Neutrino oscillations

Pablo del Amo Sánchez

GraSPA

24/07/19

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LAPP - IN2P3 - CNRS / UniSavoieMontBlanc
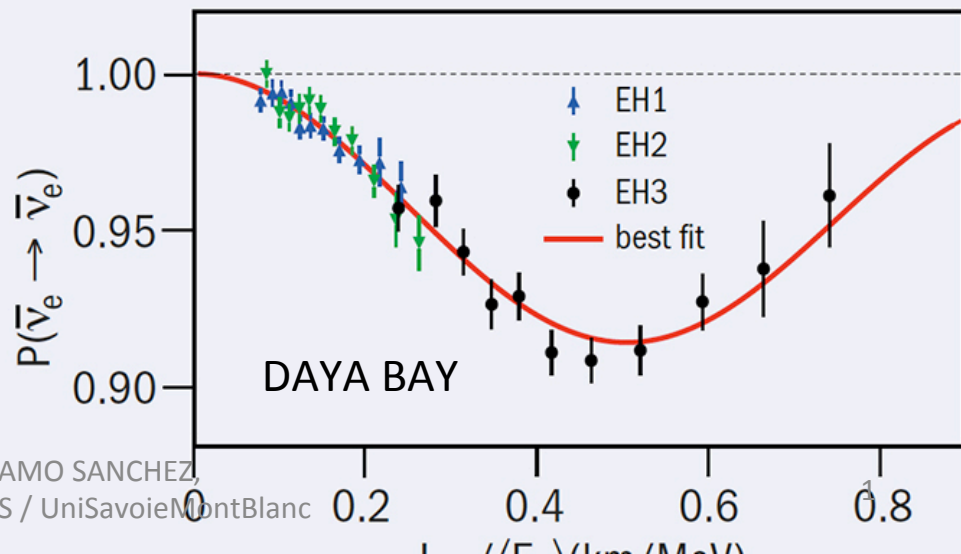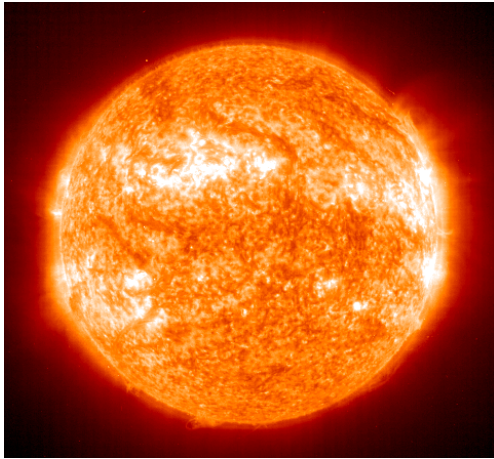
Overview

- Evidence for neutrino oscillations

  Non historical approach

- How to go about detecting neutrinos

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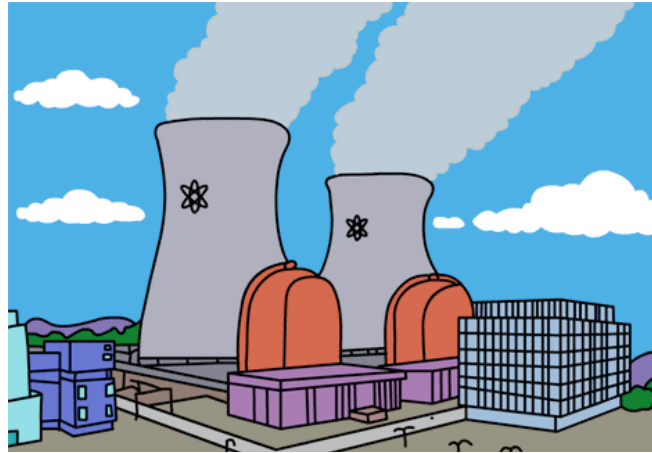LAPP - IN2P3 - CNRS / UniSavoieMontBlanc

ν sources

The Sun
65×10^9 ν_e cm^{-2} s^{-1} at Earth

Nuclear reactors
2×10^{20} $\overline{\nu}_e$ s^{-1} GW$_{th}^{-1}$

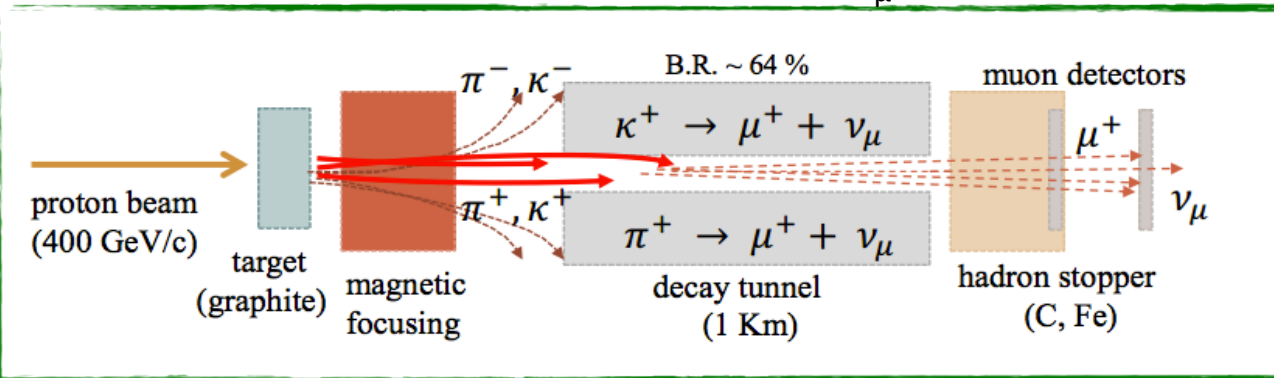## Atmospheric ν (cosmic rays)
4×10^2 $\nu_{\mu+e}$ m^{-2} s^{-1} sr^{-1} at 1 GeV
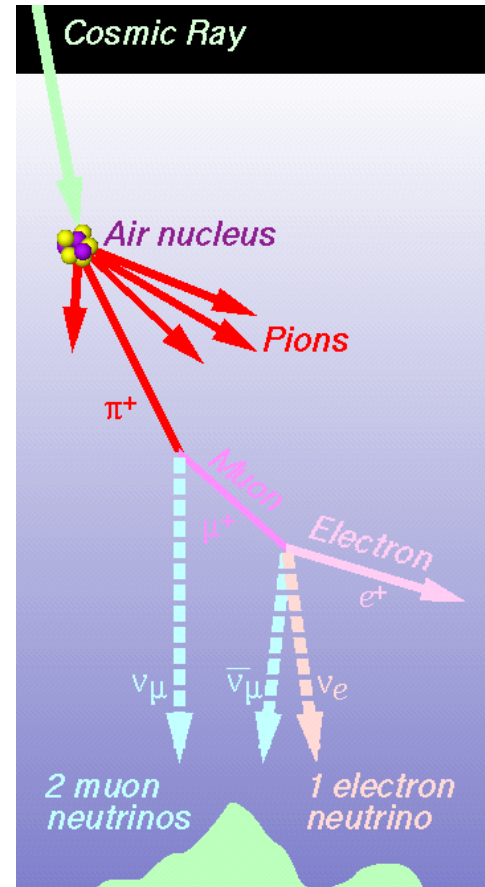
Accelerators, e.g. at OPERA: 1×10^{12} ν_μ m^{-2}

Plus: astrophysical neutrinos, CvB, etc

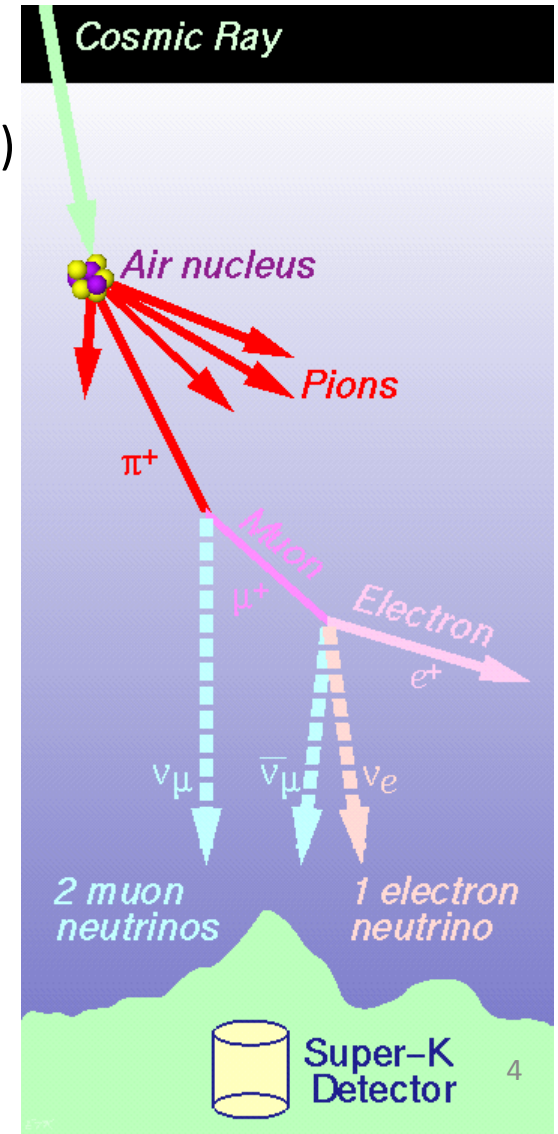Pablo DEL AMO SANCHEZ,
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Atmospheric neutrinos

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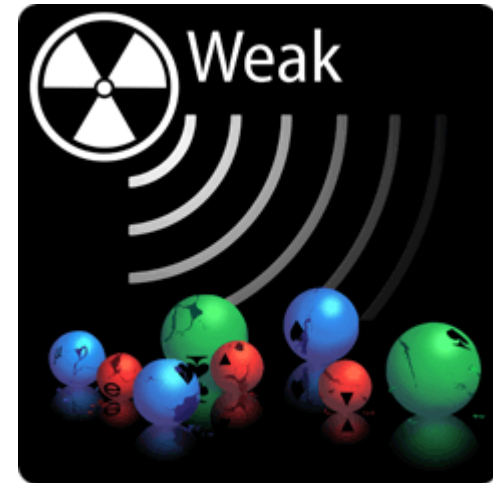- $\pi^+ \to \mu^+ \nu_\mu$ and $\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$

SO

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

(known better than 3% below 5 GeV)

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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

    → $\sigma \approx 10^{-42}$ cm^2 for IBD

➔ need copious sources and/or large detector masses

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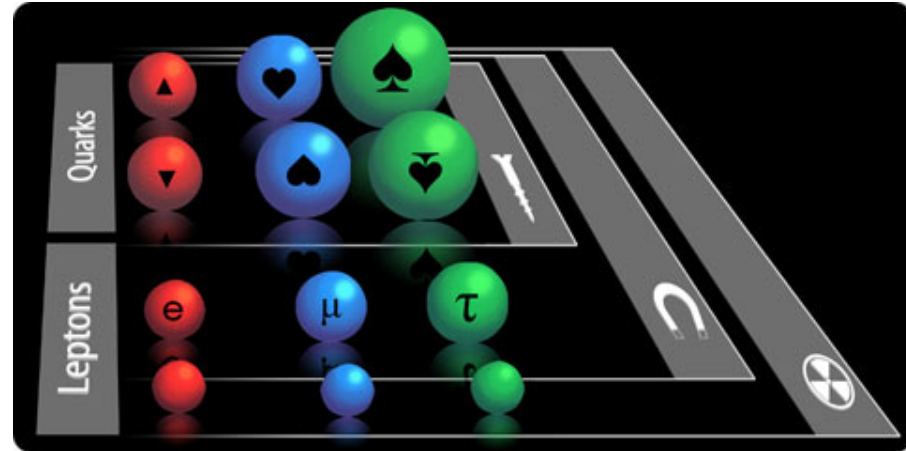
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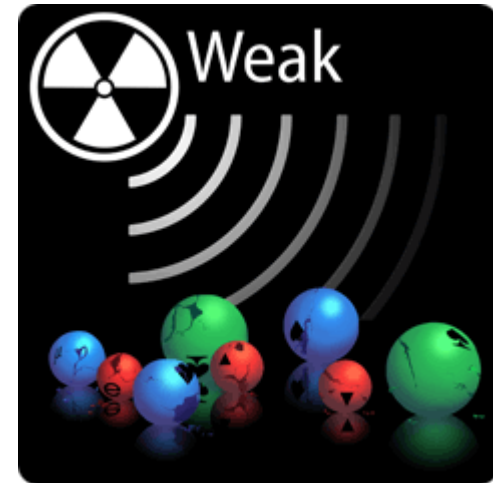➔ need copious sources and/or large detector masses

Ex: SuperKamiokaNDE

$R = \phi\ N_N\ \sigma_N$

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

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

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

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

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Water Cerenkov detectors

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

ν_e, ν_μ W^+ e^-, μ^-

n   p

- 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

$w = V_w \cdot t$

$d = V_p \cdot t$
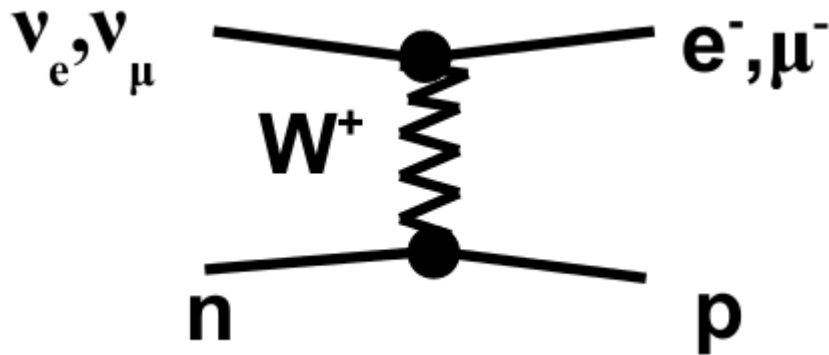
SUPERKAMIOKANDE   INSTITUTE FOR COSMIC RAY RESEARCH UNIVERSITY OF TOKYO   NIKKEN SEKKEI

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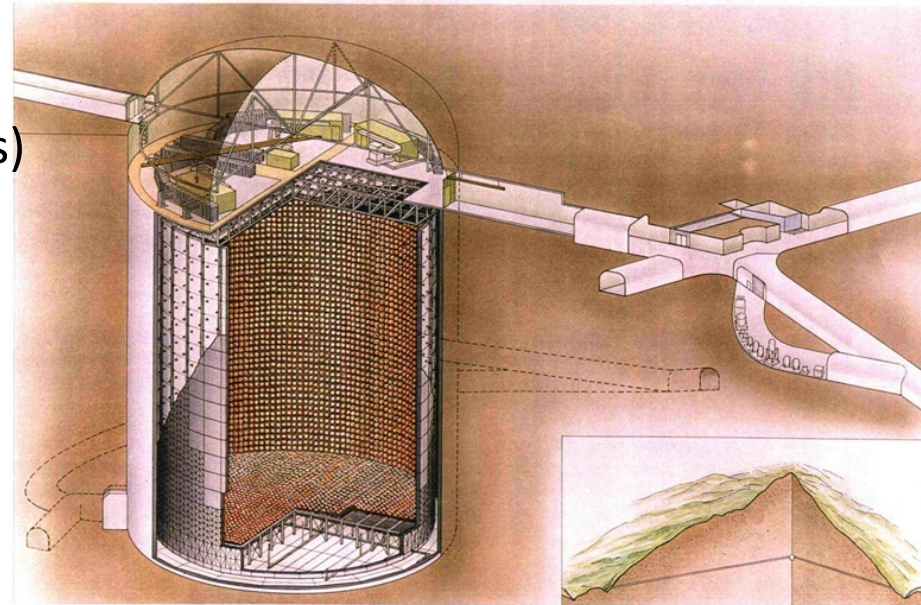
Water Cerenkov detectors

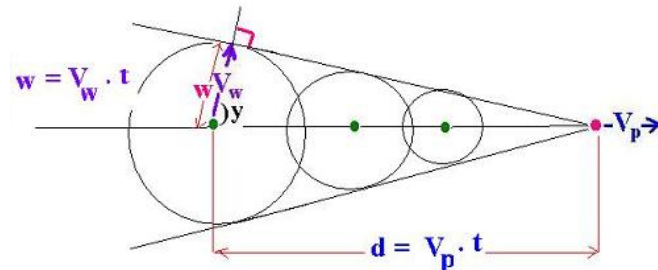- Huge underground water tanks surrounded by photomultiplier tubes (PMTs)

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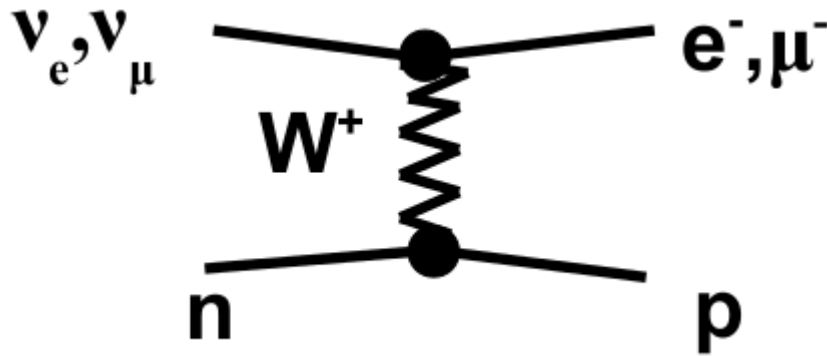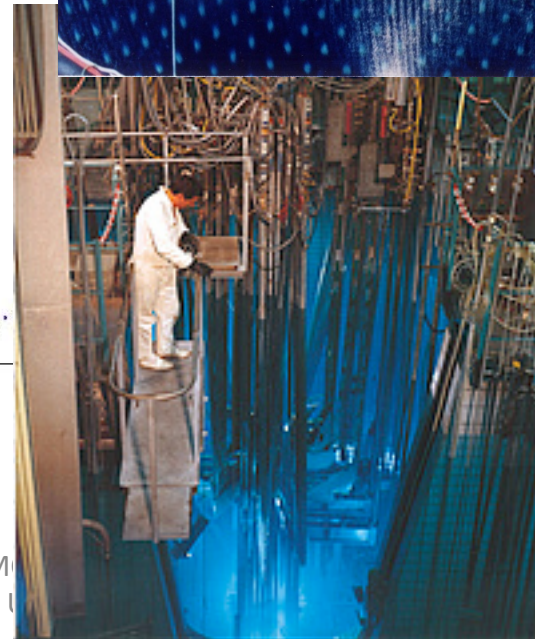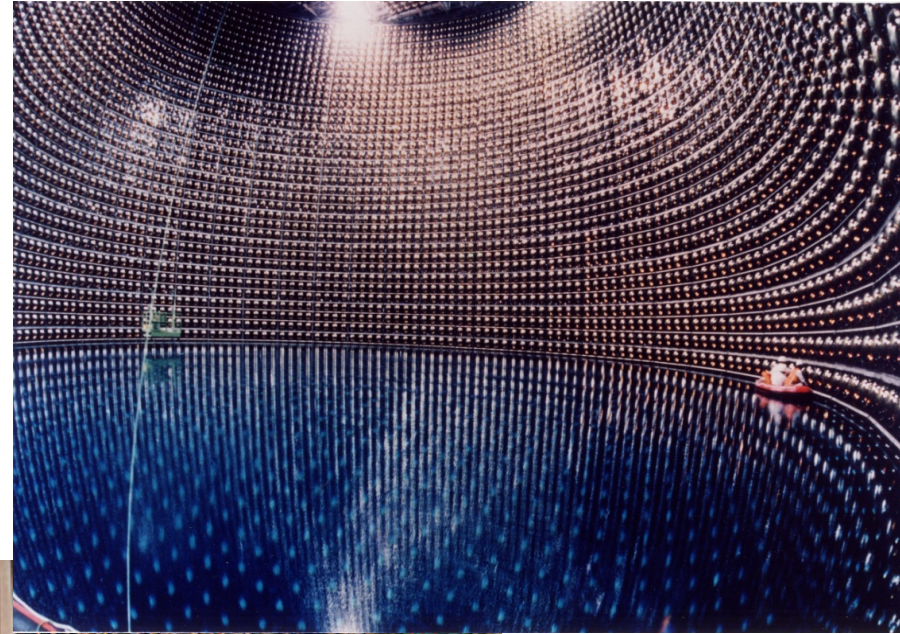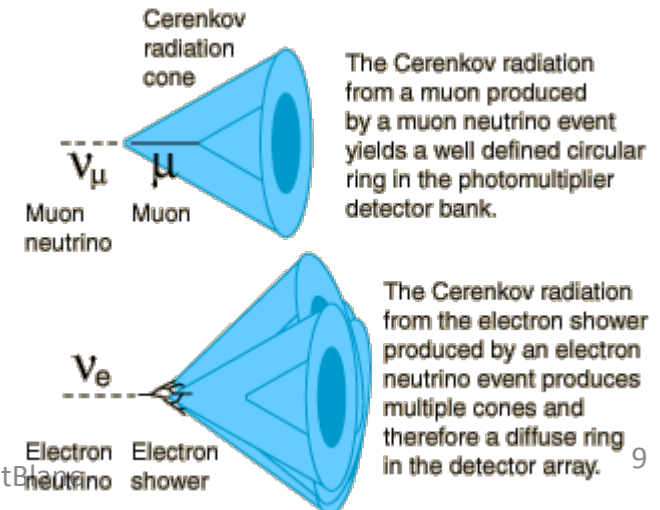
- Ex: (Super-)KamiokaNDE et SNO

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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

$$w = V_w \cdot t$$

$$d = V_p \cdot t$$

e

μ

Cerenkov radiation cone

$\overline{V}_\mu$ μ

Muon neutrino Muon

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

V_e

Electron neutrino Electron shower

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.

