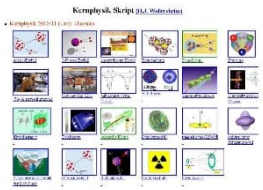
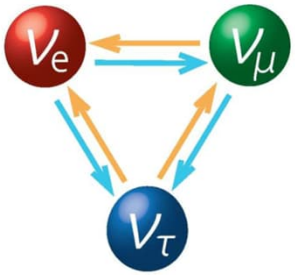
Outline: Neutrino – flavor transmutation

Lecturer: Hans-Jürgen Wollersheim

e-mail: h.j.wollersheim@gsi.de

web-page: https://web-docs.gsi.de/~wolle/ and click on







Arthur Mc Donald



Takaaki Kajita

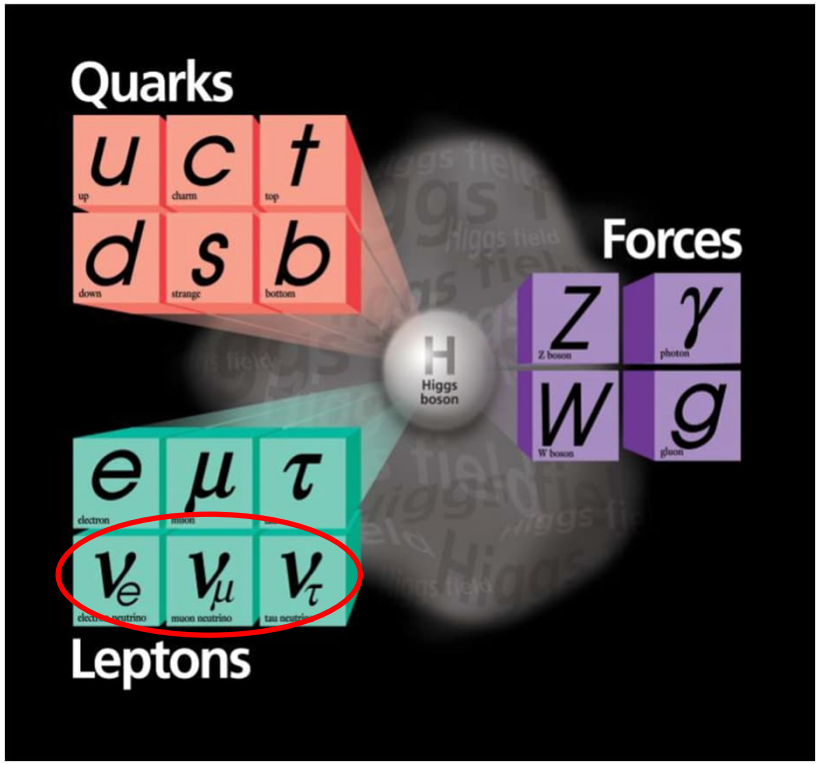


Nobel Prize 2015

1. discovery of ν_e, ν_μ, ν_τ neutrino
2. neutrino sources
3. solar & atmospheric neutrinos
4. solar neutrino problem
5. neutrino oscillations
6. neutrino mass

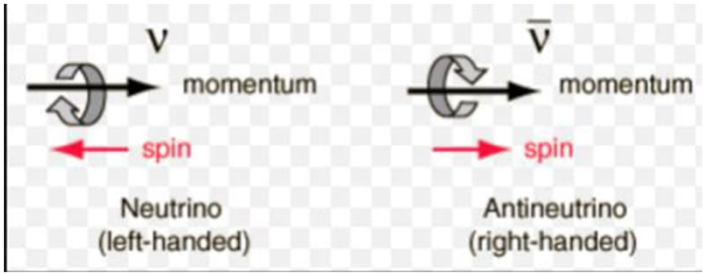
The “Standard Model”

Matter particles



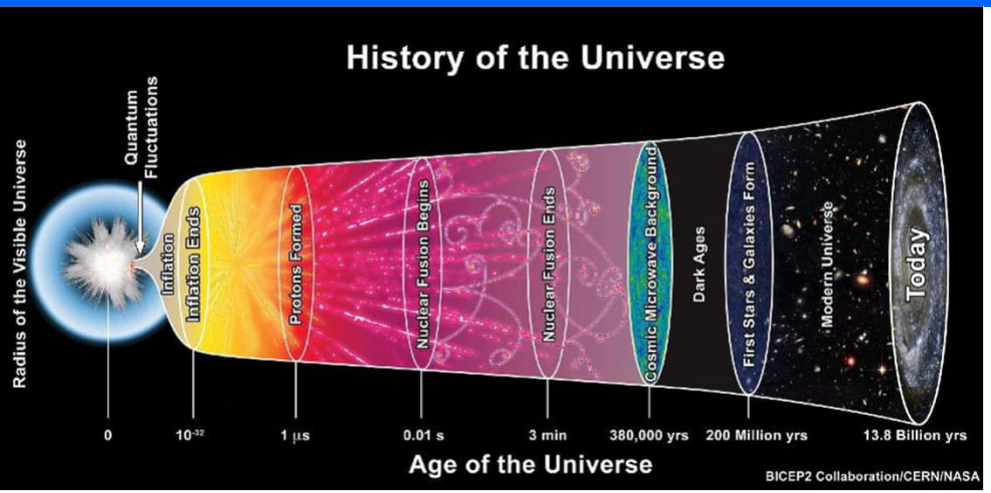
Force particles

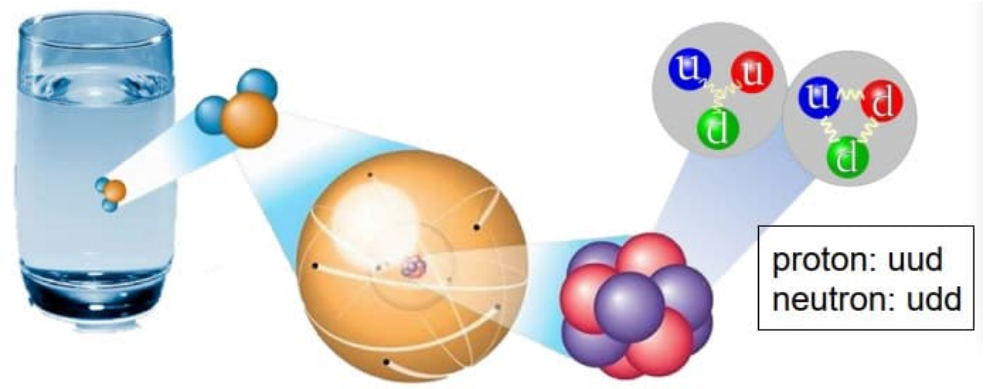
Neutrinos are leptons that do not feel the strong force (no color) or the electromagnetic force (no charge). They interact only weakly.

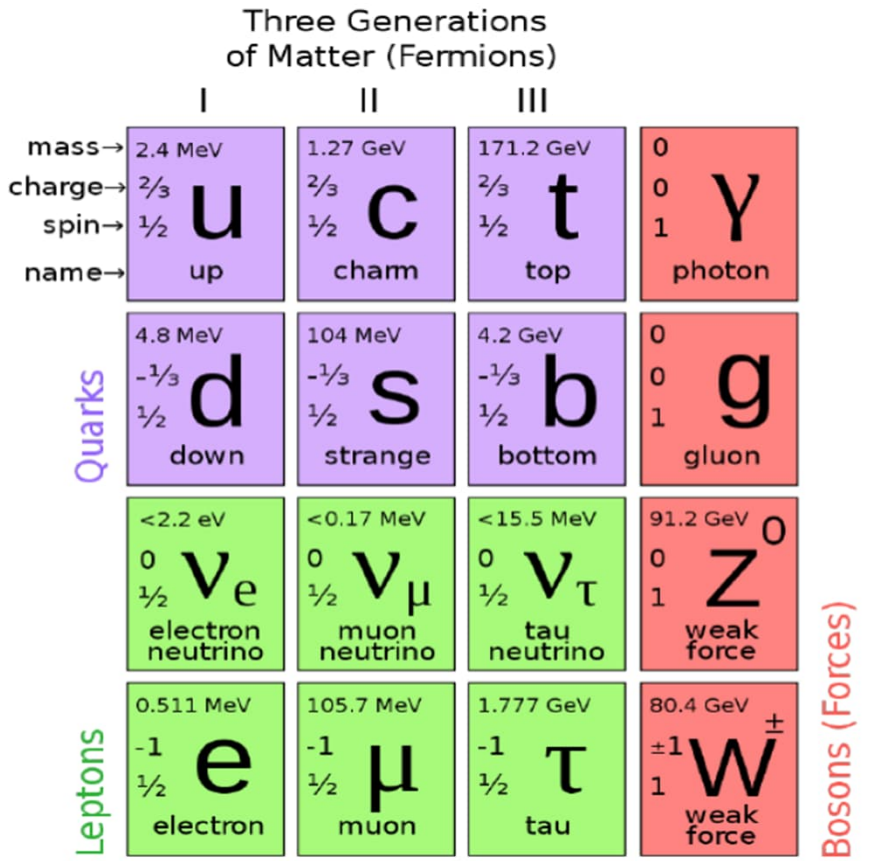


In the Standard Model they are massless, move with the speed of light and neutrinos are always left handed (opposite for anti-neutrinos)

Standard Model in Elementary Particle Physics







The Discovery of the electron neutrinos

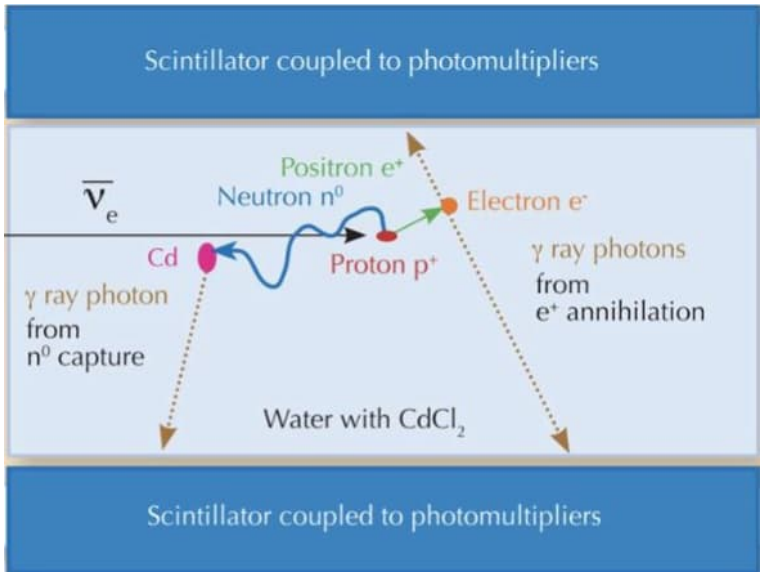


It took 26 years to detect this particle.
Cowan and Reines put a detector close to the reactor in South Carolina and observed the inverse beta decay process (few events/hour)

Reactor gives 10^{19} neutrinos/sec

The neutrino really exists!

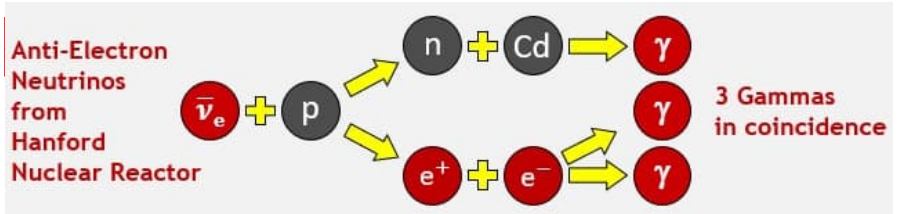
reactor flux



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

$$e^+ + e^- \Rightarrow \gamma + \gamma$$

n-capture by cadmium



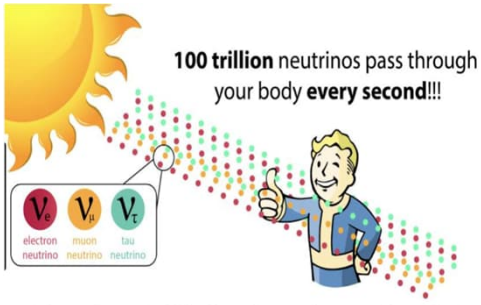


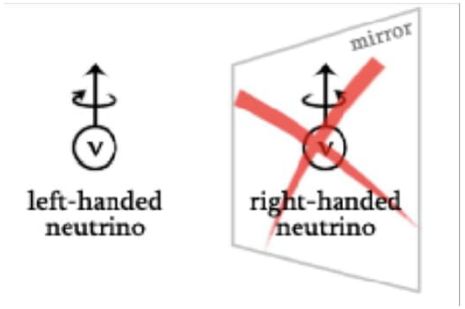
Reines Nobel prize in 1995

Neutrinos

- Neutrinos are fundamental particles
- Neutrino are ghostly particles
- Trillions (10^{12}) of neutrinos pass per second through you for every second of your life! They come from the sun
- Neutrinos need a light year of lead (~10^{13} km) be stopped with 50% chance
- There are a billion 10^9 neutrinos for each atom in the Universe. There are ~$3 \cdot 10^8$ neutrinos per cubic meter- relic neutrinos
- Their sheer number must mean they are important
- Neutrinos have a fixed chirality →







