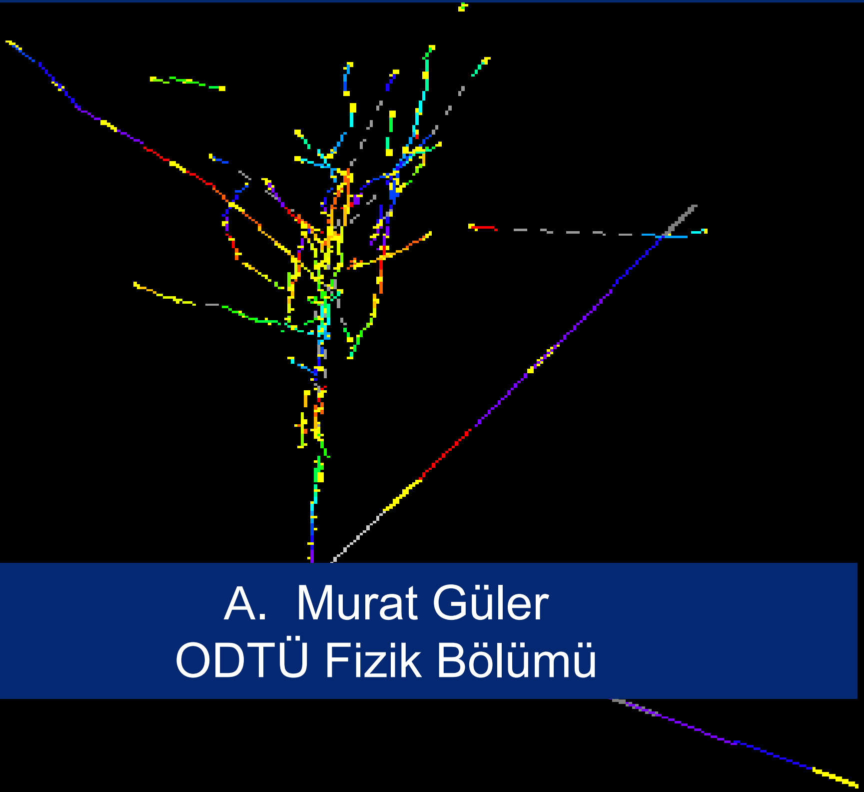
Nötrino Salınımları; Dünü, Bügünü ve Yarını



A. Murat Güler
ODTÜ Fizik Bölümü

Nötrinolar heryerde!!

Ne kadar çok!

Saniyede kaçtane nötrino tırnaklarımızdan geçmekte.

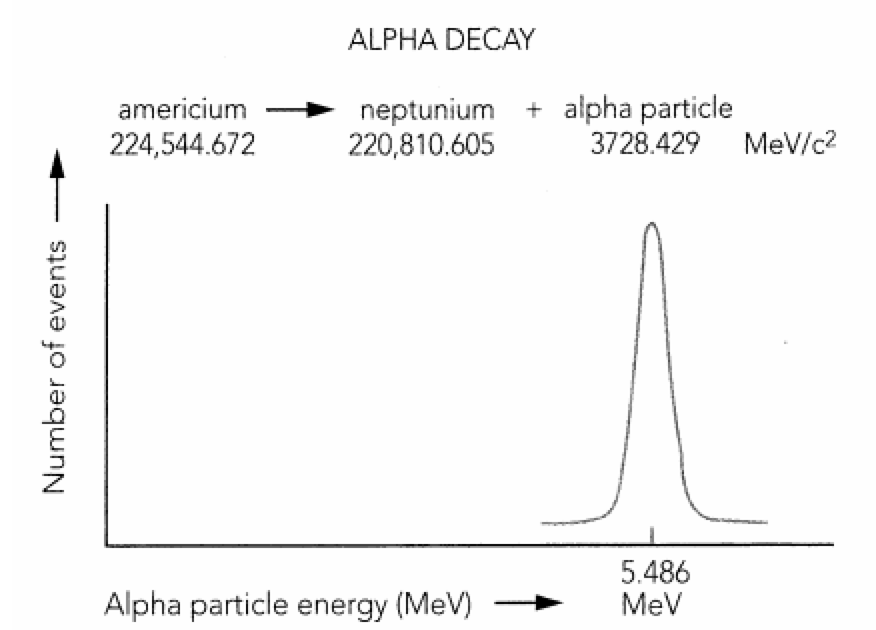
66 milyar nötrino/cm^2.s

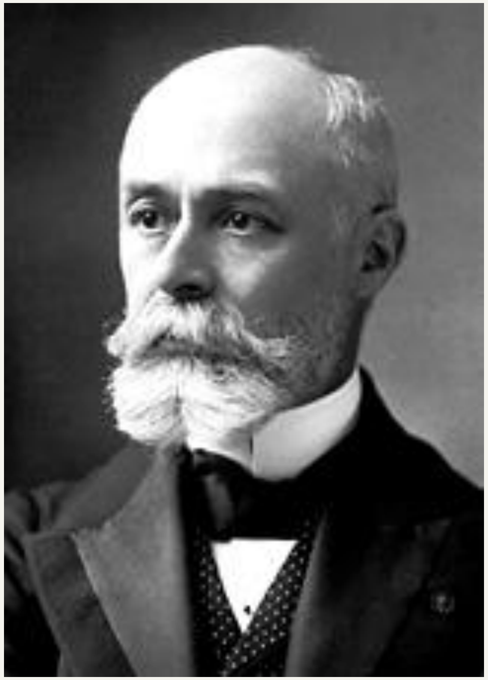
Neden Nötrino çalışmaları Önemli

- What are the neutrino masses?
- What is the pattern for neutrino flavour mixing?
- Is Neutrino a Dirac or a Majorana particle?
- Do neutrinos violate CP?
- Do neutrinos constitute dark matter?
- What can neutrinos and the universe tell us each other?
- Can neutrinos help explain matter-antimatter asymmtery in the universe?
- Do neutrinos travel faster than ligth?

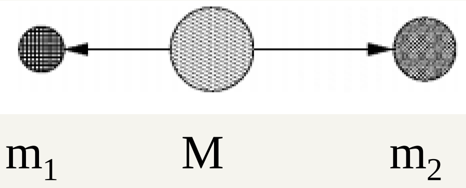
History

Radyoaktivite





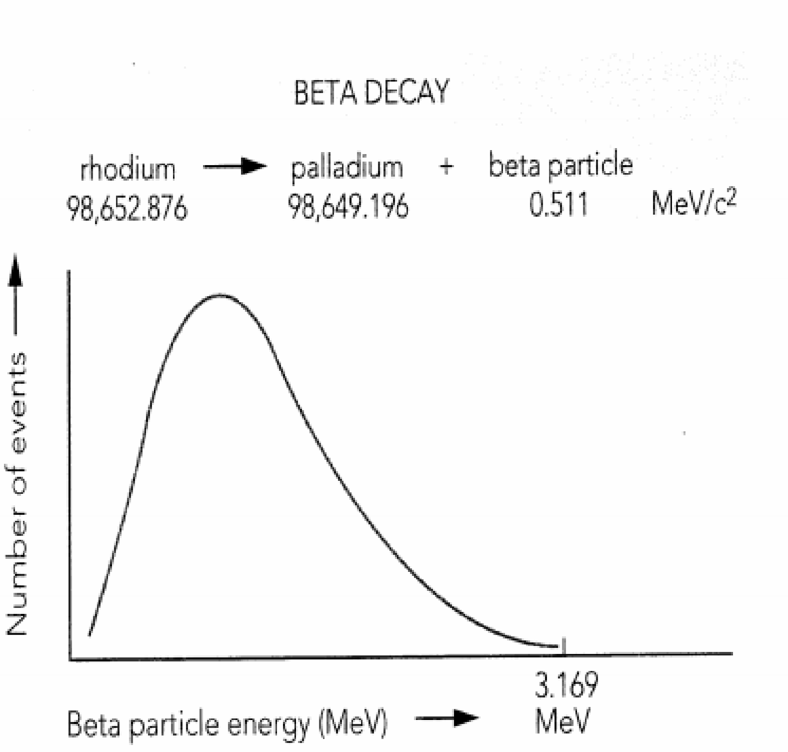
Henri Becquerel
The Nobel Prize in Physics 1903



$$E_2 = \sqrt{m_2^2 + p^2} = \frac{M^2 + m_2^2 - m_1^2}{2M}$$

Beta Bozunması

Otto Hahn and Lise Meitner



β spectrum is continues unlike α and γ (1911).

- ➢Energy is not conserved.
- ➢Momentum is not conserved.

Pauli problemi çözdü !

- I have made a terrible thing proposing a particle that can not be detected....

- This is something do theorist should ever do...

4th of December 1930
Tubingen, Germany

Dear Radioactive Ladies and Gentlemen!

"…..because of the "wrong" statistics of the N and ^{6}Li nuclei and the **continuous** β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of **conservation of energy**. Namely, the possibility that there could exist in the nuclei **electrically neutral particles**, that I wish to call **neutrons**, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The **mass** of the neutrons should be of the same order of magnitude as the electron mass and in any event **not larger than 0.01 proton masses**. -The continuous β-spectrum would then become understandable by the assumption that in β-decay, a neutron is emitted in addition to the electron such that the sum of energies of the neutron and electron is constant. …"

Farklı Fikirler

In 1929
Niels Bohr goes as far as to suggest that energy is not conserved in beta decay.

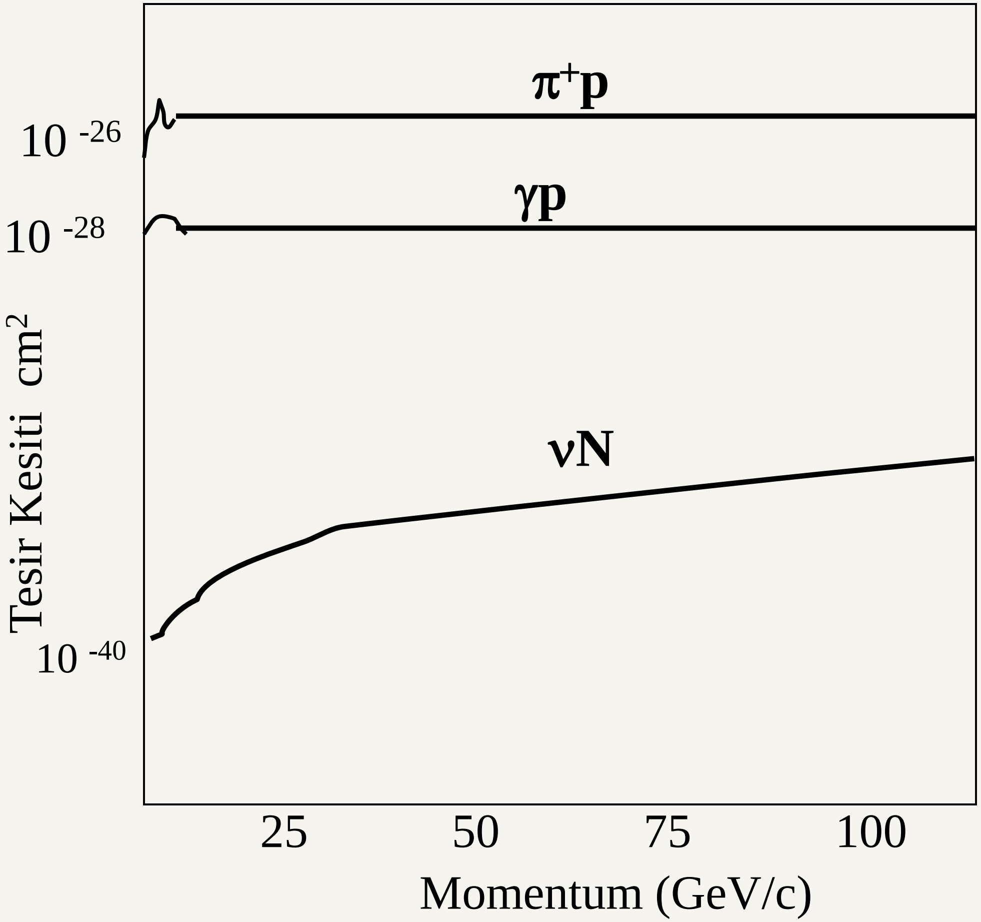
Sir Arthur Eddington:
In an ordinary way I migth say that I do not believe in neutrinos. *Dare I say that experimental physicists will not have sufficient ingenuity to make neutrinos.*

Nötrino çok zayıf etkileşiyor

- Using Fermi's theory, H. Bethe and R. Peierls Calculated the interaction cros-section to be less than 10^{-44} cm^2

- $\sigma \sim 6*10^{-44}$ cm^2 for $E_\nu = 2.5$ MeV *Mean free path (λ)* in (H_20)

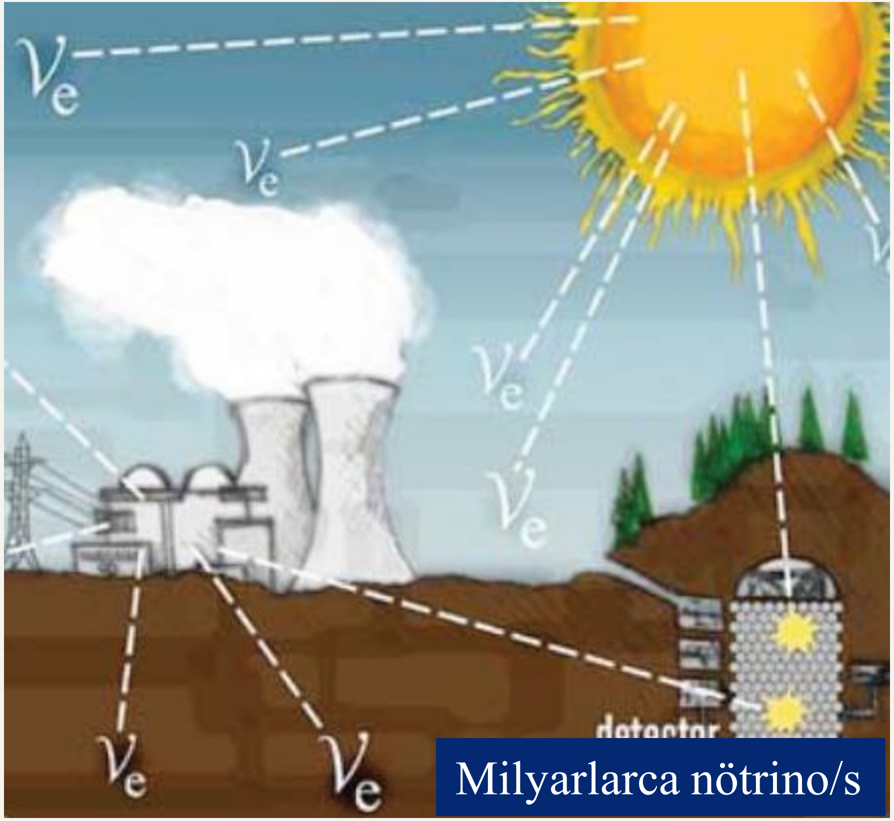
- $\lambda = 1/n\sigma \;\; = 2.5.10^{20}$ cm (n= proton yoğunluğu).



Nötrinoyu nasıl yakalanır?

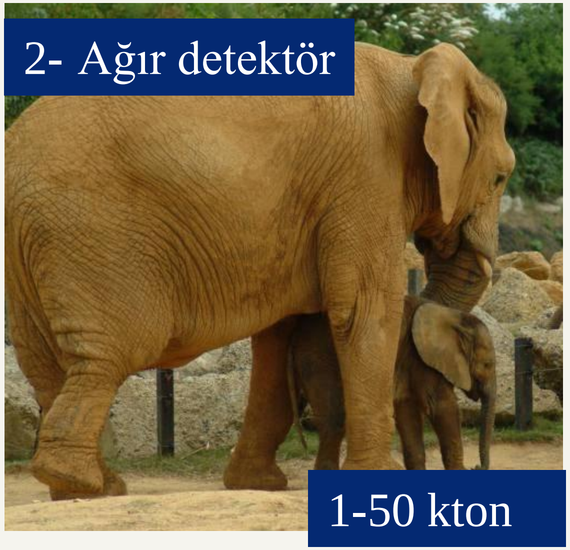
Nötrinoyu nasıl yakalanır?

1- Yoğun nötrino hüzmesi



Milyarlarca nötrino/s

2- Ağır detektör

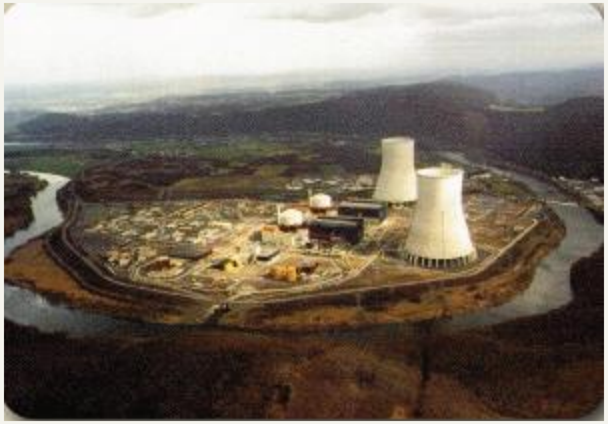


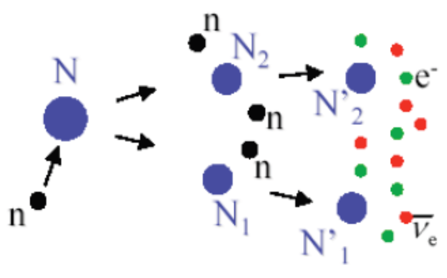
1-50 kton

3- Uzun veri alımı

10-15 yıl

Uygun yer: Nükleer reaktör

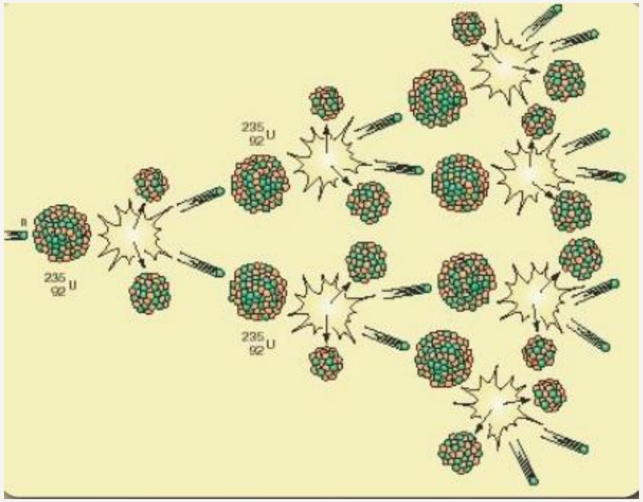




Yield :

200 *MeV* / *fission*

$6\bar{\nu}_e$ / *fission*



$$\bar{\nu}\text{ production rate} = \frac{6P_t}{200\text{ MeV}\times\underbrace{1.6\times10^{-13}}_{\substack{\text{conversion factor}\\ \text{MeV}\to\text{J}}}} = 1.87\times10^{11}P_t\ \bar{\nu}/\text{s}$$

P_t: reactor thermal power [W]

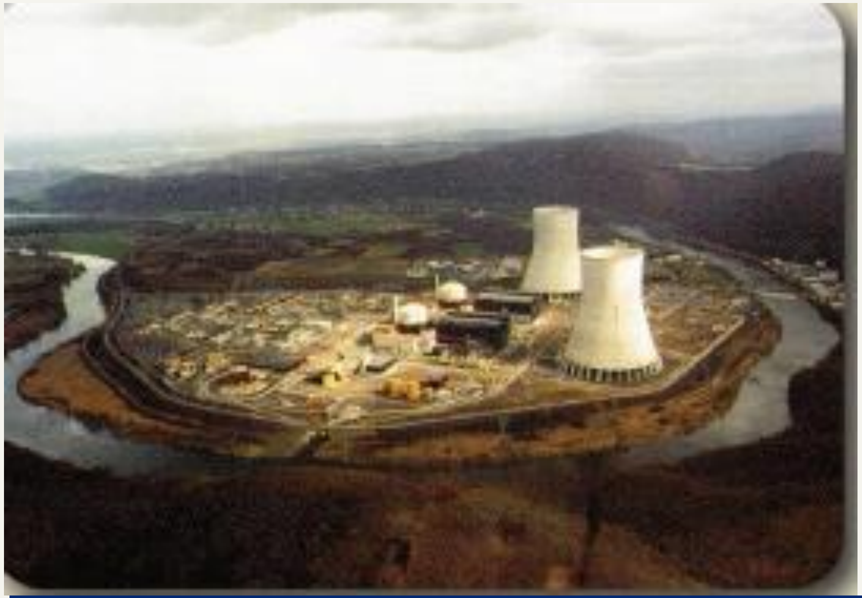
For a typical reactor: $P_t = 3\times10^{9}$ W ⇒ $5.6\times10^{20}\ \bar{\nu}$ / s (isotropic)

Continuous $\bar{\nu}$ energy spectrum – average energy ~3 MeV

Reines & Cowan

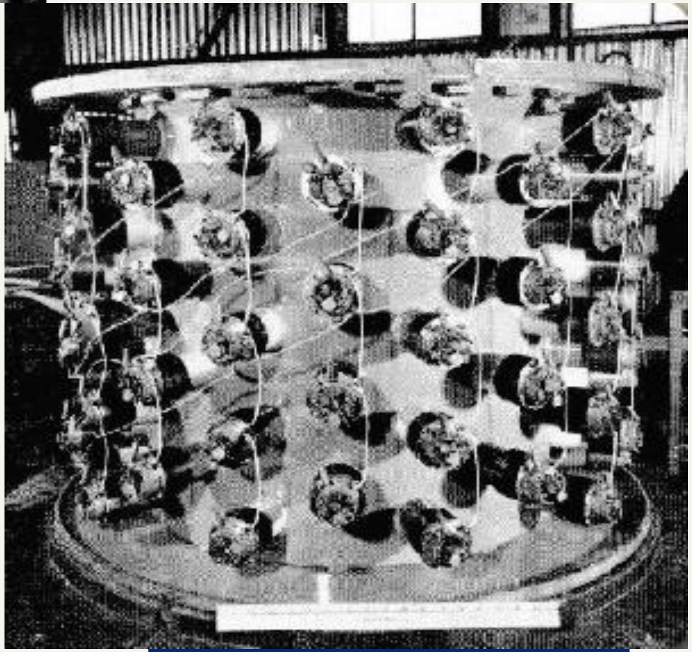
Frederic Reines

Clyde Cowan



Savannah River (South Carolina)
Los Alamos National Laboratory

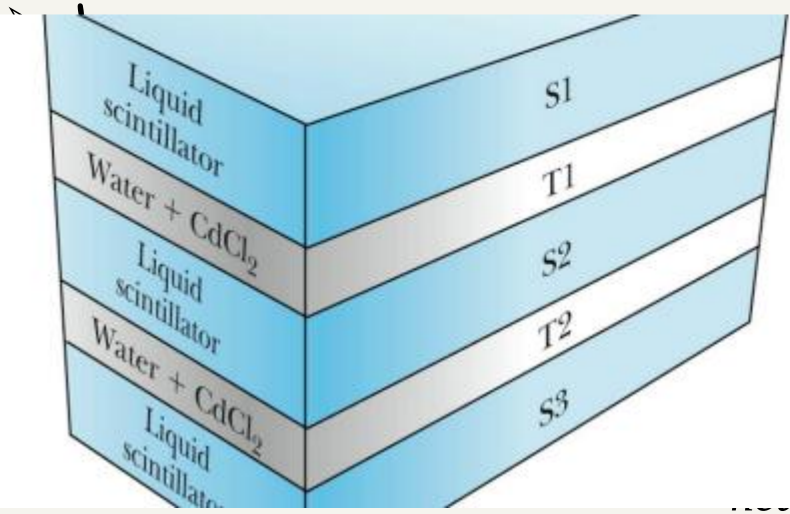
$\bar{\nu}_e$

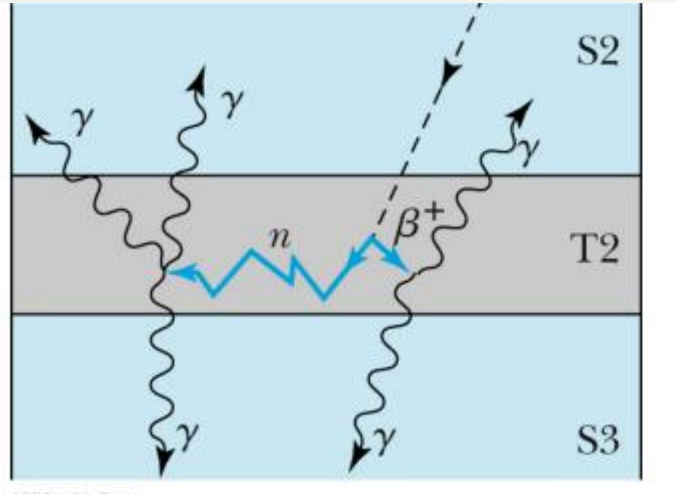


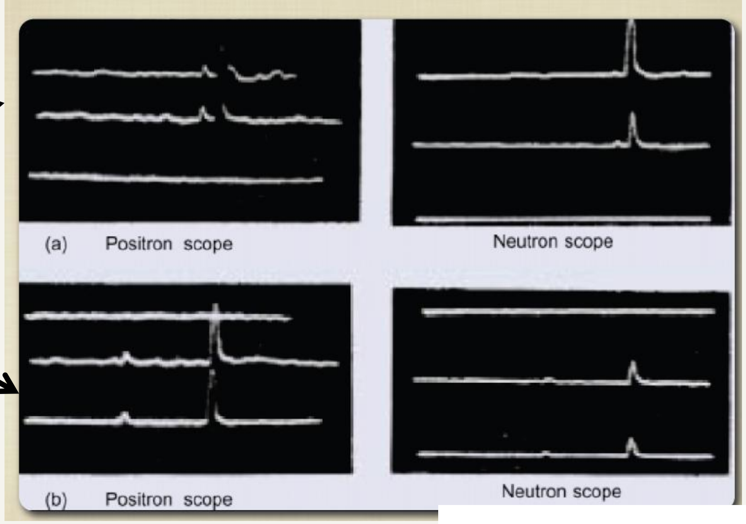
liquid scintillator

1995 yılında Nobel ödülünü aldılar (F. Reines)

Nötrinoların ilkez gözlenmesi



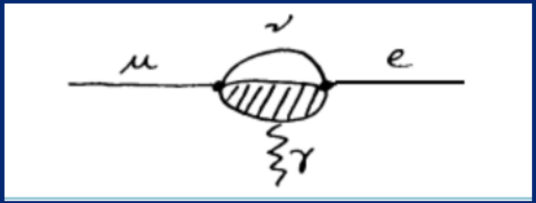




2.88 ± 0.22 collisions/hour

Kaç tane nötrino var?

- After the discovery of the muon, physicists started asking the question: why don't we see the decay $\mu \to e\,\gamma$?
  - Should proceed through intermediate state $\mu \to e\,(\nu\bar{\nu}) \to e\,\gamma$



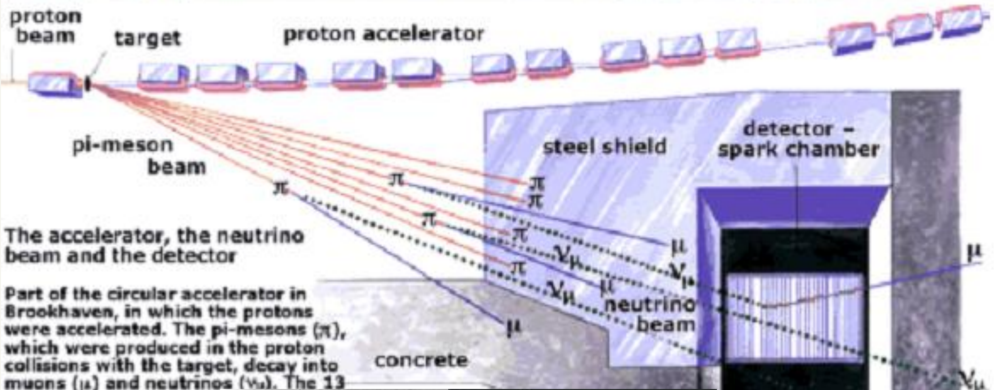
  - But if the $\nu\bar{\nu}$ pair that was produced weren't really a particle and its anti-particle, then they couldn't annihilate to a photon…
  - Look at how ν' s are produced: $\pi \to \mu\,\nu$

ν_μ nötrinonun keşfi

Alternating Gradient Synchrotron Brookhaven (1962)

15 Gev/c Proton

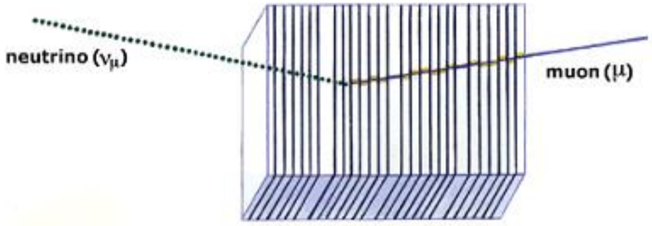
Spark chamber



The accelerator, the neutrino beam and the detector

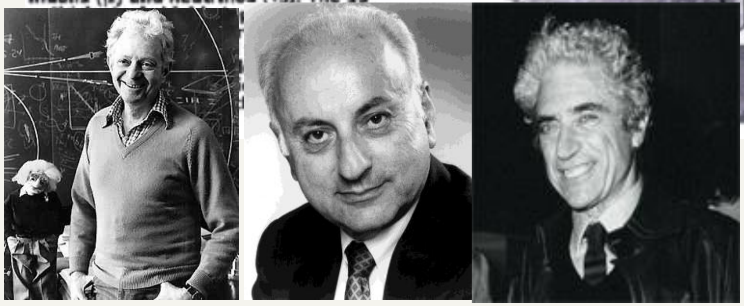
Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13

Sandwich of Aluminium plates and spark chambers



A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.

$\bar{\nu}_\mu + p \rightarrow n + \mu^+$ $\nu_\mu + n \rightarrow p + \mu^-$

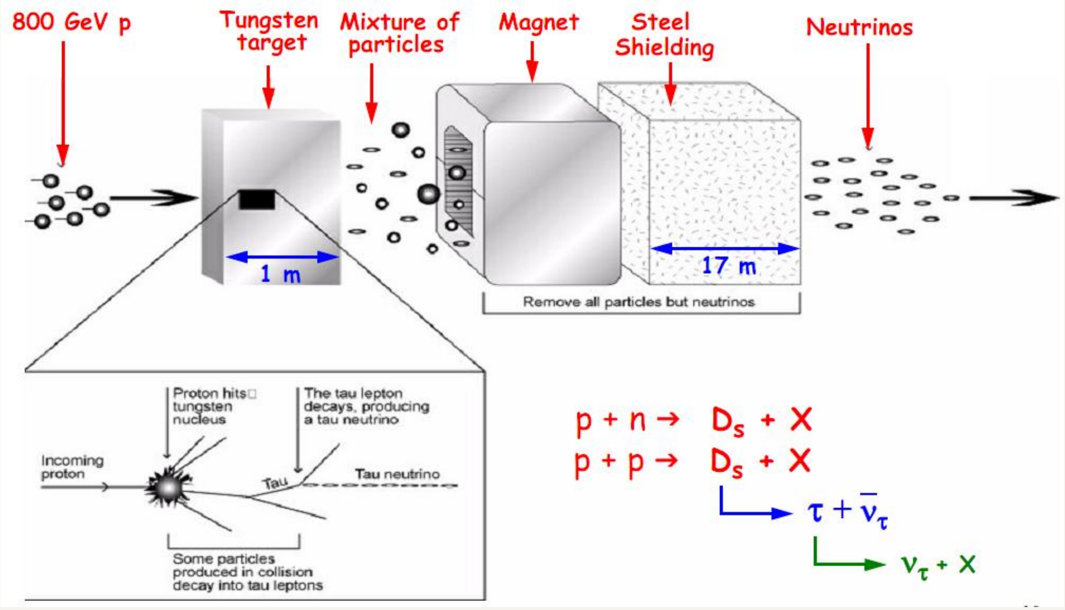


Leon Lederman, Melvin Schwartz and Jack Steinberger (Nobel Prize in 1988)

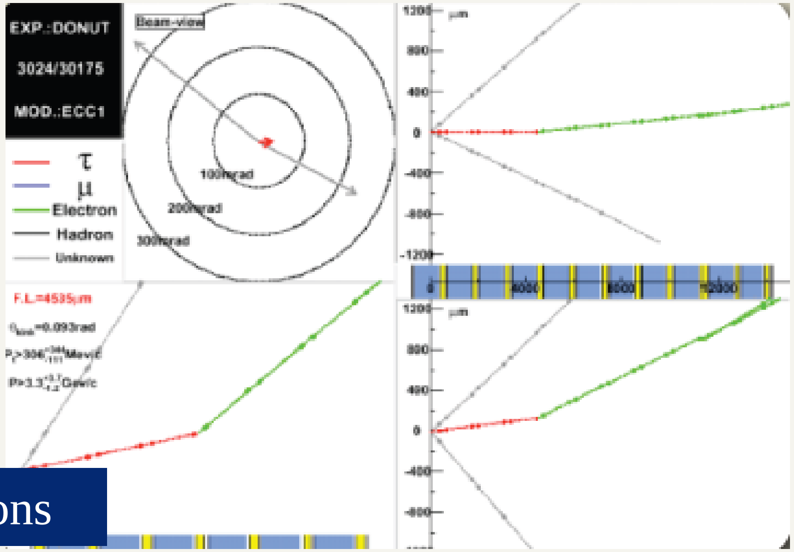
- The muon neutrino interacted with the nucleons in aluminium and photos of the ractions products were recorded. 29 events recorded with muon and non with electron

τ Nötrinonun keşfi

- 1998 DONUT (Direct Observation of the nu-Tau, E872) was an experiment at Fermilab dedicated to the search for tau neutrino interactions. Beam-dump experiment with 800 GeV Tevatron beam



Kimio Niwa



$D_s \to \tau\, \nu_\tau$ (3% of the beam)

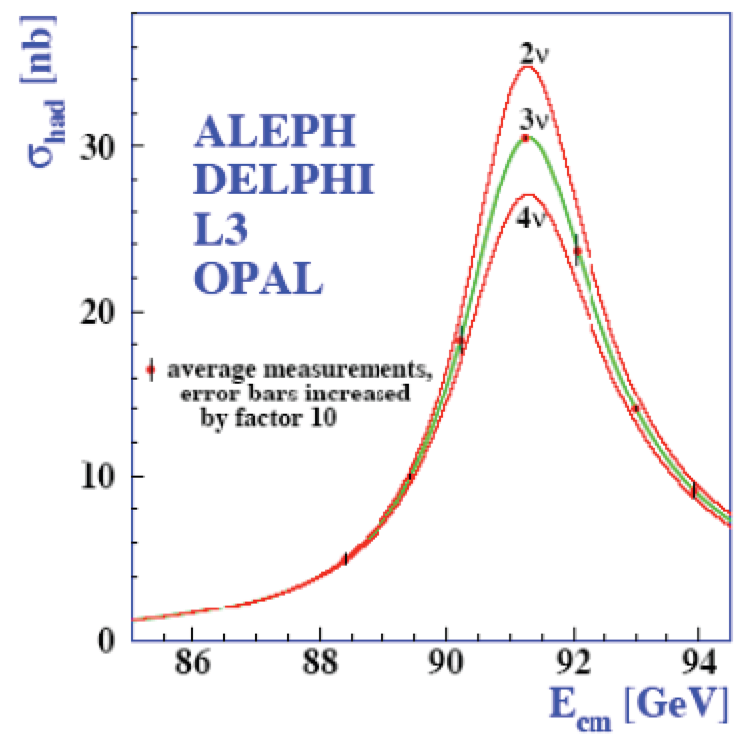
$$\nu_\tau + N \to \tau + X$$

- 9 ν_τ events were observed from 578 neutrino interactions

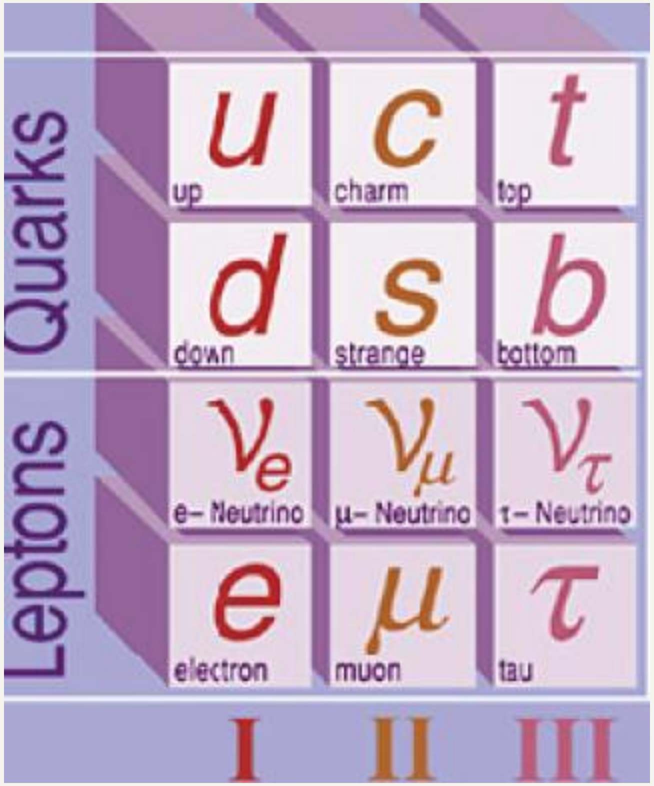
Kaç çeşit nötrino?

