Neutrino phenomenology: from Underground to the Skies

Fermilab

14 January 2015

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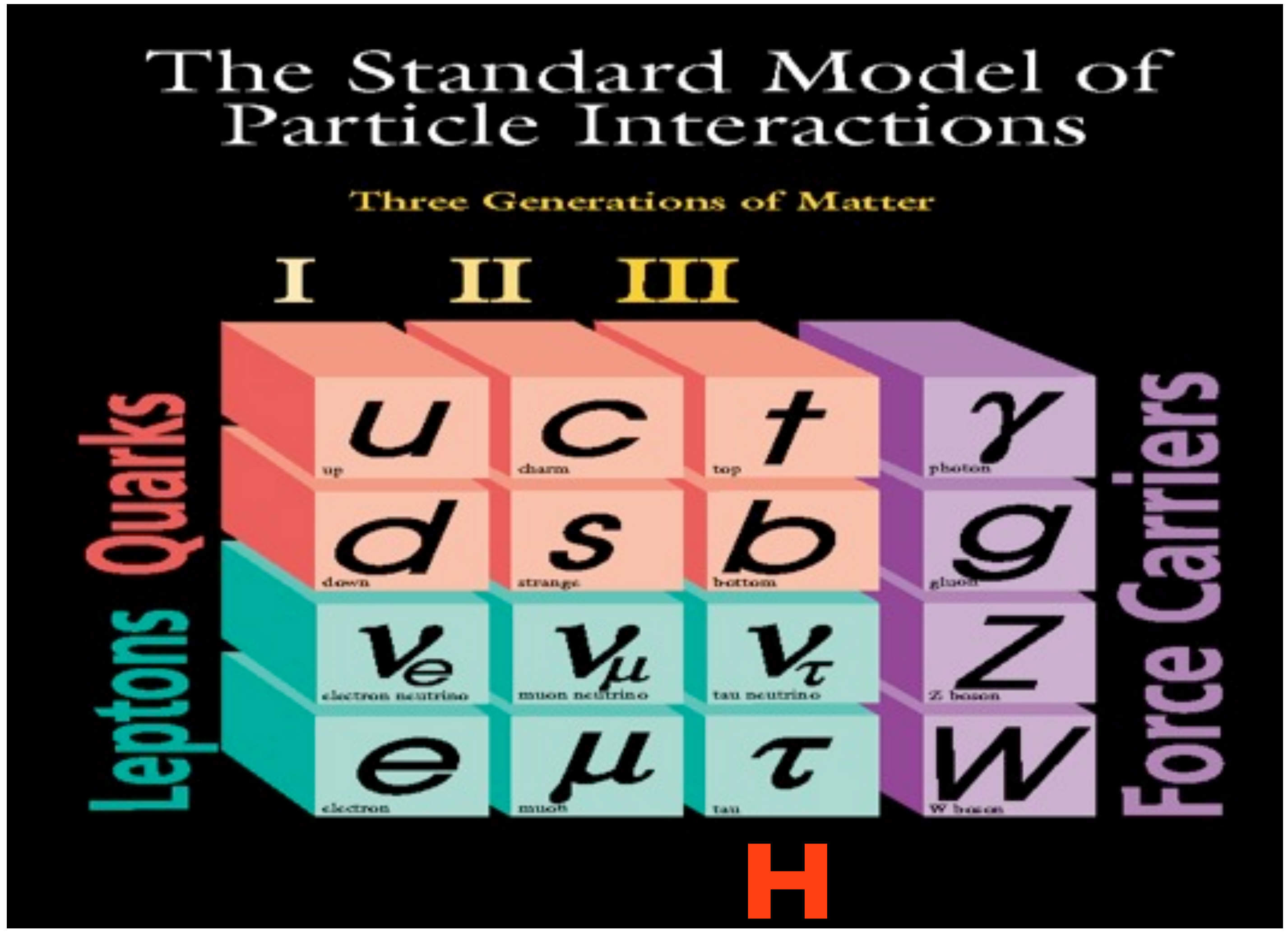
Outline

1. Neutrino production and detection
2. Neutrino oscillations
3. Past and present experiments
4. Current knowledge of ν parameters
5. Questions for the future
   - Dirac vs Majorana: 0νbb decay
   - ν masses and direct searches
   - LBL future exp: MO and CPV
   - cosmology
6. Conclusions

Neutrinos in the Standard model of particle physics



The Standard Model describes the particles which exist in Nature (fermions and bosons) and explains their interactions.

Neutrinos are the most elusive of the SM particles.

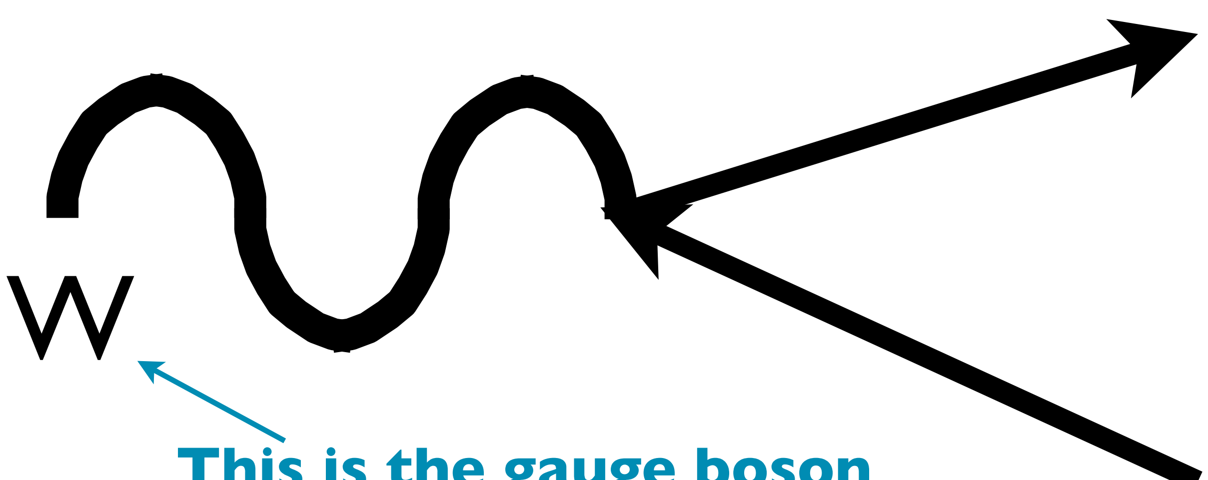
Neutrino interactions

Neutrinos come in 3 flavours, corresponding to the charged lepton in the same SU(2) doublets:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \qquad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \qquad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Same math structure as spin.

The SM tells us how neutrinos interact

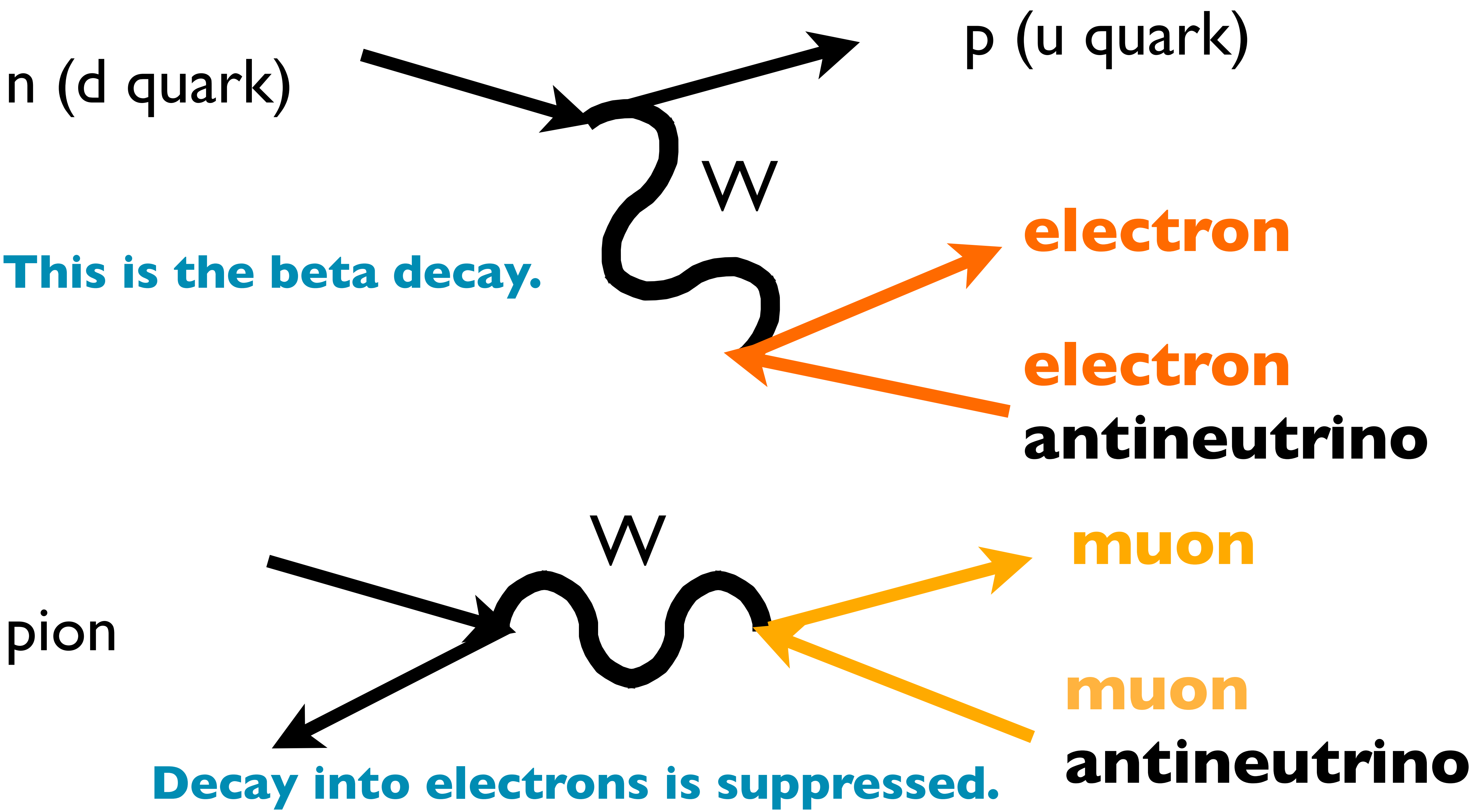


This is the gauge boson (spin 1) associated to SU(2).

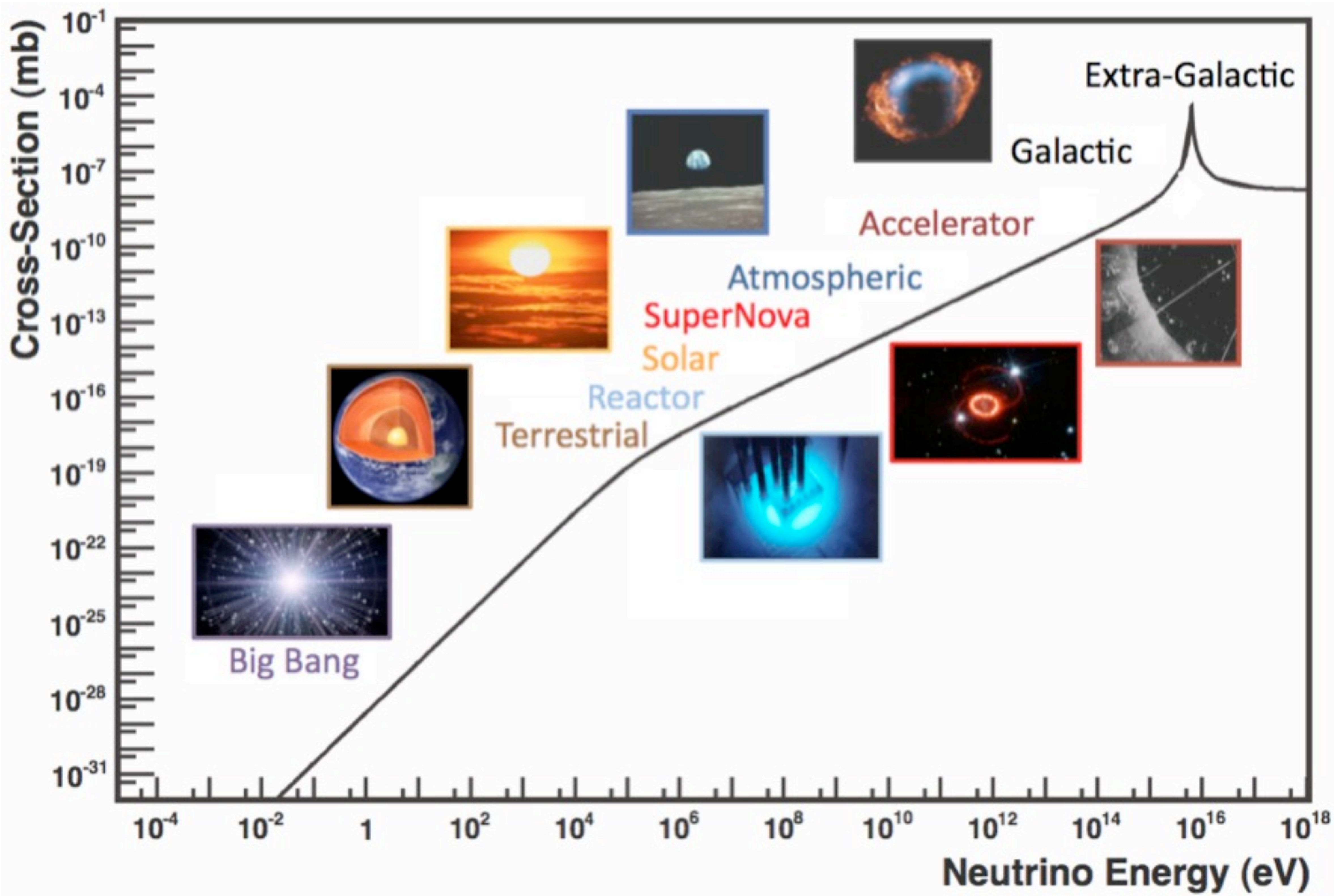
Each type of neutrino flavour interacts with the lepton of the same flavour.

Neutrino production

In CC (NC) SU(2) interactions, the W boson (Z boson) will be exchanged leading to production of neutrinos.



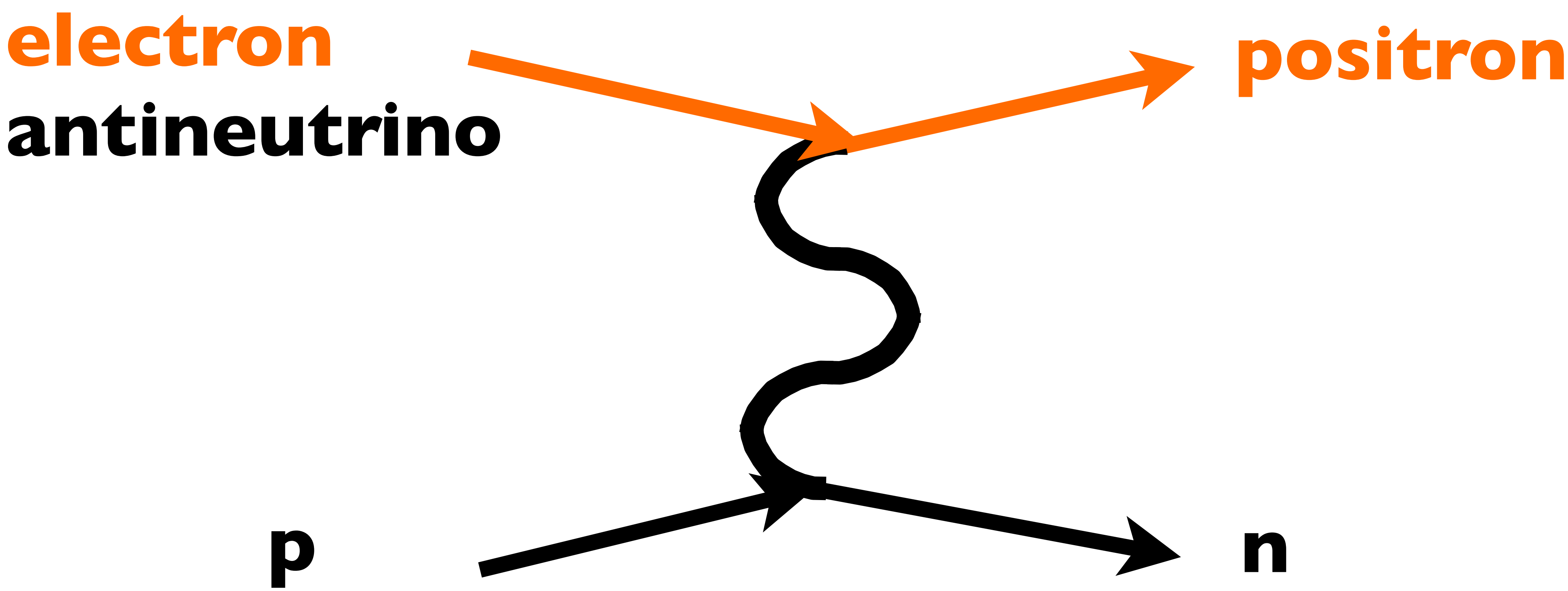
Neutrino sources



J. Formaggio and S. Zeller, 1305.7513

Neutrino detection

Neutrino detection proceeds via CC (and NC) SU(2) interactions. Example:



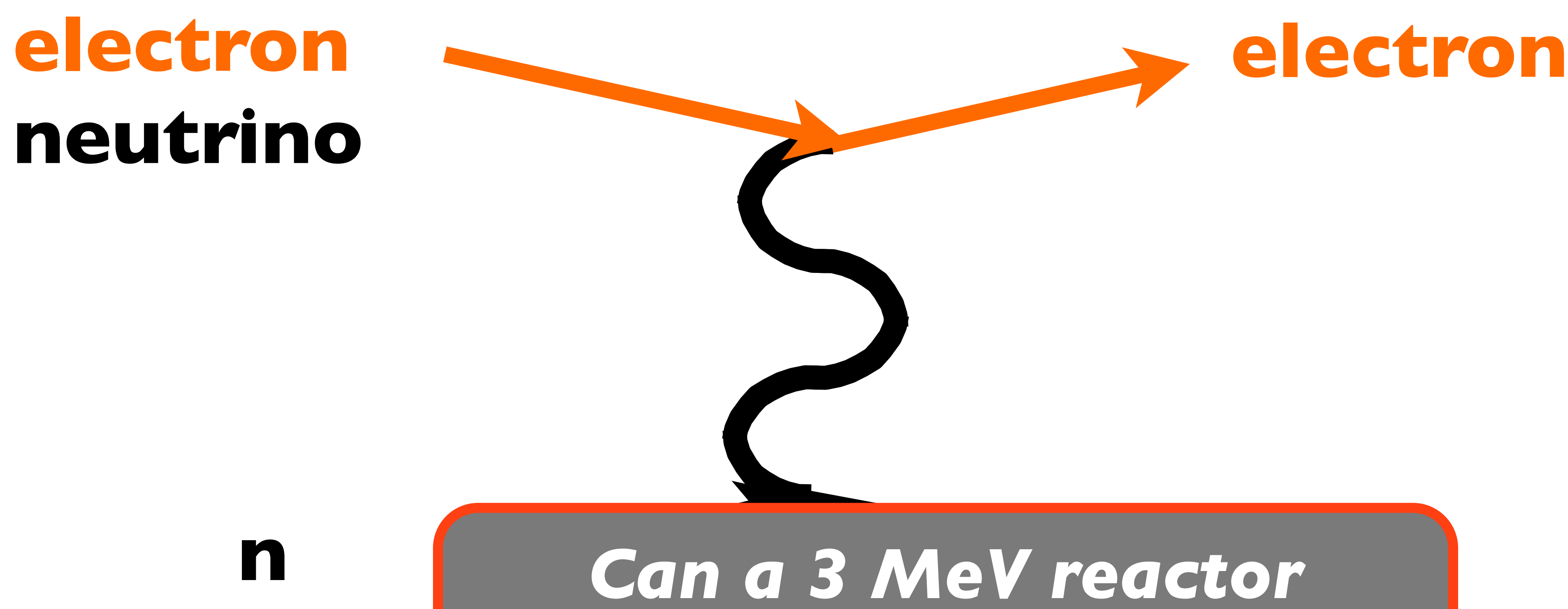
Notice that the leptons have different masses:

me = 0.5 MeV < mmu = 105 MeV < mtau= 1700 MeV

A certain lepton will be produced in a CC process only if the neutrino has sufficient energy.

Neutrino detection

Neutrino detection proceeds via CC (and NC) SU(2) interactions. Example:



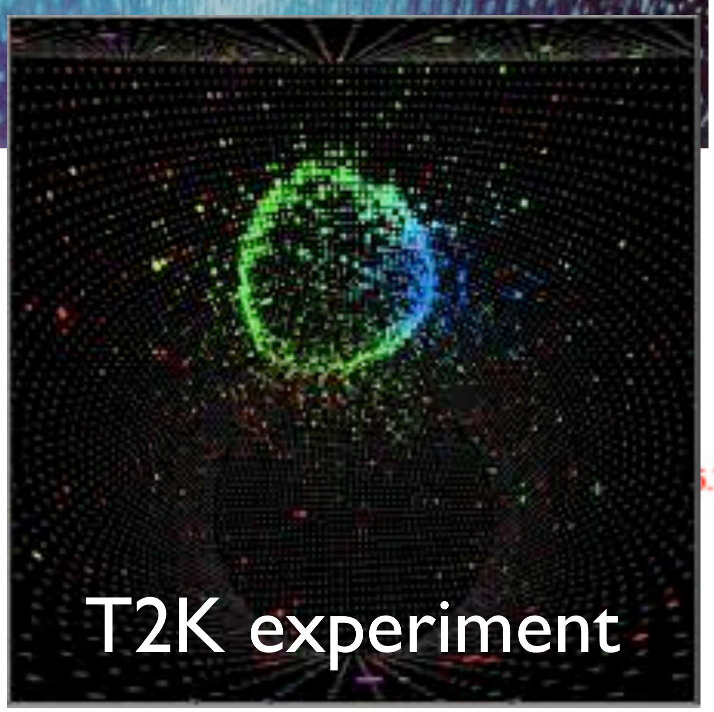
Can a 3 MeV reactor antineutrino produce a muon in a CC interaction?
NO

Notice that the ... :

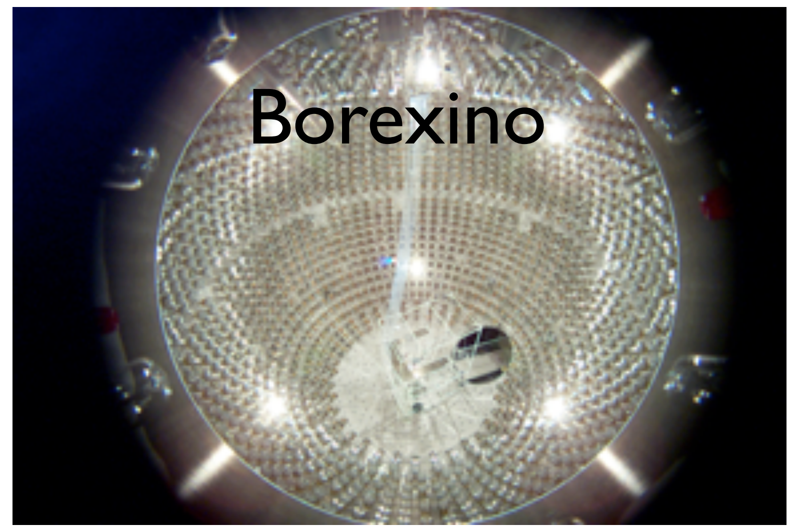
me = 0.5 MeV ... 700 MeV

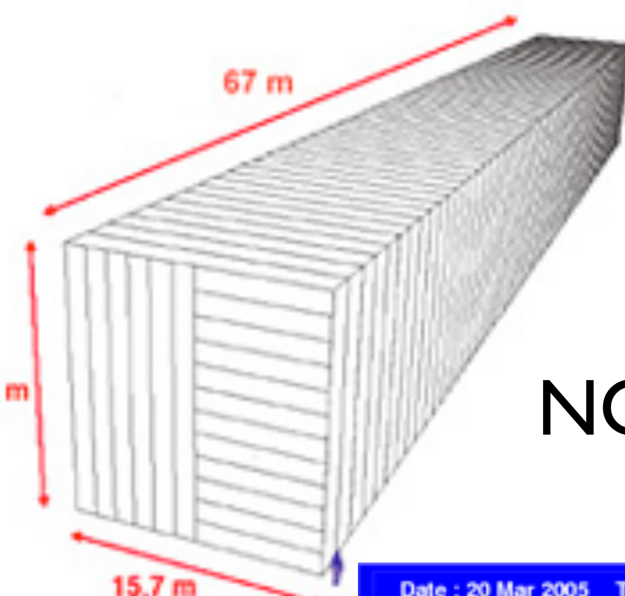
A certain lepton will be produced in a CC process only if the neutrino has sufficient energy.

We are interested mainly in produced charged particles as these can emit light and/or leave tracks in segmented detectors (magnetisation -> charge reconstruction).

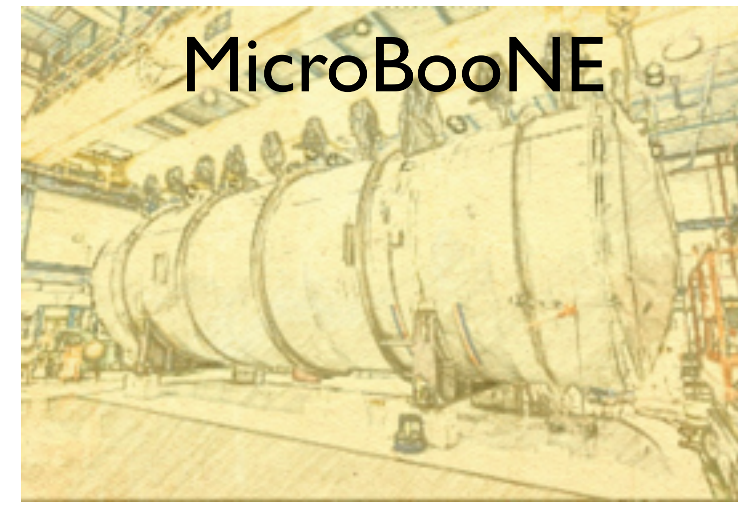


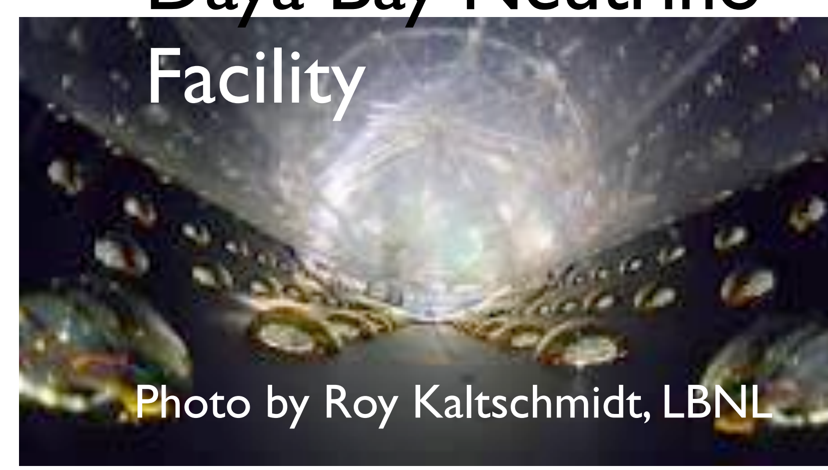
Scintillator

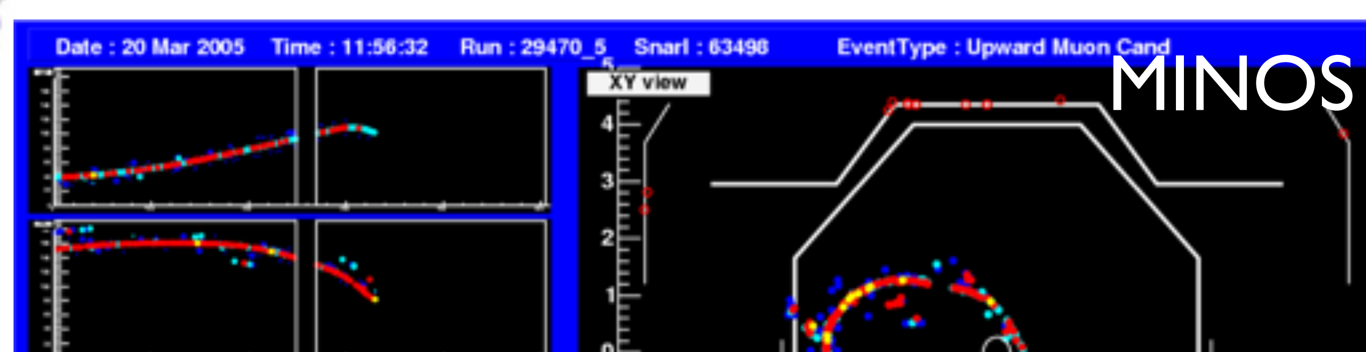




LAr







Water Cherenkov

Iron magnetised

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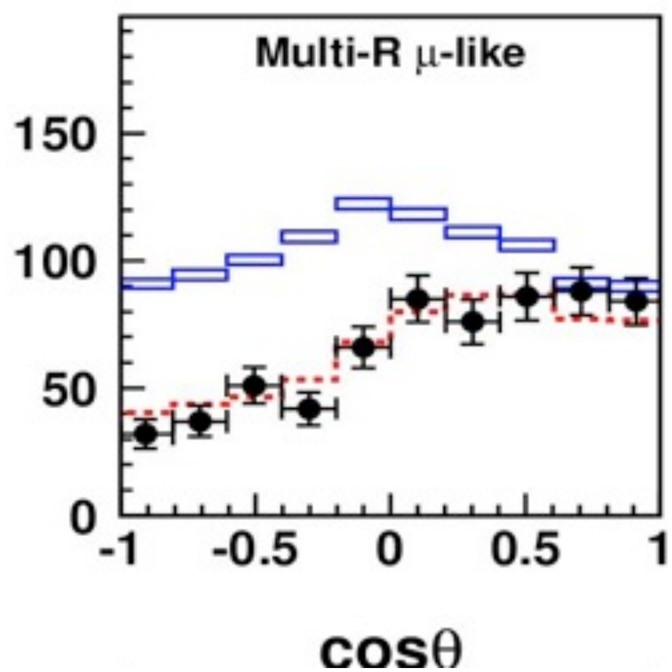
The discovery of neutrino oscillations



VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

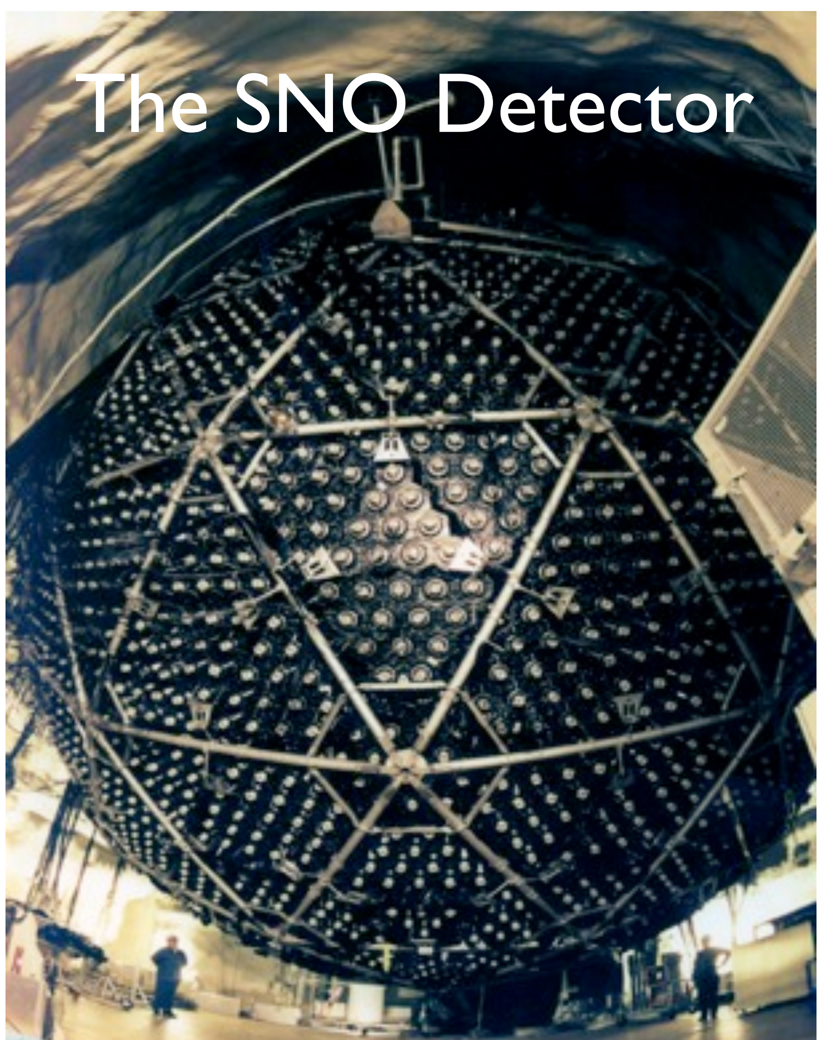
Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2] E. Kearns,[2] M.D. Messier,[2] K. Scholberg,[2] J.L. Stone,[2] L.R. Sulak,[2] C.W. Walter,[2] M. Goldhaber,[3] T. Barszczxak,[4] D. Casper,[4] W. Gajewski,[4] P.G. Halverson,[4,*] J. Hsu,[4] W.R. Kropp,[4] L.R. Price,[4] F. Reines,[4] M. Smy,[4] H.W. Sobel,[4] M.R. Vagins,[4] K.S. Ganezer,[5] W.E. Keig,[5] R.W. Ellsworth,[6] S. Tasaka,[7] J.W. Flanagan,[8,†] A. Kibayashi,[8] J.G. Learned,[8] S. Matsuno,[8] V.J. Stenger,[8] D. Takemori,[8] T. Ishii,[9] J. Kanzaki,[9] T. Kobayashi,[9] S. Mine,[9]

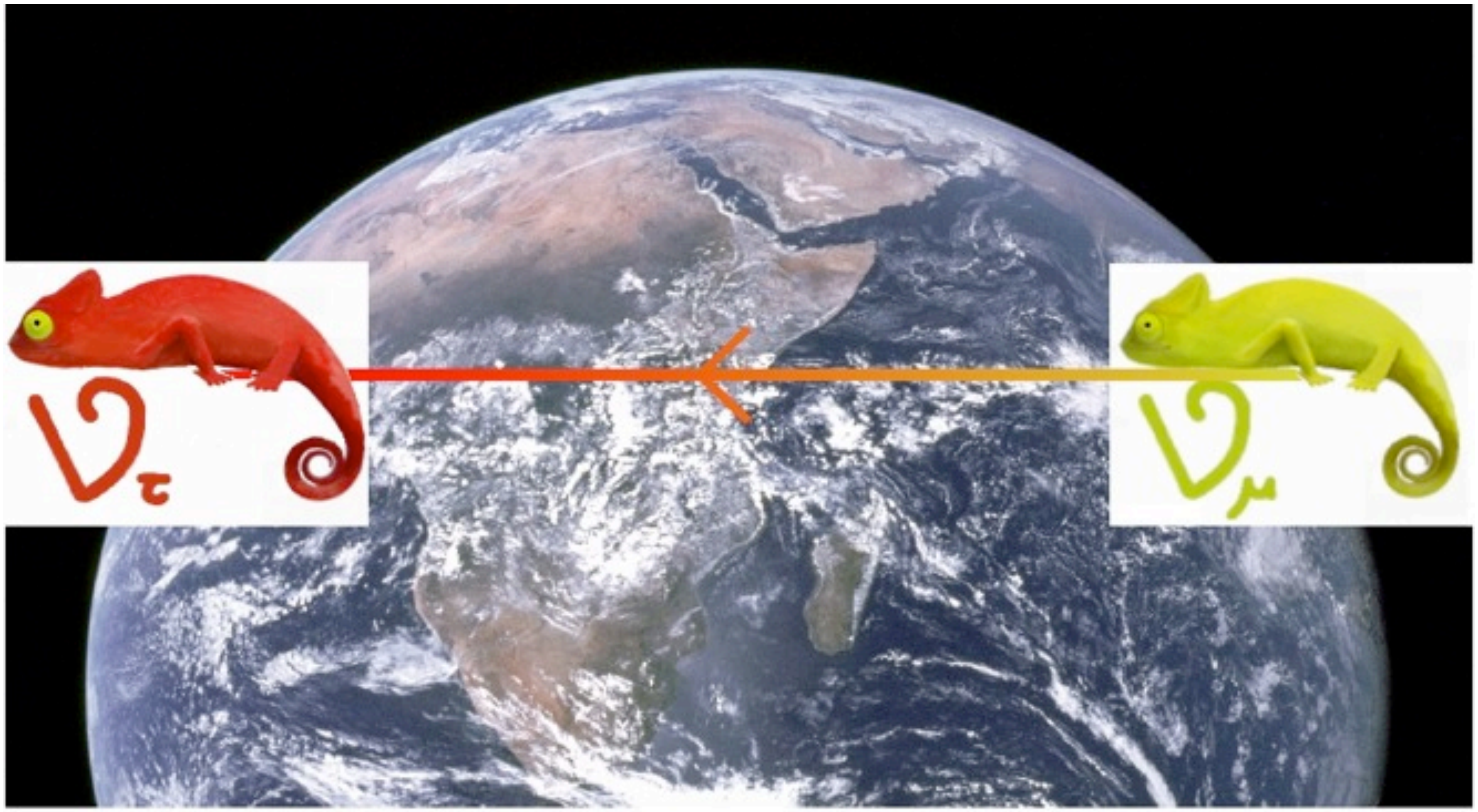
- Atmospheric neutrinos 1998: Super-Kamiokande observed a depletion of muon-like events for neutrinos which transverse the Earth.

- Solar neutrinos: In 2002, SNO observing not only electron neutrino **disappearance** but also active neutrino **appearance**.

- Reactor neutrinos: KamLAND observed the **disappearance** of electron anti-neutrinos.



Neutrinos are **chameleon** particles.



In a SM interaction a neutrino of one type (electron, muon or tau) is produced. While travelling it **changes its "flavour"** and can even become another type of neutrino. This can explain the atmospheric and solar neutrino disappearance.

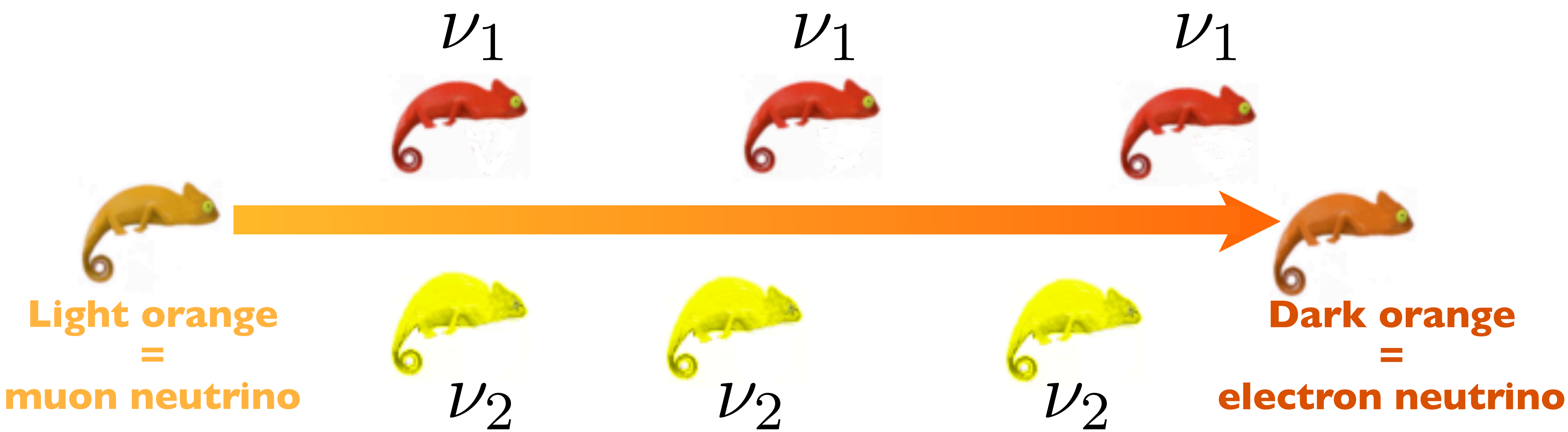
Quantum Mechanics analogs

Neutrino oscillations are analogous to many other systems in QM, in which the initial state is a **coherent superposition of eigenstates of Hamiltonian**:

- NH3 molecule: produced in a superposition of "up" and "down" states

- Spin states: for example a state with spin up in the z-direction in a magnetic field aligned in the x-direction B=(B,0,0). This gives raise to spin-precession, i.e. the state changes the spin orientation with a typical oscillatory behaviour.

Neutrino oscillations: the picture



Production

$$|\nu_\mu\rangle = \sum_i U_{\mu i} |\nu_i\rangle$$

Flavour states coherent superposition of massive states

Propagation

$$\nu_1 : \quad e^{-iE_1 t}$$

$$\nu_2 : \quad e^{-iE_2 t}$$

$$\nu_3 : \quad e^{-iE_3 t}$$

Massive states (eigenstates of the Hamiltonian)

Detection: projection over

$$\langle \nu_e |$$

Flavour states

Lets's consider for simplicity the case of 2-neutrino mixing. The time evolution is given by

$$|\nu, t\rangle = e^{-i\mathcal{H}t}|\nu, 0\rangle = -\sin\theta e^{-iE_1 t}|\nu_1\rangle + \cos\theta e^{-iE_2 t}|\nu_2\rangle$$

As neutrinos are highly relativistic,

$$E_2 - E_1 \simeq (p + \frac{m_2^2}{2E}) - (p + \frac{m_1^2}{2E}) \simeq \frac{\Delta m^2}{2E}$$

The **probability** for ν_μ to transform into ν_e is:

$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta) \sin^2 \frac{(m_2^2 - m_1^2)L}{4E}$$

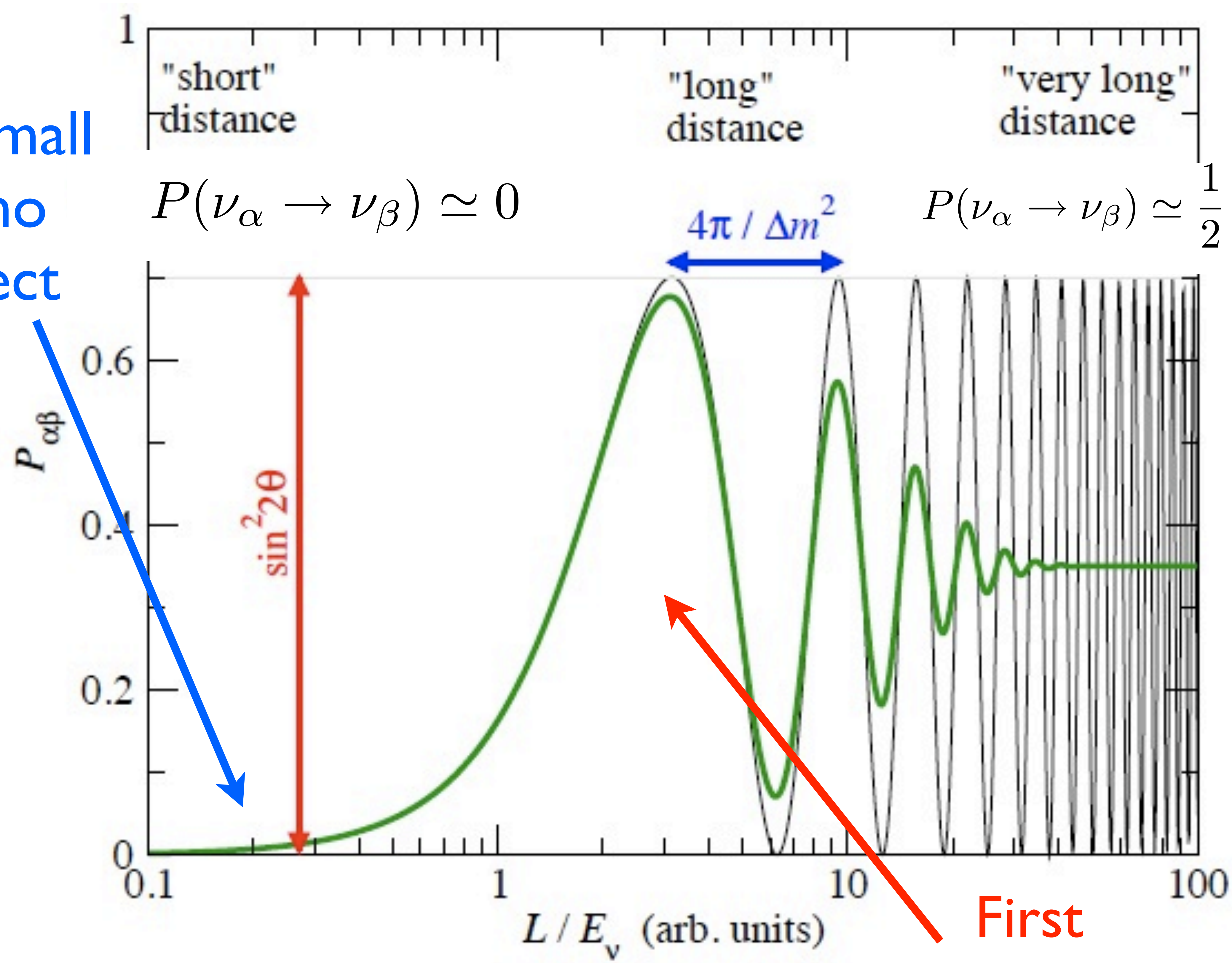
Mixing angle: disalignment between flavour and mass states

Neutrino masses

At small L no effect

$$P(\nu_\alpha \to \nu_\beta) \simeq 0$$

$$P(\nu_\alpha \to \nu_\beta) \simeq \frac{1}{2}\sin^2(2\theta)$$



First oscillation maximum

Thanks to T. Schwetz

The oscillation probability implies that

- **neutrinos have mass** (as the different massive components of the initial flavour state need to propagate with different phases)

- **neutrinos mix** (as U needs not be the identity. If they do not mix, the flavour eigenstates are also eigenstates of the Hamiltonian and they do not evolve.)

Particle physics evidence of physics beyond the Standard Model.

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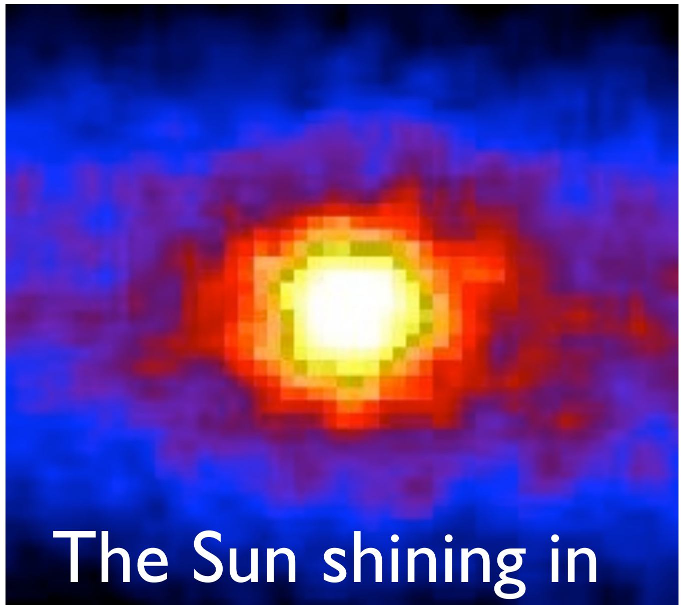
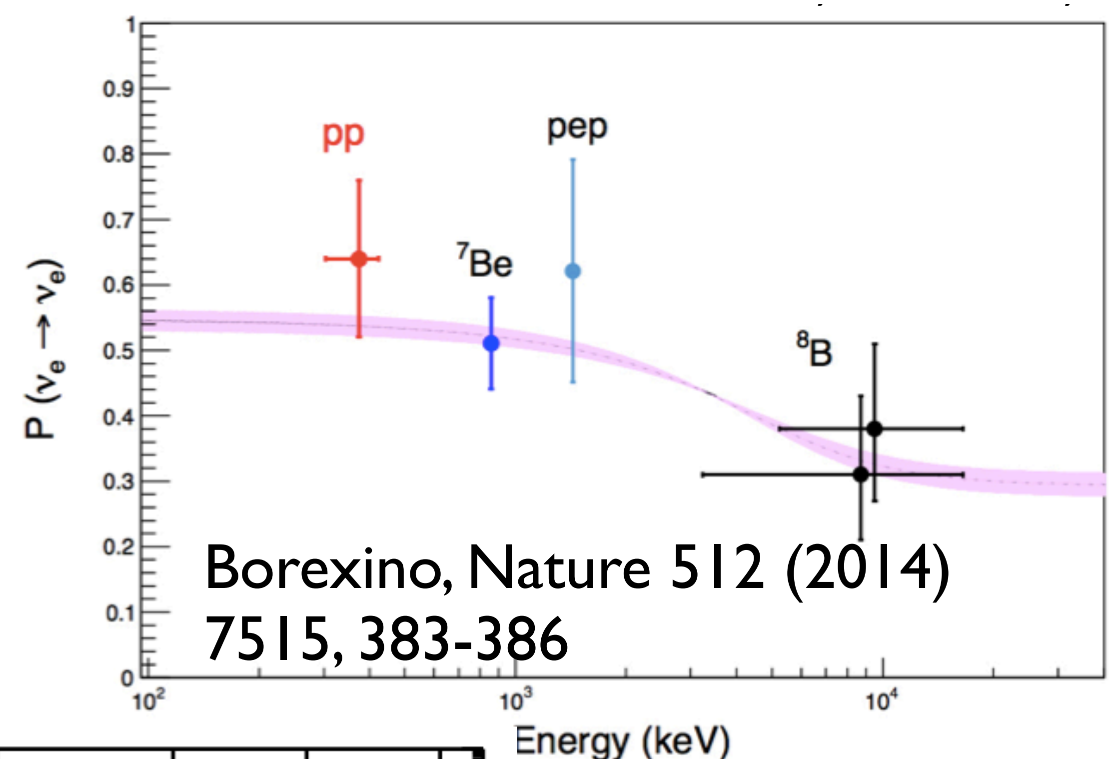
Solar neutrinos

Electron neutrinos are copiously produced in the Sun, at very high electron densities.

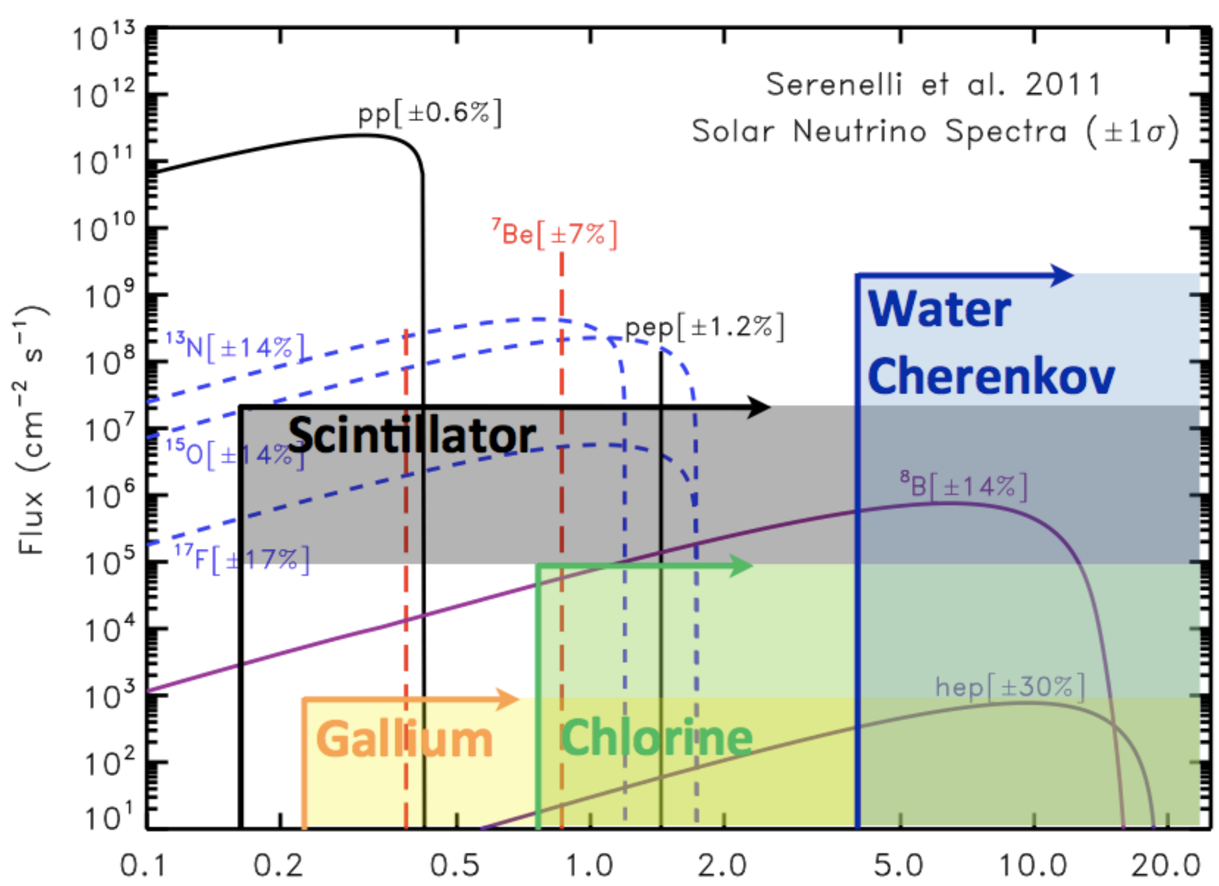


The Sun shining in neutrinos.



Borexino, Nature 512 (2014) 7515, 383-386

- Typical energies: 0.1-10 MeV.
- One can observe CC ν_e and NC.



SNO, also Cl, Ga, Super-Kamiokande

R. Davis Jr. Nobel prize in 2002

J. Wilson, talk at NuPhys 2014

Atmospheric neutrinos

The first atmospheric neutrinos were observed in 1965 by the Kolar Gold Field (KGF) and Reines' experiments.

DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

C. V. ACHAR, M. G. K. MENON, V. S. NARASIMHAM, P. V. RAMANA MURTHY and B. V. SREEKANTAN,
Tata Institute of Fundamental Research, Colaba, Bombay

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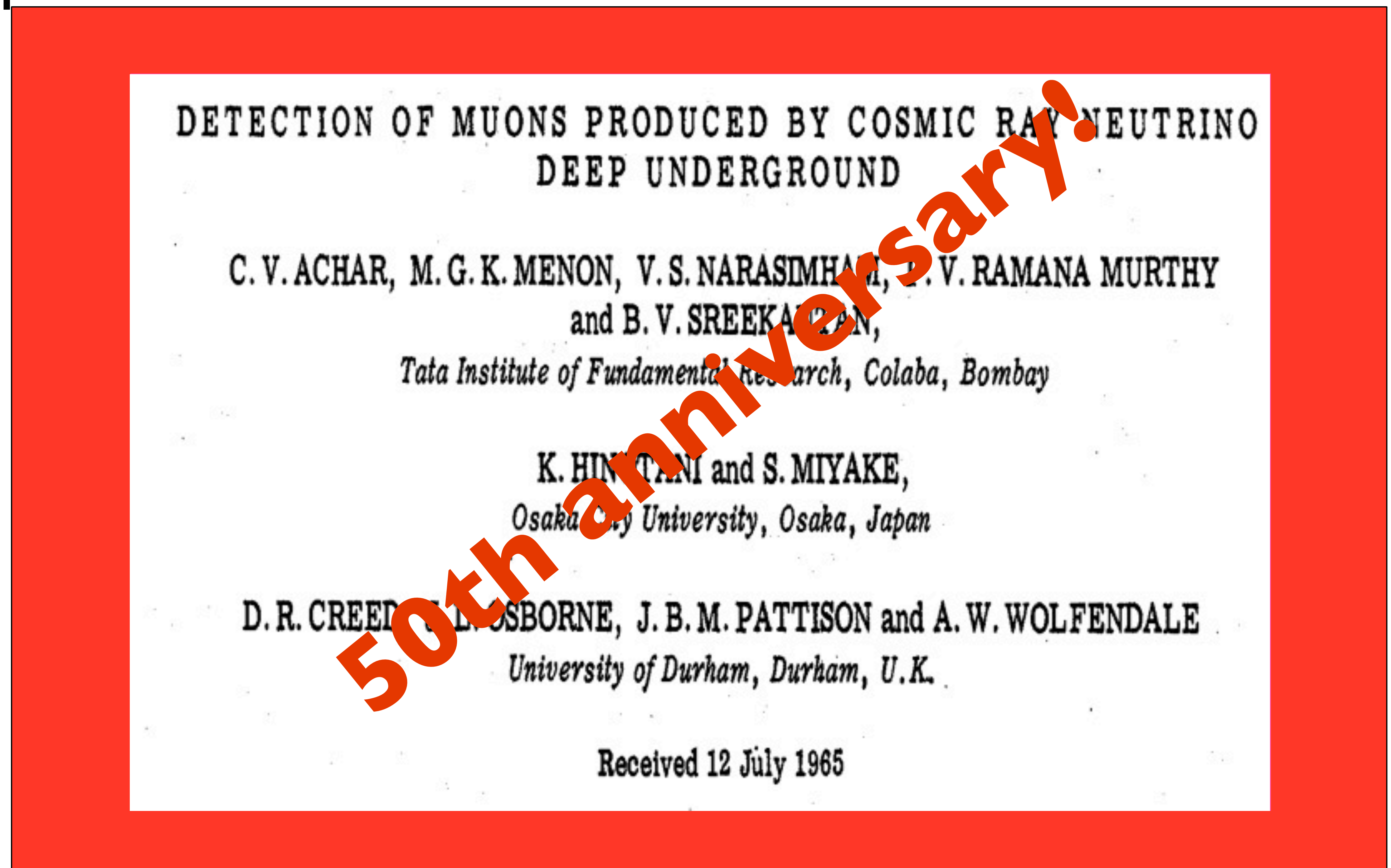
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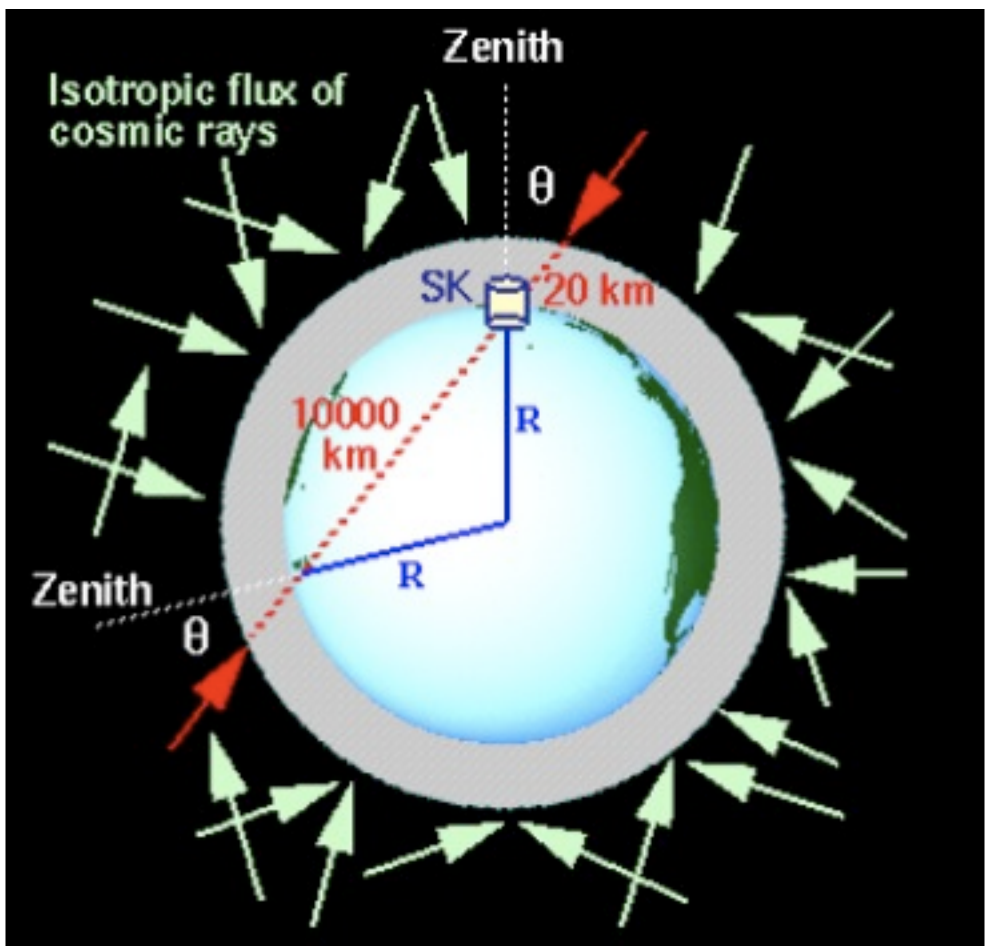
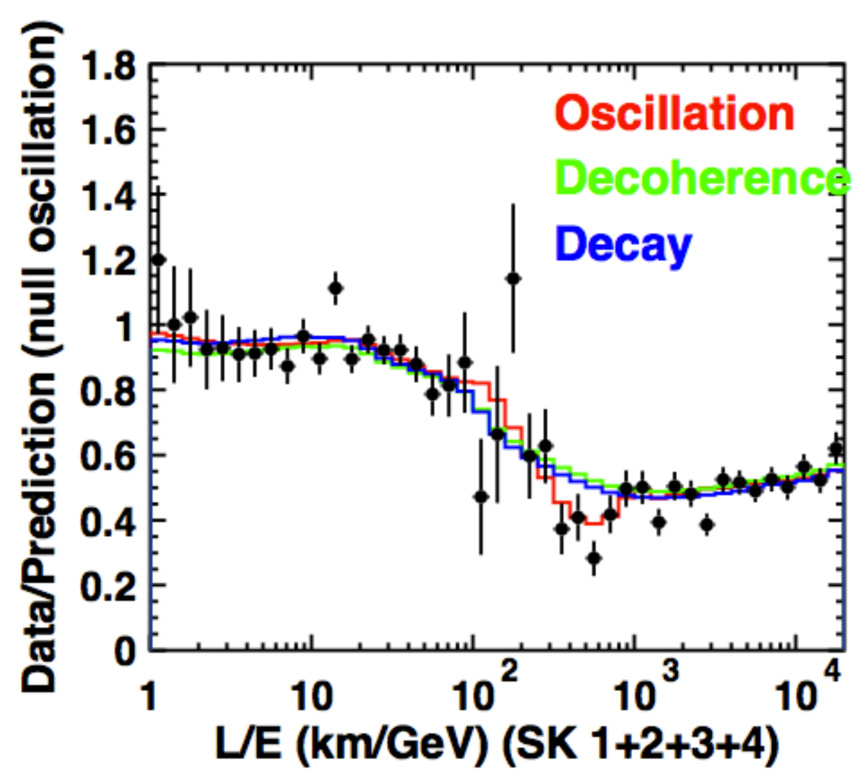
Cosmic rays hit the atmosphere and produce pions (and kaons) which decay producing lots of muon and electron (anti-) neutrinos.

