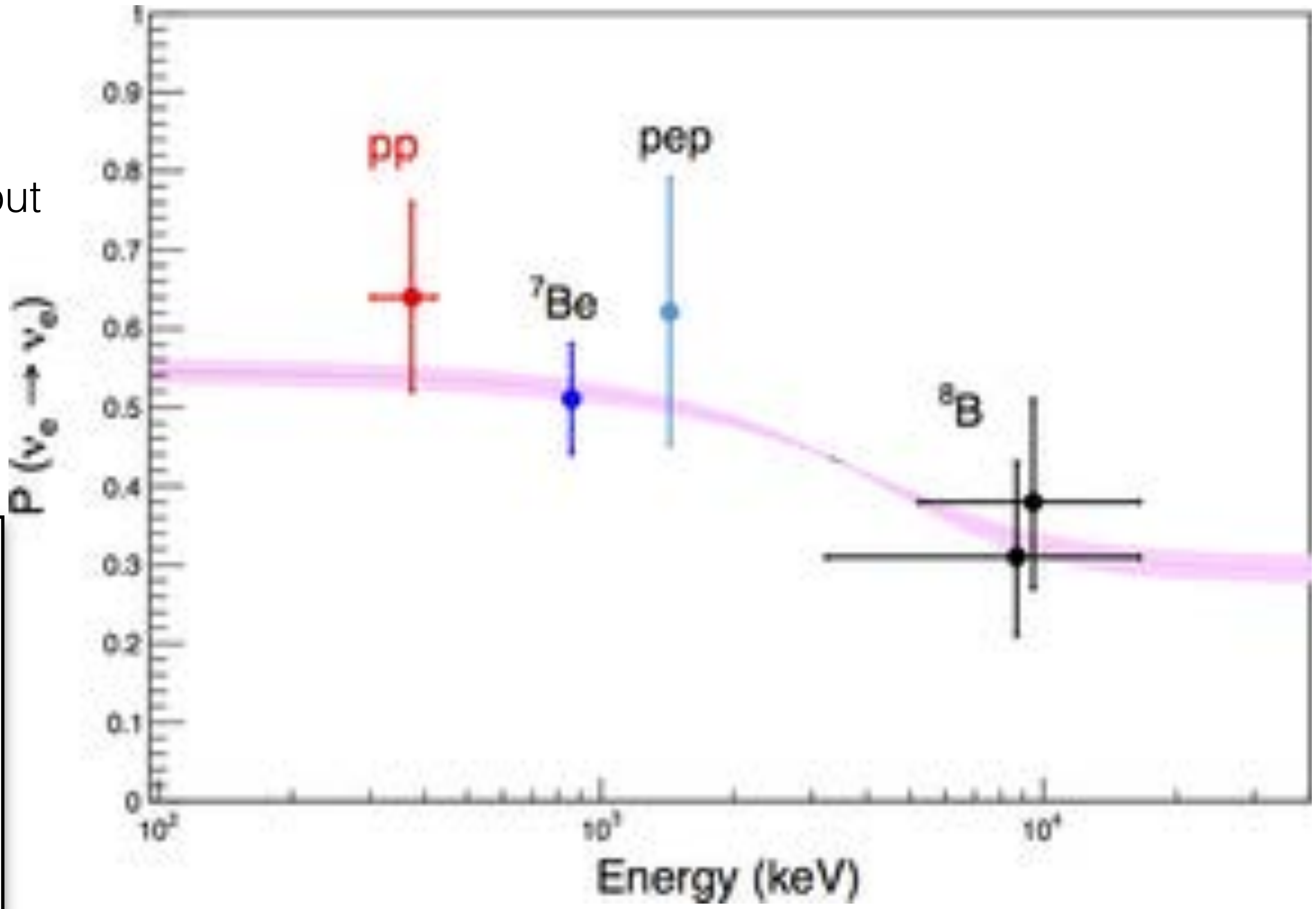


Borexino synthesis

- all solar contributions are singled out
- matter effects are evidenced

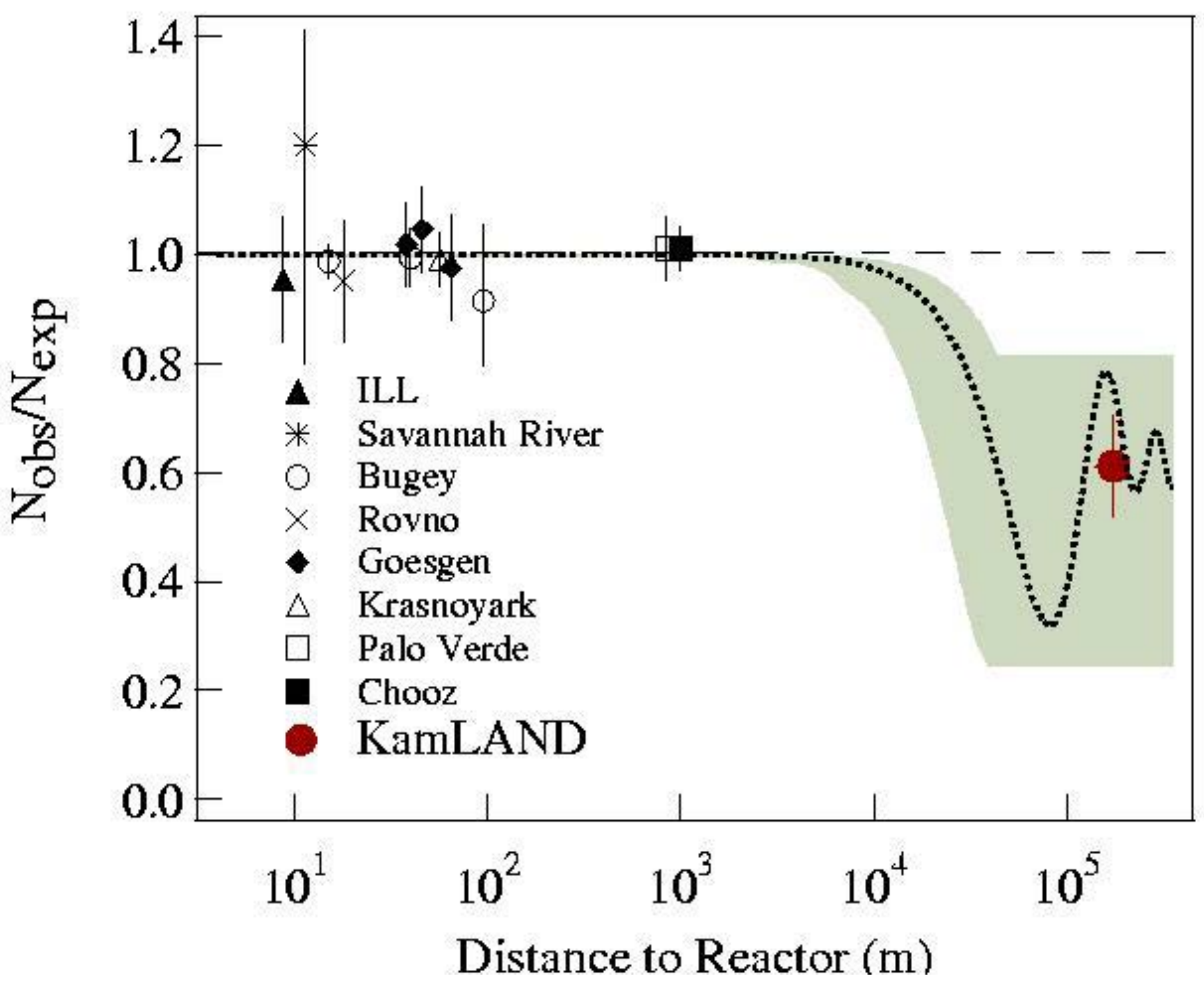


- the P_{ee} transition from "low" to "high" E is a signature of the matter effects in the sun
- it allows to determine the octant the mixing angle θ_{12}

