Alvaro@80

10 June 2024

Enjoying NEUTRINO Physics with Álvaro's work

LAUDATIO

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A Theorist NEAR Experiment

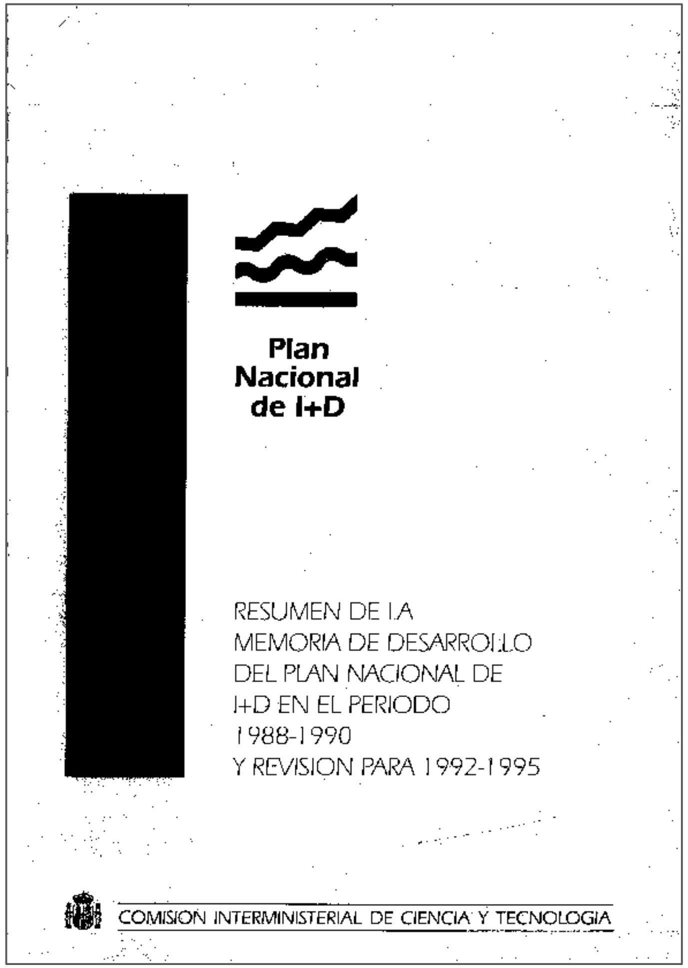
- Not only research with experimental implications
- Actual presence NEAR instrumentation

A Theorist NEAR experiment

Spanish Programme of High Energy Physics 1988-1992
of the InterMinistry Commission of Science and Technology

- **Advisory Committee** of the Programme and
for funding Research Projects

. **Álvaro De Rújula**
. Lawrence Sulak
. Friedrich Dydak
. Gunter Wolf
. Lorenzo Foà
. J B
. …


Plan
Nacional
de I+D

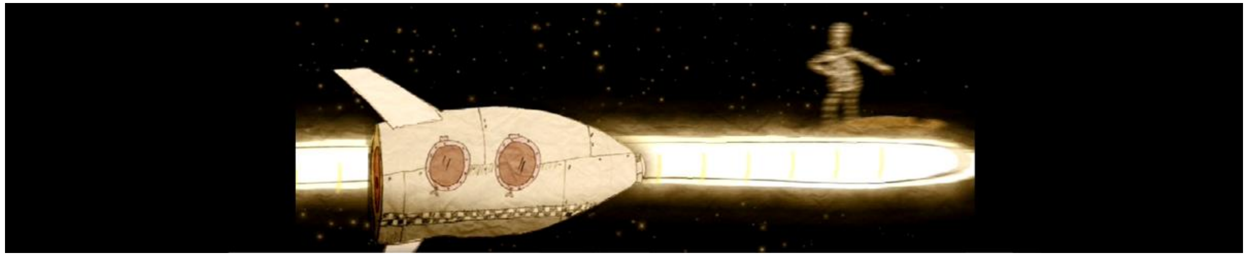
RESUMEN DE LA
MEMORIA DE DESARROLLO
DEL PLAN NACIONAL DE
I+D EN EL PERIODO
1988-1990
Y REVISION PARA 1992-1995

COMISION INTERMINISTERIAL DE CIENCIA Y TECNOLOGIA

Elementary, Dear Albert

→ BREAKING THE ARROW OF TIME

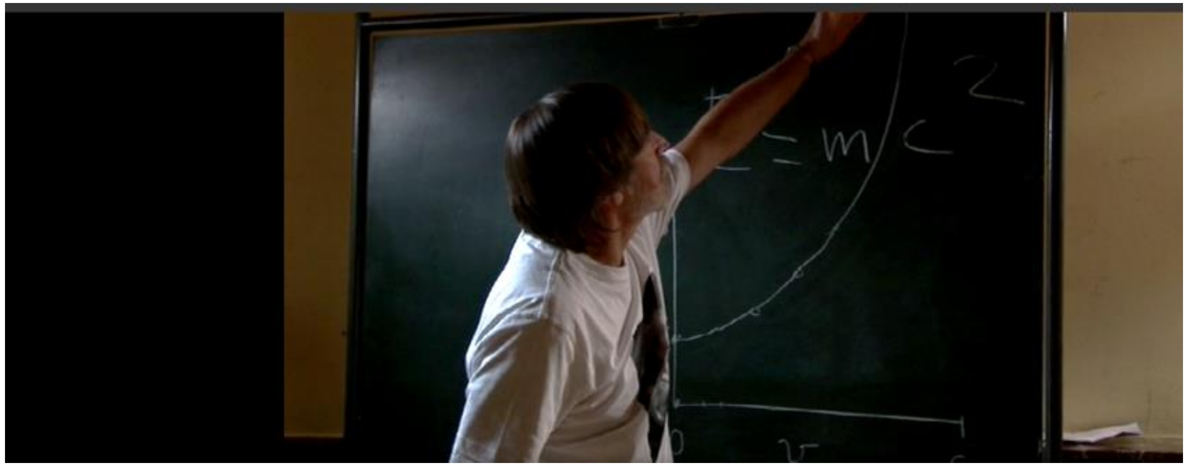
Arguiing with Albert in the laptop on the **TWIN PARADOX, at the Patent office - 1905**



Not only Álvaro got **Reversal-OF-Time**, also his laptop

Elementary, Dear Albert

→ BREAKING THE ARROW OF TIME

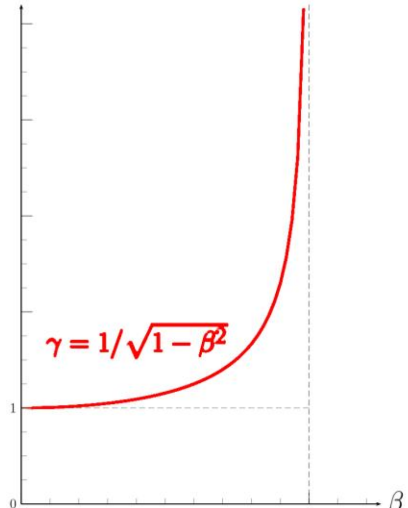


Discussing with Albert in the blackboard on the **SPEED LIMIT, at the Patent office 1905**

$$\gamma = (1-\beta^2)^{-1/2}$$

$$\gamma \equiv \frac{E}{mc^2} \in \ [1,\infty); \qquad \beta \equiv \ \frac{v}{c} \in \ [0,1)$$