- Typical energies: 100 MeV - 100 GeV
- Typical distances: 100-10000 km.



Super-Kamiokande Coll.

M. Koshiba,
Nobel Prize in 2002



Future experiments: PINGU, ORCA, INO

Reactor neutrinos

Copious amounts of electron antineutrinos are produced from reactors.

- Typical energy: 1-3 MeV;
- Typical distances:

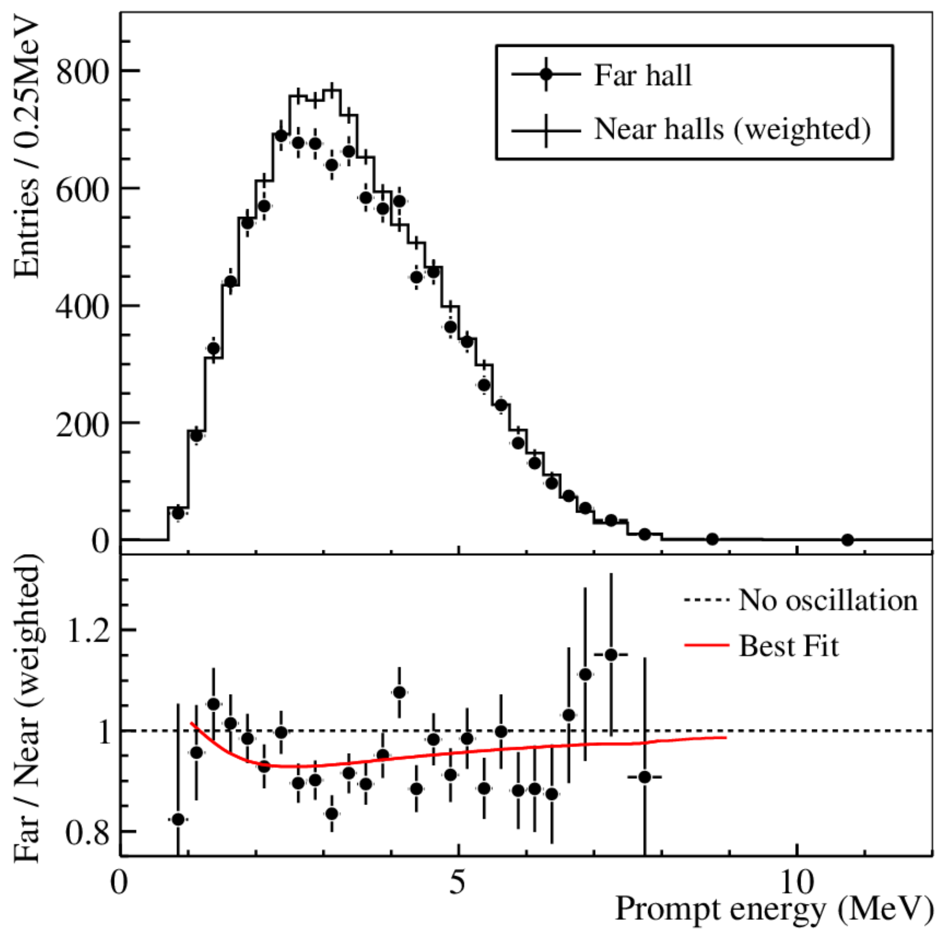
~1 km (Double-Chooz, Daya Bay, RENO)
~60 km (JUNO, RENO50).

- At 1 km the disappearance probability is

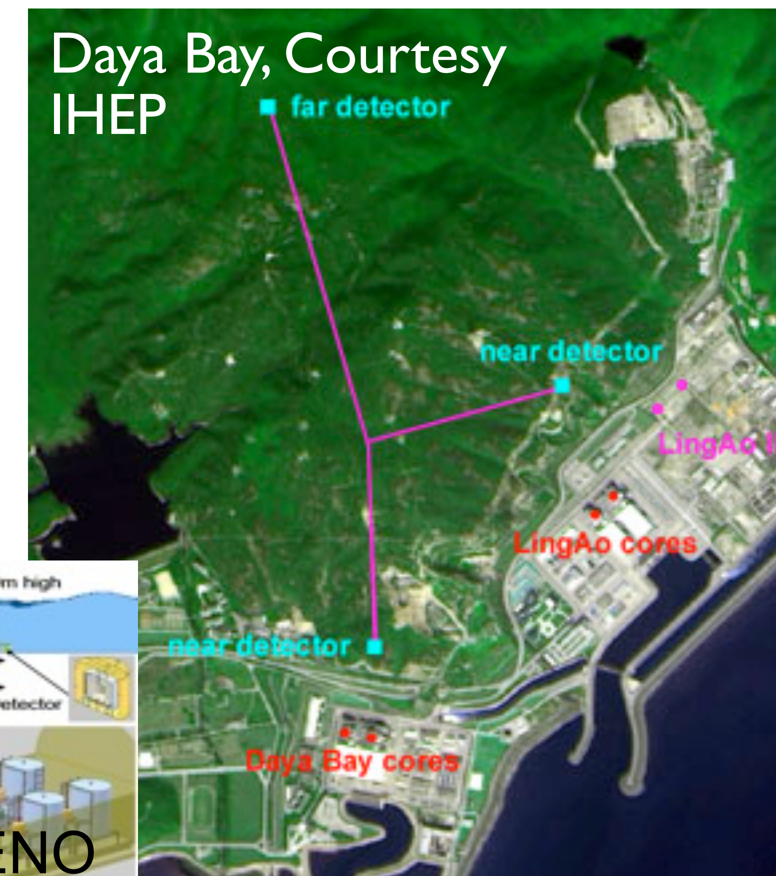
$$P(\bar{\nu}_e \to \bar{\nu}_e; t) = 1 - \sin^2(2\theta_{13}) \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

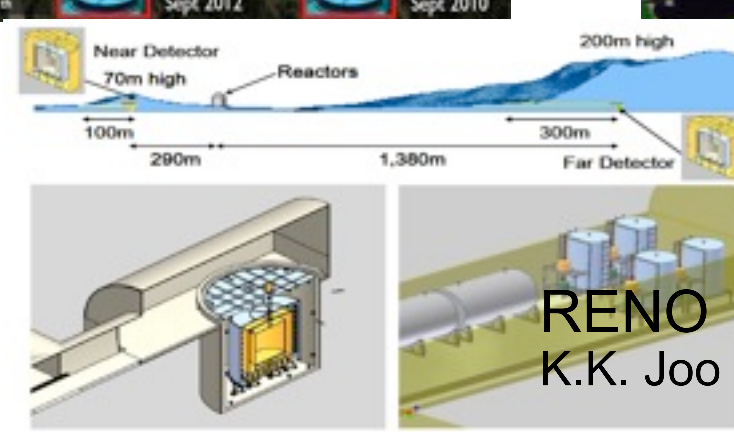
Sensitivity to θ_{13}. Reactors played an important role in the discovery of θ_{13} and in its precise measurement.

In 2012, previous hints (DoubleCHOOZ,T2K, MINOS) for a nonzero third mixing angle were confirmed by Daya Bay (and RENO): important discovery.



Daya Bay, PRL 108 (2012)

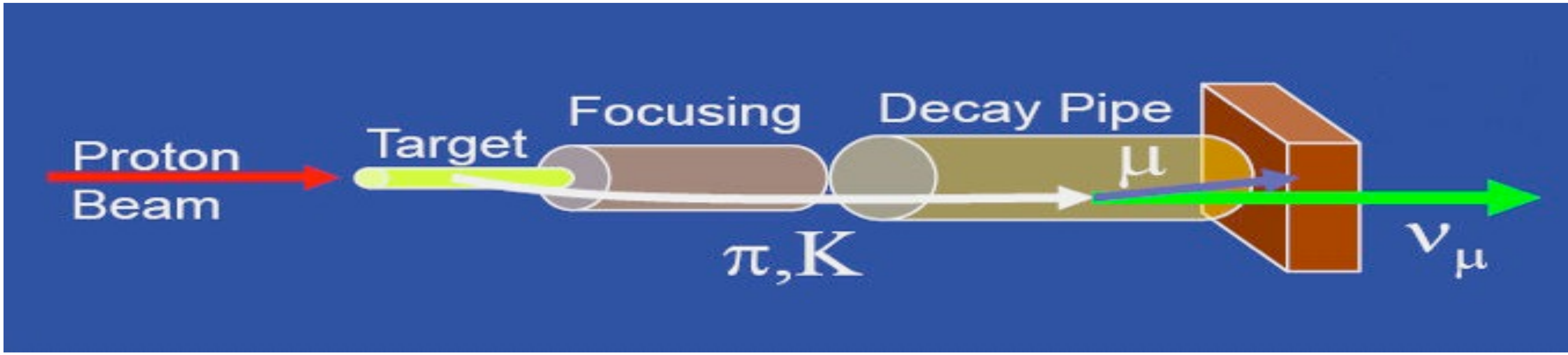




This discovery has very important implications for the future neutrino programme and understanding of the origin of mixing.

Accelerator neutrinos

Conventional beams: muon neutrinos from pion decays



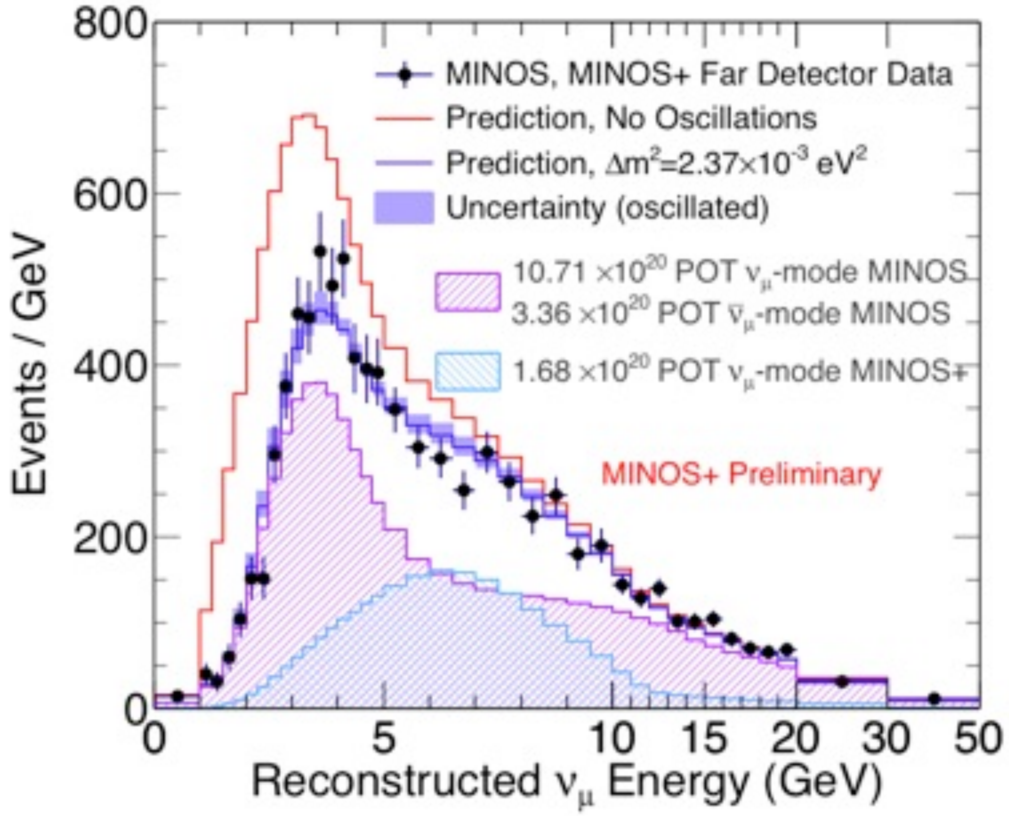
Neutrino production. Credit: Fermilab

- Typical energies:

MINOS: E~4 GeV; MINOS+: E~8 GeV; T2K: E~700 MeV; NOvA: E~2 GeV; MicroBooNE, Minerva... OPERA and ICARUS: E~20 GeV.

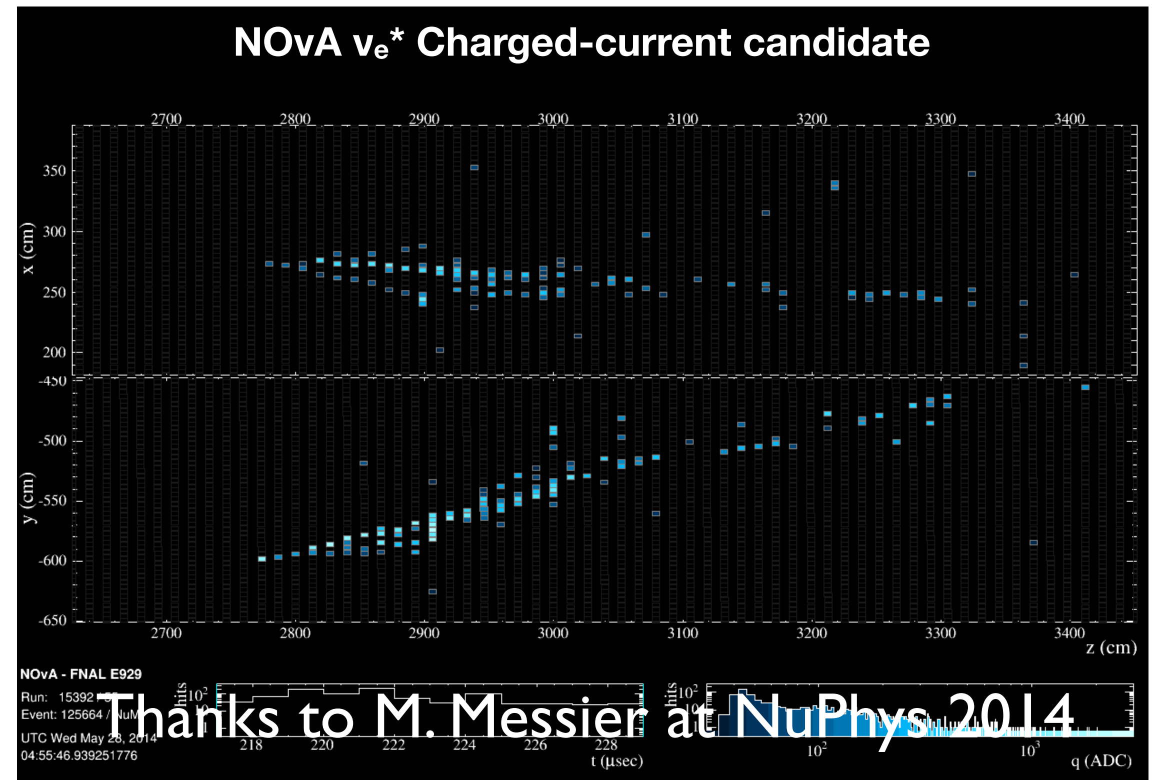
- Typical distances: 100 km - 2000 km, or ~100 m-2 km.

MINOS: L=735 km; T2K: L=295 km; NOvA: L=810 km. OPERA and ICARUS: L=700 km.

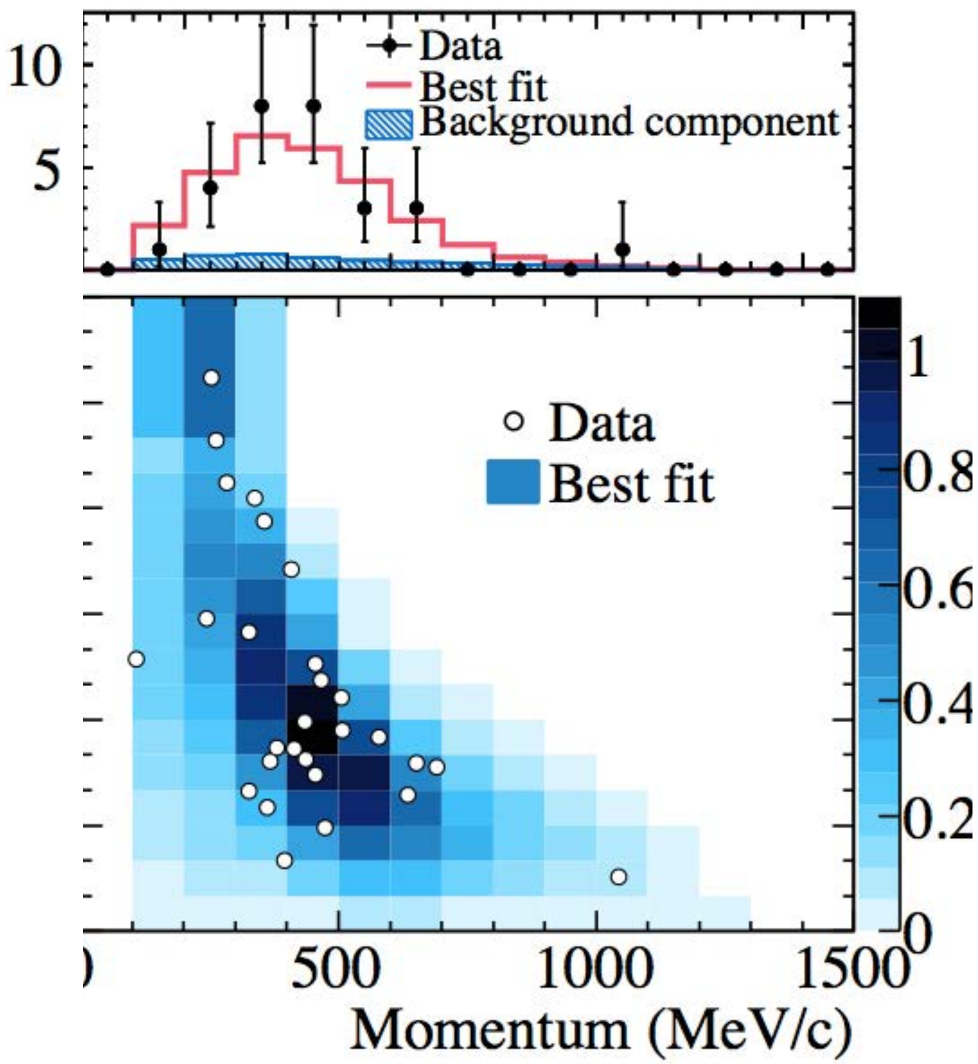


MINOS and MINOS+ search for muon ν disappearance (electron ν appearance)

http://www-numi.fnal.gov



Thanks to M. Messier at NuPhys 2014



NOvA and T2K search for muon ν disappearance and electron ν appearance

T2K: 7.3σ significance to non-zero θ13, Discovery of νe appearance!

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Current neutrino parameters

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

2 mass squared differences

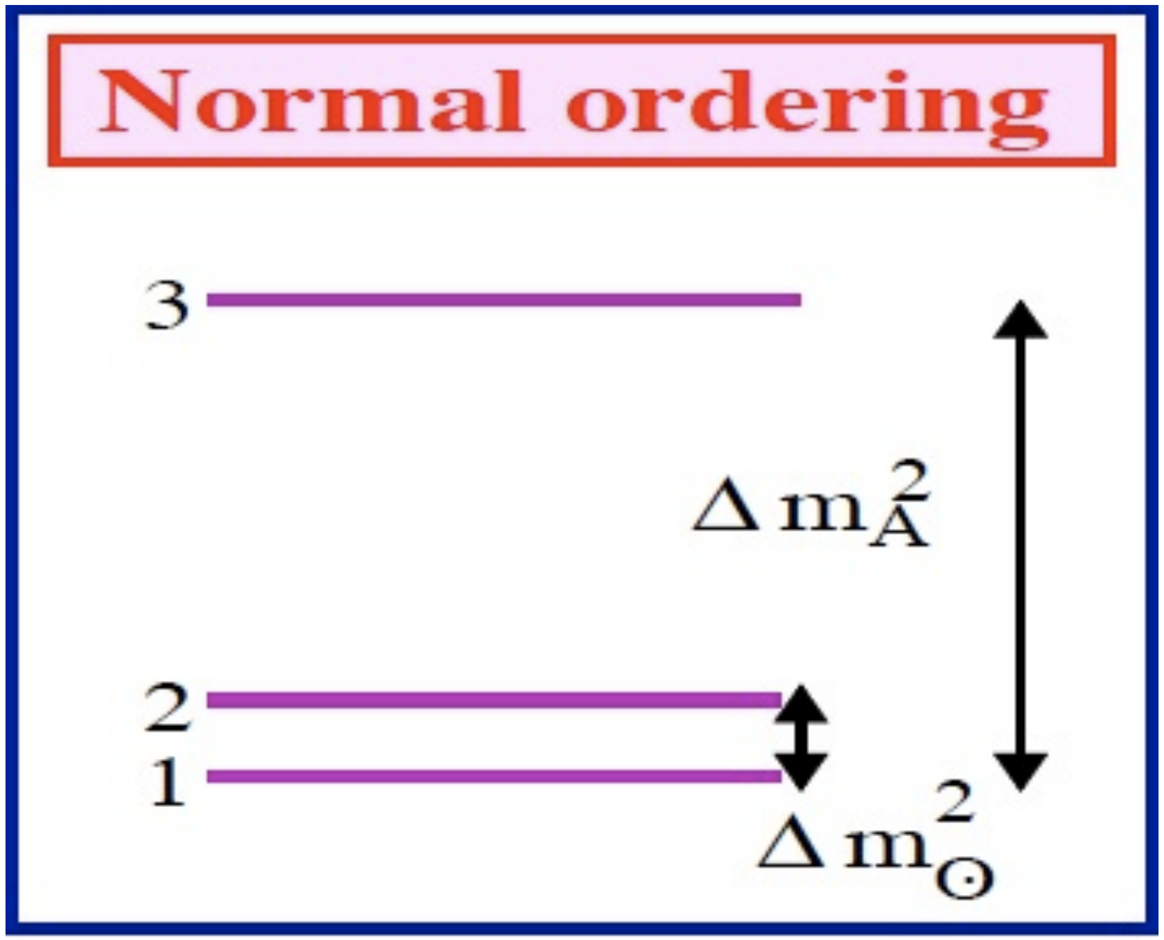
M. C. Gonzalez-Garcia et al., NuFit, 1409.5439

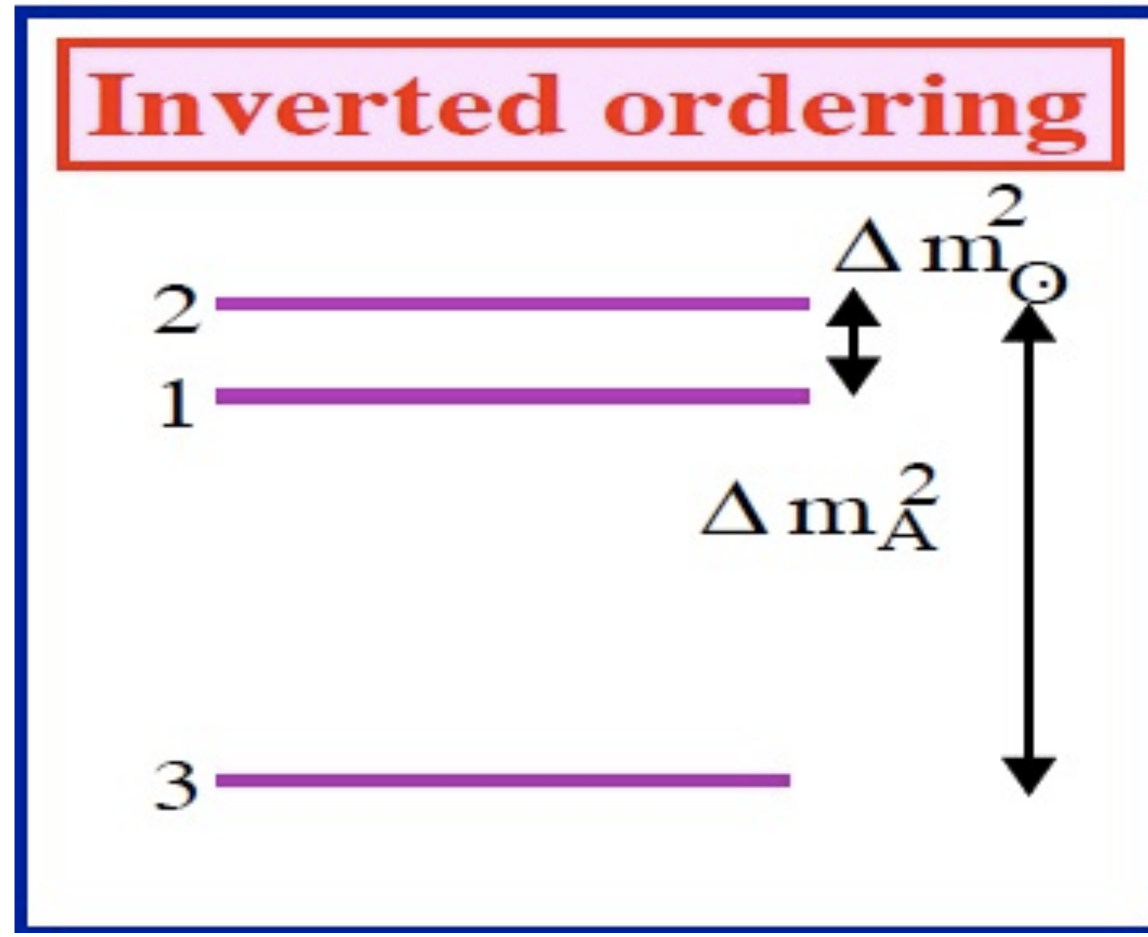
Masses are much smaller than the other fermions.

There are two possible orderings:

normal (m1<m2<m3) and inverted (m3<m1<m2).

$\Delta m_{\rm s}^2 \ll \Delta m_{\rm A}^2$ implies at least 3 massive neutrinos.





$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm sol}^2}$$
$$m_3 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2 - \Delta m_{\rm sol}^2}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2}$$

Measuring the masses requires: $m_{\rm min}$ and the ordering .

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
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$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

3 sizable mixing angles

M. C. Gonzalez-Garcia et al., NuFit, 1409.5439

Mixing is described by the Pontecorvo-Maki-Nakagawa-Sakata matrix, which enters in the CC interactions.

Mixing angles are much larger than in the quark sector.

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$

CP-violation?

Neutrinos behave differently from antineutrinos.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

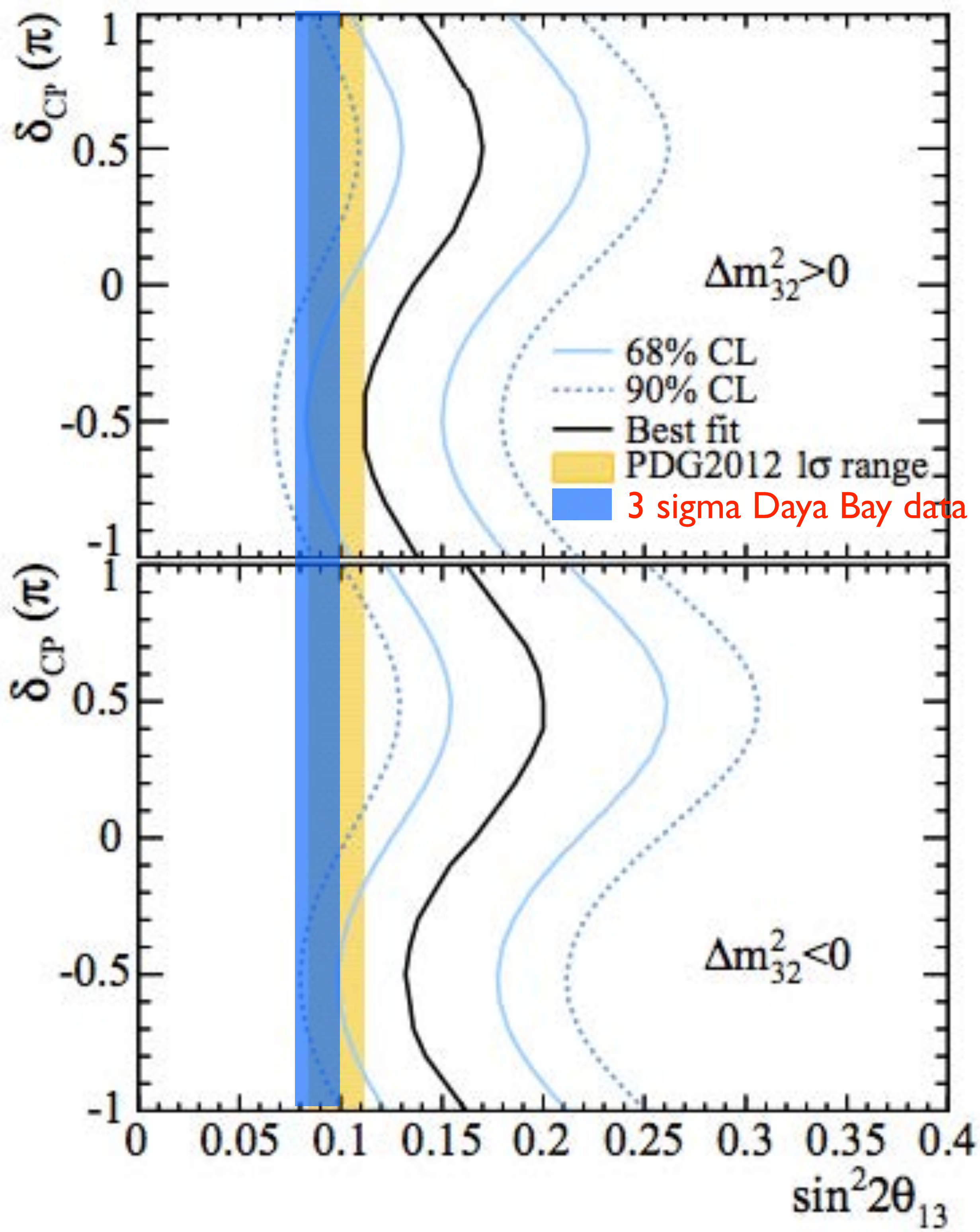
For antineutrinos,

$$U \to U^*$$

CP-conservation:

U is real $\Rightarrow \delta = 0, \pi$

Hints for CP violation?

