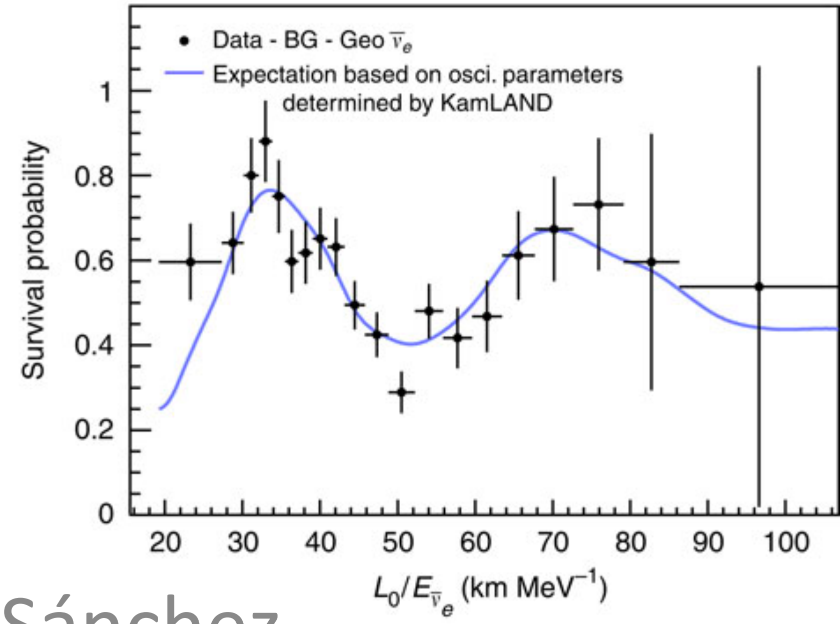
Neutrino oscillations



Pablo del Amo Sánchez

GraSPA

25/07/18

Overview

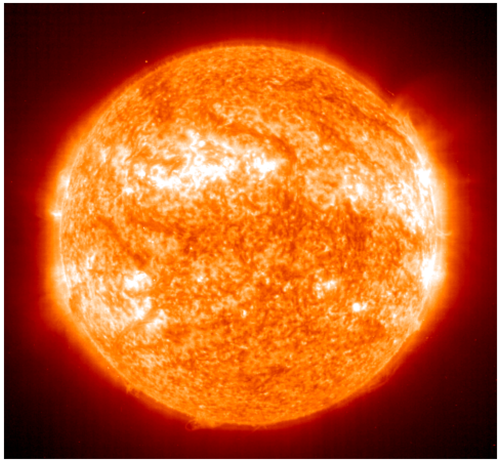
- Evidence for neutrino oscillations

  Non historical approach

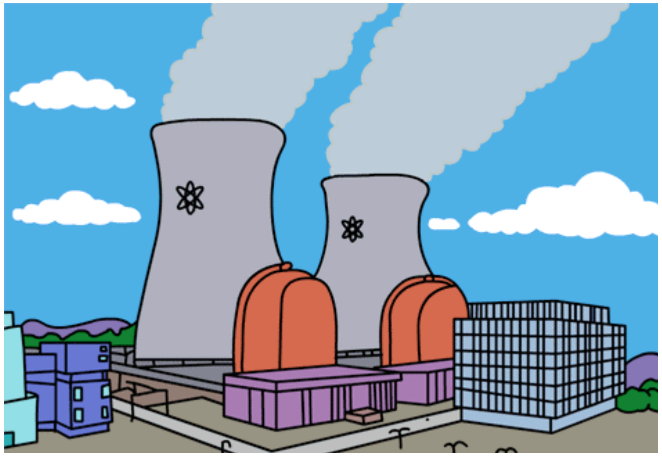
- How to go about detecting neutrinos

ν sources

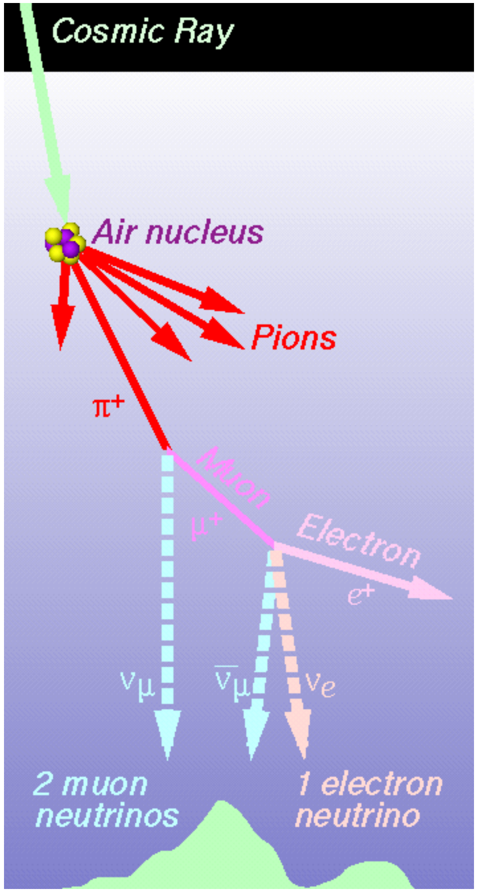
The Sun
$65\times10^{9}\ \nu_e\ \mathrm{cm^{-2}\ s^{-1}}$ at Earth



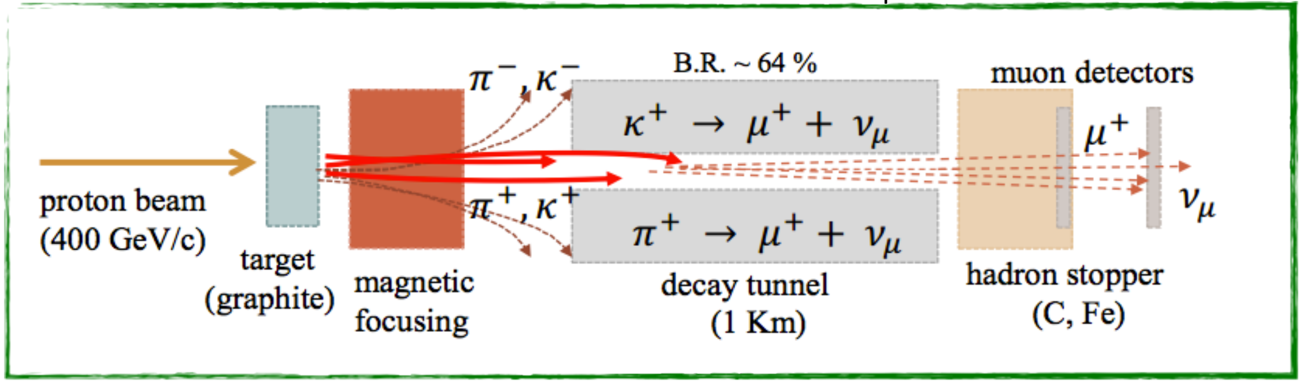
Nuclear reactors
$2\times10^{20}\ \overline{\nu}_e\ \mathrm{s^{-1}\ GW_{th}^{-1}}$



Atmospheric ν (cosmic rays)
$4\times10^{2}\ \nu_{\mu+e}\ \mathrm{m^{-2}\ s^{-1}\ sr^{-1}}$ at 1 GeV



Accelerators, e.g. at OPERA: $1\times10^{12}\ \nu_\mu\ \mathrm{m^{-2}}$



Plus: astrophysical neutrinos, CvB, etc

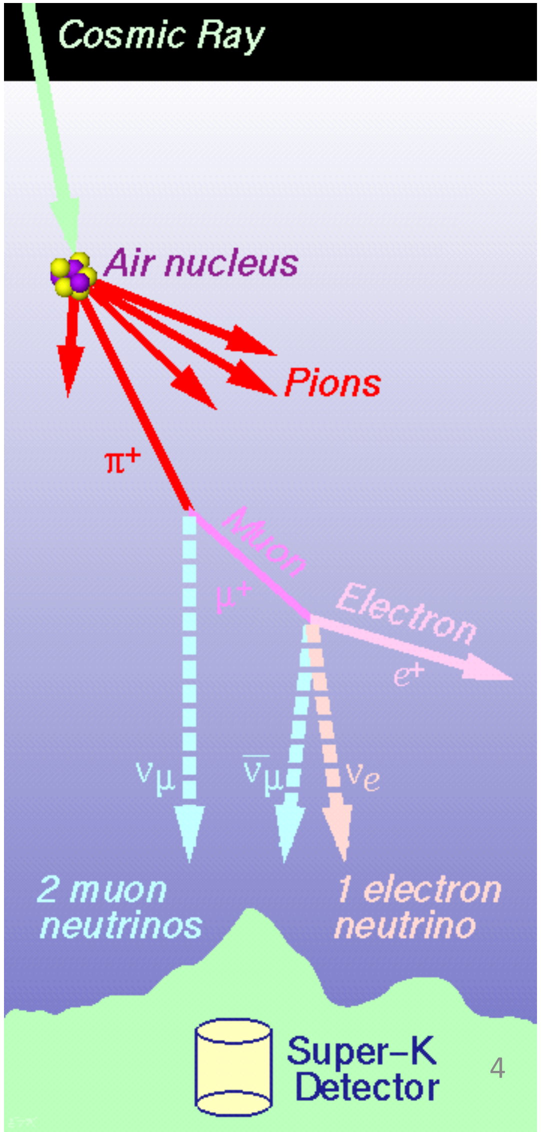
Atmospheric neutrinos

- Cosmic rays collisions in upper atmosphere (15 km)
- Plenty of pions from hadronic interactions
- $\pi^+ \rightarrow \mu^+\nu_\mu$ and $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$

so

$$\nu_\mu : \nu_e = 2 : 1$$

(known better than 3% below 5 GeV)



How to detect neutrinos?

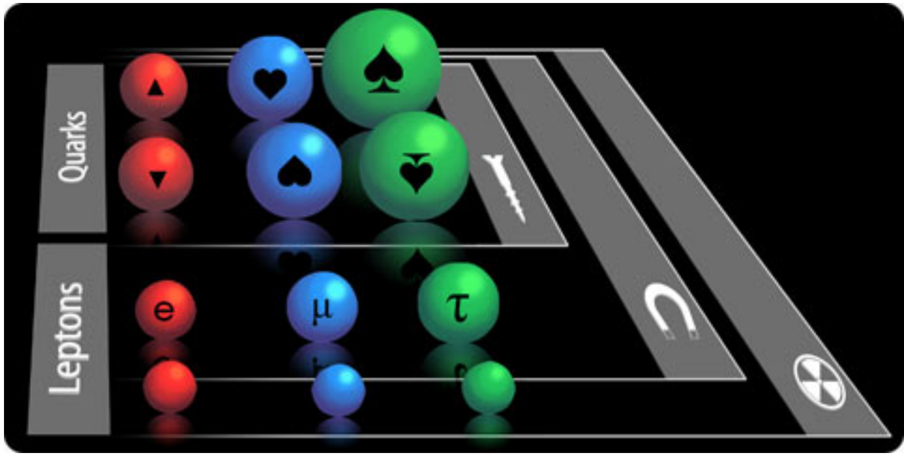
- ν electrically neutral

  → no ionization tracks!
- nearly massless

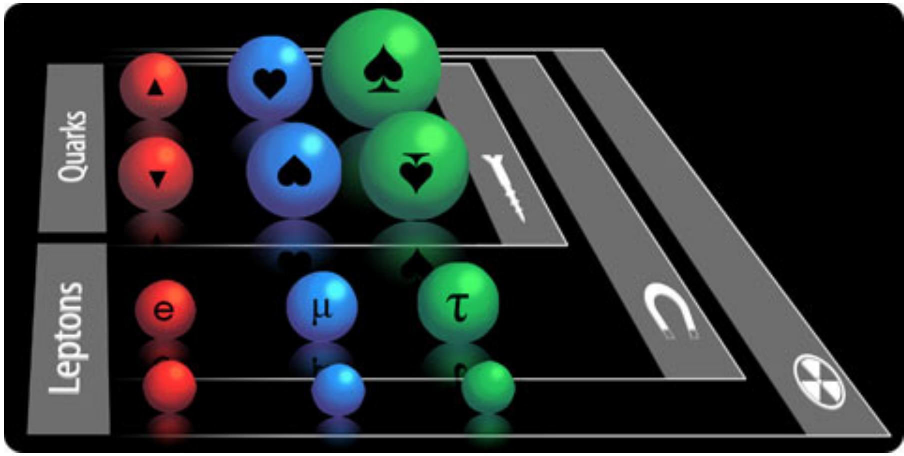
  → $m_\nu < 1$ eV but $\Sigma m_\nu > 0.06$ eV
- tiny interaction cross-section

  → $\sigma \approx 10^{-42}$ cm² for IBD

➔ need copious sources and/or large detector masses



How to detect neutrinos?



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➔ need copious sources and/or large detector masses

Ex: SuperKamiokaNDE

$R = \phi\, N_N\, \sigma_N$

$R = 5\ \nu_{\mu+e}$ evts/day

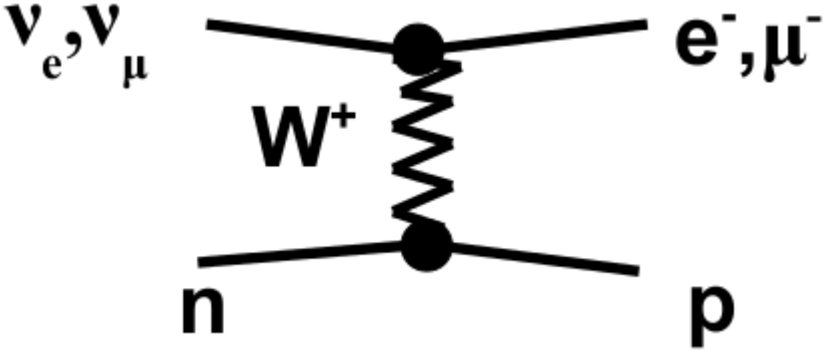
$\phi = 4\text{x}10^2\ \nu_{\mu+e}\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$ at 1 GeV = $0.5\ \text{cm}^{-2}\ \text{s}^{-1}$

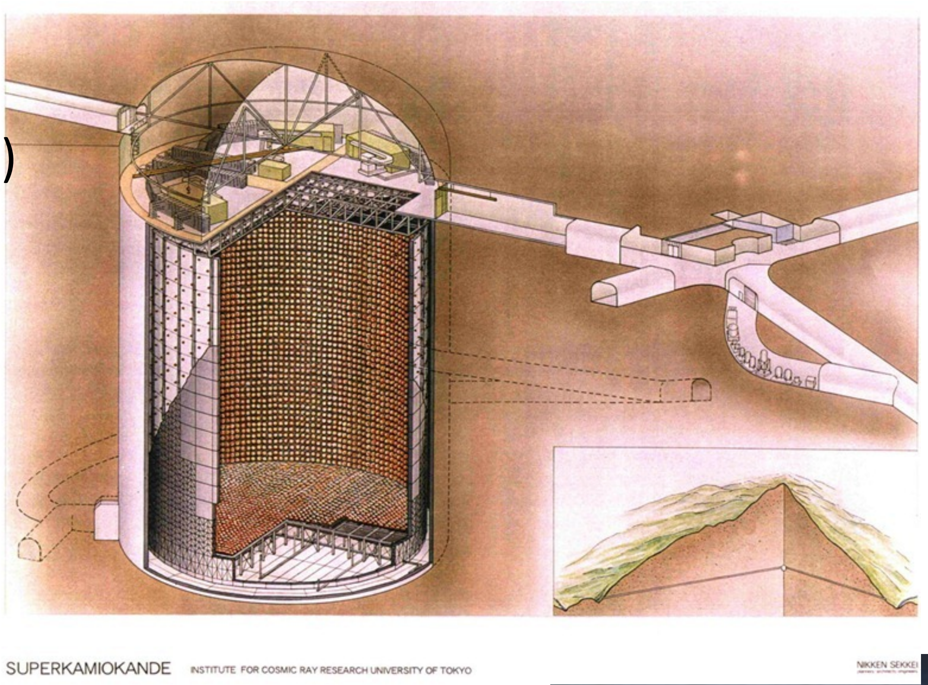
$\sigma_N = 10^{-38}$ cm^2 / nucleon at 1 GeV

$\Rightarrow N_N = 1.2\text{x}10^{38}$ nucleons $\Rightarrow$ $M = N_N \text{ x } 1.66\text{x}10^{-27}$ Kg = $19\text{x}10^6$ Kg = 19 ktonnes

Water Cerenkov detectors

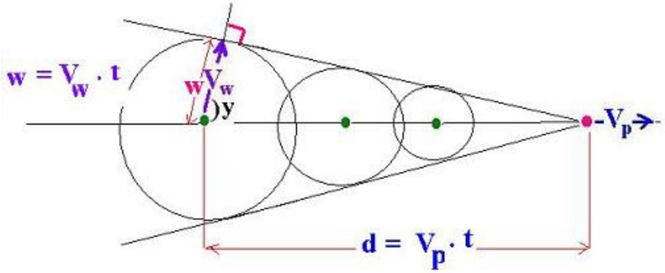
- Huge underground water tanks surrounded by photomultiplier tubes (PMTs)





- Interacting particles produce light, light gives electrical signal in PMTs

Cerenkov effect: particles faster than speed of light in medium radiate light (e.g. blueish light in nuclear reactors)



- Ex: (Super-)KamiokaNDE et SNO

Water Cerenkov detectors

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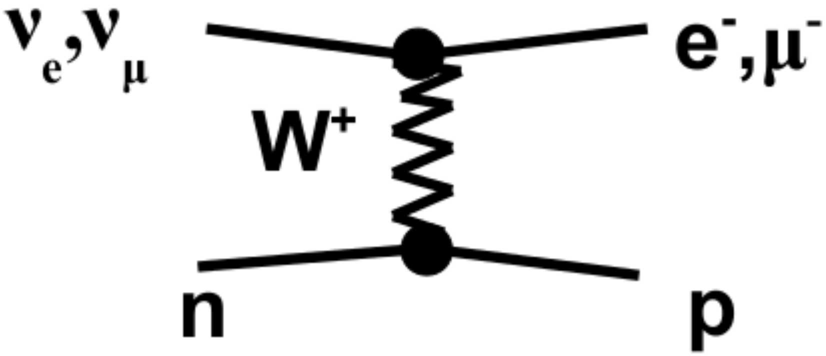

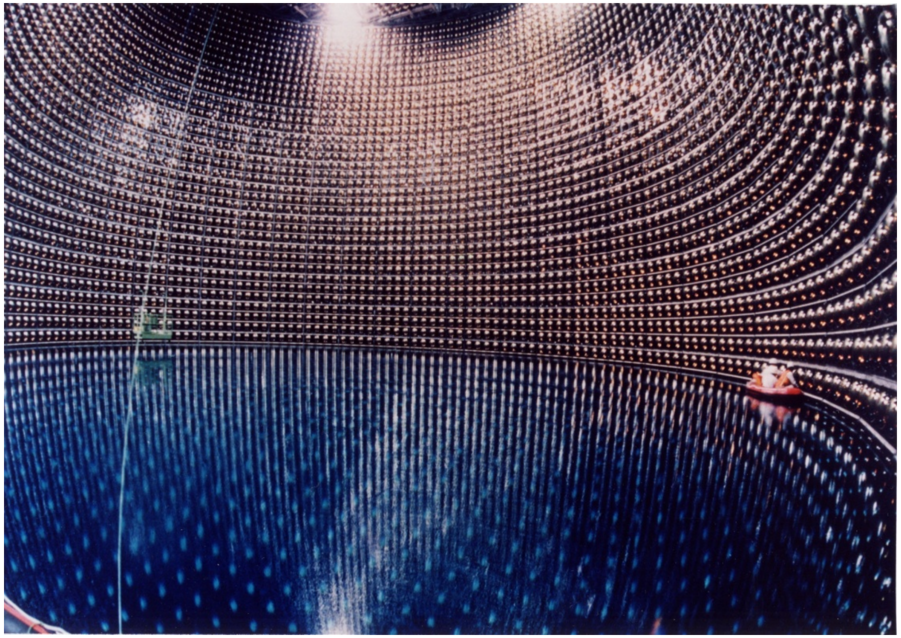

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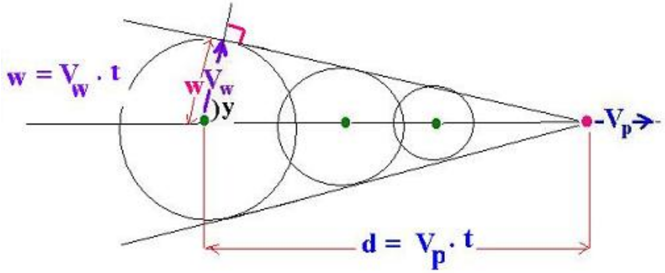
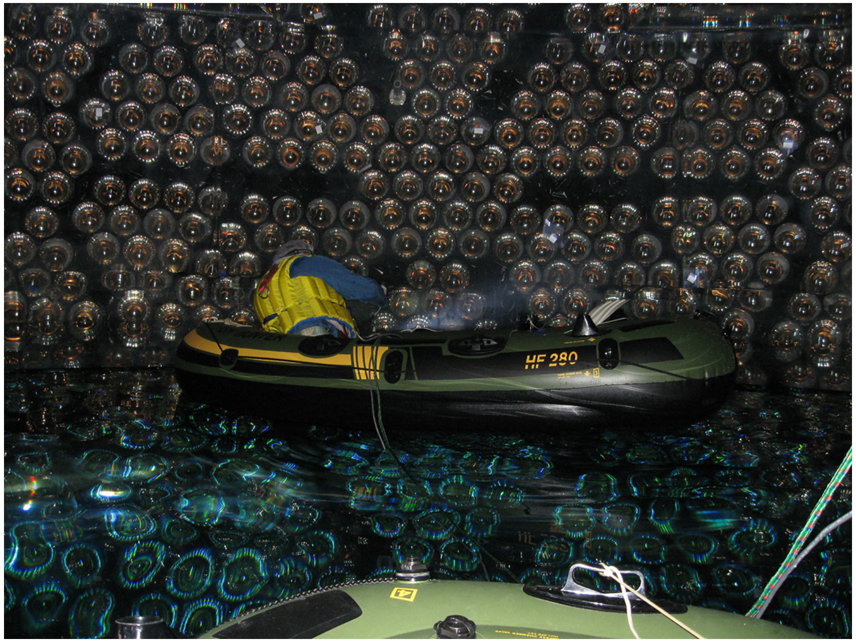
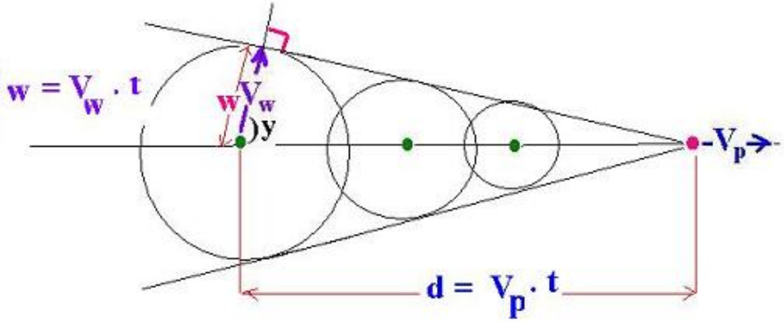
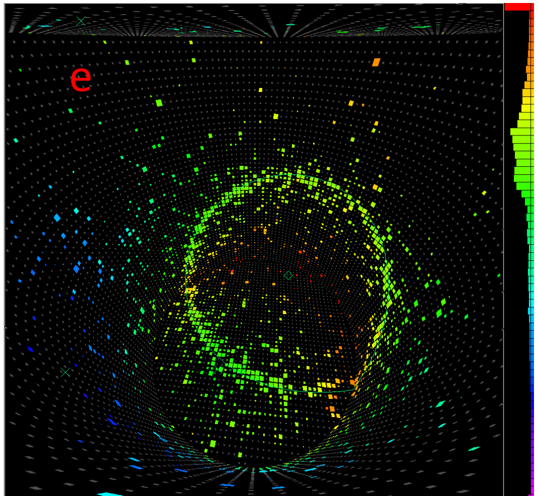


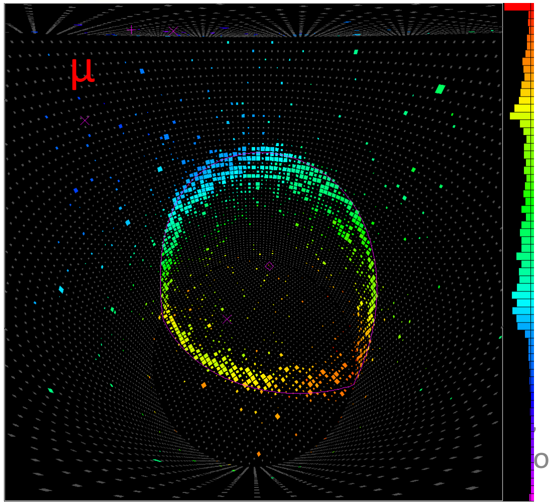
Water Cerenkov detectors

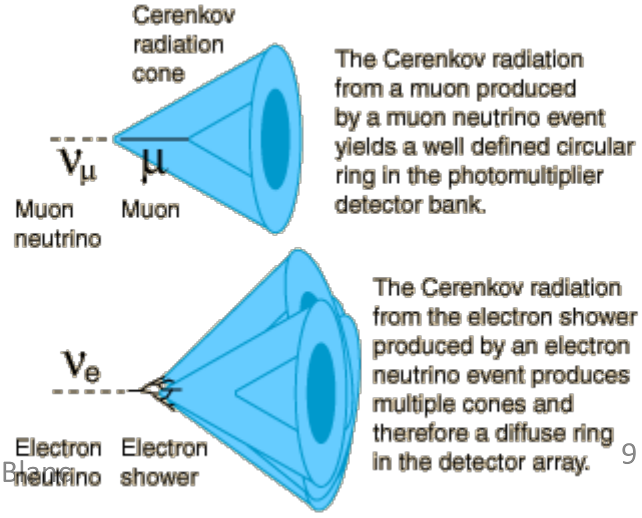
- SNO et (Super-)KamiokaNDE
- Directionality from Cerenkov cone
- Energy from total collected light
- Distinction between electrons and muons











The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.