Z^0 production cross-section and width

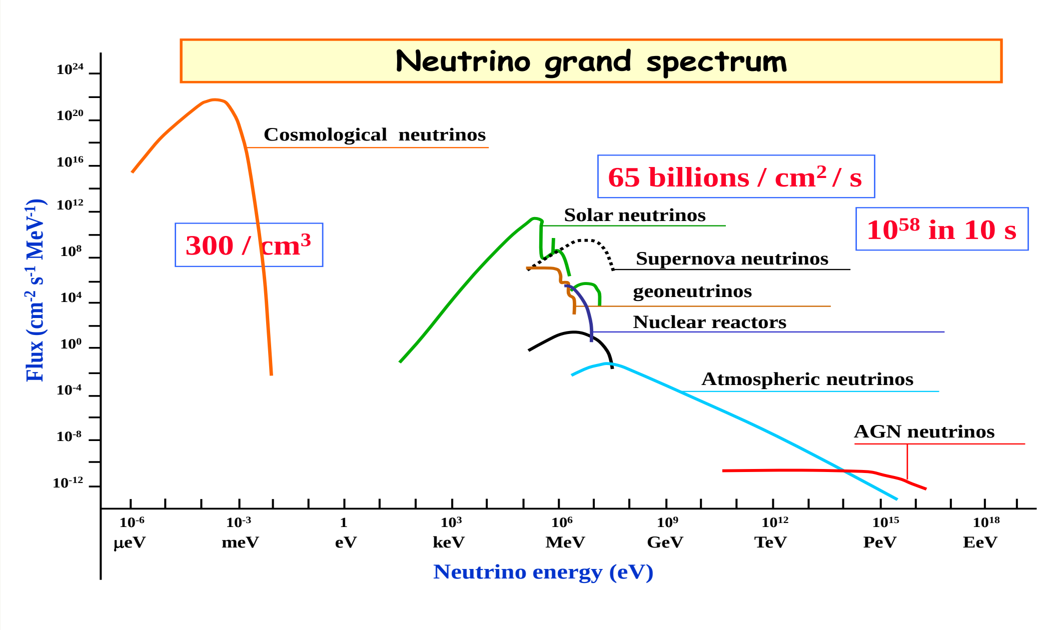
$\Gamma\mathbf{inv} = \Gamma_Z - \Gamma_{had} - \Gamma_{ee} - \Gamma_{\mu\mu} - \Gamma_{\tau\tau}$



Three ligth neutrinos



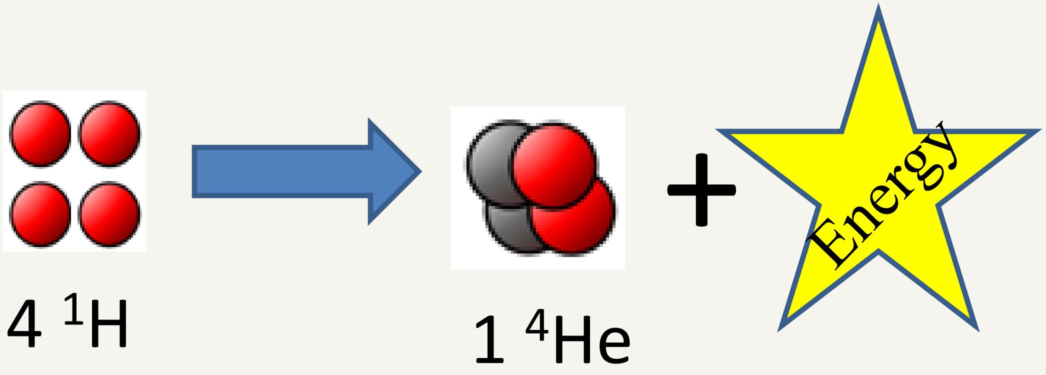
Nötrino kaynakları

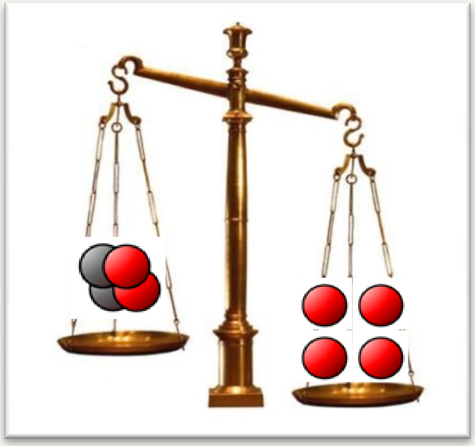


Güneş Nasıl Işık Saçıyor

- The core of the Sun reaches temperatures of ~ 15.5 million K. At these temperatures, nuclear fusion can occur transforming 4 Hydrogen nuclei into 1 Helium nucleus

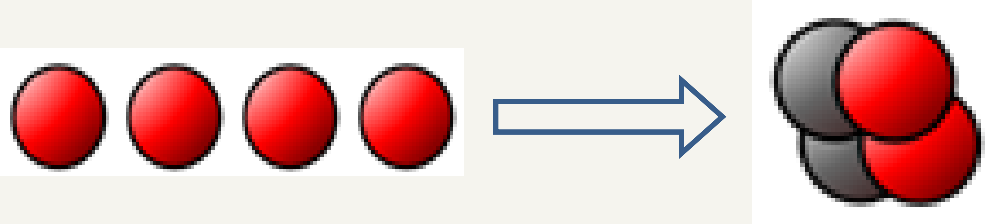
- Four hydrogen nuclei are heavier than a helium nucleus. That **“missing mass”** is converted to energy to power the Sun.





Proton’dan Nötrino’ya

We start from 4 protons and we end with 1 He nucleus which is composed of 2 protons and 2 neutrons.

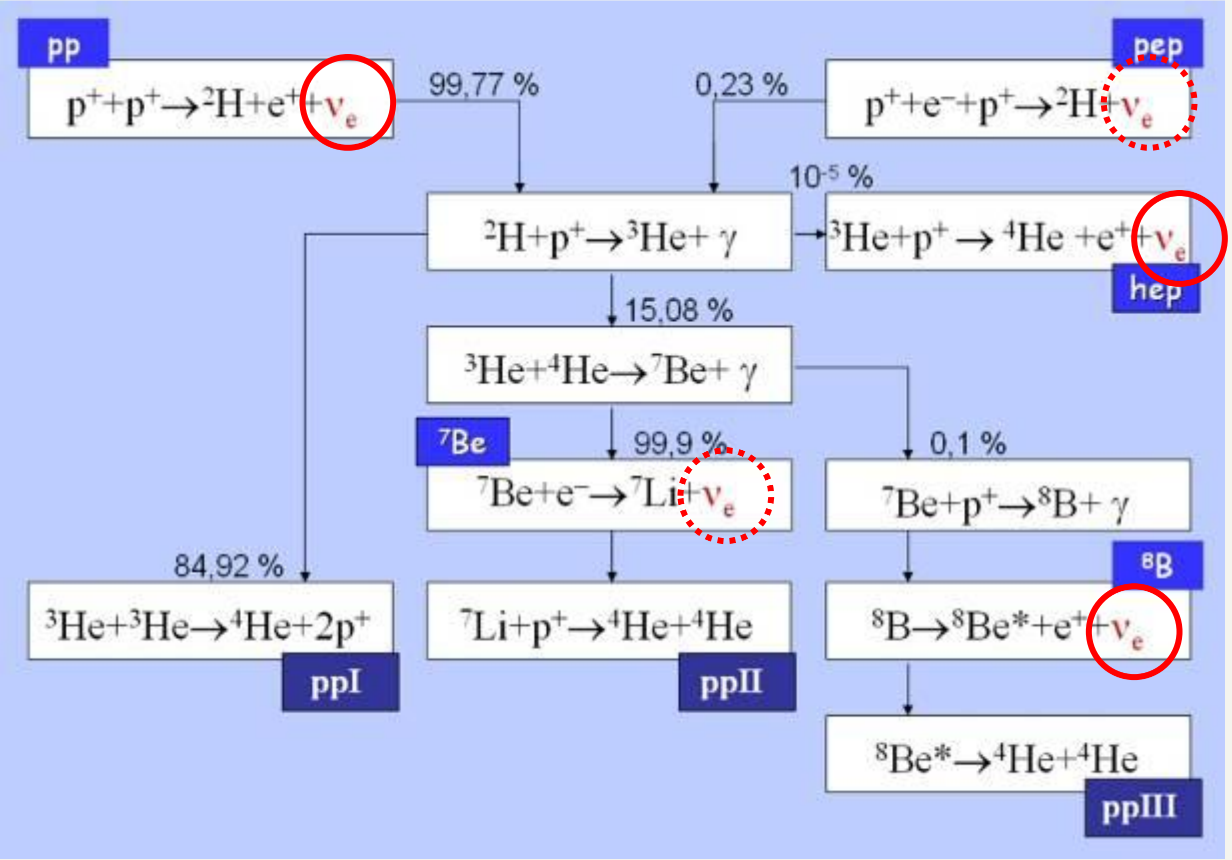


$$p \rightarrow n + e^{+} + \nu_{e}$$

In the inverse beta decay a proton becomes a neutron emitting a **positron** and an **electron neutrino ν_e**

Proton’dan Nötrino’ya

pp chain



pp

$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

99,77 %

0,23 %

pep

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

10^{-5} %

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

${}^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

hep

15,08 %

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

7Be

99,9 %

0,1 %

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

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

84,92 %

8B

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

ppI

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

ppII

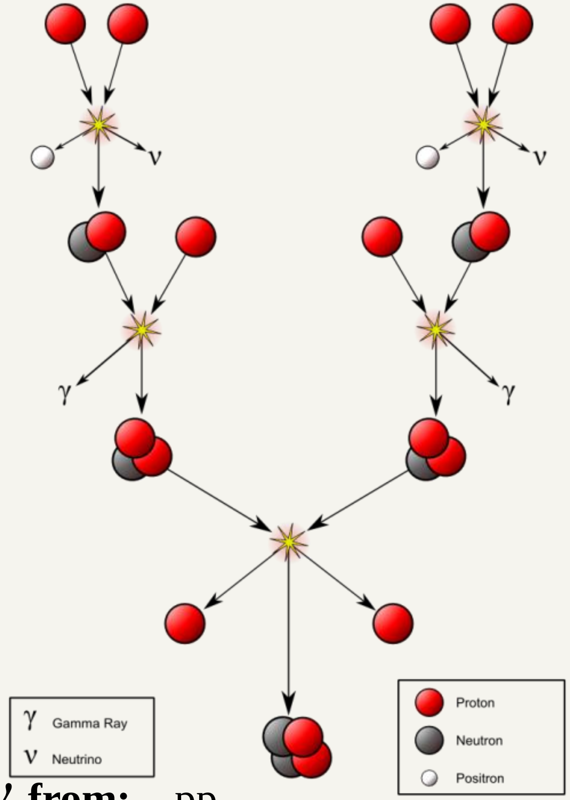
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \rightarrow {}^4He + {}^4He$

ppIII

pep and ^{7}Be are Monocrhomatic ν’s
(2 bodies in the final state)

CNO chain



ν from:

pp

pep

^{7}Be

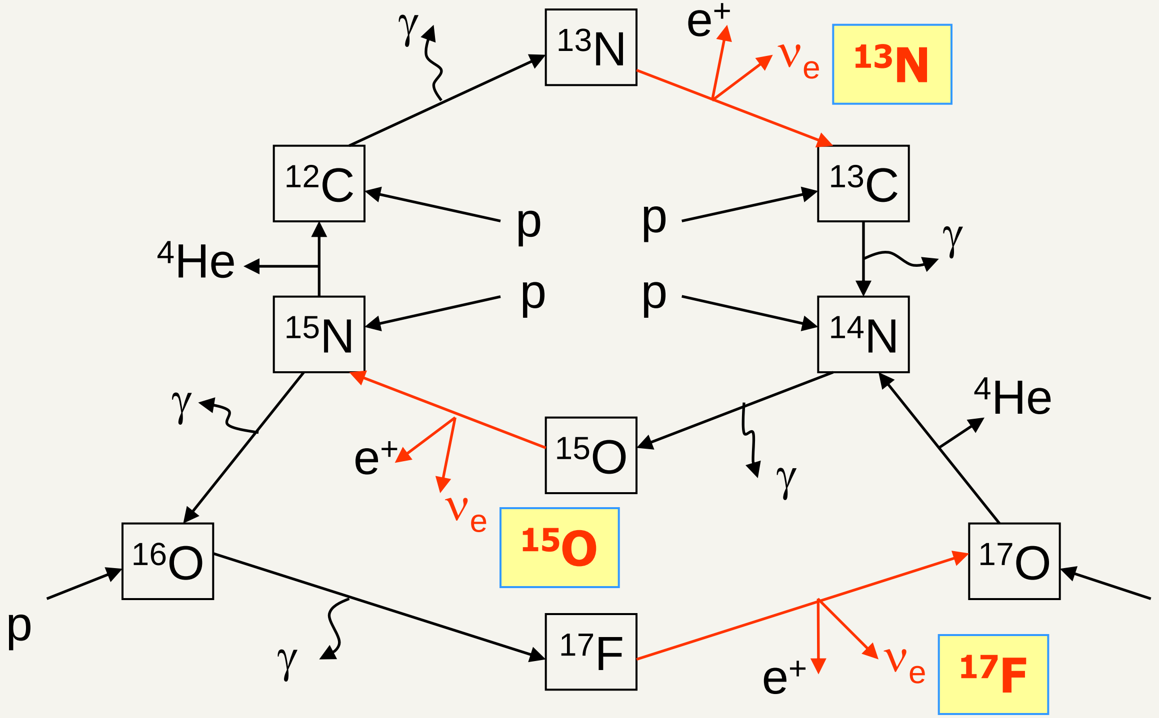
^{8}B

hep

CNO cycle

…. But pp chain is not the only reaction that transform protons into helium …..
In a star like the Sun ~ 98% of the energy is created in pp chain

Beside pp chain there is also the **CNO cycle** that become the dominant source of energy in stars heavier than the Sun (in the Sun the CNO cycle represents only 1-2 %)



ν from:

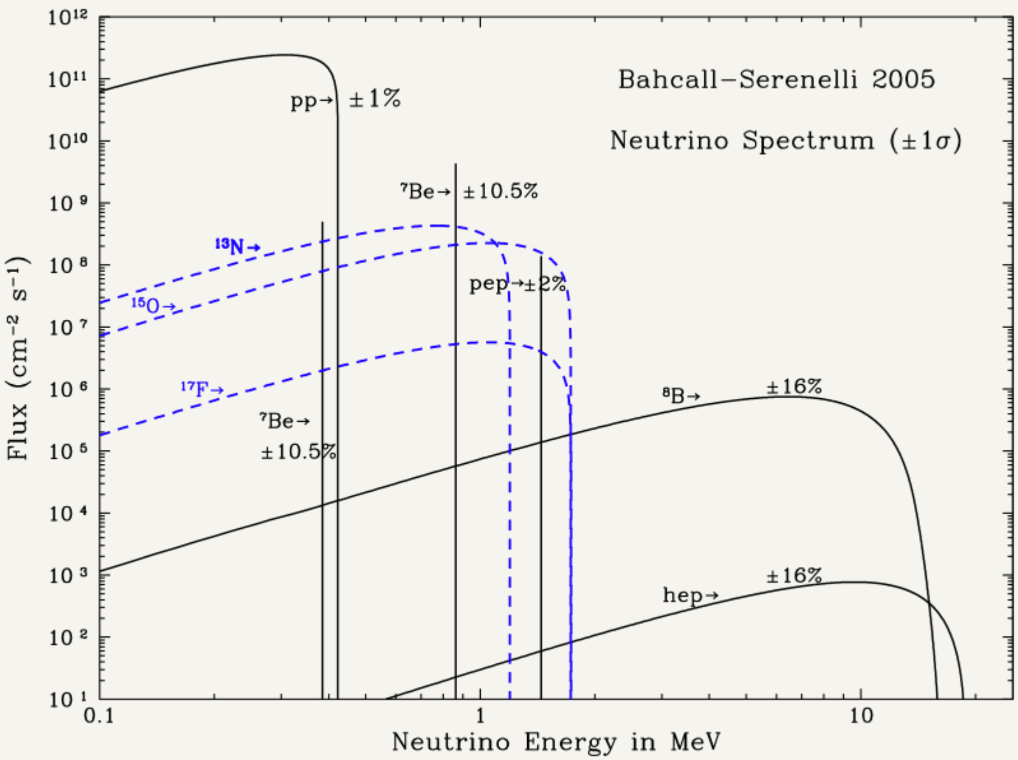
^{13}N

^{15}O

^{17}F

Neutrinos are also produced in the CNO cycle

Neutrino energy spectrum



ν from:

pp

pep

^{7}Be

^{8}B

hep

ν from:

^{13}N

^{15}O

^{17}F

^{7}Be:

384 keV (10%)

862 keV (90%)

pep:

1.44 MeV

Neutrino Hunting

There are 2 possible ways to detect solar neutrinos:

- **radiochemical experiments**
- **real time experiments**

In radiochemical experiments people uses isotopes which, once interacted with an electron neutrino, produce radioactive isotopes.

$$\nu_e + {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^-$$

The production rate of the daughter nucleus is given by

$$R = N \int \Phi(E)\sigma(E)dE$$

where

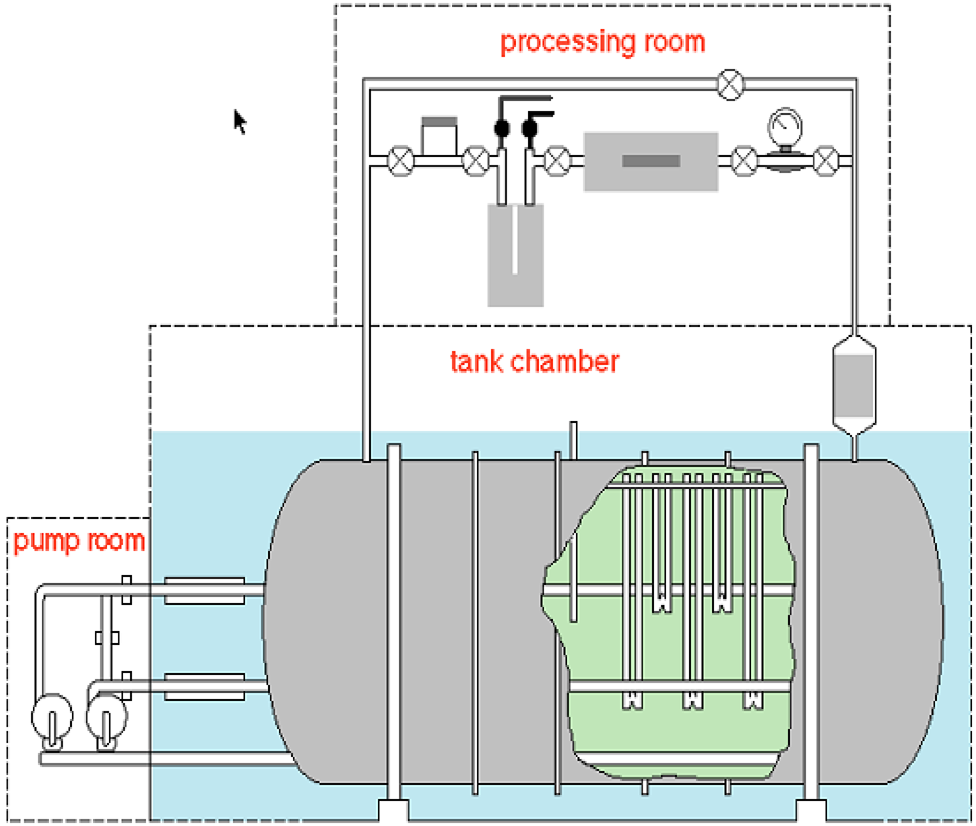
- Φ is the solar neutrino flux
- σ is the cross section
- N is the number of target atoms.

With a typical **neutrino flux** of **10^{10} ν cm^{-2} s^{-1}** **cross section** of about **10^{-45} cm^2**

we need about <u>10^{30} target atoms</u> *(that correspond to ktons of matter)* to produce **<u>one event per day</u>**.

Radiochemical Experiments

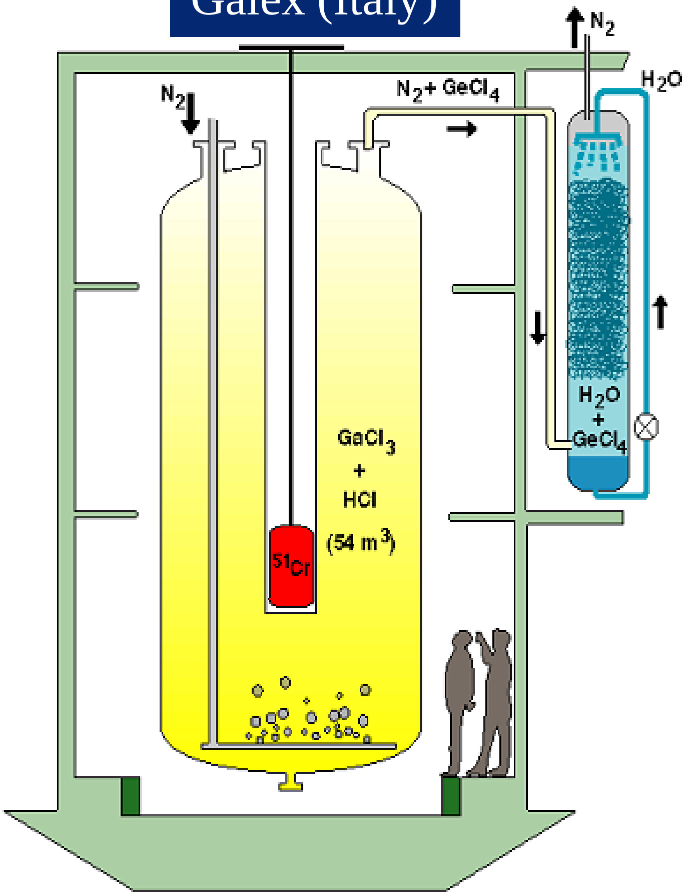
Homestake (USA)



614 Tons of C_2Cl_4

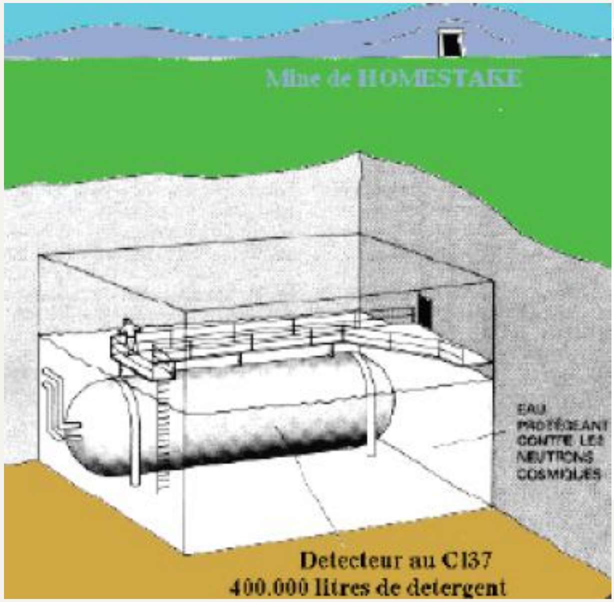
$\nu_e + {}^{37}Cl \rightarrow e + {}^{37}Ar$

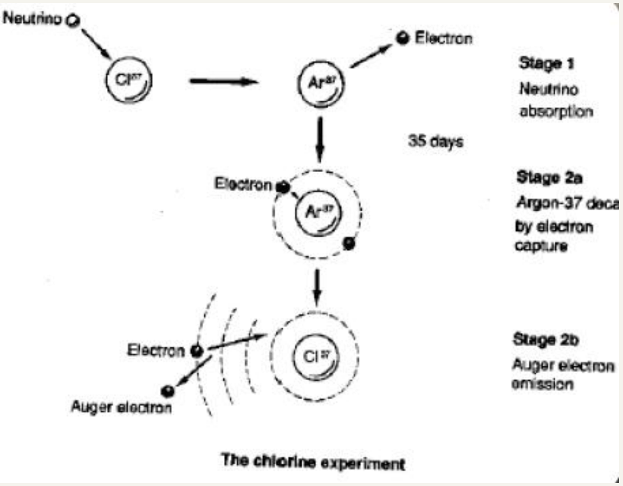
Galex (Italy)

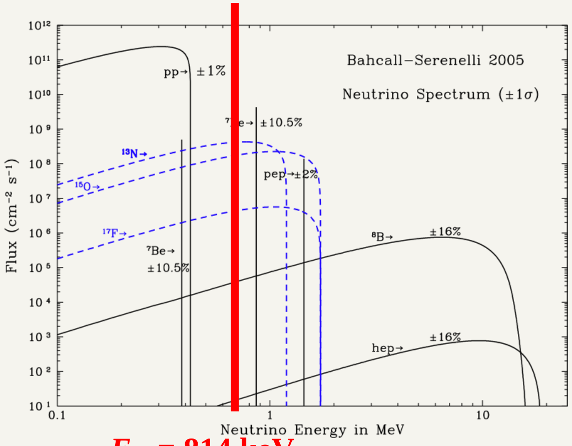


$\nu_e + {}^{71}Ga \rightarrow e + {}^{71}Ge$

Nötrino akısı







E_{th} = 814 keV

$$\nu_e + {}^{37}Cl \longrightarrow {}^{37}Ar + e^-$$

- ${}^{37}Ar$ is radioactive and decay by EC with a $\tau_{1/2}$ of 35 days into ${}^{37}Cl^*$

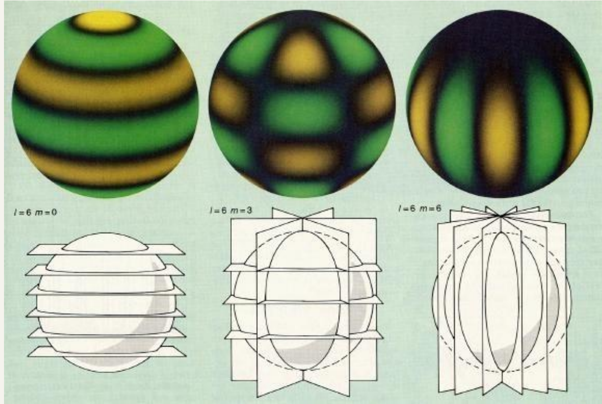
$$ {}^{37}Ar + e^- \rightarrow {}^{37}Cl^* + \nu_e $$

- ^{37}Ar atomlarının (Auger elektron) sayısı nötrino etkileşimlerini veriyor.
- Az sayıda ki Ar atomlarını ~0.4 milyon litre Cl içinden ayırmak
- Veri alımı 20 yıldan fazla sürdü

Homestake	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03 (Measured/theory)

Possible Explanations

- **Standard Solar Model is not correct**



..but Solar models have been tested independently by **helioseismology** *(that is the science that studies the interior of the Sun by looking at its vibration modes),* and the standard solar model has so far passed all the tests.

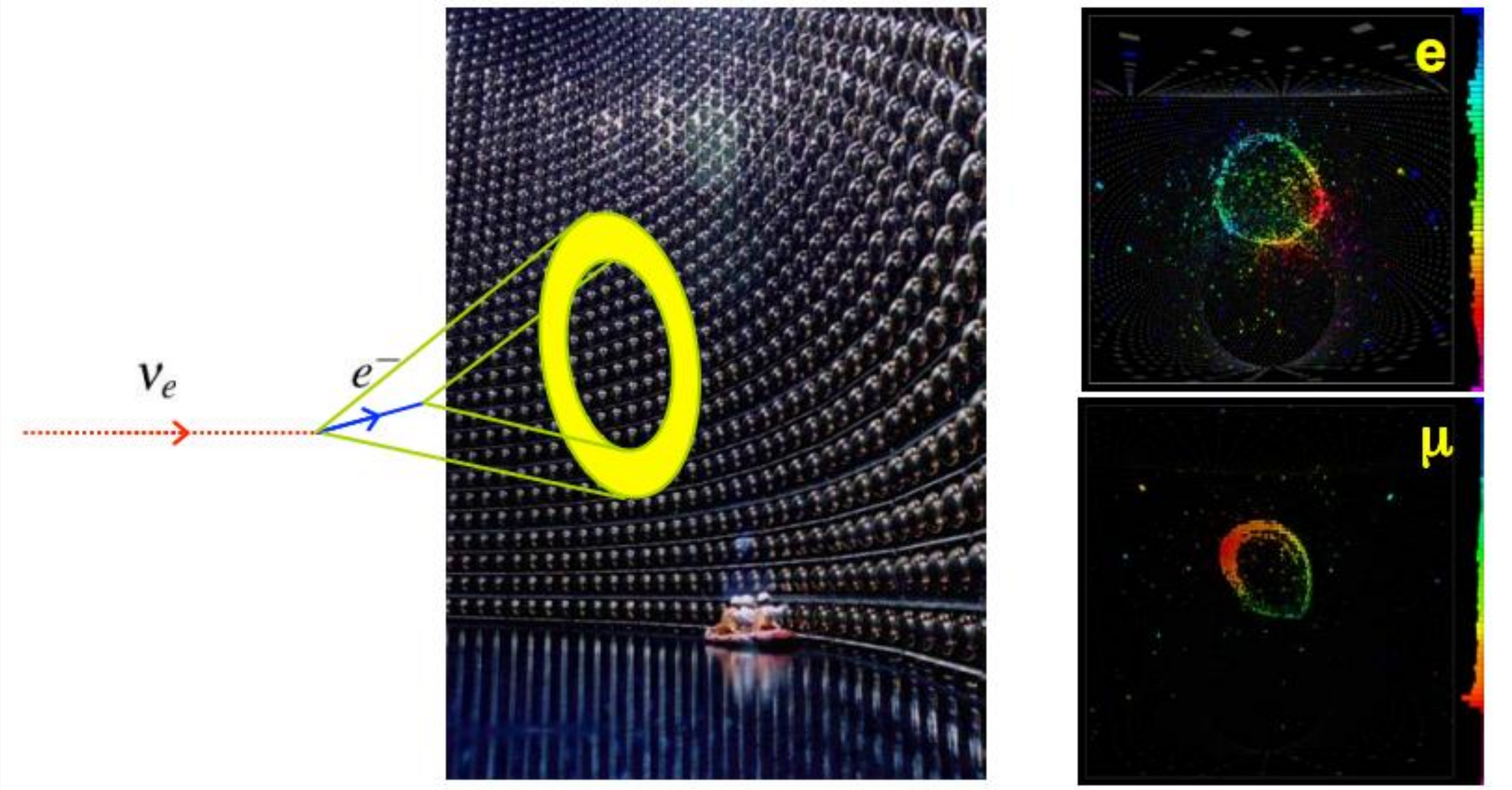
beside ..... Non-standard solar models seem very unlikely.

- **Homestake is wrong.**

- **Something happens to ν's traveling from the core of the Sun to the Earth.**

Başka bir method

- Detects neutrinos by observing Cerenkov radiation from charged particles which travels faster than speed of ligth in water .



- Can distinguish electrons from muons from pattern of ligth.

Kamiokande & SKamiokande

➢In 1982-83 was built in Japan the first real time detector. It consisted in a Large water Cherenkov Detector

Kamiokande

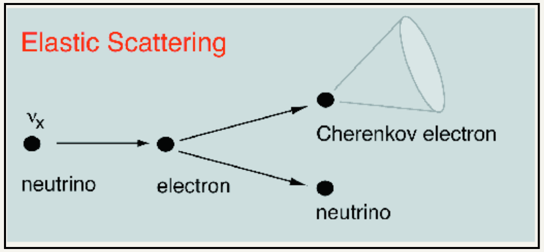
- 3000 tons of pure water
- 1000 PMTs

SuperKamiokande (1996-)

- 50000 tons of pure water
- 11200 PMTs

➢In real time experiments people looks for the light produced by the electrons scattered by an impinging neutrino

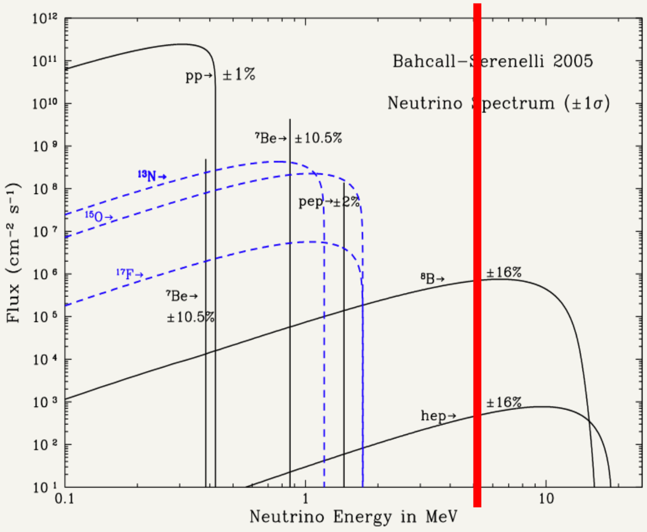
$$\nu_x + e^- \to \nu_x + e^-$$



E_{th} = 7.5 MeV (for Kamiokande)

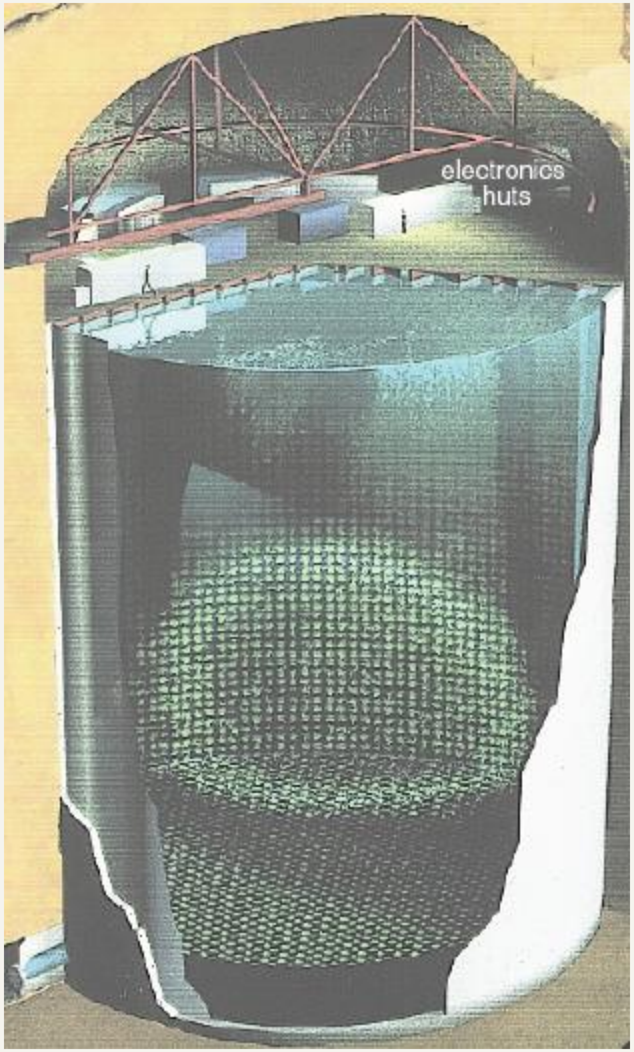
E_{th} = 5.5 MeV (for SKamiokande)

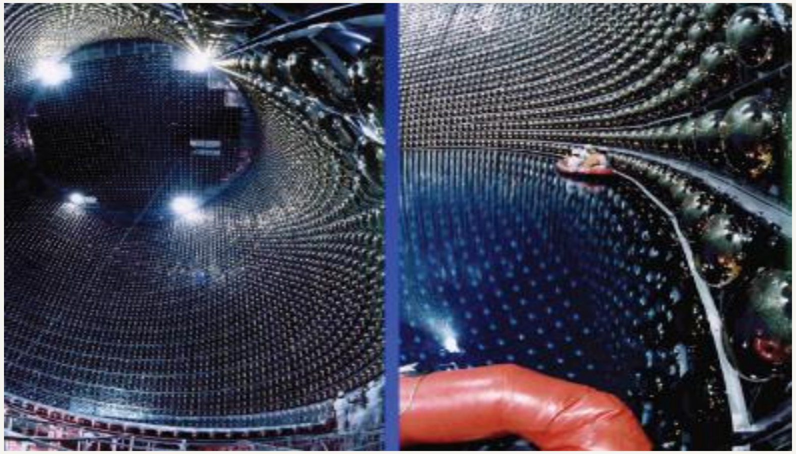
only ^{8}B neutrinos (and hep)

