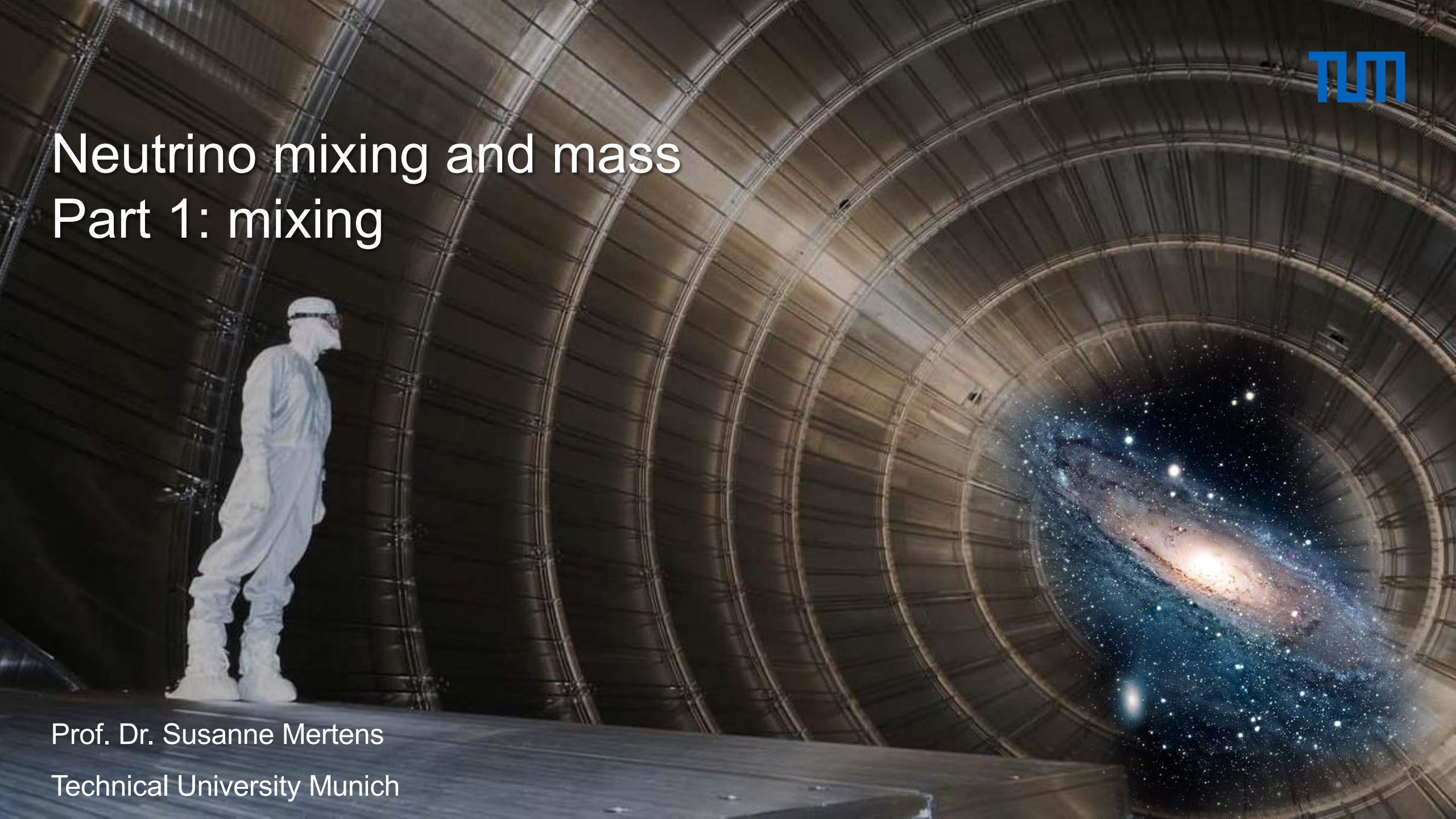
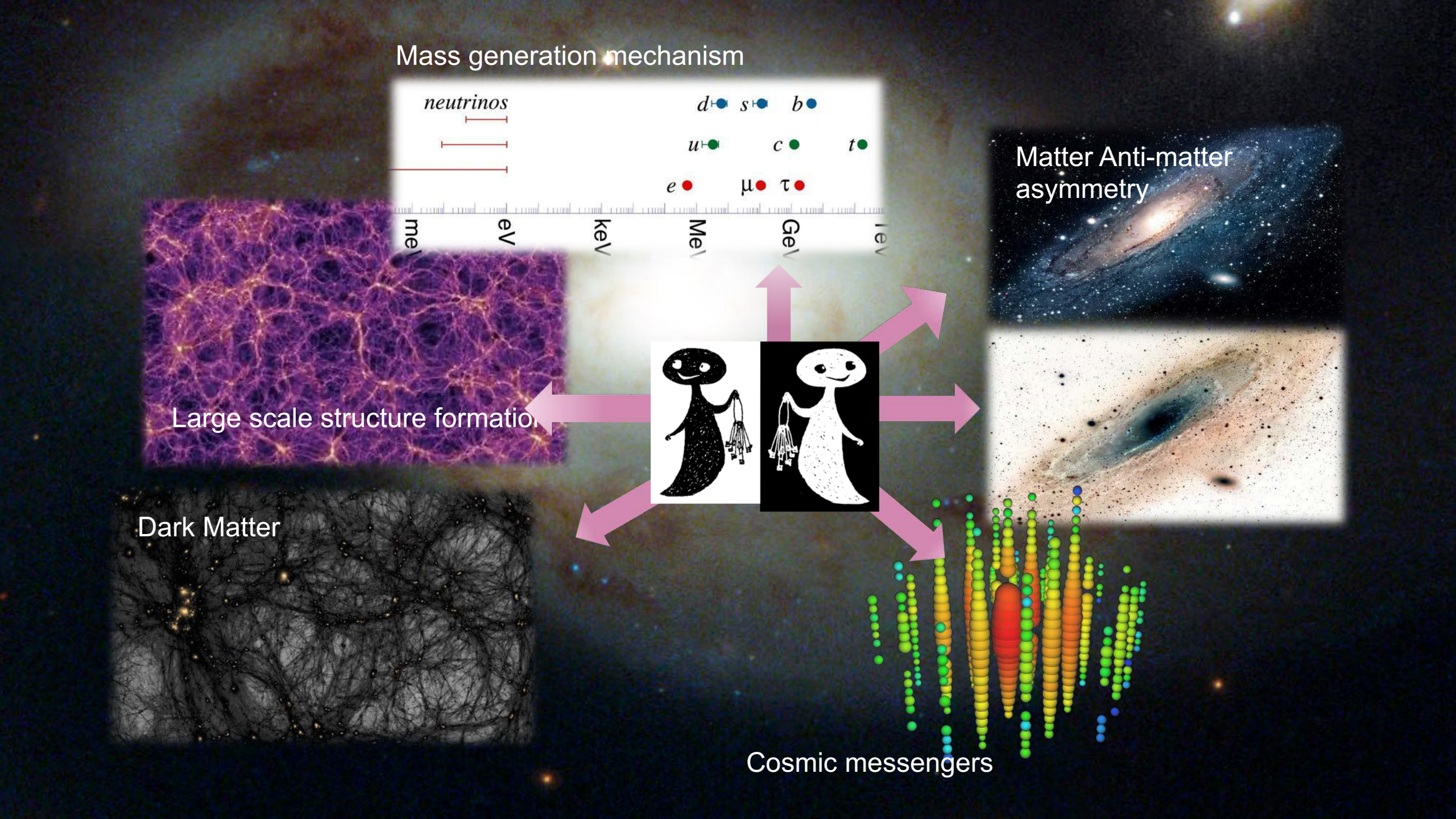
Neutrino mixing and mass
Part 1: mixing



Prof. Dr. Susanne Mertens

Technical University Munich


Mass generation mechanism
neutrinos
d
s
b
u
c
t
e
μ
τ
eV
keV
Ge
Large scale structure formatio
Dark Matter
Matter Anti-matter asymmetry
Cosmic messengers

Questions for today

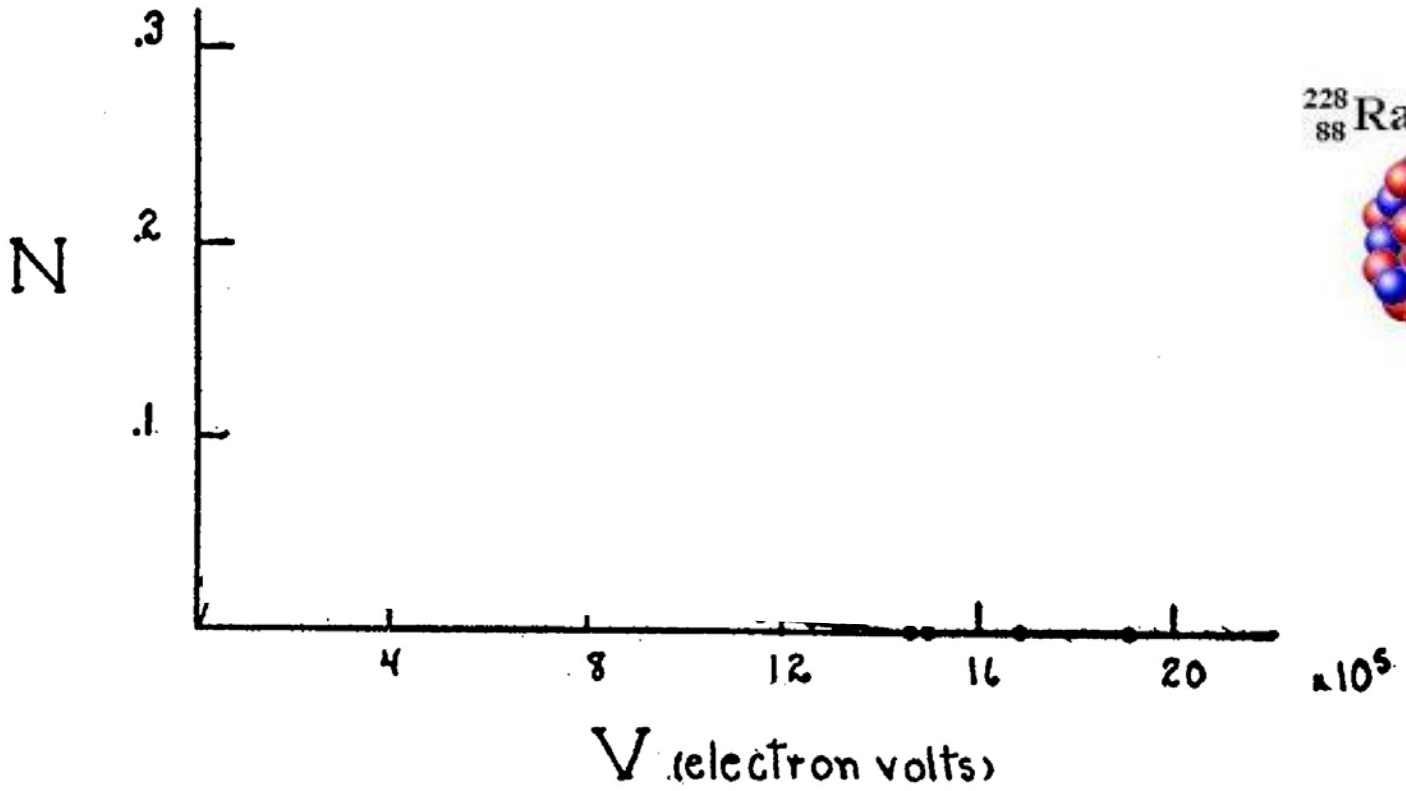
How do we know neutrinos exist?

How do we know neutrinos have a mass?

Which properties of neutrinos are still unknown?

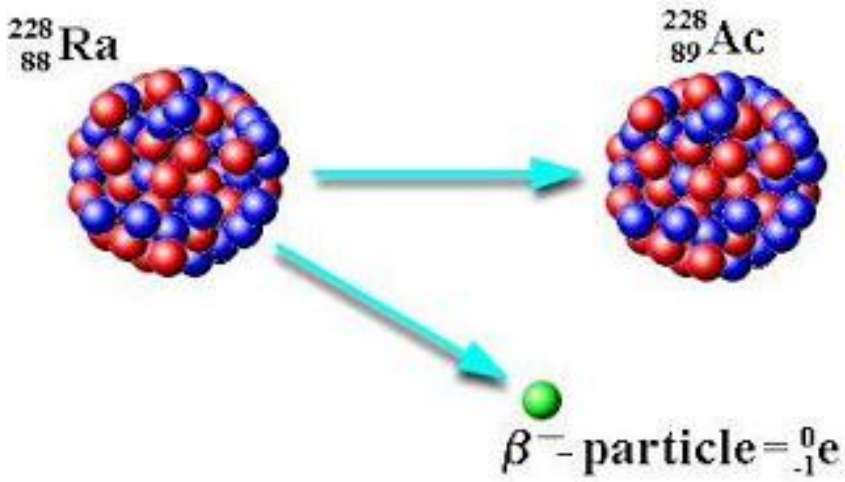
Are there more than three neutrinos?

Imagine we'd be a physicist in 1930…



Electron energy

$n \rightarrow p + e$



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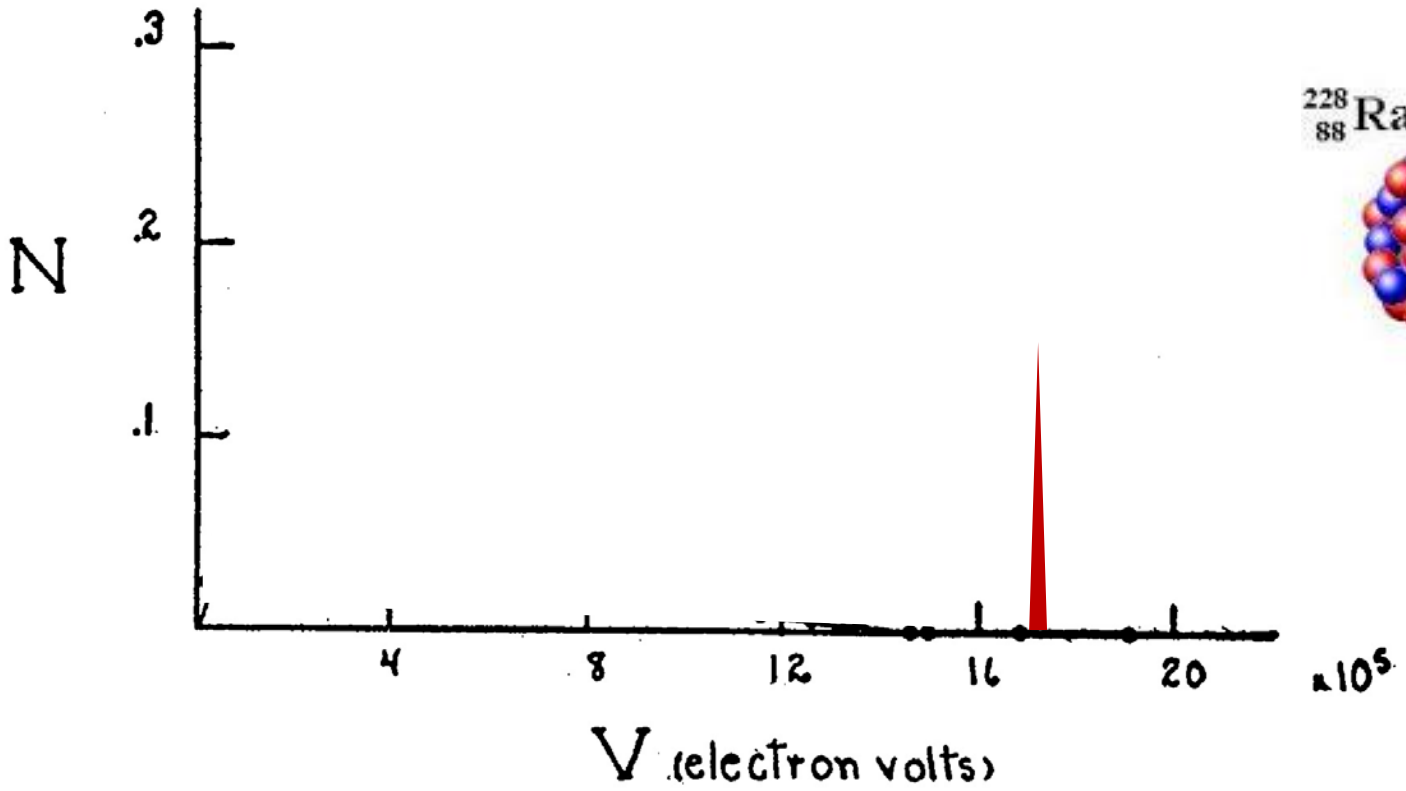

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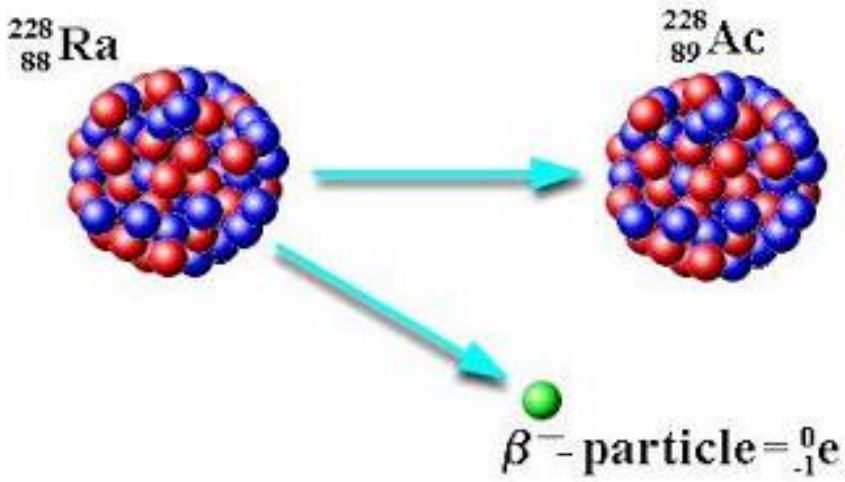

