Introduction to Neutrino Physics

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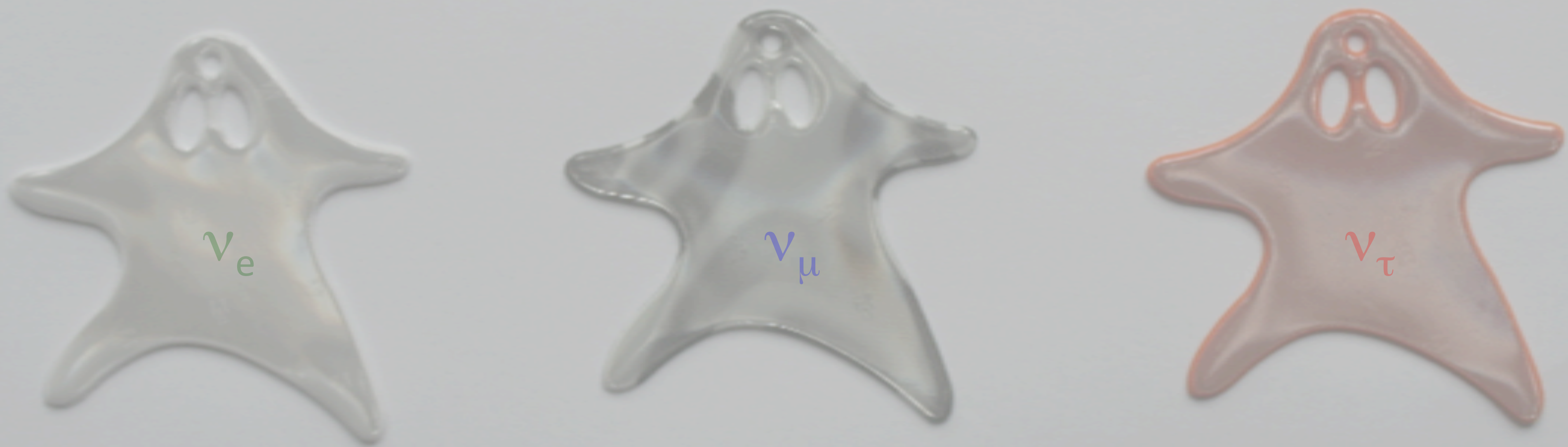


Lecture 5

The neutrino time-of-flight thing

Wrap-up and comments

University of Sussex

LUNDS UNIVERSITET

Recap

- Neutrinoless double beta decay, if it exists, violates lepton-number conservation by 2
- The only known mechanism that would reveal the Majorana nature of the neutrino
- Half-lives >10^{18} years, more likely >10^{25} years (c.f. age of the universe 10^{10} years)
- The half-live is inversely proportional to the square of the *effective* neutrino Majorana mass
- There are only 35 candidate isotopes in nature for this process
- Extremely challenging experimental requirements, e.g., amount of isotope mass, cleanliness and energy resolution
- Several experiments in preparation, which should be able to probe neutrino mass region ~100 eV

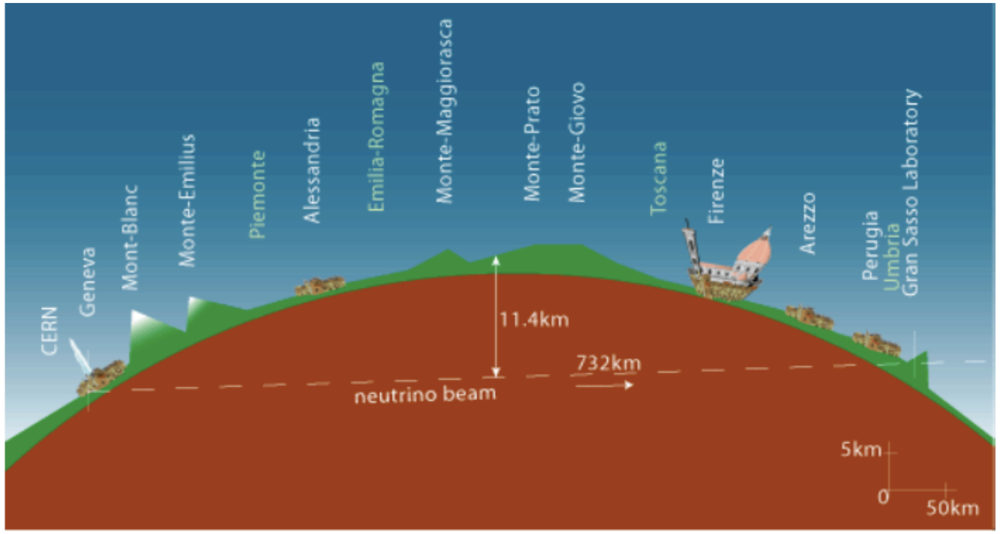
Outline lecture 5

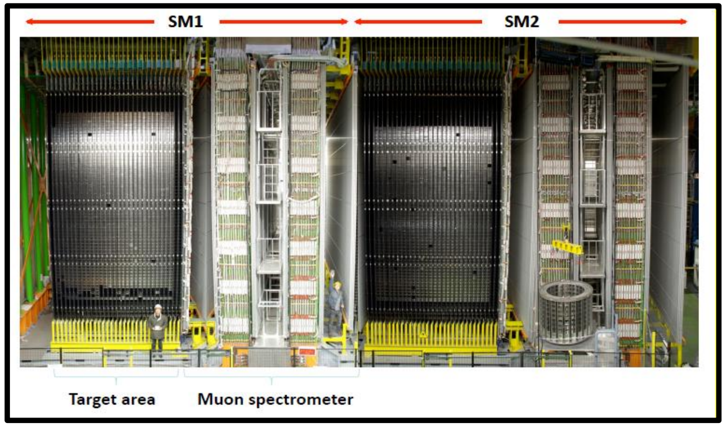
- "The neutrino speed of light thing": OPERA, the TOF measurement, criticisms and what comes hereafter
- Wrap-up and a few comments

