Universität Münster

Neutrinos in the Standard Model

Summer School on Neutrino Physics Beyond the Standard Model, Straßburg, 29.6.-11.7.2025

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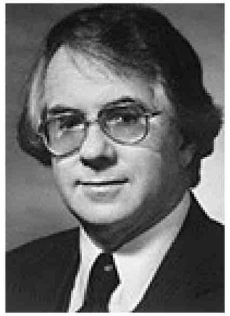
Content:

- Discovery
- Parity violation, helicity and chirality
- Weak interaction in $U(1) \otimes SU(2)_L$
- Neutrino sources
- Neutrino oscillation
- Neutrino mass searches
- Open questions in neutrino physics

ν's in the electroweak Standard Model: $U(1) \otimes SU(2)_L$



S. Glashow

S. Weinberg

A. Salam

12 fundamental fermions

6 left-handed weak isospin dublets:

Leptonen	$\begin{pmatrix}\nu_e \\ e^-\end{pmatrix}_L$	$\begin{pmatrix}\nu_\mu \\ \mu^-\end{pmatrix}_L$	$\begin{pmatrix}\nu_\tau \\ \tau^-\end{pmatrix}_L$	pure weak isospin dublets
Quarks	$\begin{pmatrix}u \\ d\end{pmatrix}_L$	$\begin{pmatrix}c \\ s\end{pmatrix}_L$	$\begin{pmatrix}t \\ b\end{pmatrix}_L$	weak isospin dublets

9 right-handed weak isospin singulets:

$e_R^-, \mu_R^-, \tau_R^-, u_R, d_R, c_R, s_R, t_R, b_R$ (no ν_R in SM)

$$\Psi_L = P_L \Psi \quad \Psi_R = P_R \Psi \quad P_L = 1/2(1-\gamma_5) \quad P_R = 1/2(1+\gamma_5)$$

For massless particles (ν in SM):

Ψ_L, Ψ_R^c have helicity H = -1 $\quad \overset{\Leftarrow \sigma}{\rightarrow p}$

Ψ_R, Ψ_L^c have helicity H = +1 $\quad \overset{\Rightarrow \sigma}{\rightarrow p}$

massive leptons in charged weak currents (CC):

- lepton:

  P(H = ±1) = (1 ± (-v/c))/2

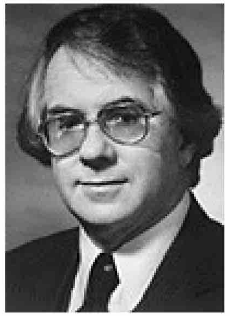
  ⇒ P_{Long} = -v/c

- anti lepton:

  P(H = ±1) = (1 ± v/c)/2

  ⇒ P_{Long} = v/c

ν's in the electroweak Standard Model: $U(1) \otimes SU(2)_L$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Quarks $\begin{pmatrix}u\\ \end{pmatrix}$ $\begin{pmatrix}c\\ \end{pmatrix}$ $\begin{pmatrix}t\\ \end{pmatrix}$ weak isospin dublets

→ Let us remind ourselves

of the foundations of neutrino physics

SM)

$1/2(1+\gamma_5)$

massive leptons in charged weak currents (CC):

- lepton:

  P(H = ±1) = (1 ± (-v/c))/2

  ⇒ P_{Long} = -v/c

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  ⇒ P_{Long} = v/c

For massless particles (ν in SM):

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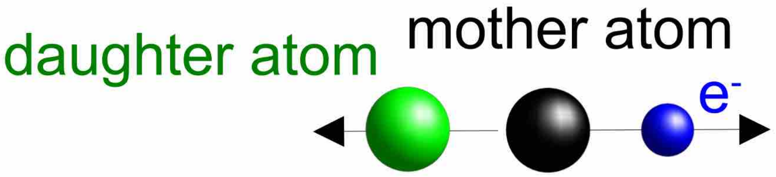
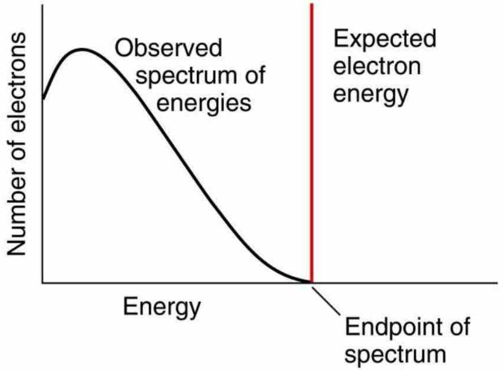
Pauli`s neutrino hypothesis

1914 β decay:

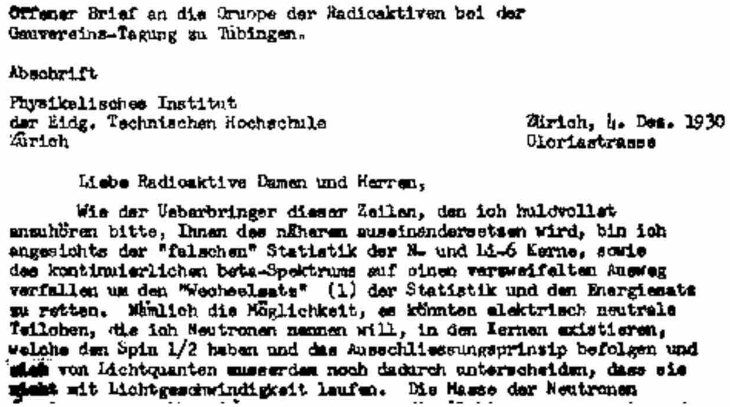


Chadwick: continuous energy spectrum of emitted e^-



⇒ looks like a violation of the energy and (angular momentum) conservation

1930: Wolfgang Pauli postulates neutrino ν: neutral, spin 1/2, very light or massless



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

Abschrift

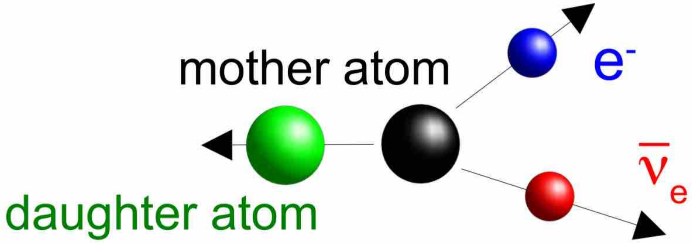
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

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

⇒ ν is emitted in addition to the e^- during β decay:



Fermi`s theory of the β decay

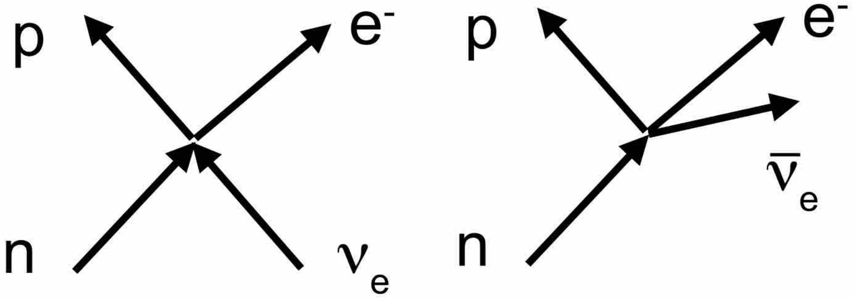
1934 Enrico Fermi formulates theory of the β decay like in electrodynamics:

four point interaction

current-current-coupling $H = G_F/\sqrt{2} \cdot J_\mu \cdot J^\mu$

hadronic current: $J_\mu = < \bar{p} \,|\, \gamma_\mu \,|\, n >$

leptonic current: $J^\mu = < \bar{e} \,|\, \gamma^\mu \,|\, \nu_e >$



Droplet model: 6 per fission process (≈ 200 MeV)

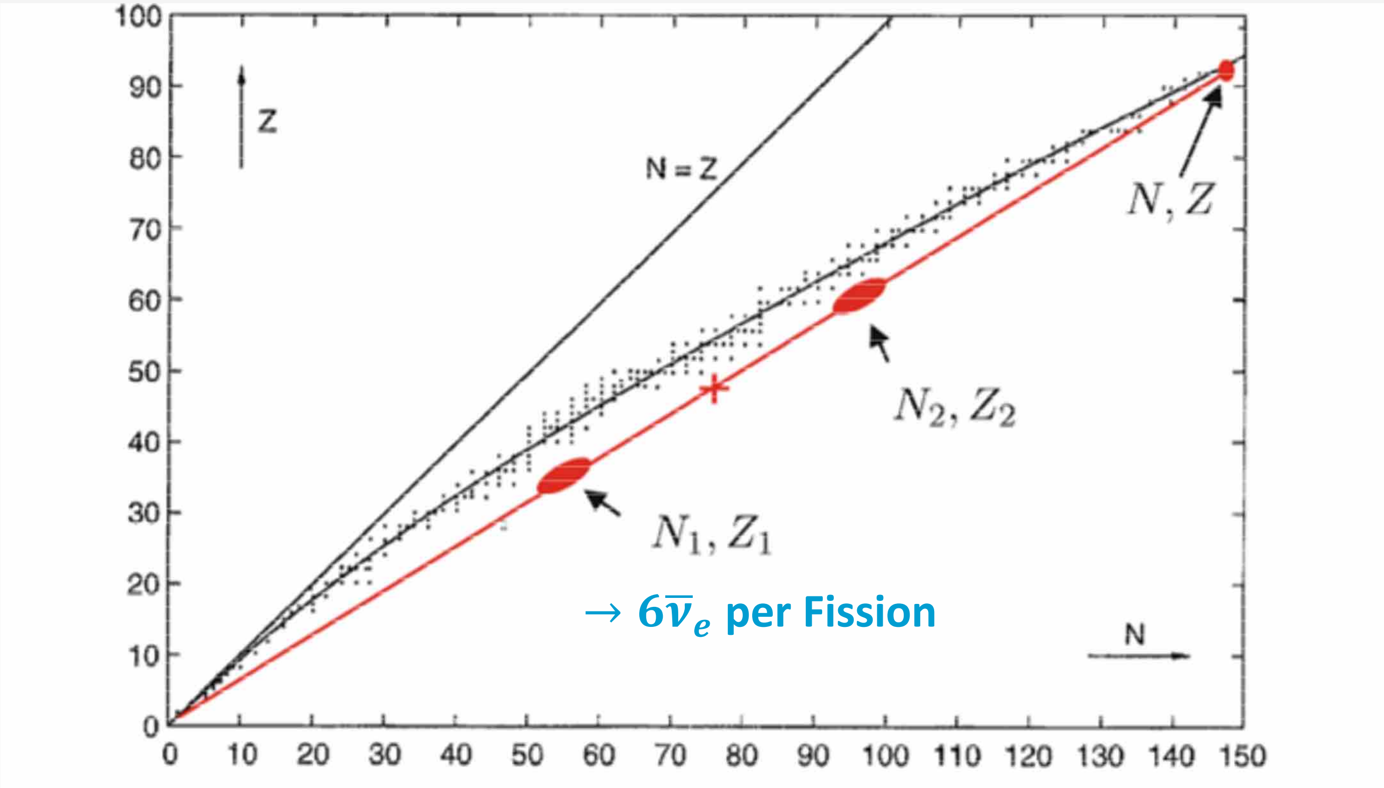


Abb. 8.2 Auf der Isotopenkarte müssen nach der Spaltung eines schweren Kerns $(N, Z) = (N_1, Z_1) + (N_2, Z_2)$ die Spaltprodukte symmetrisch zum Halbierungspunkt (*rotes Kreuz*) liegen, d. h. auf oder beidseitig der *geraden roten Linie*. Die beiden *roten Gebiete* kennzeichnen die häufigsten Kombinationen der Spaltprodukte. Wegen der Krümmung der Linie der stabilen Nuklide liegen sie auf der neutronenreichen Seite und sind daher β^--radioaktiv. (nach [58])

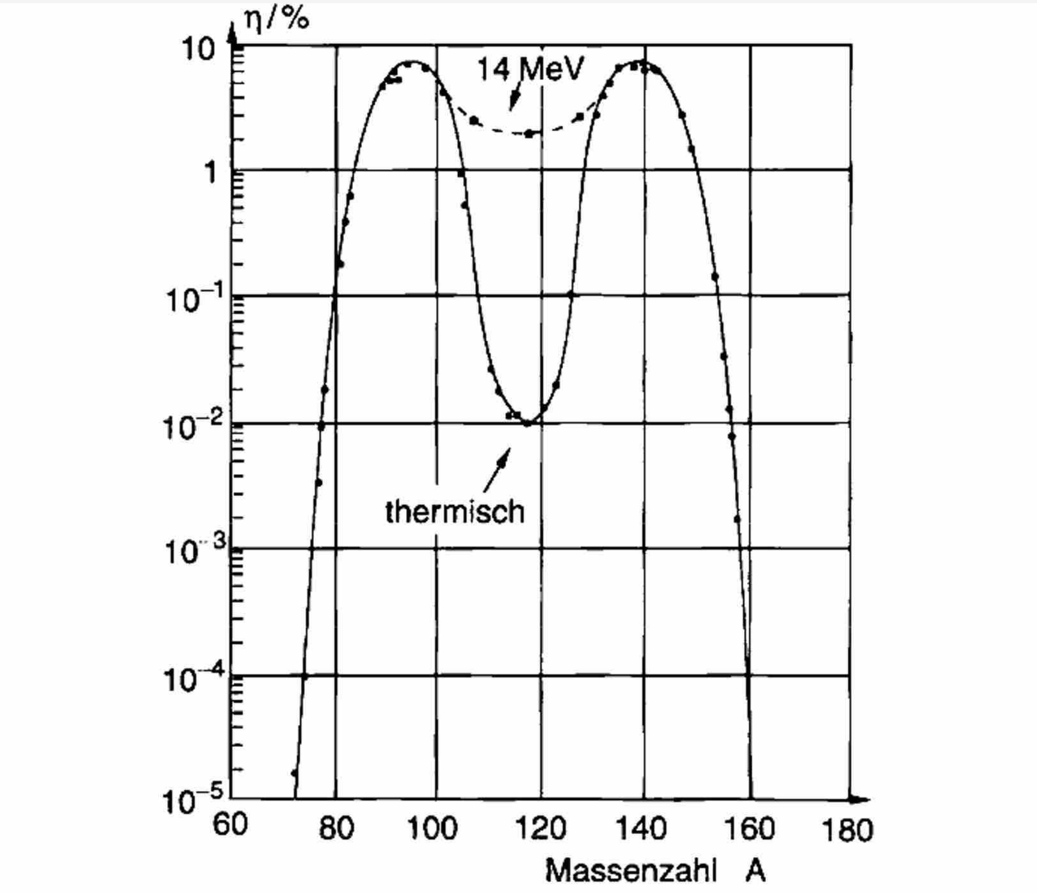
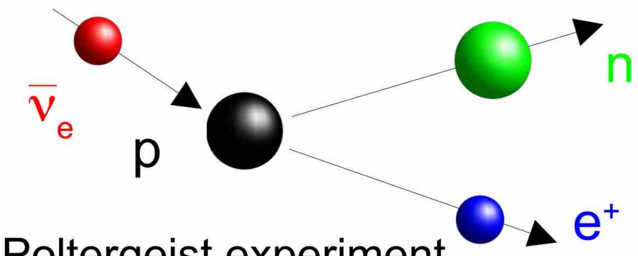
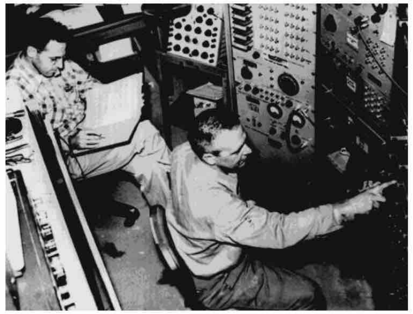


Abb. 8.3 Massenspektrum (logarithmisch aufgetragen) der Bruchstücke von $^{235}_{92}U$ nach Spaltung durch Neutronen mit Energie < 1 eV („thermisch“) bzw. 14 MeV. Der charakteristische Doppelhöcker hängt mit Unterschieden in der Bindungsenergie der Spaltprodukte zusammen: in den Maxima ist sie (im Mittel) höher als dazwischen (siehe auch Abb. 4.12 sowie Abschn. 7.6.1 – Schalenmodell). Mit zunehmender Energie des Neutrons wird dies weniger wichtig; oberhalb etwa 25 MeV setzt sich allmählich die rein statistische Verteilung in Form einer einzigen Glocken-Kurve durch (in logarithmischer Darstellung eine Parabel). (Abb. aus [58])

Figures: Bleck-Neuhaus: “Elementare Teilchen”, Springer

Experimental proof of neutrinos by using „inverse beta decay“





1956: Cowan and Reines: Poltergeist experiment

strong $\bar{\nu}_e$ source: nuclear power reactor:

6 $\bar{\nu}_e$ / fission (from fission products), $E_\nu < 9$ MeV

energy gain / fission: 200 MeV

1 GW thermal power $\Rightarrow$ $2 \cdot 10^{20}$ ν/s

Detection reaction: inverse β decay: $\bar{\nu}_e + p \rightarrow n + e^+$ (threshold: 1.8 MeV)

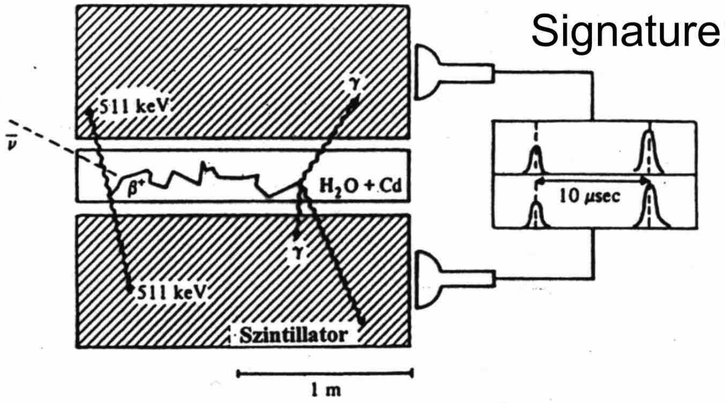


figure: Schmitz: Neutrinophysics, Teubner

Signature: a) n: thermalisation by elastic scattering, capture on Cd $\Rightarrow \gamma$'s

b) e^+: annihilation $\Rightarrow 2\,\gamma$'s (511 keV)

$\Rightarrow$ spatial and time-delayed coincidence (nearly background free)

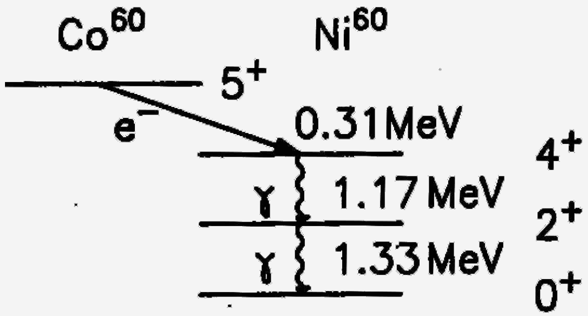
measured cross section:

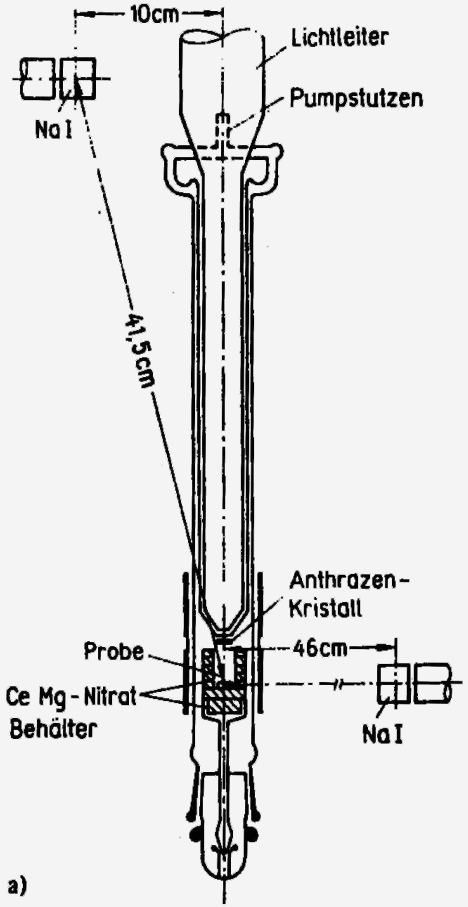
$(1.1 \pm 0.3) \cdot 10^{-43}$ cm^2

(in good agreement with Fermi`s theory for V-A)

Wu experiment: violation of parity in β decay

1957: Chien-Shiung Wu (“Madame Wu”) measured direction of β electrons from a magnetized, spin-polorized ^{60}Co source





$T \approx 10$ mK by adiabatic demagnetisation (new technology in 1957).