V = c asymptote



OUTLINE

- **Before ÁLvaro's Era** → Pauli + Pontecorvo

- A selection of Álvaro's Highlights on **NEUTRINOS**

  . Absolute **ν-mass** and Dirac versus Majorana **nature**

  . **Neutrino-Exploration** of the Earth

  . Novel oscillation physics from **ν-Factories**

  . Prompt **ν**-Physics **in the TeV-range** at the collider mode of **LHC**

- **Pending issues** in NEUTRINO Physics

From Wolfgang Pauli to Lise Meitner

Original – Photocopie of PLC 0393

Abschrift/15.12.56 PM

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.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

[This is a translation of a machine-typed copy of a letter that Wolfgang Pauli sent to a group of physicists meeting in Tübingen in December 1930. Pauli asked a colleague to take the letter to the meeting, and the bearer was to provide more information as needed.]

Copy/Dec. 15, 1956 PM

Open letter to the group of radioactive people at the
Gauverein meeting in Tübingen.

Copy

Physics Institute
of the ETH
Zürich

Zürich, Dec. 4, 1930
Gloriastrasse

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, 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" (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 principle and that 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 mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

Now it is also a question of which forces act upon neutrons. For me, the most likely model for the neutron seems to be, for wave-mechanical reasons (the bearer of these lines knows more), that the neutron at rest is a magnetic dipole with a certain moment μ. The experiments seem to require that the ionizing effect of such a neutron can not be bigger than the one of a gamma-ray, and then μ is probably not allowed to be larger than $e \cdot (10^{-13}$ cm).

But so far I do not dare to publish anything about this idea, and trustfully turn first to you, dear radioactive people, with the question of how likely it is to find experimental evidence for such a neutron if it would have the same or perhaps a 10 times larger ability to get through [material] than a gamma-ray.

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time. But nothing ventured, nothing gained, and the seriousness of the situation, due to the continuous structure of the beta spectrum, is illuminated by a remark of my honored predecessor, Mr Debye, who told me recently in Bruxelles: "Oh, It's better not to think about this at all, like new taxes." Therefore one should seriously discuss every 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 servant

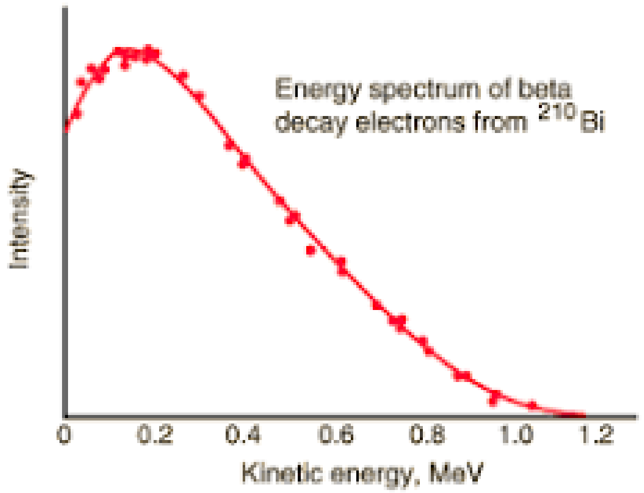
signed W. Pauli

[Translation: Kurt Riesselmann]

PRE-HISTORY

The legend about **Pauli** is not that of a kind personality, you can remember his sentence "You are not even wrong"...
However, his **recognition of Lise Meitner**, as the recipient of his letter, is scientifically **fair.**

- **1911 → Lise Meitner was**, with Otto Hahn, **the first** to measure the electron energy spectrum in nuclear beta decay → several different lines, suggesting a **continuous spectrum**.



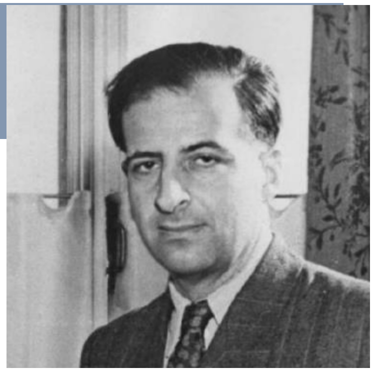
- **1914 →** James Chadwick, with a magnetic spectrometer, made more precise measurements

- **1927 →** Charles Drummond Ellis et al. → **continuous spectrum established**

→ Desperation: "iconoclast" Niels Bohr.

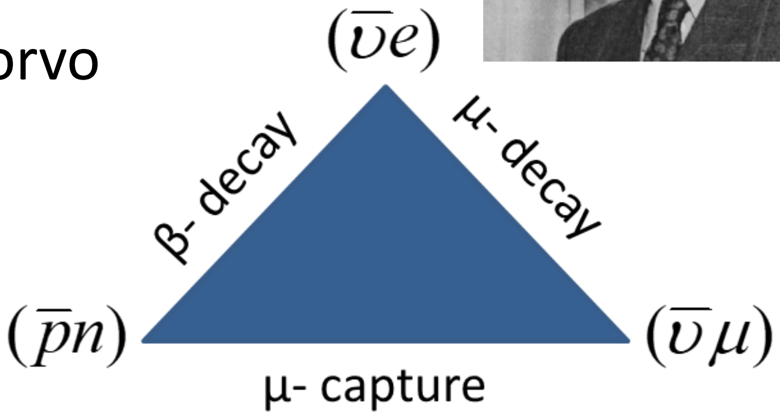
- **1930 → Pauli "neutron", renamed "neutrino" by Fermi**.

PONTECORVO's ERA: 1946-1980 -*The Lepton Family Problem*



. μ-e Universality

- **1947 →** a decade before V-A of CC weak interactions - Pontecorvo (at Chalk River Lab.) discussed it by **comparing muon captue** (Conversi et al. experiment)   **μ– + (A, Z) → ν + (A, Z – 1) with e-capture**, leading to the **Puppi triangle**.



. The Lepton Flavour Number

- **1956 → Cowan & Reines,** neutrinos detected, when Pontecorvo in Soviet Union since 1950.
- **1959 →** **Different $\nu_e - \nu_\mu$, Pontecorvo** in **"Electron and Muon Neutrinos"** + the concept of how to **prove the difference** is there.

- **1962 →** A direct proof of the existence of the **second (muon) neutrino** was obtained by Lederman, Schwartz, Steinberger et al. in the **Brookhaven experiment** with **accelerator neutrinos** from pion decay.

PONTECORVO's ERA: 1946-1980 - *Down's and Up's Neutrino Mass*

PV in processes involving neutrinos led to the advent of the **"Two-component neutrino theory".**
In terms of the chiral components of the neutrino field, Dirac equation → $i\gamma^{\mu}\,\partial_{\mu}\nu_L(x) - m\,\nu_R(x) = 0$

- m = 0 → the two components decoupled → **definite chirality-helicity**.

