Measuring the Neutrino Mass

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Dezső Horváth

Horvath.Dezso@wigner.mta.hu

Wigner Research Centre for Physics,
Institute for Particle and Nuclear Physics, Budapest, Hungary
& Atomki, Debrecen, Hungary

Outline

- Motivation
- Neutrino Sources
- Missing Neutrinos
- Neutrino Oscillations and Masses
- How to Measure It?
- Experimental Idea

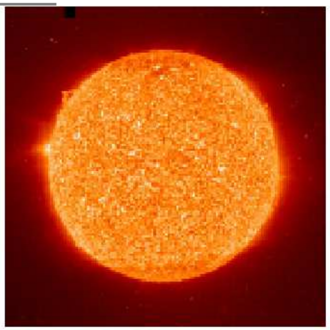
Motivation

- Ultra-fast neutrinos?
- Simple velocity measurement
- Velocity $\rightarrow$ mass
- Simulations

U. D. Jentschura, D. Horváth, S. Nagy, I. Nándori, Z. Trócsányi and B. Ujvári: *Weighing the Neutrino*
Int.J.Mod.Phys. E23 (2014) 1450004; arXiv:1312.3932

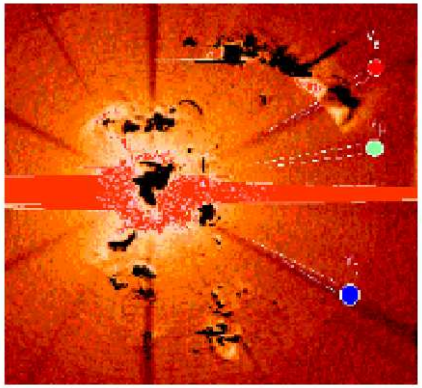
D. Horváth: *Ultra-Fast Neutrinos: What Can We Learn from a False Discovery?* In *Gribov85*, Proceedings of 4th V.N. Gribov Memorial Workshop: Theoretical Physics of XXI Century, 17-20 June 2015, Chernogolovka, Russia

