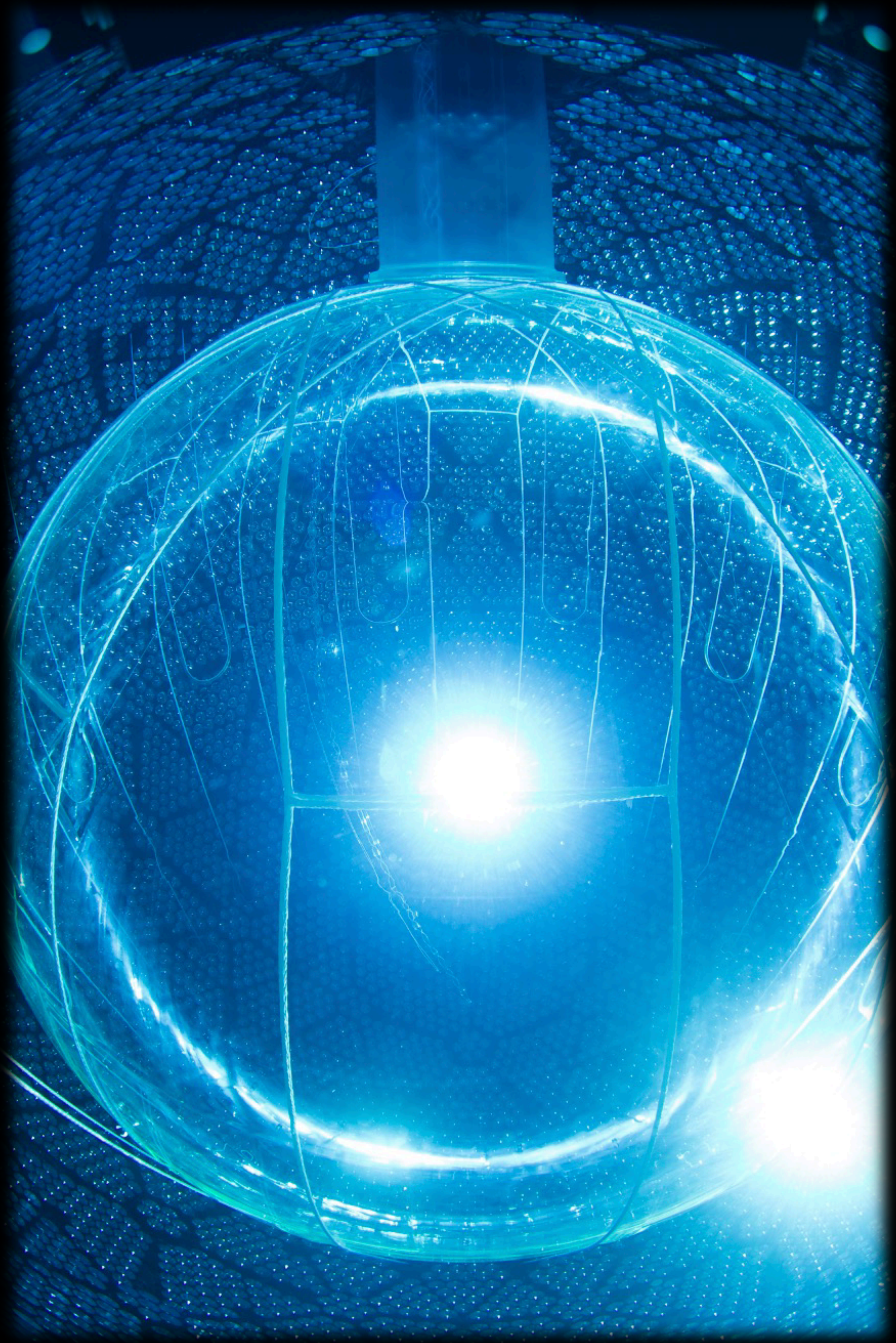


NEUTRINO SCIENCE 1

J. MANEIRA
LIP, LISBON, PORTUGAL

SUSI 2024
SNOLAB UNDERGROUND SCIENCE INSTITUTE
JULY 22 - AUGUST 2, 2024 SUDBURY, CANADA

PRESENTATION

- Research scientist at LIP - Laboratório de Instrumentação e Física Experimental de Partículas (www.lip.pt), Portugal. Adjunct professor at Univ. of Lisbon (2011-2019)
- Head and founder of the LIP Neutrino Physics group
- Research in Neutrino Physics since 1996, HEP 2004 - 2017
  - Borexino @ Gran Sasso, Italy (1996-2003)
  - SNO (since 2002)
  - SNO+ (since 2004)
  - ATLAS (2004-2017)
  - DUNE (since 2018)

MANY THANKS FOR THE INVITATION TO SUSI
IT'S GREAT TO BE HERE!

OVERALL PLAN OF THE 5 LECTURES

1. Neutrinos in the Standard Model.
2. Neutrino interactions, detectors. Solar and atmospheric neutrino problems.
3. Neutrino oscillations in 2 flavors. SNO and SK.
4. Neutrino oscillations in 3 flavors. Future experiments.
5. Theory and search for neutrino masses. Neutrinoless double-beta decay. Neutrinos in Cosmology and Astrophysics.

- Theory and experiment will be strongly mingled.
- Every lecture will have some of both.

PLAN FOR LECTURE 1

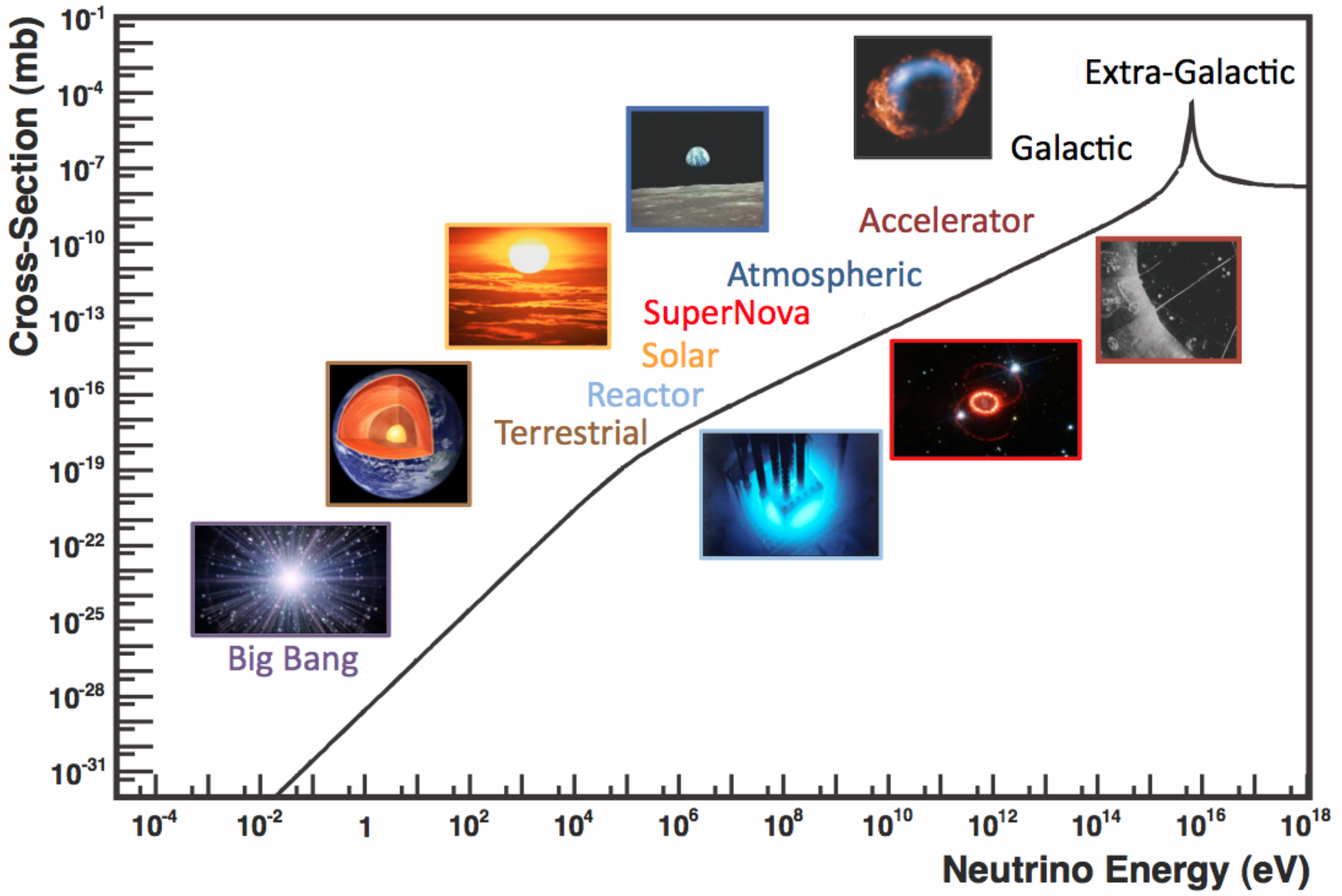
- Intro and basic properties
- Neutrinos in the Standard Model
  - The key experiments
    - Cowan/Reines, Davis, Wu, helicity
    - Steinberger, neutral currents
    - LEP Z decay, Donut
  - Recap of the SM, electroweak side
    - Parity, helicity, chirality
    - Massive bosons

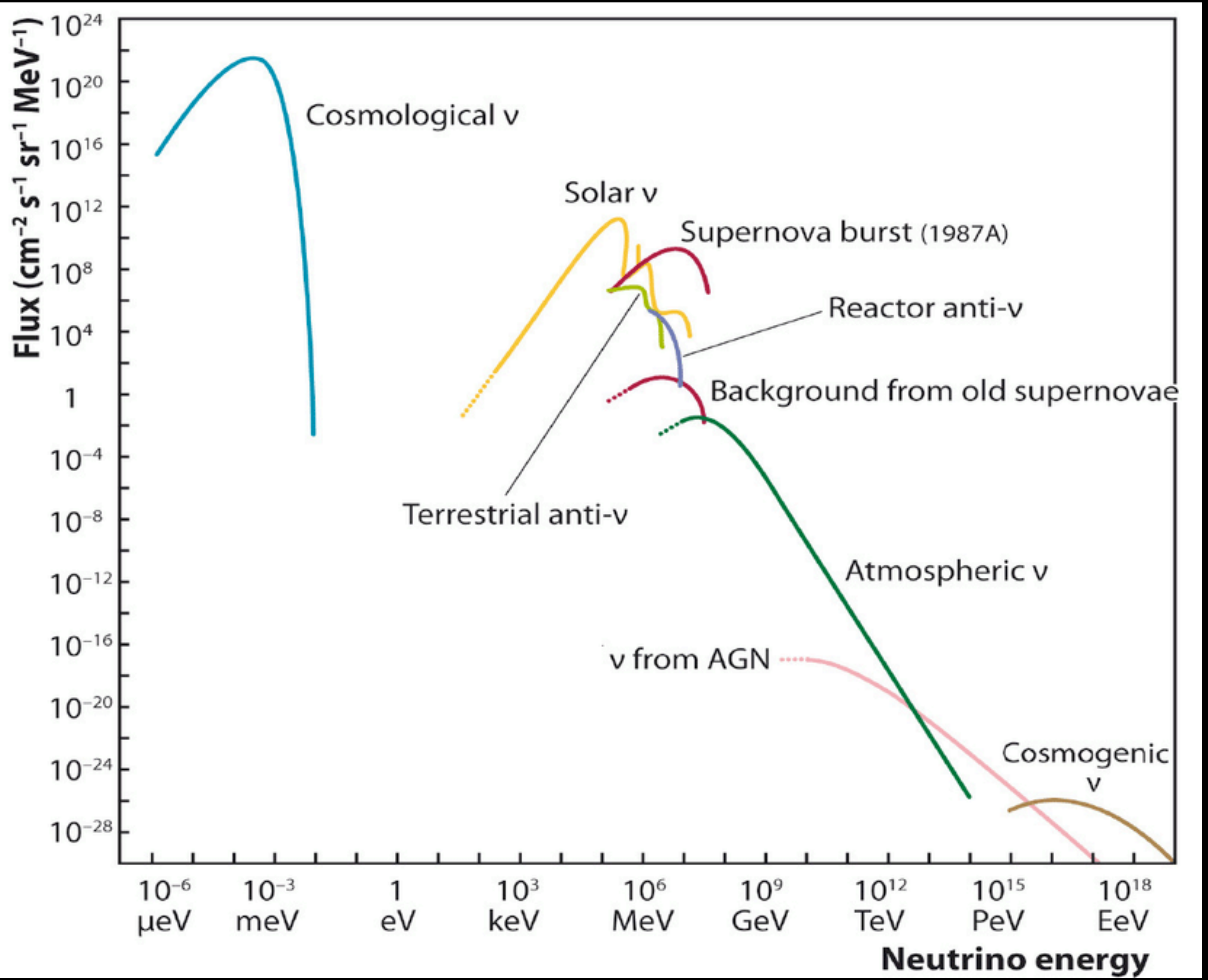
INTRODUCTION

NEUTRINO PROPERTIES

- Spin 1/2 → Fermions.
- Electrically neutral.
  - In fact, the only neutral fermions.
- “Strongly” neutral, like the other leptons.
- “Weakly” charged, interact via W, Z bosons.
  - Three active flavours. Full parity violation.
- “Gravitationally” charged (presumably).
  - Their “inertial” mass is small, gravitational effects are expected but no evidence yet.

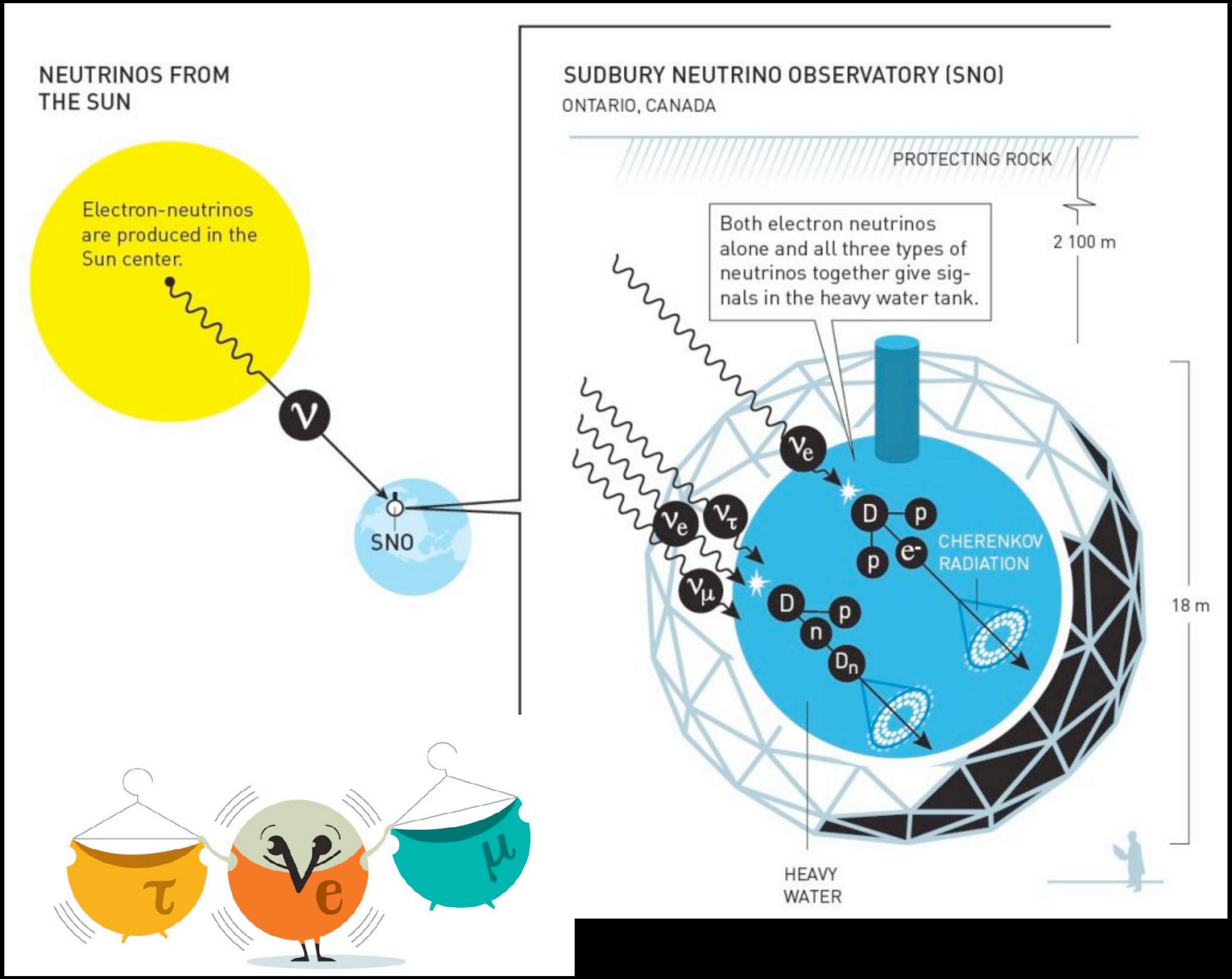
NEUTRINOS ARE EVERYWHERE



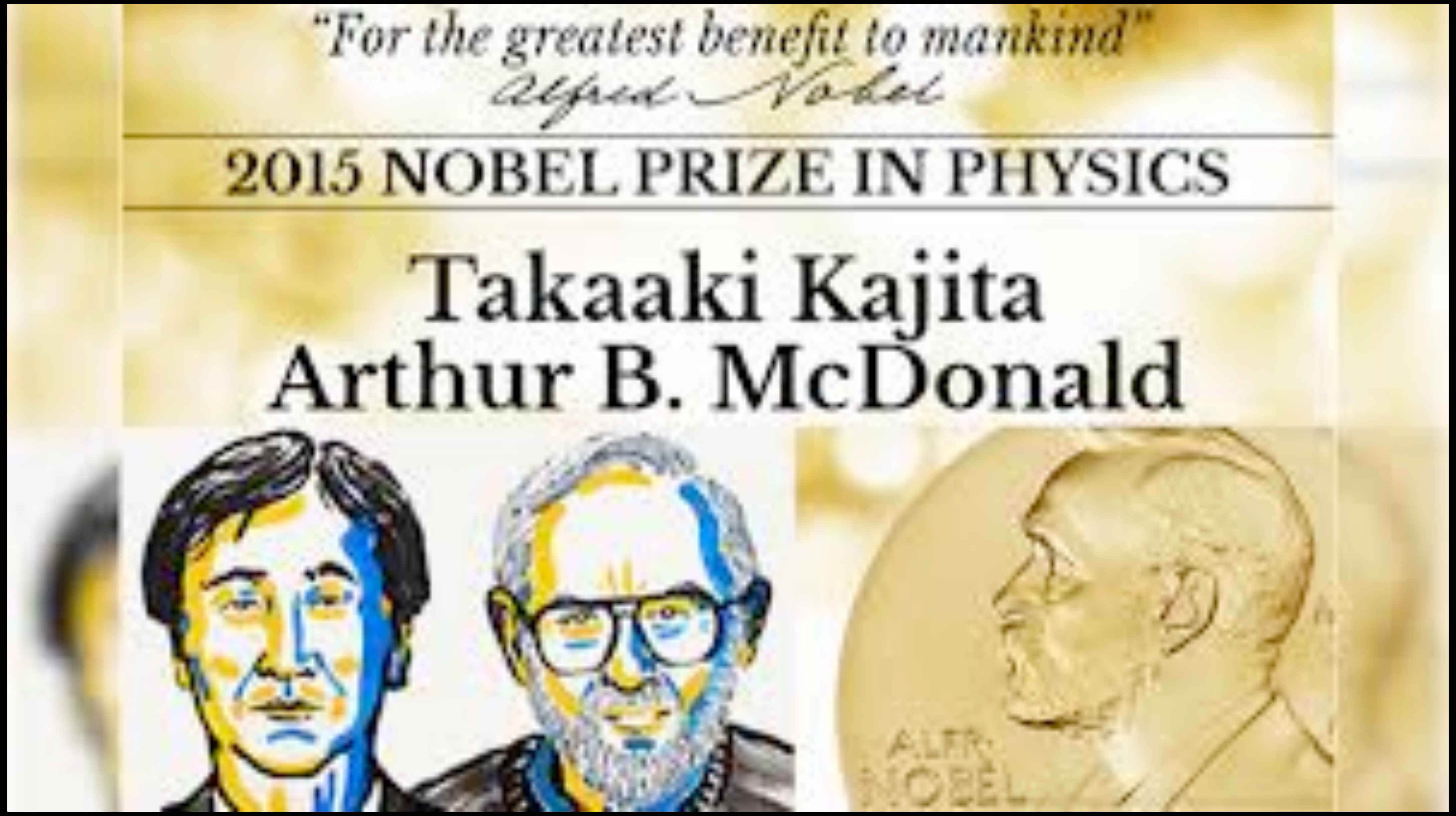


- Multiple natural and human-made sources. Second most abundant particle.
- Span over 20 orders of magnitude in energy and cross-section. Over 40 in flux!

