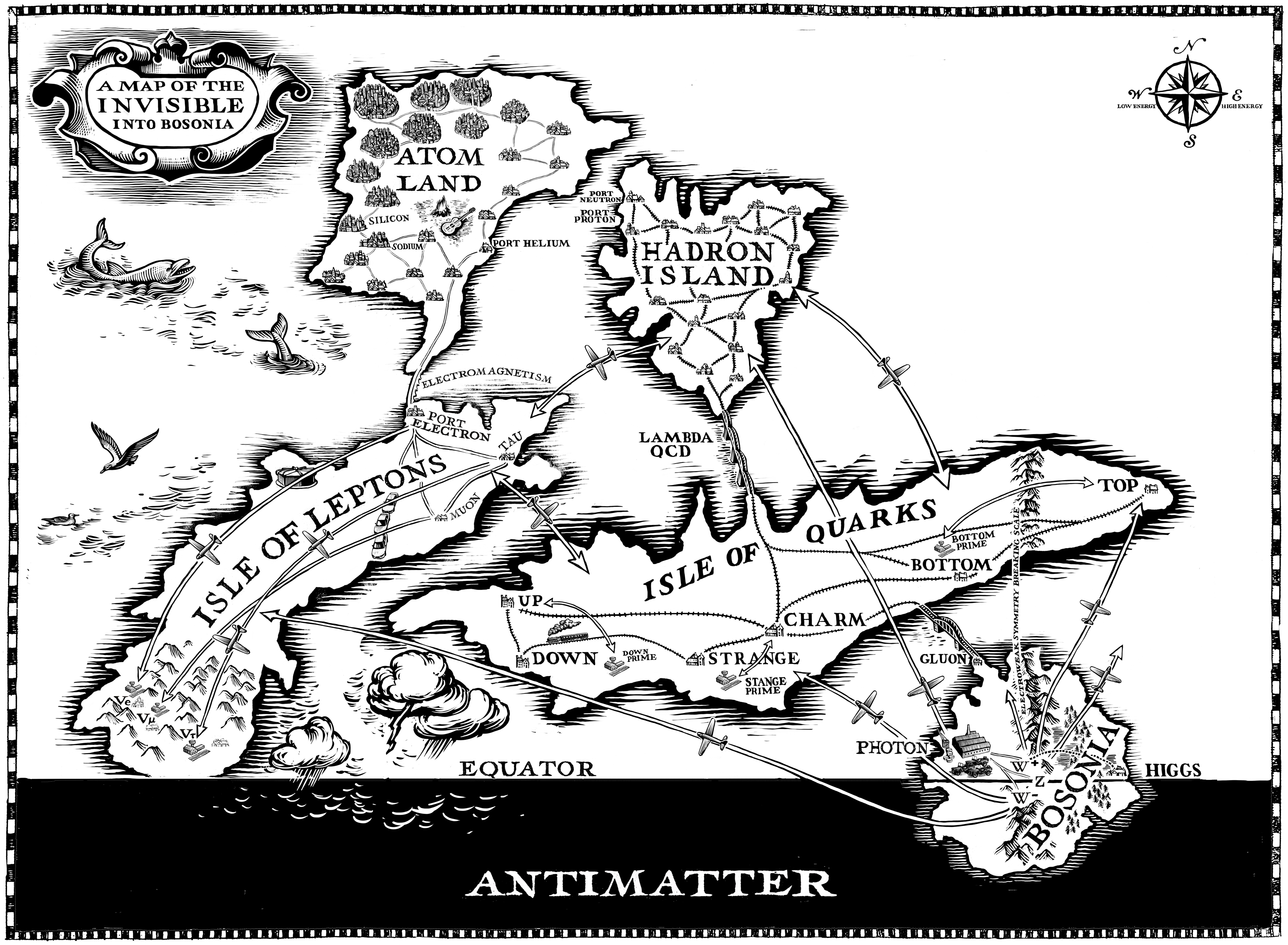
The Standard model
Day 2

Jon Butterworth



A MAP OF THE
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INTO BOSONIA
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LAND
SILICON
SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
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ISLAND
ELECTROMAGNETISM
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LAMBDA