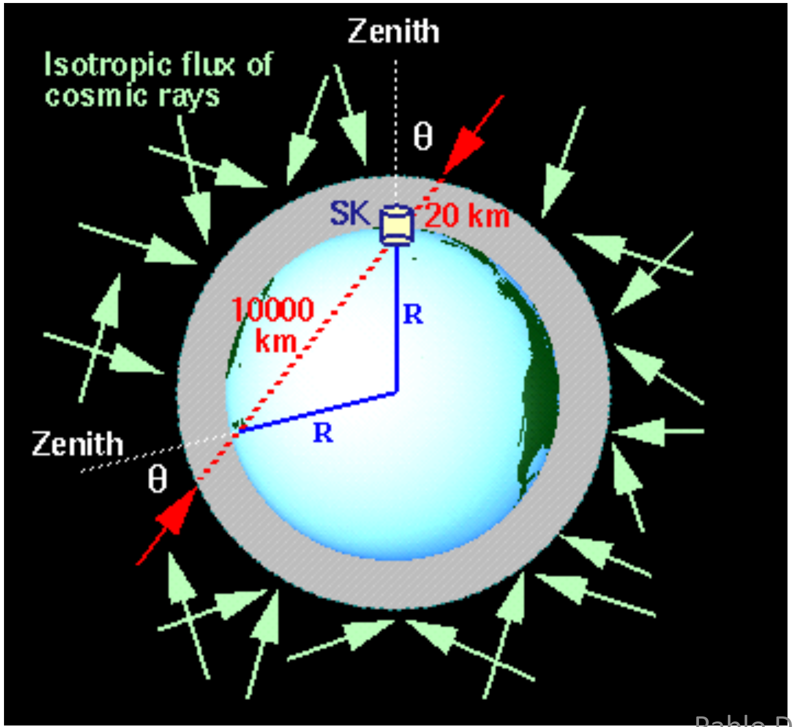
The Cerenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

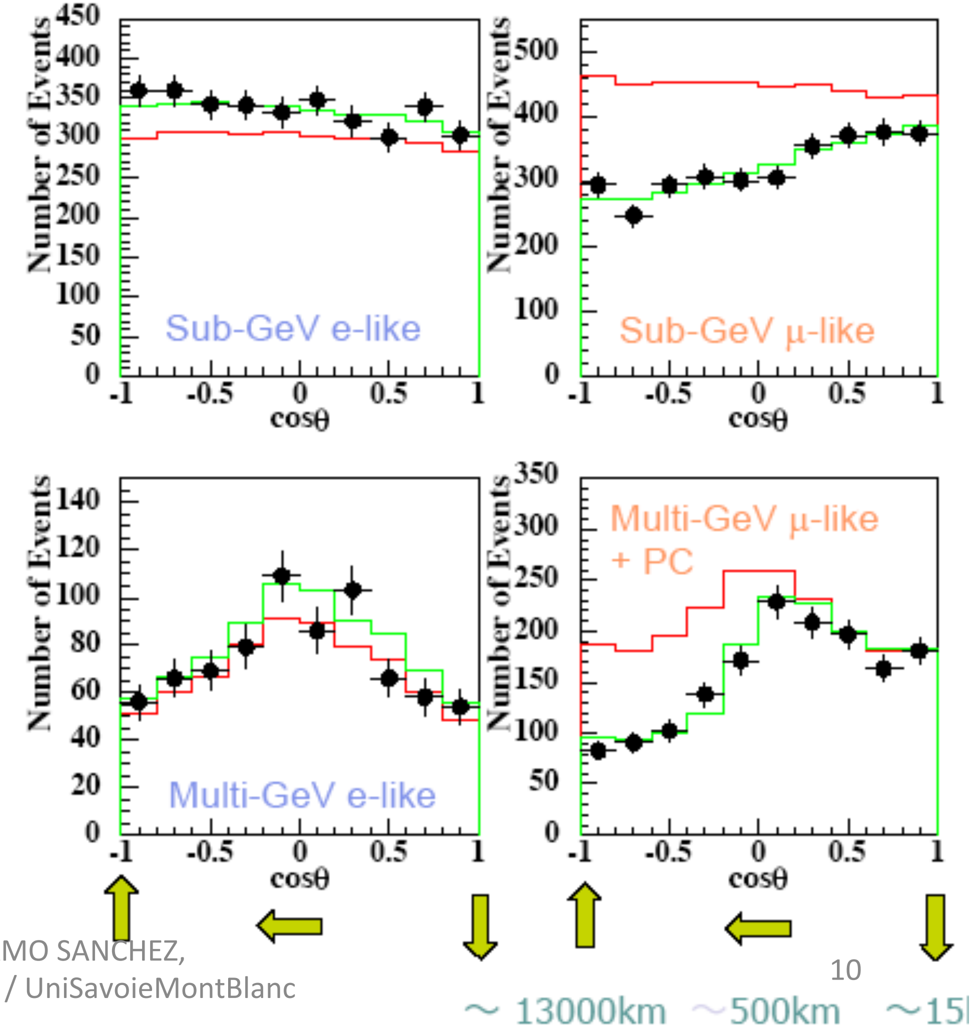
Super-KamiokaNDE

- 1000m deep, 50000 tons of water, 11000 PMTs
- Observed expected number of

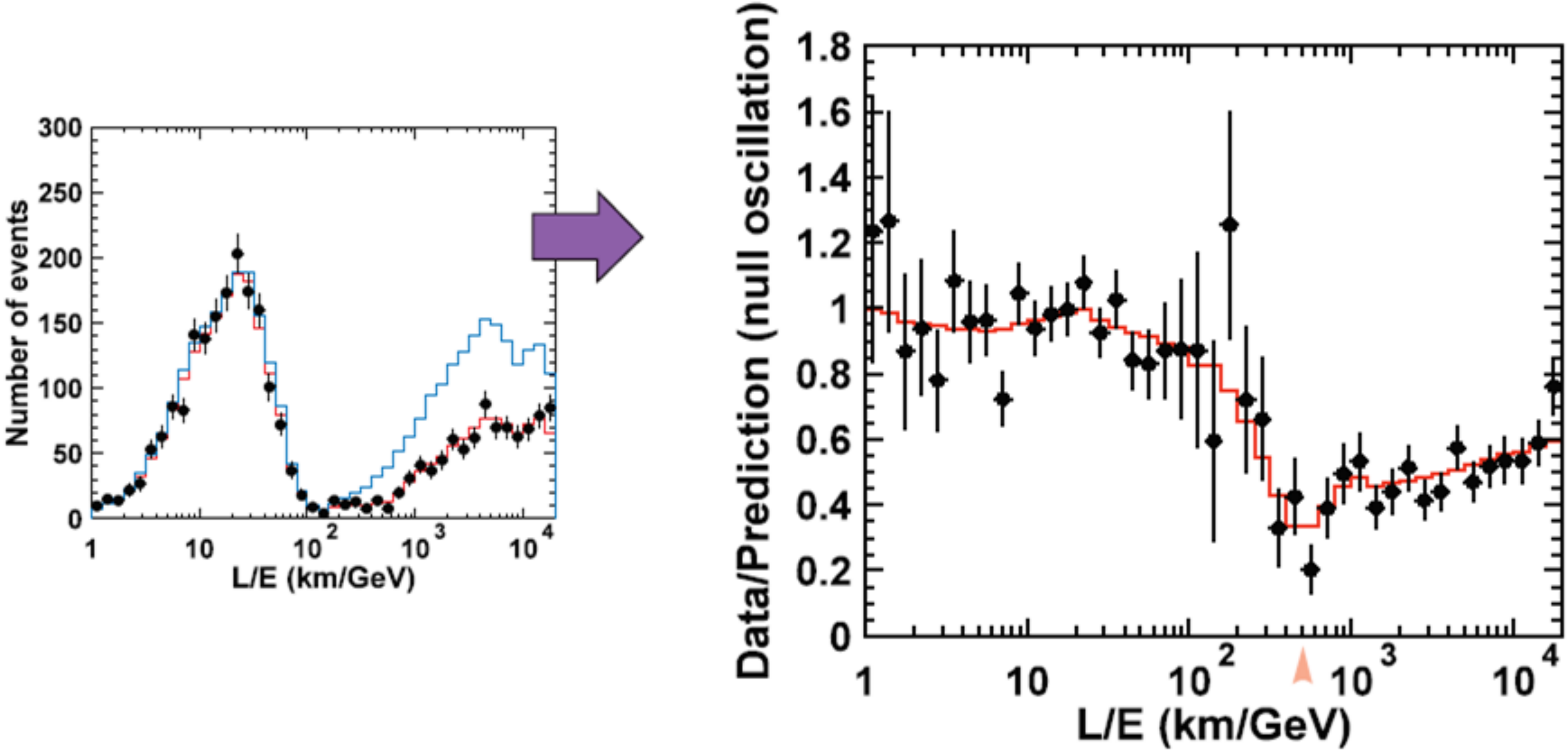
downgoing ν_μ, deficit in upgoing

- No excess in ν_e, so $\nu_\mu \rightarrow \nu_\tau$?





Atmospheric neutrinos disappear?



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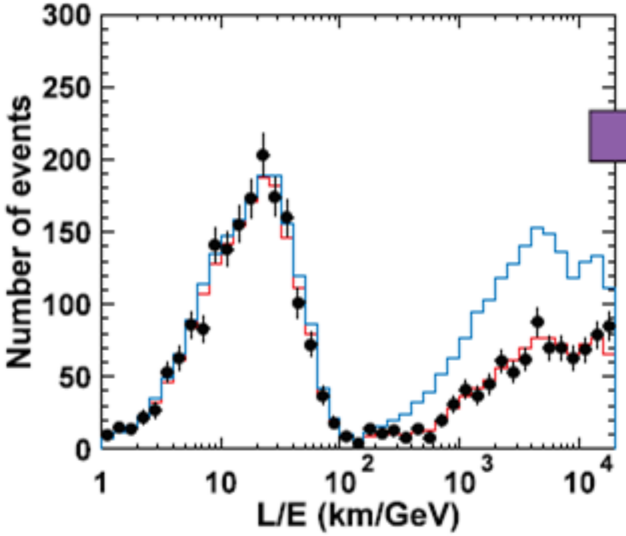
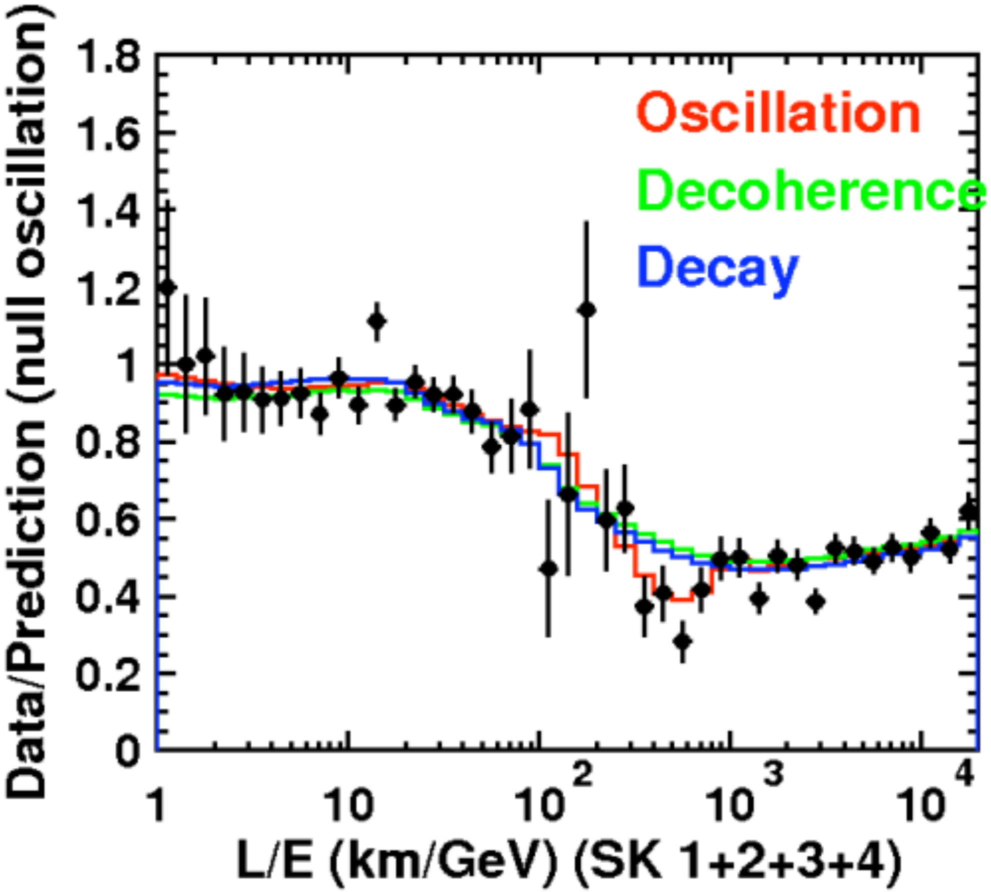
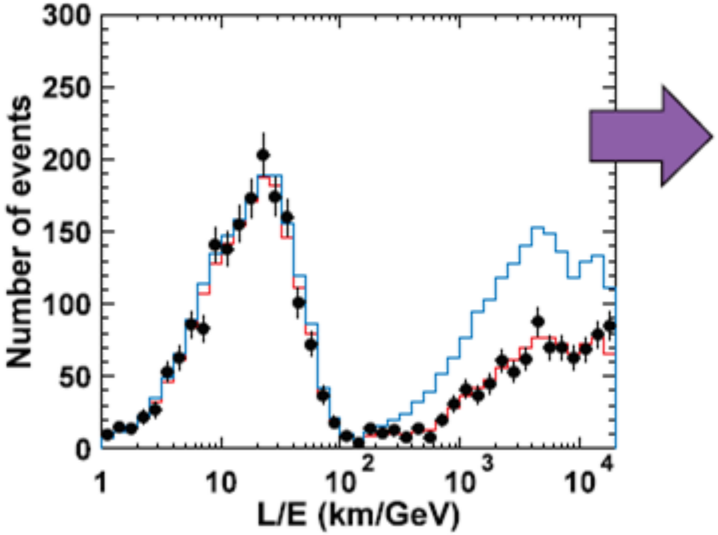
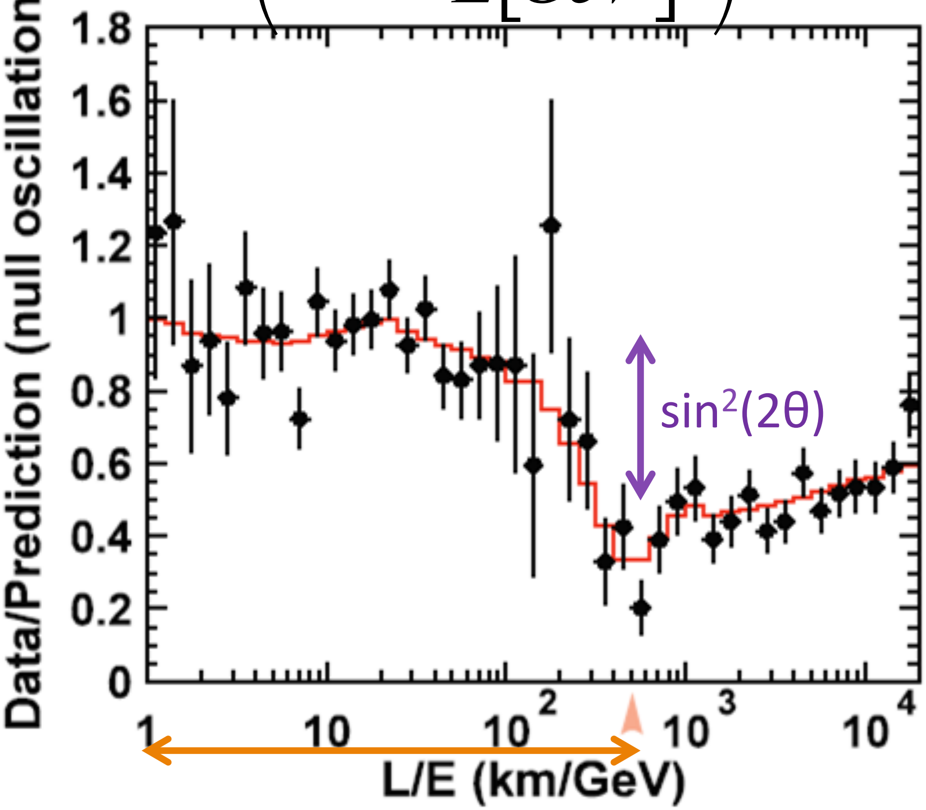




Atmospheric neutrinos oscillate!

