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Neutrino: Opening New Doors

the strengths of neutrino physics discussed via its results

Francesco Vissani
INFN, Laboratori Nazionali del Gran Sasso

introduction

Neutrino science is approaching its centenary and thus seems to be moving towards a stage of **maturity**

Yet, even thinking only of the previous main conference (Nu2024) we heard

- of very high energy events by cosmic neutrinos,
- of possible hints of supernovae throughout the history of the universe,
- of strong new limits on neutrino mass, from the laboratory and cosmology,
- of significant progress in the search for Majorana's mass...

In short, this interdisciplinary science continues to produce results and promise, i.e. innovation. As an introductory contribution to the session *'Crossing the portal'* my proposal is to discuss these important aspects

Is all fine as it is, or do we risk of missing out on something important?

on the margins of ambiguity

- concepts that we contrast with interdisciplinary

insubstantial inadequate restricted incomplete exclusive narrow standard specific defined precise fundamental

From short-sighted to essential

- concepts that we contrast with innovation

stagnation repetition conventionalism orthodoxy preservation maintenance conformity tradition

From obstructive to reliable

on the margins of ambiguity

- concepts that we contrast with interdisciplinary

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From short-sighted to essential

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From obstructive to reliable

— meaning shifts from bad to good! —

exposure plan

interdisciplinarity and innovation in neutrino physics

- essential history notes
- cases from astrophysics
- cases from particle physics
- doubtful cases
- discussion

essential history notes

innovation

neutrinos and the foundations of nuclear and particle physics

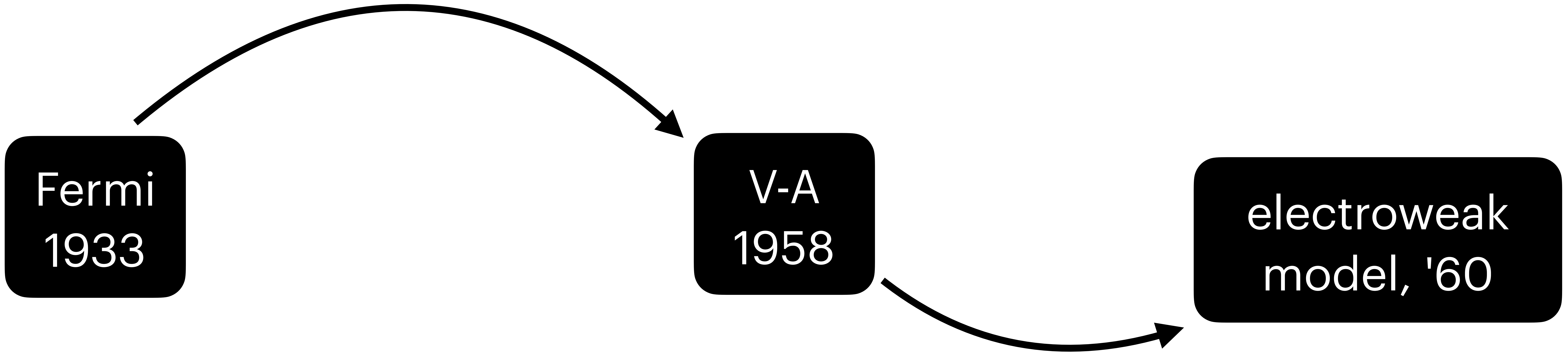
- **Pauli 1930**: non-relativistic model of the nucleus with a ghost-like particle of matter: the first concept of the neutrino
- **Perrin 1933:** neutrino can be better thought of as a *wave* just as the photon (in line with Ambarzumian & Iwanenko 1930, who talk of the electron)
- **Fermi 1933**: relativistic model of β decay with second quantisation method based on the Dirac sea, where $\nu \neq \bar{\nu}$ necessarily
- **Majorana 1937:** devises modern QFT for fermions, points out the possibility $\nu = \bar{\nu}$, resembling the photon

PS the description / understanding of β rays emission became particularly urgent in 1932, after neutron discovery and novel model of the nucleus

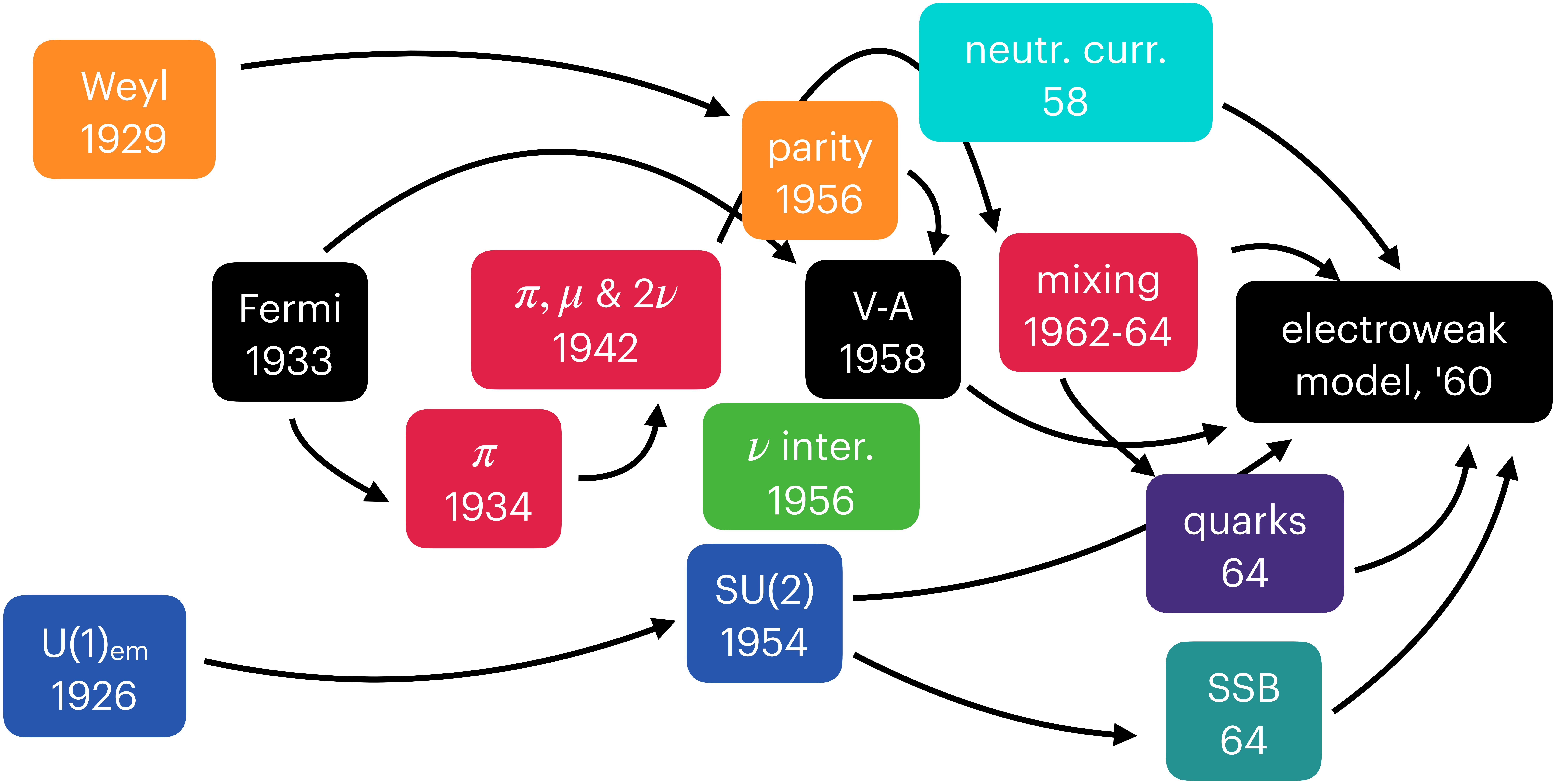
interdisciplinarity
astrophysics and cosmology

- **Bethe '30:** neutrinos - if they exist - are *unobservable* (1934, with Peierls); neutrinos *non-essential* energy-loss; *CNO dominant* in stars (1939) as H=35%, N=10%
- **Gamow '40 (+$\alpha\beta HS$):** neutrinos are important for **stars** (1940) and **cosmos** (1948)
- **Pontecorvo '46:** idea to **measure solar neutrinos** although the neutrinos known at the time all have small xsec
- **Fowler et al '58:** the PP chain branches giving rise also to ^{7}Be and ^{8}B neutrinos, with higher energy, and thus better **detectable**

PS When it was realised that PP chain is dominant? The key remark is Payne 1925. Bahcall says that this was the general belief in '50. Given for granted in B2FH



neutrino interactions (short version)

