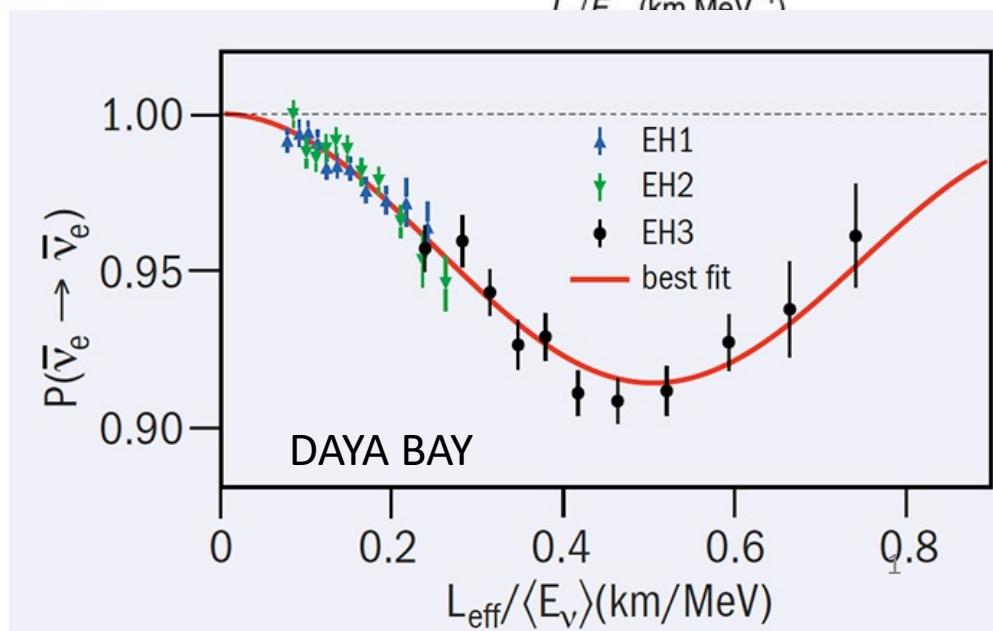
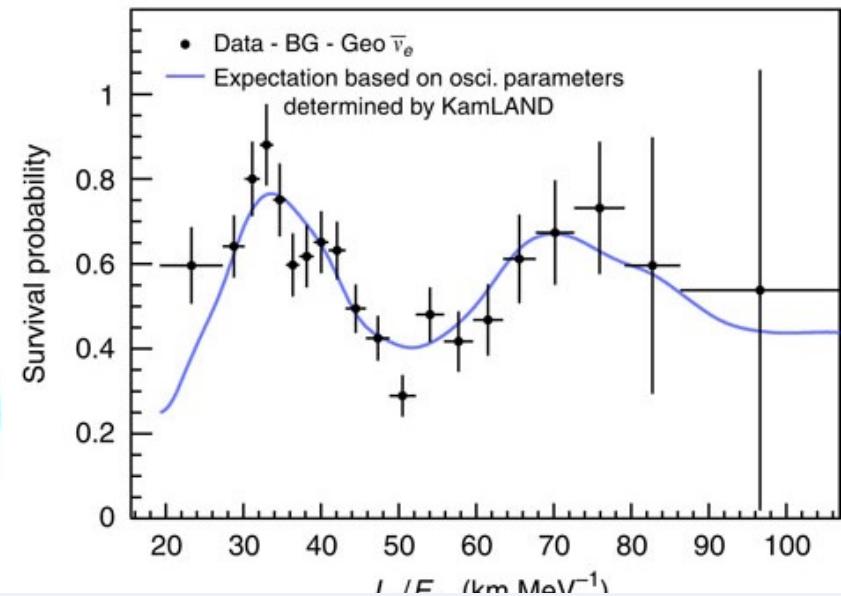


# Neutrino detection and neutrino oscillations



Pablo del Amo Sánchez  
GraSPA  
28/08/21

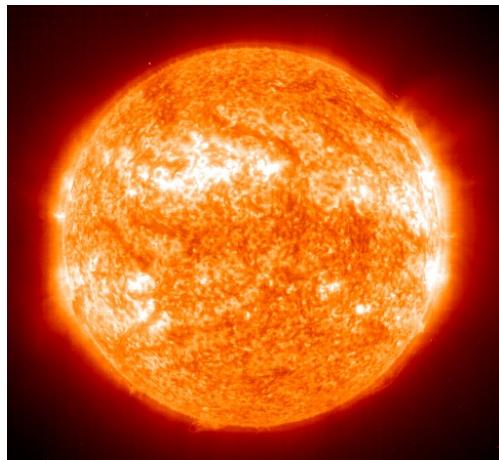


# Overview

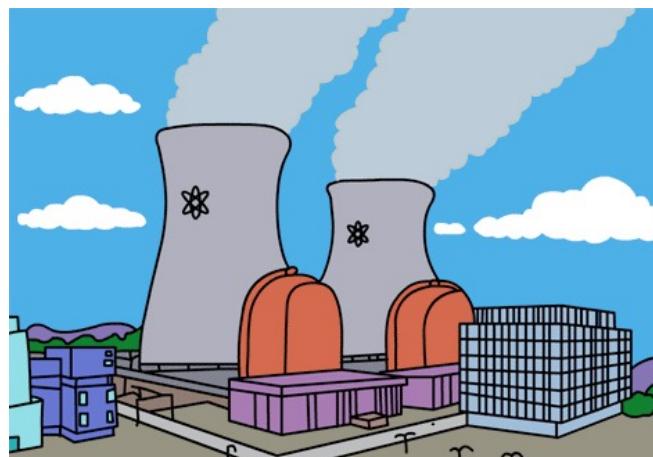
- Evidence for neutrino oscillations
  - Non historical approach
- How to go about detecting neutrinos

# $\nu$ sources

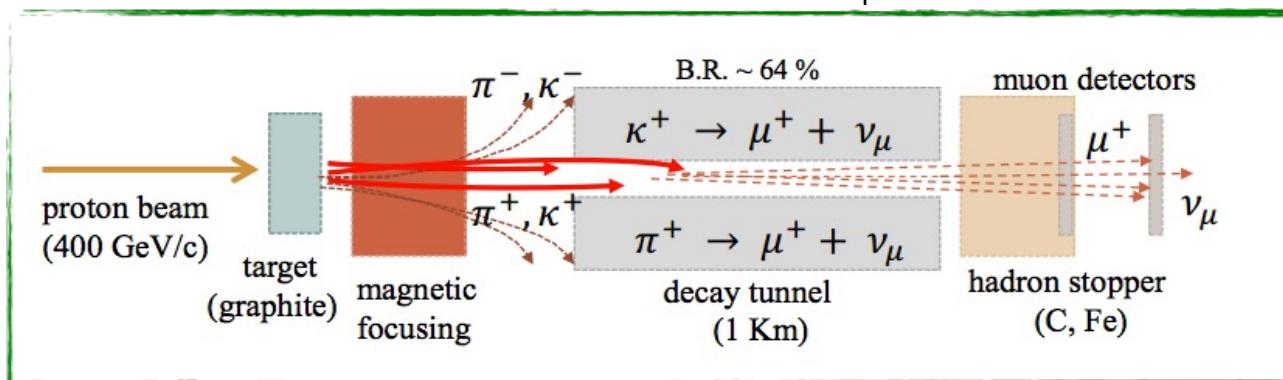
The Sun  
 $65 \times 10^9 \nu_e \text{ cm}^{-2} \text{ s}^{-1}$  at Earth



Nuclear reactors  
 $2 \times 10^{20} \nabla_e \text{ s}^{-1} \text{ GW}_{\text{th}}^{-1}$



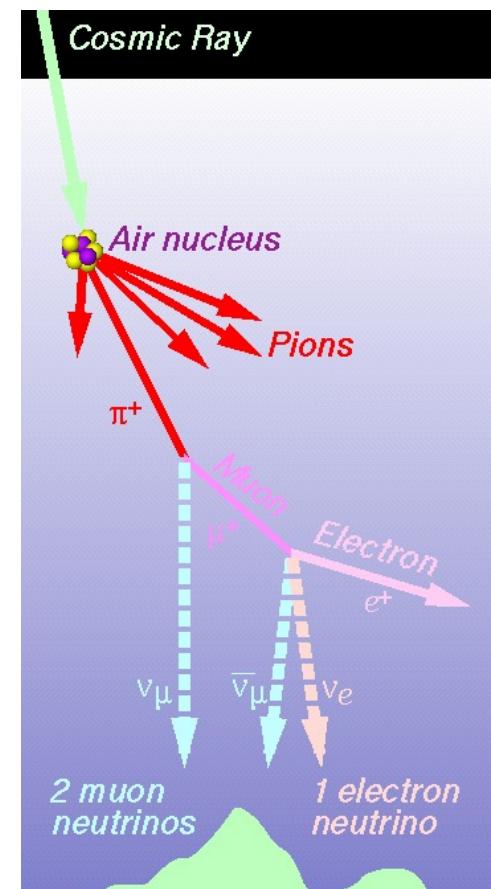
Accelerators, e.g. at OPERA:  $1 \times 10^{12} \nu_\mu \text{ m}^{-2}$



Plus: astrophysical neutrinos, CvB, etc  
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LAPP - IN2P3 - CNRS / UniSavoieMontBlanc

Atmospheric  $\nu$  (cosmic rays)  
 $4 \times 10^2 \nu_{\mu+e} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$  at 1 GeV



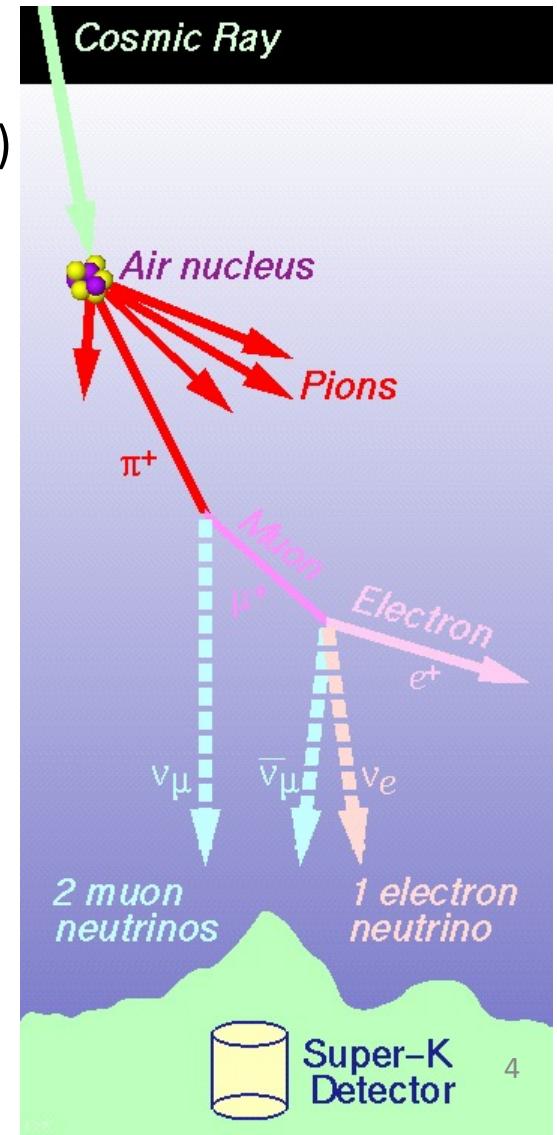
# Atmospheric neutrinos

- 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

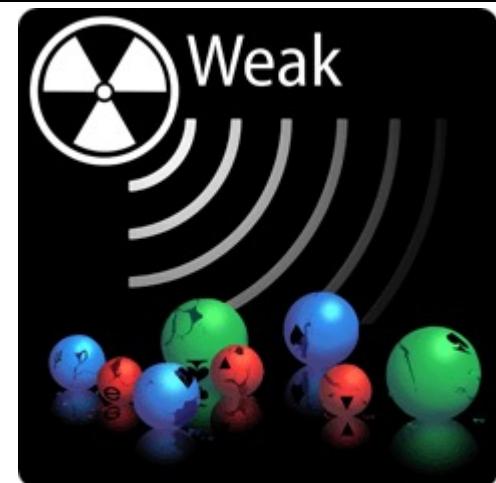
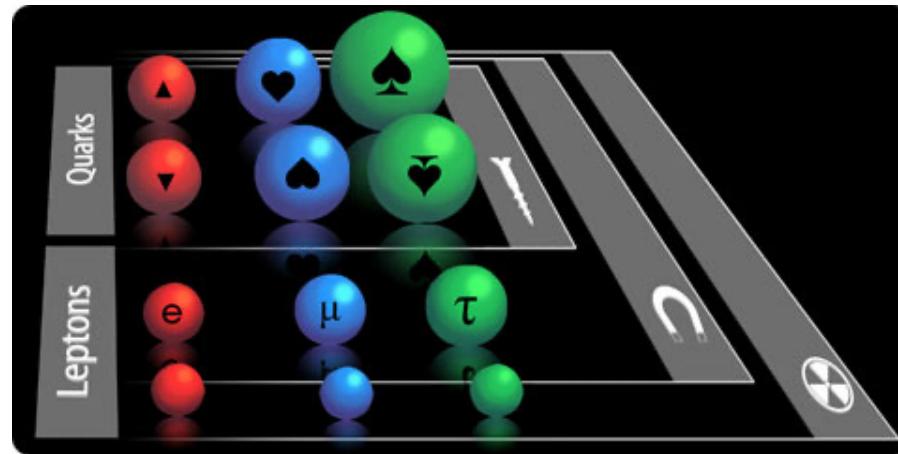
$$\nu_\mu : \nu_e = 2 : 1$$

(known better than 3% below 5 GeV)



# How to detect neutrinos?

- $\nu$  electrically neutral  
→ no ionization tracks!
  - nearly massless  
→  $m_\nu < 1 \text{ eV}$  but  $\sum m_\nu > 0.06 \text{ eV}$
  - tiny interaction cross-section  
→  $\sigma \approx 10^{-42} \text{ cm}^2$  for Inverse Beta Decay
- need copious sources and/or large detector masses



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→ need copious sources and/or large detector masses

Ex: SuperKamiokaNDE

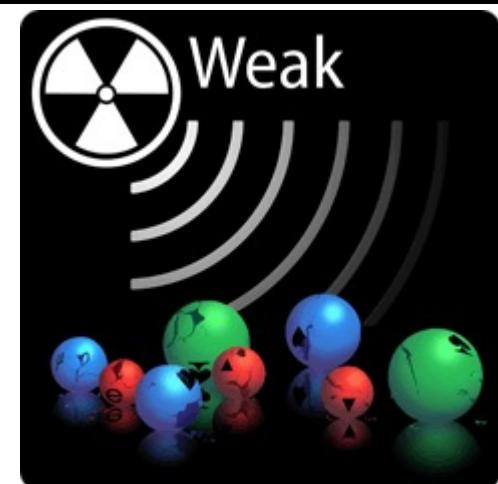
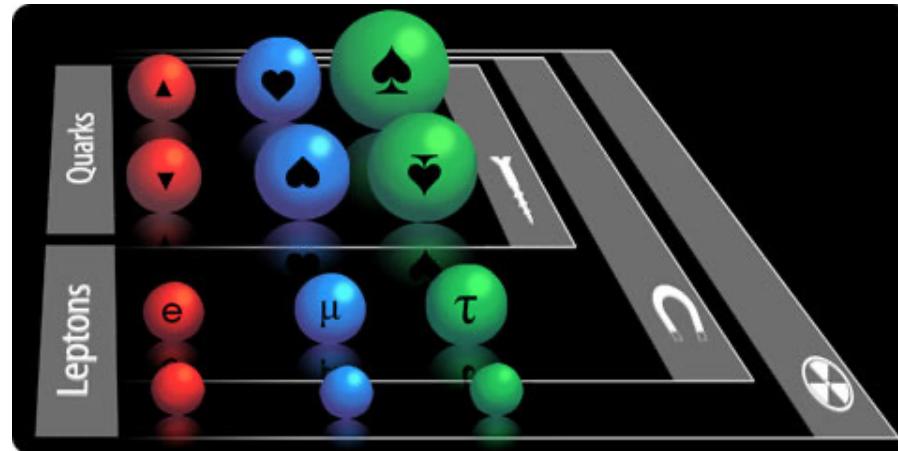
$$R = \phi N_N \sigma_N$$

In order to see  $R = 5 \nu_{\mu+e}$  evts/day

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

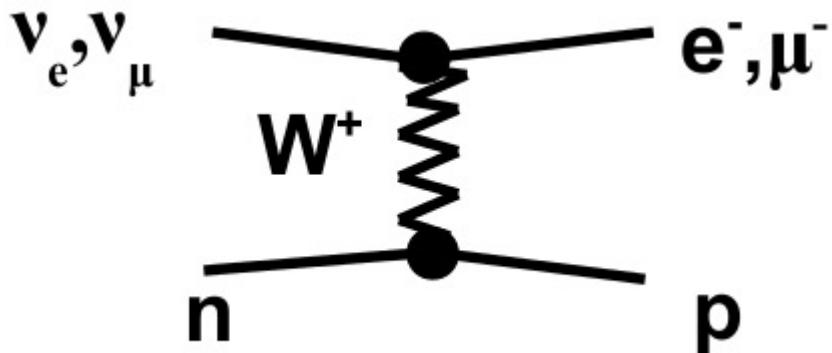
$$\sigma_N = 10^{-38} \text{ cm}^2 / \text{nucleon at } 1 \text{ GeV}$$

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



# Water Cerenkov detectors

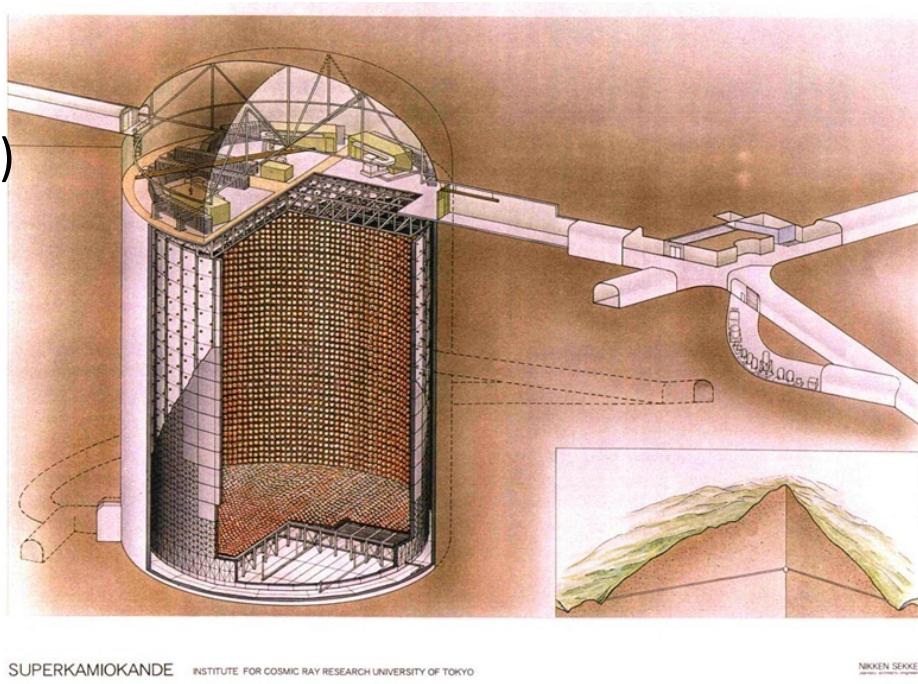
- Huge underground water tanks surrounded by photomultiplier tubes (PMTs)



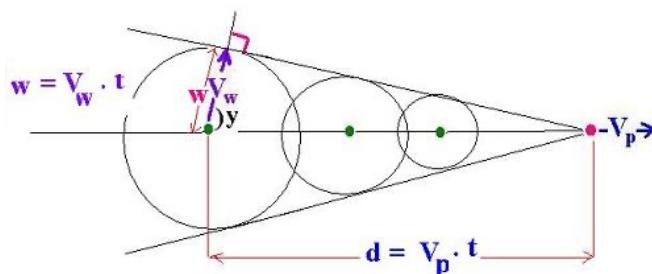
- Interacting particles produce light, light gives electrical signal in PMTs

