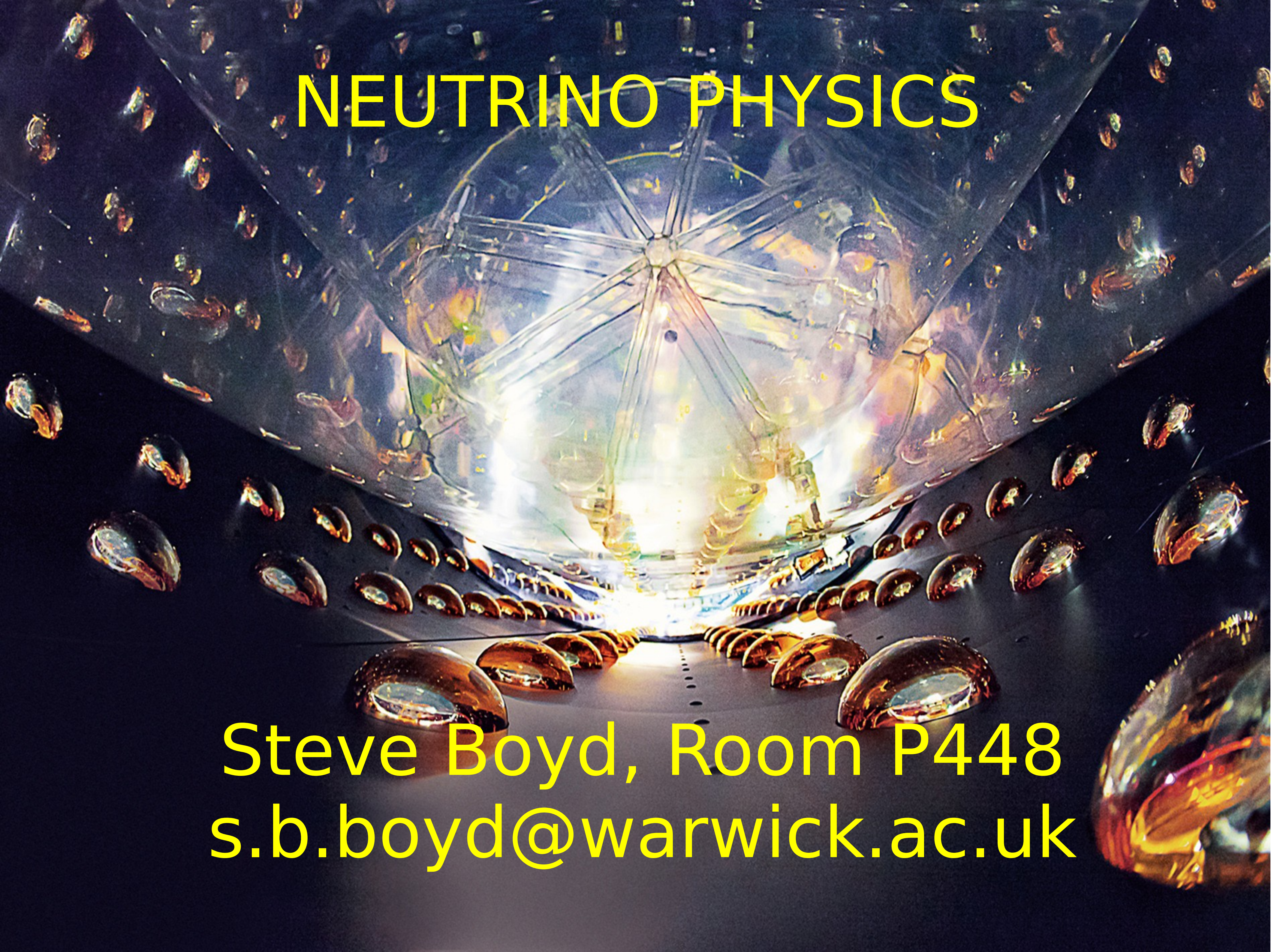


NEUTRINO PHYSICS

Steve Boyd, Room P448
s.b.boyd@warwick.ac.uk

Course Plan

- Introduction, History and motivation (1)
- Neutrinos and the Weak interaction (2)
- Neutrino Sources and Detectors (3)
- Neutrino Mass (2)
- Neutrino Oscillations (5)
- Summary and Future (2)

Module homepage:
http://www2.warwick.ac.uk/fac/sci/physics/teach/module_home/px435

All Powerpoint presentations (in handout and normal format), Lecture writeups, interesting articles etc will be posted ahead of time (but not too far ahead of time)

Recommended texts:
K. Zuber, “*Neutrino Physics*”, IoP Publishing (2004)
D. Griffiths, “*Introduction to elementary particle physics*”, Wiley
B. Martin & G.Shaw, “*Particle Physics*”, Wiley
F. Halzen & A. Martin, “*Quarks and Leptons*”, Wiley
C. Giunti & C. Kim, “Fundamentals of Neutrino Physics and Astrophysics”, Oxford
F. Close, “Neutrino”, Oxford University Press

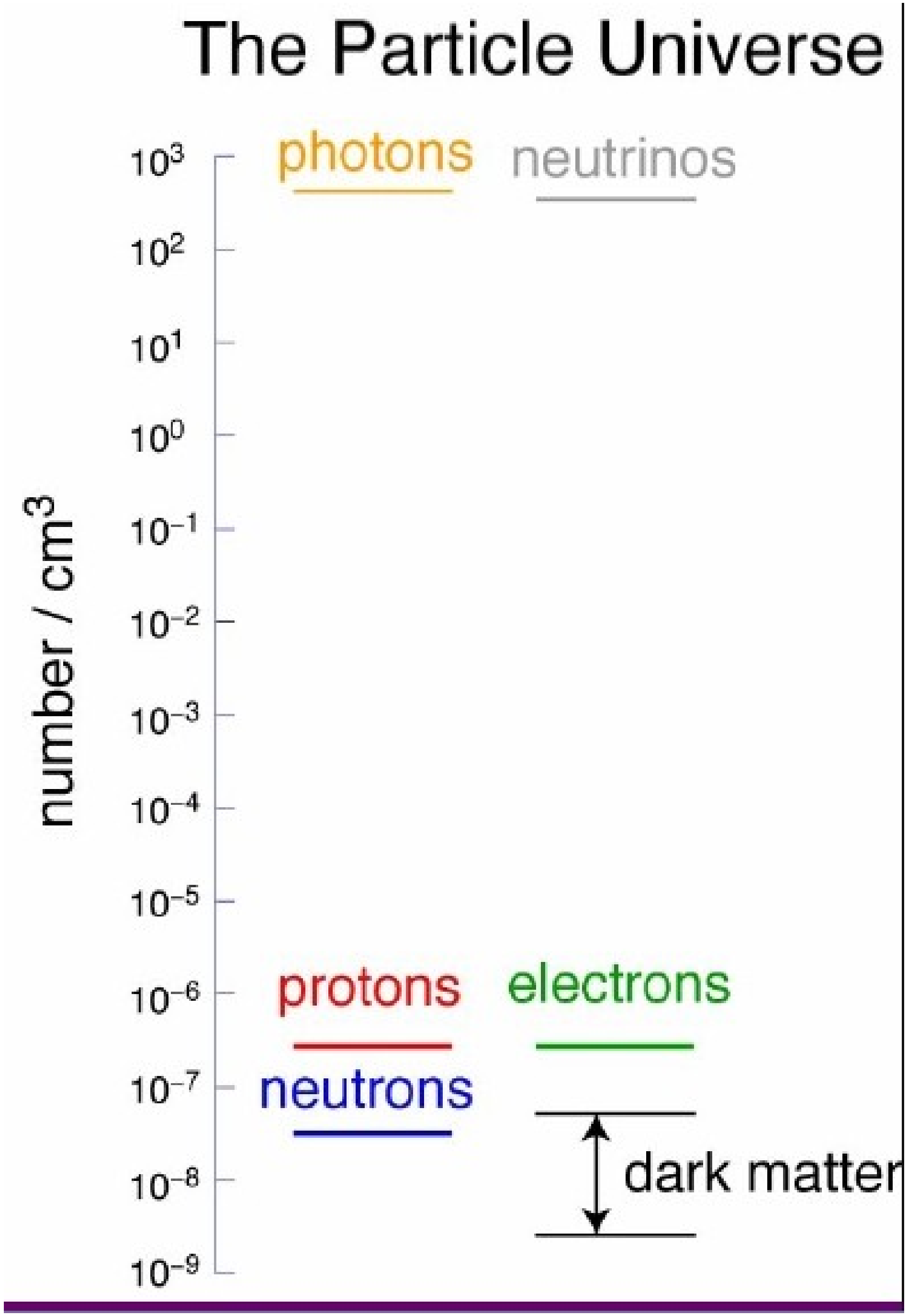
Assessment: 1.5 hour exam. 2 out of 3 questions.

The Neutrino

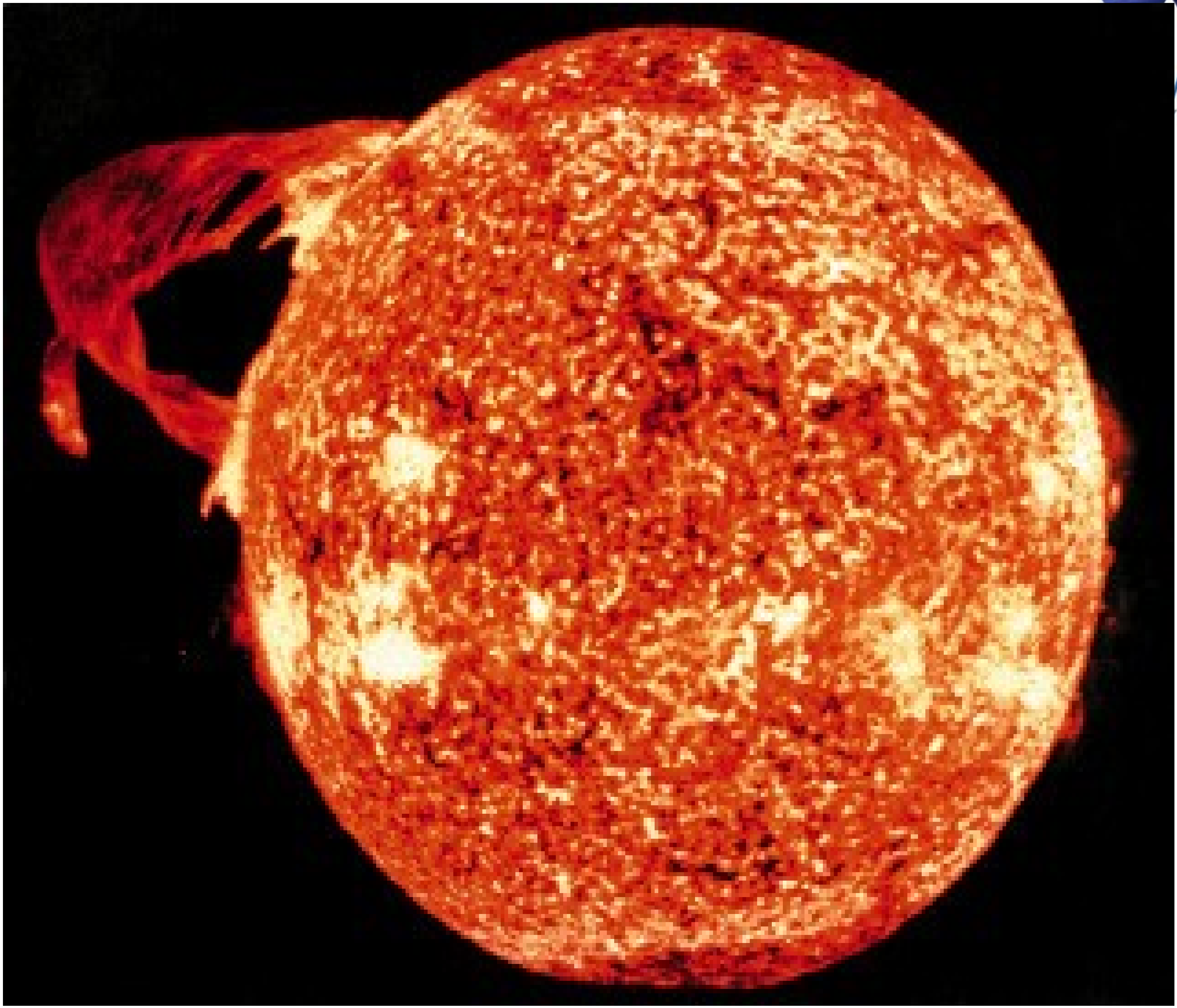
Fred Reines : ... *the most tiny quantity of reality ever imagined by a human being*

