A brief introduction to neutrino physics

Alberto Remoto
remoto@in2p3.fr

Laboratoire d'Annecy-le-vieux de Physique des Particules


Energie Nucléaire
Astroparticules
Structure du noyau
Neutrinos
Cosmologie
Médecine Nucléaire
Physique hadronique
Saveurs lourdes
Instrumentation
Astrophysique nucléaire
Au-delà du modèle standard
Modèle standard électrofaible
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JRJC 2015
Journées de Rencontres Jeunes Chercheurs
Du 15 au 21 novembre 2015
La Saulaie, CHEDIGNY


STAR WARS
PADAWAN TRAINING
DISNEY
LUCASFILM
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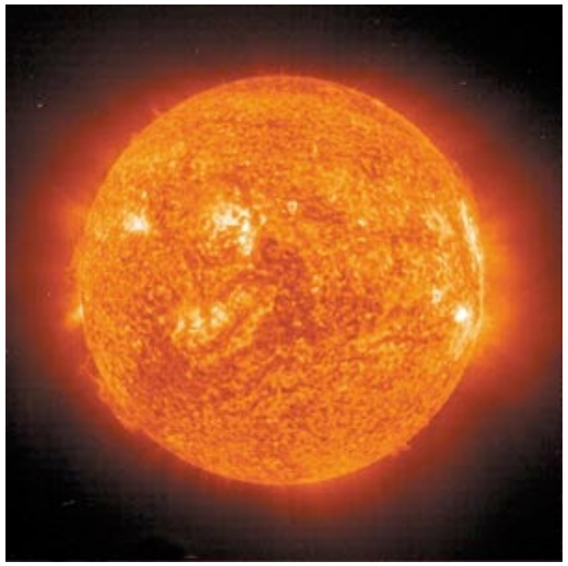
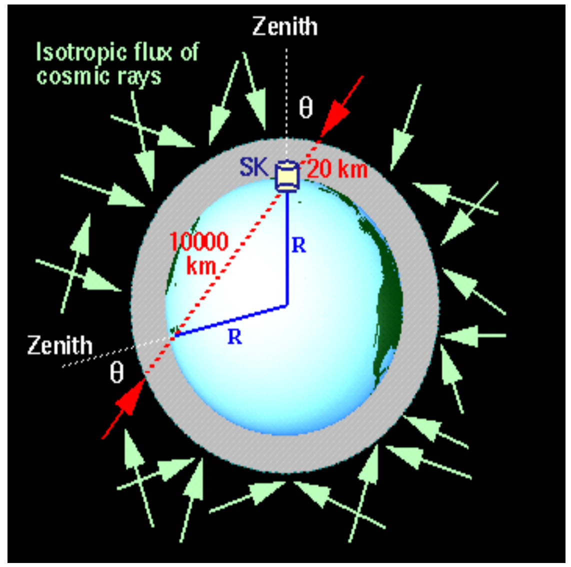
JRJC
2015
Journées de Rencontres Jeunes Chercheurs

You can't escape: they are everywhere

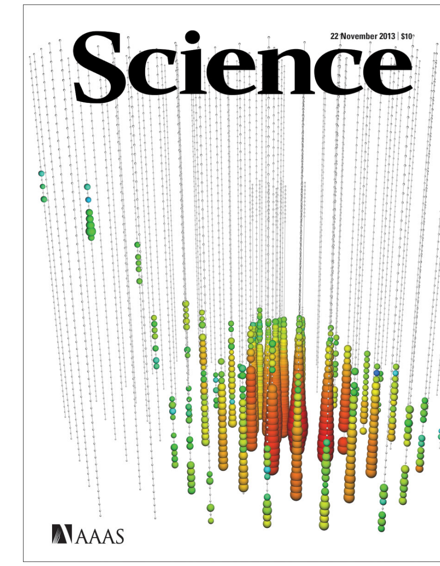


solar neutrinos

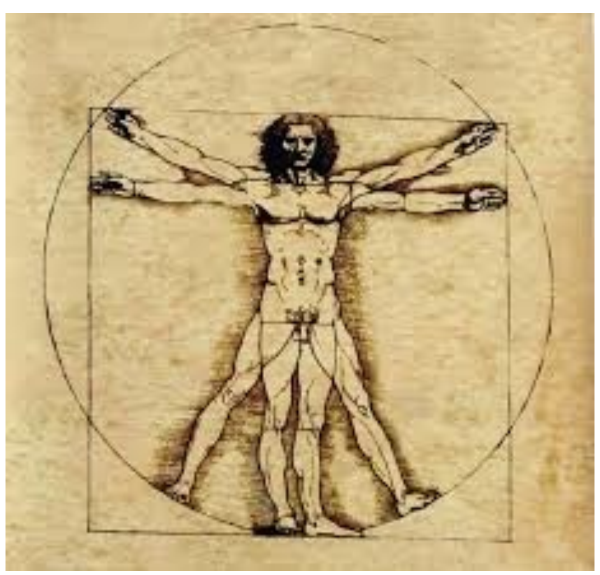


atmospheric neutrinos

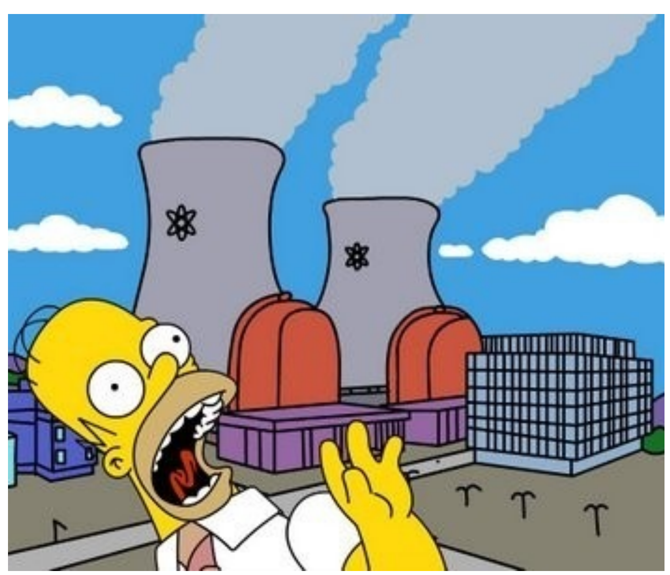
supernova neutrinos



astrophysical neutrinos



human neutrinos



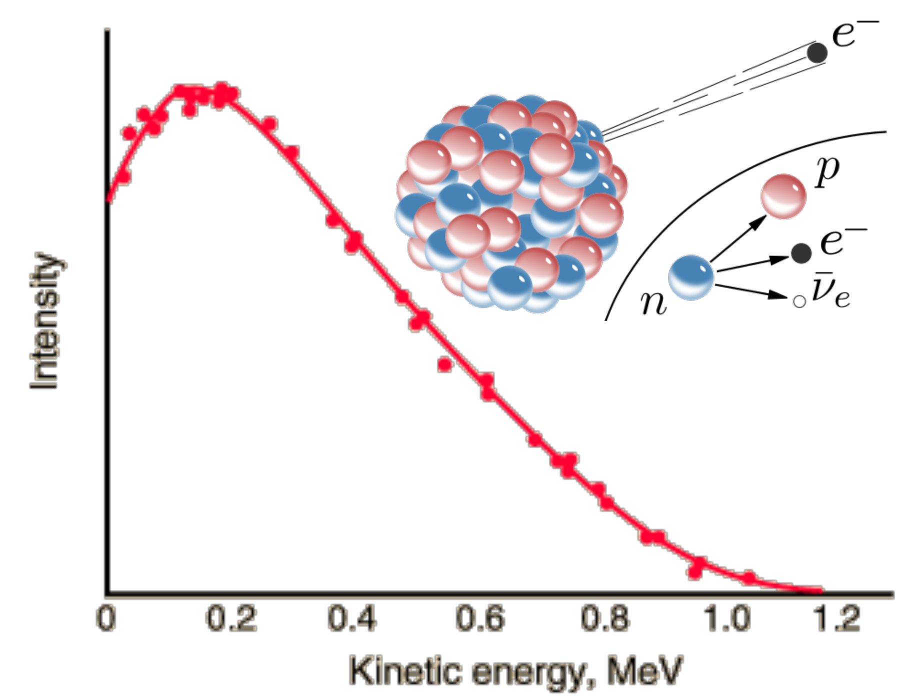
reactor neutrinos

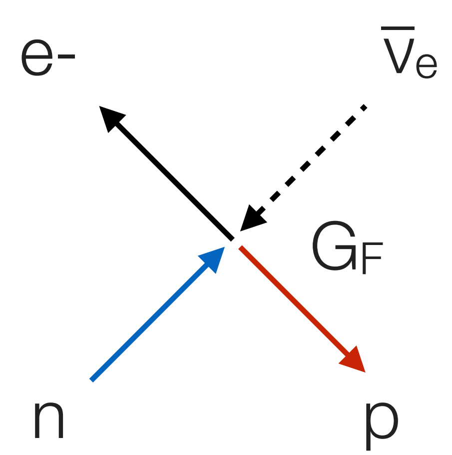
geo neutrinos

accelerator neutrinos

Pauli was desperate but Fermi was cool…

- 1914 - Chadwick observes a **continuous** spectrum in the β decay
- 1931 - Pauli suggests **new particle** escapes detection and takes the missing energy
- 1934 - Fermi provides **first theoretical interpretation** of the weak interaction

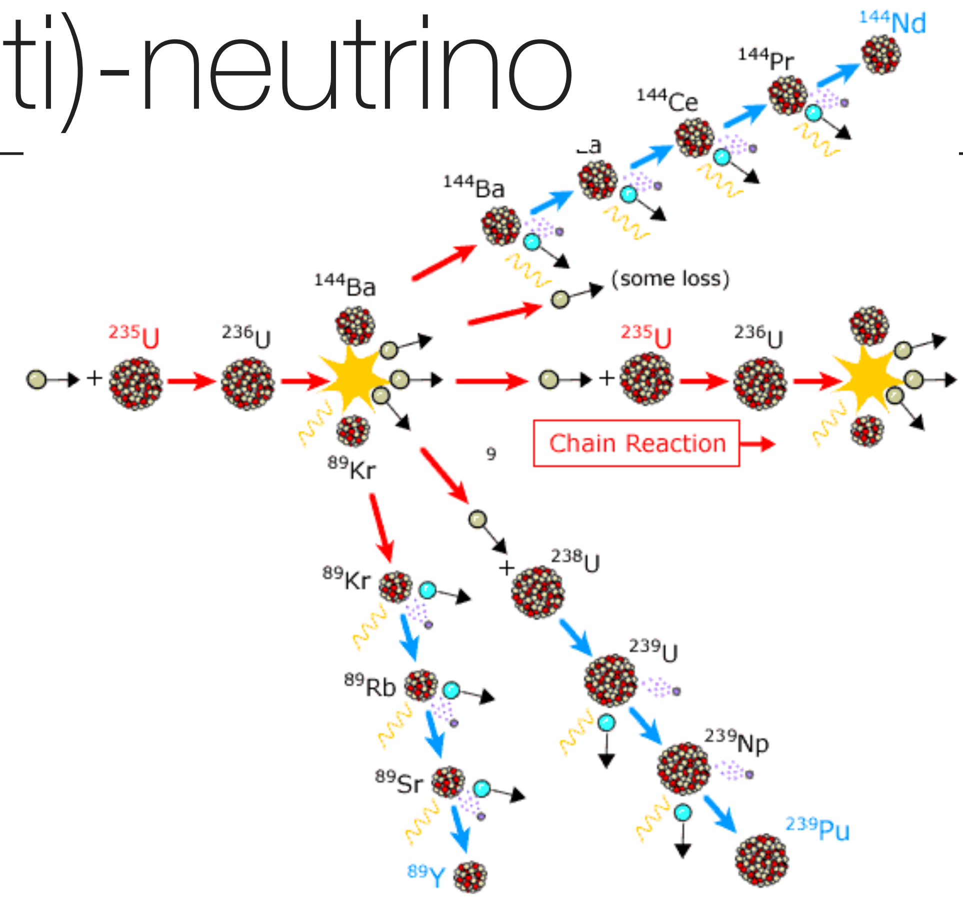




$$^{A}_{Z}X \rightarrow \, ^{A}_{Z\pm1}Y + e^{\pm} + \overset{(-)}{\nu}_e$$

- Nature rejected Fermi's paper: the theory was **too remote from reality**
- The general lack of interest in his theory caused him to **switch to experimental physics** → first nuclear reactor

First observation: electron (anti)-neutrino



- Fermi's theory: neutrinos are expected to be **produced in beta decay:**
  - Nuclear Bomb: ~10^{40} neutrinos \ s x cm^2
  - Nuclear Reactor: ~5×10^{13} neutrinos \ s x cm^2
- 1942 - Ganchang propose to use **inverse beta decay** to experimentally detect neutrinos:

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

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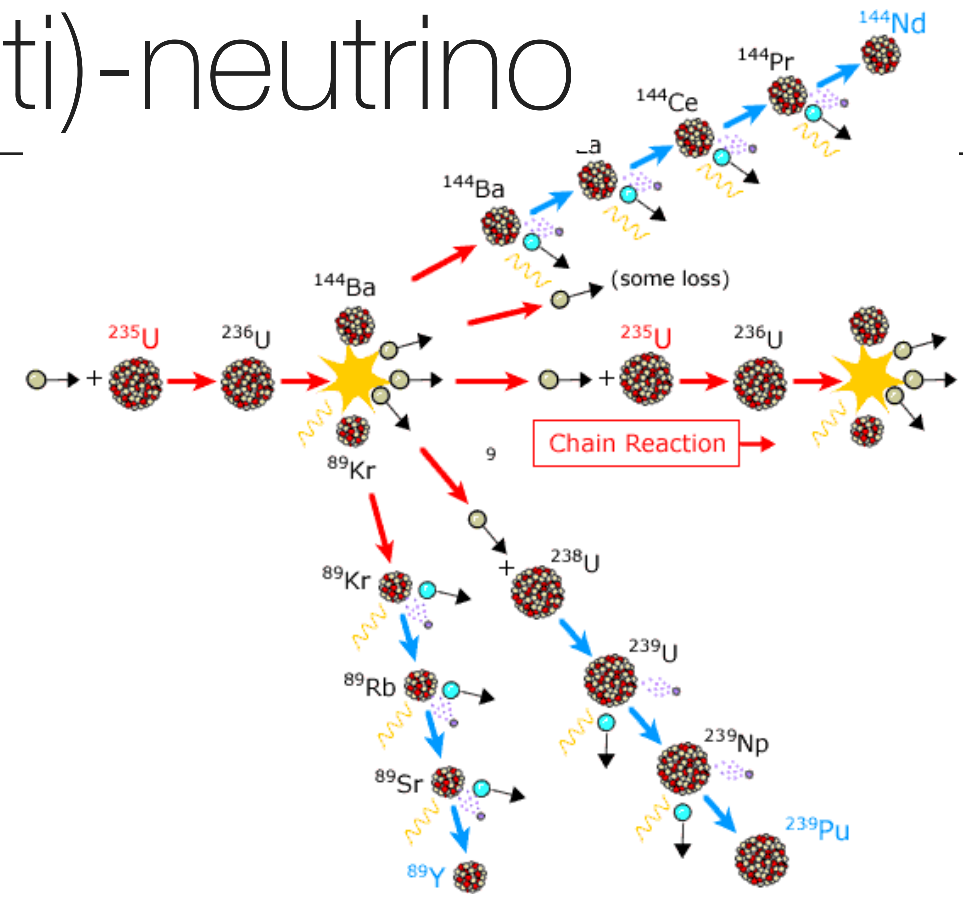
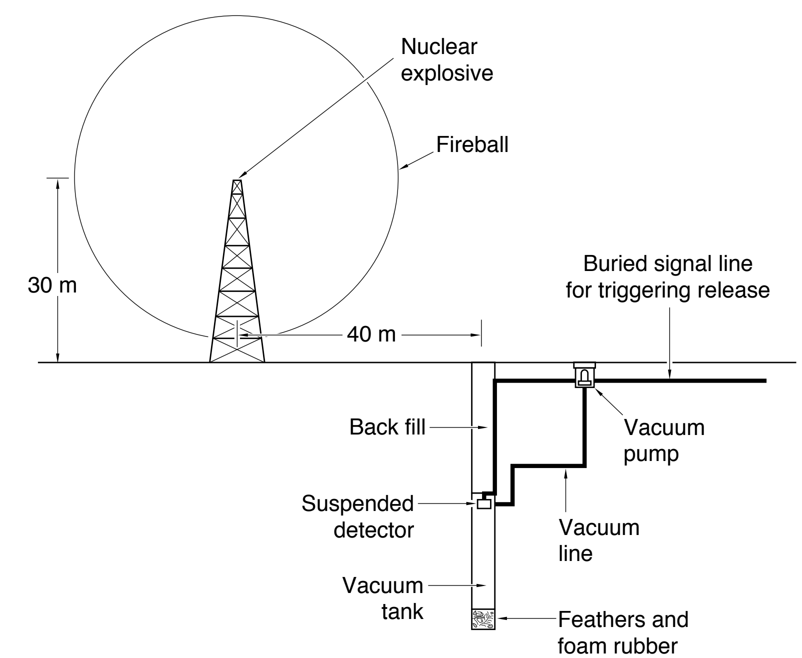
- Cowan & Reines @ Los Alamos National Lab
- 1st idea: let's use a nuclear bomb…





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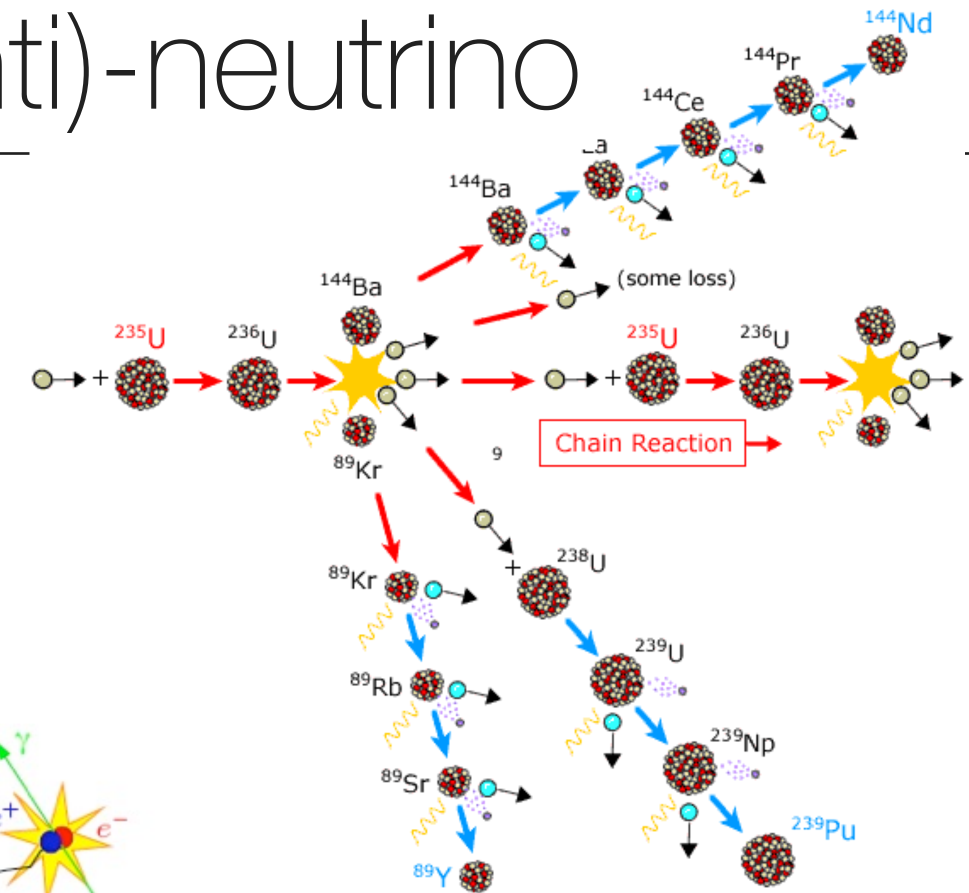