QCD
ISLE OF LEPTONS
ISLE OF
QUARKS
TOP
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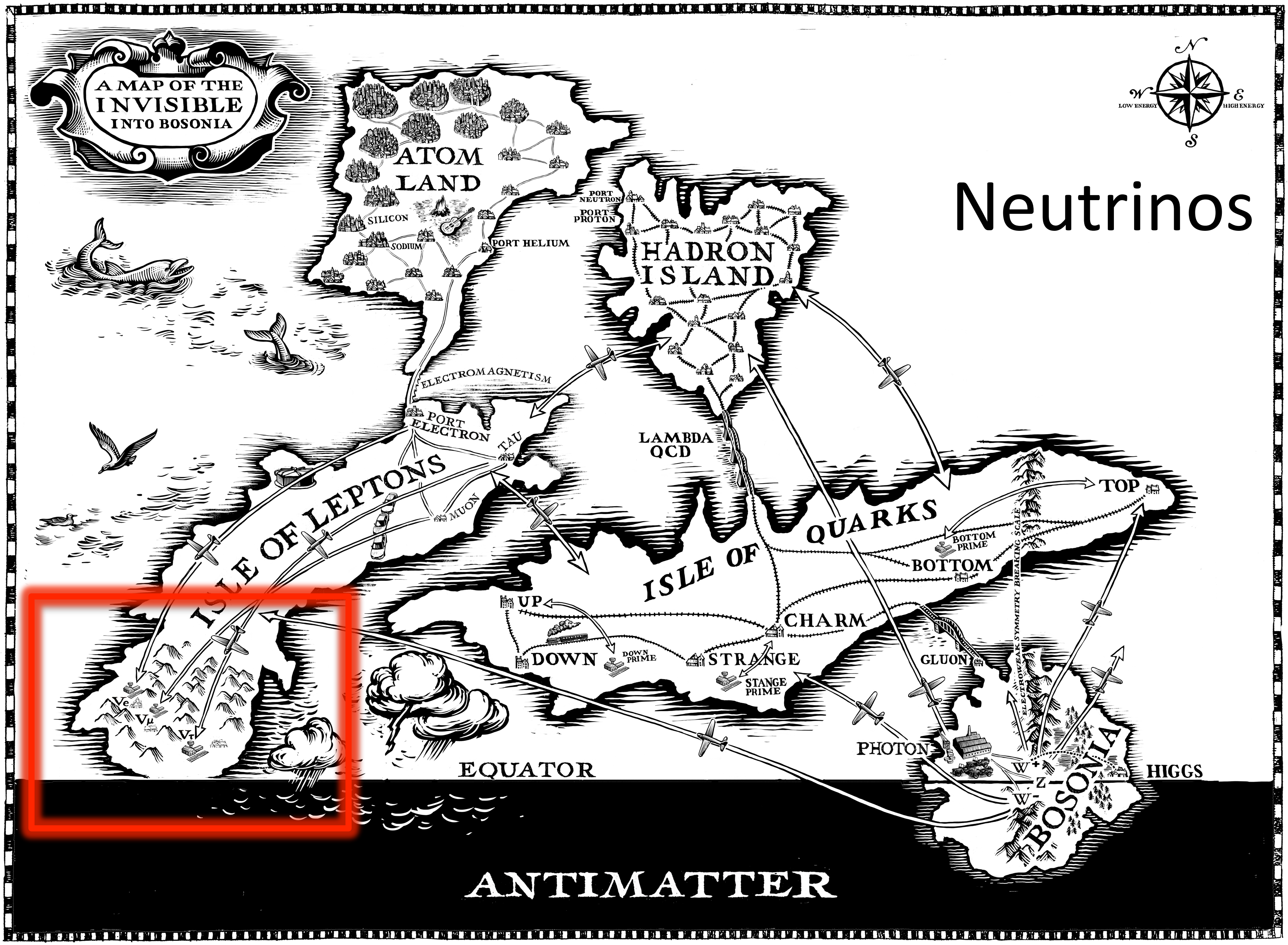
EQUATOR
ANTIMATTER

Neutrinos



A MAP OF THE INVISIBLE INTO BOSONIA
ATOM LAND
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SODIUM
PORT HELIUM
PORT NEUTRON
PORT PROTON
HADRON ISLAND
ELECTROMAGNETISM
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Neutrinos