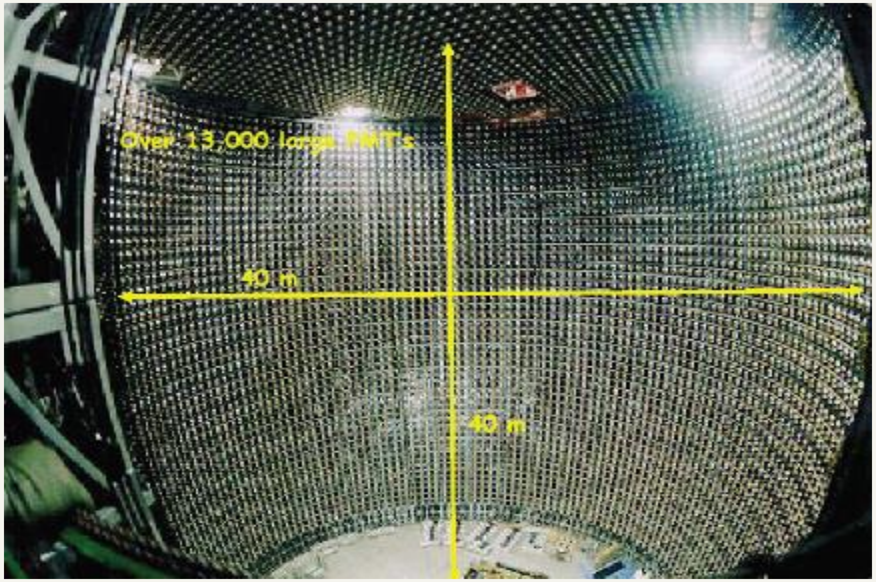


E_{th} = 5.5 MeV

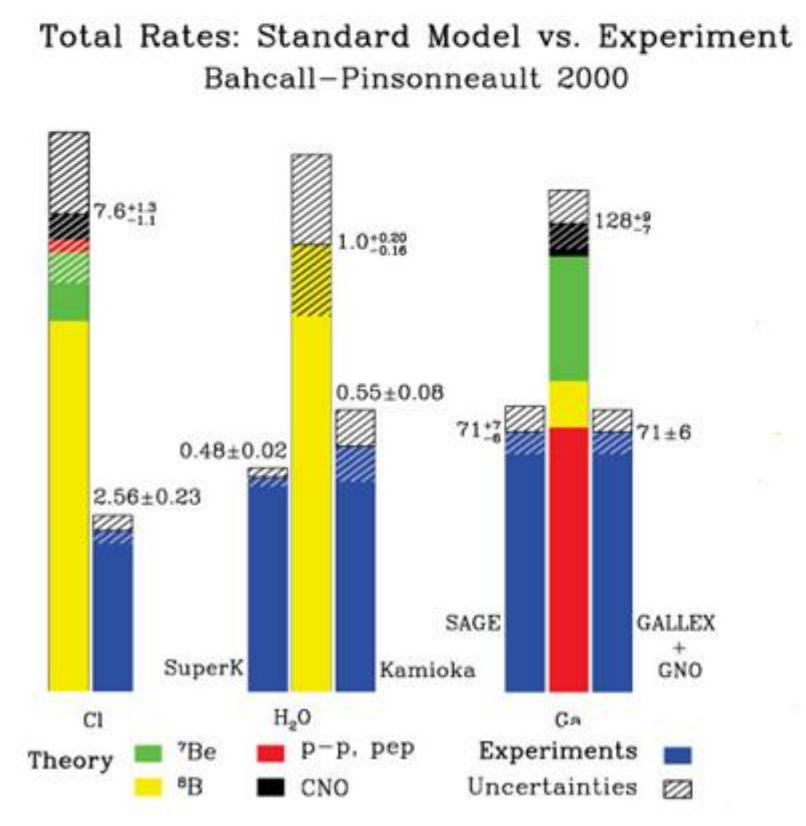
SKamiokande

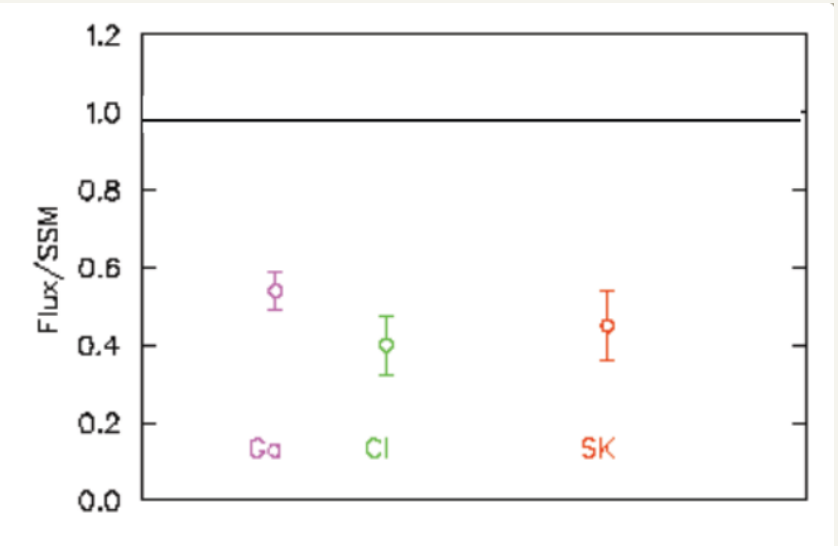






Solar nötrino problemi



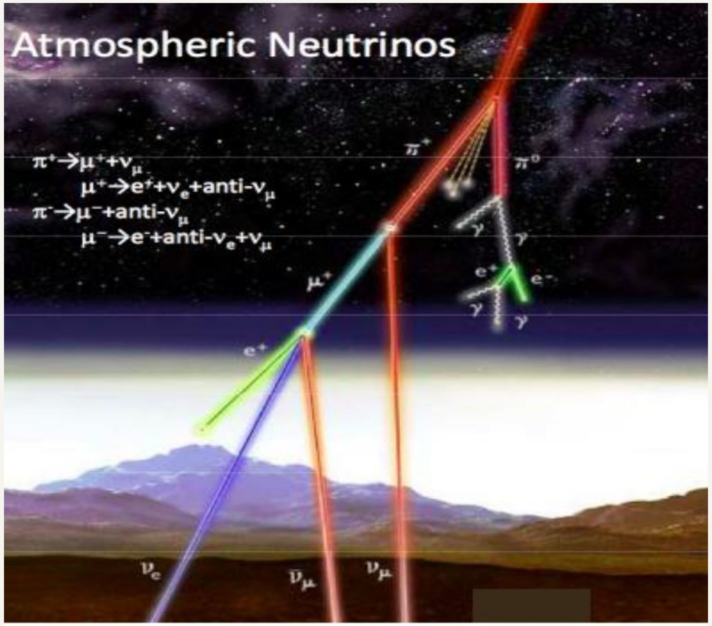


Rate measurement	**Reaction**	**Obs / Theory**
Homestake	$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	0.34 ± 0.03
Super-K	$\nu_x + e^- \rightarrow \nu_x + e^-$	0.46 ± 0.02
SAGE	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	0.59 ± 0.06
Gallex+GNO	$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$	0.58 ± 0.05

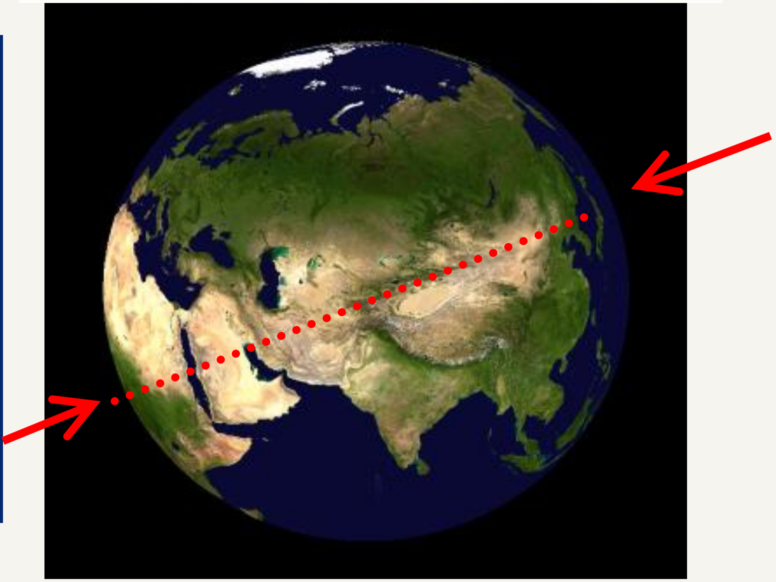
1 SNU (Solar Neutrino Unit) = 1 capture/sec/10^{36} atoms

Atmosferik Nötrinolar

- Cosmic-ray protons strike upper atmosphere.
- End of cascade two ν_μ and one ν_e.
- Typical energy O(GeV).



- Measurements of neutrinos from atmosphere:
  - 15 to 13,000 km Muon Neutrinos from above don’t disappear.
  - Muon Neutrinos from below disappear.
  - Electron neutrinos don’t seem to be disappearing!



Deneysel sonuçlar

- Solar Nötrino Problemi
  - *Disapparence of* ν_e
- Atmosferik Nötrino Problemi
  - *Disapparence of* ν_μ

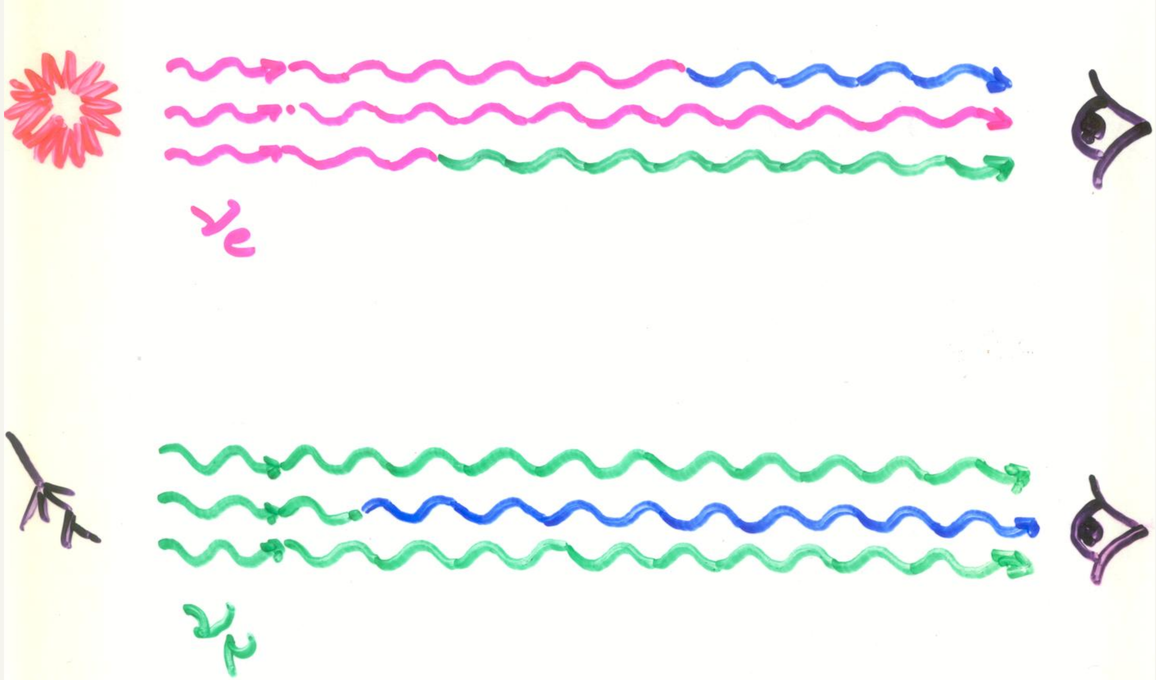
Note:

Experimentally 2 complementary search methods,

- Disappearance of initial neutrinos or
- Appearance of new flavor not present at the source

Someting happens to Neutrino

Nötrinolar salınıyorlar mı?



- The *deficits* can be explained by a change of flavor during propagation.

Nötrino Salınımları

1956

İlk fikir Buruno Pontecorvo dan: $K^0 - \bar{K}^0$ salınımlarıyla aynı

- Weak interaction eigenstates ν_e, ν_μ different from mass eigenstates (propagation) ν_1, ν_2

1962 Maki, Nakagawa and Sakata

- suggest flavor mixing and neutrino oscillation

Nötrino Salınımları

- Neutrinos have the peculiar property that their flavour eigenstates do not coincide with their mass eigenstates.

Flavour eigenstates ν_e, ν_μ, ν_τ

$\neq$

Mass eigenstates ν_1, ν_2, ν_3

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

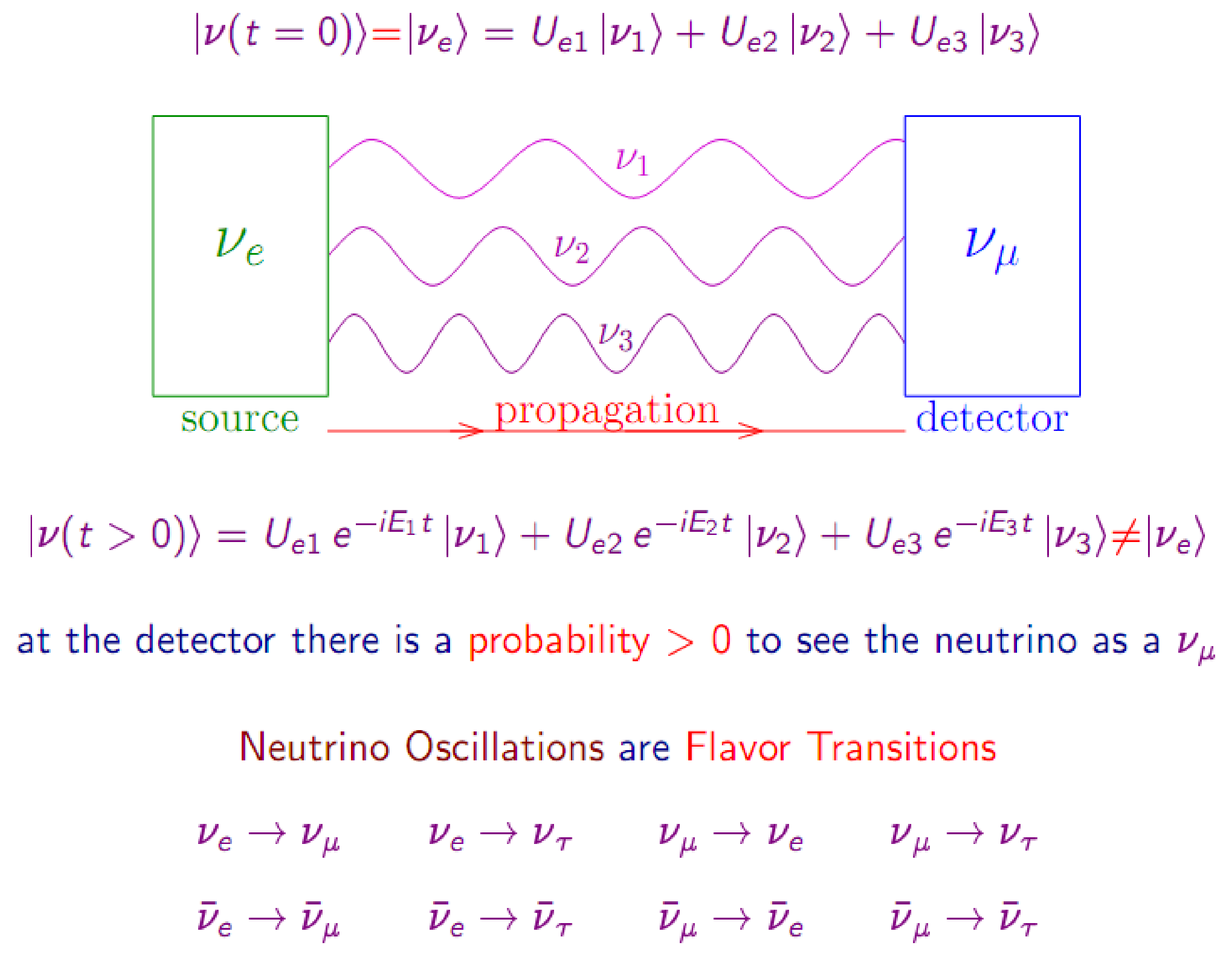
- Flavour states can be expressed in the mass eigenstate system and vice versa.

- The neutrino **flavour states** $\boldsymbol{\nu_e , \nu_\mu , \nu_\tau}$ are related to the **mass states** $\boldsymbol{\nu_1 , \nu_2 , \nu_3}$ by the linear combinations.

- Consequently, for a given energy the mass states propagate at different velocities and the flavour states change with time.

- This effect is known as **neutrino oscillations**.

Nötrino Salınımları



$$|\nu(t=0)\rangle = |\nu_e\rangle = U_{e1}\,|\nu_1\rangle + U_{e2}\,|\nu_2\rangle + U_{e3}\,|\nu_3\rangle$$

$$|\nu(t>0)\rangle = U_{e1}\,e^{-iE_1t}\,|\nu_1\rangle + U_{e2}\,e^{-iE_2t}\,|\nu_2\rangle + U_{e3}\,e^{-iE_3t}\,|\nu_3\rangle \neq |\nu_e\rangle$$

at the detector there is a probability > 0 to see the neutrino as a ν_μ

Neutrino Oscillations are Flavor Transitions

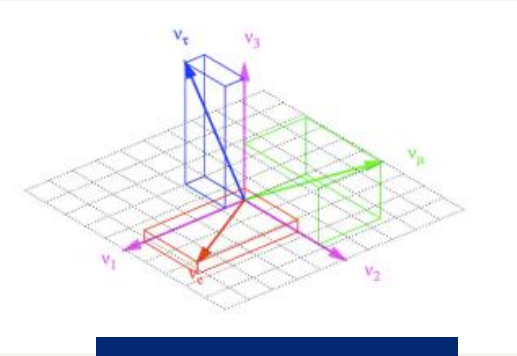
$\nu_e \to \nu_\mu \qquad \nu_e \to \nu_\tau \qquad \nu_\mu \to \nu_e \qquad \nu_\mu \to \nu_\tau$

$\bar{\nu}_e \to \bar{\nu}_\mu \qquad \bar{\nu}_e \to \bar{\nu}_\tau \qquad \bar{\nu}_\mu \to \bar{\nu}_e \qquad \bar{\nu}_\mu \to \bar{\nu}_\tau$

Nötrino Salınımları

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

Pontecorvo-Maki-Nakagawa-Sakata



3 mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$

- Mixing matrix U_{PMNS} can be factored into three rotaional matrices and U_{maj}

Three independent mixing angles

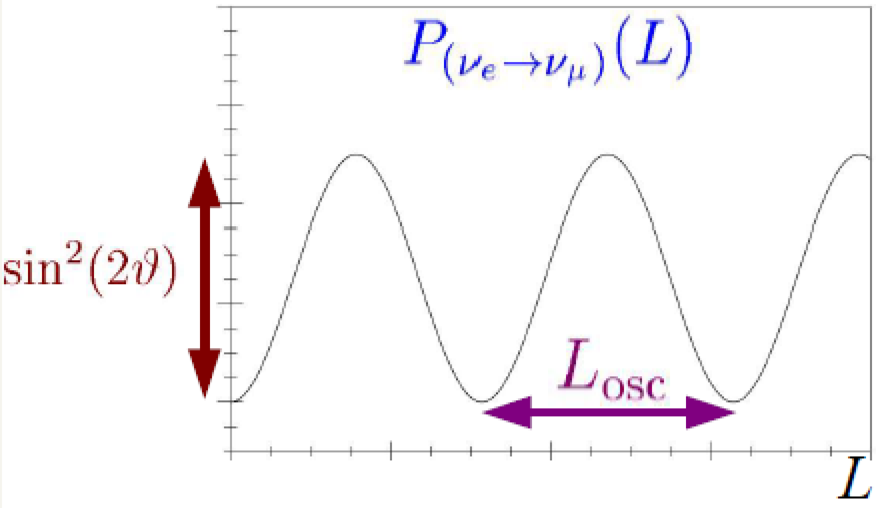
CP-violation phase

$$U_{\text{PMNS}} = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{13} & 0 & e^{-i\delta_{\text{CP}}}\sin\theta_{13}\\ 0 & 1 & 0\\ -e^{-i\delta_{\text{CP}}}\sin\theta_{13} & 0 & \cos\theta_{13}\end{pmatrix} \times \begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \times U_{\text{Maj}}^{\text{diag}}$$

Salınım Olasılığı

Because one of the three mixing angles in very small (i.e. θ_{13}), and because two of the mass states are very close in mass compared to the third, for solar neutrinos we can restrict to **2 neutrinos case** and consider the **oscillation between $\nu_e \leftrightarrow \nu_{\mu,\tau}$**

$$P_{(\nu_e \to \nu_\mu)}(L) = \sin^2(2\vartheta)\sin^2\left(1.27\frac{\Delta m^2(\mathrm{eV}^2)}{E(\mathrm{GeV})}L(\mathrm{km})\right)$$



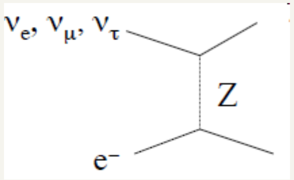
$$L_{\mathrm{osc}}(\mathrm{km}) = 2\pi\,\frac{E(\mathrm{GeV})}{1.27\,\Delta m^2(\mathrm{eV}^2)}$$

The Mikheyev Smirnov Wolfenstein Effect (**MSW**) … or Matter Effect

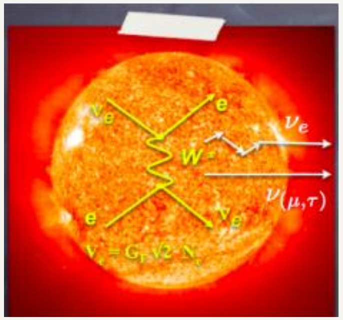
Neutrino oscillations can be enhanced by traveling through matter

The core of the Sun has a density of about 150 g/cm^3

The Sun is made of up/down quarks and electrons



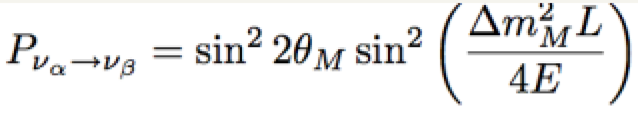
ν_e, ν_μ, ν_τ. All neutrinos can interact through NC equally.



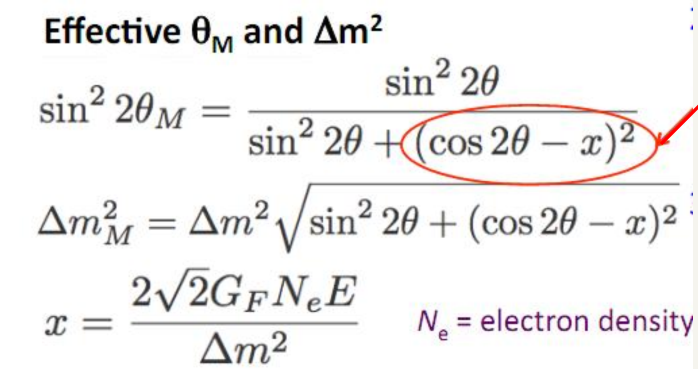
ν_e, Only electron neutrino can interact through CC scattering:

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

The interaction of ν_e is different from ν_μ and ν_τ .



$$P_{\nu_\alpha \to \nu_\beta} = \sin^2 2\theta_M \sin^2\left(\frac{\Delta m_M^2 L}{4E}\right)$$



Effective θ_M and Δm^2

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

$$\Delta m_M^2 = \Delta m^2 \sqrt{\sin^2 2\theta + (\cos 2\theta - x)^2}$$

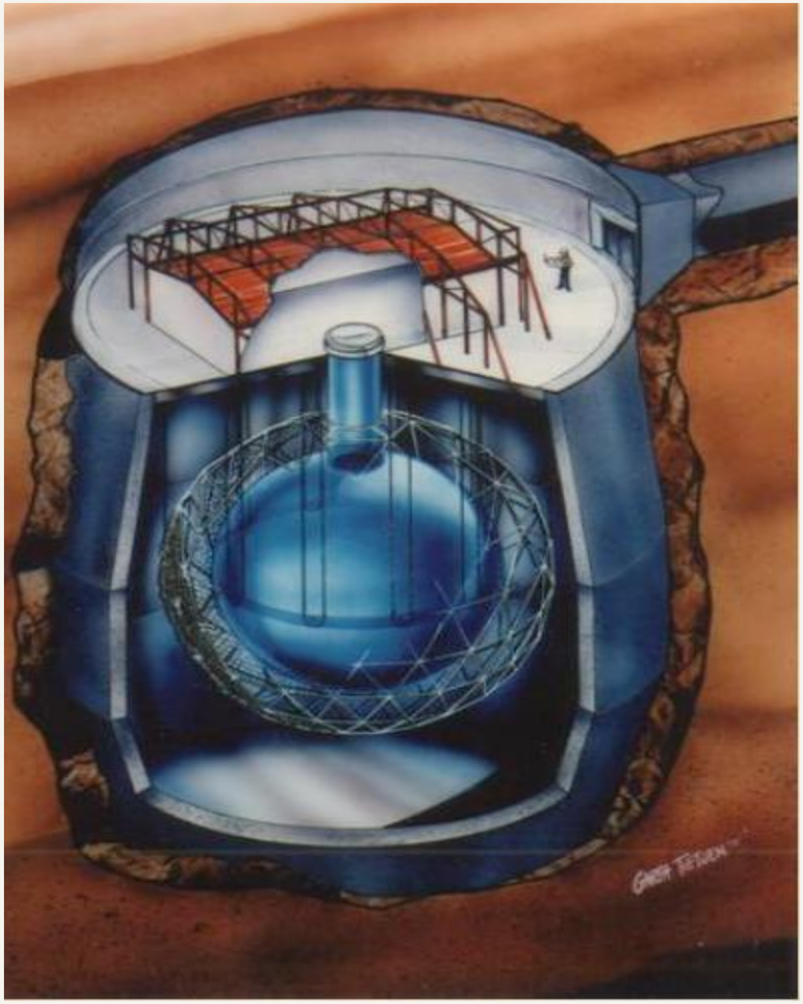
$$x = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

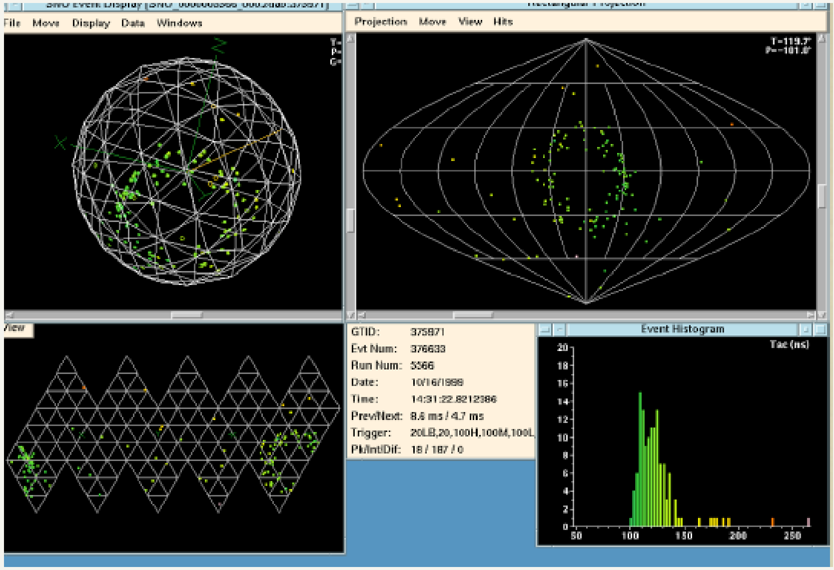
N_e = electron density

Resonant MSW
$\Theta = \pi/4$

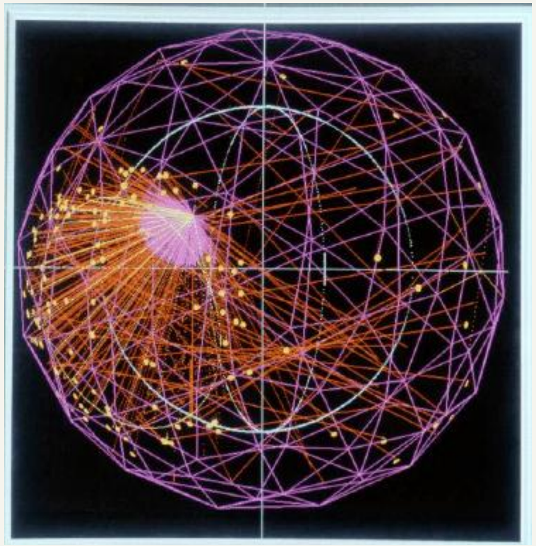
Varing transition between effective mass eigenstates
Adiabatic transition effective mass.

The Sudbury Neutrino Observatory (SNO)





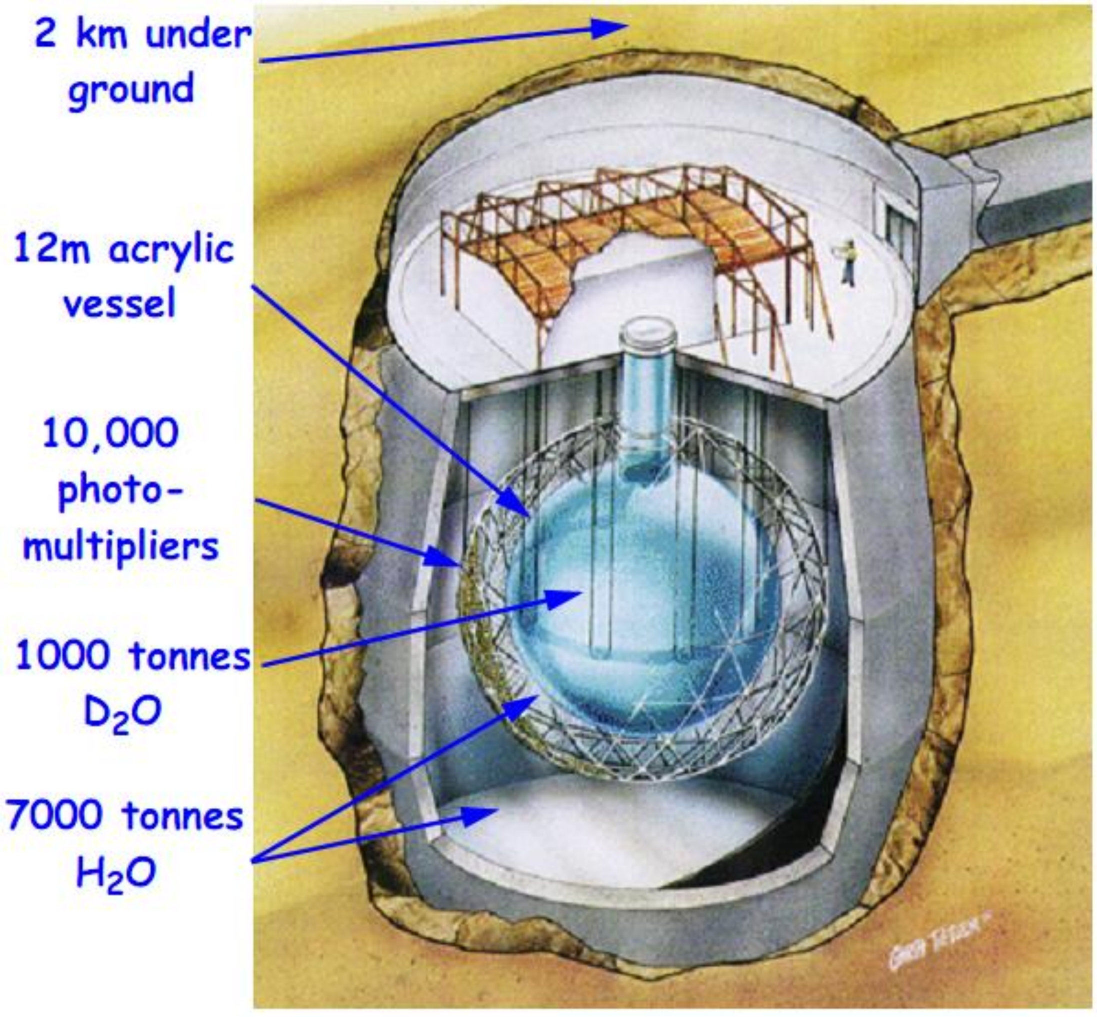
GTID: 375971
Evt Num: 376633
Run Num: 5366
Date: 10/16/1999
Time: 14:31:22.8212386
Prev/Next: 8.6 ms / 4.7 ms
Trigger: 20LB,20,100H,100M,100L,
Pk/Int/Dif: 18 / 187 / 0

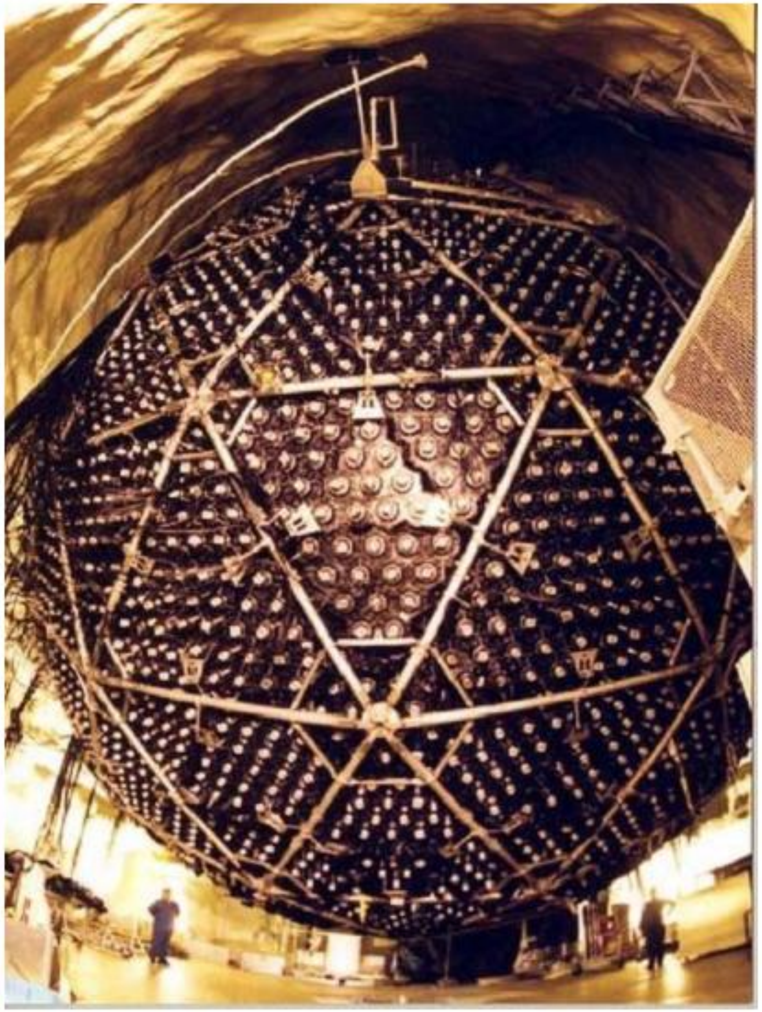


The Sudbury Neutrino Observatory SNO

…… detecting all ν types

Near Sudbury, Ontario





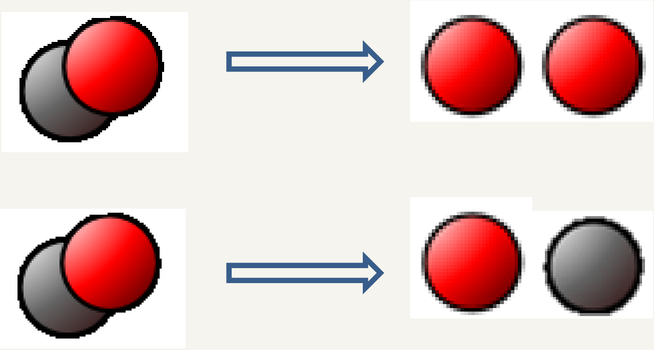
The Sudbury Neutrino Observatory SNO

CC $\nu_e + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{p} + \mathrm{e}^-$

Possible only for electron ν

NC $\nu_x + \mathrm{d} \rightarrow \mathrm{p} + \mathrm{n} + \nu_x$

Equal cross section for all ν flavors

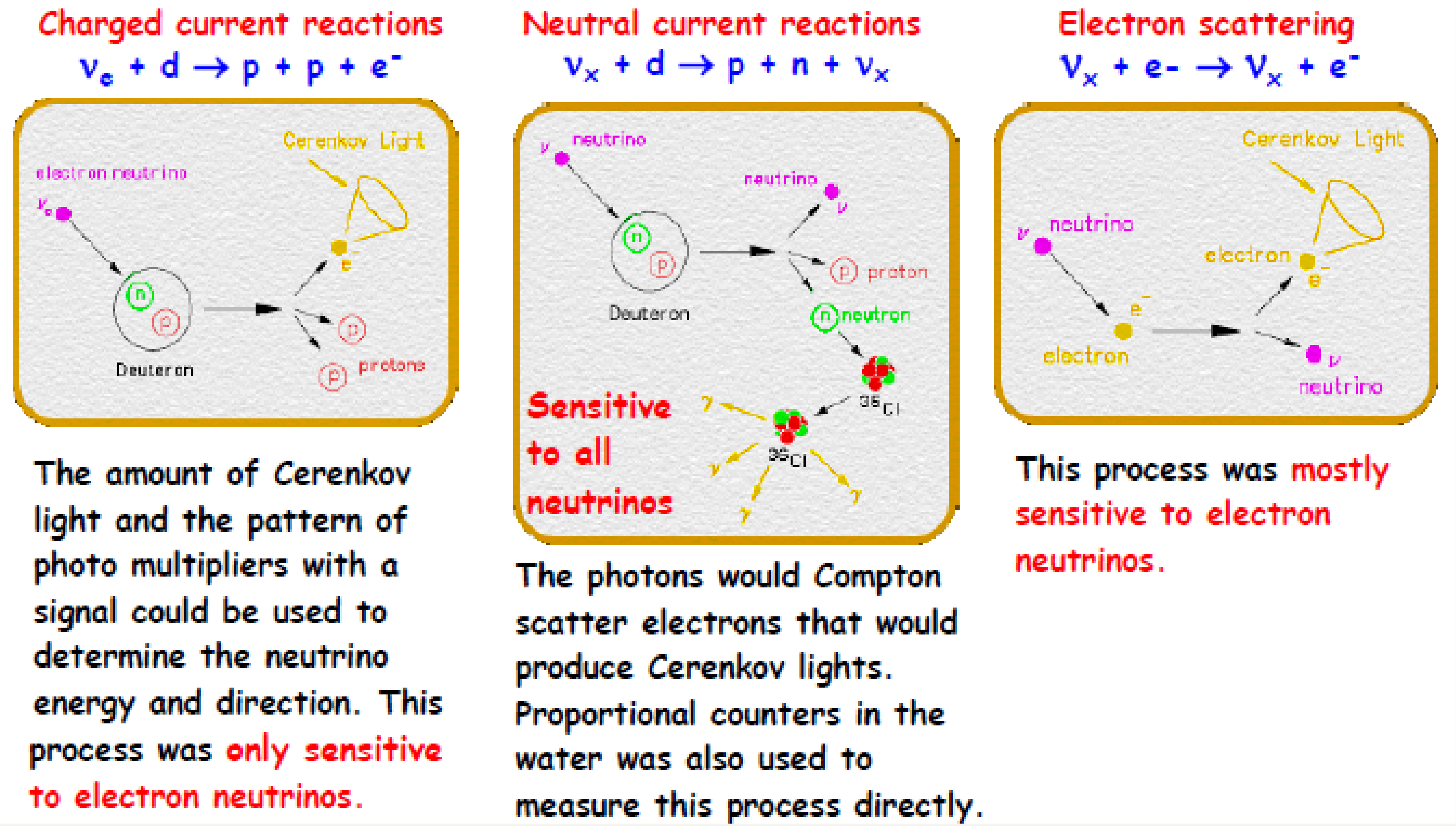


Experiment	**Theory**
$\phi_{CC} = 1.68\ ^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.}) \cdot 10^6\ cm^{-2}s^{-1}$ $\phi_{NC} = 4.94\ ^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.}) \cdot 10^6\ cm^{-2}s^{-1}$	**The total flux calculated with the solar standard model is (*BPS07*)** $(4.7 \pm 0.5) \cdot 10^6\ cm^{-2}s^{-1}$

$$\begin{cases} \phi_{CC} = \phi_{\nu_e} \\ \phi_{NC} = \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} \end{cases}$$

$$\frac{\phi_{CC}}{\phi_{NC}} = \frac{1.68}{4.94} = \frac{1}{3}$$

The Sudbury Neutrino Observatory SNO



Charged current reactions

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

The amount of Cerenkov light and the pattern of photo multipliers with a signal could be used to determine the neutrino energy and direction. This process was only sensitive to electron neutrinos.