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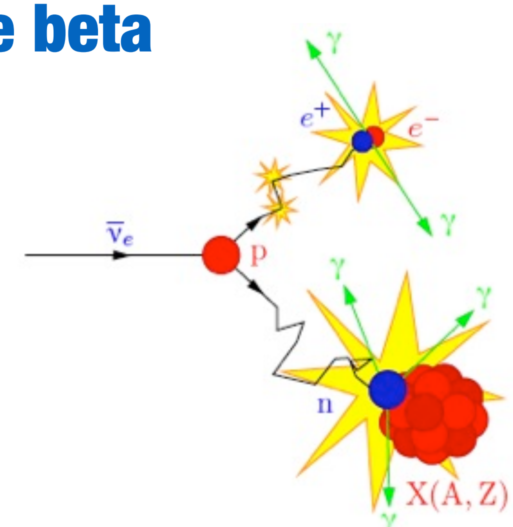
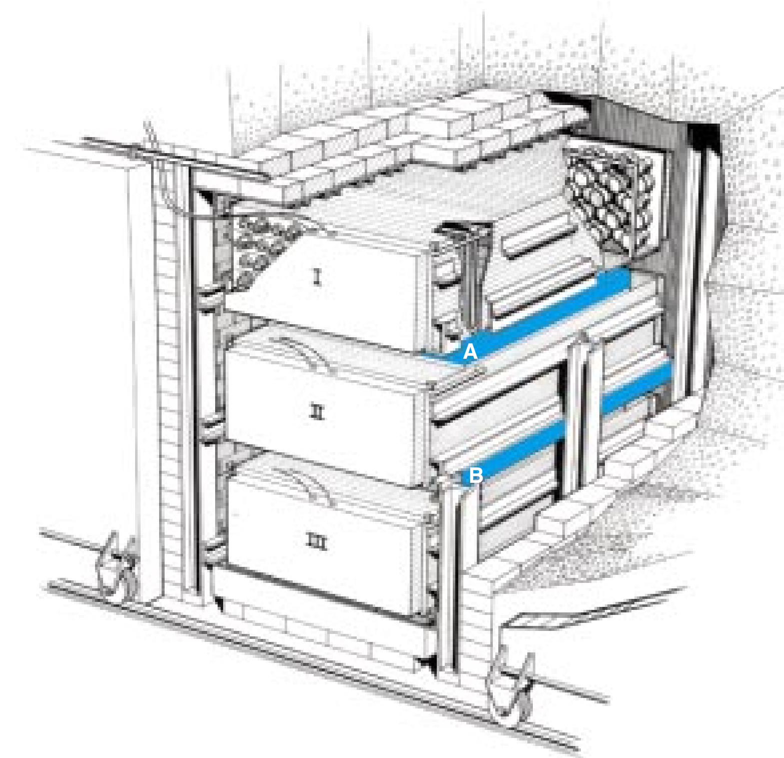


- Cowan & Reines @ Los Alamos National
- 1st idea: let's use a nuclear bomb…
- 2nd idea: let's use a nuclear reactor (1956)
  - Water target **doped with Cd** + Liquid scintillator
  - **Positron annihilation** + **delayed neutron capture** on Cd



[The Reines-Cowan Experiments]

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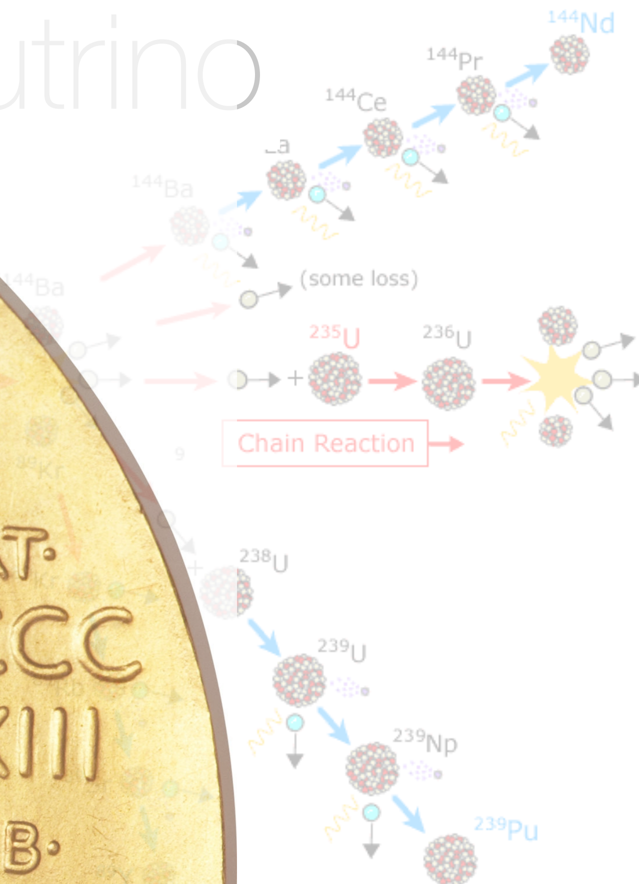
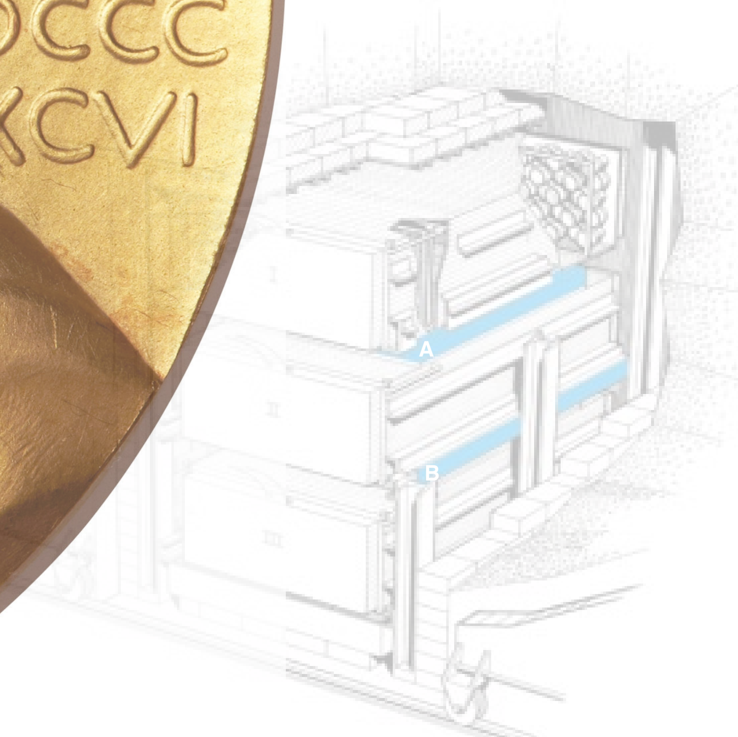


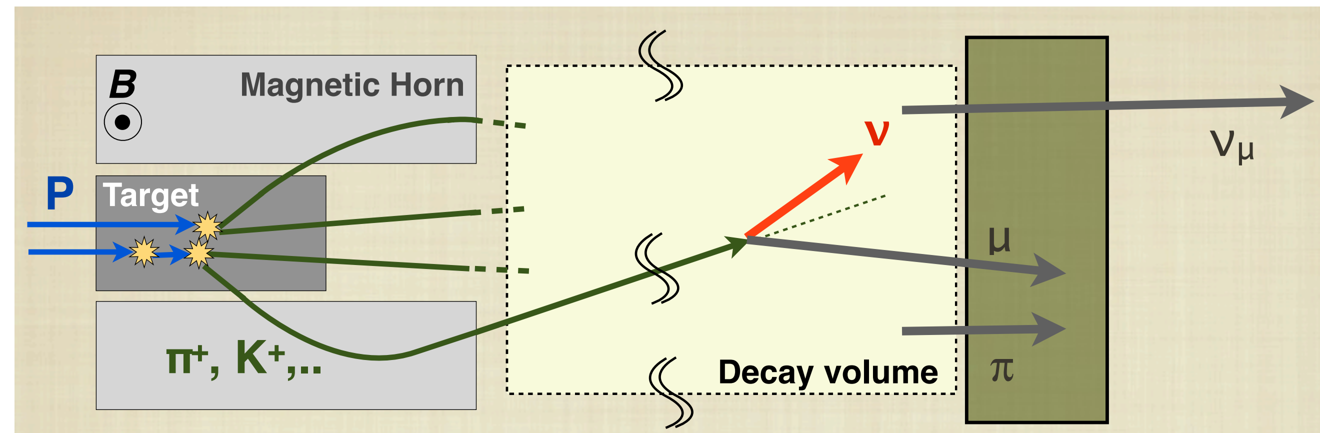


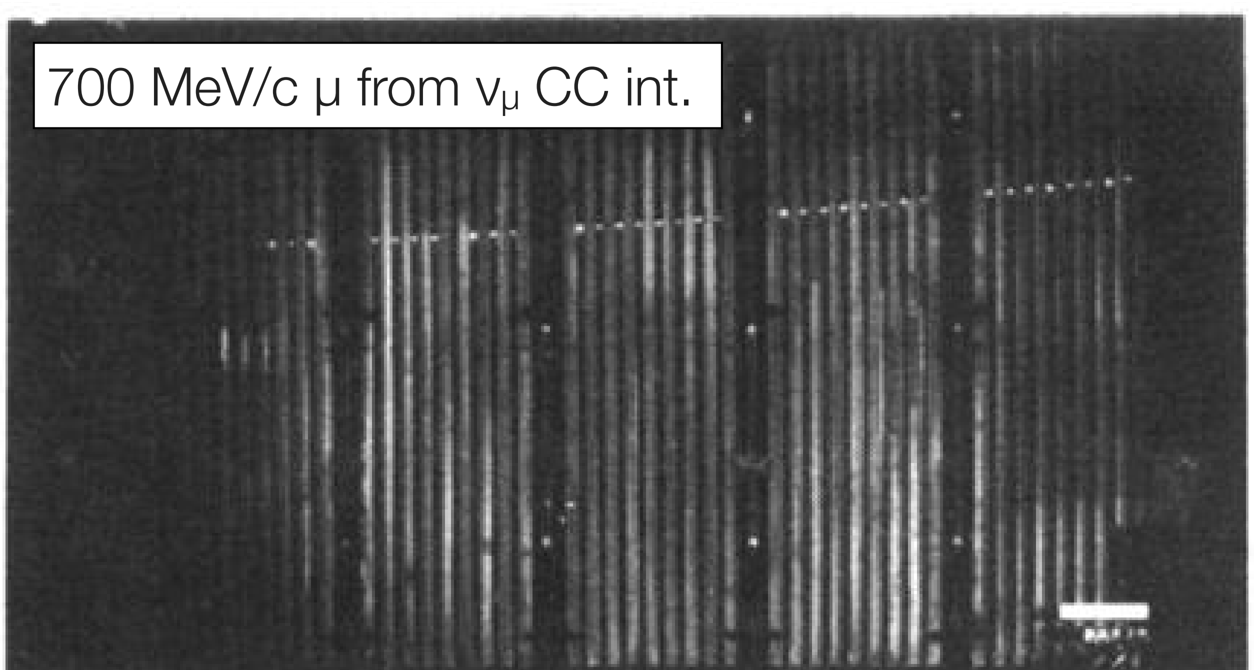
[The Reines-Cowan Experiments]

First observation of muon & tau neutrinos

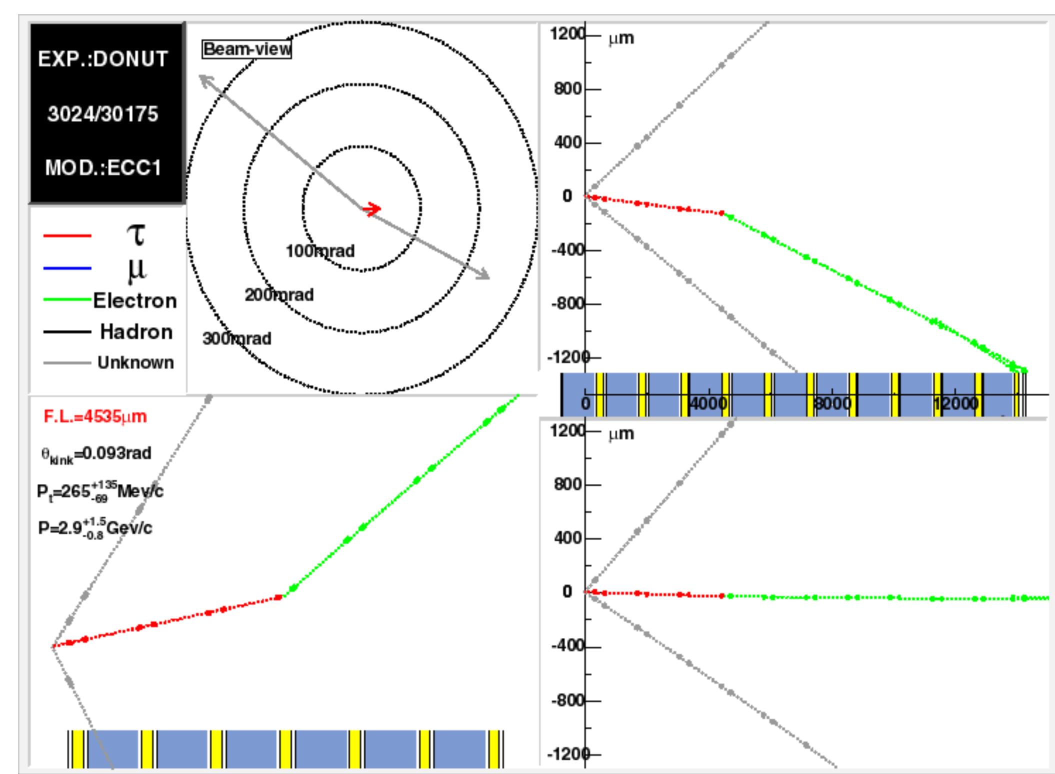
- 1962 - L.M. Lederman, M. Schwartz and J. Steinberger first ν_μ detection
- First human-made **neutrino beam**
- ν_μ detection through **charged current interaction** producing **μ track**
- 2000 - ν_τ discovery by DONUT (ν_τ beam from charmed mesons decay)

[How to make a neutrino beam]





τ from ν_τ CC int. in photographic emulsion



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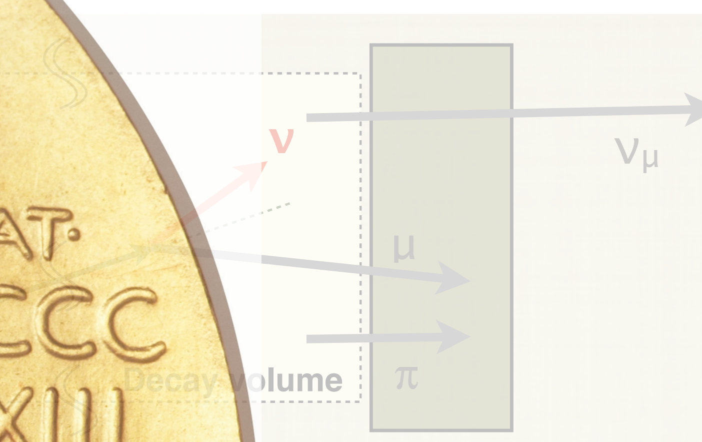