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L[km]}{E[GeV]}\right)$$





L/E ~500 km/GeV ↔$\Delta m^2 \sim 2.3 \times 10^{-3}$ eV^2

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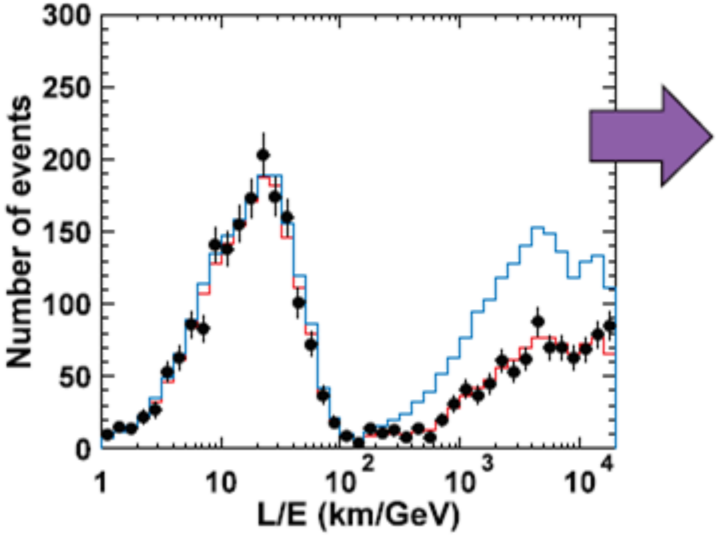
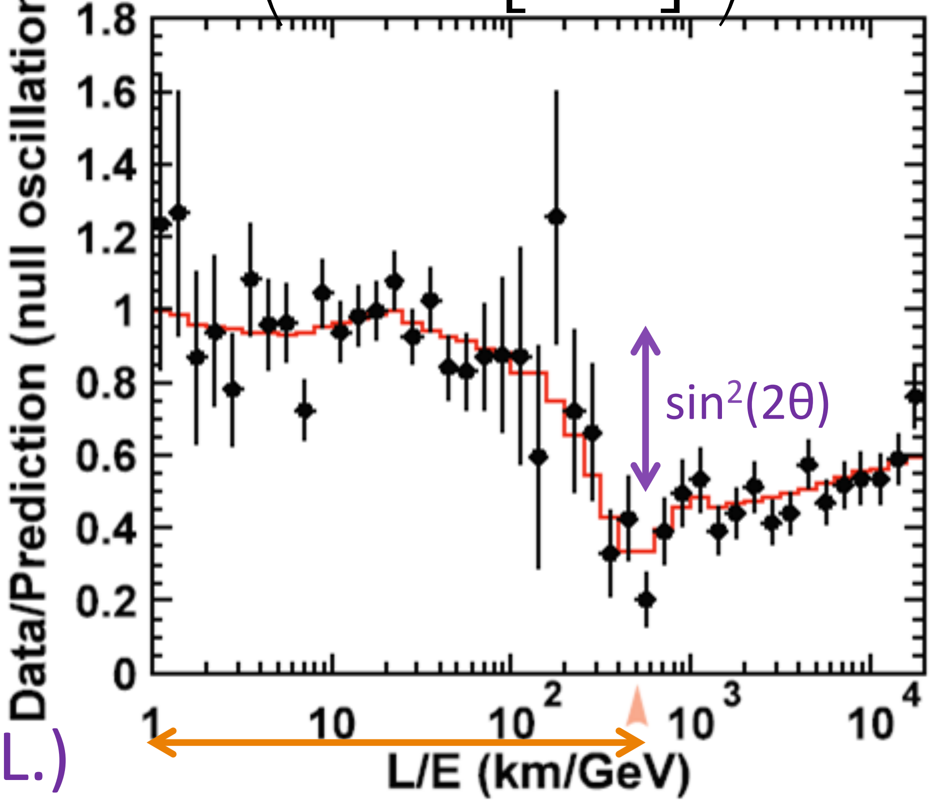




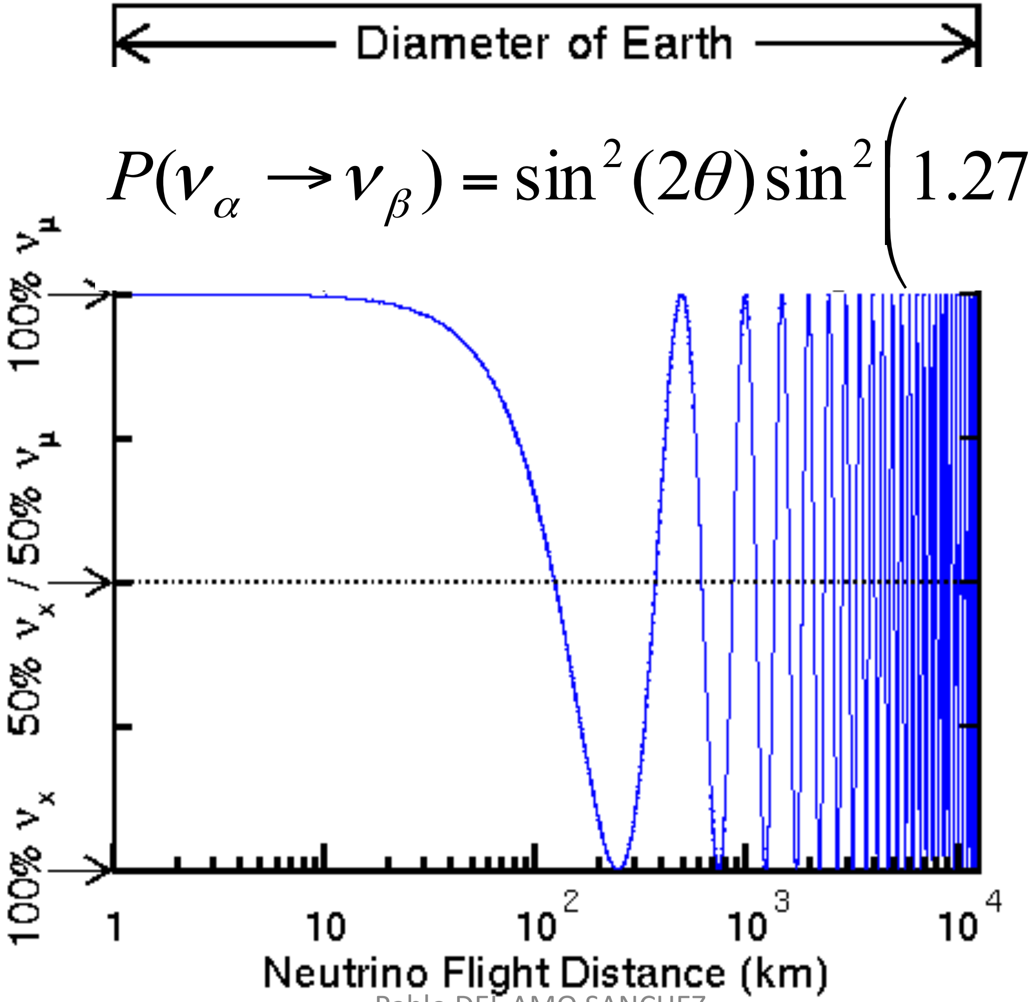
$\sin^2(2\theta)$ = 1.00 (>0.93 90% C.L.)

$\Delta m^2 = (2.50 \pm 0.27) \times 10^{-3}$ eV^2

L/E ~500 km/GeV ↔ $\Delta m^2 \sim 2.3 \times 10^{-3}$ eV^2

But why don't we see this?

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\,\frac{\Delta m^2 L[km]}{E[GeV]}\right)$$

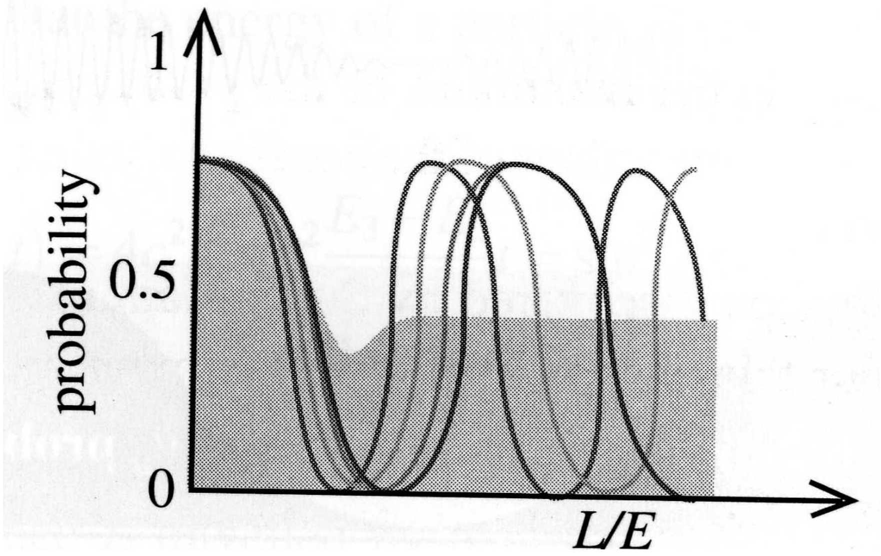


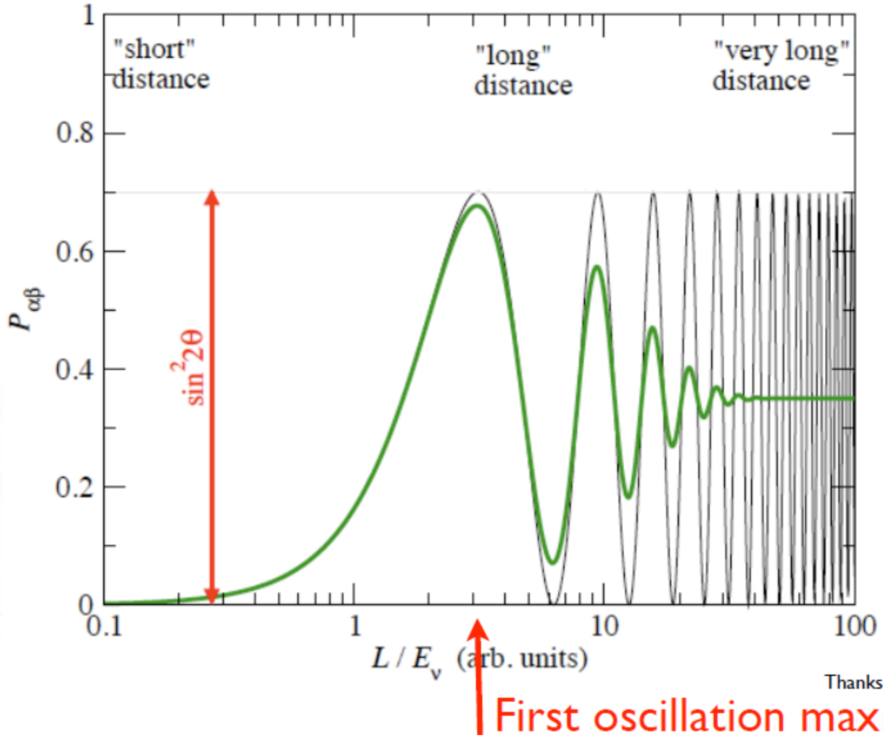
Because…

- Two effects:

  Neutrinos not monochromatic → different oscillation lengths

  Experimental resolution: if too close, maxima and minima blurred





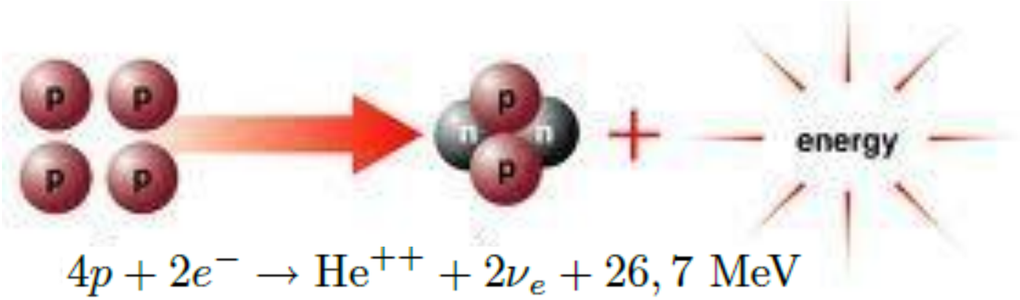
Thanks to T. Schwetz

First oscillation maximum

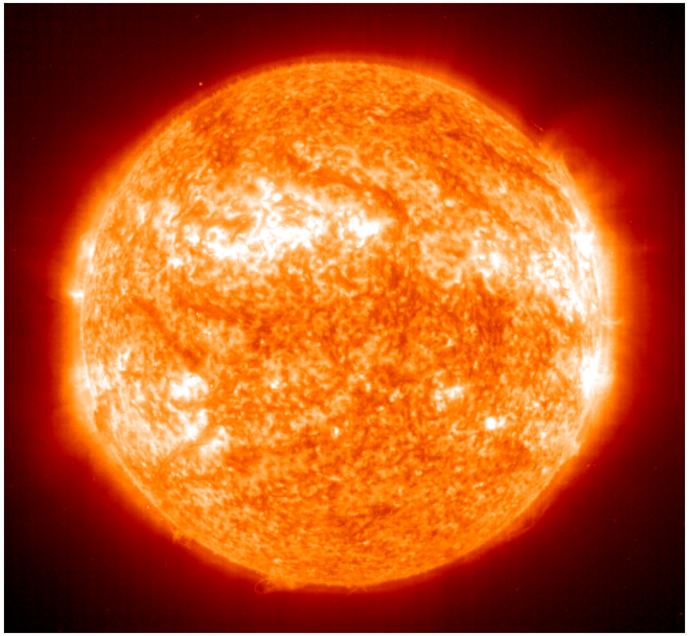
The solar neutrino saga

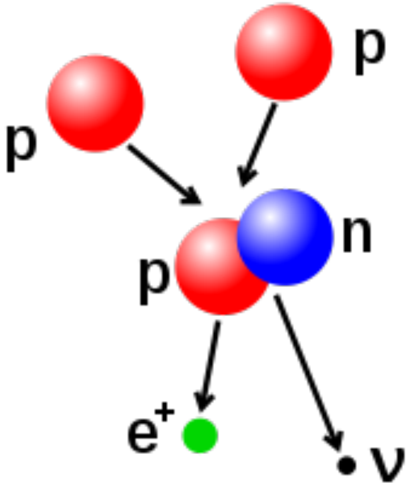
Neutrinos from the Sun

- Hydrogen fusion in the Sun requires inverse beta decay:



$$4p + 2e^- \rightarrow \mathrm{He}^{++} + 2\nu_e + 26,7\ \mathrm{MeV}$$



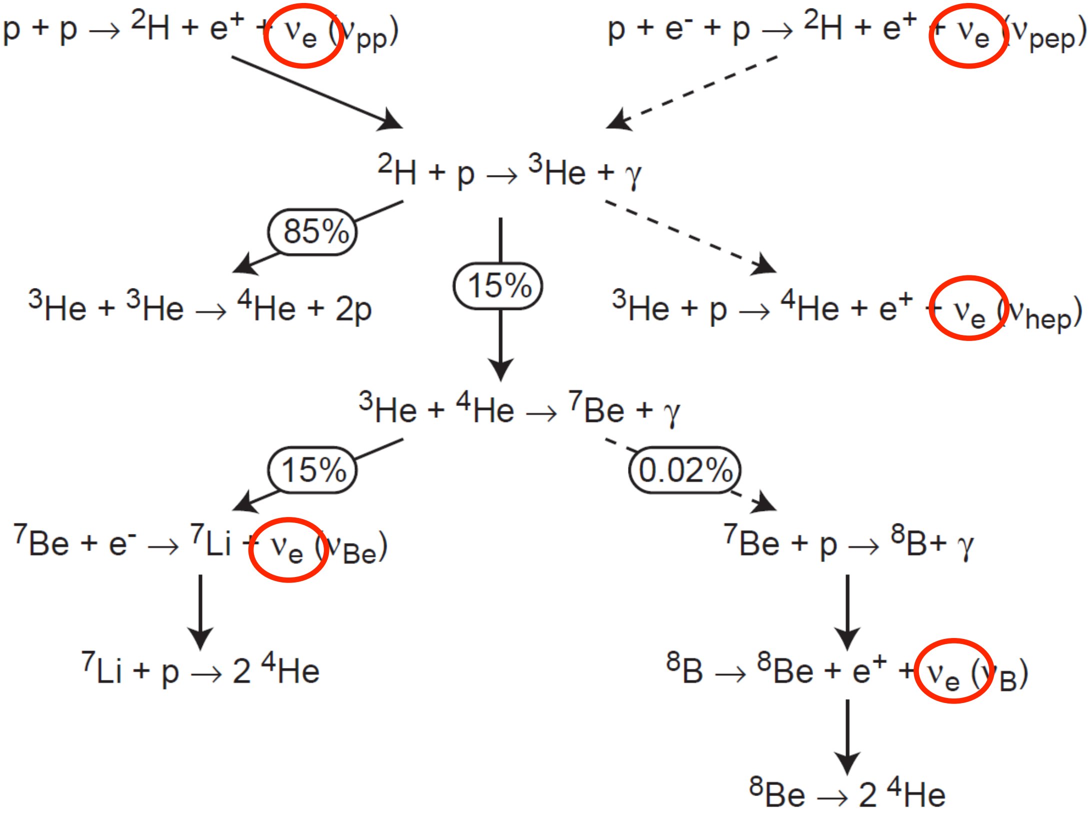


Solar constant = 1361 J/s m^2

$\phi_{\nu e}^{sun} = 6.4 \times 10^{14}\ \nu_e/\mathrm{s\ m}^2$

Neutrinos from the Sun

- Neutrino flux from the Sun accurately predicted (Bahcall et al)



$p + p \rightarrow {}^2H + e^+ + \nu_e\ (\nu_{pp})$

$p + e^- + p \rightarrow {}^2H + e^+ + \nu_e\ (\nu_{pep})$

${}^2H + p \rightarrow {}^3He + \gamma$

85%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

15%

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e\ (\nu_{hep})$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

15%

${}^7Be + e^- \rightarrow {}^7Li + \nu_e\ (\nu_{Be})$

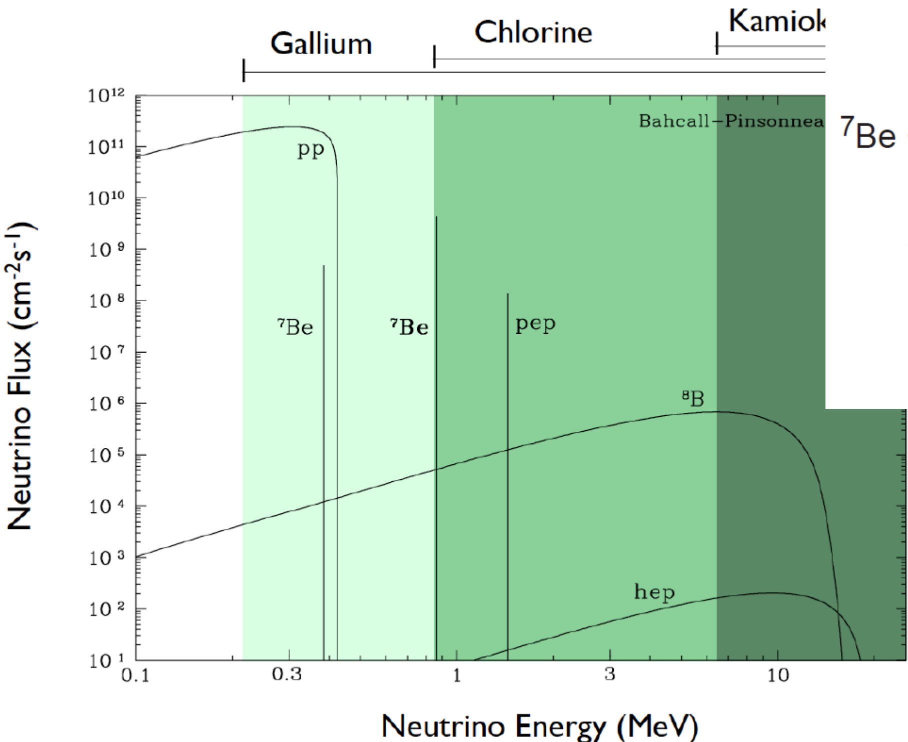
${}^7Li + p \rightarrow 2\ {}^4He$

0.02%

${}^7Be + p \rightarrow {}^8B + \gamma$

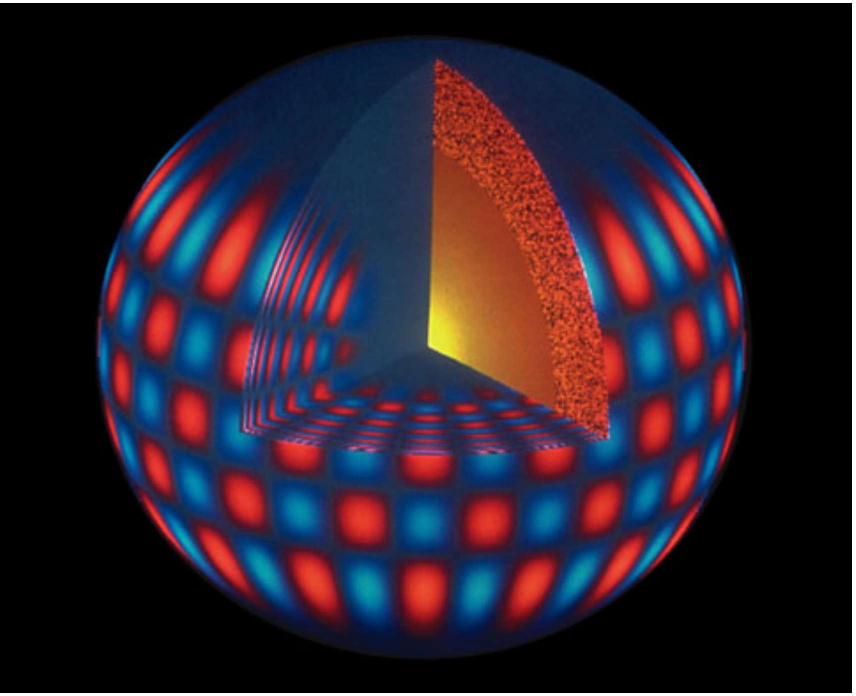
${}^8B \rightarrow {}^8Be + e^+ + \nu_e\ (\nu_B)$

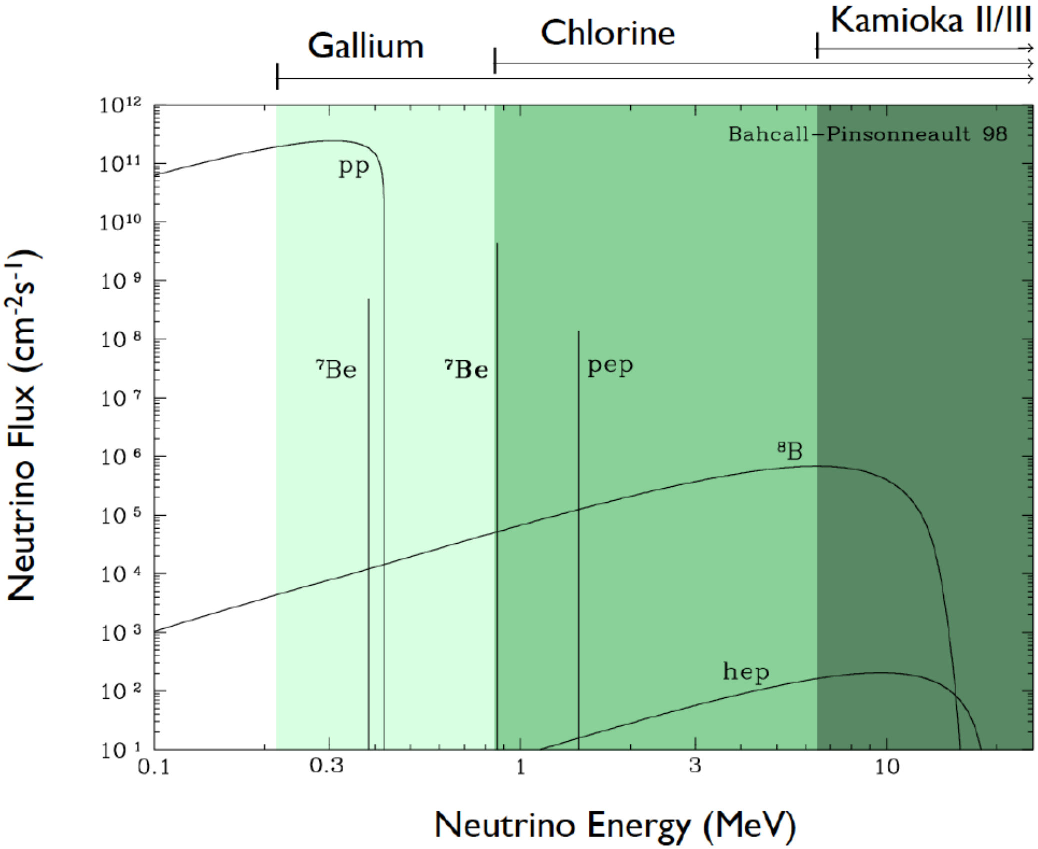
${}^8Be \rightarrow 2\ {}^4He$



Neutrinos from the Sun

- Neutrino flux from the Sun accurately predicted (Bahcall et al)
- Model in good agreement with results from helioseismology





Homestake experiment

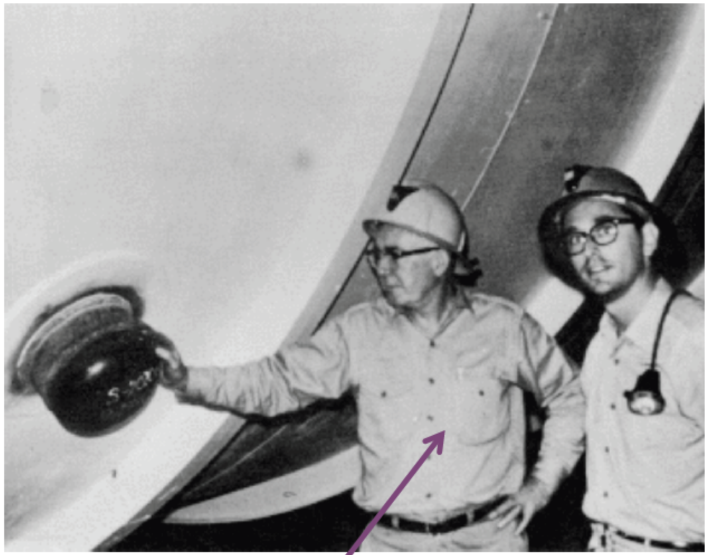
Late 1960s: Ray Davis set to test ν_e flux predictions in underground mine (under 1500m of rock)