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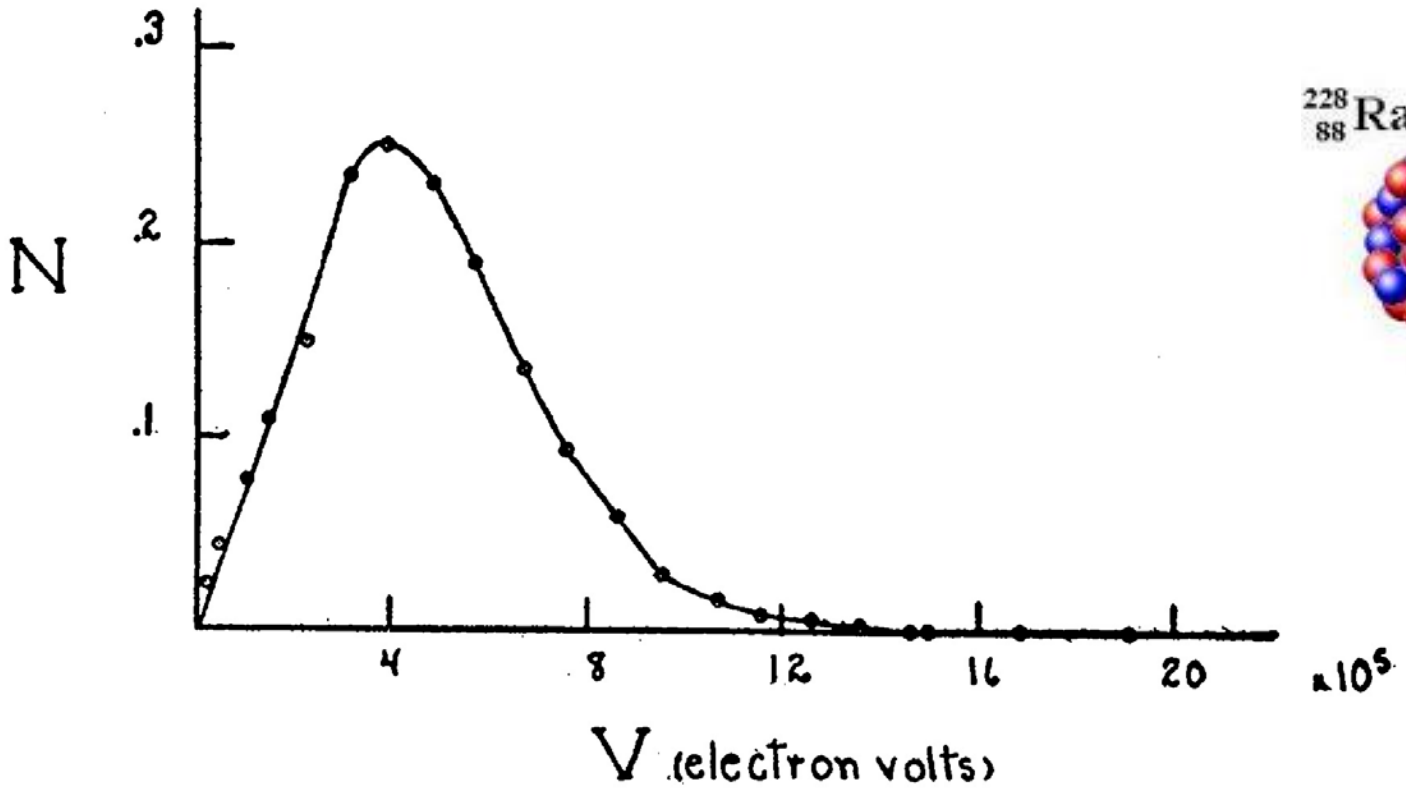
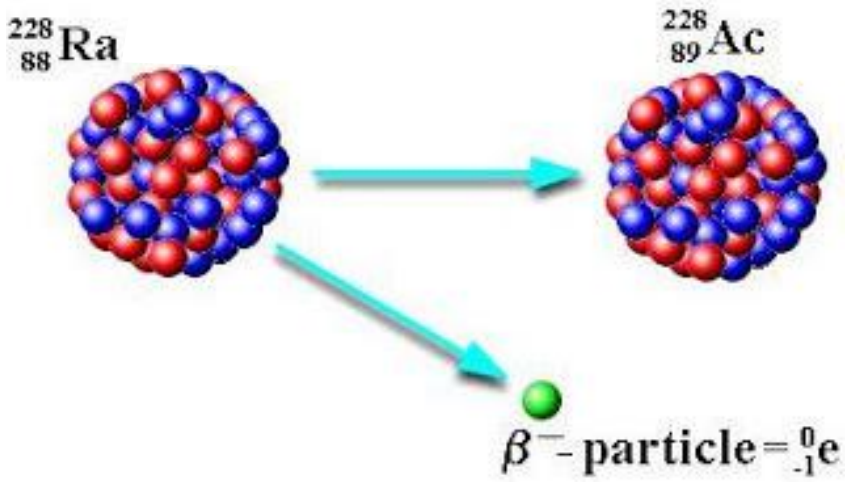
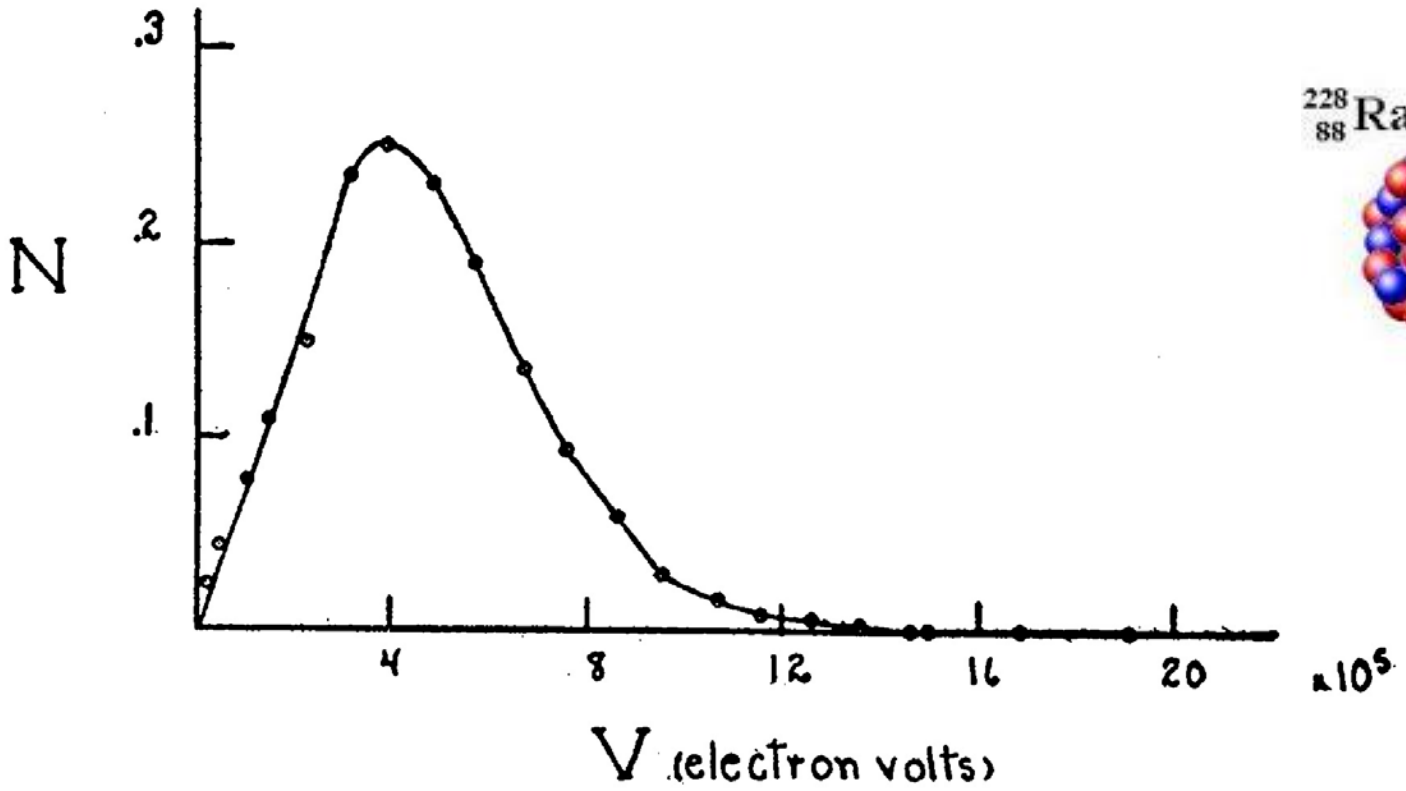
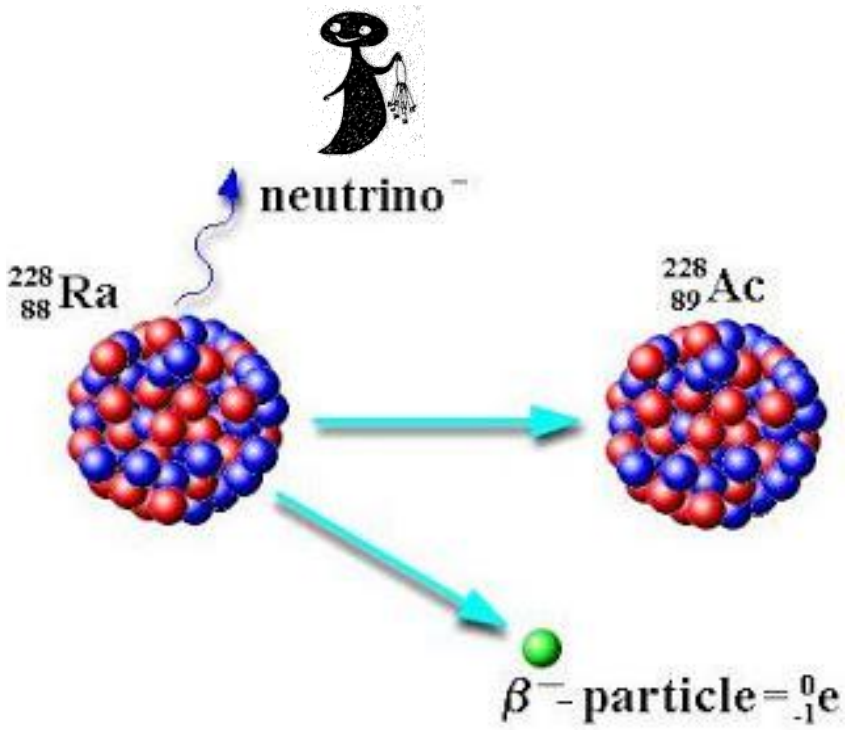




1930: Postulation of the neutrino





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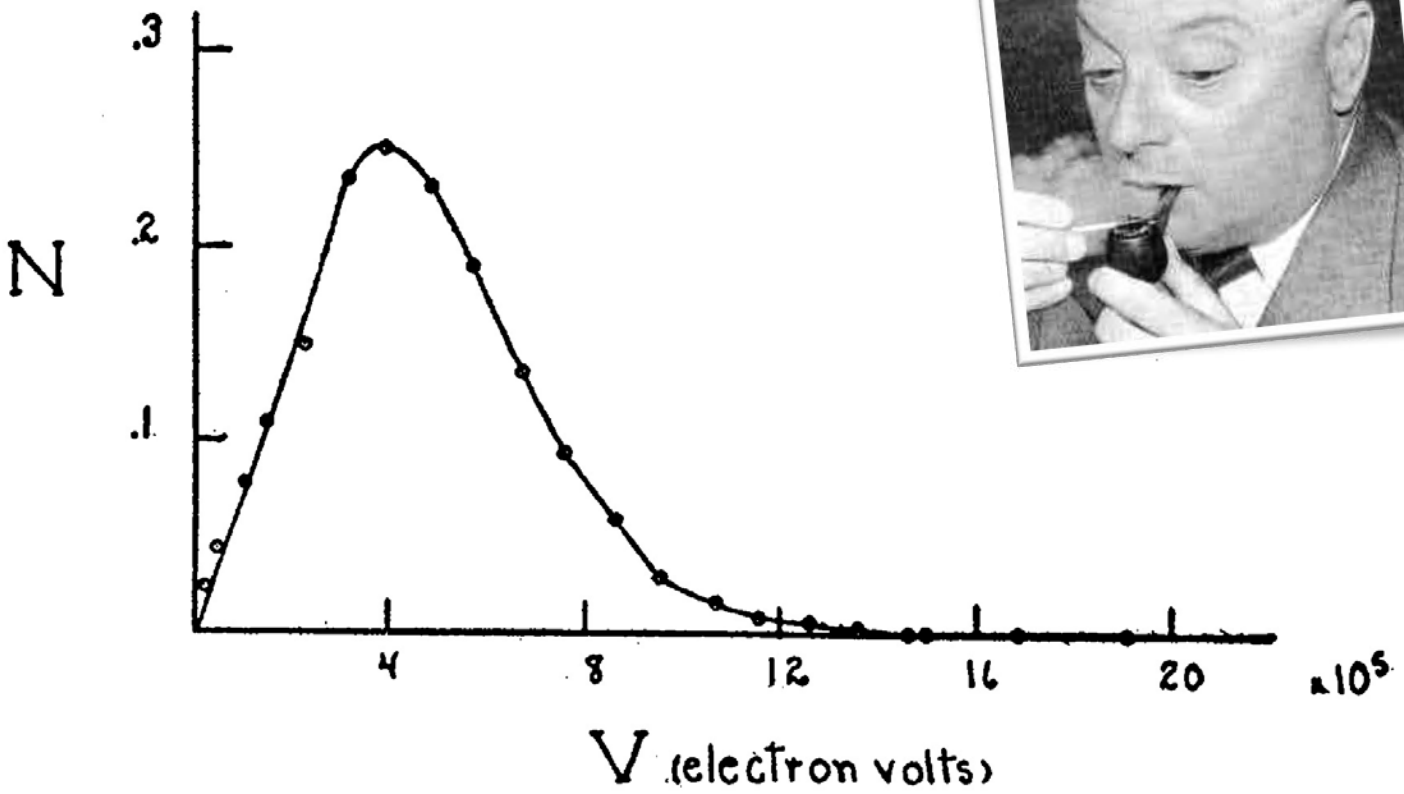


Original - Photocopie of PLC 0393

Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

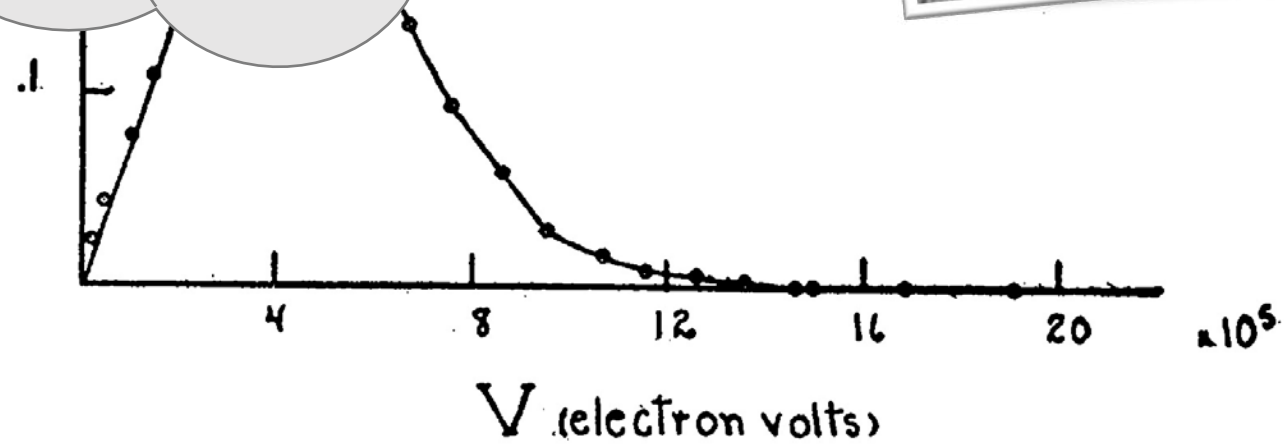
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

1930: Postulation of the neutrino

"Today I did something terrible, something no theoretical physicist should ever do. I proposed something that can never be verified experimentally."



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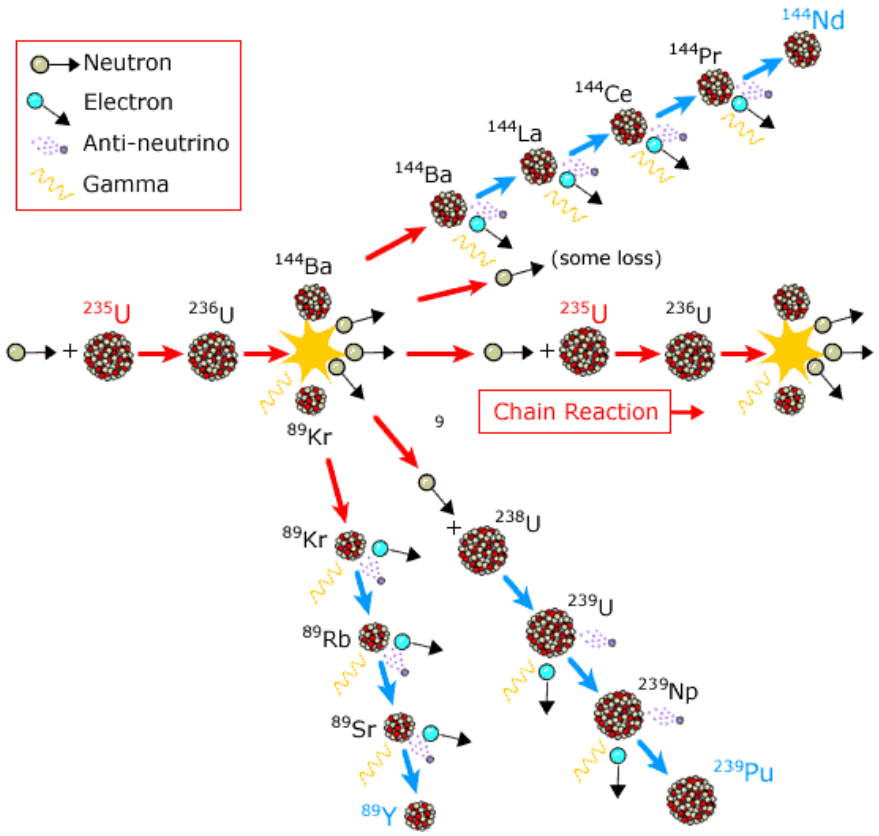
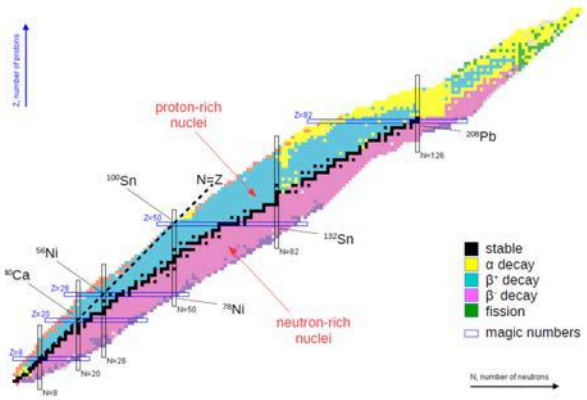
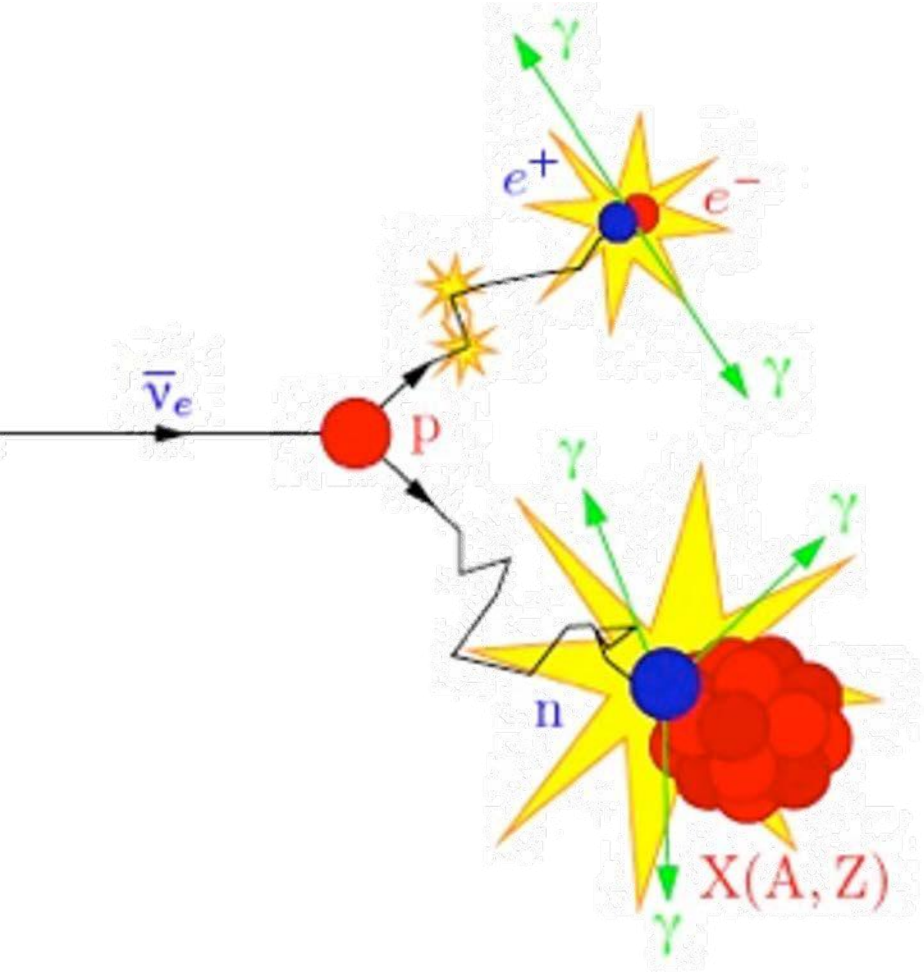
Neutrinos from a reactor



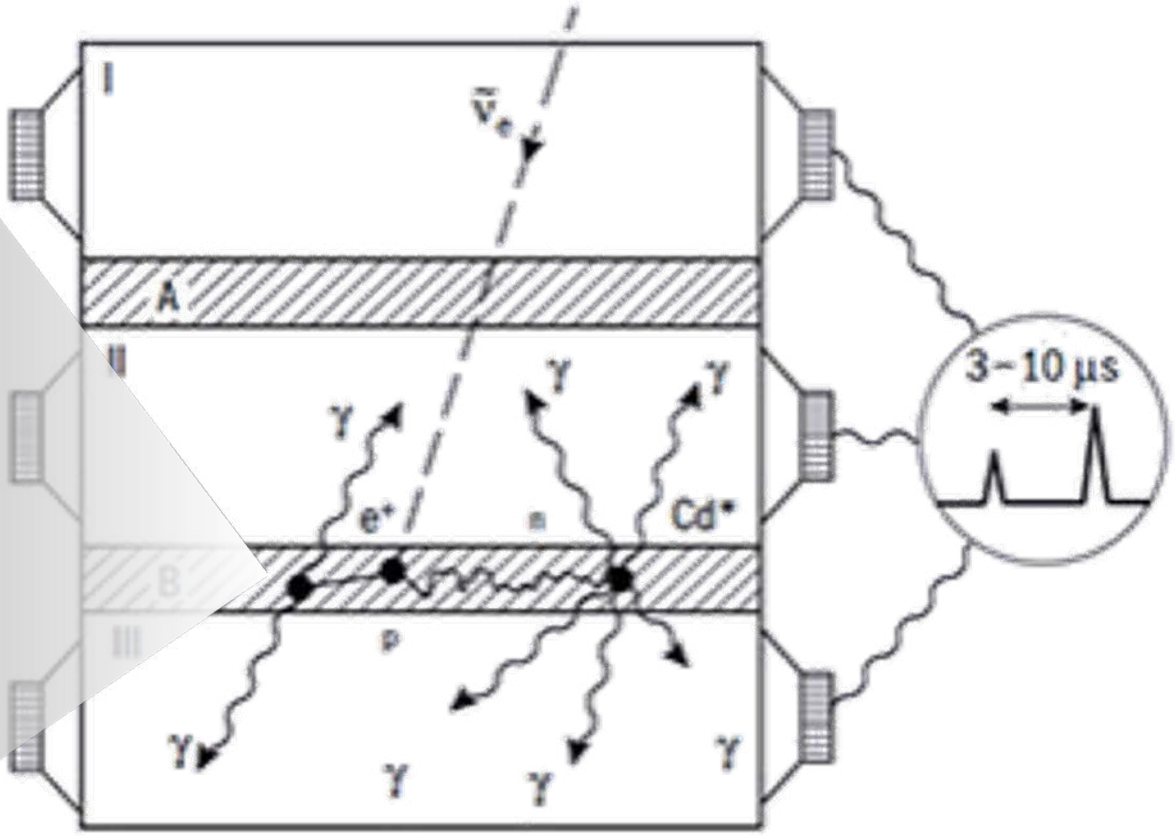
On average six anti-neutrinos per fission