Neutral current reactions

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

Sensitive to all neutrinos

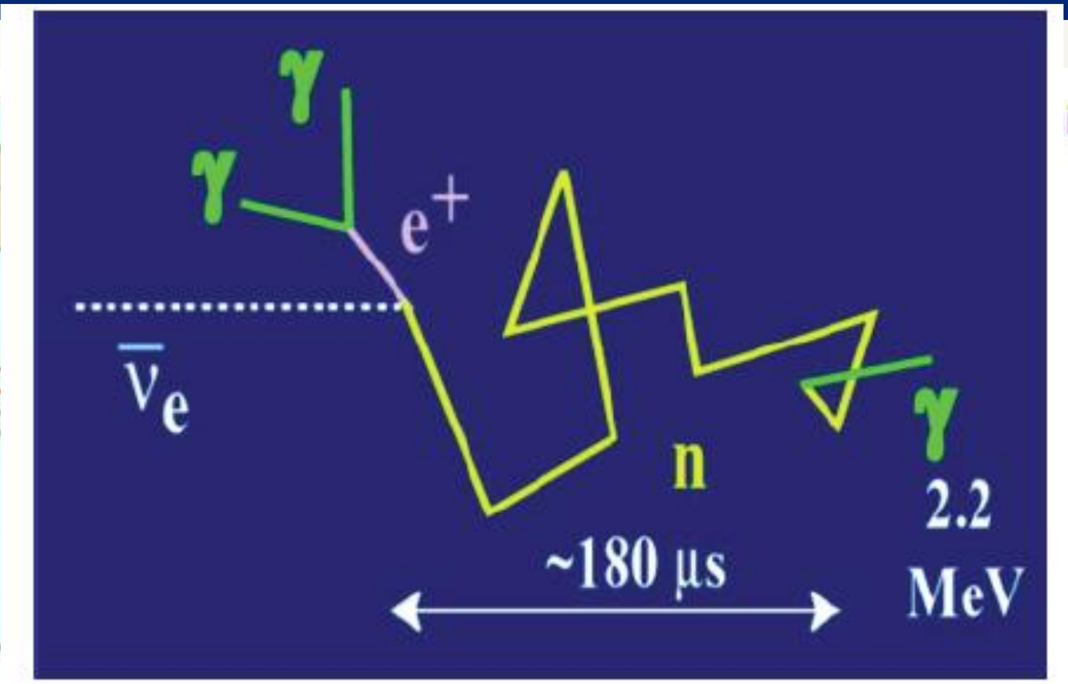
The photons would Compton scatter electrons that would produce Cerenkov lights. Proportional counters in the water was also used to measure this process directly.

Electron scattering

$\nu_x + e- \rightarrow \nu_x + e^-$

This process was mostly sensitive to electron neutrinos.

KamLAND



iokande

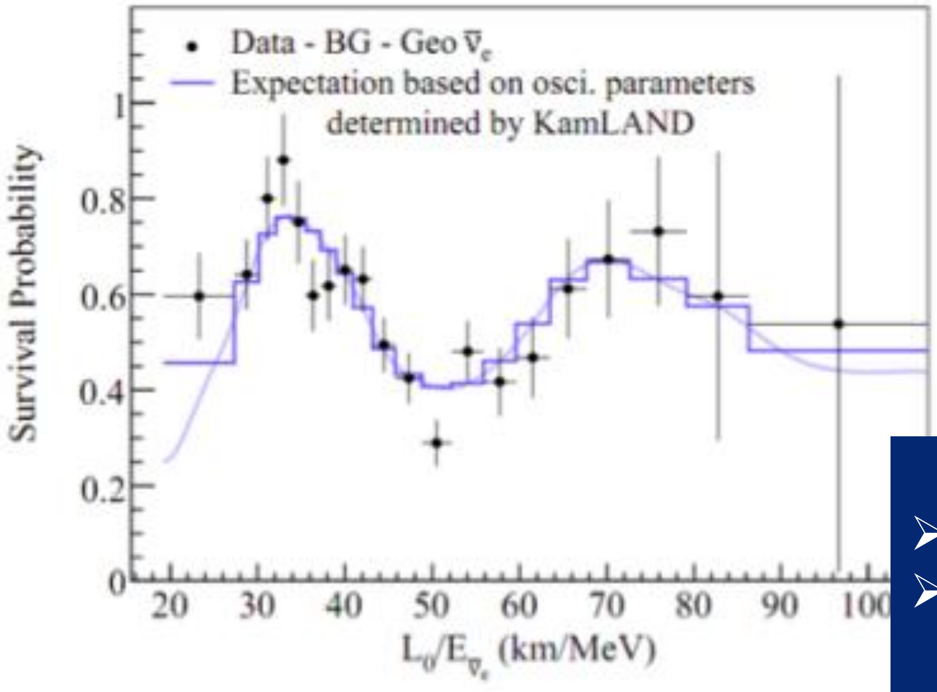
- 70 GW from nuclear power (7% of World total) from reactors within **130-240 km**
- Liquid scintillator detector, 1789 PMTs
- Detection via inverse beta decay: $\nu_e + p \rightarrow e^+ + n$

  Followed by $e^+ + e^- \rightarrow \gamma + \gamma$ prompt

  $n + p \rightarrow d + \gamma(2.2\,\mathrm{MeV})$ delayed

Phys. Rev. Lett. **90** (2003) 021802,

KamLAND Results



Anti-ν_e survival probability

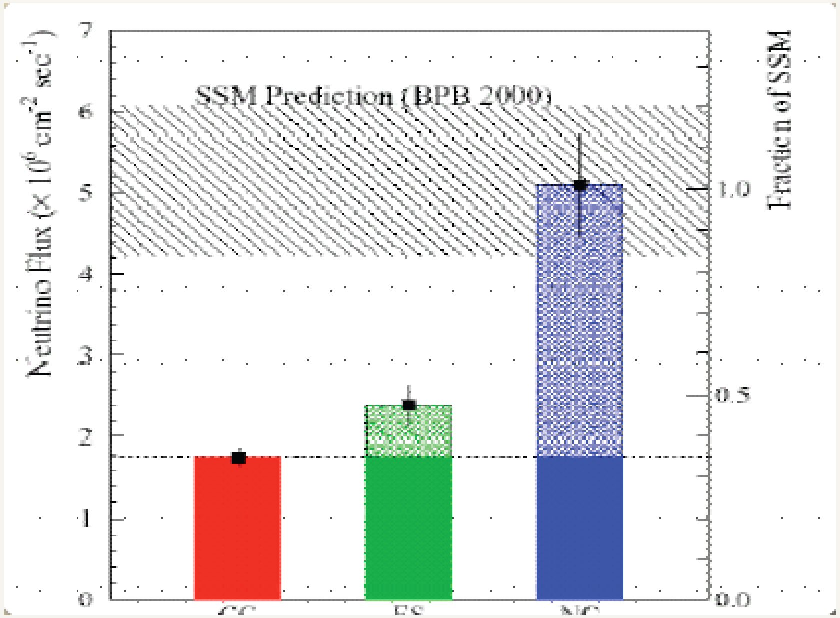
- ➢Observe: 1609 events
- ➢Expect : 2179±89 events (if no oscillations)

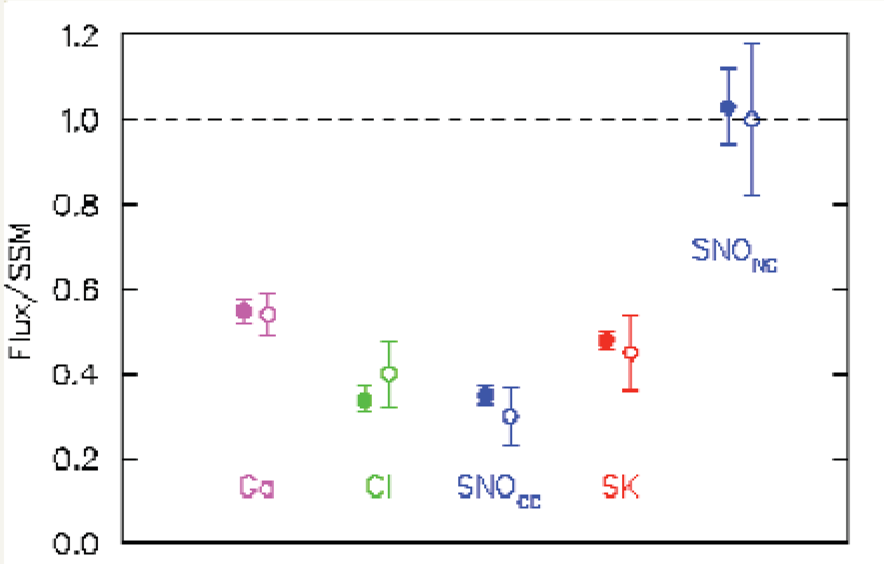
- ➢Clear evidence of electron anti-neutrino Oscillations consistent with results from Solar neutrinos.

$\Delta m^2_{12} = 7.59^{+0.21}_{-0.21}\ 10^{-5}\ eV^2$

$\Theta_{12} \approx 34.4^o$

Solar nötrino problemi/çözümü



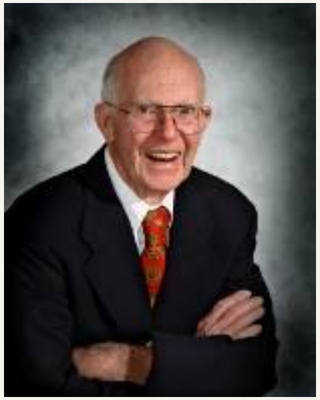


- ➢Güneş hesaplanan sayıda nötrino üreterek parlamaya devam ediyor fakat sadece ν_e degil ν_μ ve ν_τ üreterek.

- ➢Hem Bahcall hemde Davis yanılmadı.

Solar nötrino problemi/çözümü

- April 2002: SNO Experiment
  "Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino"
- October 2002: Nobel prize for
  - Raymond Davis (Homestake)
  - Masatoshi Koshiba (Superkamiokande)
- December 2002:
  "First Results from KamLAND: Evidence for Reactor Anti-Neutrino Disappearance"


Raymond Davis


Masatoshi Koshiba

Borexino detector

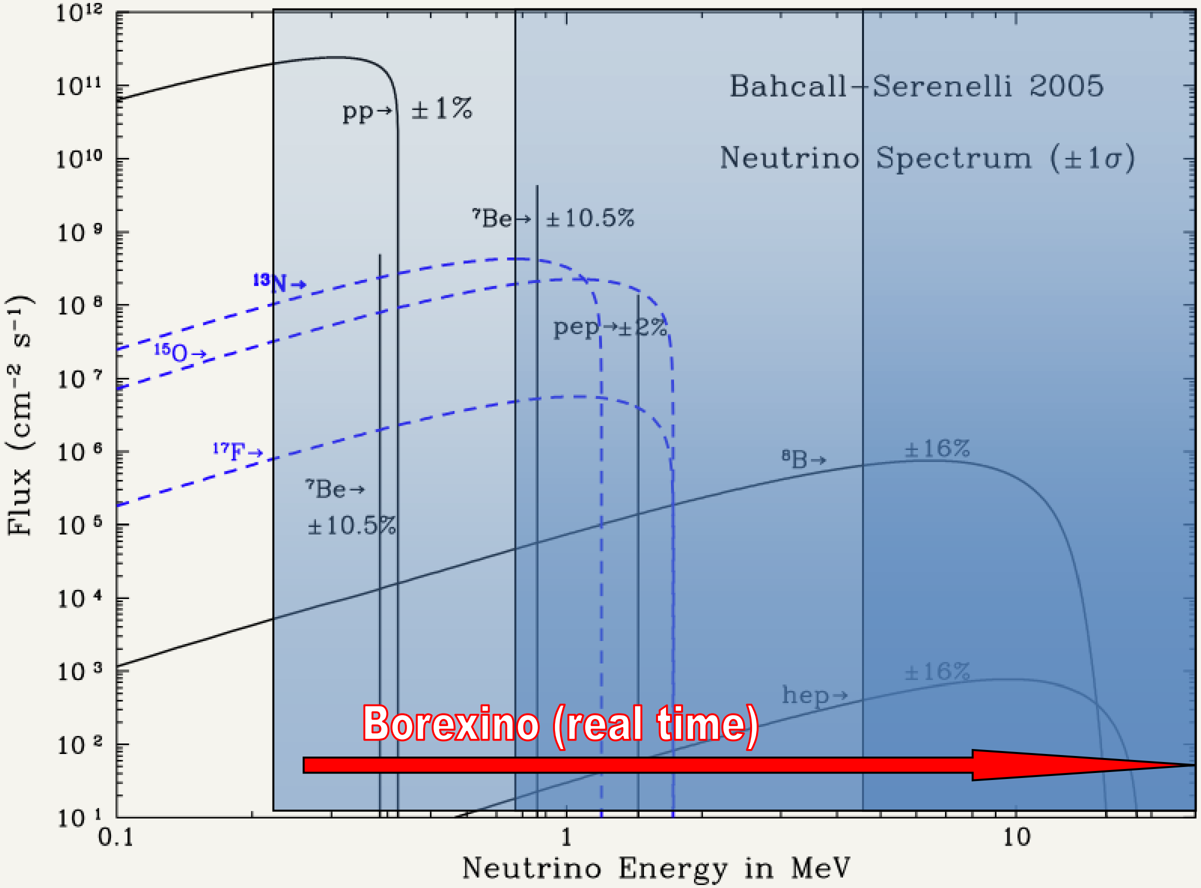
Radiochemical

Real time measurement
(only 0.01 %!)

Gallex
SAGE

Homestake

SNO &
SuperKamiokande



$E_{th} \sim 200$ keV

Borexino is able to measure neutrino coming from the Sun in real time with low energy (~ 200 keV) and high statistic.

→ It is possible to distinguish the different neutrino contributions.

Borexino Detection Principle

Elastic scattering (ES) on electrons in very high purity liquid scintillator

$$\nu + e^- \rightarrow \nu + e^-$$

Detection via scintillation light:

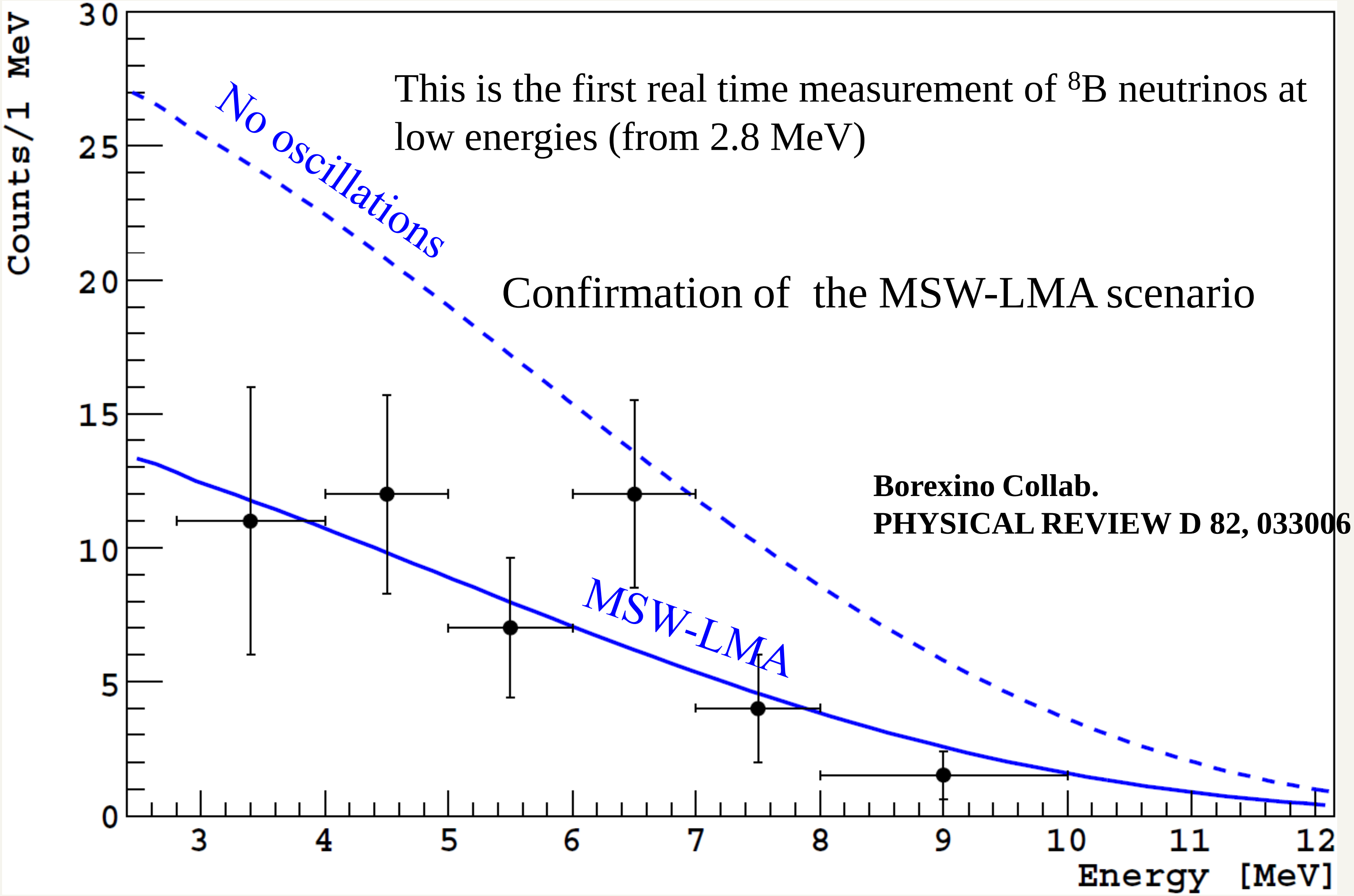
- Very low energy threshold
- Good position reconstruction
- Good energy resolution
- Good alpha/beta discrimination

But…

- No direction measurement
- The ν induced events can't be distinguished from other **γ/β** events due to natural radioactivity

<u>Extreme radio-purity of the scintillator is a must!</u>

Results on solar ^{8}B - neutrinos



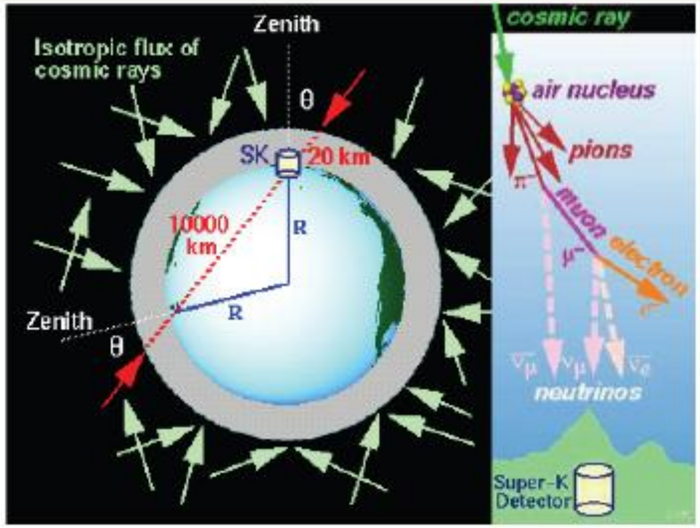
This is the first real time measurement of ^{8}B neutrinos at low energies (from 2.8 MeV)

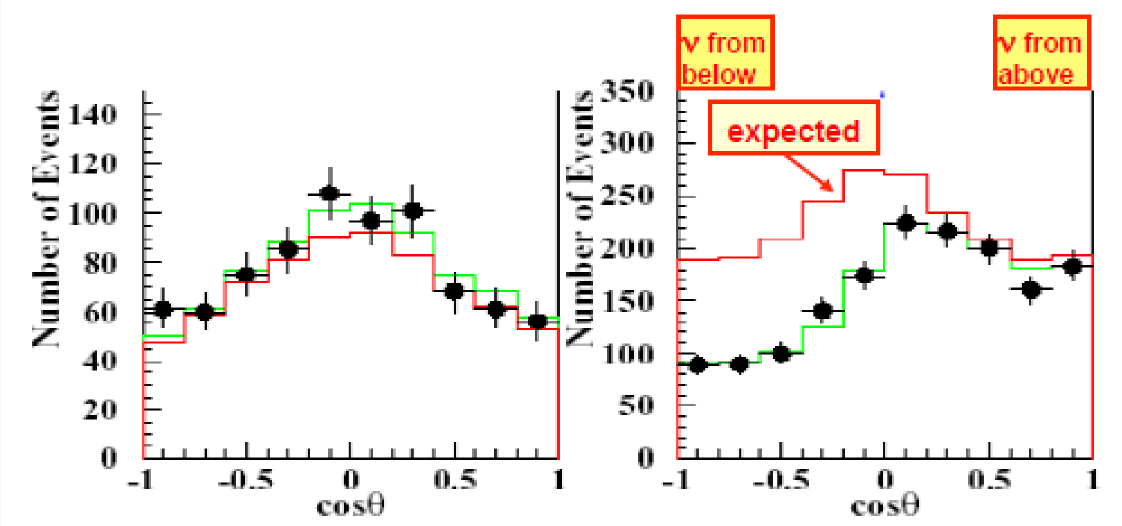
Confirmation of the MSW-LMA scenario

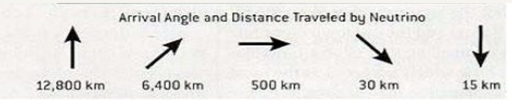
Borexino Collab.
PHYSICAL REVIEW D 82, 033006 (2010)

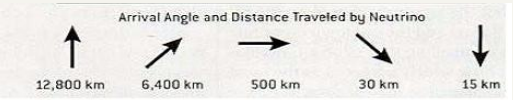
SuperKamiokande Results

- ➢Typical energy: E_ν~1 GeV (much greater than solar neutrino-no confusion)
- ➢Identify ν_e and ν_μ interactions from nature of Cerenkov rings
- ➢Measure rate as a function of angle with respect to local vertical
- ➢Neutrino coming from above tavel ~20 Km
- ➢Neutrino coming from below (i.e. Other side of the Earth ~12800 km)







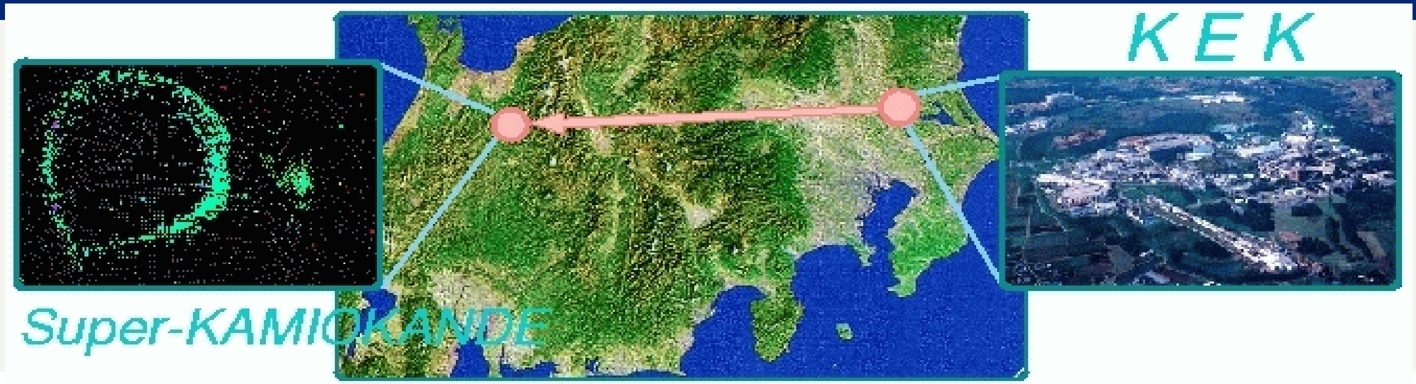


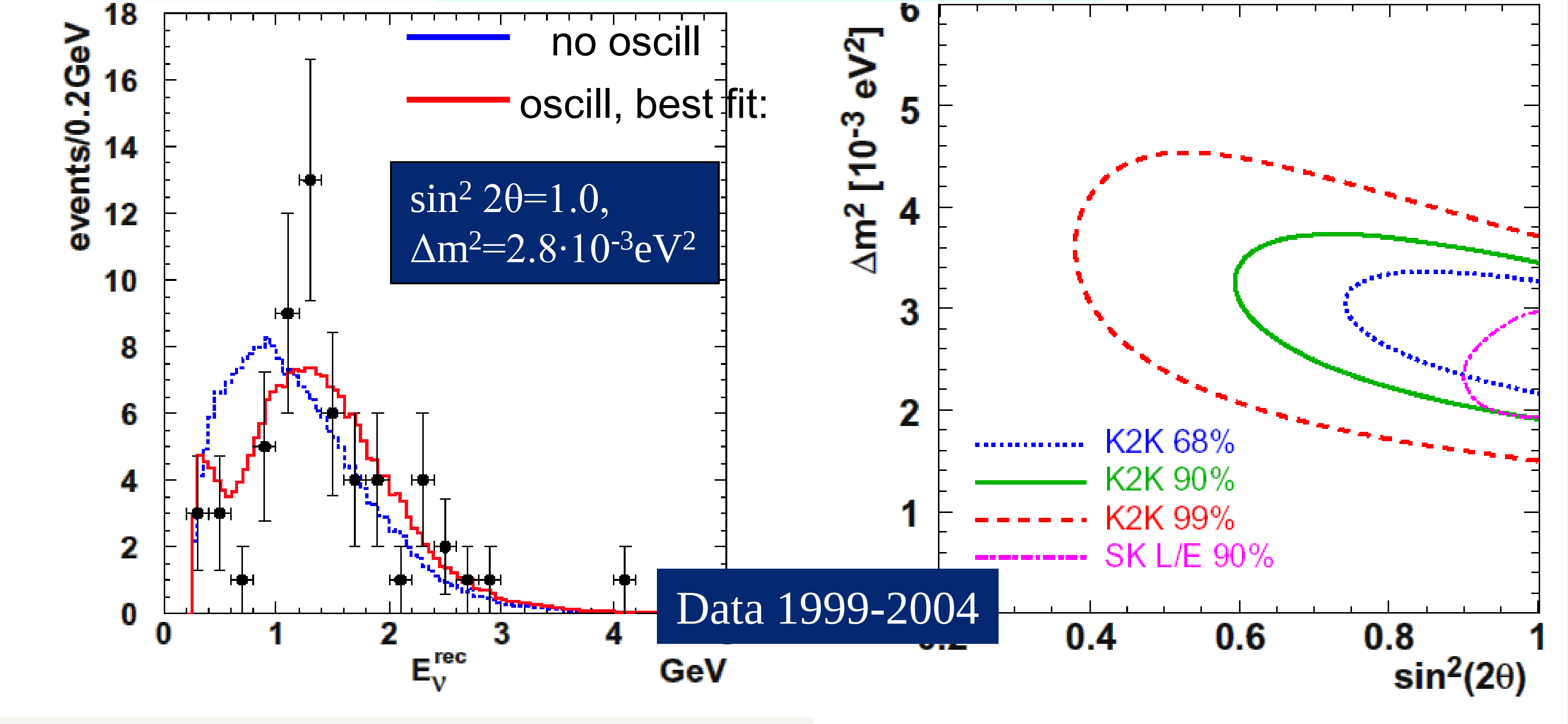
Observed:
Depletion of ν_μ events
But not ν_e events

$2 \times 10^{-3} < \Delta m^2 < 3 \times 10^{-3}\ eV^2$

$\sin^2(2\theta) > 0.90$

K2K

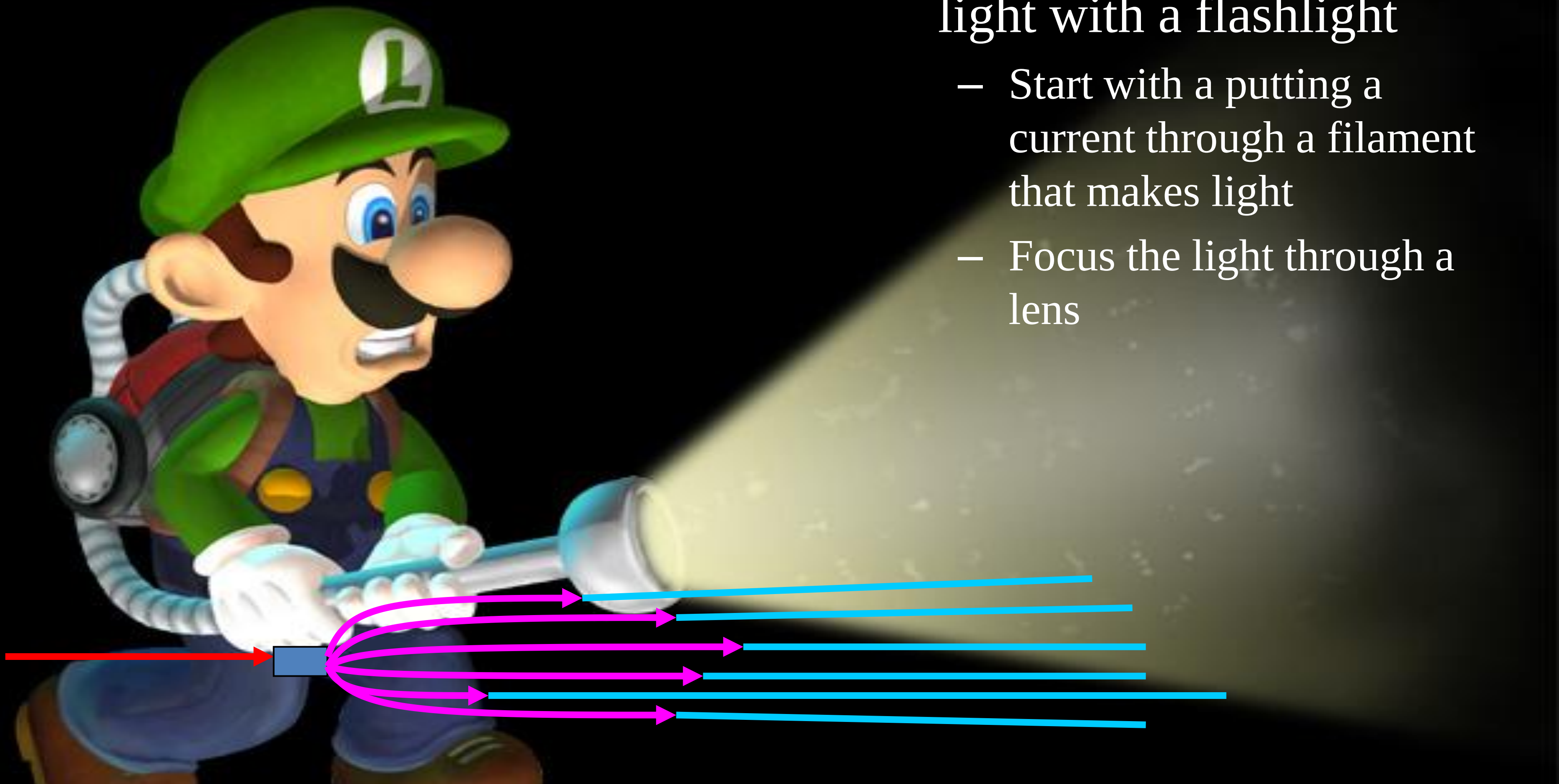




"Measurement of Neutrino Oscillation by the K2K Experiment"
The K2K collaboration, M. H. Ahn et al, hep-ex/0606032, Phys. Rev. D **74**, 072003 (2006)

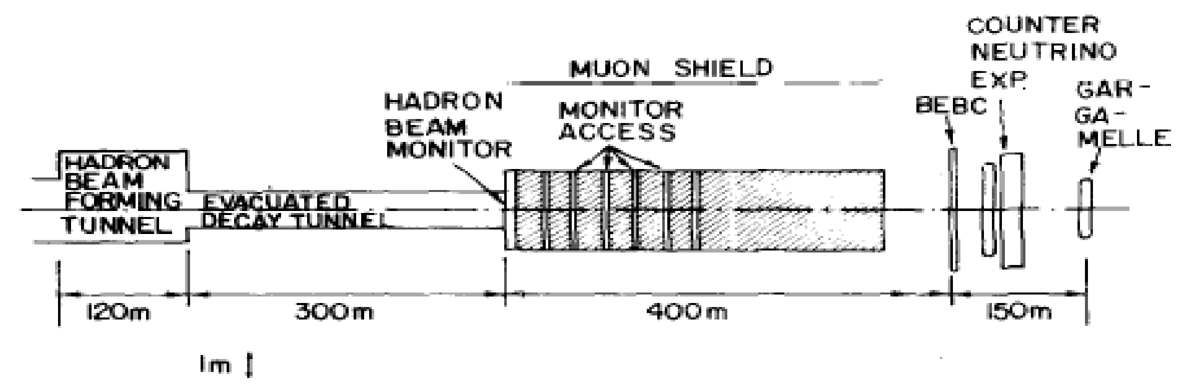
How can you make a beam of neutrinos?

- Like making a beam of light with a flashlight
  - Start with a putting a current through a filament that makes light
  - Focus the light through a lens



protons→target→unstable particles→neutrinos

Hızlandırıcı nötrino deneyleri



- 1965’den günümüze kadar CERN’de nötrino deneyleri yapılmakta.

- *Wide band beam* : maksimum yoğunluk (99% ν_{μ}, 1% ν_e)

ν_{μ} veya anti-ν_{μ}

Nötrino detektörleri

Compromise between resolution measurement and statistics

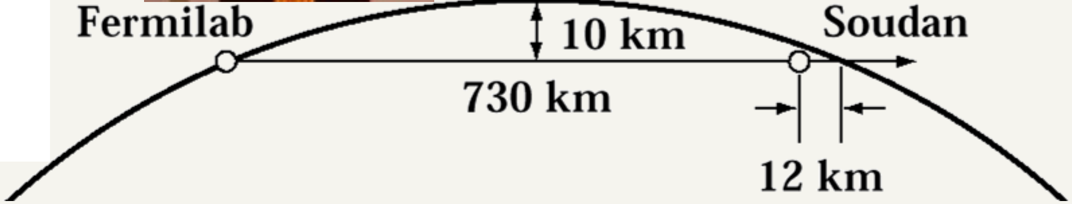
- Pioneer detectors: bubble chambers
  - They studied in interactions in a non-biased way (<1985)
  - GGM, BEBC
  - Precise info but slow technique, limited statistics
- Calorimeter type
  - CDHS, Charm, HPW, CCFR
  - High statistics, limited resolution
- Emulsion technology
  - CHORUS, OPERA high statistics and resolution

Hızlandırıcı nötrino deneyleri

MINOS

Soudan Mine in northern Minnesota.