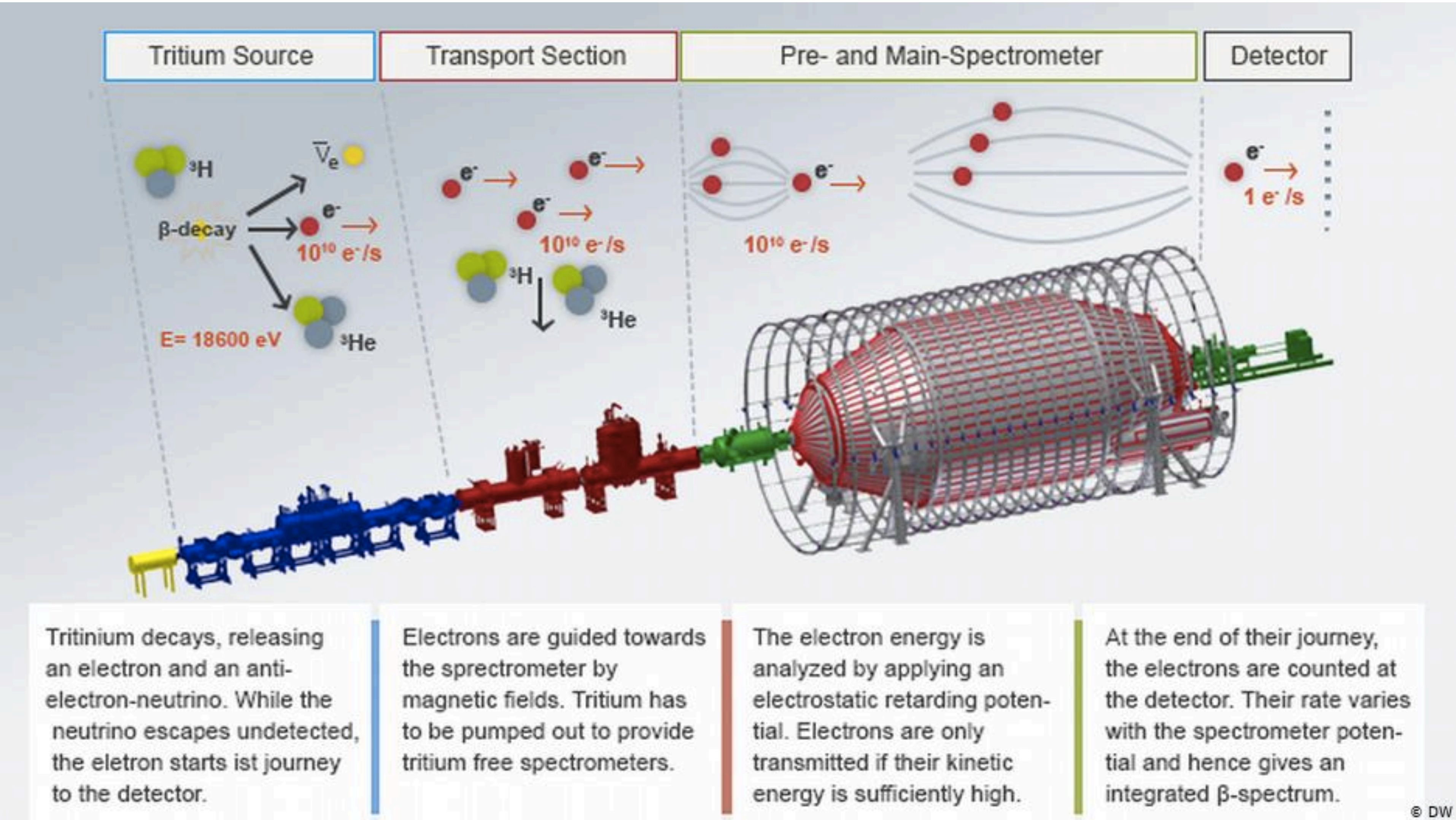
- Neutrino = Italian for neutral [‘neu’] small [‘ino’] one
- First the *electron neutrino* was conceived in the mind of Wolfgang Pauli in 1930 as a ‘desperate remedy’ to explain electron energy spectrum in β decay, thought to be
  - To conserve lepton flavour number, ν_e has $L_e(\nu_e) = +1$
  - Electron neutrinos were subsequently discovered by Reines and Cowan in 1956 [!]
  - Muon neutrino ‘discovered’ in 1962
  - Tau neutrino existence implied by previous experiments, but finally ‘discovered’ only in 2000. (The last matter particle of the SM.)