Nuclear spin (J=5) aligns with external magnetic field: $\Delta E = \pm\vec{\mu}\cdot\vec{B}$

Polarisation given by Boltzmann factor:

$$P \propto e^{-\frac{2\Delta E}{k_B T}}$$

Determination of ^{60}Co polarisation by angular correlation of the two decay $\gamma's$

Wu experiment: violation of parity in β decay

Experimental results: β electrons emitted preferentially antiparallel to $\vec{B}$

in particular $(\vec{p}_e \cdot \vec{J}) \propto \cos\theta$

$\overrightarrow{p_e} \cdot \vec{J}$ ist pseudo-scalar operator:

$$\vec{p}_e \cdot \vec{J} \rightarrow \ (-\vec{p}_e) \cdot (+\vec{J}) = -\vec{p}_e \cdot \vec{J}$$

→ β decay violates parity, even maximally:

Polarisation of β electrons is $^{v}/_{c}$

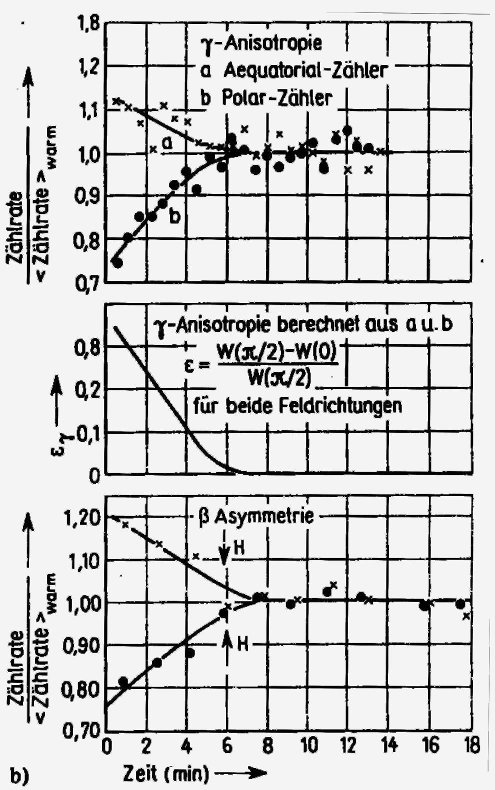
More generally: Parity is in weak charged current ($W^{\pm}$ exchange) maximally violated

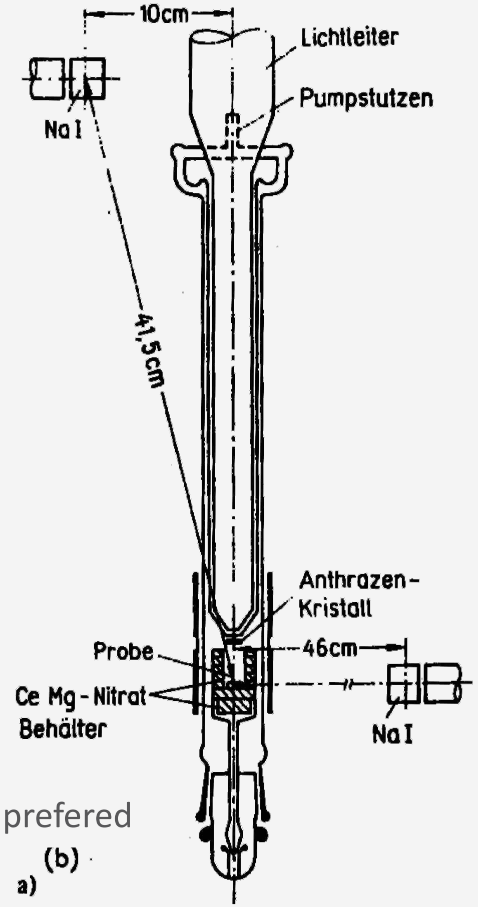
– in contrast to electromagnetic or strong interaction

→ Particles, such as e^-, ν_e , have preferentially negative "helicity"

spin projektion onto direction of momentum $\mathcal{H} = \frac{\vec{p}\cdot\vec{\sigma}}{|p|\cdot|\sigma|}$

antiparticles, such as e+, $\bar{\nu}_e$, possess preferentially positive helicity





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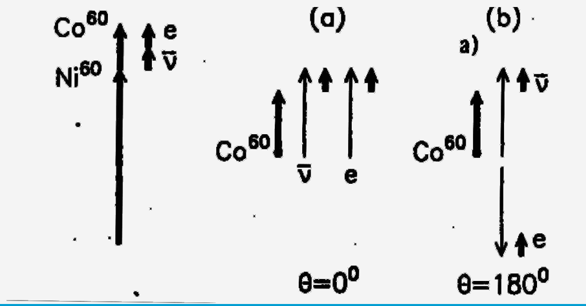
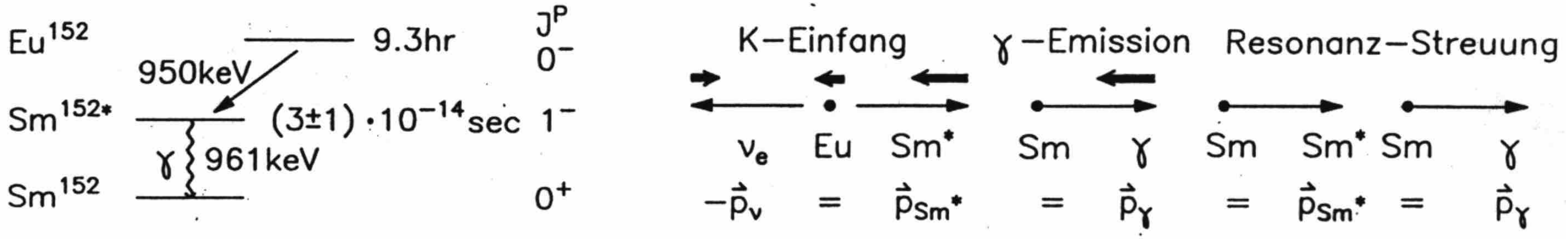
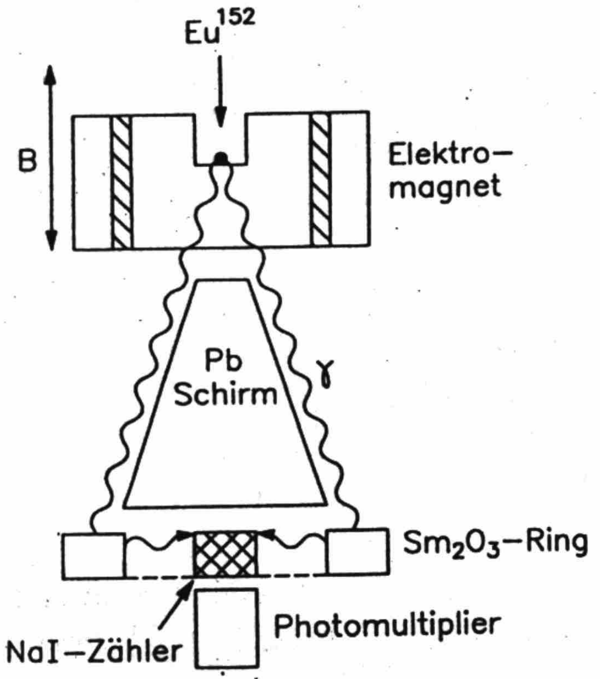


Helicity of the neutrinos: Goldhaber experiment

Helicity: projection of the spin onto flight direction $H = \vec{\sigma}\, \vec{p} / |\vec{p}|$





figures: Schmitz: Neutrinophysics, Teubner

Determination of the helicity of the neutrinos:

- Detect γ by resonance scattering on ^{152}Sm
  Usually not possible due to red shift from γ recoil !
- But resonance scattering is possible,
  if primary ν recoil gives the right blue shift:
  $\Rightarrow$ 180° emission of ν and γ
- Due to spin structure of transissions:
  $H(\nu) = H(\gamma)$ for detected photons
- Measure $H(\gamma)$ by determination of transmission through magnetized iron

Result: $H(\nu_e) = -1$

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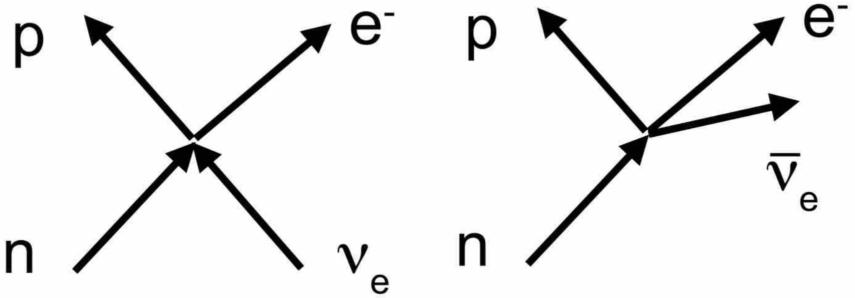

This ansatz is still right as a low-energy approximation,

only the γ_μ operator has to be more generalized due to parity violation:

$$< \bar{e} \mid \gamma^\mu \mid \nu_e > \quad \rightarrow \quad < \bar{e} \mid \gamma^\mu (1 - \gamma_5) \mid \nu_e >$$

$$\gamma^\mu - \gamma^\mu \gamma_5 =: V - A$$

Helicity and chirality in charge current weak interactions

- **Helicity of fermions in charged current weak interactions (e.g. β decay) :**

  Probability of a certain helicity for particles: $\boldsymbol{W_L(\mathcal{H}=+1)=\frac{1-\beta}{2}}$ and $W_L(\mathcal{H}=-1)=\frac{1+\beta}{2}$

  Probability of a certain helicity for antiparticles: $\boldsymbol{W_L(\mathcal{H}=+1)=\frac{1+\beta}{2}}$ and $W_L(\mathcal{H}=-1)=\frac{1-\beta}{2}$

- **Chirality (Lorentz-invariant description of a quantity connected to helicity)**

  Chirality operator: $\gamma_5=\gamma^5=i\,\gamma^0\,\gamma^1\,\gamma^2\,\gamma^3=\begin{pmatrix}0_{2x2} & 1\\ 1_{2x2} & 0_{2x2}\end{pmatrix}$

  Chirality projectors: $P_L=\frac{1}{2}\cdot(1-\gamma^5)$ and $P_R=\frac{1}{2}\cdot(1+\gamma^5)$

  Spinor decomposition: $\psi=1\cdot\psi=(P_L+P_R)\cdot\psi=\psi_L+\psi_R$

  Chirality of helicity eigenstates in high energy limit: $P_L u_1\xrightarrow{E\gg m}0,\ P_R u_1\xrightarrow{E\gg m}u_1$ **⇒ helicity = chirality in high energy limit**

- **Weak charged current and maximal parity violation:**

  The QED current $j^{\mu}_{QED}=\bar{\psi}\gamma^{\mu}\psi$ will be extended for charged weak current interactions by the projection operator P_L:

  $$\boldsymbol{j^{\mu}_{CC}}=\bar{\psi}\gamma^{\mu}P_L\psi=\bar{\psi}\gamma^{\mu}\tfrac{1}{2}(1-\gamma^5)\psi=\tfrac{1}{2}\,\boldsymbol{\bar{\psi}(\gamma^{\mu}-\gamma^{\mu}\gamma^5)\psi}$$

- **This "V-A" theory describes low-energy** with **V is vector** γ^{μ} and **A is axial vector** $\boldsymbol{\gamma^{\mu}\gamma^5}$,
  "low energy" means, that W appears not explicitely in the propagator, it is "integrated out", because it is too heavy

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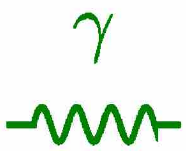
Weakness of weak interaction: compare photon with weak gauge boson propagator

Remember photon propagator:



$$\frac{g_\alpha^{\ \beta}}{q^2} \rightarrow \frac{1}{Q^2}$$

But W propagator:

$$\frac{i \cdot g_\alpha^{\ \beta} - \frac{q_\alpha \cdot q^\beta}{M_W^2}}{q^2 - M_W^2} \overset{q^2 \ll M_W^2}{\rightarrow} \frac{-i \cdot g_\alpha^{\ \beta}}{M_W^2} = \text{const.}$$

$\Rightarrow$ **weak cross section increases linearly with s,**

but is much smaller due to $1/M_W^4$ $\quad$ ($M_W \approx 80$ GeV)

Consequences of parity violating weak charge current $(\gamma^\mu - \gamma^\mu\gamma^5)$ in pion and decay

- **Charged pion decay, e.g. $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and $\pi^+ \rightarrow e^+ + \nu_e$** with Fermi's golden rule: $\Gamma = 2\pi \cdot |M|^2 \cdot \frac{\partial\rho}{\partial E}$:

  Branching ratio $B\left(\frac{\pi^+\rightarrow e^+ + \nu_e}{\pi^+\rightarrow \mu^+ + \nu_\mu}\right) = \frac{|M(\pi^+\rightarrow e^+ + \nu_e)|^2}{|M(\pi^+\rightarrow \mu^+ + \nu_\mu)|^2} \cdot \frac{\frac{\partial\rho}{dE(\pi^+\rightarrow e^+ + \nu_e)}}{\frac{\partial\rho}{dE(\pi^+\rightarrow \mu^+ + \nu_\mu)}} = \frac{\frac{1}{2}(1-\beta_e)}{\frac{1}{2}(1-\beta_\mu)} \cdot 3.49 = 3.52 \cdot 10^{-5} \cdot 3.49 = 1.23 \cdot 10^{-4}$

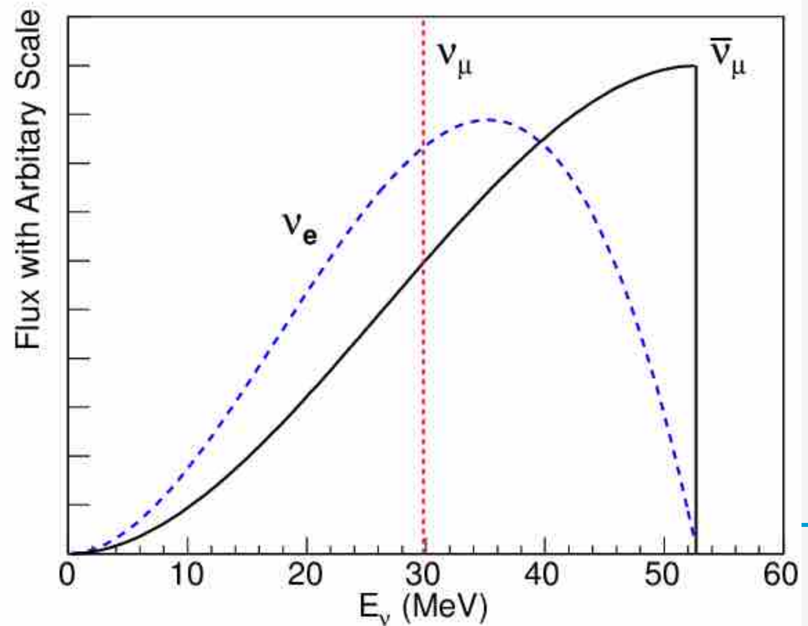
  strong effect of parity violation

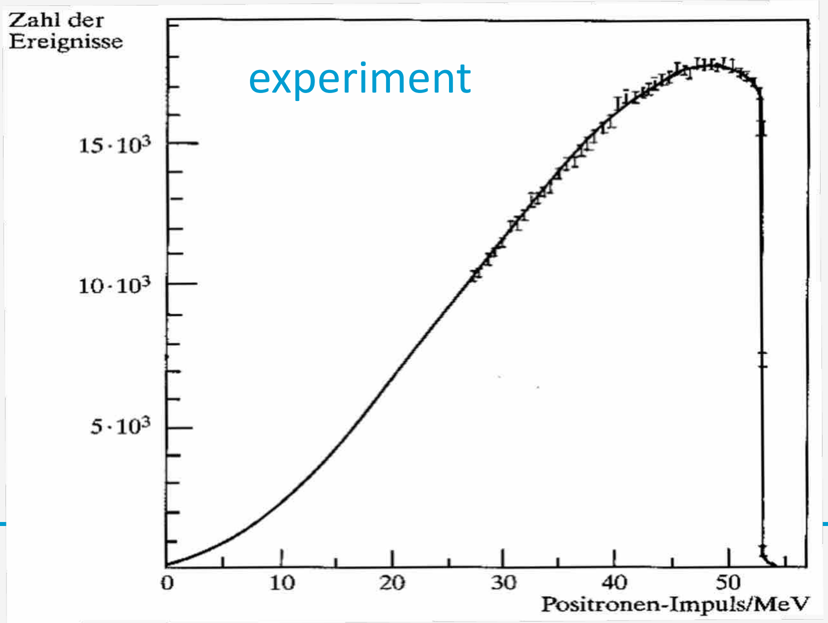
- **Muon decay: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ looks like β decay, but there are helicity constraints**

  $m_\mu = 105.6583745(24)$ MeV

  mean lifetime $\tau(\mu)$ =2.1969811(22) µs)

- neutrinos from stopped $\pi^+$and μ^+ beam:





Source: www.researchgate.net

CHARM experiment at CERN to measure neutrino electron scattering via neutral weak current