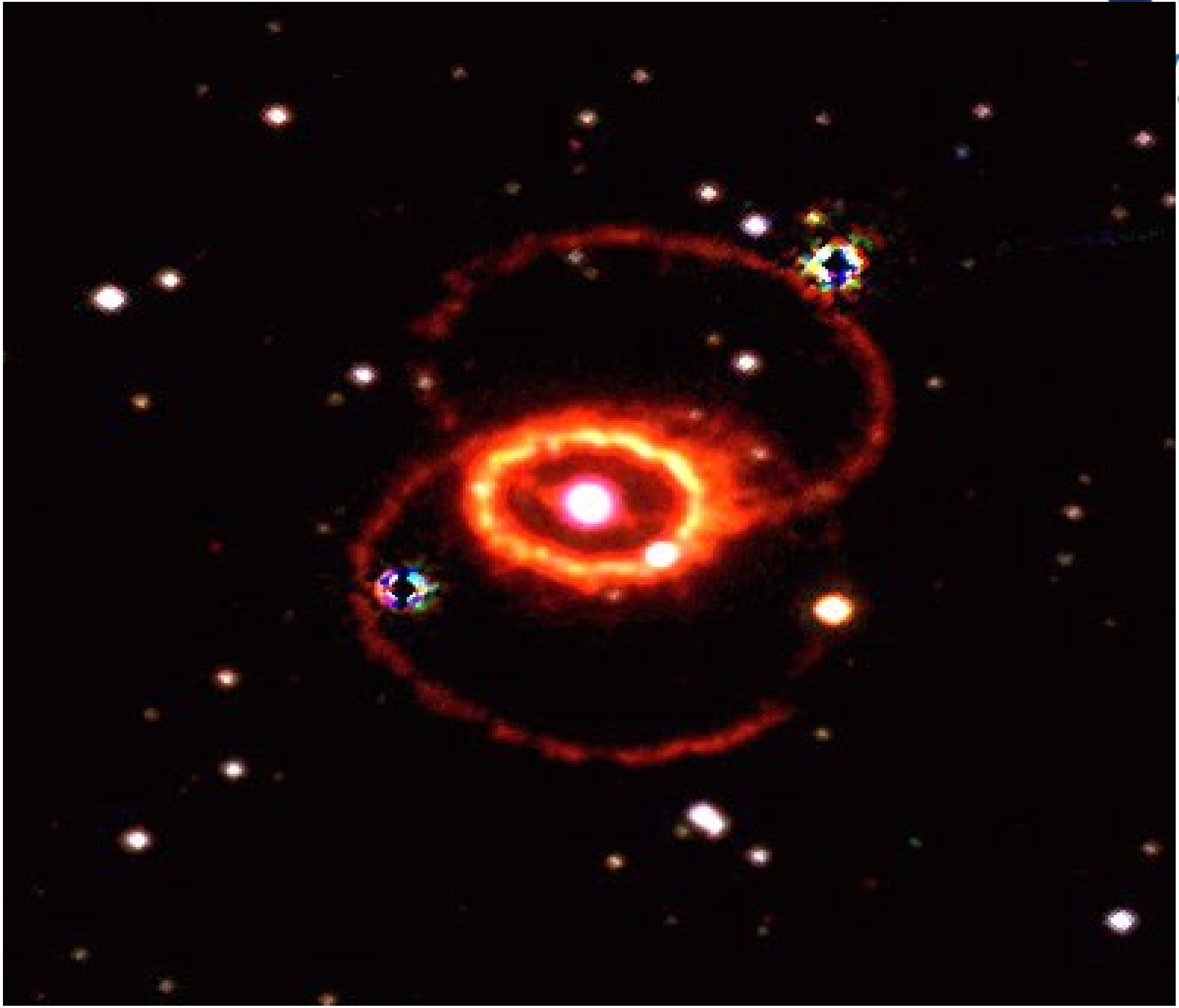
and yet

The Sun produces 2 x 10^{38} ν/s
The Earth receives > 5×10^{10} ν/s/cm^2
The Universe contains 300 ν/cm^3

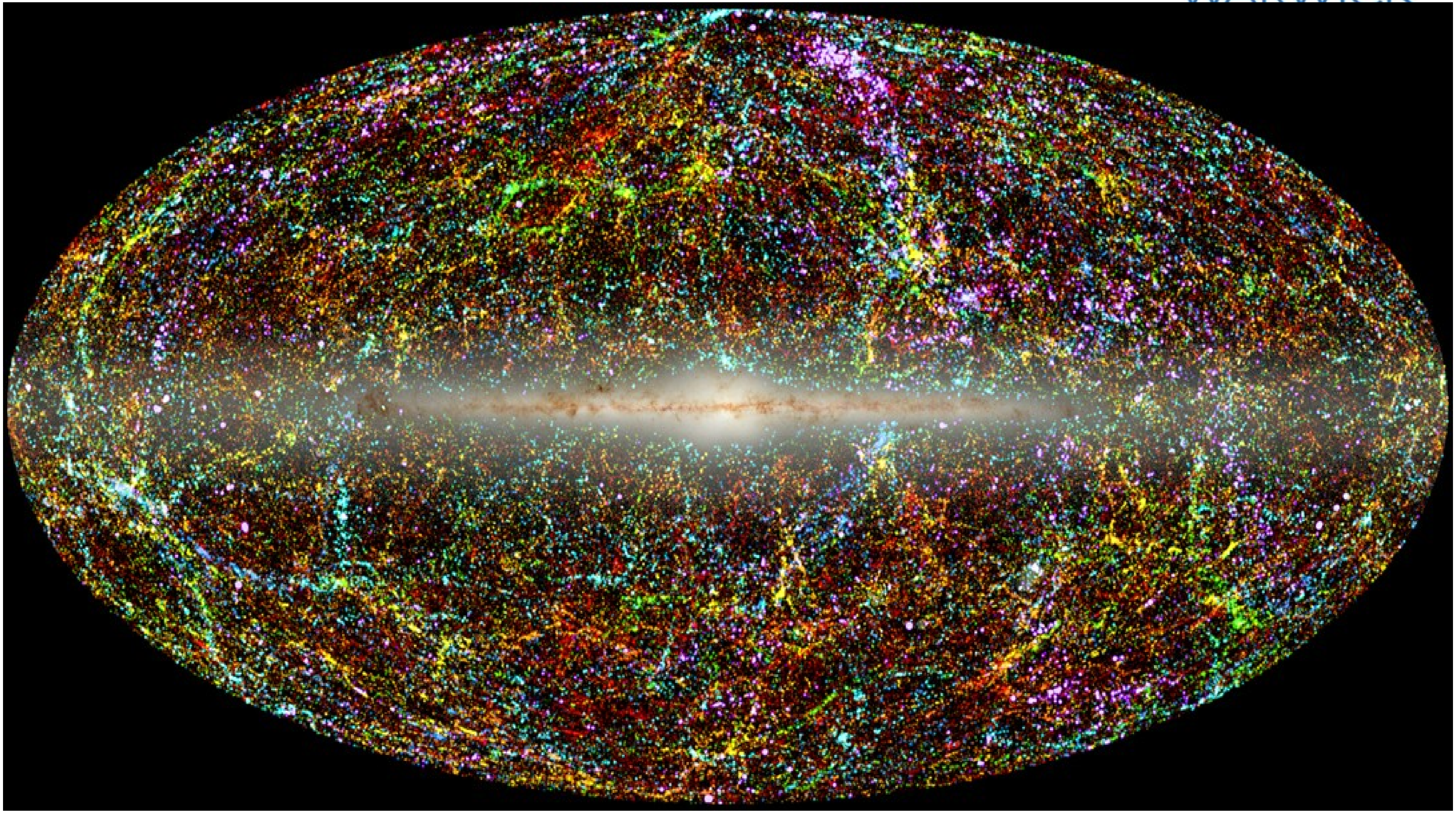

The Particle Universe
number / cm3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
photons
neutrinos
protons
electrons
neutrons
dark matter

Neutrinos are critical for…..





Neutrinos *might be* responsible for.....




MATTER
ANTI-MATTER
S. Harris

Why study neutrinos?

- Could help explain the matter-antimatter asymmetry
- Could be a component of dark matter
- Can be a probe for environments that other techniques cannot.
- ~~Could~~ Don't go faster than light

- Knowing so little about a fundamental particle is just plain embarrassing

Basic Concepts

- The Standard Model and History
- The Dirac Equation
- The Weak Interaction

Assumptions

- This is a particle physics course, so we'll use particle physics units

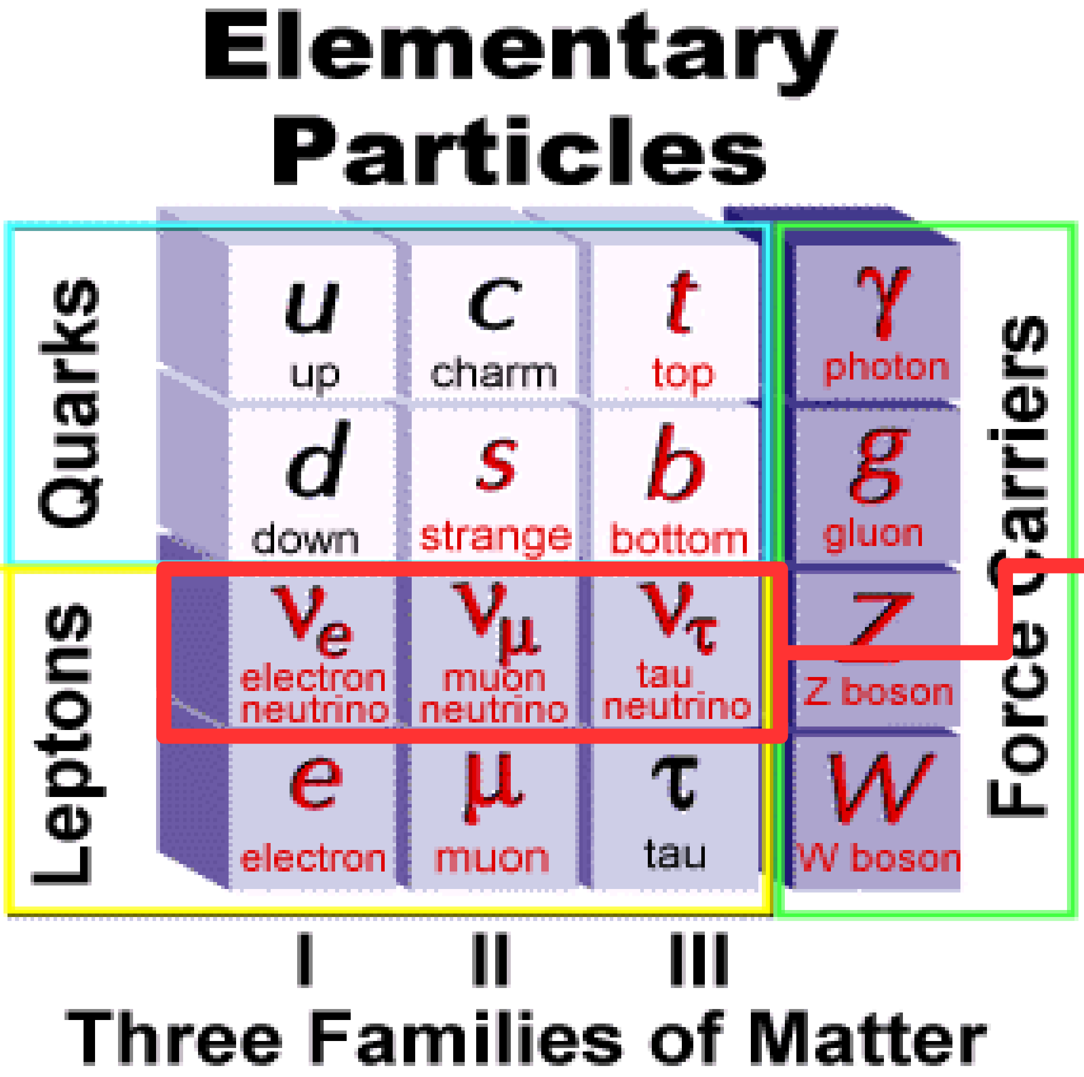
$$\hbar = c = 1$$

- This is a particle physics course, so we'll use appropriate covariant notation

$$x_\mu = (t, -x, -y, -z) \quad ; \quad x^\mu = g_{\mu\nu} x^\nu = (t, x, y, z)$$

$$p_\mu = (E, -p_x, -p_y, -p_z) \quad ; \quad p^\mu = g_{\mu\nu} p^\nu = (t, p_x, p_y, p_z)$$

The Standard Model



- Spin ½
- Massless (almost)
- Electrically neutral
- 3 Flavours
- Flavours mix

Neutrinos in the Standard Model

$$\begin{pmatrix} \nu_l \\ l \end{pmatrix}_L$$

$$l_R$$

- Neutrinos form part of a *left-handed weak isospin SU(2) doublet*

Electric charge, Q	0
Weak isospin, T_3	+1/2
Weak hypercharge, Y	-1
Handedness	Left
Lepton number	+1

No observed right hand neutrino singlet

Standard Model

- The Standard Model describes ALL experimental data
- Yet it's quite clunky and contains unanswered questions
- There are 26 free parameters (15 are particle masses)
- There are 3 generations of basically the same particle
- The neutrino are orders or magnitude lighter than all the other particles.
- Interactions aren't unified
- It's not the ultimate theory.