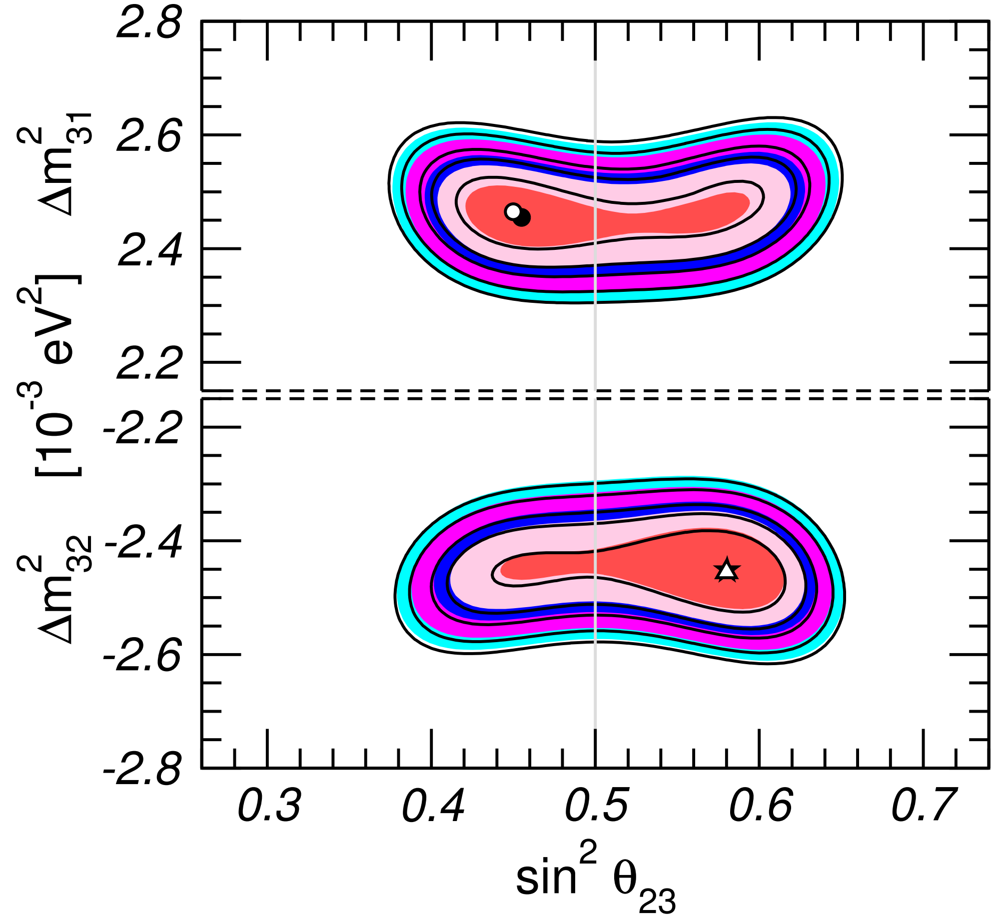


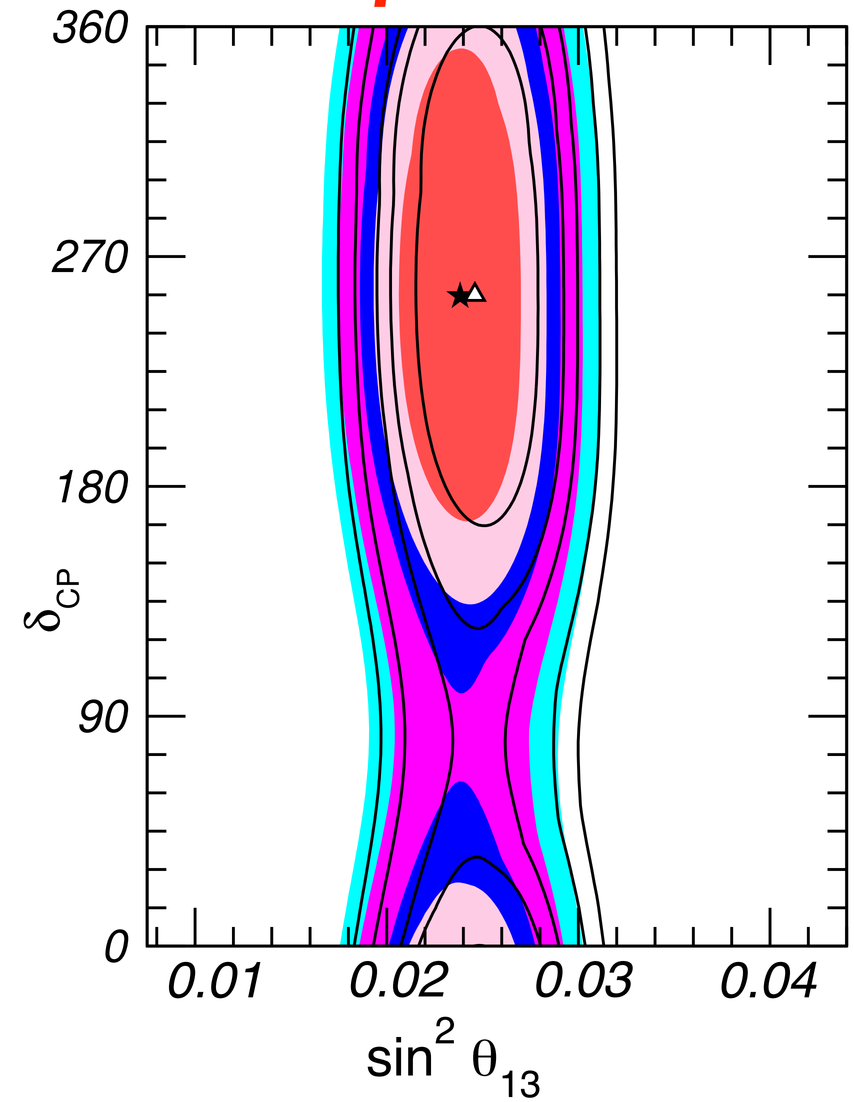
T2K Coll. PRL 112, 061802 (2014)

There is a slight preference for CP-violation, which is mainly due to the combination of T2K and reactor neutrino data.

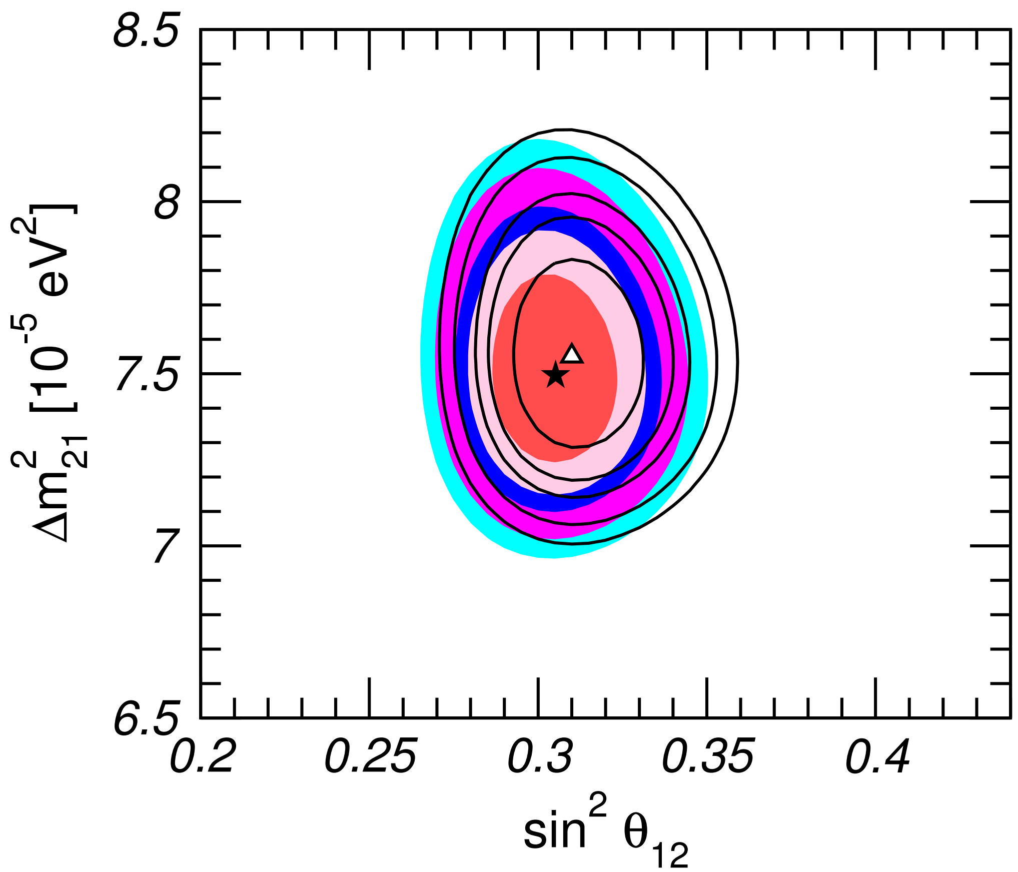
Wait and see!

Summary of current neutrino parameters





M. C. Gonzalez-Garcia et al., NuFit, 1409.5439



Global fit to neutrino oscillation data

www.invisibles.eu

All oscillation parameters are measured with good precision, except for the mass hierarchy and the delta phase. One needs to check the 3-neutrino paradigm (sterile neutrino?).

Outline

1. Neutrino production and detection
2. Neutrino oscillations
3. Past and present experiments
4. Current knowledge of v parameters
5. **Questions for the future**
   Dirac vs Majorana: 0vbb decay
   v masses and direct searches
   LBL future exp: MO and CPV
   cosmology
6. Conclusions

Open Phenomenology questions

- **1. What is the nature of neutrinos?**
- **2. What are the values of the masses?** Absolute scale (KATRIN, ...?) and the mass ordering (MO).
- **3. Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **4. What are the precise values of mixing angles?** Do they suggest a underlying pattern?
- **5. Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

Nature of Neutrinos: Majorana vs Dirac

e^- **electron** negative charge

e^+ **positive** positive charge

Charged particles can be distinguished from their antiparticles.
Neutrinos are neutral and can be **Majorana** or **Dirac** particles.

Majorana: particle ~ antiparticle

Majorana condition: $\nu = C\bar{\nu}^T$

ν	$\bar{\nu}$
neutrino	**antineutrino**
Lepton number +1	Lepton number -1

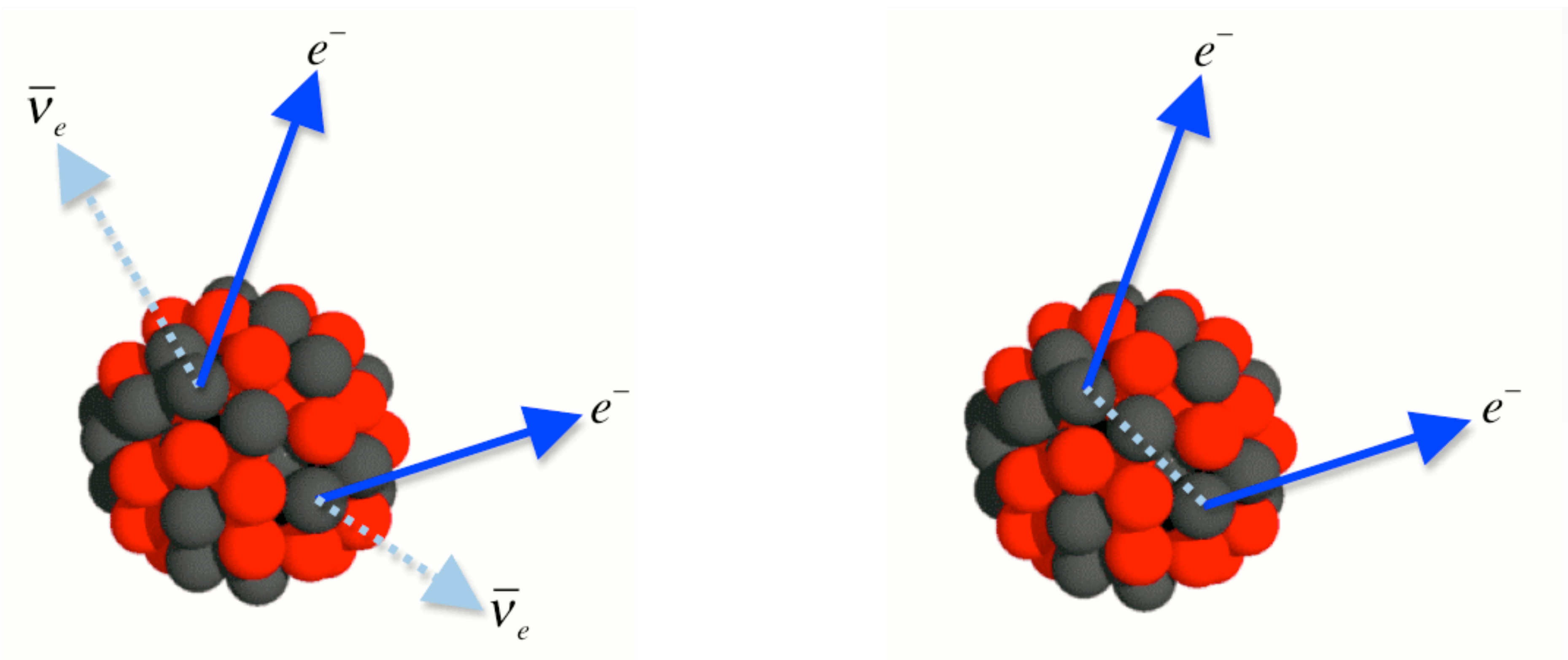
The **nature of neutrinos** is linked to the conservation of the **Lepton number (L)**.

- This is crucial information to understand the **Physics BSM** responsible for neutrino masses: **with or without L-conservation**?

- Lepton number violation is a necessary condition for **Leptogenesis**, together with CV, CPV and out of equilibrium.

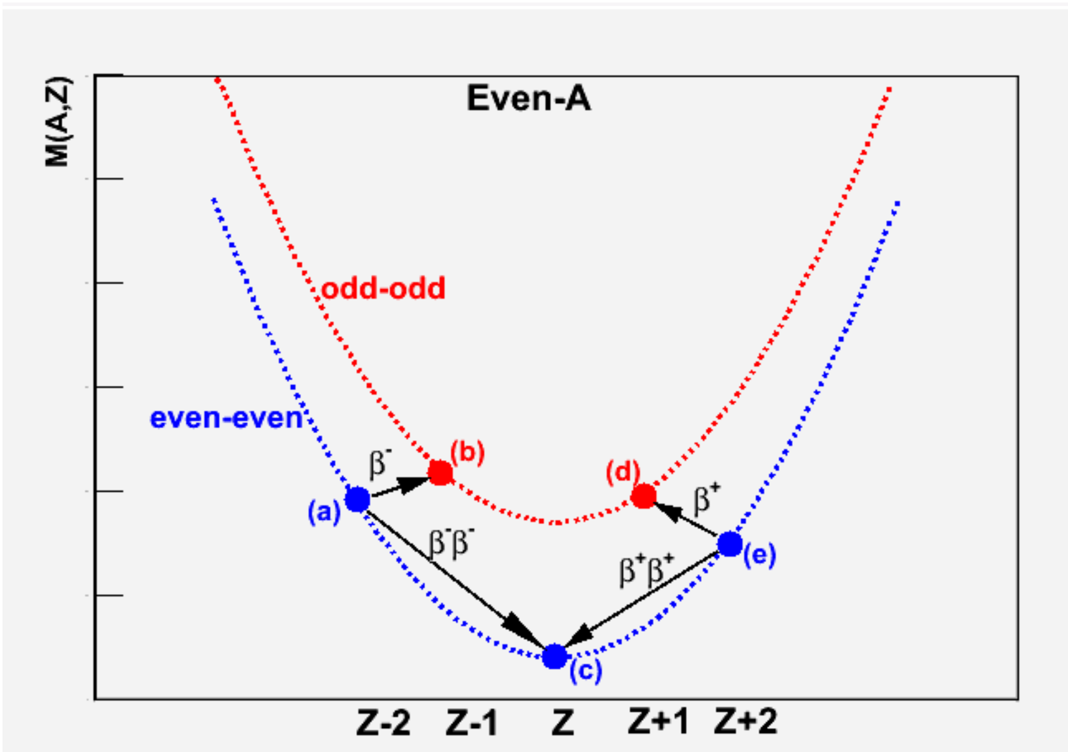
Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2 e, will test the nature of neutrinos.

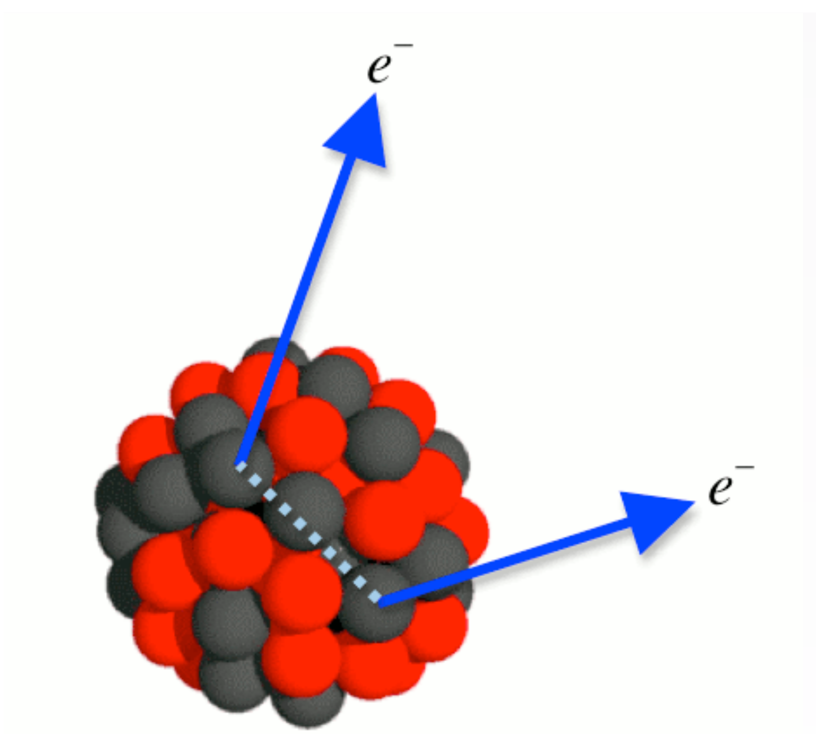


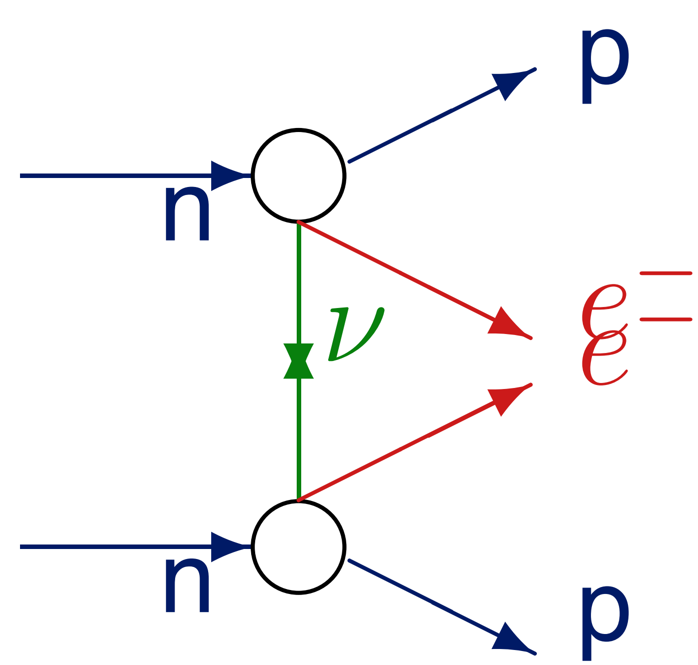
Thanks to R. Saakyan, talk at NuPhys 2014

This process has a special role in the study of neutrino properties as it probes lepton number violation and can provide information on neutrino masses and (possibly) on CP-violation.



Neutrinoless double beta decay proceeds in nuclei in which single beta decay is kinematically forbidden but double beta decay (A, Z) → (A, Z+2) + 2 e + 2 ν is allowed.





At the fundamental level, exchange of light Majorana neutrino (or other exotic mechanism).

The half-life time depends on neutrino properties

$$\left[T^{1/2}_{0\nu}(0^+ \rightarrow 0^+)\right]^{-1} \propto |M_F - g_A^2 M_{GT}|^2 \, |<m>|^2$$

- $|\langle m \rangle| = m_{ee}$: the effective Majorana mass parameter

$$| < m > | \simeq |m_1 \sin^2\theta_{12} + m_2 \cos^2\theta_{12} e^{i\alpha_{21}} + m_3 \sin^2\theta_{13} e^{i\alpha_{31}}$$

Mixing angles (known)

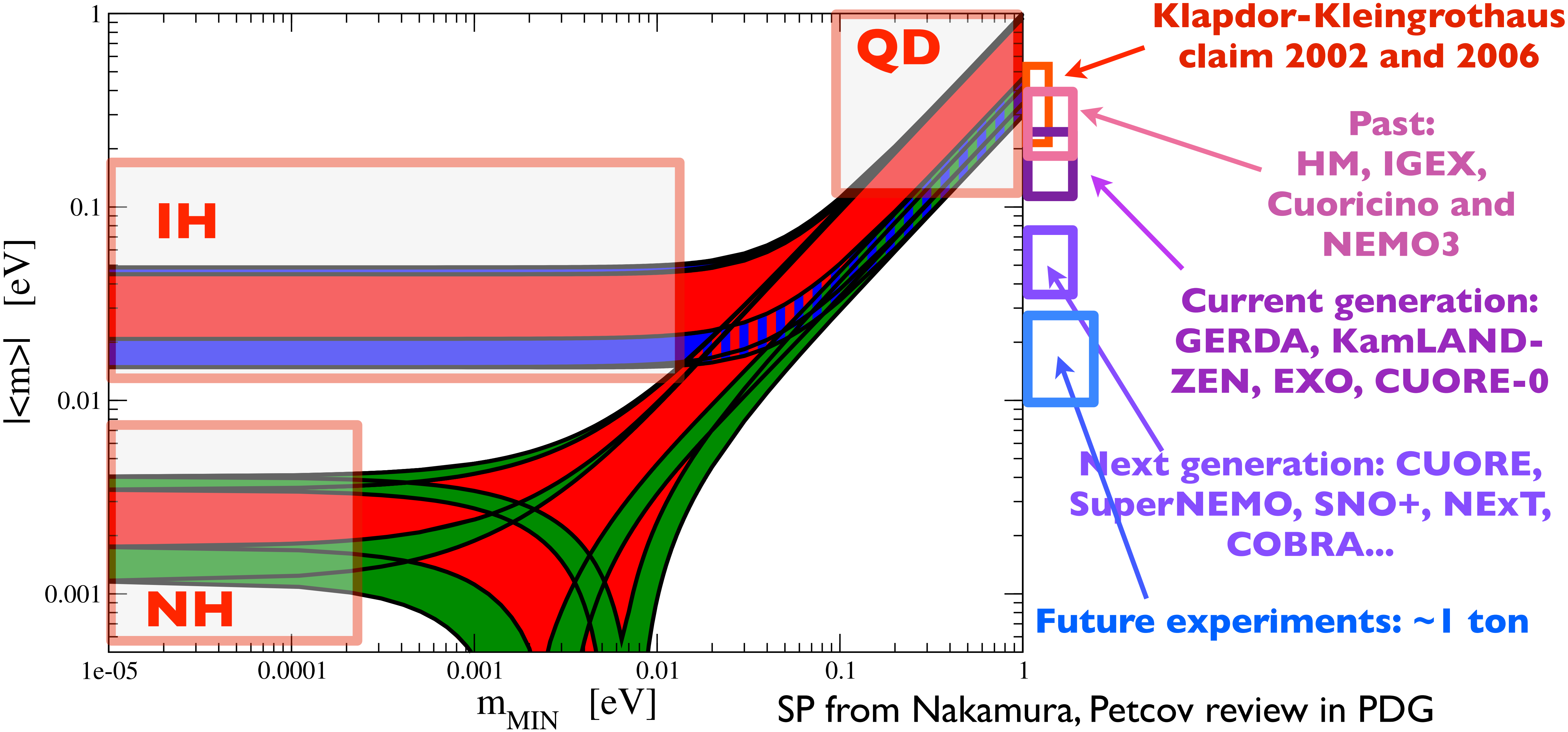
CPV phases (unknown)

Masses (partially known)

- $|M_F - g_A^2 M_{GT}|^2$: the nuclear matrix elements. They need to be computed theoretically.

Example: QD (m1~m2~m3): $44\ \text{meV} < |\langle m\rangle| < m_1$

$$|\langle m\rangle| \simeq m_{\bar{\nu}_e}\left|\left(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}}\right)\cos^2\theta_{13} + \sin^2\theta_{13} e^{i\alpha_{31}}\right|$$

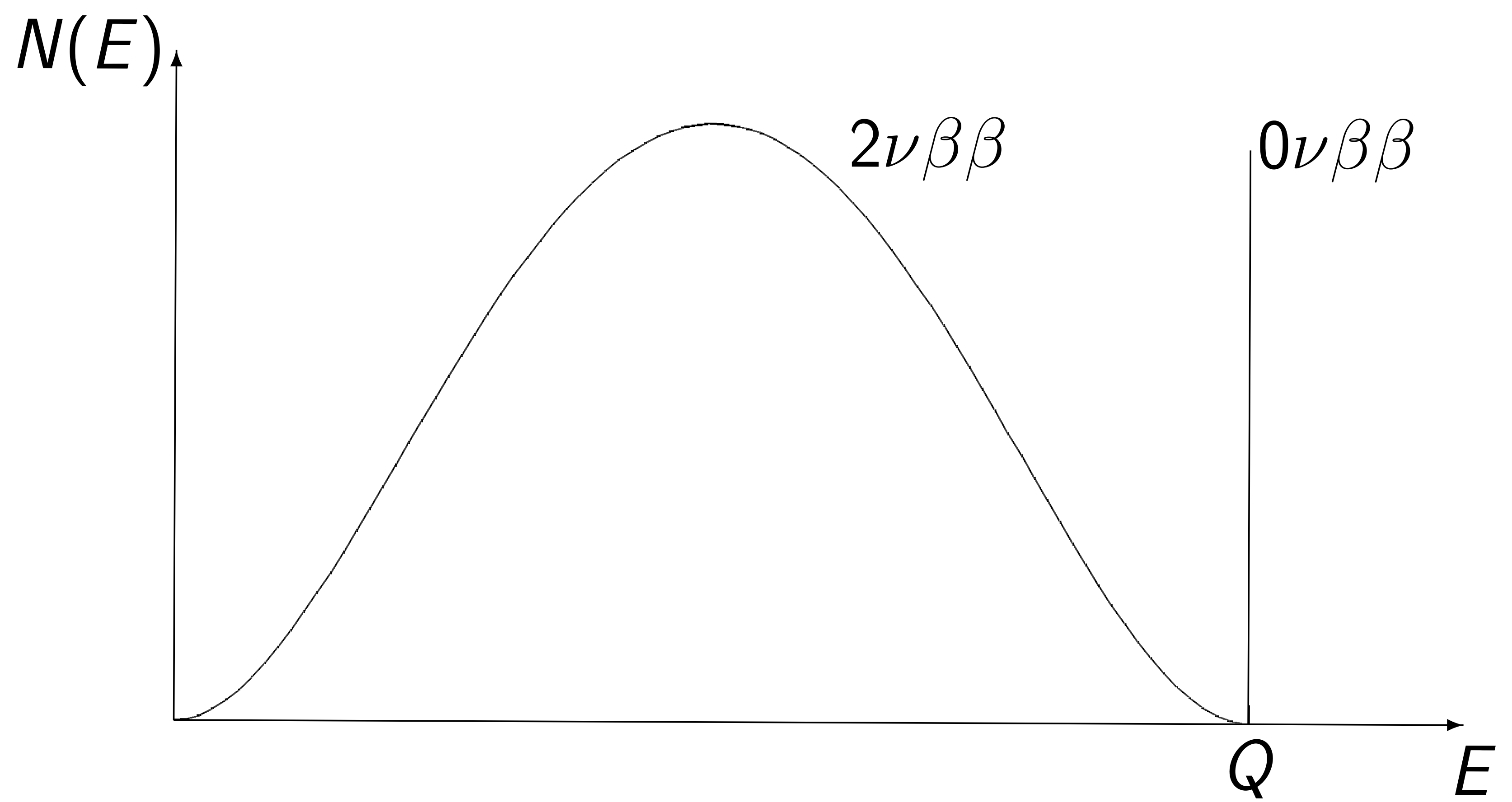


SP from Nakamura, Petcov review in PDG

Wide experimental program for the future: **a positive signal would indicate that L is violated!**

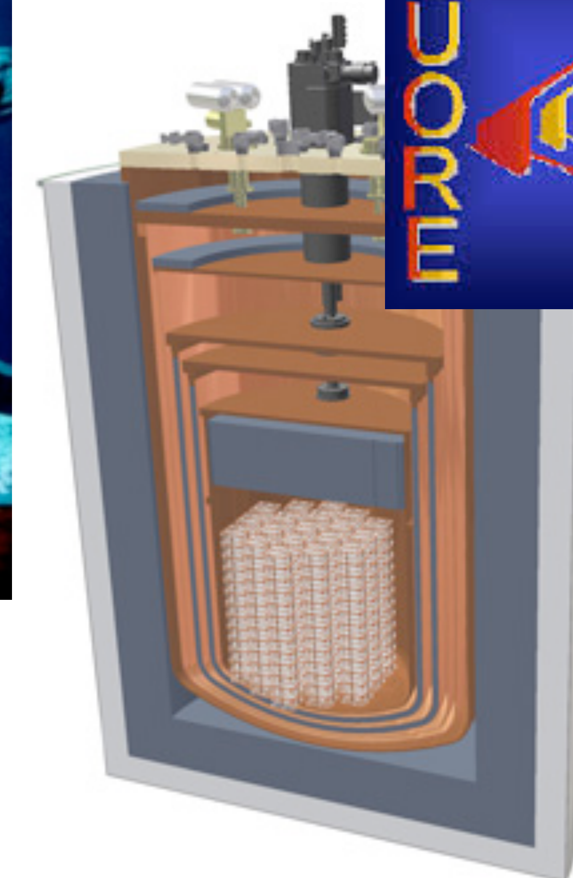
Experimental searches of betabeta decay

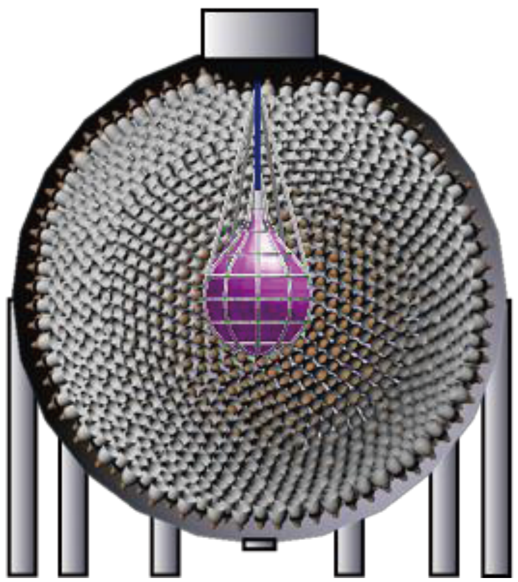
One looks for a tiny peak at the end point of the 2-electron spectrum in the decay.