Experiment run for 30 years (till 1994):

observed 2.56 ± 0.23 SNU
expected 8.2 ± 1.8 SNU

} ~30%

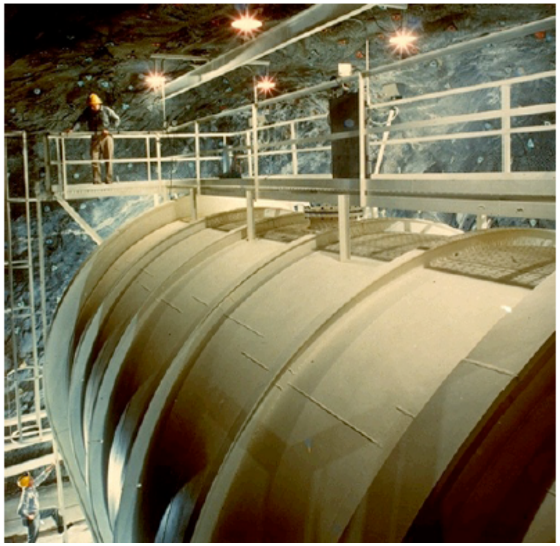
1 Solar Neutrino Unit = 10^{-36} interactions/s atom



Raymond Davis, Nobel Prize 2002

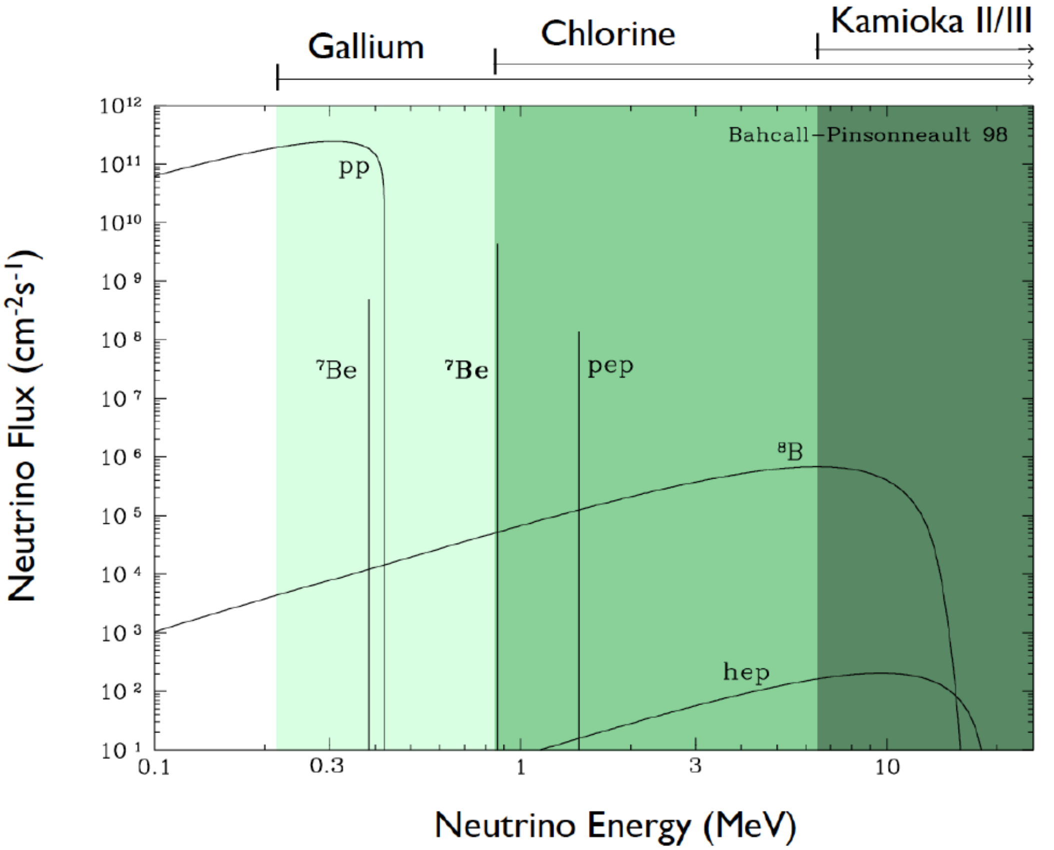
$\nu_e + n \rightarrow p + e^-$

- **Homestake:** $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$
  - Located in Lead, SD
  - 615 tons of C_2Cl_4 (Cleaning fluid)
  - Extraction method:
    - Pump in He that displaces Ar
    - Collect Ar in charcoal traps
    - Count Ar using radioactive decay
  - Never Calibrated with source



Problems?

- Problems with experiment? With ν_e flux predictions?
- Test other parts of the ν_e spectrum with different experimental techniques

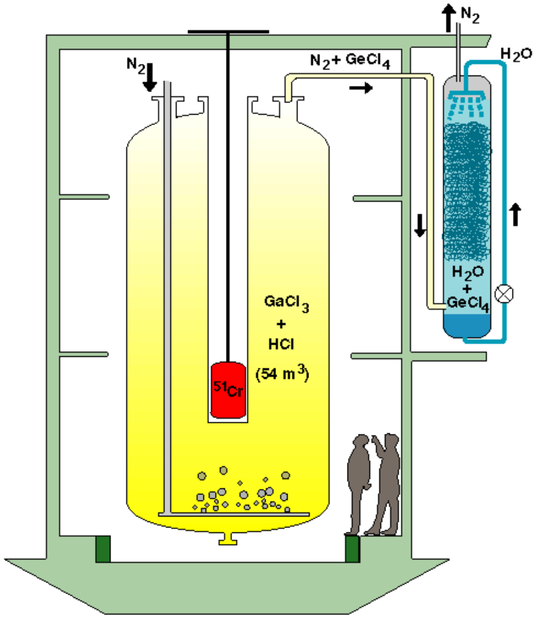


Gallex: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$

Observed 68.1 ± 3.75 SNU

Expected 127 ± 12 SNU

~50%



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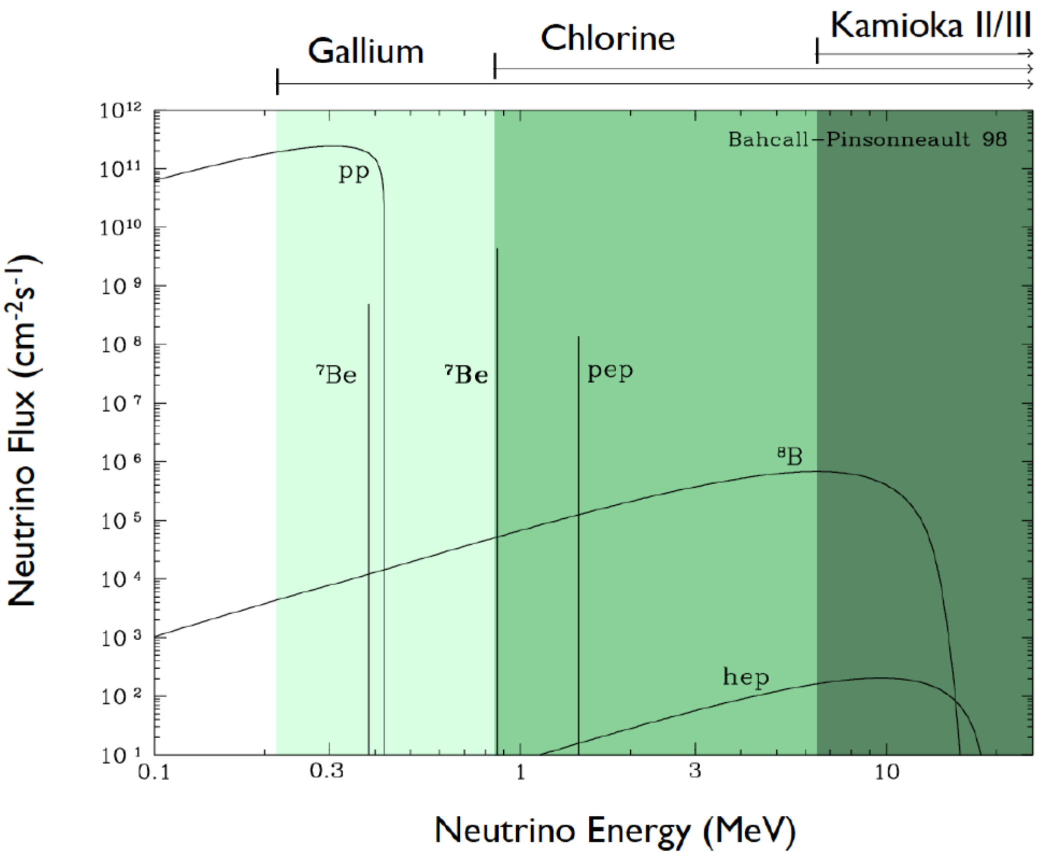
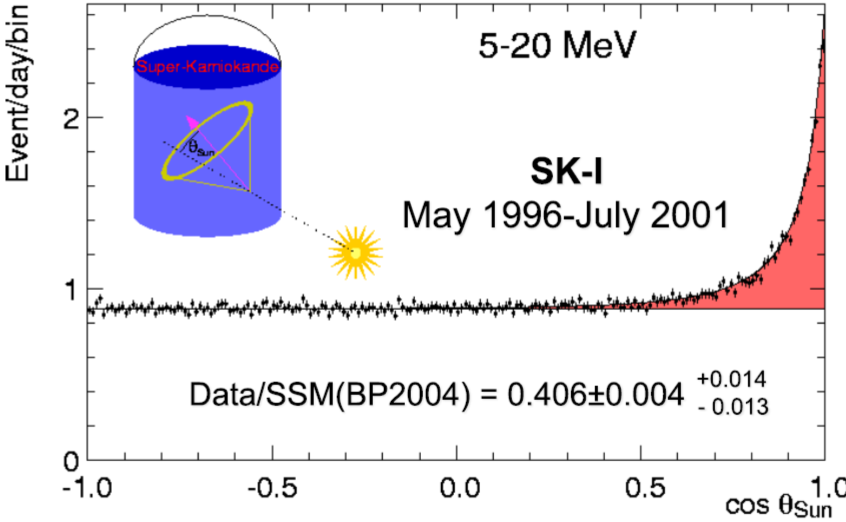
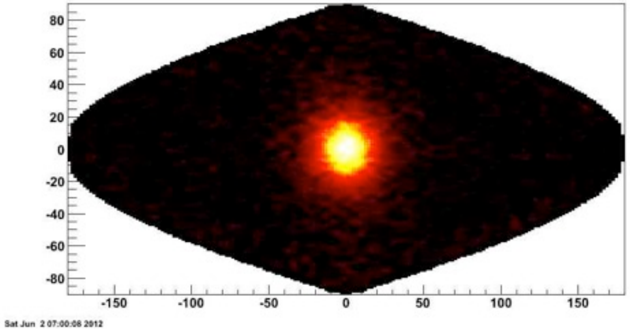


KamiokaNDE: $\nu_e + e^- \rightarrow \nu_e + e^-$

Observed ~40% of expectation





Problems?

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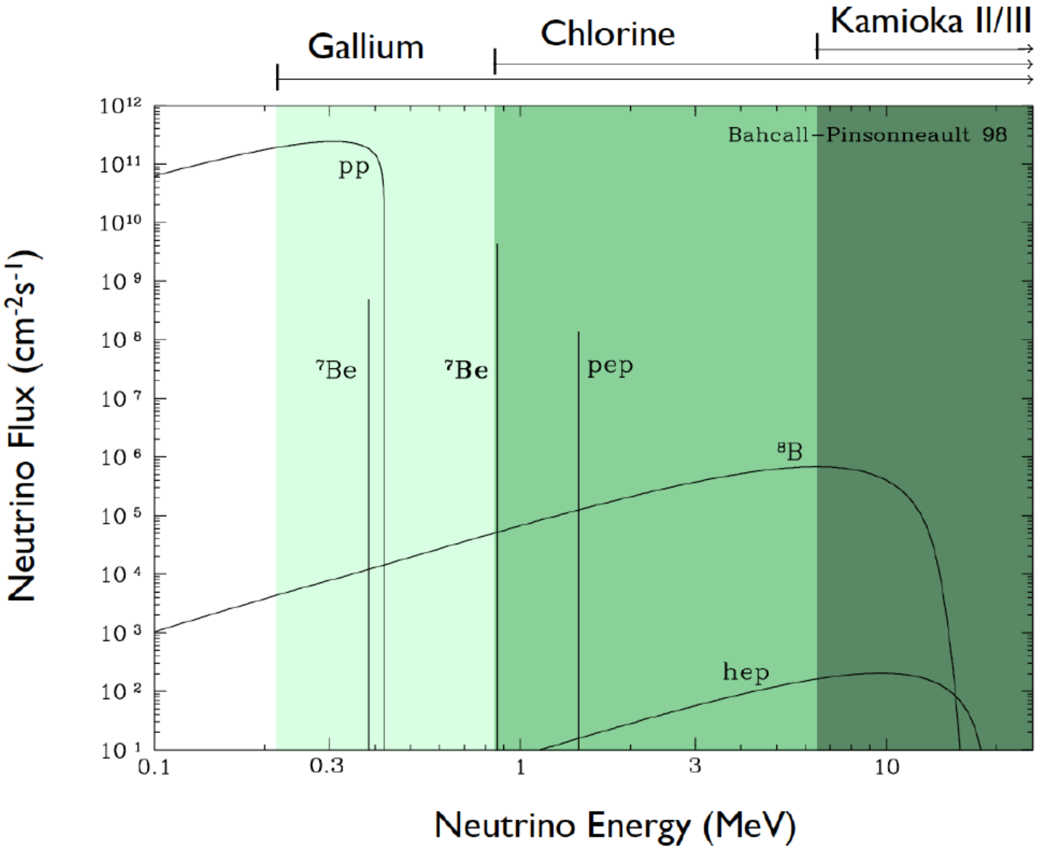
- Test other parts of the ν_e spectrum with different experimental techniques

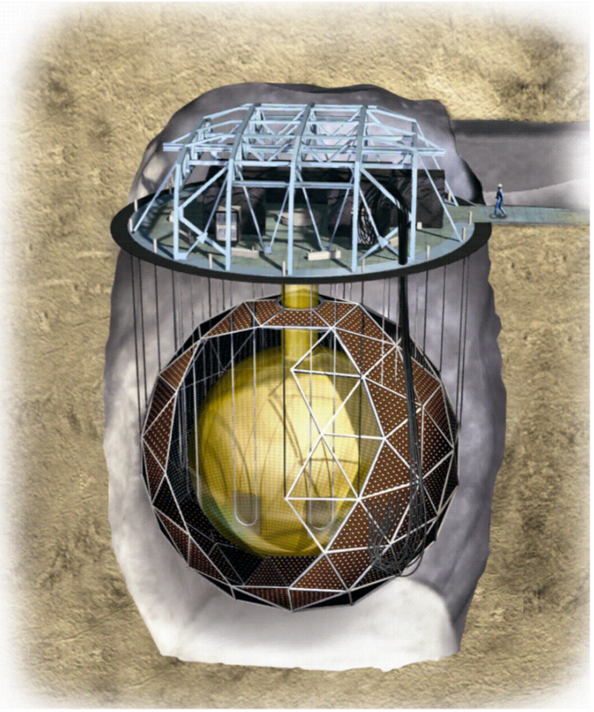


Experiment type	Observed/Expected
Chlorine	~30%
Gallium	~60%
KamiokaNDE	~40%

Perhaps neutrinos are oscillating after all, as suggested by Pontecorvo et al?

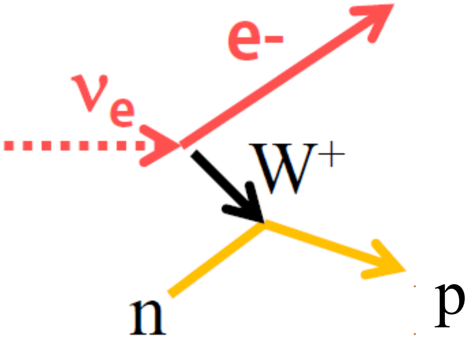
These experiments only sensitive to ν_e try and detect ν_μ and ν_τ too! → SNO

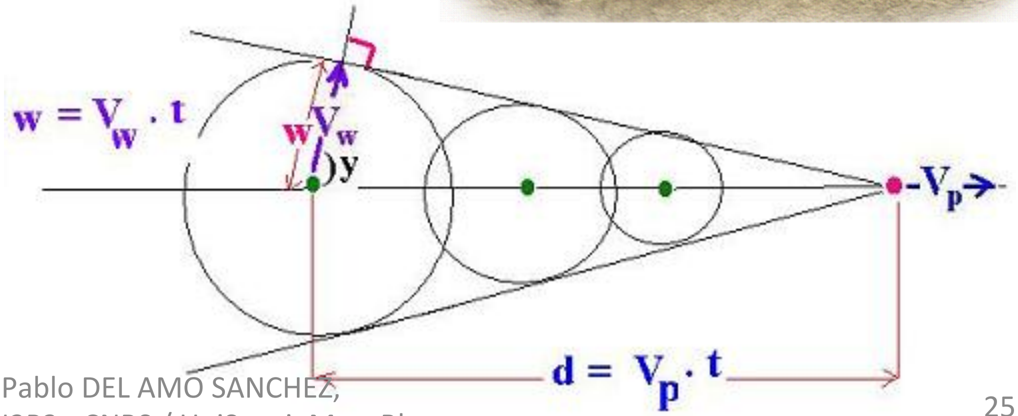
Sudbury Neutrino Observatory (SNO)



- 2000 m deep (Sudbury, Ontario)
- Cosmics veto
- 1000 tons of Heavy water (D_20),
  shielded by 7000 tons light water (H_20)
  seen by 9500 photomultiplier tubes (PMTs)
- So-called Water Cerenkov detector

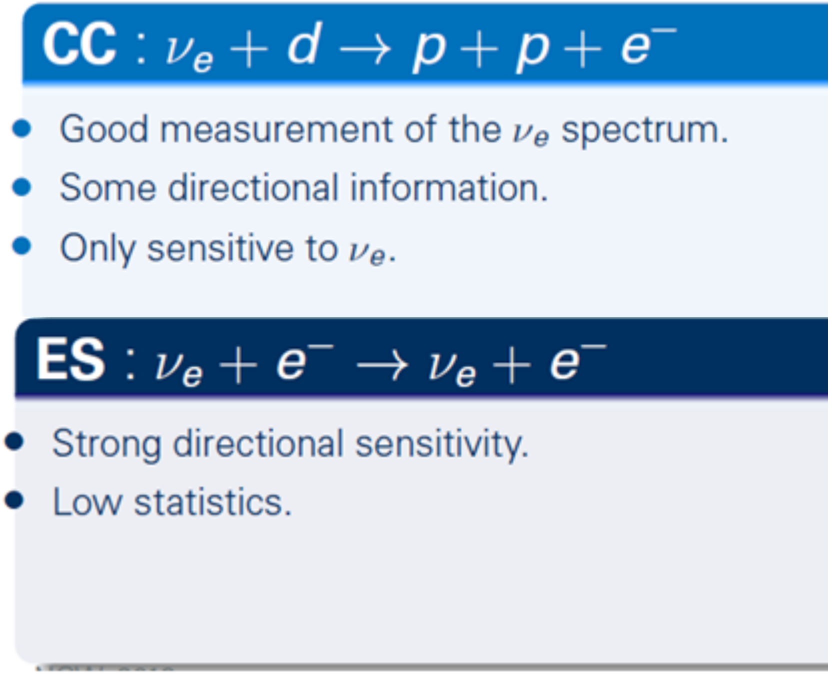
Particles faster than speed of light in medium radiate light (e.g. blueish light in nuclear reactors)





SNO

- SNO measures well ν_e flux:

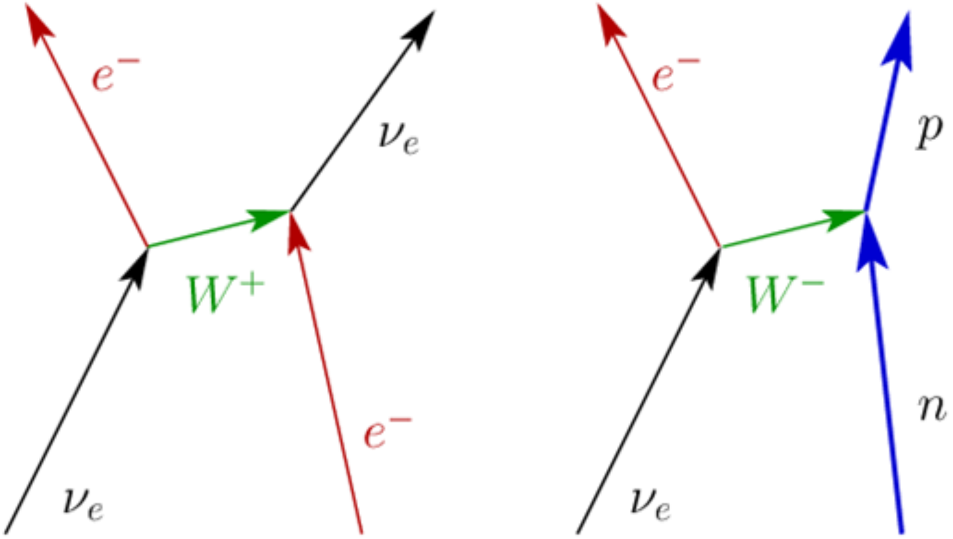


CC : $\nu_e + d \rightarrow p + p + e^-$

- Good measurement of the ν_e spectrum.
- Some directional information.
- Only sensitive to ν_e.

ES : $\nu_e + e^- \rightarrow \nu_e + e^-$

- Strong directional sensitivity.
- Low statistics.

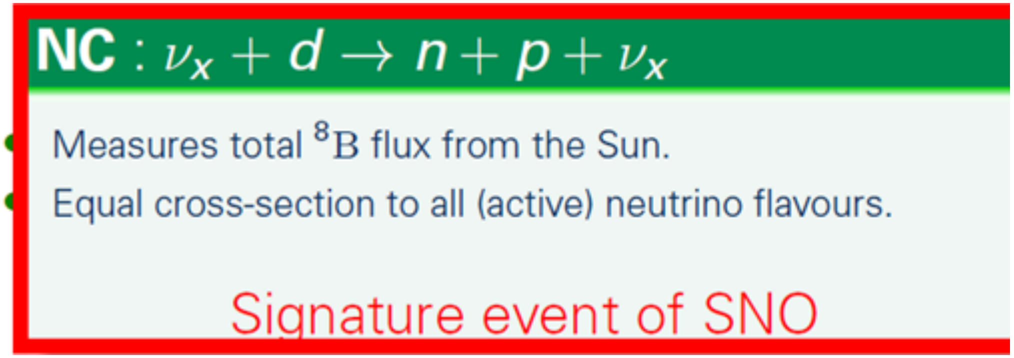


Charged current

- Cannot see ν_μ / ν_τ flux in this way: neutrinos from Sun not energetic enough to produce heavy μ or τ particles in interactions

SNO

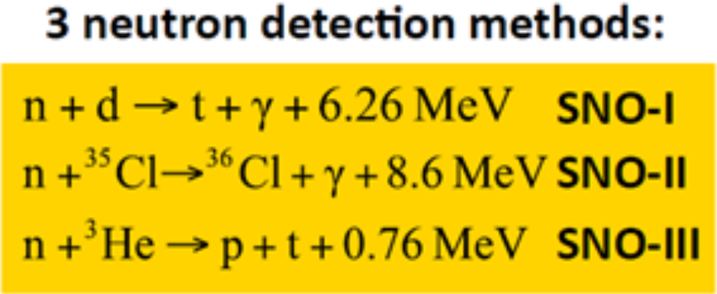
- But it measures the total ν_e+ν_μ+ν_τ flux by means of Neutral Current interactions!



