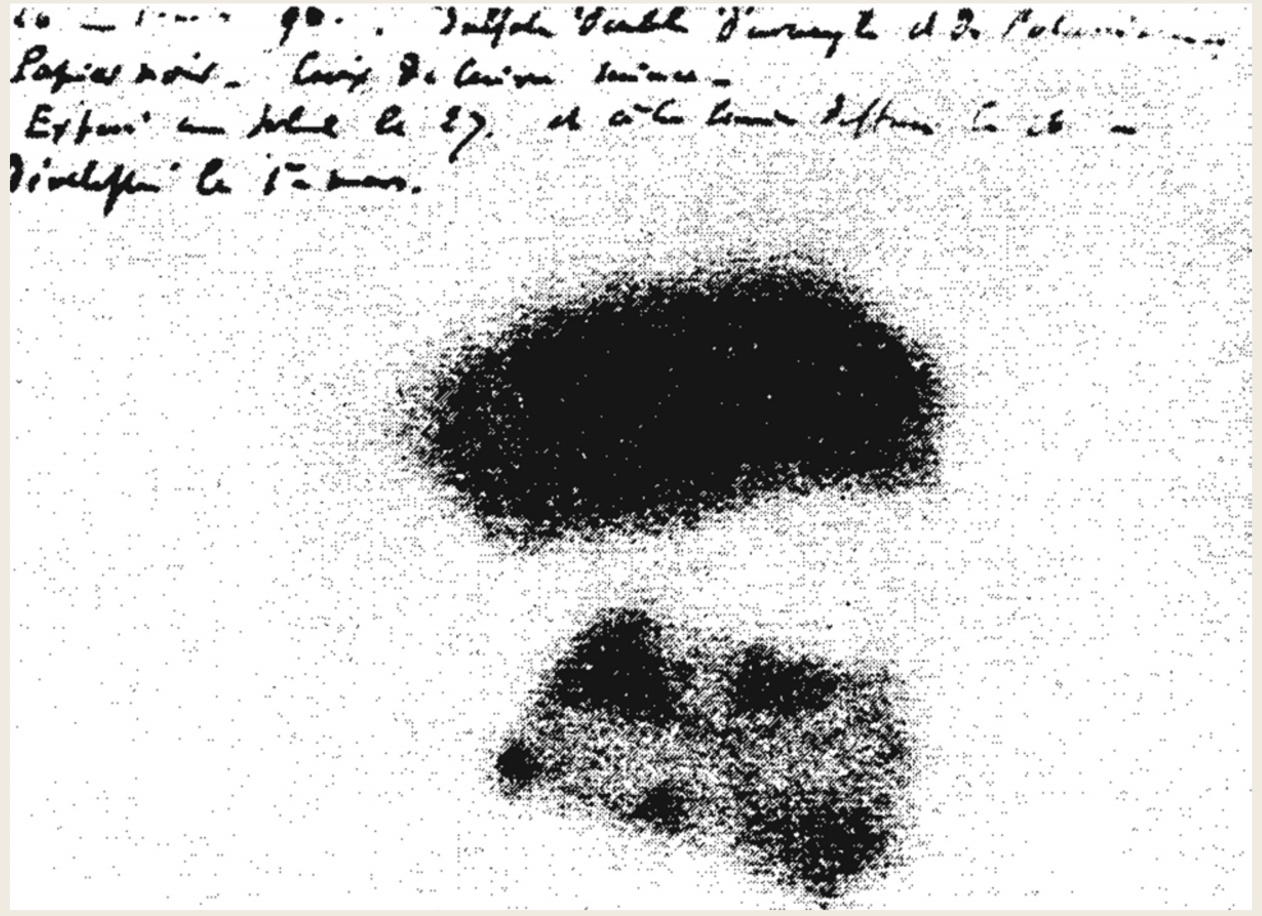
The 50th Anniversary

Chris Quigg

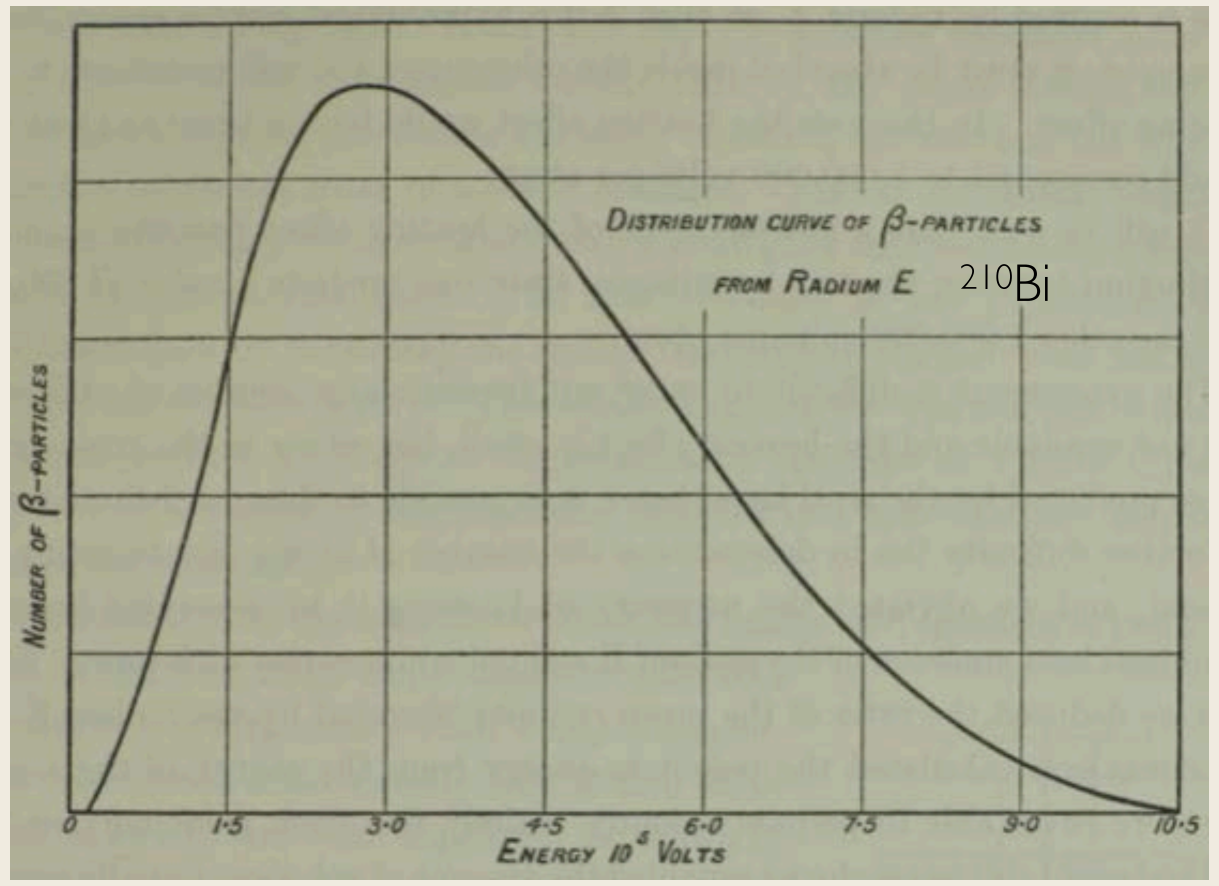
Benjamin Whisoh Lee (1935–1977)

Neutrino '72, Balatonfüred, Hungary

Participants of Neutrino '72 conference. In the front row: T. D. Lee, G. L. Radicati, R. P. Feynman, B. Pontecorvo, G. Marx, V. F. Weisskopf, F. Reines, C. L. Cowan and P. Budini



Becquerel, 1896



Chadwick, 1914; Ellis–Wooster, 1927

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben 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.

Pauli, 1930

TENTATIVO DI UNA TEORIA DEI RAGGI β

Nota [1] di ENRICO FERMI (1932–4)

Sunto. - *Si propone una teoria quantitativa dell'emissione dei raggi β in cui si ammette l'esistenza del « neutrino » e si tratta l'emissione degli elettroni e dei neutrini da un nucleo all'atto della disintegrazione β con un procedimento simile a quello seguito nella teoria dell'irradiazione per descrivere l'emissione di un quanto di luce da un atomo eccitato. Vengono dedotte delle formule per la vita media e per la forma dello spettro continuo dei raggi β, e le si confrontano coi dati sperimentali.*

β^+-emission observed

$$\alpha + {}^{27}\text{Al} \rightarrow {}^{30}\text{P} + n$$
$$\hookrightarrow \beta^+ + {}^{30}\text{Si}$$

1932: *n* (Chadwick), e^+ (Anderson)

Curie & Joliot, 1934

Other rare processes foreseen:

Inverse β decay Bethe & Peierls, 1934

ννββ decay Goeppert–Mayer 1935

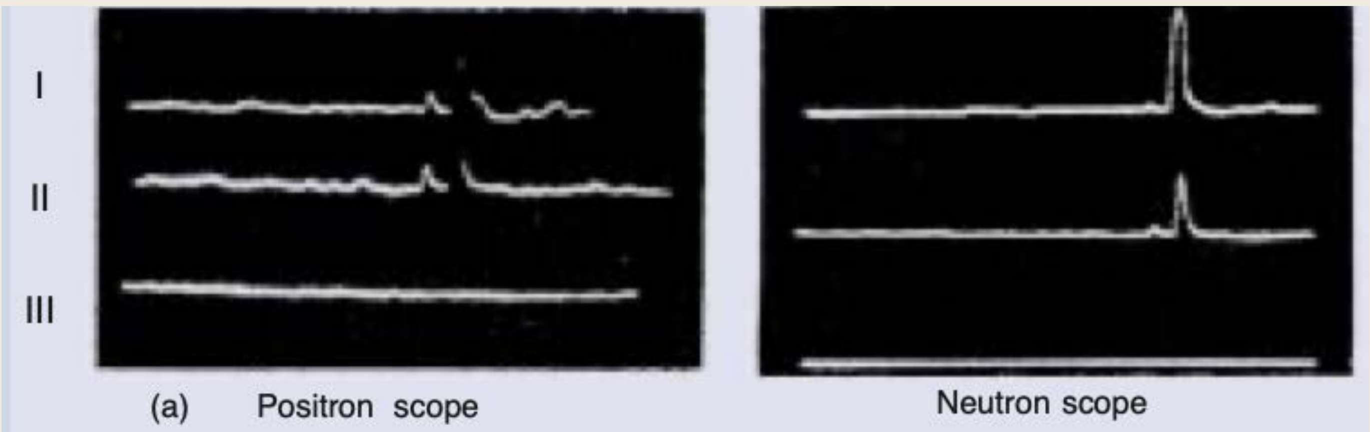
and, following Majorana 1937,

0νββ decay Furry, 1939

1932–1946: Leptonic nature of μ

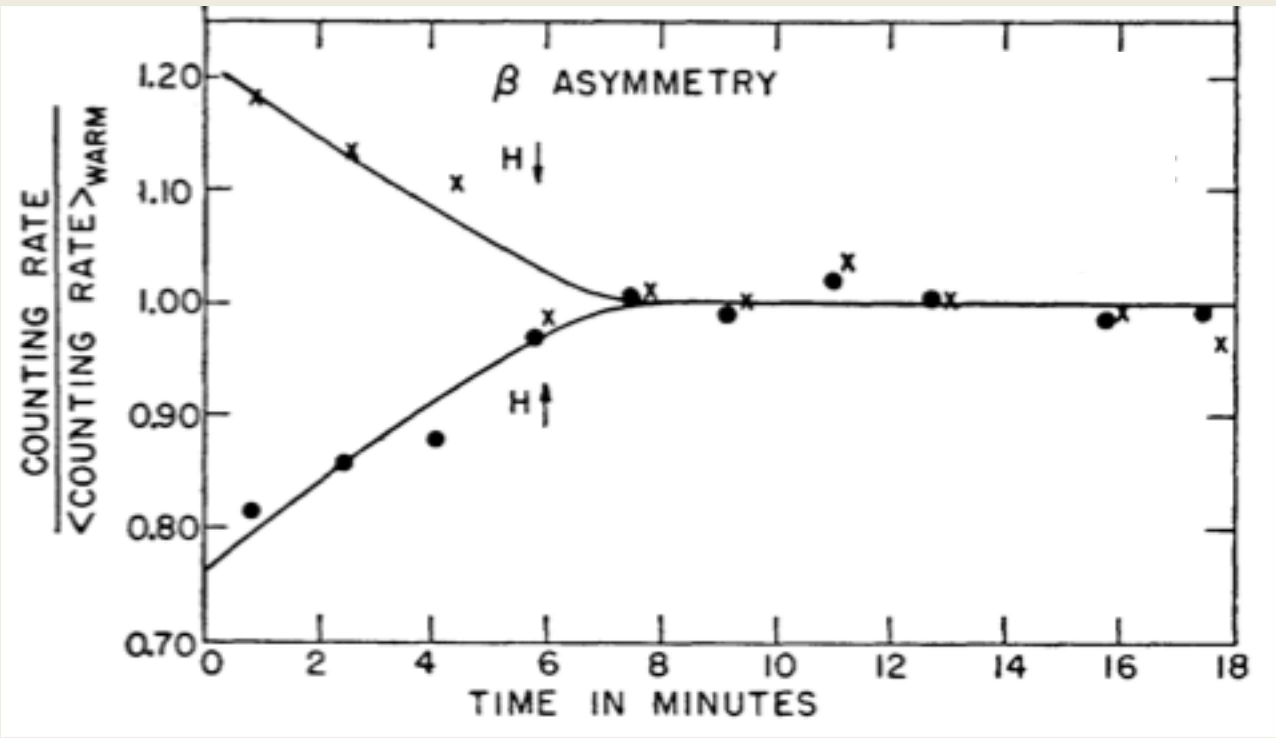
Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire