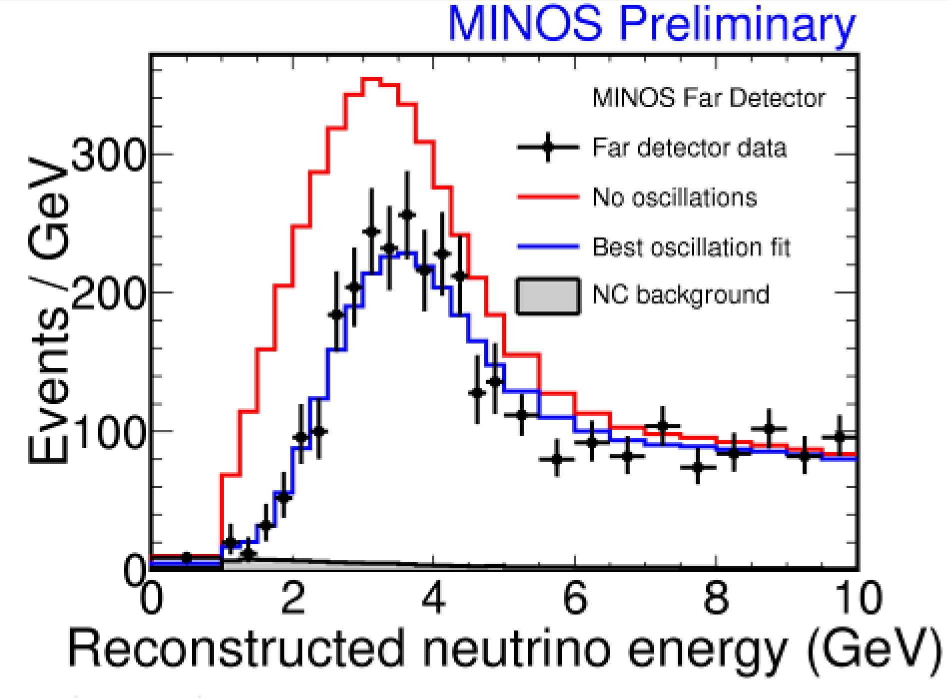
A neutrino beam from Illinois to Minnesota

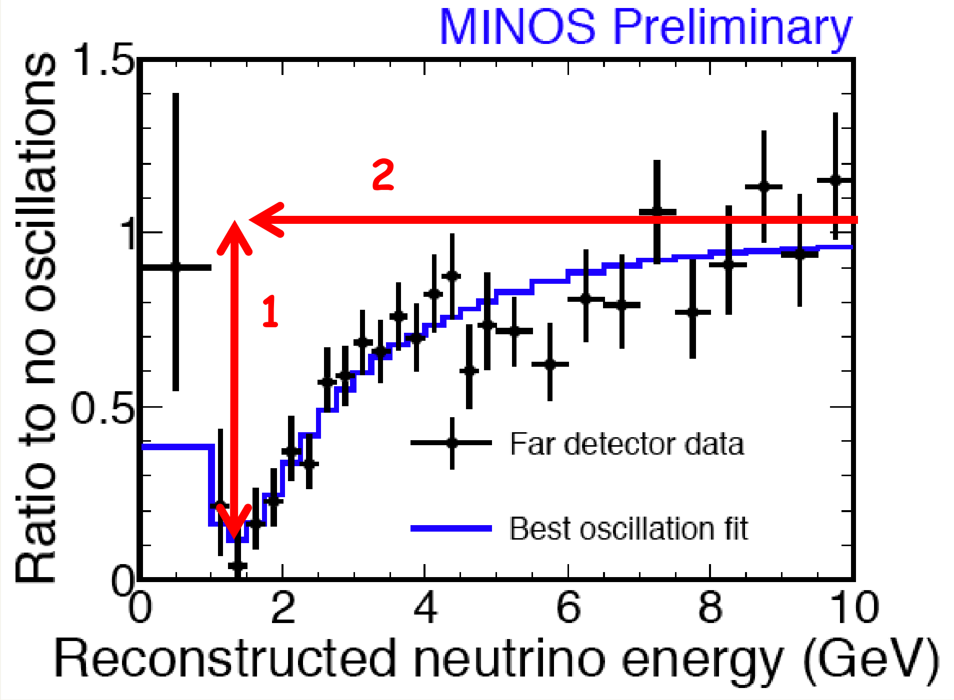


2005-2014

MINOS ν_μ Results

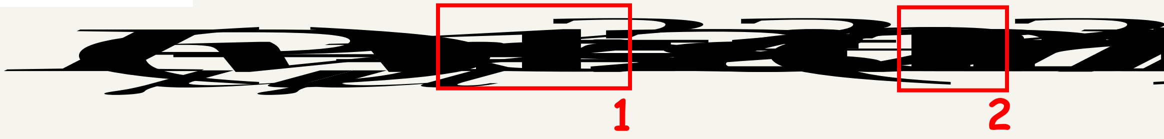
- **Two detector experiment** to reduce systematic errors:
  - Flux, cross-section and detector uncertainties minimized
  - Measure unoscillated ν_μ spectrum at Near detector
    - extrapolate using MC
  - Compare to measured spectrum at Far detector



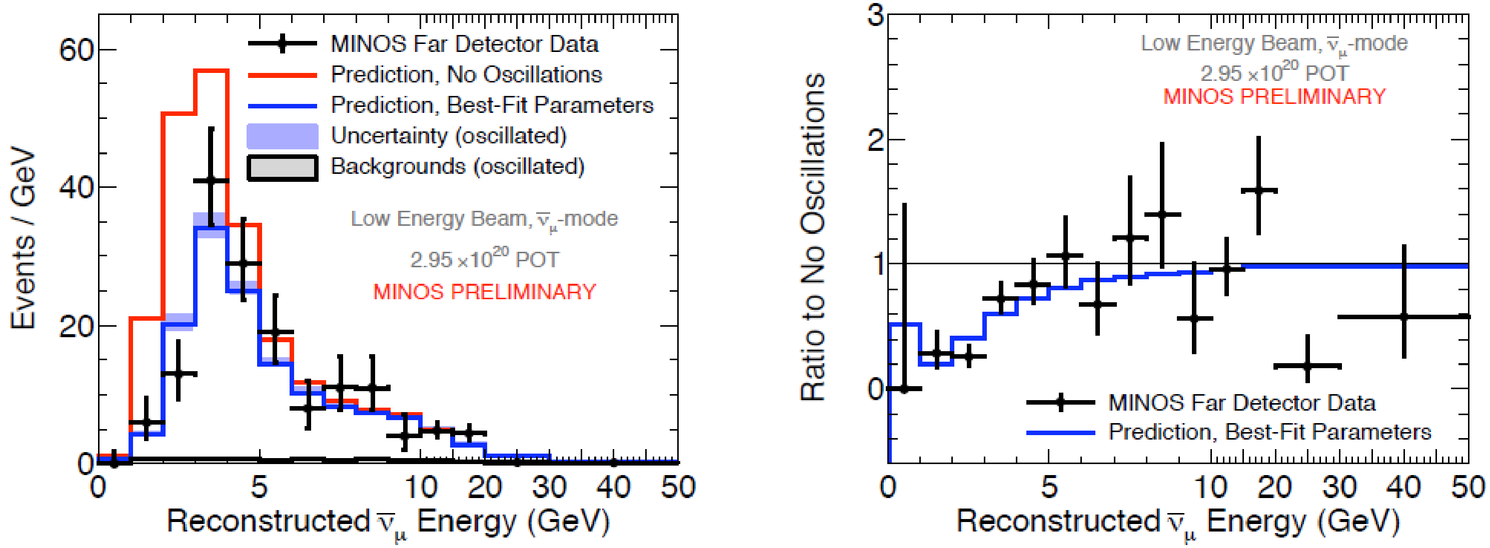


$$|\Delta m^2| = (2.32^{+0.12}_{-0.08}) \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta_{23}) > 0.9\ (90\%\ \mathrm{C.L.})$$



MINOS $\bar{\nu}_\mu$ Results



Prediction, No Oscillations: **273 events**

Observed: **193 events**

Null-oscillations excluded at **7.3σ**

$\bar{\nu}_\mu$ Oscillations Best Fit Parameters

$$|\Delta\bar{m}^2_{\mathrm{atm}}| = [2.62^{+0.31}_{-0.28}(\mathrm{stat}) \pm 0.09(\mathrm{syst})] \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}_{23}) = 0.95^{+0.10}_{-0.11}(\mathrm{stat}) \pm 0.01(\mathrm{syst})$$

ν_e Appearance Results

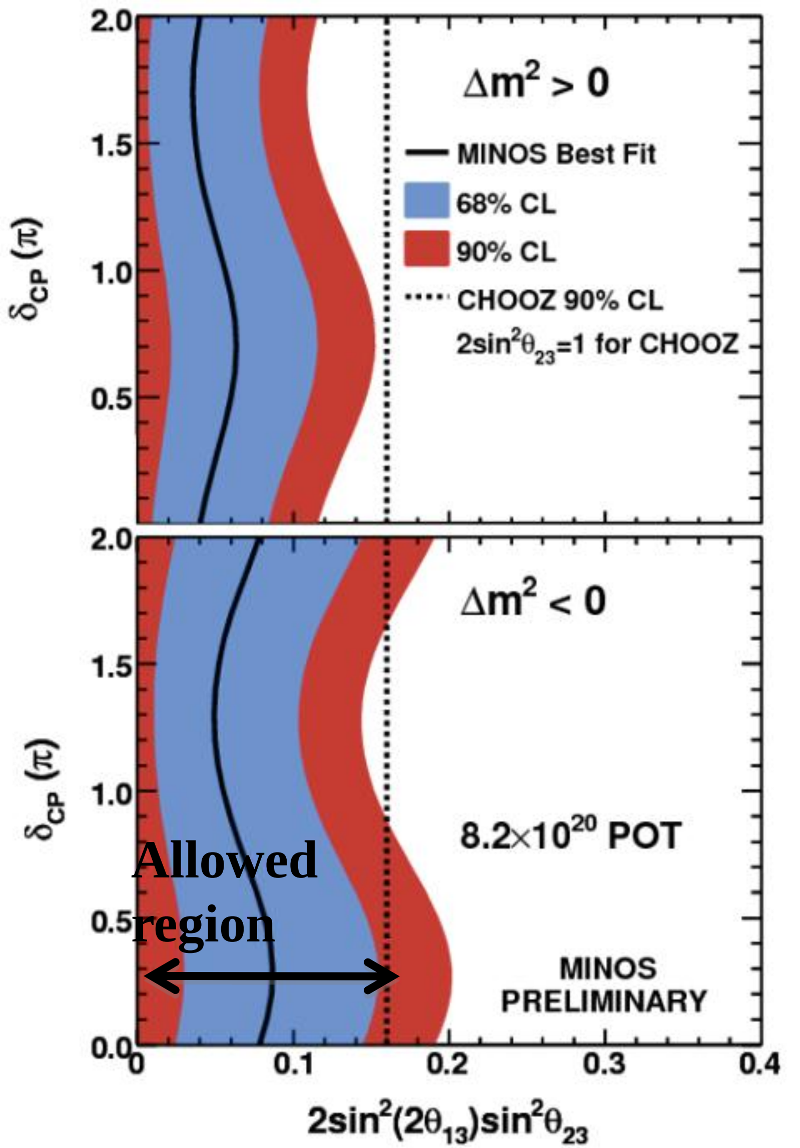
- ☐ Based on ND data, expect:

  49.6 ± 7.0(stat) ± 2.7(syst)
- ☐ Observe: **62** events in the FD

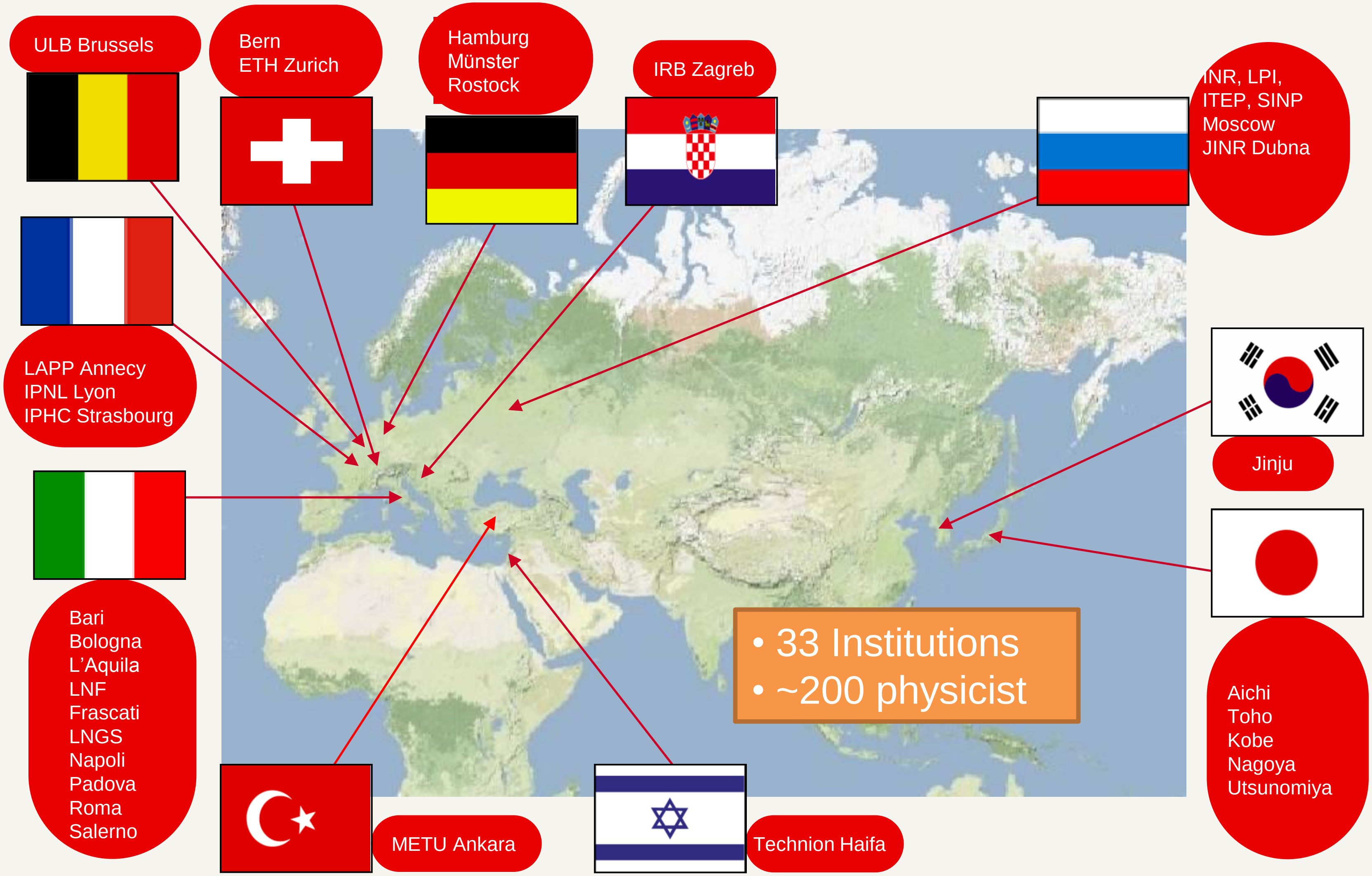
Assuming $\delta_{CP} = 0$, $\theta_{12} = \pi/4$, $|\Delta m^2_{32}| = 2.32 \times 10^{-3}$ eV^2 and normal (inverted) hierarchy:

$\sin^2(2\theta_{13}) < 0.12\ (0.19)$ at 90% C.L.

$\sin^2(2\theta_{13}) = 0$ disfavored at 89% C.L.



OPERA Deneyi



ULB Brussels

Bern
ETH Zurich

Hamburg
Münster
Rostock

IRB Zagreb

INR, LPI,
ITEP, SINP
Moscow
JINR Dubna

LAPP Annecy
IPNL Lyon
IPHC Strasbourg

Jinju

Bari
Bologna
L'Aquila
LNF
Frascati
LNGS
Napoli
Padova
Roma
Salerno

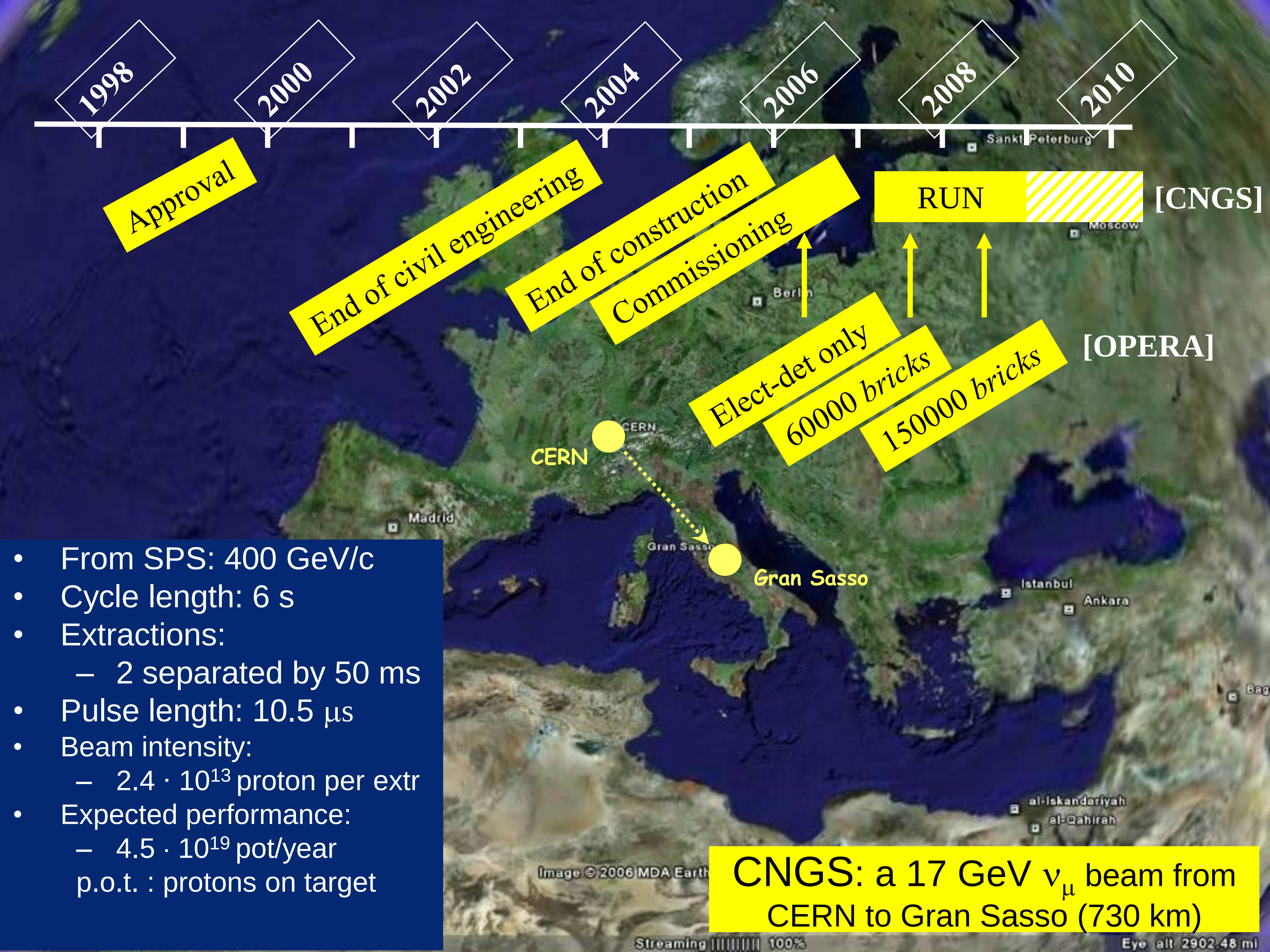
Aichi
Toho
Kobe
Nagoya
Utsunomiya

METU Ankara

Technion Haifa

- 33 Institutions
- ~200 physicist

CNGS: a 17 GeV ν_μ beam from CERN to Gran Sasso (730 km)



1998
2000
2002
2004
2006
2008
2010

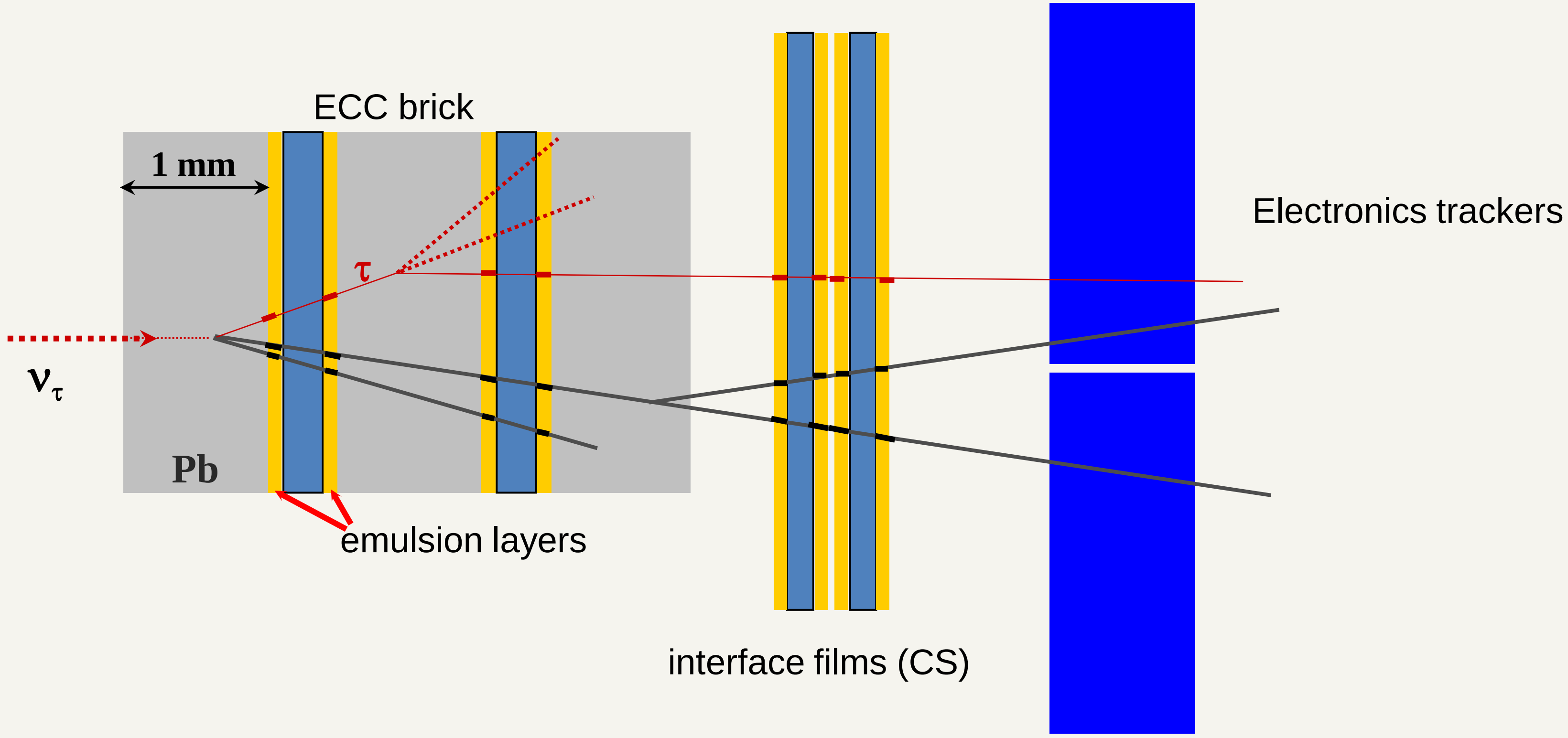
Approval
End of civil engineering
End of construction
Commissioning
RUN
[CNGS]

Elect-det only
60000 bricks
150000 bricks
[OPERA]

- From SPS: 400 GeV/c
- Cycle length: 6 s
- Extractions:
  - 2 separated by 50 ms
- Pulse length: 10.5 μs
- Beam intensity:
  - $2.4 \cdot 10^{13}$ proton per extr
- Expected performance:
  - $4.5 \cdot 10^{19}$ pot/year

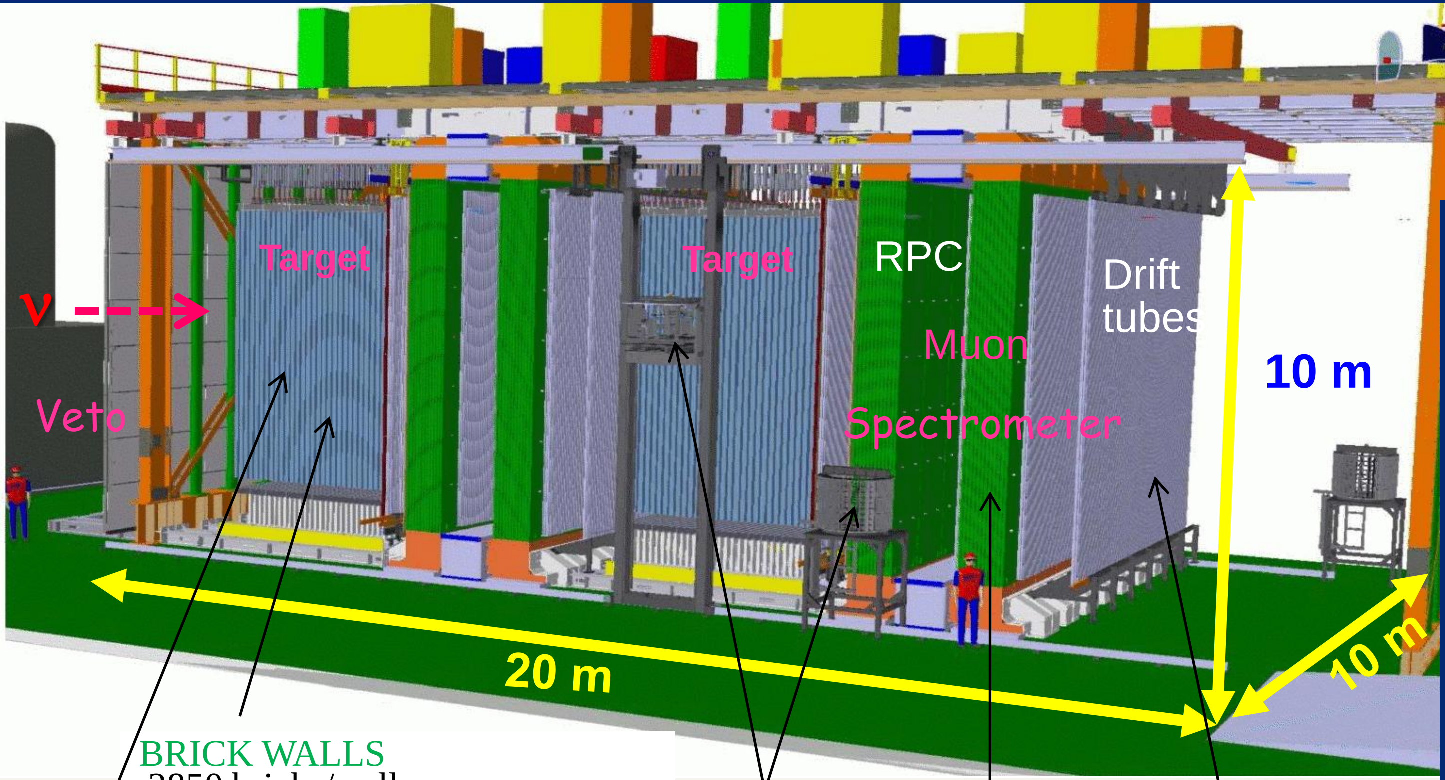
p.o.t. : protons on target

Kullanılan Teknik



- Intense, high-energy muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Use electronic detectors to provide “time resolution” to the emulsions
- and preselect the interaction region

OPERA detektörü



The **bricks** are stand-alone passive detectors

→ **Electronic Detectors** are needed for:

- ➢Triggering, Timing
- ➢Neutrino interactions Location
- ➢Calorimetry
- ➢Muon I.D. and Spectrometry

BRICK WALLS
2850 bricks/wall
- 53 walls
- **150000 bricks ~ 1.25 kton**

BMS
Brick Manipulator System

HIGH PRECISION TRACKERS
6 drift-tube layers/spectrometer
spatial resolution < 0.5 mm

TARGET TRACKERS
- 2x31 scintillator strips walls
- 256+256 X-Y strips/wall
- WLS fiber readout
- 64-channel PMTs
- 63488 channels
- 0.8 cm resolution, 99% e
- rate 20 Hz/pixel @1 p.e.

INNER TRACKERS
- 990-ton dipole magnets
(B= 1.55 T) instrumented with 22 RPC planes
- 3050 m^2, ~1.3 cm res.

OPERA beklenen performans

τ decay channel	B.R. (%)	Signal $\Delta m^2 = 2.5 \times 10^{-3}\ \text{eV}^2$	Background
$\tau \to \mu$	17.7	2.9	0.17
$\tau \to e$	17.8	3.5	0.17
$\tau \to h$	49.5	3.1	0.24
$\tau \to 3h$	15.0	0.9	0.17
Total		10.4	0.75

Main background sources:

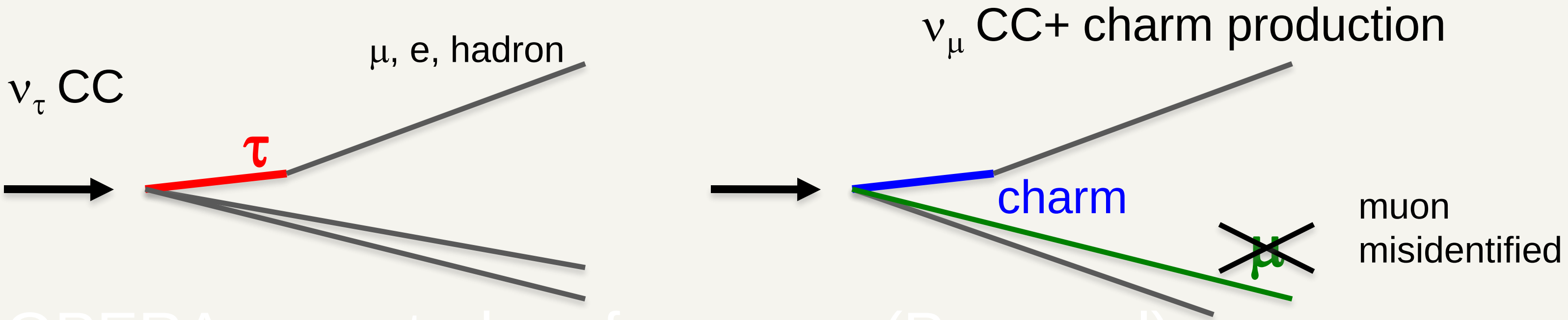
- Production and decay of charmed particles
- Hadron reinteractions
- Large angle muon scattering

Assume 22.5×10^{19} pot

Example: charm BG to tau decays

Signal

Background



ν_τ CC

τ

μ, e, hadron

ν_μ CC+ charm production

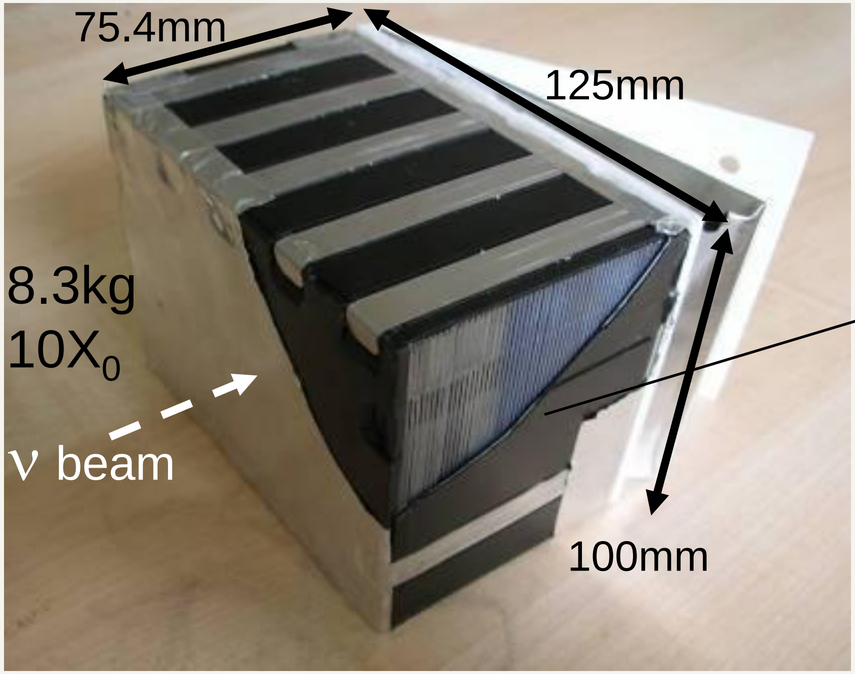
charm

μ

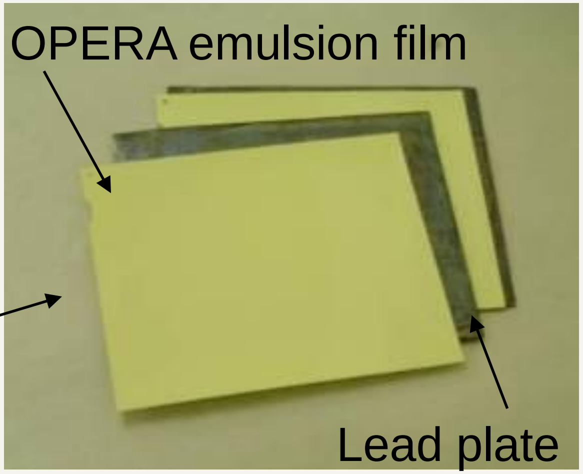
muon
misidentified

OPERA expected performance (Proposal)

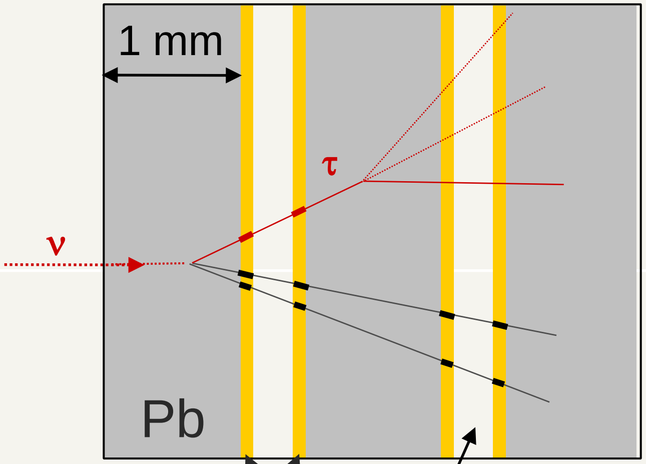
OPERA ECC



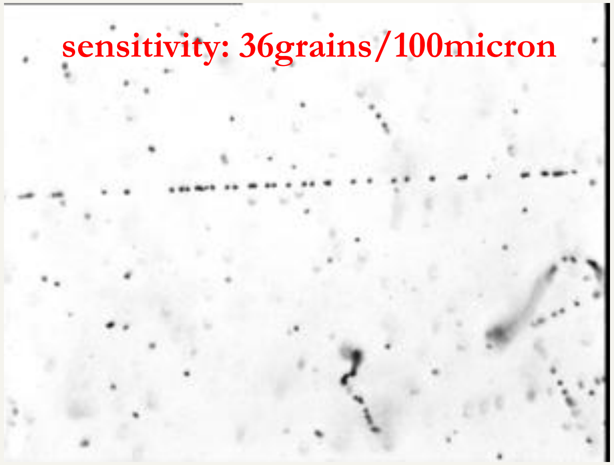
“Emulsion Cloud Chamber”

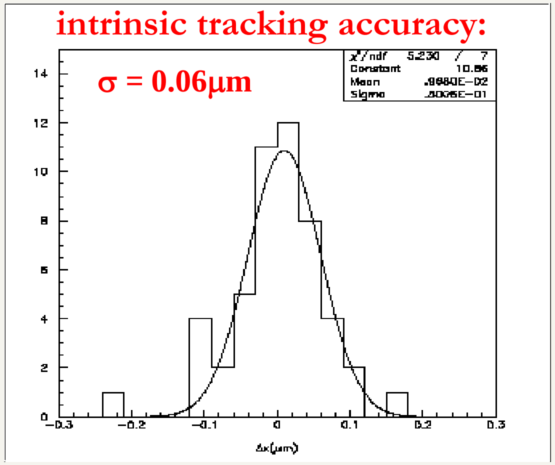


57 emulsion films
56 Pb plates



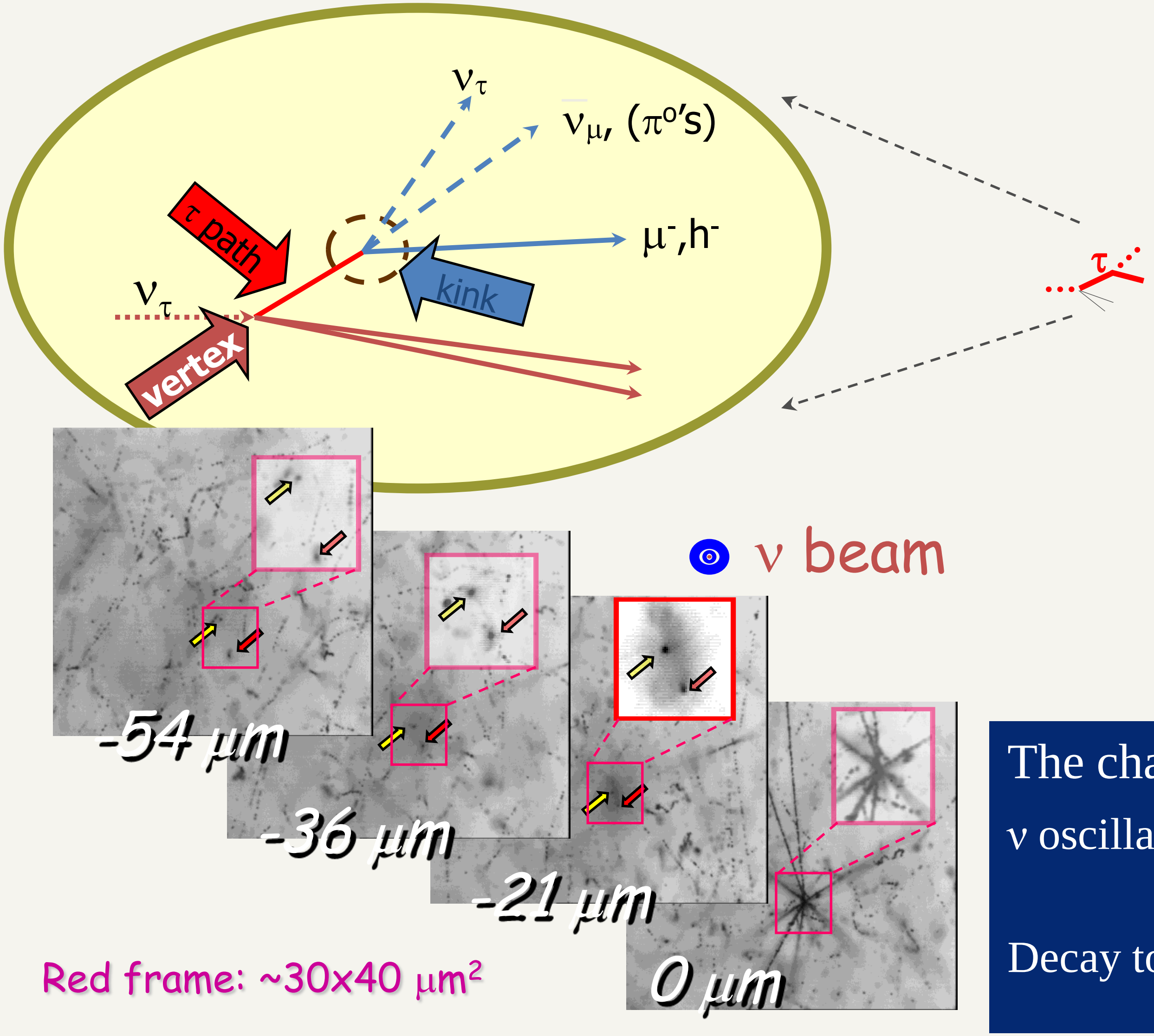
2 emulsion layers (44 μm thick) poured on a 200 μm plastic base


sensitivity: 36grains/100micron

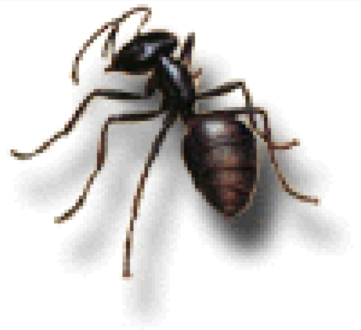

intrinsic tracking accuracy:

σ = 0.06μm

Tau Bozunum Topolojisi



Red frame: ~30x40 μm²



The challenge:

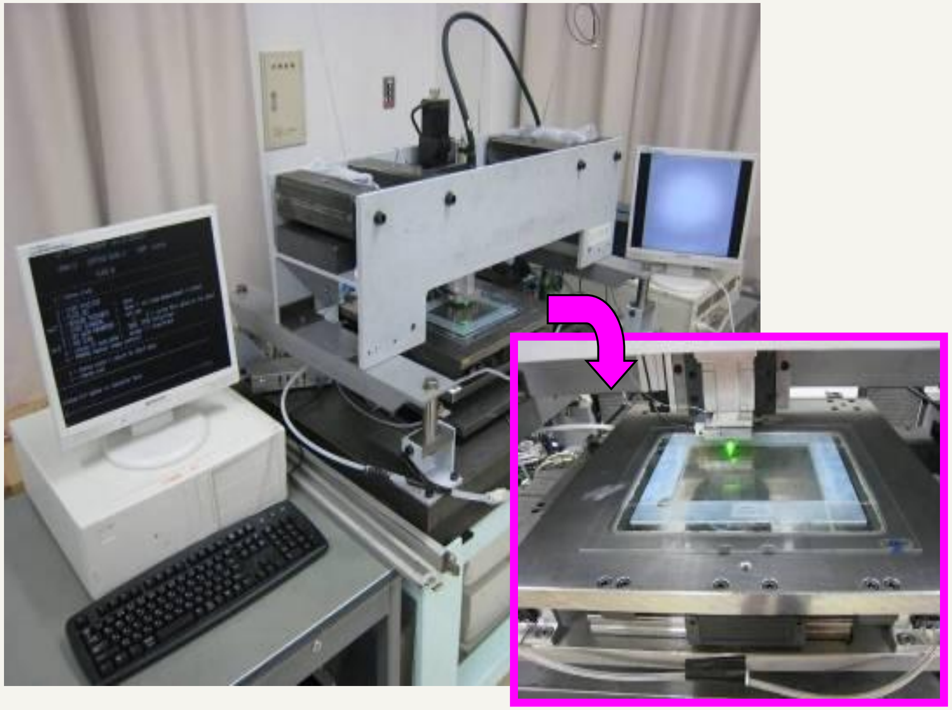
ν oscillation→ massive target
&
Decay topology →Micron resolution