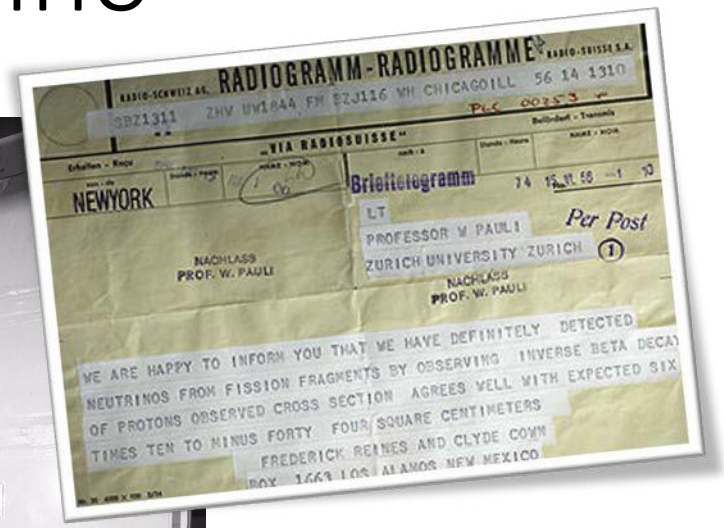
Neutrino detection



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



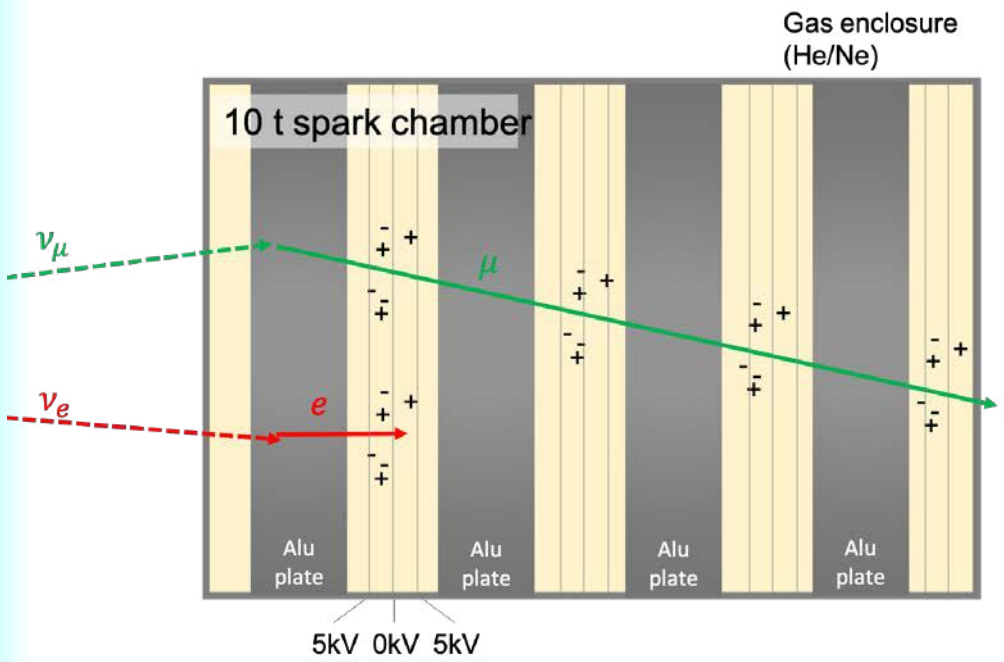
1956: Discovery of Neutrino



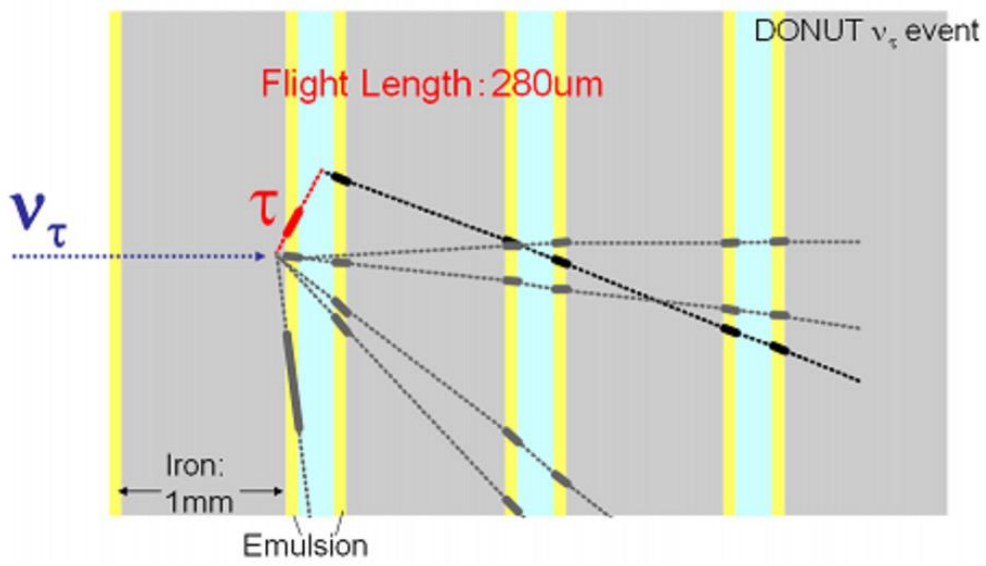
1995: Nobel price in physics
(Frederick Reines)

More neutrinos

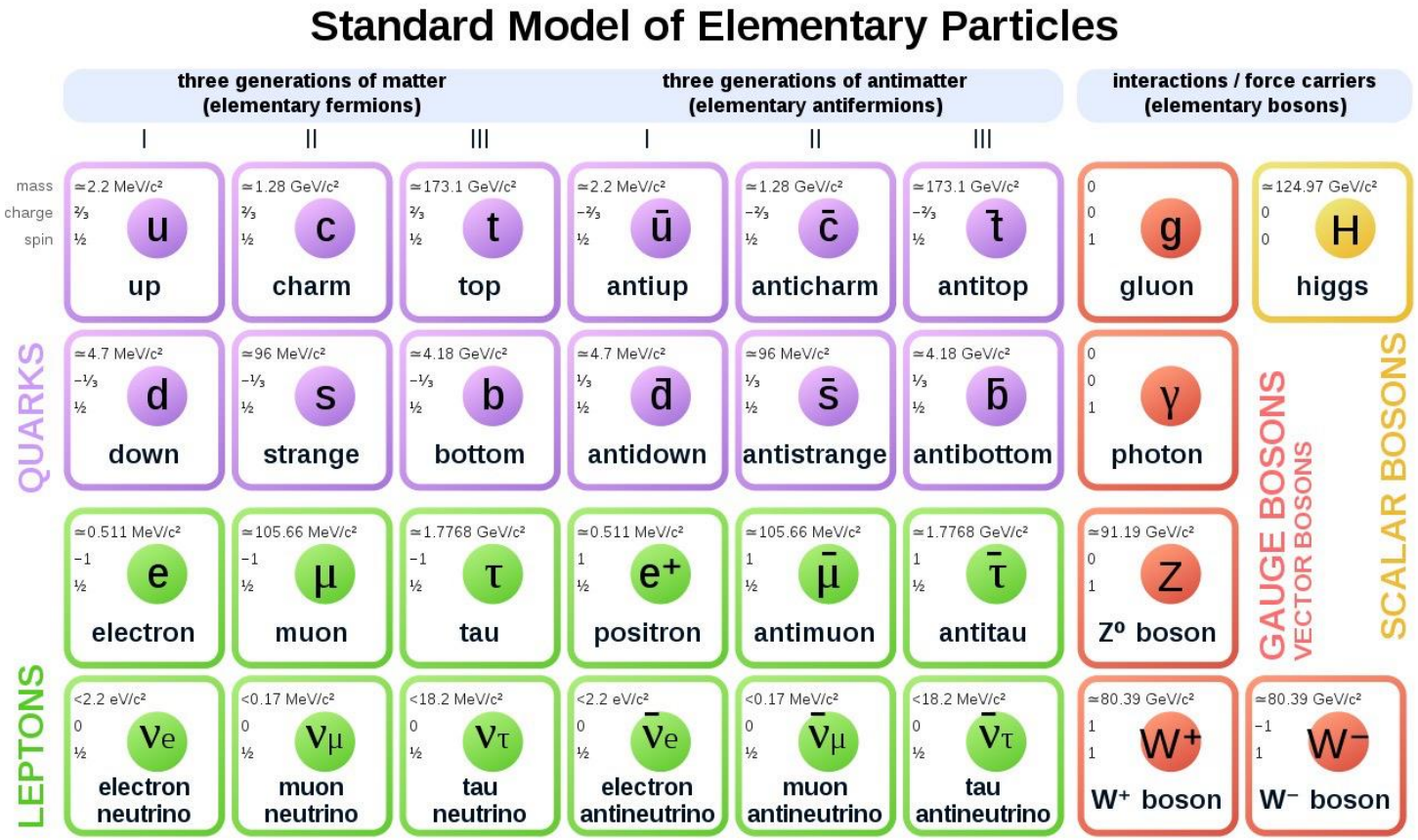
Muon neutrinos (1962)



Tau neutrinos (2000)



Neutrinos in the Standard Model



Neutrinos:

- 3 Flavours
- Spin ½
- Electrically neutral
- Only interact weakly

Questions for today

How do we know neutrinos exist?

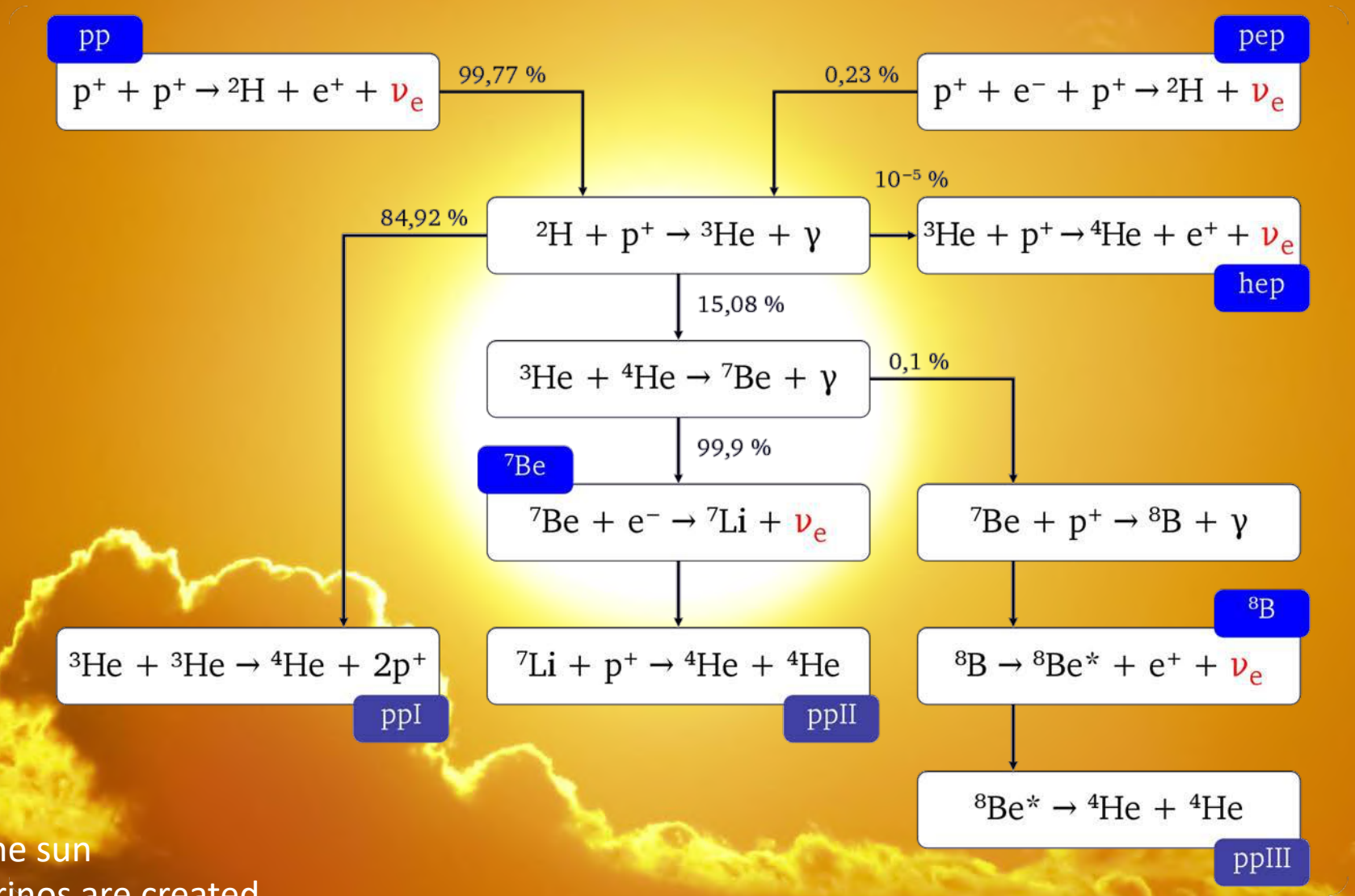
How do we know neutrinos have a mass?

Which properties of neutrinos are still unknown?

Are there more than three neutrinos?

- Postulation by Pauli in 1930 (continuous beta decay spectrum)
- Experimental discovery in 1956 (reactor neutrinos, inverse beta decay)

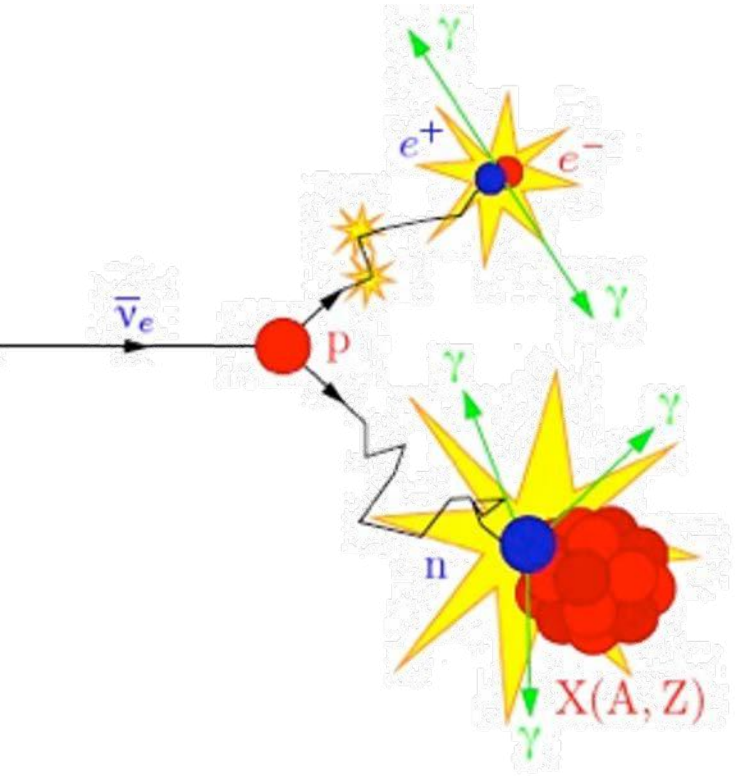
Ray Davis swimming in the water shield of the Homestake experiment



Nuclear fusion in the sun
Only electron neutrinos are created
60 Billion ν's/cm^2/s on earth

Is this possible?

$$\nu_e + p \rightarrow n + e^+$$



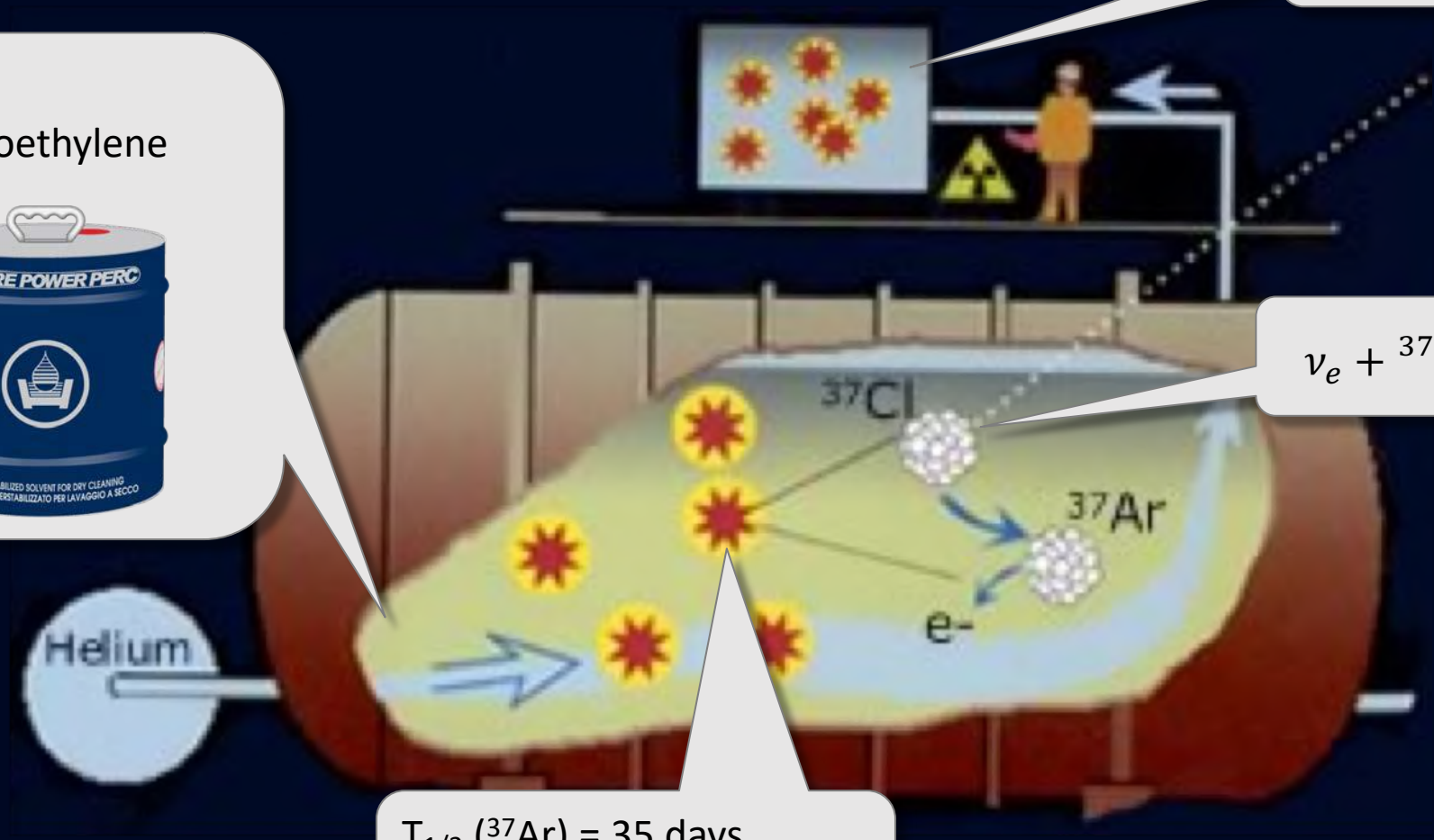
This is possible:

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

Radiochemical Detection

1 neutrino every 2 days

615 t perchloroethylene



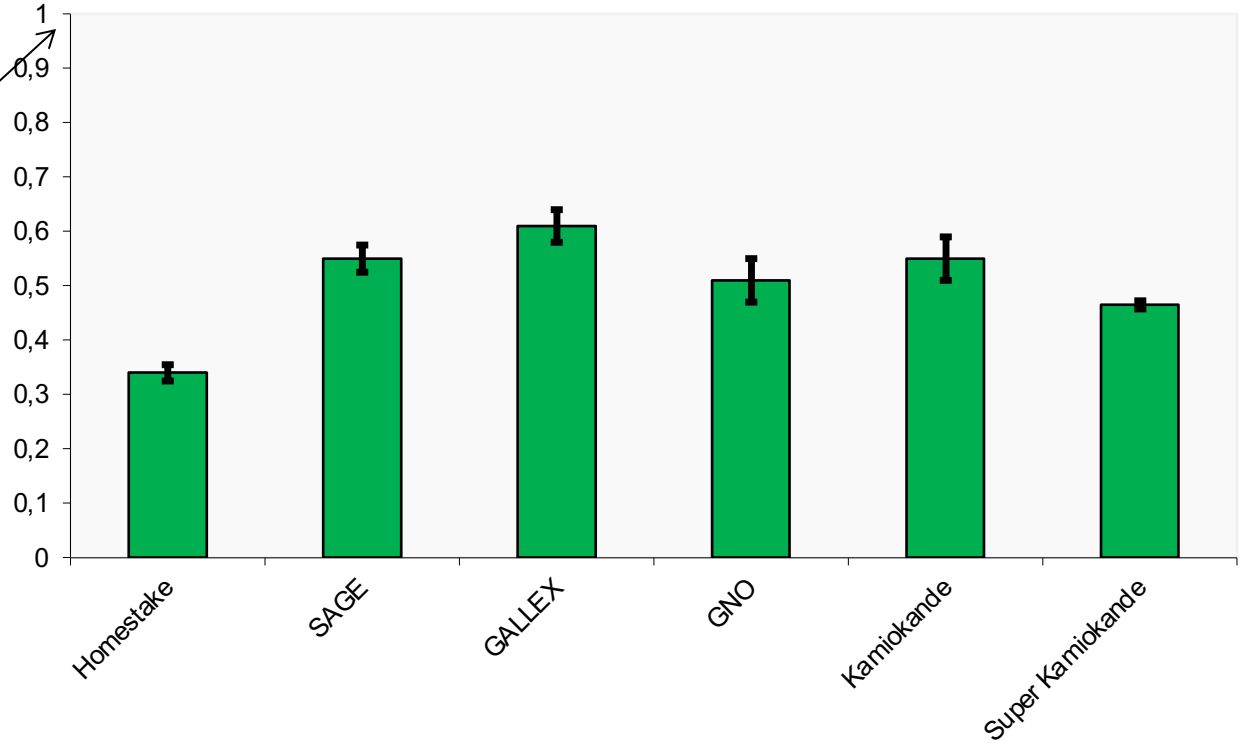
$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e$

$T_{1/2}$ (^{37}Ar) = 35 days

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

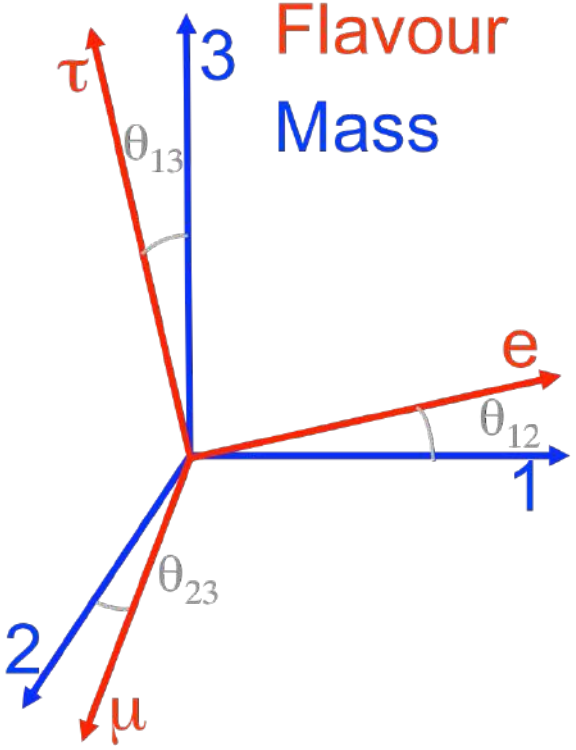
Solar Neutrino Problem

Prediction of
John Bahcall



- …All experiments measure less neutrinos than expected
- What is wrong? The expectation? The measurement?