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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 $\nu_\mu \rightarrow \nu_\tau$?
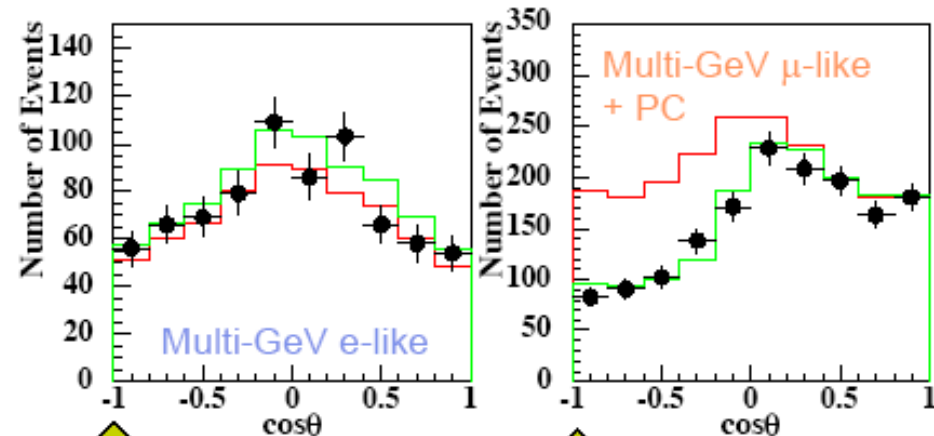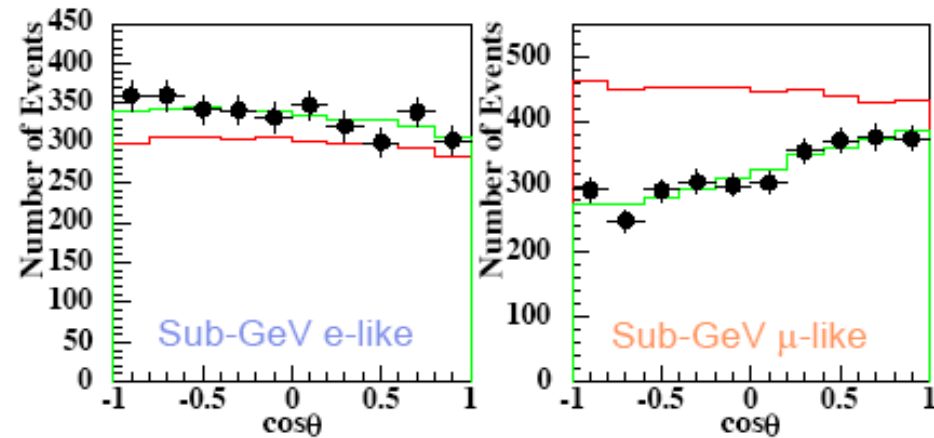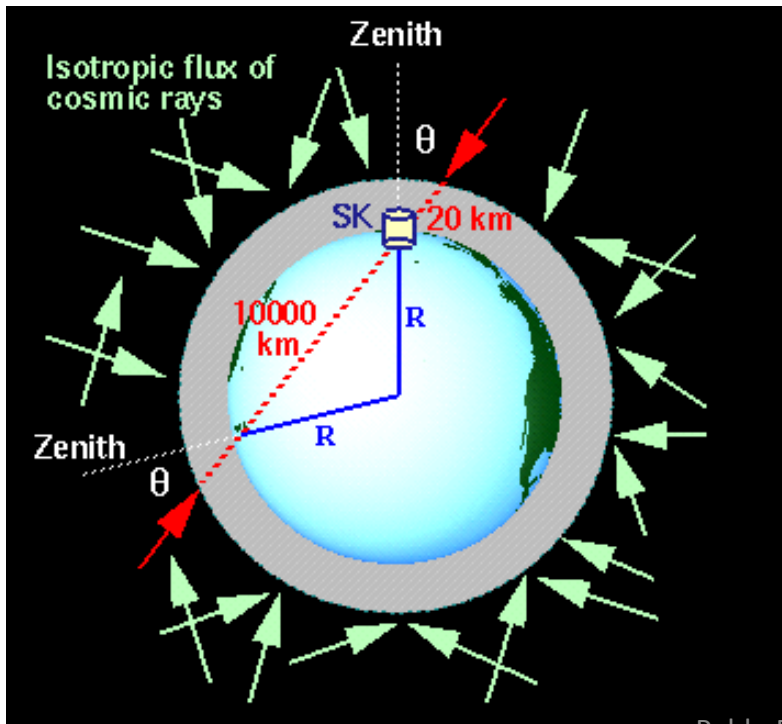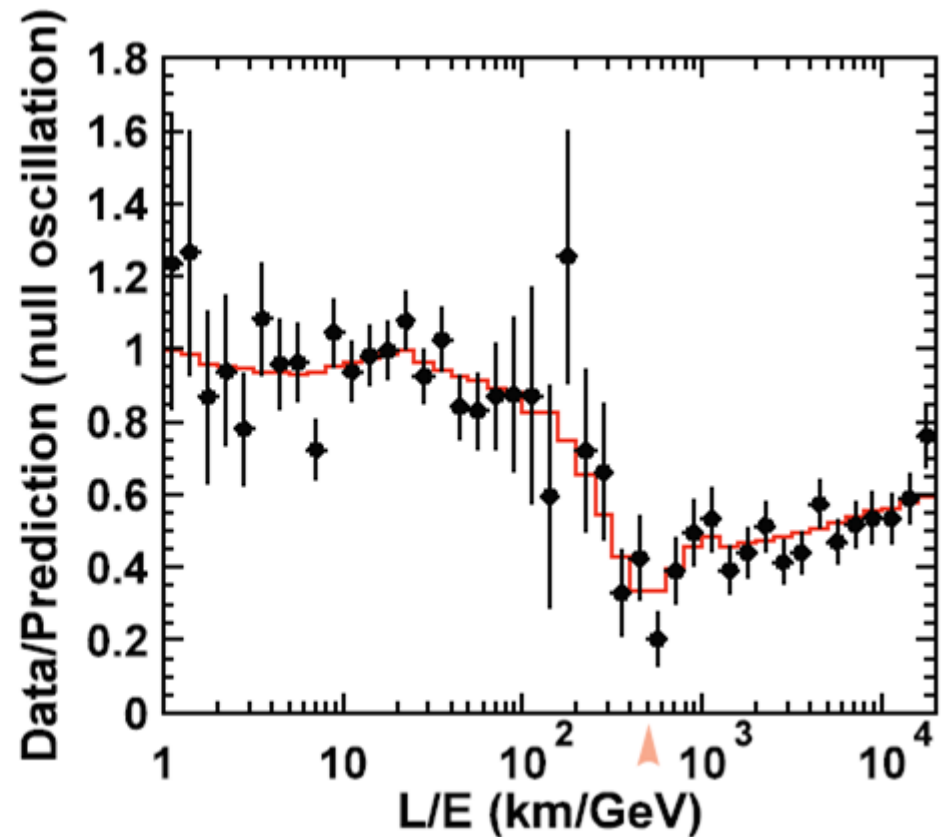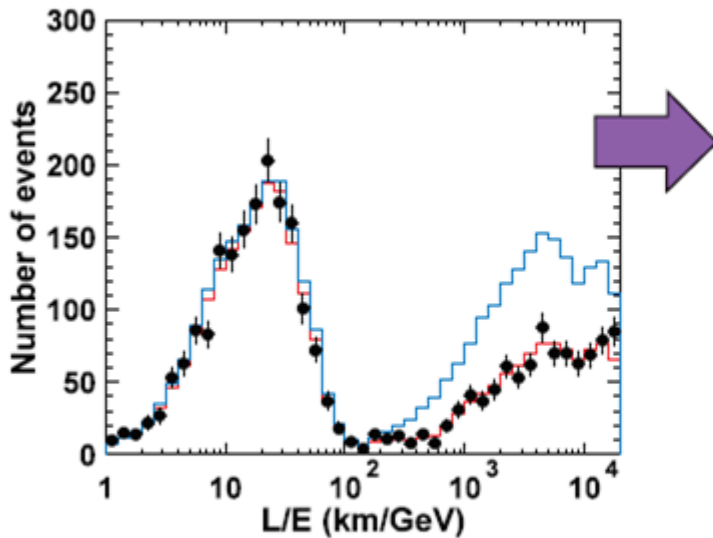
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~ 13000km   ~500km   ~15k

Atmospheric neutrinos disappear?

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Atmospheric neutrinos disappear?

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Atmospheric neutrinos oscillate!

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

$sin^2(2\theta)$
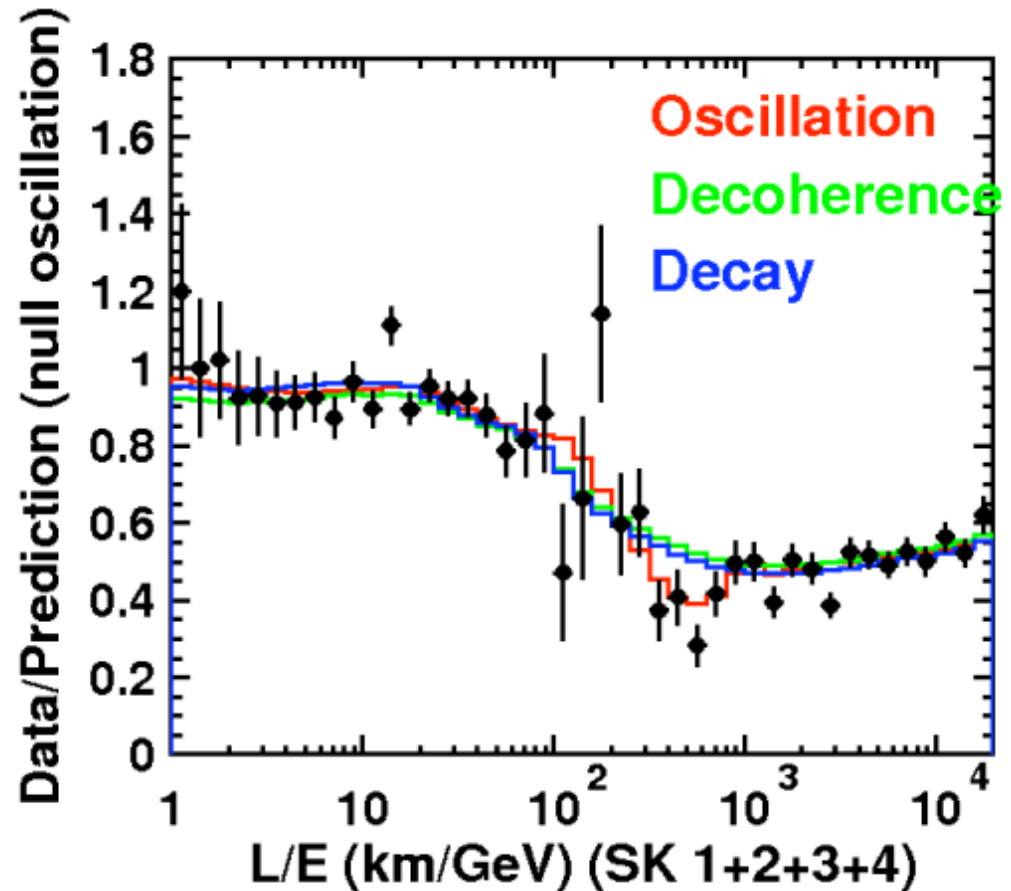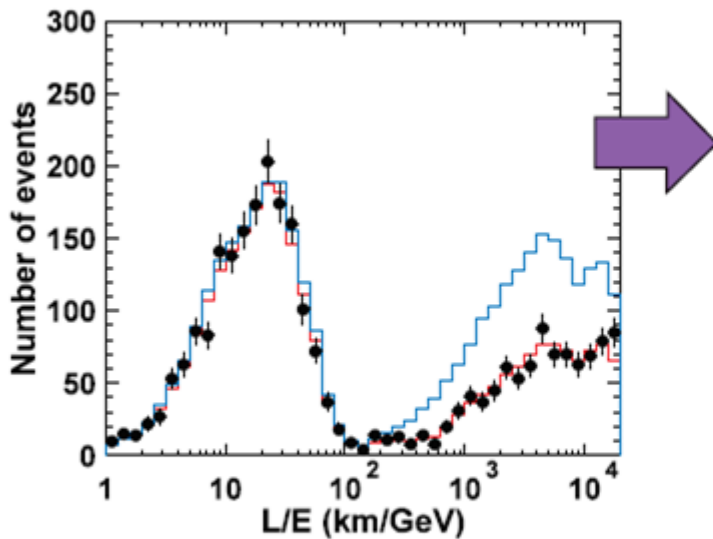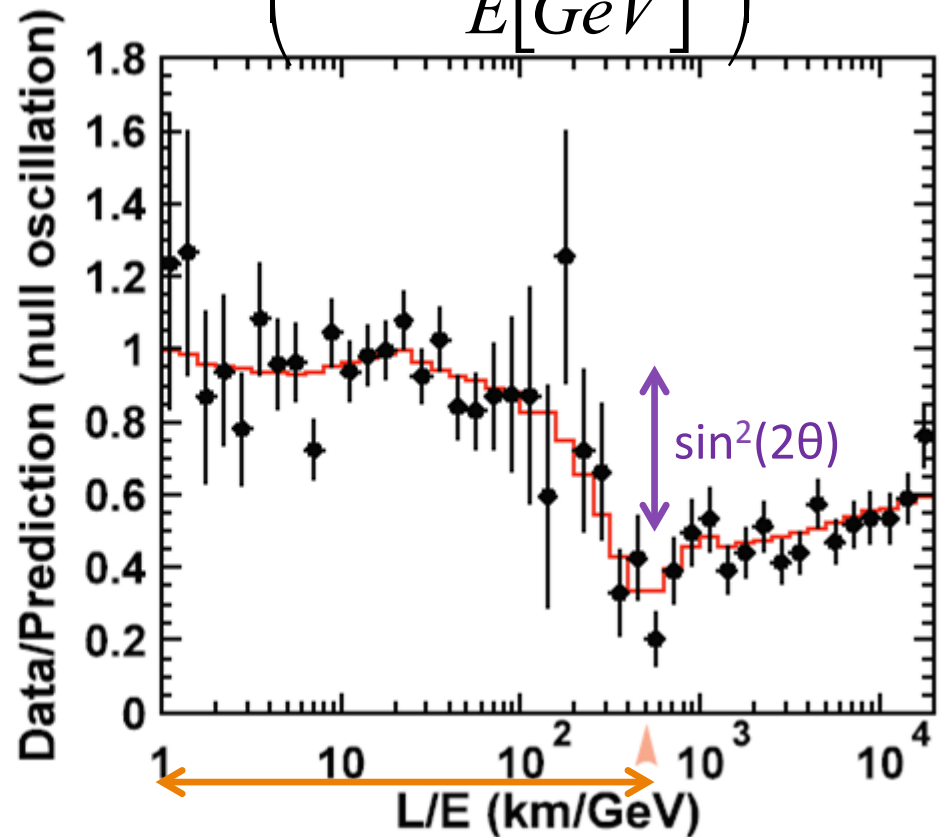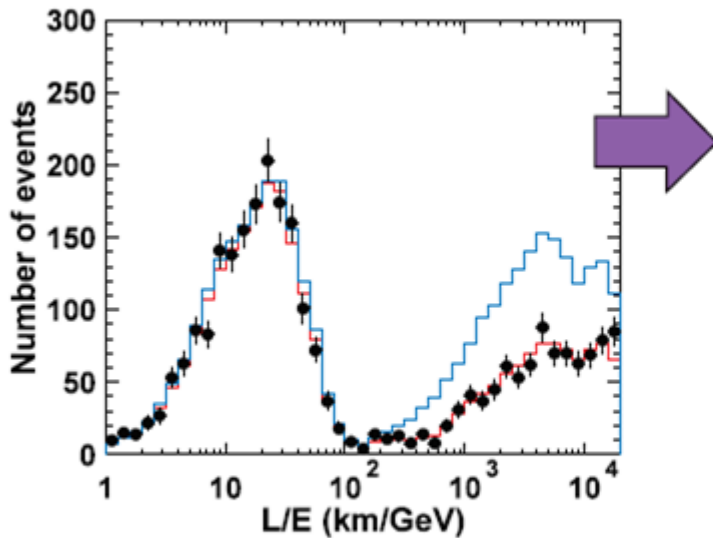
L/E ~500 km/GeV $\leftrightarrow$ Δm^2 ~ 2.3 x10^{-3} eV^2

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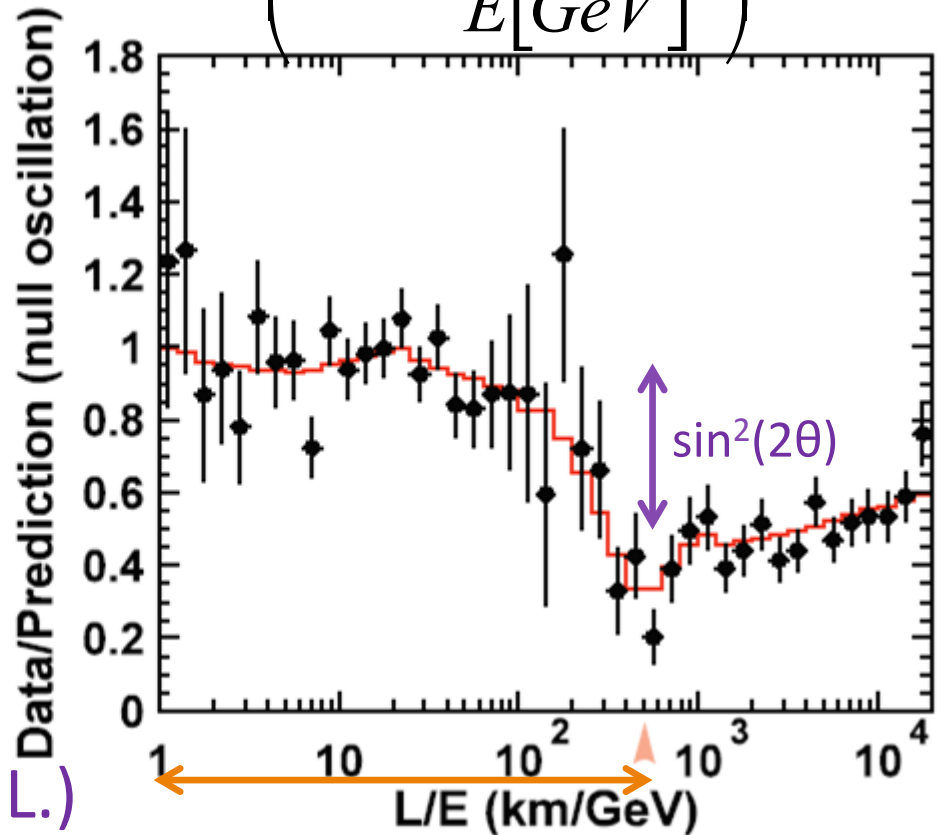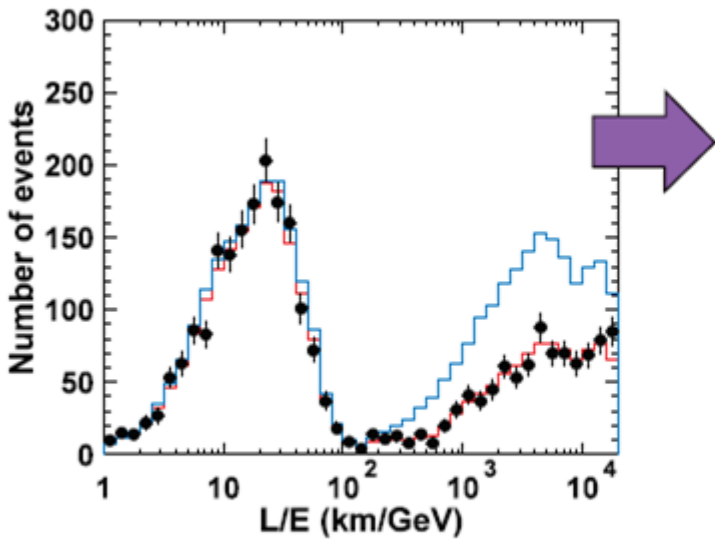
$\sin^2(2\theta) = 1.00 \ (>0.93 \ 90\% \ \text{C.L.})$

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

L/E ~500 km/GeV $\leftrightarrow \Delta m^2$ ~ 2.3 x10^{-3} eV^2

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But why don't we see this?