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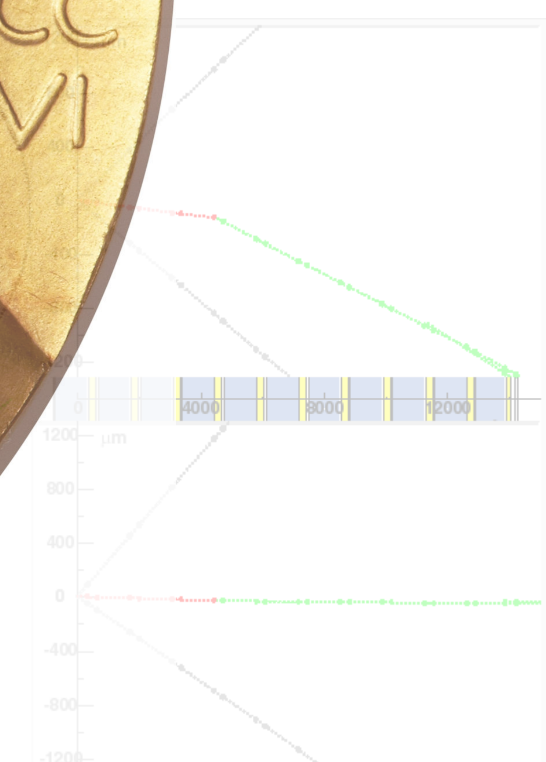
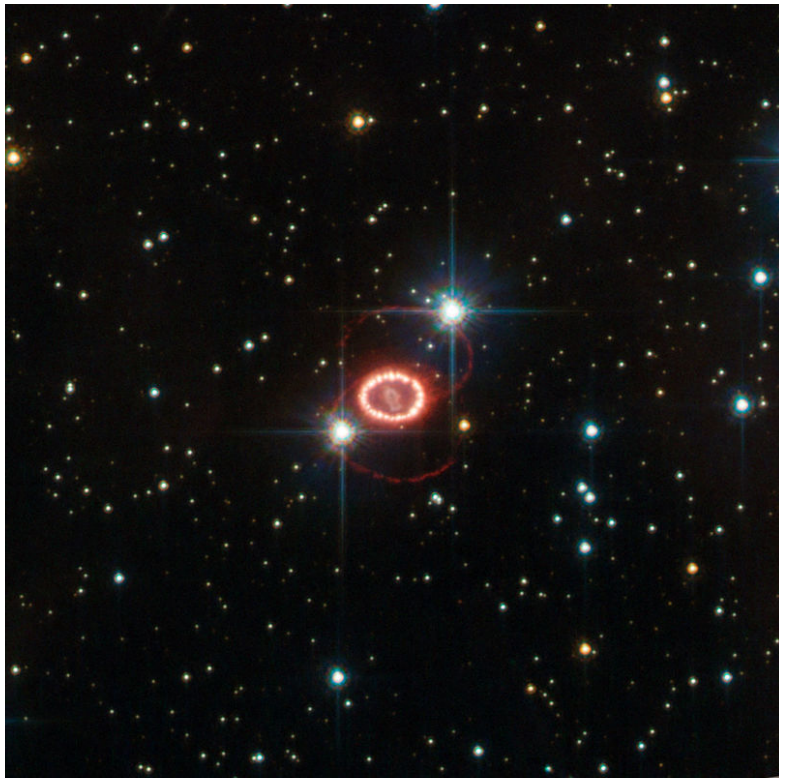
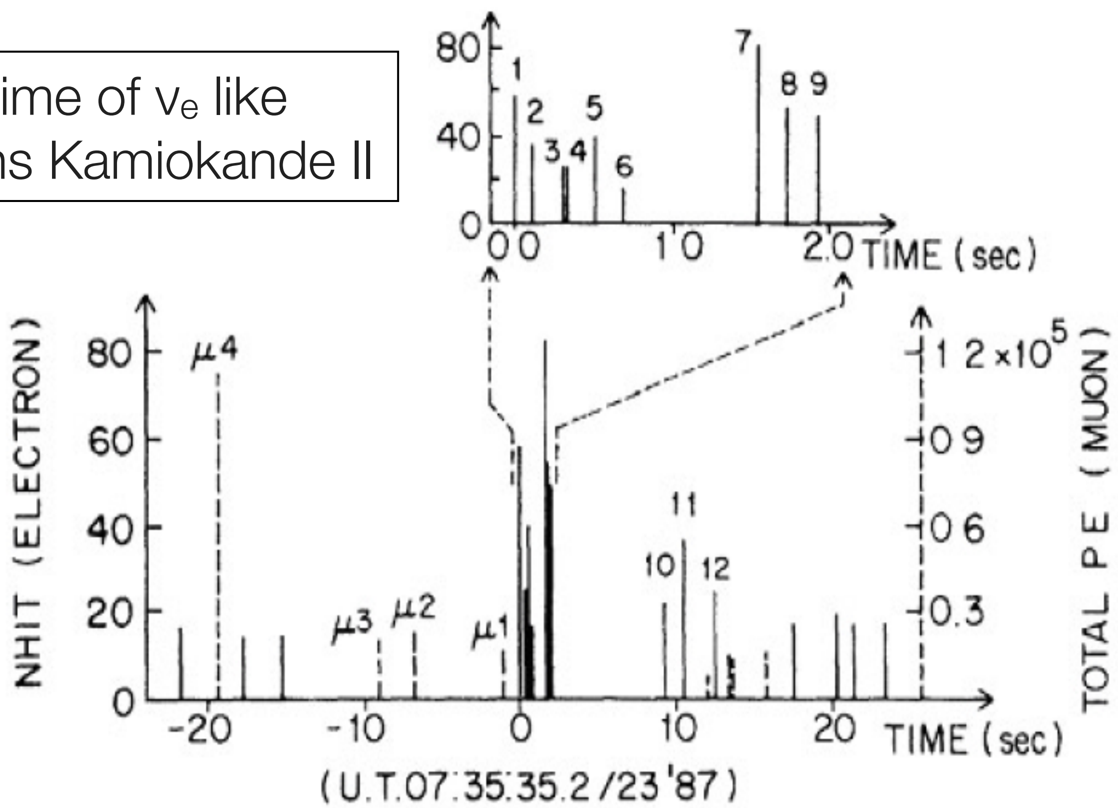


First neutrinos from SN explosion

- The 23rd February 1986 a **burst of neutrinos** is observed at 3 separate detector
- 2 - 3 h **before visible light** from SN1987A reached Earth
- Observations **consistent** with theoretical supernova models (99% of the energy radiated away by neutrinos)
- Marked the beginning of **neutrino astronomy**



Arrival time of ν_e like event ins Kamiokande II



Experiment	Neutrino events
Kamiokande II	11
IMB	8
Baksan	5

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Neutrinos in the standard model

- The SM has been built assuming neutrino is **massless** with **left chirality** only
- The electroweak sector interacts with the symmetry group U(1) × SU(2)$_L$

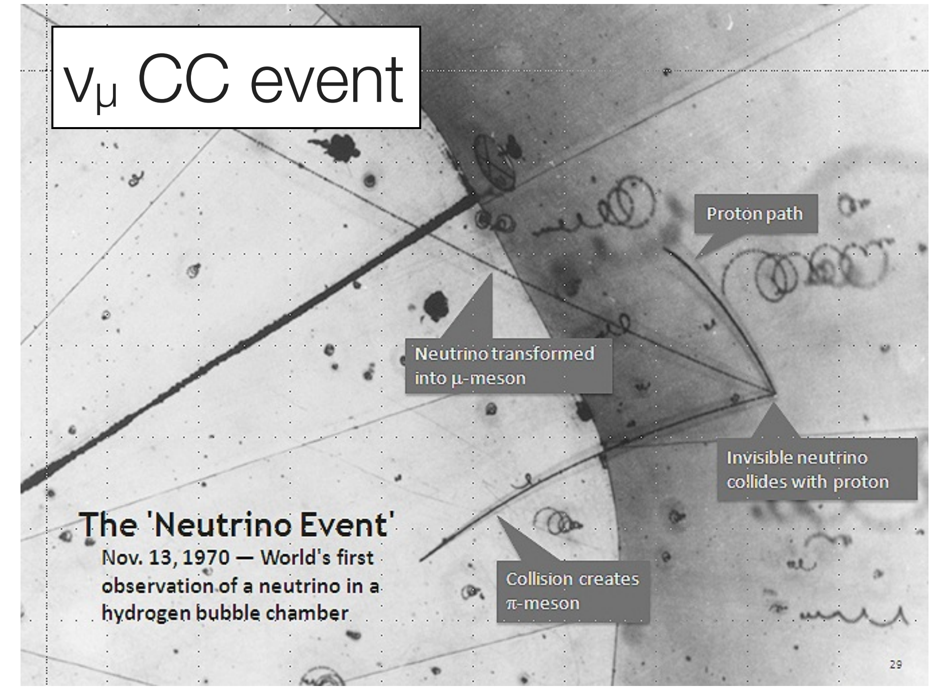
$$\mathcal{L}_{EW} = \sum_{\psi} \bar{\psi}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{1}{2}Y_W B_{\mu} - g\frac{1}{2}\tau W_{\mu}\right)\psi$$

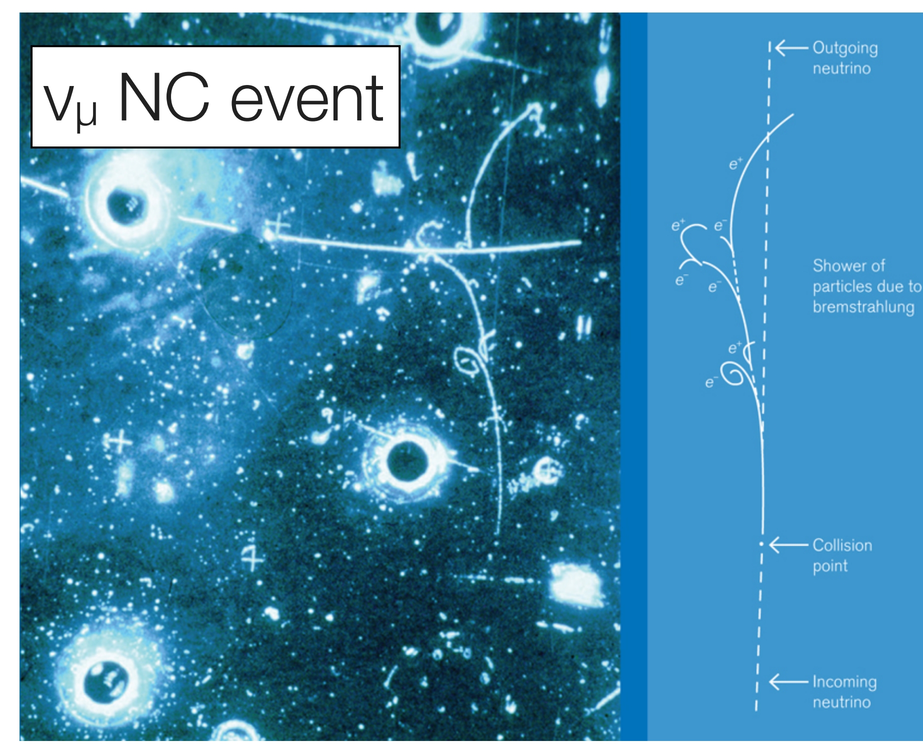
- Charge current sector:

$$\mathcal{L}_C = -\frac{g}{\sqrt{2}}\left[\bar{u_i}\gamma^{\mu}\frac{1-\gamma^5}{2}M_{ij}^{CKM}d_j + \bar{\nu_i}\gamma^{\mu}\frac{1-\gamma^5}{2}e_i\right]W_{\mu}^{+} + h.c.$$

- Neutral current sector:

$$\mathcal{L}_N = eJ_{\mu}^{em}A^{\mu} + \frac{g}{\cos\theta_W}(J_{\mu}^{3} - \sin^2\theta_W J_{\mu}^{em})Z^{\mu}$$





How many neutrinos are there?

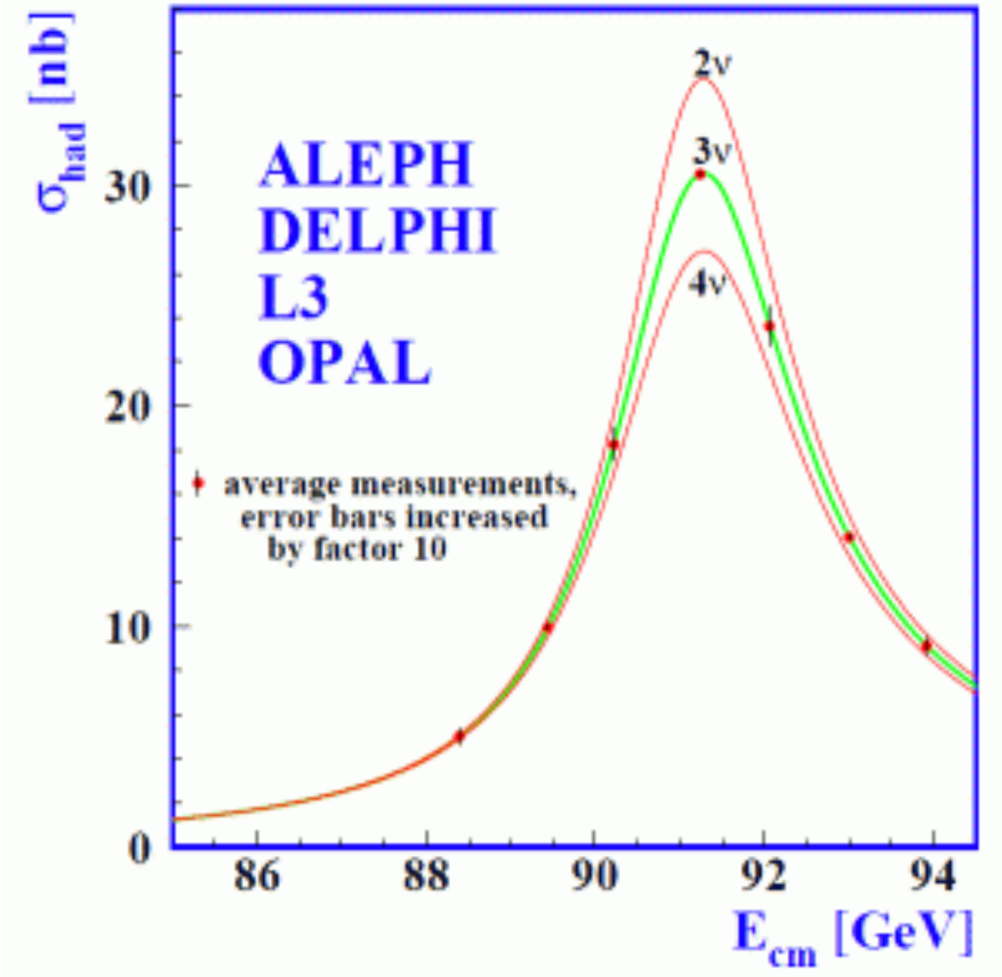
- LEP provided the most precise measurement of the number of light neutrino flavours
- Study the **invisible Z width**: the more light neutrino families the shorter the Z half-life

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_l}\left(\frac{\Gamma_l}{\Gamma_\nu}\right)_{SM}$$

$\Gamma_{inv} = (\Gamma_{Tot})_{SM} - \Gamma_l$

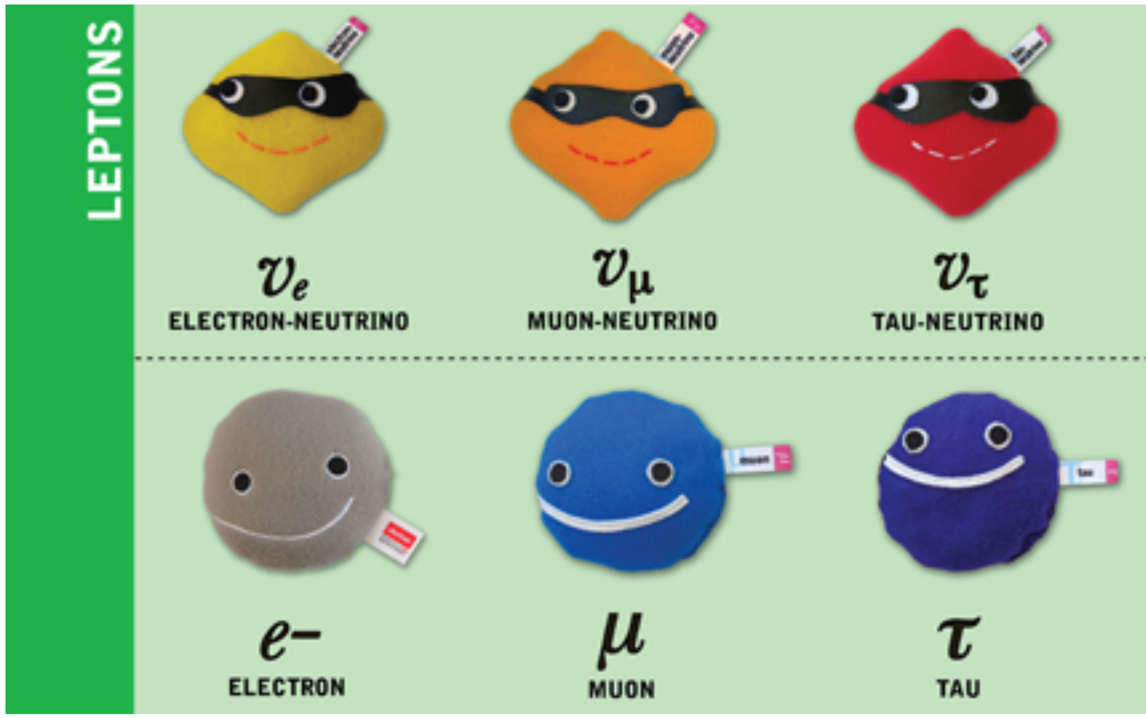
LEP measurements

SM prediction

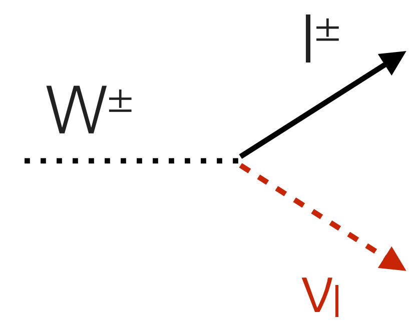


- Combination of the 4 LEP experiments gives **N_ν = 2.984 ± 0.008**
- Cosmological observations (WMAP, Planck) provide additional constraint