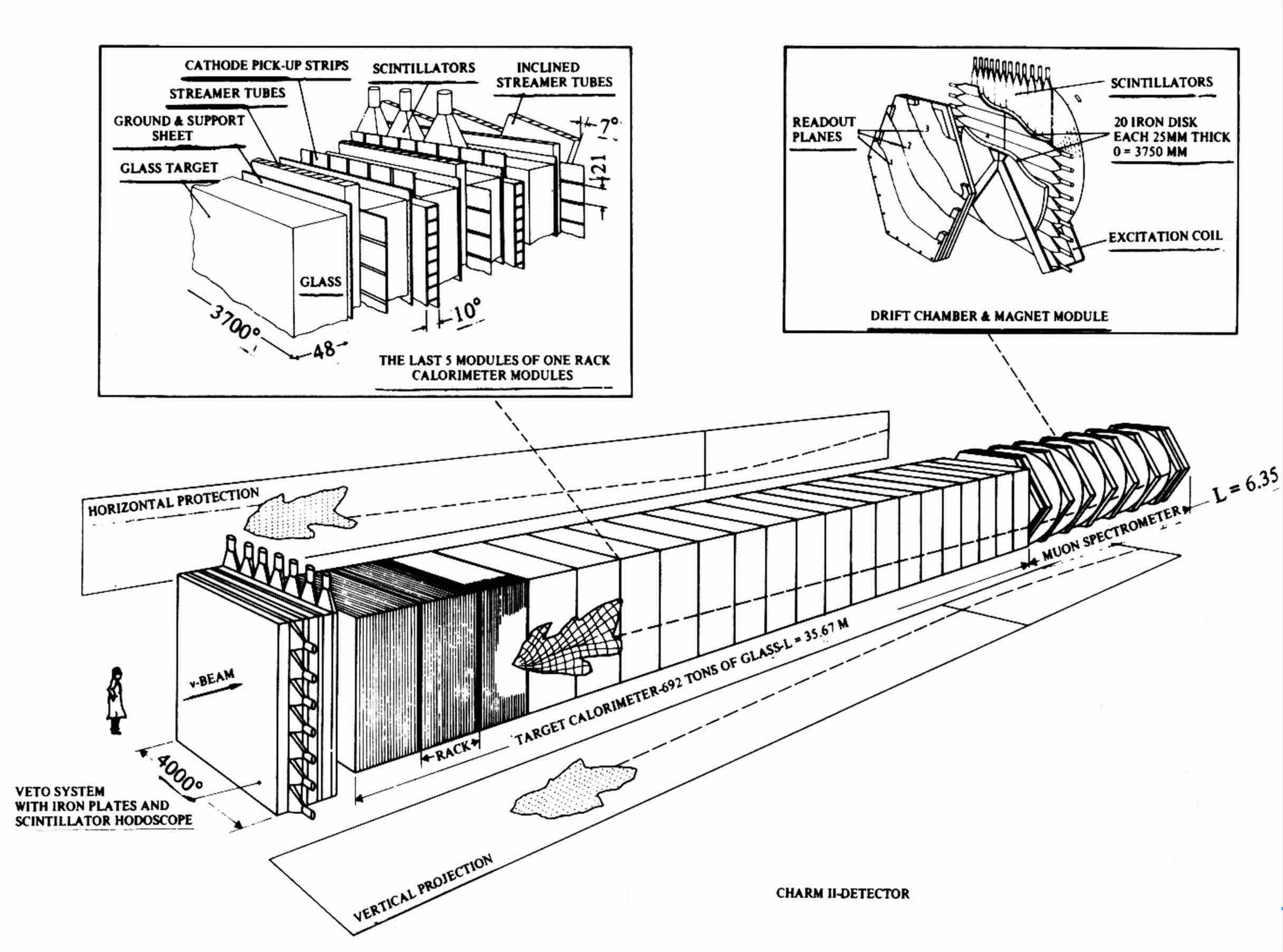
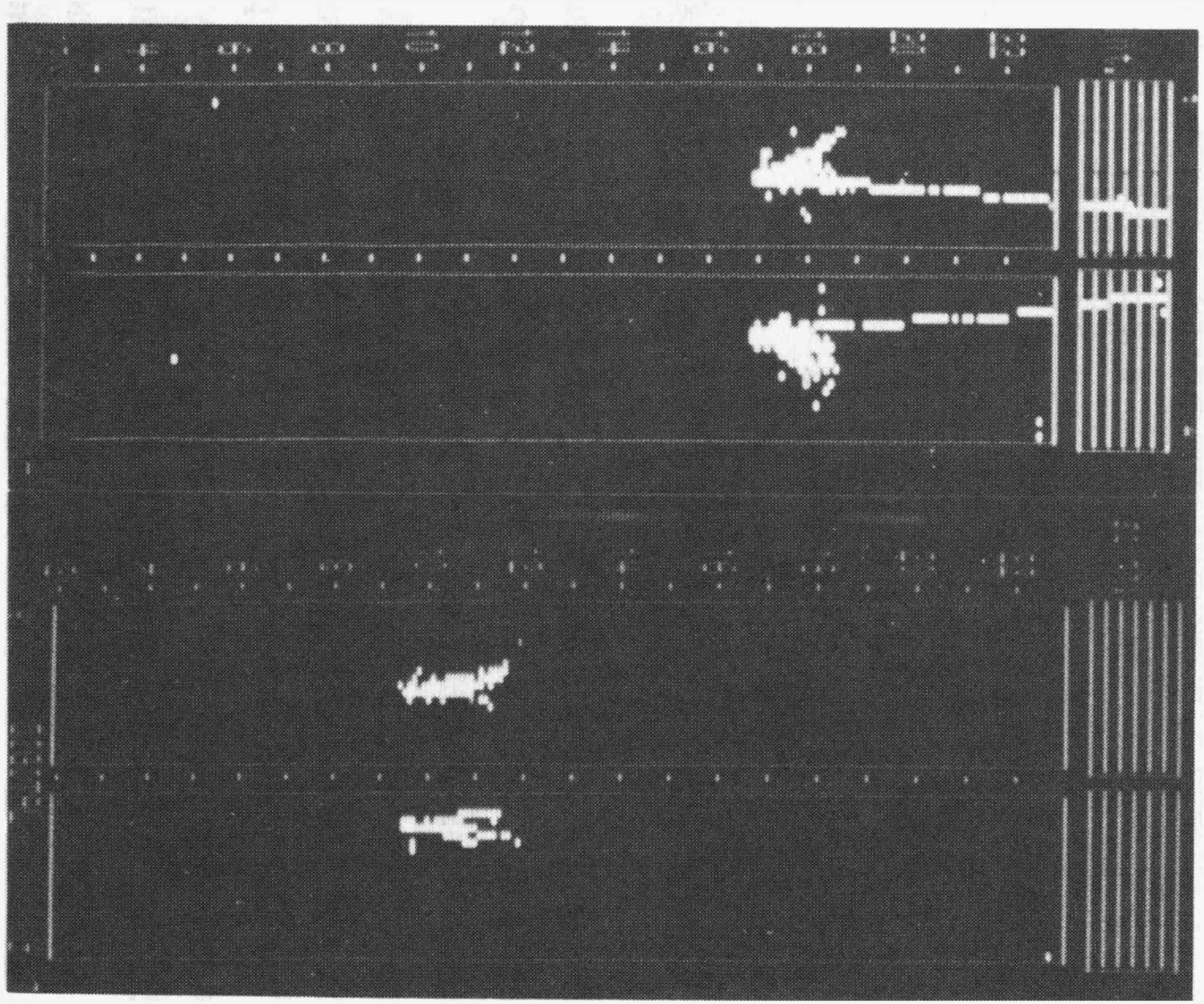


Figure: Winter: Neutrino Physics Cambridge University Press

CHARM experiment at CERN
differentiating weak charged / neutral currents



charged current:
long muon track
$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$

neutral current:
only short electron track
$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$

Figure: Winter:
Neutrino Physics
Cambridge University Press

CHARM experiment at CERN
differentiating scattering off nucleon / off electron

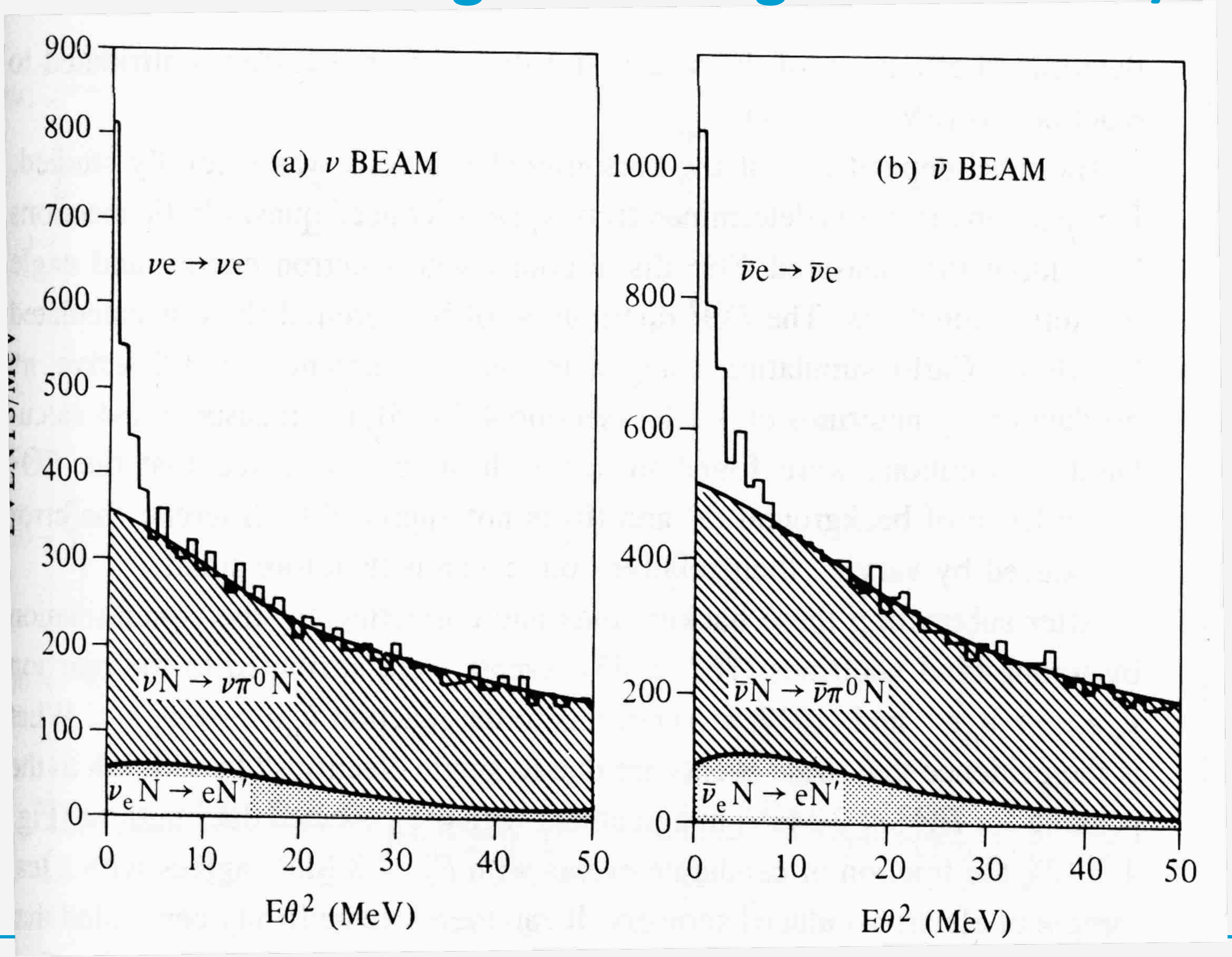


Figure: Winter:
Neutrino Physics
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Z^0-couplings: g_V , g_A

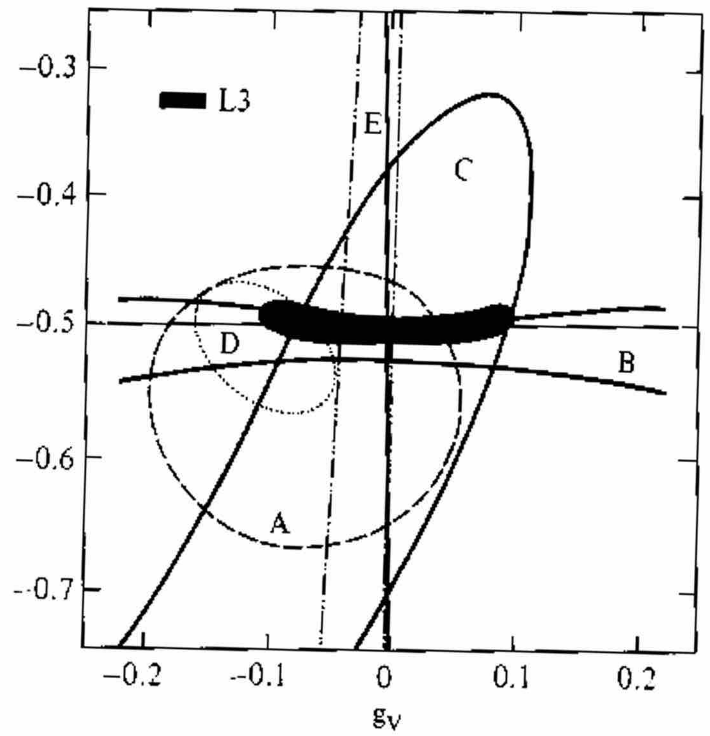


Fig. 4.2.13 Results obtained from neutrino experiments and the e^+e^- experiments expressed as contours in g_A and g_V. Area (A) is the result of the CHARM collaboration (68 percent confidence level) [DOR 89]; area (B) is the combined e^+e^- result from PETRA and PEP (95 percent confidence level) [SWU 87]; area (C) is the reactor $\bar{\nu}_e e$ result (68 percent confidence level) [FRE 76]; area (D) is the BNL result (68 percent confidence level) [ABE 89]; and are (E) is the CHARM II result (68 percent confidence level) [CHA 89]. The black area is based on the L3 measurements of Γ_{ll} and the asymmetry (68 percent confidence level) at the Z^0 [ADE 90].

Figure: Winter:
Neutrino Physics
Cambridge University Press

LEP: determination of number of neutrino generations

LEP:

$e^- + e^+ \rightarrow Z^0(\gamma) \rightarrow$

visible:
- $e^- + e^+$,
- $\mu^- + \mu^+$,
- $\tau^- + \tau^+$,
- $u + \bar{u}$,
- $d + \bar{d}$,
- $s + \bar{s}$,
- $c + \bar{c}$,
- $b + \bar{b}$,

invisible:
- $\nu_e + \bar{\nu}_e$,
- $\nu_\mu + \bar{\nu}_\mu$,
- $\nu_\tau + \bar{\nu}_\tau$,
- ????

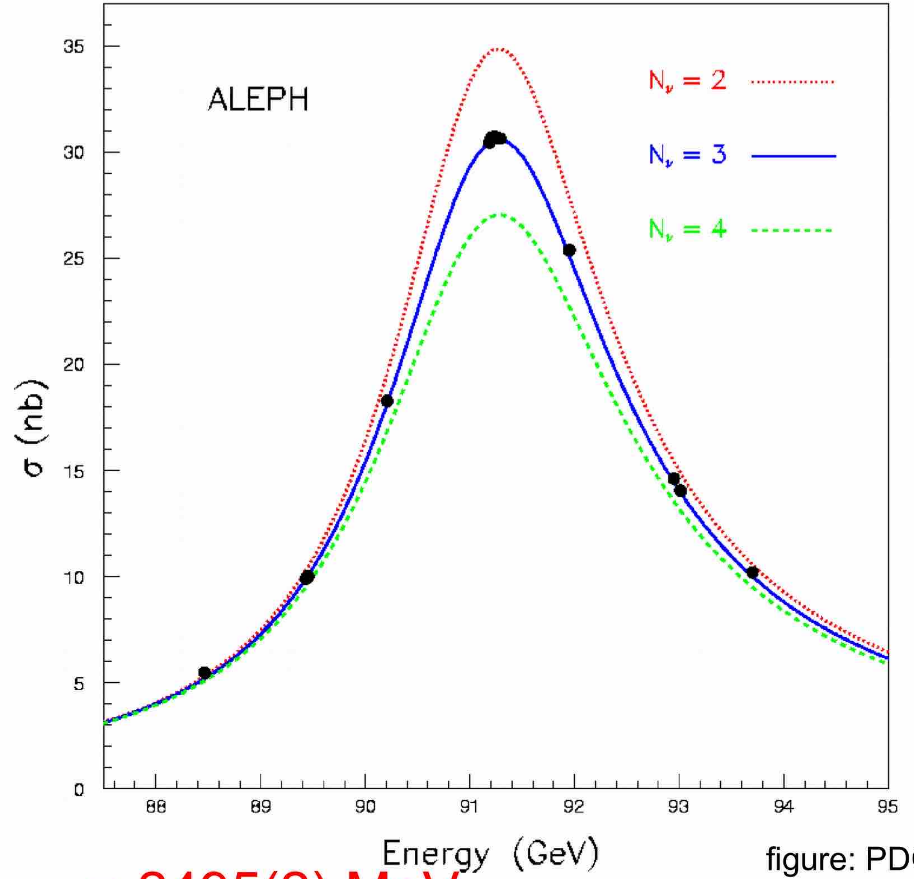


figure: PDG

Exp: full width: Γ = 2495(2) MeV

invisible width: $\Gamma_{\text{invisible}}$ = 499(2) MeV

ν partial width Γ_ν = 167.1 MeV $\Rightarrow N_\nu = 2.9840 \pm 0.0082$

Electroweak Standard Model: $U(1) \otimes SU(2)_L$

Components:

- a hypercharge field B_μ ($U(1)$), 3 weak gauge fields $W_{1,\mu}$, $W_{2,\mu}$, $W_{3,\mu}$ ($SU(2)$)
- a complex scalar Higgs doublet (4 components)
- left-chiral weak fermion doublets and right-chiral weak fermion singulets

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L \quad \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L \quad \begin{pmatrix}u\\ d\end{pmatrix}_L \quad \begin{pmatrix}c\\ s\end{pmatrix}_L \quad \begin{pmatrix}t\\ b\end{pmatrix}_L \quad e^-_R, \mu^-_R, \tau^-_R, u_R, d_R, c_R, s_R, t_R, b_R$$

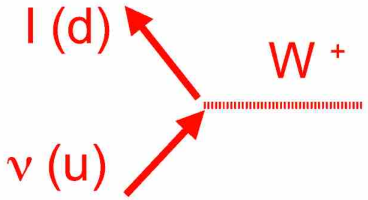
Electroweak Standard Model:

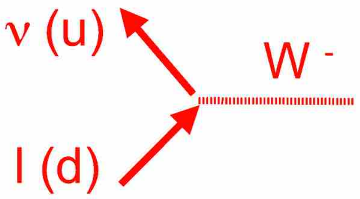
- $W_{1,\mu}$ and $W_{2,\mu}$ mix into W_μ^+ and W_μ^- (weak charged currents, ladder operators, CC)
- $W_{3,\mu}$ and B_μ mix into Z_μ^0 (neutral weak current, NC) and A_μ (photon)
  with weak mixing angle θ_W with $sin^2(\theta_W) \approx 0.231$

Spontaneous symmetry breaking:

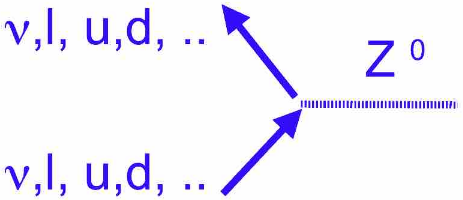
- 4 component Higgs provides masses to W_μ^+, W_μ^- and Z_μ^0 (loosing 3 degrees of freedom)
  → Higgs field H remains giving mass to the leptons via the Yukawa coupling

Electroweak interactions: Lagrangian for weak currents

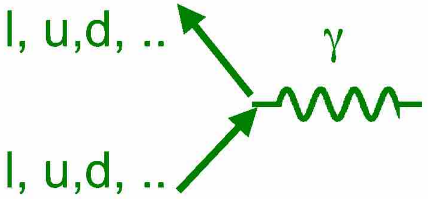




$$\mathcal{L} = \underbrace{\frac{g}{\sqrt{2}}\left(J_\mu^- W^{+\mu} + J_\mu^+ W^{-\mu}\right)}_{\text{weak charged current (CC)}}$$



$$+ \underbrace{\frac{g}{\cos\theta_W}\left(J_\mu^3 - \sin^2\theta_W J_\mu^{e.m.}\right) Z^{o\mu}}_{\text{weak neutral current (NC)}}$$



$$+ \underbrace{g \sin\theta_W J_\mu^{e.m.} A^\mu}_{\text{em neutral current}} \quad \ldots$$

coupling to electromagnetic current $J_\mu^{e.m.}$ as in QED: $g \sin\theta_W = e$

$\theta_W = 28.7°$ ⇒ coupling of weak interaction ≈ coupling of em. interaction,

but there is a term „m_W^2" (m_Z^2) in the denominator of the propagator, see later

