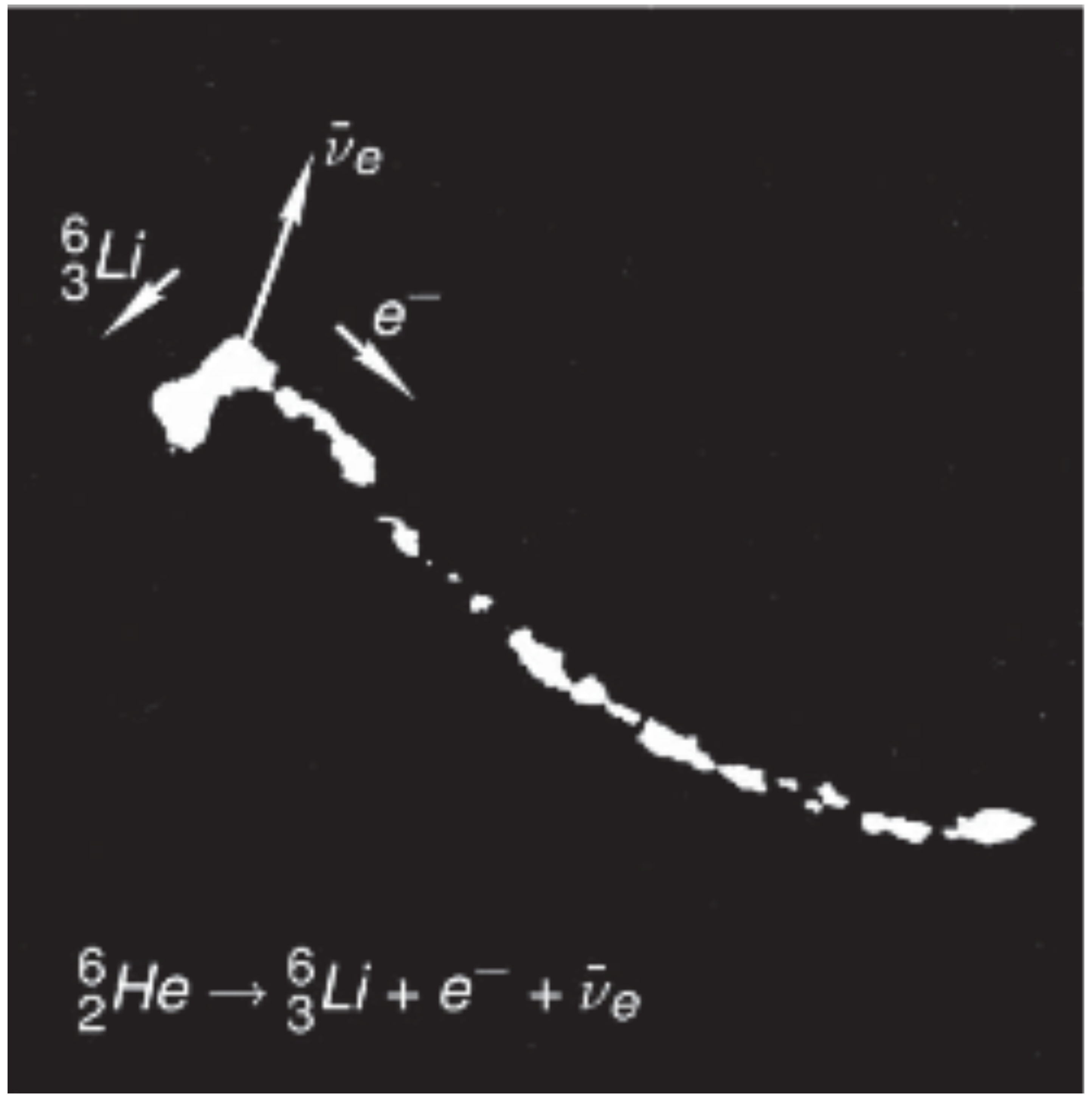
First cloud chamber image of β decay
J. Csikai and A. Szalay, Budapest, fall 1956



Introduction to Experimental Neutrino Physics

SOUP School

Bertinoro, Oct. 14th, 2024

Marco Pallavicini
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Outline (I)

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

- **Neutrino phenomenology from 0 eV up to PeV scale [and random selection of experiments]**
  - 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 **exceeds** what may be discussed thoroughly in only **4 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

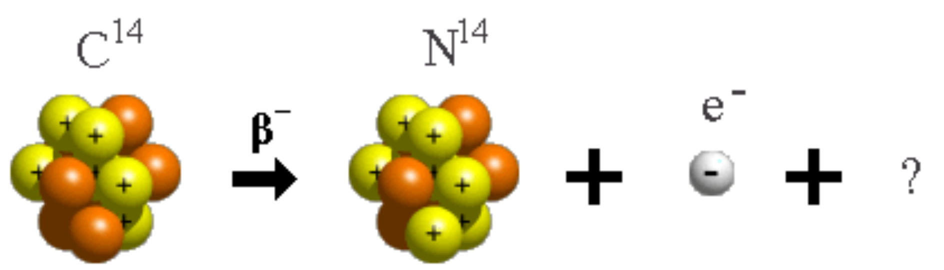
- **VERY IMPORTANT**
  - **I refer to SOME experiments in order to offer examples.**
  - **I am NOT listing ALL experiments.**
  - **The fact that I did not mention one experiment (particularly, maybe, YOURS) does not imply any judgement about it its relevance)**

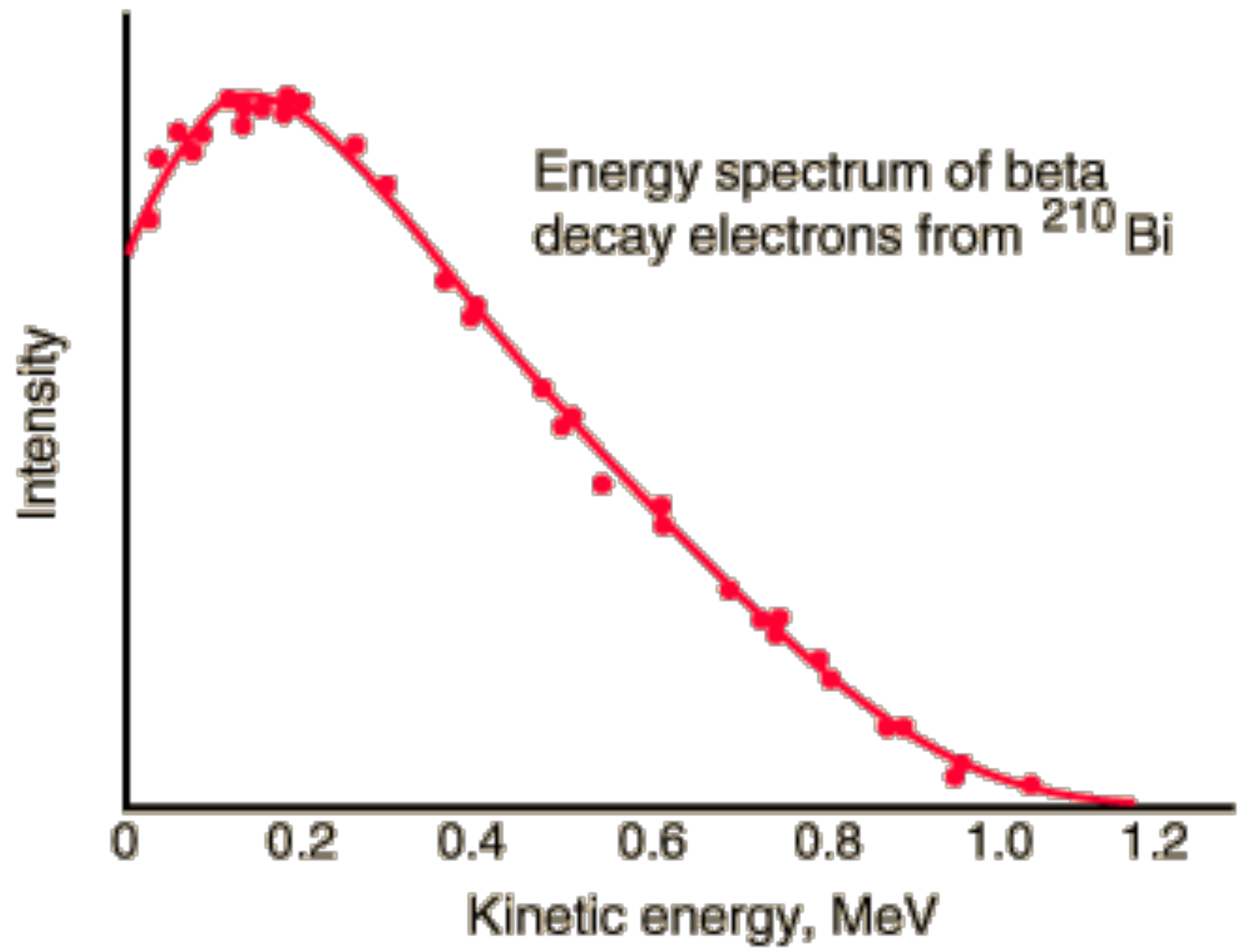
- **Indirect** evidence of neutrinos dates back to ***early discovery of radioactivity***

  - 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^-

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

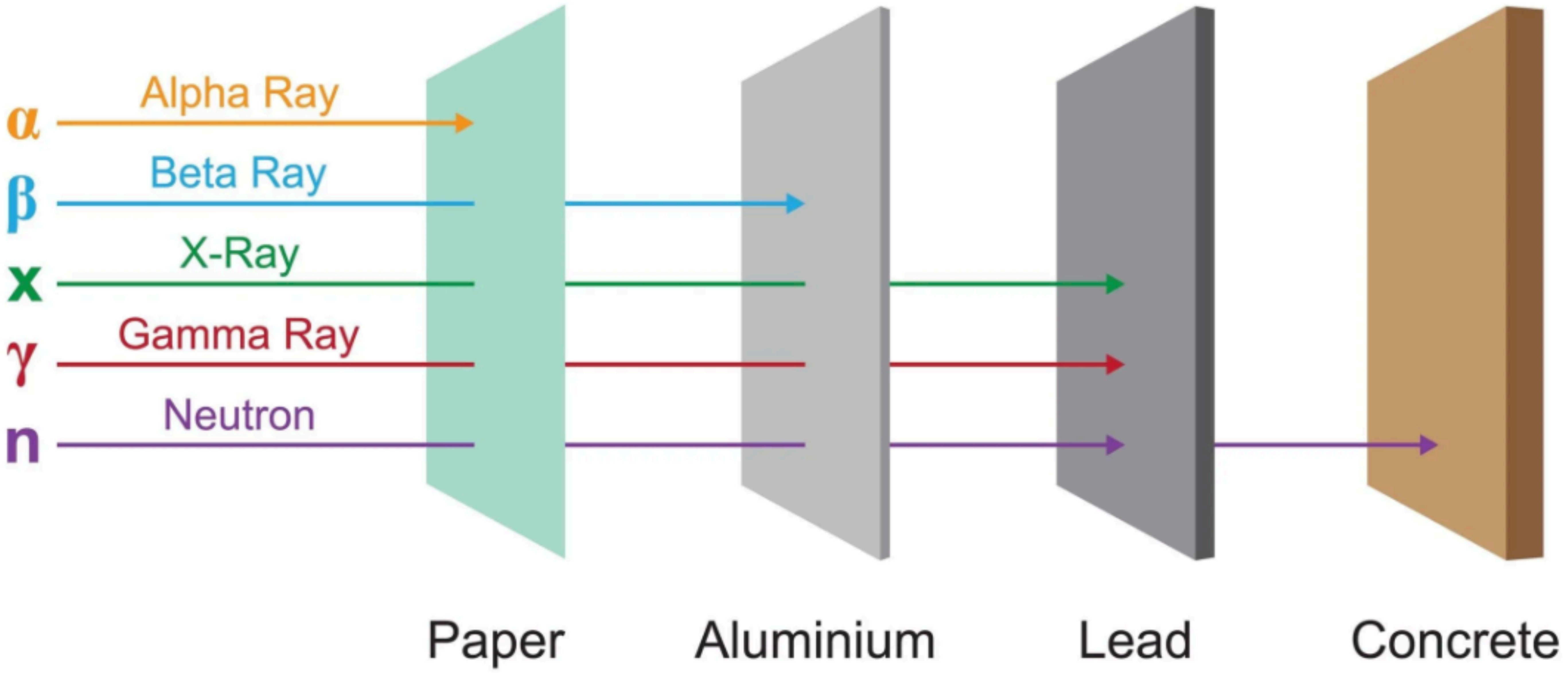
boson boson fermion

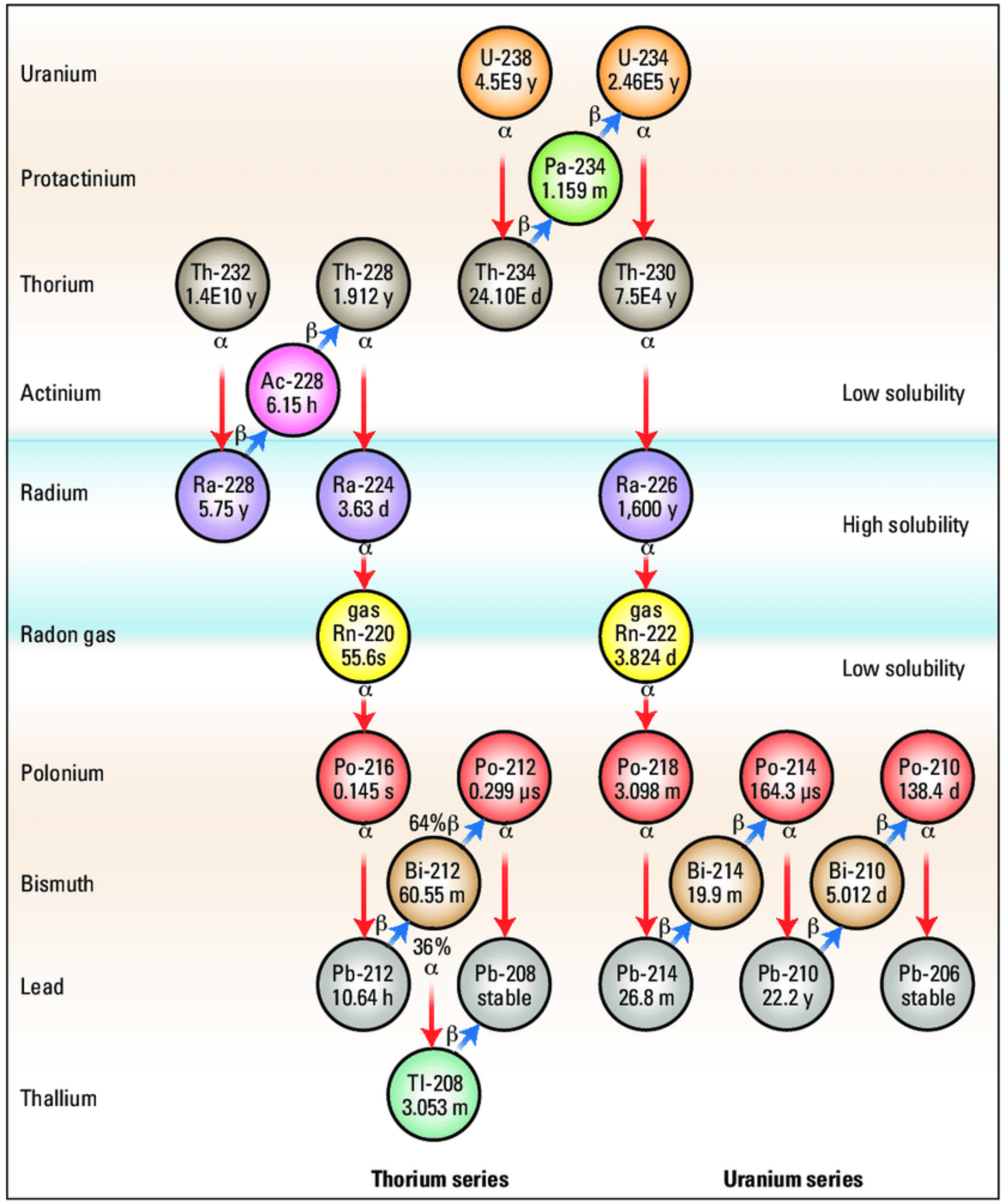




Avoiding historical miopia

- **The problem WAS difficult !**
  - Natural radioactivity comes mainly from ^{238}U and ^{232}Th decay chains
    - Many elements and decays
    - A long list of Nobel prizes to disentangle the mess





Pauli and Fermi

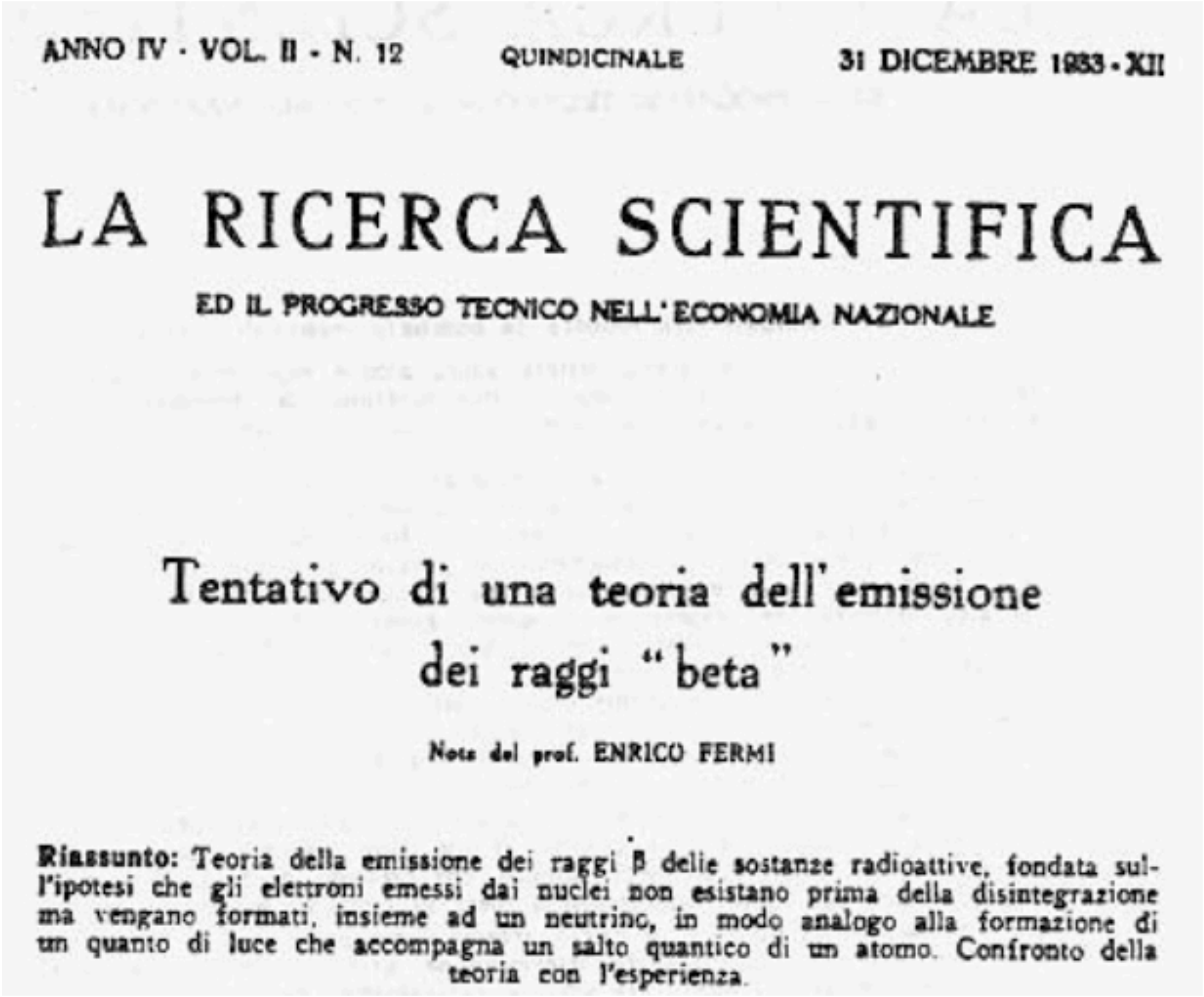
W. Pauli

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

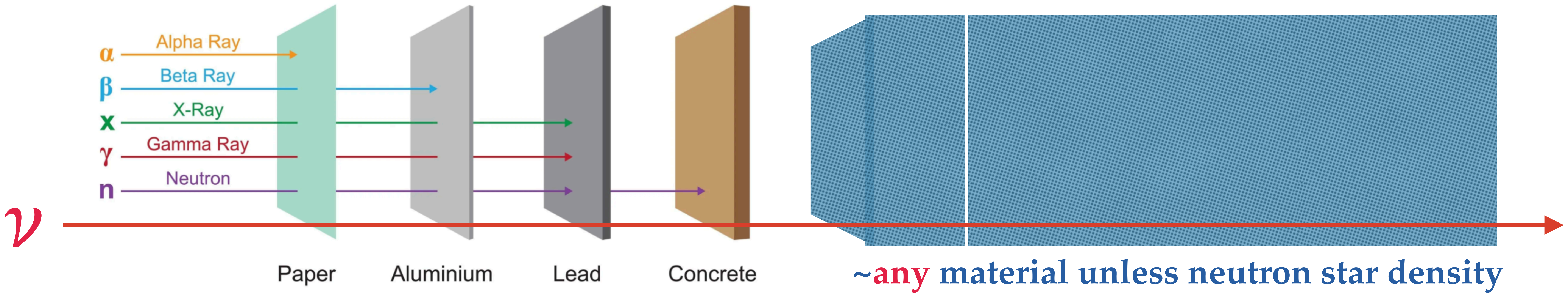
Riassunto: Teoria della emissione dei raggi β delle sostanze radioattive, fondata sull'ipotesi che gli elettroni emessi dai nuclei non esistano prima della disintegrazione ma vengano formati, insieme ad un neutrino, in modo analogo alla formazione di un quanto di luce che accompagna un salto quantico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

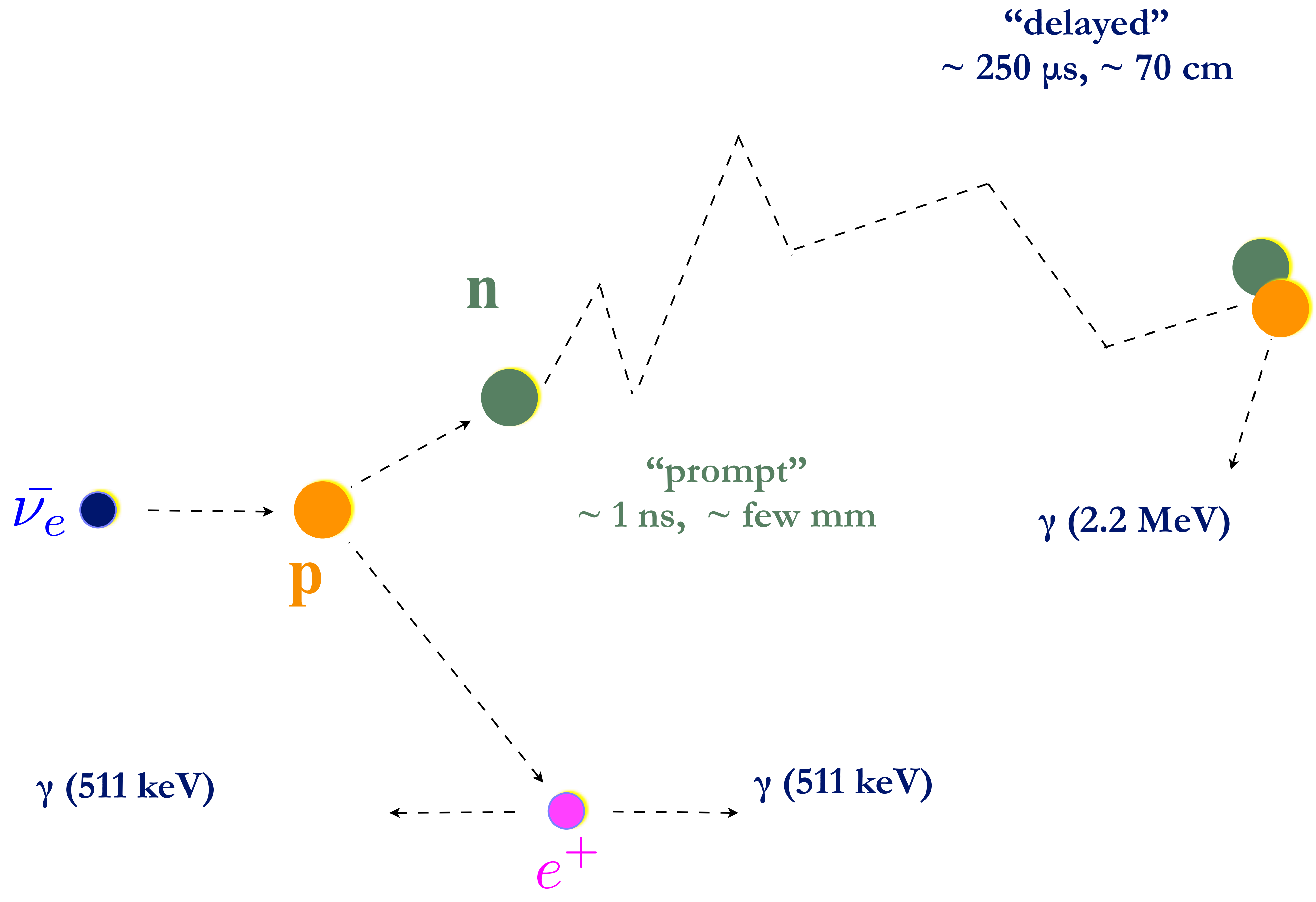
MEAN FREE PATH IN WATER

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



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 **fissiоn reactors**

  - **Reines and Cowan, 1956** (after several attempts, including the "idea" to use atomic bombs explosions!)

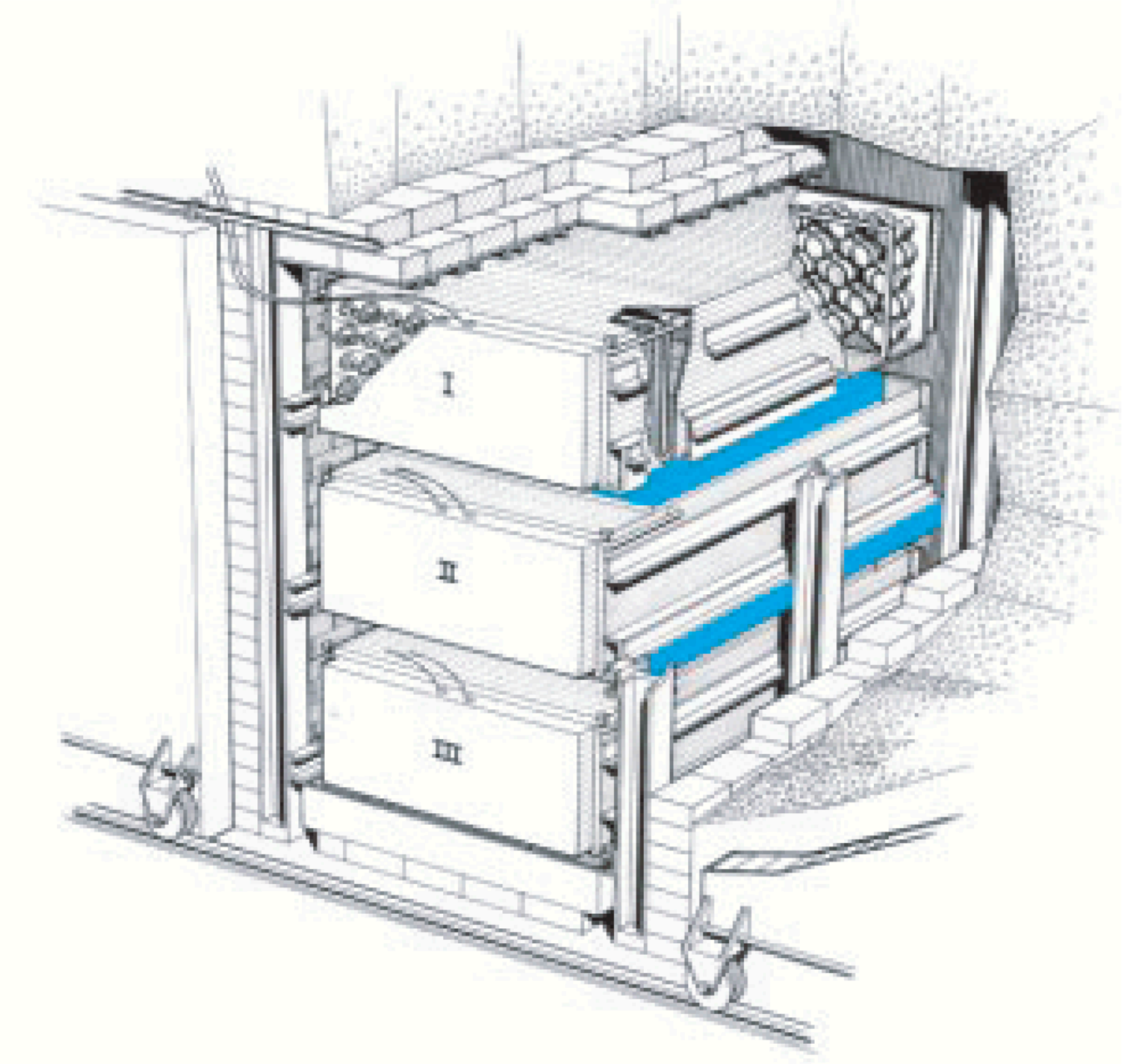
  - **Each U fission yields 200 MeV on average, and 6 ν_e**
    - Flux: ~ **2. 10^{20} s^{-1} GW^{-1},** isotropic, $\langle E_\nu \rangle \simeq 0.5$ MeV
    - About ~ **4. 10^{12} s^{-1} cm^{-2}** for 1 GW reactor at **20 m from the core**
    - For comparison **solar neutrinos: ~ 6.5 10^{10} s^{-1} cm^{-2} on Earth**

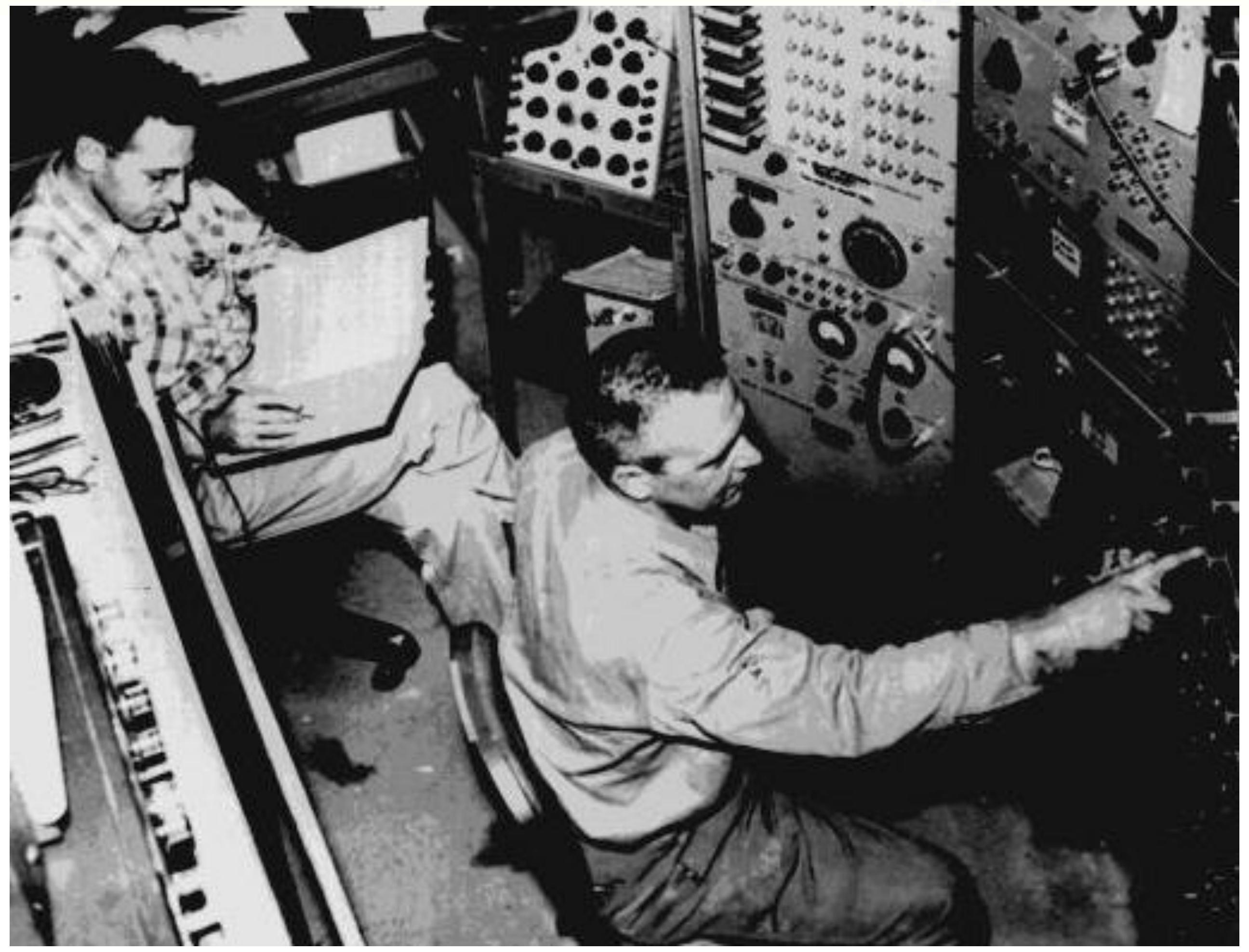
First detection of (anti)-neutrinos (II)

- 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



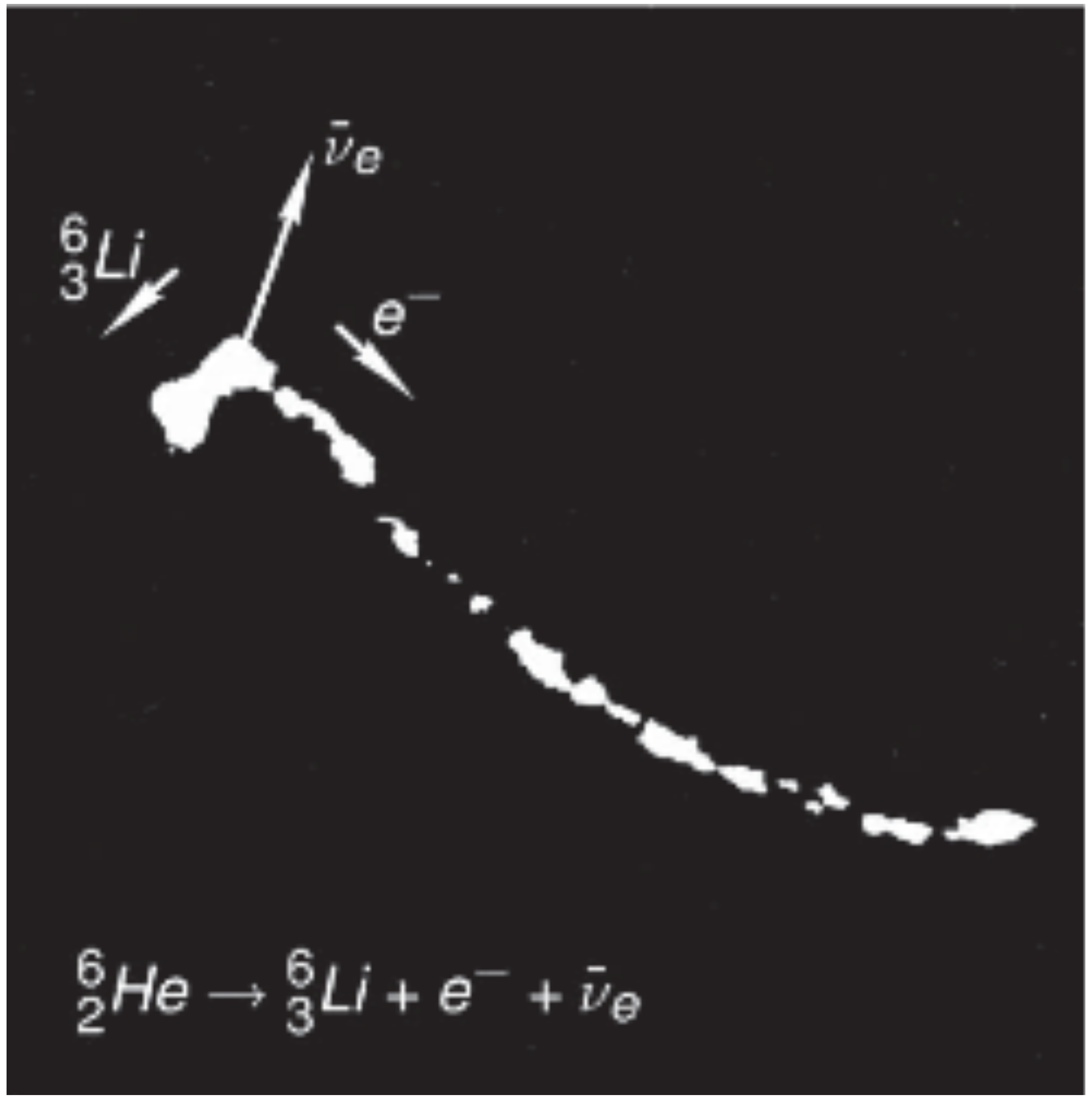


Historical note

- 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

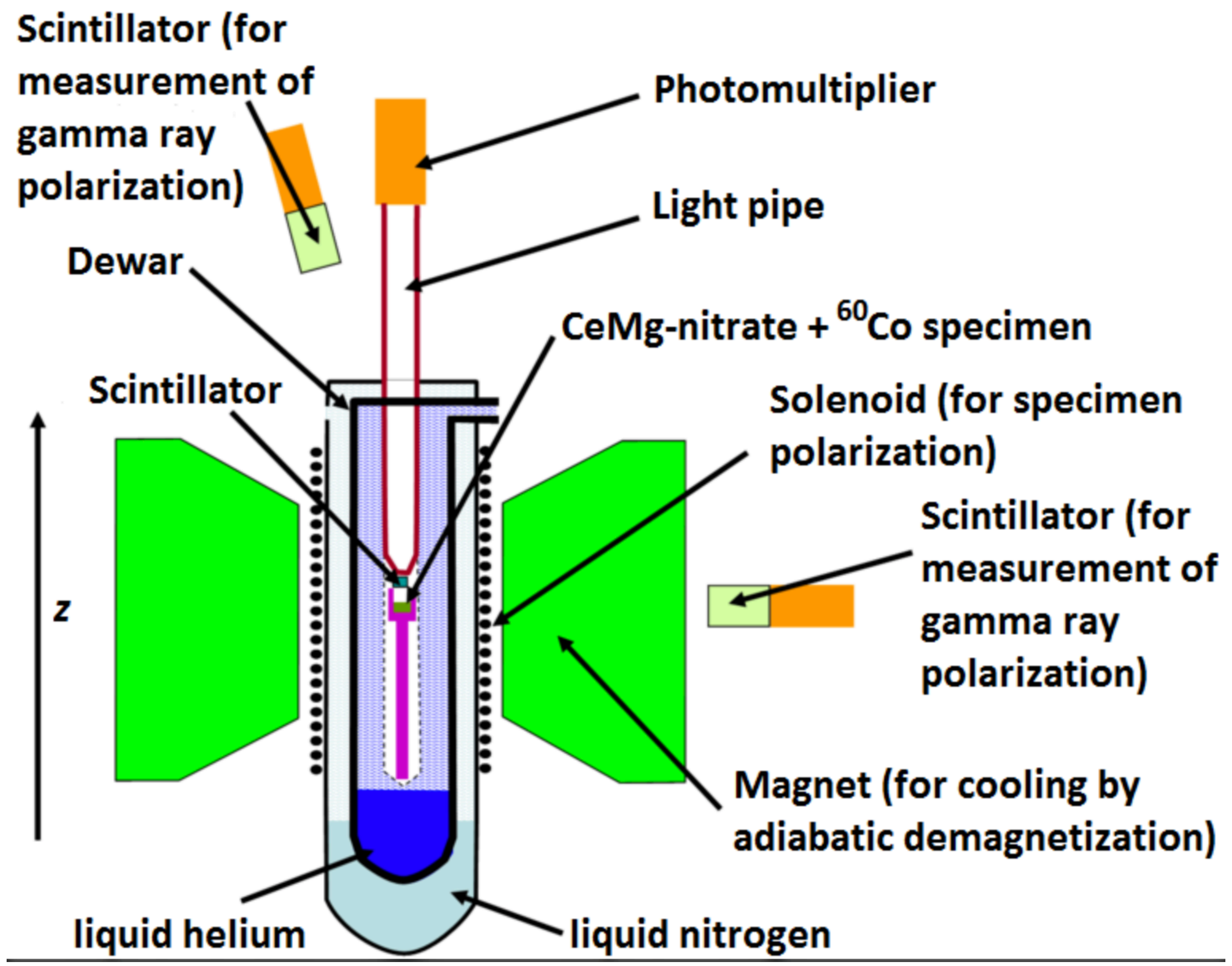
J. Csikai
A. Szalay

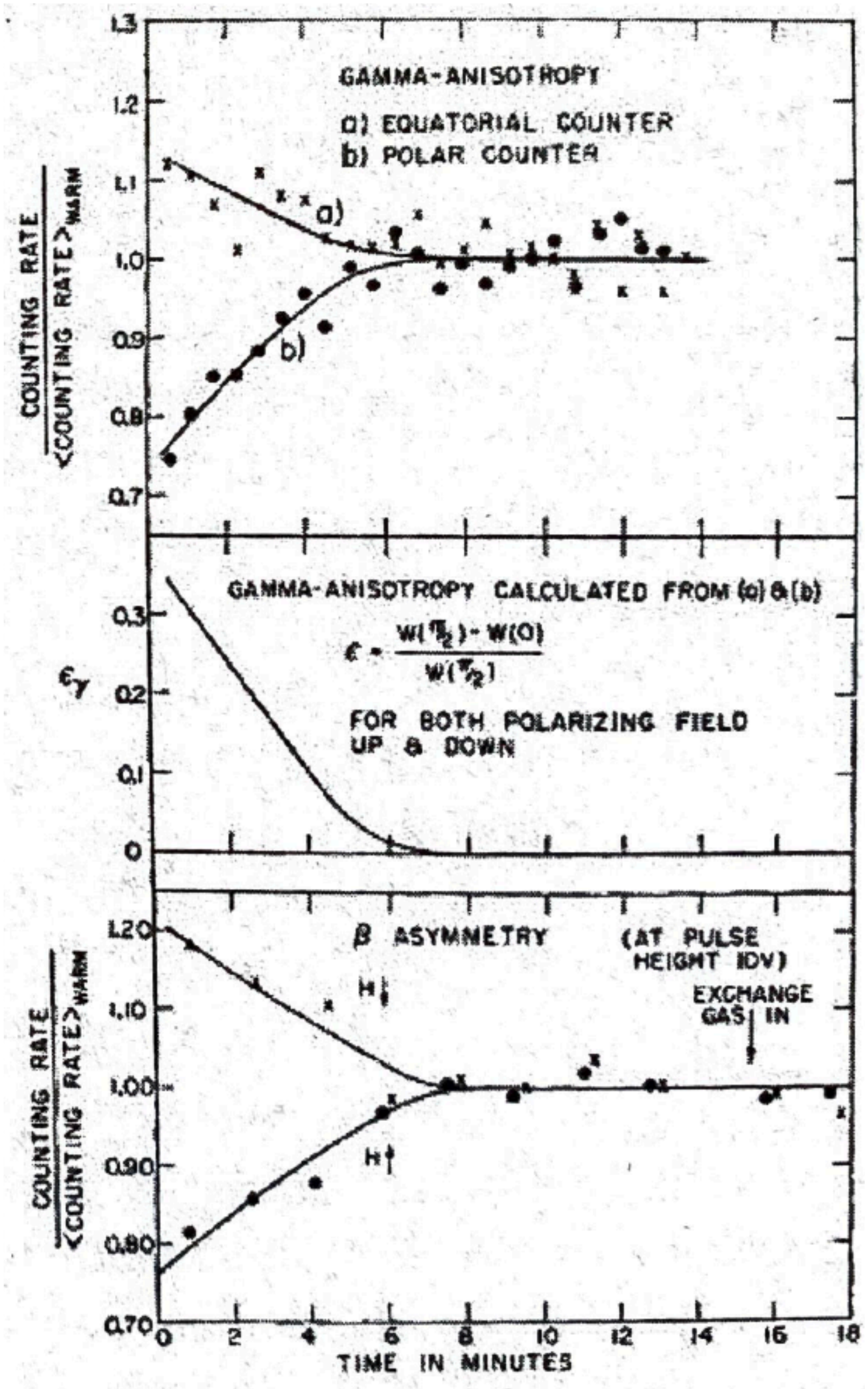
C. Budapest, fall 1956



Discovery of parity violation (1956)

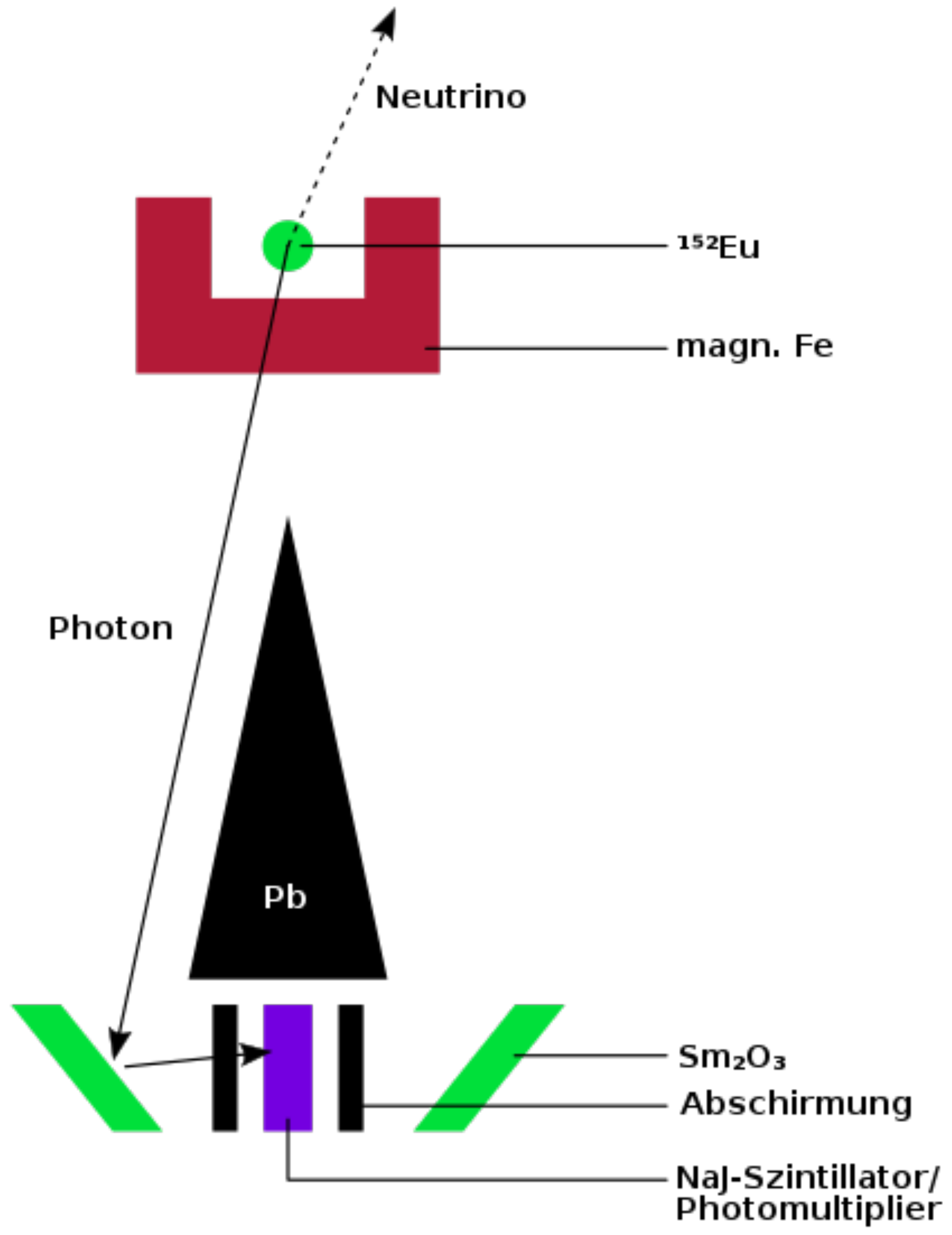
- **C.S. Wu (1956)**
  - She measures the angular distribution of e^- emitted in ultra-cold polarised ^{60}**Co** *β*-**decays** and discovers **parity violation**
    - She never got the Nobel prize she deserved





Neutrino helicity (1958)

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



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

$0^- + ½ = ½ + 1^-$

j_z … **p**

τ = **3 10^{-14} s**

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

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

p

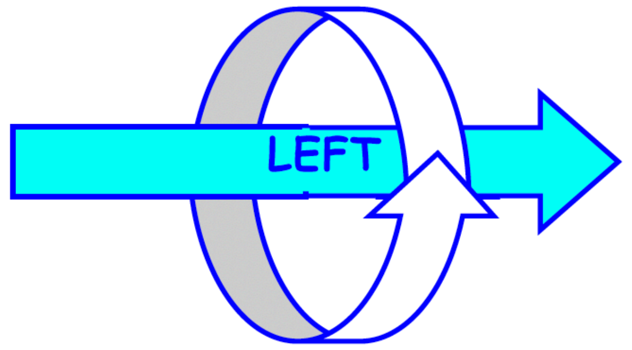
3 crucial points:

- 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

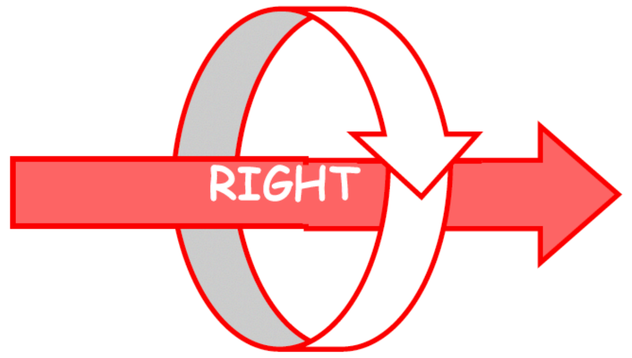
M. Goldhaber

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:

$$\Lambda^t g \Lambda = g \qquad \xi = \begin{pmatrix} \xi_1 \\ \xi_2 \end{pmatrix} \rightarrow L(\Lambda)\xi$$

- 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:

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

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

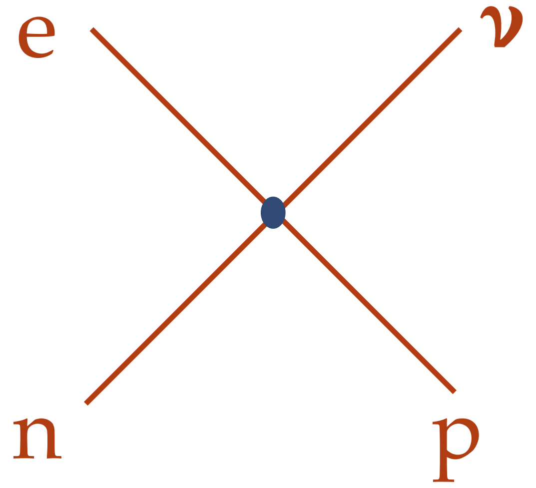
where:

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

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):

Phys.Rev. 109 (1958) 193-198

Developed after discovery of PARITY violation

$$\hat{J}^\mu = \bar{n}\gamma^\mu (g_V + g_A\gamma^5)p + \bar{\nu}\gamma^\mu(1-\gamma^5)e$$

"VECTOR" - "AXIAL" current

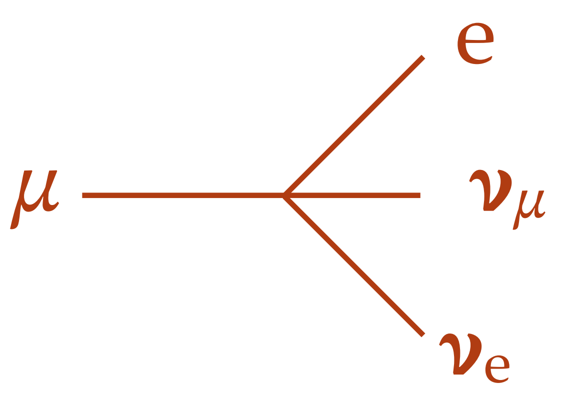
- Note 1: the ratio of axial/vector couplings to **leptons** is fixed by the theory
- Note 2: **that of hadrons is NOT**
  - We see later that the coupling to quarks is the same as that of leptons, **but strong interactions have substantial effects,** especially **on the axial coupling.**

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

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

$$K^+ \to \pi^+\pi^0$$ 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 yield:

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

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)

2 neutrino flavours (I)

- Experimental observations suggested that **muon** and **electron** share **identical weak couplings with matter**

$$n \longrightarrow p + e^- + \bar{\nu}$$ FERMI THEORY, BETA DECAY

- **Universal Fermi Interaction (1949)**

$$\mu^- + p \longrightarrow n + \nu$$ 1947 CONVERSI, PANCINI, PICCIONI

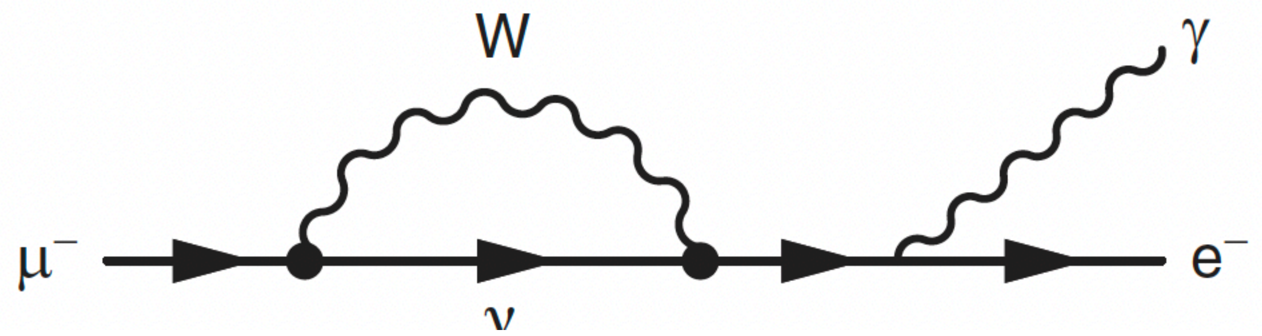
$$\mu \longrightarrow e + \nu + \bar{\nu}$$ 1948 J. STEINBERGER, PhD THESIS

- However, the “natural” **muon decay to electron and photon does not happen**

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

  - Are the two neutrinos the same particle?
    - If yes, why 2?
    - If no, what is the difference ?

With modern eyes, why this diagram does not work ?

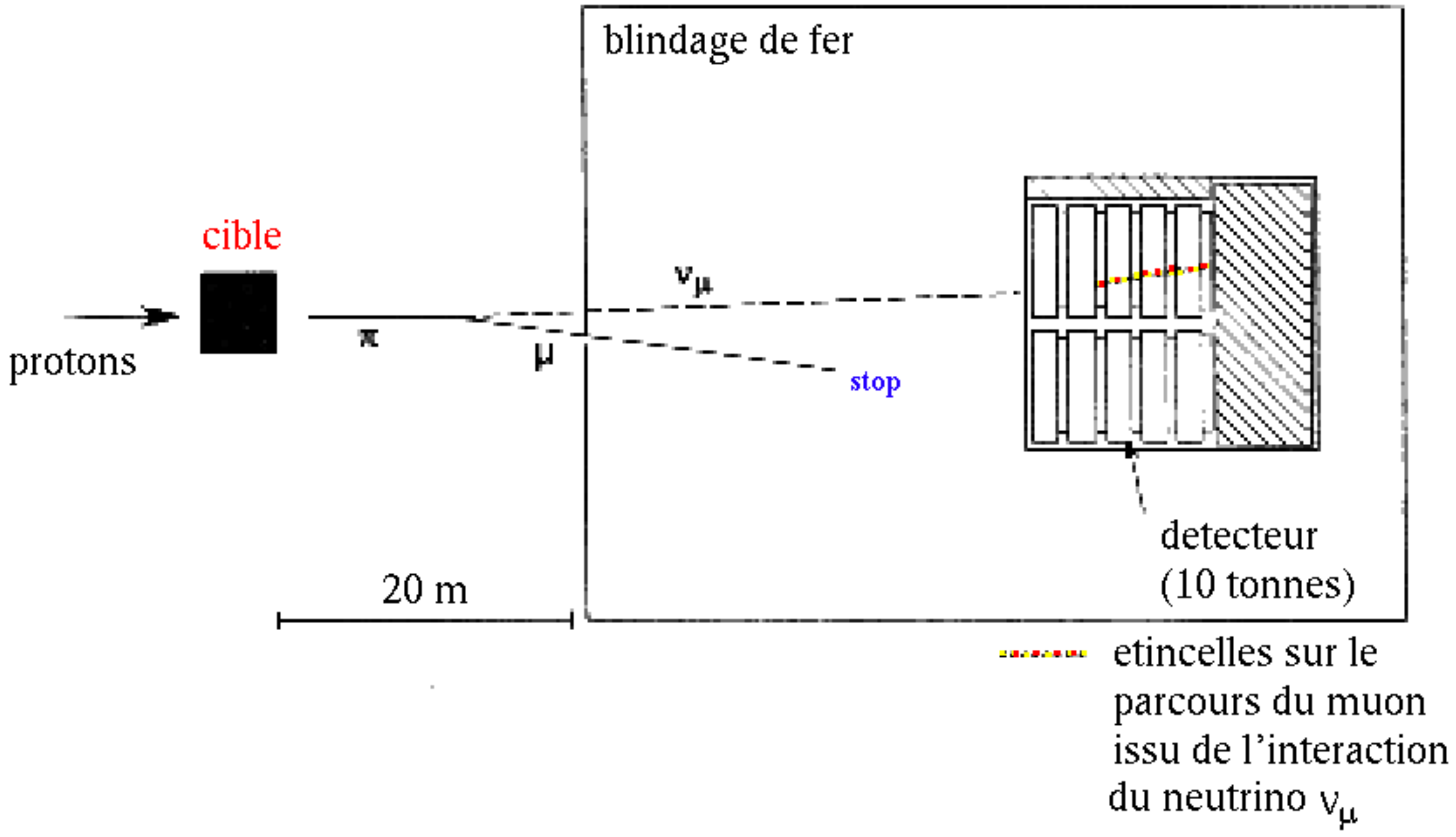


- B. Pontecorvo 1959: use neutrinos from pion decay to check if there is a real difference
- M. Schwartz 1960: use pions from an accelerator to get high energy neutrinos

2 neutrino flavours (II)

- How do we know that the neutrinos emitted in pion decay (accompanying a muon) is the same as in β decay ?