Neutrinos are still mysterious particles

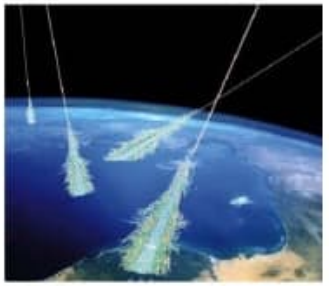
- Have only (left handed) weak interactions
- Are mass-less in the (minimal) Standard Model
- Are the only neutral fermions in the SM
- Could be Majorana or Dirac fermions
- Neutrinos come from everywhere
  - Solar neutrinos
  - Atmospheric neutrinos
  - Relic/supernova neutrinos
  - Nuclear reactor created neutrinos
  - Accelerator created neutrinos
  - Geoneutrinos, radioactive decay (^{238}U, ^{232}Th, ^{40}K),even from your body

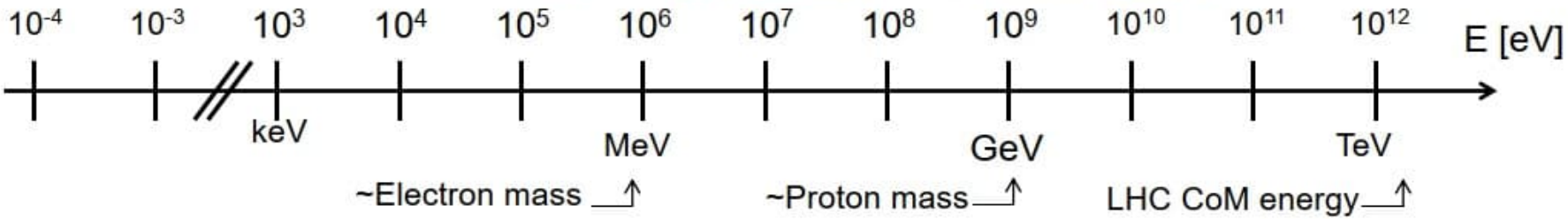
Where are neutrinos from?

Natural neutrino source



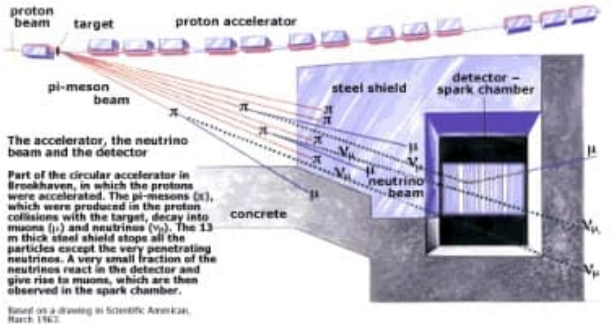




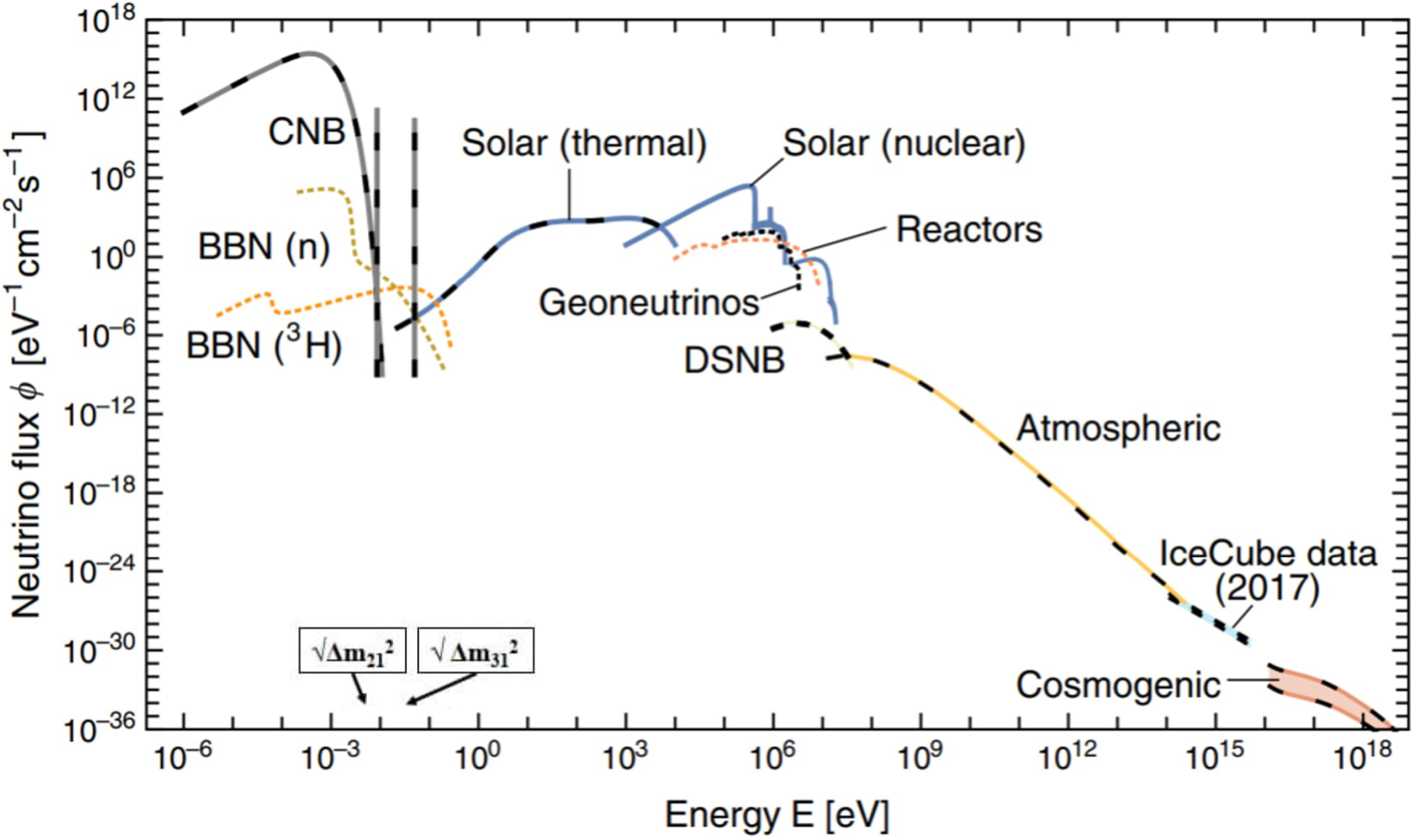



Artificial neutrino source

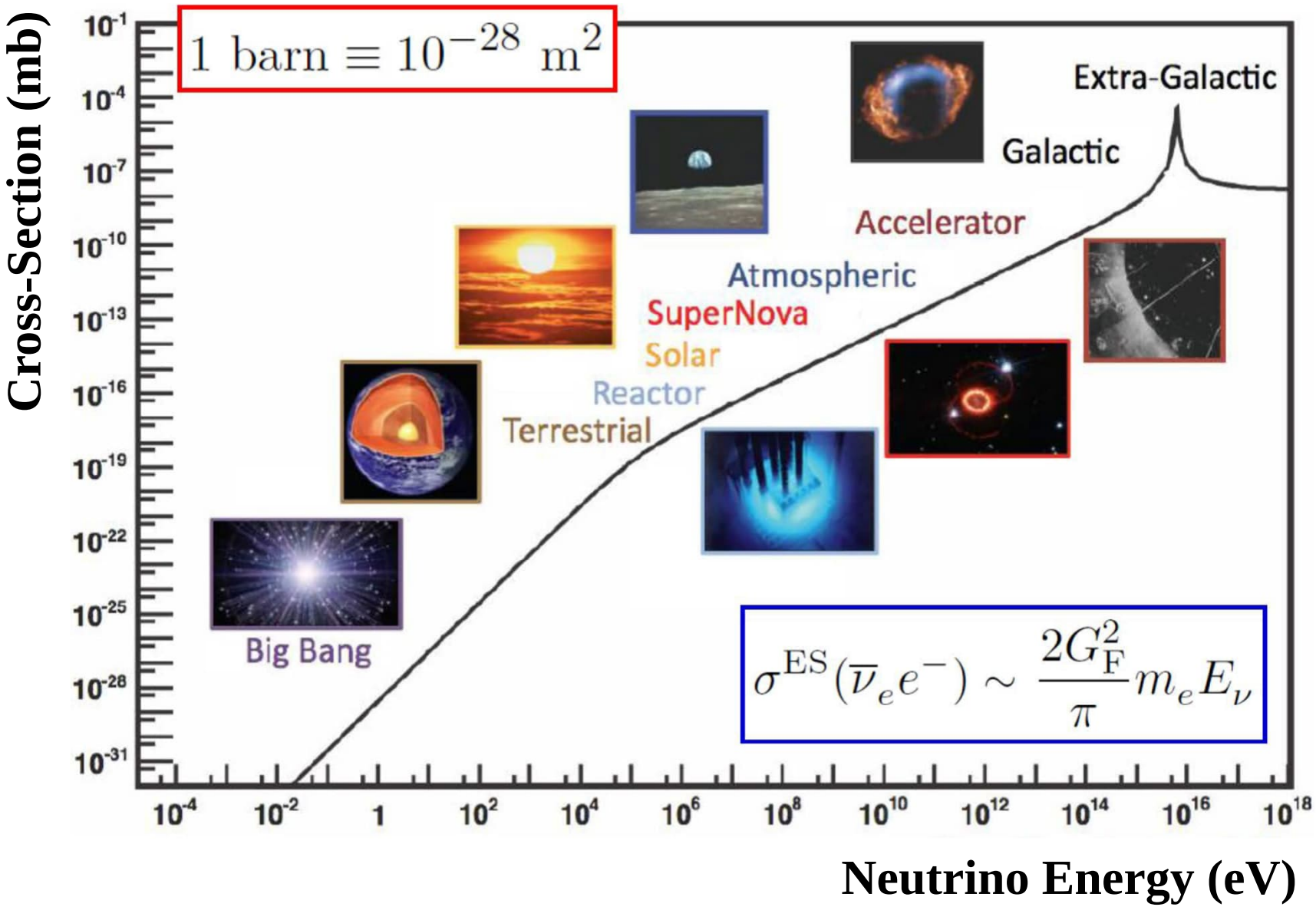




Energy spectra of various neutrino sources



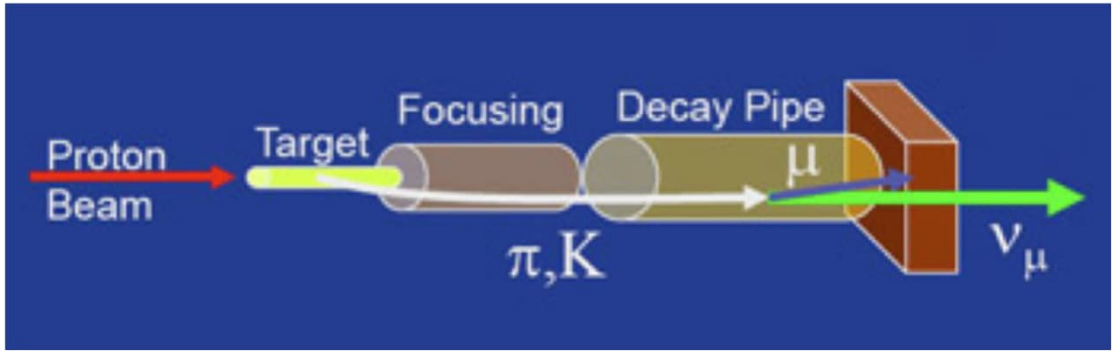
Cosmic Neutrino Background, Big Bang Neutrinos, Diffuse Supernova Neutrino Background


Cross-Section (mb)
1 barn ≡ 10^−28 m^2
Extra-Galactic
Galactic
Accelerator
Atmospheric
SuperNova
Solar
Reactor
Terrestrial
Big Bang
σ^ES(ν̄_e e^−) ~ 2G_F^2/π m_e E_ν
10^-1
10^-4
10^-7
10^-10
10^-13
10^-16
10^-19
10^-22
10^-25
10^-28
10^-31
10^-4
10^-2
1
10^2
10^4
10^6
10^8
10^10
10^12
10^14
10^16
10^18
Neutrino Energy (eV)

Muon neutrino

- In 1962 Lederman, Schwarz and Steinberger discovered the existence of second type of neutrino at the AGS in Brookhaven: the *muon neutrino*.











