School of Physics and Astronomy special seminar

NOBEL PRIZE IN PHYSICS 2015

"WHY ARE NEUTRINOS SO AWESOME?"

2015 October 14 (Wed.), 5pm
at GO Jones building lecture theatre

The Nobel prize for physics this year was awarded to Takaaki Kajita and Art McDonald for the discovery of neutrino oscillations. In this talk I will present the Super-Kamiokande and SNO experiments, including photos and anecdotes from QMUL staff. I will explain the prize winning results and their impact and how they have paved the way for the measurements QMUL physicists are involved with today at T2K and SNO+.

Dr. Jeanne Wilson at SNOLAB

Dr. Jeanne Wilson is a senior lecturer at the school of physics and astronomy, QMUL. Dr. Wilson obtained the PhD from the solar neutrino measurement at the SNO experiment.

The Nobel Prize in Physics 2015

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2015 to

Takaaki Kajita
Super-Kamiokande Collaboration
University of Tokyo, Kashiwa, Japan

Arthur B. McDonald
Sudbury Neutrino Observatory Collaboration
Queen's University, Kingston, Canada

"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Why are Neutrinos So Awesome?

J. R. Wilson, QMUL

Queen Mary University of London

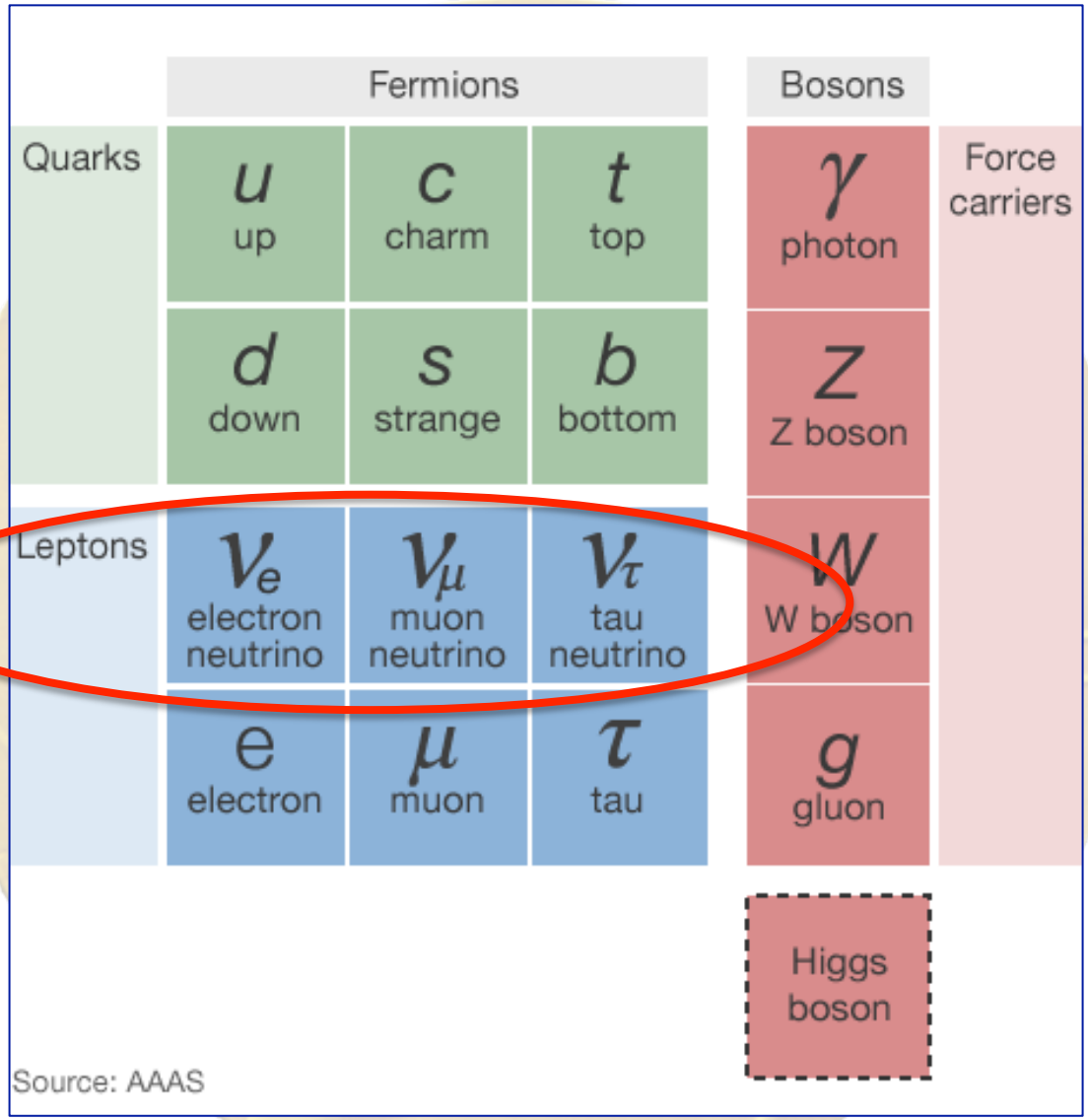
erc

European Research Council
Established by the European Commission

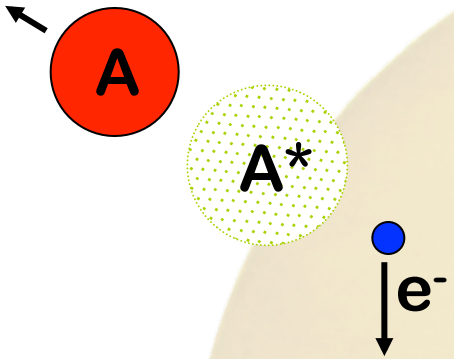
Contents

- What are neutrinos?
- How do we detect them?
- The SuperK experiment
  - SuperK's atmospheric results
- Neutrino Oscillations
- Solar Neutrinos and the Solar Neutrino Problem
- The SNO experiment
- What we still don't know
- T2K, HyperK and SNO+

The Standard Model

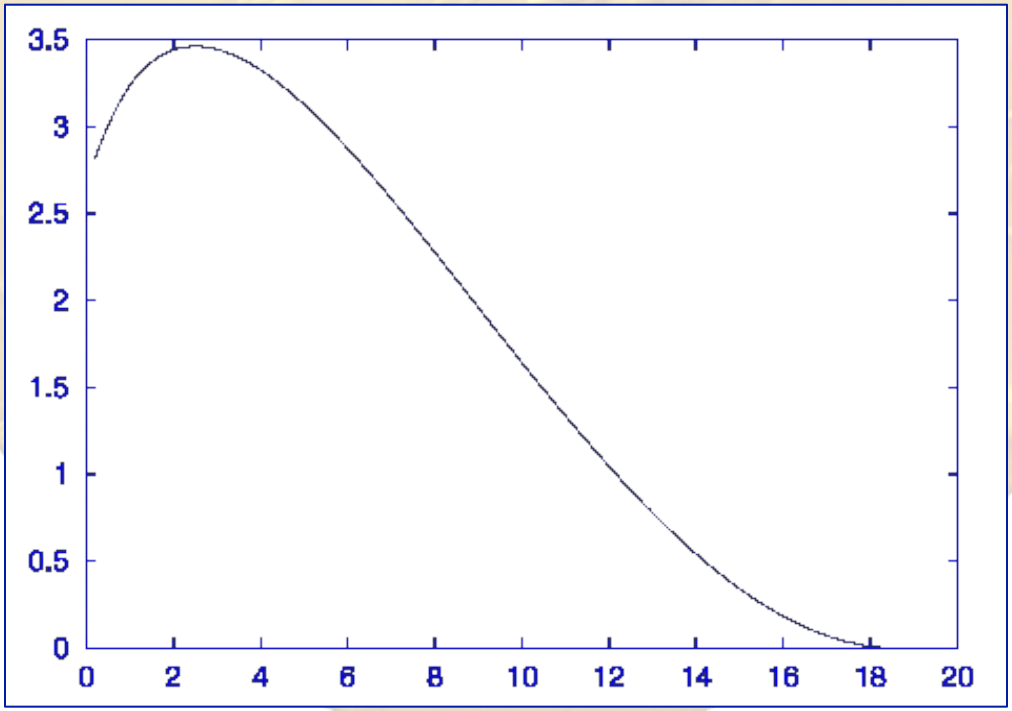


Introducing the Neutrino



The Beta Decay Puzzle

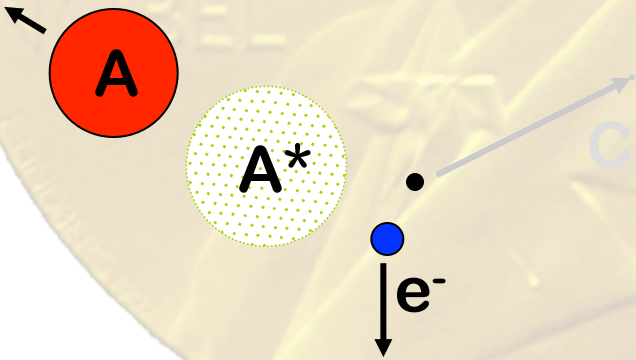
Breaks energy and momentum conservation



4th December 1930

Dear Radioactive Ladies and Gentlemen,

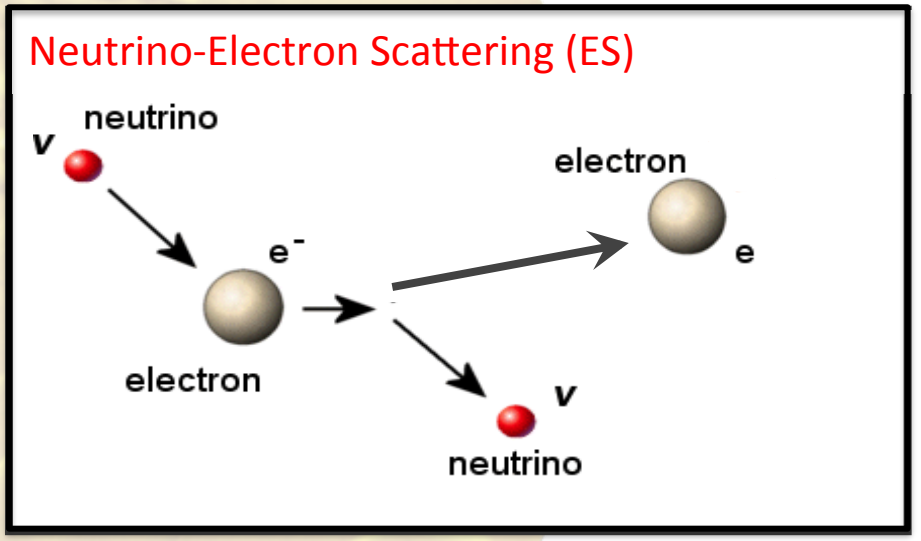
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation 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 beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...



Wolfgang Pauli, 1930

Detecting the Neutrino

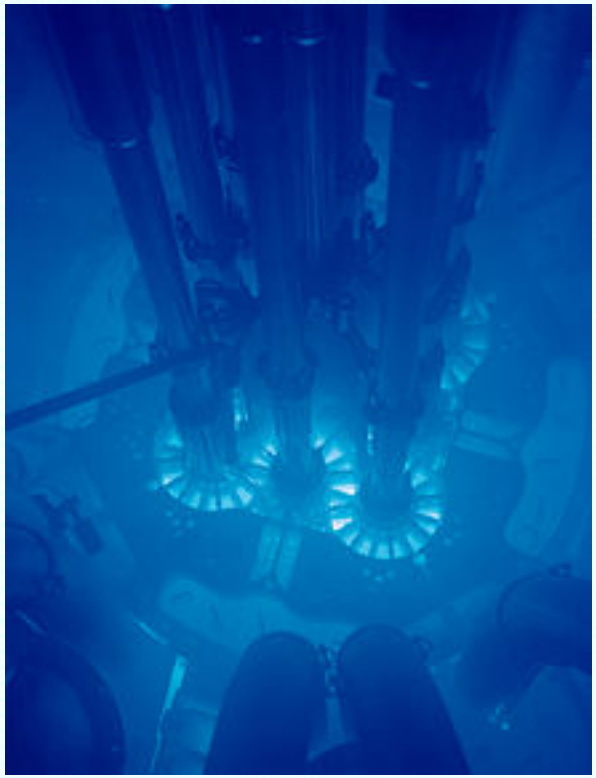
- Very light, possibly massless
- No charge
- Produced alongside leptons
- Very weakly interacting



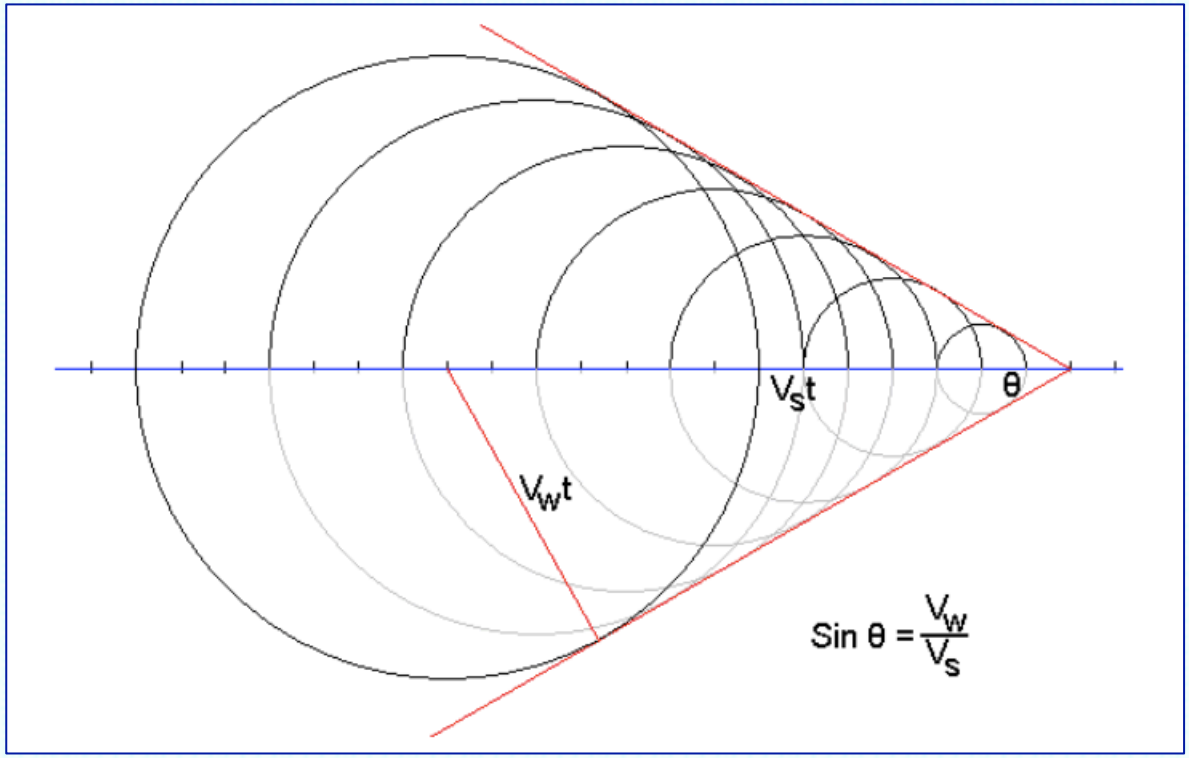
How do you spot an invisible man in a crowd?

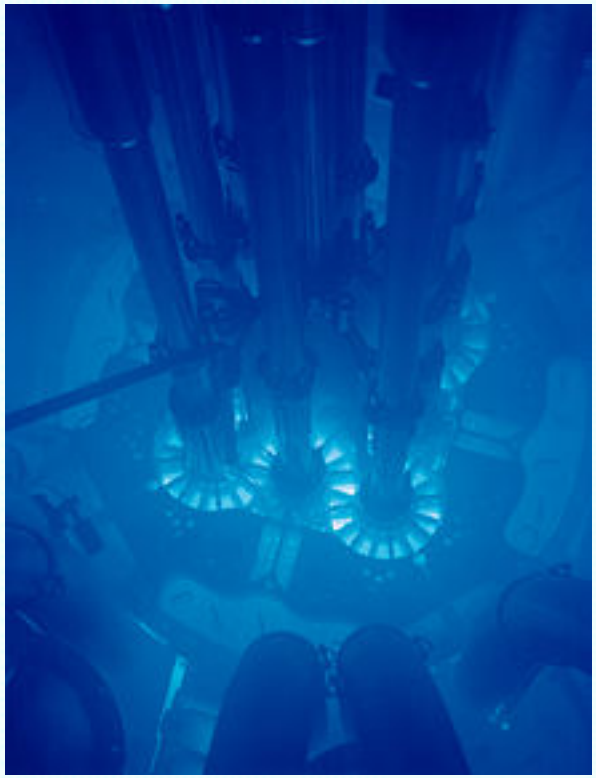
How do you increase your chances of observing an incredibly rare event?