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

- Ex: (Super-)KamiokaNDE et SNO

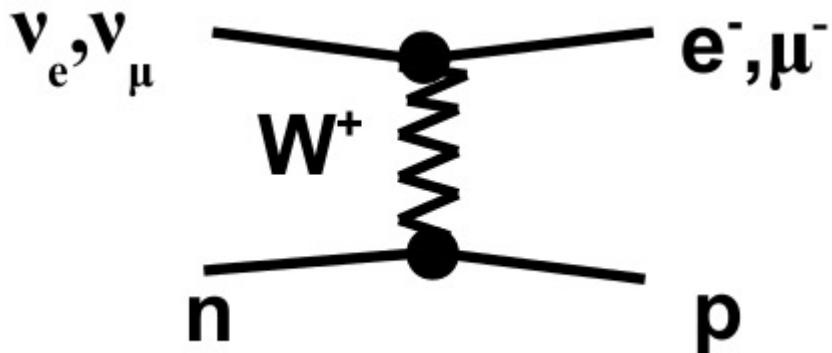


SUPERKAMIOKANDE INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO



# Water Cerenkov detectors

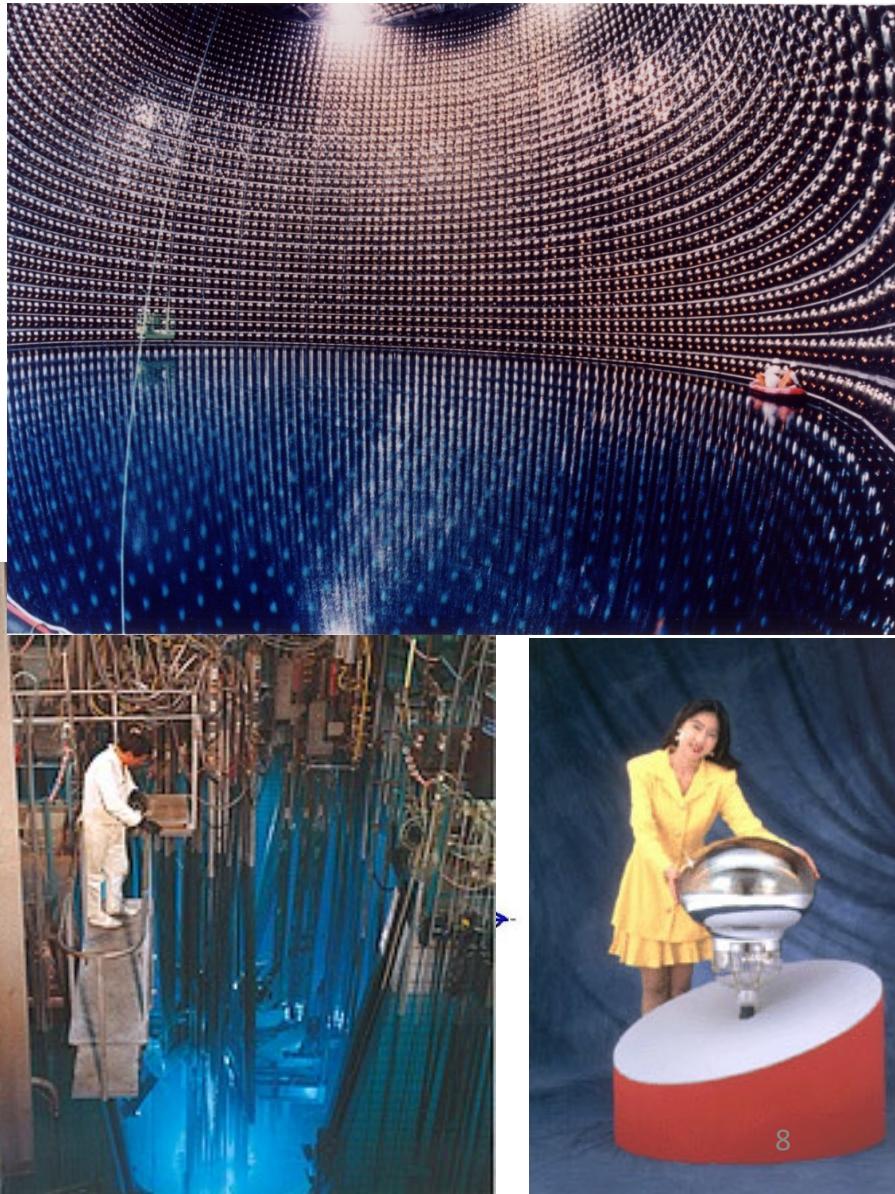
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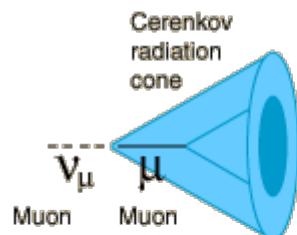
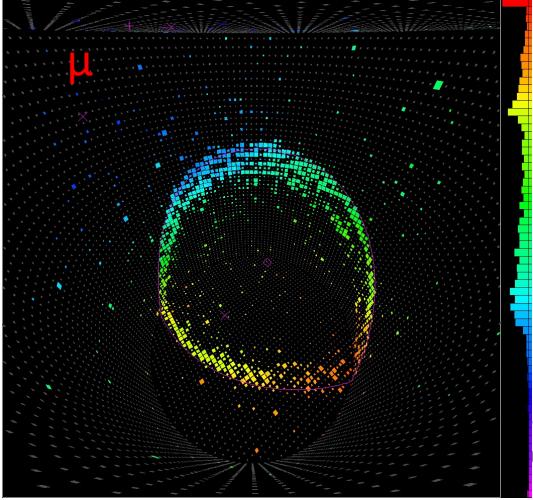
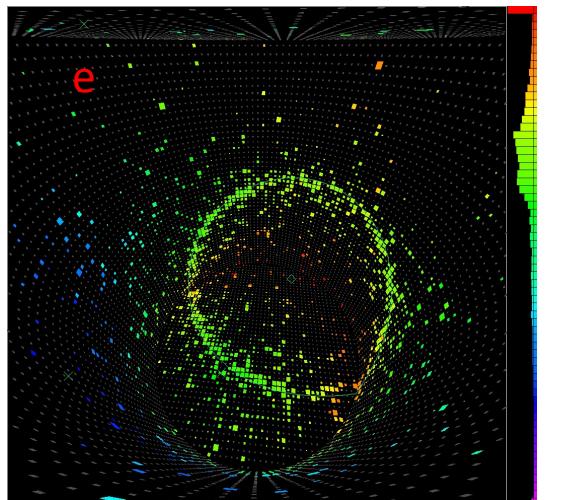
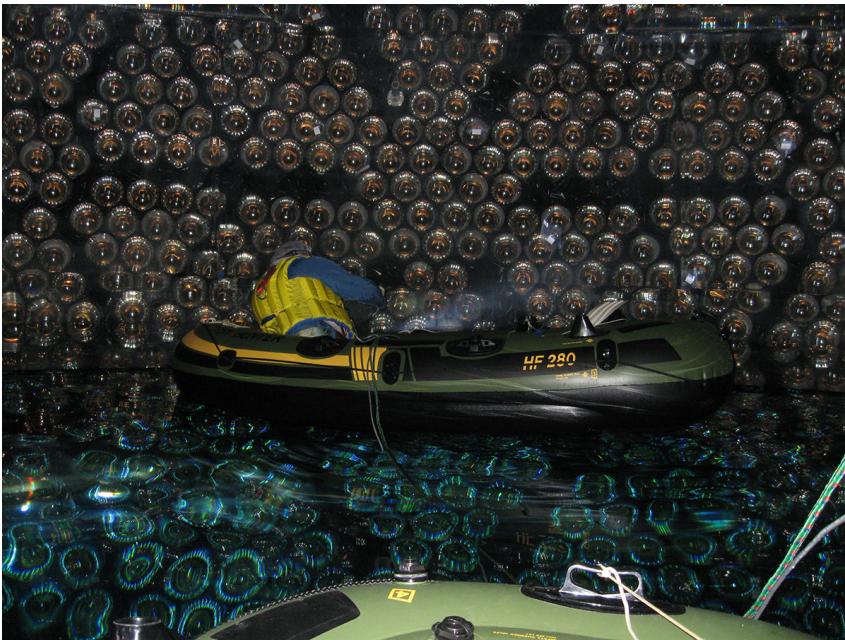
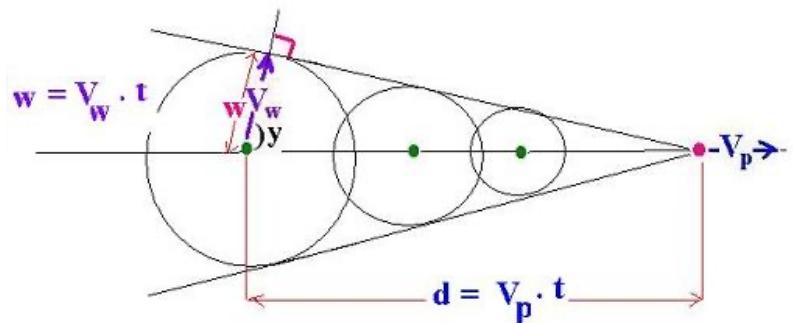
**Cerenkov effect:** particles faster than speed of light in medium radiate light (e.g. **blueish light** in nuclear reactors)

- Ex: (Super-)KamiokaNDE et SNO

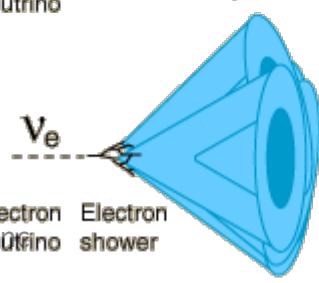


# Water Cerenkov detectors

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



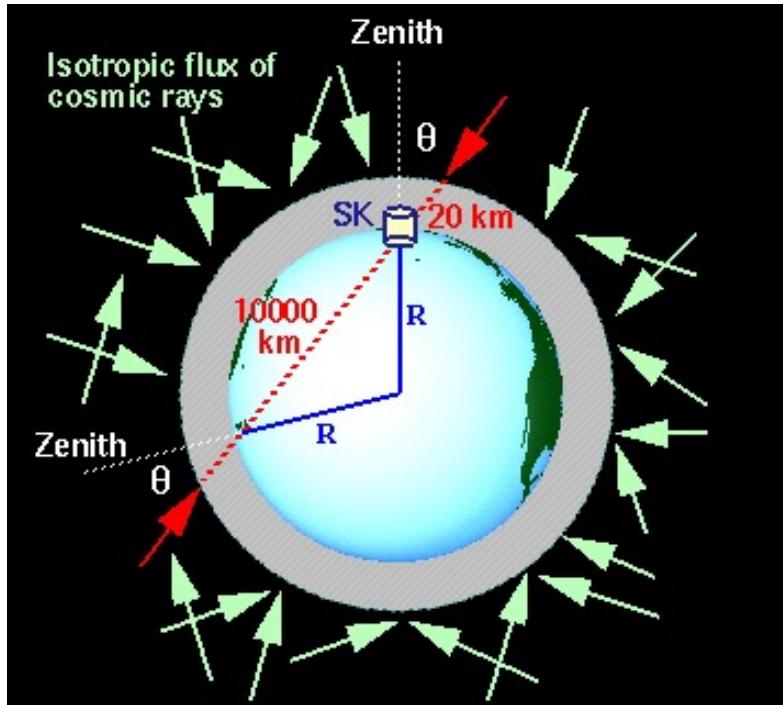
The Cerenkov radiation from a muon produced by a muon neutrino event yields a well defined circular ring in the photomultiplier detector bank.



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. 9

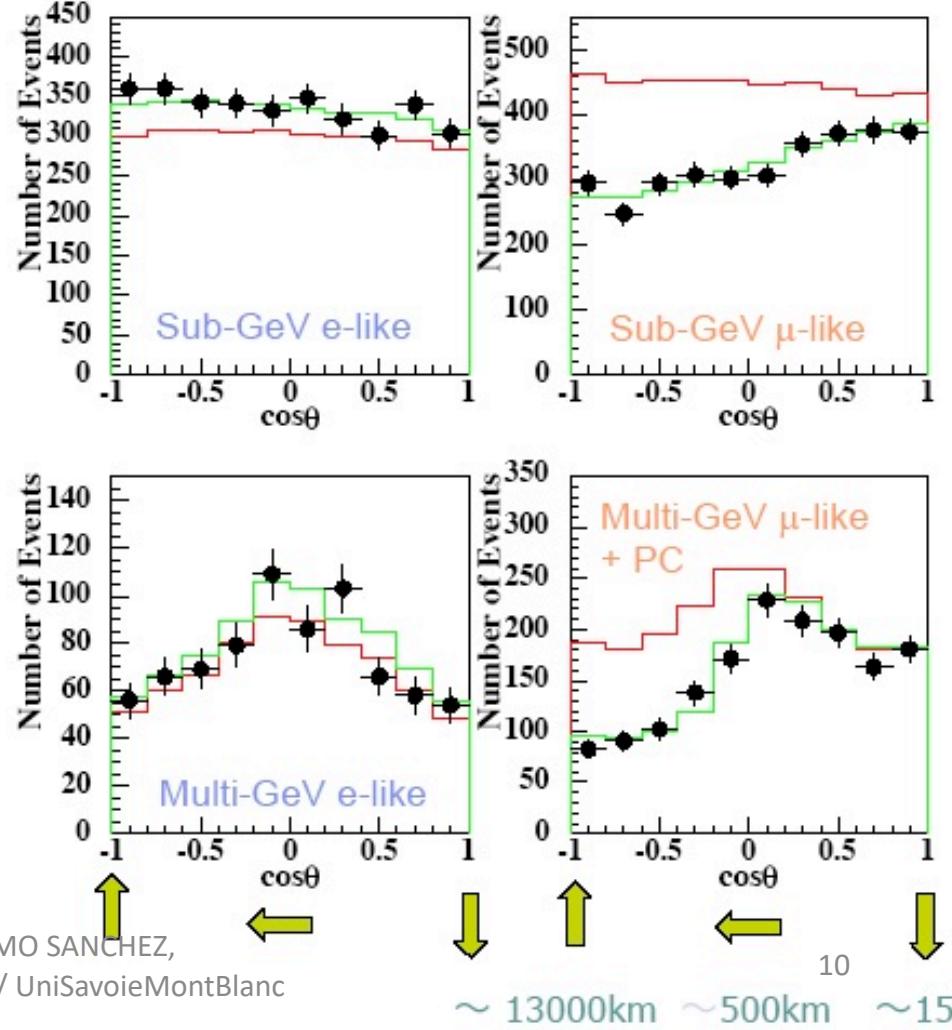
# Super-KamiokaNDE

- 1000m deep, 50000 tons of water, 11000 PMTs
- Observed expected number of downgoing  $\nu_\mu$ , deficit in upgoing
- No excess in  $\nu_e$ , so  $\nu_\mu \rightarrow \nu_\tau$  ?



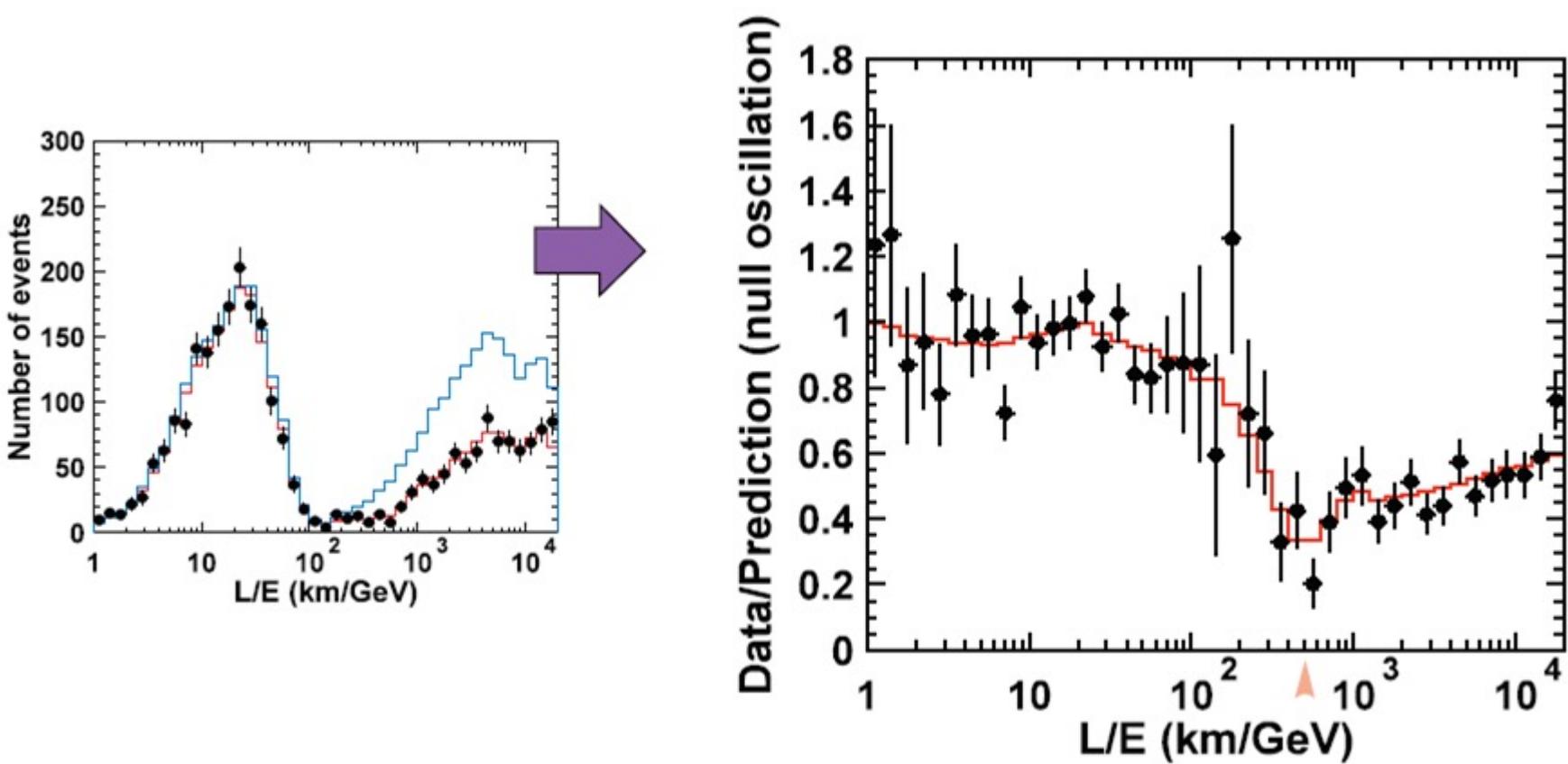
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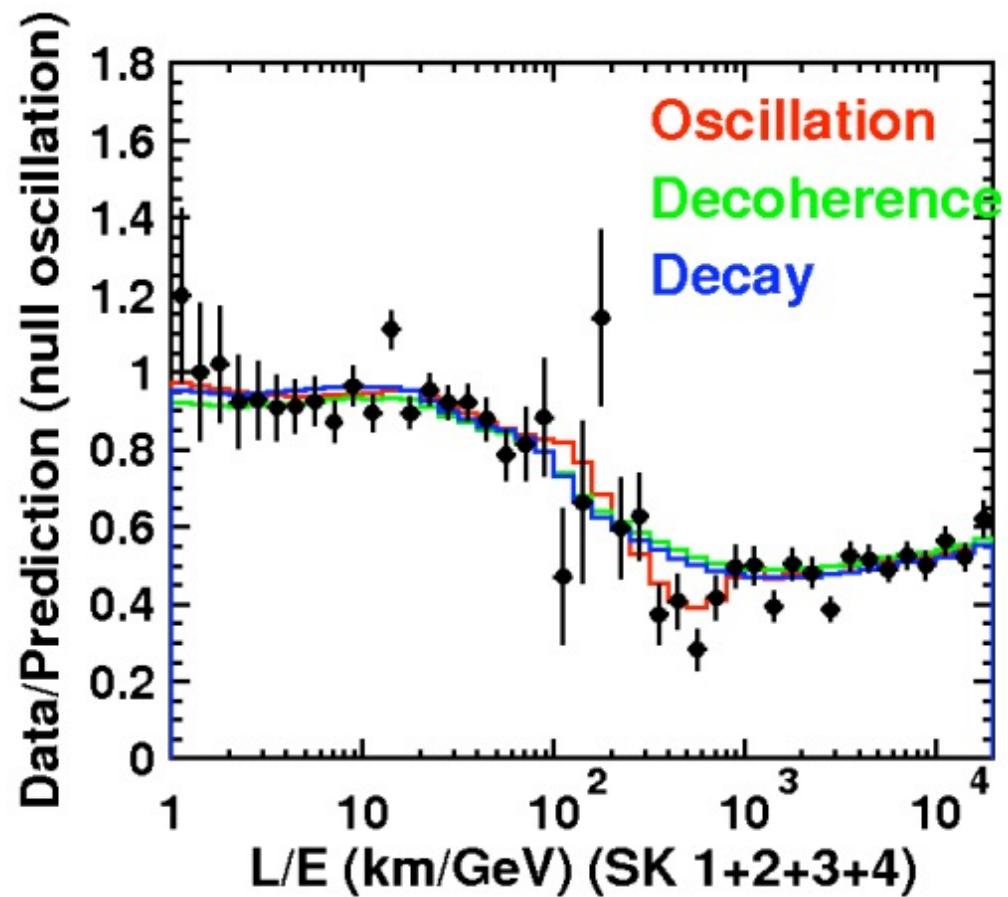
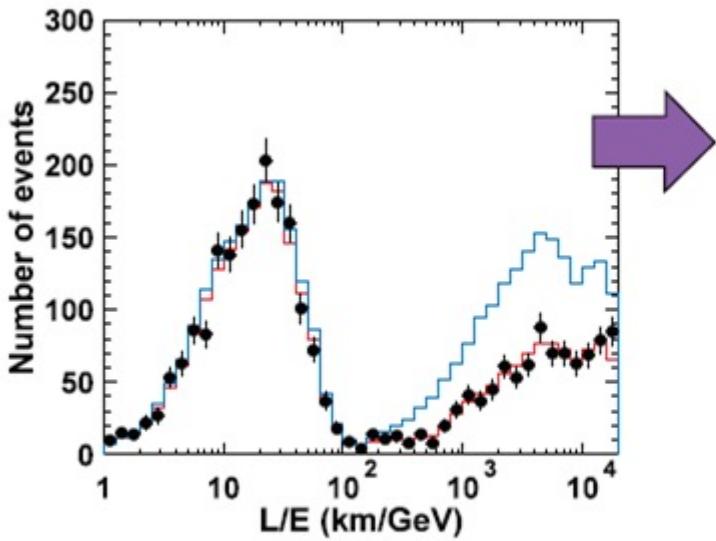


$\sim 13000\text{km}$   $\sim 500\text{km}$   $\sim 15\text{km}$

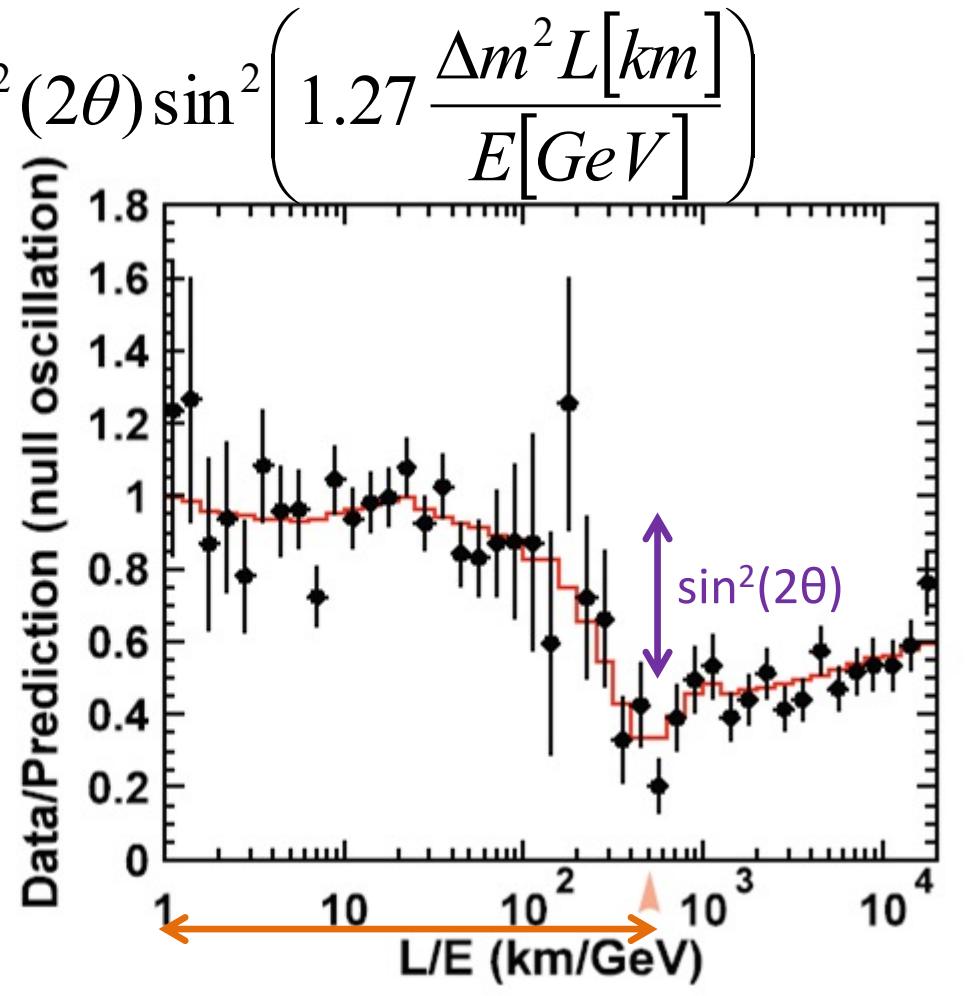
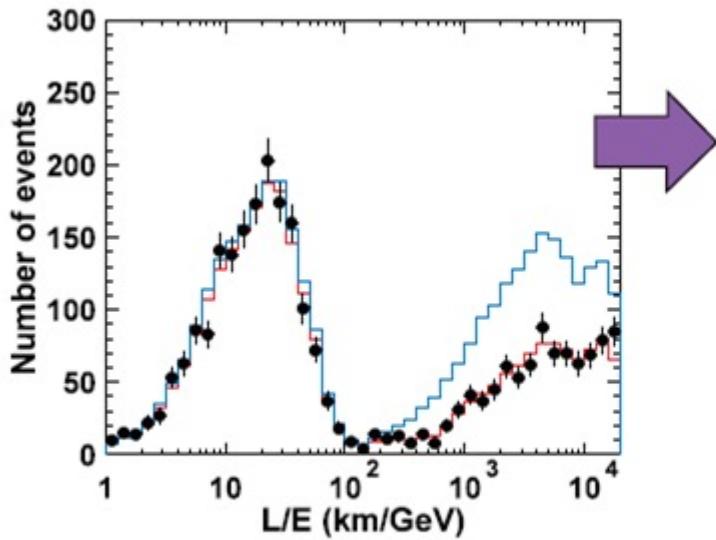
# Atmospheric neutrinos disappear?