  - 1960: 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

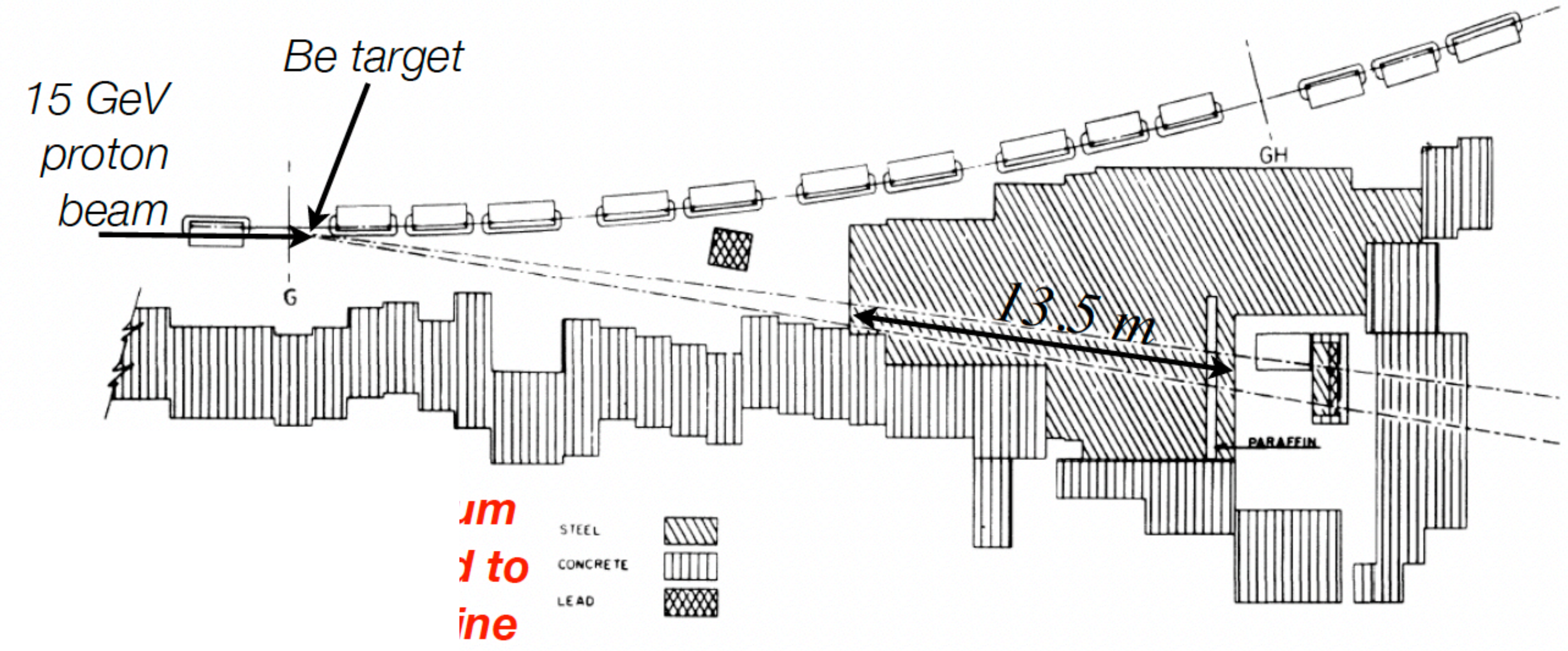


2 neutrino flavours (III)

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†

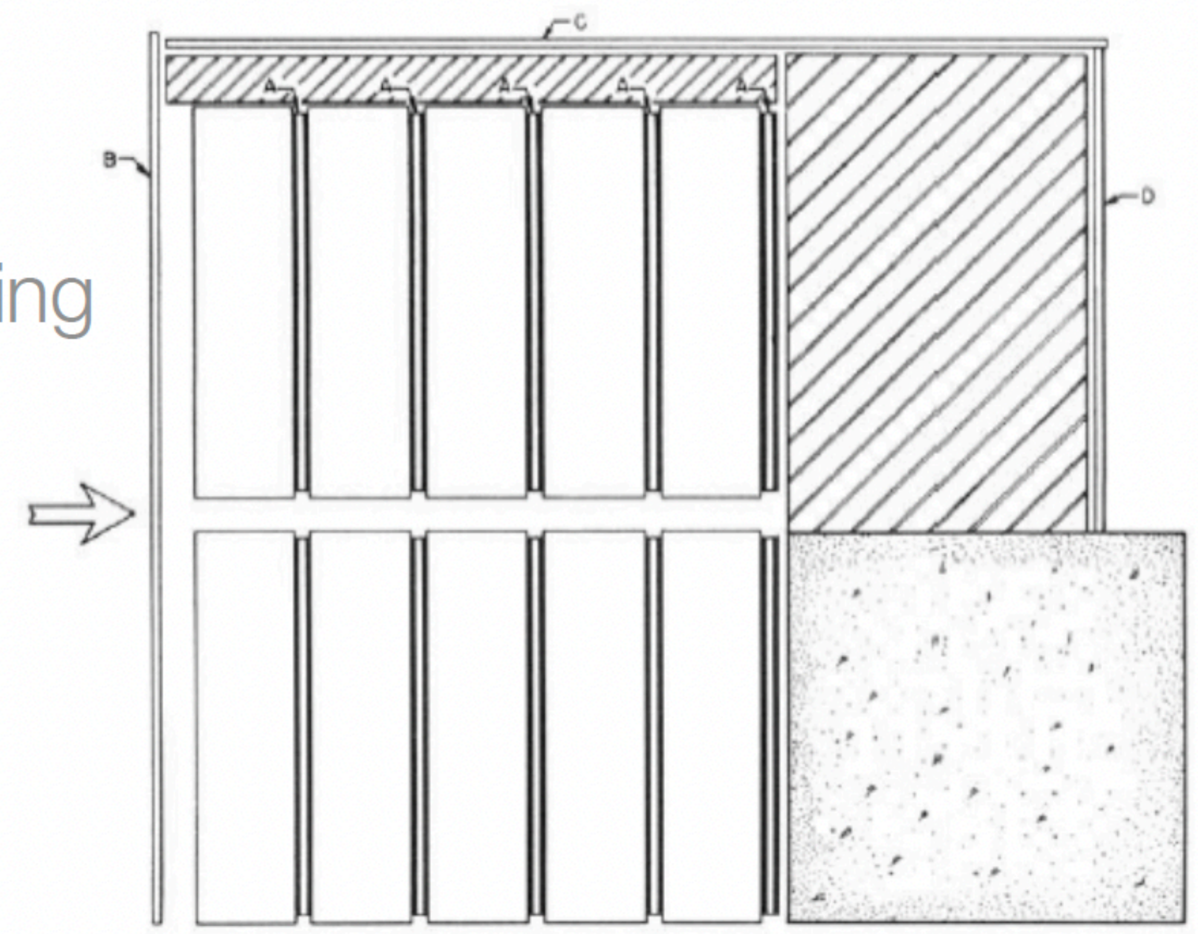
Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)



to the detector?

FIG. 1. Plan view of AGS neutrino experiment.

B,C,D vetos against entering tracks



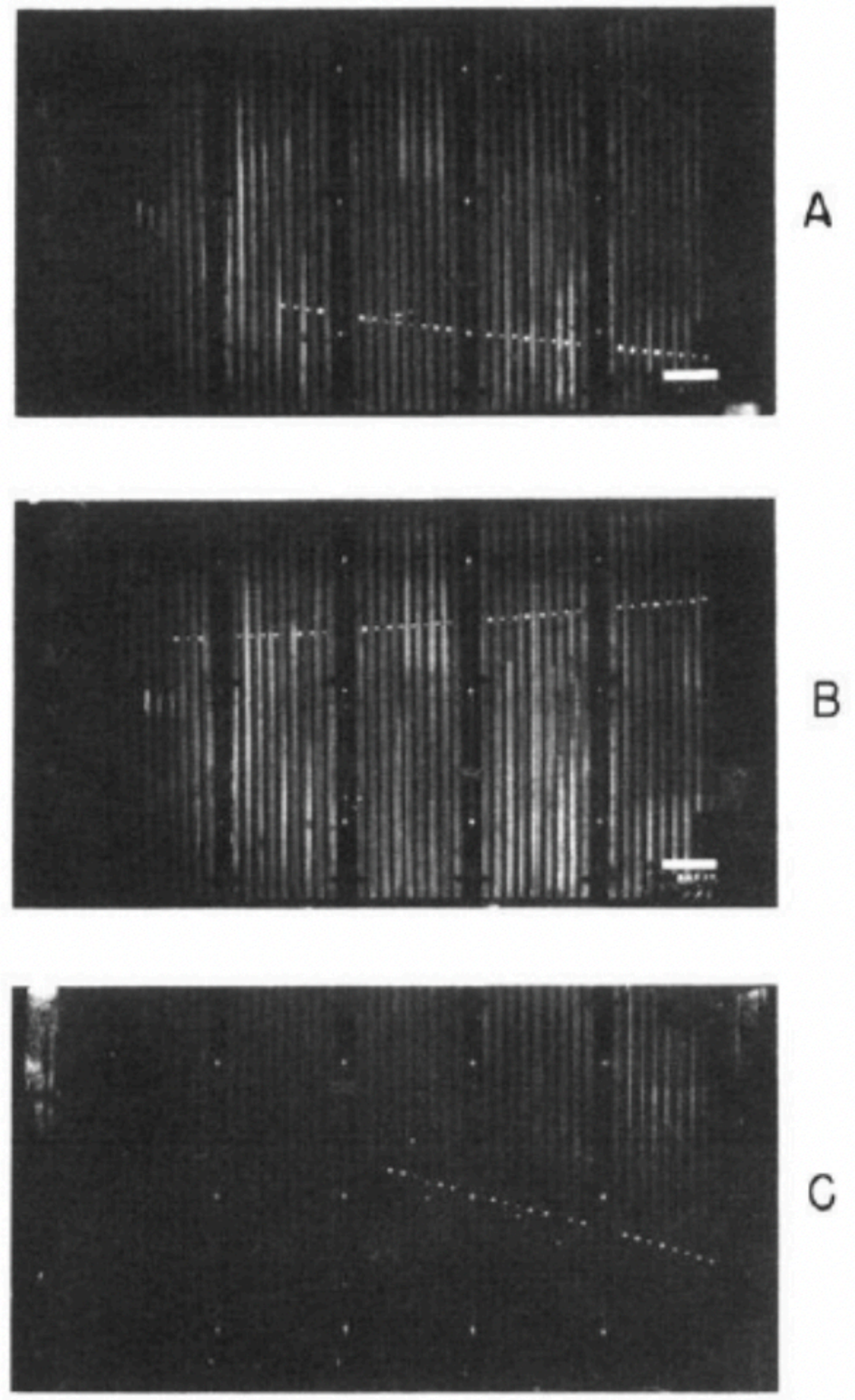
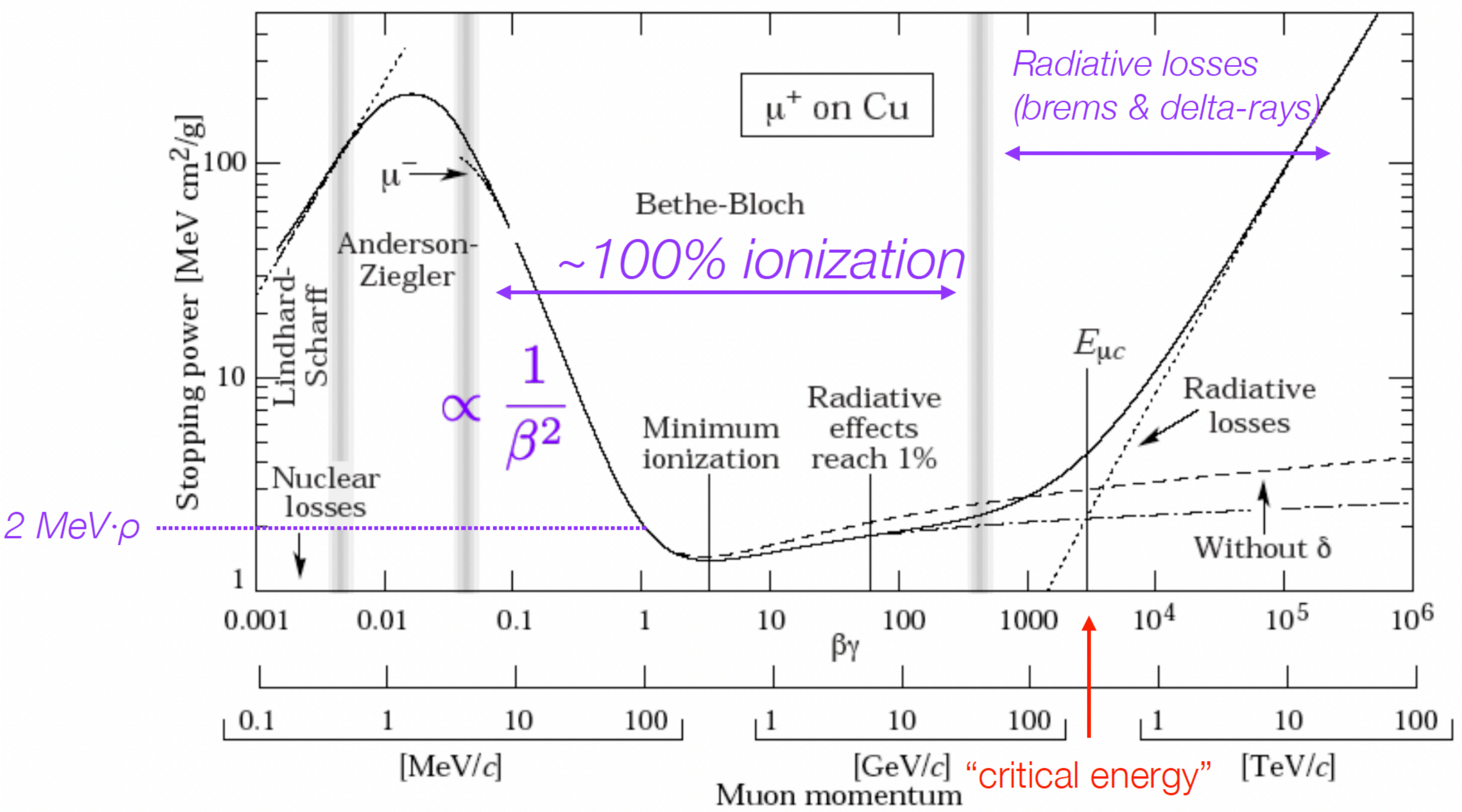


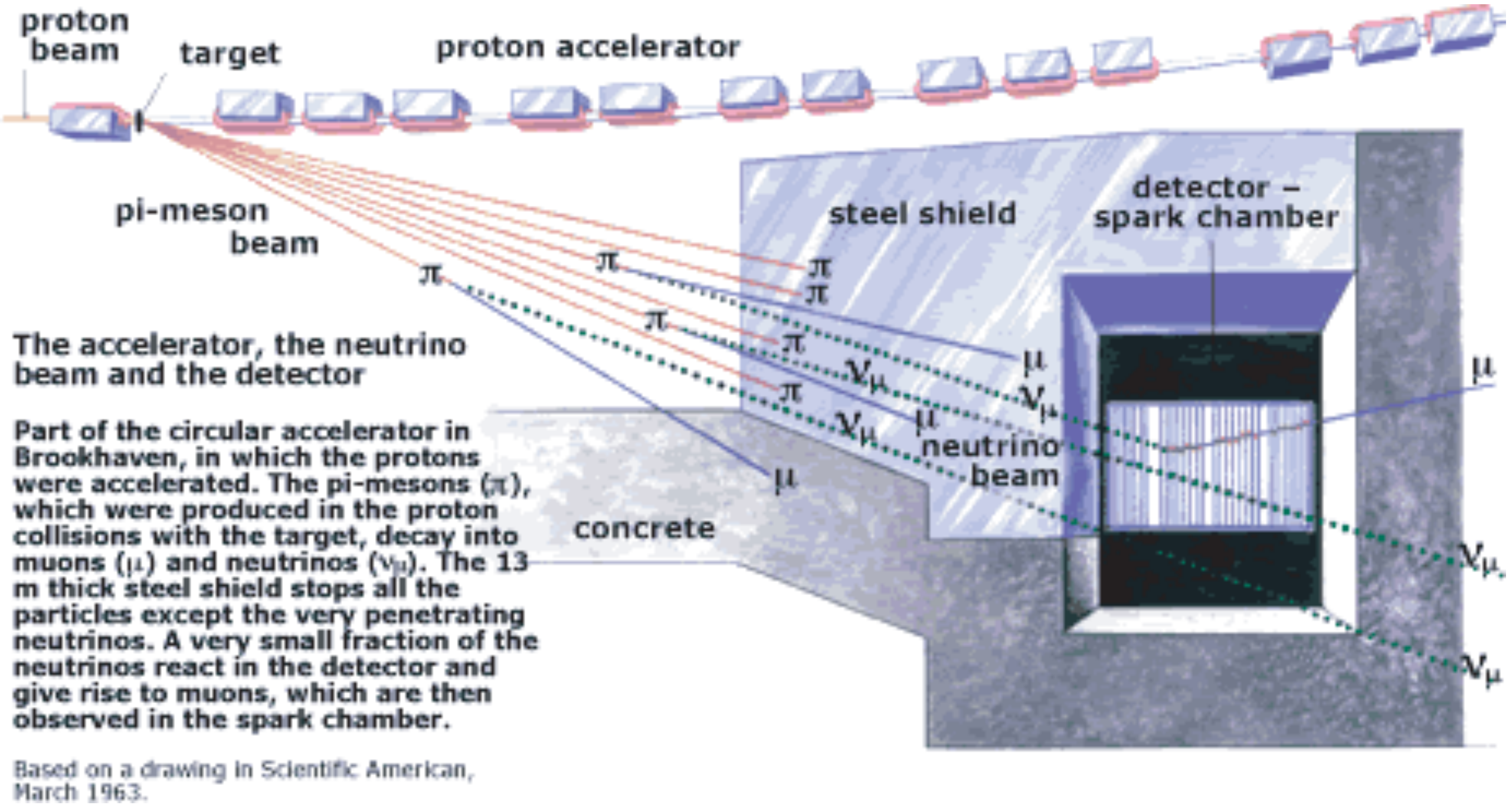
FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.

Intermezzo: Bethe-Bloch



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

2 neutrino flavours (IV)



- 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**

Hadronic weak decays

- Weak decays of hadrons are **affected by strong interactions.** We may classify the main hadronic weak matrix elements as:

  - **Leptonic decays:** $< 0|J_\mu^{(h)}|h >$ e.g. $\pi^+ \to \mu^+ \nu_\mu$
  - **Semi-leptonic decays:** $< h'|J_\mu^{(h)}|h >$ e.g. nuclear β decay, $\Lambda \to p e^- \bar{\nu}_e$
  - Semi-leptonic with **two hadrons in FS:** $< h'h''|J_\mu^{(h)}|h >$ e.g. $K^- \to \pi^+ \pi^- e^- \bar{\nu}_e$
  - **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. $\Lambda \to p\pi^-$

- 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.

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

- 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:

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

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)

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

3 QUARK families (f=1..3)

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

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

$$\mathcal{L}_k = i\bar{\ell}_L^f \partial\!\!\!/ \ell_L^f + i\bar{q}_L^f \partial\!\!\!/ q_L^f + i\bar{e}_R^f \partial\!\!\!/ e_R^f + i\bar{\nu}_R^f \partial\!\!\!/ \nu_R^f + i\bar{u}_R^f \partial\!\!\!/ u_R^f + i\bar{d}_R^f \partial\!\!\!/ d_R^f$$

- $\mathcal{L}_{cc}$ is the coupling term of fermions to charged W **(charged current)**

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\bar{\nu}_L^f \gamma^\mu e_L^f + V_{fg}^{CKM} \bar{u}_L^f \gamma^\mu d^g \right) W_\mu^+ + h.c.$$

- $\mathcal{L}_{nc}$ 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:**

$\psi_1 = e_R \ (\mathbf{1}, -2)$	$\psi_2 = \ell_L \ (\mathbf{2}, -1)$	$\psi_3 = u_R \ (\mathbf{1}, 4/3)$	$\psi_4 = d_R \ (\mathbf{1}, -2/3)$	$\psi_5 = q_L \ (\mathbf{2}, 1/3)$
SU(2) singlet, Y=-2	**SU(2) doublet, Y=-1**	**SU(2) singlet, Y=4/3**	**SU(2) singlet, Y=-2/3**	**SU(2) doublet, Y=⅓**

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

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

- Which correspond to the 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

$$J_Y^\mu = \sum_{k=1}^5 \frac{Y_k}{2} J_k^\mu$$ **$U_Y(1)$ 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:
  - $J_Y^\mu \quad J_b^\mu \quad J_\ell^\mu$ remain conserved currents, in agreement with observations
  - $J_{b5}^\mu \quad J_{\ell 5}^\mu$ 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 baryon 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:

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

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

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

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 $\overline{\nu}_R$, not to ν_R and $\overline{\nu}_L$
    - Right-handed components of all fermions are $SU_Y(2)$ 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:

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

  - **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: $-\frac{1}{2}M\,(\bar{\nu}_R^c\nu_R + \bar{\nu}_R\nu_R^c)$
    - In general, the mass term can be:

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

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

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 ~ 200 GeV** and **M ~ 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:

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

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

with very small θ: ν_1 is an almost pure very heavy right handed neutrino and ν_2 is the SM 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 (**P**ontecorvo **M**aki **N**akagawa **S**akata, PMNS):

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

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

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

Neutrino - electron interaction

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

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

$$T'_e = E'_e - m_e = E'_\nu - E_\nu$$

- 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.

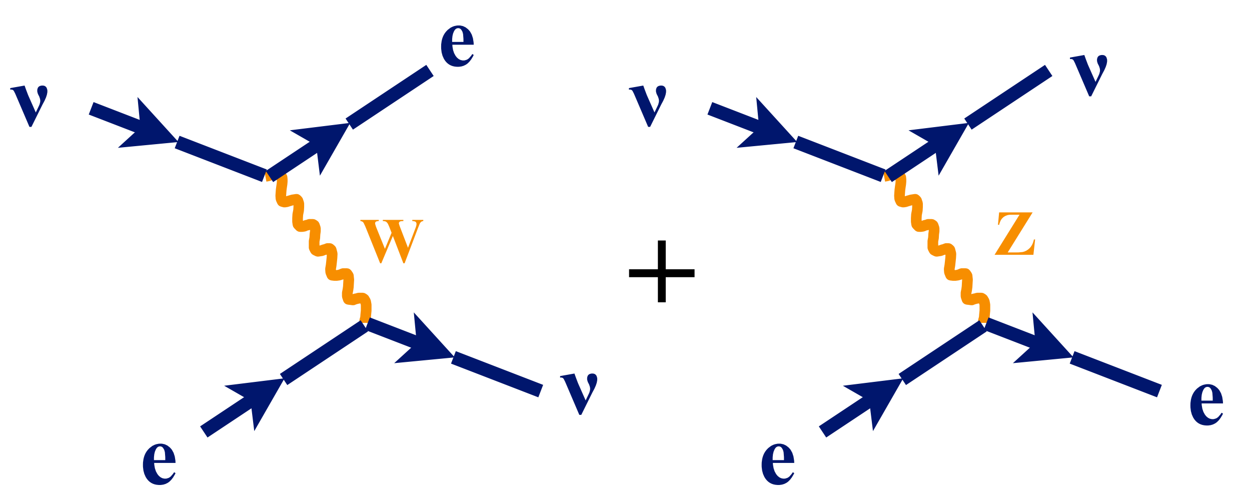
TREE level cross sections $\sin^2\theta_W = 0.2312$ $\overline{\text{MS}}$

	c_L	c_R	σ [10^{-44} cm^2]
$\nu_e\, e^-$	$\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$	0.95 E_ν [MeV]
$\nu_\mu\, e^-$	$-\frac{1}{2} + \sin^2\theta_W$	$\sin^2\theta_W$	0.16 E_ν [MeV]
$\bar\nu_e\, e^-$	$\sin^2\theta_W$	$\frac{1}{2} + \sin^2\theta_W$	0.23 E_ν [MeV]
$\bar\nu_\mu\, e^-$	$\sin^2\theta_W$	$-\frac{1}{2} + \sin^2\theta_W$	0.078 E_ν [MeV]

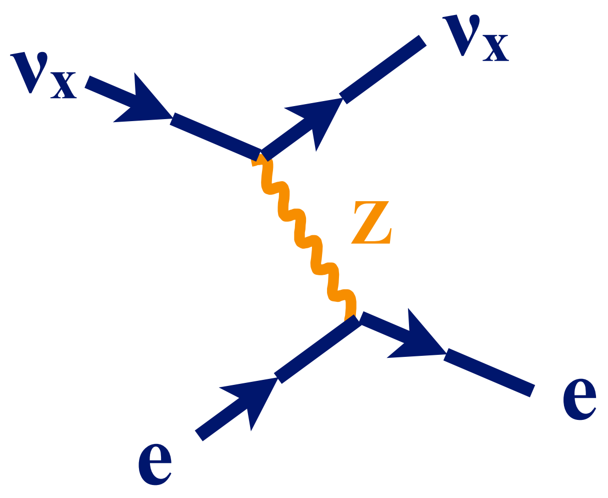
- **QED** and **EW radiative corrections** are at **few %** level and **are relevant** for high precision solar neutrino experiments and future experiments.

Example: neutrino detection in Borexino

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

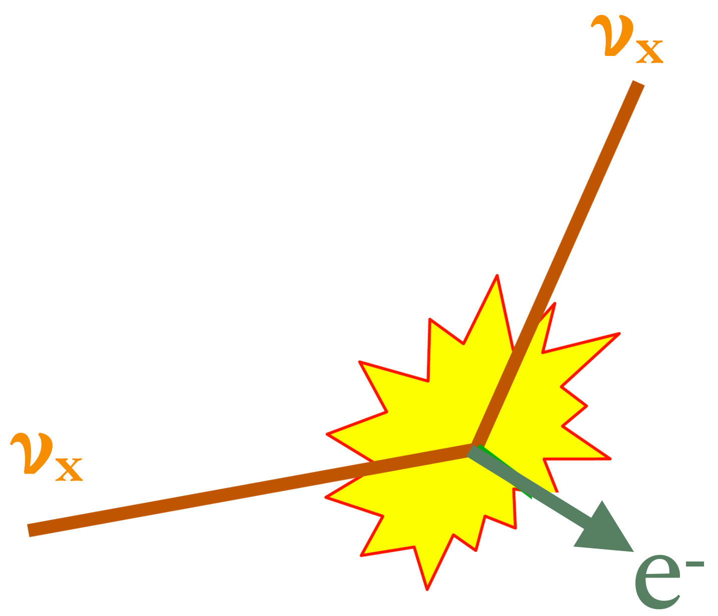


$$\xi = \sin^2\theta_W \simeq 0.23$$



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

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

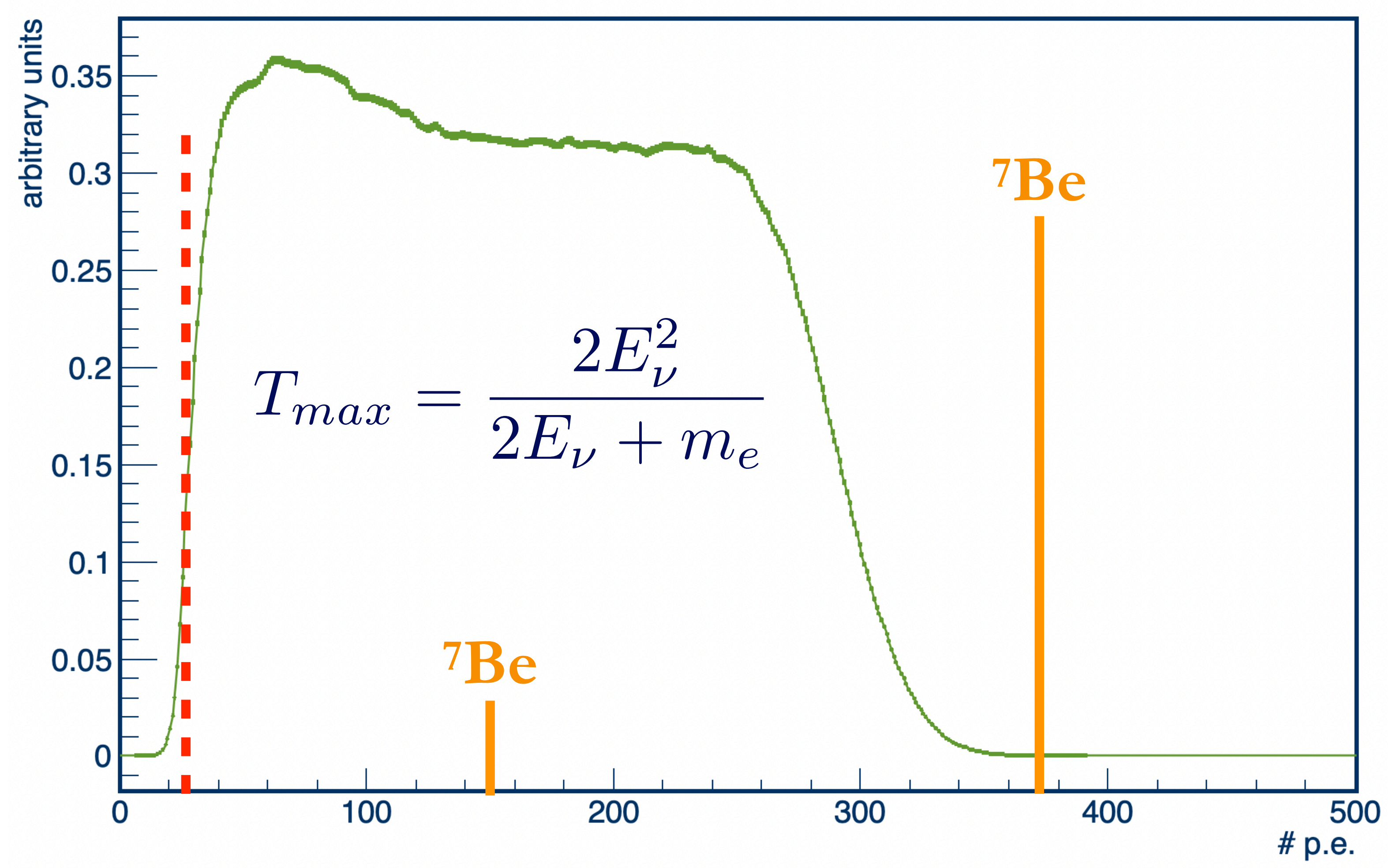


$$\sigma(\nu_x e^-) = \frac{G_F^2 s}{\pi}\left[\left(\frac{1}{2}-\xi\right)^2 + \frac{\xi^2}{3}\right]$$

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

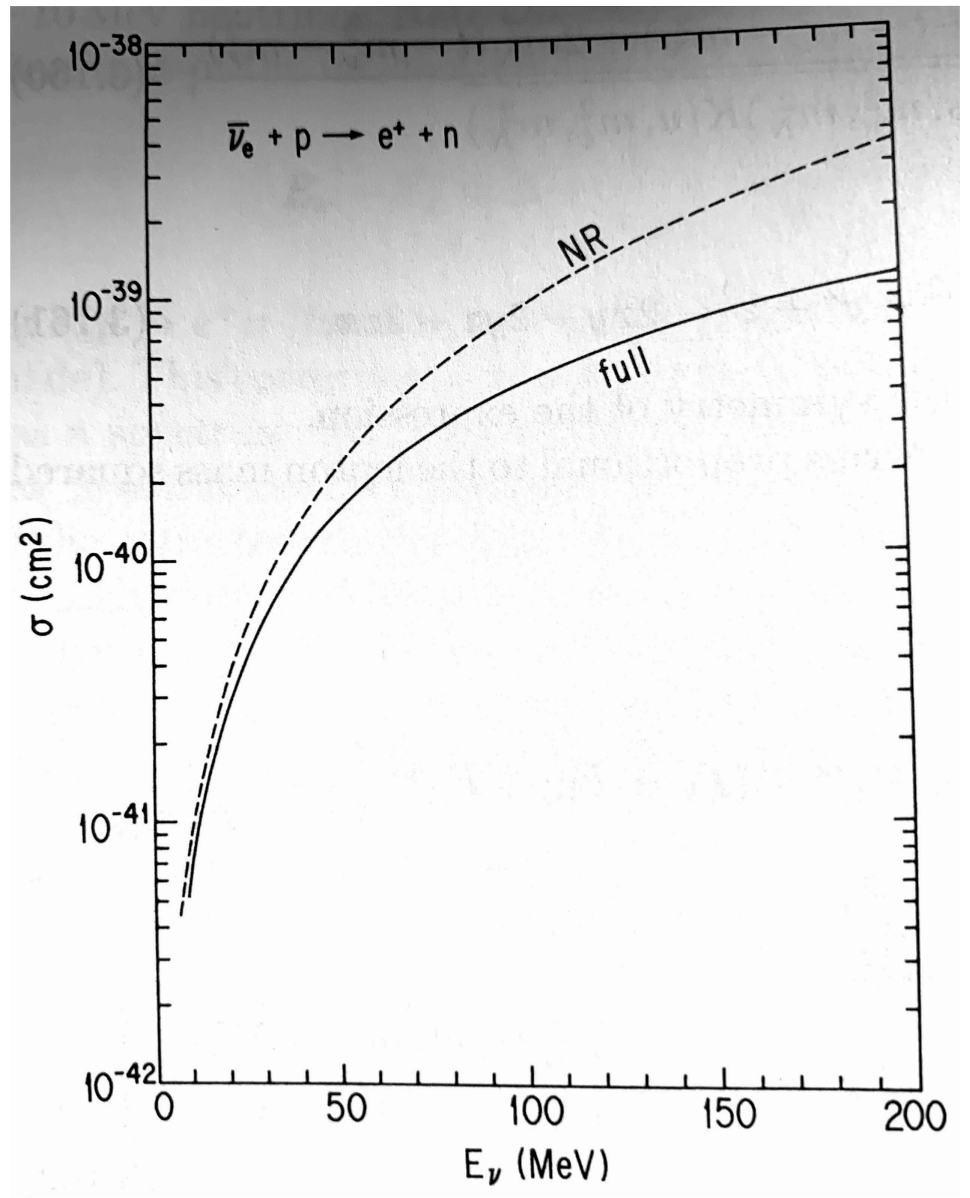
- CC ν-nucleon scattering is, for historical reasons, called "inverse β decay" (also, quasi-elastic)
  - At low E_ν ($\lesssim$ 100 MeV), only ν_e are active, being μ and τ too heavy

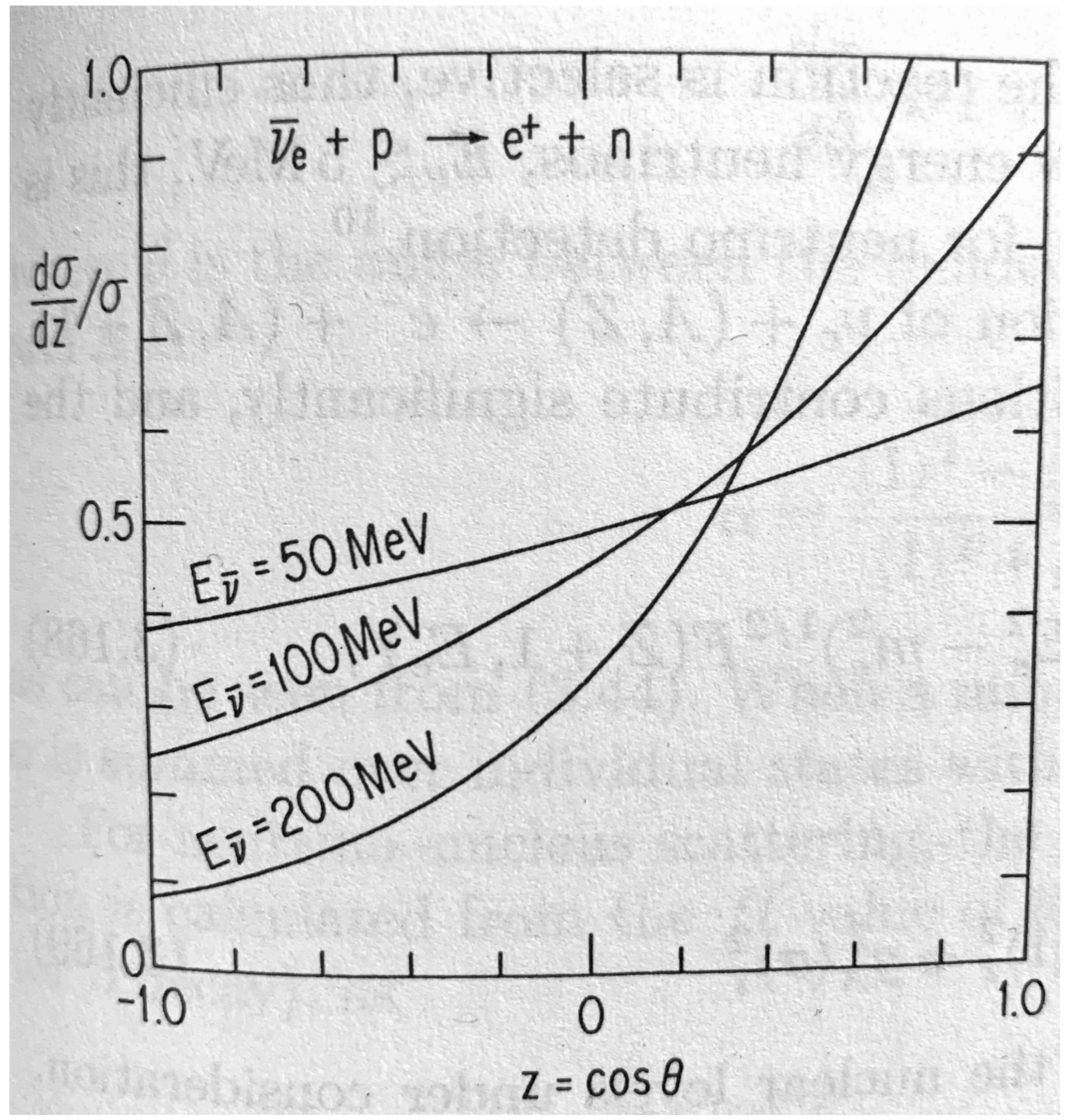
$$\bar{\nu}_e + p \to e^+ + n \qquad \nu_e + n \to e^- + p$$

  - At very low E_ν ($\lesssim$ 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_ν ~ 30 - 100 MeV the nucleon form factors become important. Without writing full formulas we show the plots:





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)**

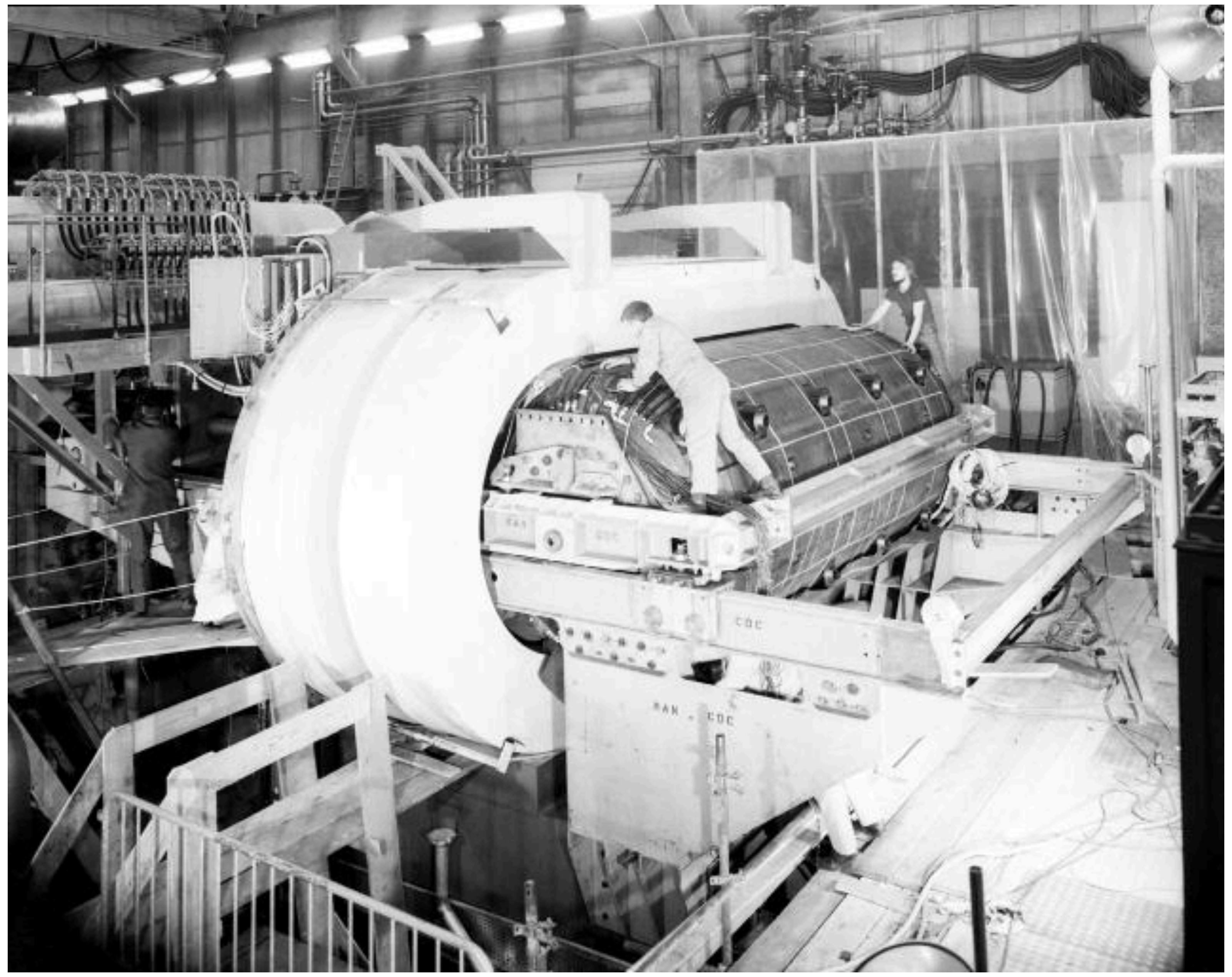
Gargamelle experiment

- 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

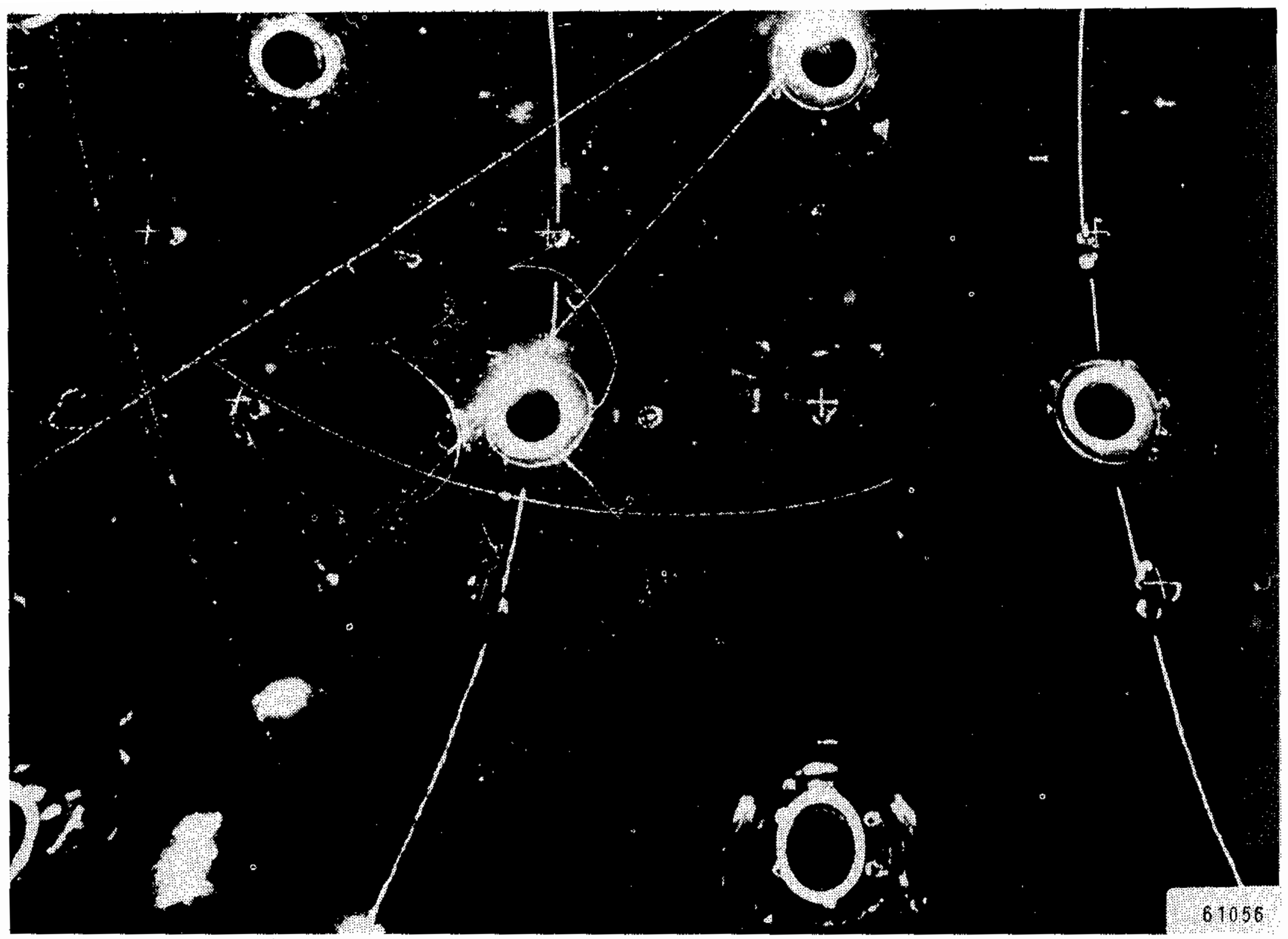
  - The fast, high volume, and high density **bubble chamber,** to visualise events
    - 6.2 m^3 of liquid freon **(CF_3Br)** with a **density of 1.5 g/cm^3**

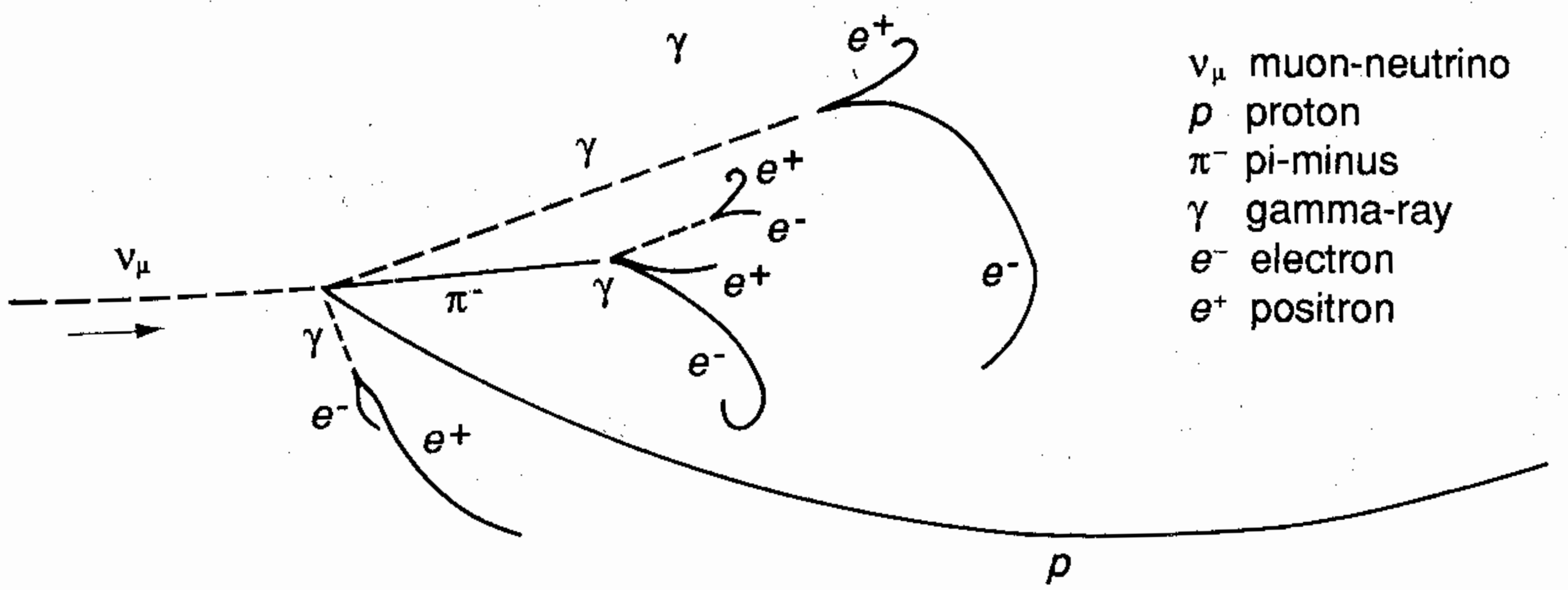
  - Ideas that are **still the key of more modern efforts** such as SBN at Fermilab, DUNE, T2K, HK



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
  - ν 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 electron, 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**

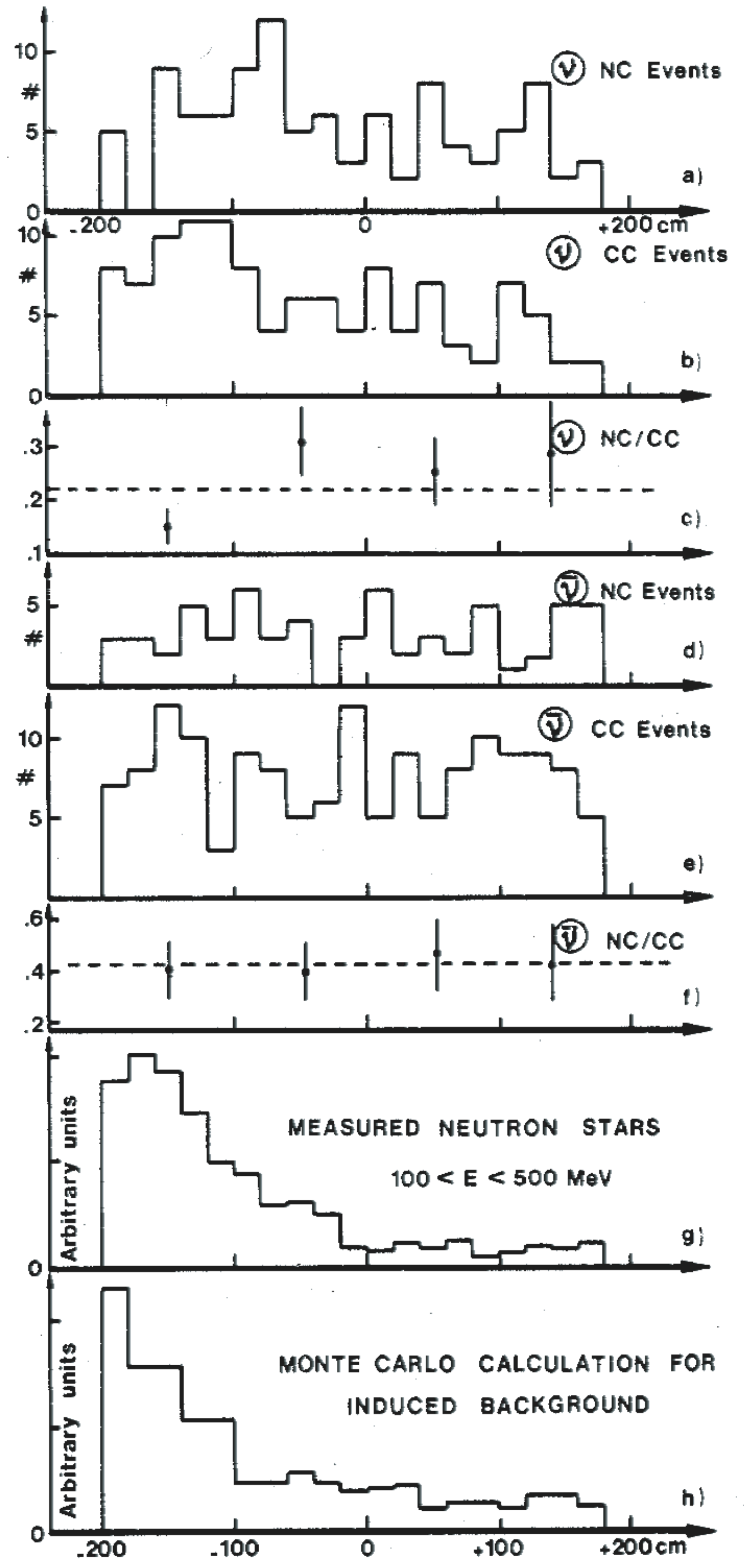


Fig. 1. Distributions along the ν-beam axis. a) NC events in ν. b) CC events in ν (this distribution is based on a reference sample of ~ 1/4 of the total ν film). c) Ratio NC/CC in ν (normalized). d) NC in $\bar{\nu}$. e) CC events in $\bar{\nu}$. f) Ratio NC/CC in $\bar{\nu}$. g) Measured neutron stars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

Three neutrinos: from cosmology

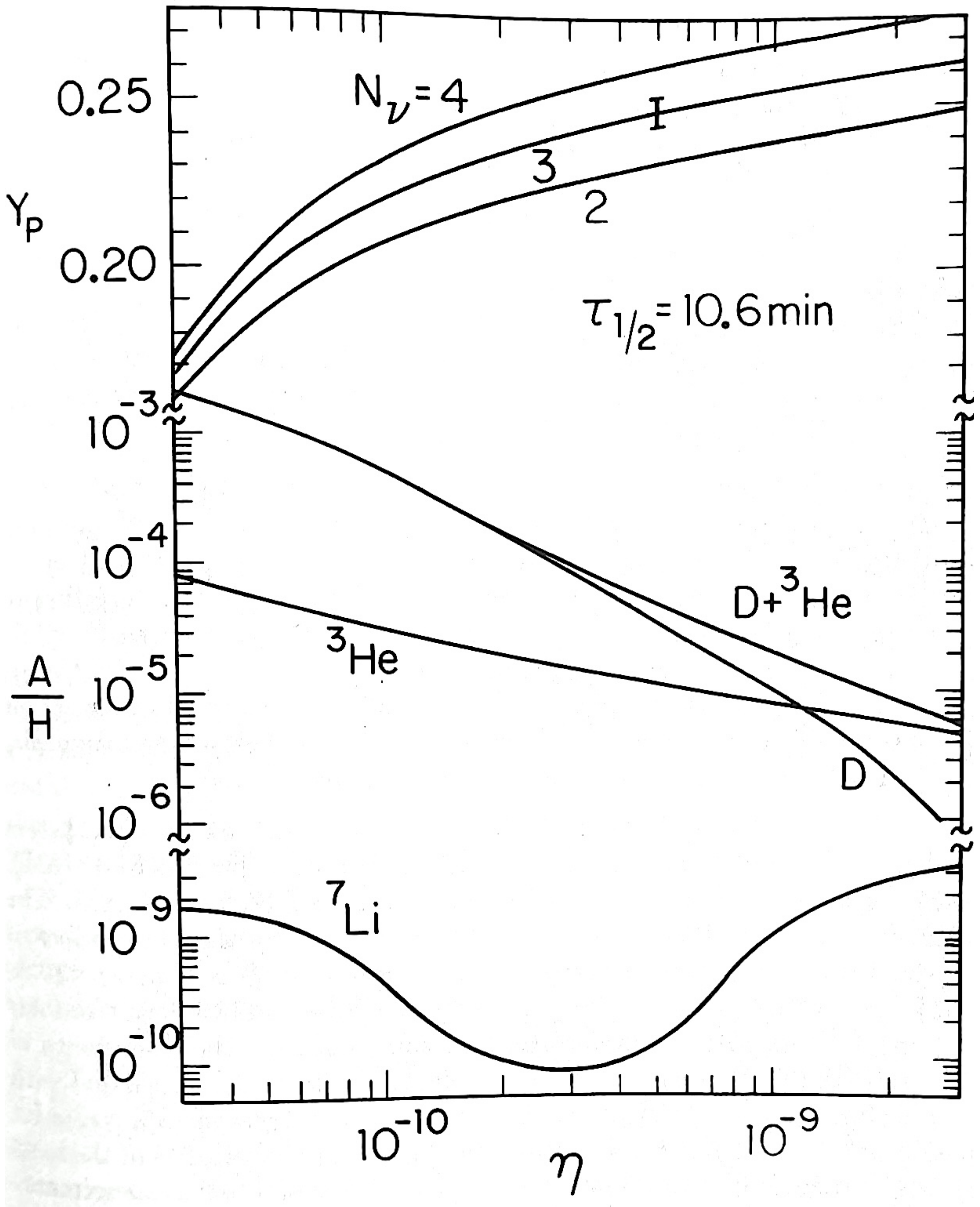
- With the simplifying conditions of:
  - **isotropy** and **homogeneity**
  - **thermal equilibrium**
  - particle content **SM of particle physics**
- and assuming expansion is governed by General Relativity (FRW metric), the **big bang nucleosynthesis (BBN) is a one parameter model dependent only on the baryon-to-photon ratio, η, at that epoch.**
- Data, already in the late 80s, showed that the measured helium abundance with the observed **η strongly favours $N_\nu = 3$**

$$\eta = \frac{n_b}{n_\gamma} = 2.74\ 10^{-8}\ \Omega_b h^2$$

$$H_0 = h \cdot 100\ km\ s^{-1} Mpc^{-1} \qquad \Omega_b h^2 \simeq 0.01 - 0.02$$

- Cosmological approach still very useful:
  - **Can constraint also light "sterile" neutrinos,** i.e. species not coupled in SM (e.g. right handed neutrinos)
  - Constraints have still significant uncertainties but **light additional neutrinos beyond the 3 SM ones are ofter disfavoured**

Helium abundance Y_p as function of number of SM neutrinos N_ν



Klob-Turner, 1990

Three neutrinos: from Z line shape at Large Electron-Positron collider (LEP)

- The precise measurement of **Z^0 "line shape"** yields a precise measurement of the **number of SM neutrinos species**
- Basic idea:
  - Total width **measured** directly by varying $\sqrt{s}$ = c.o.m. energy
  - Total width can be **computed** as sum of partial widths

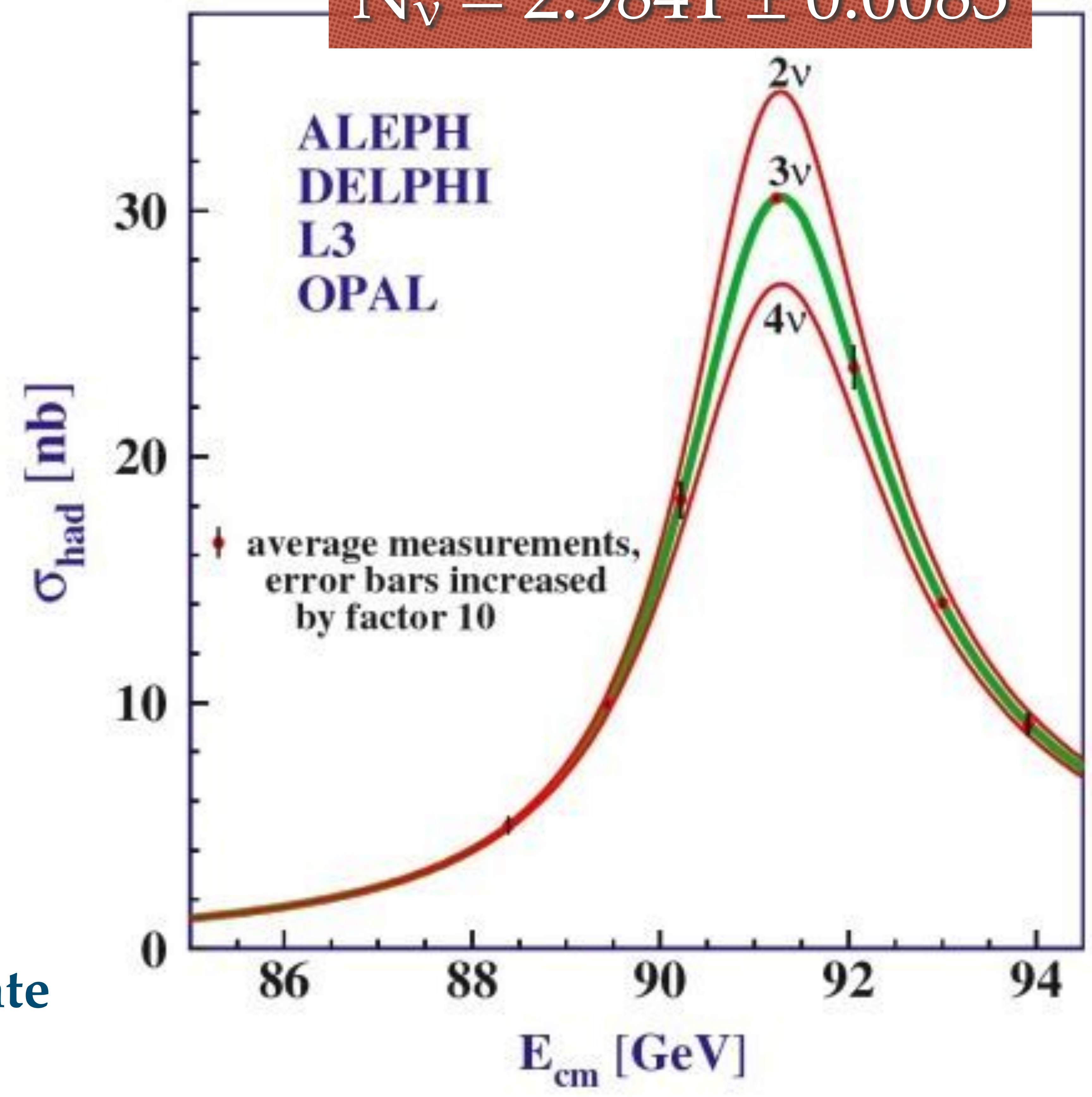
$$\Gamma_Z = \Gamma_{e\bar{e}} + \Gamma_{\mu\bar{\mu}} + \Gamma_{\tau\bar{\tau}} + \Gamma_{had} + N_\nu \Gamma_{\nu\bar{\nu}}$$

  - The individual partial widths can be computed and **all but the two neutrinos** one can be measured: e.g.