Cerenkov Light

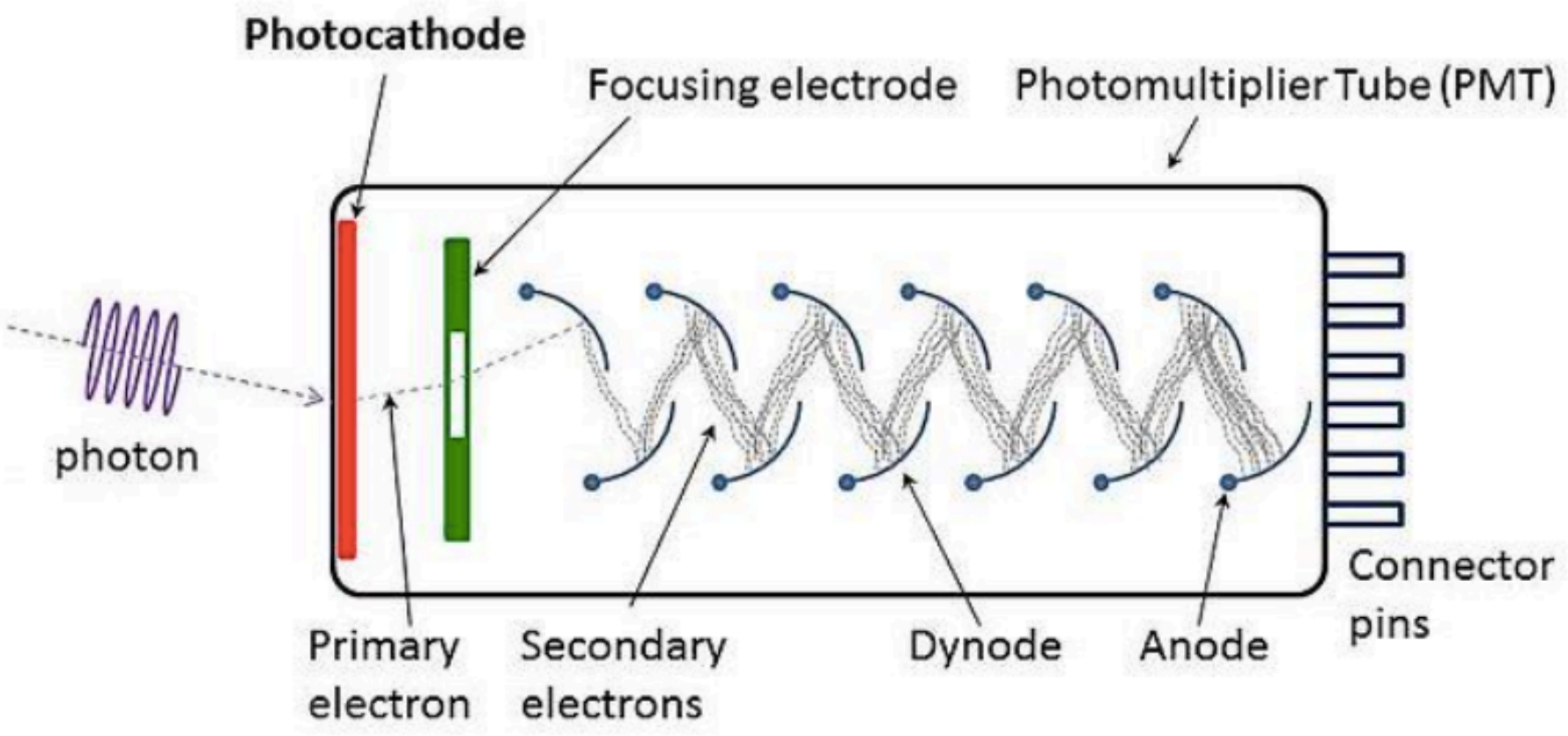


Cerenkov Light

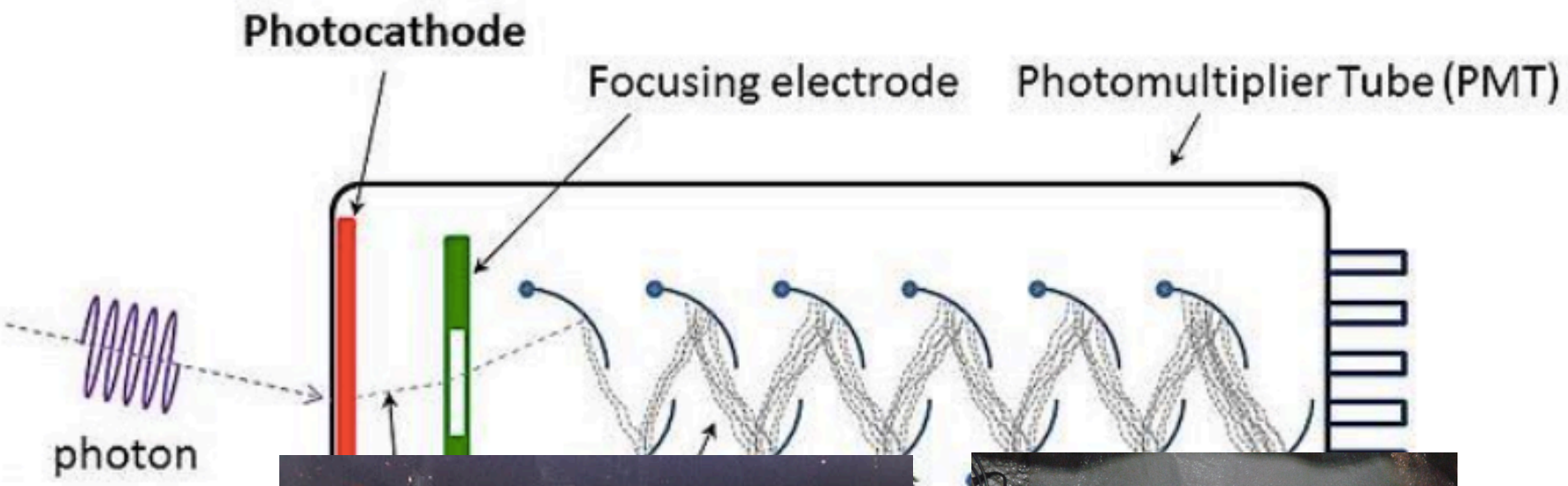


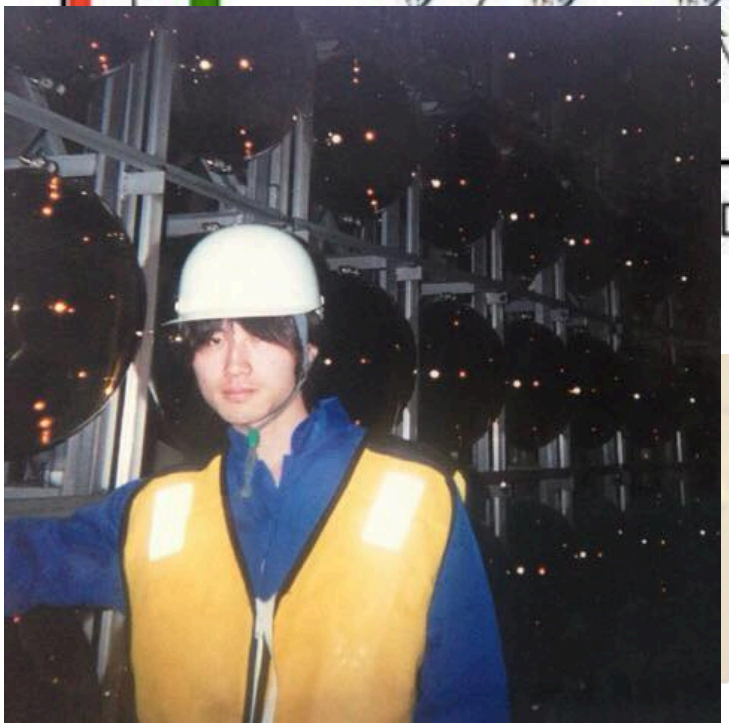


PMTs


Photocathode
Focusing electrode
Photomultiplier Tube (PMT)
photon
Primary electron
Secondary electrons
Dynode
Anode
Connector pins

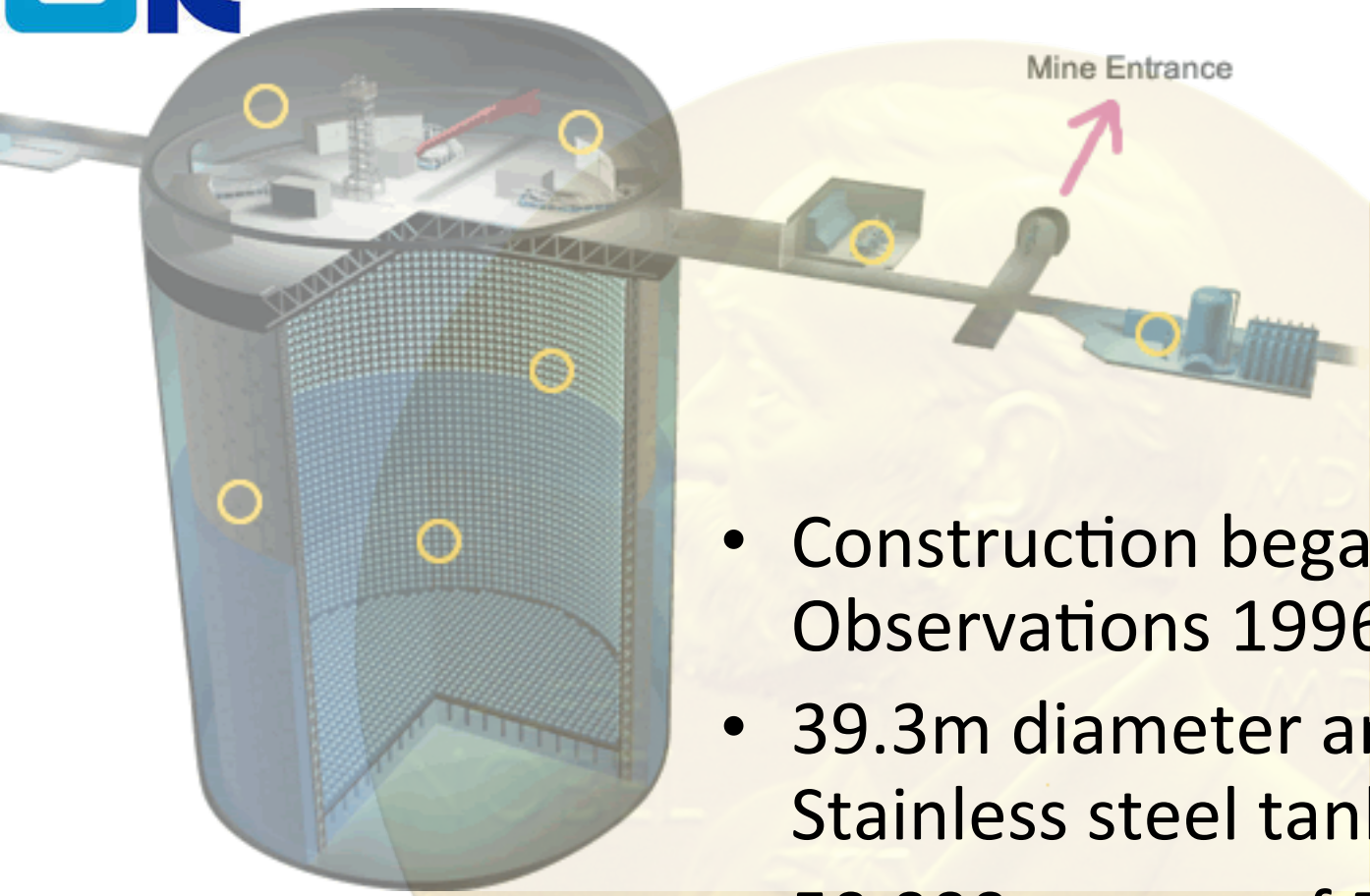
PMTs

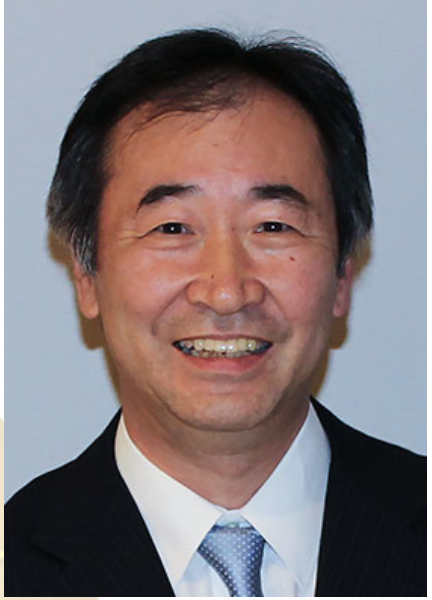

Photocathode
Focusing electrode
Photomultiplier Tube (PMT)
photon
ector



2002

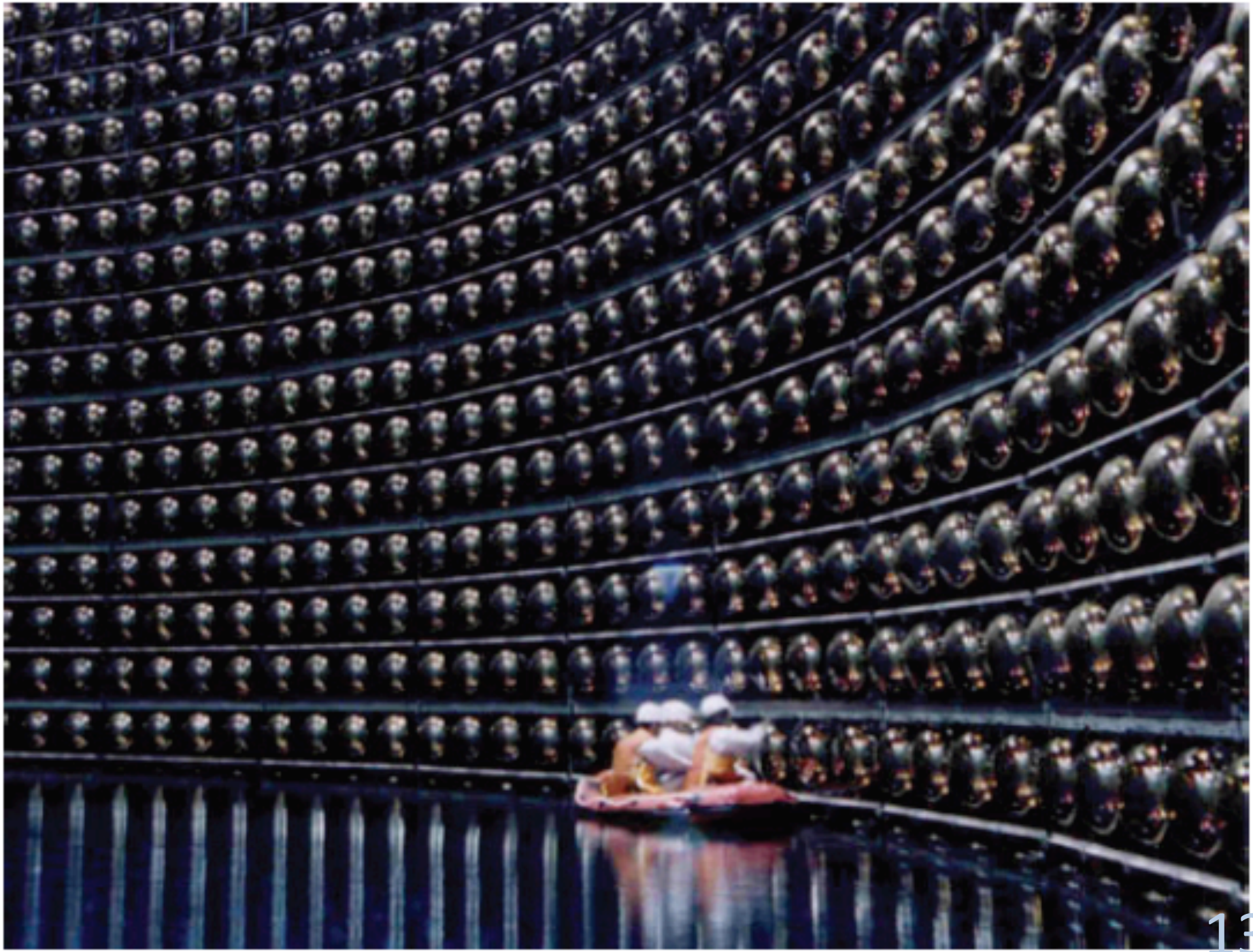
SuperKamiokande





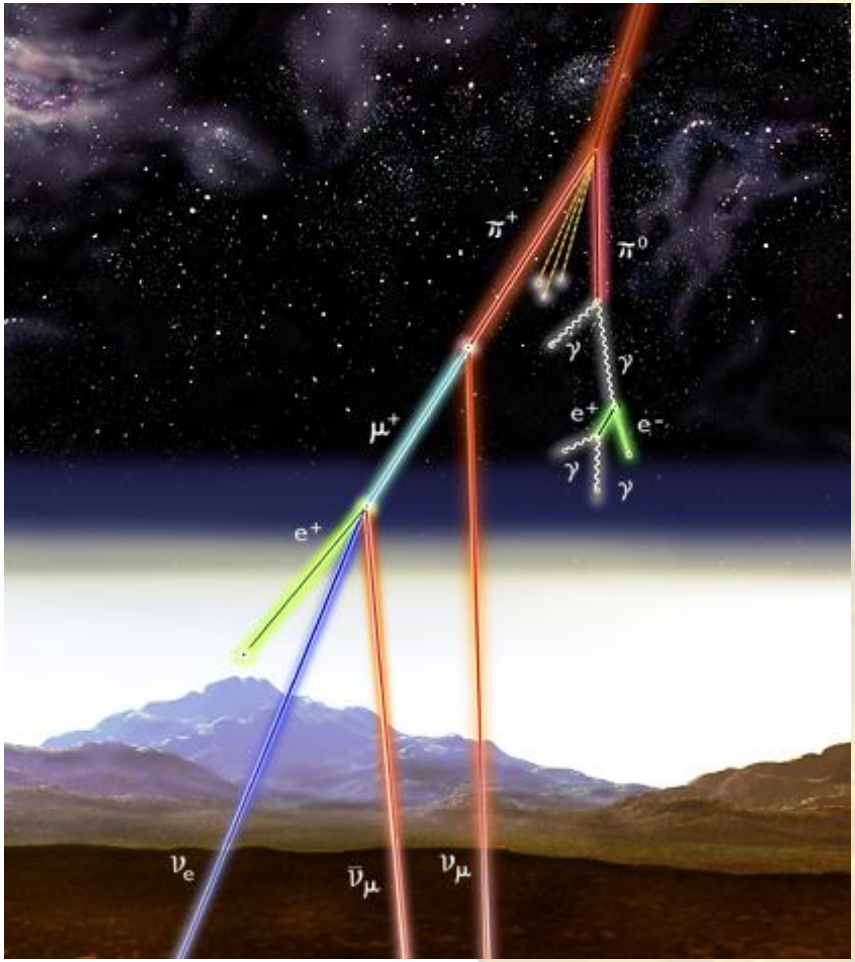
Takaaki Kajita

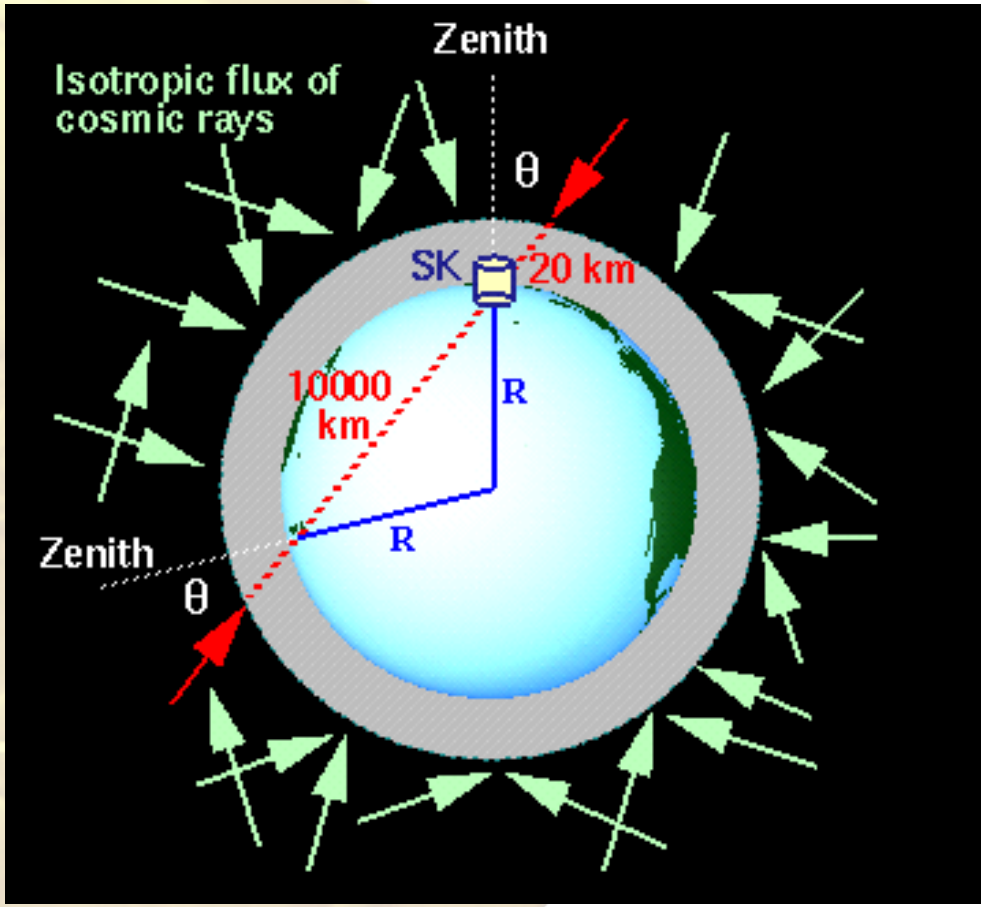
- Construction began 1991, 1st Observations 1996
- 39.3m diameter and 41.4m tall Stainless steel tank
- 50,000 tonnes of Pure H_2O
- ~13,000 photo-multipliers
- ~1km underground in the Kamioka-mine, Japan

