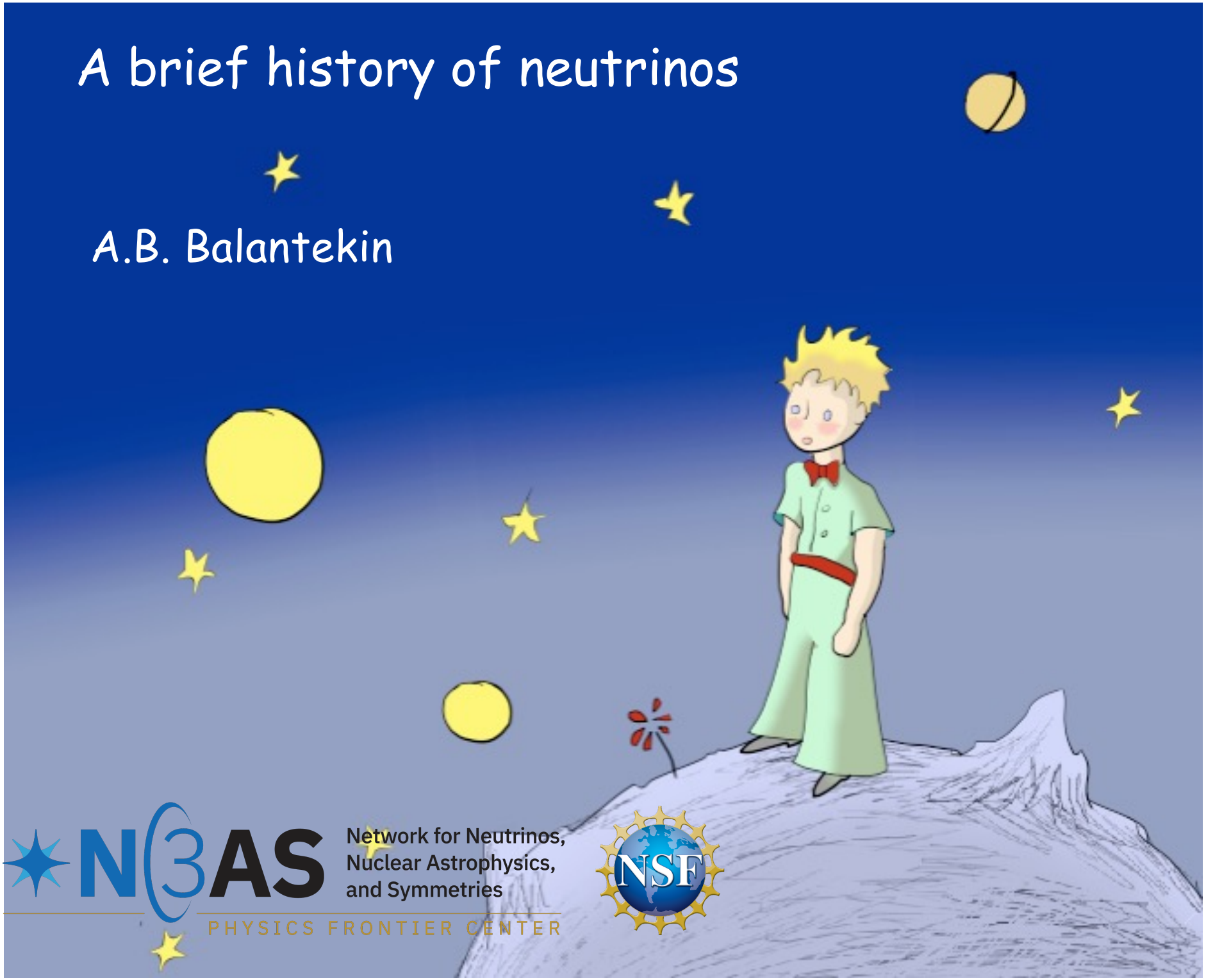
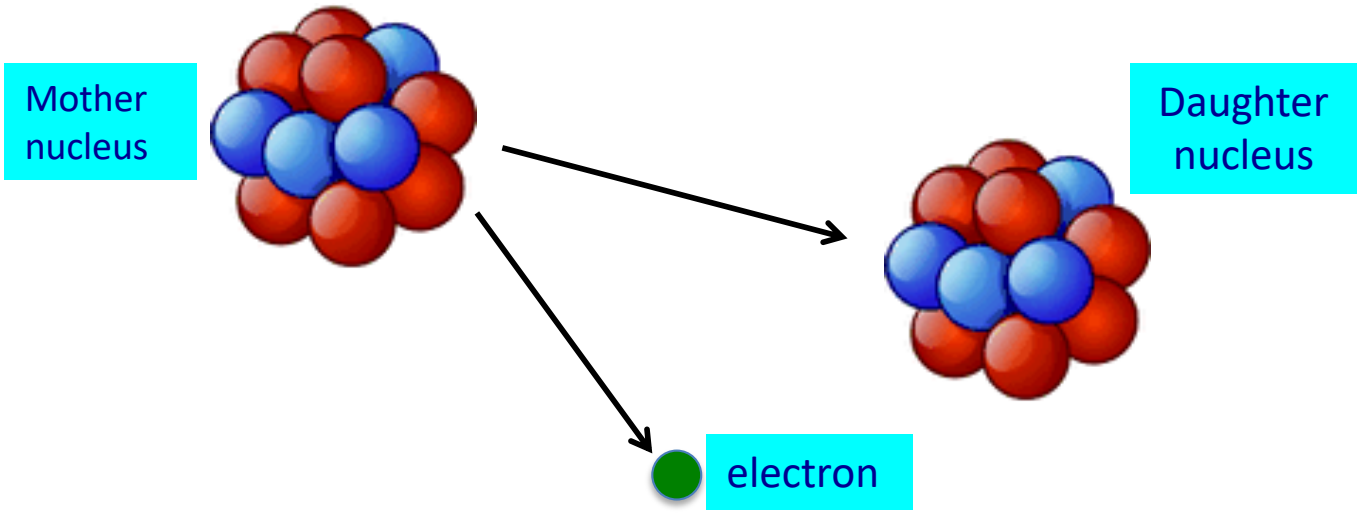
A brief history of neutrinos

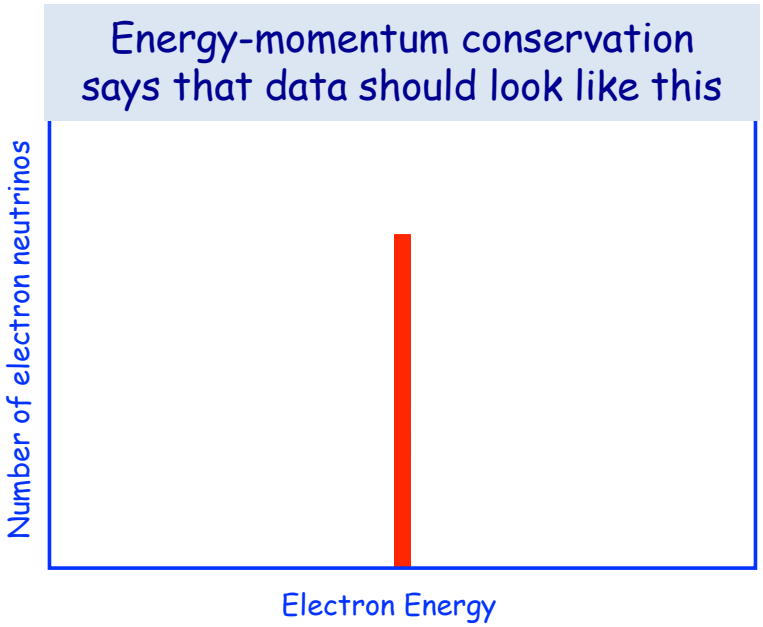
A.B. Balantekin

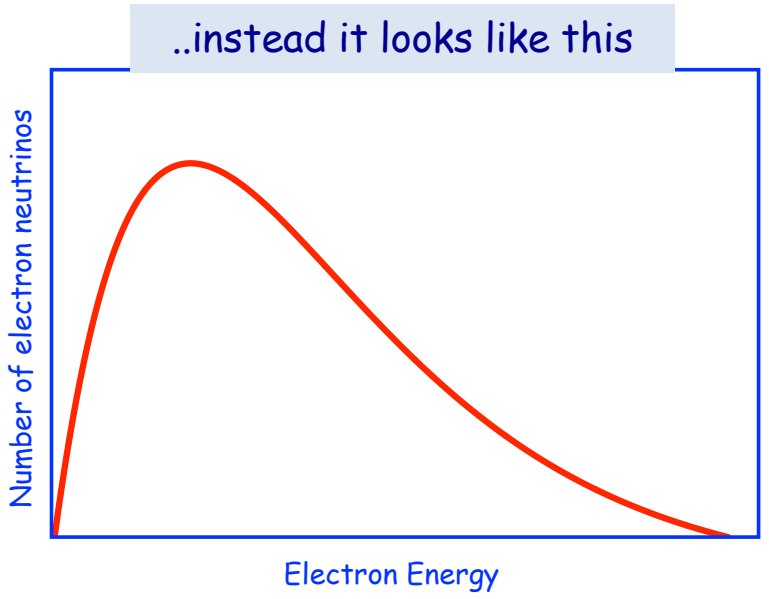


N3AS
Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER
NSF

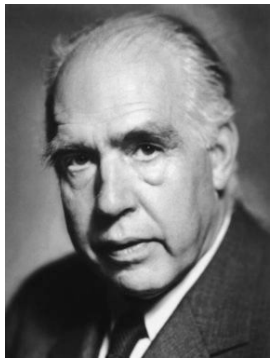
Neutrino came out of a puzzle about the radioactive decay in the early 1920's:



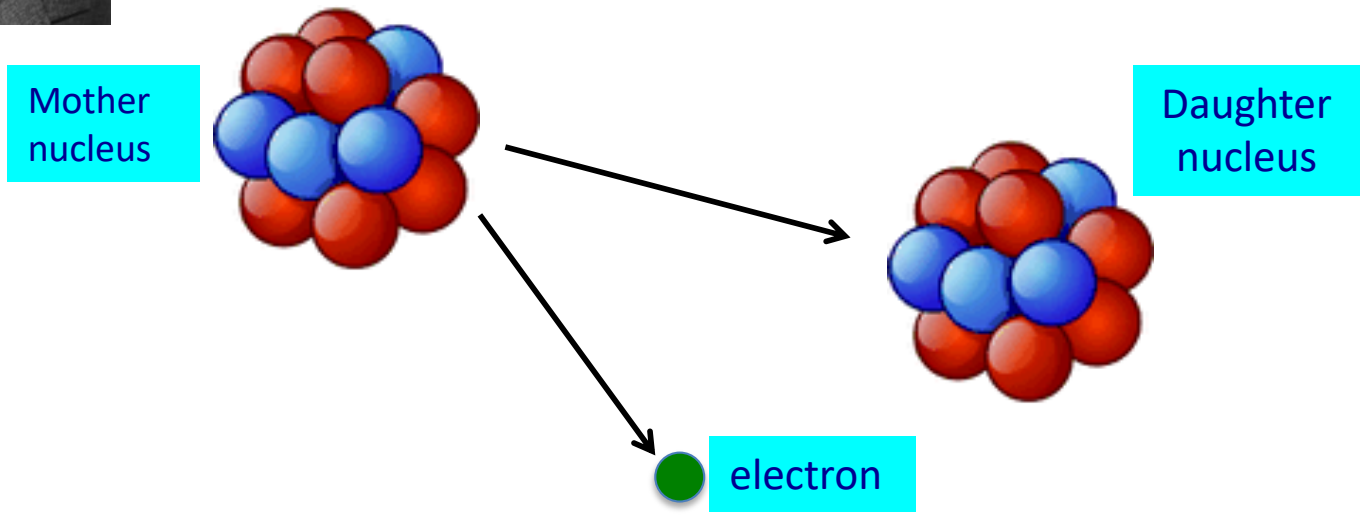




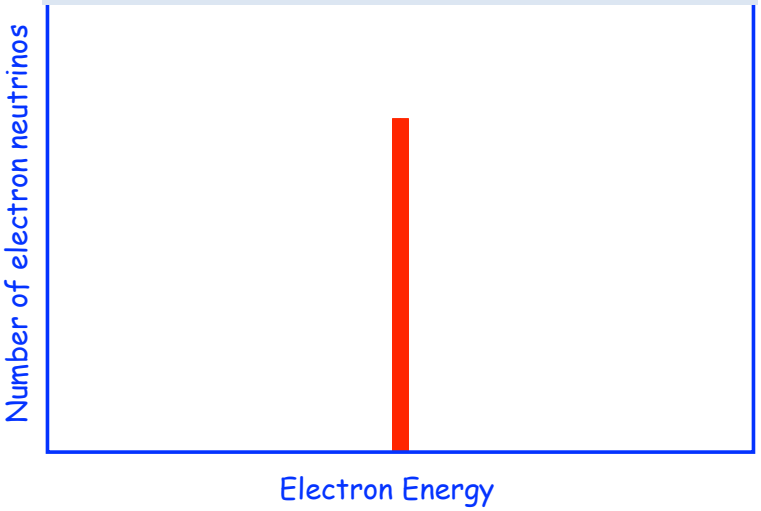
Niels Bohr



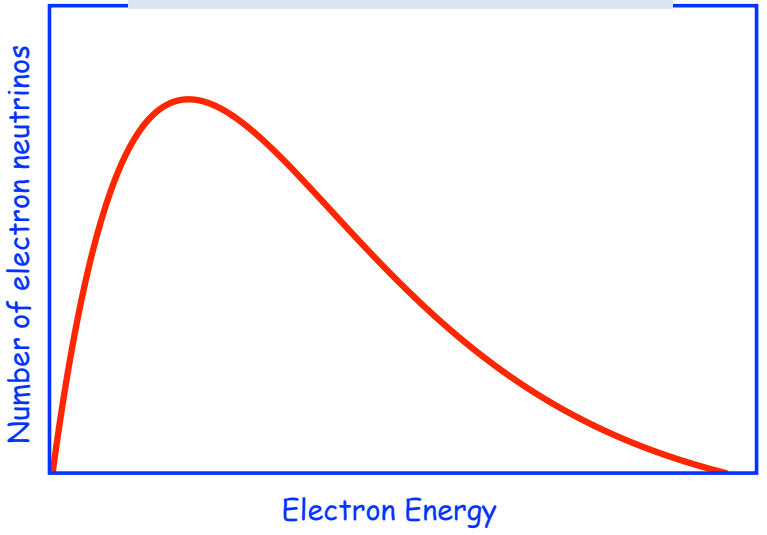
In radioactive decays energy-momentum conservation no longer holds!