Nobel prize in 1988

Tau neutrino



- Tau was discovered by M. Perl in 1975 via

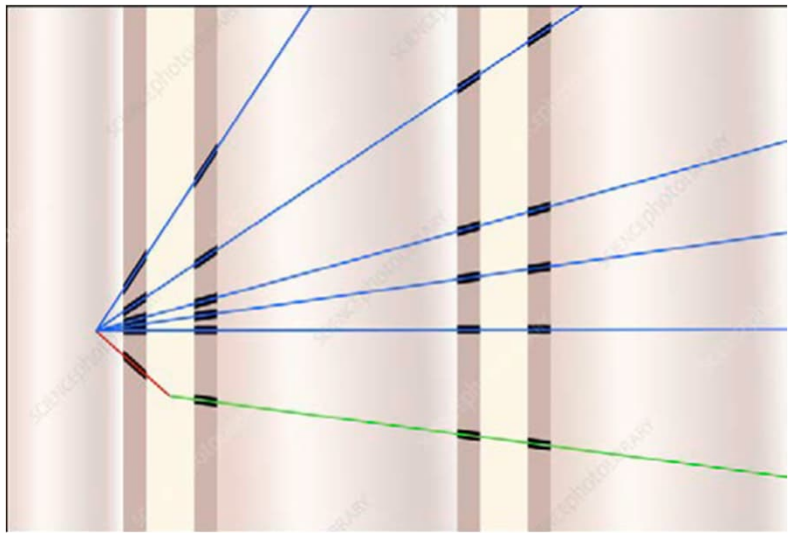
$$e^+ + e^- \rightarrow e^\pm + \mu^\pm + X \quad \text{(undetected)}$$

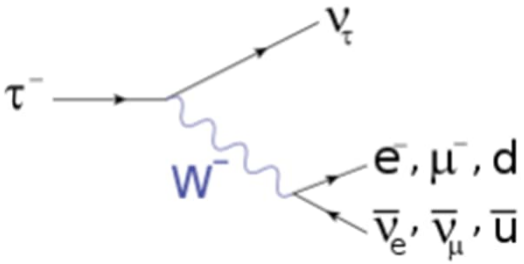
(at least two)

- It was proposed that the above can be mediated by

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \rightarrow e^\pm + \mu^\pm + 4\nu$$

- *Tau neutrino* was finally discovered by DONUT experiment at FERMILAB (2000)



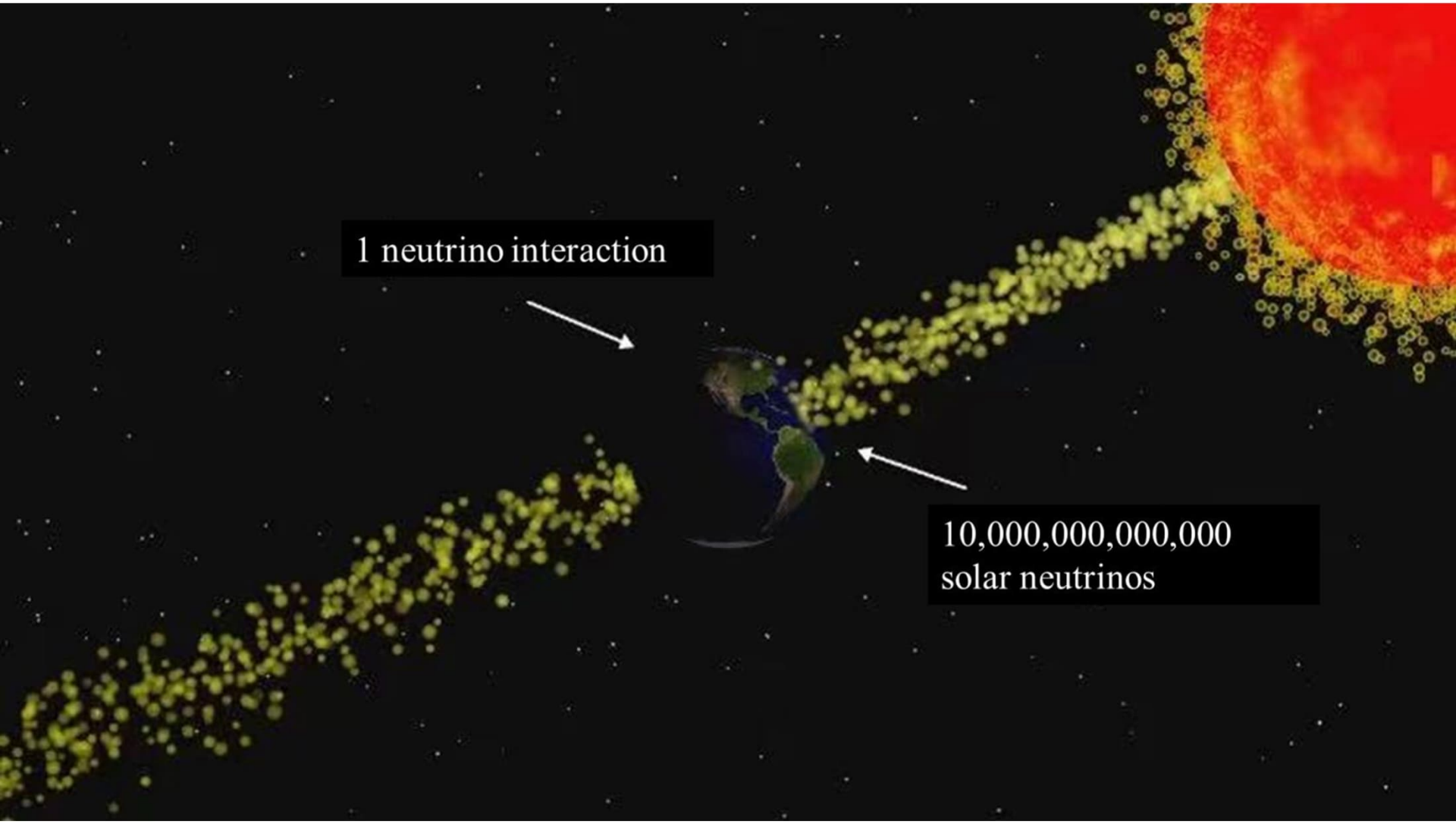


Lepton family of 3 generations is complete



Nobel prize in 1995

Neutrinos: here, there, everywhere …

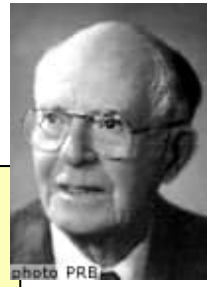


The solar neutrino problem

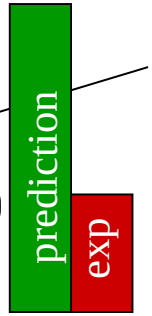


Sun
since 4.5 billion years
fusion

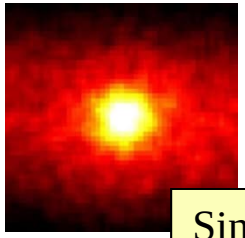
66 billion neutrinos/s/cm^2



since 1964: detection with
Homestake-experiment
expected: 1,5 reactions/d
measured: 0.5 reactions/d



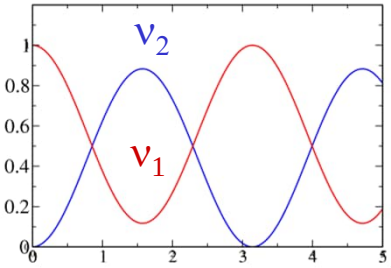
solar
neutrino
problem



Since 1986 Kamiokande:
confirms Homestake



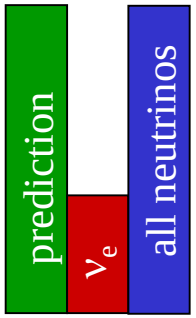
possible explanation:
neutrino-oscillation



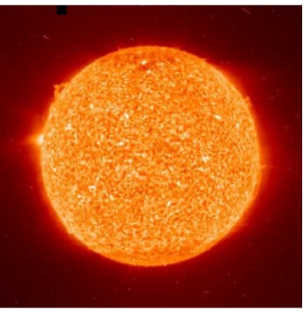


2002 SNO-experiment:
examines neutrino-oscillation

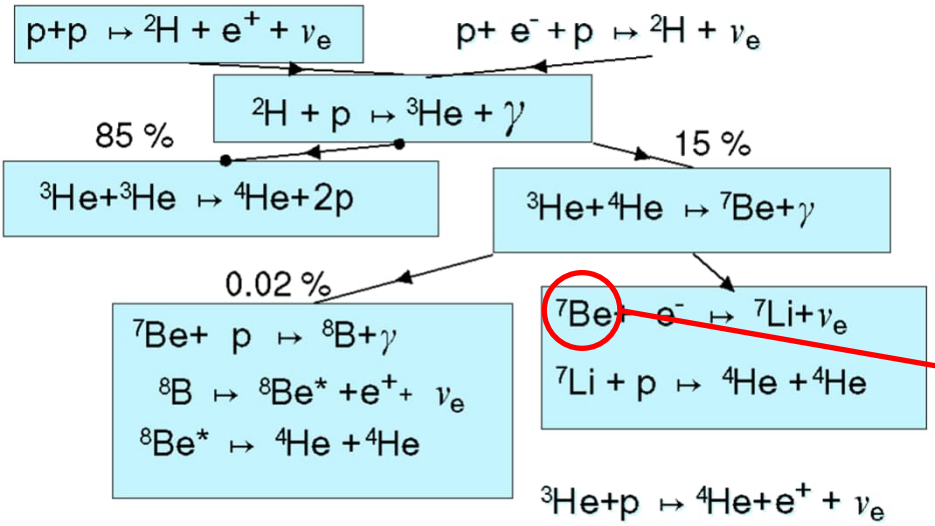
solar
neutrino
problem
solved!

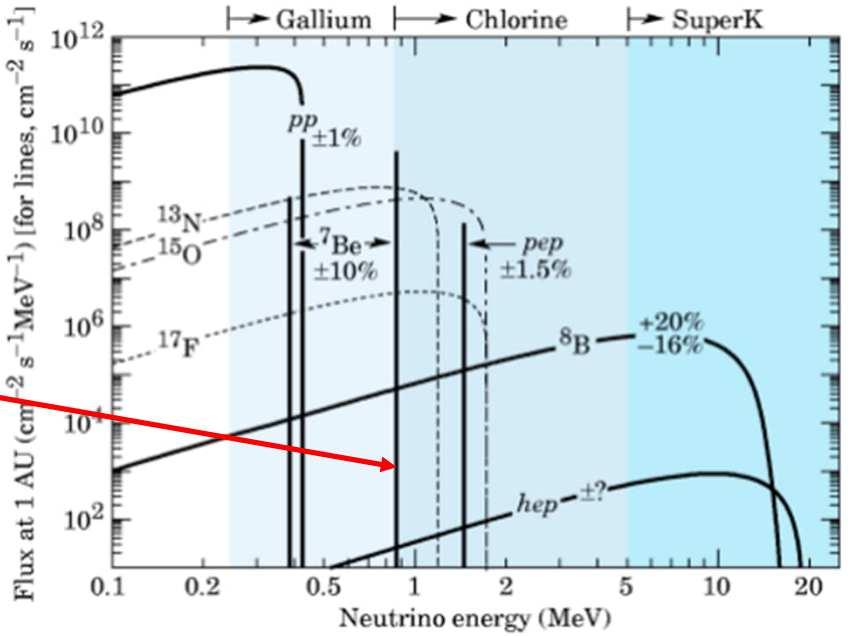


Missing solar neutrinos?



- Raymond Davis Jr. (Nobel Prize 2002) for the discovery of solar neutrinos far less than theoretical predictions by John Bahcall.
- Only **1/3** of the expected (electron) neutrino rate was observed
- What was wrong?
- Fight from 1960s to 1990s in more than 30 years.