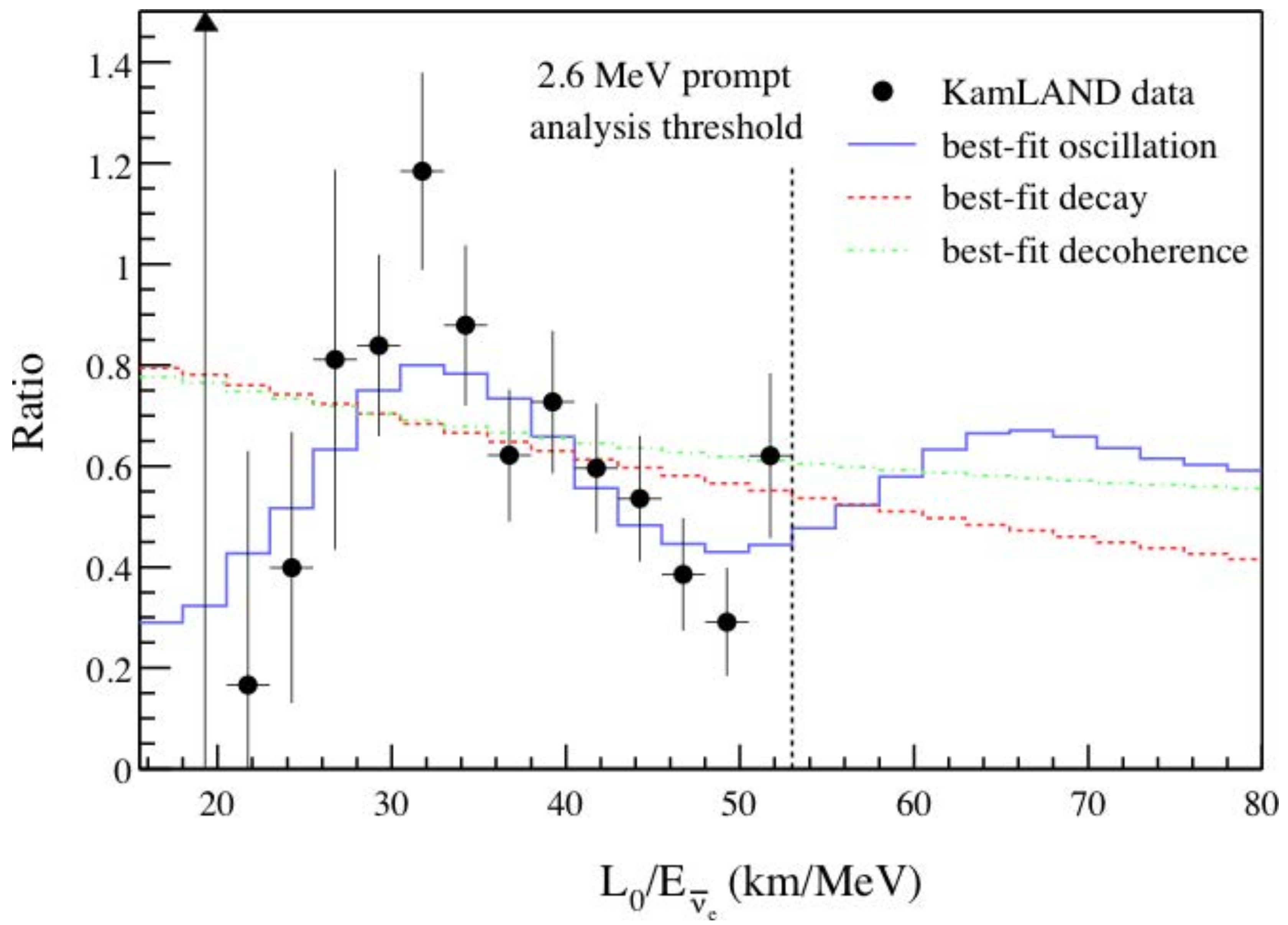


KamLAND

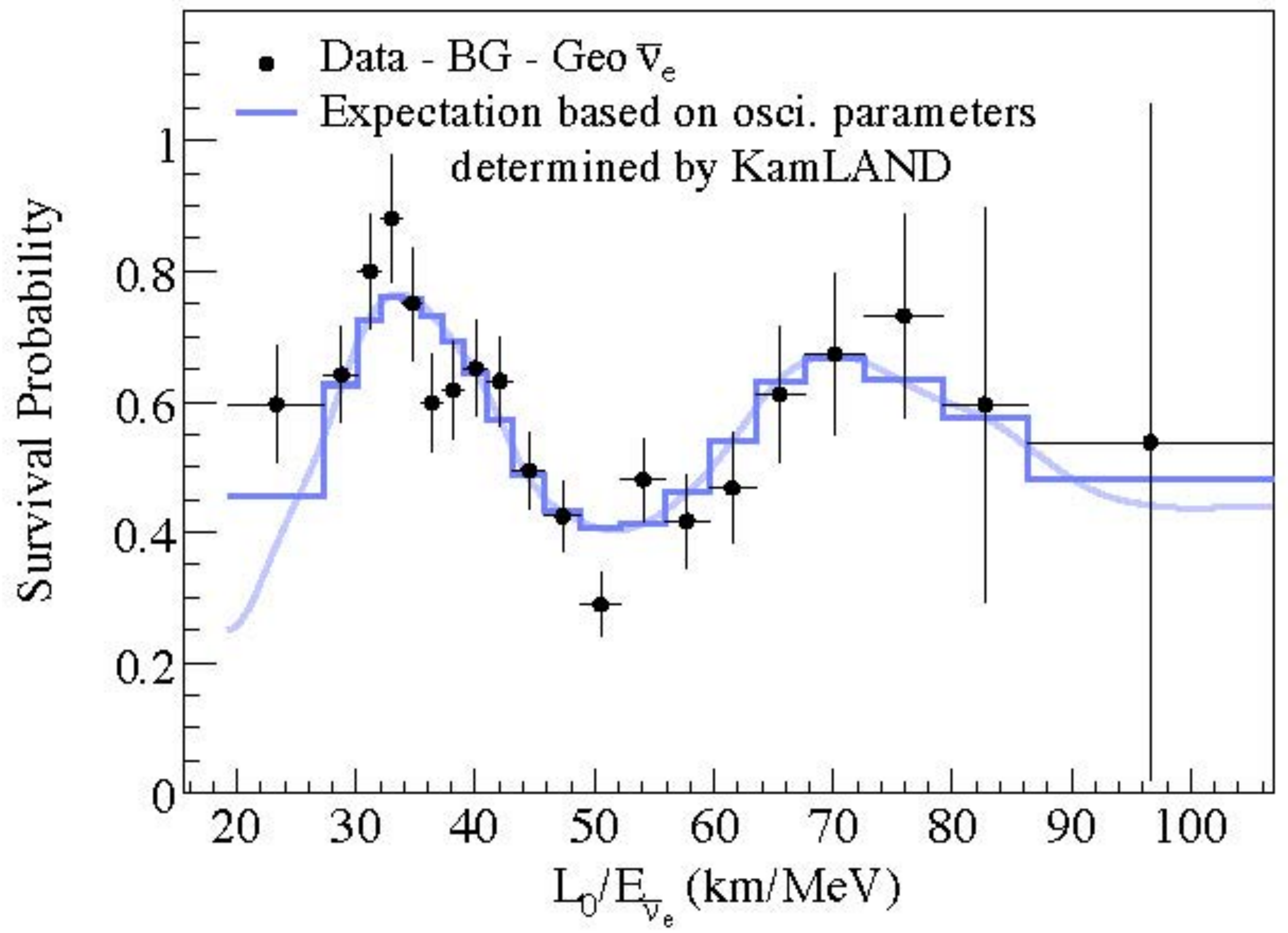
- 2002: electron flavor disappearance observed



- 2004: half--period of oscillation observed



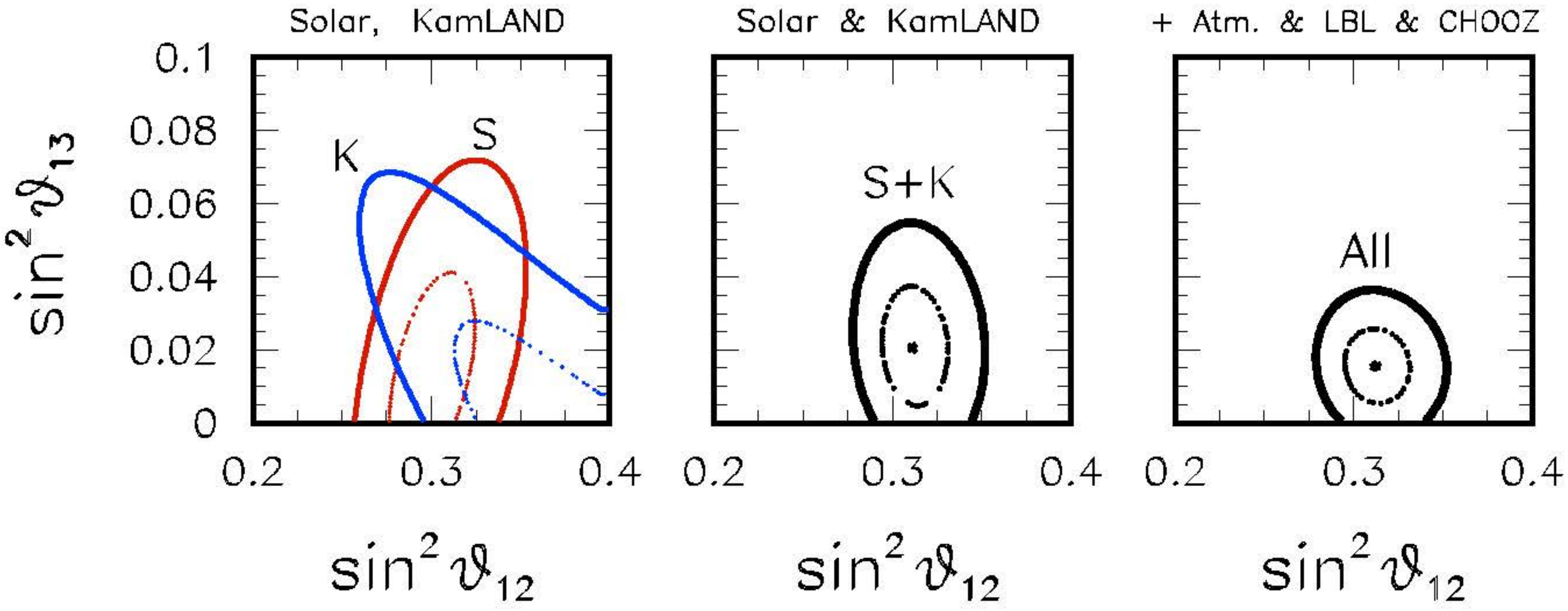
- 2007+: one period of oscillation observed



- Direct observation of δm^2 oscillations!
- Get precise δm^2 value from dip/peak position