Energy-momentum conservation says that data should look like this

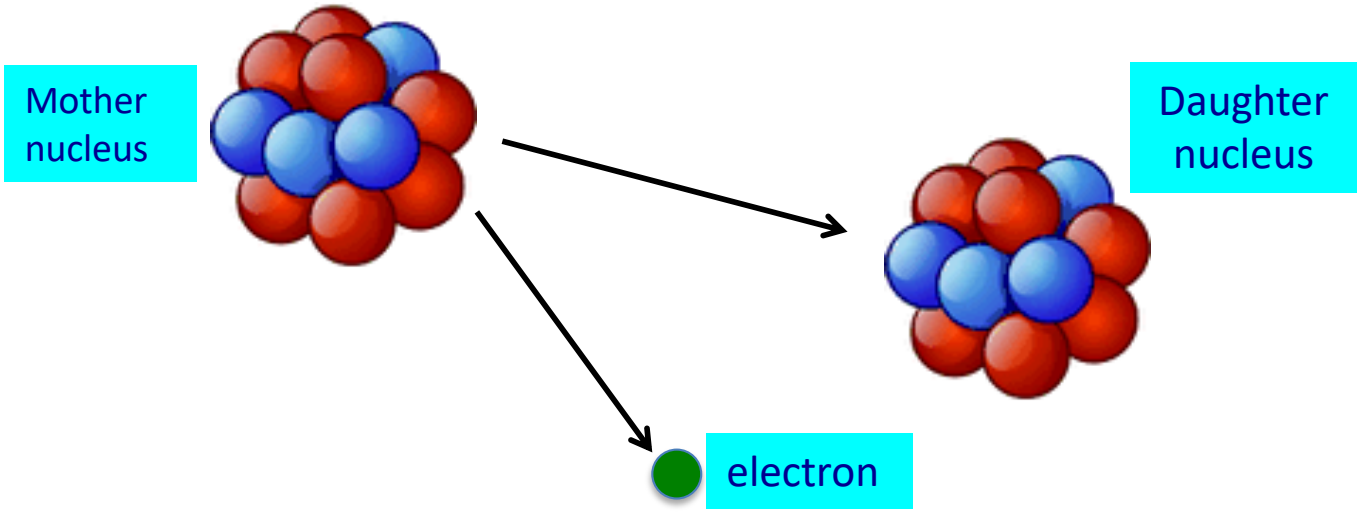


..instead it looks like this

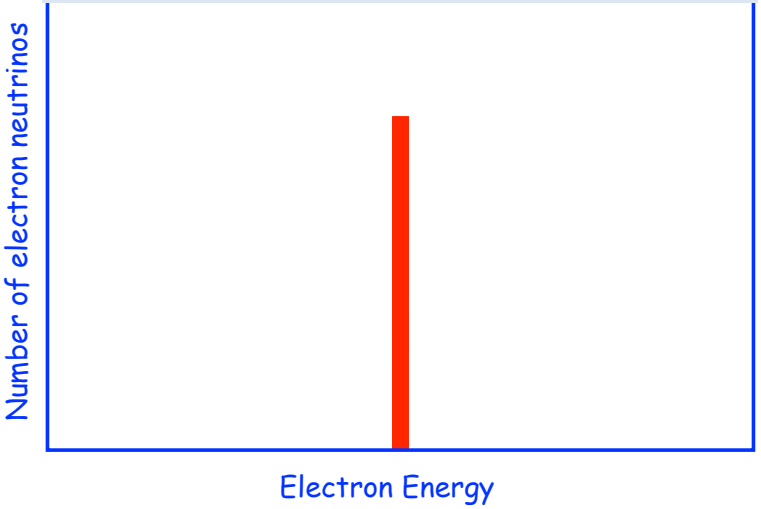


Wolfgang Pauli

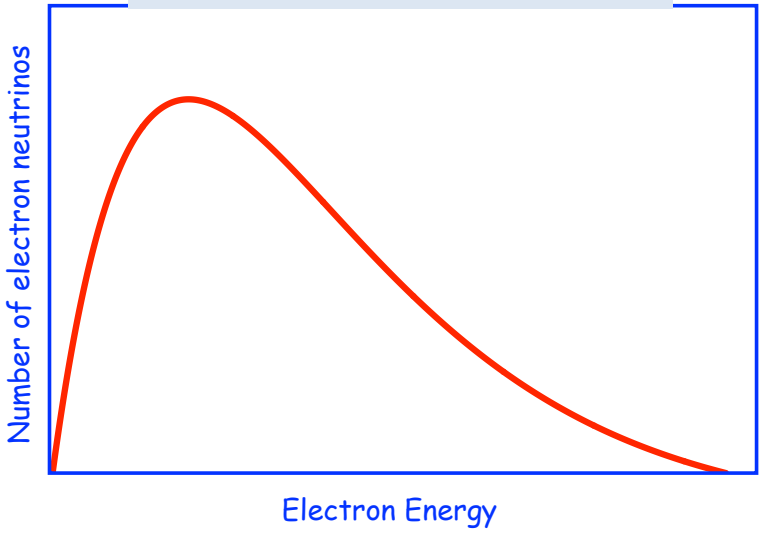
In this reaction there is a third particle produced that you cannot (yet) see!



Energy-momentum conservation says that data should look like this



..instead it looks like this

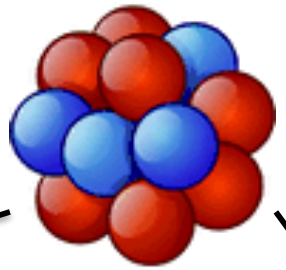


Wolfgang Pauli

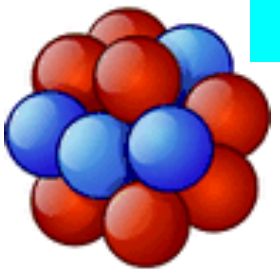
In this reaction there is a third particle produced that you cannot (yet) see!

NEUTRINO!

Mother nucleus

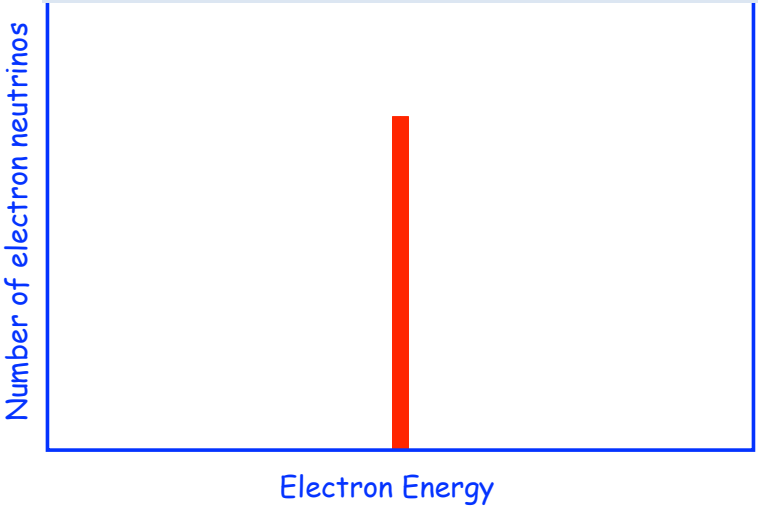


Daughter nucleus

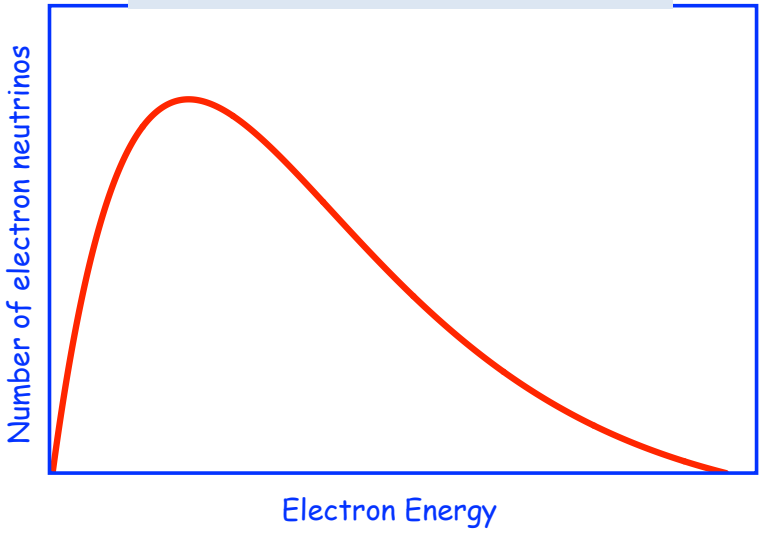


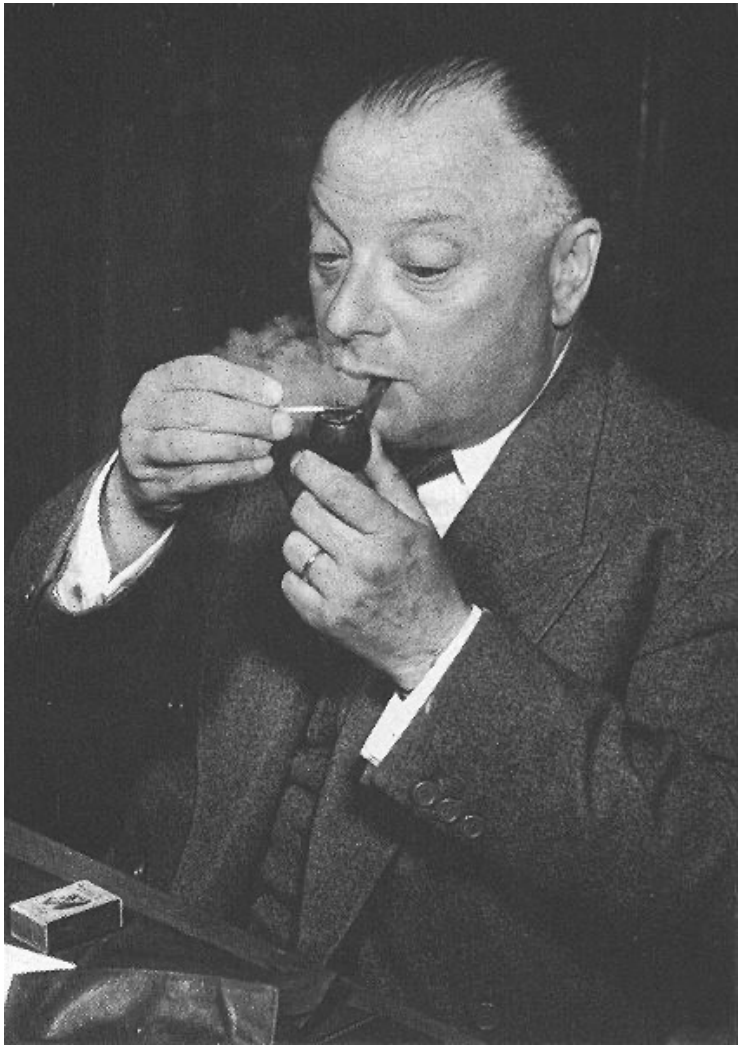
electron

Energy-momentum conservation says that data should look like this



..instead it looks like this





Wolfgang Pauli,
father of the neutrino
and Pauli exclusion
principle

Physicist goes to a ball

or

Mystery of Missing Energy

Abschrift/15.12.30

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

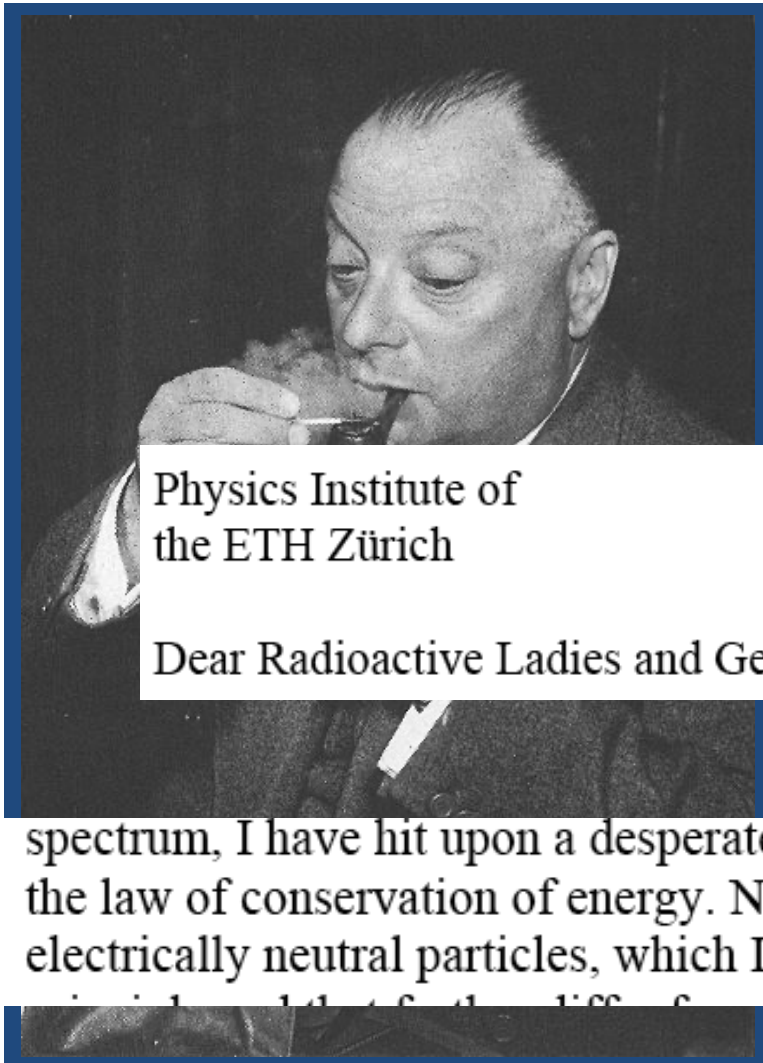
Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

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



Physicist goes to a ball

or

...ergy

Physics Institute of
the ETH Zürich

Zürich, Dec. 4, 1930

Dear Radioactive Ladies and Gentlemen,

spectrum, I have hit upon a desperate remedy to save the "exchange theorem" (1) of statistics and the law of conservation of energy. Namely, the possibility that in the nuclei there could exist electrically neutral particles, which I will call neutrons, that have spin 1/2 and obey the exclusion