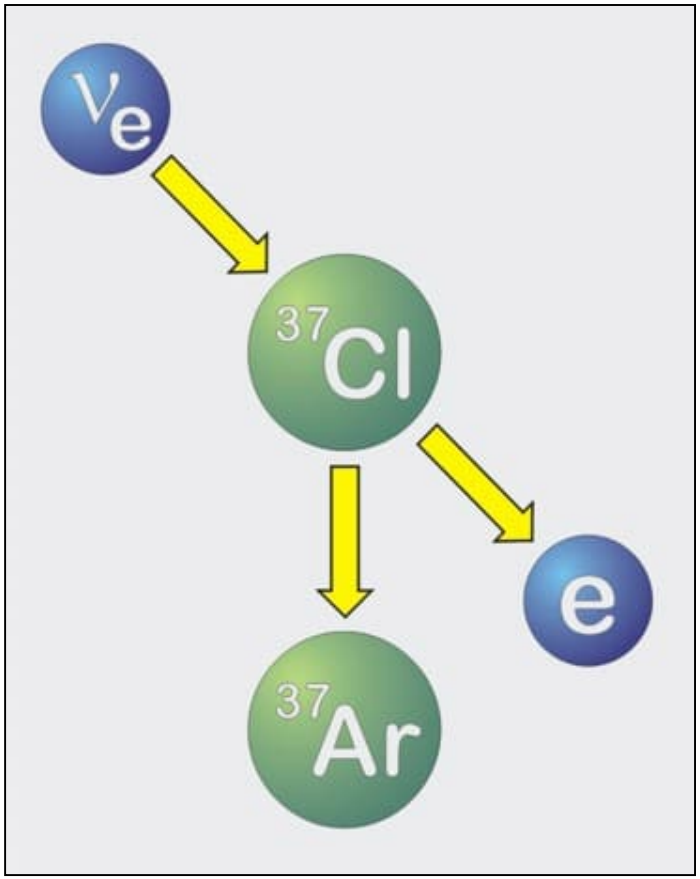


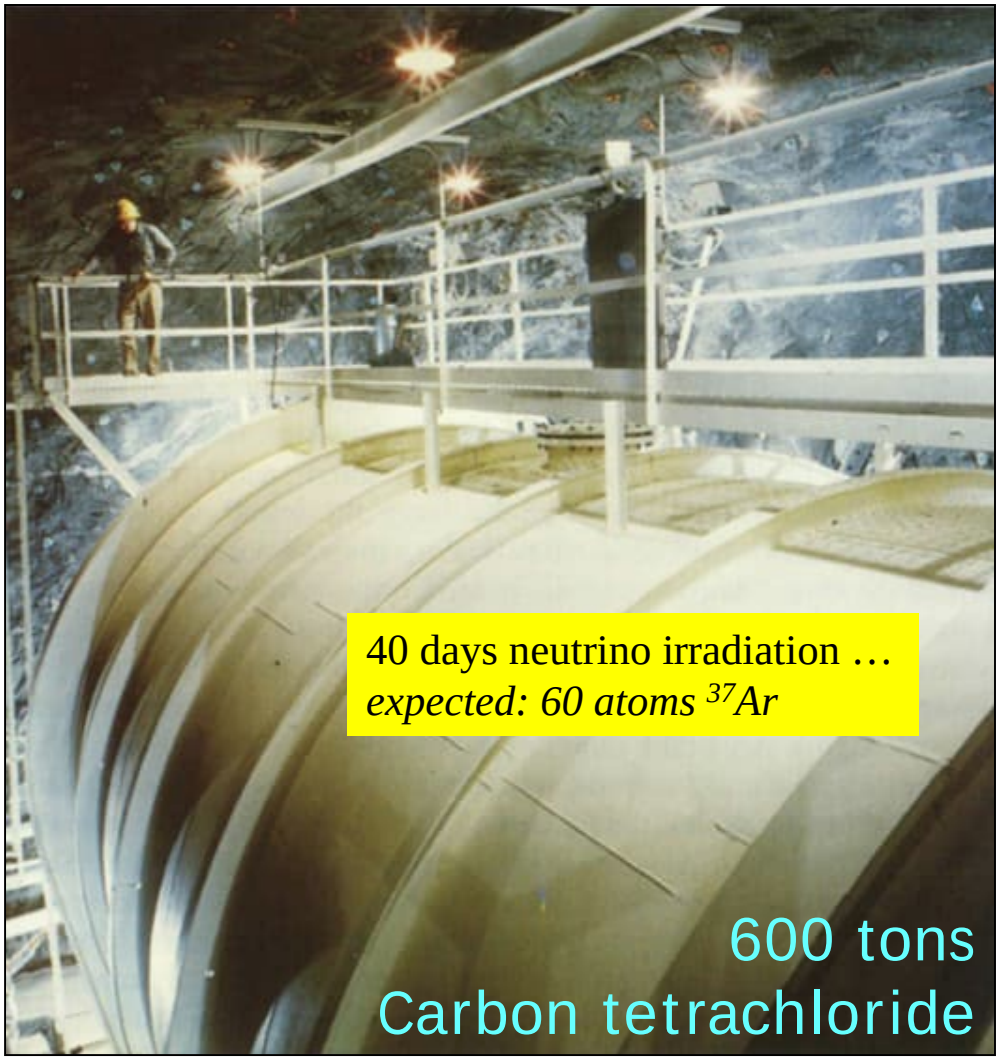
pp-fusion

Standard solar neutrino model

First measurement of the solar neutrinos

Inverse beta-decay („neutrino-capture")





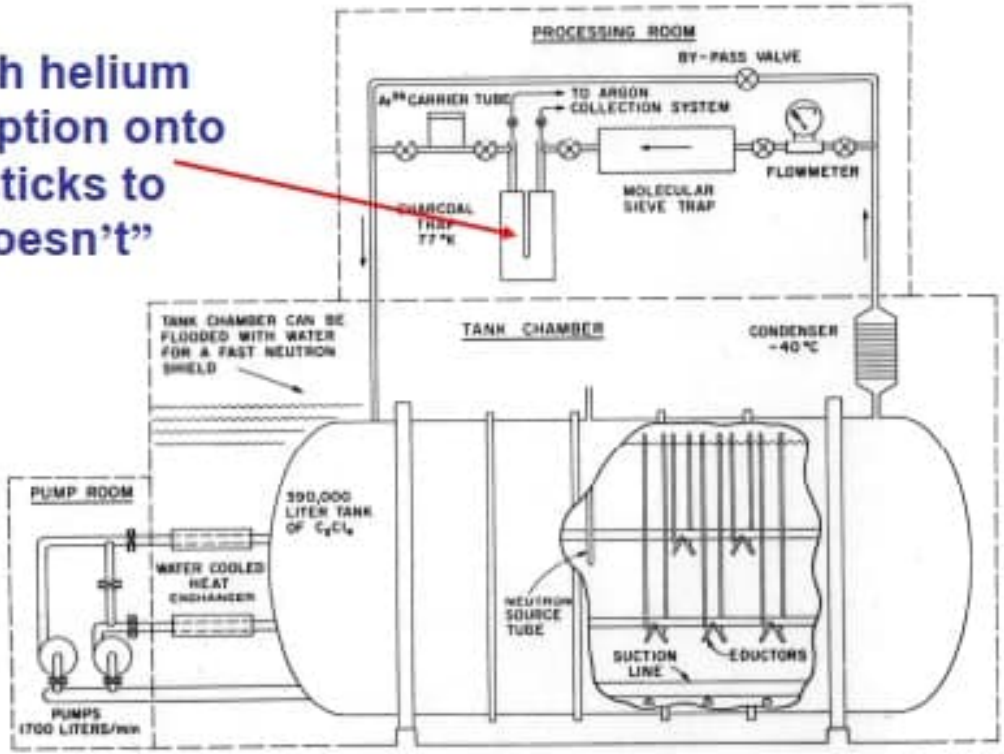
Homestake Sun neutrino-Observatory (1967–2002)

Extracting the Argon

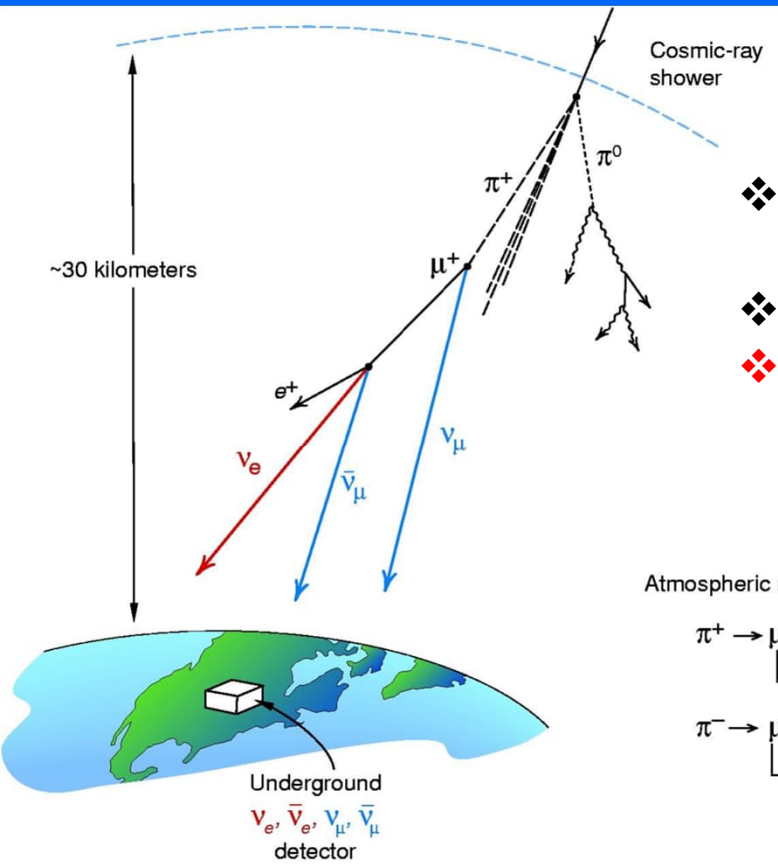
- **Every ~60 days** attempt to count argon atoms from $\nu_e + {}^{37}_{17}\mathrm{Cl} \rightarrow {}^{37}_{18}\mathrm{Ar} + \mathrm{e}^-$ (half-life ~35 days, nothing gained in waiting longer)
- Counting a few atoms is challenging - first need to get them out of the tank….
- Argon being an inert gas doesn't bind to the tetrachloroethylene
- Extracted by flushing tank with helium
- Argon is "collected" by adsorption onto carbon at 77K – i.e. "Argon sticks to surface of Carbon, Helium doesn't"
- Extracted gases then purified

CHEMISTRY

95 % Argon atoms collected



Atmospheric neutrinos?

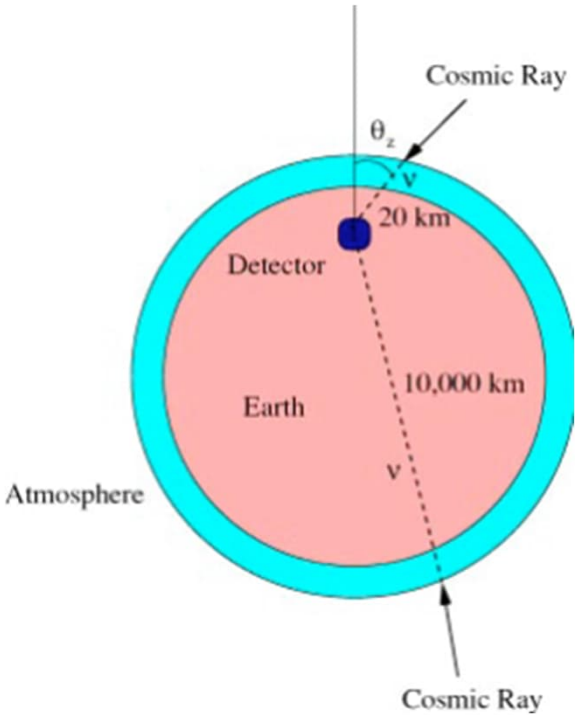


- Without neutrino oscillations, upgoing and down-going atmospheric neutrons should be the same.
- But: missing half of upgoing atmospheric neutrinos
- Neutrinos must change their flavors during propagation

(Super-Kamiokande:"Evidence for oscillations of atmospheric neutrinos", 1998
The experiment showed that muon neutrinos disappear as they travel through the earth to the detector

Atmospheric neutrino source

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



Production channels

conventional

$$p, A + \text{air} \rightarrow \pi^{\pm}, \pi^{0}, \mathrm{K}^{\pm}, \mathrm{K}^{0}_{\mathrm{S,L}}$$

muons and muon neutrinos

$$\pi^{\pm}, K^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$$

electron neutrinos

$$K^{\pm}, K^{0}_{L} \rightarrow [\pi^{\pm}, \pi^{0}]e^{\pm}\nu_{e}(\bar{\nu}_{e})$$

prompt

$$p, A + \text{air} \rightarrow \mathrm{D}, \Lambda_{\mathrm{C}} \rightarrow \nu_{\mu}, \nu_{\mathrm{e}}, \mu$$

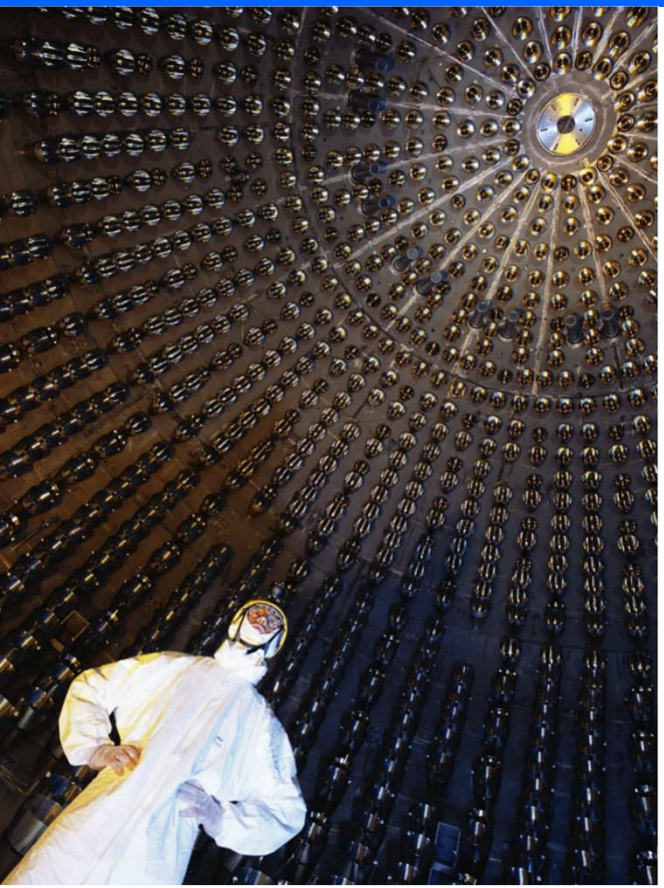
Subset of dominant decay channels

decay channel	branching ratio (BR)
$\mu^{-} \rightarrow e^{-}\bar{\nu}_{e}\nu_{\mu}$	100 %
$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$	99.9877 %
$K^{0}_{e3} : K^{0}_{L} \rightarrow \pi^{\pm}e^{\mp}\nu_{e}$	40.55 %
$K^{0}_{\mu 3} : K^{0}_{L} \rightarrow \pi^{\pm}\mu^{\mp}\nu_{\mu}$	27.04 %
$K^{+} \rightarrow \mu^{+}\nu_{\mu}$	63.55 %
$K^{+}_{e3} : K^{+} \rightarrow \pi^{0}e^{+}\nu_{e}$	5.07 %
$K^{+}_{\mu 3} : K^{+} \rightarrow \pi^{0}\mu^{+}\nu_{\mu}$	3.353 %
$D^{+} \rightarrow \overline{K}^{0}\mu^{+}\nu_{\mu}$	9.2 %
$D^{0} \rightarrow K^{-}\mu^{+}\nu_{\mu}$	3.3 %