Neutrino Sources



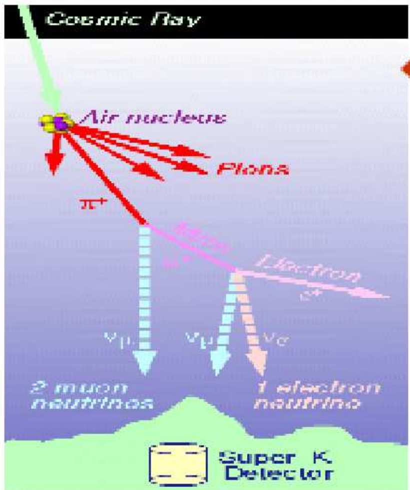
← SUN

COSMIC →



← COSMOLOGY

REACTOR →

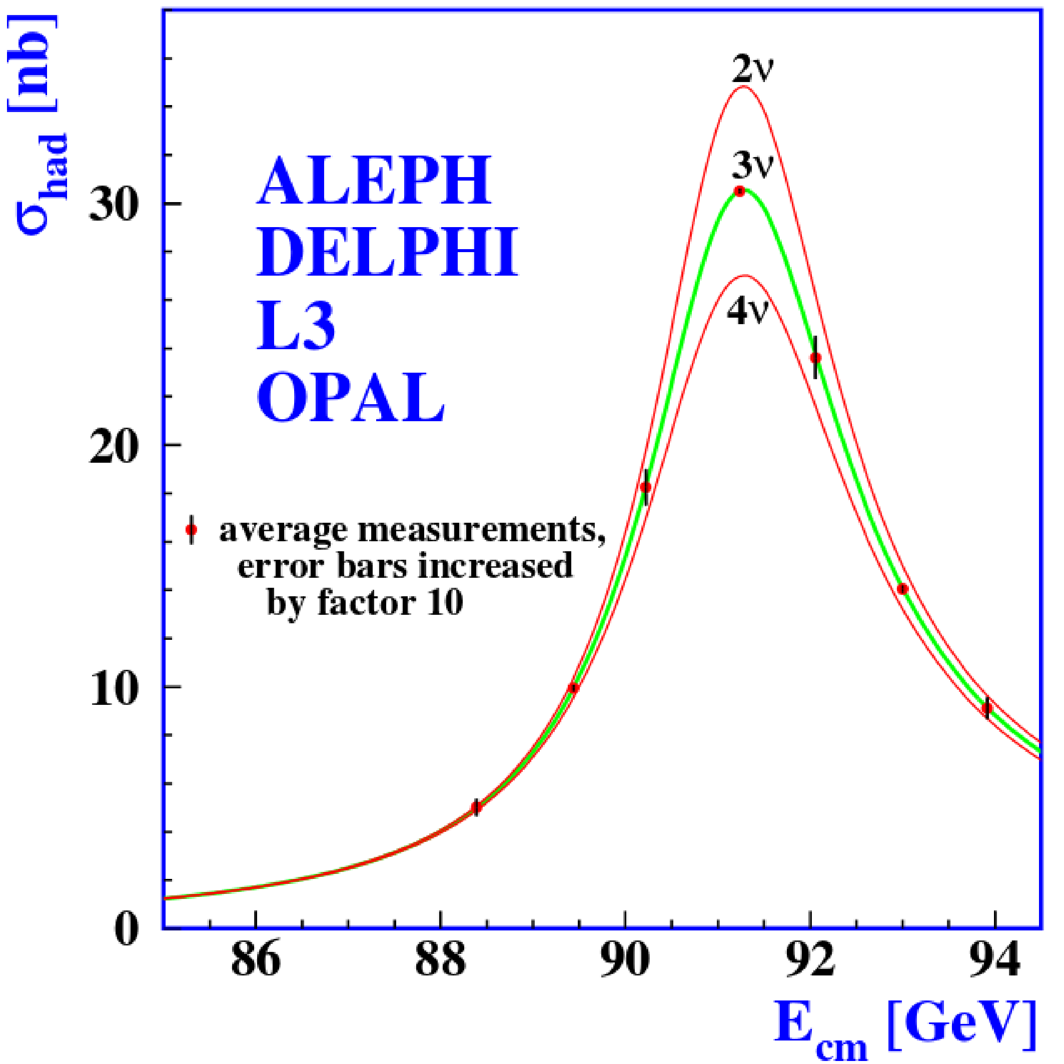


← ATMOSPHERIC

ACCELERATOR →

← GEO

Standard Model: 3 *light* neutrinos



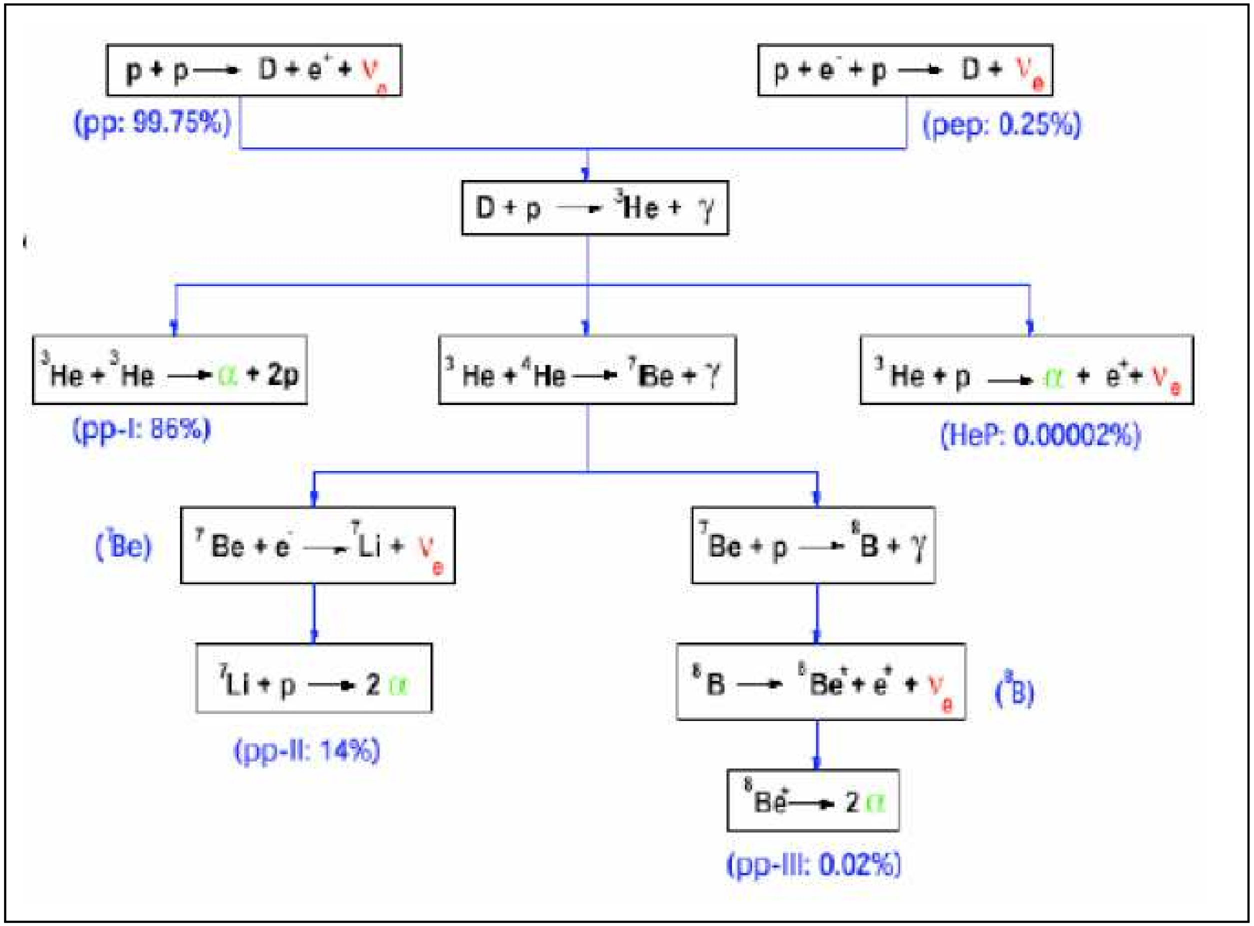
$$N_\nu = \frac{\Gamma(Z \to \text{invisible})}{\Gamma(Z \to \nu_i \bar{\nu}_i)_{\text{Th}}}$$

$$= 2.9841 \pm 0.0083$$

LEP: invisible width of the Z boson

Neutrinos from the Sun

$$4\,^1\mathrm{H} \to {}^4\mathrm{He} + 2\mathrm{e}^+ + 2\nu_\mathrm{e}$$



Detection unit:

Solar Neutrino Unit

$$1\ \mathrm{SNU} = \frac{10^{-36}\ \nu-\text{interaction}}{\text{atom}\cdot\text{sec}}$$

$\approx 1\ \nu$ interaction/day/10^{30} atoms

(10 – 100 tons of material)

Experiment:

$$\nu_\mathrm{e} + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{Ar} + \mathrm{e}^-$$

(R. Davis, Nobel prize 2002)

Expected: $8,2 \pm 1,8$ SNU;

measured: $2,56 \pm 0,23$ SNU

Lost??

What is wrong: Sun model or experiment?

Both multiply confirmed

Atmospheric neutrinos

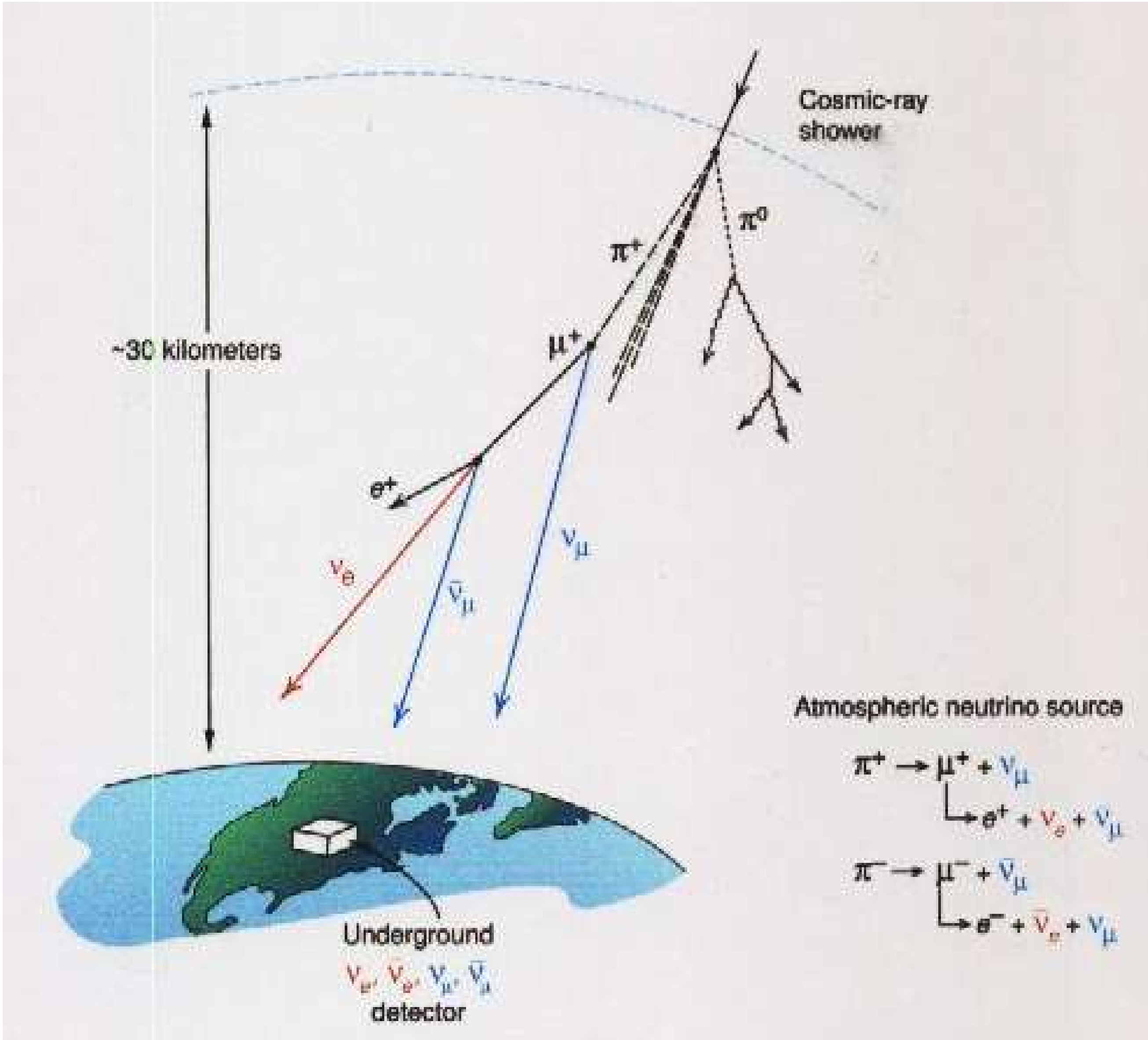
$\pi^+ \to \mu^+ \nu_\mu$
$\mu^+ \to e^+ \overline{\nu}_\mu \nu_e$