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

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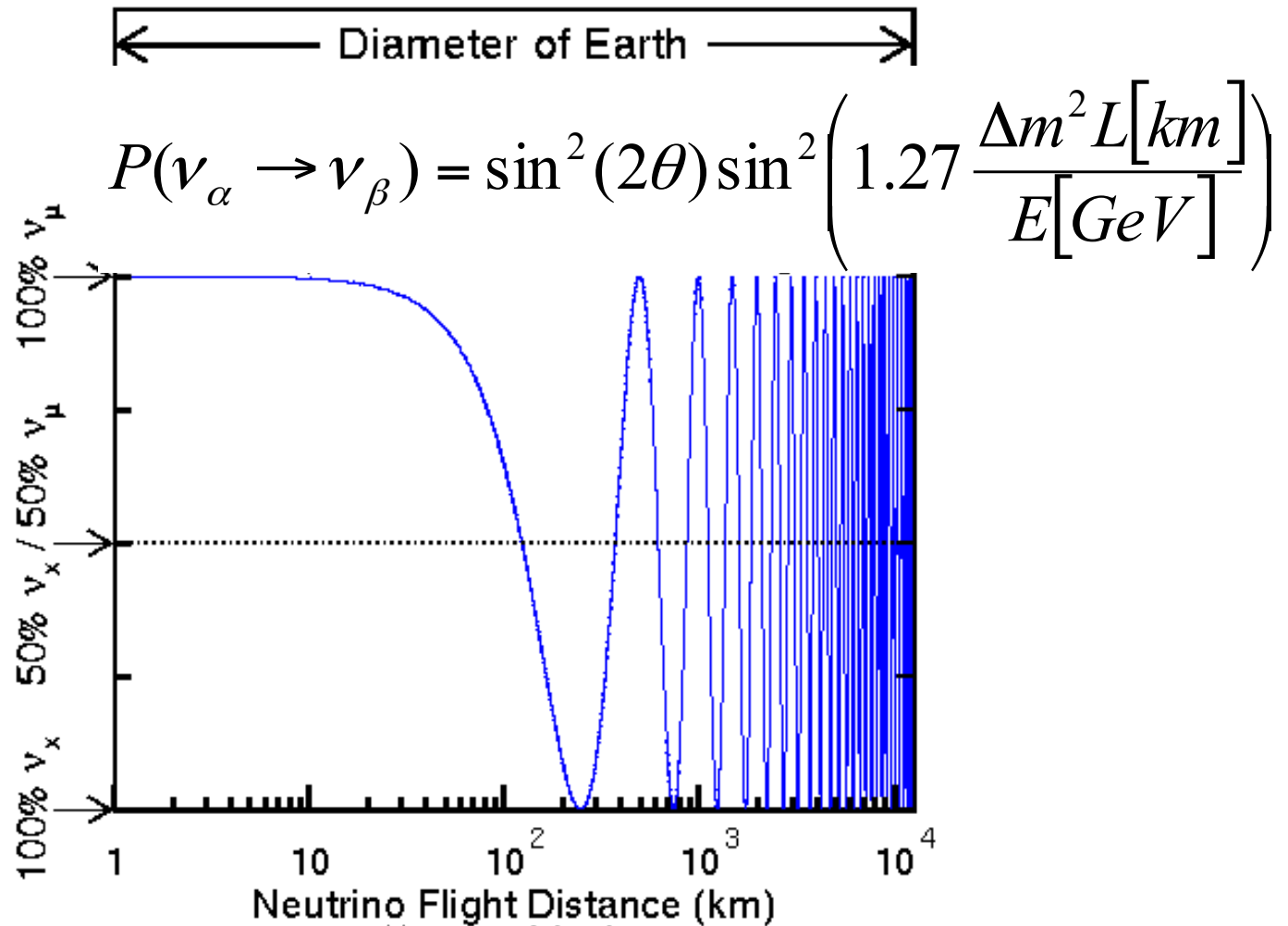
Because…

- Two effects:

Neutrinos not monochromatic → different oscillation lengths

Experimental resolution: if too close, maxima and minima blurred

Thanks to T. Schwetz

First oscillation maximum

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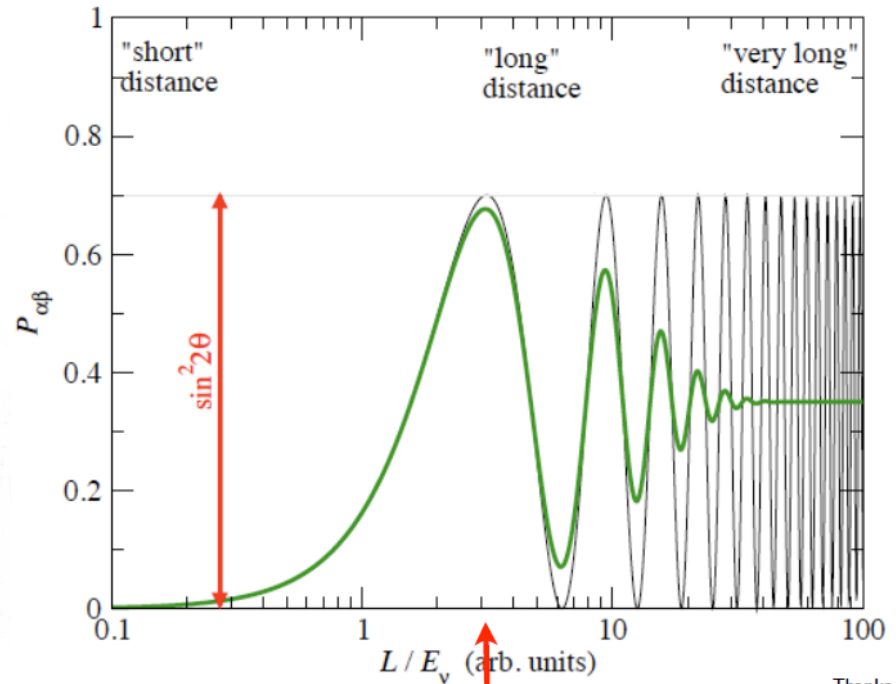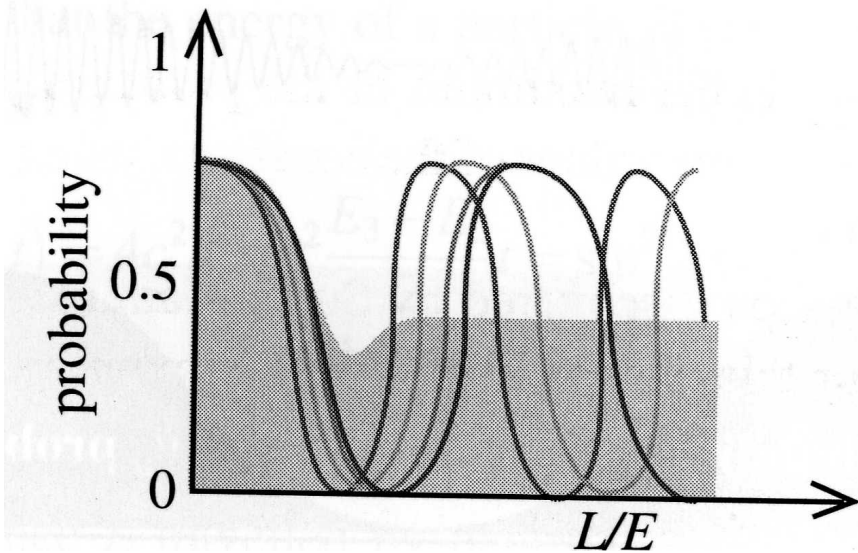
The solar neutrino saga

Neutrinos from the Sun

- Hydrogen fusion in the Sun requires inverse beta decay:

$$4p + 2e^- \to \mathrm{He}^{++} + 2\nu_e + 26{,}7 \text{ MeV}$$
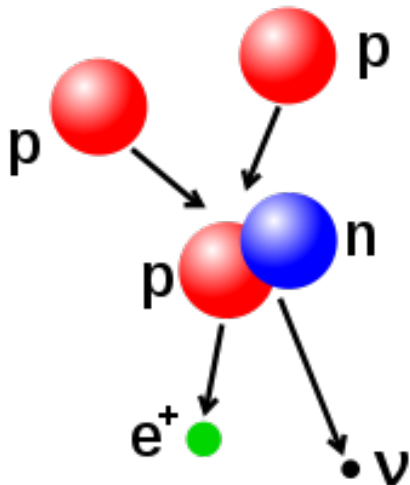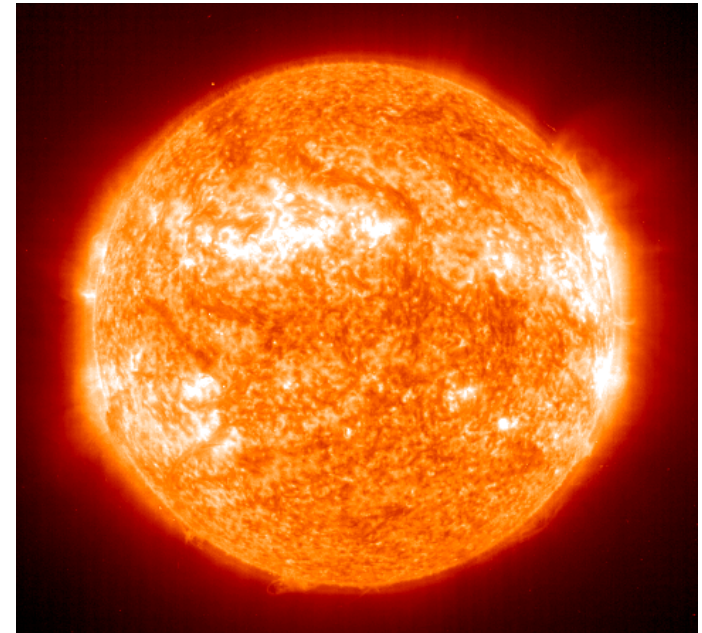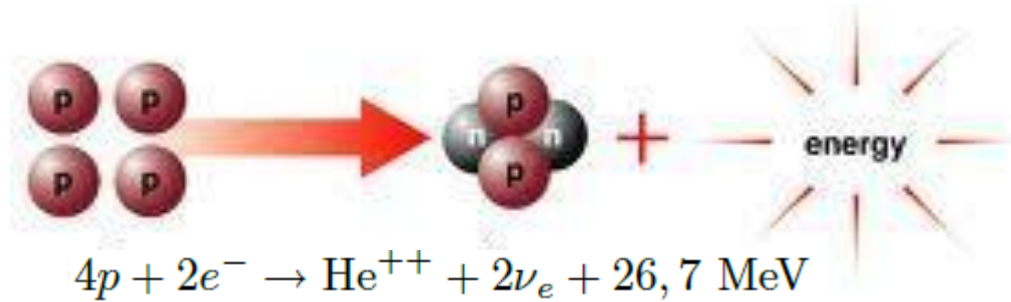
Solar constant = 1361 J/s m²

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

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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%

15%

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

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

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

15%

0.02%

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

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

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

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

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

Gallium | Chlorine | Kamiok

Bahcall–Pinsonnea

pp

^{7}Be | ^{7}Be | pep

^{8}B

hep

Neutrino Flux (cm^{-2}s^{-1})

Neutrino Energy (MeV)
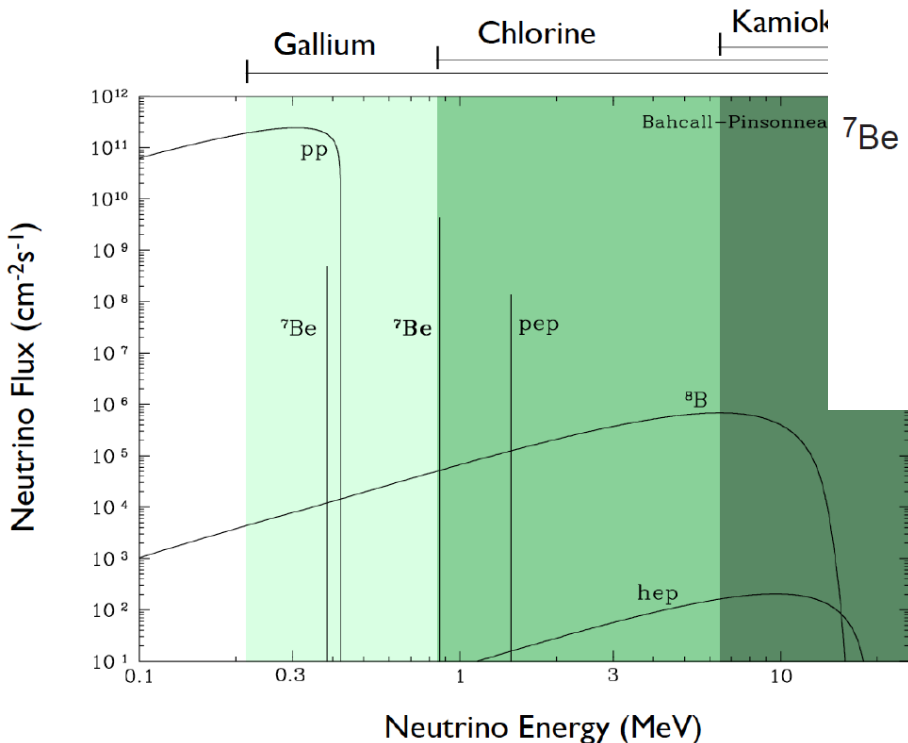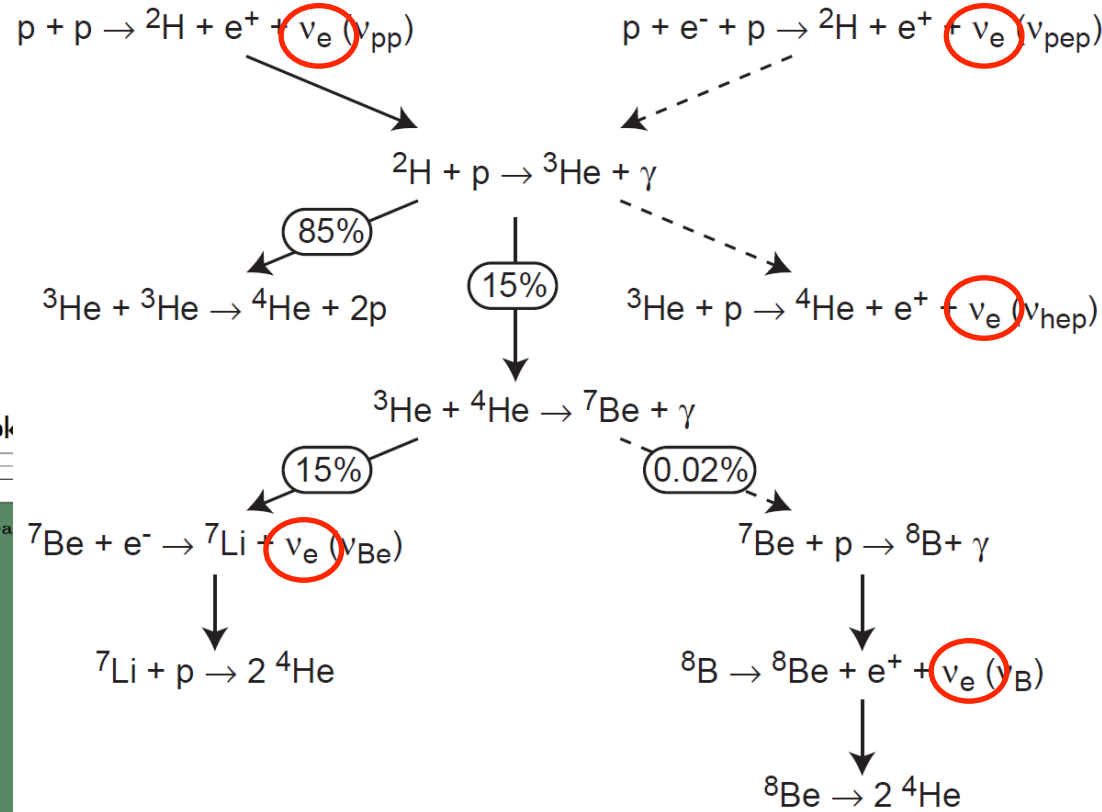
Neutrinos from the Sun

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

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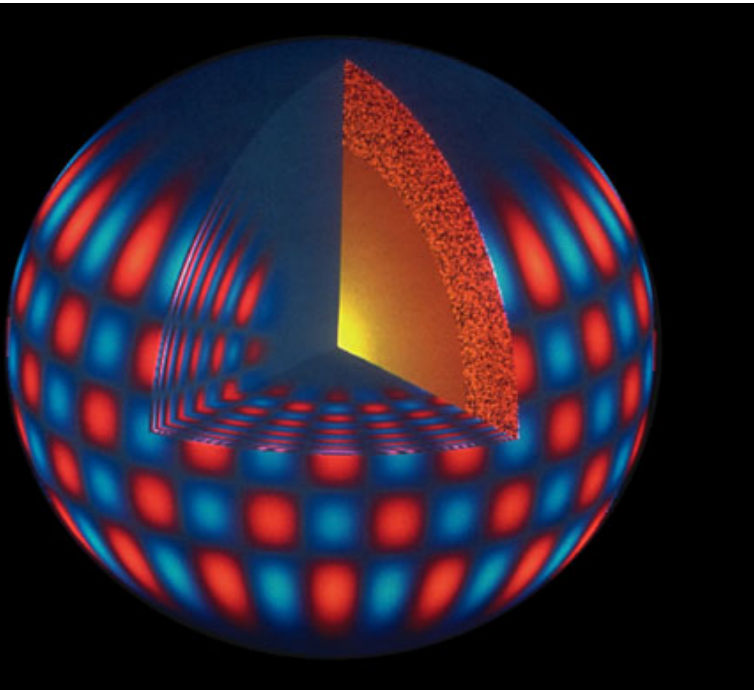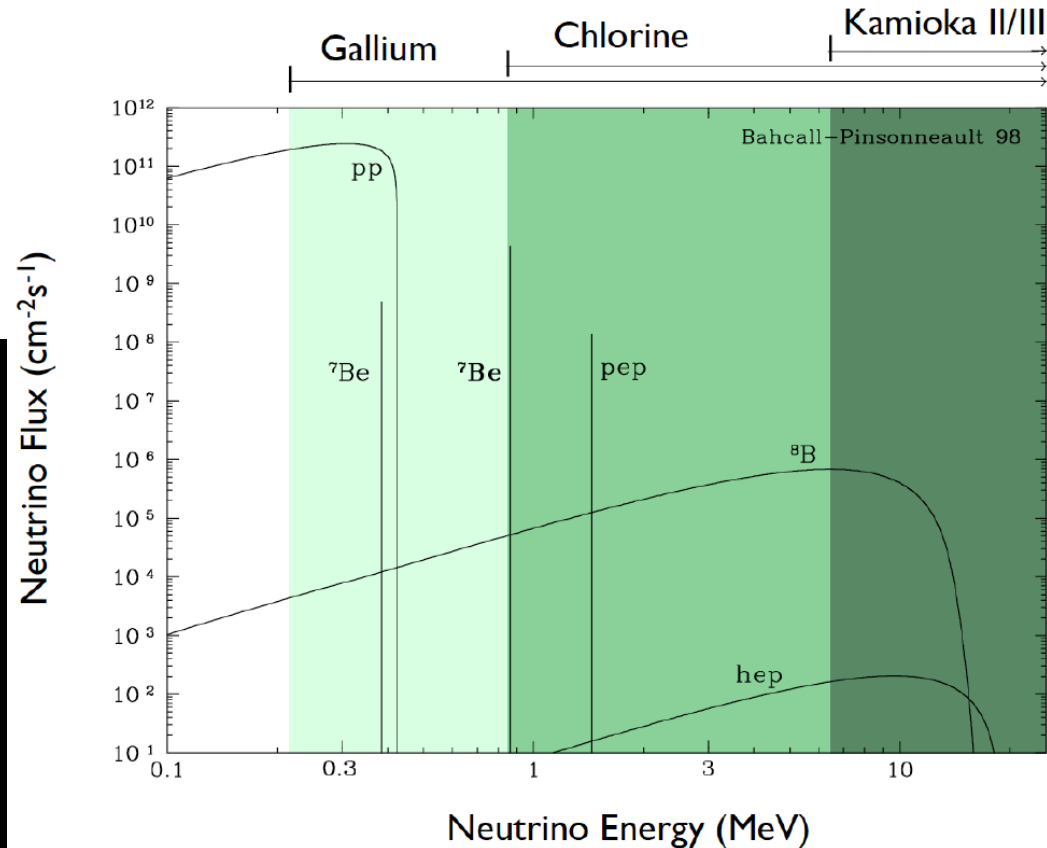
Homestake experiment