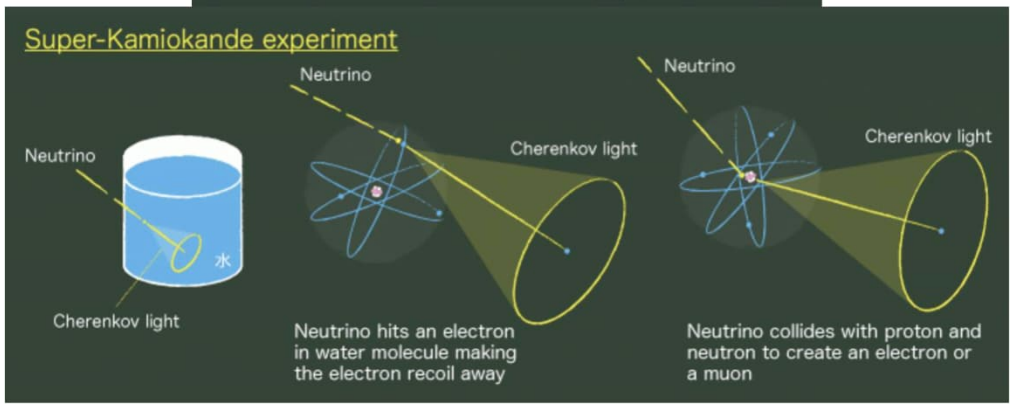
+ charge conjugates

http://pdg.lbl.gov

Super-Kamiokande (1996 - …)

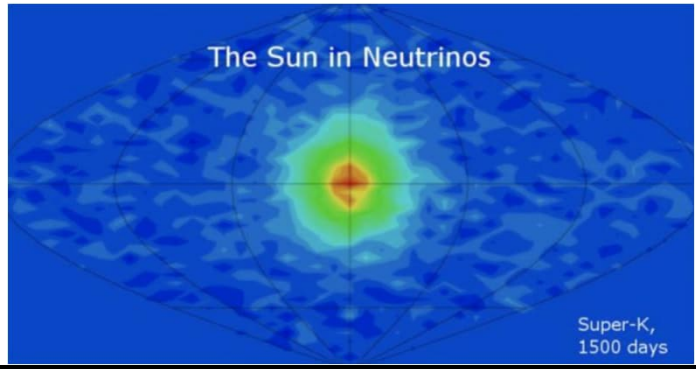




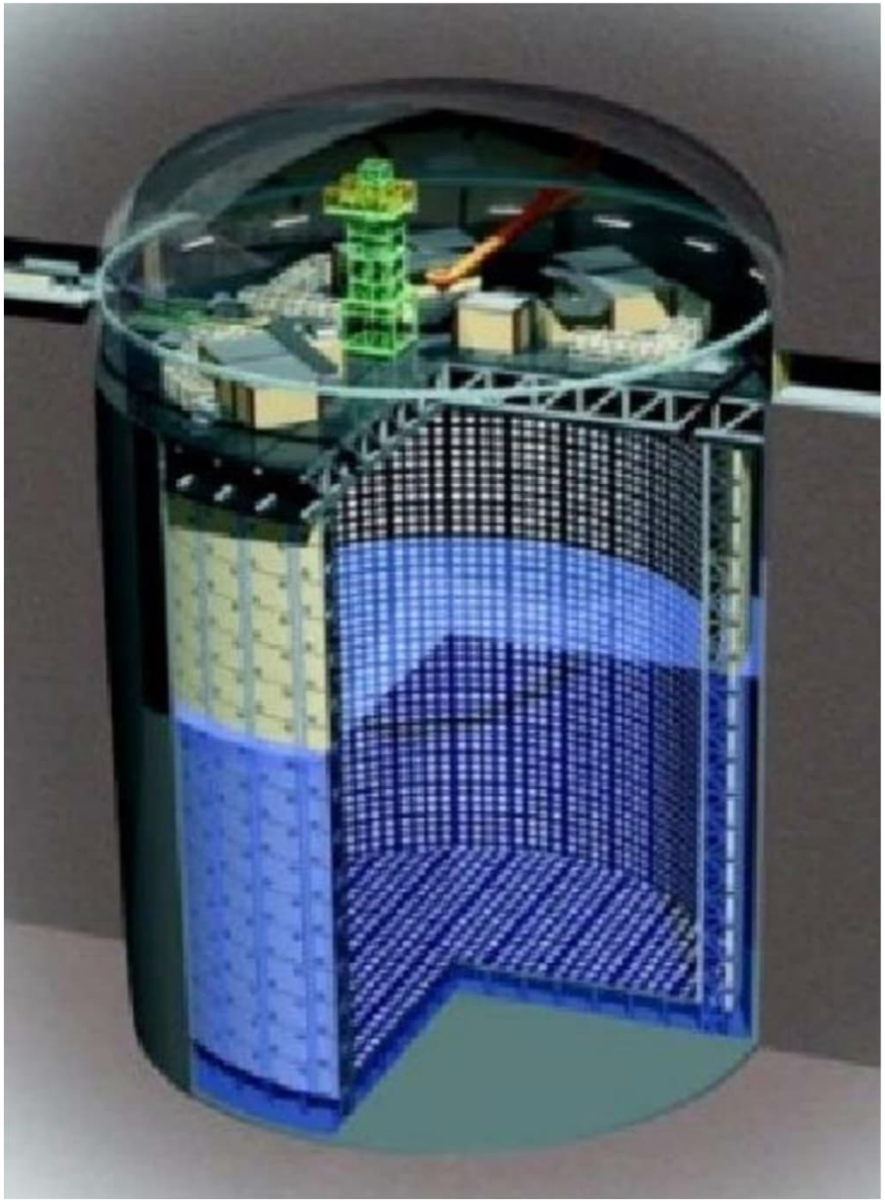


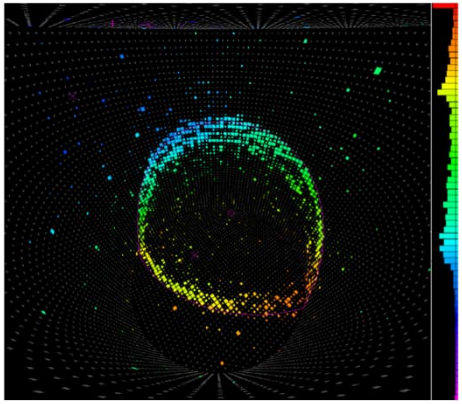


50,000 tons of ultra-pure water, watched by 13,000 photomultipliers

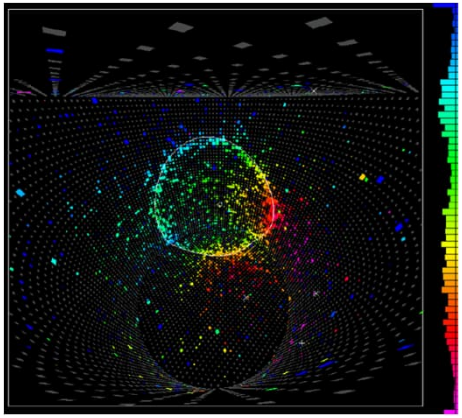


Water Cherenkov detector Super-Kamiokande





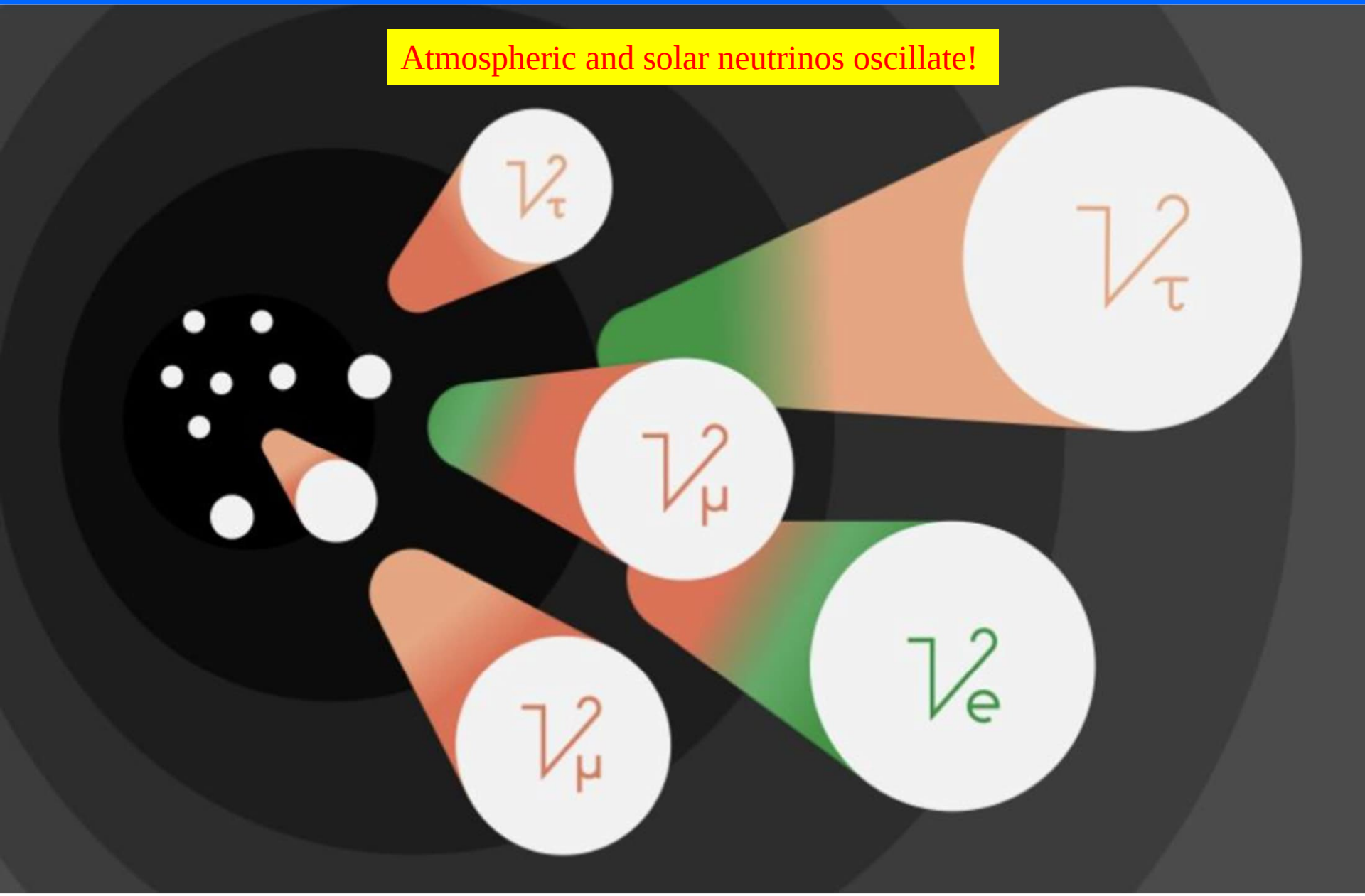
High-energy muon neutrino event.
Sharp edge of a Cherenkov ring



High-energy electron neutrino event.
Fuzzy edge of a Cherenkov ring

Neutrino Oscillations

Atmospheric and solar neutrinos oscillate!



Why we measure neutrino oscillations?