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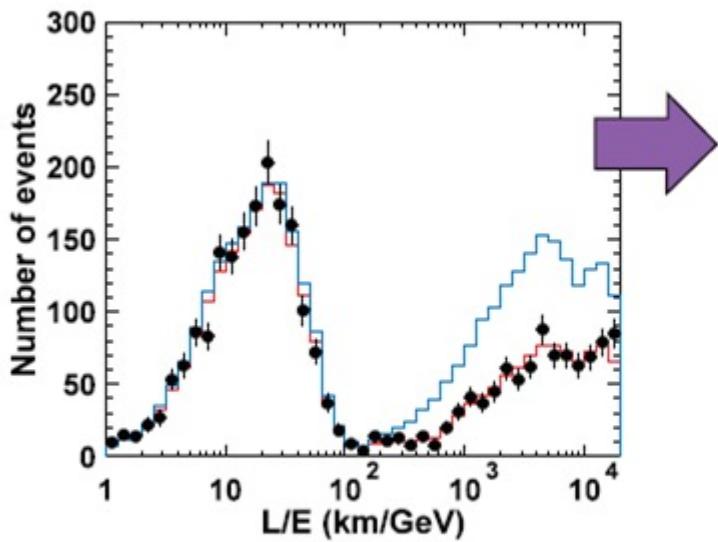


# Atmospheric neutrinos oscillate!

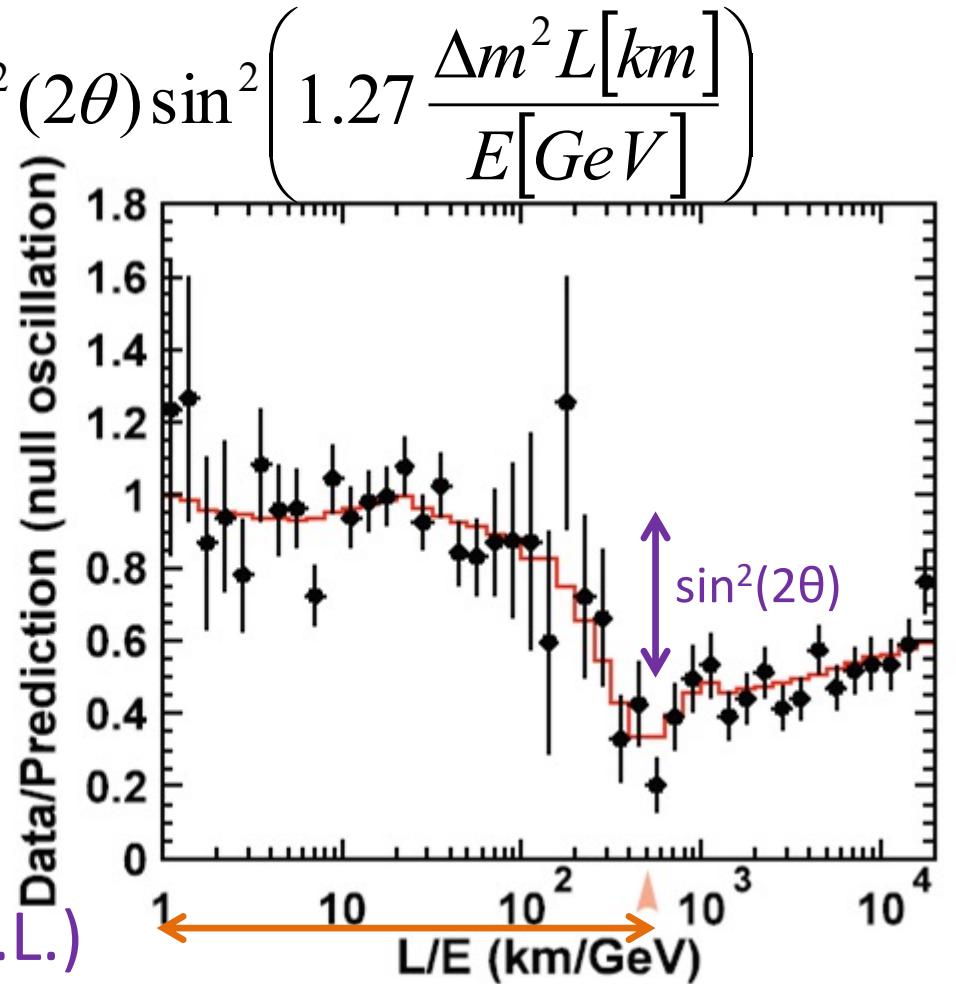


$$L/E \sim 500 \text{ km/GeV} \leftrightarrow \Delta m^2 \sim 2.3 \times 10^{-3} \text{ eV}^2$$

# Atmospheric neutrinos oscillate!



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



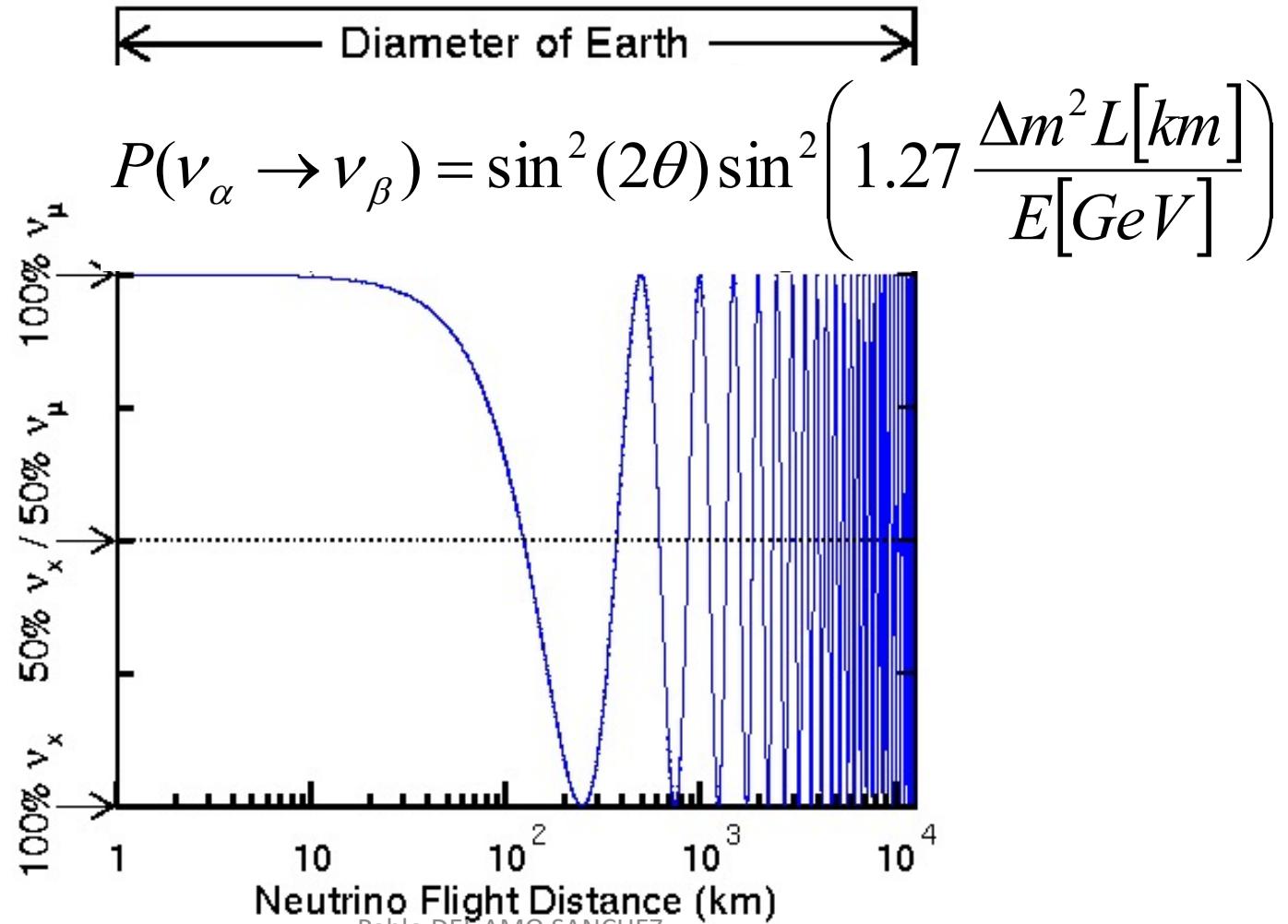
$$\sin^2(2\theta) = 1.00 (>0.93 \text{ 90% C.L.})$$

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

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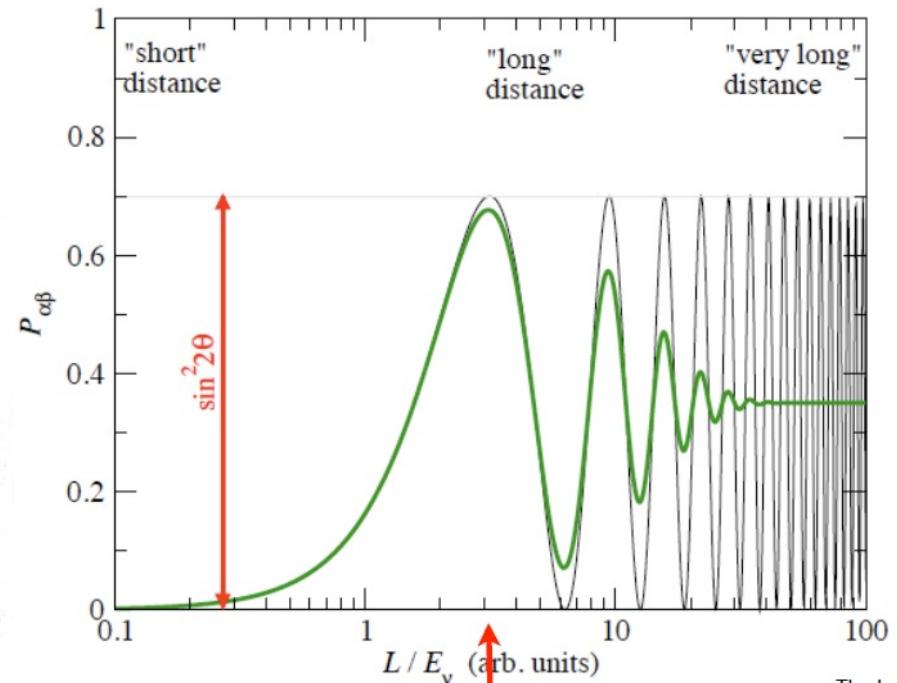
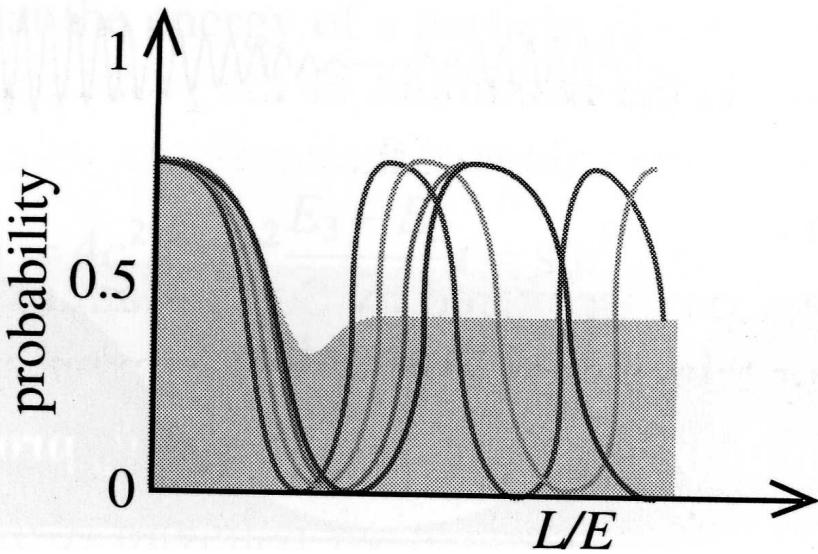
Pablo DEL AMO SANCHEZ,  
LAPP - IN2P3 - CNRS / UniSavoieMontBlanc

# But why don't we see this?



# Because...

- Two effects:
  - Neutrinos not monochromatic  $\rightarrow$  different oscillation lengths
  - Experimental resolution: if too close, maxima and minima blurred

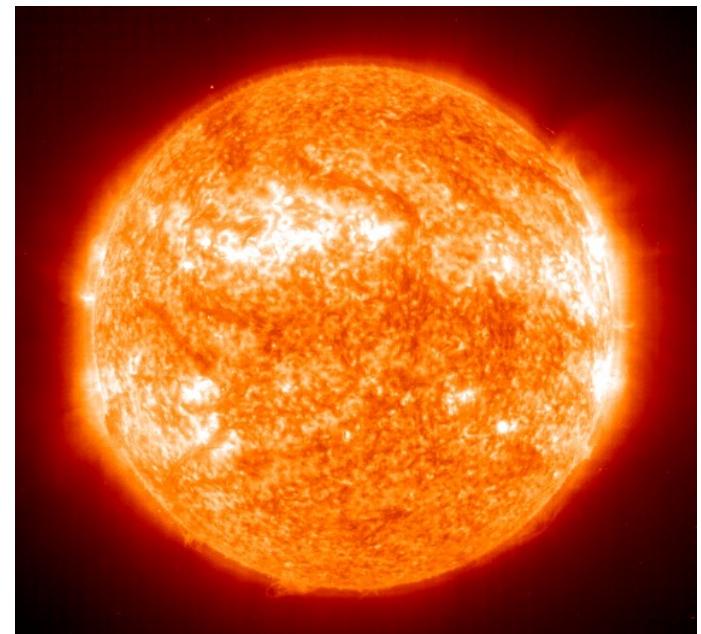
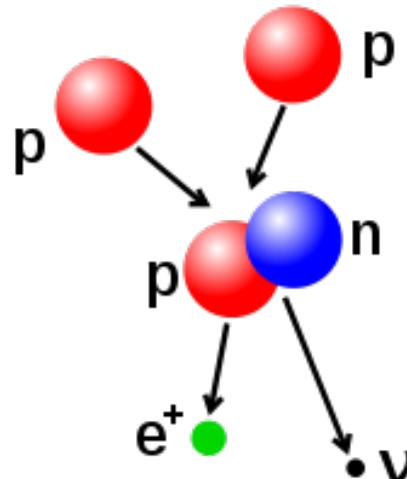
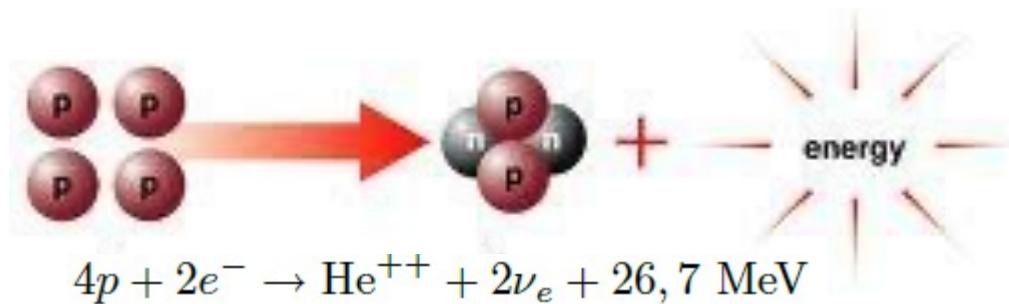


Thanks to T. Schwetz

# The solar neutrino saga

# Neutrinos from the Sun

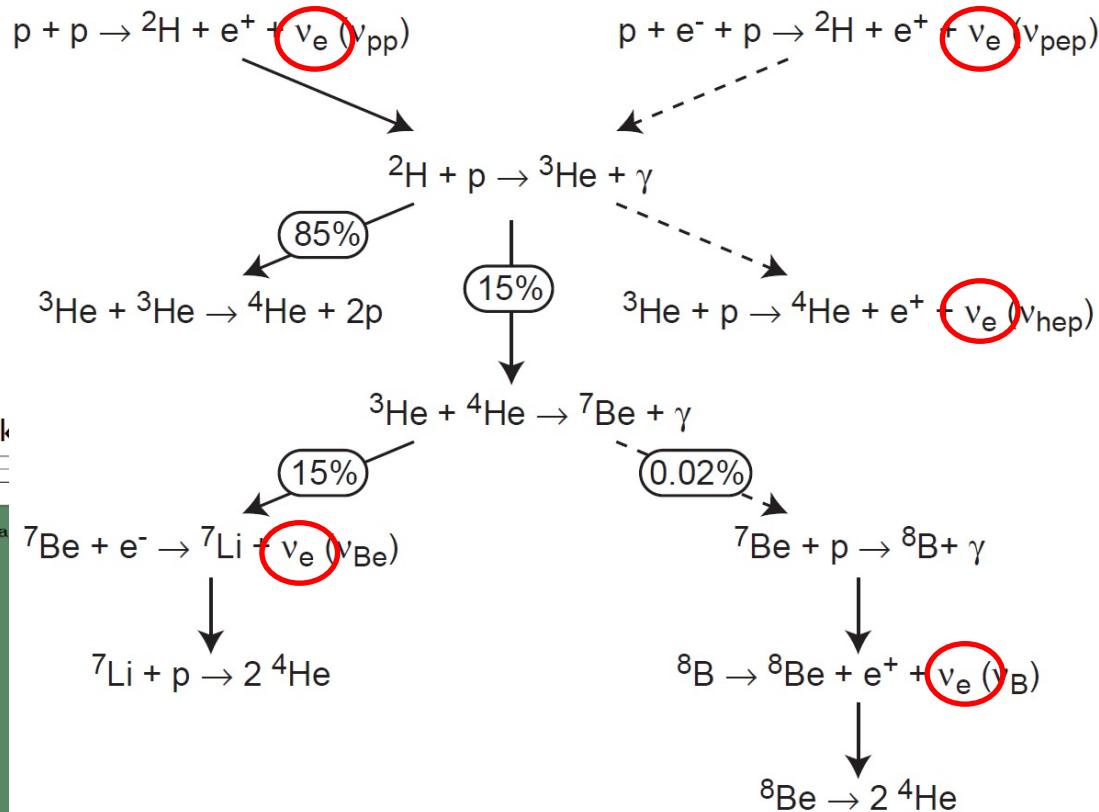
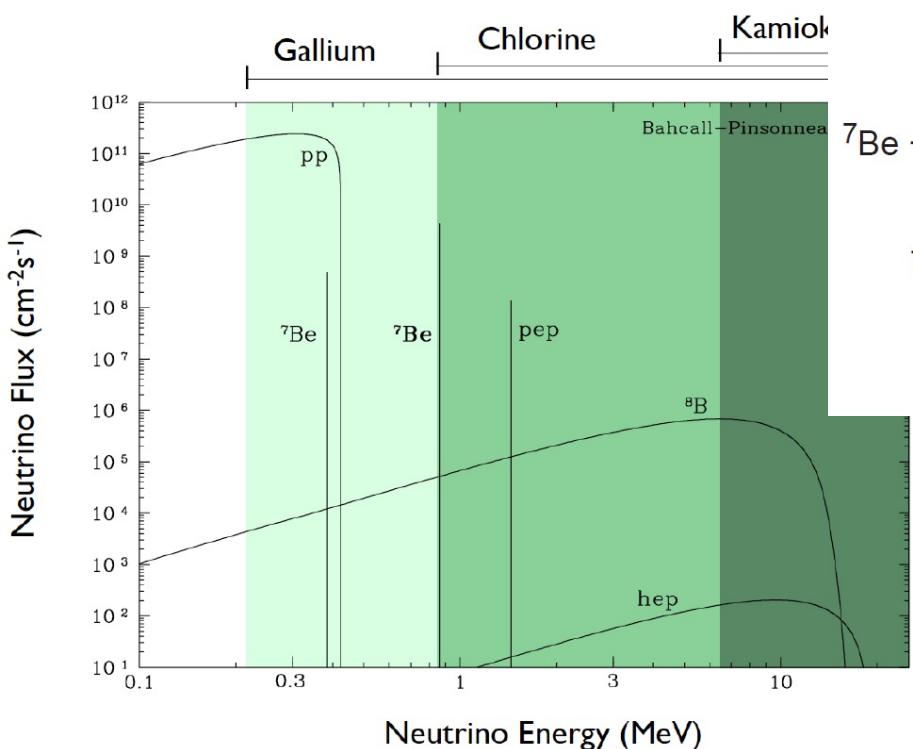
- Hydrogen fusion in the Sun requires inverse beta decay:



$$\text{Solar constant} = 1361 \text{ J/s m}^2$$
$$\Phi_{\nu_e}^{\text{sun}} = 6.4 \times 10^{14} \nu_e / \text{s m}^2$$

