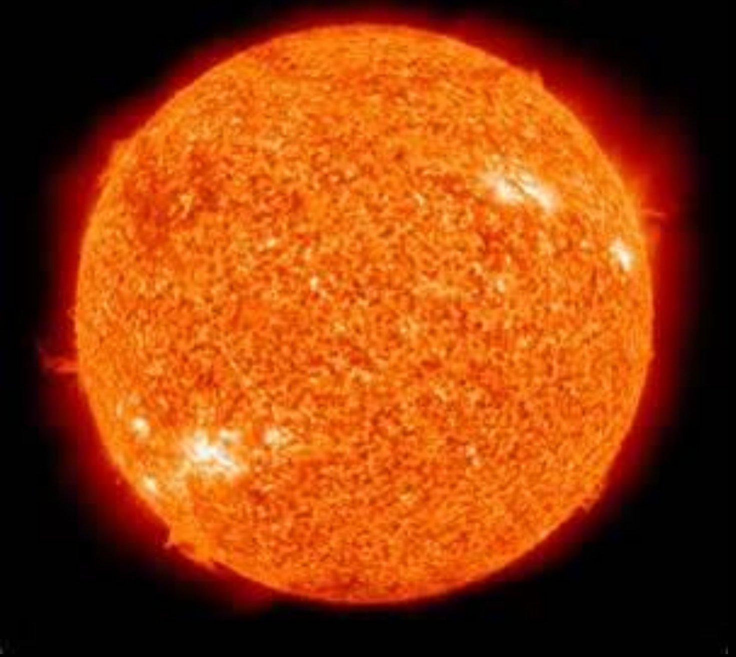
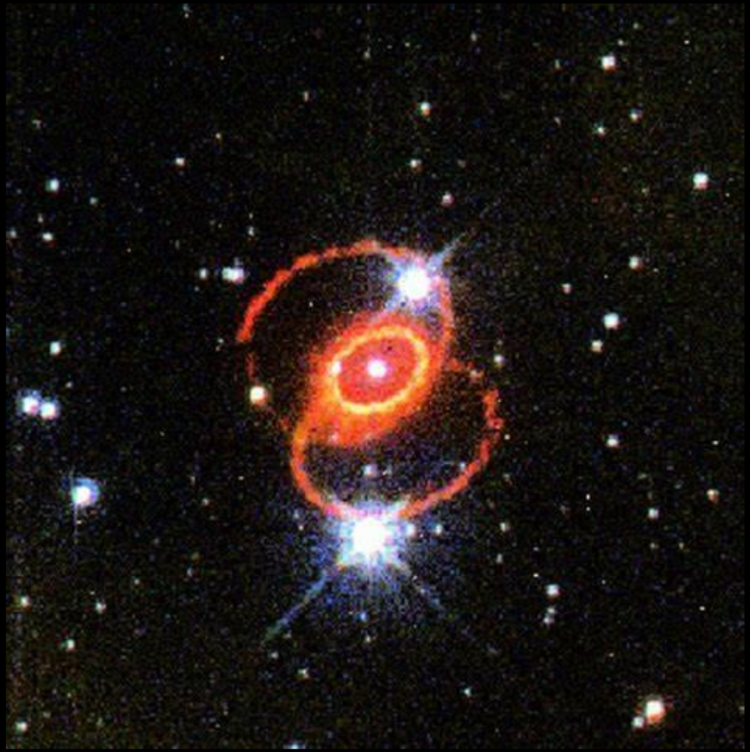
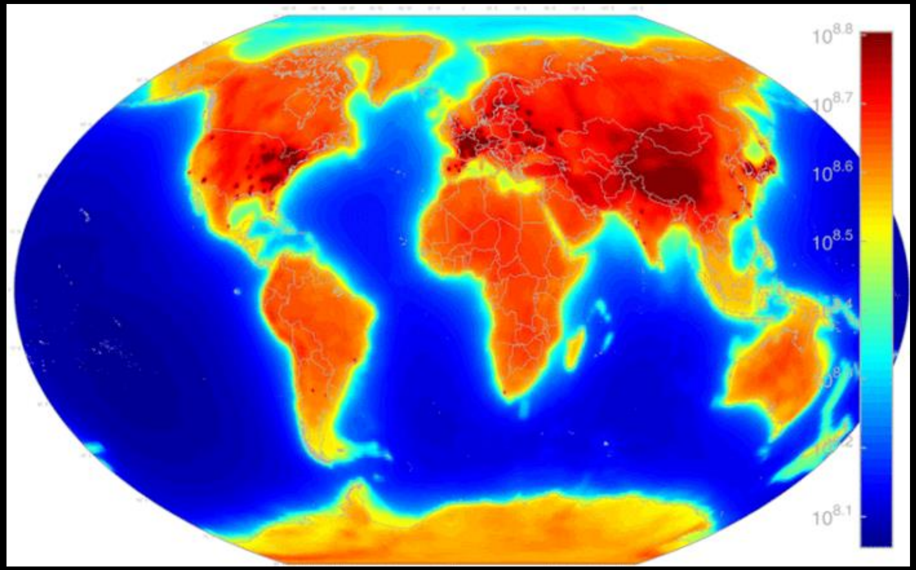
Low Energy Neutrinos