➢ **1957** → **Goldhaber experiment**, from e-capture → left-handed !
For muon neutrinos, in **1975** from μ-capture (JB, L. Grenacs, V. L. Telegdi)

- HOWEVER, **Universal V-A and Standard Model** → chiral field for all fermions → **no special status for neutrinos**.

- STILL, **the other fermions NEED both chiral fields** for e.m. intereactions ⟷ masses ≠ 0 .

- **Already in 1946 !!!** → Pontecorvo asked whether **antineutrinos** from reactors could produce **electrons**?

➢ **1956** → **First Davies experiment** $\bar{\boldsymbol{\nu}} + {}^{37}\boldsymbol{Cl} \overset{?}{\rightarrow} \boldsymbol{e}^{-} + {}^{37}\boldsymbol{Ar}$ NO!, using Pontecorvo **radiochemical method**.

⟹ **Assign an additive GLOBAL LEPTON NUMBER**

PONTECORVO's ERA: 1946-1980- *ν-Mixing and Oscillations*

. **Majorana Mixing**

- **1957 →** Pontecorvo writes: "If the theory of **two component neutrino** was **not valid**, and if the conservation law for **"neutrino charge" took not place, neutrino ⟷ antineutrino transitions would be possible**".

⟹ The two essential ingredients for oscillations found: **neutrino mass and mixing**. In these early ideas, Pontecorvo discussed oscillations in analogy with Gell-Mann & Pais for $K^0 - \overline{K^0}$ mixing and oscillations.

- Besides active ν_L and $(\bar{\upsilon})_R$, Pontecorvo assumed $(\bar{\upsilon})_L$ and ν_R with the name of **"sterile" neutrinos** → First Davis experiment: active ⟷ sterile $(\bar{\upsilon})_R$ ⟷ ν_R **mixing, an Appearance Experiment**.

- Reines-Cowan experiment: Pontecorvo calculates the Survival $(\bar{\upsilon})_R$ –L→$(\bar{\upsilon})_R$ as function of L → **KamLAND experiment in 2003!**

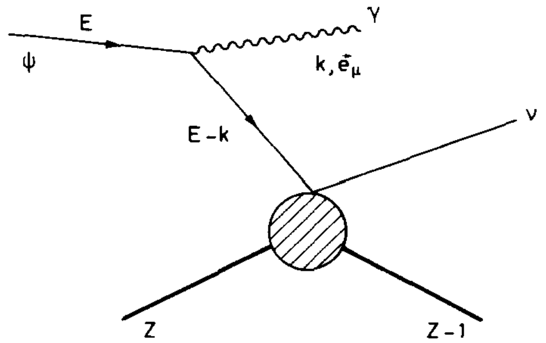
. Neutrino Oscillation Phenomenology

- **1967 →** After ν_μ → modern views, Pontecorvo Flavor Oscillatiobs, and applied to SOLAR NEUTRINOS → **Second Davies experiment → Pontecorvo predicted the "SOLAR ν-PROBLEM"**
- **1969 → Gribov & Pontecorvo →** Flavor Transition and Majorana Masses.
- **1976 → Bilenky & Pontecorvo → Flavor Oscillations in analogy to quark mixing and applied to reactor and Accelerator ν's.**

ALVARO's ERA: 1981 - A new way to measure ν Mass

ADR, NPB (1981)

→ The **SHAPE NEAR the end-point of the IBEC spectrum**



$$Z \rightarrow (Z-1)^{H} + \nu_e + \gamma(bremss)$$
$$\hookrightarrow (z-1)^{H'} + X_{HH'}$$

$$m^2_{\nu_e} \equiv \sum_i |U_{e\,i}|^2 \;\; m_i^2$$

Feynman-Stueckelberg

IBEC process, in coincidence with X(HH')

- **Large FRACTION OF EVENTS** near the end-point of spectrum
  ↔ **Small Q-value** →low n=1 capture forbidden → large half-life

  +
- **Selection Rules** in Angular Momentum States → E1-radiation
  for virtual e-transition in **atomic environment**
- Possible **RESONANT ENHANCEMENT** for nP capture: iff Q ~ E(n'S)

ALVARO's ERA: 1981 - A new way to measure ν Mass

IBEC theory BELOW the X-ray region
(à la Glauber & Martin)

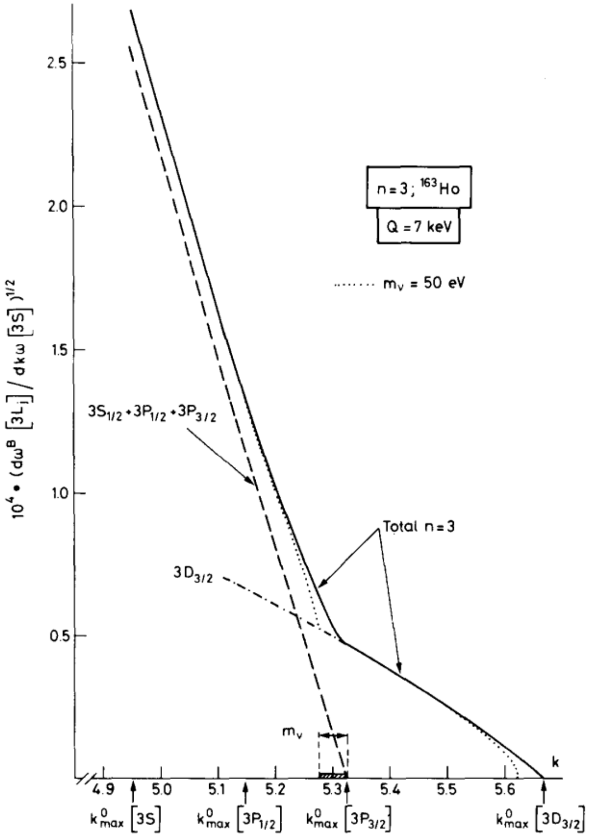
- For "allowed" nP radiative capture:

  Two good candidates →
  $^{193}Pt_{78}$, $^{163}Ho_{67}$

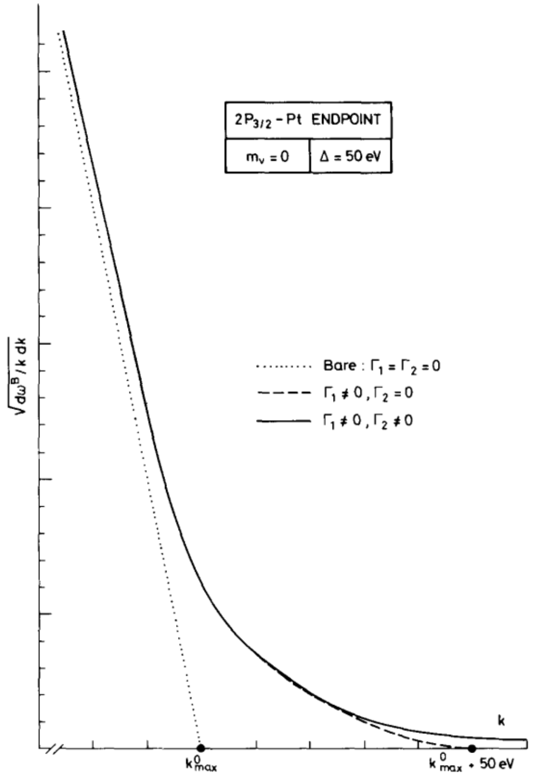
- ^{163}Ho → ^{163}Dy, n=3
  IBEC from M-shell = 3P