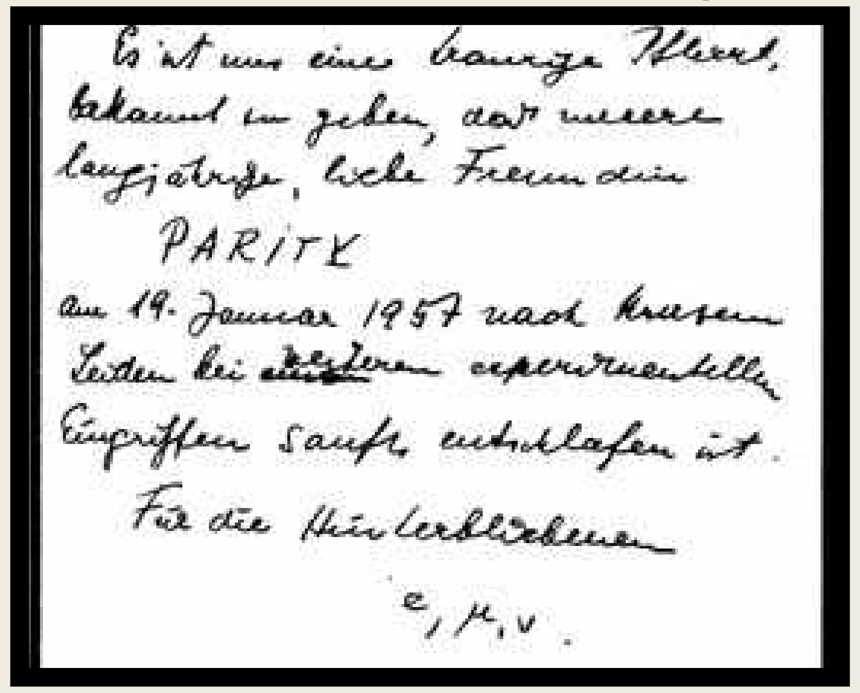
$\bar{\nu}p \rightarrow e^+ n$, 1956

P violation in polarized ^{60}Co β decay



Wu, Ambler, ..., 1957

P and **C** violation in π→μ→e chain


Es ist uns eine traurige Pflicht, bekannt zu geben, dass unsere langjährige liebe Freundin PARITY am 19. Januar 1957 nach kurzem Leiden bei weiteren experimentellen Eingriffen sanft entschlafen ist.
Für die Hinterbliebenen
e, μ, ν

Pauli to Weisskopf

Garwin, et al., 1957

ν mass too small to measure,
ν helicity = –½
⤳ Universal Fermi Interaction (V–A)
with only ν_L
"two-component neutrino"
CVC hypothesis

1960s: Golden Age of β decay

Cf. Wu & Moszkowski, 1966

High-energy π, K decay → ν beams

$\nu_\mu \neq \nu_e$

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†
Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

Possibility of $\nu_\mu - \nu_e$ mixing
⤳ oscillations

$\nu \leftrightarrow \bar{\nu}$ oscillations?

(Pontecorvo, 1957)
Maki, Nakagawa, Sakata, 1962

SU(3)$_{\text{flavor}}$ symmetry inspires
Cabibbo universality, 1963

$$J_\lambda^{(+)} = \bar{u}\gamma_\lambda(1-\gamma_5)\, d \cos\theta_C + \bar{u}\gamma_\lambda(1-\gamma_5)\, s \sin\theta_C$$

⤳ current algebra,
Kobayashi–Maskawa 3×3, 1973

Rising $\sigma(\nu_\mu e \to \mu \nu_e) \propto E_{cm}^2$
⤳ new physics by $E_{cm} \approx 300$ GeV
Second-order needs cutoff

intermediate boson?

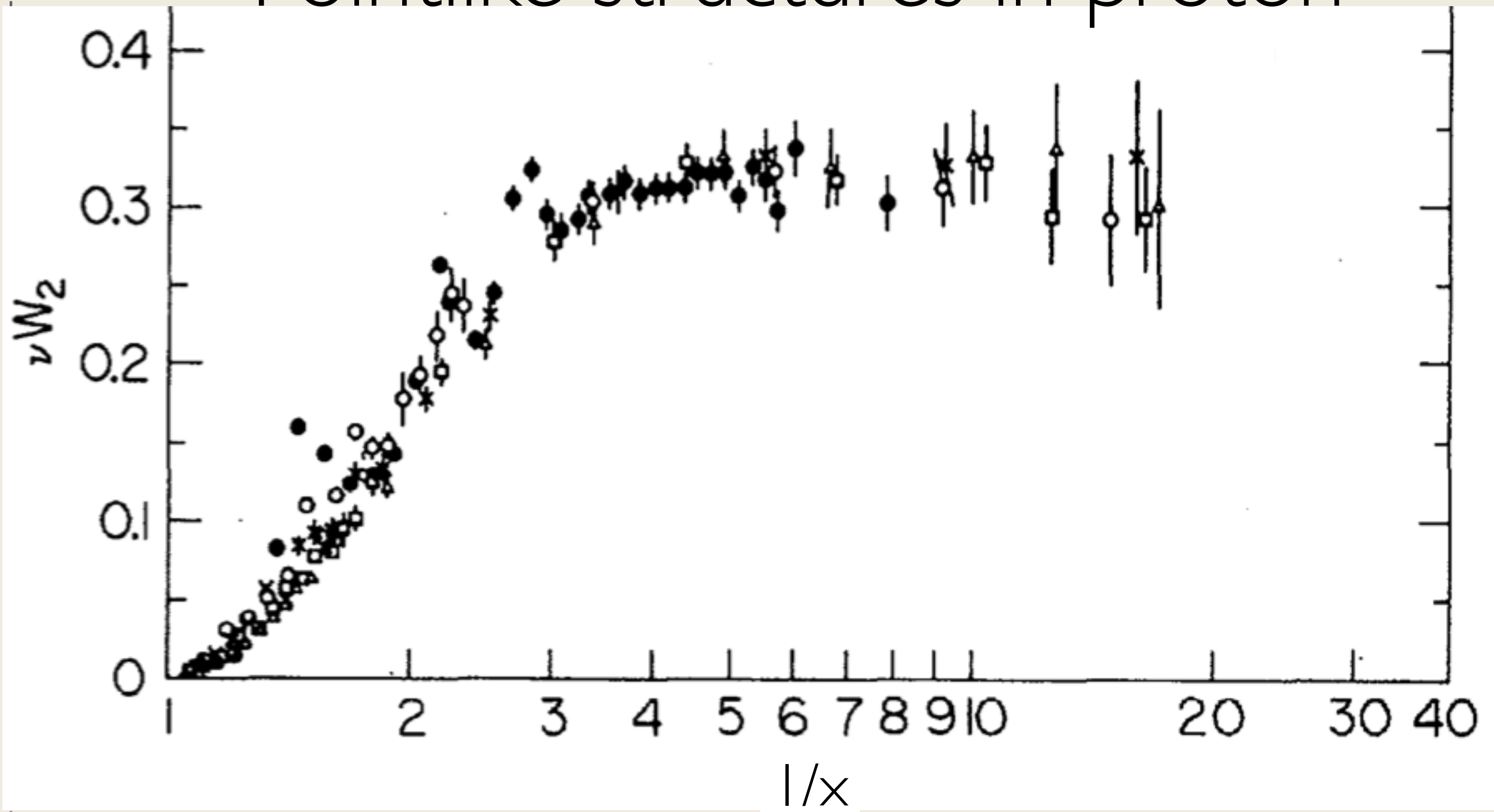
CP violation in weak decay

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

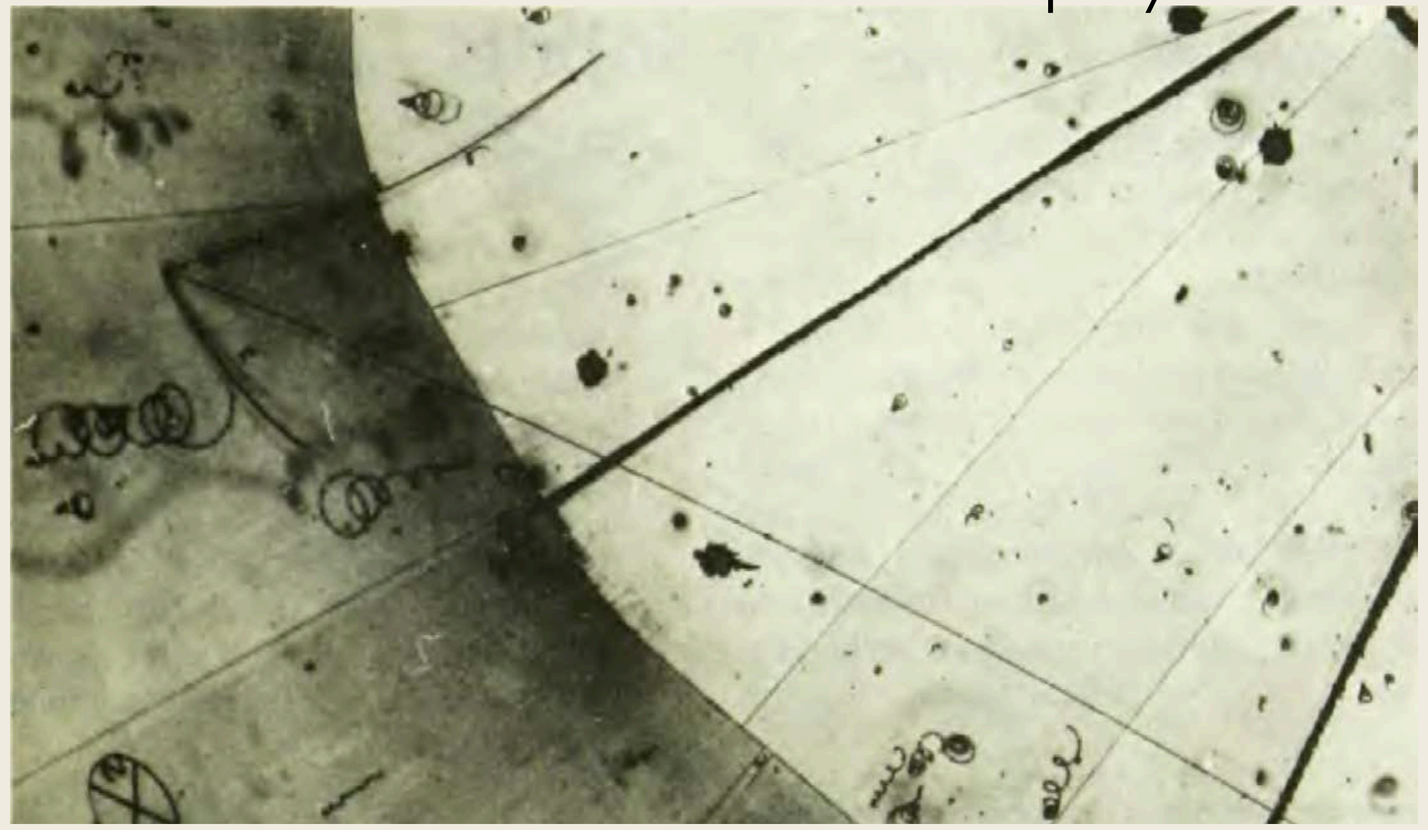
A new *superweak* interaction?

Pointlike structures in proton



SLAC–MIT, 1969

Bubble chambers for ν physics



$\nu_\mu p \to \mu^- \pi^+ p$, ANL 12', 1970

Issues in the air approaching ν'72*

Status and origin of $\Delta I = \frac{1}{2}$ rule

Existence of Intermediate Vector Bosons, $W^{\pm}$

Testing lepton universality:

$\sigma(\nu_e e) \leq 40\sigma_{V-A}$; $\sigma(\bar{\nu}_e e) \leq 4\sigma_{V-A}$

Existence, properties of Neutral Currents

$K_L \rightarrow \mu^+\mu^-$ Puzzle

CP Violation!

Search for second-class currents

Implications of Bjorken scaling, partons: CERN propane BC, $\sigma \propto E_\nu$

High-energy ν beams coming at Fermilab and CERN SPS

* Sam Treiman (1971)

From ν'72 Summary Talks

Bruno Pontecorvo

"ambitious and difficult investigations in which somebody tries very hard to find and measure something, but does not see anything."