BIG DISCOVERIES, RIGHT HERE

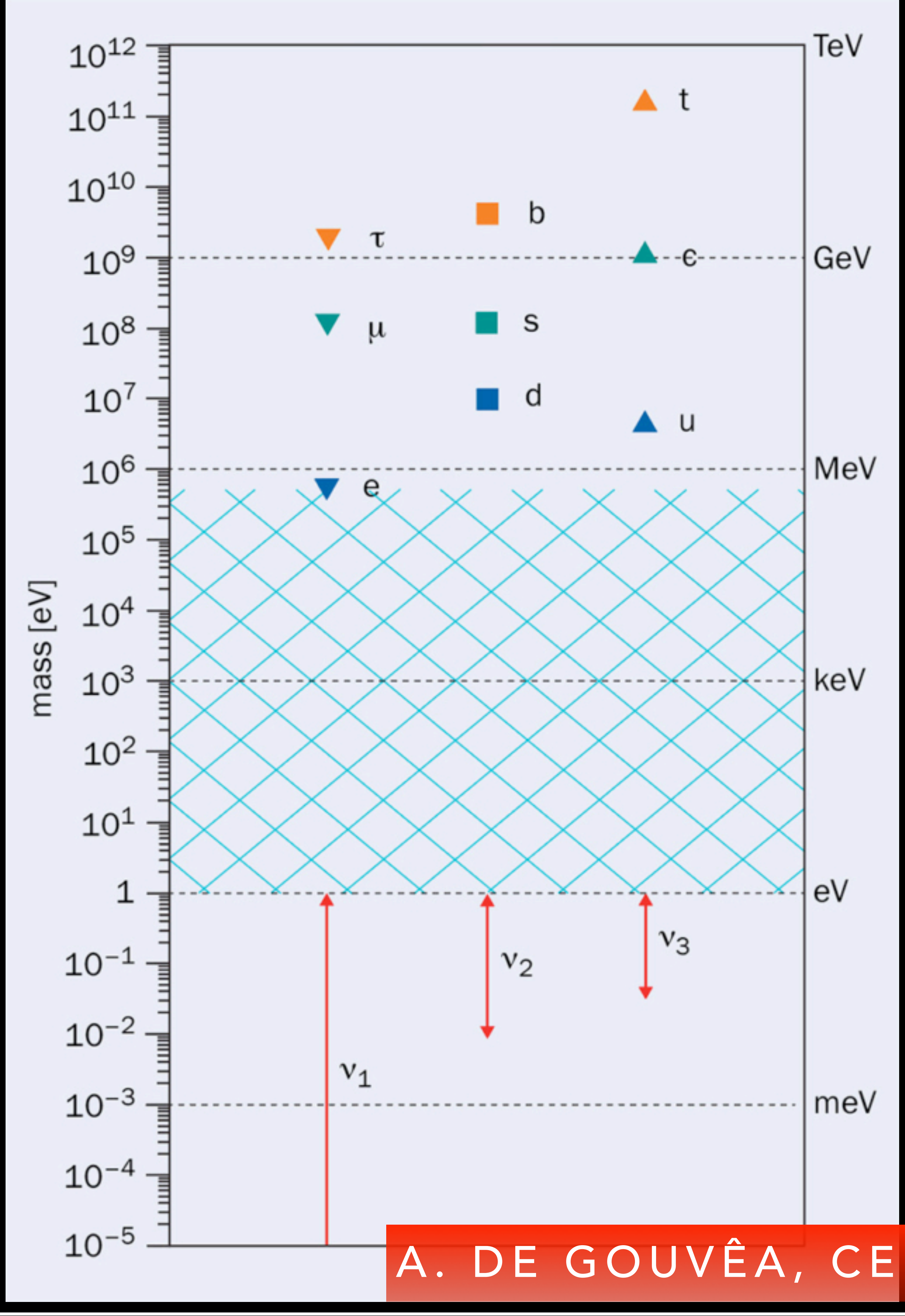


- Solving the puzzles of solar (SNO) and atmospheric (SuperK) neutrinos
- Neutrino oscilations, one of the two biggest discoveries in particle physics in the last decades!



NEUTRINO MASS, WHY SO TINY?

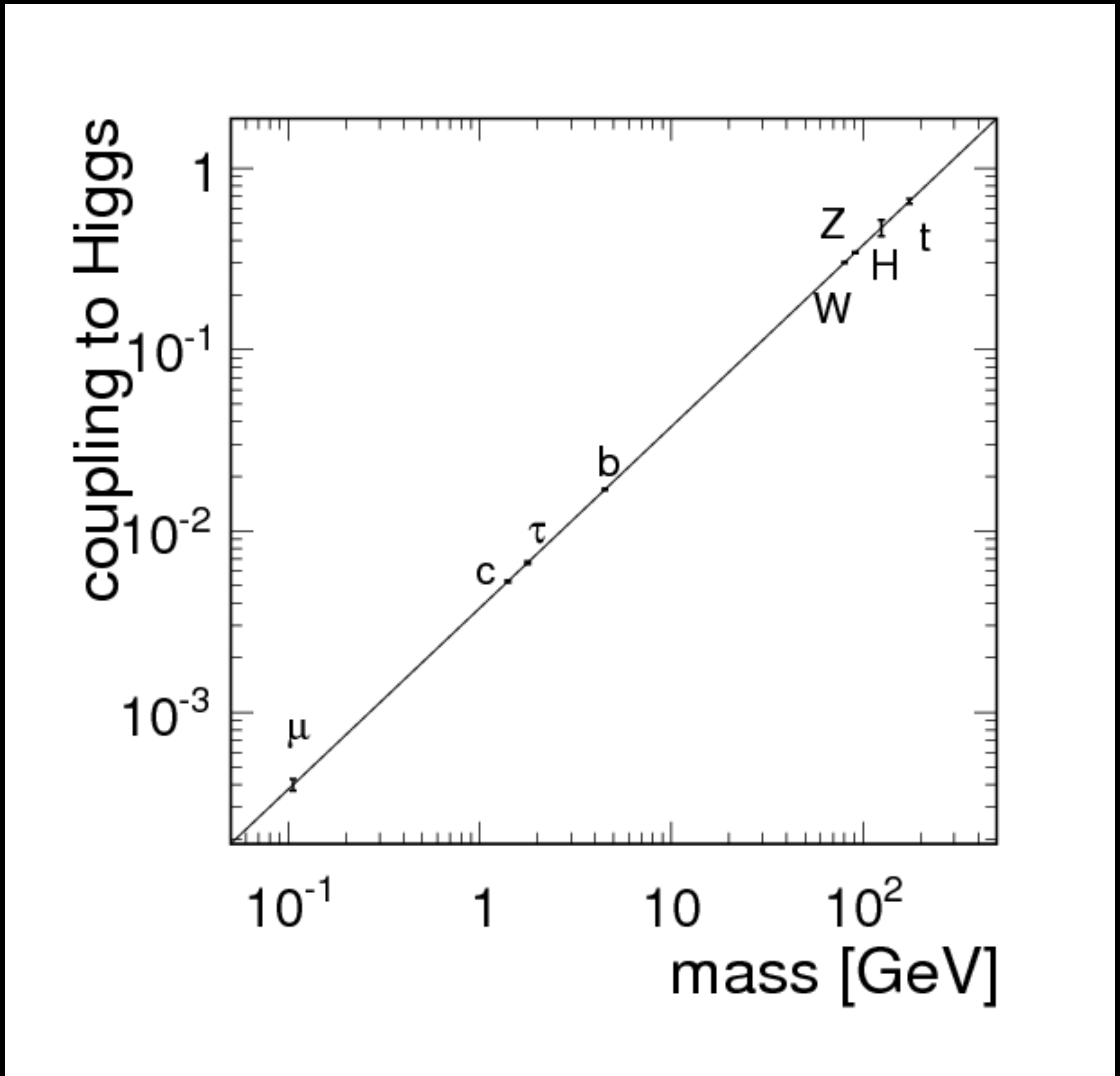
Fermion masses



Why this huge gap?

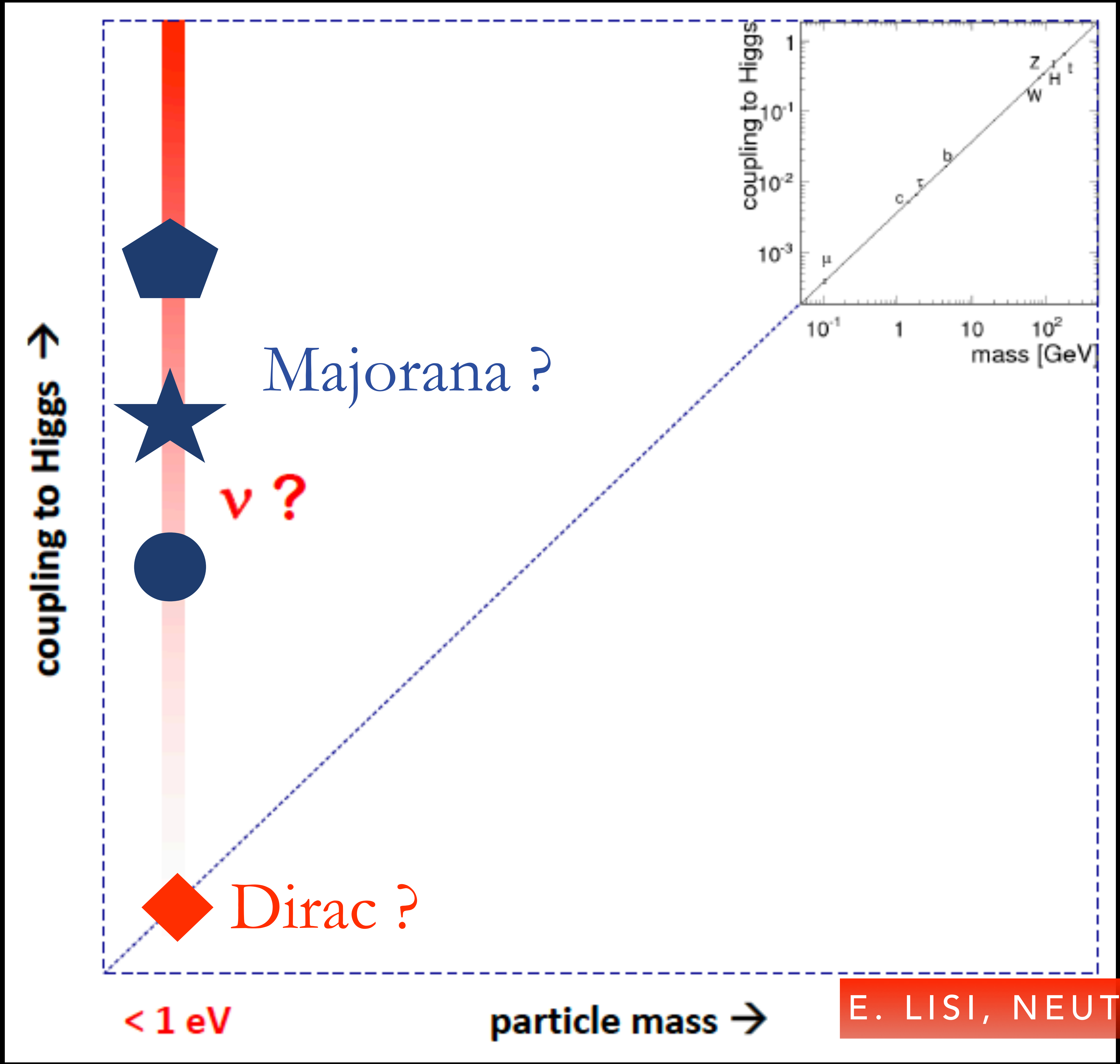
A. DE GOUVÊA, CERN COURIER

Mass directly related to Higgs interaction, confirmed > 100 MeV

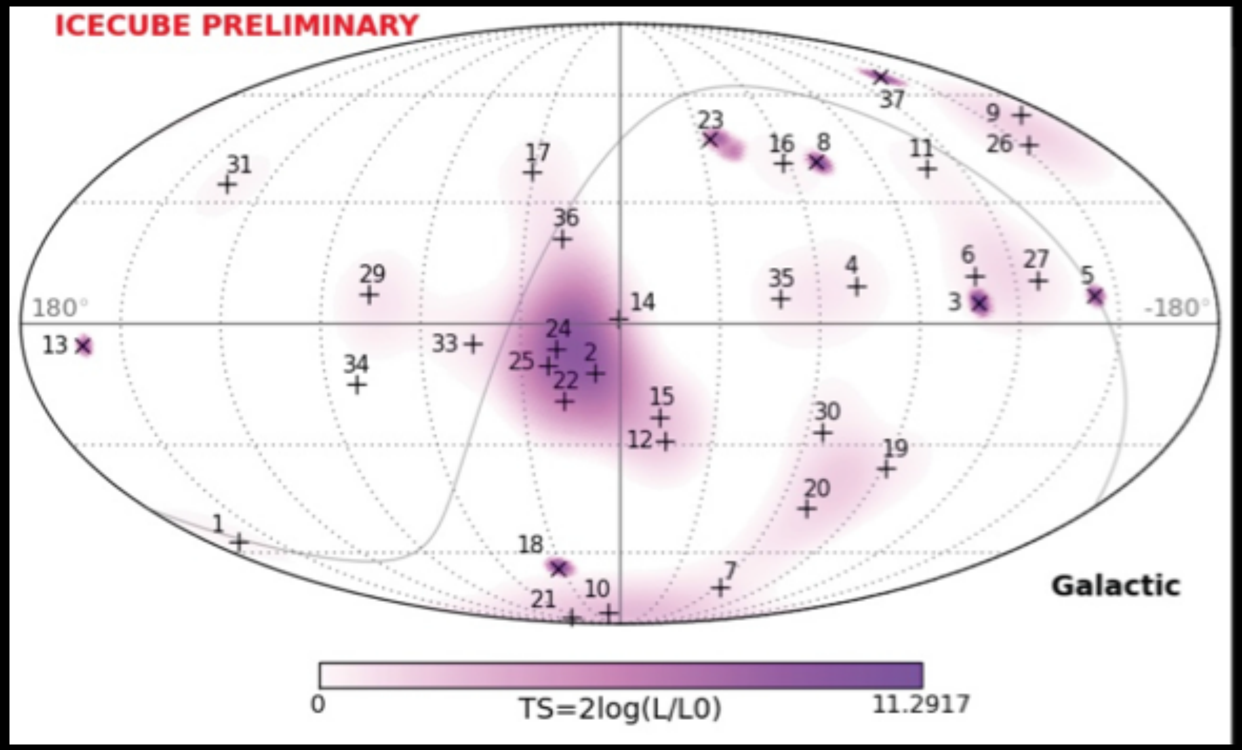


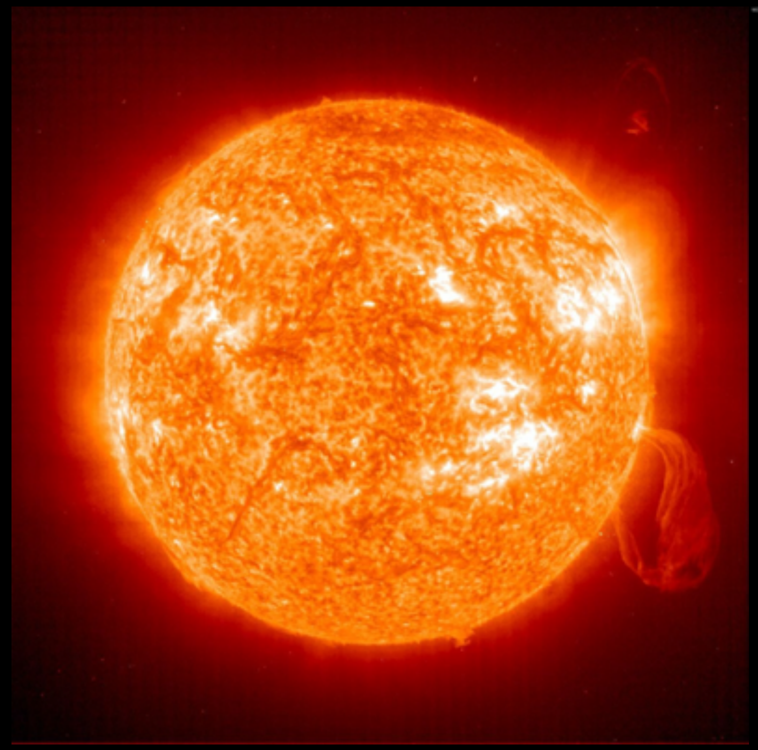
NEUTRINO MASS, WHY SO TINY?

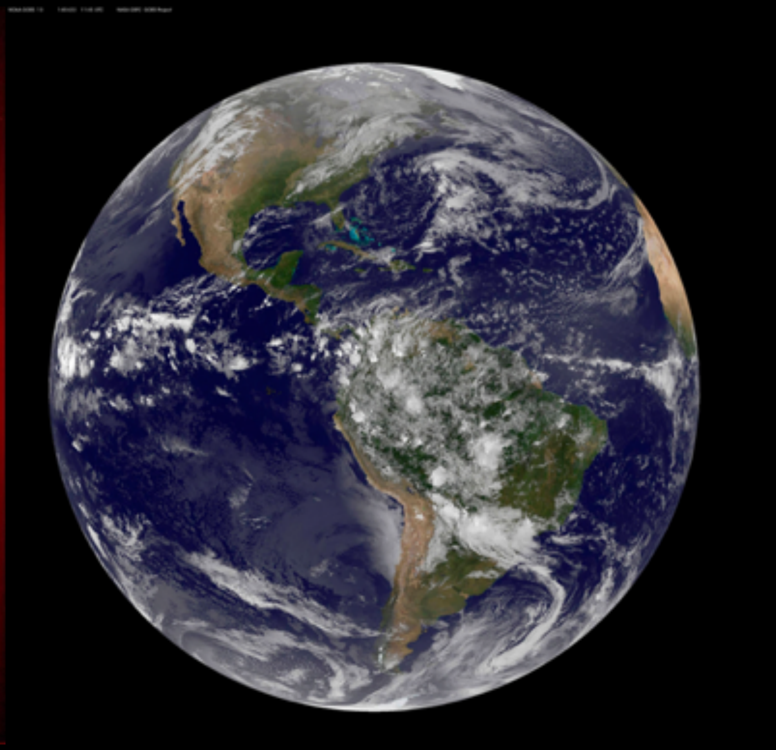
Do neutrinos couple to Higgs in the same way as charged fermions?



E. LISI, NEUTRINO 2024 (ADAPTED)



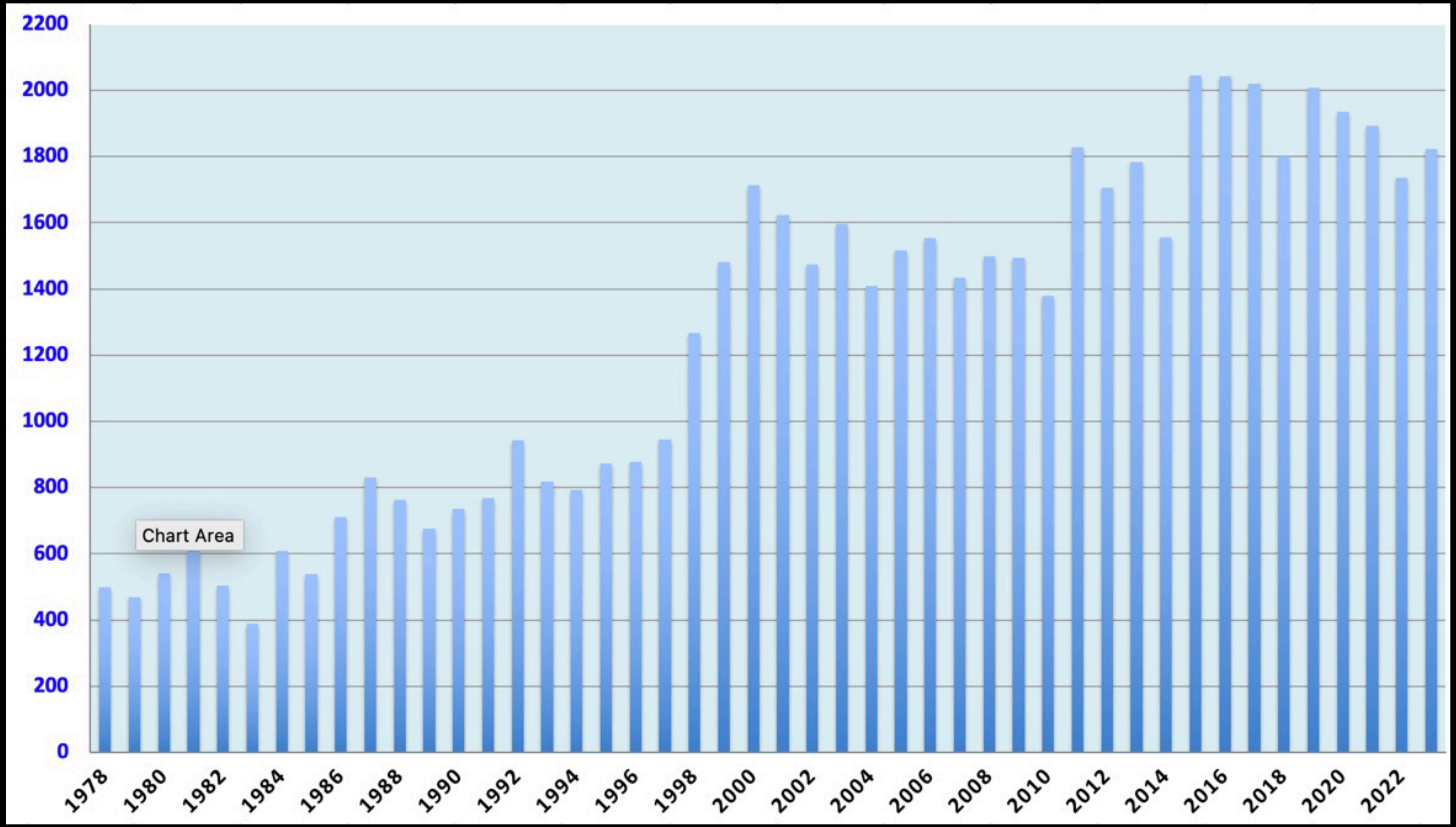




- Where do ultra-high energy cosmic rays come from?
- How do Supernovae explode?
- How does the Sun shine?
- How does the Earth heat?
- Is that nuclear reactor on?