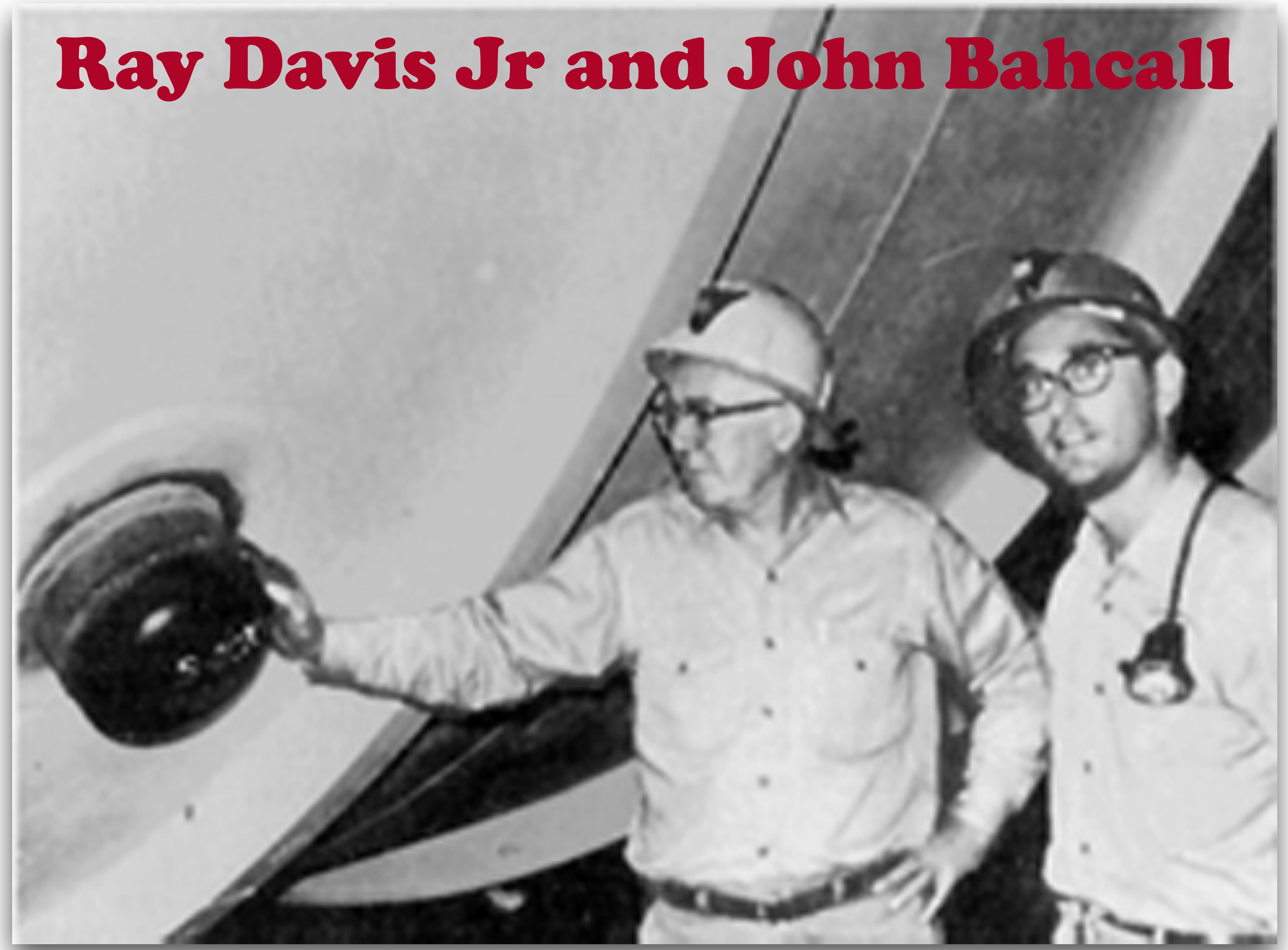


Weyl 1929
neutr. curr. 58
parity 1956
Fermi 1933
π, μ & 2ν 1942
V-A 1958
mixing 1962-64
electroweak model, '60
π 1934
ν inter. 1956
quarks 64
SU(2) 1954
U(1)$_{em}$ 1926
SSB 64

cases from astrophysics

Homestake & SSM

- In mid '60, **Ray Davis Jr** & **Bahcall** lead the first serious effort to observe solar neutrinos
- This is a theoretical, experimental, astrophysical *nuclear physics* enterprise
- 20 years reservations on the **solar neutrino deficit**, especially from particle physicists
- The **standard solar model** will provide (and still provides) guidance and inspiration
- This is true, e.g., for SNO, as documented by Herbie Chen' proposal (1985)



KamiokaNDE

- **Koshiba** initially a CR physicist ('50) then at accelerators ('70). He met Yukawa, Nambu, Feynman, Fermi, Occhialini, Sugawara, Sato, Arafune...
- KamiokaNDE, motivated by *GUT theory* (NDE=Nucleon Decay Experiment) begun in '80 thanks to the photomutipliers he projected [photo from Nobel lecture]
- Results: **SN1987A & hints of neutrino mass** with atmospheric neutrinos
- The latter is considered **seriously.** In '96 the experiment grows into Super-KamiokaNDE (NDE=Neutrino Detector Experiment)

one remark on SN1987A

Supernovae are a very interesting undertakings for theorists and experimenters interested in neutrinos. C. Volpe will discuss this, I will not dwell on it.

However I would like to emphasise a result on SN1987A, which illustrates once more and most clearly the importance of interdisciplinarity.

There has been much debate as to whether this supernova is 'standard'. Probably the hottest questions, until recently, concerned the absence of an ***identifiable neutron star.***

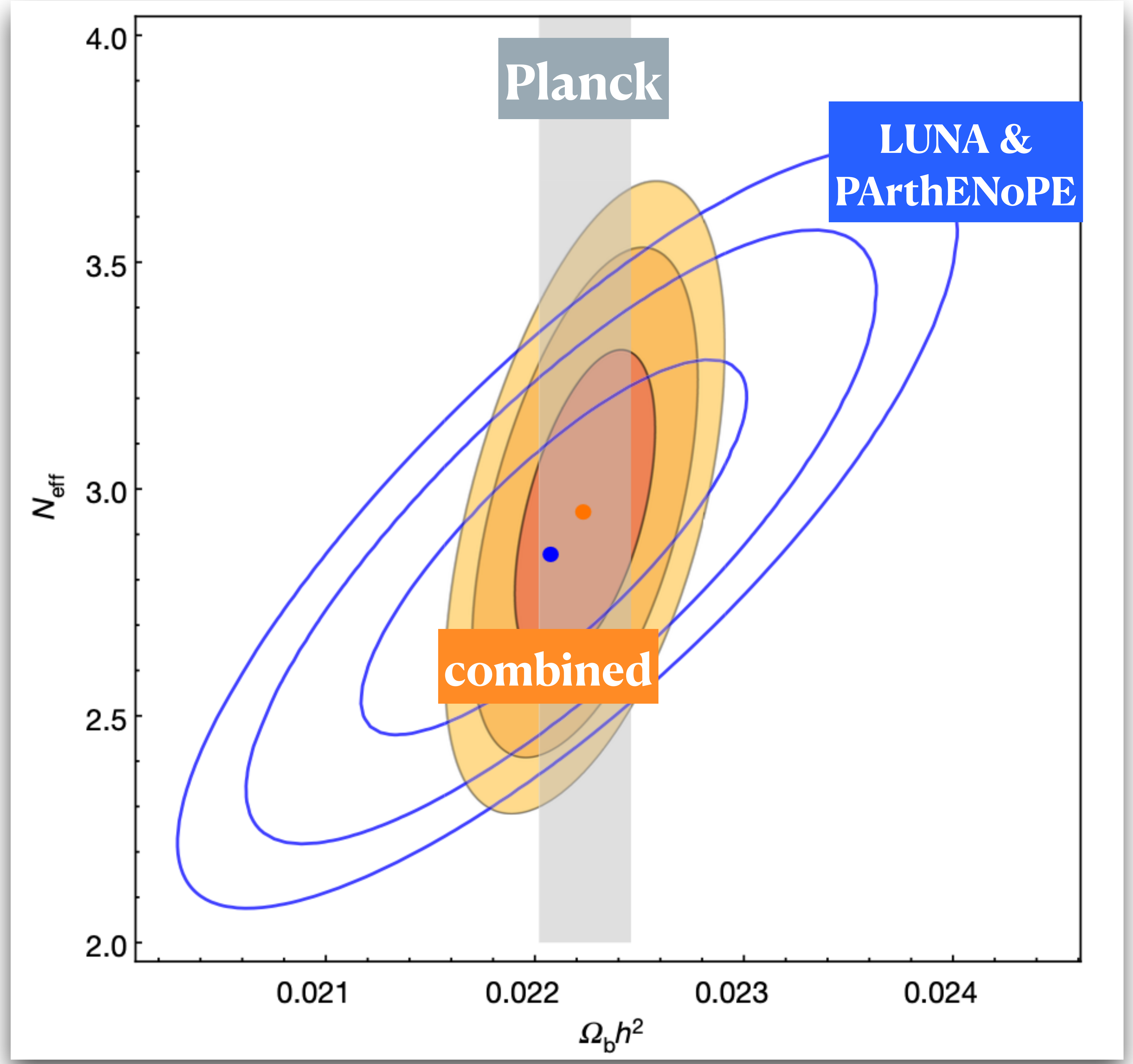
But guided by the astrophysical simulations of 2015 of Miceli, Orlando et al., the first hints of such a star have been found eventually. No need to say that this result is very important for many disciplines

The measurement of 4/5 individual components of the PP chain and the test of the CNO cycle are extraordinary results, enabled by the care taken in preparing the detector. Much goes to due to G.Bellini and the staff of Borexino, including A. Ianni, N. Rossi, O. Smirnov, ... however