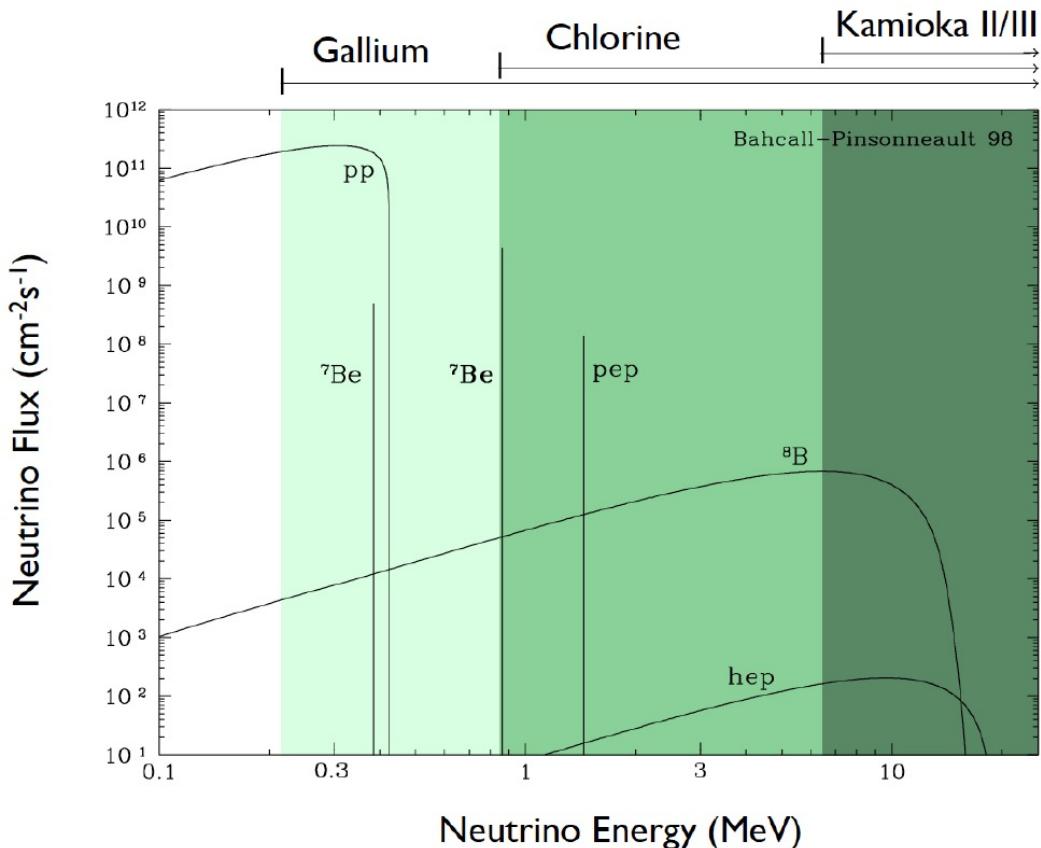
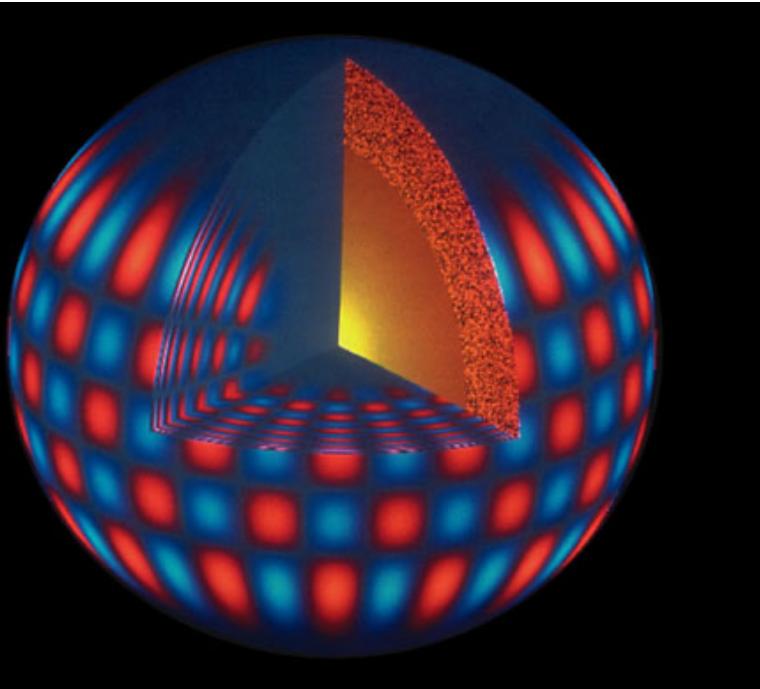
# Neutrinos from the Sun

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



# 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  $\nu_e$  flux predictions in underground mine (under 1500m of rock)

Experiment run for 30 years (till 1994):

observed  $2.56 \pm 0.23$  SNU  
expected  $8.2 \pm 1.8$  SNU

} ~30%

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

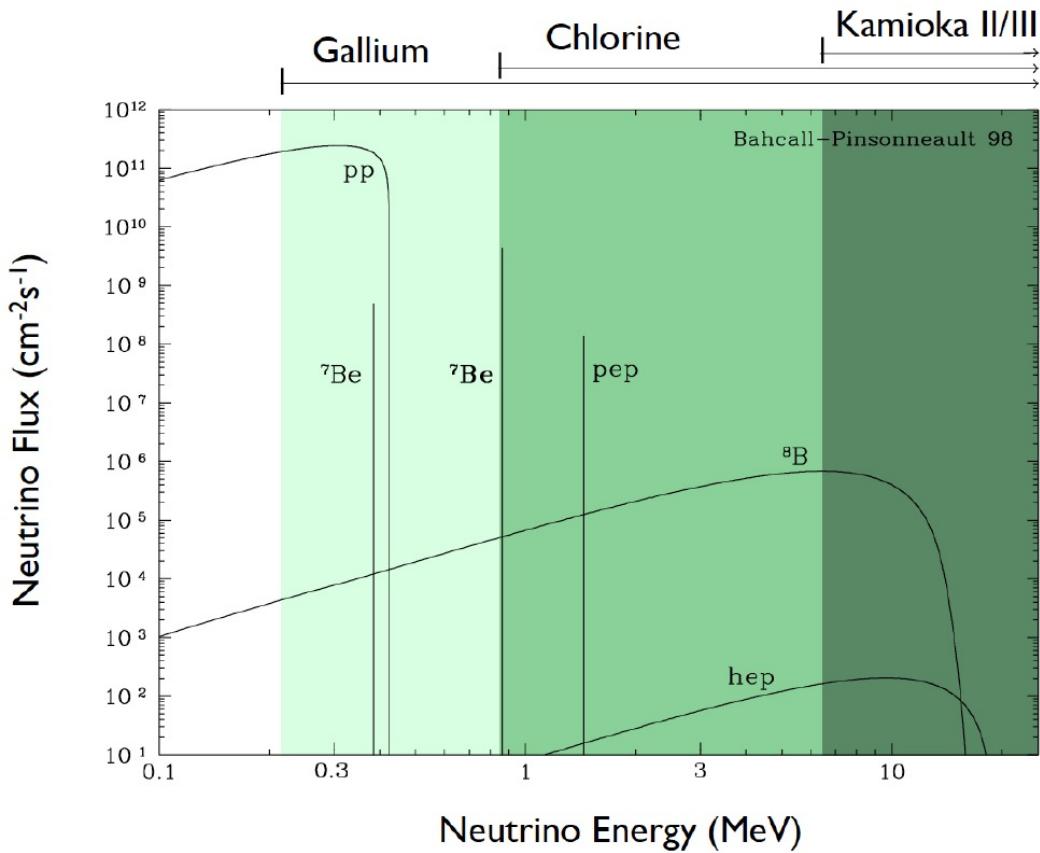


- **Homestake:**  $\nu_e + n \rightarrow p + e^-$   
 $\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^-$
- Located in Lead, SD
- 615 tons of  $\text{C}_2\text{Cl}_4$  (Cleaning fluid)
- Extraction method:
  - Pump in He that displaces Ar
  - Collect Ar in charcoal traps
  - Count Ar using radioactive decay
- Never Calibrated with source

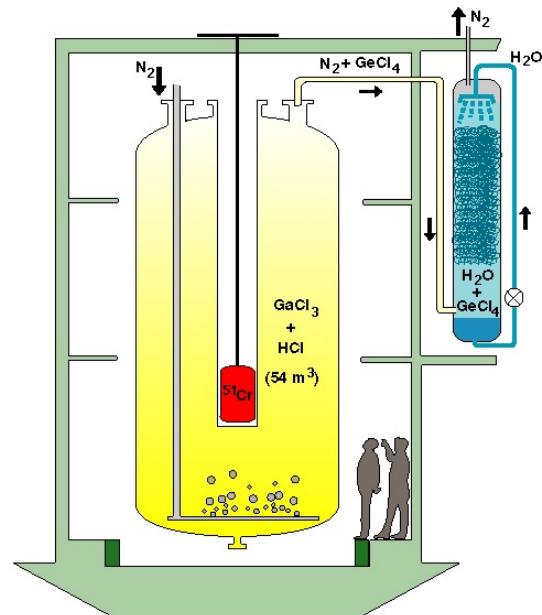


# Problems?

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

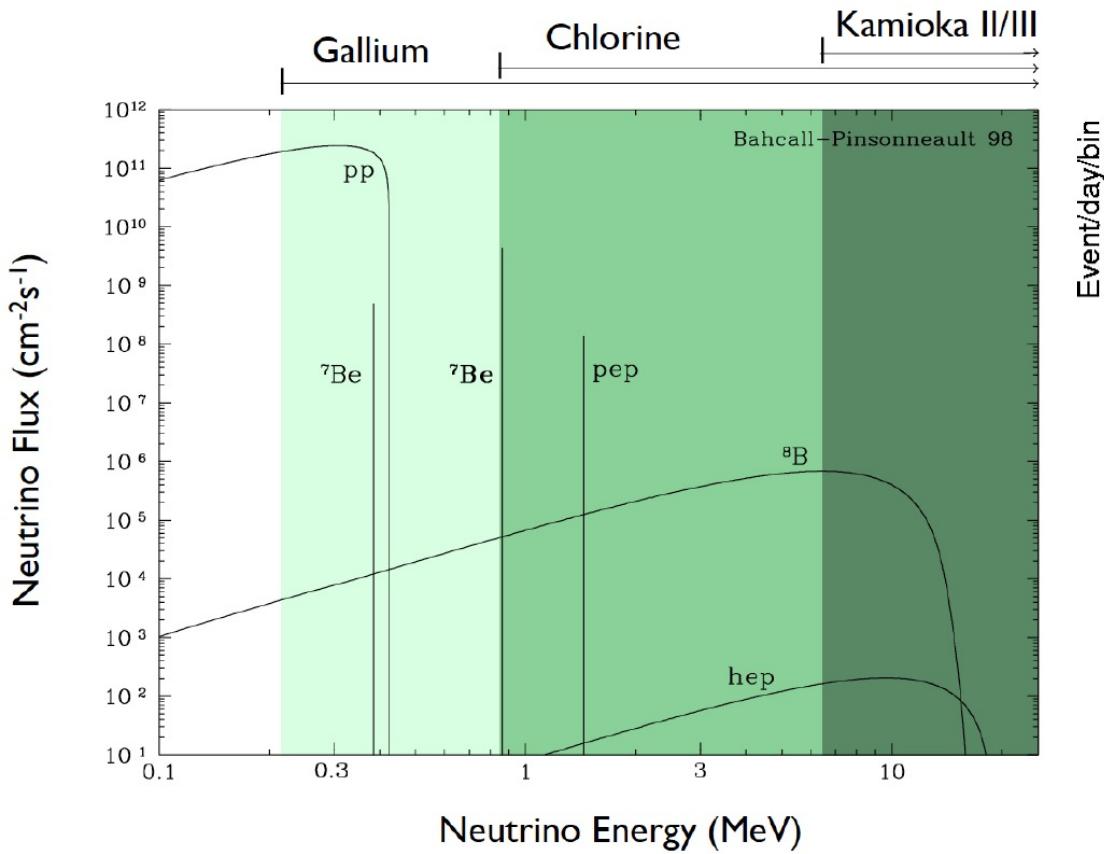


Gallex:  $\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$   
Observed  $68.1 \pm 3.75 \text{ SNU}$   
Expected  $127 \pm 12 \text{ SNU}$  }  $\sim 50\%$

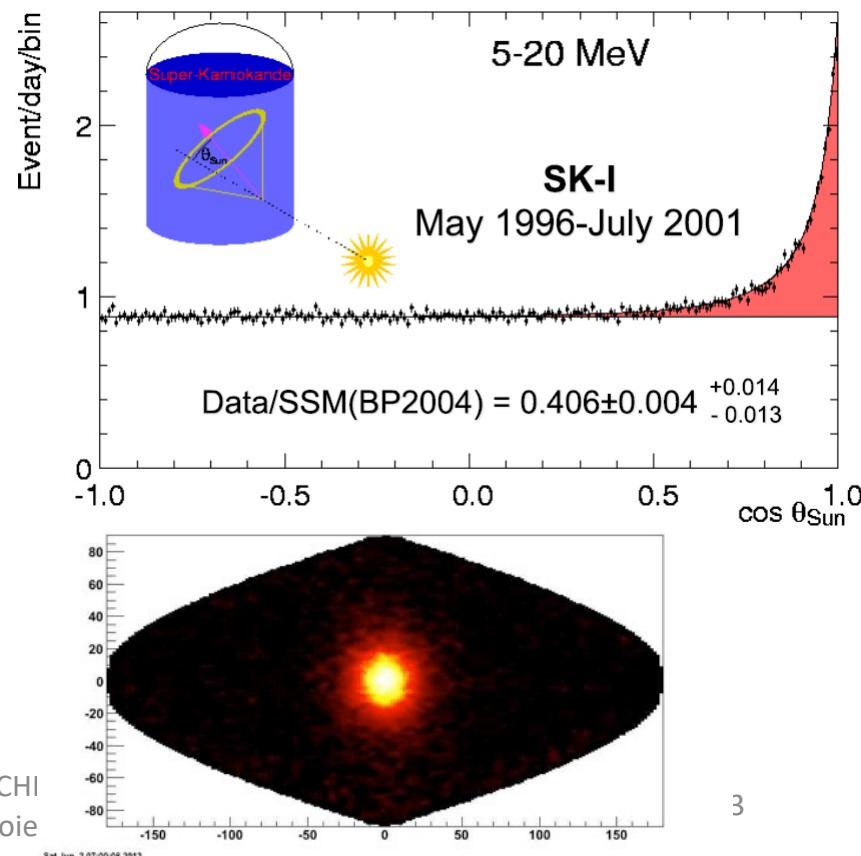


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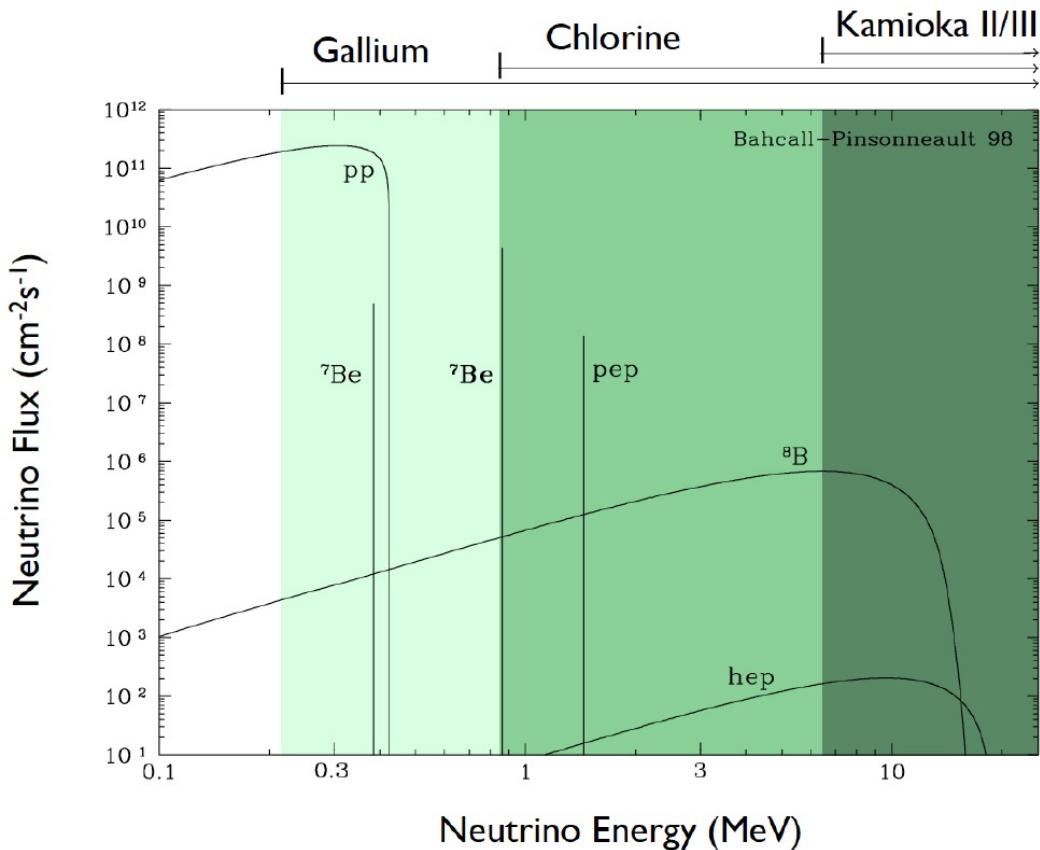


KamiokaNDE:  $\nu_e + e^- \rightarrow \nu_e + e^-$   
Observed  $\sim 40\%$  of expectation



# Problems?

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

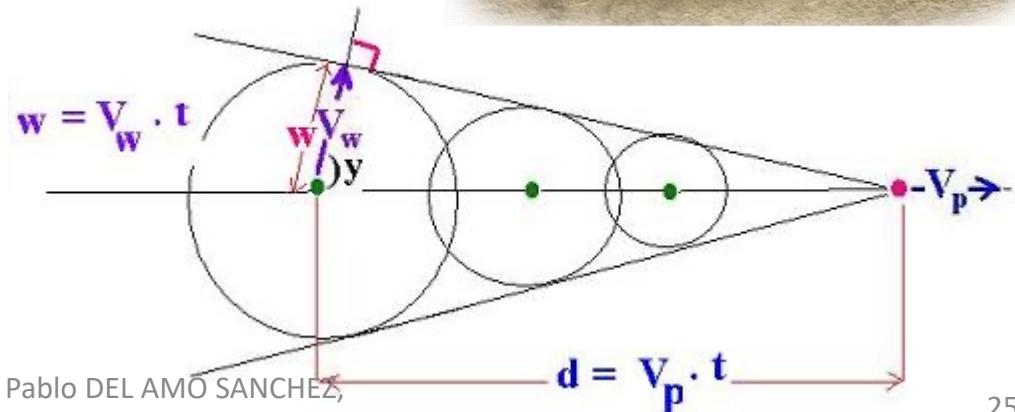
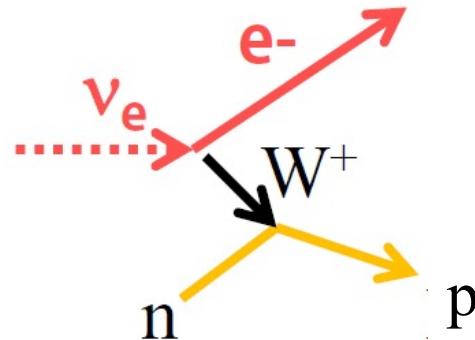
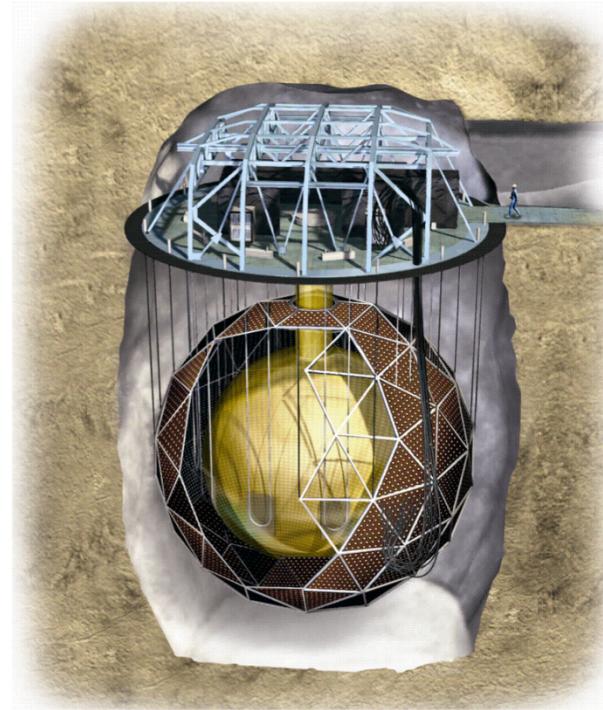


Experiment type	Observed/Expected
Chlorine	~30%
Gallium	~60%
KamiokaNDE	~40%

Perhaps neutrinos are oscillating after all, as suggested by Pontecorvo et al?  
These experiments only sensitive to  $\nu_e$   
try and detect  $\nu_\mu$  and  $\nu_\tau$  too! → SNO

# Sudbury Neutrino Observatory (SNO)

- Water Cerenkov detector
- 2000 m deep (Sudbury, Ontario)
- Cosmics veto
- 1000 tons of Heavy water ( $D_2O$ ),  
shielded by 7000 tons light water ( $H_2O$ )  
seen by 9500 photomultiplier tubes (PMTs)



# SNO

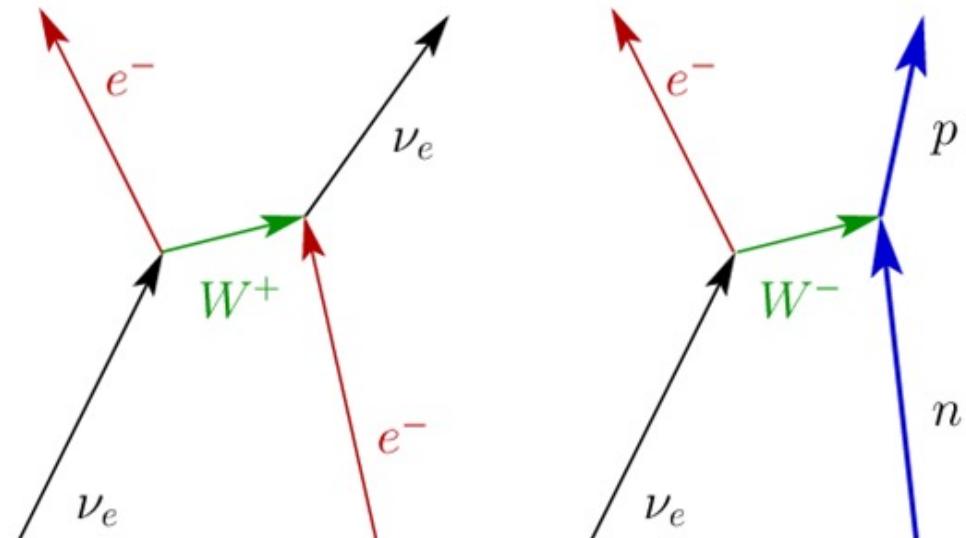
- SNO measures well  $\nu_e$  flux:

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

- Good measurement of the  $\nu_e$  spectrum.
- Some directional information.
- Only sensitive to  $\nu_e$ .