NEUTRINO PHYSICS IS BOOMING

- Papers with the word "neutrino" in the title*

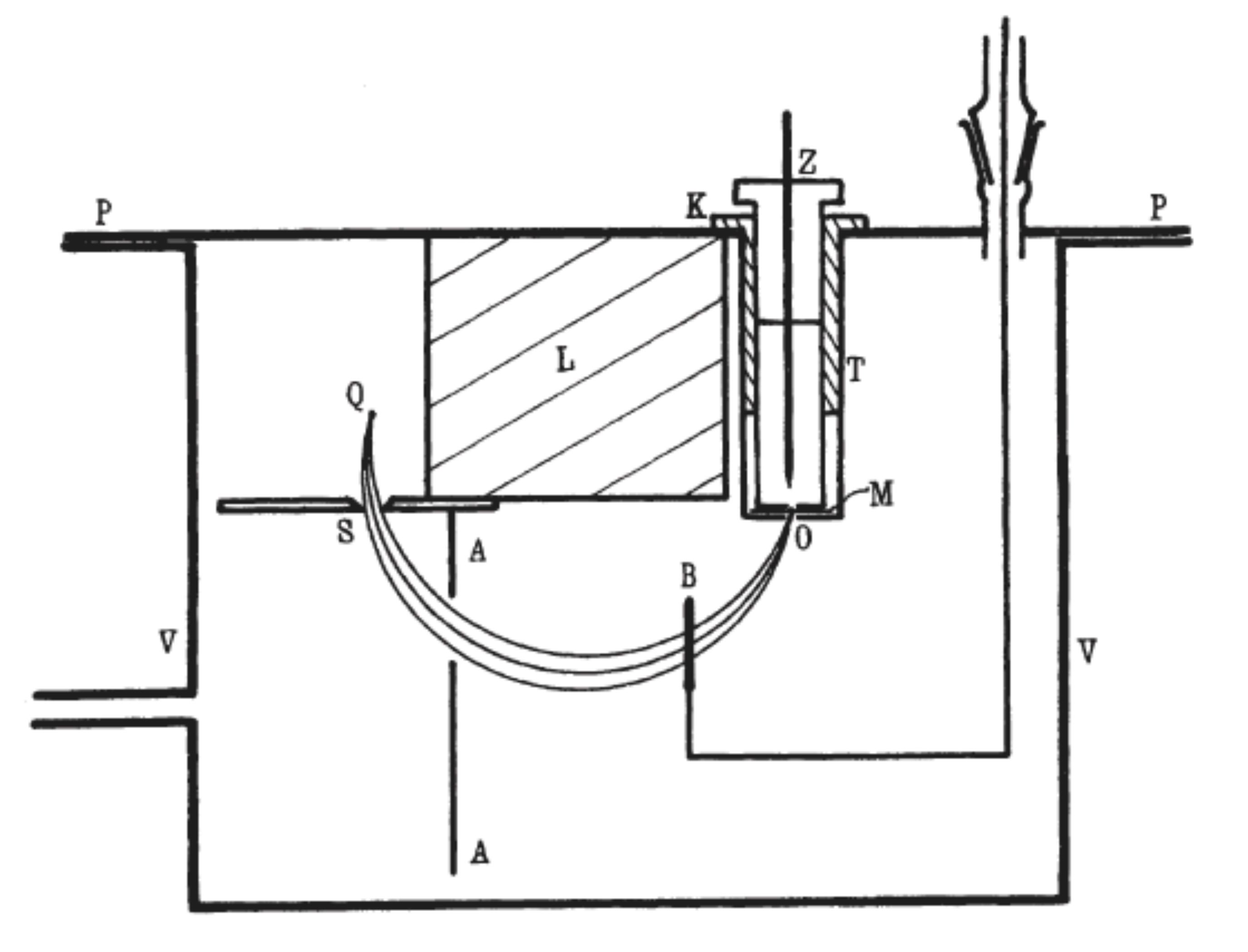


* surpassed "electron", "proton", "LHC"

THE KEY EXPERIMENTS

HIPOTHESIS AND DISCOVERY

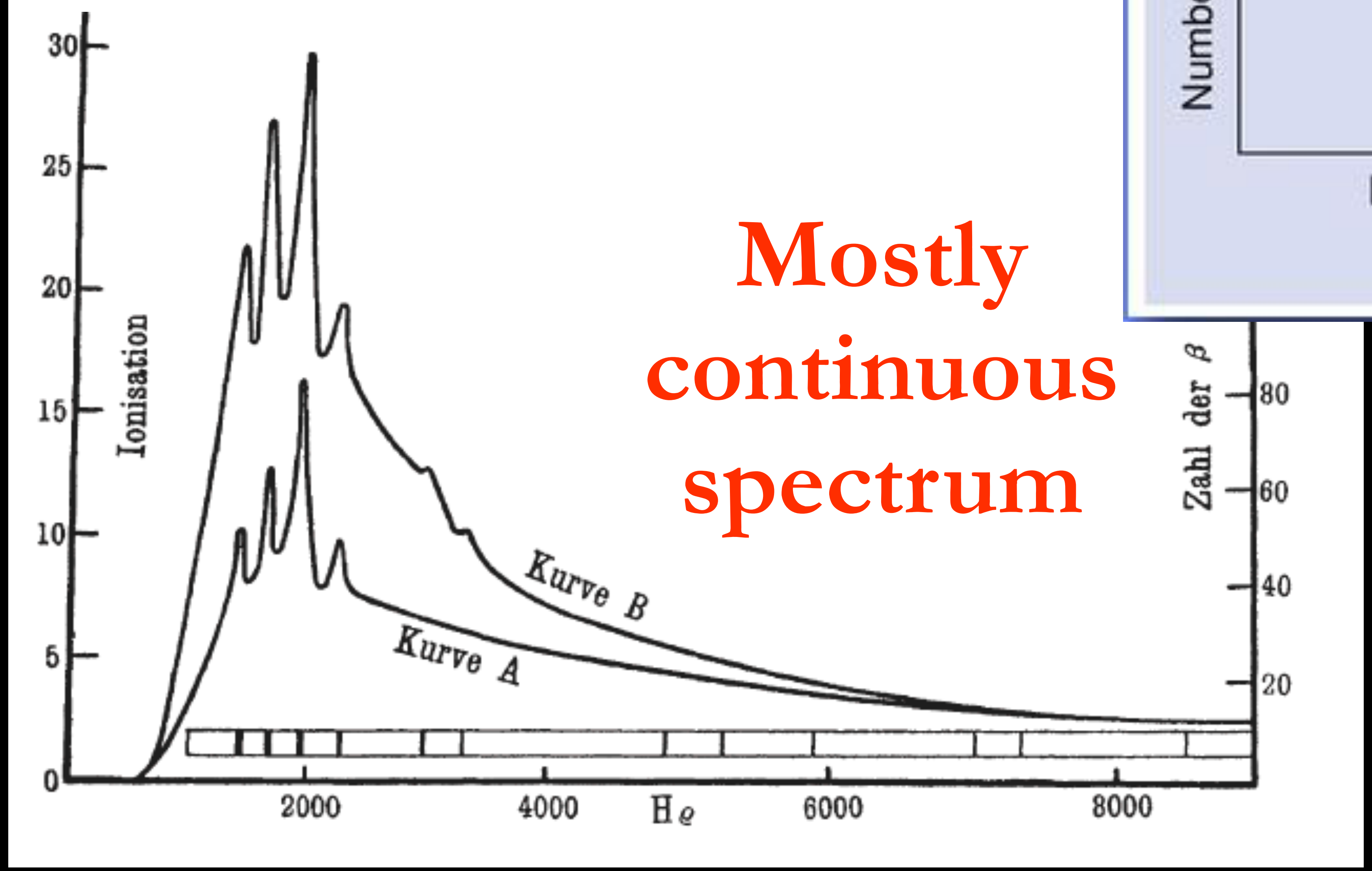
BETA DECAY MISTERY



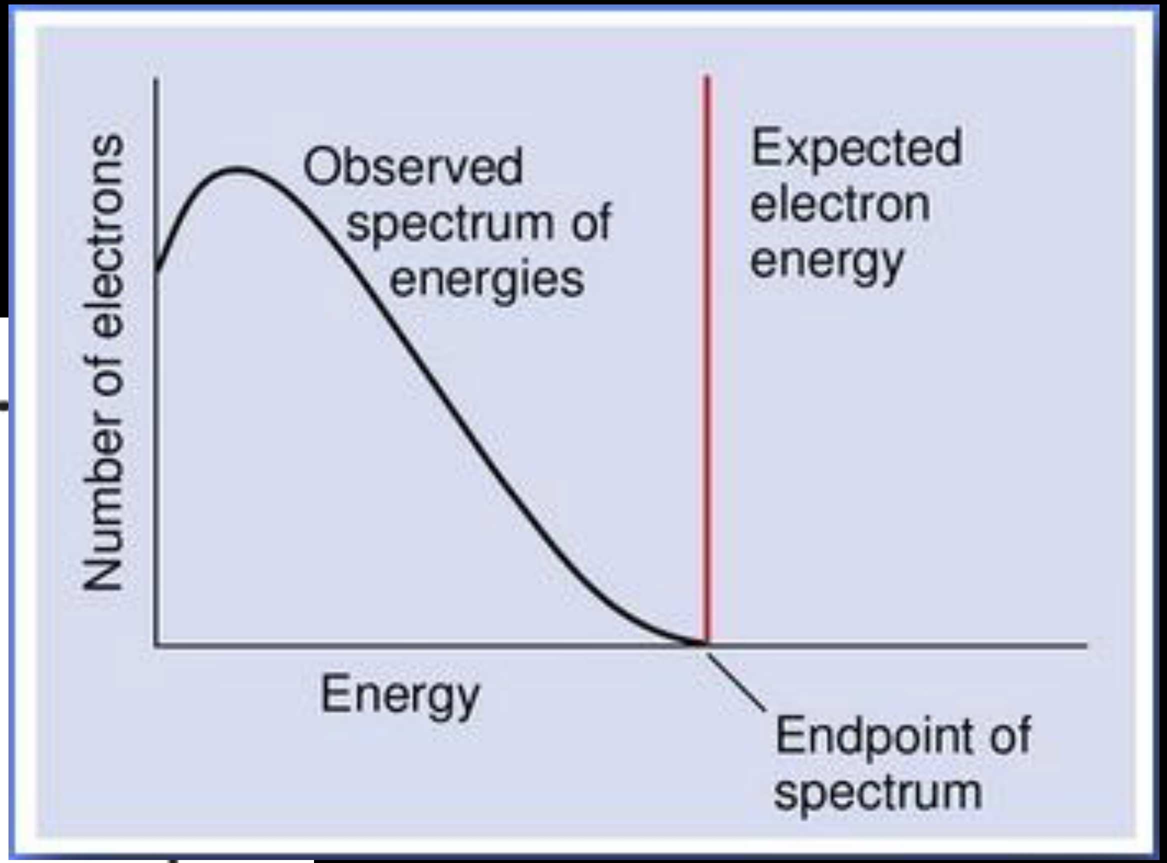
- Energy-momentum conservation for two-body decay leads to fixed lines, like in α and γ decays
- Key measurements by Chadwick in Berlin, 1914, using magnetic deflection and a Geiger counter.

James Chadwick [Nobel 1935, for neutron discovery]

Lines from internal conversion of gammas



Mostly continuous spectrum



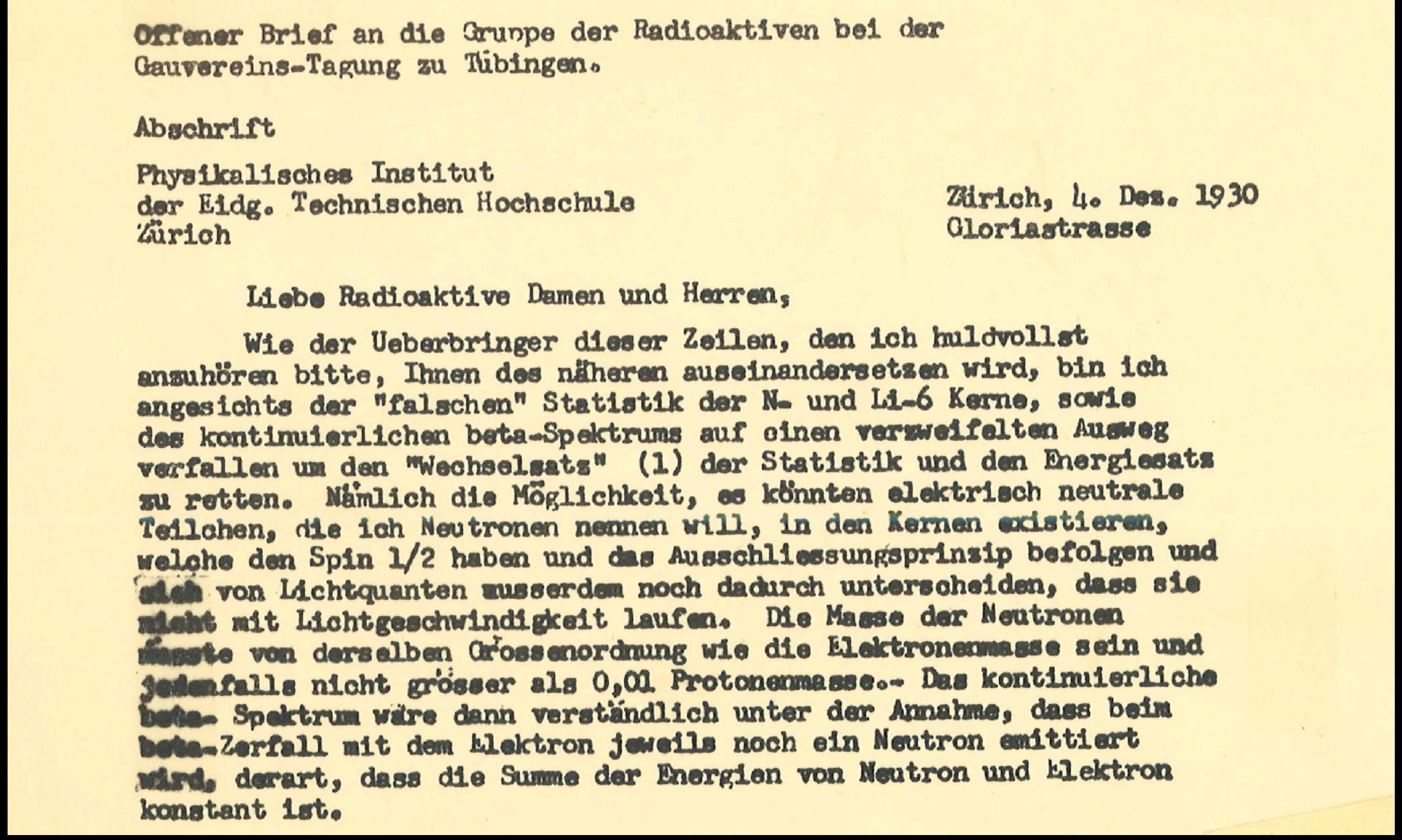
Letter to Rutherford, 1914: “There is probably some silly mistake somewhere.”

Niels Bohr: energy may not be conserved, or only on average

PAULI'S NEUTRINO HYPOTHESIS

- Dear Radioactive Ladies and Gentlemen

- 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…



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 Grossenordnung 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.

alpha decay

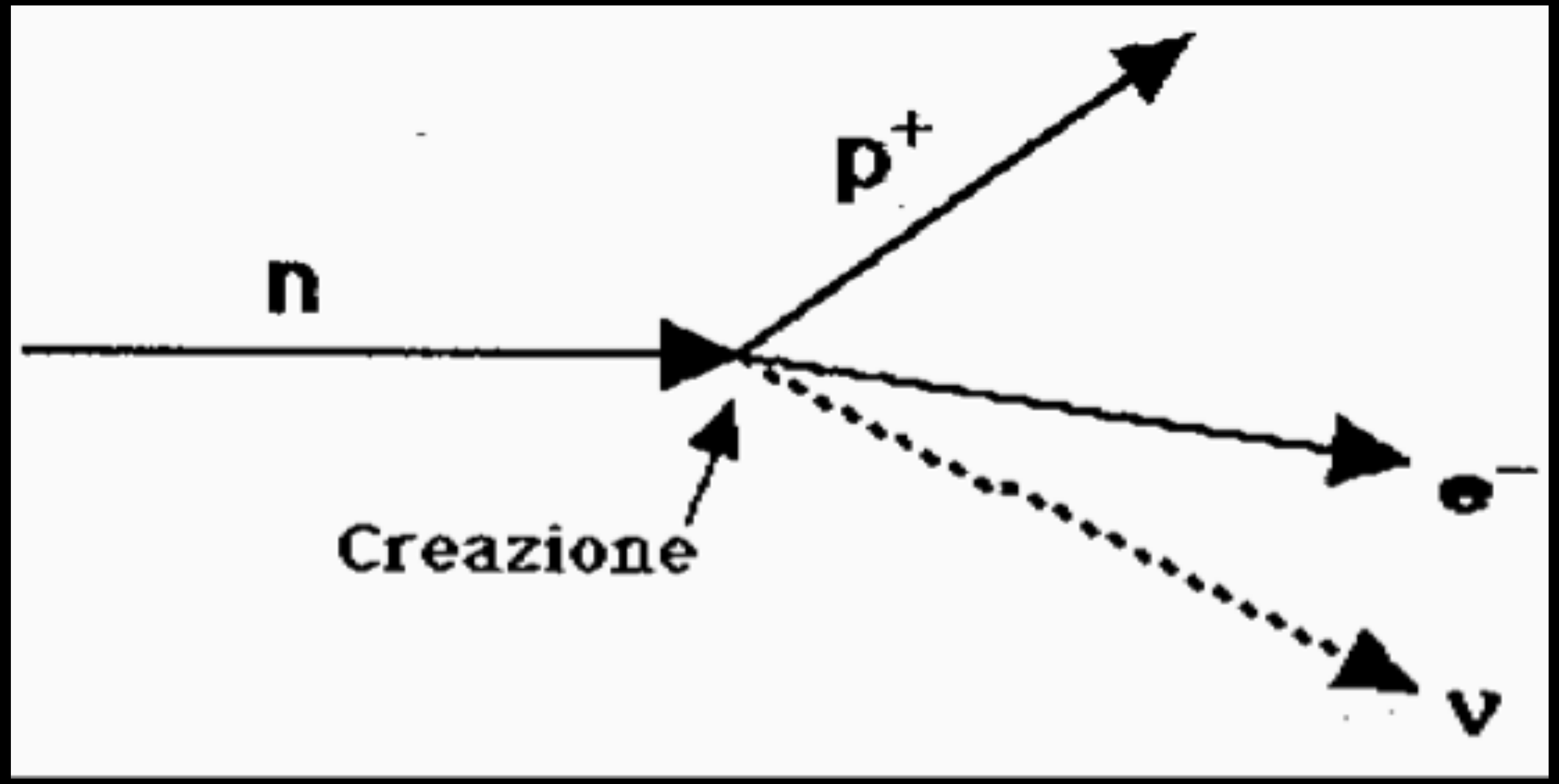
beta decay

- 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.

Wolfgang Pauli
[Nobel 1945, for the exclusion principle]

FERMI'S THEORY OF BETA DECAY

- Contact interaction between four fermions: n, p, e and ν
  - first inclusion of neutrino in a physics theory
  - neutron and proton as isospin states
  - spin considered for all, but not parity violation (yet)

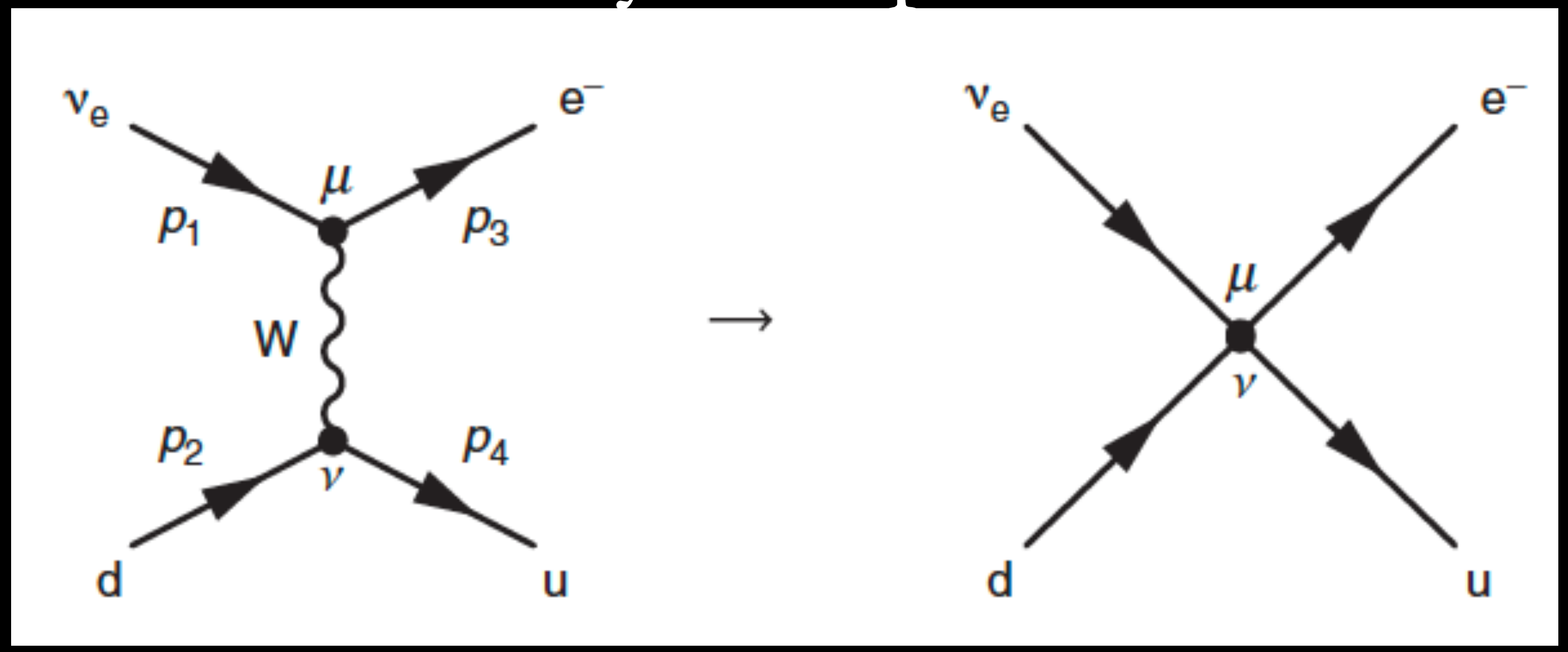


$$\mathcal{M}_{fi} = G_F\, g_{\mu\nu}[\overline{\psi}_3\gamma^\mu\psi_1][\overline{\psi}_4\gamma^\nu\psi_2],$$

- Intensity given by coupling "Fermi constant", determined from experimental decay rates
- Main problem: cross sections grow with energy "forever"

$$\sigma \approx G_F^2 E^2$$

  - This is a problem at high energies, solved later by the presence of the massive W and Z bosons



Enrico Fermi
[Nobel 1938, for induced radioactivity]

INDIRECT HINTS FOR NEUTRINOS

- Measurement of nuclear recoil T in electron capture decay

$$^{37}Ar + e^- \rightarrow ^{37}Cl + \nu_e$$

- Two-body final state, T_{Cl} well-defined (Q=816 keV, T_{Cl} = 9.67 eV):

$$T_{Cl} = \frac{E_\nu^2}{2m_{CL}} \approx \frac{Q^2}{2m_{CL}}$$

- Recoil experimentally measured, so there must be a second particle in final state
- Still, not *direct* evidence …

RODEBACK, ALLEN, PR 86, 446 (1952)

PONTECORVO IN CANADA

- How to actually be sure?
- "Direct proof of the existence of the neutrino […], must be based on [a process] produced by free neutrinos […]"
- He described the generic features of "Inverse β Processes", and suggested a specific one:

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

- giving details on radiochemical method (later used by Davis), backgrounds, cross sections, etc
- Assumed Sun and nuclear reactors as sources (no distinction between neutrinos and antineutrinos)

  - Chalk River, early connection of Canada to neutrino physics!