- equally exciting geo-neutrino results were reached with the help of *F. Mantovani, M. Lissia, G. Fiorentini* ('03)
- a useful contribution for CNO was given by *L'Aquila theoretical group, F. Villante et al.* ('11)
- the PhD theses by *S. Marcocci, I. Drachnev, X. Ding and D. Guffanti ('16-'19)* deserve being commended

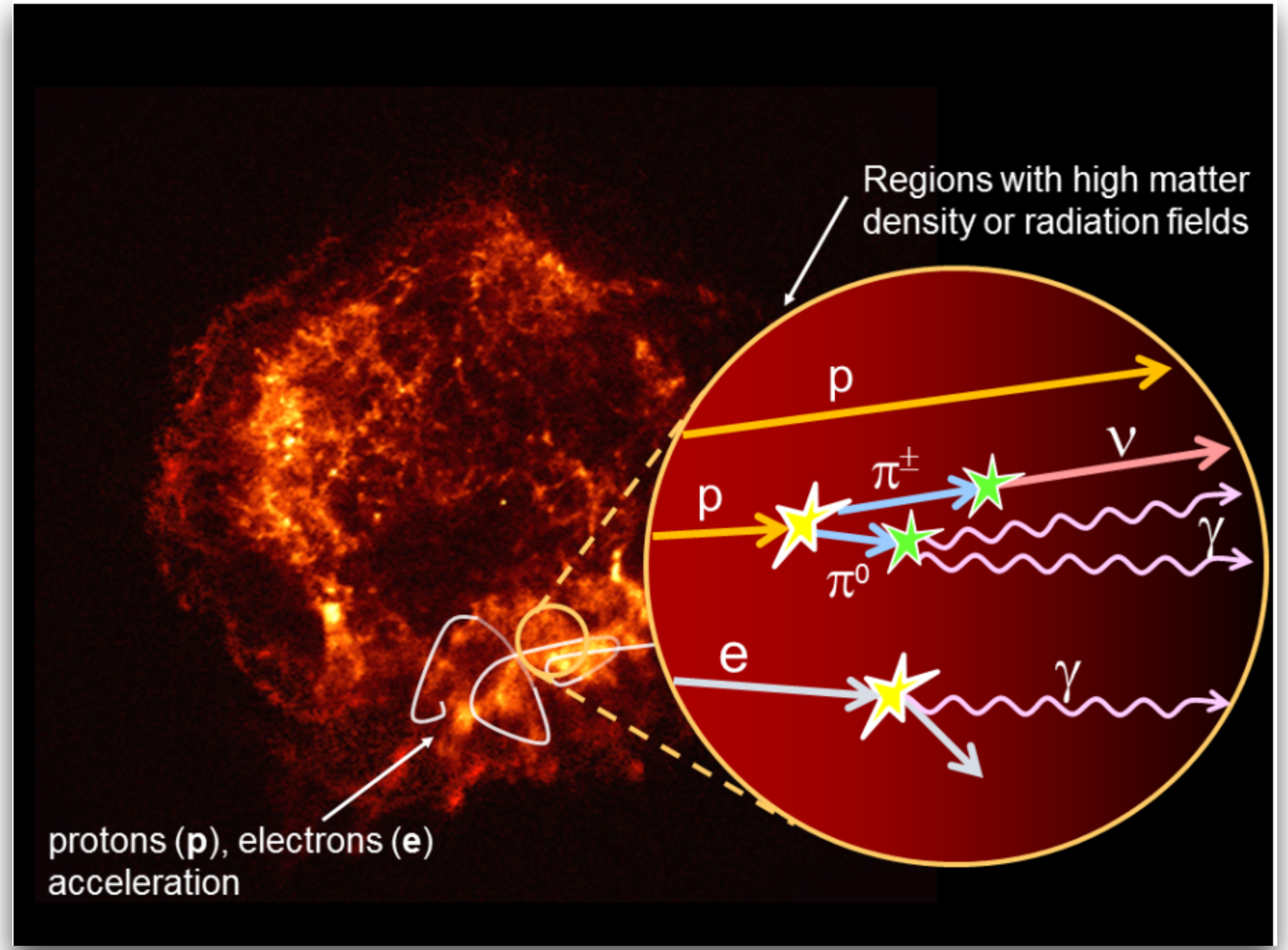
LUNA & PArthENoPE

- an improved description of deuterium dynamics in early universe conditions was obtained by LUNA
- this allowed the BBN simulations of PArthENoPE, based on Gamow's ideas, to claim a good agreement with **baryon mass fraction** $\Omega_b h^2$
- moreover this has implications on the **number of neutrinos** N_{eff} see figure



from Nature 2020

IceCube, Km3NET, GVD...



- Observatories for high-energy neutrinos and gamma rays, produced as *secondary radiation* by CR, were conceived in the late 1950s
- Icecube results finally revealed a **signal** attributable to cosmic neutrinos of this type, even w/o arriving at a clear understanding of what the sources are
- ***New tests are needed***, they'll carried out in Km3NET and elsewhere with much more precise pointing and ability to investigate the Milky Way accurately
- Also explore *extreme environments, high pressures,* allow new science *marine, glaciology, geophysics...*

cases from particle physics

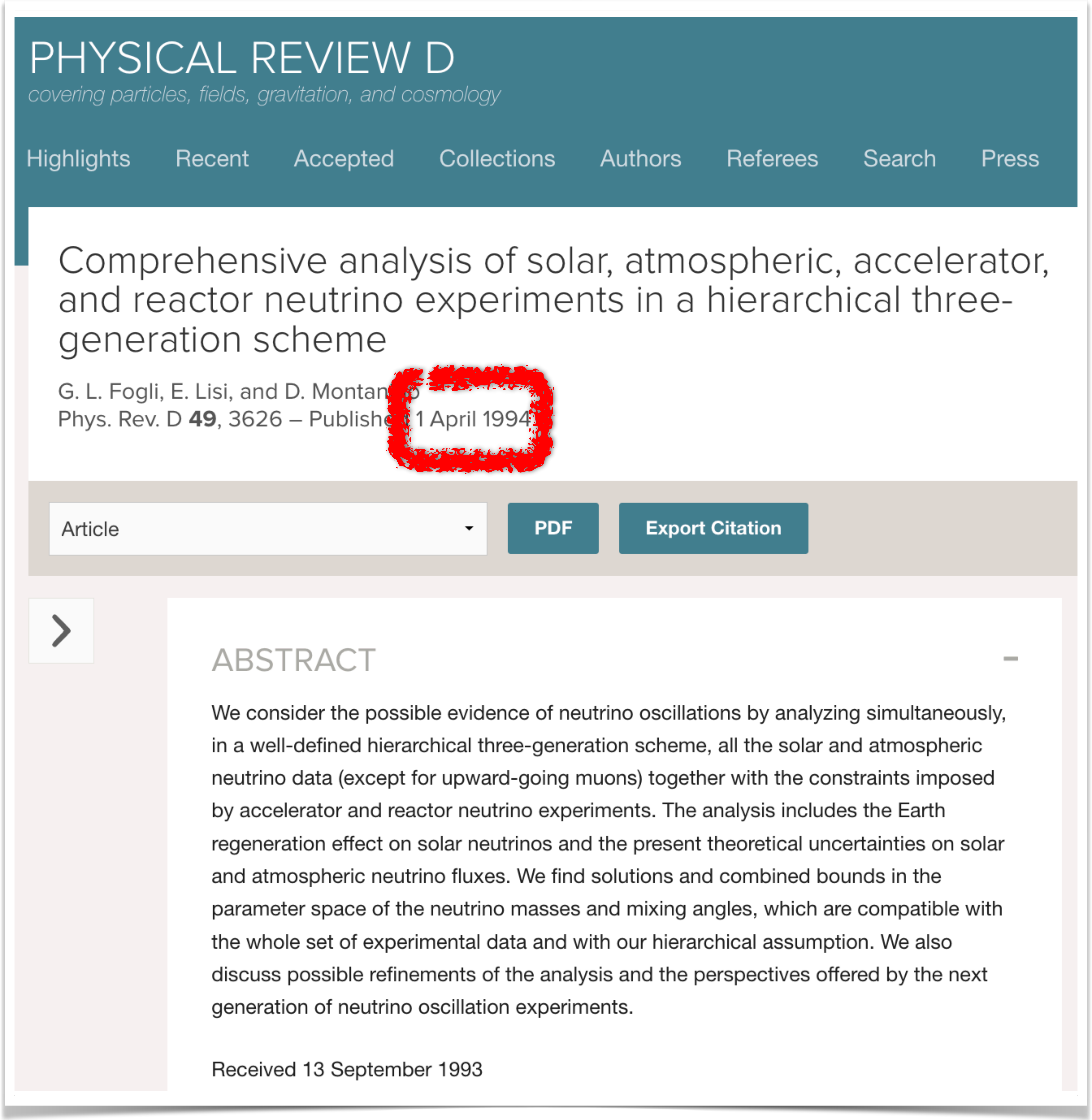
neutrinos in gauge theory - seesaw and all that

* Interest in extended gauge theories originally focused on **proton decay**
* Peter Minkowki, one of the proponents of SO(10), first spoke of **neutrino mass** in the context of left-right gauge theory (1977)
* as discussed yesterday by ZZ-Xing, this gives meaning to the small neutrino mass and it is still a open line of research

an anniversary: 30 years of global analyses

. . . .