Wolfgang Pauli

way of rescue. Thus, dear radioactive people, scrutinize and judge. - Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7. With my best regards to you, and also to Mr. Back, your humble

principle

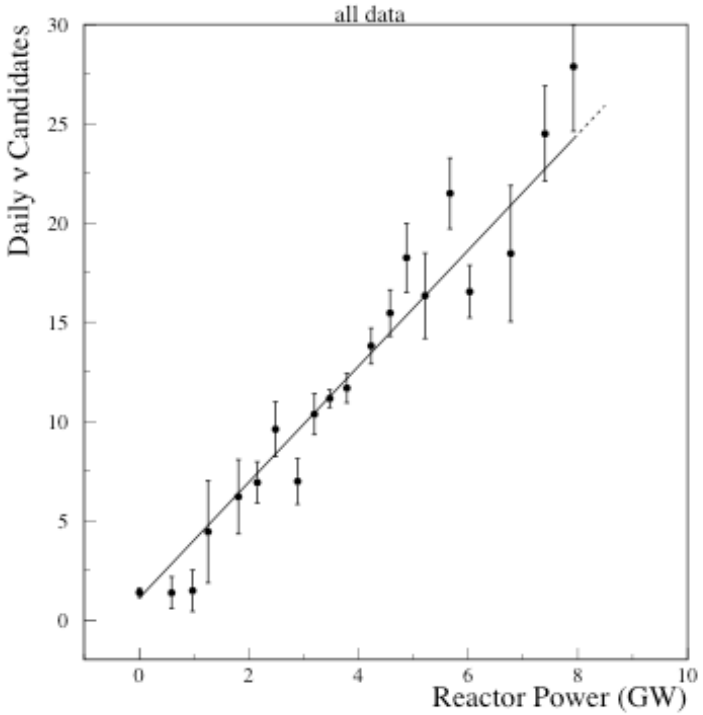
Note that these experiments did not observe

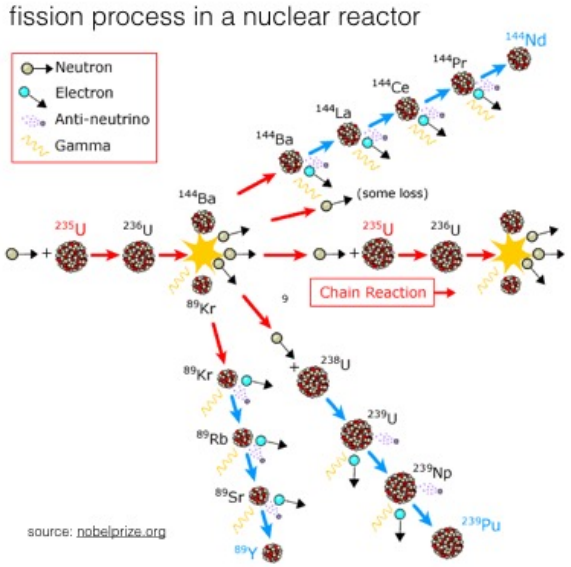
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

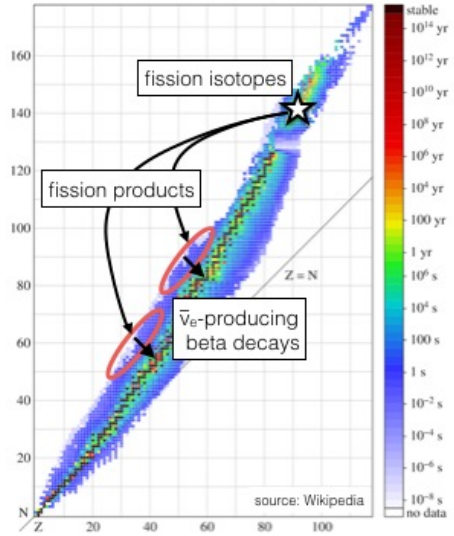
Because neutron was not discovered yet.
Instead they observed

$$^{A}Z \rightarrow {}^{A}(Z+1) + e^{-} + \bar{\nu}_e$$

Sources of neutrinos: Nuclear Reactors

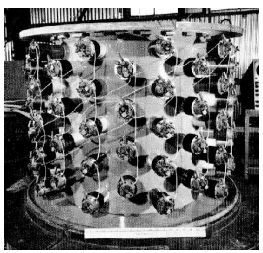






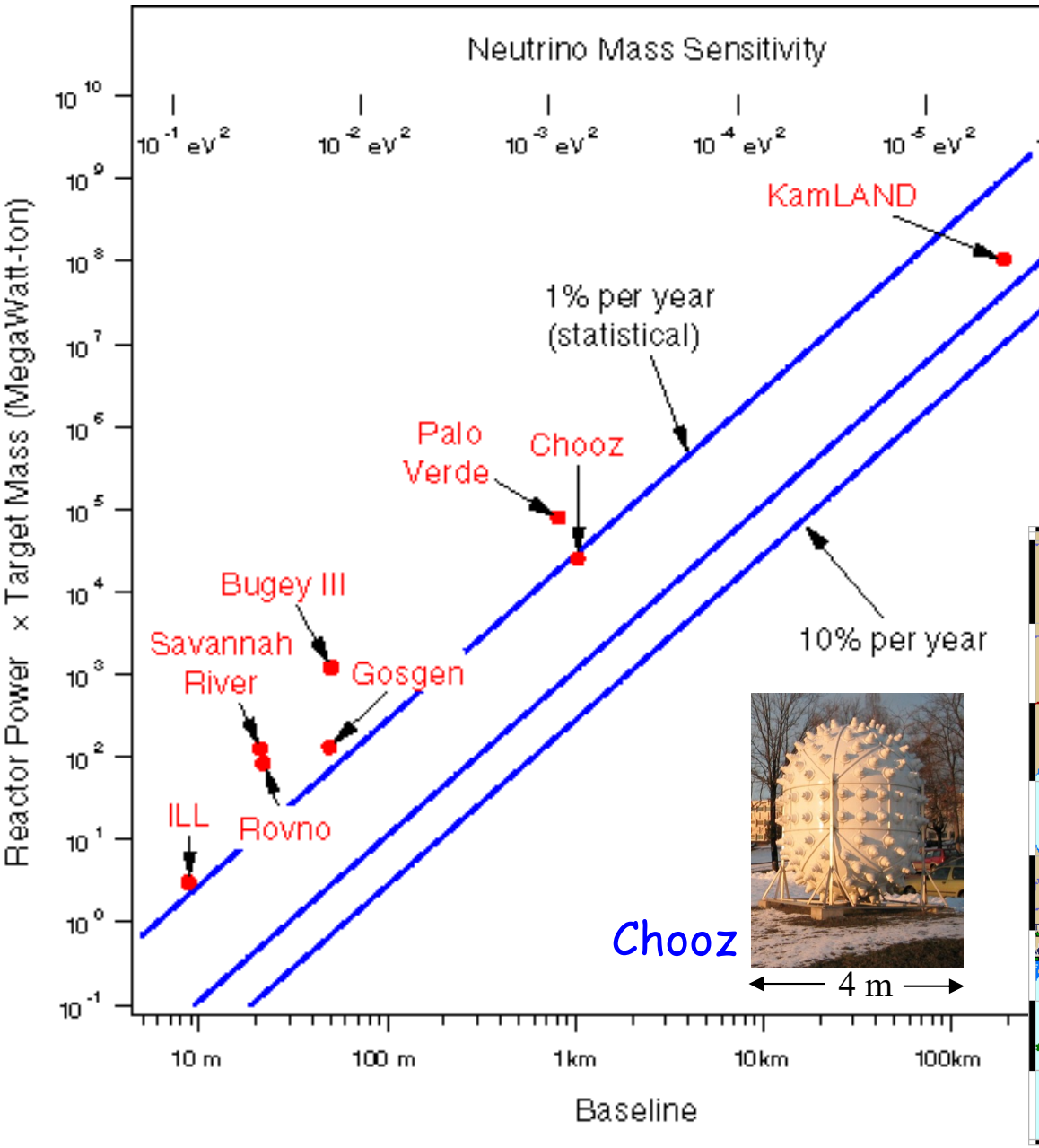
If you can get close enough by far the most abundant source of neutrinos on Earth are commercial fission reactors.

Earlier Reactor Neutrino Experiments

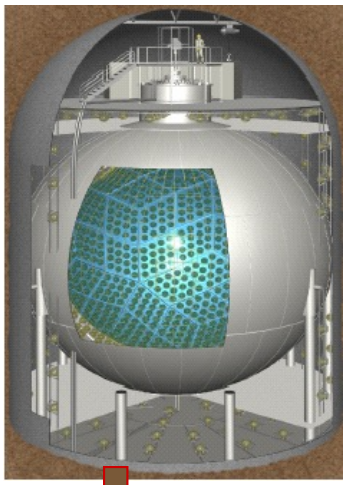


1m

Poltergeist



KamLAND



20 m

Chooz

4 m

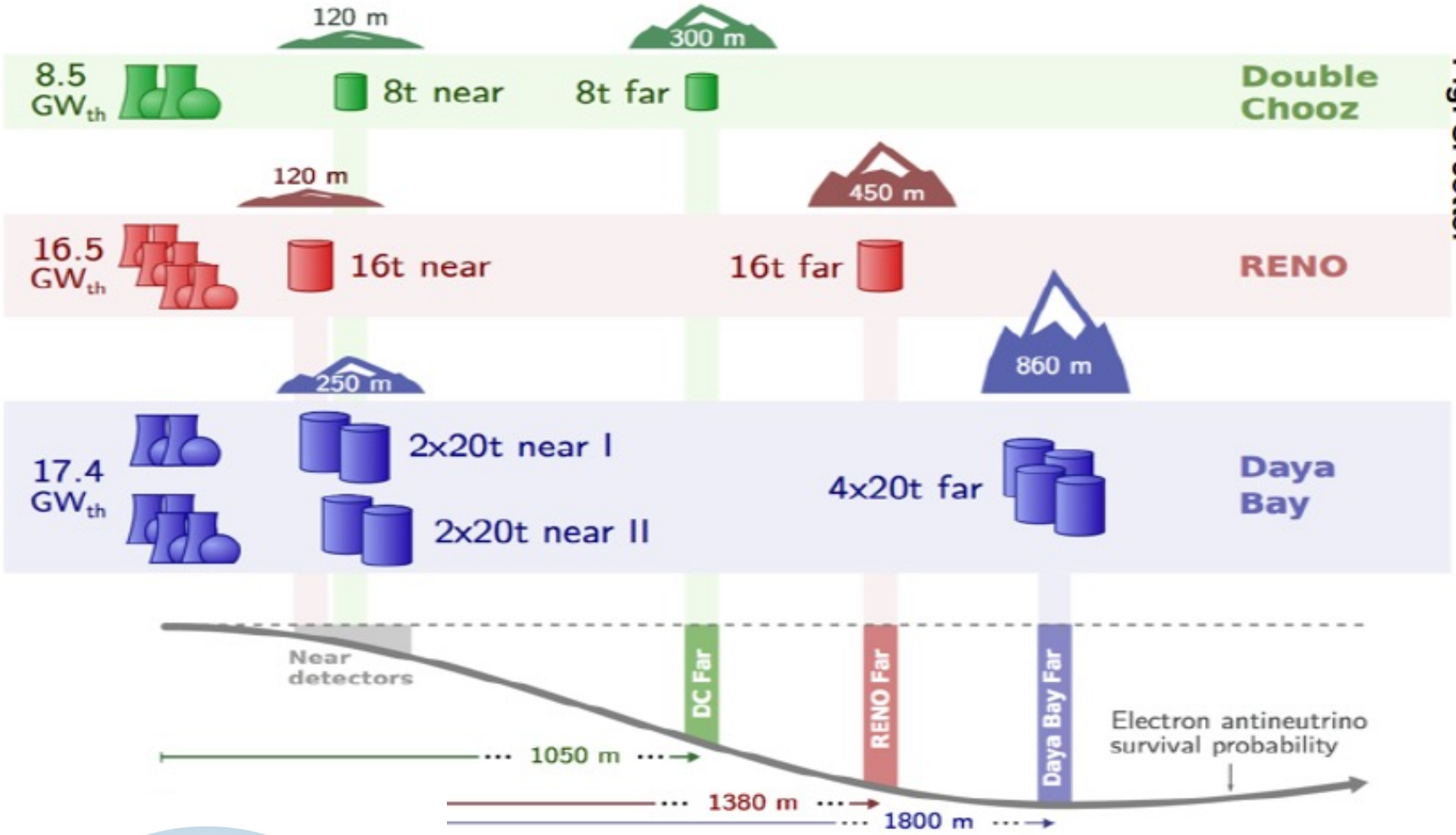
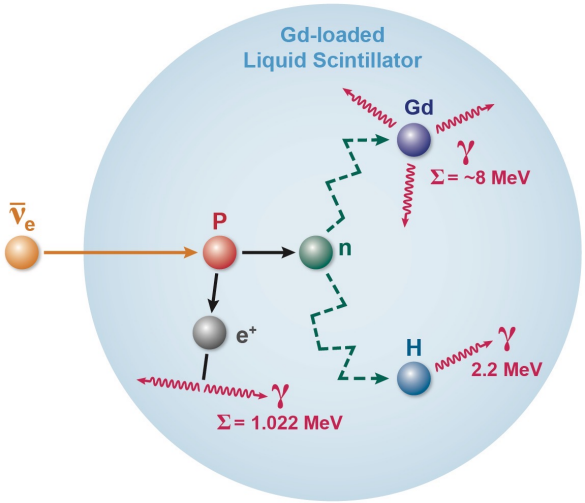
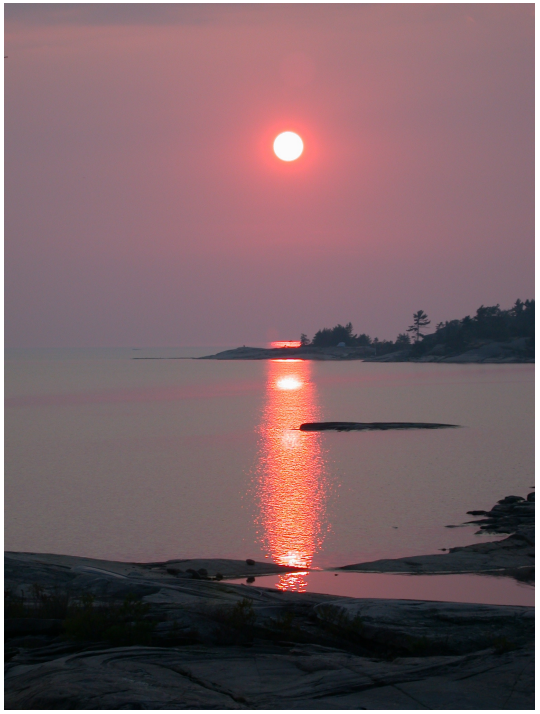