solar + KL: 3ν interpretation

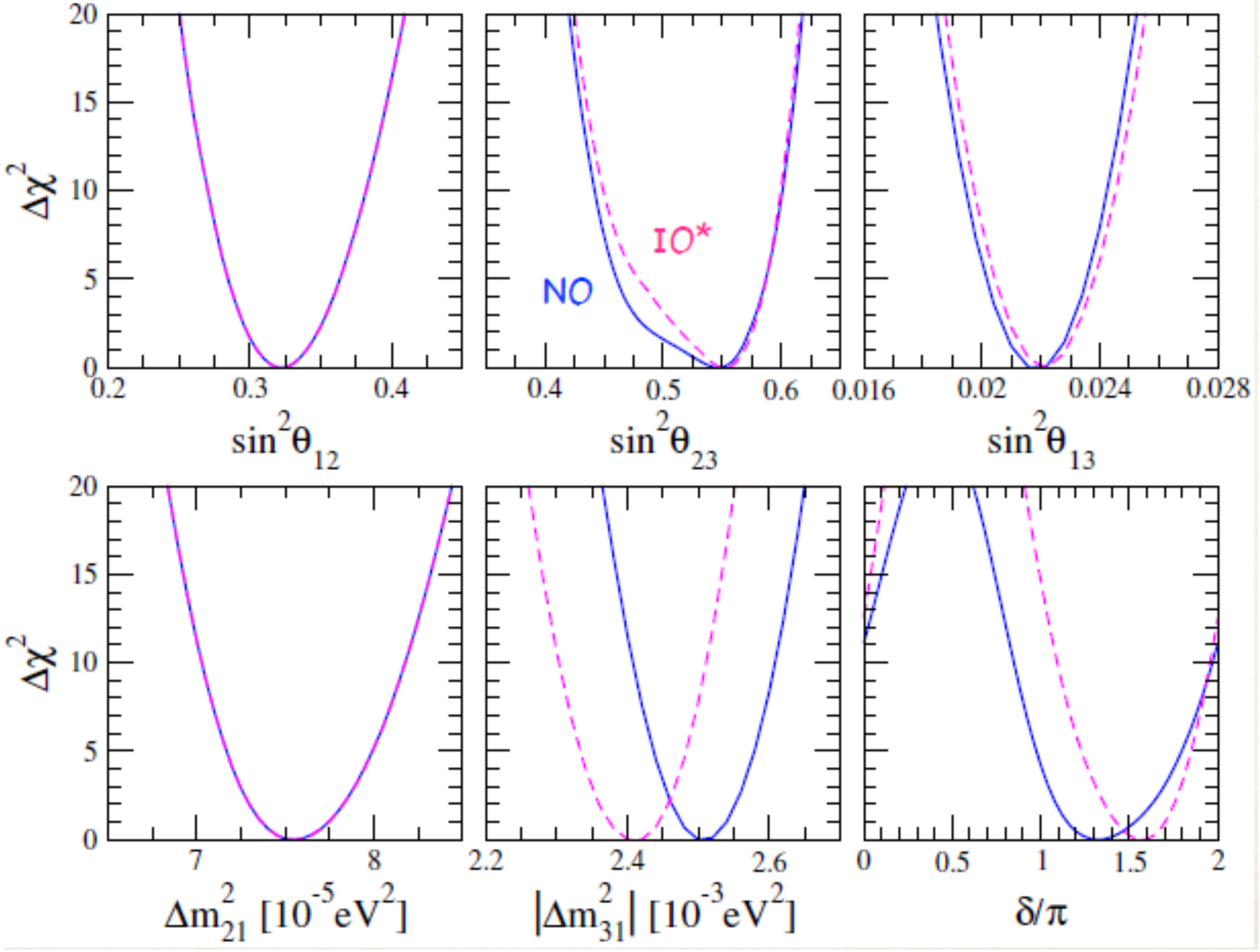
- Dominant 3ν oscillatons
- Include subleading θ_{13} effects in solar+KamLAND combination
- Hints for $\theta_{13} > 0$ (as early as 2008 ... established by reactors in 2012)



$$P_{ee}^{3\nu} = c_{13}^4 \, P_{ee}^{2\nu}(\delta m^2, \theta_{12}) \; + \; s_{13}^4$$

ν oscillations global results

- **$\nu_\mu \rightarrow \nu_\tau$ oscillations (Δm_{23}, θ_{23})**
  - **Atmospheric**:Super-K, IceCube, ANTARES…
  - LBL: K2K, MINOS, OPERA, T2K, NOvA, …
- **$\nu_e \rightarrow (\nu_\mu + \nu_\tau)$ oscillations (Δm_{12}, θ_{12})**
  - **Solar**: SNO, Super-K, Borexino, …
  - **Reactor**: KamLAND
- **θ_{13} experiments**
  - **LBL**: MINOS, T2K, NOvA, …
  - **Reactor**:DayaBay, RENO, Double Chooz



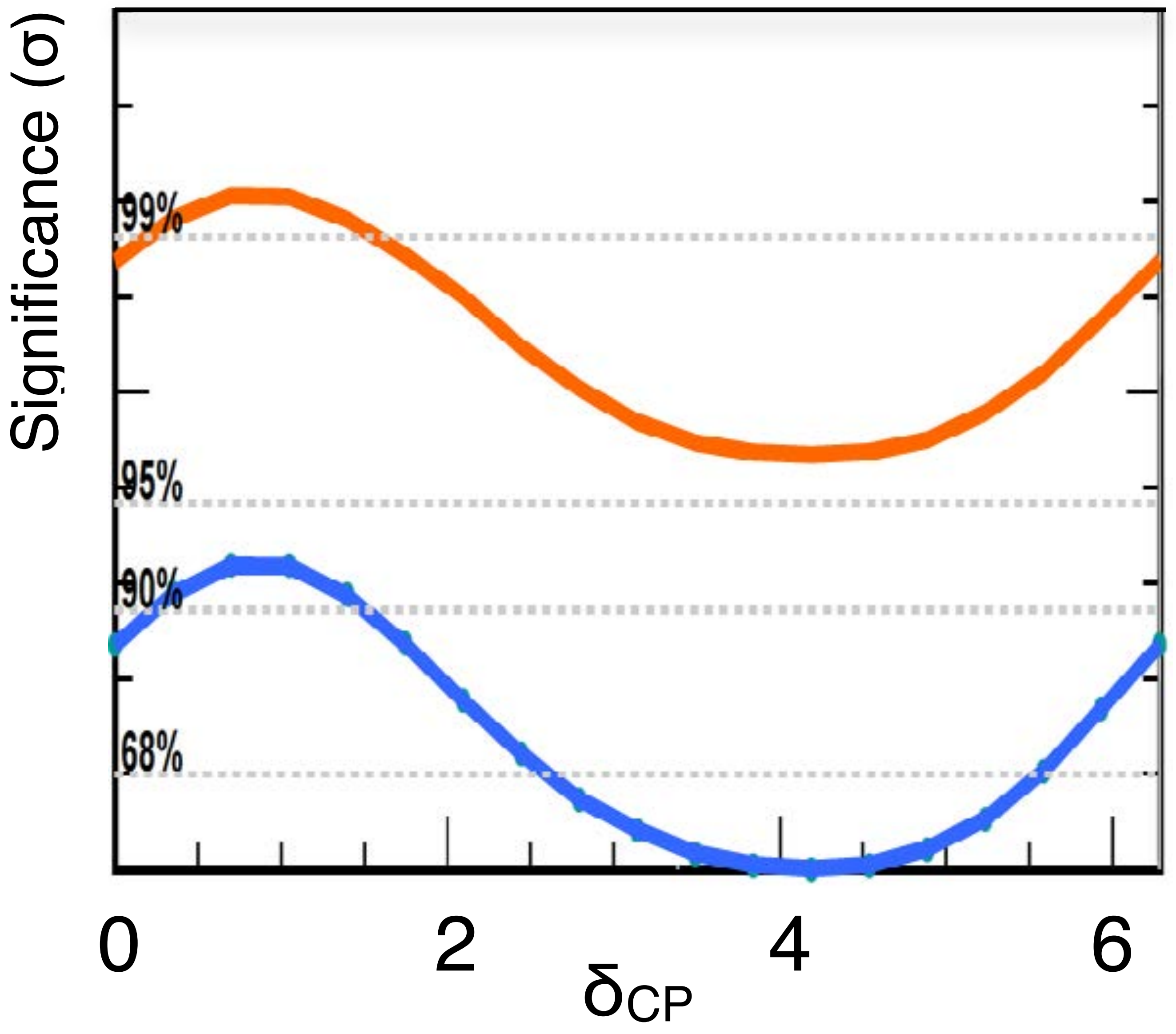
- Current 1σ errors

δm^2	2.3%
Δm^2	1.6%
$\sin^2\theta_{12}$	5.8%
$\sin^2\theta_{13}$	4.0%
$\sin^2\theta_{23}$	~9%

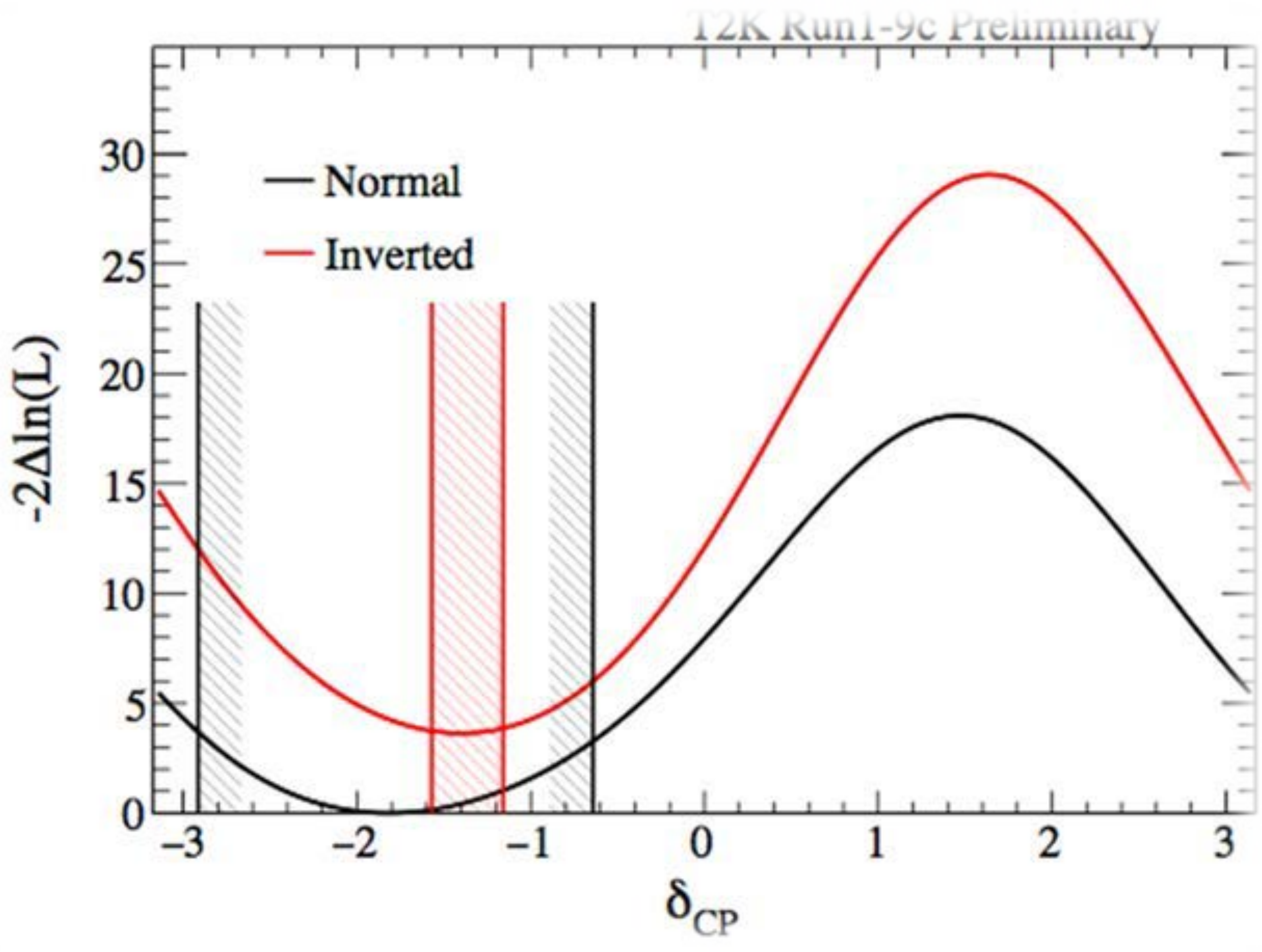
- Basic structure for 3 flavor oscillations has been understood!
- Information for Physics Beyond the Standard Model (at very high energies) !