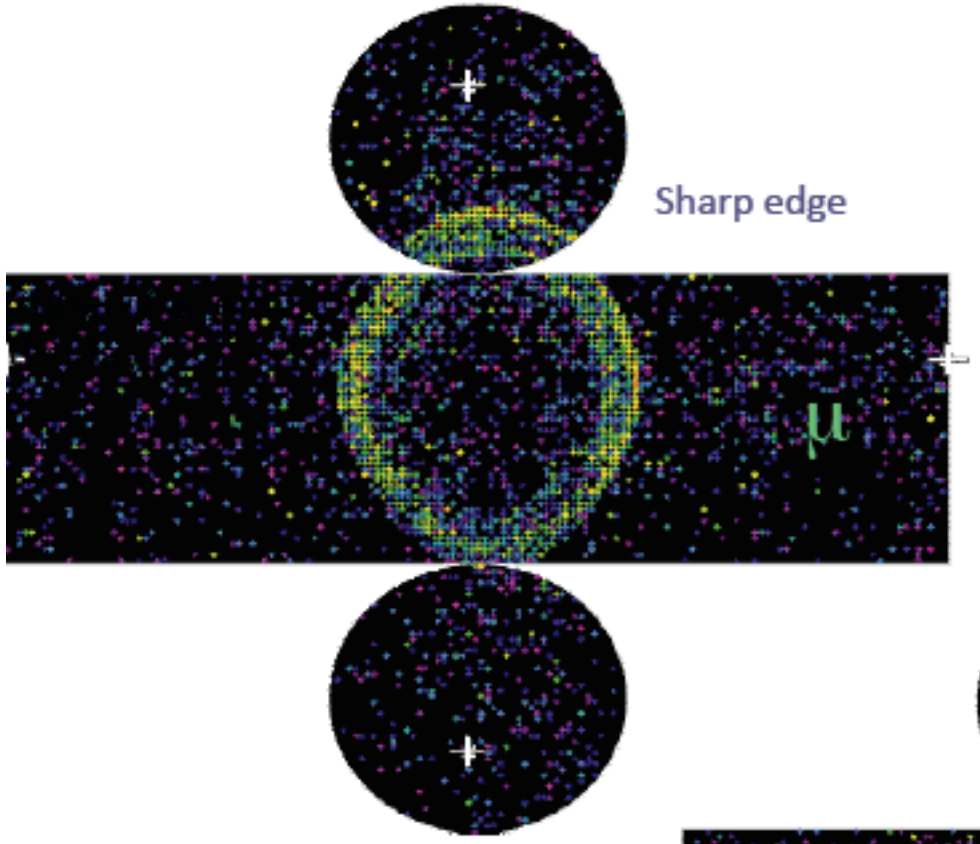


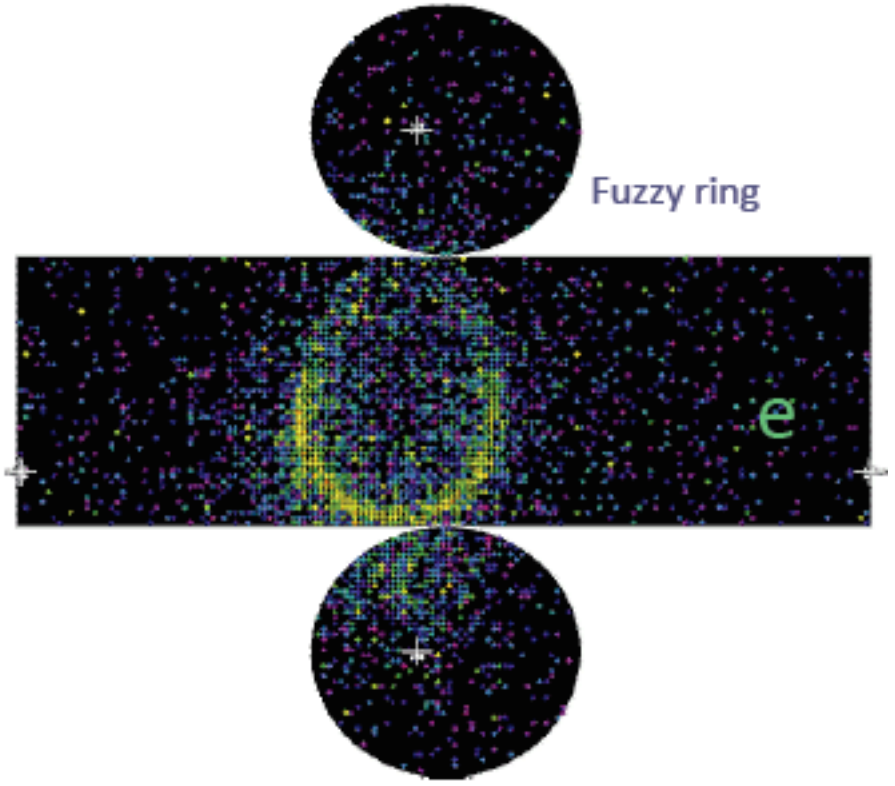

宇宙
The Universe・宇宙・宇宙
スーパーカミオカンデ
10分の1模型
SUPER-KAMIOKANDE
1:10 MODEL

Atmospheric Neutrinos









Real time event display

SuperK Atmospheric Results

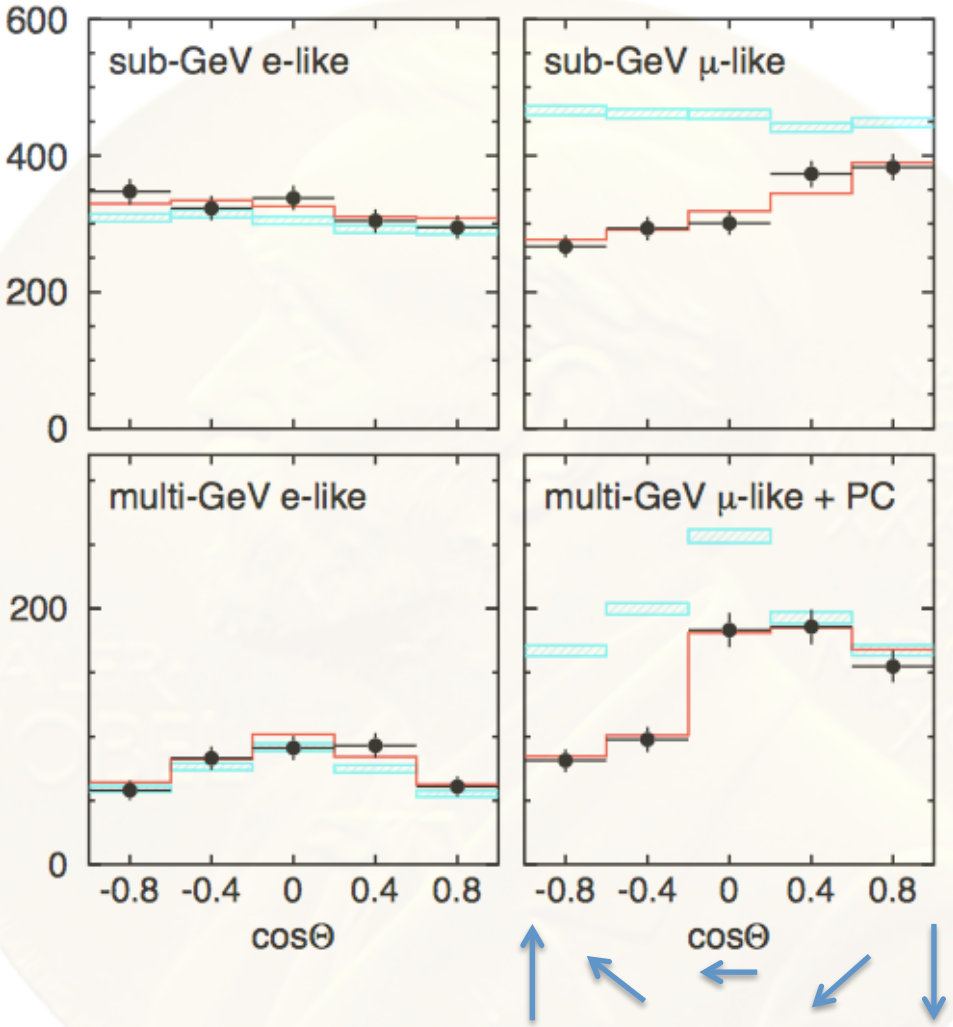
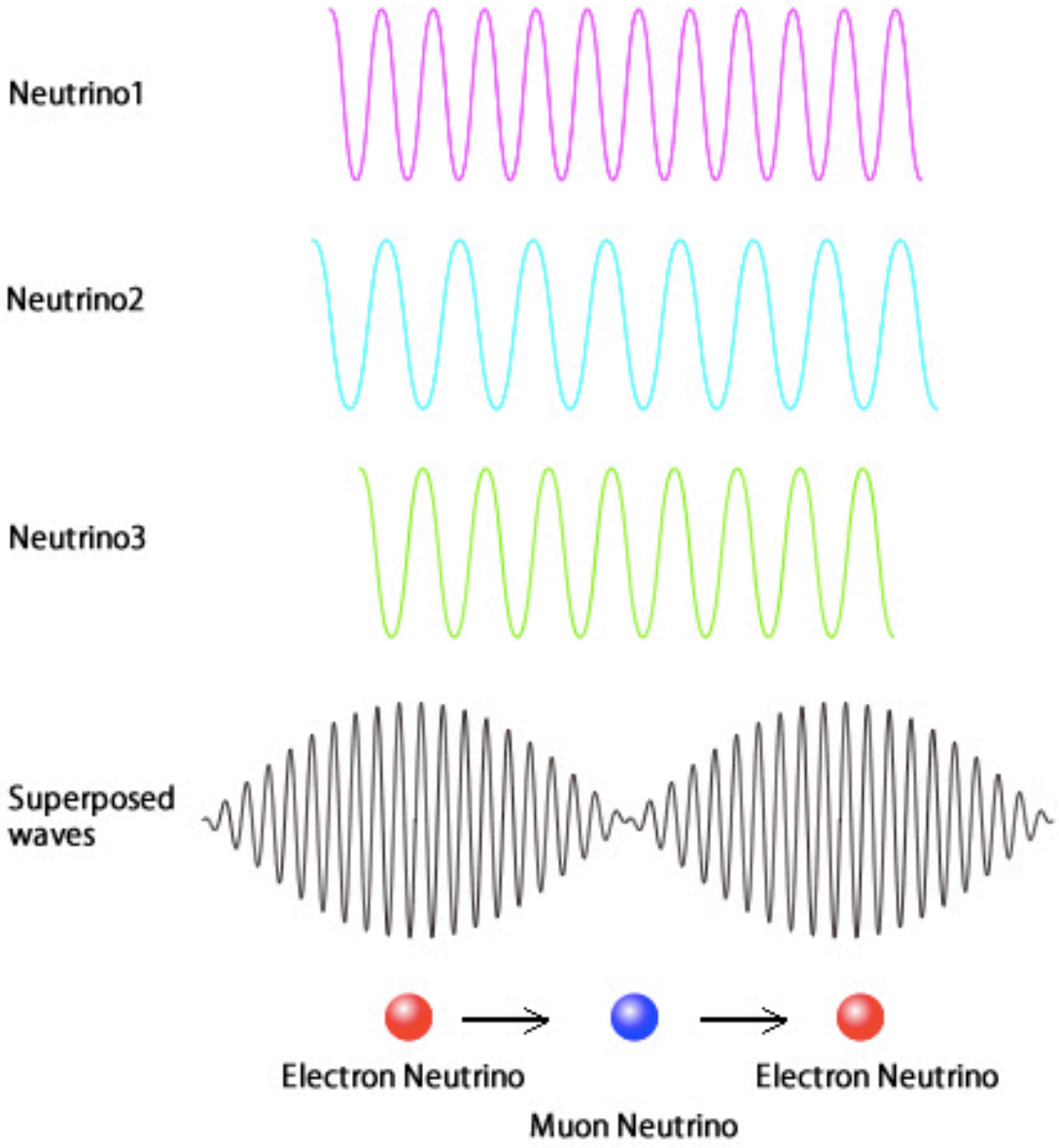


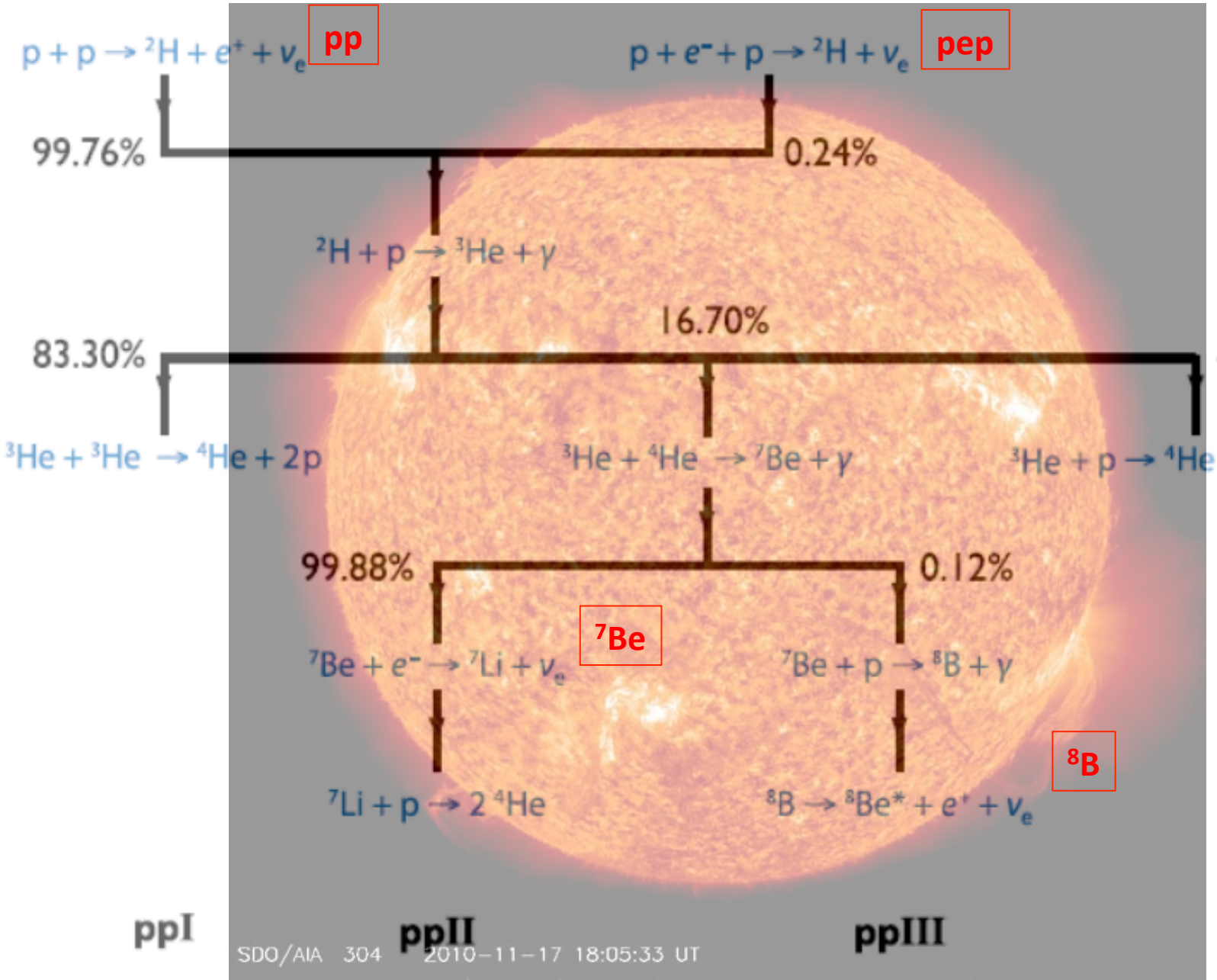
Figure 5: Zenith angle distributions of e-like and μ-like events in Super-Kamiokande with momenta above and below 1.33 GeV [52]. The boxes show the expectation assuming no oscillations, whereas the full drawn lines show the results of the best fit.