$\pi^- \to \mu^- \overline{\nu}_\mu$
$\mu^- \to e^- \overline{\nu}_e \nu_\mu$

Expected:
$N_\mu / N_e \sim 2$

Measured:
$N_\mu / N_e \ll 2$

Lost? Where?



Many neutrino experiments

In mines, tunnels, under water or ice

17 completed, 34 working, 9 under construction, 7 planned

4 Nobel Prizes in physics for ν expts

- The Nobel Prize in Physics 1988 was awarded jointly to Leon M. Lederman, Melvin Schwartz and Jack Steinberger "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino".
- The 1995 Nobel Prize in Physics was awarded for pioneering experimental contributions to lepton physics with one half to Martin L. Perl for the discovery of the tau lepton and with one half to Frederick Reines for the detection of the neutrino.
- The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos*
- The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *for the discovery of neutrino oscillations, which shows that neutrinos have mass*.

Neutrino oscillation

Bruno Pontecorvo, 1963

Neutrino states are mixed by weak interaction

Weak eigenstates:

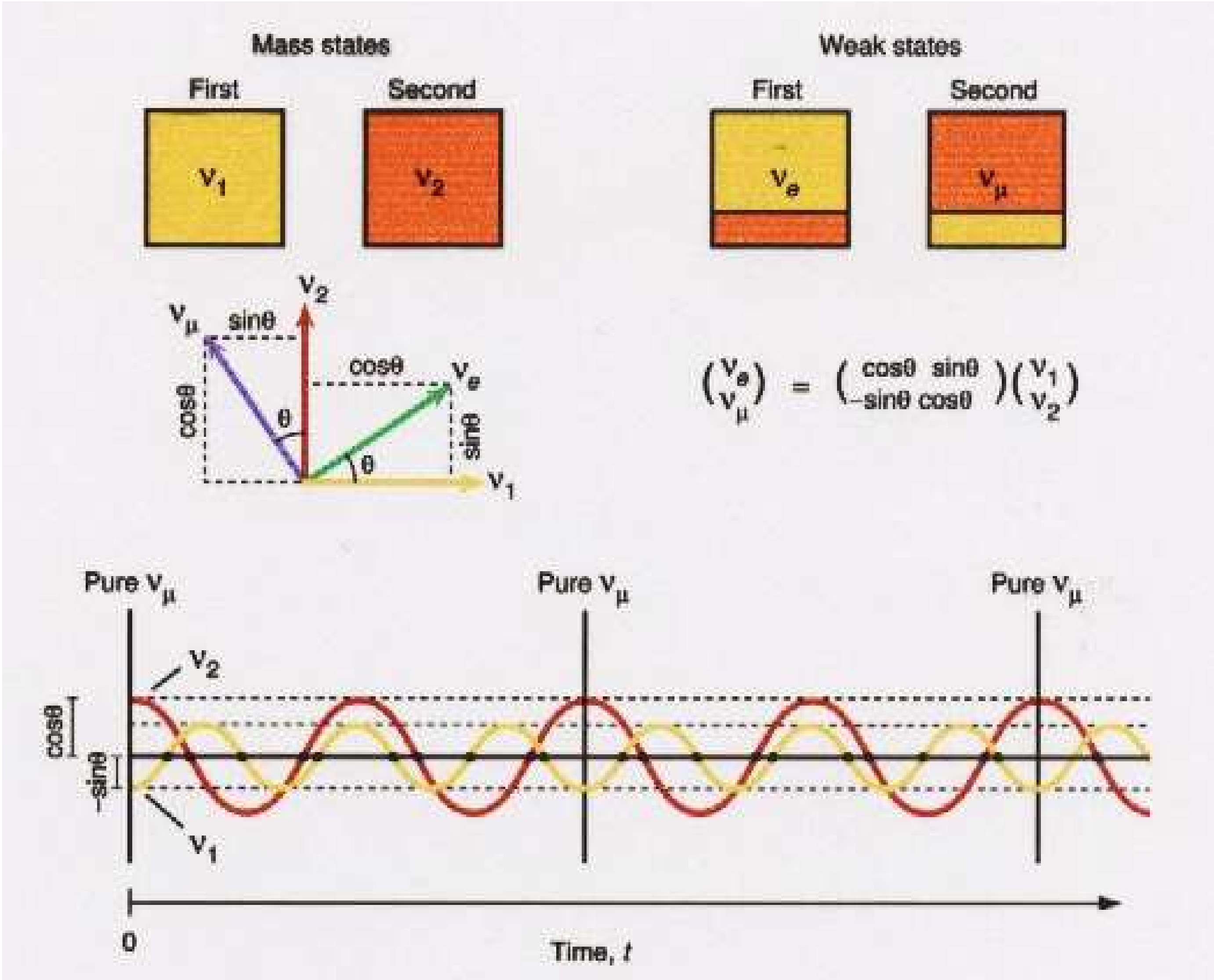
$(\nu_e, \ \nu_\mu)$

Mass (eigen)states:

$(\nu_1, \ \nu_2)$

(Θ: mixing angle)

Oscillation: $\nu_e \Leftrightarrow \nu_\mu$



SKK: Atmospheric neutrinos

Kamioka Nucleon Decay Experiment (originally for proton decay)