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

- Strong directional sensitivity.
- Low statistics.



Charged current

- Cannot see  $\nu_\mu$  /  $\nu_\tau$  flux in this way: neutrinos from Sun not energetic enough to produce heavy  $\mu$  or  $\tau$  particles in interactions

# SNO

- But it measures the total  $\nu_e + \nu_\mu + \nu_\tau$  flux by means of Neutral Current interactions!

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

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

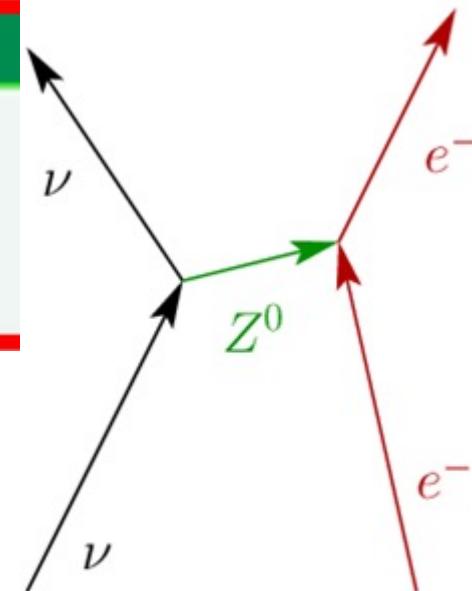
Signature event of SNO

3 neutron detection methods:

$n + d \rightarrow t + \gamma + 6.26 \text{ MeV}$  SNO-I

$n + {}^{35}\text{Cl} \rightarrow {}^{36}\text{Cl} + \gamma + 8.6 \text{ MeV}$  SNO-II

$n + {}^3\text{He} \rightarrow p + t + 0.76 \text{ MeV}$  SNO-III



Neutral current



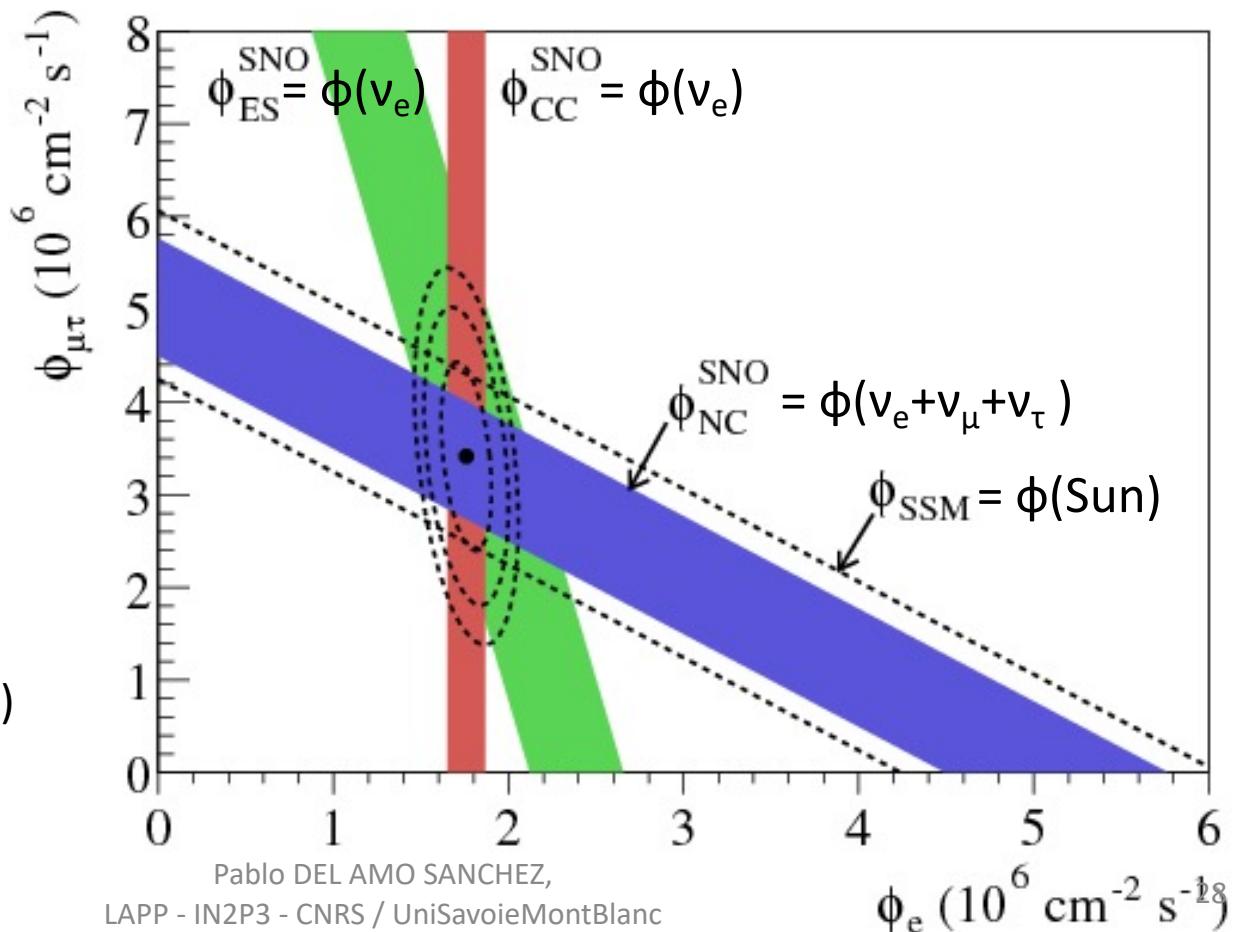
# Solar neutrinos oscillate!

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



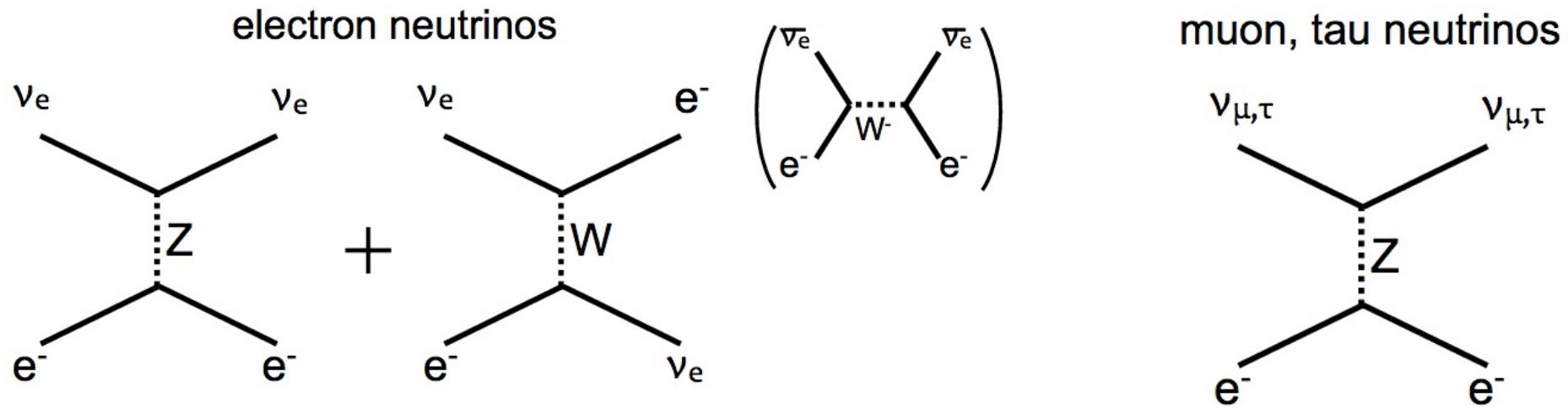
Бруно Понтекорво

Bruno Pontecorvo (1957)



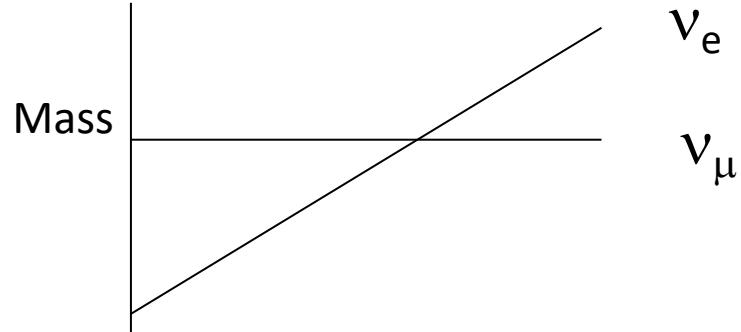
# Matter effects are important!

- High electron density in Sun  $\rightarrow$  matter effects!
- $\nu_e$  get heavier,  $\nu_\mu$  &  $\nu_\tau$  unaffected.

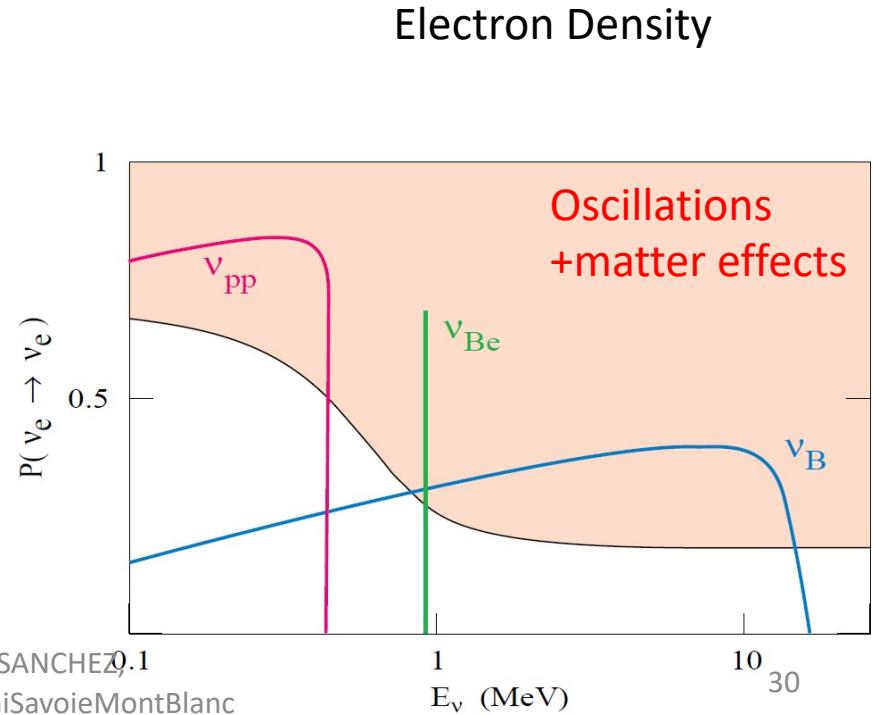
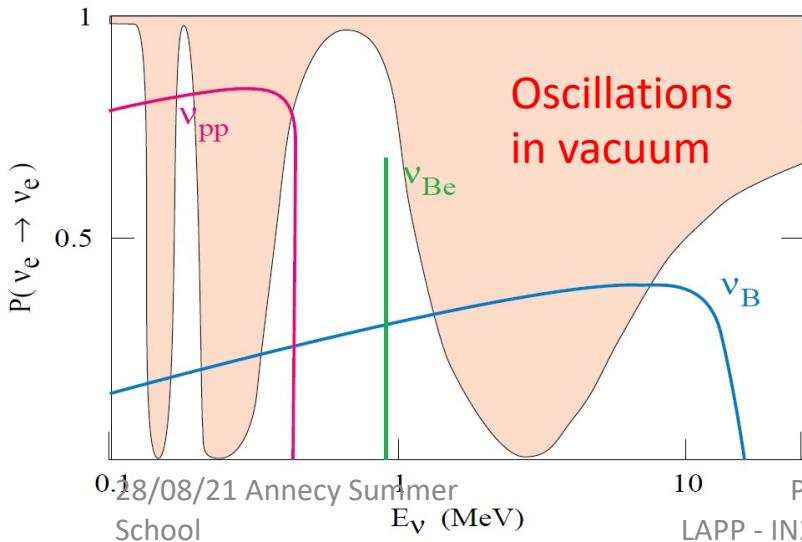


# Matter effects are important!

- High electron density in Sun → matter effects!
- $\nu_e$  get heavier,  $\nu_\mu$  &  $\nu_\tau$  unaffected.  
Resonance effects may enhance oscillation



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



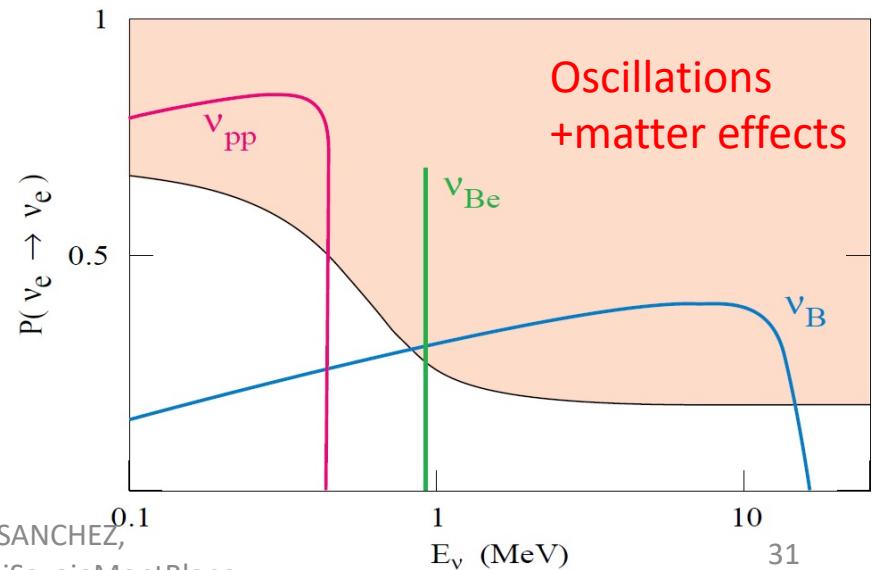
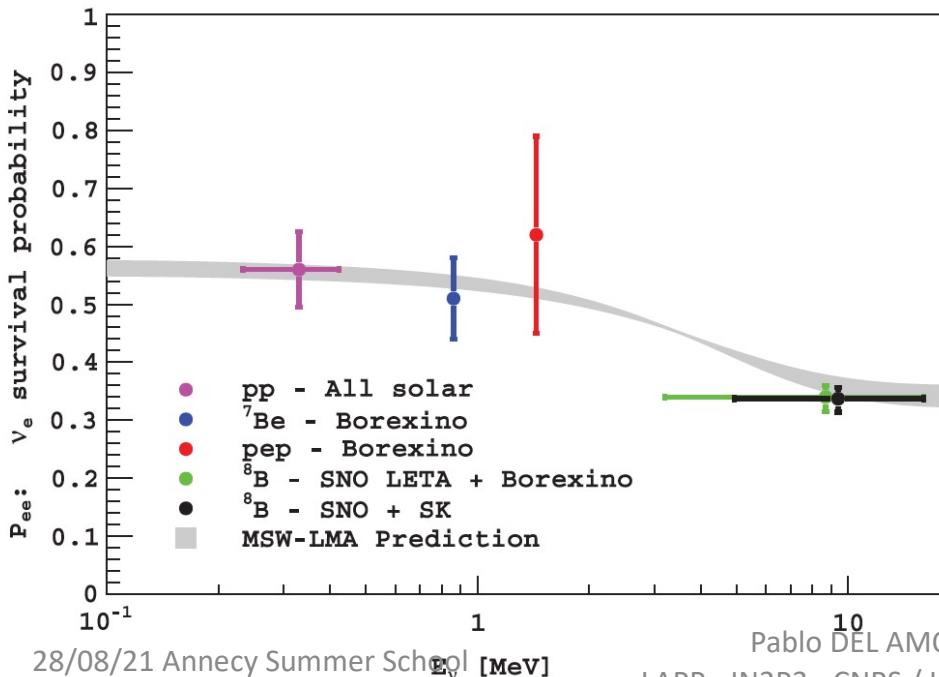
# Matter effects are important!

- Found oscillation parameters for solar neutrinos:

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

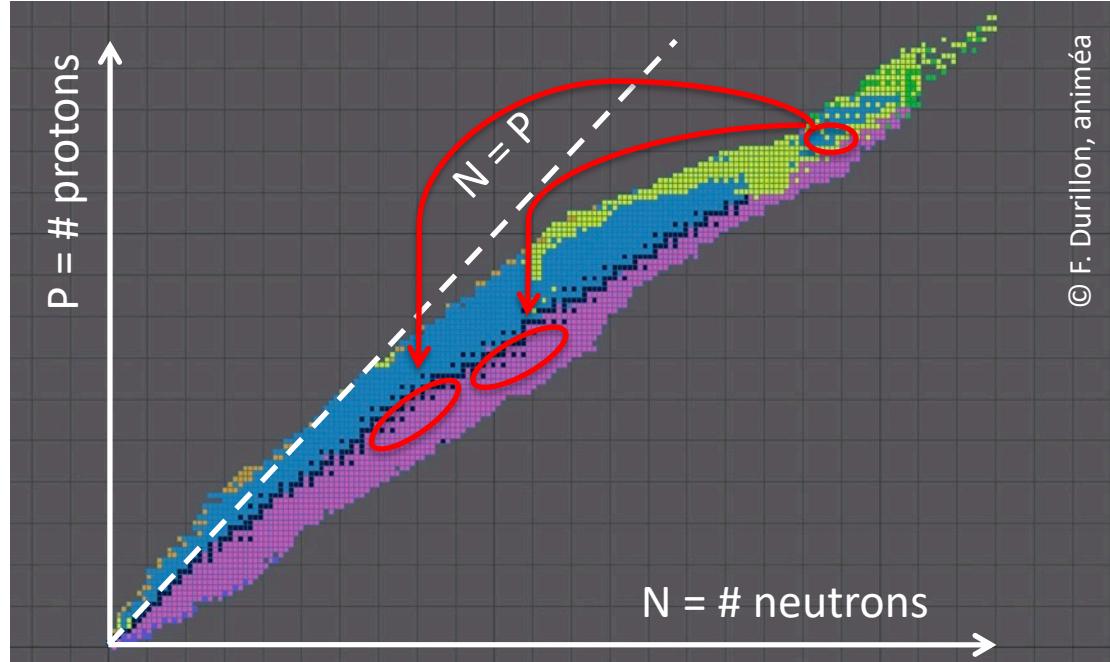
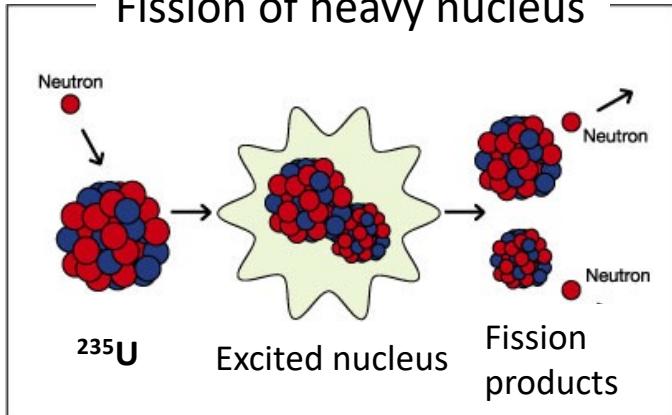
$$\sin^2(2\theta) = 0.857 \pm 0.024$$

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



# Reactor neutrino experiments

# $\nu$ from nuclear reactors



© F. Durillon, animée

- Fission products are neutron rich and undergo beta decay:  $n \rightarrow p e^- \bar{\nu}_e$