Caren Hagner, Universität Hamburg

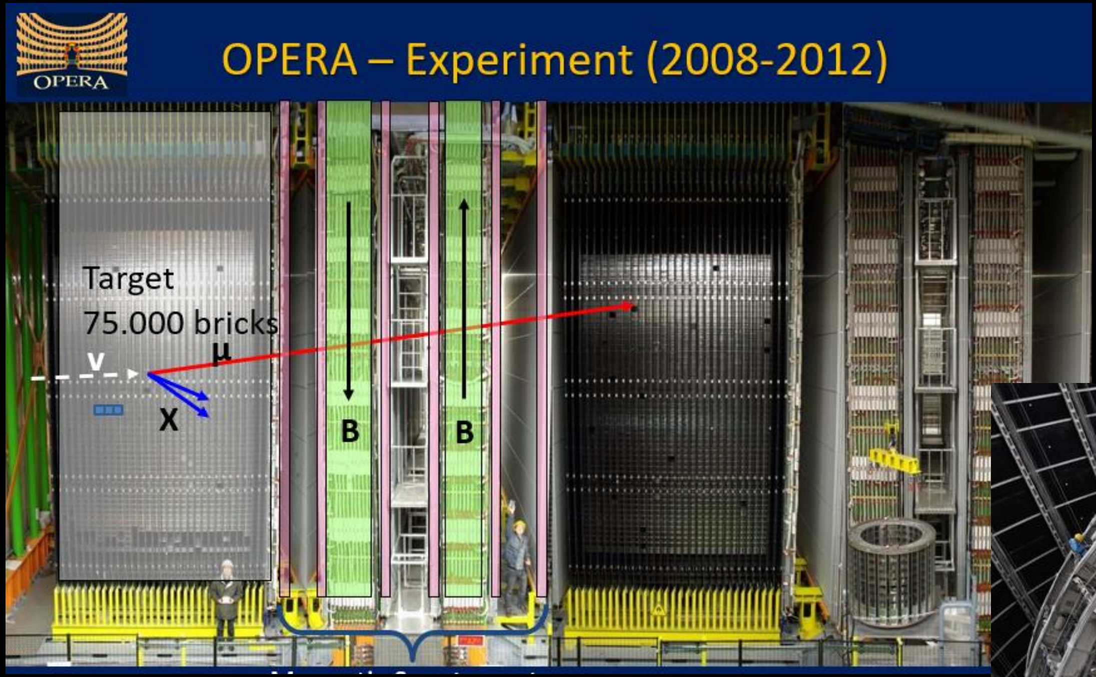


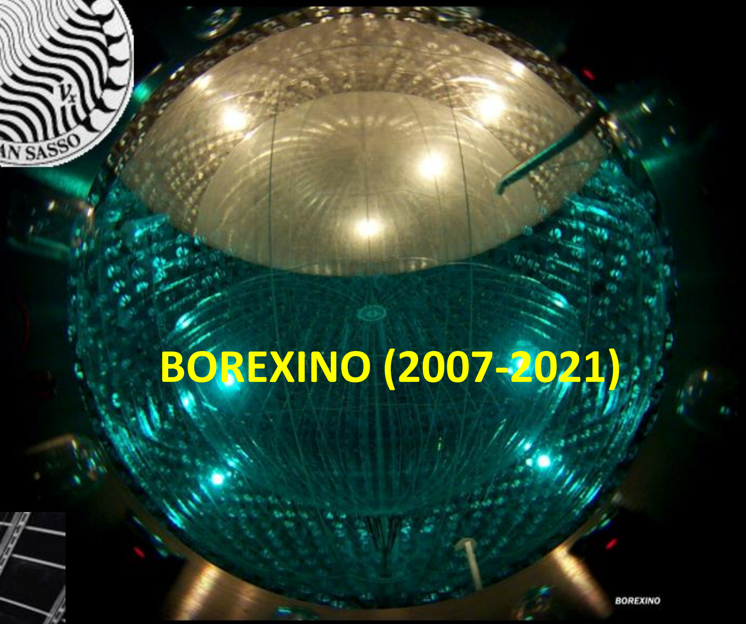




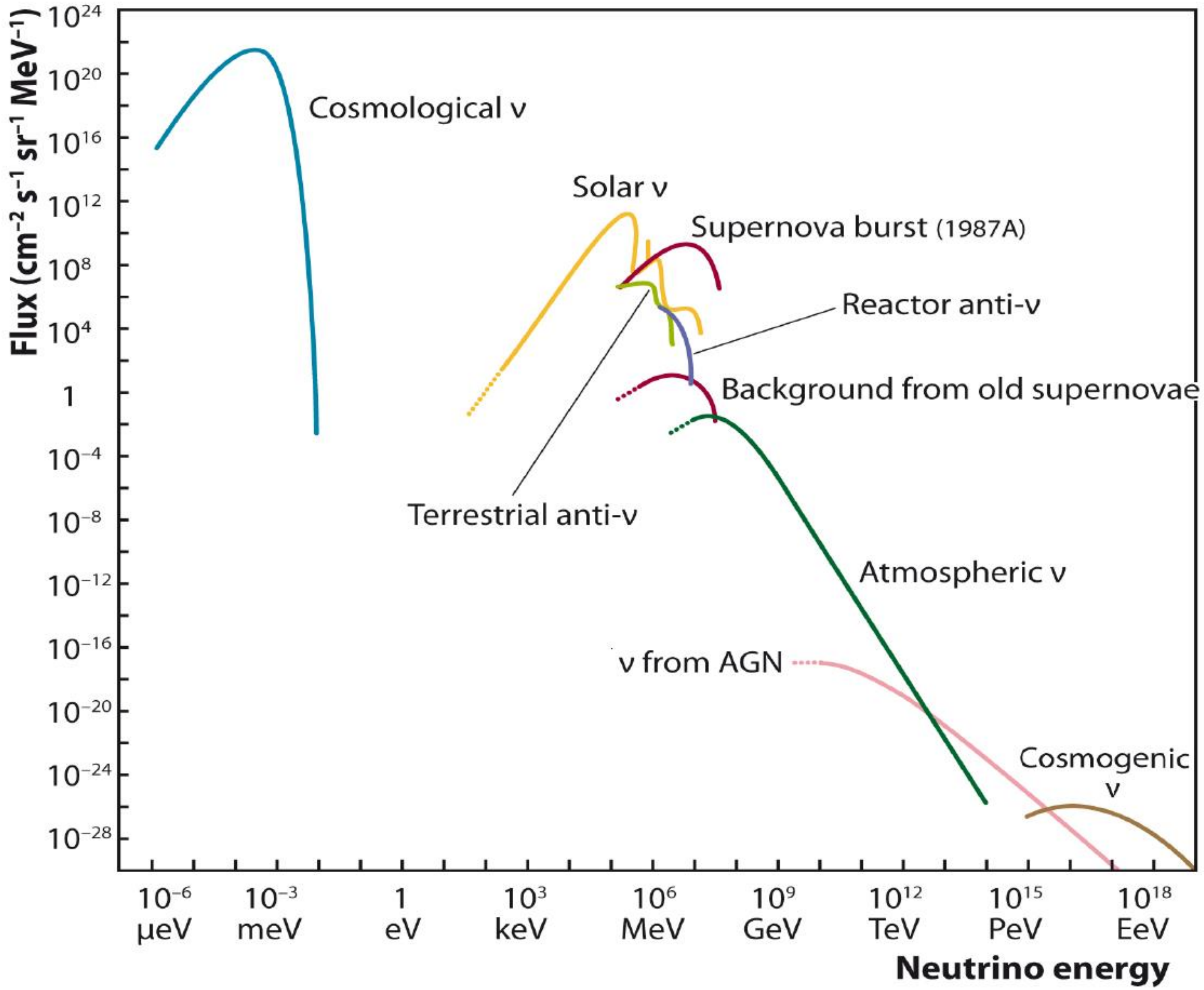
my personal neutrino experience

(Some experiments I participated)





Grand Unified Neutrino Spectrum at Earth (old version)