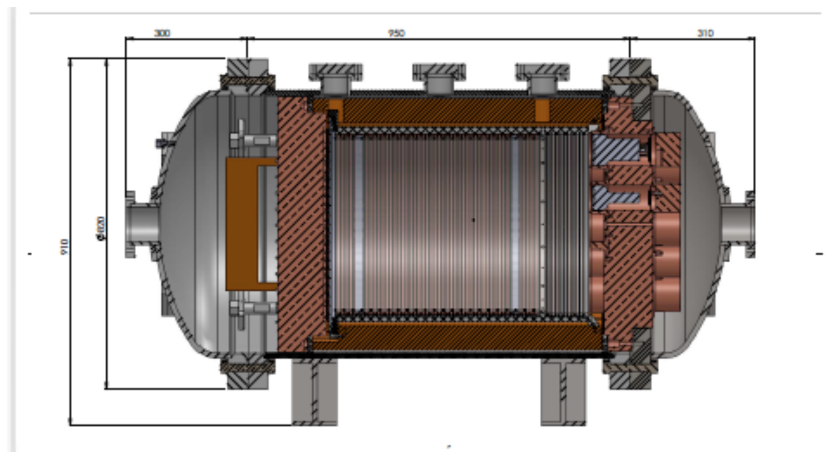


Requirements:

- Rare process -> large mass
- low backgrounds -> deep underground
- 2vbb background -> excellent energy resolution





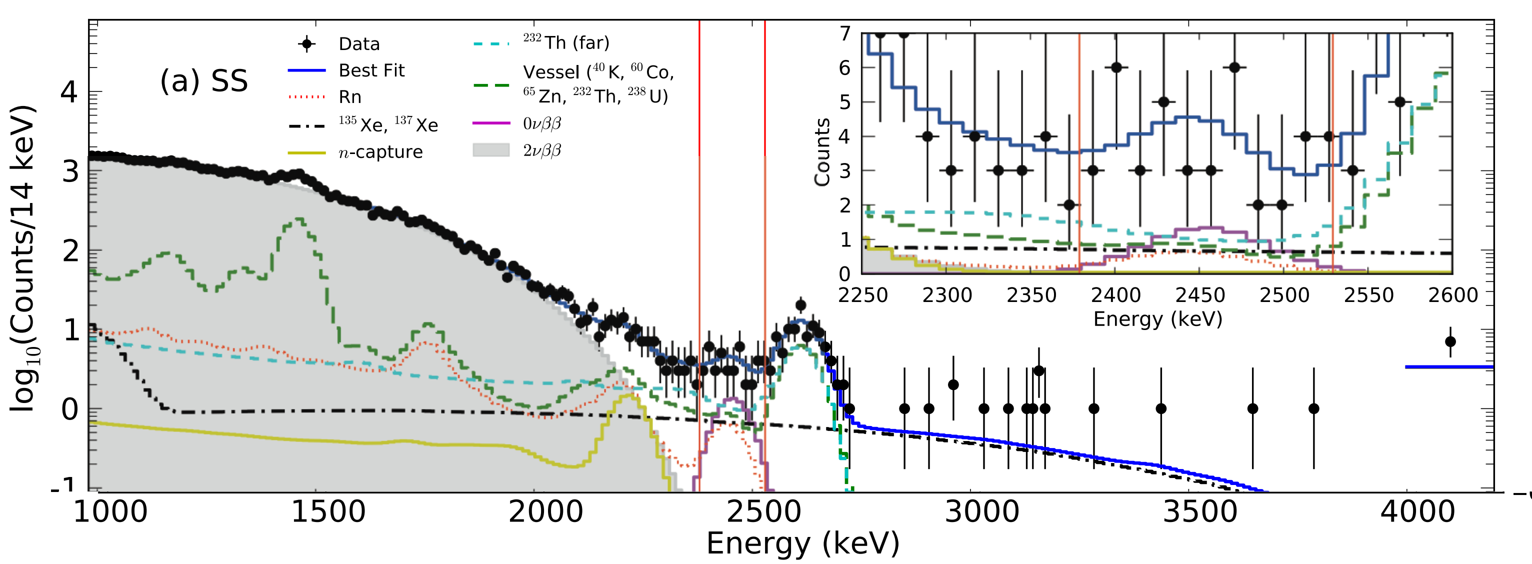


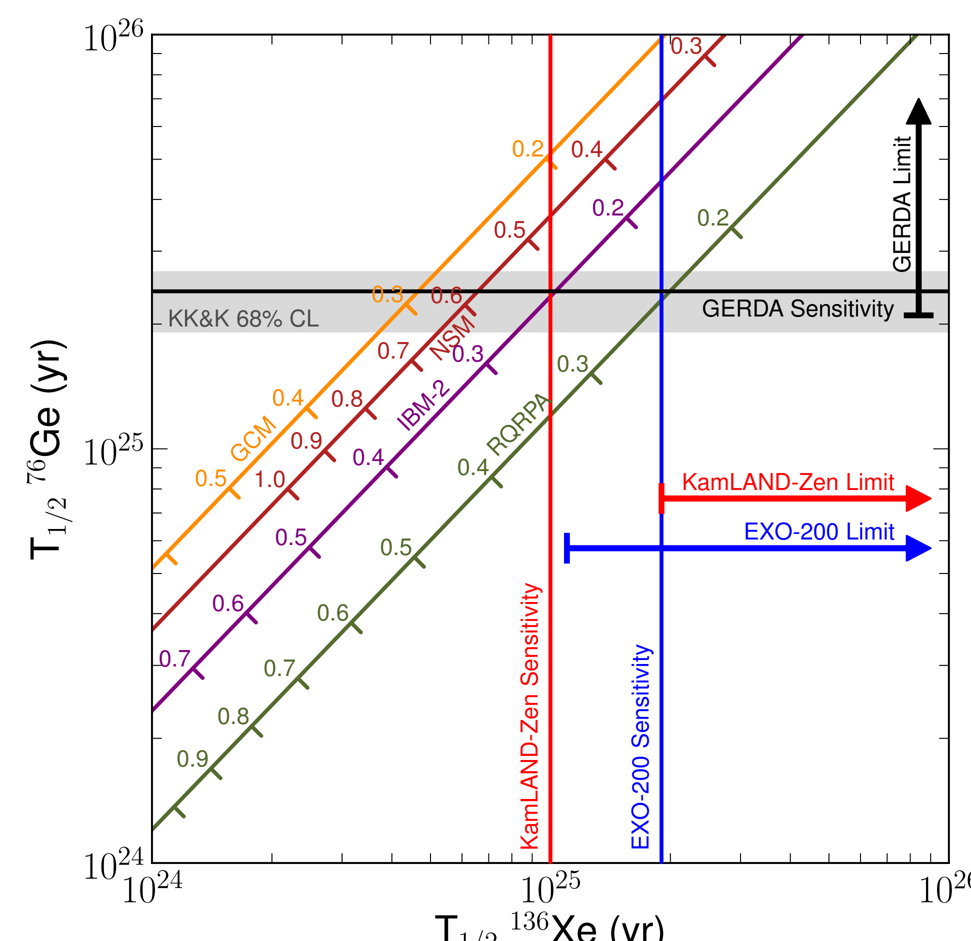
NEXT
5ton of Xe
now 10 kg

crio.mib.infn.it

KamLAND-Zen

EXO-200 Nature 510 (2014) 229.





Experiment	Isotope(s)	Technique	Main characteristics
NEMO-3	Mo100+6other	Tracking + calorimeter	Bckg rejection, isotope choice,
SuperNEMO	Se82, Nd150,	Tracking + calorimeter	Bckg rejection, isotope choice,
CUORE	Te130	Bolometers	Energy resolution, efficiency
LUCIFER	Se82	Scintillating bolometers	Energy resolution, efficiency
AMoRE	Mo100	Scintillating bolometers	Energy resolution, efficiency
GERDA	Ge76	Ge diodes	Energy resolution, eficiency
Majorana	Ge76	Ge diodes	Energy resolution, efficiency
COBRA	Te130, Cd116	CdZnTe semi-conductors	Efficiency, particle ID
EXO	Xe136	TPC ionisation + scintil.	Mass, efficiency, particle ID
MOON	Mo100	Tracking + calorimeter	Compactness, Bckg rejection
CANDLES	Ca48	CaF	Efficiency, Active background
SNO+	Te130	Te loaded liquid scintillator	Mass, efficiency
XMASS	Xe136	Liquid Xe	Mass, efficiency
CARVEL	Ca48	CaWO4 scintillating	Mass, efficiency
Yangyang	Sn124	Sn loaded liquid scintillator	Mass, efficiency
DCBA	Nd150	Gaseous TPC	Bckg rejection
KamLAND-Zen	Xe136	Xenon balloon	Mass, efficiency
NEXT	Xe136	Gaseous TPC	Bckg rejection, efficiency

Thanks to R. Saakyan, talk at NuPhys 2014

The new generation of experiments is already taking data (EXO, KamLAND-ZEN, CUORE, GERDA,...) and more powerful ones are planned (e.g., NExT, SNO+, SuperNEMO, Majorana,...)!!

Absolute values of neutrino masses

Neutrino oscillations are not sensitive to the absolute mass scale. However, via matter effects they can establish the mass ordering.

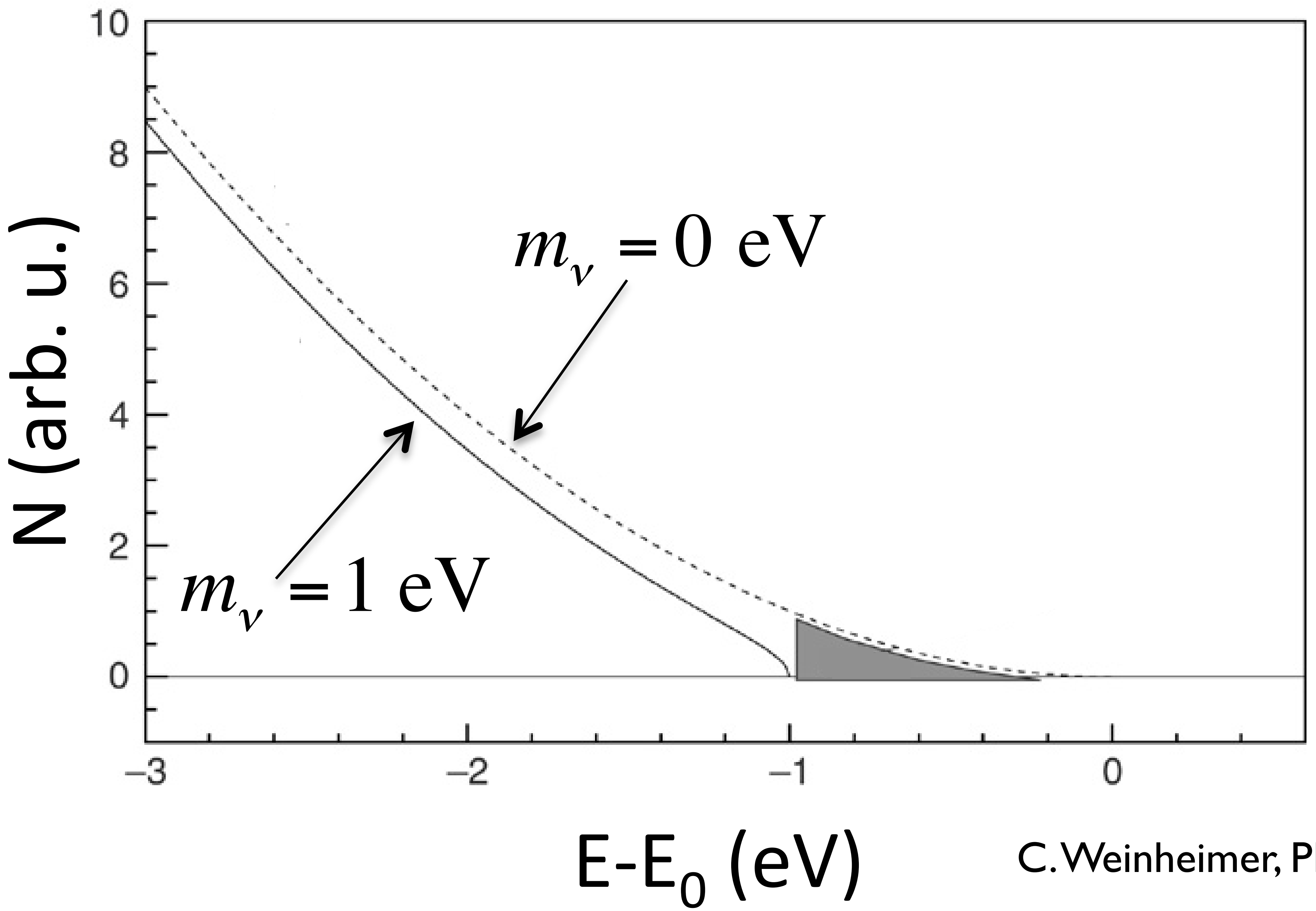
- Direct mass searches in beta decays: model-independent but feasible only for QD spectrum.

- Neutrinoless double beta decay: if dominant mechanism is light neutrino masses.

- Neutrino masses from cosmology by probing the DM distribution (observing the distribution of biased tracers and/or gravitational lensing)

Direct mass measurements

The electron spectrum in beta decays is affected close to the end point by neutrino masses as

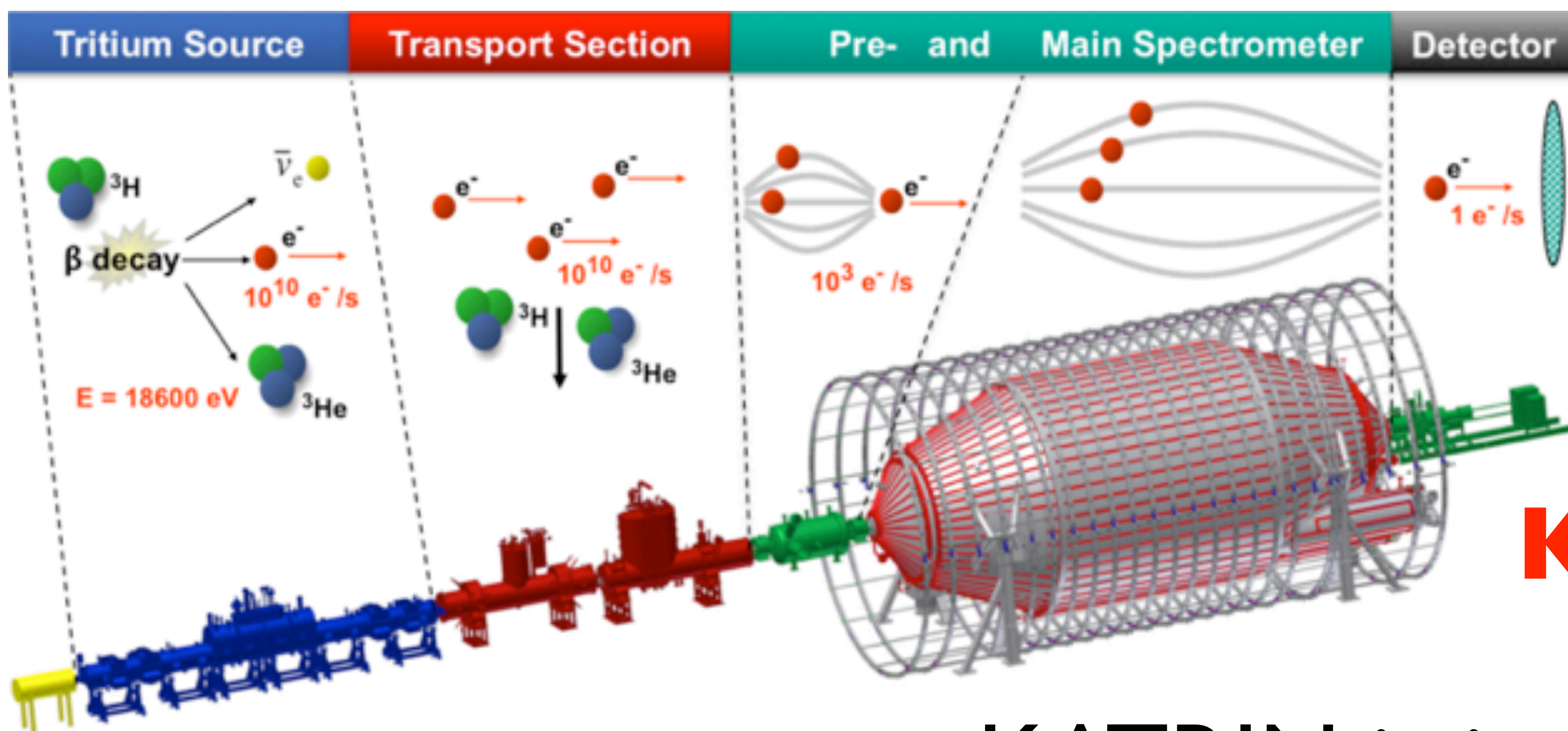


C. Weinheimer, PNPP 2006

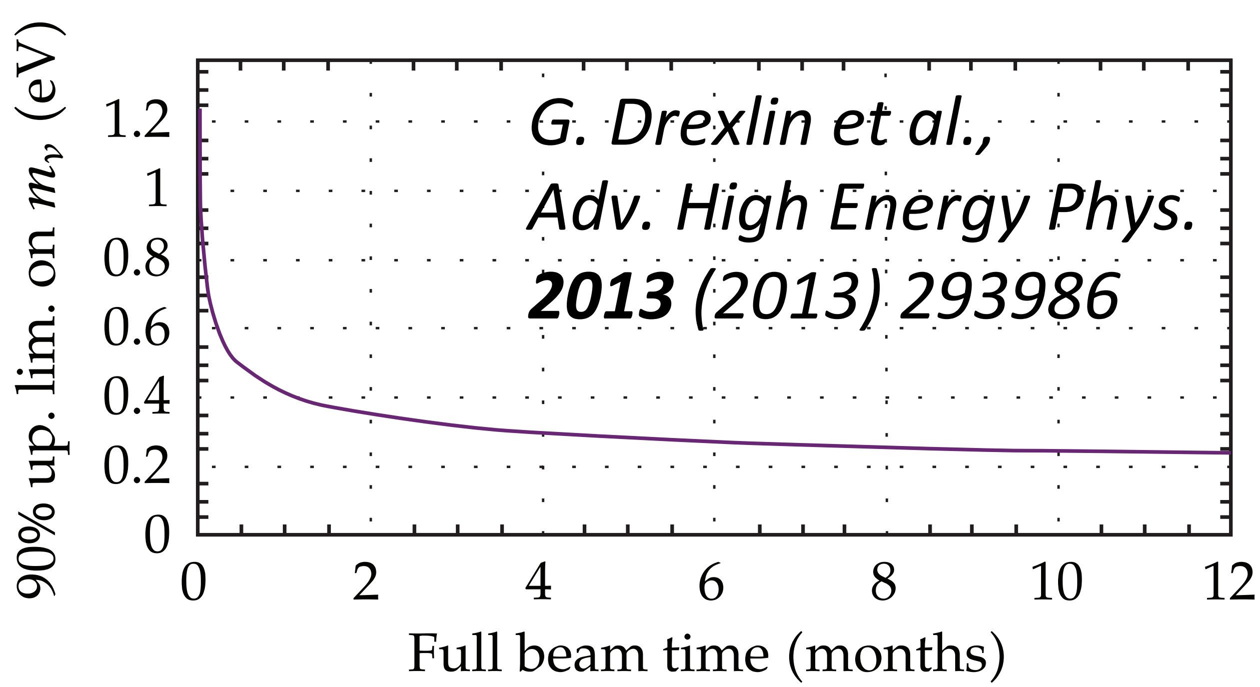
Troitsk and Mainz provide the most stringent limit:

$m_0 < 2.3$ eV (at 95% CL) $m_0 < 2.05$ eV

Kraus et al., EPJC 40 — Aseev et al., PRD 84



KATRIN



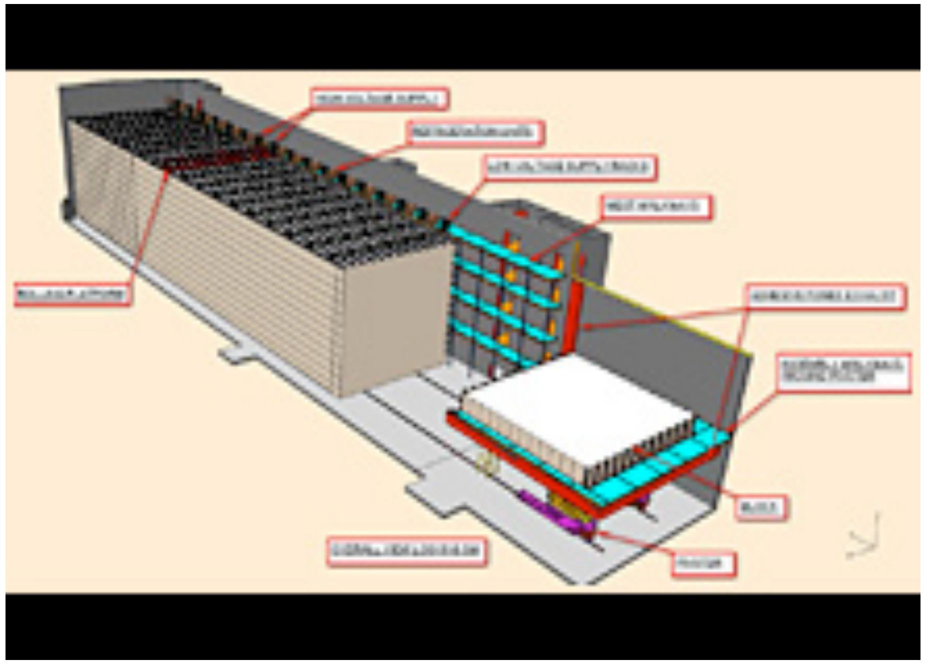
KATRIN is in the commissioning phase. Data taking will start in 2016. It will reach a sensitivity to m<0.2 eV and a 5-sigma discovery of m=0.35 eV.

How can we search for the mass ordering and leptonic CP-violation?

How can we search for the mass ordering and leptonic CP-violation?

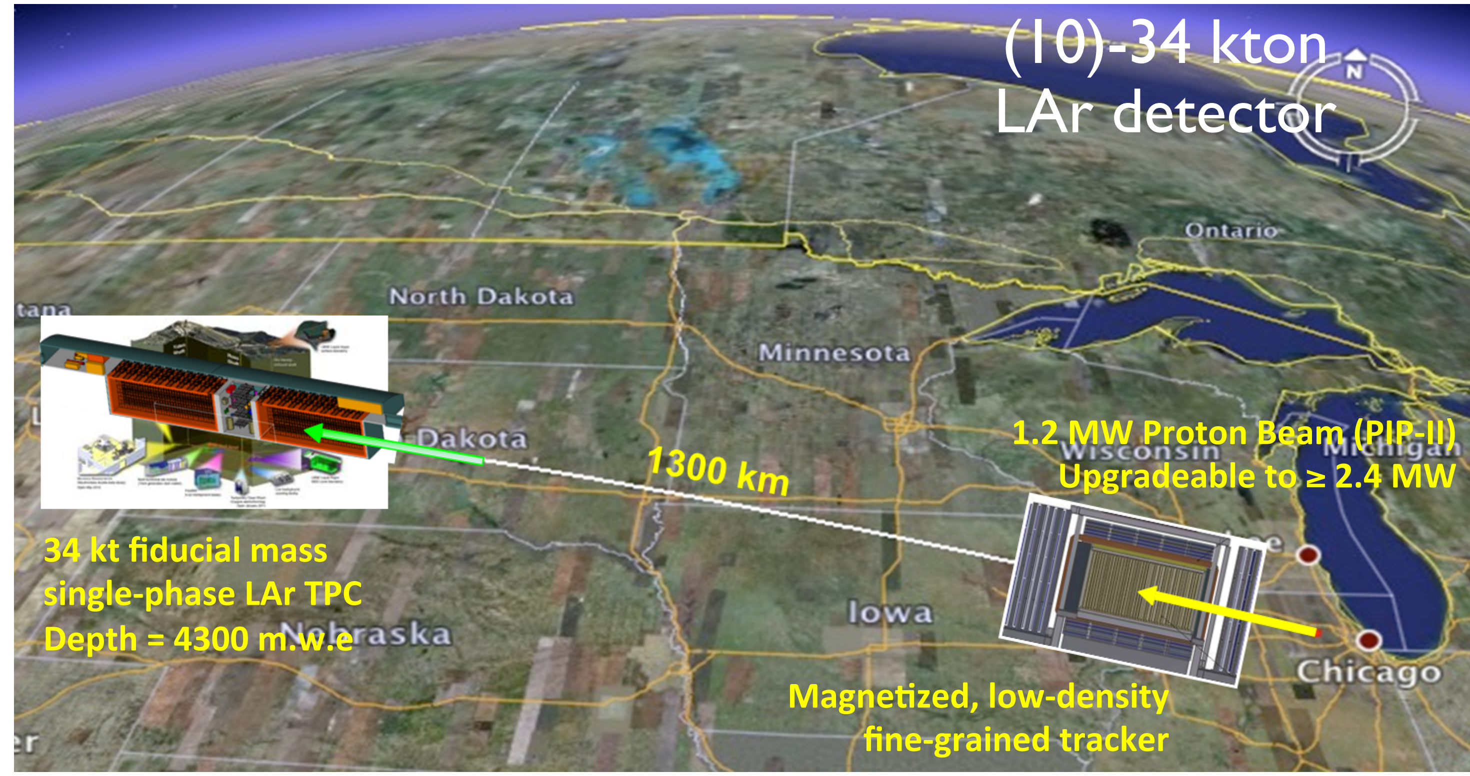
- Long-baseline neutrino oscillation experiments
- Reactor neutrinos
- Atmospheric neutrinos
- Neutrinoless double beta decay
- Daedalus...