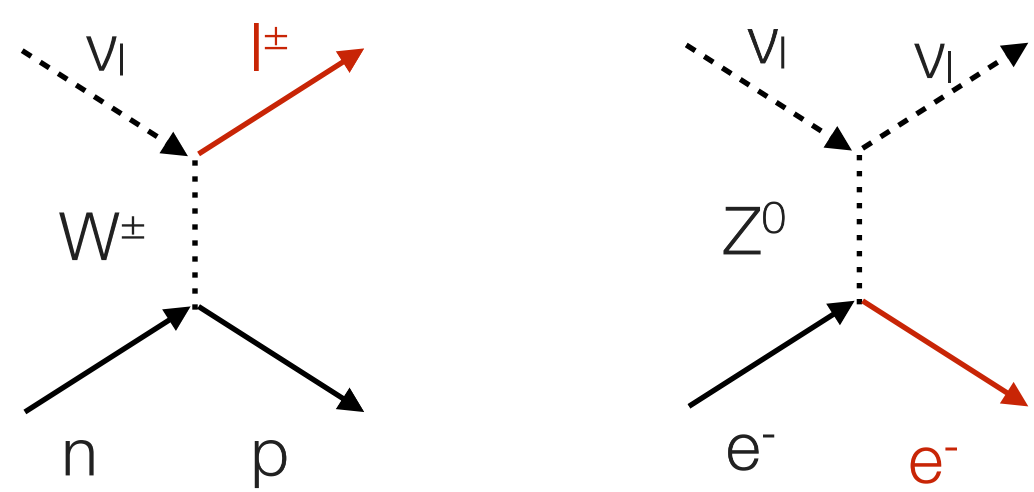
So far so good, but…



Produced in CC interaction

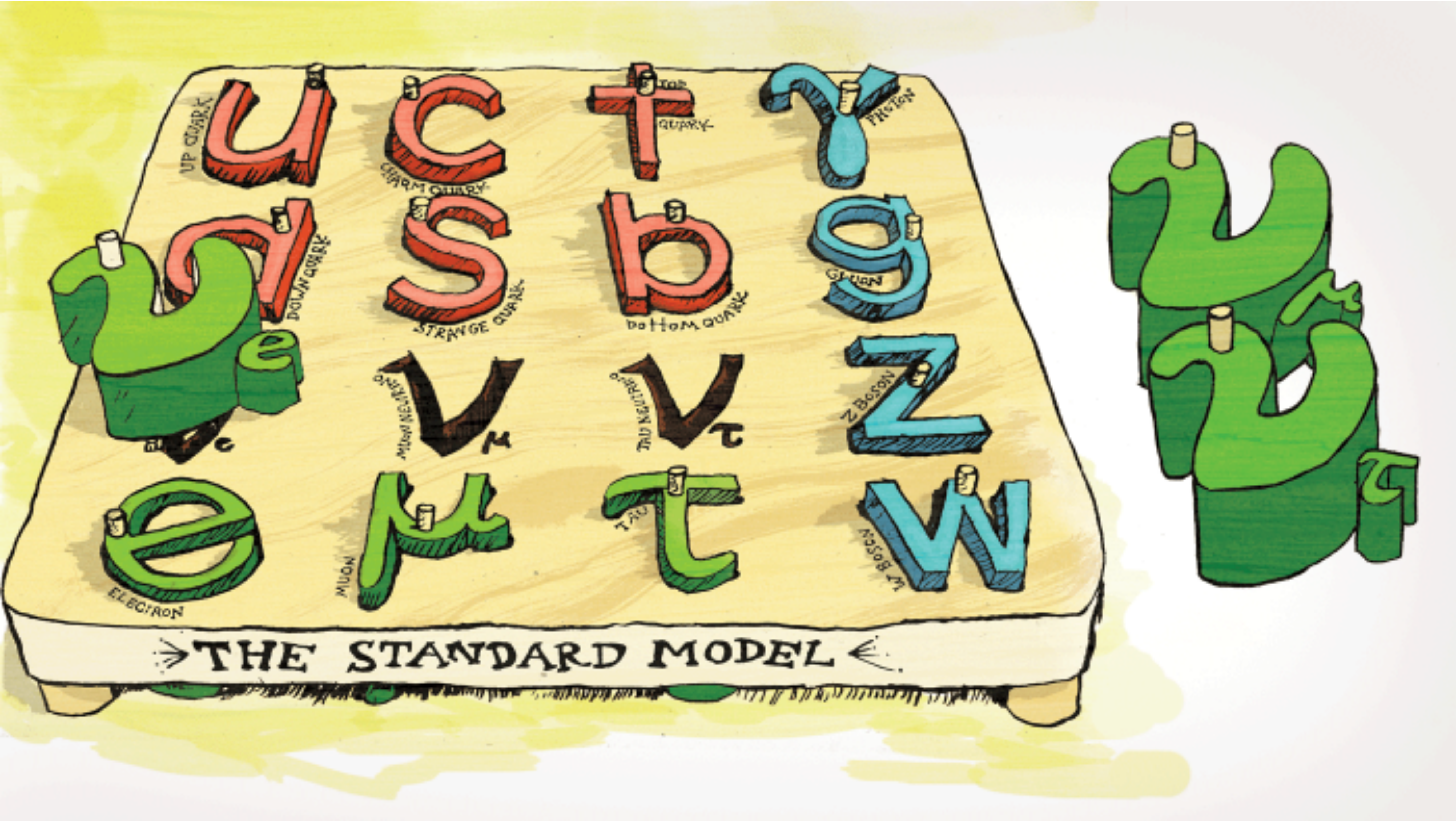


Detected in CC/NC interaction

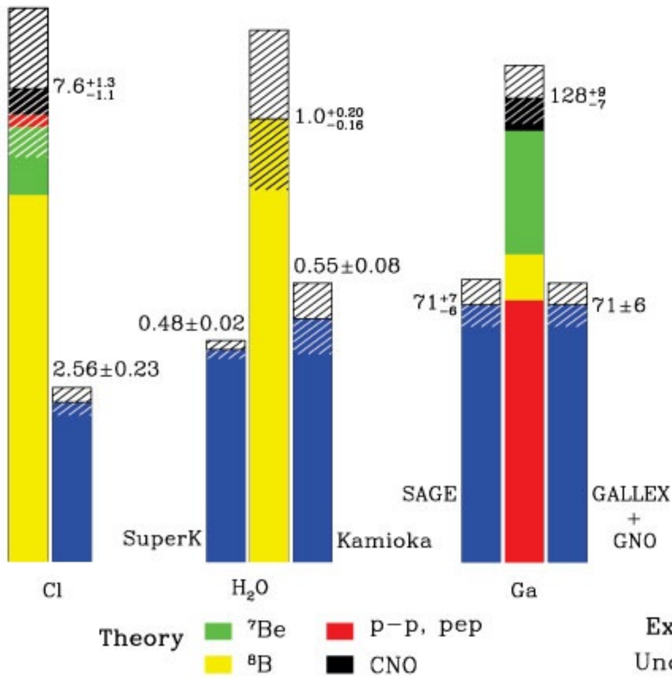


- Three families of mass-less neutrinos
- We know how they interact
- We know how to detect them
- Fit well in the Standard Model

So far so good, but…



Solar/Atmospheric anomalies

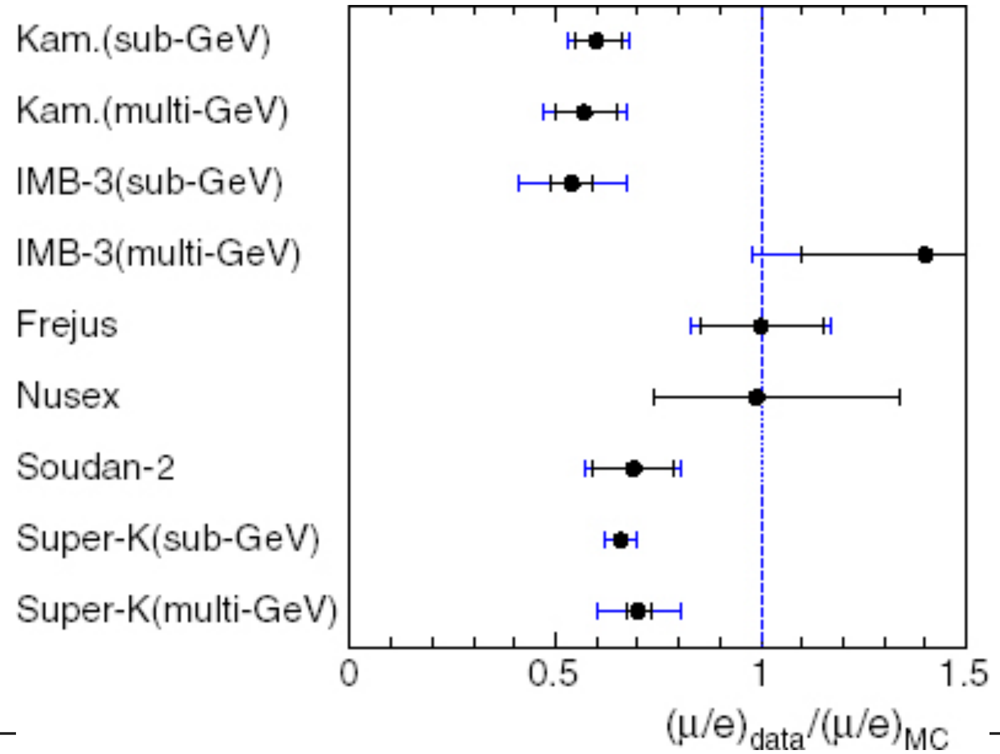


- The Sun is a fusion reactor which emits **ν_e in great quantity**
- 1968 - R. Davies first detection of solar neutrinos (ν_e + ^{38}Cl → ^{37}Ar + e$^-$)
- **2/3 of expected ν_e are missing**

- The ratio of muon and electron neutrino produced in atmosphere ~ 2

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

- The ratio is observed to be ~1
- **1/2 of expected ν_μ are missing**



Neutrino oscillation (and other exotic explanations)

Neutrino decay, Flavour changing neutral current and **Neutrino oscillations**

(1) Masses & flavours eigenstates not the same:

Mixing between flavour & mass states is possible

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

(2) Non-degenerate mass spectrum: $\Delta m^2 \neq 0$

Quantum interference during neutrino propagation

$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta \sin^2 \left(\Delta m^2 L/E\right)$$

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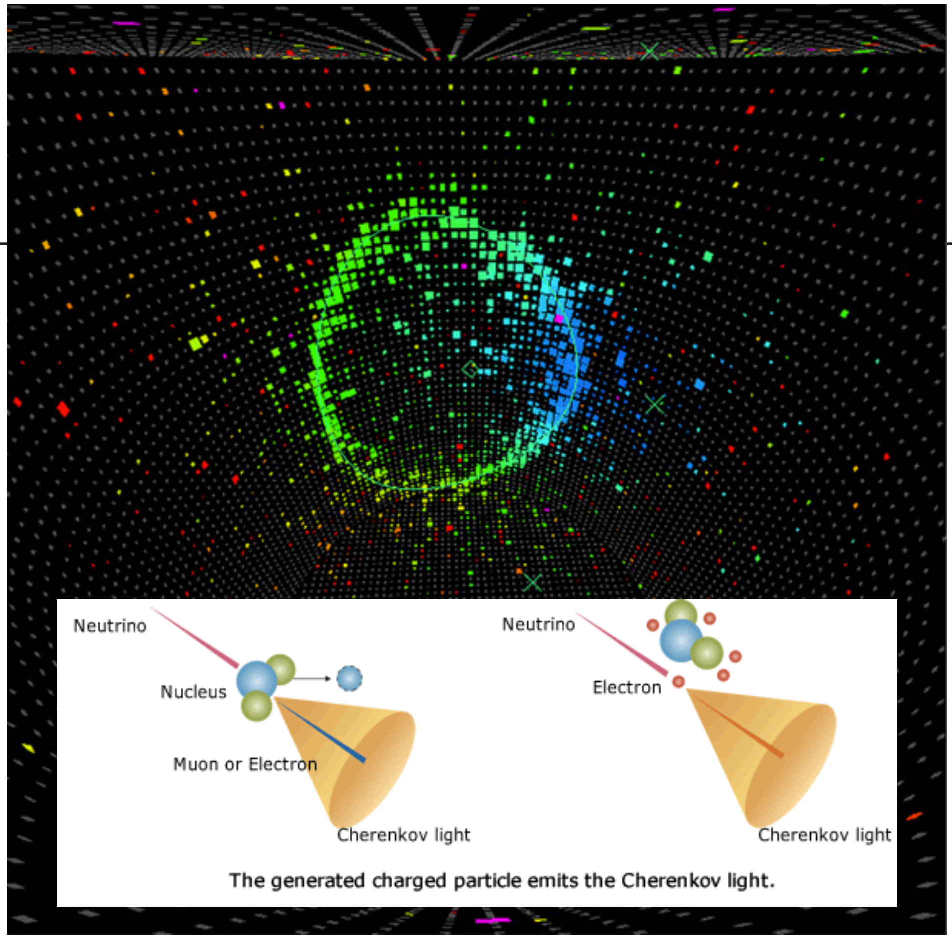
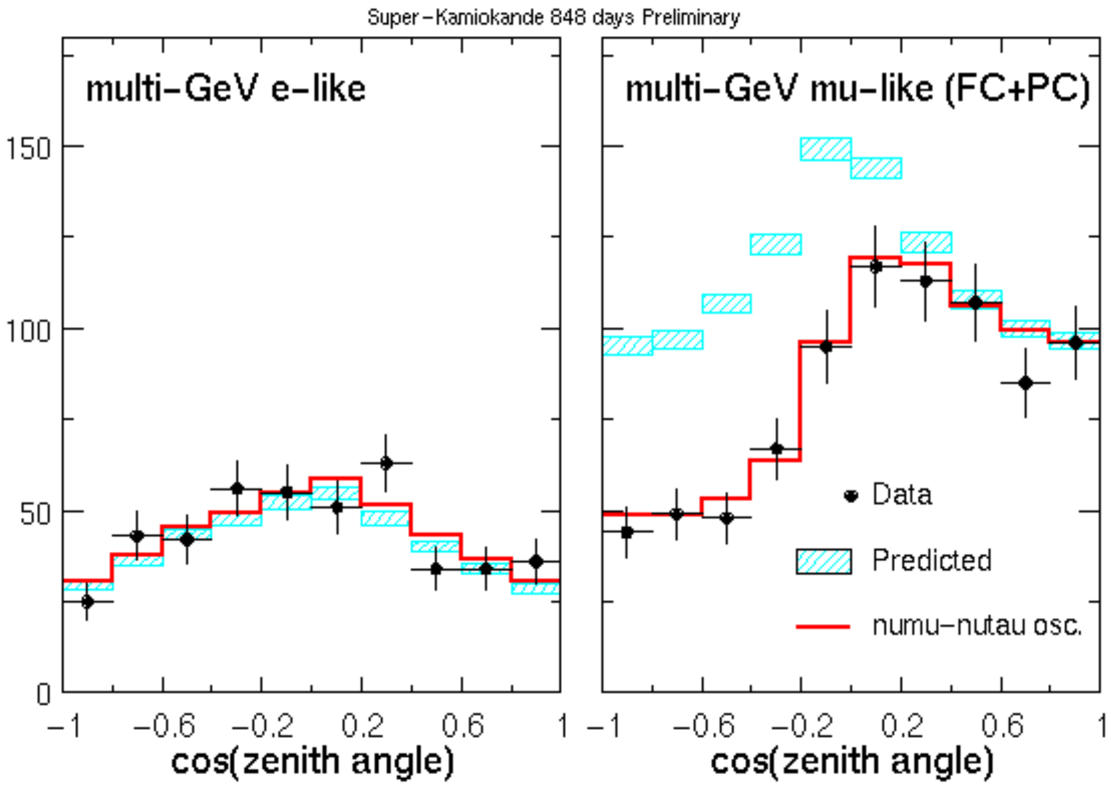
Super Kamiokande



- 50 kT water Cherenkov detector ~40m tall ~40m diameter viewed by > 11000 PMTs
- **Sensitive to CC int. of atmospheric ν_e and ν_μ**
- Observe atmospheric ν_μ and ν_e from different zenith angles → different propagation length
- 1998 - Confirm atmospheric ν_μ oscillate (to ν_τ ?), **L/E signature of neutrino oscillation!**



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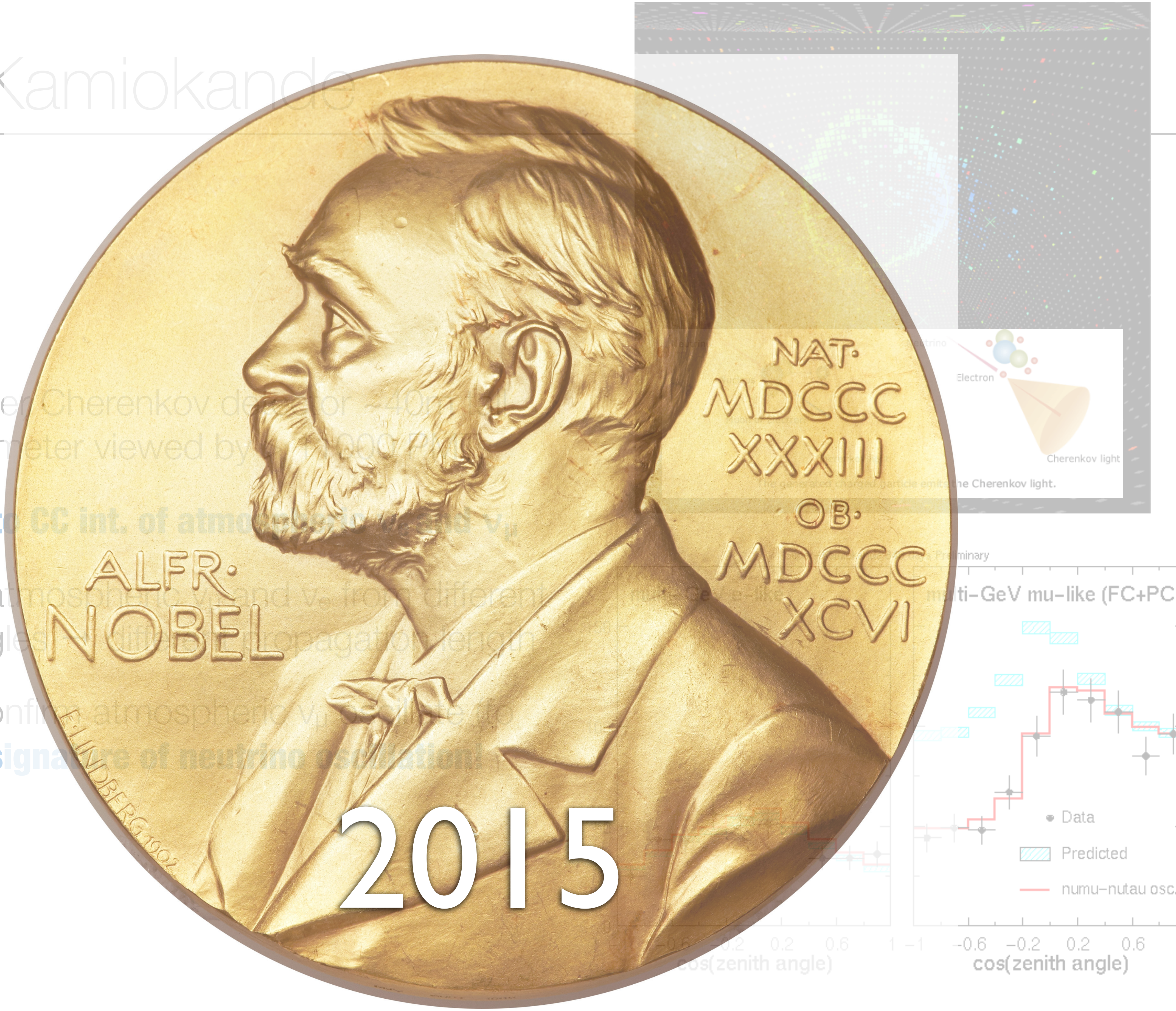
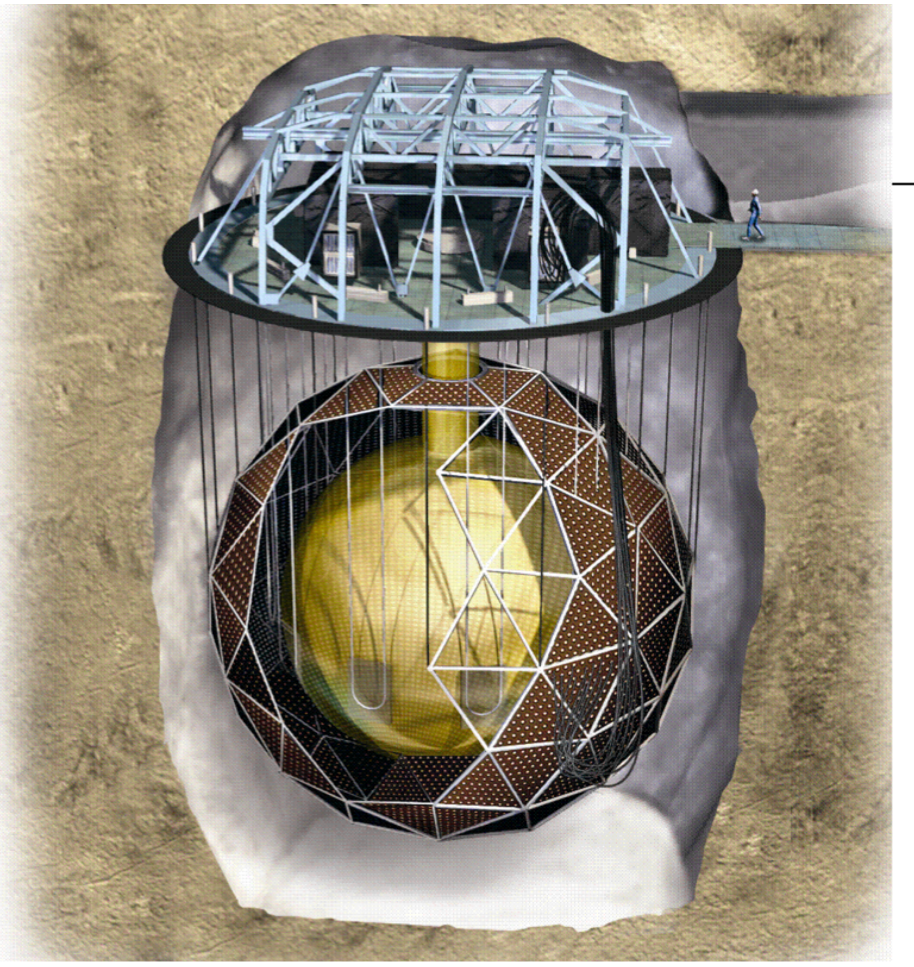
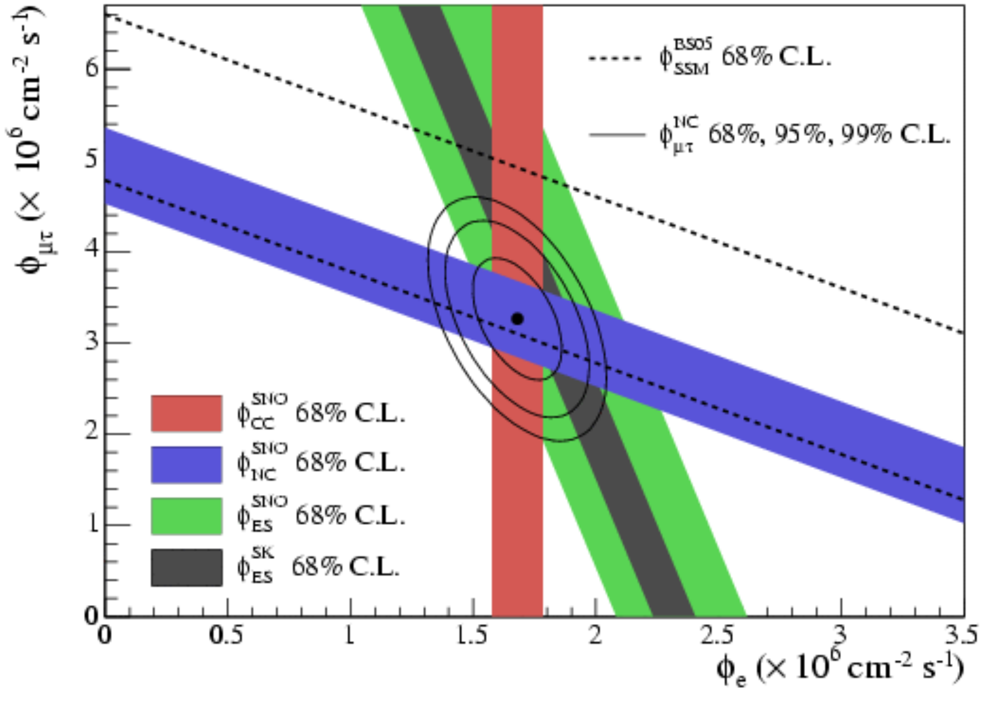