Fig: S. Jetter



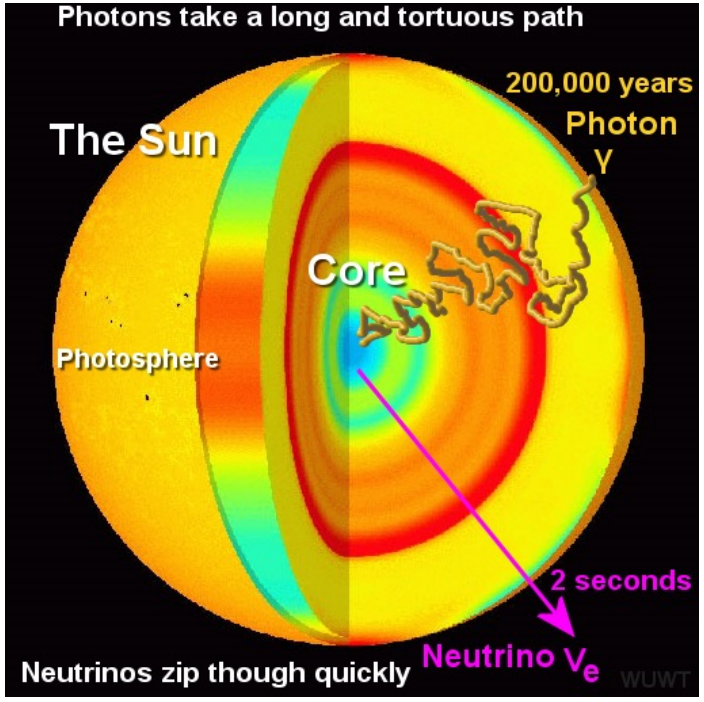
Current reactor neutrino experiments

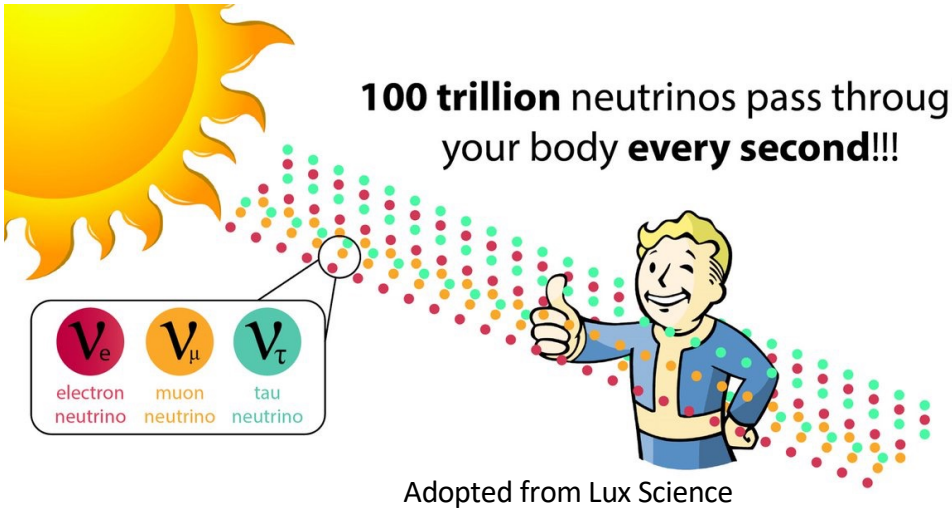


Sources of neutrinos: Sun

A minor league star (such as our Sun) produces neutrinos mainly through the reaction

$$p + p \rightarrow d + e^{+} + \nu_e$$

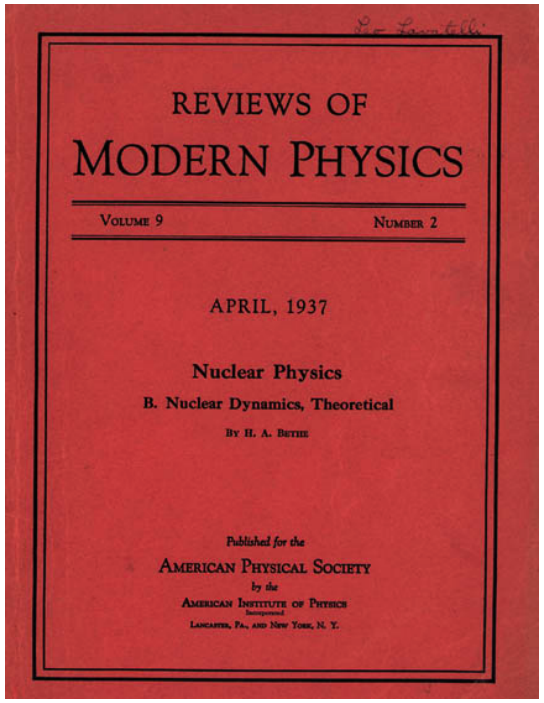


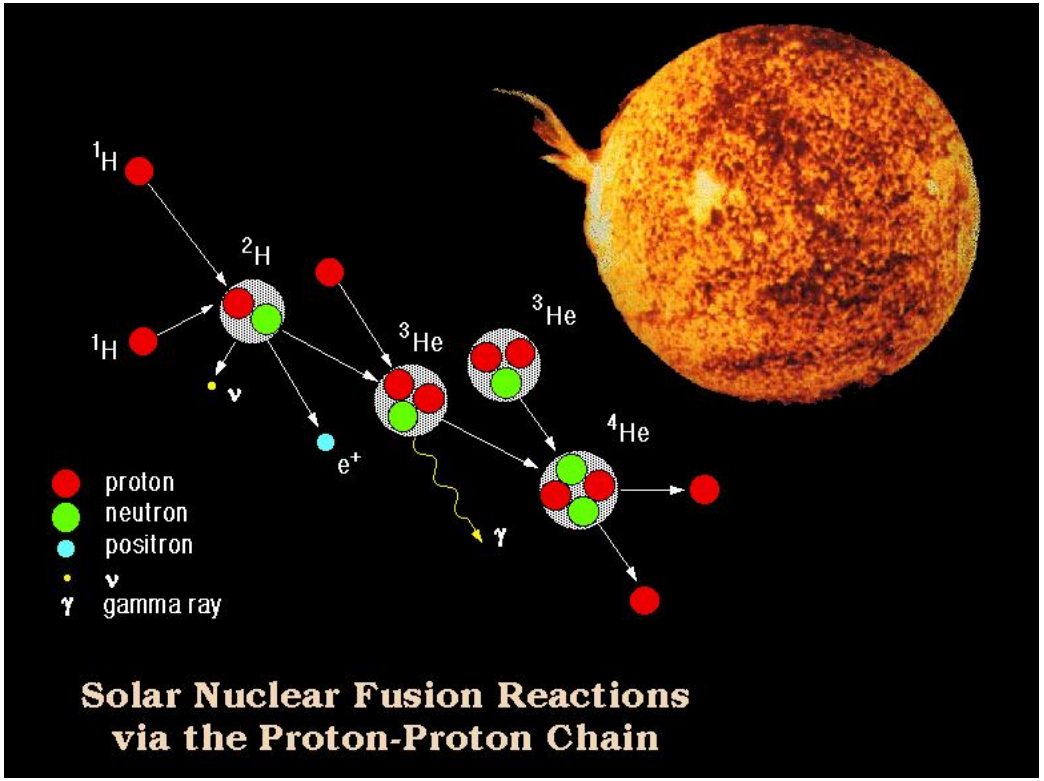


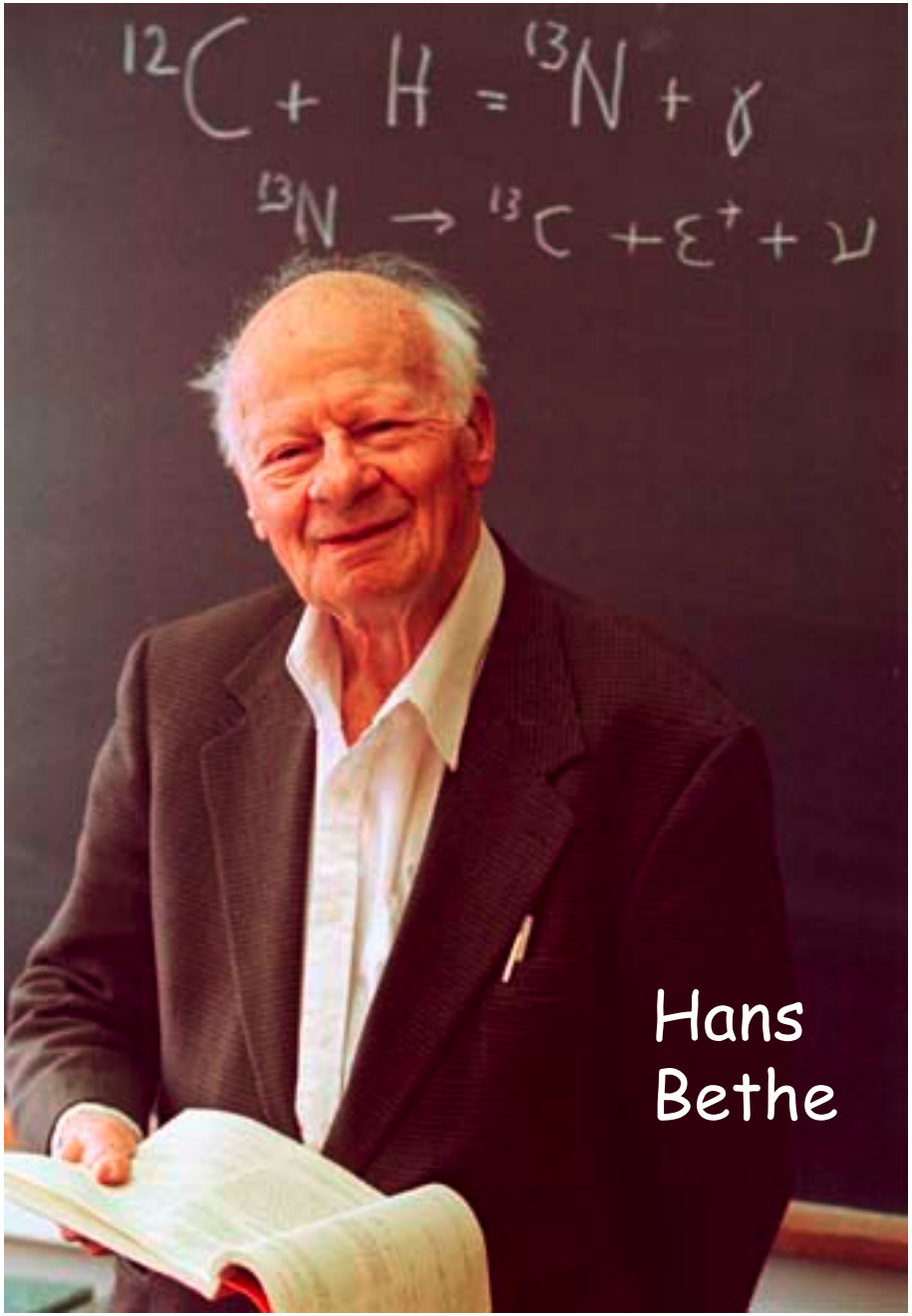
Adopted from Lux Science

Where does the Energy of the Sun come from?

- 1854 von Helmholtz gravitational
- 1920 Eddington nuclear fusion "We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place."
- 1938 Bethe and Critchfield $p+p \rightarrow {}^2H + e^+ + \nu_e$ + ...


REVIEWS OF
MODERN PHYSICS
VOLUME 9
NUMBER 2
APRIL, 1937
Nuclear Physics
B. Nuclear Dynamics, Theoretical
BY H. A. BETHE
Published for the
AMERICAN PHYSICAL SOCIETY
by the
AMERICAN INSTITUTE OF PHYSICS
LANCASTER, PA., AND NEW YORK, N. Y.

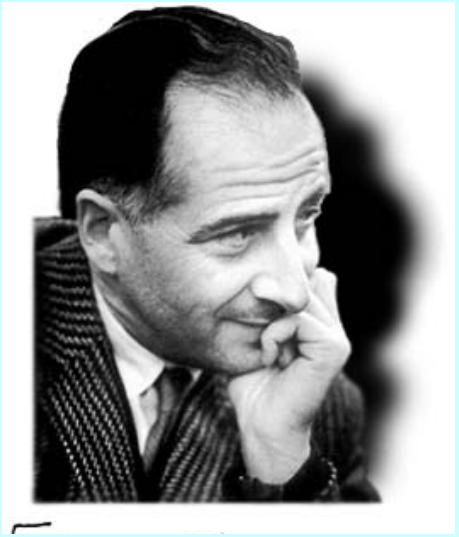

1H
2H
1H
3He
3He
4He
ν
e+
γ
proton
neutron
positron
ν
γ gamma ray
Solar Nuclear Fusion Reactions
via the Proton-Proton Chain


12C + H = 13N + γ
13N → 13C + ε+ + ν
Hans
Bethe

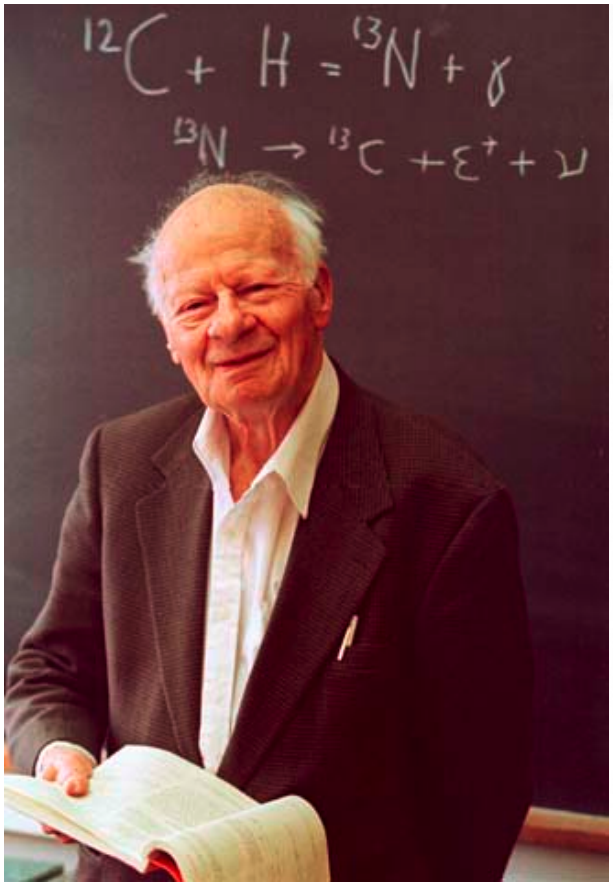
Where does the Energy of the Sun come from?