The OPERA experiment

Demonstrate explicitly that ν_μ oscillates into ν_τ

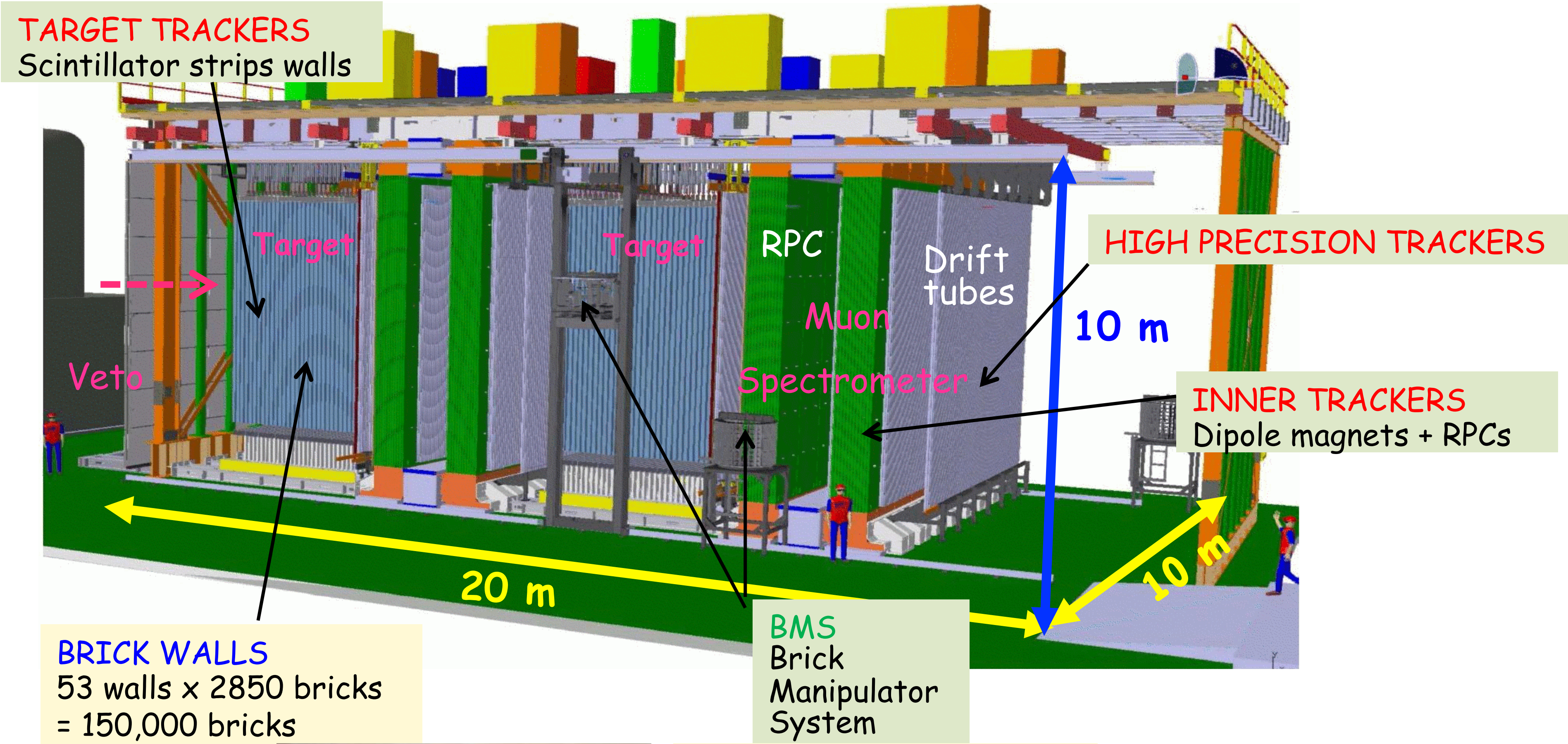
Muon neutrino beam from CERN to Gran Sasso (CNGS)



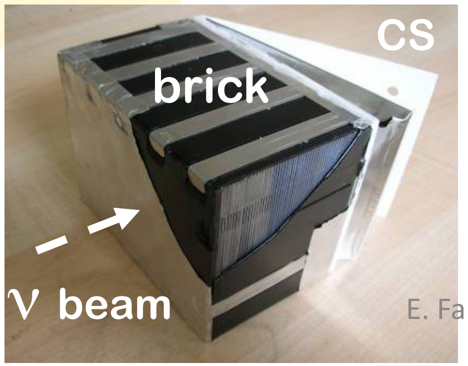


- Baseline almost identical to that of NuMI (732 km)
- Peak neutrino energy ~17 GeV in order to be able to produce and detect ν_τ (c.f. ~3.5 GeV for MINOS)
  → a long way away from oscillation max

The OPERA experiment



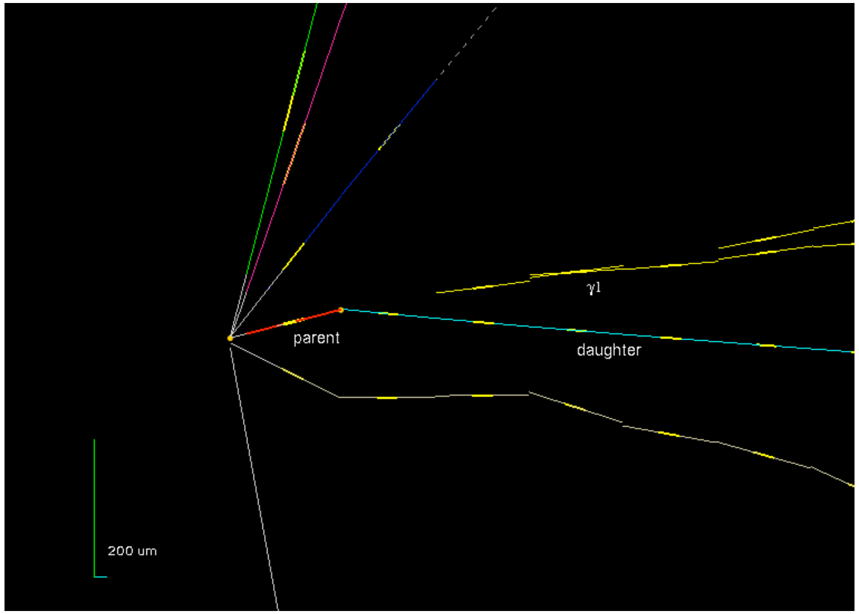
BRICK WALLS
53 walls x 2850 bricks
= 150,000 bricks
= 1.25 kton



BRICK
57 emulsion films + 56 Pb plates
A box with a removable pair of films (Changeable Sheets)

ν_τ CC event: $\nu_\tau + N \rightarrow \tau + X$
Must detect τ
"Bricks" of nuclear emulsions
(~photographic film)

The OPERA experiment



τ candidate event (May 2010)

- Data-taking since 2008
- Scheduled to run for another year; depends on CERN shutdown
- Expect to observe 3-5 ν_τ in total
- No measurement of mixing parameters, but do search for ν_e appearance