SNO



- 1 kT heavy water tank (~12 m diameter) viewed by 9’600 PMT
- **Sensitive to CC, NC and Elastic Scattering**
- Solar ν_e energies < 10 MeV: CC for ν_μ and ν_τ are forbidden ($E < M_{\mu/\tau}$)
- CC (ν_e only) : ~1/3 of expected flux
- NC (all flavour) : Expected flux
- 2001 - Confirm solar neutrinos emitted as ν_e reach the Earth as **mixture of ν_e, ν_μ and ν_τ**



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KamLAND, MINOS, and others…

KamLAND:

- **Confirmation** of solar neutrino L/E oscillation with reactor neutrino
- **Precise measurement of θ_{12} and Δm_{12}**

MINOS:

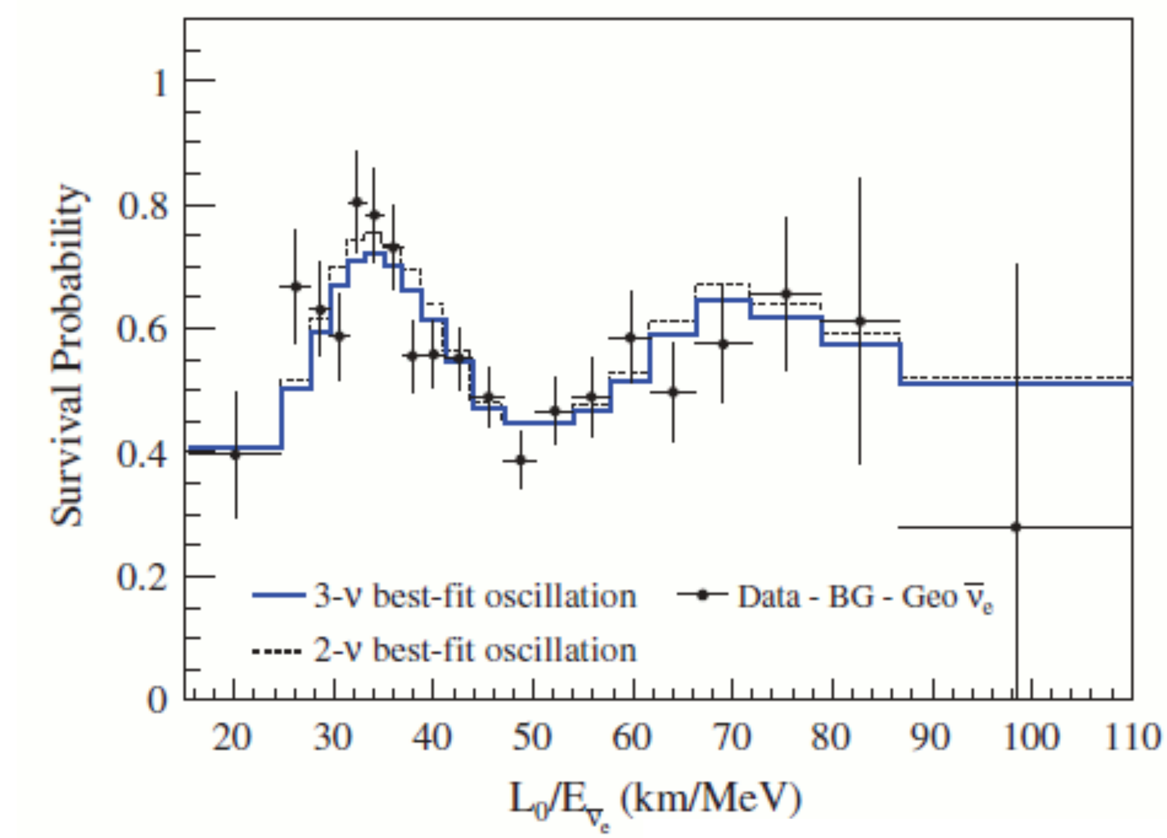
- Confirmation of atmospheric neutrino oscillation with accelerator neutrino
- **Precise measurement of θ_{23} and Δm_{32}**

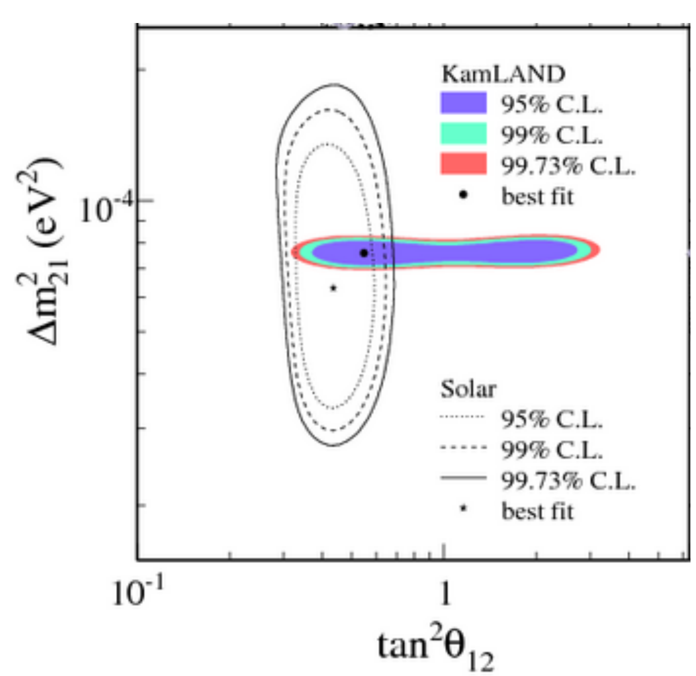
OPERA:

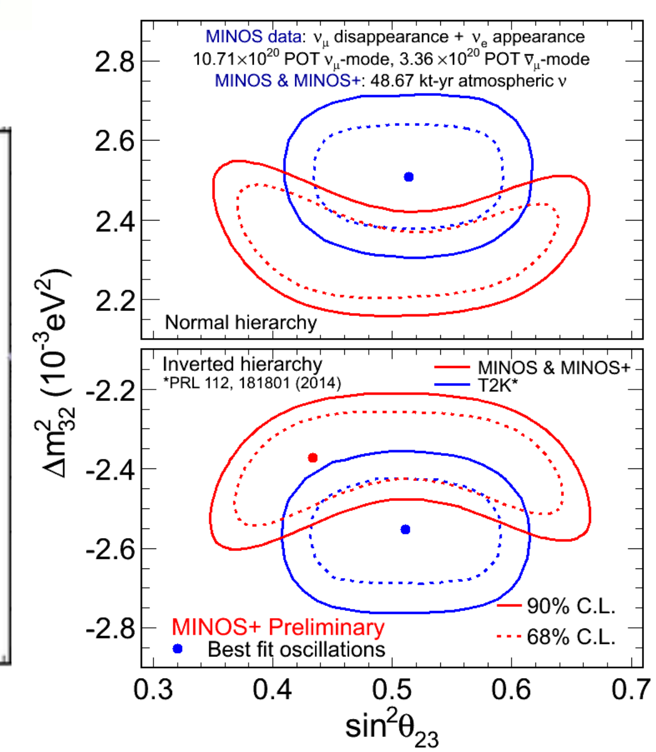
- **Direct** detection of $\nu_\mu \rightarrow \nu_\tau$ oscillation

Borexino:

- **Precise** solar neutrino physics…







Hunting θ_{13}, the last missing angle…till 2011

The most difficult angle to measure: quite small value w.r.t. other oscillation parameters

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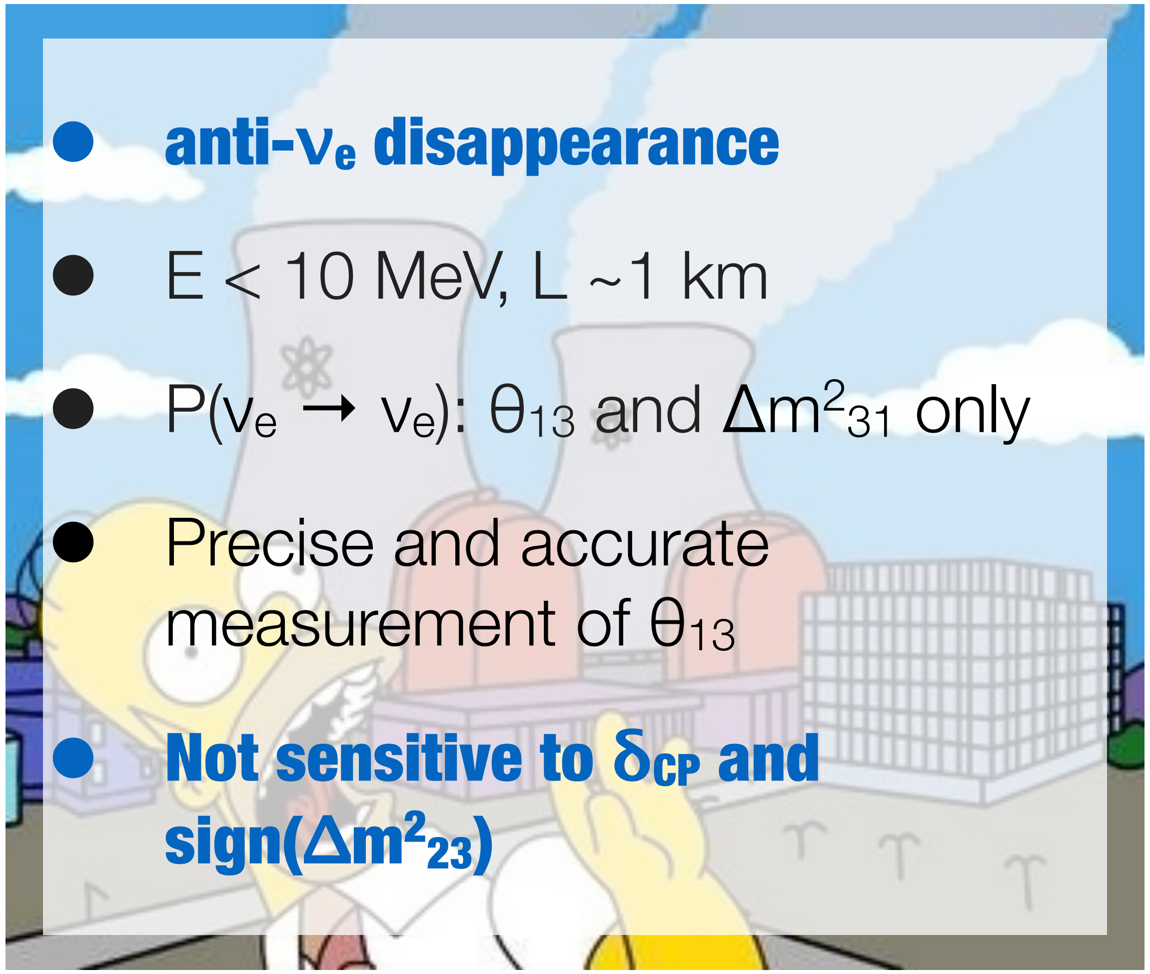
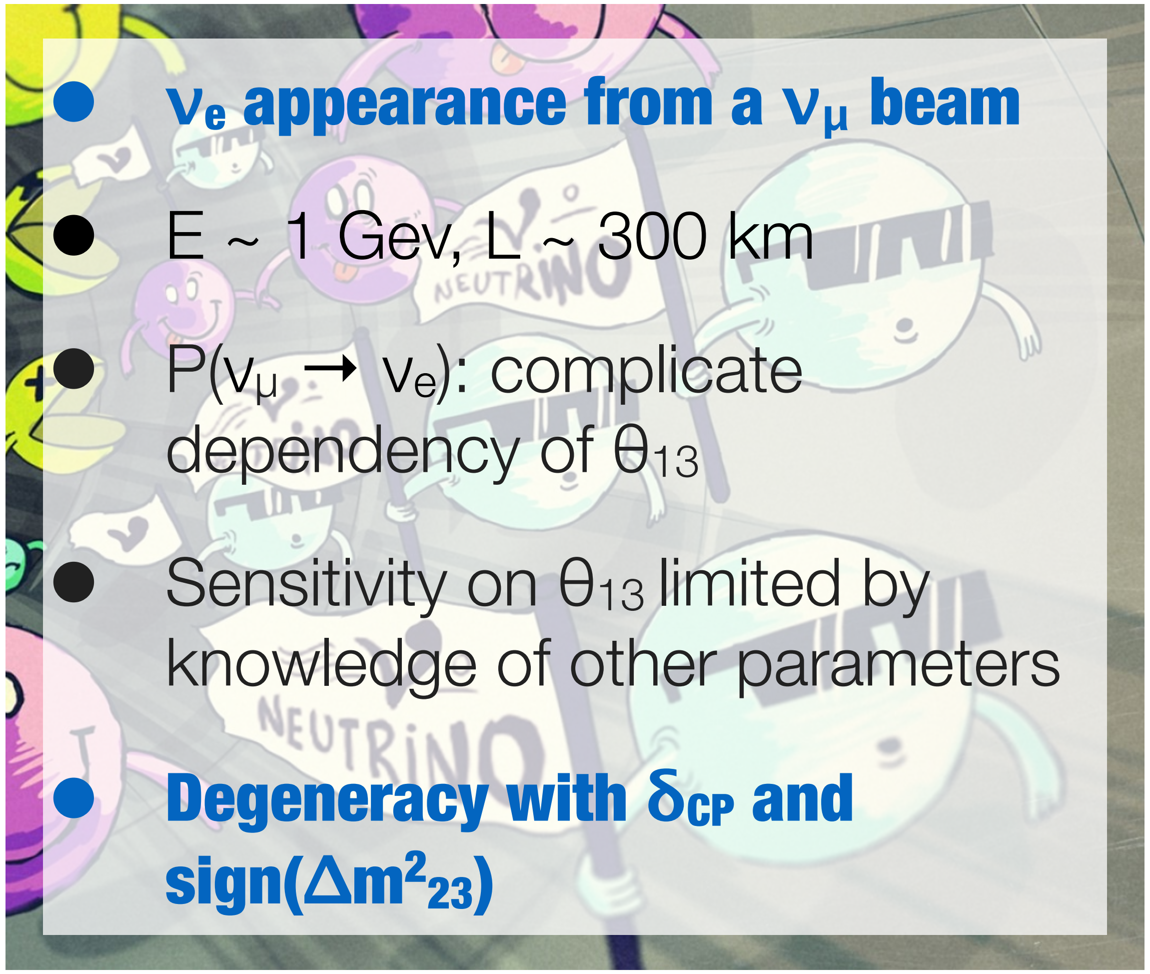


- **anti-ν_e disappearance**
- E < 10 MeV, L ~1 km
- $P(\nu_e \rightarrow \nu_e)$: θ_{13} and Δm^2_{31} only
- Precise and accurate measurement of θ_{13}
- **Not sensitive to δ_{CP} and sign(Δm^2_{23})**



- **ν_e appearance from a ν_μ beam**
- E ~ 1 Gev, L ~ 300 km
- $P(\nu_\mu \rightarrow \nu_e)$: complicate dependency of θ_{13}
- Sensitivity on θ_{13} limited by knowledge of other parameters
- **Degeneracy with δ_{CP} and sign(Δm^2_{23})**