Can you remember every(any?)thing about….

- The Dirac equation
- γ matrices
- the adjoint spinor and the vector current $j_V^{\mu} = \overline{\psi}\gamma^{\mu}\psi$
- helicity
- chirality
- chiral projection operators: $P_{L,R} = \frac{1}{2}(1 \mp \gamma^5)$
- C, P, CP and their operators
- S, V, A and P currents and their operators

Neutrino History and properties

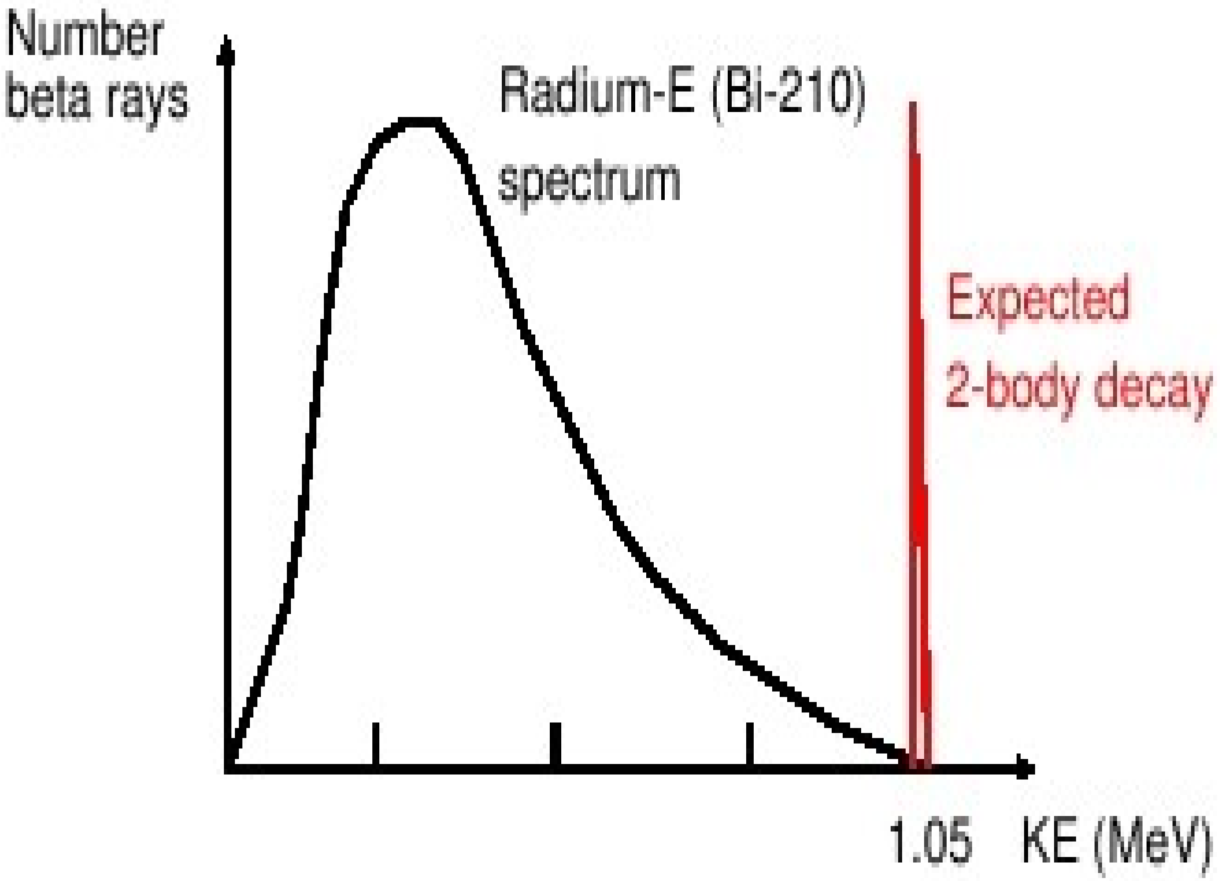
Neutrinos they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a dusty hall….

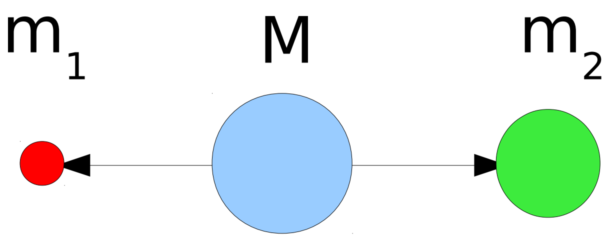
”Cosmic gall”,
John Updike,
Telephone Poles and other Poems,
1963


Davis
Fermi
Pauli
Dirac
Majorana
Pontecorvo
Reines
Koshiba
photo PRB
Goeppert Mayer

CRISIS

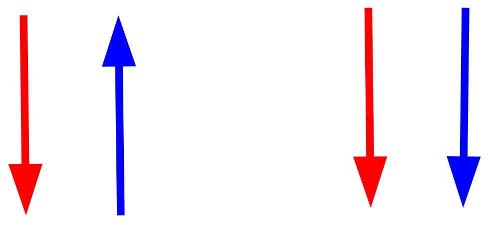
Energy conservation violated!





$$E_2 = \frac{M^2 + m_2^2 - m_1^2}{2M}$$

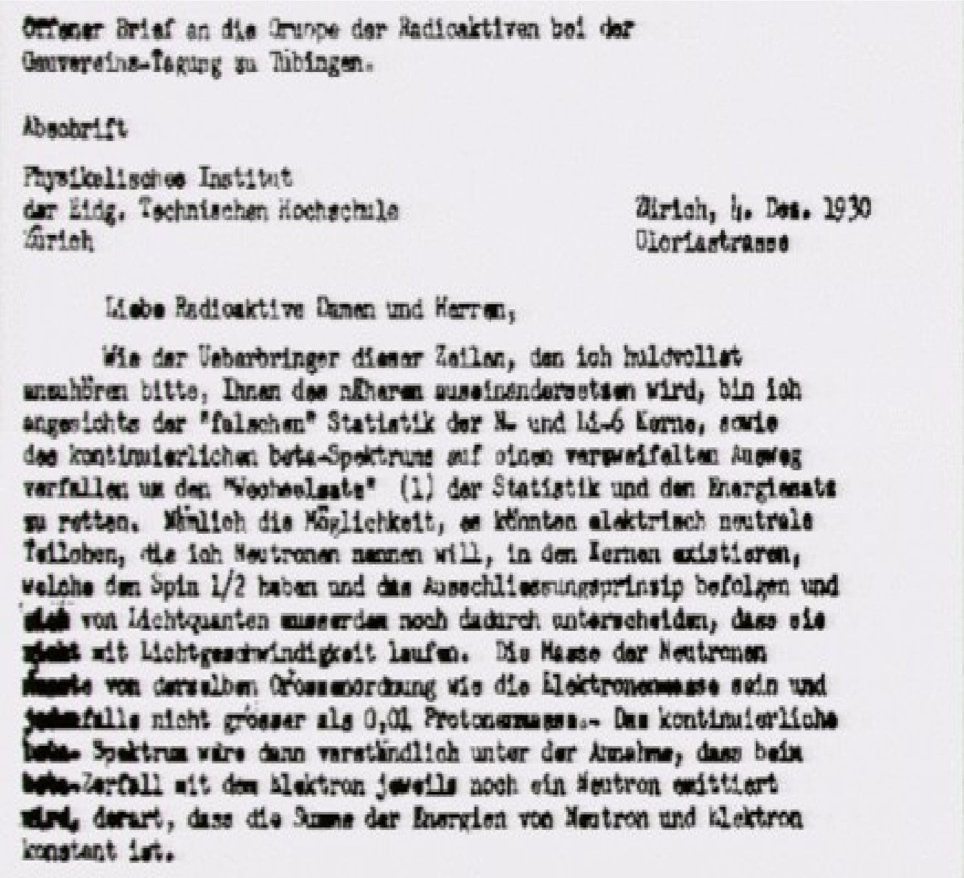
Spin crisis : spin 1/2 ≠ spin 1/2 + spin 1/2



Spin 0

Spin 1

Pauli's Desperate Remedy



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

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 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.

The birth of the neutrino

4th December 1930
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 ^{6}*Li 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 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...*
From now on, every solution to the issue must be discussed. Thus, dear radioactive people, look and judge. Unfortunately I will not be able to appear in Tubingen personally, because I am indispensible here due to a ball which will take place in Zurich during the night from December 6 to 7...

Your humble servant,
W. Pauli

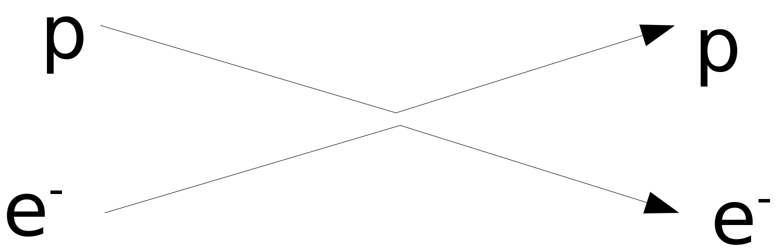
Oh the pain

“I have done something very bad today by proposing a particle that cannot be detected. It is something that no theorist should ever do.”

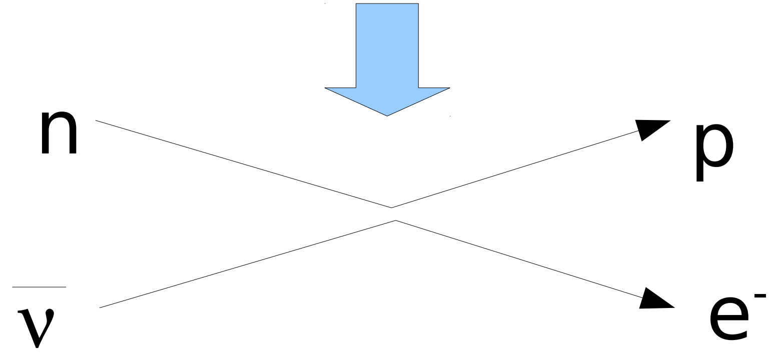
Pauli, 1930

Pauli did not publish this idea until 1934 as he thought it too speculative

Fermi Theory (1926)

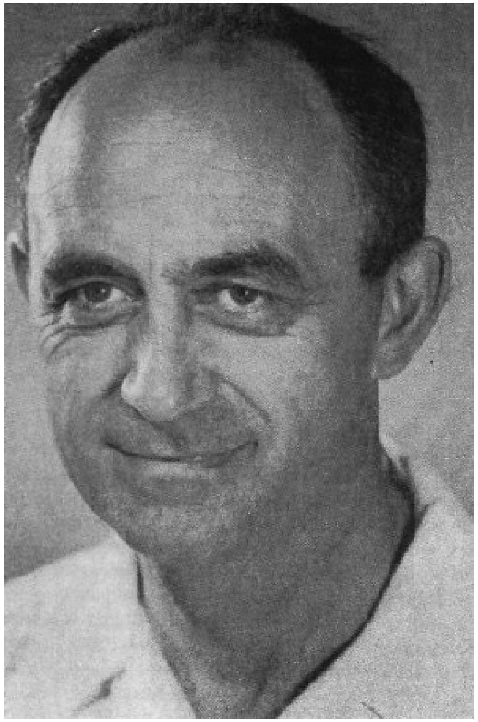


$$L=e^2[\bar{\phi}_p(x)\gamma^\mu\phi_p(x)][\bar{\phi}_e(x)\gamma_\mu\phi_e(x)]$$