ν cross sections

$\sigma \propto s$

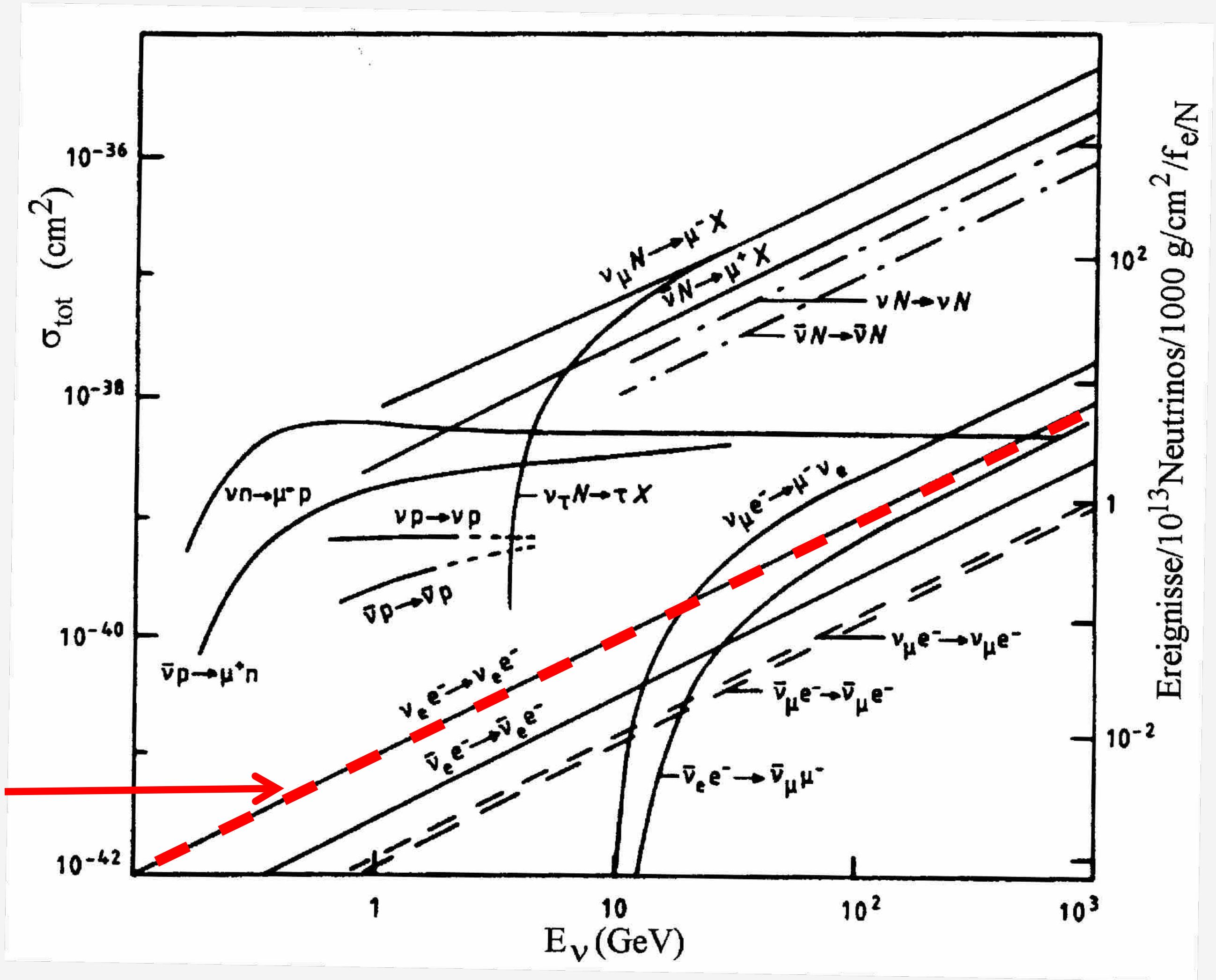


figure: Schmitz: Neutrinophysics, Teubner

ν-fermion scattering cross sections on fixed target: $\sigma \propto s = m_f^2 + 2 \cdot E_\nu \cdot m_f \rightarrow \sigma \propto E_\nu$

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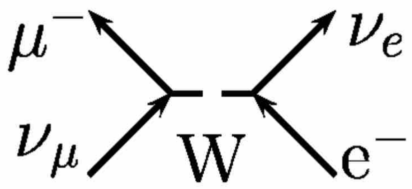
Angular distribution of neutrino-fermion scattering

Neutrino-fermion scattering:

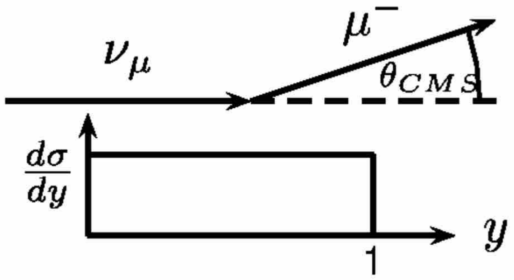


$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2} \cdot s \qquad (q^2 \ll M_W^2)$$

no angular dependence:

$$(\nu_\mu e^- \rightarrow \mu^- \nu_e)$$

$$\begin{array}{cc} \nu_\mu & e^- \\ \rightarrow & \leftarrow \\ \Leftarrow & \Rightarrow \end{array} \qquad J = 0$$

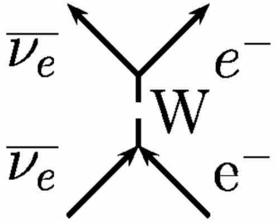


$$y = \frac{1 - \cos(\theta_{CMS})}{2}$$

y distribution is flat for νl scattering !

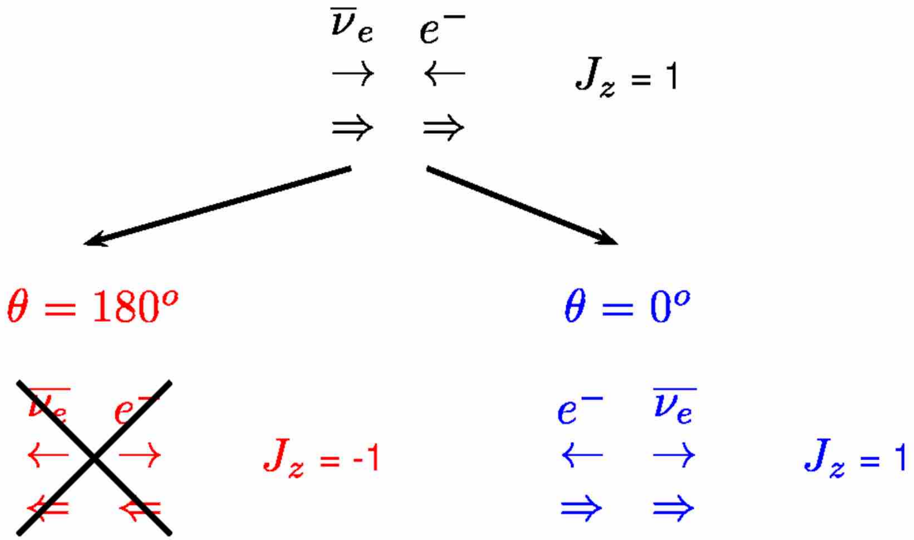
Angular distribution of antineutrino-fermion scattering

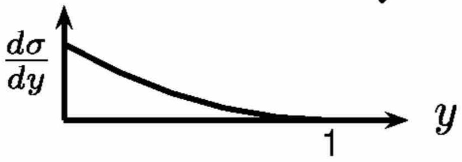
Antineutrino-fermion scattering (neglect NC):



$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2} \cdot s \cdot (1-y)^2$$

angular dependence:





y distribution $\Rightarrow \sigma_{\bar{\nu}l} = 1/3 \cdot \sigma_{\nu l}$

y distribution is not flat for $\bar{\nu}$l scattering !

Deep inelastic (anti)neutrino-nucleon scattering

Average: $\langle (1-y)^2 \rangle = 1/3$

$\Rightarrow$ expect: $\sigma^{\nu l} = 3\sigma^{\bar{\nu} l}$ and $\sigma^{\nu N} = 3\sigma^{\bar{\nu} N}$

Experiment:

$\sigma^{\nu l} = 3\sigma^{\bar{\nu} l}$, but $\sigma^{\nu N} \approx 2\sigma^{\bar{\nu} N} < 3\sigma^{\bar{\nu} N}$

From helicity arguements we deduce for the y distribution and for σ_{tot}:

$\bar{\nu}\, q = \nu\, \bar{q}$ and $\nu\, q = \bar{\nu}\, \bar{q}$

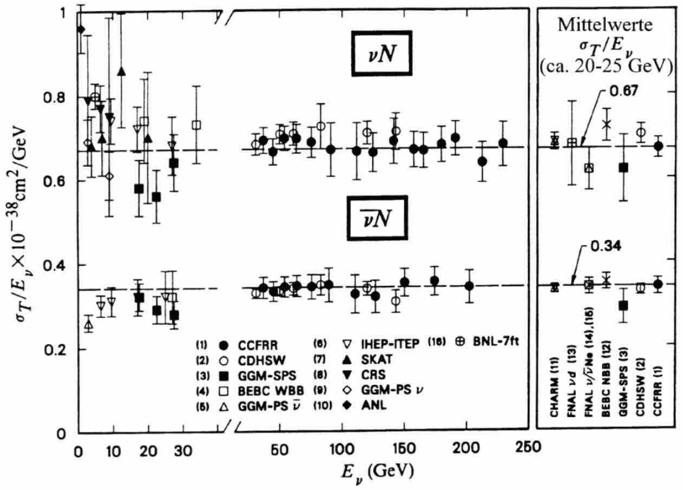
$$\frac{d^2\sigma^{\nu N}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi}\left(q(x) + (1-y)^2 \bar{q}(x)\right)$$

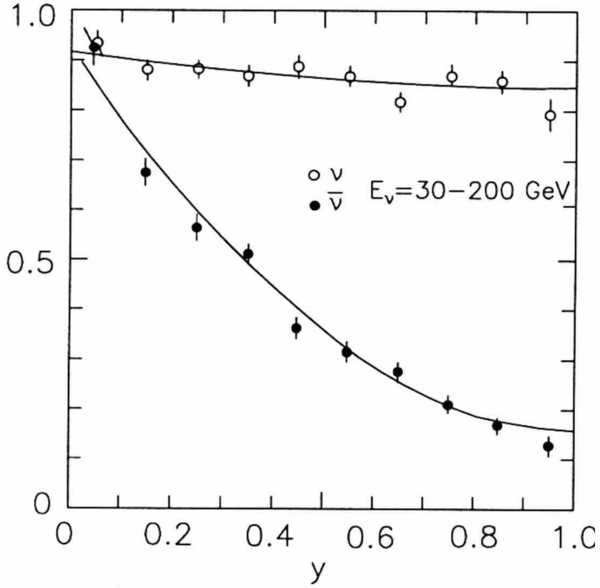
$$\frac{d^2\sigma^{\bar{\nu} N}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi}\left(\bar{q}(x) + (1-y)^2 q(x)\right)$$

with $q(x) = x\,(u(x) + d(x) + s(x) + ...)$

with $\bar{q}(x) = x\,\left(\bar{u}(x) + \bar{d}(x) + \bar{s}(x) + ...\right)$

$\Rightarrow$ Sea quark fraction $\bar{q}(x)$ is about 15%





figures: Perkins: Introduction to High Energy Physics, Cambridge

Deep inelastic (anti)neutrino-nucleon scattering

Average: $\langle (1-y)^2 \rangle = 1/3$

$\Rightarrow$ expect: $\sigma^{\nu l} = 3\sigma^{\bar{\nu} l}$ and $\sigma^{\nu N} = 3\sigma^{\bar{\nu} N}$

Experiment:

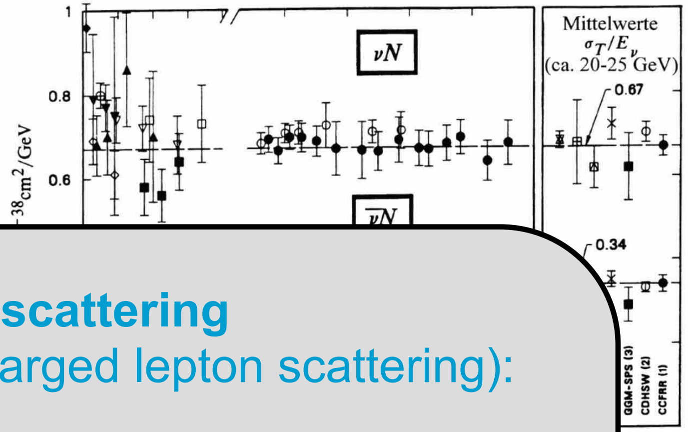
$\sigma^{\nu l}$

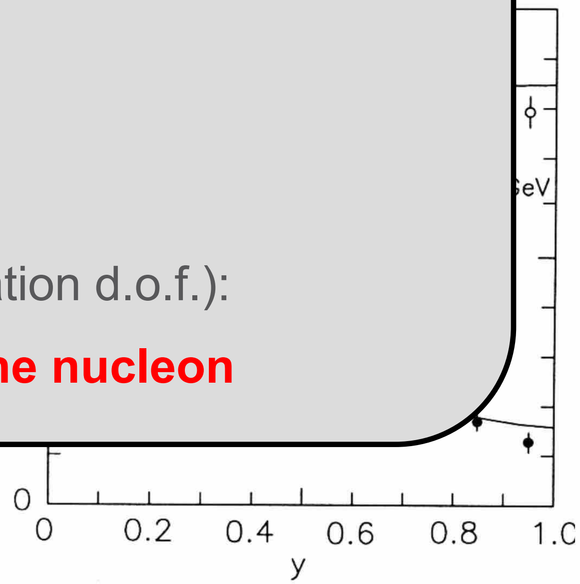
From

for the

$\frac{d^2\sigma^{\nu N}}{dxdy}$

$\frac{d^2\sigma^{\bar{\nu} N}}{dxdy}$





Results from neutrino-nucleon scattering
(in addition to in deep inelastic charged lepton scattering):

Nucleon consists of partons:

- point-like
- charges of $\pm 1/3$ and $\pm 2/3$
- spin ½
- Only with neutrinos (or with polarisation d.o.f.):

$\rightarrow$ **there are sea-quarks in the nucleon**

$\Rightarrow$ Sea quark fraction $\bar{q}(x)$ is about 15%

figures: Perkins: Introduction to High Energy Physics, Cambridge

Lagrangian of the Standard Model: mass terms

Dirac mass terms in the Standard Model with the Higgs doublet

$$\mathcal{L} = -f_e\,(\overline{\nu_e},\overline{e})_L \begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix} e_R - f_u\left(\bar{u},\bar{d}\right)_L \begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix}^C u_R - f_d\left(\bar{u},\bar{d}\right)_L \begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix} d_R + \ldots + h.c.$$

No neutrino mass terms, since there exist no right-handed neutrinos ν_R in the classical Standard Model !

Spontaneous symmetry breaking (loose 3 d.o.f. to give W^+, W^- and Z^0 mass):

$$\begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix} = \begin{pmatrix}0\\ v/\sqrt{2}\end{pmatrix}$$

Fermion mass terms:

$$\mathcal{L} = -\underbrace{\frac{f_e\cdot v}{\sqrt{2}}}_{:=m_e}\overline{e_L}\,e_R - \underbrace{\frac{f_u\cdot v}{\sqrt{2}}}_{:=m_u}\overline{u_L}\,u_R - \underbrace{\frac{f_d\cdot v}{\sqrt{2}}}_{:=m_d}\overline{d_L}\,d_R + \ldots + h.c.$$

General: Dirac mass terms for fermions in the standard model:

$$\mathcal{L} = m_D\left(\overline{\Psi_L}\Psi_R + \overline{\Psi_R}\Psi_L\right) + \ldots$$

Lagrangian of the Standard Model: mass terms

Dirac mass terms in the Standard Model with the Higgs doublet

$\mathcal{L} \quad = \quad -f$ ... $+ \ldots \quad + h.c.$

We could introduce neutrino masses the same way (Dirac mass term) into the Standard Model by allowing right-handed neutrinos,

but then we have to motivate why the Yukawa couplings f_ν are at least 6 and more orders of magnitude smaller than the ones of the charged fermions !

→ other solutions are preferred:
neutrinos are neutral

→ Majorana-type neutrinos are possible

→ Beyond the Standard Model, see other talks

No neutrin... the
classical S...
Spontaned... s):

Fermion m...

$\mathcal{L} \quad = \quad - \ldots \quad + \ldots \quad + h.c.$

$:= m_e \qquad := m_u \qquad := m_d$

General: Dirac mass terms for fermions in the standard model:

$$\mathcal{L} \quad = \quad m_D \left(\overline{\Psi_L} \Psi_R + \overline{\Psi_R} \Psi_L \right) \quad + \ldots$$