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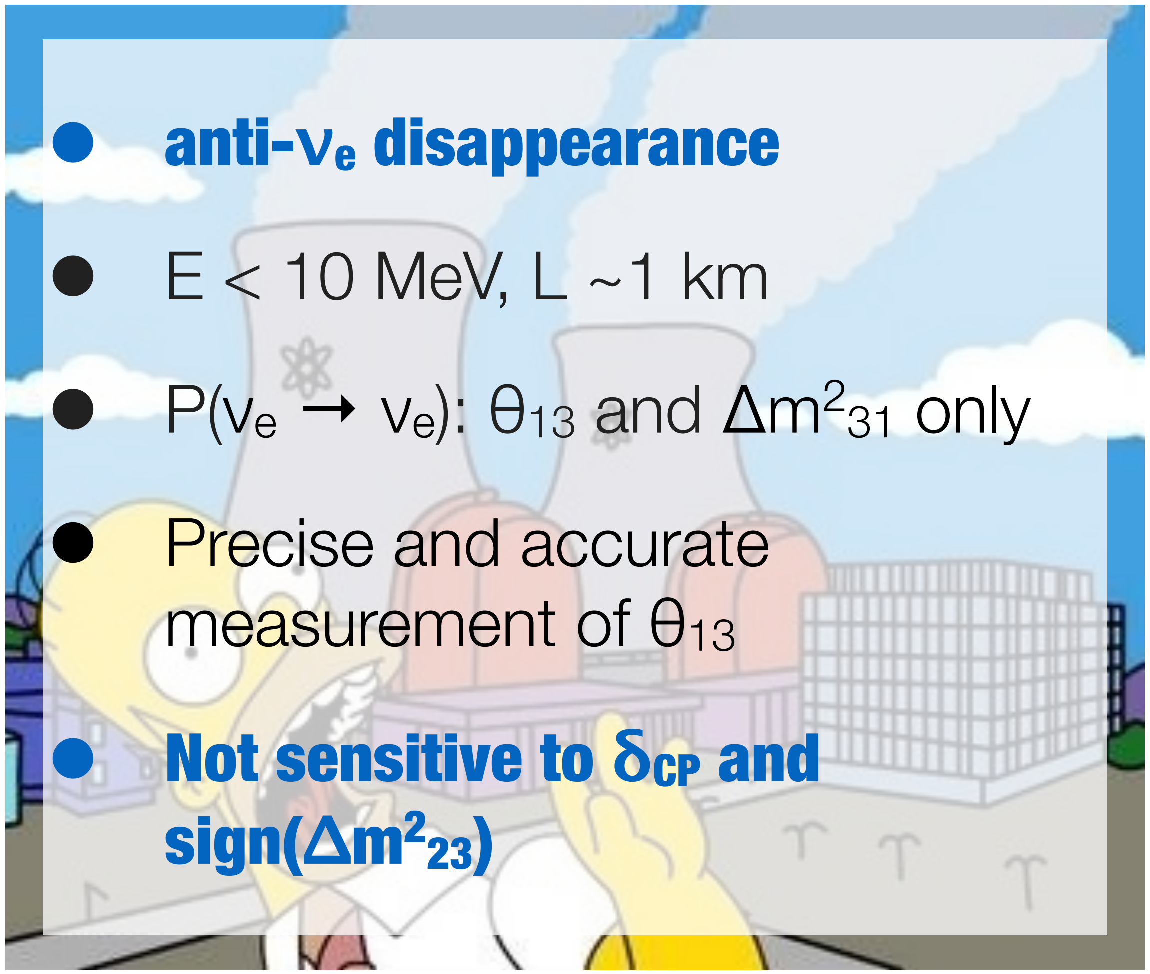

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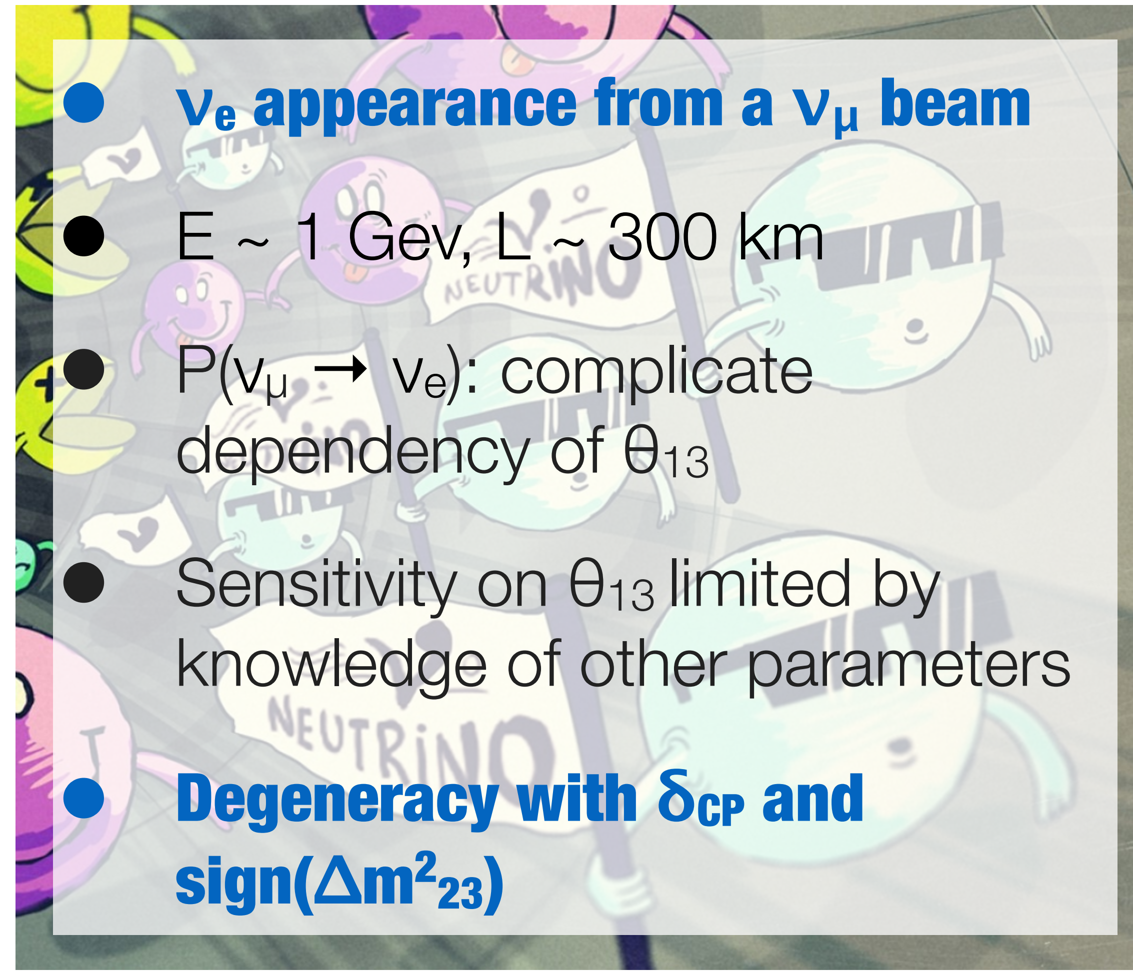

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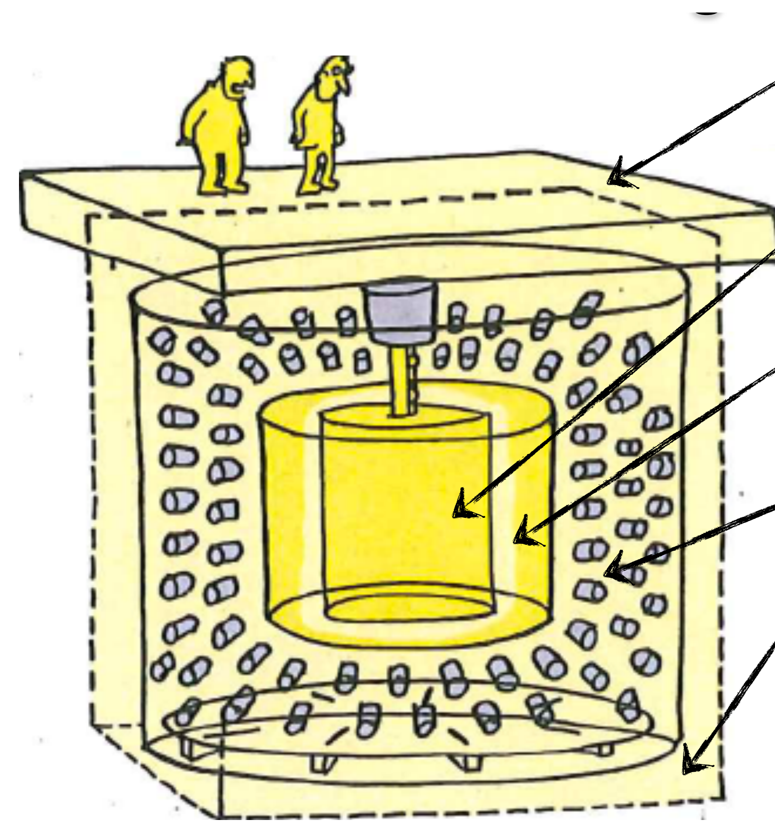
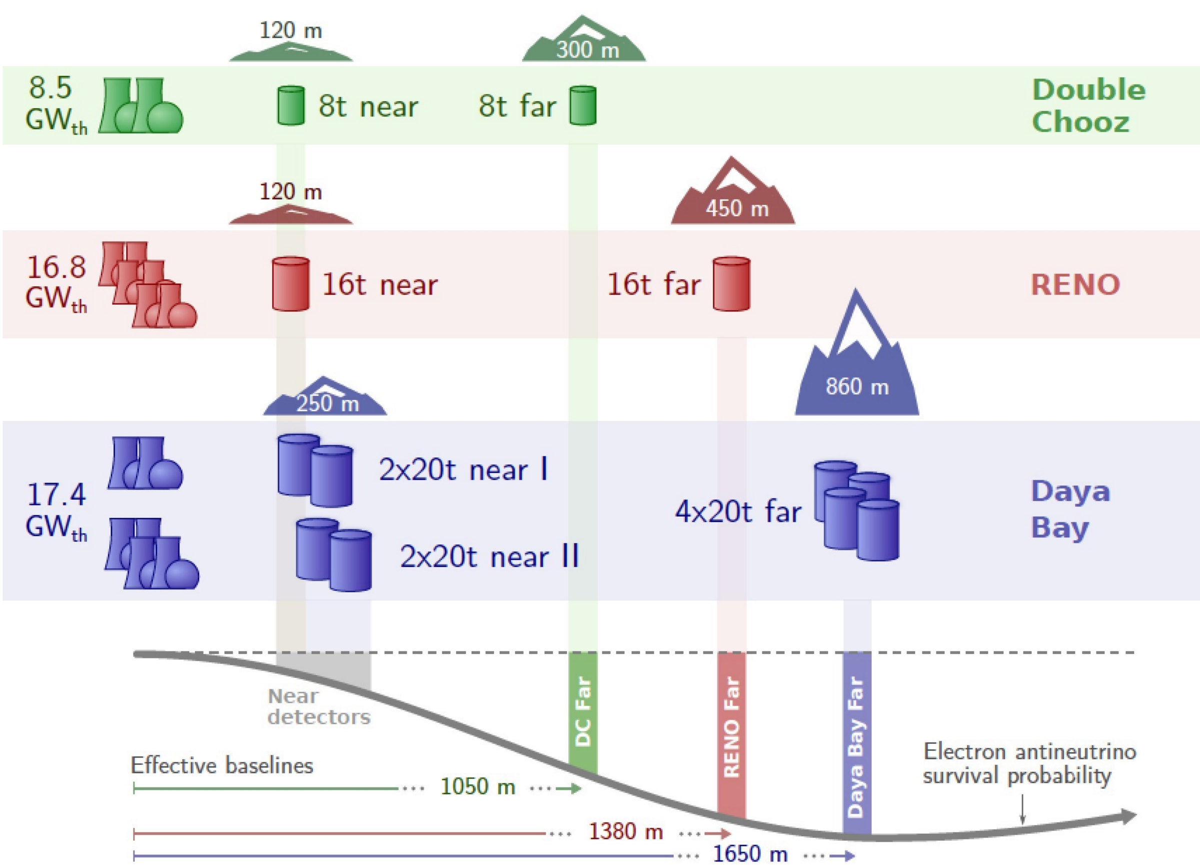
- 2011 - first indication of non zero θ_{13} from T2K [PRL 107, 041801 (2011)]
- 2012 - first indication of non zero θ_{13} from Double Chooz [PRL 108, 131801, (2012)]
- 2012 - measurement of θ_{13} from Daya Bay [PRL 108, 171803] and RENO [PRL 108, 191802]
- 2013 - Observation of ν_e appearance from T2K [PRL 112, 061802 (2014)]

θ_{13} @ reactor (DayaBay and others)

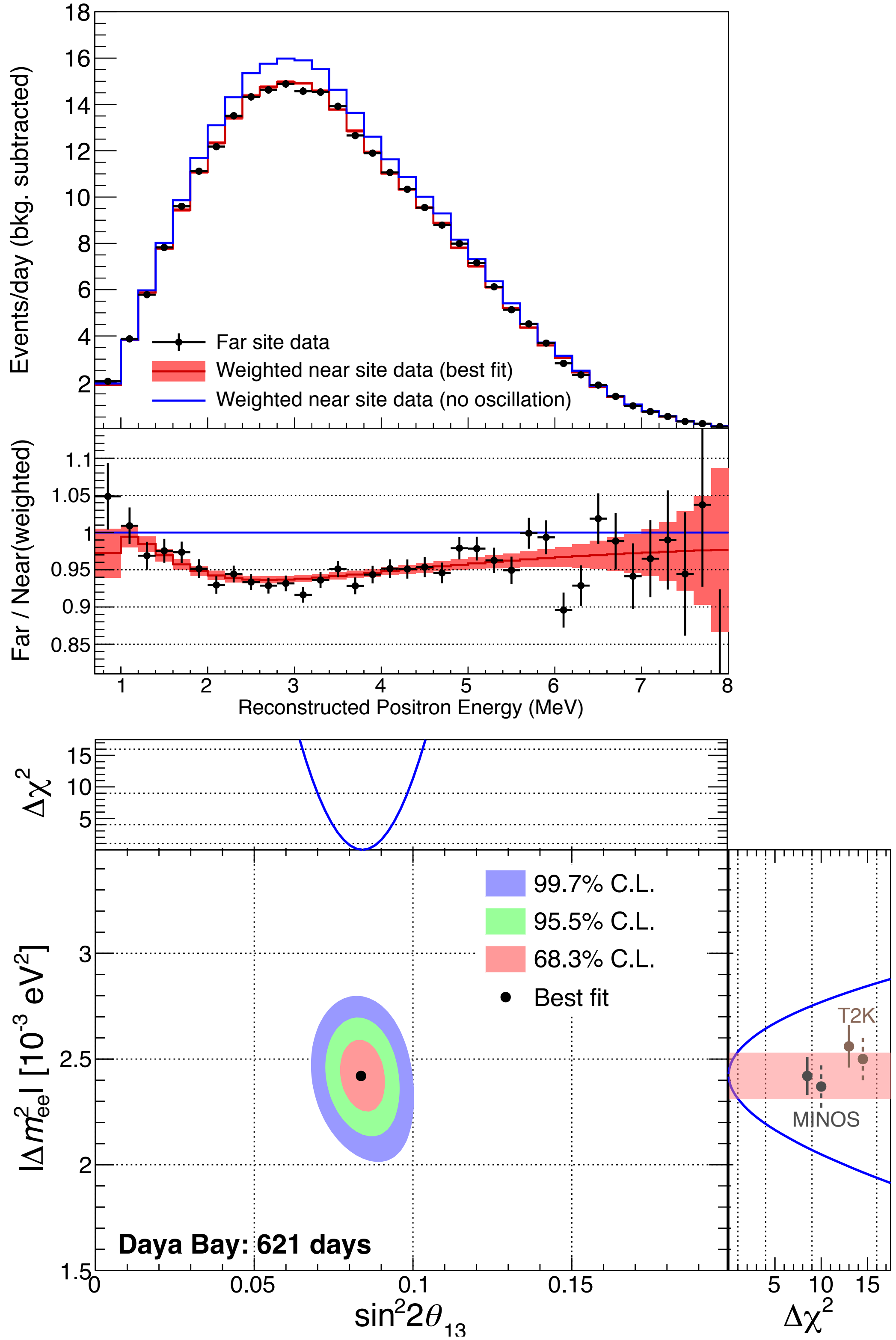
- **Daya Bay, Double Chooz & RENO**
- Similar detector design
- Different baselines, reactor powers and detector mass





- Inverse-β decay with delayed **n capture on Gadolinium**
- Near detector to **constrain un-oscillated reactor ν_e flux**
- Far detector to **measure oscillated ν_e flux**

θ_{13} @ reactor (Daya Bay and others)



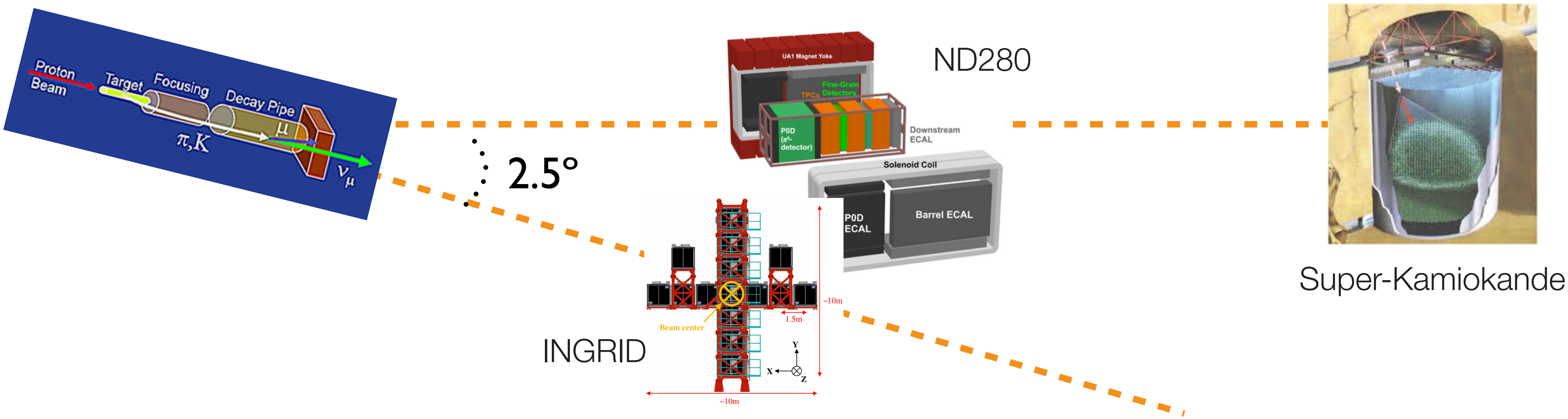
- Best measurement of θ_{13} by Daya Bay
- θ_{13} from **shape distortion** in energy spectrum: P ~ $\sin^2(L/E)$
- Reduce systematic uncertainty with Near detector measurement

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} eV^2$$

[arXiv:1505.03456]

θ_{13} @ T2K



- High intensity ~700 MeV ν_μ beam (off-axis) produced from a 30 GeV protons @ J-PARC
- Neutrinos observed in different detectors:

@ INGRID (on-axis near detector) : beam direction and intensity monitoring

@ ND280 (off-axis near detector) : neutrino flux measurement **before** oscillation

@ Super-Kamiokande (off-axis far detector): neutrino flux measurement **after** oscillation

+ NA61/SHINE (at CERN) to **constrain flux systematics** → **See Matej's talk**

Neutrino oscillation @ T2K

- Compare oscillated flux @ SK w.r.t unoscillated flux at ND280
- ND280 — SK extrapolation: main source of systematics → **See Francesco's talk**