1. $K_L \rightarrow \mu\mu$ puzzle (inequalities)
2. Solar neutrinos (upper limit)
3. Lepton charge conservation (upper limits)
4. "Stable heavy leptons" ("negative" results)
5. $\bar{\nu}e$ scattering, reactors (upper limits)
6. Neutral currents (upper limits)

"danger if you believe really in extraordinary things even before you are forced [to] by hard facts"

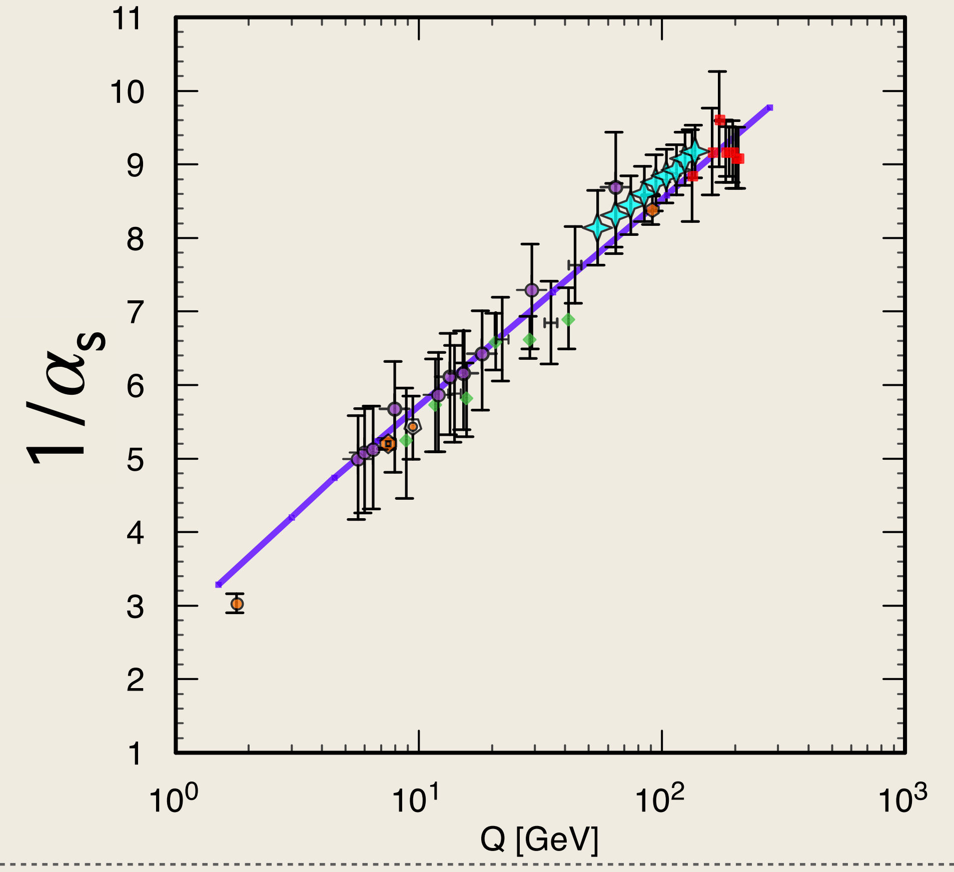
Viki Weisskopf

"You cannot talk about weak interactions alone."

1. Troubles with V–A "Fermi" interaction: unitarity, nonrenormalizability, **CP** violation
2. Weinberg's Theory of Leptons
   spontaneously broken $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{EM}$
   ↪ neutral lepton currents
   gauge cancellation in $e^+e^- \rightarrow W^+W^-$
   "whole approach disregards **CP** violation"
3. Weak & EM: tools to investigate hadrons
   Field theory *vs.* partons; sum rules as diagnostics; quarks seemed to have Bose statistics

$\nu_\mu e \to \nu_\mu e$ specimen

Gargamelle, 1973



ASF ↪ QCD, 1973

Unified Theories ↪ Proton Decay

$SU(5) \supset SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

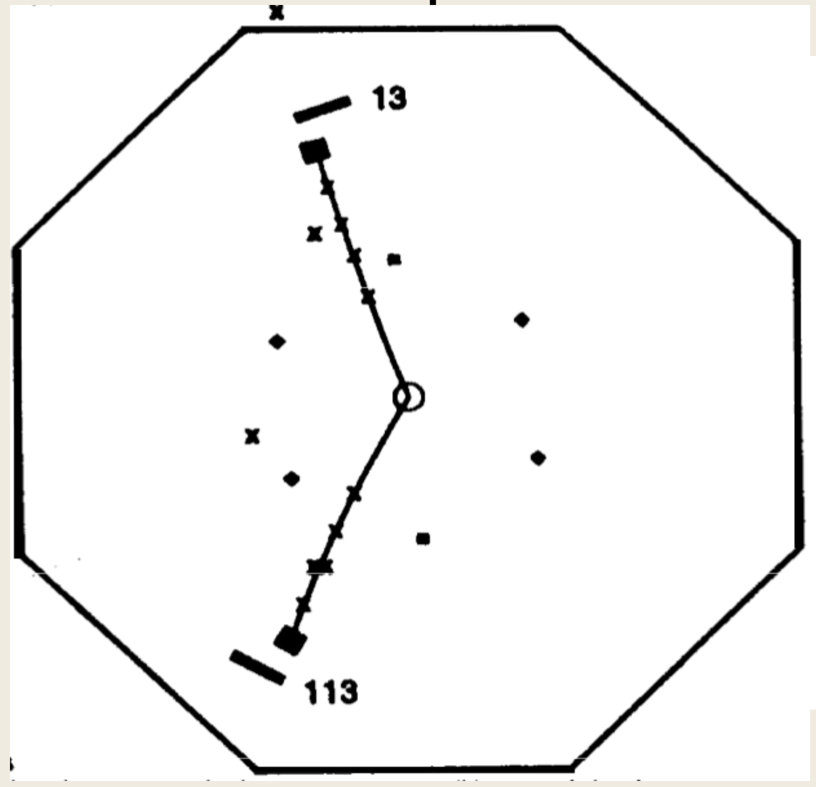
$SO(10) \supset SU(4)_c \otimes SU(2)_L \otimes SU(2)_R$

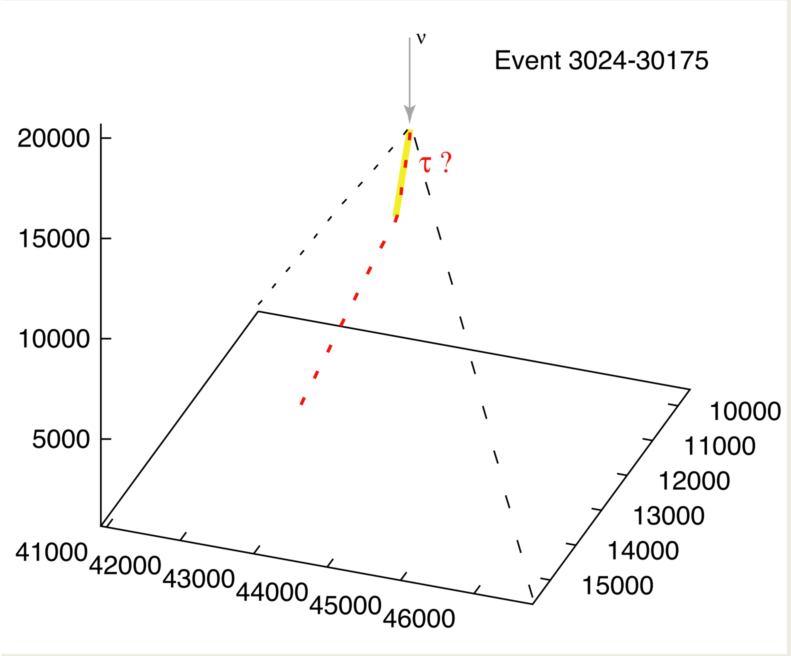
$\Longrightarrow$ Large-volume detectors