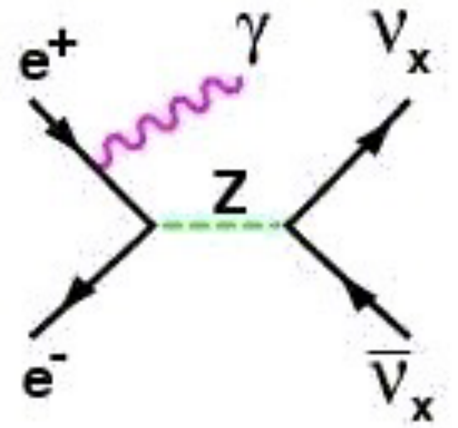
$$\sigma_{q\bar{q}} = \frac{12\pi}{M_Z^2} \frac{s\Gamma_{e\bar{e}}\Gamma_{q\bar{q}}}{(s-M_Z^2)^2 + \frac{s^2\Gamma_Z^2}{M_Z^2}} \quad \xrightarrow{\sqrt{s} = M_Z} \quad \sigma^p_{q\bar{q}} = \frac{12\pi}{M_Z^2} \frac{s\Gamma_{e\bar{e}}\Gamma_{q\bar{q}}}{\Gamma_Z^2}$$

Γ_{had} measured adding up all events with hadrons in the final state

$N_\nu = 2.9841 \pm 0.0083$



  - **L3** has also obtained an independent measurement from the same line shape by checking how it is deformed by **QED corrections with a photon in the final state**

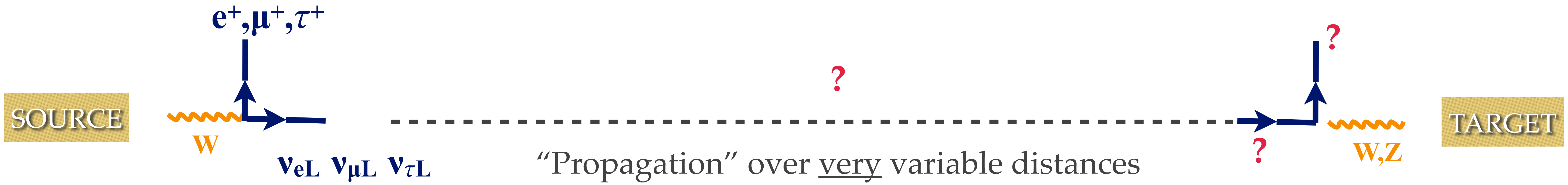


~ 700 single photon events $E_\gamma > 1$ GeV (out of millions of Zs) in LEP Phase 1

$N_\nu = 2.98 \pm 0.10$ [L3]

Neutrino propagation

CHIEFLY:
- nuclear $\beta^{\pm}$ decay
- e^-, μ^- nuclear capture
- $\mu^{\pm}$, $\tau^{\pm}$, $\pi^{\pm}$ decay

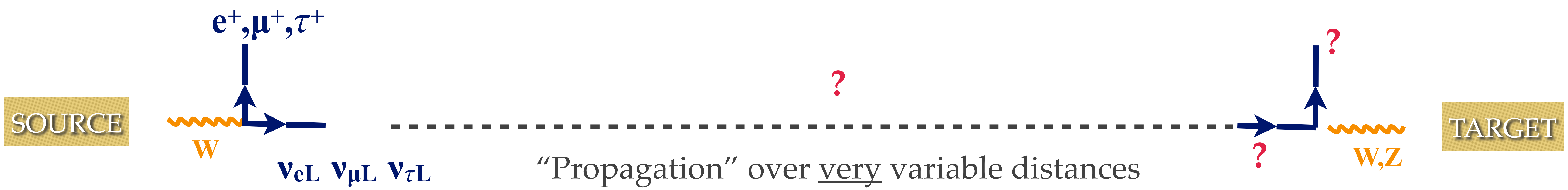


"Propagation" over <u>very</u> variable distances
[from 1 fm in $0\nu\beta\beta$ up to 50 kpc SN1987a]

36 orders of magnitude

Neutrino propagation

CHIEFLY:
- nuclear $\beta^{\pm}$ decay
- e^-, μ^- nuclear capture
- $\mu^{\pm}$, $\tau^{\pm}$, $\pi^{\pm}$ decay



"Propagation" over very 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(m² L / E)**
    - Observed with the right L and m²/E values
  - Propagation in matter (Earth, Sun, neutron star cores) may amplify oscillations
  - In principle: **EPR** long distance correlation on flavour; in practice, **no way,** cross section too small to correlate two events.

Example: you might seek at reactors:

$$\nu_e + p \rightarrow e^+ + n$$ ✗ (not seen)

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:

$$L \simeq t; \qquad E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2E} \quad \Rightarrow \quad |\nu_\alpha(L)\rangle \simeq \sum_{i=1}^{n} U^*_{\alpha i}\,\exp\left(-i\frac{m_i^2}{2E}L\right)|\nu_i(0)\rangle$$

- 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:**

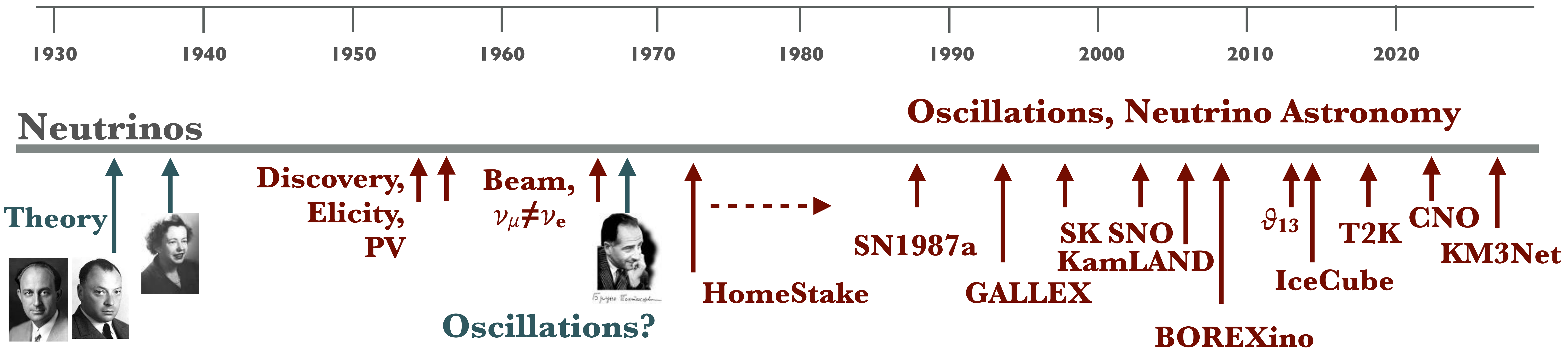
$$\xi_i^{\alpha\beta} = U^*_{\alpha i}U_{\beta i}; \qquad \epsilon_i = \frac{m_i^2}{2E}.$$

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

- **DISCLAIMER:** This calculation, reported almost everywhere, is **WRONG. Plane waves have exactly defined 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



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

KM3Net

$|\Delta m^2| = 2.47 \pm 0.04\ 10^{-3}$ 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

$\theta_{12} = 33.6 \pm 0.77°$

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

Atmospheric
Accelerators LBL
L ~ 700 km

Reactors L ~ 1 km
LBL L ~ 200 km

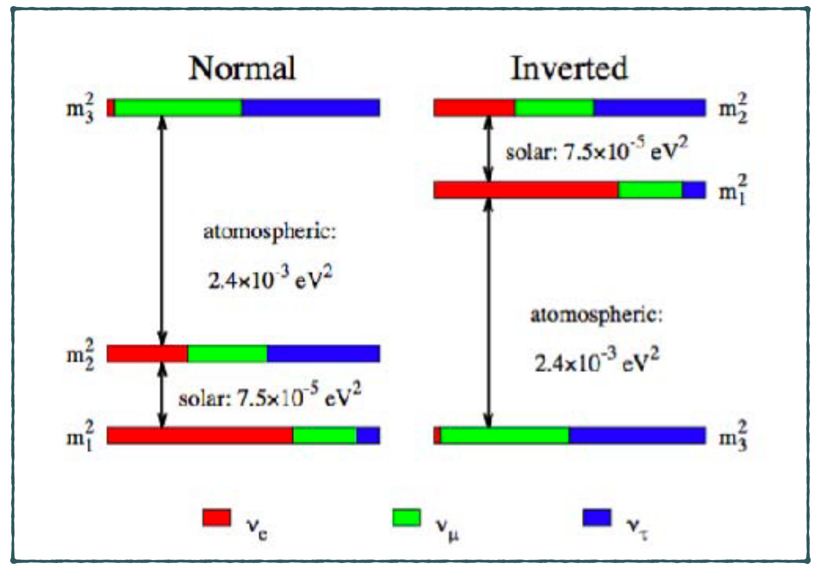
Solar
Reactors
L ~ 200 km

$0\nu\beta\beta$

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

$\nu \neq \bar{\nu}$?



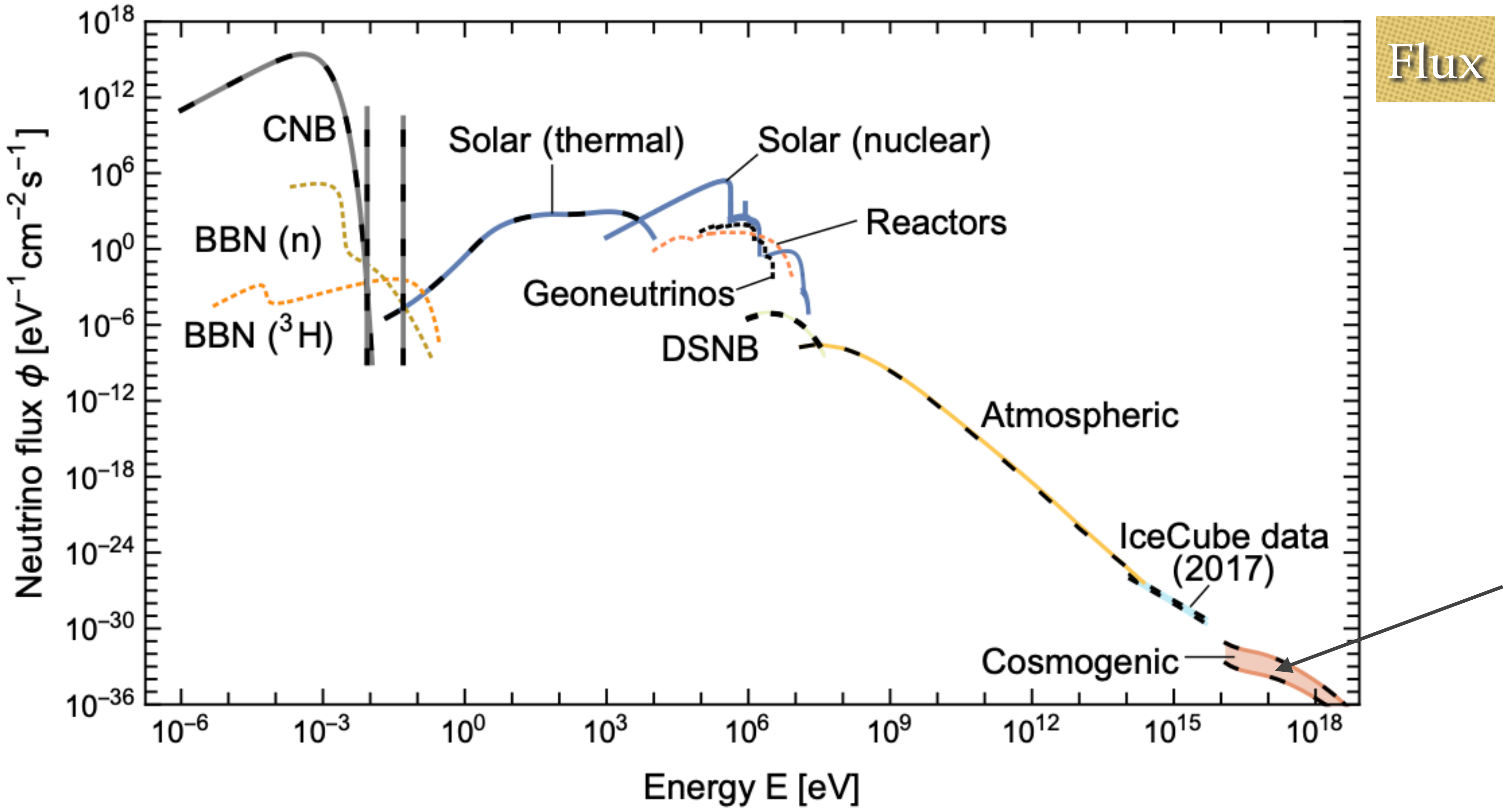
Dirac vs Majorana ($\nu \neq \bar{\nu}$?)	**0νββ**
U_{PMNS} unitary? **$\delta_{CP} \neq 0$?** **$\Delta m^2 > 0$?** **ϑ_{23} maximal? Octant ?**	**OSCILLATIONS**
Absolute Mass scale	**Spectrometers, μBolometers, EUCLID**
Astrophysics	**IceCUBE, KM3Net**
Multi-messenger (GW, photons)	**VIRGO-LIGO + Astronomy**
CνB	**R&D for PTolemy, Euclid, CMB fits**
SN (pulse and relics)	**LVD, JUNO, SK, HK, DUNE**

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

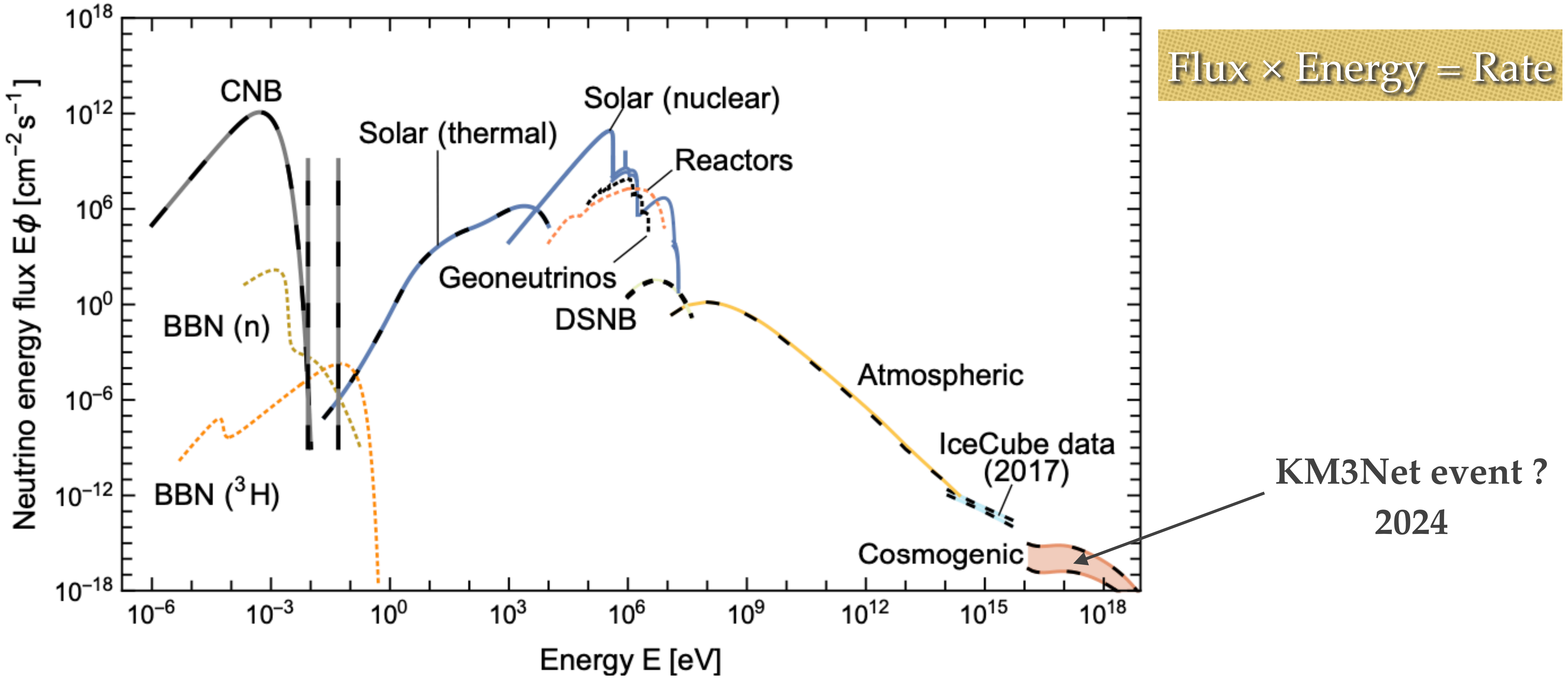


KM3Net event ?
2024

Neutrinos

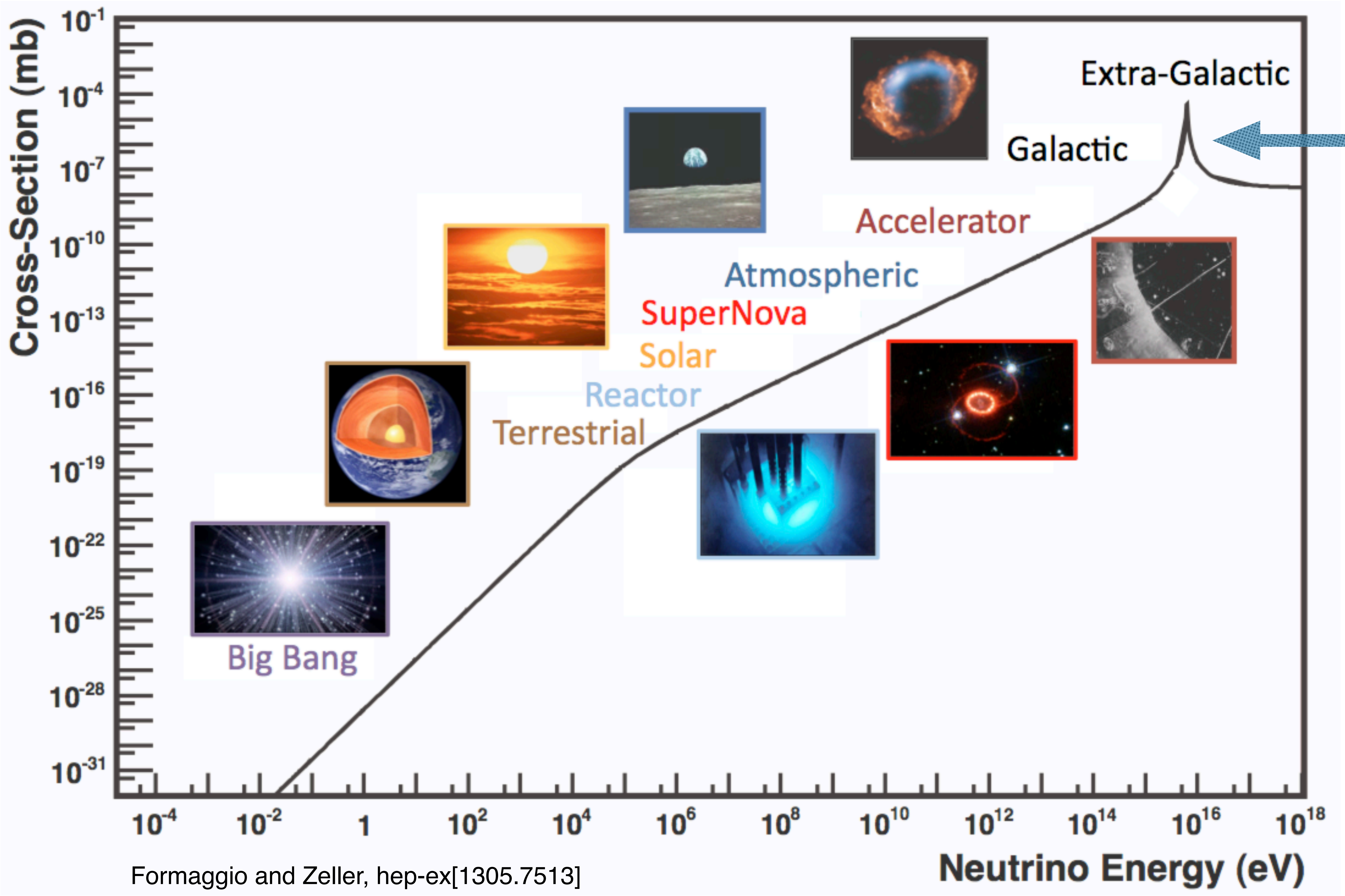
Anti-Neutrinos

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



KM3Net event ?
2024

Neutrino detection cross section vs energy



Earth is **not** anymore **transparent** at ~ 10^{15} - 10^{16} eV

$$\lambda[cm] = \frac{1}{n\sigma} \simeq \frac{1}{5 \cdot N_A\ cm^{-3}\ 10^{-4}\ mb} \simeq \frac{1}{5 \cdot 6\ 10^{23}\ 10^{-28}\ cm^{-1}} \simeq 30\ m$$

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)**

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

[including oscillations]

100 t — **1 day** — **flux** — **cross section**

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

$$N_{obs} = [\frac{M}{1.67\ 10^{-27}\ kg}] \cdot [2.\ 10^7\ s\ ] \cdot [1\ cm^{-2}s^{-1}] \cdot \epsilon \cdot \left[\frac{0.7\ 10^{-38}\ E_\nu\ cm^2}{GeV}\right] \simeq 40\ 10^{-6} \frac{E_\nu}{GeV} \epsilon \frac{M}{kg}$$

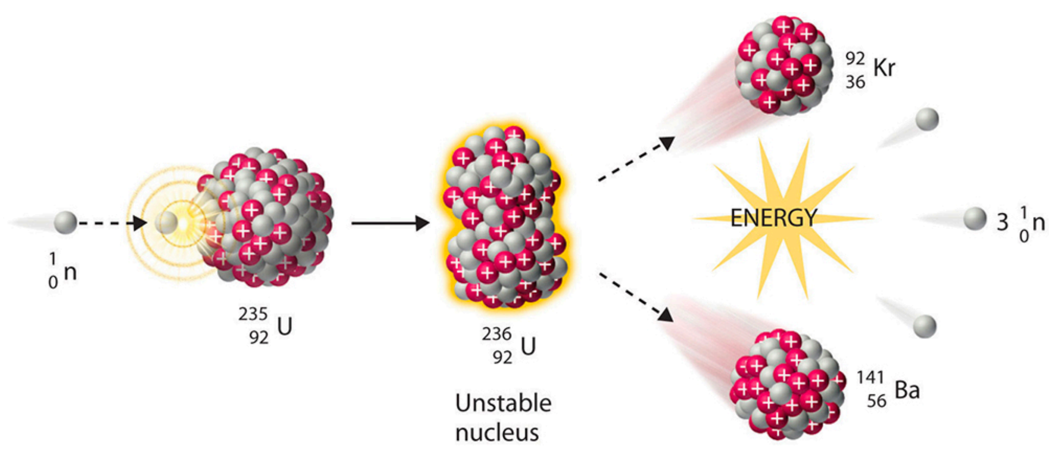
kTon scale required

Number of nucleons — **Effective year** — **Strong beam @ 1000 km** — **cross section**

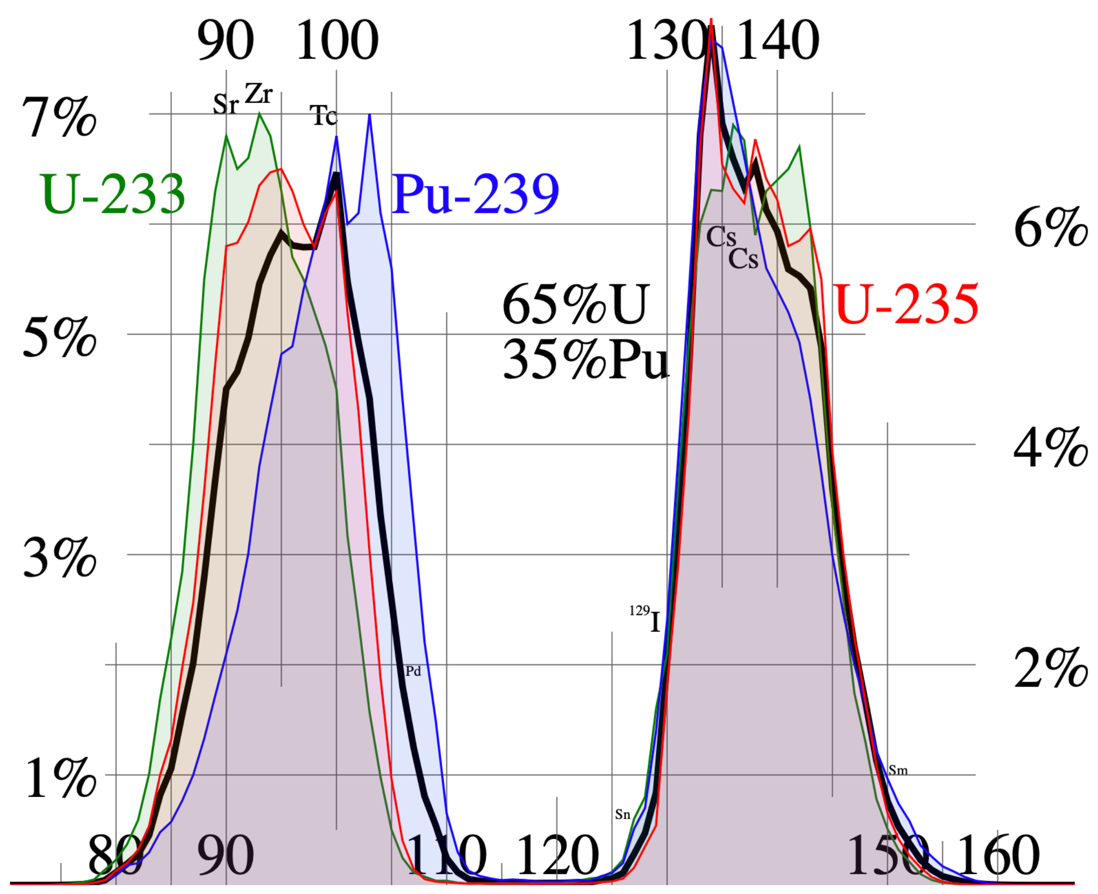
Nuclear reactors

- 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$_\nu$> ≃ 0.5 MeV
    - About ~ **4. 10^{12} s^{-1} cm^{-2}** for 1 GW at **20 m from the core**

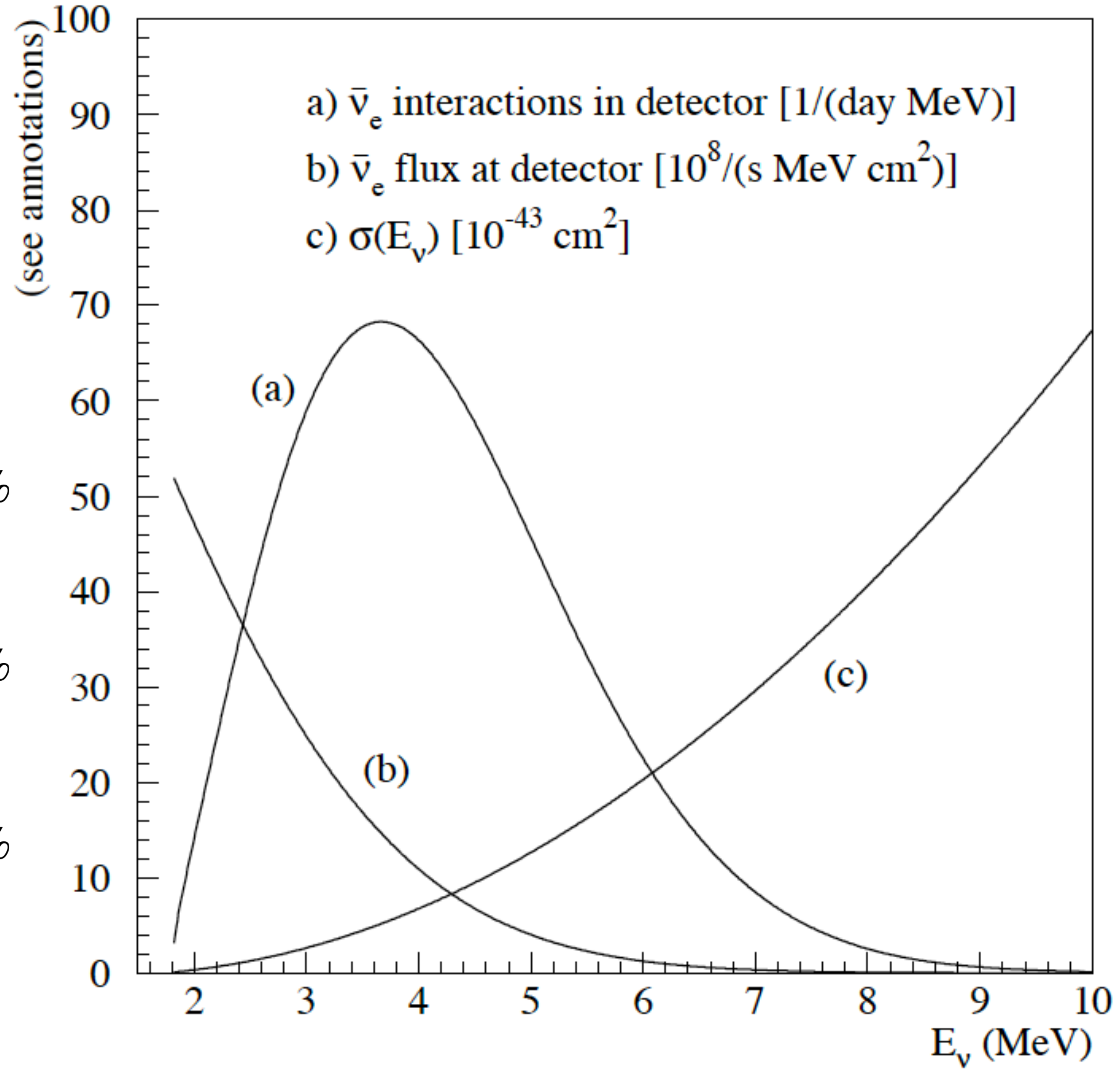
- **The details of the anti-neutrino spectrum are hard to compute, and still subject of research**
  - Dominating process: ^{235}U **fission** and sub-sequent β decays **(6 on average)**



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

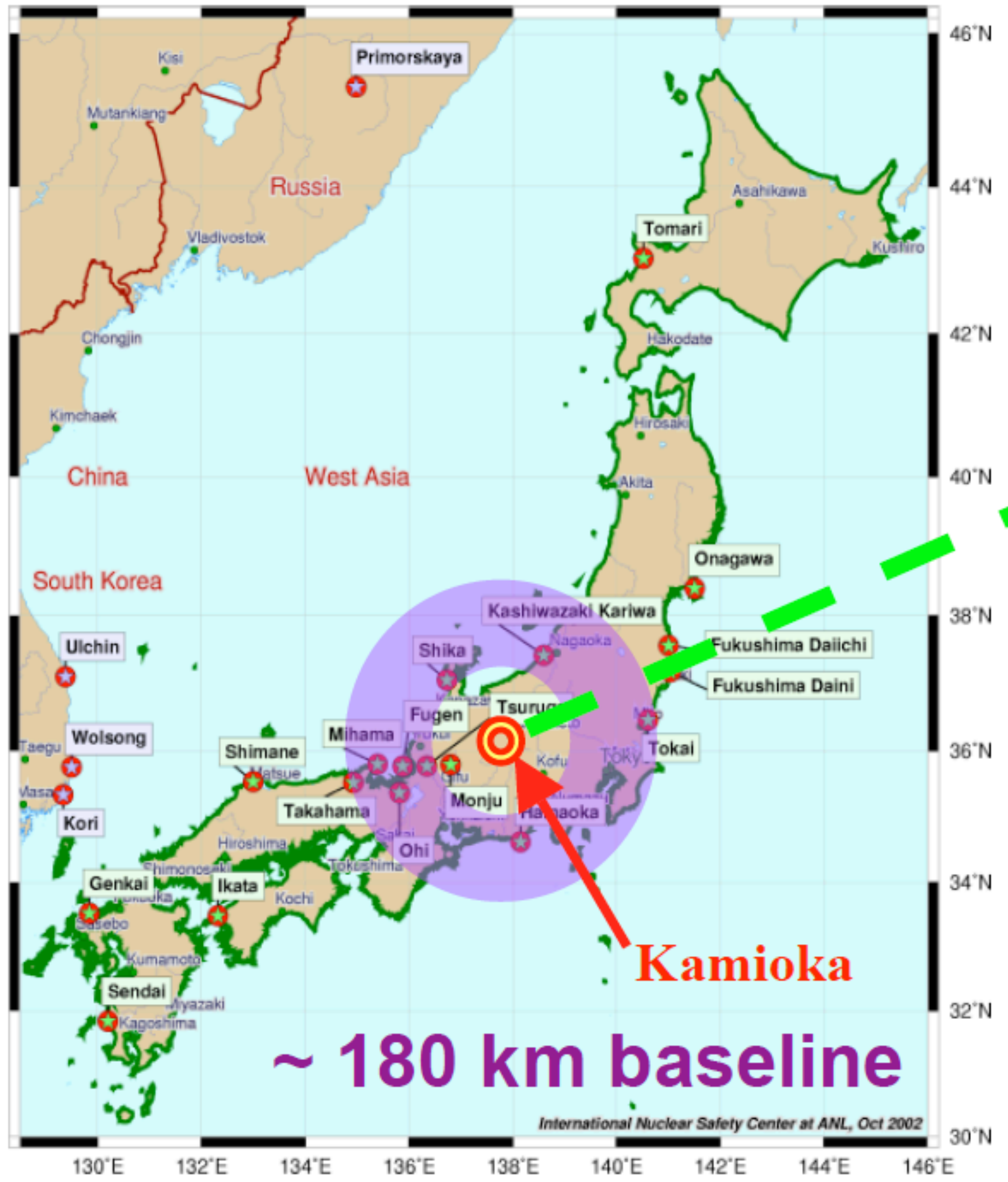


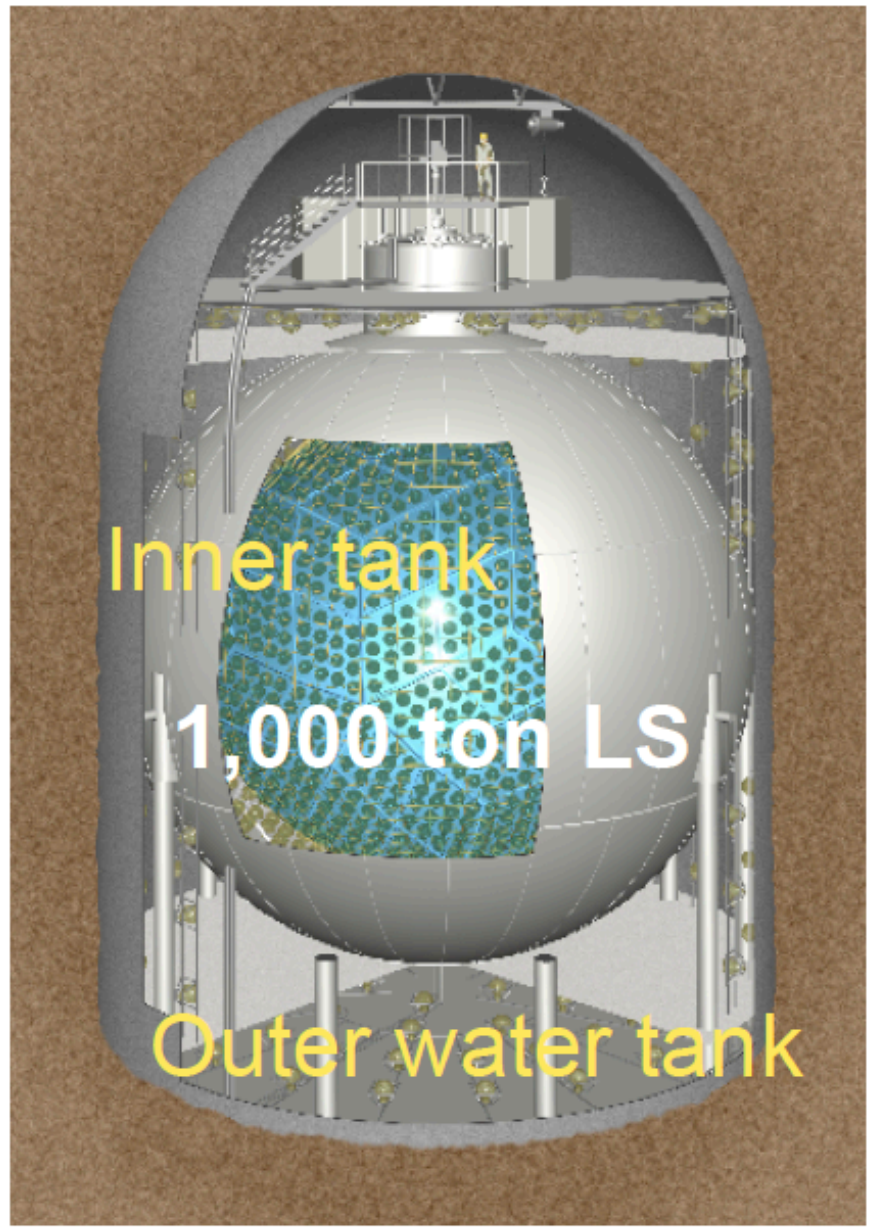
Fission products mass number A



Example: KamLAND experiment

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





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

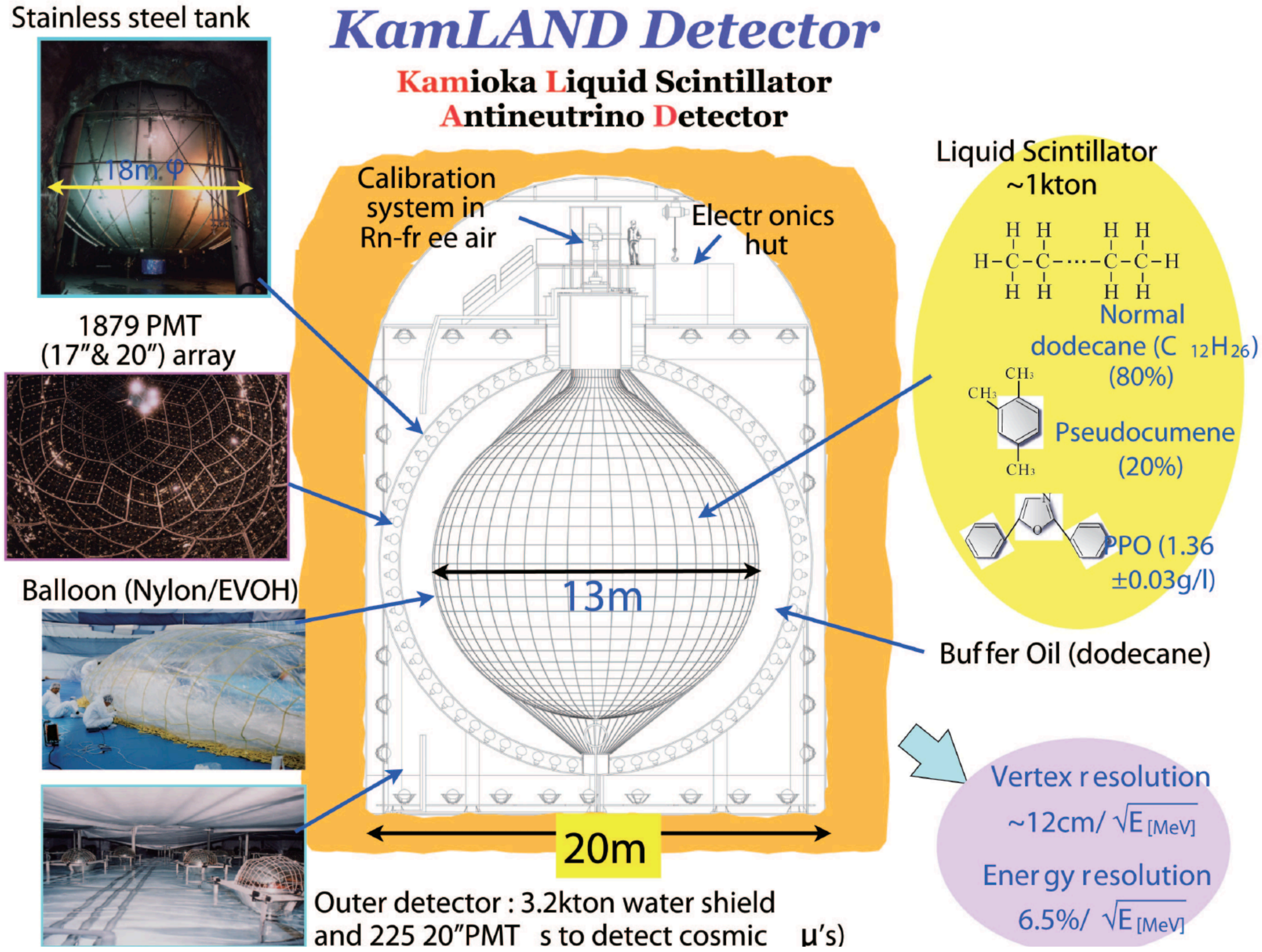
2 flavor neutrino oscillation

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

most sensitive region

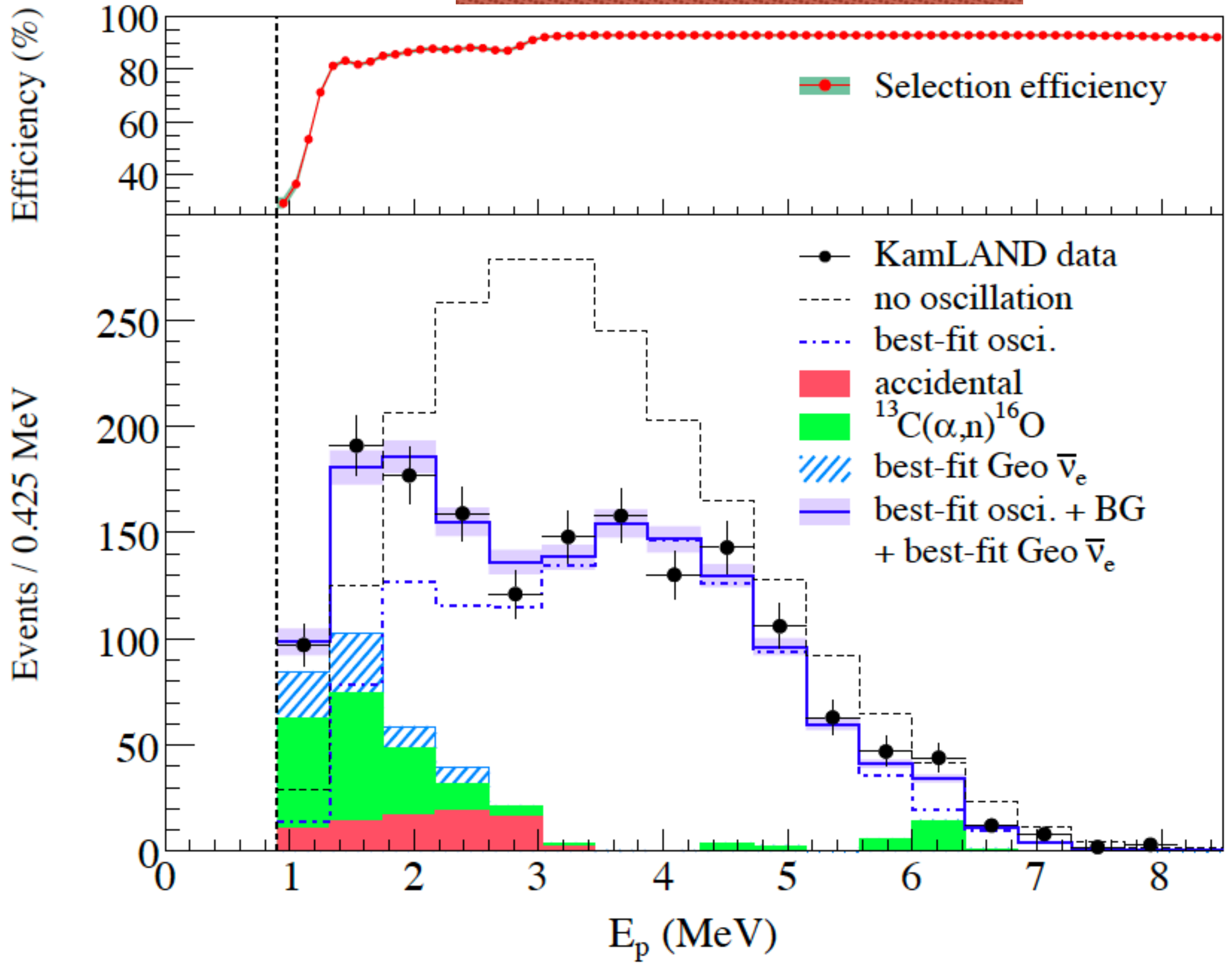
$$\Delta m^2 = (1/1.27)\cdot(E[\text{MeV}]/L[m])\cdot(\pi/2)$$
$$\sim 3\times 10^{-5}\text{eV}^2$$

KamLAND detector

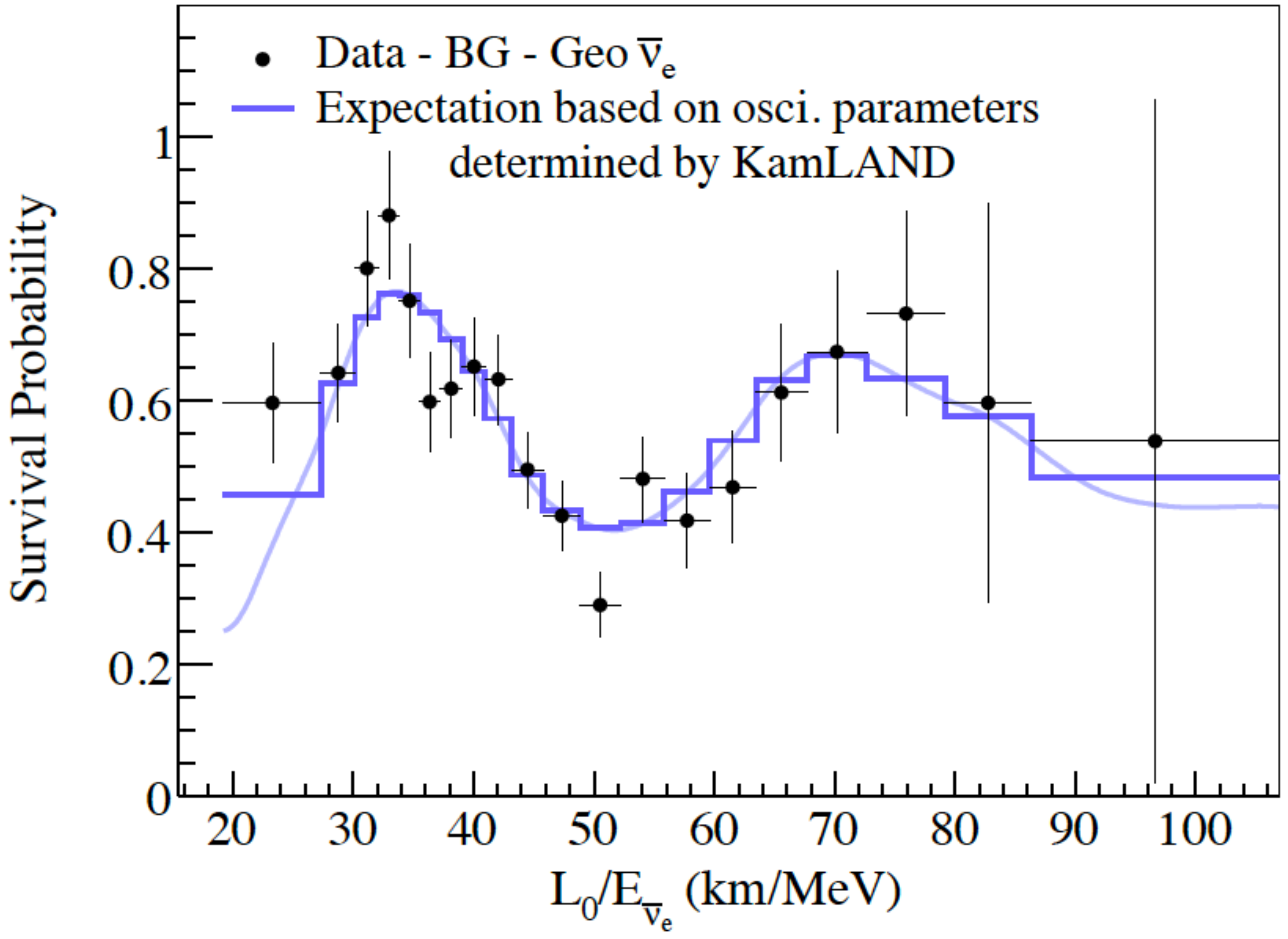


A neat oscillation experiment

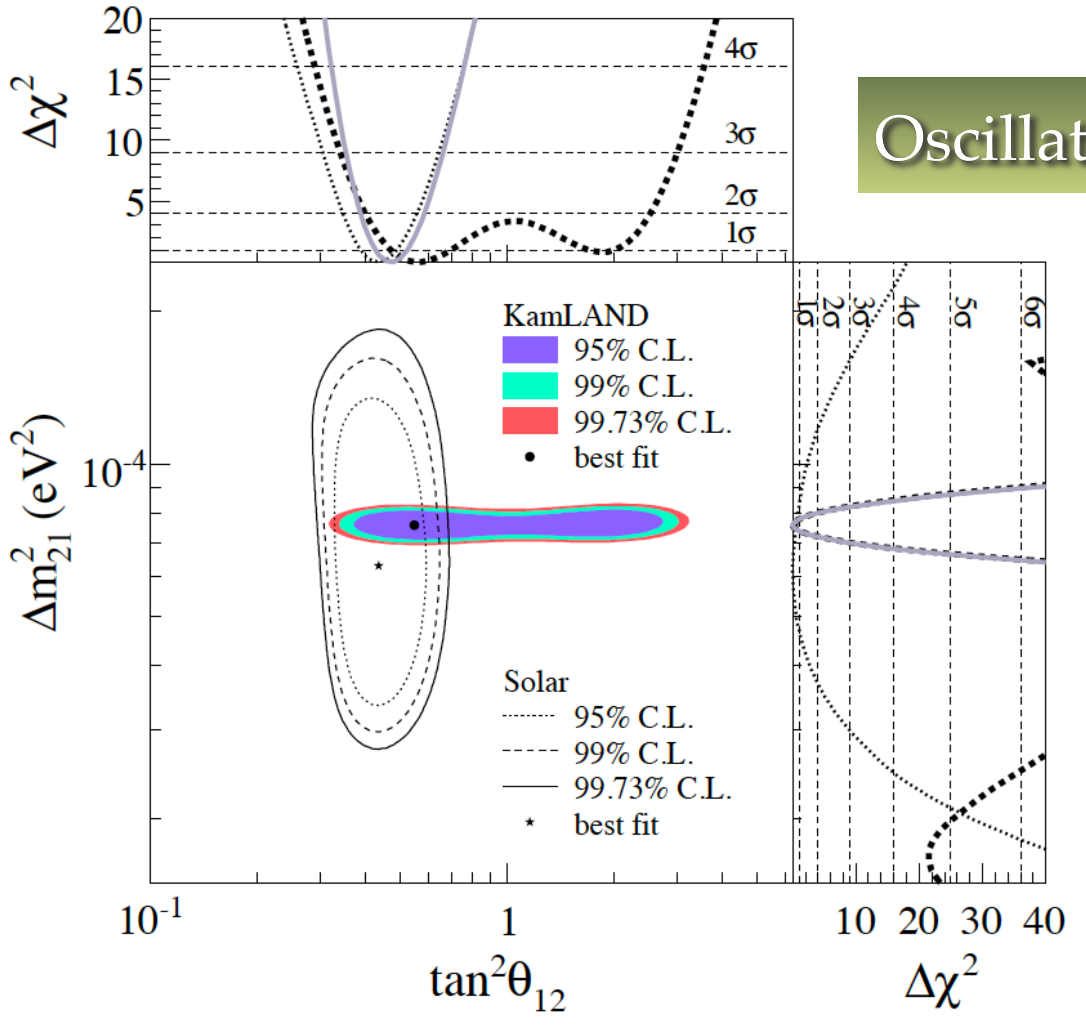
Prompt Event Spectrum



Survival probability



Oscillation parameters



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

How to make a neutrino beam

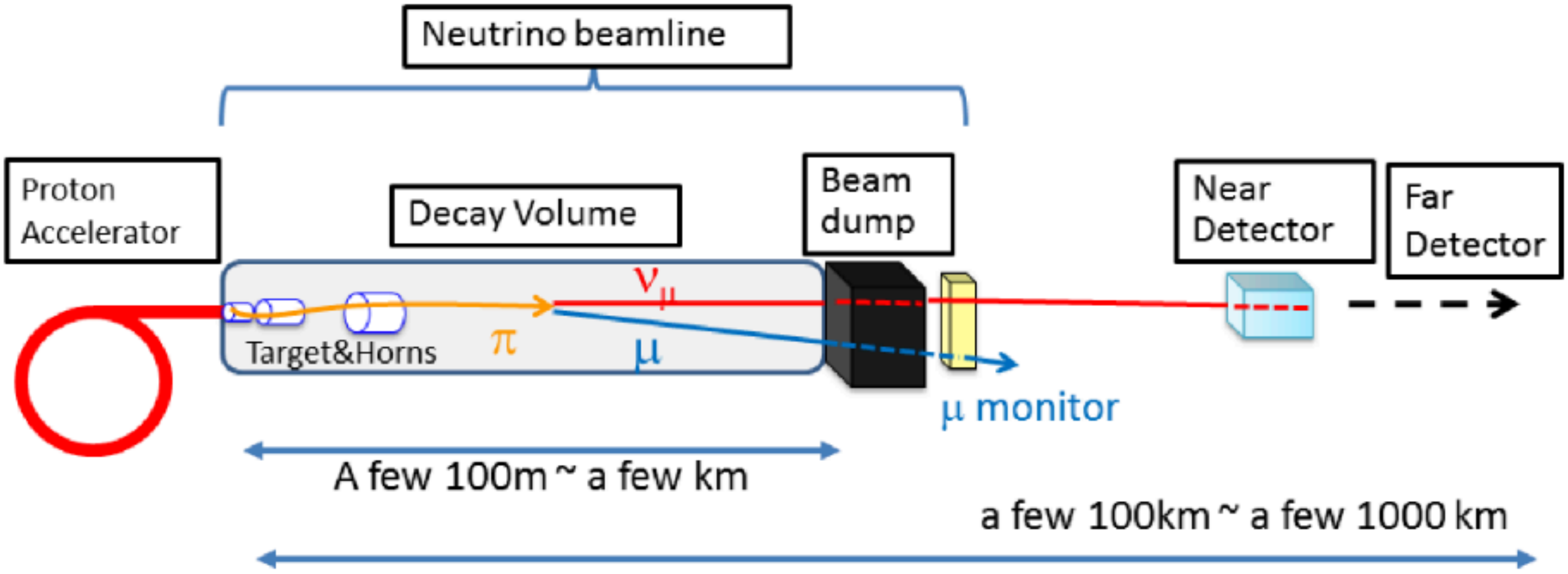
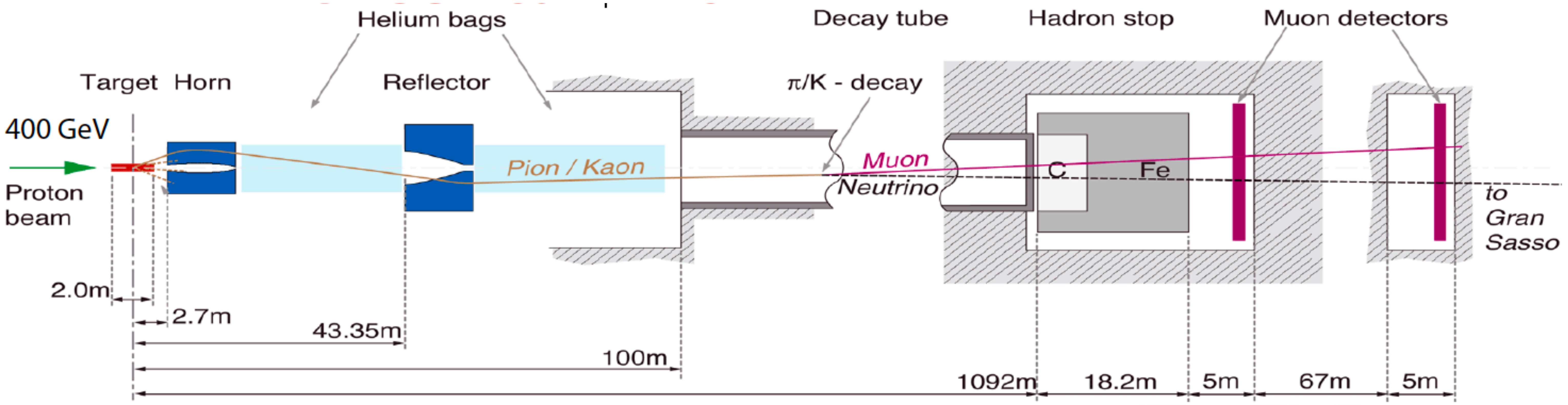