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

$$\nu_e + n \rightarrow p + e^-$$
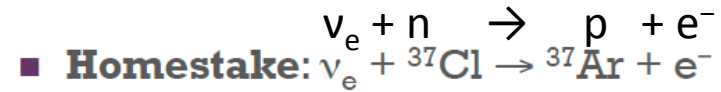
- **Homestake:** $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$
- Located in Lead, SD
- 615 tons of C_2Cl_4 (Cleaning fluid)
- Extraction method:
  - Pump in He that displaces Ar
  - Collect Ar in charcoal traps
  - Count Ar using radioactive decay
- Never Calibrated with source
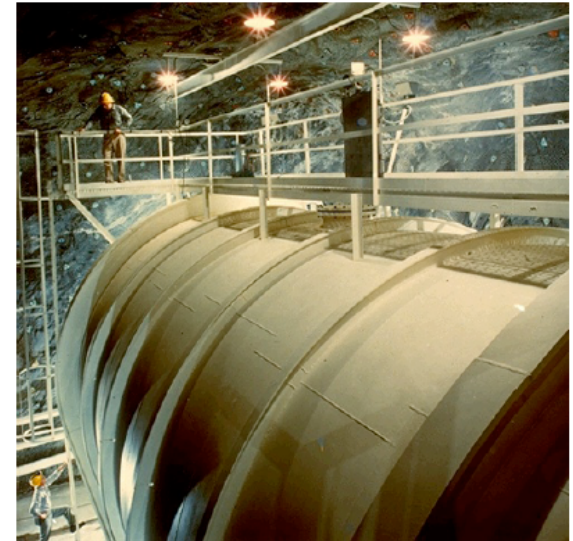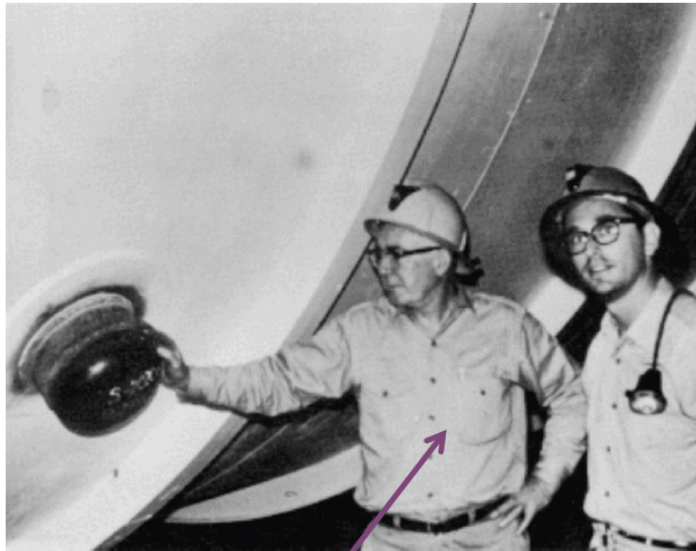
Raymond Davis, Nobel Prize 2002

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Problems?

- Problems with experiment? With ν_e flux predictions?
- Test other parts of the ν_e spectrum with different experimental techniques
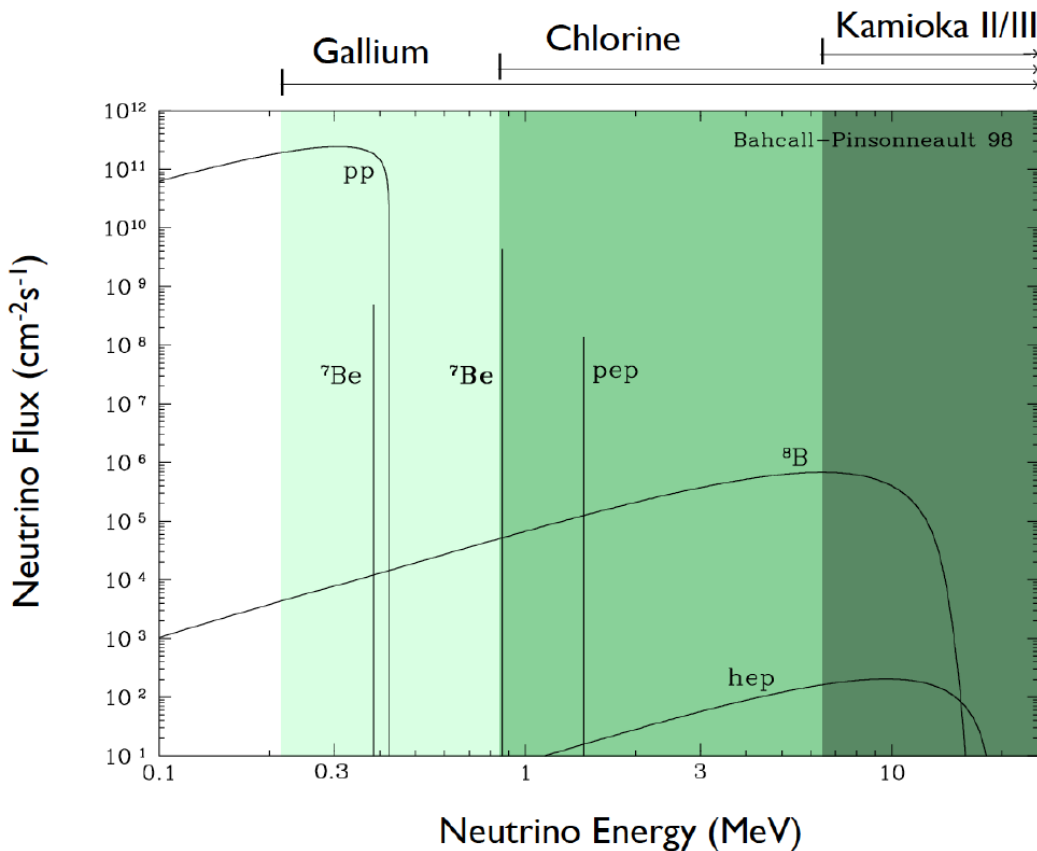
Gallex: $\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$
Observed 68.1 ± 3.75 SNU
Expected 127 ± 12 SNU
~50%
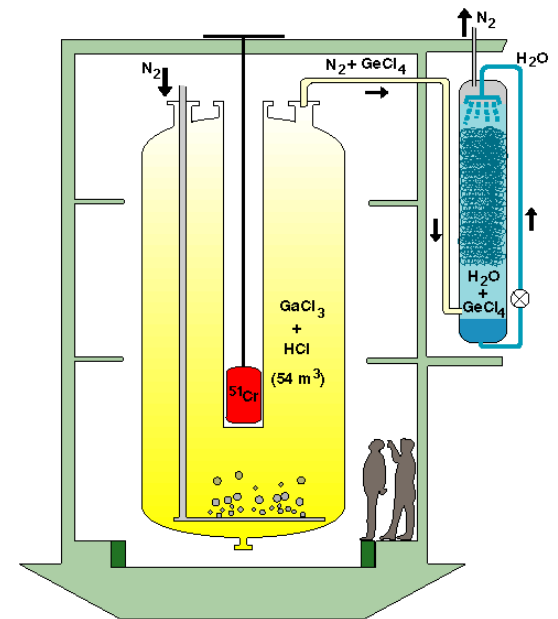
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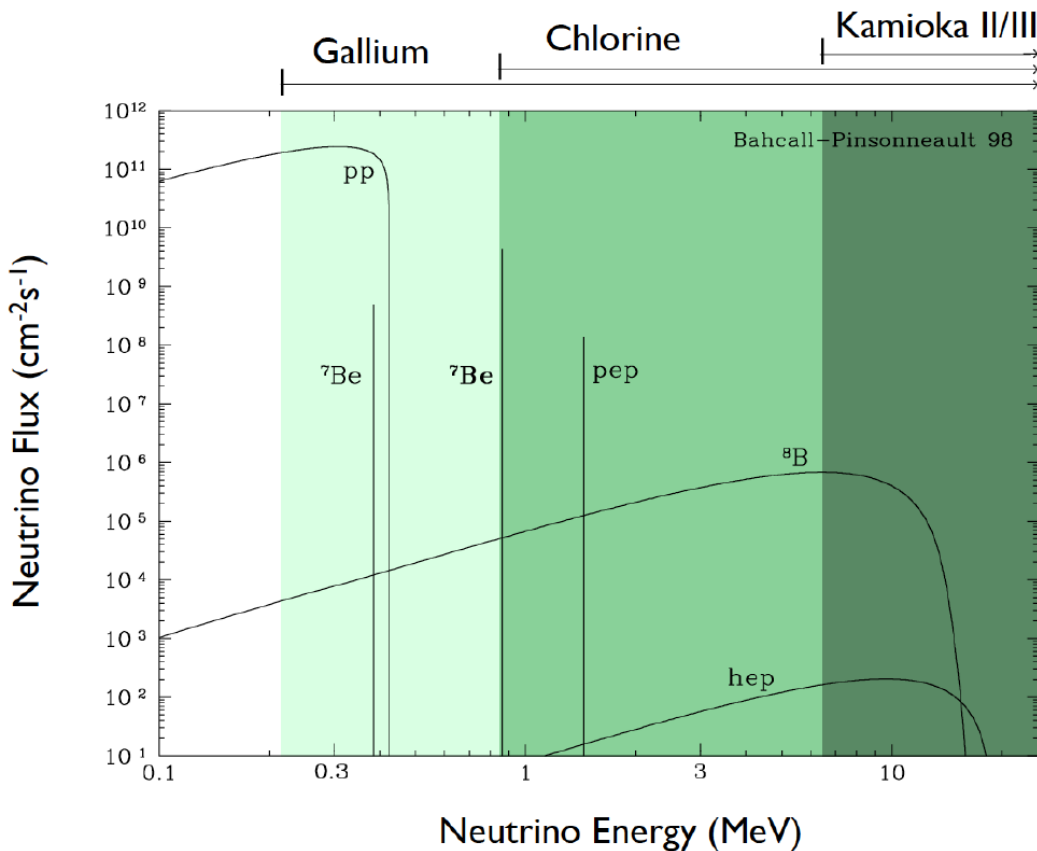
KamiokaNDE: $\nu_e + e^- \rightarrow \nu_e + e^-$
Observed ~40% of expectation
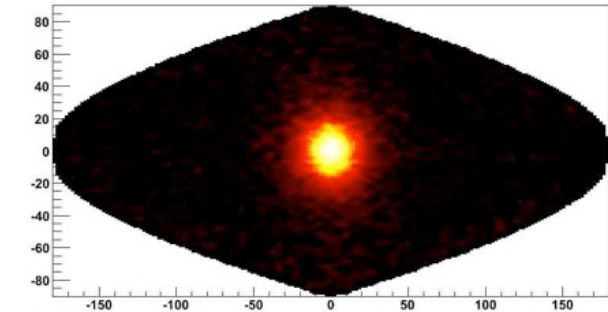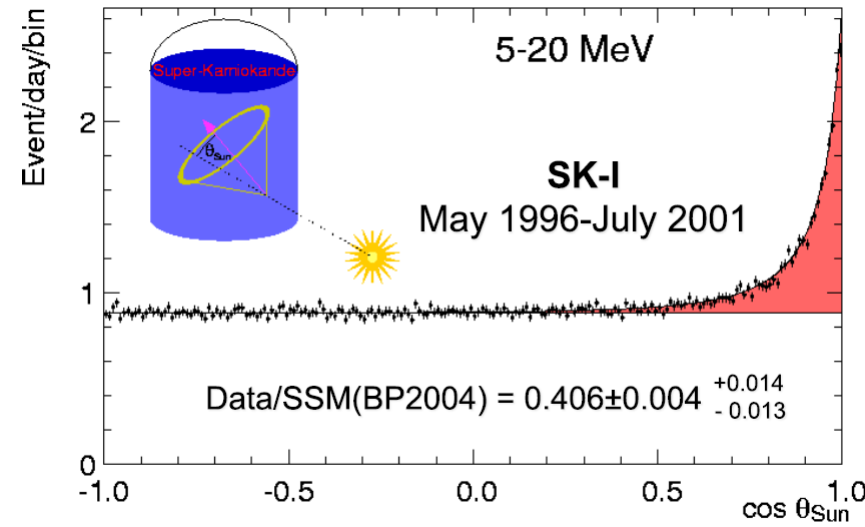
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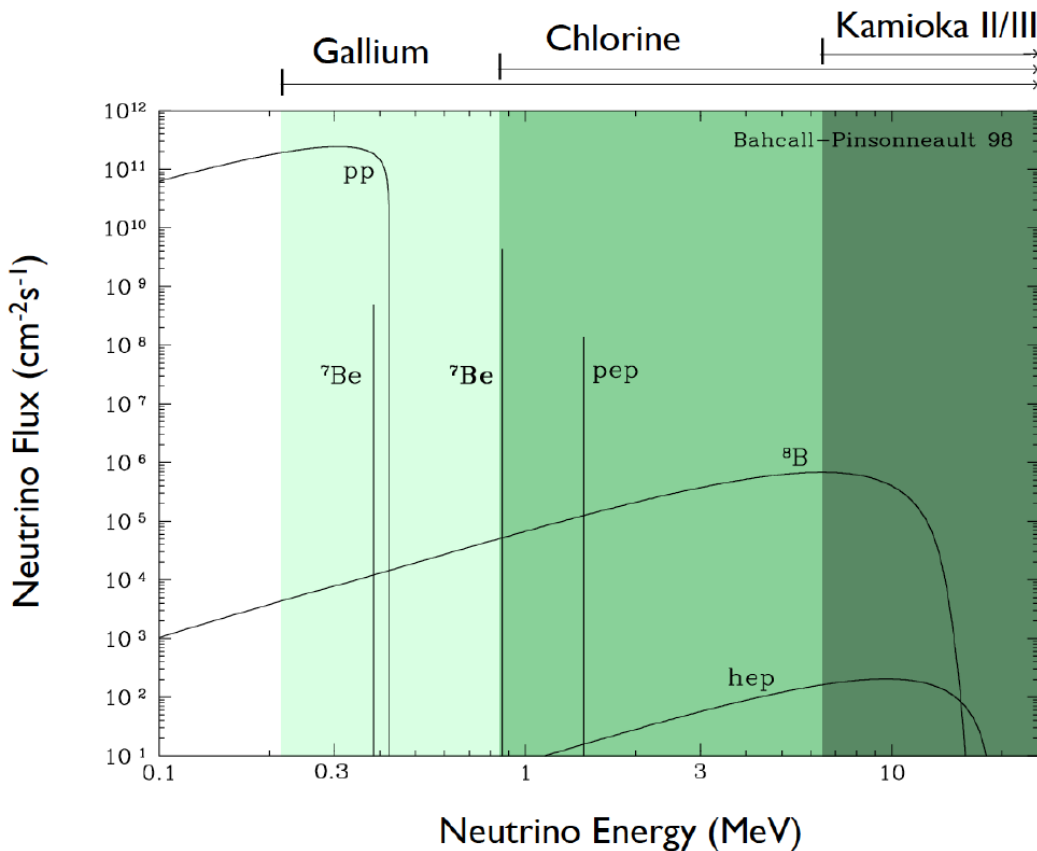
Experiment type	Observed/Expected
Chlorine	~30%
Gallium	~60%
KamiokaNDE	~40%

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

These experiments only sensitive to v_e try and detect v_μ and v_τ too! → SNO

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Sudbury Neutrino Observatory (SNO)

- 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)

- So-called Water Cerenkov detector

Particles faster than speed of light in medium

radiate light (e.g. blueish light in nuclear reactors)

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

$$w = V_w \cdot t$$

$$d = V_p \cdot t$$

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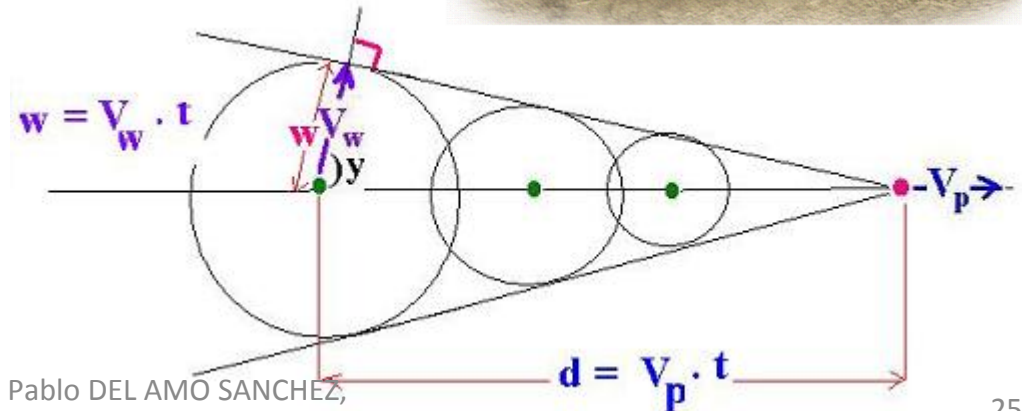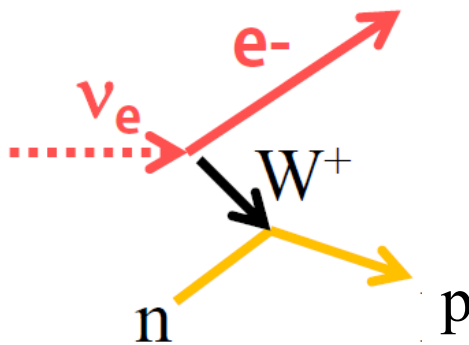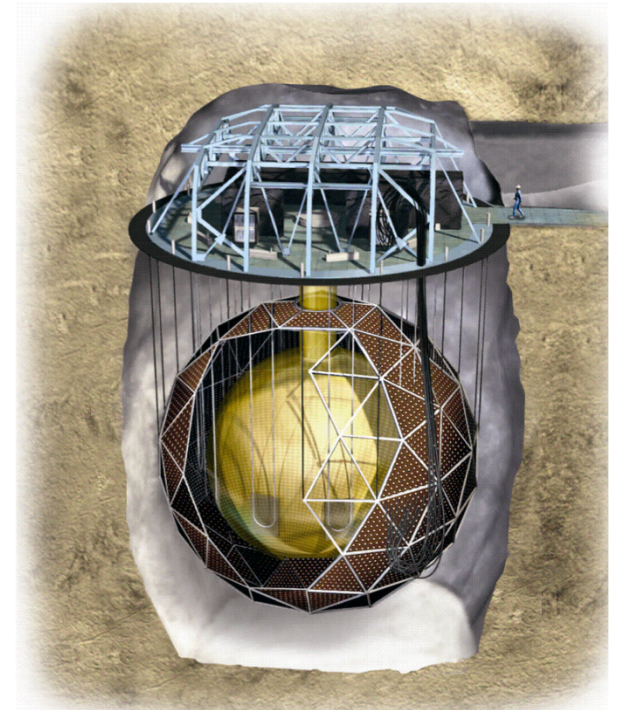
SNO

- 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.
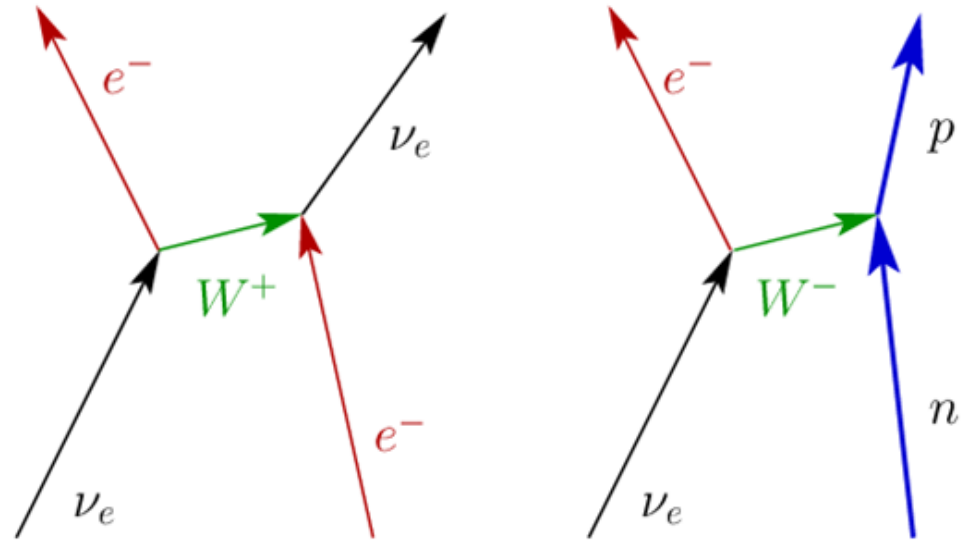
Charged current

- 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

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SNO

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

$$\text{NC} : \nu_x + d \rightarrow n + p + \nu_x$$
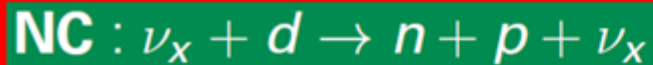
Measures total ^{8}B flux from the Sun.