- ^{193}Pt → ^{193}Ir, n=2
  IBEC from L-shell = 2P

- **CONCLUSION at that time →**
  m_ν ~ eV could become observable



n = 3 IBEC end-point
for ^{163}Ho



Effects of natural widths
for $2P_{3/2}$ IBEC in ^{193}Pt
in coincidence with one X-ray

A LIMIT ON m_{ν_e}: ^{163}Ho

ADR in Aarhus-CERN Collaboration at the ISOLDE Facility, PLB (1982)

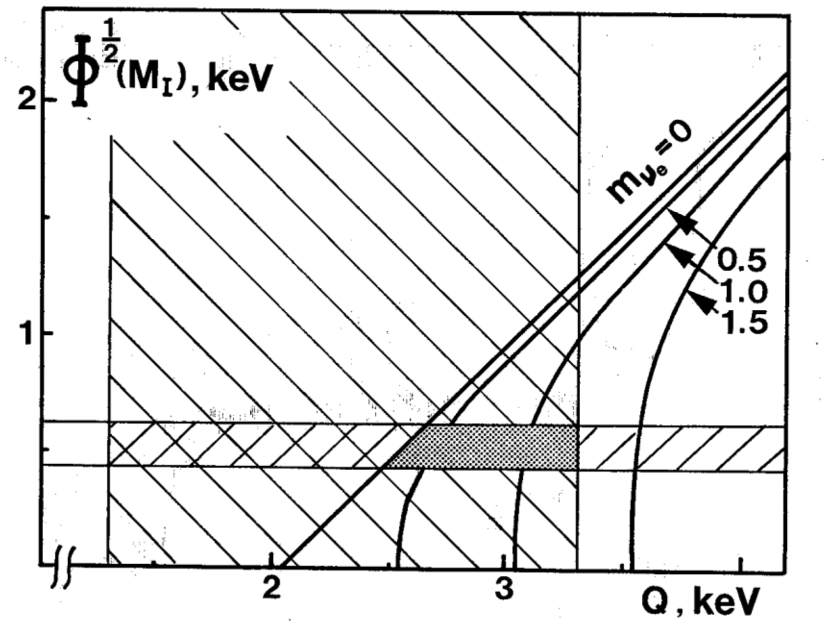
- ^{163}Ho → ^{163}Dy EC : **Q-value ???**
- Two complementary experiments

- M-capture partial rate T(M)$_{1/2}$ = (4.0 ± 1.2). 10^4 y
+ nuclear matrix element →

PHASE SPACE Factor

$$\phi(M_I) = (Q-E(M_I))\,[(Q-E(M_I))^2 - m^2]^{1/2}$$

- Independent determination of **Q from nuclear reactions**



Plot of $\phi^{1/2}$ (M_I) versus Q for different assumptions on the neutrino mass. The cross hatched area corresponds to the limits set by the two present experiments and gives an upper limit $m_{ve}\, c^2$ < 1.3 keV

RECORD Q = (2.3 ± 1.0) keV and Half-life (7 ± 2).10^3 y → m_{ν_e} < 1.3 keV

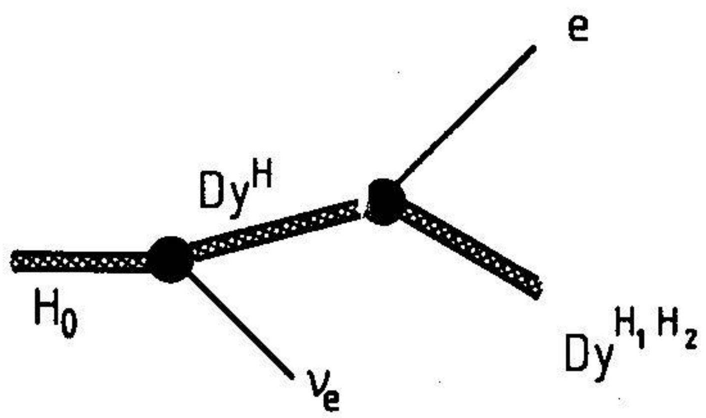
SEEEC for ν_e mass

The spectral e- end-point of three-body

ADR, M. Lusignoli, MPB (1983)

$^{163}H_0 \rightarrow {}^{163}Dy^{H} + \nu_e$

$\quad\quad\quad \hookrightarrow {}^{163}Dy^{H_1 H_2} + e^-$



Similar to IBEC, but $Dy^{H_1 H_2}$ ion

- $m(\nu_e)$ dependence in

$$\frac{dw(H_1H_2)}{dE\alpha|M(H_1H_2)|^2\ E_\nu p_\nu} = |M(H_1H_2)|^2(E_{end}-E)\sqrt{(E_{end}-E)^2-m_\nu^2}$$

$$E_{end}(H_1H_2) \cong Q - E(H_1) - E(H_2)$$

Superposition of channels **with different** $E_{end}(H_1\ H_2)$
$M(H_1, H_2)$ dominated by **nearby resonances** $\rightarrow$

$$\mathbf{E_{max} - E_{res} \approx Q\text{-}E(M_I)}$$

CALORIMETRIC MEASUREMENTS OF EC ^{163}Ho DECAY

ADR, M. Lusignoli, PLB18(1982)

“**Calorimetric” energy spectrum** means $^{163}Ho \rightarrow \nu_e\ (E_\nu) + {}^{163}Dy^H$

$\hookrightarrow {}^{163}Dy + E_c$

allows an spectrum with $\boxed{Q = E_\nu + E_c}$

→Neutrino recoiling against a **series of states with non-zero widths.**

- EC from H=nS, n $P_{1/2}$; n>2
- Dy^H decays predominantly by electron de-excitations **H→ H’ H’’ e$^-$**
  (Coster –Kronig transitions and Meitner-Auger emission)