Neutrino Oscillations

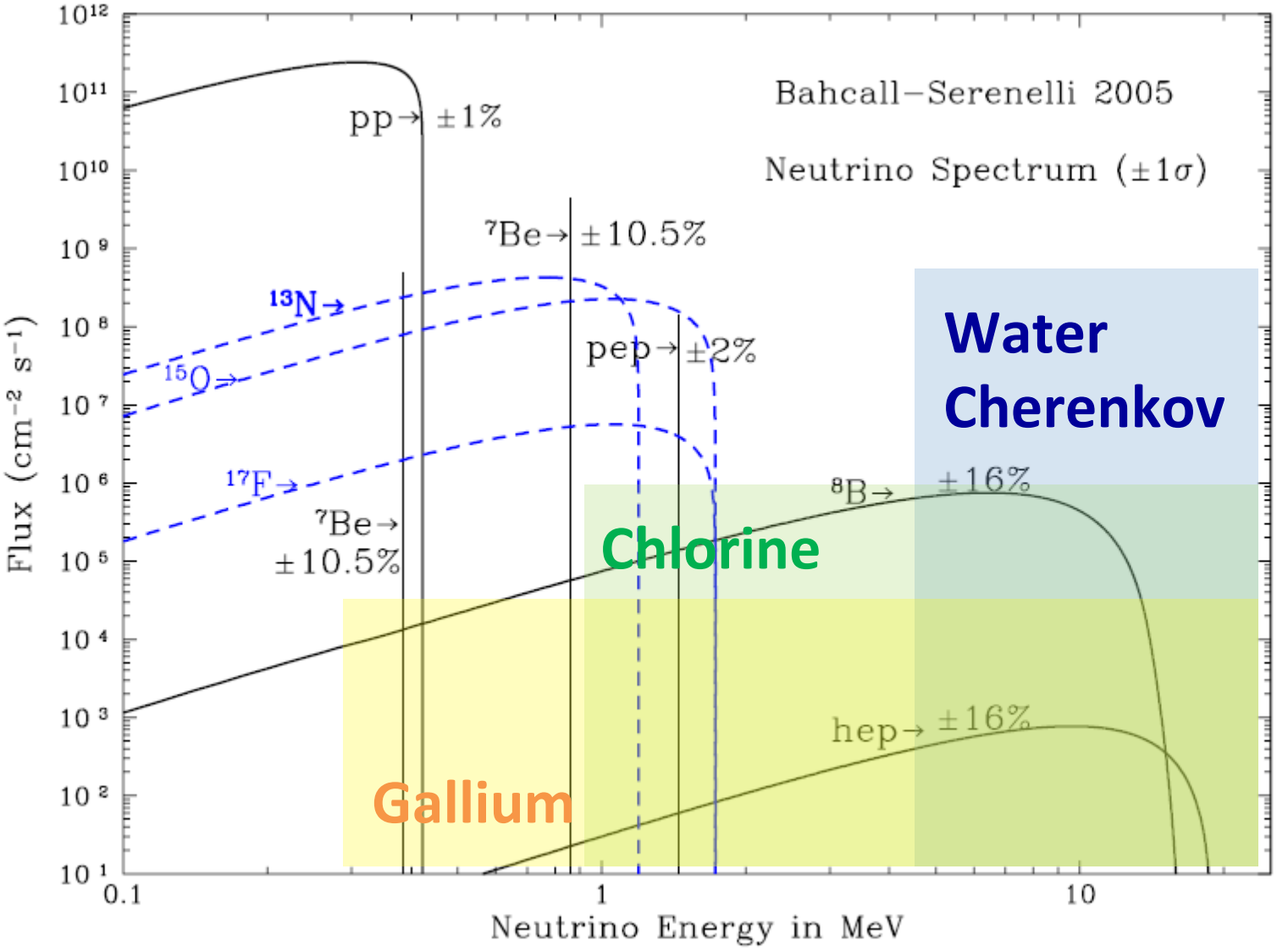


http://www.hyper-k.org/en/img/waves.jpg

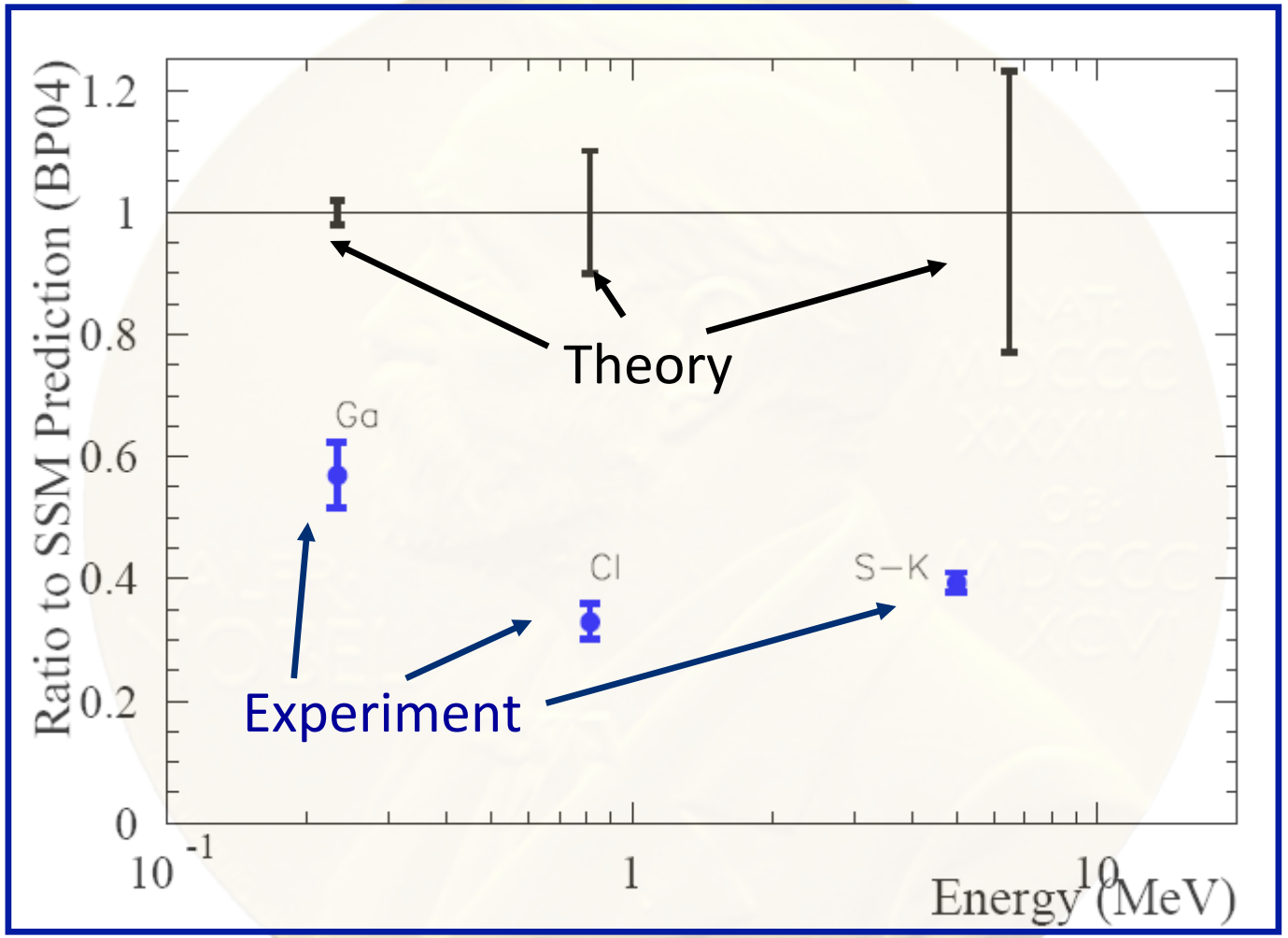
Solar Neutrinos



Solar Neutrinos



Solar Neutrino Problem



The Nobel Prize in Physics 2002

Raymond Davis Jr.

Prize share: 1/4

Masatoshi Koshiba

Prize share: 1/4

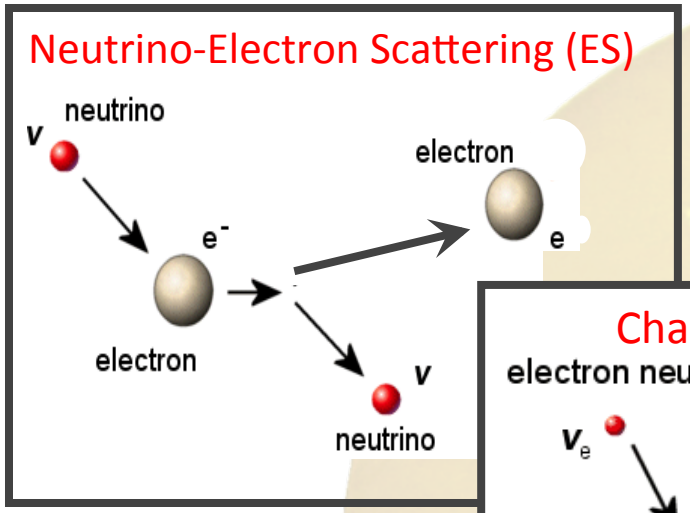
Riccardo Giacconi

Prize share: 1/2

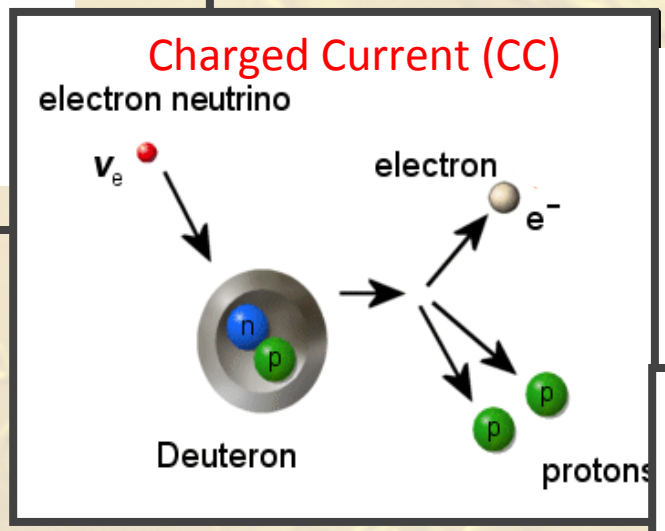
The Nobel Prize in Physics 2002 was divided, one half jointly to Raymond Davis Jr. and Masatoshi Koshiba *"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"* and the other half to Riccardo Giacconi *"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"*.

The Answer: Heavy Water

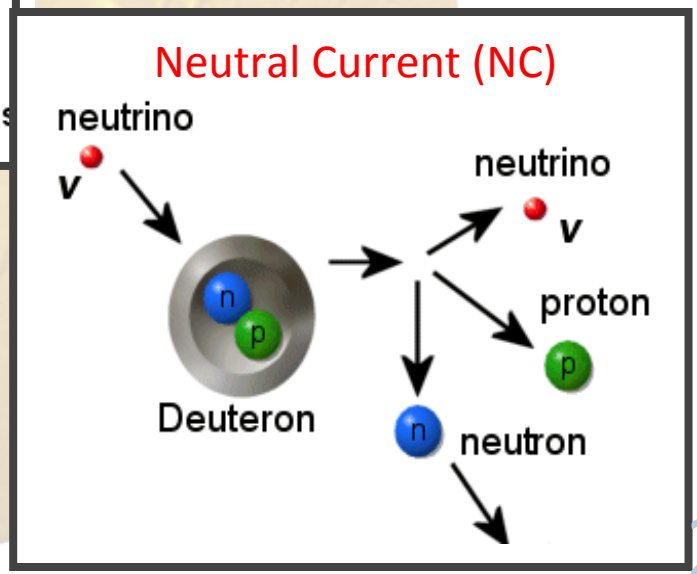
Herb Chen 1984
Phys. Rev. Lett. **55** 14



1. Elastic Scattering
Primarily sensitive to ν_e
Measures ν direction



2. Charged Current
Sensitive only to ν_e
Measures ν energy



3. Neutral Current
Sensitive to all flavours
Measures total ^{8}B ν flux

Sudbury Neutrino Observatory

3 phases:

1. Pure D_2O
2. D_2O + NaCl
3. D_2O + ^3He proportional counters

2km underground

Cavern height of 10 storey building

3 years to excavate

$$$330Million!