- *Nobel 1995 to Cowan for neutrino observation*
- *Nobel 2002 to Davis and Koshiba for neutrino astronomy*
- *Nobel 2015 to Kajita & McDonald for neutrino oscillations*



PHYSICAL REVIEW D

covering particles, fields, gravitation, and cosmology

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Comprehensive analysis of solar, atmospheric, accelerator, and reactor neutrino experiments in a hierarchical three-generation scheme

G. L. Fogli, E. Lisi, and D. Montanino

Phys. Rev. D **49**, 3626 – Published 1 April 1994

Article PDF Export Citation

ABSTRACT

We consider the possible evidence of neutrino oscillations by analyzing simultaneously, in a well-defined hierarchical three-generation scheme, all the solar and atmospheric neutrino data (except for upward-going muons) together with the constraints imposed by accelerator and reactor neutrino experiments. The analysis includes the Earth regeneration effect on solar neutrinos and the present theoretical uncertainties on solar and atmospheric neutrino fluxes. We find solutions and combined bounds in the parameter space of the neutrino masses and mixing angles, which are compatible with the whole set of experimental data and with our hierarchical assumption. We also discuss possible refinements of the analysis and the perspectives offered by the next generation of neutrino oscillation experiments.

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Valencia	NuFit	Bari

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Published: February 9, 2021

2020 global reassessment of the neutrino oscillation picture

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Abstract: We present an updated global fit of neutrino oscillation data in the simplest three-neutrino framework. In the present study we include up-to-date analyses from a number of experiments. Concerning the atmospheric and solar sectors, besides the data considered previously, we give updated analyses of IceCube DeepCore and Sudbury Neutrino Observatory data, respectively. We have also included the latest electron antineutrino data collected by the Daya Bay and RENO reactor experiments, and the long-baseline T2K and NOνA measurements, as reported in the Neutrino 2020 conference. All in all, these new analyses result in more accurate measurements of θ_{13}, θ_{12}, Δm^2_{21} and $|\Delta m^2_{31}|$. The best fit value for the atmospheric angle θ_{23} lies in the second octant, but first octant solutions remain allowed at $\sim 2.4\sigma$. Regarding CP violation measurements, the preferred value of δ we obtain is 1.08π (1.58π) for normal (inverted) neutrino mass ordering. The global analysis still prefers normal neutrino mass ordering with 2.5σ statistical significance. This preference is milder than the one found in previous global analyses. These new results should be regarded as robust due to the agreement found between our Bayesian and frequentist approaches. Taking into account only oscillation data, there is a weak/moderate

https://doi.org/10.1007/JHEP02(2021)071

universe

MDPI

Review

NuFIT: Three-Flavour Global Analyses of Neutrino Oscillation Experiments

Maria Concepcion Gonzalez-Garcia [1,2,3,*], Michele Maltoni [4,*] and Thomas Schwetz [5,*]

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3 C.N. Yang Institute for Theoretical Physics, SUNY at Stony Brook, Stony Brook, NY 11794-3840, USA
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Abstract: In this contribution, we summarise the determination of neutrino masses and mixing arising from global analysis of data from atmospheric, solar, reactor, and accelerator neutrino experiments performed in the framework of three-neutrino mixing and obtained in the context of the NuFIT collaboration. Apart from presenting the latest status as of autumn 2021, we discuss the evolution of global-fit results over the last 10 years, and mention various pending issues (and their resolution) that occurred during that period in the global analyses.

PHYSICAL REVIEW D **104**, 083031 (2021)

Unfinished fabric of the three neutrino paradigm

Francesco Capozzi,[1] Eleonora Di Valentino,[2] Eligio Lisi,[3] Antonio Marrone,[4,3] Alessandro Melchiorri,[5,6] and Antonio Palazzo[4,3]

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(Received 5 July 2021; accepted 24 September 2021; published 26 October 2021)

In the current 3ν paradigm, neutrino flavor oscillations probe three mixing angles $(\theta_{12}, \theta_{23}, \theta_{13})$, one CP-violating phase δ, and two independent differences between the squared masses m_i^2, that can be chosen as $\delta m^2 = m_2^2 - m_1^2 > 0$ and $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$, where $\mathrm{sign}(\Delta m^2) = +(-)$ for normal (inverted) mass ordering. Absolute ν masses can be probed by the effective mass m_β in beta decay, by the total mass Σ in cosmology and—if neutrinos are Majorana—by another effective mass $m_{\beta\beta}$ in neutrinoless double beta decay. Within an updated global analysis of oscillation and nonoscillation data, we constrain these 3ν parameters, both separately and in selected pairs, and highlight the concordance or discordance among different constraints. Five oscillation parameters $(\delta m^2, |\Delta m^2|, \theta_{12}, \theta_{23}, \theta_{13})$ are consistently measured, with an overall accuracy ranging from $\sim$1% for $|\Delta m^2|$ to $\sim$6% for $\sin^2\theta_{23}$ (due to its persisting octant ambiguity). We find overall hints for normal ordering (at $\sim 2.5\sigma$), as well as for $\theta_{23} < \pi/4$ and for $\sin\delta < 0$ (both at 90% C.L.), and discuss some tensions among different datasets. Concerning nonoscillation data, we include the recent KATRIN constraints on m_β, and we combine the latest ^{76}Ge, ^{130}Te and ^{136}Xe bounds on $m_{\beta\beta}$, accounting for nuclear matrix element covariances. We also discuss some variants related to cosmic microwave background (CMB) anisotropy and lensing data, which may affect cosmological constraints on Σ and hints on $\mathrm{sign}(\Delta m^2)$. The default option, including all Planck results, irrespective of the so-called lensing anomaly, sets upper bounds on Σ at the level of $\sim 10^{-1}$ eV, and further favors normal ordering up to $\sim 3\sigma$. An alternative option, that includes recent ACT results plus other independent results (from WMAP and selected Planck data) globally consistent with standard lensing, is insensitive to the ordering but prefers $\Sigma \sim$ few $\times\, 10^{-1}$ eV, with different implications for m_β and $m_{\beta\beta}$ searches. In general, the unfinished fabric of the 3ν paradigm appears to be at the junction of diverse searches in particle and nuclear physics, astrophysics and cosmology, whose convergence will be crucial to achieve a convincing completion.

Valencia | **NuFit** | **Bari**

- 3 flavor analyses have always displayed consistency
- are still crucial after so many years
- will continue to be so after JUNO, HyperK, DUNE

JHEP Published for SISSA by Springer
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2020 global reassessment of the neutrino oscillation picture

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Abstract: We present an updat… three-neutrino framework. In th… number of experiments. Concerni… considered previously, we give up… trino Observatory data, respective… data collected by the Daya Bay an… and NOνA measurements, as reported in the Neutrino 2020 conference. All in all, these new analyses result in more accurate measurements of θ_{13}, θ_{12}, Δm^2_{21} and $|\Delta m^2_{31}|$. The best fit value for the atmospheric angle θ_{23} lies in the second octant, but first octant solutions remain allowed at $\sim 2.4\sigma$. Regarding CP violation measurements, the preferred value of δ we obtain is 1.08π (1.58π) for normal (inverted) neutrino mass ordering. The global analysis still prefers normal neutrino mass ordering with 2.5σ statistical significance. This preference is milder than the one found in previous global analyses. These new results should be regarded as robust due to the agreement found between our Bayesian and frequentist approaches. Taking into account only oscillation data, there is a weak/moderate

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Unfinished fabric of the three neutrino paradigm

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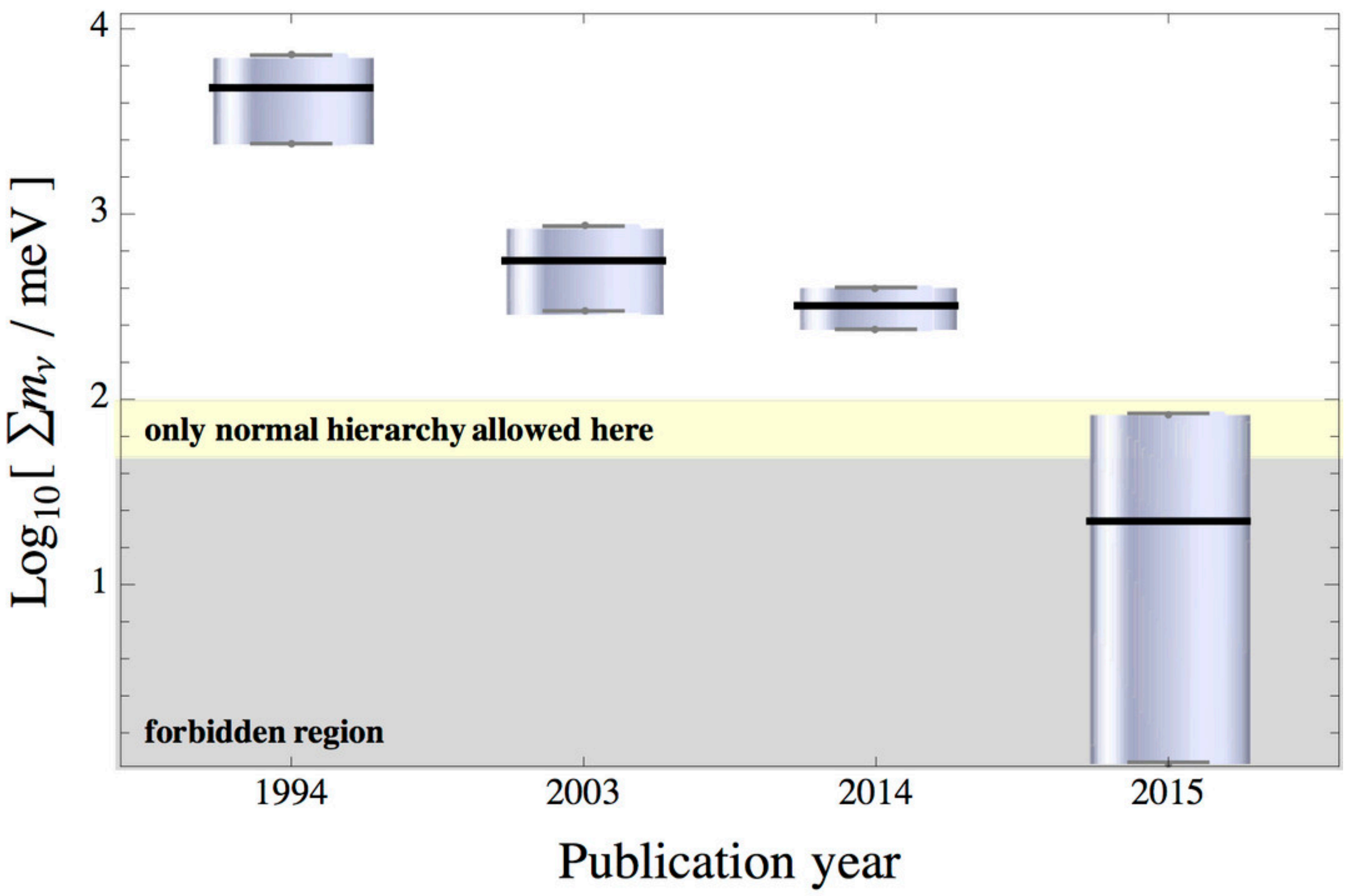
…26 October 2021)