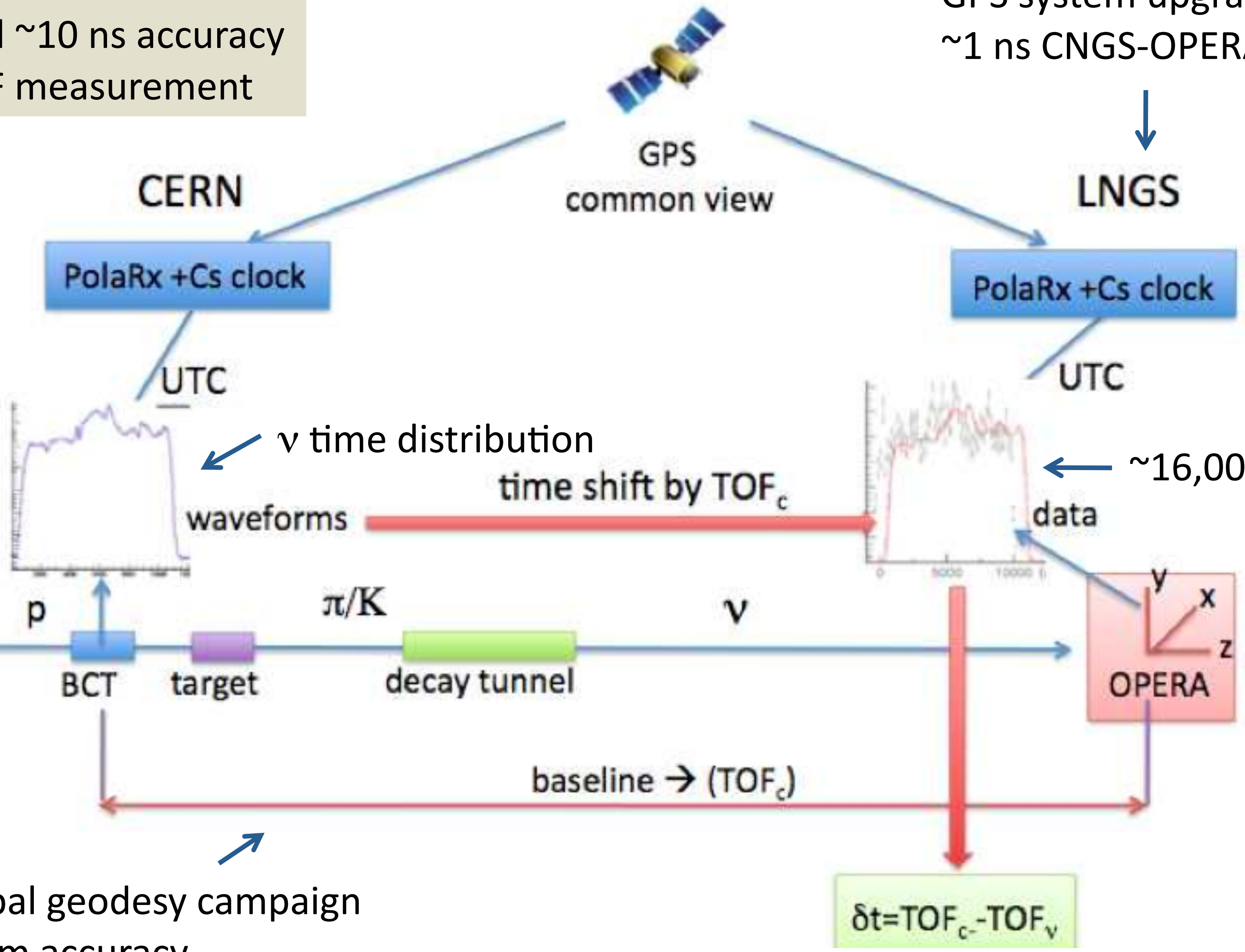
OPERA time-of-flight measurement

- 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
  - $(v\text{-}c)/c = \delta t /(TOF_c - \delta t) = (2.49 \pm 0.28\ (stat.) \pm 0.30\ (sys.))\ \times 10^{-5}$
  - 6σ significance