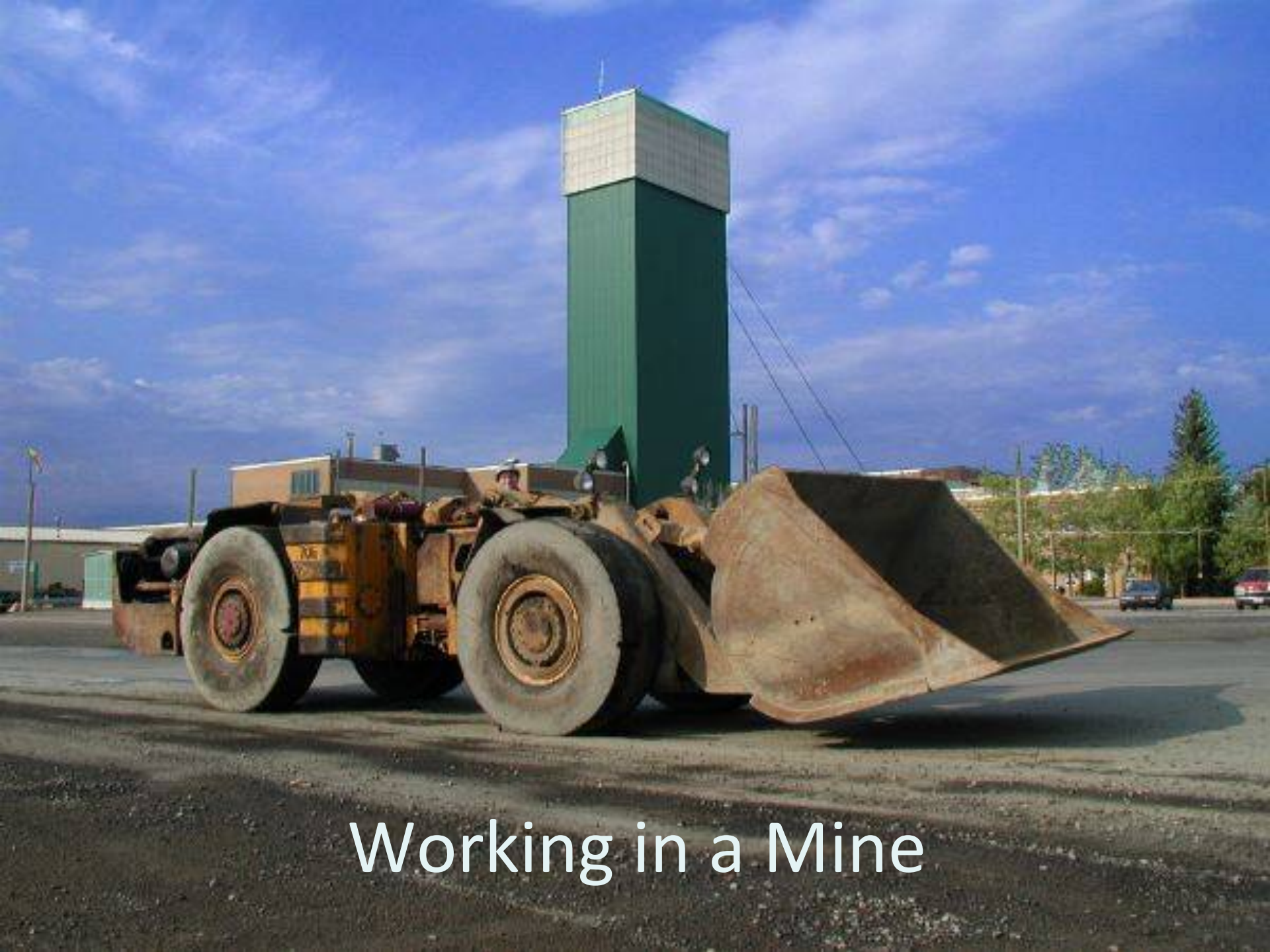
loaned by AECL

1000 tonnes D_2O

Support structure for 9500 PMTS
54% coverage

12 m diameter acrylic vessel

7000 tonnes H_2O shielding



Working in a Mine

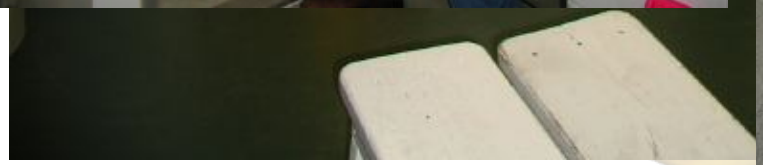
Going Underground

Construction

Going Underground

Water Purity

Class 2000 Clean Room

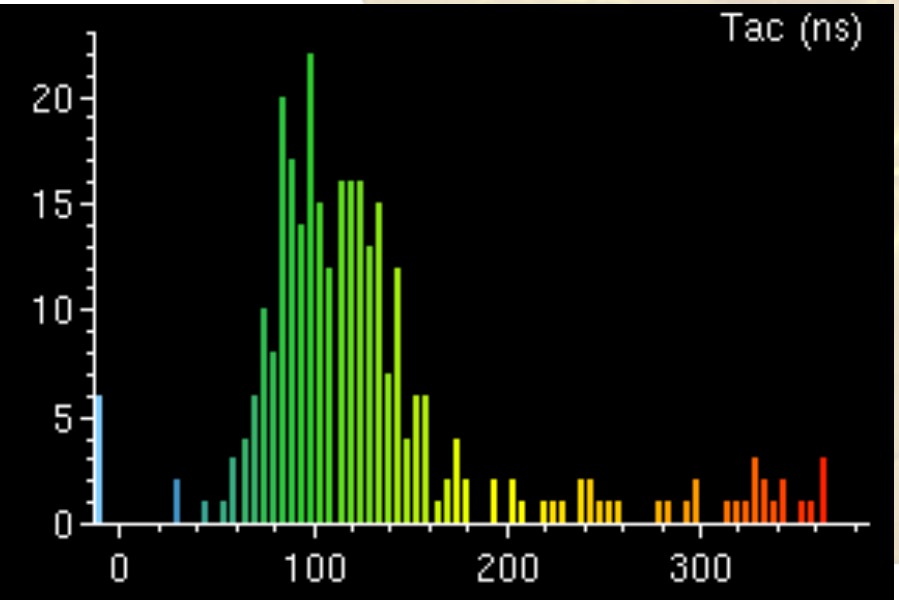


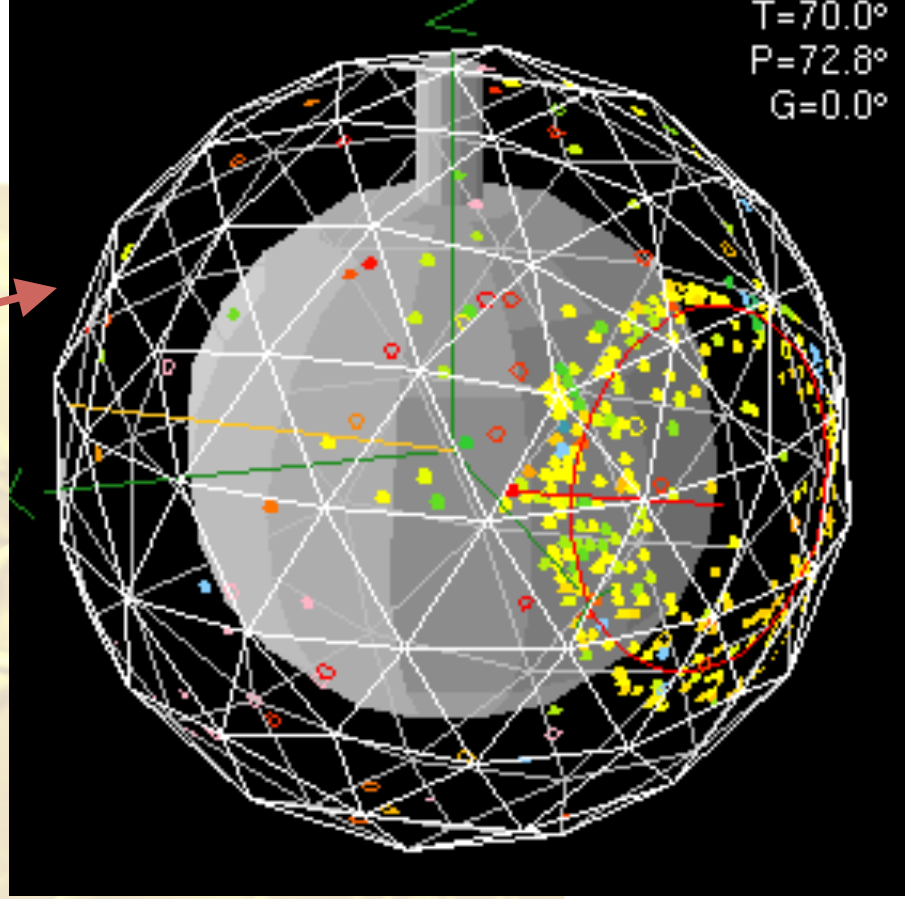
Detector Operation

What SNO Measured

PMT Measurements

-position
-charge
-time

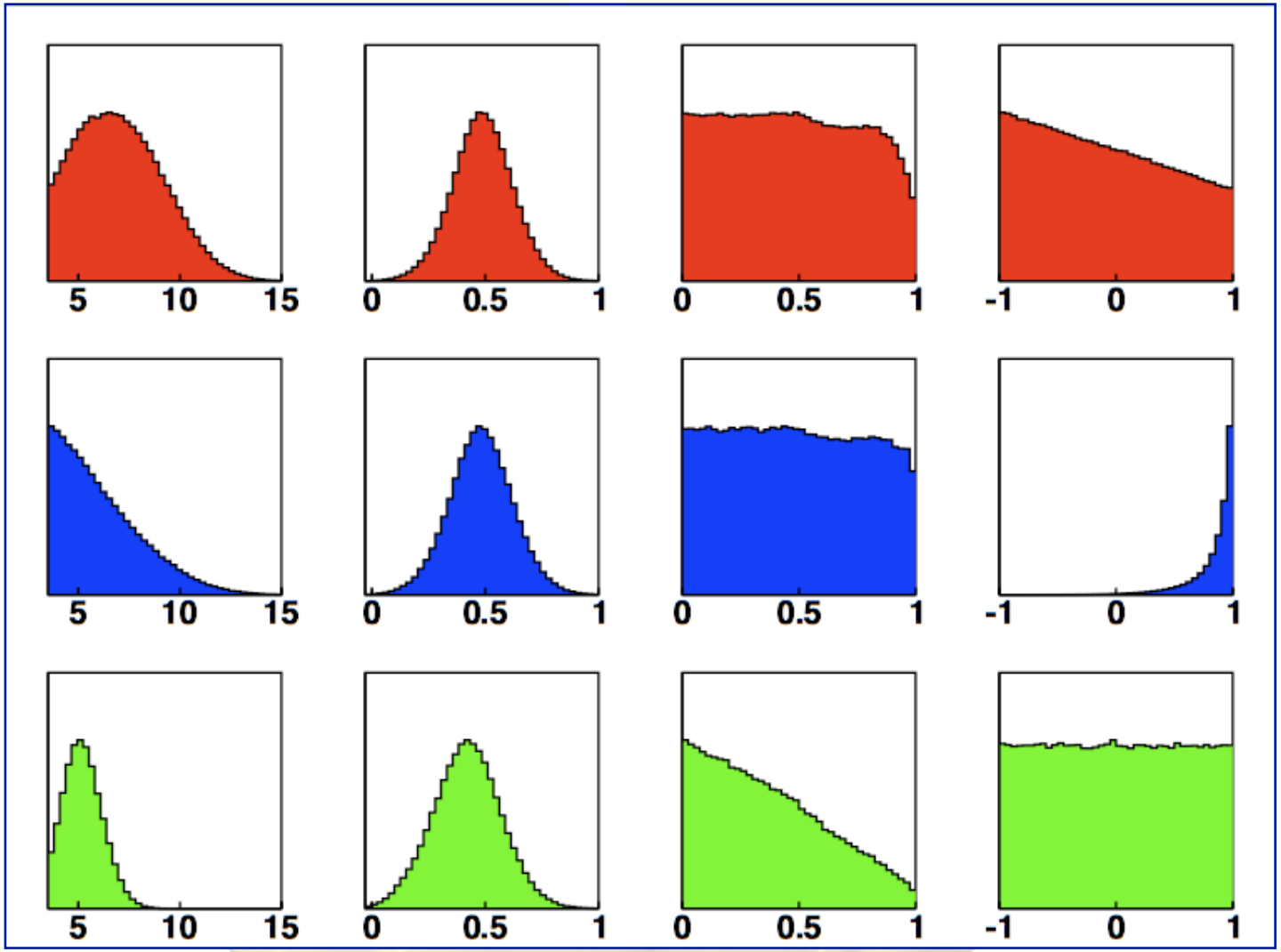




Reconstructed Event

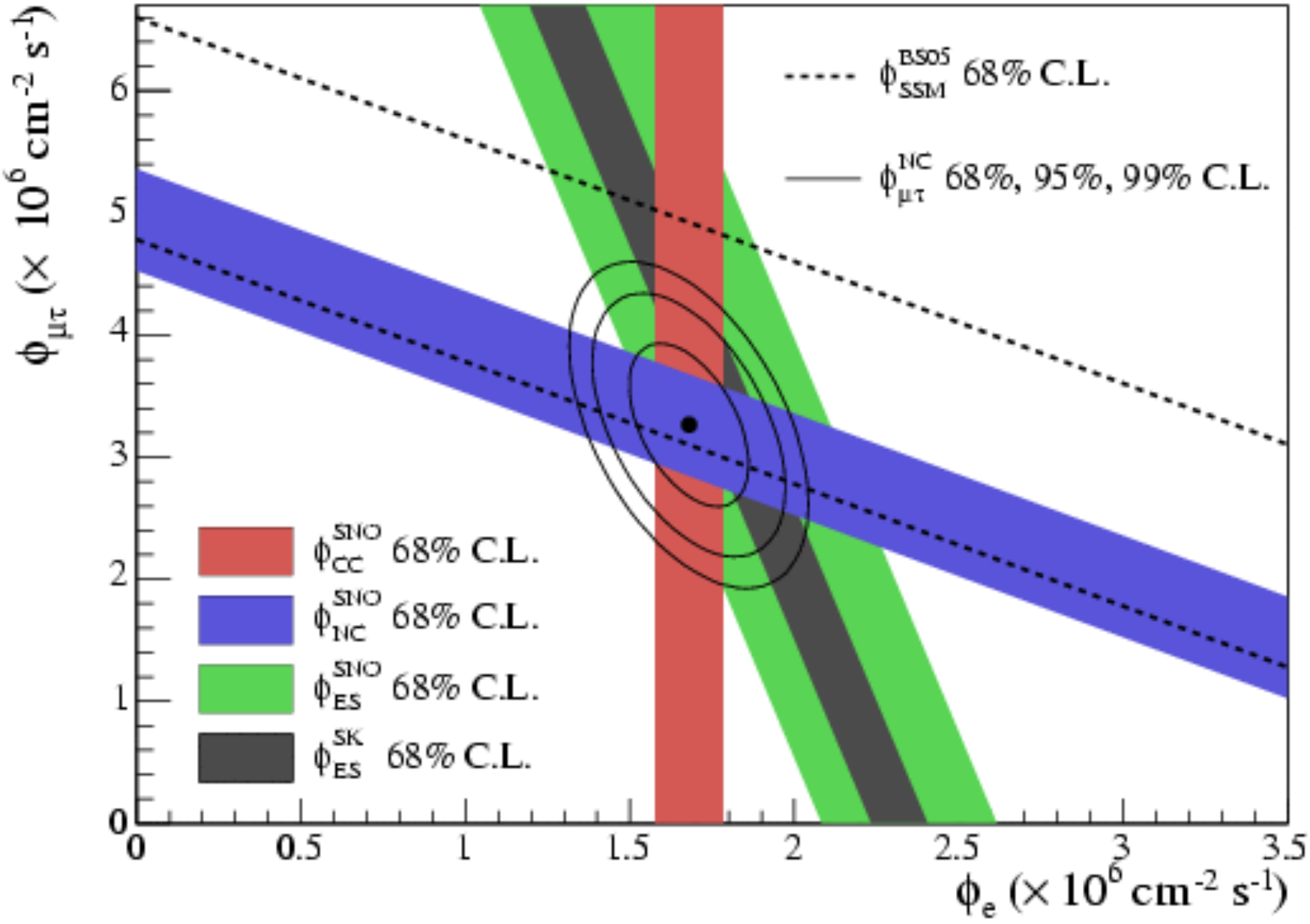
-event vertex
-event direction
-energy
-isotropy

Phase 1: D_2O

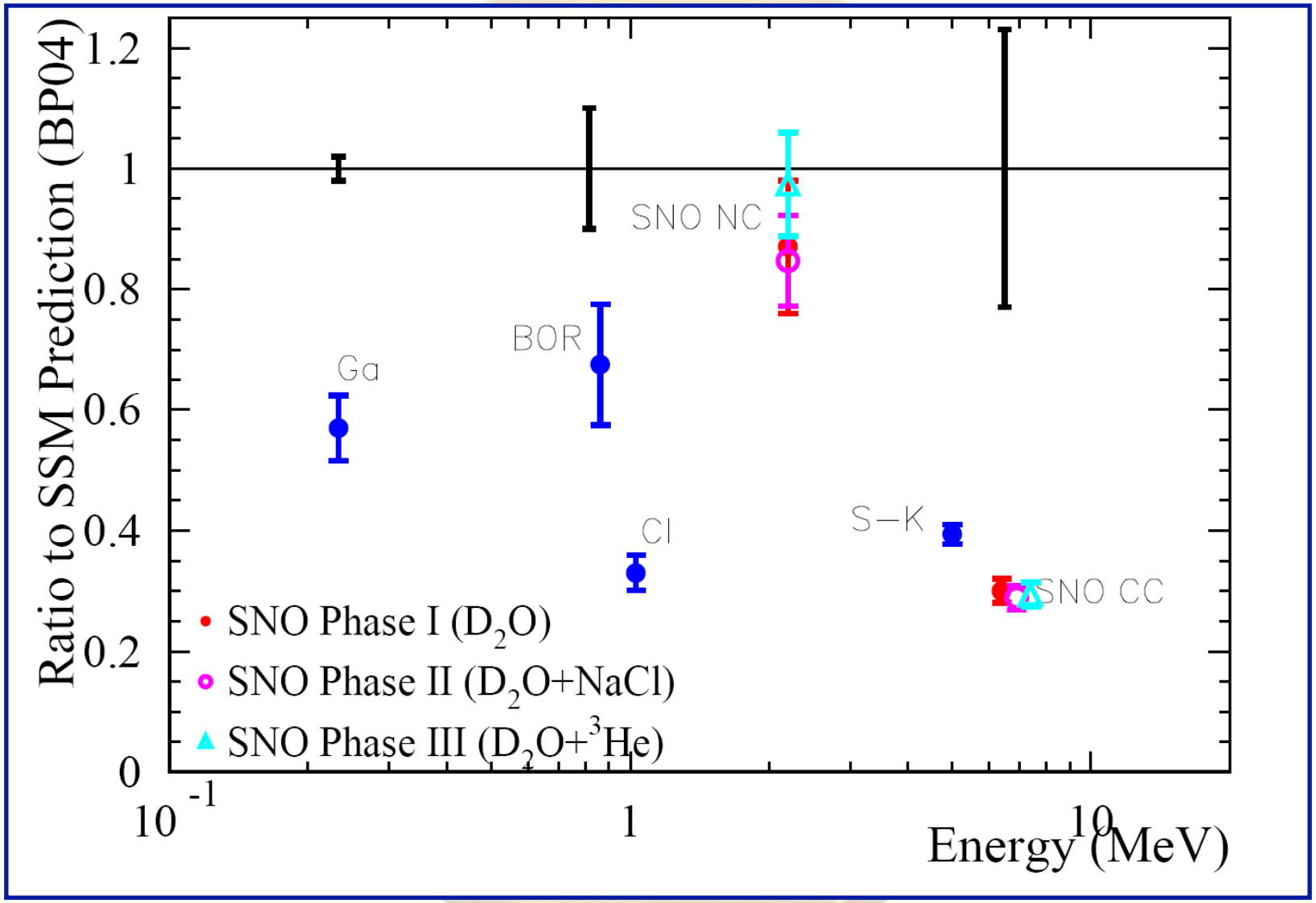


Energy	Isotropy	Position	Direction
T_{eff}	β_{14}	$R^3 = R_{fit}^3/R_{AV}^3$	$\cos(\theta_\Theta)$

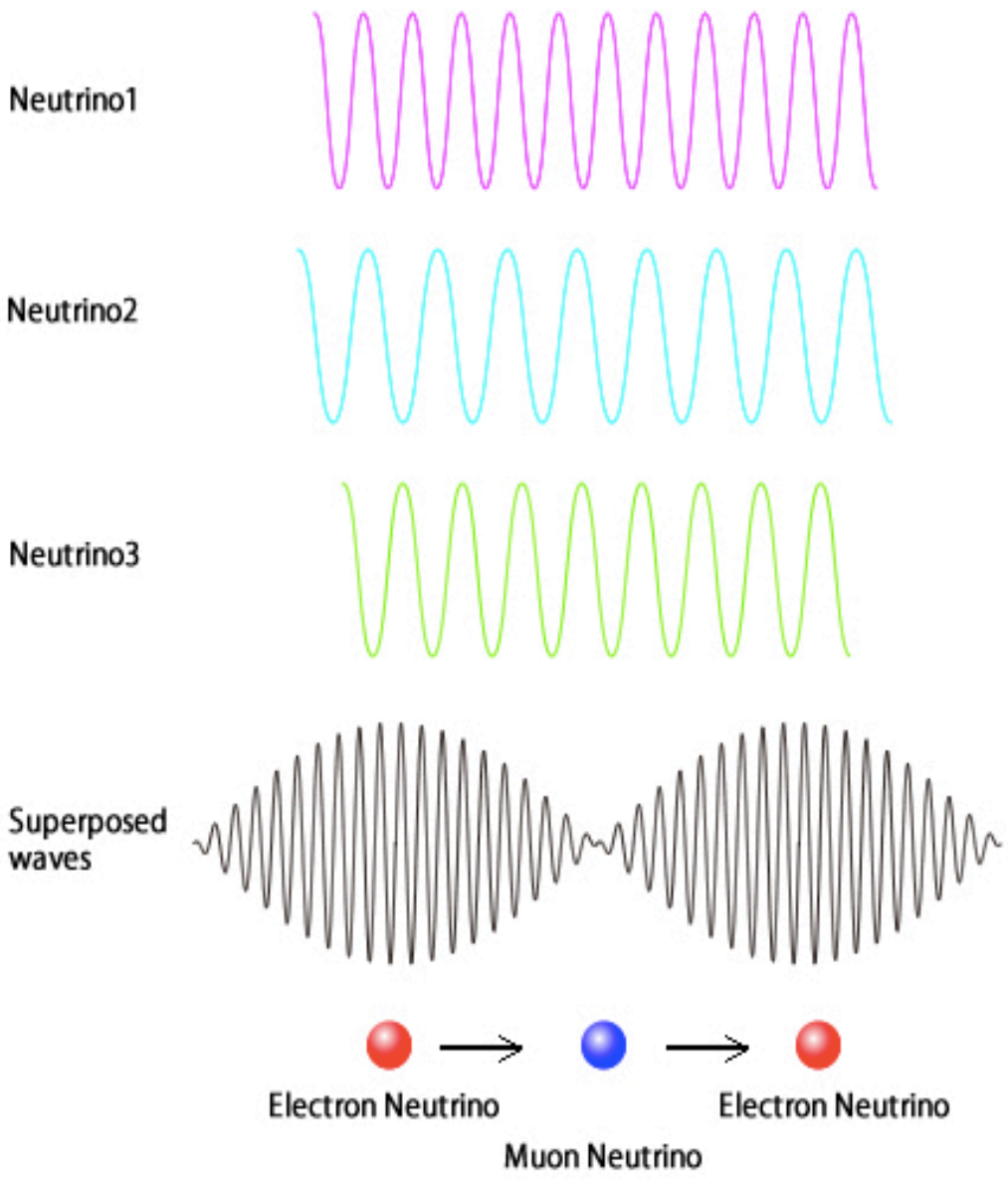
SNO Results


ϕ_{SSM}^{BS05} 68% C.L.
$\phi_{\mu\tau}^{NC}$ 68%, 95%, 99% C.L.
ϕ_{CC}^{SNO} 68% C.L.
ϕ_{NC}^{SNO} 68% C.L.
ϕ_{ES}^{SNO} 68% C.L.
ϕ_{ES}^{SK} 68% C.L.
$\phi_{\mu\tau}$ ($\times 10^6$ cm^{-2} s^{-1})
ϕ_e ($\times 10^6$ cm^{-2} s^{-1})
0
0.5
1
1.5
2
2.5
3
3.5
1
2
3
4
5
6

Solar Flux results



Neutrinos Do Oscillate



http://www.hyper-k.org/en/img/waves.jpg

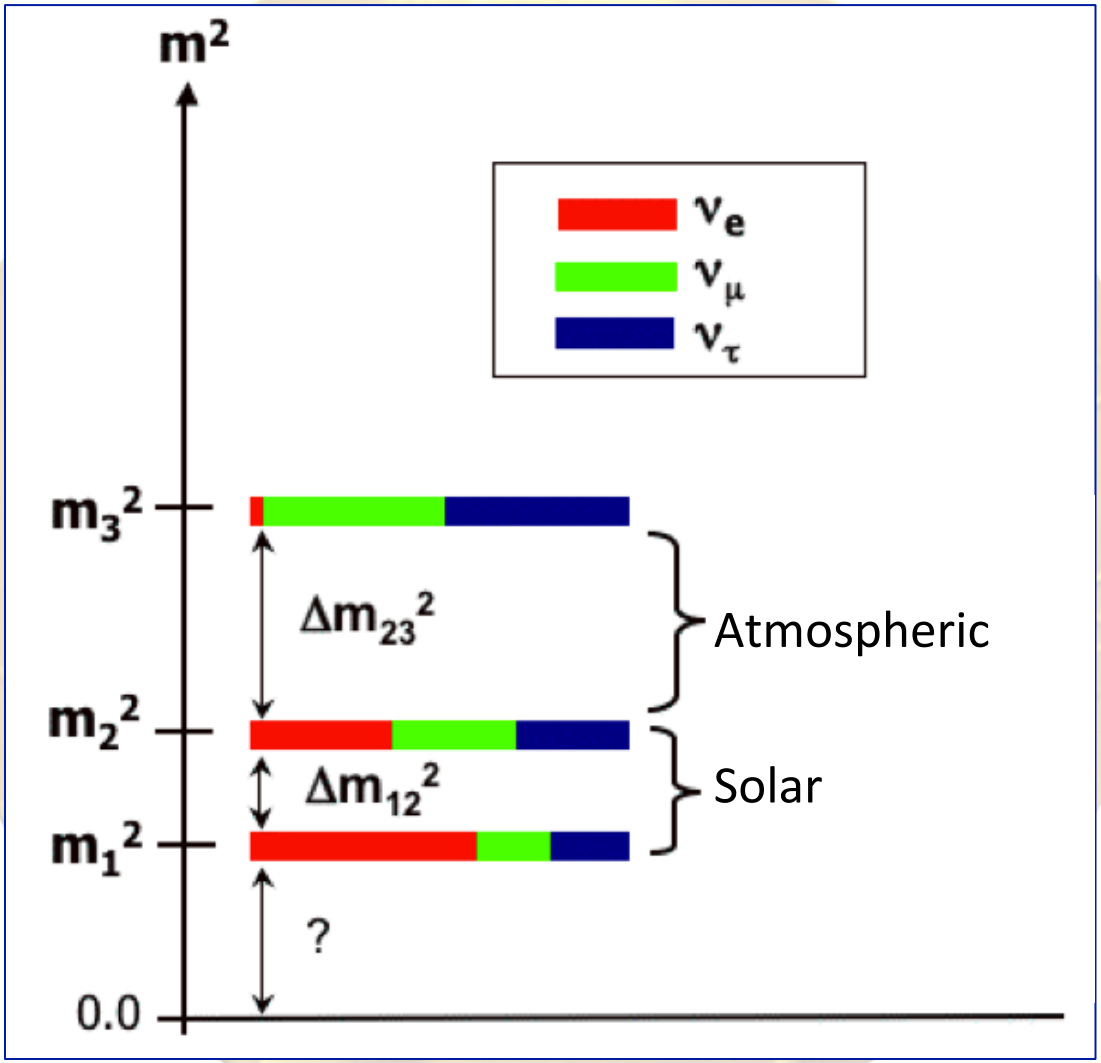
Mass differences: Δm_{12}, Δm_{23}
Govern at what distance/ energy you see the maximum effect.

Mixing angles: θ_{12}, θ_{23}, θ_{13}
The relative contributions of mass states to flavour states.
Govern the amplitude of the effect

Atmospheric Neutrinos:
Δm_{23}, θ_{23}

Solar Neutrinos:
Δm_{12}, θ_{12}

3 Flavour Oscillations



What about θ_{13}?