B. PONTECORVO, INVERSE BETA PROCESS, CHALK RIVER REPORT (1946)

Bruno Pontecorvo
[no Nobel]
life is very unfair!
more on him later…

- Are neutrinos and antineutrinos different ?
  - If so:
  - $\nu_e + ^{37}Cl \rightarrow ^{37}Ar + e^-$ and
  - $\bar{\nu}_e + ^{37}Cl \rightarrow ^{37}Ar + e^-$ are different reactions
  - Ray Davis used Pontecorvo's radiochemical method to search for ^{37}Ar production in a large tank of CCl_4 close to a nuclear reactor (emitting antineutrinos but not neutrinos).
  - No excess over background was observed. Upper limit on antinu cross section.
  - Conclusion: (if they exist…) **Antineutrinos ≠ Neutrinos !**

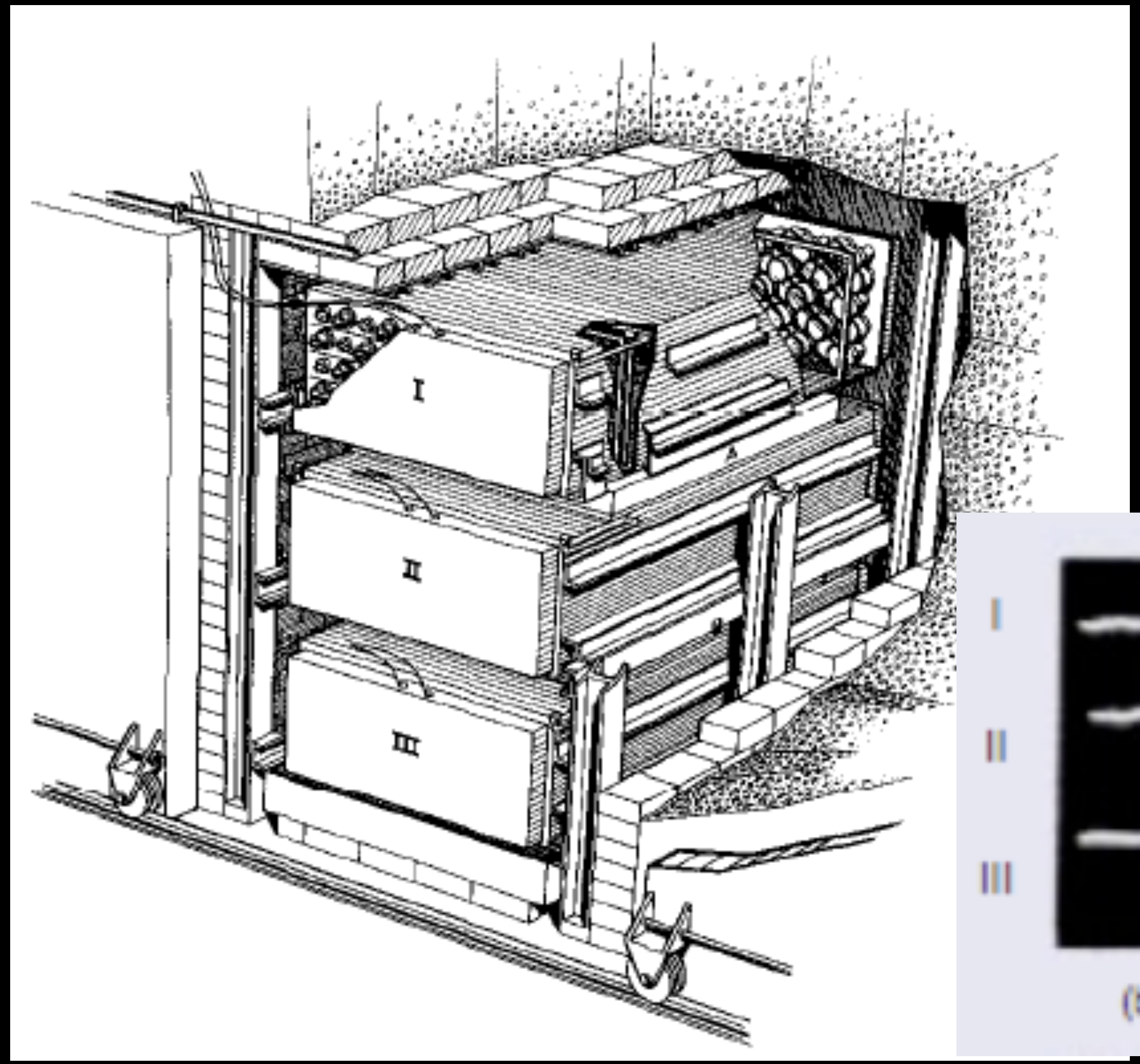
Ray Davis Jr
[Nobel 2002]
solar neutrinos
more on him later

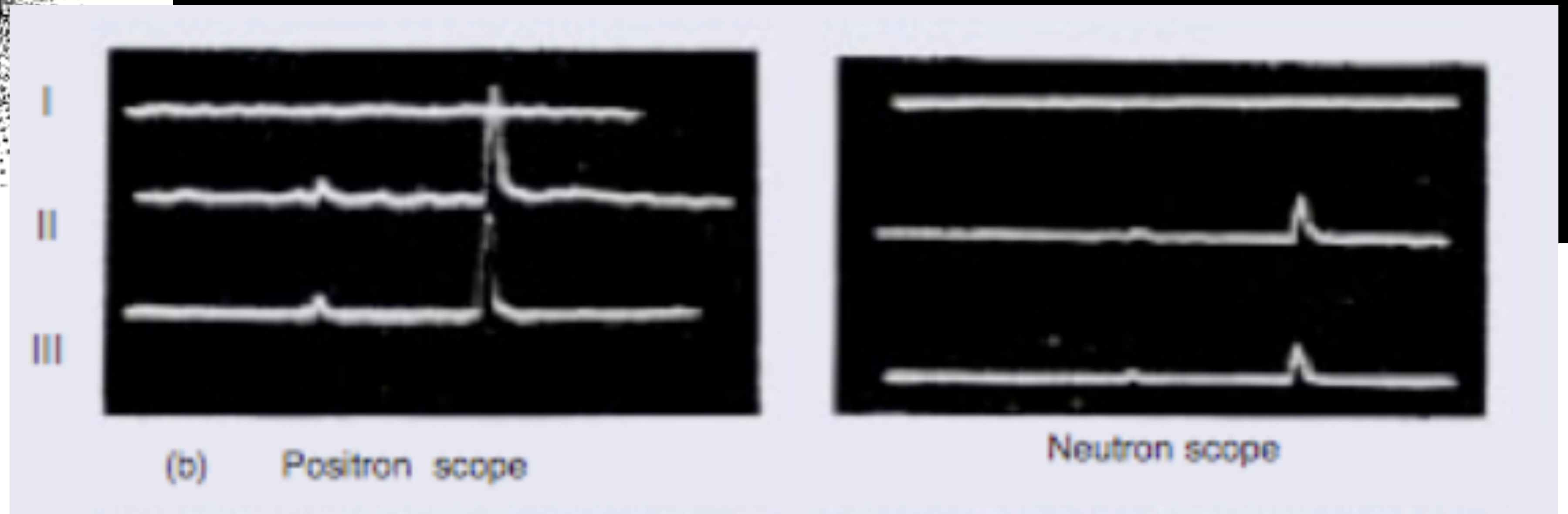
R. DAVIS JR., PR 97, 3, 746 (1955)

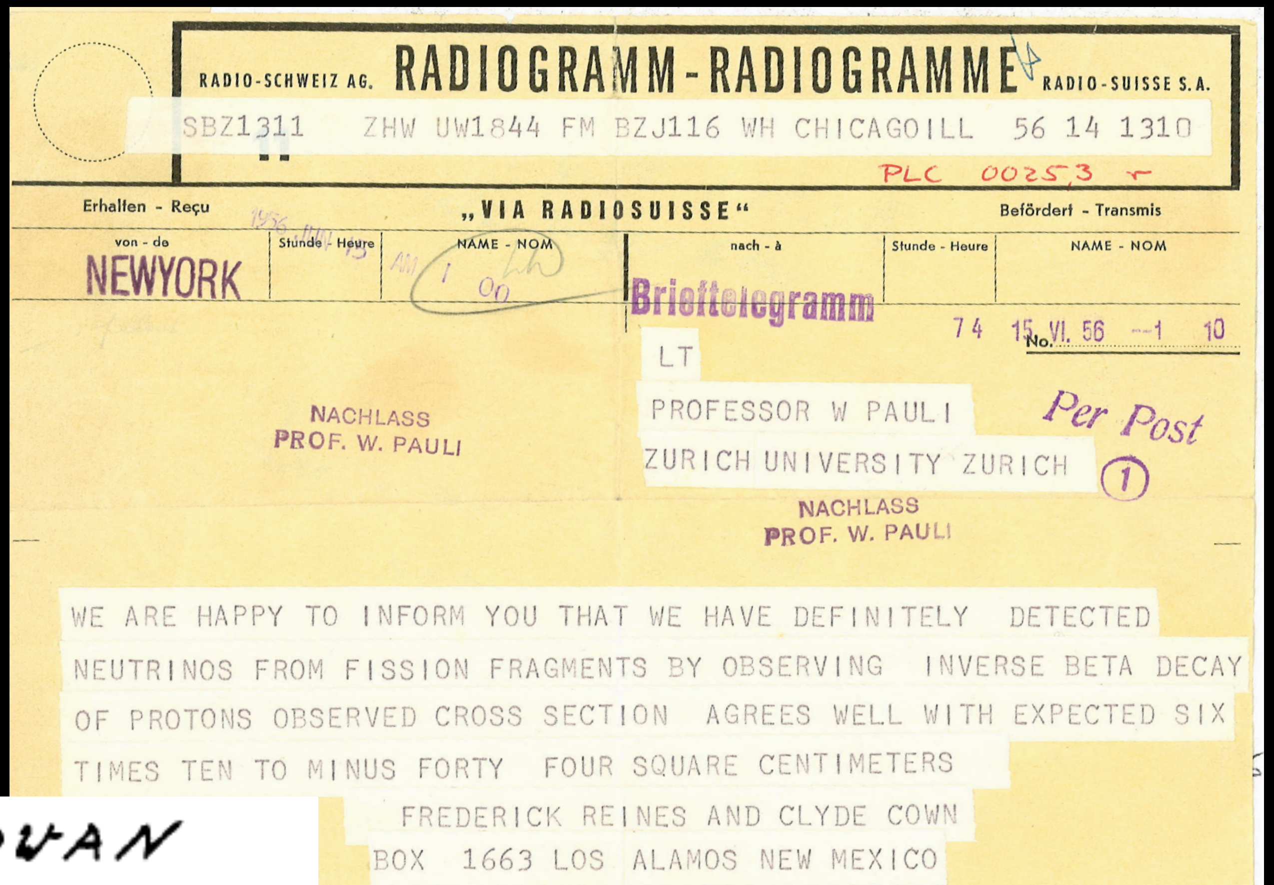
DISCOVERY OF THE NEUTRINO

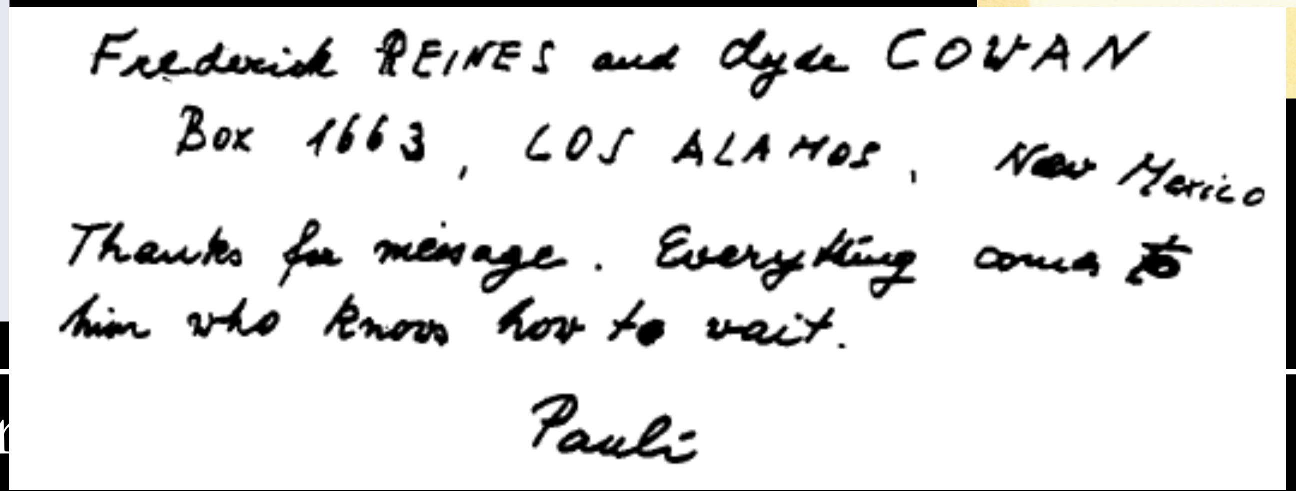
Fred Reines [Nobel 1995] & Clyde Cowan

- Inverse beta decay process $\bar{\nu}_e + p \rightarrow n + e^+$
  - sensitive to antineutrinos from reactors
  - delayed time coincidence between positron and neutron allows background suppression
- Detector:
  - Target: water (provides many free protons) loaded with Gadolinium (captures neutrons)
  - Surrounded by liquid scintillator modules observed by PMTS
- Cosmic ray shielding
  - @Hanford: none (too much background)
  - @Savannah River: 12 m was enough…






RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.
SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310
„VIA RADIOSUISSE"
NEWYORK
Brieftelegramm
LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
NACHLASS PROF. W. PAULI
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


Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli

HANFORD REACTOR, WASHINGTON STATE
(PRODUCED PLUTONIUM FOR MANHATTAN PROJECT)

SAVANNAH RIVER REACTOR, SOUTH CAROLINA (SITE ALLOWED 12 M SHIELDING)

PARITY AND HELICITY

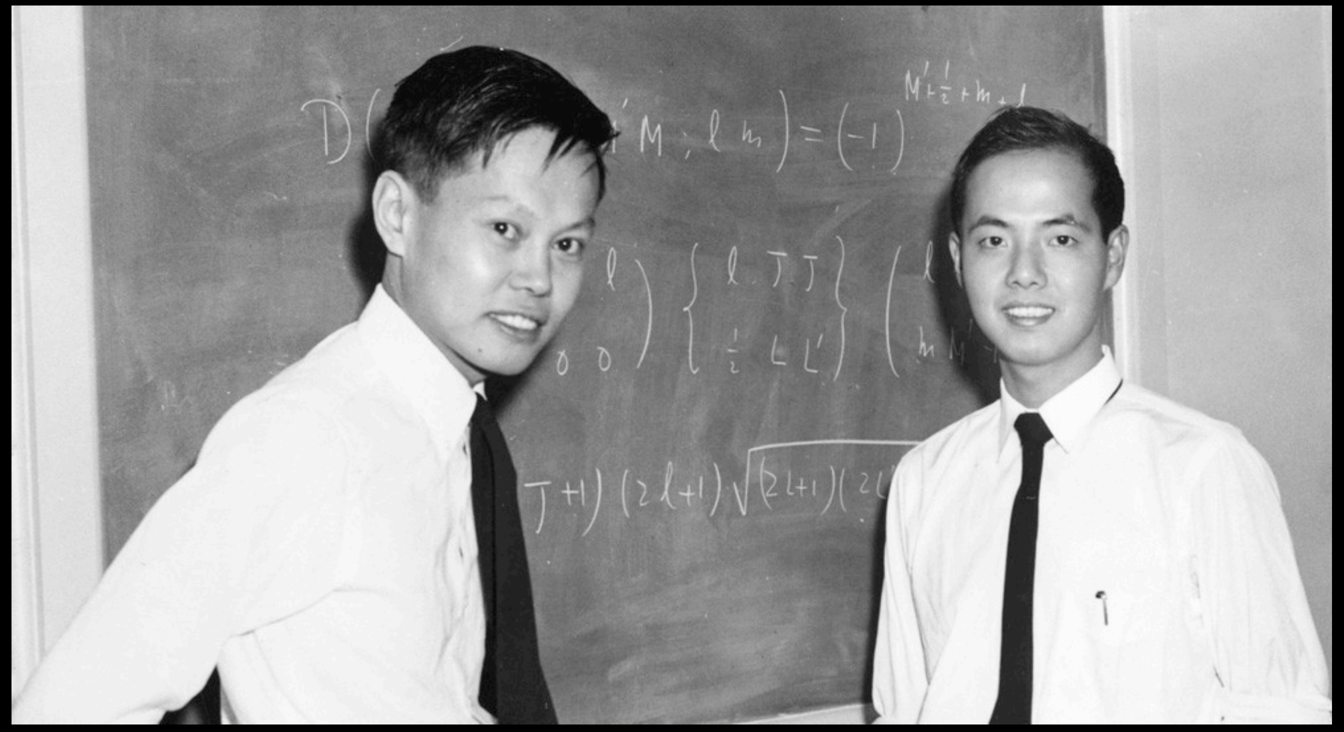
PARITY VIOLATION IN WEAK DECAYS

- Electromagnetic and strong interactions are invariant with respect to **parity, i.e., the inversion of spatial coordinates**
- Are weak interactions invariant too, or not ?
- Lee and Yang proposed a test based on comparing rates of parity-reversed configurations of beta decays
  - Vectors change sign (e.g. position, momentum)

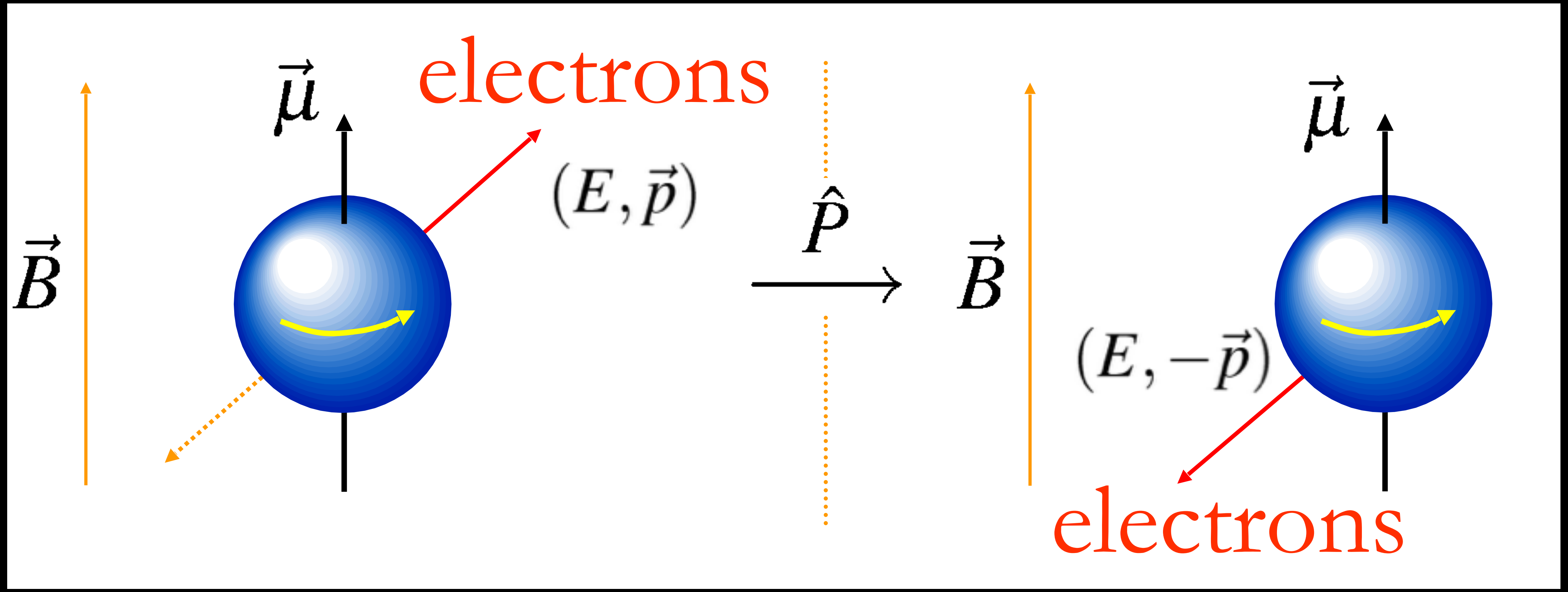
$$\vec{r} \xrightarrow{\hat{P}} -\vec{r} \qquad \vec{p} \xrightarrow{\hat{P}} -\vec{p} \qquad (p_x = \frac{\partial}{\partial x}, \, etc.)$$

  - Axial vectors remain unchanged (e.g., angular momentum)

$$\vec{L} \xrightarrow{\hat{P}} \vec{L} \qquad (\vec{L} = \vec{r} \wedge \vec{p}) \qquad \vec{\mu} \xrightarrow{\hat{P}} \vec{\mu} \qquad (\vec{\mu} \propto \vec{L})$$

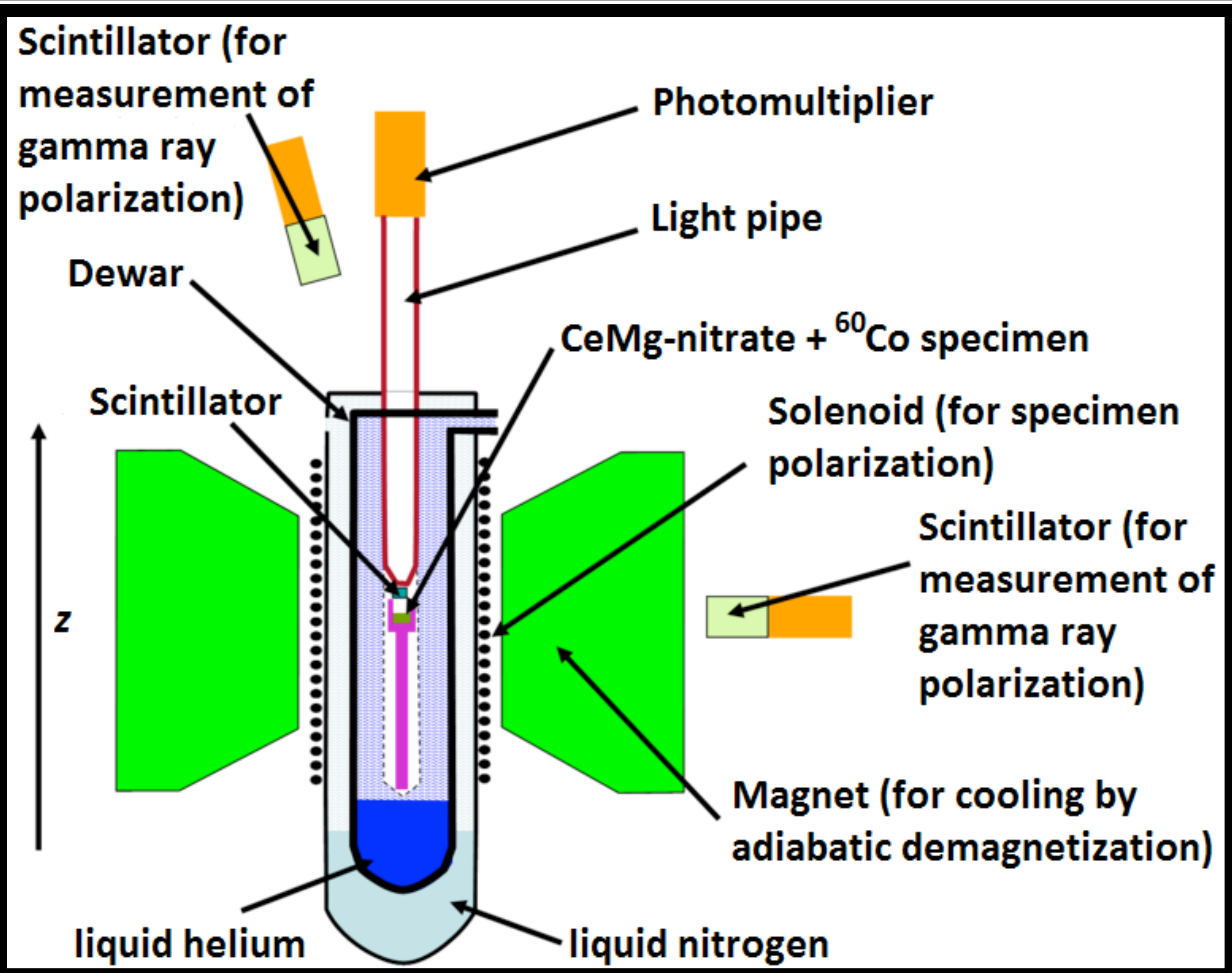


C. Yang, T. Lee
[Nobel 1957]



If parity is conserved in weak decays, rate should be the same for electrons in the same direction and opposite the nuclear spin (magnetic field)