There are many oscillations (Irrespective to it is observable or not)

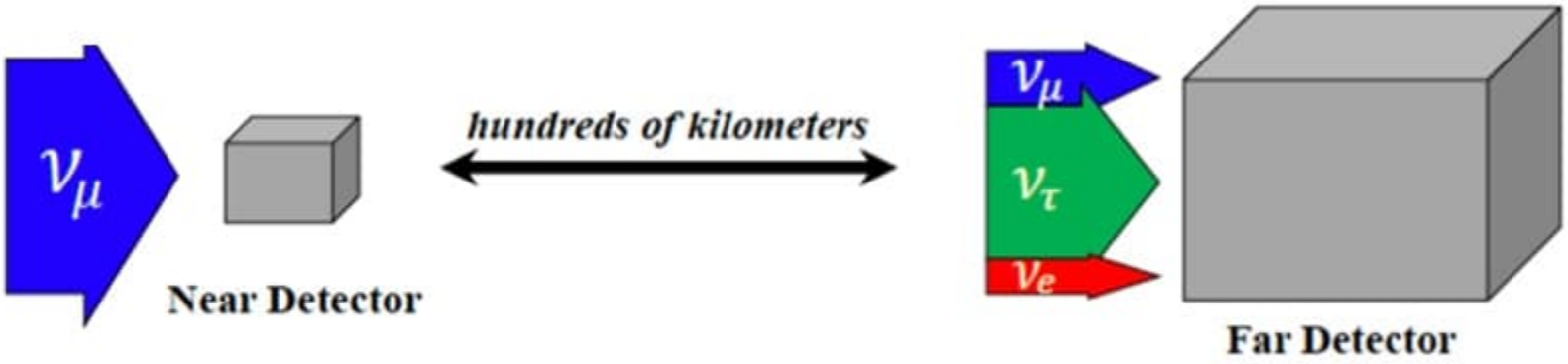
- $K^0 \Leftrightarrow \overline{K^0}$, $B^0 \Leftrightarrow \overline{B^0}$ oscillation → CP violation
- spin precession by B $(= |\Uparrow\rangle \Leftrightarrow |\Downarrow\rangle\, oscillation)$ → Formation of Q.M.
- $|u\bar{u}\rangle \Leftrightarrow |d\bar{d}\rangle$ oscillation in π^0, η → Hadron mass, quark model, QCD
- $d \Leftrightarrow s$ oscillation → Cabbibo angle, Higgs-quark coupling.
- $B \Leftrightarrow W_3$ oscillation → Weinberg angle, Higgs-GB coupling.

→ we have learned a lot from these “Oscillations”

We can expect to learn more from ν-oscillations: $\nu_\alpha \Leftrightarrow \nu_\beta$

Neutrino Oscillations

- Important discovery in 1998: neutrino oscillations
- Neutrino oscillations is a quantum mechanical phenomenon whereby a neutrino created with a specific lepton flavor (electron, muon, or tau) can later be measured to have a different flavor. The probability of measuring a particular flavor for a neutrino varies between 3 known states as it propagates through space.
- *A specific flavor state is superposition of three mass eigenstates with definite masses*
- Neutrino oscillations are only possible if neutrinos have a non-zero mass.



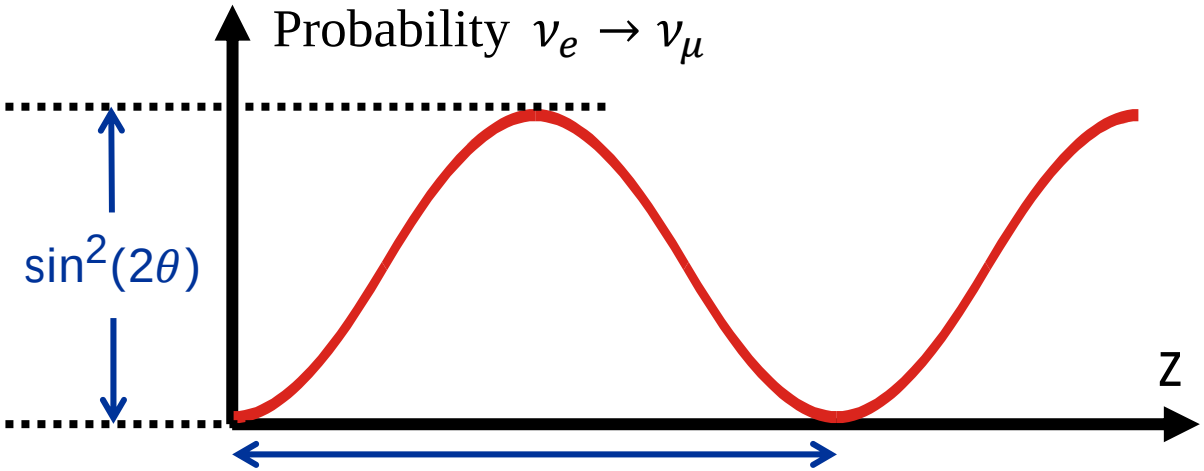
Neutrino Flavor Oscillations

Two-flavor mixing $\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$

Each mass eigenstate propagates as e^{ipz}

with $p = \sqrt{E^2 - m^2} \approx E - m^2/2E$

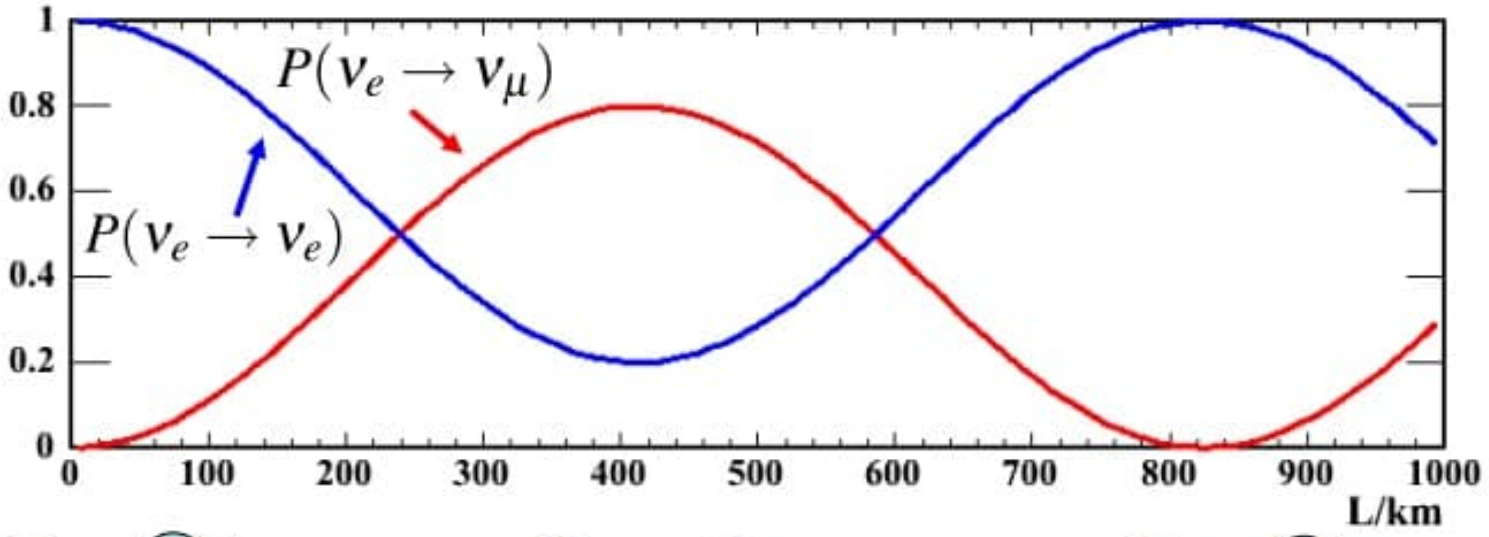
Phase difference $\frac{\delta m^2}{2E} z$ implies flavor oscillations

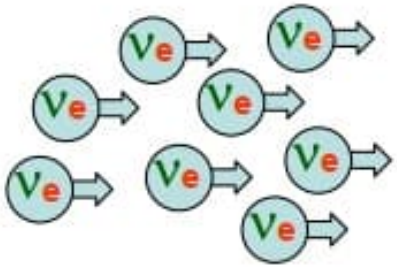


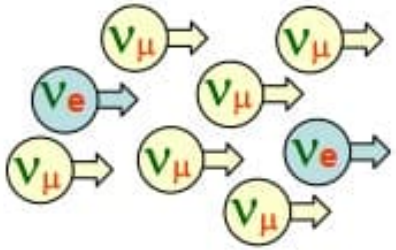
Oscillation Length $\frac{4\pi E}{\delta m^2} = 2.5\ \text{m}\ \frac{E}{\text{MeV}}\left(\frac{\text{eV}^2}{\delta m}\right)$

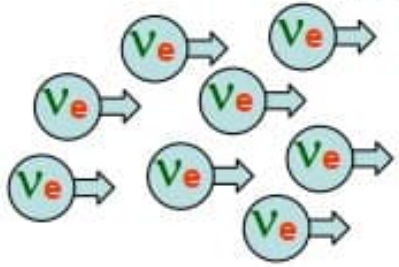


Ntwo-flavor Neutrino Oscillations







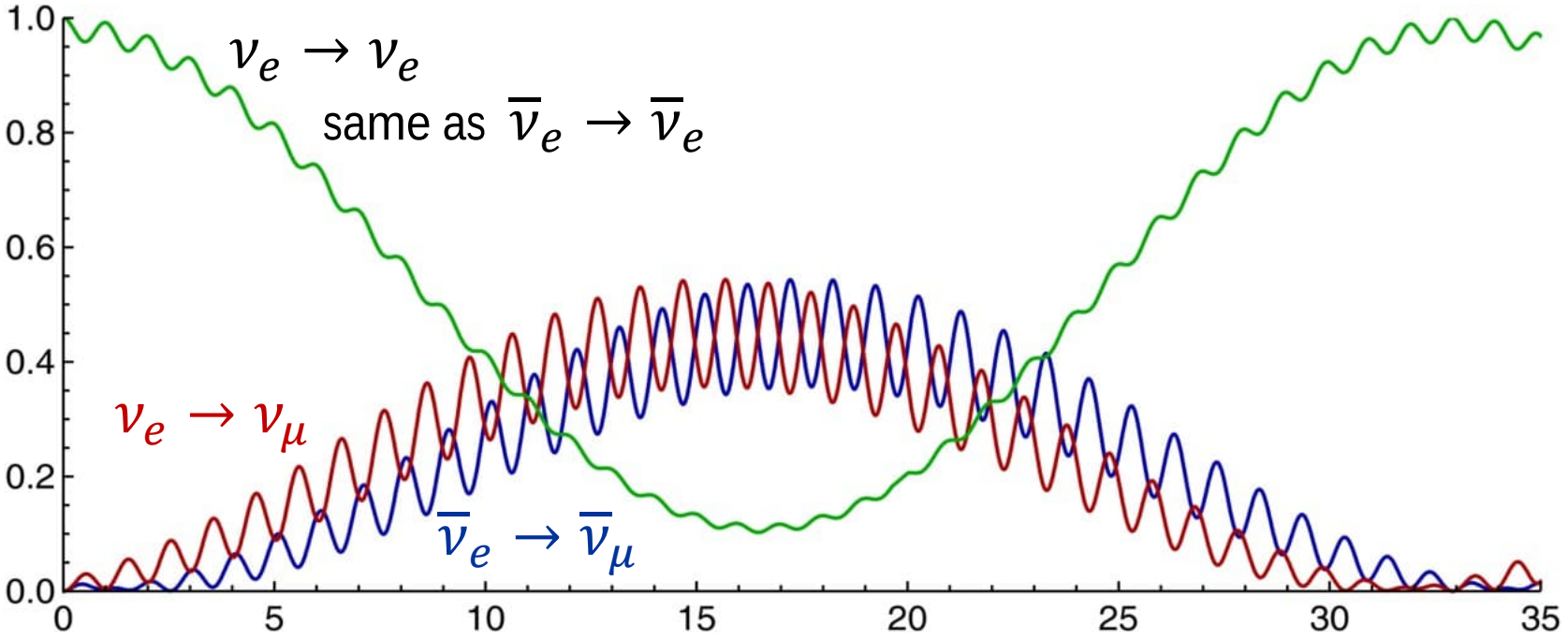


Antineutrino Oscillations different from Neutrinos?