…angles ($\theta_{12}, \theta_{23}, \theta_{13}$), one …ses m_i^2, that can be chosen …(−) for normal (inverted) … decay, by the total mass Σ …n neutrinoless double beta …ta, we constrain these 3ν …ce or discordance among …nsistently measured, with …e to its persisting octant …$_{23} < \pi/4$ and for $\sin\delta < 0$ …rning nonoscillation data, …e, ^{130}Te and ^{136}Xe bounds … variants related to cosmic …smological constraints on …espective of the so-called …vors normal ordering up to $\sim 3\sigma$. An alternative option, that includes recent ACT results plus other independent results (from WMAP and selected Planck data) globally consistent with standard lensing, is insensitive to the ordering but prefers $\Sigma \sim$ few $\times 10^{-1}$ eV, with different implications for m_β and $m_{\beta\beta}$ searches. In general, the unfinished fabric of the 3ν paradigm appears to be at the junction of diverse searches in particle and nuclear physics, astrophysics and cosmology, whose convergence will be crucial to achieve a convincing completion.

absolute neutrino mass
in cosmology and in lab

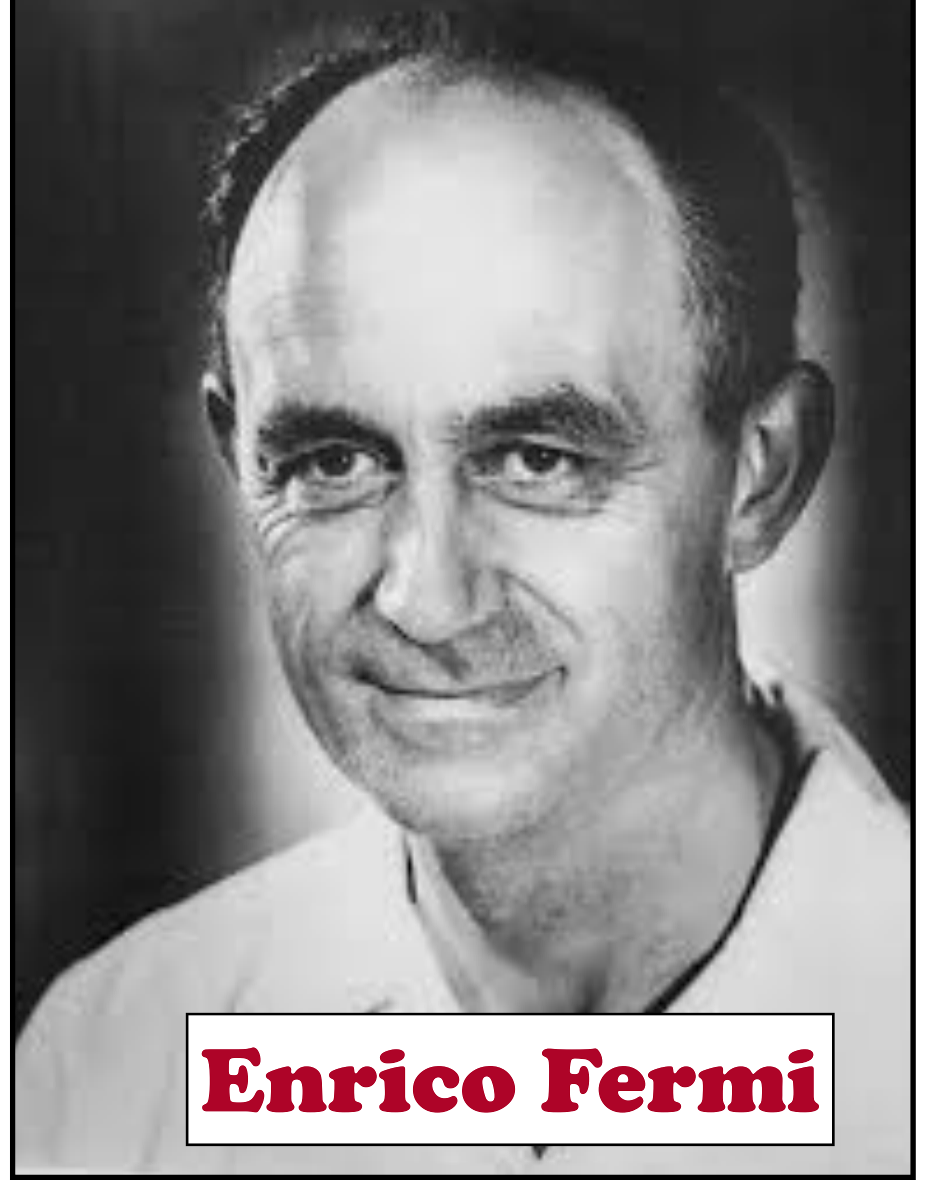
- the strong limits of cosmology have been consistent for 10 years and I would not forget Seljak 2004
- the recent DESI results simply show, in my opinion, that the method has great potential
- even in lab physics there have been doubtful results: 30 eV (Lubimov ‘80) 17 keV (Simpson ’85) etc.
- I believe that KATRIN's perseverance, which after 20 years is achieving its goal, is highly commendable