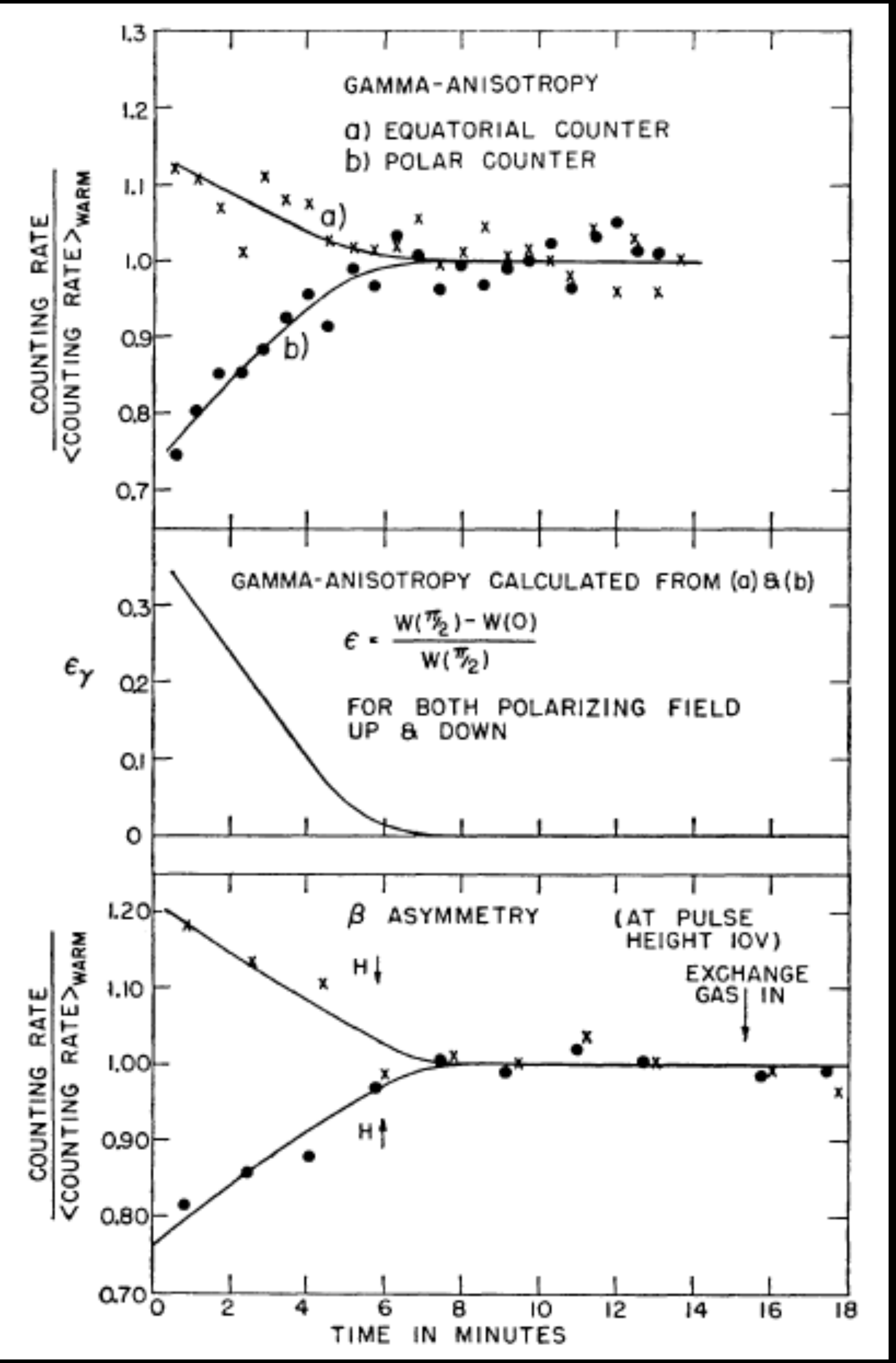
WU EXPERIMENT



C. Wu
[no Nobel]
unfair!

$$^{60}Co \rightarrow ^{60}Ni^* + \bar{\nu}_e + e^-$$
$$\rightarrow ^{60}Ni + \gamma + \gamma$$

- Cobalt **nuclei spin aligned** with strong magnetic fields
  - Cryo-cooled to keep it so
  - Checked by measuring asymmetric gamma distribution
- Measured beta decay asymmetry
  - correlated to gamma asymmetry
  - changes sign according to B field polarity



HELICITY OF THE NEUTRINO

- Helicity = projection of spin on momentum
- Observe electron capture decay of a spin 0 nucleus

$$H = \frac{\vec{\sigma}\cdot\vec{p}}{|\vec{\sigma}|\cdot|\vec{p}|}$$

$$^{152m}Eu + e^- \to {}^{152}Sm^* + \nu_e \to {}^{152}Sm + \gamma + \nu_e$$

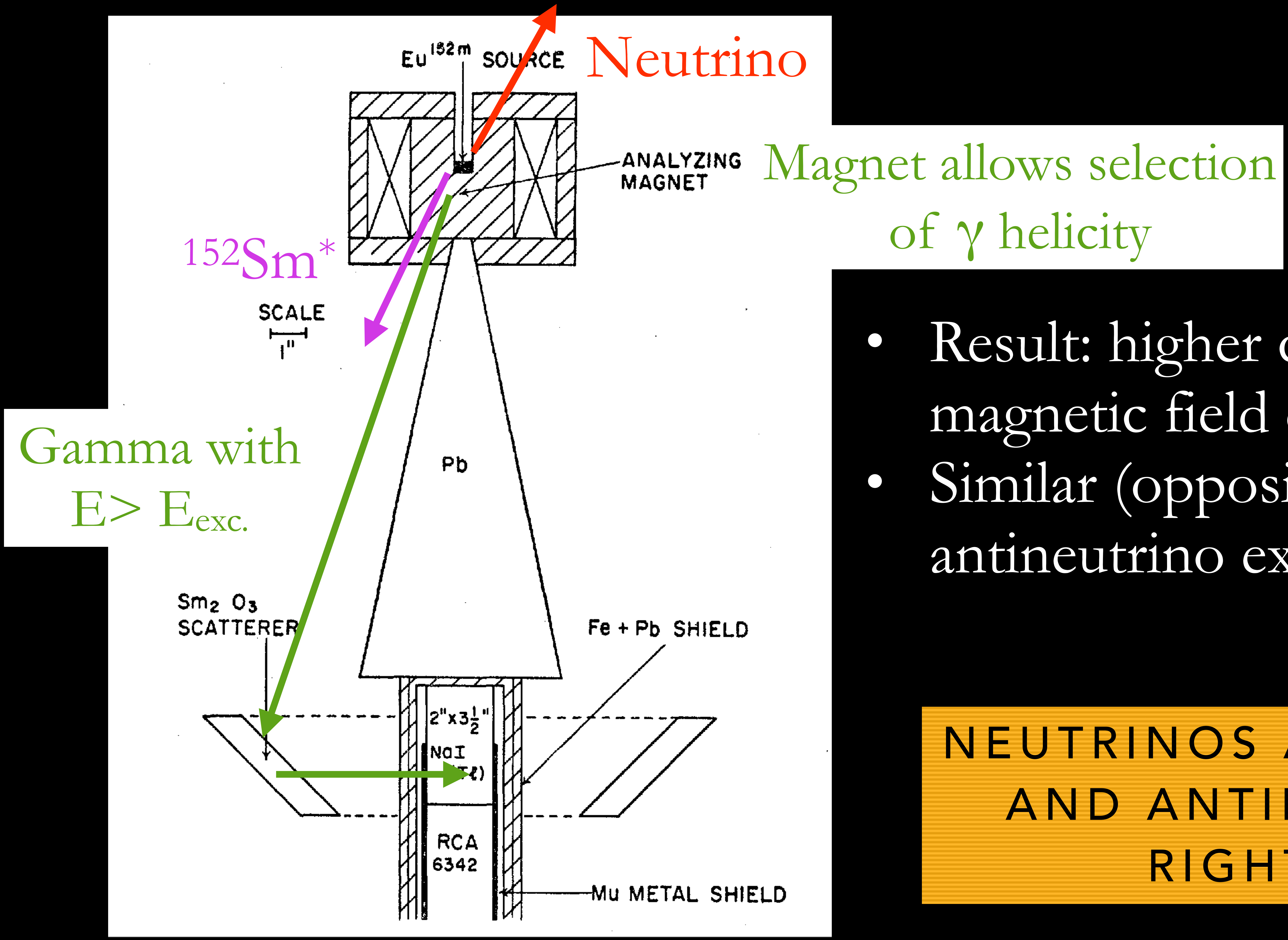
	^{152m}Eu	e^-	$^{152}Sm^*$	ν_e	^{152}Sm	γ	ν_e
Momentum	0		↓	↑	↓	?	↑
Spin	0	½	1	- ½	0	1	- ½
	0	- ½	-1	½	0	-1	½

$H(\nu) = H(^{152}Sm^*)$

Are both these spin states possible?

- Photon direction: if aligned with $^{152}Sm^*$, extra recoil energy, can resonantly excite another ^{152}Sm nucleus; opposite direction, not enough energy for excitation
- So, if we observe the production (and decay) of the second ^{152}Sm nucleus, we know that the photon and the $^{152}Sm^*$ are aligned. In this case $H(\nu) = H(\gamma)$
- And the photon helicity? Photon absorption in magnetized iron depends on their helicity. Use this to select left (H=-1) and right-handed (H=+1) photons

GOLDHABER'S EXPERIMENT



- Result: higher count rate with magnetic field down.
- Similar (opposite) results for antineutrino experiments

Maurice Goldhaber, 1957

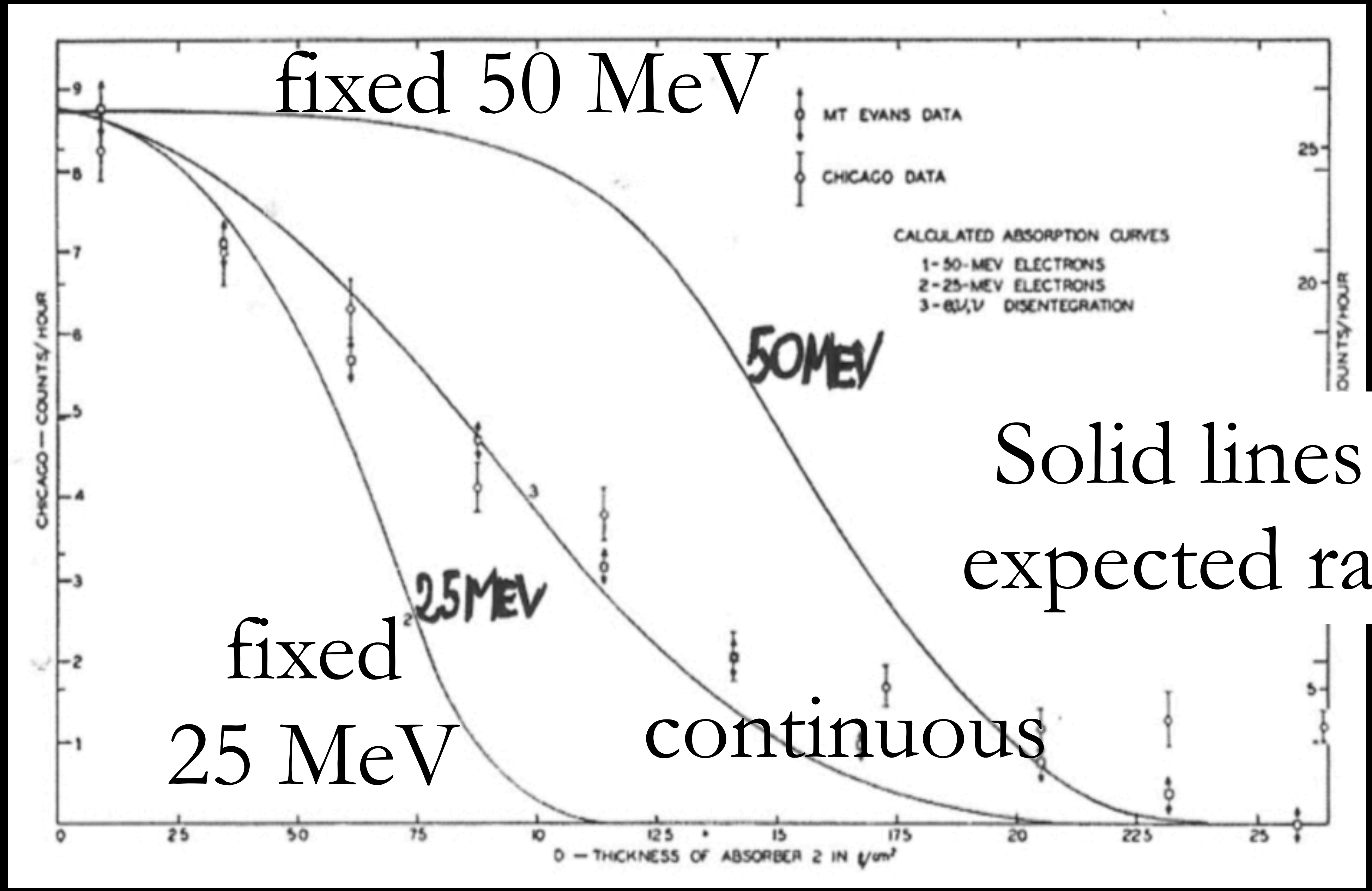
NEUTRINOS ARE LEFT-HANDED AND ANTINEUTRINOS ARE RIGHT-HANDED!

FLAVOUR

MUON DECAY

$$\mu^- \rightarrow e^- + \nu \qquad \text{or} \qquad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \qquad ?$$

- Measurement of the energy spectrum of the electrons from muon decay
  - Fixed energy: two-body decay
  - Continuous energy: three-body decay

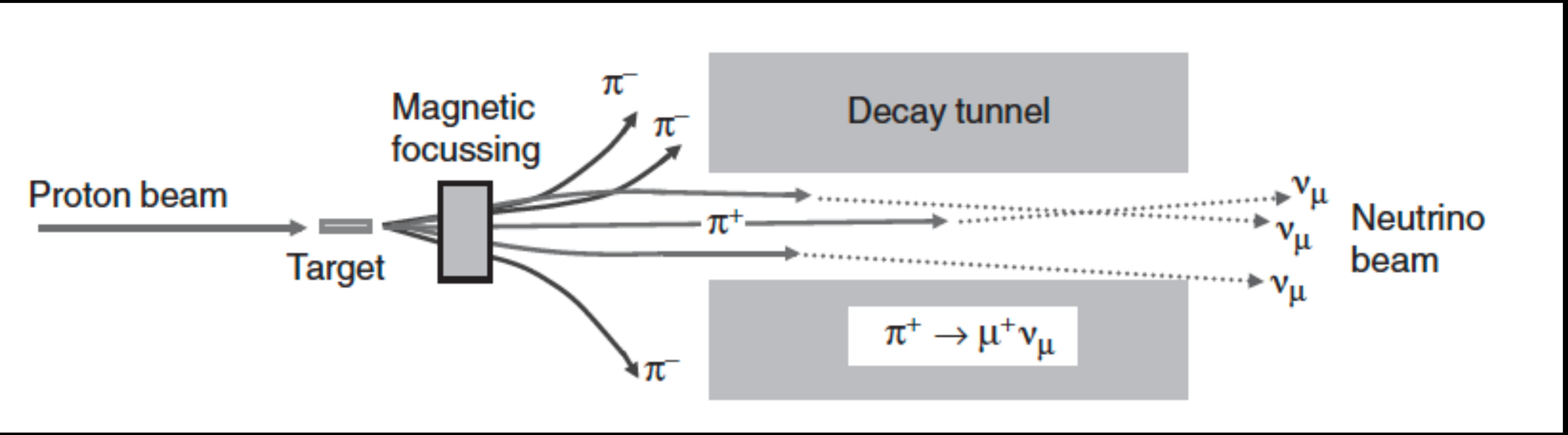


electron range

- Only one neutrino emitted in beta decay
- Not one, but two neutrinos emitted in muon decay

J. STEINBERGER, PHD THESIS, 1949

- Almost all produce muon neutrinos from pion decay (from protons hitting target)
  - Can switch between neutrinos and antineutrino by flipping the magnetic field polarity
  - Energy can be tuned by tuning proton energy and magnetic field intensity



FIRST EXPERIMENT WITH A NEUTRINO BEAM, AGS, BROOKHAVEN (1962)

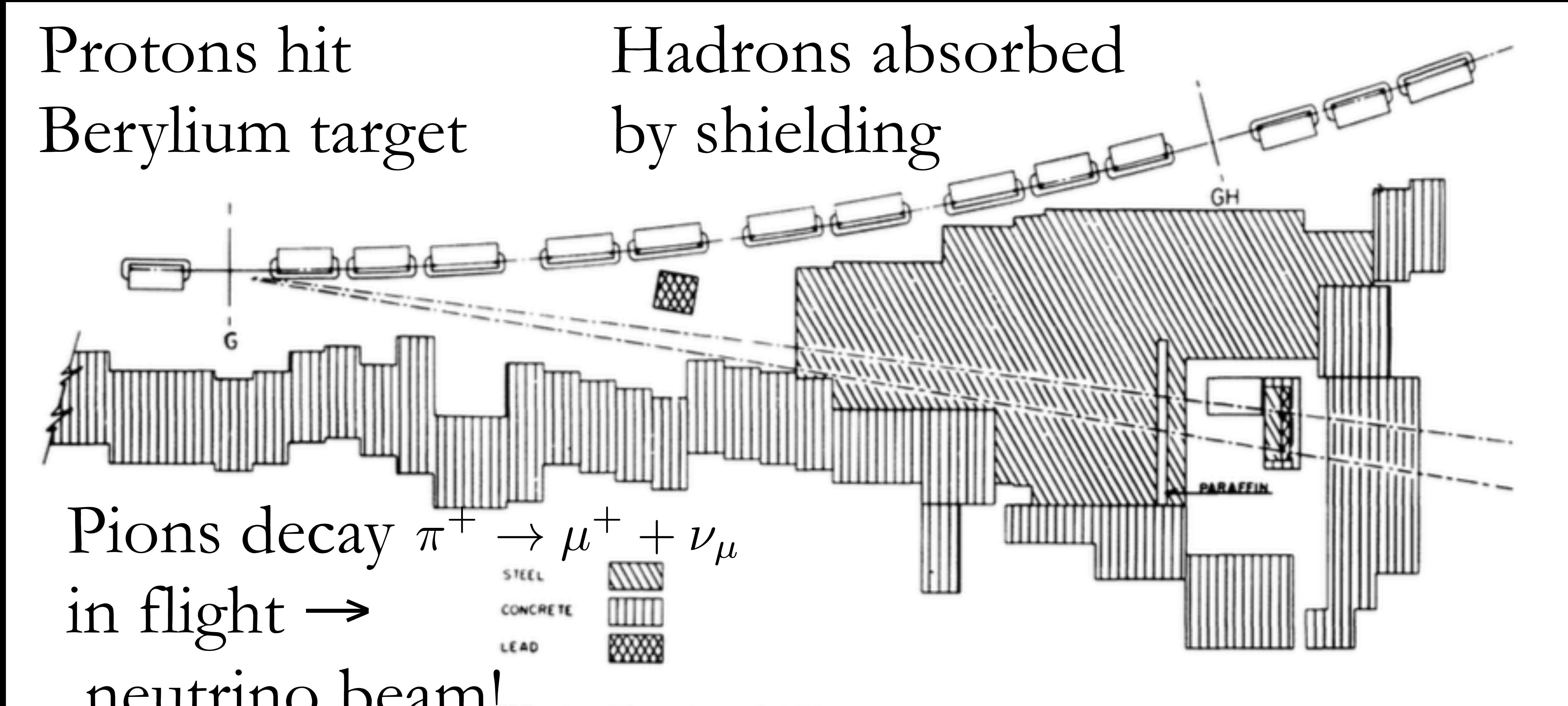
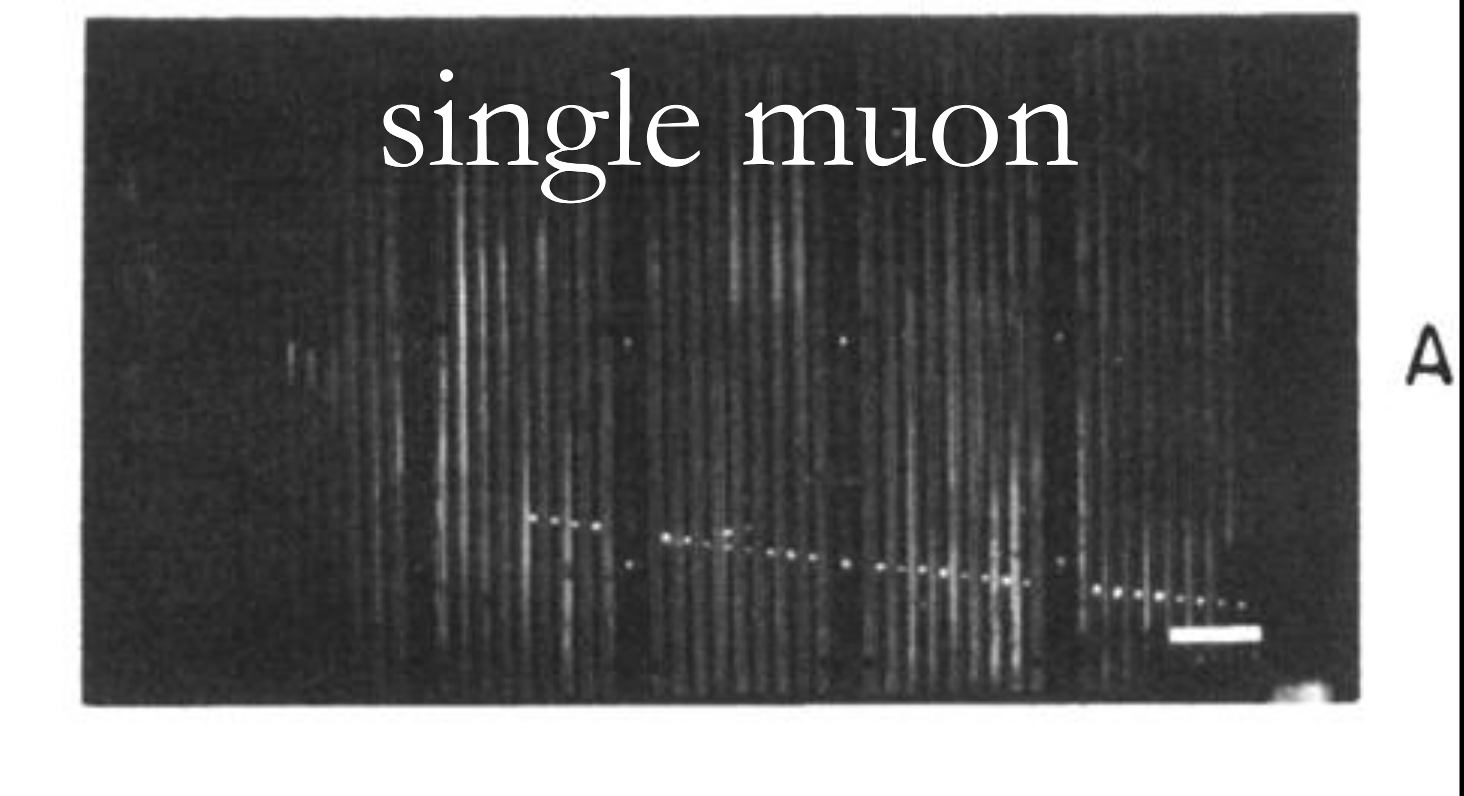


FIG. 1. Plan view of AGS neutrino experiment.