TOF measurement principle

Overall ~10 ns accuracy on TOF measurement

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



ν time distribution

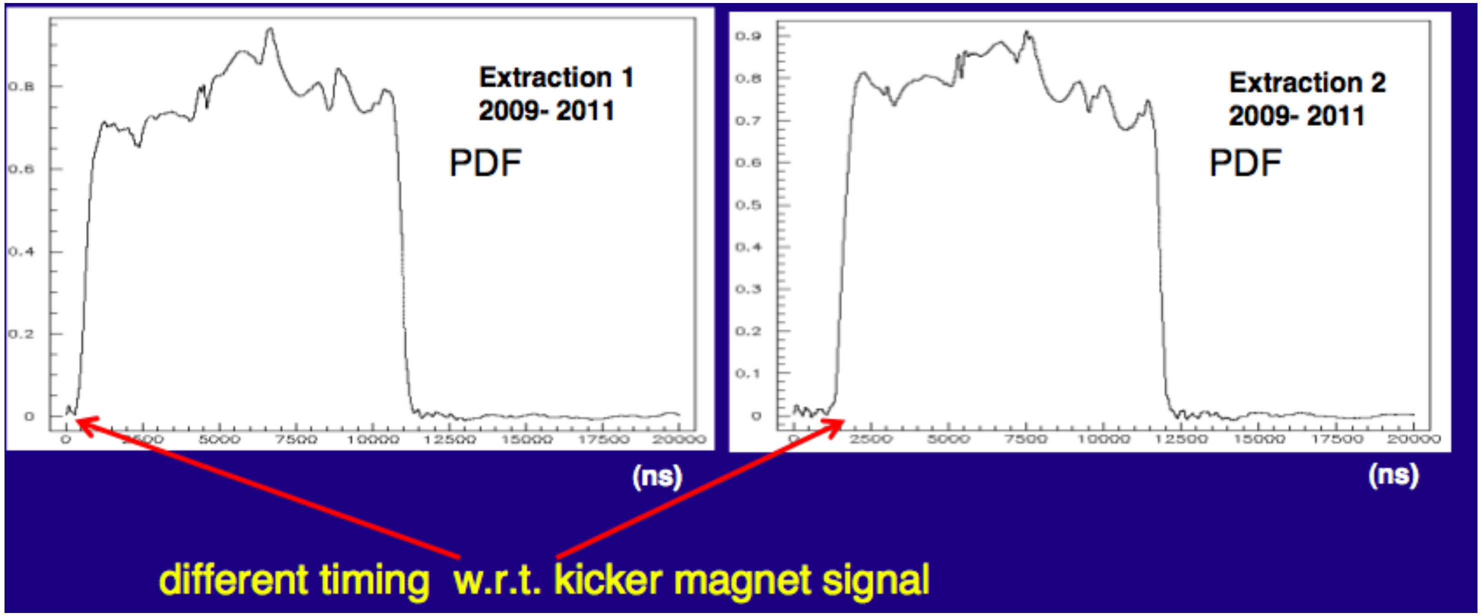
~16,000 events

Calibration of timing chains to ~1ns

Global geodesy campaign
20 cm accuracy

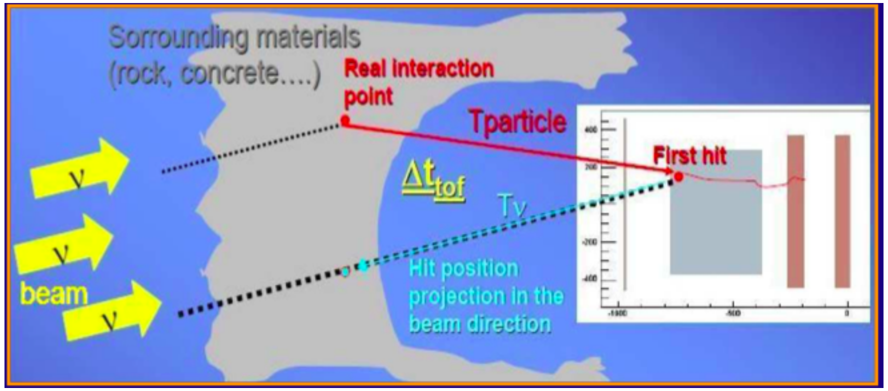
Neutrino event-time distribution PDF

- 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

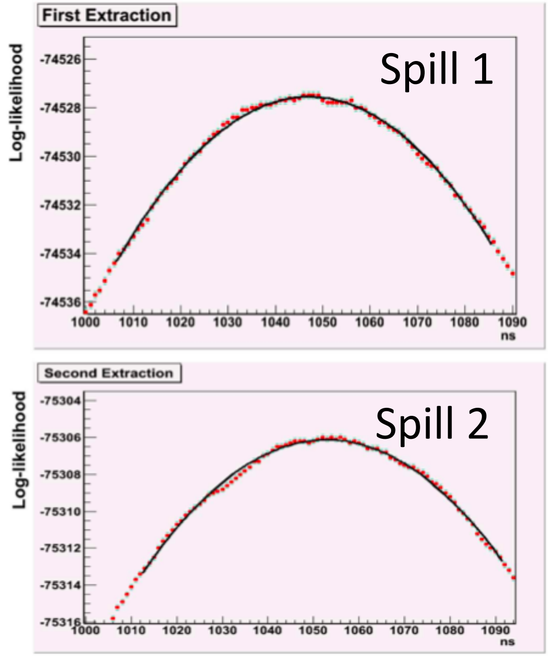


Analysis

- 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)