NC : $\nu_x + d \rightarrow n + p + \nu_x$

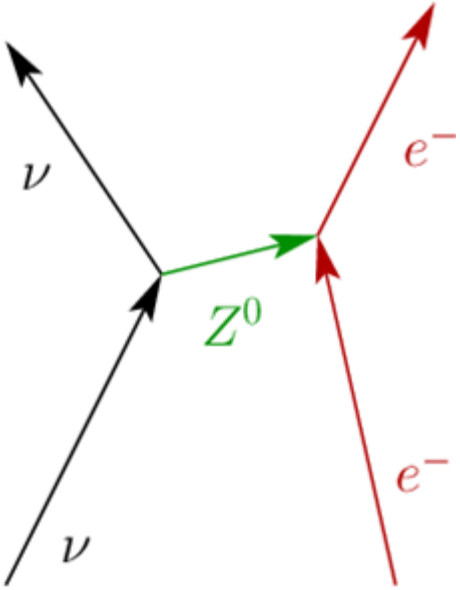
- Measures total ^{8}B flux from the Sun.
- Equal cross-section to all (active) neutrino flavours.

Signature event of SNO



3 neutron detection methods:

$n + d \rightarrow t + \gamma + 6.26\,\mathrm{MeV}$	**SNO-I**
$n + {}^{35}\mathrm{Cl} \rightarrow {}^{36}\mathrm{Cl} + \gamma + 8.6\,\mathrm{MeV}$	**SNO-II**
$n + {}^{3}\mathrm{He} \rightarrow p + t + 0.76\,\mathrm{MeV}$	**SNO-III**



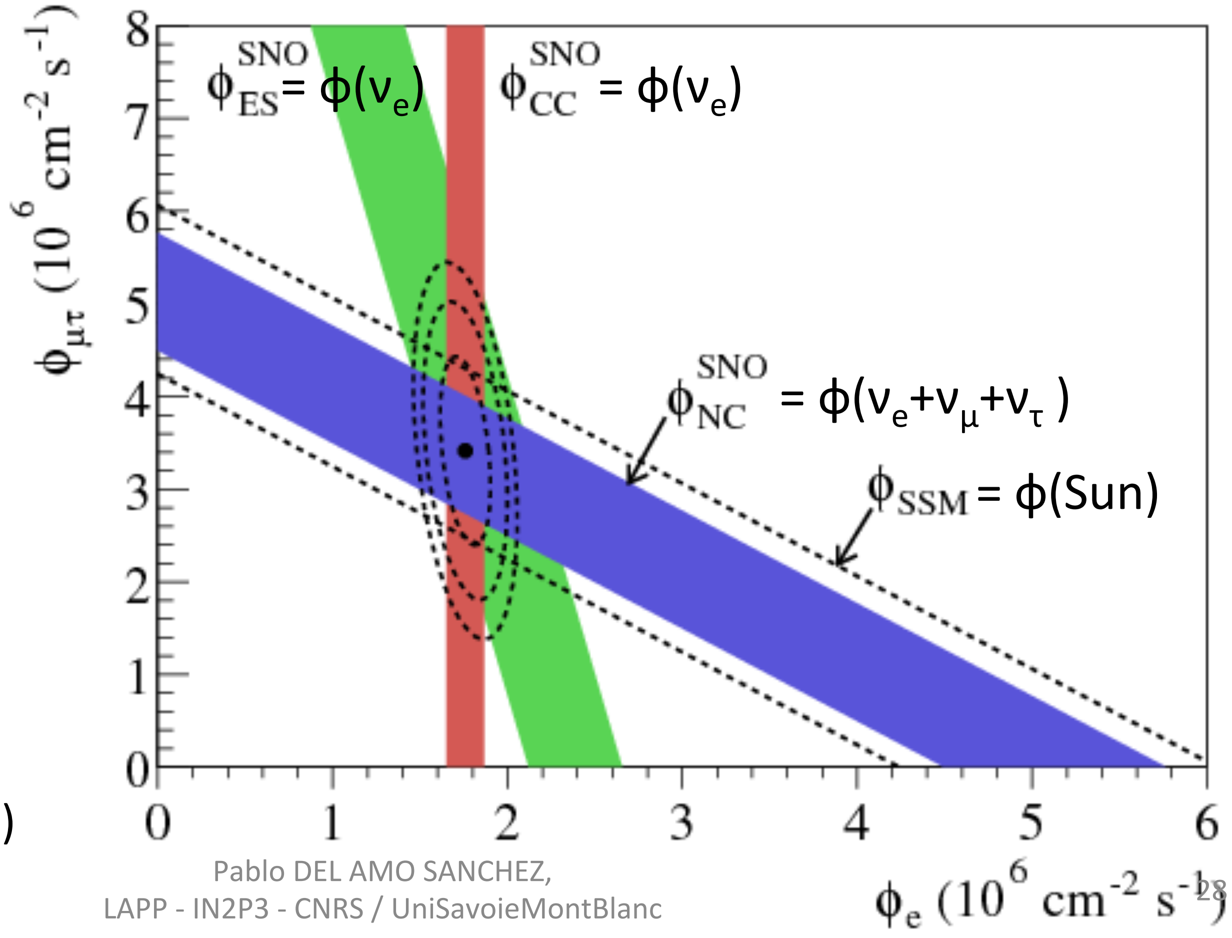
Neutral current

Solar neutrinos oscillate!

Less ν_e than predicted but total $\nu_e+\nu_\mu+\nu_\tau$ correct!

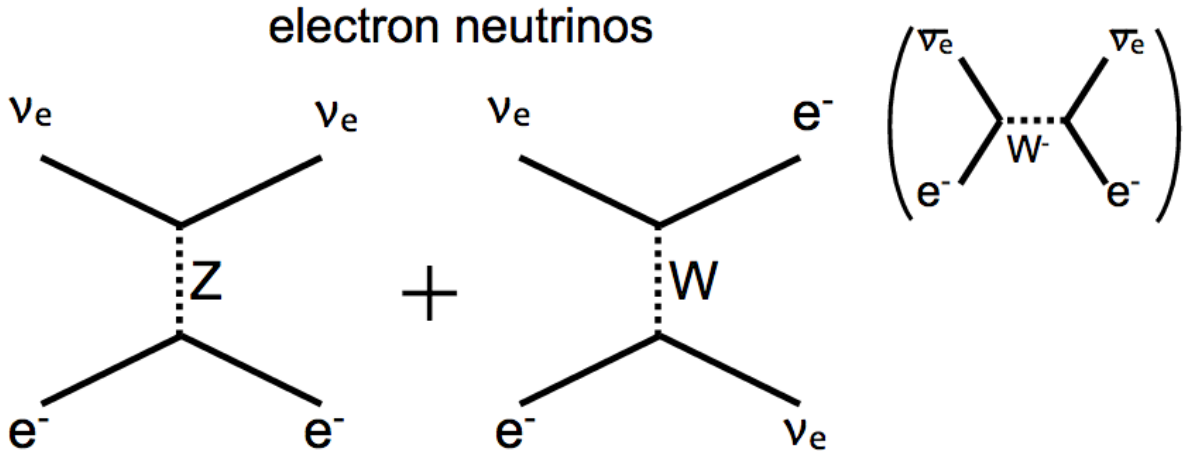
Бруно Понтекорво

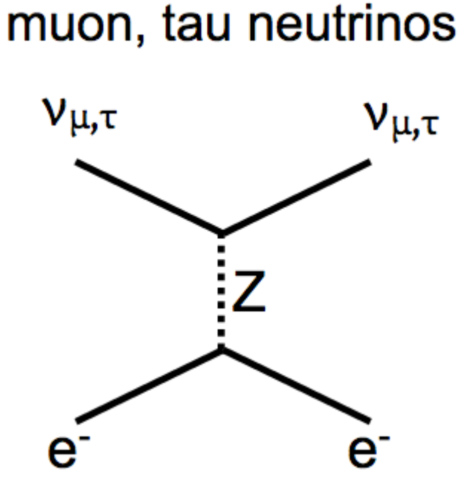
Bruno Pontecorvo (1957)



Matter effects are important!

- High electron density in Sun → matter effects!
- ν_e get heavier, ν_μ & ν_τ unaffected.





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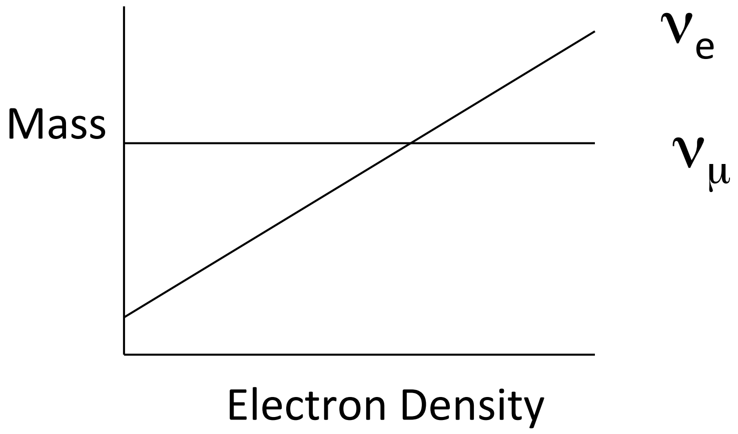
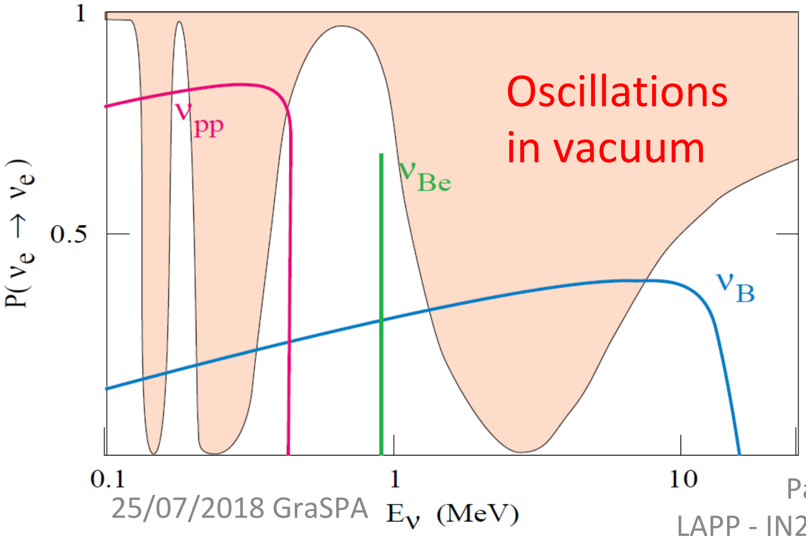
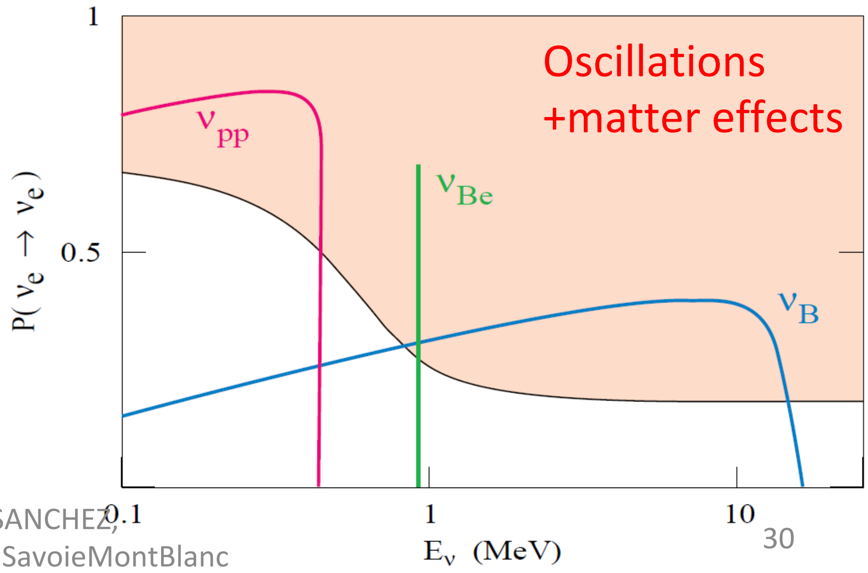
- ν_e get heavier, ν_μ & ν_τ unaffected.

  Resonance effects may enhance oscillation



$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L[km]}{E[GeV]}\right)$$





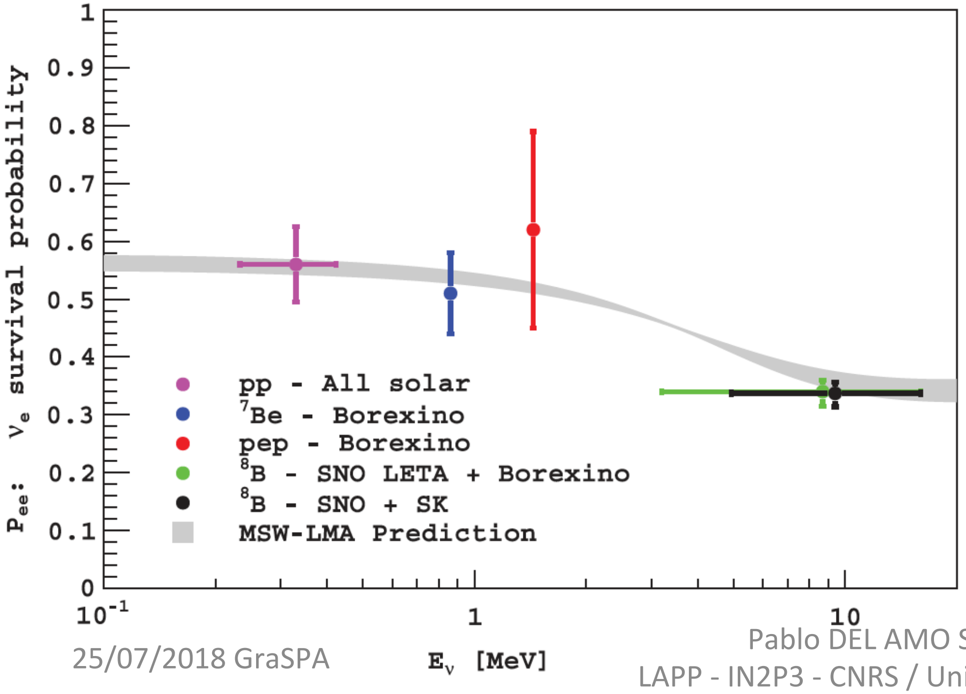
Matter effects are important!

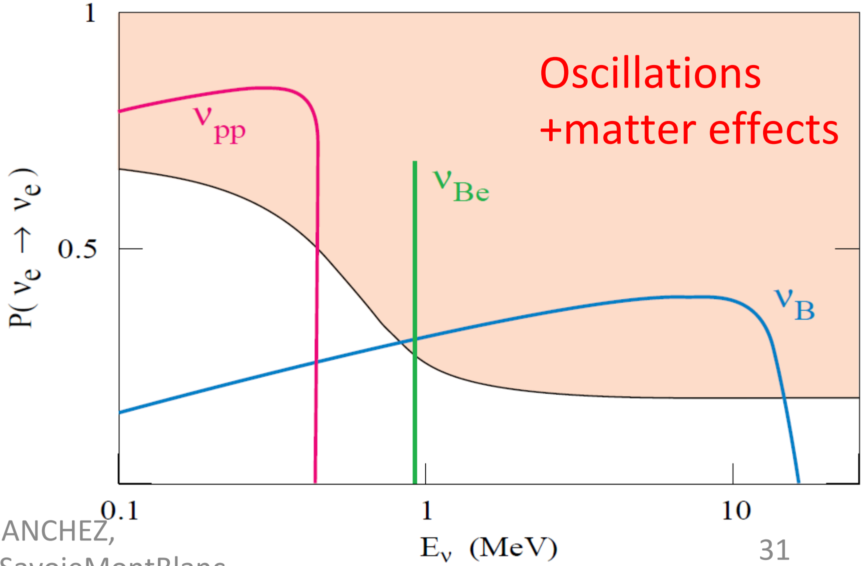
- Found oscillation parameters for solar neutrinos:

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L[km]}{E[GeV]}\right)$$

$\sin^2(2\theta) = 0.857 \pm 0.024$

$\Delta m^2 = (7.5 \pm 0.20) \times 10^{-5} eV^2$





The trilogy:
reactor neutrino experiments

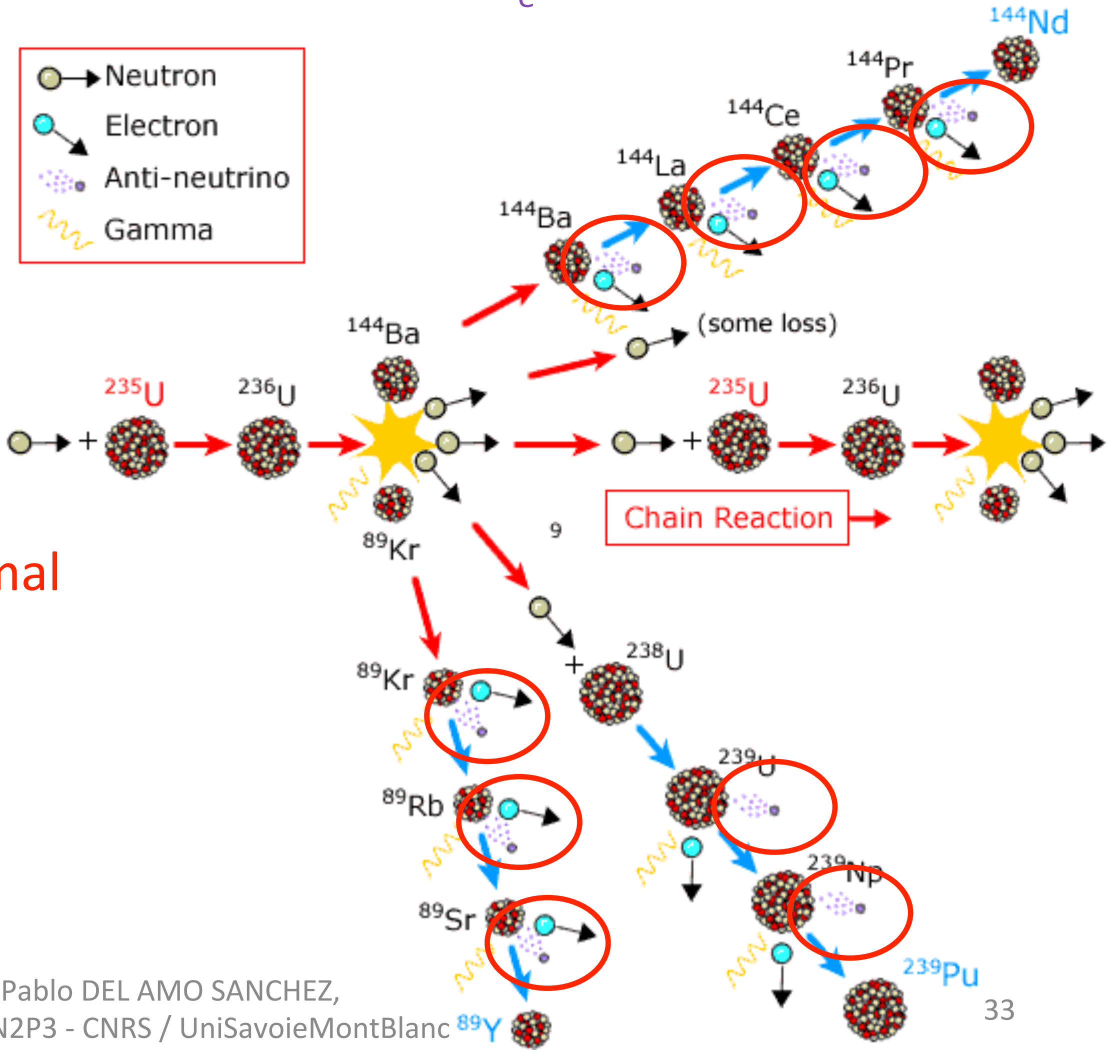
Reactor neutrinos

- Nuclear reactors, source of abundant antineutrinos! $\bar{\nu}_e$

Fission products are neutron rich

Too many neutrons to be stable

→ plenty of beta decays!