DISCOVERY OF MUON NEUTRINOS

- Are the neutrinos produced with muons the same as those produced with electrons? I.e. are $\nu_\mu = \nu_e$?

Spark chamber tracks:



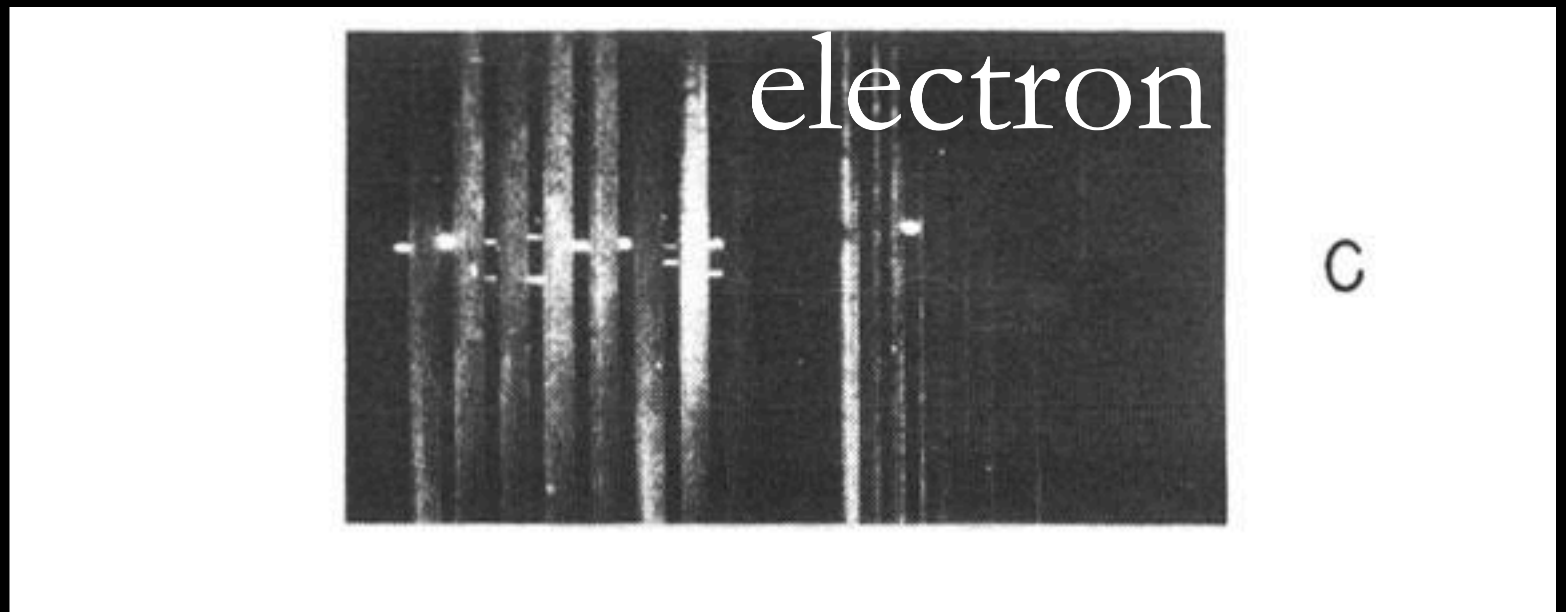
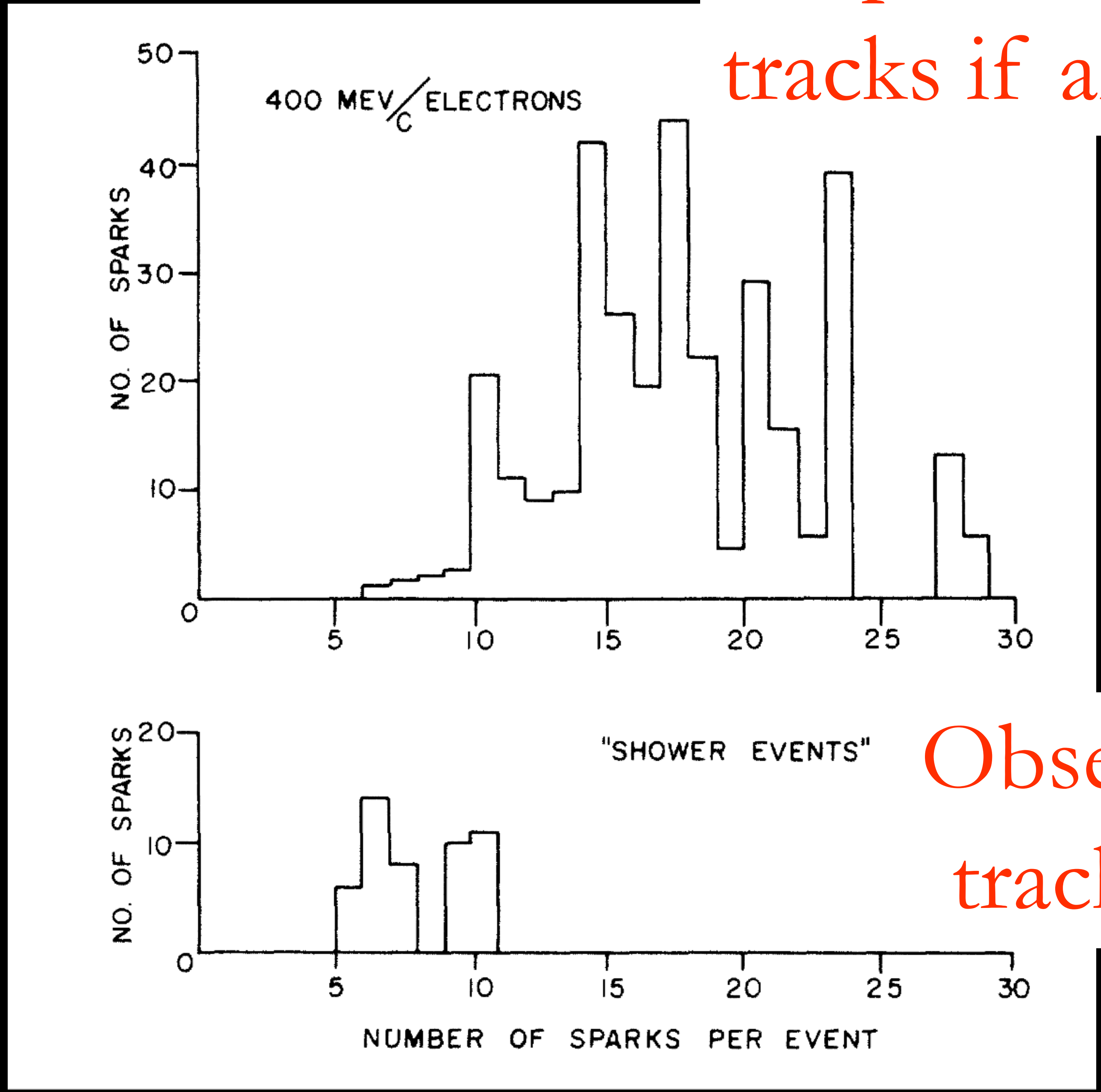


FIG. 8. 400-MeV electrons from the Cosmotron.

Expected electron tracks if are $\nu_\mu = \nu_e$



Observed electron tracks $\rightarrow \nu_\mu \neq \nu_e$

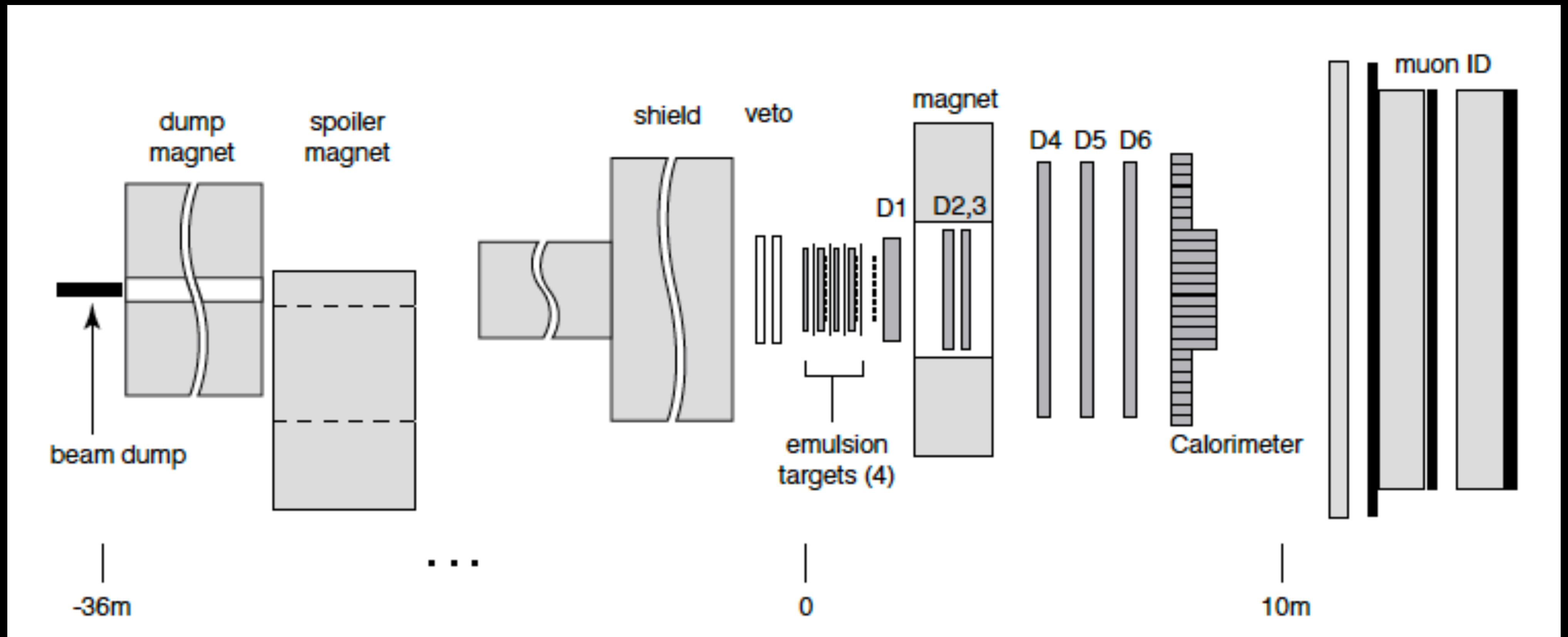
Melvin Schwartz
(Leon Lederman, Jack Steinberger)
[Nobel 1988]

DISCOVERY OF TAU NEUTRINOS

- DONUT experiment@Fermilab (2000)
- High energy needed to produce Ds meson

$$D_s \to \tau^- + \nu_\tau$$

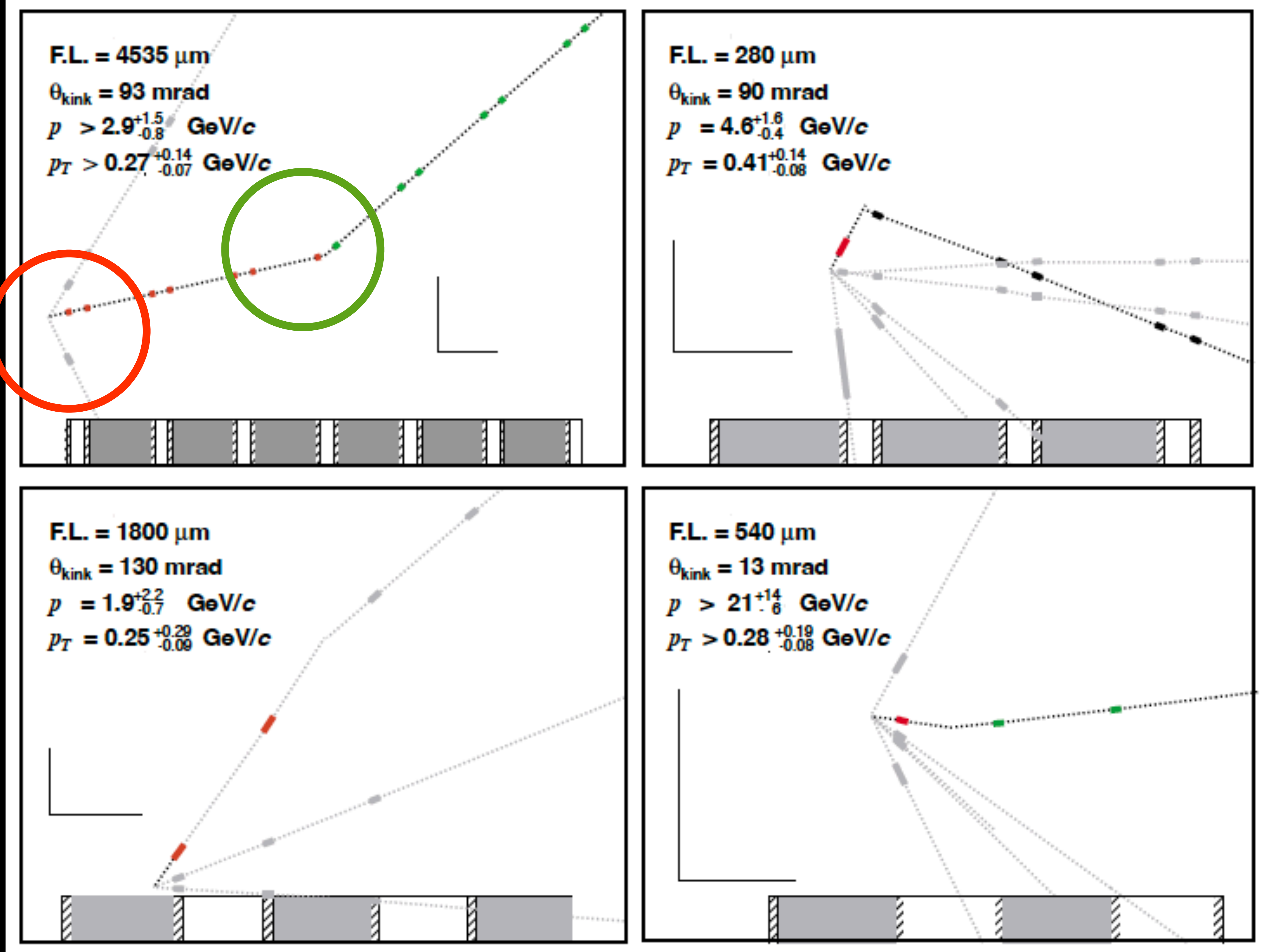
- Beam with same amounts of ν_τ, ν_μ, ν_e



- Tau leptons very short lived (0.29 ps)
  - Sub-mm resolution needed to identify decay kink
  - Emulsion technique

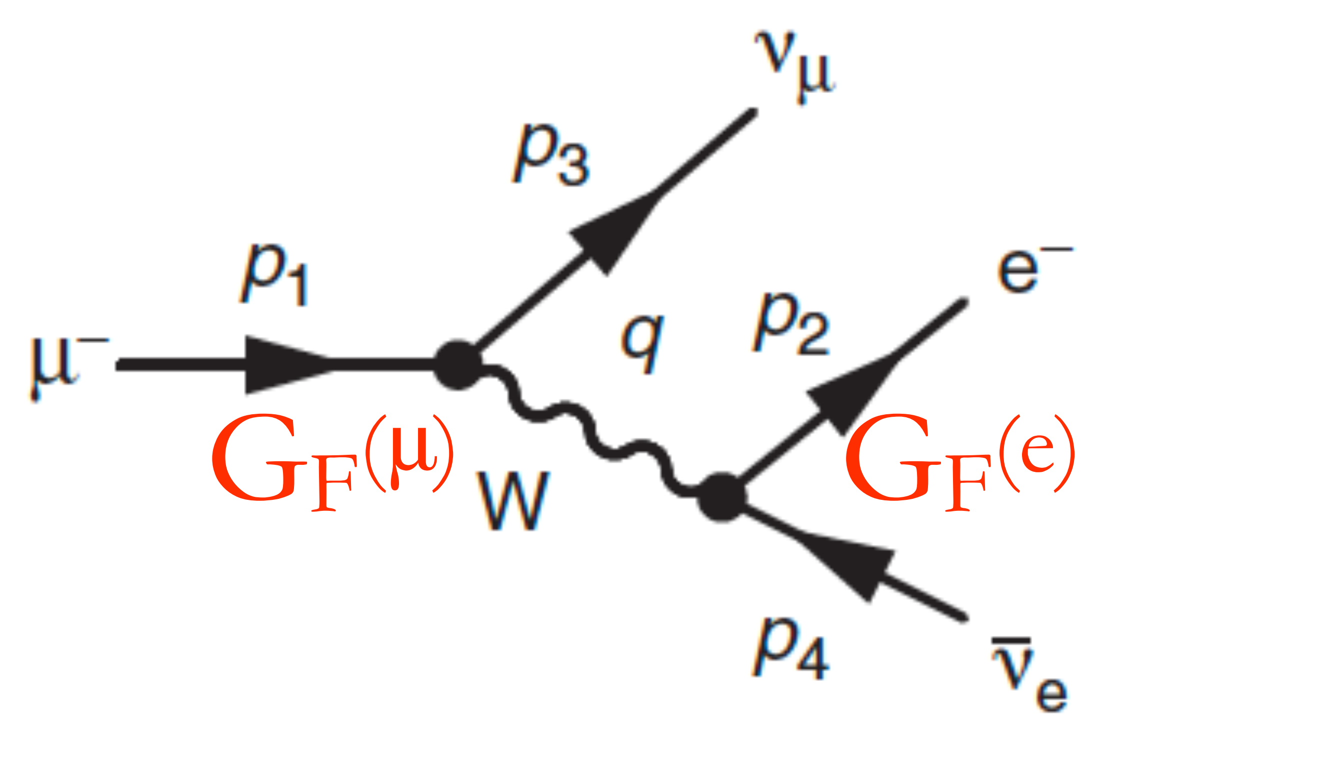
$$\nu_\tau + X \to \tau^- + X'$$

$$\tau^- \to \pi^- + \nu_\tau$$

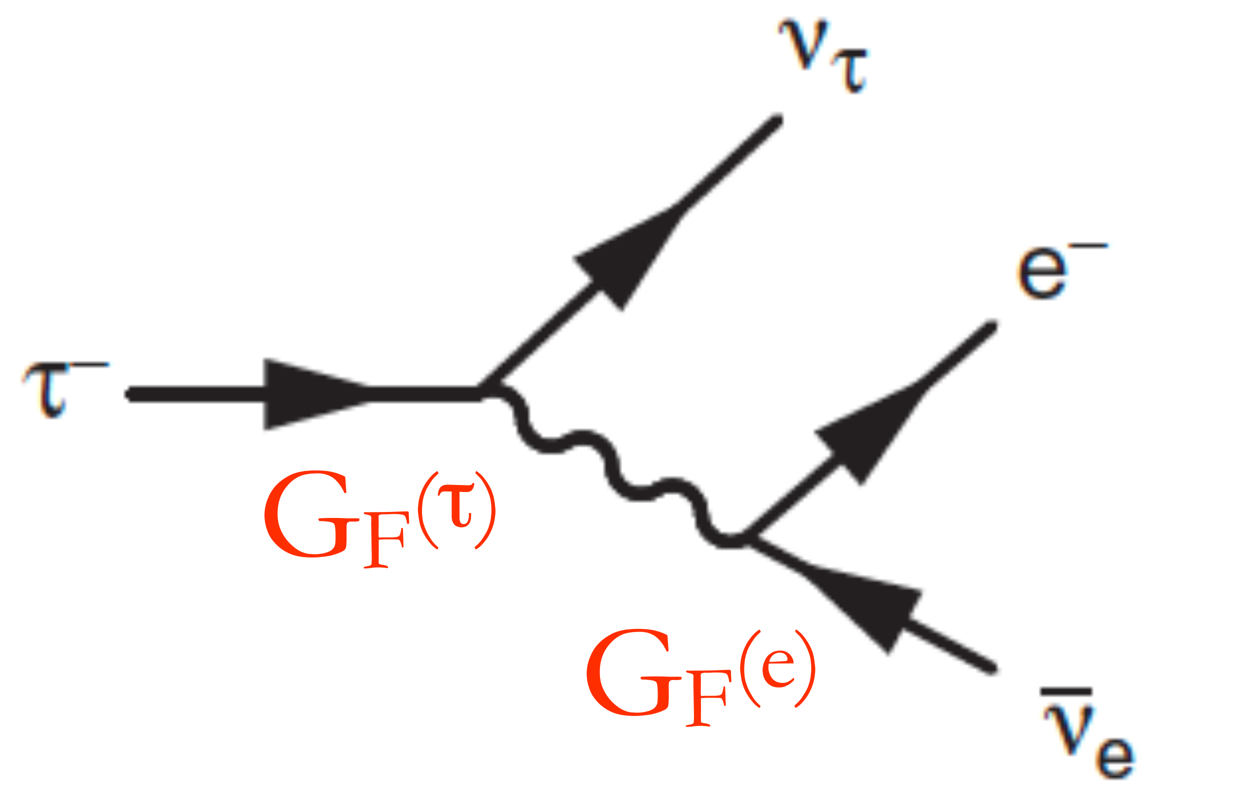


- Is the weak coupling constant the same for all three lepton families ?
-

$$\Gamma(\mu^- \to e^-\overline{\nu}_e\nu_\mu) \equiv \frac{1}{\tau_\mu} = \frac{G_F^{(e)}G_F^{(\mu)}m_\mu^5}{192\pi^3}$$



$$\Gamma(\tau^- \to e^-\overline{\nu}_e\nu_\tau) = \frac{G_F^{(e)}G_F^{(\tau)}m_\tau^5}{192\pi^3}$$



$$Br(\tau^- \to e^-\overline{\nu}_e\nu_\tau) = \frac{\Gamma(\tau^- \to e^-\overline{\nu}_e\nu_\tau)}{\Gamma} = \Gamma(\tau^- \to e^-\overline{\nu}_e\nu_\tau) \times \tau_\tau$$

$$\frac{G_F^{(\tau)}}{G_F^{(\mu)}} = \frac{m_\mu^5\tau_\mu}{m_\tau^5\tau_\tau} Br(\tau^- \to e^-\overline{\nu}_e\nu_\tau).$$

and similarly for $G_F^{(e)}$

$$Br(\tau^- \to e^-\overline{\nu}_e\nu_\tau) = 0.1783(5) \quad \text{and} \quad Br(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau) = 0.1741(4),$$

$$m_\mu = 0.1056583715(35)\,\text{GeV} \quad \text{and} \quad \tau_\mu = 2.1969811(22)\times 10^{-6}\,\text{s},$$
$$m_\tau = 1.77682(16)\,\text{GeV} \quad \text{and} \quad \tau_\tau = 0.2906(10)\times 10^{-12}\,\text{s}.$$

$$\frac{G_F^{(\tau)}}{G_F^{(\mu)}} = 1.0023 \pm 0.0033. \qquad \frac{G_F^{(e)}}{G_F^{(\mu)}} = 1.000 \pm 0.004.$$

