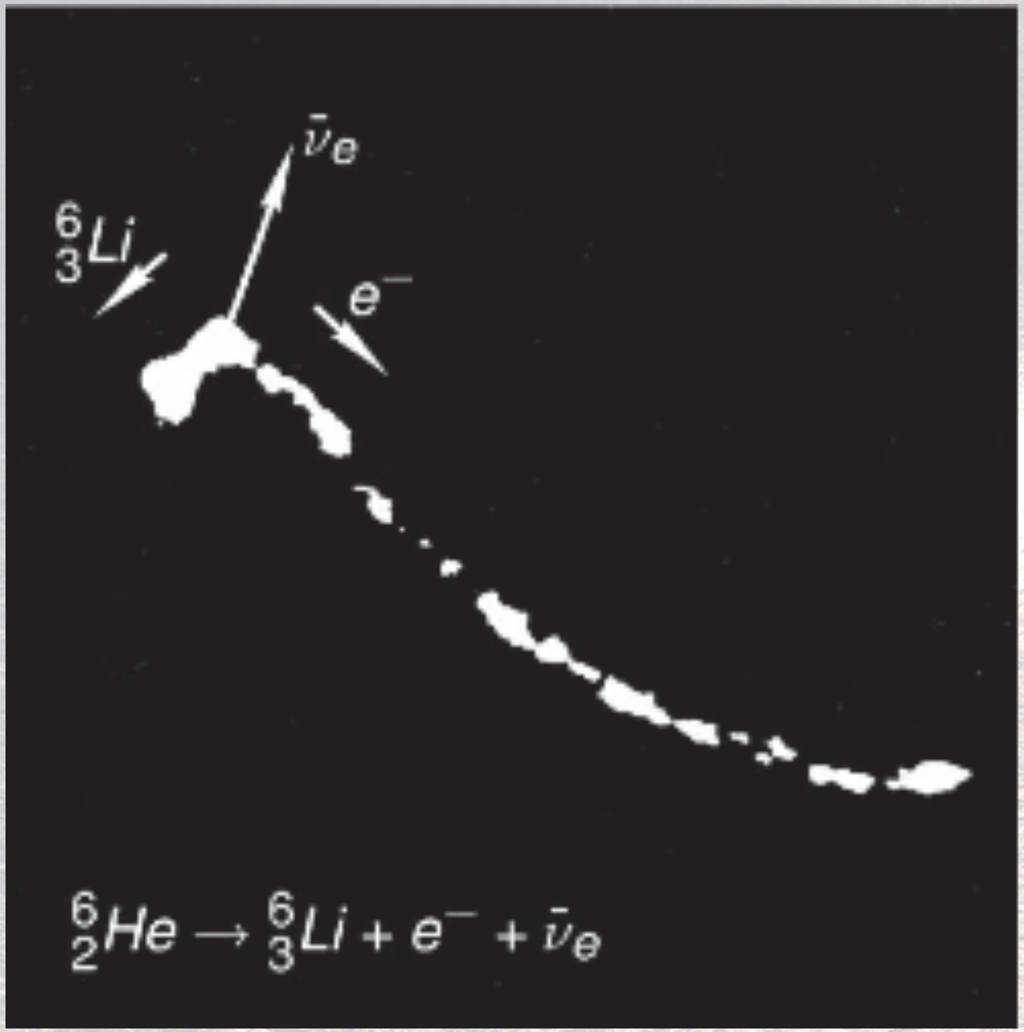
First cloud chamber image of β decay

J. Csikai and A. Szalay, Budapest, fall 1956



Introduction to Experimental Neutrino Physics

Majorana School

Modica, 2023

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Università di Genova and INFN

Outline (I)

- Quick review of relevant neutrino physics
  - Neutrinos in the SM and low energy Fermi effective theory
  - Charged and Neutral currents
  - Interaction with Leptons and Hadrons
  - Mixing and oscillation; neutrino propagation through matter
  - Dirac and Majorana mass terms

- Neutrino phenomenology from 0 eV up to PeV scale
  - Zero threshold processes
  - Low energy nuclear processes
  - Scattering on electrons
  - Elastic, quasi elastic, resonant, deep inelastic scattering on nucleon and nuclei

Outline (II)

- Experimental techniques
  - Radiochemistry
  - Water/Ice (and D_2O) Cherenkov detectors
  - Organic scintillators
  - Sampling calorimeters
  - LAr
  - Accelerator experiments

Disclaimer

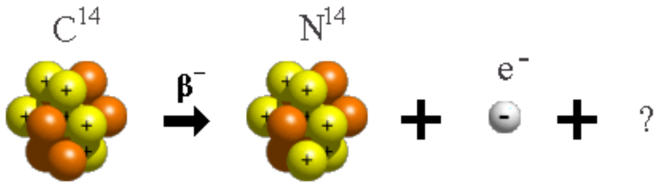
- The list of items shown before clearly exceeds what may be discussed thoroughly in only 5 hours.
- Therefore:
  - I assume you are somewhat familiar with basic neutrino physics and the basics of the Standard Model. I hope the first part is mostly a recall of known things.
    - I will focus on key points or on some points often mis-understood
  - I will fly quickly over some of the slides: they are meant to be just a reference for home work
  - If I go too quick, you complain and we focus on fewer topics

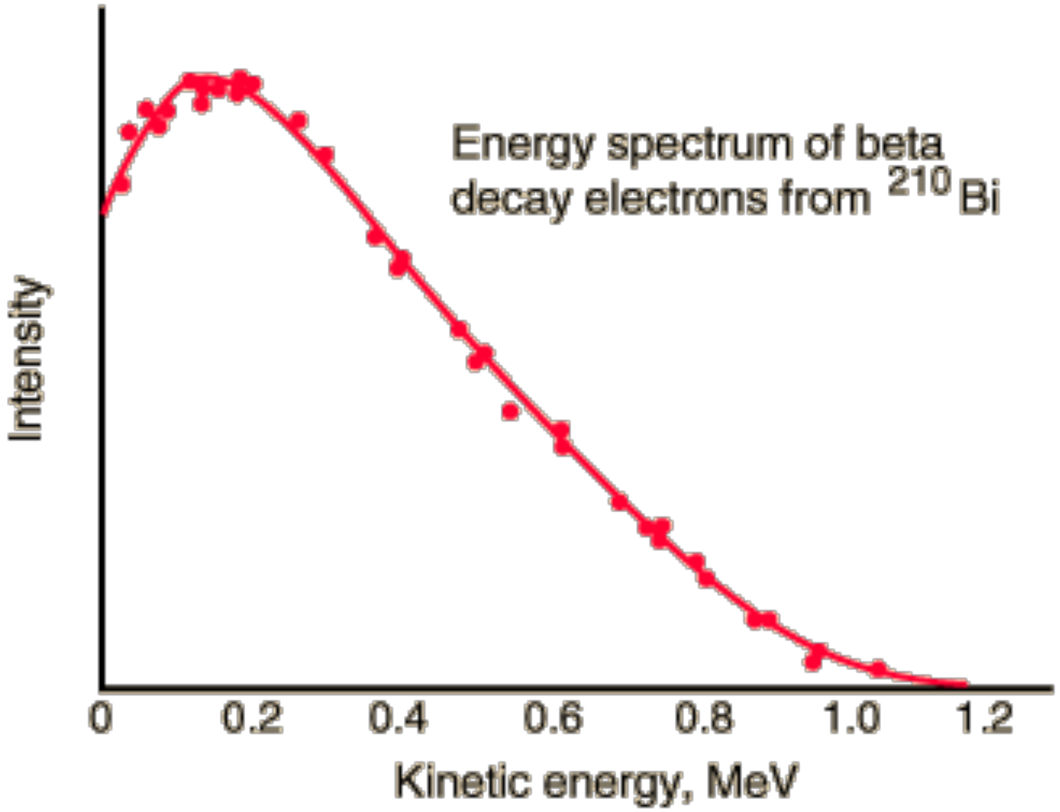
A touch of history

- **Indirect** evidence of neutrinos dates back to ***early discovery of radioactivity***
  - Becquerel (1896) discovers β radioactivity, .i.e. the spontaneous emission of an electron off an atomic nucleus [Rutherford, 1899].
  - Several experiments in the period 1911-1927 [O. Hahn, L. Meitner, Chadwick, Ellis-Wooster] prove that the ***e^- spectrum is continuous***, contradicting two-body kinematics.
    - N. Bohr dares saying: "*Maybe in β decays energy is conserved only on average*"
  - Even worse, the β decay, e.g., of ^{14}C (and of all nuclei with an even number of nucleons) **violates statistics,** if the final state is made of a single e^-

$$^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + e^-$$

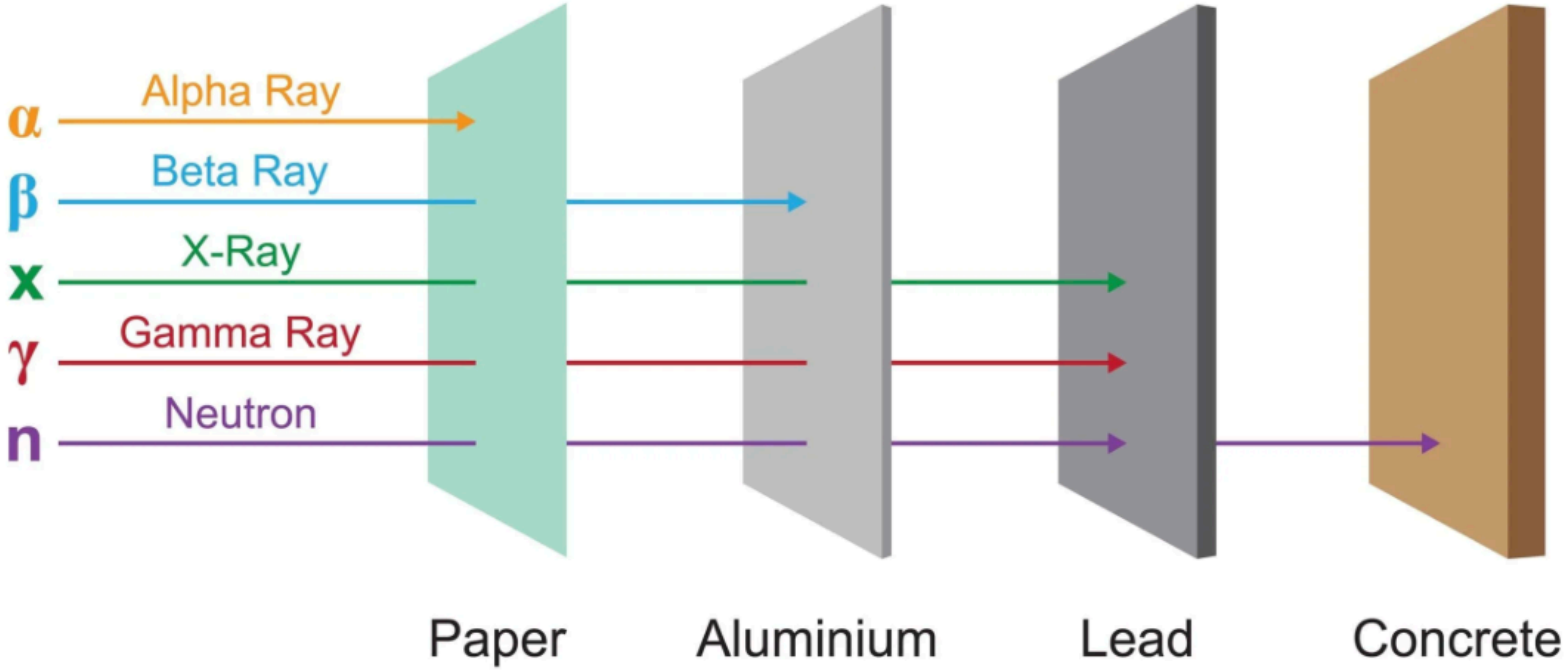
boson boson fermion



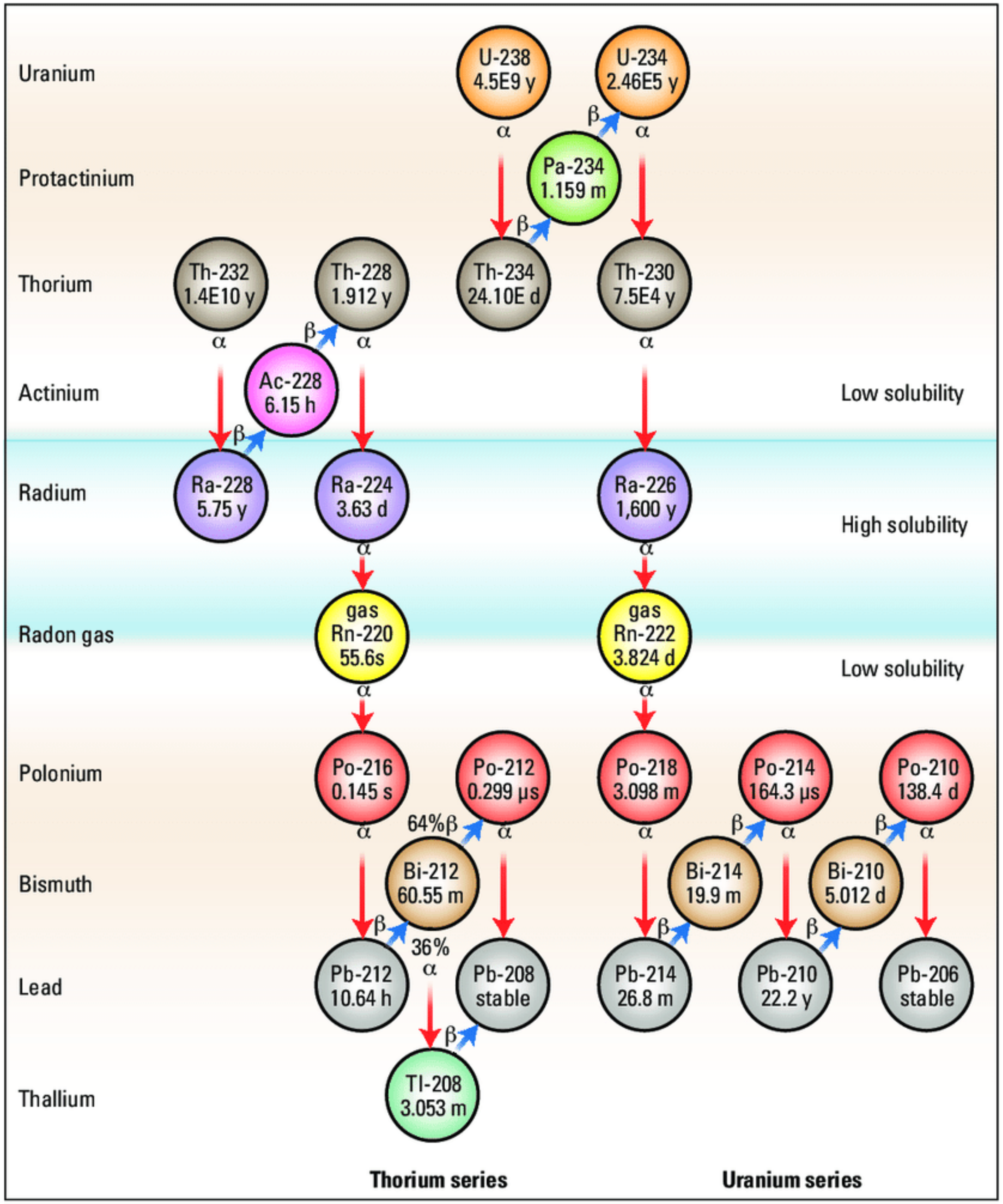


Avoiding historical miopia

- The problem WAS difficult !



The problem WAS difficult



Pauli and Fermi

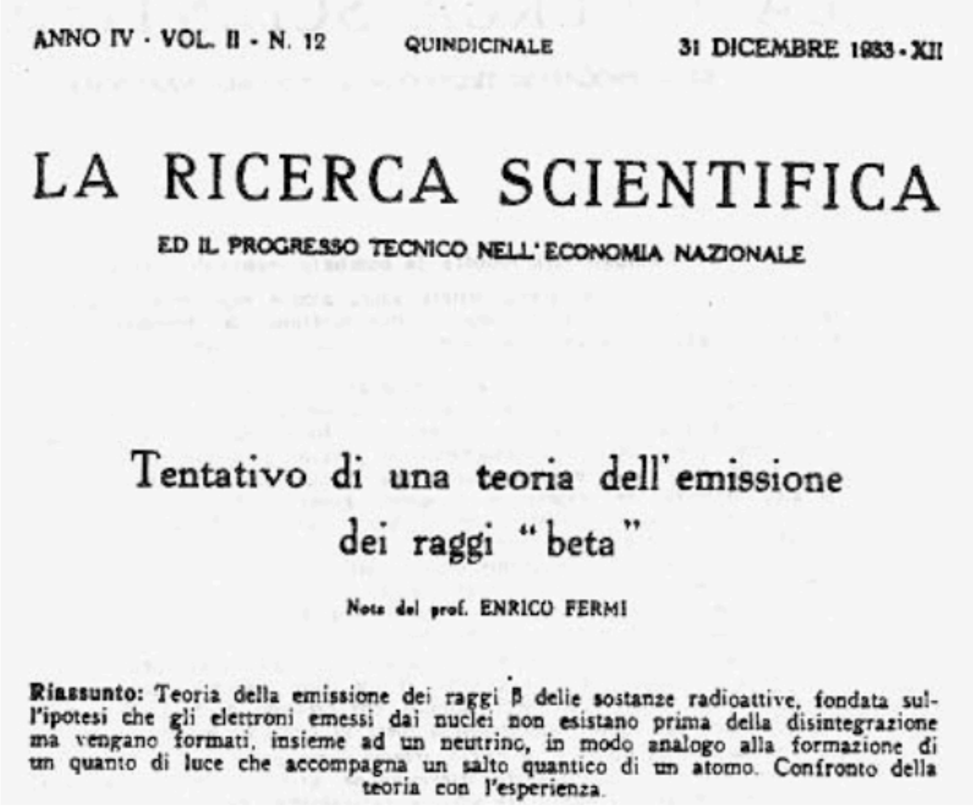
W. Pauli

E. Fermi

- Both problems are solved by a single idea: **a three-body final state** obtained by adding a **light neutral spin ½ particle**
  - Pauli letter, **1930**

- The discovery of the **neutron** (1932, Chadwick) clarifies nuclear structure:
  - The nucleus is made of protons and neutrons (Heisenberg model, 1932-1933)
  - No electrons are within the nucleus
  - The neutrons are not the neutrinos (neutrons are heavy and strong interacting)

- These ideas, in the hands of **Enrico Fermi**, bring to the first **"attempt"** to describe weak interactions:
  - Many breakthroughs in a single paper:
    - **It is the first Quantum Field Theory beyond QED**
    - Neutrinos and electrons ***are not in the nucleus***, but are **created** by the interaction
    - Explains the Q^5 behaviour of some β decays life-times



ANNO IV · VOL. II · N. 12 QUINDICINALE 31 DICEMBRE 1933 · XII

LA RICERCA SCIENTIFICA

ED IL PROGRESSO TECNICO NELL'ECONOMIA NAZIONALE

Tentativo di una teoria dell'emissione dei raggi "beta"

Nota del prof. ENRICO FERMI

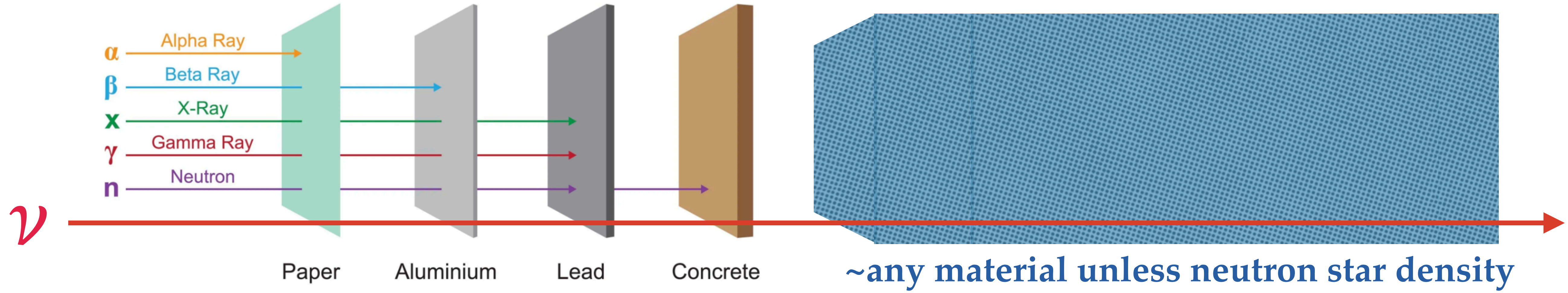
Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico di un atomo. Confronto della teoria con l'esperienza.

Fermi theory

- Fermi theory is a blessing which gives the "desperate remedy" a convincing theoretical framework
  - But it almost killed neutrino physics at its infancy
  - Bethe and others compute the neutrino-matter cross sections and the result is despairing
    - **~ 10^{-42} - 10^{-44} cm^2 @ 1 MeV**

MEAN FREE PATH IN WATER

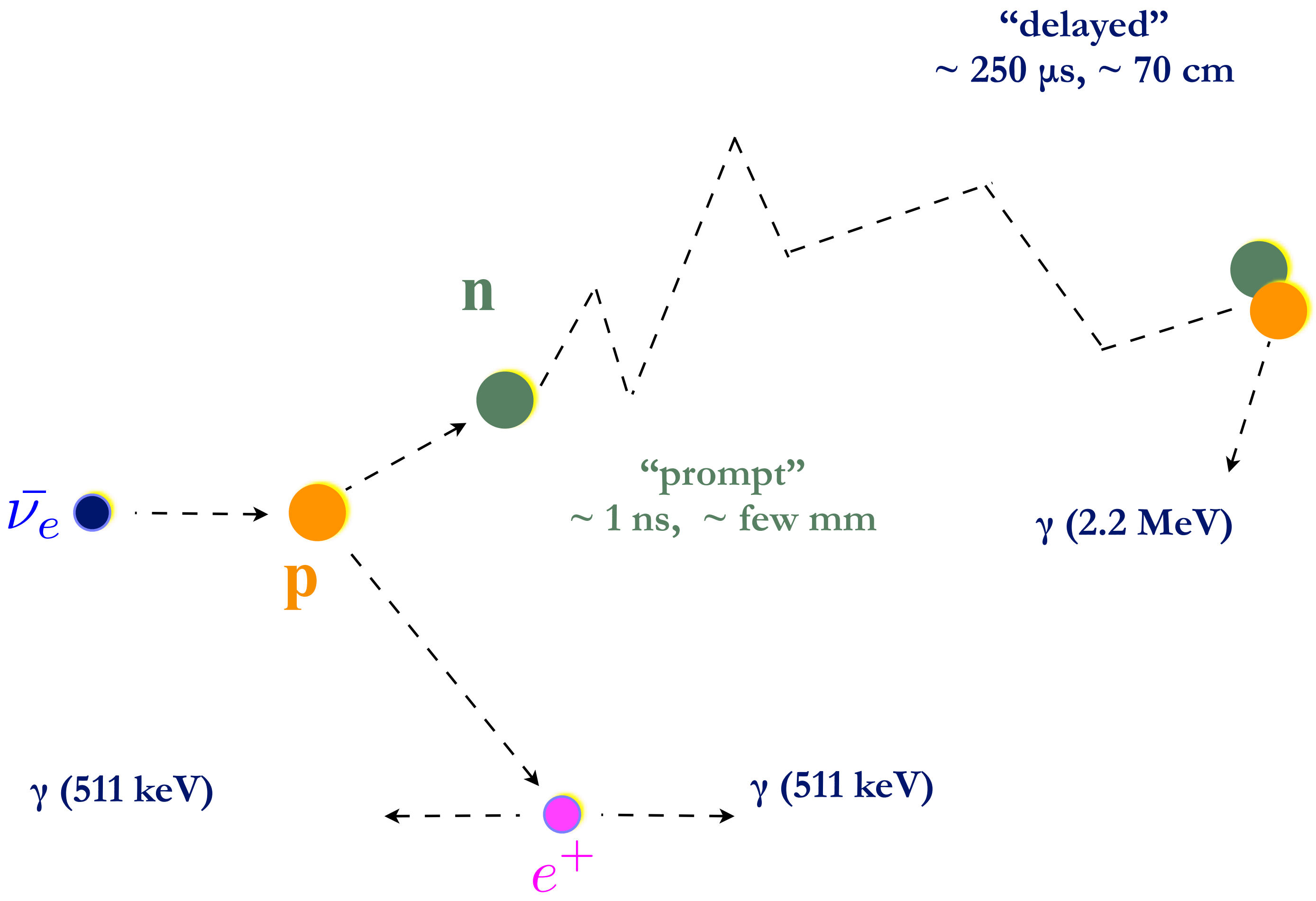
$$\boxed{\lambda = \frac{1}{n\sigma} \simeq \frac{1}{6\ 10^{23} \cdot 10^{-42}} = 1.7\ 10^{18}\ cm = 1.7\ ly}$$



~any material unless neutron star density

Inverse β decay

- Historically and physically, is a key process for neutrino physics
  - "The golden channel" for anti-neutrino detection at low energy
    - Large cross section, clean signature of final state
  - First detection by Reines and Cowan was done using this technique



First detection of (anti)-neutrinos (I)

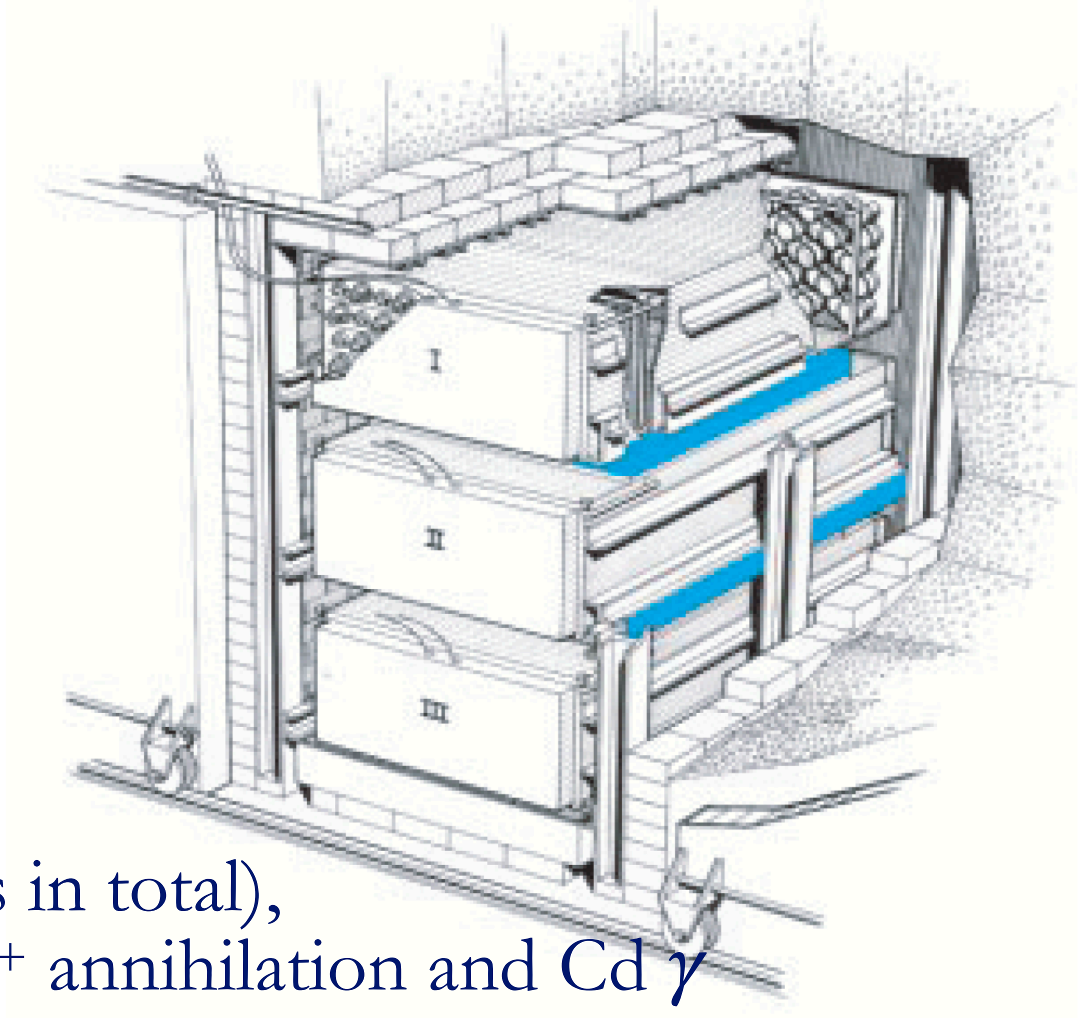
- Key point: **ν-matter cross sections are (always) small**
  - To detect some νs you need a **huge integrated luminosity,** which is obtained with large **detector masses,** very large ν **fluxes,** and **patience.**

- ν detection was at first made possible by the development of **fission reactors**
  - **Reines and Cowan, 1956** (after several attempts, including the "idea" to use atomic bombs explosions!)
  - **Each U fission yields 200 MeV on average, and 6 ν_e**
    - Flux: ~ **$2.\,10^{20}$ s^{-1} GW^{-1},** isotropic, $<E_\nu> \simeq 0.5$ MeV
    - About ~ **$4.\,10^{12}$ $s^{-1}\,cm^{-2}$** for 1 GW reactor at **20 m from the core**
    - For comparison **solar neutrinos:** ~ **$6.5\,10^{10}$ $s^{-1}\,cm^{-2}$ on Earth**

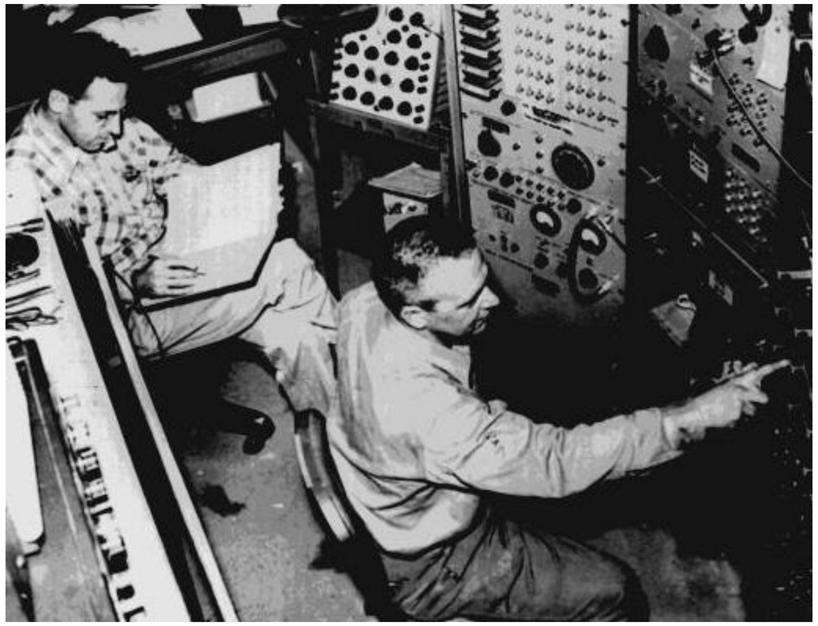
First detection of (anti)-neutrinos (II)

- A first conceptual drawing to detect ν from nuclear explosions in 1952. Never done.
- First detection at Hanford fission reactor in 1953.
  - **300 lit of liquid scintillator observed by photomultipliers**
    - At that time, a record. Largest detector before was about 10 litres.
    - Neutrons and photons from reactor successfully shielded by lead and borated-paraffin
    - **Lesson learned: cosmic rays make a substantial background,** 10 times more than signal.
      - *"The lesson of the work was clear: It is easy to shield out the noise men make, but impossible to shut out the cosmos. Neutrons and gamma rays from the reactor, which we had feared most, were stopped in our thick walls of paraffin, borax and lead, but the cosmic ray mesons penetrated gleefully, generating backgrounds in our equipment as they passed or stopped in it. We did record neutrino-like signals, but the cosmic rays with their neutron secondaries generated in our shields were 10 times more abundant than were the neutrino signals. We felt we had the neutrino by the cottails, but our evidence would not stand up in count."*
- **No surprise:** today most **low energy ν experiments are underground**
  - The group had to develop **technologies** that are still crucial today
    - Improve quality and stability of liquid scintillator and large scale production
    - **Low radioactivity** components, shielding and **tagging of external radiation**
    - **Electronics to detect delayed coincidence**

First detection of (anti)-neutrinos (III)



- Conclusive result at Savanah River in 1956
  - Two plastic tanks filled with water (blue)
    - $\Rightarrow \nu$ target (protons)
  - Cadmium dissolved in water
    - $\Rightarrow$ Cd has a **huge neutron capture cross section** and emits high energy γ
  - Between the water tanks, 3 large liquid scintillators detectors (I, II e III) (4200 litres in total), each equipped with 110 PMTs to detector e^+ annihilation and Cd γ
  - Each ν **event in the water produces**:
    - A positron, whose annihilations yields two back-to-back γs $\Rightarrow$ fast coincidence in tanks I and II.
    - A neutron, captured by Cd $\Rightarrow$ again signals in tanks I or II, delayed by 3-10 μs.
    - No signal in tank III because Tank II is a good shield

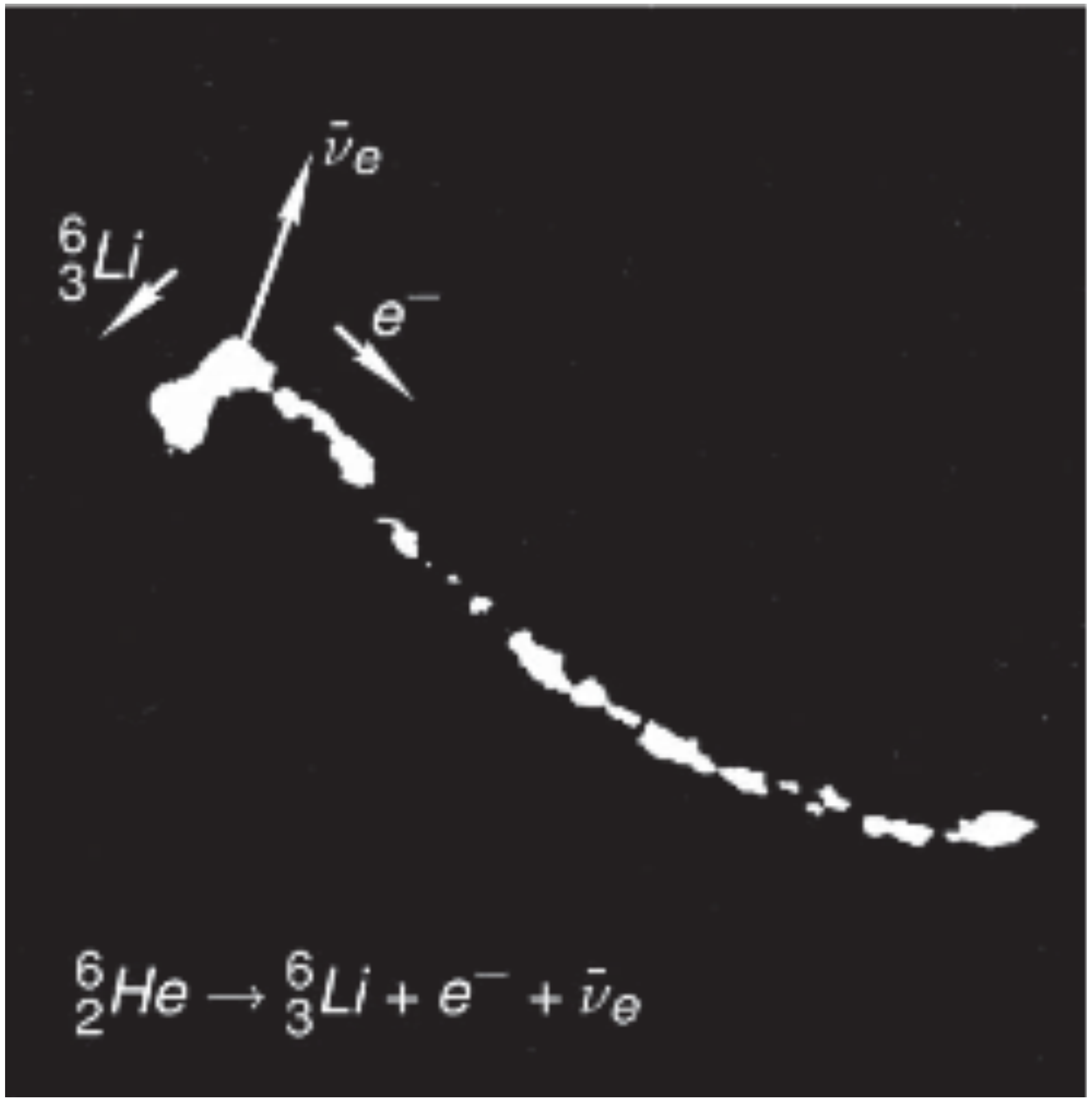


Historical note

- First visual image of a β decay (^{6}He in a cloud chamber)
  - Clearly showing that it is a 3-body final state
  - Obtained in Hungary in 1956, a few weeks before Soviet invasion, which stopped completely this activity

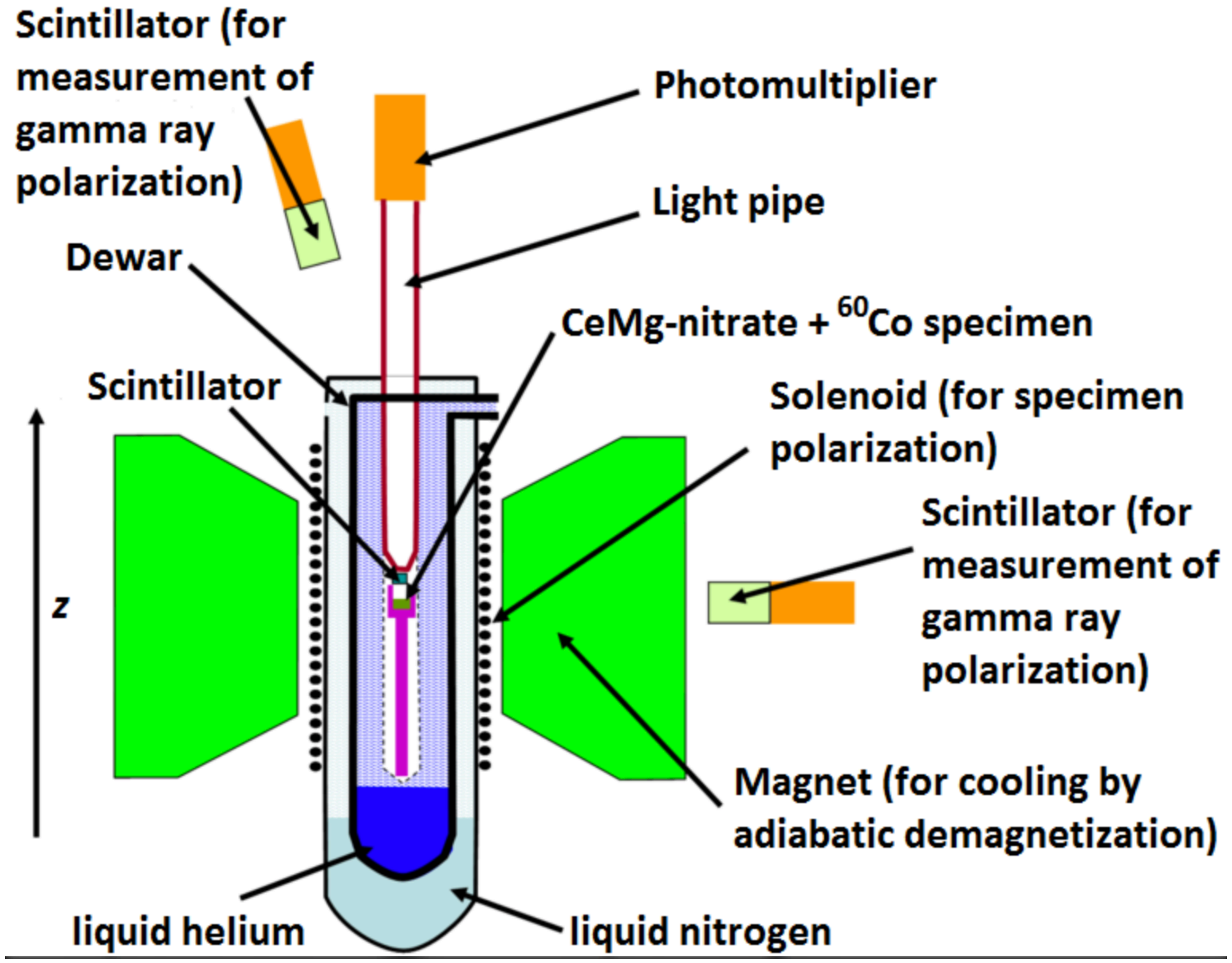
J. Csikai
A. Szalay

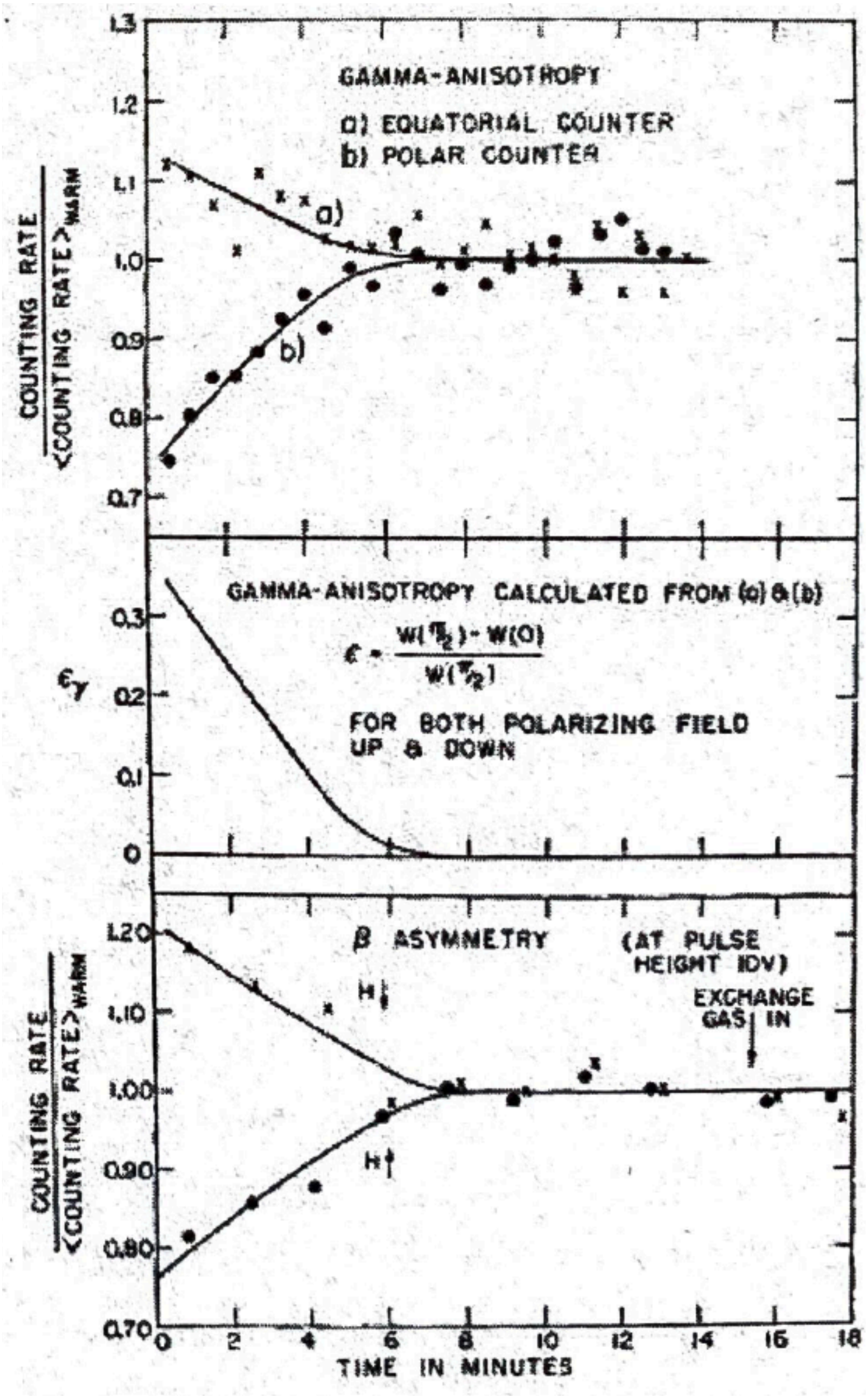
C. Budapest, fall 1956



Discovery of parity violation (1956)

- **C.S. Wu (1956)**
  - She measures the angular distribution of e^- emitted in ultra-cold polarised **^{60}Co β-decays** and discovers **parity violation**
    - She never got the Nobel prize she deserved

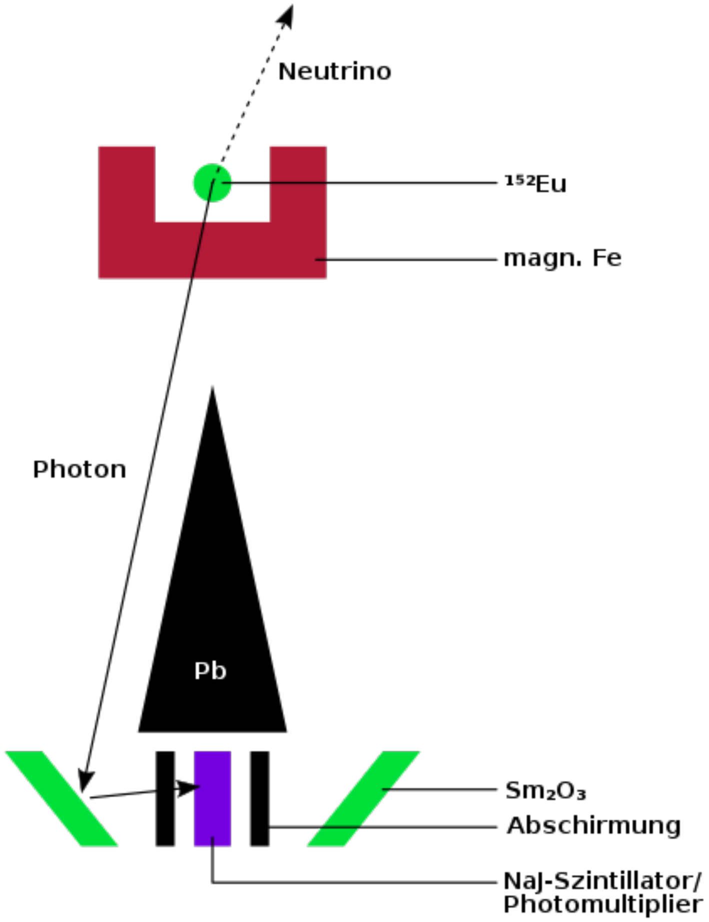




Neutrino helicity (1958)

M. Goldhaber

- Goldhaber, Grodzinns and Sunyar (1958)
  - ν emitted in β-decay have **fixed helicity**
  - A beautiful trick transfers helicity to a detectable γ



$$^{152m}\mathrm{Eu} + e^- \to \nu + {}^{152}\mathrm{Sm}^*$$

$$0^- + \tfrac{1}{2} = \tfrac{1}{2} + 1^-$$

j_z ⇇ ⇉ **p**

τ = 3 10^{-14} s

$$^{152}\mathrm{Sm}^* \to {}^{152}\mathrm{Sm} + \gamma\ (963\ keV)$$

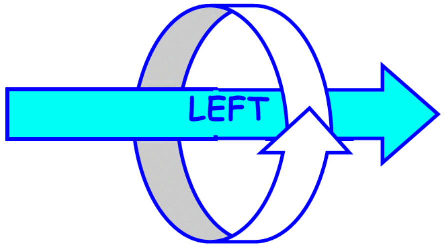
$$1^- = 0^+ + 1^-$$

p ⇉ ⇉

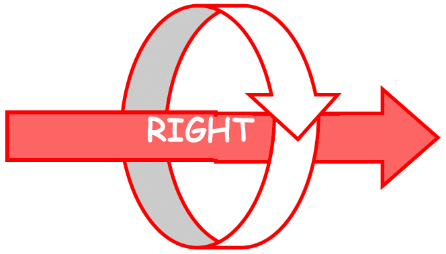
3 crucial points:

- neutrino helicity is transferred to photon helicity
- neutrino recoil is the same as photon recoil
- Sm-152 decays fast, it is not disturbed by crystal

Helicity



- **NEUTRINOS**
    - Are (always) created left-handed



- (So called) **ANTI-NEUTRINOS**
    - Are (always) created right-handed
- If **m=0**, helicity is conserved. No problem.
- If **m≠0**, a question arises: **what happens if I run faster?**
  [i.e. if I make a **Lorentz boost** that changes the direction of motion?]
    - Answer **connected to nature of mass term** and to whether neutrinos are their own anti-particle
    - CASE 1: boosting a left-handed neutrino, I find the same "anti-neutrino" emitted by beta decay
        - The word anti-neutrino is **mis-leading.** They are **just two helicity states of the same particle**
    - CASE 2: boosting a left-handed neutrino, I find a right-handed neutrino DIFFERENT from a right-handed anti-neutrino
        - In this case neutrinos and anti-neutrinos are **distinguishable** and the **wrong helicity components** are completely **"sterile",** i.e. have **no interactions with the Standard Model**

Recalling SPINORs properties

- A spinor is a 2-component quantity transforming under Lorentz transformations Λ as:

$$\xi = \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} \to L(\Lambda)\xi$$

- Where L(Λ) $\in$ SL(2$\mathbb{C}$) is a complex 2x2 matrix defined as:

$$\frac{1}{2} Tr\left(\bar{\sigma}_\mu L \sigma_\nu L^\dagger\right) = 2 g_{\mu\rho} \Lambda^\rho_\nu$$

2 SOLUTIONS for each Λ

With $\sigma_0 = \bar{\sigma}_0 = I$ and $\sigma_i = -\bar{\sigma}_i$ are Pauli matrices.

- A Dirac spinor is a 4-component quantity transforming under Lorentz transformations Λ as:

$$\psi(x) = \begin{pmatrix} \varphi_1 \\ \varphi_2 \\ \chi_1 \\ \chi_2 \end{pmatrix} \quad \to \quad L(\Lambda)\ \psi(\Lambda^{-1}x)$$

where $$L(\Lambda) = e^{\left(\frac{1}{2}\omega_{\mu\nu}\sigma^{\mu\nu}\right)} \qquad \sigma^{\mu\nu} = \frac{1}{2}[\gamma^\mu, \gamma^\nu]$$

Lorentz transformation of spinor bilinear

- It can be proved that, given a Dirac spinor, the following bilinears have the transformation properties below:

$\bar{\psi}\psi$	SCALAR
$\bar{\psi}\gamma^5\psi$	PSEUDO SCALAR
$\bar{\psi}\gamma^\mu\psi$	VECTOR
$\bar{\psi}\gamma^5\gamma^\mu\psi$	PSEUDO VECTOR (AXIAL VECTOR)
$\bar{\psi}\sigma^{\mu\nu}\psi$	TENSOR

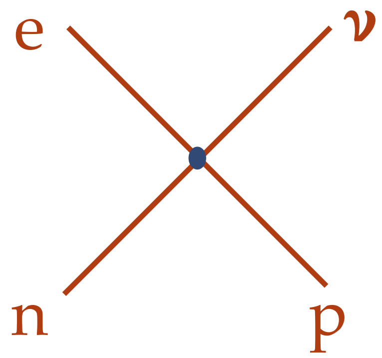
where:

$$\bar{\psi} = \psi^\dagger\gamma^0$$

Fermi weak interactions

- Assuming **point-like 4-fermion interaction** the Fermi Hamiltonian reads:

$$H_W = \frac{G_F}{\sqrt{2}} \hat{J}^\dagger_\mu \hat{J}^\mu$$



LOWEST ORDER DIAGRAM FOR NEUTRON DECAY IN FERMI THEORY

- Original Fermi theory (1934): $\hat{J}^\mu = \bar{n}\gamma^\mu p + \bar{\nu}\gamma^\mu e$ **pure "VECTOR" current**

- Gell-Mann - Feynman V-A (1958): $\hat{J}^\mu = \bar{n}\gamma^\mu (g_V + g_A \gamma^5) p + \bar{\nu}\gamma^\mu (1-\gamma^5) e$

Phys.Rev. 109 (1958) 193-198

Developed after discovery of PARITY violation

"VECTOR" - "AXIAL" current

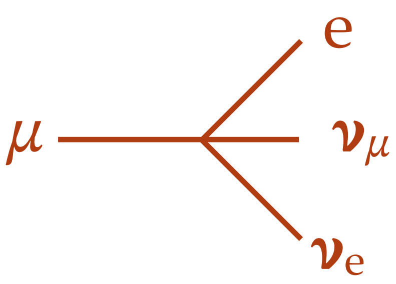
- Note 1: the ratio of axial/vector couplings to **leptons** is fixed by the theory
- Note 2: **that of hadrons is NOT**
  - We see later that the coupling to quarks is the same as that of leptons, **but strong interactions have substantial effects,** especially **on the axial coupling.**

Universal weak interactions

- Gell-Mann and Feynman introduce two key ideas:
  - The weak current has a V-A structure
  - The interaction is **universal**, i.e. it explains leptons and hadrons weak interactions, assuming that all hadrons are coupled to weak interactions.
  - Many results: chiefly
    - μ lifetime is calculated at % level

$$H_W = \frac{G_F}{\sqrt{2}}\,\bar{\nu}_\mu \gamma^\alpha (1-\gamma^5)\mu\ \bar{e}\gamma_\alpha (1-\gamma^5)\nu_e$$

$$\tau = \frac{1}{\Gamma} = \frac{G_F^2 m_\mu^5}{192\pi^3}$$



$$\tau = \frac{1}{\Gamma} = \frac{G_F^2 m_\mu^5}{192\pi^3}\left[1 - \frac{\alpha}{2\pi}\left(\pi^2 - \frac{25}{4}\right)\right]$$

WITH LEADING QED CORRECTIONS

    - Weak interactions are responsible also of processes not involving neutrinos:
      - The fact that K⁺ decays both in 2 and 3 pions (violating parity) is explained

$$K^+ \rightarrow \pi^+\pi^+\pi^-$$ BR 5.6% (Phase space is small)

$$K^+ \rightarrow \pi^+\pi^0$$ BR 20.7%

V-A structure

- The **V-A structure** of weak interactions is based on solid experimental evidence
  - For example a scalar or pseudo-scalar interaction terms would say:

$$\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = 5.5$$

WRONG !