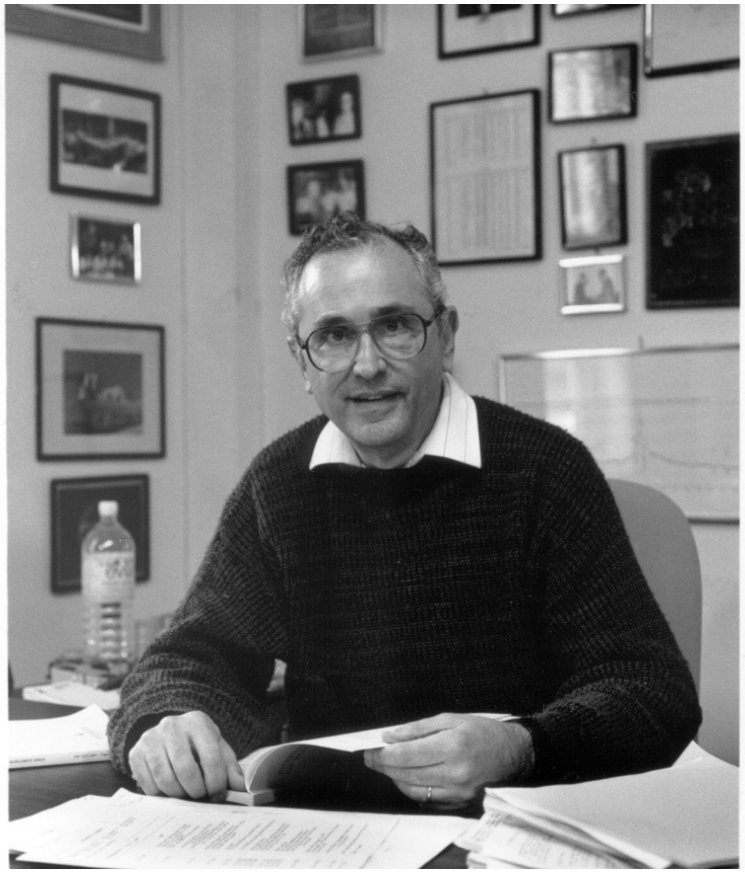
- 1854 von Helmholtz gravitational
- 1920 Eddington nuclear fusion "We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him to go and find a hotter place."
- 1938 Bethe and Critchfield $p+p \rightarrow {}^{2}H + e^{+} + \nu_e$

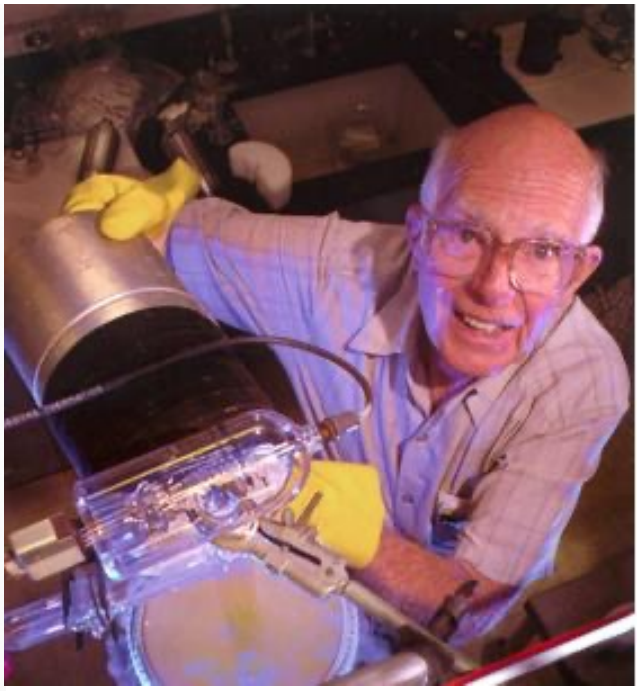
- 1946 Pontecorvo the idea of using chlorine as detector (also the idea of neutrino oscillations)



- 1964 Davis chlorine detector at Homestake Bahcall Standard Solar Model

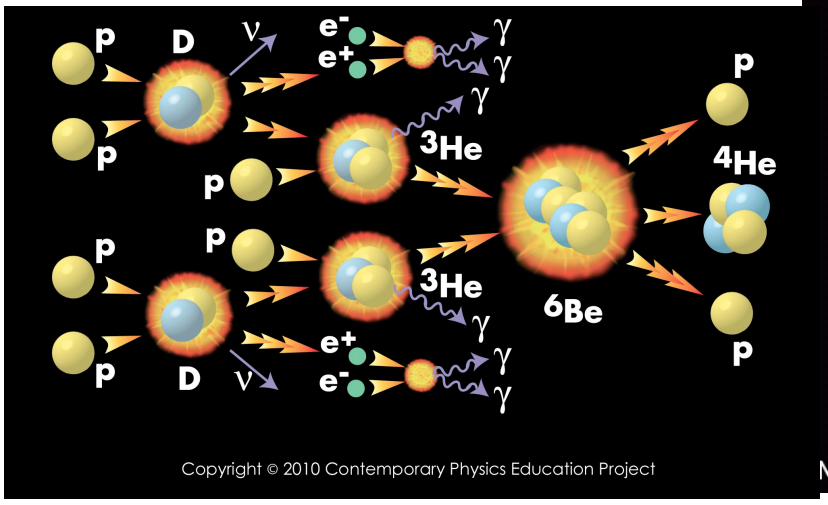


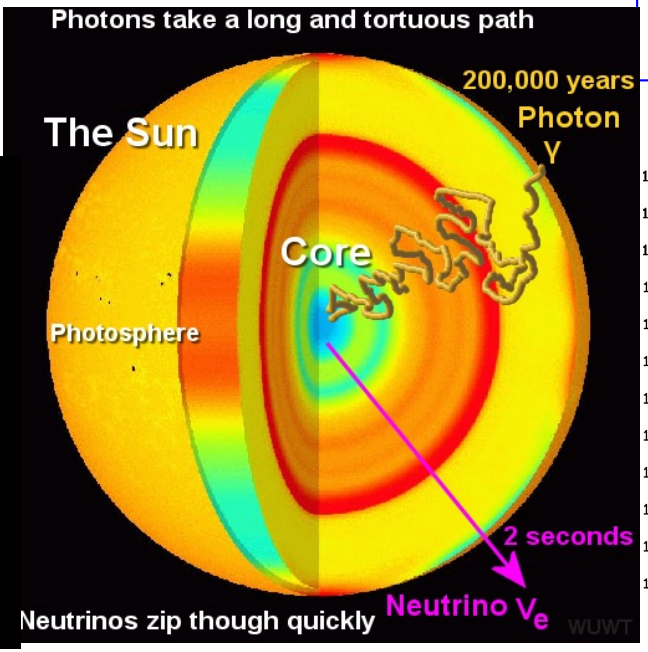


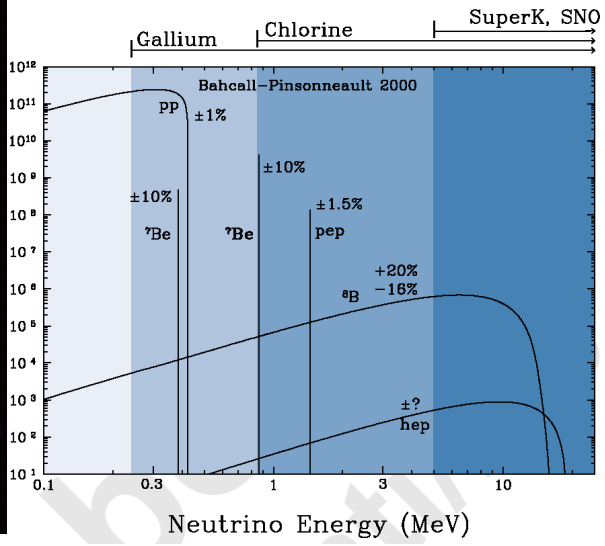


> **"...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation.."**
>
> **Bahcall and Davis, 1964**