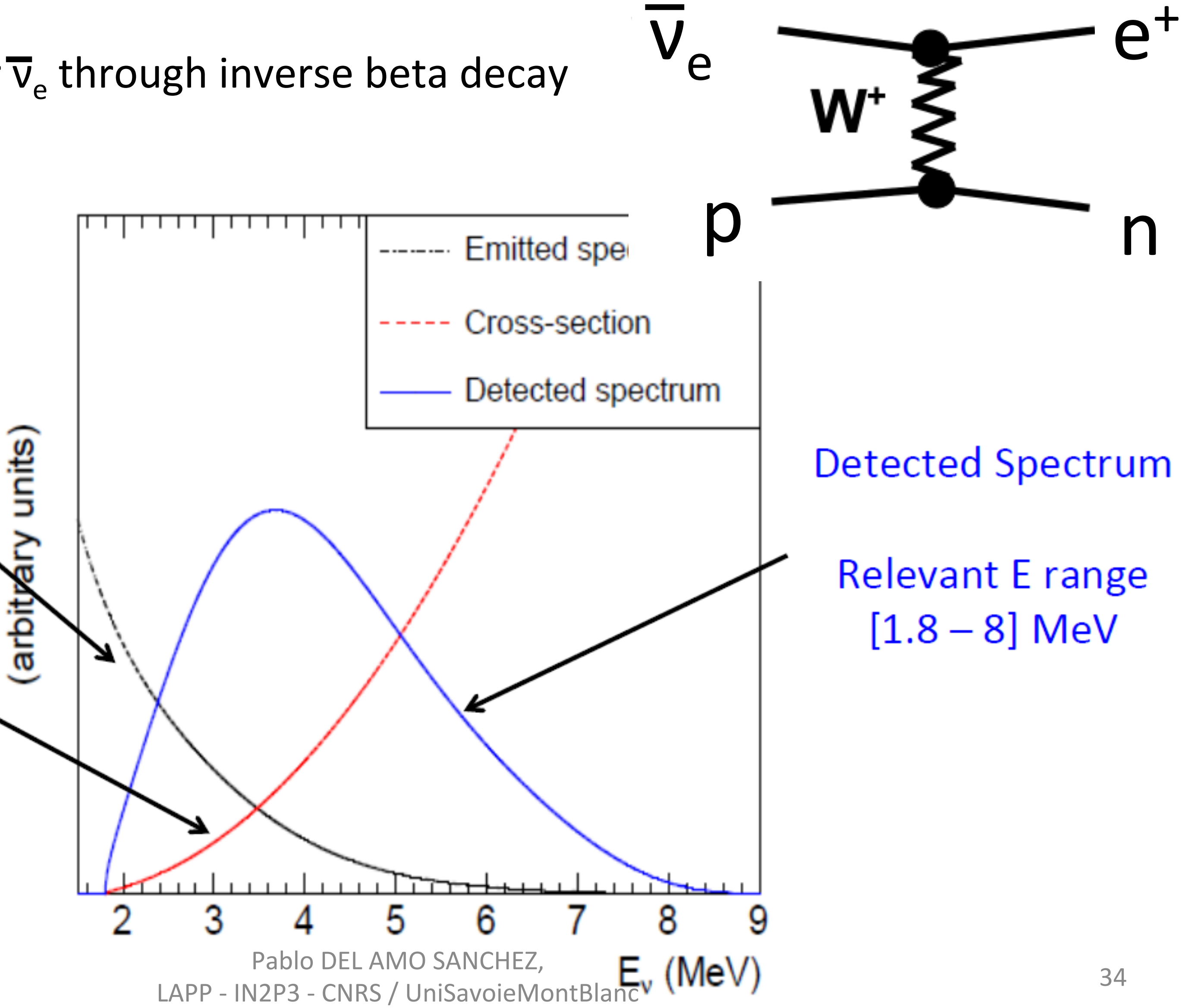
- ~ 6 $\bar{\nu}_e$ /fission

  ~ 200 MeV/fission

  $2 \times 10^{20}\ \bar{\nu}_e\ /\mathrm{GW}_{\mathrm{thermal}}$

Liquid scintillator detectors

- Detect reactor $\bar{\nu}_e$ through inverse beta decay



Exponential decrease of emitted spectrum

β−inverse detection process

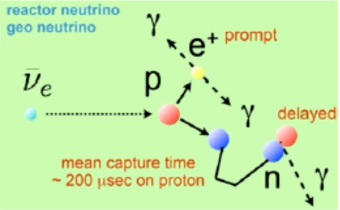
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

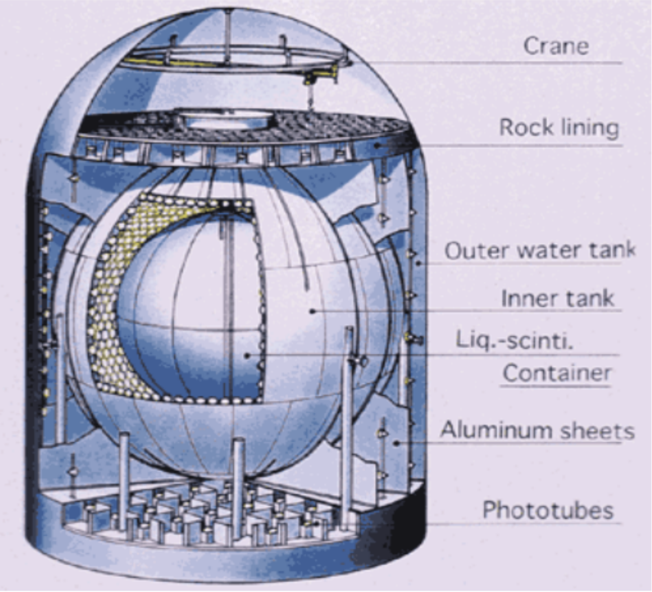
Detected Spectrum

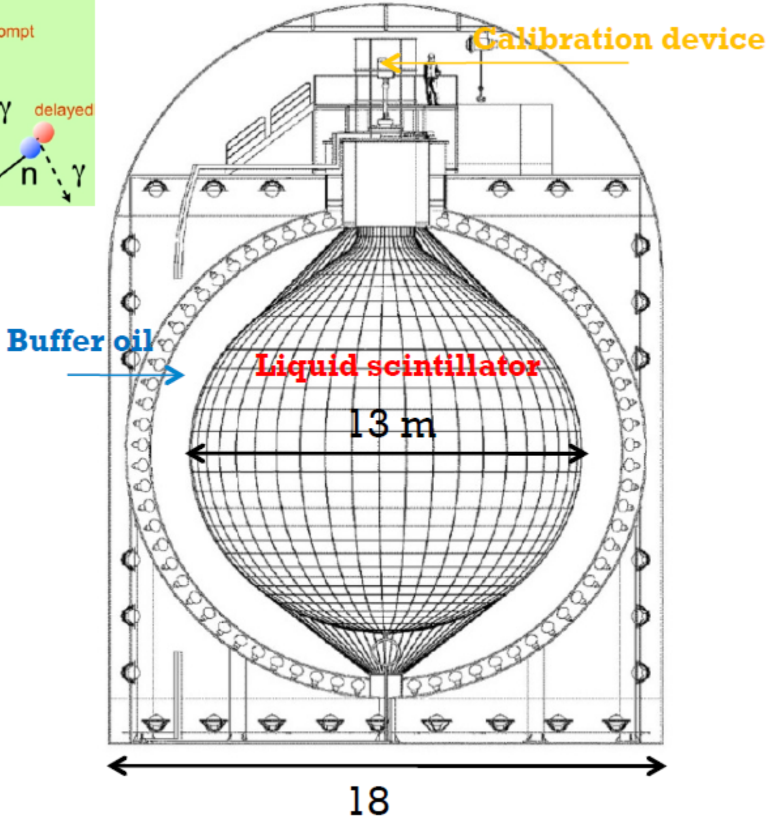
Relevant E range [1.8 – 8] MeV

Liquid scintillator detectors

- KamLAND: Kamioka Liquid scintillator AntiNeutrino Detector
  - **1000 ton liquid scintillator**:
  - Spherical plastic balloon
  - 1325 17” + 554 20” PMTs
  - Inverse β decay detection

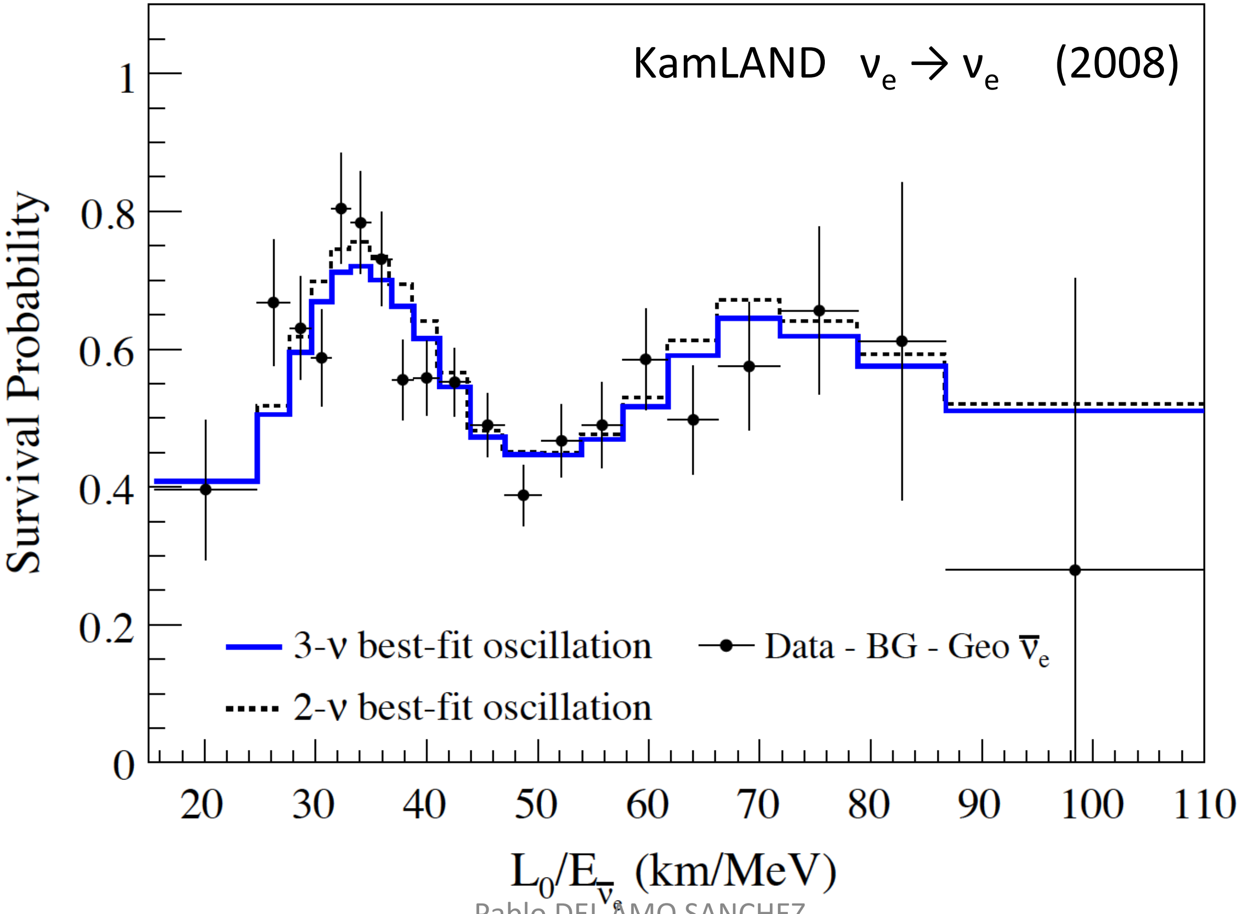






Reactor neutrinos oscillate!

- Confirm solar neutrino oscillations



What have we learnt so far?

- Neutrinos oscillate!

  ν_e, ν_μ, ν_τ different from ν_1, ν_2, ν_3

- Two different oscillation frequencies:

  fast: atmospheric, $\Delta m^2_{32} \sim \Delta m^2_{31}$

  slow: solar, Δm^2_{21} atm ~ 20 x solar

- Neutrinos mix a lot! (Mixing angles large!)

  atmospheric, maximal $\theta_{32} = 45° \pm 6°$

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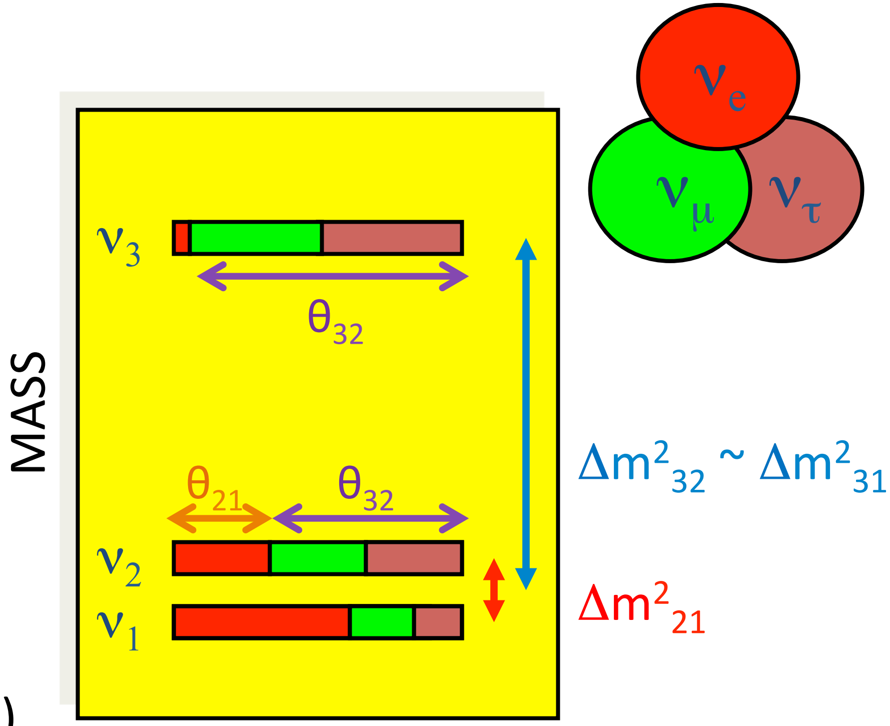

Convention: ν_1 is state with most ν_e

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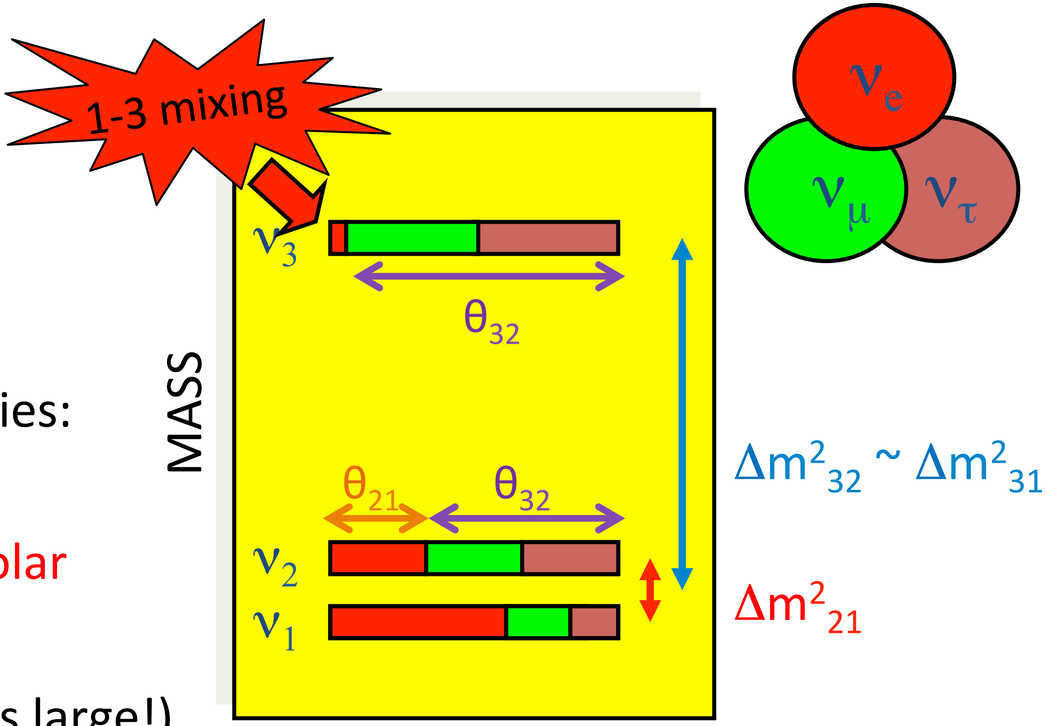
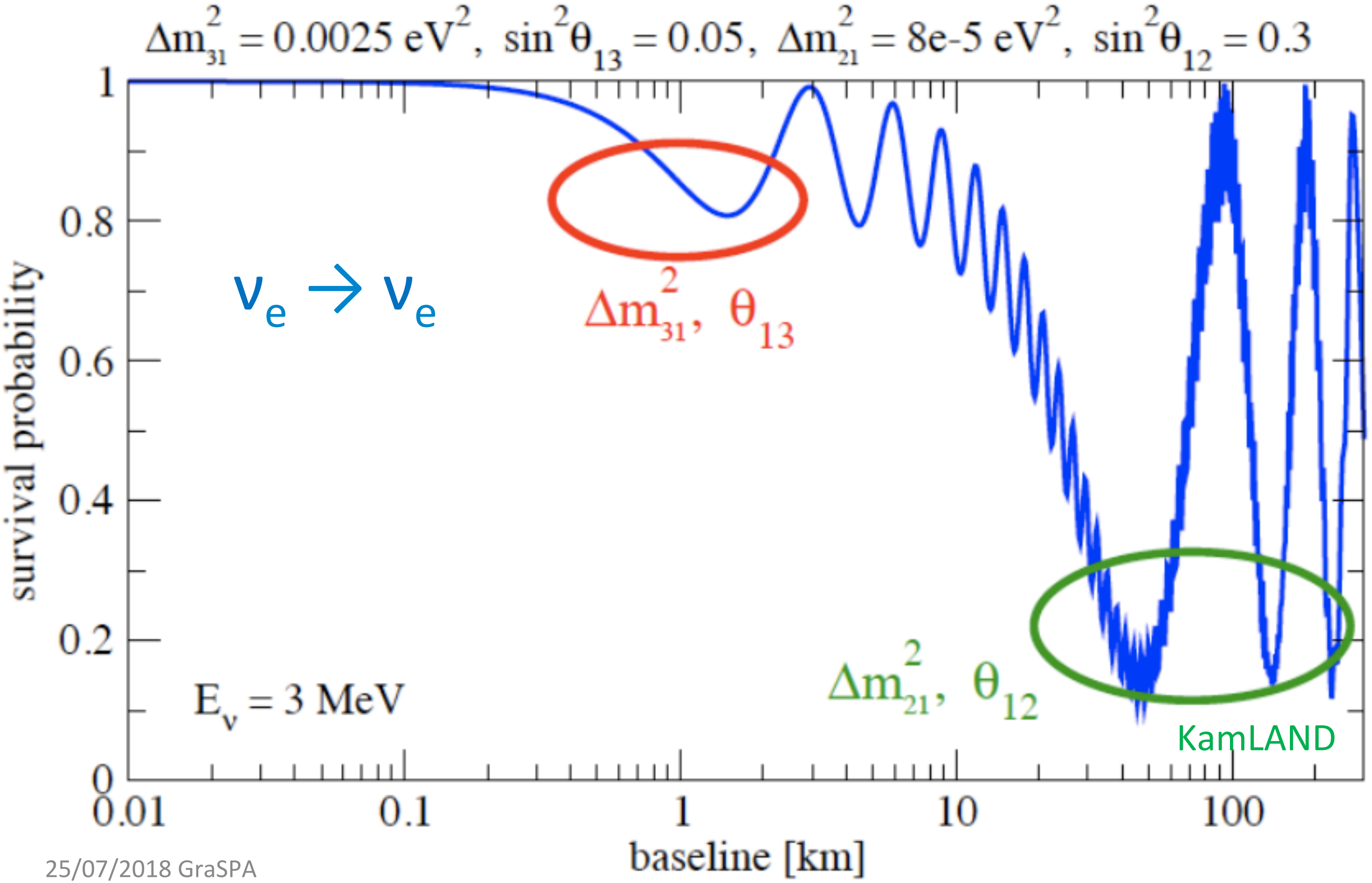
- What is the amount of ν_e in ν_3 (θ_{13})?



Convention: ν_1 is state with most ν_e

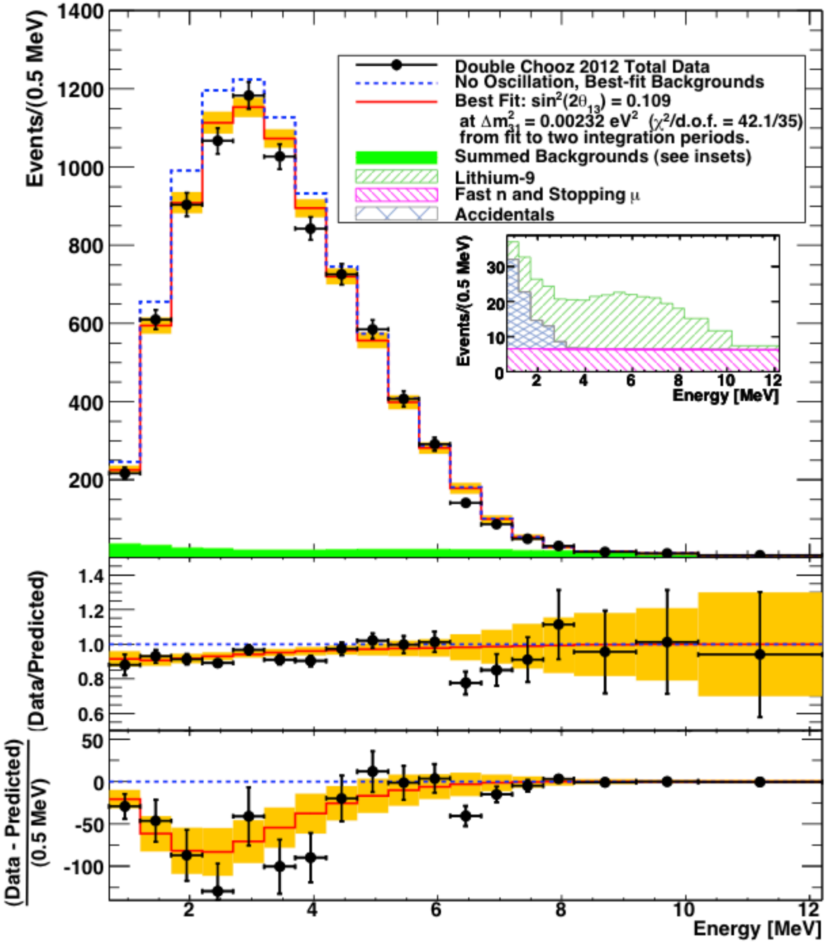
Amount of ν_e in faster oscillations (θ_{13})

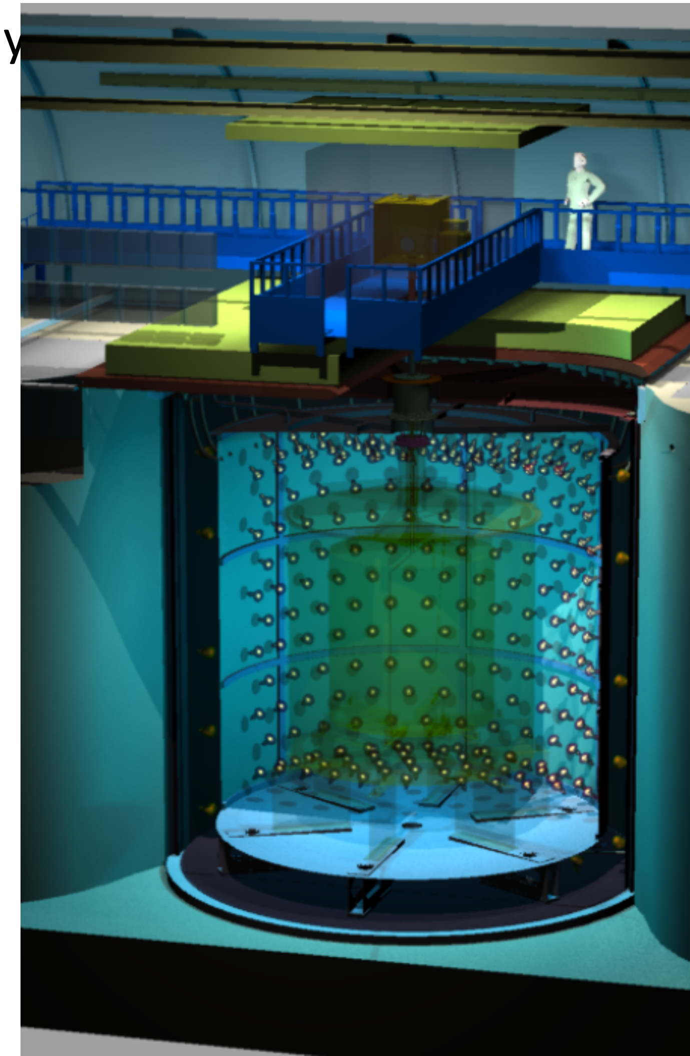


Amount of ν_e in fast oscillations (θ_{13})