Equal cross-section to all (active) neutrino flavours.

Signature event of SNO

3 neutron detection methods:

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

ν

e^-

Z^0

ν

e^-

Neutral current

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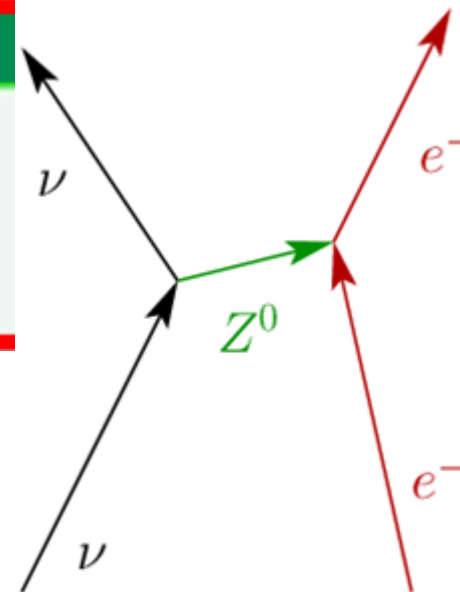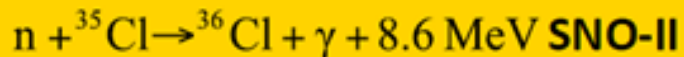
Solar neutrinos oscillate!

Less ν_e than predicted but total $\nu_e + \nu_\mu + \nu_\tau$ correct!
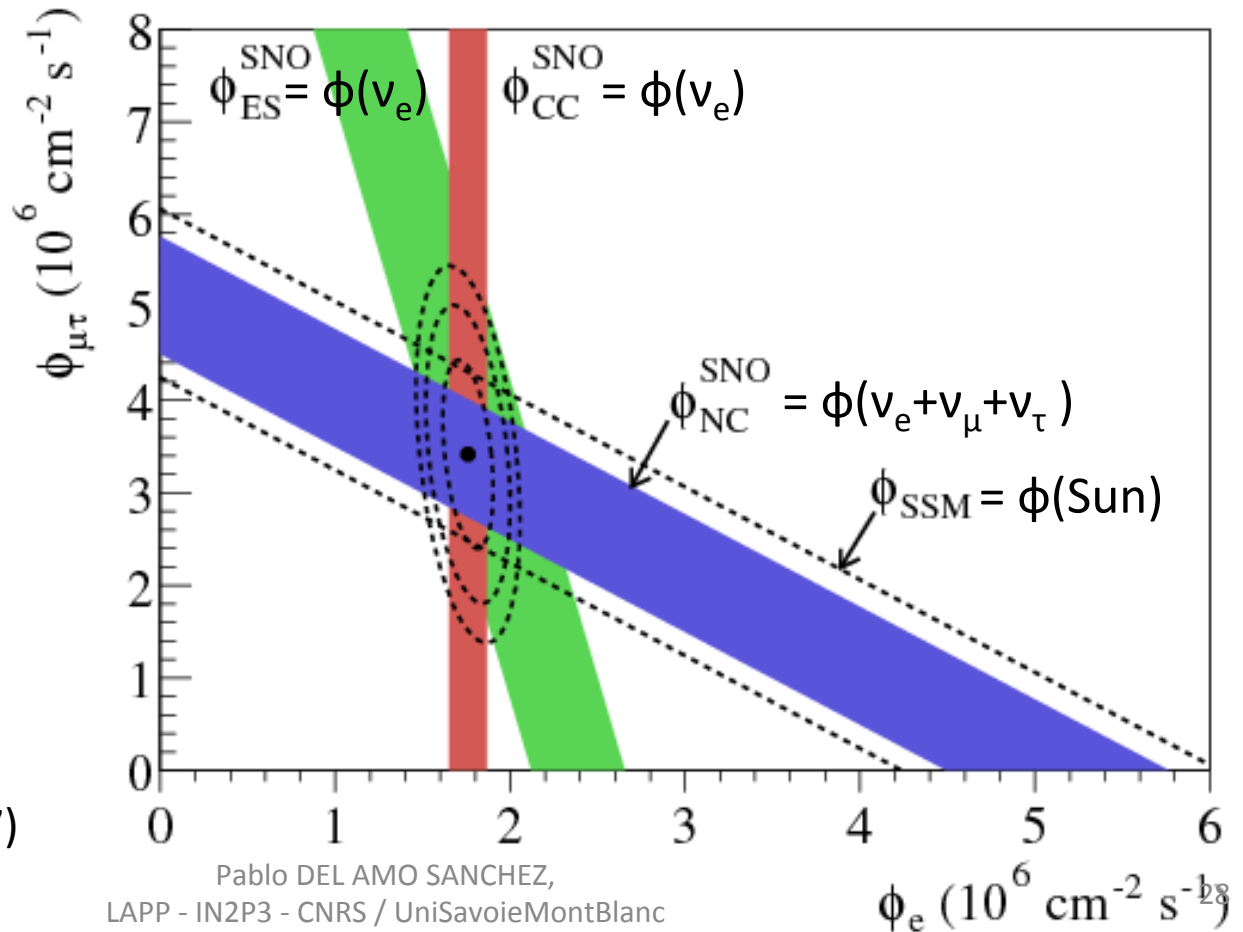
Bruno Pontecorvo (1957)

$\phi_{ES}^{SNO} = \phi(\nu_e)$ $\phi_{CC}^{SNO} = \phi(\nu_e)$

$\phi_{NC}^{SNO} = \phi(\nu_e + \nu_\mu + \nu_\tau)$

$\phi_{SSM} = \phi(Sun)$

$\phi_{\mu\tau}$ (10^6 cm^{-2} s^{-1})

ϕ_e (10^6 cm^{-2} s^{-1})

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Matter effects are important!

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

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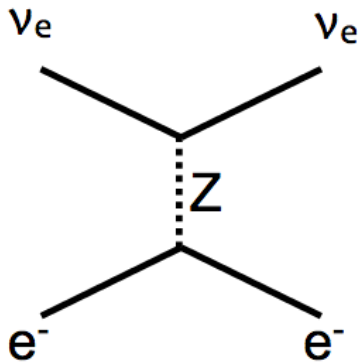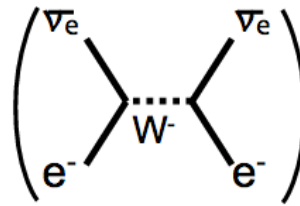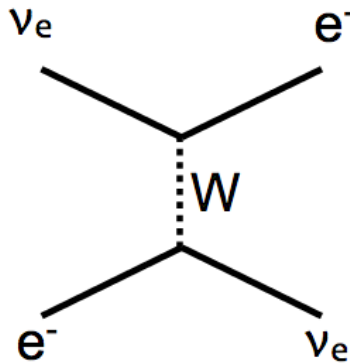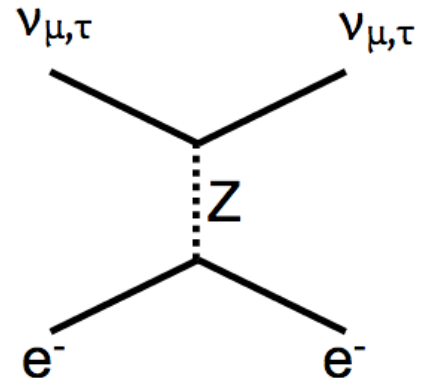
Matter effects are important!

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

Electron Density

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

Oscillations in vacuum
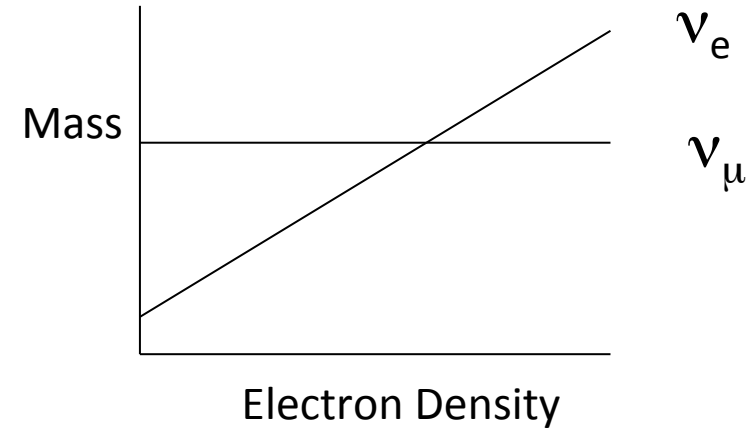
Oscillations +matter effects
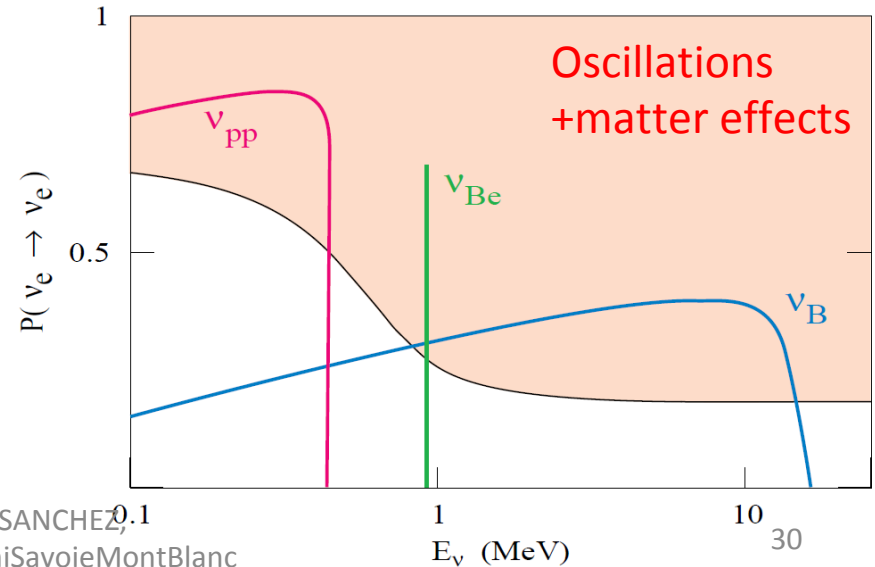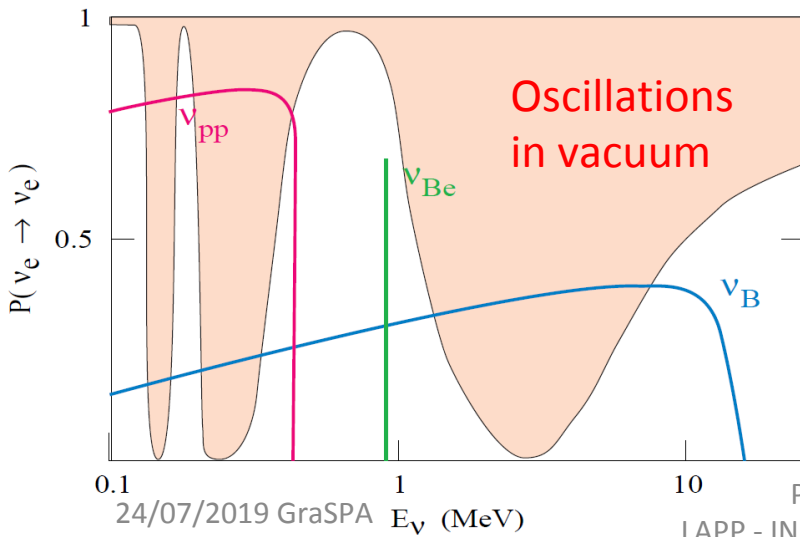
Matter effects are important!

- Found oscillation parameters for solar neutrinos:

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

$\sin^2(2\theta) = 0.857 \pm 0.024$ $\Delta m^2 = (7.5 \pm 0.20) \times 10^{-5} eV^2$

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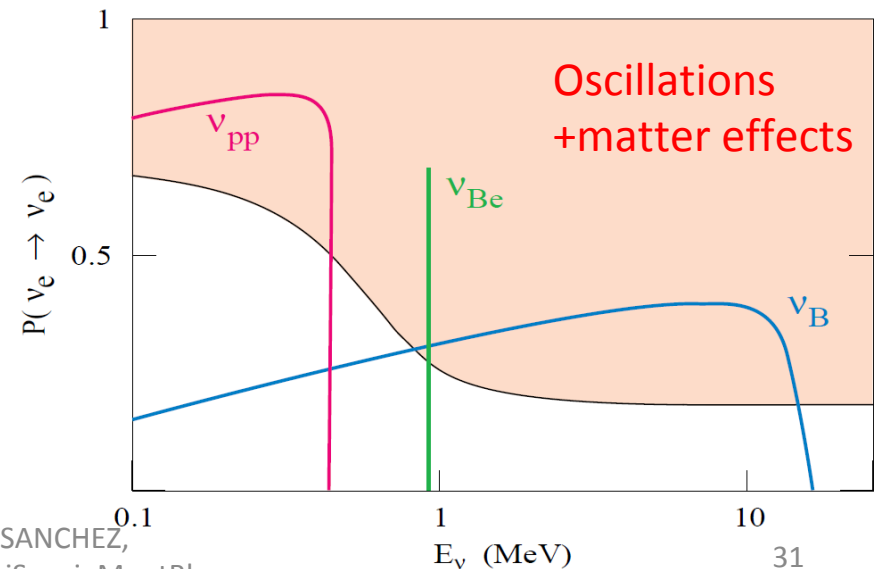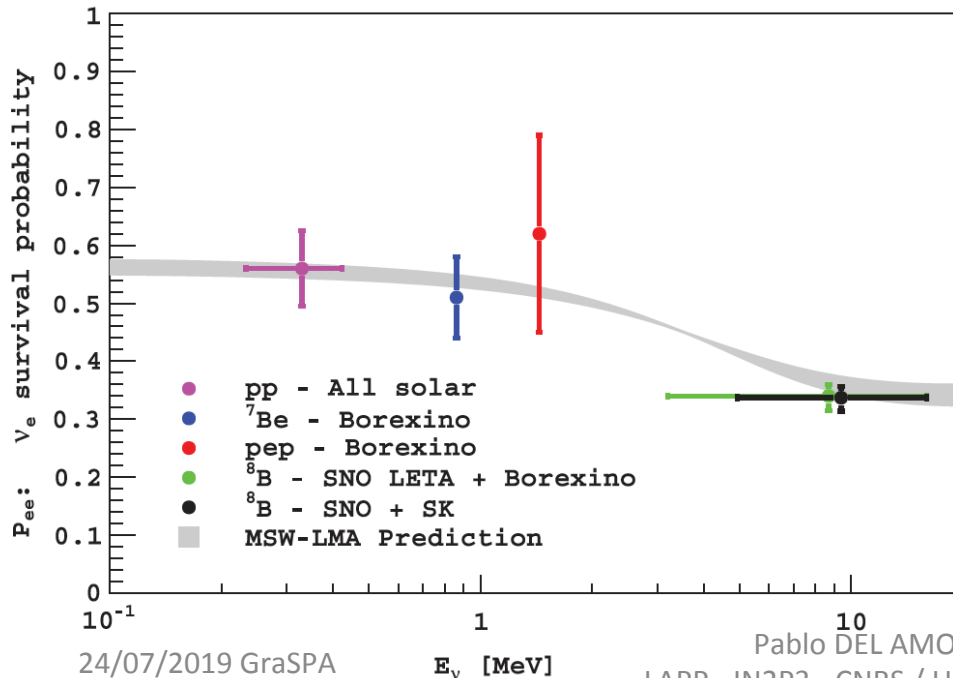
The trilogy:

reactor neutrino experiments

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ν from nuclear reactors

Fission of heavy nucleus

Neutron → ^{235}U → Excited nucleus → Fission products / Neutron

Legend:
- Neutron
- Electron
- Anti-neutrino
- Gamma

Chain Reaction

© F. Durillon, animéa
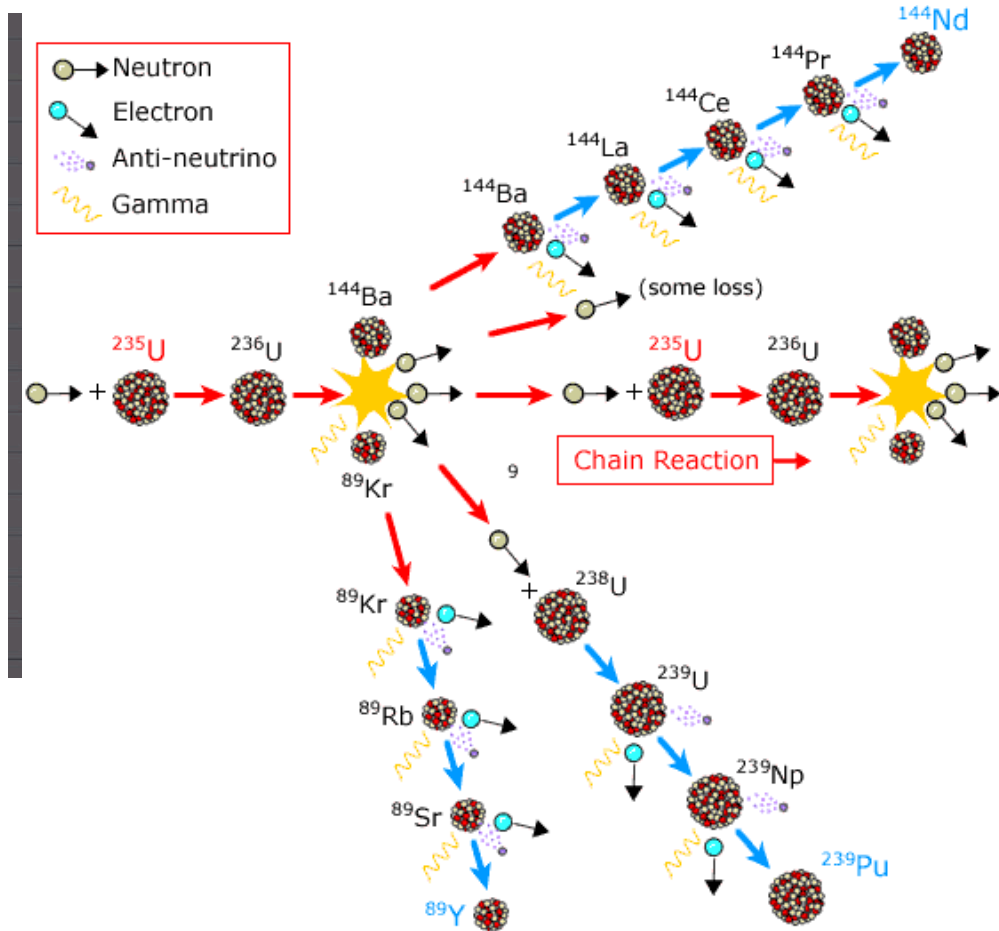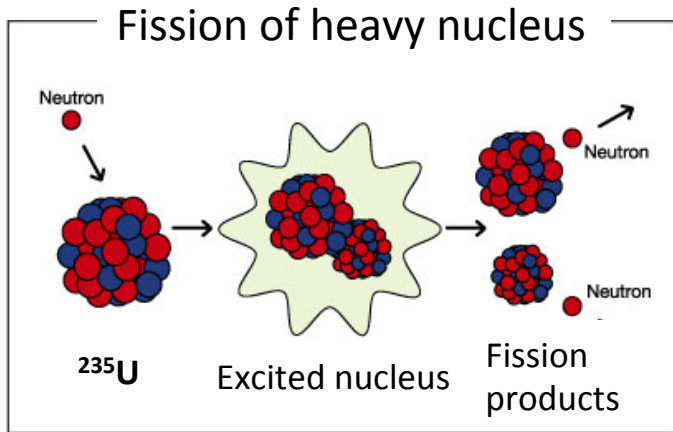
- Fission products are neutron rich and undergo beta decay: $n \rightarrow p\ e^- \ \overline{\nu}_e$
- On average, 6 $\overline{\nu}_e$ and 200 MeV per fission: $2 \times 10^{20}\ \overline{\nu}_e\ s^{-1}\ GW_{th}^{-1}$

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Reactor neutrinos

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

Fission products are neutron rich

Too many neutrons to be stable

$\rightarrow$ plenty of beta decays!