FIGURE 1. Components of the accelerator neutrino experiment

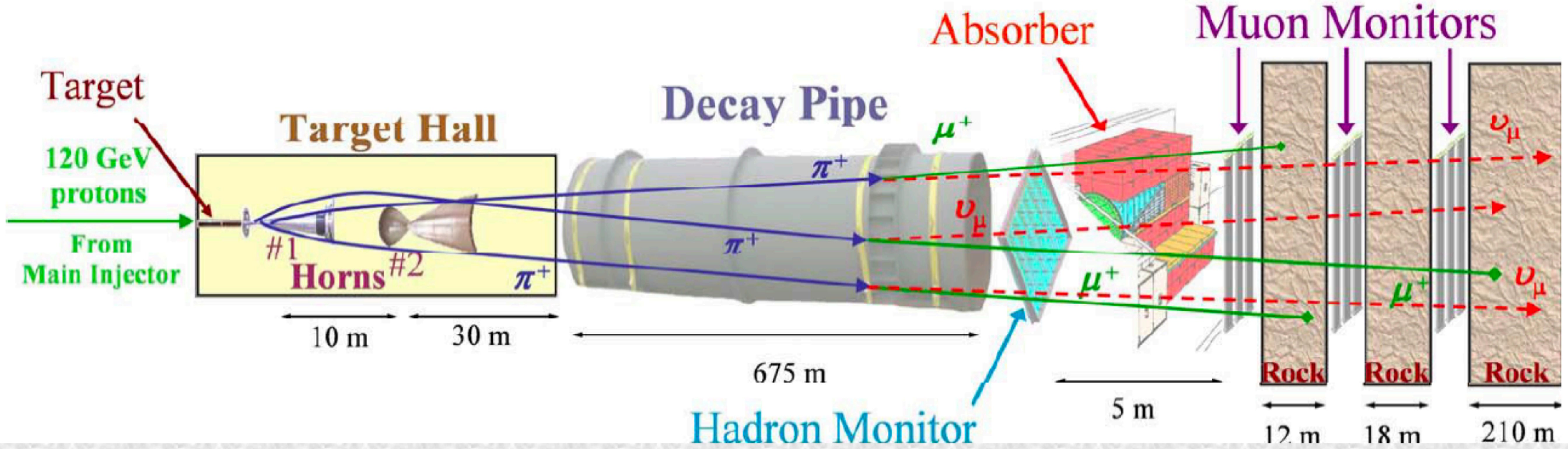
XXVI International Conference on Neutrino Physics and Astrophysics
AIP Conf. Proc. 1666, 130001-1–130001-6; doi: 10.1063/1.4915579

Neutrino beams: examples

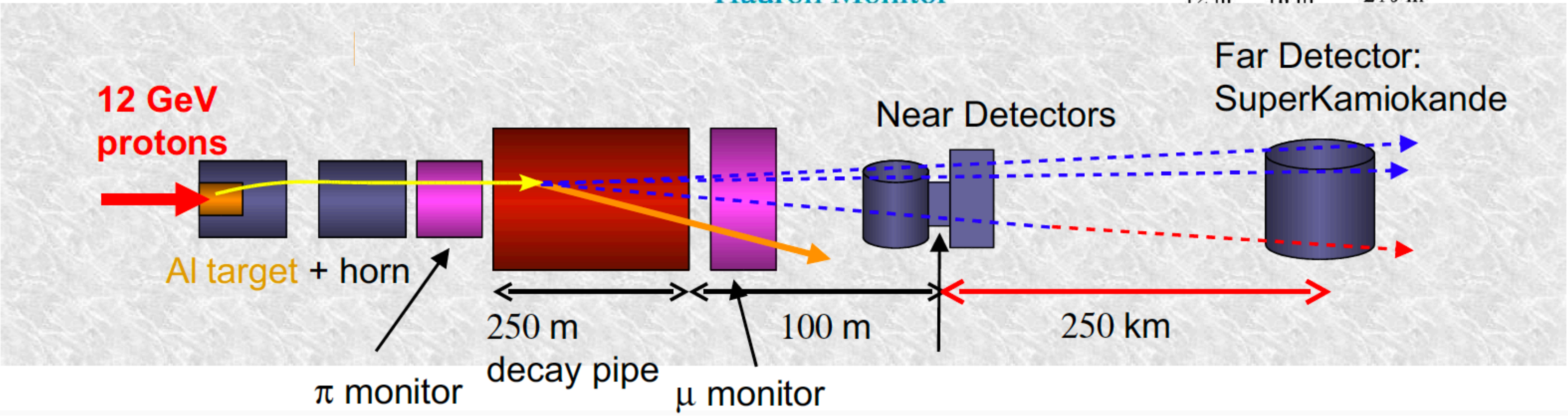
CNGS: CERN -> LNGS



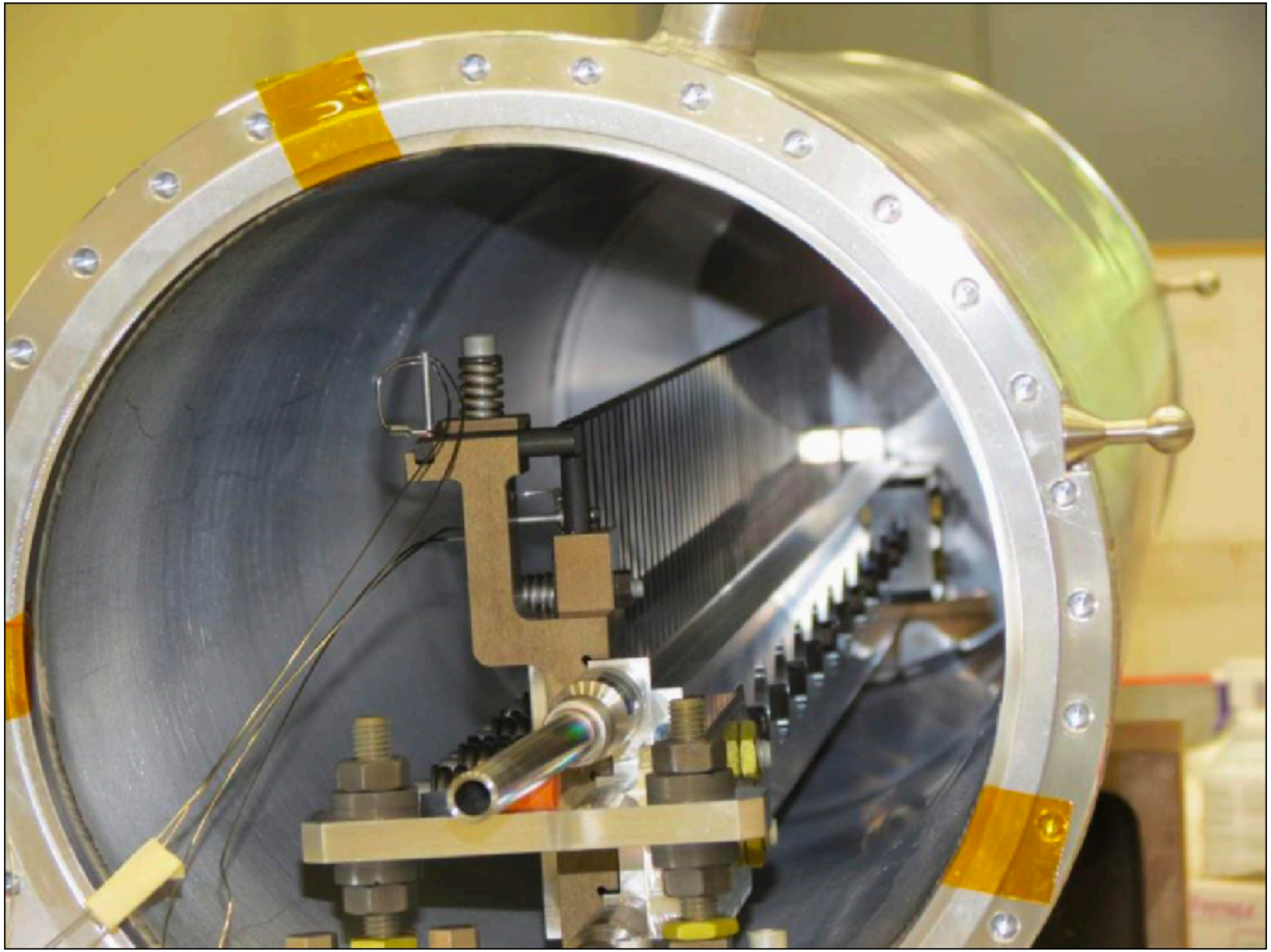
Fermilab: FNAL to MINOS, NuMi



K2K: KEK to Kamioka

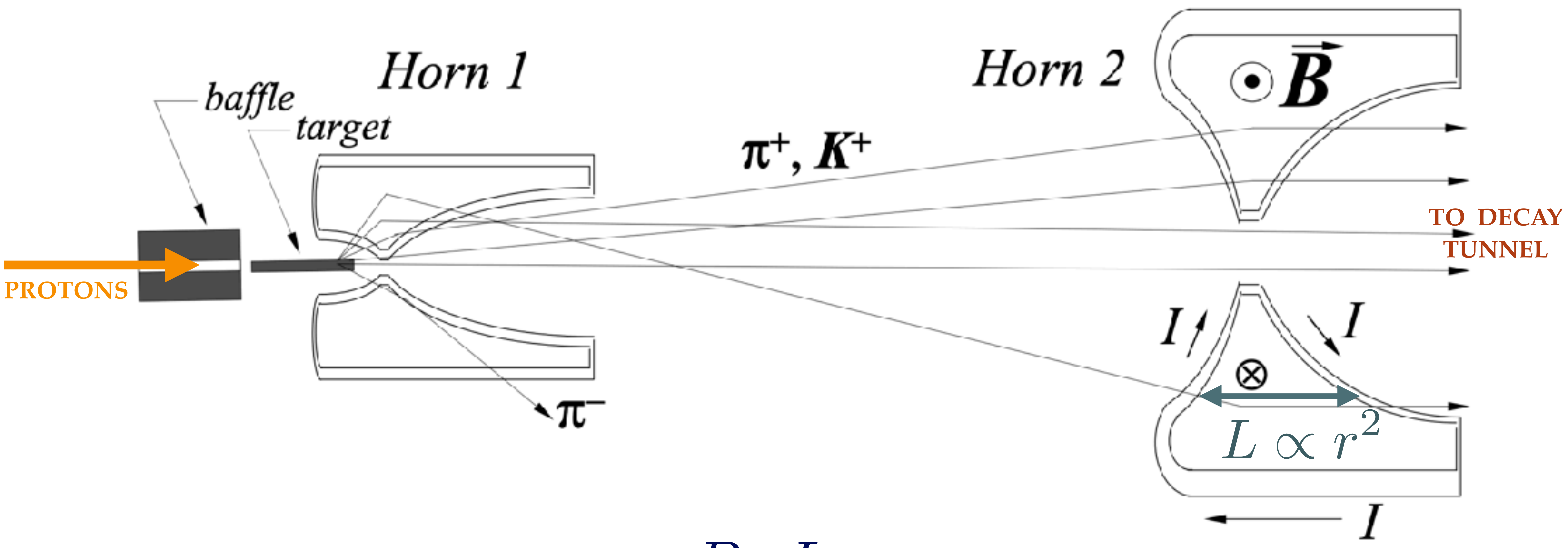


NuMi target



Focussing: conceptual scheme

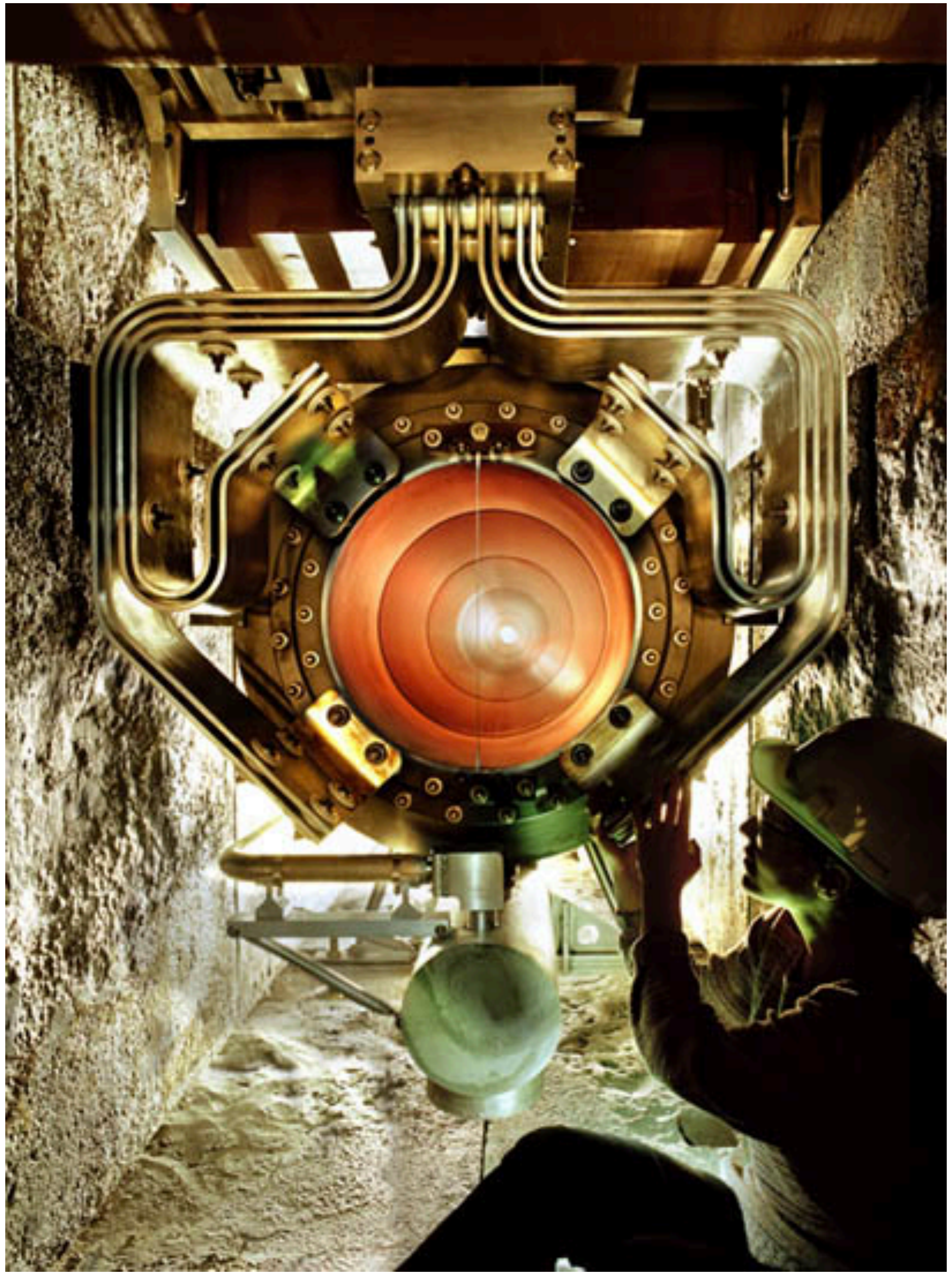
$$|\vec{B}| \propto \frac{1}{r}$$



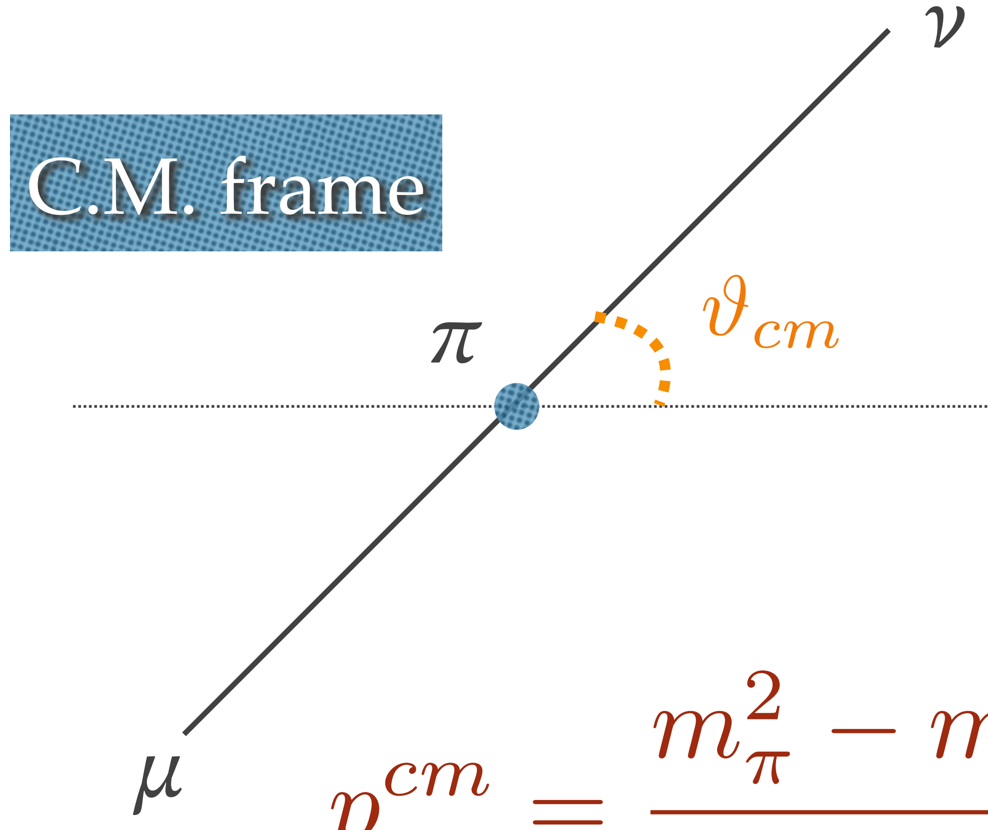
$$p_{kick} \propto B \cdot L \propto r$$

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

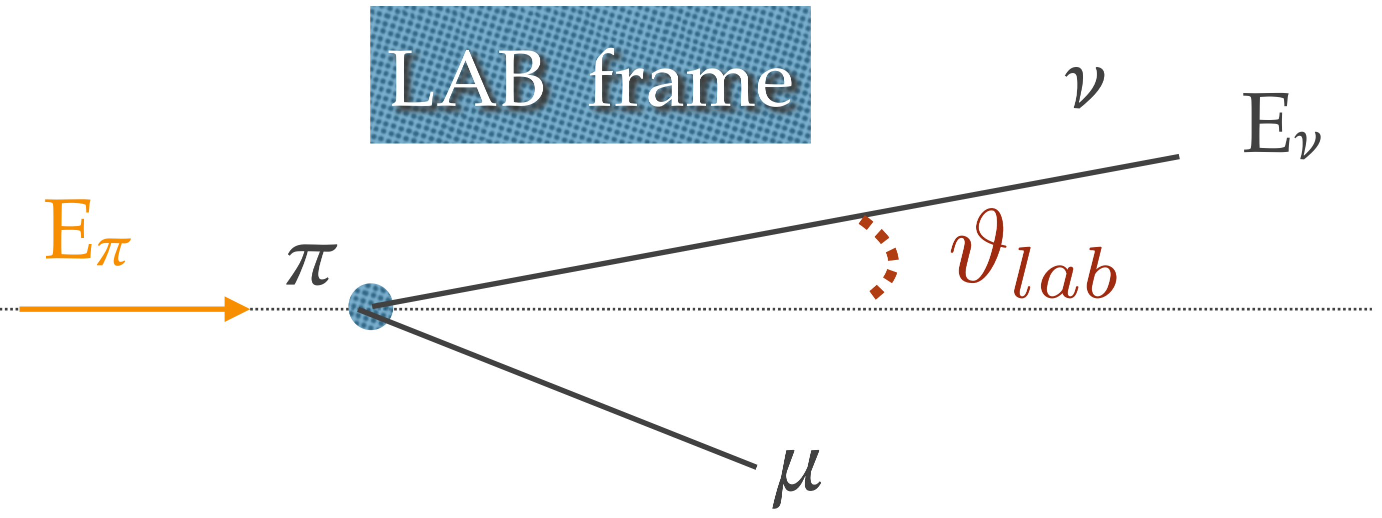
Horns



ON-axis vs OFF-axis: narrowing neutrino energy spread



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

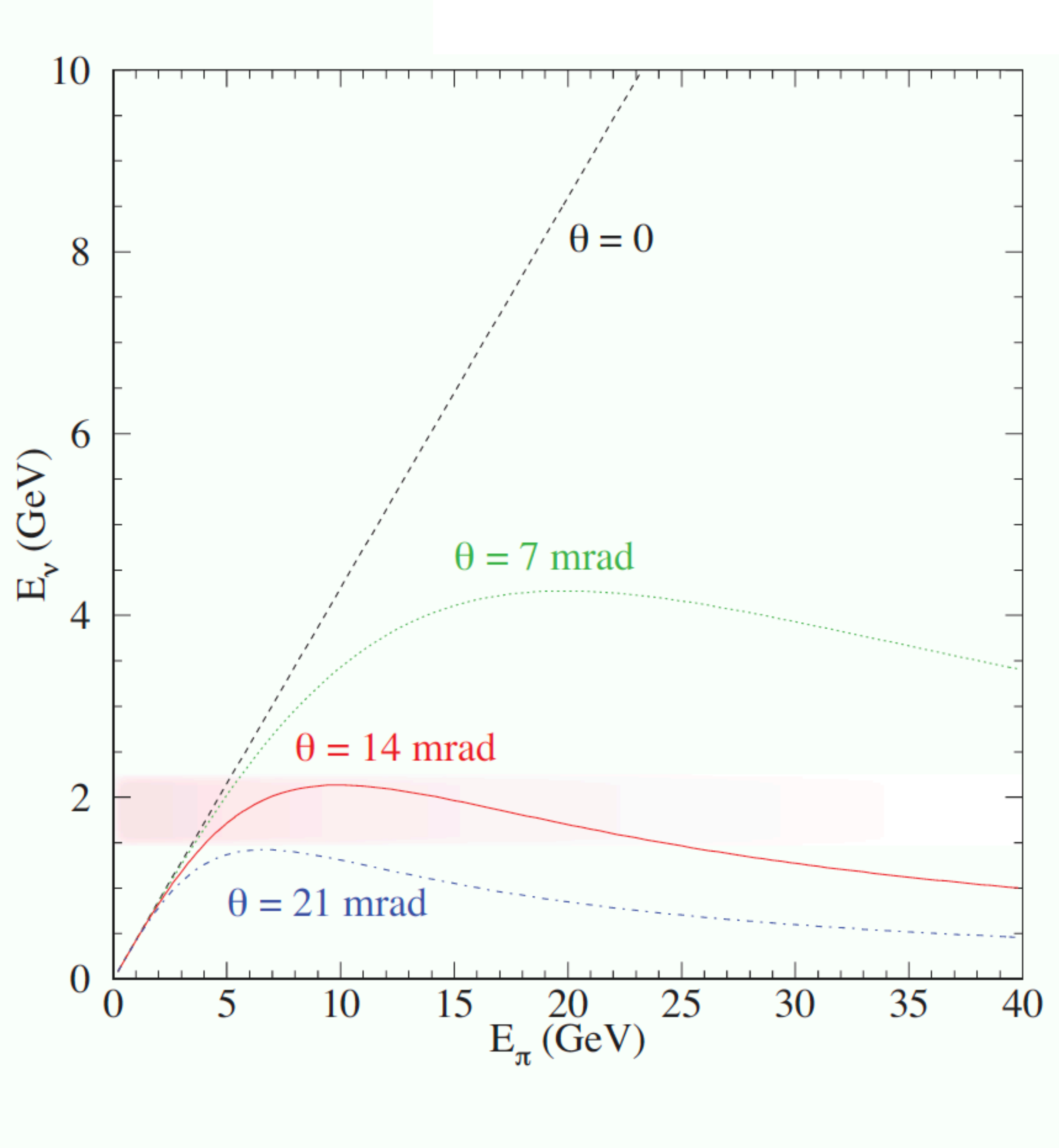


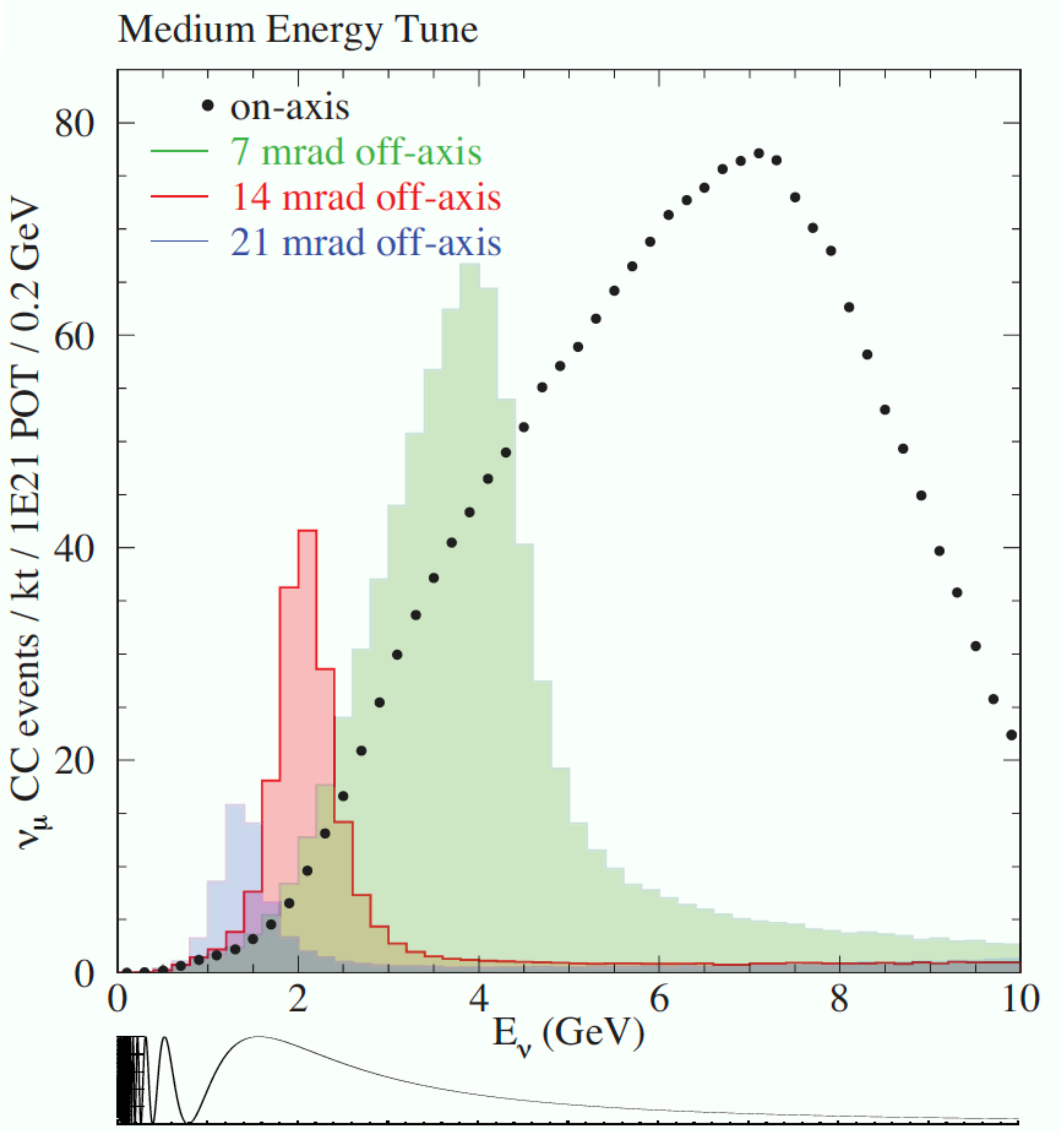
$$p_\nu^{cm} = \frac{m_\pi^2 - m_\mu^2}{2m_\pi}$$

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

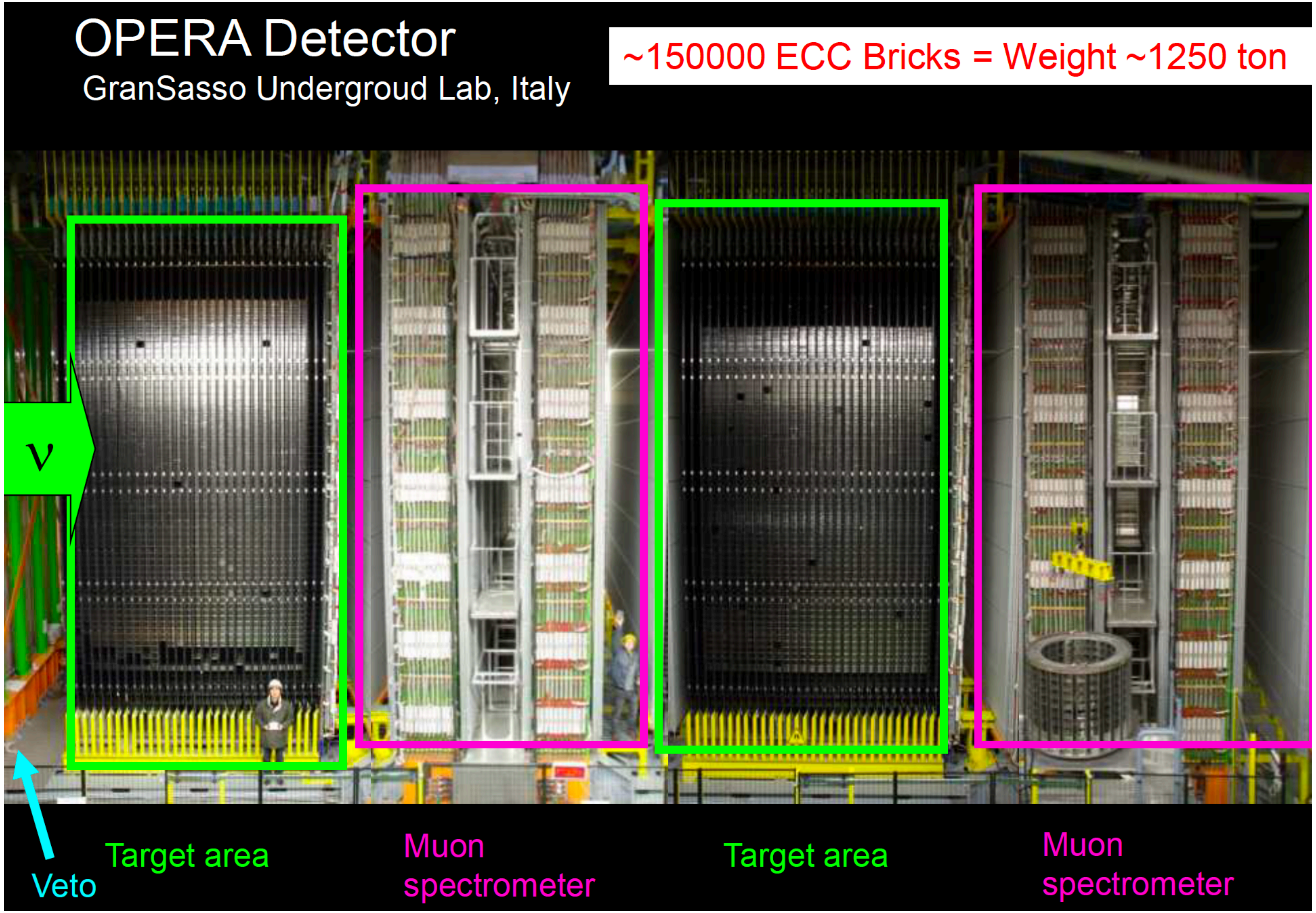
- **OFF-axis** there is a **strong correlation** between neutrino **energy and angle**

NuMi example

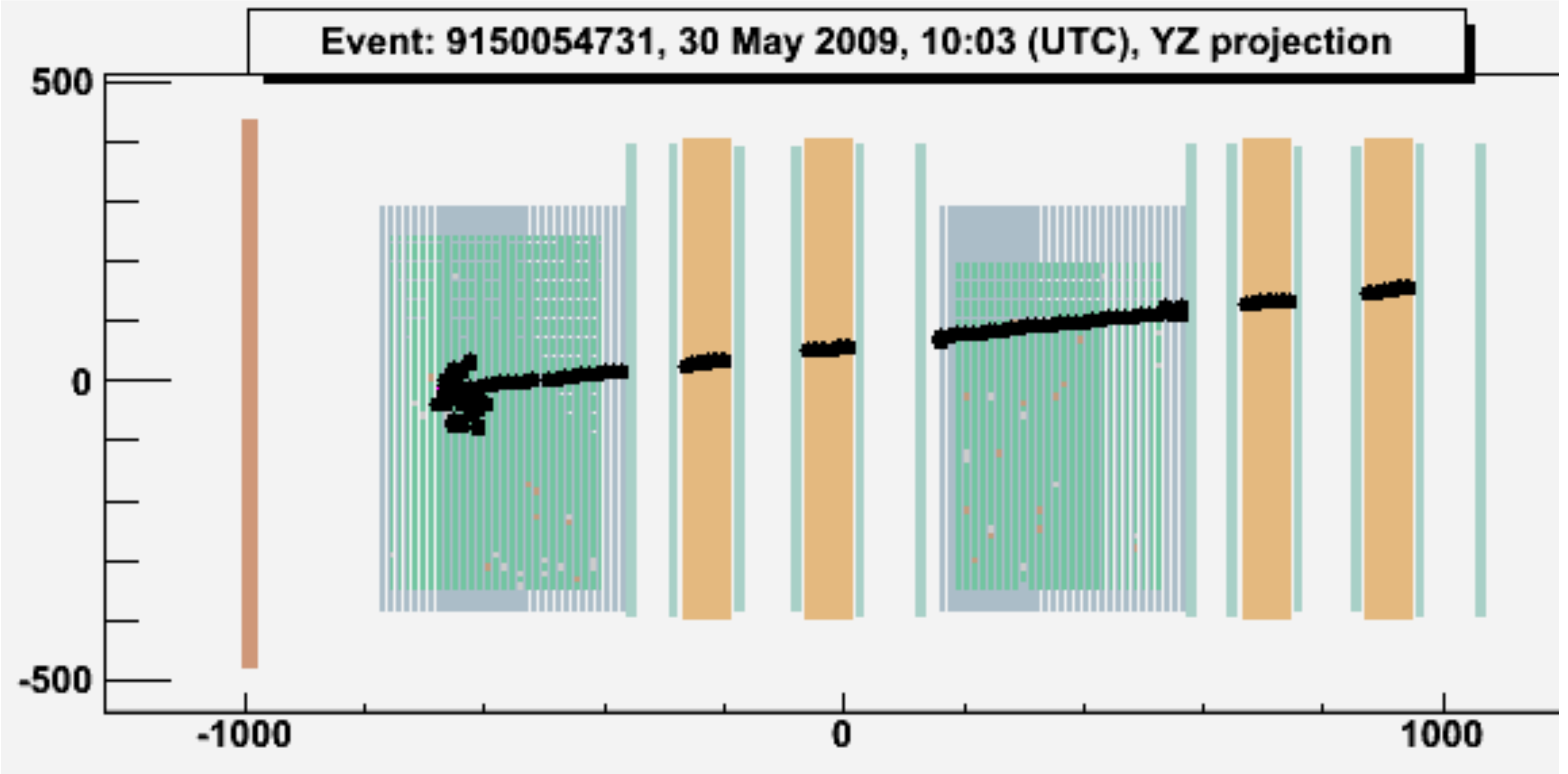


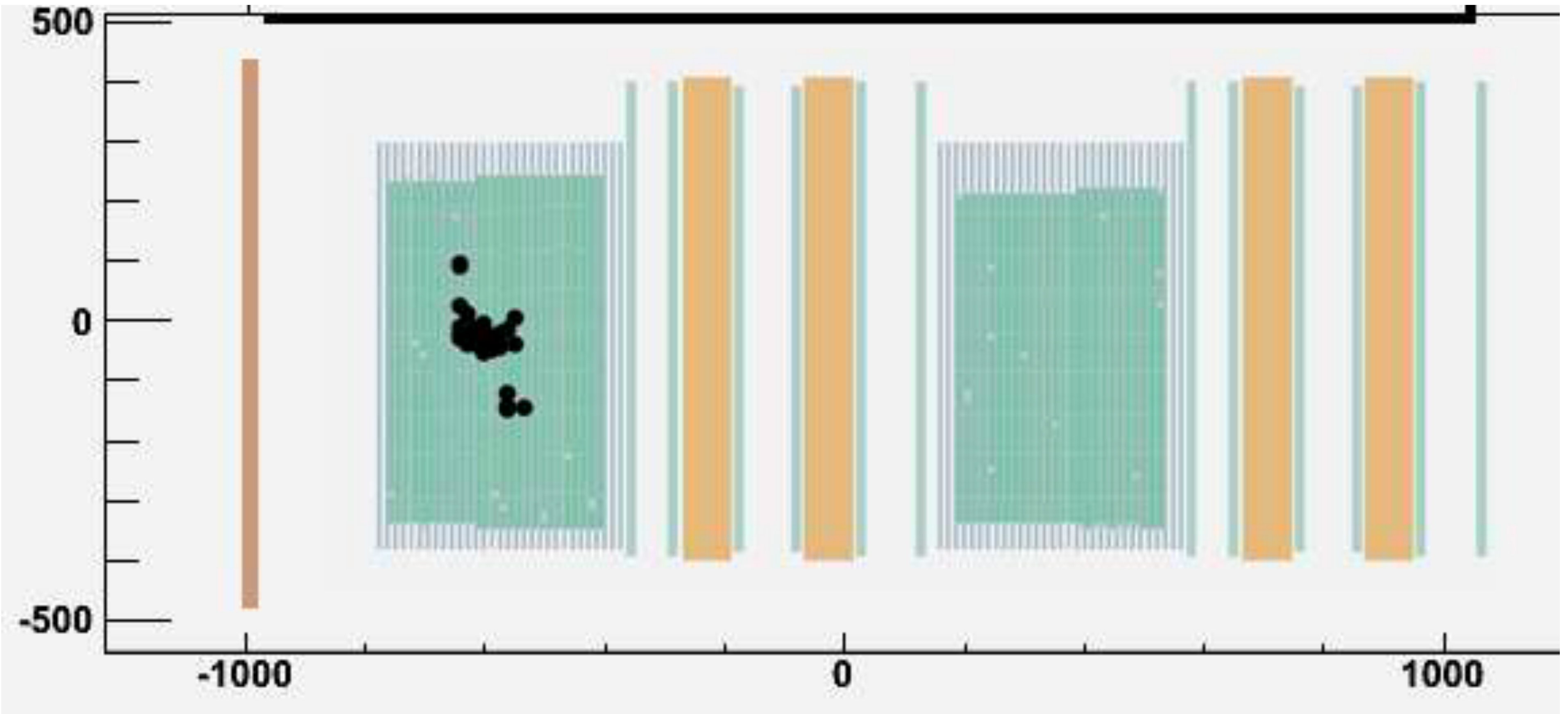


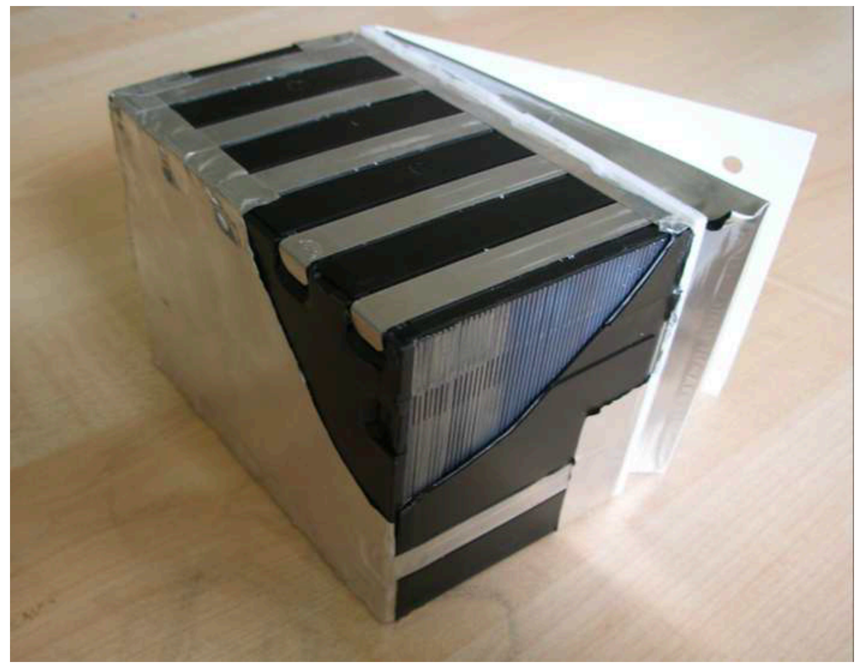
Example: Opera experiment @ LNGS



Example: Opera experiment at LNGS





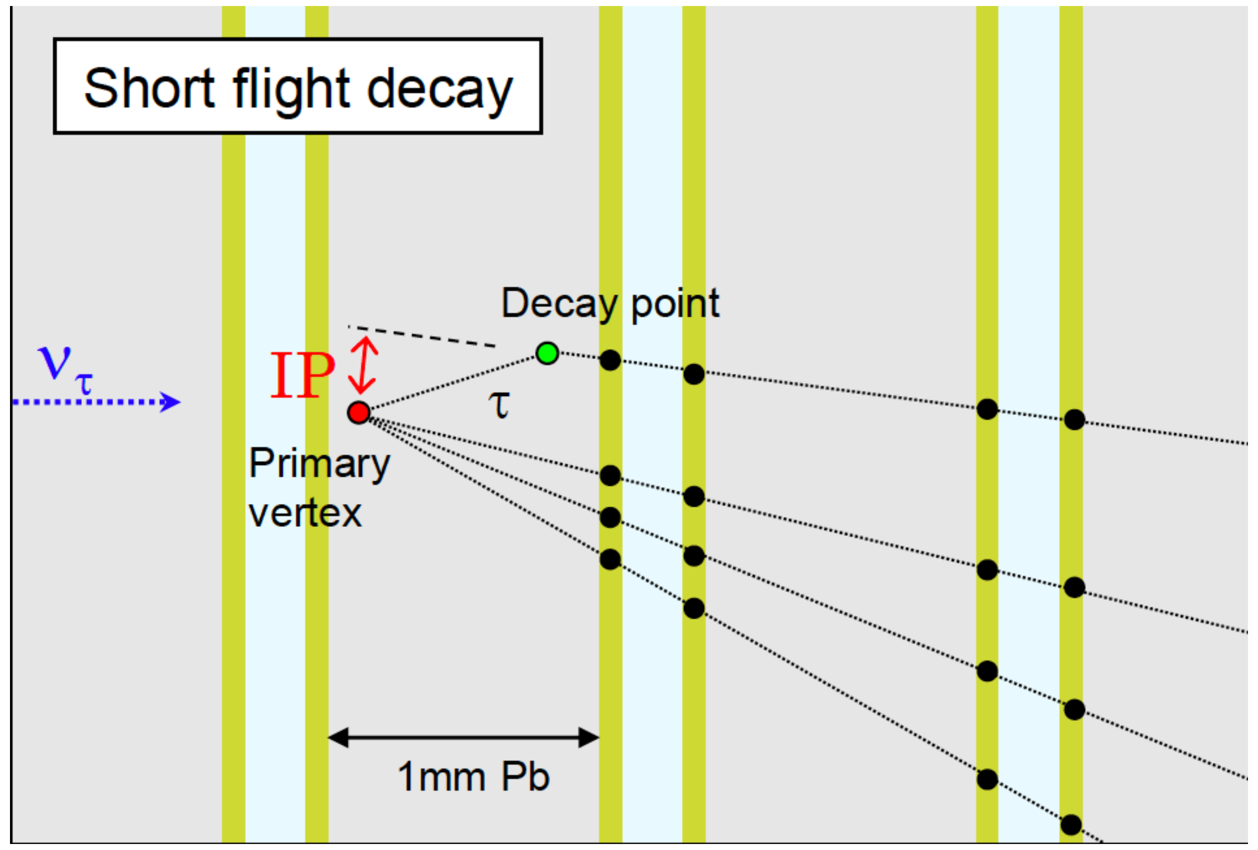


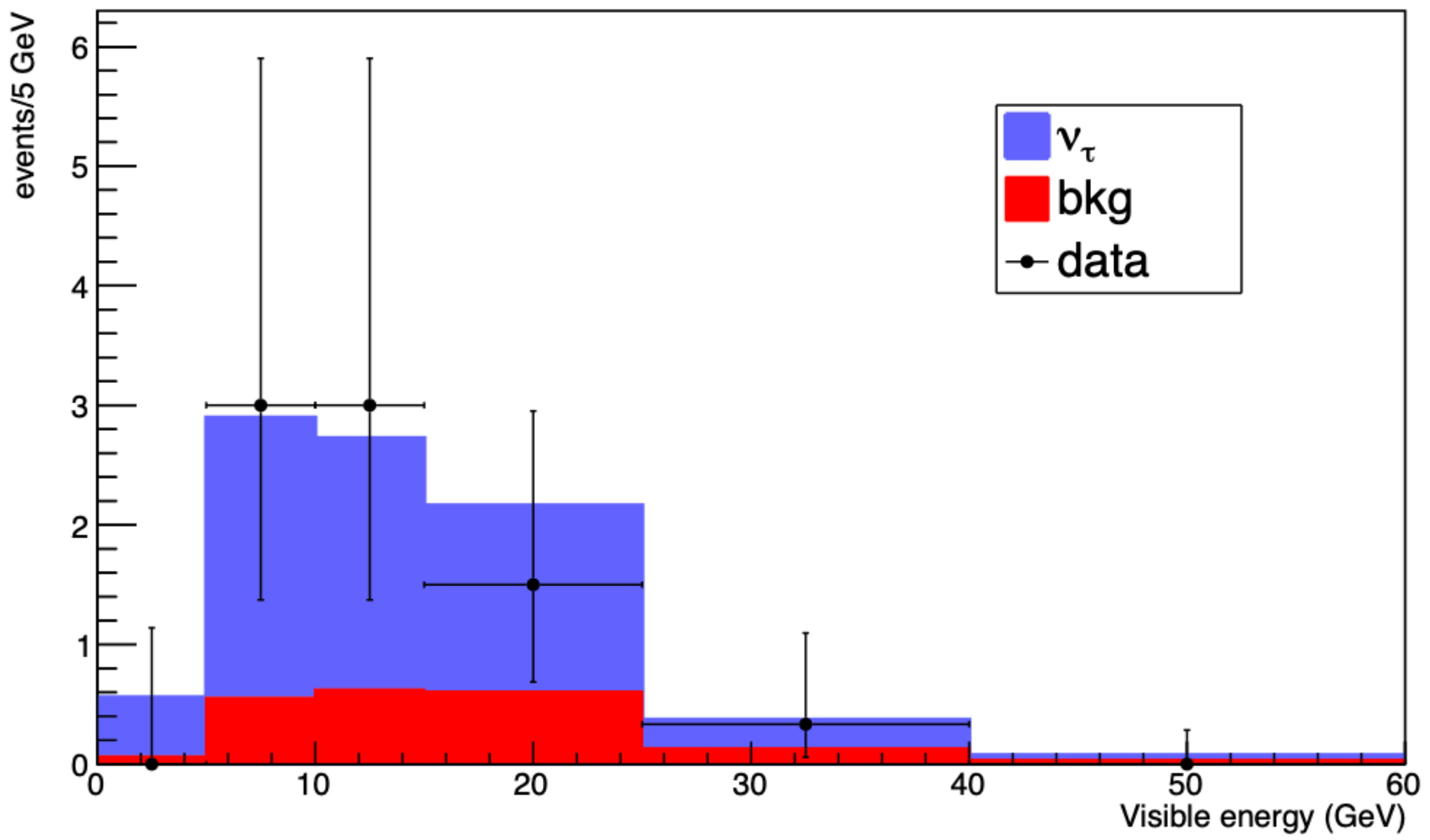
BRICK ID	72693	29570	23543	92217	130577	77152	27972	26670	136759	4838
Channel	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 1h$	$\tau \to 3h$	$\tau \to 3h$
z_{dec} (μm)	435	1446	151	406	630	430	652	303	-648	407
p^T_{miss} (GeV/c)	0.52	0.31	/	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,



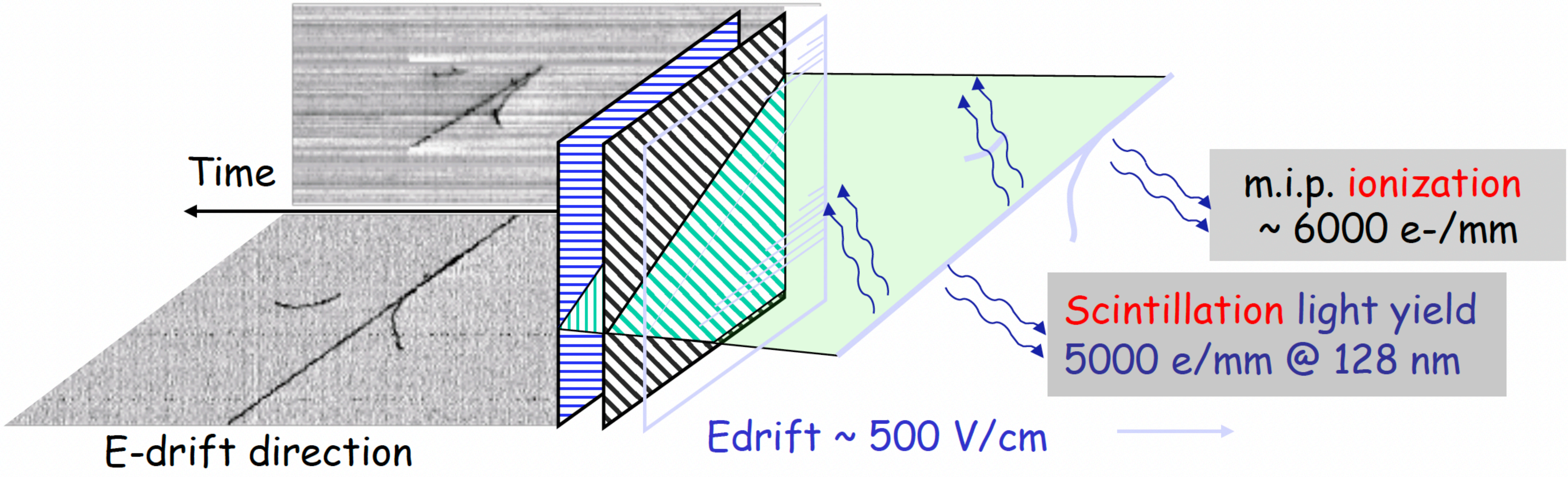


A new, powerful detection technique initiated at CNGS

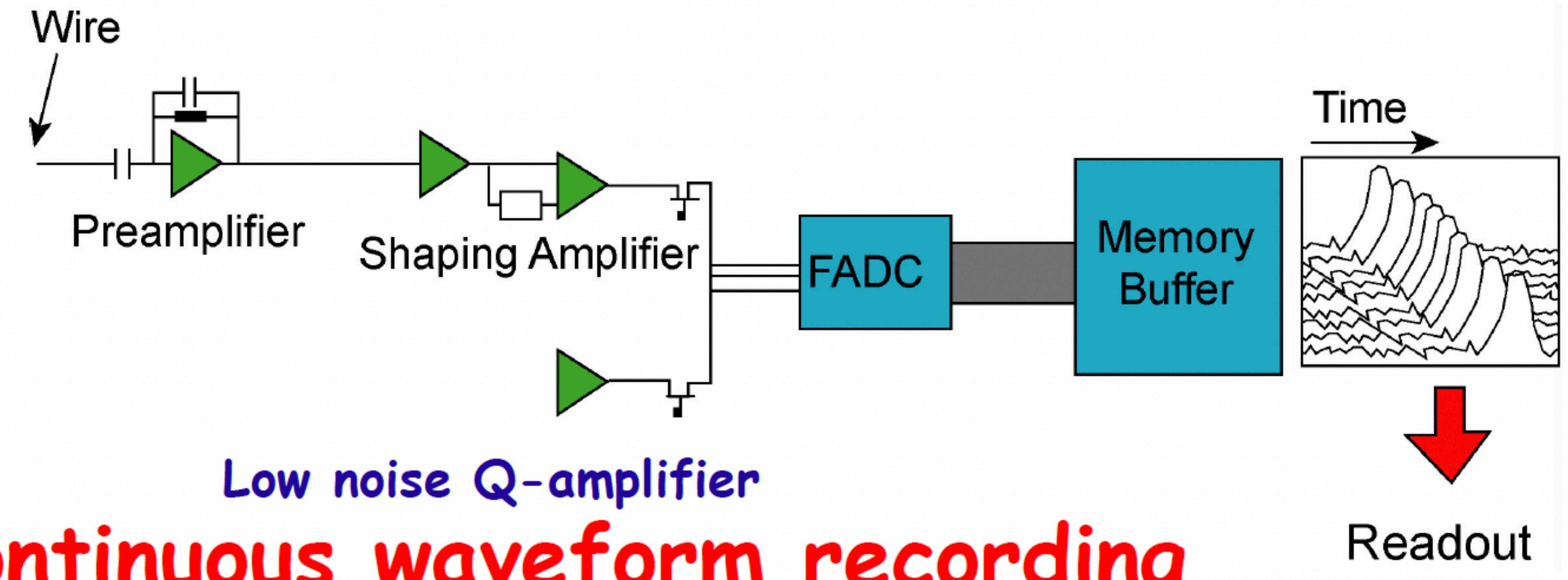
NOTE

The TPC concept (often in dual phase) has become the basis of many DM direct search experiments

See DM lectures



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

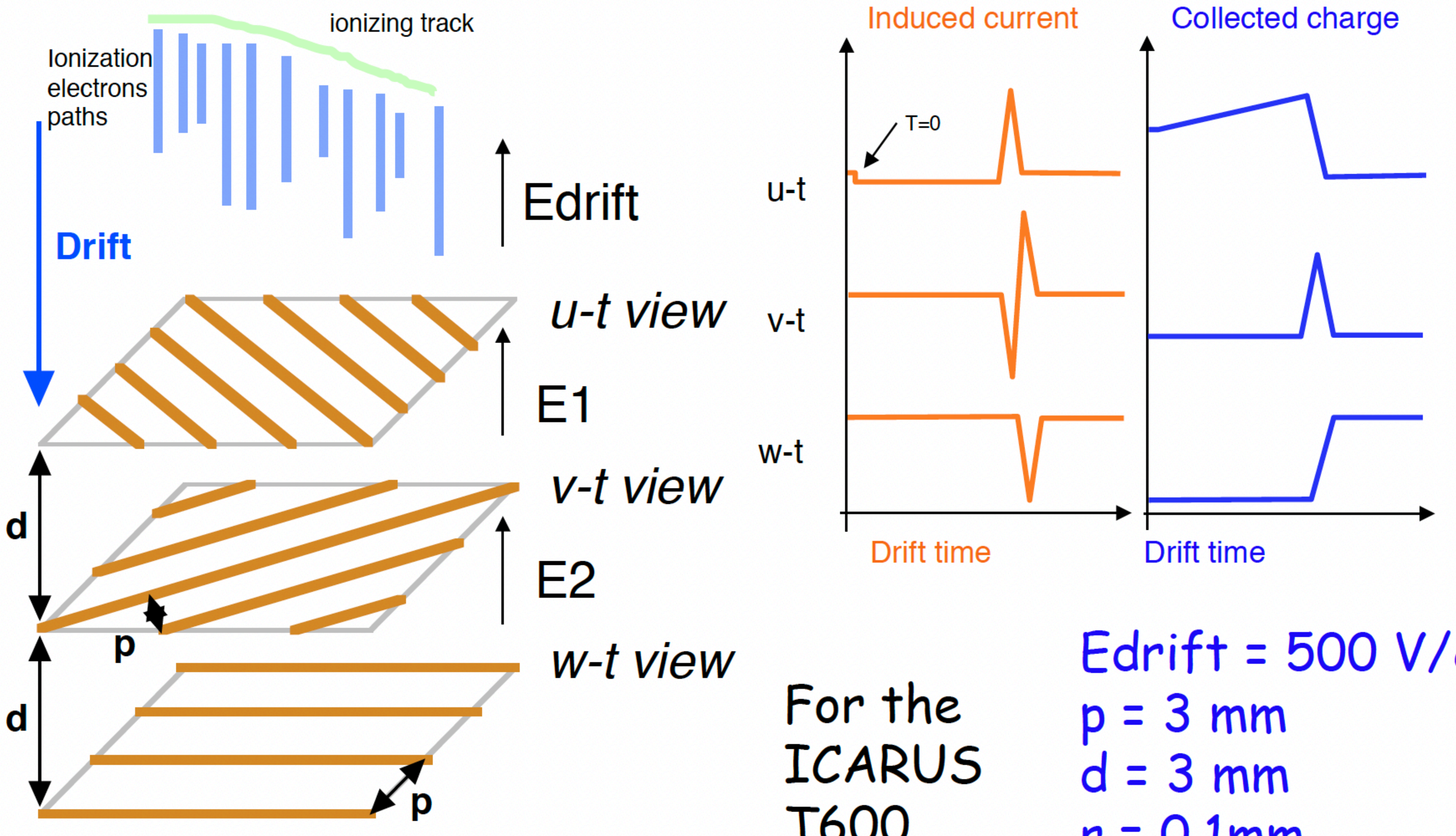


Continuous waveform recording

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

C. Rubbia, 2019

Non destructive multiple charge readout



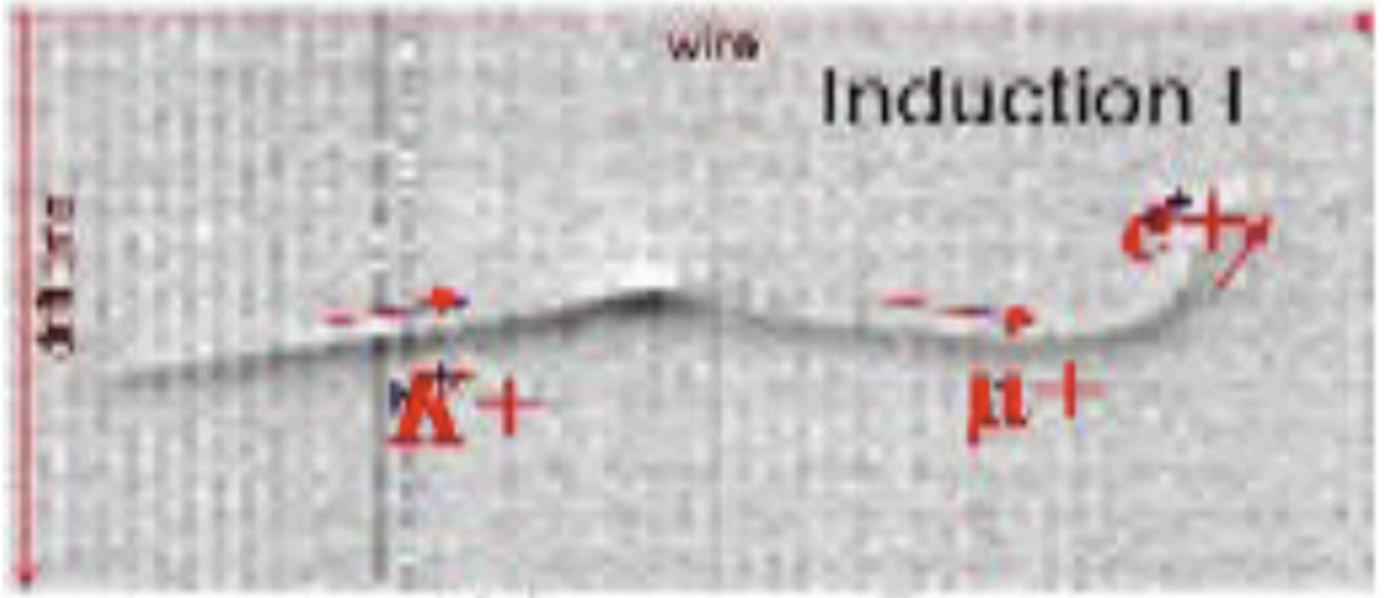
For the ICARUS T600

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

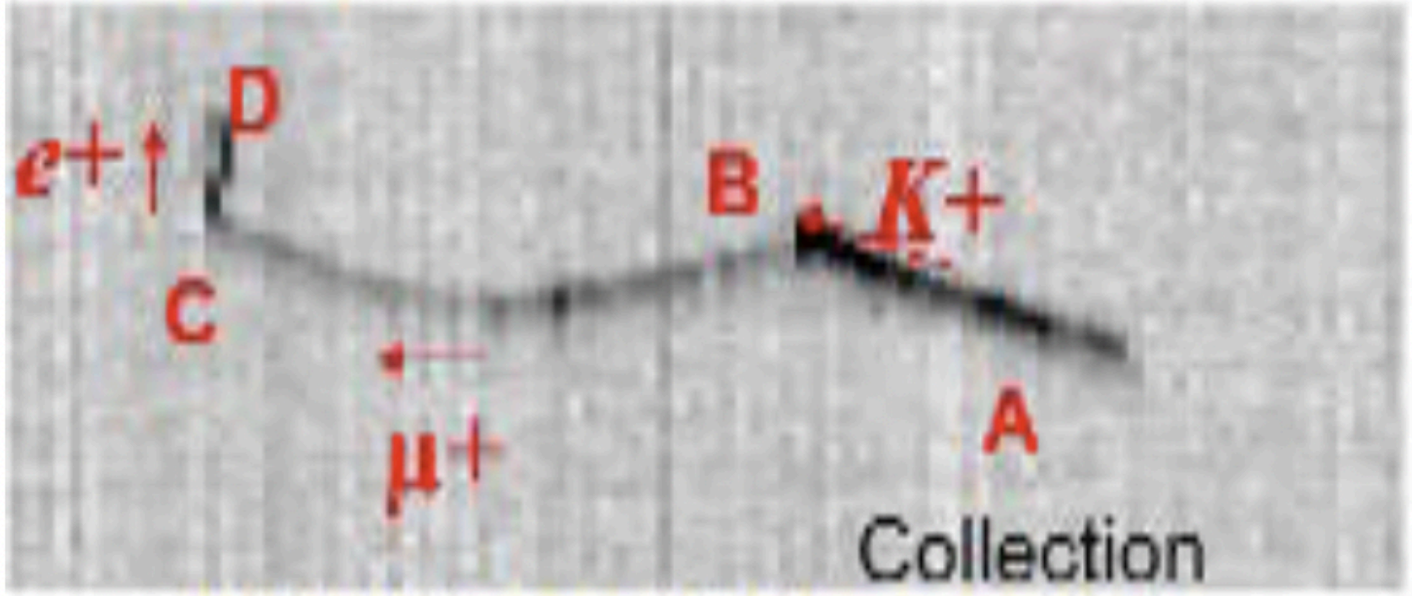
- At FNAL's shallow depth, the T600 will require two additions:
  - 3 m concrete overburden to mitigate the c. rays background,
  - Particles entering the detector must be removed with a Cosmic Rays Tagging (CRT) around the full LAr volume