Emülsiyon Tarama Sistemleri

EU: ESS (European Scanning System)

- Scanning speed/system: 20cm^2/h
- Customized commercial optics and mechanics
- Asynchronous DAQ software

Japan: SUTS (Super Ultra Track Selector)



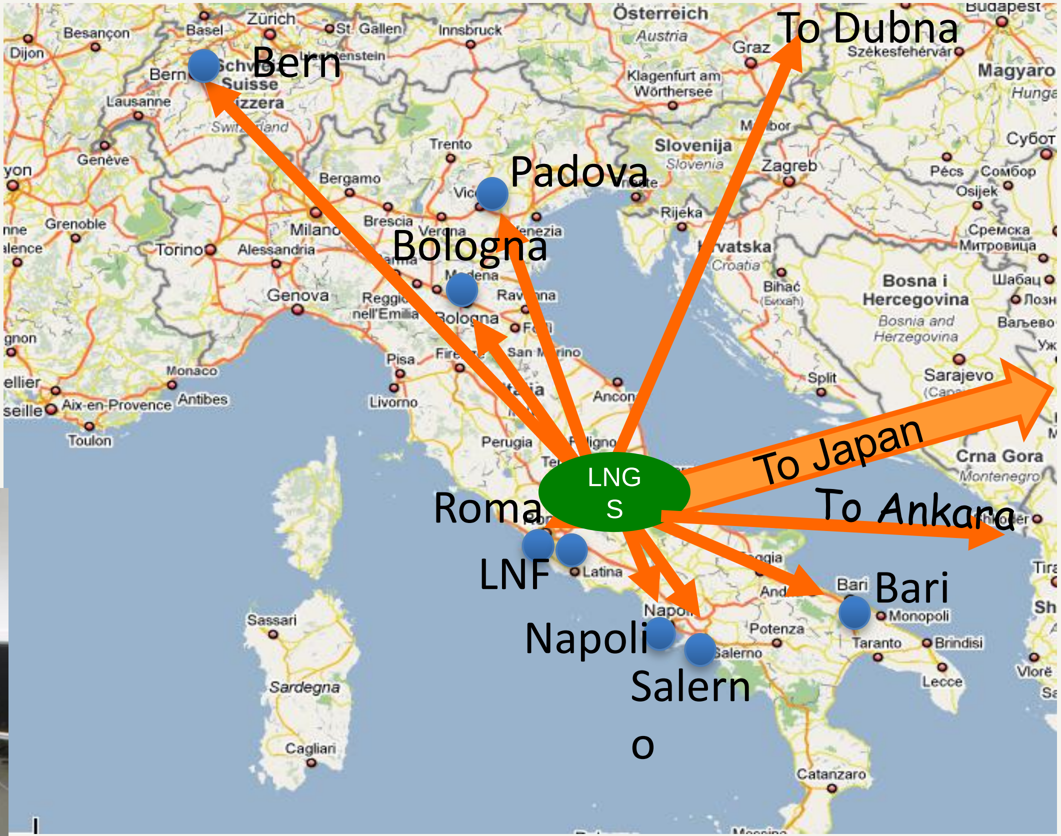
- Scanning speed/system: 75cm^2/h
- High speed CCD camera (3 kHz), Piezo-controlled objective lens
- FPGA Hard-coded algorithms

<u>Both systems demonstrate:</u>

- ~0.3 μm spatial resolution
- ~2 mrad angular resolution
- ~95% base track detection efficiency

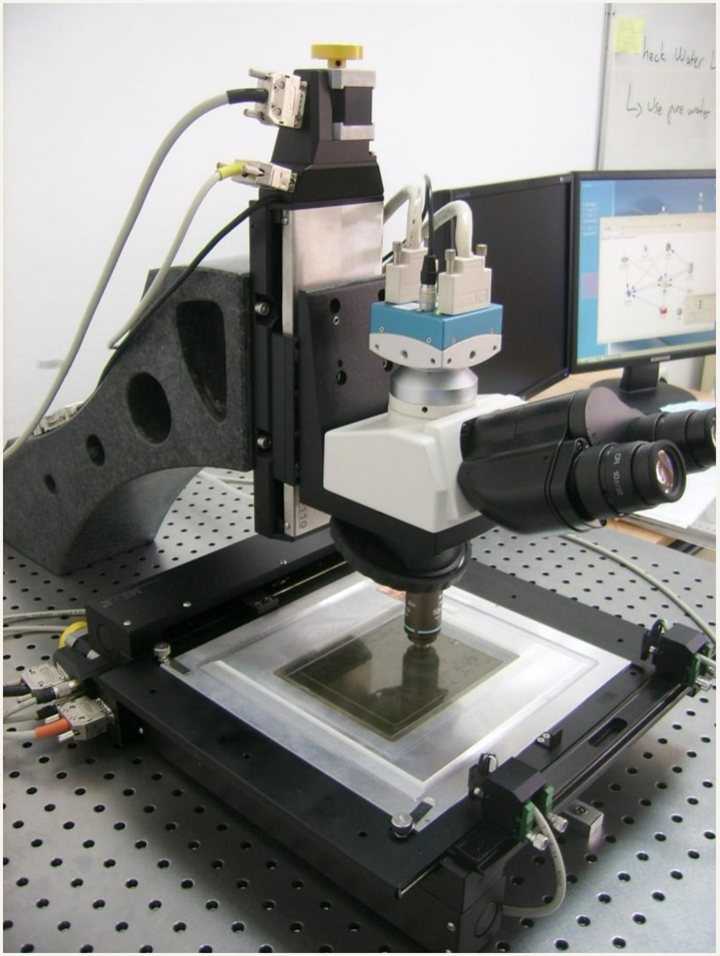
Emülsiyon tarama laboratuarları

- Seçilen ‘Brick’ler Tarama Laboratuarlara gönderiliyor (Toplam 12 lab)

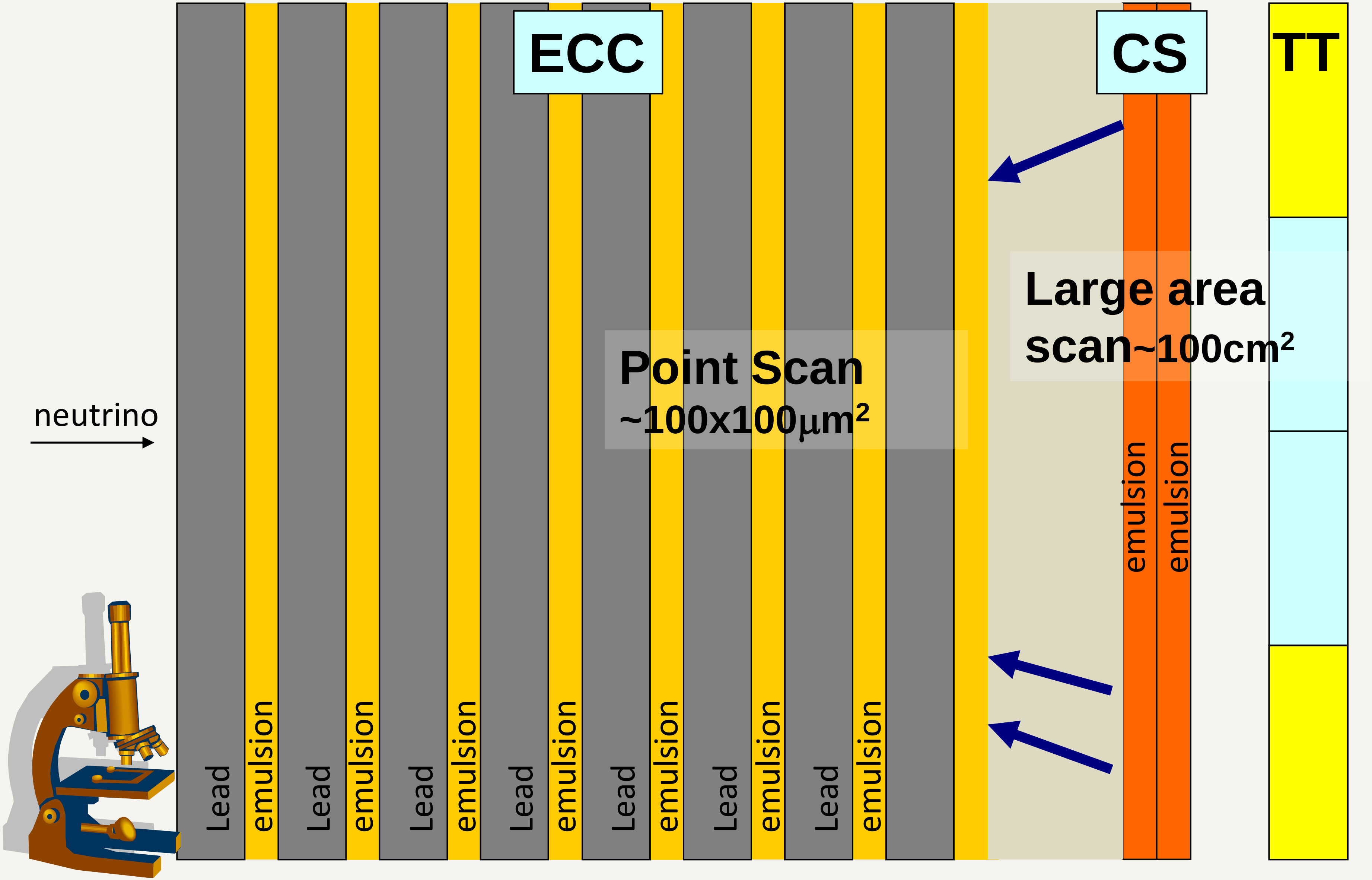


ODTÜ emülsiyon laboratuarı

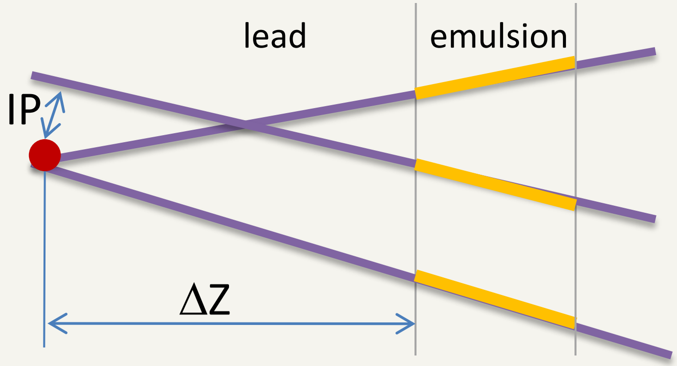
Behzad’ın konuşması

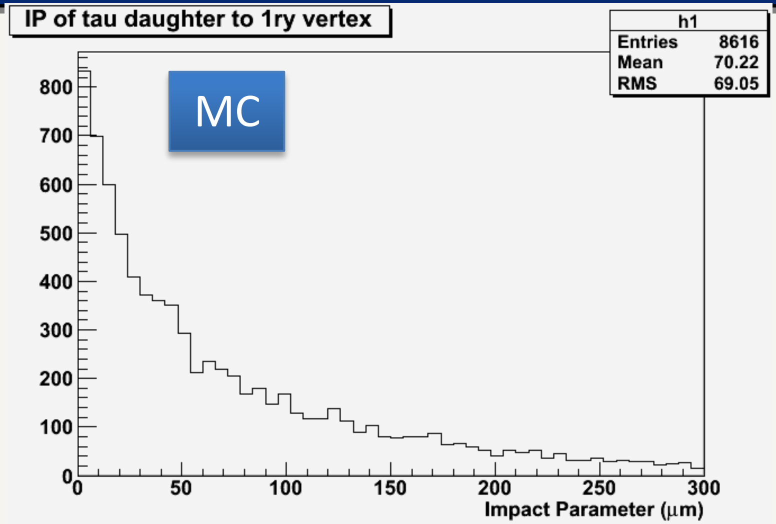


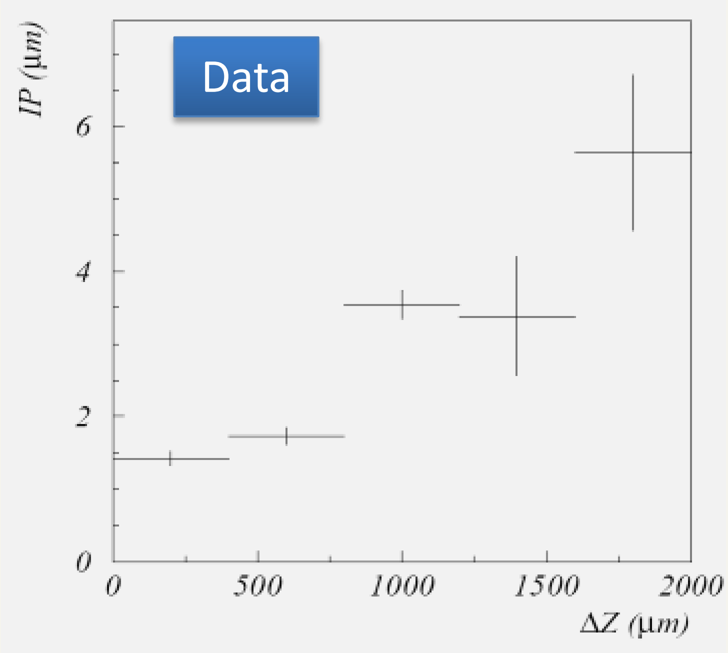
Tau bozunumlarının bulunması

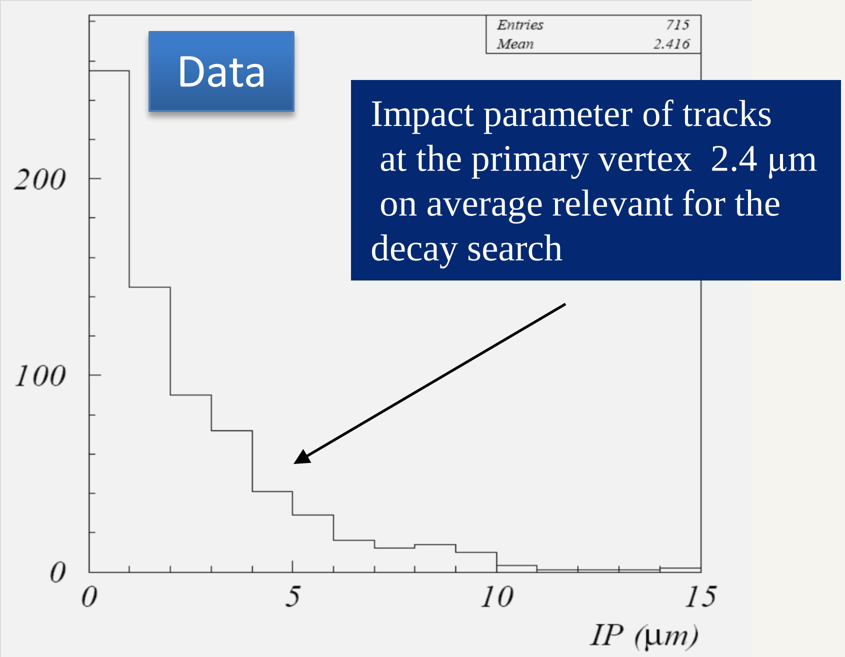


Bozunum noktasının bulunması





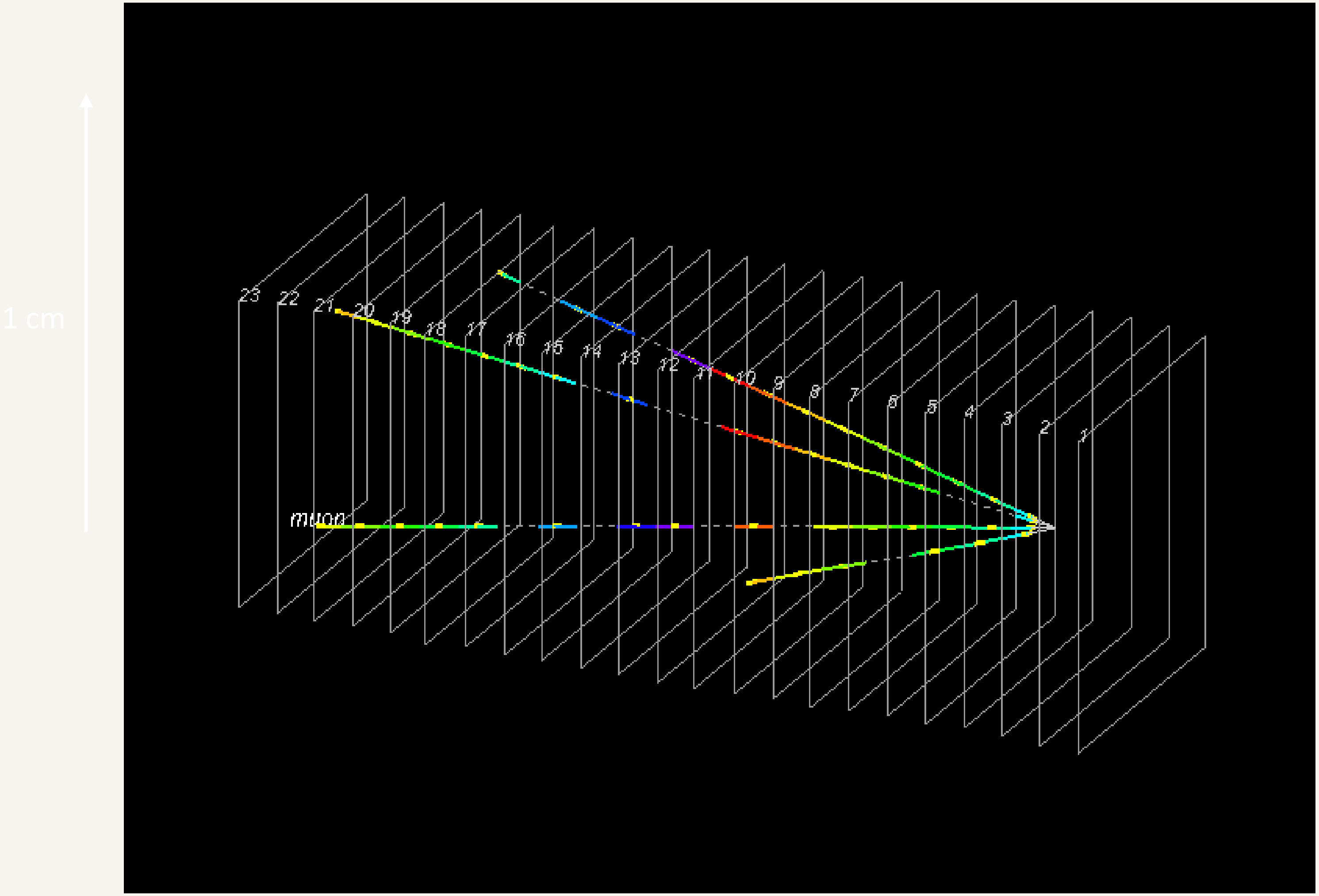




Impact parameter of tracks at the primary vertex 2.4 μm on average relevant for the decay search

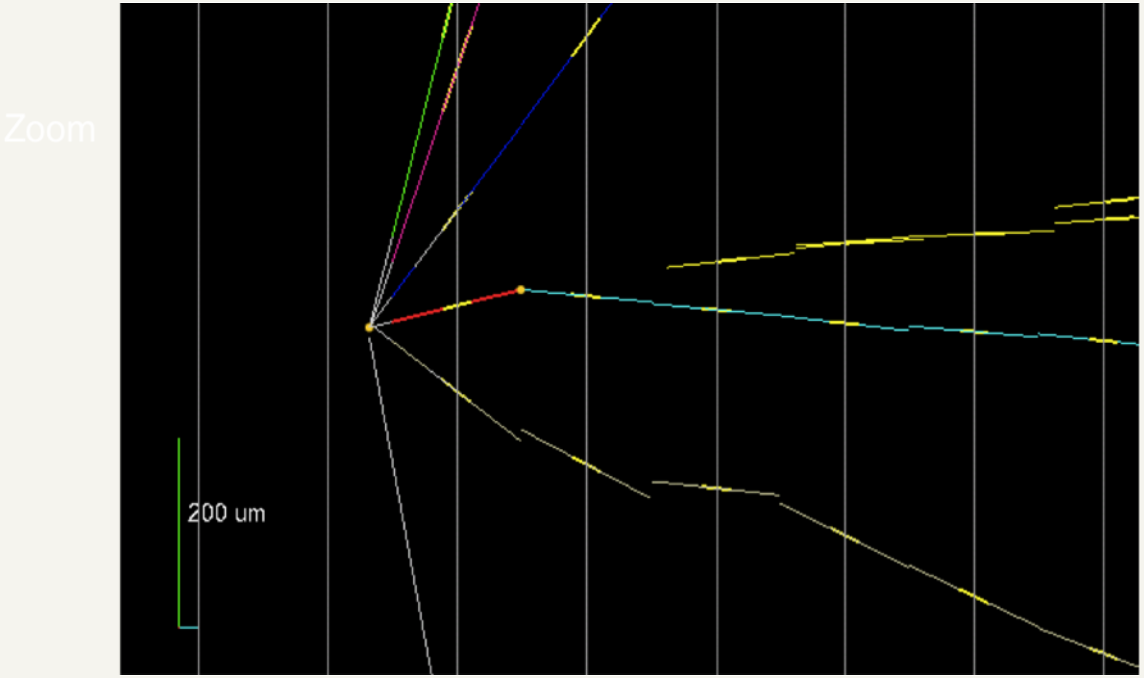
Bulunan nötrino etkileşimi

Emulsion gives 3D vector data, giving a micrometric precision of the vertexing accuracy.
(The frames correspond to scanning area. Yellow short lines → measured tracks.
The other colored lines → interpolation or extrapolation. The colors indicate the Z-depth in the module.)



İlk tau nötrino göründü

The OPERA experiment at the underground Gran Sasso Laboratory: likely seen the first tau-neutrino "appearing" out of several billion of billions muon neutrinos sent from CERN! 20.5.2010



Computer reconstruction of the tau candidate event detected in the OPERA experiment. The presence of track with the "kink" is the indication of the interaction of a tau- neutrino.

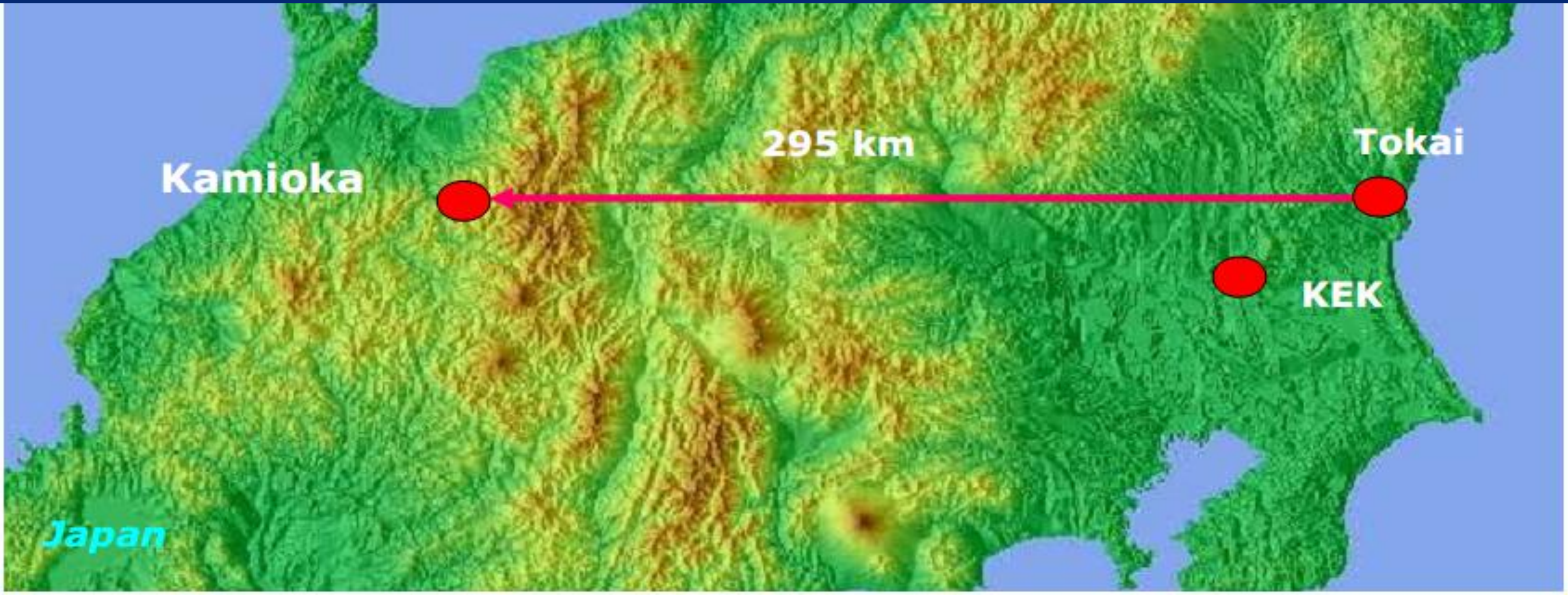
Tokai to Kamioka: T2K

Long Baseline Neutrino Oscillation Experiment

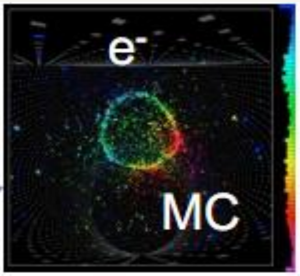
- **A muon neutrino** beam with mean energy 600 MeV (from **J-PARC**, **Japan Proton Accelerator Research Complex**), propogates ~295 km through Japan and is measured at near and far sites.

Aims

- Measure the mixing angle, θ_{13}
- Improve measurement of the atmospheric mass splitting Δm^2_{23}



T2K



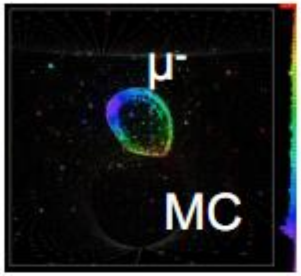
- **ν_e–appearance**

  Signal (CCQE): $\nu_e + n \to e^- + p$; **SK:** single e-like ring

  Backgrounds: beam ν_e and (NC) $\nu_x + n \to n + \pi^0$; $\pi^0 \to \gamma\gamma$

"Counting": compare *observed number* of events (N_{SK}^{obs})
with *expected number* of events in the SK (N_{SK}^{exp})

→ get θ_{13}



- **ν_μ–disappearance**

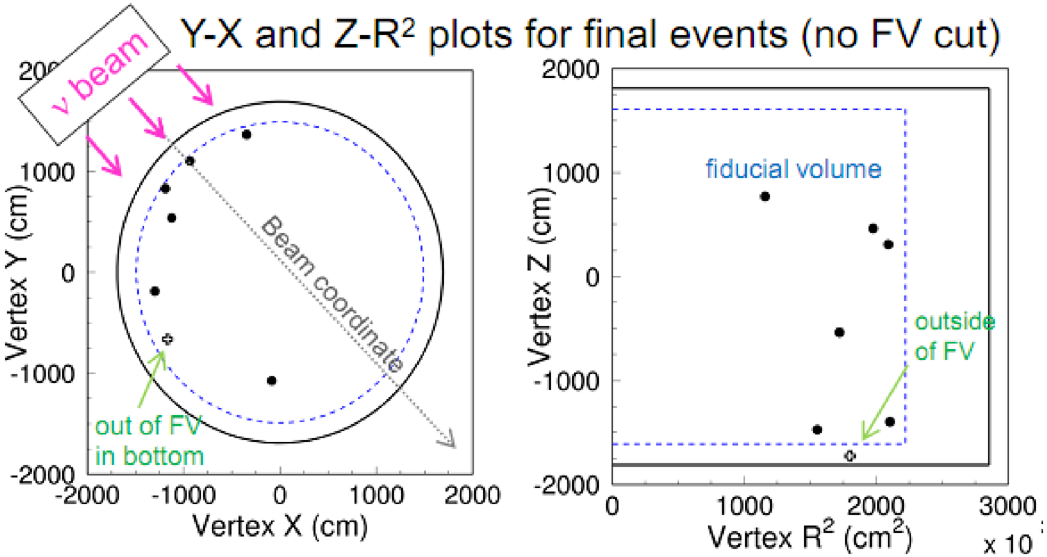
  Signal (CCQE): $\nu_\mu + n \to \mu^- + p$; **SK:** single μ-like ring

  Backgrounds (CC1π): $\nu_\mu + n \to \mu^- + n + \pi^+$; $\nu_\mu + p \to \mu^- + p + \pi^+$

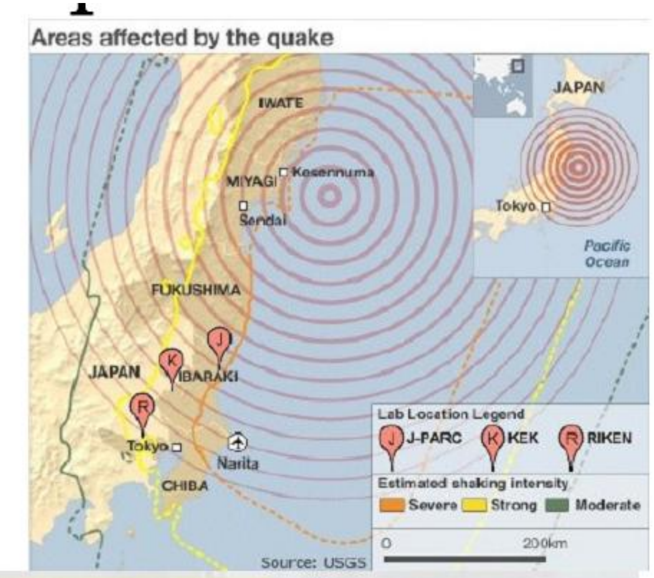
Combination of "counting" and energy spectrum fitting → get (θ_{23}, Δm_{23})

(CCQE= charged current quasi-elastic; NC = neutral current)

T2K *Appearance* Sonuçları


Y-X and Z-R^2 plots for final events (no FV cut)

Cut	Data
Single-ring e-like	8
E_{vis} > 100MeV	7
No decay electron	6
Invariant mass < 100MeV/c	6
Neutrino energy in oscillation region	6



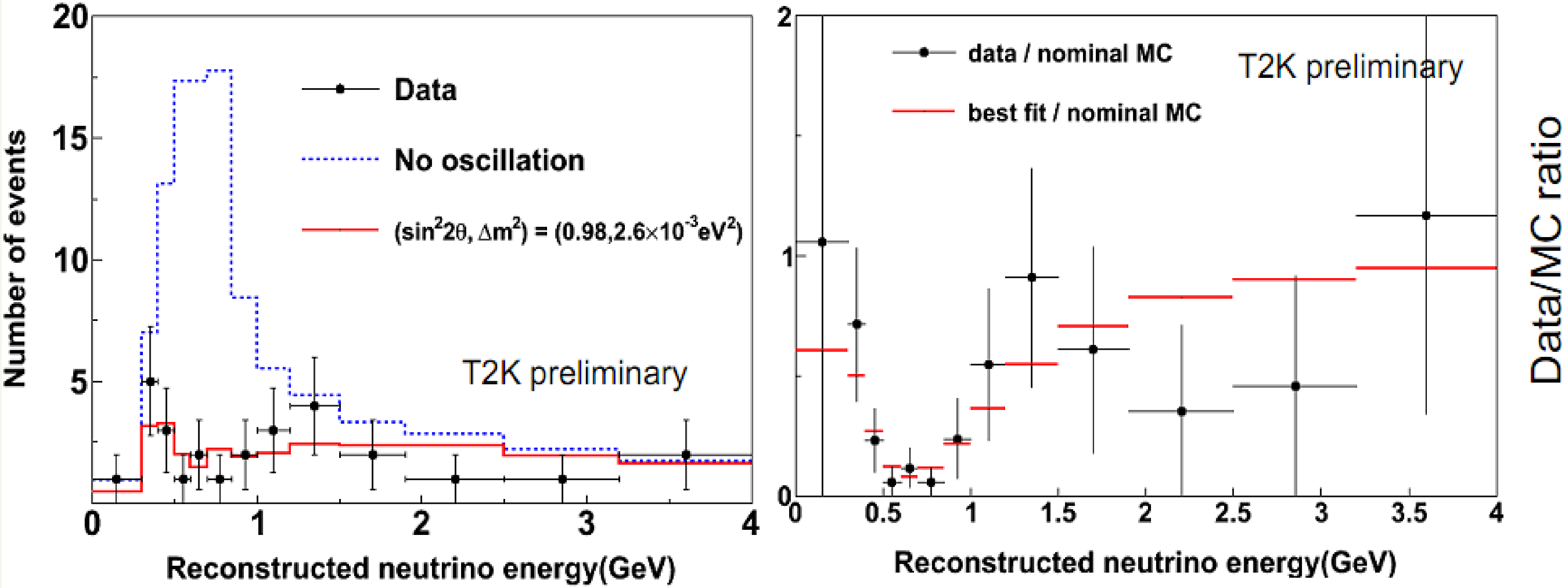
Background breakdown:

Total	ν_μ CC	ν_e CC	NC	solar $\nu_\mu \rightarrow \nu_e$
1.5	0.03	0.8	0.6	0.09

T2K *dissapearance* sonuçları

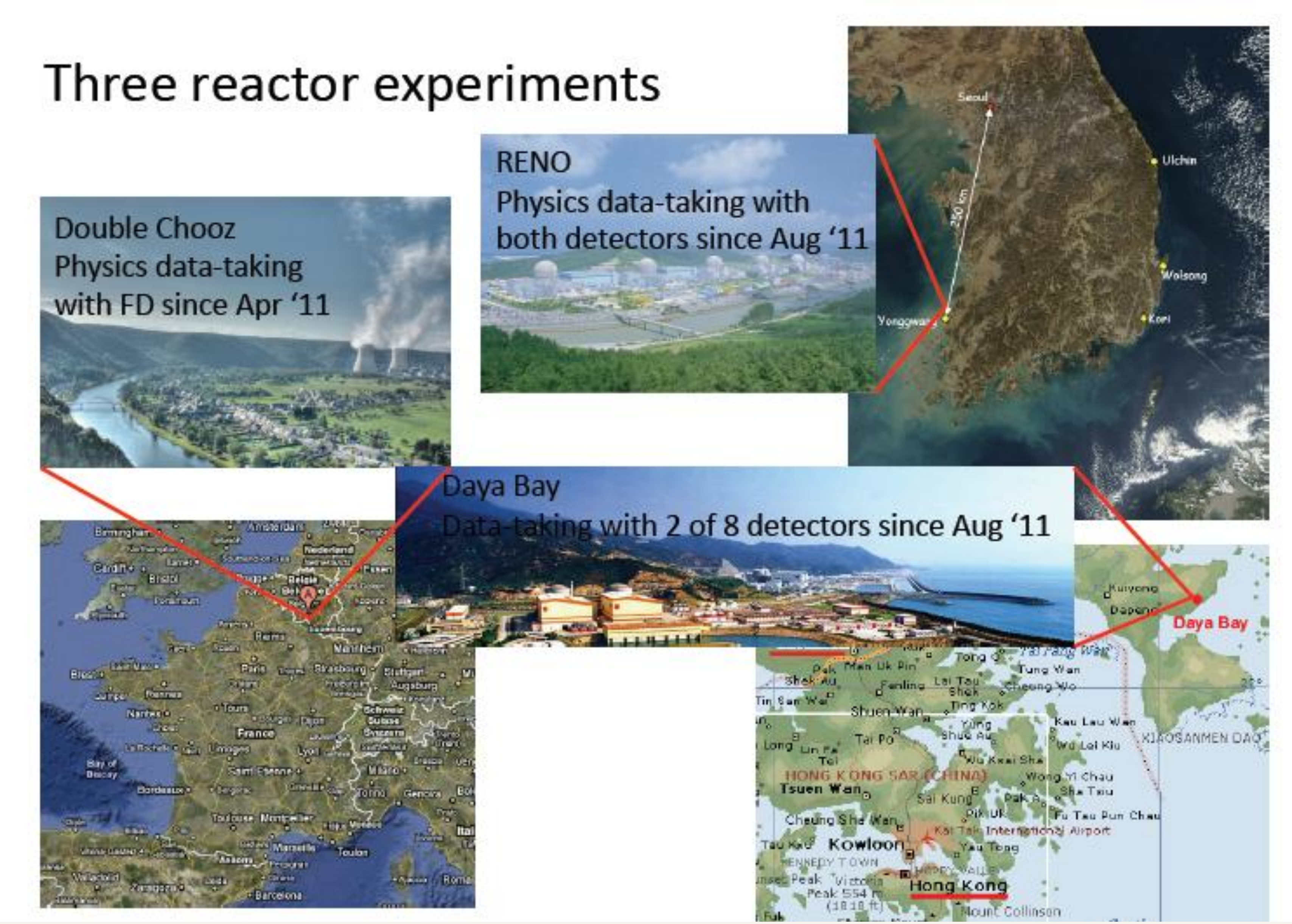
ν_μ-disappearance is confirmed by two methods:

1. "Counting": **N_{SK}^{obs} = 31** (N_{SK}^{exp} = **104** w/o osc.), **4.5σ** significance
2. Energy spectrum shape: clear oscillation pattern in the reconstructed energy spectrum and Data/MC ratio



Yeni Deneyler

Yeni Reaktor Deneyleri



Three reactor experiments

RENO
Physics data-taking with both detectors since Aug '11

Double Chooz
Physics data-taking with FD since Apr '11

Daya Bay
Data-taking with 2 of 8 detectors since Aug '11

Yeni Reaktor Deneyleri

- Θ_{13} üzerine yeni sonuçlar
  - RENO deneyi ilk sonuçları yakında ilan edecek
  - T2K deprem sonrası kontroller bitmek üzere 2012 de veri alımına kaldıkları yerden devam edecekler.
- Hazırlığı devam eden deneyler (5 yıl içinde)
  - Double Chooz 2013 yakın detektörü tamamlacak
  - Daya Bay 8 detektörle veri alımına başlacak.