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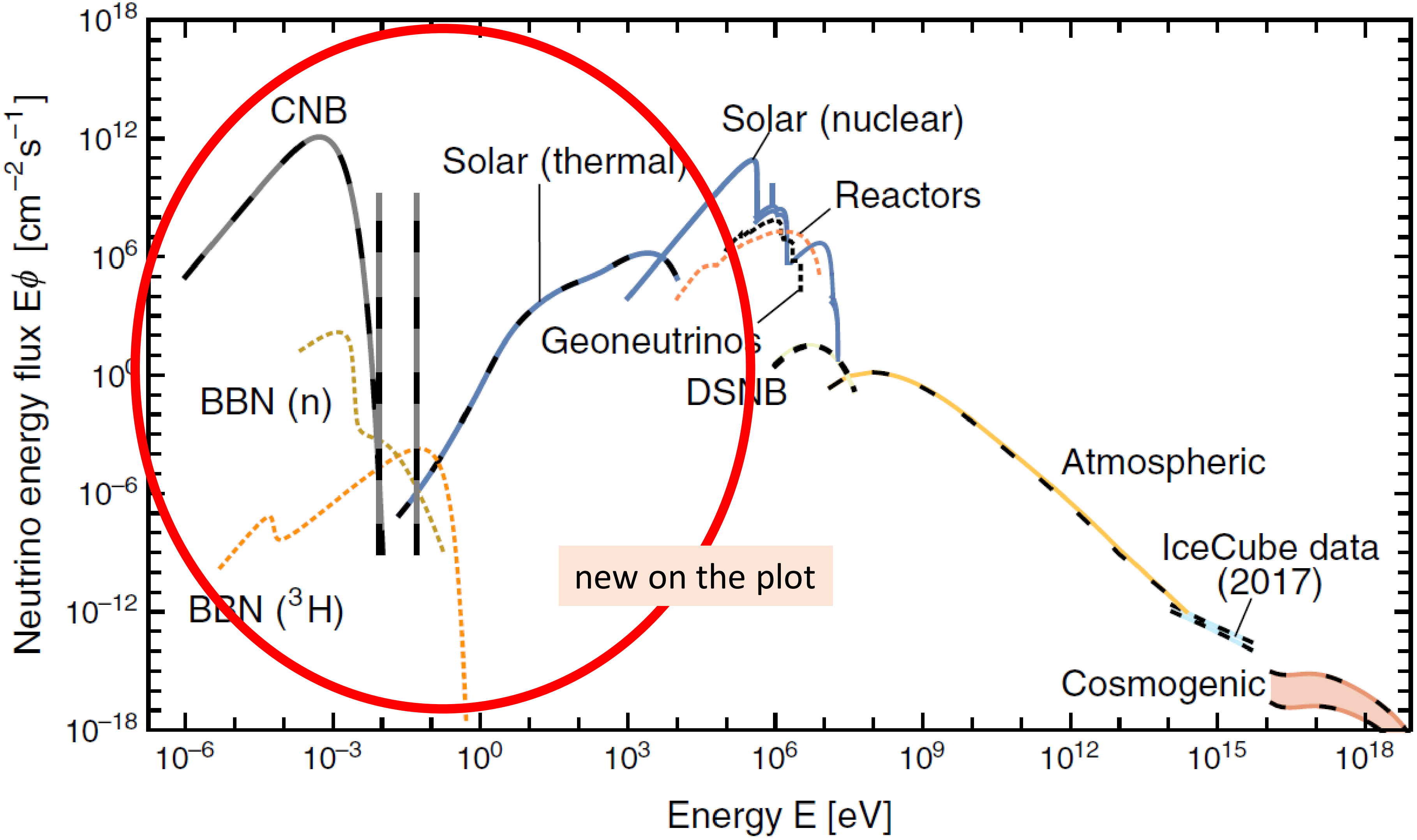
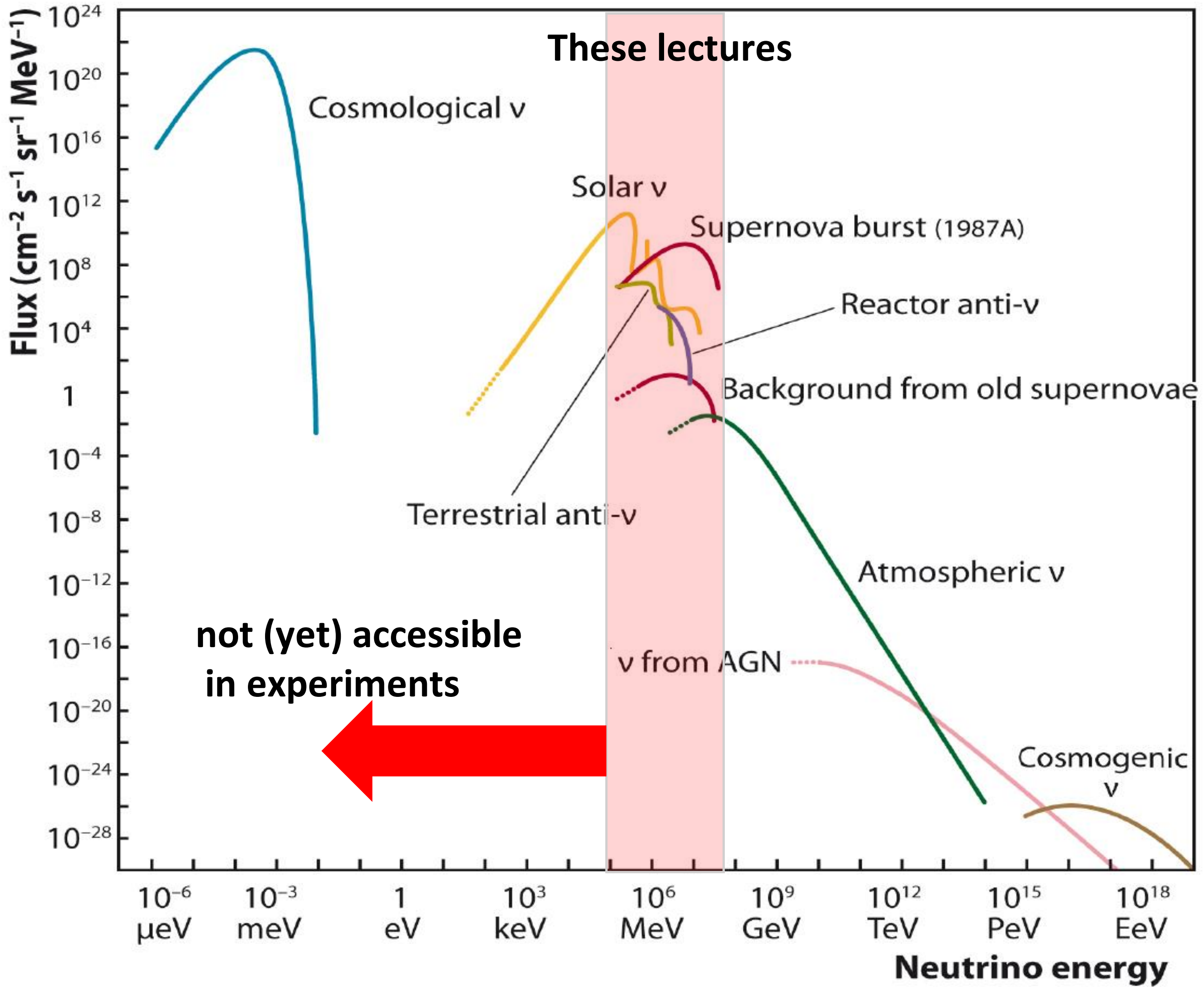


Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components, by Edoardo Vitagliano, Irene Tamborra and Georg Raffelt
arXiv:1910.11878v3 [astro-ph.HE] and REVIEWS OF MODERN PHYSICS, Vol. 92, 2020

Grand Unified Neutrino Spectrum at Earth (old version)



Low Energy Neutrinos

- Part 1 (today)
  Overview, Some neutrino history, inverse beta decay, delayed coincidence technique
  Solar neutrinos (pioneering experiments), solar neutrino puzzle, SNO

- Part 2 (tomorrow)
  neutrino oscillations, Kamland, adiabatic flavor transitions, MSW effect,
  Borexino and precision solar neutrino spectroscopy,
  3 flavor mixing, JUNO

- Part 3 (tomorrow)
  Supernova neutrinos, DSNB
  Geoneutrinos,
  Double Beta decay

Some basic facts about neutrinos

Standard model:

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$

3 active neutrinos
↑ measured at LEP (width of Z^0)

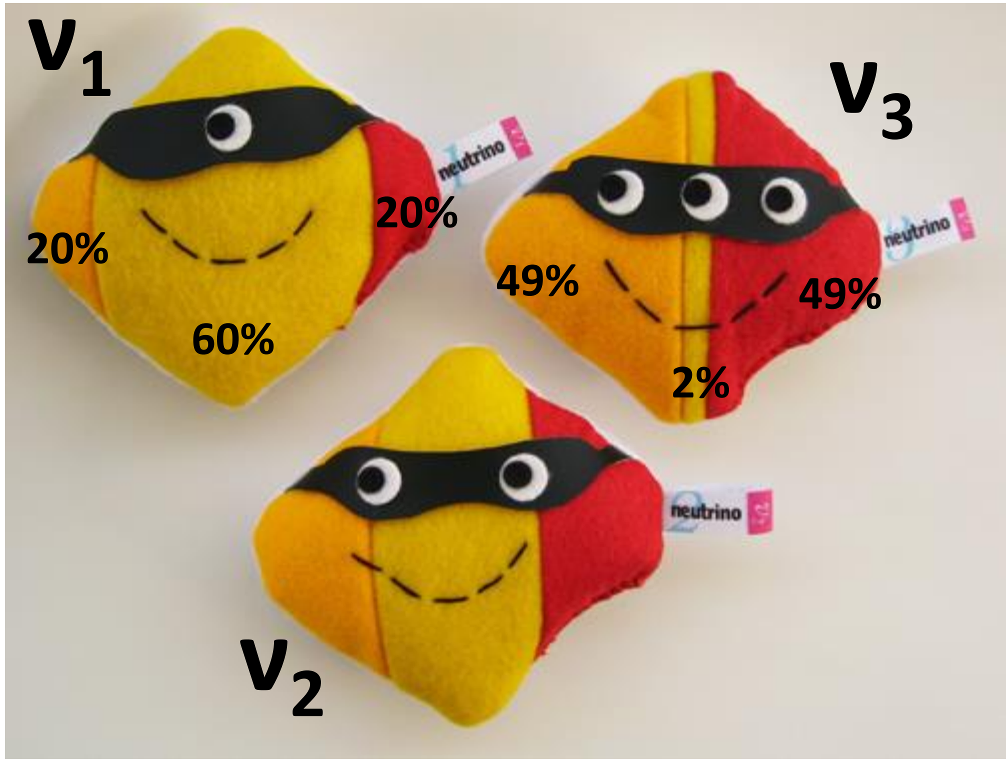
Neutrinos have no electric charge
no mass
no electric dipole moment
no magnetic dipole moment