a joke of mine on LinkedIn, May 2015

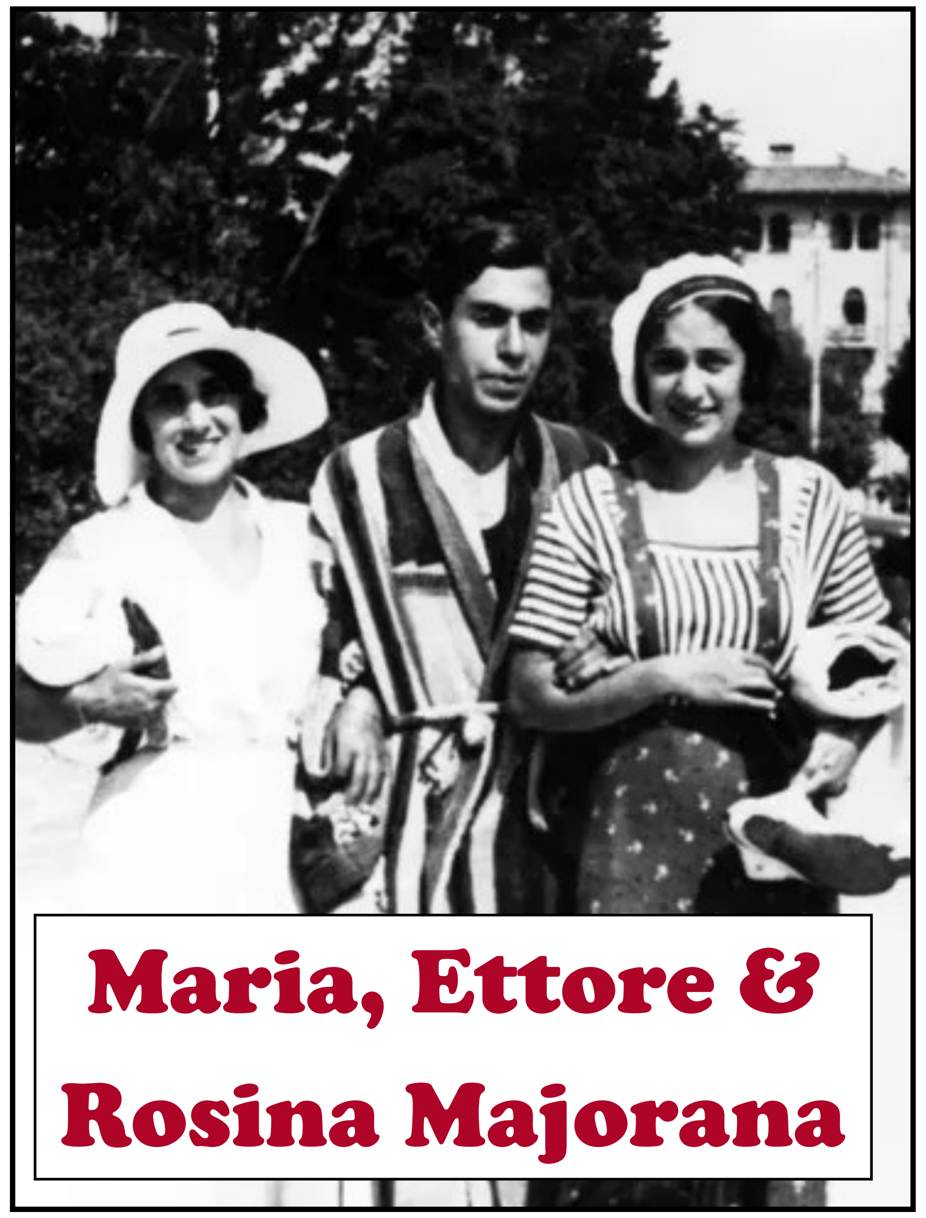


nature of the neutrino

and Majorana theory



- it is curious that the best chance to probe the lepton number of the Standard Model is a nuclear physics process discussed almost a century ago
- a plausible contribution to this process is due to Majorana's neutrino masses which are bound but not determined by oscillation and other available data (see Greuling Whitten 1960 and many works since 1998 for the connection with oscillations)
- This is the most important reason for the uncertainty, and if theory or cosmology or whatever could help reduce it, that would be great
- (The plausibility lies in the very structure of the standard model)



PS I do not know of any paper where Dirac talks of neutrinos, while I know that Fermi's neutrino differs from its own antiparticle

doubtful cases

neutrinoless double beta decay does not imply Majorana neutrinos

- *Bruno Touschek*

On the theory of double beta decay Zeitschrift fuer Physik A 125, 108 (1948)

- *Shoichi Sakata*

Superstition around Majorana Neutrino Soryushiron Kenkyu, 7, 925 (1955)

- *Gerald Feinberg and Maurice Goldhaber*

Microscopic tests of symmetry principles Proc. of Natl Ac. of Sciences 45, 1301 (1959)

- *Bruno Pontecorvo*

Superweak interactions and double beta decay Physics Letters B 26, 630–632 (1968)

neutrinoless double beta decay implies Majorana neutrinos?

Joseph Schechter and Jose' W. F. Valle

Neutrinoless double-β decay in $SU(2) \times U(1)$ theories

Physical Review D, 22, 2227 (1981)

From Wikipedia, the free encyclopedia

The same authors also formulated the Schechter-Valle theorem [3] demonstrating that an observation of neutrinoless double beta decay will necessarily imply neutrinos to be Majorana fermions and vice versa.

ABSTRACT

It is shown that gauge theories give contributions to neutrinoless double-β decay $[(\beta\beta)_{0\nu}]$ which are not covered by the standard parametrizations. While probably small, their existence raises the question of whether the observation of $(\beta\beta)_{0\nu}$ implies the existence of a Majorana mass term for the neutrino. For a "natural" gauge theory we argue that this is indeed the case.

1. *the term 'theorem' does not appear in the paper*
2. *none of the previous work is cited*
3. *it all boils down to the definition of "natural" theory*

a preprint (2011) and related papers

Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

The OPERA Collaboration: T. Adam, N. Agafonova, A. Aleksandrov, O. Altinok, P. Alvarez Sanchez, S. Aoki, A. Ariga, T. Ariga, D. Autiero, A. Badertscher, A. Ben Dhahbi, A. Bertolin, C. Bozza, T. Brugiére, F. Brunet, G. Brunetti, S. Buontempo, F. Cavanna, A. Cazes, L. Chaussard, M. Chernyavskiy, V. Chiarella, A. Chukanov, G. Colosimo, M. Crespi, N. D'Ambrosios, Y. Déclais, P. del Amo Sanchez, G. De Lellis, M. De Serio, F. Di Capua, F. Cavanna, A. Di Crescenzo, D. Di Ferdinando, N. Di Marco, S. Dmitrievsky, M. Dracos, D. Duchesneau, S. Dusini, J. Ebert, I. Eftimiopolous, O. Egorov, A. Ereditato, L.S. Esposito, J. Favier, T. Ferber, R.A. Fini, T. Fukuda, A. Garfagnini, G. Giacomelli, C. Girerd, M. Giorgini, M. Giovannozzi, J. Goldberga, C. Göllnitz, L. Goncharova, Y. Gornushkin, G. Grella, F. Griantia, E. Gschewentner, C. Guerin, A.M. Guler, C. Gustavino, K. Hamada, T. Hara, M. Hierholzer, A. Hollnagel, M. Ieva, H. Ishida, K. Ishiguro, K. Jakovcic, C. Jollet, M. Jones, F. Juget, M. Kamiscioglu, J. Kawada, S.H. Kim, M. Kimura, N. Kitagawa, B. Klicek, J. Knuesel, K. Kodama, M. Komatsu, U. Kose, I. Kreslo, C. Lazzaro, J. Lenkeit, A. Ljubicic, A. Longhin, A. Malgin, G. Mandrioli, J. Marteau, T. Matsuo, N. Mauri, A. Mazzoni, E. Medinaceli, j, F. Meisel, A. Meregaglia, P. Migliozzi et al. (75 additional authors not shown)

The OPERA neutrino experiment at the underground Gran Sasso Laboratory has measured the velocity of neutrinos from the CERN CNGS beam over a baseline of about 730 km with much higher accuracy than previous studies conducted with accelerator neutrinos. The measurement is based on high-statistics data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the CNGS timing system and of the OPERA detector, as well as a high precision geodesy campaign for the measurement of the neutrino baseline, allowed reaching comparable systematic and statistical accuracies. An early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns was measured. This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light $(v-c)/c = (2.48 \pm 0.28\ (\text{stat.}) \pm 0.30\ (\text{sys.})) \times 10^{-5}$.

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News Feature | Published: 21 December 2011

365 days: *Nature*'s 10

Declan Butler, Ewen Callaway, Erika Check Hayden, David Cyranoski, Eric Hand, Nicola Nosengo, Eugenie Samuel Reich, Jeff Tollefson & Mohammed Yahia

RELATIVITY CHALLENGER

The shy experimentalist whose team claims to have found faster-than-light neutrinos is happy for the work to stand or fall.

BY NICOLA NOSENGO

a preprint (2011) and related papers

Measurement of the neutrino velocity with the OPERA detector in the CNGS beam

The OPERA Collaboration: T. Adam, N. Agafonova, A. Aleksandrov, O. Altinok, P. Alvarez Sanchez, S. Aoki, A. Ariga, T. Ariga, D. Autiero, A. Badertscher, A. Ben Dhahbi, A. Bertolin, C. Bozza, T. Brugiére, F. Brunet, G. Brunetti, S. Buontempo, F. Cavanna, A. Cazes, L. Chaussard, M. Chernyavskiy, V. Chiarella, A. Chukanov, G. Colosimo, M. Crespi, N. D'Ambrosios, Y. Déclais, P. del Amo Sanchez, G. De Lellis, M. De Serio, F. Di Capua, F. Cavanna, A. Di Crescenzo, D. Di Ferdinando, N. Di Marco, S. Dmitrievsky, M. Dracos, D. Duchesneau, S. Dusini, J. Ebert, I. Eftimiopolous, O. Egorov, A. Ereditato, L.S. Esposito, J. Favier, T. Ferber, R.A. Fini, T. Fukuda, A. Garfagnini, G. Giacomelli, C. Girerd, M. Giorgini, M. Giovannozzi, J. Goldberga, C. Göllnitz, L. Goncharova, Y. Gornushkin, G. Grella, F. Griantia, E. Gschewentner, C. Guerin, A.M. Guler, C. Gustavino, K. Hamada, T. Hara, M. Hierholzer, A. Hollnagel, M. Ieva, H. Ishida, K. Ishiguro, K. Jakovcic, C. Jollet, M. Jones, F. Juget, M. Kamiscioglu, J. Kawada, S.H. Kim, M. Kimura, N. Kitagawa, B. Klicek, J. Knuesel, K. Kodama, M. Komatsu, U. Kose, I. Kreslo, C. Lazzaro, J. Lenkeit, A. Ljubicic, A. Longhin, A. Malgin, G. Mandrioli, J. Marteau, T. Matsuo, N. Mauri, A. Mazzoni, E. Medinaceli, j, F. Meisel, A. Meregaglia, P. Migliozzi et al. (75 additional authors not shown)

The OPERA neutrino experiment at the underground Gran Sasso Laboratory has measured the velocity of neutrinos from the CERN CNGS beam over a baseline of about 730 km with much higher accuracy than previous studies conducted with accelerator neutrinos. The measurement is based on high-statistics data taken by OPERA in the years 2009, 2010 and 2011. Dedicated upgrades of the CNGS timing system and of the OPERA detector, as well as a high precision geodesy campaign for the measurement of the neutrino baseline, allowed reaching comparable systematic and statistical accuracies. An early arrival time of CNGS muon neutrinos with respect to the one computed assuming the speed of light in vacuum of (60.7 ± 6.9 (stat.) ± 7.4 (sys.)) ns was measured. This anomaly corresponds to a relative difference of the muon neutrino velocity with respect to the speed of light (v−c)/c = (2.48 ± 0.28 (stat.) ± 0.30 (sys.)) $\times 10^{-5}$.