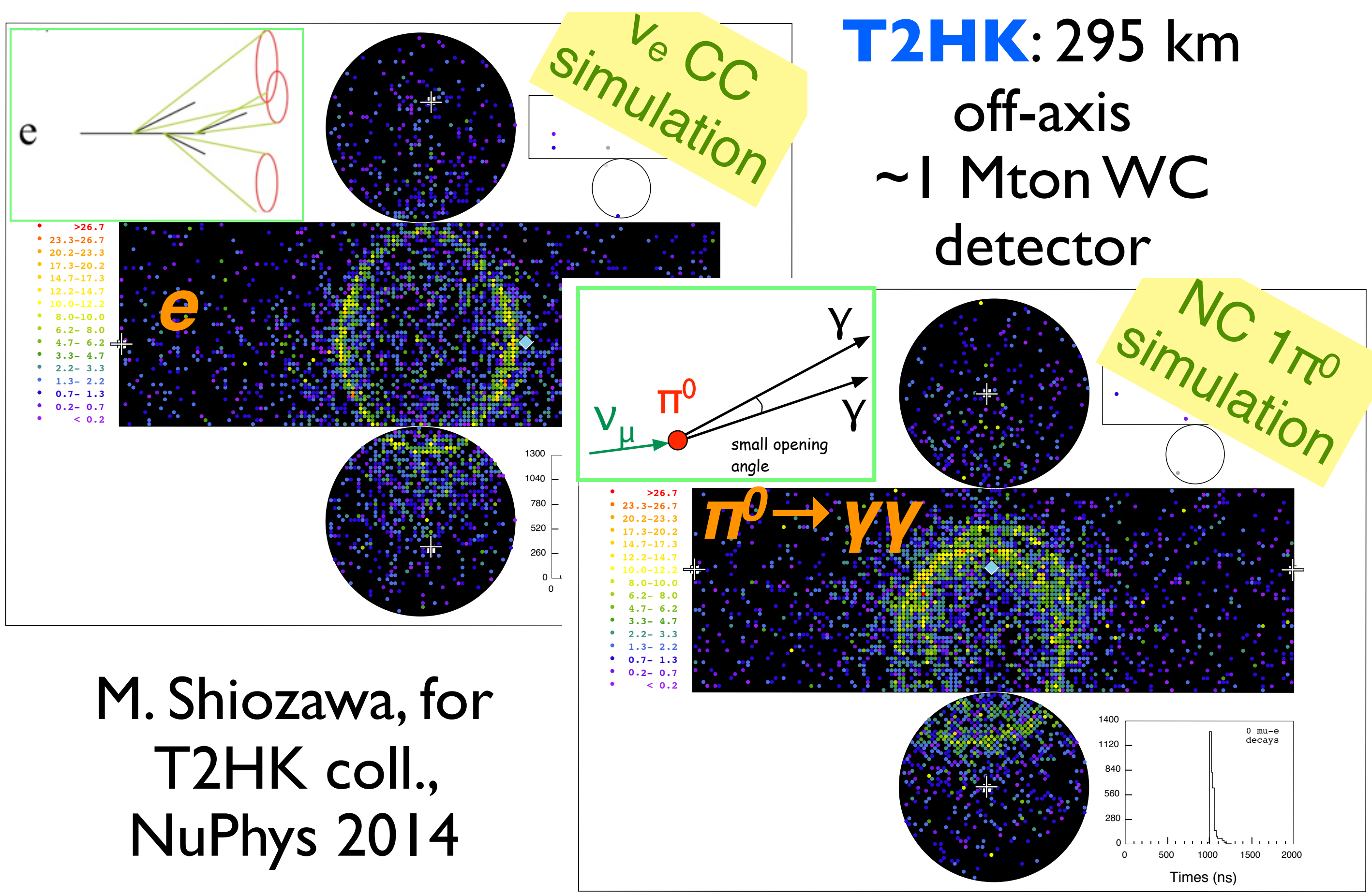
Future LBL exp



NOvA: 810 km off-axis
~14 kton plastic scintillator detector
T2K: 295 km off-axis
~22.5 kton WC detector

ELBNF: 1300 km on-axis
(10)-34 kton LAr detector

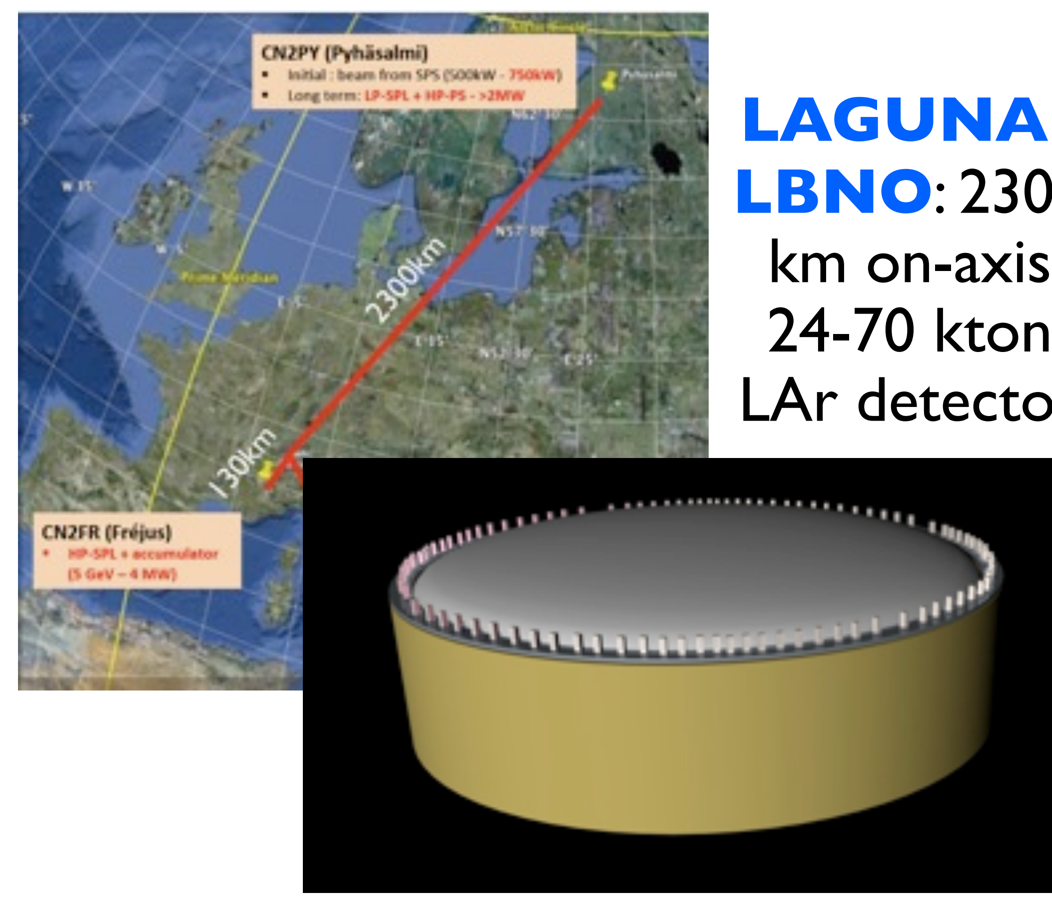




T2HK: 295 km off-axis
~1 Mton WC detector

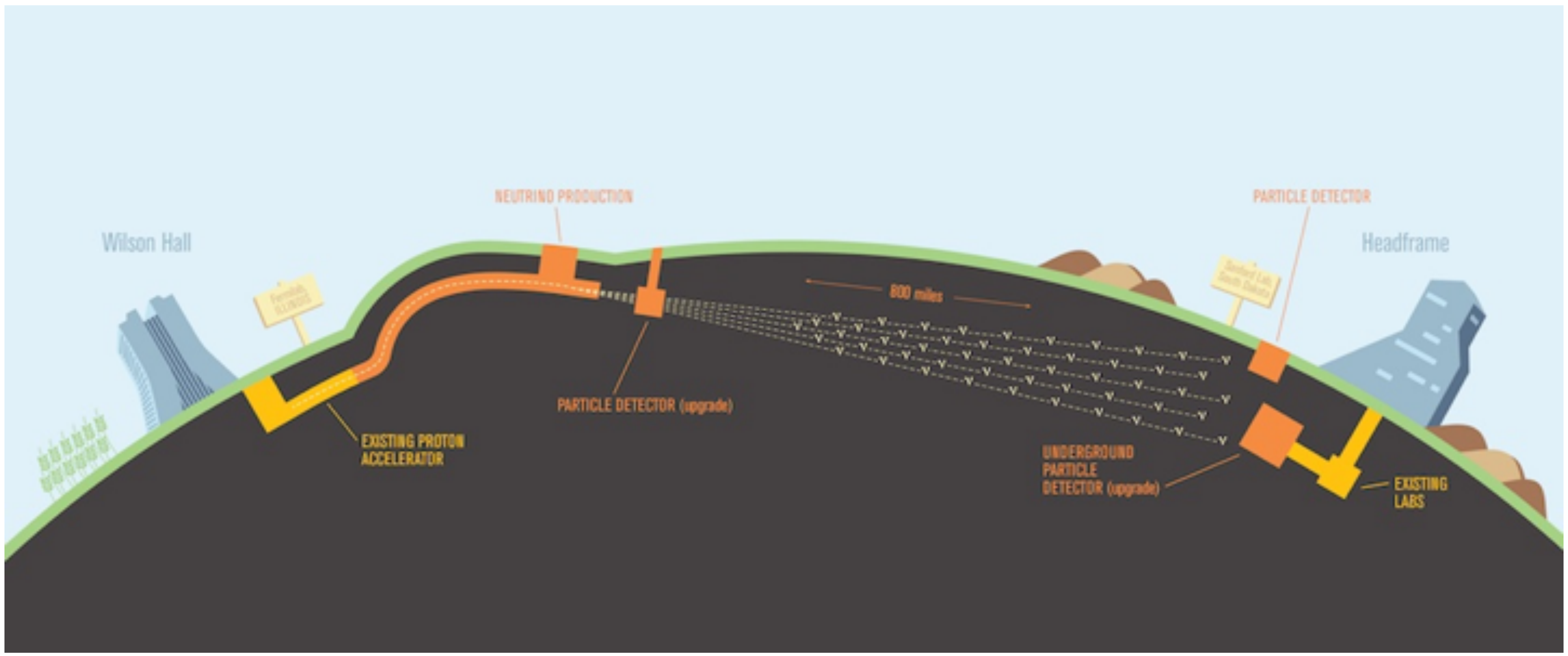
M. Shiozawa, for T2HK coll., NuPhys 2014

LAGUNA-LBNO: 2300 km on-axis
24-70 kton LAr detector



Long-baseline oscillations and MO

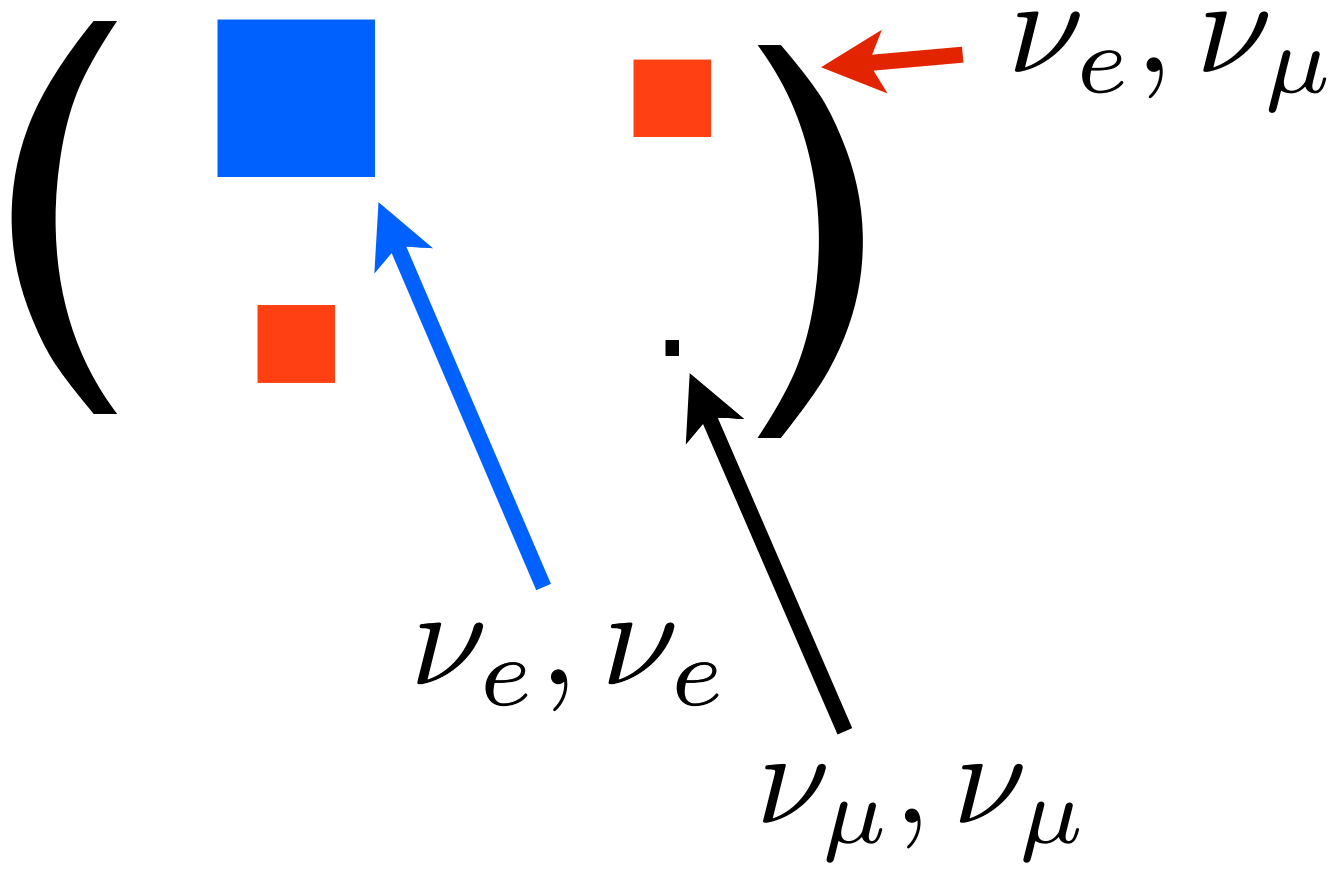
- When neutrinos travel through a medium, they interact with the background of e, p, n and get an effective mass.

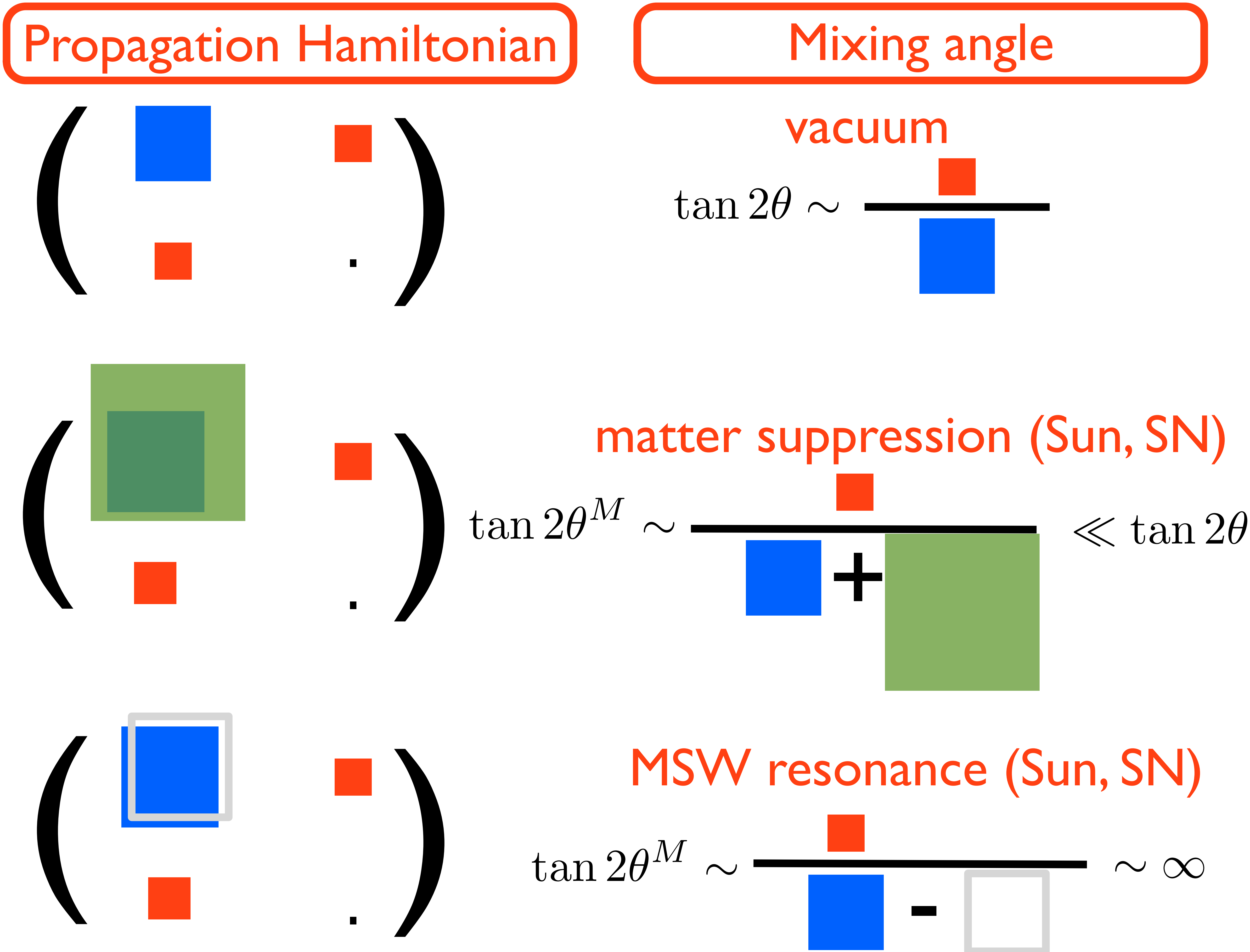


Credit: Symmetry magazine

- Typically the background is CP and CPT violating, e.g. the Earth and the Sun contain only electrons, protons and neutrons, and the resulting oscillations are CP and CPT violating (different for neutrinos and antineutrinos).

Propagation Hamiltonian in the flavour basis



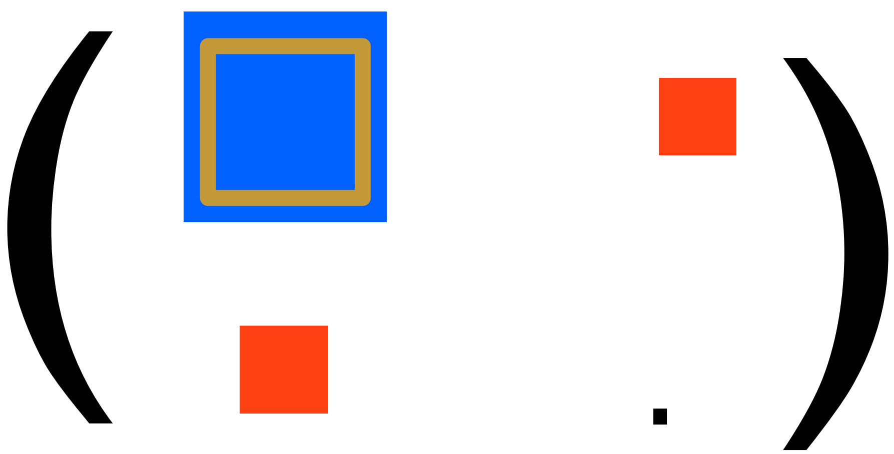

Propagation Hamiltonian
Mixing angle
vacuum
tan 2θ ~
matter suppression (Sun, SN)
tan 2θ^M ~
≪ tan 2θ
MSW resonance (Sun, SN)
tan 2θ^M ~
~ ∞

In long baseline experiments

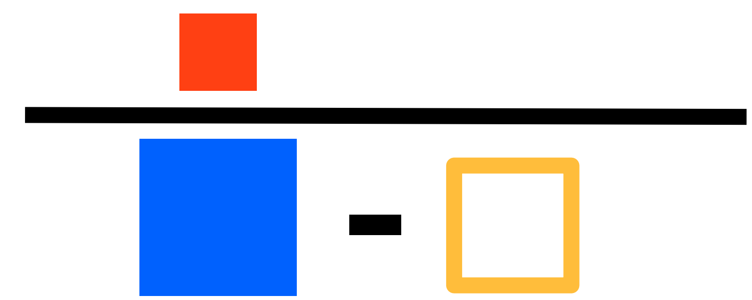
 $\frac{\Delta m^2}{2E}\cos(2\theta)$ ν $-\sqrt{2}G_F N_e$ $\bar{\nu}$ $+\sqrt{2}G_F N_e$

$$P_{\nu_\mu \to \nu_e} = \sin^2\theta_{23}\sin^2 2\theta_{13}^m \sin^2\frac{\Delta_{13}^m L}{2}$$

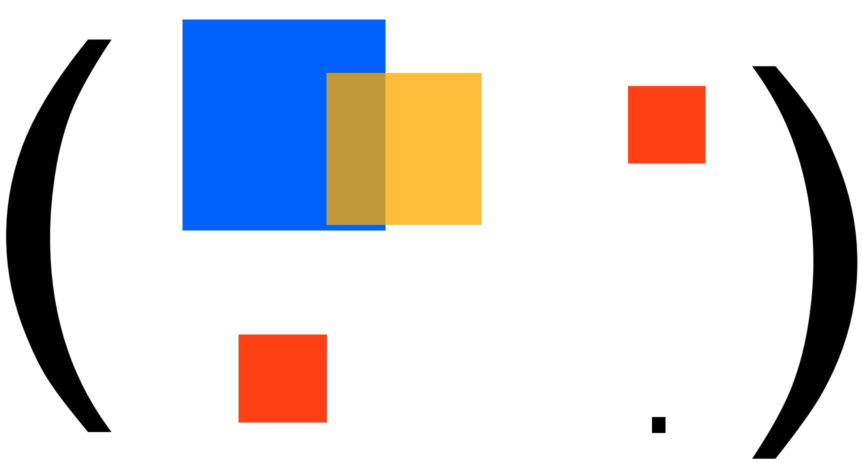
For neutrinos



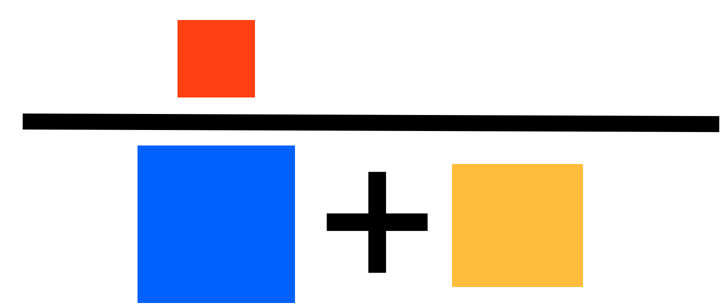
$\Delta m^2 > 0$ P enhancement

$\tan 2\theta^M \sim$ 

For antineutrinos



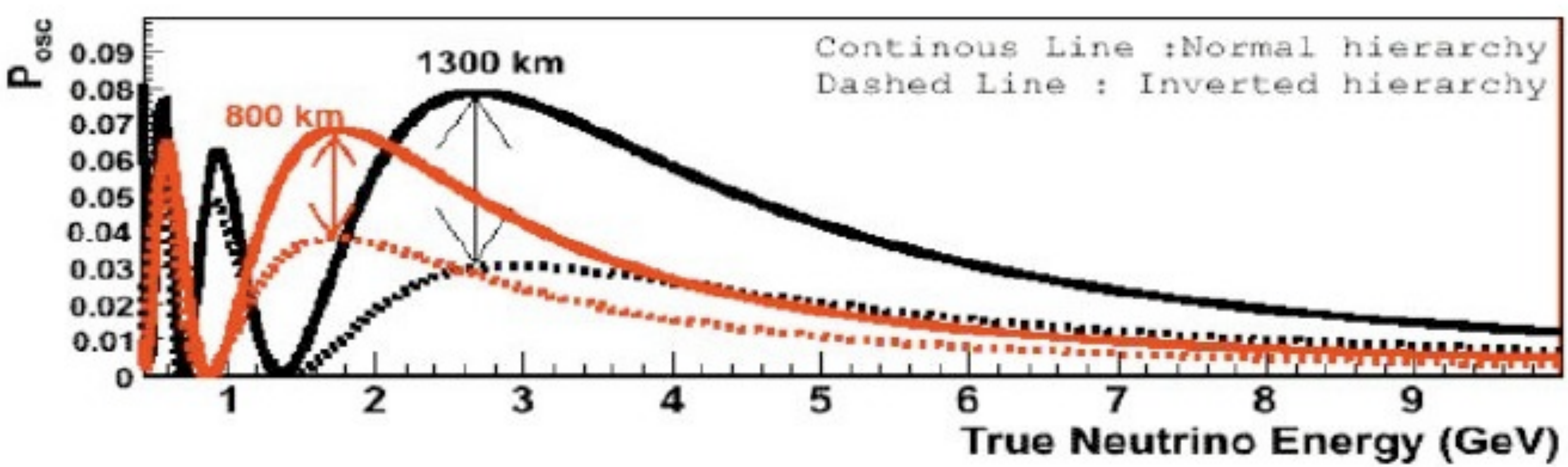
$\Delta m^2 > 0$ P suppression

$\tan 2\theta^M \sim$ 

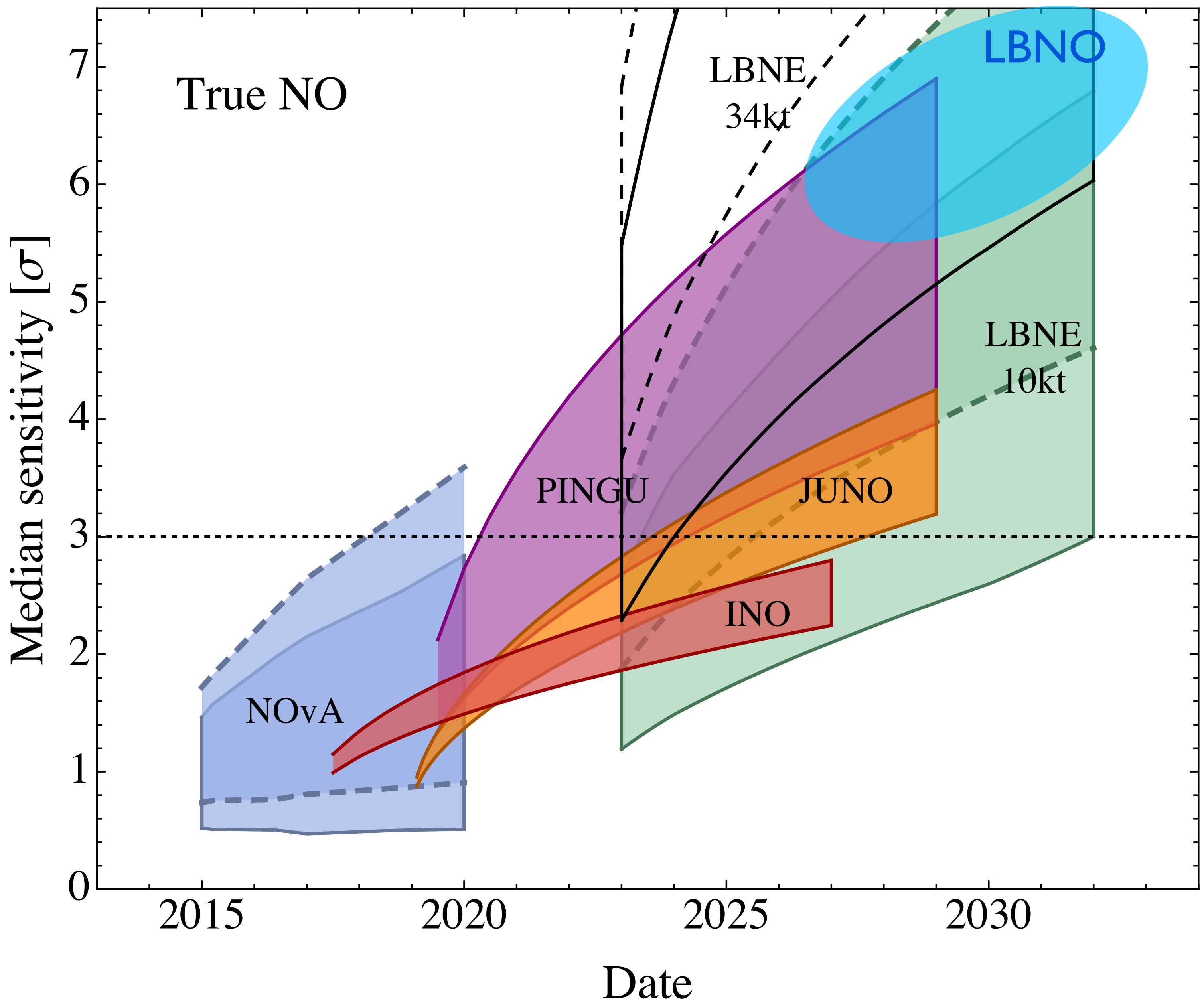
Matter effects modify the oscillation probability in LBL experiments.

The probability enhancement happens for

- neutrinos if $\Delta m^2 > 0$
- antineutrinos if $\Delta m^2 < 0$



Matter effects are stronger at high energies and at longer baselines.



Blennow, Coloma, Huber, Schwetz, 1311.1822

	Long baseline beam (e. g. LBNE)	Atmospheric (e. g. PINGU)	Reactor long baseline
Benefit	Robust, clean signal	Predictable timescale/cost	Independent technology
Risk (osc. params.)	δ_{CP}, θ_{23}	θ_{23}	-
Challenges	Timescale	Energy res., directional res., particle ID	Energy resolution!!!

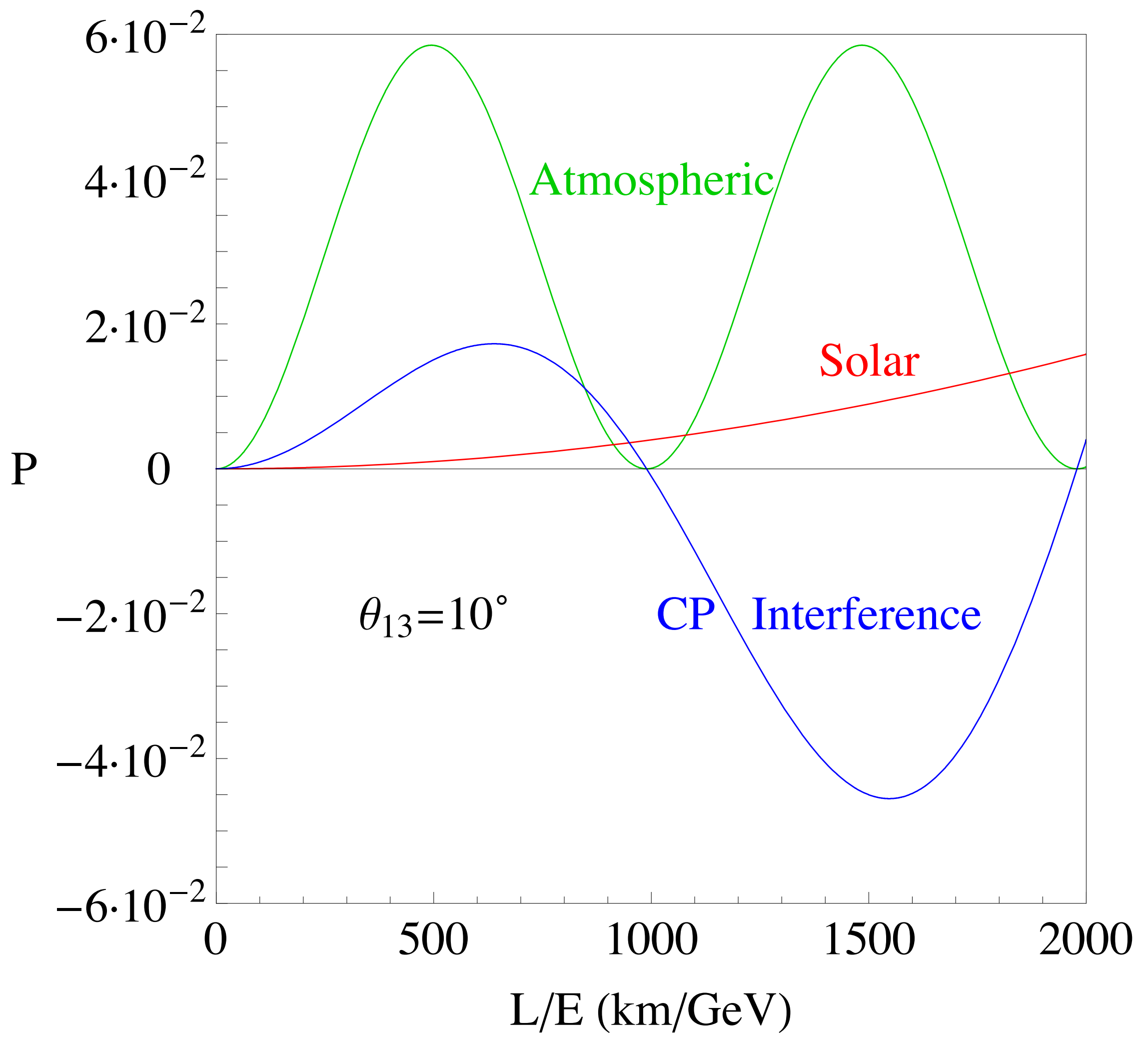
From W. Winter's talk at Neutrino 2014

CP-violation in LBL experiments

CP-violation will manifest itself in neutrino oscillations:

$$P(\nu_\mu \to \nu_e; t) - P(\bar{\nu}_\mu \to \bar{\nu}_e; t) =$$

$$= 4 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \left[\sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{23}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \right]$$



- Large theta13 makes its searches possible but not ideal.
- Degeneracies with the mass hierarchy.
- CPV effects are more pronounced at low energy.