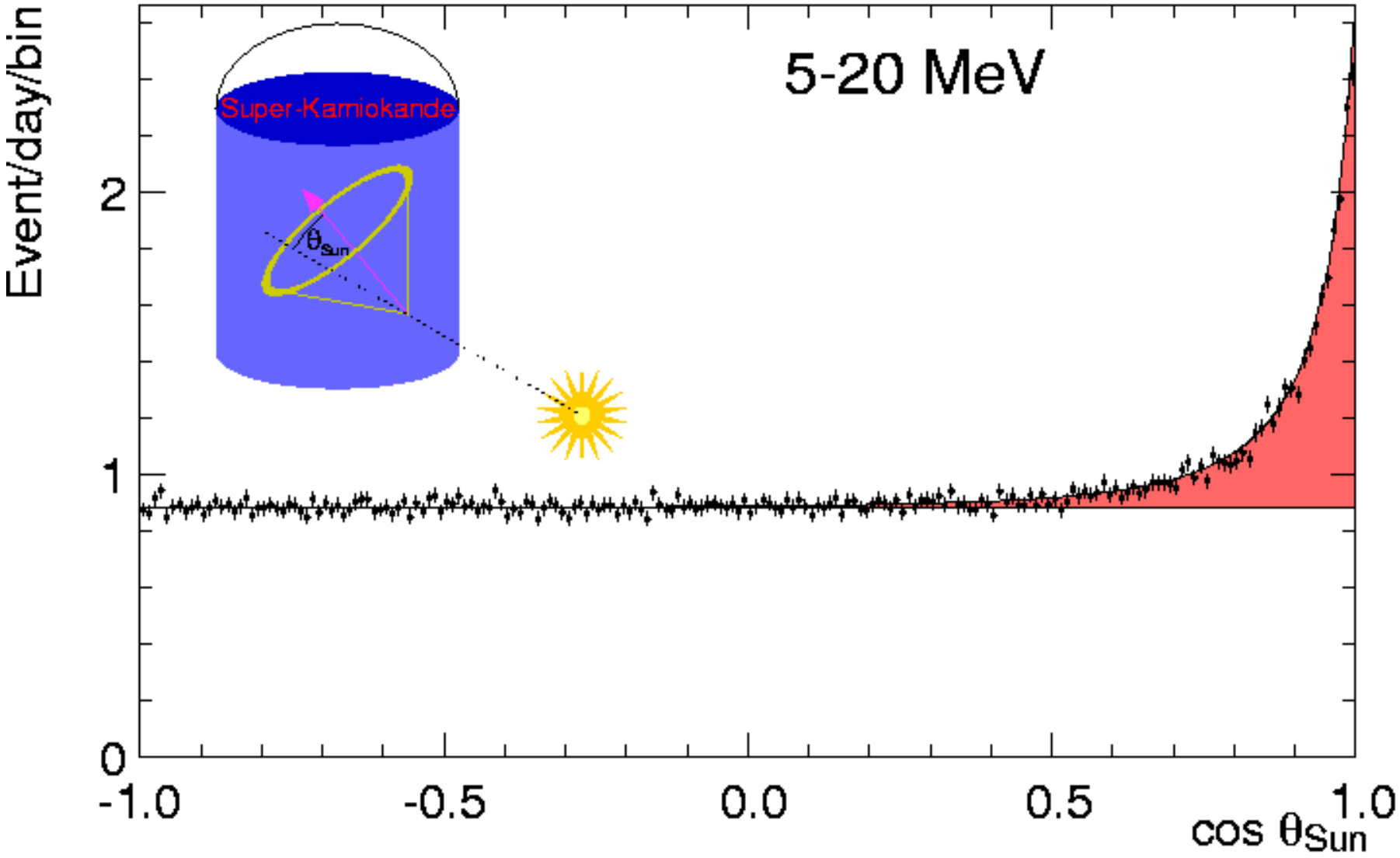
Solar Neutrinos



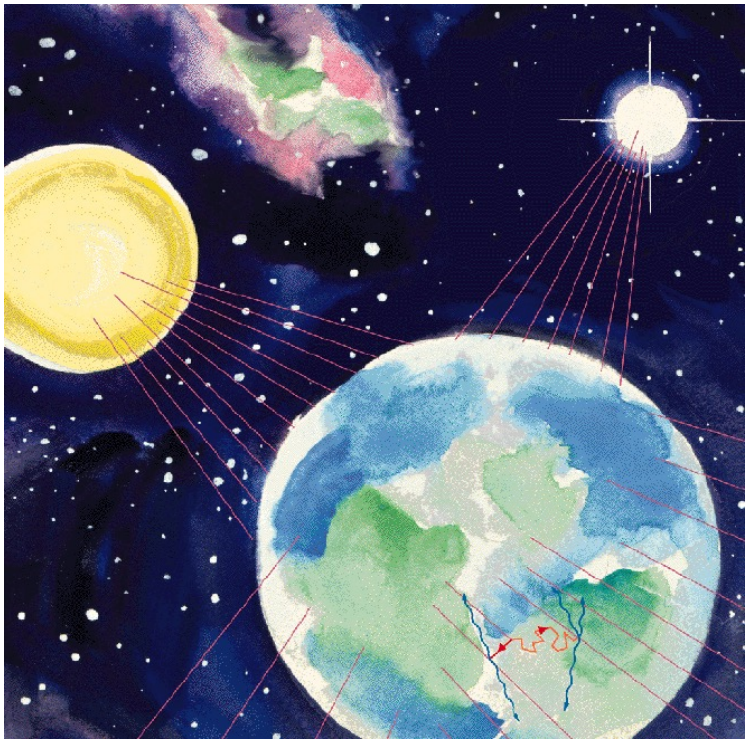




SuperKamiokande-I ^{8}B solar ν's



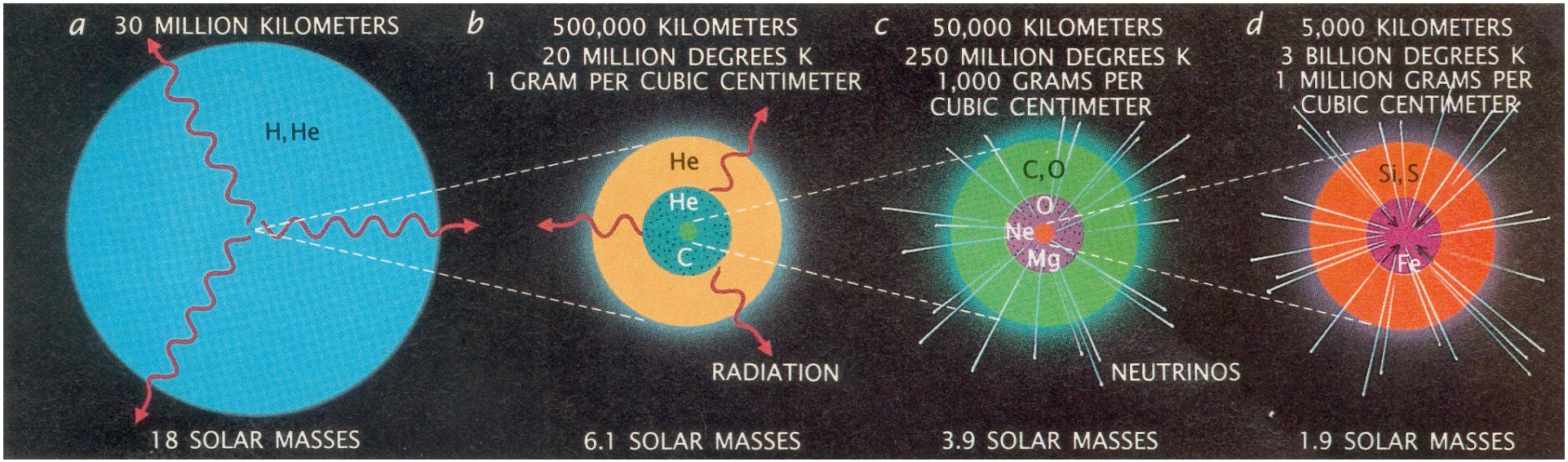
Sources of neutrinos: Supernovae

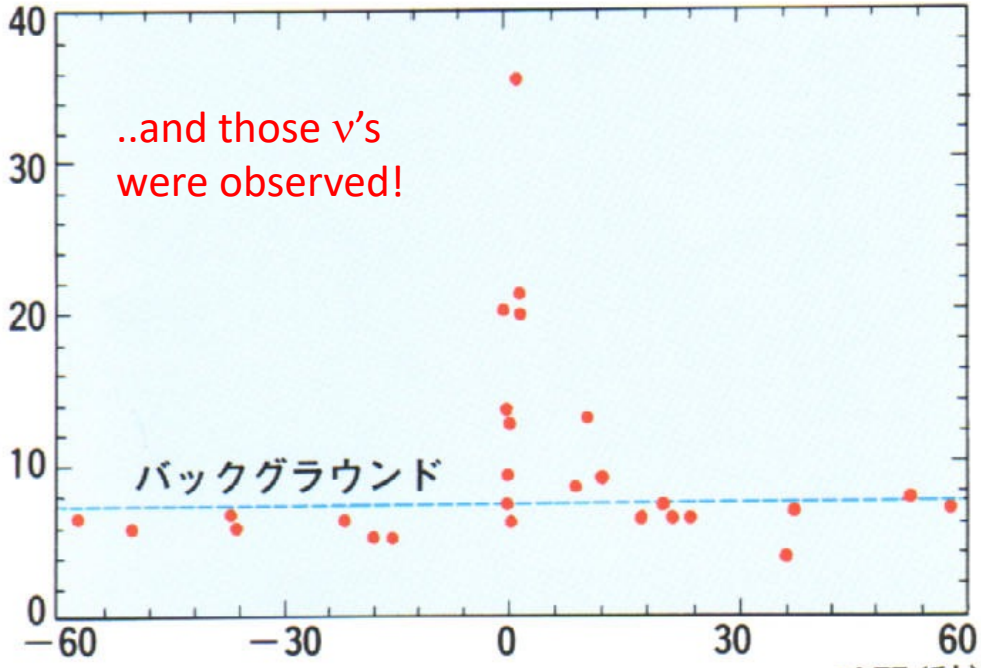


A (hopefully distant enough) core-collapse supernova produces approximately 10^{58} neutrinos in about twenty seconds via

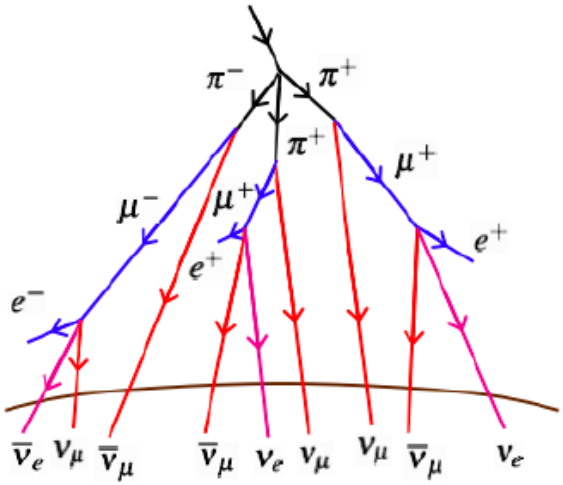
$$\text{Gravitational binding energy} \rightarrow \nu_x + \bar{\nu}_x$$

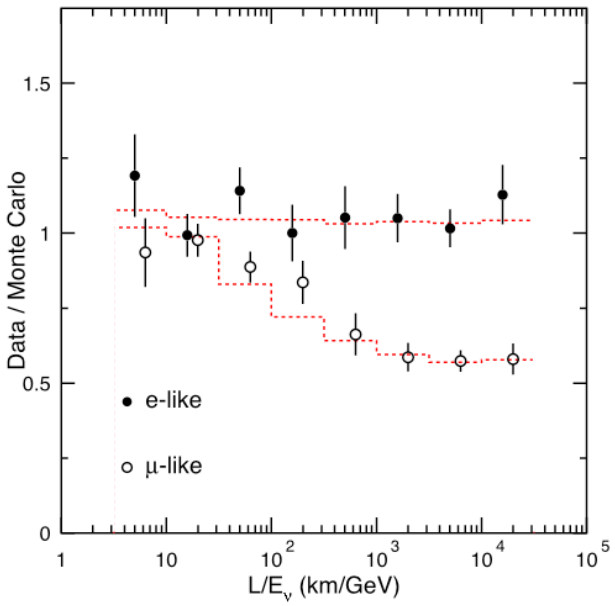
Those neutrinos produced in supernova explosions since the beginning of the Universe still stick around, forming the "Diffuse Supernova Background"

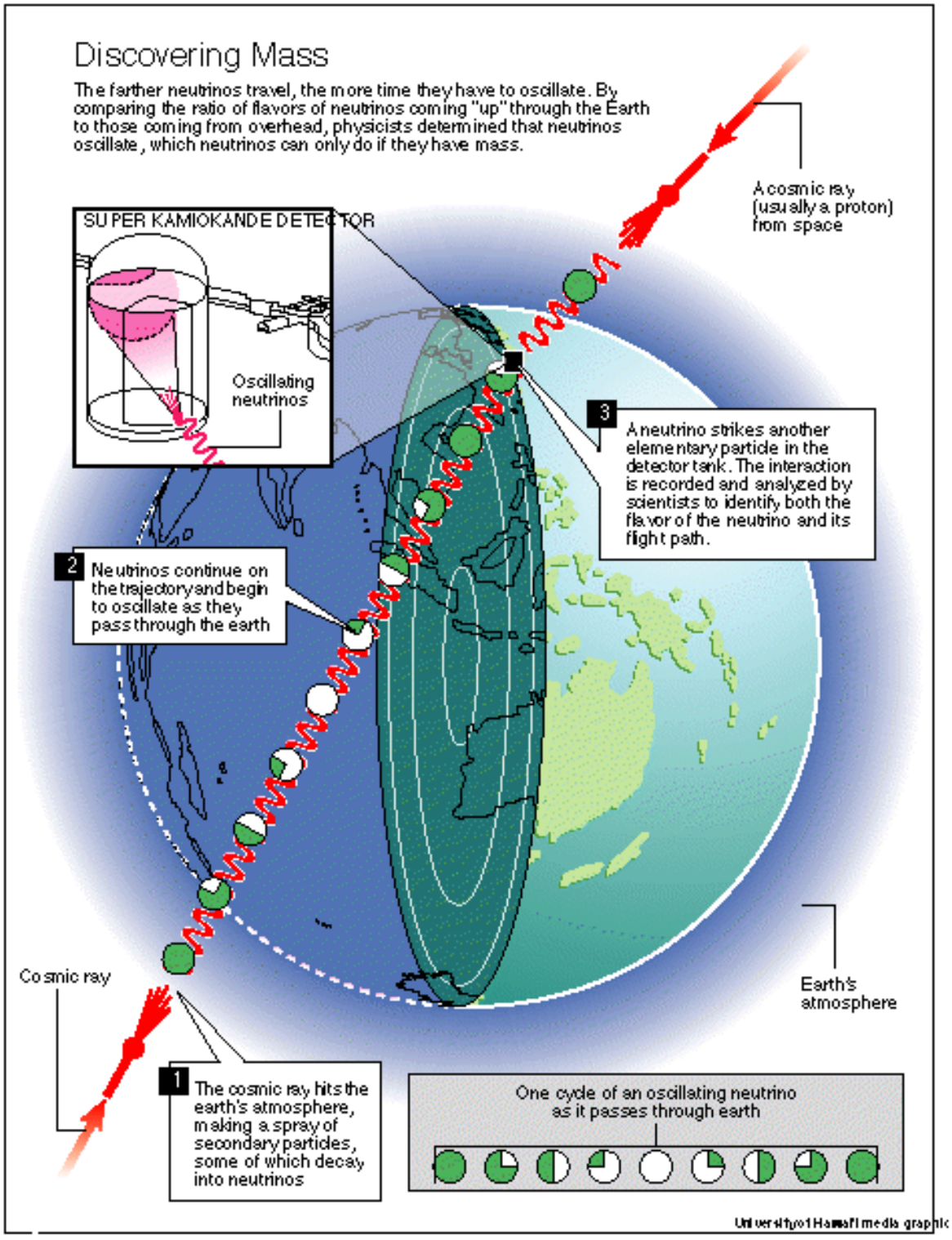

a 30 MILLION KILOMETERS
H, He
18 SOLAR MASSES
b 500,000 KILOMETERS
20 MILLION DEGREES K
1 GRAM PER CUBIC CENTIMETER
He
He
C
RADIATION
6.1 SOLAR MASSES
c 50,000 KILOMETERS
250 MILLION DEGREES K
1,000 GRAMS PER
CUBIC CENTIMETER
C, O
O
Ne
Mg
NEUTRINOS
3.9 SOLAR MASSES
d 5,000 KILOMETERS
3 BILLION DEGREES K
1 MILLION GRAMS PER
CUBIC CENTIMETER
Si, S
Fe
1.9 SOLAR MASSES


40
30
20
10
0
−60
−30
0
30
60
..and those ν's
were observed!
バックグラウンド

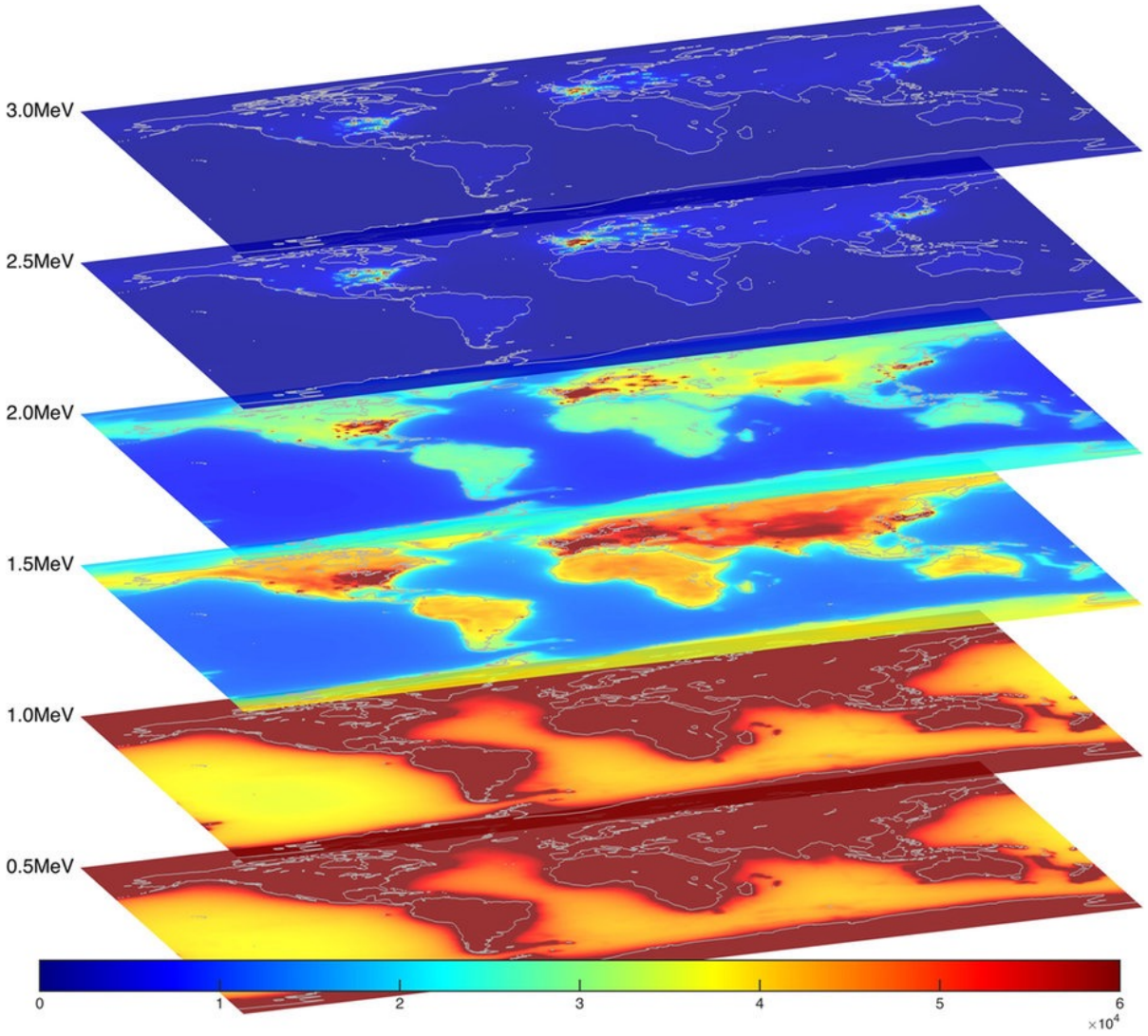
Atmospheric Neutrinos







Sources of neutrinos: Earth



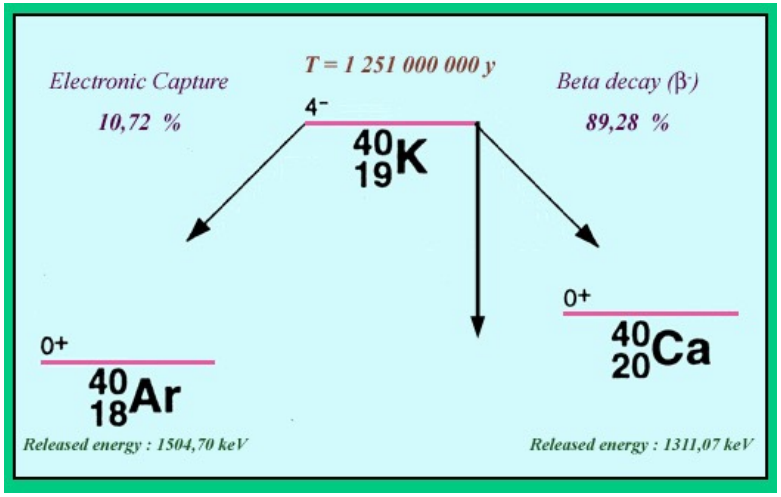
Geoneutrinos are antineutrinos coming from the decay of ^{238}U, ^{238}Th, and ^{40}K inside the Earth. Picture on the right shows the sum of reactor neutrinos and geoneutrinos.