seesaw mechanism for light ν

1973–5

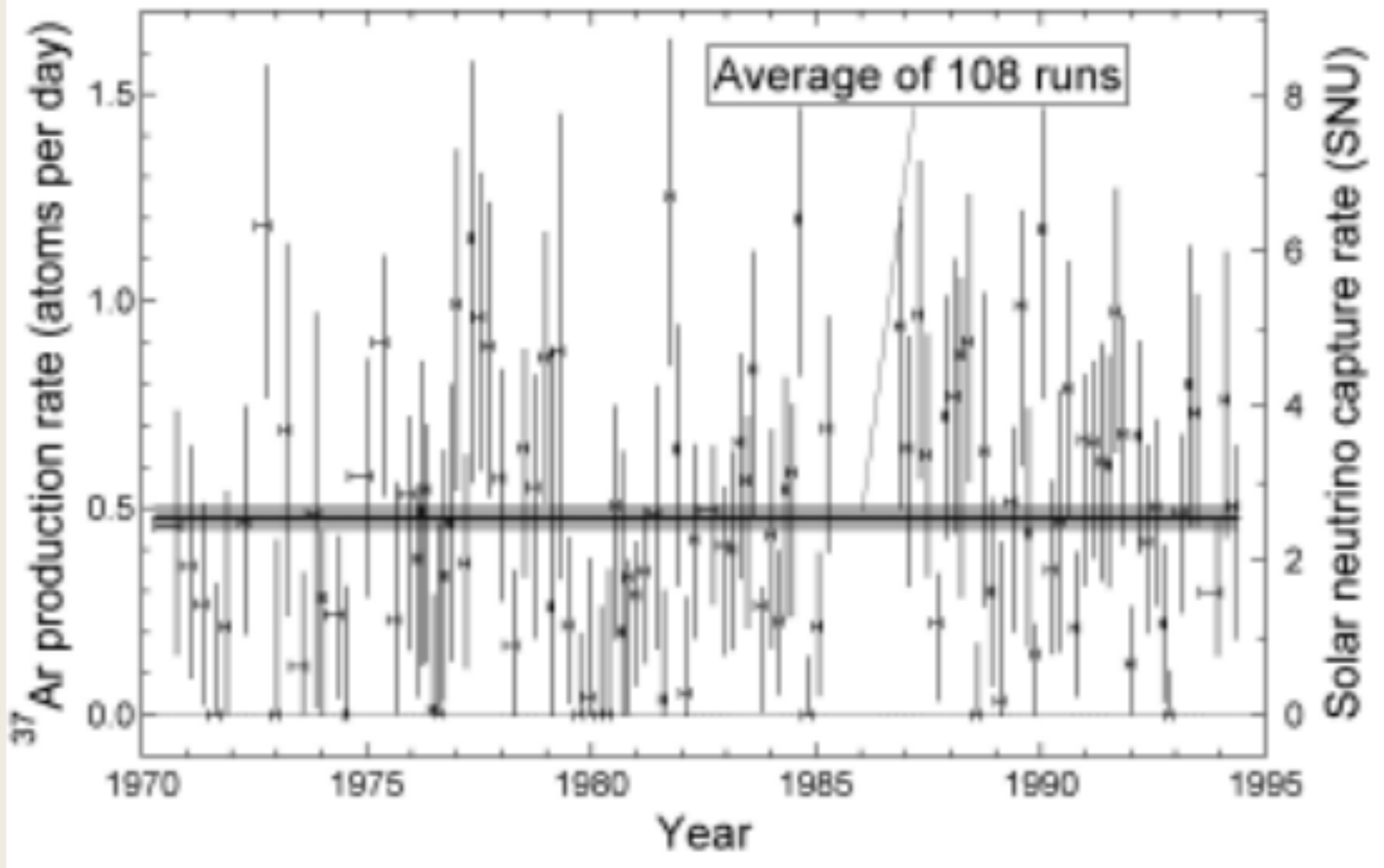
SPEAR eμ events → τ lepton ↪ ν_τ



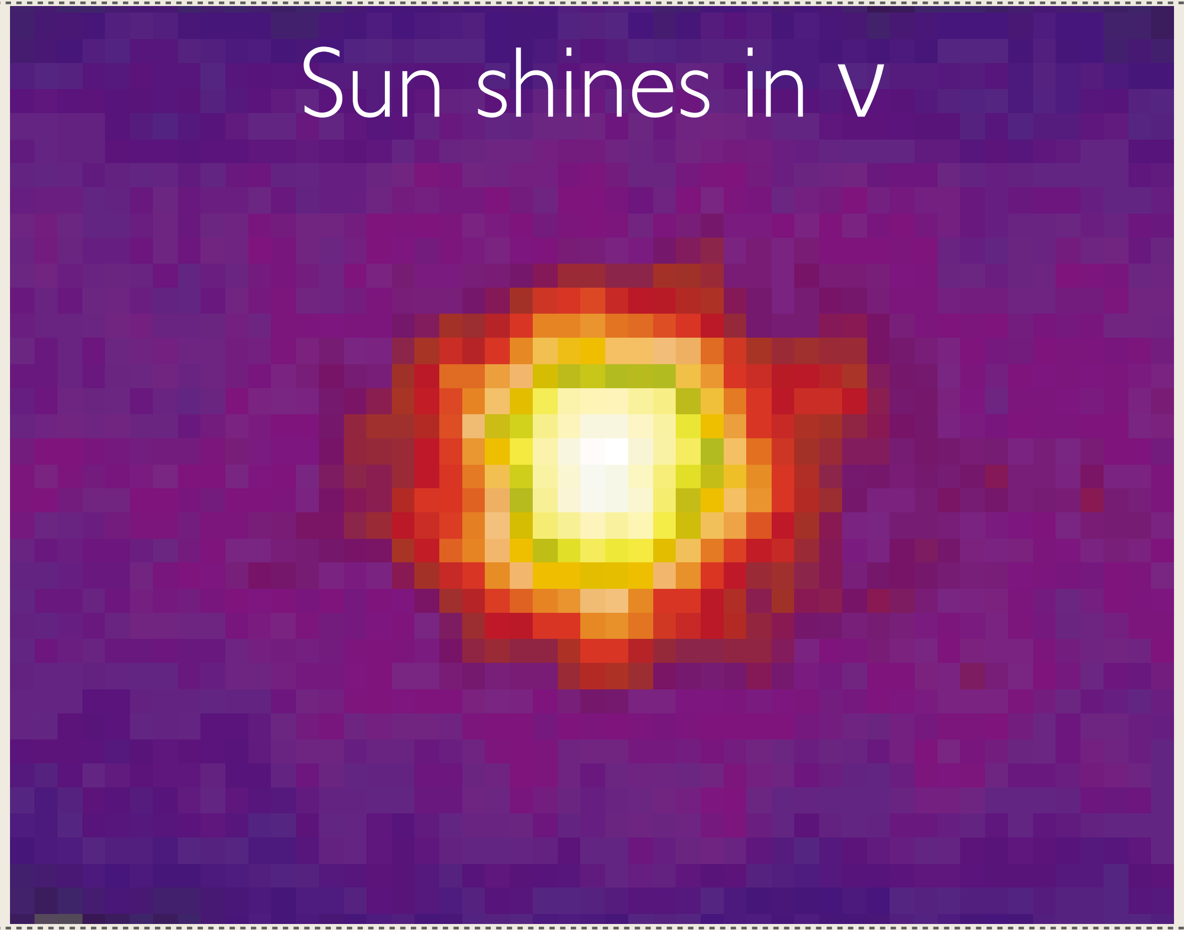


DONuT, 2000

Perl + Mark I, 1975–7

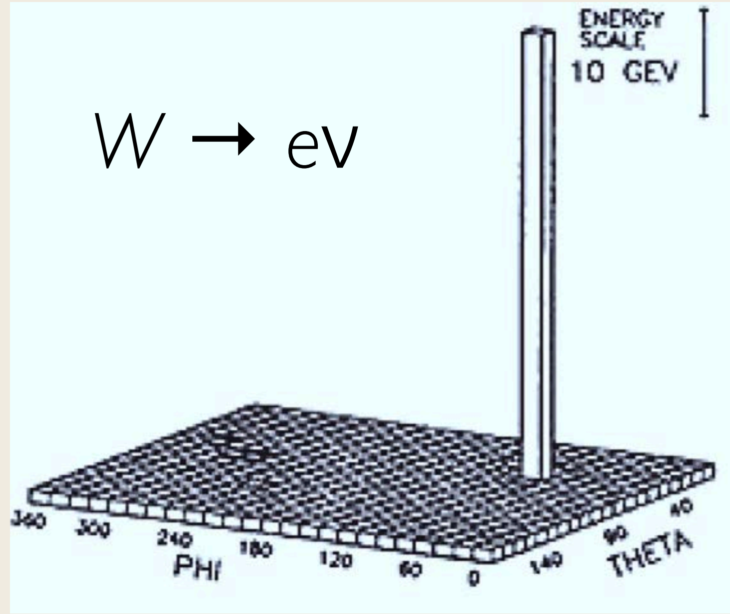


Homestake



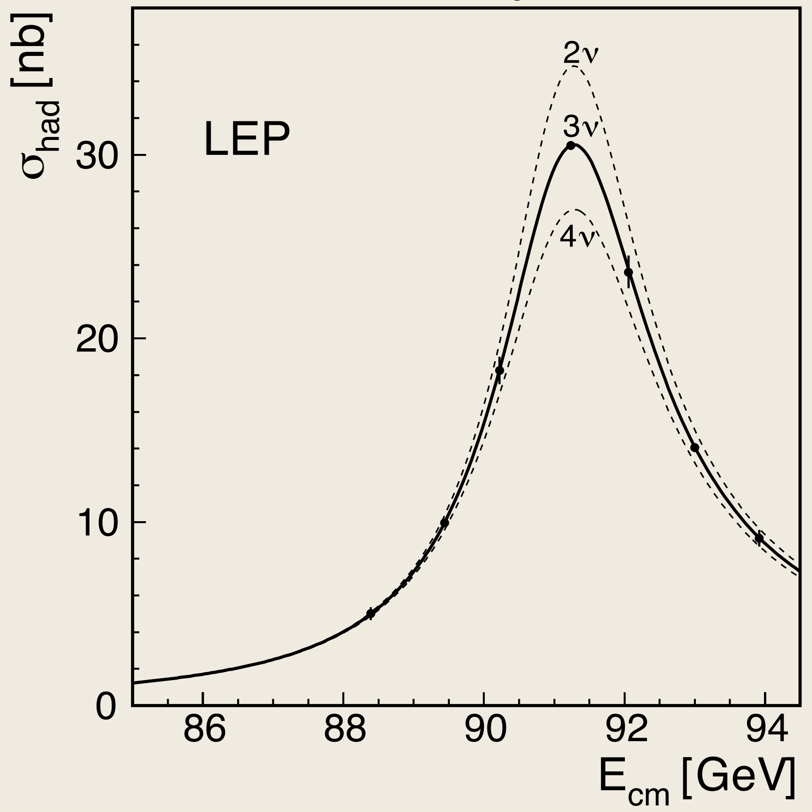
Super-Kamiokande

W, Z discovery



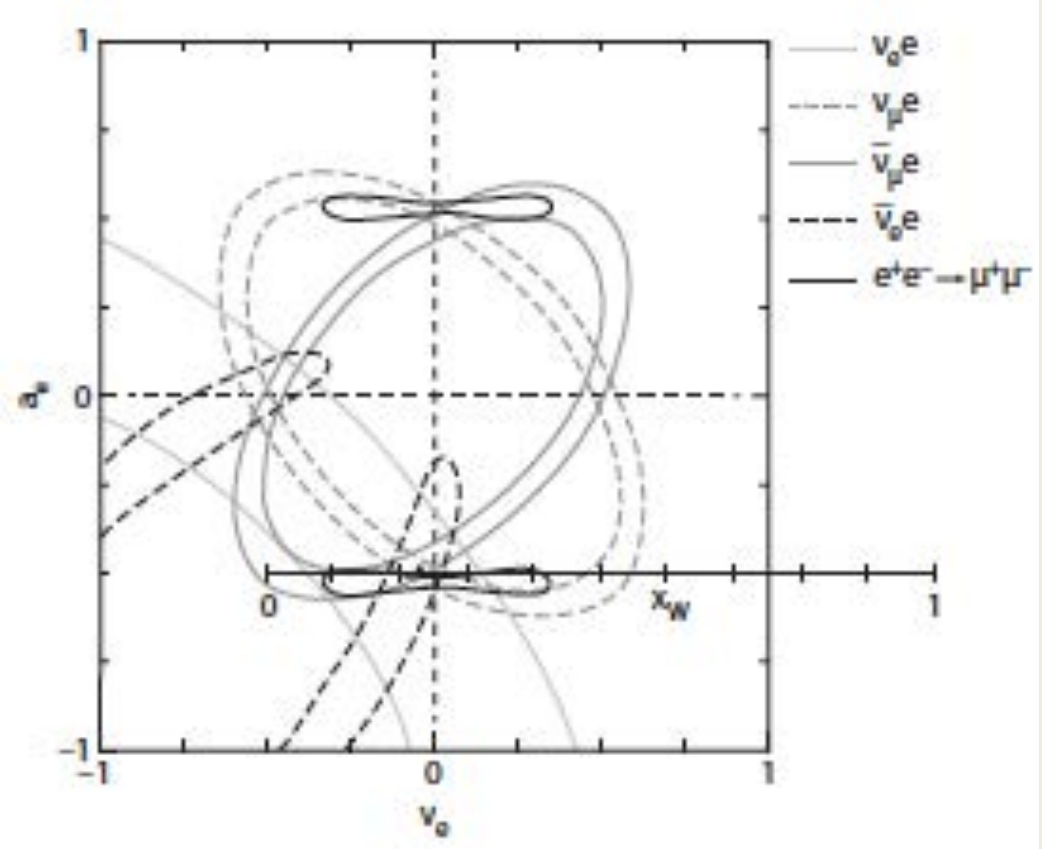
UA1/UA2, 1982–3

→ 3 ν species



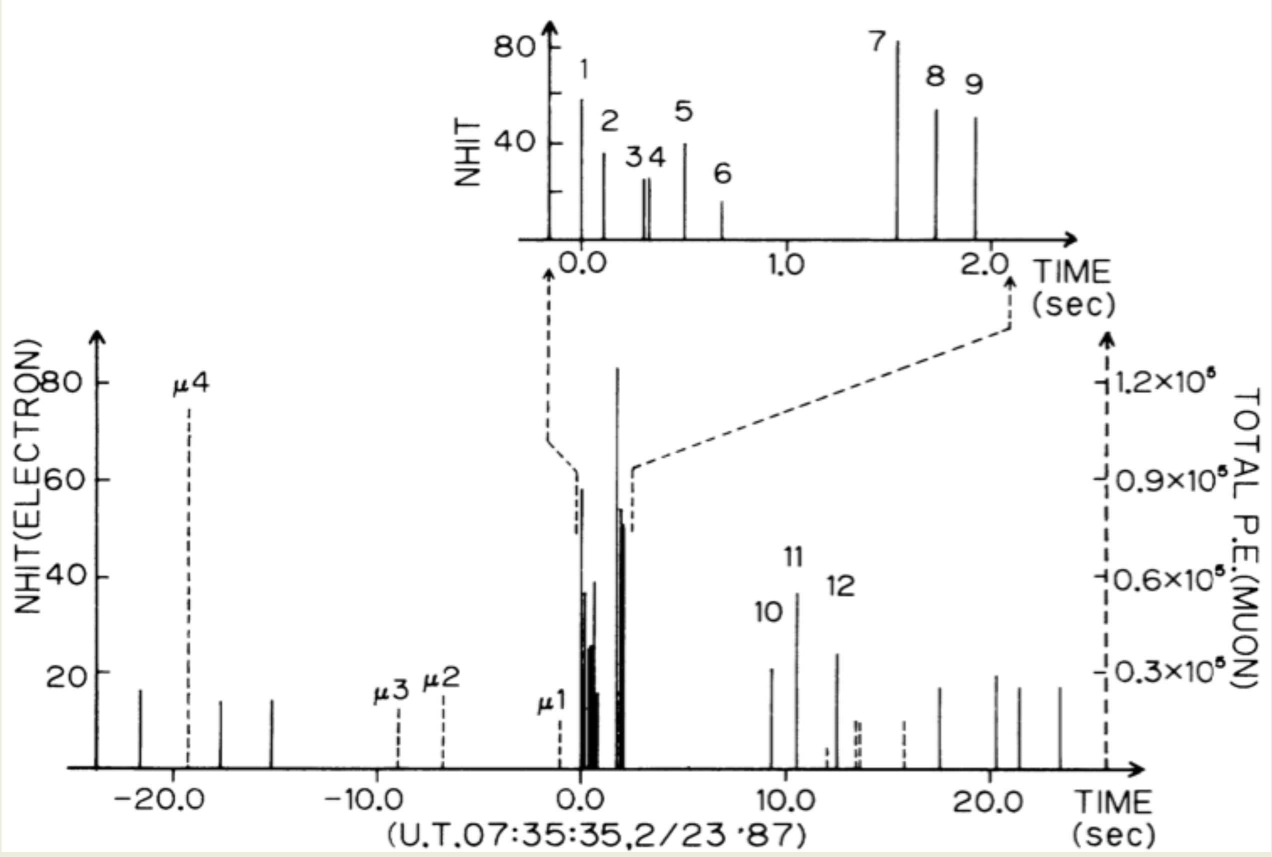
LEP, 1989–

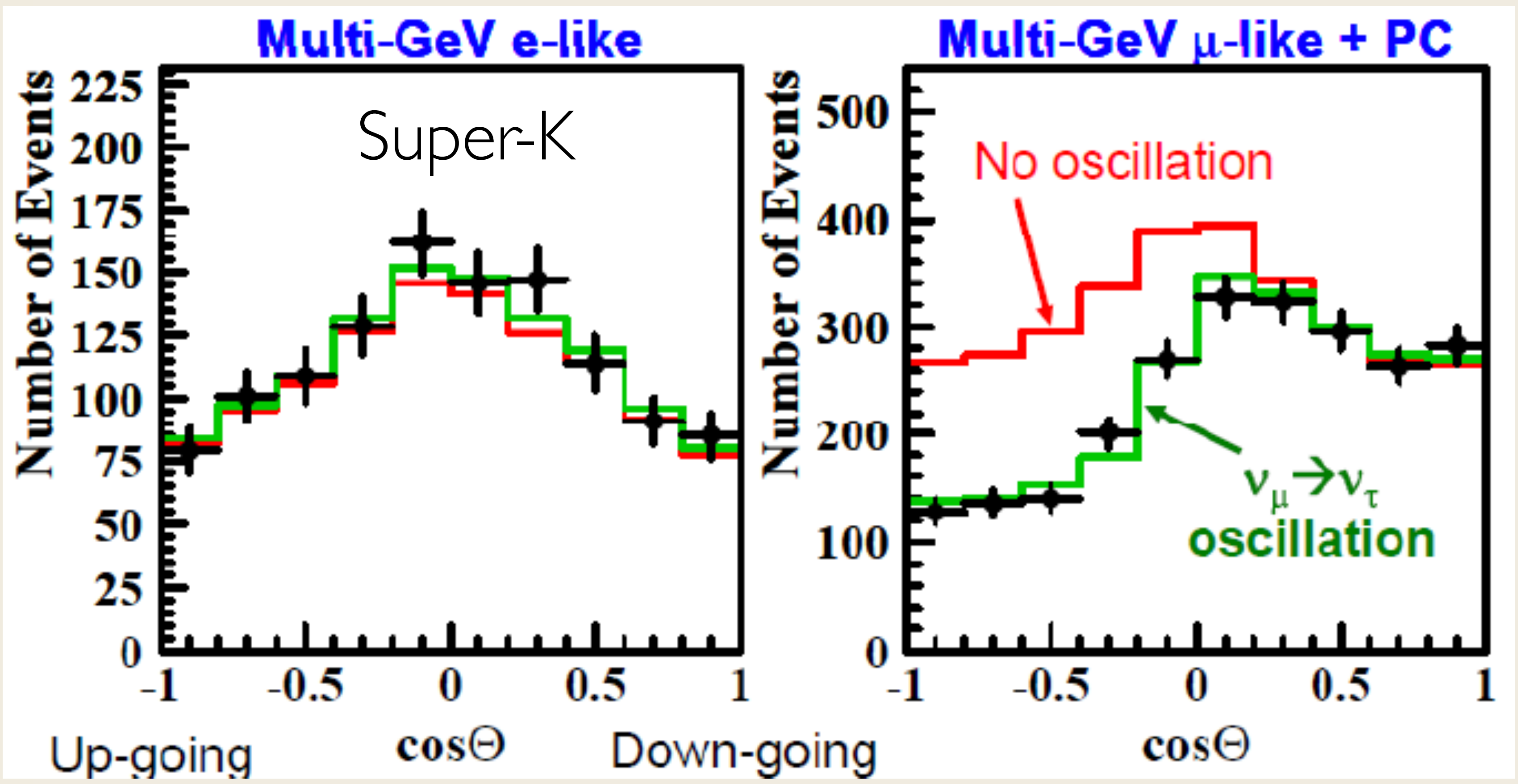
Leptonic σ favor $SU(2)_L \otimes U(1)_Y$