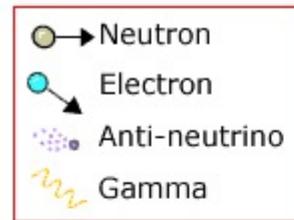
# Reactor neutrinos

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

Fission products are neutron rich

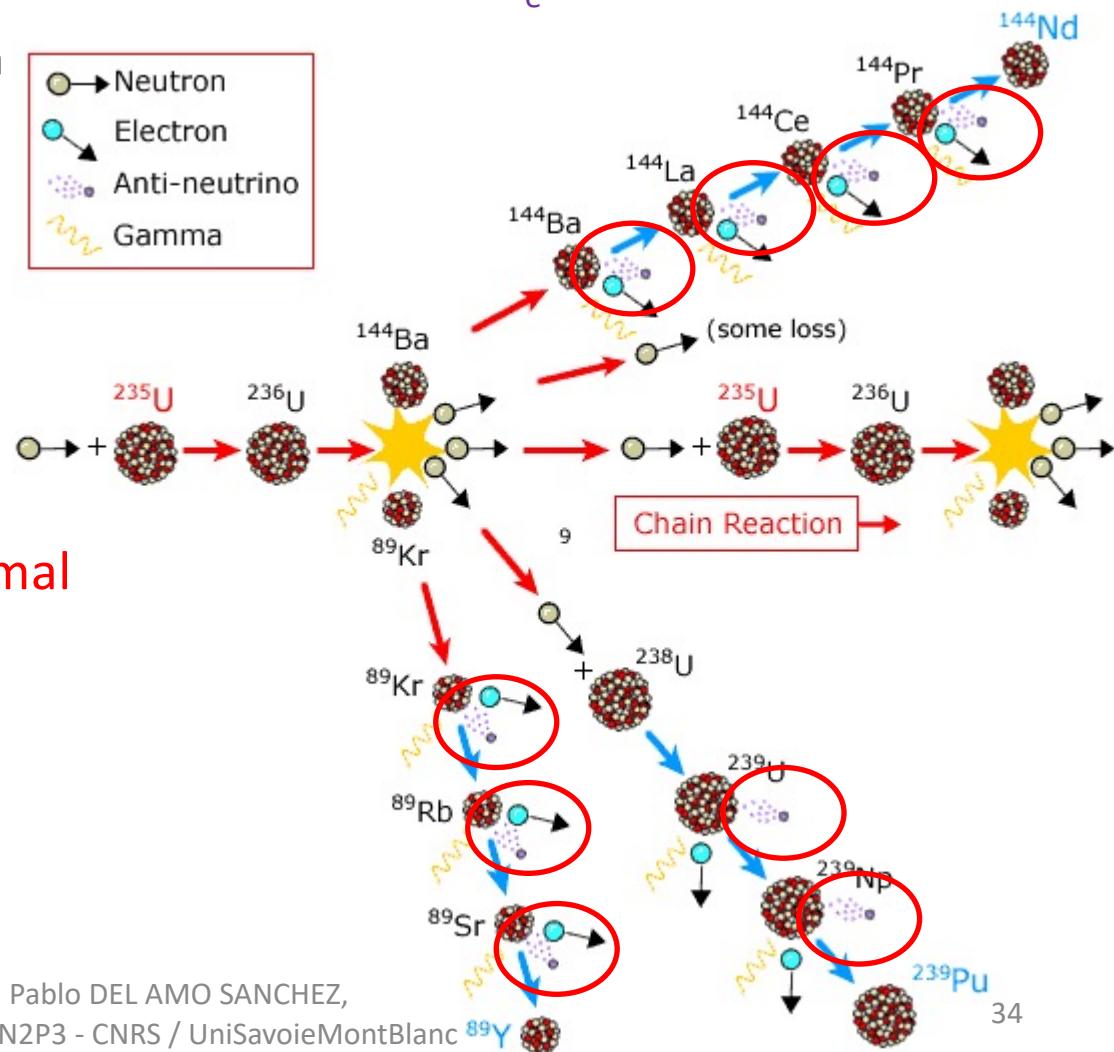
Too many neutrons to be stable

→ plenty of beta decays!



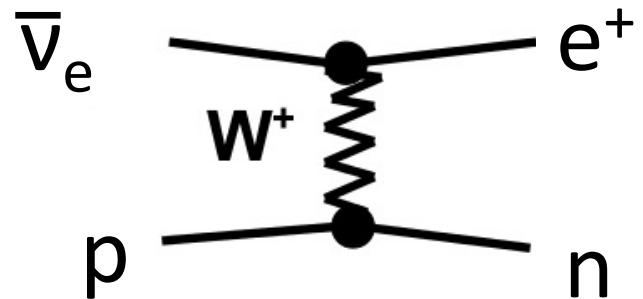
- $\sim 6 \bar{\nu}_e / \text{fission}$
- $\sim 200 \text{ MeV/fission}$

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



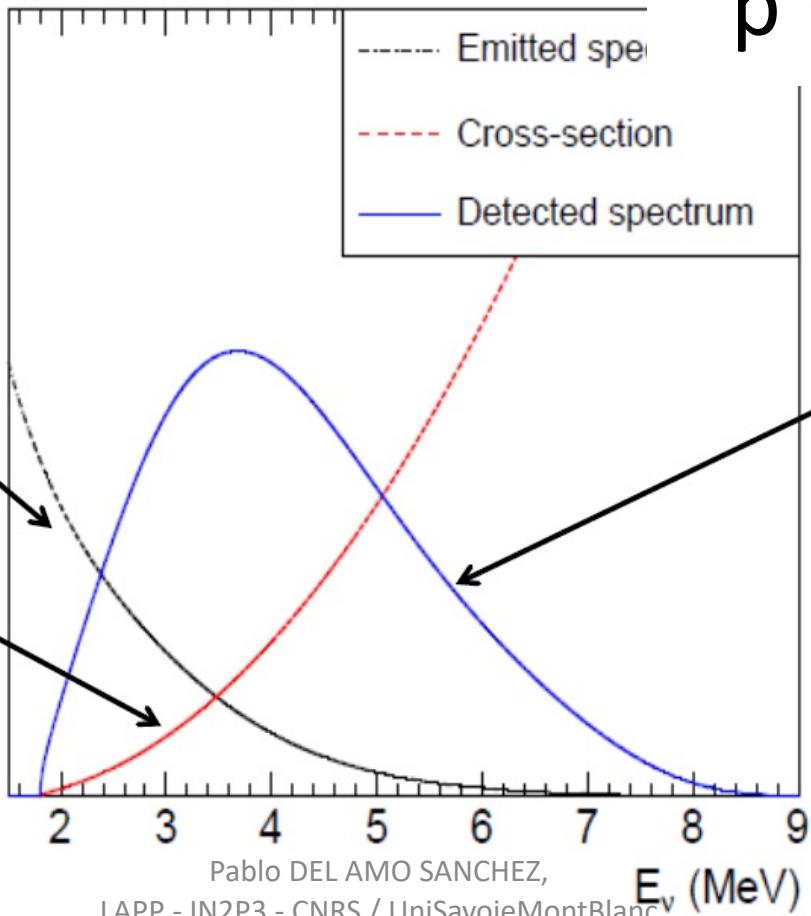
# Liquid scintillator detectors

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



Exponential decrease of emitted spectrum

$\beta$ -inverse detection process

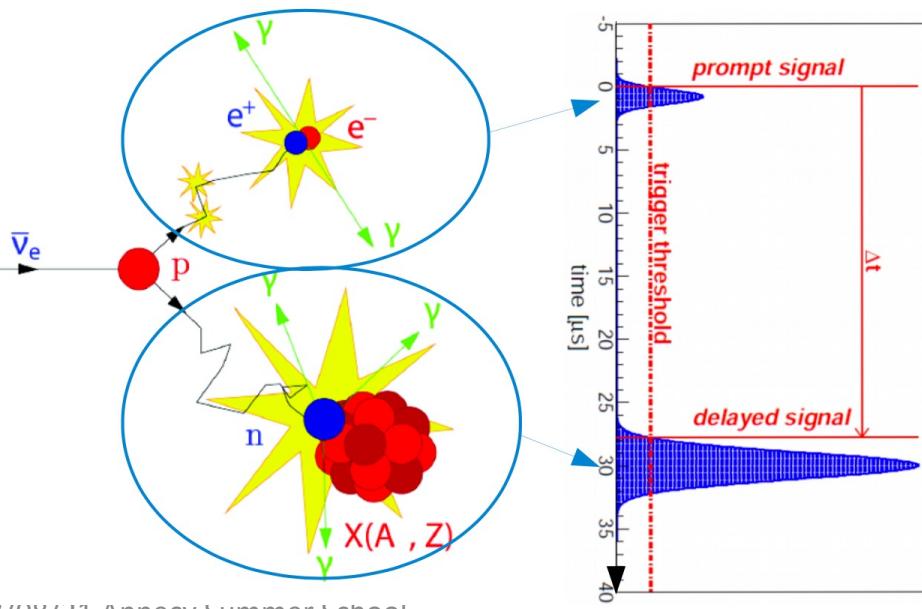
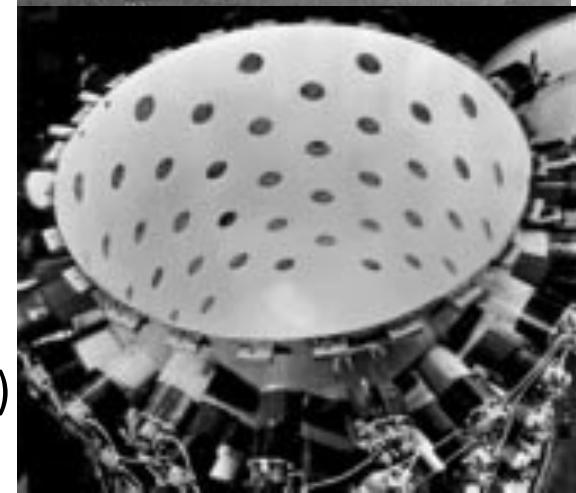


# Reines and Cowan: $\bar{\nu}$ discovery



1956  $\bar{\nu}$  discovery by Reines and Cowan at Savannah River  
already a typical reactor experiment:

- Inverse Beta Decay (IBD):  $\bar{\nu}_e p \rightarrow e^+ n$  ( $\sigma_{IBD} \sim 20 \times \sigma(\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-)$ )
- Liquid Scintillator (LS) loaded with neutron-hungry element (Cd,  $\sigma_\gamma \approx 2500$  b,  $\Sigma E_\gamma \approx 9$  MeV)
- signal a coincidence: prompt ( $e^+$ ), few  $\mu s$ , delayed (n-Cd)

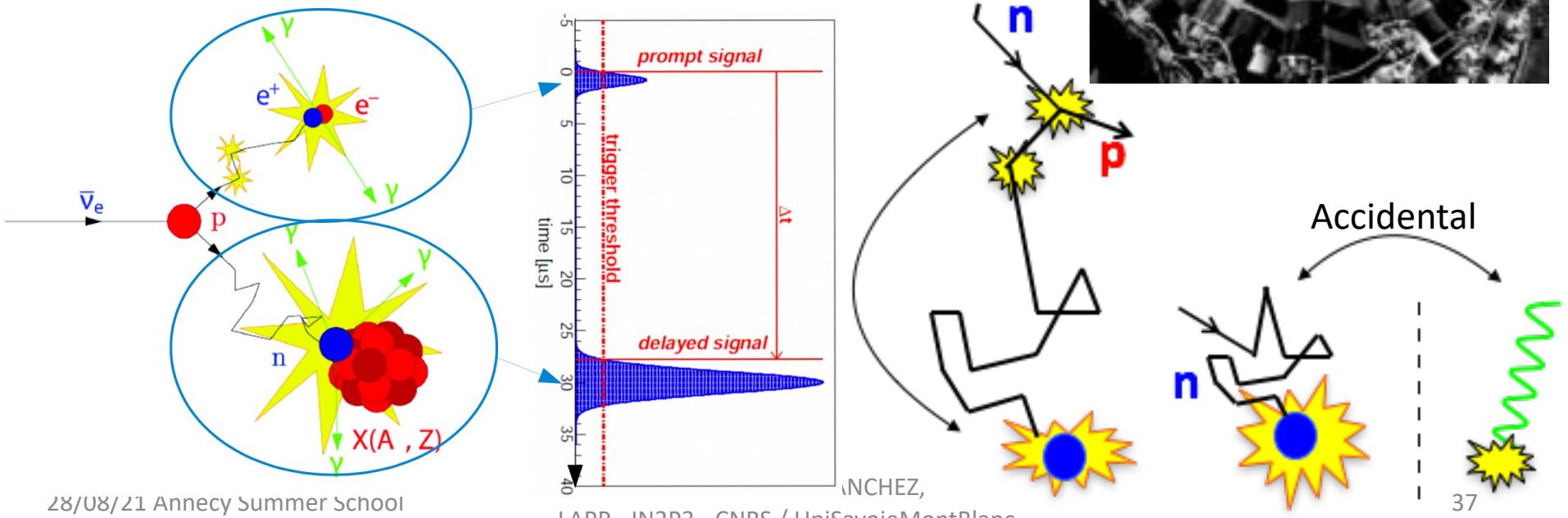


# Reines and Cowan: $\nu$ discovery



Signal a coincidence: prompt ( $e^+$ ), few  $\mu s$ , delayed ( $n$ -Cd), coincidence greatly reduces background. Remaining background:

- Accidental coincidences
- Correlated coincidences
  - from reactor
  - from cosmics



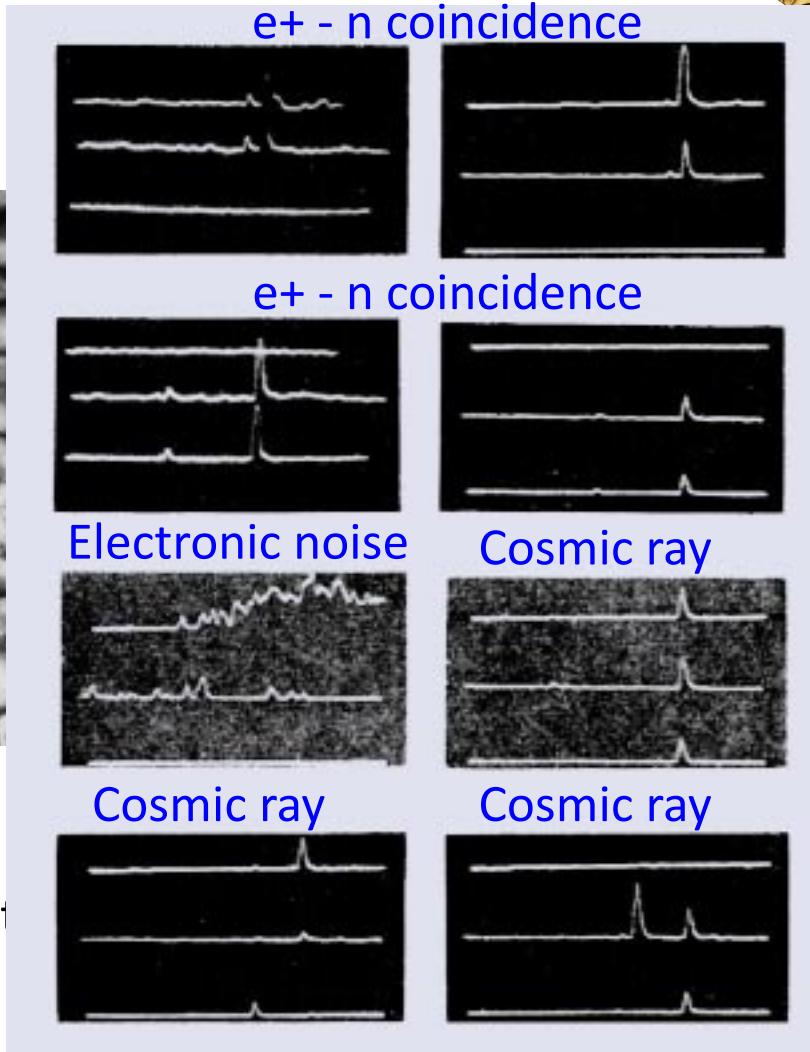
# Reines and Cowan: $\nu$ discovery



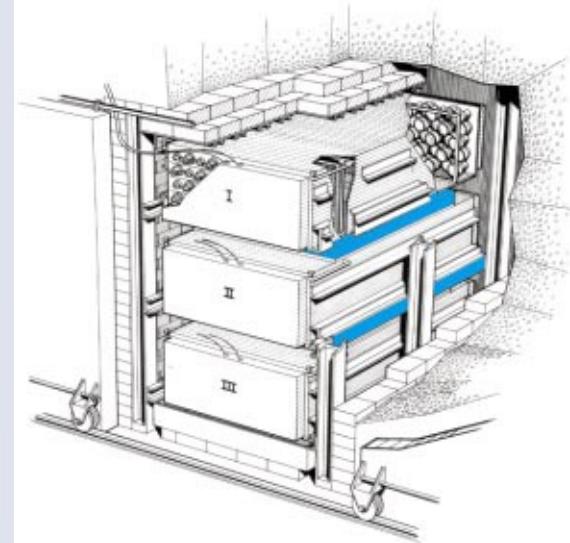
Shielding!



Concrete, paraffin,  
borax and...  
water soaked sawdust

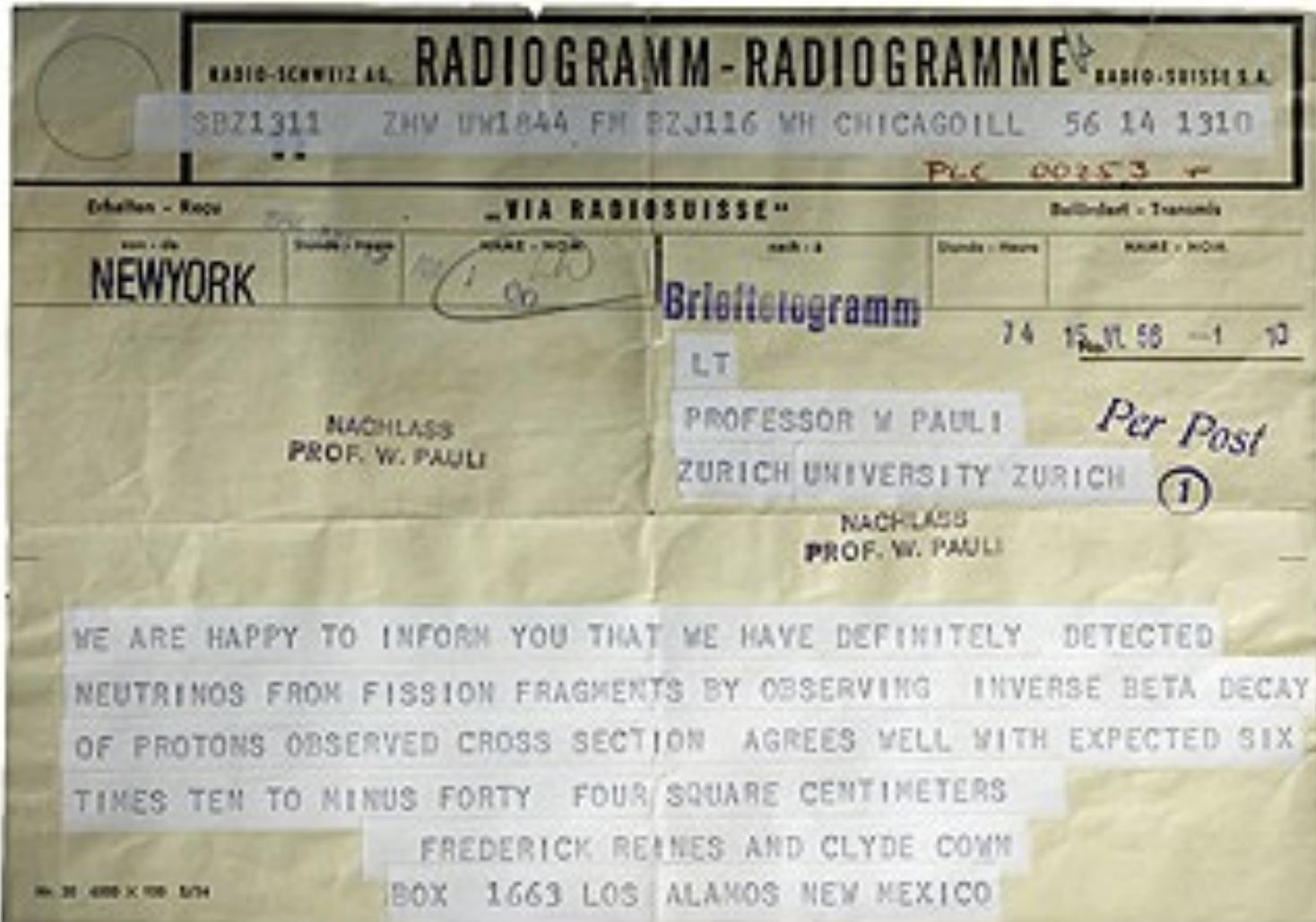


Segmentation



Cd-loaded water instead  
of LS as  $\nu$  Target,  
surrounded by LS

# Reines and Cowan: v discovery



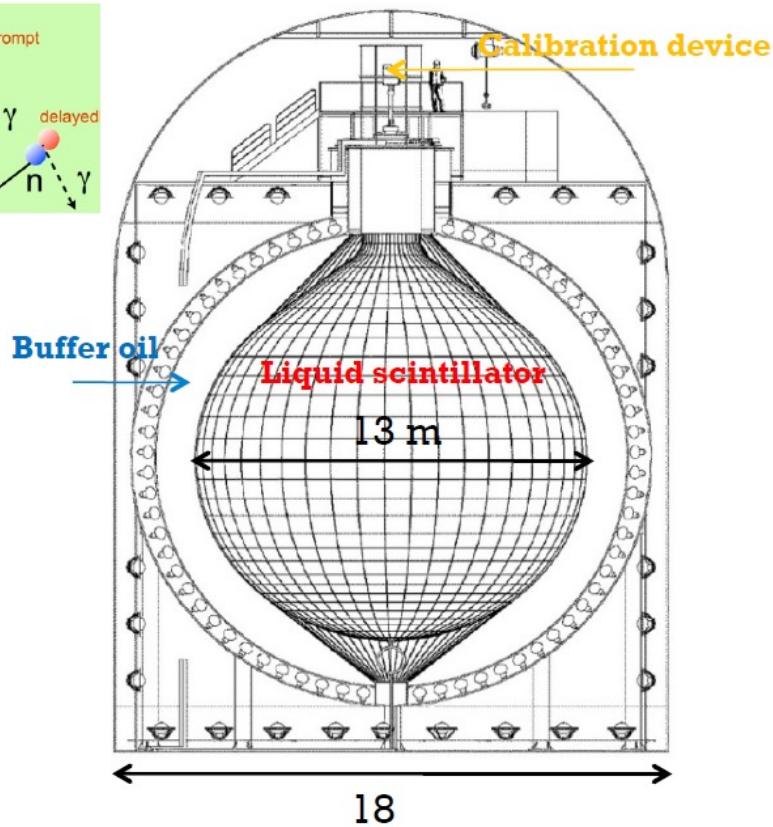
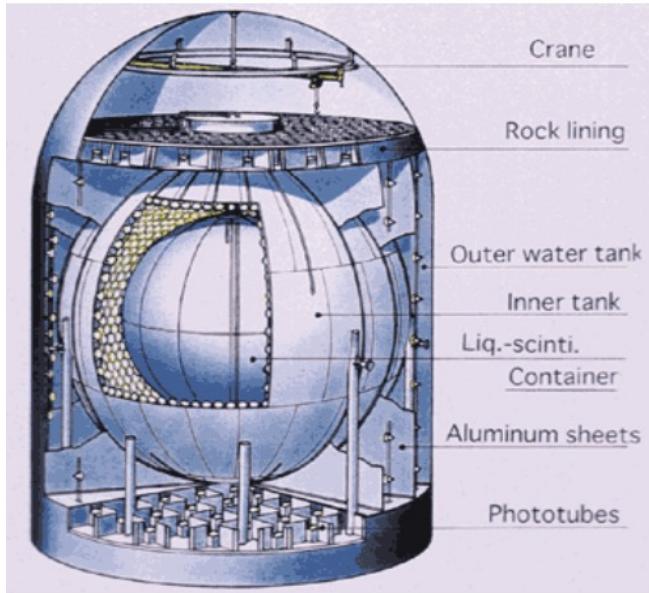
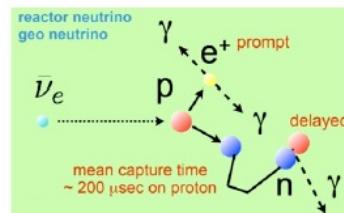
Concrete,  
borax and  
water soak