Flavours und Masses



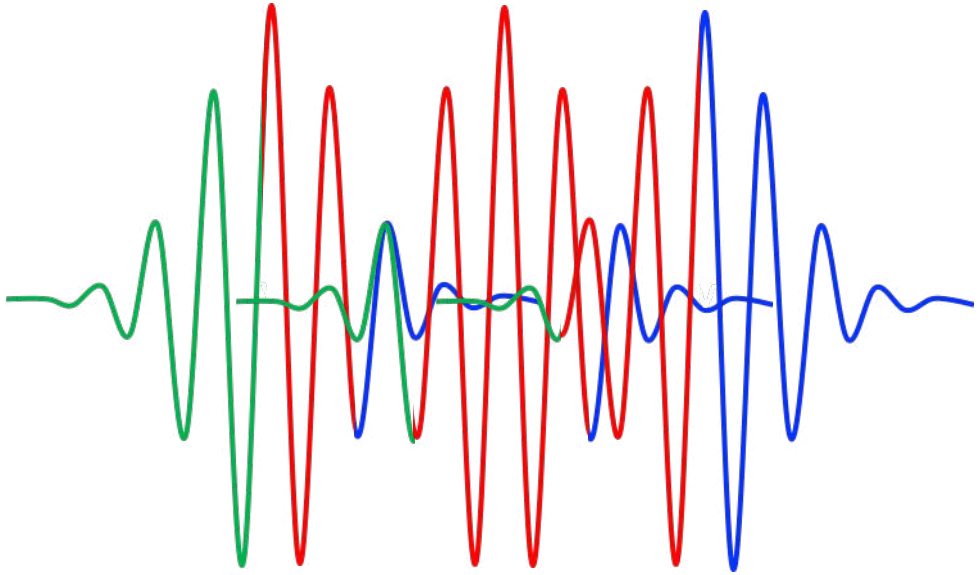
PMNS matrix

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

Neutrino Propagation

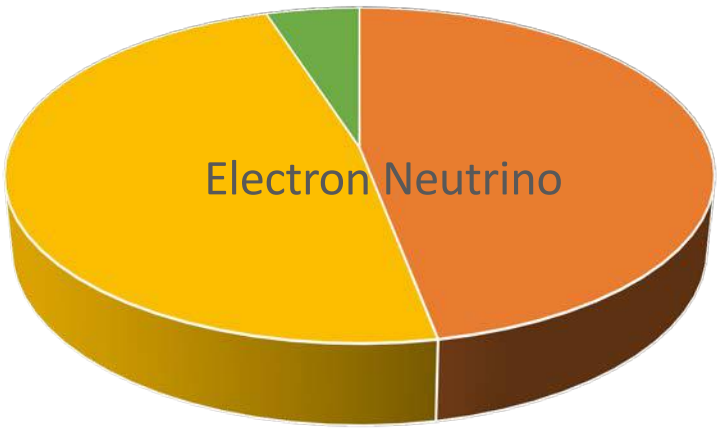
Neutrino creation

Neutrino propagation

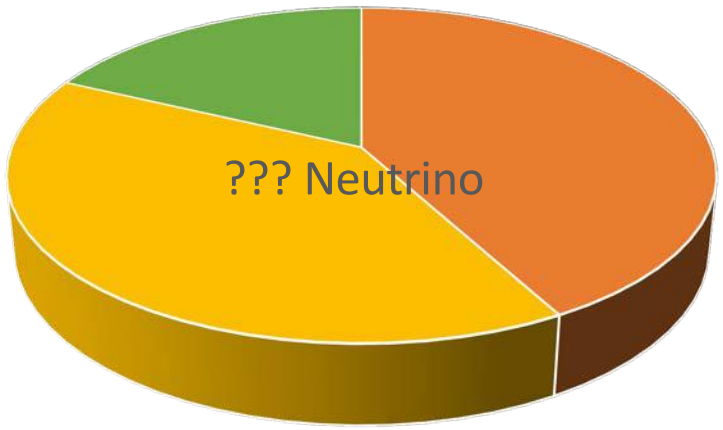


Neutrino Propagation

t = 0



t > 0

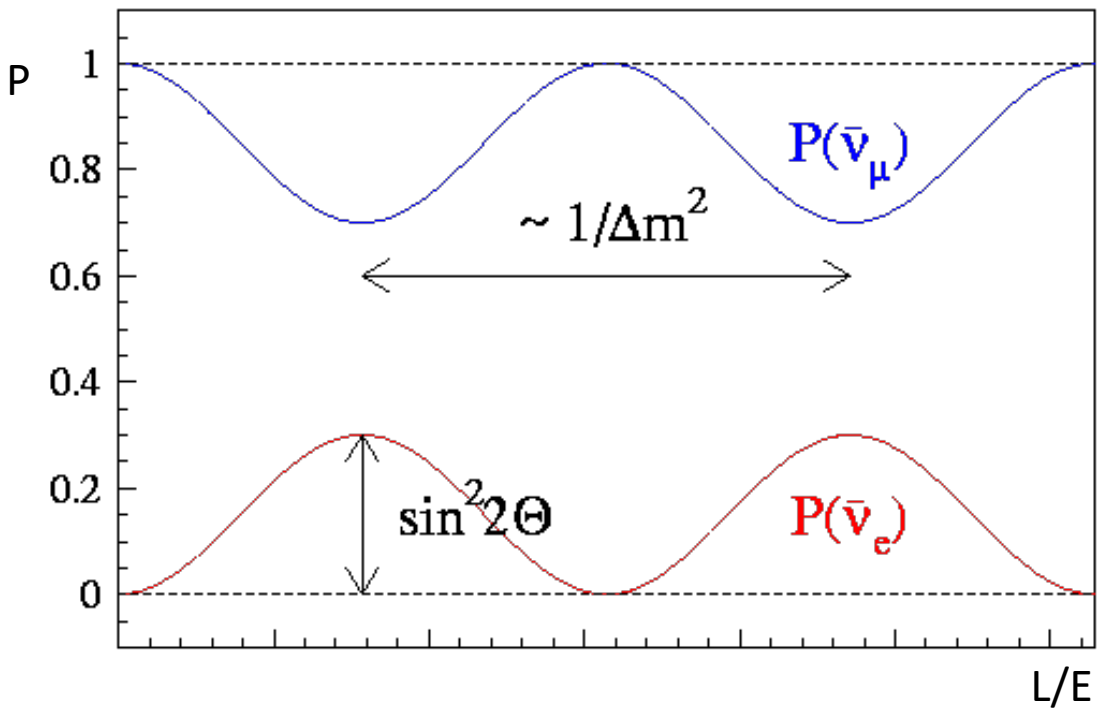


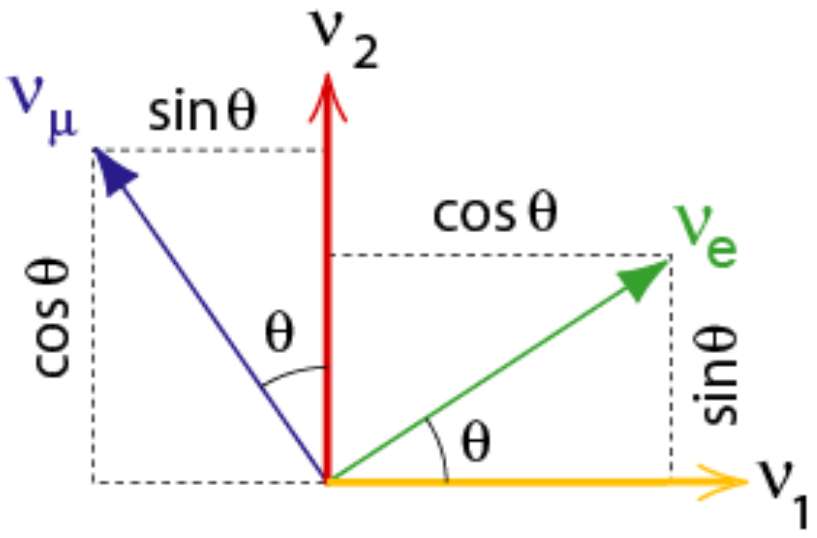
$$|\nu_e\rangle = U_{e1}\cdot|\nu_1\rangle + U_{e2}\cdot|\nu_2\rangle + U_{e3}\cdot|\nu_3\rangle$$

$$e^{-i\hat{H}t/\hbar}|\nu_e\rangle = U_{e1}\cdot e^{-i\hat{H}t/\hbar}|\nu_1\rangle + U_{e2}\cdot e^{-i\hat{H}t/\hbar}|\nu_2\rangle + U_{e3}\cdot e^{-i\hat{H}t/\hbar}|\nu_3\rangle$$

$$= U_{e1}\cdot e^{-iE_1t/\hbar}|\nu_1\rangle + U_{e2}\cdot e^{-iE_2t/\hbar}|\nu_2\rangle + U_{e3}\cdot e^{-iE_3t/\hbar}|\nu_3\rangle$$

Neutrino Oscillations (for 2 flavours)

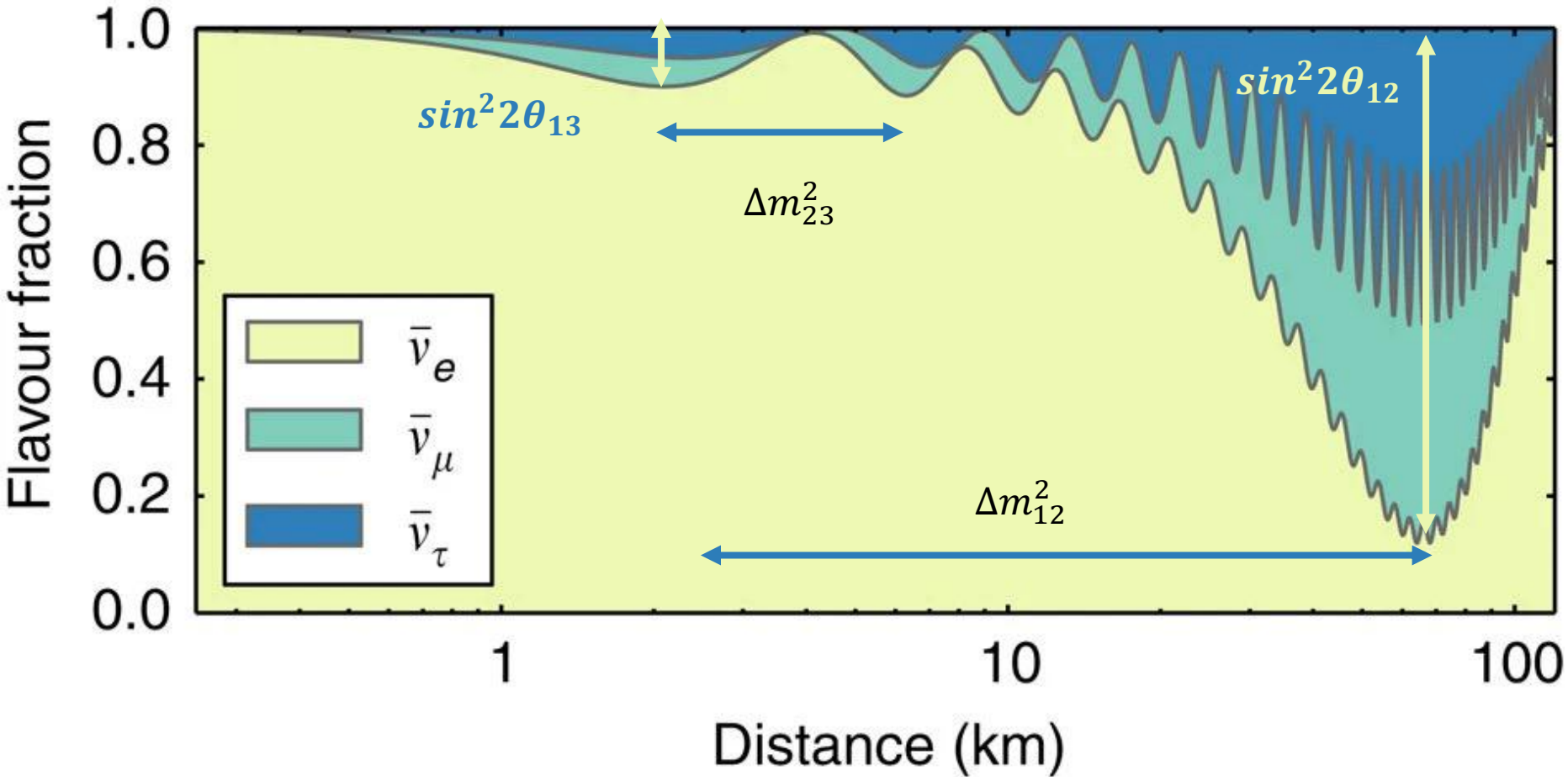


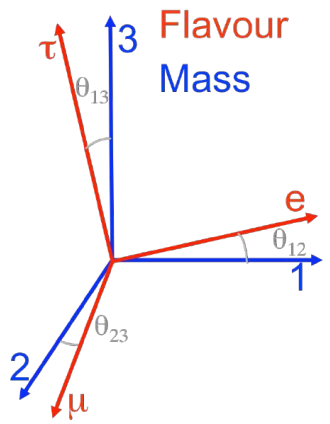


$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2(\Delta m^2 \cdot L_\nu / E_\nu)$$

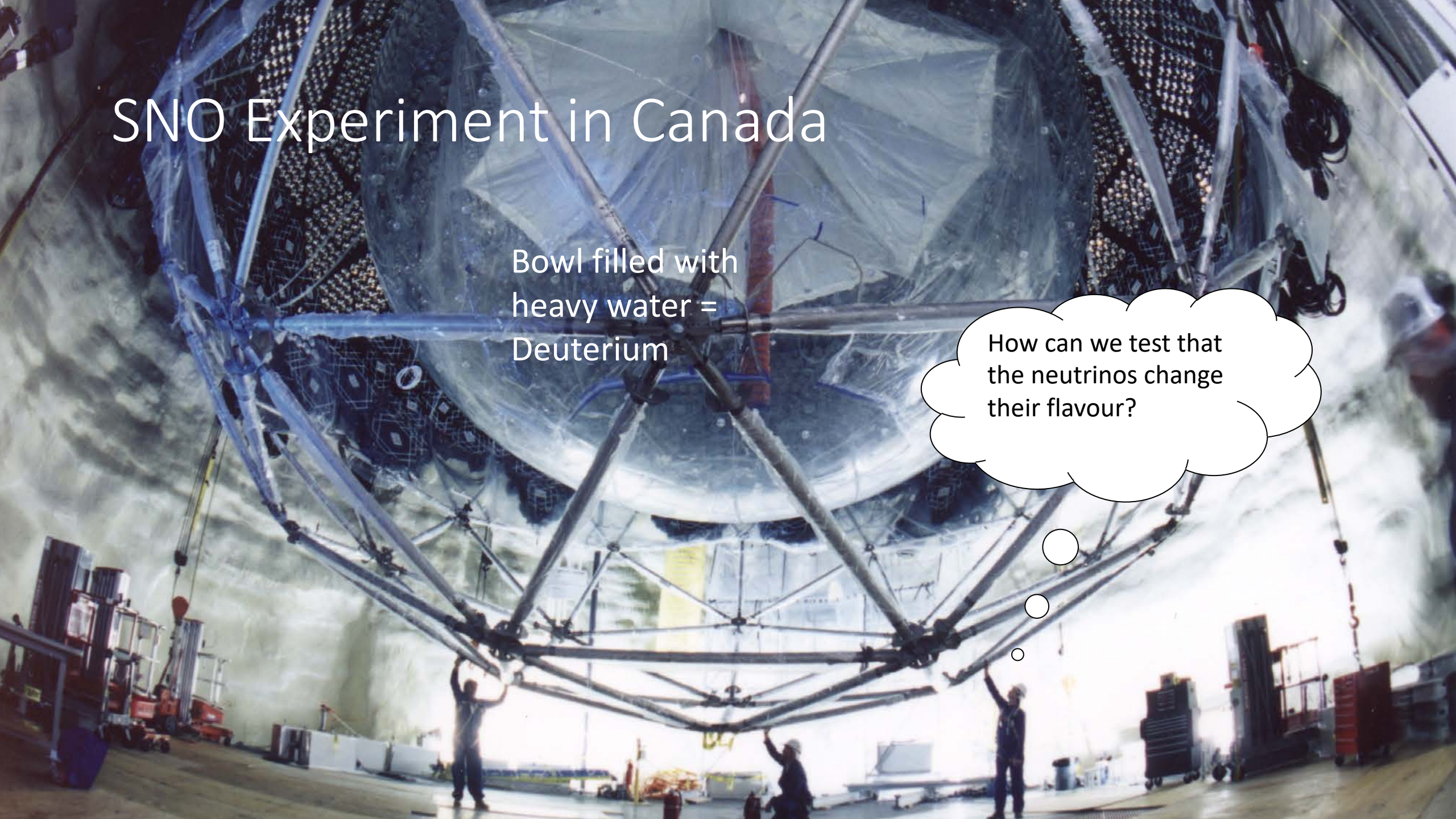
Amplitude Frequency

Neutrino Oscillations (for 3 flavours)





SNO Experiment in Canada

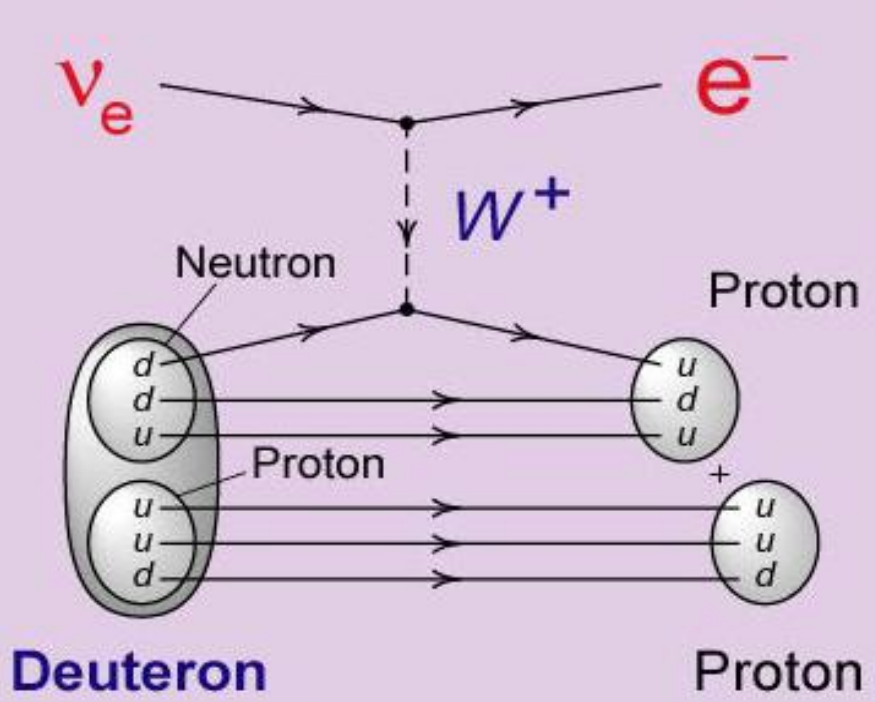


Bowl filled with heavy water = Deuterium

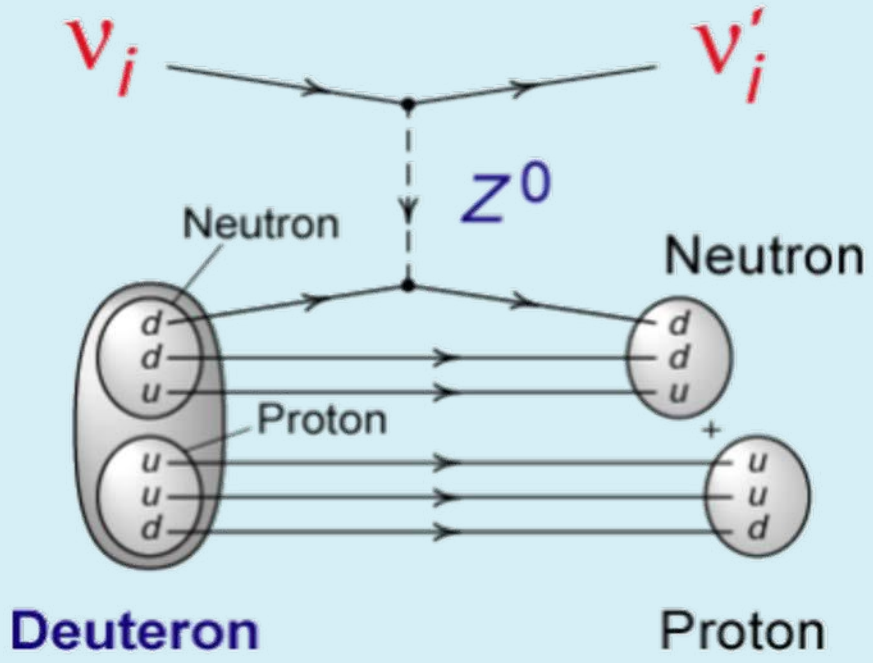
How can we test that the neutrinos change their flavour?

The Idea!