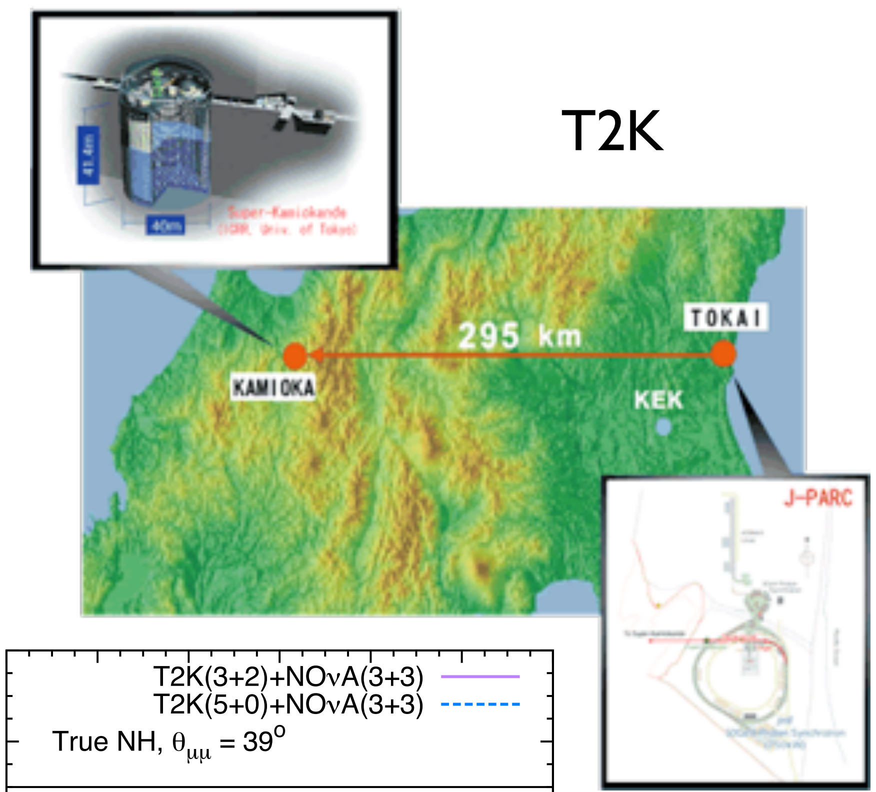
Figure from P. Coloma, E. Fernandez-Martinez, JHEP1204

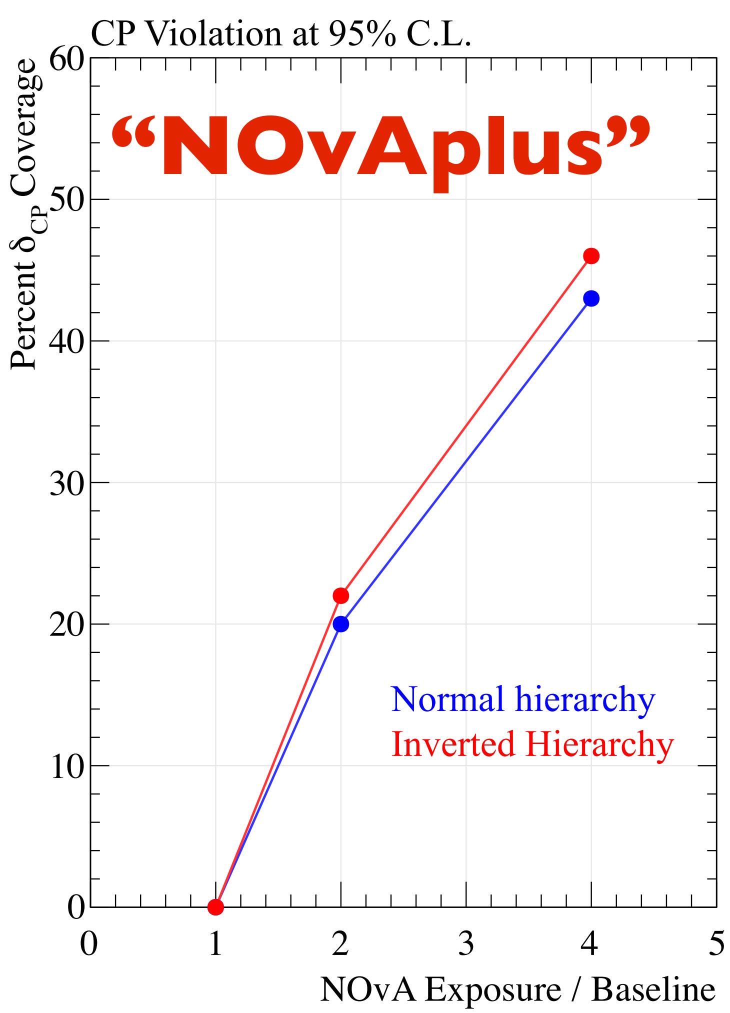
CPV Searches

Category	Experiment	Status	Oscillation parameters
Accelerator	MINOS+ [74]	Data-taking	MH/CP/octant
Accelerator	T2K [21]	Data-taking	MH/CP/octant
Accelerator	NOvA [108]	Commissioning	MH/CP/octant
Accelerator	RADAR [76]	Design/ R&D	MH/CP/octant
Accelerator	CHIPS [75]	Design/ R&D	MH/CP/octant
Accelerator	LBNE [87]	Design/ R&D	MH/CP/octant
Accelerator	Hyper-K [97]	Design/ R&D	MH/CP/octant
Accelerator	LBNO [109]	Design/ R&D	MH/CP/octant
Accelerator	ESSνSB [110]	Design/ R&D	MH/CP/octant
Accelerator	DAEδALUS [111]	Design/ R&D	CP

WG Report: Neutrinos, de Gouvea (Convener) et al., 1310.4340

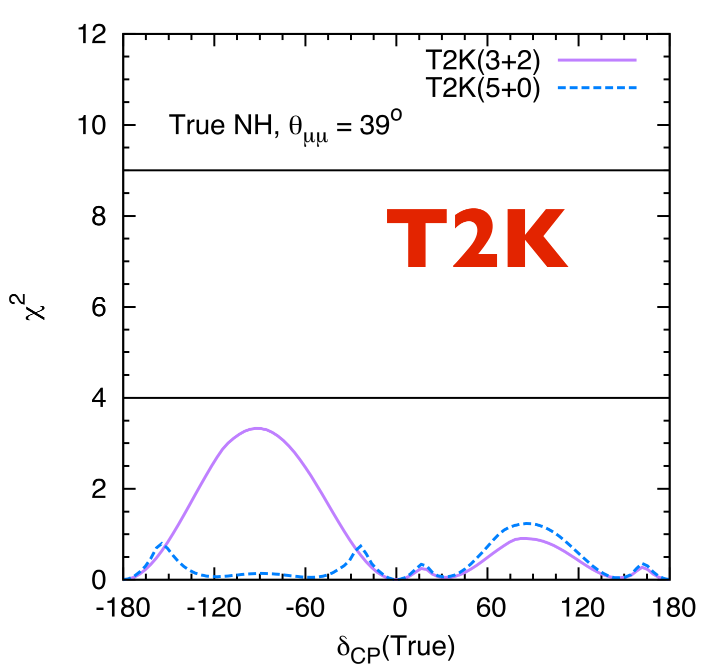
Near future: T2K and NOvA. Marginal sensitivity to CPV

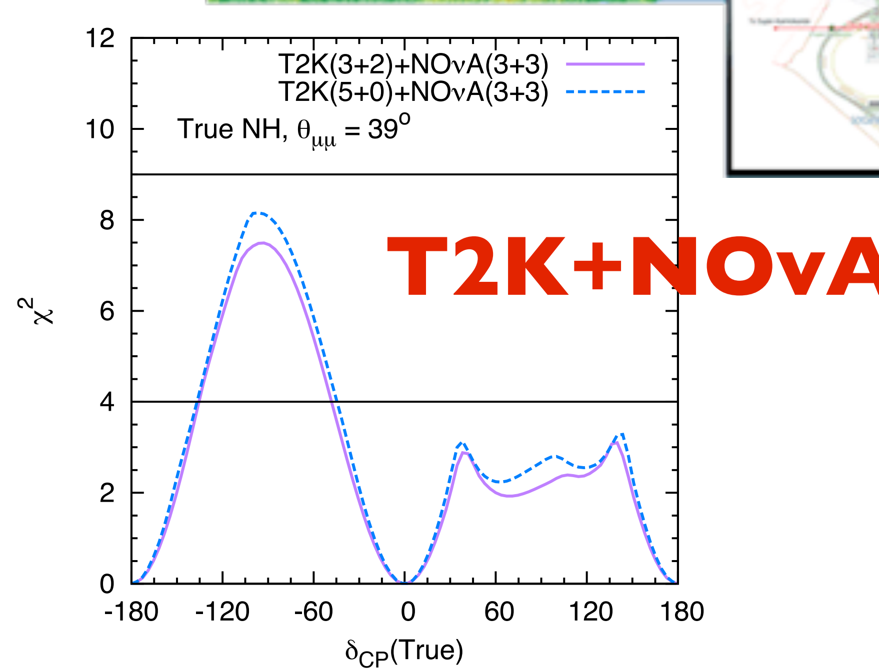




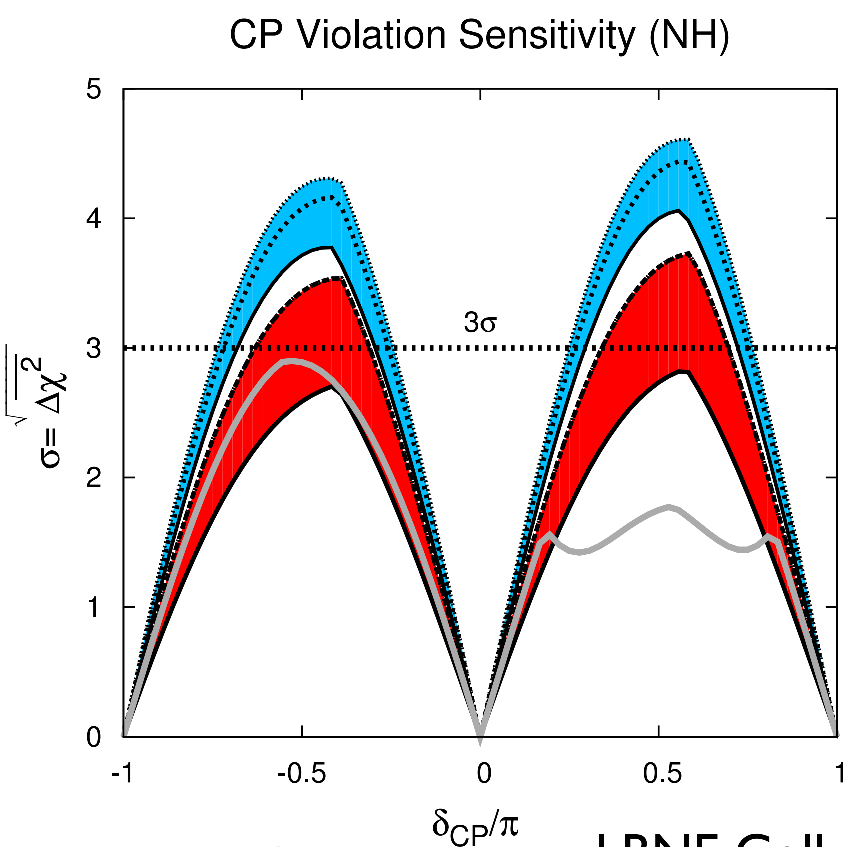
NOvA Coll., 1308.0106

M. Gosh et al., 1401.7243; see also Machado et al.; Huber et al.

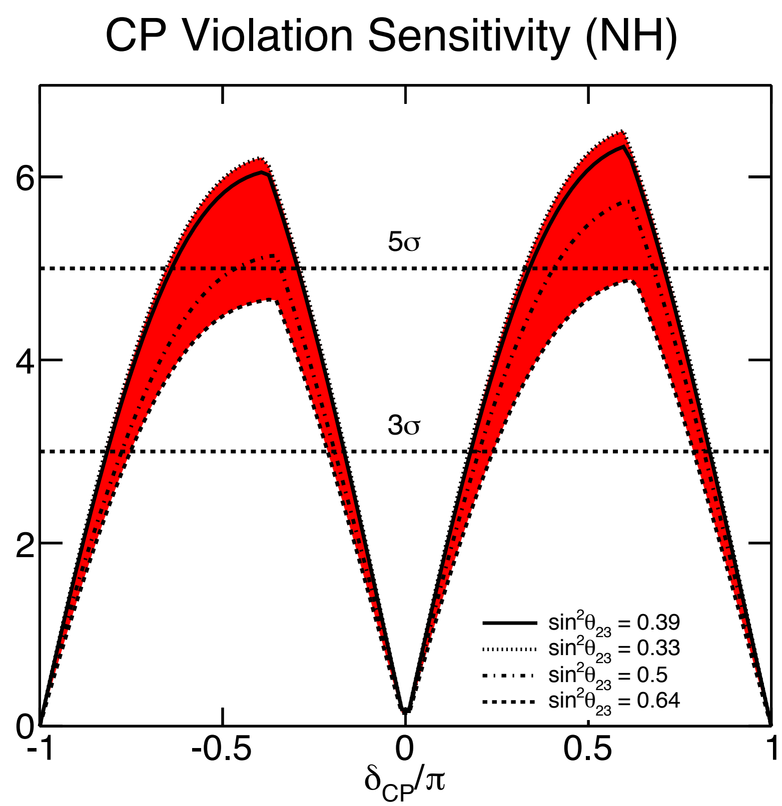




LBNE-10Kton

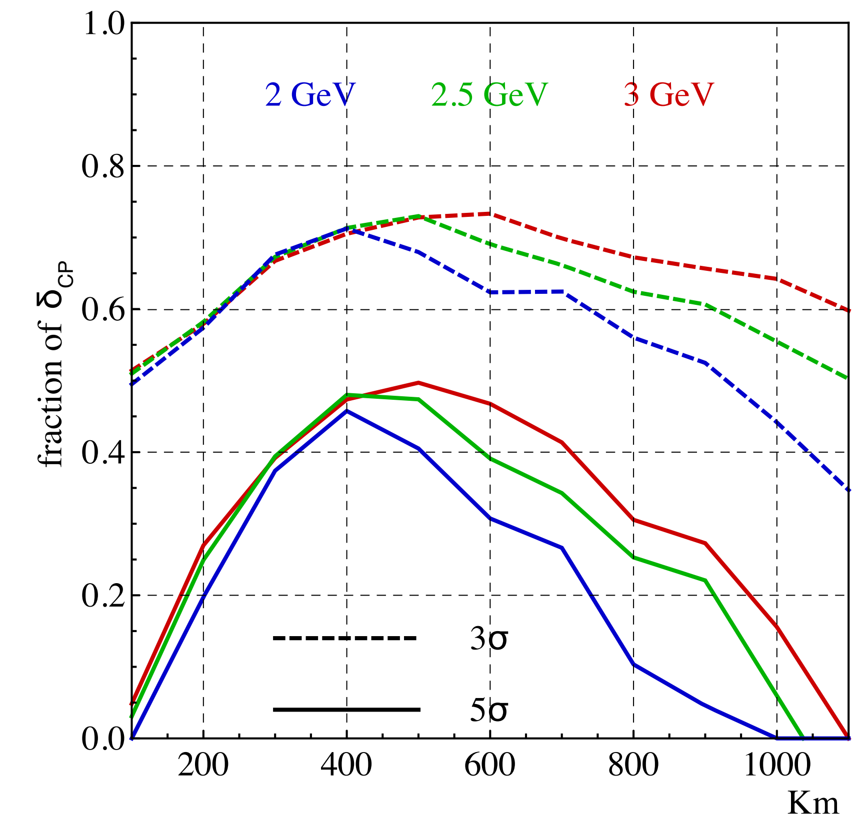


LBNE-34kton



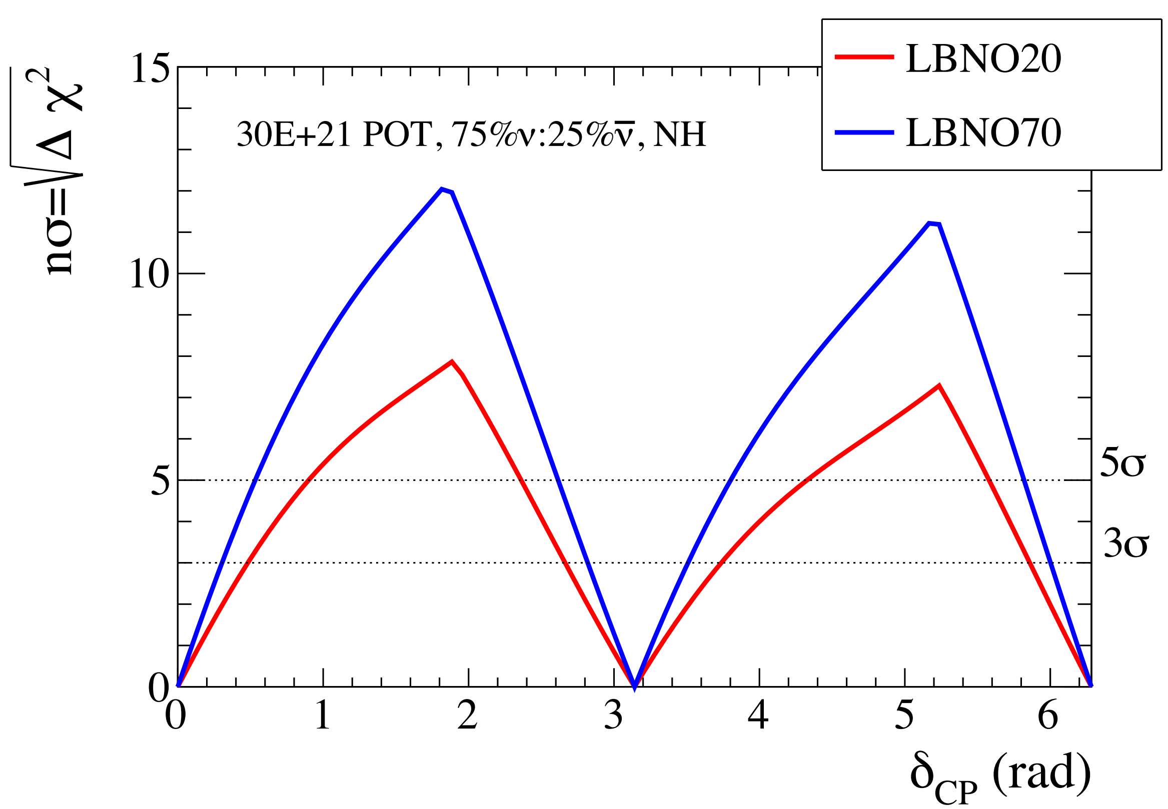
LBNE Coll., 1307.7335

ESSnuSB

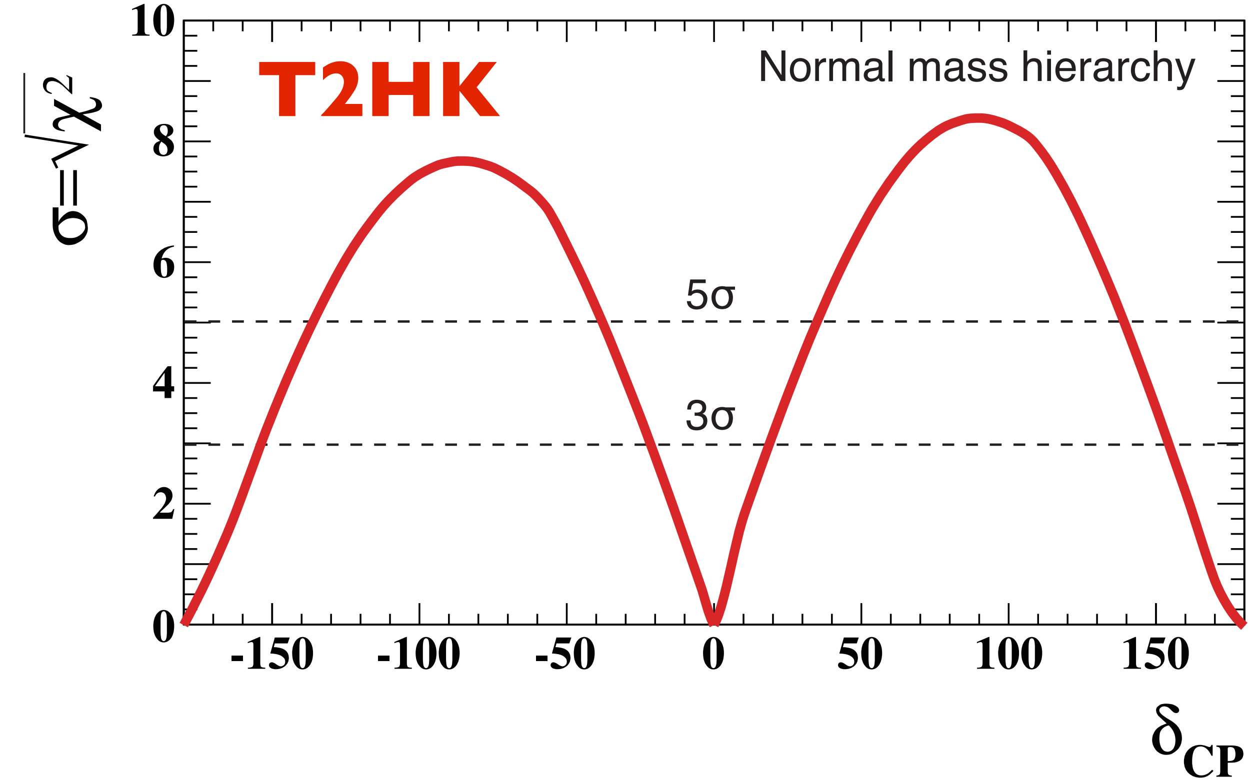


ESSnuSB, 1309.7022

LBNO

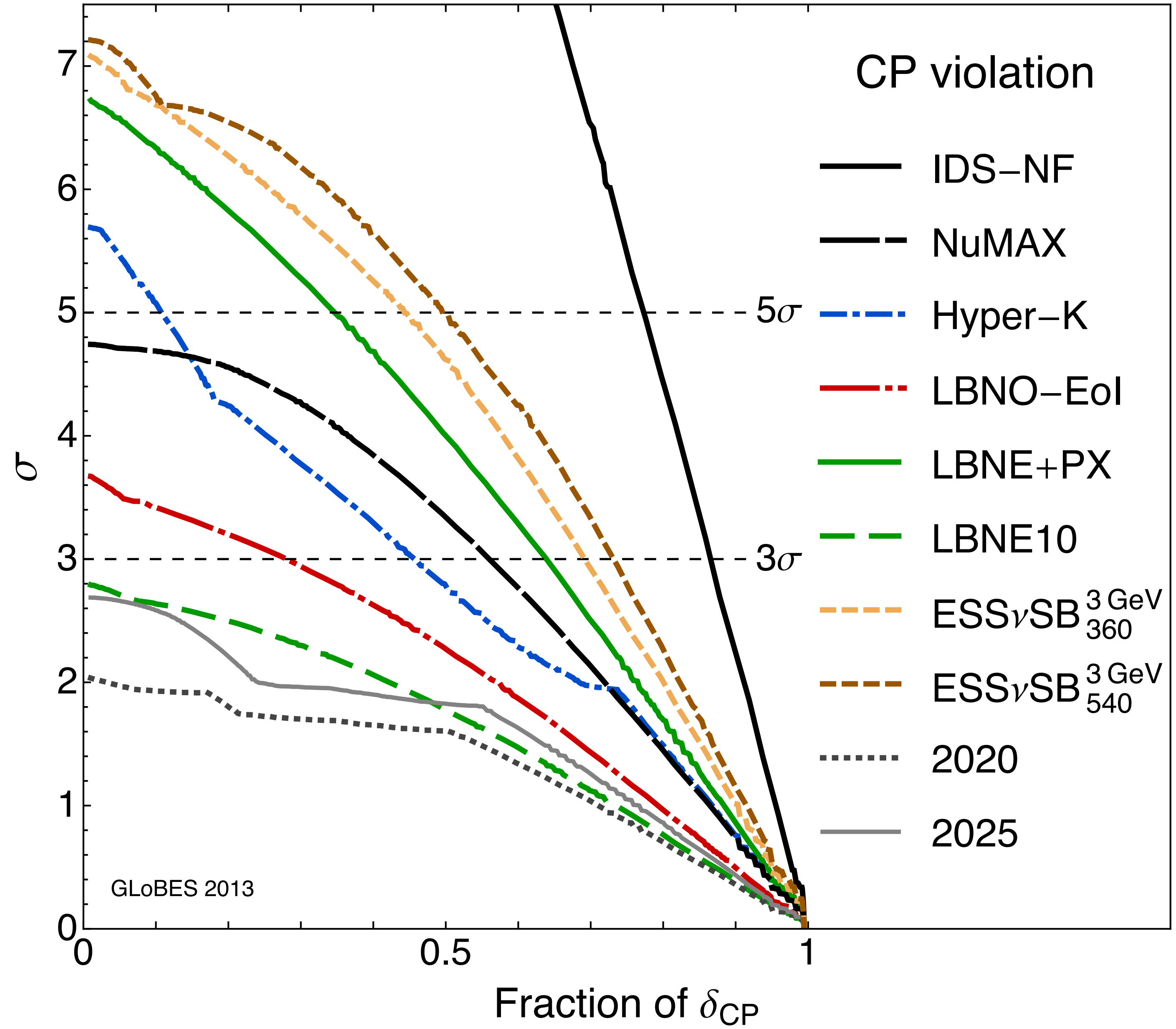


LAGUNA-LBNO, 1412.0593. See also 1312.6520



T2HK LoI, Abe et al., 1412.4673

NuFact

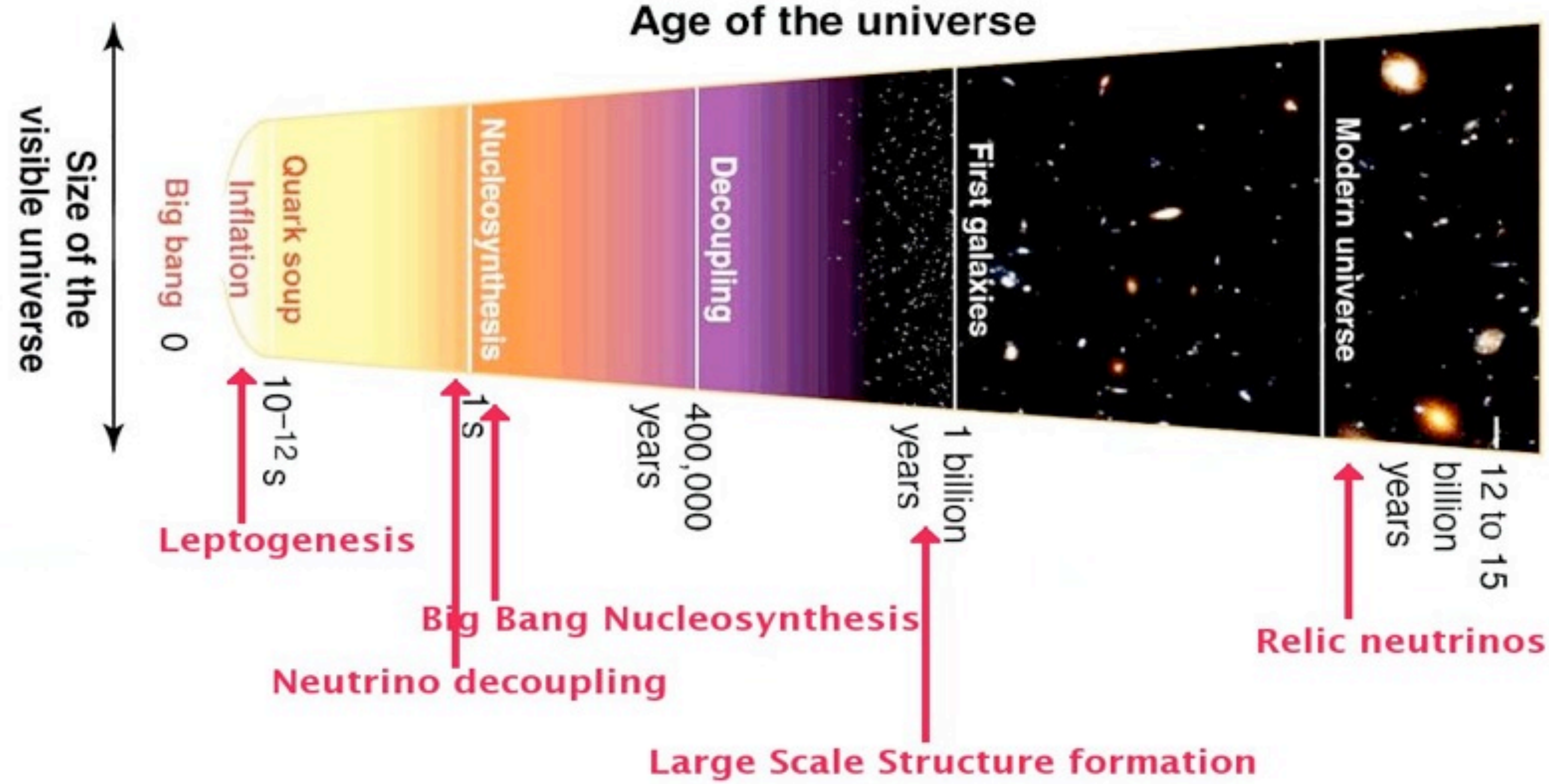


ESSnuSB, 1309.7022

Comparisons should be made with great care as they critically depend on:

- setup assumed: detector and its performance, beam and its optimisation...
- values of oscillation parameters and their errors;
- treatment of backgrounds and systematic errors.