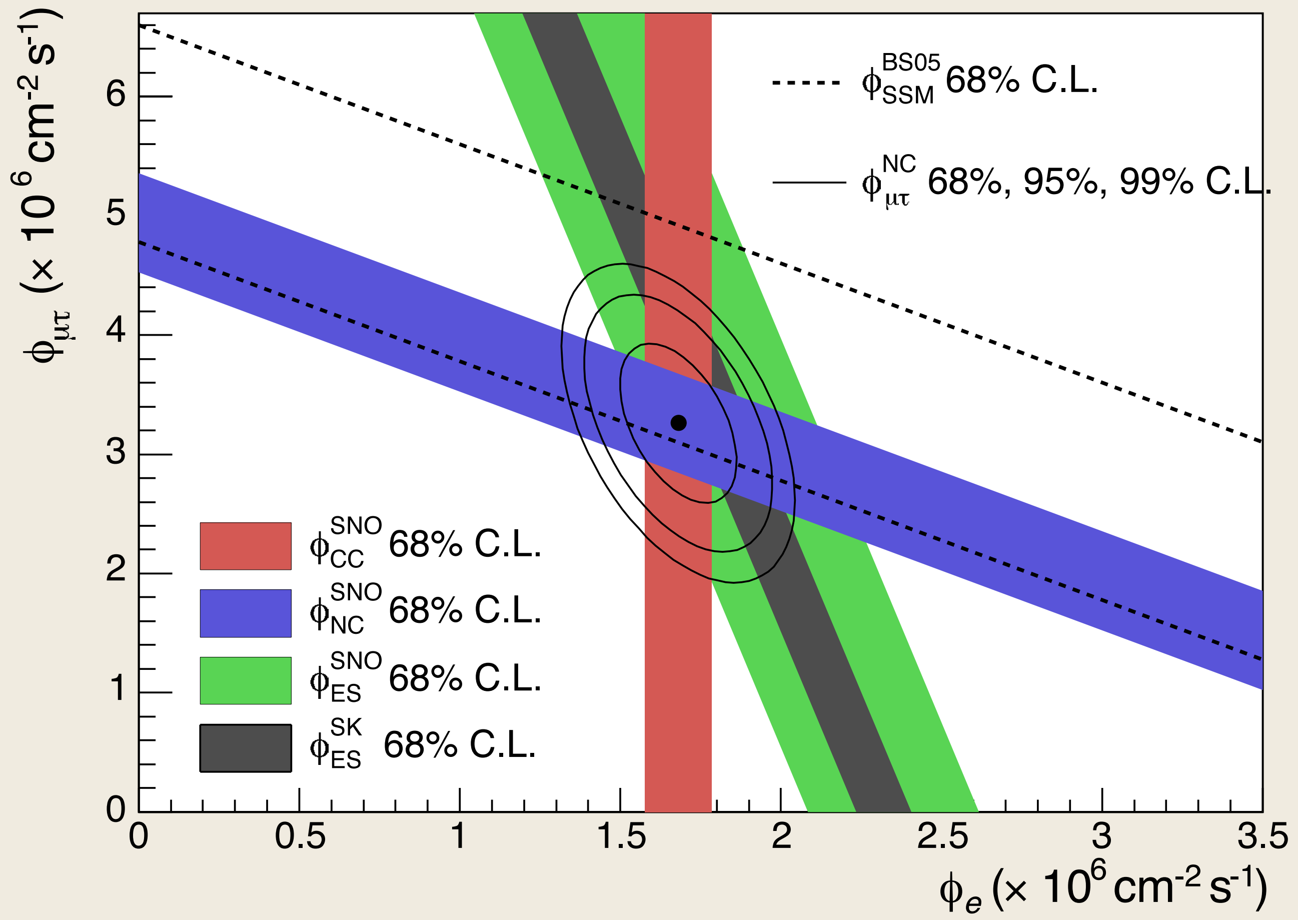


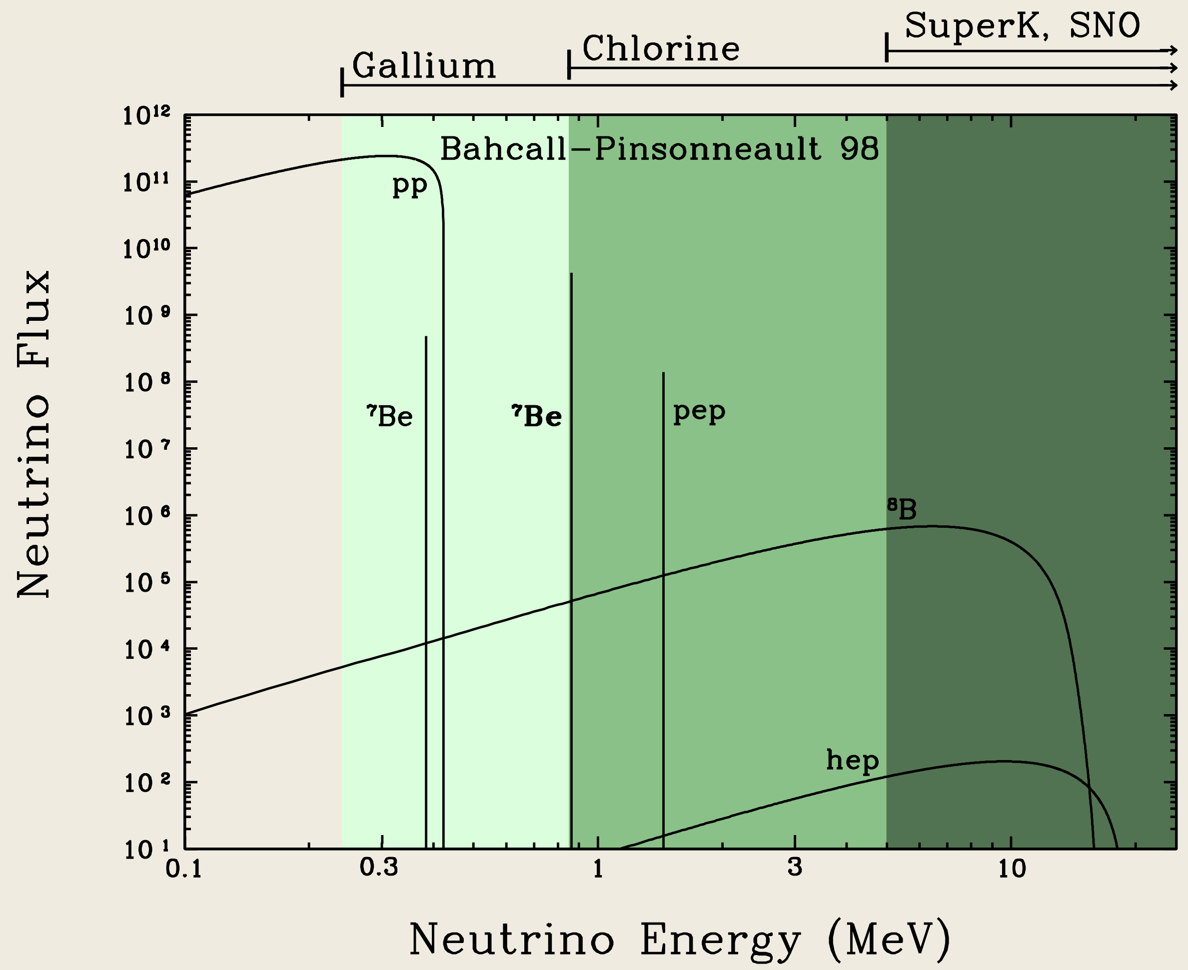
ca. 1987

SN1987a ν burst

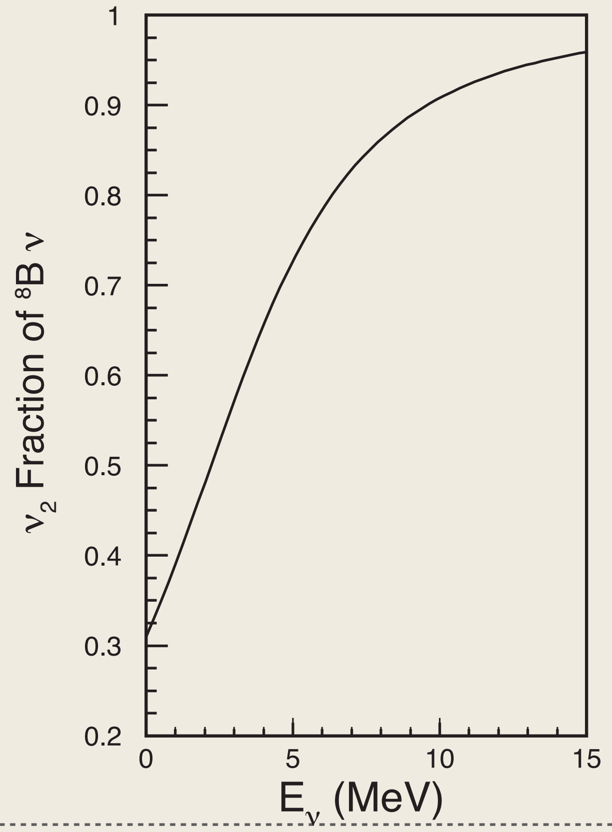






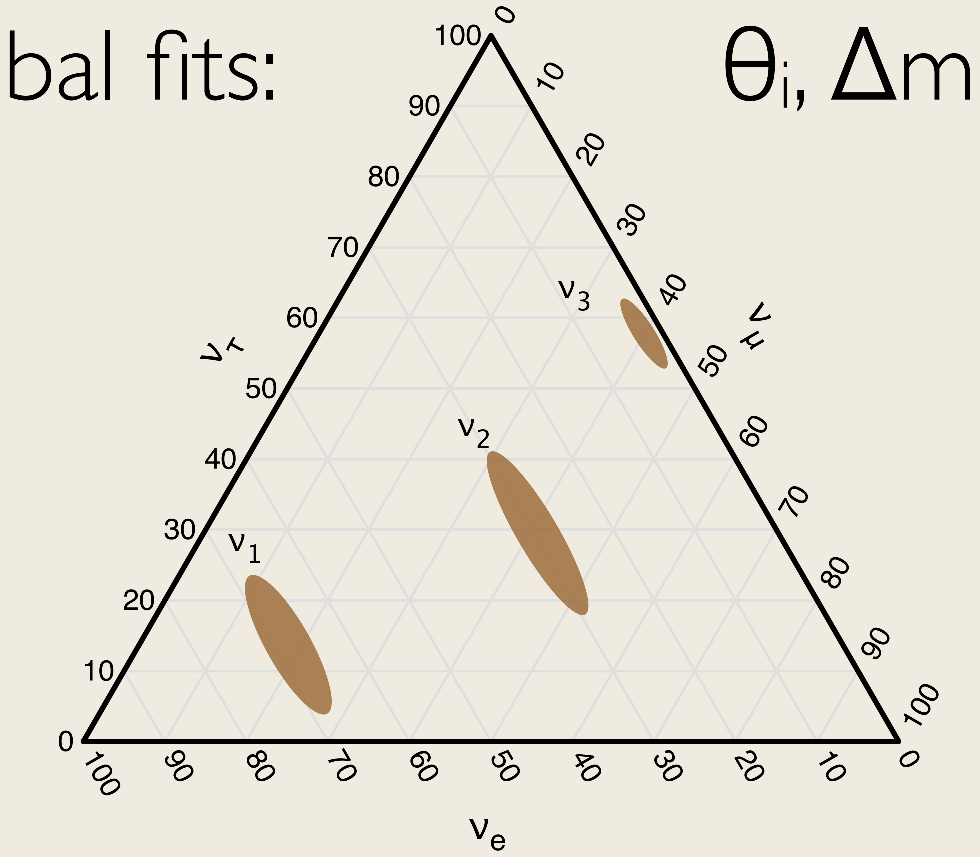


Matter-modulated oscillation (MSW)

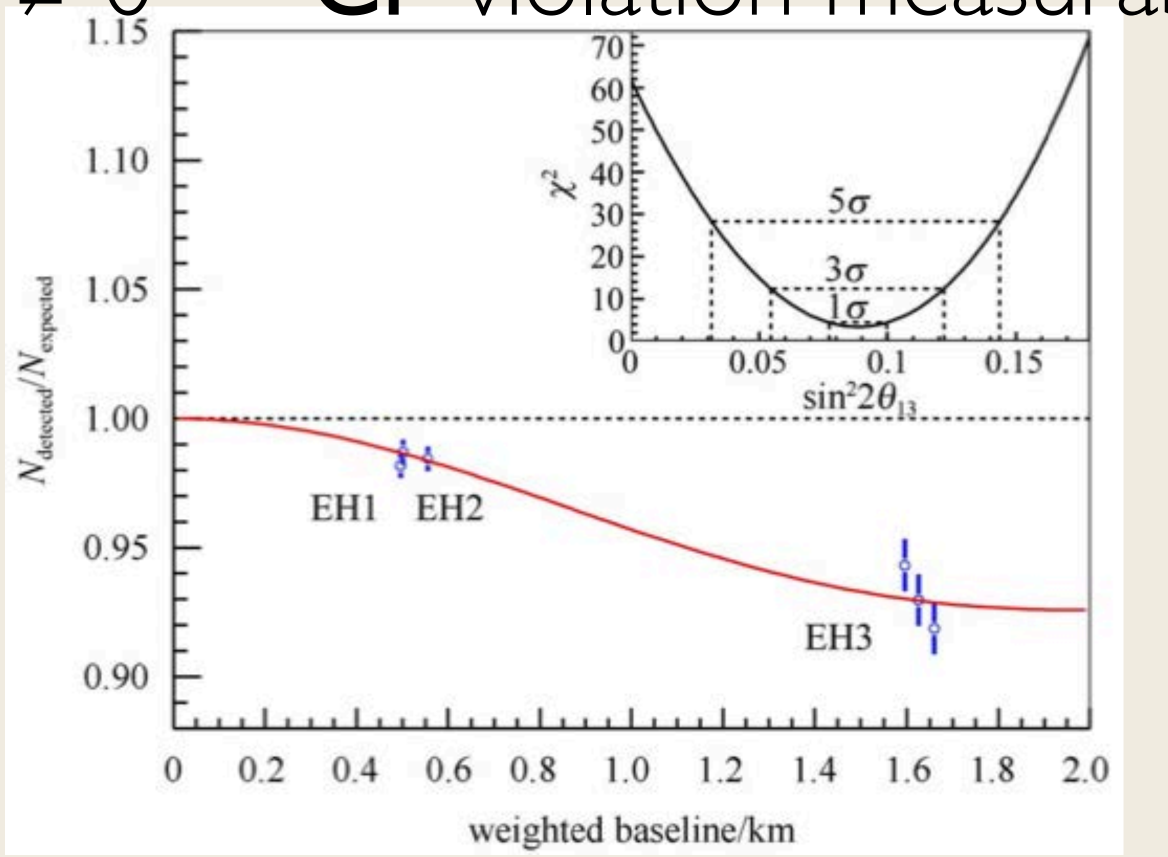


$P(\nu_e{:}\nu_2)$

Global fits: θ_i, Δm_{ij}^2, δ_{CP}



$\theta_{13} \neq 0$ ↪ **CP** violation measurable



Daya Bay, RENO, ...

Ultra-rare decays

1987: $\nu\nu\beta\beta$ ^{82}Se, $T_{1/2} \approx 10^{20}$ y