High-energy tests of Lorentz invariance

Sidney R. Coleman (Harvard U.), Sheldon L. Glashow (Harvard U.)

(Dec, 1998)

Published in: *Phys.Rev.D* 59 (1999) 116008 • e-Print: hep-ph/9812418 [hep-ph]

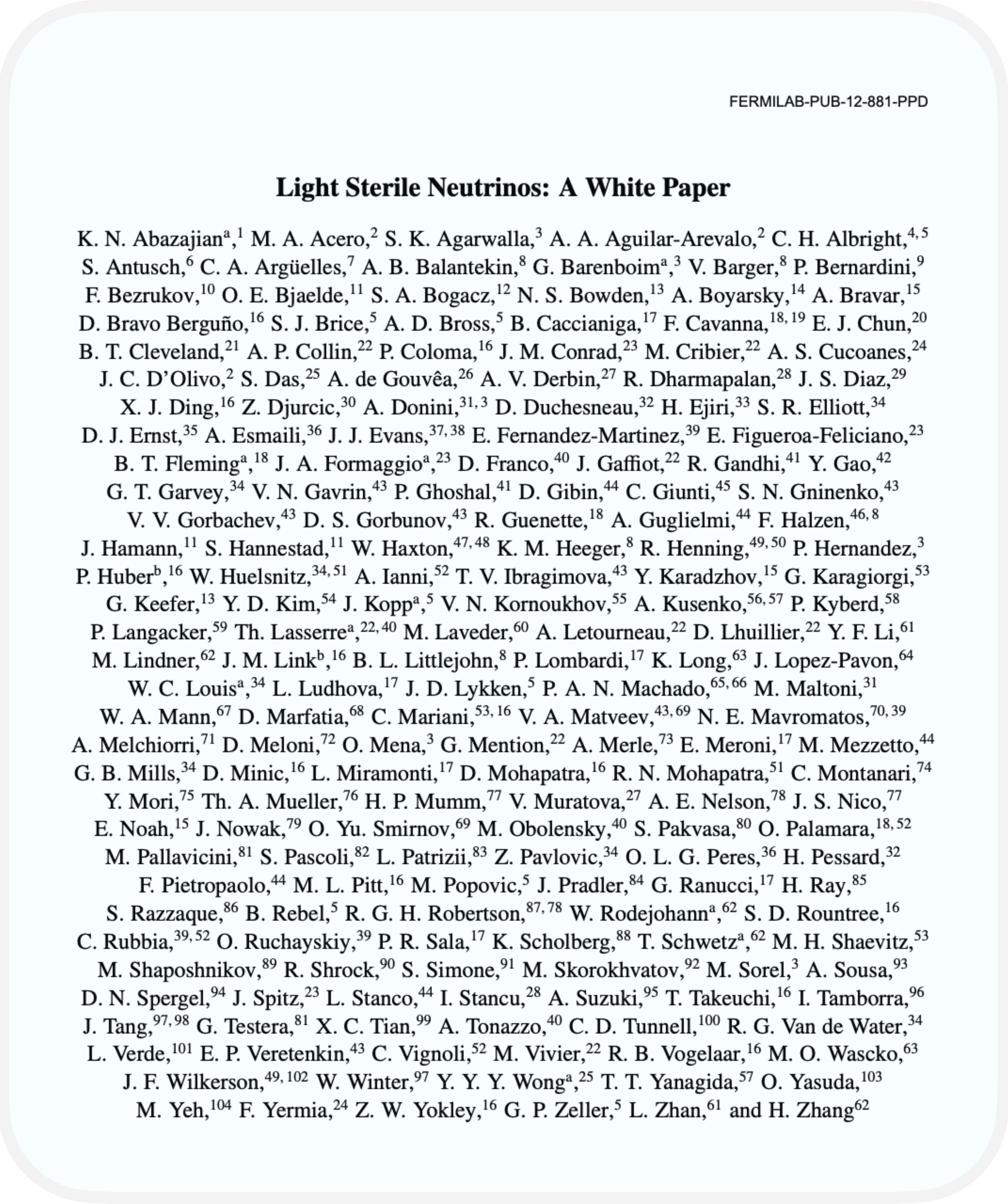
That is to say, the *a*th particle has, in addition to its own mass, m_a, its own maximum attainable velocity (“its own velocity of light”) c_a, and obeys the energy-momentum relation

$$E_a^2 = \vec{p}_a^{\,2} c_a^2 + m_a^2 c_a^4. \tag{2.19}$$

[28] AGASA Collaboration, M. Takeda *et al.*, Phys. Rev. Lett. **81**, 1163 (1998); Fly’s Eye Collaboration, D. J. Bird *et al.*, Astrophys. J. **424**, 144 (1995); Haverah Park Collaboration, M. A. Lawrence *et al.*, J. Phys. G **17**, 733 (1991); Yakutsk Collaboration, N. N. Efimov *et al.*, in 22nd International Cosmic Ray Conference, Dublin, 1991.

an influential document (2012)

on sterile neutrinos



FERMILAB-PUB-12-881-PPD

Light Sterile Neutrinos: A White Paper

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from the abstract of the paper:

"The overriding goal is to provide the motivation for a new round of measurements so that the questions laid out here can be definitively answered"

two tips from the past and points for discussion

Bruno Pontecorvo on innovation

one should neither underestimate the importance of high-energy neutrino physics, nor overestimate it. This is not pessimism, but an appeal to avoid routine

John Bahcall on interdisciplinarity

everyone agrees to do interdisciplinary science but no one wants the money to come from their budget

Neutrino physics has always been **interdisciplinary** - and still is today. It should be added that the *data do not speak for themselves*; concepts such as 'multi-messenger' help, but on their own are not enough to continue doing well

Occurred successes are due to the synergy between good theories and experiments. Main driving force doesn't seem to have been an *abstract aspiration for innovation*, as much as a commitment to **consistency** & consequent **planning**; technology counts but not exclusively

We are invited by history of neutrino physics to renew the *connections between physics, mathematics, astrophysics, cosmology* - as if to say, to **cross portals**

thanks!

a few references

[1] *Pages in the development of neutrino physics*, Bruno Pontecorvo, 1983

[2] *Inward bound: of matter and forces in the physical world*, Abraham Pais, 1986

[3] *Neutrino. the mutant particle*, Giampaolo Cò et al, 2016 - La versione italiana è pubblica `http://siba-ese.unisalento.it/index.php/ithaca/issue/view/1330`

[4] *The formalism of neutrino oscillations: an introduction*, Guido Fantini, Andrea Gallo-Rosso, Vanessa Zema, FV, arXiv:1802.05781, 2018

[5] *History of the neutrinos*, `https://neutrino-history.in2p3.fr/books/`

[6] *Neutrino unbound,* Carlo Giunti et al, website https://www.nu.to.infn.it/

- The genesis of the neutrino concept
Talk at Neutrino 2024

- First steps towards understanding neutrinos
Quaderni di Storia della Fisica, 31 1, 109 (2024)

- Majorana and the bridge between matter and anti-matter
Nuovo Cim. 47C (2024)

- A discussion of the cross section $\bar{\nu}_e + p \to n + e^+$
Nuovo Cim. 47C (2024)

- Toward the discovery of matter creation with $0\nu2\beta$ *decay*
Rev. Mod. Phys. 95 2, 025002 (2023)

- What is matter according to particle physics, and why try to observe its creation in a lab?
Universe 7 3, 61, (2021)

- Neutrino telescopes and high-energy cosmic neutrinos
Universe 6 2, 30 (2020)

- A critical appraisal of some concepts used in neutrino physics
Nuovo Cim. 36C 01, 223-228 (2013)

appendices

"If you can't measure it—it doesn't exist"

This attitude defines **empiricism**. Although it has often proved to be a valid approach, it is not without risks. For example, it leads to the belief that it is better to focus on models that allow something to be measured, which could be very misleading. It is *so easy* to imagine scenarios in which something interesting might happen, but this is far from meaning that they all have the same value - or even that they have any. On the contrary, there are theories based on profound principles that take time to explore thoroughly.

a funny situation

not infrequently some colleagues interested in "physics beyond the standard model" curiously *overlook or underestimate* the only evidence of physics beyond the standard model that is based on experiments and can be further verified

Peter Woit (not even wrong)

"the first version of this theory didn't have masses for the neutrinos, but it turns out you can throw in some right-handed neutrino fields, and it all works exactly, you know, as you expect so far"

Real-time marine data harvesting at INFN - Laboratori Nazionali del Sud marine exploiting km3net infrastructure

Bioacoustics

Annual Acoustic Presence of Fin Whale (*Balaenoptera physalus*) Offshore Eastern Sicily, Central Mediterranean Sea

PLOS ONE

Size Distribution of Sperm Whales Acoustically Identified during Long Term Deep-Sea Monitoring in the Ionian Sea