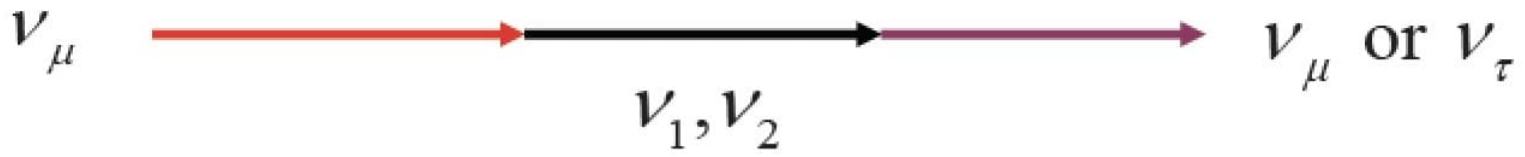
$$\nu_e = c_{12}c_{13}\,\nu_1 + s_{12}c_{13}\,\nu_2 + s_{13}e^{-i\delta}\,\nu_3$$

$$\bar{\nu}_e = c_{12}c_{13}\,\bar{\nu}_1 + s_{12}c_{13}\,\bar{\nu}_2 + s_{13}e^{+i\delta}\,\bar{\nu}_3$$

Dirac phase causes different 3-flavor oscillations for neutrinos and antineutrinos

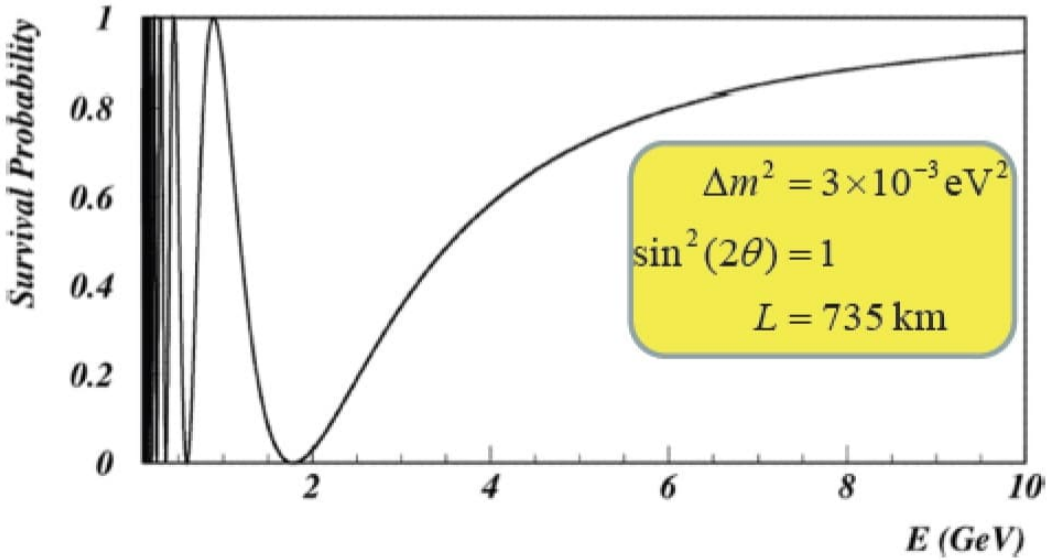


Neutrino Oscillations atmospheric neutrinos

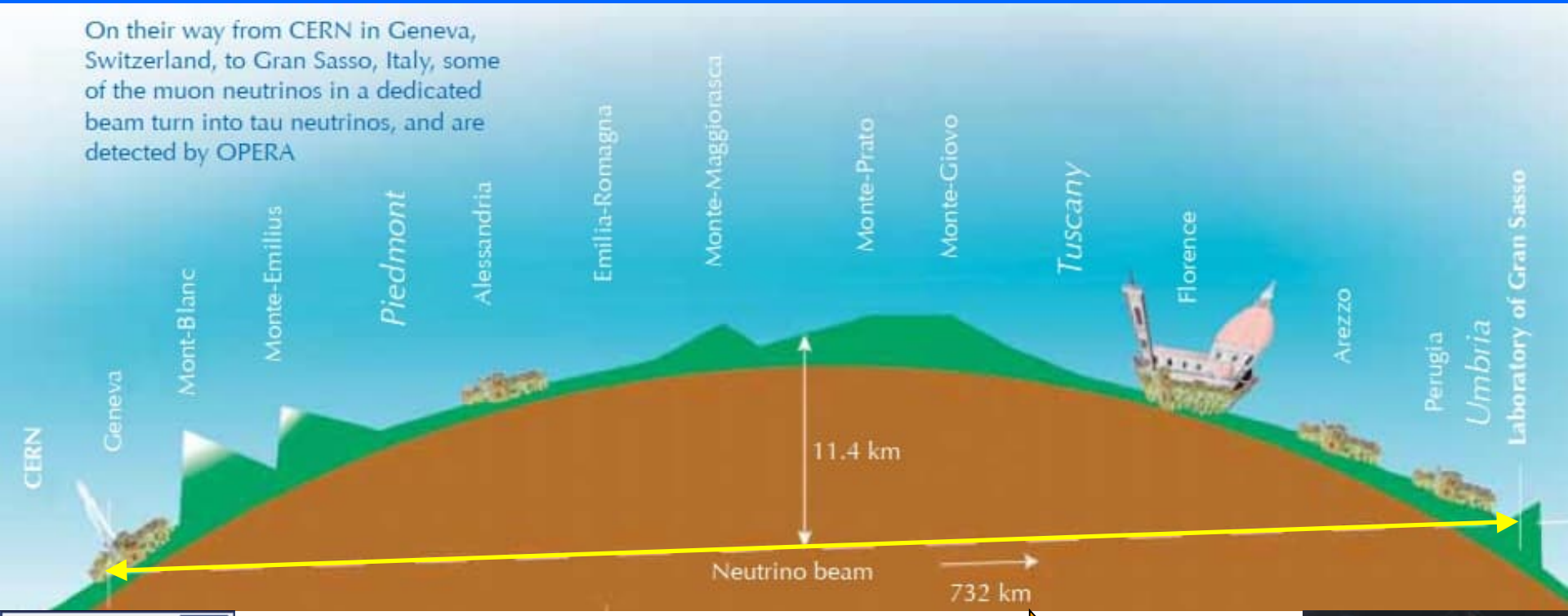


$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

- Measure probability
  - survival
  - appearance
- Result
  - mixing angle
  - mass differences



Neutrino Oscillations muon → tau neutrino 2010



$$\nu_\mu \rightarrow \nu_\tau$$



Typical numbers for oscillations

Setup/situation	Energy	Distance	Δm^2
Laboratory	1GeV	100m	$12\,\mathrm{eV}^2$
Long-baseline	5GeV	500km	$1.2 \times 10^{-2}\mathrm{eV}^2$
Atmospheric (above)	5 GeV	10 km	$0.6\,\mathrm{eV}^2$
Atmospheric (below)	5 GeV	6000 km	$10^{-3}\,\mathrm{eV}^2$
Reactor-neutrino	6 MeV	1 km	$7 \times 10^{-3}\mathrm{eV}^2$
Long-baseline reactor	6 MeV	100 km	$7 \times 10^{-5}\mathrm{eV}^2$
Solar	1 MeV	1.5×10^{11} km	$10^{-11}\mathrm{eV}^2$

We will see that the physically relevant values are $\Delta m^2 = 2.7 \times 10^{-3}\,\mathrm{eV}^2$ and $\Delta m^2 = 8 \times 10^{-5}\,\mathrm{eV}^2$.

Neutrino Oscillations

Pontecorvo-Maki-Nakagawa-Sakata Matrix (analogous to the CKM for quarks)

unitary matrix

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

by defn $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$

$$U_{PMNS} = U_{23}(\theta_{23}, 0)\; U_{13}(\theta_{13}, \delta)\; U_{12}(\theta_{12}, 0)$$

Why this order ???

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

$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$

$$\times\ \mathrm{diag}(1,\ e^{i\frac{\alpha_{21}}{2}},\ e^{i\frac{\alpha_{31}}{2}})$$

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

In total 6 parameters to determine

- 3 angles
- 2 mass differences
- 1 CP violation phase

Oscillation probability

$$P_{\nu_\alpha \to \nu_\beta} = \sum_{ij} U_{\alpha j} U^*_{\beta j} U^*_{\alpha i} U_{\beta i} e^{-i\frac{\Delta m^2_{ij} L}{2E}} \approx \sin^2 2\theta_{ij} \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right)$$

Neutrino Oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

ν_μ disappearance

Solar neutrino oscillation

ν_e appearance in ν_μ beam
Or
reactor neutrino experiments

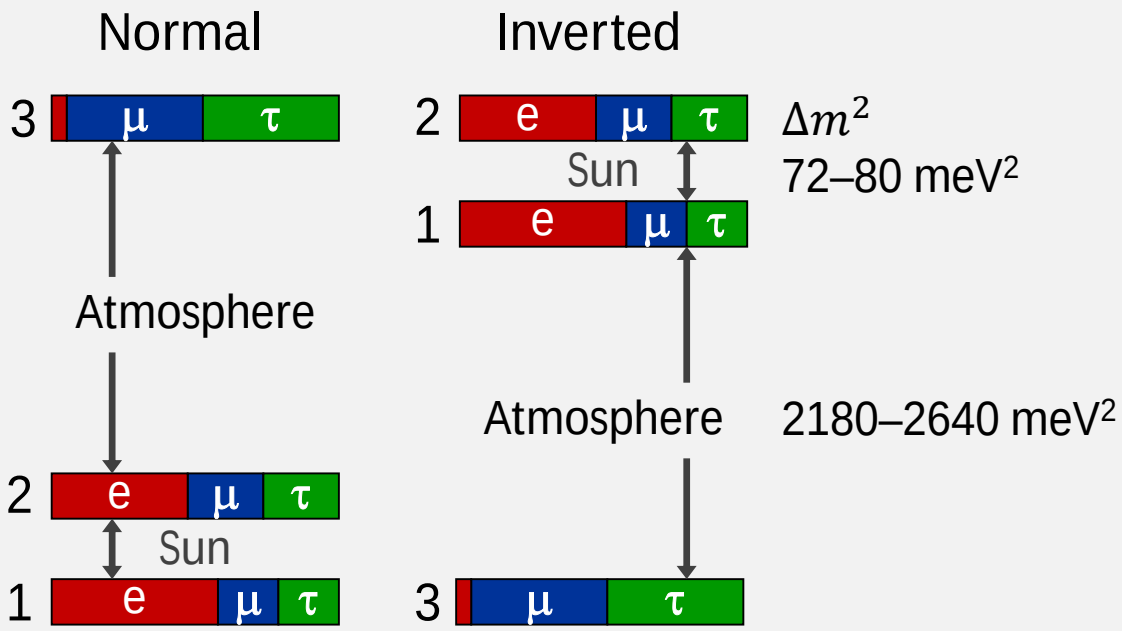
ν–less double beta decay

Three-Flavor Neutrino Parameters

Three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ (Euler angles for 3D rotation), $c_{ij} = \cos\theta_{ij}$, a CP-violating "Dirac phase" δ, and two "Majorana phases" α_2 and α_3

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{39^\circ < \theta_{23} < 53^\circ}\underbrace{\begin{pmatrix}c_{13} & 0 & e^{-i\delta}s_{13}\\ 0 & 1 & 0\\ -e^{i\delta}s_{13} & 0 & c_{13}\end{pmatrix}}_{7^\circ < \theta_{13} < 11^\circ}\underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{33^\circ < \theta_{12} < 37^\circ}\underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_2}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_3}{2}}\end{pmatrix}}_{\text{Relevant for } 0\nu2\beta \text{ decay}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric/LBL-Beams | Reactor | Solar/KamLAND



Tasks and Open Questions

- Precision for all angles
- CP-violating phase δ?
- Mass ordering? (normal vs inverted)
- Absolute masses? (hierarchical vs degenerate)
- Dirac or Majorana?

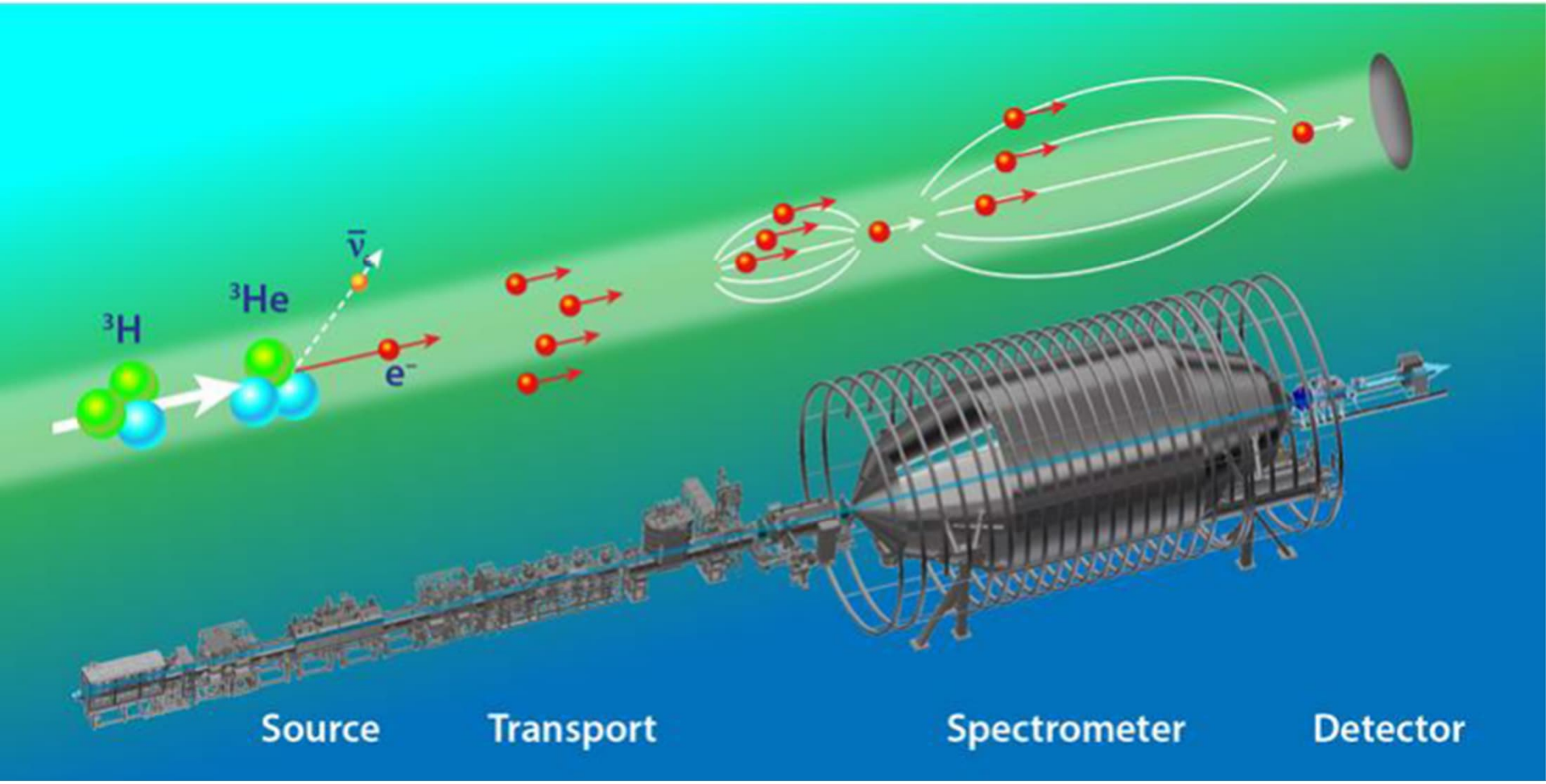
Neutrino Oscillations

- Since 20 years an active field of study and data from many experiments collected:
  - Long baseline accelerator experiment (LBL)
  - Short baseline reactor experiments
  - Atmospheric neutrinos
  - Solar neutrinos
  - Neutrinoless double beta decay experiments

Direct measurement of neutrino mass

KArlsruhe TRItium Neutrino experiment

- Goal: Measure neutrino mass with a sensitivity of 0.2 eV/c^2 (90% C.L.)