Neutrinos are stable

Neutrinos interact <u>only</u> via Weak interaction
↳ ν_L left handed neutrinos
or $\bar{\nu}_R$ right handed antineutrinos

Flavor-Eigenstates

Mass-Eigenstates



The minimal neutrino mass spectrum:

$m_1 = 0$,
$m_2 = 8.6$ meV
$m_3 = 50$ meV

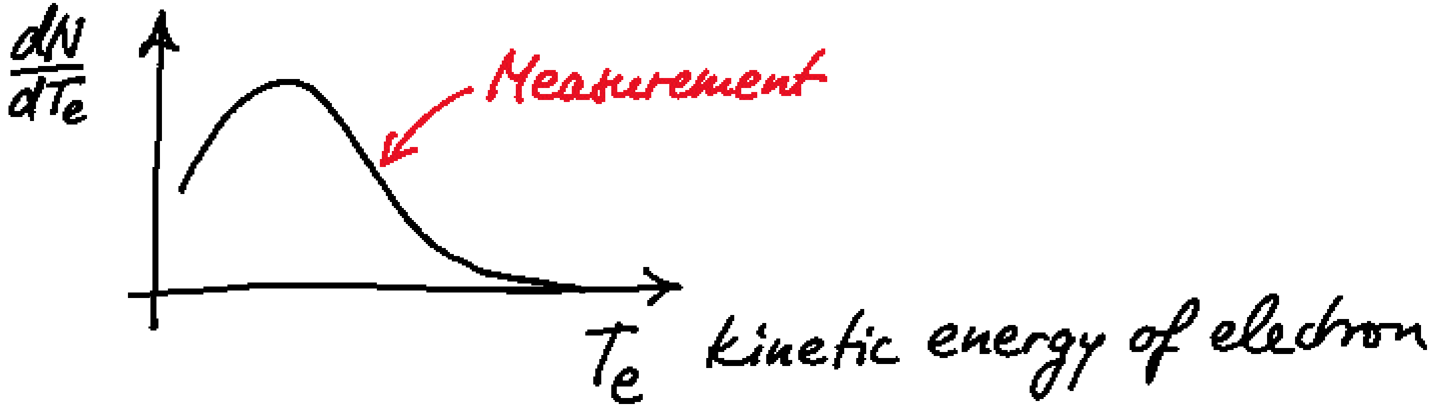
(or inverted)

KATRIN m < 800meV

The „invention" of the neutrino by Pauli

~ 1914 measurement of energy of electrons from β decay was possible (Chadwick)

β^- decay: $X(A,Z) \rightarrow Y(A,Z+1) + e^-$



Continuous spectrum of β particles was not expected!

Possible solutions to the problem of the continuous energy spectrum of electrons in β-decays:

- Error in experiments: for example, electrons could loose energy (different amounts) before reaching the detector

- Nils Bohr: energy conservation does not hold in nuclear reactions

- Wolfgang Pauli: a third particle is emitted (later called neutrino by Fermi)

Front row from left: Bohr, Heisenberg, Pauli, Stern, Meitner,… in the 1950s (CBW/Alamy)

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum**, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light.** The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

I agree that my remedy could seem incredible because one should have seen these neutrons much earlier if they really exist. But only the ones who dare can win and the difficult situation, due to the continuous structure of the beta spectrum, is lighted by a remark of my honoured predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's well better not to think about this at all, like new taxes". From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge.

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant,

W. Pauli

1932: Discovery of neutron by Chadwick

Fermi names new particle „Neutrino“ (small neutron)

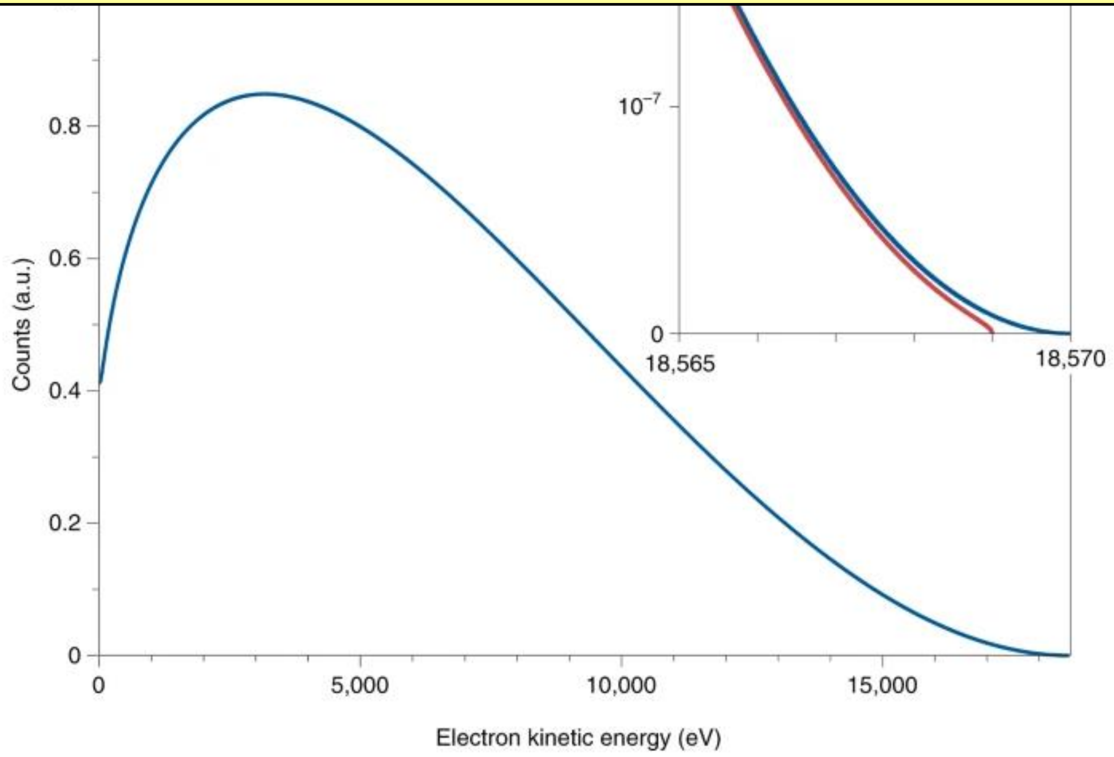
Kinematic of β-decay is still important:

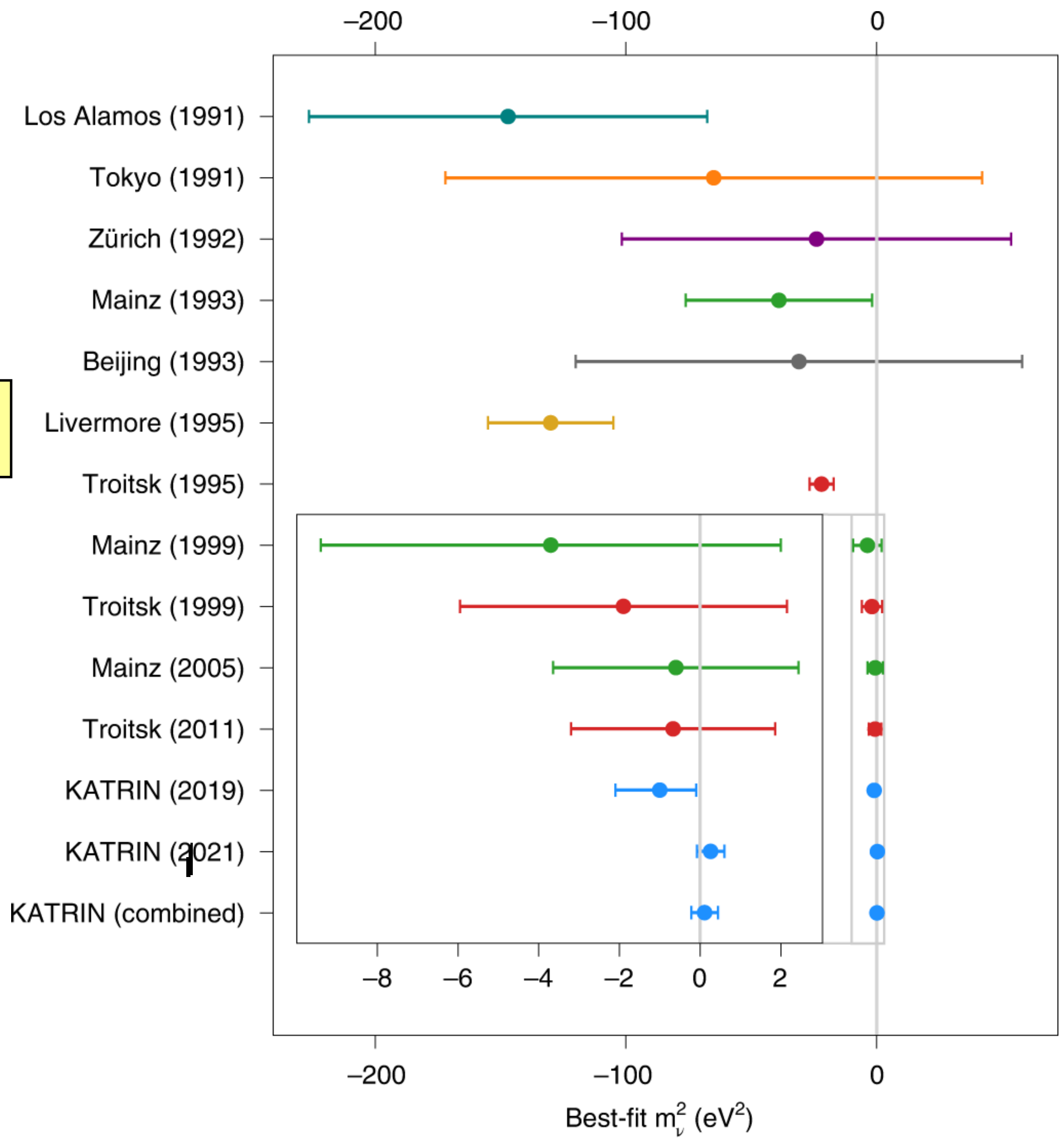
World record neutrino mass limit from tritium β-decay: KATRIN experiment

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

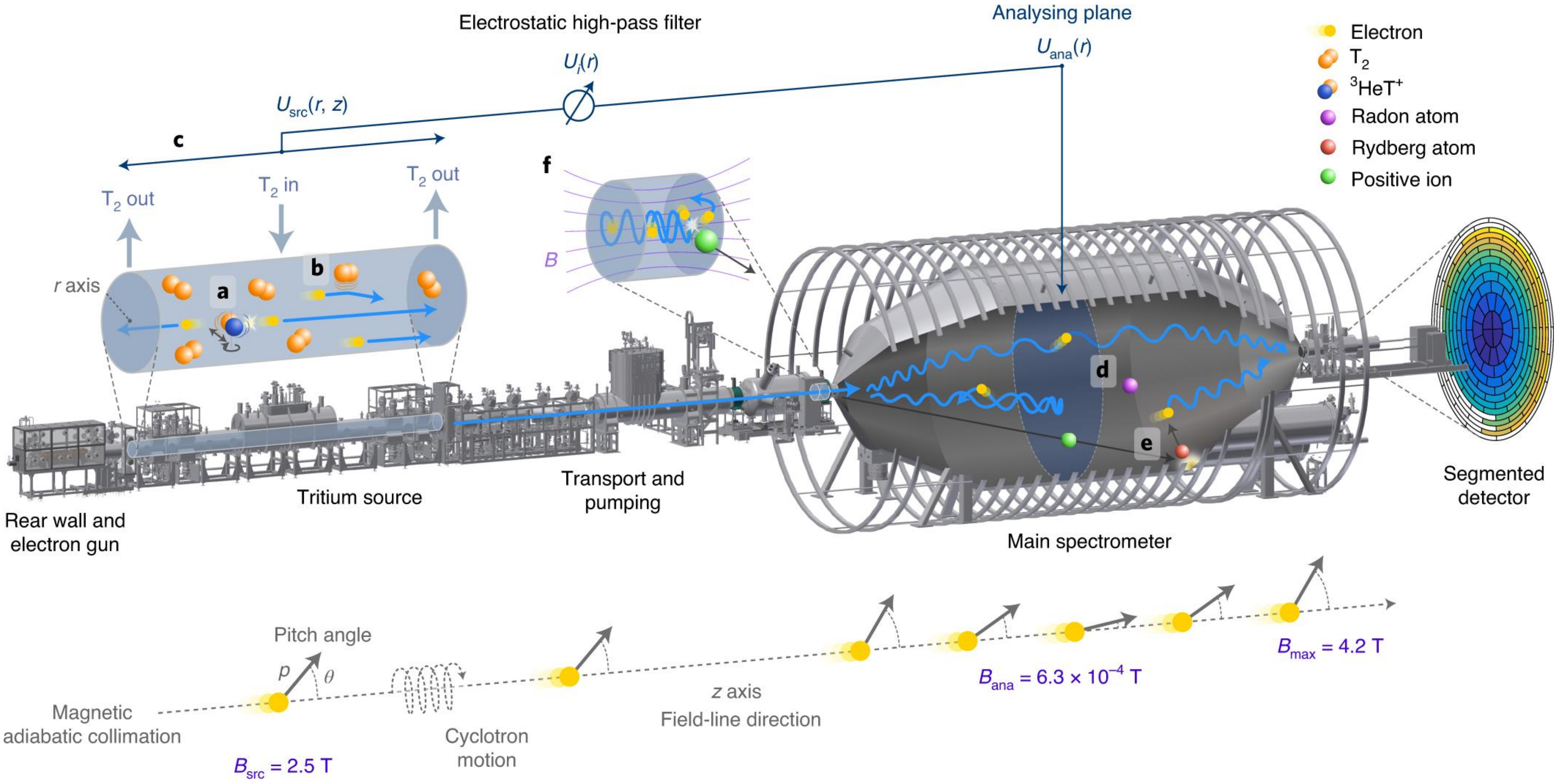
E_0 = 18.6 keV

$$dN/dE = K \times F(E,Z) \times p \times E_{tot} \times (E_0\text{-}E_e) \times [\,(E_0\text{-}E_e)^2 - m_\nu^2\,]^{1/2}$$