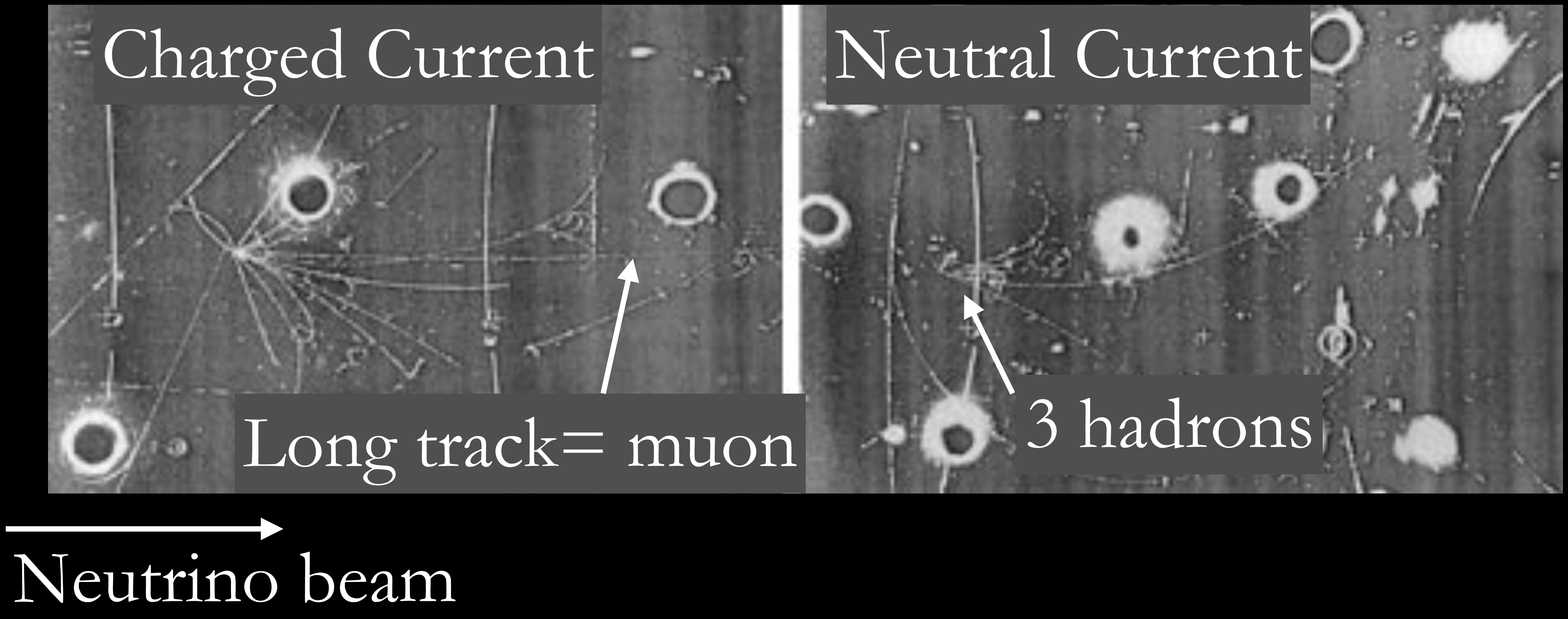
Identical vertices for $W\tau\nu_\tau$, $W\mu\nu_\mu$, $We\nu_e$

NEUTRAL CURRENTS

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

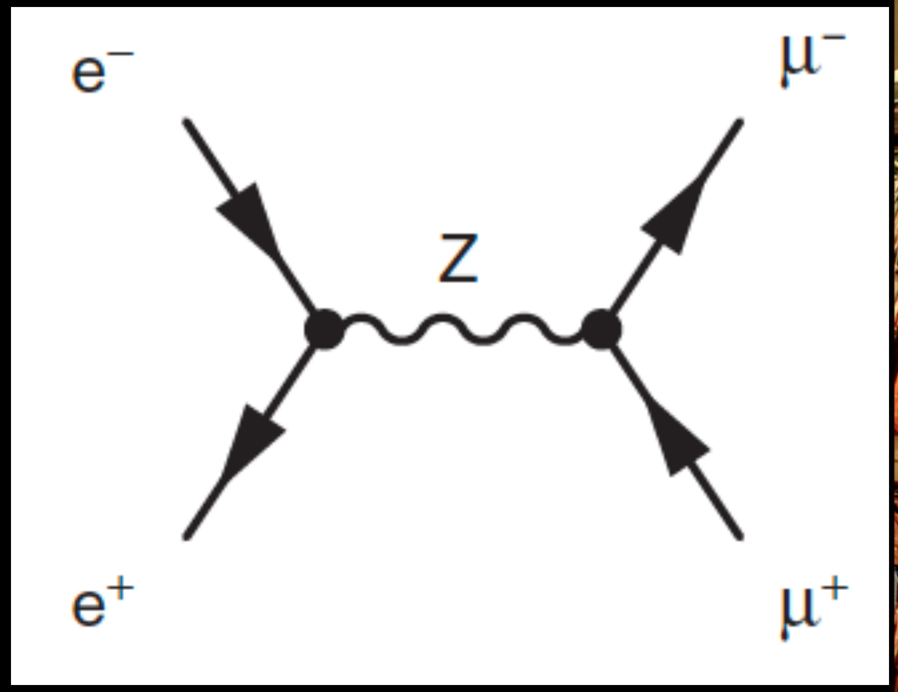
$$\nu + X \rightarrow \nu + X'$$ (no leptons!)

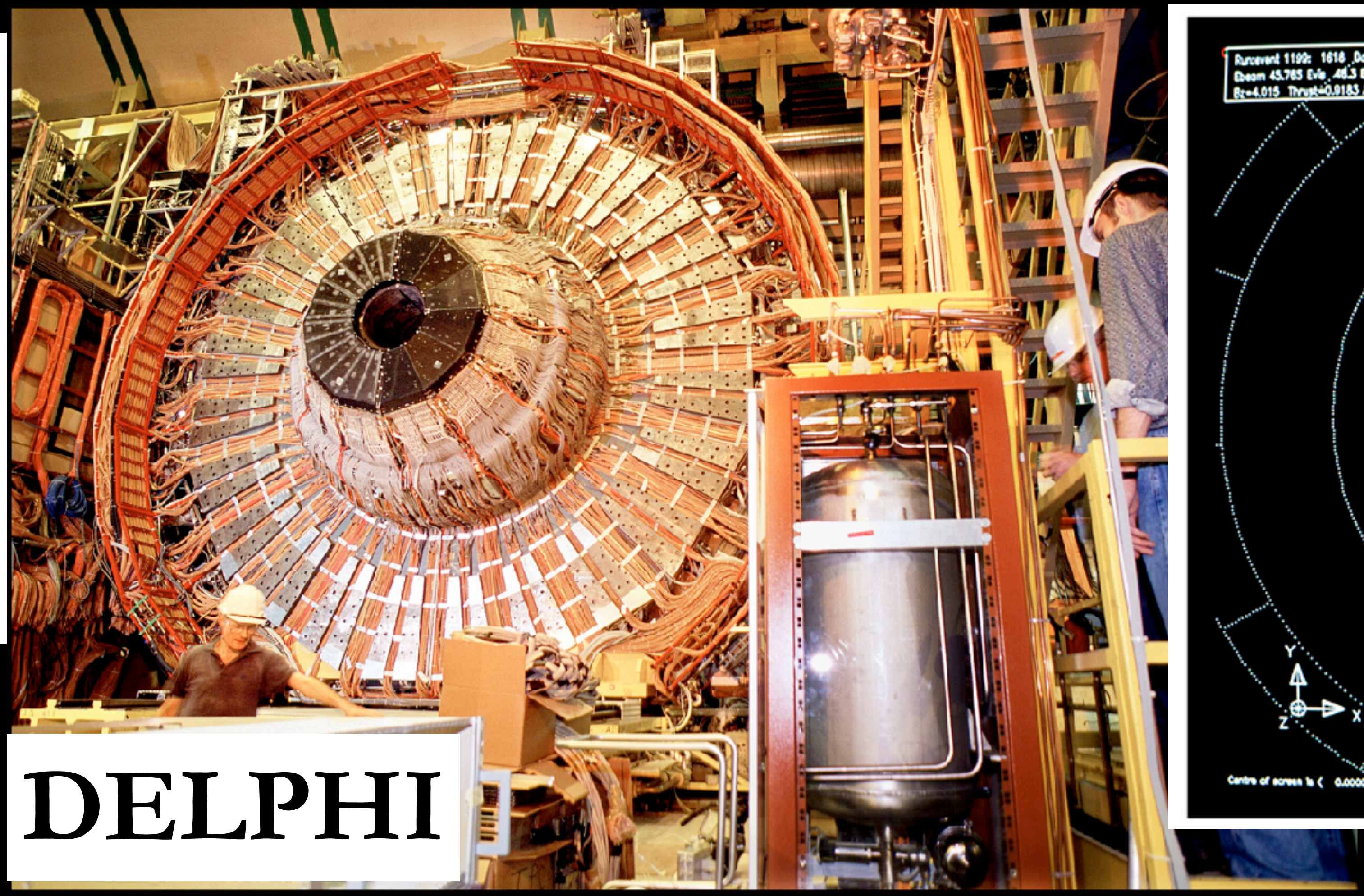
- Neutrino reactions with no charge exchange, a key prediction of the electroweak model (late 60's)
- Observed at CERN in 1973 with the magnetized bubble chamber Gargamelle

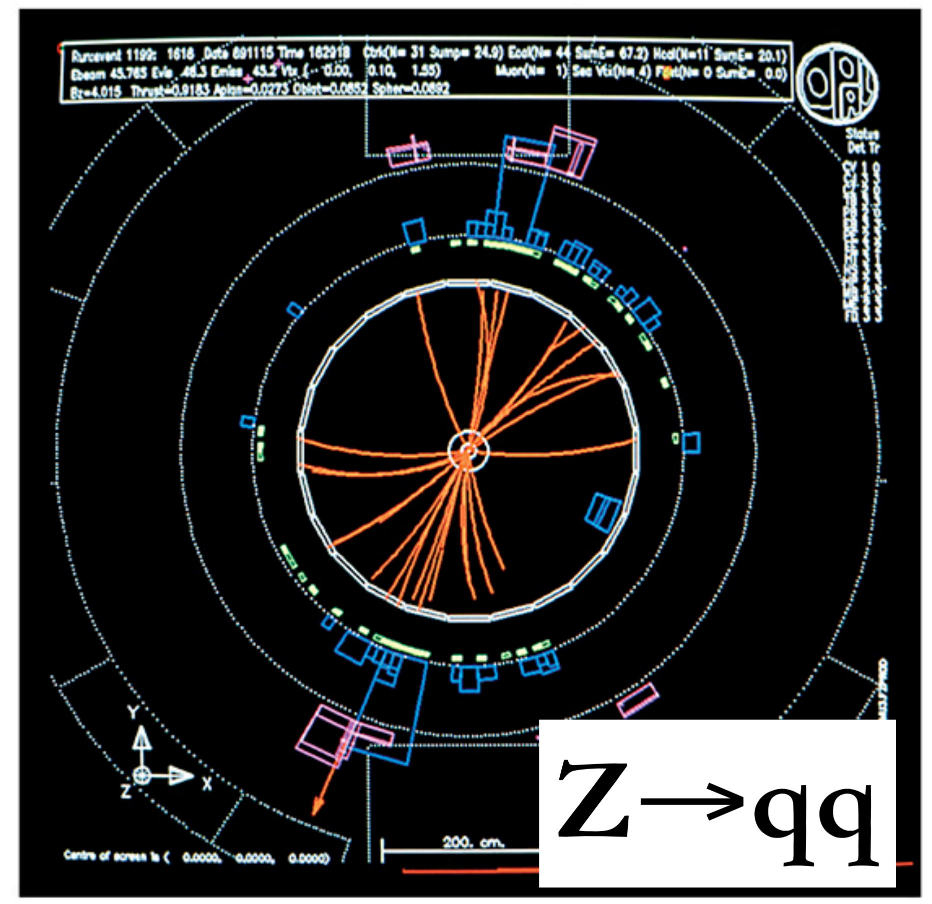


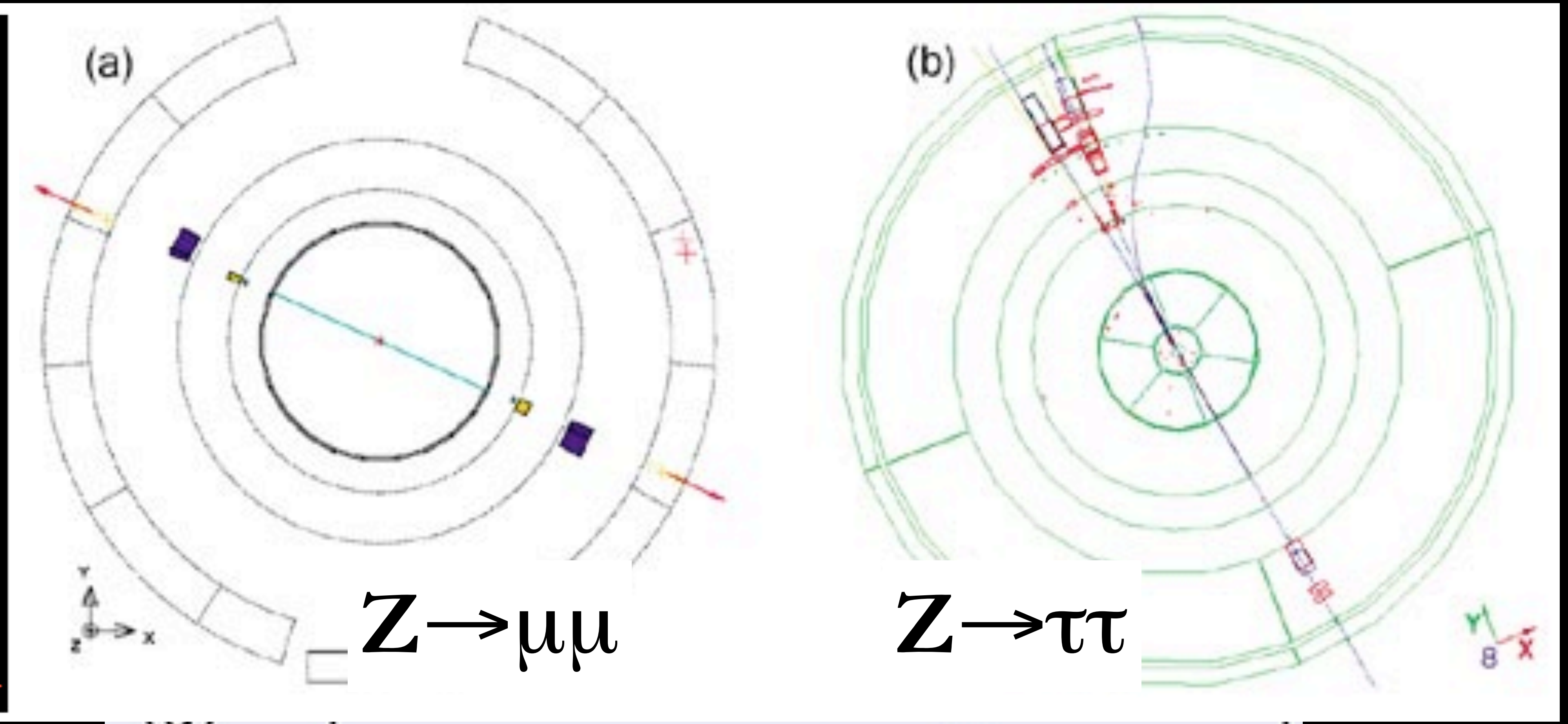
- Rate as expected for ν_μ and $\overline{\nu_\mu}$.
- Measured Weinberg angle.

Z BOSON WIDTH AND 3 FLAVOURS









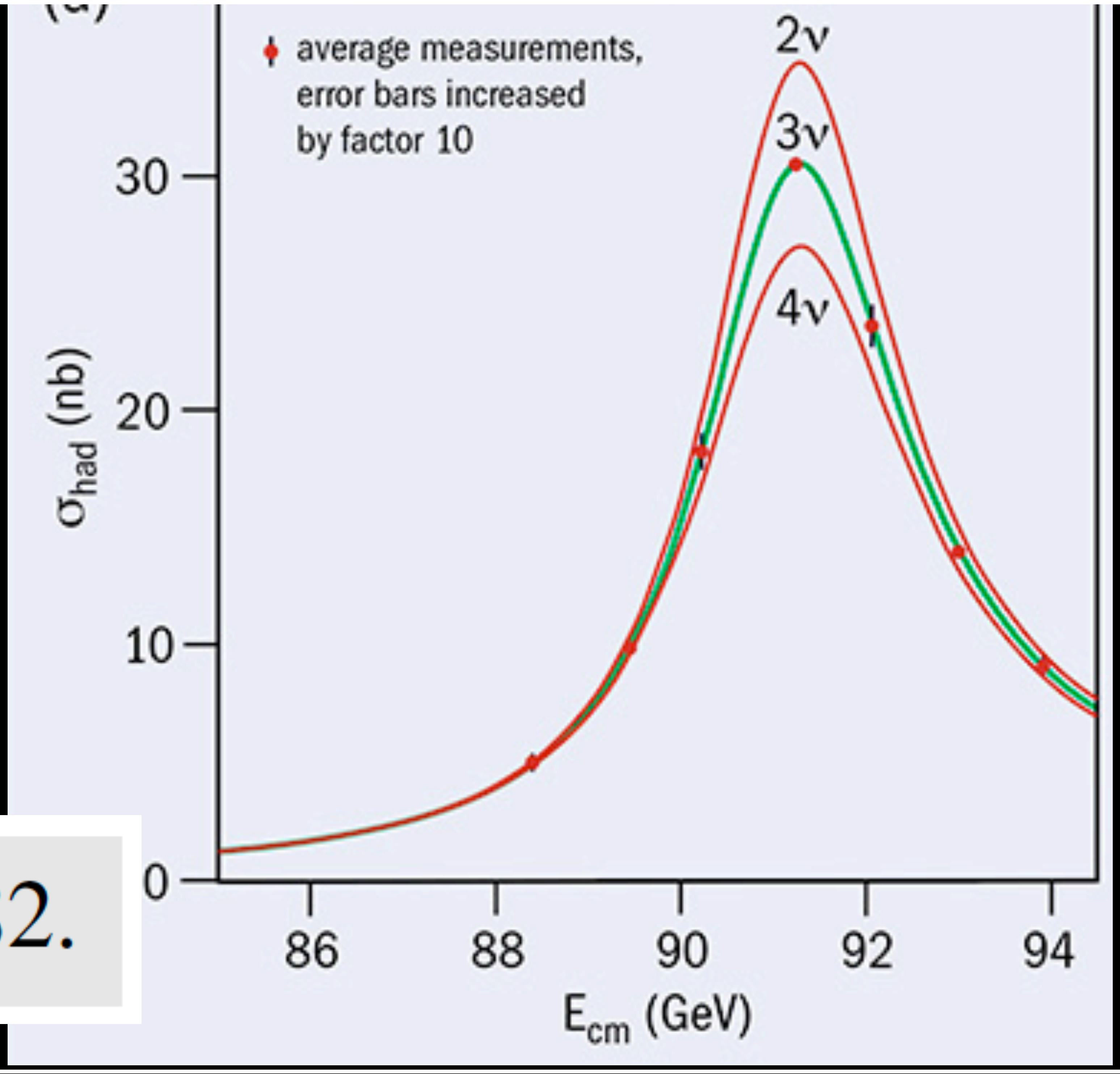
- LEP collider produced vast amounts of Z bosons at cm energies close to pole

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{hadrons} + \Gamma_{\nu_e\nu_e} + \Gamma_{\nu_\mu\nu_\mu} + \Gamma_{\nu_\tau\nu_\tau}$$

- Total width Γ from Z→qq resonance, partial widths from specific decays
- **N_ν = number of light neutrino families**

$$\Gamma_Z = 3\Gamma_{\ell\ell} + \Gamma_{hadrons} + N_\nu\Gamma_{\nu\nu}$$

$$N_\nu = 2.9840 \pm 0.0082.$$

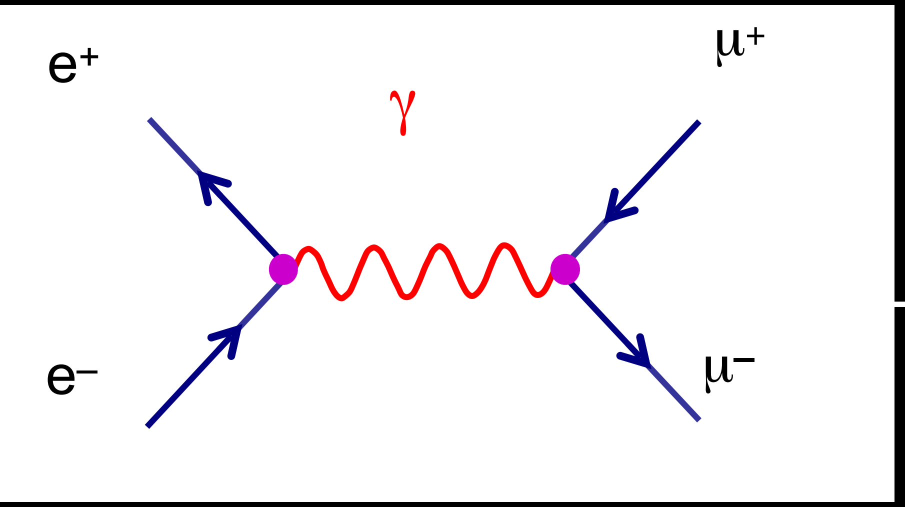


NEUTRINOS IN THE STANDARD MODEL

NEUTRINO PROPERTIES

- The SM was built from experiment (and some assumptions…)
  - Fermi's beta decay theory should be its low energy limit
  - Neutrinos are neutral, spin 1/2, massless (a widely shared assumption, at the time)
  - Complete parity violation
  - Neutrinos are left-handed, antineutrinos are right-handed fermions
  - There is one (light) neutrino associated to each charged lepton, and no more
  - They have the same fundamental coupling constant
- Key aspects of the electroweak theory
  - $SU(2)_L \times U(1)_Y$ gauge principle; weak isospin I_3 and hypercharge Y, broken by the scalar Higgs boson
  - Neutrinos are described by spinor fields. L neutrino fields are part of an isospin doublet, R neutrino fields are absent from theory.
  - Interaction terms only with W and Z bosons (massive)
  - From these one can obtain a "prescription" for Feynman rules