Sources of neutrinos: Fruits and Vegetables

Many fruits and vegetables absorb ^{40}K in addition to the stable potassium isotope. ^{40}K decays by emitting either neutrinos or antineutrinos:

$$^{40}K \rightarrow {}^{40}Ca + e^{-} + \bar{\nu}_e$$

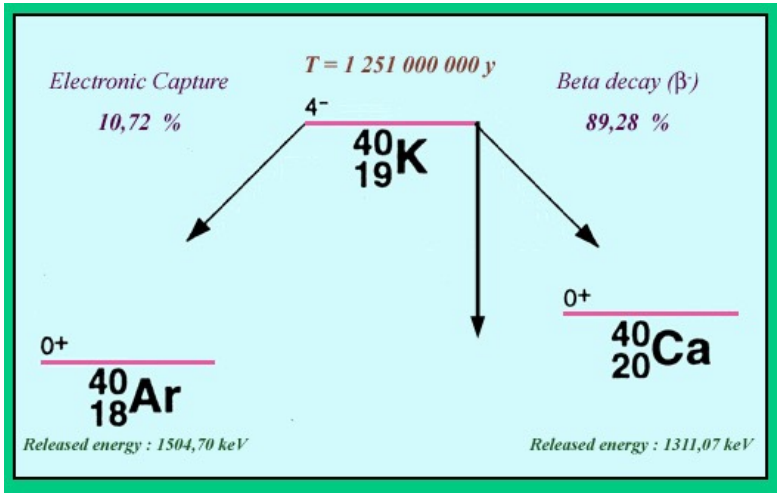
$$^{40}K + e^{-} \rightarrow {}^{40}Ar + \nu_e$$



About one million neutrinos and antineutrinos are emitted per day from one banana due to ^{40}K decay

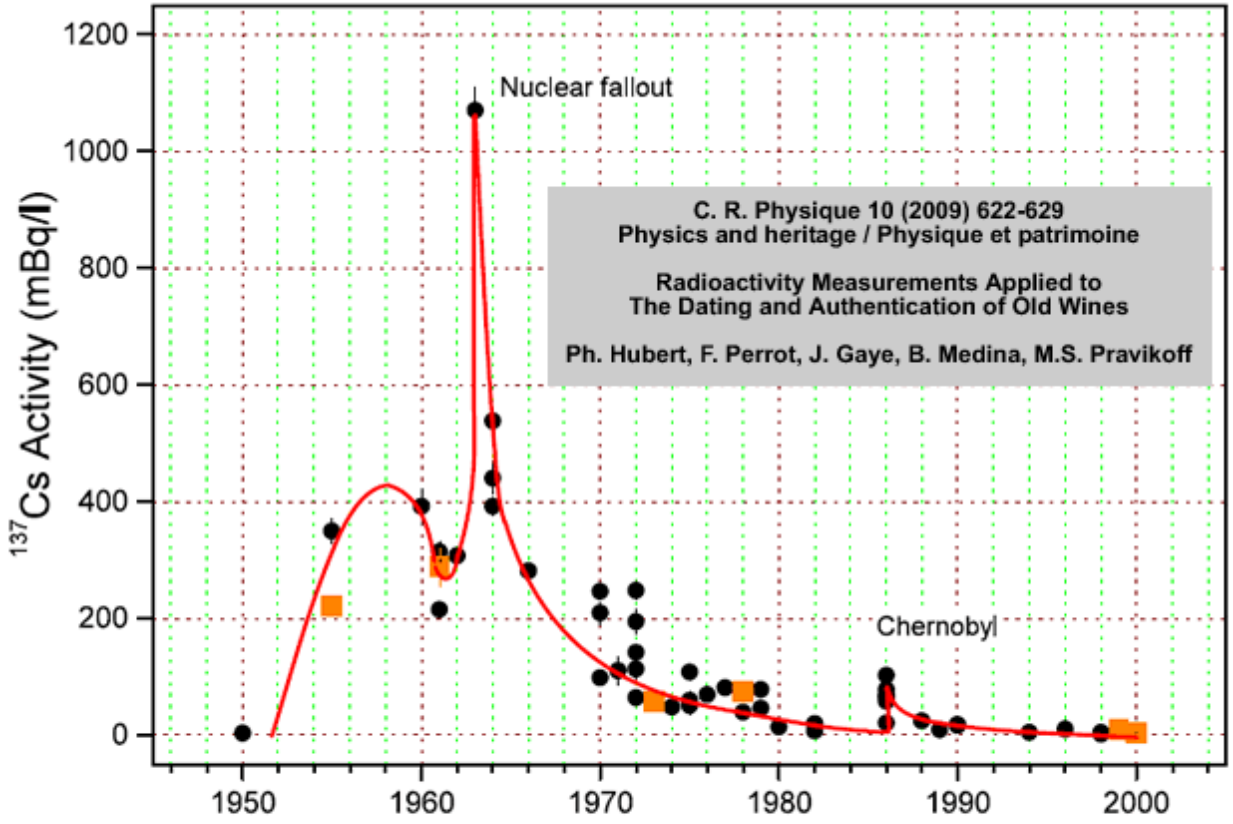
Sources of neutrinos: Humans

We also ingest ^{40}K when we eat potassium rich foods such as bananas, kidney beans, nuts, etc. Our bodies deposit ^{40}K in our bones.

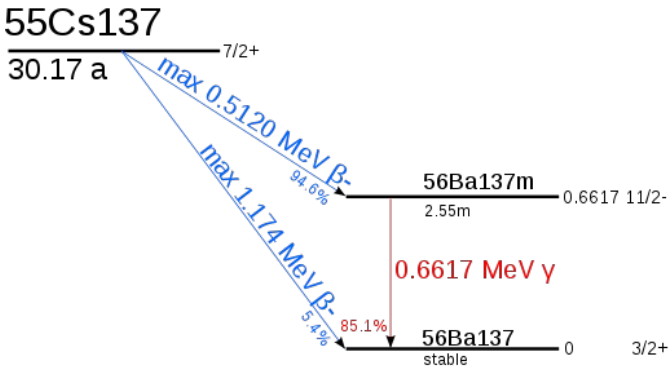


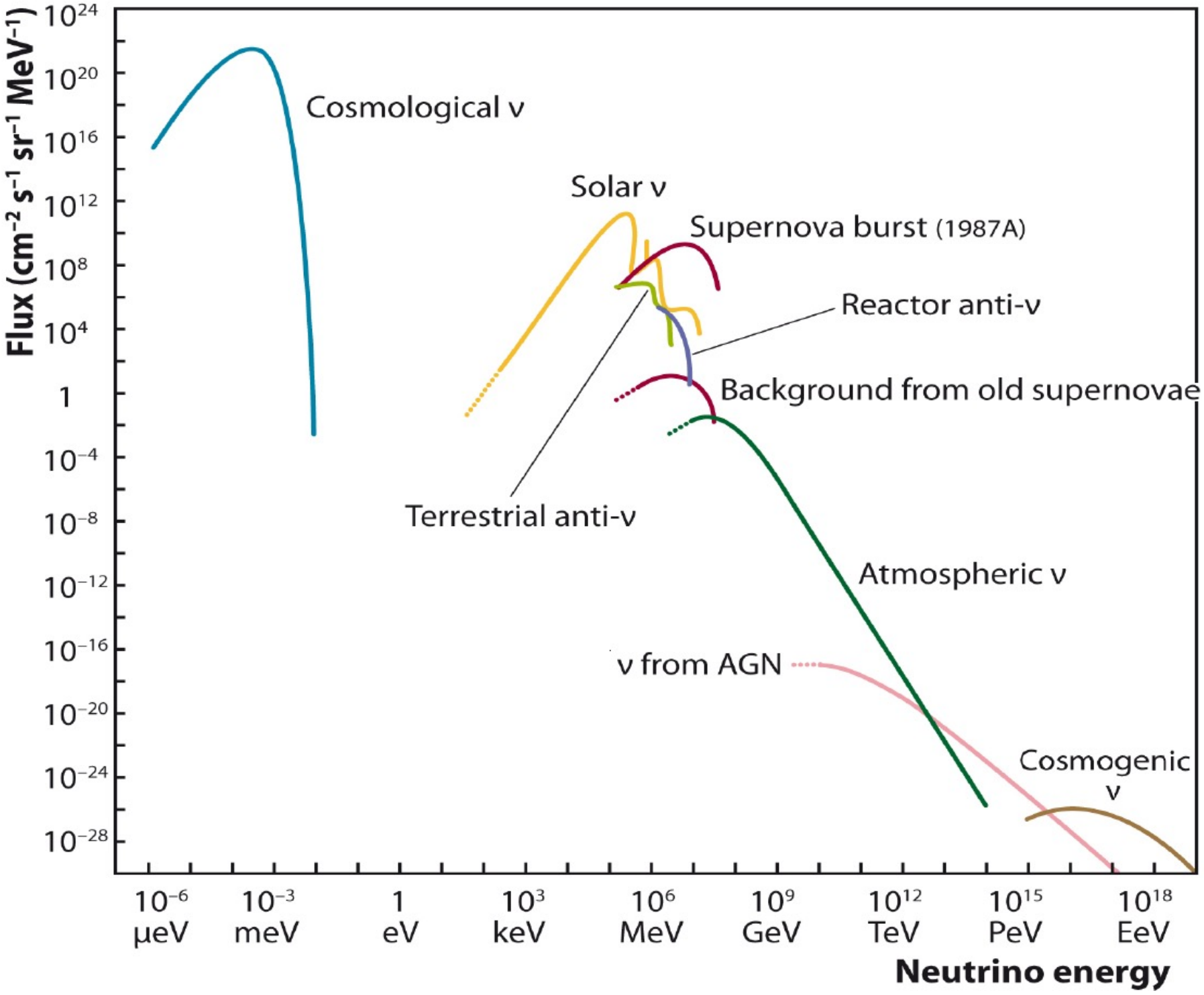
A 70 kg (154 pounds) person emits about 530 electron neutrinos and 4460 electron antineutrinos per second.

Sources of neutrinos: Wine



Activity (mBq/l) of the ^{137}Cs radioactive isotope as a function of the wine vintage.
All activities are for Bordeaux wines only, and are normalized to an arbitrary date, January 1st, 2000.
The solid circles correspond to measurements after reduction of the wine into ashes,
the orange squares correspond to nondestructive measurements, i.e., without opening the bottles.
Statistical errors are generally smaller than the dimension of the points.

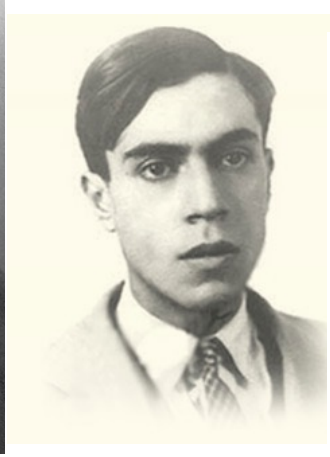



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
10²⁴
10²⁰
10¹⁶
10¹²
10⁸
10⁴
1
10⁻⁴
10⁻⁸
10⁻¹²
10⁻¹⁶
10⁻²⁰
10⁻²⁴
10⁻²⁸
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
10⁻⁶ μeV
10⁻³ meV
1 eV
10³ keV
10⁶ MeV
10⁹ GeV
10¹² TeV
10¹⁵ PeV
10¹⁸ EeV
Neutrino energy

Pauli

Fermi

Meyer



Majorana

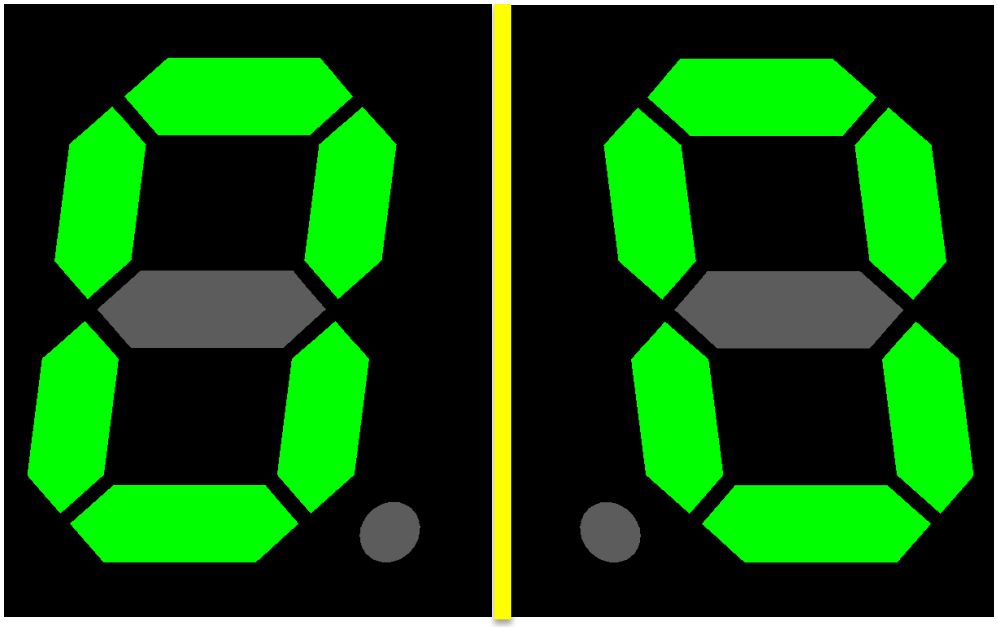
Pontecorvo

Neutrinos have an interesting history written by intriguing people some of whom are shown on the left.