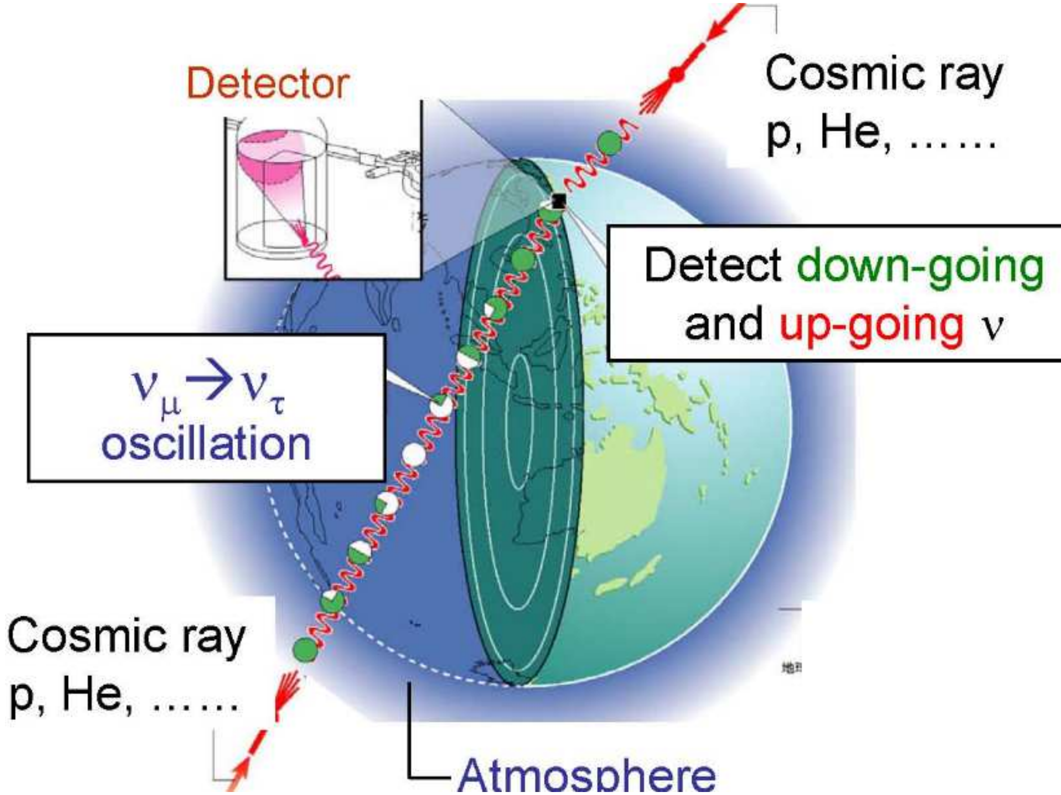
In Kamioka mine at 1000 m depth

(M. Koshiba, Nobel Prize, 2002)

For multi-GeV muon-neutrinos

$\nu_\mu \Leftrightarrow \nu_\tau$ oscillation

on Earth's diameter

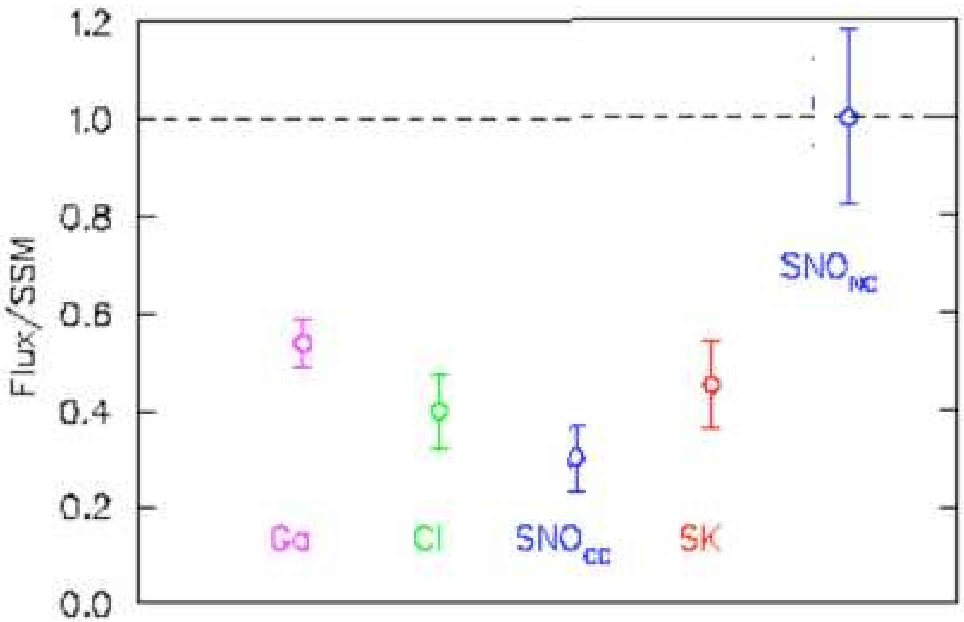


Flux upward/Flux downward = $\frac{N(-1,0<\cos\Theta<-0,2)}{N(0,2<\cos\Theta<1.0)} = 0,54 \pm 0,04$

$$1,3 \times 10^{-3}\mathrm{eV}^2 \leq \Delta M^2_{\mathrm{atm}} \leq 3,0 \times 10^{-3}\mathrm{eV}^2$$

(T. Kajita, Nobel Prize, 2015)

Sudbury Neutrino Observatory (SNO)



Total flux $\approx$ theory

ν_e oscillates into other two

$\Delta M^2 = 8 \times 10^{-5}$ eV^2
(SNOlab, A. B. McDonald, Nobel Prize, 2015)

Atmospheric neutrinos: $\nu_\mu \Leftrightarrow \nu_\tau$ oscillation along Earth's diameter

Sun neutrinos: $\nu_e \Leftrightarrow \nu_X$ oscillation on Sun–Earth distance

Thus $m_\nu > 0$ for at least 2 neutrinos!

How can neutrinos obtain mass?

Neutrino oscillation is mysterious as they have only weak interaction and should not have mixed states

The Standard Model should be violated or extended to accomodate neutrino masses

- Why so small? Seesaw mechanism: light Dirac + heavy sterile?
- Maybe extra Higgs fields give them masses?
- Mixed by a fifth force??
- The hypercharges of ν_R és $\overline{\nu}_L$ are $Y = 0$, sterile (no pairing to charged leptons) and we do not observe such states (maybe LSND or MiniBoone expts?)
- Could neutrinos be Majorana particles, $\nu = \overline{\nu}$?

Oscillation gives ΔM_ν^2 only

Direct measurement $M_\nu < 2$ eV (tritium decay)

Accelerator experiments

for studying neutrino oscillation

Cosmic protons create pions in atmosphere:

$\mathrm{pA}\rightarrow\pi^{\pm}\mathrm{X} \quad \pi^{\pm}\rightarrow\mu^{\pm}\nu_{\mu}; \;\; \mu^{\pm}\rightarrow \mathrm{e}^{\pm}\nu_{\mu}\nu_{\mathrm{e}} \;\; \mathrm{L}\sim \; 30\mathrm{km}$

Accelerator production $\sim$ atmospheric

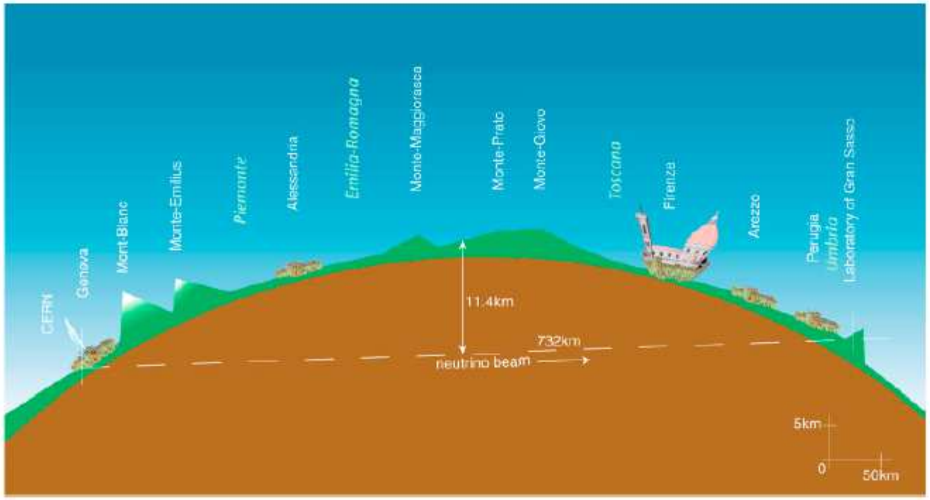
$\mathrm{L}\sim 1\ldots 1000$ km, $\nu_{\mathrm{e}}+2\nu_{\mu}$; ν és $\overline{\nu}$

At high energy $\pi^{\pm}\rightarrow\mu^{\pm}\nu_{\mu}$ forward.