  - **V-A predicts:**

THEORY (tree level)

$$\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = \frac{m_e^2(m_\pi^2 - m_e^2)^2}{m_\mu^2(m_\pi^2 - m_\mu^2)^2} = 1.26\ 10^{-4}$$

EXPERIMENT **PDG 2020**

$$\frac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)} = 1.230 \pm 0.004\ 10^{-4}$$

- **TWIST** experiment has made a high precision test with **10^{10} polarised muons**
  - The Michel parameters parameterise the general combination of the possible S+P+V+A+T interaction terms.
  - The Michel parameters ϱ and δ, which for a pure $V - A$ interaction should be $3/4$, are measured to be:
    - $\varrho = 0.74977 \pm 0.00012(\text{stat.}) \pm 0.00023(\text{syst.})$
    - $\delta = 0.75049 \pm 0.00021(\text{stat.}) \pm 0.00027(\text{syst.})$

Phys. Rev. D 85, 092013 (2012)

Hadronic weak decays

- Weak decays of hadrons are affected by strong interactions. We can classify the main hadronic weak matrix elements as:
  - **Leptonic decays:** $< 0|J_\mu^{(h)}|h >$ e.g. $\pi^+ \rightarrow \mu^+\nu_\mu$
  - **Semi-leptonic decays:** $< h'|J_\mu^{(h)}|h >$ e.g. nuclear β decay, $\Lambda \rightarrow pe^-\bar{\nu}_e$
  - Semi-leptonic with **two hadrons in FS:** $< h'h''|J_\mu^{(h)}|h >$ e.g. $K^- \rightarrow \pi^+\pi^-e^-\bar{\nu}_e$
  - **Meson oscillations:** $< h'|J_\mu^{(h)}J^{(h)\mu\dagger}|h >$ e.g. $K^0 \leftrightarrow \bar{K}^0, D^0 \leftrightarrow \bar{D}^0, B^0 \leftrightarrow \bar{B}^0$
  - Hadronic with two hadrons in final state: $< h'h''|J_\mu^{(h)}J^{(h)\mu\dagger}|h >$ e.g. $\Lambda \rightarrow p\pi^-$
- Generally, $\mathbf{J}_\mu = \mathbf{V}_\mu - \mathbf{A}_\mu$, but these **operators cannot be written exactly** because of **strong interactions**

Standard model (I)

- In the SM weak currents are **Noether currents** of the **gauge group SU(2)$_L$**, acting on L components of **fermion fields doublets,** e.g.

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \to \exp\left(ig\alpha_i \frac{\sigma_i}{2}\right) \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$$

- Leaving to others the complete construction of the model, we recall some key features:
  - The group SU(2) has **three generators,** one of which is a **neutral current**
    - This neutral current is **NOT the photon.** We must add another U(1) to the gauge group

$$SU(2)_L \times U_Y(1)$$

  - If the two neutral fields are rotated by θ_W **angle, electro-weak unification** is obtained:

$$g \sin\theta_W = g' \cos\theta_W = e \quad Y(e_L) = Y(\nu_{eL}) = -1 \quad Y(e_R) = -2 \quad Y(\nu_{eR}) = 0$$

N.B. !

  - **A weak neutral current is indeed predicted:**

$$\bar{\nu}_{eL}\gamma_\mu Q_Z \nu_{eL} Z^\mu + \bar{e}_L \gamma_\mu Q_Z e_L Z^\mu$$

  - with strength:

$$Q_Z = \frac{e}{\sin\theta_W \ \cos\theta_W}\left(T_3 - Q\sin^2\theta_W\right)$$

Standard Model (II)

- The complete SM Lagrangian **(before symmetry breaking)** reads:

$$\mathcal{L}_{SM} = \mathcal{L}_{YM} + \mathcal{L}_k + \mathcal{L}_{cc} + \mathcal{L}_{nc}$$

- with:

3 LEPTON families (f=1..3)

$$\ell^f_L = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix} \quad \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$$

3 QUARK families (f=1..3)

$$q^f_L = \begin{pmatrix} u_L \\ d'_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s'_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b'_L \end{pmatrix}$$

- $\mathcal{L}_{YM}$ is the Yang-Mills term for gauge fields (not shown)
- $\mathcal{L}_k$ is the kinetic (massless) term for all fermions

$$\mathcal{L}_k = i\bar{\ell}^f_L \not\partial \ell^f_L + i\bar{q}^f_L \not\partial q^f_L + i\bar{e}^f_R \not\partial e^f_R + i\bar{\nu}^f_R \not\partial \nu^f_R + i\bar{u}^f_R \not\partial u^f_R + i\bar{d}^f_R \not\partial d^f_R$$

- is the coupling term of fermions to charged W **(charged current)**

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\bar{\nu}^f_L \gamma^\mu e^f_L + V^{CKM}_{fg} \bar{u}^f_L \gamma^\mu d^g \right) W^+_\mu + h.c.$$

- is the coupling term of fermions to photon and Z **(neutral current)**

$$\mathcal{L}_{nc} = eQ\bar{\psi}\gamma_\mu \psi A^\mu + Q_Z \bar{\psi}\gamma_\mu \psi Z^\mu$$

where ψ is any SM fermion and Q is its electric charge.

Accidental symmetries: lepton and baryon numbers

- Without Yukawa interaction, the Lagrangian for fermion fields may be written in the compact form:

$$\mathcal{L}_f = \sum_k^5 \bar{\psi}_k i \not{D} \psi_k$$

- Where k=1..5 runs over 5 possible representations of the $SU(2)_L \times U_Y(1)$ gauge group:

$\psi_1 = e_R \; (\mathbf{1}, -2)$ — **SU(2) singlet, Y=-2**

$\psi_2 = \ell_L \; (\mathbf{2}, -1)$ — **SU(2) doublet, Y=-1**

$\psi_3 = u_R \; (\mathbf{1}, 4/3)$ — **SU(2) singlet, Y=4/3**

$\psi_4 = d_R \; (\mathbf{1}, -2/3)$ — **SU(2) singlet, Y=-2/3**

$\psi_5 = q_L \; (\mathbf{2}, 1/3)$ — **SU(2) doublet, Y=⅓**

- Masses are forbidden by gauge symmetry, so there are therefore 5 accidental global U(1) symmetries:

$$\psi_k \rightarrow e^{i\Phi_k} \psi_k$$

- Which correspond to the following Noether currents:

$$J_1^\mu = \bar{e}_R \gamma^\mu e_R$$
$$J_2^\mu = \bar{\nu}_L \gamma^\mu \nu_L + \bar{e}_L \gamma^\mu e_L$$
$$J_3^\mu = \bar{u}_R \gamma^\mu u_R$$
$$J_4^\mu = \bar{d}_R \gamma^\mu d_R$$
$$J_5^\mu = \bar{d}_L \gamma^\mu d_L + \bar{u}_L \gamma^\mu u_L$$

WHICH WE
MAY
REGROUP AS

$$J_Y^\mu = \sum_{k=1}^5 \frac{Y_k}{2} J_k^\mu$$

UY(1) gauge symmetry. Not new!

$$J_\ell^\mu = J_1^\mu + J_2^\mu = \bar{\nu}\gamma^\mu \nu + \bar{e}\gamma^\mu e$$

LEPTON NUM.

$$J_b^\mu = \frac{1}{3}(J_3^\mu + J_4^\mu + J_5^\mu) = \frac{1}{3}(\bar{u}\gamma^\mu u + \bar{d}\gamma^\mu d)$$

BARYON NUM.

$$J_{\ell 5}^\mu = J_1^\mu - J_2^\mu = \bar{\nu}\gamma^\mu \gamma_5 \nu + \bar{e}\gamma^\mu \gamma_5 e$$
$$J_{b5}^\mu = \frac{1}{3}(J_3^\mu + J_4^\mu - J_5^\mu) = \frac{1}{3}(\bar{u}\gamma^\mu \gamma_5 u + \bar{d}\gamma^\mu \gamma_5 d)$$

NOT OBSERVED !

Lepton number

- The Yukawa interaction changes the picture:
  - $J^\mu_Y \quad J^\mu_b \quad J^\mu_\ell$ remain conserved currents, in agreement with observations
  - $J^\mu_{b5} \quad J^\mu_{\ell 5}$ are not compatible with mass terms, and disappear

- With **three families,** global baryon number and individual lepton numbers are conserved, while individual are not in case of mixing
  - CKM matrix breaks "individual" baryon numbers, preserving global lepton number;
  - Without neutrino mixing, individual lepton numbers are conserved
    - Because of the accidental symmetry, neutrino mass is NOT generated by radiative corrections
  - **PMNS matrix** breaks "individual" lepton number, preserving global lepton number;

- Most relevant test of baryon and lepton number conservation:

$$\tau(p \to e^+\pi^0) > 1.6\ 10^{34}\ y$$

$$\tau(^{136}Xe \to ^{136}Ba + 2e^-) > 1.07\ 10^{26}\ y$$

$$BR(\mu^- \to e^-\gamma) < 4.2\ 10^{-13}$$

Neutrino mass (I)

- The Standard Model was built assuming massless neutrinos
  - A choice that was well motivated by the facts that, experimentally:

$$m_{\nu_e} \leq 1.1\ eV \qquad m_{\nu_\mu} \leq 0.19\ MeV \qquad m_{\nu_\tau} \leq 18.2\ MeV$$

All neutrinos are much lighter than W,Z and corresponding charge leptons

- This creates no problem:
  - **W and Z are coupled** to ν_L and $\bar{\nu}_R$, not to ν_R and $\bar{\nu}_L$
    - Right-handed components of all fermions are SU(2) singlet (i.e. Y=0);
  - Being neutrinos neutral and colour-less, they do not carry any other gauge charge
    - They right handed components can be omitted from the theory with no consequence
    - The choice is consistent, i.e. renormalisation does not re-introduce the mass, **because mass-less neutrinos brings an additional accidental symmetry**
  - ν_R are effectively decoupled and can be ignored

Neutrino mass (II)

- To build a **mass term,** you must introduce **ν_R** and **ν_L** into the theory:
  - **Option 1:** do the same as for u-quarks, i.e. add proper Yukawa coupling to Higgs doublet

ELECTRON MASS

$$\mathcal{L}_Y = -y_e\,(\bar{\nu}_{eL}, \bar{e}_L)\begin{pmatrix}\Phi^+\\ \Phi^0\end{pmatrix} e^-_R + h.c.$$

'Dirac' NEUTRINO MASS

$$-y_\nu\,(\bar{\nu}_{eL}, \bar{e}_L)\begin{pmatrix}\Phi^{0*}\\ -\Phi^-\end{pmatrix} \nu^-_R + h.c.$$

  - After spontaneous symmetry breaking:

$$-m\,(\bar{\nu}_L\nu_R + \bar{\nu}_R\nu_L) \qquad\qquad m = \frac{y_\nu v}{\sqrt{2}}$$

  - **Option 2:** Being **ν_R** not related to SU(2) gauge symmetry, they do not need to have a gauge invariant mass term
    - They admit, therefore, with M very large: $-\frac{1}{2}M\,(\bar{\nu}^c_R\nu_R + \bar{\nu}_R\nu^c_R)$
    - In general, the mass term can be:

$$\mathcal{L}_\nu = -\frac{1}{2}\,(\bar{\nu}^c_L\;\bar{\nu}_R)\begin{pmatrix}0 & m\\ m & M\end{pmatrix}\begin{pmatrix}\nu_L\\ \nu^c_R\end{pmatrix} + h.c.$$

    - where: M ≫ m. The terms proportional to m are the same as Dirac mass term [note that $\bar{\nu}^c_L\nu^c_R = \bar{\nu}_R\nu_L$]

Neutrino mass (III)

- The mass term can be diagonalised:

$$m_1 = \frac{1}{2}\left(M + \sqrt{M^2 + 4m^2}\right) \qquad m_2 = \frac{1}{2}\left(M - \sqrt{M^2 + 4m^2}\right)$$

- With M ≫ m [e.g. **$m \sim 200$ GeV** and **$M \sim 10^{16}$ GeV**]:

$$m_1 \simeq M \qquad m_2 \simeq \frac{m^2}{M} \ll m$$

SEE-SAW mechanism

  - One of the two neutrinos is very heavy and not observable, while the other one is very light without assuming very small Yukawa couplings.
    - **m_2 goes "naturally" to meV scale**
- The diagonalised mass term is that of 2 Majorana neutrinos:
  - with:

$$-\frac{1}{2}m_1\left(\bar{\nu}_1^c\nu_1 + \bar{\nu}_1\nu_1^c\right) - \frac{1}{2}m_2\left(\bar{\nu}_2^c\nu_2 + \bar{\nu}_2\nu_2^c\right)$$

$$\nu_1 = \nu_L \sin\theta + \nu_R^c \cos\theta \qquad \nu_2 = -i\nu_L \cos\theta + i\nu_R^c \sin\theta \qquad \text{with} \qquad \tan 2\theta = \frac{2m}{M} \ll 1$$

  - with very small θ ν_1 is an almost pure very heavy right handed neutrino, and ν_2 is the standard model one with very small mass.

Mixing

- With more than one SM neutrino, the model is easily generalised
  - n families (n=3) and k RH components (k is unknown)
    - **m** becomes a **k × n matrix**, while **M** becomes a **k × k matrix**
    - **CP violating phases come from both matrices,** in general.

- In the simplest case with k=n=3, the SM neutrinos are related to **mass eigenstates** by a **3 × 3** unitary matrix:

$$|\nu_\alpha >= U_{\alpha i}|\nu_i > \qquad \text{where} \quad |\nu_i > \quad \text{are mass eigenstates.}$$

and where U is often parametrised as:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_D} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_D} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Low energy neutrino - electron interaction

- At low energy ($q^2 \ll M_W$), the effective neutrino-electron interaction reads:

$$H_W^{\text{eff}} = \frac{G_F}{\sqrt{2}} \{[\bar{e}\gamma_\mu(1-\gamma_5)\nu_e]\,[\bar{\nu}_e\gamma^\mu(1-\gamma_5)e] + \rho\,[\bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\nu_\ell]\,[\bar{e}\gamma^\mu(g_V - g_A\gamma_5)e]\}$$

  - where:

$$g_V = g_L + g_R = -\frac{1}{2} + 2\sin^2\theta_W \qquad g_A = g_L - g_R = -\frac{1}{2} \qquad \rho = 1$$

- After Fierz transformation of the first term we can write:

$$H_W^{\text{eff}} = \frac{G_F}{\sqrt{2}} \{[\bar{\nu}_\ell\gamma_\mu(1-\gamma_5)\nu_\ell]\,[\bar{e}\gamma^\mu(c_V - c_A\gamma_5)e]\}$$

  - where:
    - for $\nu_e e^-$ scattering: $c_V = 1 + \rho g_V \qquad c_A = 1 + \rho g_A$
    - for $\nu_\ell e^-$ scattering: $c_V = \rho g_V \qquad c_A = \rho g_A$

Neutrino - electron interaction

- **Differential cross section** as a function of e$^-$ recoil momentum:

$$\frac{d\sigma}{dT'_e} = \frac{2G_F^2\, m_e}{\pi}\left[c_L^2 + c_R^2\left(\frac{E'_\nu}{E_\nu}\right)^2 - c_L c_R \frac{m_e}{E_\nu}\frac{E_\nu - E'_\nu}{E_\nu}\right]$$

  - where $T'_e = E'_e - m_e = E'_\nu - E_\nu$ is the electron recoil energy.

- The **total cross section** reads:

$$\sigma = \frac{2G_F^2\, m_e\, E_\nu}{\pi}\left[c_L^2 + \frac{1}{3}c_R^2 - \frac{1}{2}c_L c_R \frac{m_e}{E_\nu}\right]$$

  - For anti-neutrinos the formula is the same with c$_L$ and c$_R$ exchanged.

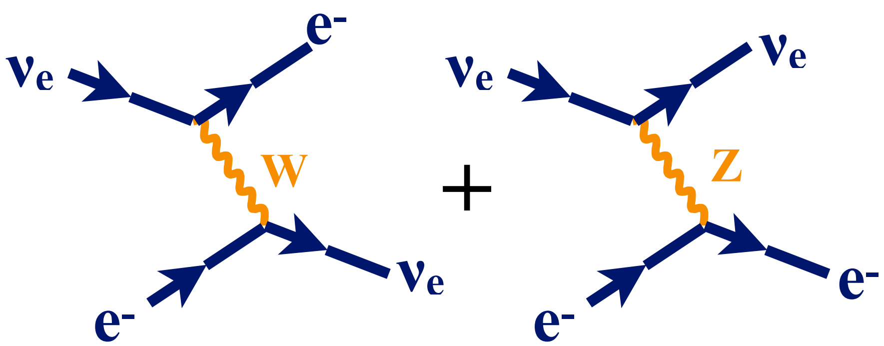
TREE level cross sections $\sin^2\theta_W = 0.2312 \quad \overline{\mathrm{MS}}$

	c$_L$	c$_R$	σ [10^{-44} cm^2]
ν_e e$^-$	$\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$	0.95 E$_\nu$ [MeV]
ν_μ e$^-$	$-\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$	0.16 E$_\nu$ [MeV]
$\bar\nu_e$ e$^-$	$\sin^2\theta_W$	$\frac{1}{2} + \sin^2\theta_W$	0.23 E$_\nu$ [MeV]
$\bar\nu_\mu$ e$^-$	$\sin^2\theta_W$	$-\frac{1}{2} + \sin^2\theta_W$	0.078 E$_\nu$ [MeV]

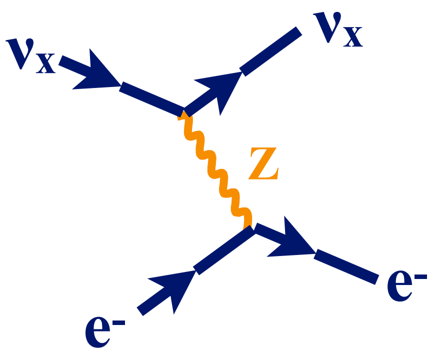
- **QED** and **EW** **radiative corrections** are at **few %** level and **are relevant** for high precision solar neutrino experiments and future experiments.

Example: neutrino detection in Borexino

- Elastic scattering on e$^-$: detects **all ν** flavours, with a **larger cross-section for ν_e**

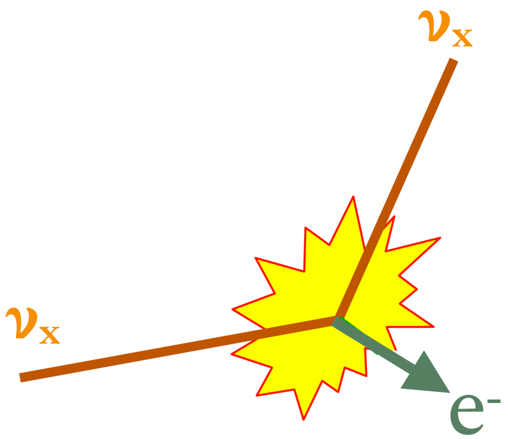


$$\xi = \sin^2\theta_W \simeq 0.23$$



$$\sigma(\nu_e e^-) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}+\xi\right)^2 + \frac{\xi^2}{3}\right]$$

9.5 10^{-45} cm^2 @ 1 MeV

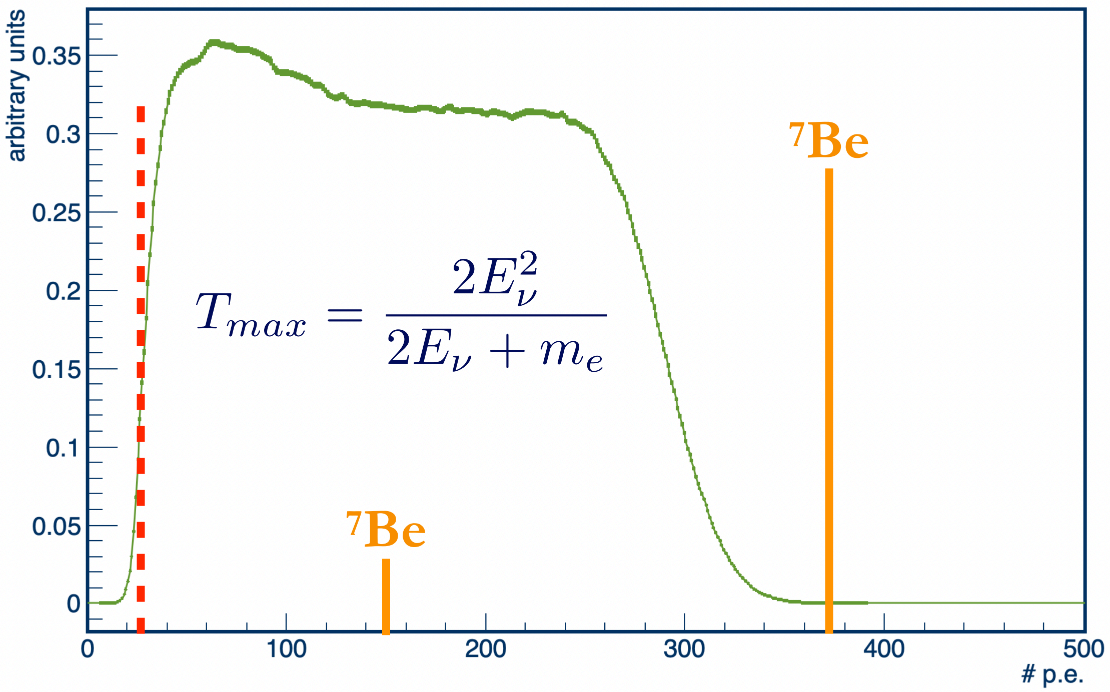


$$\sigma(\nu_x e^-) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}-\xi\right)^2 + \frac{\xi^2}{3}\right]$$

1.6 10^{-45} cm^2 @ 1 MeV

- The e$^-$ is scattered in the **liquid scintillator:**
  - **path:** **few mm**
  - **physics thresh.:** **very small**
  - **triggering thresh.:** **~40 keV** (dep.)
  - **analysis thresh.:** **~ 200 keV**

SIGNATURE: 'Compton' shoulders

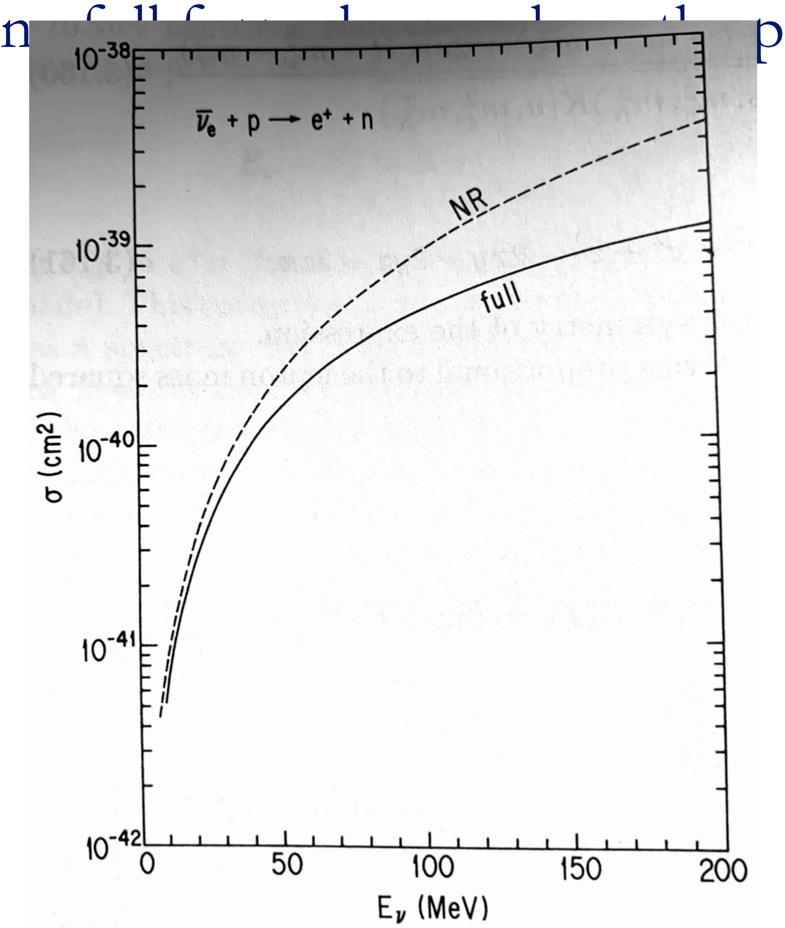


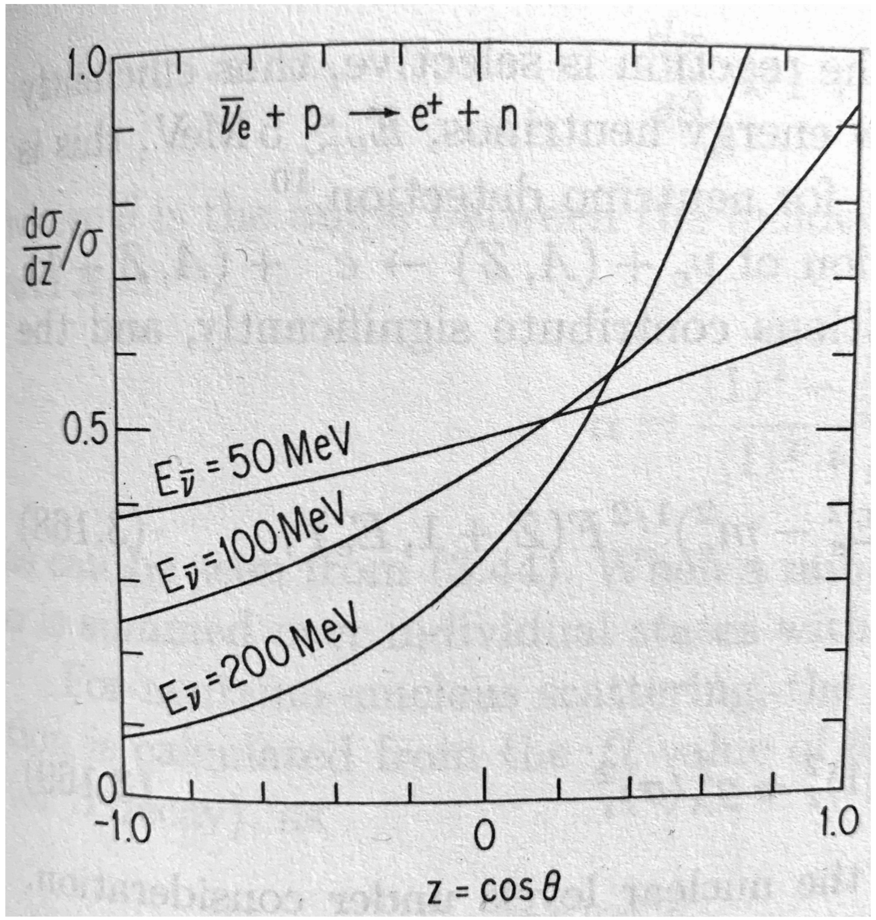
Neutrino-nucleon scattering

- CC ν-nucleon scattering is, for historical reasons, called "inverse β decay" (also, quasi-elastic)
  - At low E$_\nu$ ($\lesssim$ 100 MeV), only ν_e are active, being μ and τ too heavy
    $\bar{\nu}_e + p \to e^+ + n$ $\nu_e + n \to e^- + p$
  - At very low E$_\nu$ ($\lesssim$ 30 MeV), the cross section is well reproduced by:

$$\sigma(\bar{\nu}_e p \to e^+ n) = \sigma(\nu_e n \to e^- p) = \frac{G_F^2 E_e p_e}{\pi} |U_{ud}|^2 (1+3g_A^2) \simeq 9.3\ 10^{-42} \left(\frac{E_\nu}{10\ MeV}\right)^2 \text{cm}^2$$

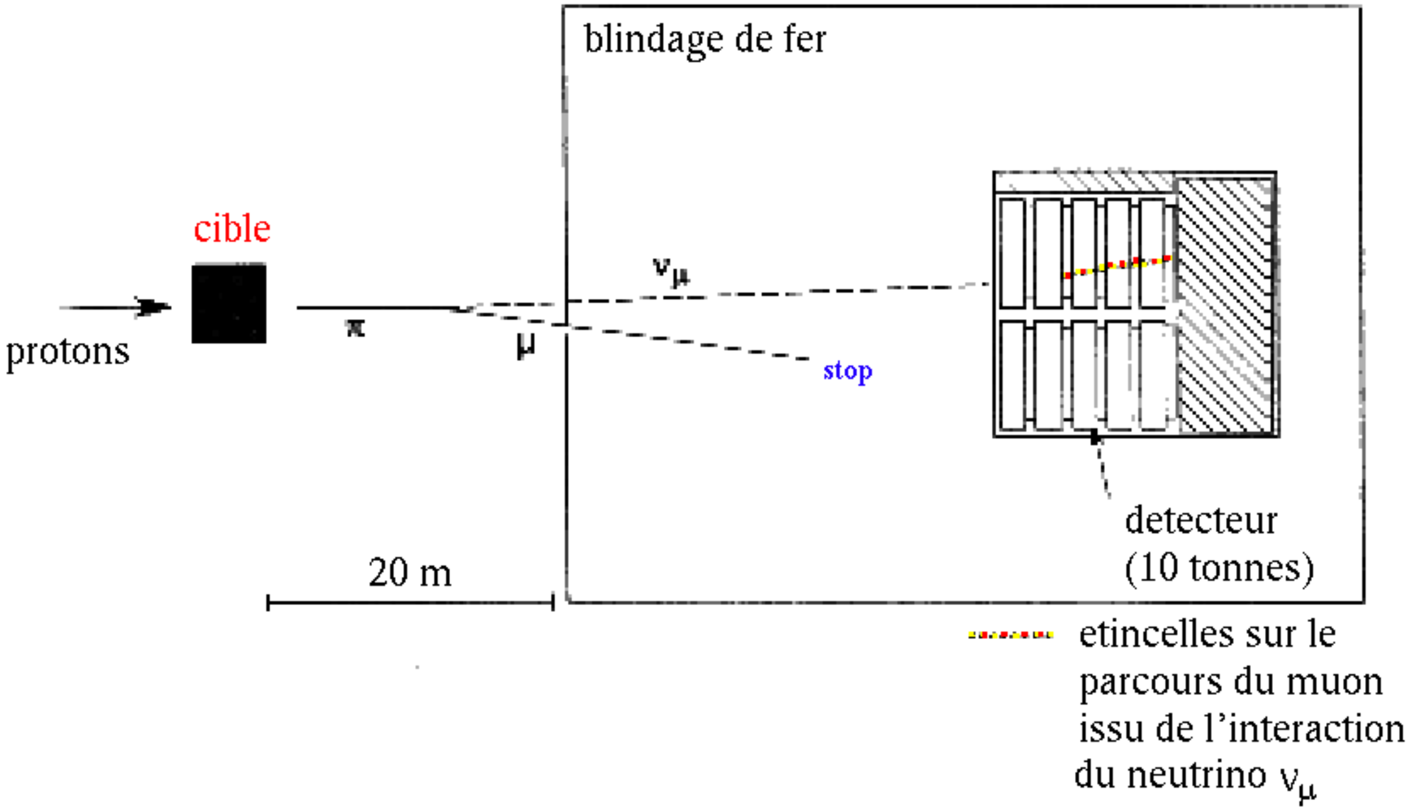
  - While in the region E$_\nu$ ~ 30 - 100 MeV the nucleon form factors become important. Without writin[illegible] plots:





2 neutrino flavours (I)

- How do we know that the neutrinos emitted in pion decay (accompanying a muon) is the same as in β decay ?
  - 1959: M. Schwartz proposes to build a neutrino beam from pion decay
  - 1962: L. Lederman, M. Schwartz and J. Steinberger build a large spark chamber (using 10 tons of neon gas) to identify muons in neutrino interactions.
  - The idea is still the one we use today to produce neutrino beams with accelerators
  - There was no pion momentum selection



2 neutrino flavours (II)

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

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M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

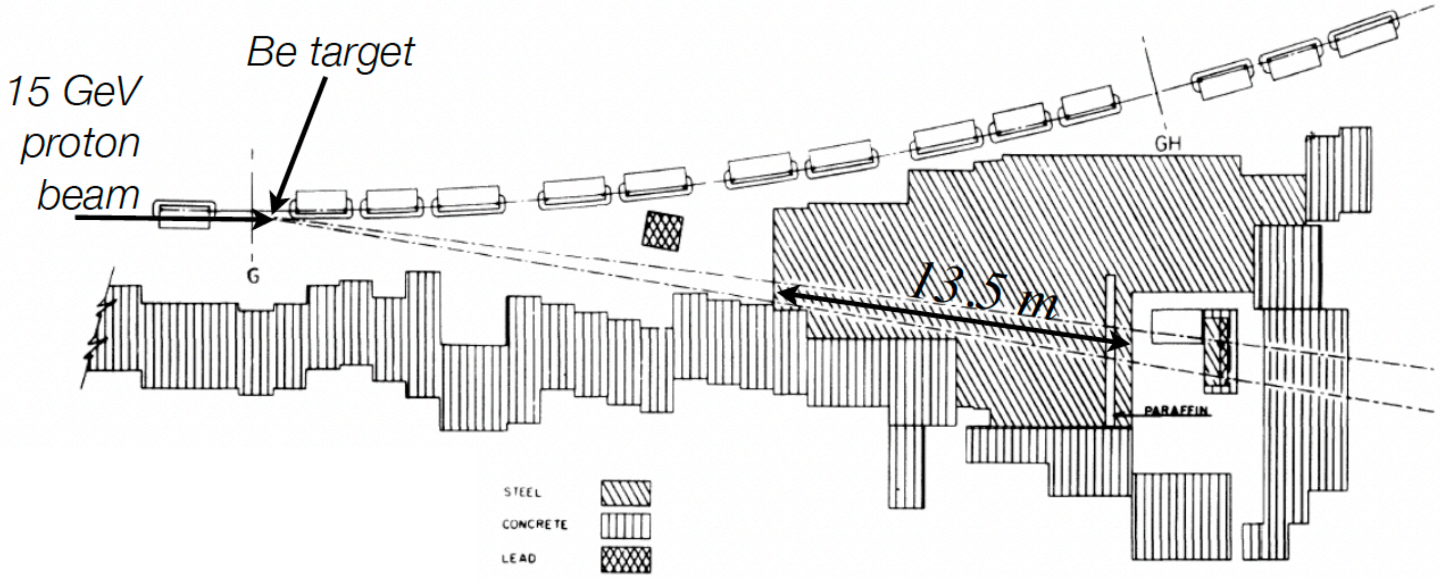
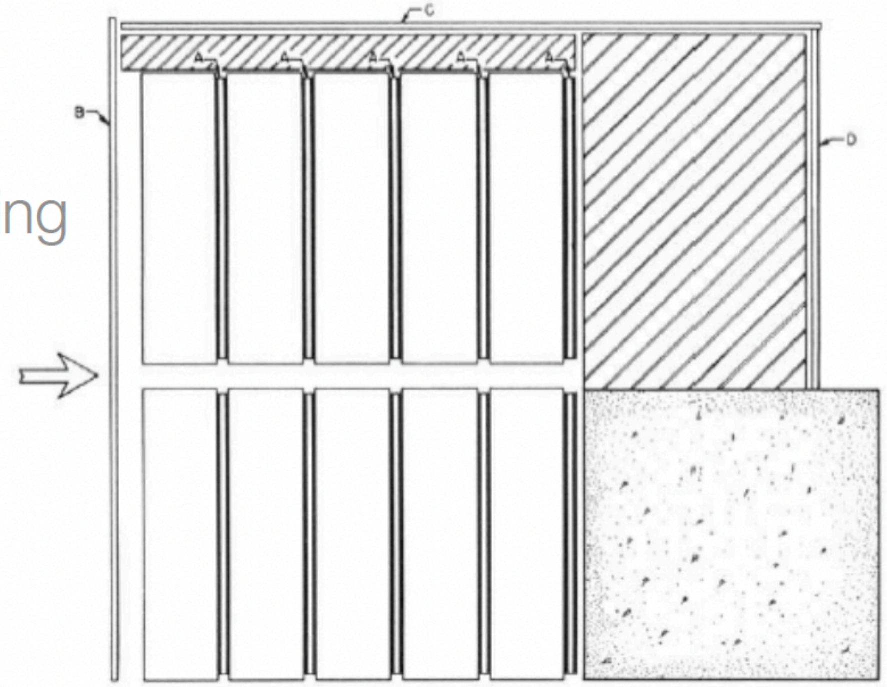


FIG. 1. Plan view of AGS neutrino experiment.

B,C,D vetos against entering tracks



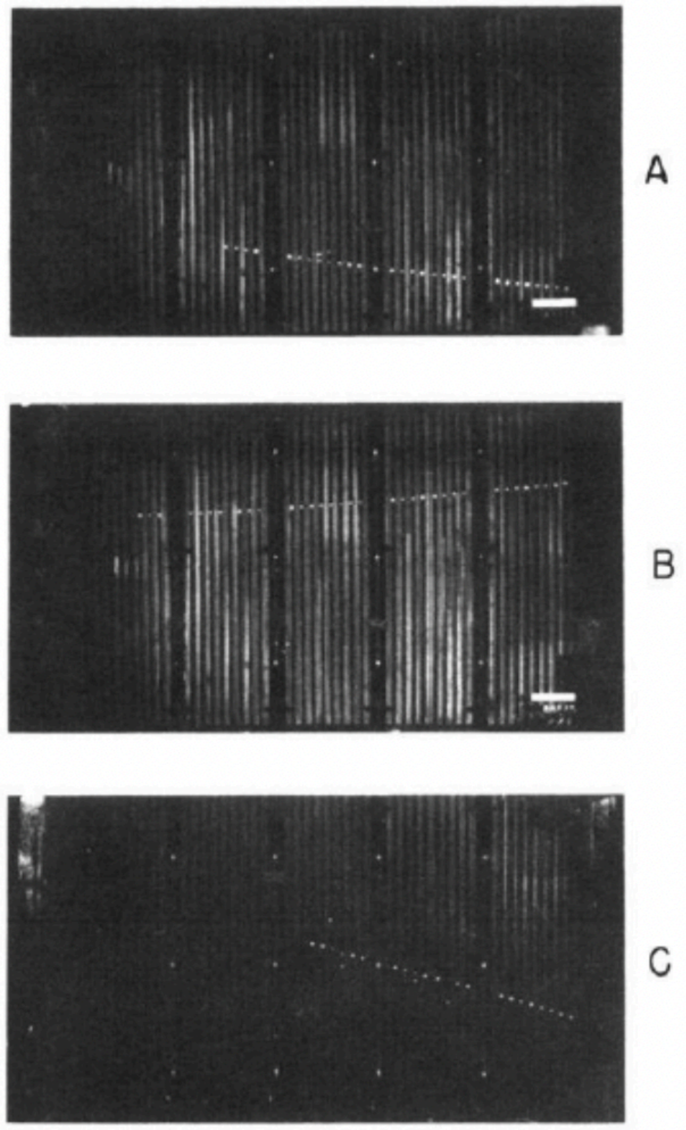
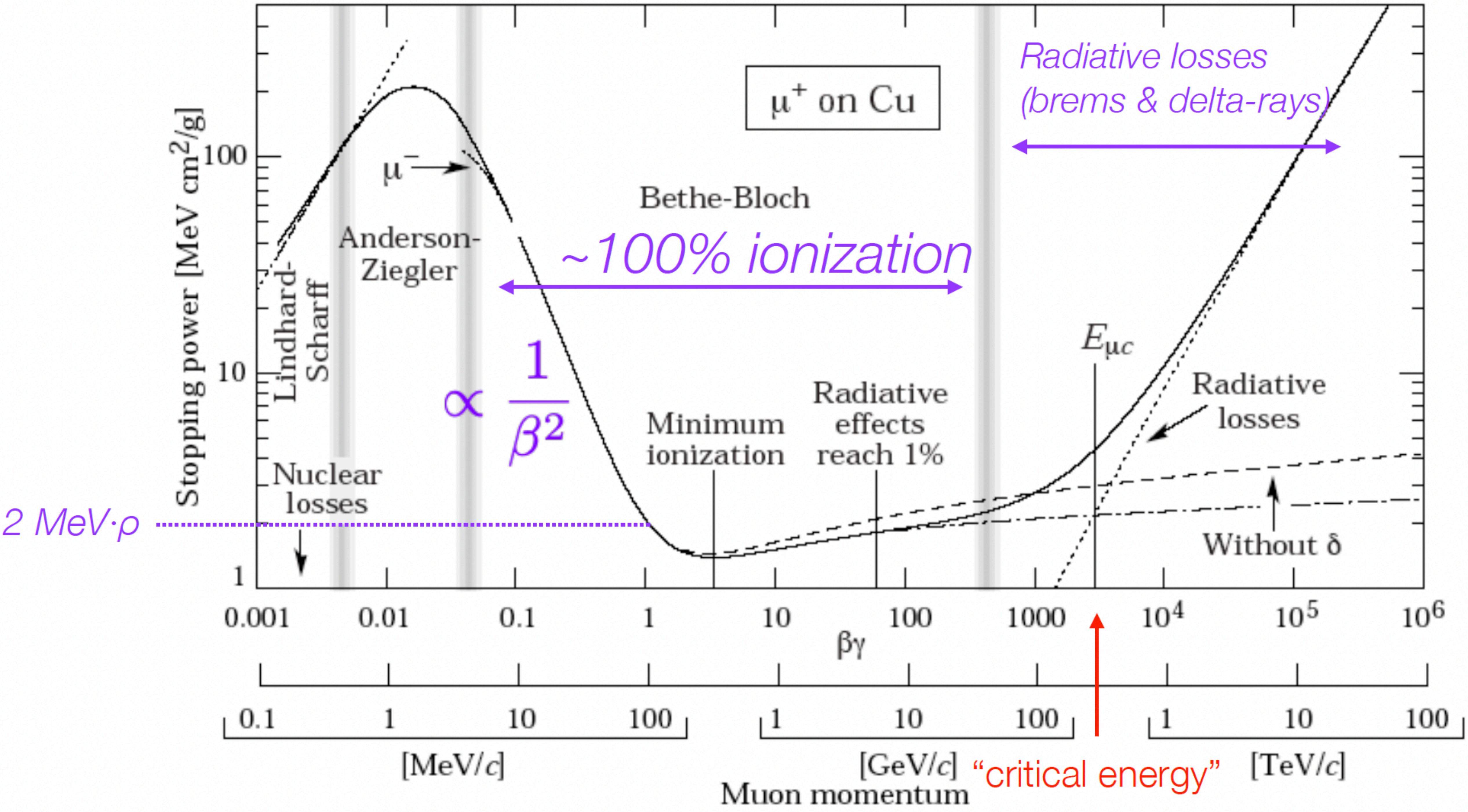


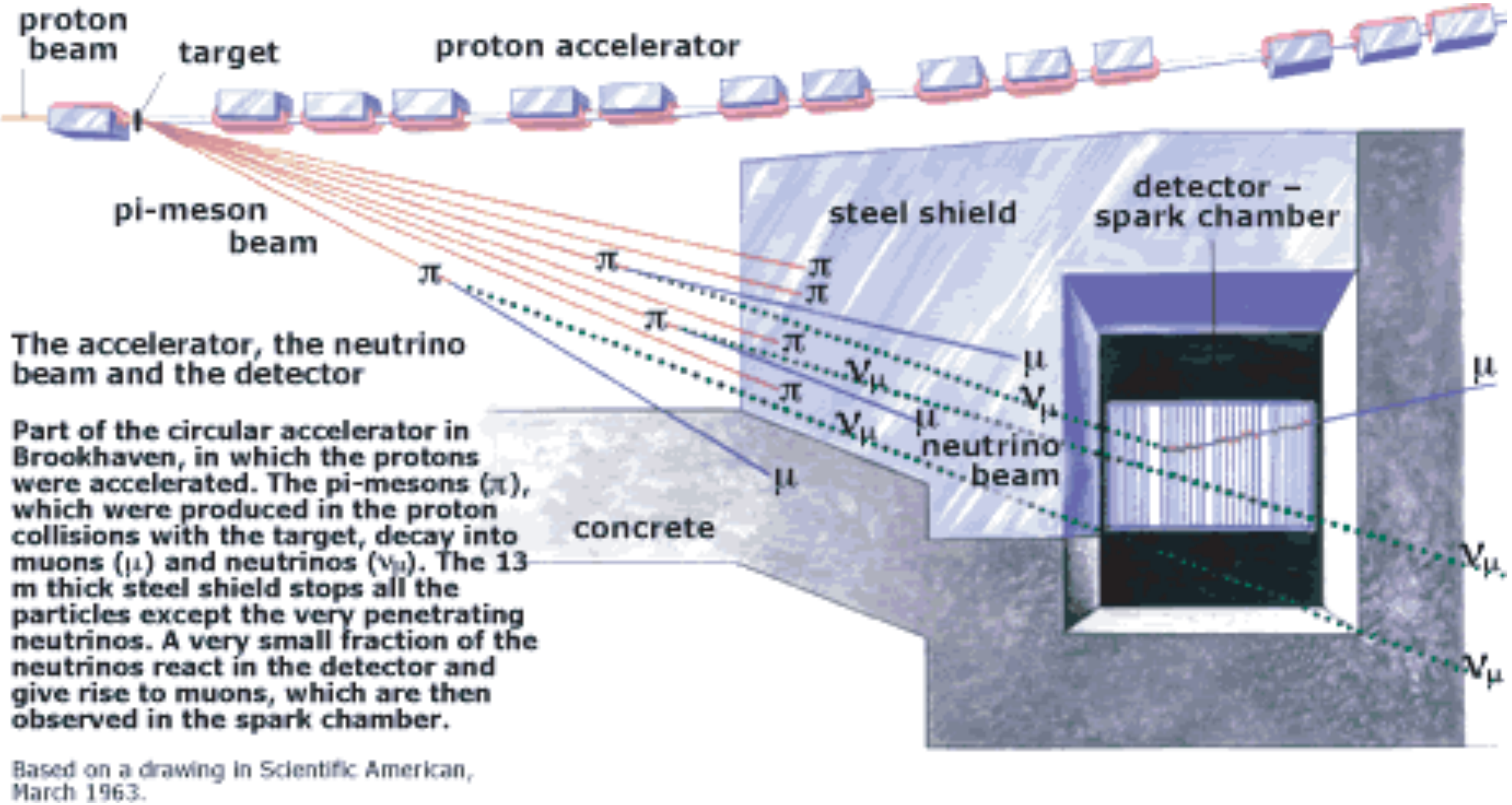
FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

Intermezzo: Bethe-Bloch



$$-\frac{dE}{dx} = Kz^2\frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

2 neutrino flavours (II)



The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.