2018 update

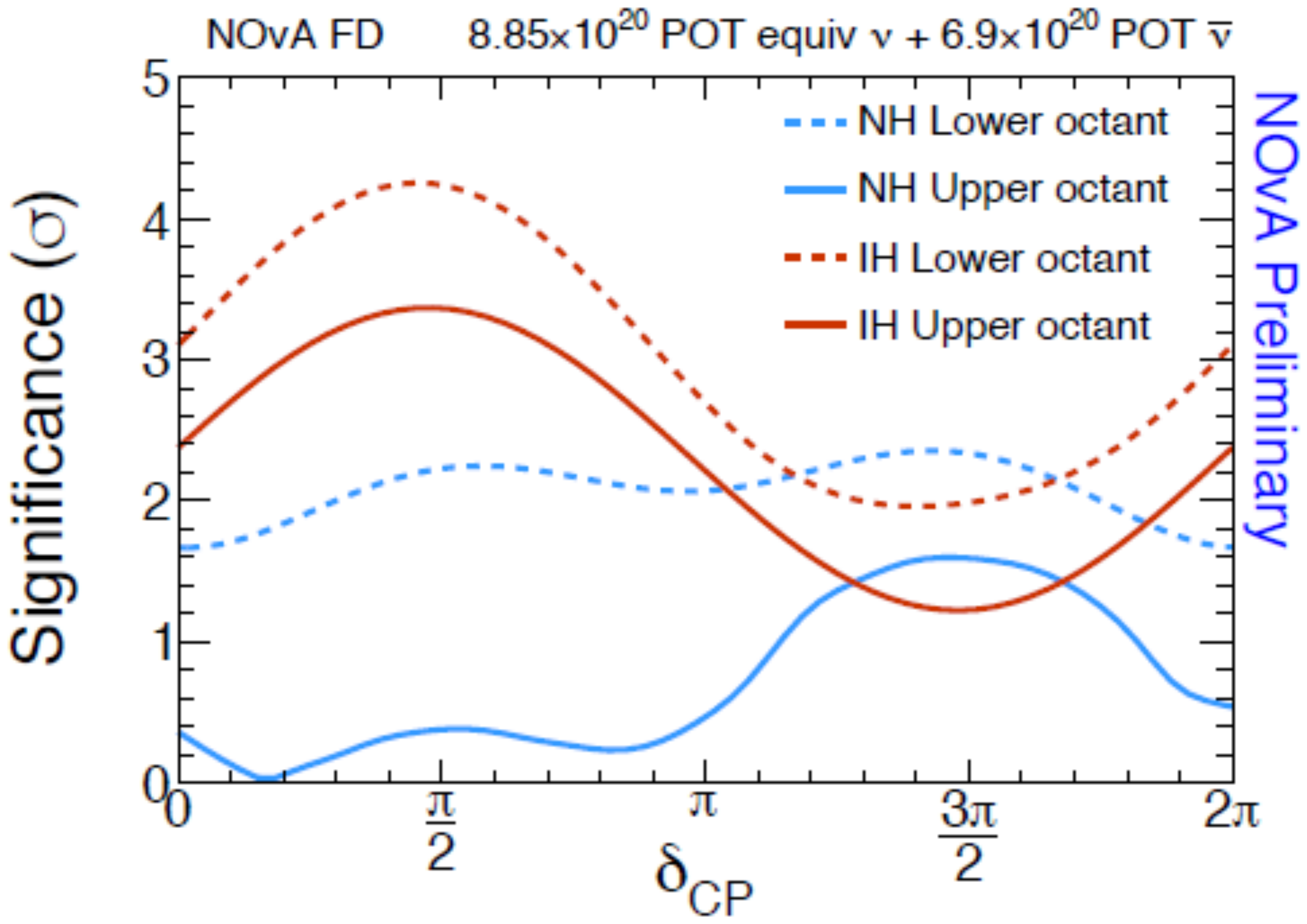
Super Kamiokande (SK)