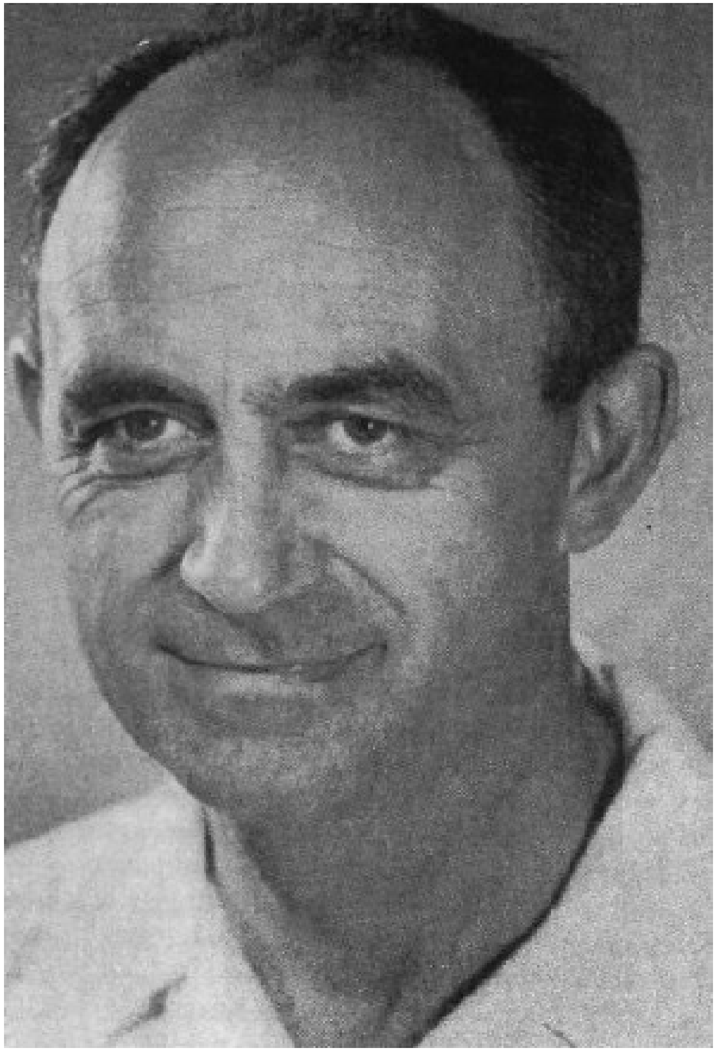
$$L=G_F[\bar{\phi}_p(x)\gamma^\mu\phi_n(x)][\bar{\phi}_e(x)\gamma_\mu\phi_\nu(x)]$$

NB Vector



Enrico Fermi

“A tentative theory of β decay”



Initial paper rejected by Nature because:

“it contains speculations to remote from reality to be of interest to the reader”

But where is it?

Still no neutrino observed experimentally? Why?
Bethe-Peierls (1934) provided some of the answer.

Fermi theory predicted cross section for ν p

$\sigma \sim 10^{-44}$ cm^2 for 2 MeV ν

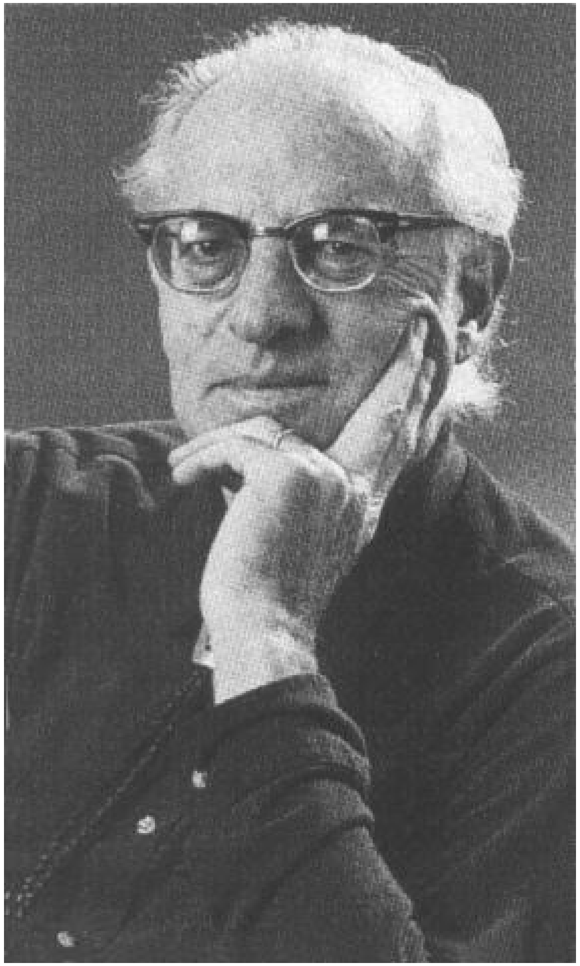
$$\lambda_{lead} \sim \frac{1}{N_A \rho \sigma} = \frac{1}{6.10^{23}(nuc/g) \times 7.9(g/cm^2) \times 10^{-44}(cm^2)}$$

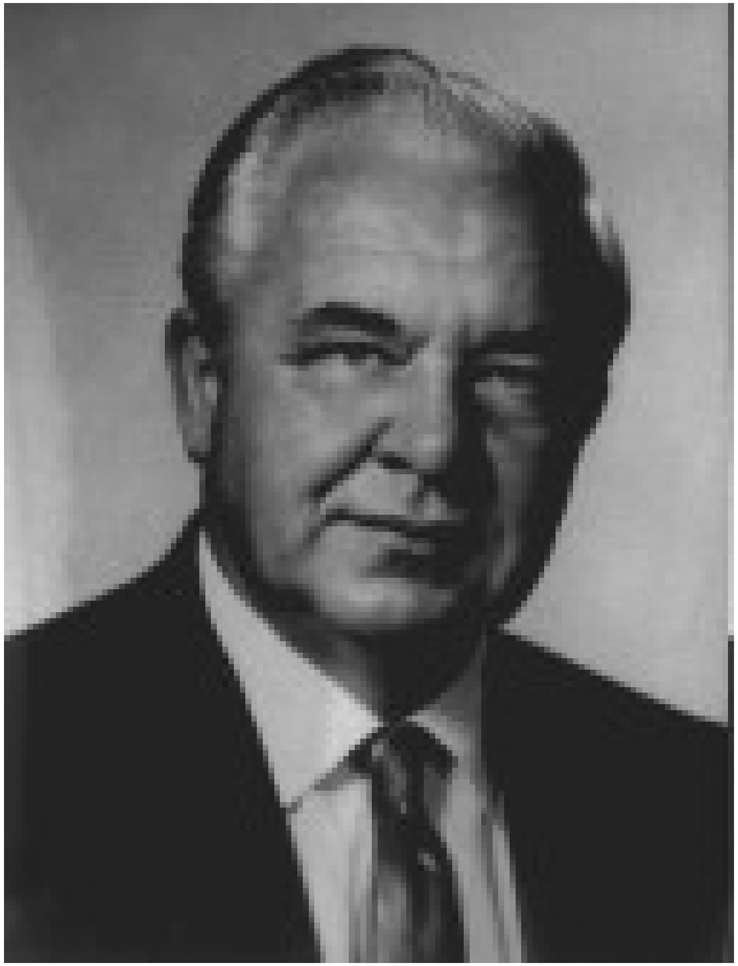
$\lambda_{\mathrm{lead}} \approx$ 22 light years

A neutrino could travel through the earth “like a bullet through a bank of fog”.”There is no practically possible way of observing the neutrino”.