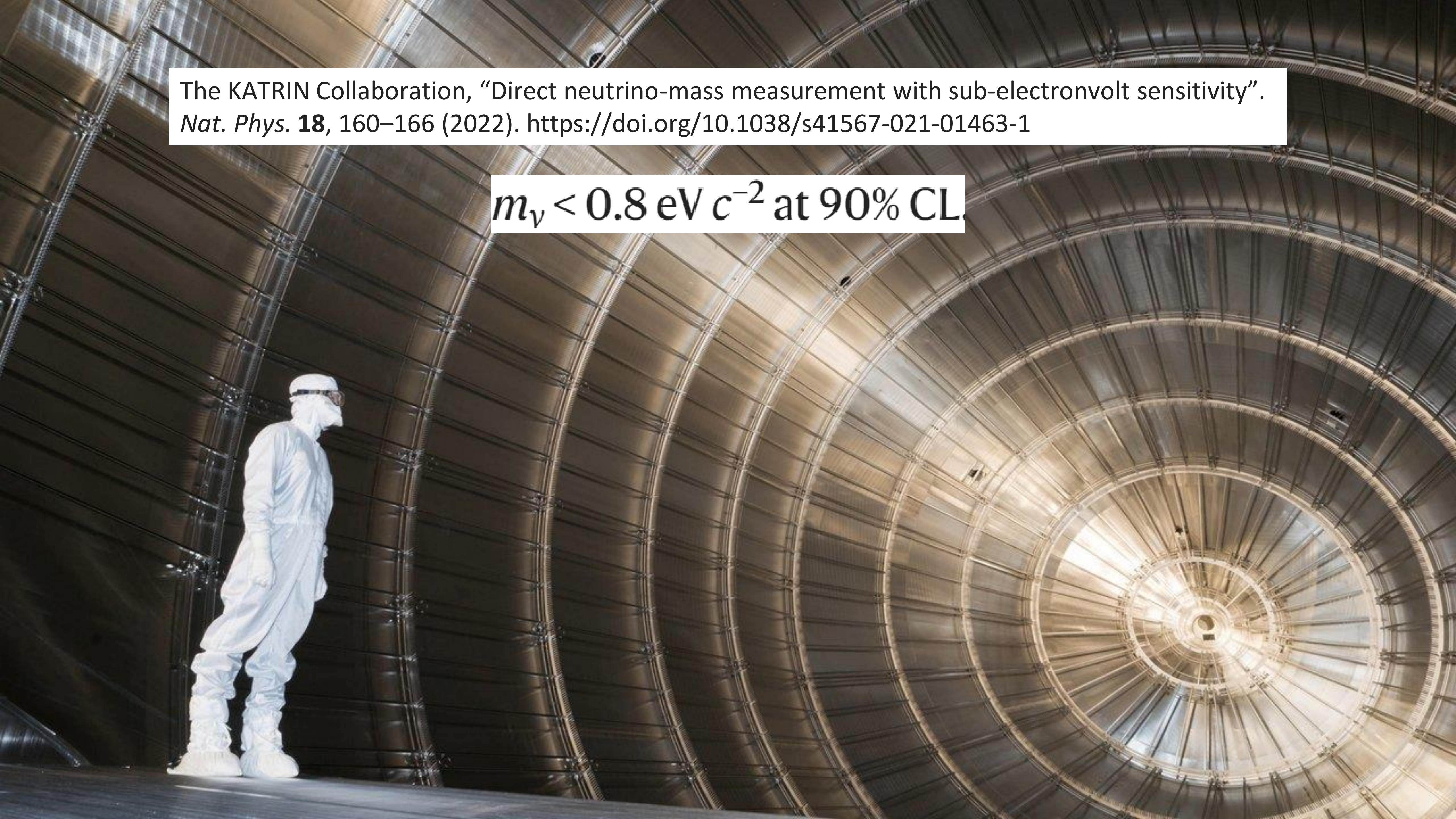


World record neutrino mass limit from tritium β-decay: KATRIN experiment



The KATRIN Collaboration, “Direct neutrino-mass measurement with sub-electronvolt sensitivity”.
Nat. Phys. **18**, 160–166 (2022). https://doi.org/10.1038/s41567-021-01463-1

$$m_\nu < 0.8 \text{ eV } c^{-2} \text{ at } 90\% \text{ CL.}$$



First detection of neutrinos by Reines and Cowan

Savannah River Nuclear Power Plant
(for nuclear weapons: tritium and plutonium-239)

$$\Phi_\nu = 1.2 \cdot 10^{13} \frac{\bar{\nu}_e}{cm^2 s}$$

Neutrino detection by inverse β-decay:

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

Energy threshold: $E_{\bar{\nu}} \geq \frac{(m_n + m_e)^2 - m_p^2}{2m_p} = 1.8\ MeV$

The delayed coincidence technique

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

1. prompt event:

e^+ looses its energy in detector

e^+ annihilates: $e^+ + e^- \rightarrow 2\gamma$

↳ 2 photons, back to back, each 511 keV

2. delayed event:

n does not ionize material

n scatters on free p, looses energy until thermal

n is captured:

for example $n + {}^{113}Cd \rightarrow {}^{114}Cd^* \rightarrow {}^{114}Cd + \gamma$

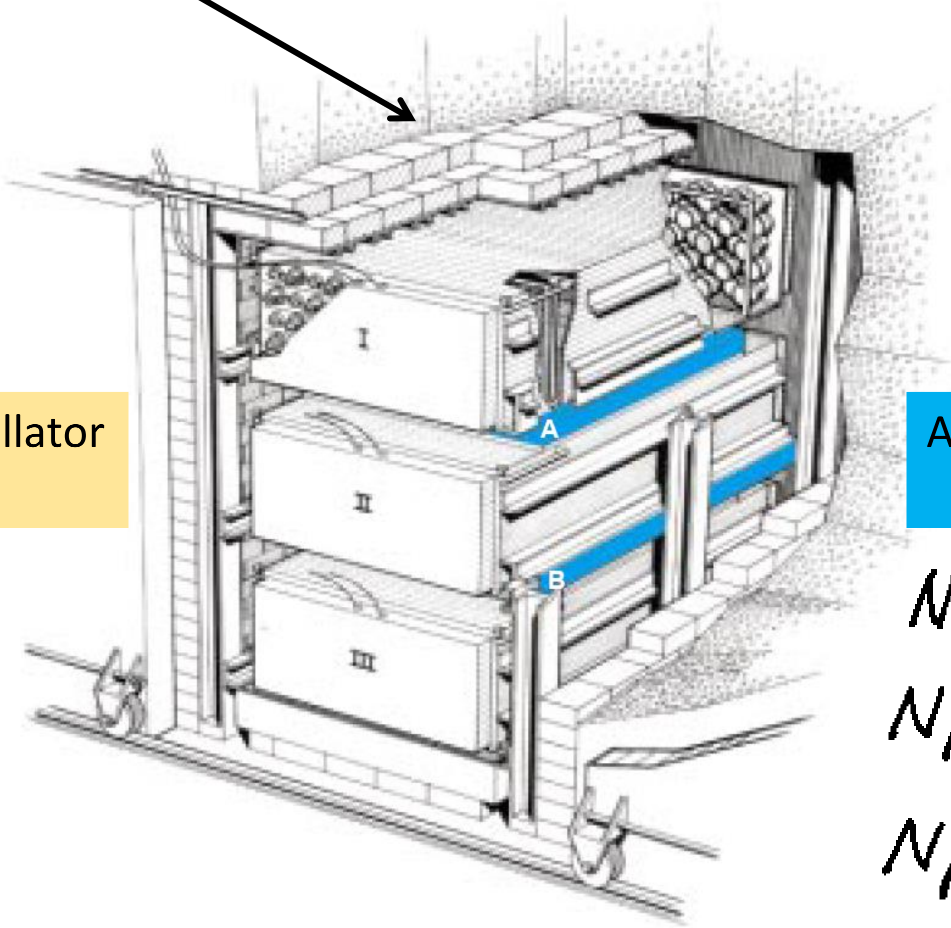
good also Gd, Cl

} 10 μs

Savannah River Experiment (1956)