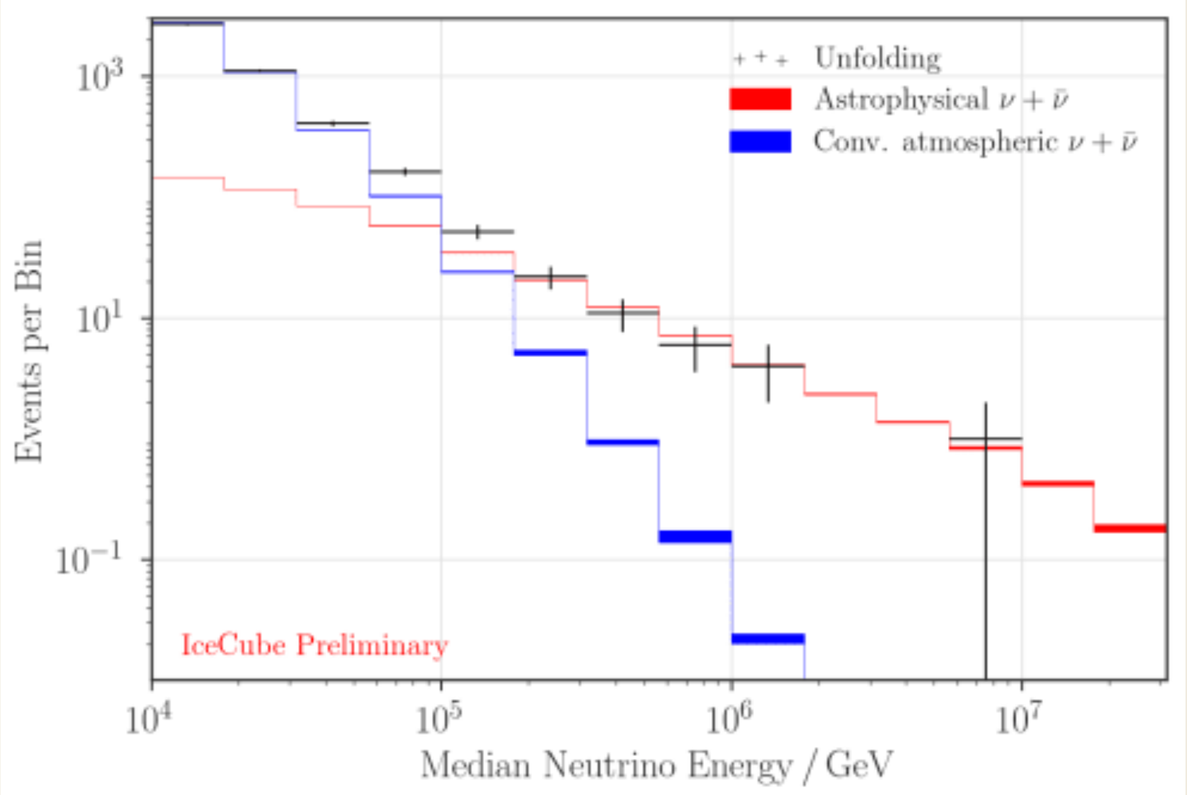
2022: $(2\nu ECEC)$ ^{124}Xe, $T_{1/2} \approx 10^{22}$ y

$0\nu\beta\beta$ decay not yet observed

at level of $T_{1/2} \approx 10^{25}$ y

[$\tau_p > 10^{31}$–10^{33} y]

Extraterrestrial ν



IceCube

ν mass constraints

Cosmological arguments:

$\Sigma_i m_{\nu_i} \lesssim (0.10\text{-}0.26)$ eV

^{3}H β decay:

$m_{\nu_\beta} < 0.8$ eV, 90% CL

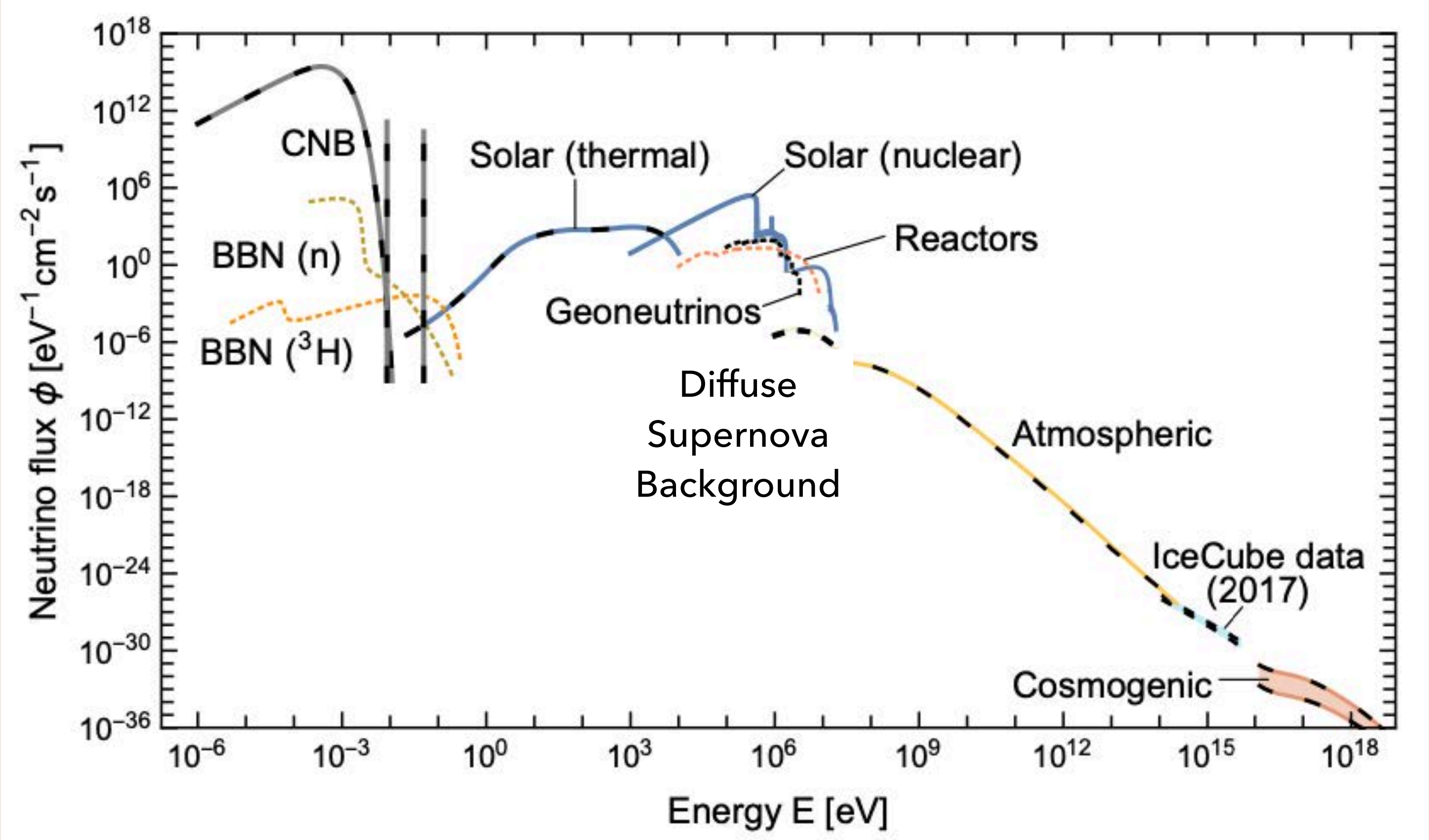
KATRIN, ...