Oscillation probability depends on energy → search for energy-dependent depletion

- Double Chooz: liquid scintillator detector, 1 km away from reactors

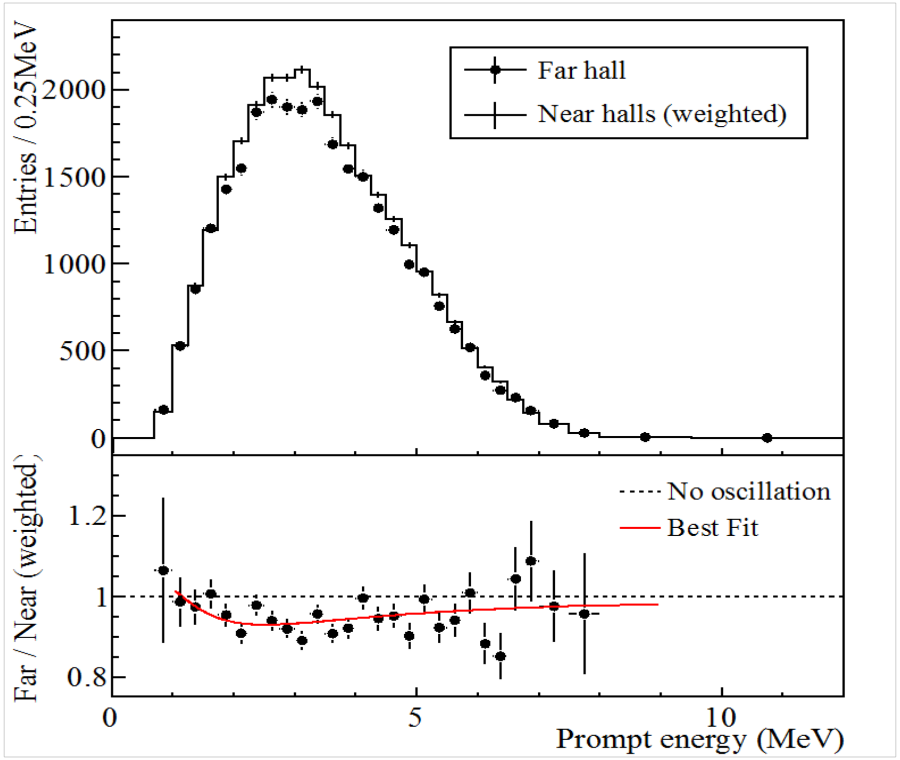




Amount of ν_e in fast oscillations (θ_{13})

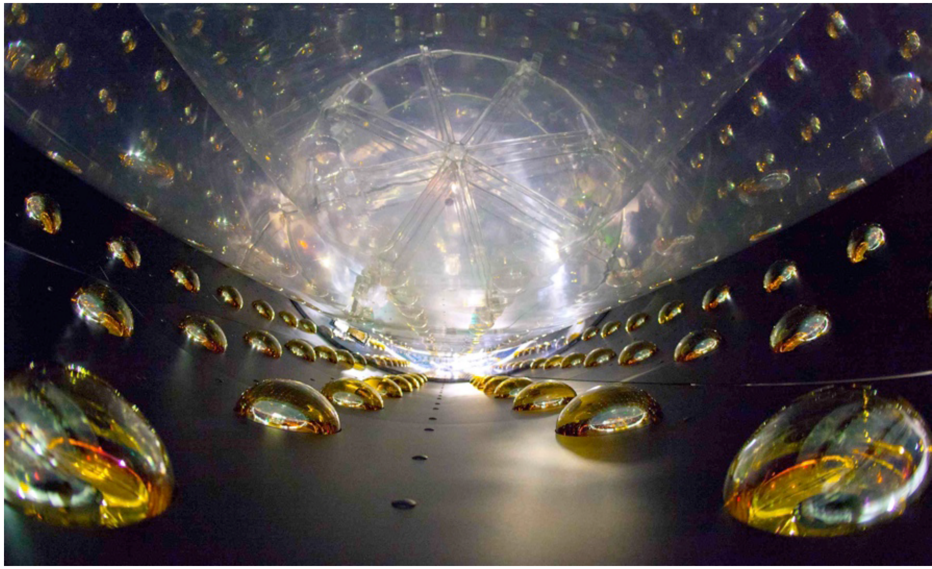
Oscillation probability depends on energy → search for energy-dependent depletion

- Daya Bay: very similar detector to Double Chooz and Reno, all 1-2 km away from reactors



$\sin^2(2\theta_{13}) = 0.089 \pm 0.012$

$\theta_{13} = 9.1° \pm 0.6°$ (≈ θ_{Cabbibo}!)

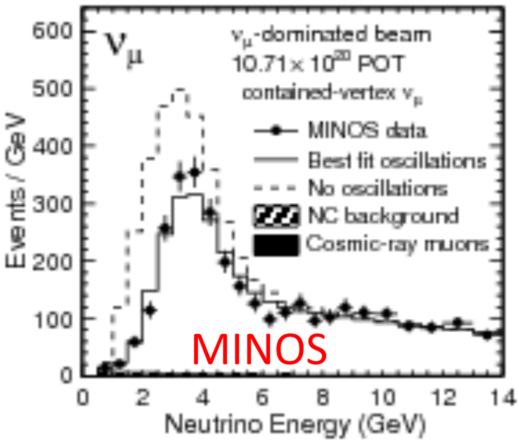


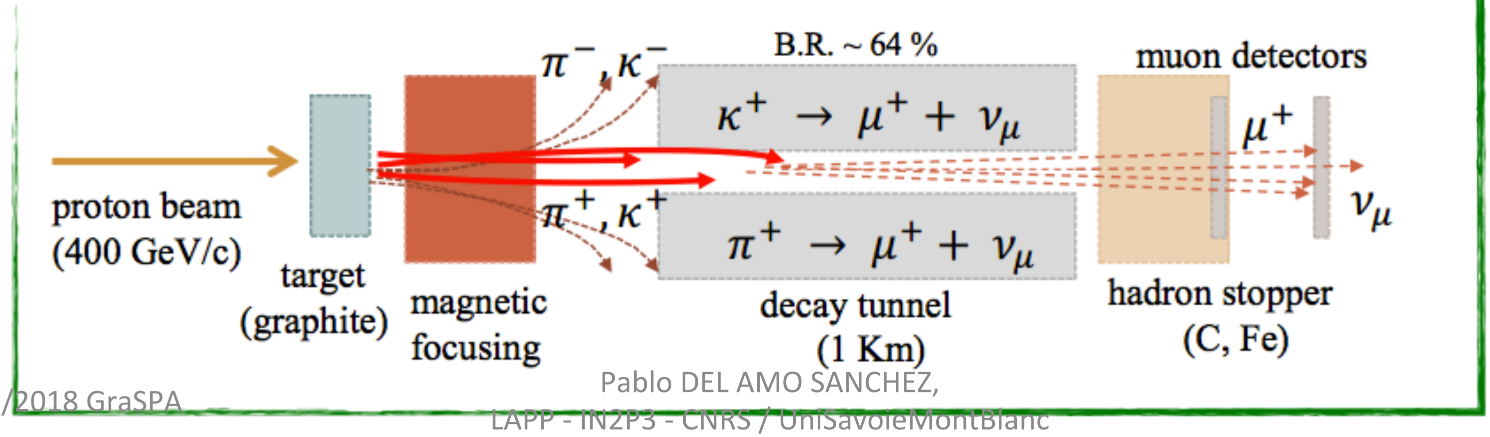
Fourth parts couldn’t be better: accelerator neutrinos

Accelerator experiments

- Can also produce neutrino beams:
- Results in excellent agreement with

other neutrino sources:





$\nu_\mu \rightarrow \nu_\tau$ appearance

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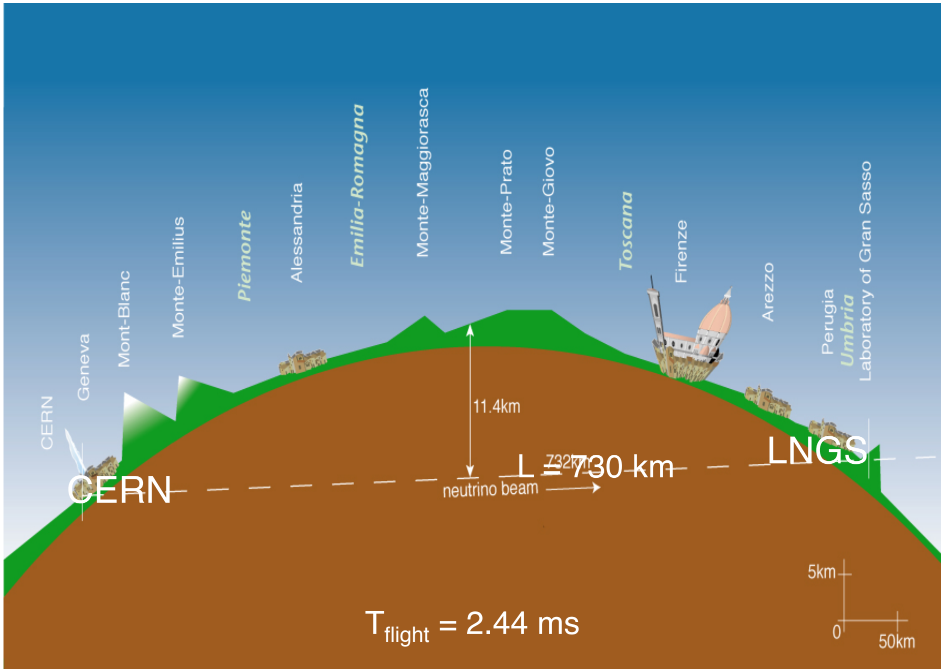
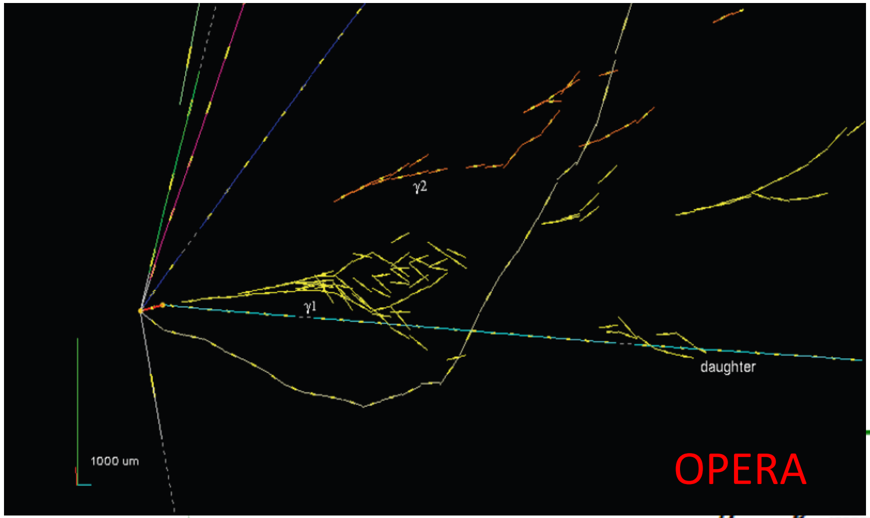
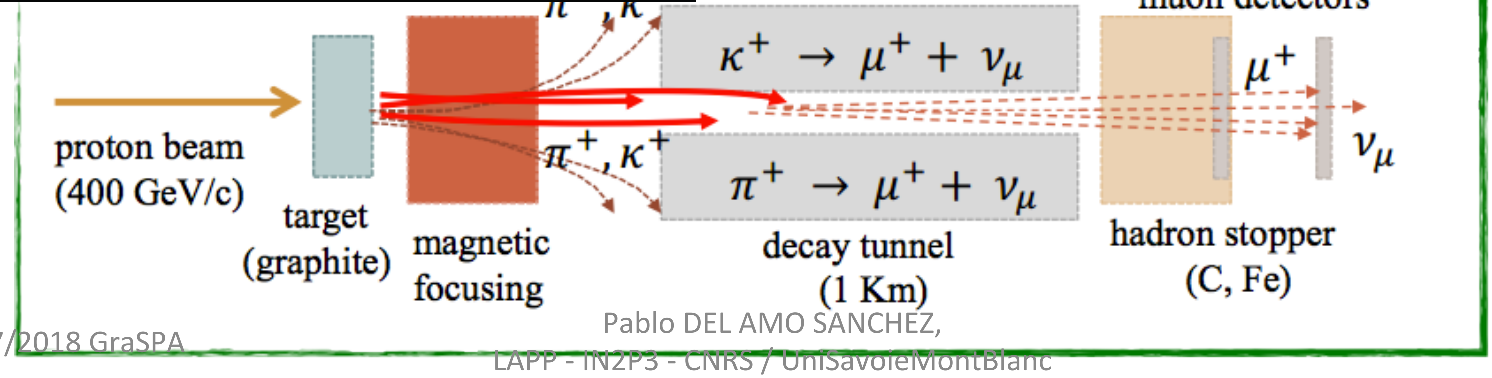
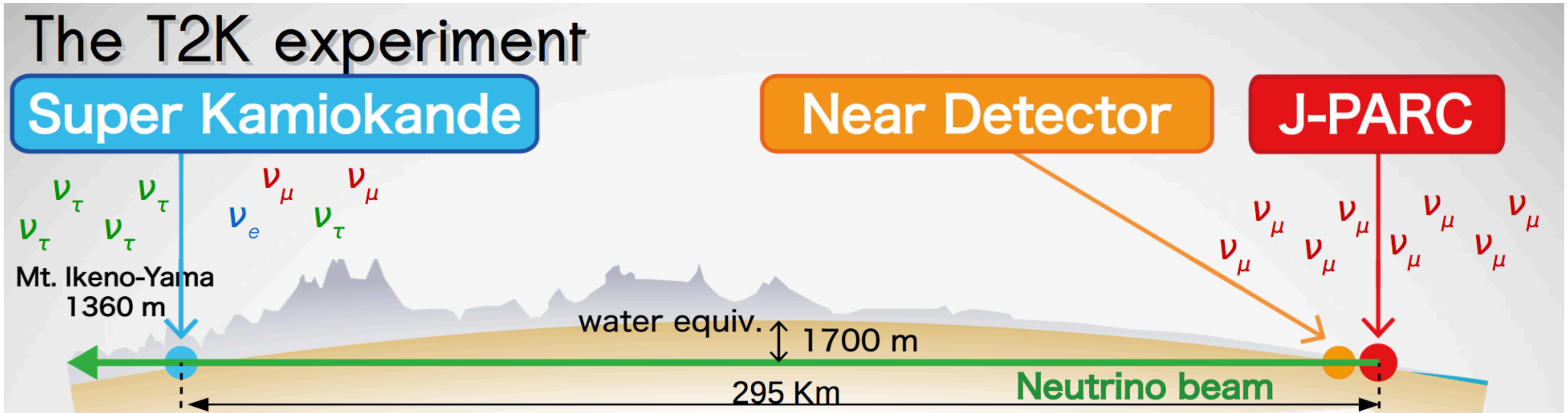
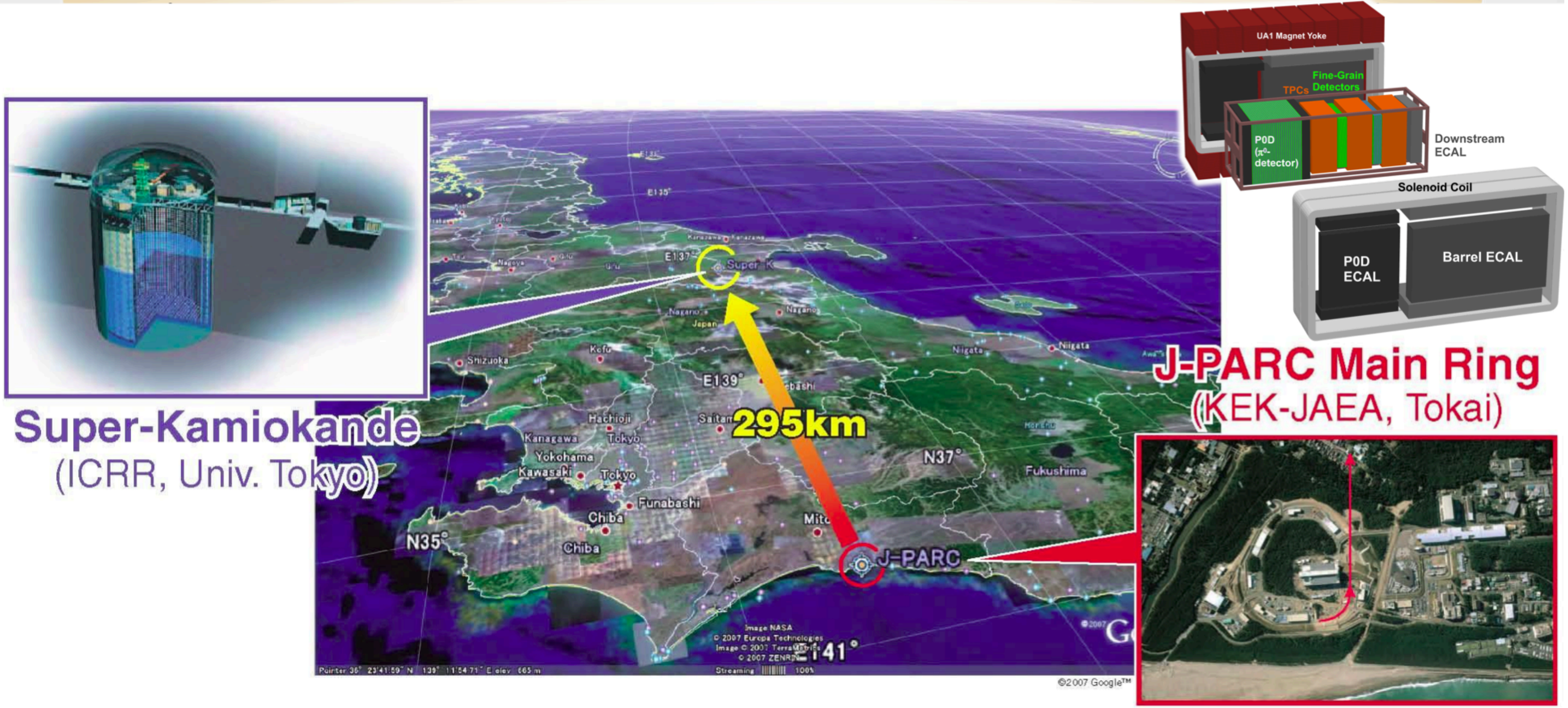






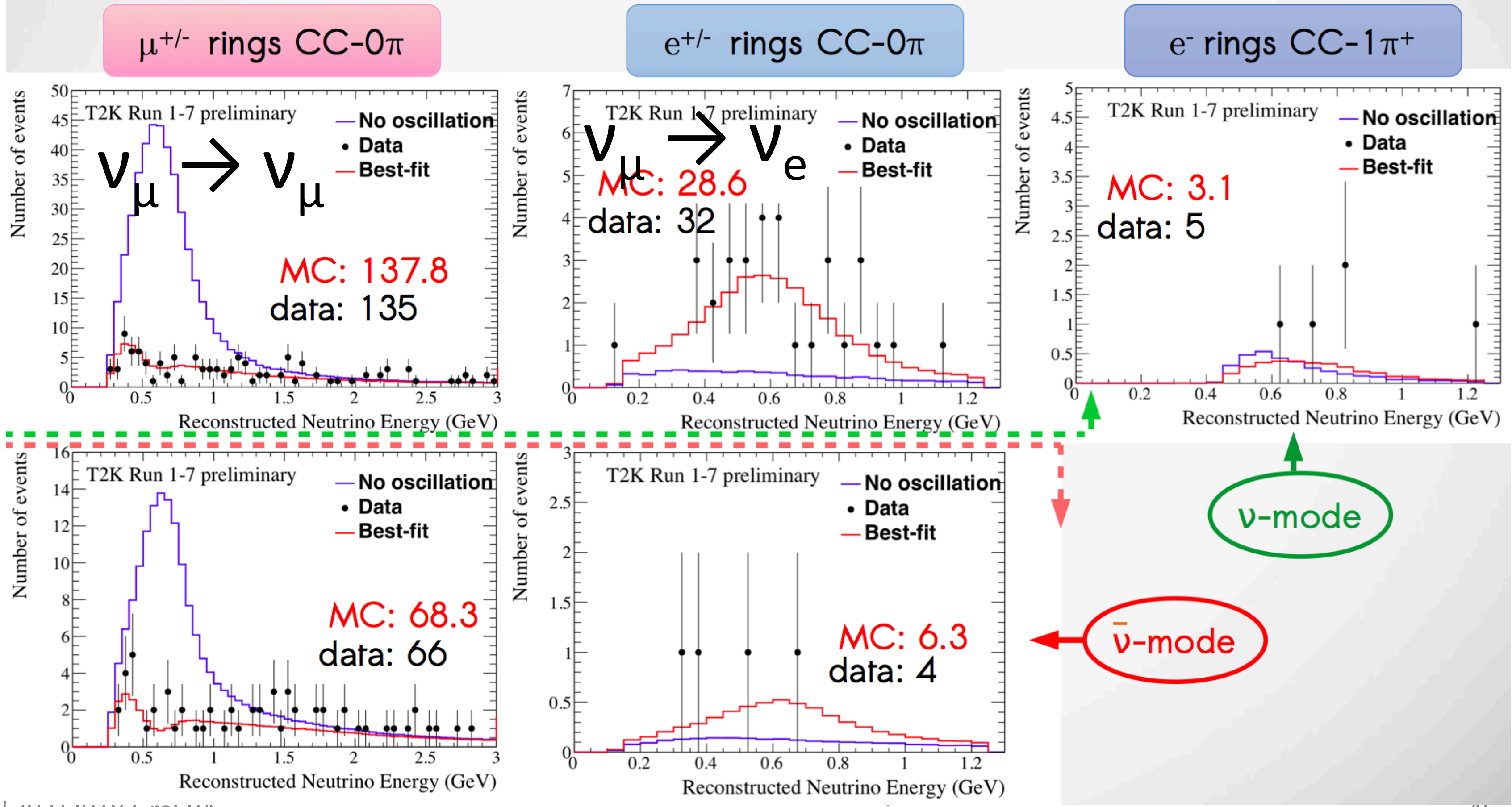
Recent results: T2K





Recent results: $\nu_\mu \rightarrow \nu_e$ appearance

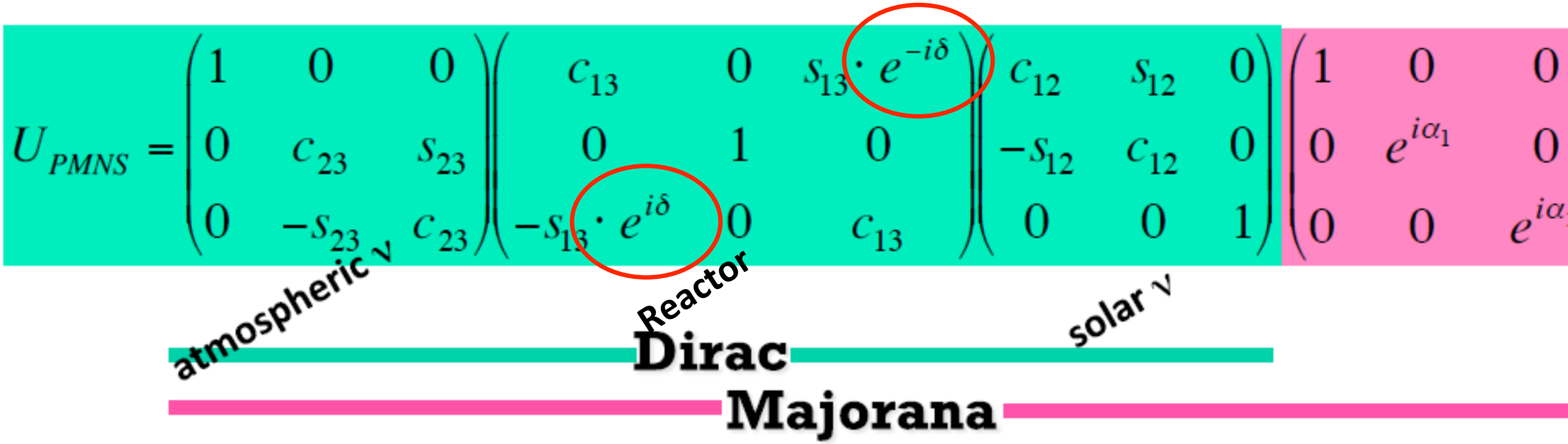
- T2K observes 32 ν_e events, 5 background events expected
- Appearance of different flavour ($\nu_\mu \rightarrow \nu_e$) at > 8 σ