- Results:
  - 64 events detected
    - 34 events with a single long track p>300 MeV
    - 22 multi-tracks
      - Of which, 8 compatible with electron showers, 6 neutrons, 2 electrons from the beam
  - **There exists a different neutrino type that produces muons and not electrons in nuclear interactions**

Discovery of neutral currents

- In 1968 Weinberg completes the Standard Model in the form we know today, adopting also GIM mechanism prescription
- 3 fundamental predictions (plus many many more….)
  - **Neutral currents must exists,** and their coupling is fixed by theory

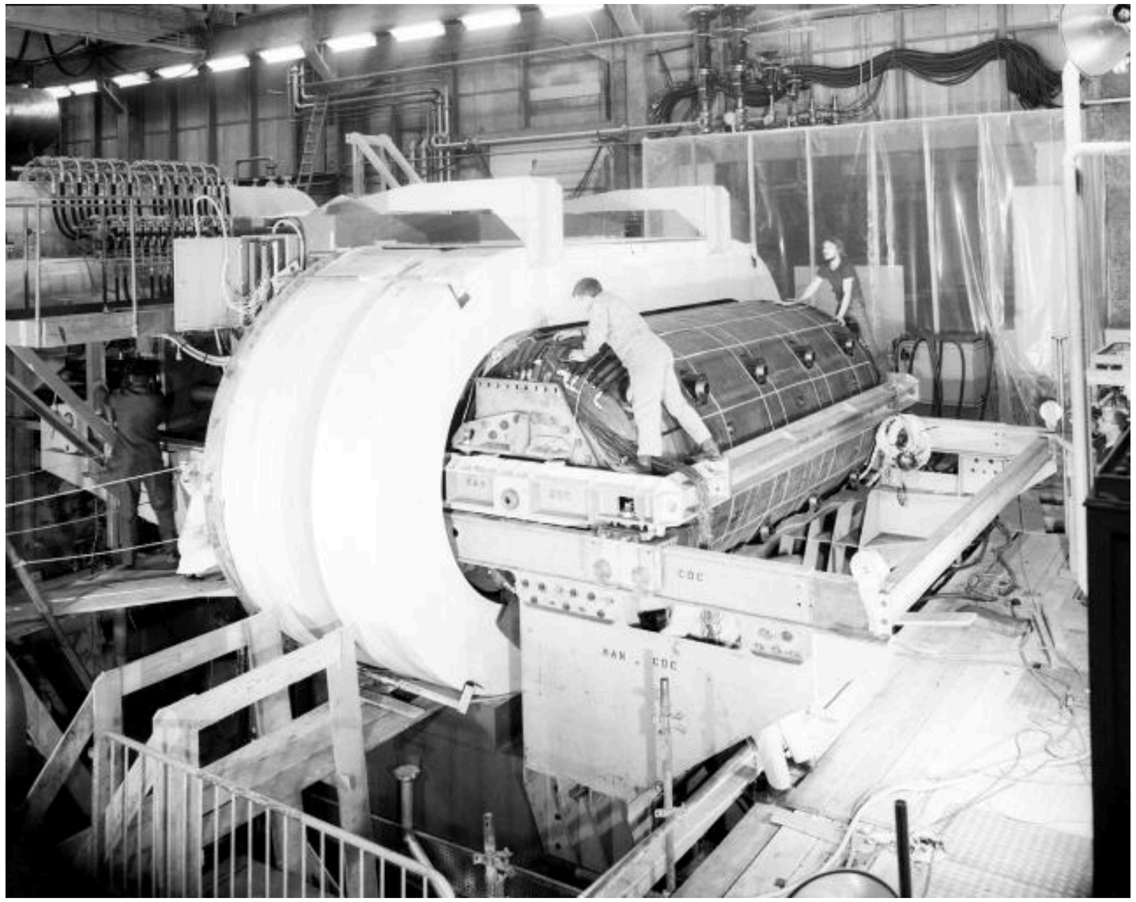
$$\bar{\nu}_{eL}\gamma_\mu Q_Z \nu_{eL} Z^\mu + \bar{e}_L \gamma_\mu Q_Z e_L Z^\mu$$

$$Q_Z = \frac{e}{\sin\theta_W \ \cos\theta_W}\left(T_3 - Q\sin^2\theta_W\right)$$

  - Fermions are organised in **doublets**, so at least **charm quark must exist**
    - Additional third family fermions are not mandatory and will come later, although they are actually required if you want CP violation in the SM
  - **There exist 2 gauge bosons,** whose mass is fixed by the theory **once neutral current strength is measured (to get the Weinberg angle)**

Gargamelle experiment

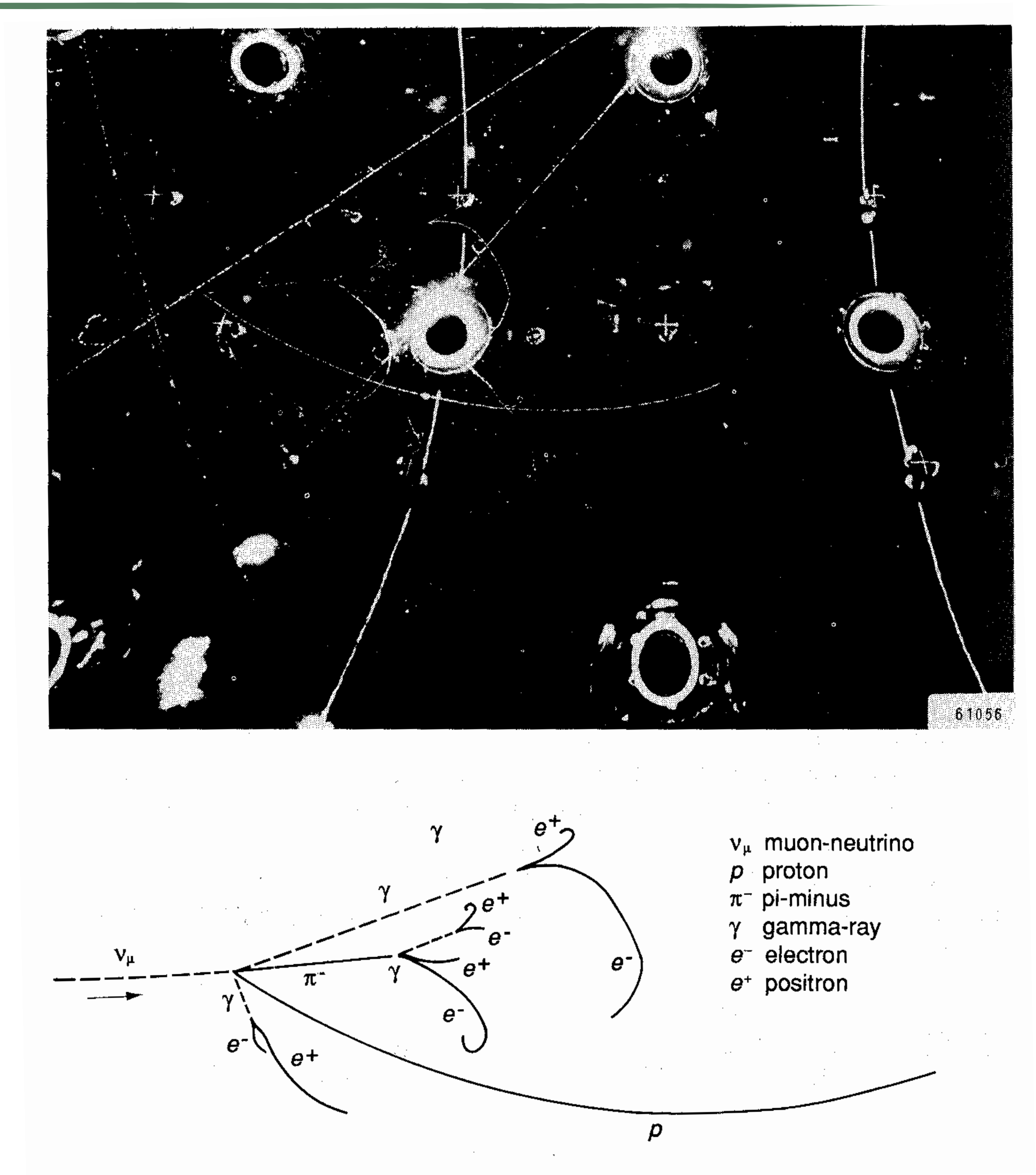
- The successful detection of neutral currents depends on two crucial technological improvements/achievements
  - **The magnetic horn,** which allows more intense and purer beams
    - It focalise mesons of one size and delocalise the other ones
  - The fast, high volume, and high density **bubble chamber,** to visualise events
    - 6.2 m^3 of liquid freon **(CF_3Br)** with a **density of 1.5 g/cm^3**



  - Ideas that are **still the key** of **more modern efforts** such as SBN at Fermilab, DUNE, T2K, HK

Magnetic horn to focalise the beam

Neutral current event in the bubble chamber



Results of Gargamelle

- **Run with both neutrinos and anti-neutrinos**
  - ν run: 102 NC, 428 CC, 15 neutrons
  - $\bar{\nu}$ run: 64 NC, 148 CC, 12 neutrons
  - Possible backgrounds
    - **Cosmic rays.** Excluded by means of asymmetries
    - CC with **lost muon because of low momentum:** good agreement with calculations
    - Direct and indirect **neutrons:** significant but much smaller than signal
  - **ALL these are still a key issue for today's experiments!**

- **Final result of Gargamelle:**
  - *"We have observed events without secondary muon or electr induced by neutral penetrating particles. We are not able to explain the bulk of the signal by any known background."*
    - $(NC/CC) = 0.21 \pm 0.03$
    - $(NC/CC) = 0.45 \pm 0.09$
    - $\sin\vartheta_w$ in range **0.3 - 0.4**

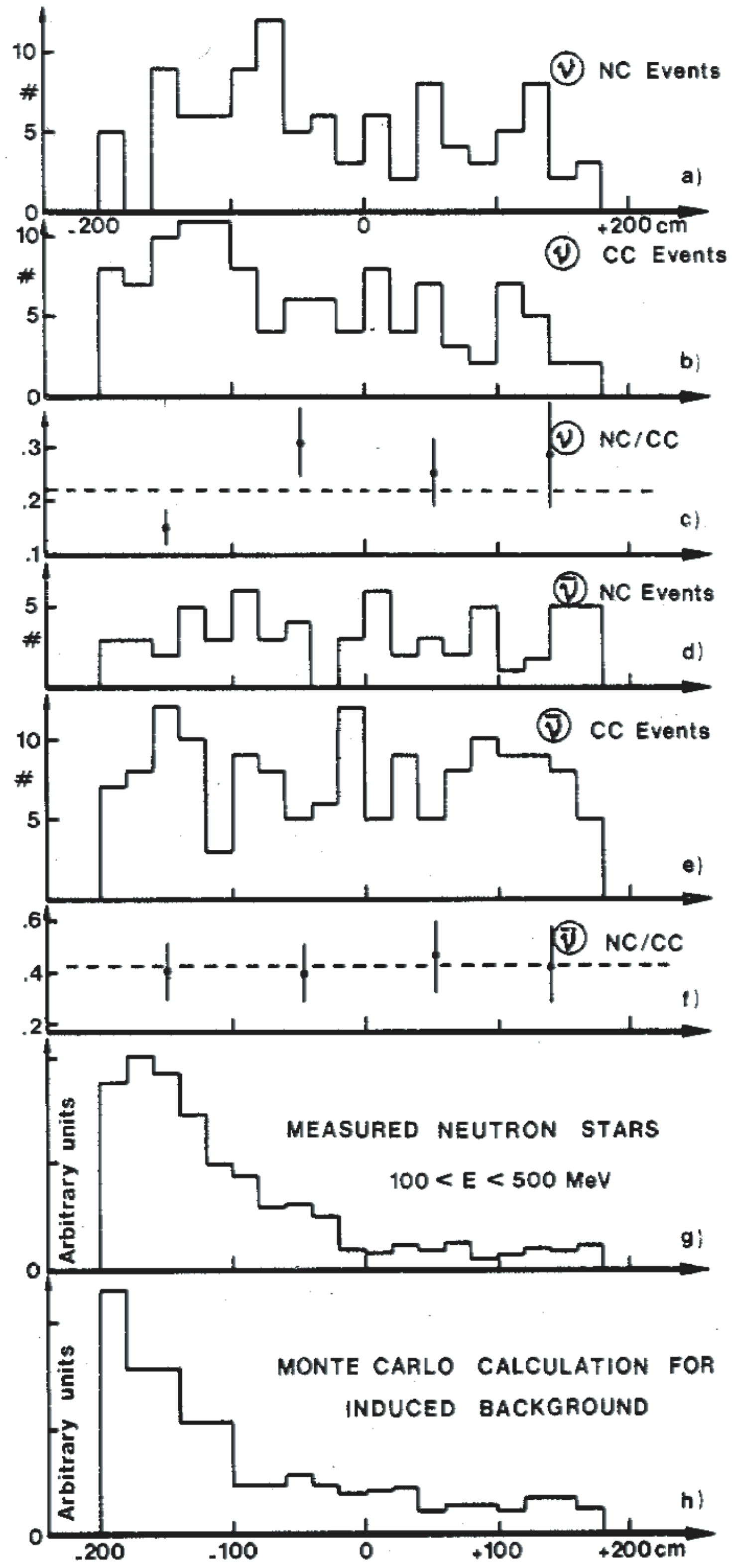
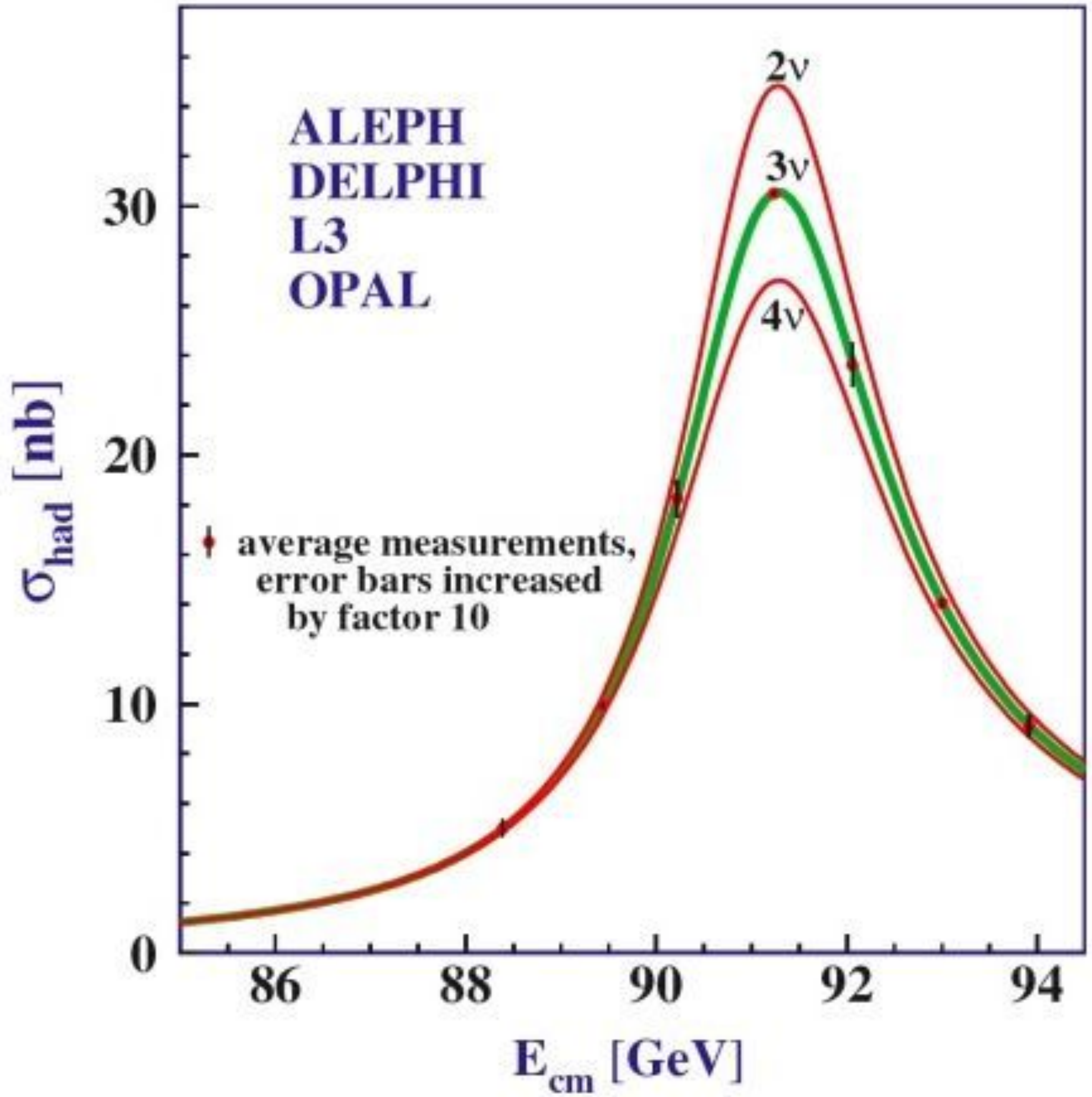


Fig. 1. Distributions along the ν-beam axis. a) NC events in ν. b) CC events in ν (this distribution is based on a reference sample of ~ 1/4 of the total ν film). c) Ratio NC/CC in ν (normalized). d) NC in $\bar{\nu}$. e) CC events in $\bar{\nu}$. f) Ratio NC/CC in $\bar{\nu}$. g) Measured neutron stars with $100 < E < 500$ MeV having protons only. h) Computed distribution of the background events from the Monte-Carlo.

Three neutrinos

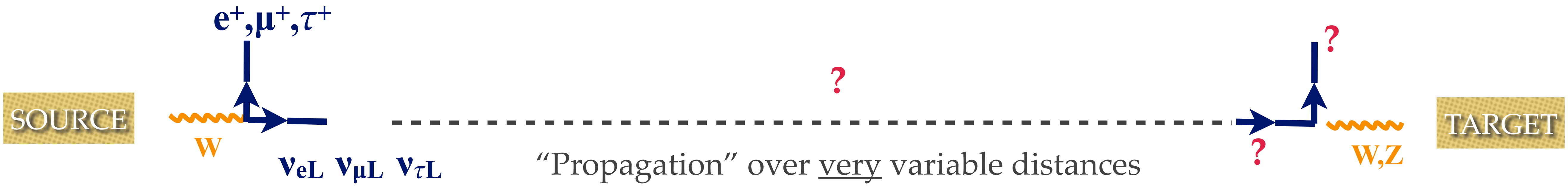


$\Gamma_{tot} = \Gamma_e + \Gamma_\mu + \Gamma_\tau + \Gamma_{had} + \Gamma_{inv}$ **Measured**

$\Gamma_e \quad \Gamma_\mu \quad \Gamma_\tau \quad \Gamma_{had}$ **Measured (adding up all events with hadrons in FS)**

$\Gamma_{inv} = 3\Gamma_\nu$ Can be checked

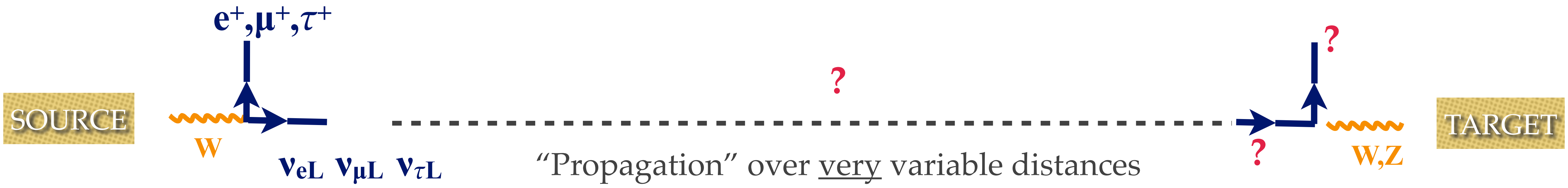
Neutrino propagation



“Propagation” over very variable distances
[from 1 fm in O$\nu\beta\beta$ up to 50 kpc SN1987a]

36 orders of magnitude

Neutrino propagation



"Propagation" over <u>very</u> variable distances
[from 1 fm in $O\nu\beta\beta$ up to 50 kpc SN1987a]

36 orders of magnitude

- For **massless neutrinos,** nothing happens
    - Clock is frozen (v=c) and helicity is conserved
- For **massive neutrinos,** many different things may happen to handed-ness and flavour
    - Dirac and Majorana equations couple right-handed and left-handed states
        - Wrong helicity state gets a term of order **O(m/E)**
        - Never observed so far because **m<<E**
        - The wrong handed-ness component can be observed only for Majorana neutrinos
            - For Dirac neutrinos is sterile
    - MIXING induce flavour transitions **O(m^2 L / E)**
        - Observed with the right L and m^2/E values
    - Propagation in matter (Earth, Sun, neutron star cores) may amplify oscillations

$\nu_e + p \to e^+ + n$ ✗ (not seen)

REACTOR m/E ~ 10^{-7} !

Neutrino Oscillations

- Massive neutrinos are mixed: $$|\nu_\alpha\rangle = \sum_{i=1}^{n} U^*_{\alpha i}\,|\nu_i\rangle$$
- Mass eigenstates evolve as:

$$|\nu_i(\tau)\rangle = e^{-im_i\tau}\,|\nu_i(0)\rangle,$$

REST FRAME

$$|\nu_i(t)\rangle = e^{-i(E_i t - p_i L)}\,|\nu_i(0)\rangle$$

LAB FRAME

- Exploiting the fact that neutrinos are almost massless:

$$L \simeq t; \qquad E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2E}$$

$$|\nu_\alpha(L)\rangle \simeq \sum_{i=1}^{n} U^*_{\alpha i}\,\exp\left(-i\frac{m_i^2}{2E}L\right)|\nu_i(0)\rangle$$

- The amplitude for observing a state α at distance L with initial state β is given by:

$$\langle\nu_\beta|\nu_\alpha(L)\rangle = \sum_{i=1}^{n} U^*_{\alpha i}\,\exp\left(-i\frac{m_i^2}{2E}L\right)\sum_{j=1}^{n} U_{\beta j}\,\langle\nu_j|\nu_i\rangle$$

- Which yields **the probability:**

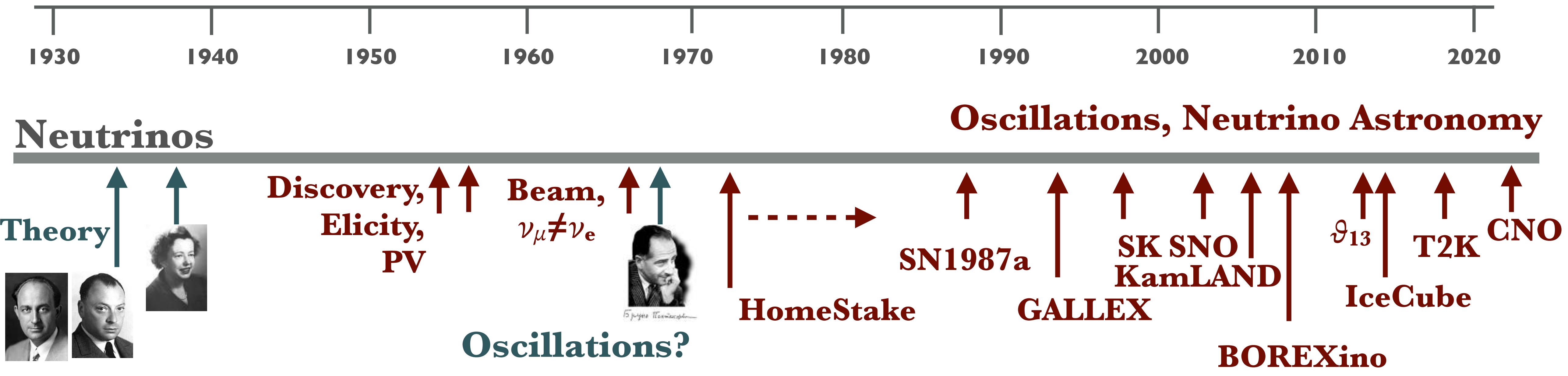
$$\xi_i^{\alpha\beta} = U^*_{\alpha i}\,U_{\beta i}; \qquad \epsilon_i = \frac{m_i^2}{2E}.$$

$$\boxed{\begin{aligned} P_{\alpha\beta}(L) = |\langle\nu_\beta|\nu_\alpha(L)\rangle|^2 = \delta_{\alpha\beta} &- 4\sum_{i=1}^{n}\sum_{j=i+1}^{n} \mathrm{Re}\left(\xi_i^{\alpha\beta}\,\xi_j^{*\alpha\beta}\right)\sin^2\frac{1}{2}(\epsilon_j - \epsilon_i)L \\ &-2\sum_{i=1}^{n}\sum_{j=i+1}^{n} \mathrm{Im}\left(\xi_i^{\alpha\beta}\,\xi_j^{*\alpha\beta}\right)\sin(\epsilon_j - \epsilon_i) \end{aligned}}$$

- **DISCLAIMER:** This calculation, reported almost everywhere, is **WRONG. Plane waves have exactly defined momentum,** and in that case there can be no oscillation!
  - However, the correct calculation with **wave packets** yields the same result, up to the distance at which wave packets cease to overlap. **The formula is RIGHT, until coherence is lost.**

For a correct calculation with wave packets see e.g. Giunti-Kim

Experimental neutrino physics: state of the art



1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

Neutrinos

Oscillations, Neutrino Astronomy

Theory

**Discovery,
Elicity,
PV**

**Beam,
$\nu_\mu \neq \nu_e$**

Oscillations?

HomeStake

SN1987a

GALLEX

**SK SNO
KamLAND**

BOREXino

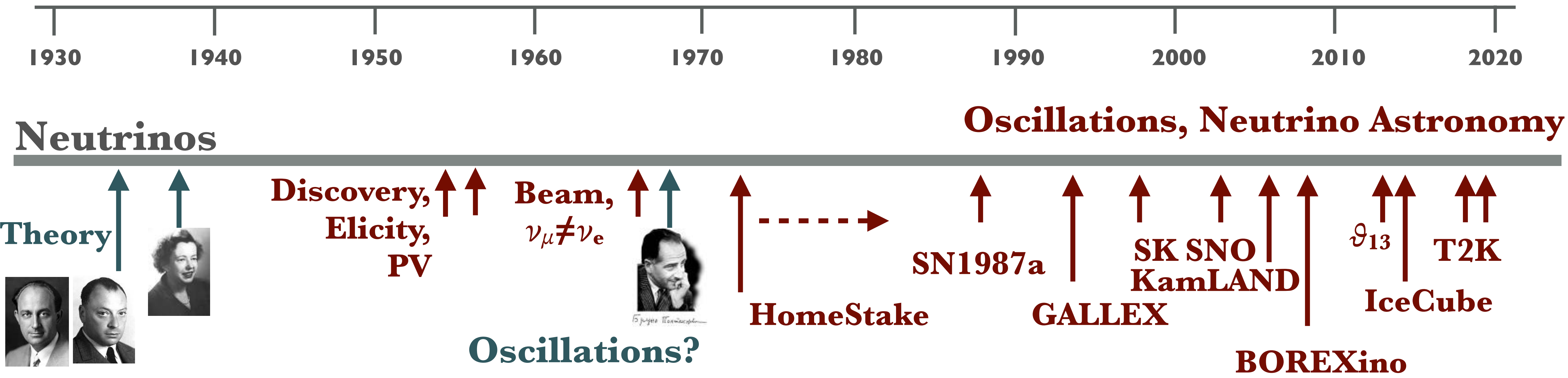
ϑ_{13}

IceCube

T2K

CNO

Experimental neutrino physics: state of the art



1930 1940 1950 1960 1970 1980 1990 2000 2010 2020

Neutrinos

Oscillations, Neutrino Astronomy

Theory

Discovery, Elicity, PV

Beam, $\nu_\mu \neq \nu_e$

Oscillations?

HomeStake

SN1987a

GALLEX

SK SNO KamLAND

BOREXino

ϑ_{13}

IceCube

T2K

$|\Delta m^2| = 2.47 \pm 0.04 \; 10^{-3}$ eV^2
$\theta_{23} = 47.5 \pm 3.2°$

δ_D= ? ($-\pi/2$?)
$\theta_{13} = 8.56 \pm 0.15°$

$\delta m^2 = 7.40 \pm 0.21 \; 10^{-5}$ eV^2
$\theta_{12} = 33.6 \pm 0.77°$

$$\mathbf{U}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_D}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta_D} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha_1} & 0\\ 0 & 0 & e^{i\alpha_2}\end{pmatrix}$$

Atmospheric
Accelerators LBL
L ~ 700 km

Reactors L ~ 1 km
LBL L ~ 200 km

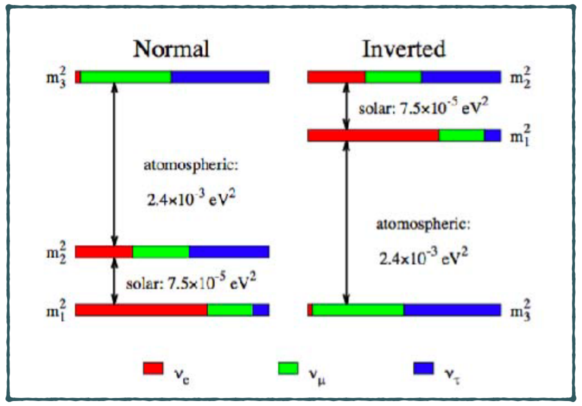
Solar
Reactors
L ~ 200 km

$0\nu\beta\beta$

Next generation (JUNO, T2HK, DUNE) has sufficient precision for global fits to almost all parameters

Combined T2K, Nova, etc analysis may yield an early "detection" of CP violation phase δ_D

$\nu \neq \overline{\nu}$?



OPEN QUESTIONS and the path to their answers

Dirac vs Majorana ($\nu \neq \nu$?) **$0\nu\beta\beta$**

U_{PMNS} unitary?

$\delta_{CP} \neq 0$?

$\Delta m^2 > 0$? **OSCILLATIONS**

ϑ_{23} maximal? Octant ?

Absolute Mass scale **Spectrometers, μBolometers, EUCLID**

CNO from the Sun **BOREXino. DONE ! 2020**

Astrophysics **IceCUBE, KM3Net**

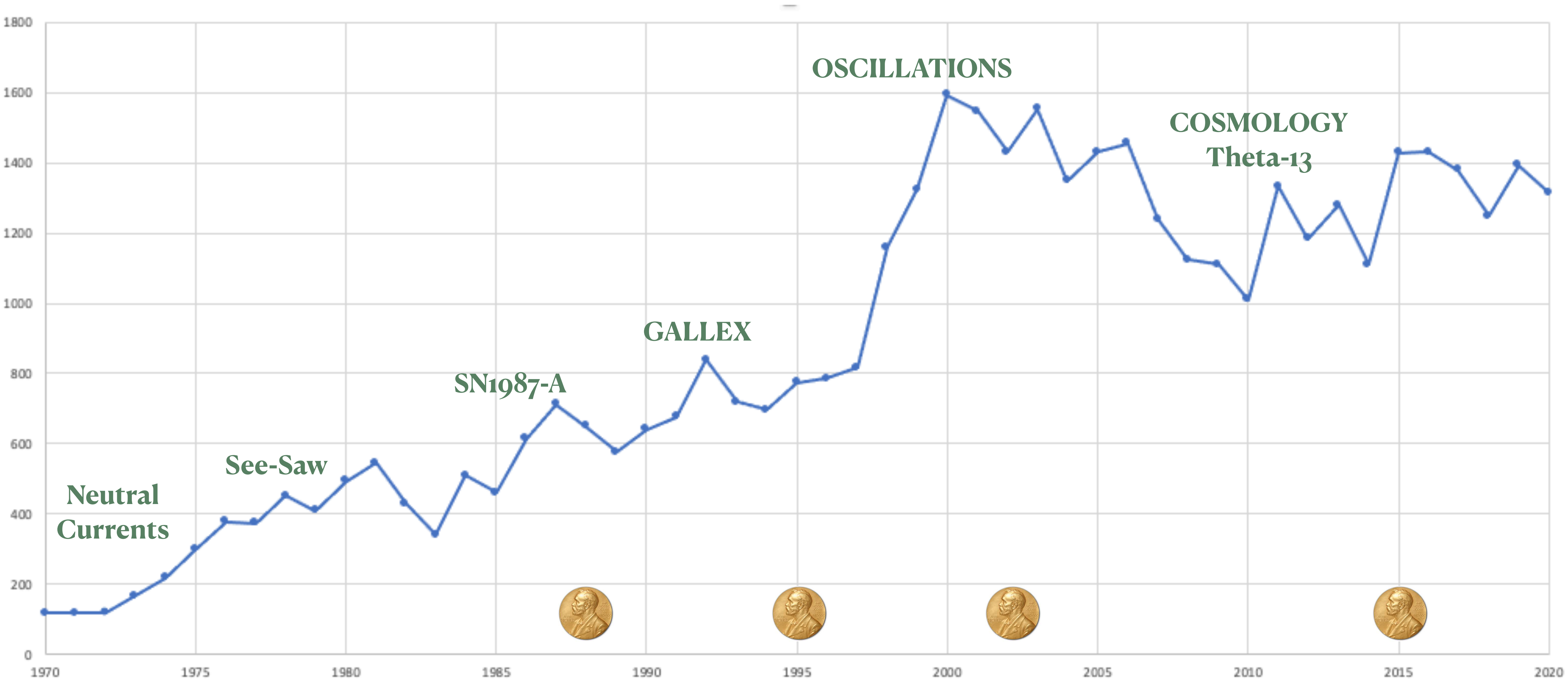
Multi-messenger (GW, photons) **VIRGO-LIGO + Astronomy**

CνB **R&D for PTolemy, Euclid, CMB fits**

SN (pulse and relics) **Borexino, LVD, JUNO, SK, HK, DUNE**

An active and growing field

PAPERS WITH ‘neutrino’ IN TITLE
1970 - 2020 [inspire.hep]



Artificial and natural neutrino sources

- **Artificial**
  - Nuclear Reactors
  - Accelerators
  - Radioactive sources (in some special cases)

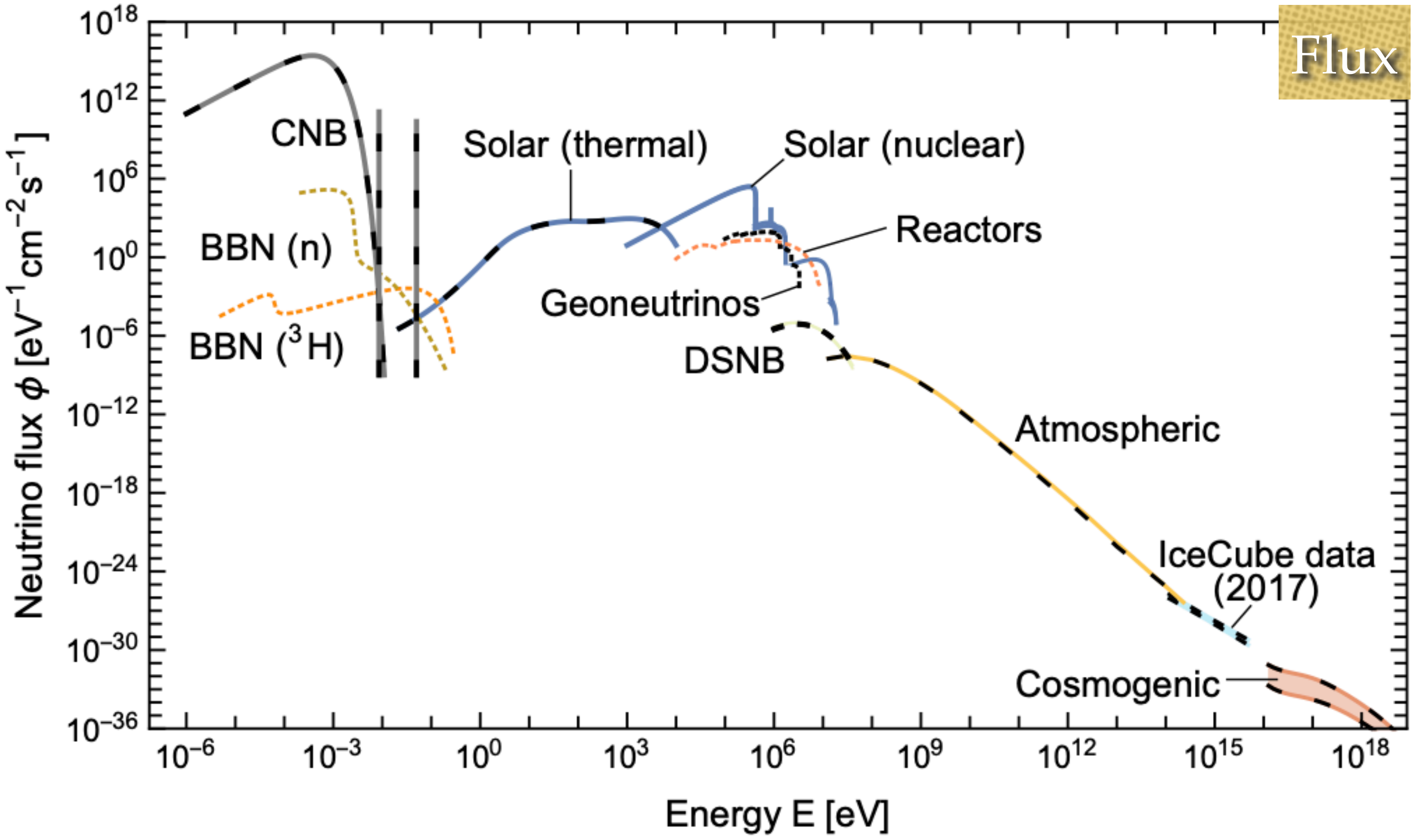
- **Natural**
  - Sun
  - Atmospheric
    - secondary from cosmic rays interaction in atmosphere
  - Cosmic
    - coming from outside Earth
  - Geo-neutrinos
    - from Earth bulk and crust radioactivity
  - Diffuse SN (statistical sum of many past SN events)
  - SN
    - only once so far, **SN1987a**
  - Relic (from big bang)

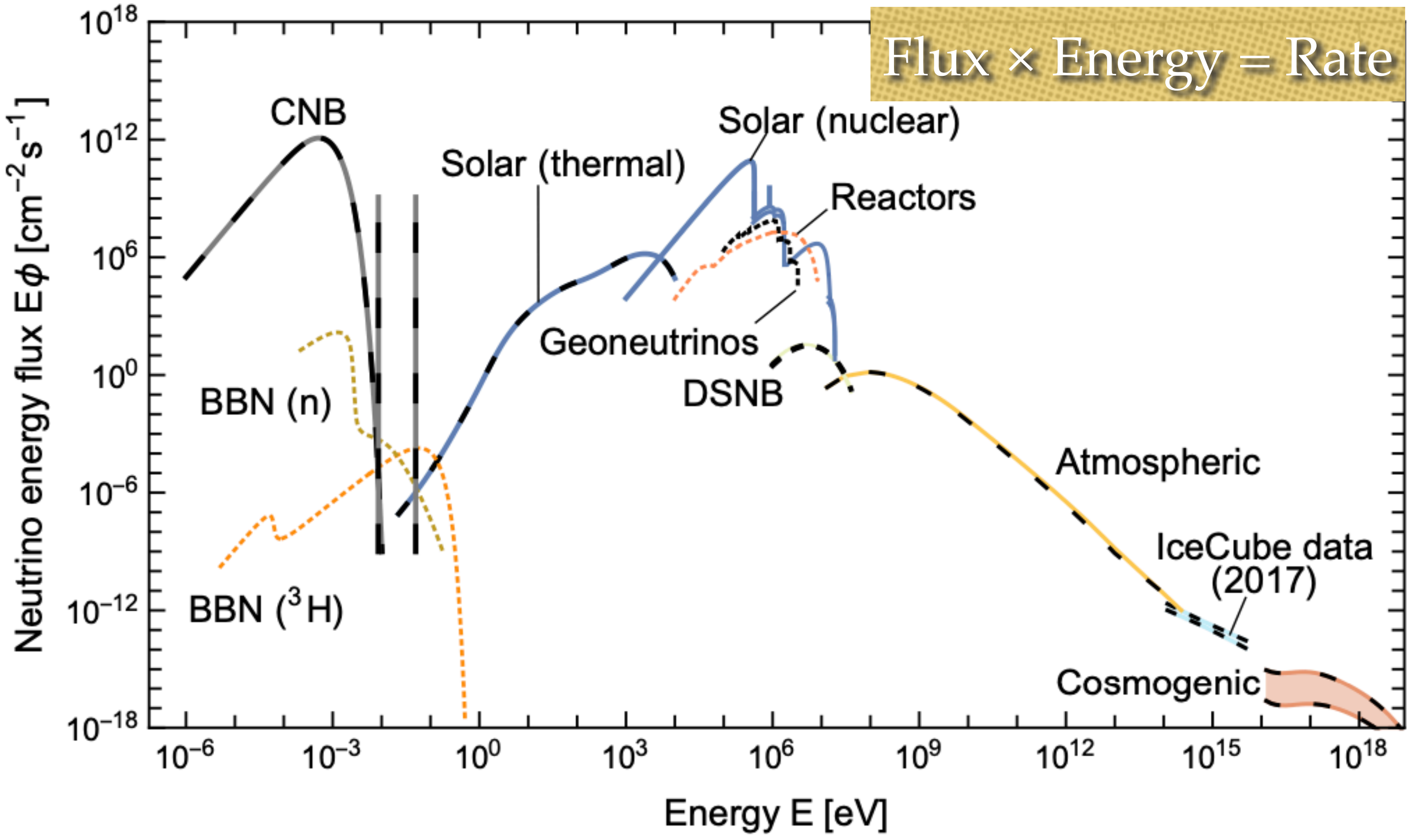
Natural neutrino sources

Neutrinos ——

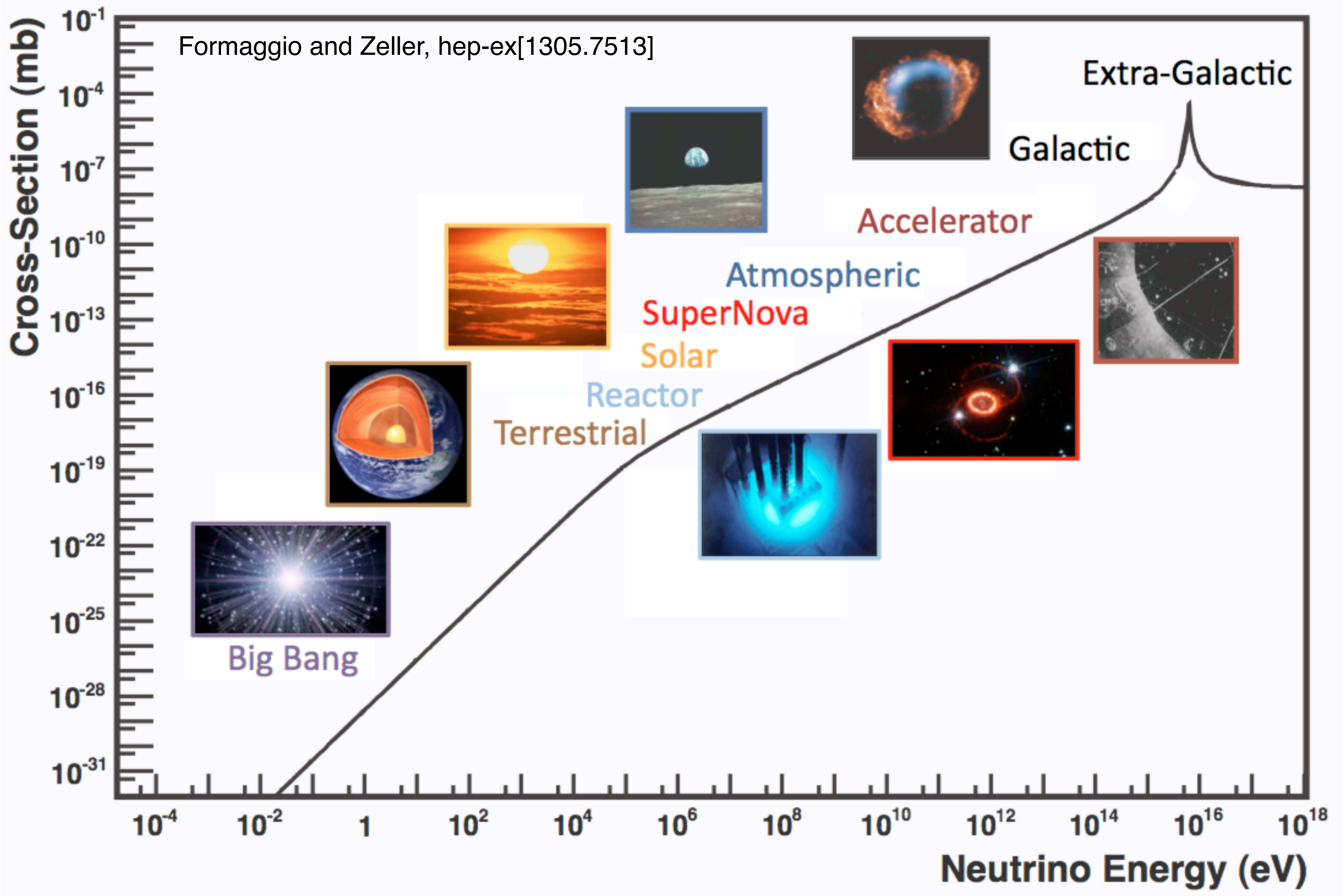
Anti-Neutrinos - - - - - - -

From: arXiv: 1910.11878v3
(Vitagliano, Tamborra, Raffelt)





Neutrino energy ranges



Detecting neutrinos: key parameters and processes

$$N_{obs} = N_{targ}\ T \int_{E_{thr}}^{\infty} \Phi(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)dE_\nu$$

- **N_{obs} :** number of detected events above
- **E_{thr}:** lower detection threshold (strongly dependent on technology)
- **N_{targ}:** number of targets (electrons, protons, nuclei)
  - Typical value $N_{targ} \sim 6\ 10^{26}\ kg^{-1}$ (e^- or p)
- **T:** exposure time ($2.7\ 10^7$ s / y typical up-time)
- ϕ: neutrino flux
  - **Sun:** ~ **10^6 - 10^{10} $cm^{-2}\ s^{-1}$** at Earth; **Reactors:** ~ **10^{12} $cm^{-2}\ s^{-1}$** @ 20 m; **Accelerators:** ~ **1 $cm^{-2}\ s^{-1}$** @ 1000 km
- **σ:** cross section (total for the specific FS)
- **ε:** efficiency/acceptance; usually large, but not always

NOTE: this formula is good for MC simulations. Real neutrino energy is usually unknown, so data analysis must be done using **reconstructed energy.** **A complex issue,** not covered.

- TWO SIGNIFICANT EXAMPLES:
  - **SOLAR (Borexino, elastic scattering on electrons)**

$$N_{obs} = \underbrace{[3.\ 10^{31} e^-]}_{\textbf{100 t}} \times \underbrace{[86400\ s\ ]}_{\textbf{1 day}} \times \underbrace{[6\ 10^9\ cm^{-2}s^{-1}]}_{\textbf{flux}} \underbrace{\left[\frac{0.7\ 10^{-45}\ cm^2}{(MeV)}\right]}_{\textbf{cross section}} \simeq\ 50\ ev/day$$

  - **ACCELERATOR (DUNE, inelastic scattering on Liquid Argon)**

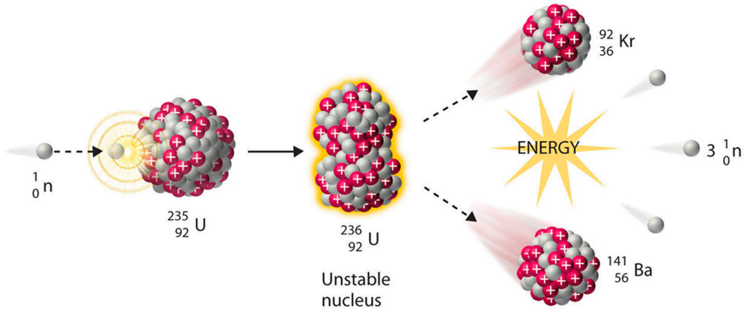
kTon required

$$N_{obs} = \underbrace{[\frac{M}{1.67\ 10^{-27}\ kg}]}_{\textbf{Number of nucleons}} \cdot \underbrace{[2.\ 10^7\ s\ ]}_{\textbf{Effective year}} \cdot \underbrace{[1\ cm^{-2}s^{-1}]}_{\textbf{Strong beam @ 1000 km}} \cdot \epsilon \cdot \underbrace{\left[\frac{0.7\ 10^{-38}\ E_\nu\ cm^2}{GeV}\right]}_{\textbf{cross section}} \simeq 40\ 10^{-6}\frac{E_\nu}{GeV}\epsilon\frac{M}{kg}$$

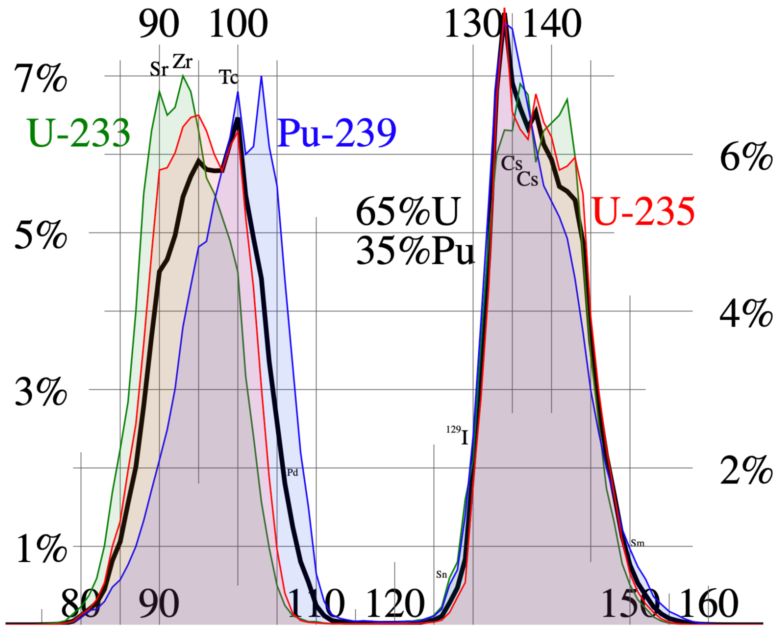
Nuclear reactors

- A reactor is a powerful source of **anti-neutrinos**
  - Each U fission yields 200 MeV on average, and 6 ν_e
    - Flux: ~ **2. 10^{20} s^{-1} GW^{-1}**, isotropic, $<E_\nu> \simeq 0.5$ MeV
    - About ~ **4. 10^{12} s^{-1} cm^{-2}** for 1 GW at **20 m from the core**

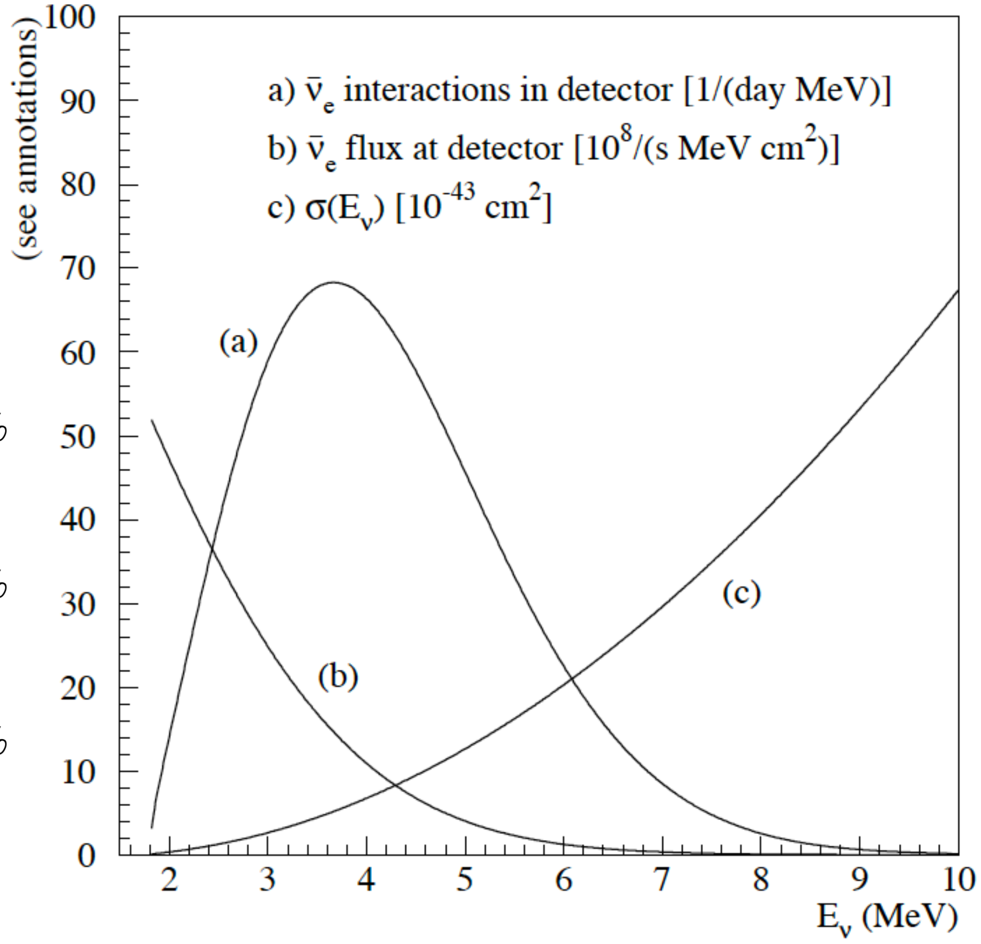
- **The details of the anti-neutrino spectrum are hard to compute, and still subject of research**
  - Dominating process: ^{235}U **fission** and sub-sequent β decays **(6 on average)**



  - The flux depends on **reactor type** and also on **time** because **fuel composition evolves**

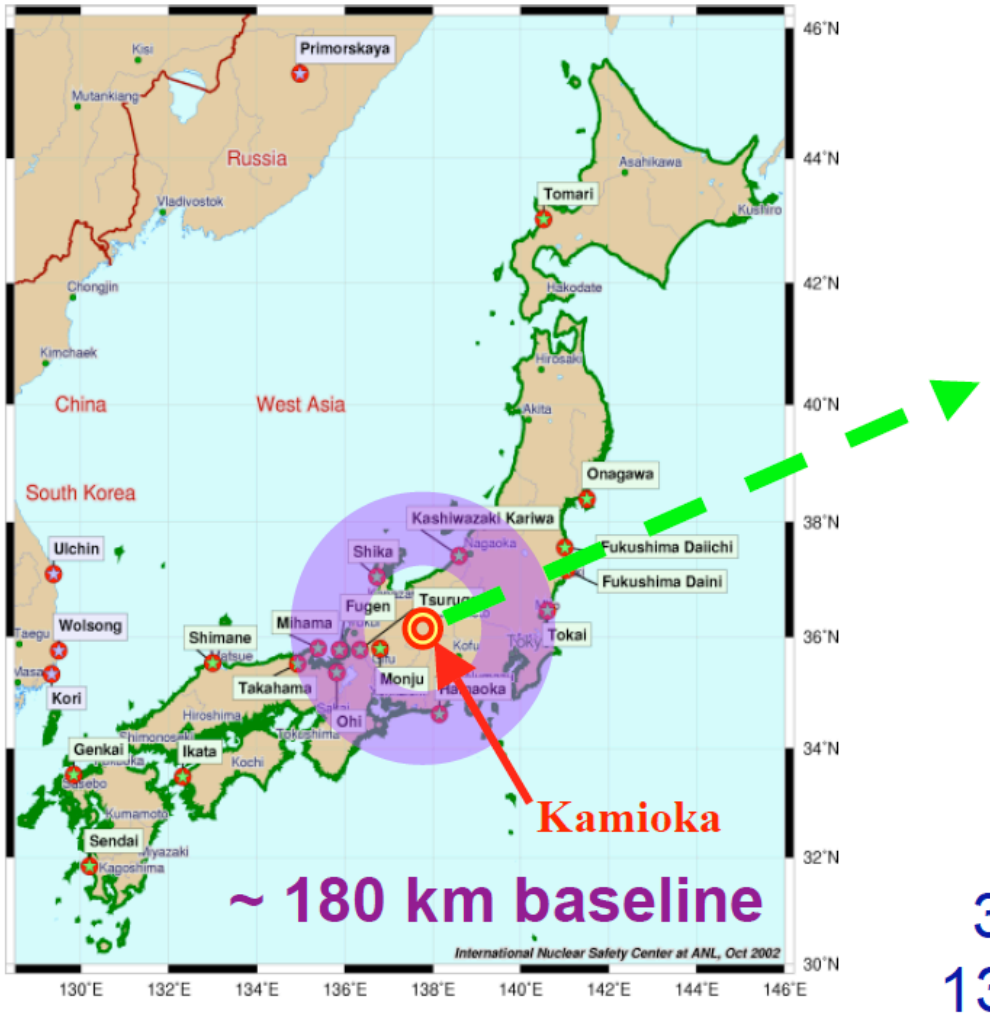


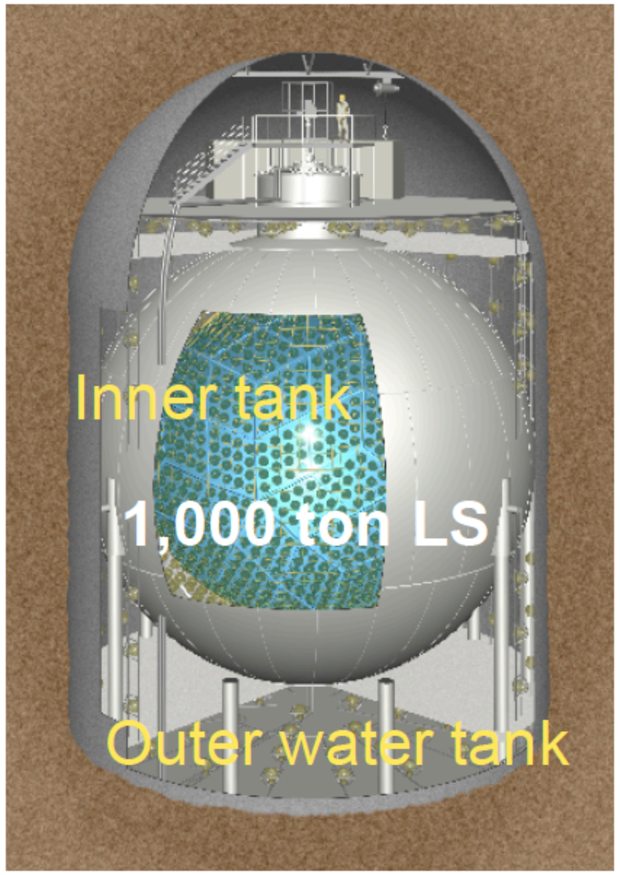
Fission products mass number A



Example: KamLAND experiment

- **Kam**ioka **L**iquid Scintillator **A**nti-**N**eutrino **D**etector





34% photo-coverage with 1325 17” and 554 20” PMTs

2 flavor neutrino oscillation

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2[\mathrm{eV}^2] l[m]}{E[\mathrm{MeV}]}\right)$$

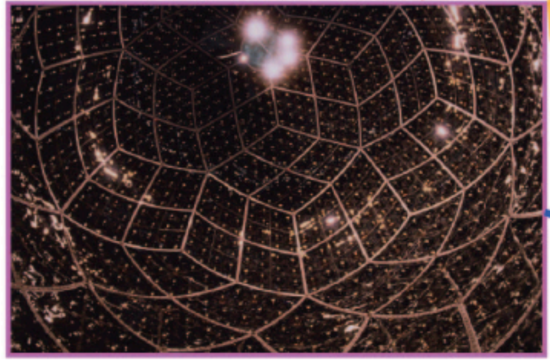
most sensitive region

$$\Delta m^2 = (1/1.27) \cdot (E[\mathrm{MeV}]/L[m]) \cdot (\pi/2)$$
$$\sim 3 \times 10^{-5} \mathrm{eV}^2$$