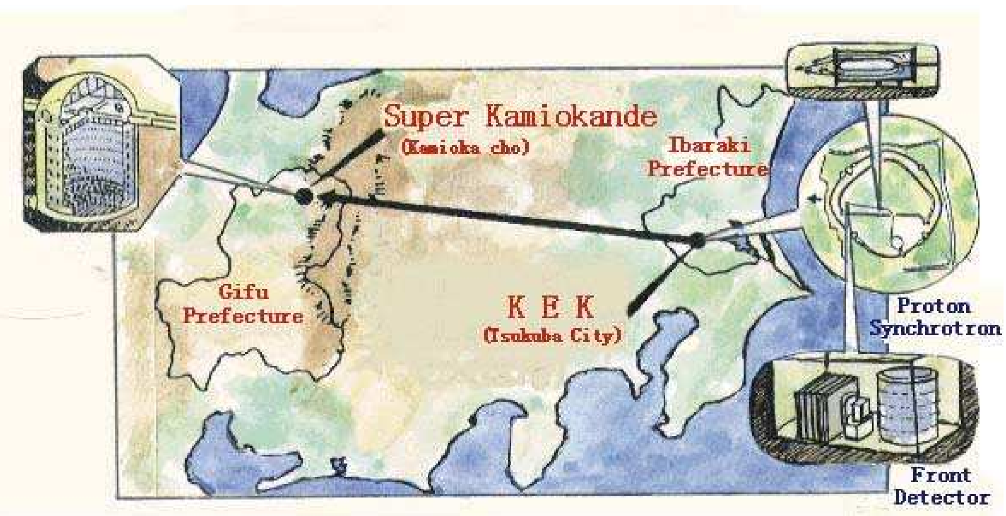
Muon slows down before decay $\Rightarrow$ products in 4Π.

$\sim$ pure ν_{μ} beam along proton direction.

Long distance accelerator experiments

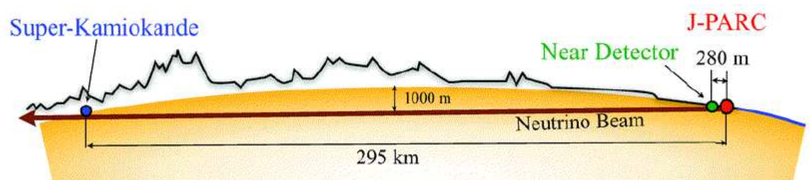


CNGS: CERN → Gran Sasso: OPERA, 732 km



K2K: KEK → Kamioka: 250 km

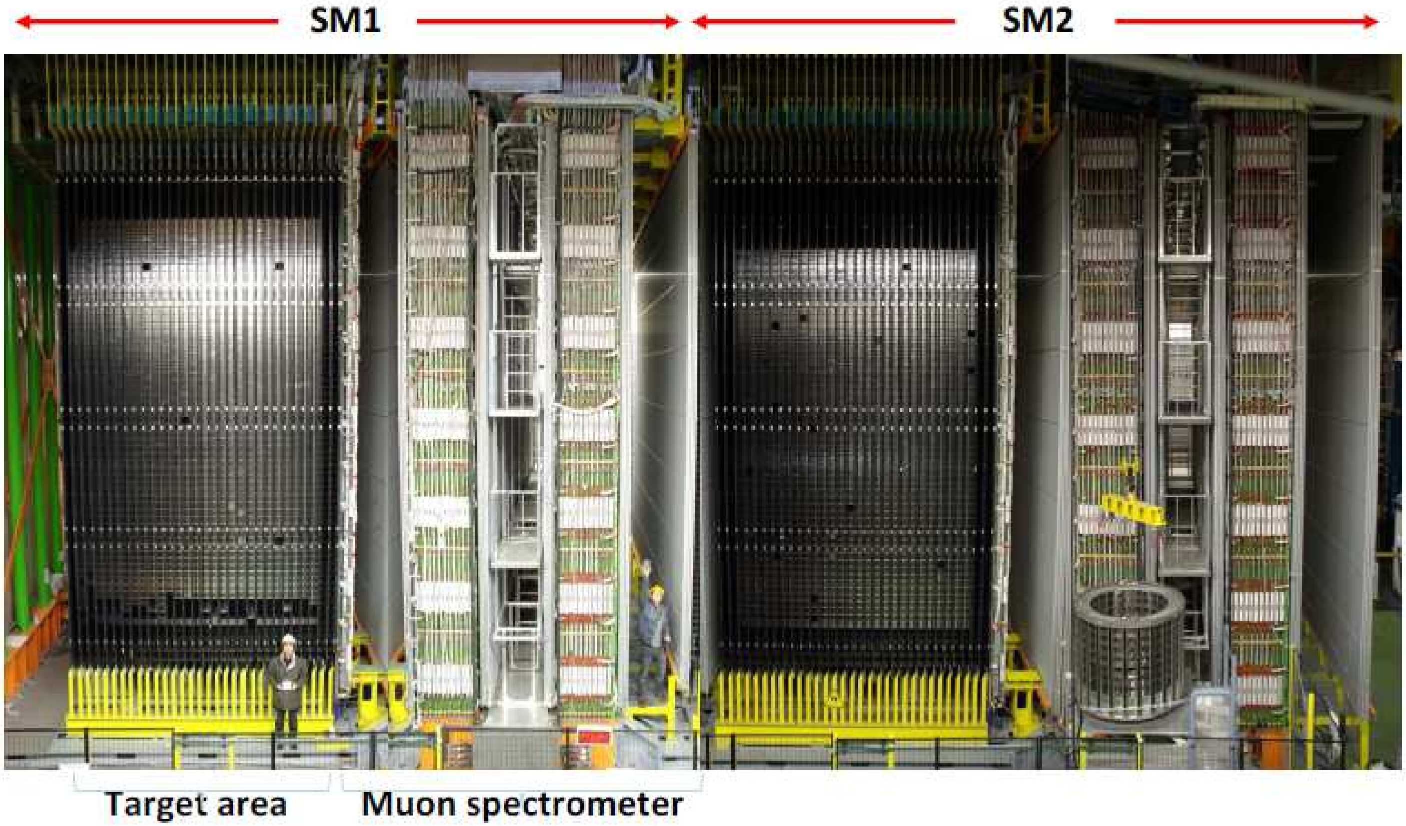
Fermilab → MINOS: 735 km



T2K (Tokai → Kamioka): 295 km

The OPERA experiment at Gran Sasso

Oscillation Project with Emulsion-tRacking Apparatus



to study $\nu_\mu \to \nu_\tau$ oscillation

They have indentified 5 τ neutrinos!