by Reines und Cowan

Antineutrinos from Savannah River Nuclear Power Plant



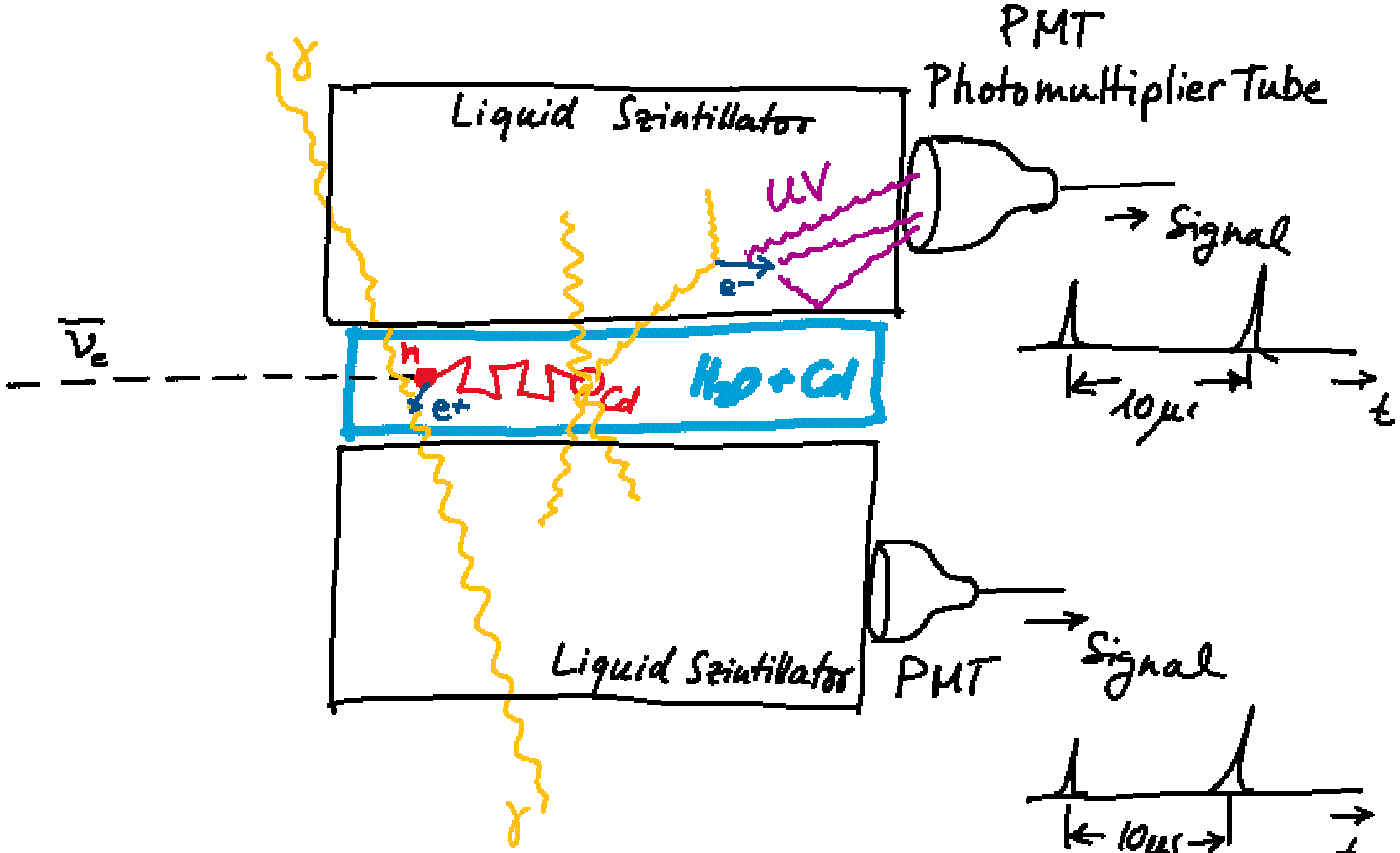
I, II, III: Liquid scintillator + PMTs

A,B: Vessel with water + CdCl

Number of free p in 200l

$$N_{H_2O} = \frac{200\,kg \cdot N_A}{18\,g}$$

$$N_p = 2 \cdot H_2O = 1{,}3 \cdot 10^{28}$$



PMT
Photomultiplier Tube
Liquid Szintillator
UV
e⁻
→ Signal
$\bar{\nu}_e$
n
e+
Cd
H_2O + Cd
10μs
t
Liquid Szintillator
PMT
→ Signal
10μs
t
γ
γ

Measurement/Calculation of the cross section

$$R = \phi \cdot N \cdot \sigma$$

(Theory predicted $1.0 \cdot 10^{-43}\,cm^2$)

Rate $\frac{1}{s}$ — flux $\frac{1}{cm^2 s}$ — number of target atoms — cross section cm^2

Here:

$$R = \phi_\nu \cdot N_p \cdot \sigma_\nu \cdot \varepsilon_n \cdot \varepsilon_{e+}$$

$\varepsilon_n = 0.17$ efficiency to detect neutron

$\varepsilon_{e+} = 0.15$ efficiency to detect e^+

$R = 1.5\ 1/h$

$\phi_\nu = 1.2 \cdot 10^{13}\ \frac{1}{cm^2 s}$

$N = 1.3 \cdot 10^{28}$

$$\rightarrow \sigma_\nu = \frac{R}{\phi_\nu \cdot N_p \cdot \varepsilon_n \cdot \varepsilon_{e+}} = 1.2 \cdot 10^{-43}\,cm^2$$

PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

Detection of the Free Antineutrino*

F. REINES,† C. L. COWAN, JR.,‡ F. B. HARRISON, A. D. MCGUIRE, AND H. W. KRUSE
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 27, 1959)

The antineutrino absorption reaction $p(\bar{\nu},\beta^+)n$ was observed in two 200-liter water targets each placed between large liquid scintillation detectors and located near a powerful production fission reactor in an antineutrino flux of 1.2×10^{13} cm^{-2} sec^{-1}. The signal, a delayed-coincidence event consisting of the annihilation of the positron followed by the capture of the neutron in cadmium which was dissolved in the water target, was subjected to a variety of tests. These tests demonstrated that reactor-associated events occurred at the rate of 3.0 hr^{-1} for both targets taken together, consistent with expectations; the first pulse of the pair was due to a positron; the second to a neutron; the signal dependended on the presence of protons in the target; and the signal was not due to neutrons or gamma rays from the reactor.

Cross Section

Using our experimental numbers, we are now in a position to calculate the cross section for the reaction $p(\bar{\nu},\beta^+)n$ induced by antineutrinos from fission fragments. As pointed out above, our object is only to check whether the cross section which we deduce from our experiment is consistent with expectations. The cross section, σ, is calculated from the equation