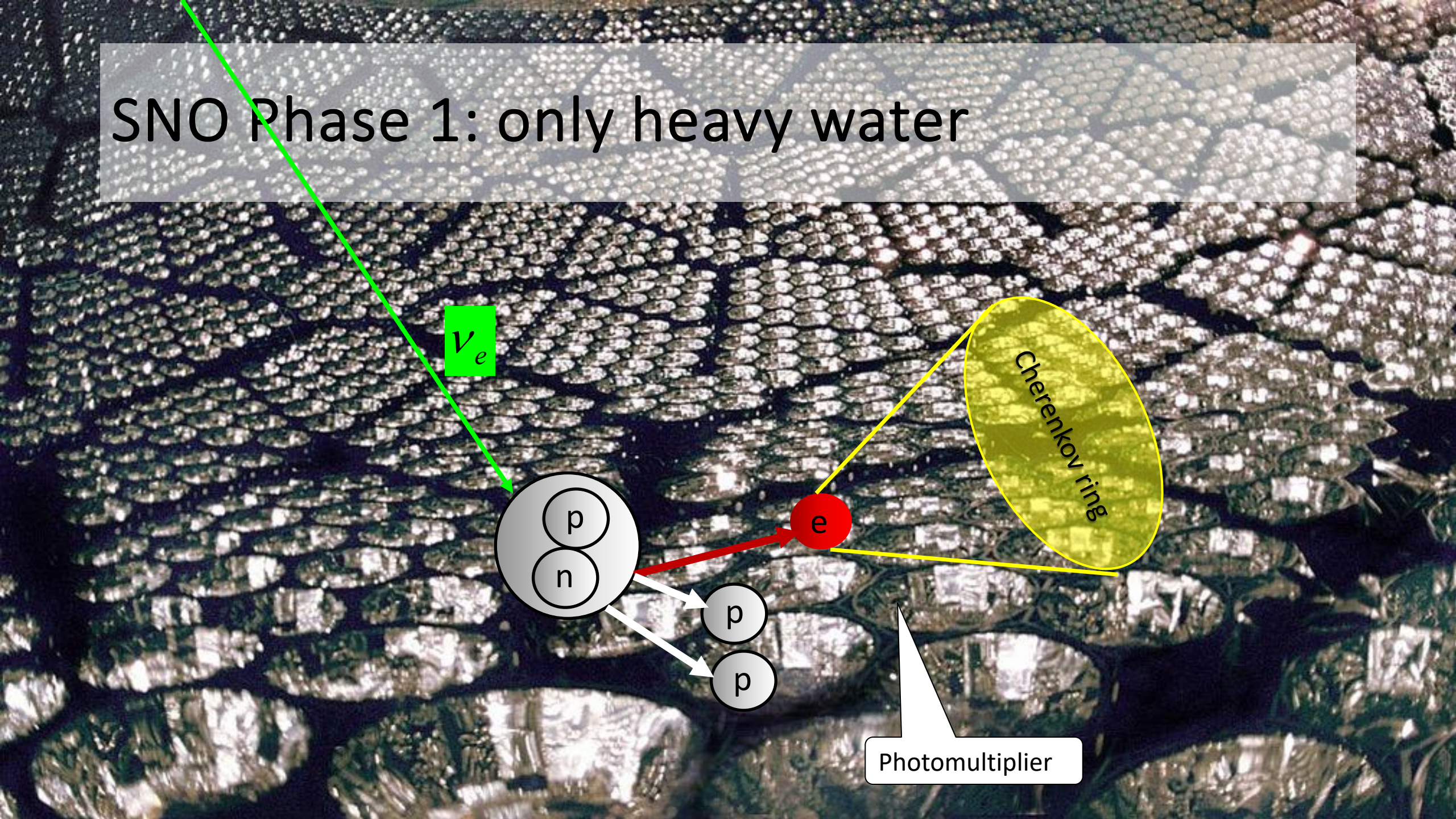
charged current (CC) → only electron flavour



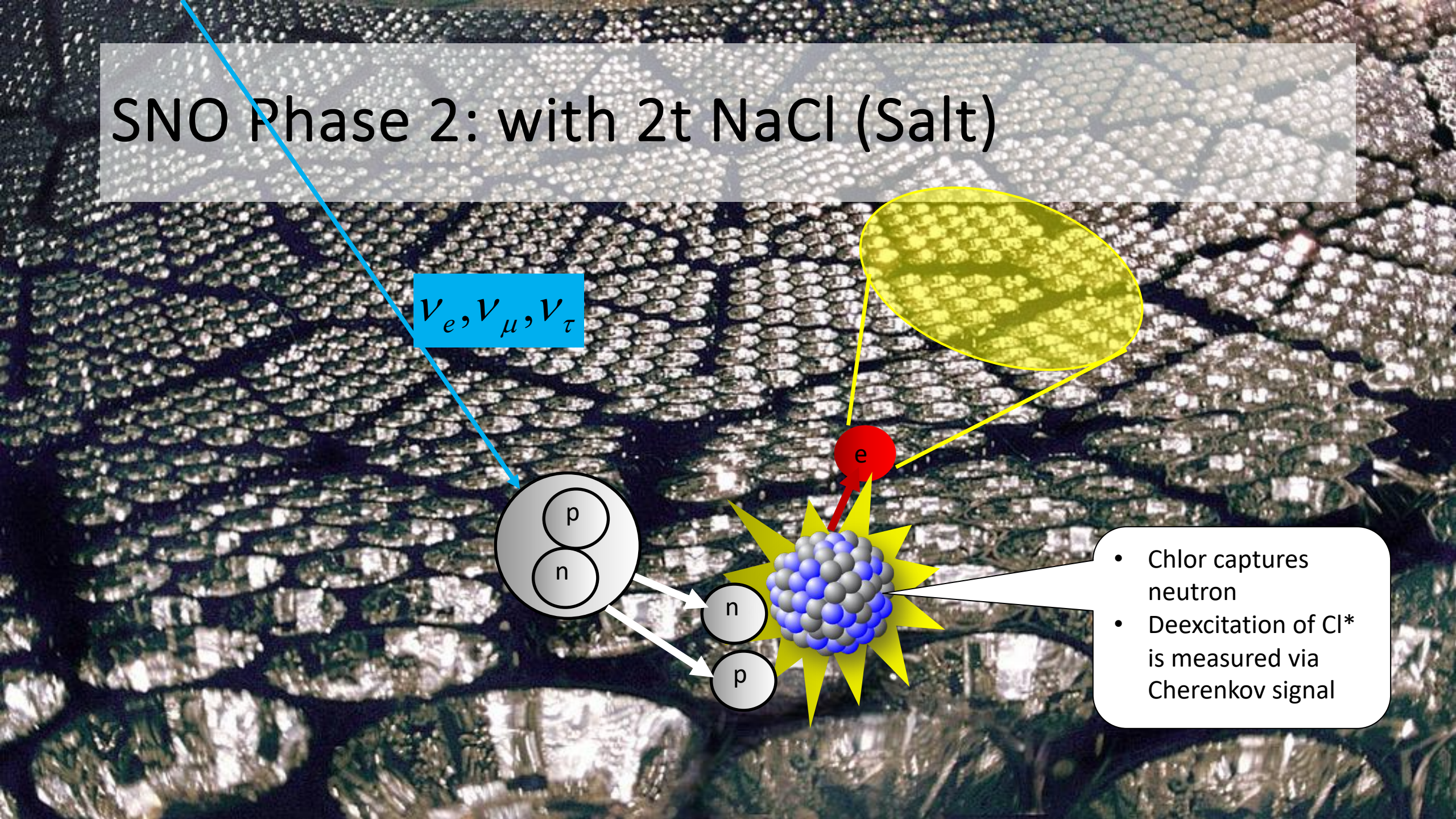
neutral current (NC) → all flavours



SNO Phase 1: only heavy water

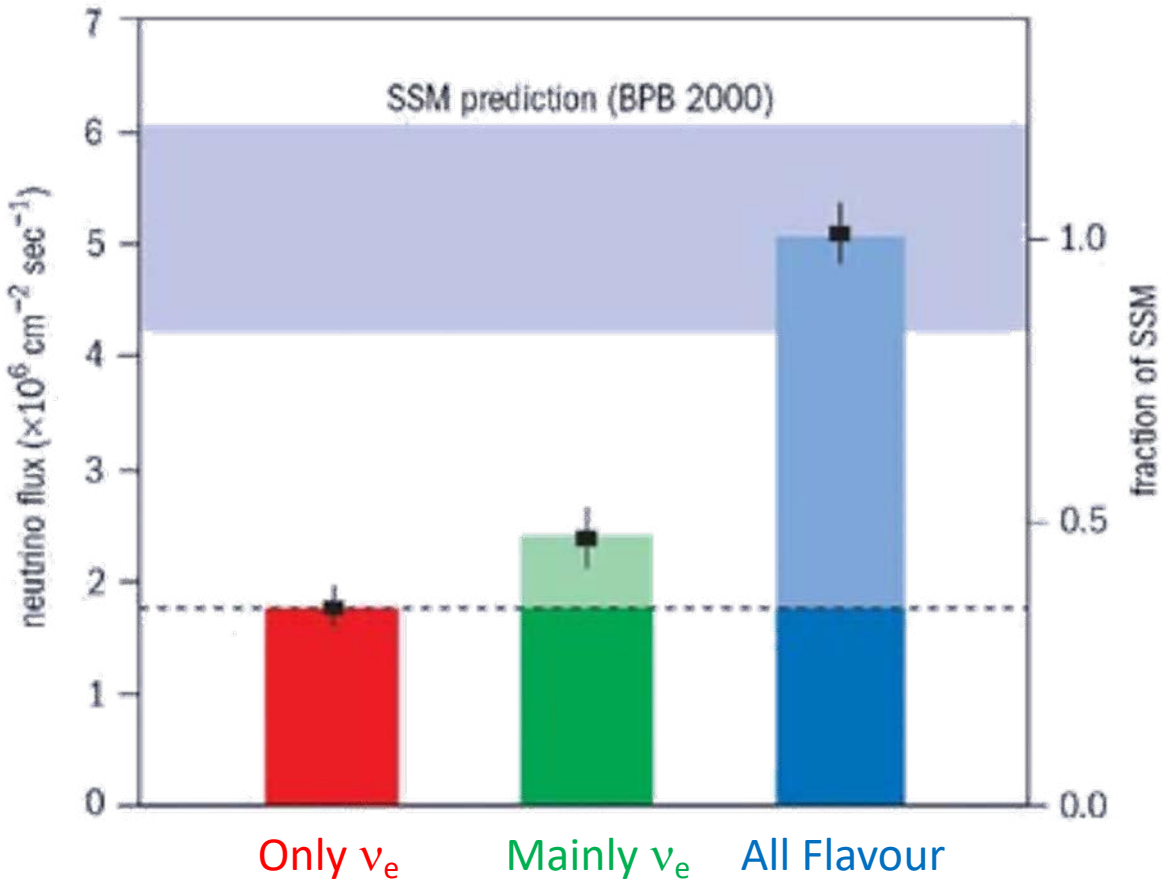


SNO Phase 2: with 2t NaCl (Salt)



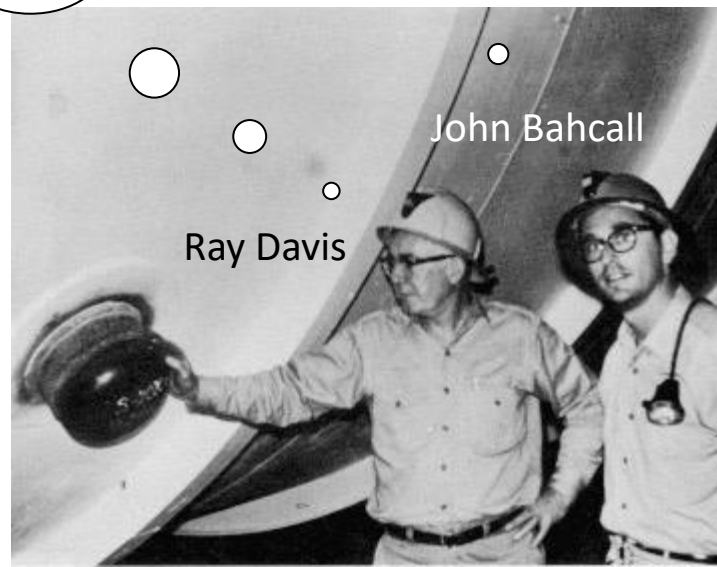
- Chlor captures neutron
- Deexcitation of Cl* is measured via Cherenkov signal

…and what did SNO find?



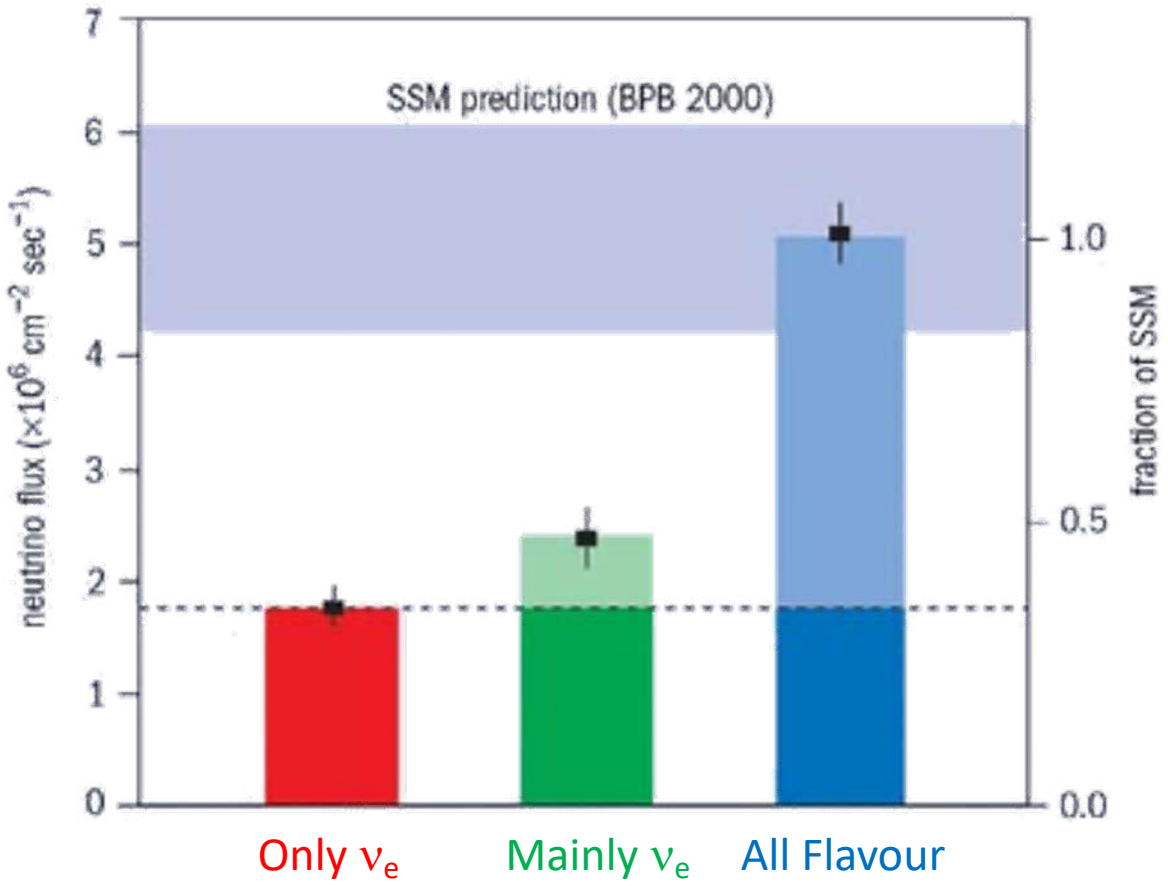
So my calculations were right…

… and my measurements, too



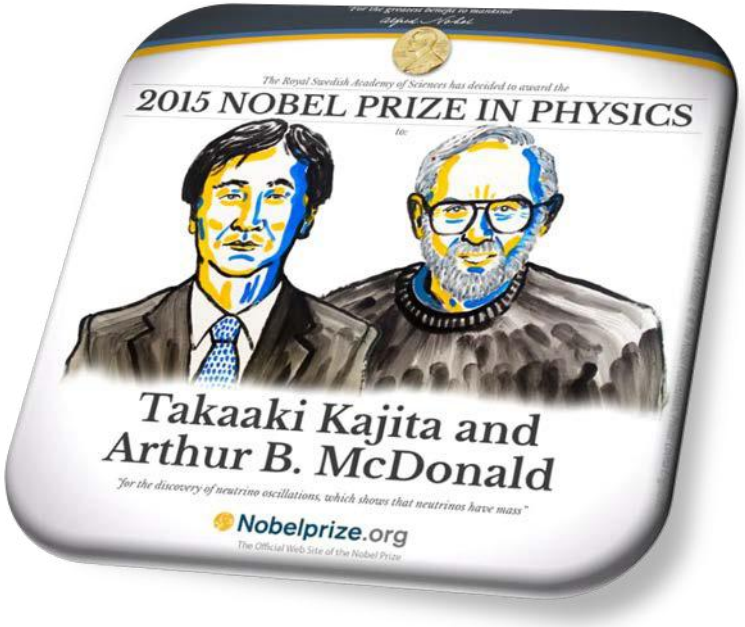
2001 (30 years later)…

…and what did SNO find?



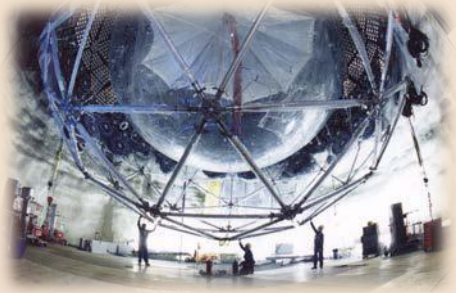
Takaaki Kajita and Arthur B. McDonald:

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

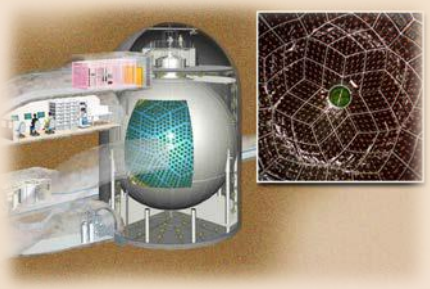


$\theta_{12} = 33\,°\,(\theta_{sol})$

SNO, Kanada
(Sun)



KamLAND, Japan
(Reactor)

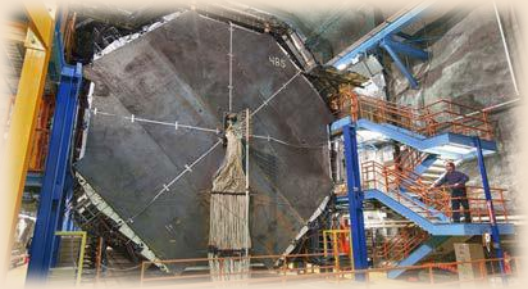


$$\Delta m_{21}^2 = 8 \cdot 10^{-5}\,\mathrm{eV}^2\ (\Delta m_{sol}^2)$$

$\theta_{23} = 45\,°\,(\theta_{atm})$

Super Kamokande, Japan (Atmosphere)
T2K, (Accelerator)

Minos, USA
(Accelerator)



$$\Delta m_{32}^2 \approx \Delta m_{31}^2 = (\pm)\ 2.5 \cdot 10^{-3}\,\mathrm{eV}^2\ (\Delta m_{atm}^2)$$

$\theta_{13} = 9\,°$

Double Chooz, FR
(Reactor)

Daya Bay, China
(Reactor)

RENO, Korea
(Reactor)

Questions for today

How do we know neutrinos exist?

- Postulation by Pauli in 1930 (continuous beta decay spectrum)
- Experimental discovery in 1956 (reactor neutrinos, inverse beta decay)

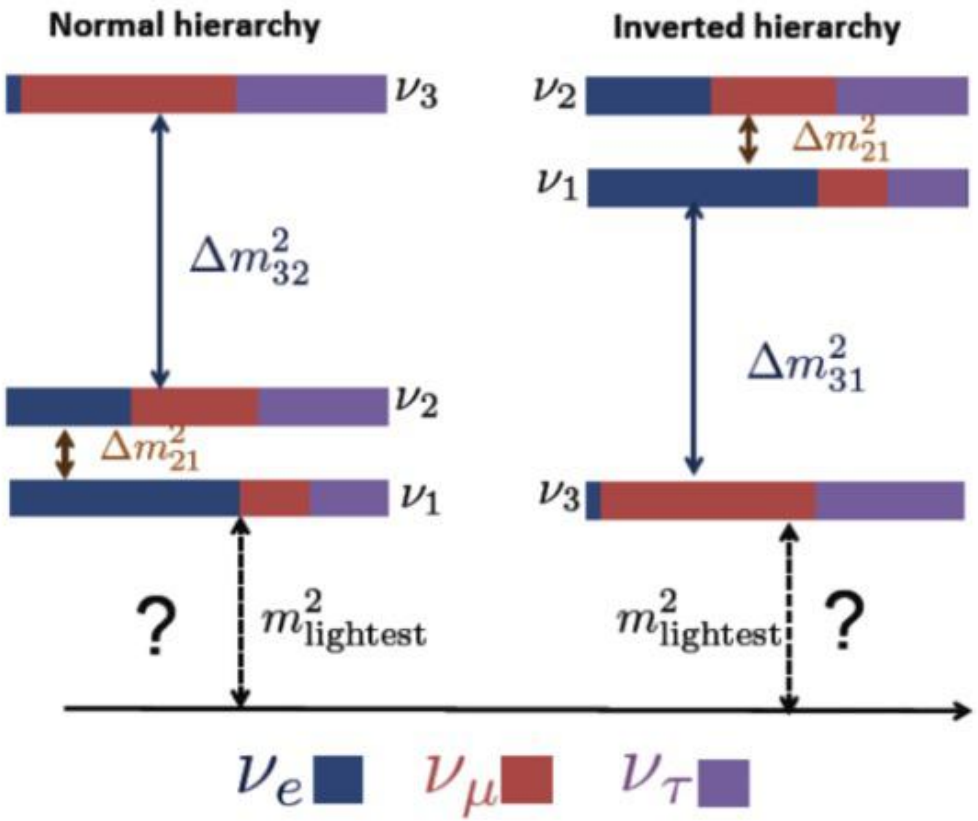
How do we know neutrinos have a mass?

- Solar (+atmospheric) neutrino problem
- Discovery of neutrino oscillations
- Senstive to mass squared difference

Which properties of neutrinos are still unknown?

Are there more than three neutrinos?

What we know, and don't know…



- At least two neutrinos have a mass
- $\Delta m^2_{21} = 8 \cdot 10^{-5}$ eV², $\Delta m^2_{31} = 2.5 \cdot 10^{-3}$eV²
- ν_1 is lighter than ν_2 (matter effects)

- How are the neutrinos masses ordered?
- Do neutrinos violate CP?
- Are there more than three neutrinos?
- What is the mass of the lightest neutrino?
- Is the neutrino its own antiparticle?