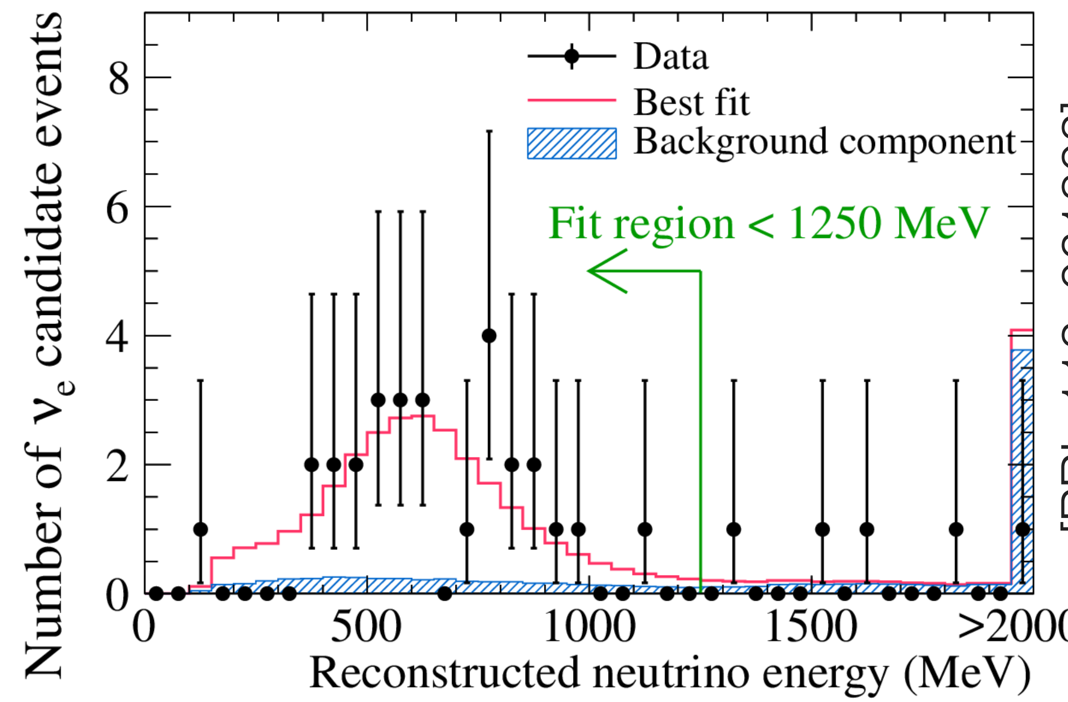
ν_e appearance mode: θ_{13} (and δ_{CP}):

- 28 evt. obs. (4.9 ± 0.6 exp. if no oscillation)
- 7.3σ significance to non-zero θ_{13}

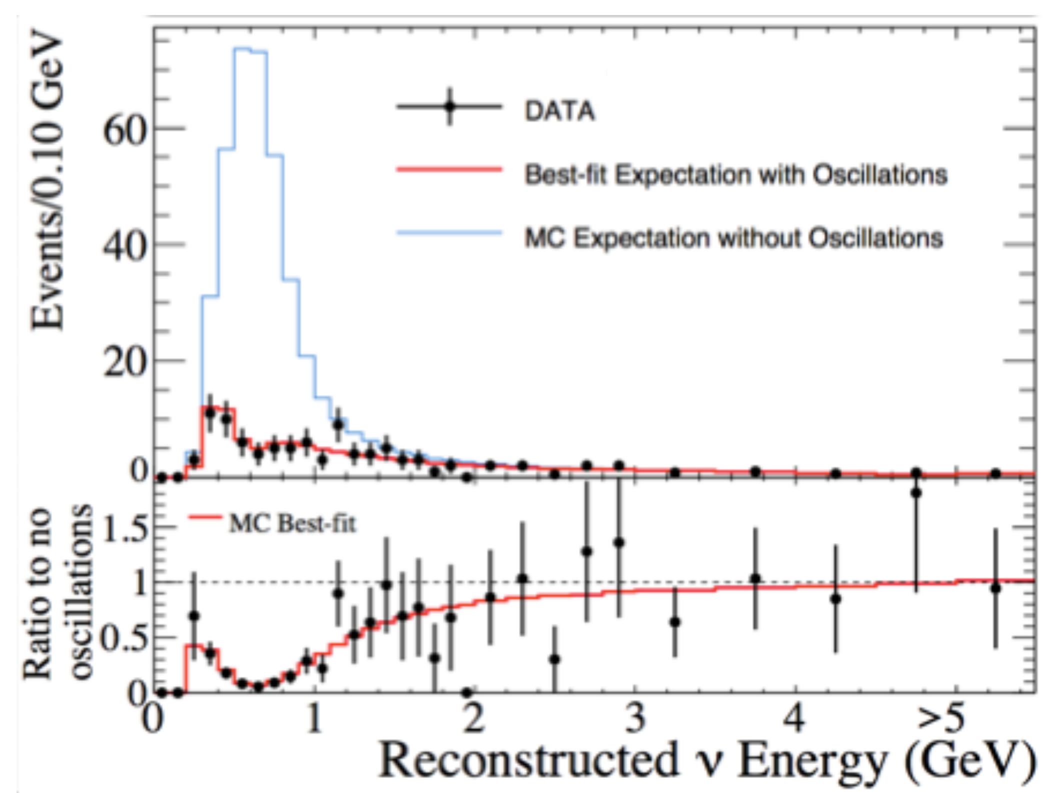
ν_μ disappearance mode: θ_{23} and Δm^2_{23}:

- 120 evt. obs. (446 ± 23 exp. if no oscillation)
- world leading measurement of the mixing angle θ_{23}

Recently start running in anti-ν_μ mode [NuFact2015]



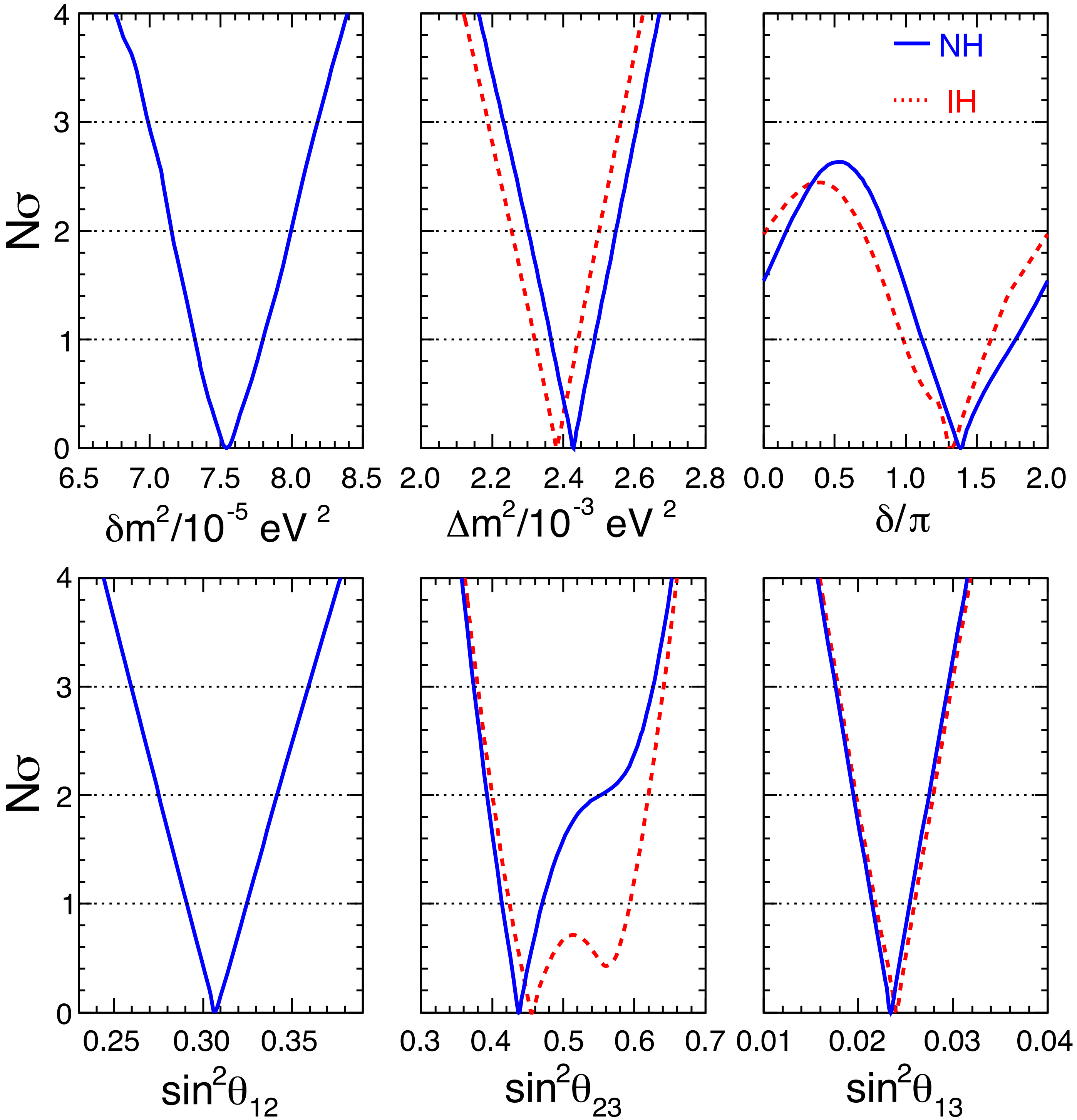
[PRL 112, 061802]



[PRL 112, 181801]

Oscillation: a comprehensive summary

LBL Acc + Solar + KL + SBL Reactors + SK Atm



- [x] θ_{12} , θ_{23}, θ_{13}
- [x] Δm^2_{13}, Δm^2_{23}
- [ ] Sign of Δm^2_{23}
- [ ] θ_{23} octant
- [ ] δ_{CP}

Parameter	Best fit	1σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.37 – 2.49
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.38	2.32 – 2.44
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.15 – 2.54
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	2.18 – 2.59
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.37	4.14 – 4.70
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.55	4.24 – 5.94
δ/π (NH)	1.39	1.12 – 1.77
δ/π (IH)	1.31	0.98 – 1.60

[PRD 89, 093018 (2014)]


STEVEN SPIELBERG PRESENTS
BACK TO THE FUTURE
PG
A ROBERT ZEMECKIS FILM
OUTATIME

Mass hierarchy?

CP Violation?

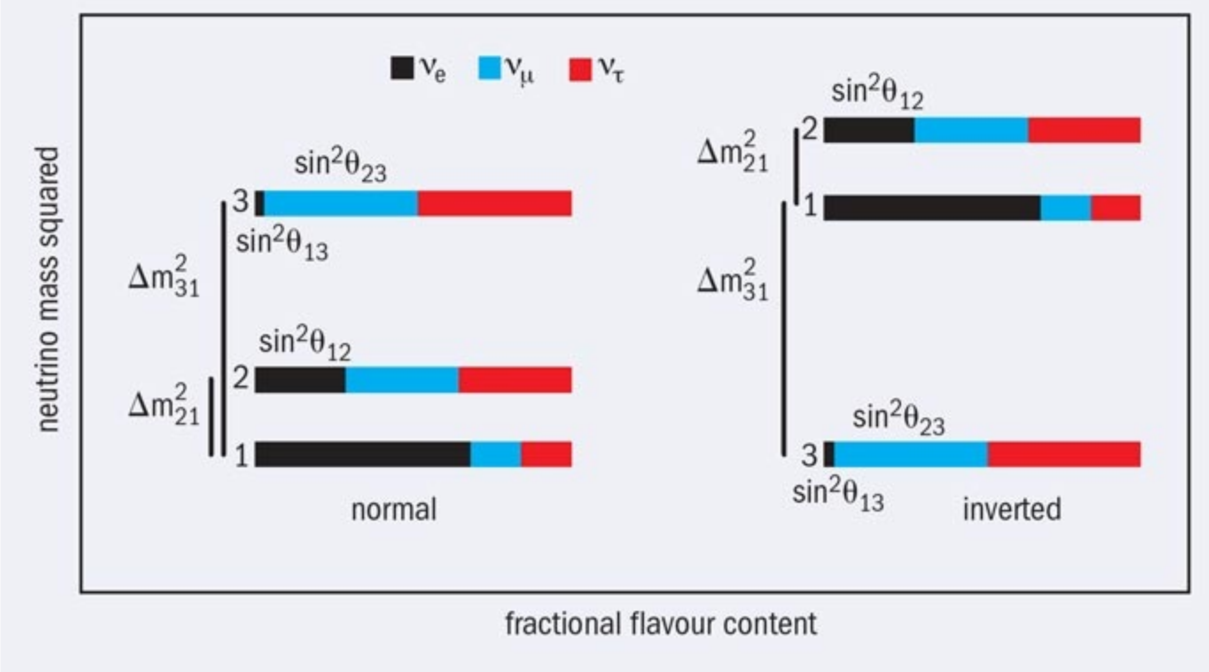
Sterile neutrinos?

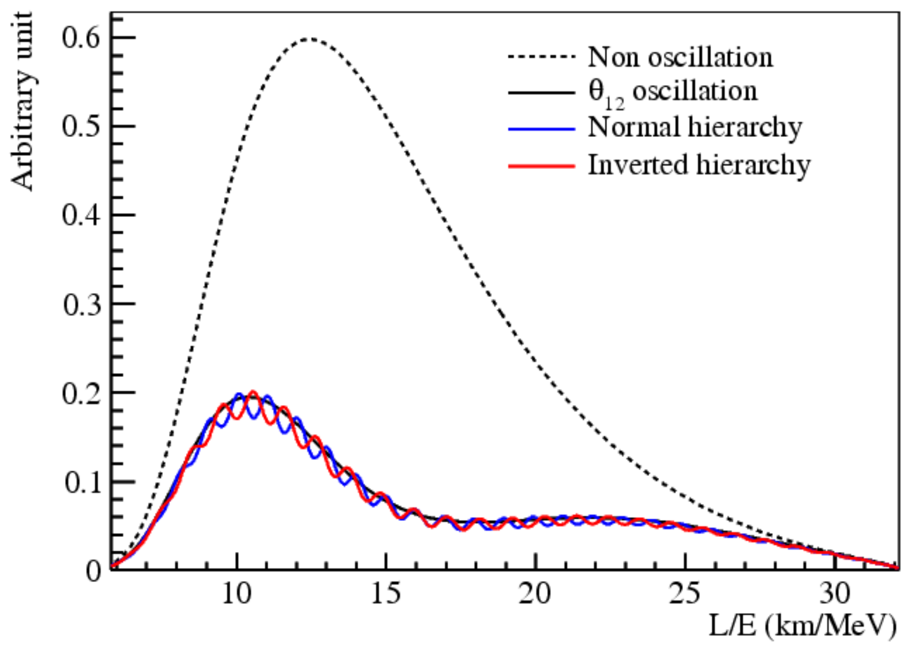
Neutrino masses?

Dirac/Majorana?

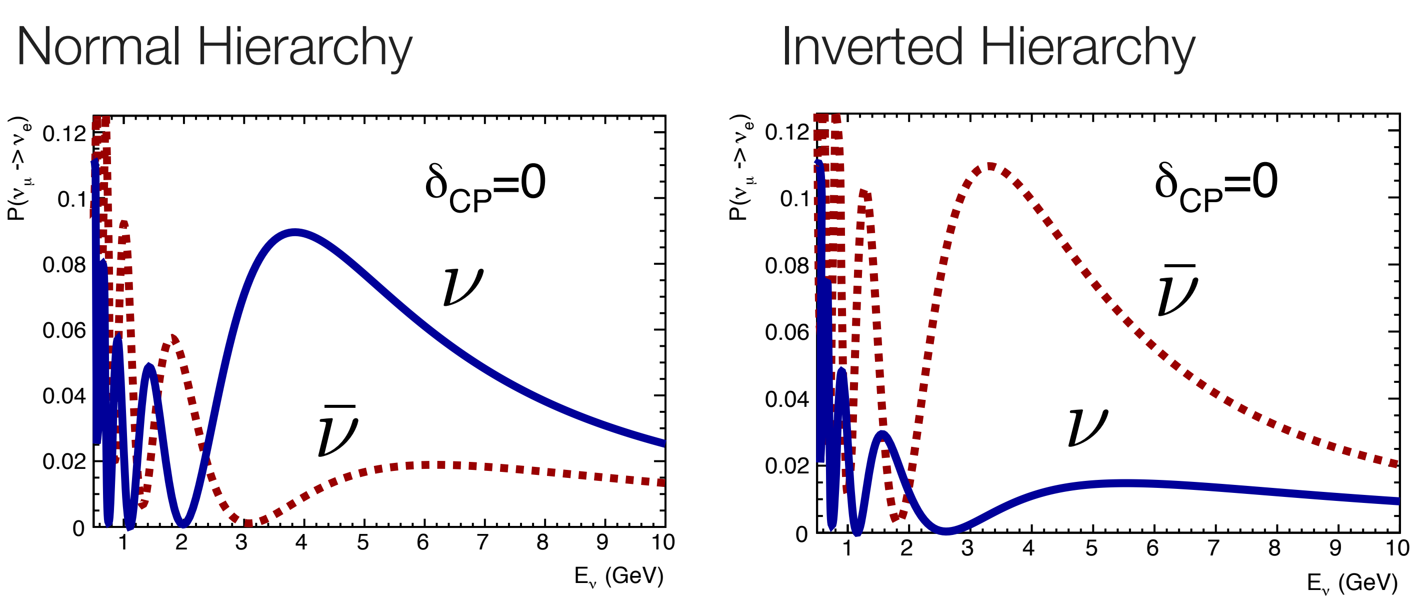
The problem of the mass hierarchy

- Frequency of the oscillation probability depends on $|\Delta m^2|$ at first order
- **Sub-leading effects** depend on the MH, but hard to highlight
- **Matter effect** enhances ν/anti-ν oscillation depending on the MH
- Different strategies but **beyond 2020**