PARITY (P)

If a process is permitted by the laws of physics, its "3D" mirror image is also permitted.

Not always true



$$\mathbf{r} \xrightarrow{P} -\mathbf{r}$$

$$\mathbf{p} = -i\hbar\nabla \xrightarrow{P} -\mathbf{p}$$

$$\mathbf{A} \xrightarrow{P} -\mathbf{A}$$

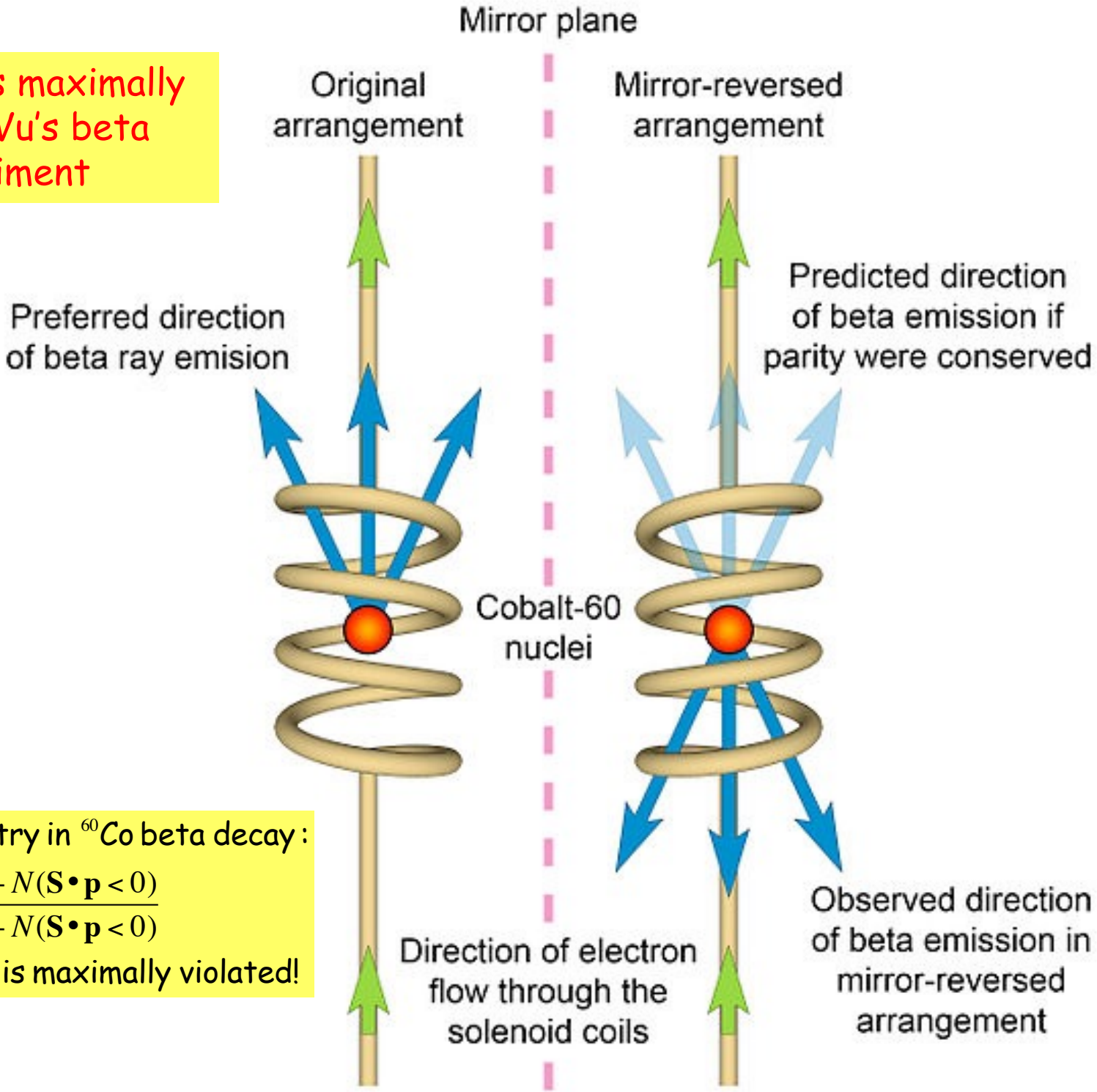
$$\underbrace{\mathbf{E} = -\nabla\varphi - \frac{1}{c}\frac{\partial \mathbf{A}}{\partial t} \xrightarrow{P} -\mathbf{E}}_{\text{vectors}}$$

$$\mathbf{L} = \mathbf{r} \times \mathbf{p} \xrightarrow{P} \mathbf{L}$$

$$\mathbf{S} \xrightarrow{P} \mathbf{S}$$

$$\underbrace{\mathbf{B} = \nabla \times \mathbf{A} \xrightarrow{P} \mathbf{B}}_{\text{pseudo-vectors}}$$

Weak interactions maximally violate parity: Wu's beta decay experiment

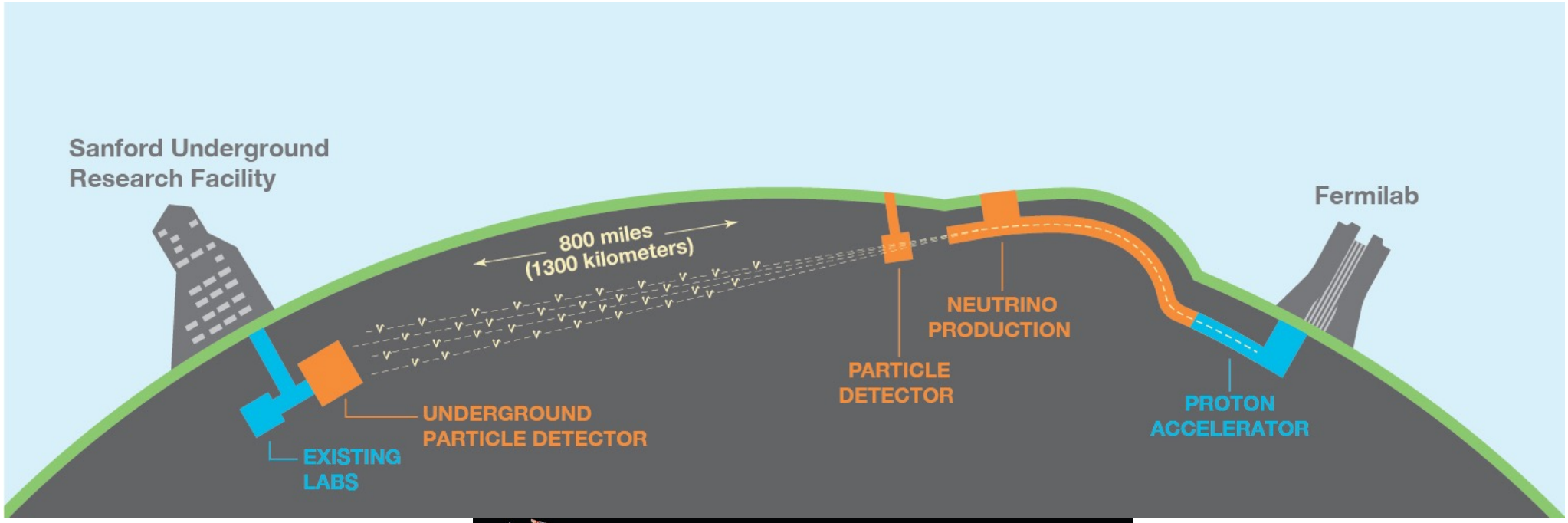


Wu searched for asymmetry in ^{60}Co beta decay :

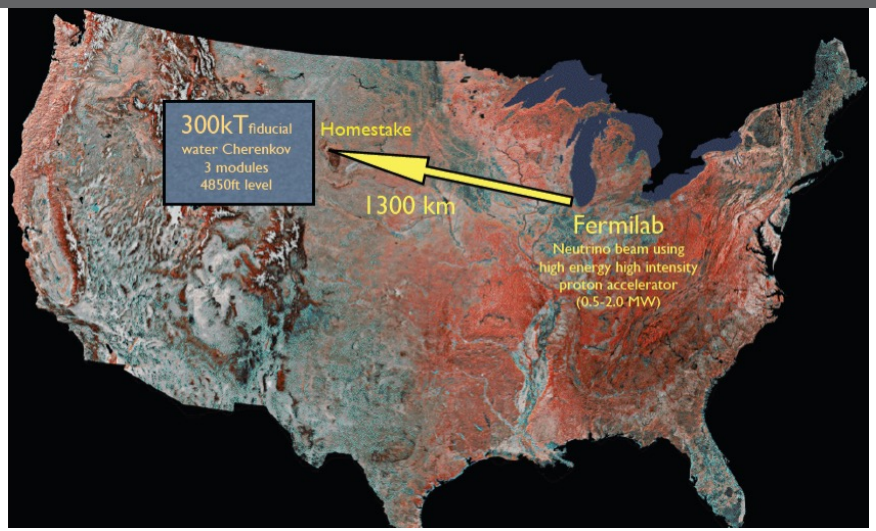
$$A = \frac{N(\mathbf{S}\bullet\mathbf{p}>0) - N(\mathbf{S}\bullet\mathbf{p}<0)}{N(\mathbf{S}\bullet\mathbf{p}>0) + N(\mathbf{S}\bullet\mathbf{p}<0)}$$

Large asymmetry : parity is maximally violated!

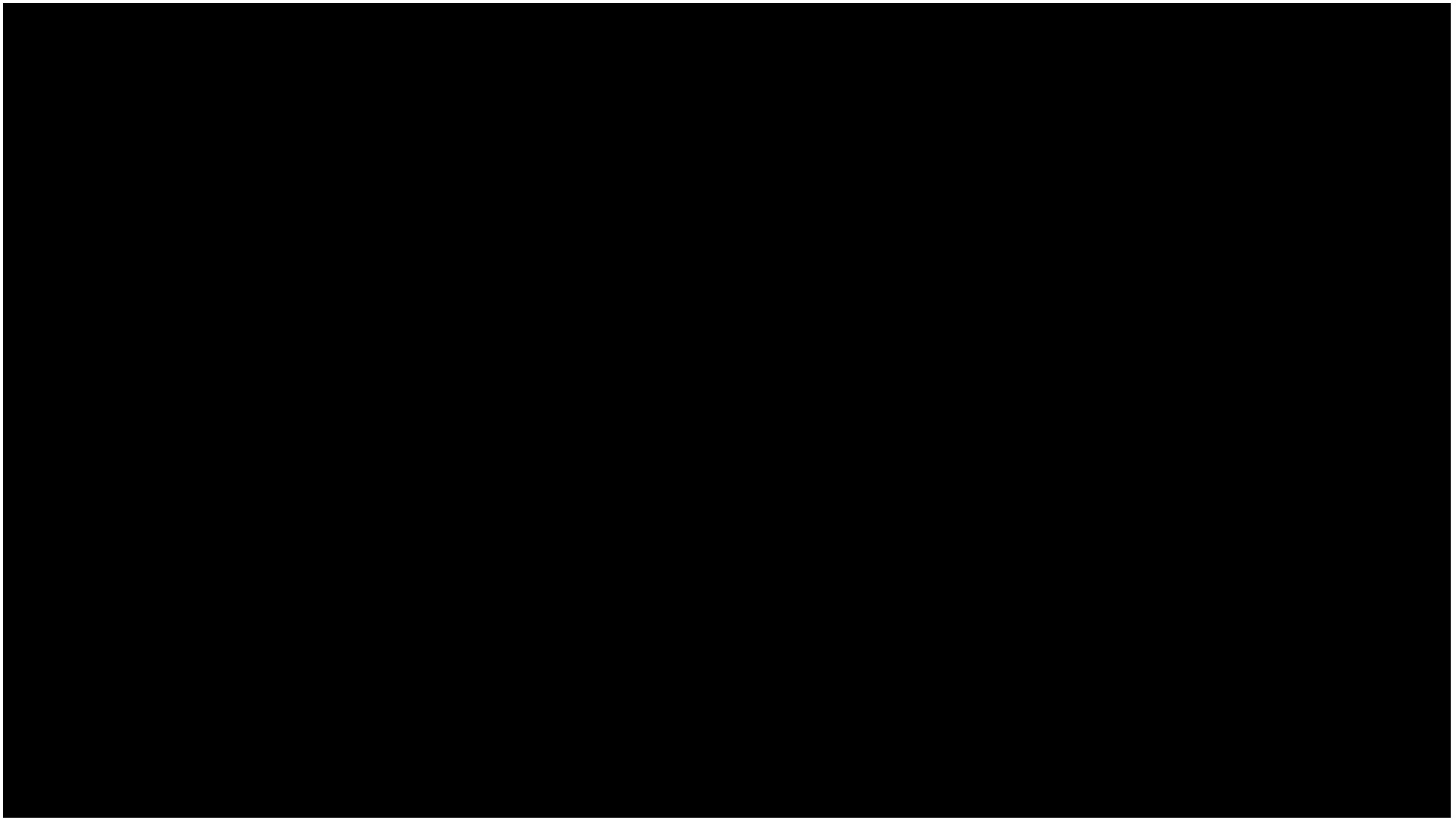
DEEP UNDERGROUND NEUTRINO EXPERIMENT



The flagship experiment…



DUNE – An international mega-science project



Thank you


N3AS
Network for Neutrinos,
Nuclear Astrophysics,
and Symmetries
PHYSICS FRONTIER CENTER

NSF