C. Rubbia, 2019

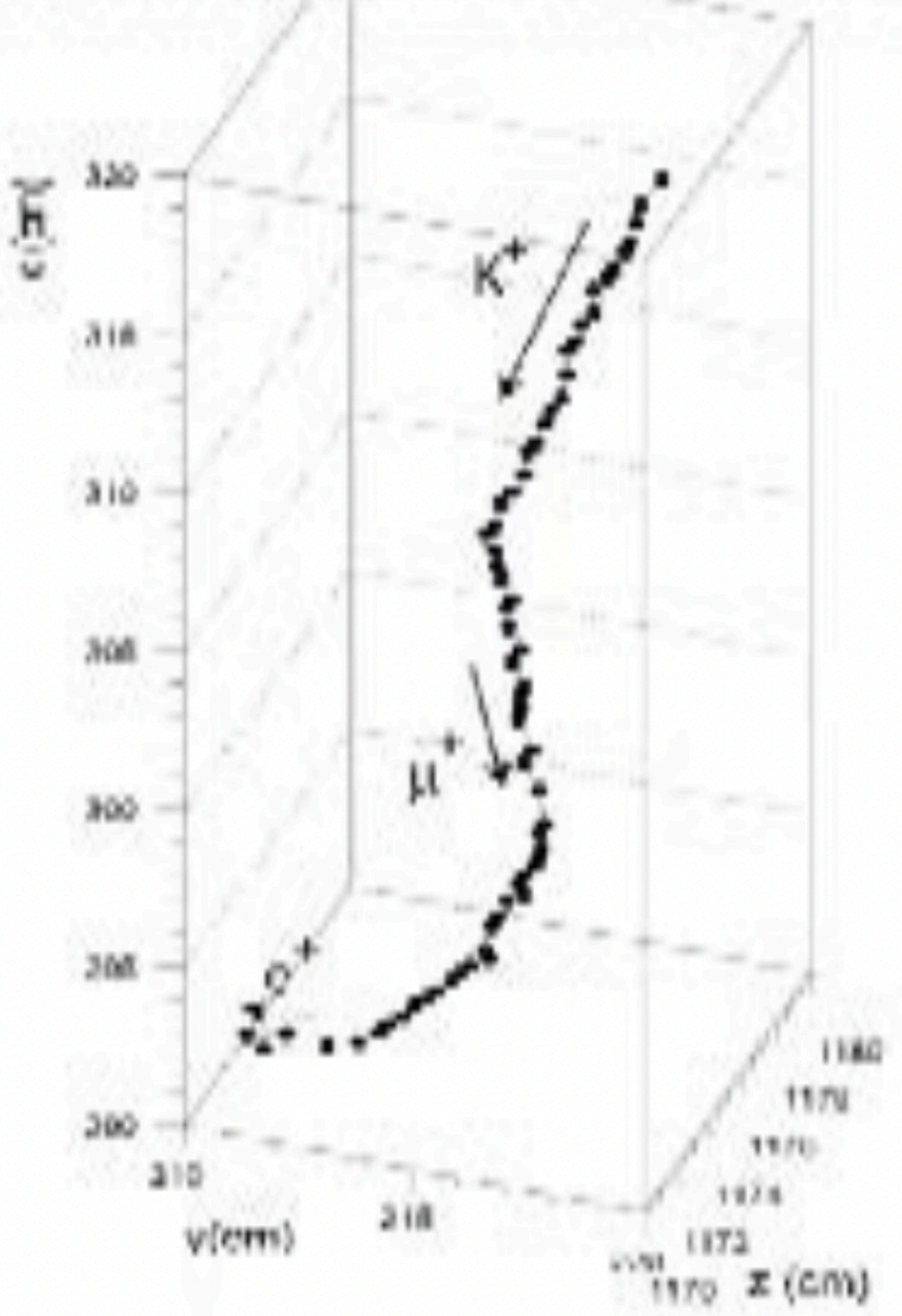
Example: 3 D particle identification : $K^+ \longrightarrow \mu^+ \longrightarrow e^+$



ICARUS EVENT

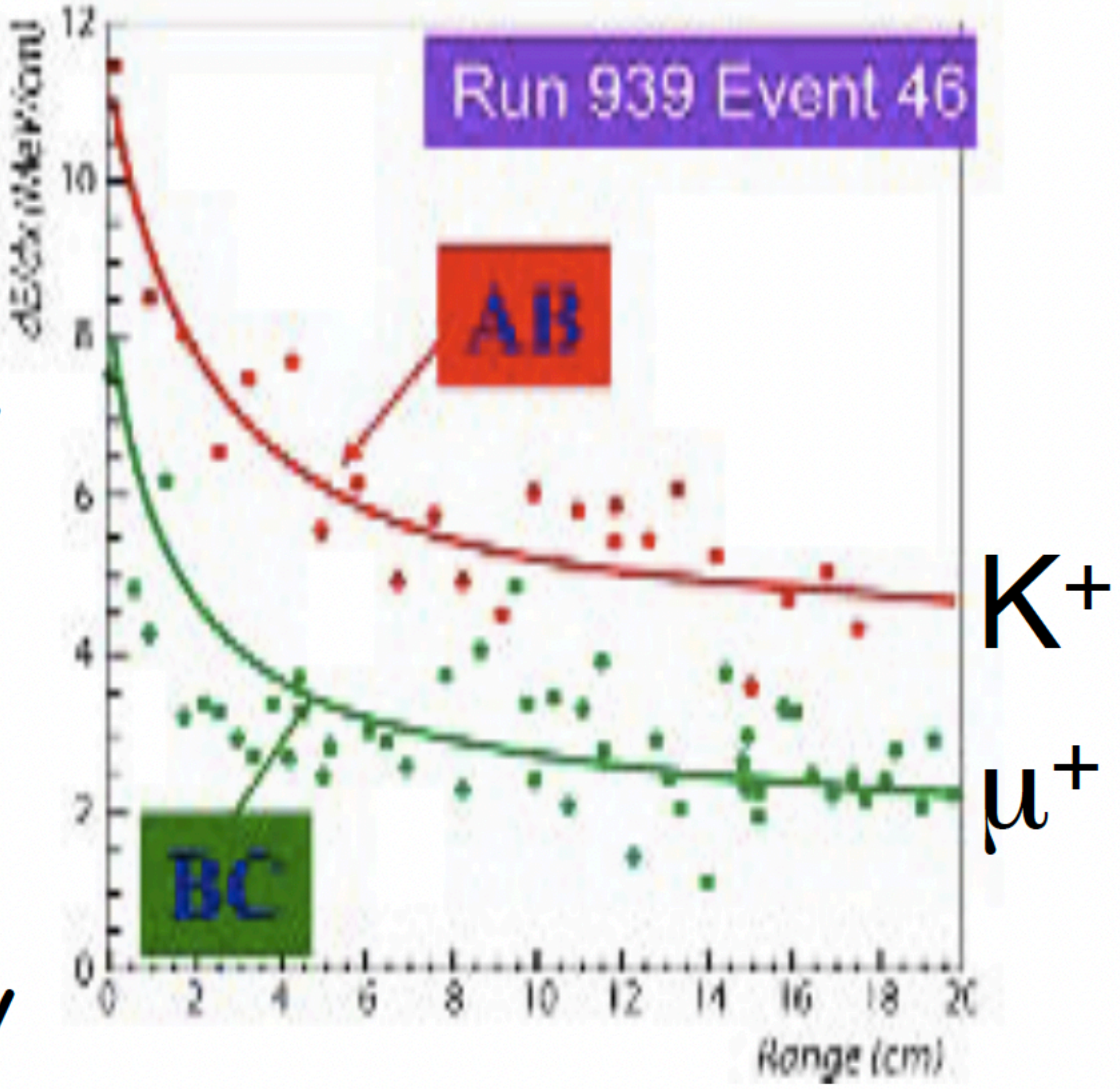


$K^+[AB] \rightarrow \mu^+[BC] \rightarrow e^+[CD]$



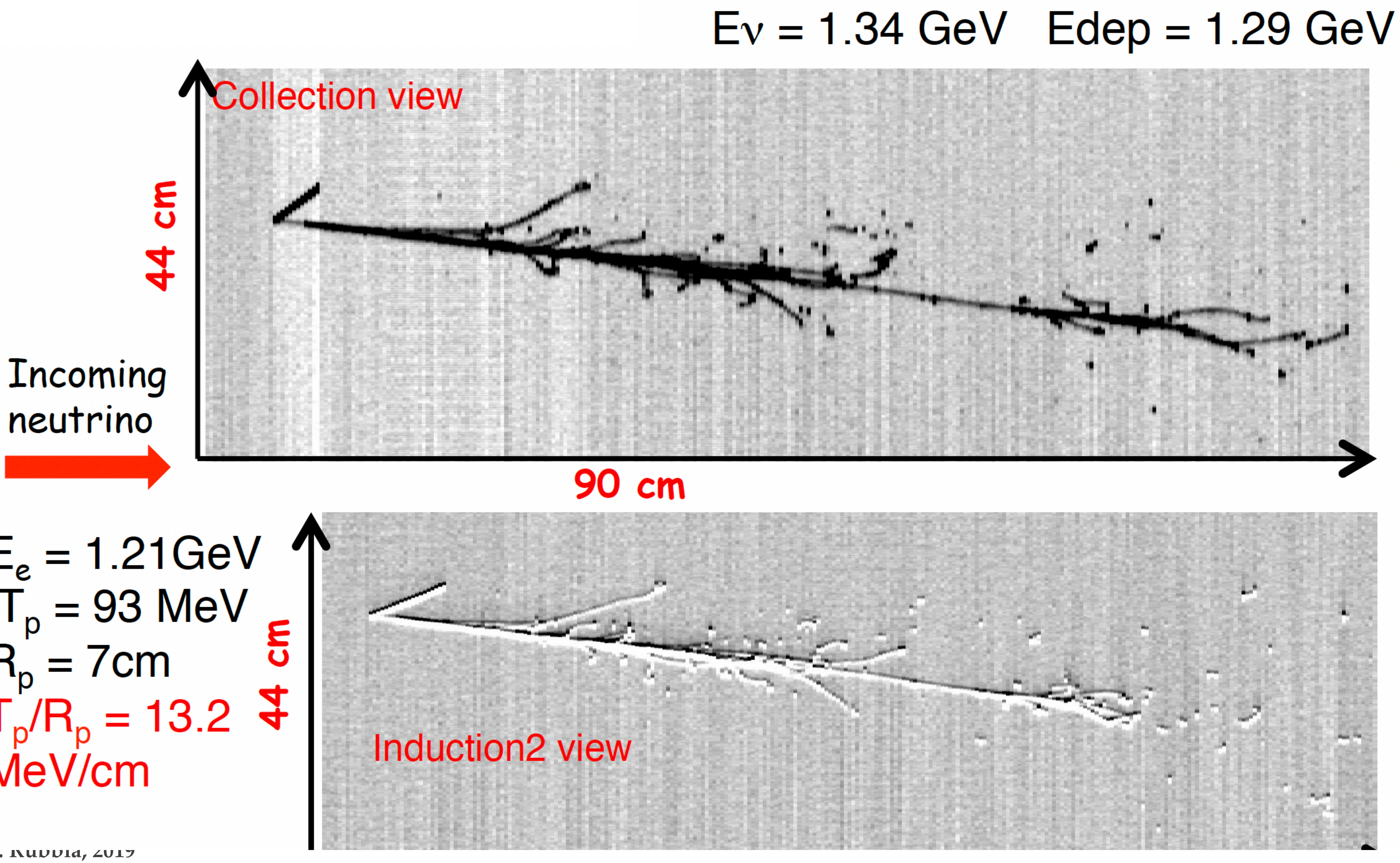
Efficient, low mis-identification, due to precise 3D reconstruction, dE/dx, range measurement

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



C. Rubbia, 2019

A quasi elastic neutrino event: electron neutrino yielding a proton and a e.m. shower

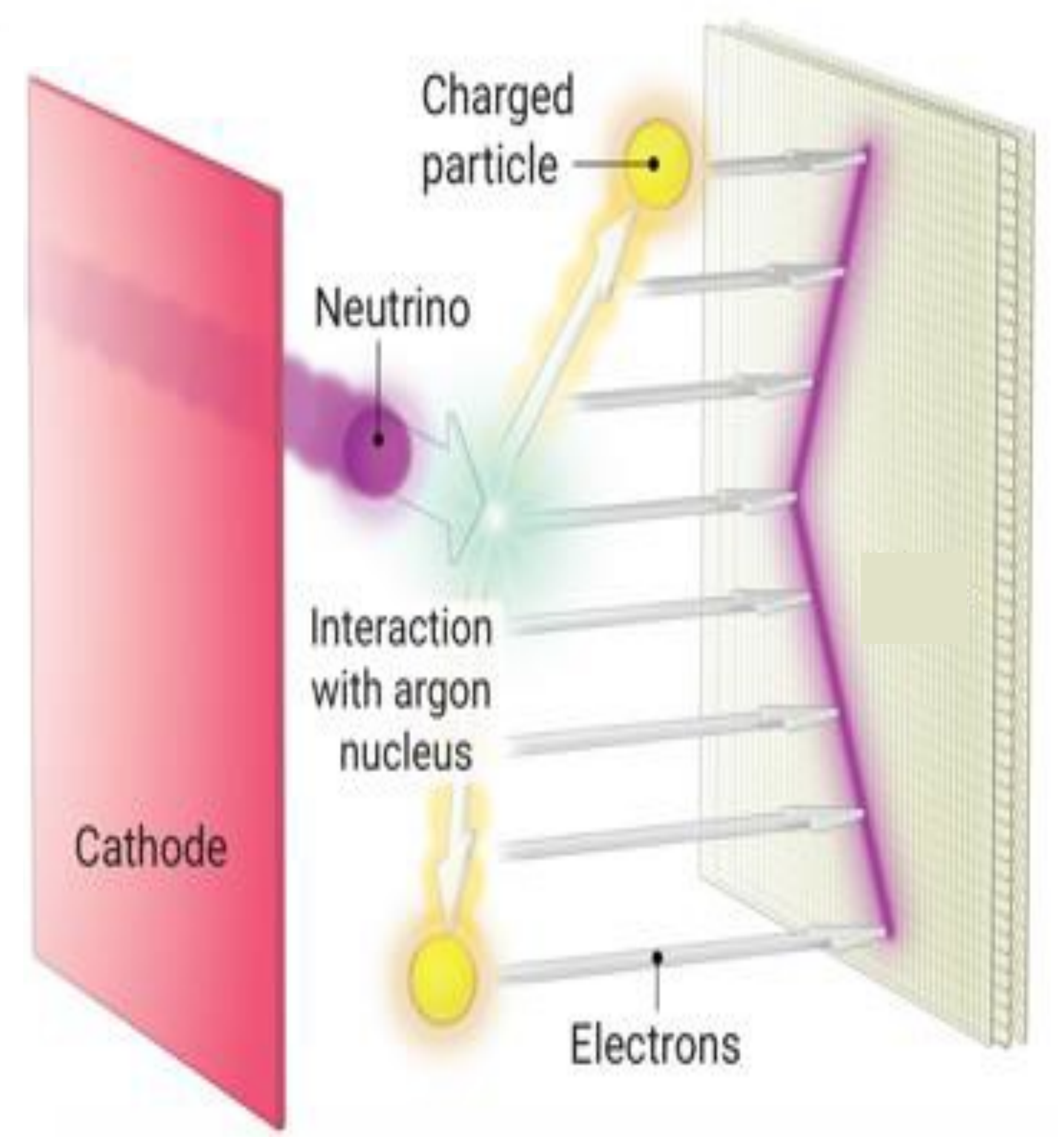


E_e = 1.21GeV
T_p = 93 MeV
R_p = 7cm
T_p/R_p = 13.2 MeV/cm

C. Rubbia, 2019

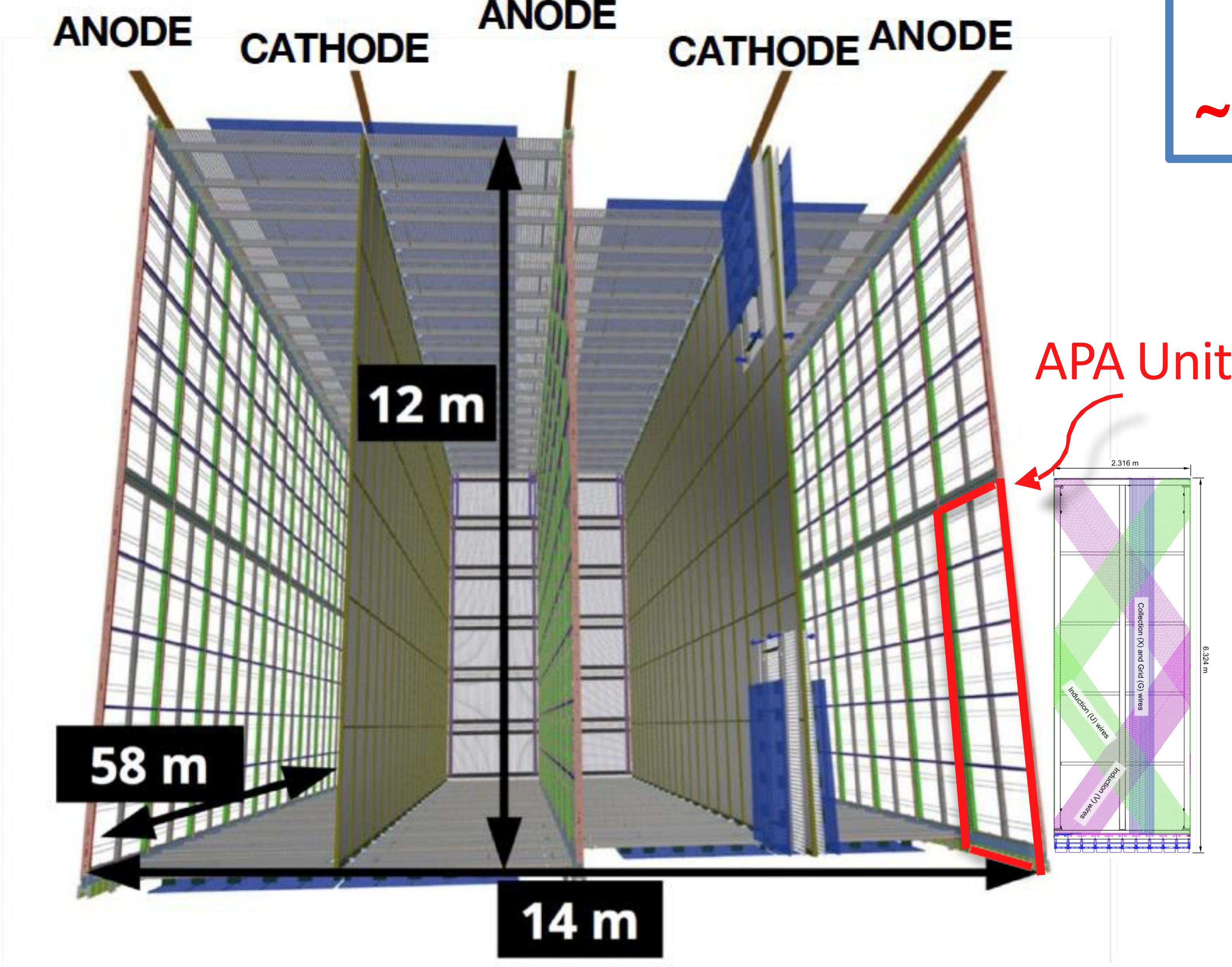
The future of LAr: DUNE

LAr TPC technology



Liquid Argon TPC (C. Rubbia, 1977) is the technique with the best particle imaging capability at kton scale:

FD1-HD «Horizontal drift» (ICARUS concept, wires)



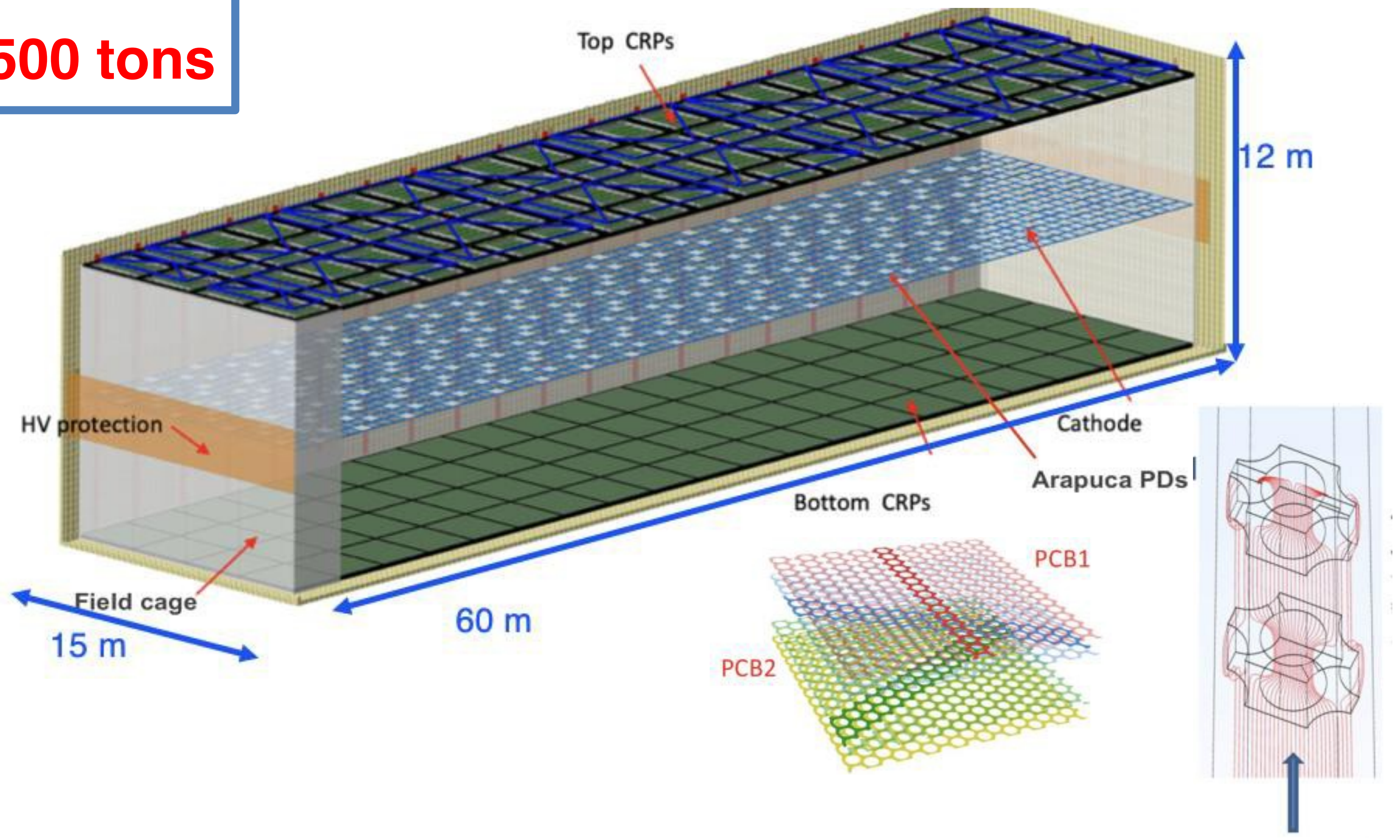
- 150 Anode Plane Assemblies (APAs)
- 384,000 readout wires
- Anode-Cathode 3.5 m drift;
- 500 V/cm field; cathode at -180 kV;
- 6000 photon detection system (PDS) channels
- PDS X-Arapuca modules embedded in APA

BOTH:

28’500 m³

~17’500 tons

FD2-VD «Vertical drift» (Simpler, no wires)



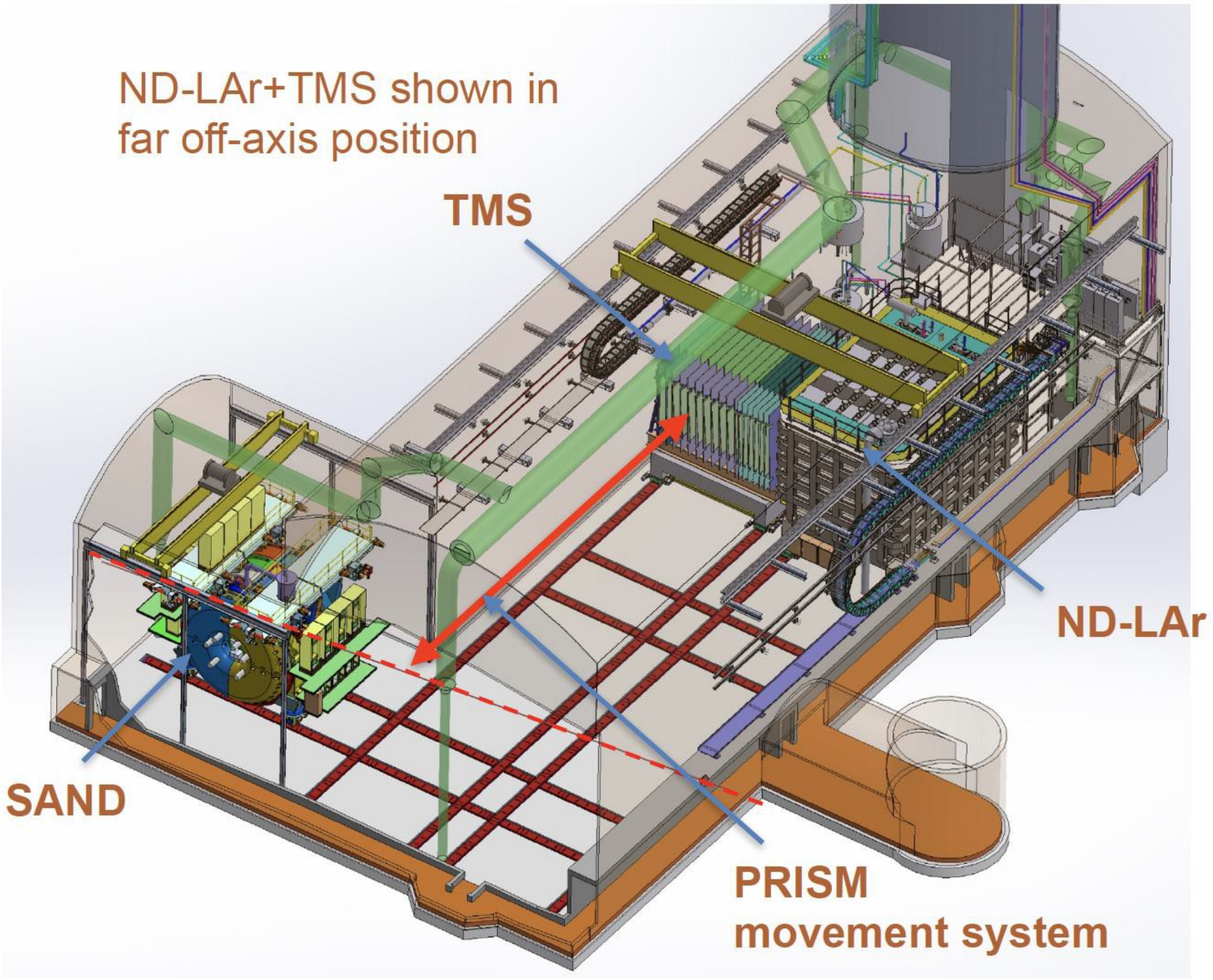
- Charge Readout Planes : perforated PCB’s with segmented electrodes (strips)
- CRPs at the top and bottom
- Cathode (-300 kV) in the middle
- two 6.5 m drift chambers 450 V/cm field
- X-Arapuca modules integrated on cathode and on cryostat walls.

Near detector

$$\frac{\frac{dN_{\nu_e}^{far}}{dE_{rec}}}{\frac{dN_{\nu_\mu}^{near}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu) * \sigma_{\nu_e}^{Ar}(E_\nu) * D_{\nu_e}^{far}(E_\nu, E_{rec})\ dE_\nu}{\int \phi_{\nu_\mu}^{near}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu) * D_{\nu_\mu}^{near}(E_\nu, E_{rec})\ dE_\nu}$$

- Neutrino beam **rate** and **spectrum** to **predict un-oscillated event rates in the FD**
- Constrains **flux**, **cross sections** and **detector response** for **oscillation measurements** and monitor **beam stability**
- Additional physics program on neutrino physics and BSM

- Configuration (Phase I):
  - **ND-LAr:** 7x5 array 1x1x3 m³ LArTPCs with pixel readout
  - **TMS:** Magnetised steel range stack for muon momentum and sign from ν_μ CC interactions in ND-LAr
  - **DUNE-Prism:** movable system for ND-LAr+TMS up to 28.5 m off-axis (ANGOLO!)
  - **SAND:** On-axis magnetised detector with LAr target (GRAIN), tracking (STT) and calorimeter (ECAL)



Experimental strategy for high prevision neutrino oscillations

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta m^2}{a-\Delta m^2}\right)\sin^2\left(\frac{a-\Delta m^2}{4E}L\right) + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{a}\right)\left(\frac{\Delta m^2}{a-\Delta m^2}\right)\sin\left(\frac{aL}{4E}\right)\sin\left(\frac{a-\Delta m^2}{4E}L\right)\cos\left(\frac{\Delta m^2 L}{4E}\right)\cos\delta \;+$$

$\overline{\nu}_\mu \to \overline{\nu}_e$

$a \to -a$

$\delta \to -\delta$

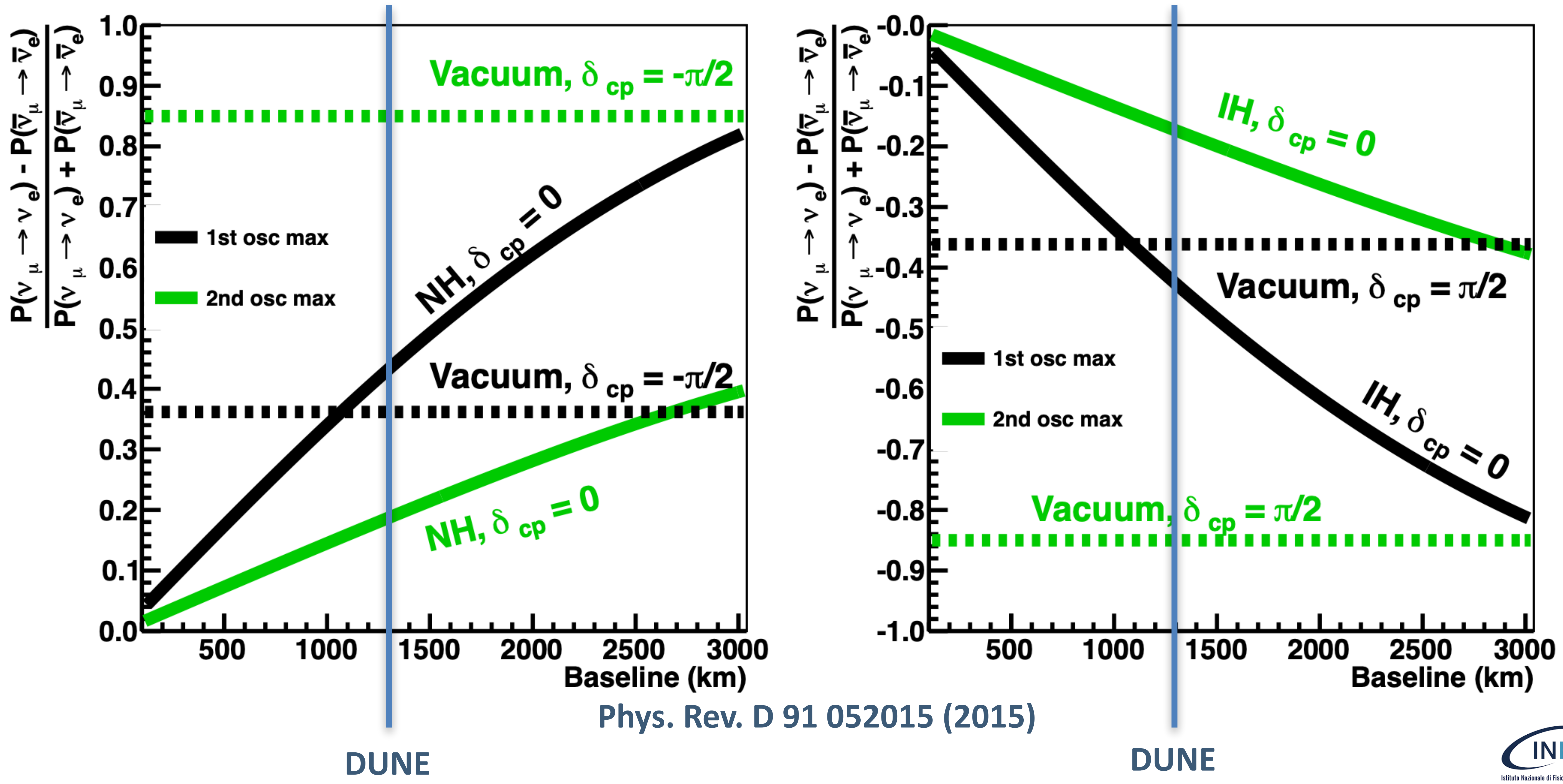
$$+\cos^2\theta_{13}\sin^2 2\theta_{12}\left(\frac{\delta m^2}{a}\right)^2\sin^2\left(\frac{aL}{4E}\right) - \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\left(\frac{\delta m^2}{a}\right)\left(\frac{\Delta m^2}{a-\Delta m^2}\right)\sin\left(\frac{aL}{4E}\right)\sin\left(\frac{a-\Delta m^2}{4E}L\right)\cos\left(\frac{\Delta m^2 L}{4E}\right)\sin\delta$$

Leading order approximation

$$\mathcal{A}_{cp}(E_\nu) = \left[\frac{\mathrm{P}(\nu_\mu \to \nu_e) - \mathrm{P}(\bar\nu_\mu \to \bar\nu_e)}{\mathrm{P}(\nu_\mu \to \nu_e) + \mathrm{P}(\bar\nu_\mu \to \bar\nu_e)}\right] \approx \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{CP}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right) + \text{matter effects.}$$

- Long baseline + wide-band beam: **unfold CPV and matter effects** using information from the **first** and **second oscillation maxima**

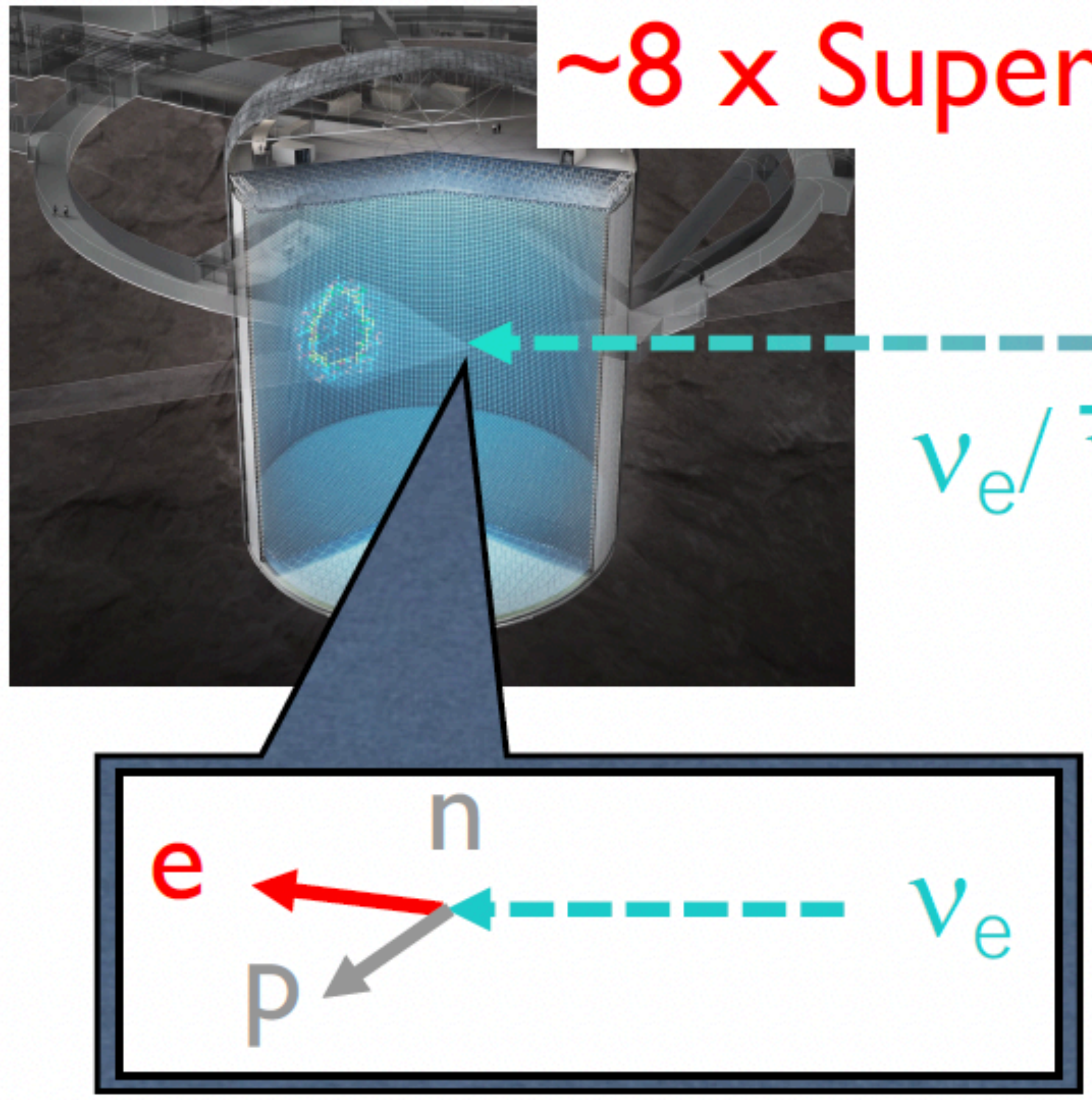
  - Baseline ~ 1300 km
    - 1st peak at ~ 2.6 GeV
    - 2nd peak at ~ 0.65 GeV



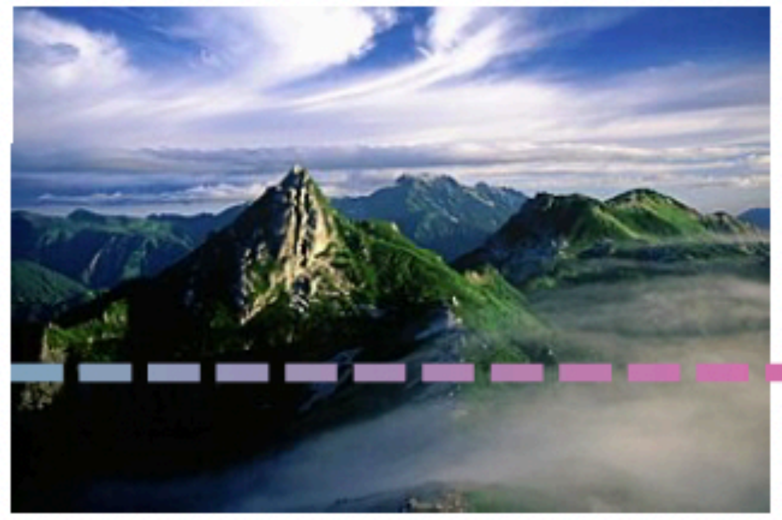
Phys. Rev. D 91 052015 (2015)

HyperKamiokande: J-PARC off-axis, 0.6 GeV, 295 km

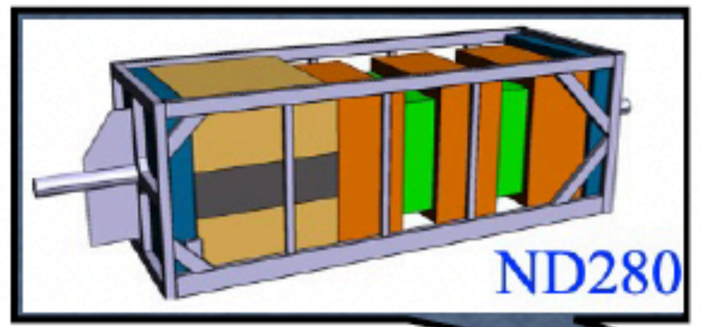
~8 x Super-K



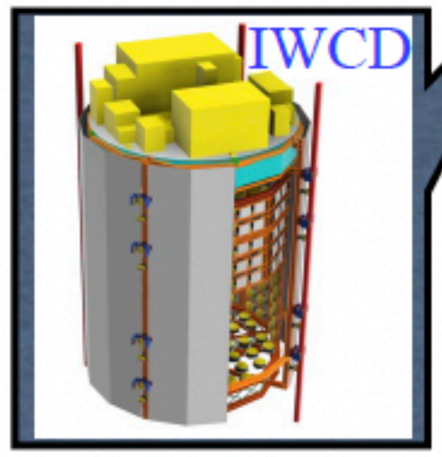
$\nu_e / \overline{\nu}_e$



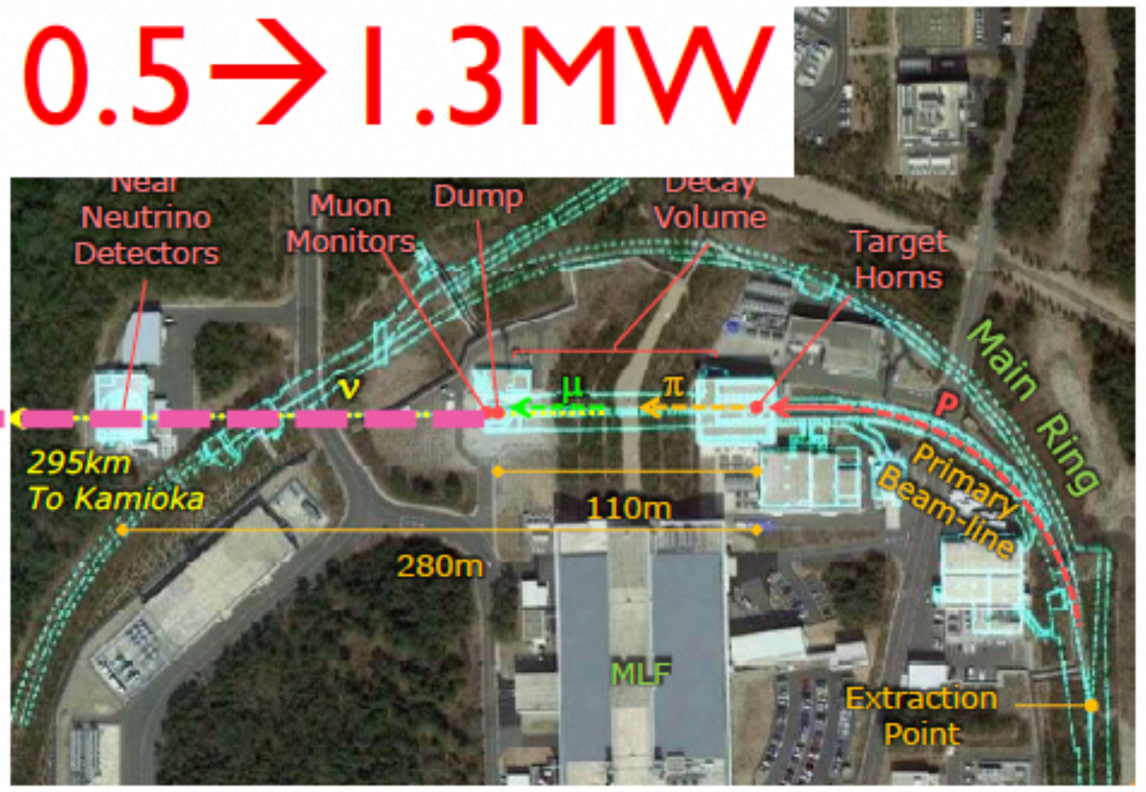
The Japanese Alps



$\nu_\mu / \overline{\nu}_\mu$



0.5→1.3MW

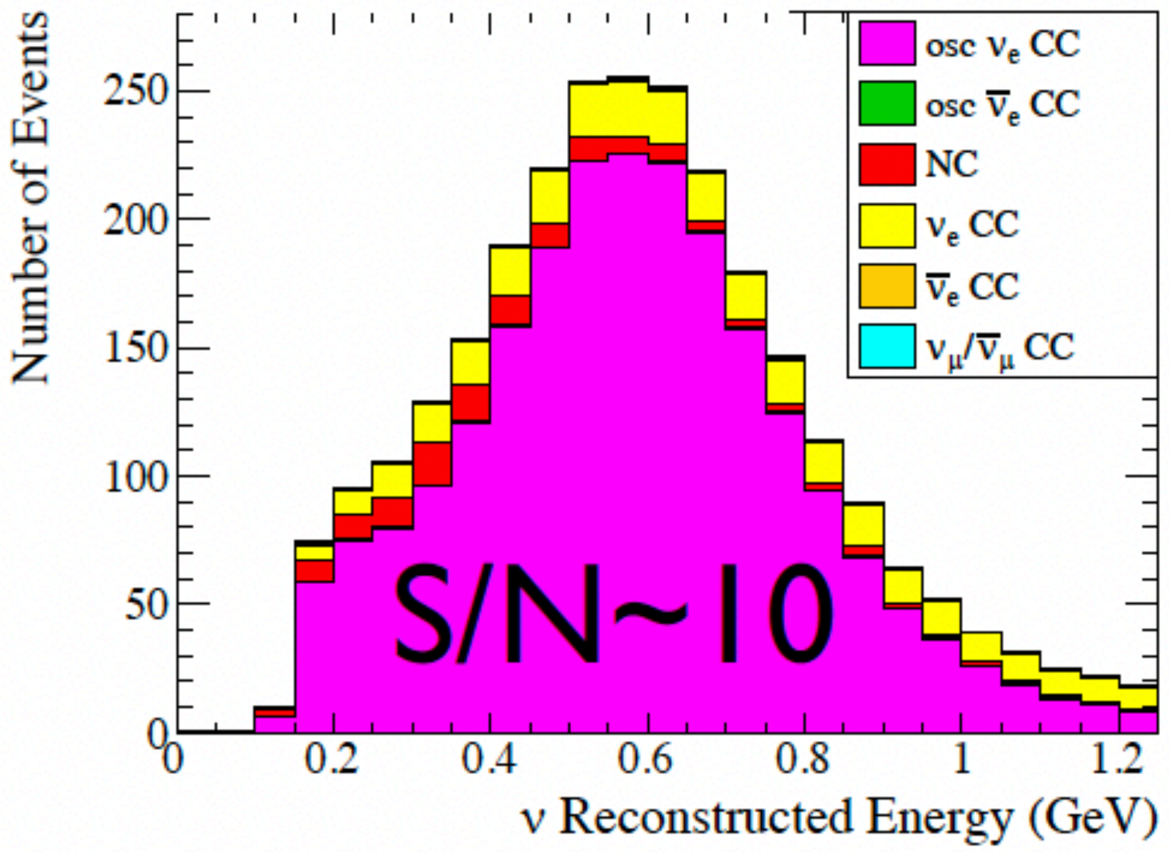


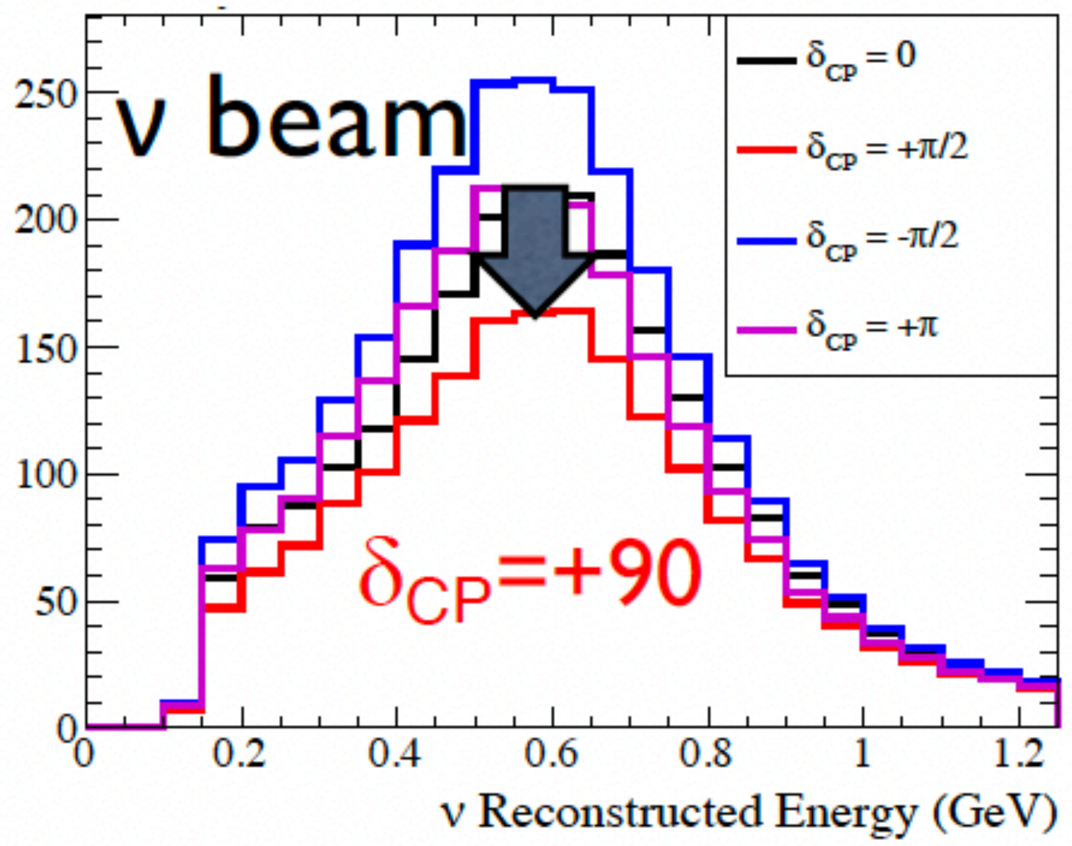
2.5 deg. off-axis

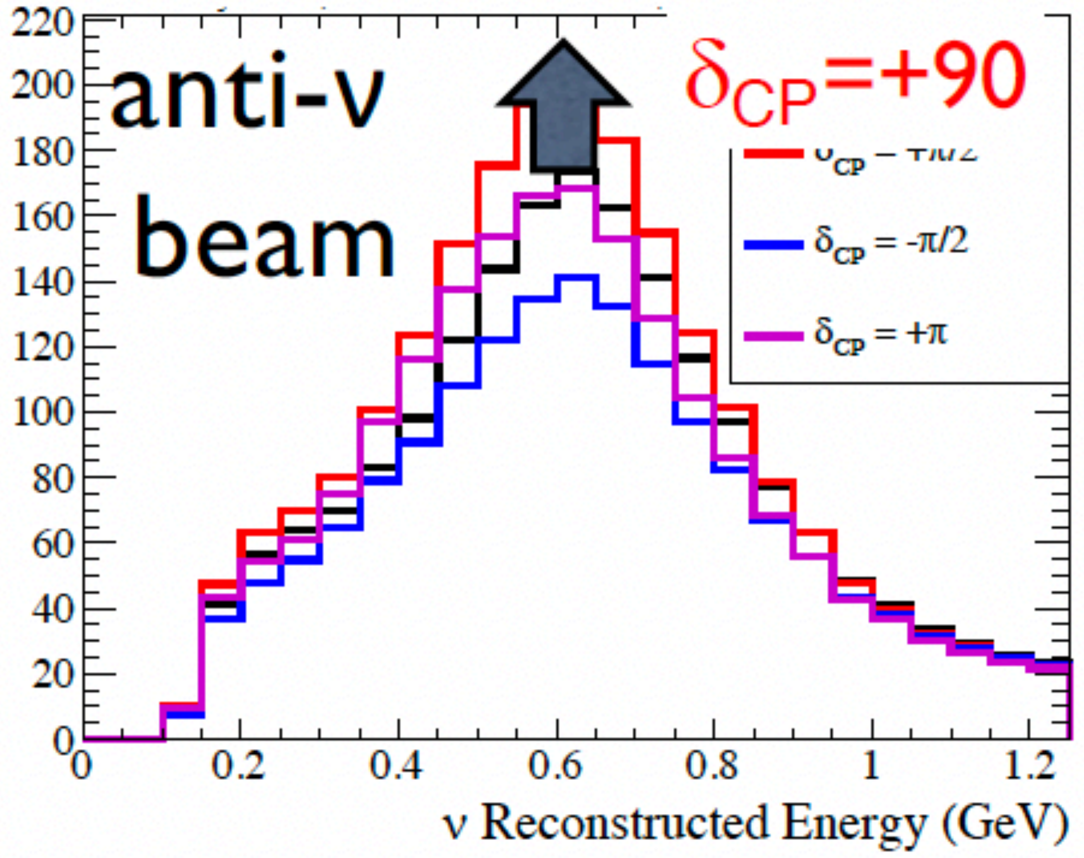
ν_e appearance signal = single e event

CCQE : $\nu_e + n \rightarrow e + p$

(dominant process at J-PARC beam energy)





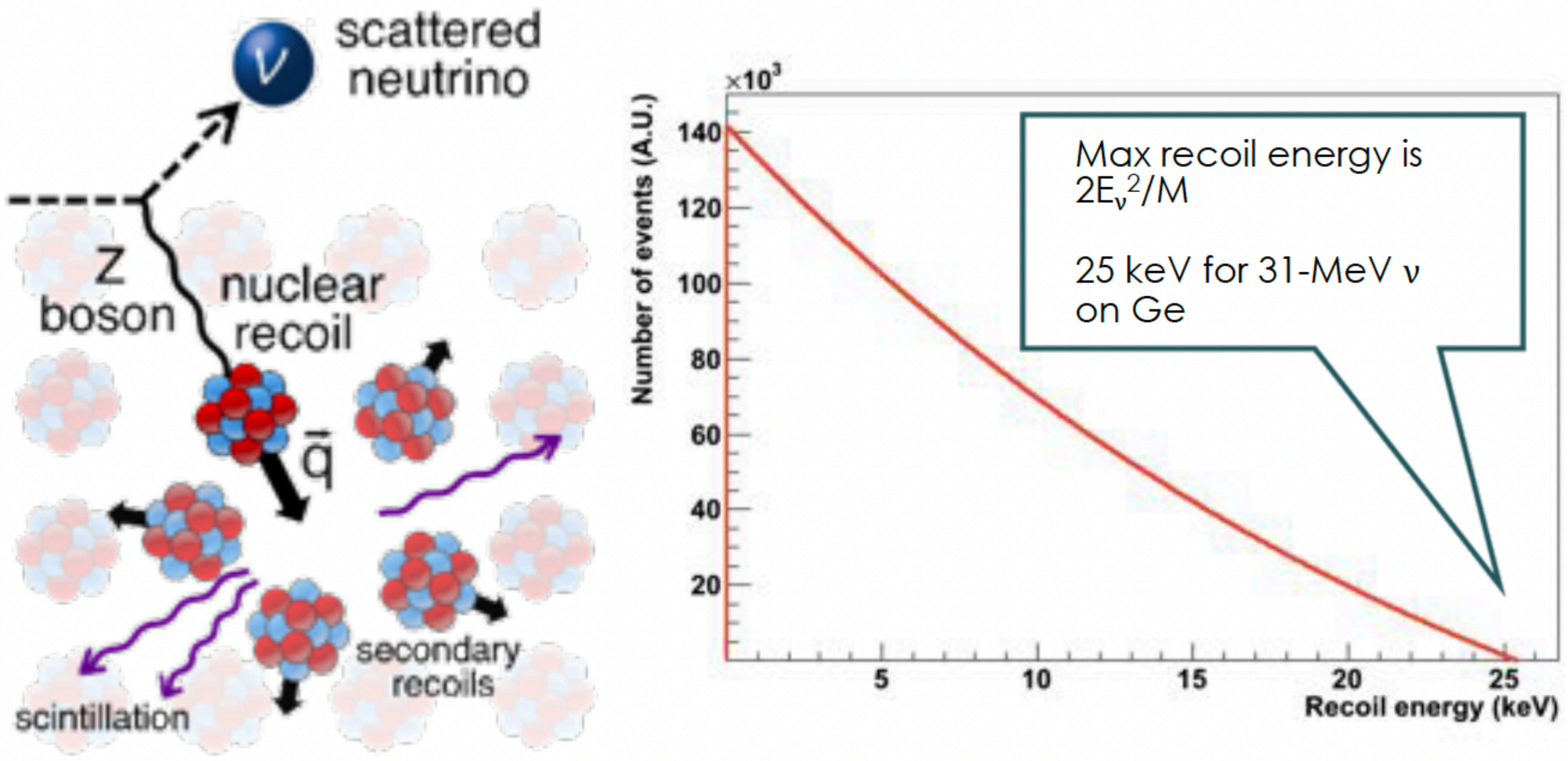


Relatively Small matter Effect & Large CPV Effect

HK 10 yr, 2.7×10^{22} POT 1:3 $\nu:\overline{\nu}$, 1-ring e-like + 0 decay e, > 1000 events each