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

  ~ 200 MeV/fission

  ## 2 x 10^{20} $\overline{\nu}_e$ /GW$_{thermal}$
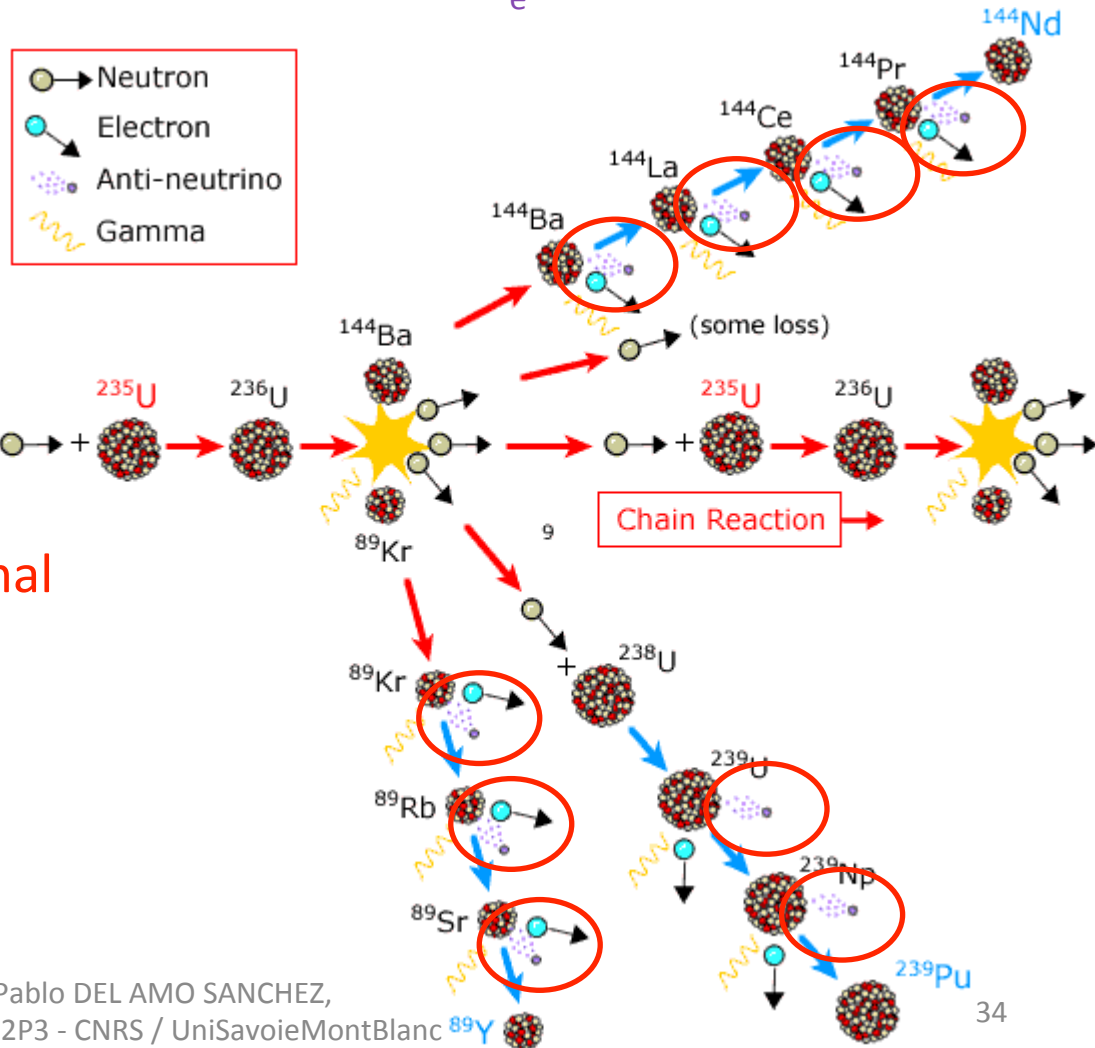
Liquid scintillator detectors

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

$$\overline{\nu}_e \qquad e^+$$
$$W^+$$
$$p \qquad n$$
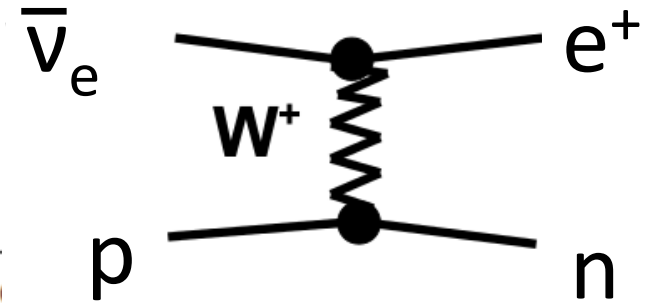
Exponential decrease of emitted spectrum

β−inverse detection process

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

Emitted spe

Cross-section

Detected spectrum

(arbitrary units)
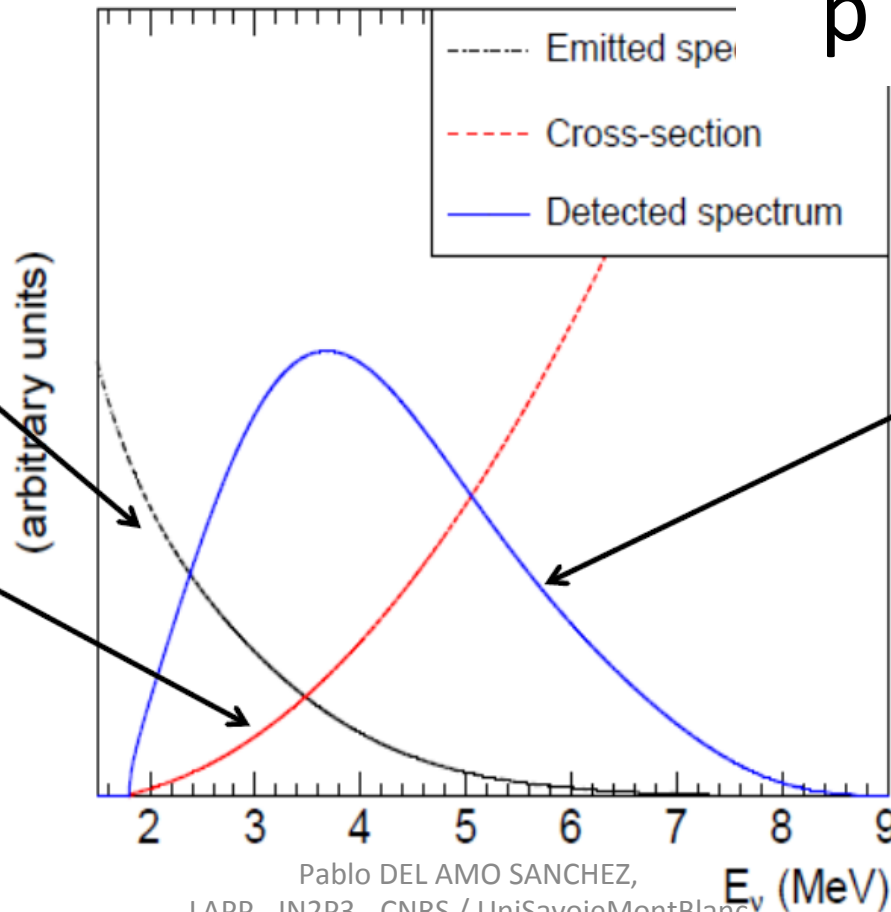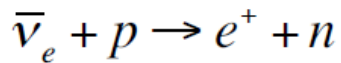
Detected Spectrum

Relevant E range
[1.8 − 8] MeV

E_ν (MeV)

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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 neutrino geo neutrino

$\bar{\nu}_e$ p e+ prompt

γ γ delayed

mean capture time ~ 200 μsec on proton n γ

Crane

Rock lining

Outer water tank

Inner tank

Liq.-scinti. Container

Aluminum sheets

Phototubes

Calibration device

Buffer oil

Liquid scintillator

13 m

18

Reactor neutrinos oscillate!

- Confirm solar neutrino oscillations

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Reactor neutrinos oscillate!

- Confirm solar neutrino oscillations

Pablo DEL AMO SANCHEZ,
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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 $\theta_{32} = 45° \pm 6°$

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

MASS

ν_3

θ_{32}

θ_{21} θ_{32}

ν_2

ν_1

$\Delta m^2_{32} \sim \Delta m^2_{31}$

Δm^2_{21}

ν_e

ν_μ ν_τ

Convention: ν_1 is state with most ν_e

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What have we learnt so far?

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

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

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

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

1-3 mixing

ν_3

θ_{32}

MASS

θ_{21} θ_{32}

ν_2

ν_1

$\Delta m^2_{32} \sim \Delta m^2_{31}$

Δm^2_{21}

ν_e

ν_μ ν_τ

Convention: ν_1 is state with most ν_e

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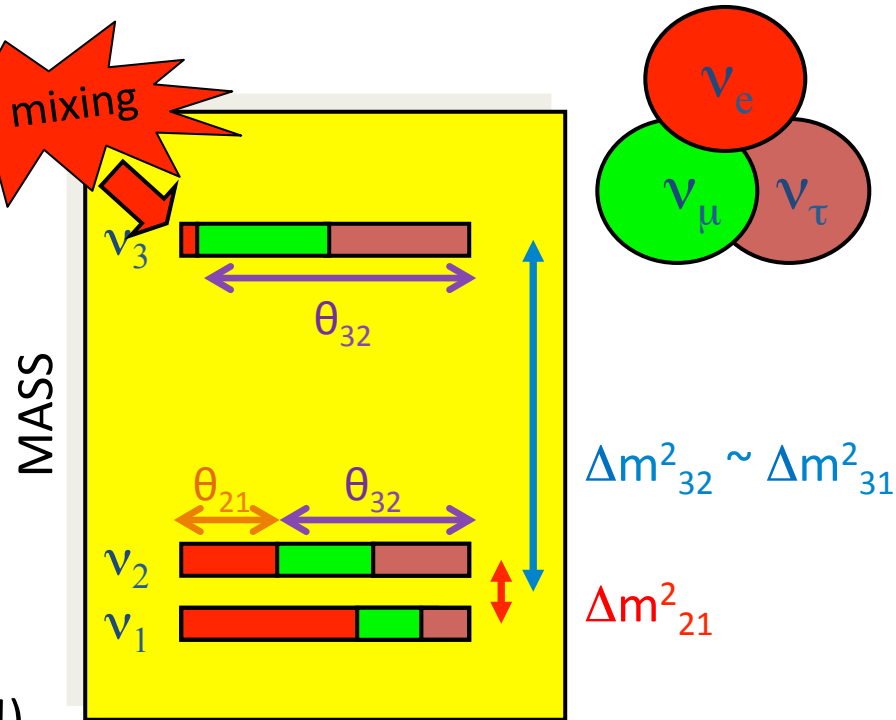
Amount of ν_e in faster oscillations (θ_{13})
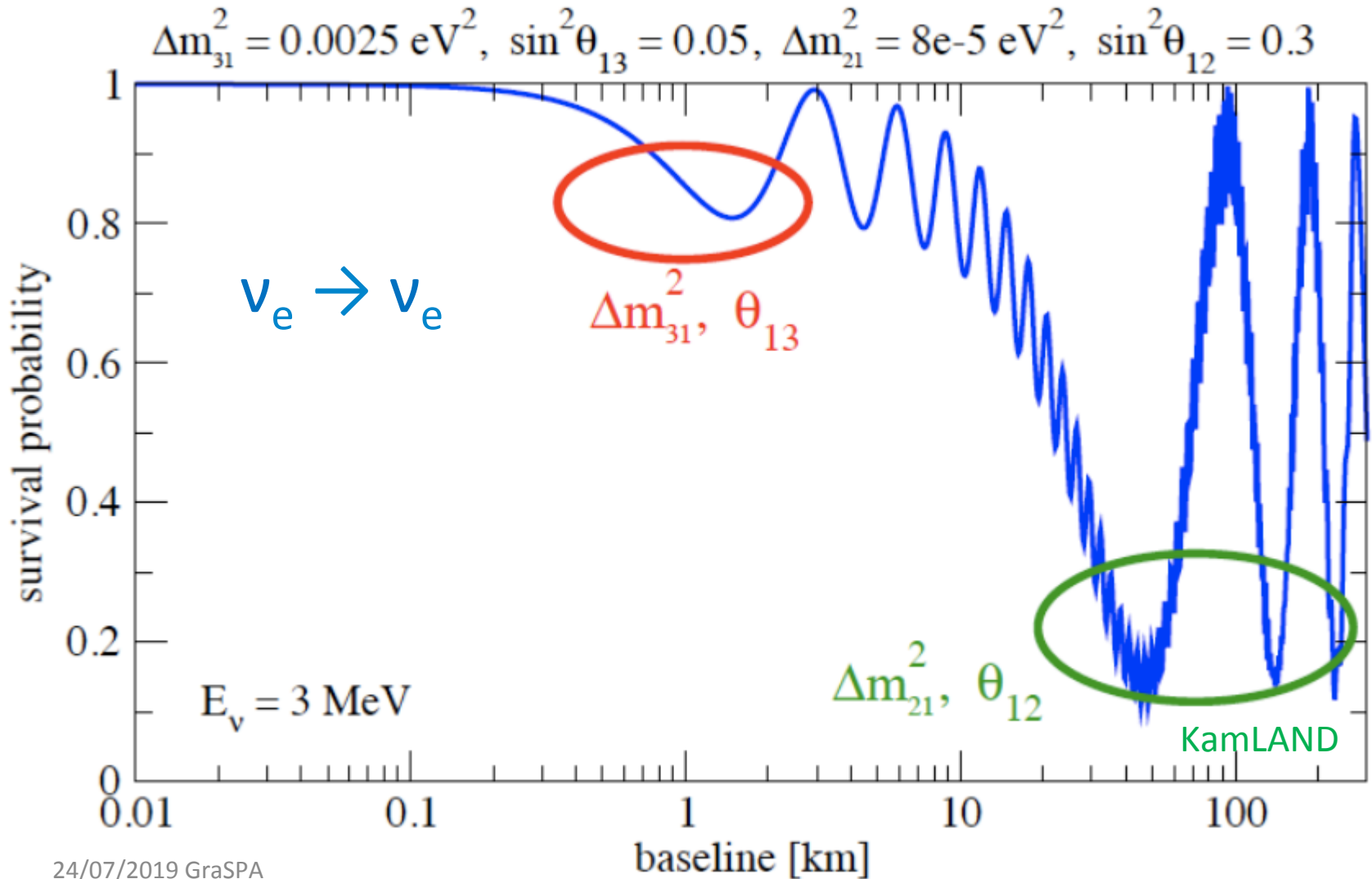
$\Delta m^2_{31} = 0.0025 \text{ eV}^2, \quad \sin^2\theta_{13} = 0.05, \quad \Delta m^2_{21} = 8\text{e-}5 \text{ eV}^2, \quad \sin^2\theta_{12} = 0.3$

$\nu_e \rightarrow \nu_e$

$\Delta m^2_{31}, \quad \theta_{13}$

$\Delta m^2_{21}, \quad \theta_{12}$

KamLAND

$E_\nu = 3 \text{ MeV}$

survival probability

baseline [km]

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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
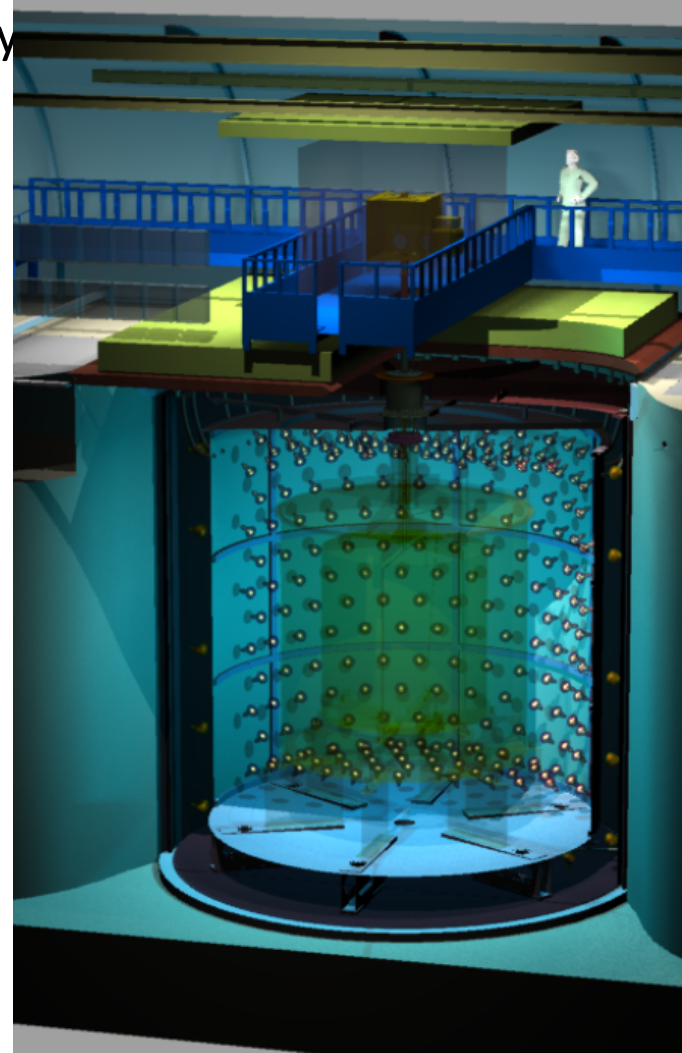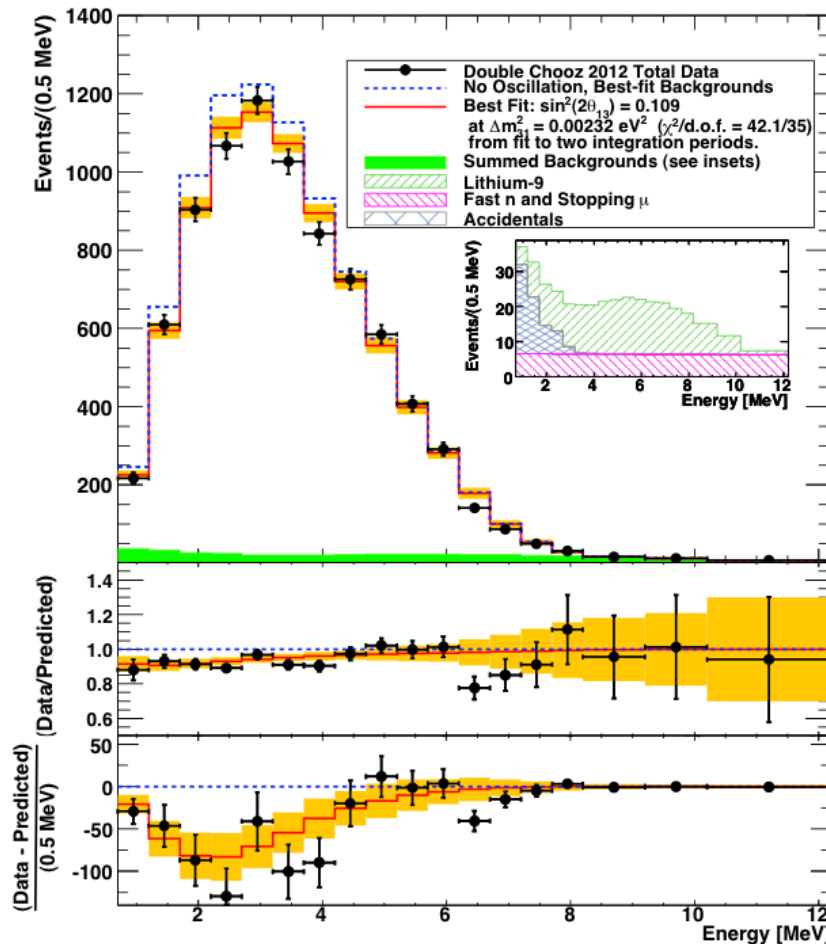
The plot legend reads:
- Double Chooz 2012 Total Data
- No Oscillation, Best-fit Backgrounds
- Best Fit: $\sin^2(2\theta_{13}) = 0.109$ at $\Delta m^2_{31} = 0.00232$ eV^2 (χ^2/d.o.f. = 42.1/35) from fit to two integration periods.
- Summed Backgrounds (see insets)
- Lithium-9
- Fast n and Stopping μ
- Accidentals