KATRIN

Karlsruhe Tritium Neutrino Experiment

KATRIN


IRELAND
UNITED KINGDOM
NETHERLANDS
BELARUS
POLAND
Rhine River
BELGIUM
GERMANY
0 200
Km
UKRAINE
Deggendorf
Danube River
Atlantic Ocean
Karlsruhe
Munich
HUNGARY
FRANCE
ROMANIA
ITALY
Black Sea
Adriatic Sea
BULGARIA
Balearic Sea
SPAIN
Tyrrhenian Sea
GREECE
TURKEY
Mediterranean Sea
ALGERIA


Tritium Source
Transport Section
Pre- and Main-Spectrometer
Detector
^{3}H
$\bar{\nu}_e$
β-decay
e$^-$
10^{10} e$^-$/s
E= 18600 eV
^{3}He
e$^-$
e$^-$
e$^-$
10^{10} e$^-$/s
^{3}H
^{3}He
e$^-$
10^{10} e$^-$/s
e$^-$
1 e$^-$/s
Tritinium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the eletron starts ist journey to the detector.
Electrons are guided towards the sprectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.
The electron energy is analyzed by applying an electrostatic retarding poten-tial. 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 poten-tial and hence gives an integrated β-spectrum.
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Neutrino masses and Mixing

- Neutrinos have mass
  - New unitary mixing matrix, potential new source of CP violation