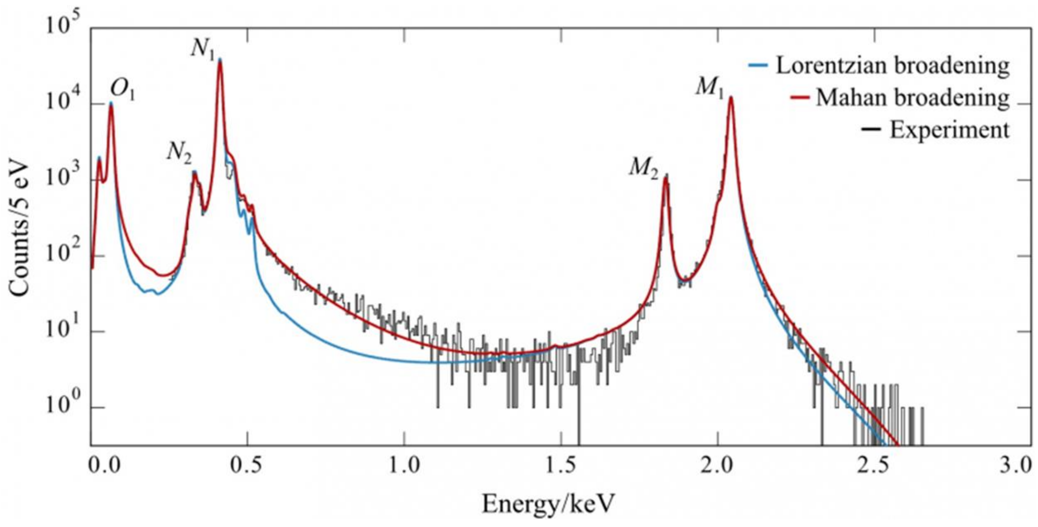
→ **Determination of Q-value.**

End-point of EC-spectrum resonant-enhanced by proximity to M_I binding

CALORIMETRIC SPECTRUM: ^{163}Ho EC-decay

ADR, M. Lusignoli, JHEP (2016)

- Optimal nuclide ^{163}Ho → H ≥ M orbitals
- Best experimental technique → calorimetric
- Theory → Sum over B-W contributions from different H → Reasonable **(ECHo, HOLMES, Nu-MECS experiments)** near single peaks spectrum



- When feeble -tail- resonance enhancement near the end-point
  ⇨ **SHAKE-OFF** effect (Robertson, PRC (2015)) ↔
  H-state is NOT stationary of ^{163}Dy: It has an important contribution near the end-point.

- e- ejection to the continuum from a secondary hole H' in "sudden" perturbation

  Ho → Dy[H, H'] + e^- + ve

- E_t = Dy ion energy excess ⇨

$E_\nu + T_e = Q - E_t$ → **Calorimetric** $E_c = T_e + E_t$

- Need of measurements in the relevant energy domain →

from the single peaks to the spectral end-point shape

- $\tau_{1/2} \cong 4570$ years
- **$Q_{EC} = (2.833 \pm 0.030_{stat} \pm 0.015_{syst})$ keV**

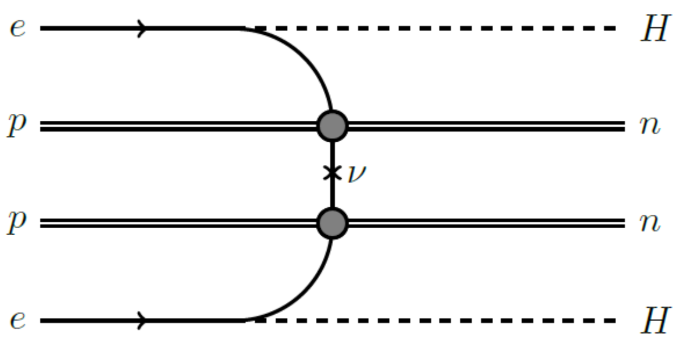
S. Eliseev et al., PRL (2015)
F. Schneider et al., EPJA (2015)

Neutrinoless Double Electron Capture

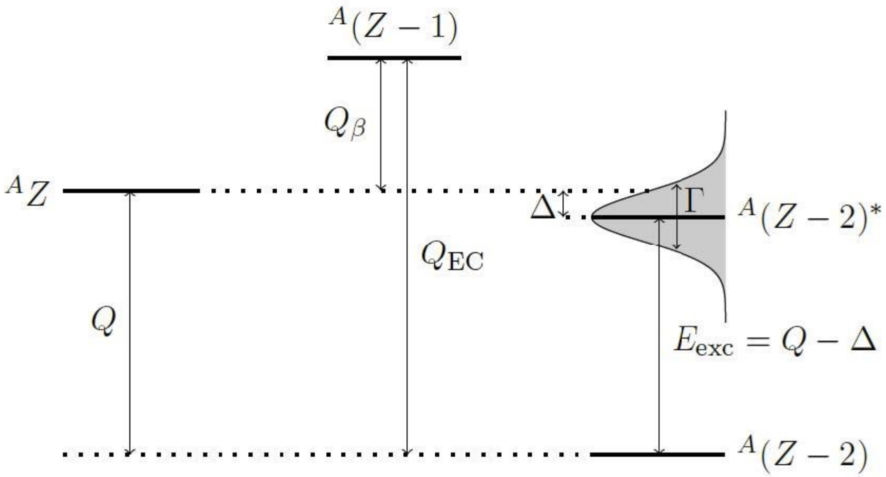
JB, ADR, C. Jarlskog, NPB (1983)

Atom Mixing $^{A}Z \rightarrow {}^{A}(Z-2)^*$

$$m_{\beta\beta} \equiv \sum_i U_{ei}^2 \, m_{\nu_i}$$



Majorana Mixing $M_{21} \sim m_{\beta\beta}^* \langle F_{21} \rangle M_{0\nu}$



- $\Delta L = 2$ mixing, only if Majorana ν, followed by 2 X-ray emission
- Signature: $T_{\gamma\gamma} = Q$

- No intrinsic background **on resonance, enhancement**

$$\frac{^{152}\mathrm{Gd} \rightarrow {}^{152}\mathrm{Sm}}{\Delta \sim 30\,\Gamma}$$

Eliseev et al, PRL (2011)

$$\Delta \sim \Gamma$$

ATOM MAJORANA OSCILLATIONS

Two–state Hamiltonian

$$\mathbb{H} = \mathbb{M} - \frac{i}{2}\mathbb{\Gamma} = \begin{bmatrix} M_1 & M_{21}^* \\ M_{21} & M_2 \end{bmatrix} - \frac{i}{2}\begin{bmatrix} 0 & 0 \\ 0 & \Gamma \end{bmatrix}$$

$$[\mathbb{M}, \mathbb{\Gamma}] \neq 0$$

$$\langle \lambda_S | \lambda_L \rangle = \alpha - \beta$$

Non-orthogonal eigenstates:

$$|\lambda_L\rangle = |1\rangle + \alpha\,|2\rangle\,, \quad E_L \approx M_1\,, \quad \Gamma_L \approx |\alpha|^2\,\Gamma\,,$$

$$|\lambda_S\rangle = |2\rangle - \beta^*\,|1\rangle\,, \quad E_S \approx M_2\,, \quad \Gamma_S \approx \Gamma\,.$$