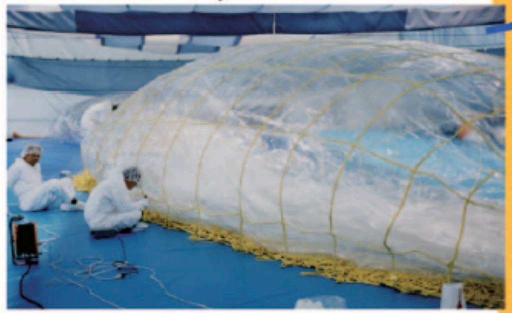
KamLAND detector

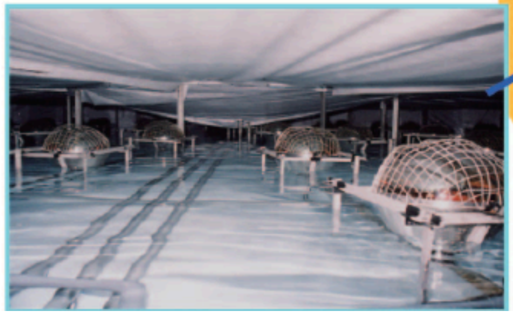
Stainless steel tank

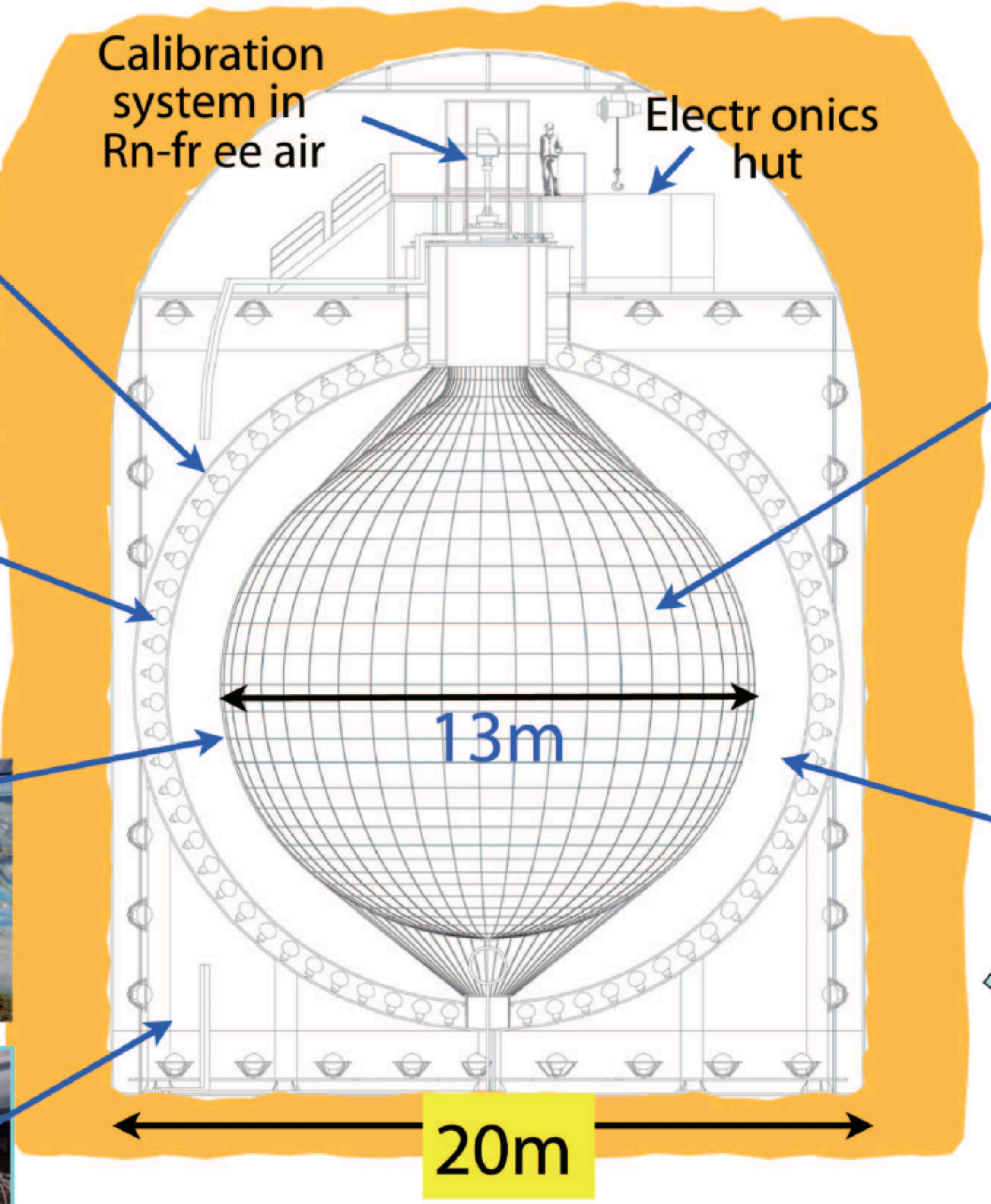
1879 PMT (17"& 20") array



Balloon (Nylon/EVOH)





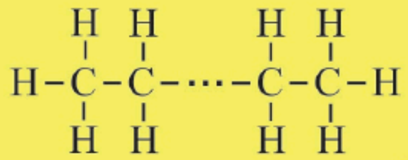


Calibration system in Rn-free air

Electronics hut

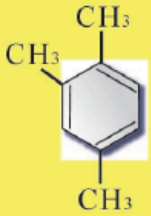
Outer detector : 3.2kton water shield and 225 20"PMTs to detect cosmic μ's)

Liquid Scintillator ~1kton

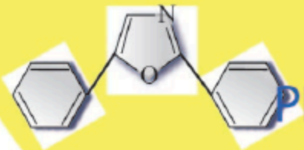


$$H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\cdots-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-H$$

Normal dodecane ($C_{12}H_{26}$) (80%)



Pseudocumene (20%)



PPO (1.36 ±0.03g/l)

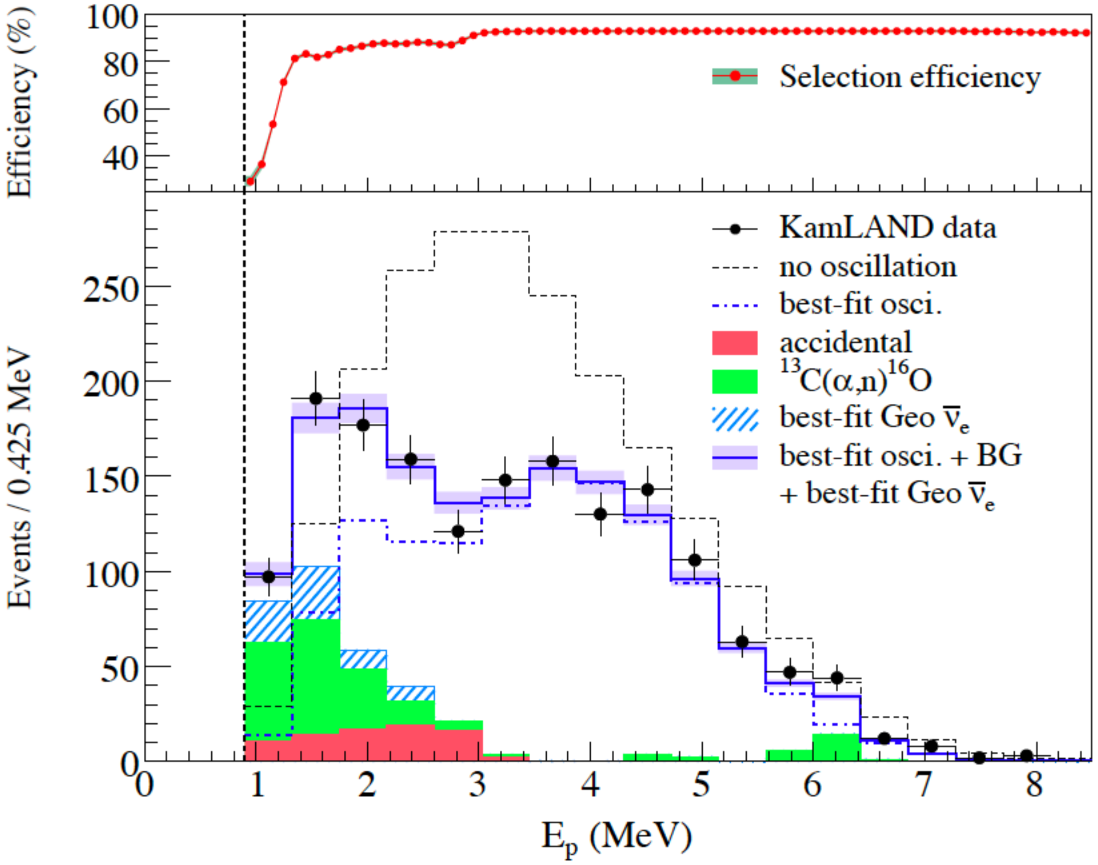
Buffer Oil (dodecane)

Vertex resolution ~12cm/ $\sqrt{E_{[MeV]}}$

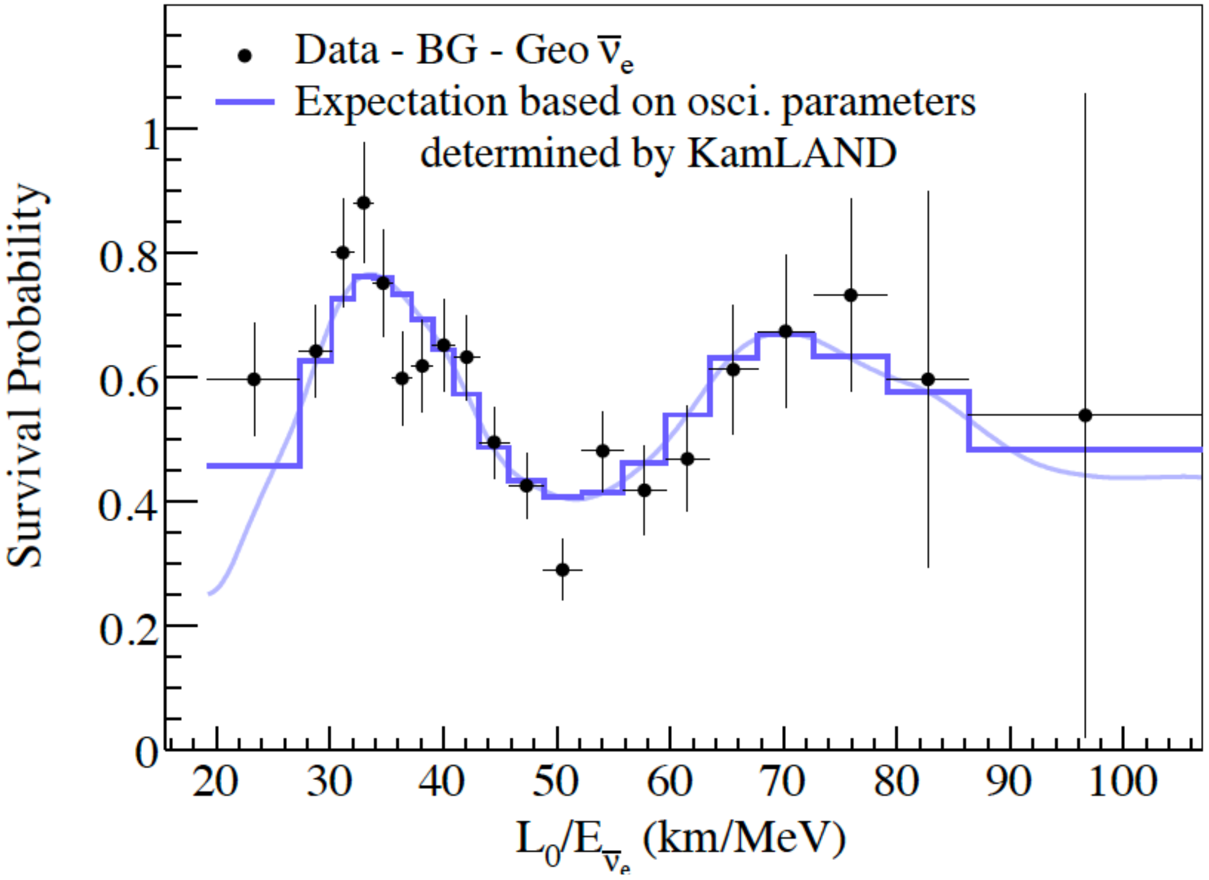
Energy resolution 6.5%/ $\sqrt{E_{[MeV]}}$

A neat oscillation experiment

Prompt Event Spectrum

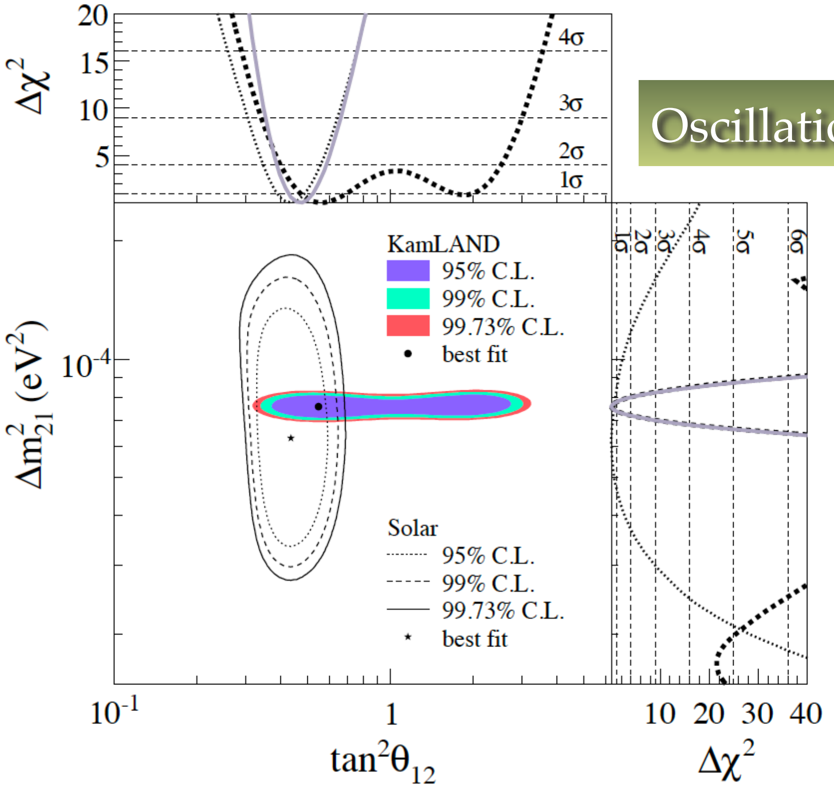


Survival probability



$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2(\frac{1.27\Delta m^2[\mathrm{eV}^2] l[m]}{E[\mathrm{MeV}]})$$

Oscillation parameters



How to make a neutrino beam

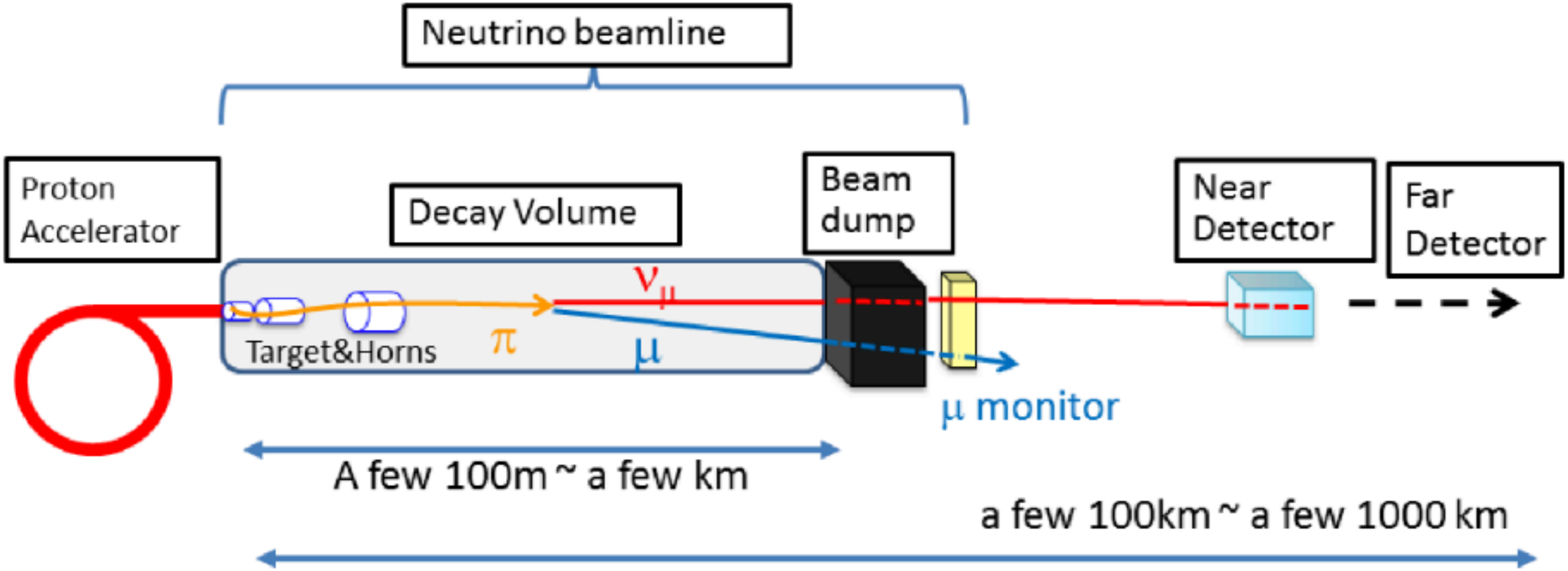
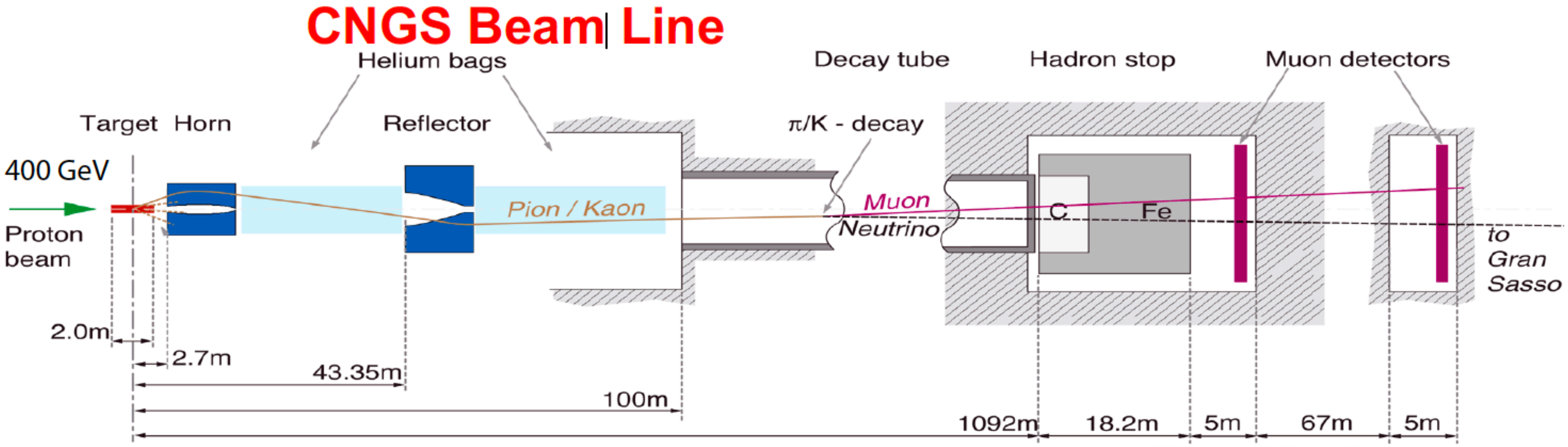
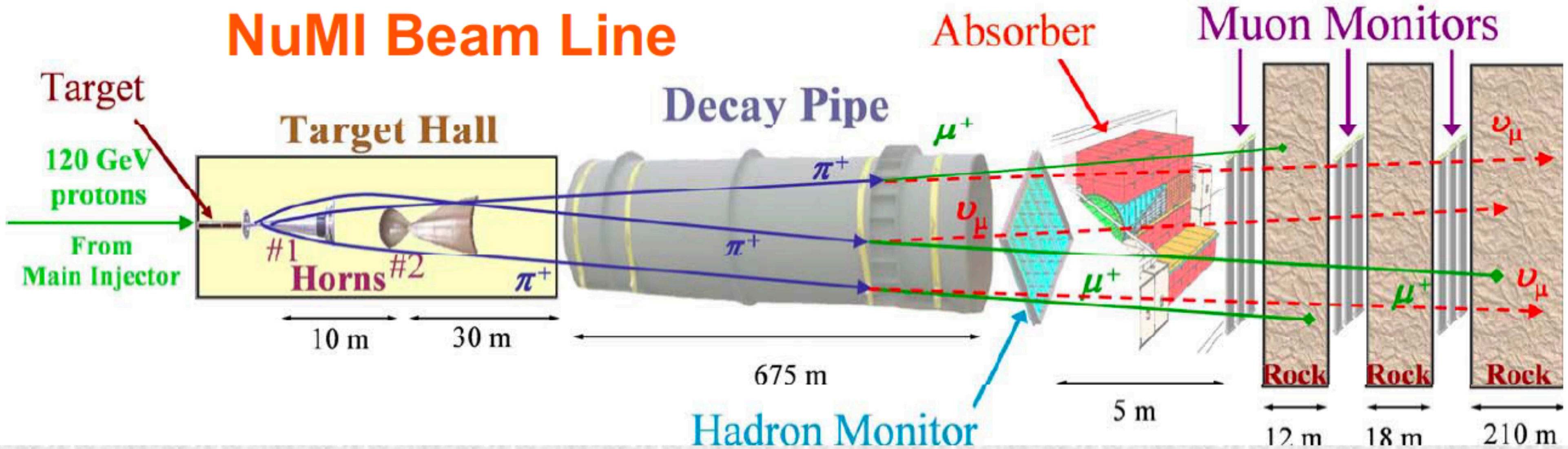


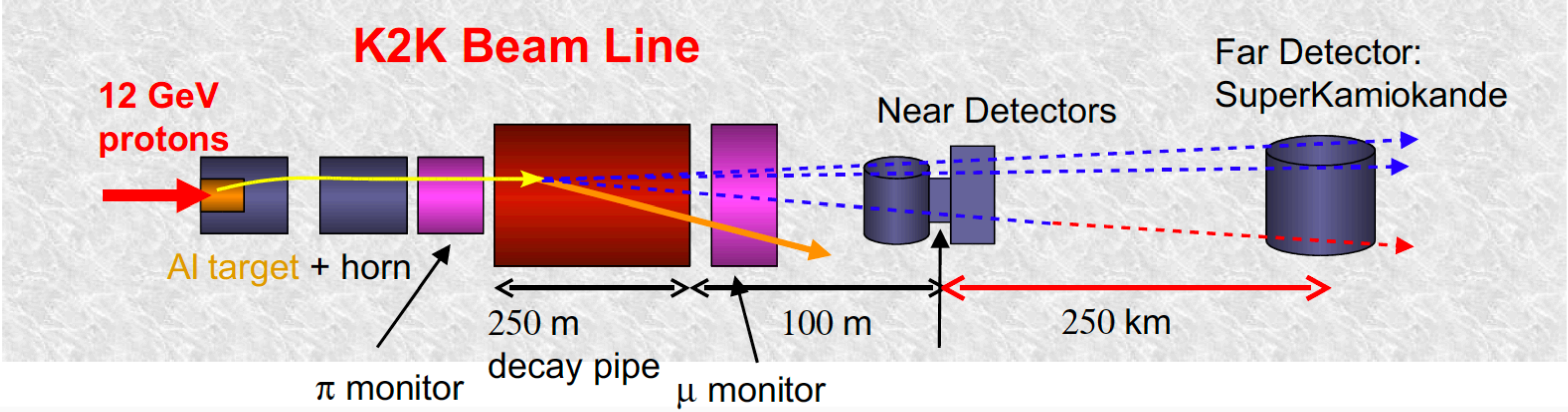
FIGURE 1. Components of the accelerator neutrino experiment

XXVI International Conference on Neutrino Physics and Astrophysics
AIP Conf. Proc. 1666, 130001-1–130001-6; doi: 10.1063/1.4915579

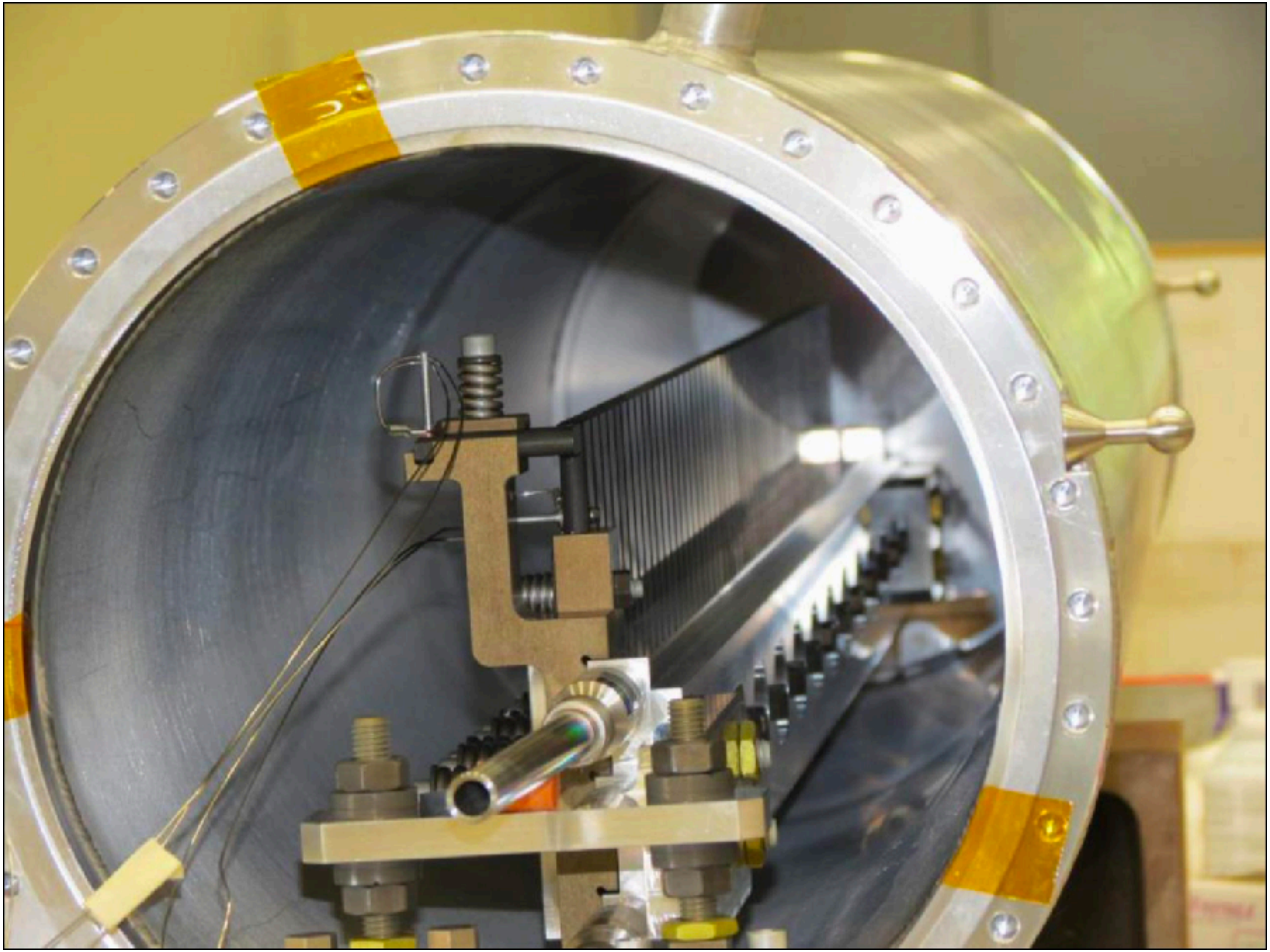
Neutrino beams: examples



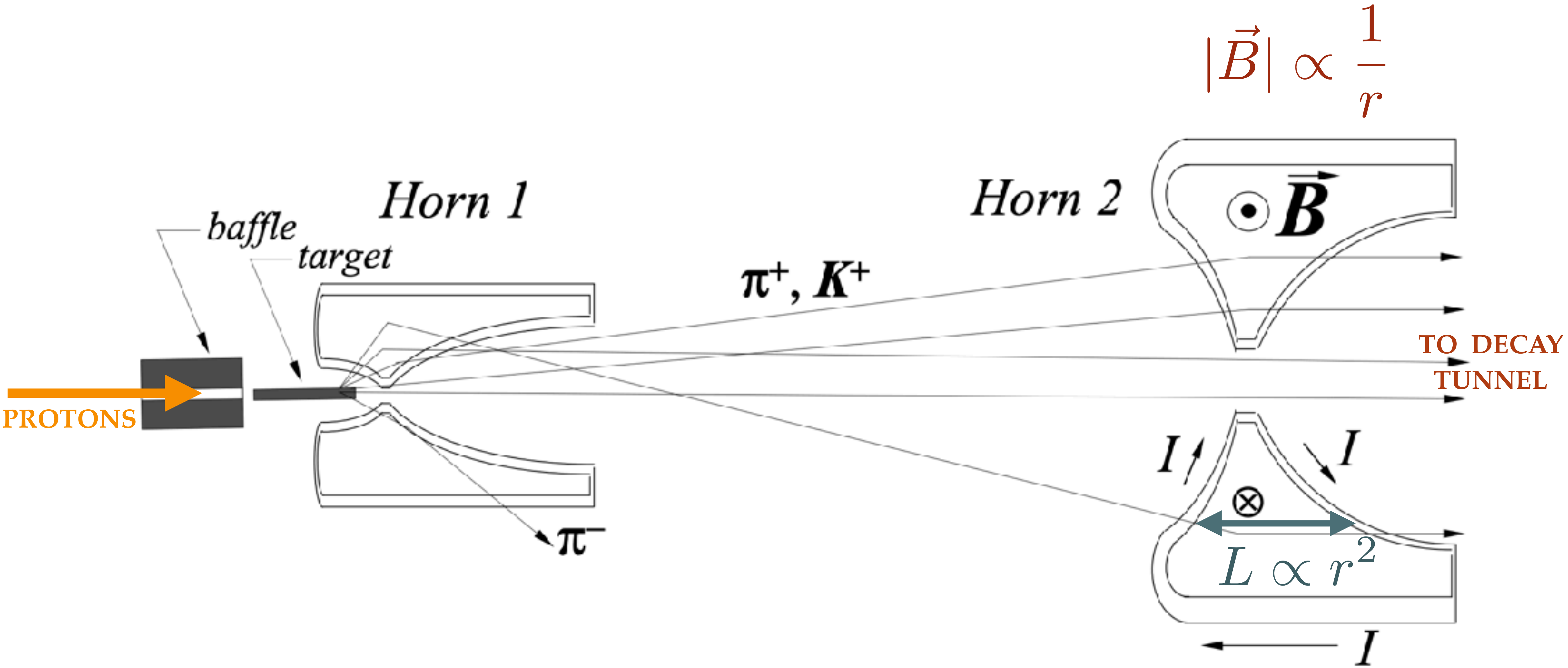




NuMi target



Focussing

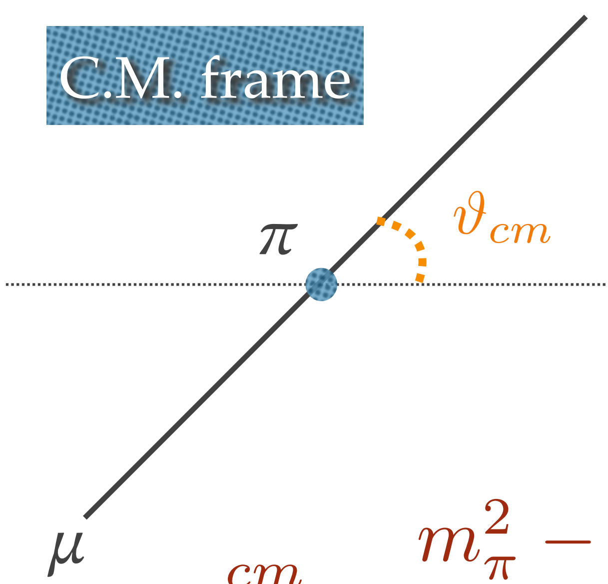


$$p_{kick} \propto B \cdot L \propto r$$

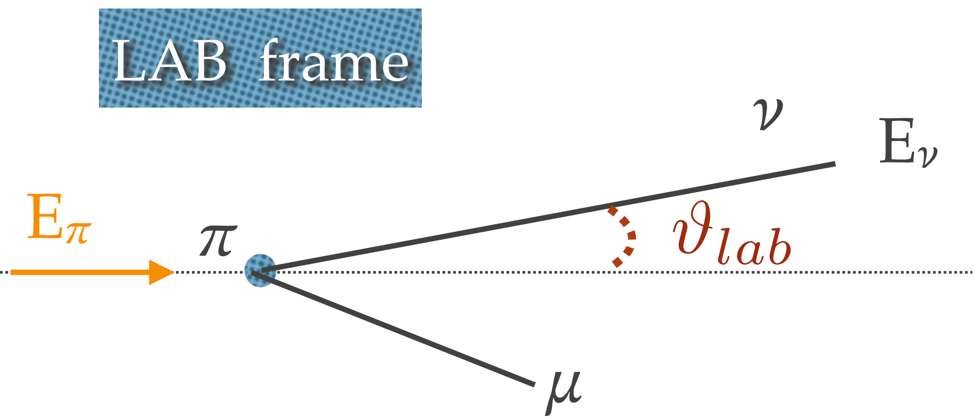
- "Forward" current: select π^+, and get mainly ν_μ
- "Reversed" current: select π^-, and get mainly $\bar{\nu}_\mu$

Horns

ON-axis vs OFF-axis: selecting neutrino energy



$$\gamma = \frac{E_\pi}{m_\pi}$$

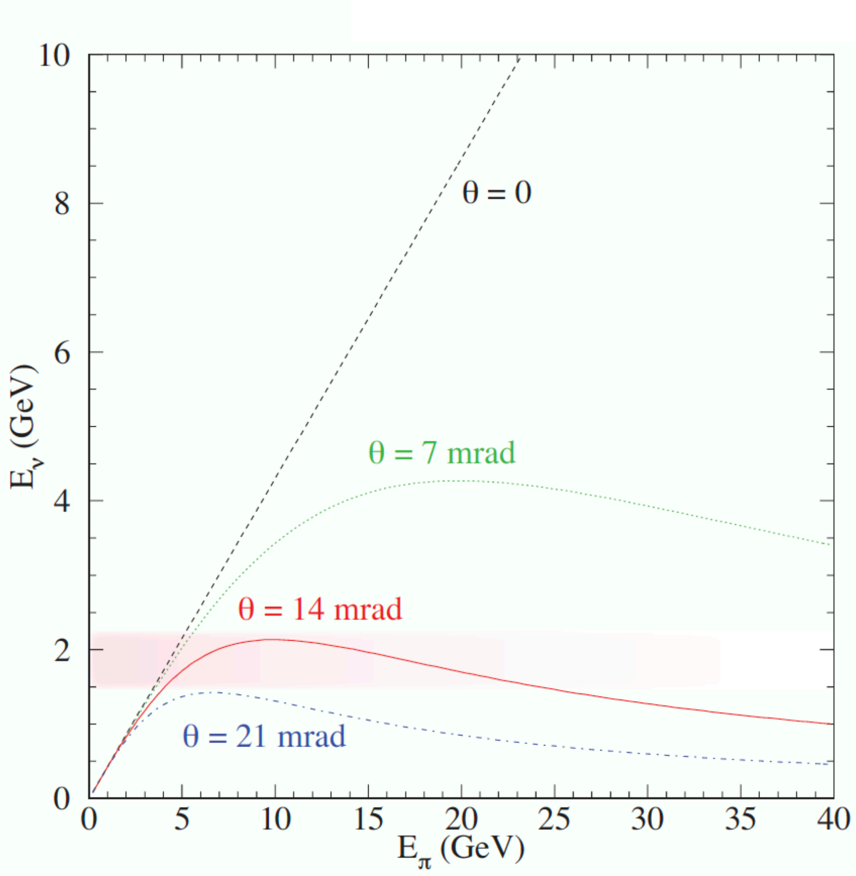


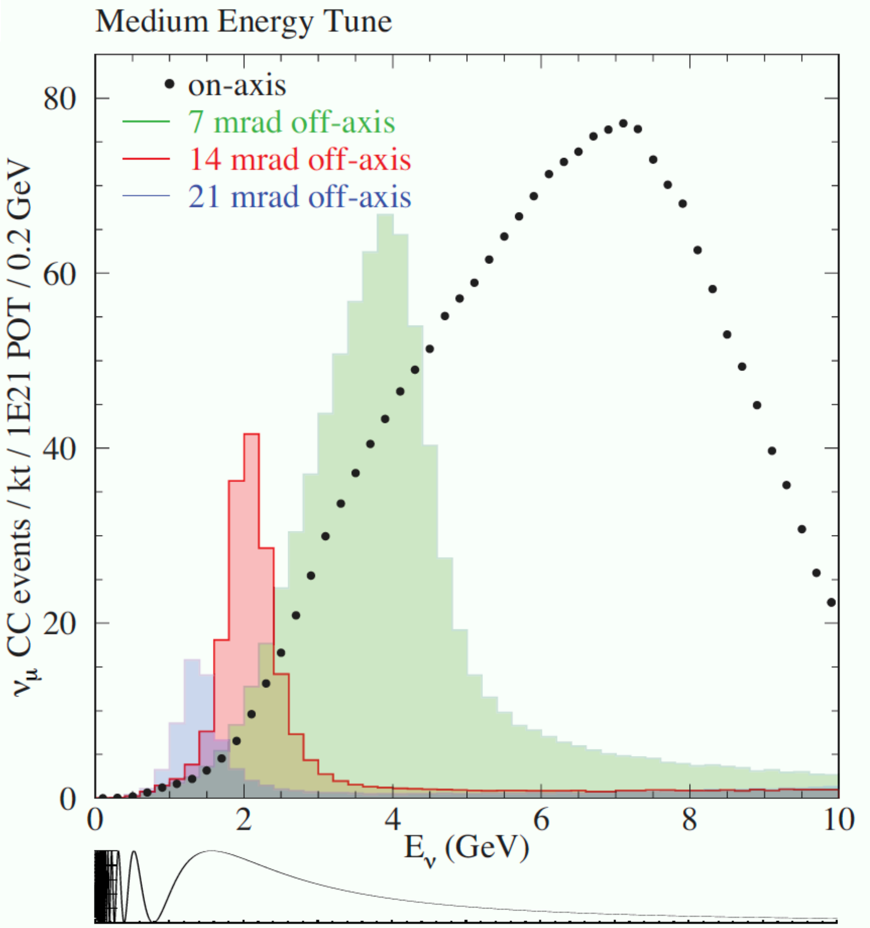
$$p_\nu^{cm} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}$$

$$p_\nu^{lab} = E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \vartheta_{lab}^2}$$

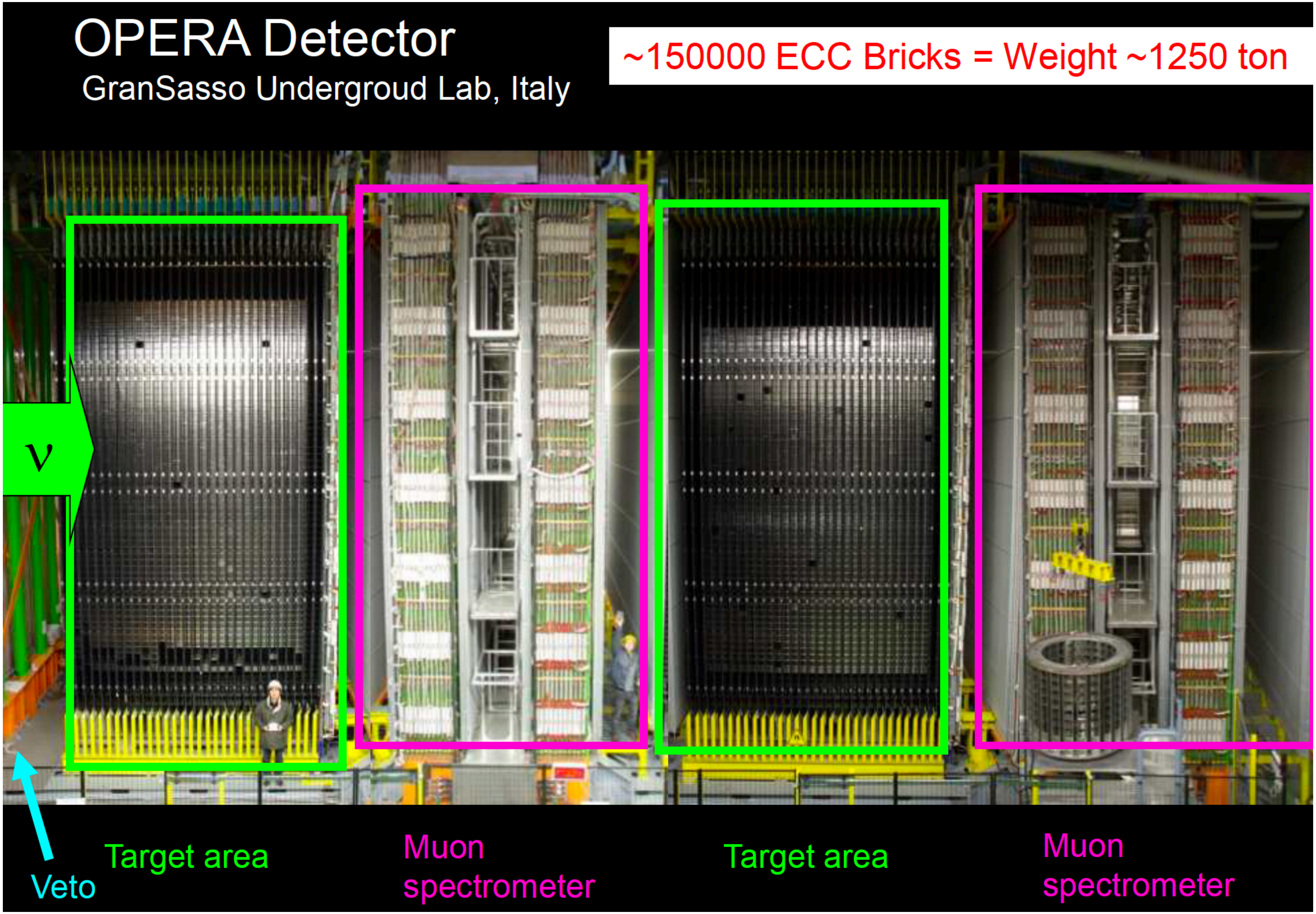
- **OFF-axis** there is a **strong correlation** between neutrino **energy and angle**

NuMi example

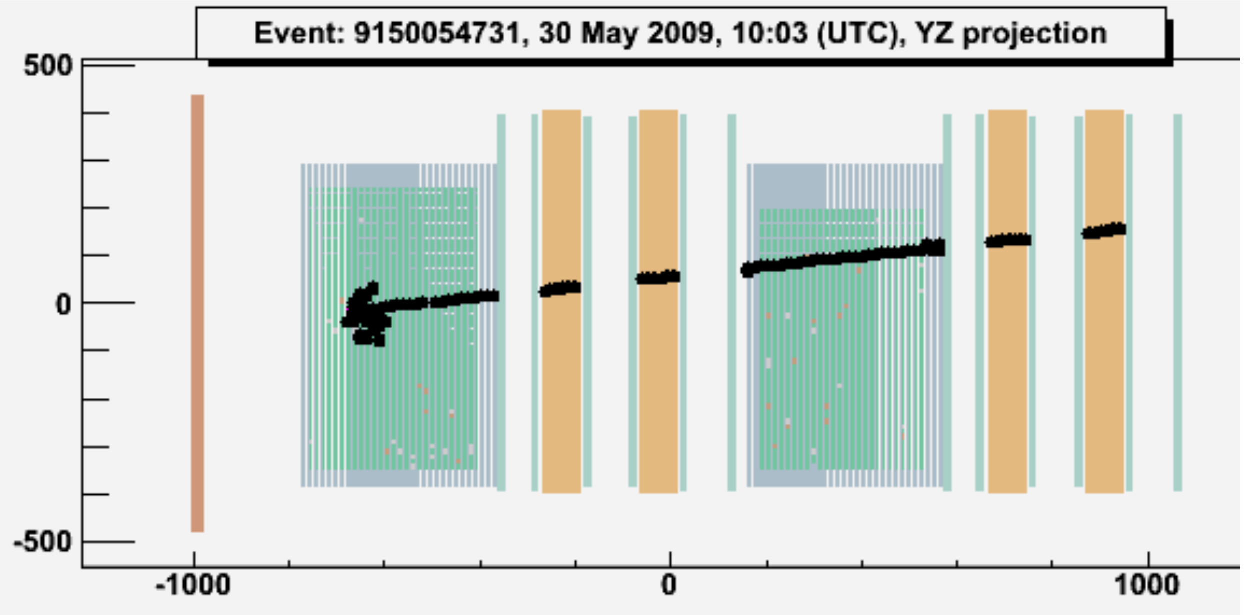


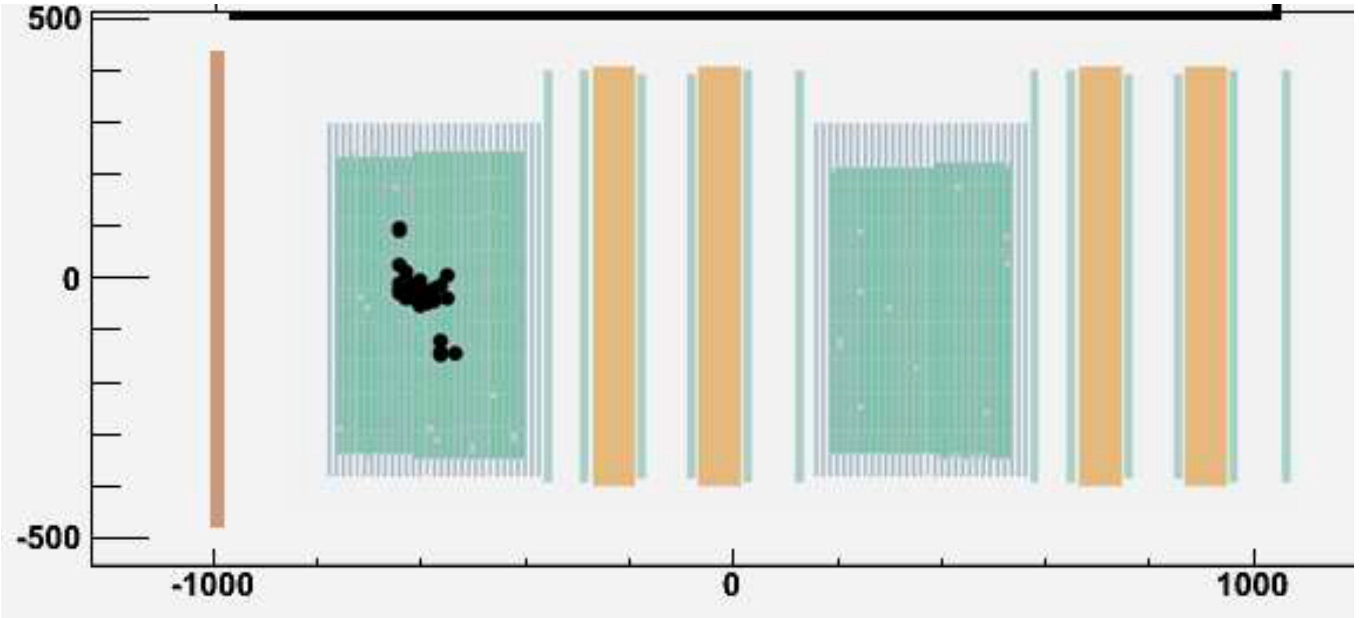


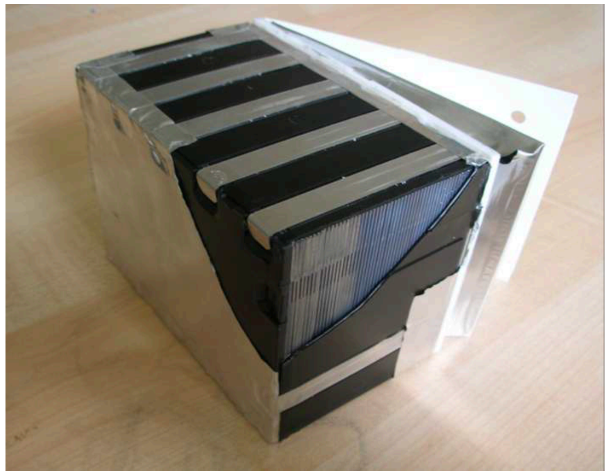
Example: Opera experiment @ LNGS



Example: Opera experiment at LNGS



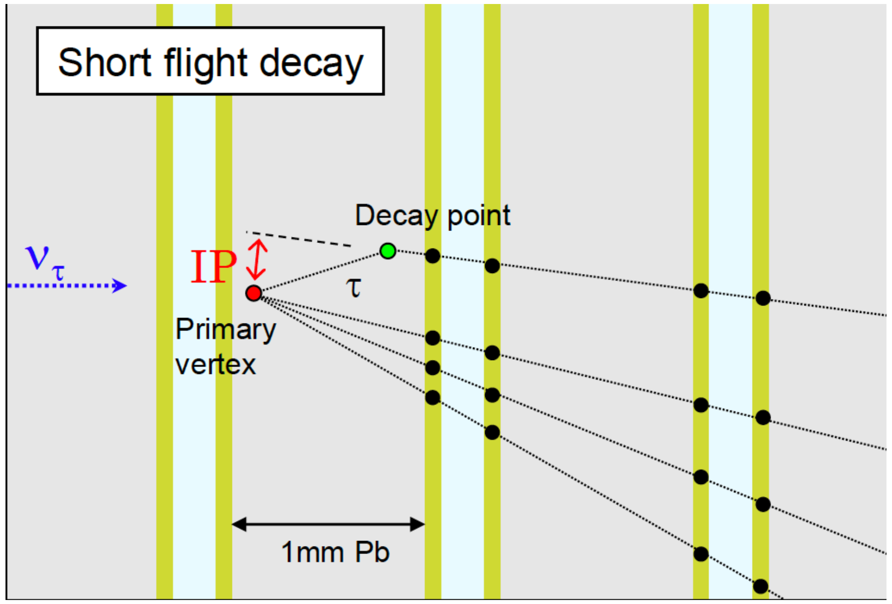




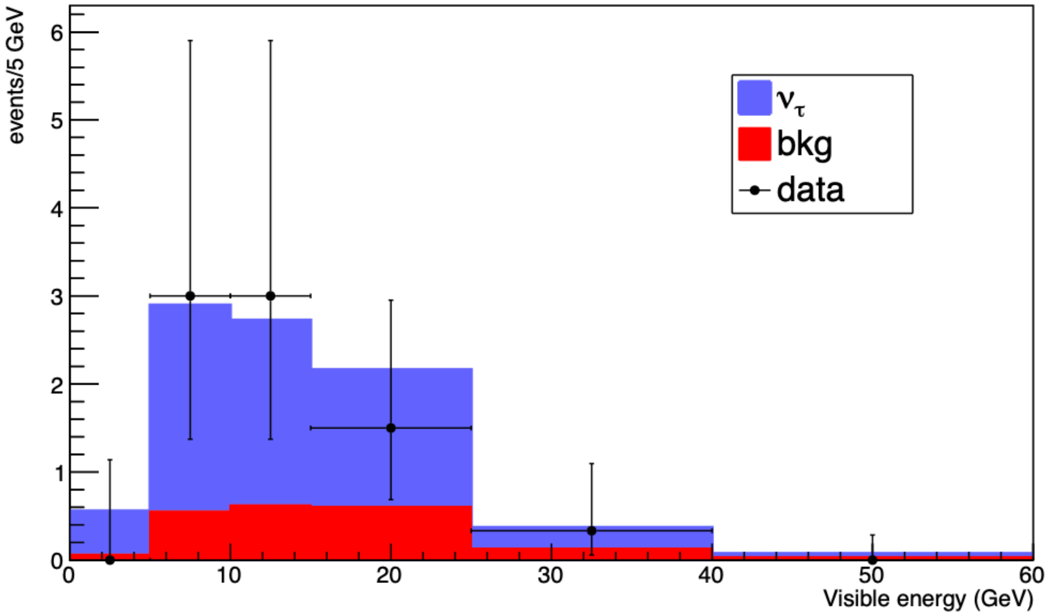
BRICK ID	72693	29570	23543	92217	130577	77152	27972	26670	136759	4838
Channel	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 3h$	$\tau \to 3h$
z_{dec} (μm)	435	1446	151	406	630	430	652	303	-648	407
p^T_{miss} (GeV/c)	0.52	0.31	/	0.55	0.30	0.88	1.29	0.46	0.60	> 0.50
ϕ_{lH} (degrees)	173	168	/	166	151	152	140	143	82	47
p^T_{2ry} (GeV/c)	0.47	/	0.69	0.82	1.00	0.24	0.25	0.33	/	/
p_{2ry} (GeV/c)	12	8.4	2.8	6.0	11	2.7	2.6	2.2	6.7	> 6.3
θ_{kink} (mrad)	41	87	245	137	90	90	98	146	231	83
m (GeV/c^2)	/	0.80	/	1.2	> 0.94	/	/	/	1.2	> 0.94
γ at decay vtx	2	0	0	0	0	1	0	0	0	2
charge$_{2ry}$	/	/	-1	/	/	/	/	/	/	/
BDT Response	0.32	-0.05	0.37	0.12	0.35	0.18	-0.25	-0.10	-0.04	-0.03

TABLE IV. Kinematical variables and BDT response for all ν_τ candidates.