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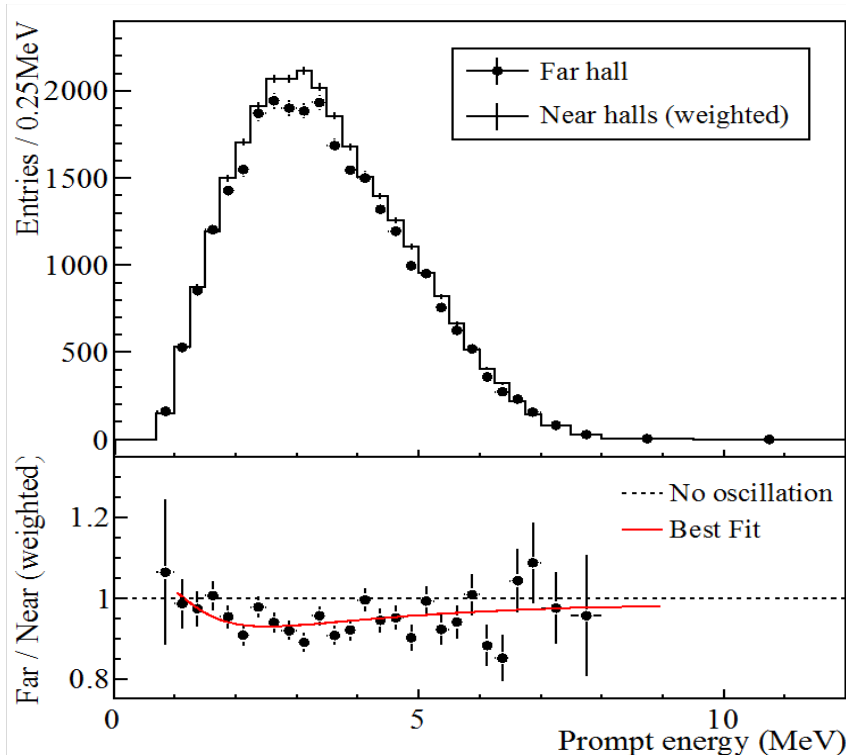
$$\sin^2(2\theta_{13}) = 0.089 \pm 0.012$$
$$\theta_{13} = 9.1° \pm 0.6° \quad (\approx \theta_{Cabbibo}!)$$

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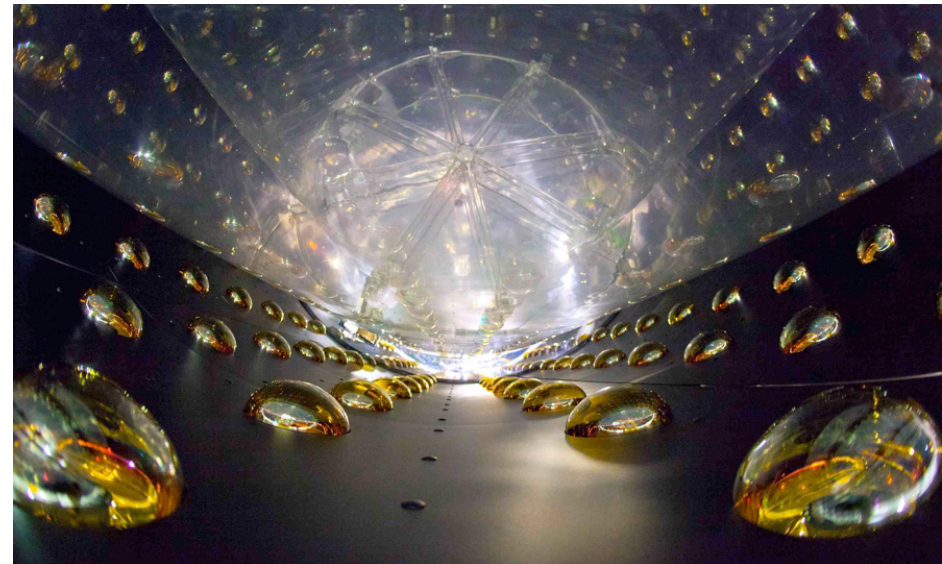
Fourth parts couldn't be better: accelerator neutrinos

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Accelerator experiments

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

other neutrino sources:

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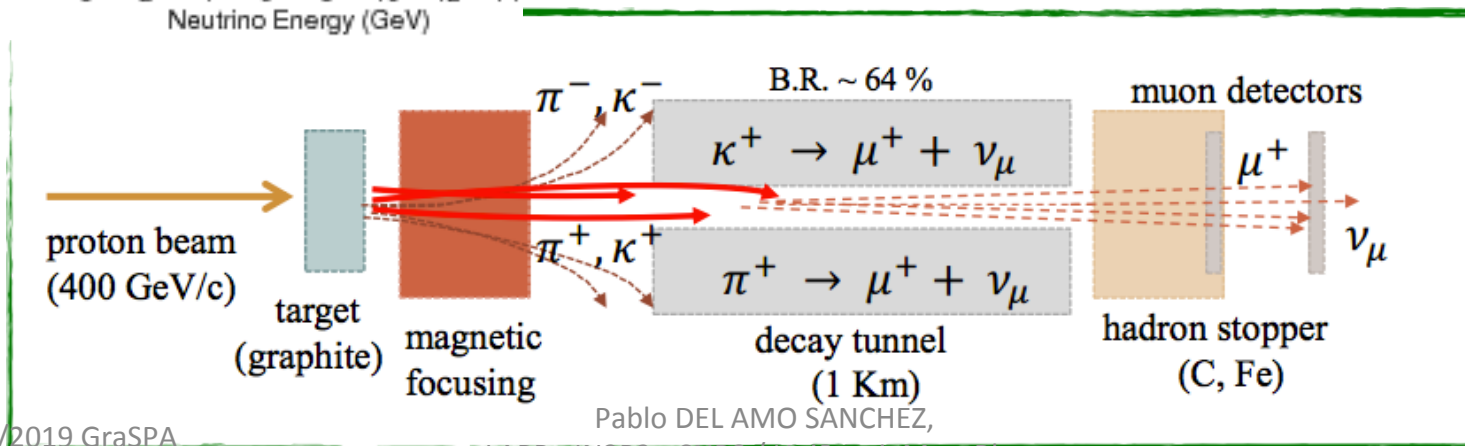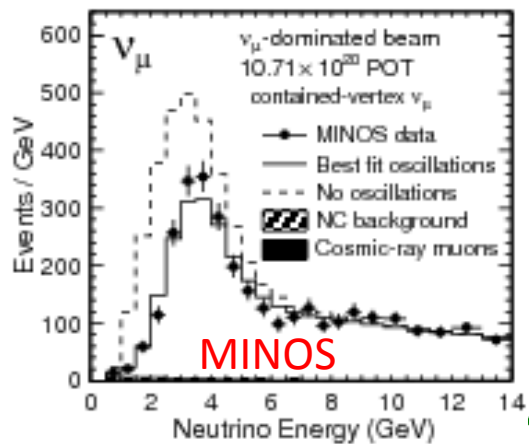
$\nu_\mu \rightarrow \nu_\tau$ appearance

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

OPERA

L = 730 km

T_{flight} = 2.44 ms

CERN

LNGS

B.R. ~ 64 %

muon detectors

$\kappa^+ \rightarrow \mu^+ + \nu_\mu$

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

proton beam
(400 GeV/c)

target
(graphite)

magnetic
focusing

decay tunnel
(1 Km)

hadron stopper
(C, Fe)

μ^+

ν_μ
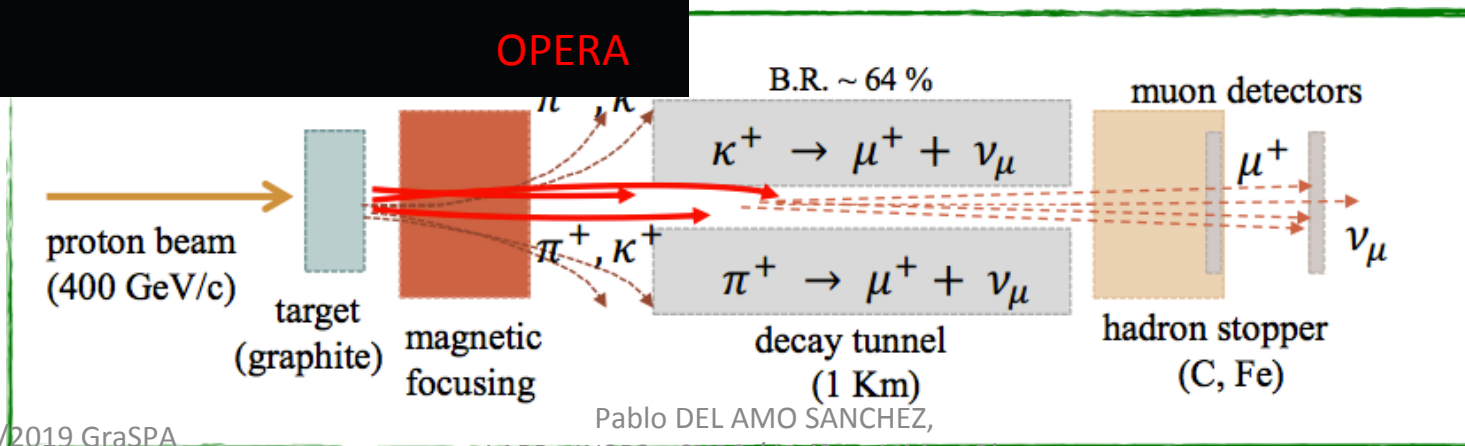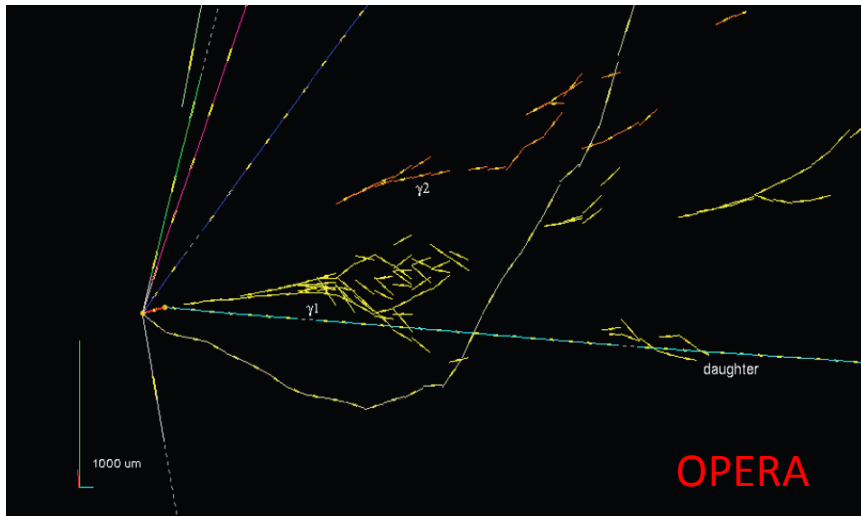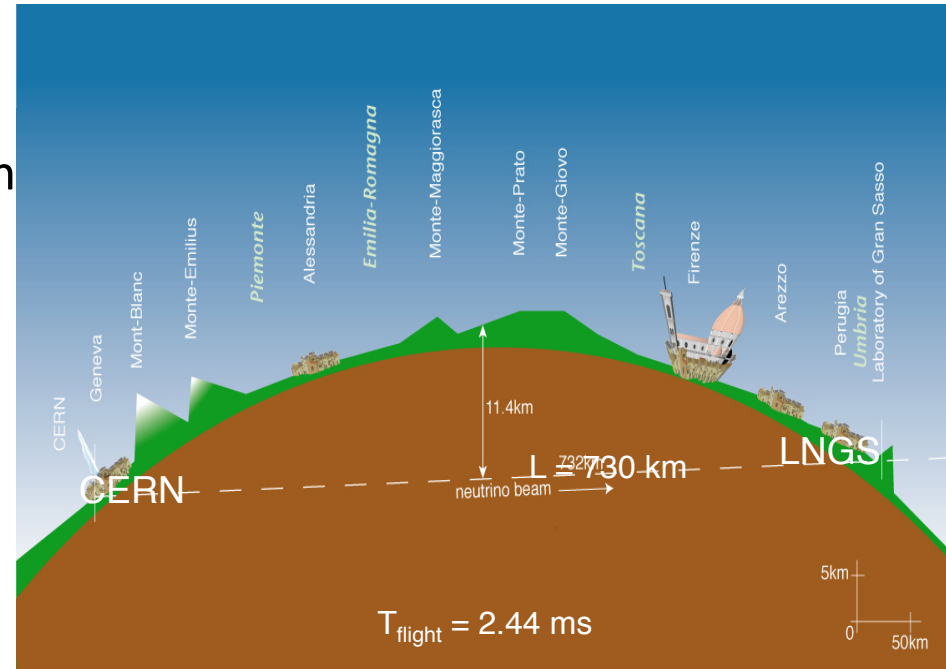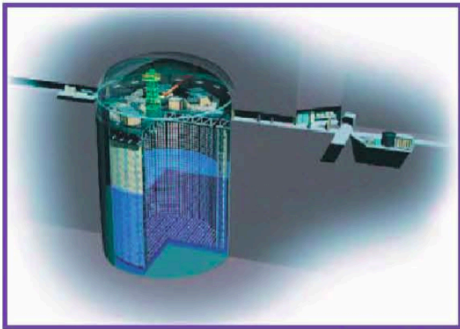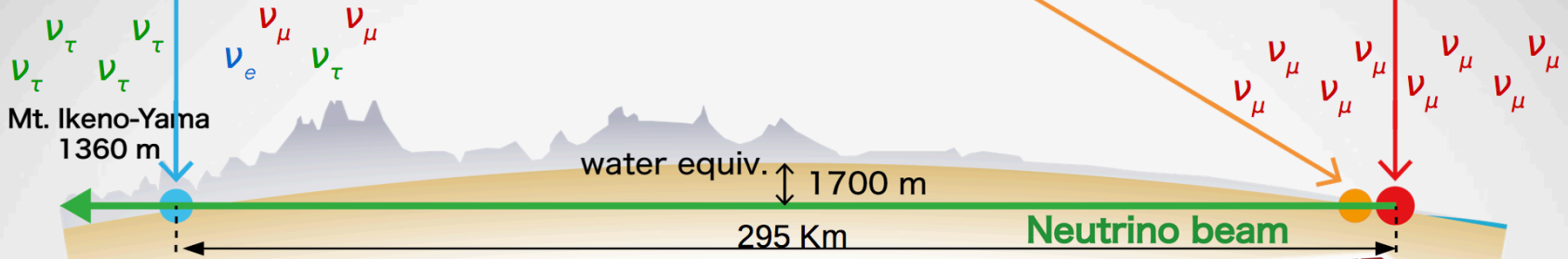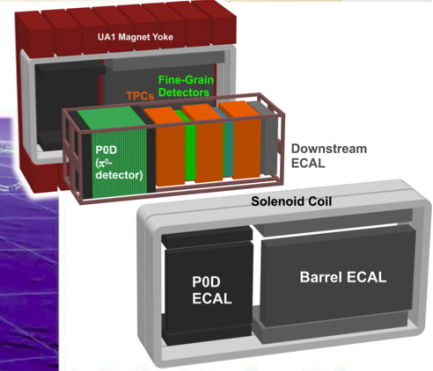
Recent results: T2K

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

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

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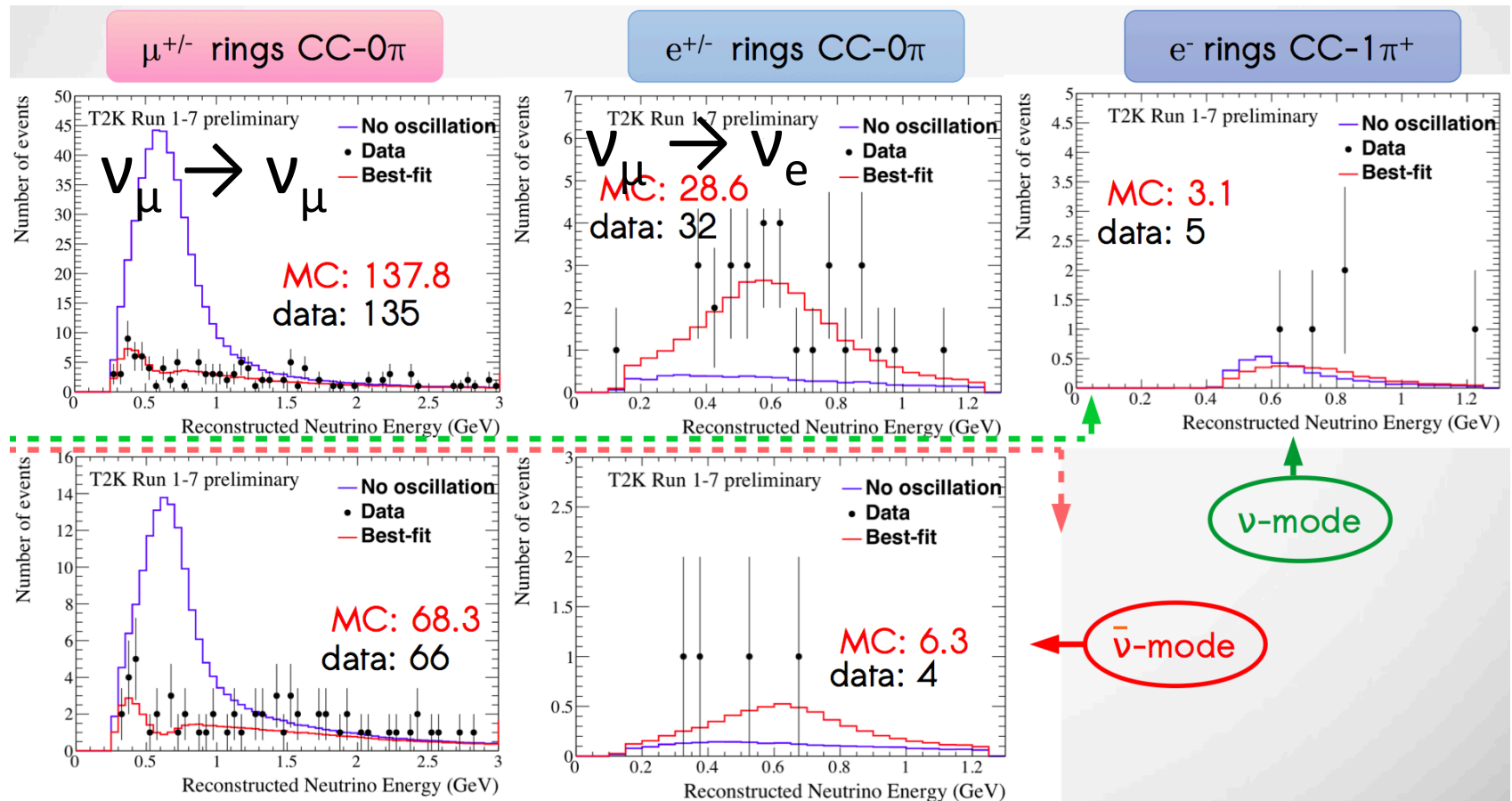
Neutrino mixing matrix

3 angles and 1 CP phase: θ_{12}, θ_{13}, θ_{23}, δ + 2 phases

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

atmospheric ν   Reactor   solar ν

Dirac

Majorana

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

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

δ, matter-antimatter asymmetry in neutrinos?

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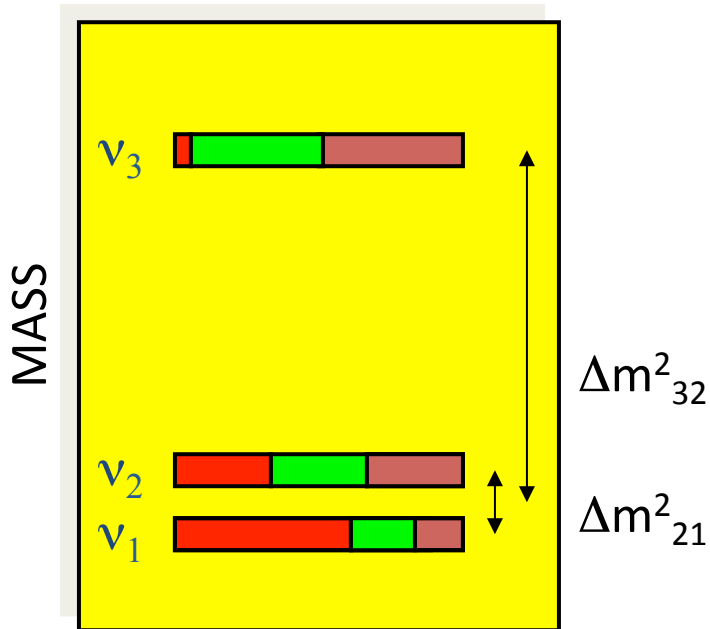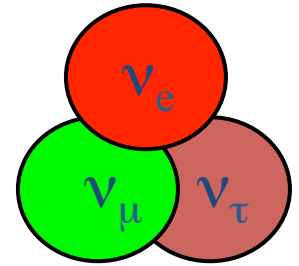
Mass ordering?

Normal mass ordering
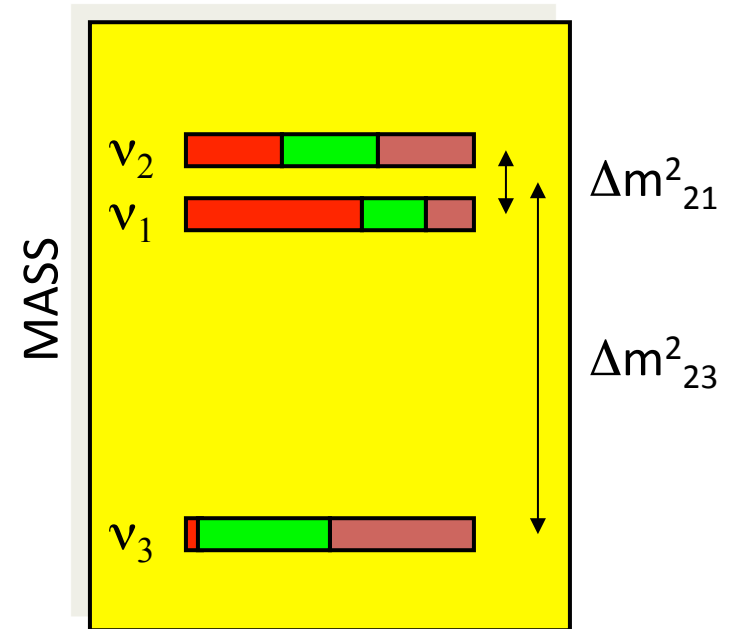
Inverted mass ordering

Which mass state is the lightest?