T2K



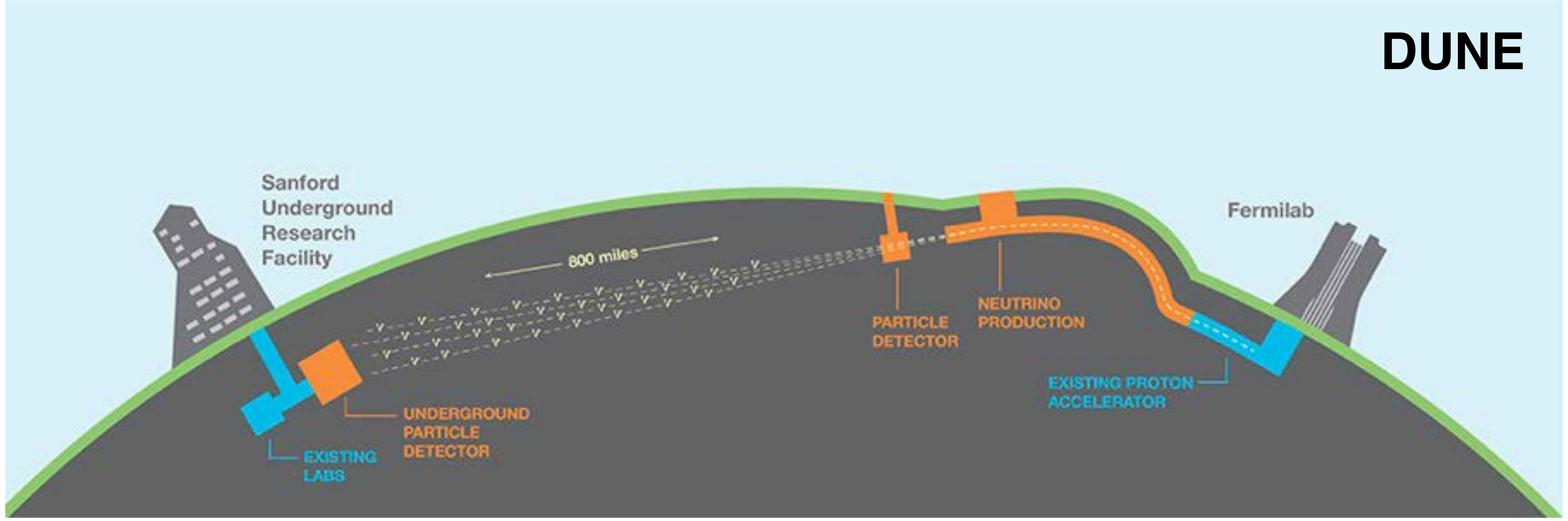
Nova

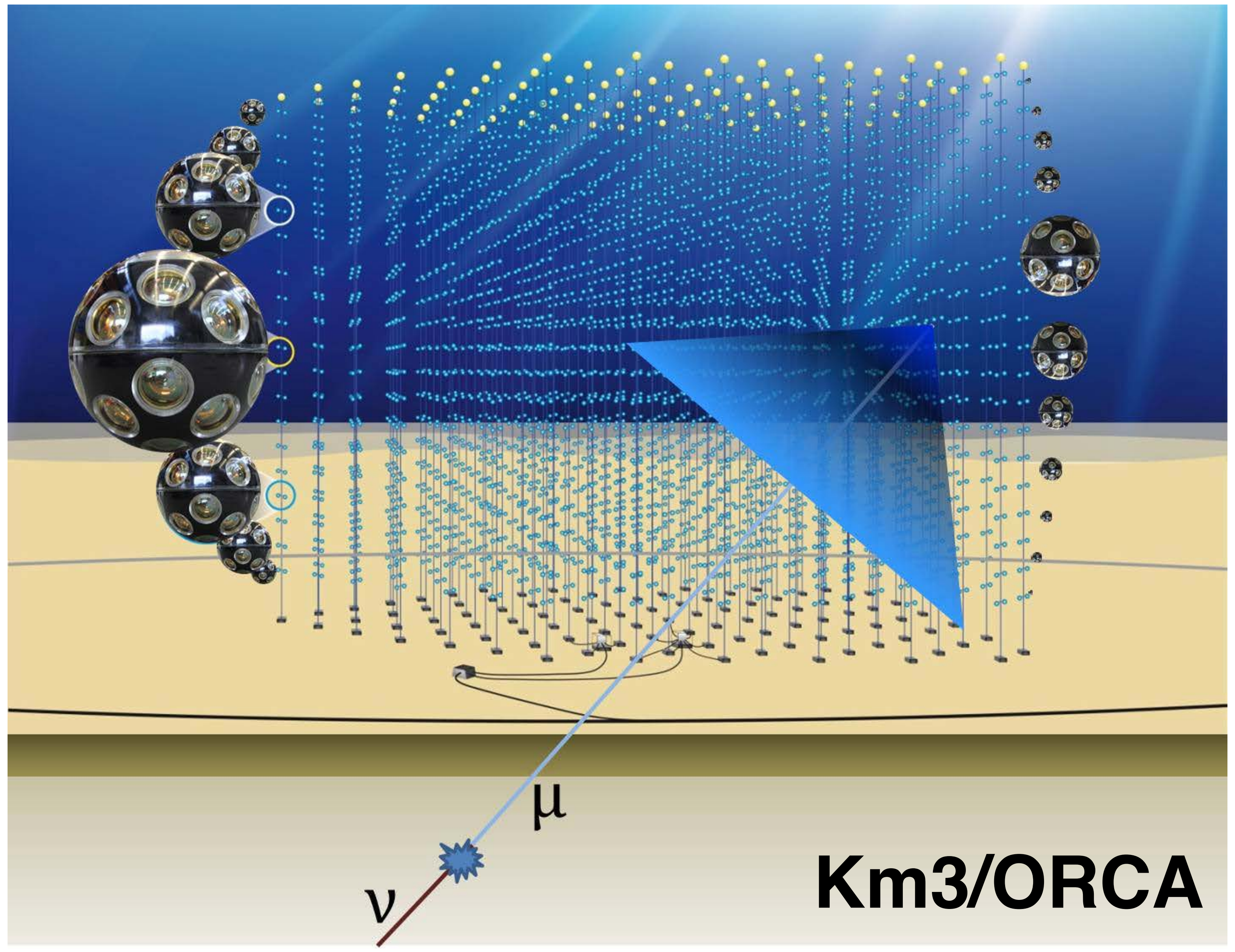


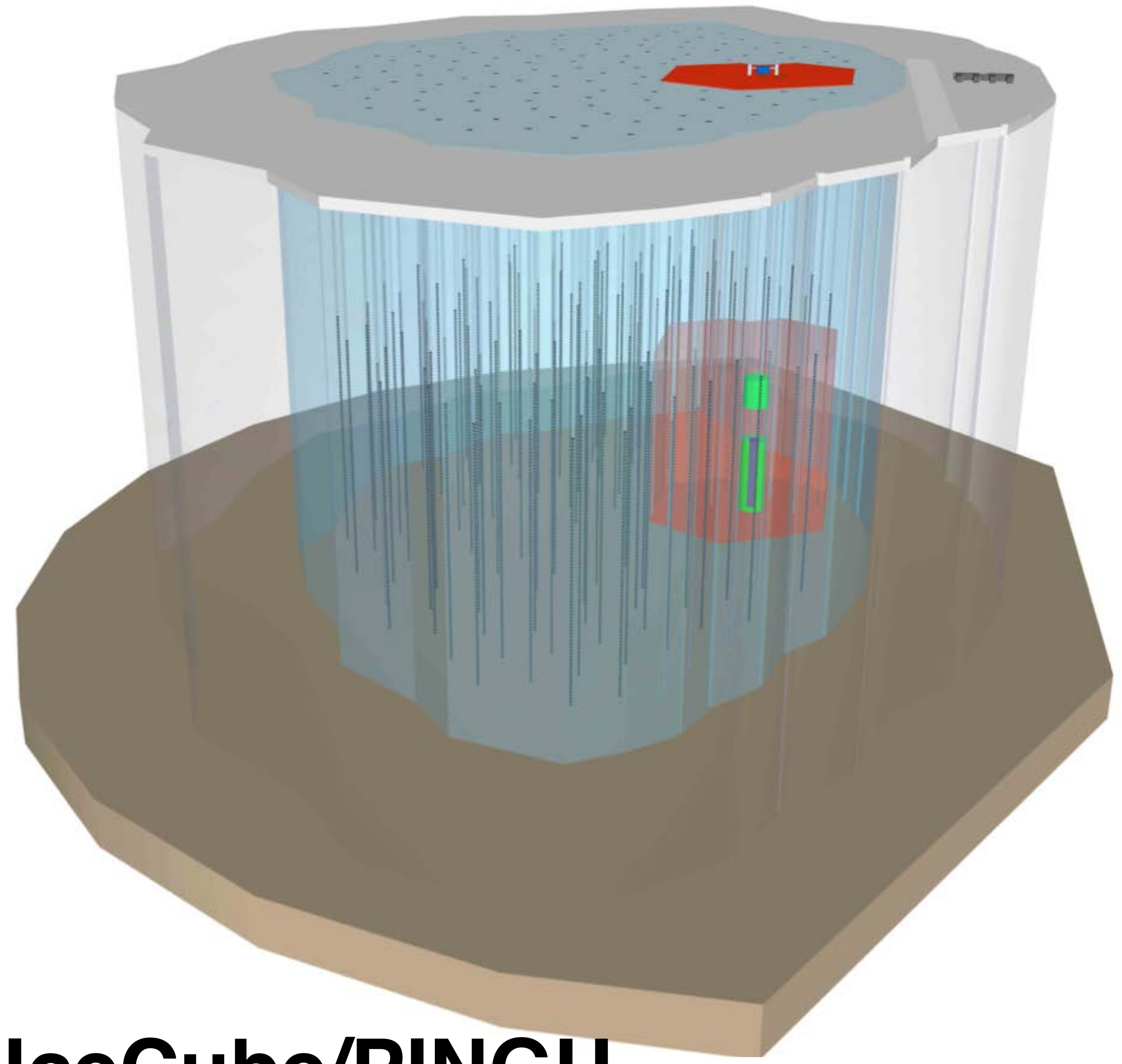
- Normal ordering (NO) favored at ~(1 ~ 2) sigma level
- Some favored δ_{CP} region(s).

Oscillations future: Hierarchy and CP phase

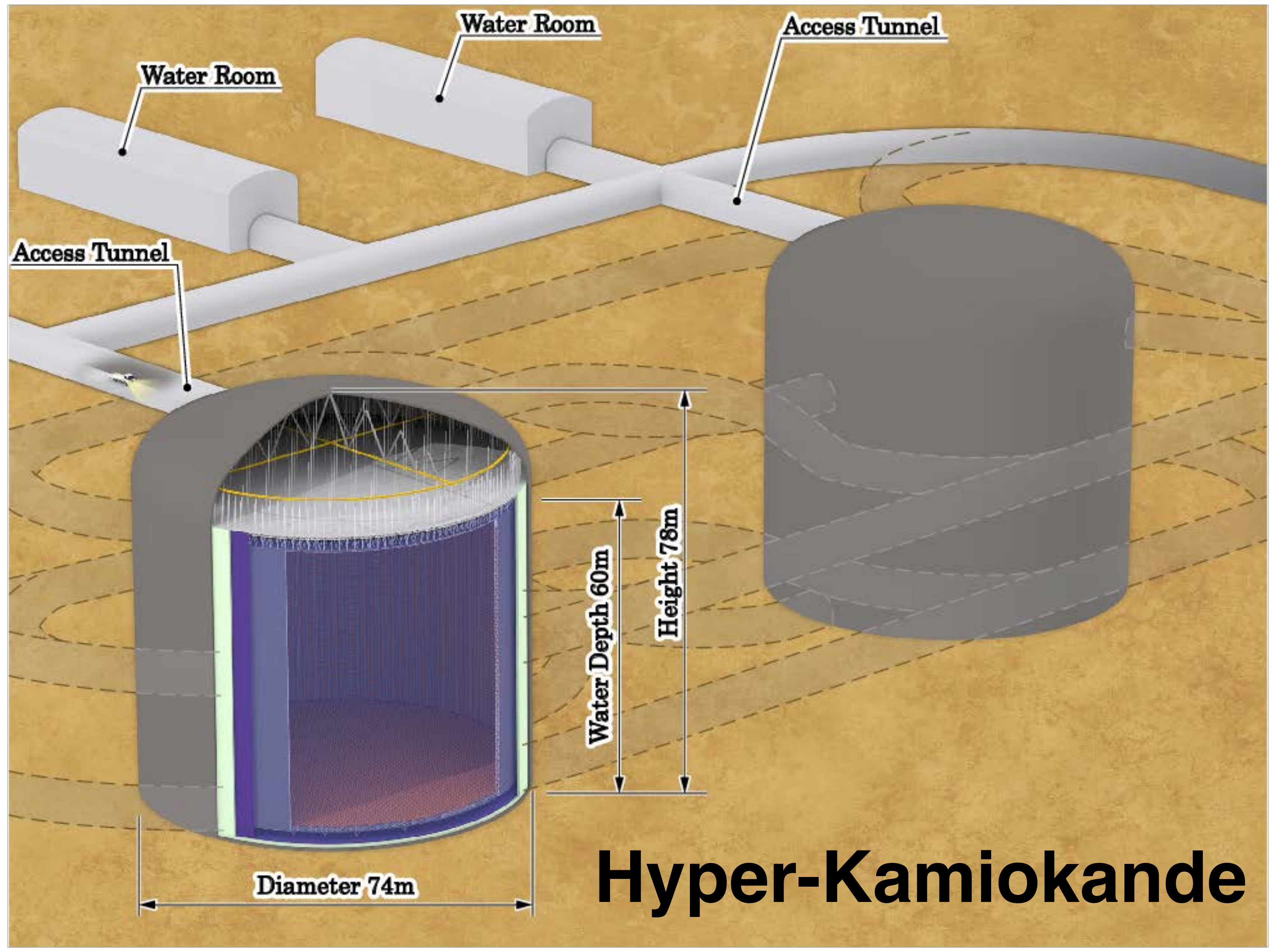
- The search for CPV, hierarchy, octant, and other subleading (non)standard effects in vacuum and in matter is motivating new big experimental projects, both **underground** and underwater/ice