10 candidates

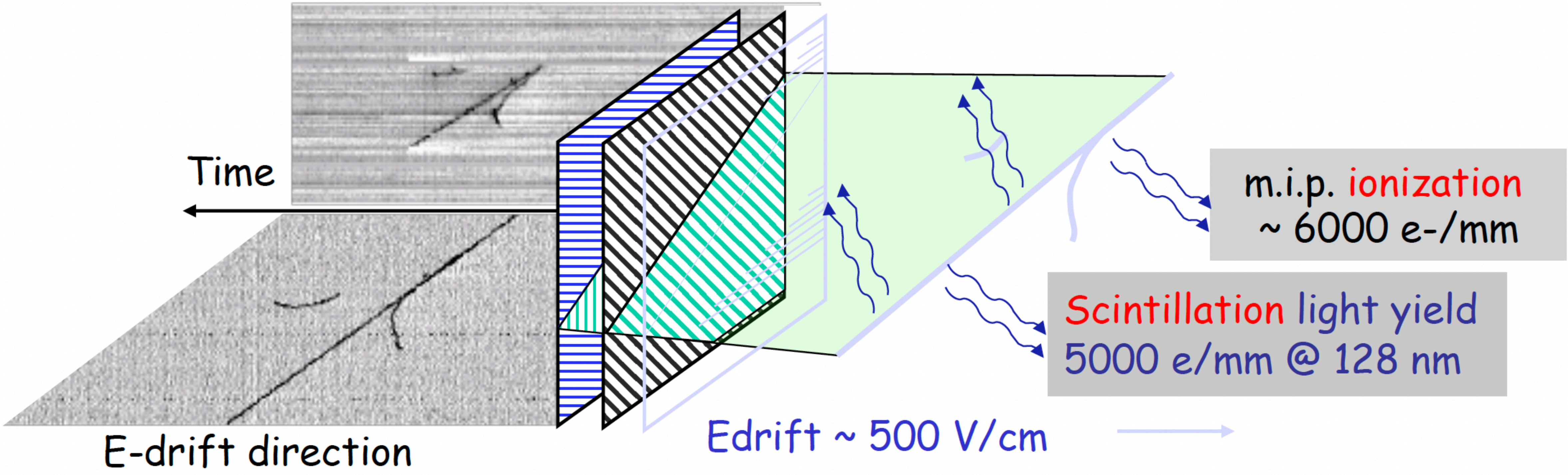


Phys.Rev.Lett. 120 (2018) 21, 211801,

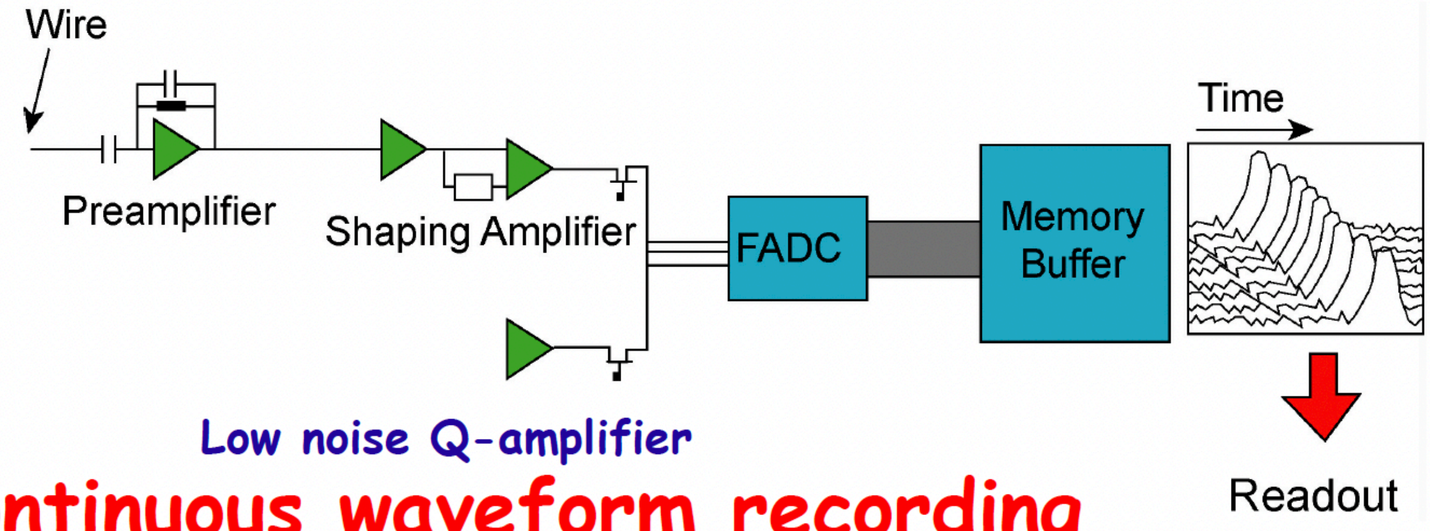


Example: Noble Liquid Detectors

A new, powerful detection technique initiated at CNGS



Drifting electrons are moving to transparent wire arrays oriented in different directions, where signals are recorded.



Continuous waveform recording

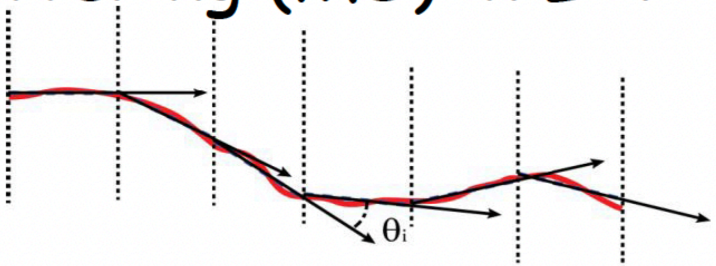
- High density
- Non-destructive readout
- Continuously sensitive
- Self-triggering
- Very good scintillator: T0

C. Rubbia, 2019

Measurement of muon momentum via multiple scattering

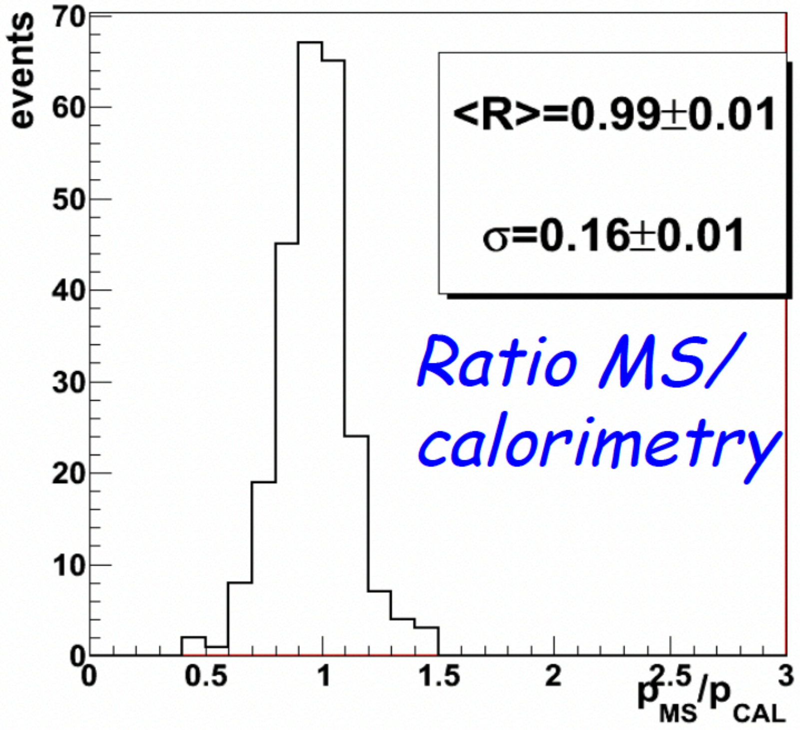
In absence of a magnetic field, the initial m momentum may be determinec through the reconstruction of multiple Coulomb Scattering (MS) in LAr

RMS of θ deflection of μ depends on p, spatial resolution σ and track segmentation

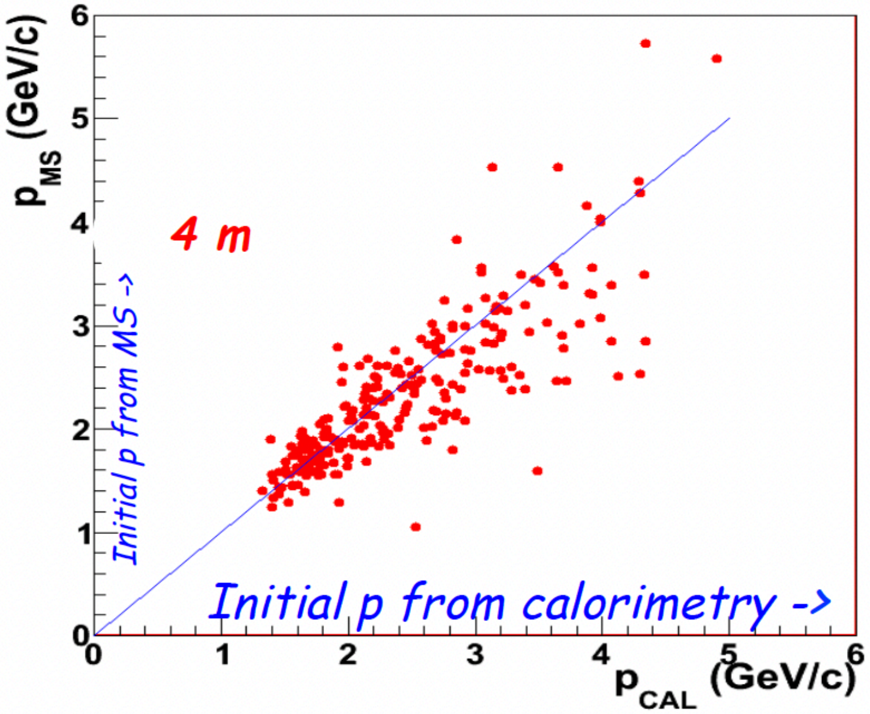


$$\theta_{RMS} \div \frac{13.6MeV}{p}\sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$

Method tested on ~103 stopping μ's from CNGS ν interactions in upstream rock, comparing PMS measured by MS with the corresponding calorimetric PCAL



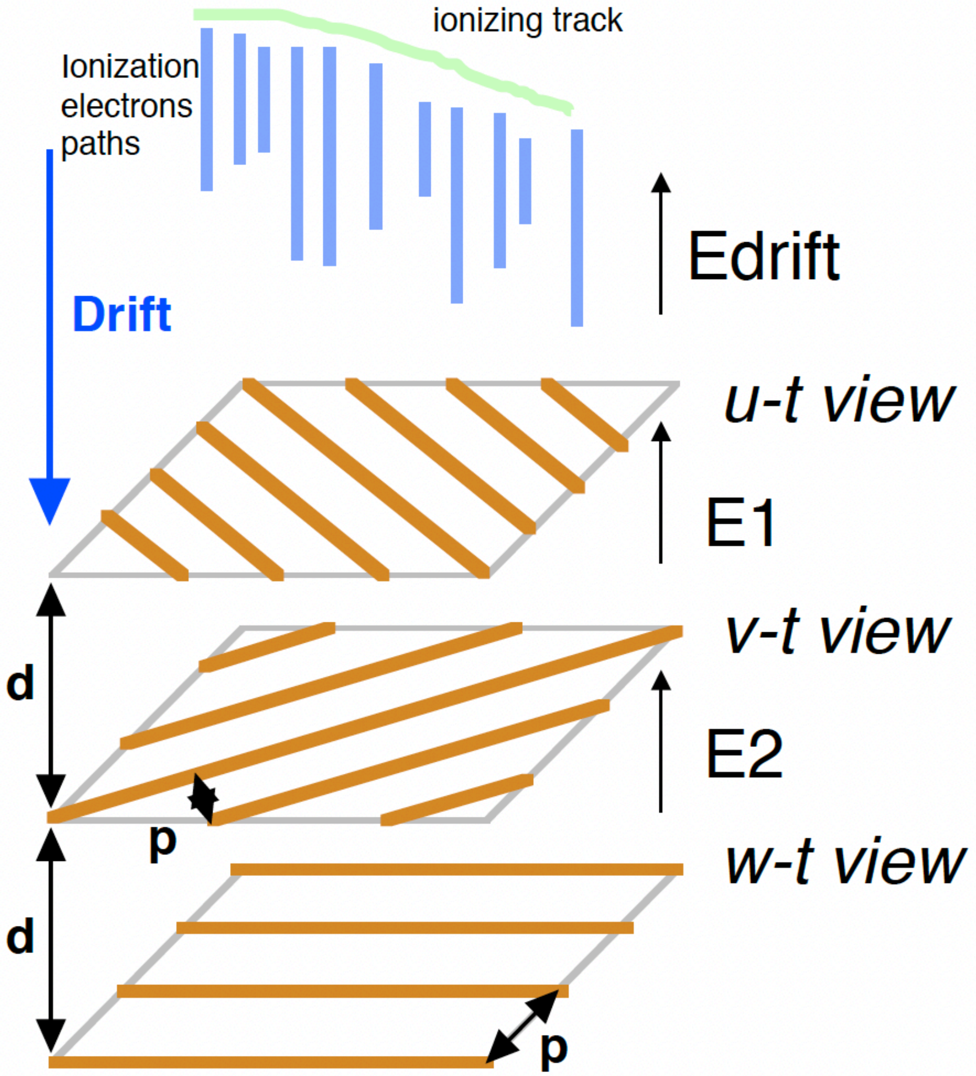
μ track length: > 5m
Used length: 4m

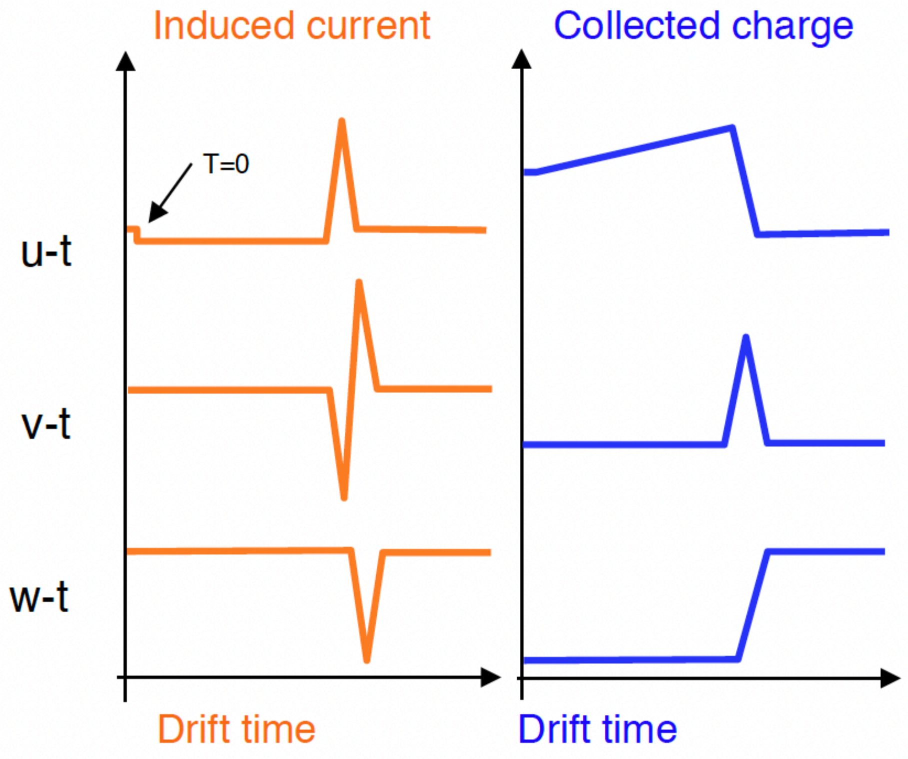


~16% resolution has been obtained in the 0.4-4 GeV /c momentum range of interest for the future short/long base-line experiments

C. Rubbia, 2019

Non destructive, multiple charge readout





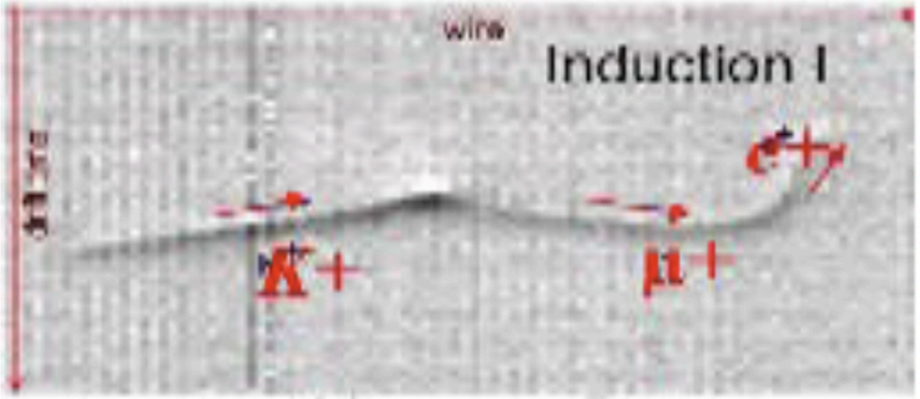
For the ICARUS T600

Edrift = 500 V/cm
p = 3 mm
d = 3 mm
r = 0.1mm

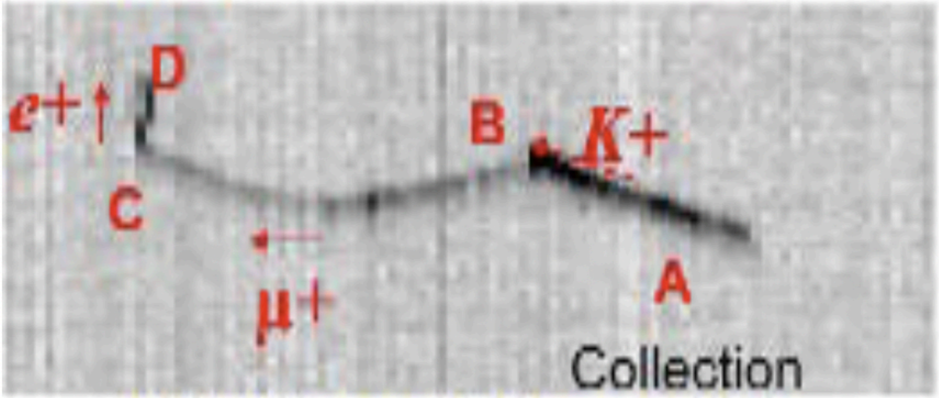
- At FNAL's shallow depth, the T600 will require two additions:
  - 3 m concrete overburden to mitigate the c. rays background,
  - Particles entering the detector must be removed with a Cosmic Rays Tagging (CRT) around the full LAr volume

C. Rubbia, 2019

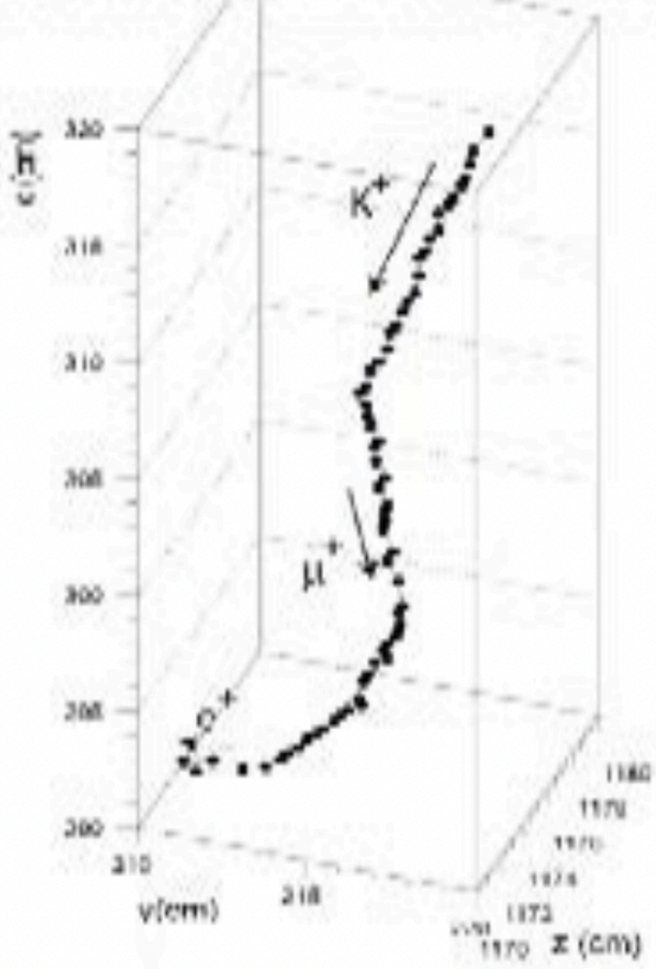
3 D particle Identification ($k^+ \to \mu^+ \to e^+$) at CNGS



ICARUS EVENT

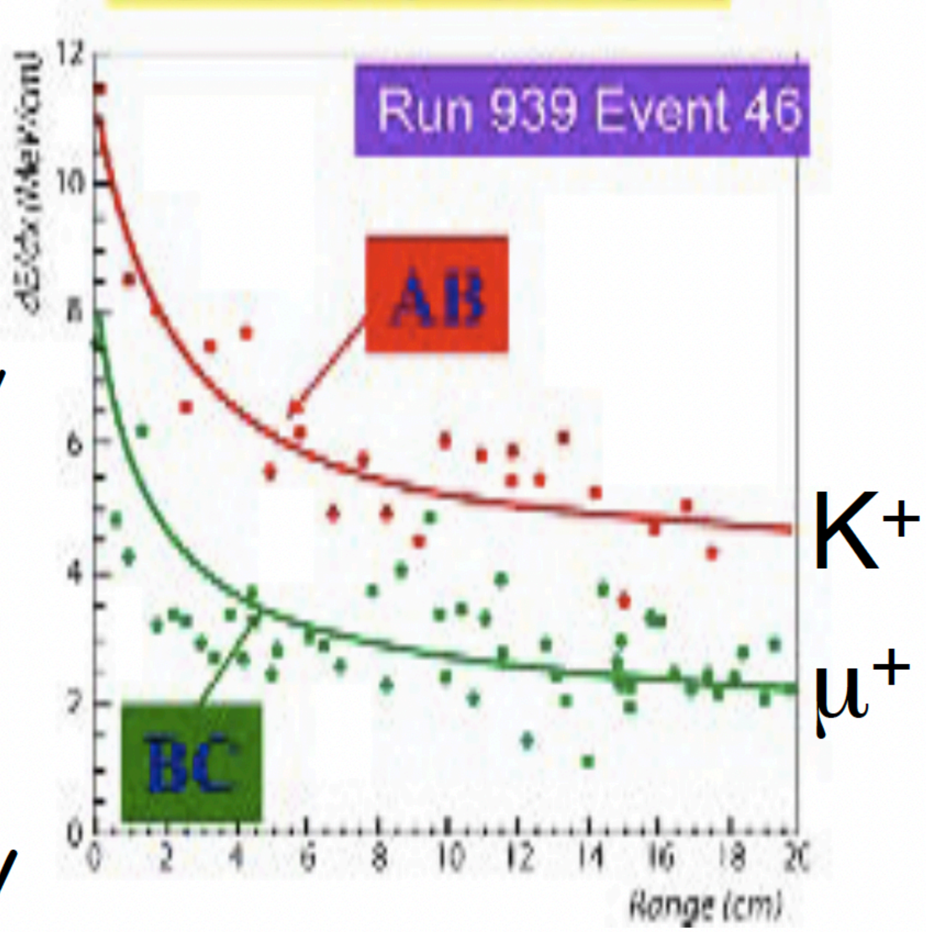


$K^+[AB] \to \mu^+[BC] \to e^+[CD]$



Efficient, low mis-identification, due to precise 3D reconstruction, dE/dx, range measurement

- stopping power
- recognition of secondary particle production after decay interaction

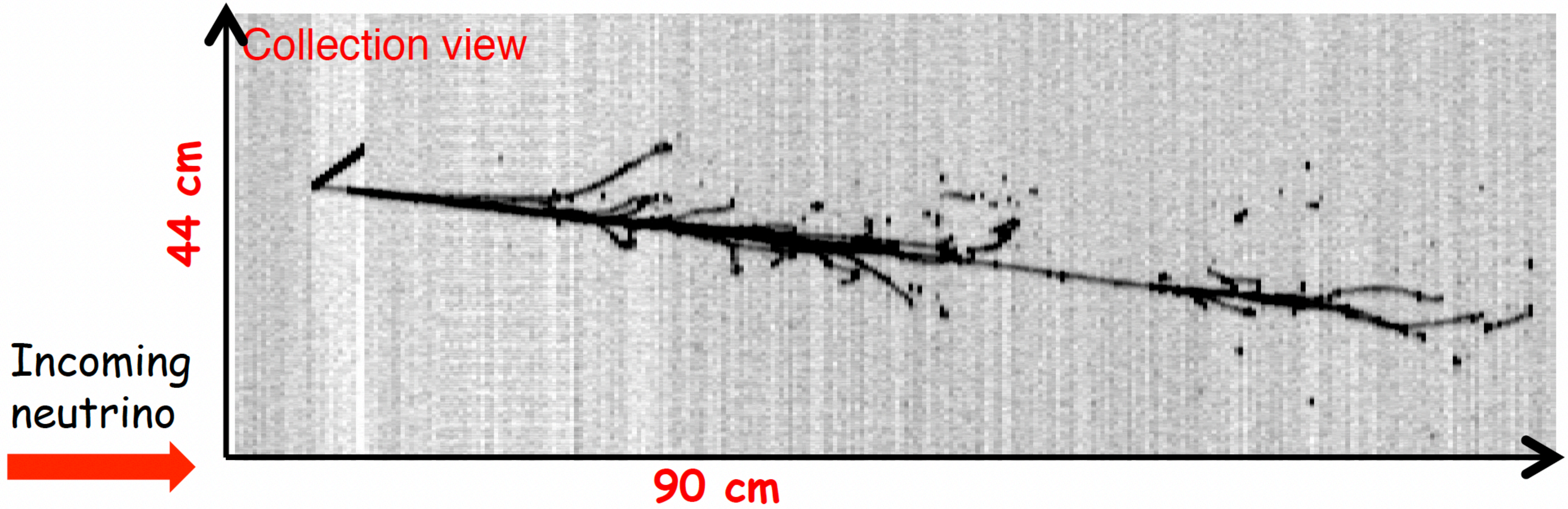


C. Rubbia, 2019

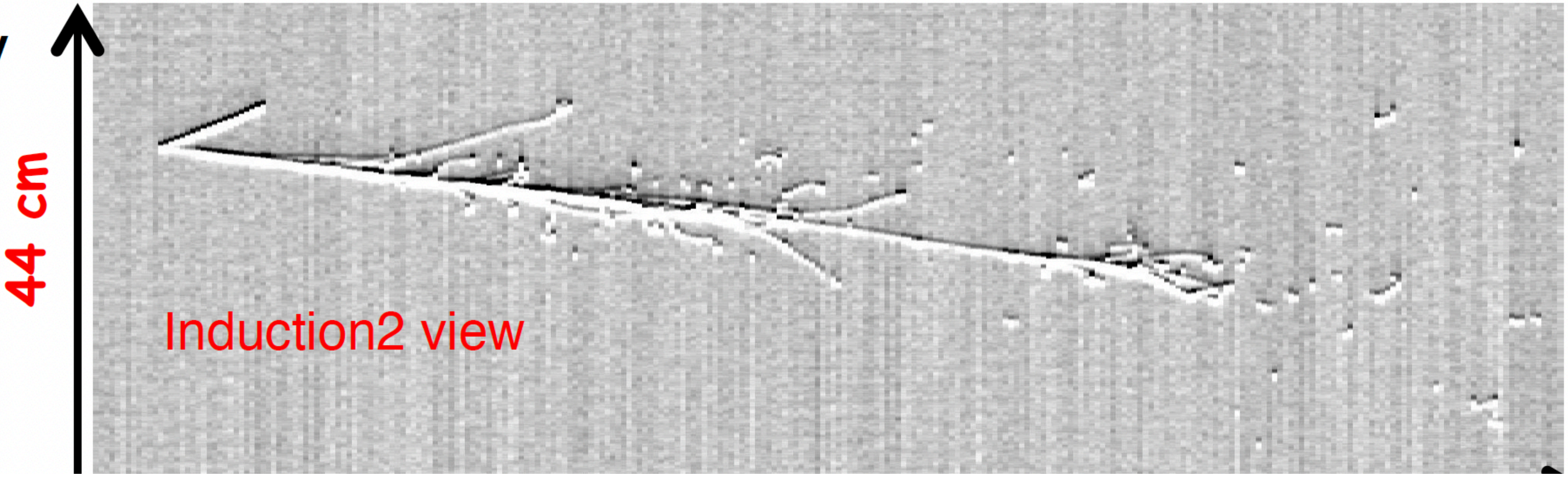
MC event Run 5 SubRun 44 Event 64

- A clear q.e. νe event: p + e.

Eν = 1.34 GeV Edep = 1.29 GeV



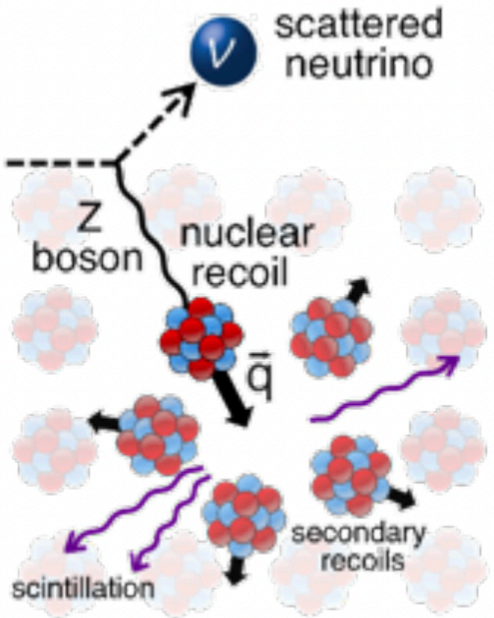
E_e = 1.21GeV
T_p = 93 MeV
R_p = 7cm
T_p/R_p = 13.2 MeV/cm

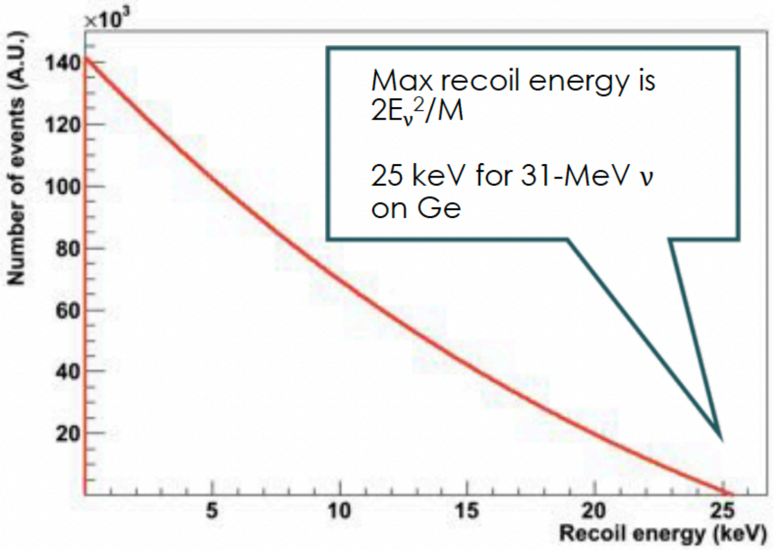


C. Rubbia, 2019

Coherent elastic neutrino-nucleus scattering (CEvNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to E_ν~ 50 MeV





Max recoil energy is $2E_\nu^2/M$

25 keV for 31-MeV ν on Ge

CEvNS cross section is well calculable in the Standard Model

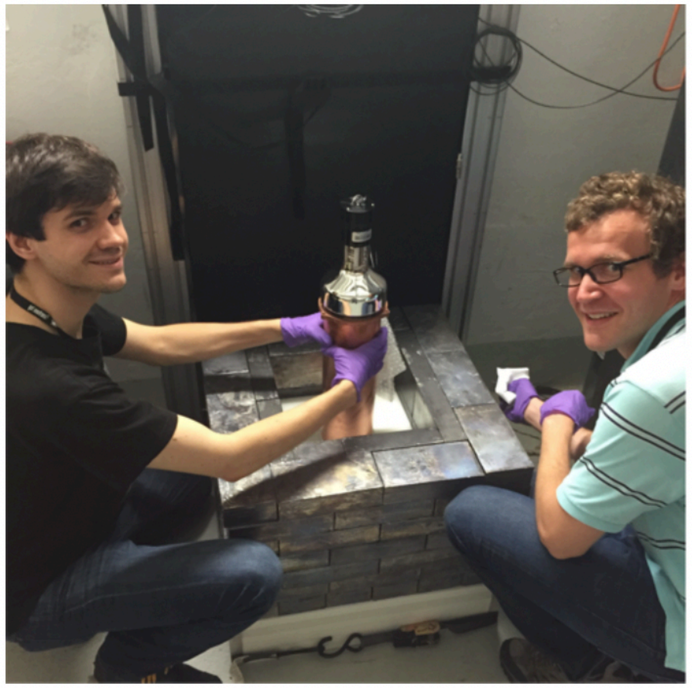
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

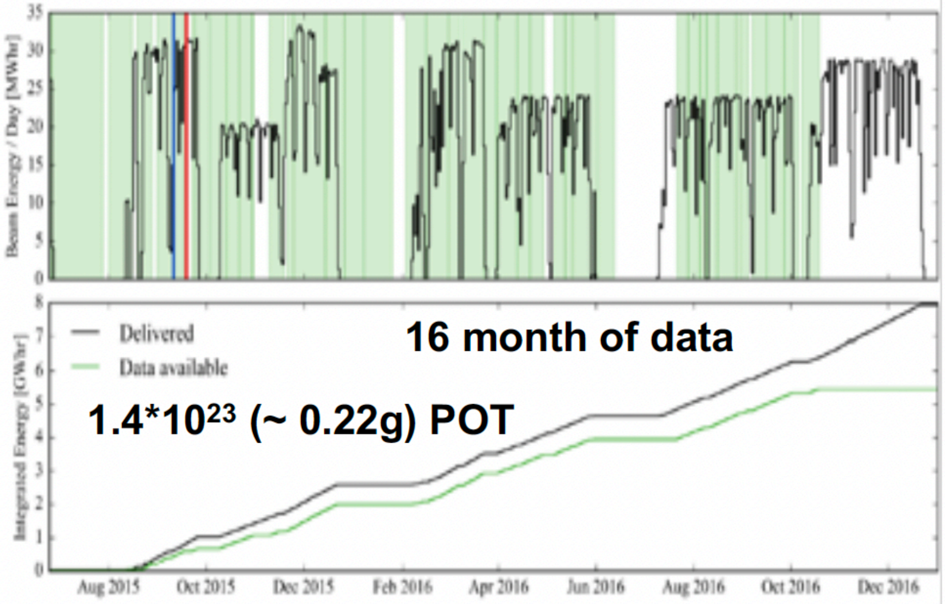
CEvNS cross section is large! $\boxed{\propto N^2}$

- Predicted in 1974 by D. Freedman
- Interesting test of the standard model
  - Sensitive to **non-standard interactions**
  - Largest cross section in **supernovae** dynamics
  - Background for future **dark matter** experiments
  - Sensitive to nuclear physics, **neutron skin** (neutron star radius)
- "act of hubris" - D. Freedman
  - Need a low threshold detector
  - Need an intense neutrino source

J. Newby, Neutrino 2020

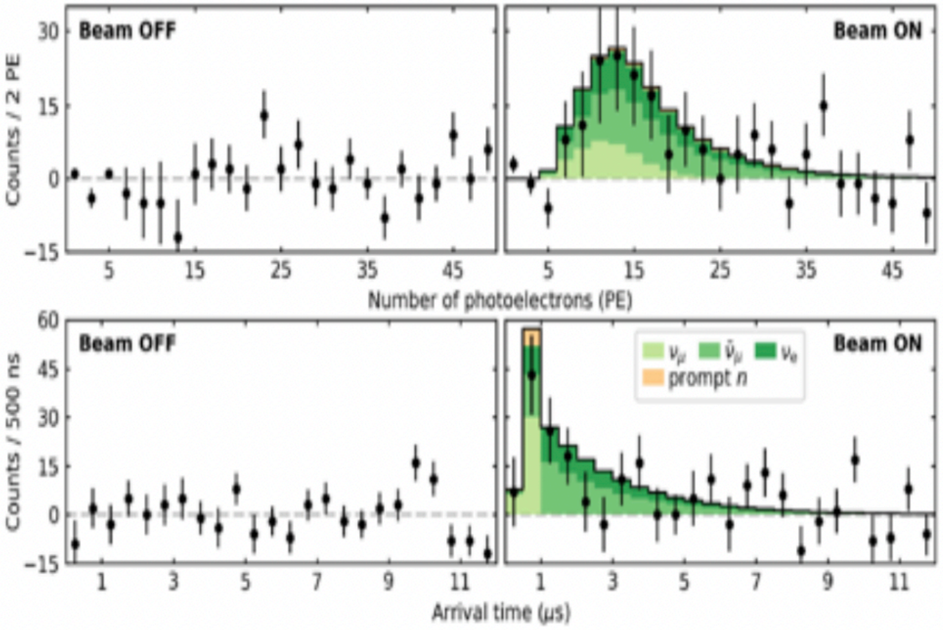
First Detection of CEvNS with CsI detector





16 month of data

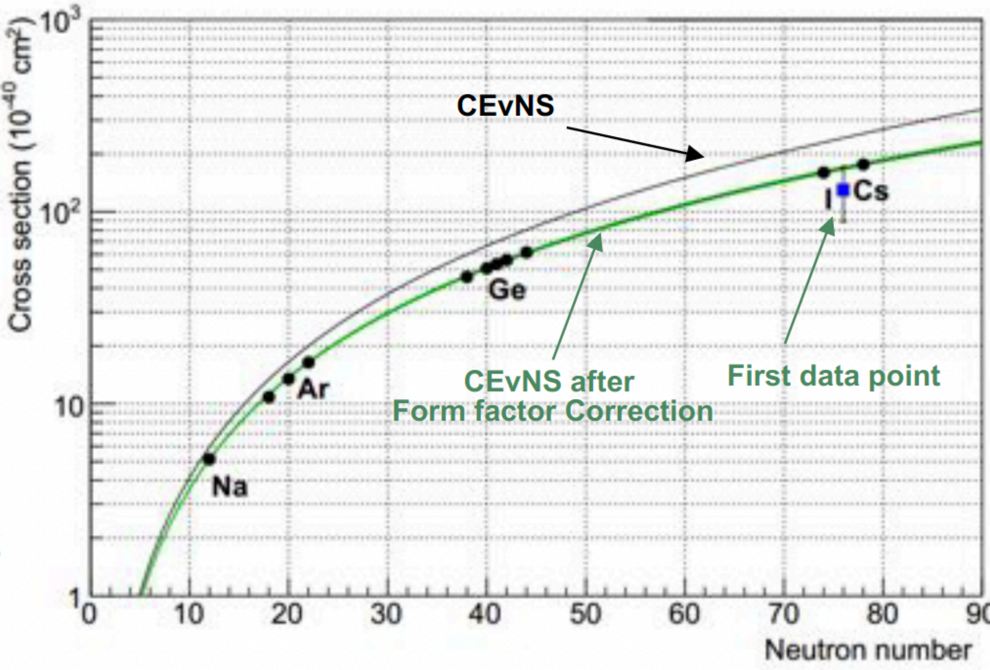
$1.4*10^{23}$ (~ 0.22g) POT



First working, hand held neutrino detector -14kg!!!

After 40 years, all the pieces have finally come together

✓ Intense Neutrino Source
✓ Sensitive Detectors
✓ Mitigation of Backgrounds



CEvNS after Form factor Correction

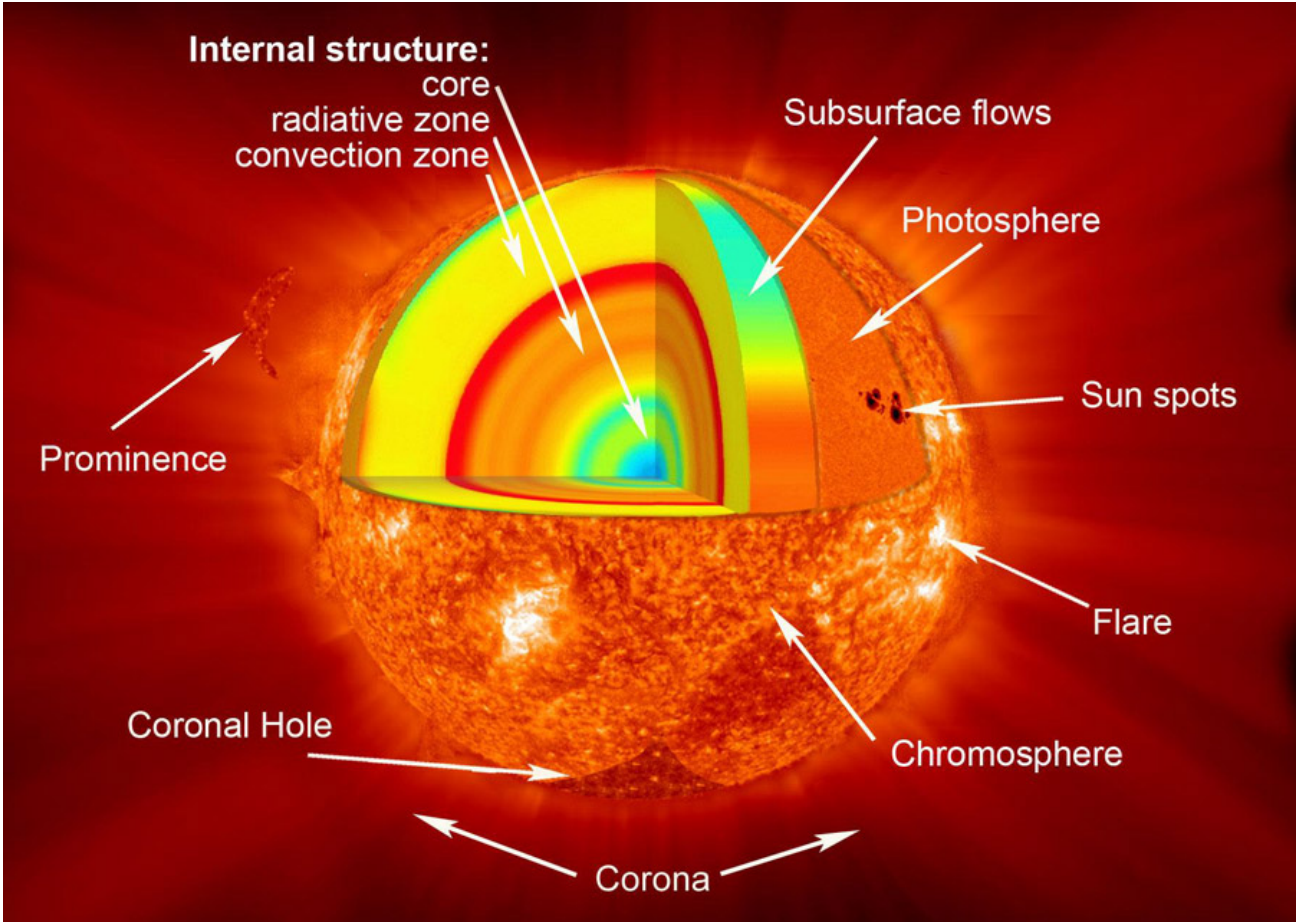
First data point

Neutrino 2020 Virtual Meeting

J. Newby

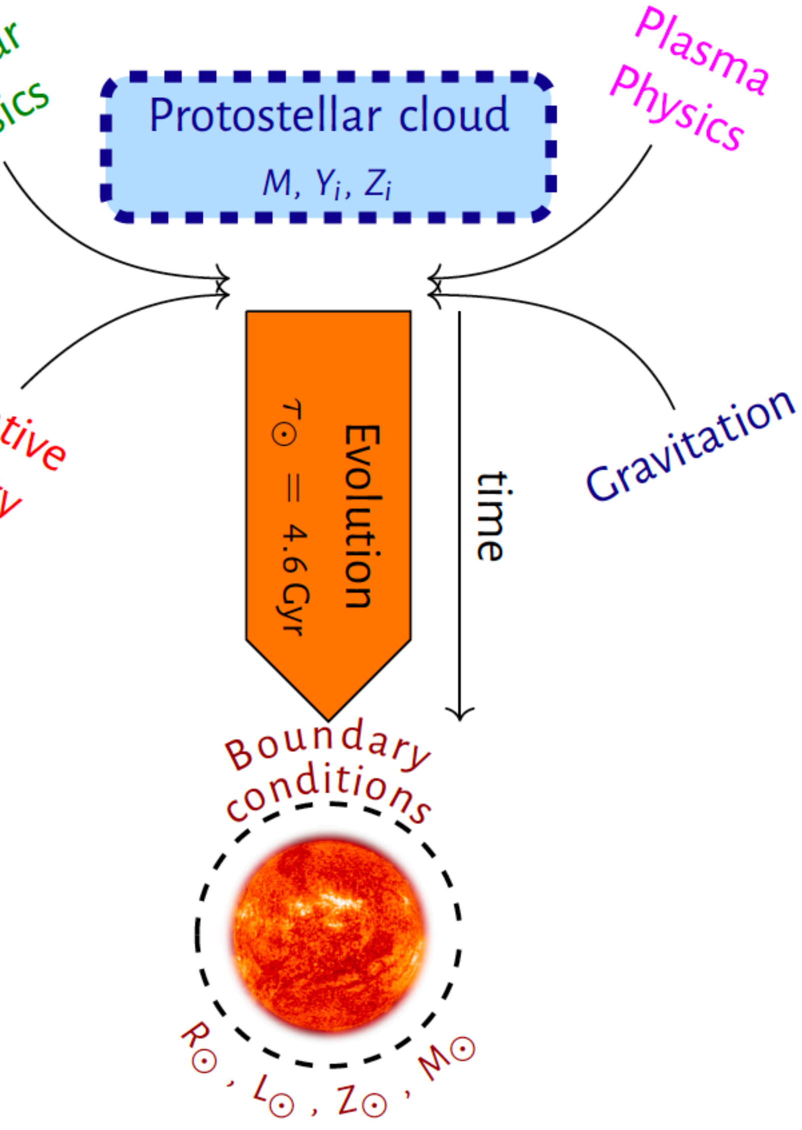
J. Newby, Neutrino 2020

The structure of the Sun

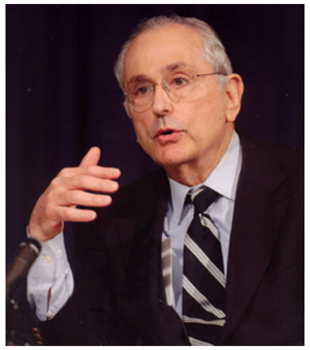


The Standard Solar Model

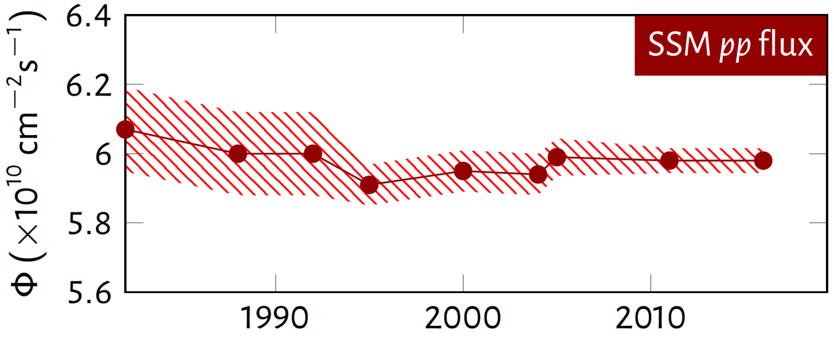
- **The observable is the Sun we see now,** which depends on a **complex evolution process**
  - Gravity
  - **Composition**: X (hydrogen), Y (helium), , Z ("metals")
  - Radiative **opacity** and plasma physics
  - Temperature and density profiles
  - Energy transport: radiative until 0.71 $R_\odot$, then convective
- Todays conditions act as boundary conditions
  - Two crucial **observables:**
    - Elio-seismology
    - **Solar neutrinos**

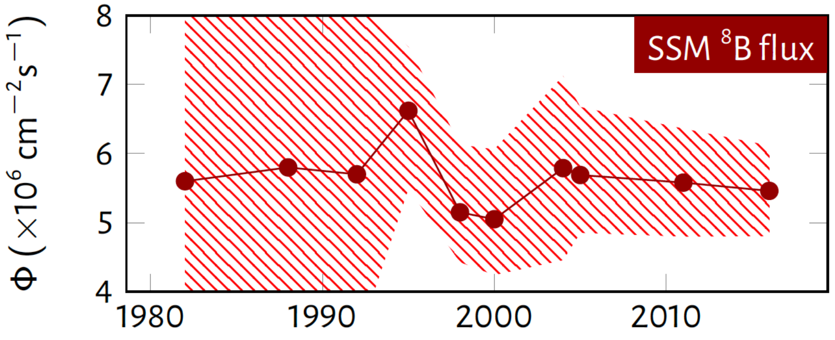


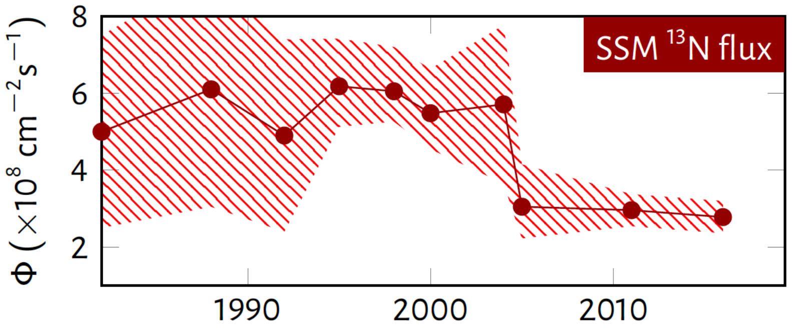
John Bahcall
[1934-2005]



- The model as well has evolved (better cross sections, opacity and diffusion models)







Solar neutrinos from hydrogen burning

A.S. Eddington Observatory 43 (1920), Nature (1920)

Bethe & Critchfield 1938

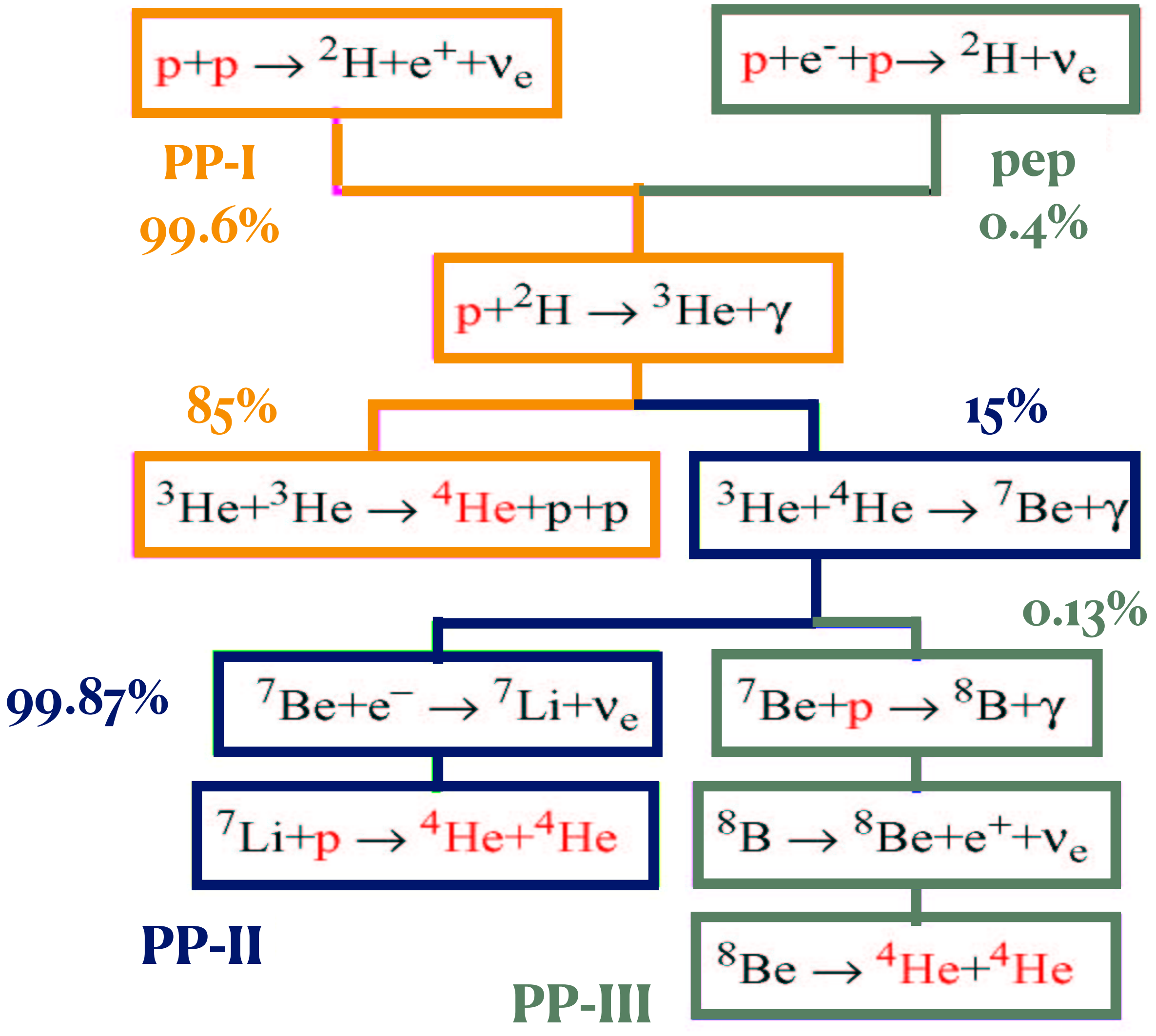
pp chain

(99% energy)

CNO cycle

(~ 1% energy)

Weizsäcker (1937, 1938), Bethe (1939)