In 2011 *observed* faster-than-light ν_μ due to faulty time synchronization.

Let us measure the mass of ν_μ!

MINOS and OPERA measured time-of-flight
on the distance of 730 km using GPS with $\Delta t = 10$ ns precision

Particle detectors can do $\Delta t = 10$ ps
At $L = 1 \ldots 10$ km no GPS needed, one can directly compare ν_μ to light.

Velocity is uninteresting, but one can use it to measure mass
ν_μ can travel in vacuo or in matter
(although its effect must be small for low-energy neutrinos)

U. D. Jentschura, D. Horváth, S. Nagy, I. Nándori,
Z. Trócsányi and B. Ujvári: *Weighing the Neutrino*
Int.J.Mod.Phys. E23 (2014) 1450004; arXiv:1312.3932

Measuring the mass of ν_μ?

But what is it? What is ν_μ mass??

$$m^2(\nu_f) = \sum_{i=1}^{3} U_{fi}\, m^2(\nu_i)$$

where ν_f: flavor, ν_i: mass eigenstate,

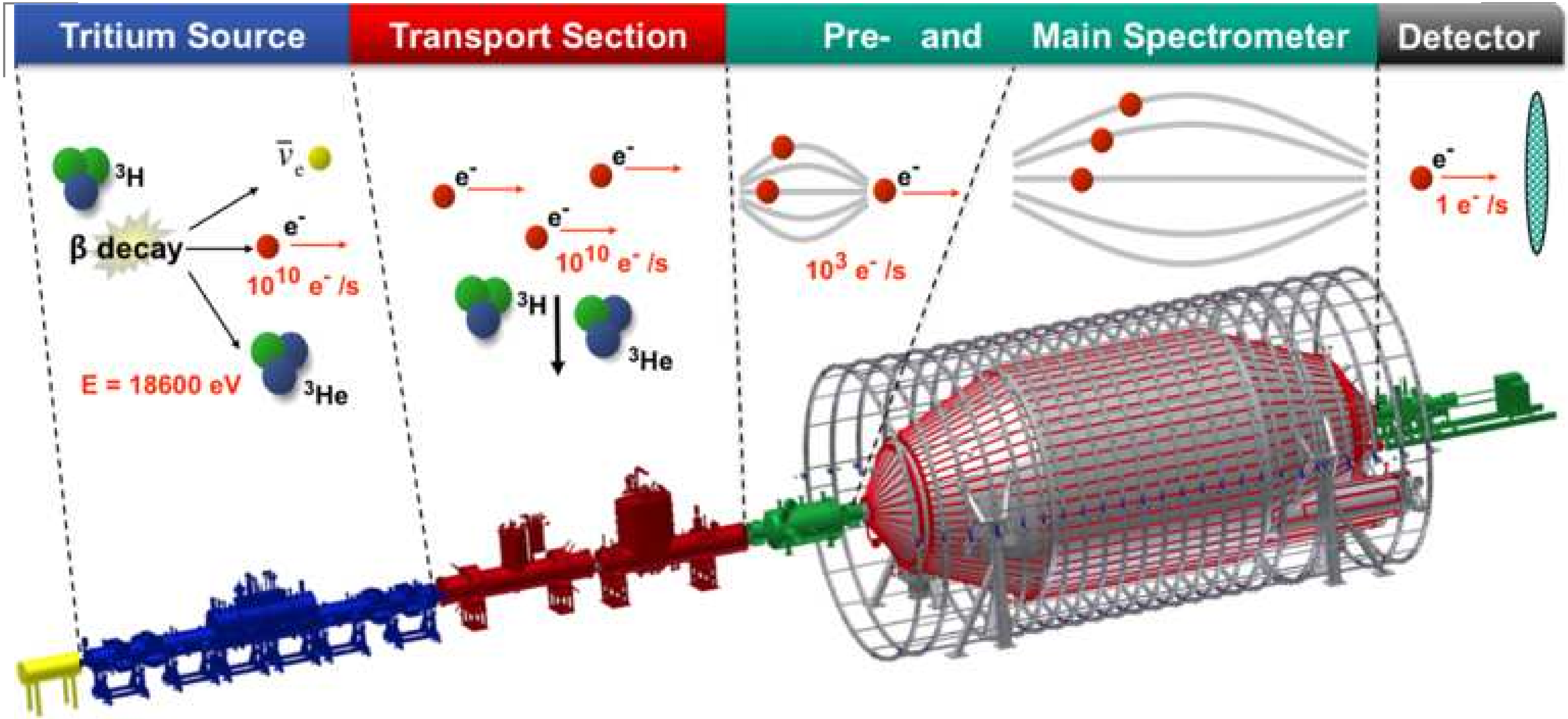
U_{fi}: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix

Only direct measurement: $m(\nu_\mu) < 2.2$ MeV/c^2 (90% konf.) by one event detected by OBELIX at LEAR in 1996:

N. Angelov et al., Nucl. Phys. A 780 (2006) 78

Cosmology (Planck, 2015): $\sum_{i=1}^{3} m(\nu_i) < 0.23$ eV

KArlsruhe TRItium Neutrino: $M(\nu_\mathrm{e})$



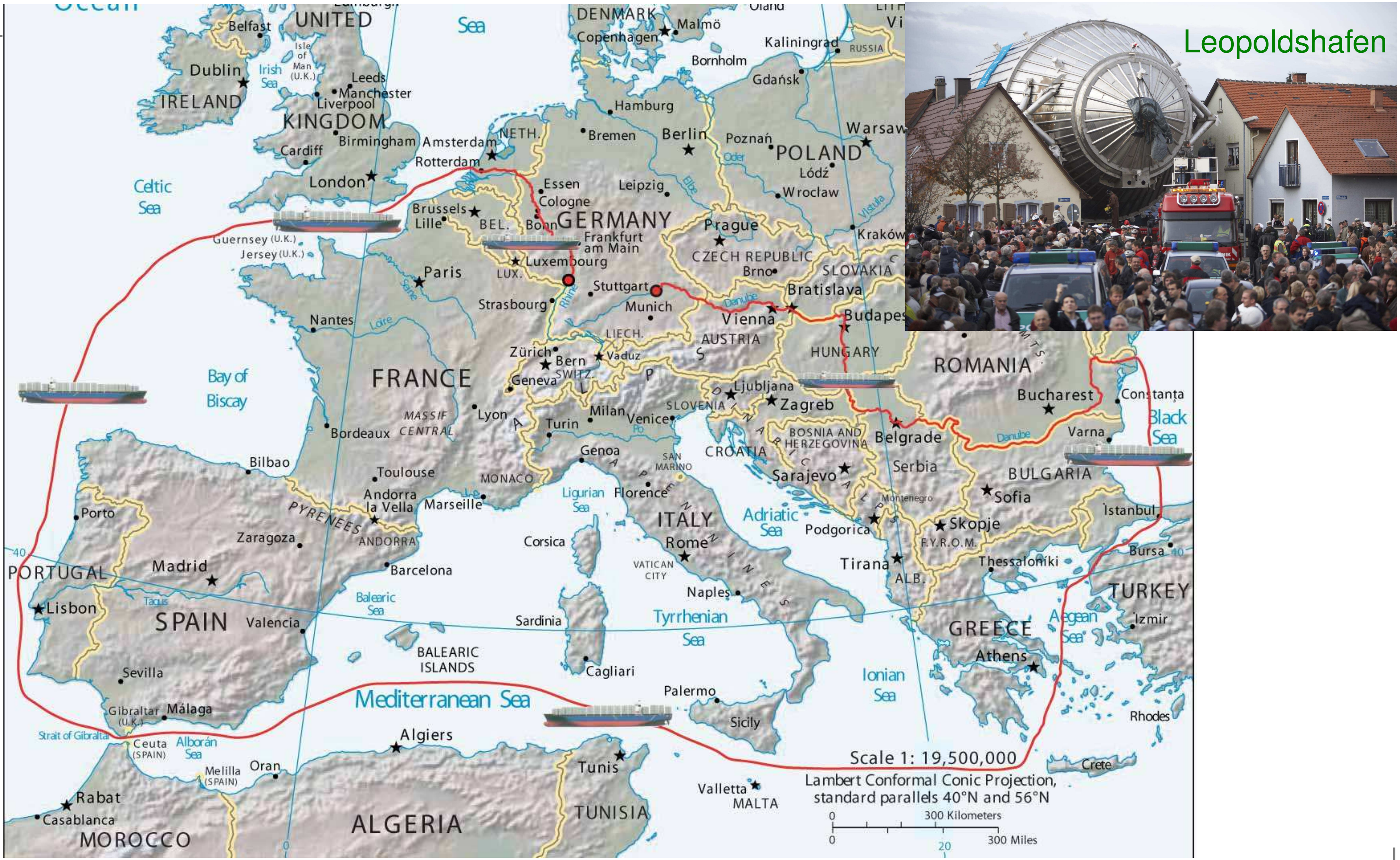
Tritium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the electron starts its journey to the detector.

Electrons are guided towards the spectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.

The electron energy is analyzed by applying an electrostatic retarding potential. Electrons are only transmitted if their kinetic energy is sufficiently high.

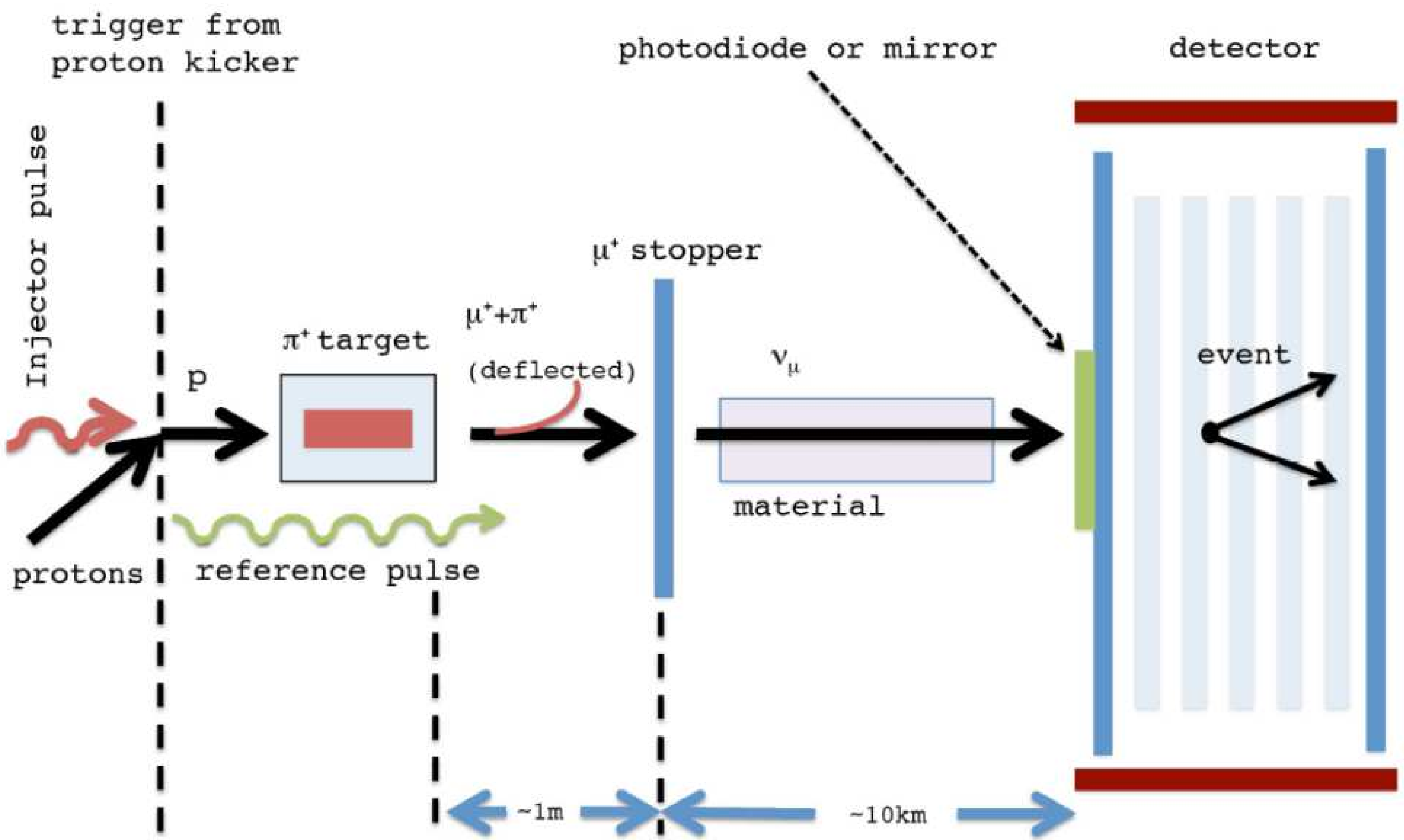
At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer potential and hence gives an integrated β-spectrum.