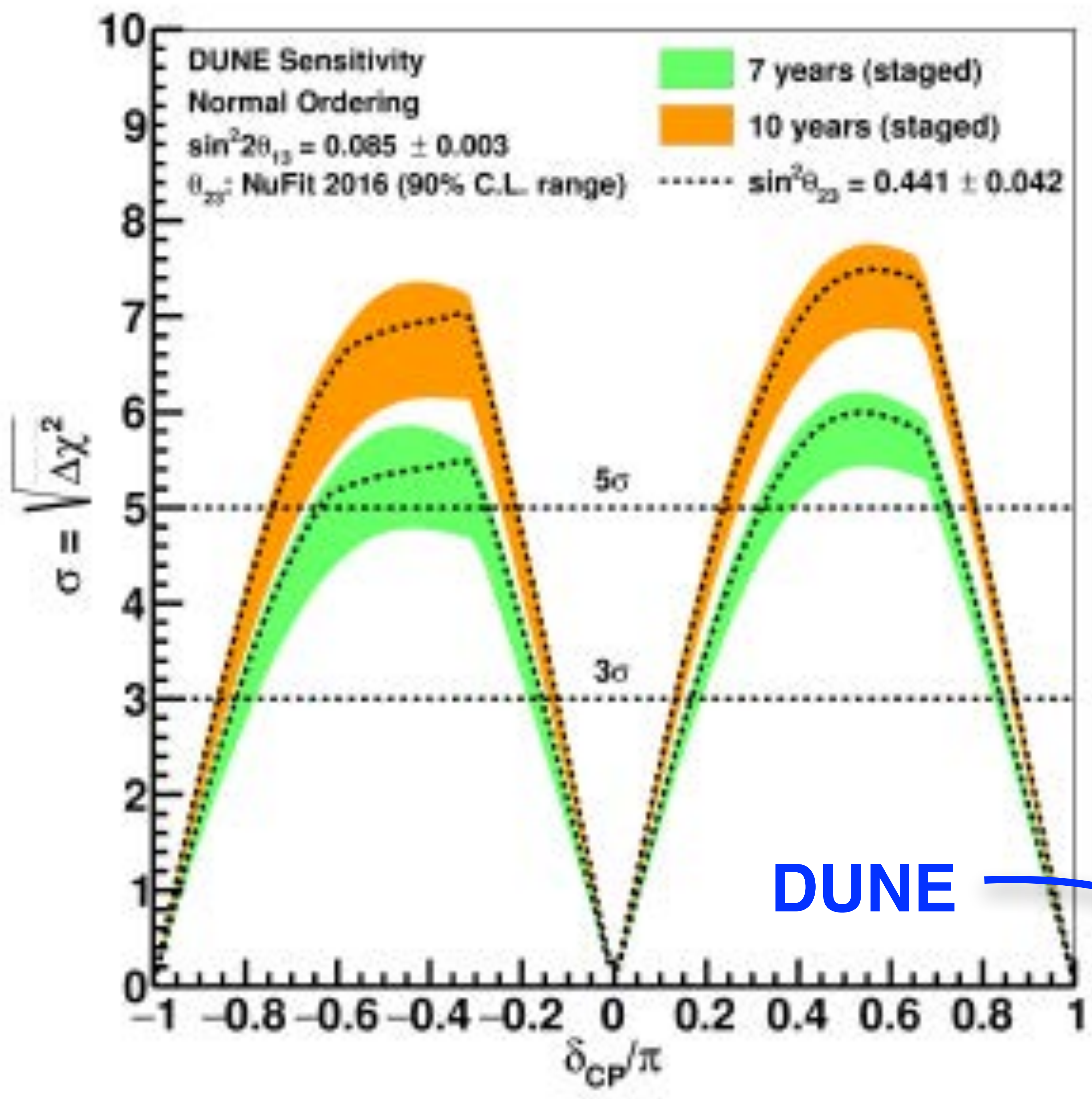


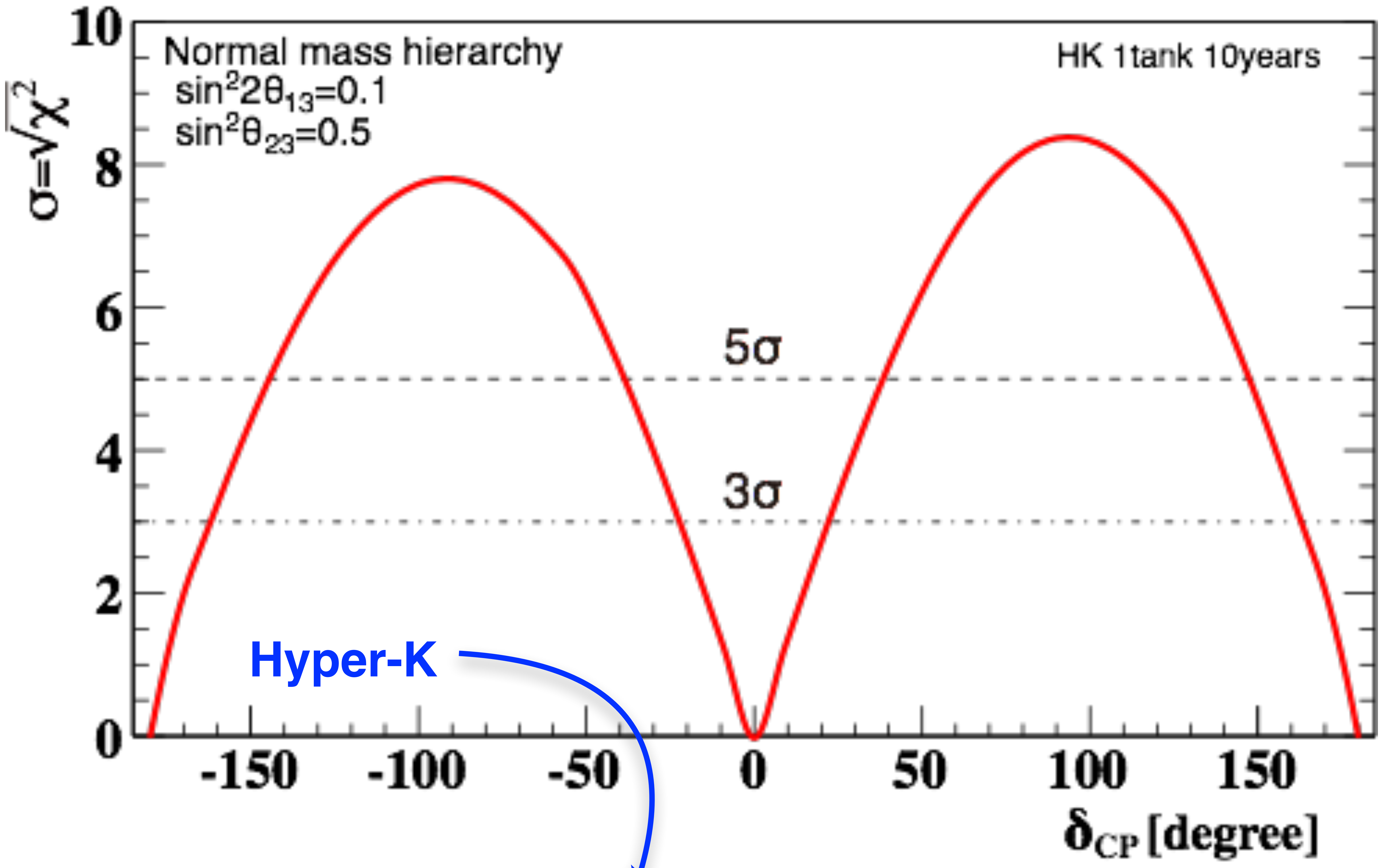
IceCube/PINGU



Next generation neutrino CPV experiments

Have neutrinos and anti-neutrinos different oscillation properties?





Baseline	1300km - Large matter effect (Good for MO)	295km - Small matter effect
Beam energy	~ Multi-GeV	~ Sub-GeV
Detector technology	Liq. ArTPC	Water Cherenkov

Supernovae neutrinos

Rich physics scenario

- Astrophysics
  - Massive stars dynamics and evolution
  - Neutrino sources in different stages of life
- Neutrino oscillations
  - Vacuum (propagation) and matter (source, earth) effects
  - Collective effects (ν-ν interactions)
- Neutrino non oscillation variables
  - Timing, pointing, lifetime

SN oscillations

Vacuum oscillations depend on neutrino mass matrix M Overall minus sign for antineutrinos

$$\frac{\Delta m^2}{2E}$$

MSW effect depends on ordinary matter density L, i.e. mainly electron density

$$\sqrt{2} G_F N_e$$

Collective effects depends on the neutrino density

$$\sqrt{2} G_F N_\nu$$

- 7 dimensional problem
  - 3 momentum (E, θp, ϕp) + 3 space (r, θ, ϕ) + 1 time (t)

SN core collapse

- The evolution of isolated Fe core stars (SNII) terminates with the collapse of the nucleus
- The Gravitational energy is released in ν and $\bar{\nu}$: $E_b = 3 \cdot 10^{46}$ J
  - Larger than the EM radiation of the host galaxy
  - ν and $\bar{\nu}$ with all flavours are produced in the core
  - $\langle E(\nu_e) \rangle \approx 10$ MeV $\neq \langle E(\bar{\nu}_e) \rangle \approx 12$-$15$ MeV
  - $\langle E(\nu_\mu, \nu_\tau) \rangle \approx 20$-$25$ MeV, (uncertain values)
- Propagating states are the eigenstates in matter

- Observable effects on
  - total flux
  - energy spectrum
  - time evolution of spectra

Net result:

- $|\theta_{13}|^2 <$ few 10^{-4} → adiabatic condition
- $\Delta m^2 > 0$ → harder ν_e spectrum
- $\Delta m^2 < 0$ → harder $\bar{\nu}_e$ spectrum
- 1 to multi kton, complementary, detectors
- Existing detectors: (mainly sensitive to $\bar{\nu}$): LVD, SK, BOREXINO, ICECUBE

SN frequency

- 3-4 per century in our Galaxy
- 0.3-0.4 /yr < 5 Mpc
- Good perspectives for 1Mt WC