$p+p \rightarrow {}^2H+e^++\nu_e$

$p+e^-+p \rightarrow {}^2H+\nu_e$

PP-I

99.6%

pep

0.4%

$p+{}^2H \rightarrow {}^3He+\gamma$

85%

15%

${}^3He+{}^3He \rightarrow {}^4He+p+p$

${}^3He+{}^4He \rightarrow {}^7Be+\gamma$

0.13%

99.87%

${}^7Be+e^- \rightarrow {}^7Li+\nu_e$

${}^7Be+p \rightarrow {}^8B+\gamma$

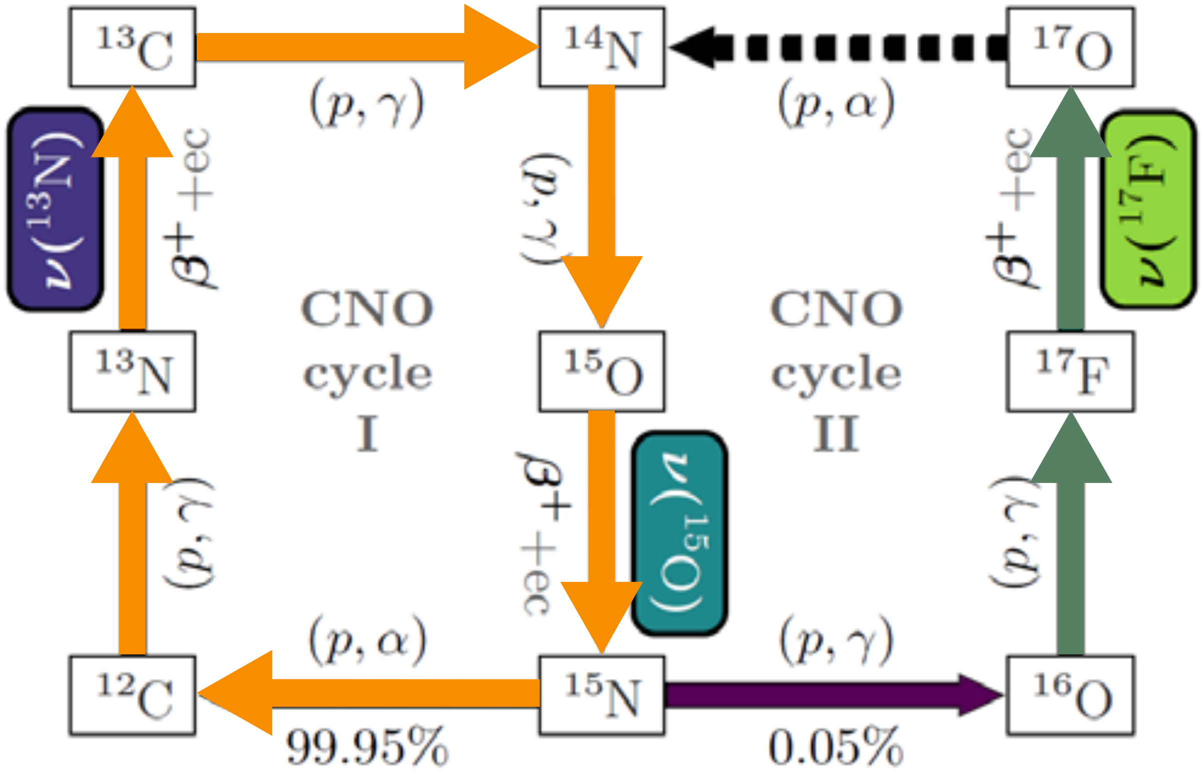
${}^7Li+p \rightarrow {}^4He+{}^4He$

${}^8B \rightarrow {}^8Be+e^++\nu_e$

PP-II

PP-III

${}^8Be \rightarrow {}^4He+{}^4He$



^{12}C is the main catalyst

CNO-II is suppressed in the Sun

REACTION

$$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$$

ENERGY YIELD

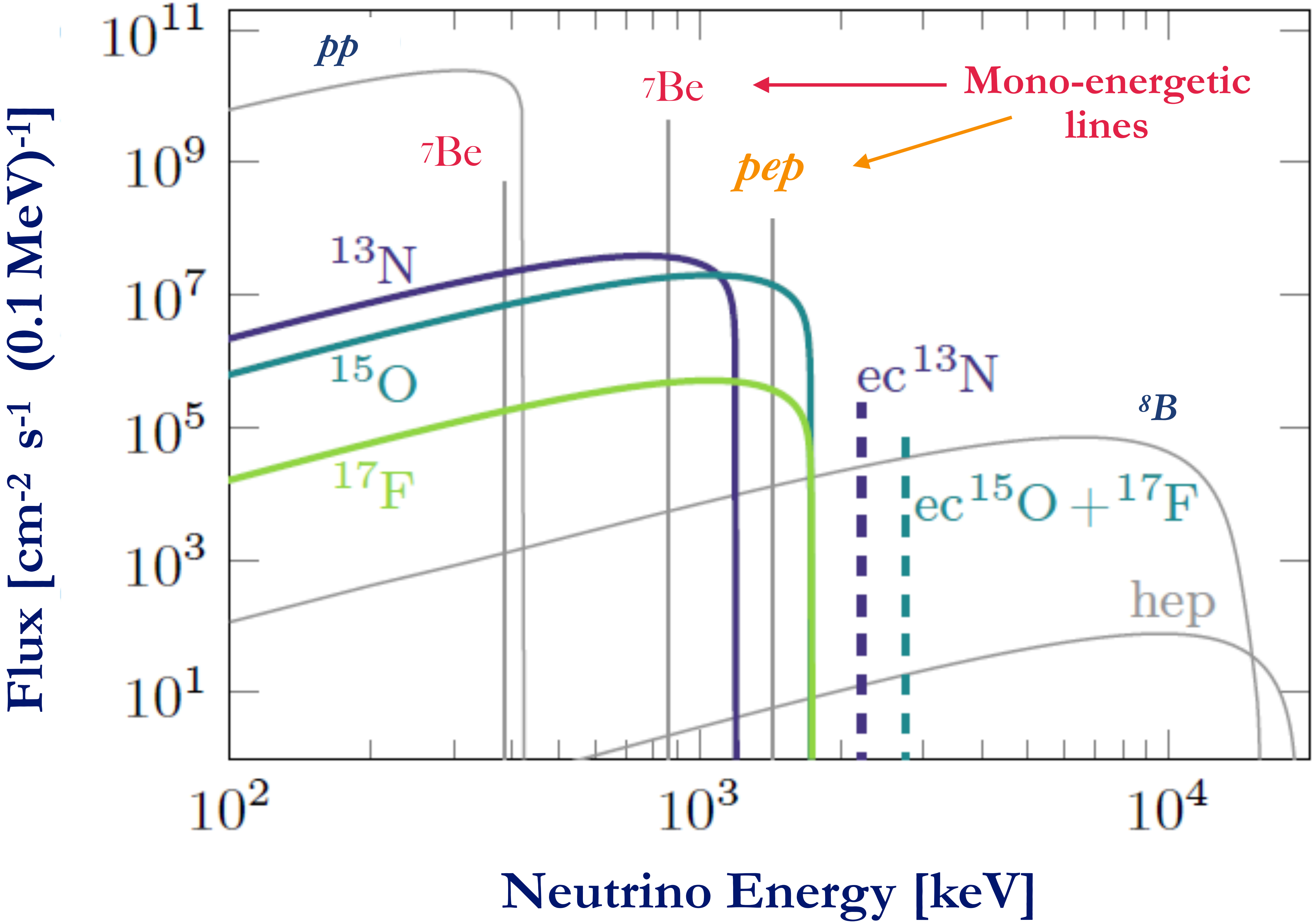
$$24.7\ MeV + 2m_ec^2$$

2% of E in NEUTRINOS

$$< E_\nu > = 0.53\ MeV$$

Neutrino spectrum from the SSM

$L_\odot = 3.846 \pm 0.015 \; 10^{26}$ W



N. Vinyoles et al., The Astrophysical Journal (2017), 835:202 Feb. 1st. doi:10.3847/1538-4357/835/2/202

History: counting an atom a day at Homestake

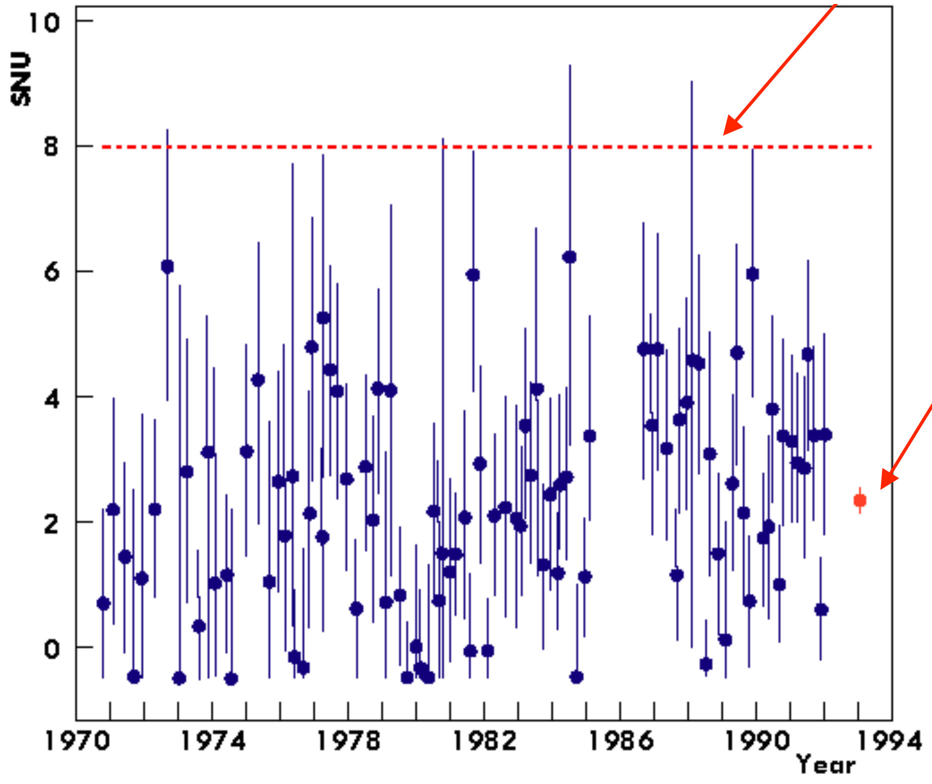
- Extract a single atom out of ~ 10^{31}

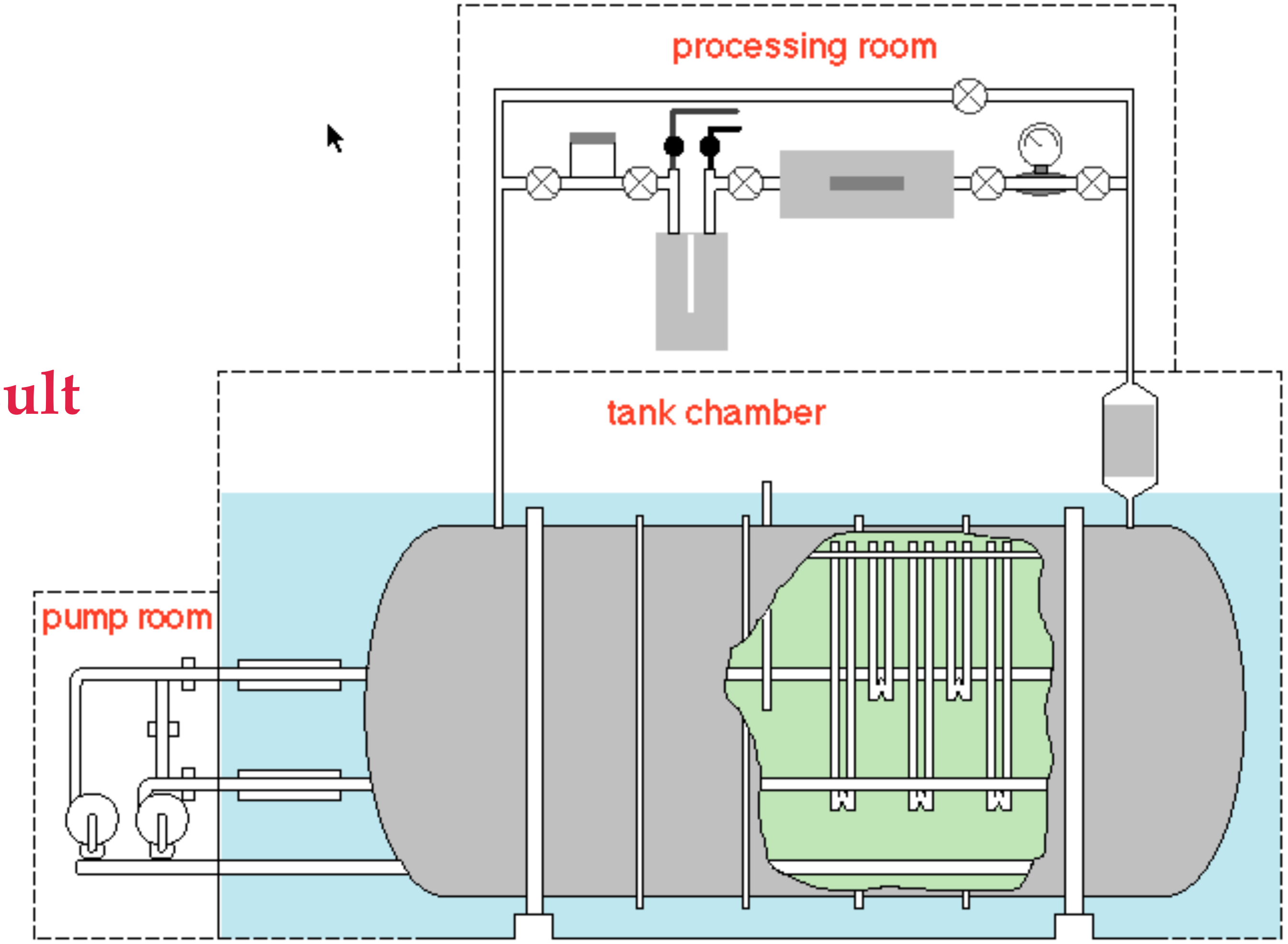
$$\nu_e + {}^{37}Cl \dashrightarrow {}^{37}Ar + e^-$$

  - Target: **614 t of liquid soap**
  - ^{37}Ar atoms extraction with charcoal filters (every ~ months)
  - Very low background proportional counters to count **^{37}Ar** atoms (which decays by **e^- capture** with $\tau_{1/2}$ **~ 35 d**)

Solar model

Final result



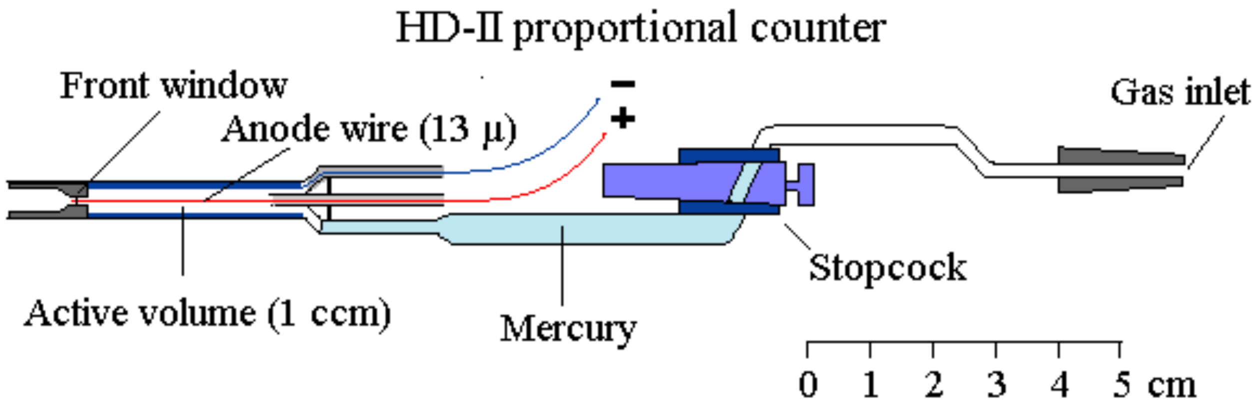


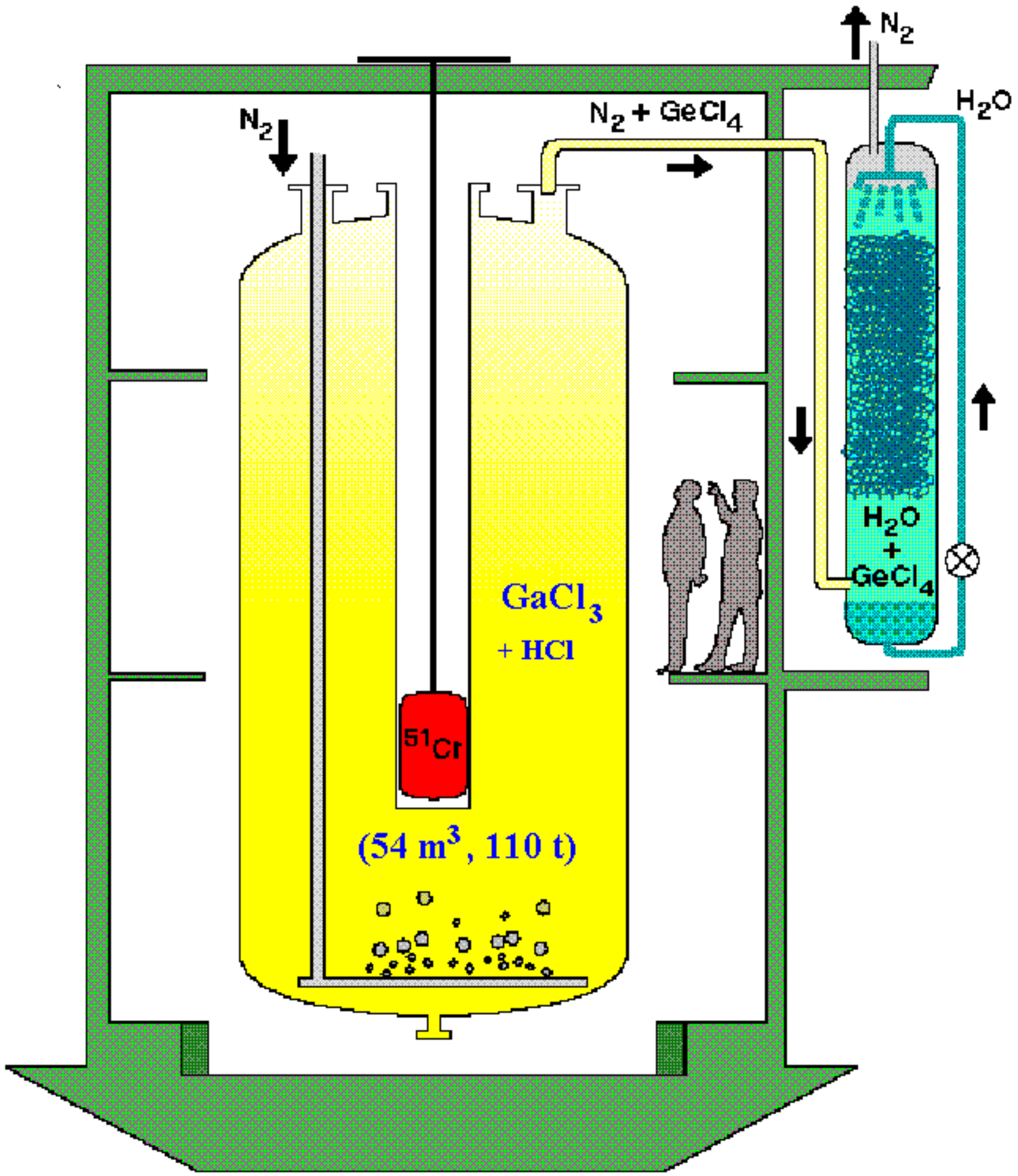
History: Gallex/GNO @ LNGS

- **A key radio-chemical experiment** for solar neutrino physics
  - **The first sensitive to all solar neutrino components** (through an **integrated,** energy-weighted spectrum)
  - 30.3 ton of Ga in $GaCl_3 -$ HCl solution.

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

  - **Threshold: 233 keV**
  - Extraction every ~ 3 weeks
  - The volatile $GeCl_4$ is extracted using N_2 flow and then inserted into proportional counters [^{71}Ge **e^- capture $\tau_{1/2}$ ~ 11.43 d**]

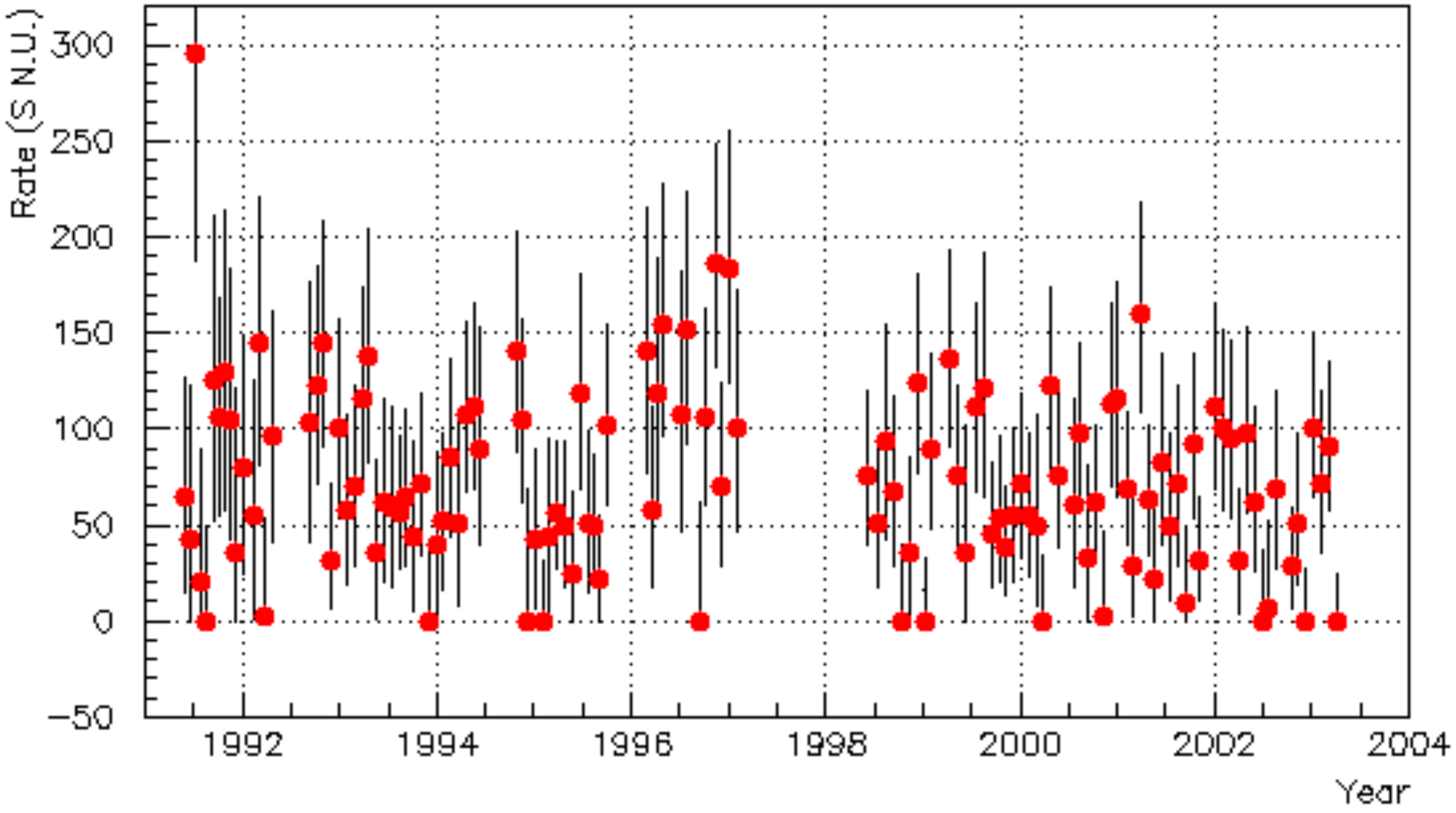




Gallex/GNO results [1990-2004]

- Extraction efficiency checked with:
  - 1.6 MCi (!) ν_e source [based on ^{51}Cr e-capture decay, obtained from irradiated ^{50}Cr in reactor]
    - Initial ν_e flux 5 times the Sun
    - ε=95±3 %
    - Mono-chromatic ν_e flux, E_ν=0.75 MeV
  - At the end only, insertion of ^{71}As
    - $^{71}As \rightarrow {}^{71}Ge + e^- + \nu_e$
    - [$\tau_{1/2}$ =2.72 d];
    - ε=100±1 %

GALLEX/GNO results



Experiment	Runs	Result
GALLEX	65	77.5 ± 6.2 (stat) ± 6.2 (sys) SNU
GNO	58	62.9 ± 5.4 (stat) ± 2.5 (sys) SNU
GALLEX+GNO	123	69.3 ± 4.1 (stat) ± 3.6 (sys) SNU

STANDARD SOLAR MODEL prediction: 129 ± 7 SNU

Neutrino detection in water/ice: Cherenkov light

In a medium with refractive index n the light speed is c/n. When a charged particle travel in the medium with a speed higher than light speed, it emits Cerenkov light. The minimum energy to emit Cerenkov light is:

Particle	Cerenkov threshold (Energy (MeV))
e	0.768
μ	158.7
π	209.7

Cerenkov light is emitted in a cone with a θ opening in the track direction:

$$cos\theta = \frac{1}{n\beta}$$

$\theta = 42^\circ$ for $\beta = 1.0$ in water.

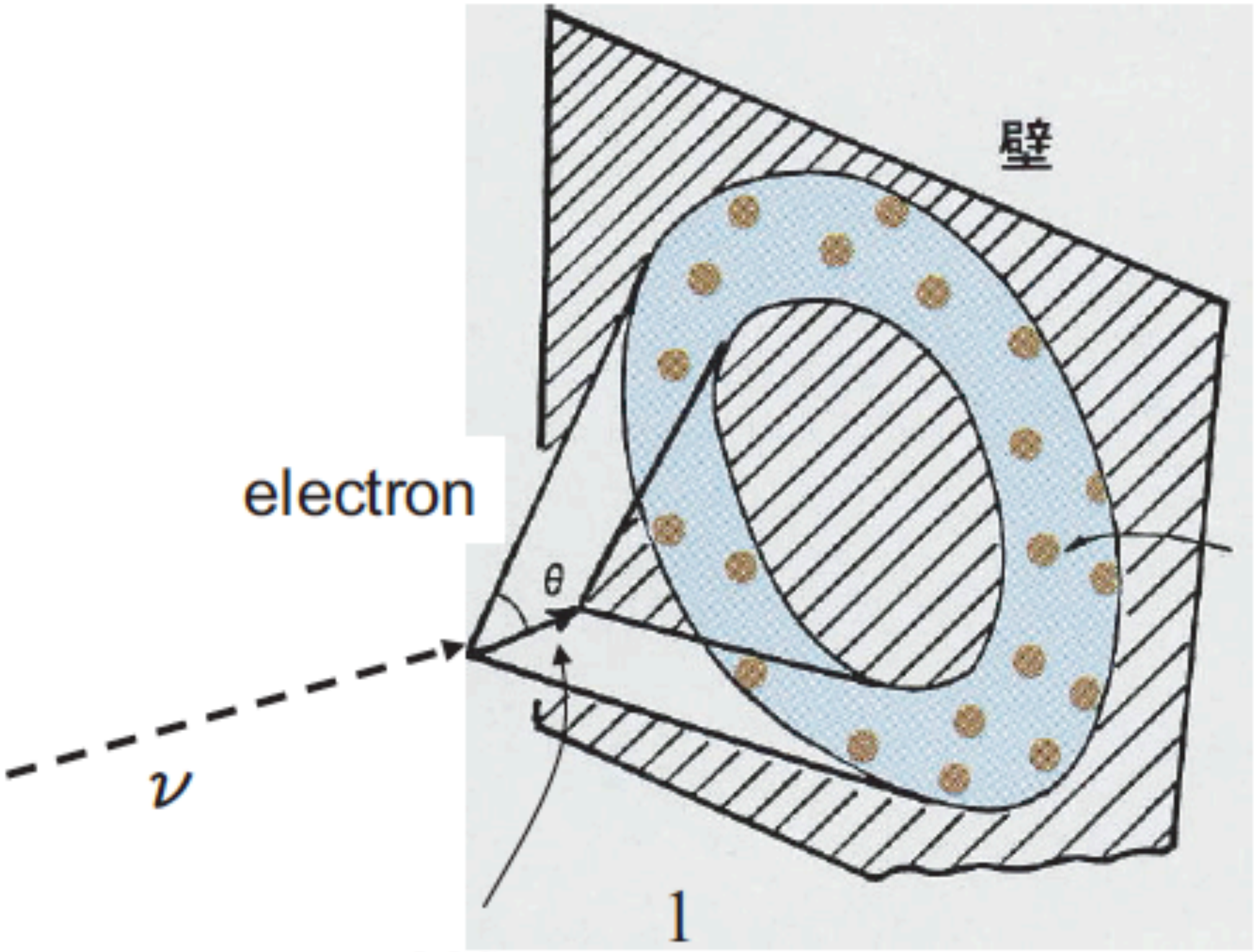
Cerenkov light spectrum as function of wavelength λ:

$$\frac{dN}{d\lambda} = \frac{2\pi\alpha l}{c}\left(1 - \frac{n^2}{beta^2}\right)\frac{1}{\lambda^2}$$

where α is the fine structure constant and l is the track length.

A charged particle emits about 390 photons for 1cm track length in water with $300\,\mathrm{nm} < \lambda < 700\mathrm{nm}$.

Detection of light in water



$$\cos \quad \frac{1}{n}$$

n (refractive index)=1.34 in water

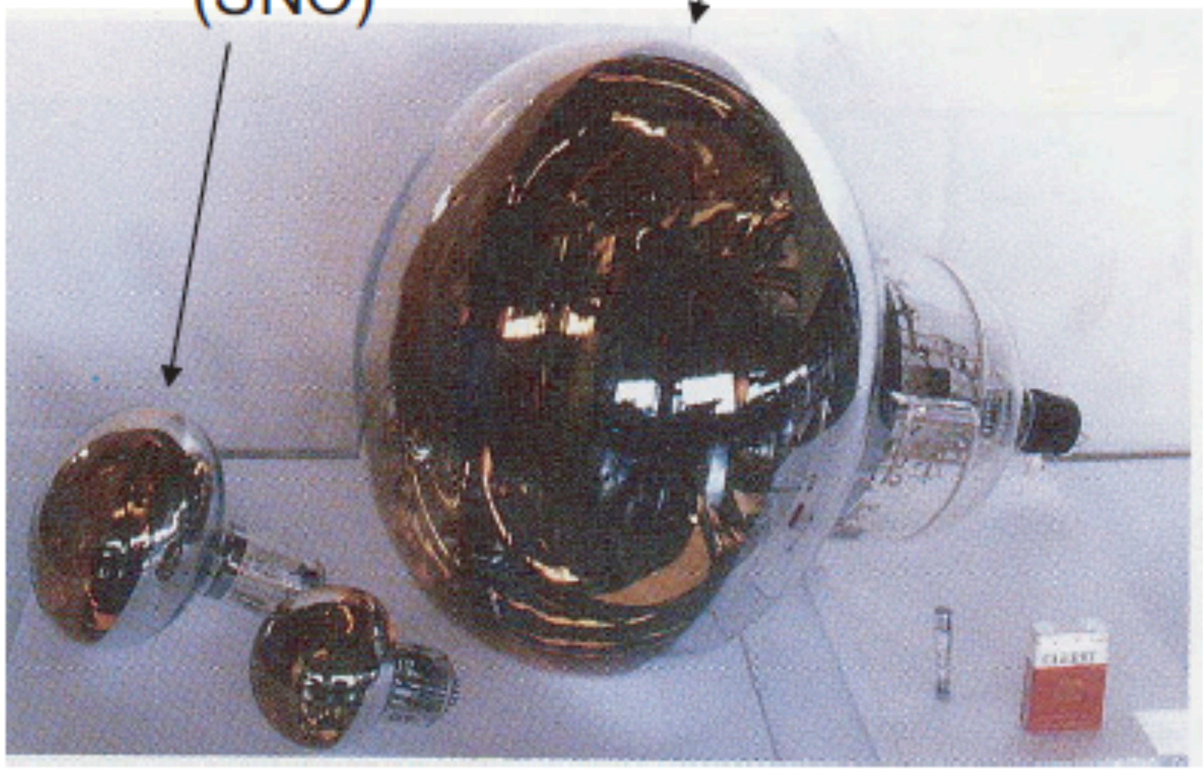
⇨ θ =42deg. for β =1

Number of Ch. photons with λ =300-600 nm emitted by a relativistic particle per cm = 340.

⇩

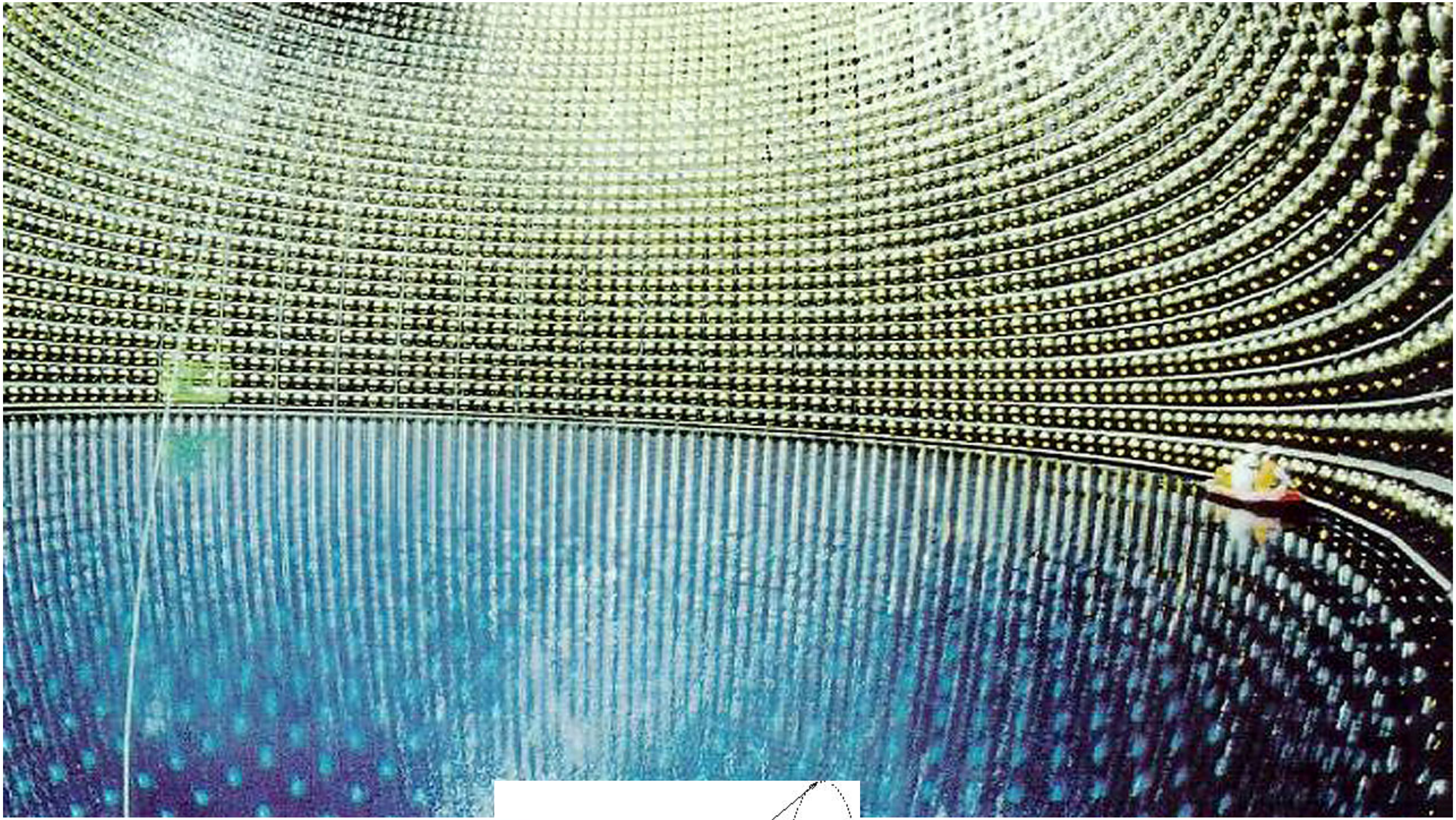
Need an efficient detection of the photons. ⇨ Large PMTs

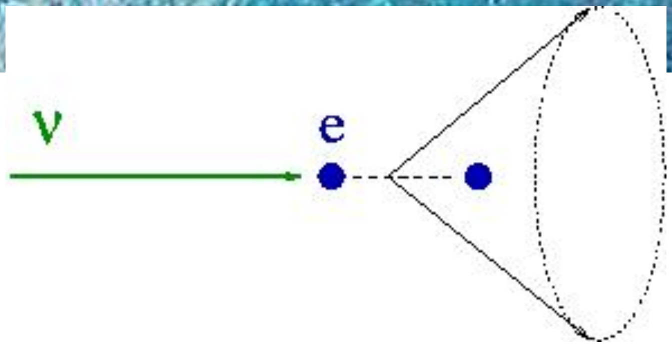
Photomultiplier tube (PMT)



T. Kajita - Nufact 05 School

SK experiment

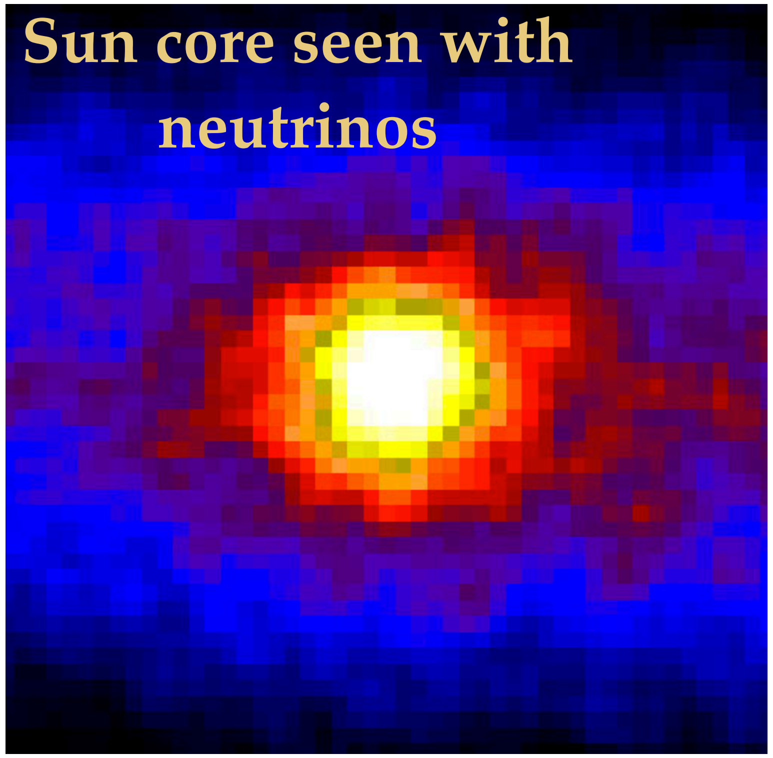


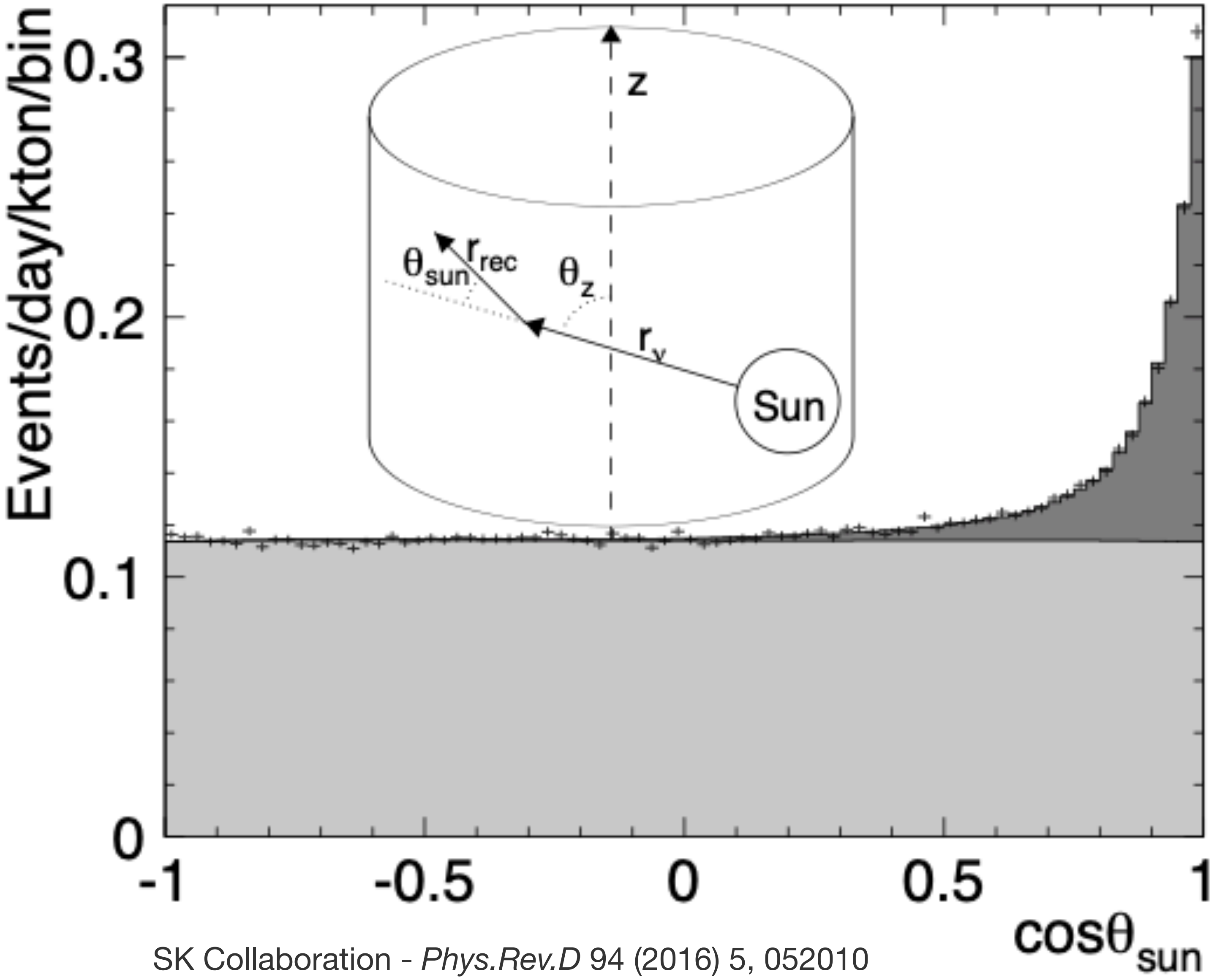


Cherenkov detector for solar, accelerator and atmospheric neutrinos

Solar neutrinos at SK

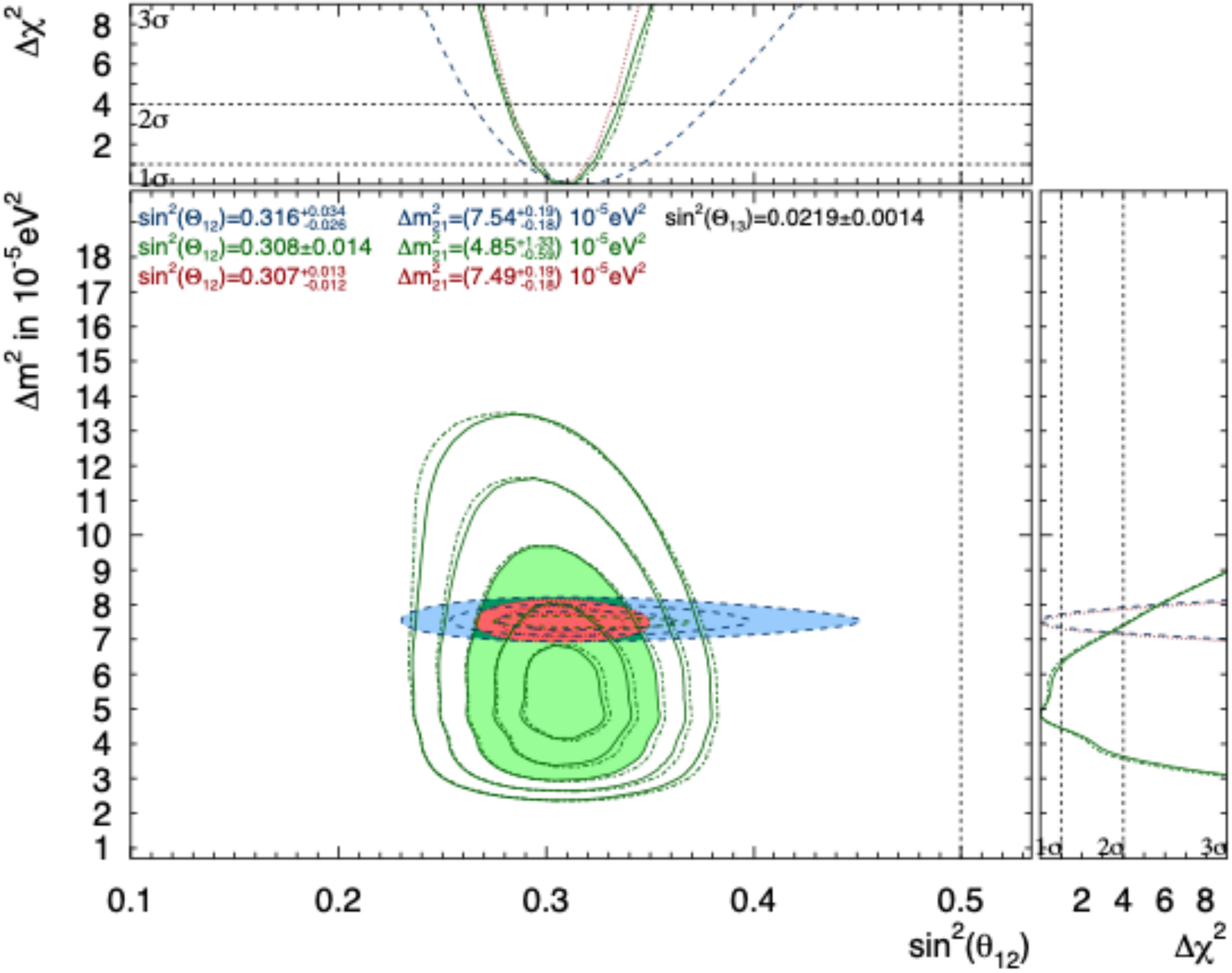
- Detection technique: elastic scattering on electrons
  - Cherenkov light gives direction of incoming neutrino
  - Threshold ~ 3.5 - 5 MeV (depending on period)





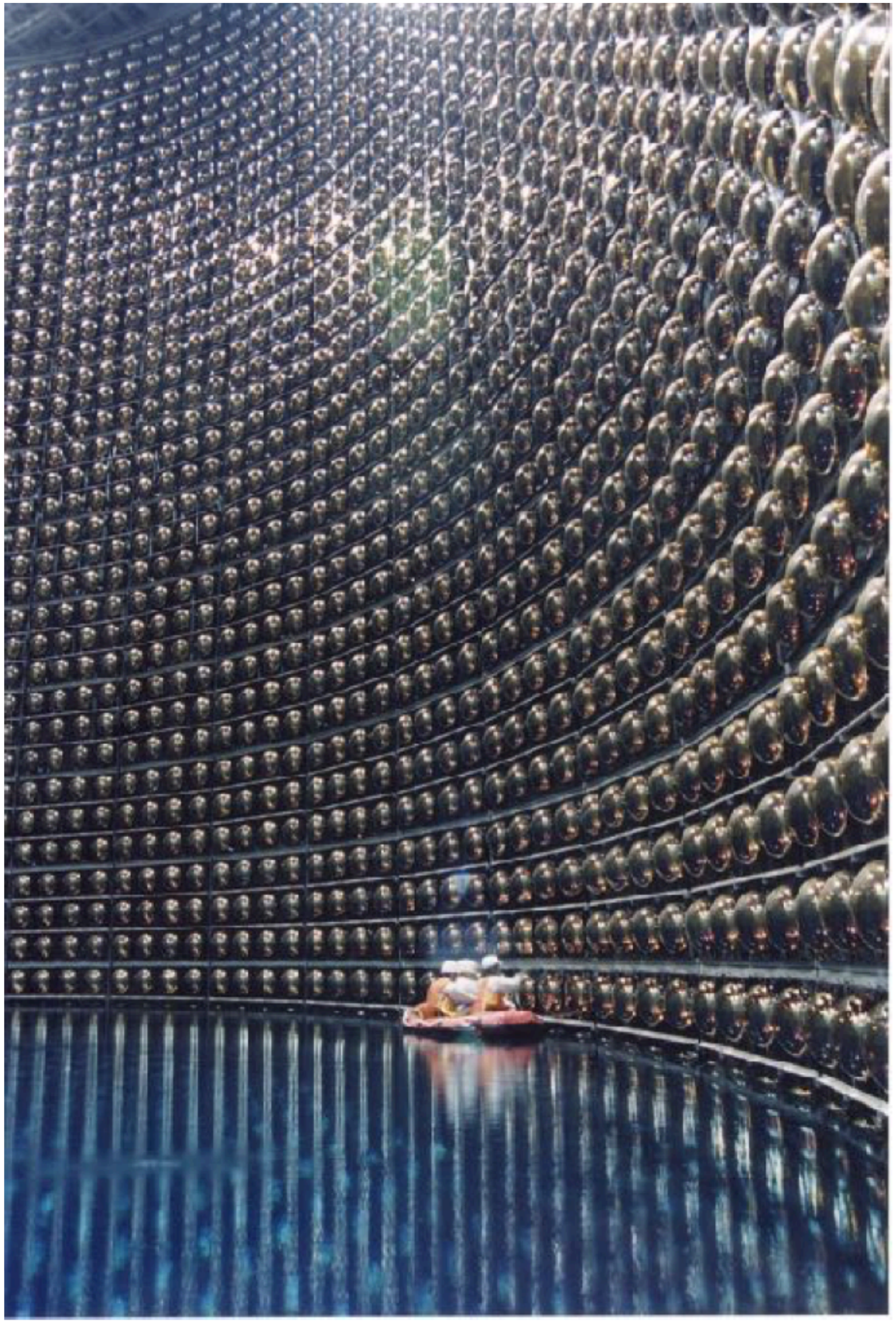
SK Collaboration - *Phys.Rev.D* 94 (2016) 5, 052010

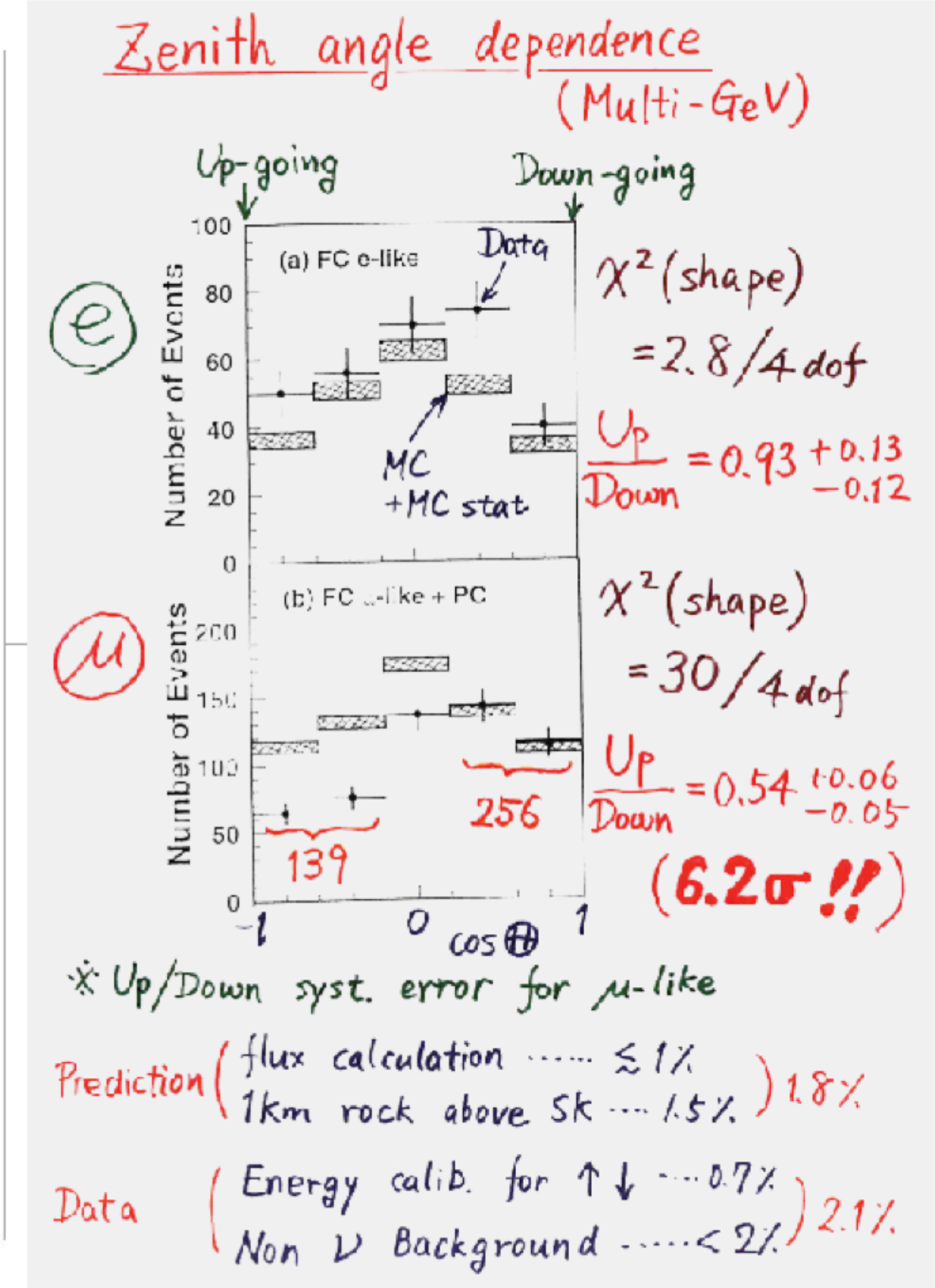
Recent solar neutrino analysis with SK+KamLAND



SK Collaboration - *Phys.Rev.D* 94 (2016) 5, 052010

Discovery of atmospheric neutrinos at SK: 1998





Zenith angle dependence

(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

χ^2(shape) $= 30/4$ dof

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

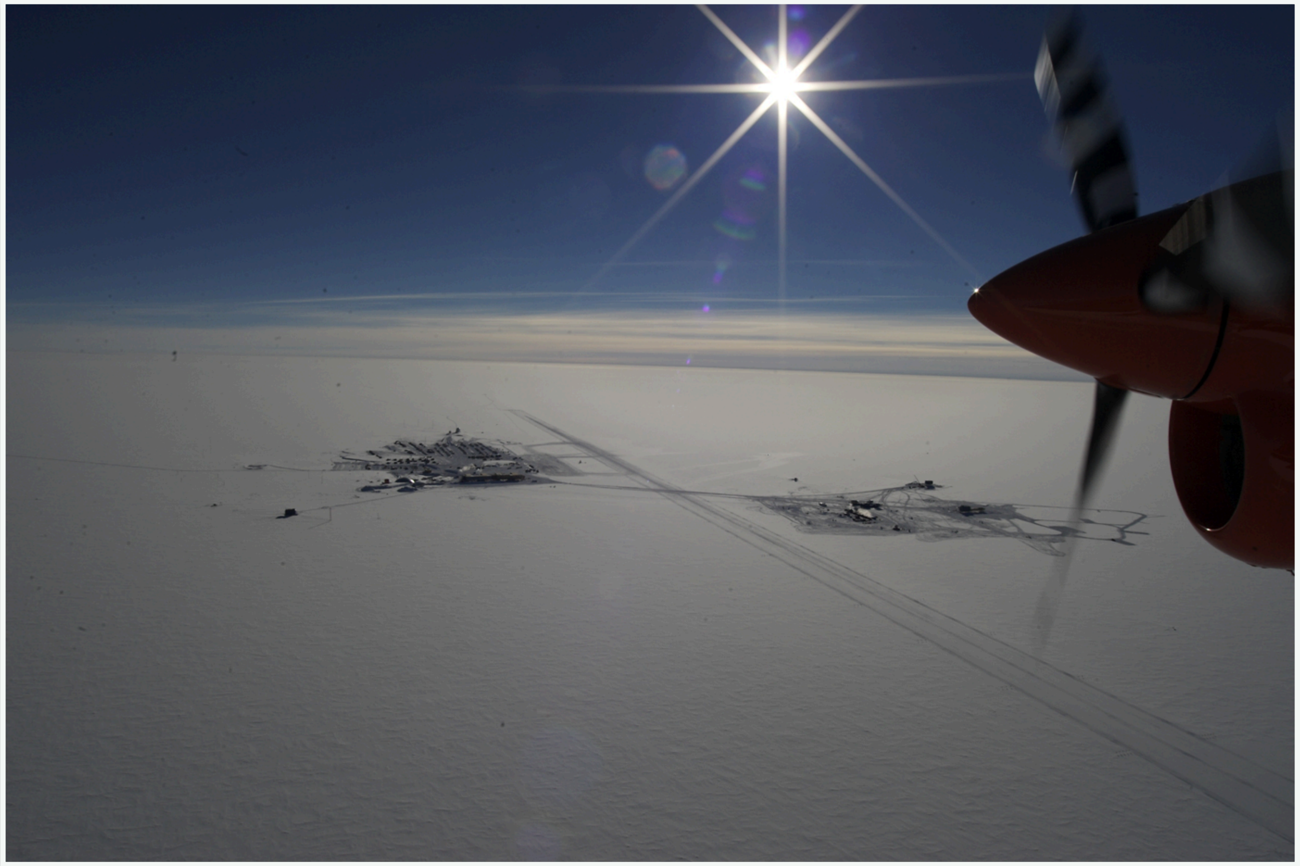
(6.2σ!!)