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1}, U_{e2}, U_{e3} \\ U_{\mu 1}, U_{\mu 2}, U_{\mu 3} \\ U_{\tau 1}, U_{\tau 2}, U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = U_{\mathrm{MNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U_{\mathrm{MNS}} = U_{23} U_{13} U_{12}$$

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

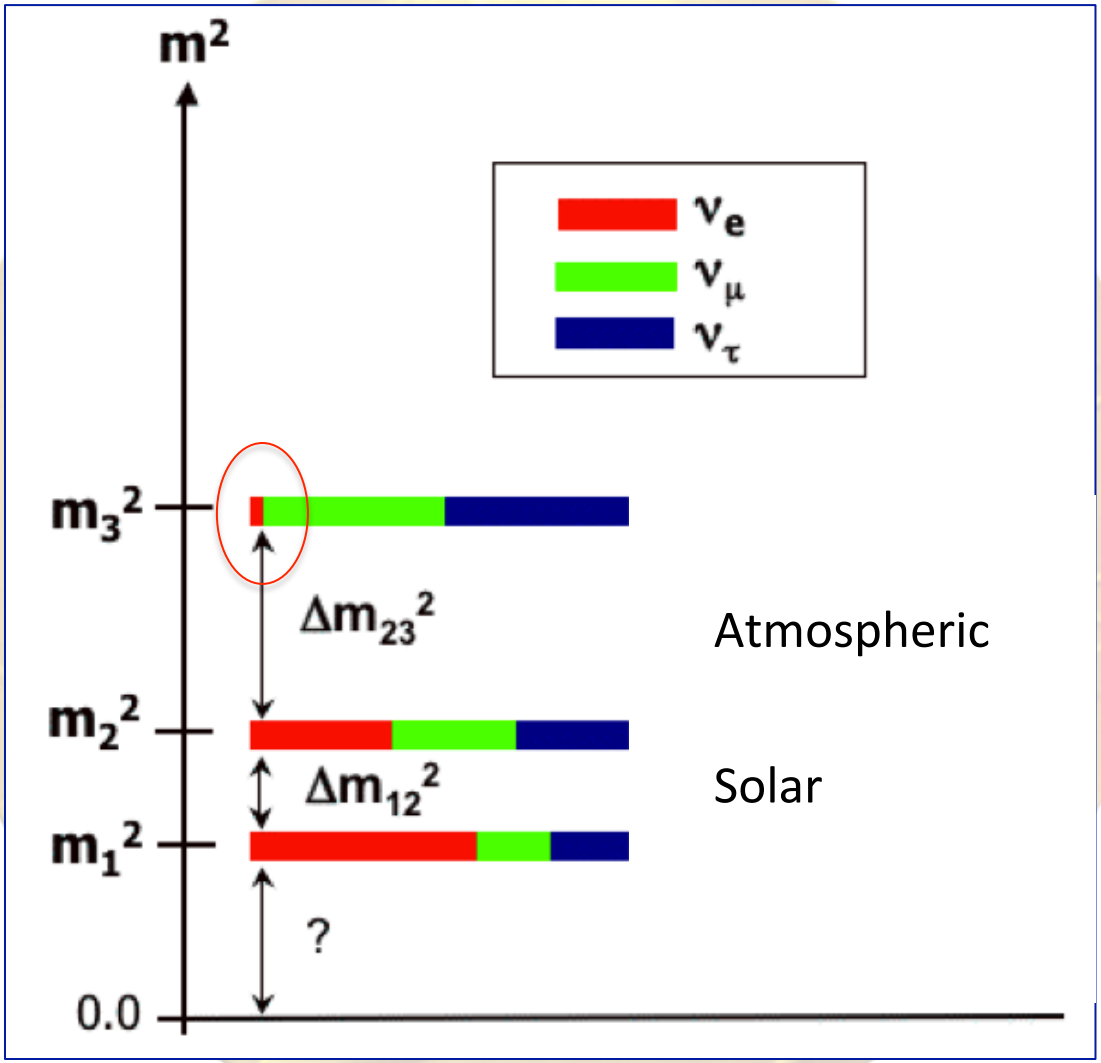
atmospheric

solar

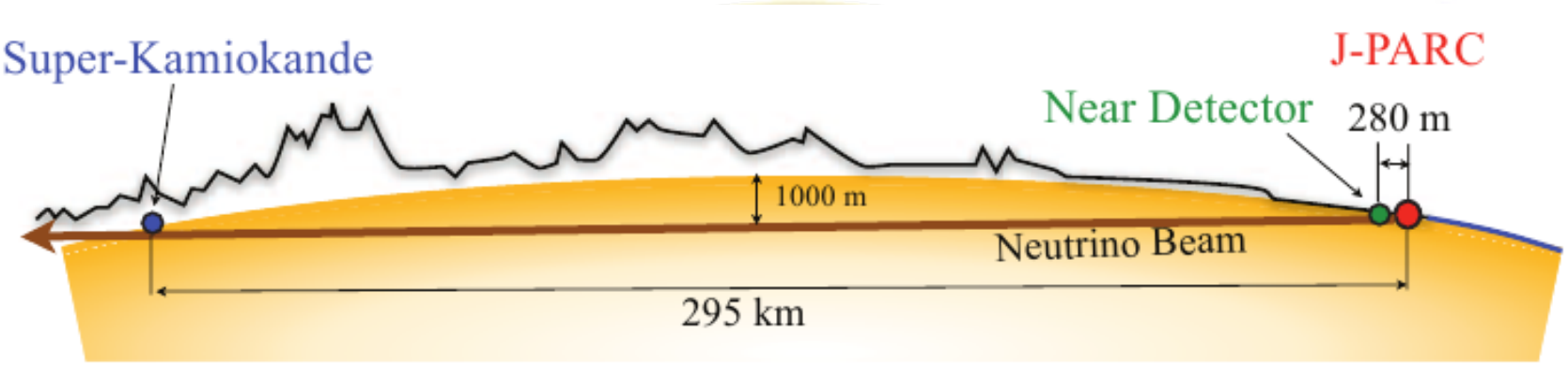
where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

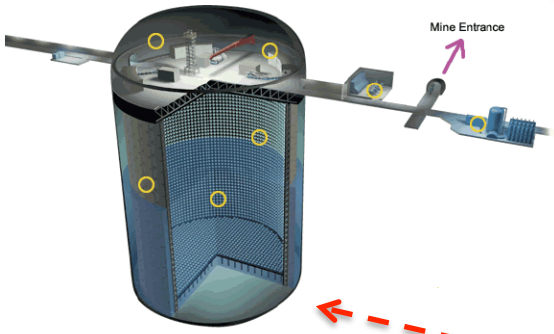
CP violation?

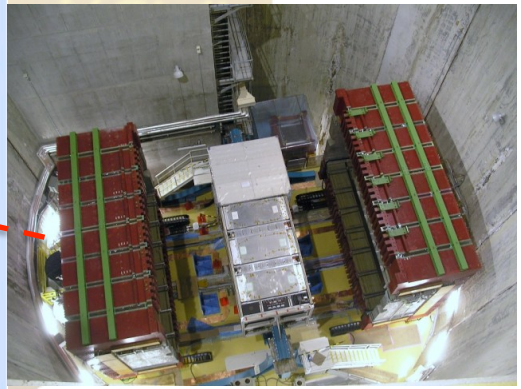
3 Flavour Oscillations



T2K Neutrino Oscillations



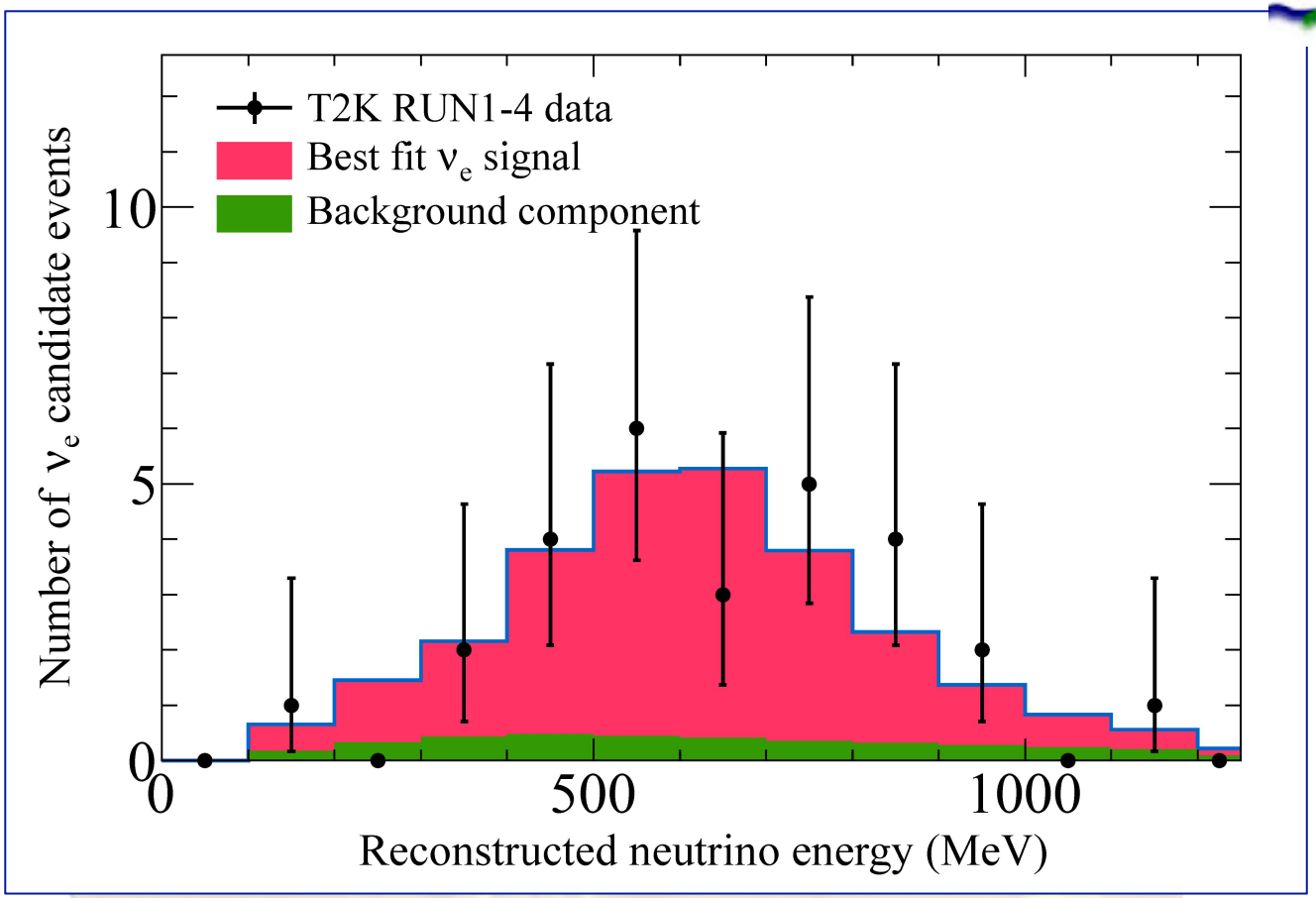




Do electron neutrinos appear?

Start with Muon neutrino beam

T2K results



Phys. Rev. Lett. 112, 061802

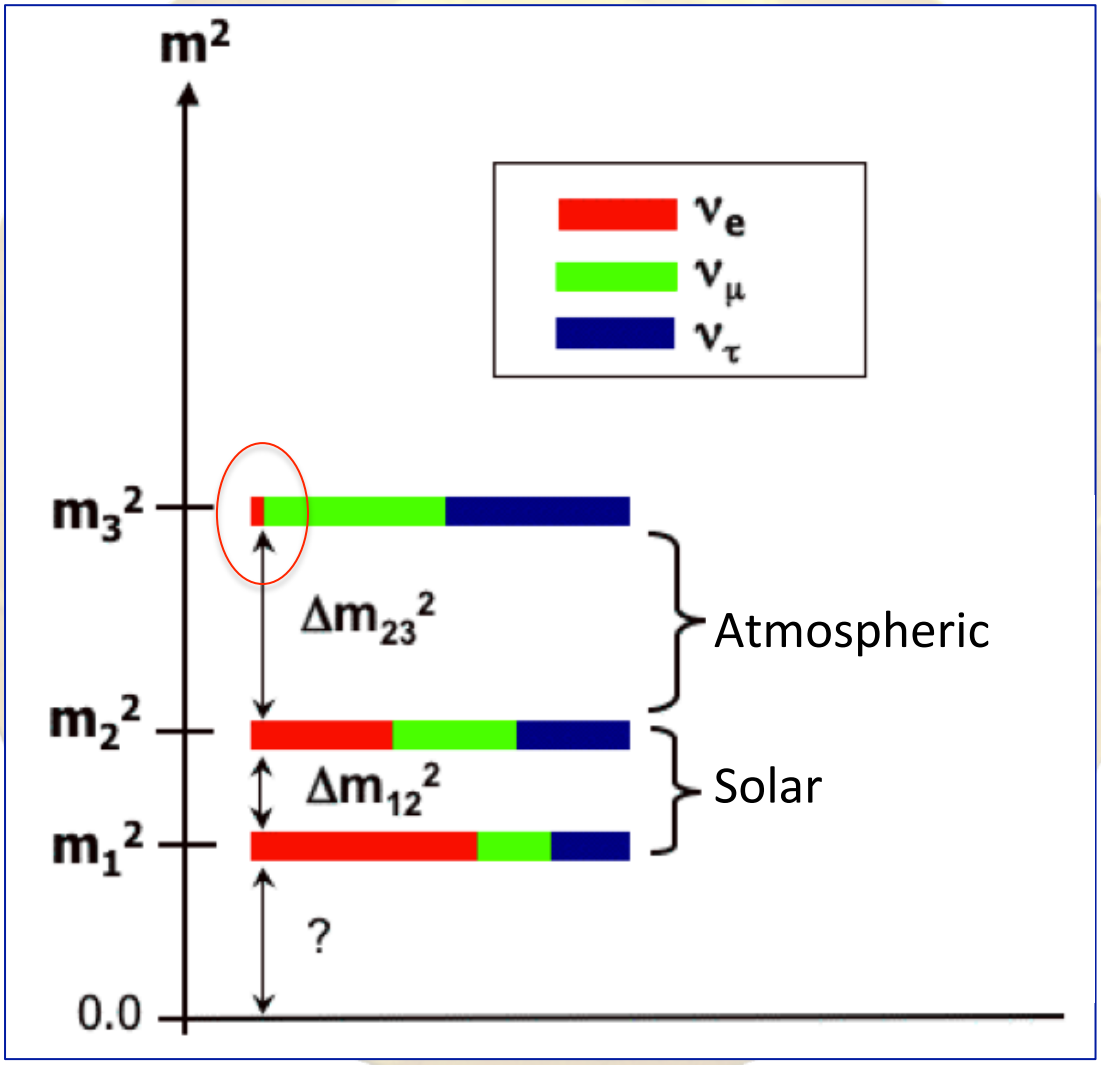
T2K saw 28 electron-like events in SK,

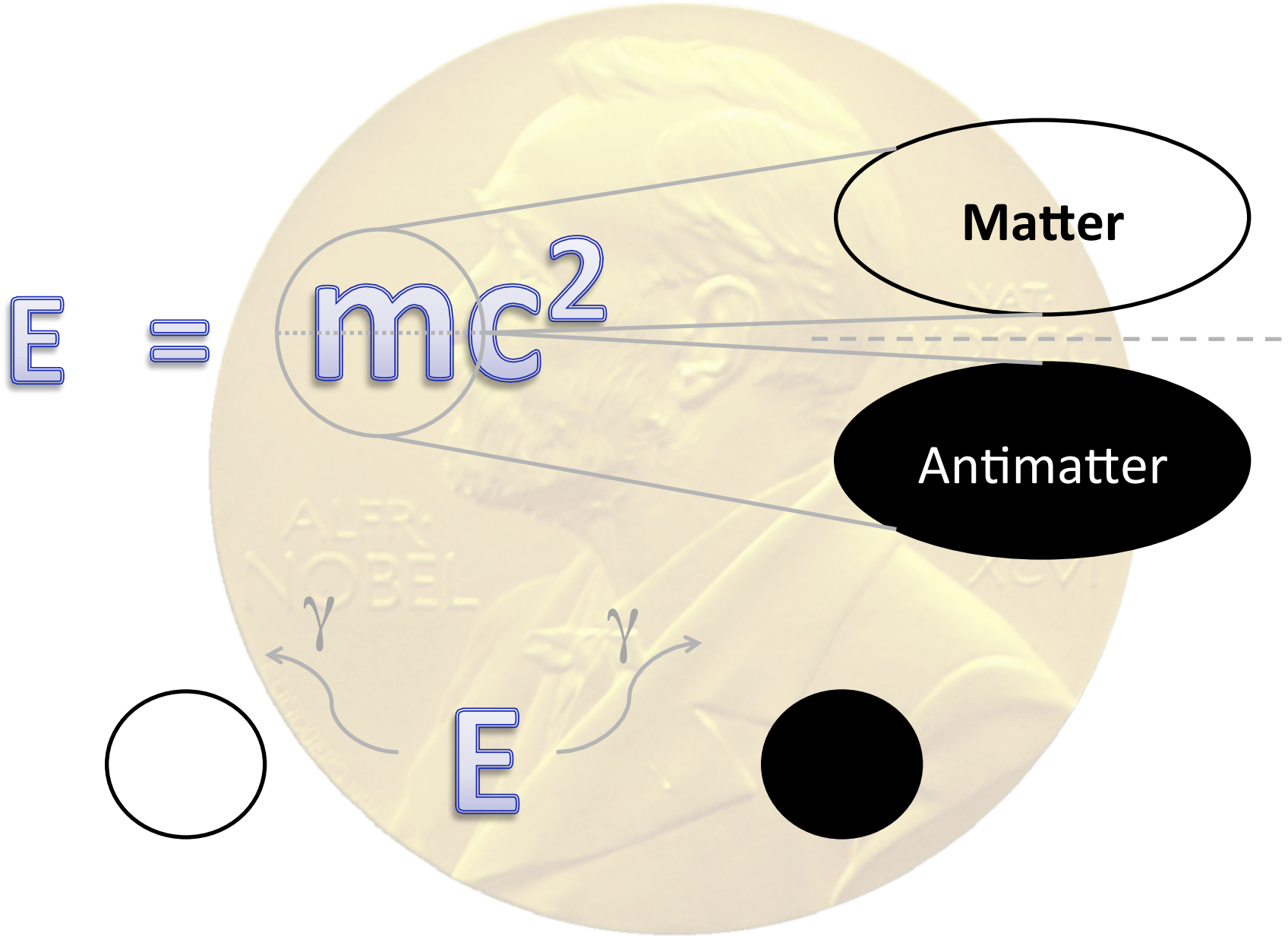
expected ~5 background events

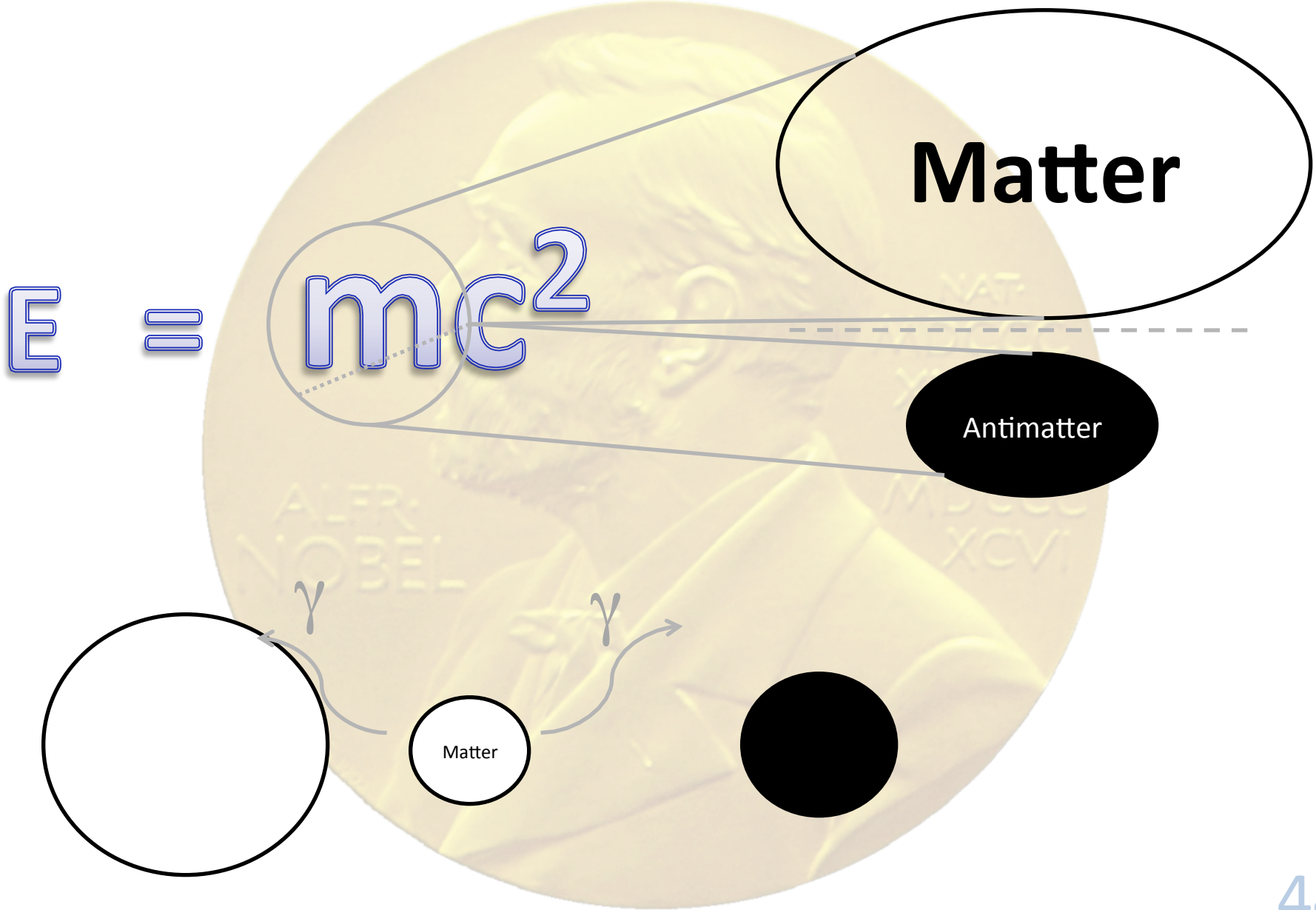
First ever explicit observation of ν_e appearance