Neutrinos through cosmological history

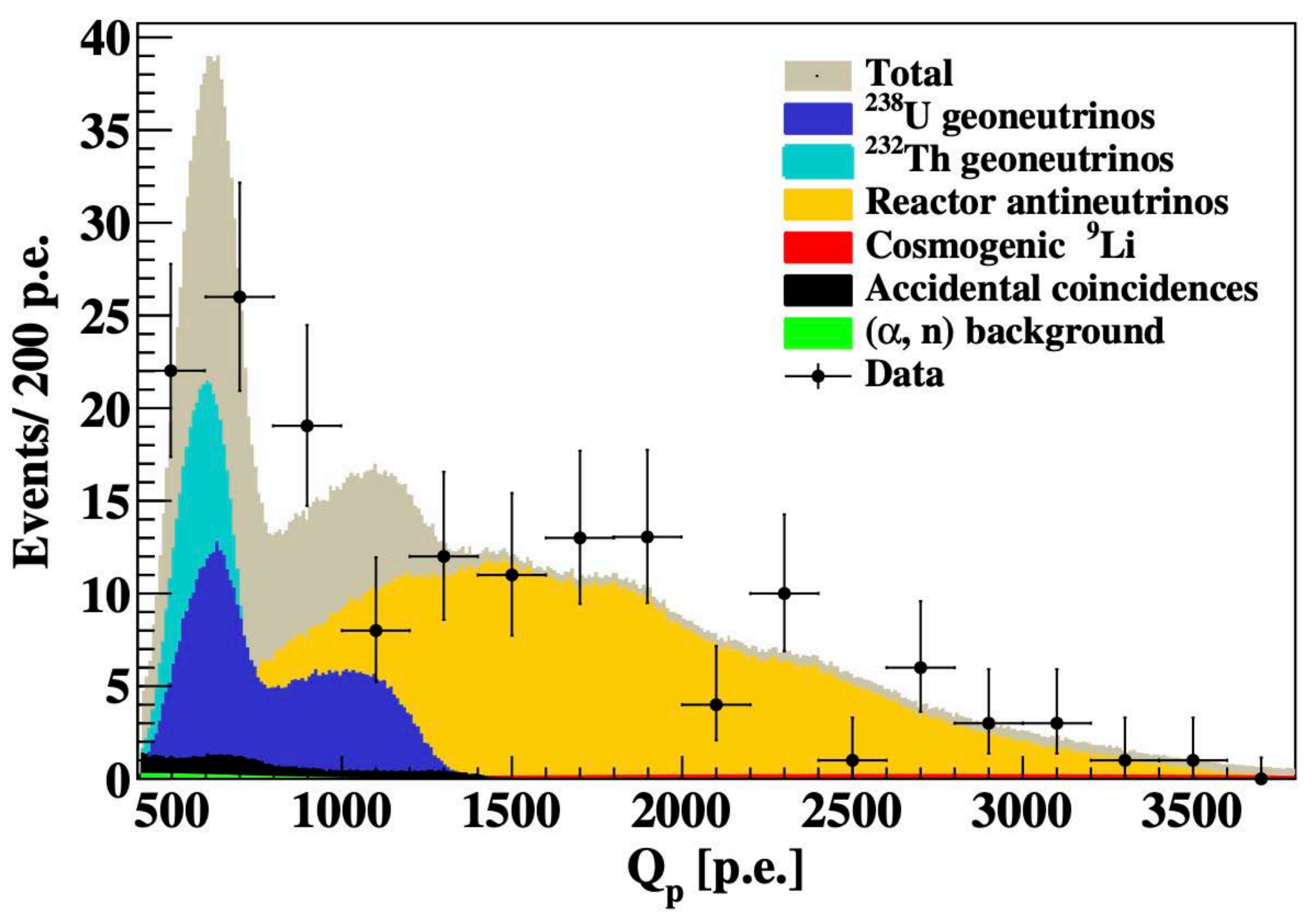
Relic neutrinos present at
Big-bang nucleosynthesis (few minutes),
Decoupling era (380 ky),
Large-scale structure formation (few %)

WMAP, Planck, …

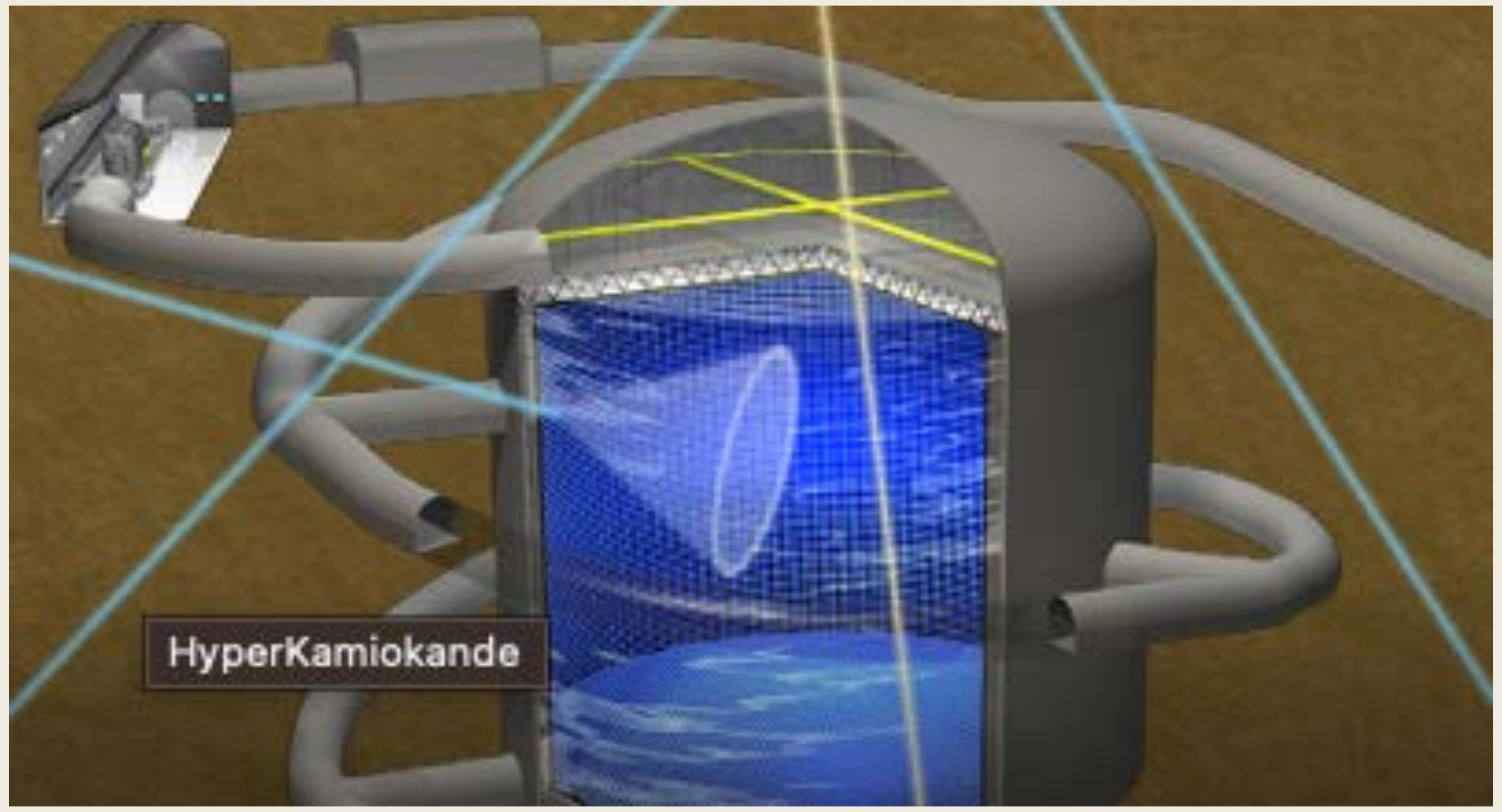
“Grand Unified ν Spectrum”