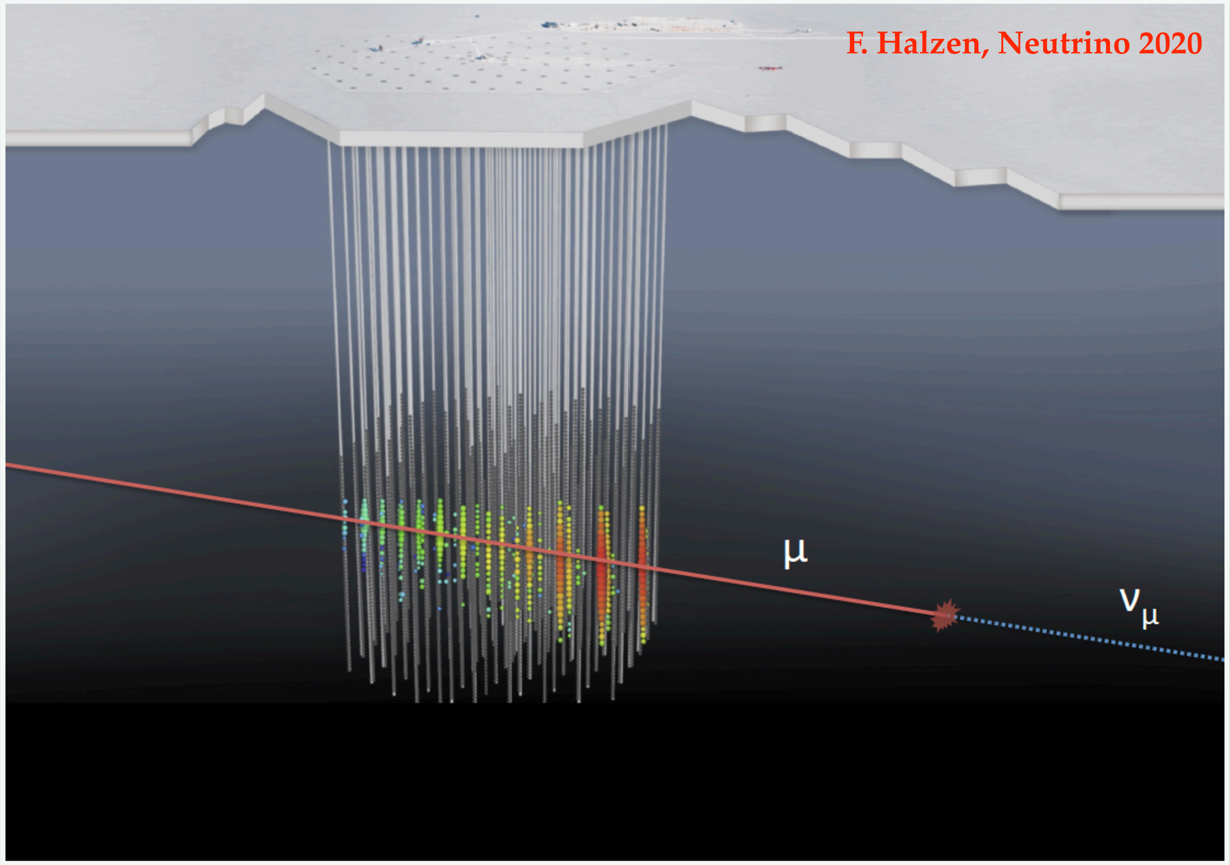
※ Up/Down syst. error for μ-like

Prediction (flux calculation ······ ≲ 1% ; 1km rock above SK ···· 1.5%) 1.8%

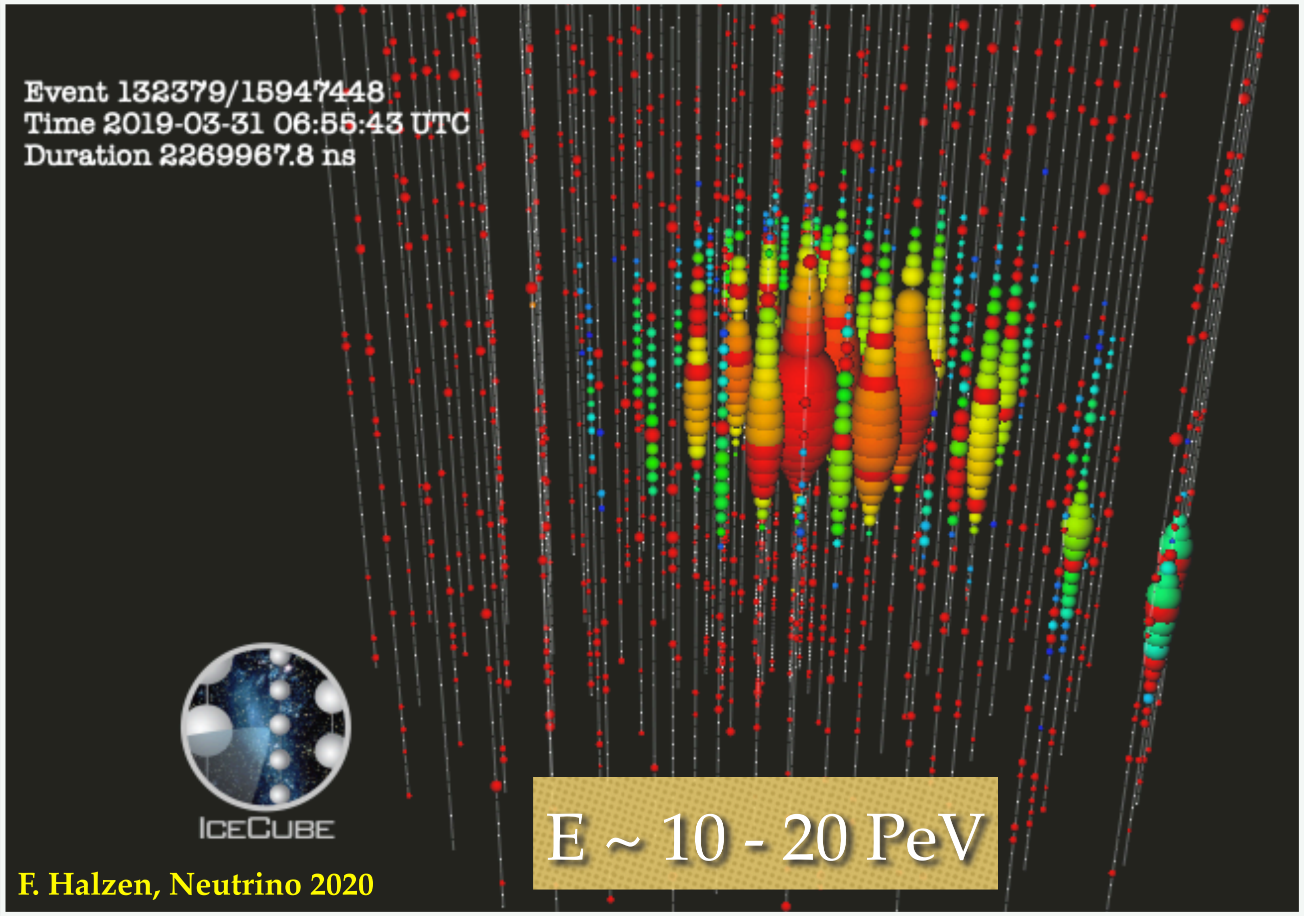
Data (Energy calib. for ↑↓ ···· 0.7% ; Non ν Background ····· < 2%) 2.1%

Intermezzo: neutrino detection in ice (Ice-Cube)



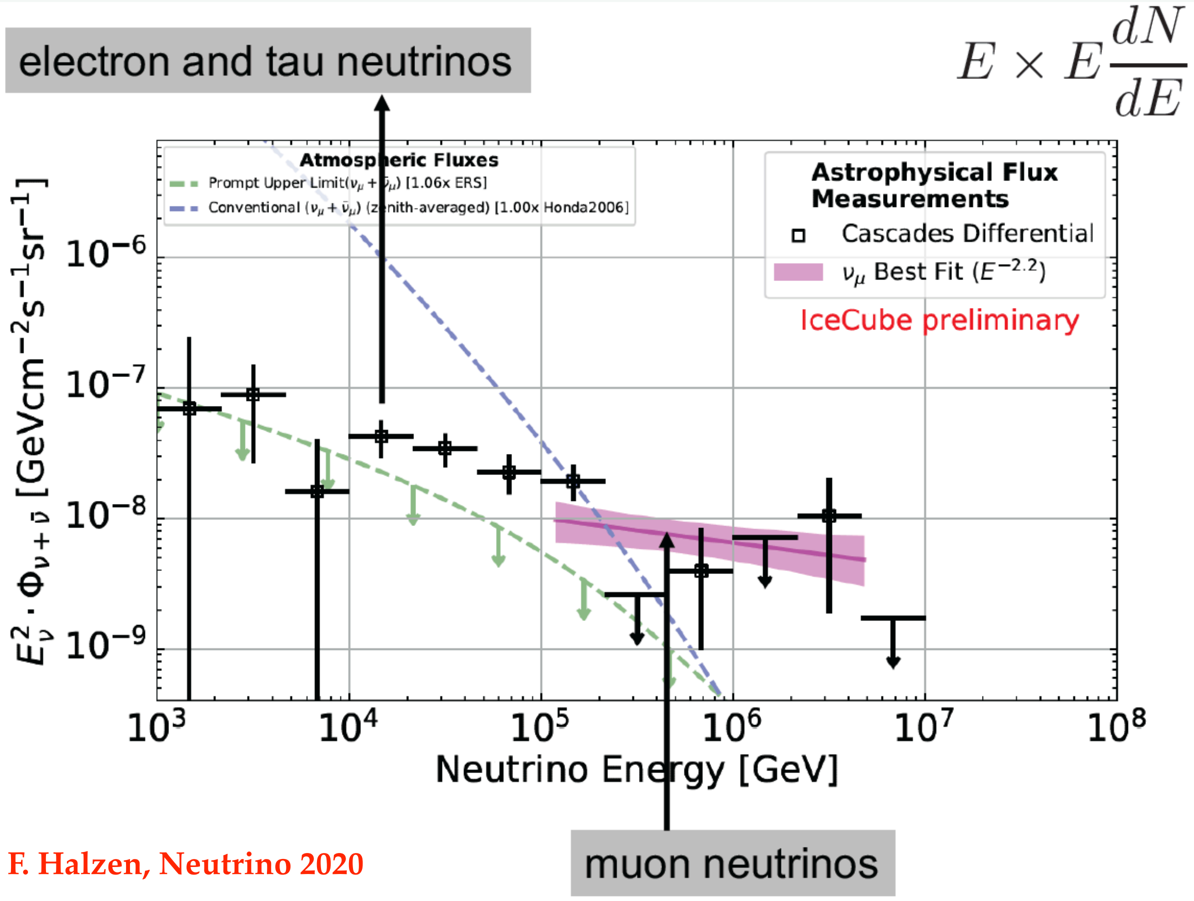


F. Halzen, Neutrino 2020



E ~ 10 - 20 PeV

F. Halzen, Neutrino 2020



F. Halzen, Neutrino 2020

Solution of Solar Neutrino Problem: SNO

- **S**udbury **N**eutrino **O**bservatory
  - Key feature: 1 kt D_2O
    - Ability to identify electron type neutrinos, and measurethe others

- Three key reactions:
  - **CC:** ν_e only

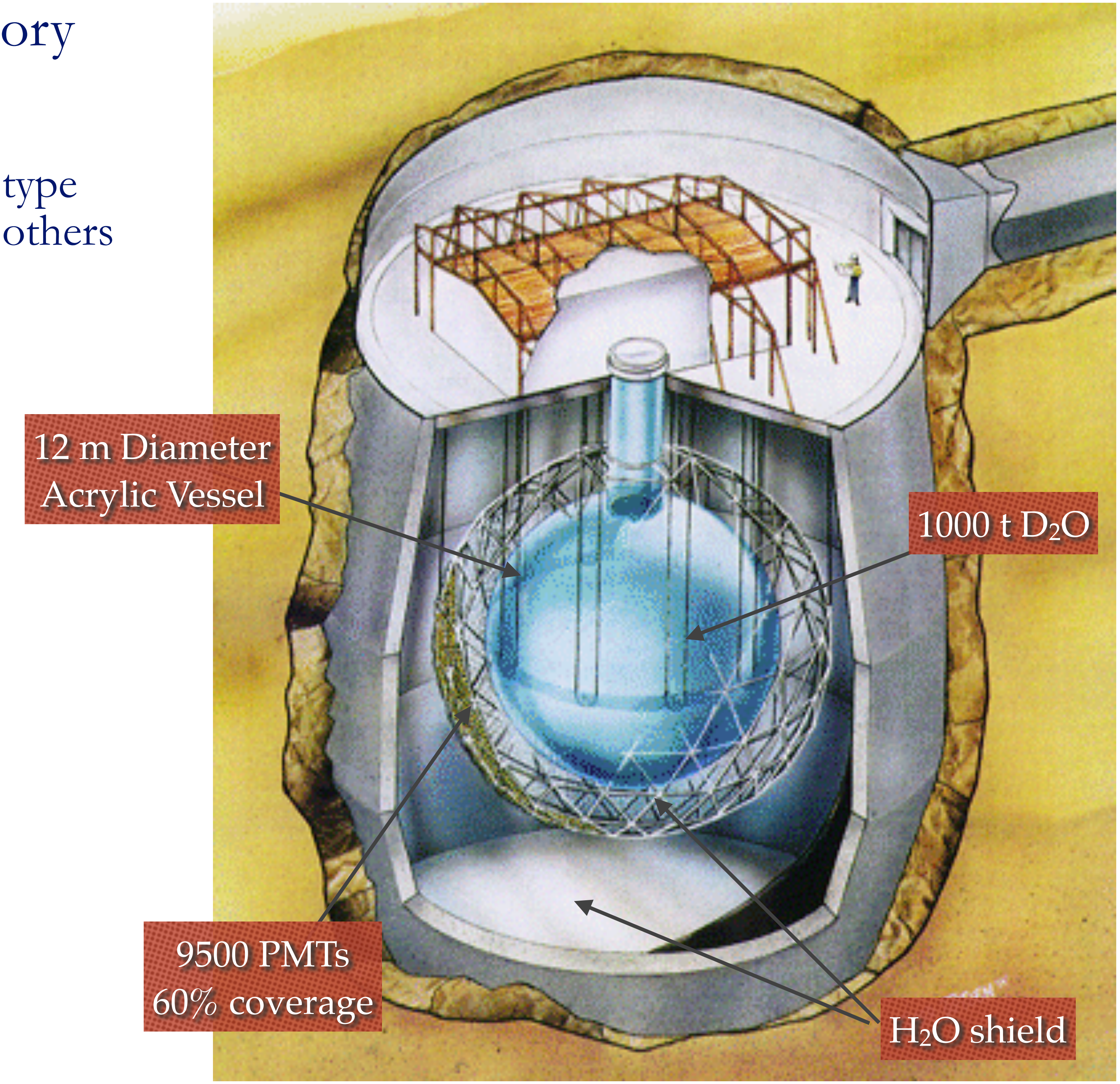
$$\nu_e + d \rightarrow p + p + e^+$$

  - **NC:** All types, equal

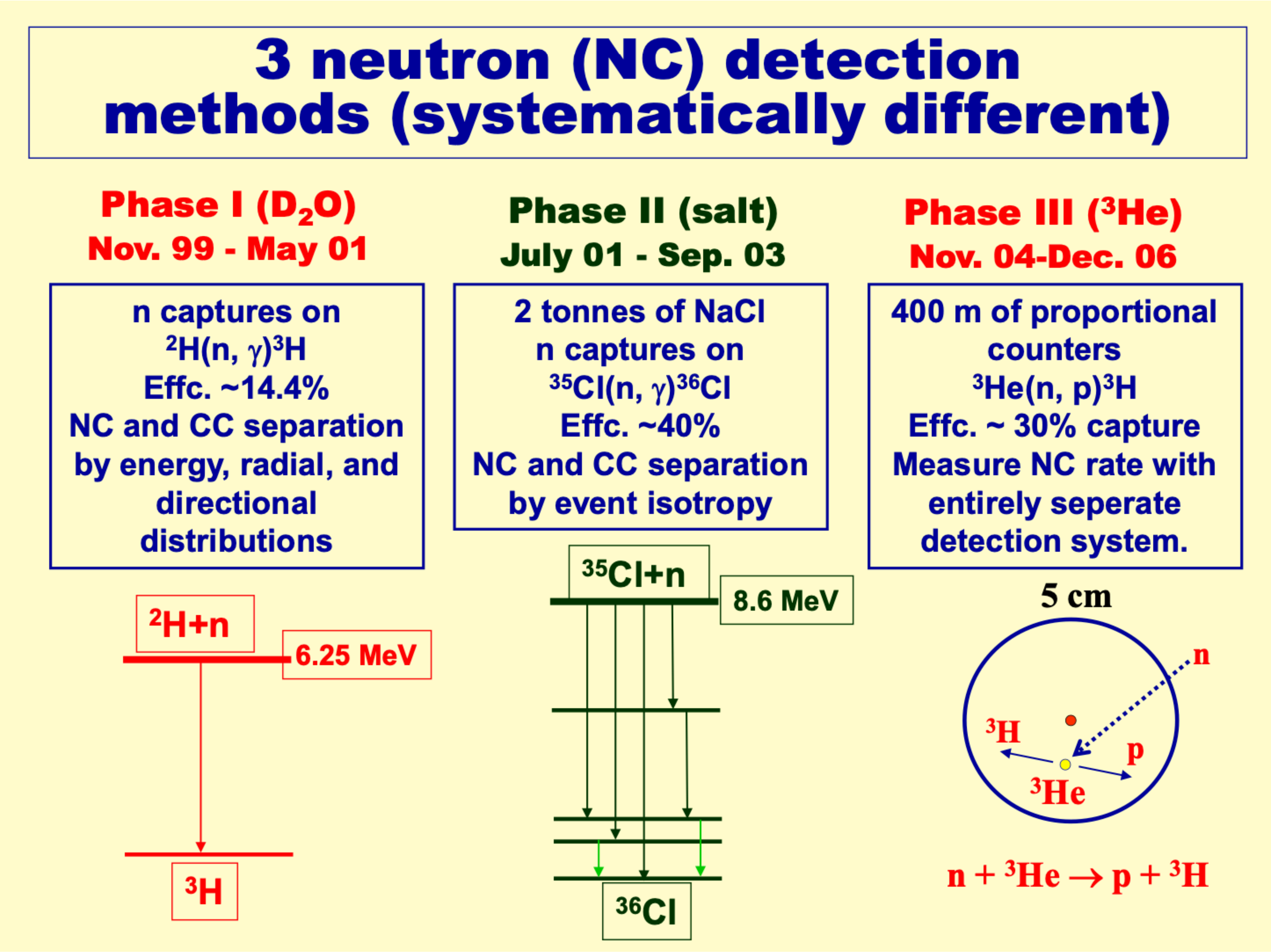
$$\nu_x + d \rightarrow \nu_x + p + n$$

  - **ES:** All types, un-equal

$$\nu_x + e^- \rightarrow \nu_x + e^-$$



SNO neutron measurements



3 neutron (NC) detection methods (systematically different)

Phase I (D_2O)
Nov. 99 - May 01

n captures on
$^2H(n, \gamma)^3H$
Effc. ~14.4%
NC and CC separation by energy, radial, and directional distributions

Phase II (salt)
July 01 - Sep. 03

2 tonnes of NaCl
n captures on
$^{35}Cl(n, \gamma)^{36}Cl$
Effc. ~40%
NC and CC separation by event isotropy

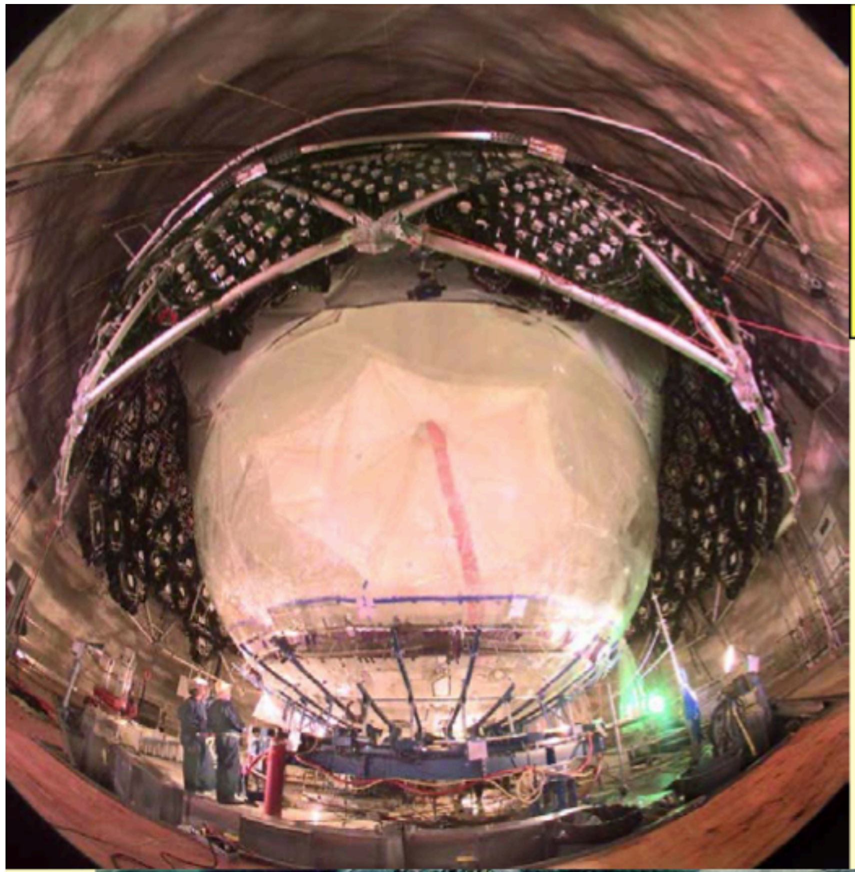
Phase III (^3He)
Nov. 04-Dec. 06

400 m of proportional counters
$^3He(n, p)^3H$
Effc. ~ 30% capture
Measure NC rate with entirely seperate detection system.

$n + {}^3He \rightarrow p + {}^3H$

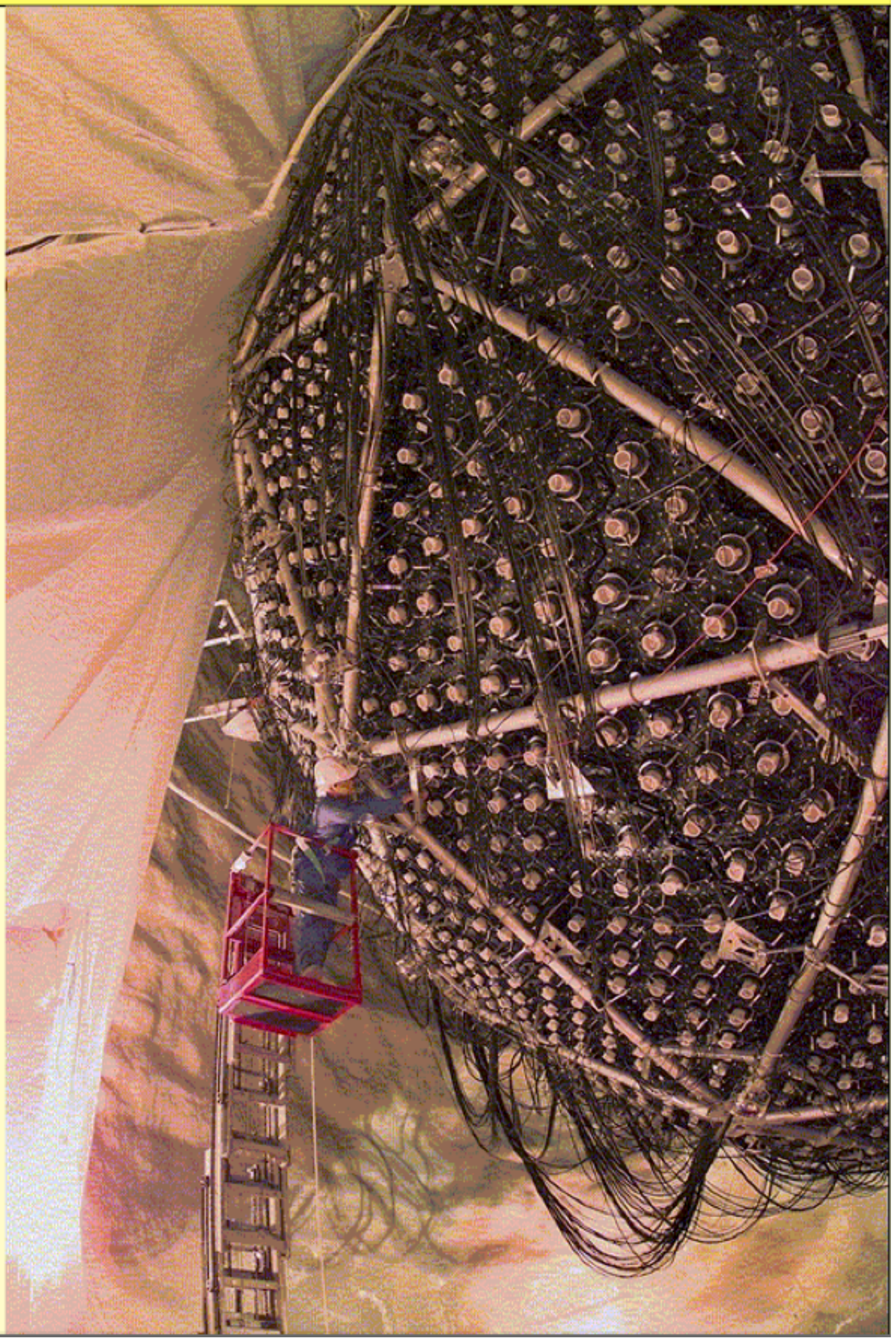
Art McDonald: Neutrino 2016

SNO picture gallery



SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

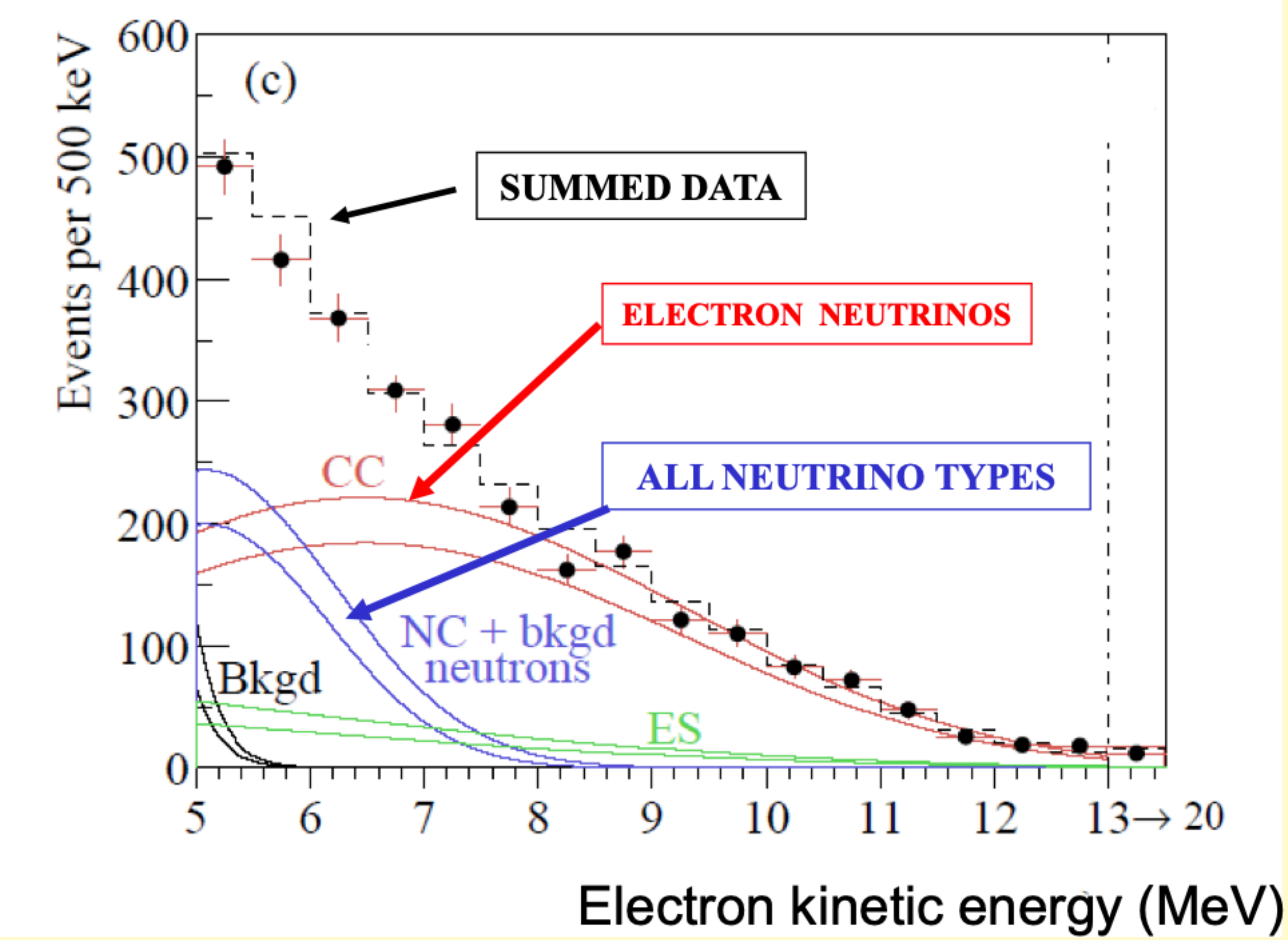
70,000 showers during the course of the SNO project



Art McDonald: Neutrino 2016

SNO spectrum

WE OBSERVED NEUTRINOS FROM THE SUN
WITH ALMOST NO RADIOACTIVE BACKGROUND



SUMMED DATA

ELECTRON NEUTRINOS

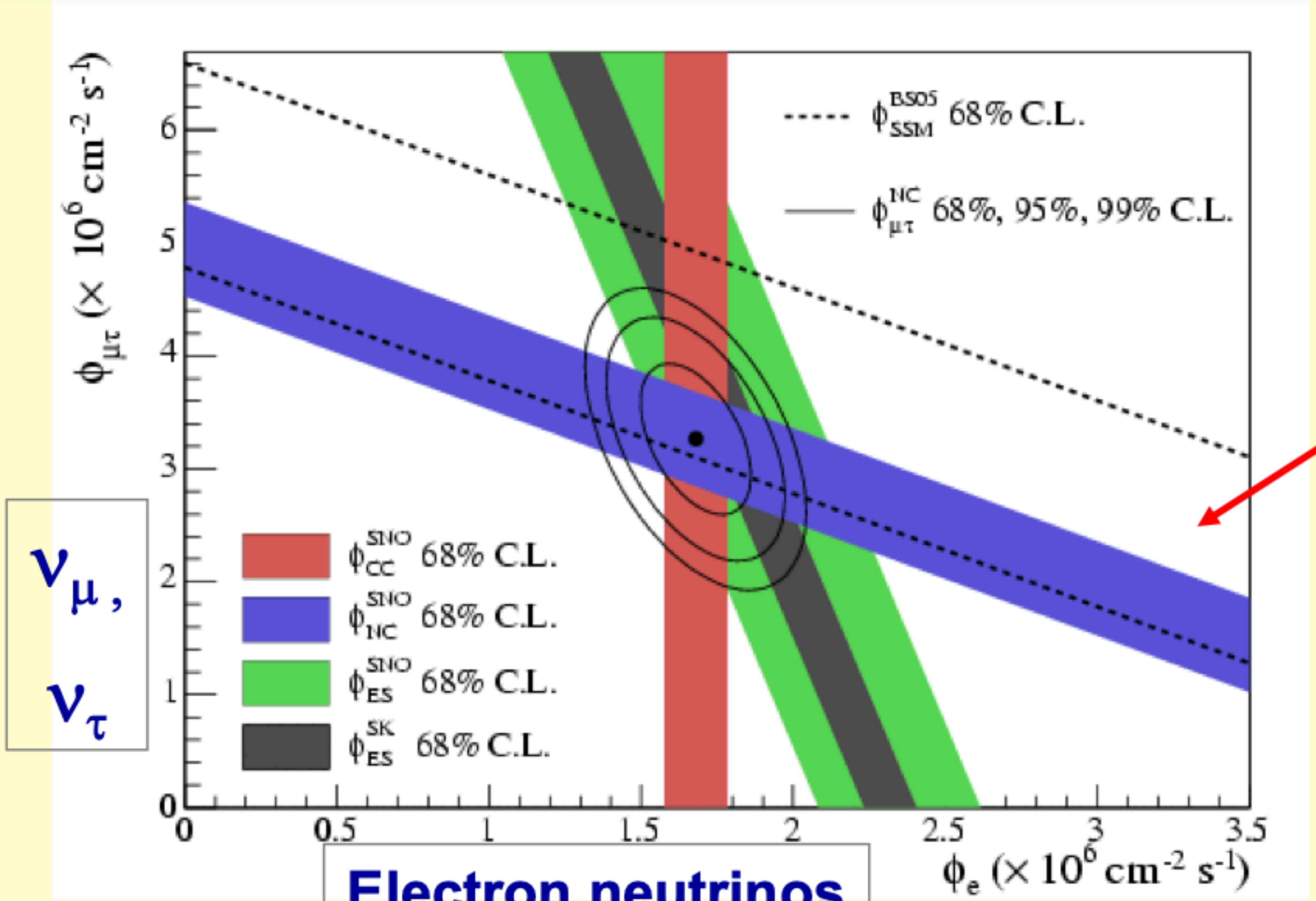
ALL NEUTRINO TYPES

After Calibration:
ELECTRON
NEUTRINOS
AT EARTH ARE
ONLY 1/3
OF ALL
NEUTRINOS

Data from Pure Heavy Water Phase in 2002

Art McDonald: Neutrino 2016

SNO results



ν_μ , ν_τ

Electron neutrinos

SNO Results for Salt Phase

Flavor change determined by > 7 σ.

New physics beyond The Standard Model of Elementary Particles!

The Total Flux of Active Neutrinos is measured independently (NC) and agrees well with solar model Calculations:

5.82 +- 1.3 (Bahcall et al),

5.31 +- 0.6 (Turck-Chieze et al)

$$\phi_{CC} = 1.68 \; {}^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94 \; {}^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35 \; {}^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

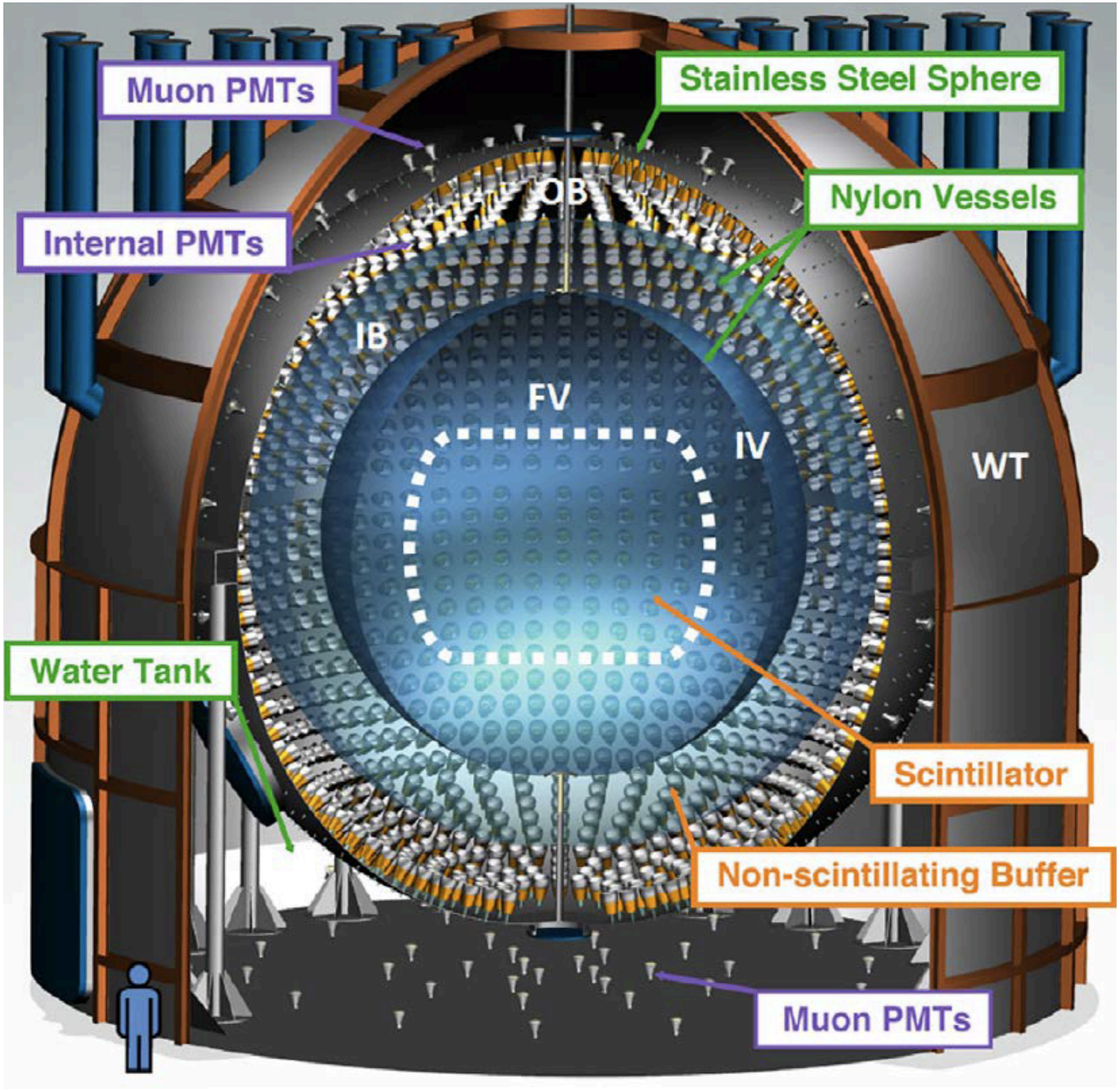
(In units of $10^6 \text{cm}^{-2}\text{s}^{-1}$)

$$\frac{\phi_{CC}}{\phi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

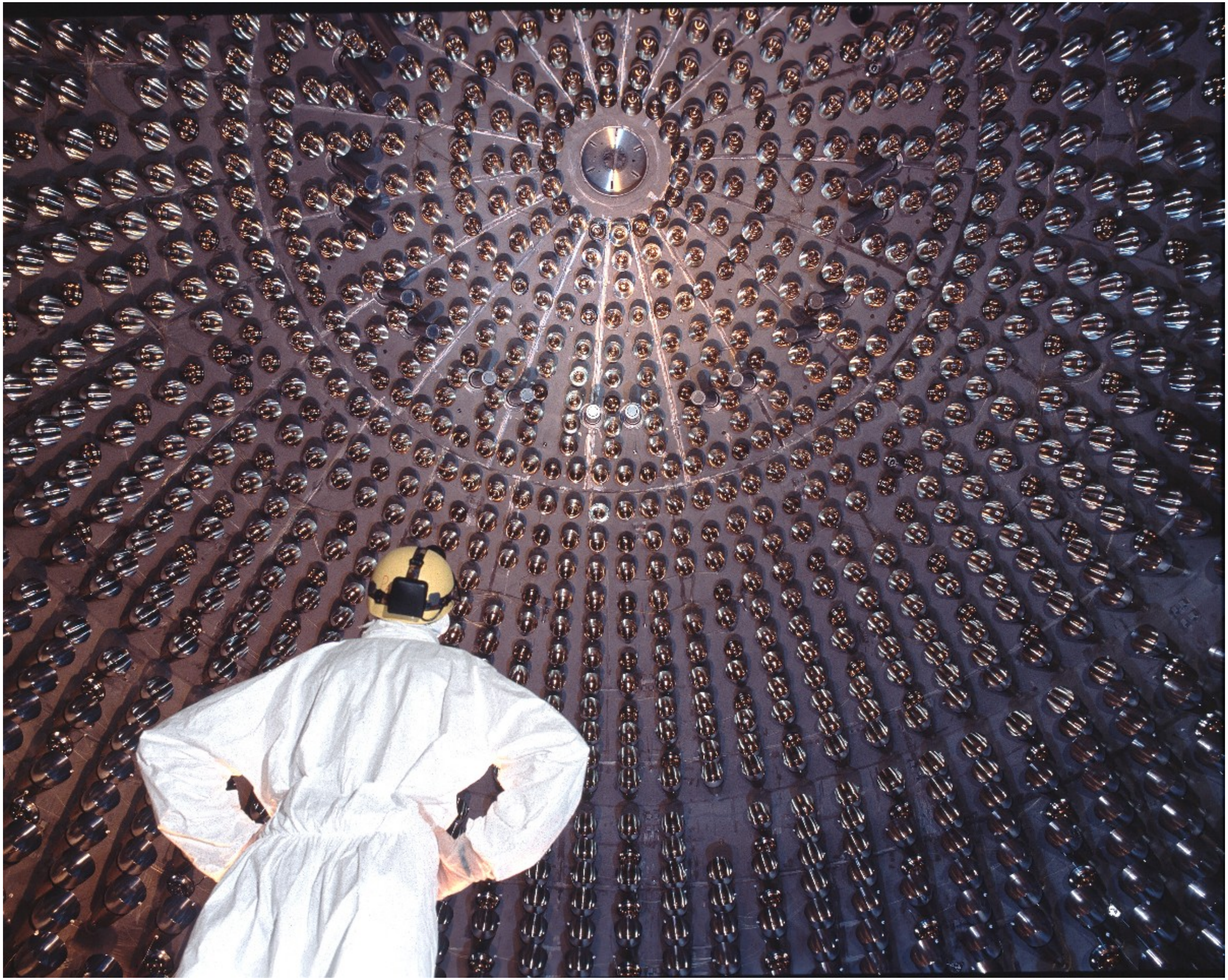
Electron Neutrinos are only 1/3 of Total

Art McDonald: Neutrino 2016

The Borexino detector



Internal view, empty



Internal view: inflated vessels (with N_2)

Internal view, filled, during calibration in 2009

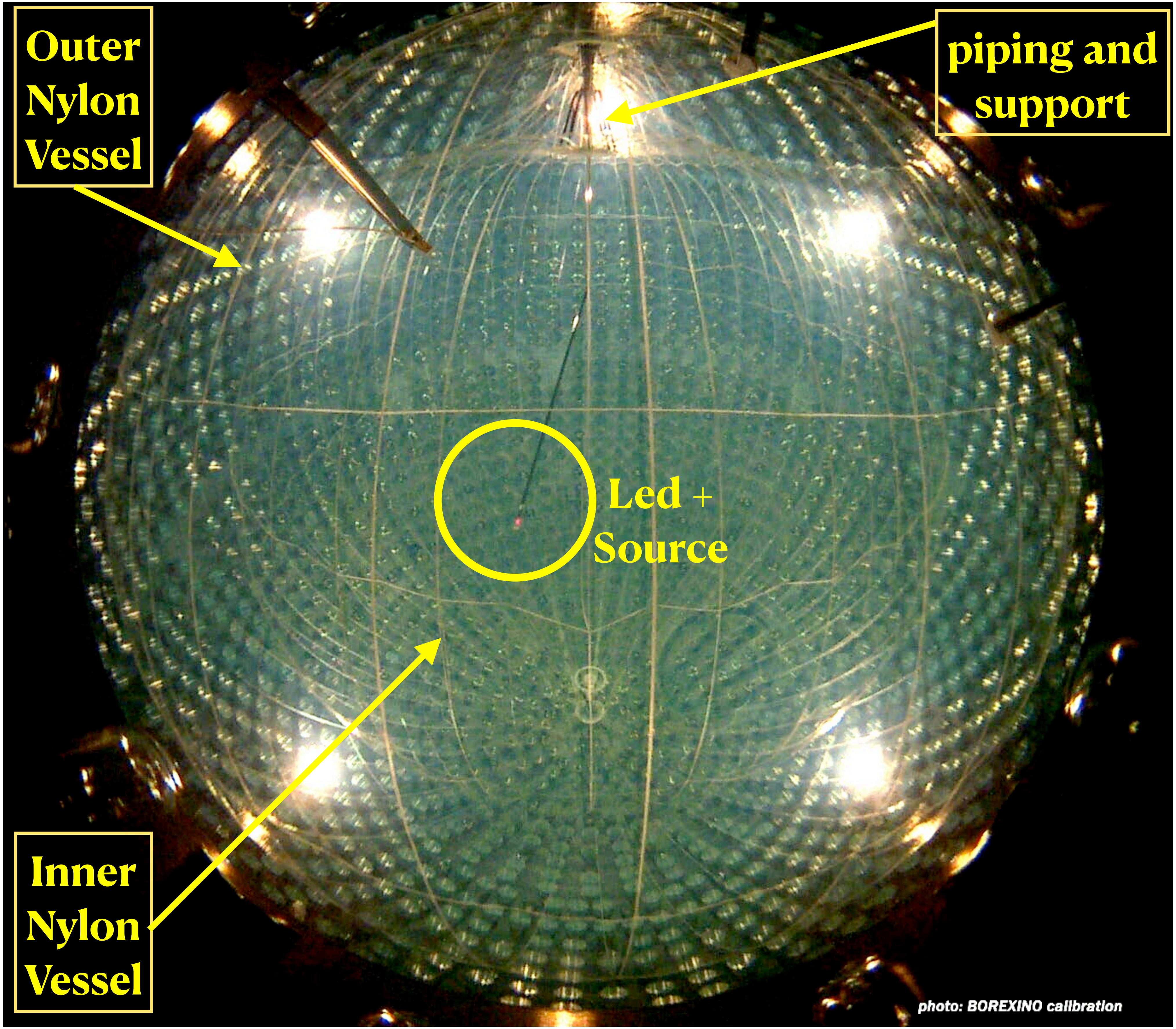
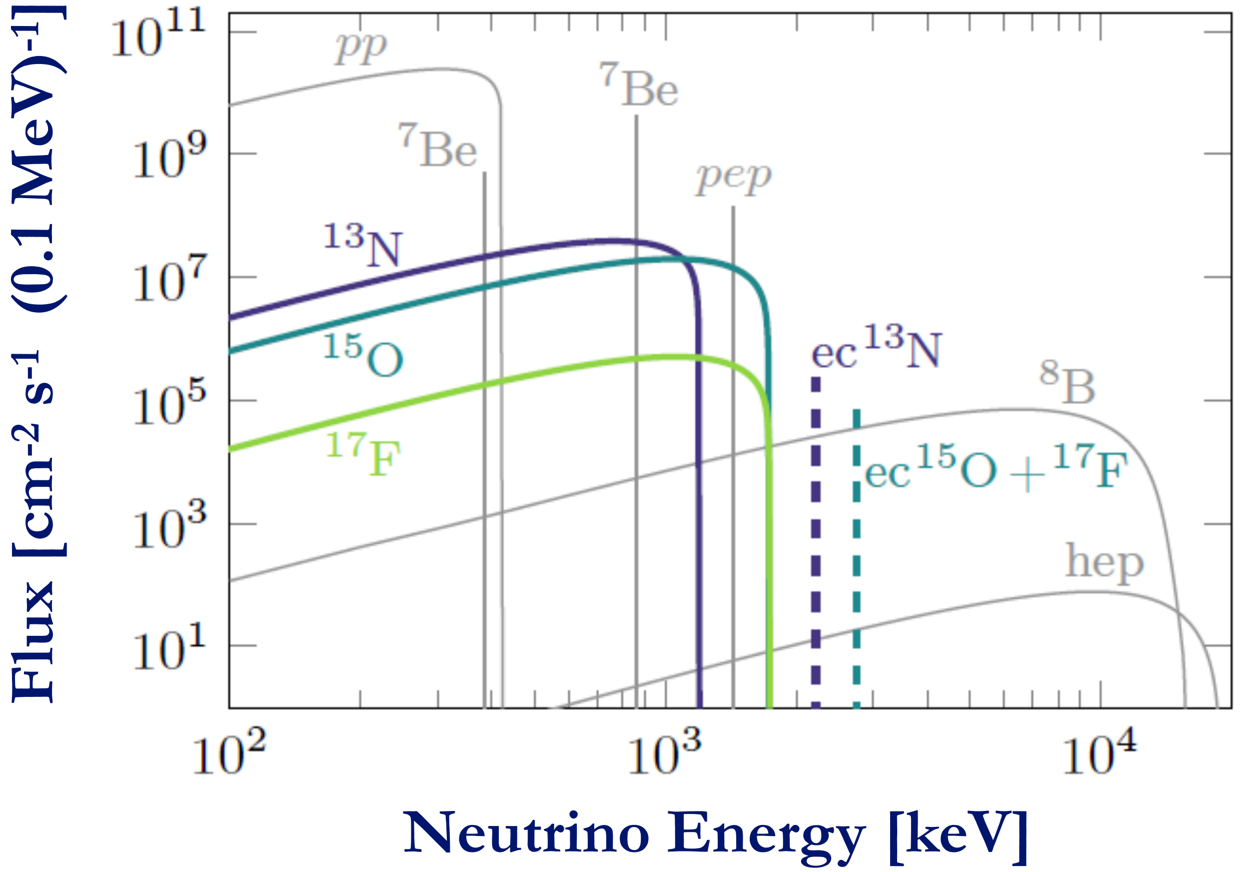