Coherent elastic neutrino-nucleus scattering (CEνNS)

A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim$ 50 MeV



CEvNS cross section is well calculable in the Standard Model

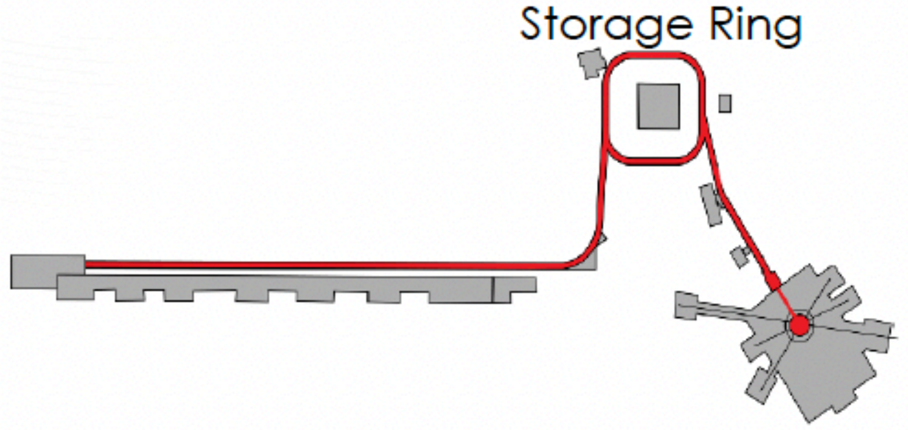
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

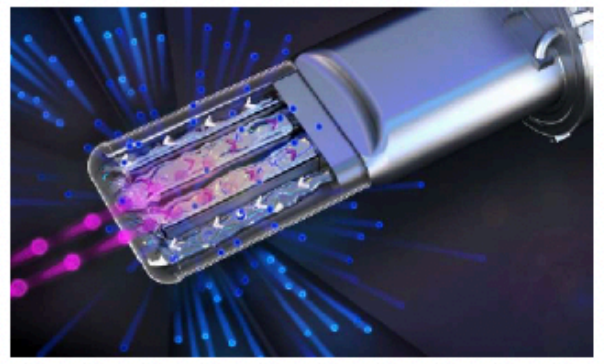
CEvNS cross section is large! $\propto N^2$

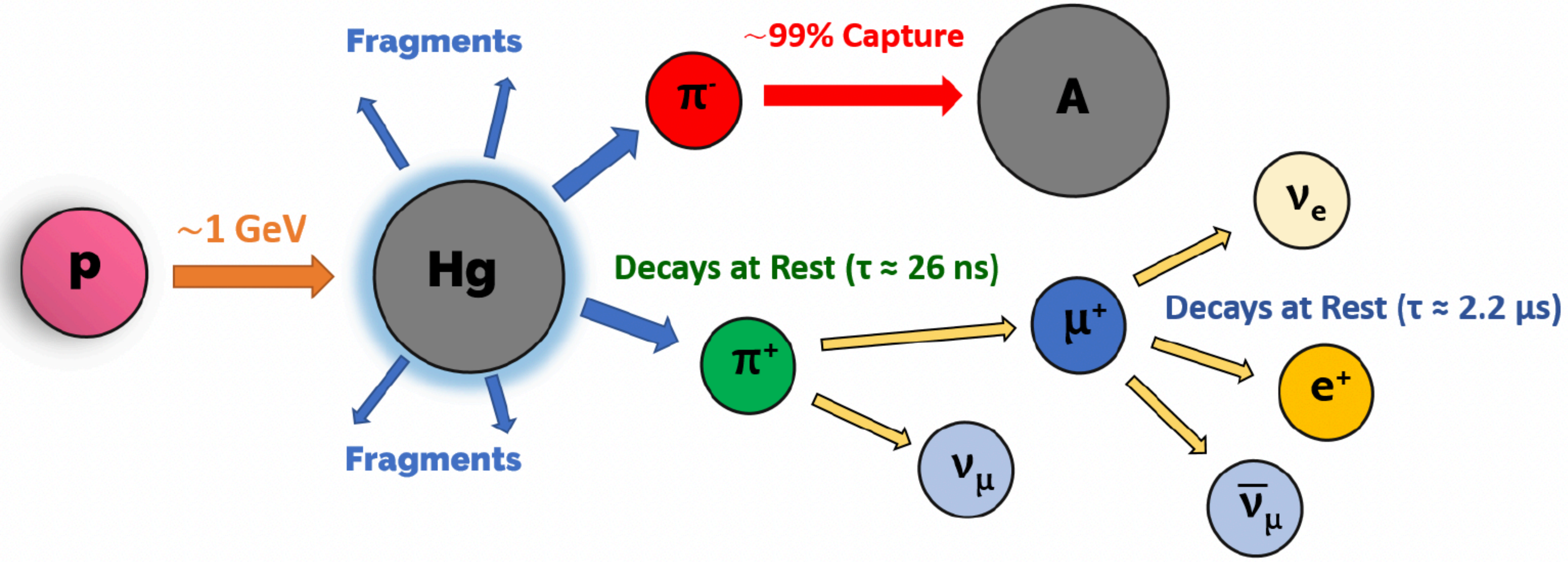
- Predicted in 1974 by D. Freedman
- Interesting test of the standard model
  - Sensitive to **non-standard interactions**
  - Largest cross section in **supernovae** dynamics
  - Background for future **dark matter** experiments
  - Sensitive to nuclear physics, **neutron skin** (neutron star radius)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

J. Newby, Neutrino 2020

CEνNS







- Proton Beam:
  - 0.9-1.3GeV
  - 0.9-1.7MW, **soon 2MW (PPU)**.
- Total ν flux: ~4.3 x 10^7 cm^{-2} s^{-1} at 20m
- Beam timing & duty cycle (60Hz, 380ns FWHM) allow for powerful reduction of steady-state backgrounds (~10^{-4})

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

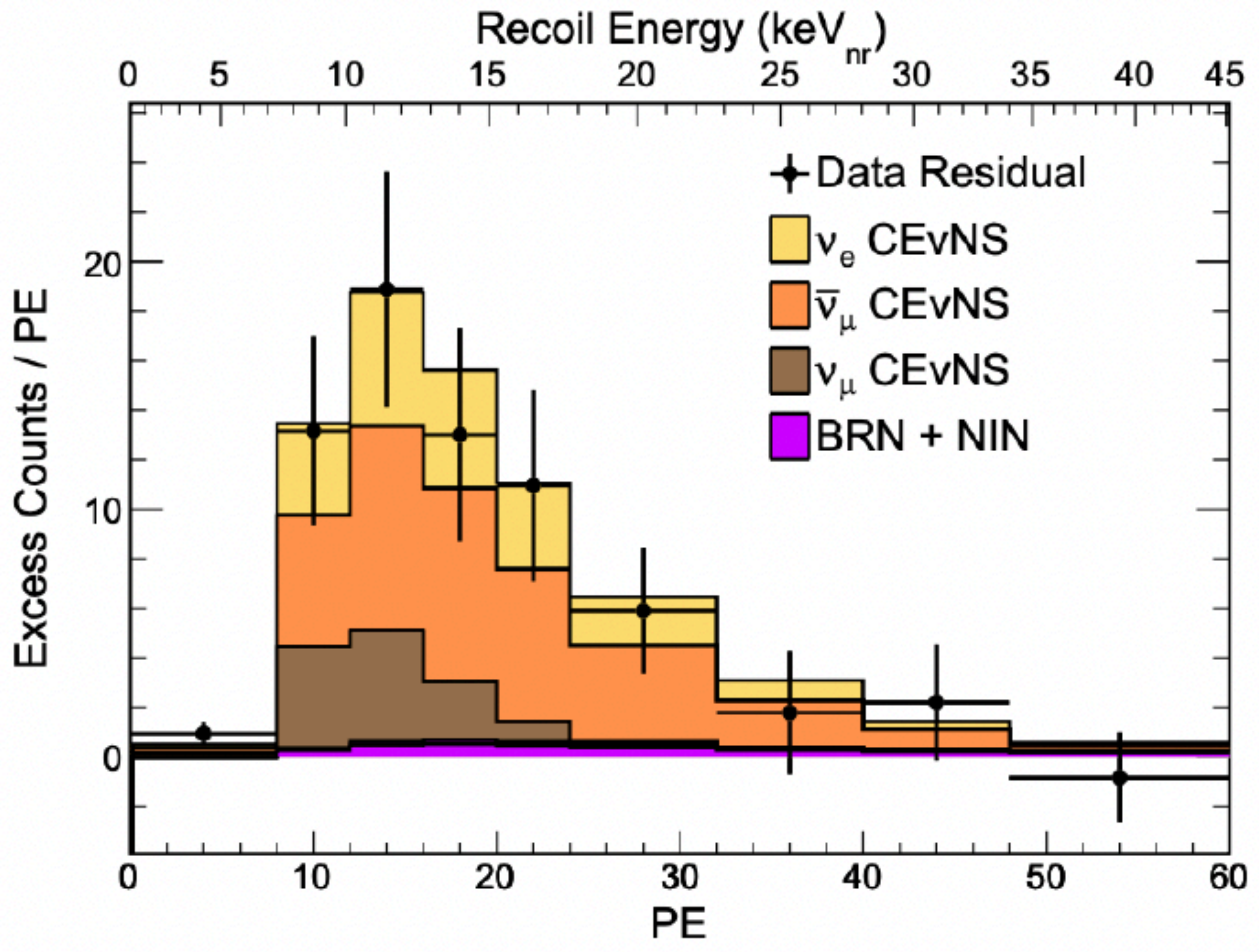
2-body π^+-decay: Prompt (26nsec)
Monochromatic: 29.9MeV ν_μ

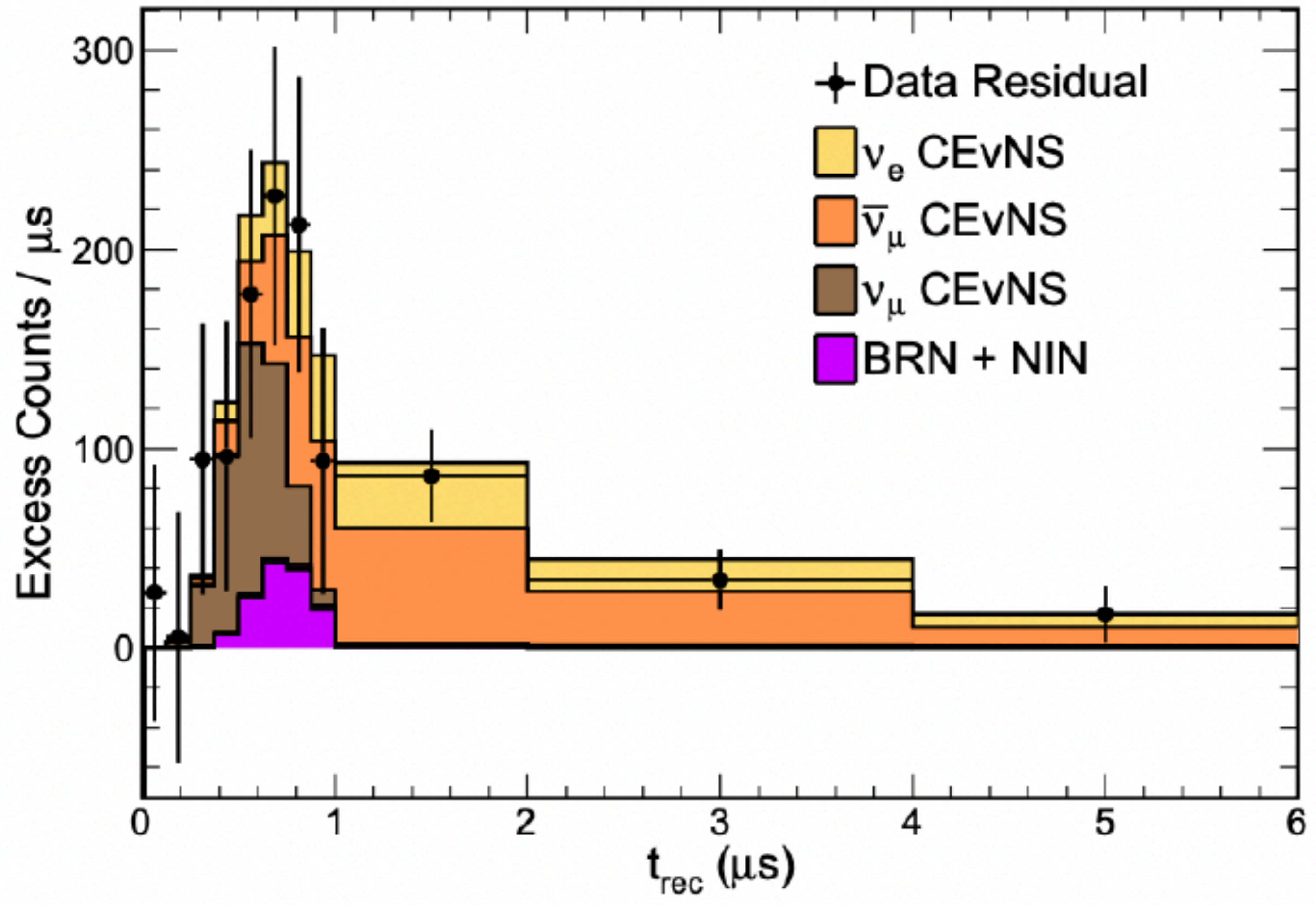
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body μ-decay:
Delayed (2.2μsec)
0-53MeV $\bar{\nu}_\mu$, ν_e

CEνNS: example of detections (there are more)

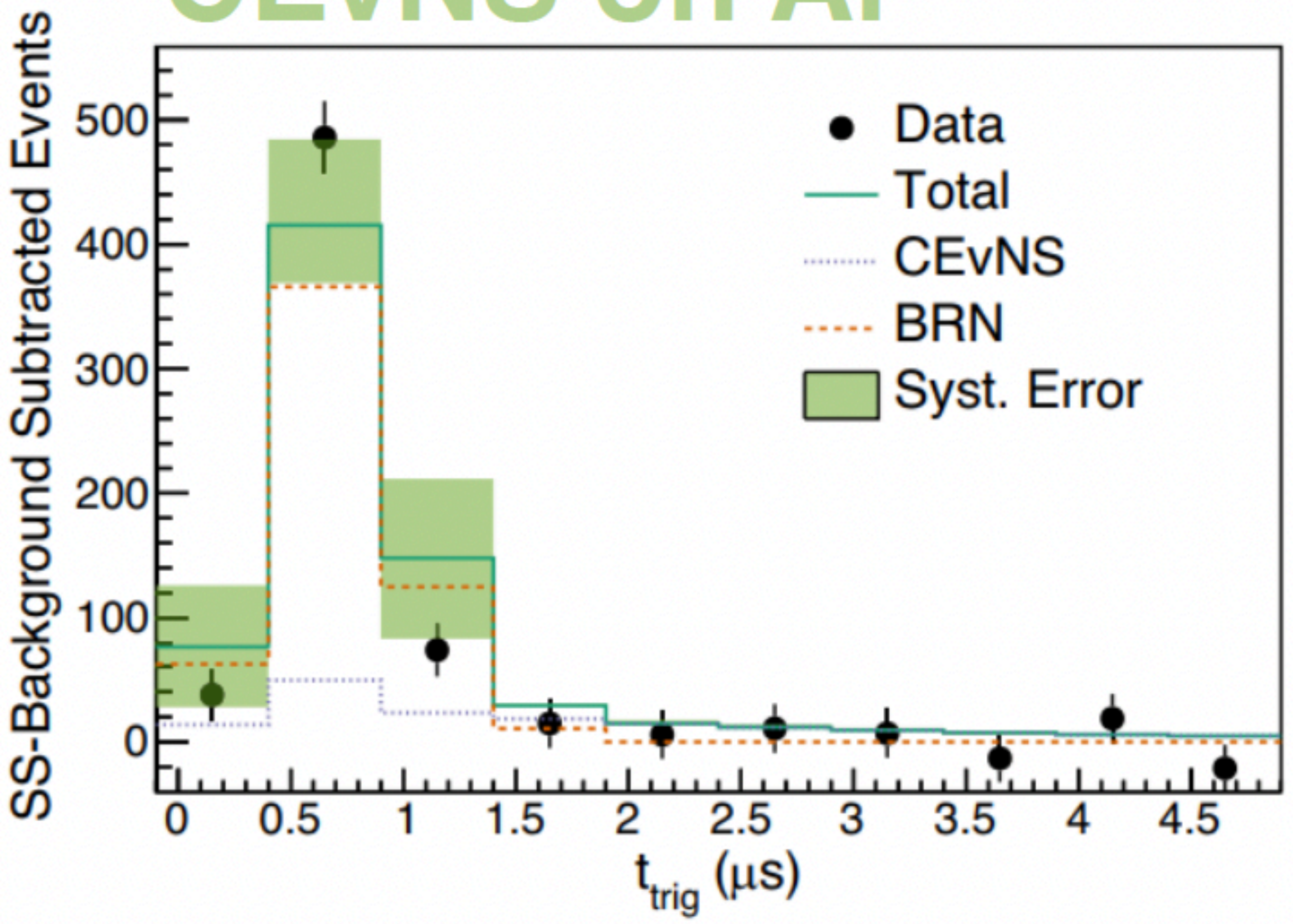
CEvNS on CsI

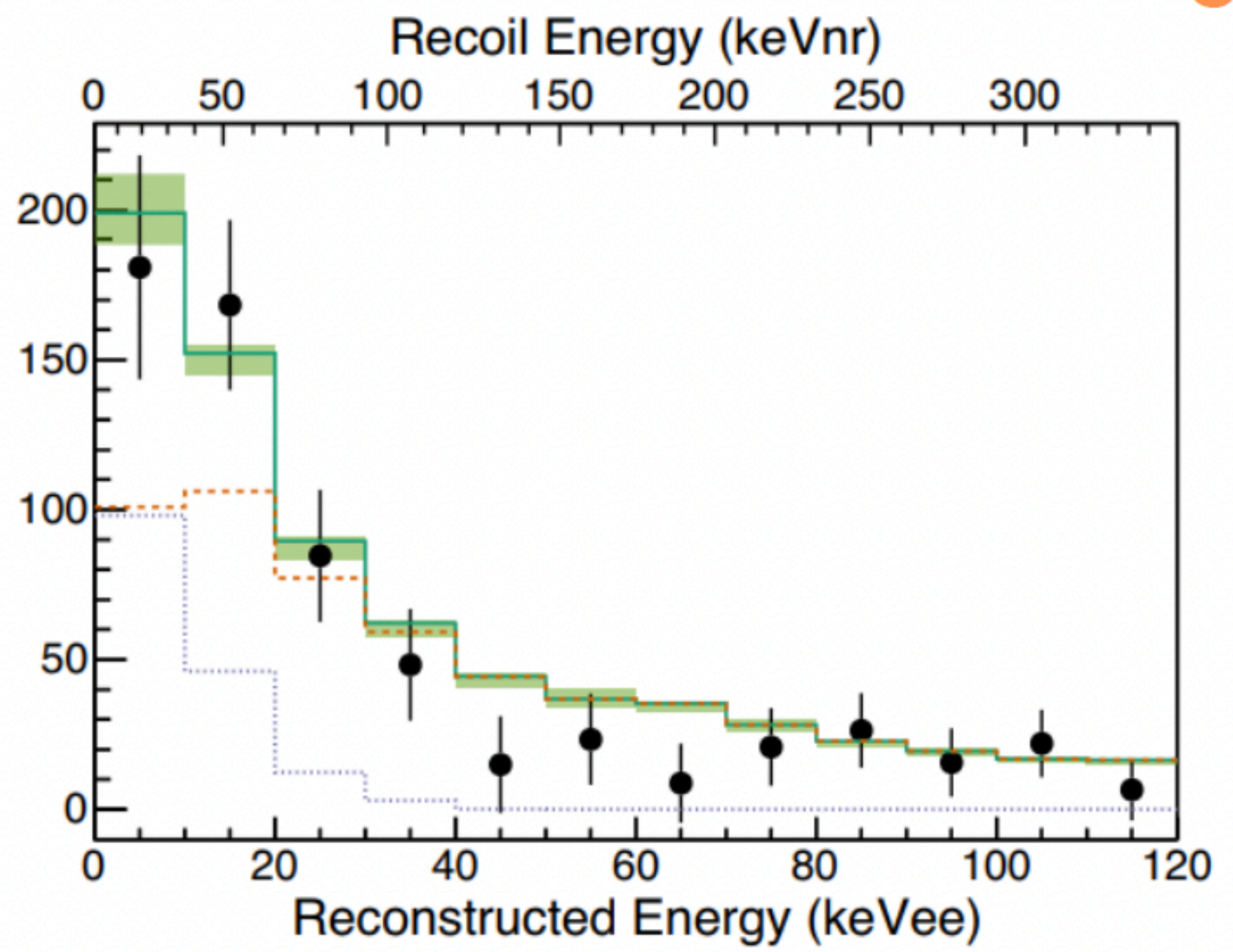


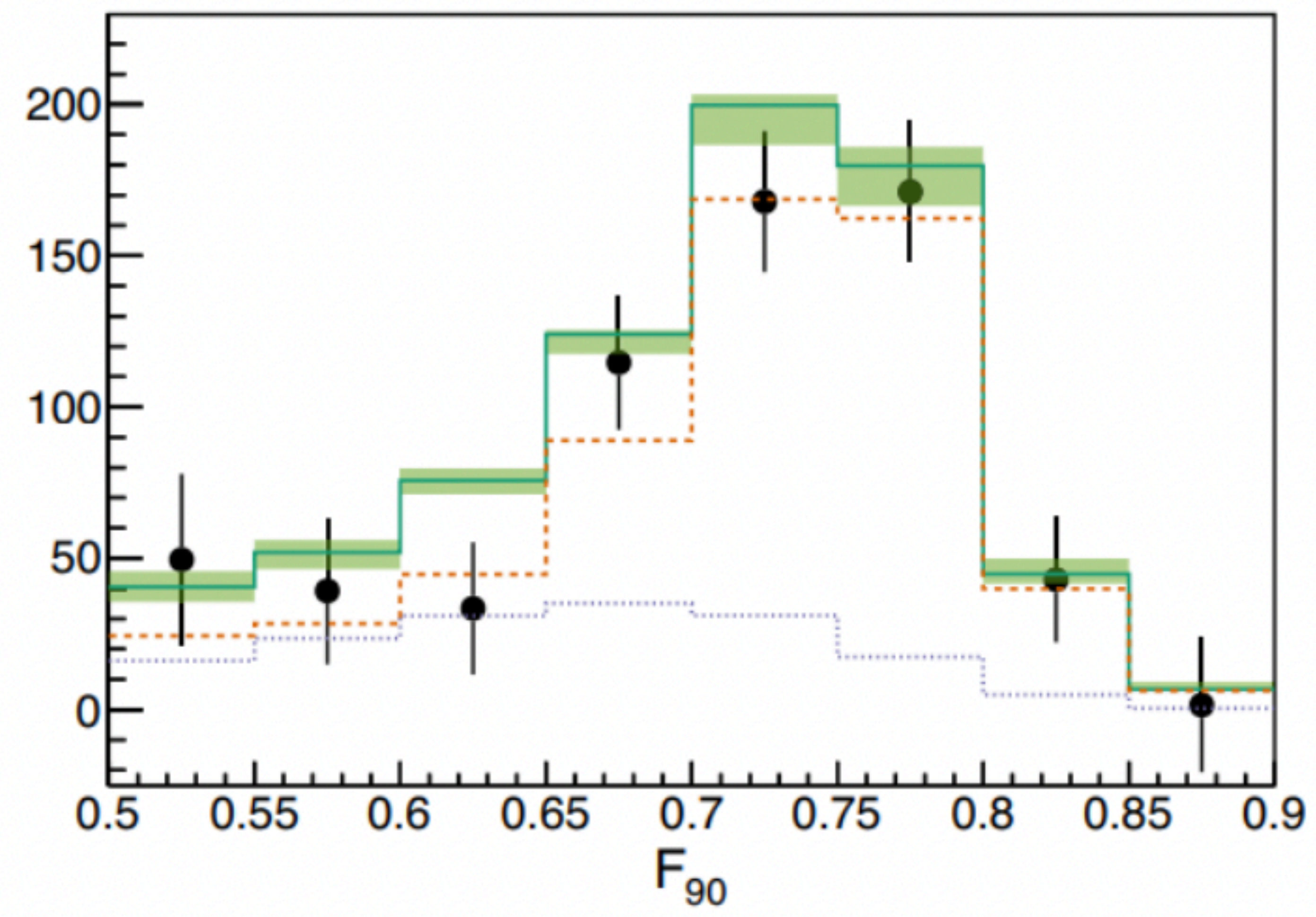


COHERENT, PRL 129 081801 (2022)

CEvNS on Ar

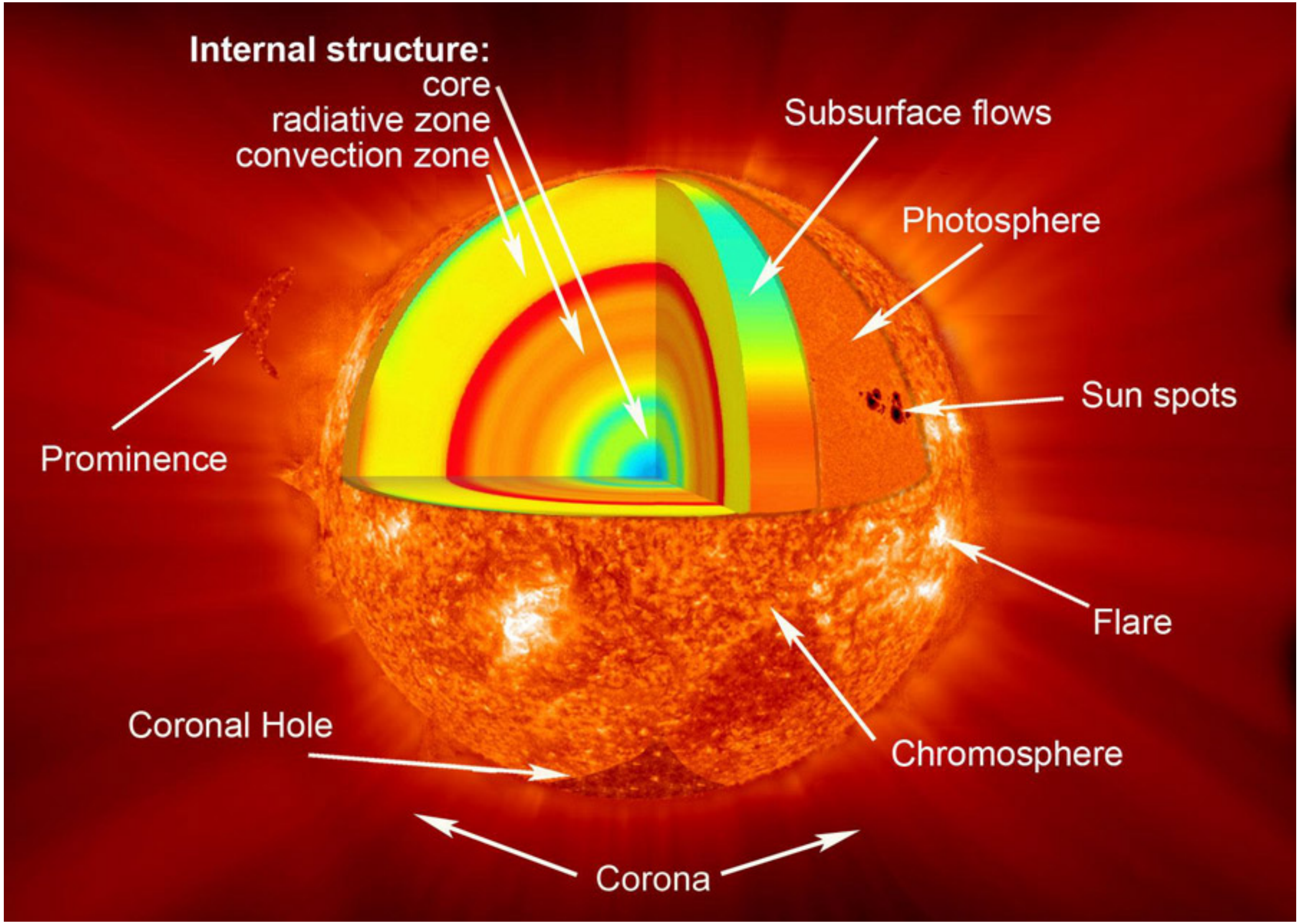






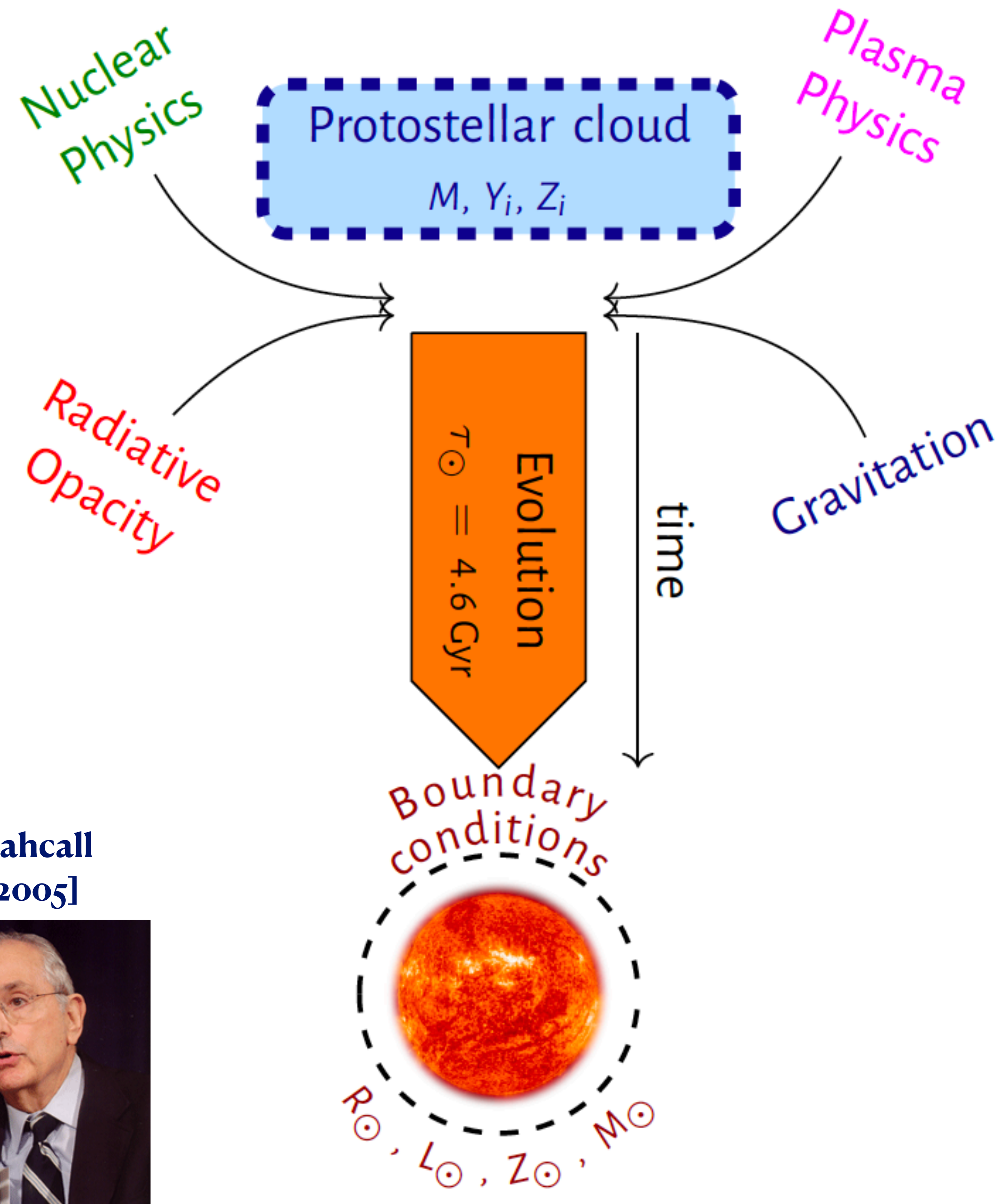
COHERENT, PRL 126 012002 (2021)

The structure of the Sun

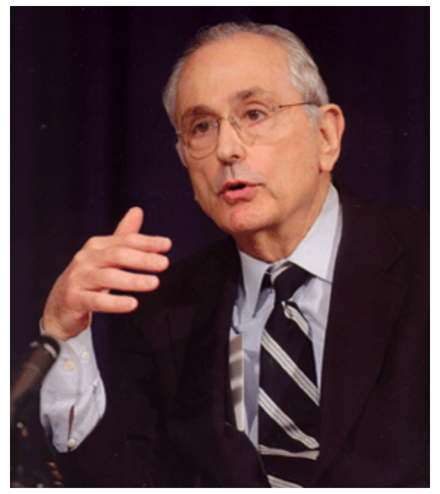


The Standard Solar Model

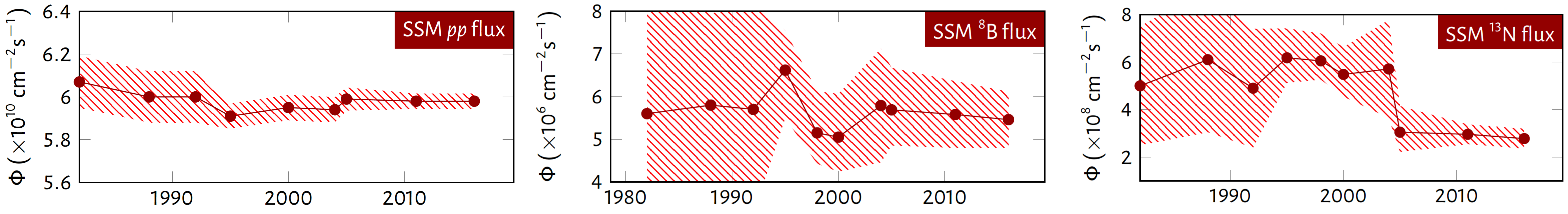
- **The observable is the Sun we see now,** which depends on a **complex evolution process**
  - Gravity
  - **Composition**: X (hydrogen), Y (helium), , Z (“metals”)
  - Radiative **opacity** and plasma physics
  - Temperature and density profiles
  - Energy transport: radiative until 0.71 $R_\odot$, 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)
-



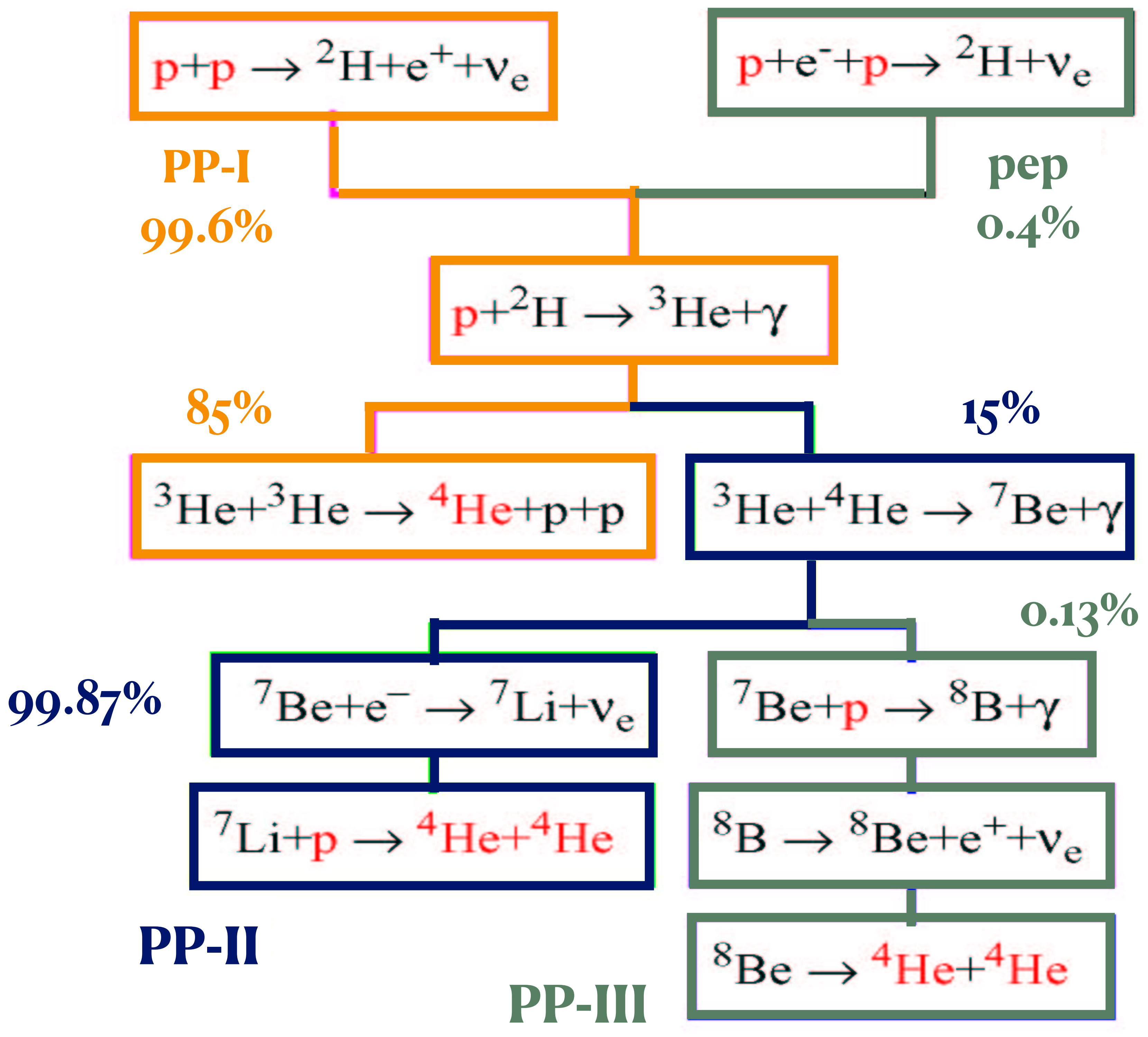
Solar neutrinos from hydrogen burning

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

Bethe & Critchfield 1938

pp chain

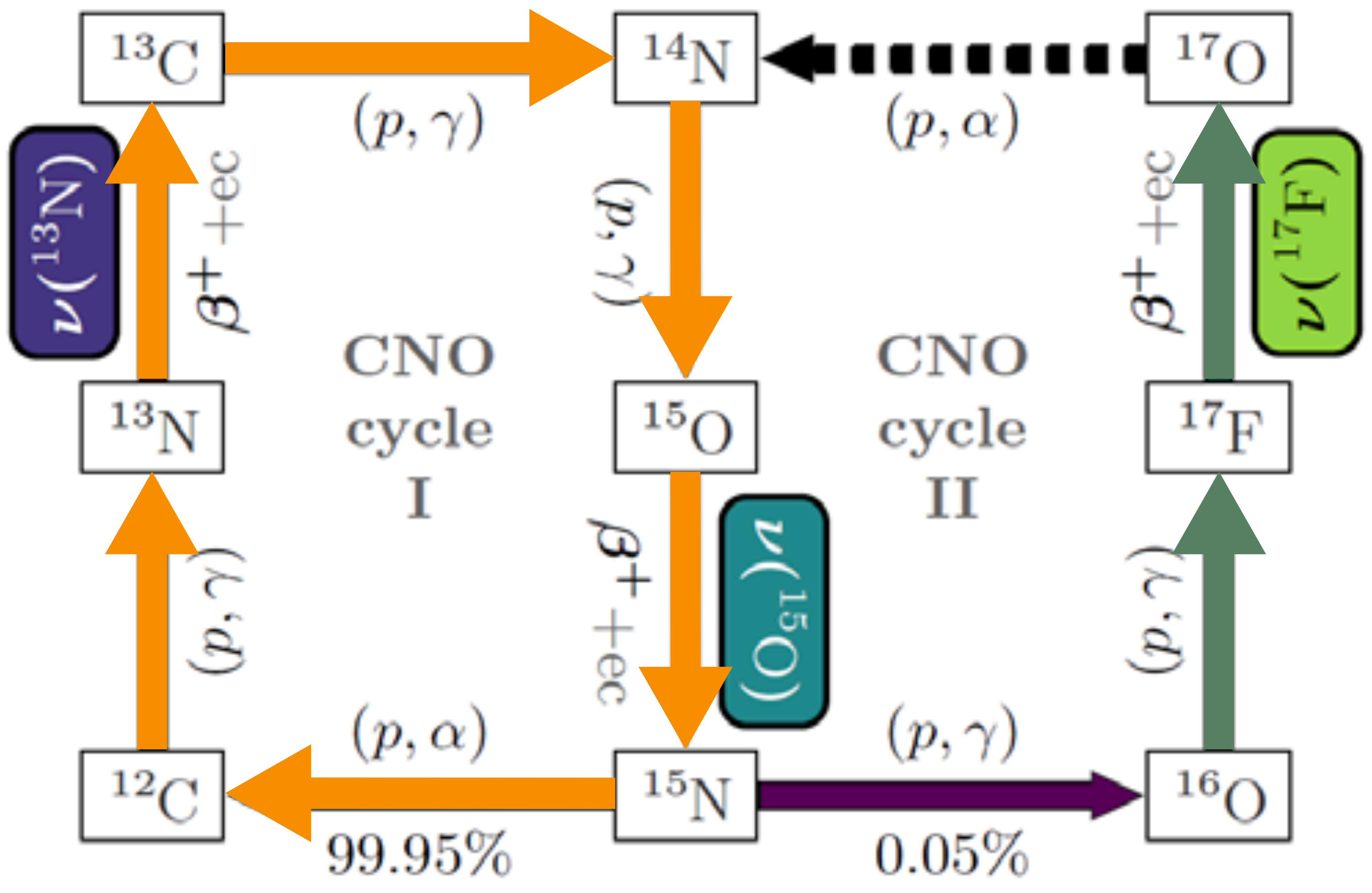
(99% energy)



CNO cycle

(~ 1% energy)

Weizsäcker (1937, 1938), Bethe (1939)



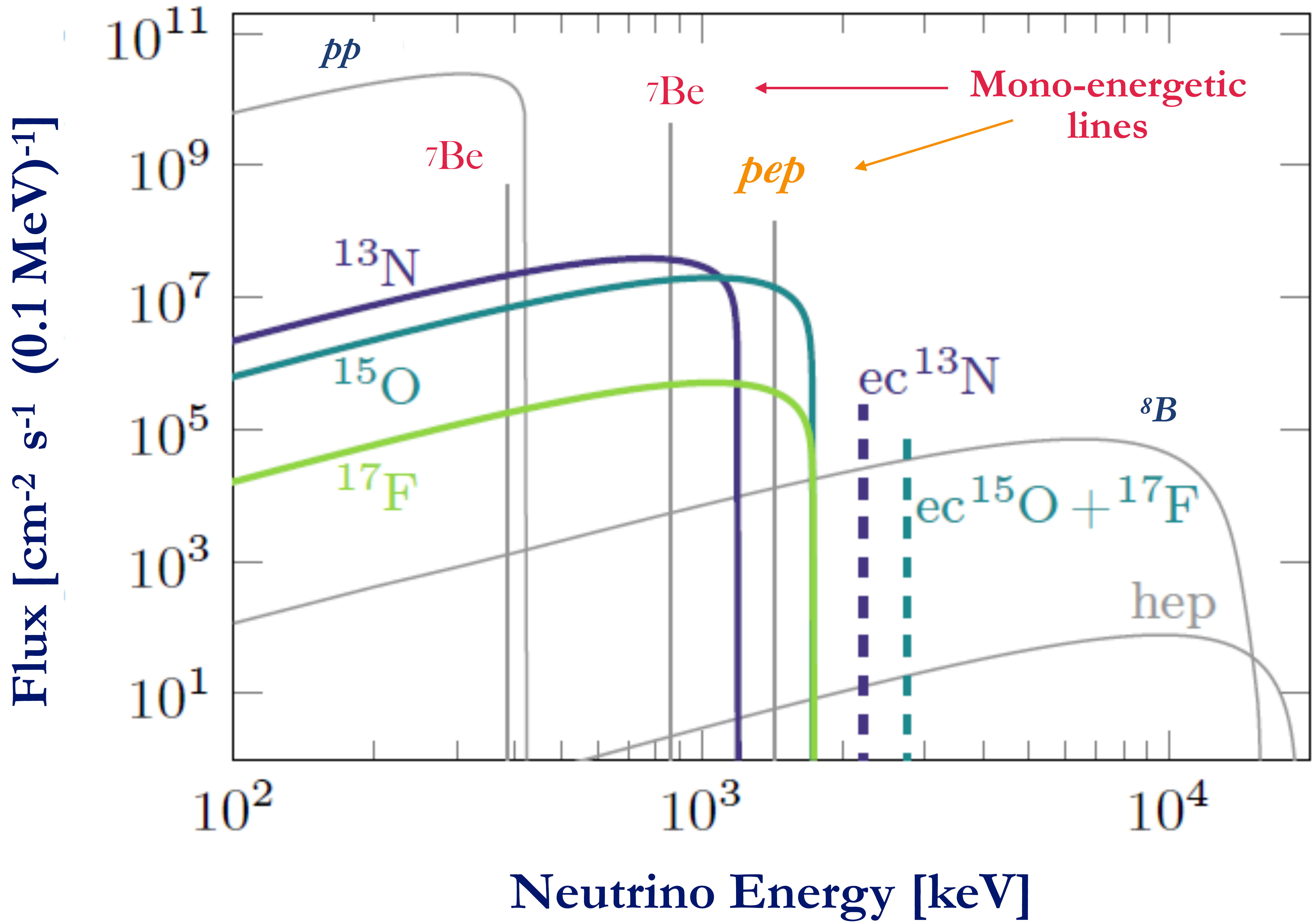
${}^{12}C$ is the main catalyst

CNO-II is suppressed in the Sun

REACTION	**ENERGY YIELD**	**2% of E in NEUTRINOS**
$4p \rightarrow {}^4He + 2e^+ + 2\nu_e$	$24.7\ MeV + 2m_ec^2$	$< E_\nu >= 0.53\ MeV$

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.

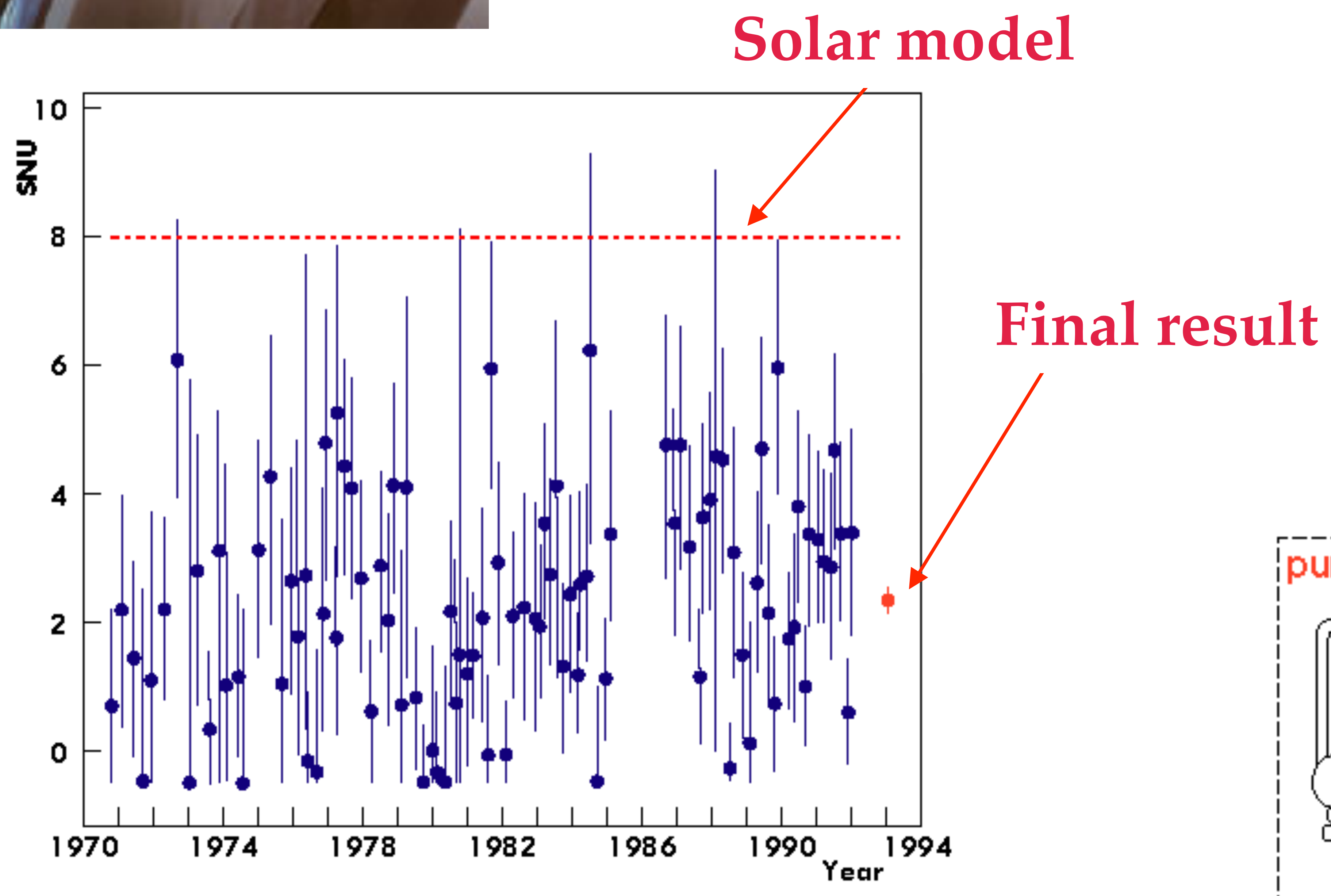
doi:10.3847/1538-4357/835/2/202

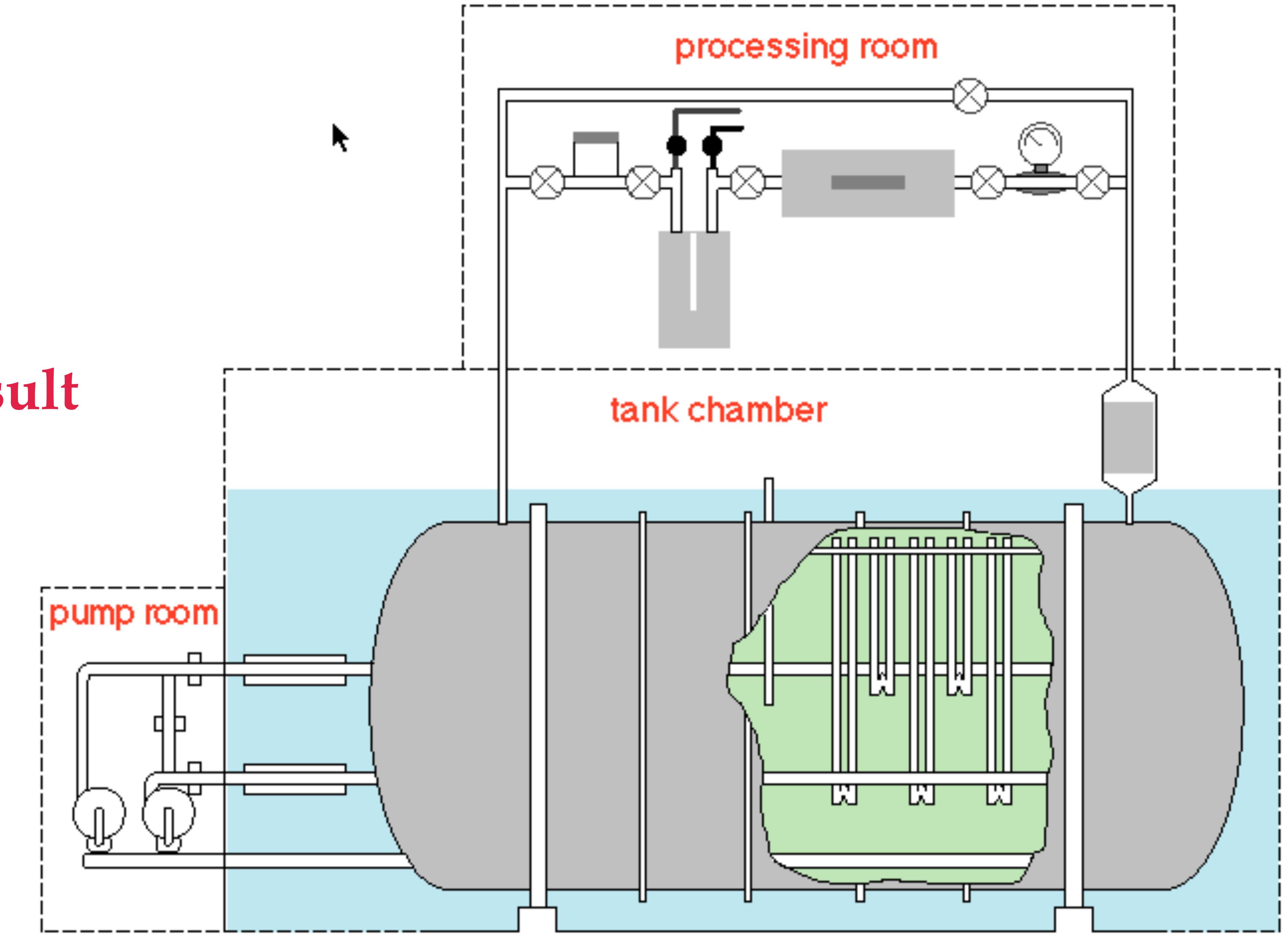
History: counting an atom a day at Homestake

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

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

  - 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**)



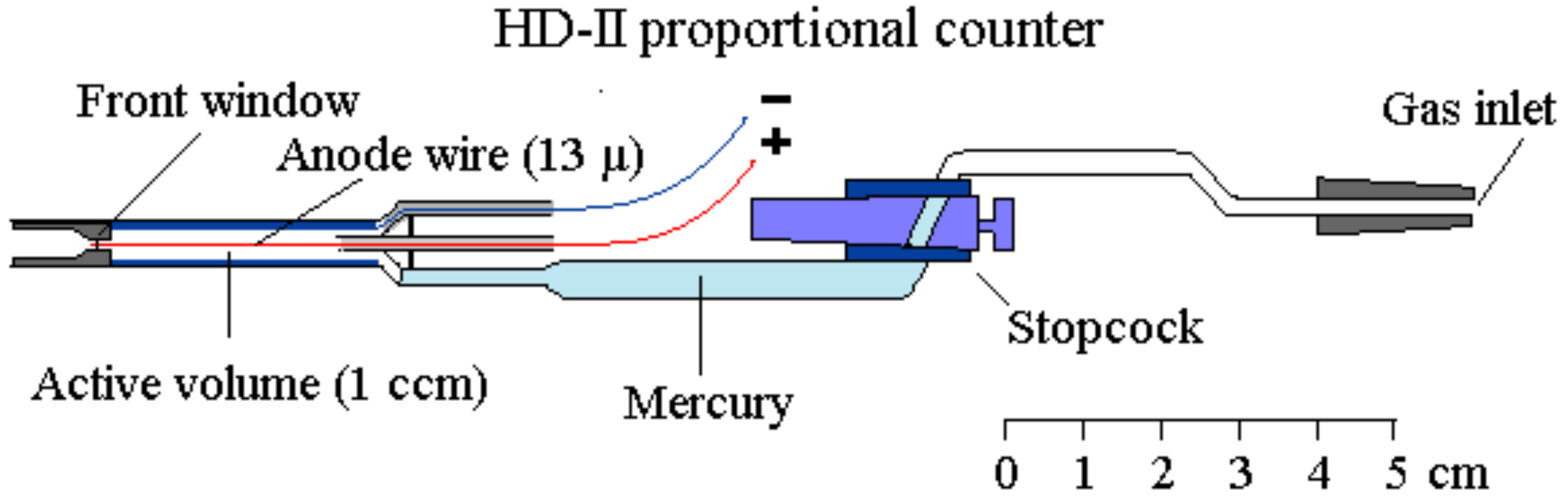


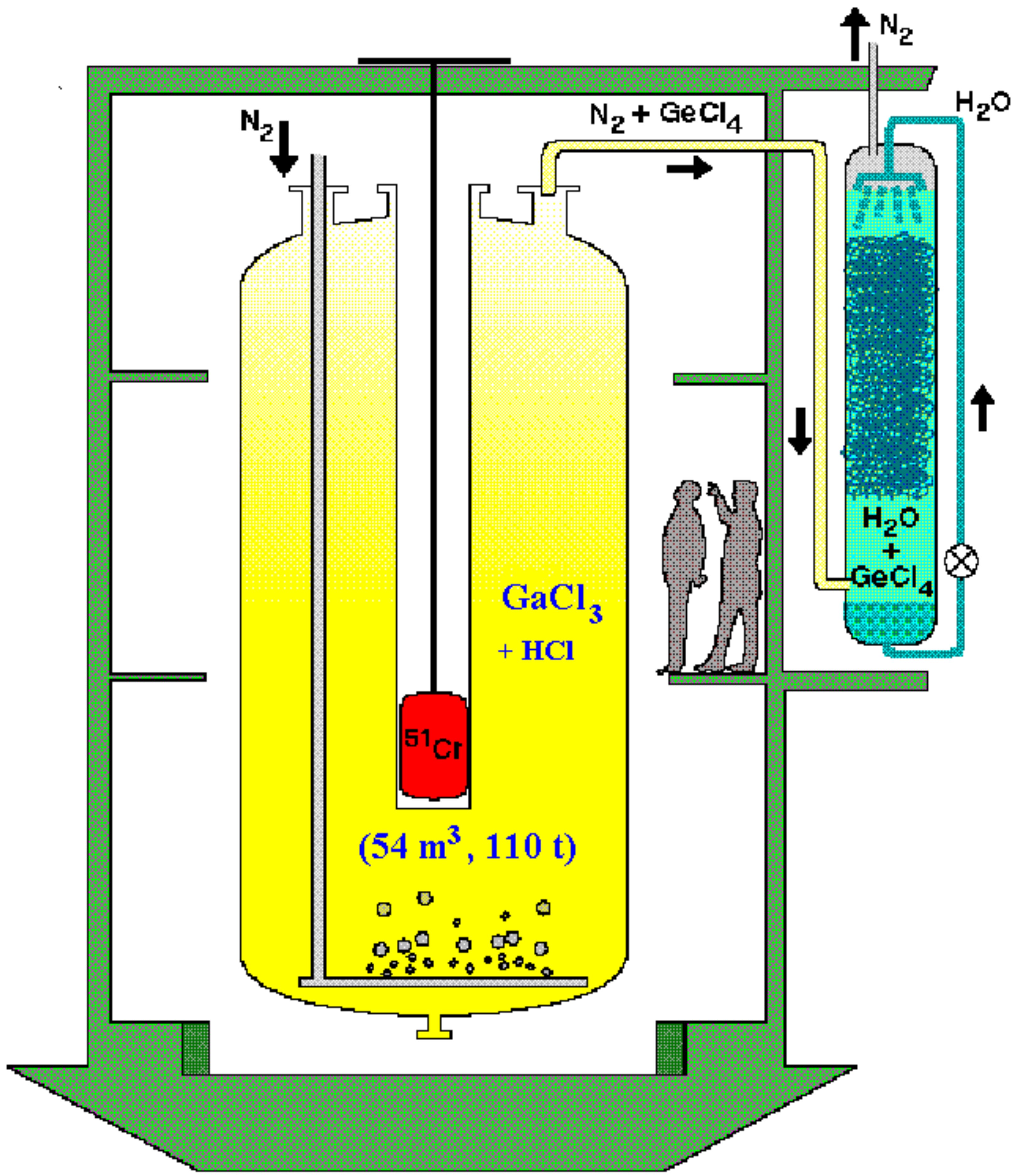
History: Gallex/GNO @ LNGS and SAGE in Russia (Baksan)