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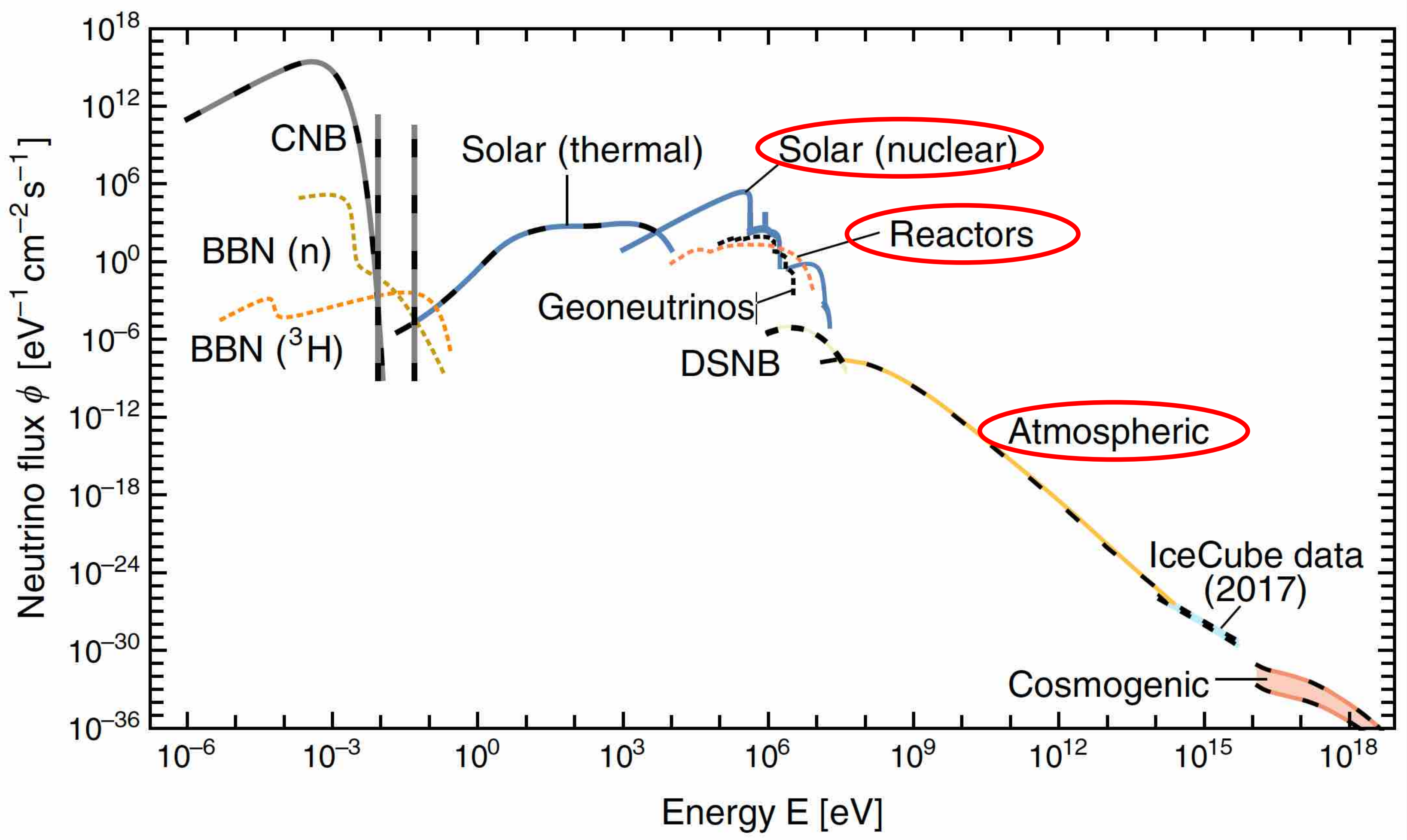
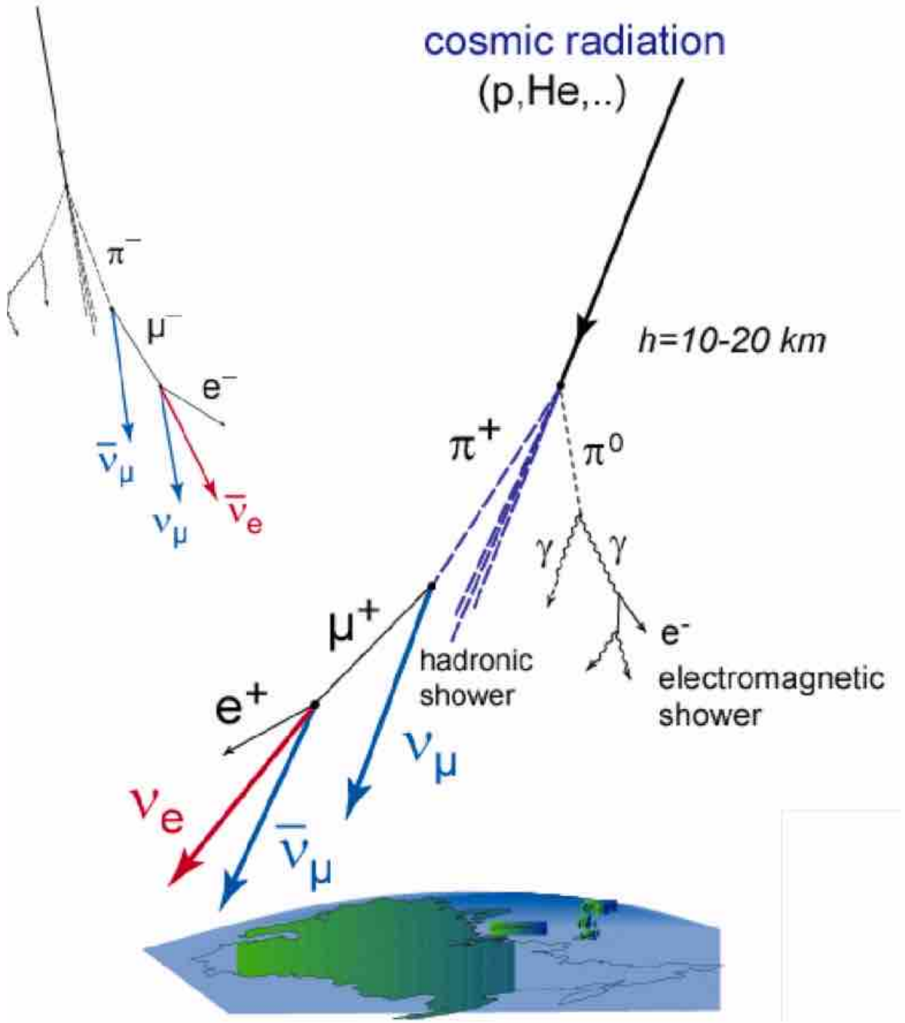
Neutrino sources and energy spectra



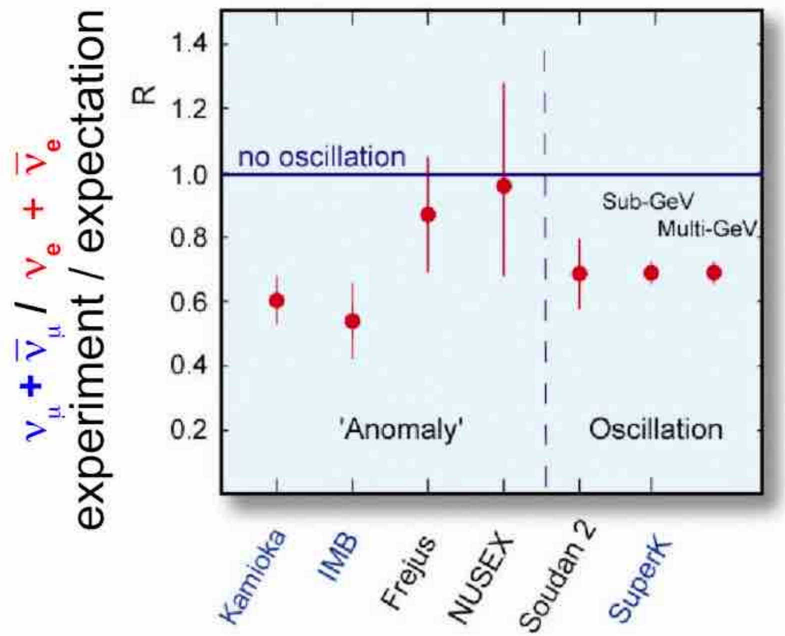
Rev. Mod. Phys. 92, 045006 (2020)

Atmospheric neutrinos



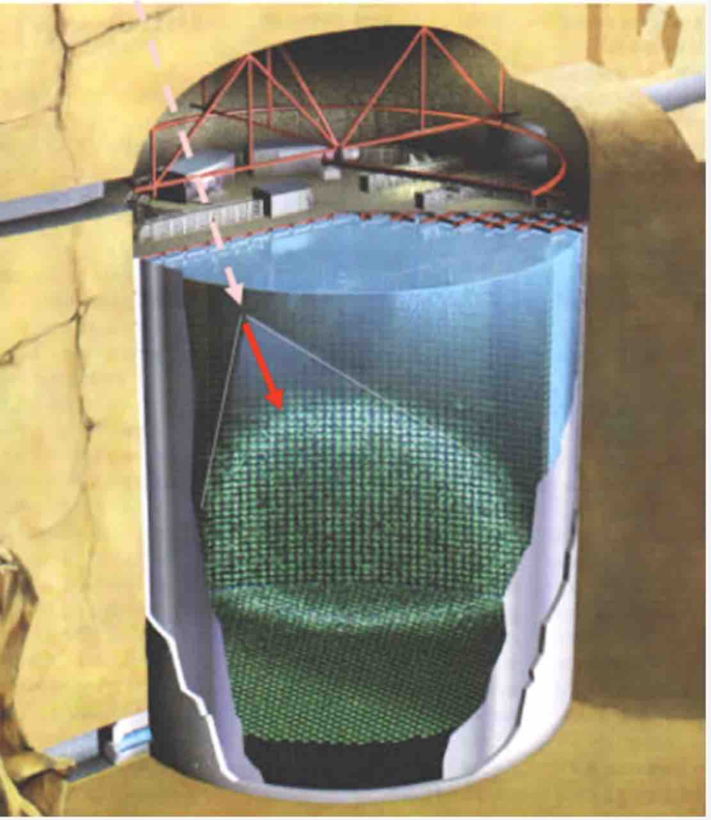
Interaction of cosmic rays (p,α, ..)
in outer atmosphere: $\Rightarrow \pi^\pm$, $K^\pm$,...

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\rightarrow e^- + \nu_\mu + \bar{\nu}_e$$
$$\Rightarrow \quad \nu_\mu + \bar{\nu}_\mu \,/\, \nu_e + \bar{\nu}_e \geq \mathbf{2}$$



Super-Kamiokande Detector

50 000 t water Cherenkov detector



40 m high

40 m ∅

11146

light sensors

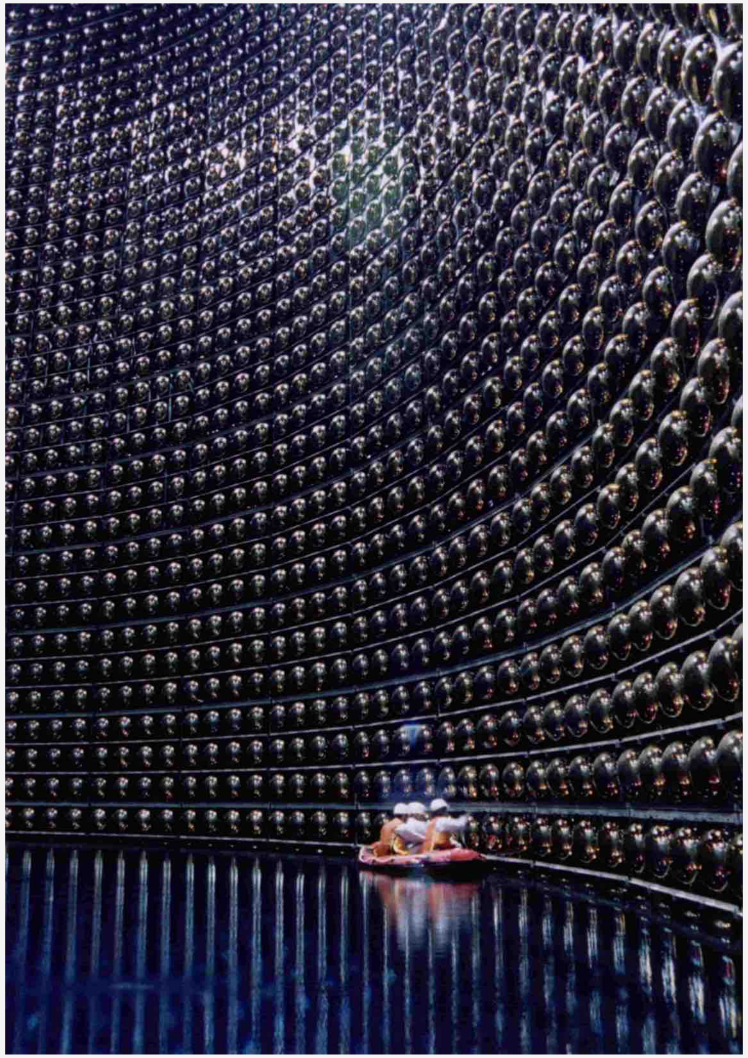
(photomultiplier)

50 cm ∅

1 km deep in the

Kamioka mine

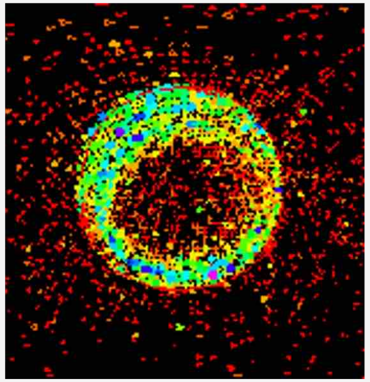
in Japan



Cherenkov cone provides:

- energy
- direction
- differentiate electron / muon:

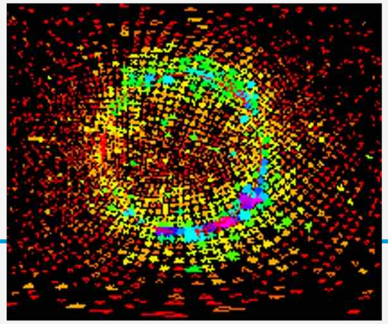
  muns: sharp ring



electrons:

smeered ring

(scatterig, el-mag. shower)



Super-Kamiokande's first result at Int. Conf. Neutrino 1998 at Takayama

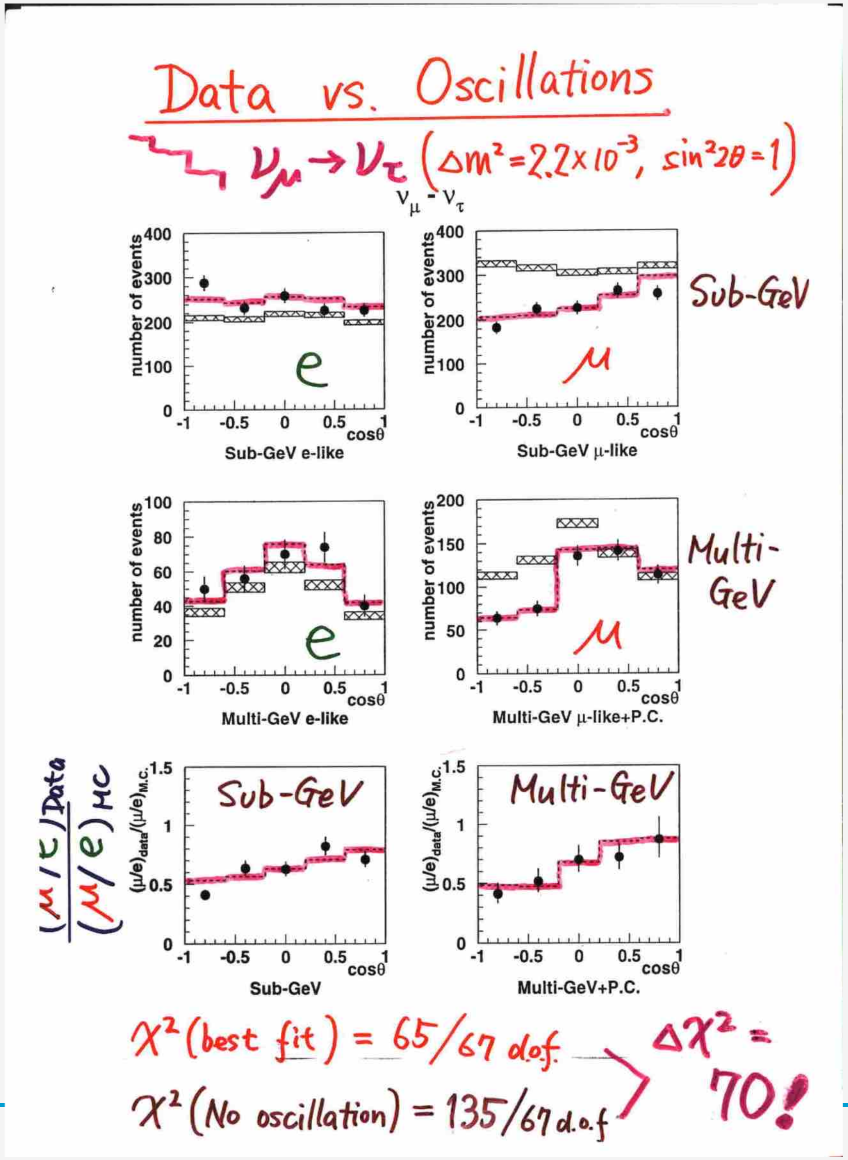
@Takayama 1998

Atmospheric neutrino results from Super-Kamiokande & Kamiokande

— Evidence for ν_μ oscillations —

T. Kajita
Kamioka observatory, Univ. of Tokyo
for the {Kamiokande, Super-Kamiokande} Collaborations

Nobel prize 2015 to Takaaki Kajita



Solar nuclear fusion and neutrinos from the sun

Universität Münster

Nuclear fusion in sun core:

$$4\,p \rightarrow {}^4He + 2e^+ + 2\nu_e \qquad (+\,26.7\ \text{MeV})$$

in more detail:

$p + p \mapsto {}^2H + e^+ + \nu_e$

$p + e^- + p \mapsto {}^2H + \nu_e$

${}^2H + p \mapsto {}^3He + \gamma$

85 %: ${}^3He + {}^3He \mapsto {}^4He + 2p$

15 %: ${}^3He + {}^4He \mapsto {}^7Be + \gamma$

0.02 %:
- ${}^7Be + p \mapsto {}^8B + \gamma$
- ${}^8B \mapsto {}^8Be^* + e^+ + \nu_e$
- ${}^8Be^* \mapsto {}^4He + {}^4He$

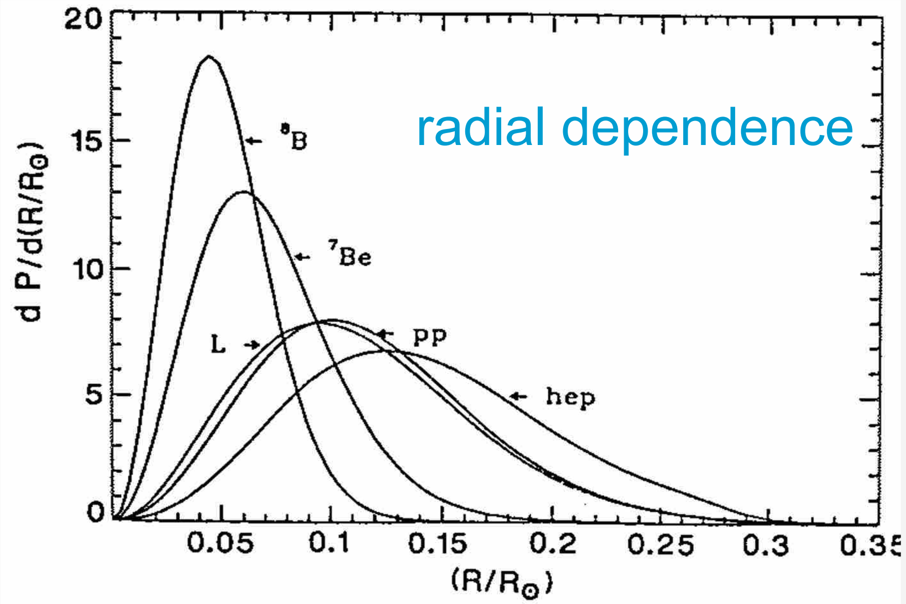
- ${}^7Be + e^- \mapsto {}^7Li + \nu_e$
- ${}^7Li + p \mapsto {}^4He + {}^4He$

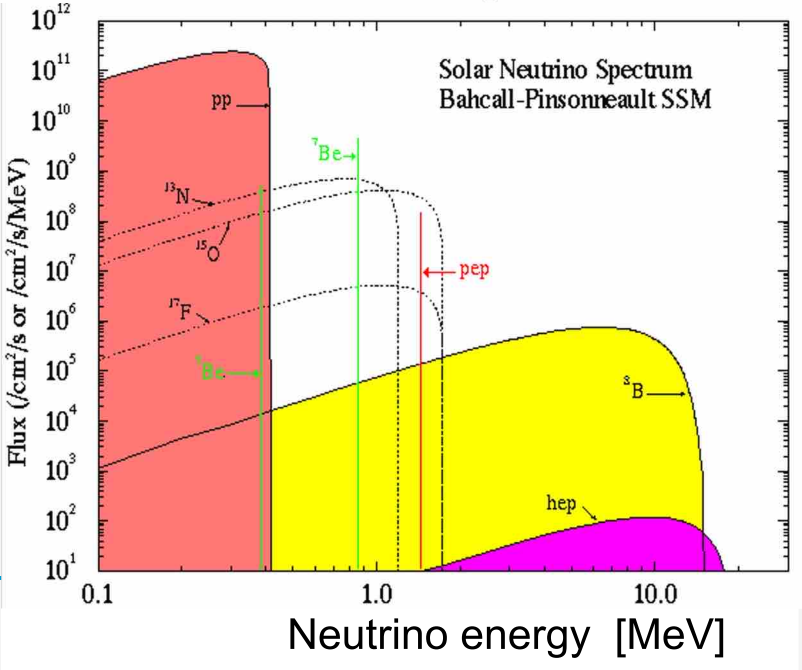
${}^3He + p \mapsto {}^4He + e^+ + \nu_e$