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

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{23}c_{13} \end{bmatrix}.$$

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

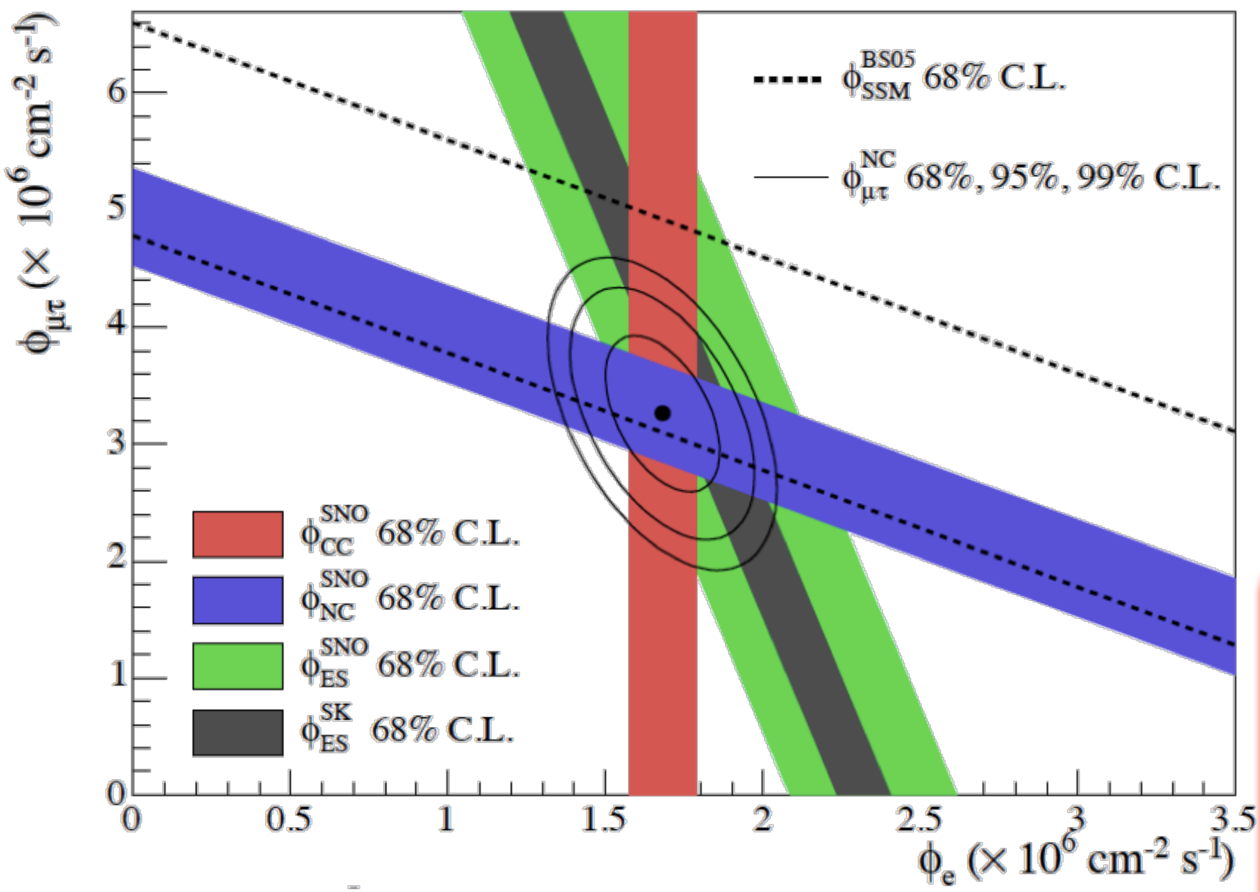
Neutrino masses and Mixing

- Neutrinos have mass
  - New unitary mixing matrix, potential new source of CP violation
  - Maybe new (Majorana?) mass terms

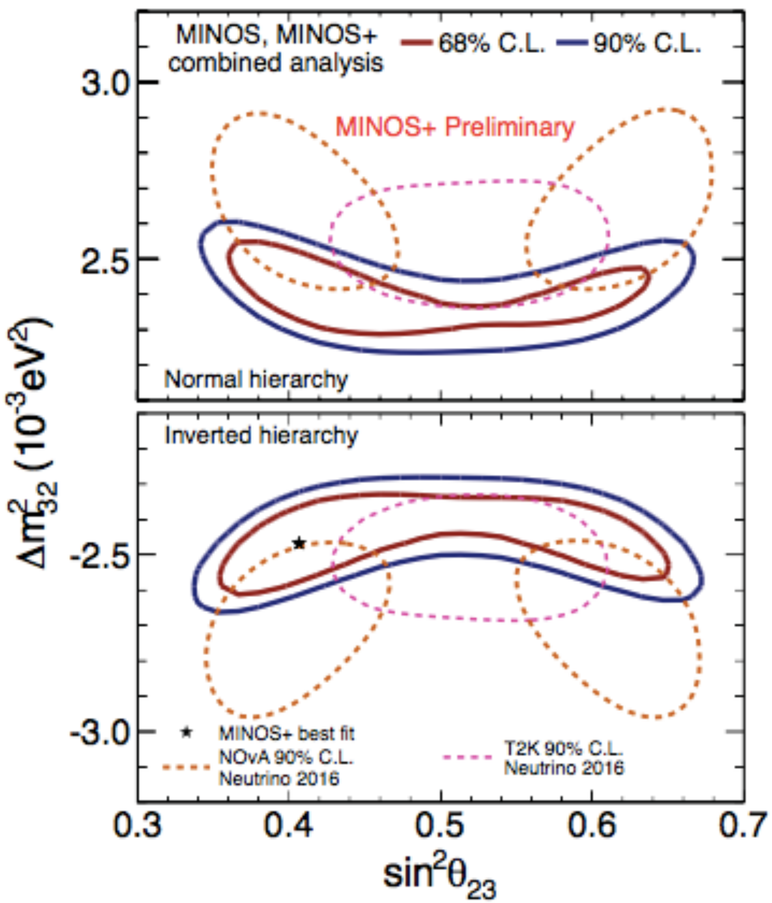
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}.$$