After massive attention, commentary, critique…

OPERA time-of-flight 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

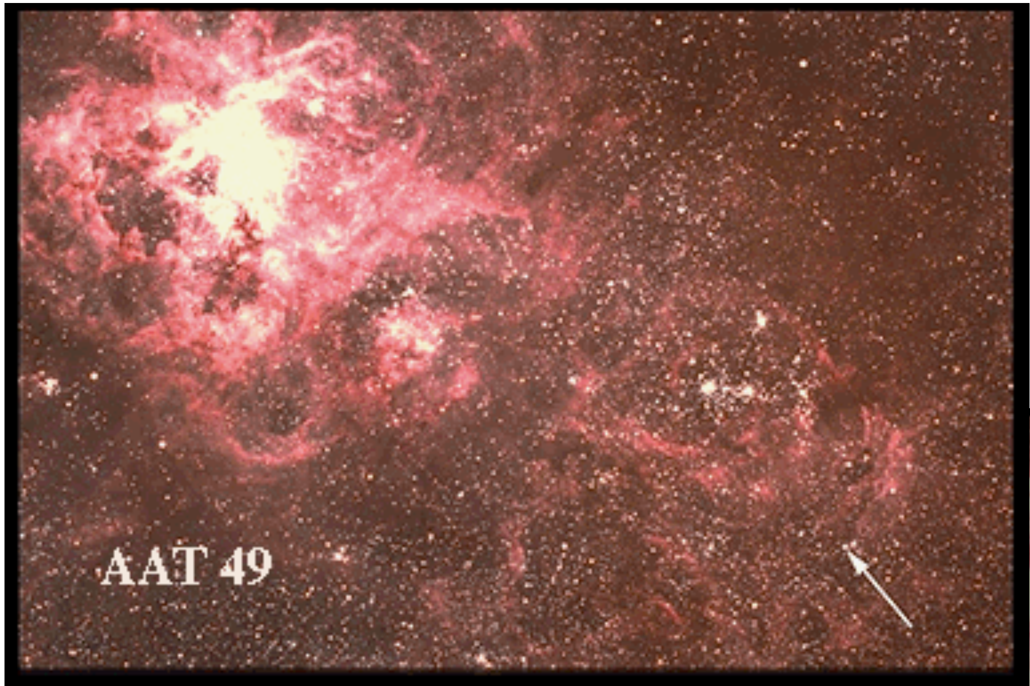
OPERA time-of-flight measurement

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

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

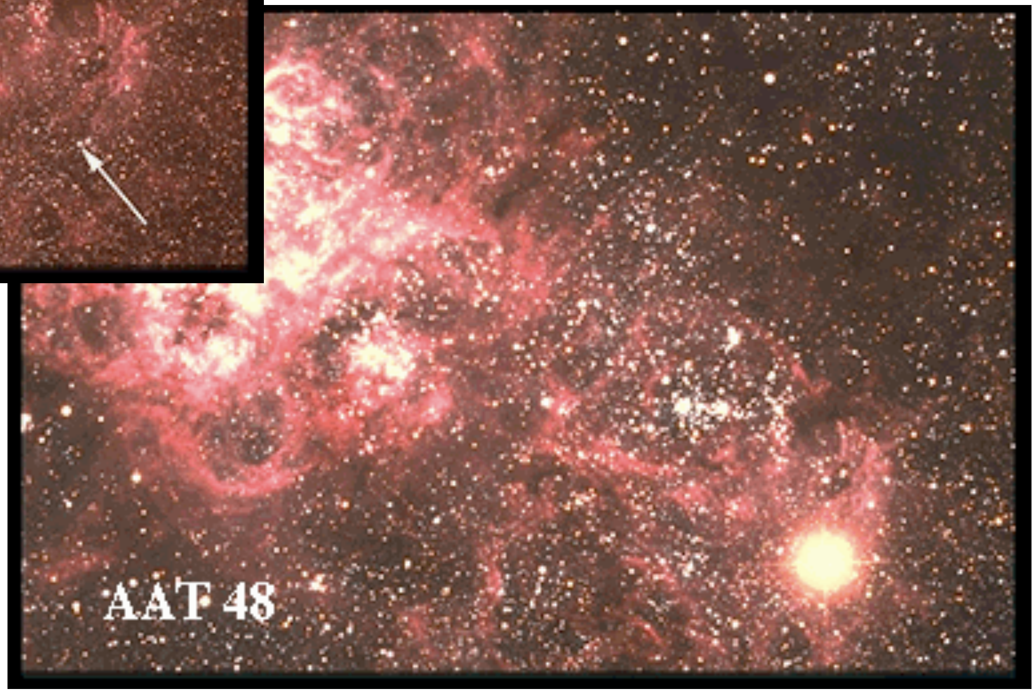
- Paper submitted to Journal of High Energy Physics on 17 Nov
  arXiv:1109.4897v2

Main criticism 1: SN1987A



Large Magellanic Cloud
(160,000 ly away)
23 February 1987

First supernova visible to the naked eye since Kepler SN in 1604



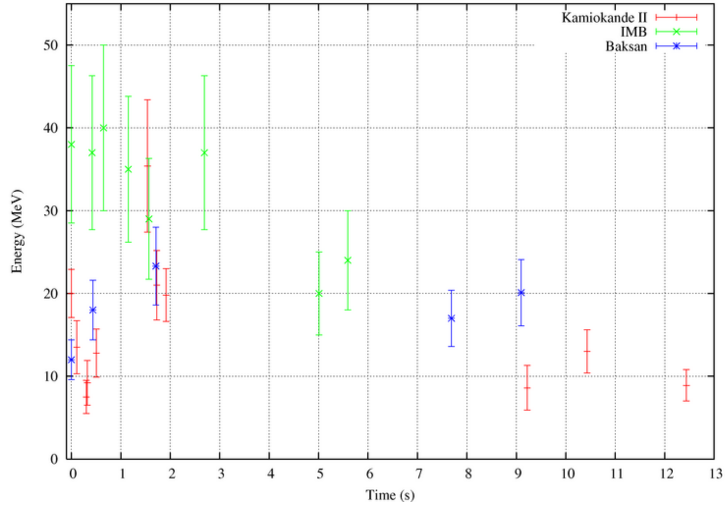
Only supernova to have been detected also through its neutrino burst

Core-collapse supernova: 99% of released energy emitted as neutrinos!

Observation of neutrinos from SN1987A

- 24 February 1987:
  Observation of very bright type II (core-collapse) supernova
- Four large underground detectors potentially sensitive to SN neutrinos were in operation
  - Kamiokande-II, IMB, Baksan, LSD
- All observed an unusual number of events with energy O(10 MeV) within a time window O(10 s) in the hours before the optical discovery
- K-II, IMB, Baksan happened at the same time, modulo precision of their clocks
- LSD was five hours before the others
  - Controversial; usually not included in data analyses

Ca 2 dozen events

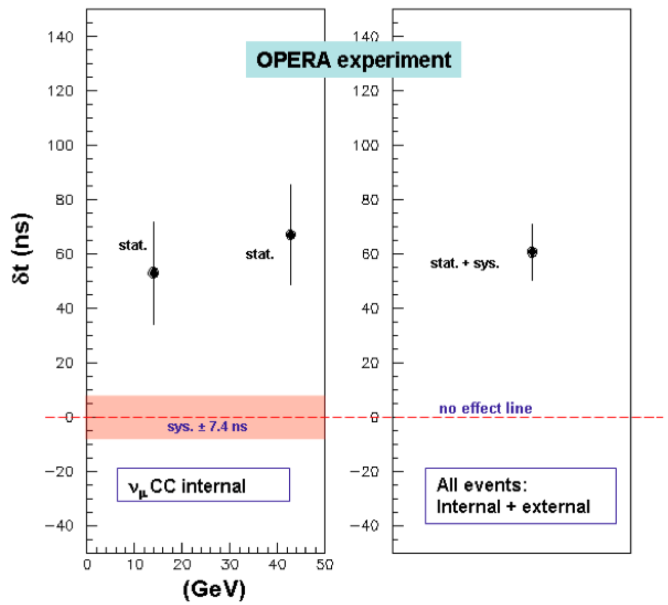


Based on these events, approximately one theory paper has been published every ten days
— for the last twenty-four years!

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

Main criticism 2: Cohen and Glashow

arXiv:1109.6562v1

New Constraints on Neutrino Velocities

Andrew G. Cohen* and Sheldon L. Glashow†
Physics Department, Boston University
Boston, MA 02215, USA

(Dated: September 30, 2011)

Abstract

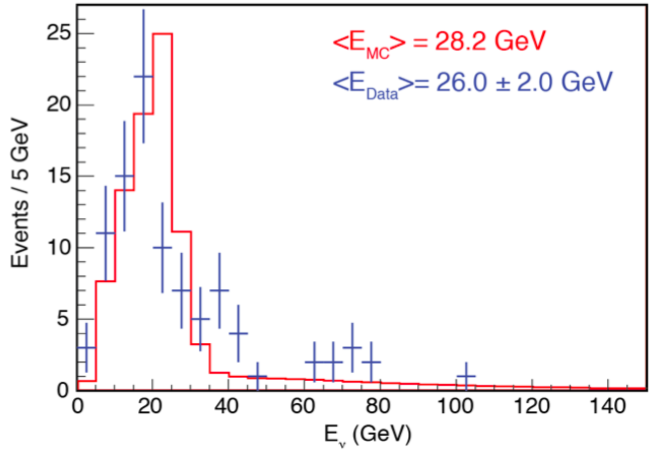
The OPERA collaboration has claimed that muon neutrinos with mean energy of 17.5 GeV travel 730 km from CERN to the Gran Sasso at a speed exceeding that of light by about 7.5 km/s or 25 ppm. However, we show that such superluminal neutrinos would lose energy rapidly via the bremsstrahlung of electron-positron pairs ($\nu \rightarrow \nu + e^- + e^+$). For the claimed superluminal neutrino velocity and at the stated mean neutrino energy, we find that most of the neutrinos would have suffered several pair emissions en route, causing the beam to be depleted of higher energy neutrinos. Thus we refute the superluminal interpretation of the OPERA result. Furthermore, we appeal to Super-Kamiokande and IceCube data to establish strong new limits on the superluminal propagation of high-energy neutrinos.