$$\alpha = \frac{M_{21}}{\Delta + \frac{i}{2}\Gamma}$$

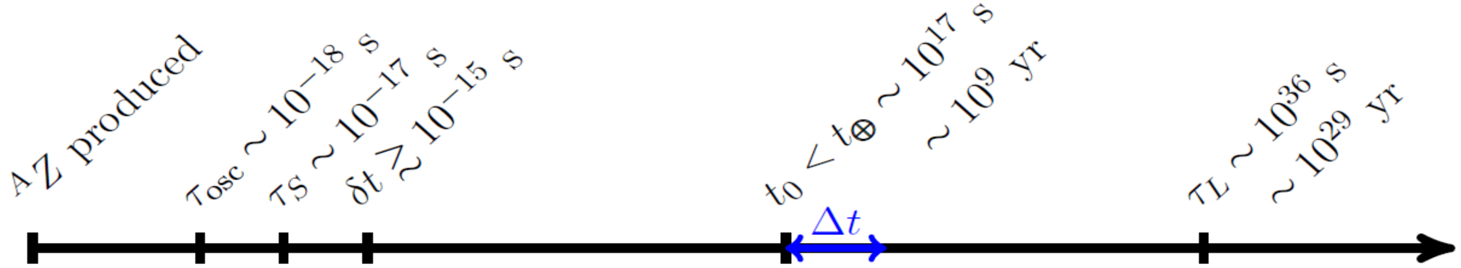
$$\beta = \frac{M_{21}}{\Delta - \frac{i}{2}\Gamma}$$

$$\left|\langle {}^A(Z-2)^* | {}^A Z(t) \rangle\right|^2 = |\alpha|^2 \left\{1 + e^{-\Gamma t} - 2e^{-\frac{1}{2}\Gamma t}\cos(\Delta \cdot t)\right\}$$

Different time-scales given by $|\Delta|$, Γ and Γ_L

For observable times, the system has evolved to three “stationary” states

$$\tau_S \ll t \ll \tau_L \quad \Longrightarrow \quad \begin{cases} P_L(t) \approx 1 - \Gamma_L\, t \\ P_S(t) \approx 0 \\ P_{\text{g.s.}}(t) \approx |\alpha|^2\,\Gamma\, t \end{cases}$$



0ν 2EC Recent Novelties

- **Q-value with Penning Traps** ^{152}Gd, ^{156}Dy, ^{164}Er, ^{180}W
  L. Blaum, S.Eliseev et al., Rev. Mod. Phys. 92(2020)

- $M_{0\nu}$ from nuclear **QRPA** (Faessler et al, PRC(2012)) and **IBM** (Iachello et al, PRC (2014))

- **XFEL- stimulated X-ray emission, natural population inversion at observable times**
  J.B, A. Segarra, JHEP (2018)
  No resonant cavity; nano-focusing feasible (M. Altarelli)

- **2ν 2EC observation in ^{124}Xe**
  XENON Collaboration, E. Aprile et al., Nature 568 (2019)

- **Shake-off** in ^{164}Er 0ν 2EC → **Auto-ionization** of the $e^{-}-shell$
  F.F. Karpeshin et al., PRC (2022)

NEUTRINO EXPLORATION OF THE EARTH

ADR, S. Glashow, R. Wilson, G. Charpak, Phys. Rep. (1983)

Proposal of the **GEOTRON**, a MOBILE CIRCULAR SUBMARINE ACCELERATOR AT ~ 10 TeV ! → COLLIMATED **ν BEAM FROM MESONS**

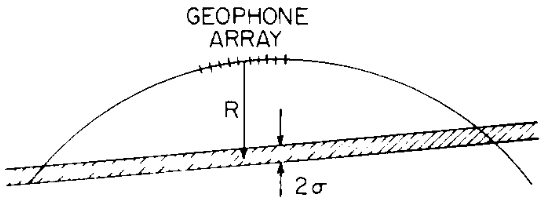
- Why ~TeV neutrinos ? → **range in matter ~ size of the Earth**

ν-interactions with the medium → signal to be interpreted for useful information in 3 projects:

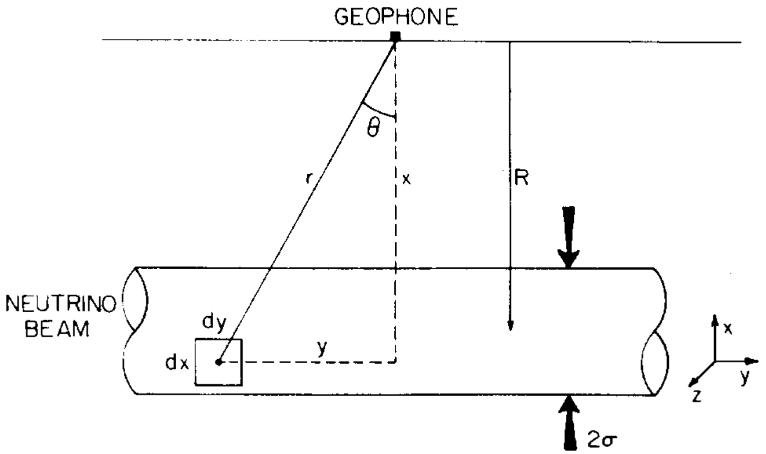
- (1) With the GEOTRON at small declination angle → **GENIUS** → Search for deposits of oil or gas → ν-energy converted into ionizing radiation

→ **Underground Coherent SOUND**

→ SOUND signal generated **at ~1000 Km from the GEOPHONE ARRAY detector**



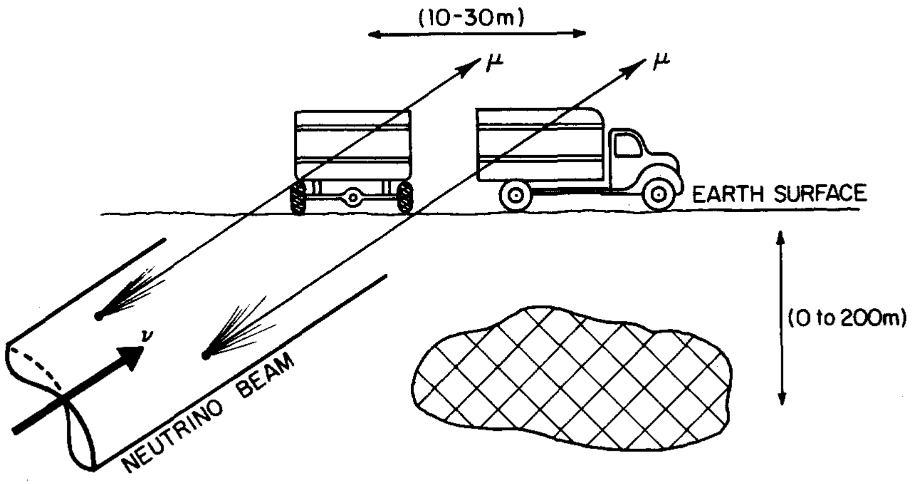
(a)



(b)

NEUTRINO EXPLORATION OF THE EARTH

- (2) Again the **GEOTRON at small declination angle** → **GEMINI** → Search for deposits of high-Z ores →
  Muons induced by ν-interactions at ~ 100 m. from the truck-mounted detector



- (3) With the **GEOTRON** deflected to **VERTICAL** inclination → **GEOSCAN** →
  Vertical Profile of the **Density of the Earth**, especially of its core →

  Attenuation of the ν- beam, ~ %, upon E(ν) → EFFECT of ν-ATTENUATION UPON THE SURFACE MUON FLUX
  (Proposed in 1983 ! → Alternative post MATTER-EFFECT in ν-oscillations)

. **Conceptual Designs of ALL** components for the 3 Projects, including Technical solutions ↔ IMPRESSIVE !!!