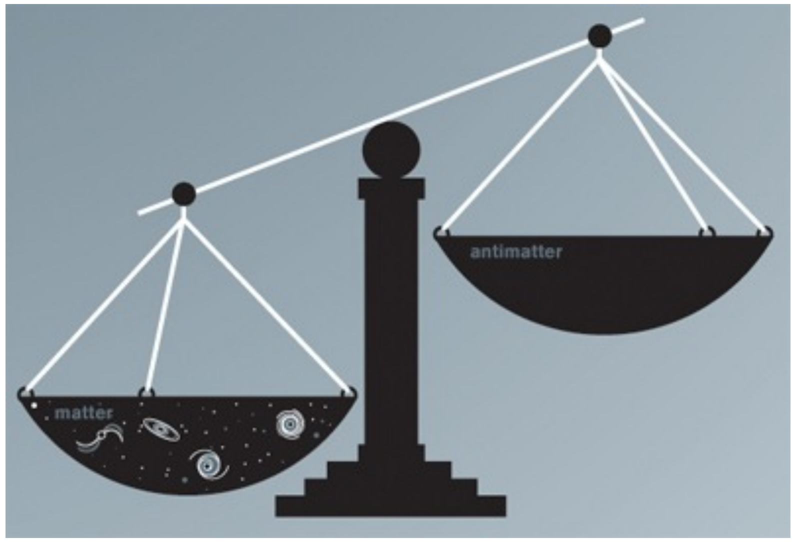
JUNO

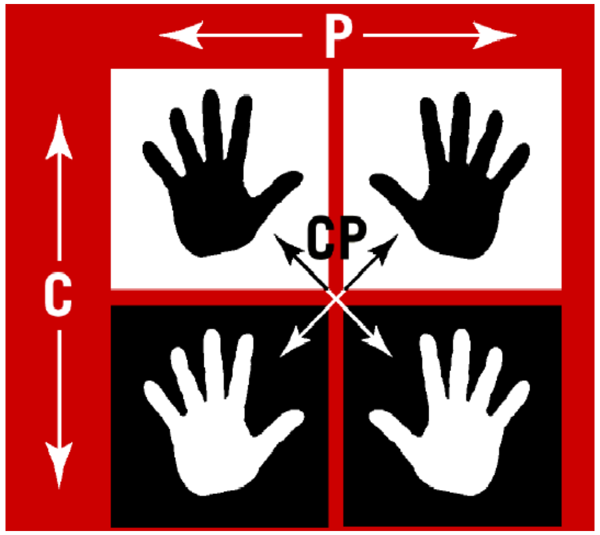


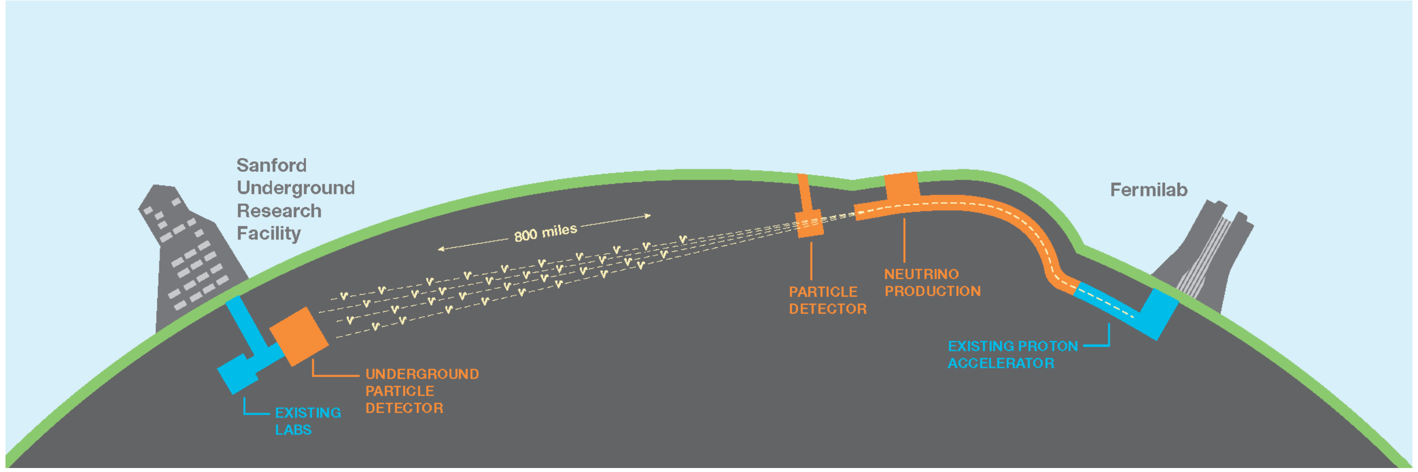
T2K+NOvA, ORCA, PINGU, DUNE

CP violation in the lepton sector

- Big-bang: symmetry between matter and antimatter
- Matter is dominant in the universe right now → asymmetry
- **CP violation in baryon sector** is not enough
- **CP violation in the lepton sector + leptogenesis** → might explain current asymmetry
- Planned DUNE/HyperK experiments aim to measure δ_{CP} with long baseline



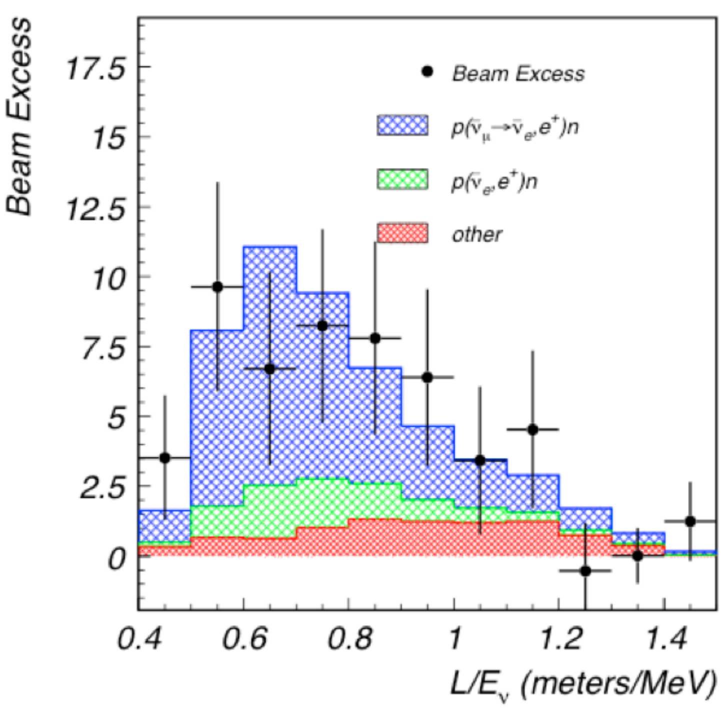


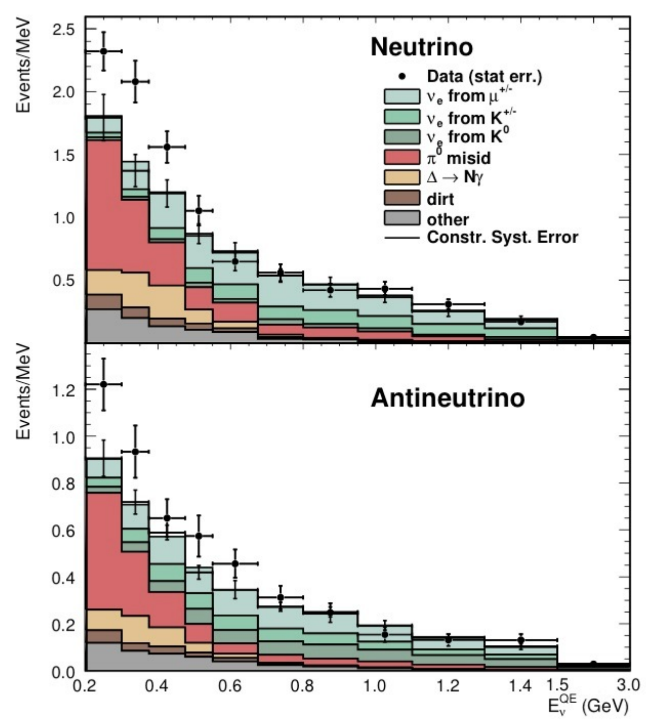


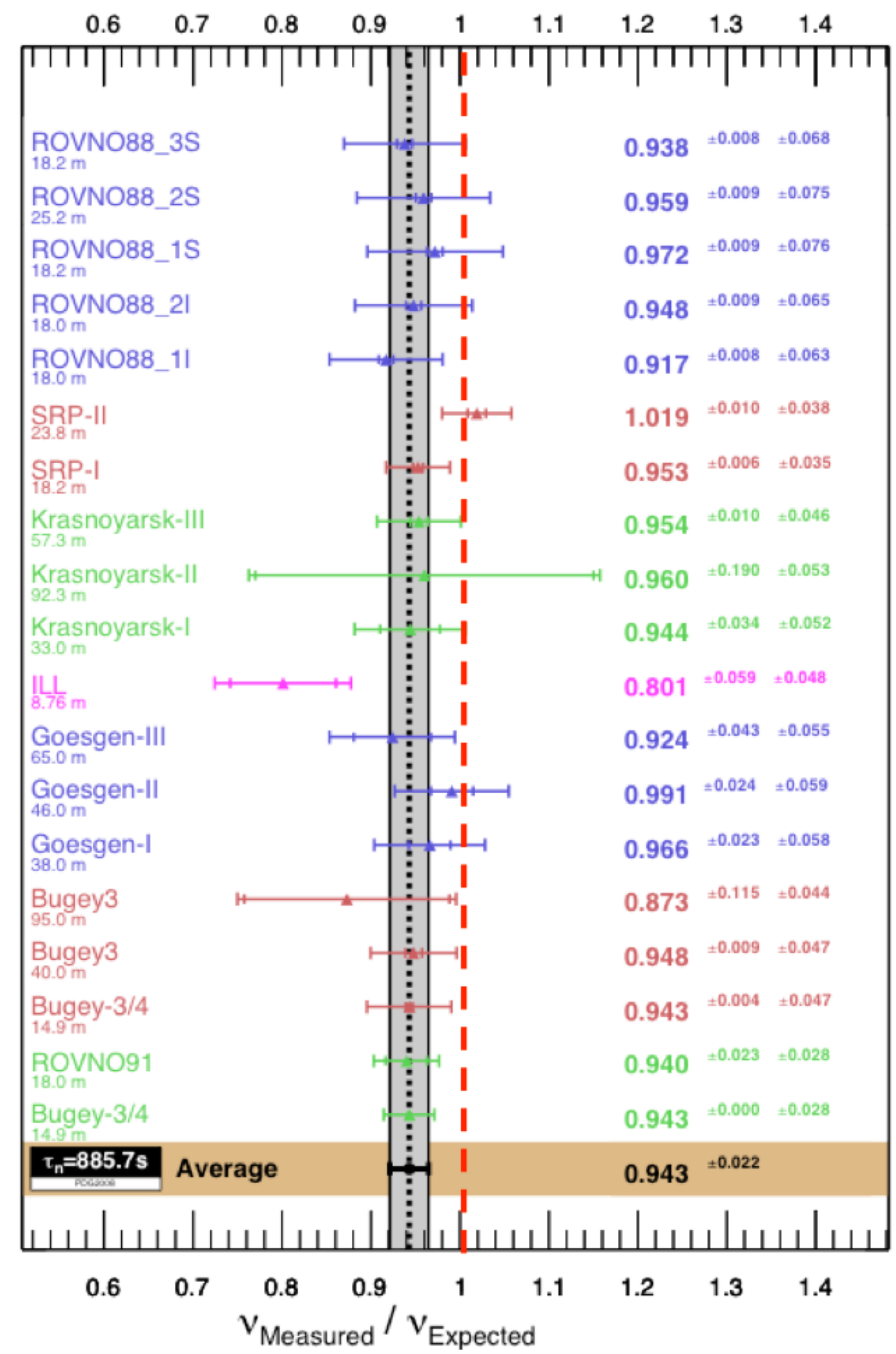
see Davide's talks

Like the solar and the atmospheric anomalies…

- Reactor anti-ν_e disappearance at very-short baseline
- LSND & MiniBooNE: ν_e appearance at high Δm^2
- **Additional neutrinos** may explain the anomalies
- LEP data constrain number of active neutrino: the additional neutrinos **must be sterile**



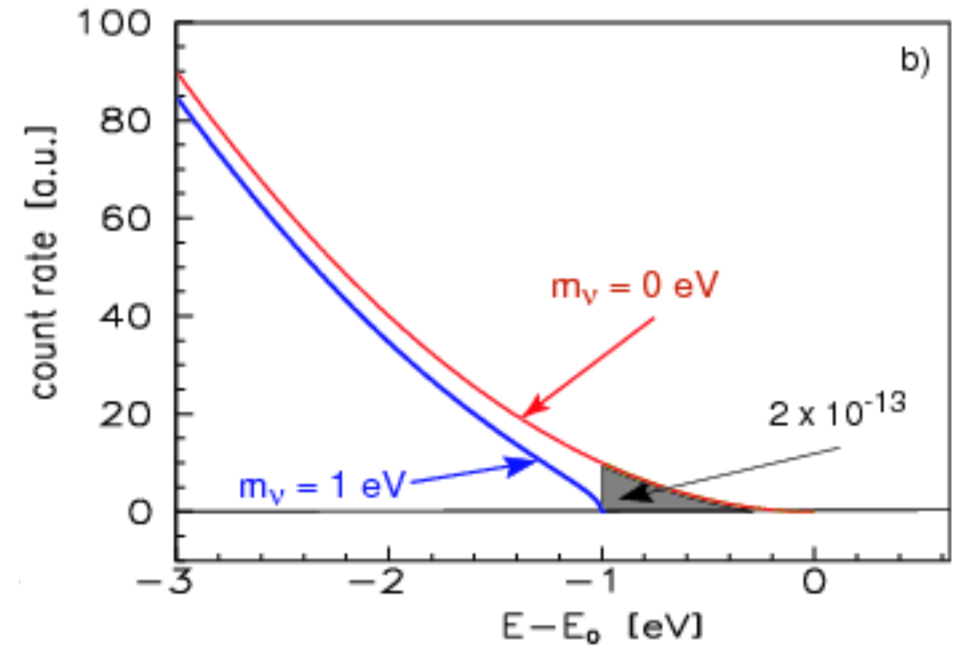


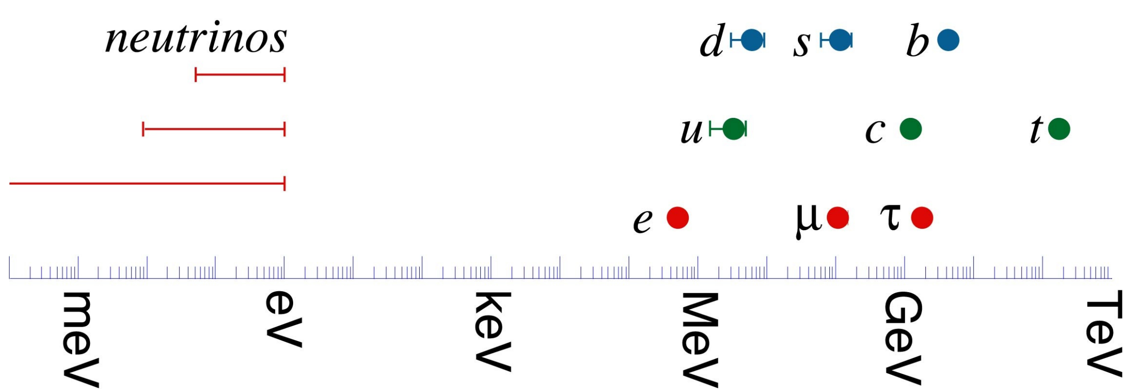


see Thomas' & Luis' talks

The problem of the mass

- Oscillations provide information about neutrino mass splittings
- **Direct** measurement of neutrino mass from precise measurement of ^{3}H β-decay gives $\mathbf{m_\nu \lesssim 1}$ **eV**
- **Indirect** limit from cosmological observation (Plank 2015) $\mathbf{\Sigma m \lesssim 0.2}$ **eV**





$$\mathcal{L}_D = m_D(\nu_L \bar{\nu}_R + \bar{\nu}_L \nu_R)$$

$$m_D = \frac{v}{\sqrt{2}} Y_\nu \longleftarrow Y_\nu \simeq 10^{-12}$$

$(Y_e \sim 0.3 \times 10^{-5})$

- The smallness of ν masses is also an issue, **Higgs coupling is "unnatural"**
- **See-saw** mechanism as possible explanation but **requires Majorana neutrinos**

$$\nu_R = C\bar{\nu}_L^T = (\nu_L)^C$$

$$m = \frac{m_D^2}{m_R}$$

m_D^2 ← Higgs-coupled

m_R ← Arbitrary big

Neutrino-less double beta decay

- The neutrino is the only massive fermion to be neutral
- Could be its own antiparticle: **Majorana particle**
- The only practical way to test Majorana/Dirac nature:

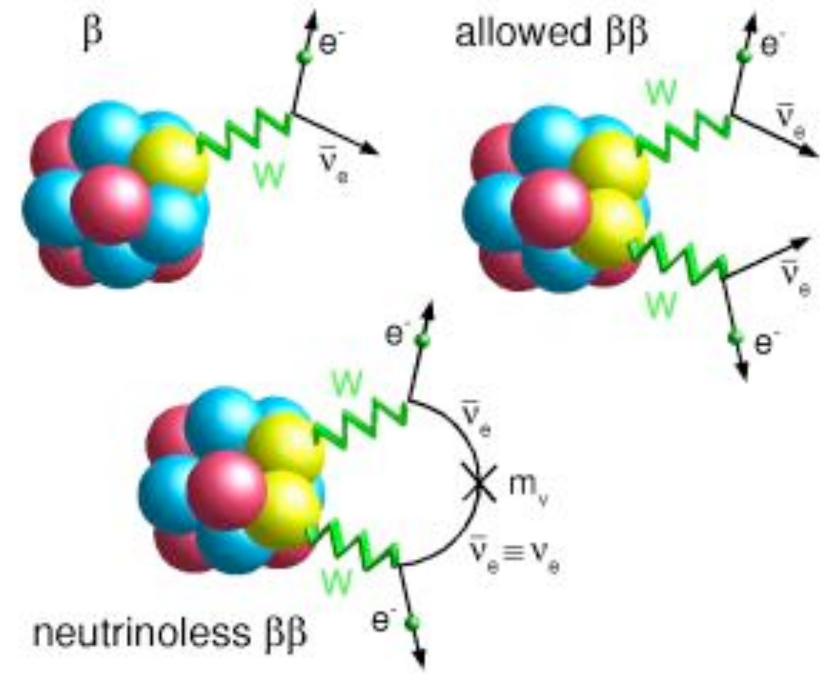
2νββ decay: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

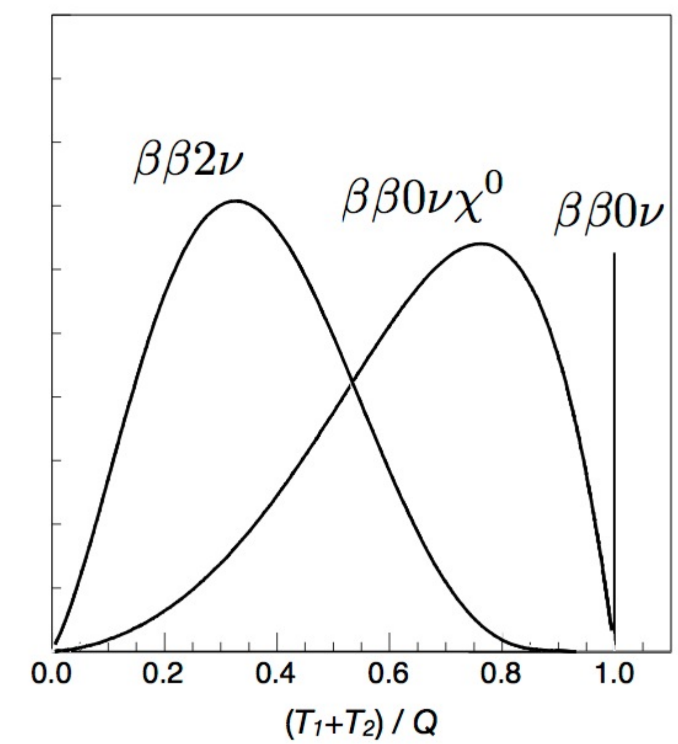
0νββ decay: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

- process **forbidden** in the SM

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\eta^2$$

- Light Majorana neutrino exchange
- Right-handed current (V+A), SUSY, Majoron(s), etc.





see Steven's talks


That's all Folks!

- Neutrino physics full unexpected surprises
- First and only sign of physics beyond SM
- The only particle worth 4 nobel prizes
- Many open questions still waiting for answers