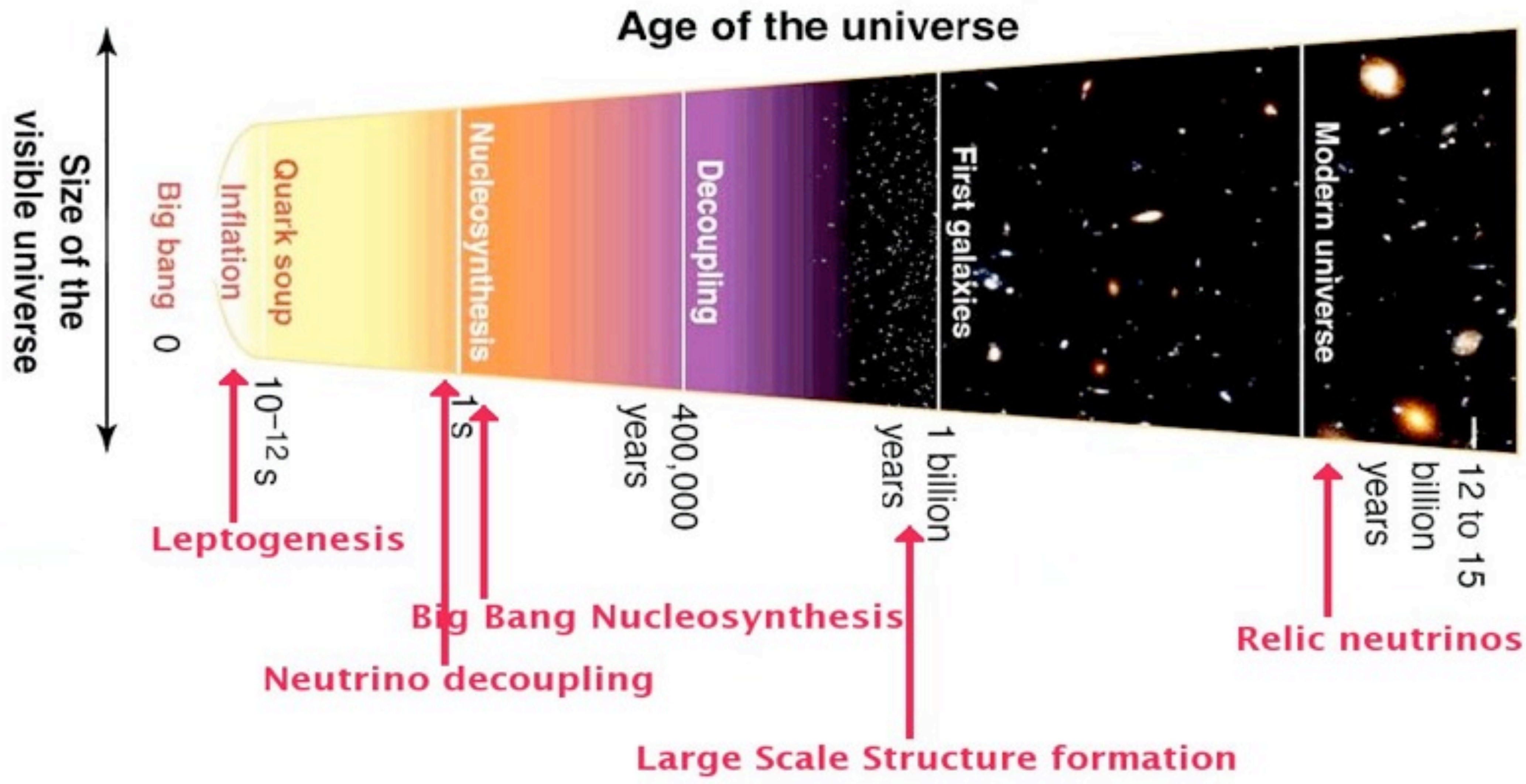
Neutrinos in cosmology



Neutrinos were in thermal equilibrium with thermal plasma at the beginning of the Universe. As their interactions got "too slow", they decoupled: T~1 MeV.

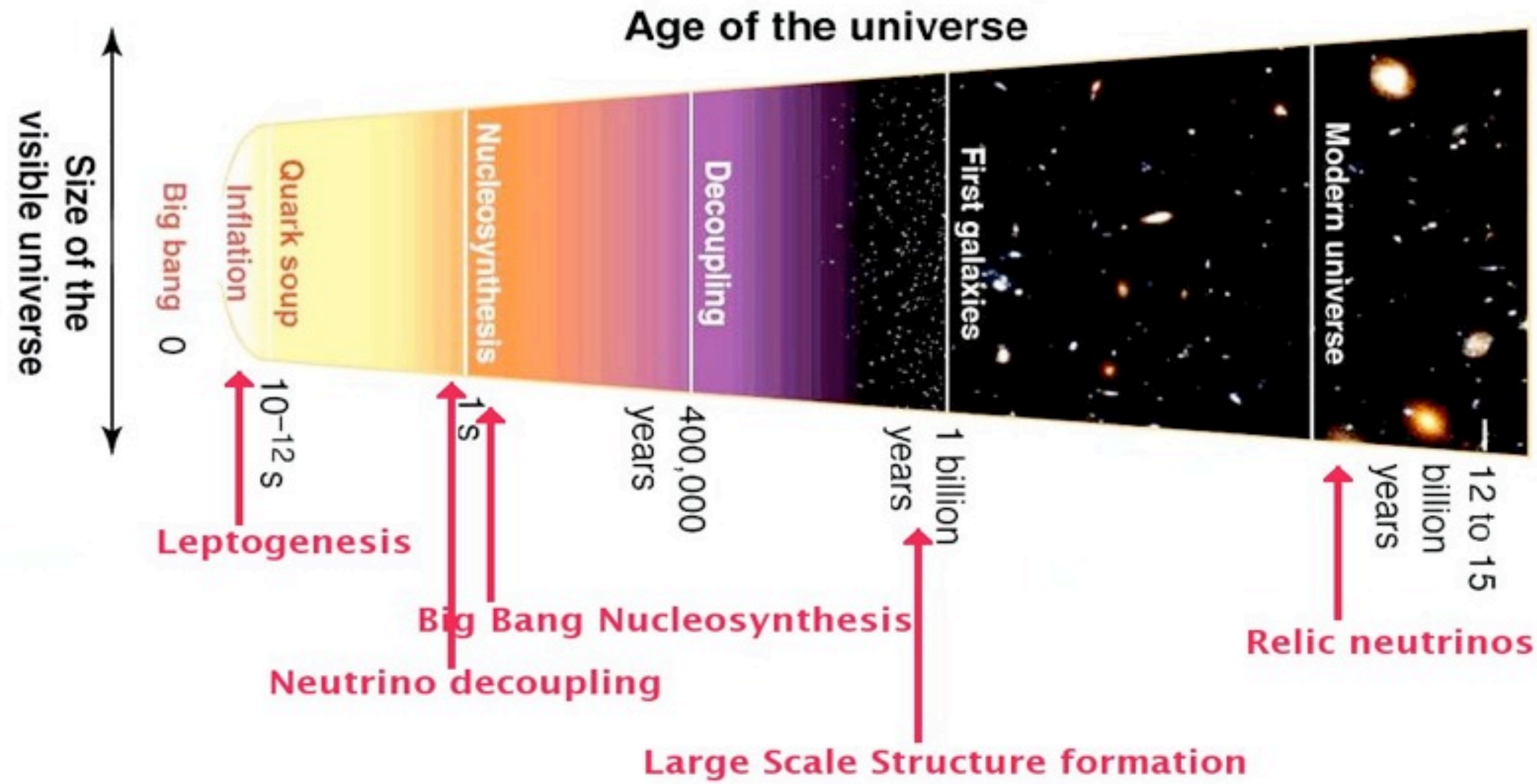
$$\Gamma_{\text{interactions}} = \sigma n \propto G_F^2 T^2 T^3 \quad \sim \quad H \propto \frac{T^2}{m_{\text{Pl}}}$$

After decoupling, neutrinos have played an important role in shaping the Universe: BBN, CMB, LSS.



How many **relic neutrinos** are in a **cup of tea**?

After decoupling, neutrinos have played an important role in shaping the Universe: BBN, CMB, LSS.



How many **relic neutrinos** are in a **cup of tea**?

5600!

New Scientist 05 March 2008: **Universe submerged in a sea of chilled neutrinos**

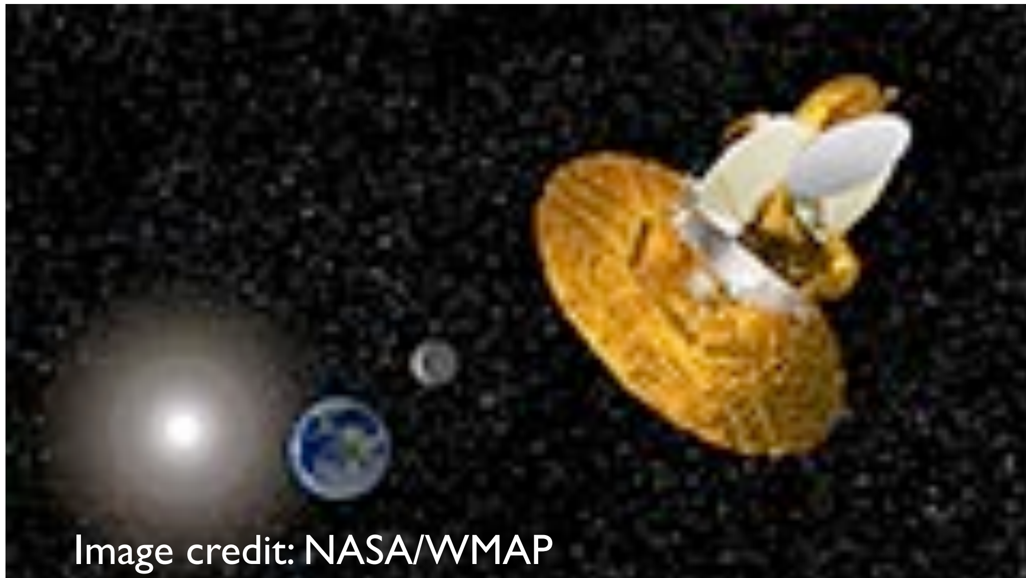


Image credit: NASA/WMAP

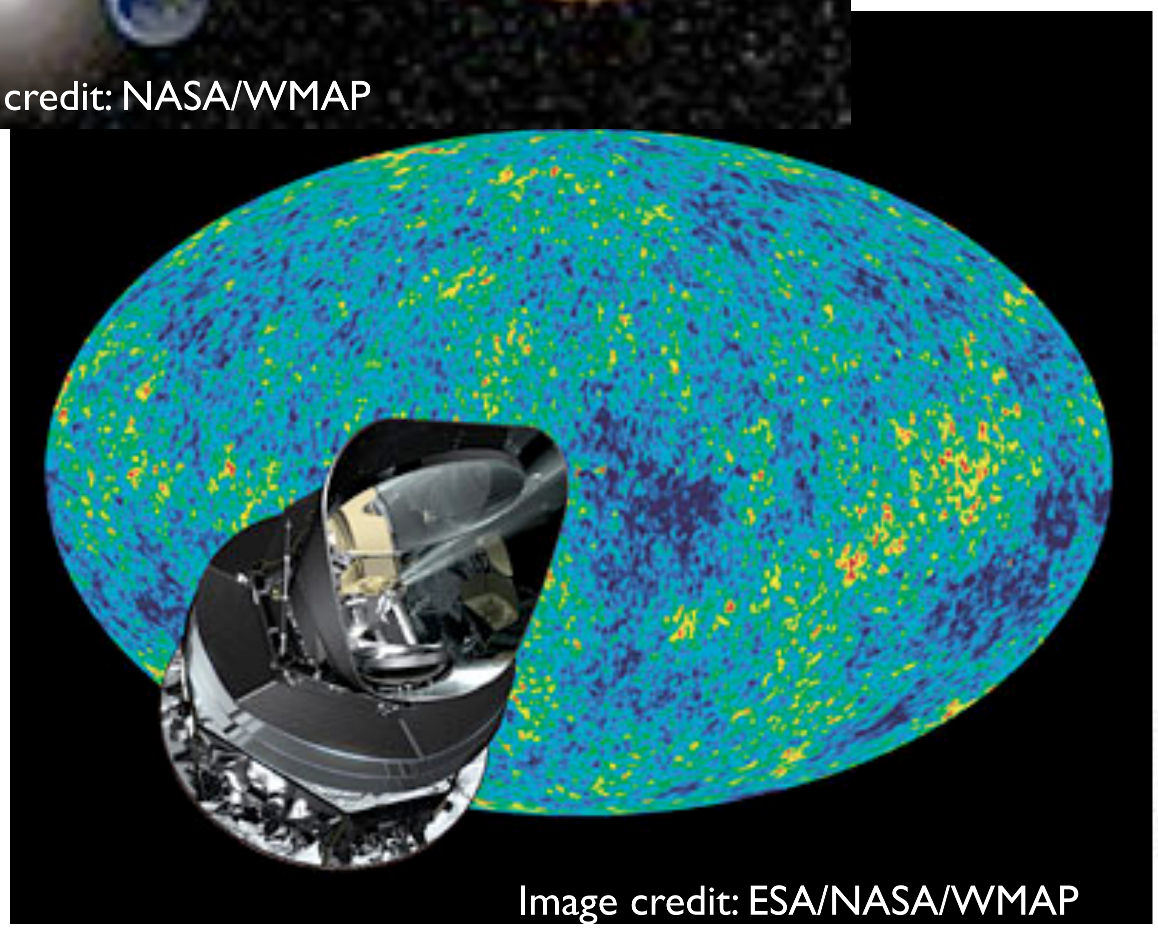
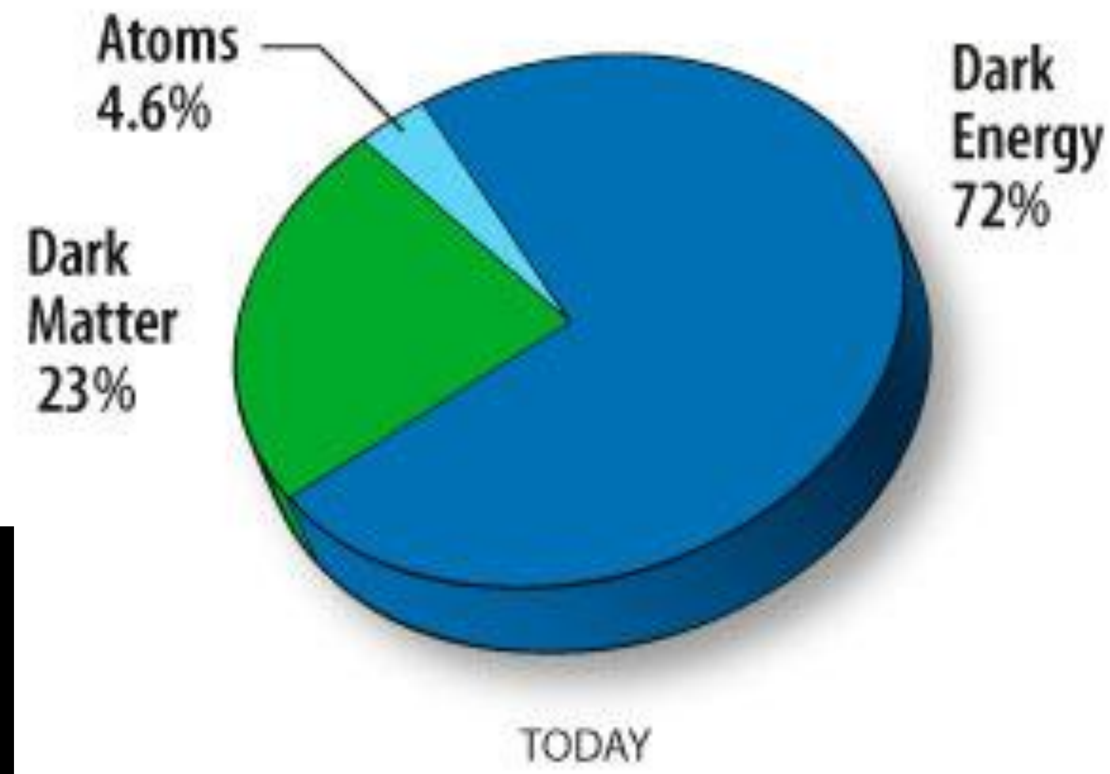
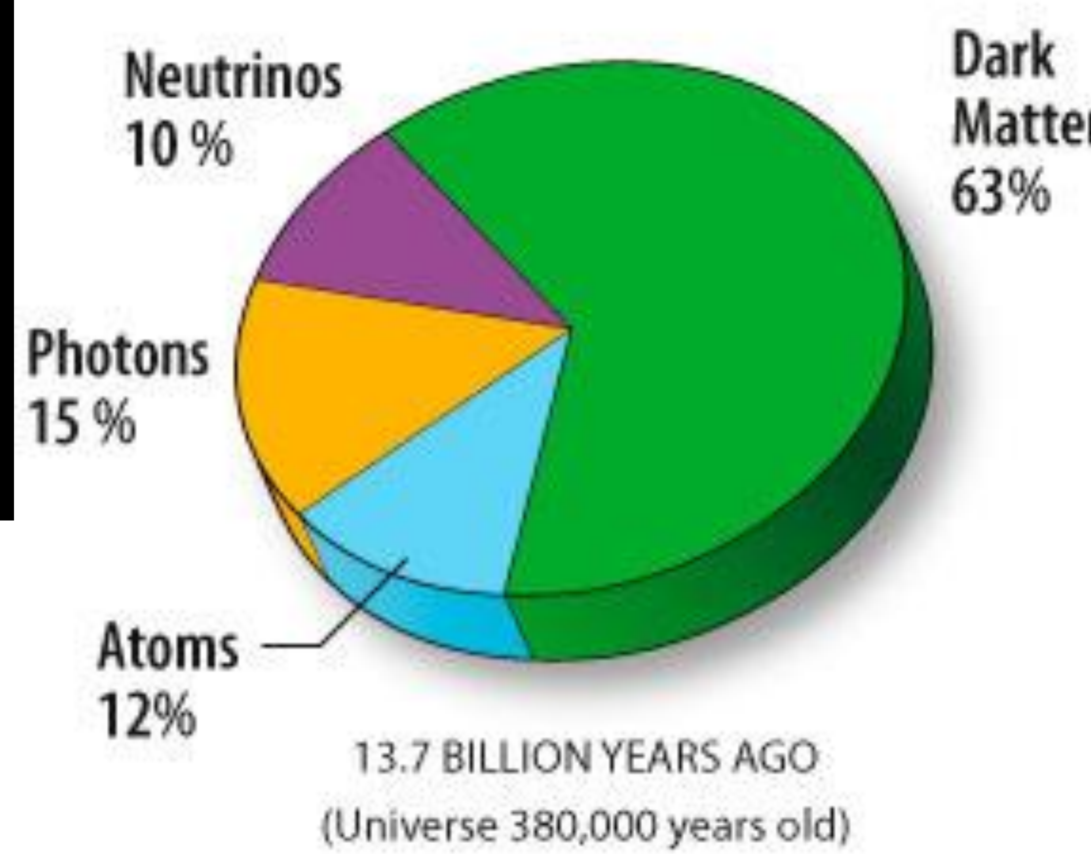


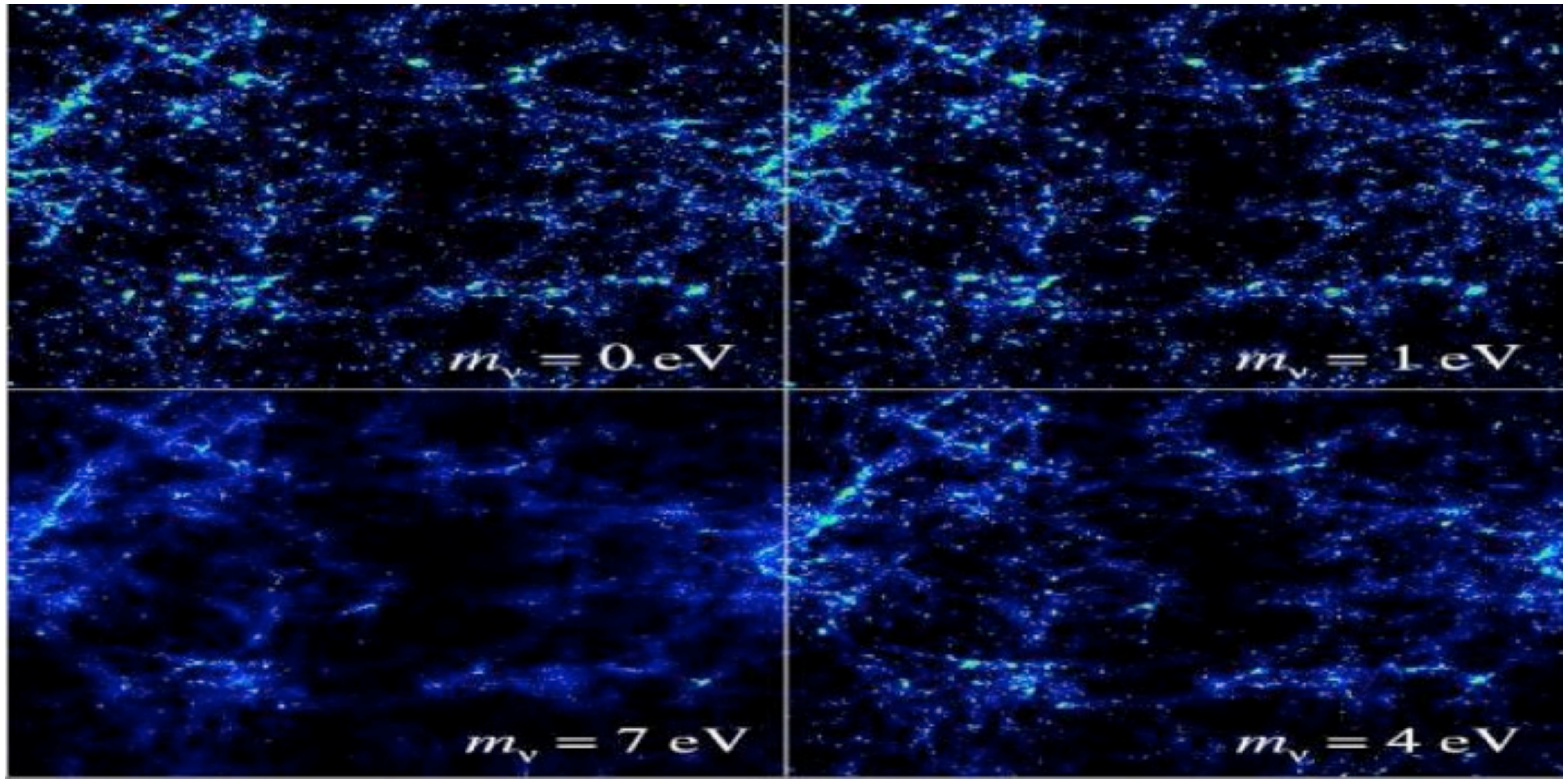
Image credit: ESA/NASA/WMAP





Neutrinos are the only known component of Dark Matter.

Neutrinos played a role in the formation of clusters of galaxies. Early on in the Universe, they travelled too fast to be gravitationally bound (they free-streamed).



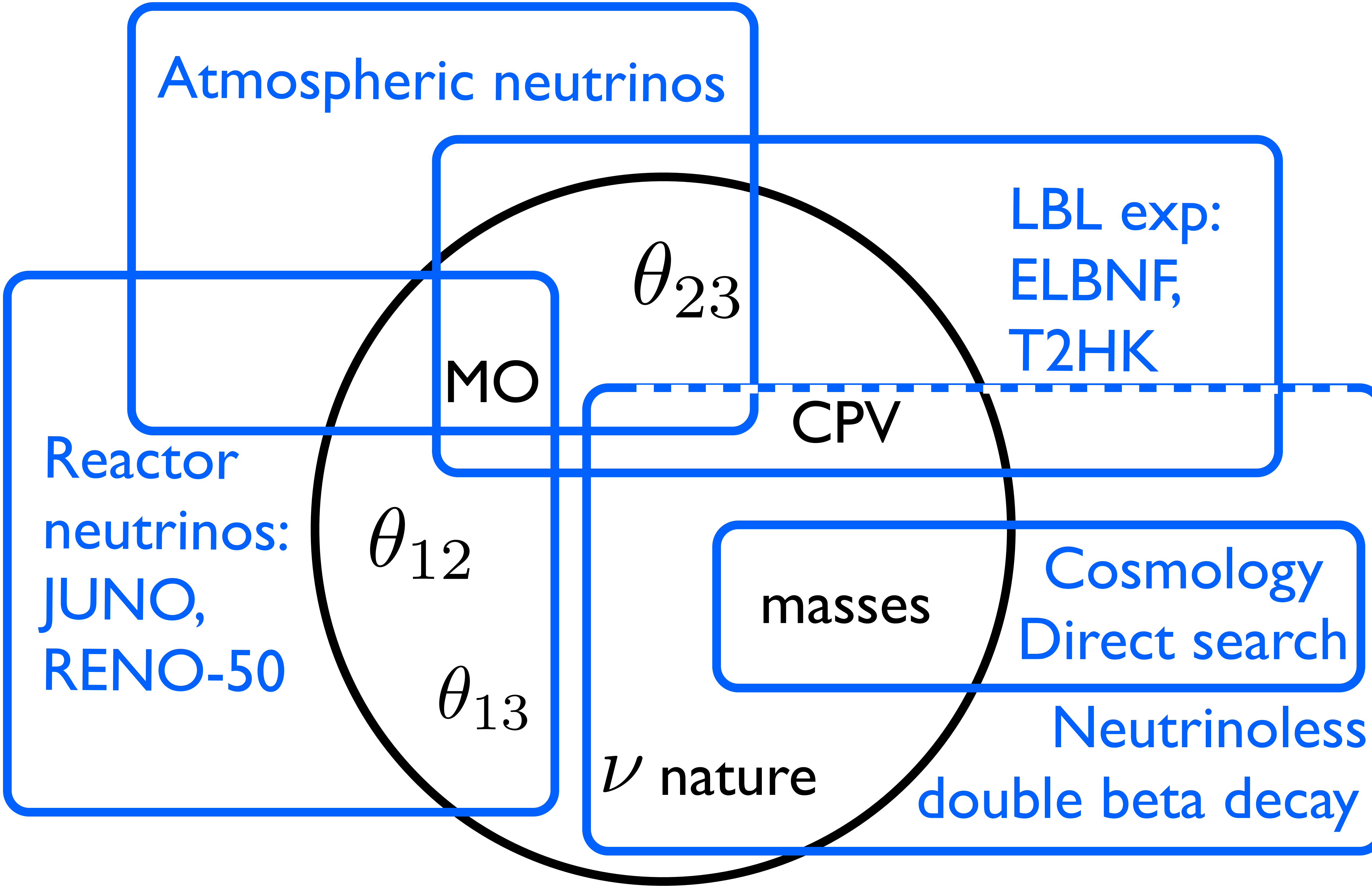
Cosmology, in the standard model, allows to set very stringent bounds on neutrino masses:

$$\sum m_i < 0.3 - 1 \text{ eV}$$

In the coming years data on neutrino properties will be provided both by particle physics, in many experiments, and cosmology.

Do we need all these experiments?
Why?

Complementarity



Also: Tests of standard neutrino paradigm

Synergy

If:

LBL	Neutrinoless double beta decay
finds IO	No signal down to mee ~ 10 meV

Nus are Dirac particles or cancellations in double beta decay (e.g. low energy see-saw)

If:

KATRIN	Cosmology
m>0.3 eV	No signal down to m < 0.1 eV

Non-standard cosmology and/or non-standard evolution in the Universe for neutrinos

If:

Cosmology

Precise measurement of m

Neutrinoless double beta decay

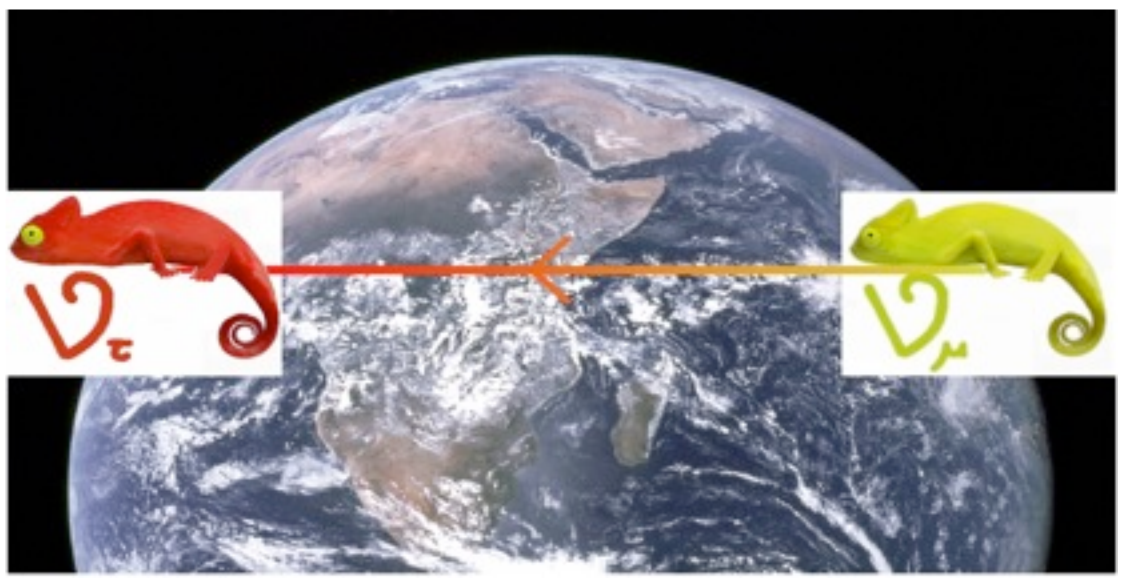
Precise mee (NME needed)

For light neutrino mass exchange, Majorana CPV could be searched for/discovered

- Information not obtainable from a single experiment (e.g. Dirac neutrinos) could be found.
- If an incompatibility between data is found, this would indicate the need to go beyond the standard picture (of particle physics/cosmology).

Conclusions

Neutrinos are the most elusive of the SM particles and the only known component of dark matter.



The discovery of neutrino oscillations has opened a new perspective: neutrino have masses and mix implying new physics beyond the Standard Model of Particle Physics.

An exciting broad experimental programme is ongoing and in preparation for the future, with strong complementarity and synergy.