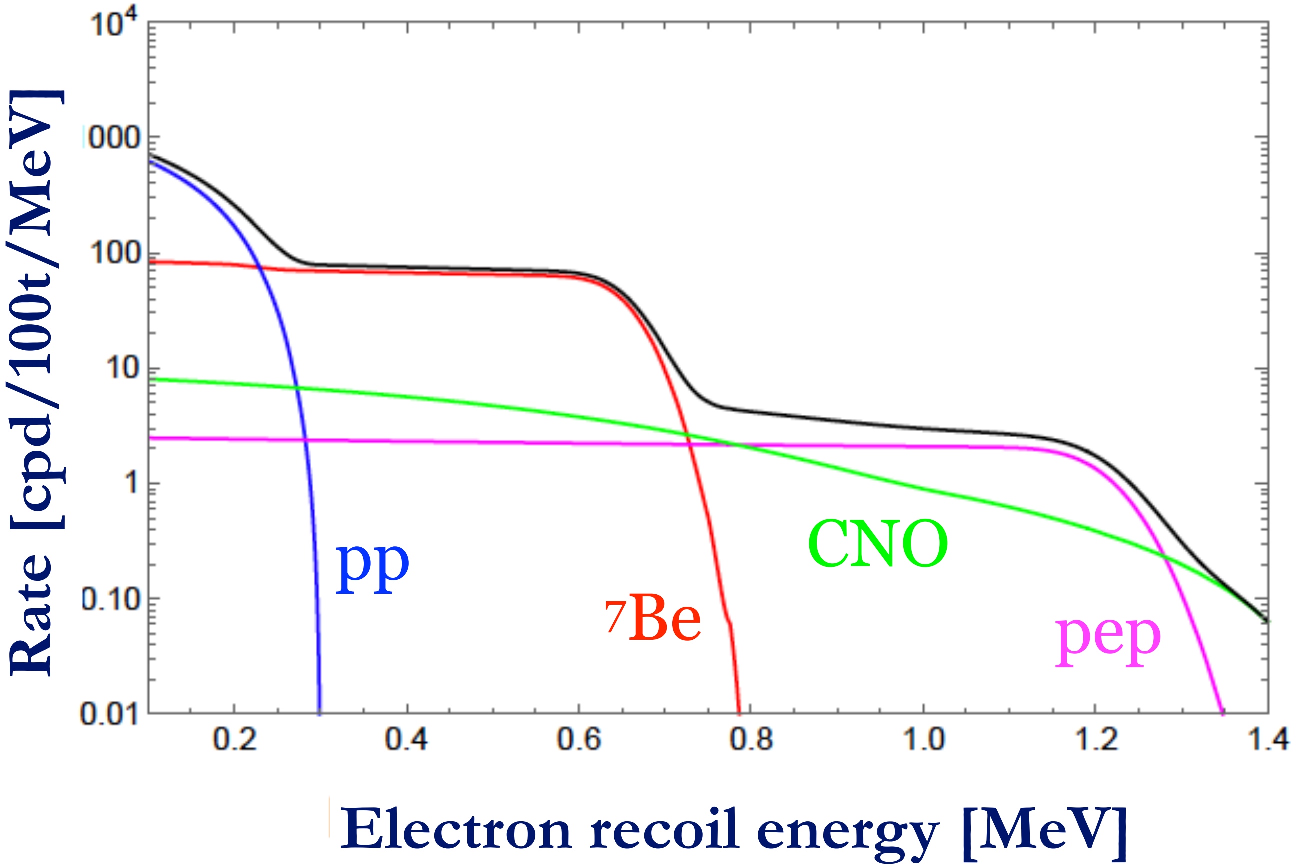
photo: BOREXINO calibration

Neutrino detection in Borexino

SOLAR NEUTRINO SPECTRUM

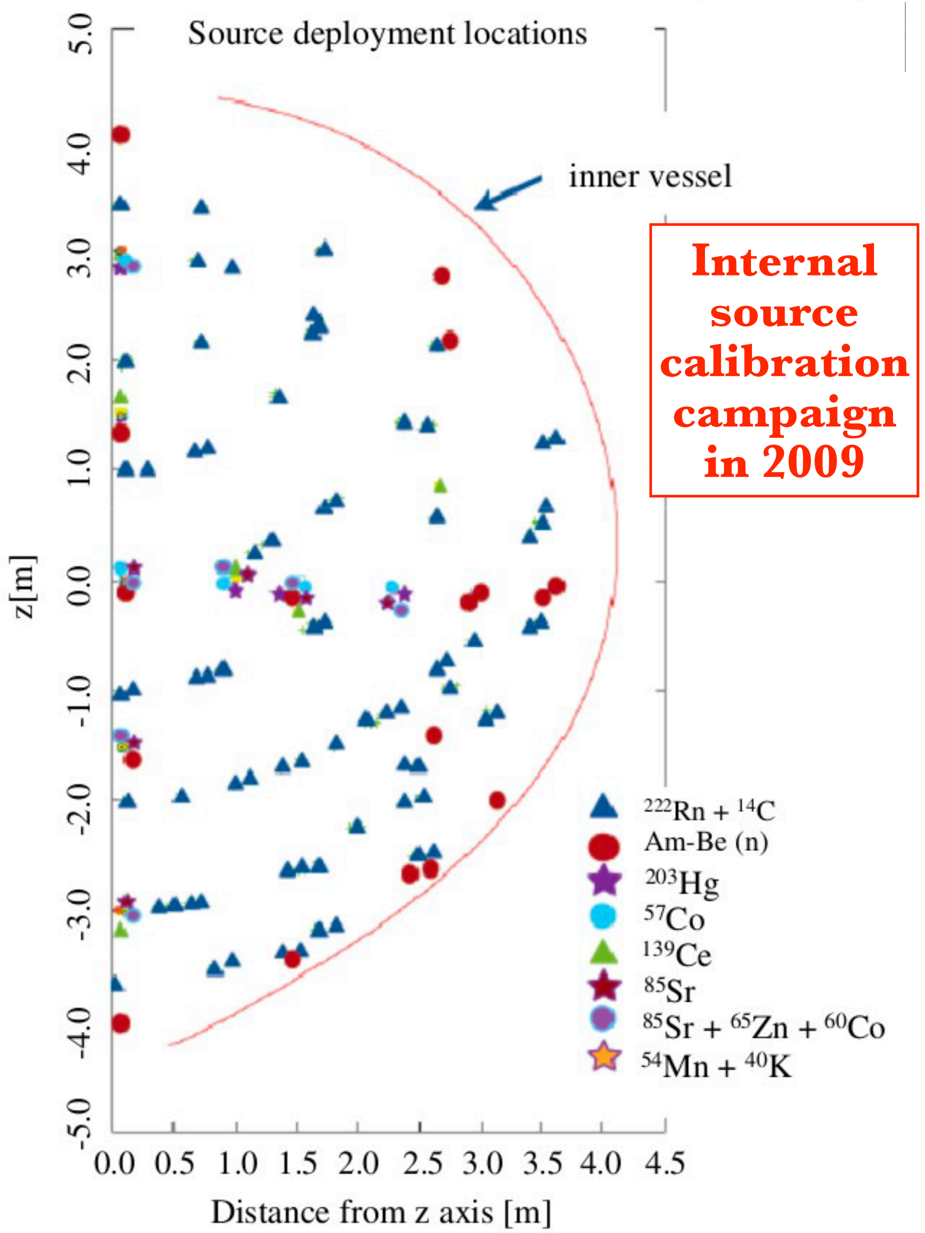


DETECTION RATE IN BOREXINO



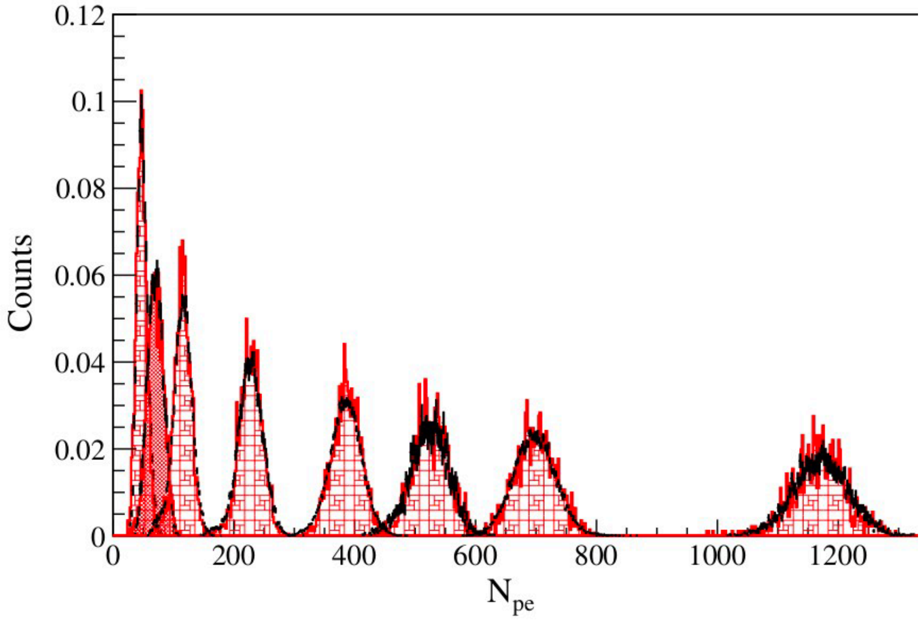
Detector response

- Large liquid scintillator signal yields:
  - # photo-electrons:
    - **energy: 6% @ 1 MeV**
  - time-of-flight:
    - **position: ~11 cm @ 1 MeV**
  - pulse shape:
    - very good α/β and (weak) β^+/β^- **discrimination**

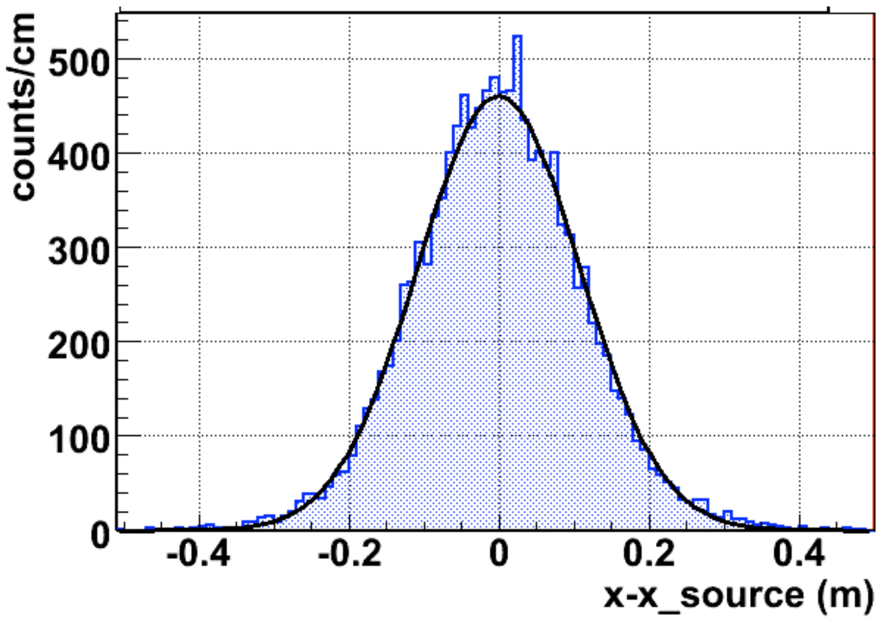


Internal source calibration campaign in 2009

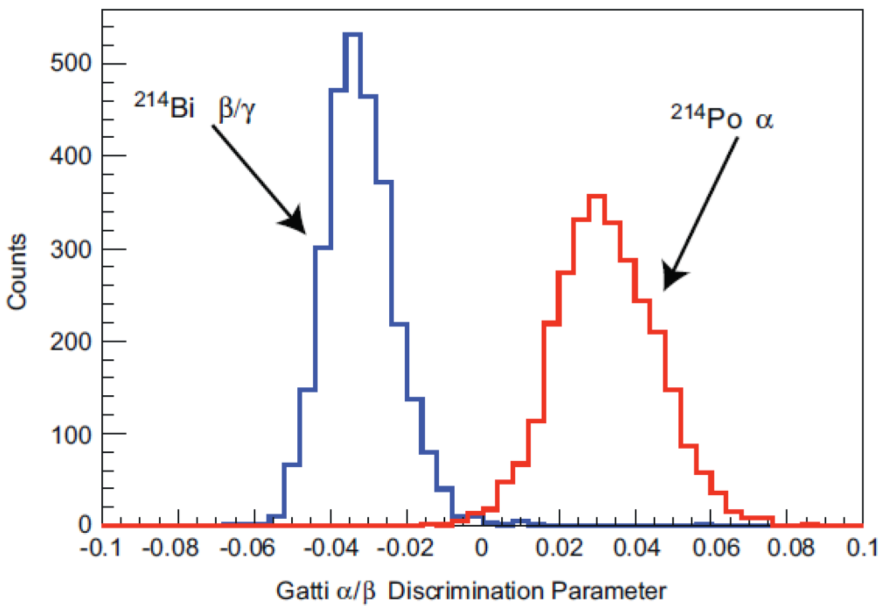
Energy: γ sources



Position: ^{214}Po



α/β: ^{214}Bi - ^{214}Po



Fighting backgrounds

- Quasi-point-like energy deposits mimic neutrino events

EXTERNAL

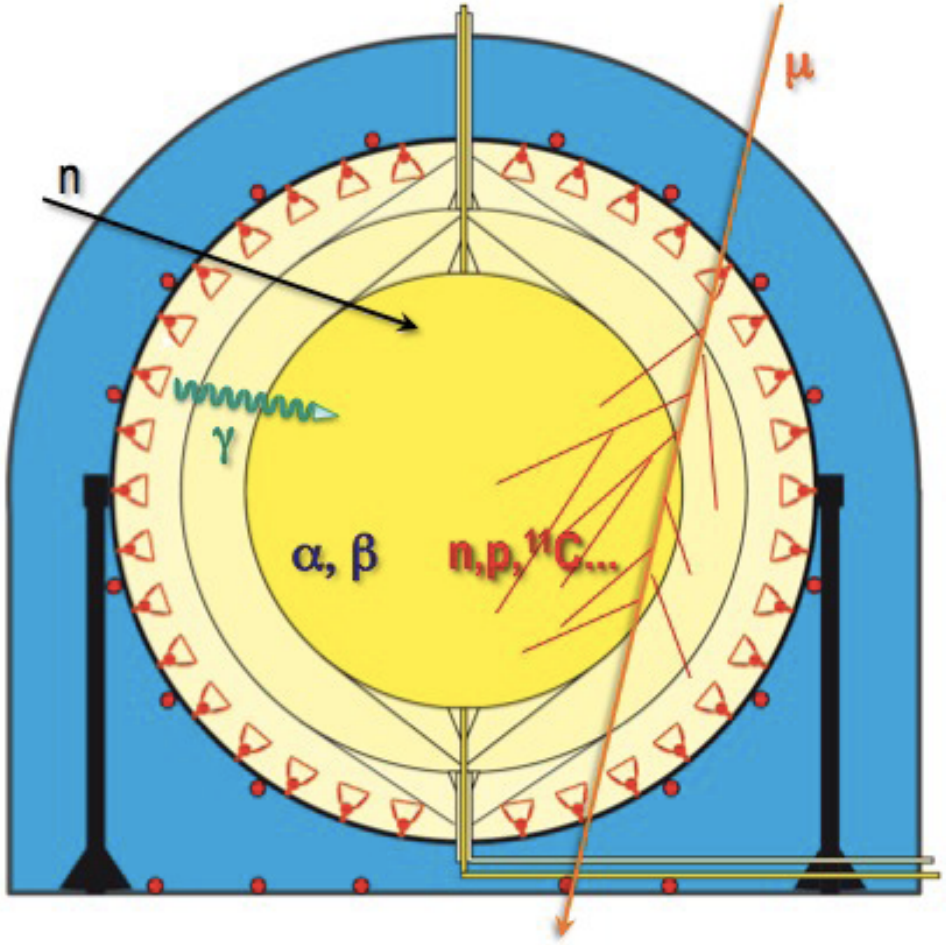
- γs (and n) from environment and detector materials (PMTs and SSS, mostly)

A tiny amount reaches FV

INTERNAL

- α and β emitters dissolved in the scintillator

^{14}C, ^{238}U, ^{232}Th, ^{40}K, ^{39}Ar, ^{7}Be, …
^{85}Kr, ^{210}Pb, ^{210}Po



COSMOGENIC

- Residual muons produce long living isotopes (μs to days range)

^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

MIGRATING

- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

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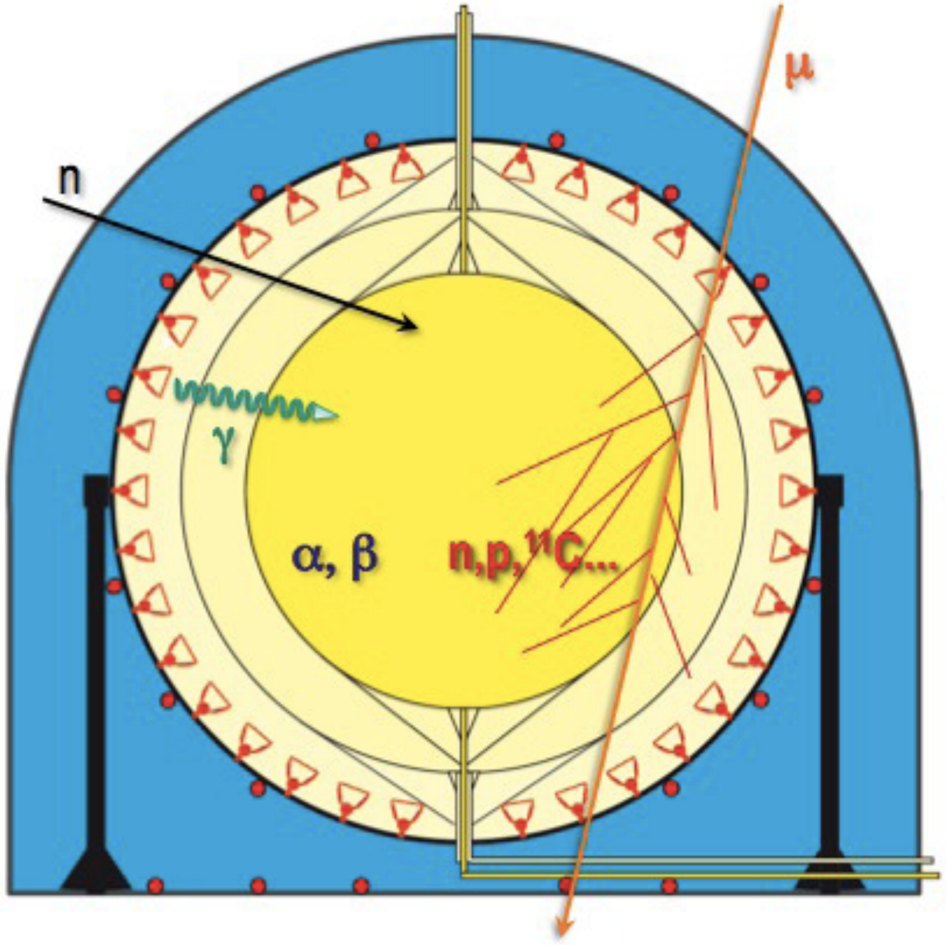

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FIGHTING STRATEGY

- Shielding, muon tagging and tracking
- Material selection (steel, PMTs, nylon)
- Nylon vessel (material selection, clean construction, no air exposure)

Fighting backgrounds

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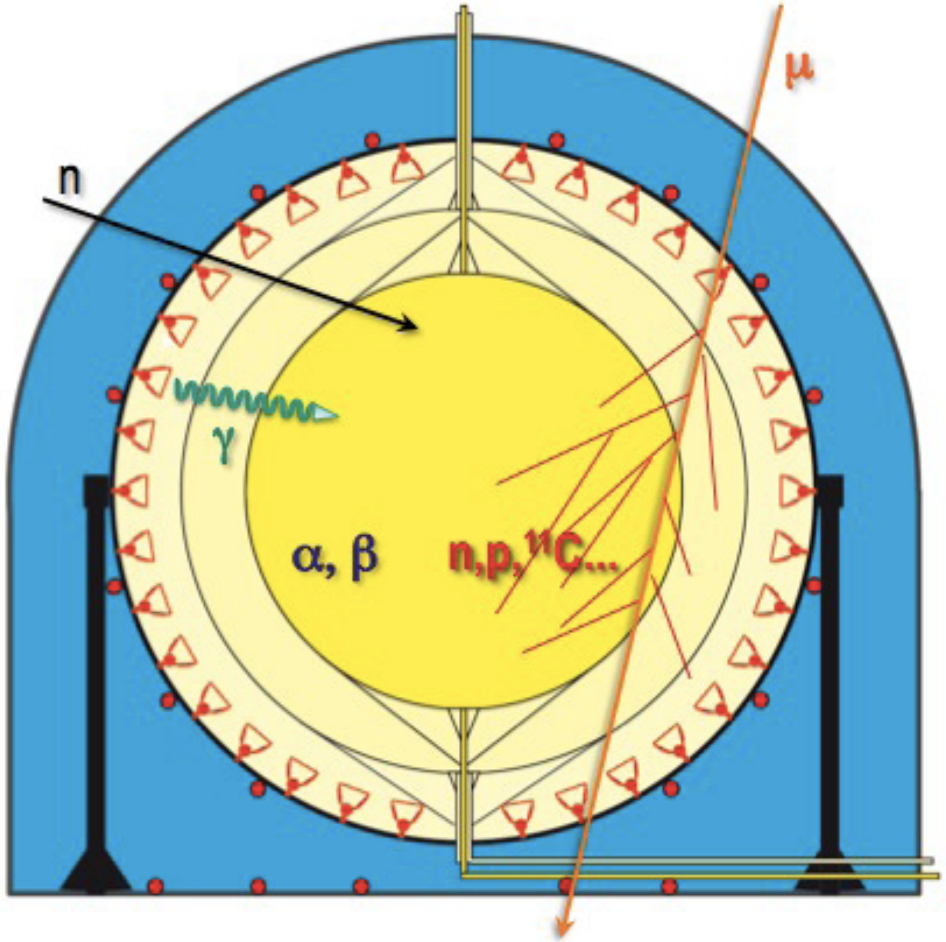

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MIGRATING

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^{210}Po, ^{222}Rn

FIGHTING STRATEGY

- Selection of PC vendor for low ^{14}C, dedicated plant, and custom transportation
- **Distillation** of PC, **Water Extraction** of PC+PPO solution
- Development of **low Ar and Kr N_2** to remove dissolved contaminants
- Extreme cleanliness of plants, carefully designed filling procedures

A long story made short!

Fighting backgrounds

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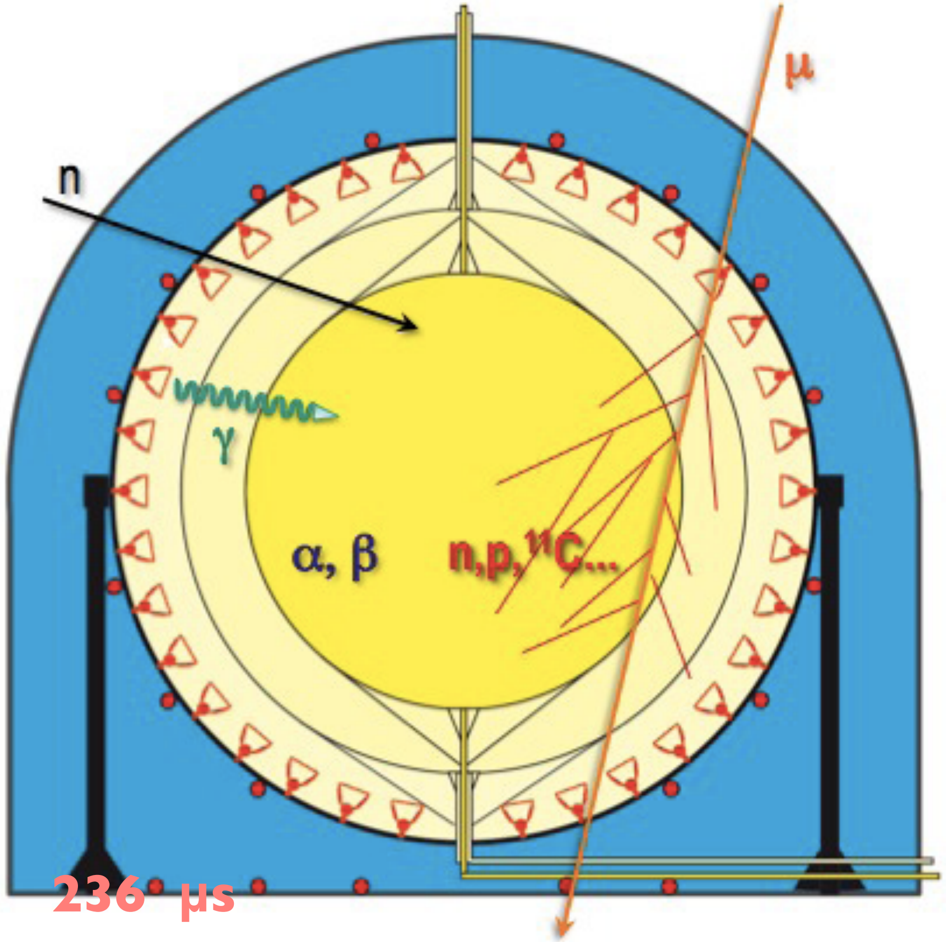

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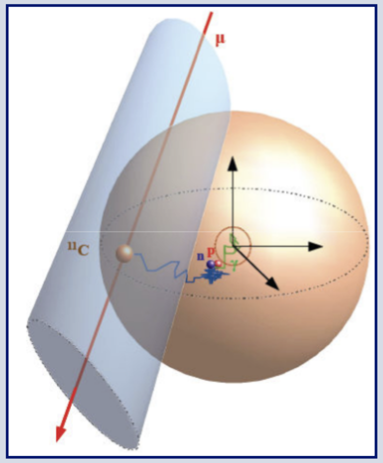

FIGHTING STRATEGY

$$\mu + {}^{12}C \rightarrow n + {}^{11}C + \mu$$

29.4 min

$${}^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$$

$$n + p \rightarrow D + \gamma\ (2.2\ \text{MeV})$$

236 µs

Other isotopes:
removed by
“after muon”
veto cuts

Fighting backgrounds

- **Quasi-point-like energy deposits mimic neutrino events**

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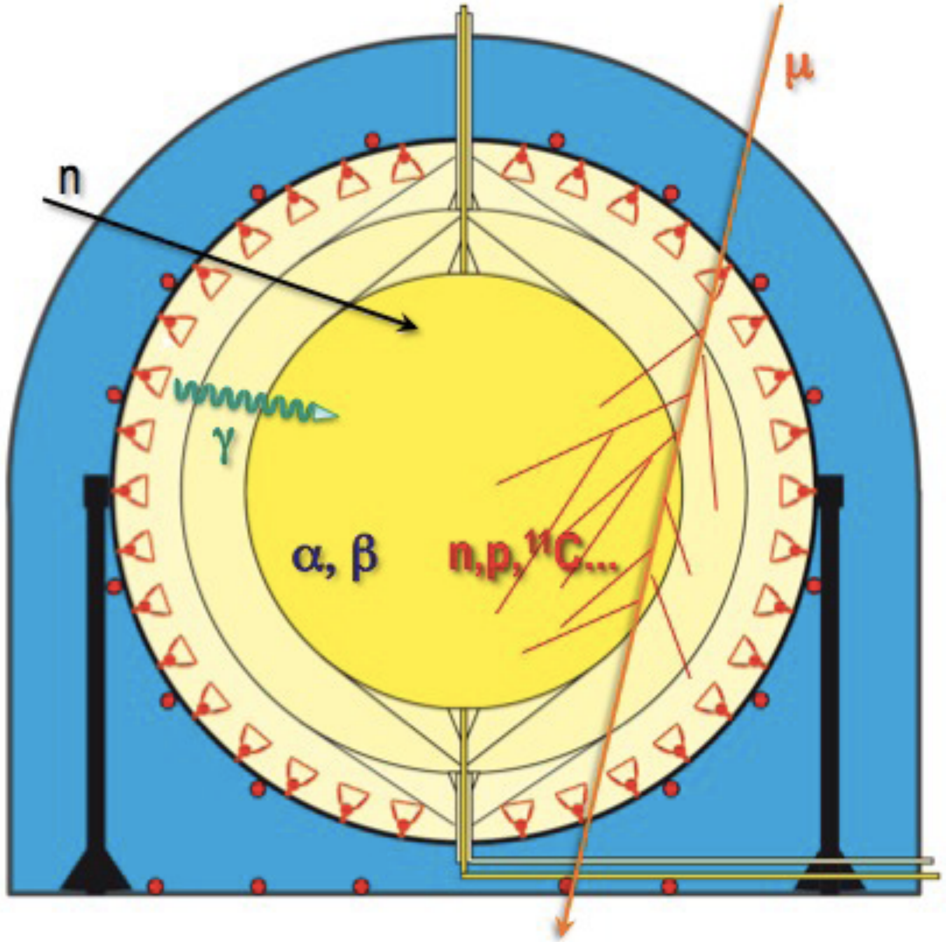

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- Residual muons produce long living isotopes (μs to days range)

^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

MIGRATING

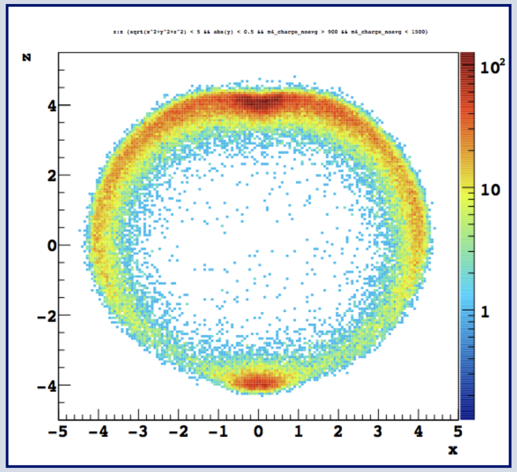
- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

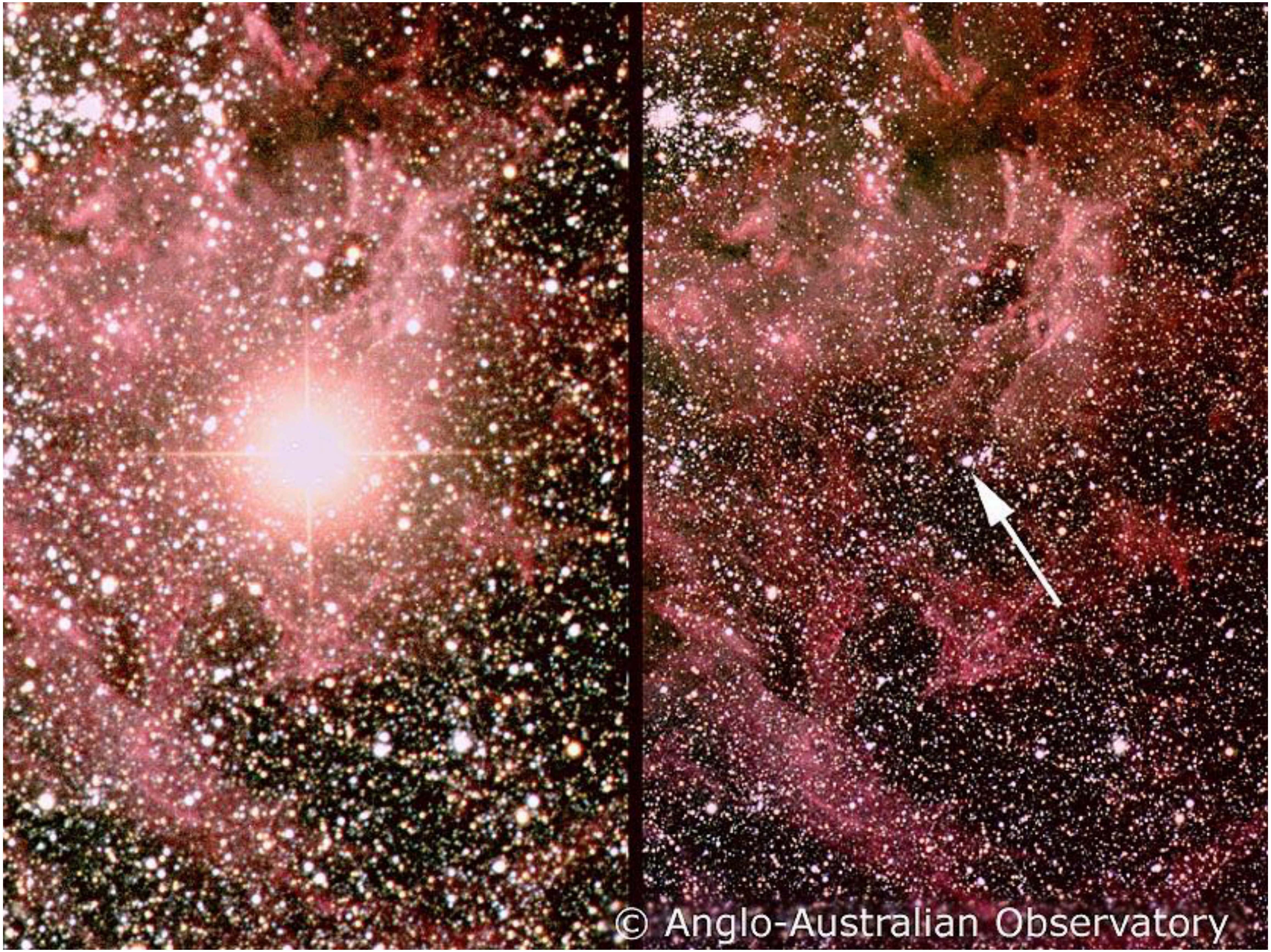
FIGHTING STRATEGY

- Isotopes detaching from IV may reach the FV
  - ^{210}Po (chiefly) and ^{222}Rn daughters
- Leaching rate (chemistry) and speed (convection currents)
  - Only if they live long enough!

See later



SN1987a: optical image before and after



SN1987a

- The first (and so far unique) neutrino detection for a star other than our Sun

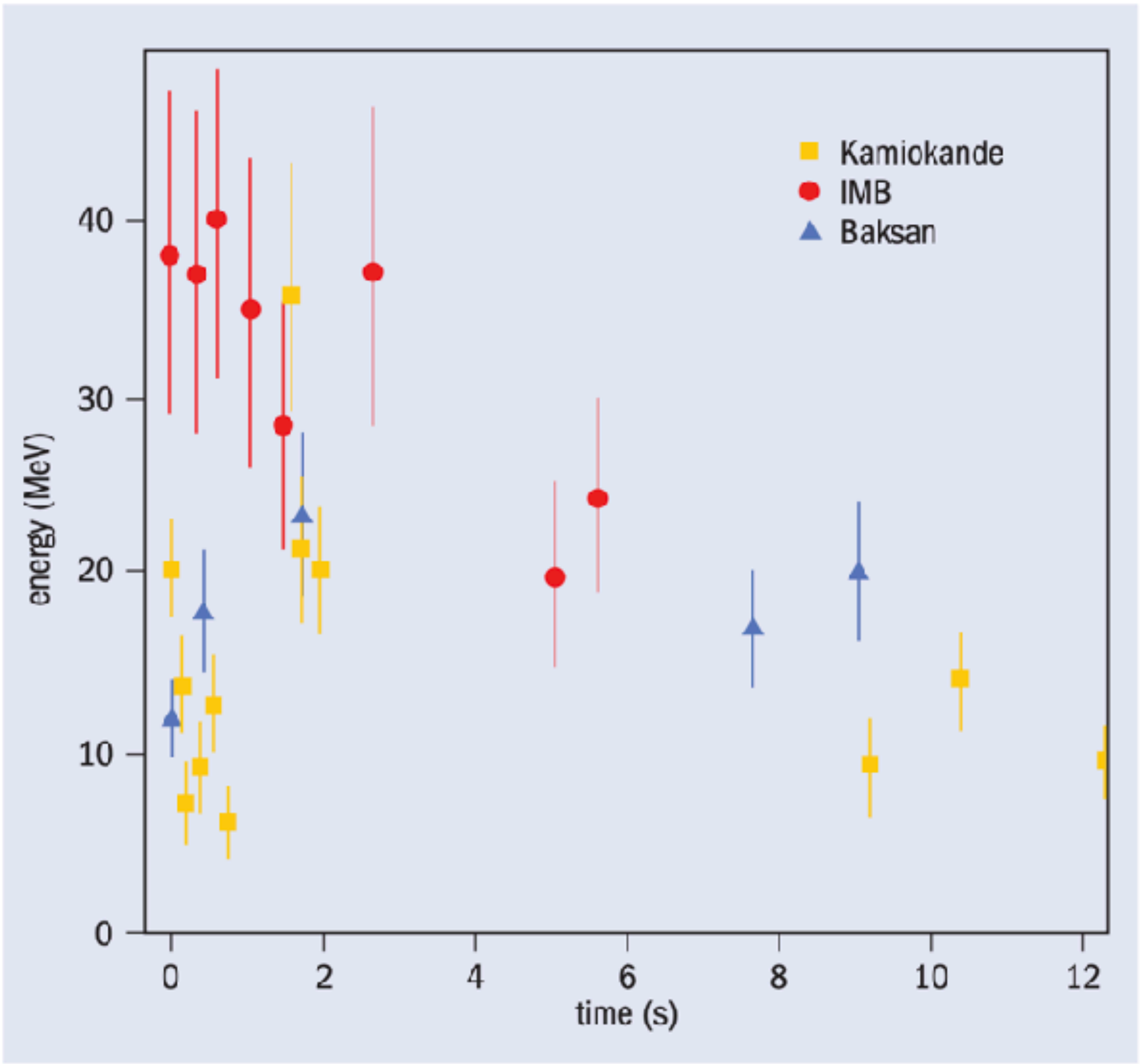


Fig. 3. SN1987A neutrino events observed by Kamiokande, IMB and Baksan showed that the neutrino burst lasted about 13 s.

Open problems

- **Neutrino mass type**
  - Majorana vs Dirac
    - **NEUTRINOLESS DOUBLE BETA DECAY**

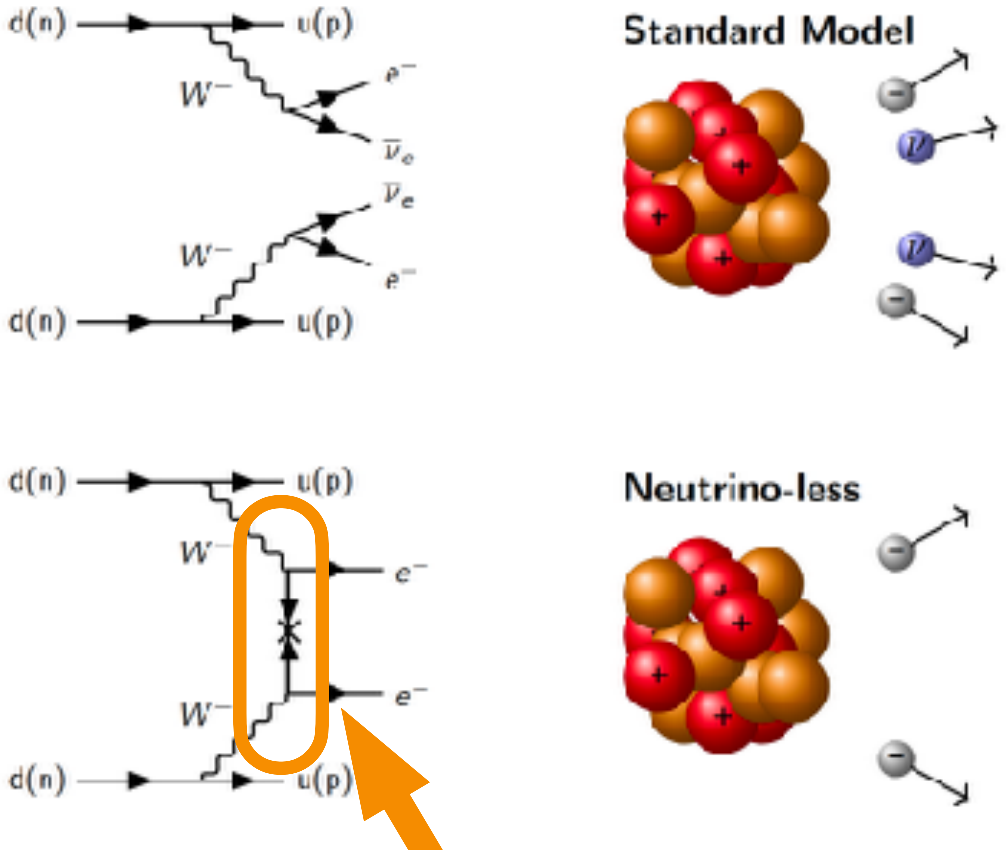
- **Neutrino mass scale**
  - What is the value of m_1 ?
    - **DIRECT NEUTRINO MEASUREMENTS** (not covered)

- **Neutrino mass ordering**
  - $m_3>m_1$ or $m_3<m_1$?
    - JUNO, ORCA, DUNE

- **CP violation in lepton sector ?**
  - What is the value of δ_{CP} ?
    - T2K and Nova, then (>2028) DUNE and T2HK

Why $0\nu\beta\beta$ is important ?

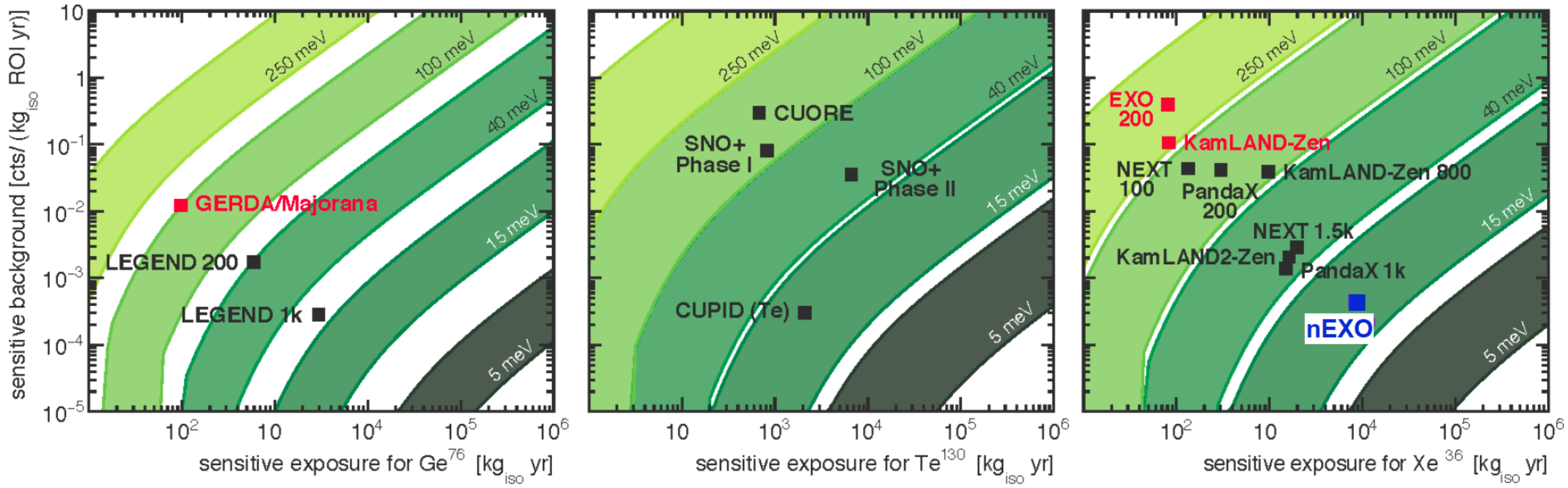
- The only know process that can **distinguish** between **Majorana and Dirac mass terms**
  - i.e. $0\nu\beta\beta$ can happen only if neutrinos are their own anti-particle (truly neutral)
  - i.e. lepton number is violated
  - **In all scenarios $0\nu\beta\beta$ implies new physics**



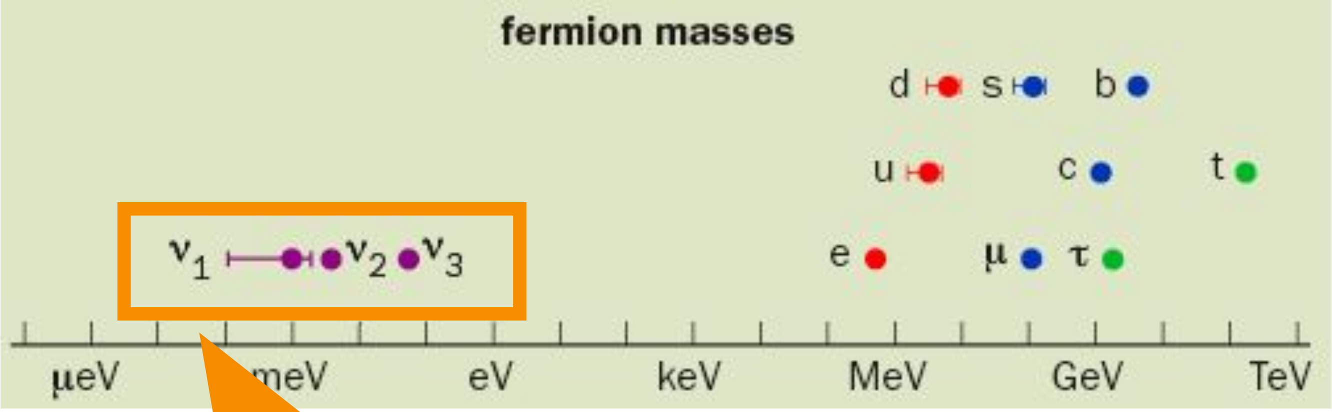
NOT NECESSARILY MAJORANA NEUTRINOS

SENSITIVITY OF NEXT GENERATION EXPERIMENTS

PRD 96 (2017) 053001
PRD 96 (2017) 073001)



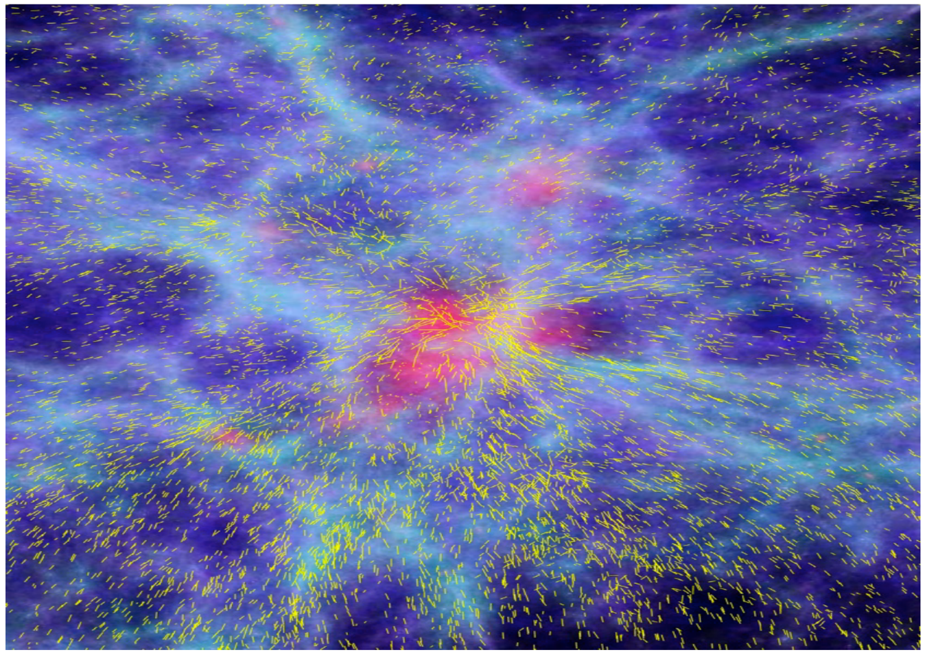
Why mass is important: three ways, three “masses” !



NEUTRINOS
ARE DIFFERENT ?

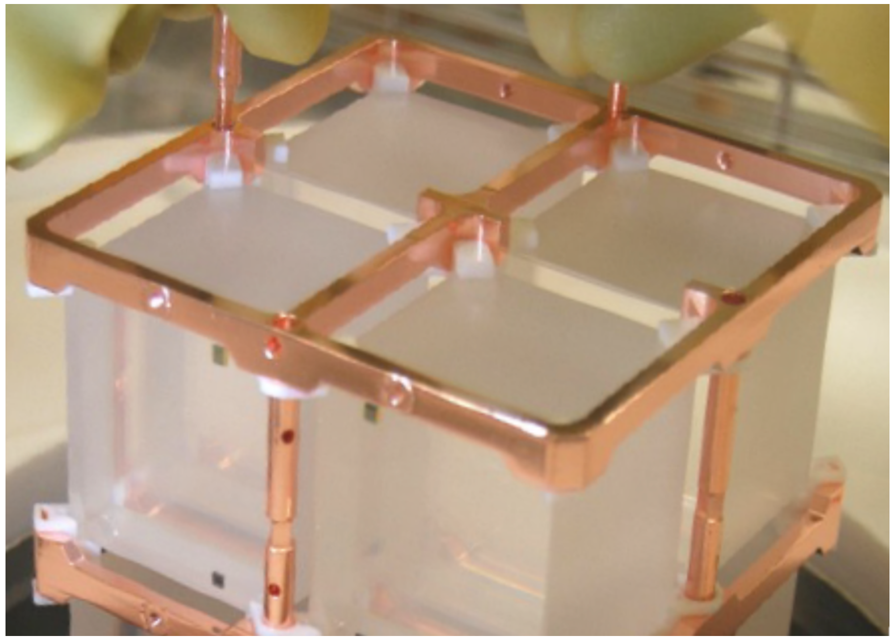
GRAVITY

$$\Sigma_\nu = m_1 + m_2 + m_3$$



β DECAY KINEMATICS

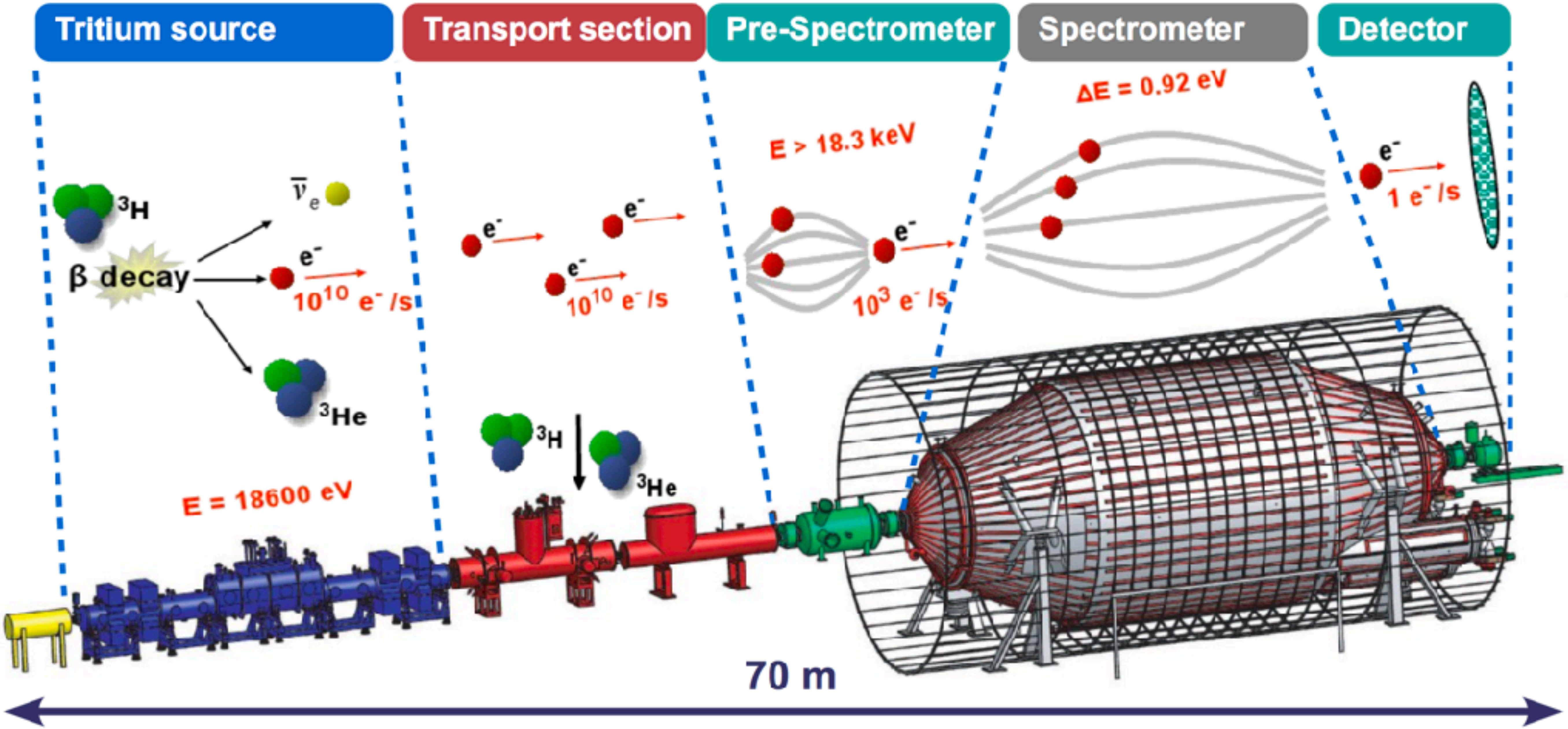
$$m_\beta = \sqrt{|U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2}$$



LEPTON NUMBER VIOLATION ($0\nu\beta\beta$ DECAY)

$$m_{\beta\beta} = \left| U_{e1}^2\, m_1 + U_{e2}^2\, m_2 + U_{e3}^2\, m_3 \right|$$

Katrin



Potential sensitivity: 0.35 eV (discovery at 5 σ, 0.2 upper limit)

Why measuring δ_{CP} is important ?

- We do not understand the **origin of matter-antimatter asymmetry in the Universe**
  - To get it you need CP violation (and baryon number violation)
  - Is the CP violation required explained by Standard Model + PMNS ?

- CP violation is proportional to so called Jarlskog invariant

$$J = \sin\vartheta_{12}\cos\vartheta_{12}\sin\vartheta_{23}\cos\vartheta_{23}\sin\vartheta_{13}\cos^2\vartheta_{13}\sin\delta_{CP} = J_{max}\sin\delta_{CP}$$

$$J_{max}^{quarks} = (3.18 \pm 0.15)\cdot 10^{-5}$$

$$J_{max}^{leptons} = (3.3 \pm 0.06)\cdot 10^{-2}$$

  - Quarks are ruled out
  - Leptons, not necessarily. They may play a role, possibly not unique.

- **Be aware:** you need, anyway, a **baryon number violation mechanism,** which cannot be related to SM

Thank you