- **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**]
  -

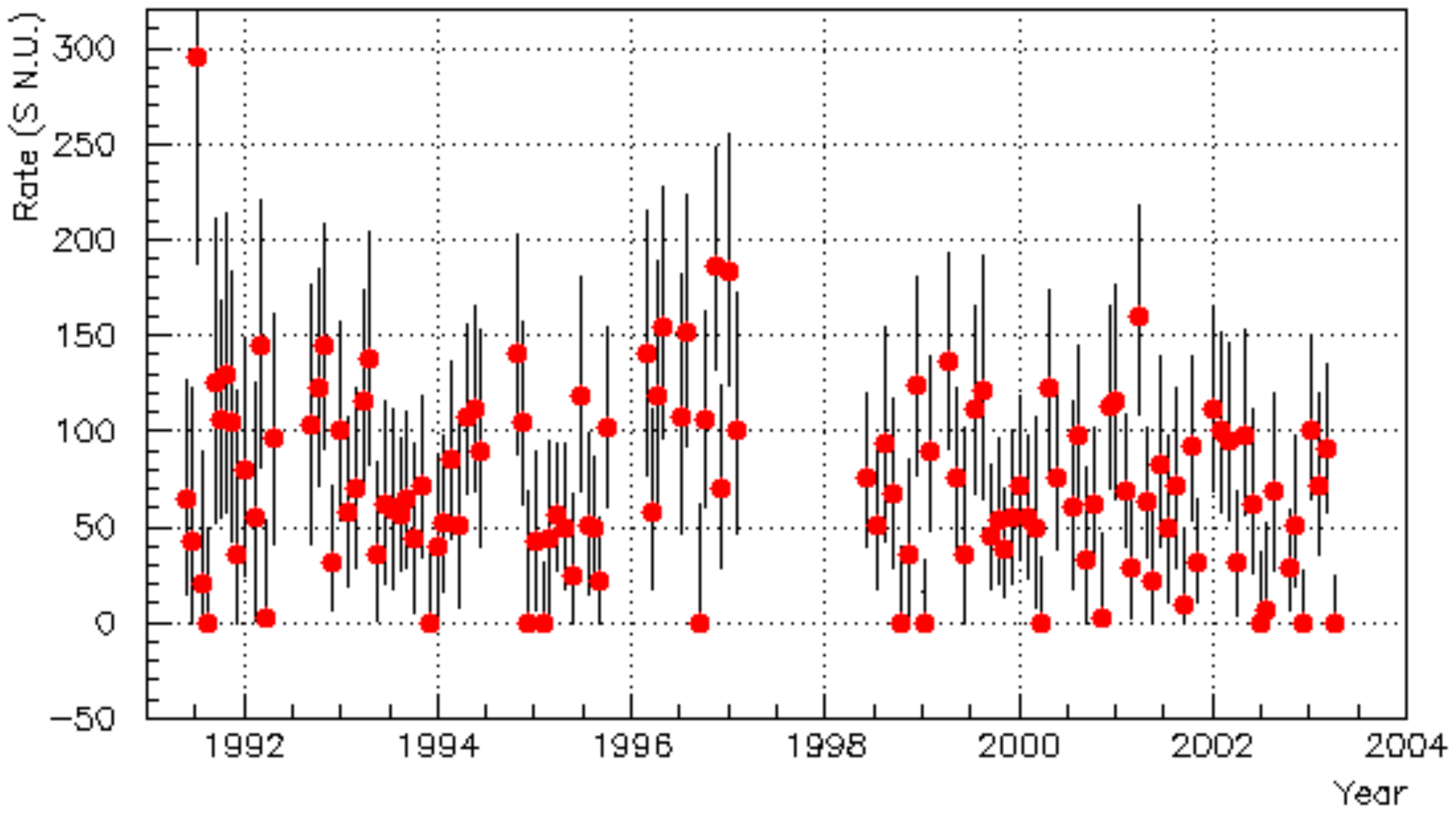




Gallex/GNO results [1990-2004]

- 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:

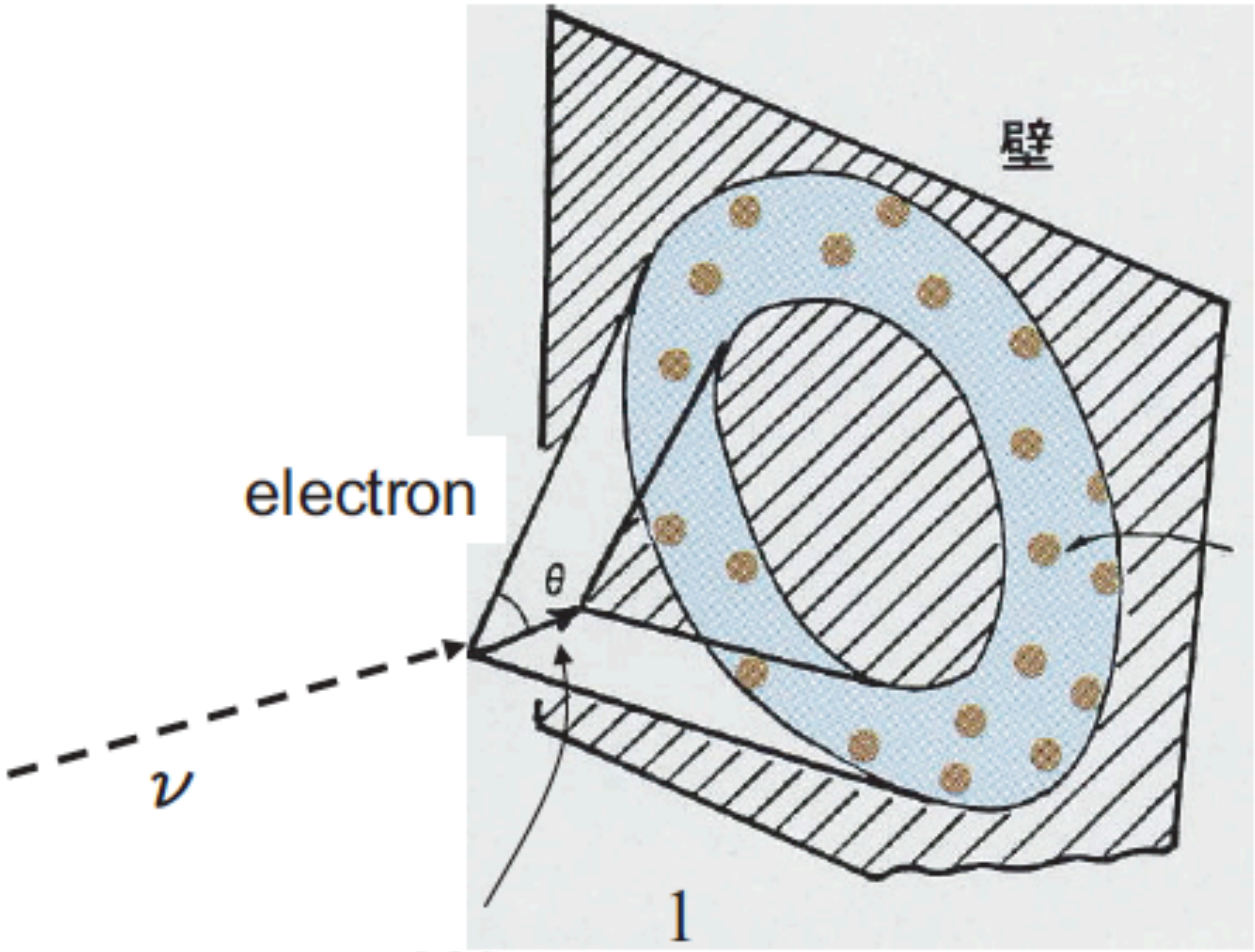
$$cos\theta = \frac{1}{n\beta}$$

$\theta = 42°$ 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



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

n (refractive index)=1.34 in water

⇨ θ =42deg. for β =1

Photomultiplier tube (PMT)

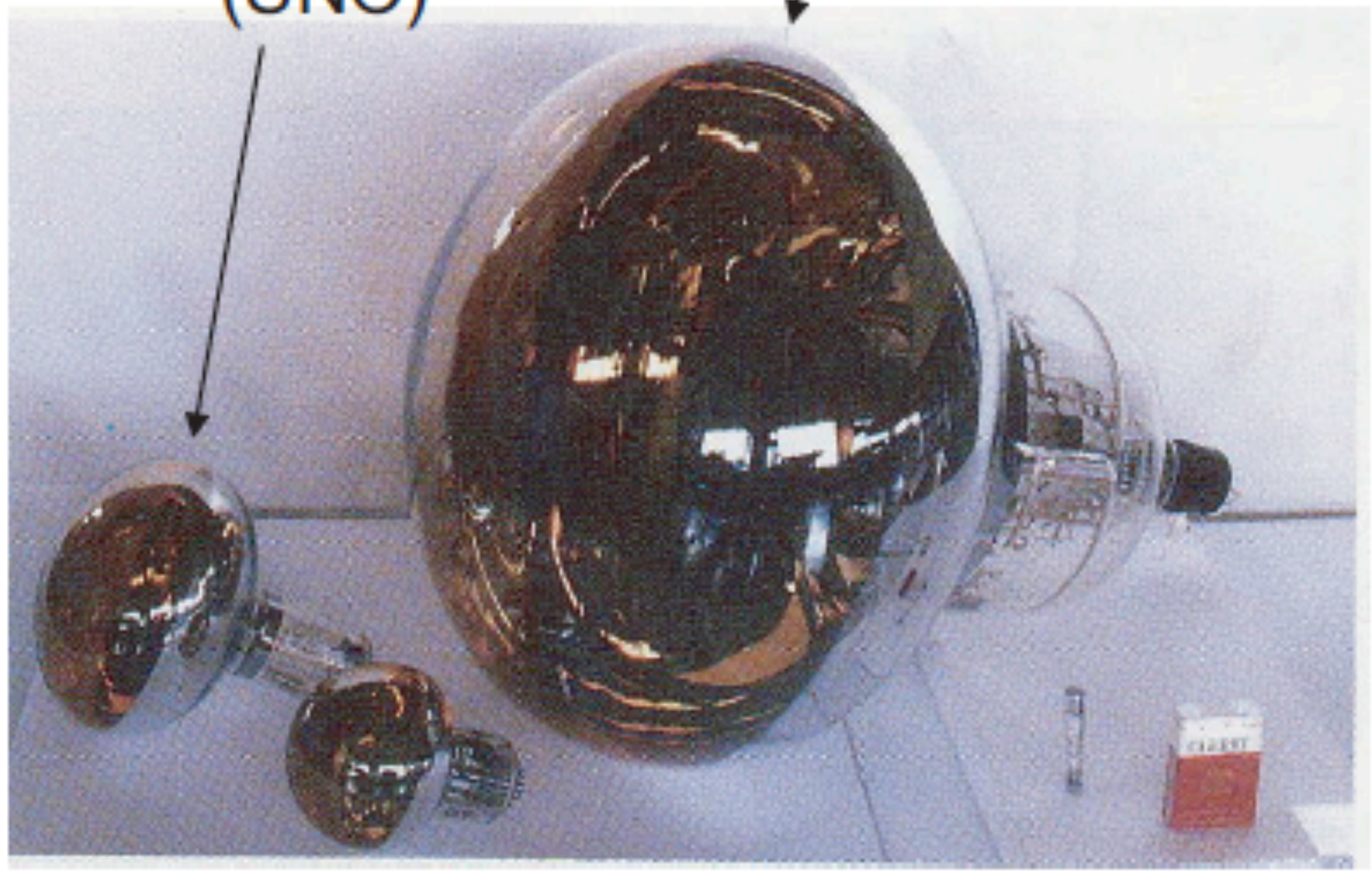
Number of Ch. photons with λ =300-600 nm emitted by a relativistic particle per cm = 340.

⇩

Need an efficient detection of the photons. ⇨ Large PMTs

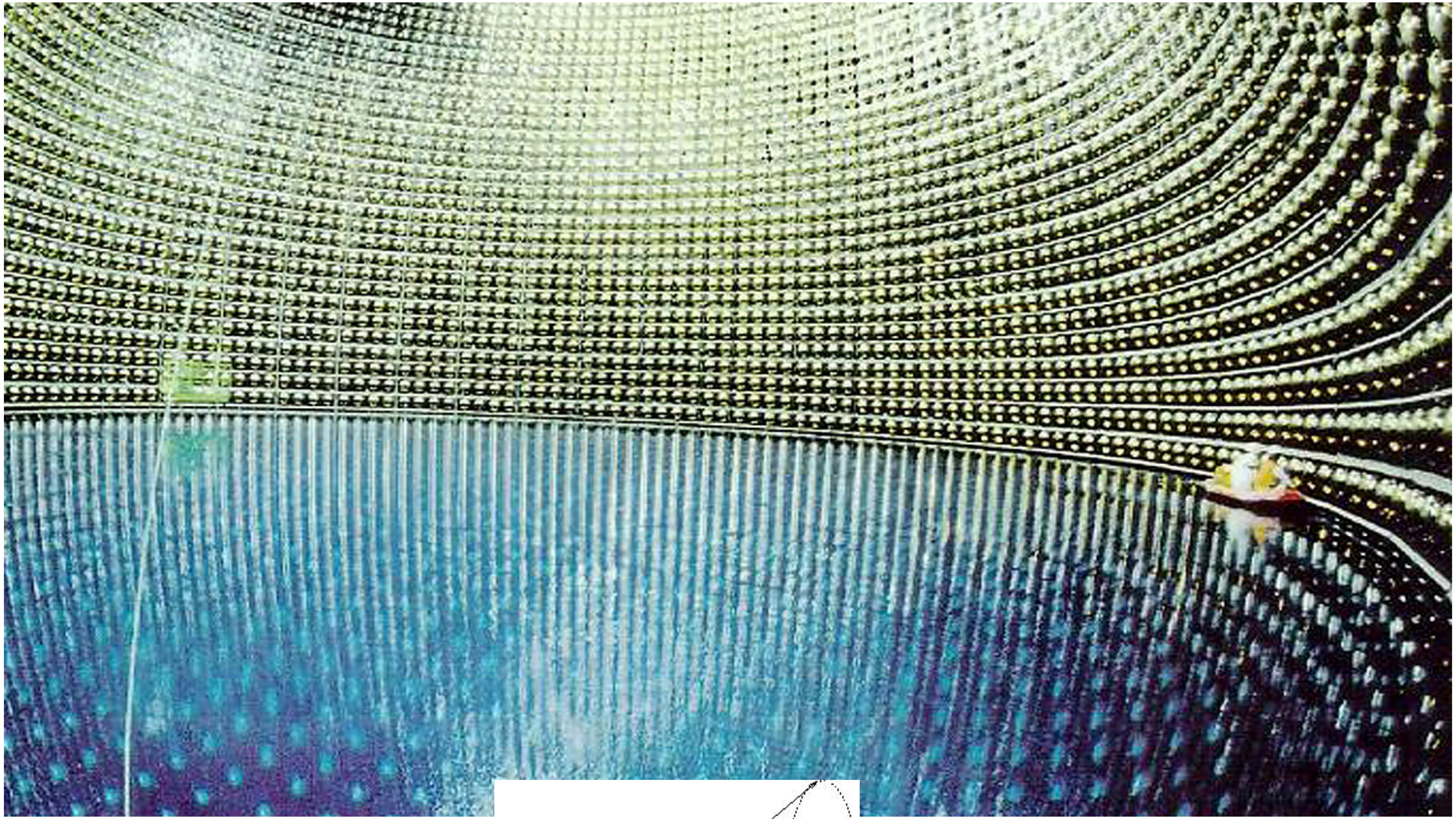
50cm ϕ (Super-K)

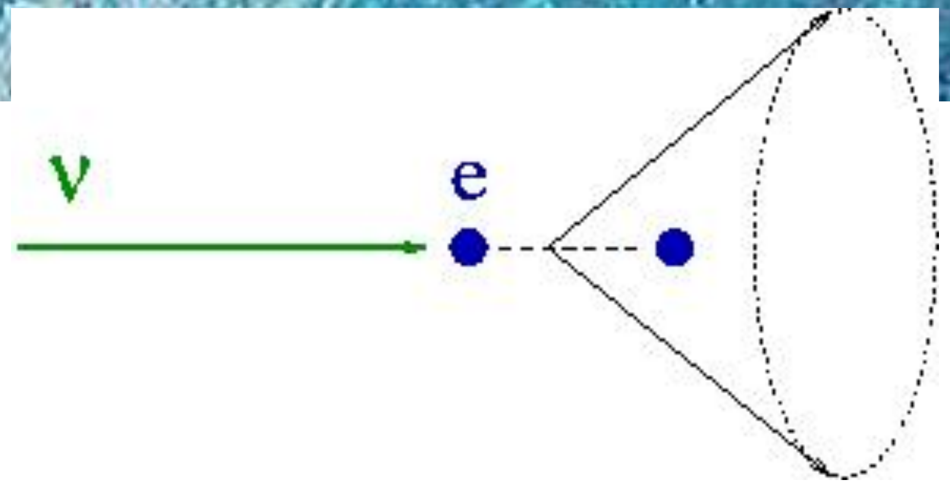
20cm ϕ (SNO)



T. Kajita - Nufact 05 School

SK experiment

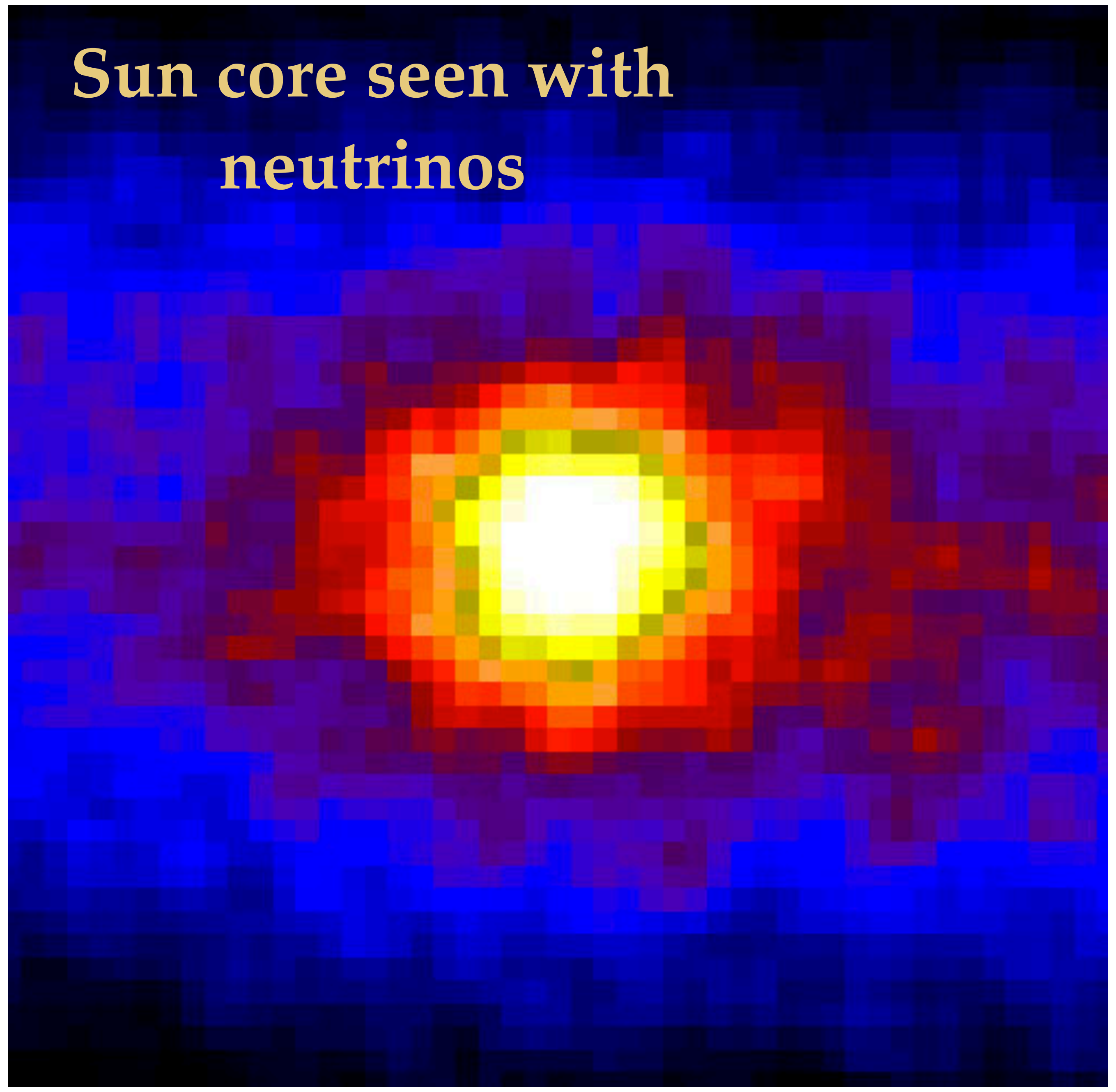


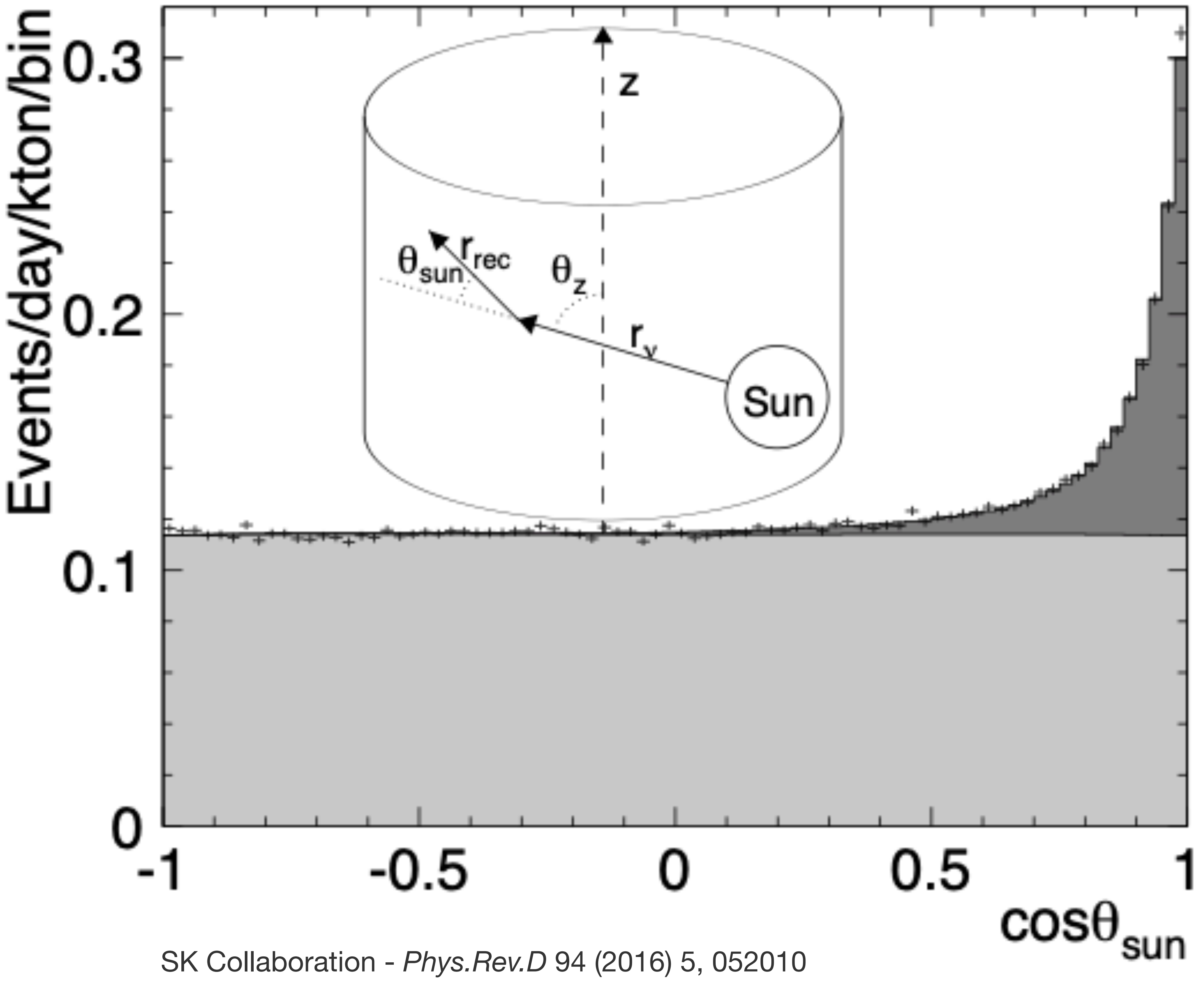


Cherenkov detector for solar, accelerator and atmospheric neutrinos

Solar neutrinos at SK

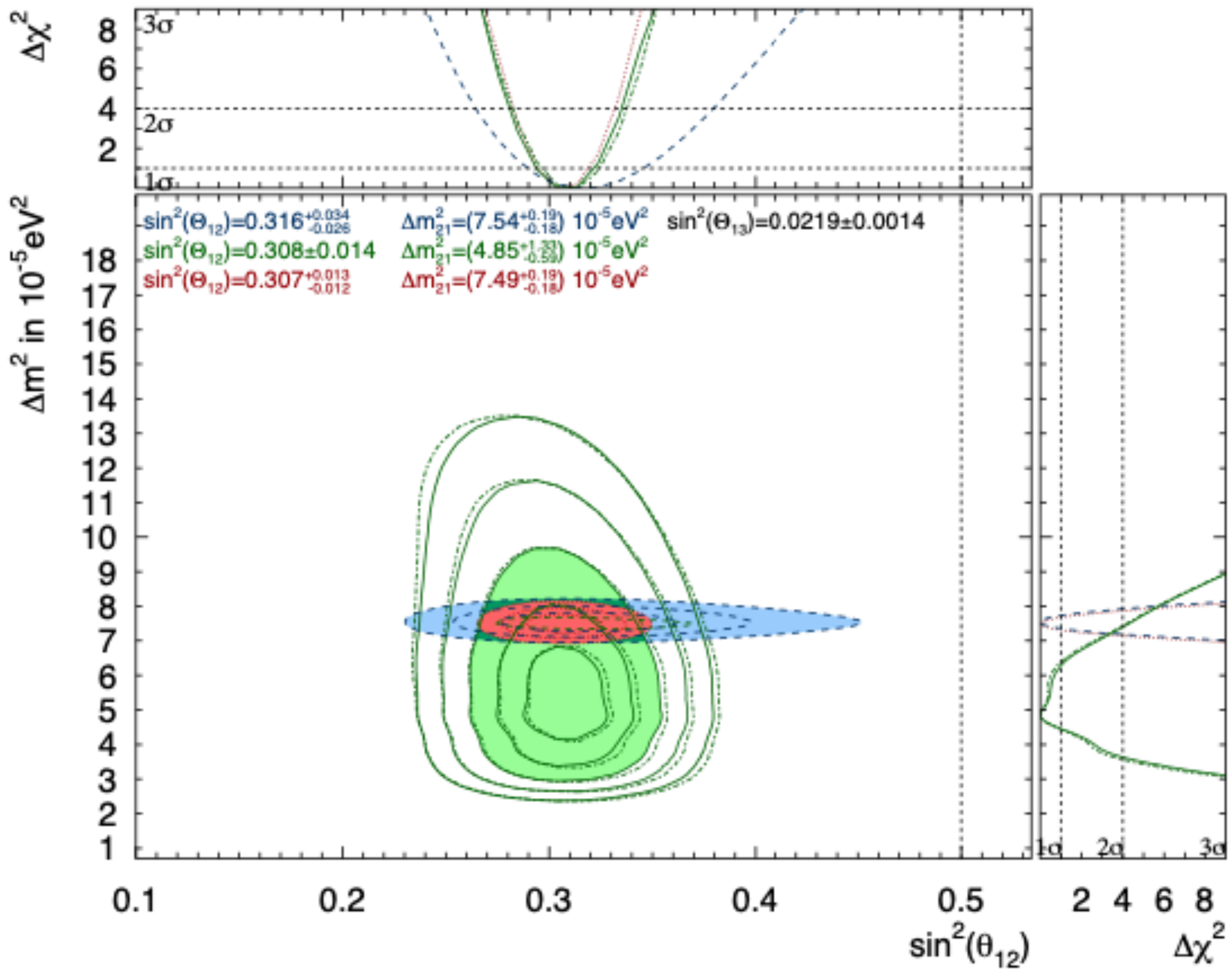
- Detection technique: elastic scattering on electrons
  - Cherenkov light gives direction of incoming neutrino
  - Threshold ~ 3.5 - 5 MeV (depending on period)





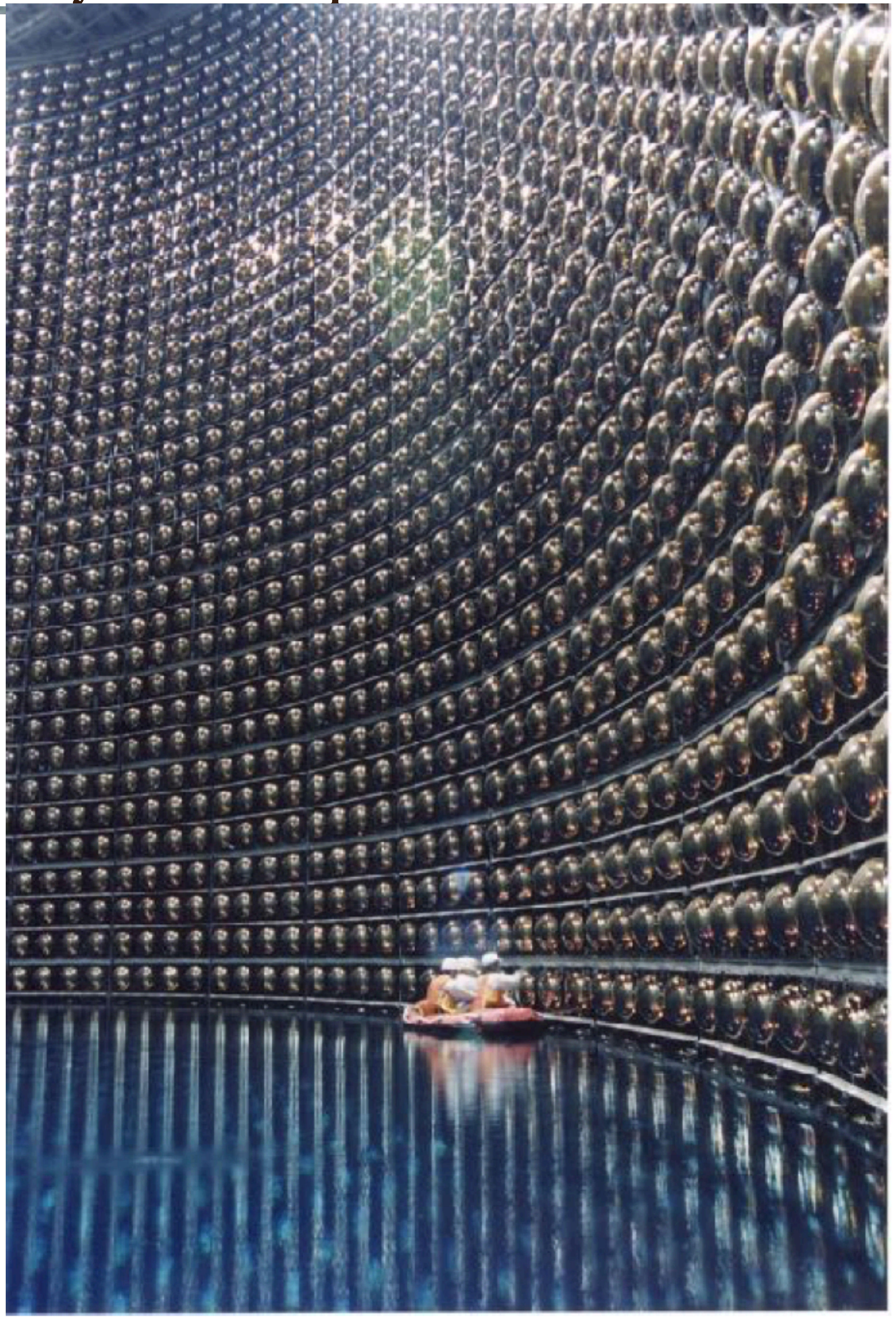
SK Collaboration - *Phys.Rev.D* 94 (2016) 5, 052010

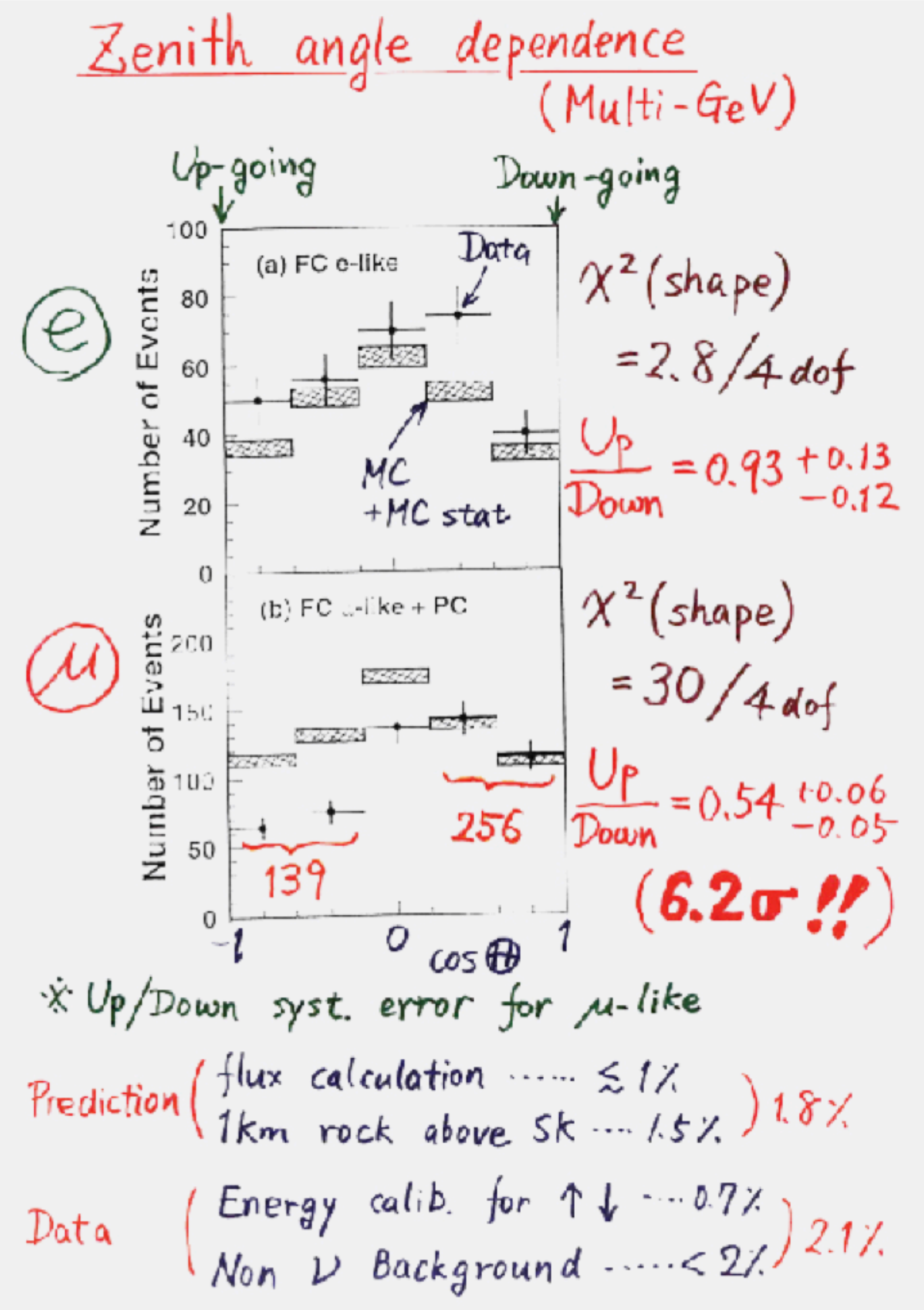
Recent solar neutrino analysis with SK+KamLAND



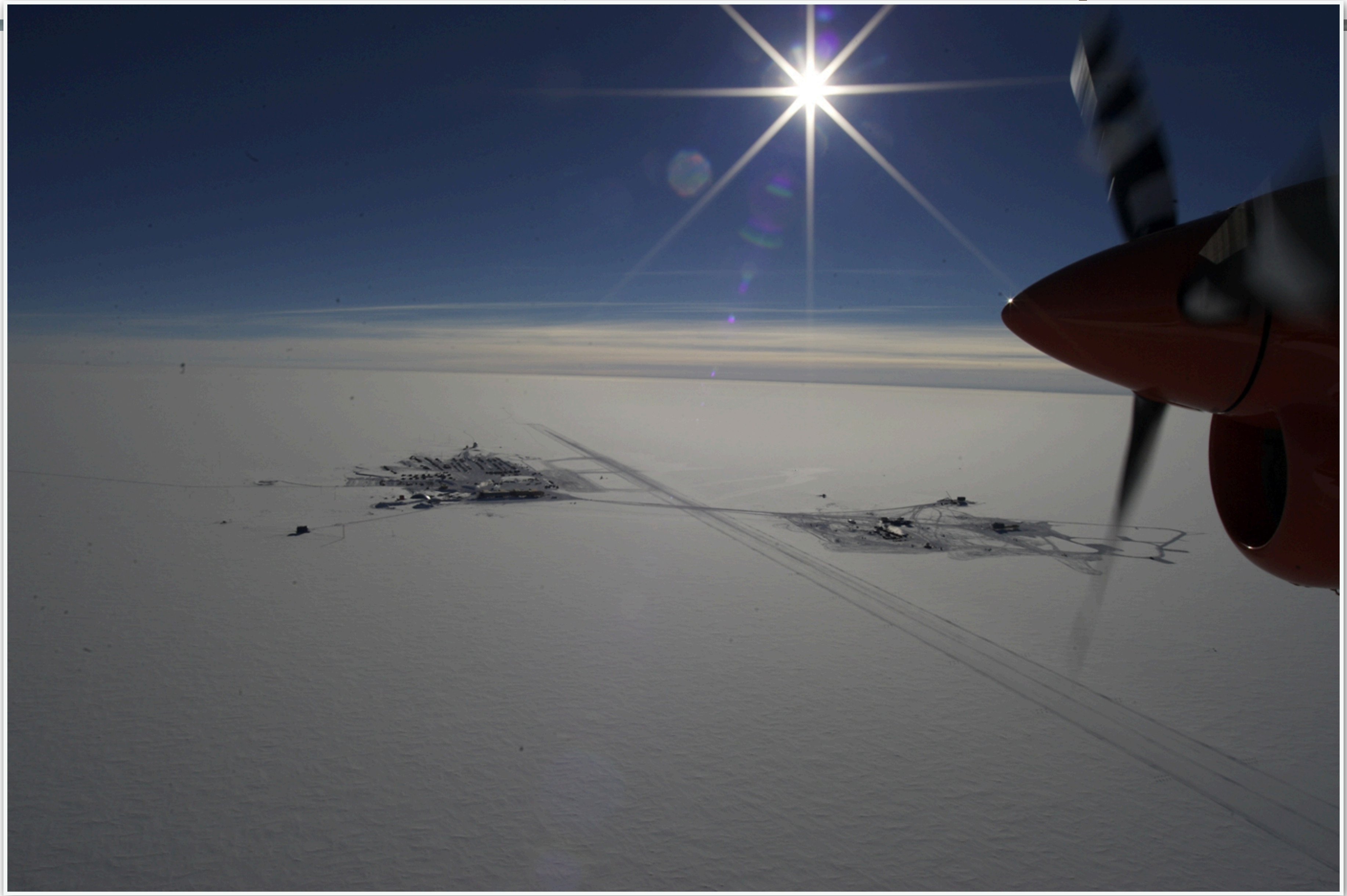
SK Collaboration - *Phys.Rev.D* 94 (2016) 5, 052010

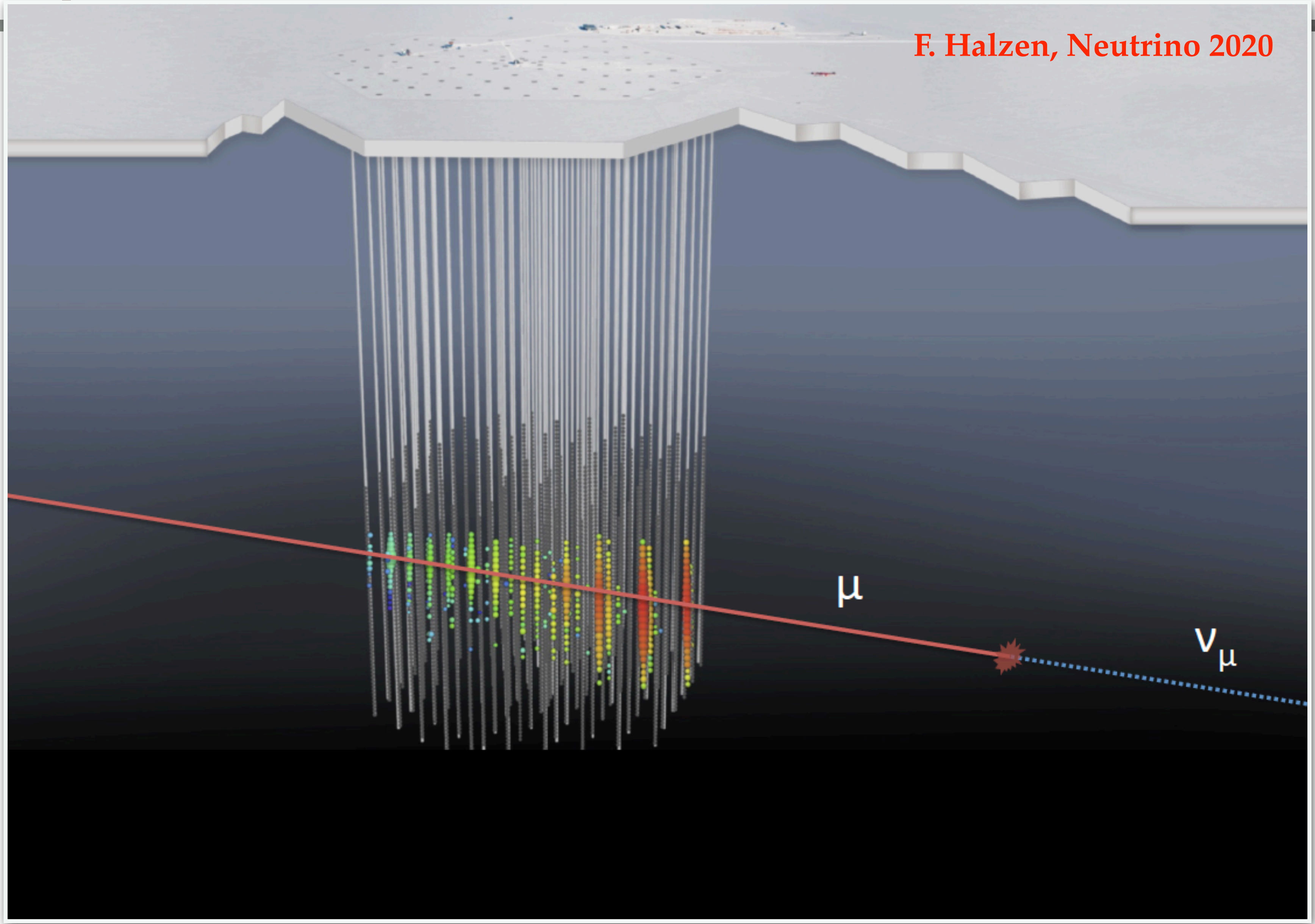
Discovery of atmospheric neutrinos at SK: 1998

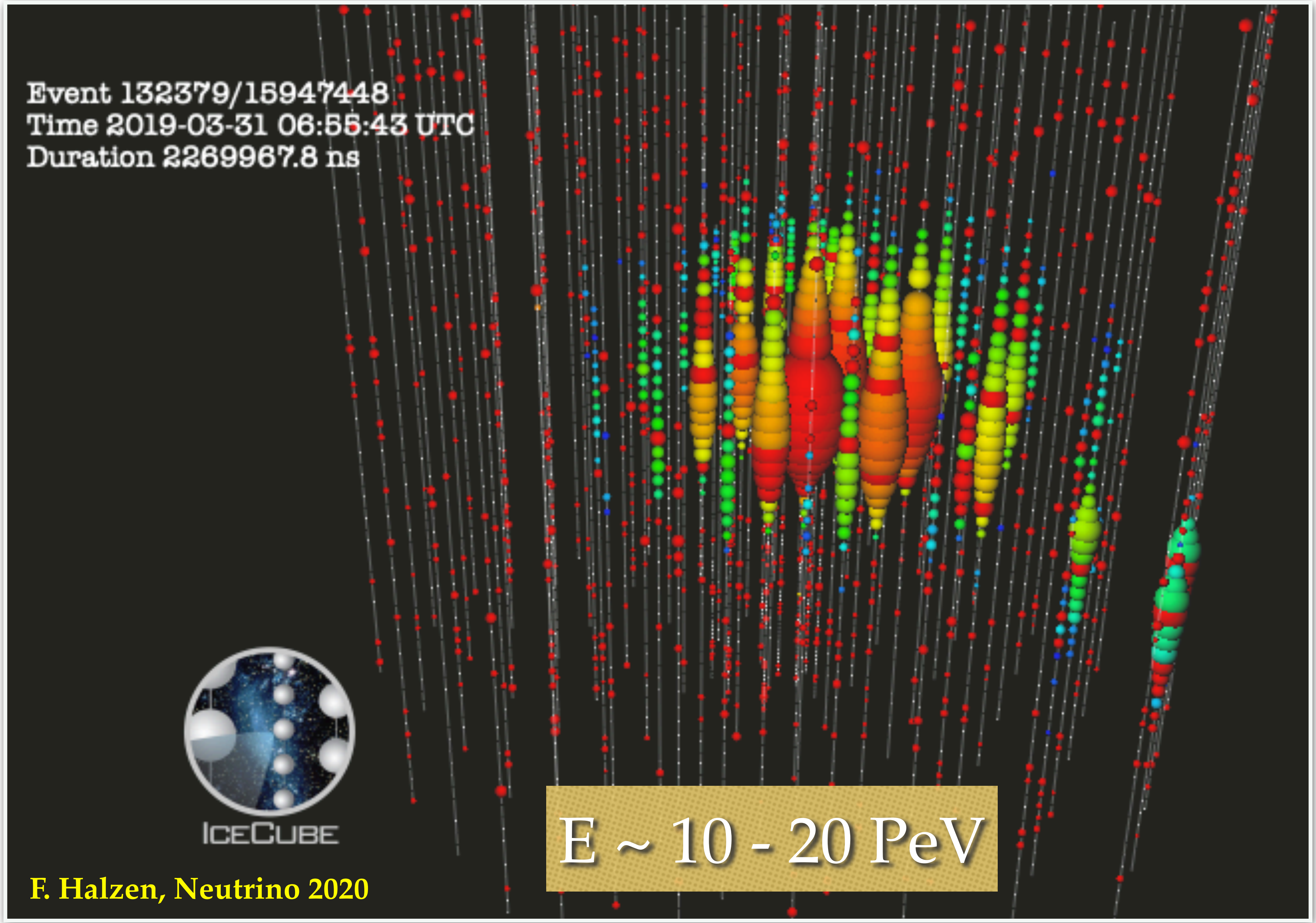


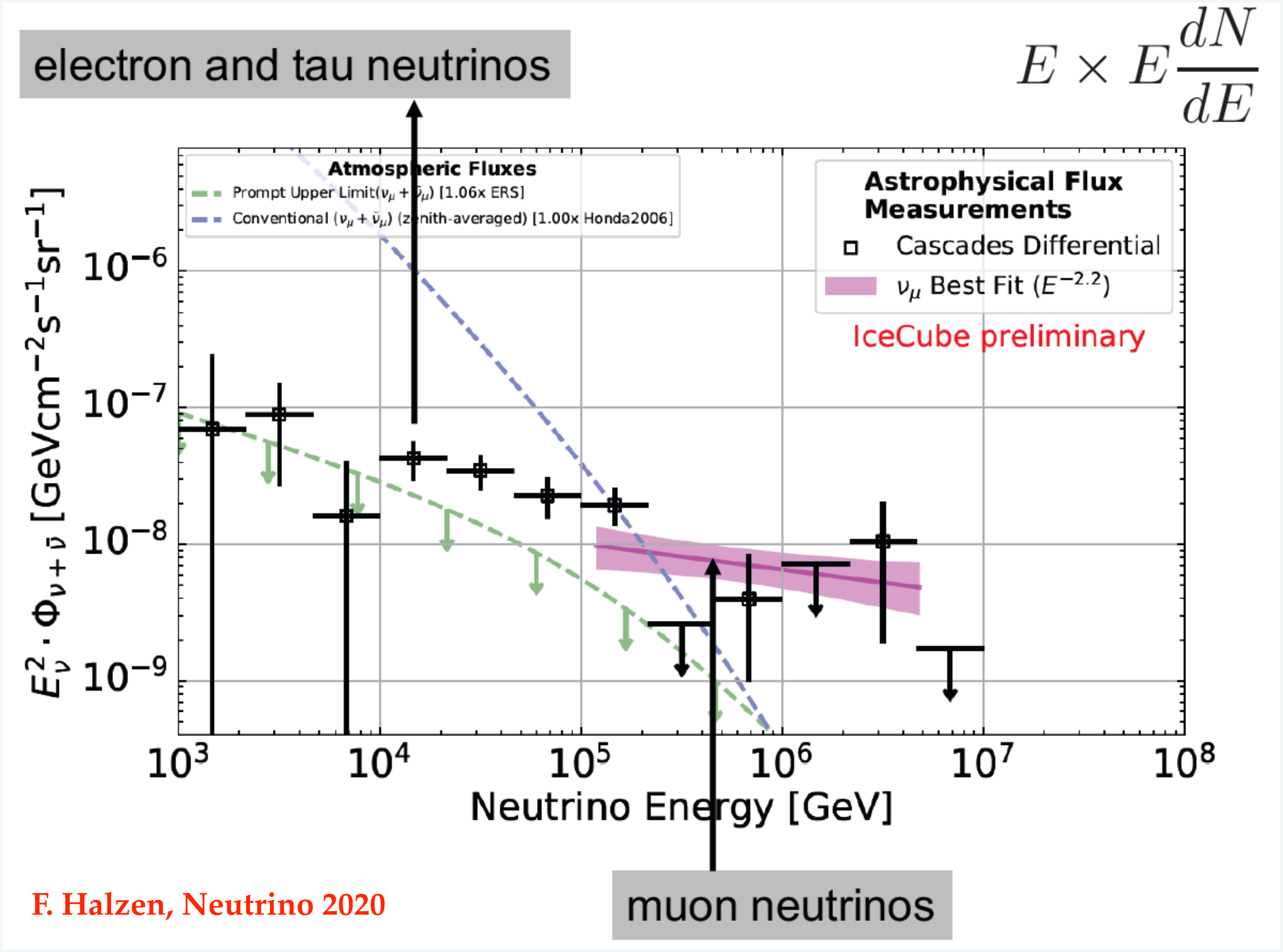


Intermezzo: neutrino detection in ice (Ice-Cube)

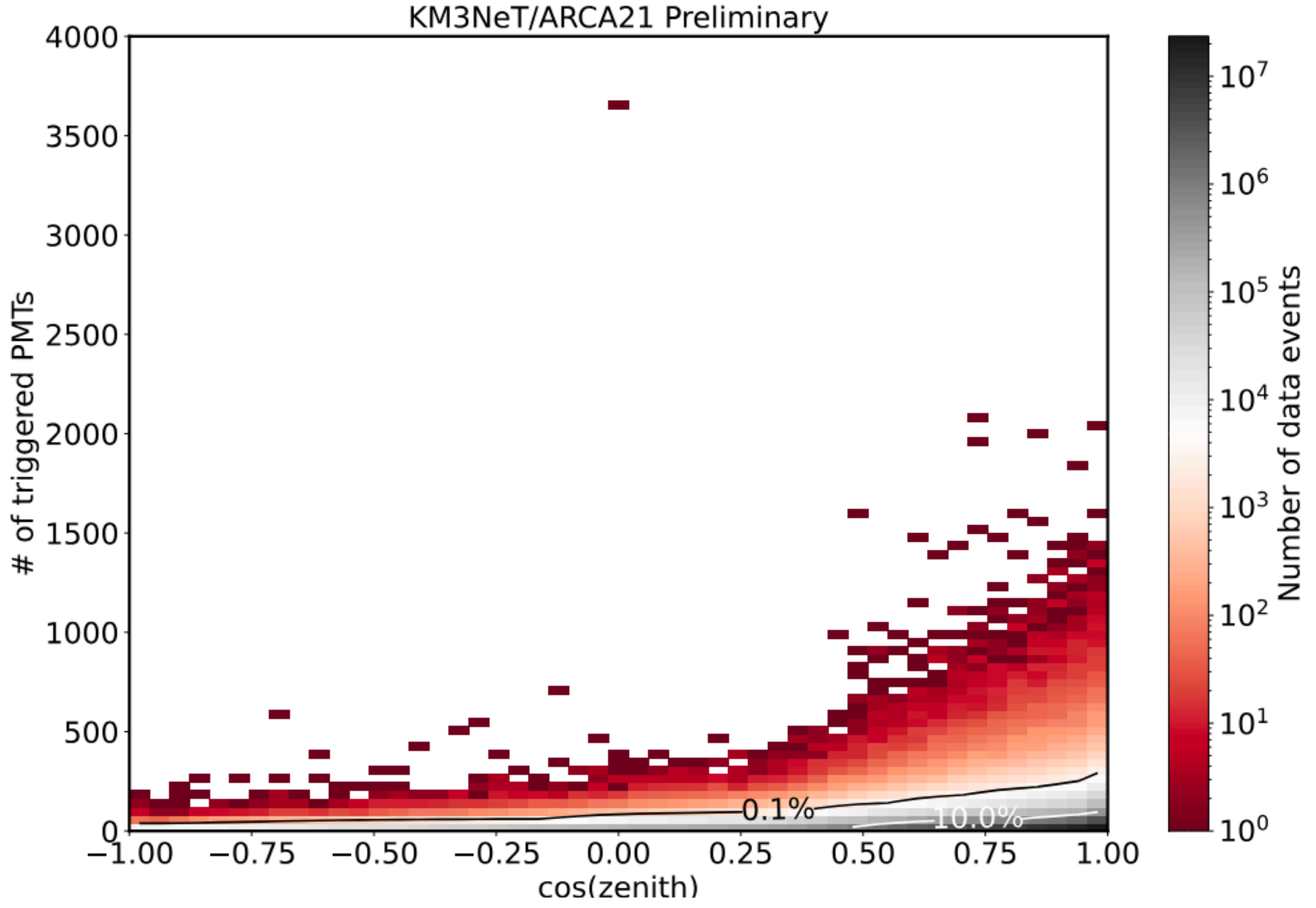


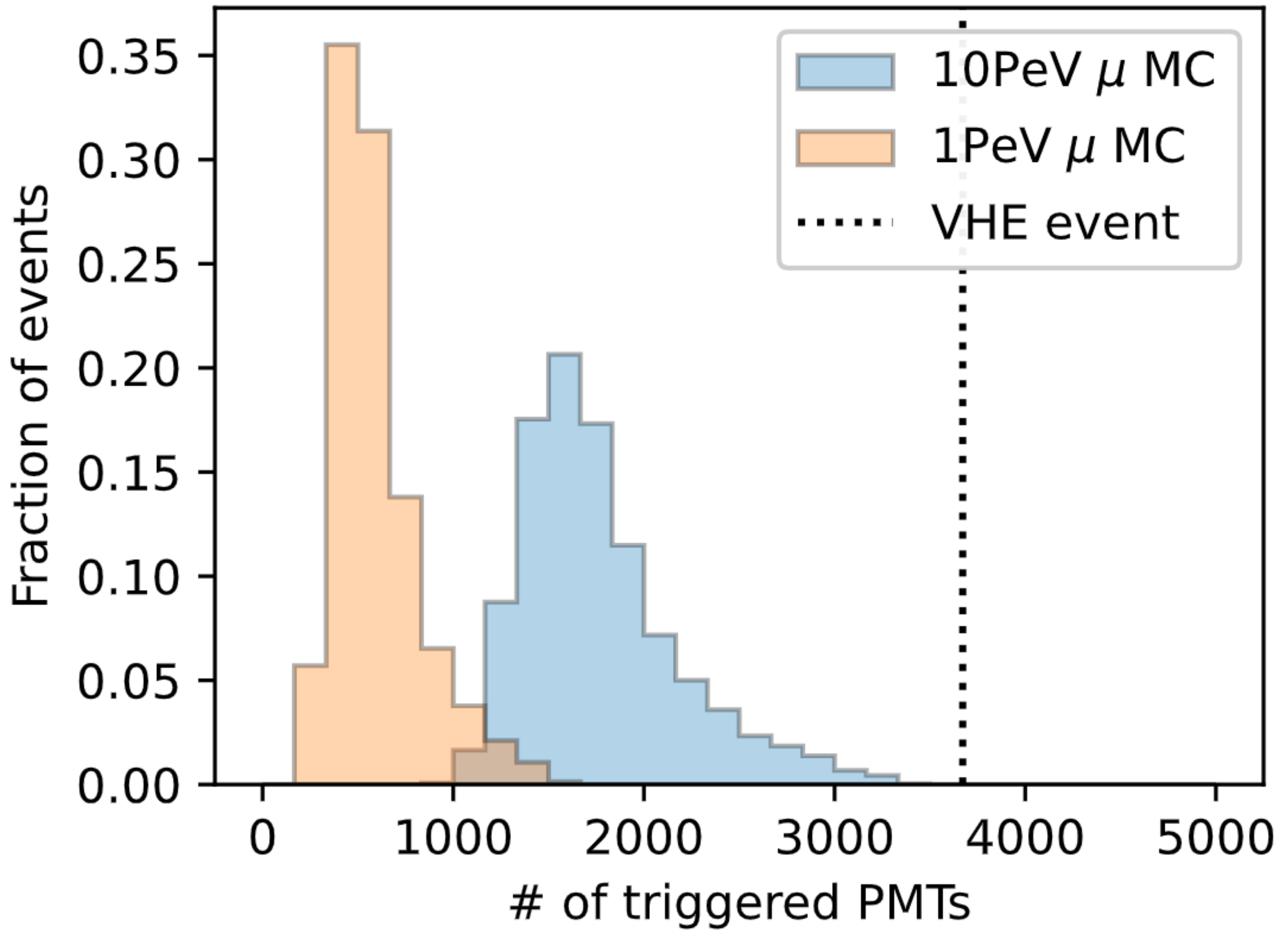






Monster beautiful event from KM3Net - 2024





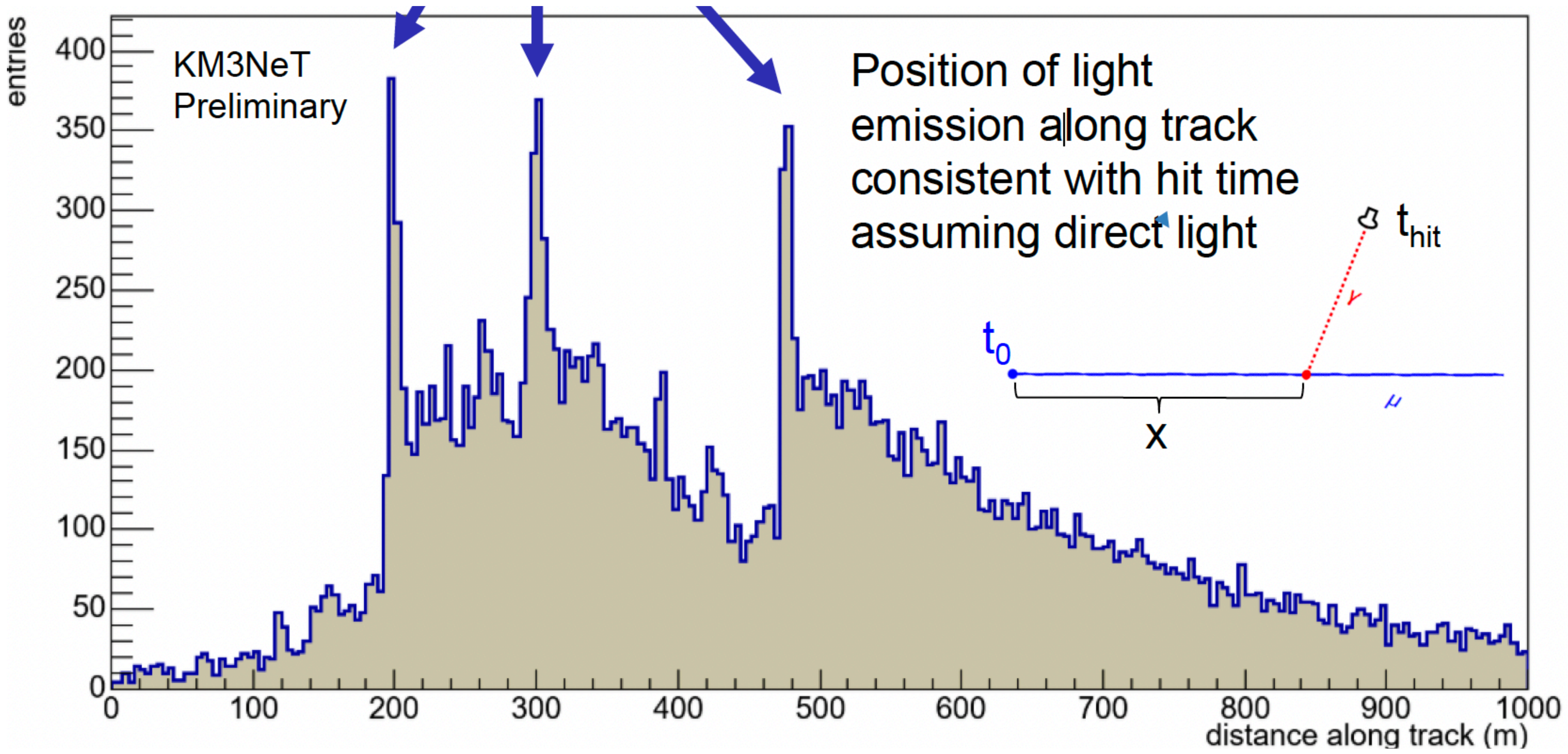
Light profile consistent with at least 3 large energy depositions along the muon track