FEYNMAN RULES FOR QED



- Start by drawing all possible Feynman diagrams for the process
- Prescription to calculate Lorentz-invariant matrix element M_{fi}

External lines

spin 1/2
- incoming particle — $u(p)$
- outgoing particle — $\overline{u}(p)$
- incoming antiparticle — $\overline{v}(p)$
- outgoing antiparticle — $v(p)$

spin 1
- incoming photon — $\varepsilon^{\mu}(p)$
- outgoing photon — $\varepsilon^{\mu}(p)^*$

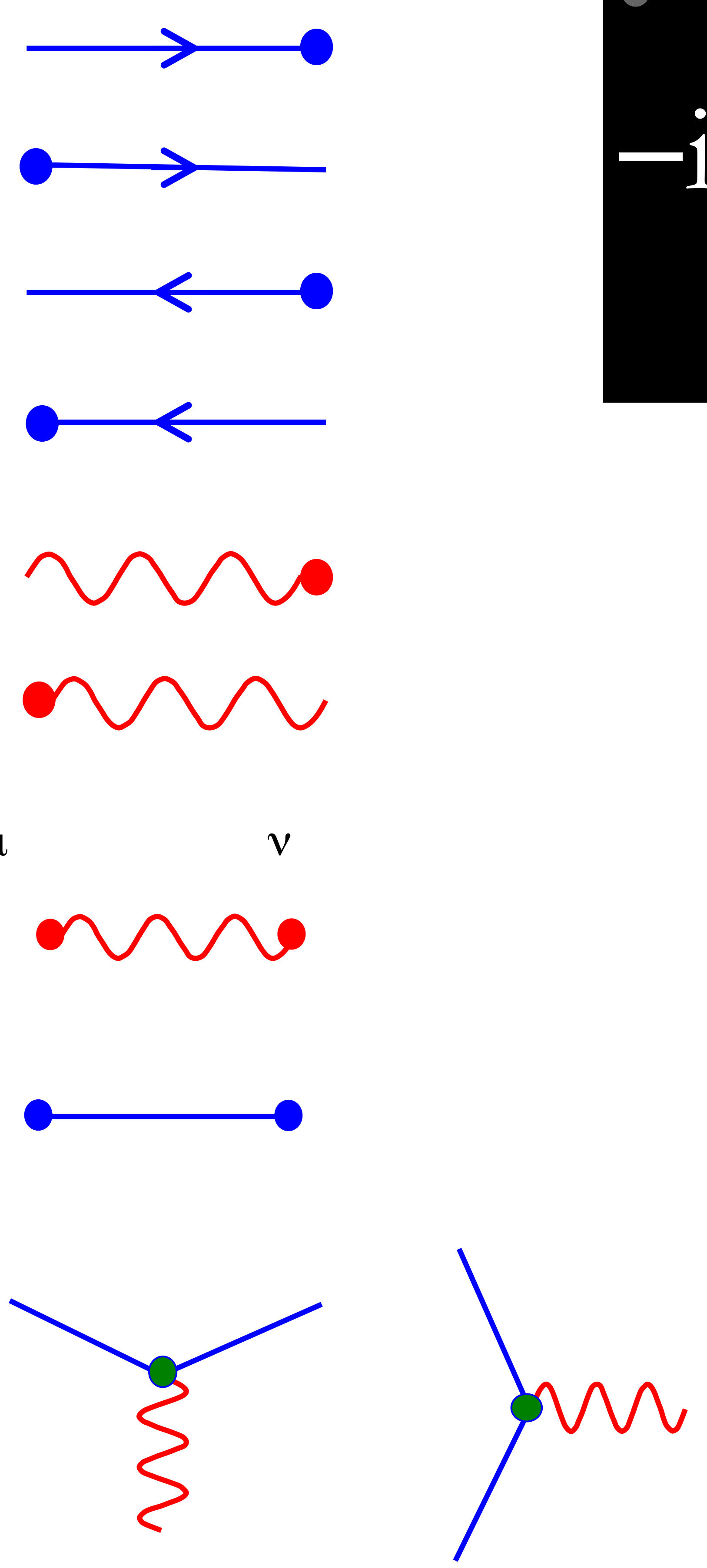
Internal lines (propagators)

spin 1
- photon — $-\frac{ig_{\mu\nu}}{q^2}$

spin 1/2
- fermion — $\frac{i(\gamma^{\mu}q_{\mu}+m)}{q^2-m^2}$

Vertices

- fermion — $ie\gamma^{\mu}$



- Matrix element

$-i\,M_{fi}$ = product of all factors

Decay rate: a → 1+2

$$\Gamma = \frac{p^*}{32\pi^2 m_a^2}\int |\mathcal{M}_{fi}|^2 d\Omega,$$

Scattering differential cross section: a + b → c + d

$$\frac{d\sigma}{d\Omega^*} = \frac{1}{64\pi^2 s}\frac{p_f^*}{p_i^*}|\mathcal{M}_{fi}|^2,$$

AND FOR WEAK INTERACTIONS?

- Parity violation needs to come out naturally from theory
  - Particles are eigentates of parity operator with +/- 1 eigenvalues
  - Gauge bosons have negative parity $P_\gamma = P_g = P_{W^+} = P_{W^-} = P_Z = -1$
  - Parity of fermion particles opposite antiparticles $P_{e^-} = P_{\mu^-} = P_{\tau^-} = P_\nu = P_q = +1$ (convention)
  - For Dirac spinors parity operator = γ^0 matrix
- Vertex + fermion lines form bilinear "currents" $j^\mu = \overline{\psi}\gamma^\mu \phi$

	Type	Form	Components	"Boson Spin"
	SCALAR	$\overline{\psi}\phi$	1	0
	PSEUDOSCALAR	$\overline{\psi}\gamma^5\phi$	1	0
QED →	VECTOR	$\overline{\psi}\gamma^\mu\phi$	4	1
	AXIAL VECTOR	$\overline{\psi}\gamma^\mu\gamma^5\phi$	4	1
	TENSOR	$\overline{\psi}(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)\phi$	6	2

- Only 16 respect Lorentz invariance. Of those, only vector $\overline{\psi}\gamma^\mu\phi$ or axial vector $\overline{\psi}\gamma^\mu\gamma^5\phi$ can couple to spin 1 bosons. From γ matrices properties: product of two currents is invariant for pure vector or pure axial vector. General form for vertex: $g_V\, \gamma^\mu + g_A\, \gamma^\mu\gamma^5$
- From experiment: $g_V = 1$, $g_A = -1$. Charged current vertex: $\frac{-ig_w}{\sqrt{2}}\frac{1}{2}\gamma^\mu(1-\gamma^5)$

CHIRALITY AND HELICITY

- Eigenstates of the γ^5 matrix are the L and R chiral states

$$\gamma^5 u_R = +u_R \quad \text{and} \quad \gamma^5 u_L = -u_L,$$
$$\gamma^5 v_R = -v_R \quad \text{and} \quad \gamma^5 v_L = +v_L.$$

- Projection operators

$$P_R = \tfrac{1}{2}(1+\gamma^5),$$
$$P_L = \tfrac{1}{2}(1-\gamma^5).$$

- CC weak vertex

$$\frac{-ig_W}{\sqrt{2}}\frac{1}{2}\gamma^\mu(1-\gamma^5)$$

  - includes P_L!
- P_L projects left component in weak current:

$$\overline{\psi}\tfrac{1}{2}\gamma^\mu(1-\gamma^5)\phi = \overline{\psi}\gamma^\mu\phi_L = \overline{\psi}_L\gamma^\mu\phi_L$$

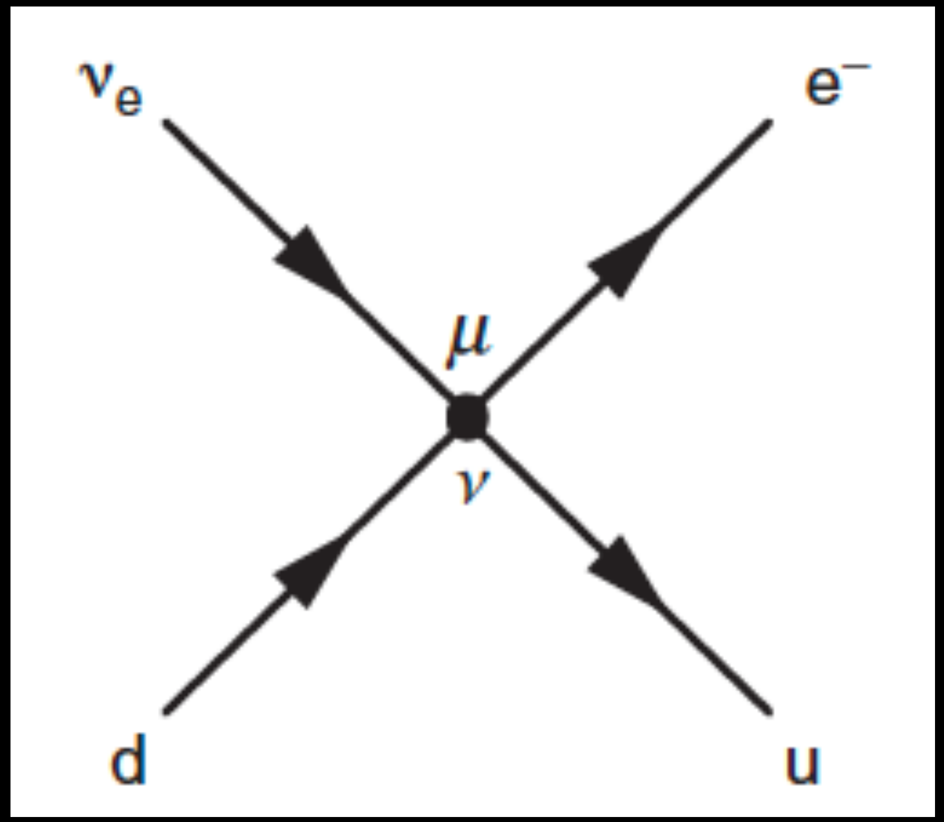
- Only left-handed chiral components participate in charged weak interactions!
- From properties of Dirac spinors, the helicity eigenstate is

$$u_\uparrow \propto \frac{1}{2}(1+k)u_R + \frac{1}{2}(1-k)u_L \qquad k = \frac{p}{E+m}$$

- In the relativistic case E >> m: k~1, so chiral states are helicity eigenstates
- Recover the experimental result that neutrinos are left-handed !

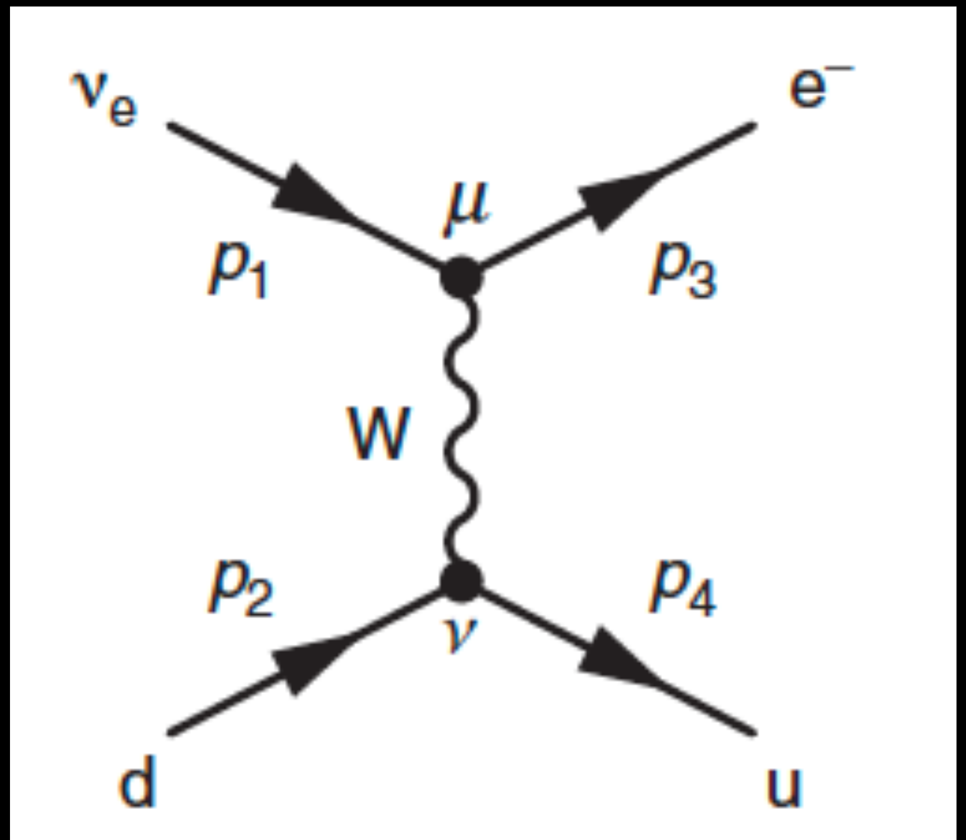
WEAK MASSIVE BOSONS

Fermi



→

SM



Propagators

EM $\frac{-ig_{\mu\nu}}{q^2}$.

Weak $\frac{-ig_{\mu\nu}}{q^2 - m_W^2}$.

When $q^2 << m_W^2$, becomes constant

$$i\frac{g_{\mu\nu}}{m_W^2},$$

Unlike the photon, W and Z are heavy bosons. They are short-lived and the interaction has a short range.

- Relation between Fermi and g_W $\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2}$
- Obtain g_W, α_W $\alpha_W = \frac{g_W^2}{4\pi} = \frac{8m_W^2 G_F}{4\sqrt{2}\pi} = \frac{1}{30}$
- Compare to $\alpha_{EM} = 1/137$
- Weakness of weak interactions due to massive bosons (not true @ high energies!)

ELECTROWEAK SYMMETRY

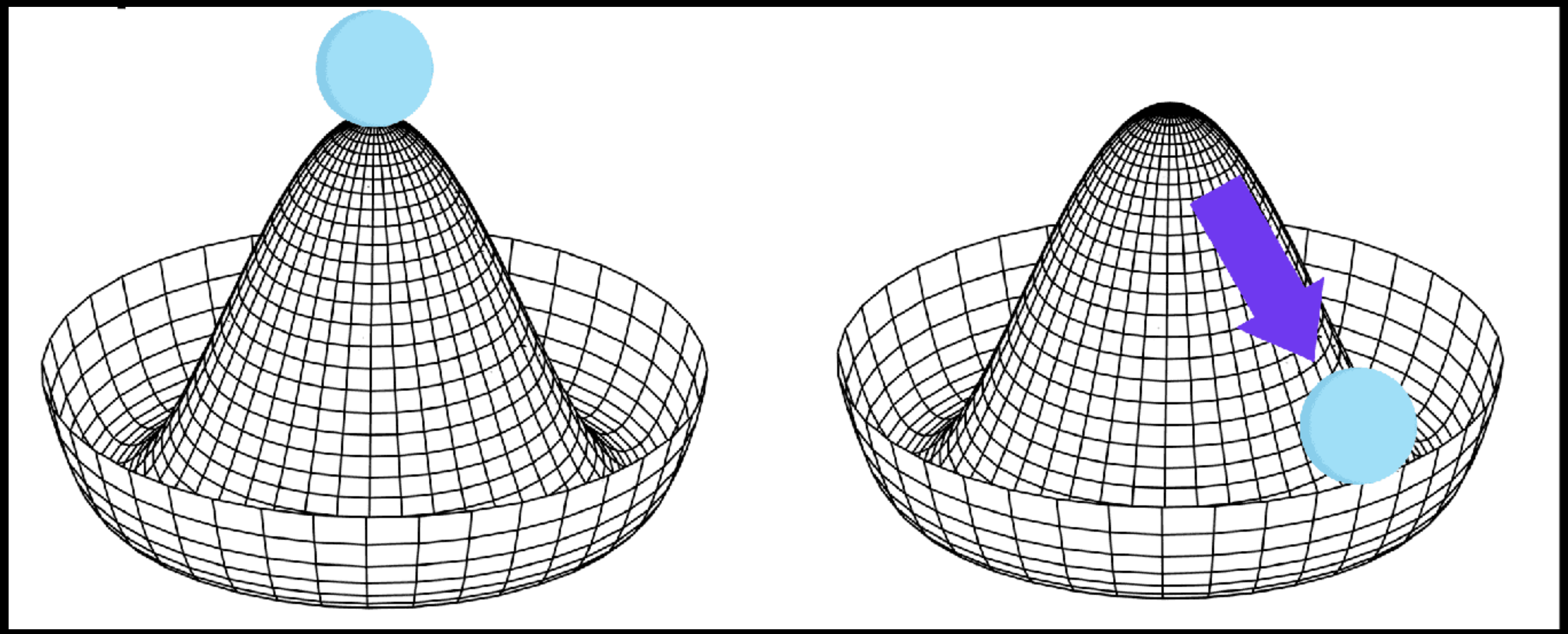
- Similarities between weak and EM interaction
  - W boson has EM charge
  - If chirality is "absorbed" in definition of states, vertex is similar $\overline{\psi}\frac{1}{2}\gamma^{\mu}(1-\gamma^{5})\phi = \overline{\psi}_L\gamma^{\mu}\phi_L$
  - Considering effect of massive propagator, coupling constant also similar

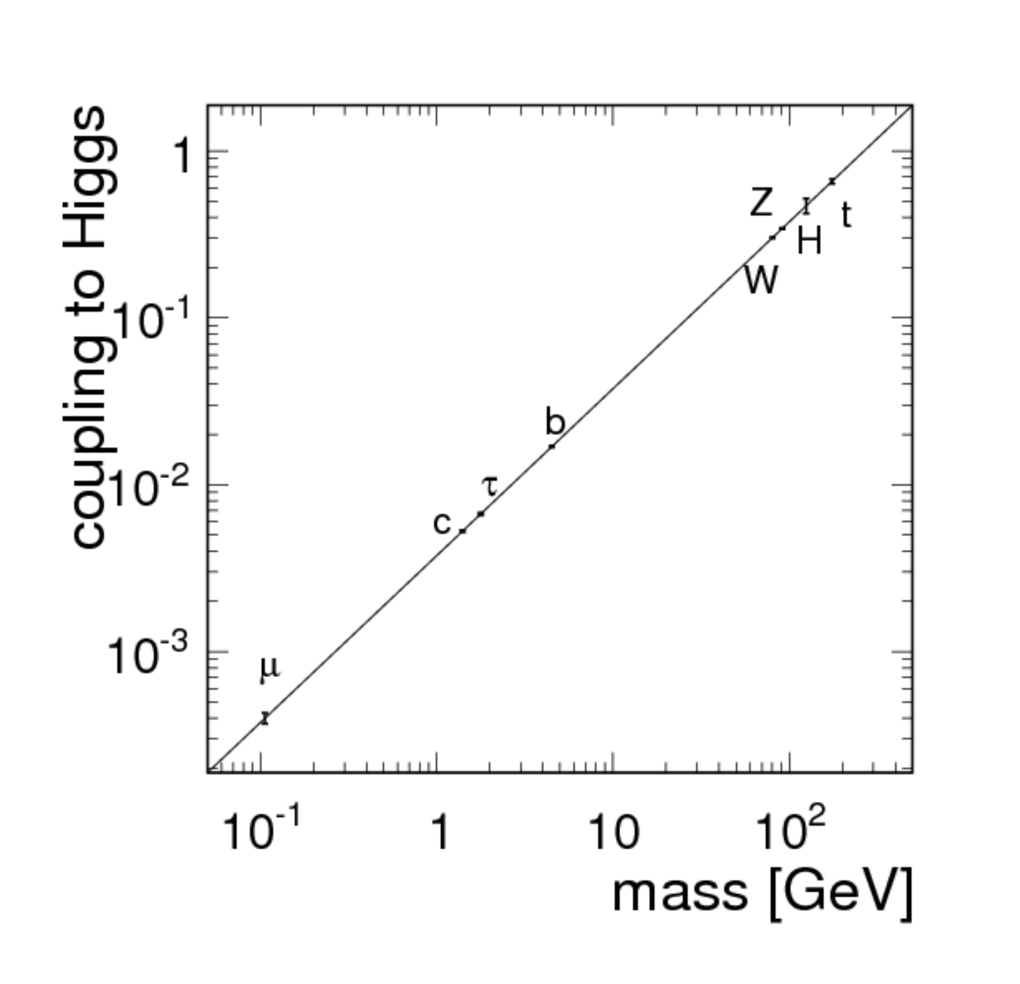
- Unification of EM and weak interactions
  - Quantum Field Theories based on imposing local symmetries on Lagrangian
  - From Noether's theorem, to each symmetry corresponds a conservation law
    - EM: U(1) symmetry, conservation of charge
    - QCD: SU(3) symmetry, conservation of color
    - Electroweak; SU(2)xU(1), conservation of weak isospin and hypercharge
  - Consequences of unification
    - Predict neutral Z boson
    - Masses of W and Z bosons, weak/EM coupling constants are all related (via Weinberg angle)

HIGGS AND MASS

NOTE: MUCH MORE ABOUT LAGRANGIANS, GAUGE, MASS TERMS IN LECTURE 4.

- Major problem of Higgs-less electroweak unification: mass
- Mass terms in Lagrangian are not gauge-invariant
- Need to introduce a scalar (spin-0) field
- Higgs field symmetry broken at “low” energies
- Interaction wth Higgs field gives mass
  - to W and Z bosons
  - to fermions, via terms like $-m\bar{\psi}\psi = -m\left(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R\right)$





- But there are no right-handed neutrino fields (ν_R) in the theory! No ν_R interactions (weak, EM or strong).
- Neutrinos are massless in the Standard model!
- How can we extend it? Tune in for Lecture 4!