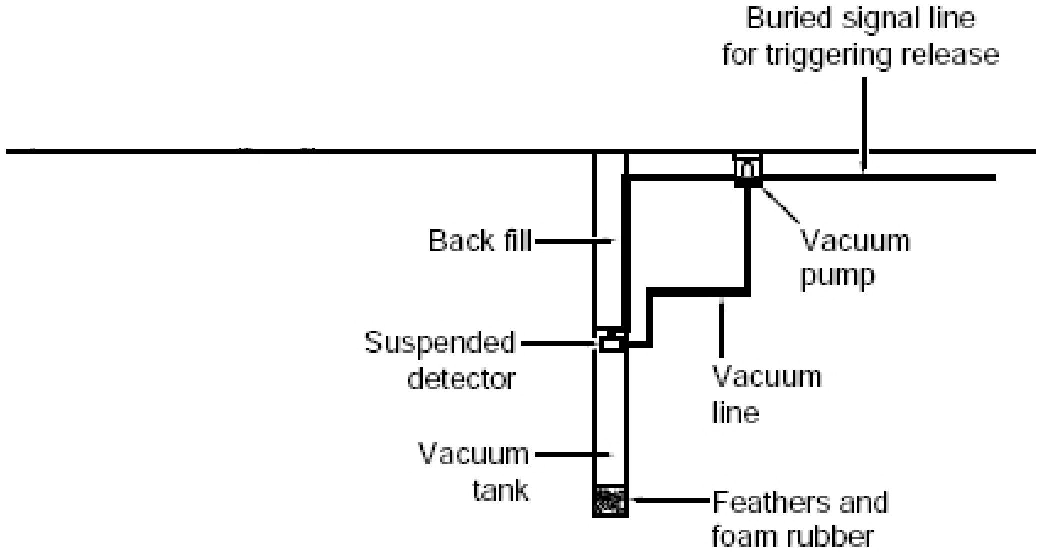
Detection of the Neutrino

1950 – Fred Reines and Clyde Cowan set out to detect ν

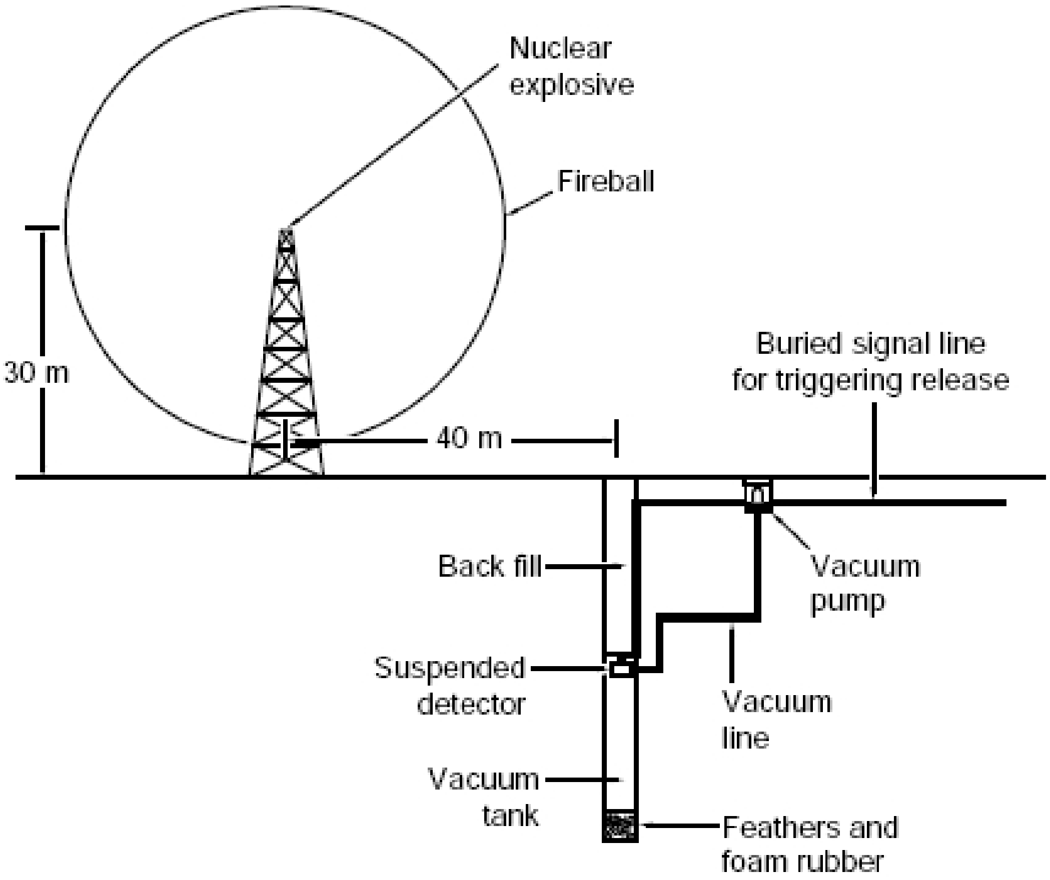




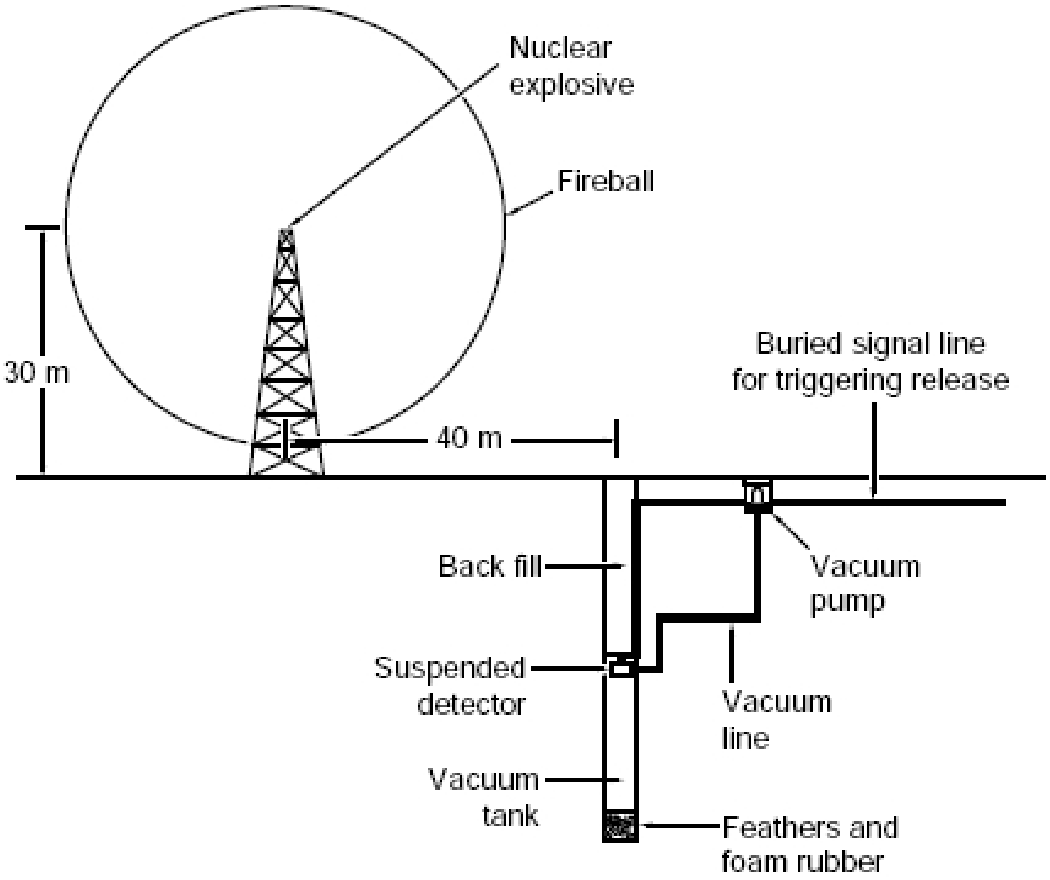
Project Poltergeist - 1951



Project Poltergeist - 1951



Project Poltergeist - 1951



I. Explode bomb
II.At same time let detector fall in vacuum tank
III. Detect neutrinos
IV. Collect Nobel prize

OK – but repeatability is a bit of a problem

A conversation

(Verbatim from Reines to Fermi)

Reines : I have been thinking about detecting neutrinos and the bomb may be the best source
Fermi : (silence) Yes, that appears to be so.
Reines : It would need a detector with a sensitive mass of about a ton.
Fermi : That's right
Reines : I have no idea how to build such a detector
Fermi : Neither do I

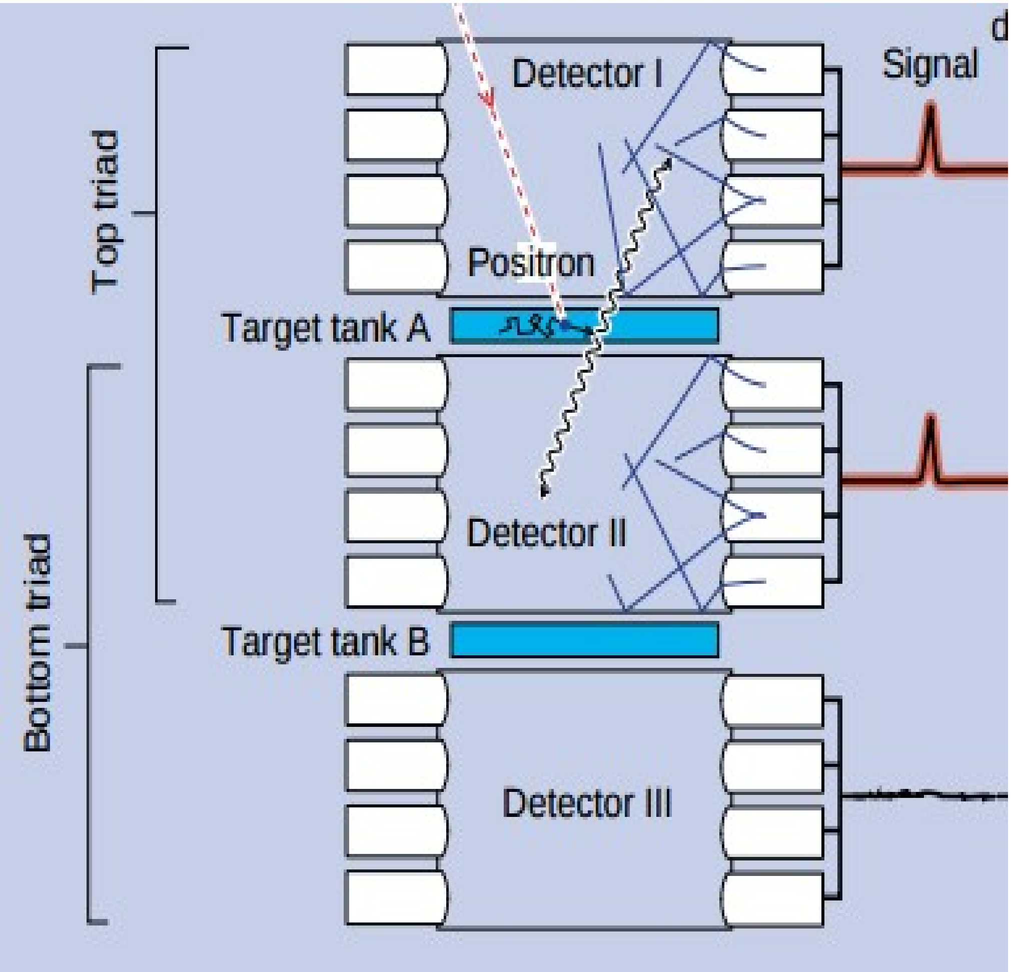
Exit - stage left.

(Reines memoirs)

Idea Number 2 - 1956

A nuclear reactor is the next best thing

Fission of U^{235} produces a chain of β decays



1. $\overline{\nu}_e + p \rightarrow e^+ + n$

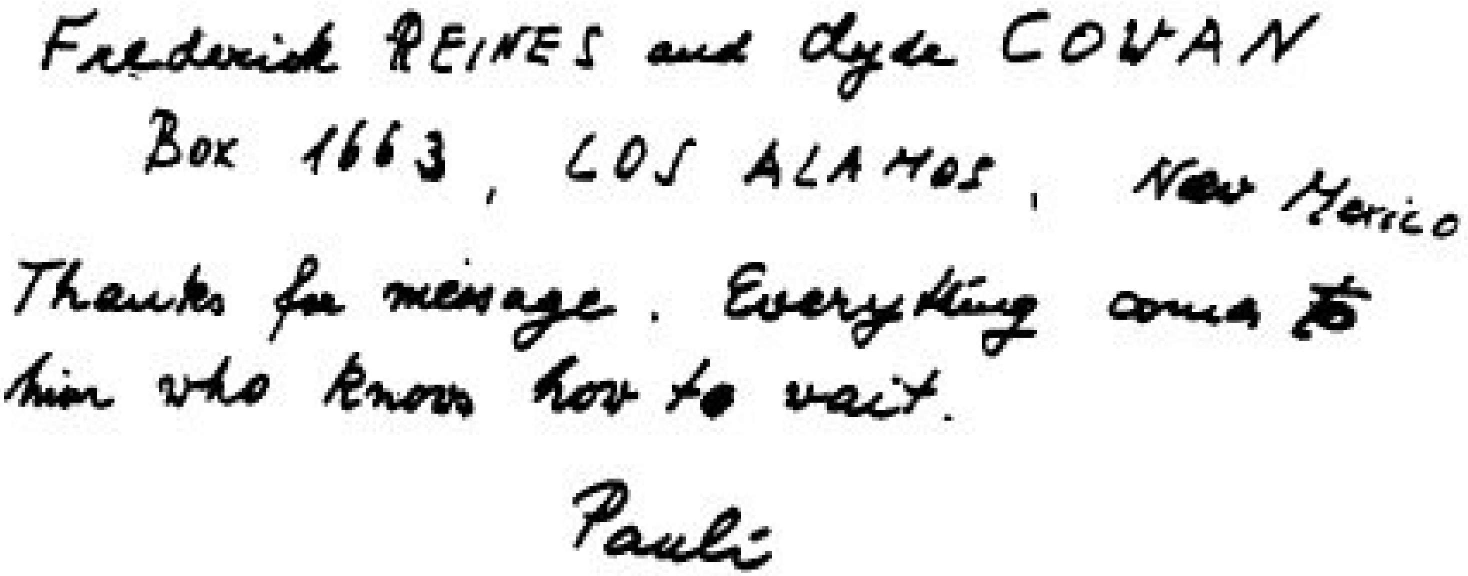
2. Neutron capture on Cd

Signal is two neighboring tanks in coincidence

Reactor on – Reactor off
2.88 +/- 0.22 hr^{-1}
$\sigma = (11 \pm 2.6) \times 10^{-44}\ cm^2$
$\sigma\ (Pred) = (5 \pm 1) \times 10^{-44}\ cm^2$

Finally – 26 years after being proposed the neutrino is discovered

Telegram to Pauli : “We are happy to inform you that we have definitely detected neutrinos” - Pauli and friends put away an entire crate of Champagne.



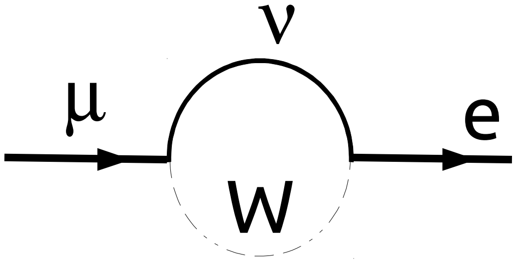
Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

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

Pauli

In 1995 Reines received the Noble Prize for this work - 40 years after doing it.

More than one?

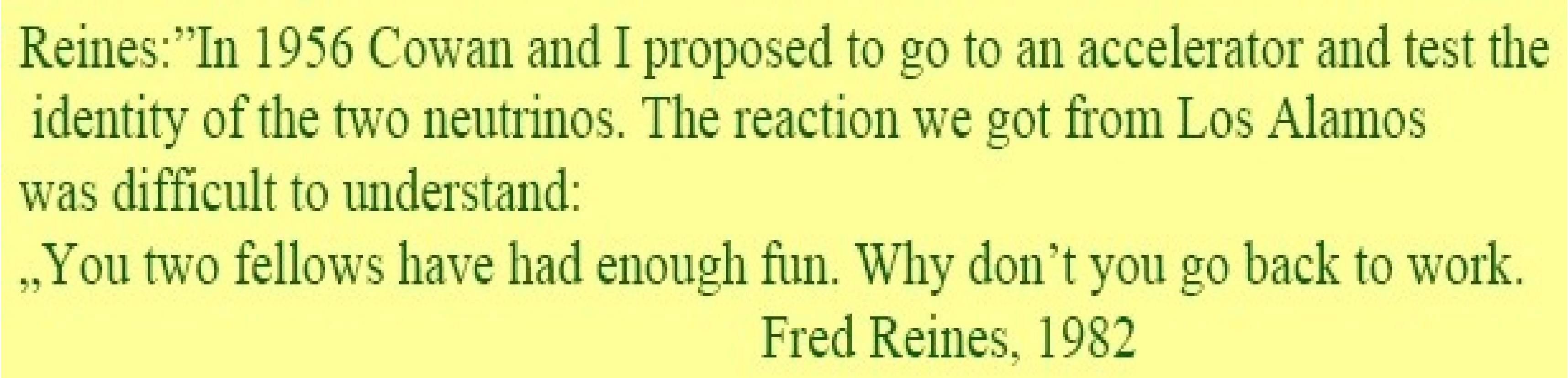


Bruno Pontecorvo was fascinated by the inability of observe simple μ→e decay

He suggested that the muon carried some sort of “muon-ness” that prevented it from decaying like this

Today we call it “flavour”

He suggested that if electrons and muons were different, then perhaps electron neutrinos and muon neutrinos were different too!