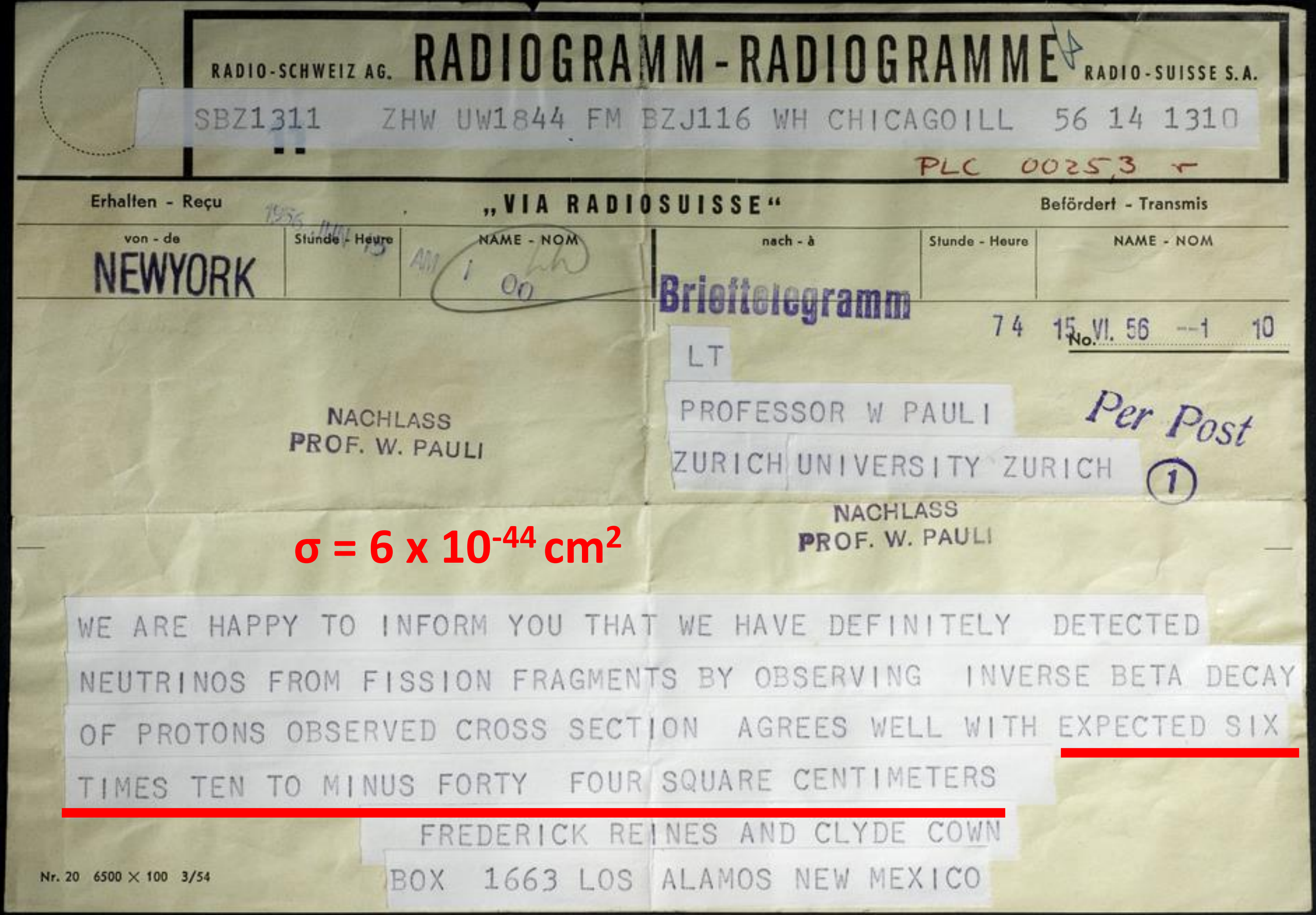
$$\sigma=\frac{R}{3600FN\epsilon_n\epsilon_\beta}\ \text{cm}^2, \qquad (3)$$

where $R=1.5\pm0.1$ hr^{-1}, the average signal rate per triad, $\epsilon_n=0.17\pm0.06$, $\epsilon_\beta=0.15\pm0.02$, $N=1.1\times10^{28}$, the number of hydrogen nuclei in each target tank, and $F=1.2\times10^{13}$ cm^{-2} sec^{-1}, the average $\bar{\nu}$ flux at the detector.[11] Therefore

$$\sigma=\frac{1.5\pm0.1}{3600\times1.2\times10^{13}\times1.1\times10^{28}(0.17\pm0.06)(0.15\pm0.02)},$$

$$\sigma=(1.2_{-0.4}^{+0.7})\times10^{-43}\ \text{cm}^2.$$

This value is in agreement with the theoretically expected value[12] of $(1.0\pm0.17)\times10^{-43}$ cm^2.



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PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

$\sigma = 6 \times 10^{-44}\ cm^2$

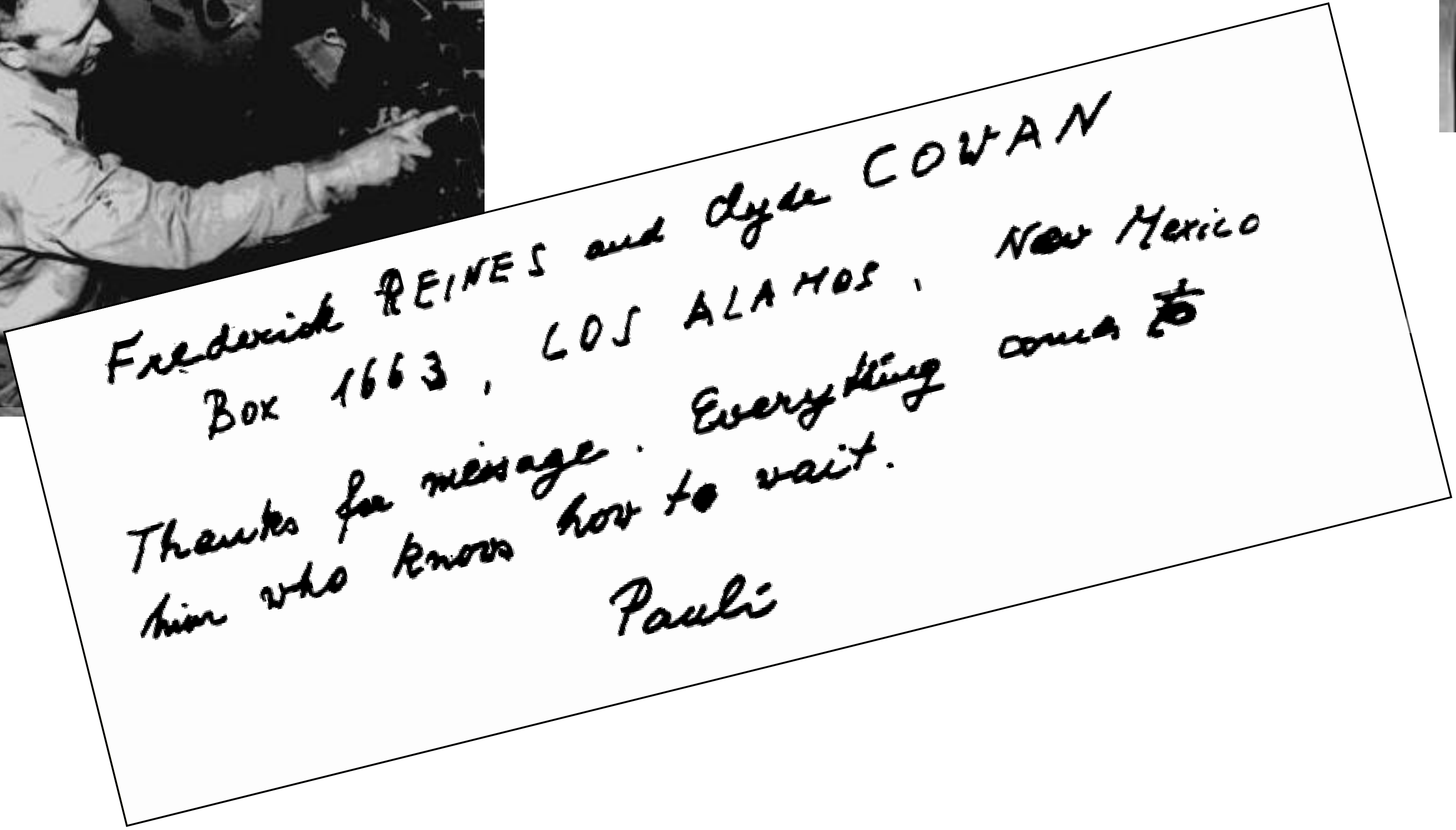
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

Nr. 20 6500 × 100 3/54

Cowan und Reines **1956**



Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to
him who knows how to wait.

Pauli

Fred Reines
Nobel prize1995
for the detection
of neutrinos

Why Astroparticle Physics?

Particles as **messengers** to understand the **sources**

New: Multi-Messenger Astronomy

Particles travel large distances, production in extreme environments

Study **fundamental properties** of particles and their interactions

Particles could be relics from Big Bang:
Dark matter, cosmic microwave background, relic neutrinos
Cosmology, early universe

Example Solar Neutrinos

1. Verify Energy Production In the Sun

Particles as **messengers** to understand the **sources**

3. Study energy production in Sun with neutrinos

Particles travel large distances, production in extreme environments

Study **fundamental properties** of particles and their interactions

2. Something is „wrong“ discovery of neutrino oscillations and neutrino masses

Particles could be relics from Big Bang:
Dark matter, cosmic microwave background, relic neutrinos
Cosmology, early universe

4. Consequences of neutrino masses for early universe, structure formation, dark matter

5.Something unexpected

Background for DM experiments