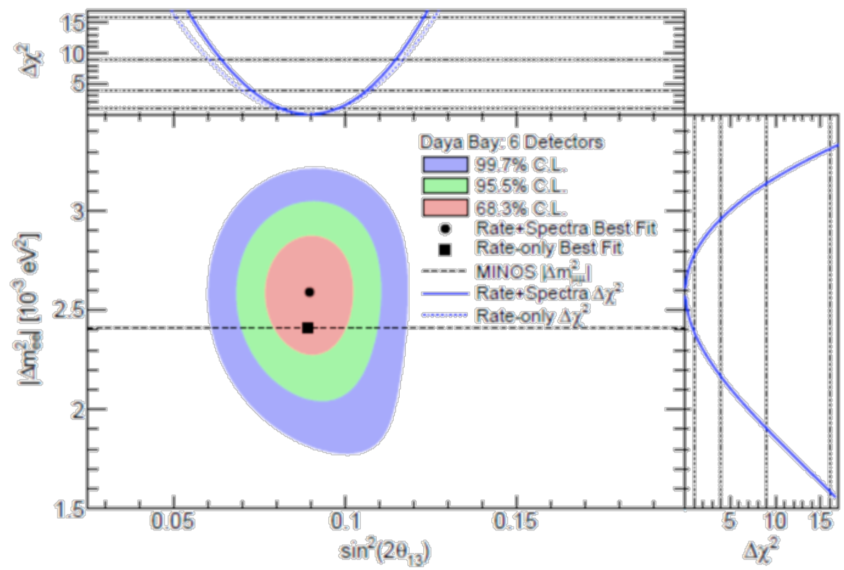
$$\begin{aligned} U &= \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix} \\ &= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}, \end{aligned}$$

Neutrino masses and Mixing

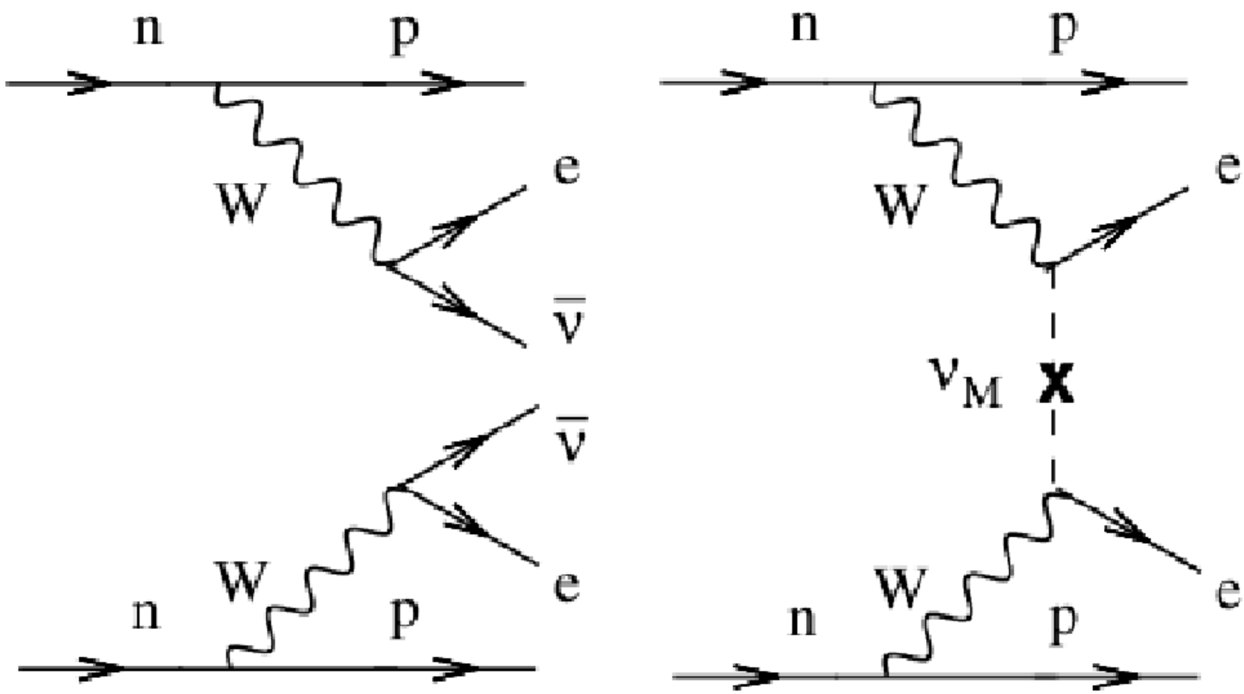


Neutrino masses and Mixing





Neutrinoless double beta decay(?)



Three lepton generations

Generation	Particle	Mass (MeV)	Q/e	L_{e}	L_μ	L_τ
1	ν_{e}	$< 2 \times 10^{-6}$	0	1	0	0
	e^-	0.511	-1	1	0	0
2	ν_μ	< 0.19	0	0	1	0
	μ^-	105.658	-1	0	1	0
3	ν_τ	< 18.2	0	0	0	1
	τ^-	1777	-1	0	0	1

QUIZ