$T_\odot = 1.56 \cdot 10^7$K, $T_{photosphere} = 5777$ K

neutrino rate arriving on earth surface:

65 billion of neutrinos per s and cm^2





Discovery of neutrino oscillations → m(ν)≠0

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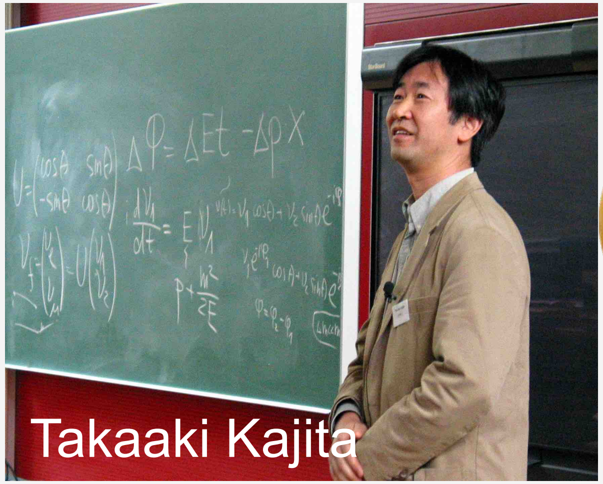
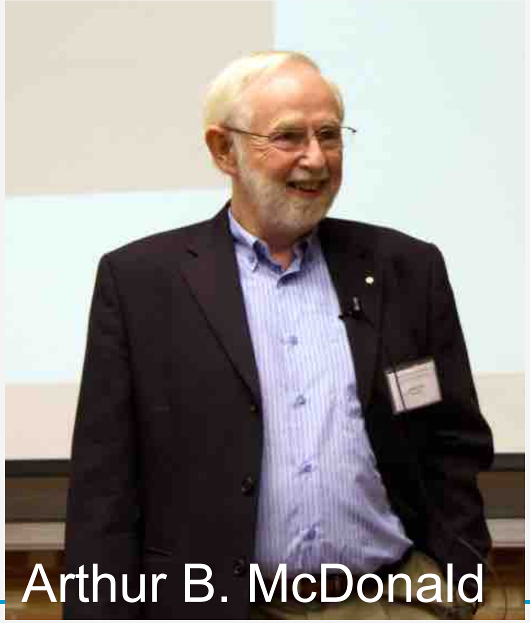
Super Kamiokande experiment (1998)

atmospheric neutrinos: $\nu_\mu \rightarrow \nu_\tau$



Sudbury Neutrino Observatory SNO (2001/02)

solar neutrinos: $\nu_e \rightarrow \nu_\mu/\nu_\tau$



Nobel Prize in physics 2015

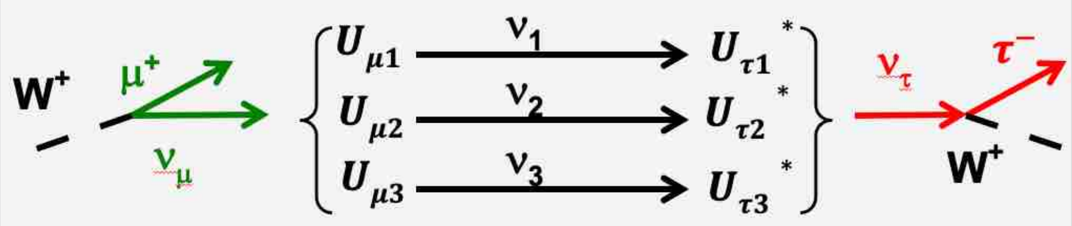
Neutrino (vacuum) oscillation:

3 flavor ν_e, ν_μ, ν_τ & 3 mass eigenstates ν_1, ν_2, ν_3

mixed by a unitary 3×3 matrix U_{PMNS}

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\cdot\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

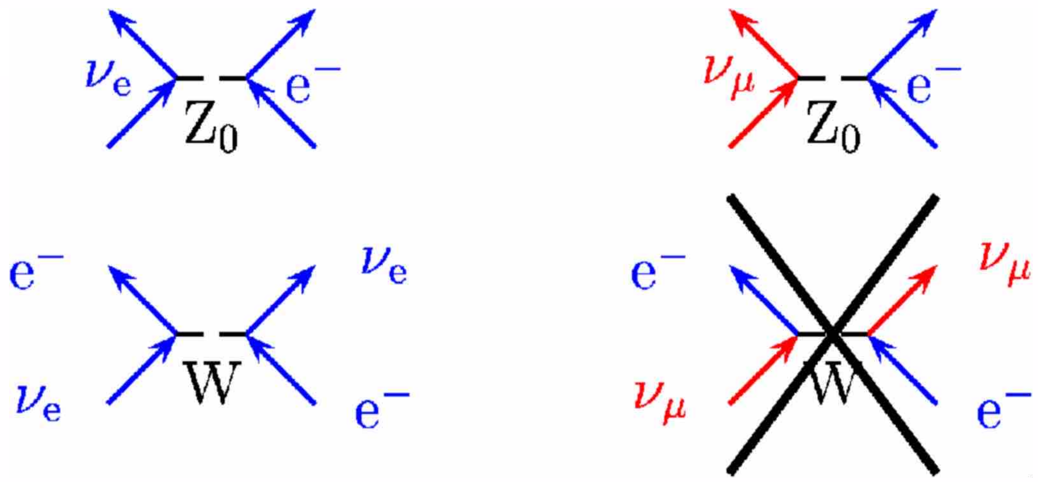
→ **„tripple slit“ exp.**: solar $\nu_e \rightarrow \nu_\mu, \nu_\tau$, atmospheric $\nu_\mu \rightarrow \nu_\tau$



Matter-enhanced neutrino oscillation

MSW effect (Mirkheyev-Smirnov-Wolfenstein)

Coherent forward scattering of ν on e⁻



General idea:

Different refraction index for ν_e and ν_μ

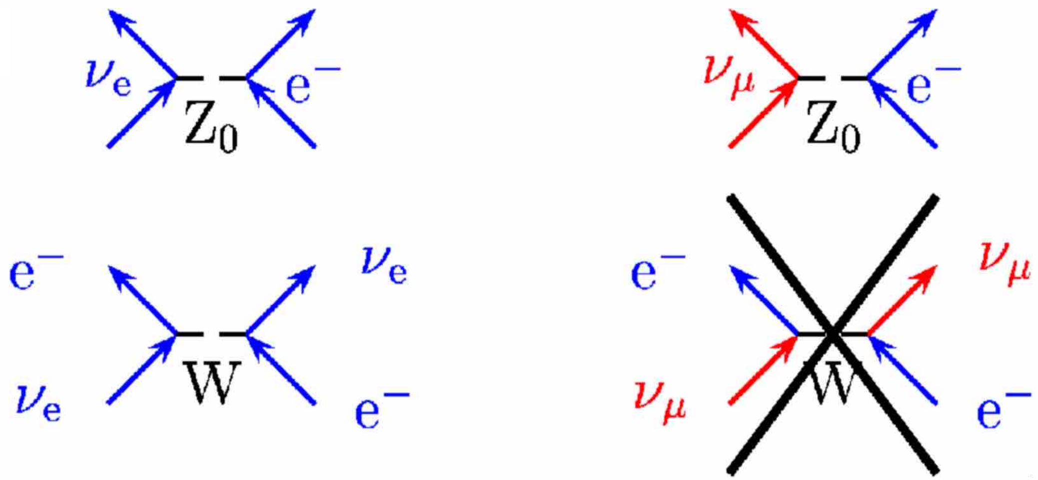
$\Rightarrow$ Different phase difference during propagation

$\Rightarrow$ Neutrino oscillation

Matter-enhanced neutrino oscillation

MSW effect (Mirkheyev-Smirnov-Wolfenstein)

Coherent forward scattering of ν on e^-

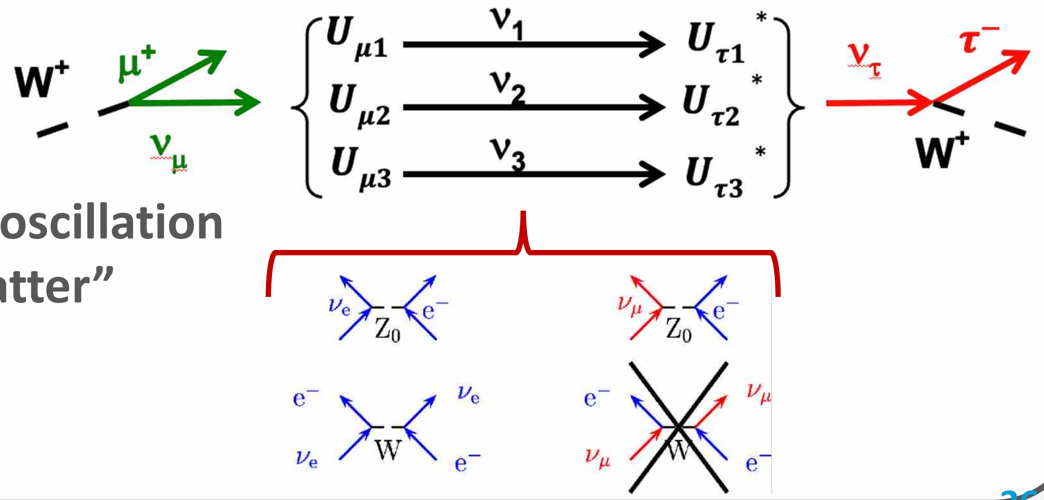


General idea:

Different refraction index for ν_e and ν_μ

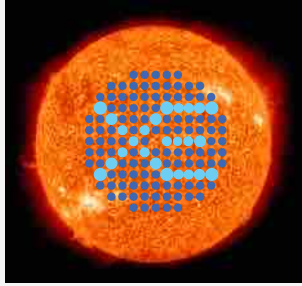
$\Rightarrow$ Different phase difference during propagation

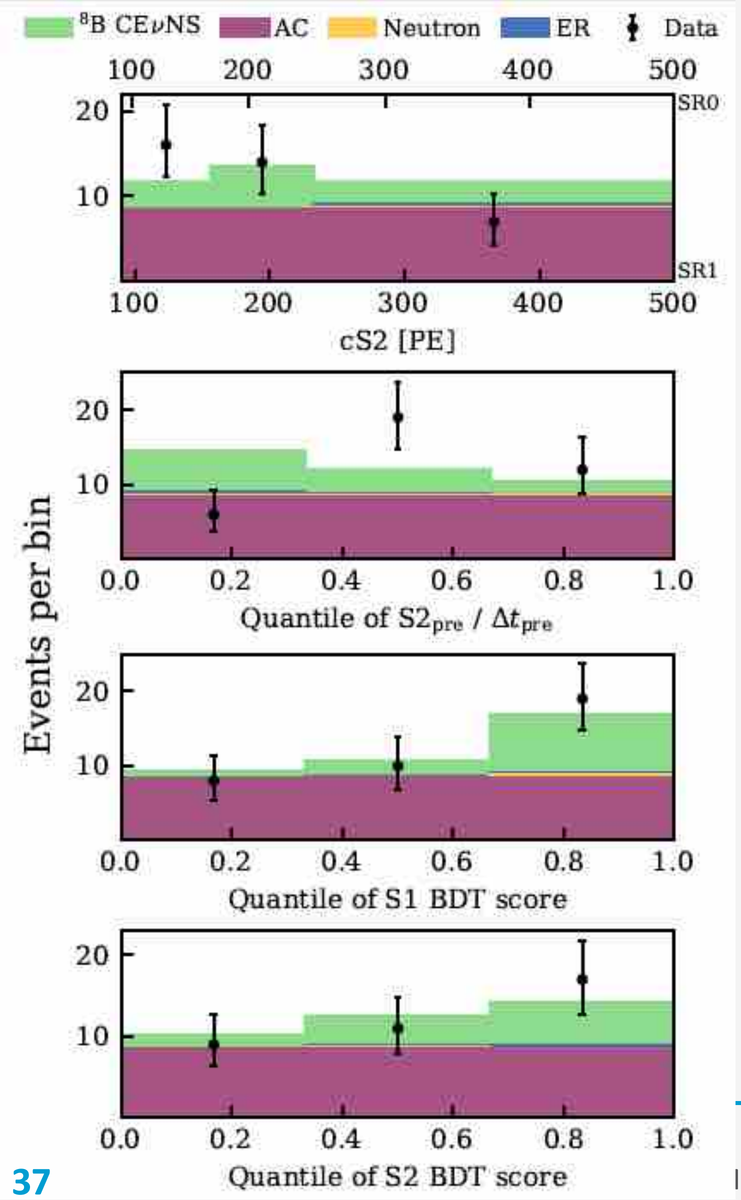
$\Rightarrow$ Neutrino oscillation



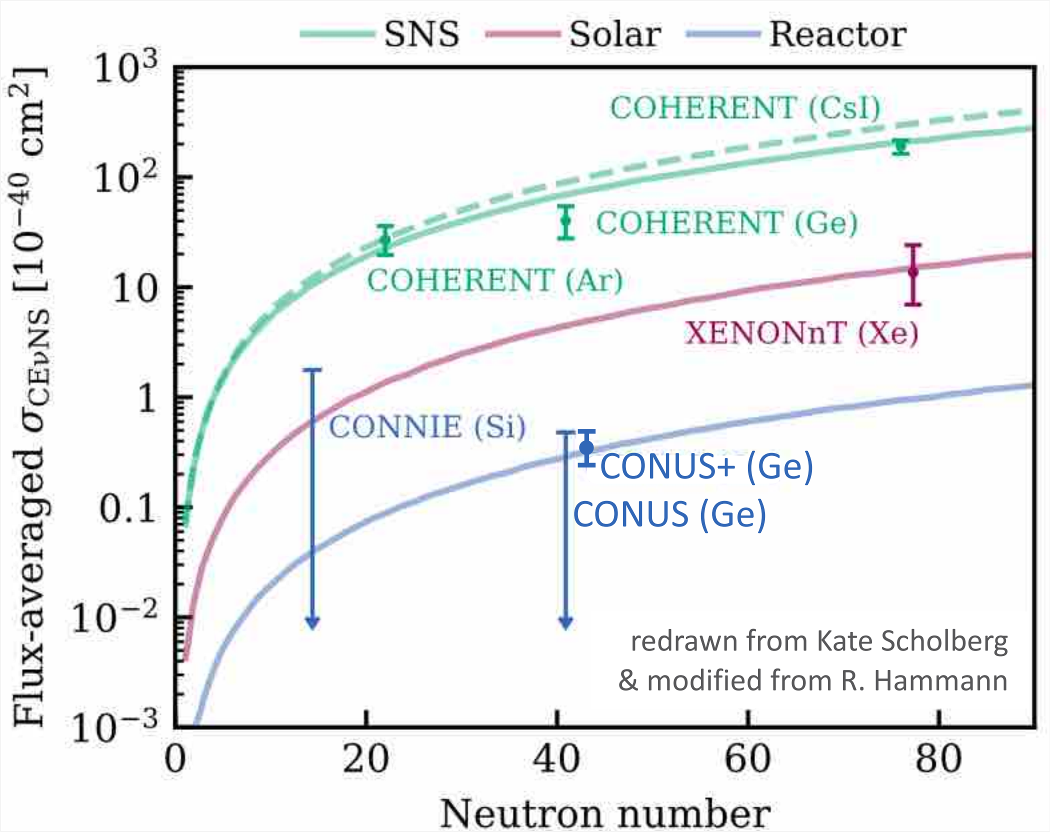
"Neutrino oscillation in matter"

First measurement of solar ^{8}B neutrinos (SR0+SR1) by coherent elastic neutrino nuclear scattering (CEνNS)





$$\sigma_{CE\nu NS} \propto Q_W^2 \propto \left[N - \left(1 - 4\sin^2 Q_W\right)Z\right]^2 \approx N^2$$



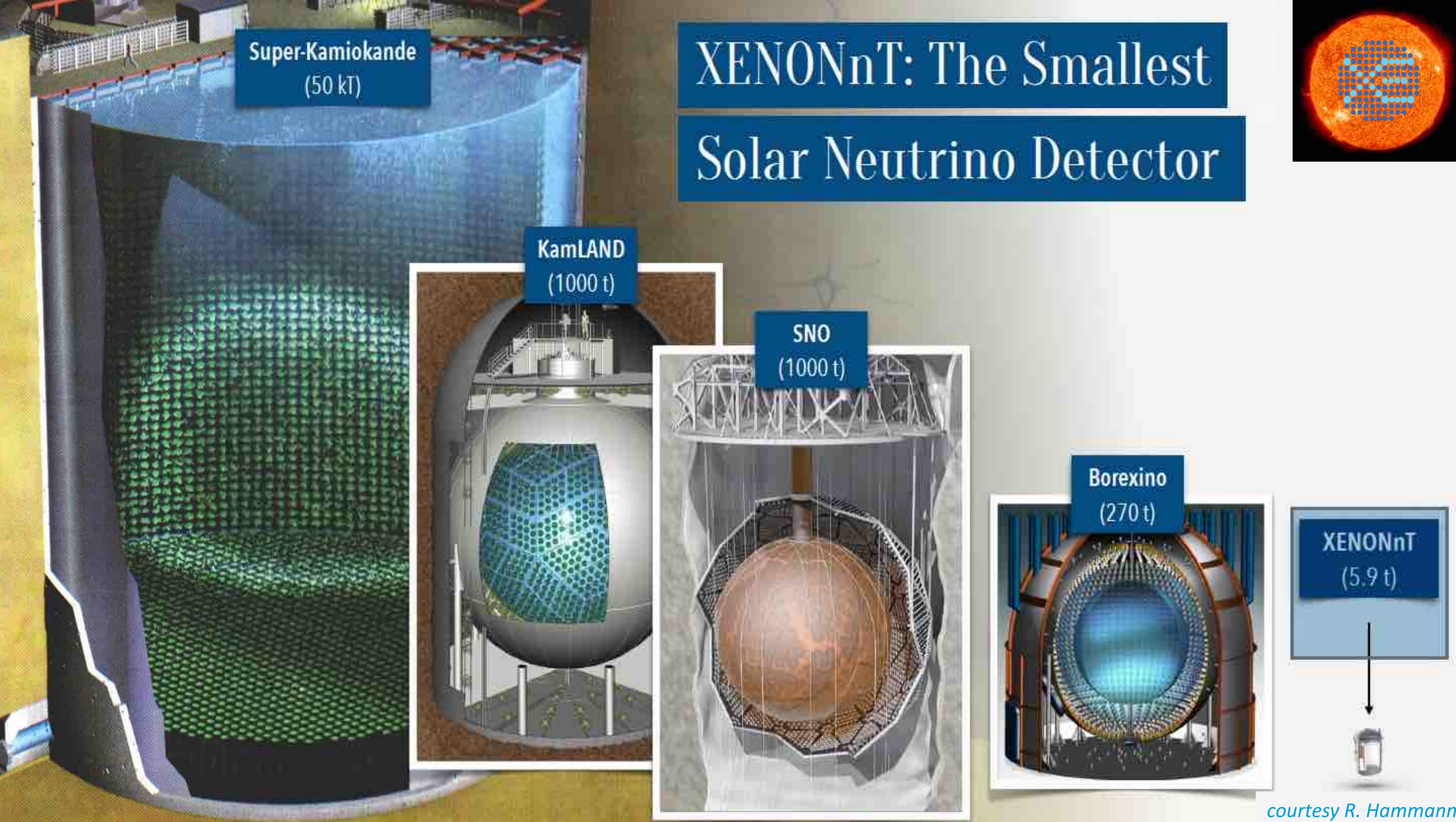
XENONnT confirms the solar ^{8}B fneutrino flux from SNO by CEνNS with 2.7σ