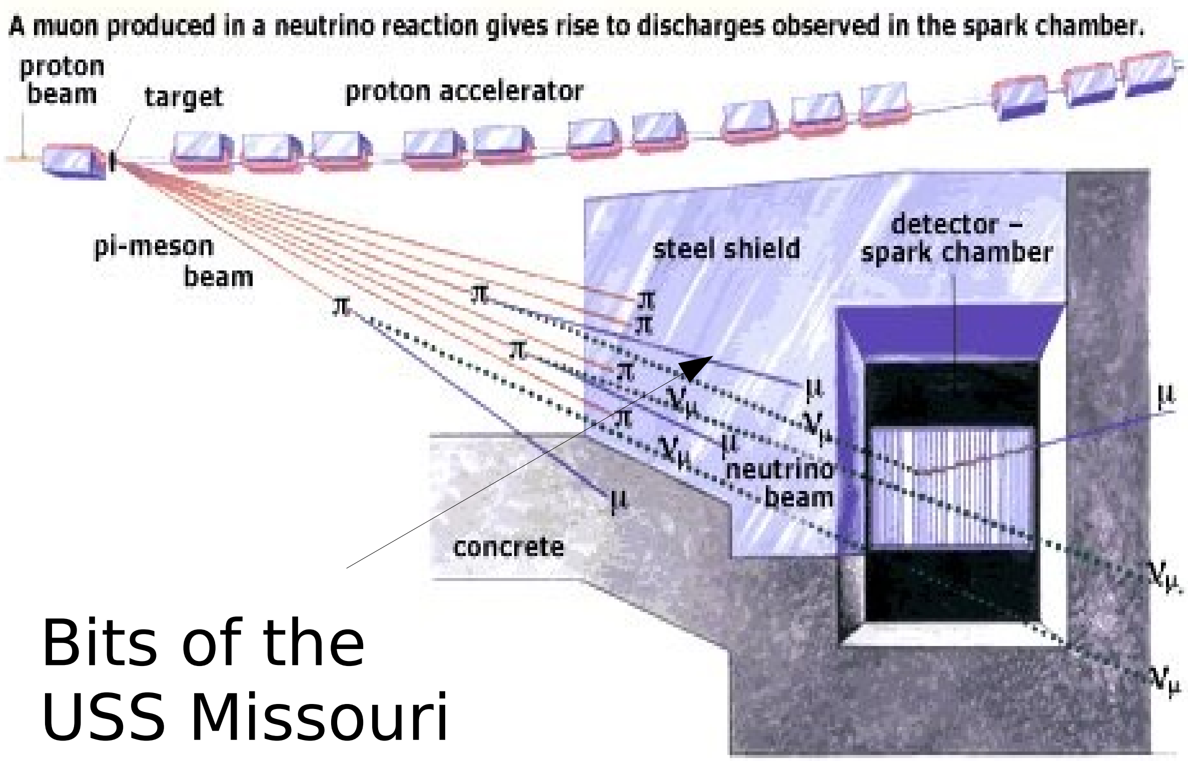


Reines:”In 1956 Cowan and I proposed to go to an accelerator and test the identity of the two neutrinos. The reaction we got from Los Alamos was difficult to understand:
„You two fellows have had enough fun. Why don’t you go back to work.

Fred Reines, 1982

Lederman,Schwarz and Steinberger

In 1962, Schwartz, Steinberger and Lederman presented evidence for the muon neutrino and built the very first neutrino beam!

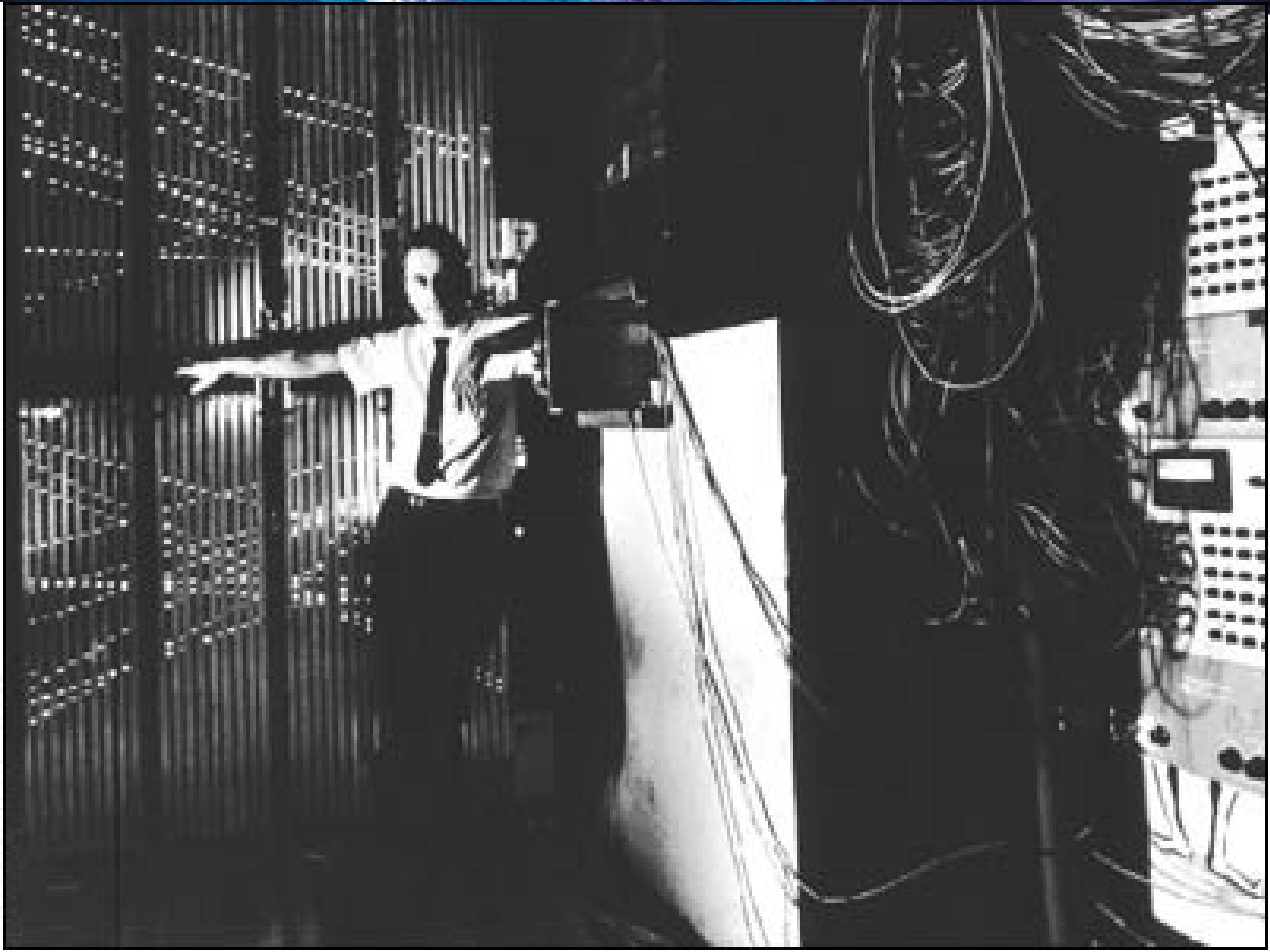

A muon produced in a neutrino reaction gives rise to discharges observed in the spark chamber.

Bits of the USS Missouri

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\nu_\mu + n \rightarrow \mu^- + p$$ OK

$$\nu_\mu + n \rightarrow e^- + p$$ ~~OK~~



Brookhaven Photo

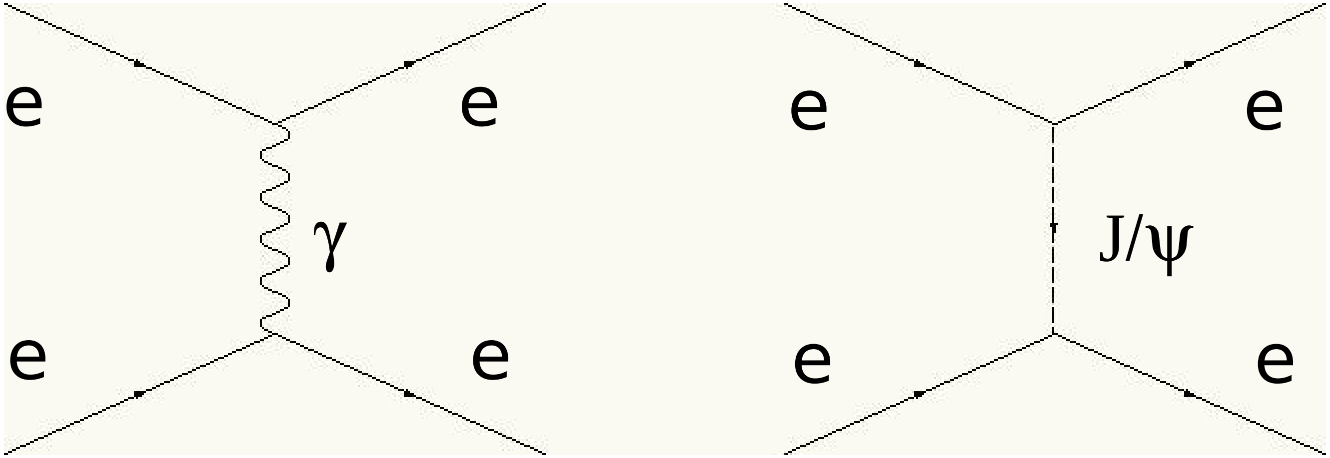
The State of Play 1976

Flavour	Mass (GeV)	Charge
ν_e	$< 1 \times 10^{-8}$	0
e	0.000511	-1
ν_μ	< 0.0002	0
μ	0.106	-1
τ	1.7771	-1

? →

Aside - resonance

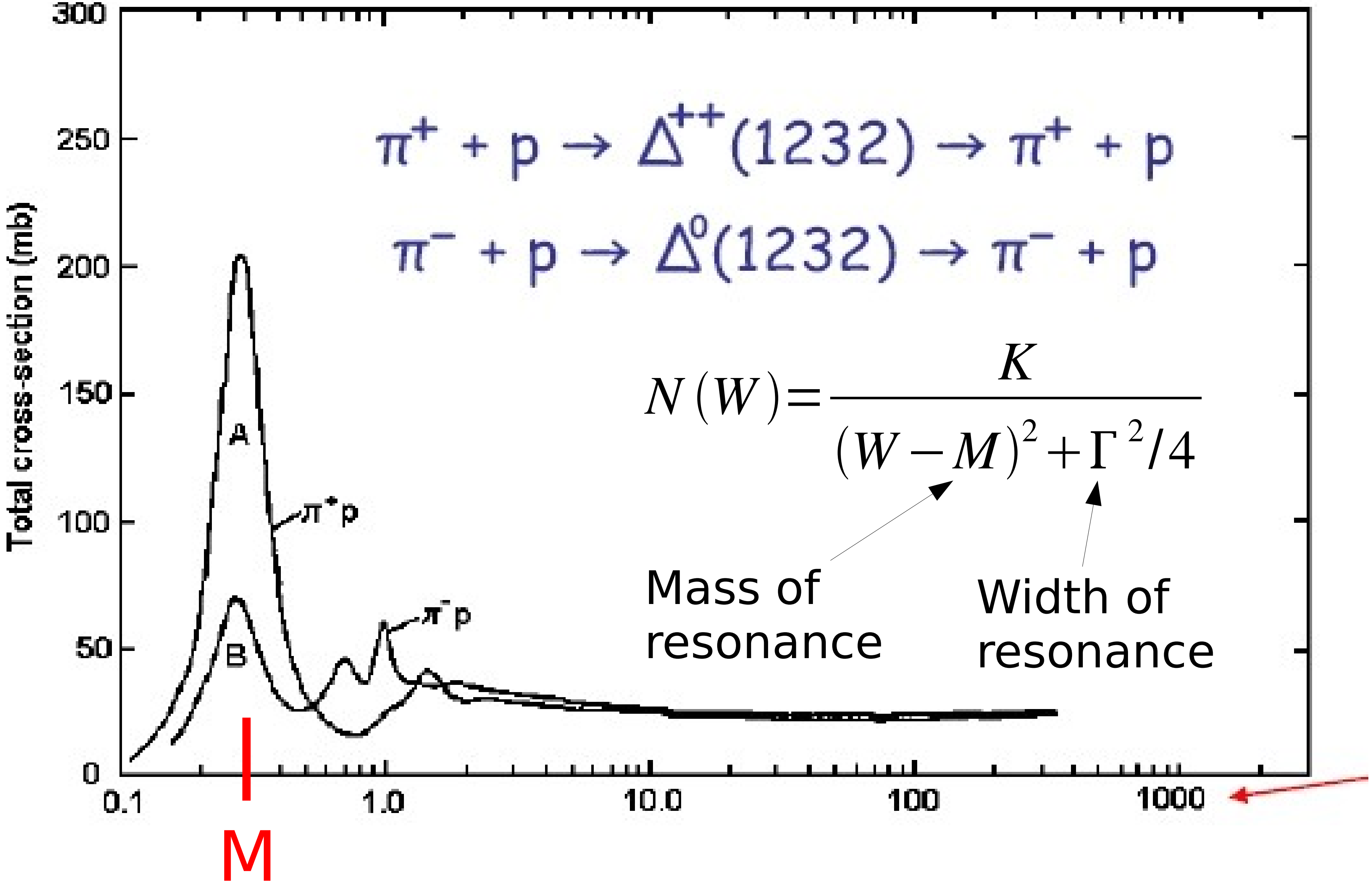
Very short-lived compound states. These barely last long enough to traverse a nucleus.In the region of a resonance, the cross section for an interaction increases