Vitagliano +, RMP **92**, 45006

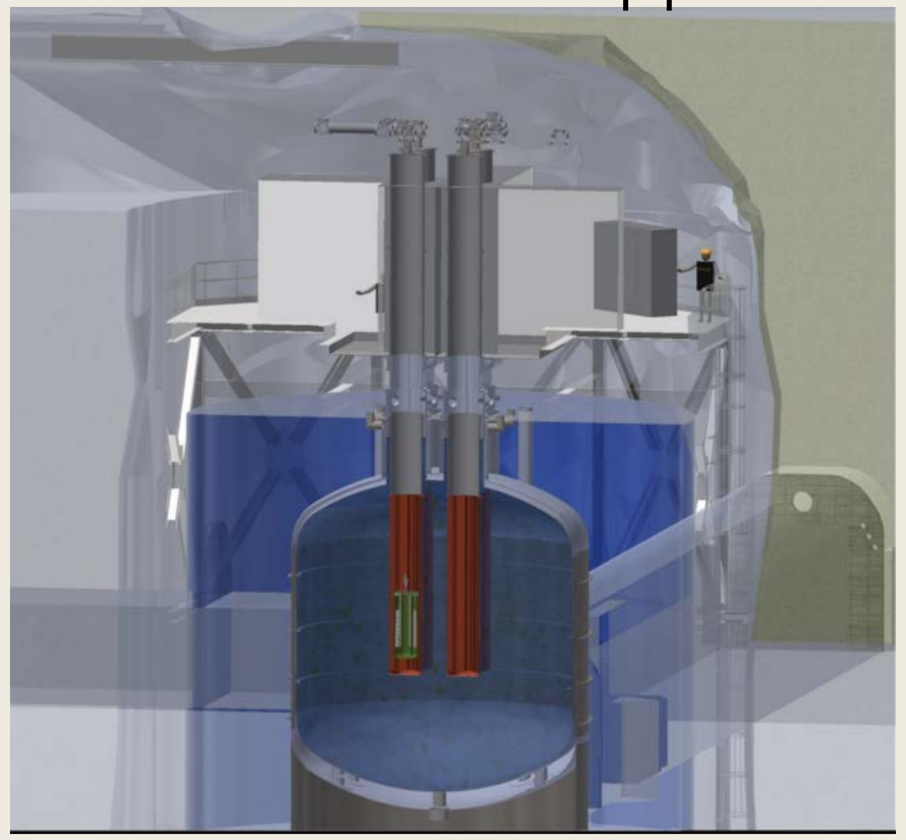


Borexino

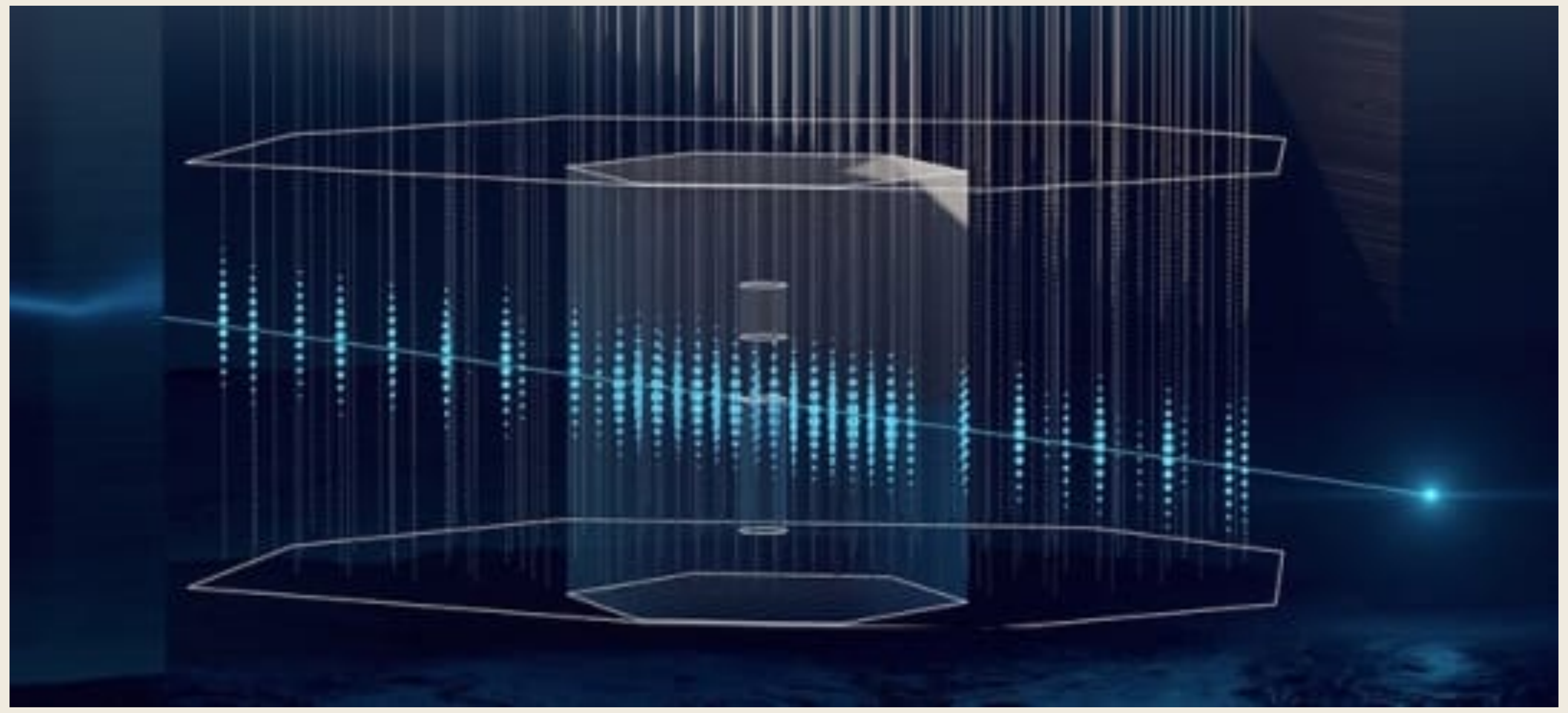


DUNE

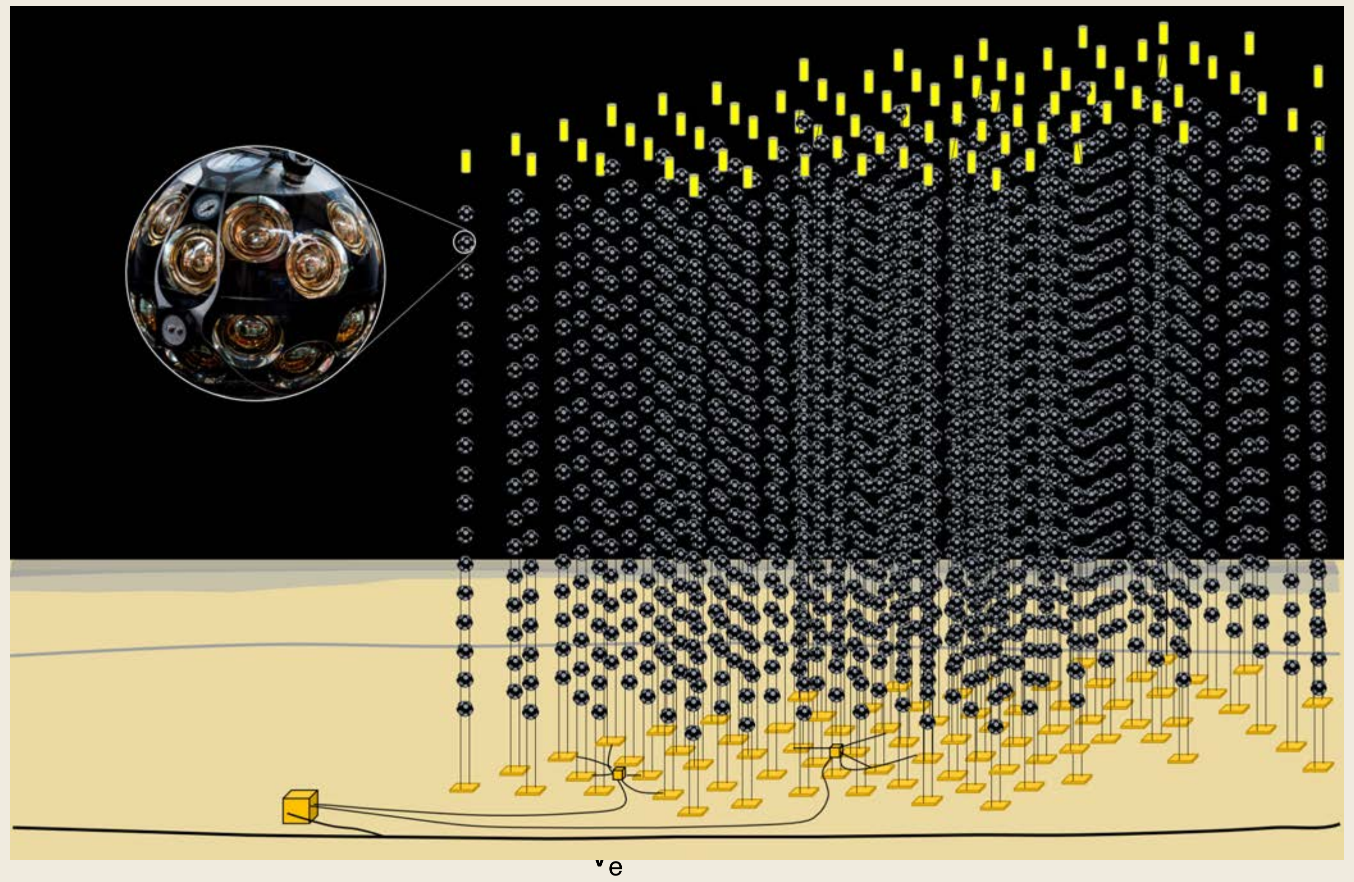
LEGEND: ^{76}Ge ββ0ν



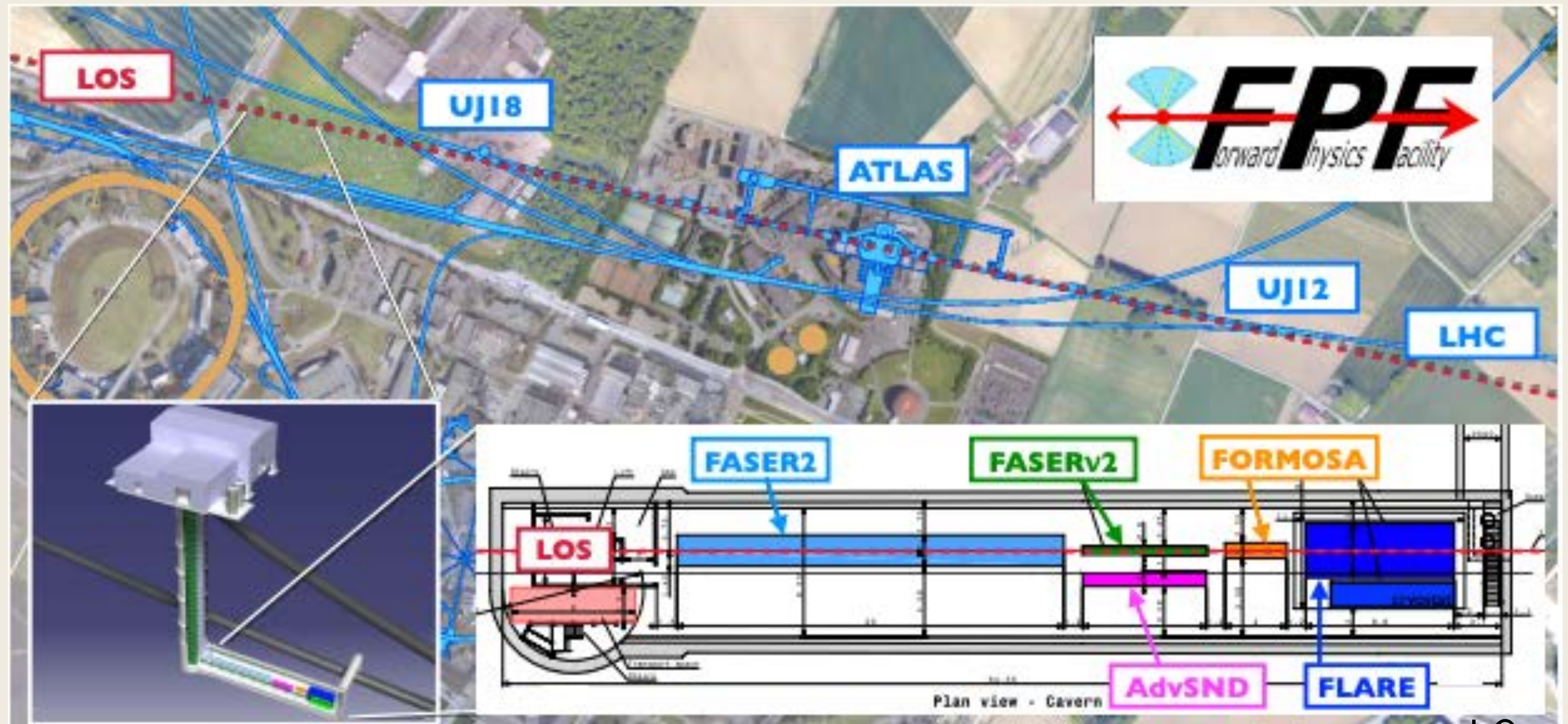
Ice-Cube-Gen2



KM3NeT



Forward Physics Facility for LHC



Some issues approaching ν2022

Why does the neutrino weigh? At what scale are m_ν set?

What is the order of the levels ν_1, ν_2, ν_3? Absolute scale?

How is $m_\nu \neq 0$ a sign of BSM physics? Is Higgs field implicated?

How much (how little) do ν contribute to the dark matter?

Can we find a link between ν and dark matter?

Do neutrinos have nonstandard interactions, not mediated by *W* and *Z*?

Can we observe electromagnetic properties of ν?

Can we detect right-handed charged-current interactions?

What is the nature of right-handed ν? Are there light noble sterile ν?

Do 3 light (LH) ν suffice?

Some issues approaching ν2022[bis]

Are neutrinos Majorana particles?

Are ν_1, ν_2, ν_3 stable on cosmological time scales?
How can we detect the cosmic neutrino background?

Is **CP** violated in ν oscillations? How does it arise?
Will ν yield insight into the matter excess in the universe?

What can we learn from the next supernova?

Some issues approaching ν2022[ter]

Are the interactions of ν_e, ν_μ, ν_τ universal?
What about the interactions of charged leptons?

Can we detect charged-lepton flavor violation?
What is its relation to neutrino mixing?

Need to resolve outstanding anomalies:
neutron lifetime, LSND/MiniBooNE, reactor flux, *W* mass,
LHC*b* hints of departures from lepton universality.

What have we overlooked? What do we know that is not true?

A Preview: Highlights of ν2072

Long-baseline experiments will establish oscillation parameters with admirable precision, but real predictions are still lacking.

The study of leptonic **CP** violation will take on a life of its own; the connection to leptogenesis remains psychological.

The answer to the matter asymmetry will be "none of the above."

ν observatories will locate point sources, including transients. Flavor identification will characterize flavor mix at steady sources.

A neutrino factory will enable precise ν_e / ν_μ comparisons and revolutionize nucleon femtoscopy using polarized and active targets.

A meta-analysis will elucidate LSND/Mini-BooNE as a cocktail.

Large-scale experiments will hint that some neutrinos decay.

A Preview: Highlights of ν2072^{bis}

Systematics of 2νββ will provide new insights into nuclear dynamics.

Intense high-energy beams of ν_τ will suggest subtle differences with ν_e, ν_μ.

0νββ will be observed for several isotopes.

Someone in today's audience will connect quark and neutrino mixing, but debate persists: are particle parameters deeply meaningful or environmental?

Neutrino cosmology will precisely measure light degrees of freedom and the sum of neutrino masses; ^{3}H β-decay will yield a larger m_ν, calling into question the canonical history of the universe.

Relic neutrinos will be detected after prodigious effort, and "soon" will be studied in undergraduate labs.

Detection of cosmogenic (GZK) neutrinos will fix birth of first stars.

A Preview: Highlights of ν2072ter

Neutrino tomography of Earth's interior and widespread detection of geoneutrinos (+ lunar counterpart) draws planetary scientists to ν2072.

Extensive studies of CNO ν will inform solar physics and test understanding of matter-modulated flavor change.

Collider experiments will find multi-TeV neutral leptons.

Neutrino observatories will complement multi-messenger astronomy, enriching understanding of the Sun, supernovae, and cataclysmic mergers.

RH charged-current interactions, *W*-bosons suggest new paths to unification.

We will learn to use undersea fiber-optic networks and ubiquitous environmental surveillance infrastructure to study ν.

Proton decay will be observed in several modes.

Thanks to ν'22 Organizers & Participants,
and to my ν Collaborators, Advisors, Teachers

Carl Albright, Gabriela Barenboim, John Beacom,
Marcela Carena, Debajyoti Choudhury, Gene Commins,
Raj Gandhi, Dave Jackson, Joachim Kopp, Ben Lee, Magda Lola,
Pedro Machado, Olga Mena, Irina Mocioiu, Stephen Parke,
Mary Hall Reno, Ina Sarcevic, Robert Shrock, Jack Smith, Terry Walker,
and many inspiring experimental colleagues.

NEUTRINO '72

EUROPHYSICS CONFERENCE

BALATONFÜRED, HUNGARY,

11-17 JUNE 1972

organized by

THE HUNGARIAN PHYSICAL SOCIETY

PROCEEDINGS VOLUME I.

A. FRENKEL
G. MARX — **Editors**

OMKDK-TECHNOINFORM

Also see J. Schneps, "Brief history of 'Neutrino', the International Conference on Neutrino Physics and Astrophysics," in *Neutrino 2014*.

Special Issue to commemorate the 50th anniversary of ν '72