3 Flavour Oscillations

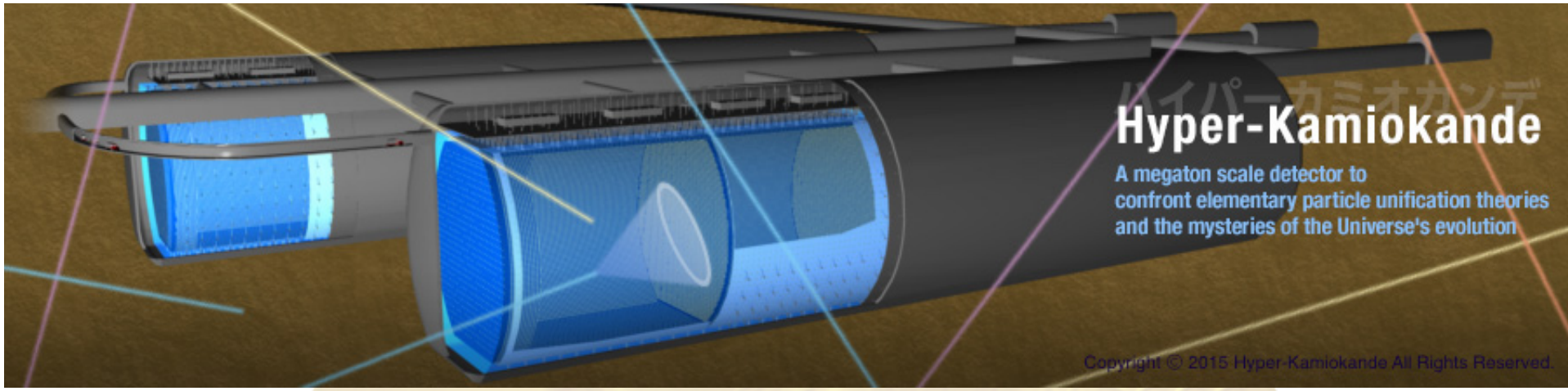
- Θ_{13} is Not zero! leptonic CP violation is possible




E = mc²
Matter
Antimatter
γ
γ
E

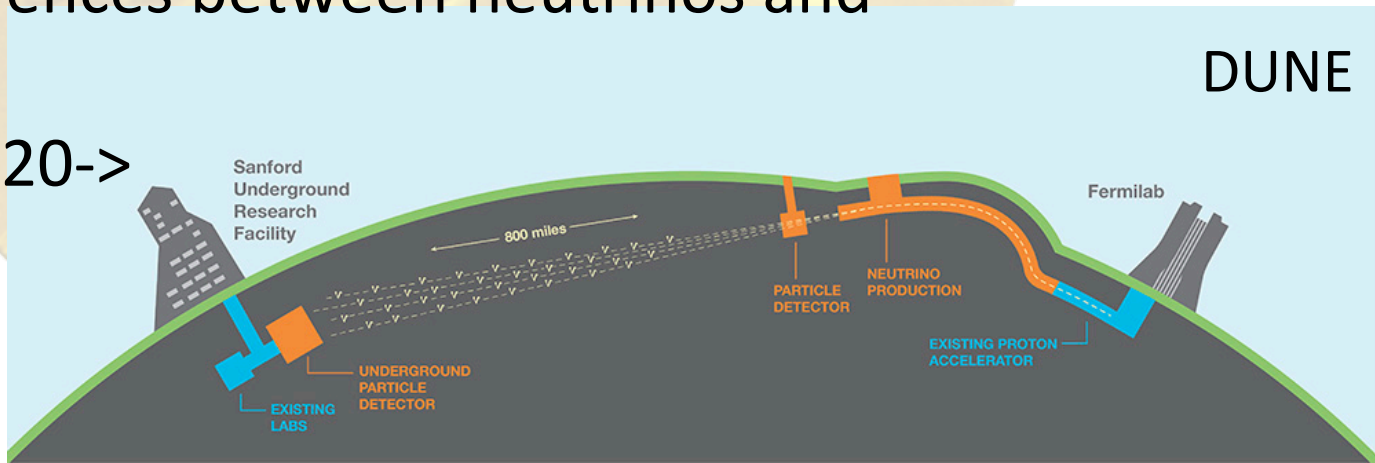

Matter
$E = mc^2$
Antimatter
γ
γ
Matter

Lets look for CP Violation!

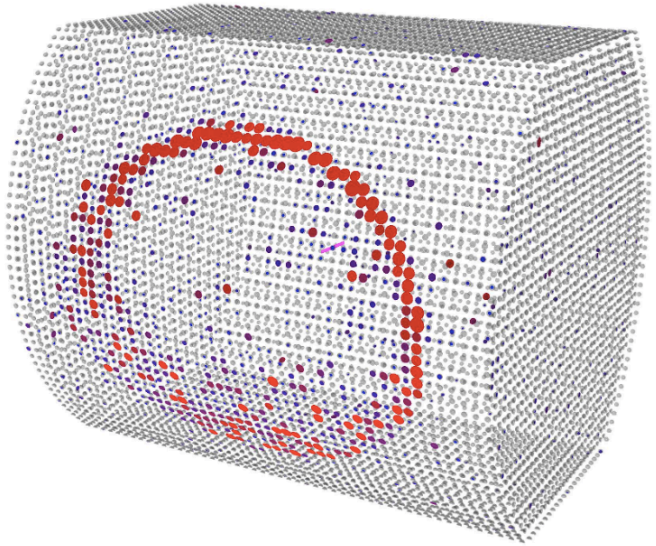


- Powerful muon neutrino *and* antineutrino beams
- Very large far detectors
- Precision measurements of oscillation parameters
- Look for differences between neutrinos and antineutrinos
- Timeframe 2020->

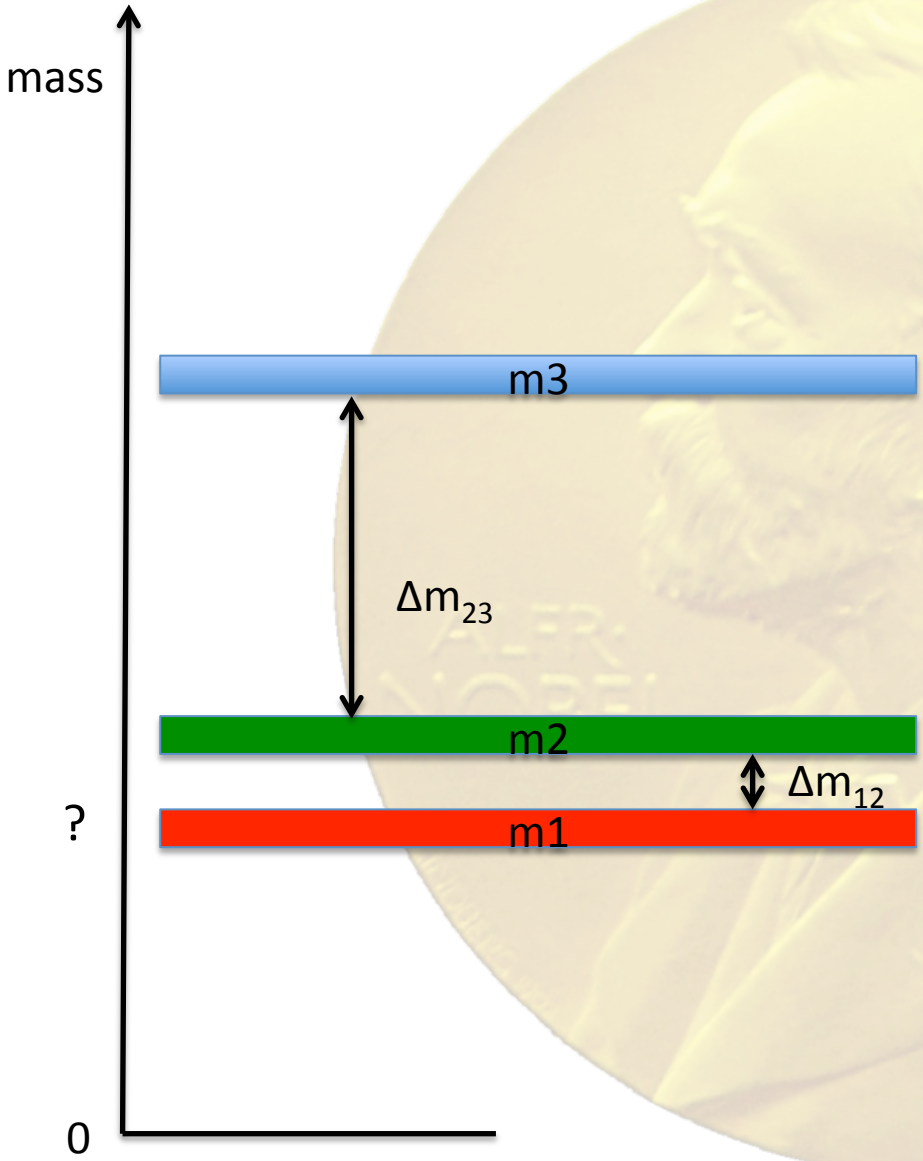
DUNE



HyperKamiokande

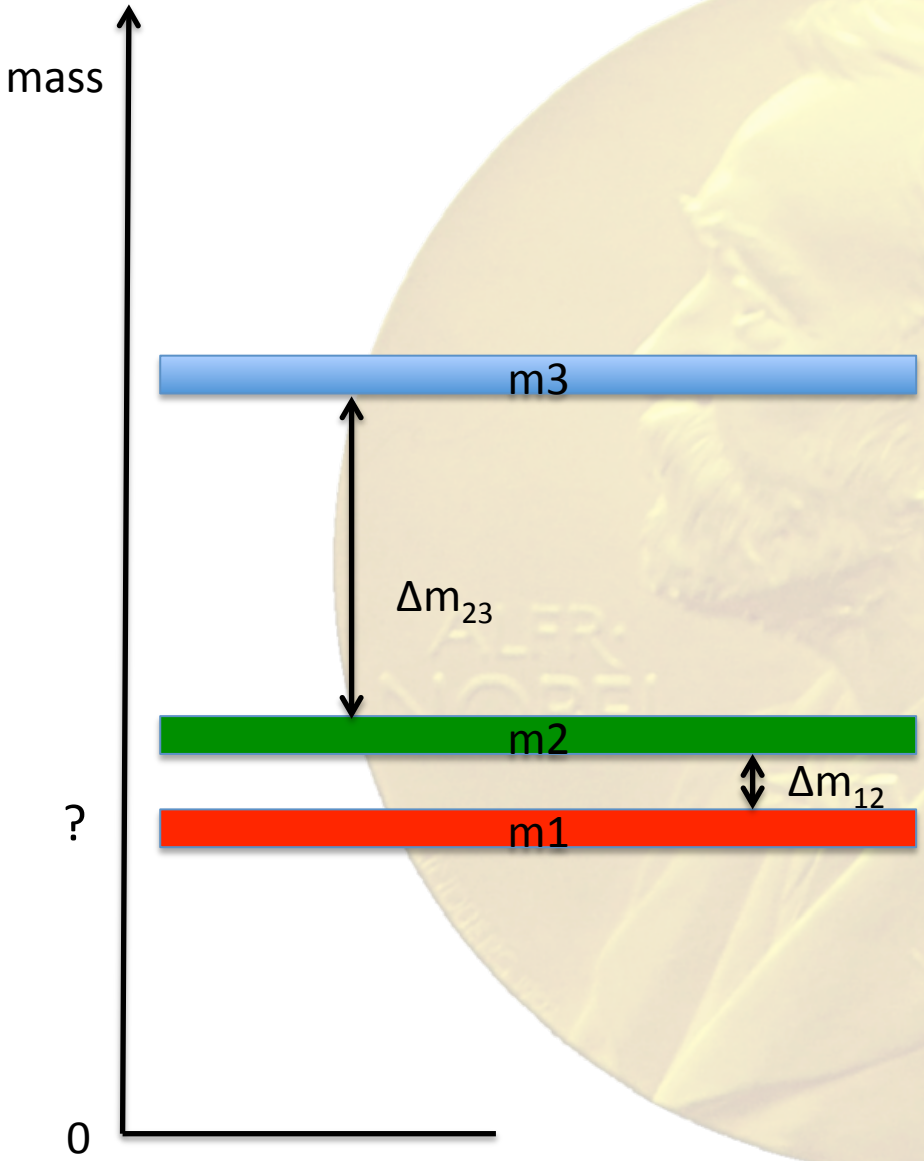


Know mass differences…



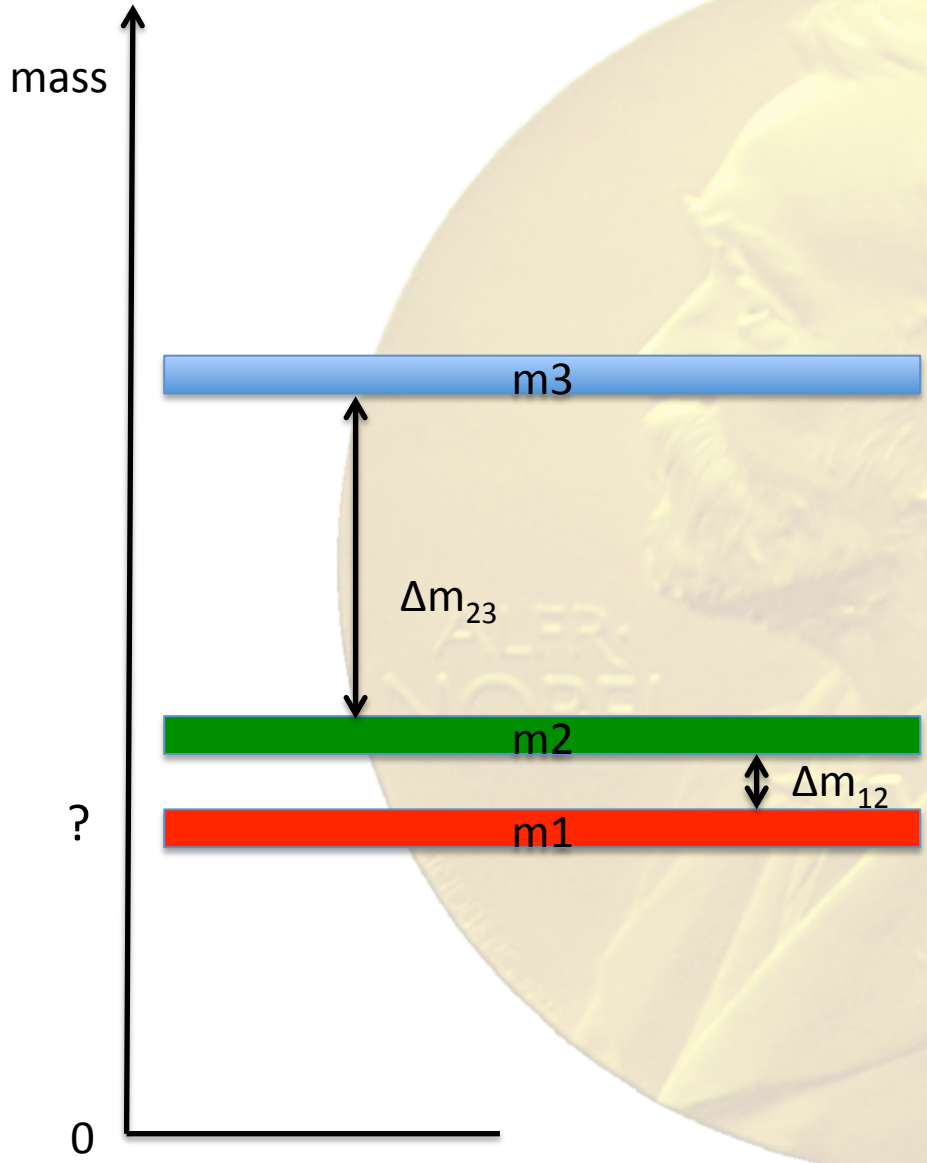
- Don't know absolute masses
- Oscillations only measure mass difference (squared)

Know mass differences…



- Don't know absolute masses
- Oscillations only measure mass difference (squared)

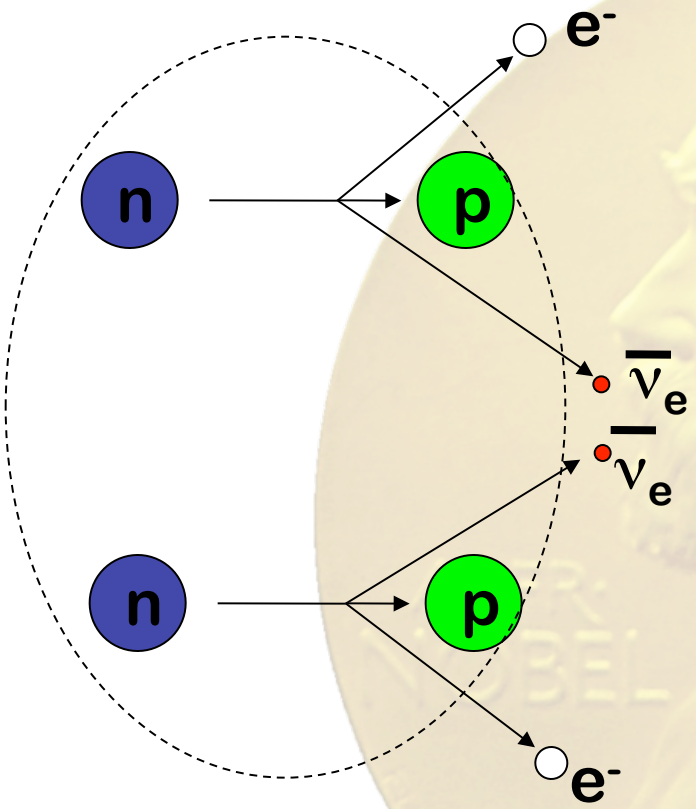
Know mass differences…

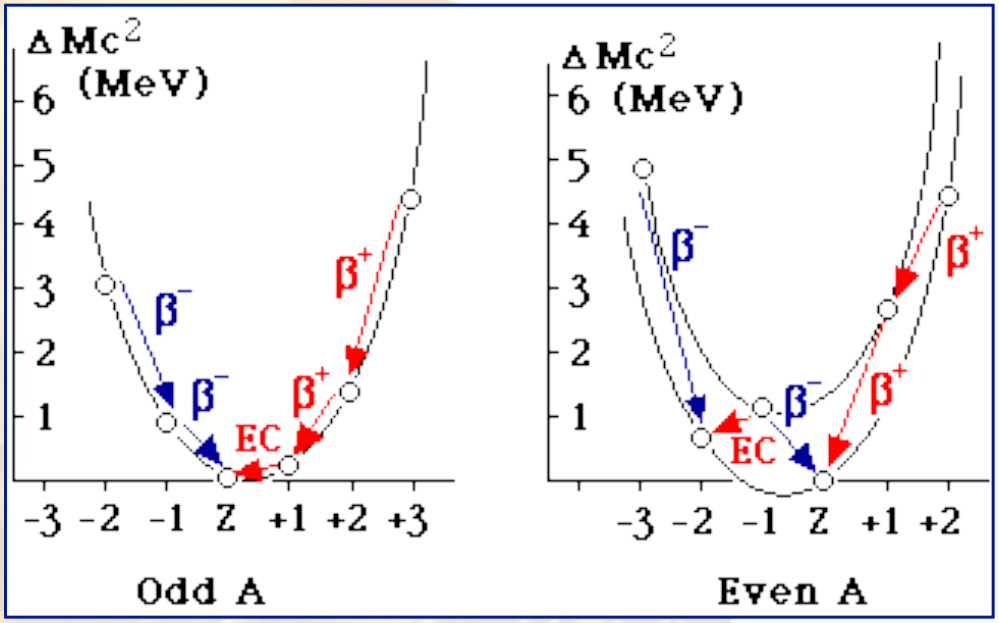


- Don't know absolute masses
- Or their ordering

- Need to know this before CP measurements

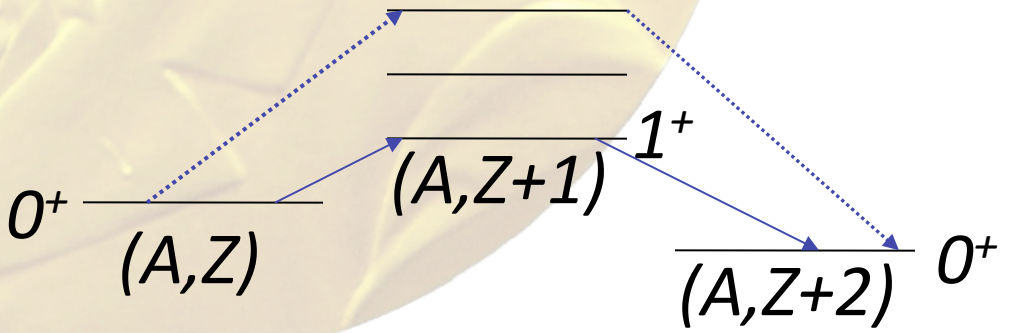
Double Beta Decay ($2\nu\beta\beta$)