THREE-FAMILY OSCILLATIONS WITH A NEUTRINO FACTORY

ADR, B.Gavela, P. Hernández, NPB (1999)

- Importance of **charge identification in the detector** with the strategy of **APPEARANCE OF WRONG SIGN MUONS**
- Difference between 2-family mixings (atmospheric θ_{23}, solar θ_{12}) and 3-family mixing from $\mu^- \to e^- \ \nu_\mu \ \bar{\nu}_e$
- **2-family dominance**
  - No need of charge identificacion

$$\bar{\nu}_e \to \bar{\nu}_e \to e^+ \ normalization,$$
$$\nu_\mu \to \nu_\mu \to \mu^- \ disappearence,$$
$$\nu_\mu \to \nu_\tau \to \tau^- \ appearance$$

- **3-family connected (θ_{13})**,
  - even with Δm^2_{21} neglected ,

$$\bar{\nu}_e \to \bar{\nu}_e \to e^+ \ disappearance$$
$$\bar{\nu}_e \to \bar{\nu}_\mu \to \mu^+ \ appearance$$
$$\bar{\nu}_e \to \bar{\nu}_\tau \to \tau^+ \ appearance \ (\tau^+ \to \mu^+; \ e^+)$$
$$\nu_\mu \to \nu_\mu \to \mu^- \ \text{disappearance}$$
$$\nu_\mu \to \nu_e \to e^- \ \text{appearance}$$
$$\nu_\mu \to \nu_\tau \to \tau^- \ \text{appearance} \ (\tau^- \to \mu^-; \ e^-)$$

- **Recommendation → Better $\nu_e \leftrightarrow \nu_\mu$ oscillations, with wrong sign muon appearance, rather than difficult $\nu_\mu \to \nu_\tau$**

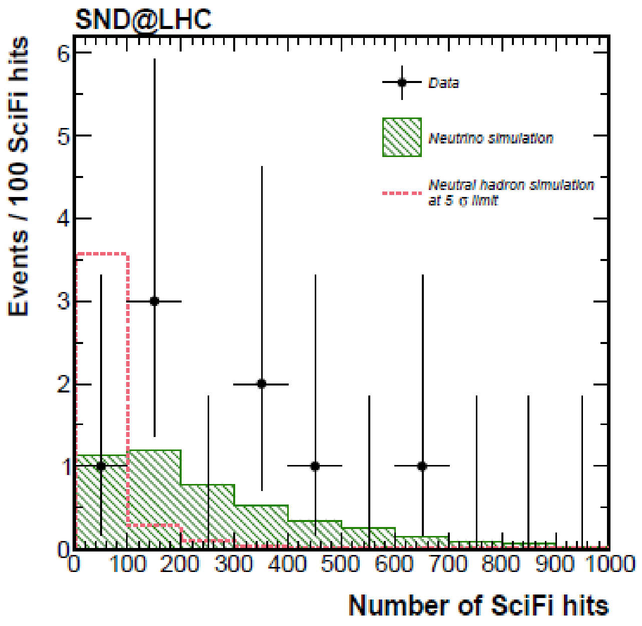
PROMPT FORWARD NEUTRINOS AT COLLIDERS

- **ADR et al, SND@LHC Collaboration, PRL (2023), EPJC (2024)**
- ADR, E. Fernández, J. Gómez-Cadenas, NPB (1993)
- ADR, R. Ruckl, SSC Workshop, CERN (1984)

- Measurements with **neutrinos produced in p-p collisions at the LHC,**
E_ν ~ 100 GeV - 1 TeV

- **Detector** → 480 m downstream of ATLAS intersection point: tungsten plates interleaved with emulsion and SciFi trackers, hadronic calorimeter and Muon System

- **Observation of muon neutrinos in the active electronic components**



- Identified from CC interactions → track through the detector length

PROMPT FORWARD NEUTRINOS AT COLLIDERS

- **8 ν_μ interaction events → 7 σ significance**
- **Background** from muon-induced (EPJC(2024)) and neutral hadrons (neutrons and K_L) produced by muons in the rock
- Very forward flux (η > 7) from b, c decays
- Off-axis set-up → enhancing ν-flux from charm
- p-p $\sqrt{s}$ = 13.6 TeV ↔ LHC Run 3 ($\mathcal{L}$ = 250 fb^{-1})
- **$O(10^{12})$ neutrinos in the far forward, E_ν up to a few TeV**
- **Precise SM tests and probe for NP with high-energy neutrinos**

PENDING ISSUES IN NEUTRINO PHYSICS

- Neutrino Flavour Oscillations observed in atmospheric, solar, reactor and accelerator sectors have demonstrated that

NEUTRINOS HAVE MASS AND FLAVOUR MIXING

Two mass differences and Three Mixings already measured: $|\Delta m^2_{32}|, \Delta m^2_{21}, \theta_{ij}$

- Most important Open Questions:

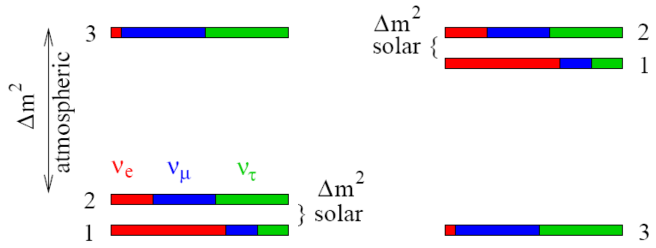
ARE NEUTRINOS DIRAC OR MAJORANA PARTICLES ?

$\bar{\nu}_R \; m_D \; \nu_L$	$\overline{\nu_L^C} m_M \, \nu_L$
Needs sterile ν_R	*Breaks Global Lepton Number*
Origin by Standard Higgs Doublet	*Without* ν_R → *Beyond Standard Origin*

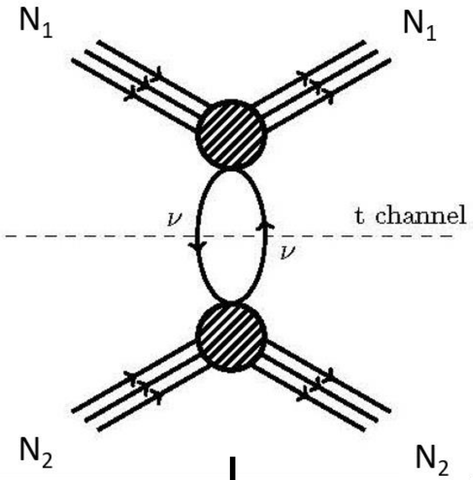
- CP-Violating Flavour Phase and (?) Two CPV Majorana Phases **U(PMNS)**

$$U=\begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix}\begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix}\begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{bmatrix}$$

- Absolute Neutrino Mass Scale
- Neutrino Mass Spectrum Hierarchy → normal, inverted
- (2,3) Mixing above or below 45 degrees?