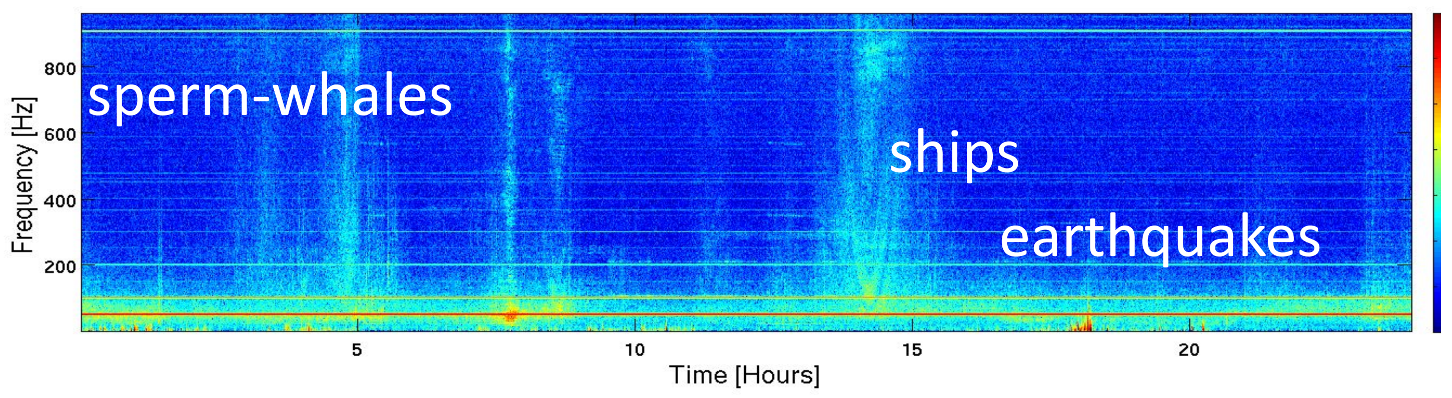
SCIENTIFIC REPORTS

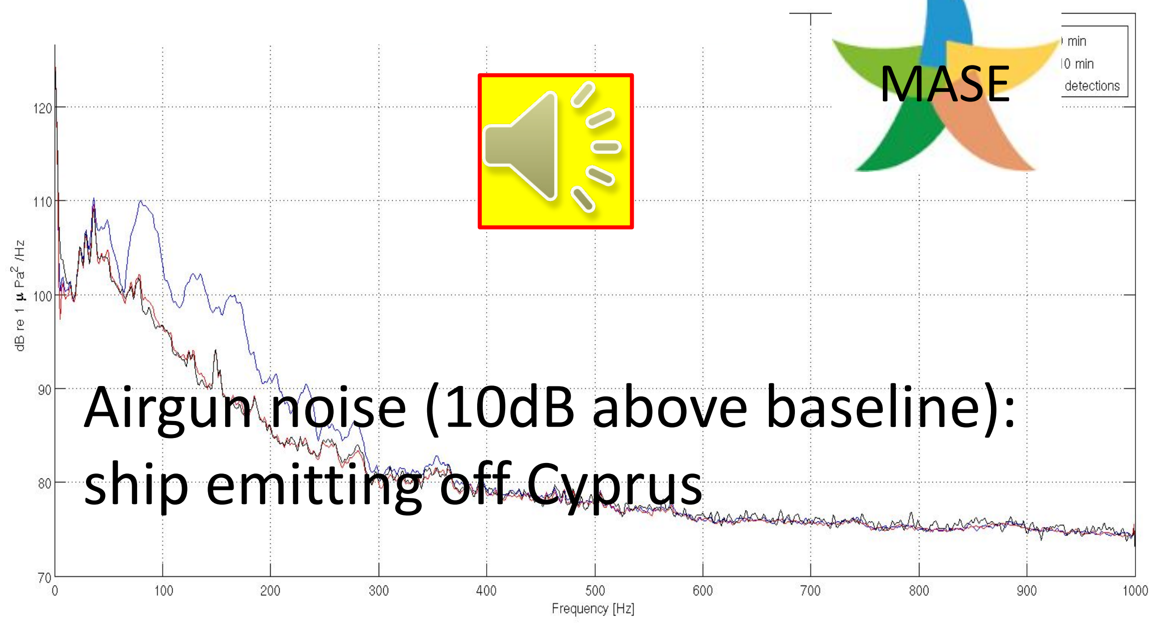
OPEN Long-Term Monitoring of Dolphin Biosonar Activity in Deep Pelagic Waters of the Mediterranean Sea

Sea soundscape monitoring

Continuous monitoring of noise levels in the Gulf of Catania (Ionian Sea). Study of correlation with ship traffic

Marine Pollution Bulletin





Deep sea current monitoring

Abyssal undular vortices in the Eastern Mediterranean basin

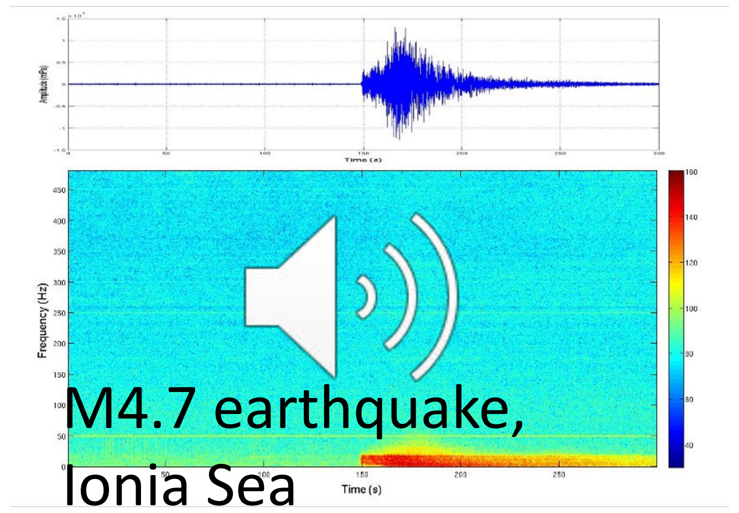
nature COMMUNICATIONS

Study of Bioluminescence

Integrating Diel Vertical Migrations of Bioluminescent Deep Scattering Layers Into Monitoring Programs

frontiers in Marine Science

Geophysics and volcanology



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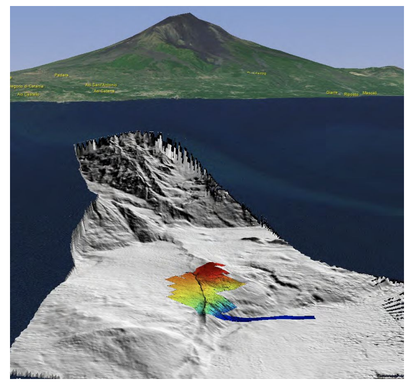
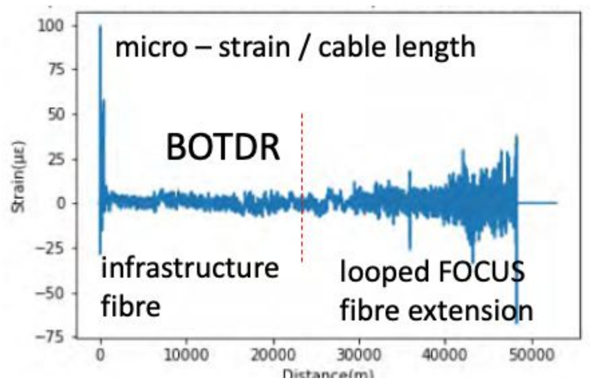
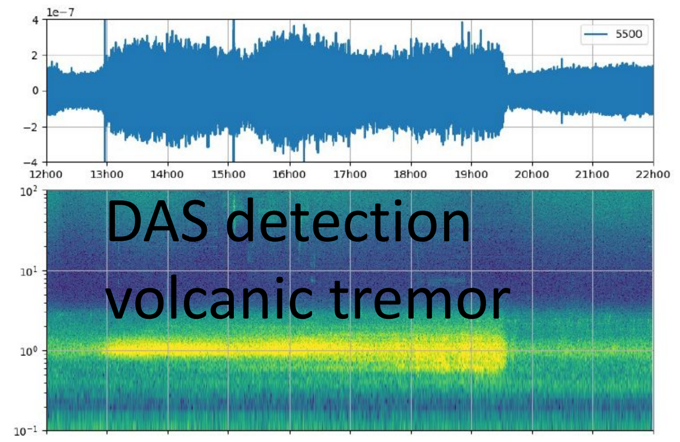
Geo-INQUIRE

Exploiting real-time optical reflectometry technique using optical fibres of the Catania and Capo Passero subsea networks
Brillounin and Distributed Acoustic Sensing OTDR







Courtesy Piera Sapienza and Giorgio Riccobene

Access to data and infrastructures

https://emso.eu/physical-access/

Geosphere INfrastructures for QUestions into Integrated REsearch

https://www.geo-inquire.eu/transnational-access/how-to-apply-for-access

Italian Integrated Environmental Research Infrastructures System

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Finanziato dall'Unione europea NextGenerationEU

News in 2024

Lownoiser (EU): development of techniques to measure and reduce ship noise

Vongola (PNRR-CNB):DAS measurements for Bioacoustics (Centro Siciliano di Fisica nucleare e Struttura della Materia)

Courtesy Piera Sapienza and Giorgio Riccobene