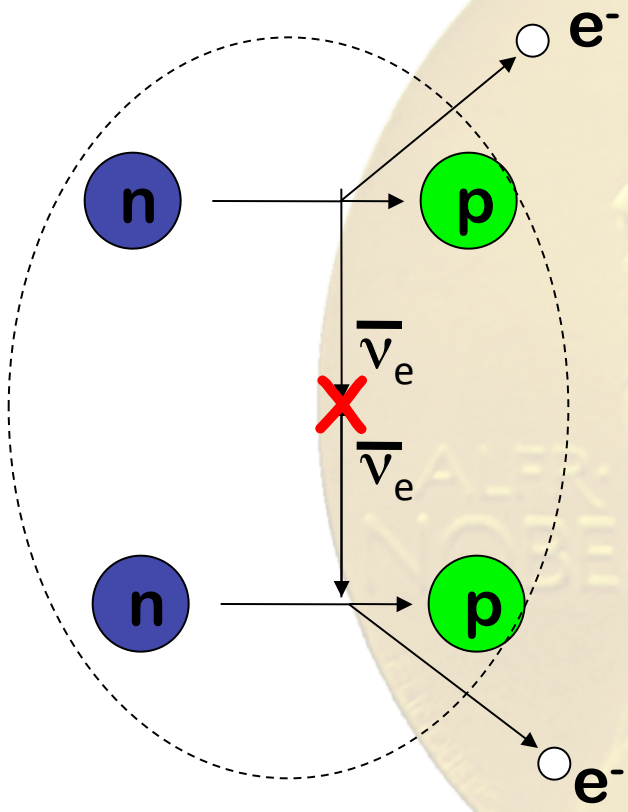
$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\nu_e$

Only 35 isotopes known in nature



Neutrinoless mode ($0\nu\beta\beta$)

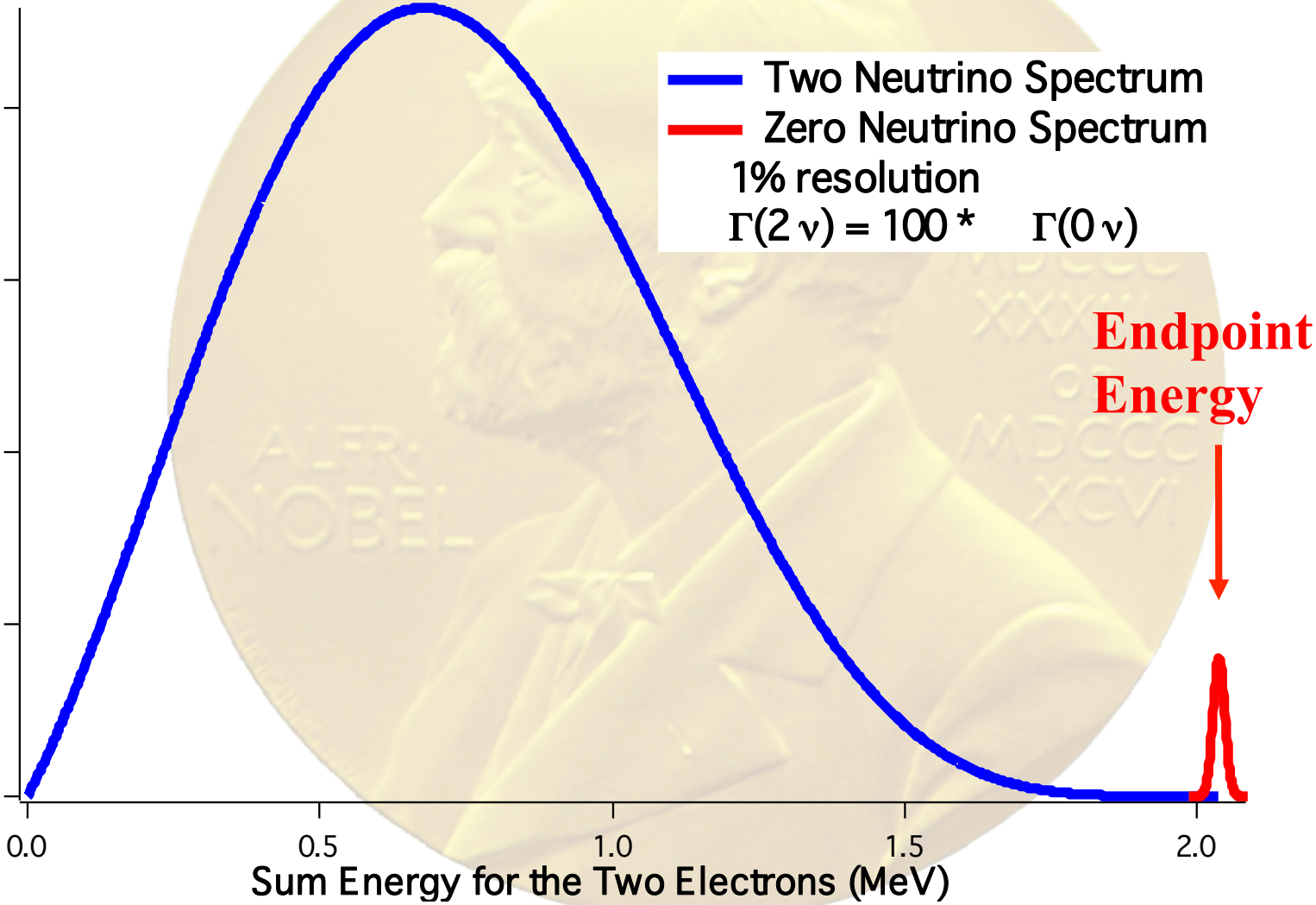
- Tests Neutrino fundamental nature
- Proceeds with rate proportional to absolute neutrino mass.

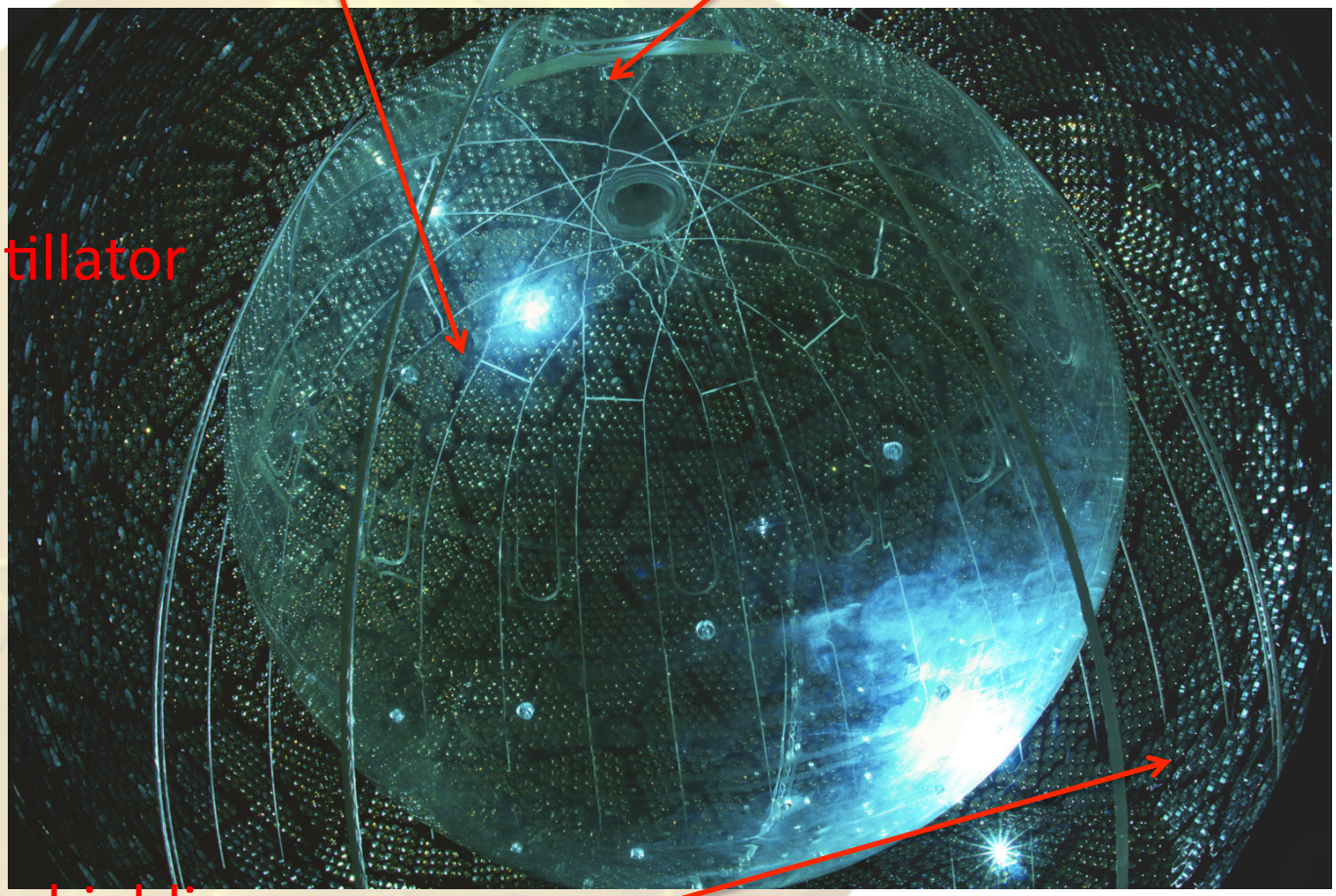


$\Delta L = 2$

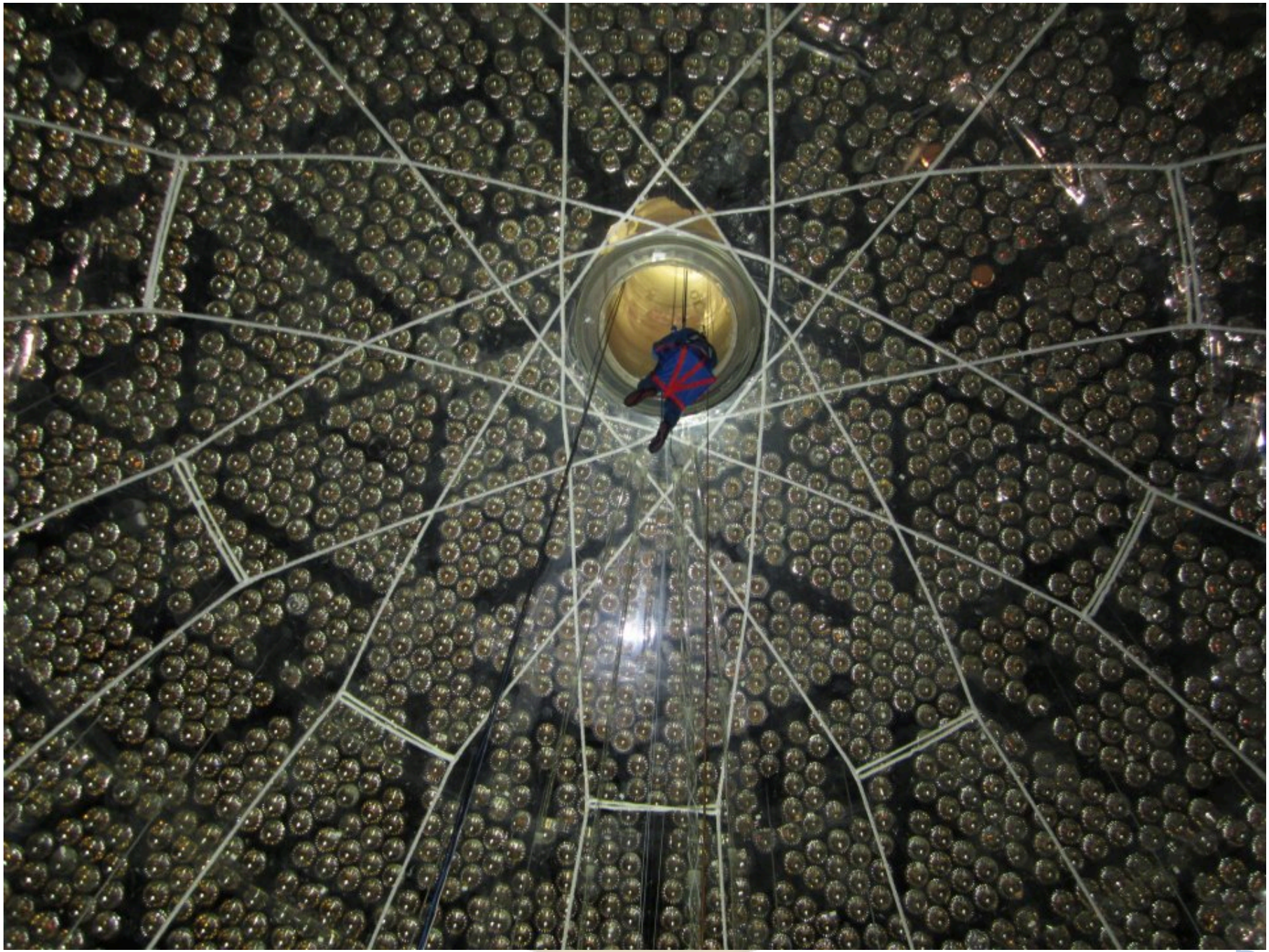
$(A,Z) \rightarrow (A,Z+2) + 2\ e^-$

ββ Decay


Two Neutrino Spectrum
Zero Neutrino Spectrum
1% resolution
Γ(2ν) = 100 * Γ(0ν)
Endpoint Energy
0.0
0.5
1.0
1.5
2.0
Sum Energy for the Two Electrons (MeV)



- 12m diameter Acrylic Vessel
- 780 tonnes scintillator
- Load with ^{130}Te
- 7ktonnes water shielding
- ~9500 8inch PMT array

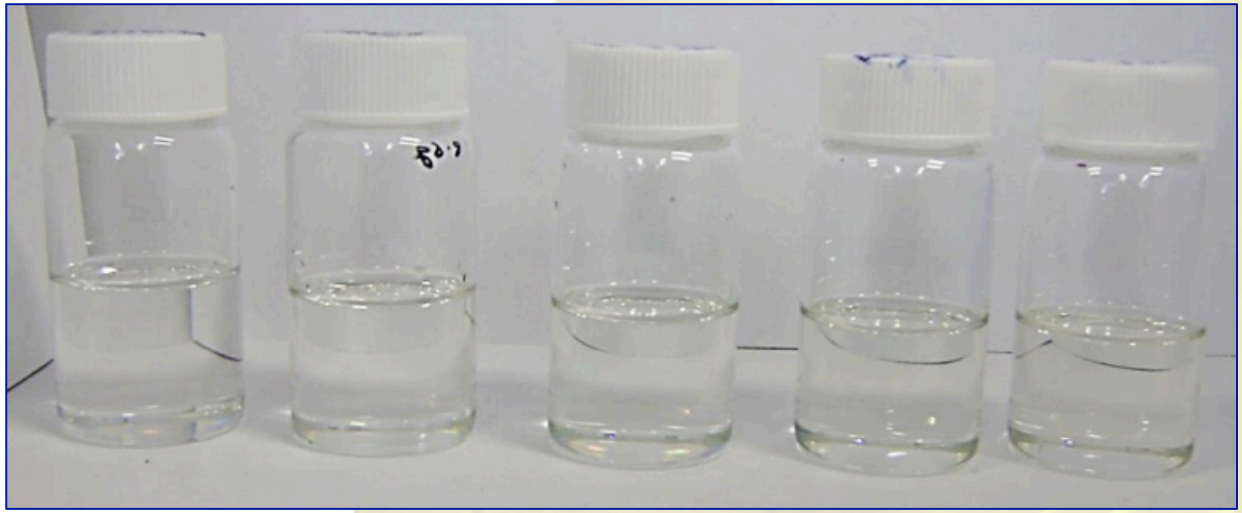


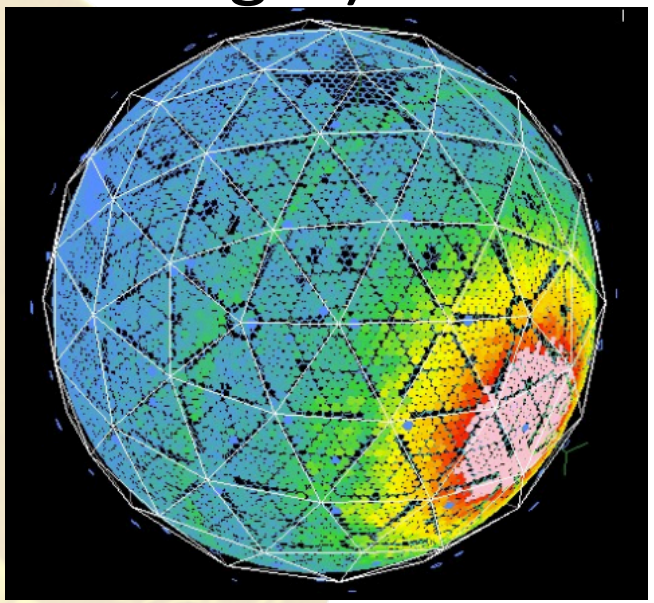
Radiopurity of detector components

- Many step purification of the scintillator

Lots of light, lots of Isotope

- 0.3%, 0.5%, 1%, 3%, 5% (from left to right)





- 3% Te in SNO+ Phase II DBD corresponds to <u>8 tonnes</u> of ^{130}Te *isotope*
- Cost for this much tellurium is only ~$15M

Summary

- Super-Kamiokande measured atmospheric neutrino oscillations -> Nobel prize for Takaaki Kajita
- SNO Proved solar neutrinos oscillate -> Nobel prize for Art McDonald
- We now have measurements of all neutrino oscillation parameters. Current experiments improving precision
  - But we don't know the mass hierarchy
  - Or the absolute mass scale
- Future experiments will search for differences between neutrino and antineutrino oscillations
  - CP violation could explain why the Universe is even here
  - QMUL important part in HyperKamiokande
- Neutrinoless double beta decay can test absolute neutrino mass scale
  - QMUL important part in SNO+

Neutrinos are awesome… but we don't completely understand them yet!

+ others that didn't have logos…

Thank you for listening