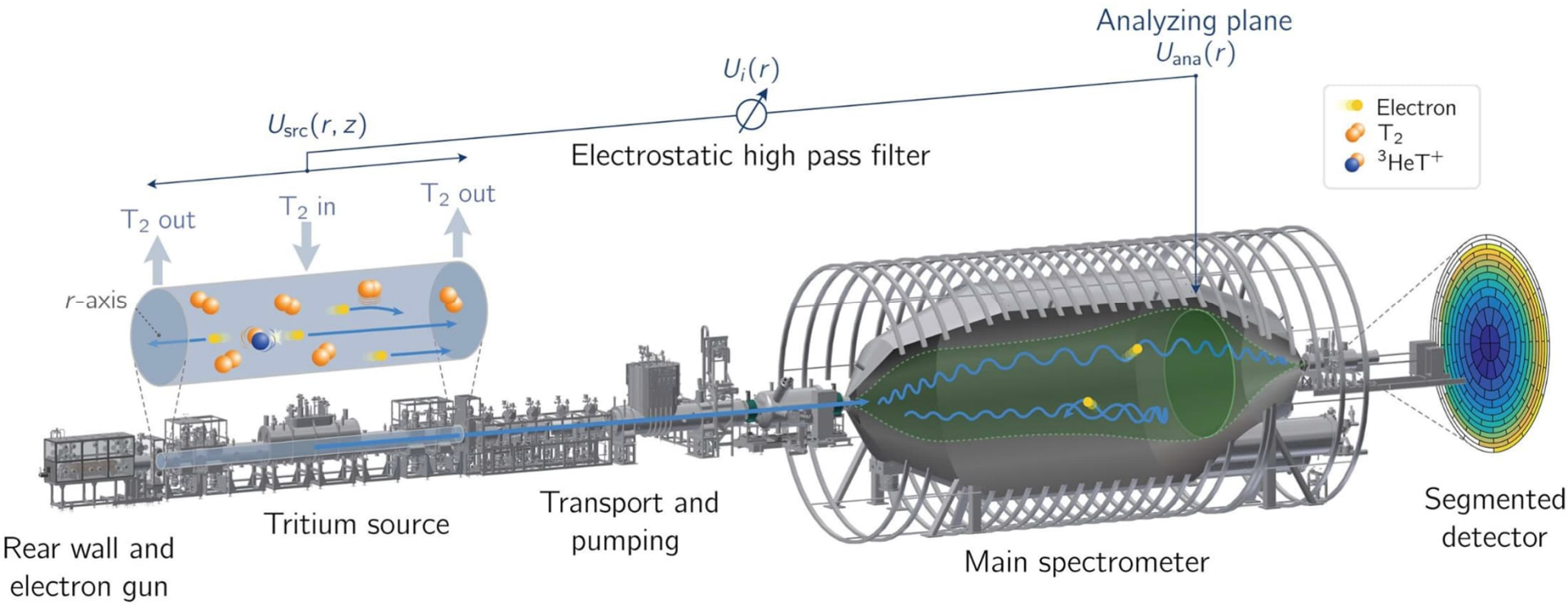


Direct measurement of neutrino mass

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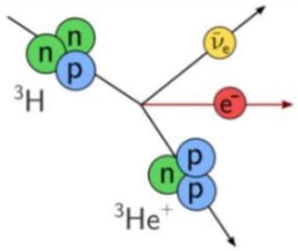


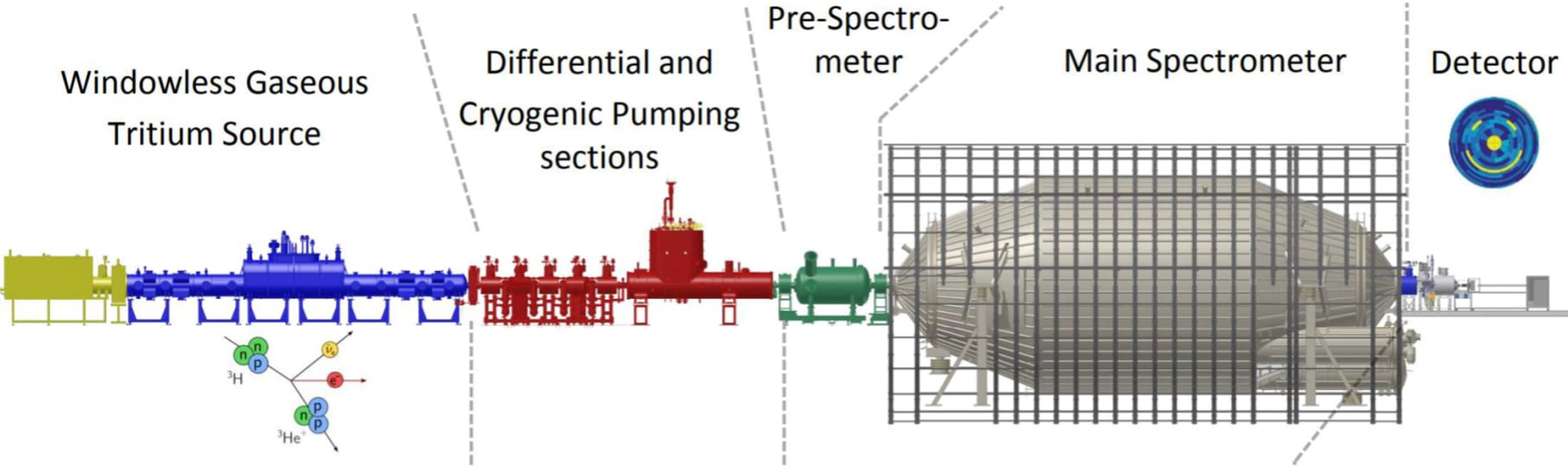


Direct measurement of neutrino mass

KArlsruhe TRItium Neutrino experiment

❖ Goal: Measure neutrino mass with a sensitivity of 0.2 eV/c^2 (90% C.L.)





- tritium β-decay
- decay rate: 10^{11} 1/s
- T_2 pressure: 10^{-3} to 10^{-6} mbar

- β-electron transport
- tritium retention (factor < 10^{-12})

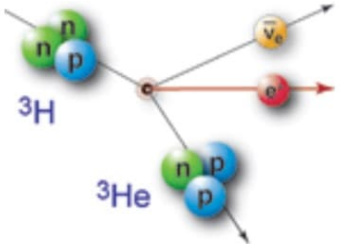
- energy analysis of β-electrons
- resolution 0.93 eV @ 18.6 keV
- pressure < 10^{-10} mbar

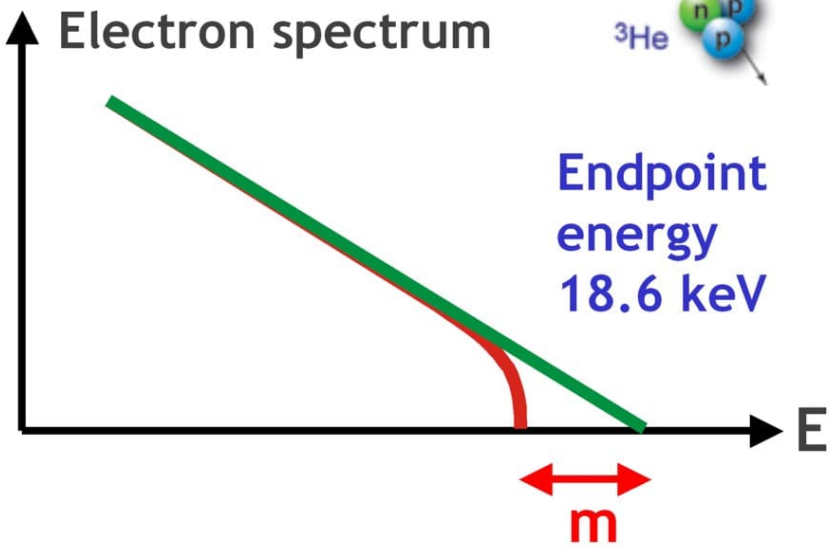
- counting of transmitted β-electrons

“Weighing” Neutrinos with KATRIN

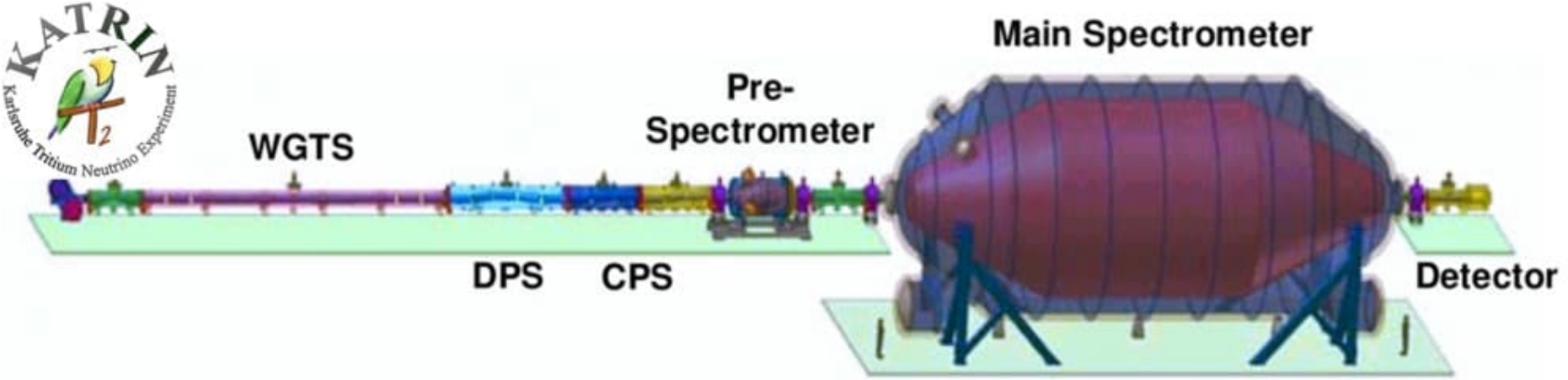
Tritium β-decay

$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

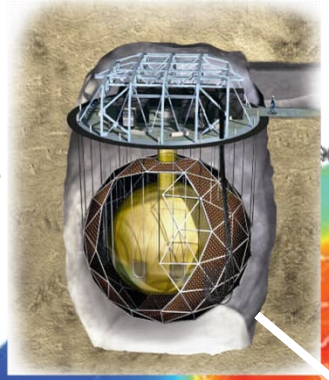




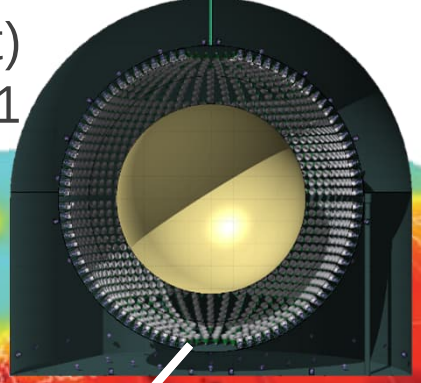
- Sensitive to common mass scale m for all flavors because of small mass differences from oscillations
- Best limit from Mainz und Troitsk
  m < 2.2 eV (95% CL)
- KATRIN can reach 0.2 eV
- Under construction
- Data taking to begin 2015/16
- http://www.katrin.kit.edu



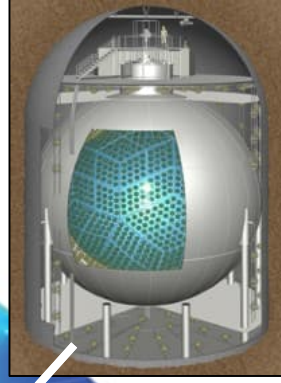
SNO+
(800 t)
since 2023



Borexino (300 t)
2007–2021



KamLAND
(1000 t)
since 2002



JUNO (20 000 t)
commissioning 2025

Neutrino Flavor Conversion