$$\Delta E \Delta t \leq \hbar$$

Shorter the lifetime, the larger the uncertainty in the mass of the resonance state

Aside - Resonances



$\pi^+ + p \rightarrow \Delta^{++}(1232) \rightarrow \pi^+ + p$

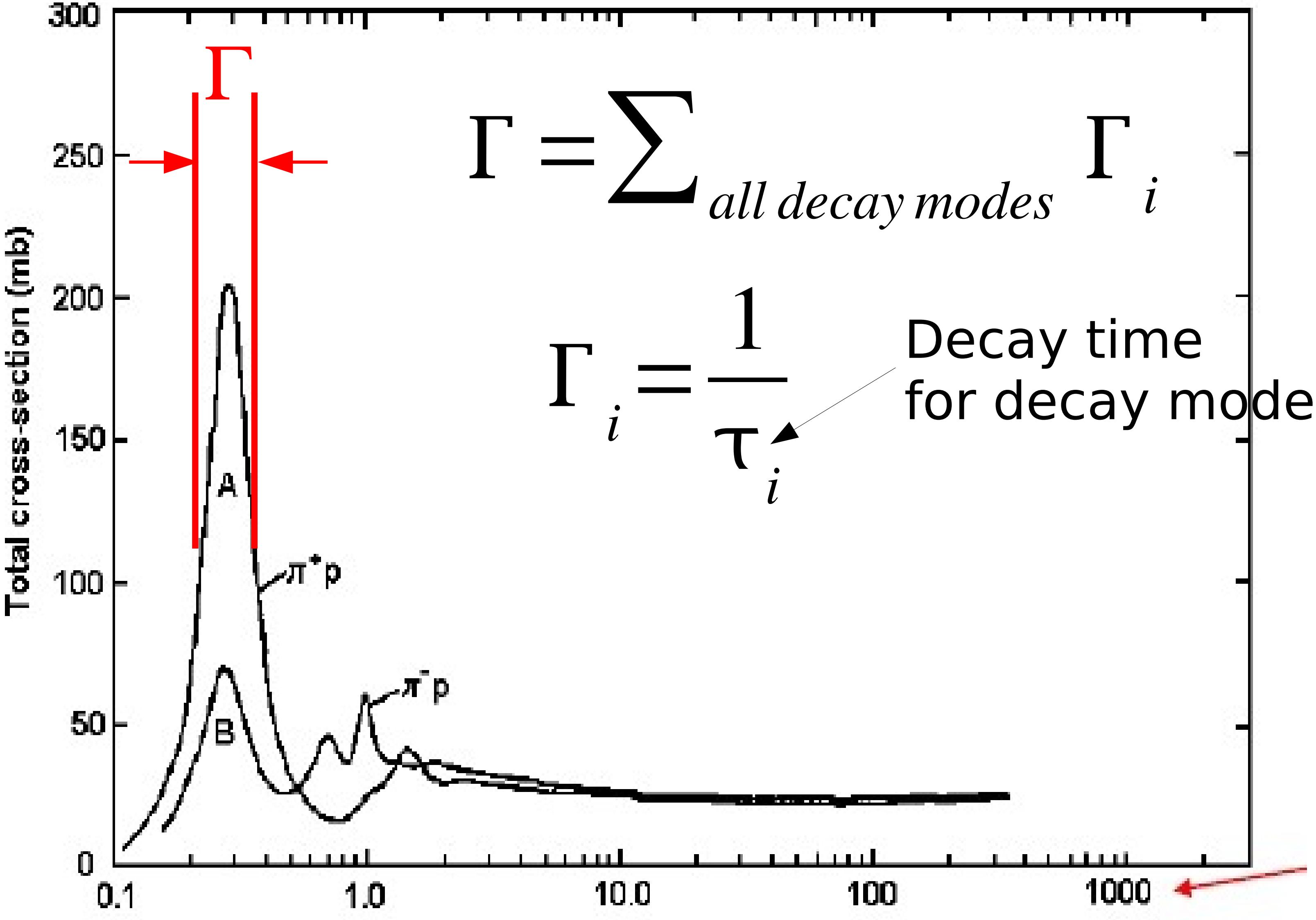
$\pi^- + p \rightarrow \Delta^0(1232) \rightarrow \pi^- + p$

$$N(W) = \frac{K}{(W-M)^2 + \Gamma^2/4}$$

Mass of resonance

Width of resonance

Decay Widths

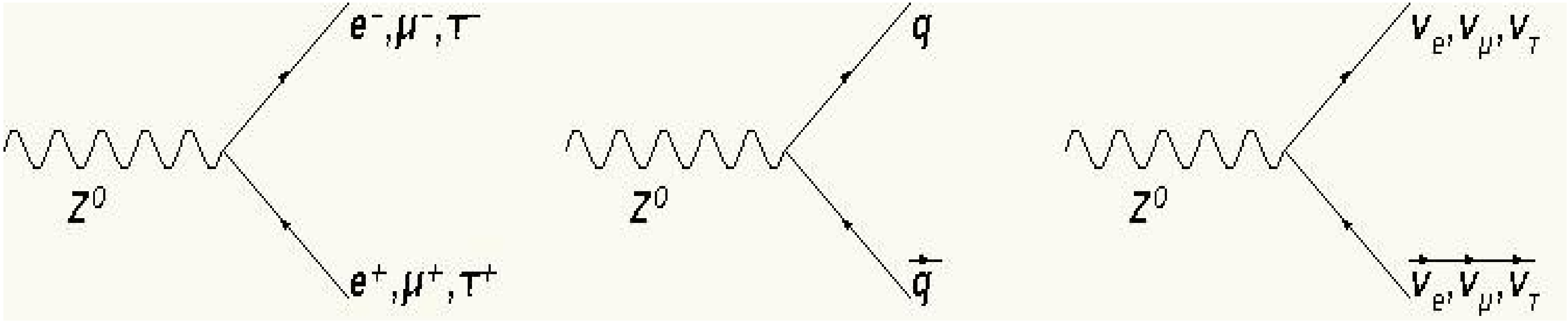


$$\Gamma = \sum_{all\ decay\ modes} \Gamma_i$$

$$\Gamma_i = \frac{1}{\tau_i}$$

Decay time
for decay mode, i

Decay of the Z^0

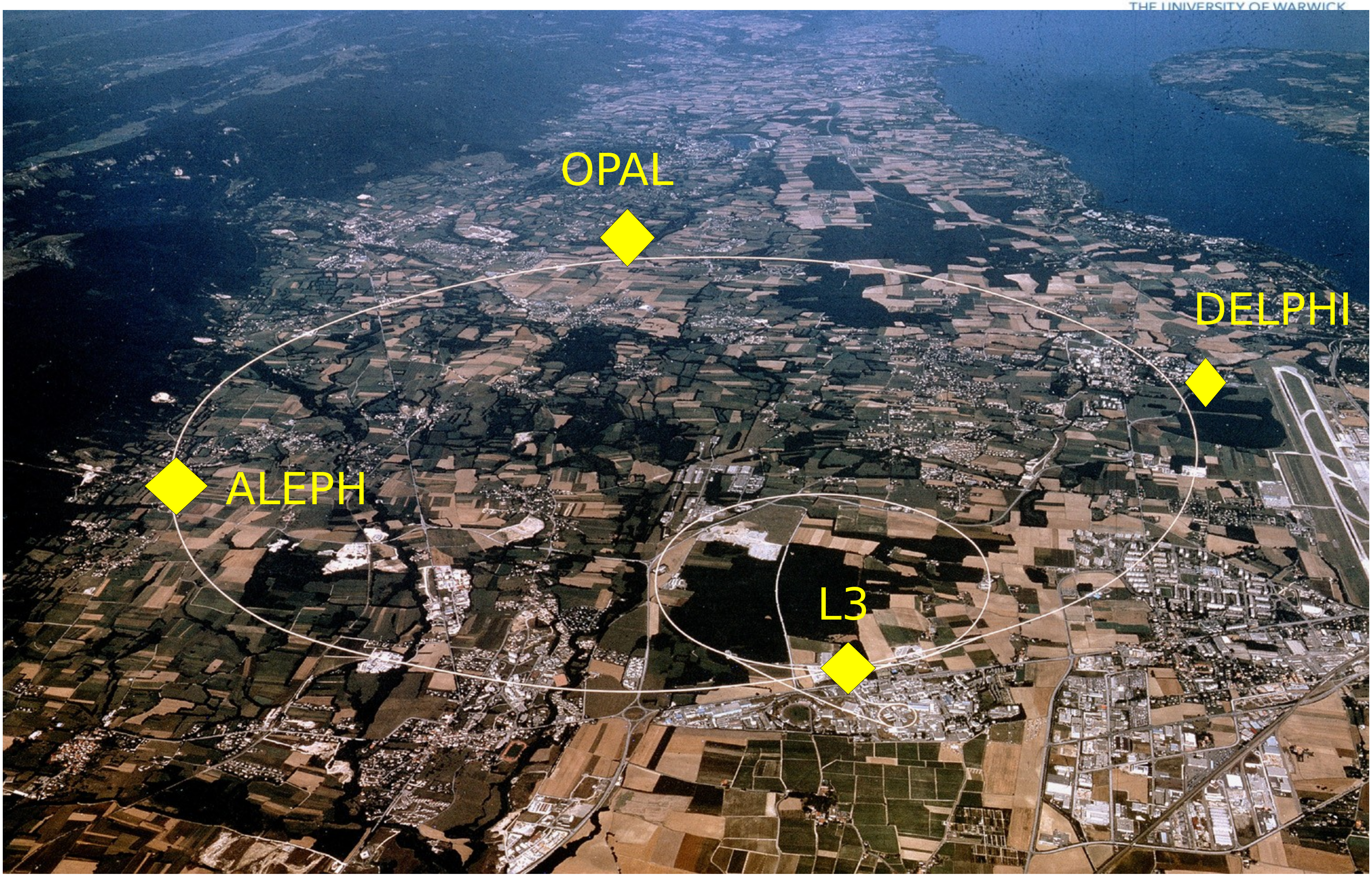


$$\sigma_{f\bar{f}} \propto \frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z}$$