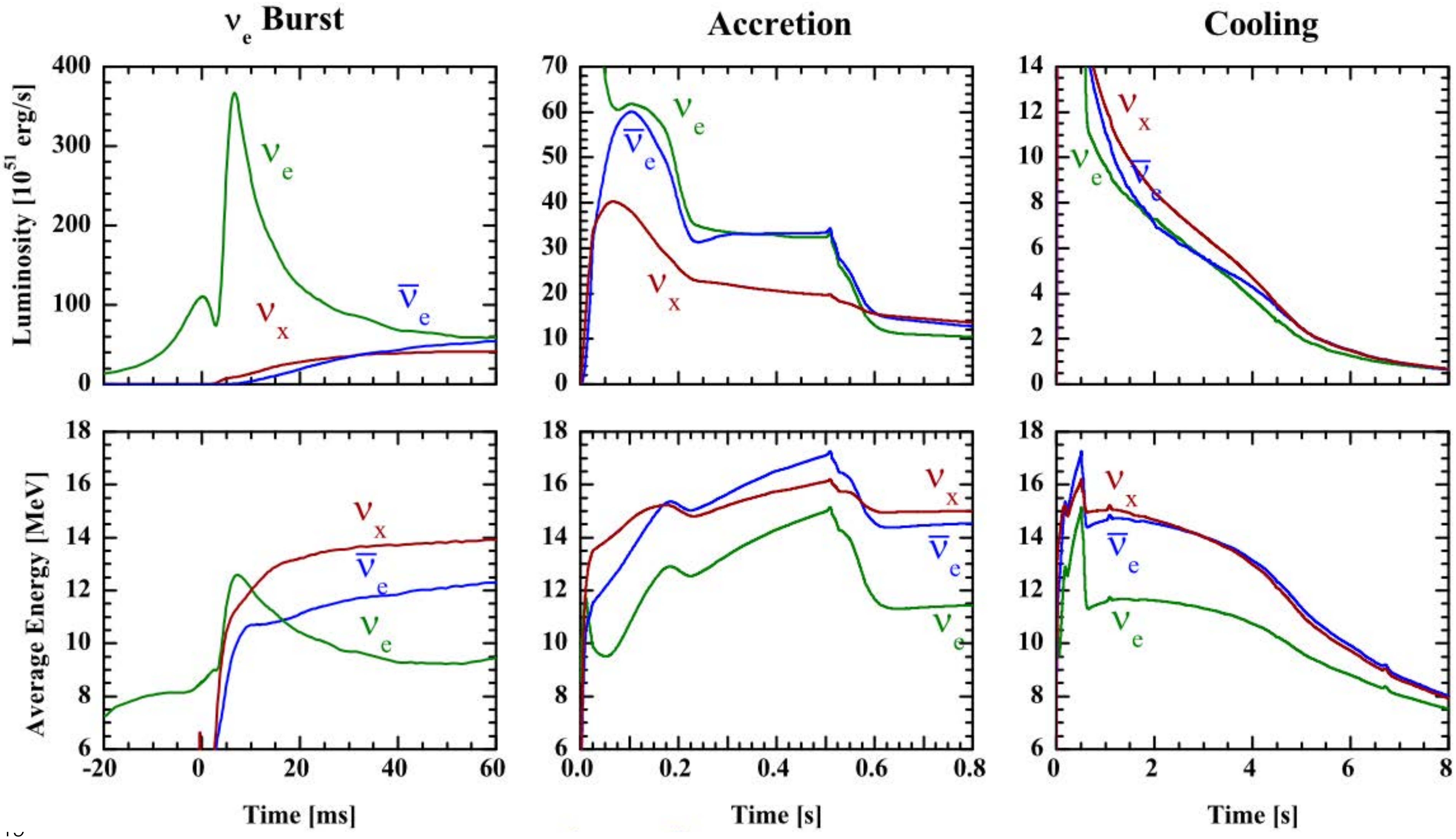
Supernovae neutrinos

- 1st simulation of a 27 M_{sun} star by Garching group

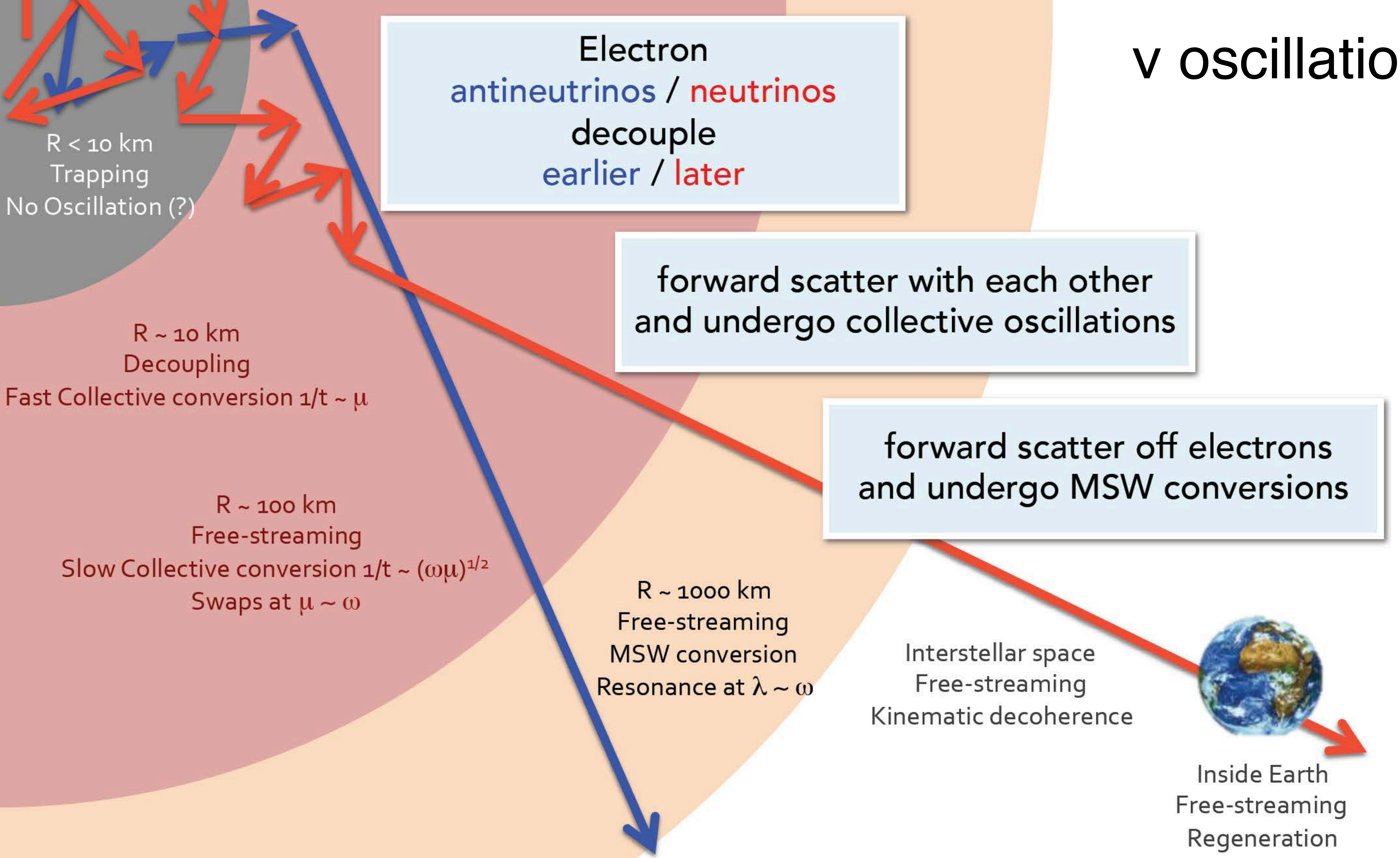
Janka, Melson, and Summa (2016)

Flux of outgoing neutrinos

Spectrum of emitted neutrinos



ν oscillations

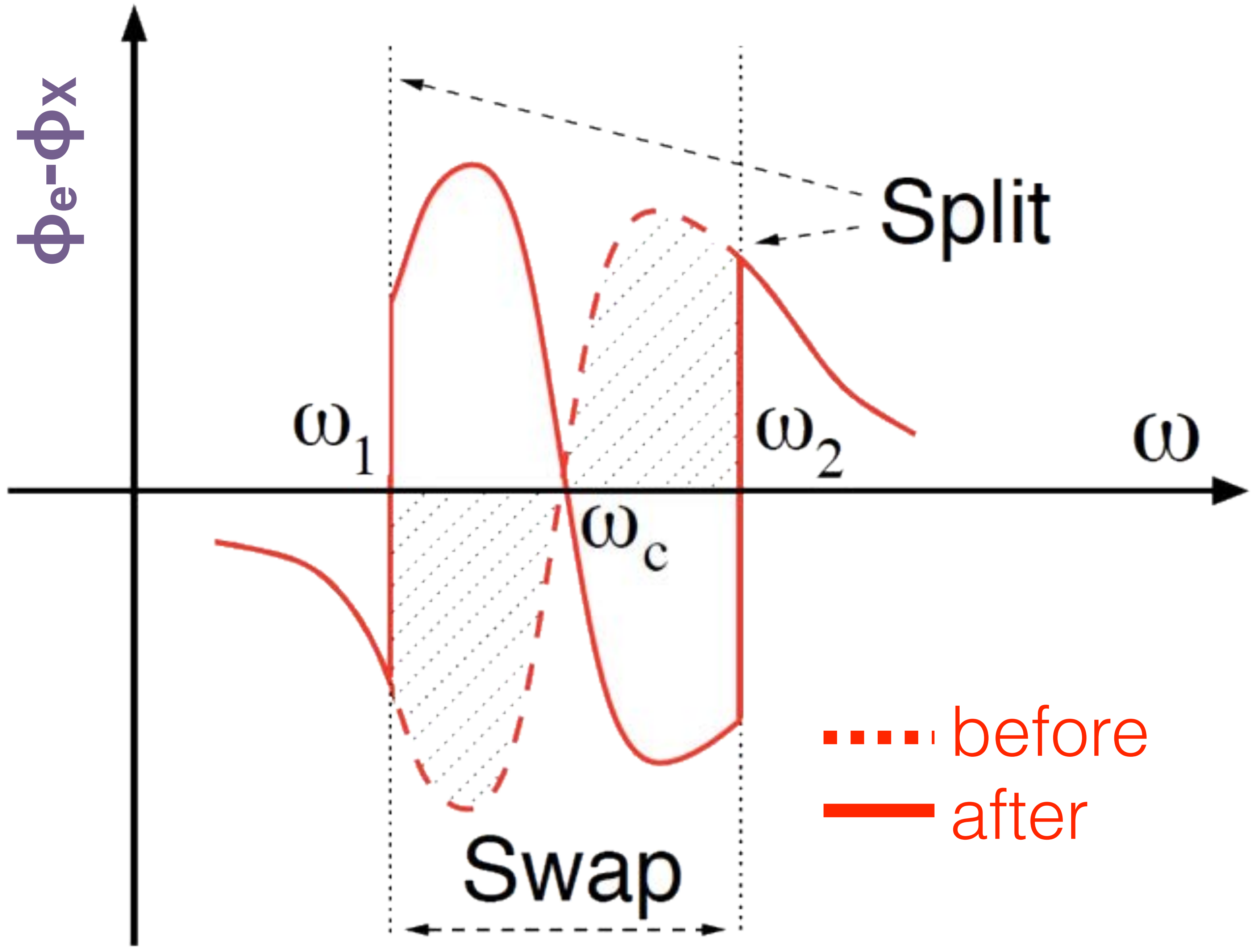


SN detectors

	Detector	Type	Mass (kt)	Location	Events	Flavors
Running	Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$
	LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$
	KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$
	Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$
	IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$
	Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$
	MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$
	HALO	Pb	0.08	Canada	30	ν_e, ν_x
	Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$
	NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$
	SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$
Future	MicroBooNE*	Ar	0.17	USA	17	ν_e
	DUNE	Ar	34	USA	3,000	ν_e
	Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$
	JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$
	RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$
	LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$
	PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$