Analogue to Cherenkov radiation

- ICARUS should have seen a significant deformation of the E_ν spectrum
- Instead, their limit on δt is comparable to SN1987A

http://arxiv.org/abs/1110.3763

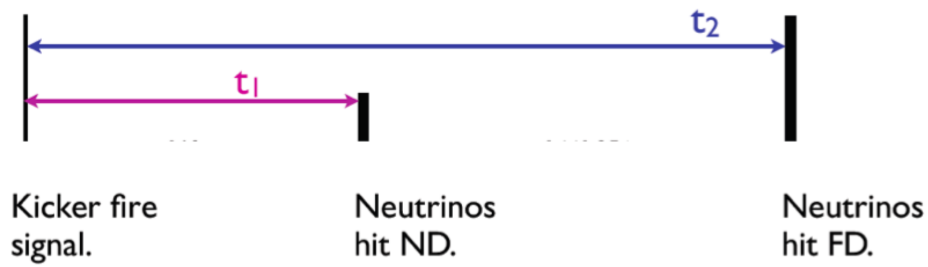
ICARUS experiment at LNGS



What will happen next?

- CERN will provide another bunched run (2 ns), foreseen for about one week in May 2012
- Another such run could be done at the end of the summer, if required
- LNGS experiments ICARUS, Borexino (solar neutrinos), LVD (neutrino astrophysics) will make use of this beam to make independent checks
- OPERA proceeding to use global timing system based on existing fibre cable network (using a channel not used by telecoms; claim 10^{-16} precision); aided by French metrology institute

MINOS 2007 TOF measurement

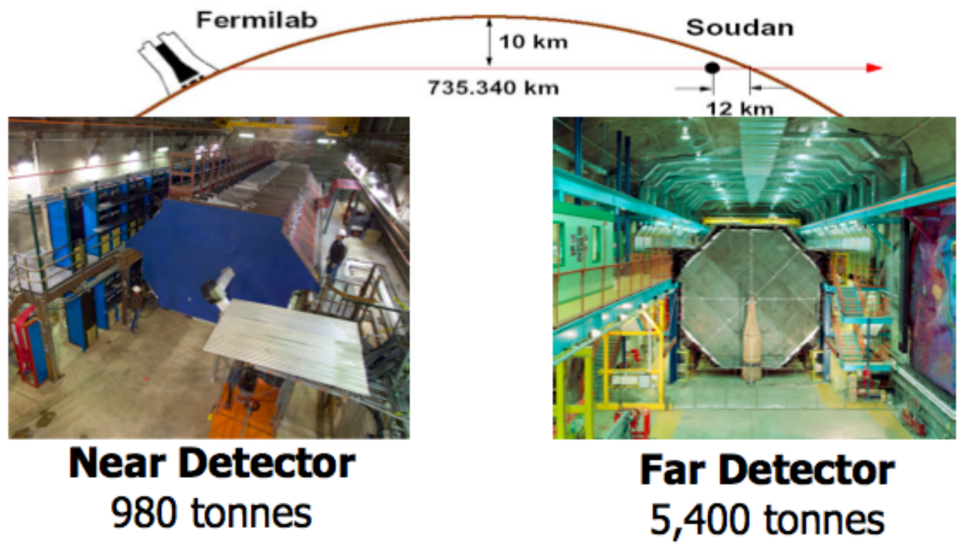


Measure time of flight as $t_2 - t_1$

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

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

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



MINOS improvements

2007 TOF measurement:

Source of uncertainty	Size
Distance between detectors	2 ns
ND antenna fibre length	27 ns
FD antenna fibre length	46 ns
Near Detector electronics latencies	32 ns
Far Detector electronics latencies	3 ns
Detector readout differences	9 ns
GPS timing system	12 ns
Total (sum in quadrature)	64 ns

Working on this, NOT firm promises

Phase 1 (to spring 2012):
Improve uncertainties in existing data
- Re-survey cable delays
- Use auxiliary detectors to measure electronics & detector latencies

19-35 ns precision

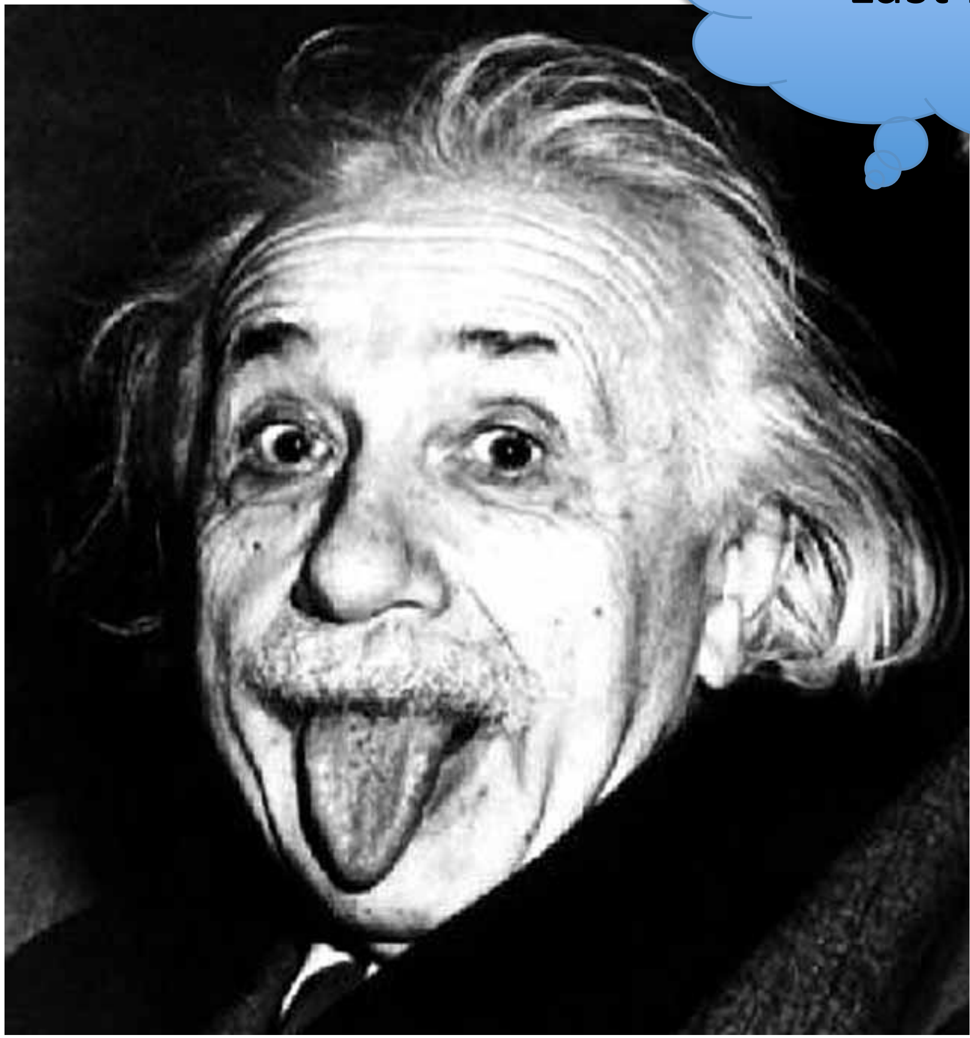
Phases 2 & 3
Bring all uncertainties to ns level:
- **Improve GPS system**
- Continuous monitoring of fibre lengths
- Improved use of auxiliary data
- Precision comparable to OPERA