Yeni Hızlandırıcı Deneyleri

NOνA: NuMI Off-Axis ν_e Appearance Experiment

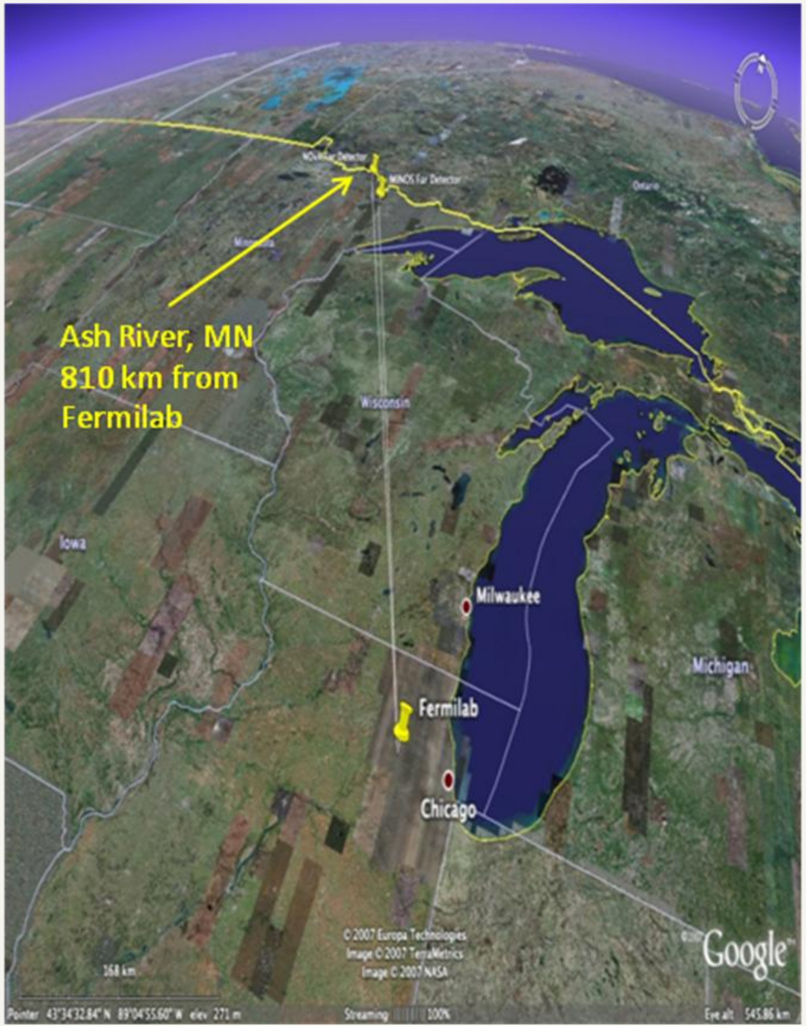
ν_e = electron neutrino

- NOvA is a second-generation experiment on the NuMI beamline
- The NOvA project also includes accelerator upgrades to bring the NuMI beam intensity from 400 kW to 700 kW
- Main physics goal will be the study of

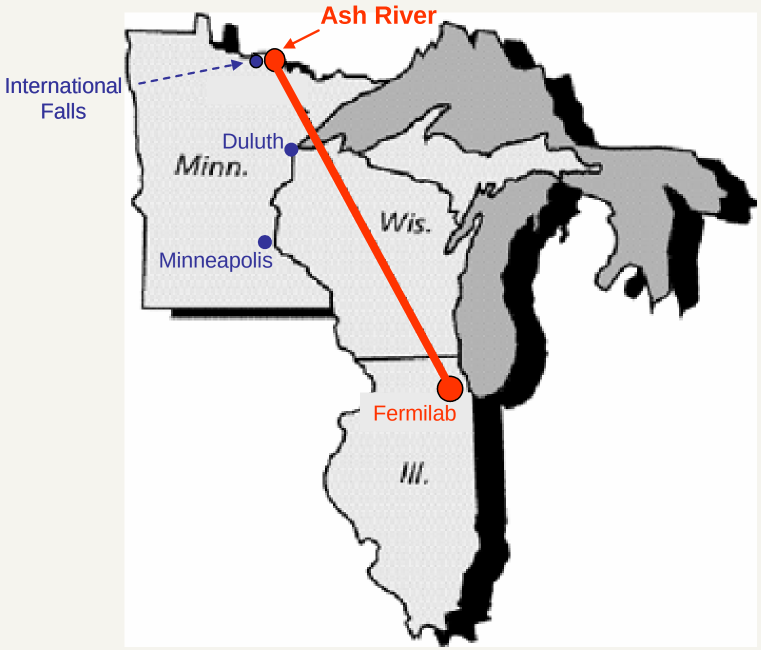
  $\nu_\mu \rightarrow \nu_e$ oscillations
- Uses two detectors:

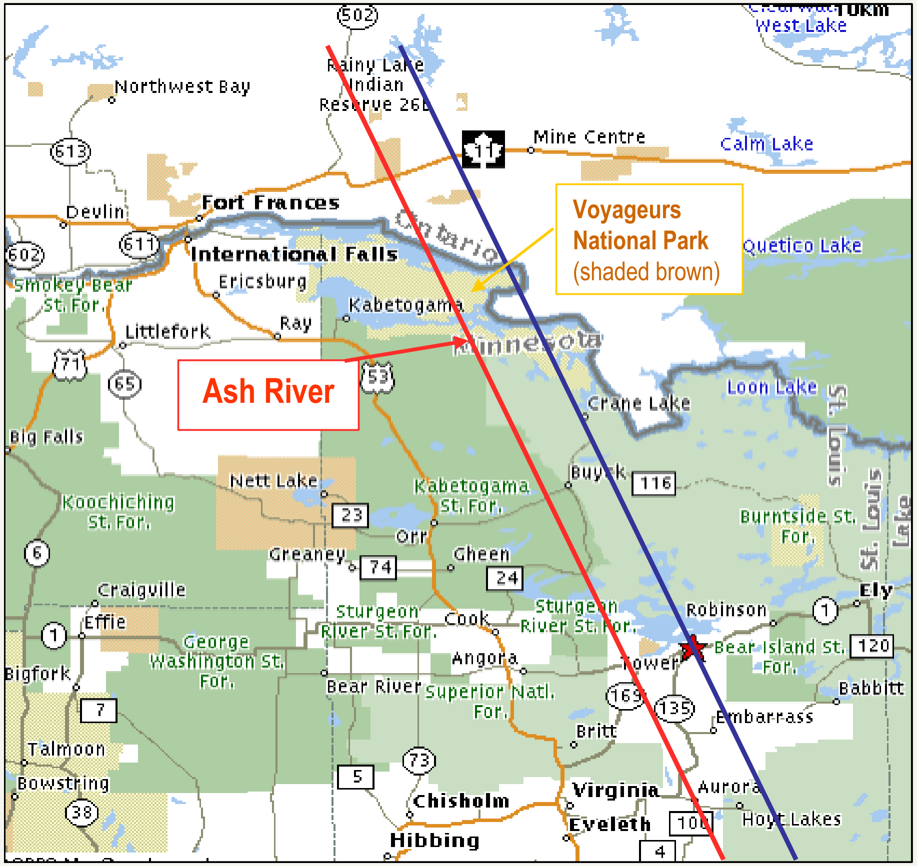
  Far Detector in Ash River, Minnesota

  Near Detector at Fermilab
- Run for 6 years



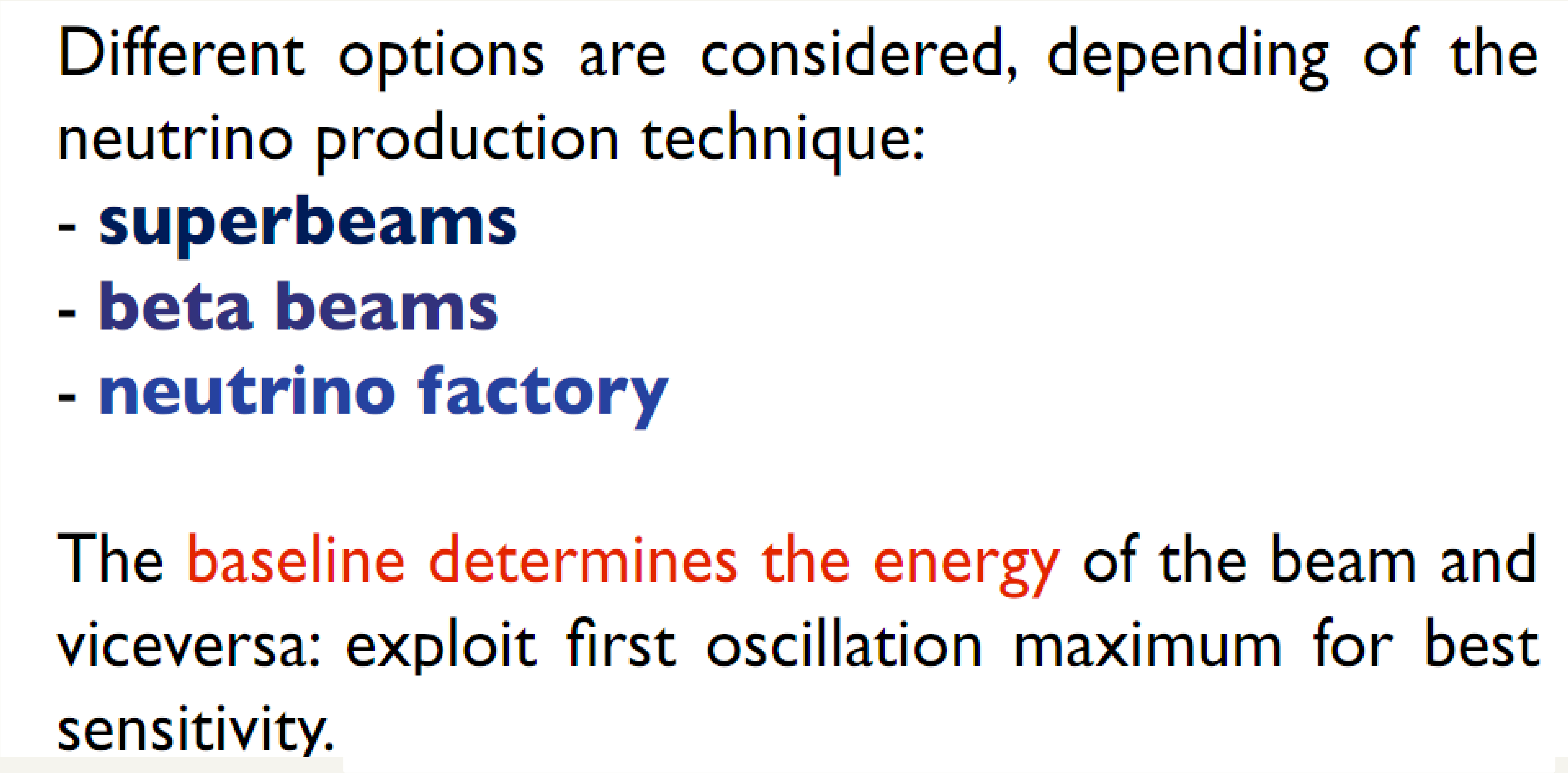
Nova





- This site is at 810 km from Fermilab, 12 km off-axis
- The Ash River site is the farthest available site from Fermilab in the U.S. along the NuMI beamline

Gelecek Nesil LBL Deneyleri

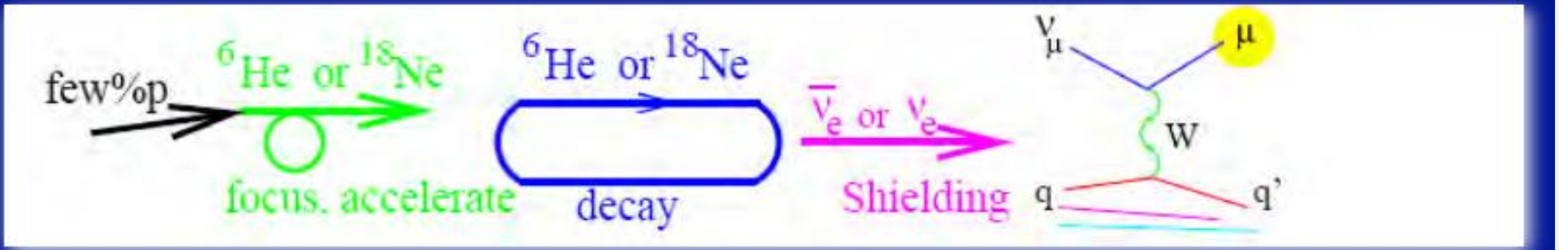


Different options are considered, depending of the neutrino production technique:

- **superbeams**
- **beta beams**
- **neutrino factory**

The baseline determines the energy of the beam and viceversa: exploit first oscillation maximum for best sensitivity.

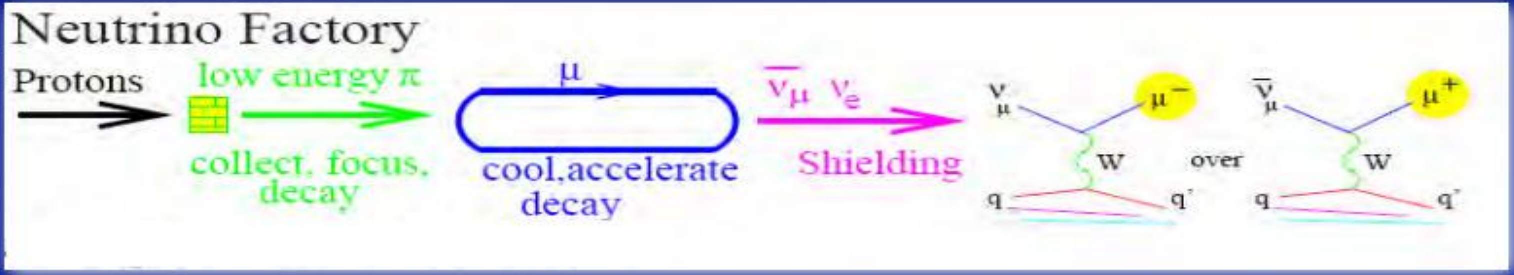
Gelecek Nesil LBL Deneyleri



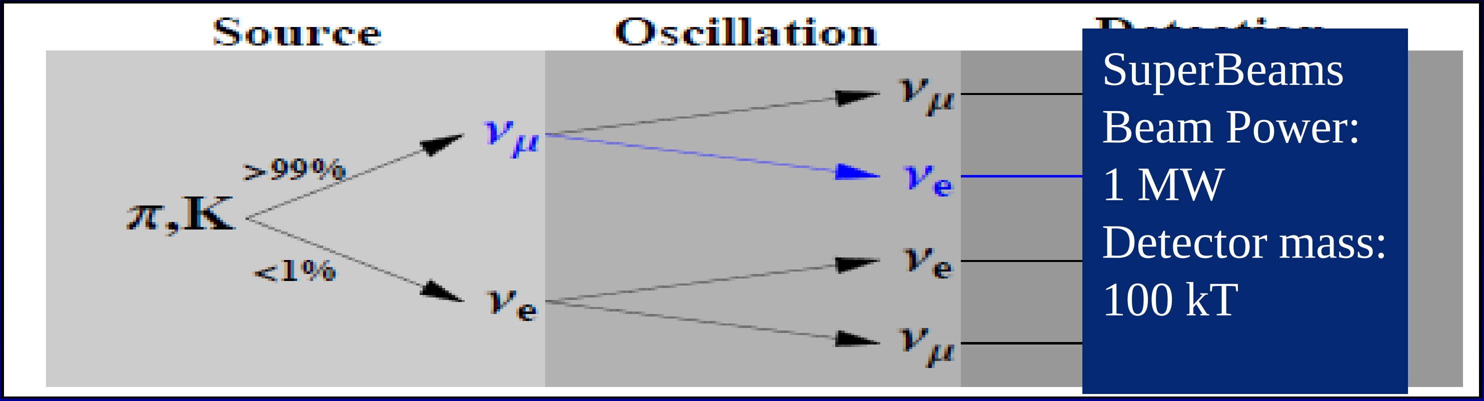
Beta-Beam (low energy ν_e beam, < 1 GeV)

Muon detection

(non magnetized, massive detectors, good event analysis for π BG rejection)

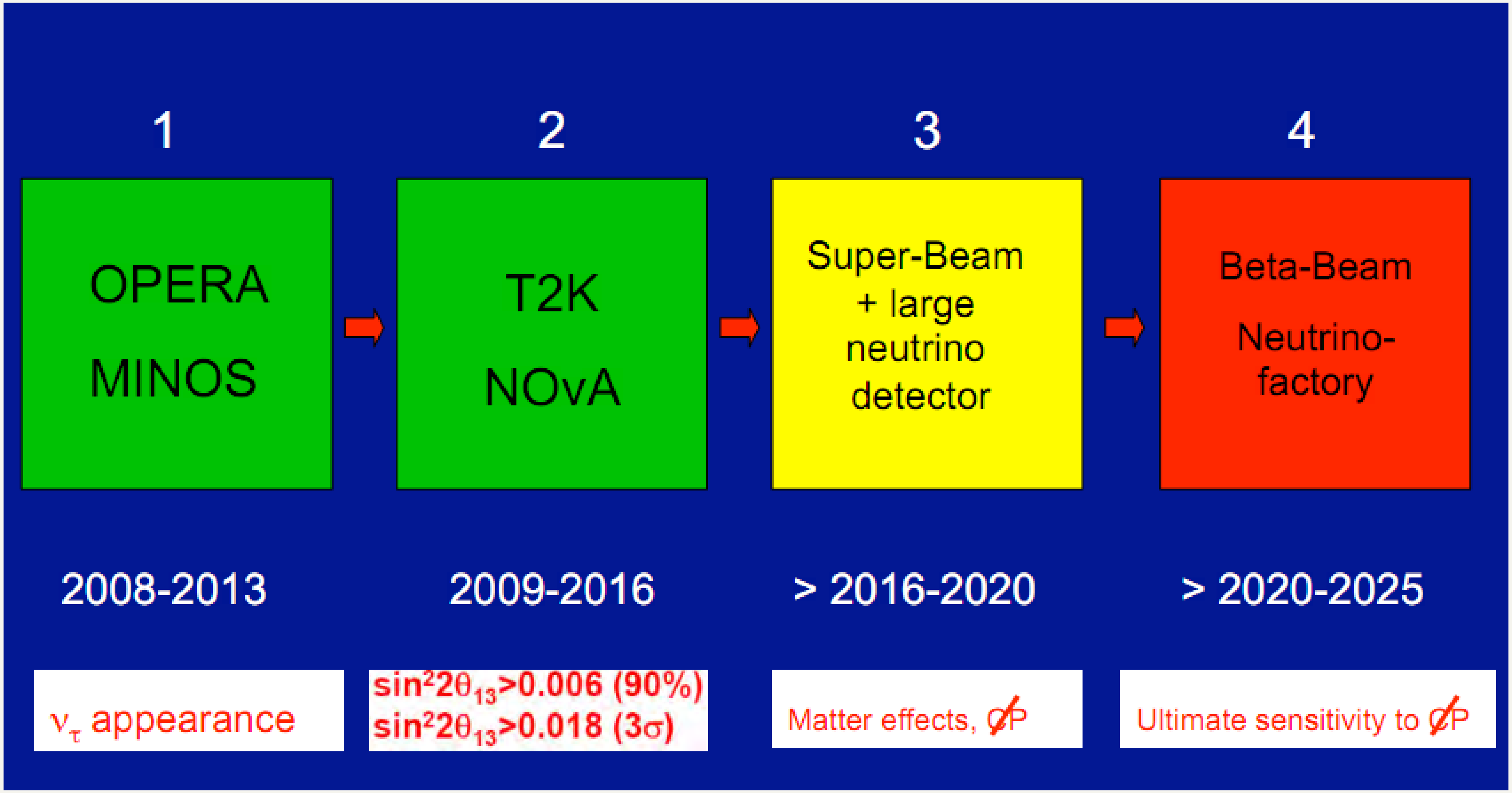

Neutrino Factory

Neutrino beam from π-decay



SuperBeams
Beam Power:
1 MW
Detector mass:
100 kT

Gelecek Nesil LBL Deneyleri



1

OPERA

MINOS

2008-2013

ν_τ appearance

2

T2K

NOvA

2009-2016

$\sin^2 2\theta_{13} > 0.006$ (90%)

$\sin^2 2\theta_{13} > 0.018$ (3σ)

3

Super-Beam
+ large
neutrino
detector

> 2016-2020

Matter effects, $\not{C}P$

4

Beta-Beam

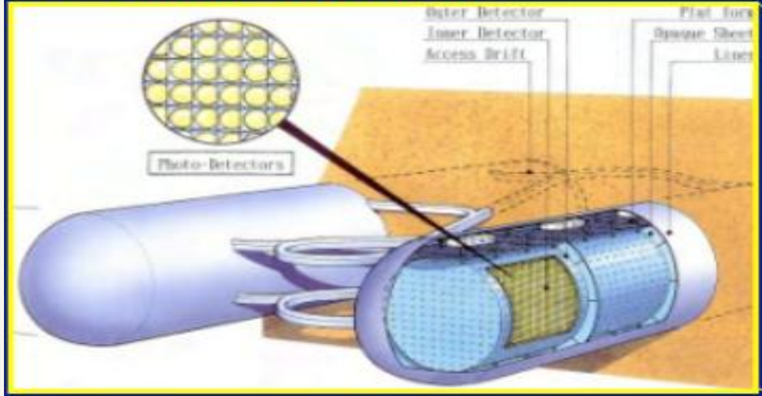
Neutrino-
factory

> 2020-2025

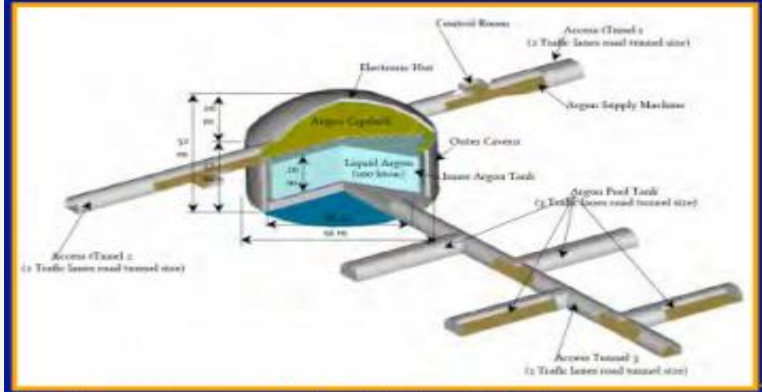
Ultimate sensitivity to $\not{C}P$

Japonya

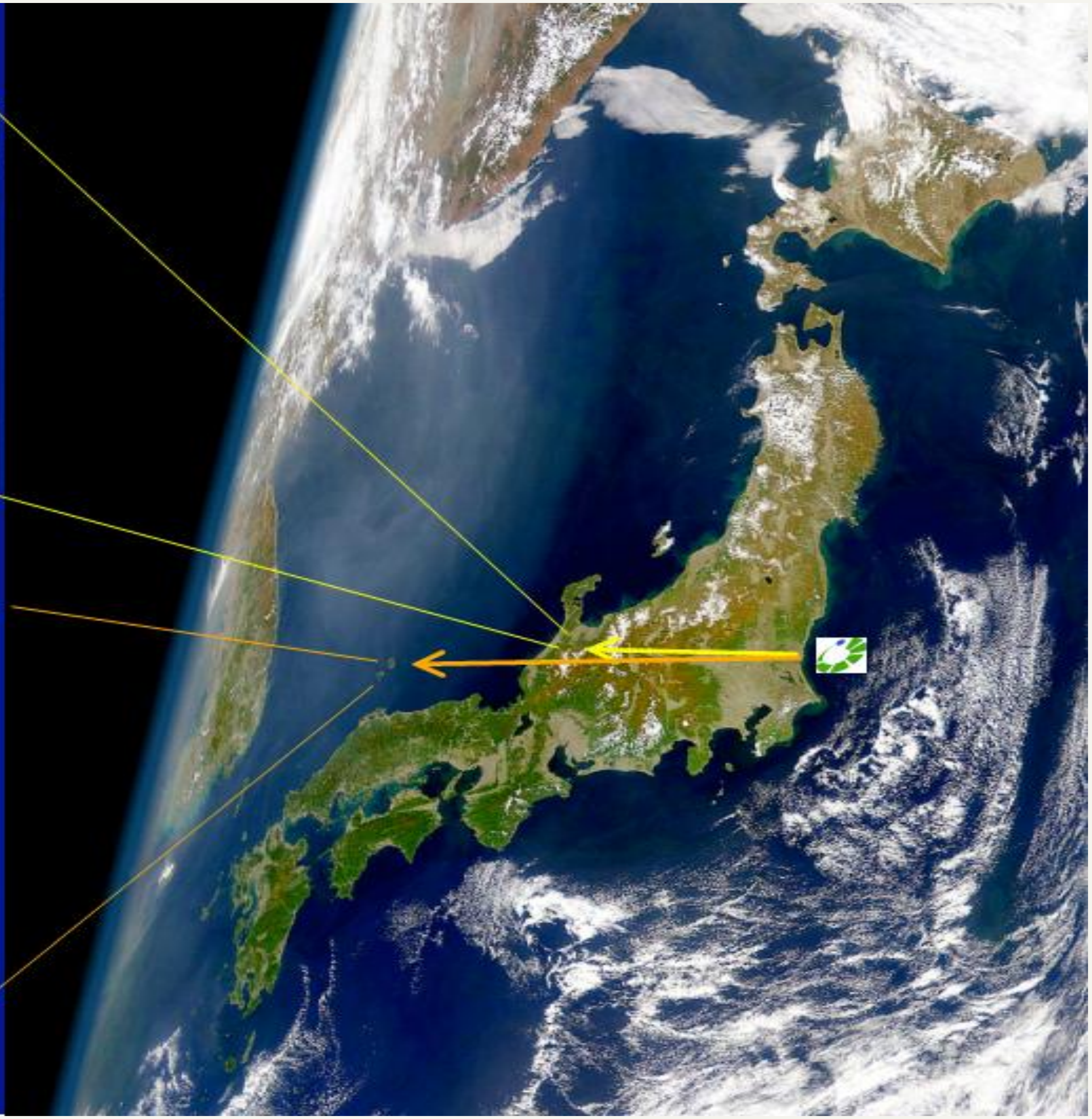
Kamioka L=295km OffA=2.5deg:
neut-antineut difference



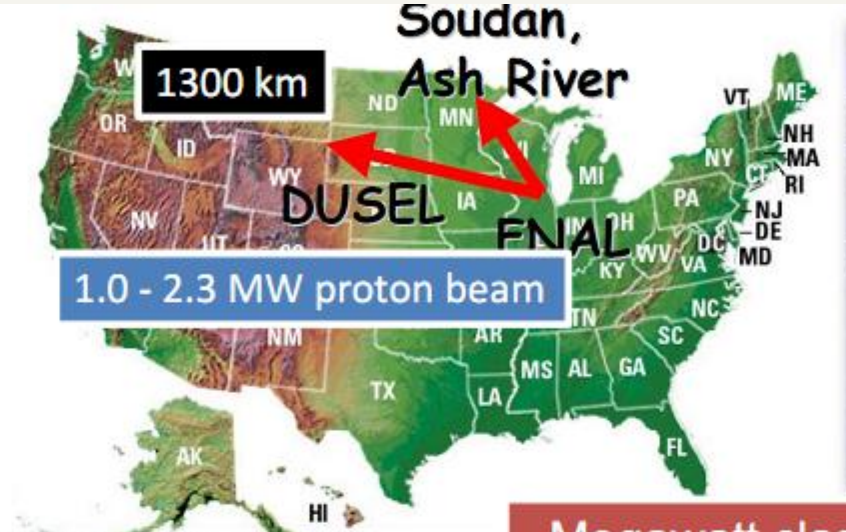
Okinoshima L=658km OnA:
2^{nd} oscillation max.



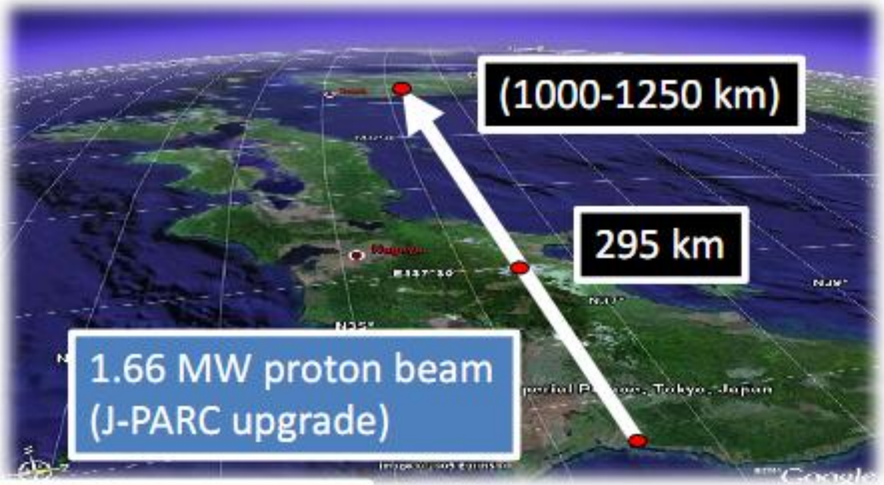
P32 proposal (LAr TPC R&D)
Recommended by J-PARC PAC
(Jan 2010), arXiv:0804.2111



Amerika

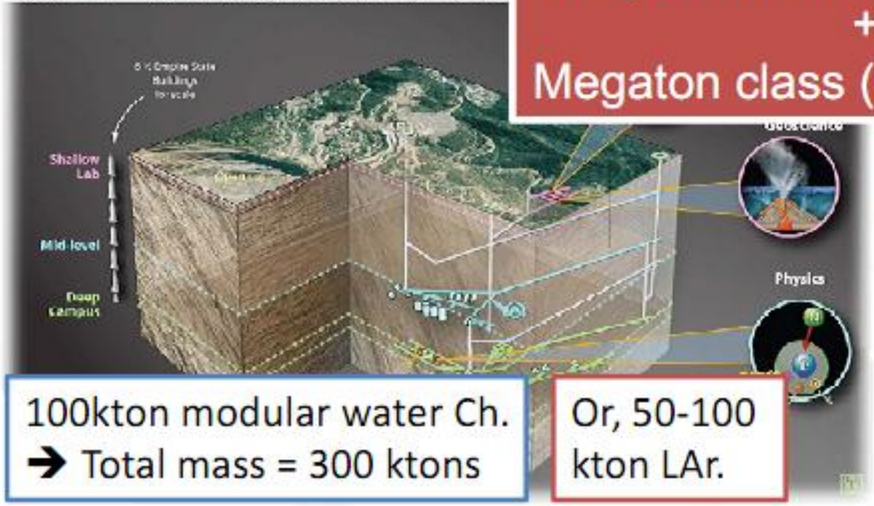


1.0 - 2.3 MW proton beam

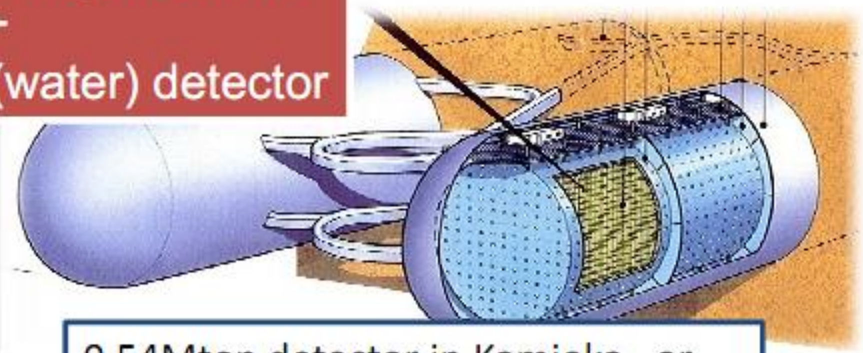


1.66 MW proton beam
(J-PARC upgrade)

DUSEL Deep Underground Science and Engineering Laboratory at Homestal



Megawatt class super-beam
+
Megaton class (water) detector

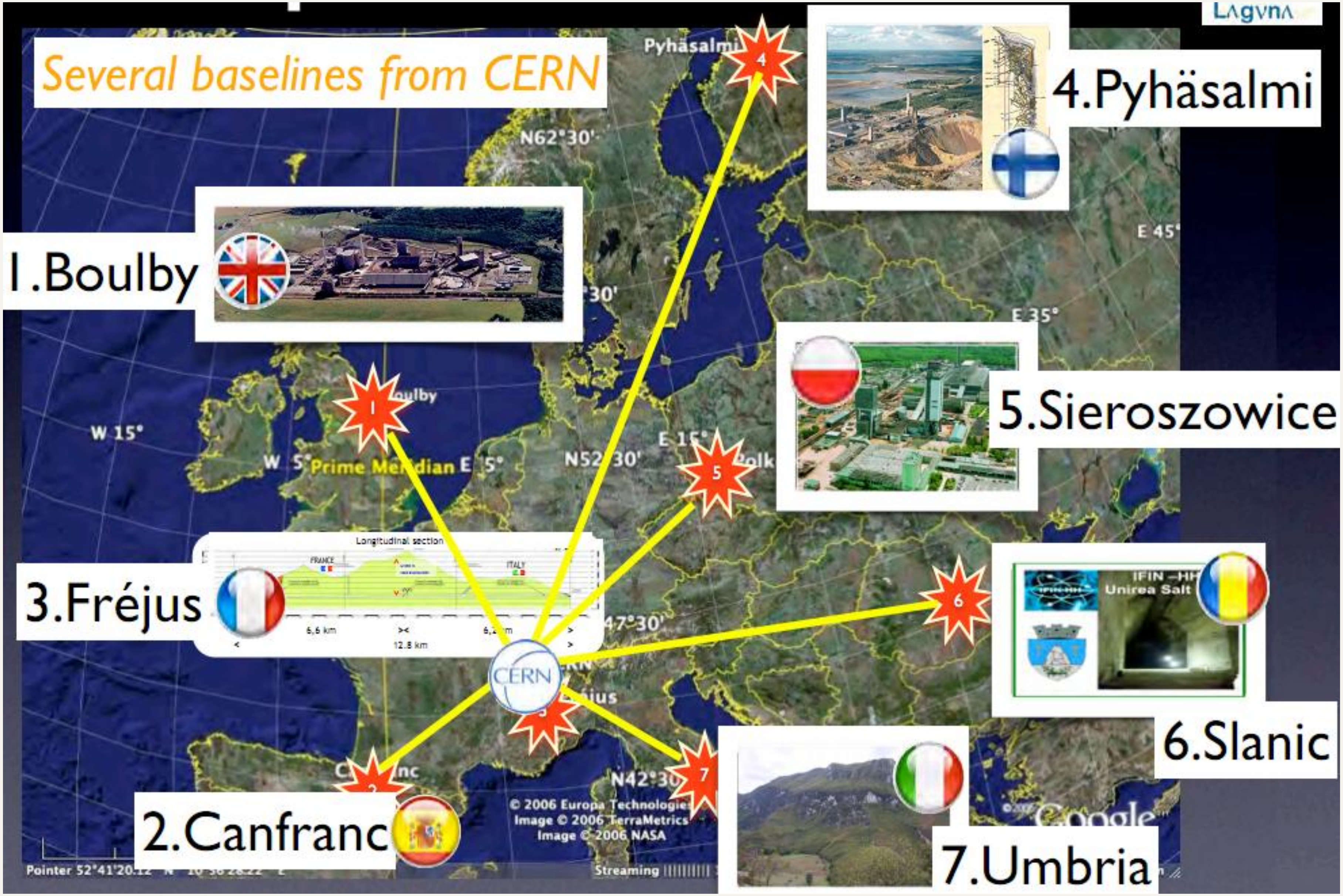


100kton modular water Ch.
➔ Total mass = 300 ktons

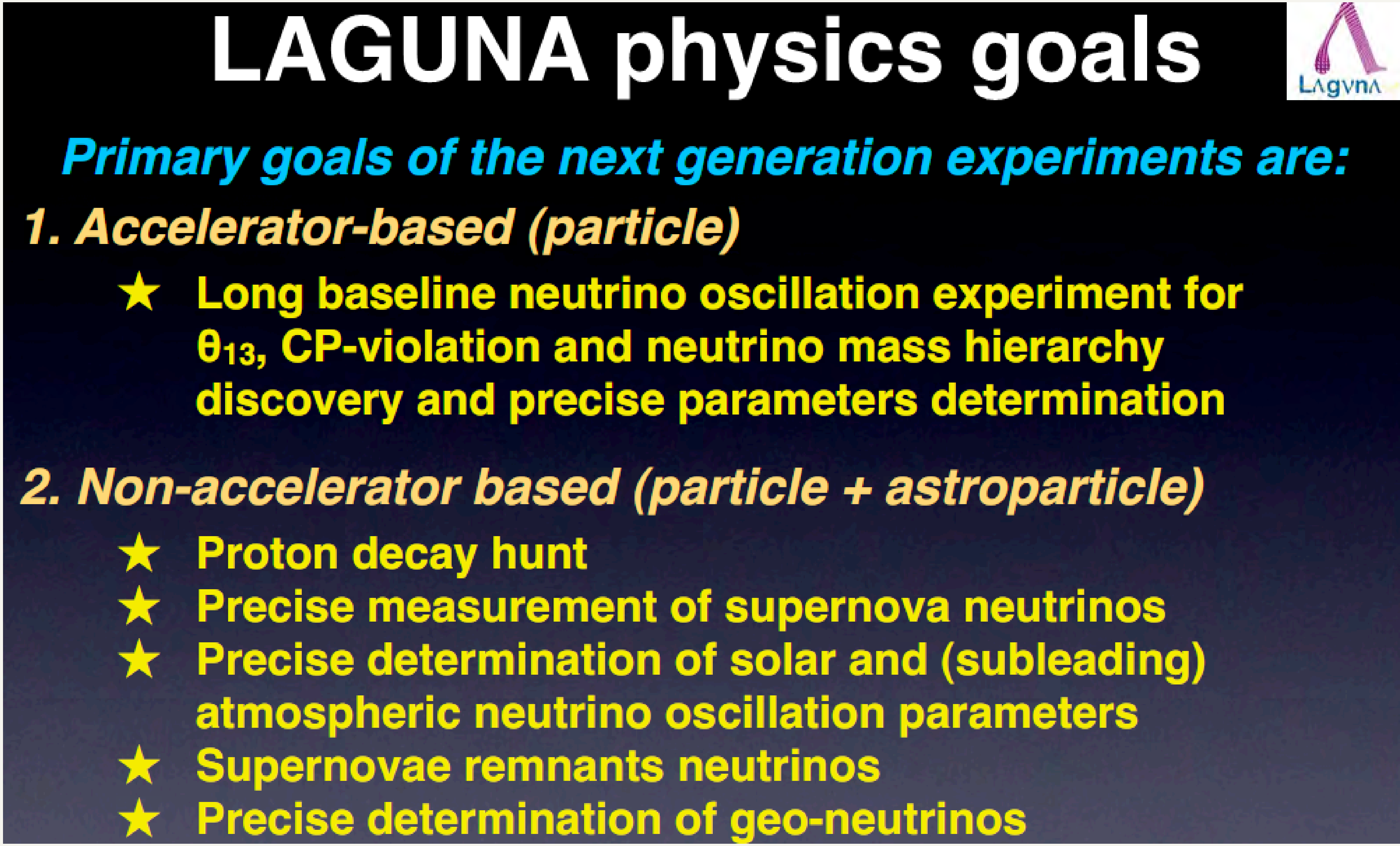
Or, 50-100 kton LAr.