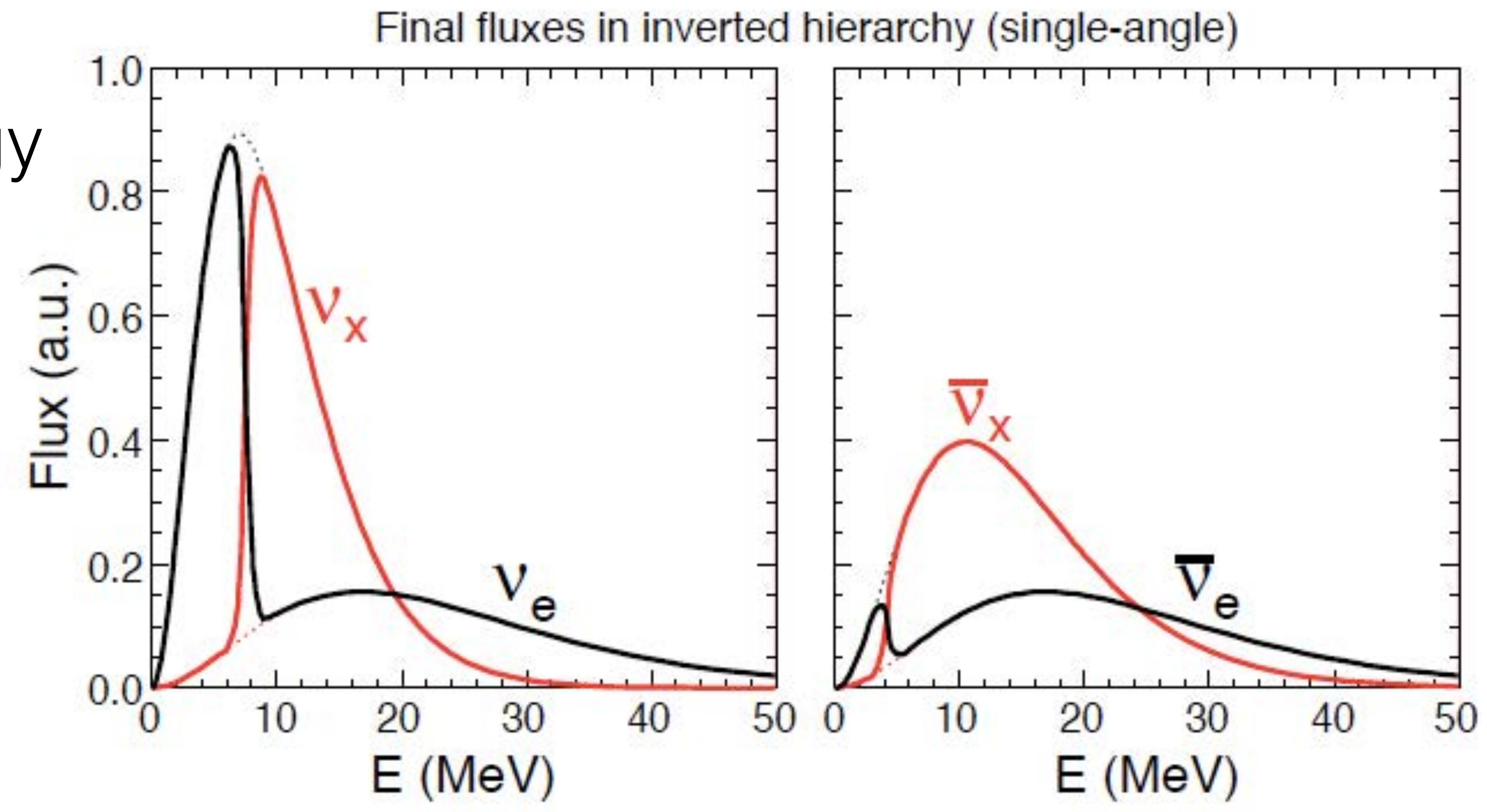
Collective effects

Dasgupta, Dighe, Raffelt, Smirnov (2009)

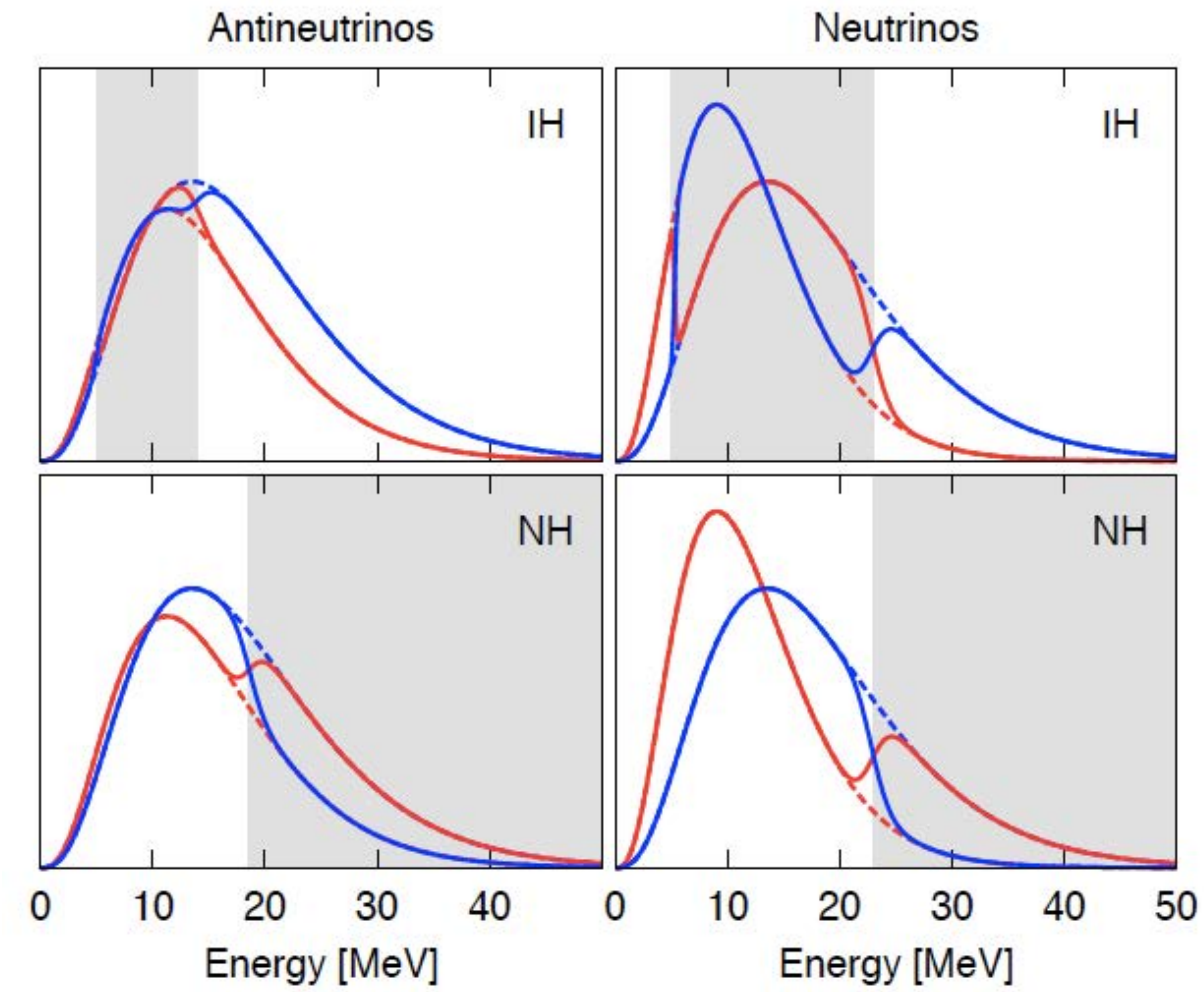


- ϕ_e-ϕ_X critical "crossing"
  - system becomes unstable
  - flavor conversion of ν_e ($\bar{\nu}_e$) to ν_x ($\bar{\nu}_x$) in certain energy intervals as an effect of the interaction with other neutri- nos and antineutrinos

- Portions of the energy spectra get exchanged



- Occurs for both orderings and there can be multiple spectral splits



DSNB

Diffuse Super-nova Neutrino Background:

- Even if a SN explosion is a rare event in our Galaxy, neutrinos of the past explosions form an isotropic flux
  - Is it detectable?
    - ➡ $\bar{\nu} + p \rightarrow e + n$
  - Best limit from SuperKamiokande
  - Close to theoretical expectations
  - Background limited

SK doped with Gd

- Tag n to suppress background
  - n capture cross section on Gd: 49 kbarn
  - γ cascade 8 MeV
  - Low threshold possible
  - 0.2 % of GdCl3 ⇒90% tag efficiency
- 5 ev./yr almost backgroud free
- tests with 1 kt WC near detector of K2K

➡ Maybe close to DSNB detection