Transport of KATRIN: 400 ⇒ 9000 km



Deggendorf → Karlsruhe: Danube, seas, Rhine

Measuring $M(\nu_\mu)$



Flying $M(\nu_\mu)$ together with photons, $L = 10$ km

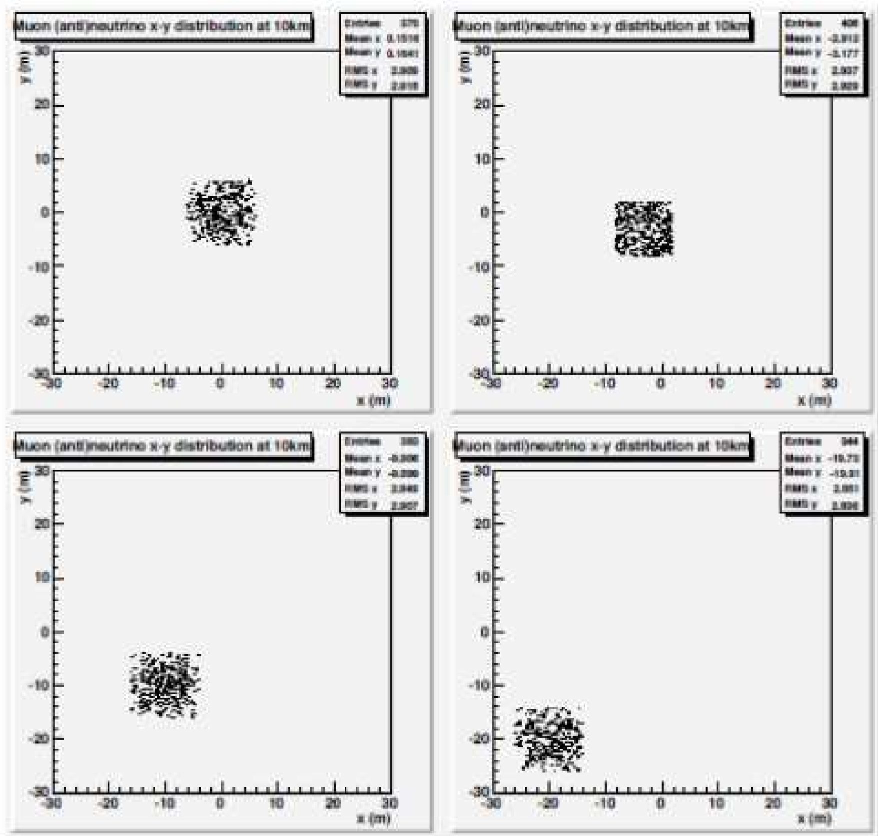
A lot of protons are needed: laser accelerator (ELI?)

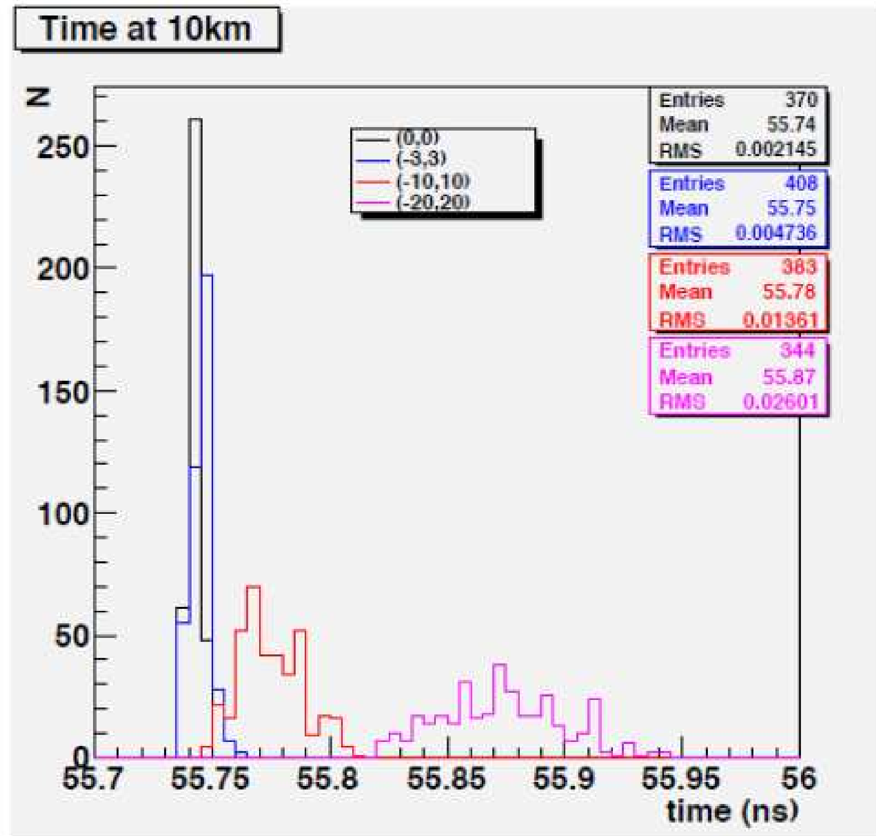
Detector: e.g. liquid scintillator (Borexino)

Experimental conditions

- CERN Super Proton Synchrotron (SPS), $E_{\rm p} = 450$ GeV
- $t = 0$ for timing: proton kicker or laser start
- Thin (2 mm) graphite target: p+N $\rightarrow \pi^{\pm}$+X
- $\pi \rightarrow \mu + \nu_\mu \ \ (\gamma \approx 2)$, flight on 10 cm.
- $B = 8$ T deflects $\pi^{\pm}, \ \mu^{\pm}$ ($\Delta t \approx 10^{-10}$ s)
- Decaying pions: 0.57%, can be handled
- Neutrino flight, ν_μ és $\overline{\nu}_\mu$ (in vacuo or matter) together with photons (in vacuo): $s_0 = 10$ km (no need to measure time and distance separately)
- Detector: liquid scintillator (Borexino): good for low energies, $E_\nu > 0.2$ MeV (Cherenkov is faster, but $E_\nu > m_\mu = 105$ MeV). Cosmic veto around it.

Monte Carlo simulations





Time resolution depends on precise positioning of neutrino beam. If it is centered on a $10\,\mathrm{m} \times 10\,\mathrm{m}$ liquid scintillator:

$\delta t \approx 3$ ps.

Expected precision

10×10 m liquid scintillator in the middle of the neutrino beam: $\delta t \approx 3$ ps.

10^{11} protons, $E_p = 450$ GeV, target: 2 mm graphite;
$E(\pi^{\pm}) = 100 \pm 1$ GeV, $S_0 =$ 10 km ν_μ flight:

$$\delta c = \frac{c^2\,\delta t}{s_0} \approx 30\mathrm{m/s}$$

$E(\nu_\mu) = 1$ MeV: $\quad \delta m(\nu_\mu) \approx 420$ eV $\ll 2,2$ MeV

This is also a CPT (Lorentz-violation) test, which could mean a significant improvement to previous limits.

Summary

- Neutrinos are mysterious, experiments needed
- Questions ⇒ new physics?
  - Where is their mass coming from?
  - Should the Higgs sector be extended?
  - Majorana, Dirac or both?
  - Is there a sterile ν?
  - A new force to mix them?
- A new measurement of $m(\nu_\mu)$:
  - Shorter distance
  - Simpler setup
  - Higher precision

Thank you for your attention!

Spare slide

Expected precision of mass measurement

- Time measurement:
  - TOF: $0.01 * \Delta t \approx 1$ ps
  - Detector: $\Delta t \approx 3$ ps.
- Velocity: $v_\nu = s_0/t_0 = (1-\delta)c, \;\delta = c\Delta t/s_0$
- $s_0 = 10$ km: $\delta c = c^2\Delta t/s_0 = 30$ m/s $\Rightarrow \delta \approx 10^{-7}$
- $m(\nu_\mu) = 1$ MeV, $\Delta m(\nu_\mu) \approx 420$ eV.