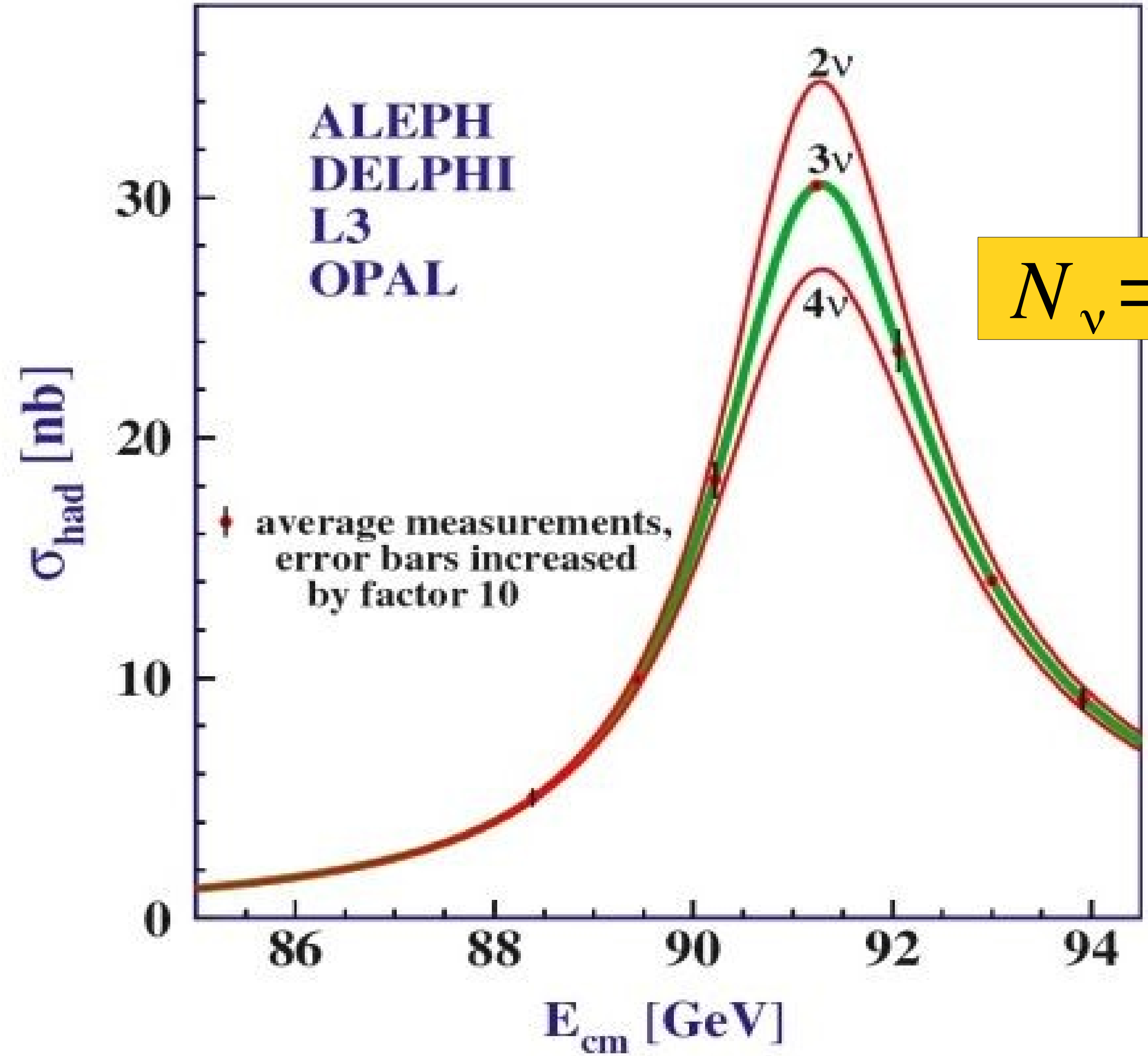
More neutrinos would make the cross section for visible particles decrease.

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{q\bar{q}} + N_\nu \Gamma_{\nu\nu}$$

LEP



The Number of light neutrinos



$N_\nu = 2.92 \pm 0.05$

The State of Play 1976

Flavour	Mass (GeV)	Charge
ν_e	< 1 x 10^{-8}	0
e	0.000511	-1
ν_μ	< 0.0002	0
μ	0.106	-1
	There has to be something here!	
τ	1.7771	-1

The Tau Neutrino

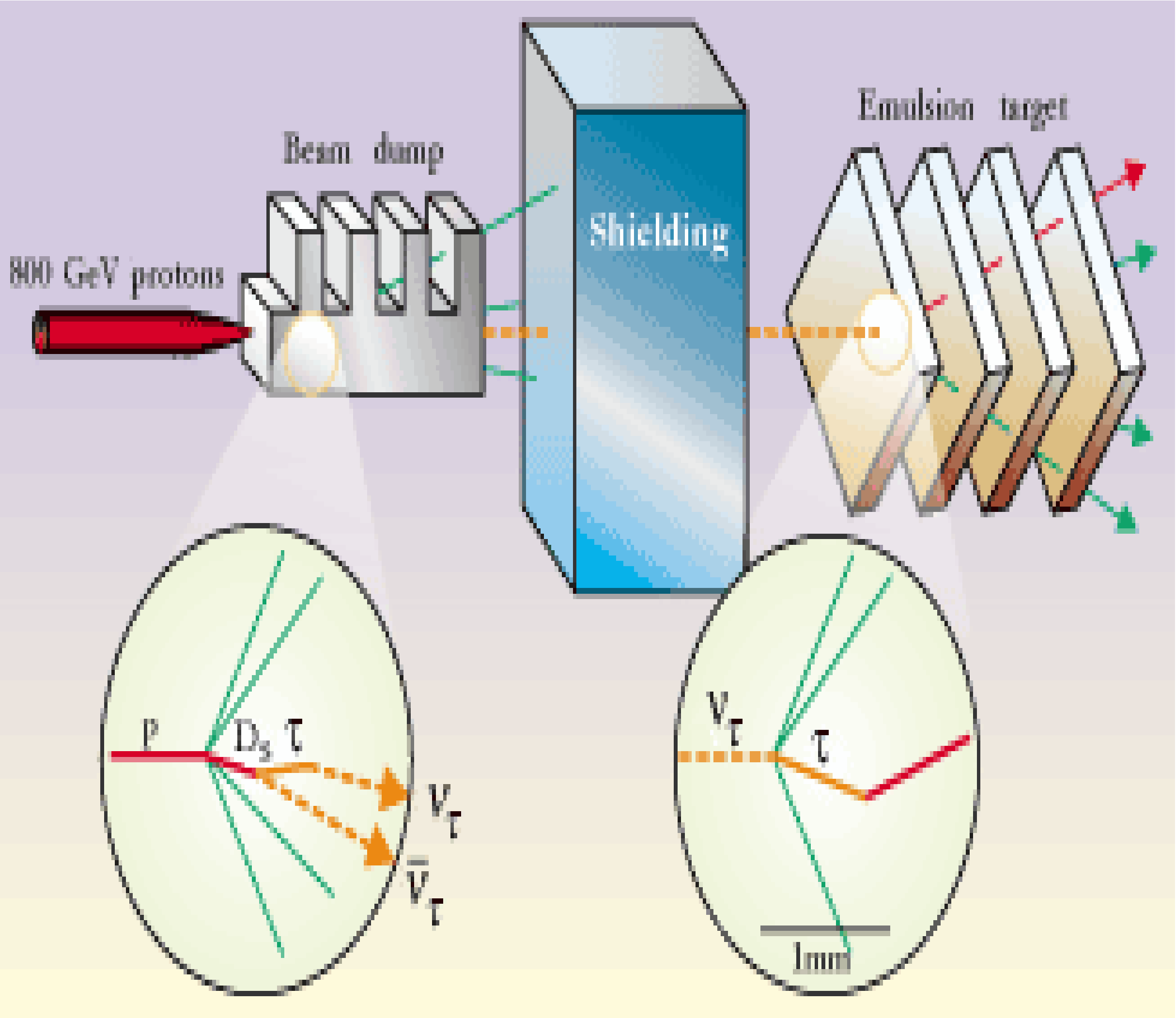
ν_τ was finally discovered by DONUT in 2000.

800 GeV protons on Tungsten produce D_s ($=c\bar{s}$) mesons

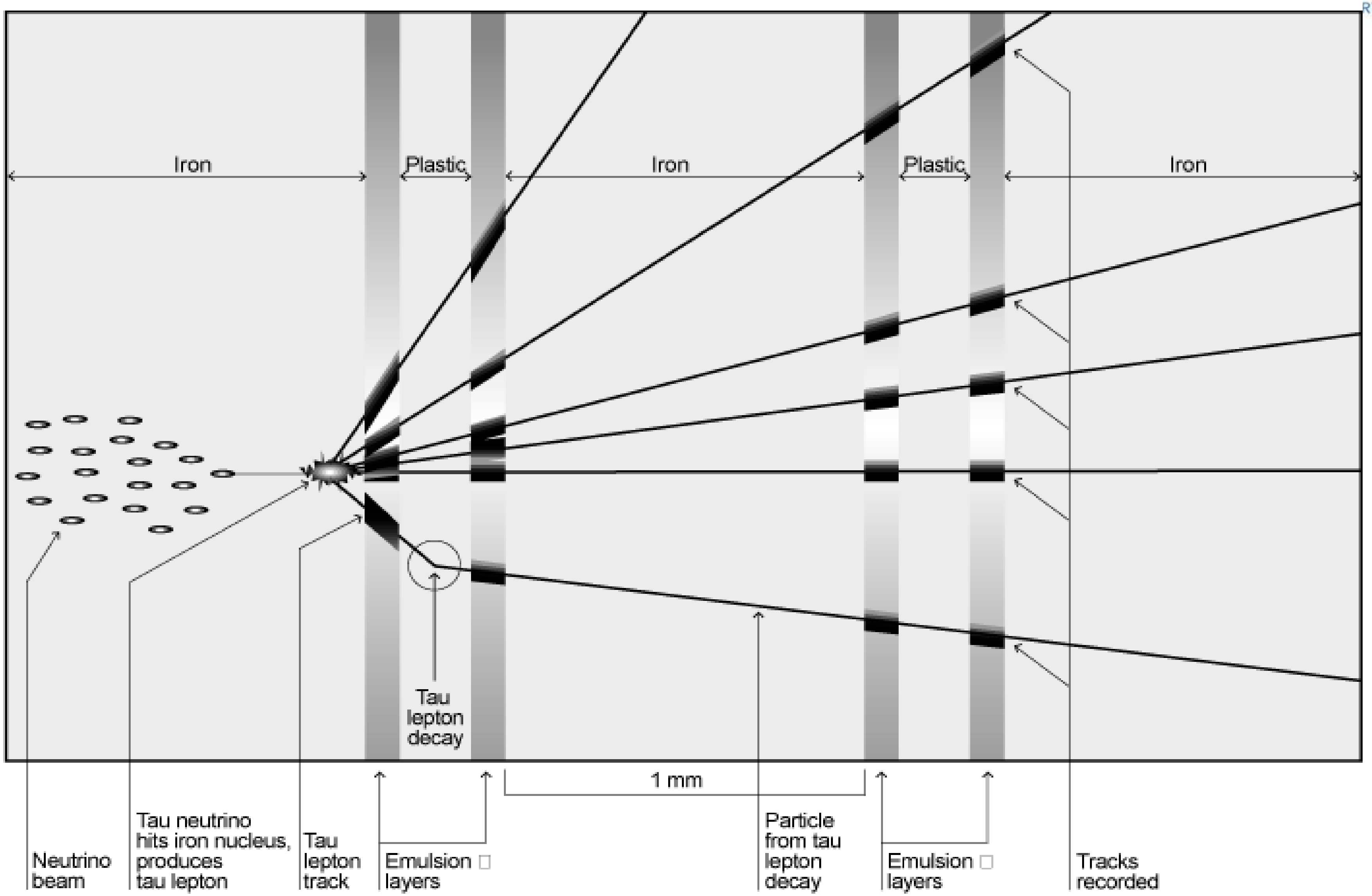
$$D_s \to \tau + \nu_\tau$$

$$\nu_\tau + N \to \tau + X$$

$$\tau \to \mu + \nu_\tau + \overline{\nu}_\mu$$



The Tau Neutrino



Of one million million tau neutrinos crossing the DONUT detector, scientists expect about one to interact with an iron nucleus.

Neutrino Properties

- Electrically neutral and interact only via the weak interaction.
- (Anti)neutrinos are chirally (right)left-handed.
- Exist in (at least) 3 active flavours
- Are almost massless
- Are the most common fermions in the universe

- Is a neutrino it's own anti-particle (Majorana particle)?
- Are there sterile neutrinos?
- What is the absolute neutrino mass?
- Is there CP violation in the neutrino sector?
- Does the neutrino have a magnetic moment?
- Are they stable?

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