Neutrino mixing matrix

3 angles and 1 CP phase: $\theta_{12}, \theta_{13}, \theta_{23}, \delta$

+ 2 phases



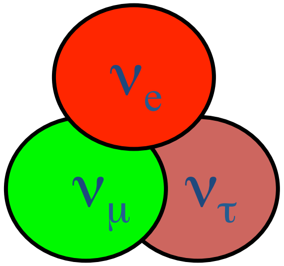
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \cdot \boxed{e^{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13} \cdot \boxed{e^{i\delta}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha} \end{pmatrix}$$

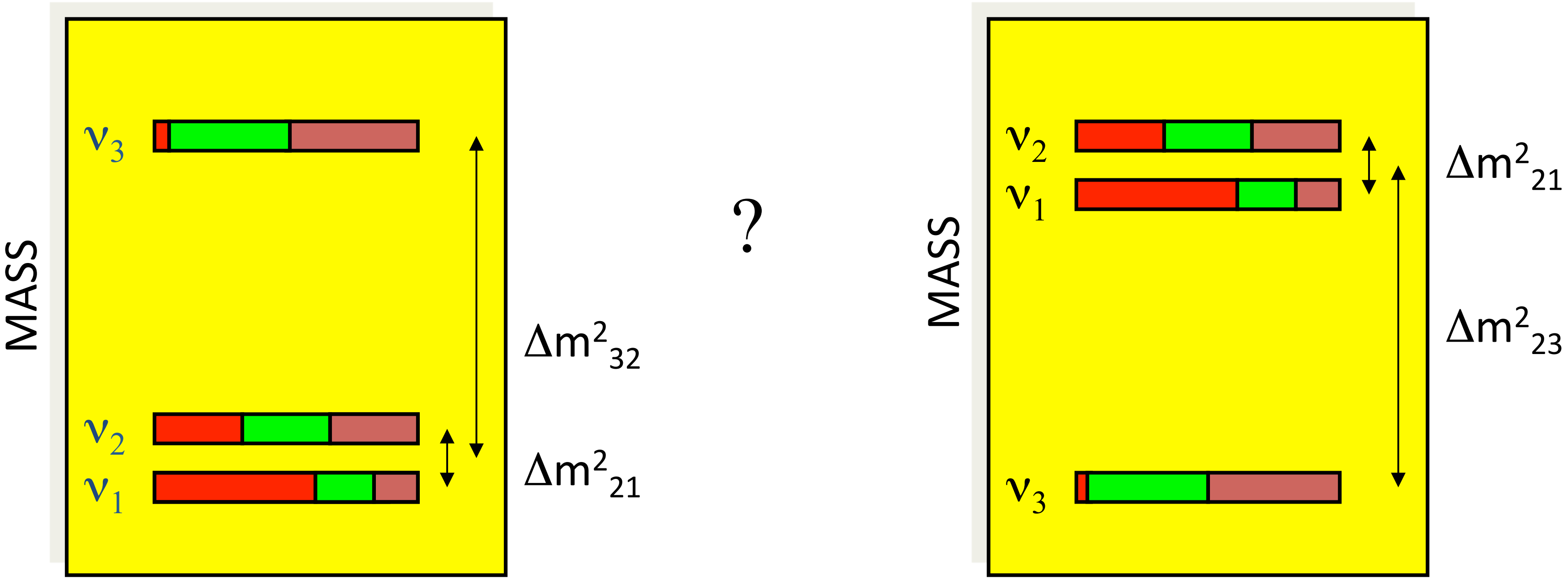
$$c_{ij} = \cos\theta_{ij}$$

$$s_{ij} = \sin\theta_{ij}$$

δ, matter-antimatter asymmetry in neutrinos?

Mass ordering?





Normal mass ordering

Inverted mass ordering

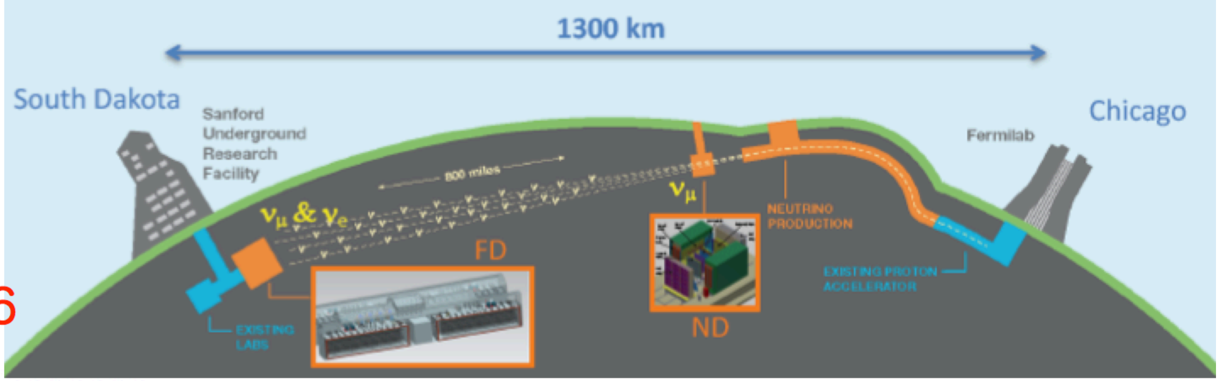
Which mass state is the lightest?

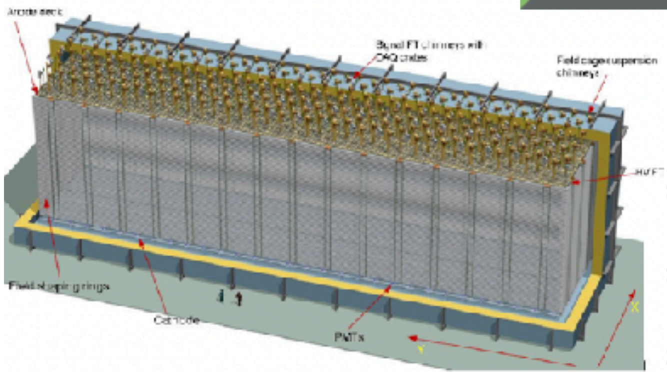
Future long baseline projects…

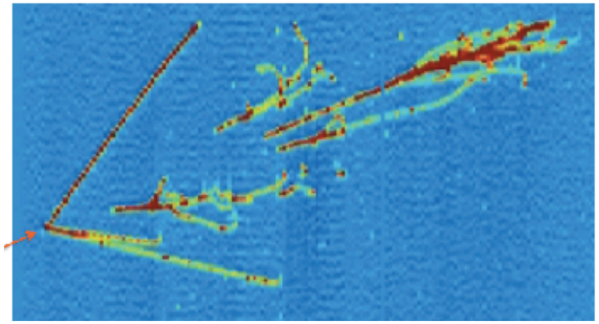
DUNE

40 kton Lq. Ar TPC

Starting around 2026

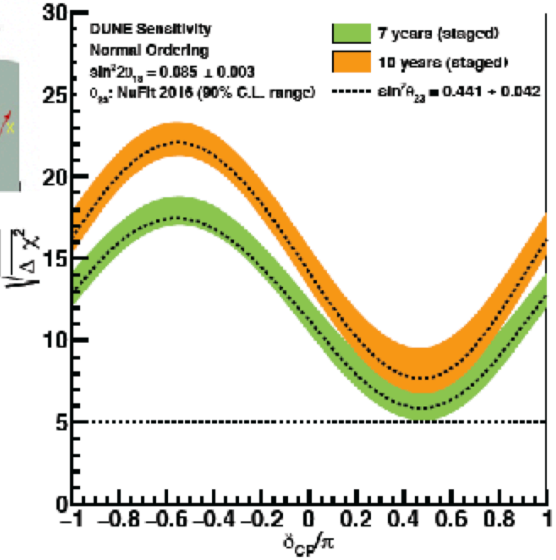




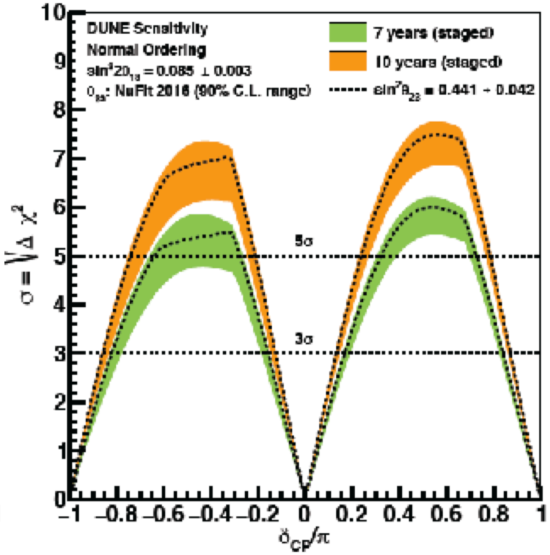


Sensitivity

Mass Hierarchy



CP Violation



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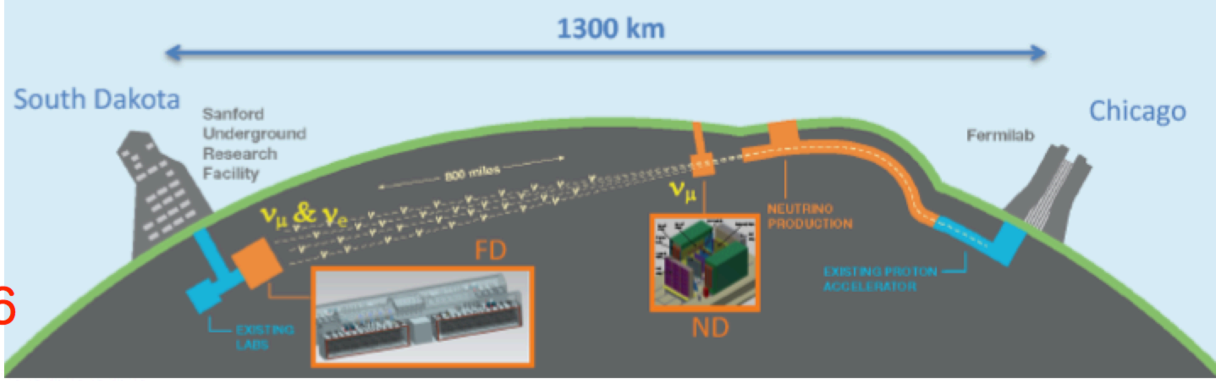
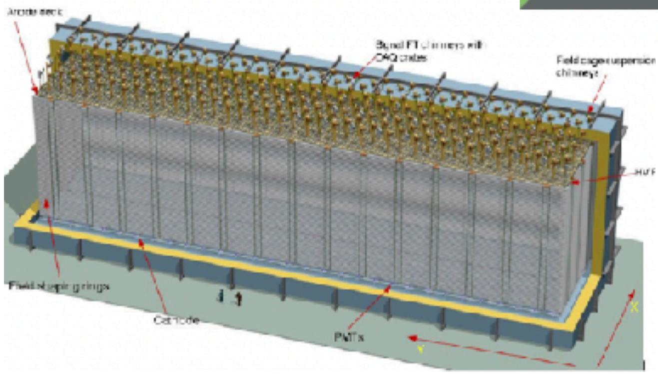
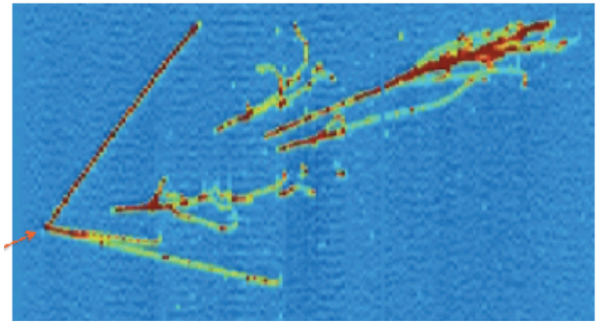






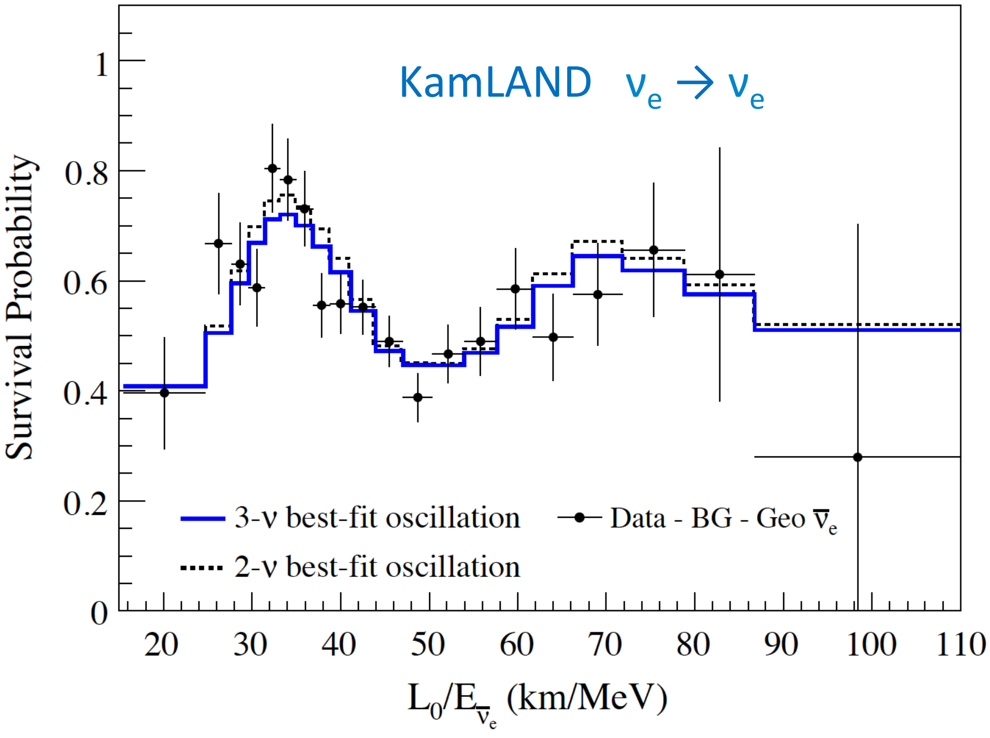
Broad physics programme!

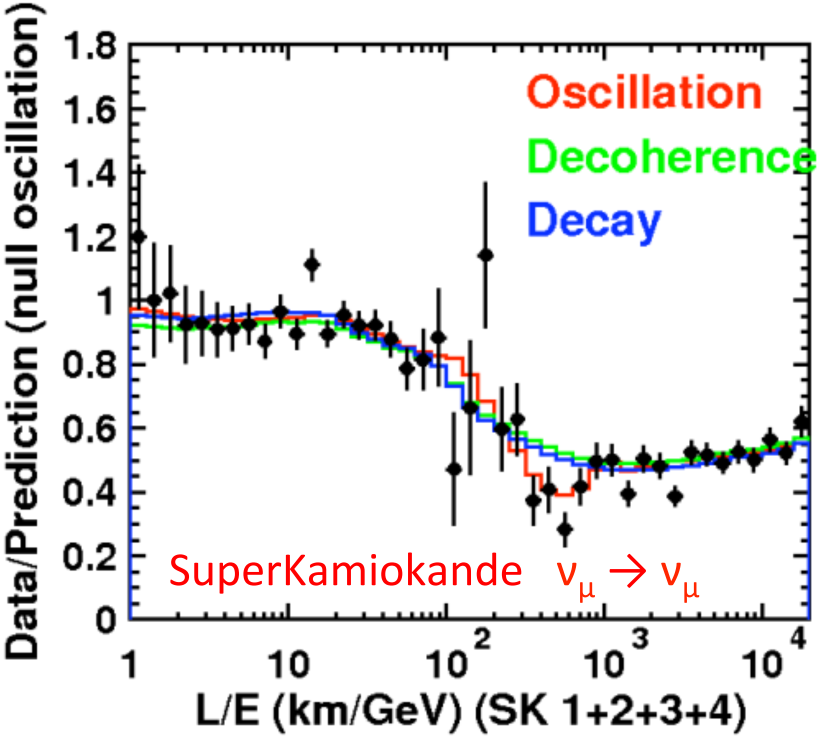
- Long baseline oscillations
- Mass ordering
- Matter-antimatter asymmetry
- SN neutrinos
- Proton decay
- And more…

Conclusions

- Neutrinos oscillate! Masses ≠ 0 (2015 Nobel prize)

ν_e, ν_μ, ν_τ different from ν_1, ν_2, ν_3





Conclusions

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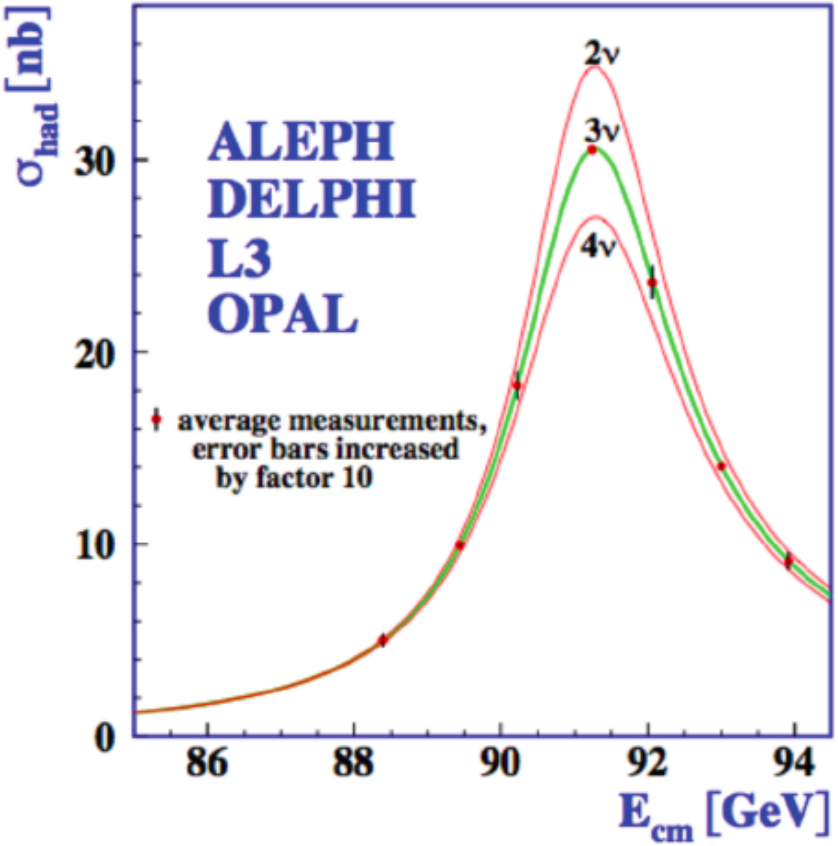
  reactor, not so small $\theta_{13} = 9.1° \pm 0.6°$

- For the future: matter-antimatter asymmetry in neutrinos?

  which is the lightest mass state?

BACK UP SLIDES

How many neutrinos are there?



$$\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_{\text{had}} - 3\Gamma_l$$

$$\Gamma_{\text{inv}} = N_\nu \cdot \Gamma_\nu$$

PDG K. Nakamura et el., JPG 37, 075021 (2010)

Number N = 2.984 ± 0.008
(Standard Model fits to LEP data)

Number N = 2.92 ± 0.05 (S=1.2)
(Direct measurement of invisible Z width)

Etats propres de saveur et de masse

- Matrice PMNS (Pontecorvo-Maki-Nakagawa-Sakata) relie états propres de masse (ν_1, ν_2, ν_3) et de saveur (ν_e, ν_μ, ν_τ)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

p.ex.

$$\left|\nu_\mu\right\rangle = U_{\mu 1}\left|\nu_1\right\rangle + U_{\mu 2}\left|\nu_2\right\rangle + U_{\mu 3}\left|\nu_3\right\rangle$$

Oscillations des neutrinos

- Neutrinos sont créés dans des états propres de saveur, se propagent comme des états propres de masse, et sont détectés comme des états propres de la saveur : (ex : neutrinos atmosphériques, issus des désintégrations des pions)

Production
États propres de saveur
ν_e, ν_μ, ν_τ

Propagation
États propres de masse
ν_1, ν_2, ν_3

Détection
États propres de saveur
ν_e, ν_μ, ν_τ

(Analogue aux oscillations des kaons neutres : production et détection en termes des états de saveur K^0 et $\overline{K}^0$, propagation en termes de K_{short} et K_{long})

Oscillations des neutrinos

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Propagation dans le vide

ν_1 : $\exp(-iE_1t)$
ν_2 : $\exp(-iE_2t)$
ν_3 : $\exp(-iE_3t)$

Production

$$|\nu_\mu\rangle = U_{\mu1}|\nu_1\rangle + U_{\mu2}|\nu_2\rangle + U_{\mu3}|\nu_3\rangle$$

Détection

$$\langle\nu_e|$$

Masses m_1, m_2, m_3 différentes → phases $-iE_1t$, $-iE_2t$, $-iE_3t$ différentes →

→ proportion des composantes e, μ, τ change avec le temps

Un peu d'histoire

- Oscillation neutrino-antineutrino proposée par Bruno Pontecorvo (1957) par analogie avec les oscillations K^0 et $\overline{K^0}$
- Mélange entre les saveurs proposé par Maki, Nakagawa et Sakata (1962)
- Calcul de la probabilité d'oscillation entre saveurs par Gribov et Pontecorvo (1967, 1969)

- Etudes expérimentales expliquées en détail page 12 et suivantes