for data from 2013 onwards

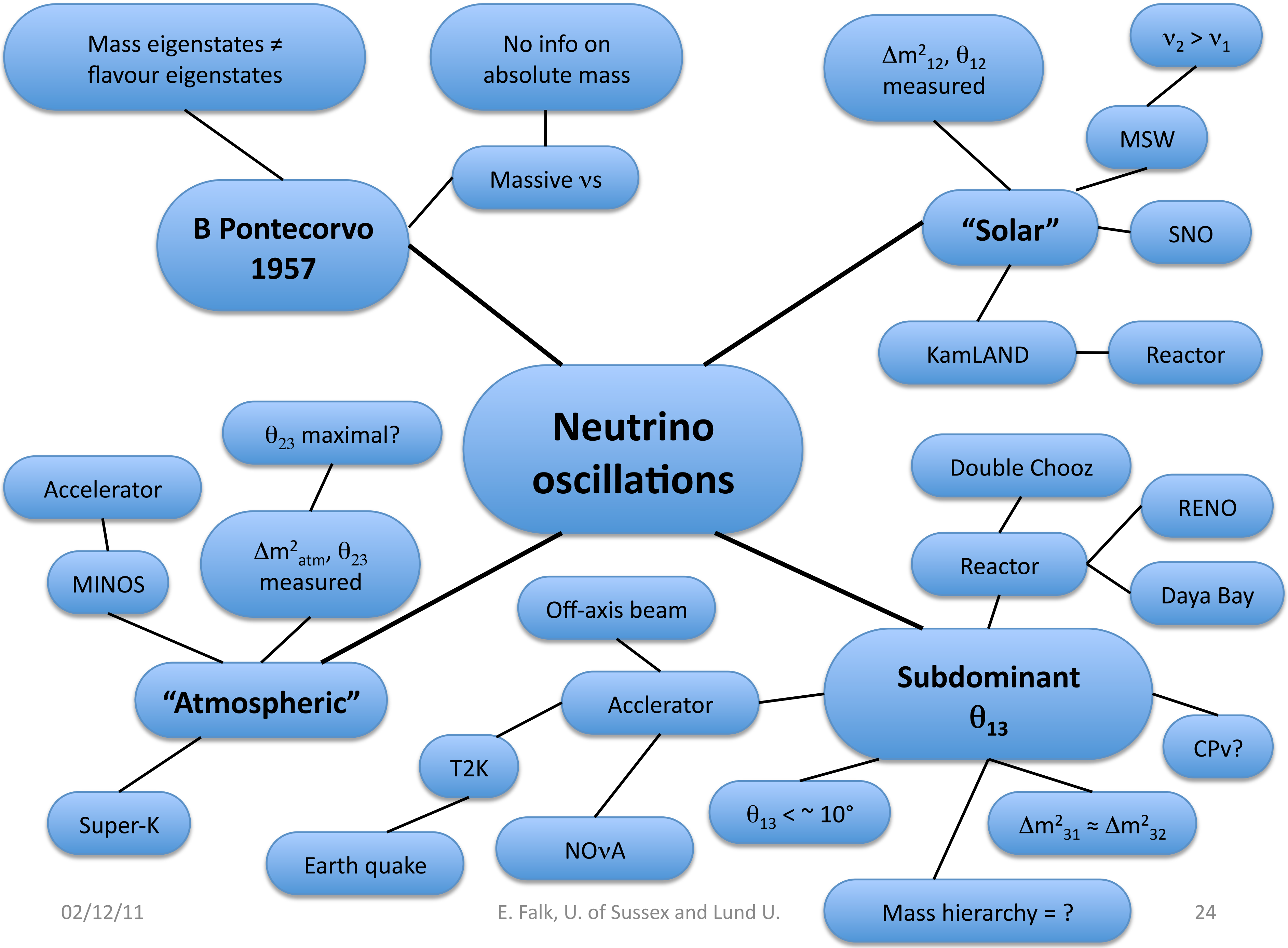
T2K improvements

- Already have a short bunch structure, so no modifications required
- Shorter baseline (300 km) so would need a precision of 5 ns to be comparable to OPERA
- Upgrading timing systems for this measurement
- Restart (after the earthquake) at the end of January 2012
- Will need one year or a bit more for conclusive results