# Liquid scintillator detectors

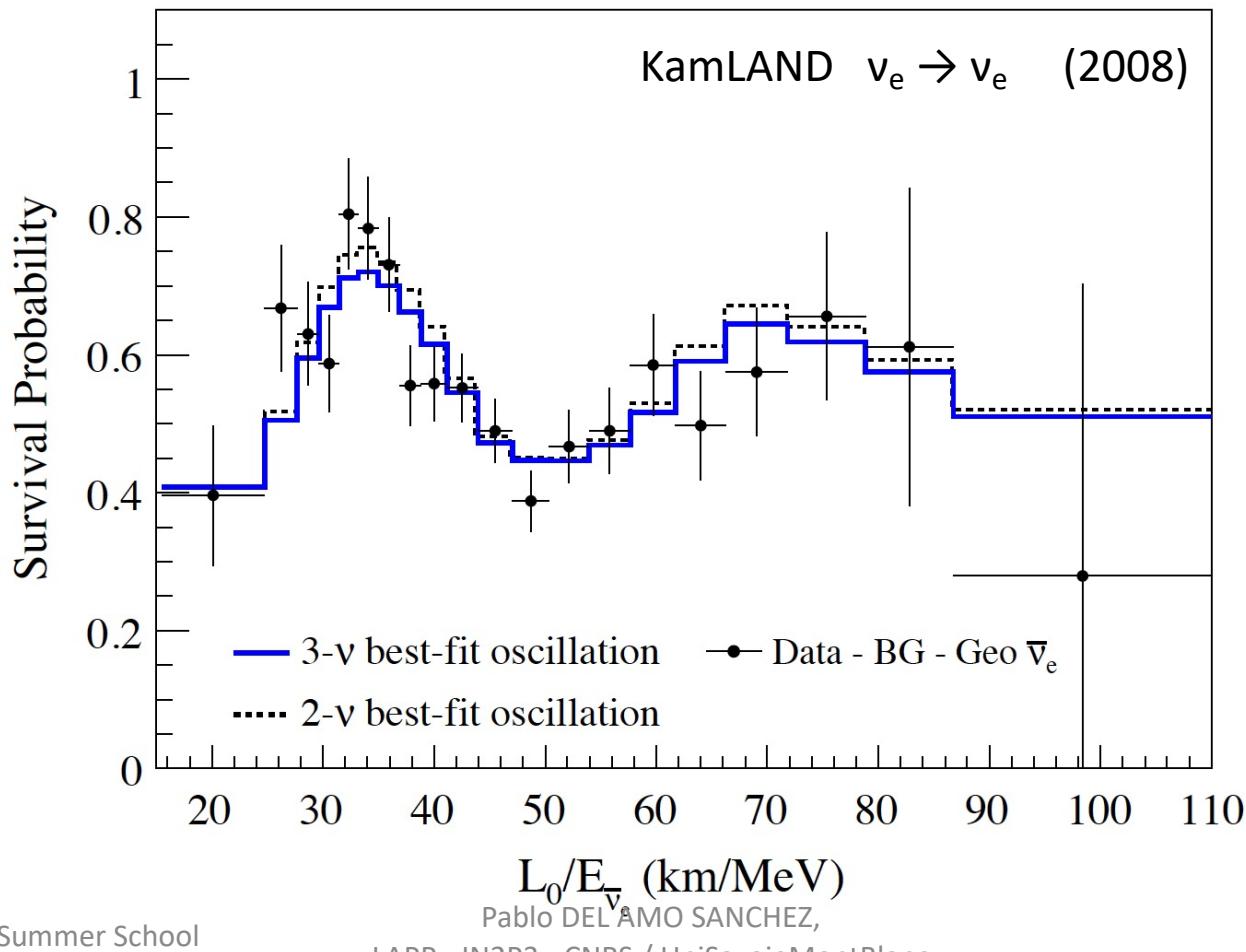
- KamLAND: Kamioka Liquid scintillator AntiNeutrino Detector

- 1000 ton liquid scintillator:
- Spherical plastic balloon
- 1325 17" + 554 20" PMTs
- Inverse  $\beta$  decay detection



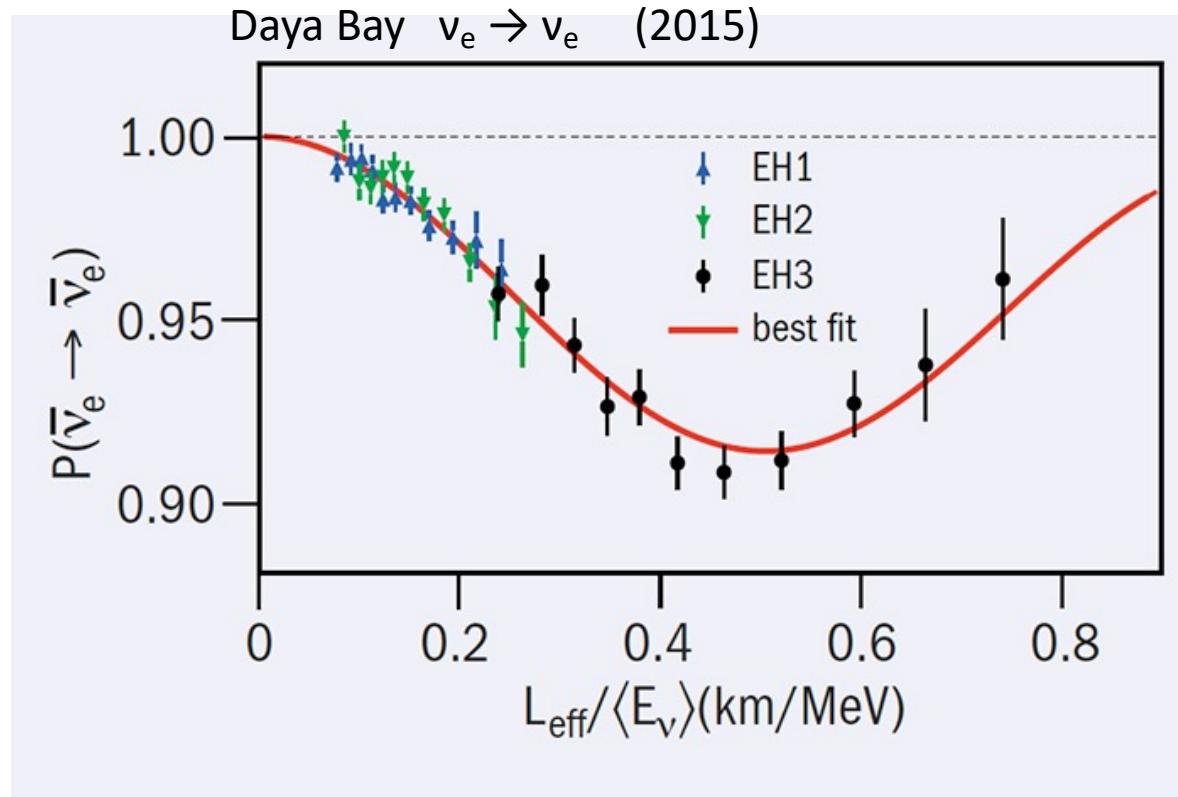
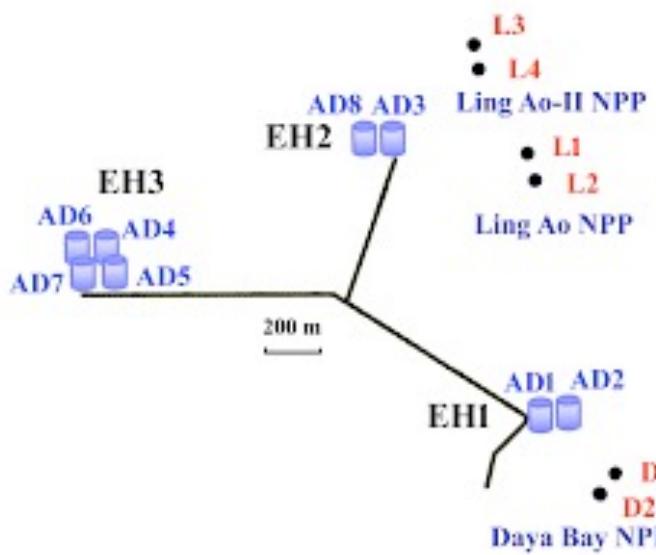
# Reactor neutrinos oscillate!

- Confirm solar neutrino oscillations



# Reactor neutrinos oscillate!

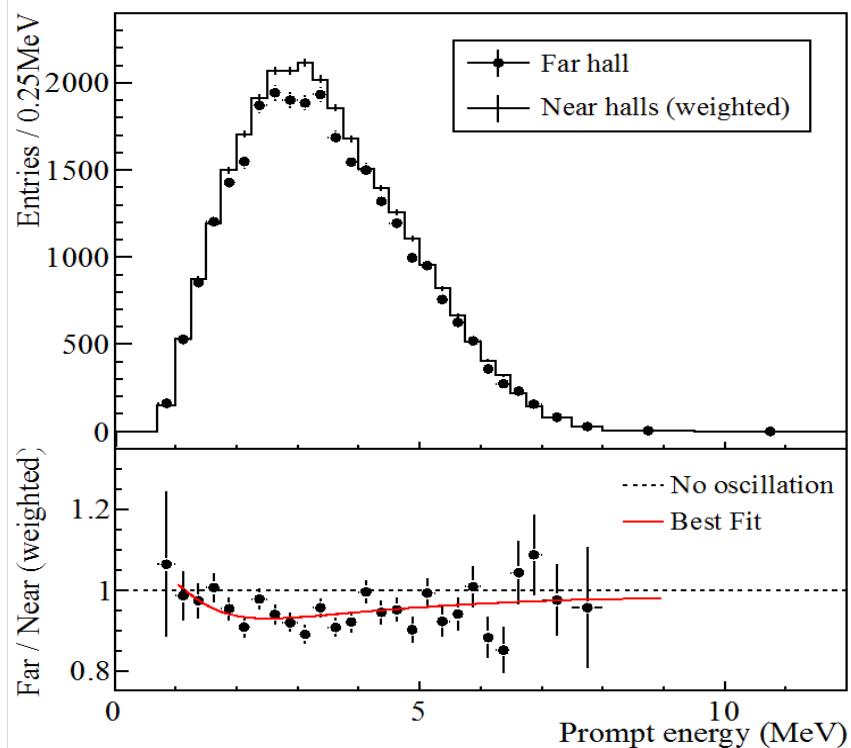
- Confirm solar neutrino oscillations



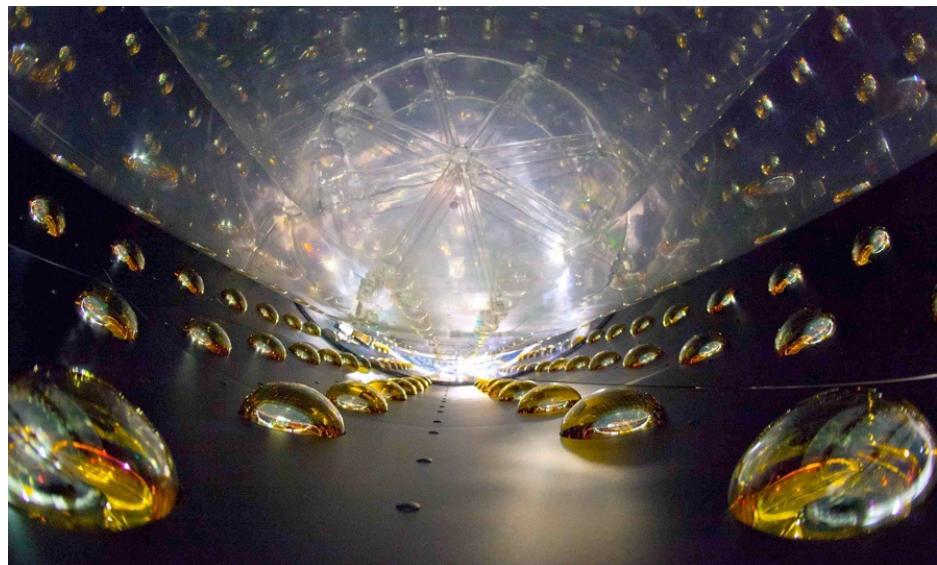
# Fast oscillations in reactors

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

- Daya Bay: 1-2 km away from reactors



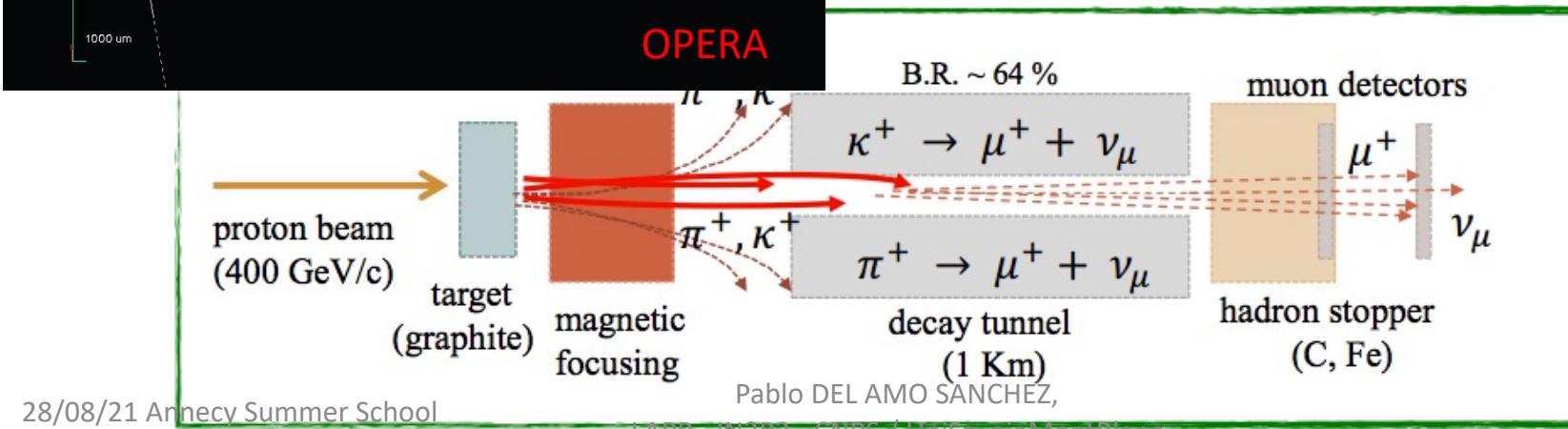
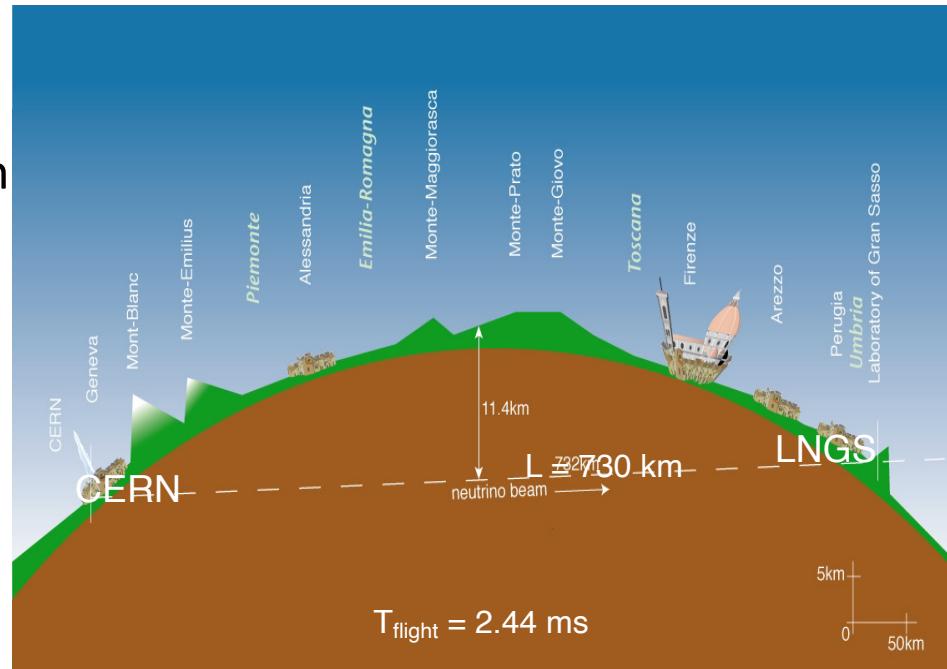
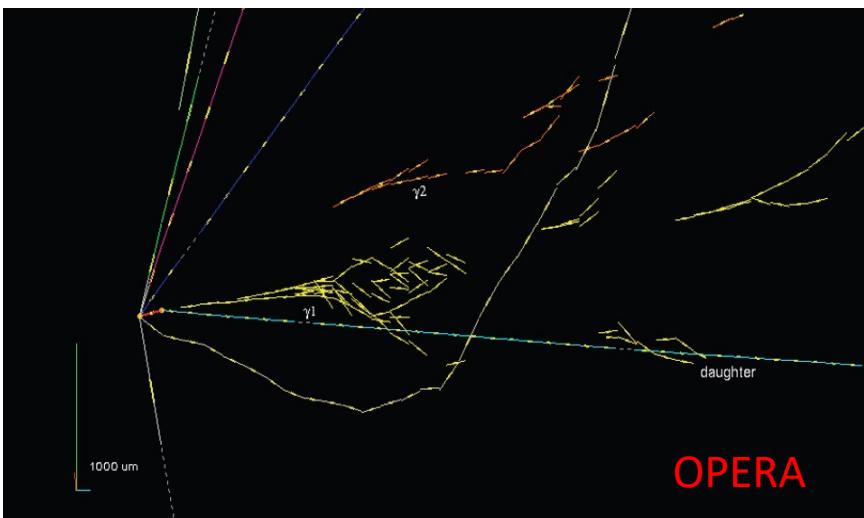
$$\sin^2(2\theta_{13}) = 0.089 \pm 0.012$$
$$\theta_{13} = 9.1^\circ \pm 0.6^\circ \quad (\approx \theta_{\text{Cabbibo}}!)$$



# Accelerator neutrinos

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

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



# What have we learnt so far?

- Neutrinos oscillate!