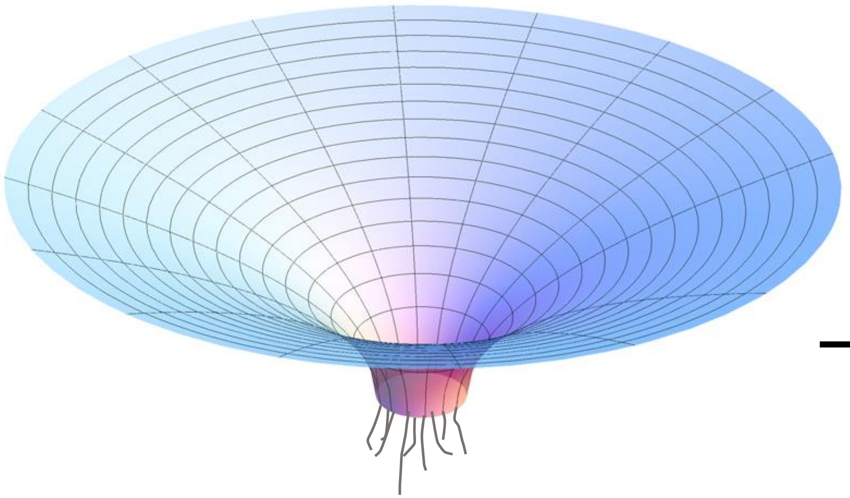
Neutrinos prevent space-time breakdown



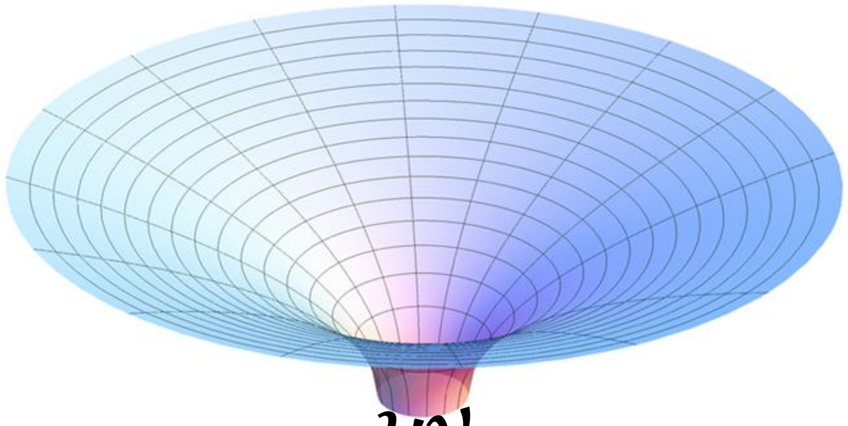
$\nu\ \nu$

NESP

JB, 2312.09419 [physics.gen-ph]



Space-Time Singularity



$\nu\nu$

Universal Equilibrium at $R_B \sim$ nm

FLAMM's PARABOLOID

Ilustrated by TAndreu

THANK YOU VERY MUCH FOR YOUR ATTENTION

AND

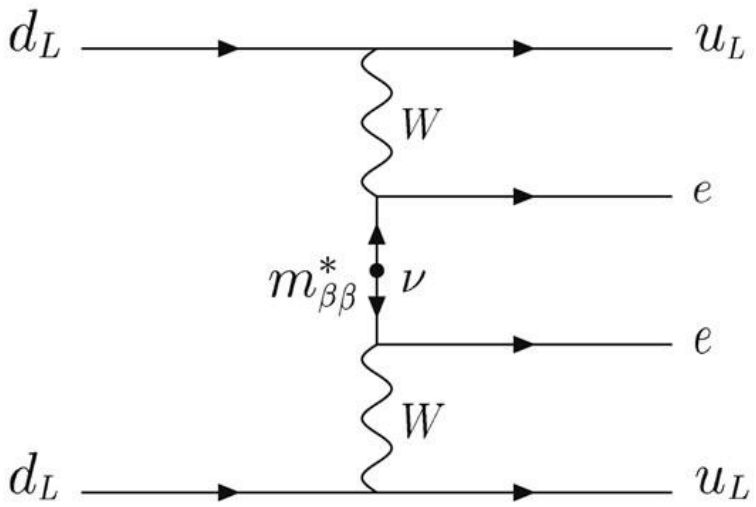
THANK YOU, ÁLVARO, FOR BEING THERE

BACK UP

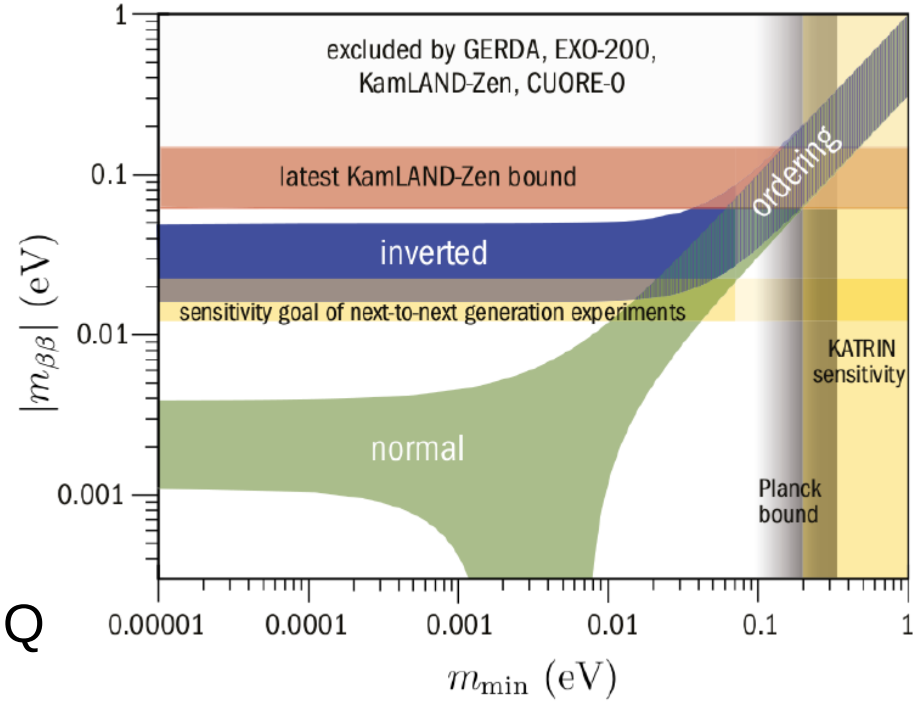
Neutrinoless Double BetaDecay

$${}^{A}Z \rightarrow {}^{A}(Z+2) + 2e^{-}$$

$$m_{\beta\beta} \equiv \sum_i U_{ei}^2\, m_{\nu_i}$$



[S. Pascoli, CERN Courier, July-August 2016]



- ΔL=2 process, only if Majorana ν
- Signature: $T_{ee} = Q$
- Background by 2ν mode with $T_{ee} < Q$