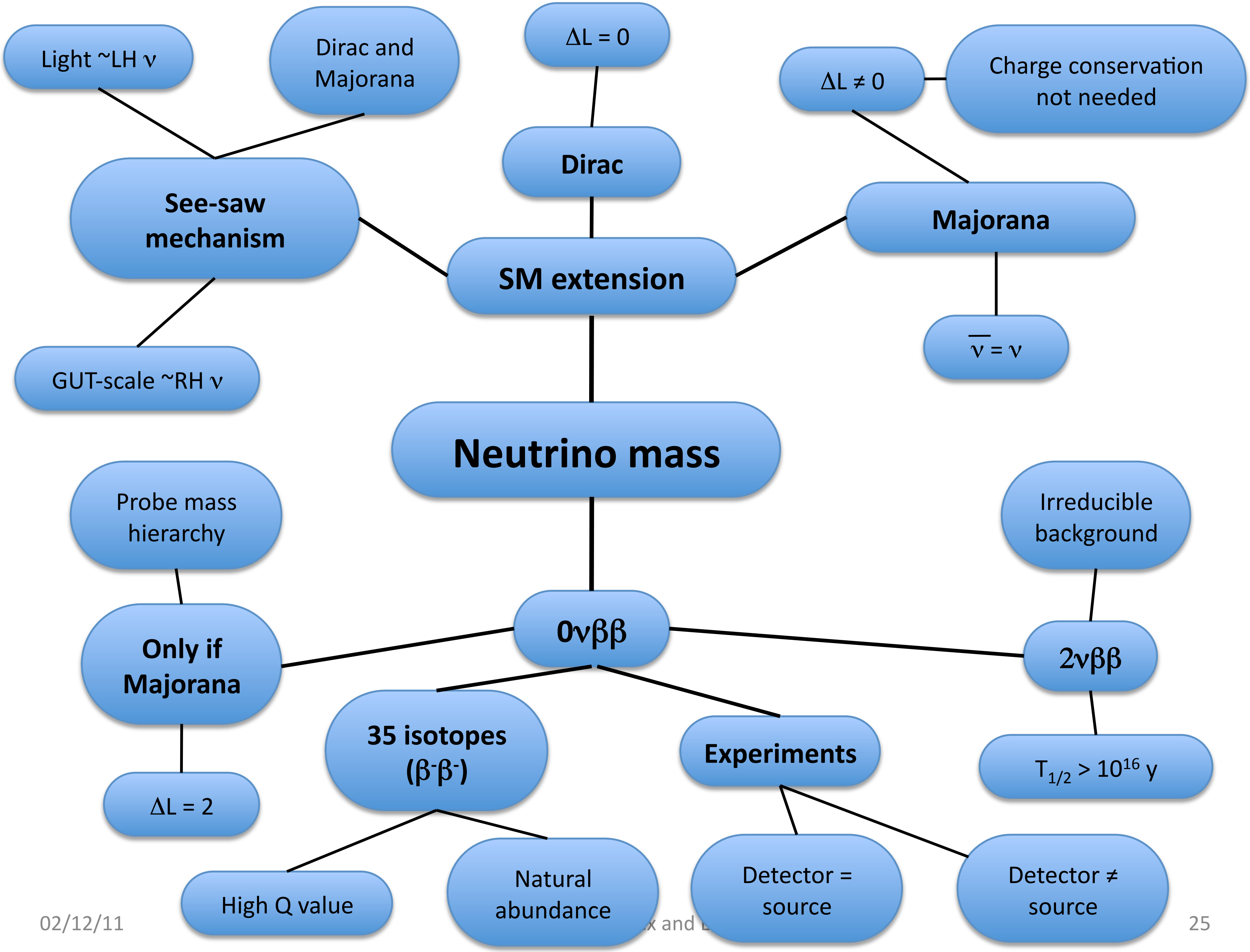
Last laugh?



Summing up earlier parts of the course…



Mass eigenstates ≠ flavour eigenstates
No info on absolute mass
Δm^2_{12}, θ_{12} measured
$\nu_2 > \nu_1$
MSW
Massive νs
B Pontecorvo 1957
"Solar"
SNO
KamLAND
Reactor
Neutrino oscillations
θ_{23} maximal?
Accelerator
Double Chooz
RENO
MINOS
Δm^2_{atm}, θ_{23} measured
Reactor
Daya Bay
Off-axis beam
"Atmospheric"
Acclerator
Subdominant θ_{13}
CPv?
T2K
Super-K
θ_{13} < ~ 10°
$\Delta m^2_{31} \approx \Delta m^2_{32}$
Earth quake
NOνA
Mass hierarchy = ?


Light ~LH ν
Dirac and Majorana
ΔL = 0
ΔL ≠ 0
Charge conservation not needed
Dirac
See-saw mechanism
SM extension
Majorana
GUT-scale ~RH ν
$\bar{\nu} = \nu$
Neutrino mass
Probe mass hierarchy
Irreducible background
Only if Majorana
0νββ
2νββ
35 isotopes ($\beta^-\beta^-$)
Experiments
ΔL = 2
$T_{1/2} > 10^{16}$ y
High Q value
Natural abundance
Detector = source
Detector ≠ source

Possible developments and directions

- Future of the field depends very much on the value of θ_{13} (next 5 years)
- Future long-baseline facilities:
  - Upgrades to T2K
  - LBNE (Fermilab – Homestake)
  - LBNO (CERN – Pyhäsalmi)

- … Sterile neutrinos (no cover in these lectures) likely to continue to receive some interest

Thank you!

Back-ups

MINOS

- I think the information we can give is that we are working on it, that our timing in the far detector is good (so that is a showstopper we don't have – it would have been too expensive and lengthy to upgrade). We can upgrade the synchronisation between the sites relatively inexpensively and are working on this. We can make some improvements to the past data by re-measuring cable lengths etc and will do that, but we should not presume that some of the smaller systematic errors from the earlier measurement will not increase when re-examined. We will do this speedily, but also very carefully. Justin gave a very nice talk earlier this week at Kings College which is in docdb-8690 v5 which covers these things and gives numbers. I think the thing to emphasise (As Justin did) is that we are in the business here of looking into the crystal ball, so these are NOT firm promises. Changing bunch structure> Don't know the answers to these questions… We are not the main users of the beam, Minerva and then NOvA are. Our first step is to augment the GPS.

Opera time-of-flight measurement

- Have gone through long list of comments and input; main points:
  - Nothing major found; effects at 1-2 ns level in both directions
- 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 (cf 10-5 effect under discussion here)Effect of beam moving in direction of Earth's rotation: not taken into account, 2.2ns, making effect largerRelativity effects checked independently (E. Kiritsis) covering geodesic and gravity, clock redshift, moon/sun/galactic gravity, biggest effect ~2cm

- “Travelling clocks” claim: not used, misunderstanding
- Contacts with BIMP, Belgium Royal Observatory confirming methods
- Proton vs neutrino timing: Lossless beamline
- 50μm target impact point precision, beam position control overdesigned
- Target expansion leading to drop in density and beam time profile modification: max effect 3‰ in 1 of 13 rods (simulation)
- Horn timing: 10ms pulse (cf 10μs bunch in flat top), tests with 100μs shift gave 1% effect on muon monitors
- High-low proton intensity: compatible results
- Likelihood fit:Extensive validations with toy-MC, convincing results for mean value, rms, goodness of fit
- Real fit residuals flat along proton pulseSeparate fits to rising part, falling part, central part of pulse give consistent results
- Proton timing extracted from BTK beam monitors agrees with BCT used in measurement