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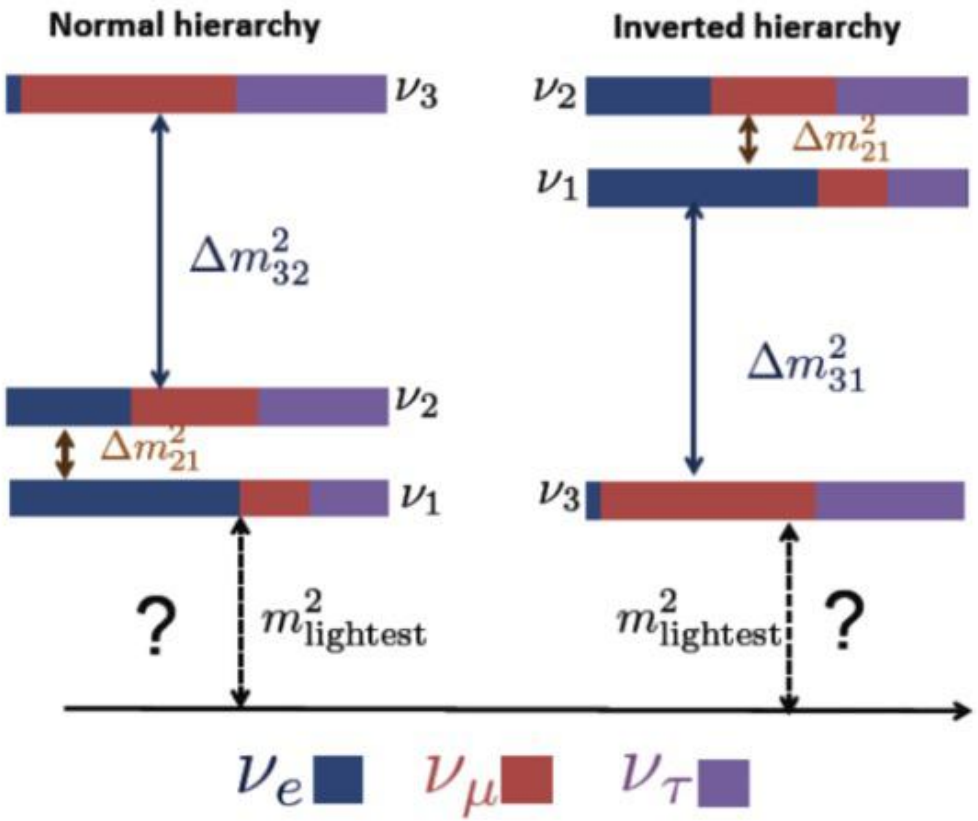

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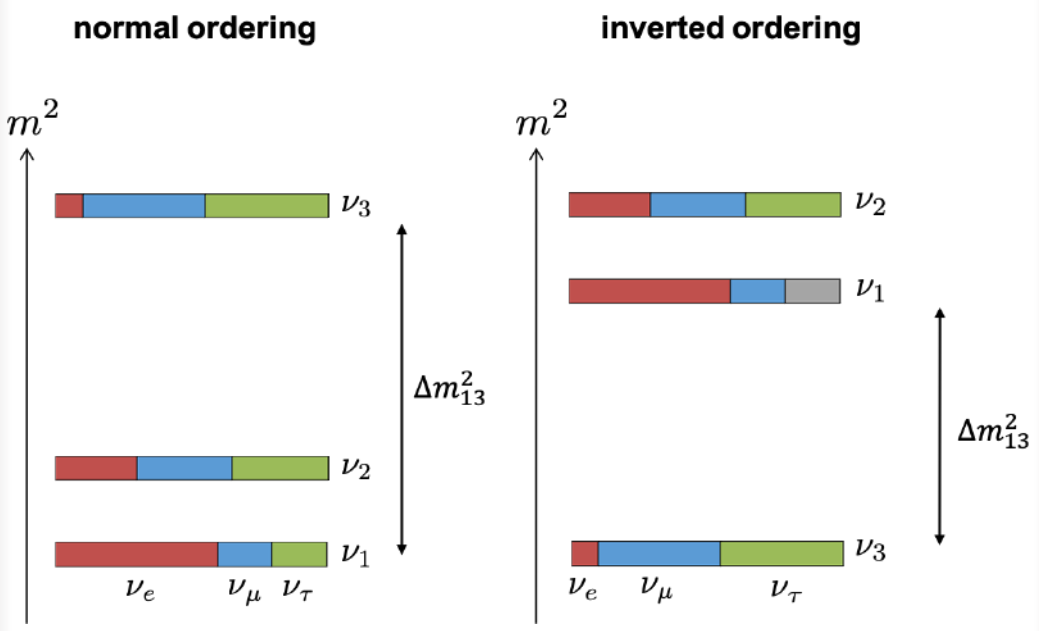
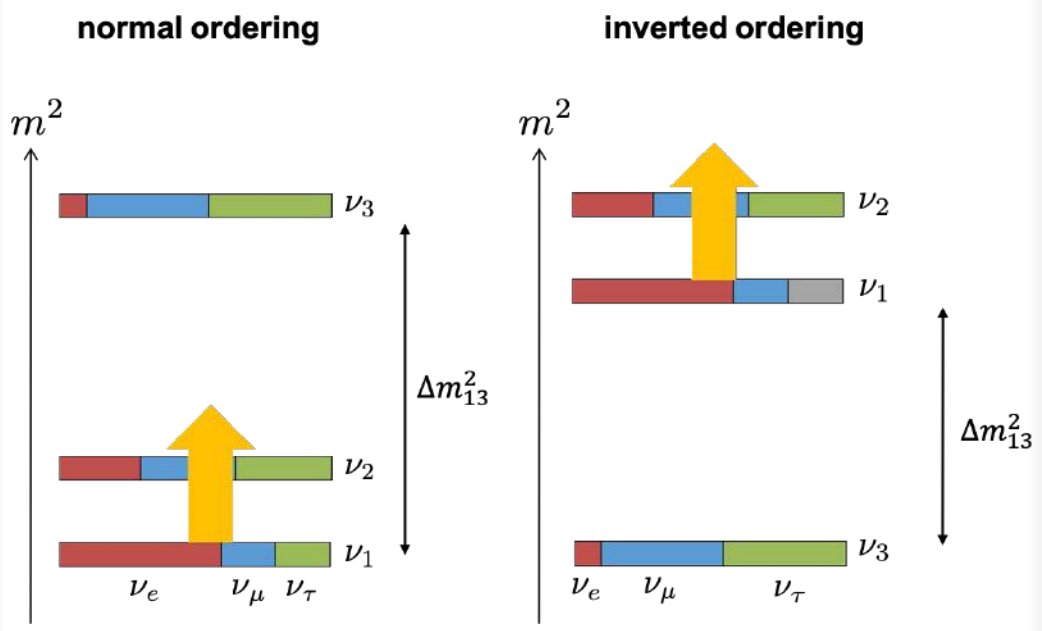
Two ways to resolve the ordering

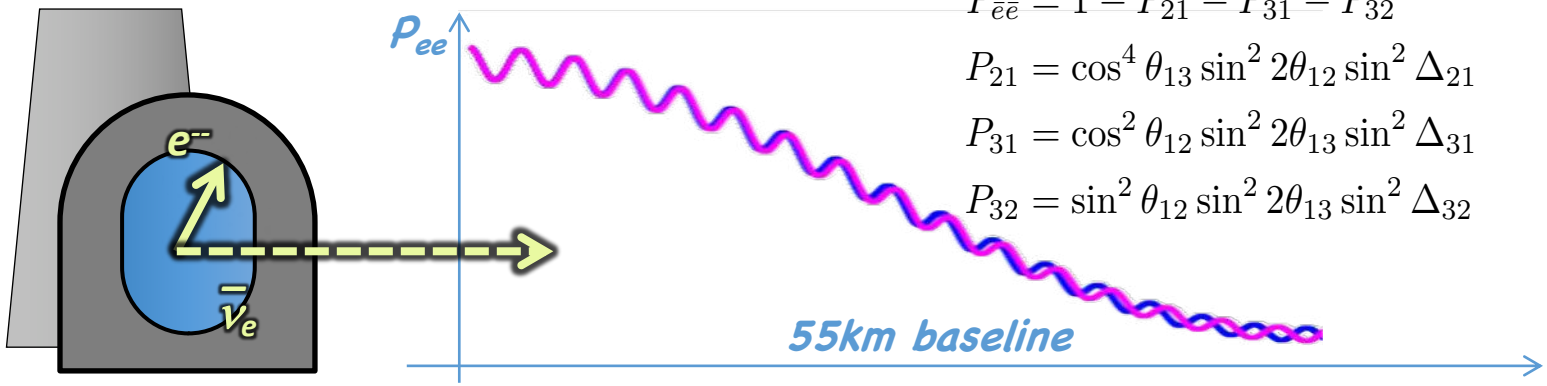
Precision



Matter effects



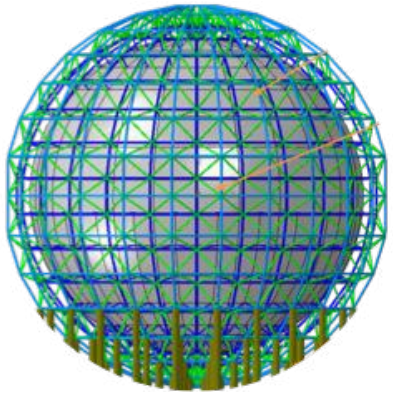
Neutrino ordering



neutrino source:
only $\bar{\nu}_e$ created

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$P_{31} = \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$
$$P_{32} = \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{32}$$

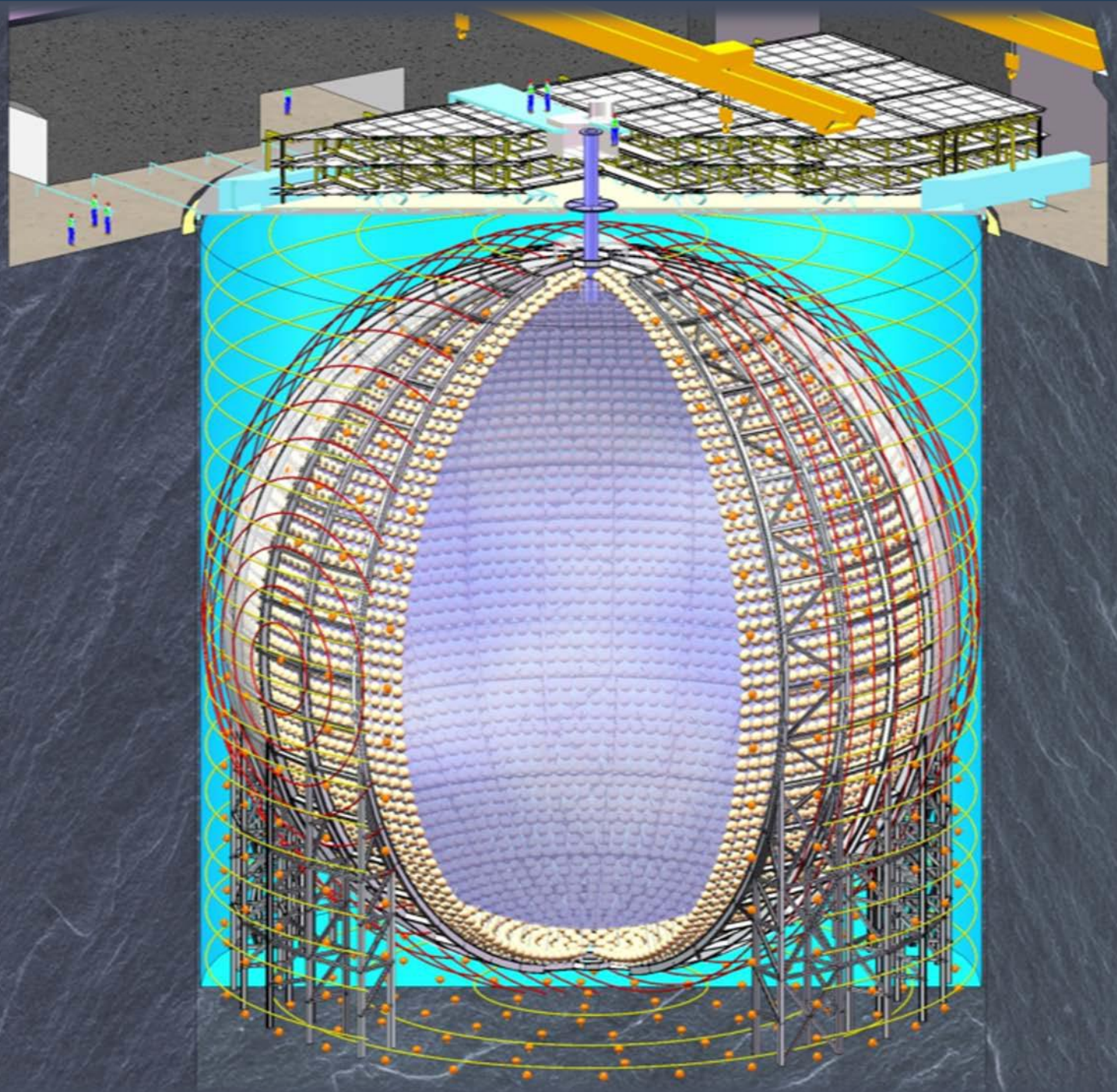
JUNO



- Reactor neutrino oscillation → simplification: $\Delta m^2_{13} \approx \Delta m^2_{23}$
- But in reality: The oscillation frequency is slightly different for normal and inverted ordering

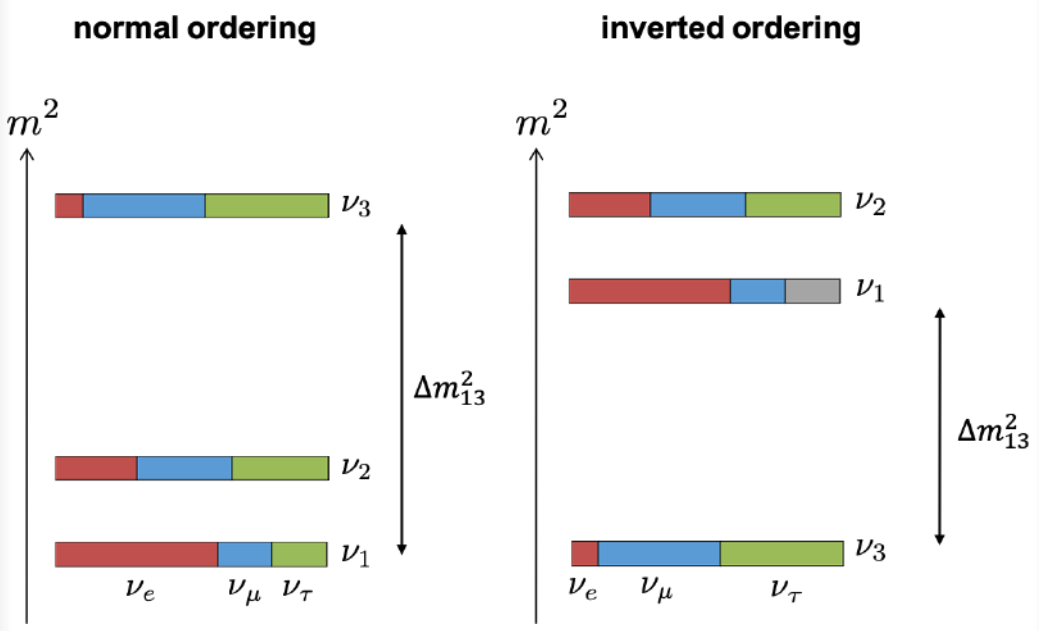
JUNO

- Experiment in China
- Detection of reactor neutrinos with large underground detector
- 35 m diameter, 20 000 tons of liquid scintillator, 15 000 PMTs
- Starts data taking soon

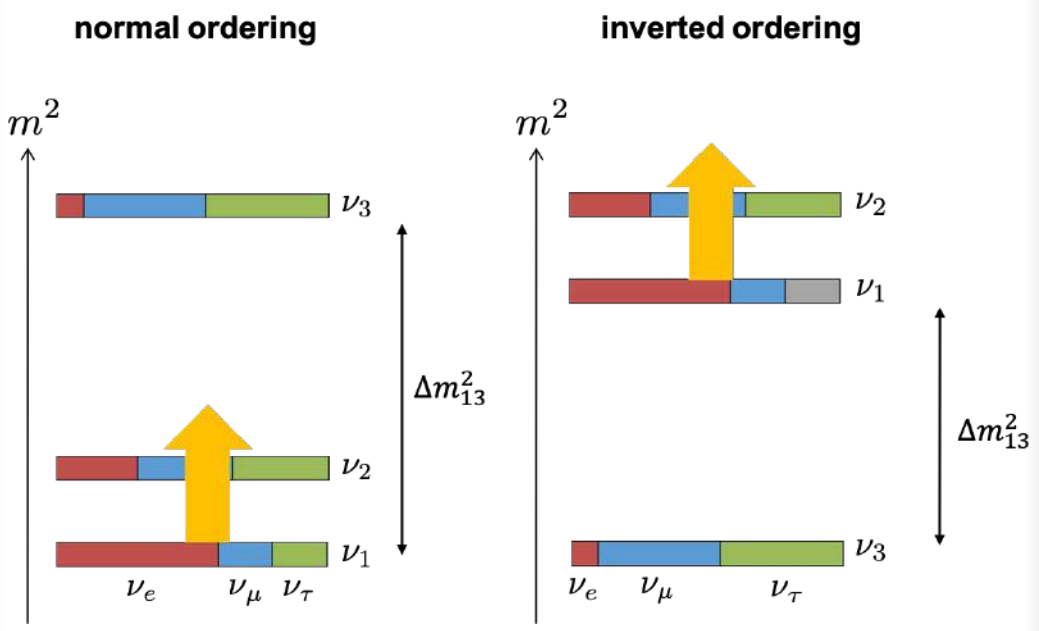


Two ways to resolve the hierarchy

Precision

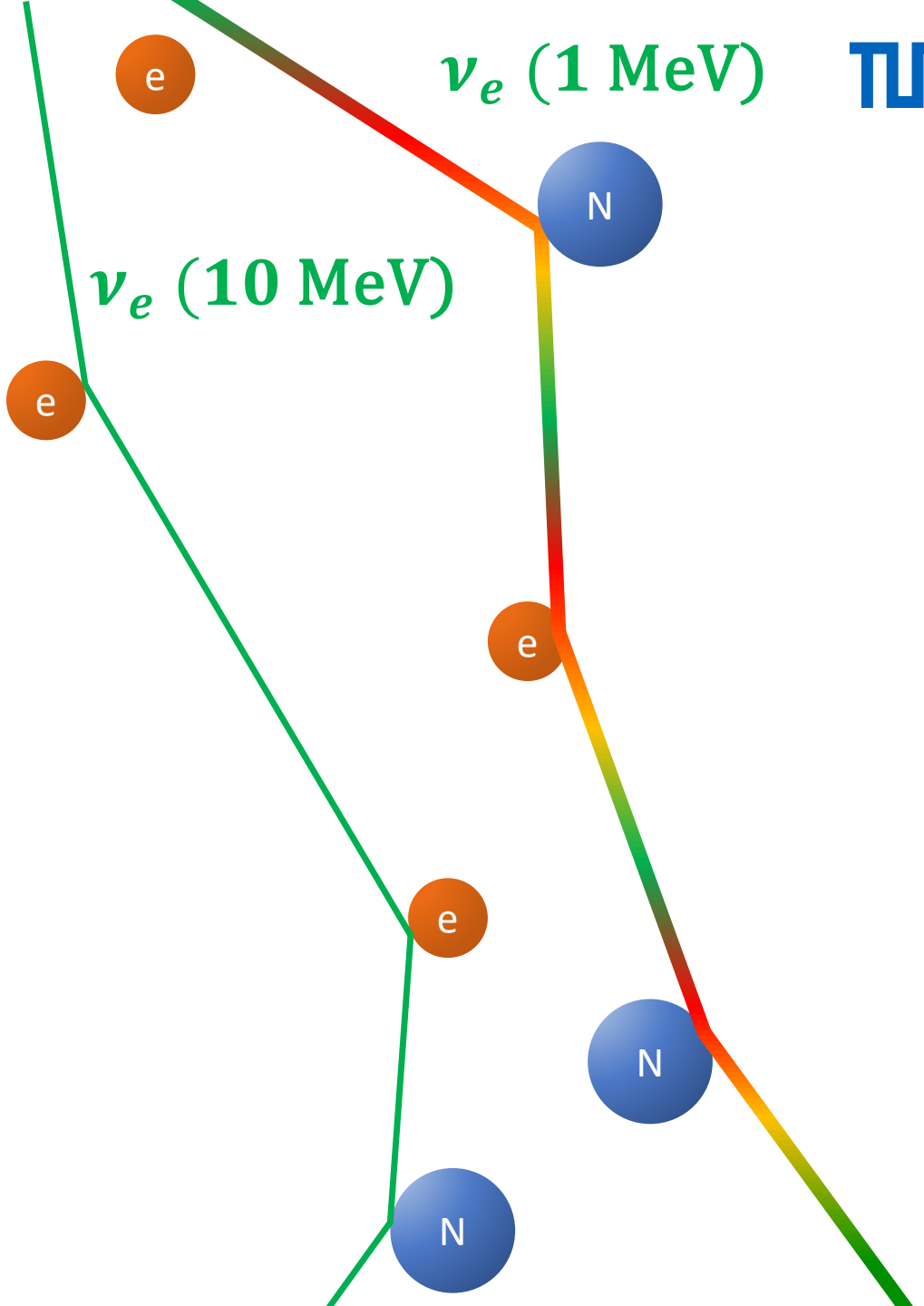


Matter effects



Matter effects

$$P(\nu_\mu \to \nu_e)$$
$$= \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L_\nu}{E_\nu}\right)$$



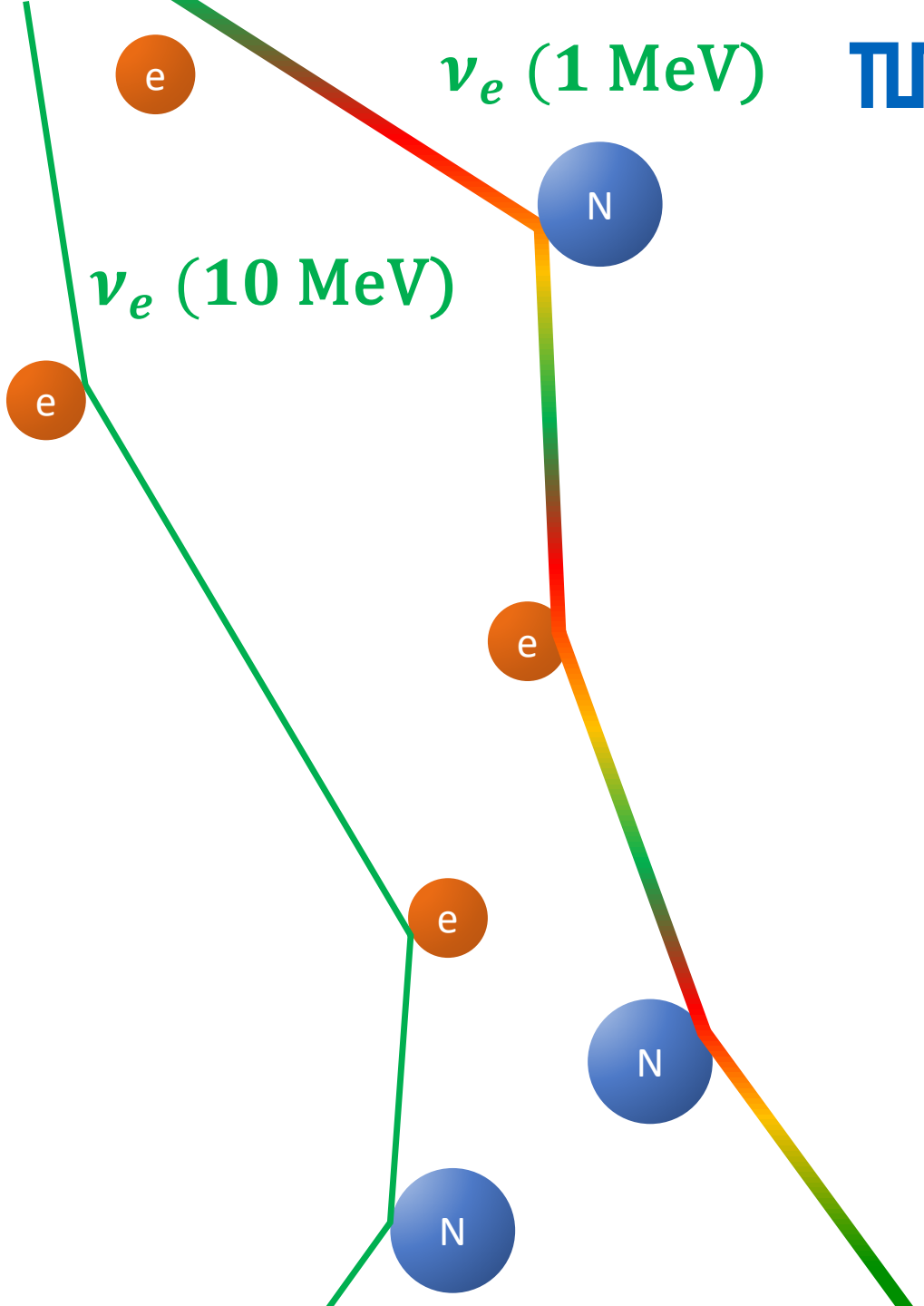
Matter effects

Small energies (1 MeV):