$\nu_e, \nu_\mu, \nu_\tau$  different from  $\nu_1, \nu_2, \nu_3$

- Two different oscillation frequencies:

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

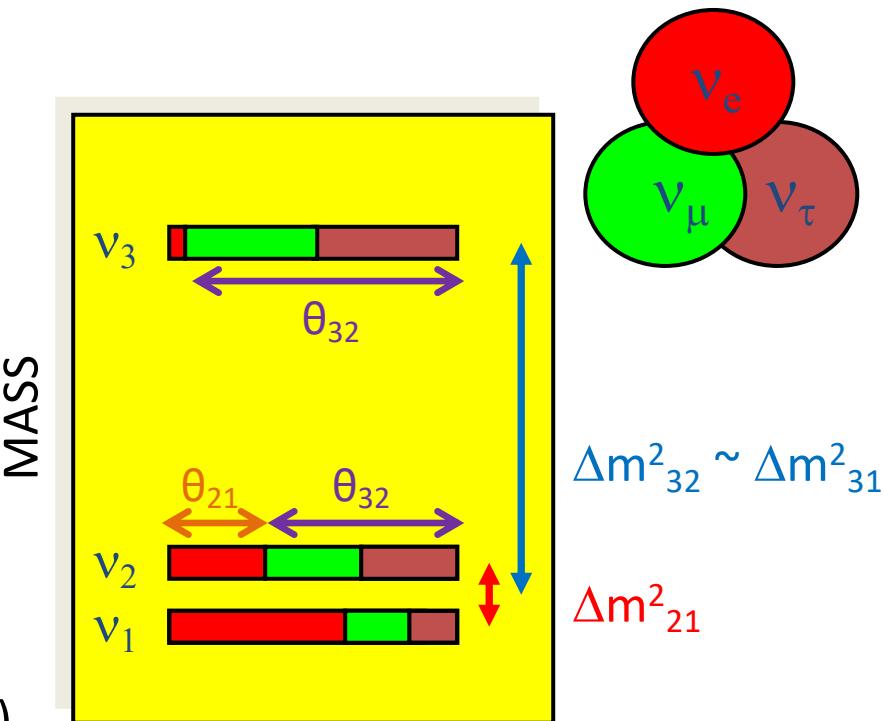
slow: solar,  $\Delta m^2_{21}$  atm  $\sim 20 \times$  solar

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

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

solar, large  $\theta_{21} = 34^\circ \pm 1^\circ$

not so small  $\theta_{13} = 9.1^\circ \pm 0.6^\circ$  (c.f. biggest angle in quarks, Cabibbo's =  $13^\circ$ )



Convention:  $\nu_1$  is state with most  $\nu_e$

# Neutrino mixing matrix

3 angles and 1 CP phase:

$$\theta_{12}, \theta_{13}, \theta_{23}, \delta$$

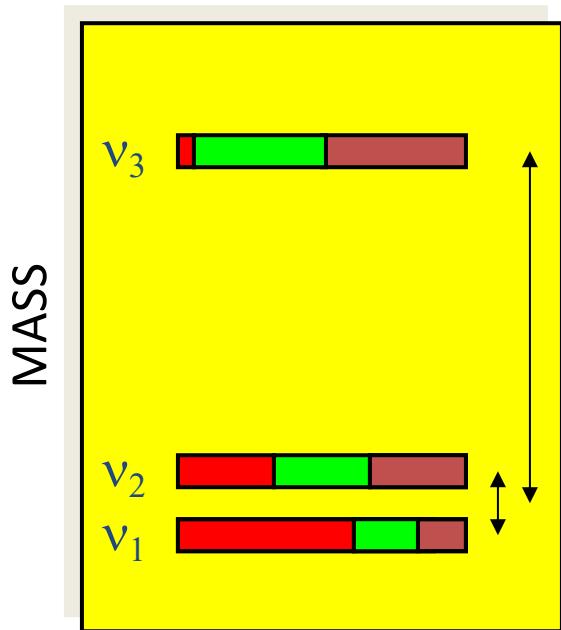
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \cdot e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} \cdot e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

*atmospheric*  $\nu$       *Reactor*      *solar*  $\nu$

**Dirac**

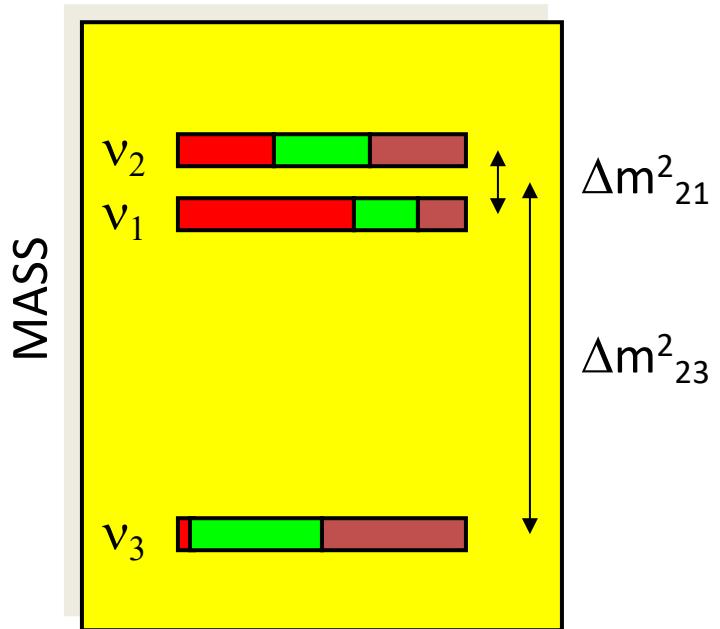
$\delta$ , matter-antimatter asymmetry in neutrinos?

# Mass ordering?



Normal mass ordering

?



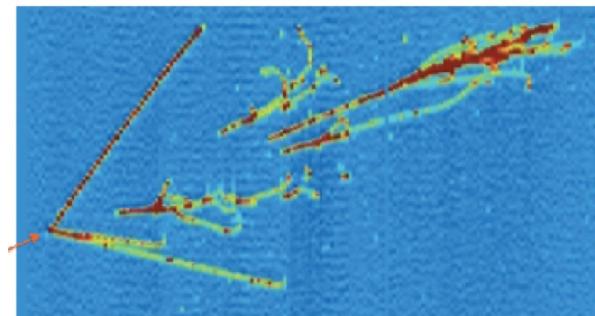
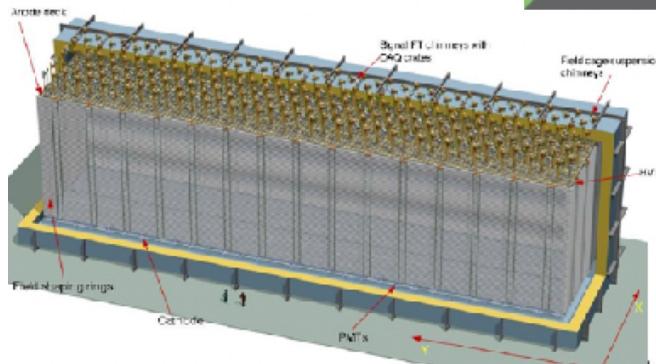
Inverted mass ordering

Which mass state is the lightest?

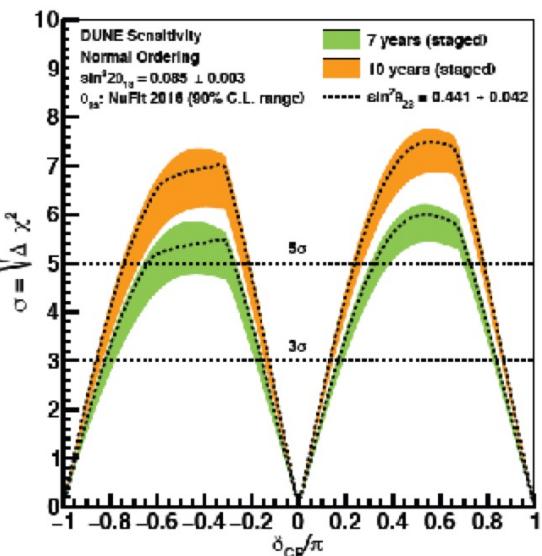
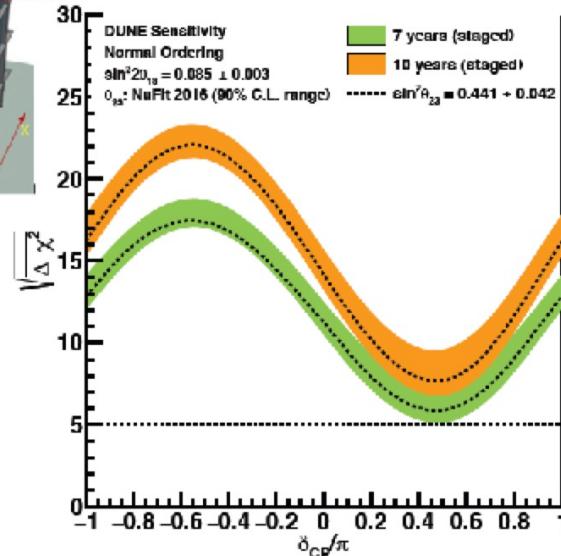
# Future long baseline projects...

# DUNE

40 kton Lq. Ar TPC  
Starting around 2026



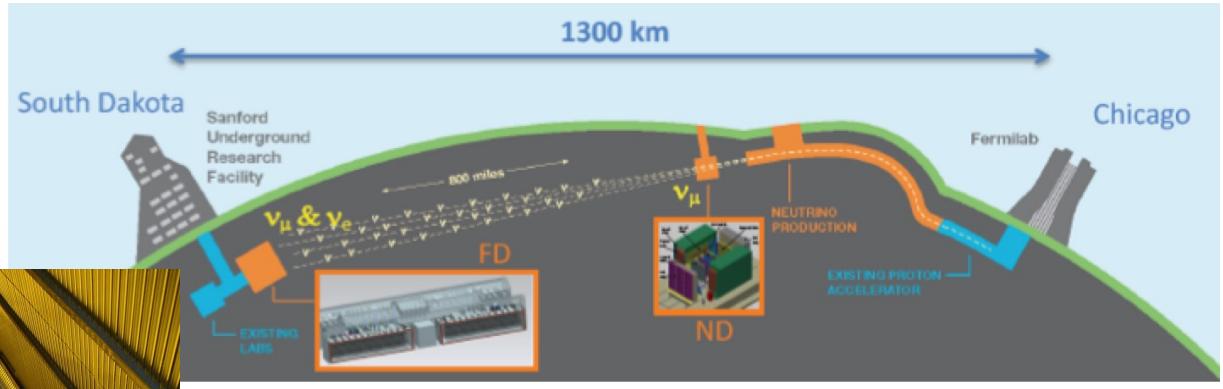
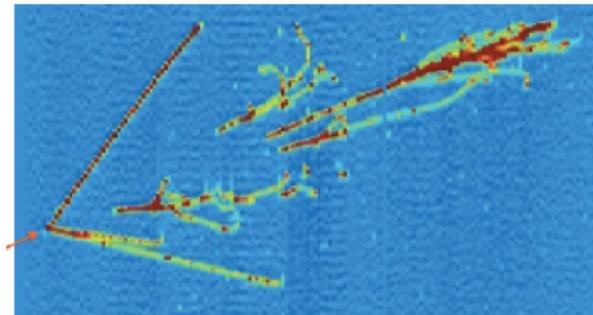
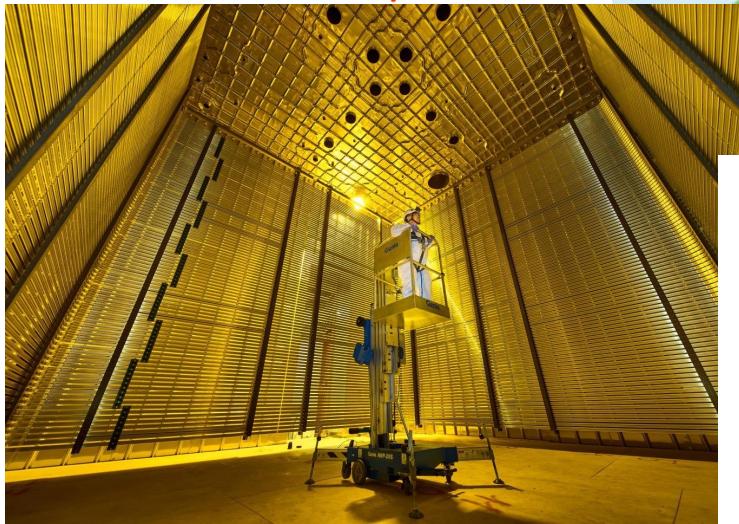
Sensitivity  
Mass Hierarchy      CP Violation



# Future long baseline projects...

DUNE

40 kton Lq. Ar TPC

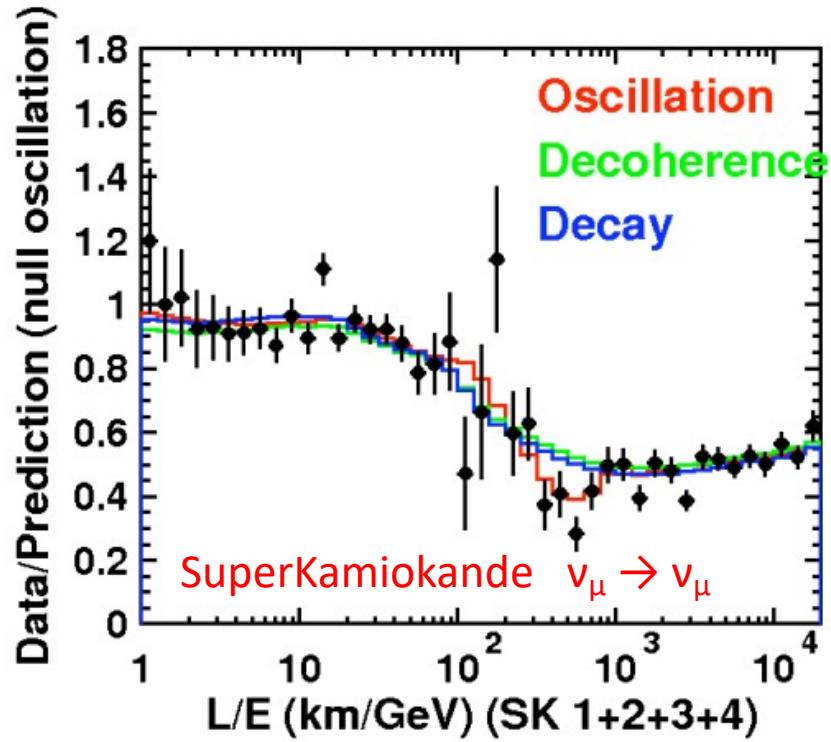
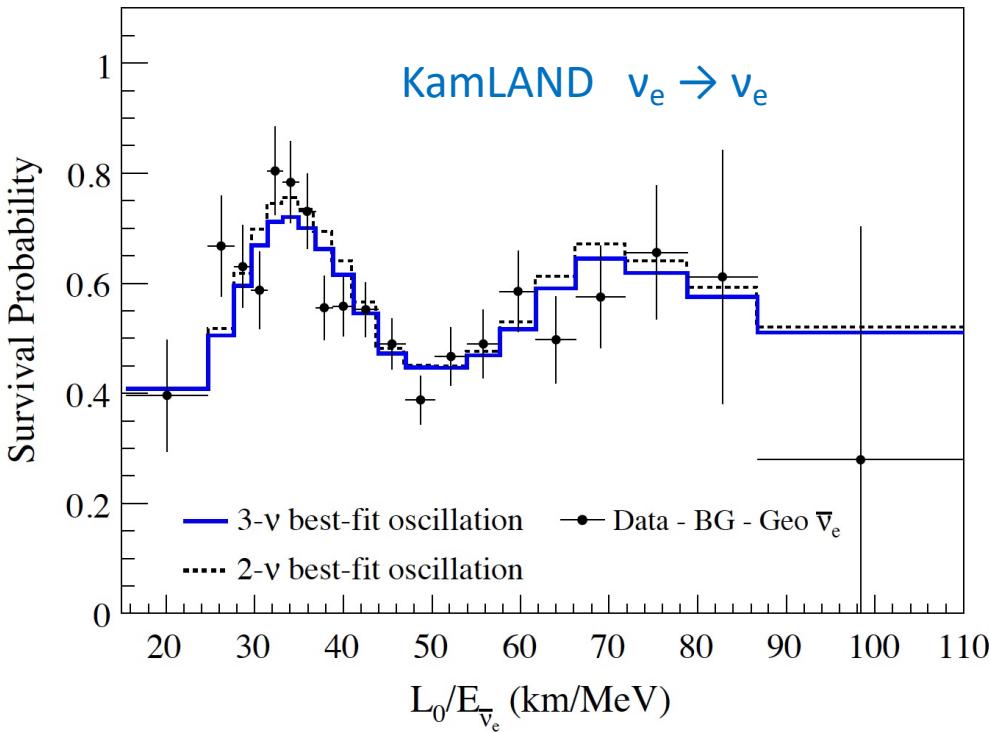


Broad physics programme!

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

# Conclusions

- Neutrinos oscillate! Masses  $\neq 0$  (2015 Nobel prize)  
 $\nu_e, \nu_\mu, \nu_\tau$  different from  $\nu_1, \nu_2, \nu_3$

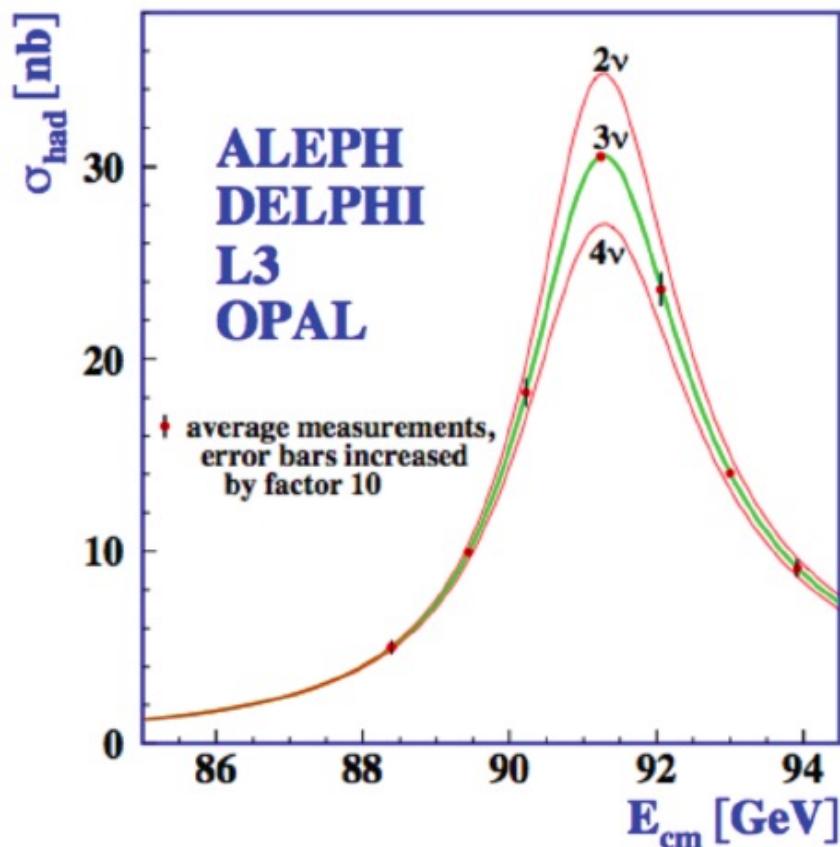


# Conclusions

- Neutrinos oscillate! Masses  $\neq 0$  (2015 Nobel prize)  
 $v_e, v_\mu, v_\tau$  different from  $v_1, v_2, v_3$
- Two different oscillation frequencies:  
fast: atmospheric,  $\Delta m^2_{32} \sim \Delta m^2_{31}$   
slow: solar,  $\Delta m^2_{21}$  atm  $\sim 20 \times$  solar
- Neutrinos mix a lot! (Mixing angles large compared to quarks' mix angles!)  
atmospheric, maximal  $\theta_{32} = 45^\circ \pm 6^\circ$   
solar, large  $\theta_{21} = 34^\circ \pm 1^\circ$   
reactor, not so small  $\theta_{13} = 9.1^\circ \pm 0.6^\circ$  (c.f. biggest angle in quarks, Cabibbo's =  $13^\circ$ )
- 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 al., JPG 37, 075021 (2010)

Number  $N = 2.984 \pm 0.008$   
(Standard Model fits to LEP data)

Number  $N = 2.92 \pm 0.05$  ( $S=1.2$ )  
(Direct measurement of invisible Z width)

# Etats propres de saveur et de masse

- Matrice PMNS (Pontecorvo-Maki-Nakagawa-Sakata) relie états propres de masse ( $\nu_1, \nu_2, \nu_3$ ) et de saveur ( $\nu_e, \nu_\mu, \nu_\tau$ )

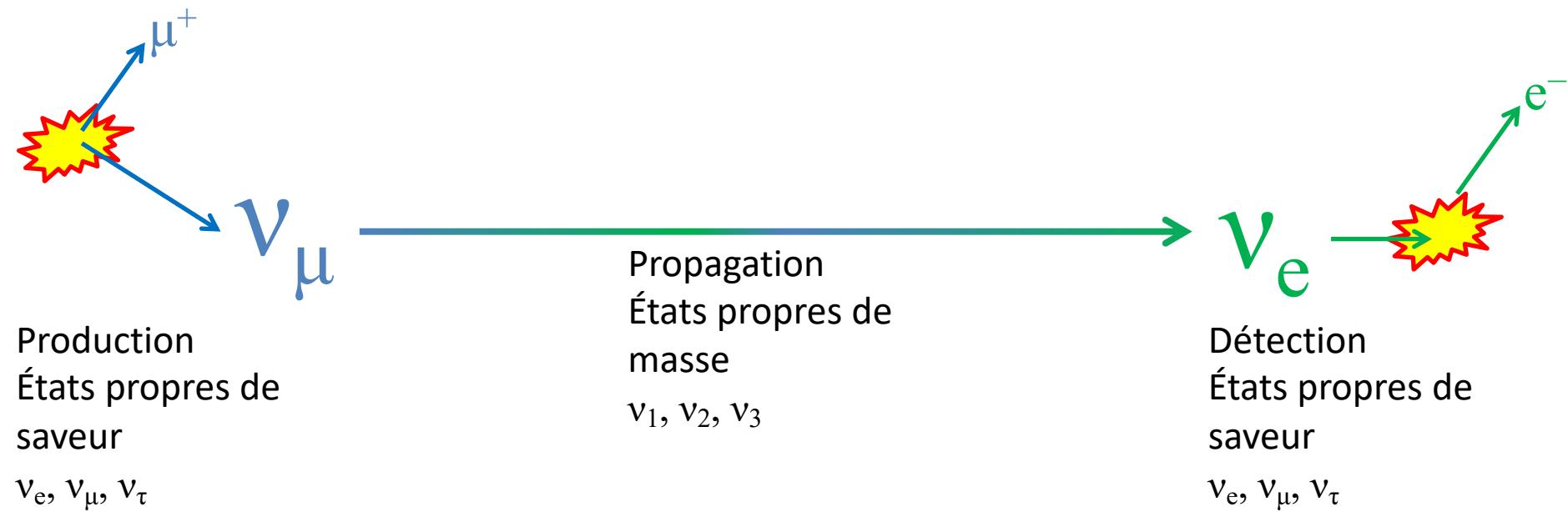
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

p.ex.

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

# 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)



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

# 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  
 $|\nu_\mu\rangle =$

$$U_{\mu 1} |\nu_1\rangle + U_{\mu 2} |\nu_2\rangle + U_{\mu 3} |\nu_3\rangle$$

Propagation dans le vide

$$\nu_1 : \exp(-iE_1 t)$$

$$\nu_2 : \exp(-iE_2 t)$$

$$\nu_3 : \exp(-iE_3 t)$$

Détection

$$\langle \nu_e |$$

Masses  $m_1, m_2, m_3$  différentes  $\rightarrow$  phases  $-iE_1 t, -iE_2 t, -iE_3 t$  différentes  $\rightarrow$   
 $\rightarrow$  proportion des composantes e,  $\mu$ ,  $\tau$  change avec le temps

# Un peu d'histoire

- Oscillation neutrino-antineutrino proposée par Bruno Pontecorvo (1957) par analogie avec les oscillations  $K^0$  et  $\bar{K}^0$
- 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