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Future long baseline projects...

DUNE

40 kton Lq. Ar TPC
Starting around 2026
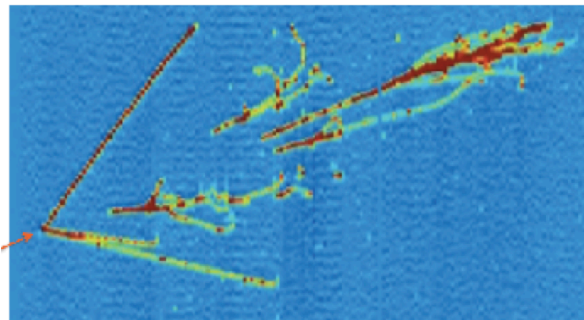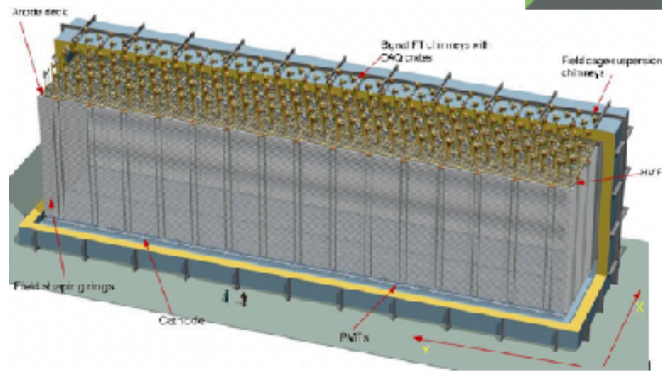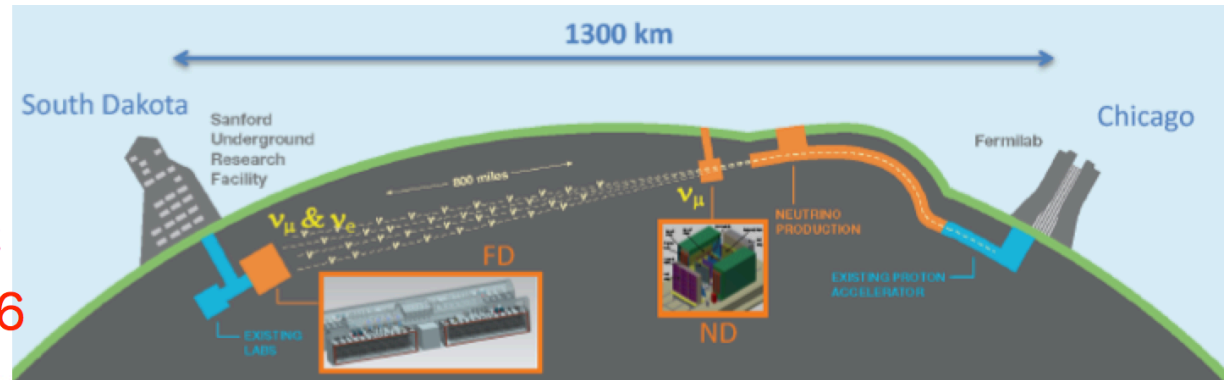
Sensitivity

Mass Hierarchy

CP Violation

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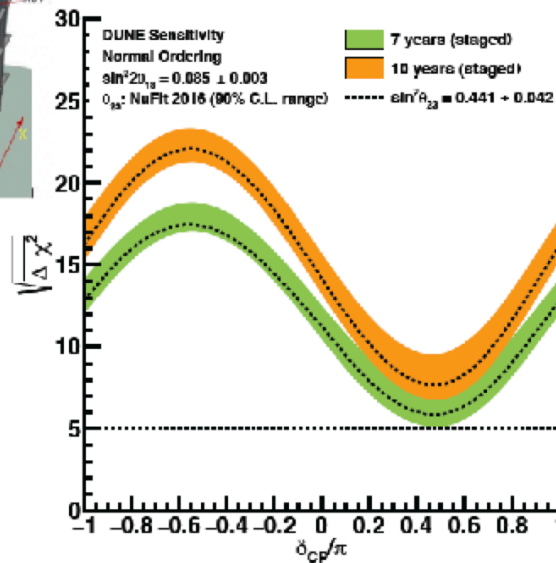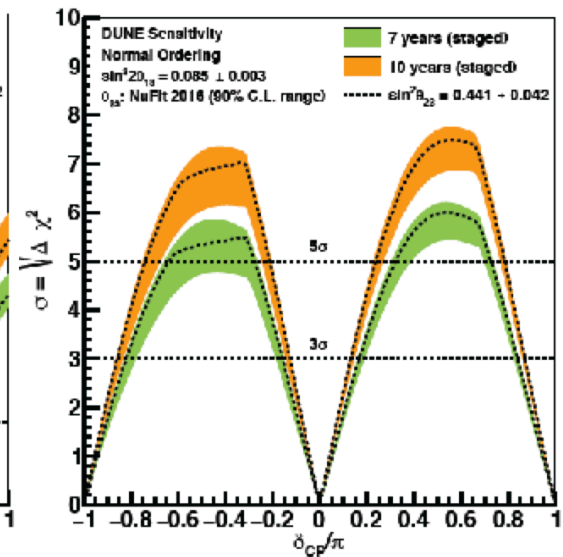
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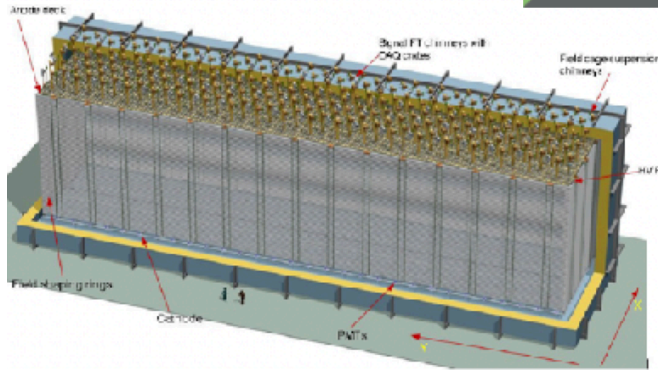
Broad physics programme!

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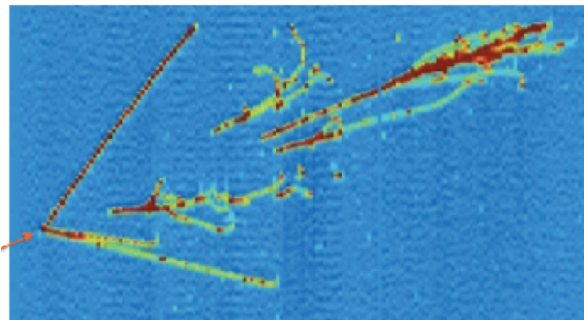
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Conclusions

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

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

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Conclusions

- Neutrinos oscillate! Masses $\neq$ 0   (2015 Nobel prize)

  ν_e, ν_μ, ν_τ different from ν_1, ν_2, ν_3
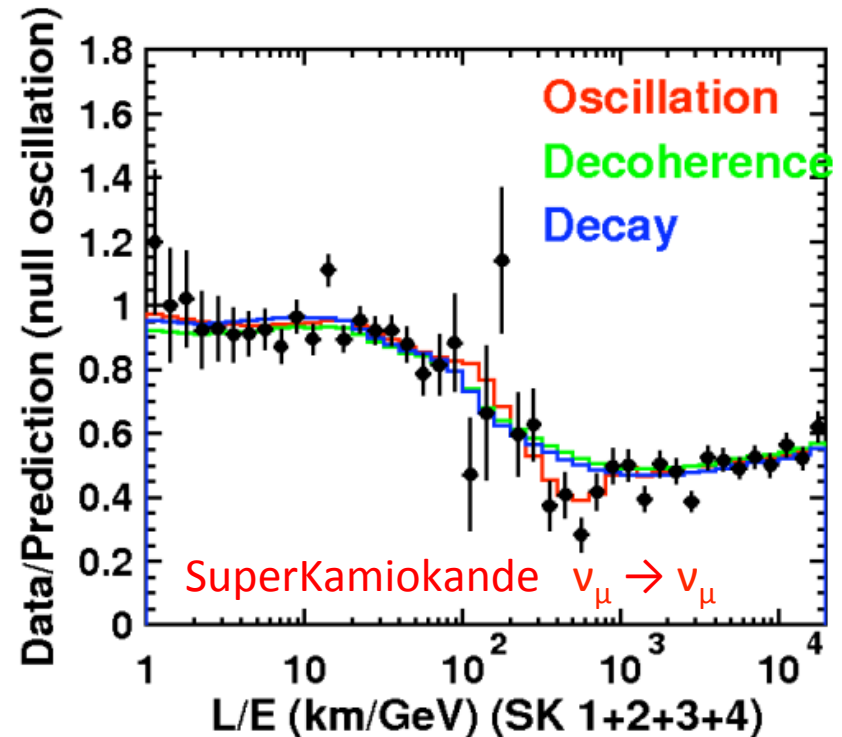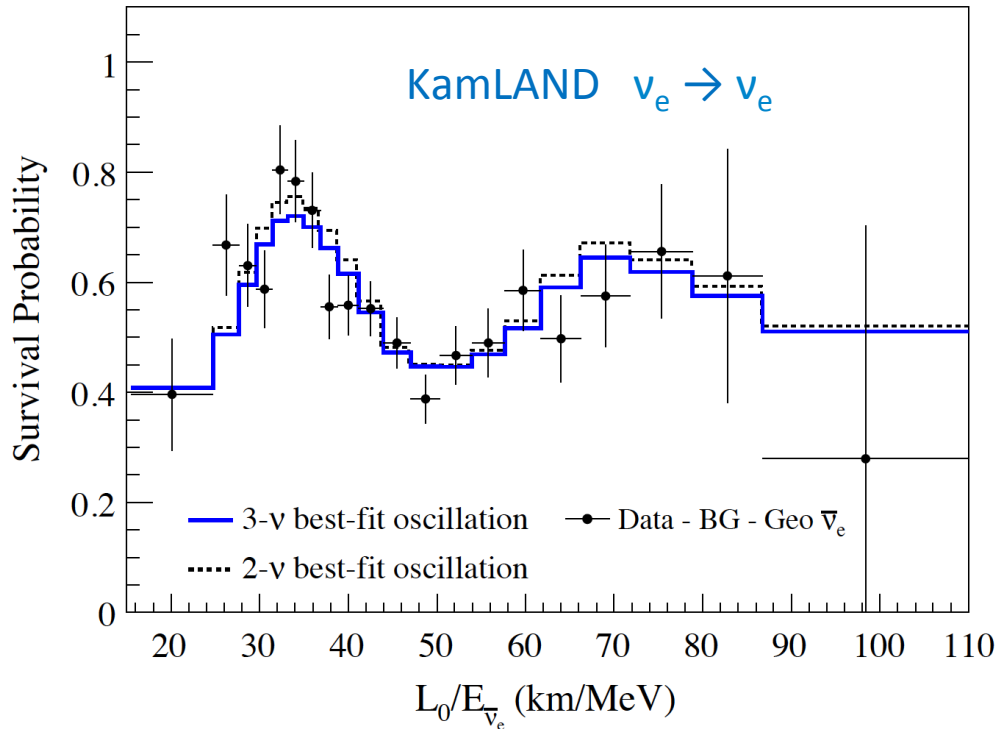
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  fast: atmospheric, $\Delta m^2_{32} \sim \Delta m^2_{31}$

  slow: solar, Δm^2_{21} atm $\sim$ 20 x solar

- Neutrinos mix a lot! (Mixing angles large compared to quarks' mix angles!)

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

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

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

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

                which is the lightest mass state?

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BACK UP SLIDES

How many neutrinos are there?
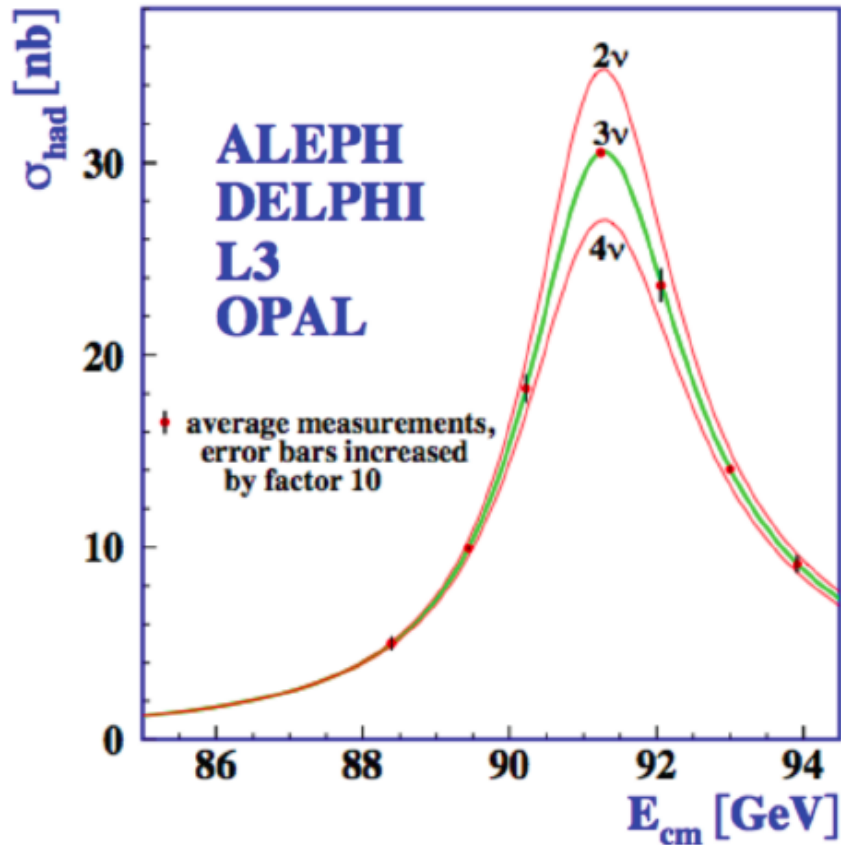
$$\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - 3\Gamma_l$$

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

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)

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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)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$

p.ex.

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

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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)

μ^+

ν_μ

Propagation
États propres de masse
ν_1, ν_2, ν_3

e^-

ν_e

Production
États propres de saveur
ν_e, ν_μ, ν_τ

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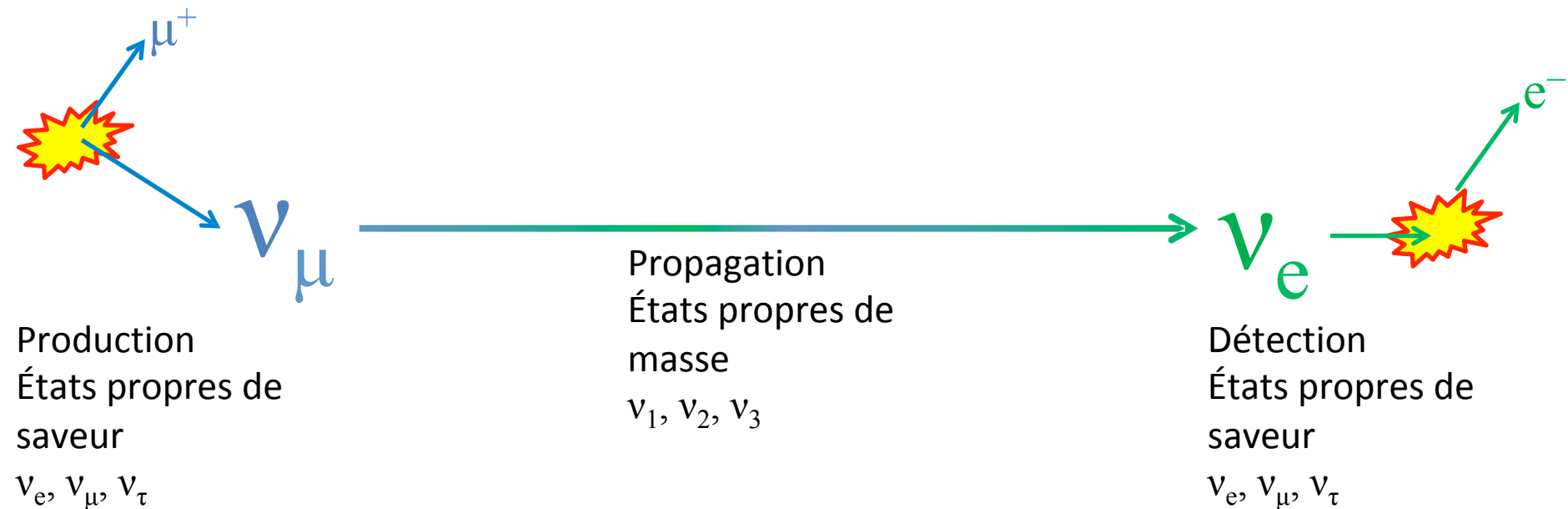
(Analogue aux oscillations des kaons neutres : production et détection en termes des états de saveur K^0 et $\overline{K}^0$, propagation en termes de K_{short} et K_{long})

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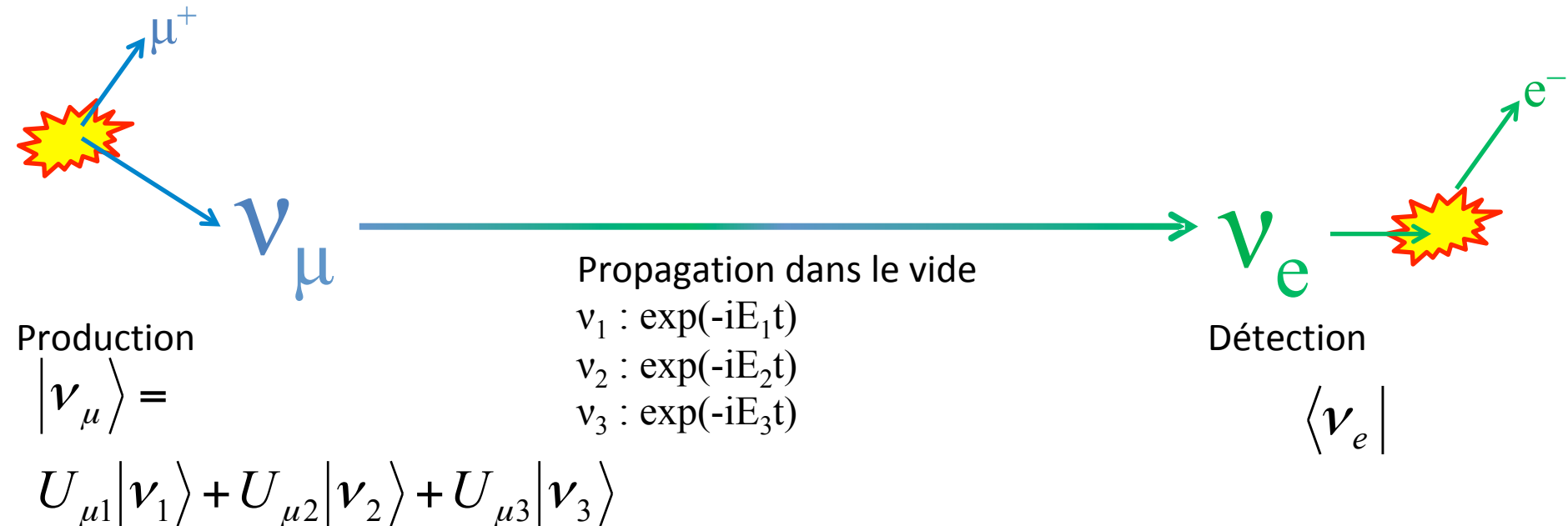
- Neutrinos sont créés dans des états propres de saveur, se propagent comme des états propres de masse, et sont détectés comme des états propres de la saveur : (ex : neutrinos atmosphériques, issus des désintégrations des pions)

μ^+

e^-

ν_μ

ν_e

Propagation dans le vide
$\nu_1 : \exp(-iE_1 t)$
$\nu_2 : \exp(-iE_2 t)$
$\nu_3 : \exp(-iE_3 t)$

Production

$$\left| \nu_\mu \right\rangle =$$

Détection

$$\left\langle \nu_e \right|$$

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

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, μ, τ change avec le temps

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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

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