- The oscillation length is shorter than the mean free path
- Neutrino changes its flavor before it interacts
- Matter effects don't matter

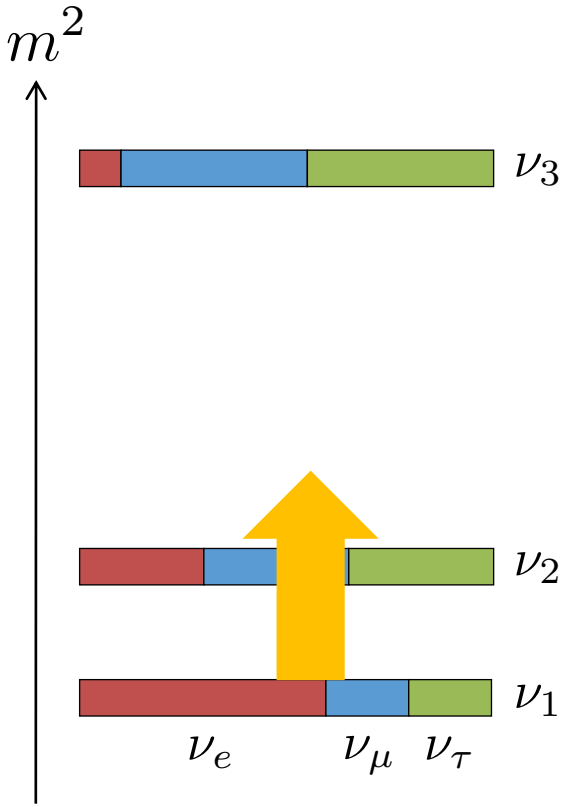
Large energies (10 MeV):

- Oscillation length larger than mean free path
- Neutrino interacts before it oscillates
- Neutrino stays in electron flavor eigenstate
  (electron flavor eigenstate = effective mass eigenstate)
- Matter effects matter

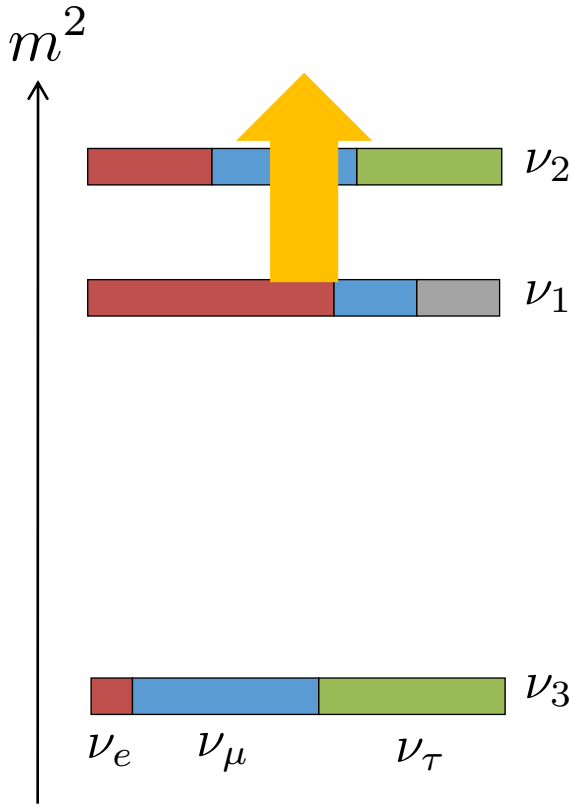


Neutrino ordering – matter effects

normal ordering

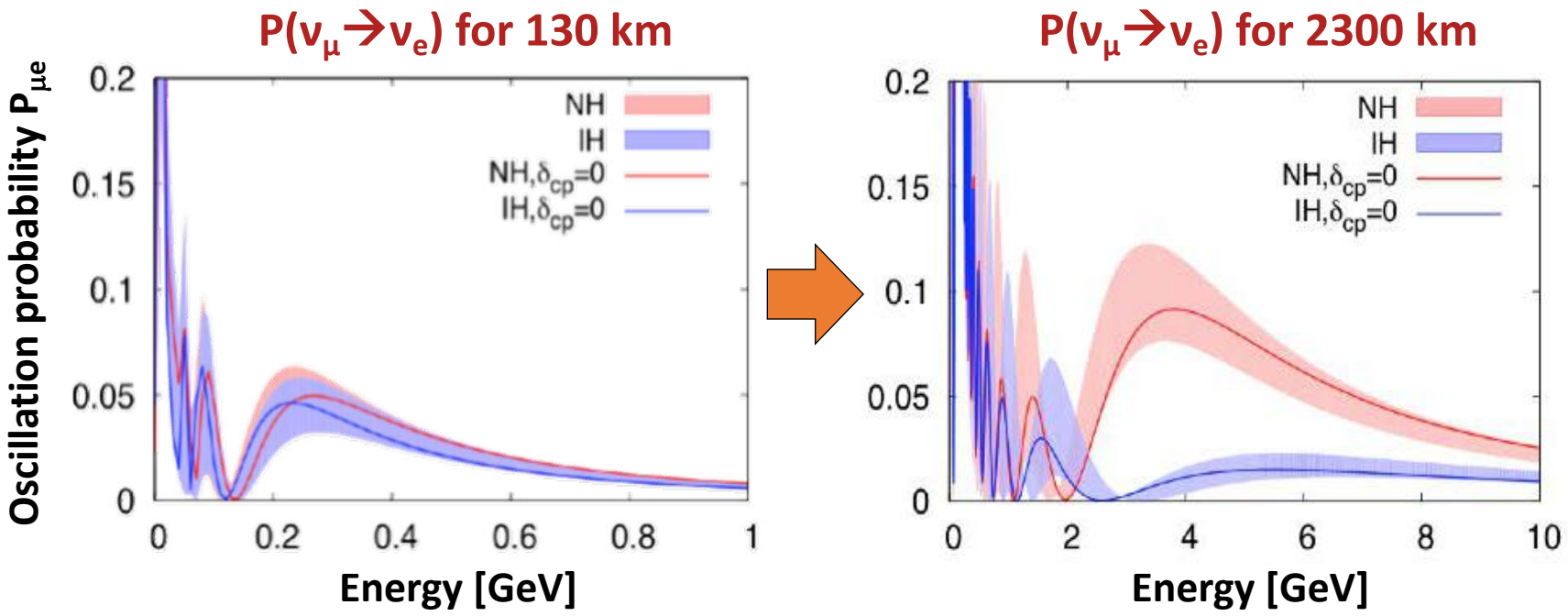


inverted ordering



Signature of mass hierarchy

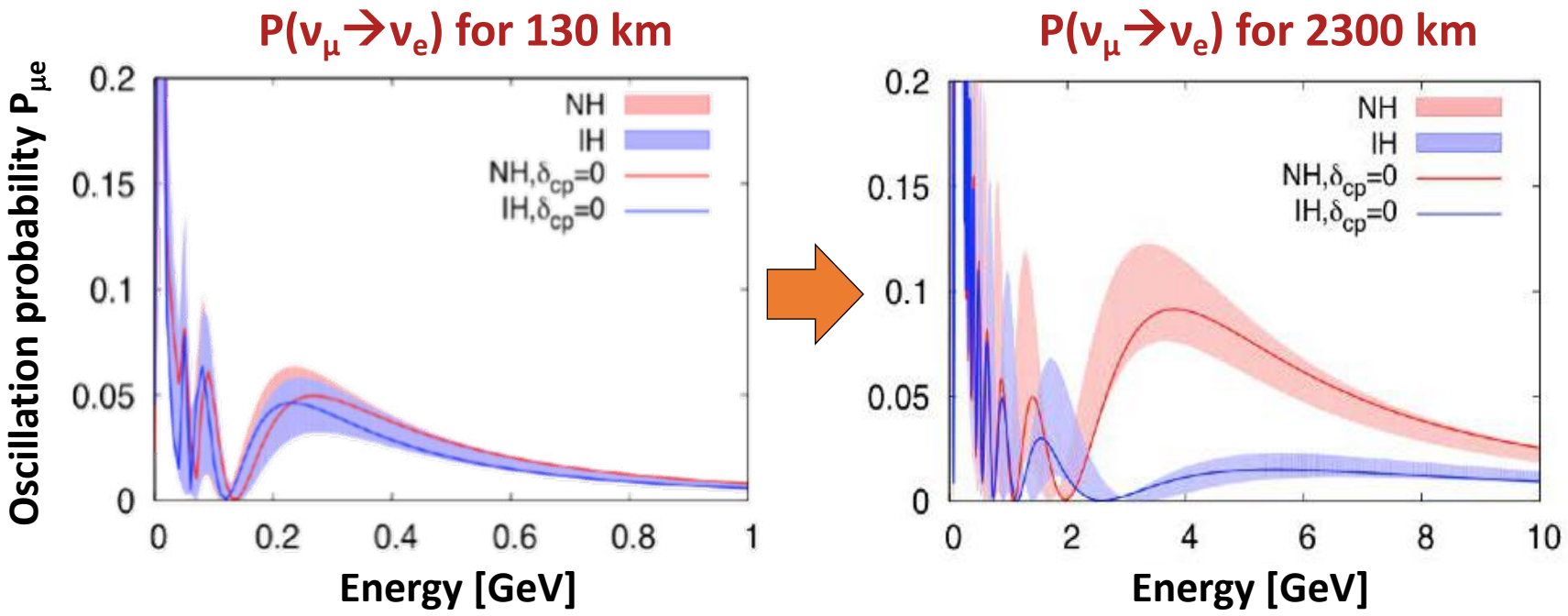
$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L_\nu}{E_\nu}\right)$$



- Why is the signal more prominent for longer baseline?

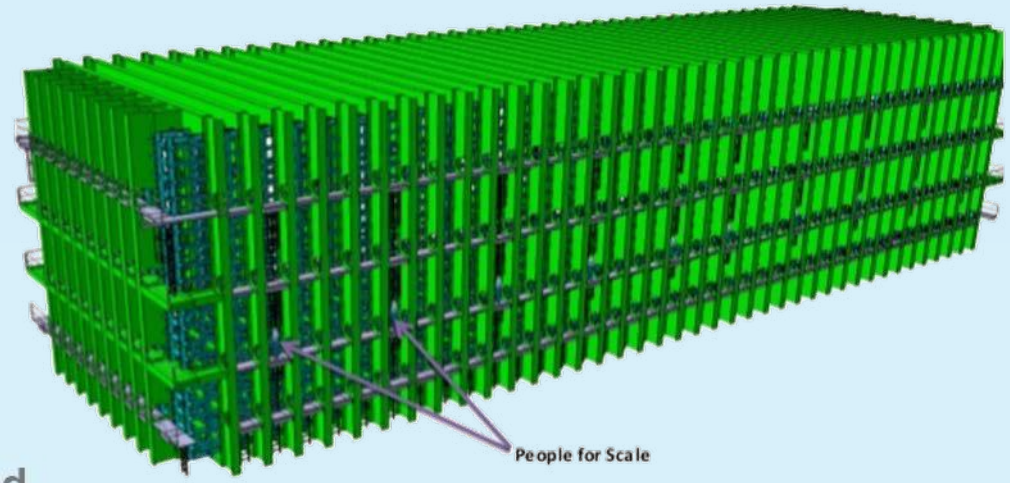
Signature of mass hierarchy

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2 \cdot L_\nu}{E_\nu}\right)$$

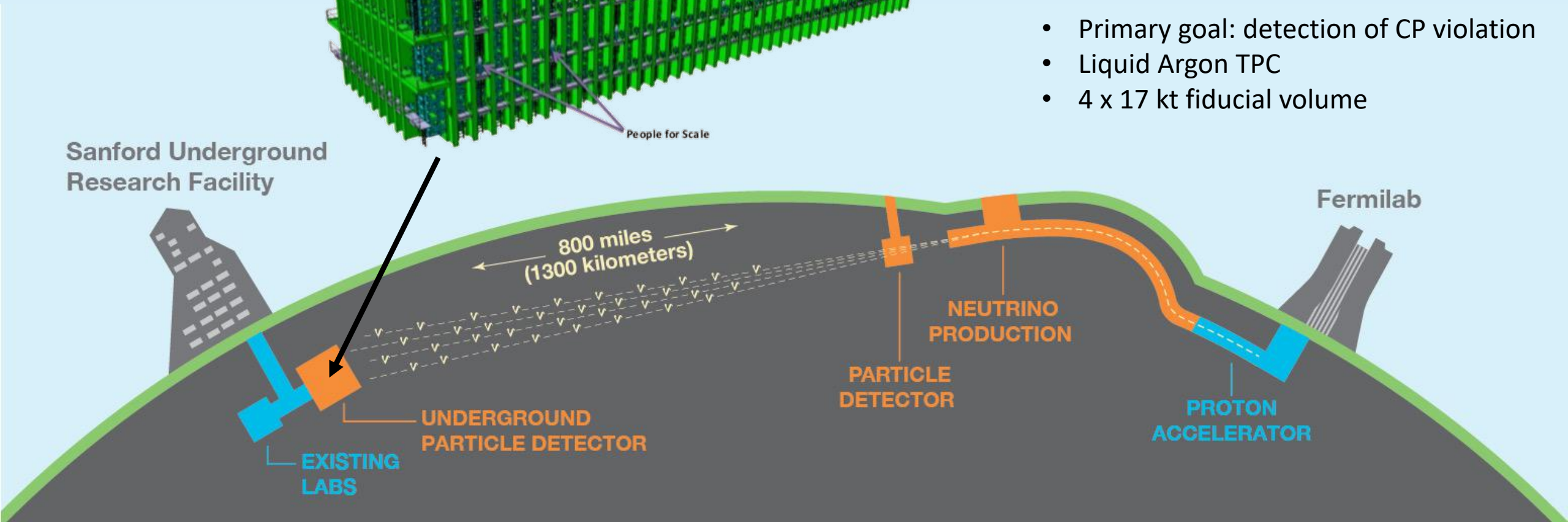


- Longer baseline → larger energy (to be at the oscillation maximum) → larger matter effect!

The DUNE experiment



- Primary goal: detection of CP violation
- Liquid Argon TPC
- 4 x 17 kt fiducial volume



Questions for today

How do we know neutrinos exist?

- Postulation by Pauli in 1930 (continuous beta decay spectrum)
- Experimental discovery in 1956 (reactor neutrinos, inverse beta decay)

How do we know neutrinos have a mass?

- Solar (+atmospheric) neutrino problem
- Discovery of neutrino oscillations
- Senstive to mass squared difference

Which properties of neutrinos are still unknown?

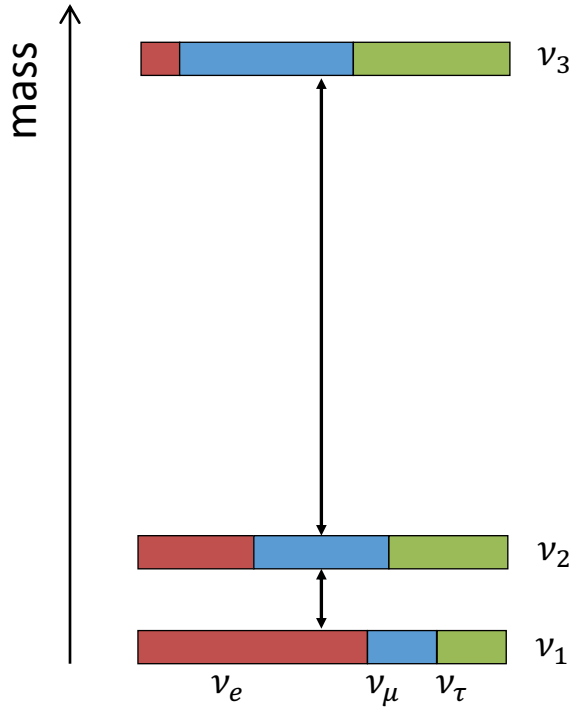
- Mass ordering
- CP violation
- Important experiments: DUNE, JUNO, Hyper-K, IceCube

Are there more than three neutrinos?

Sterile neutrinos

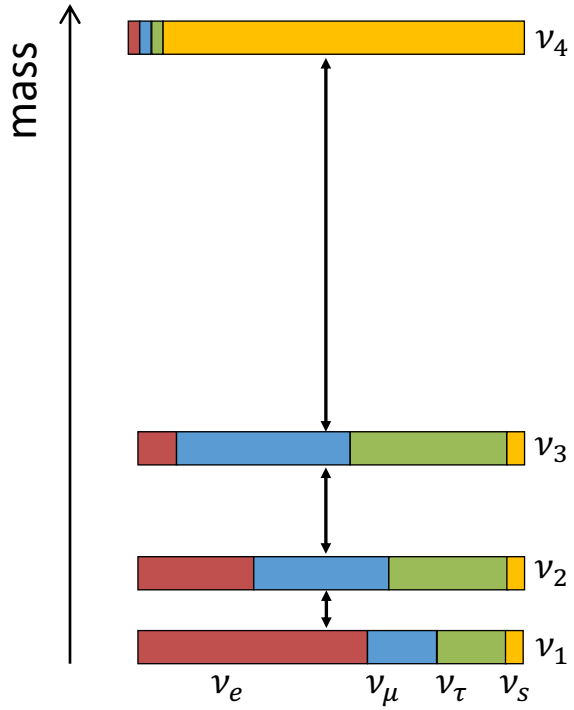
This is what we call „sterile“ neutrino

Active neutrinos: 3x3 PMNS matrix



$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{1e} & U_{1\mu} & U_{1\tau} \\ U_{2e} & U_{2\mu} & U_{2\tau} \\ U_{3e} & U_{3\mu} & U_{3\tau} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Sterile neutrinos: 4x4 PMNS matrix

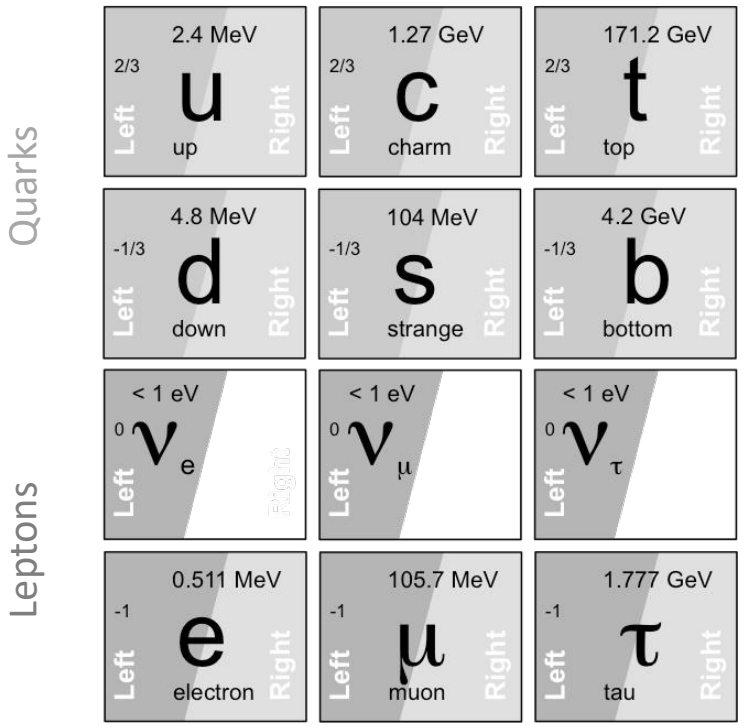


$$\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix} = \begin{pmatrix} U_{1e} & U_{1\mu} & U_{1\tau} & U_{1s} \\ U_{2e} & U_{2\mu} & U_{2\tau} & U_{2s} \\ U_{3e} & U_{3\mu} & U_{3\tau} & U_{3s} \\ U_{4e} & U_{4\mu} & U_{4\tau} & U_{4s} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix}$$

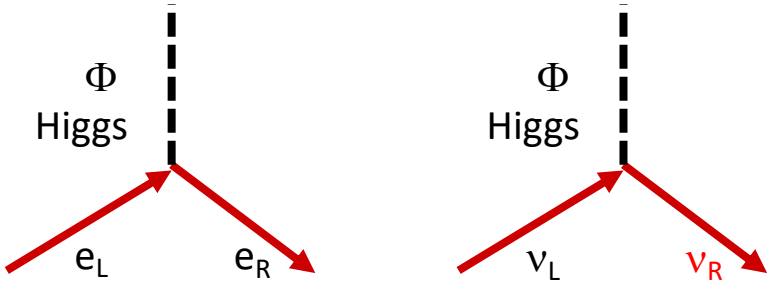
Large
Small

Right-handed neutrino

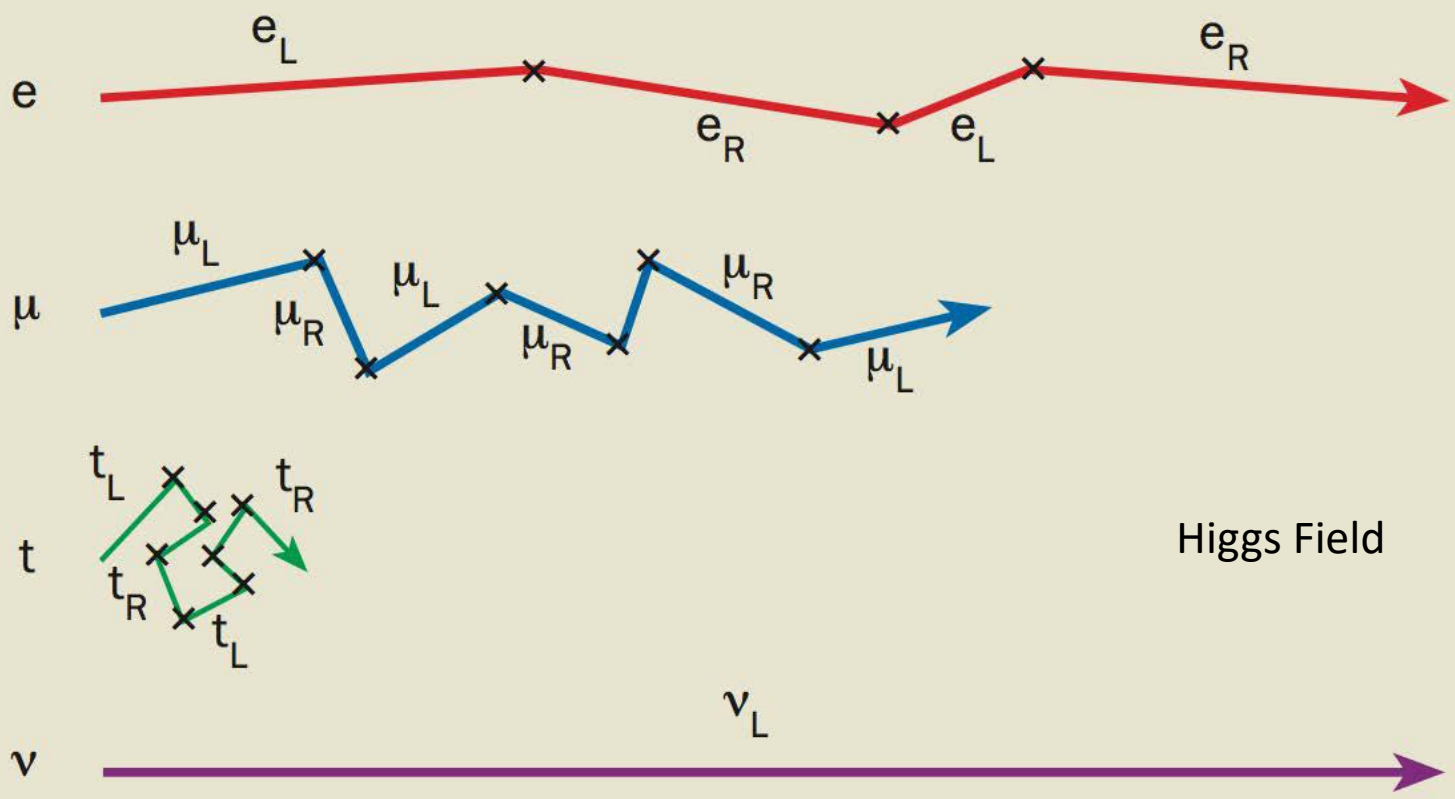
Standard Model (SM)