Phys. Rev. Lett. 133 (2024) 191002

XENONnT: The Smallest Solar Neutrino Detector

courtesy R. Hammann

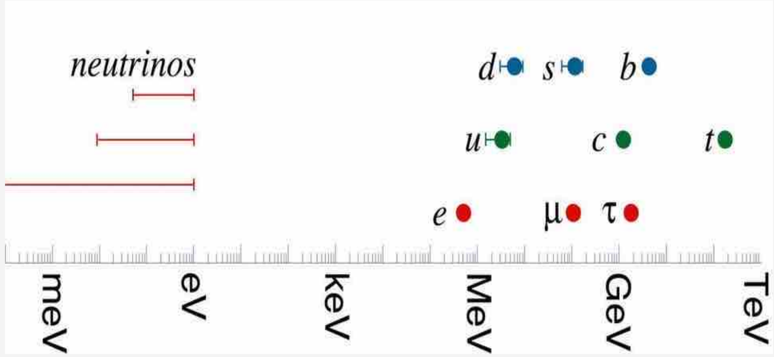
XENONnT: The Smallest Solar Neutrino Detector



courtesy R. Hammann

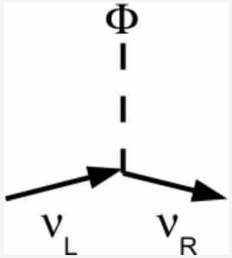
Majorana neutrinos

Neutrinos are so much lighter than the other 9 charge particles of the 12 fermions in our Standard Model of particle physics



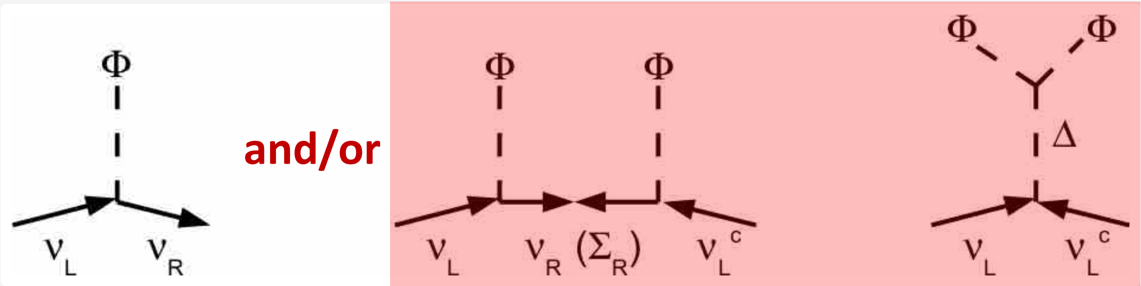
http://hitoshi.berkeley.edu

These 9 particles obtain their mass through the direct Yukawa coupling to the Higgs ϕ:



Would it be not natural that the neutrinos obtain their mass through a different mechanism?
This could be a seesaw mechanism requirering neutrinos to be their own anti-particles (Majorana neutrinos)

See saw mechanism with Majorana neutrinos and BSM physics at very large energy scales



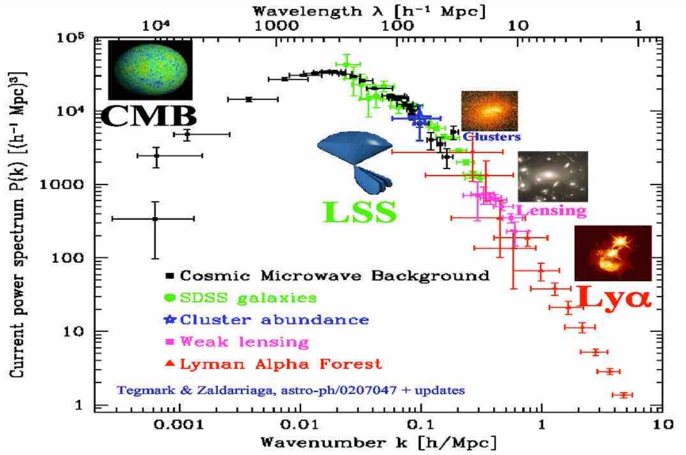
Complementary ways to the neutrino mass

Cosmology

$\sum_i m(\nu_i) = 3 \cdot \overline{m(\nu_i)}$

very sensitive, but model dependent

compares power at different scales



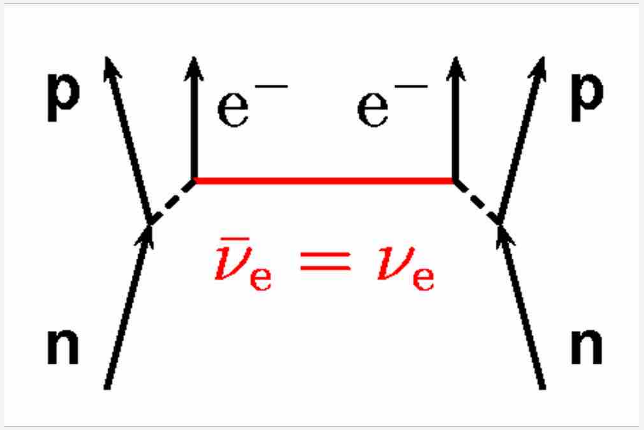
upper limit: $\sum_i m(\nu_i) \approx$ 0.072 eV (CMB+BAO)

close to minimal values for
60 meV (NO), 100 meV (IO)

0νββ

$m_{\beta\beta} := \left|\sum_i U_{ei}^2 \cdot m(\nu_i)\right|$

sensitive to Majorana ν only,
nuclear matrix elements



upper limits by CUORE, EXO-200,
GERDA, KamLAND-Zen, ..

**disovery of 0νββ would be BSM:
Majorana ν & lepton number violation**

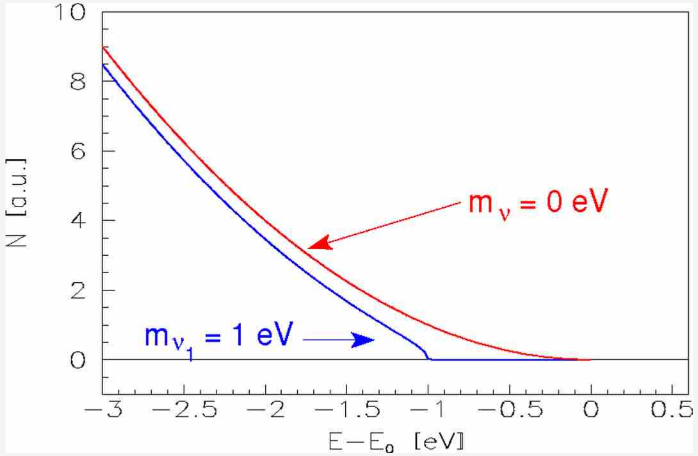
Direct neutrino mass search

$m^2(\nu_e) := m_\beta^2 := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$

no further assumptions needed

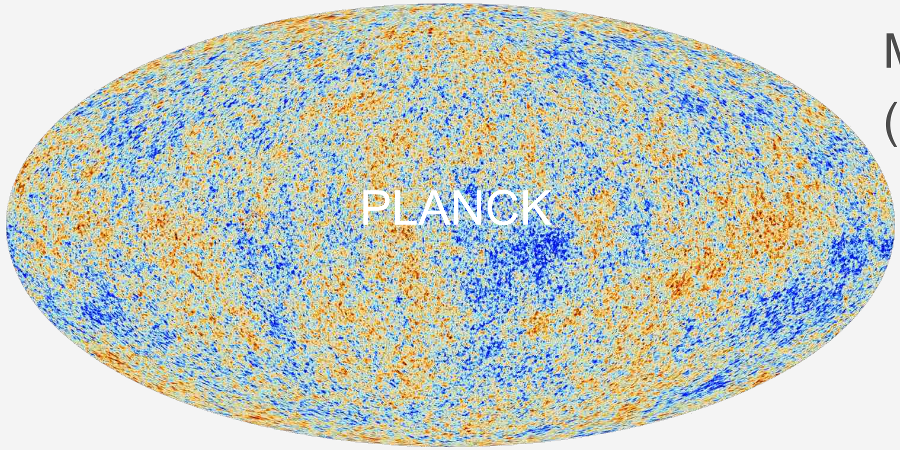
Time-of-flight measurements
(ν from supernova)

Kinematics of weak decays,
e.g. tritium (β^-), ^{163}Ho (EC)

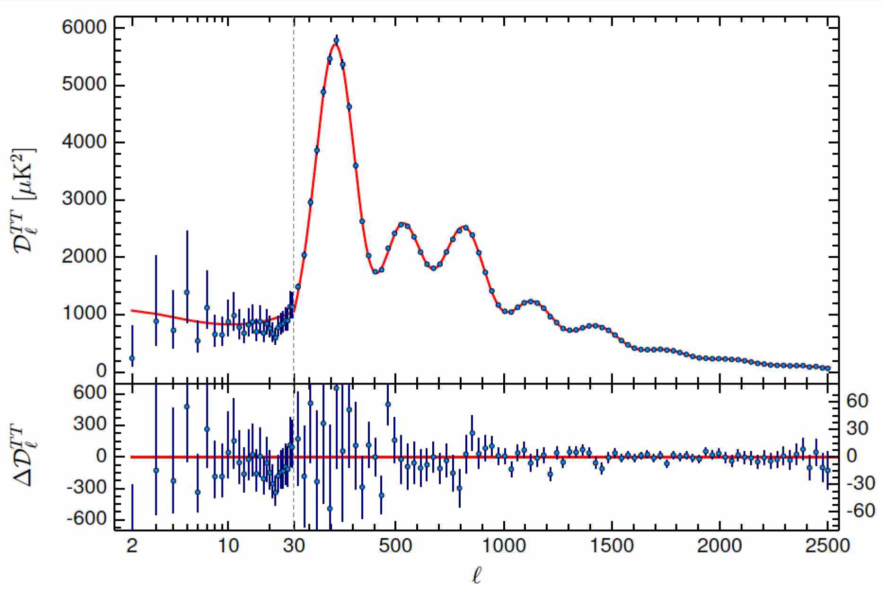


measure charged decay products,
use E-, $\vec{p}$-conservation

Neutrino mass from cosmology

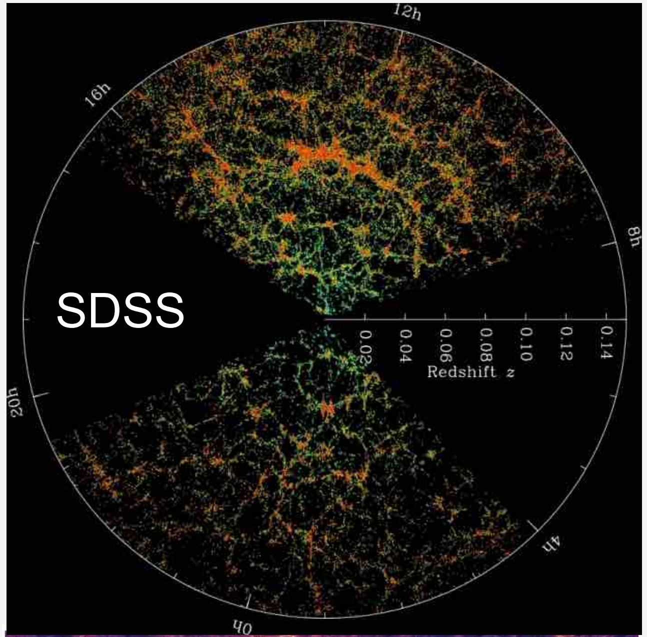


Measurement of CMB
(Cosmic Microwave Background radiation)



Planck Collaboration:
P. A. R. Ade et al., arXiv:1502.01589

Measurement of matter density distribution LSS (Large Scale Structure) by 2dF, SDSS, ...



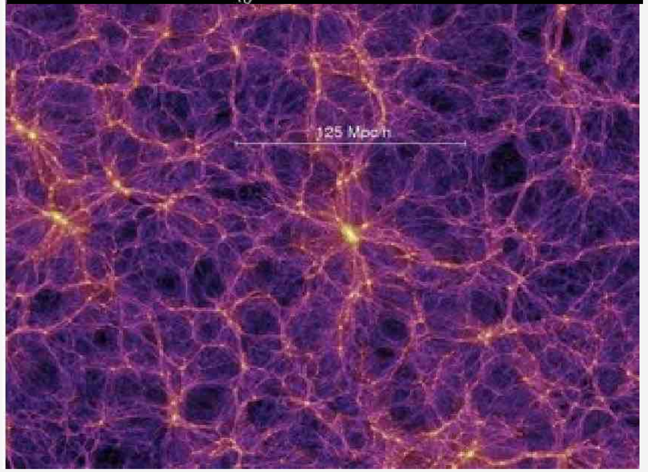
Compare to numerical models including relic neutrino densitiy of 336 cm^{-3}

→ within the ΛCDM model:

$\sum m(\nu_i) < 0.12$ **eV / 0.071 eV**

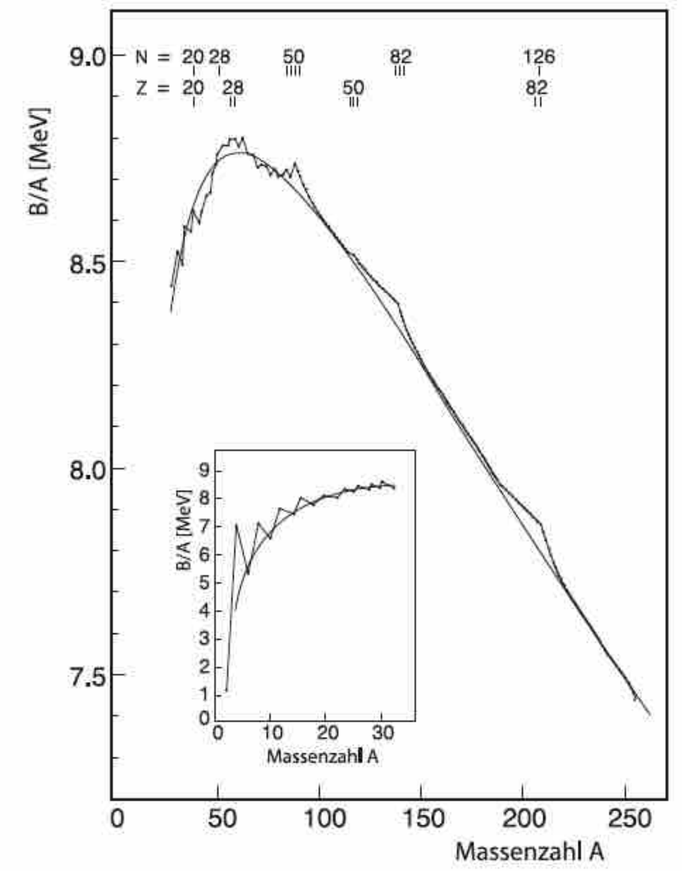
Planck Collaboration, A&A 641, A6 (2020)

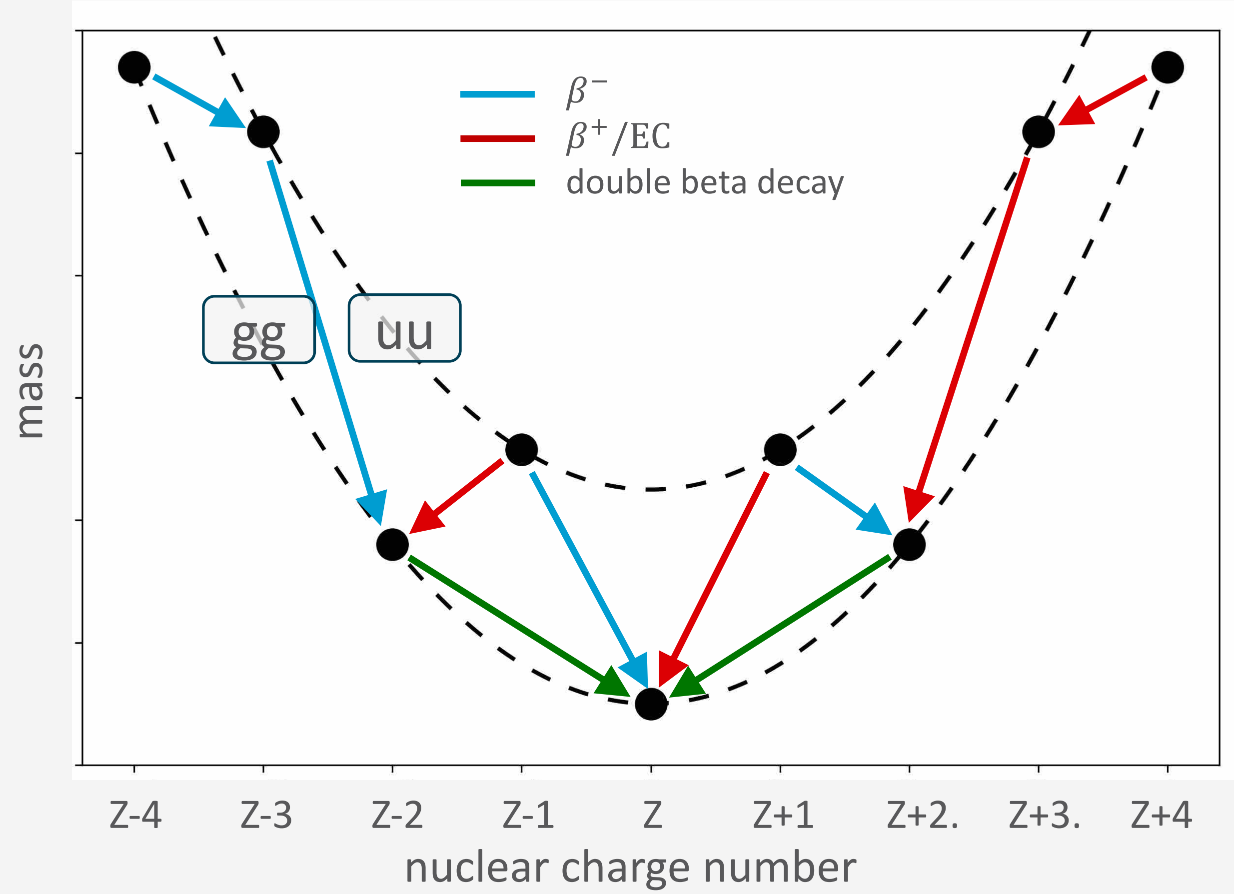
DESI, arXiv:2411.12022



Millenium simulation
http://www.mpa-garching.mpg.de/galform/presse/

Repetition of droplet model: Isobars (A=const) for odd and even mass numbers A

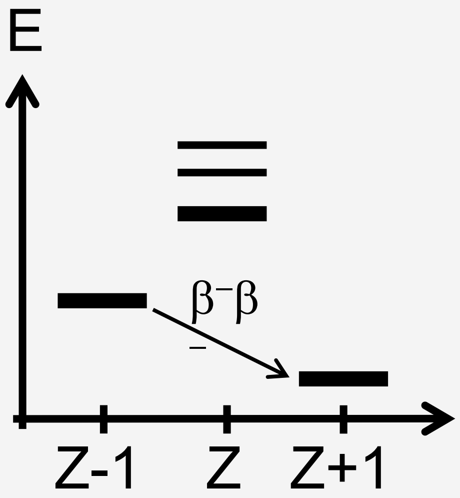




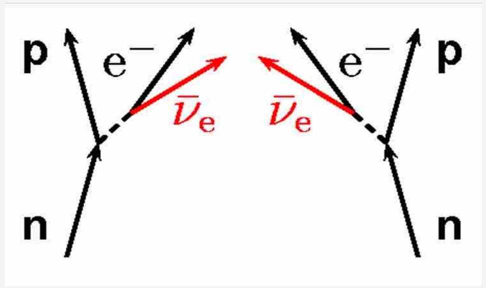
$$\frac{B}{A} = a_v \cdot A - a_s \cdot A^{2/3} - \boldsymbol{a_C} \cdot \frac{\boldsymbol{Z^2}}{\boldsymbol{A^{1/3}}} - \boldsymbol{a_a} \cdot \frac{\boldsymbol{(N-Z)^2}}{\boldsymbol{4A}} - \delta \cdot \frac{1}{A^{1/2}}$$

$$\text{mit } \delta = \left\{ \begin{array}{c} -11.2 \text{ MeV for gg} \\ 0 \text{ for ug or gu} \\ +11.2 \text{ MeV for uu} \end{array} \right\}$$