0.54Mton detector in Kamioka, or 0.27 Mton water Cherenkov detector in Kamioka and Korea.

Avrupa


LAGUNA
Several baselines from CERN
1.Boulby
4.Pyhäsalmi
5.Sieroszowice
3.Fréjus
6.Slanic
2.Canfranc
7.Umbria
CERN
Pyhäsalmi
N62°30'
W 15°
W 5°
Prime Meridian
E 5°
N52°30'
E 15°
E 35°
E 45°
47°30'
N42°30'
Longitudinal section
FRANCE
ITALY
6,6 km
12.8 km
IFIN –HH
Unirea Salt
© 2006 Europa Technologies
Image © 2006 TerraMetrics
Image © 2006 NASA
Google
Pointer 52°41'20.12" N
Streaming

LAGUNA



LAGUNA physics goals

Primary goals of the next generation experiments are:

1. Accelerator-based (particle)

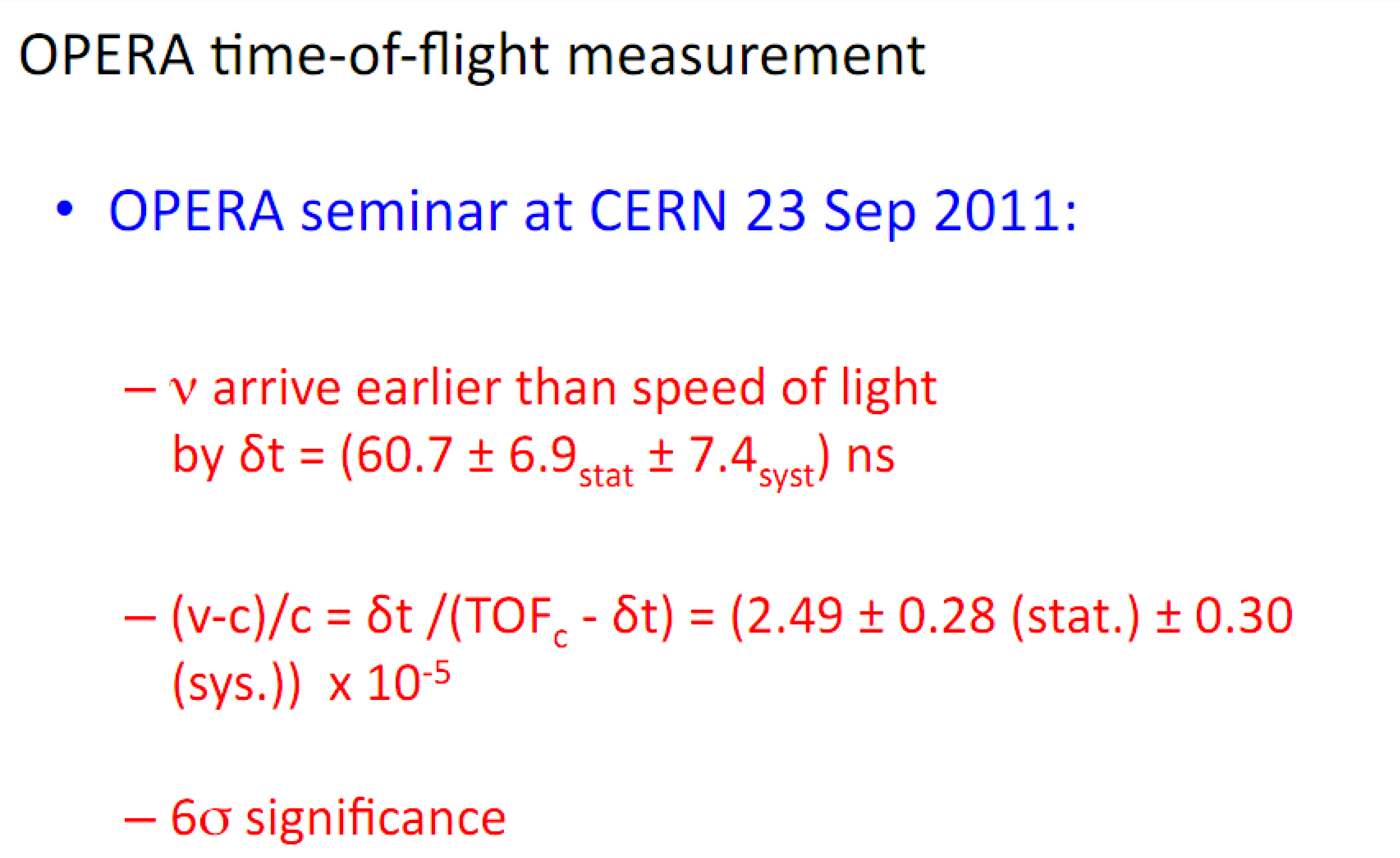
- Long baseline neutrino oscillation experiment for θ_{13}, CP-violation and neutrino mass hierarchy discovery and precise parameters determination

2. Non-accelerator based (particle + astroparticle)

- Proton decay hunt
- Precise measurement of supernova neutrinos
- Precise determination of solar and (subleading) atmospheric neutrino oscillation parameters
- Supernovae remnants neutrinos
- Precise determination of geo-neutrinos

Neutrino Velocity Measurement

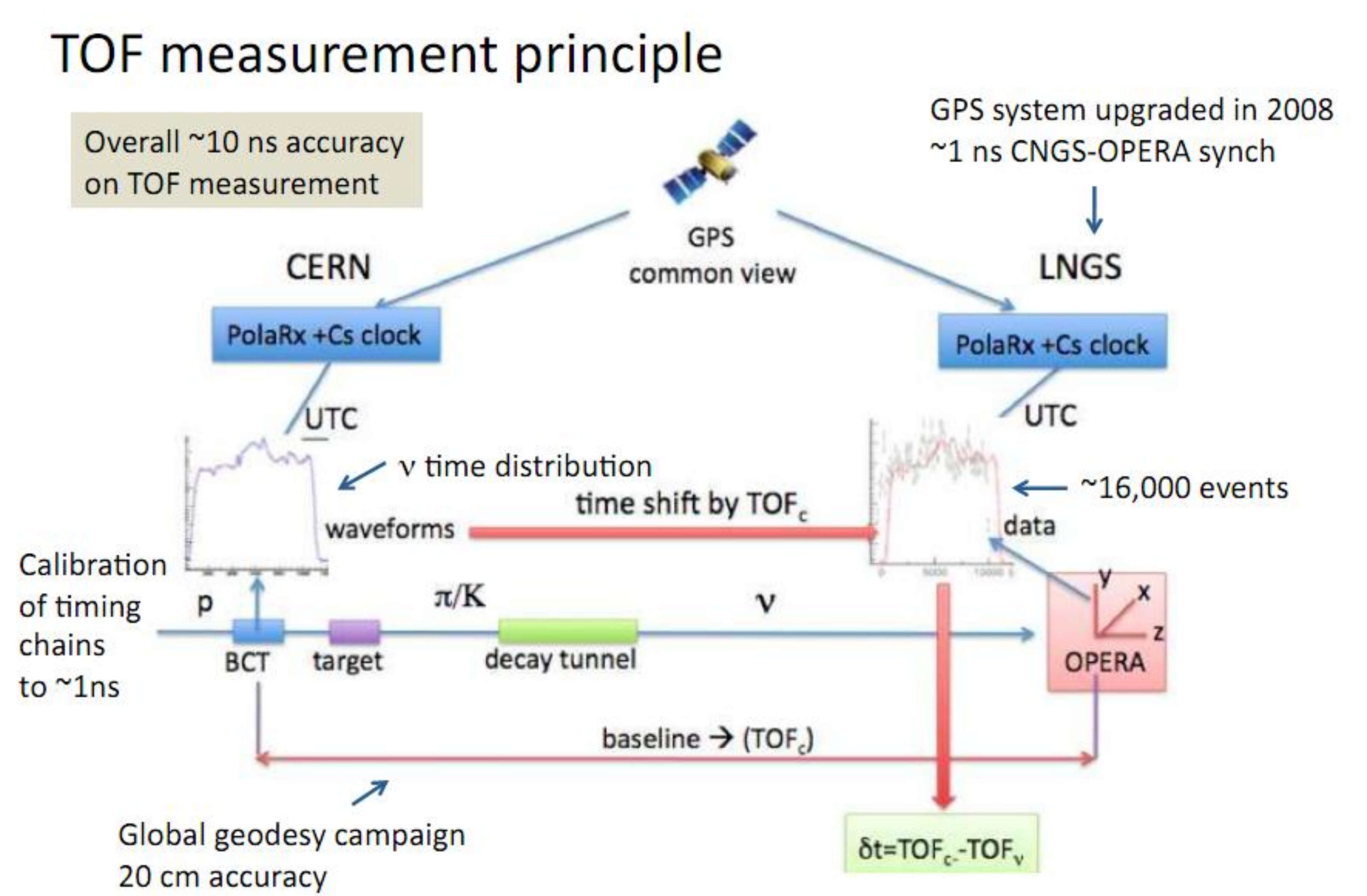
Neutrino Velocity Measurement



OPERA time-of-flight measurement

- OPERA seminar at CERN 23 Sep 2011:
  - ν arrive earlier than speed of light by $\delta t = (60.7 \pm 6.9_{stat} \pm 7.4_{syst})$ ns
  - $(v-c)/c = \delta t /(TOF_c - \delta t) = (2.49 \pm 0.28\ (stat.) \pm 0.30\ (sys.))\ \times 10^{-5}$
  - 6σ significance

Neutrino Velocity Measurement



TOF measurement principle

Overall ~10 ns accuracy
on TOF measurement

GPS system upgraded in 2008
~1 ns CNGS-OPERA synch

GPS
common view

CERN

LNGS

PolaRx +Cs clock

PolaRx +Cs clock

UTC

UTC

ν time distribution

time shift by TOF_c

waveforms

~16,000 events

data

Calibration
of timing
chains
to ~1ns

p

π/K

ν

BCT

target

decay tunnel

OPERA

baseline → (TOF_c)

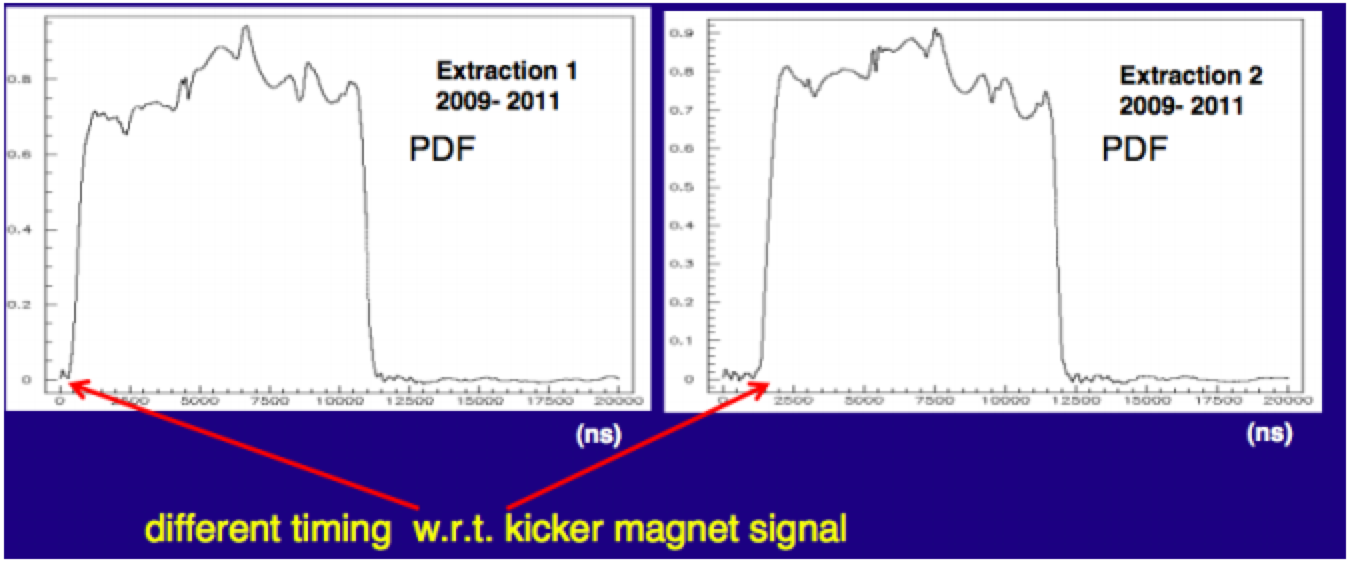
Global geodesy campaign
20 cm accuracy

$\delta t = TOF_c - TOF_\nu$

Neutrino Velocity Measurement

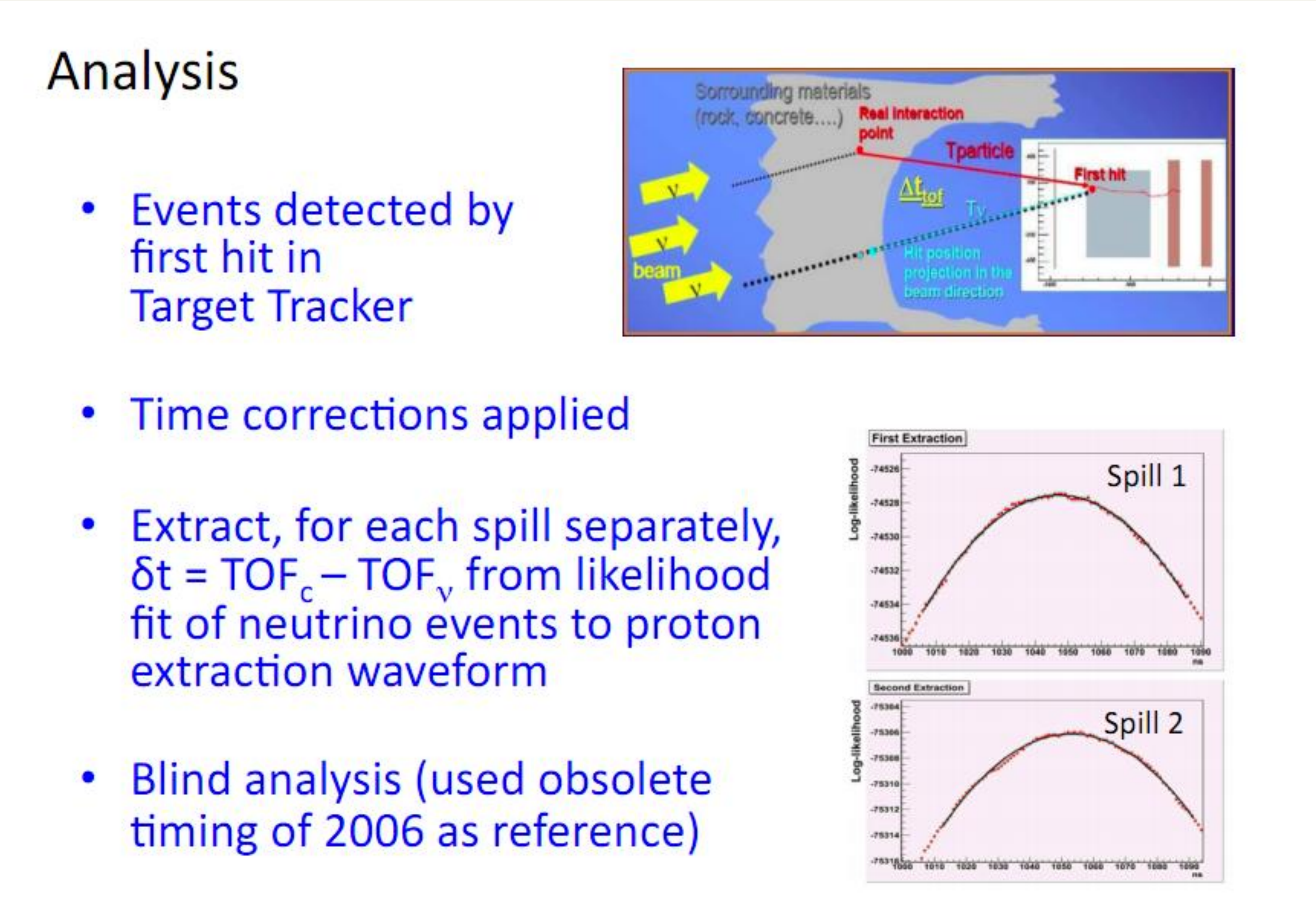
Neutrino event-time distribution PDF

- 2 10.5 μm beam spills separated by 50 ms
- Each event associated to its proton spill waveform
- Parent proton unknown
- PDF of *predicted* time distribution compared to OPERA *detected* events



different timing w.r.t. kicker magnet signal

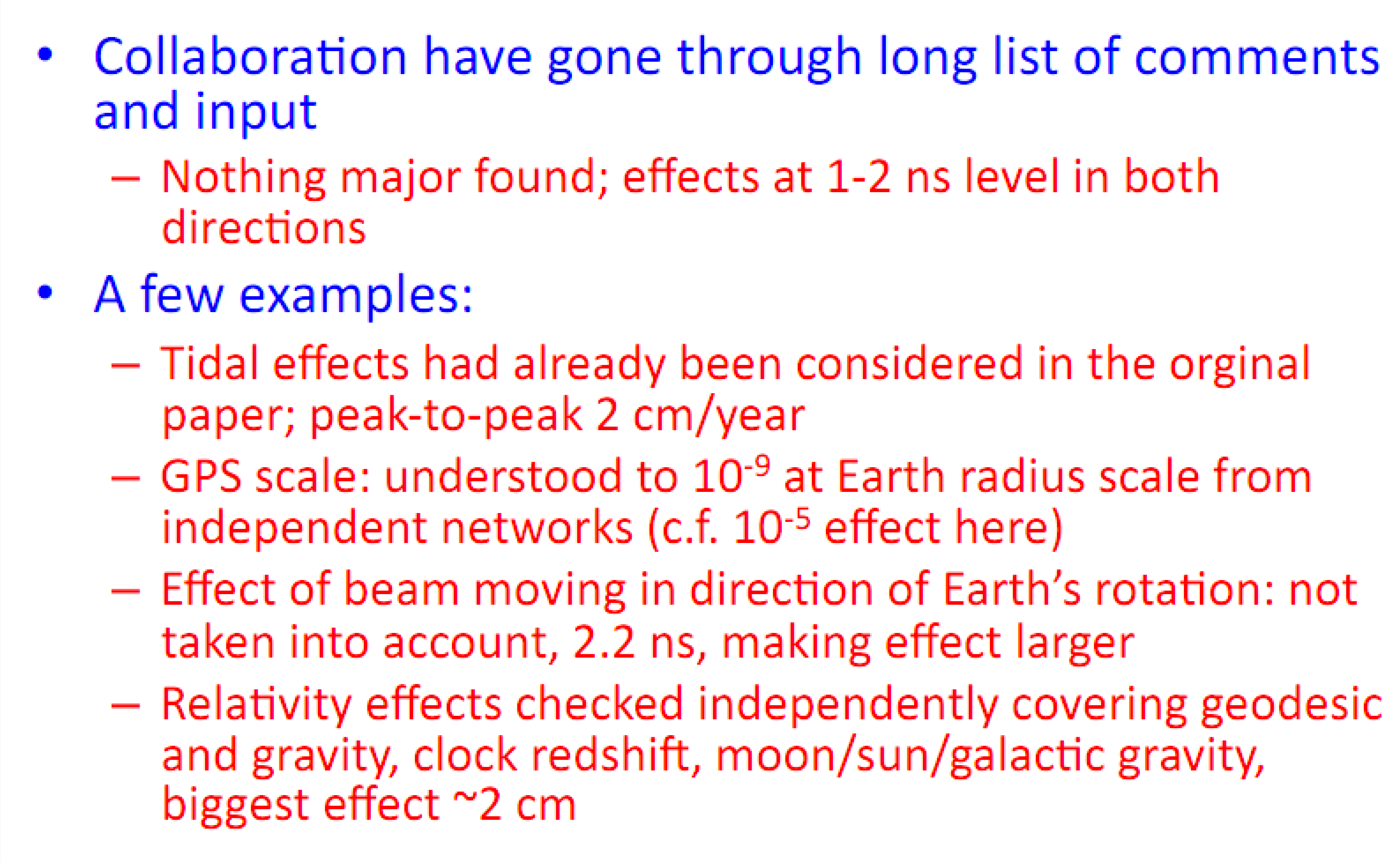
Neutrino Velocity Measurement



Analysis

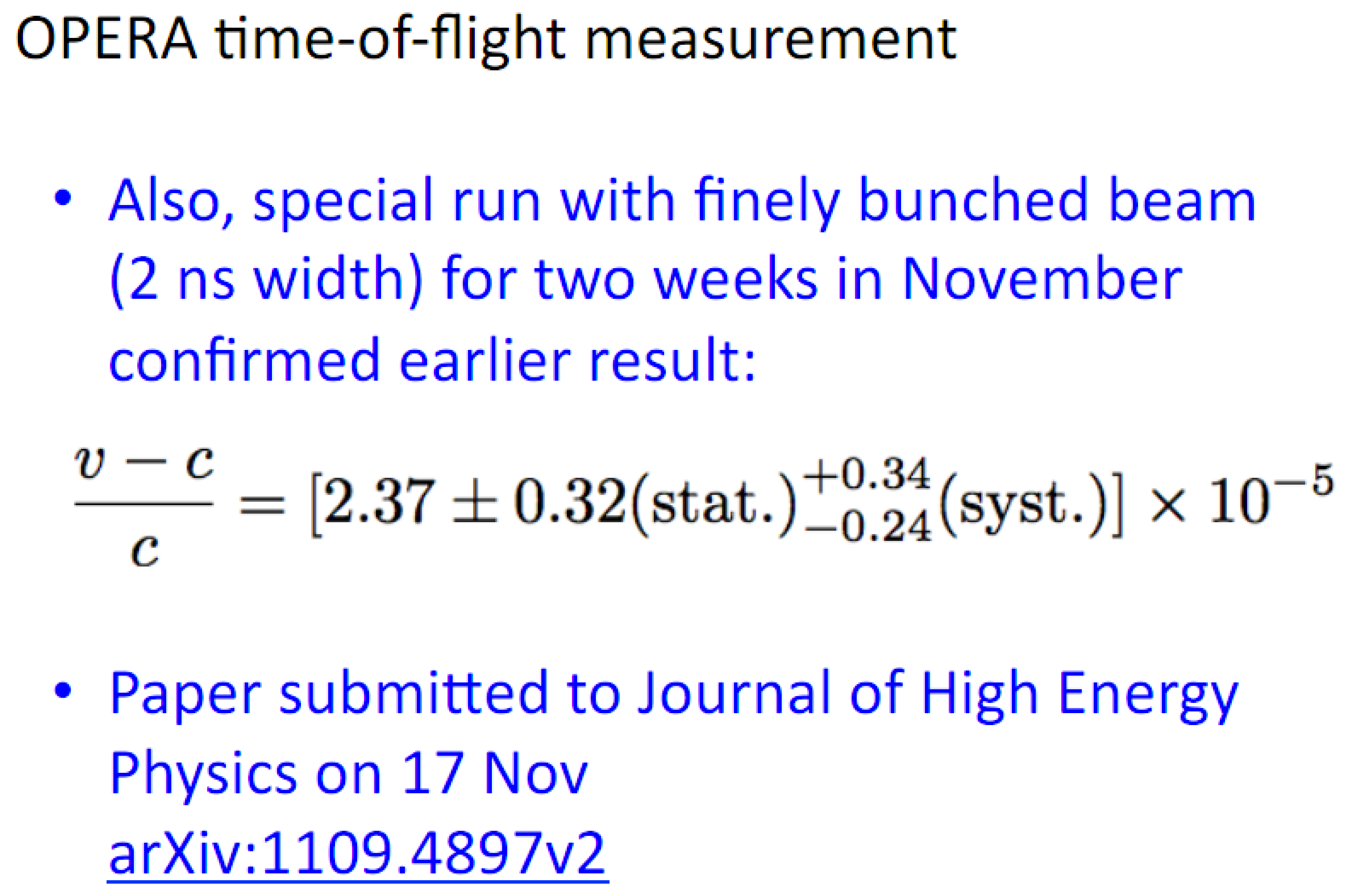
- Events detected by first hit in Target Tracker
- Time corrections applied
- Extract, for each spill separately, $\delta t = TOF_c - TOF_\nu$ from likelihood fit of neutrino events to proton extraction waveform
- Blind analysis (used obsolete timing of 2006 as reference)

Neutrino Velocity Measurement



- Collaboration have gone through long list of comments and input
  - Nothing major found; effects at 1-2 ns level in both directions
- A few examples:
  - Tidal effects had already been considered in the orginal paper; peak-to-peak 2 cm/year
  - GPS scale: understood to 10^{-9} at Earth radius scale from independent networks (c.f. 10^{-5} effect here)
  - Effect of beam moving in direction of Earth's rotation: not taken into account, 2.2 ns, making effect larger
  - Relativity effects checked independently covering geodesic and gravity, clock redshift, moon/sun/galactic gravity, biggest effect ~2 cm

Neutrino Velocity Measurement



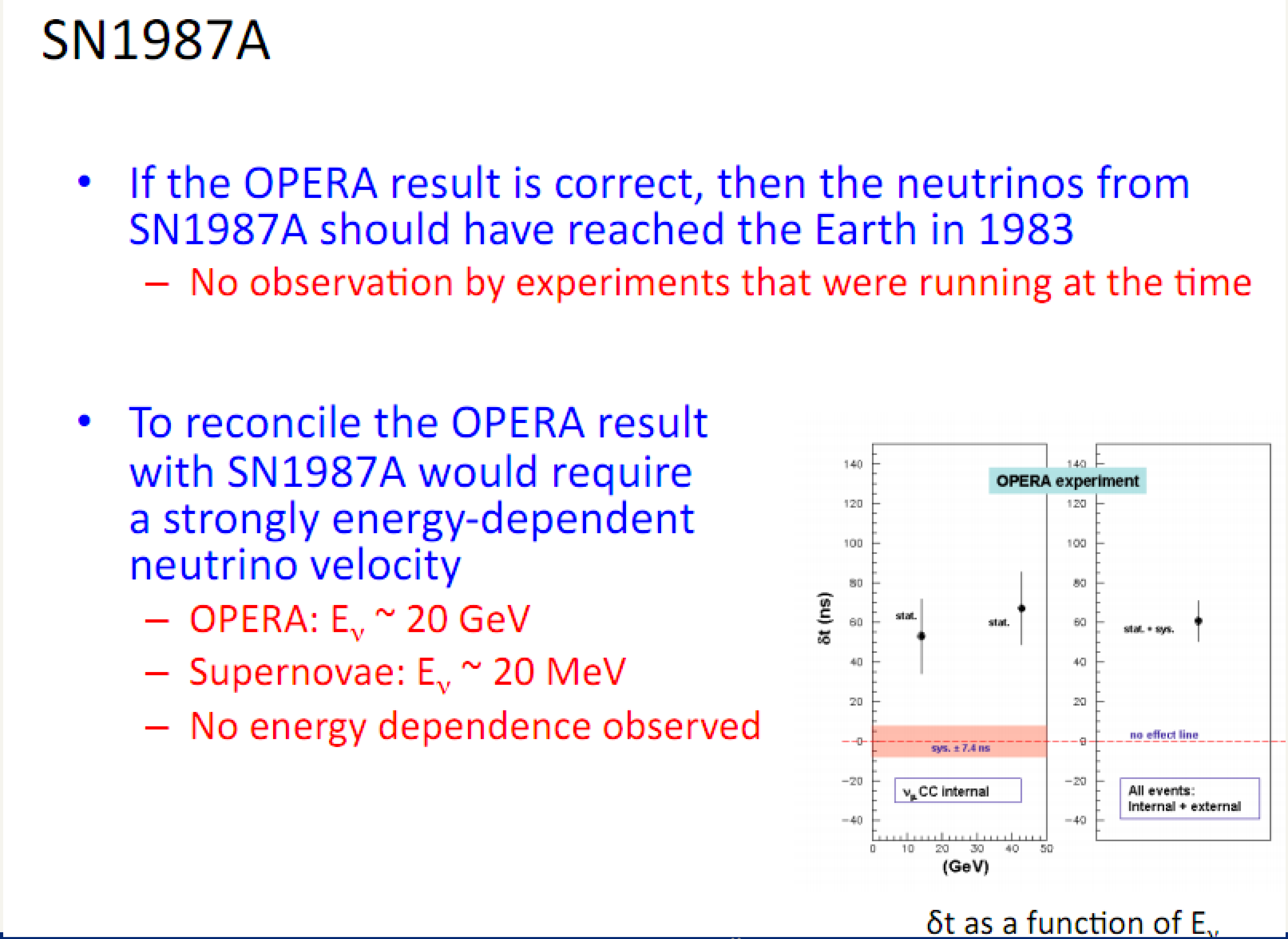
OPERA time-of-flight measurement

- Also, special run with finely bunched beam (2 ns width) for two weeks in November confirmed earlier result:

$$\frac{v-c}{c} = [2.37 \pm 0.32(\mathrm{stat.})^{+0.34}_{-0.24}(\mathrm{syst.})] \times 10^{-5}$$

- Paper submitted to Journal of High Energy Physics on 17 Nov
  arXiv:1109.4897v2

Neutrino Velocity Measurement



SN1987A

- If the OPERA result is correct, then the neutrinos from SN1987A should have reached the Earth in 1983
  - No observation by experiments that were running at the time

- To reconcile the OPERA result with SN1987A would require a strongly energy-dependent neutrino velocity
  - OPERA: E_ν ~ 20 GeV
  - Supernovae: E_ν ~ 20 MeV
  - No energy dependence observed

δt as a function of E_ν

Neutrino Velocity Measurement

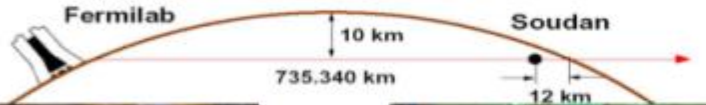
MINOS 2007 TOF measurement

Measure time of flight as t_2 - t_1

$$\delta = -126 \pm 32(\mathrm{stat.}) \pm 64(\mathrm{syst.})\,\mathrm{ns} \qquad 68\%\mathrm{C.L.}$$

$$\frac{v-c}{c} = (5.1 \pm 2.9) \times 10^{-5}$$

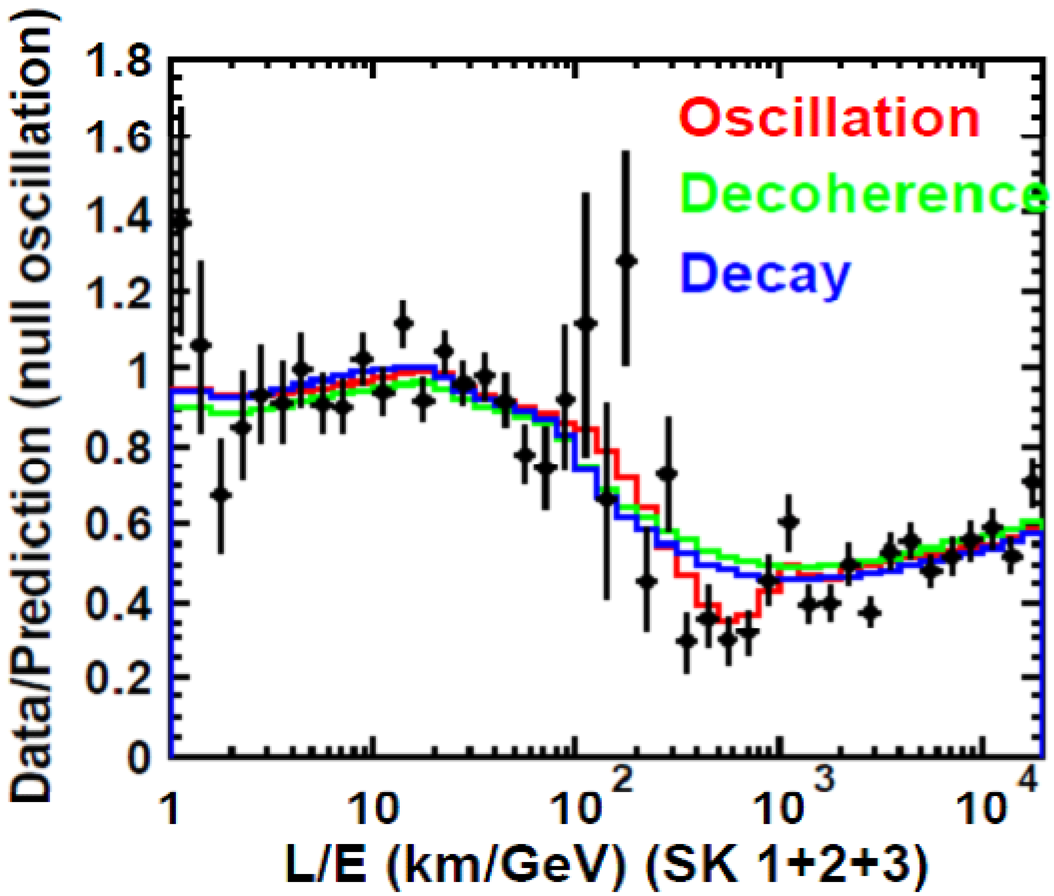
[Phys. Rev. **D76**, 072005 (2007)]



Near Detector
980 tonnes

Far Detector
5,400 tonnes

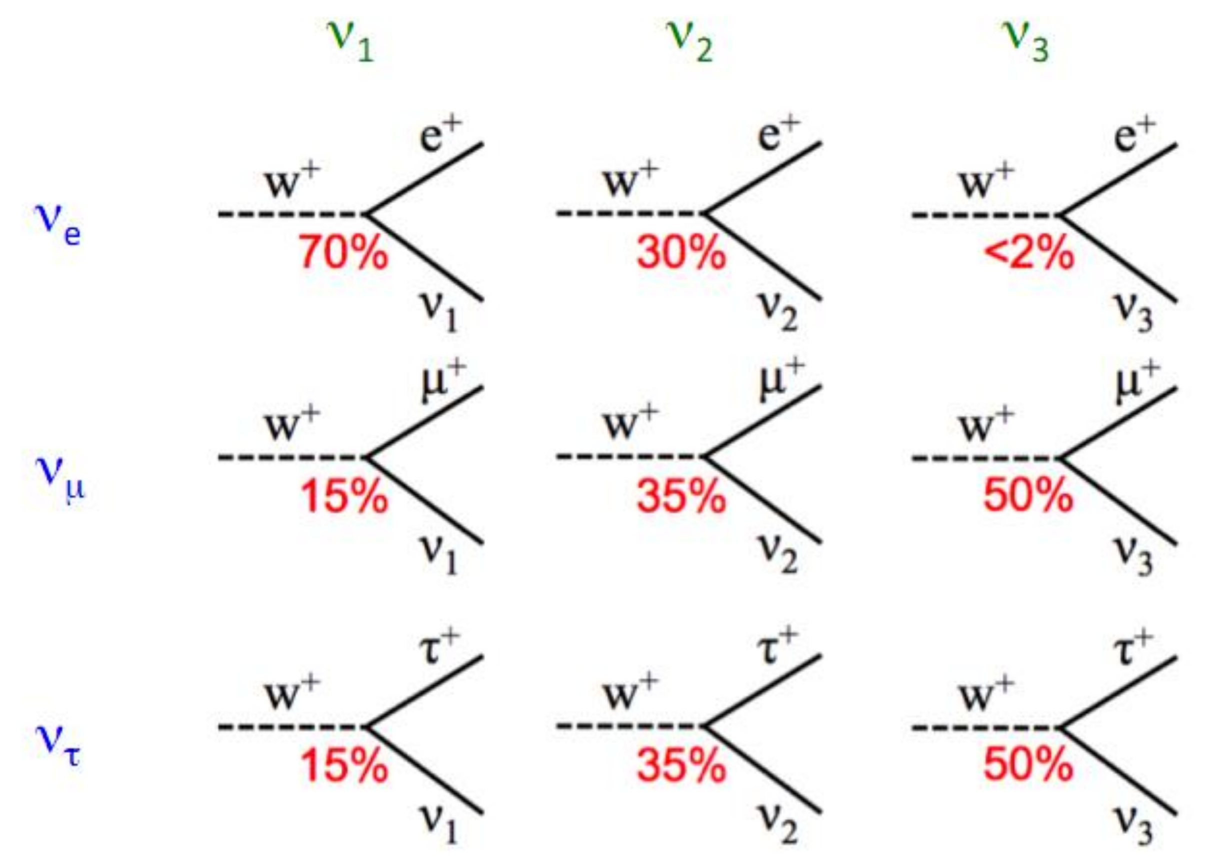
Nötrino Salınım/Bozunum analizi



Preliminary

Neutrino decay (4.4σ)

Neutrino decoherence (5.4σ)


ν_1
ν_2
ν_3
ν_e
w^+ e^+ 70% ν_1
w^+ e^+ 30% ν_2
w^+ e^+ <2% ν_3
ν_μ
w^+ μ^+ 15% ν_1
w^+ μ^+ 35% ν_2
w^+ μ^+ 50% ν_3
ν_τ
w^+ τ^+ 15% ν_1
w^+ τ^+ 35% ν_2
w^+ τ^+ 50% ν_3