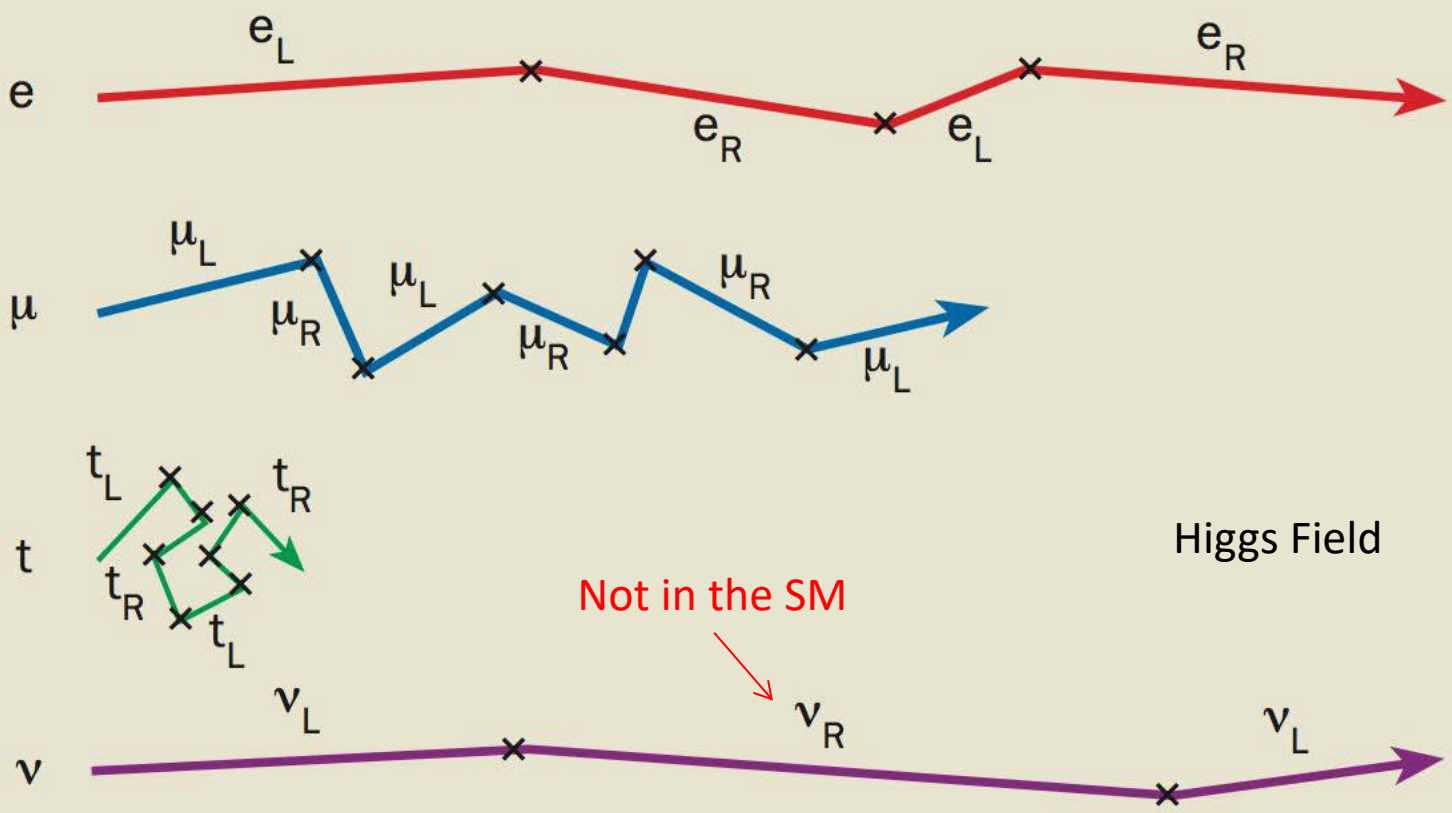
- The Higgs transforms left- to right-handed chirality



No neutrino mass in the SM

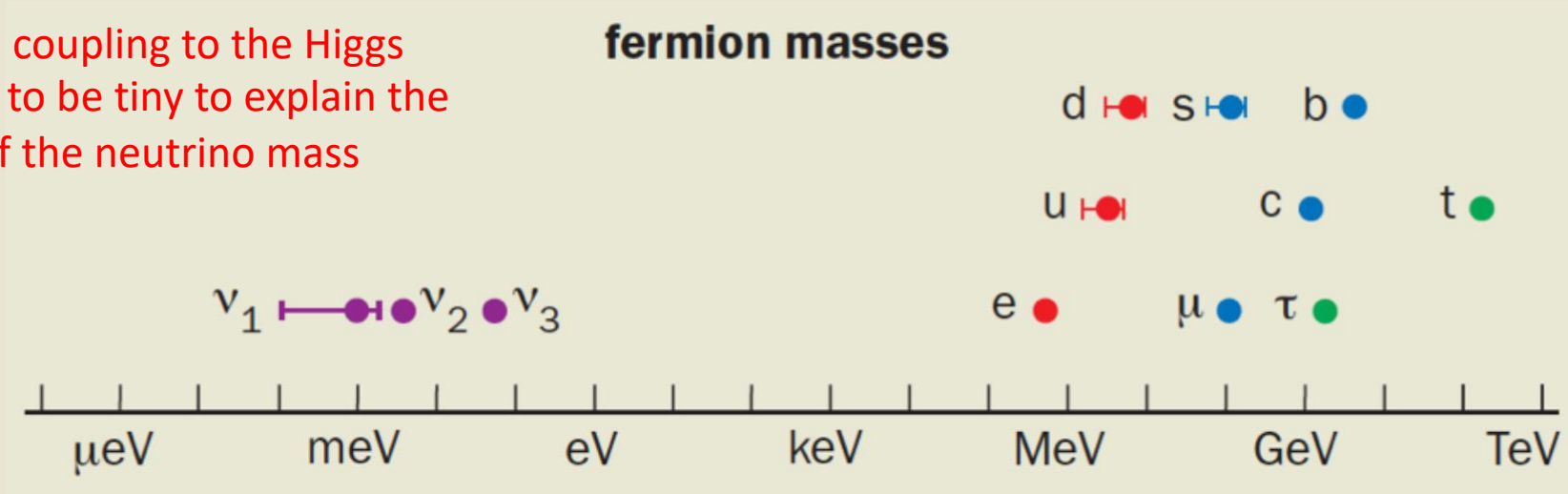


Adding a right-handed neutrino

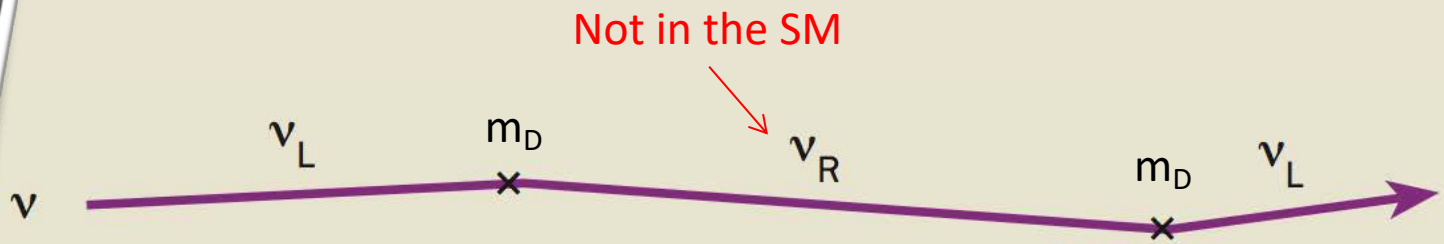


Dirac neutrino mass

The Yukawa coupling to the Higgs would have to be tiny to explain the smallness of the neutrino mass



Dirac



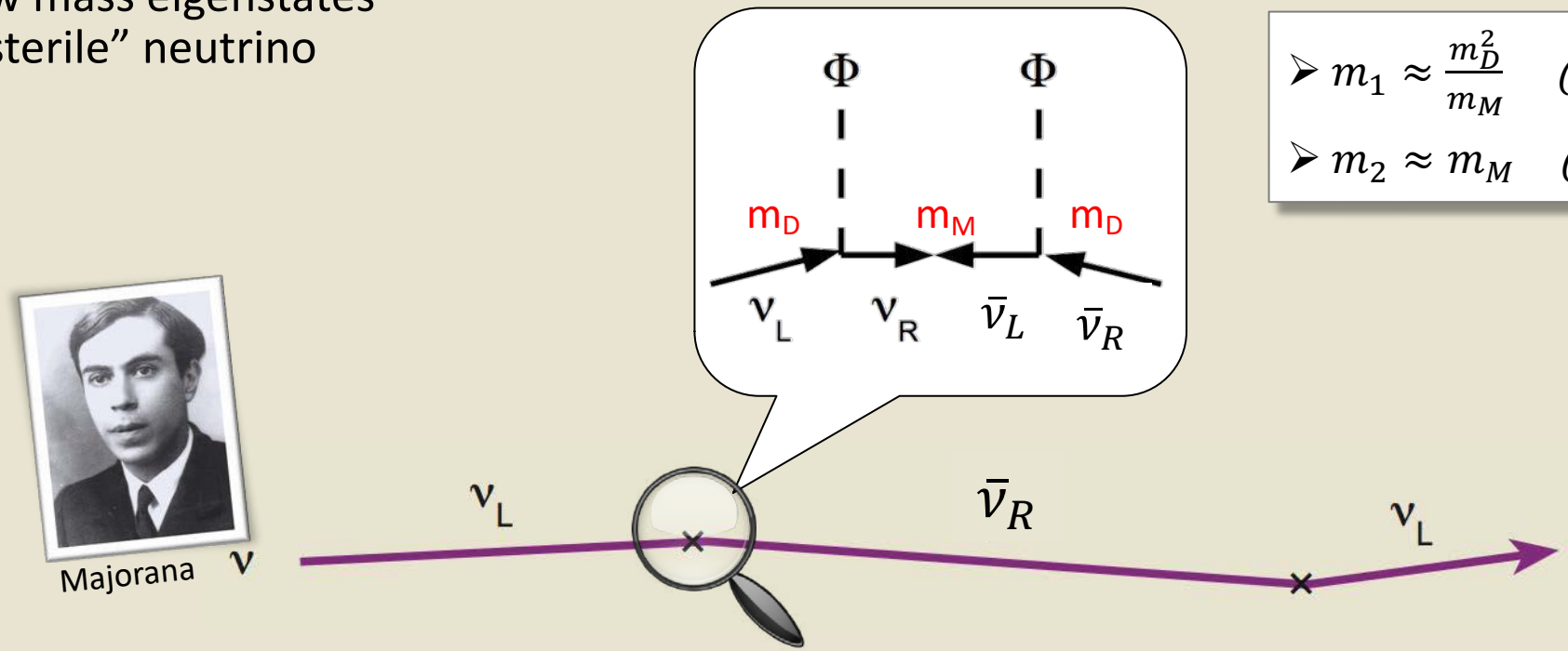
Majorana neutrino mass

- A mass term for ν_r is allowed without Higgs mechanism

➢ New mass eigenstates = "sterile" neutrino

See Saw Type 1:

Heavy right-handed ν



➢ $m_1 \approx \frac{m_D^2}{m_M}$ *(small)*

➢ $m_2 \approx m_M$ *(large)*

Sterile Neutrinos

Heavy sterile neutrinos (> GeV)

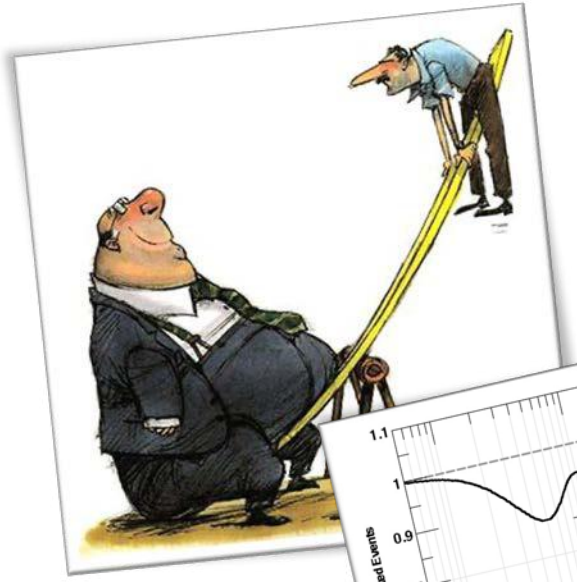
- Lightness of neutrinos
  + Matter/Anti-matter asymmetry

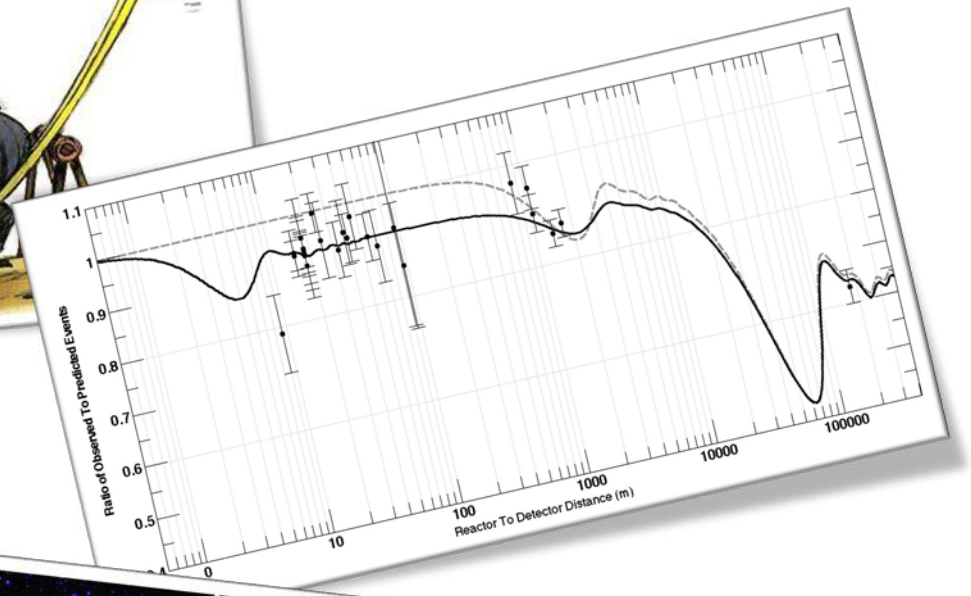
Light sterile neutrinos (~1 eV)

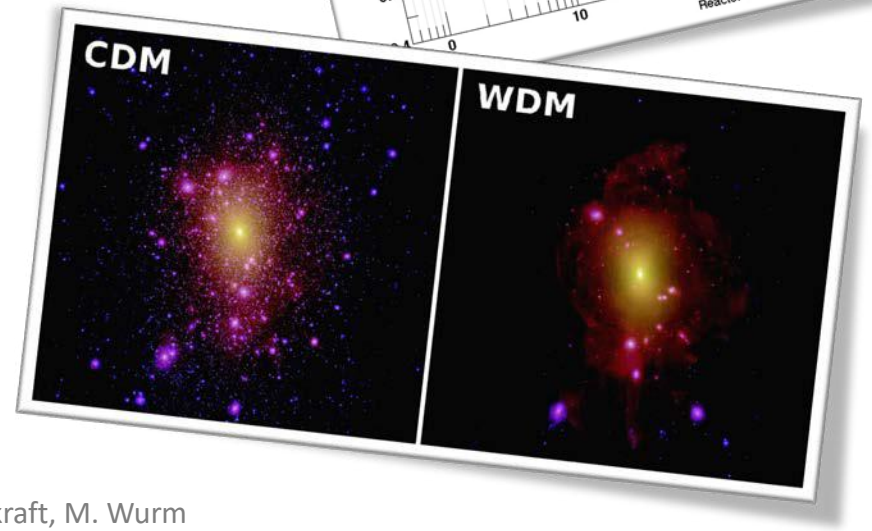
- Short-baseline neutrino oscillation anomalies

KeV-scale sterile neutrinos (~ 1 - 50 keV)

- Dark matter candidate







arXiv:1901.08330v2 (2019), Carlo Giunti and Thierry Lasserre
arXiv:1906.01739 (2019): S. Böser, C. Buck, C. Giunti, J. Lesgourgues, L. Ludhova, S. Mertens, A. Schukraft, M. Wurm
Prog.Part.Nucl.Phys. 104 (2019): A. Boyarsky, M. Drewes, T. Lasserre, S. Mertens, O. Ruchayskiy

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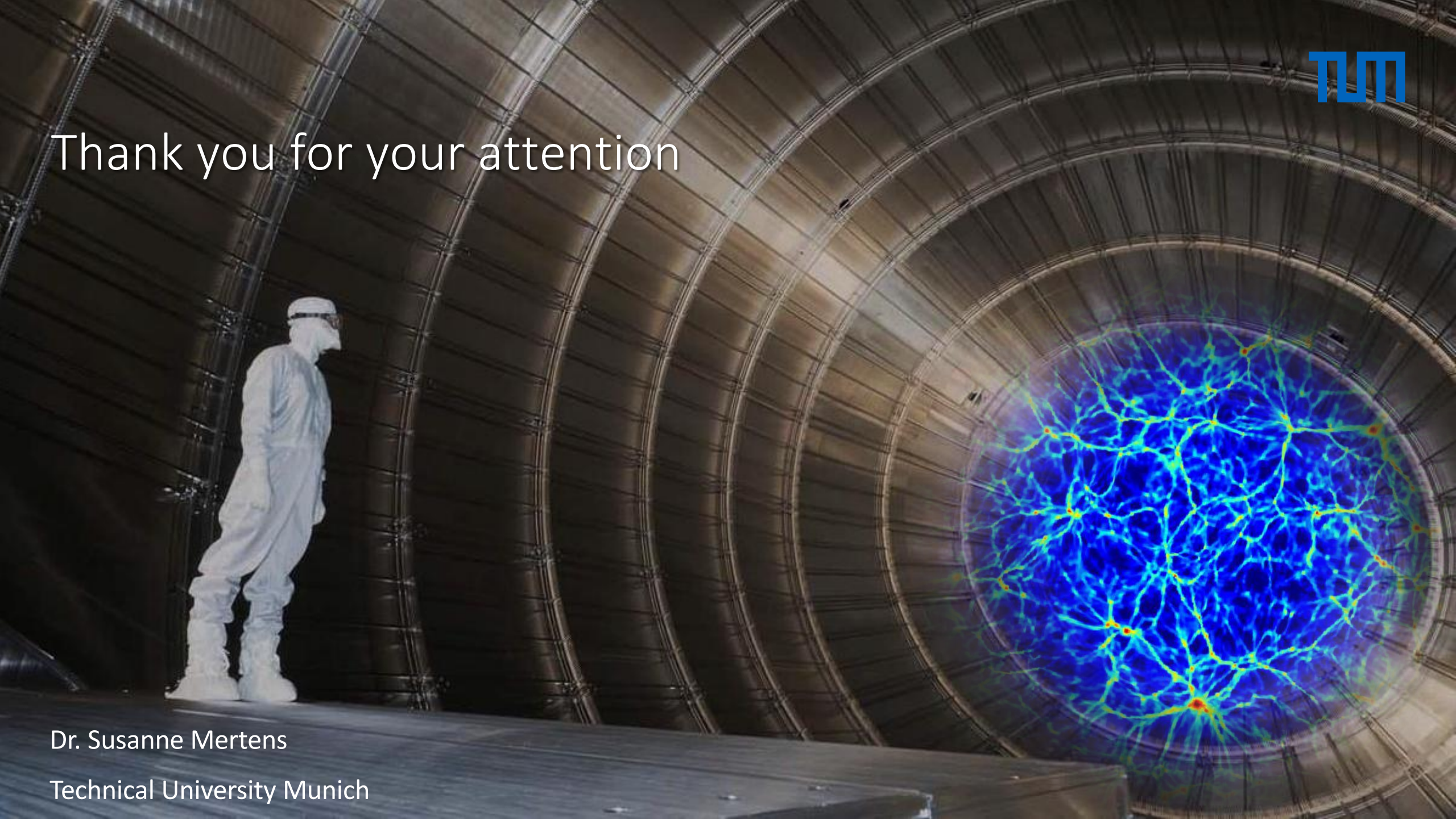
- CP violation
- Important experiments: DUNE, JUNO, and others

Are there more than three neutrinos?

- Maybe.
- New neutrino mass eigenstates = almost sterile
- eV = oscillation anomalies
- keV= dark matter
- very heavy = see saw



Thank you for your attention

Dr. Susanne Mertens

Technical University Munich