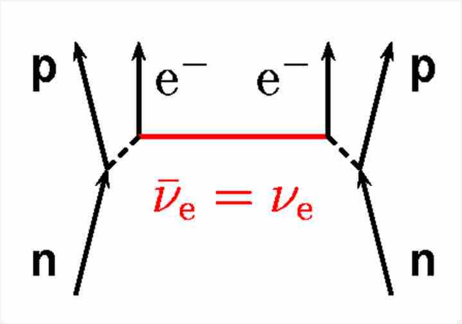
Double β decay



normal (2νββ)



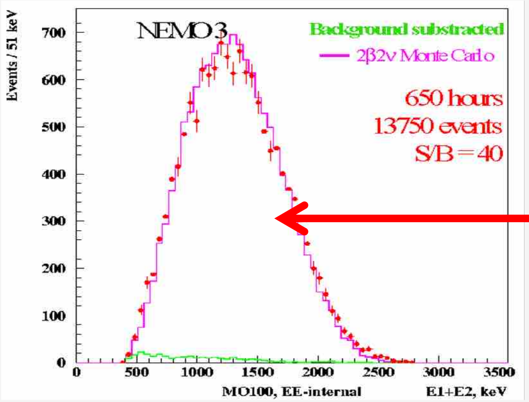
neutrinoless (0νββ)

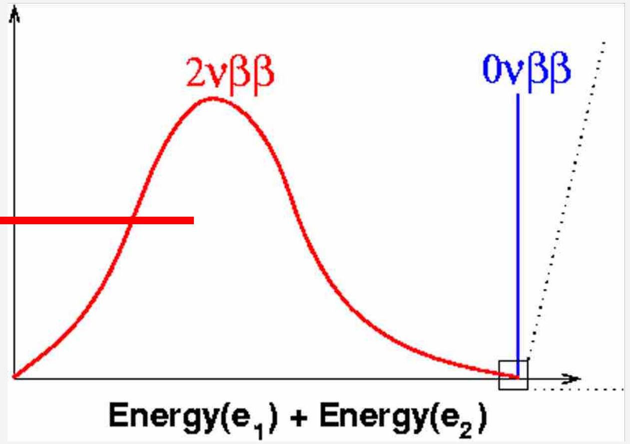


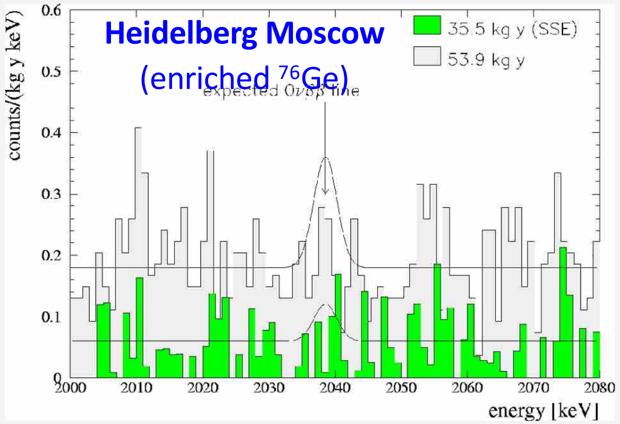
a) $\nu = \bar{\nu}$ (Majorana)

b) unfavored helicity: m(ν) ≠ 0

or other new physics





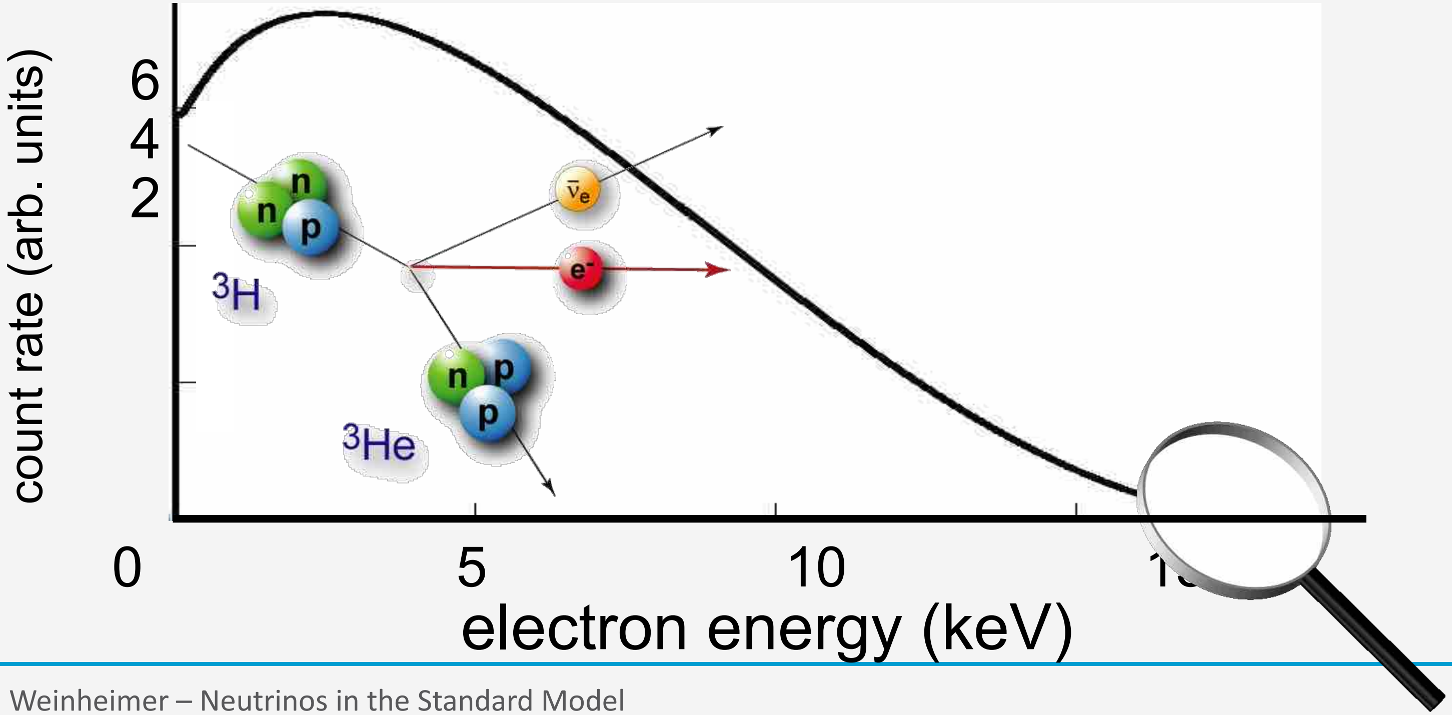


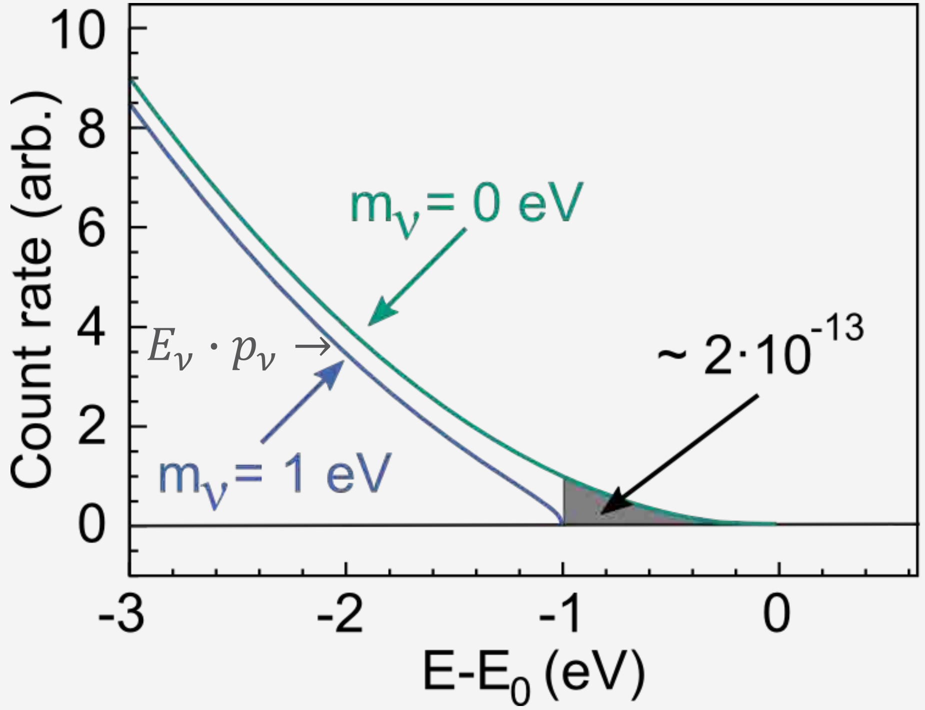
Direct determination of “$m(\nu_e)$“ from β-decay (EC)

β-spectrum: $\frac{dN}{dE} = K \cdot F(E,Z) \cdot p \cdot E_{tot} \cdot (E_0 - Ee) \cdot \sum_i |U_{ei}|^2 \cdot \sqrt{(E_0 - E_e)^2 - m^2(\nu_i)}$

essentially phase space: p_e E_e E_ν p_ν

with “electron neutrino mass”: $"m^2(\nu_e)" := \sum_i |U_{ei}|^2 \cdot m^2(\nu_i)$, complementary to 0νββ & cosmology
(modified by electronic final states, recoil corrections, radiative corrections)

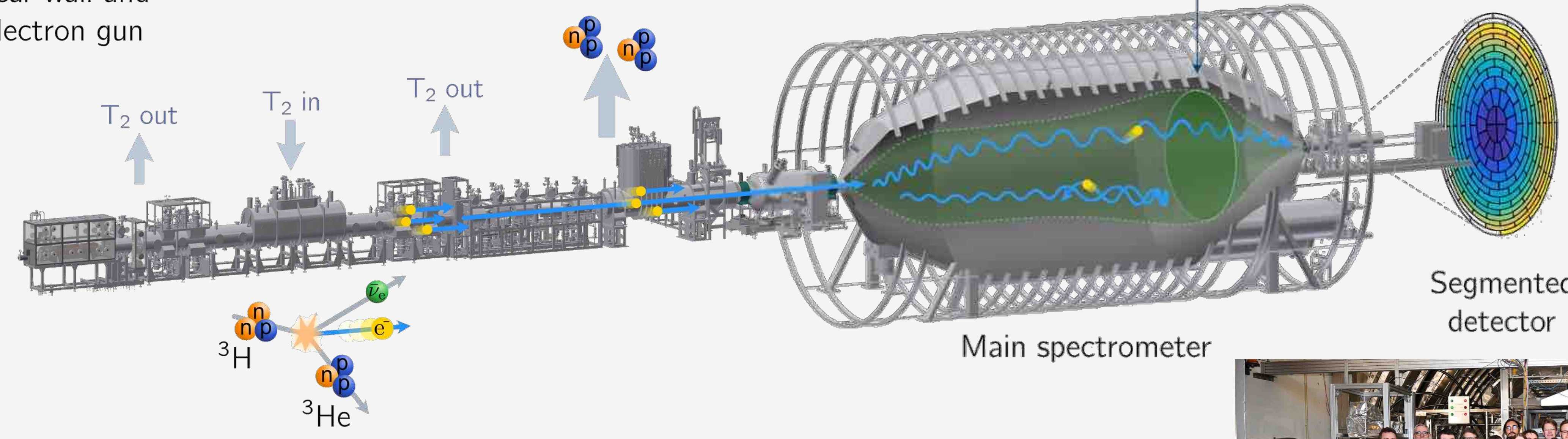




KArlsruhe TRItium Neutrino experiment KATRIN

Universität Münster

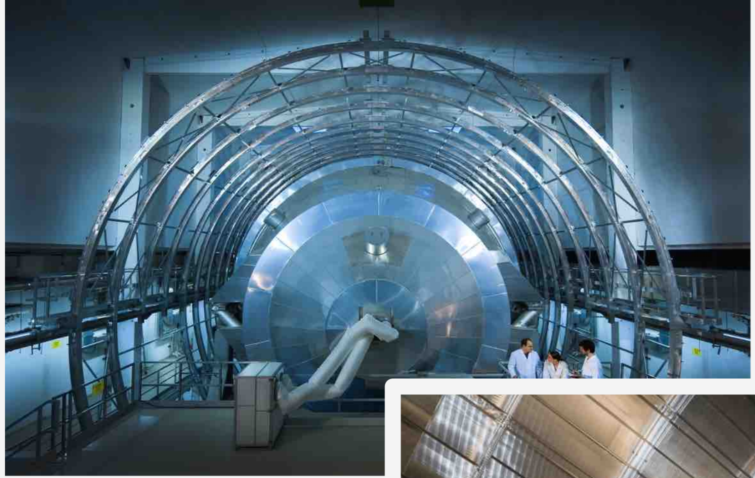
A **10^{11} Bq windowless T_2** source with an **high acceptance & eV-resolution integrating spectrometer**

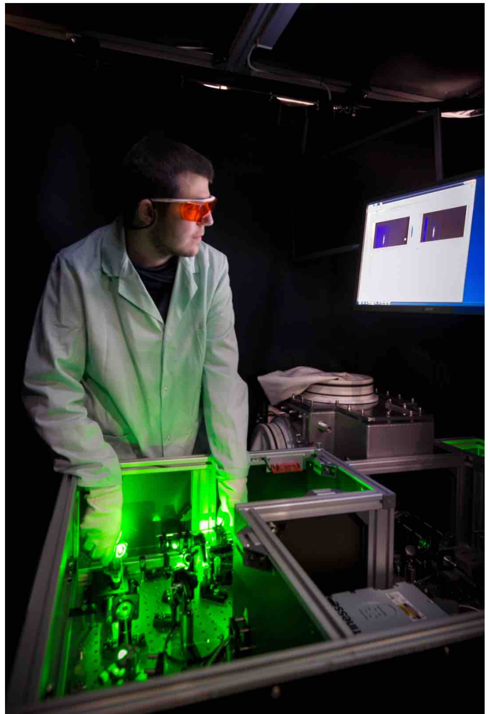


The international KATRIN Collaboration: 150 authors from 24 institutions from 8 countries

Universität Münster

Photos: source & transport section



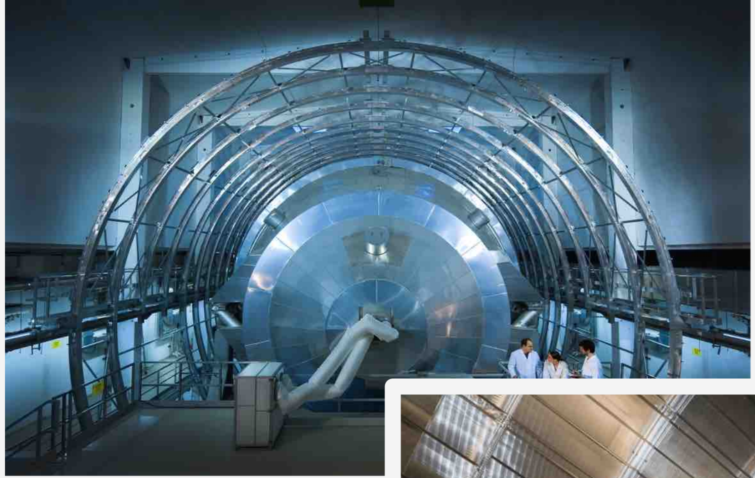


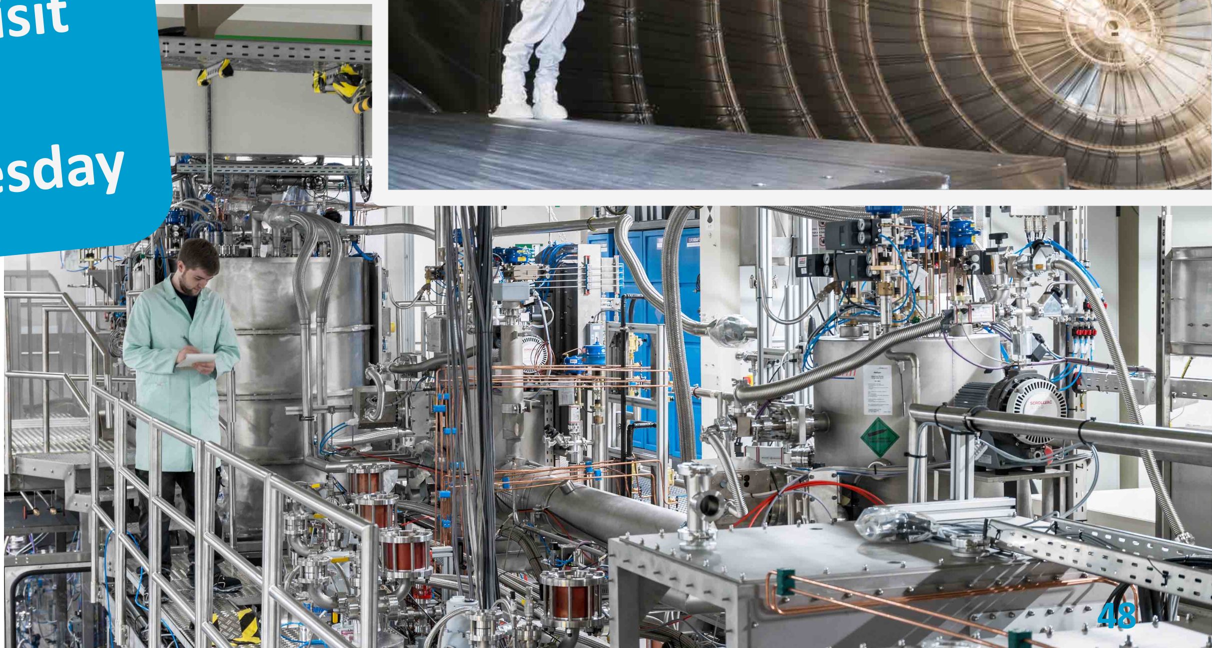
Universität Münster

Photos: source & transport section

KATRIN

KARLSRUHE TRITIUM NEUTRINO EXPERIMENT





Enjyou your visit at KATRIN on next Wednesday

Universität
Münster

Current most urgent questions in neutrino physics after the discovery of neutrino oscillation

- **Mass ordering:** m(ν_3) > m($\nu_{2,1}$) or m($\nu_{2,1}$) > m(ν_3) ?
- **CP violating phase δ_{CP} in mixing matrix U_{PMNS}**:
  connected to baryon asymmetry of universe via leptogensis ?
- **Neutrino particle character ?**
  are neutrinos their own antiparticles (Majorona)? Leptogenesis might explain baryon asymmetry of universe,
  $\rightarrow$ **seach for $0\nu\beta\beta$**
- **Absolute neutrino mass scale ?**
  10^9 more neutrinos than atoms in the universe. Smallness of m_ν: more than just the Yukawa coupling to the H?
  $\rightarrow$ **3 complementary methods: cosmology, seach for $0\nu\beta\beta$, direct neutrino mass search**
- **Is there a 4th** (or even a 5th) **light but sterile neutrino ?**
  experimental indications for light steriles, keV steriles are candidates for "warm dark matter"