Characteristic of stochastic losses from very high energy muons

Estimated energy ~ 100 PeV scale

To be published soon

(Shown at Neutrino 2024 conference)



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

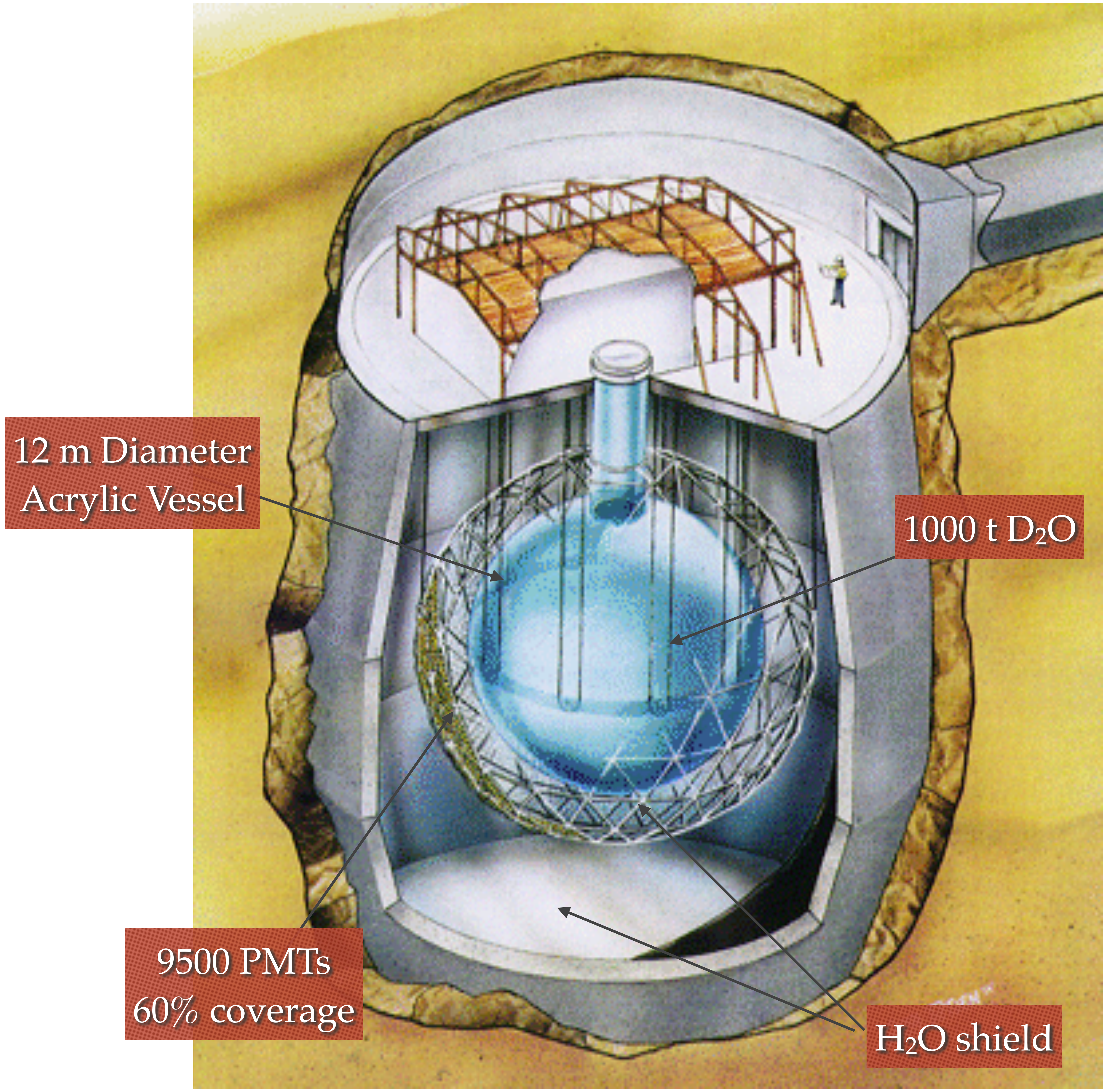
$$\nu_e + d \to p + p + e^+$$

  - **NC:** All types, equal

$$\nu_x + d \to \nu_x + p + n$$

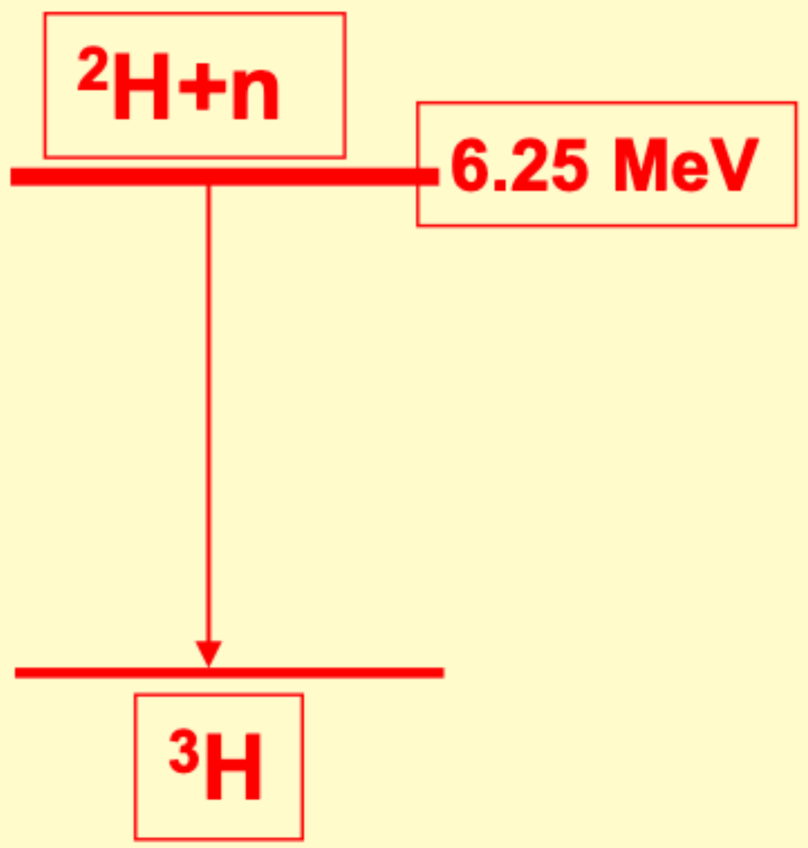
  - **ES:** All types, un-equal

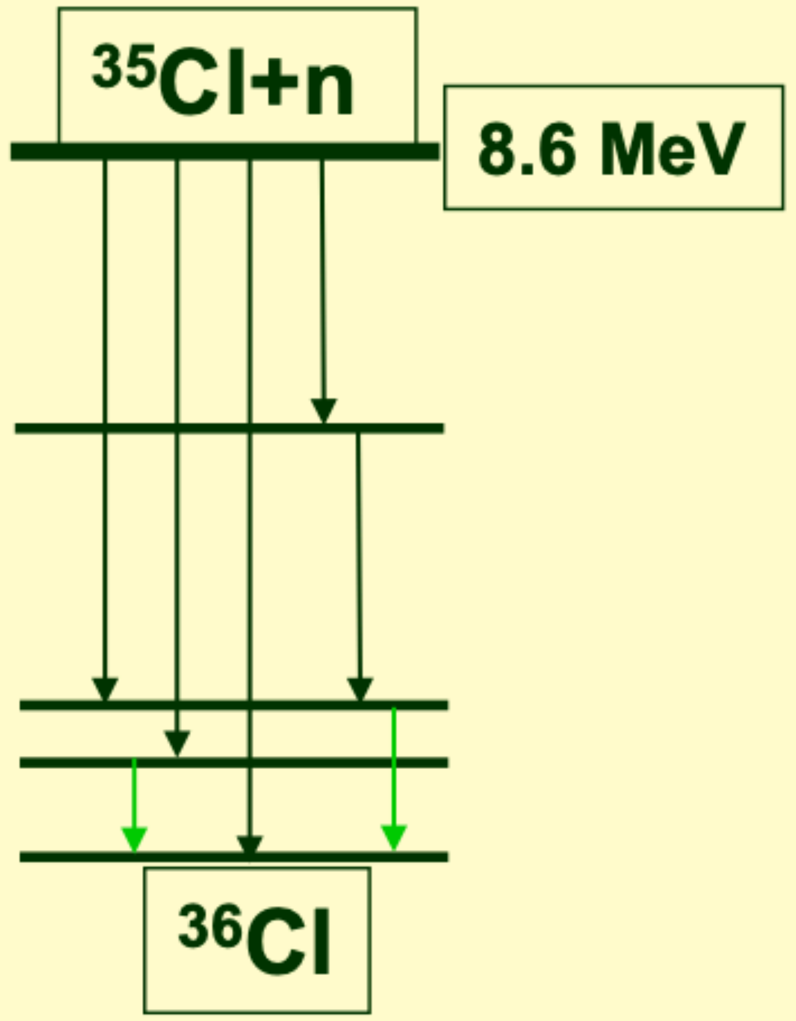
$$\nu_x + e^- \to \nu_x + e^-$$

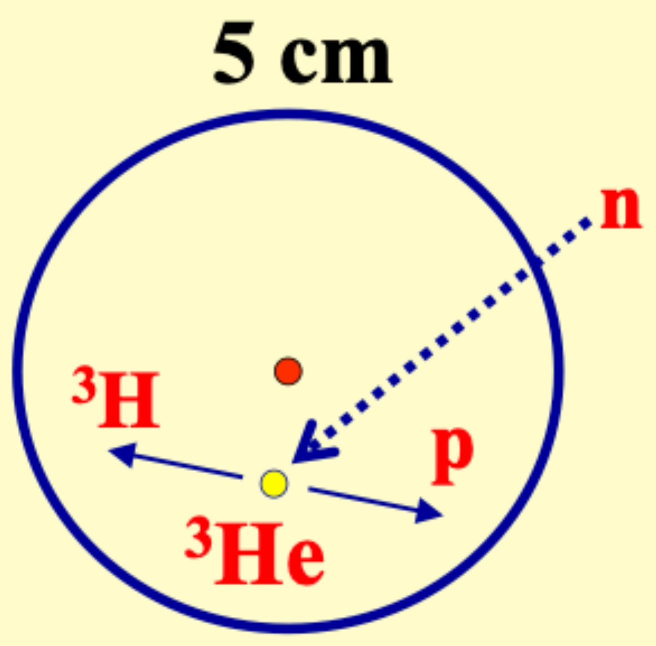


3 neutron (NC) detection methods (systematically different)

Phase I (D_2O) Nov. 99 - May 01	Phase II (salt) July 01 - Sep. 03	Phase III (^3He) Nov. 04-Dec. 06
n captures on $^2H(n, \gamma)^3H$ Effc. ~14.4% NC and CC separation by energy, radial, and directional distributions	2 tonnes of NaCl n captures on $^{35}Cl(n, \gamma)^{36}Cl$ Effc. ~40% NC and CC separation by event isotropy	400 m of proportional counters $^3He(n, p)^3H$ Effc. ~ 30% capture Measure NC rate with entirely seperate detection system.



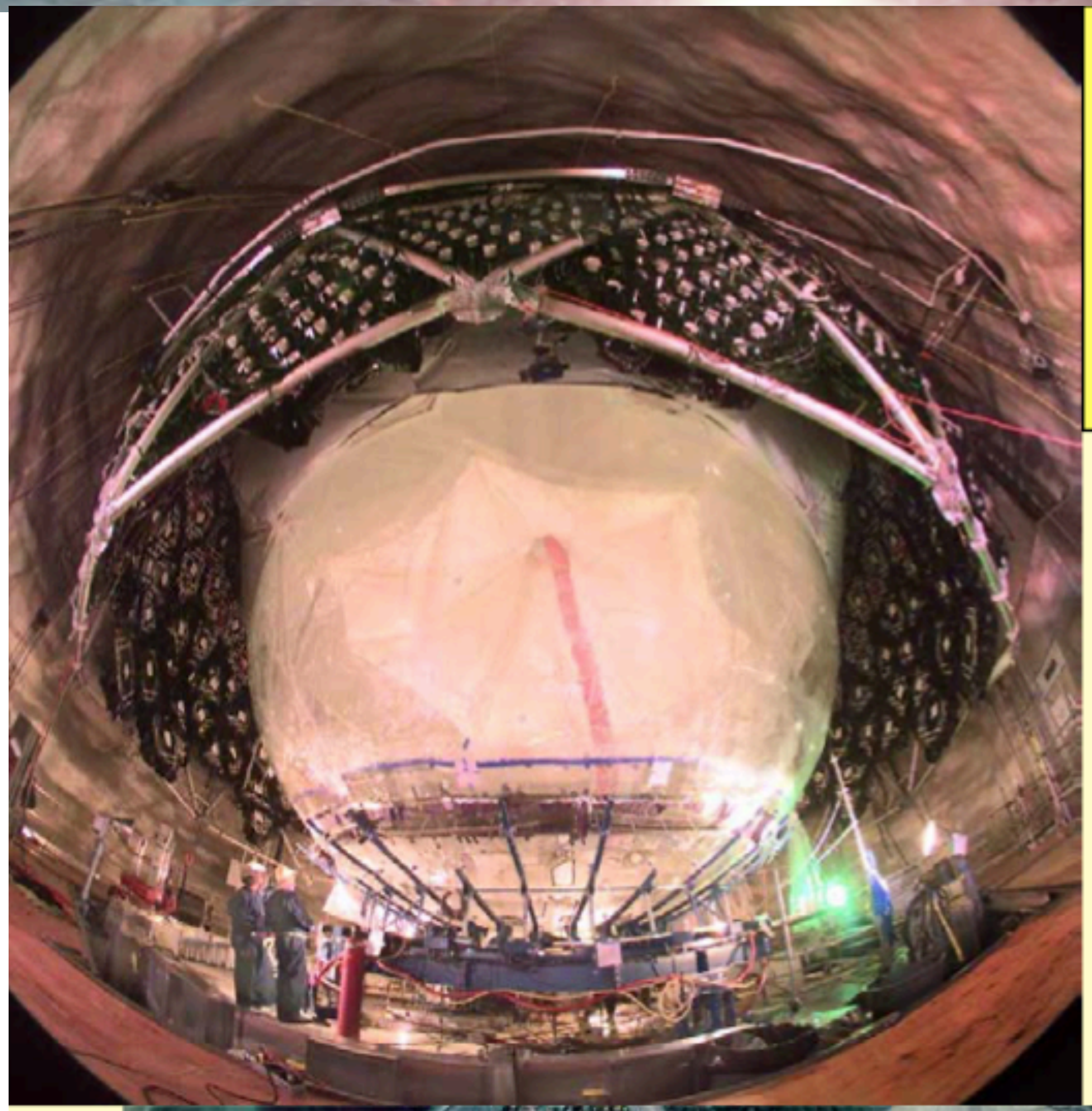




$$n + {}^3He \rightarrow p + {}^3H$$

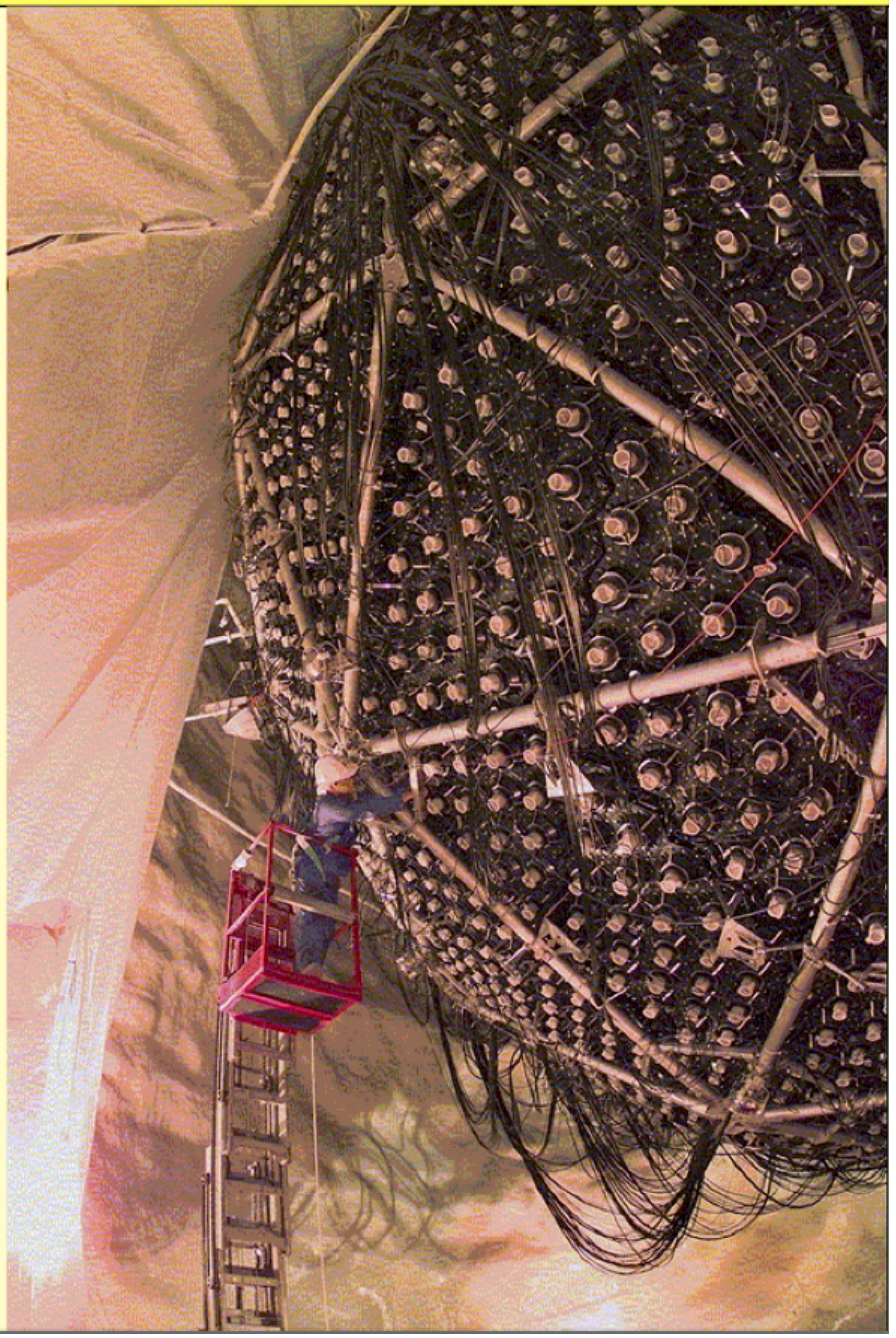
Art McDonald: Neutrino 2016

SNO picture gallery



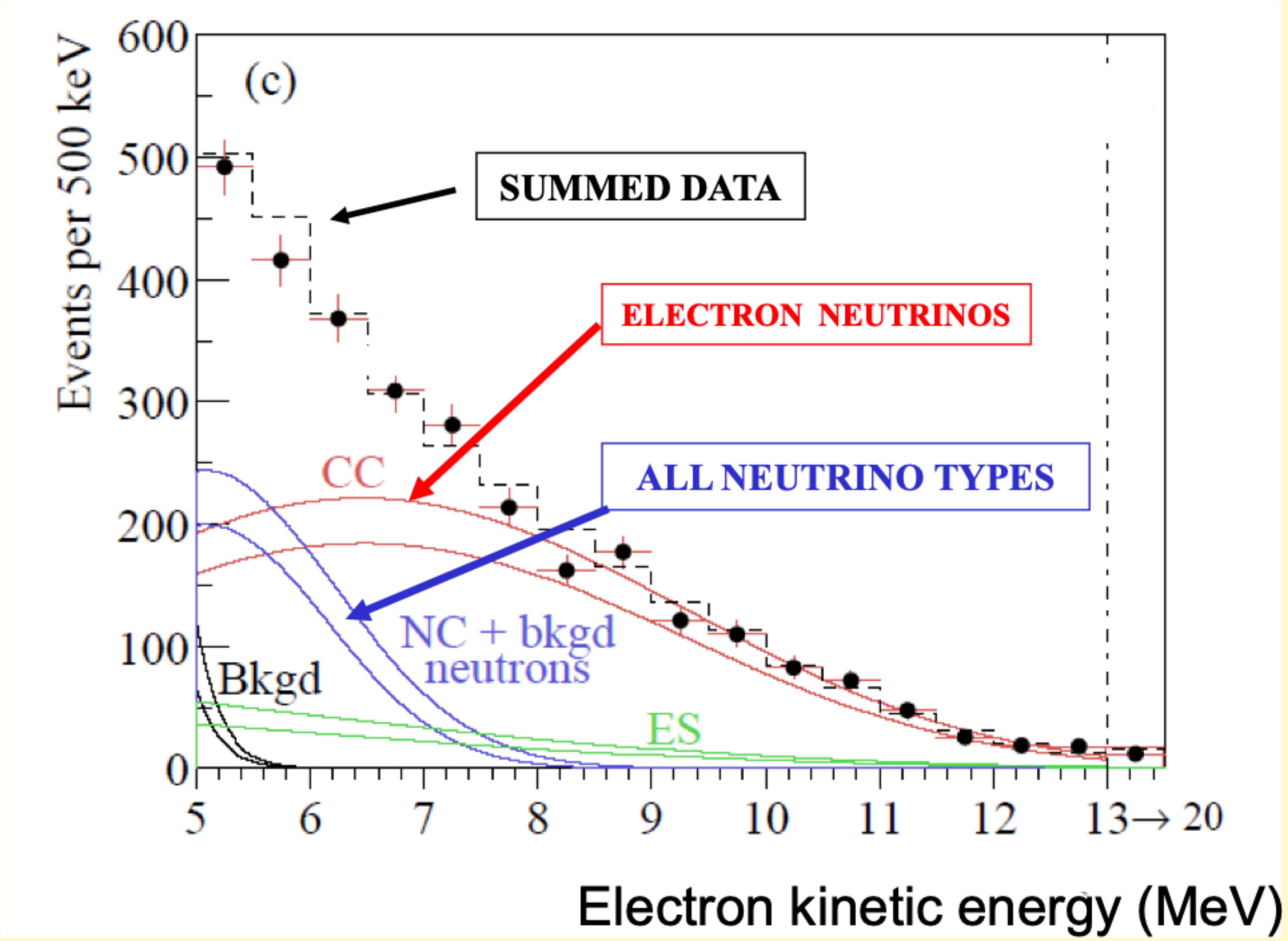
SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

70,000 showers during the course of the SNO project



Art McDonald: Neutrino 2016

WE OBSERVED NEUTRINOS FROM THE SUN WITH ALMOST NO RADIOACTIVE BACKGROUND

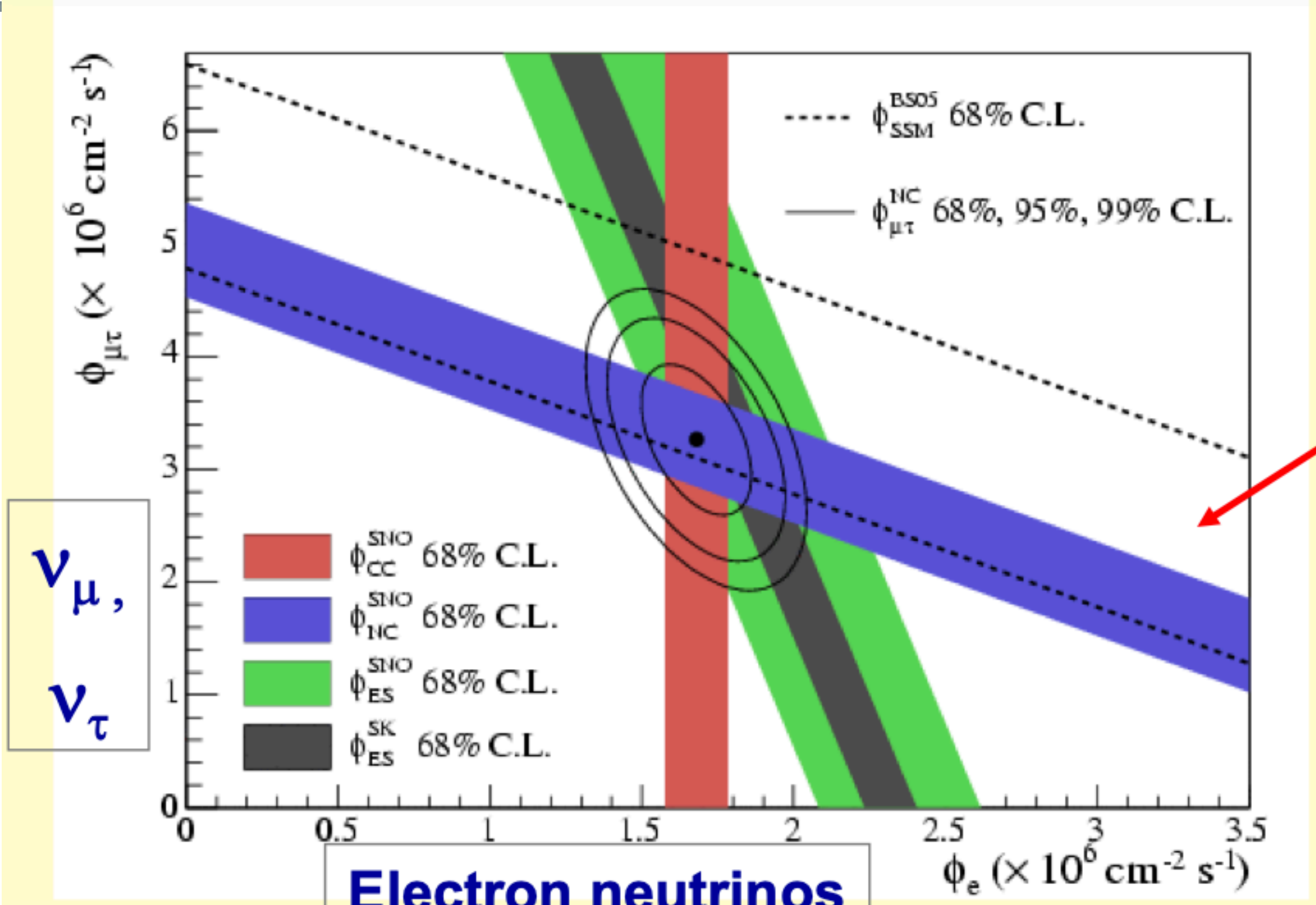


After Calibration: ELECTRON NEUTRINOS AT EARTH ARE ONLY 1/3 OF ALL NEUTRINOS

Data from Pure Heavy Water Phase in 2002

Art McDonald: Neutrino 2016

SNO results



SNO Results for Salt Phase

Flavor change determined by > 7 σ.

New physics beyond The Standard Model of Elementary Particles!

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

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

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

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

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

5.82 +- 1.3 (Bahcall et al),

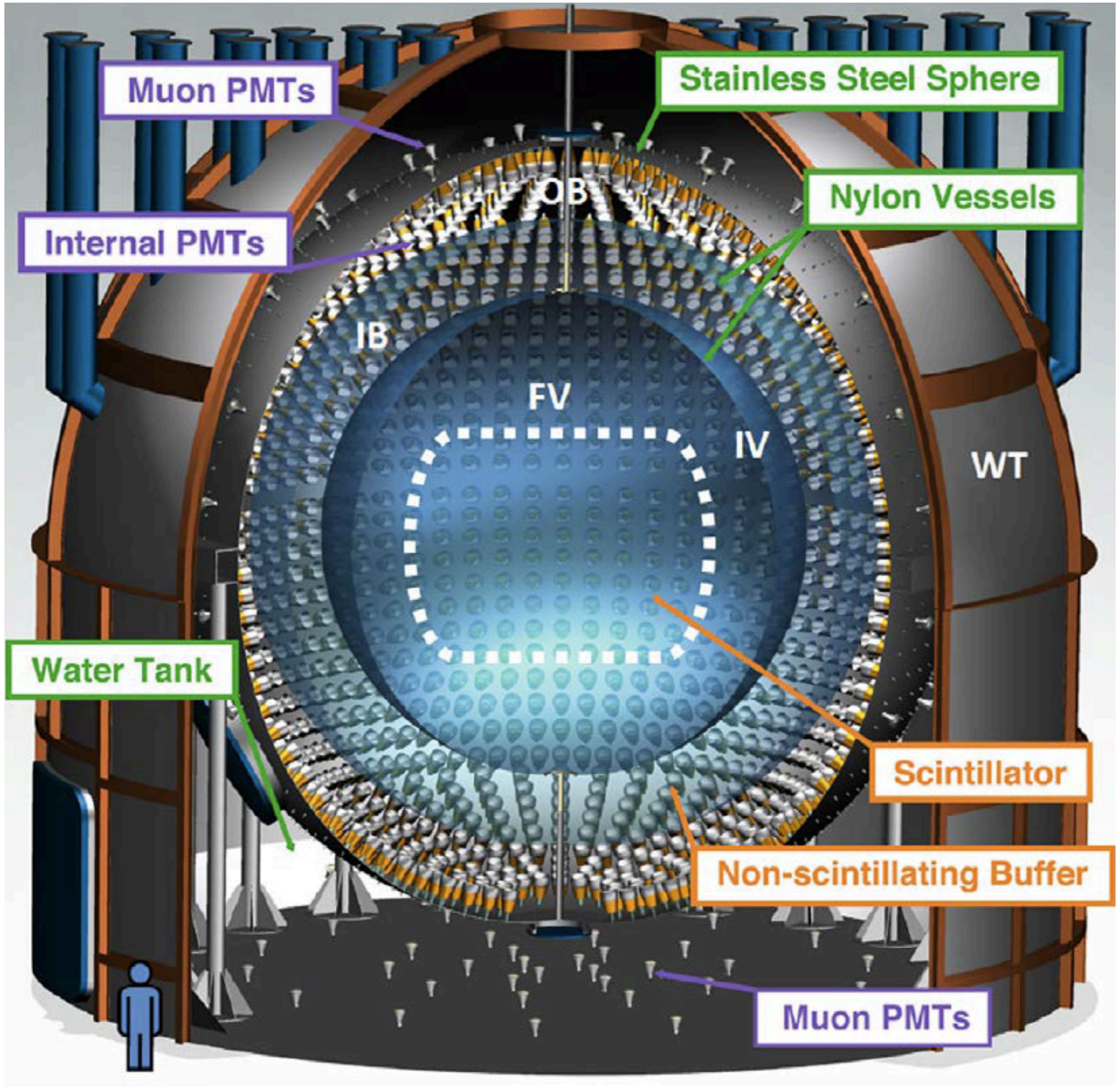
5.31 +- 0.6 (Turck-Chieze et al)

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

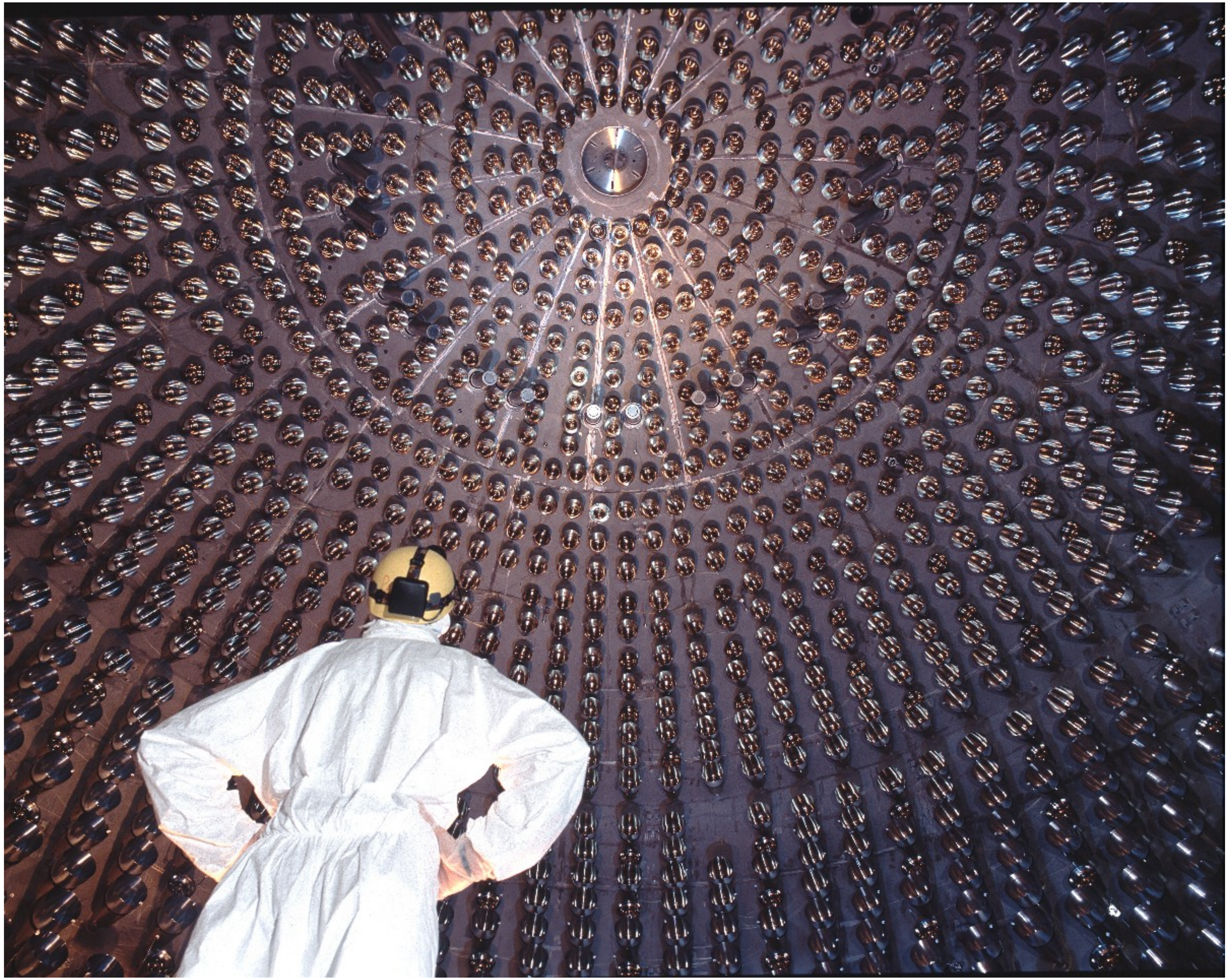
Electron Neutrinos are only 1/3 of Total

Art McDonald: Neutrino 2016

The Borexino detector

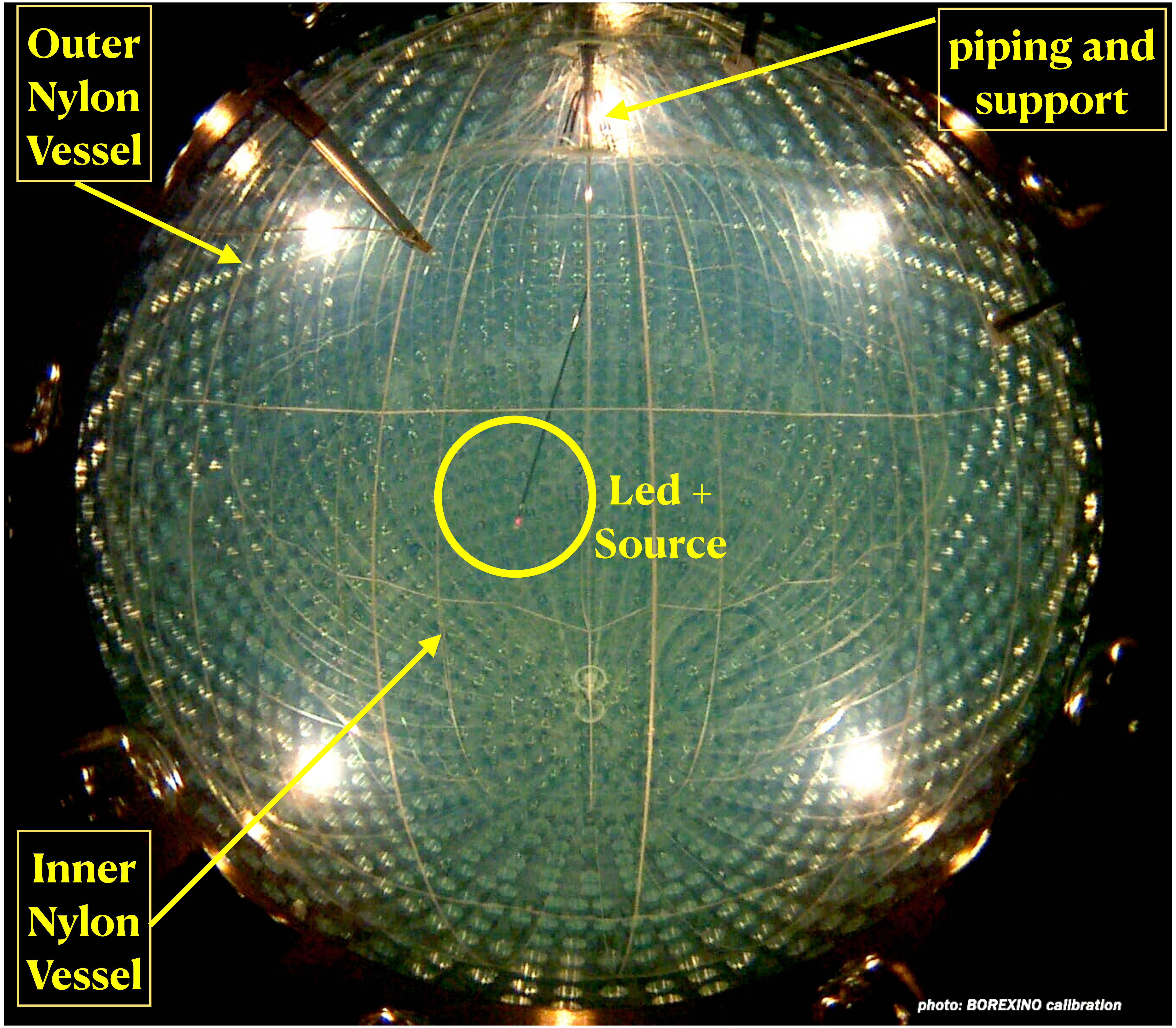


Internal view, empty

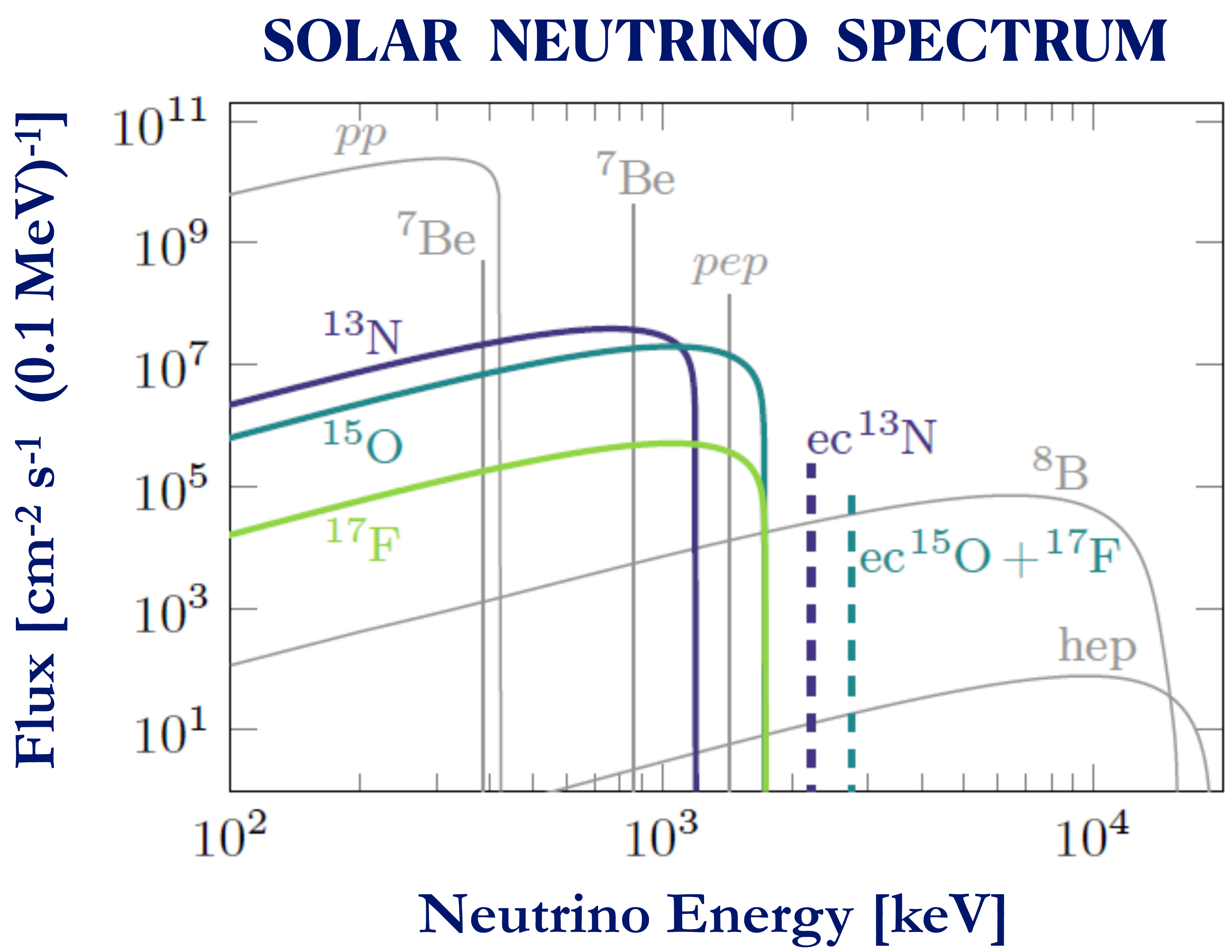


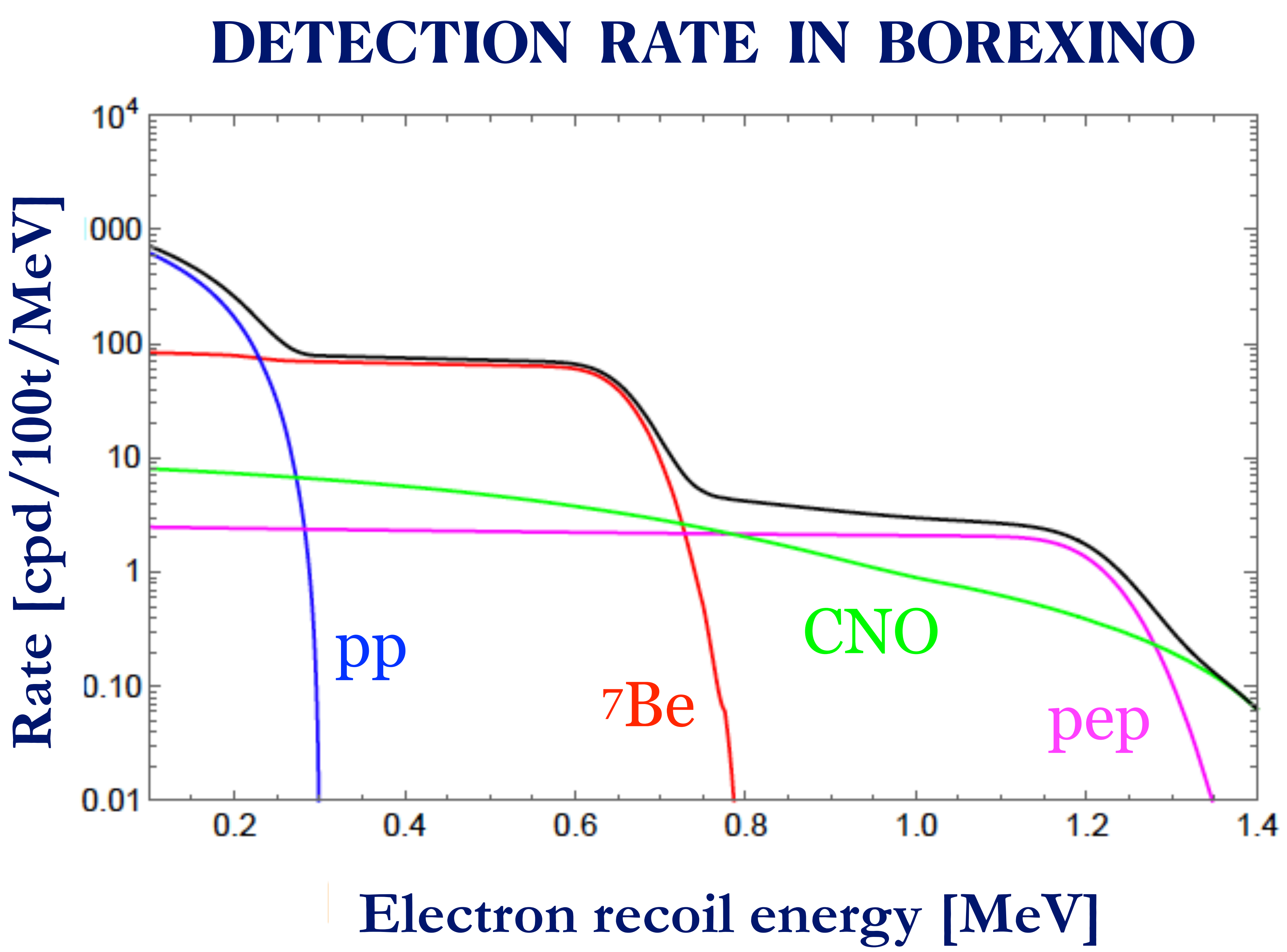
Internal view: inflated vessels (with N_2)

Internal view, filled, during calibration in 2009



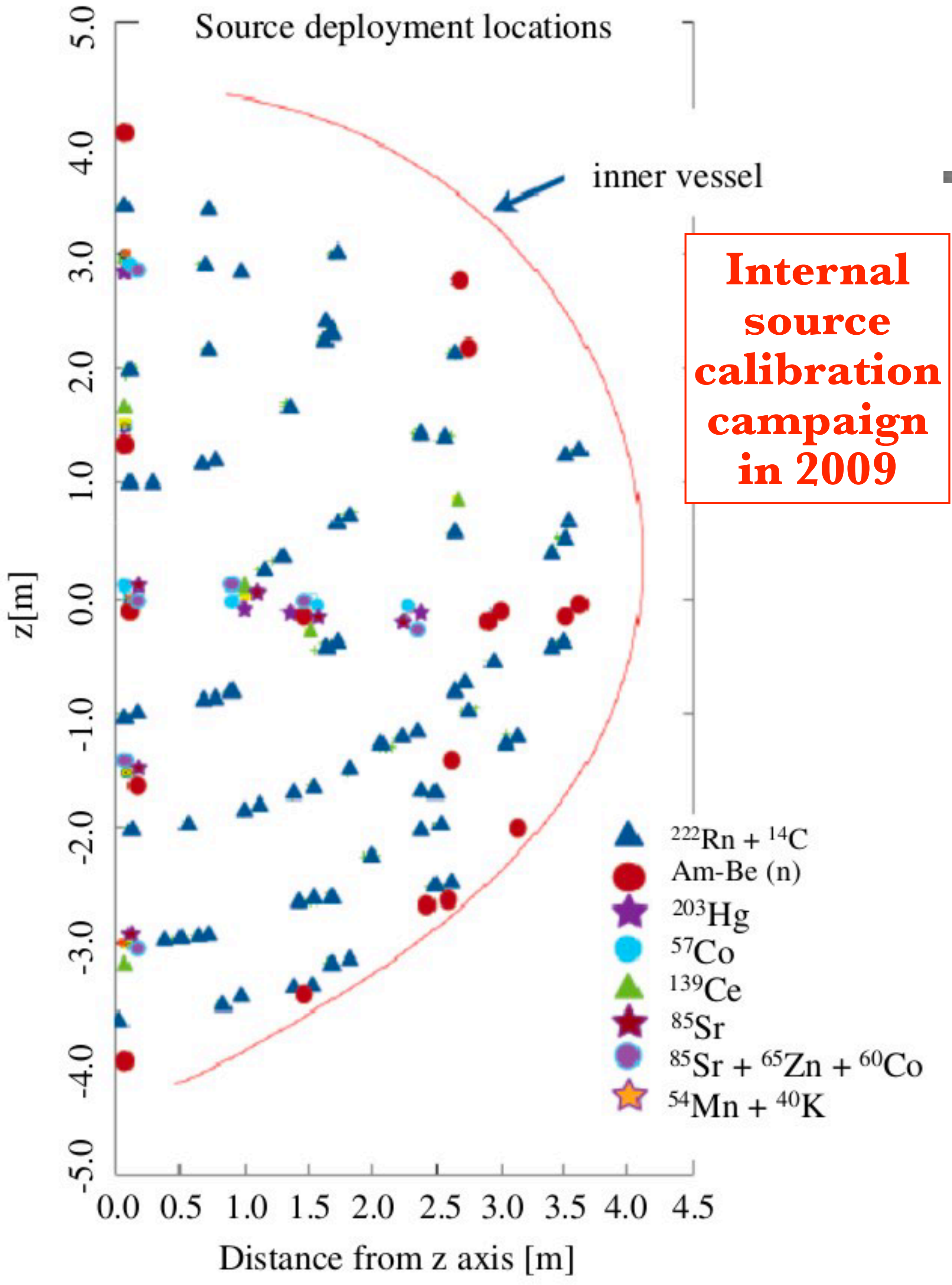
Neutrino detection in Borexino





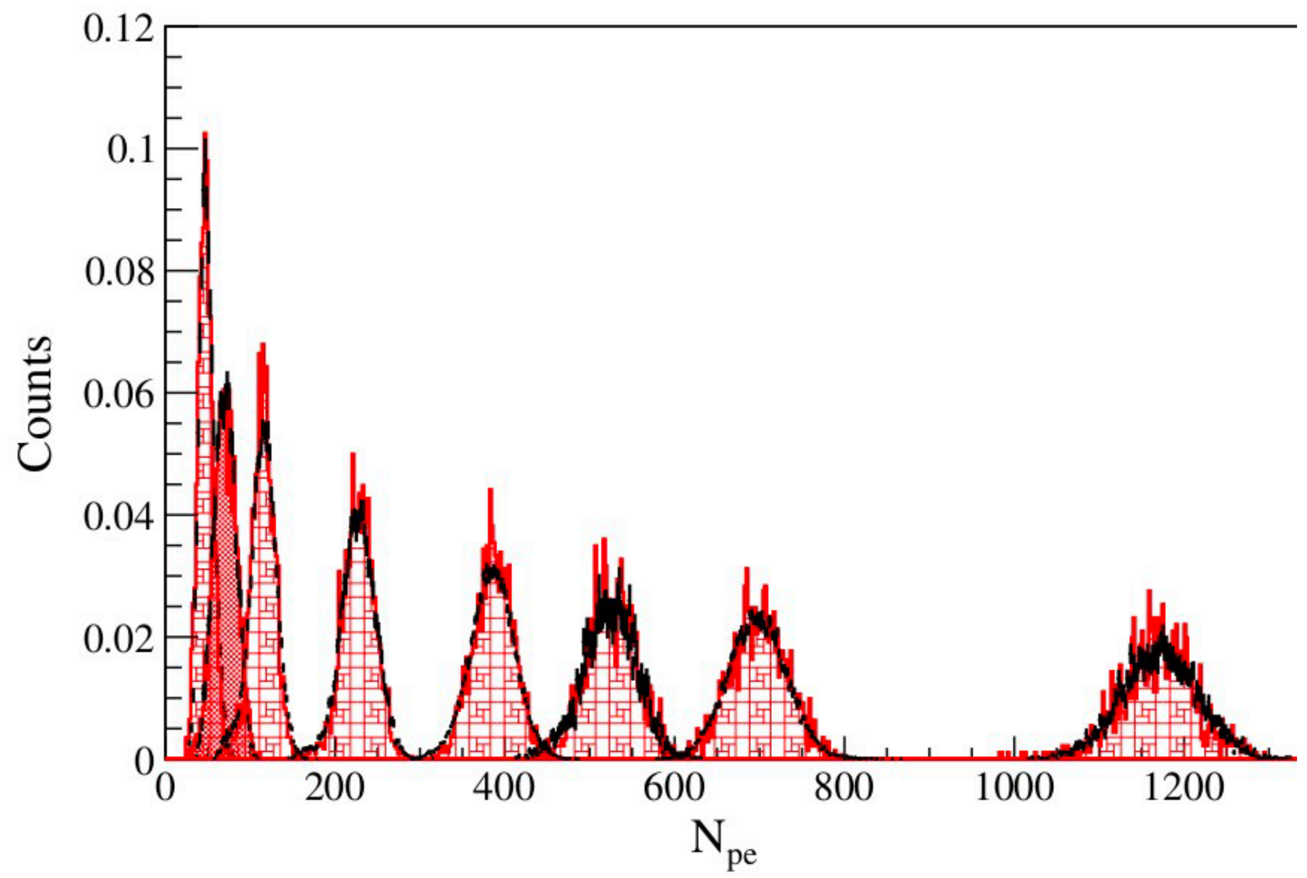
Detector response

- 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**

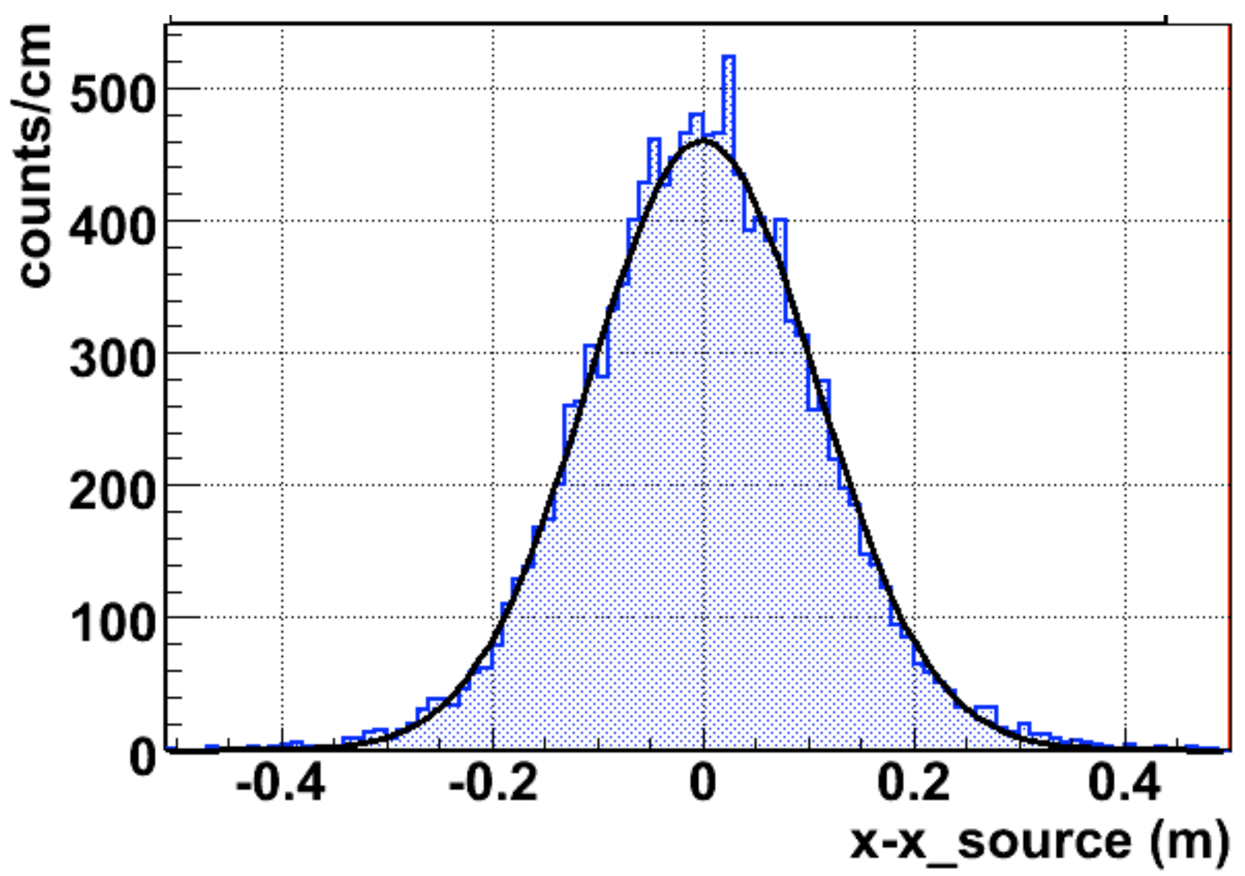


Internal source calibration campaign in 2009

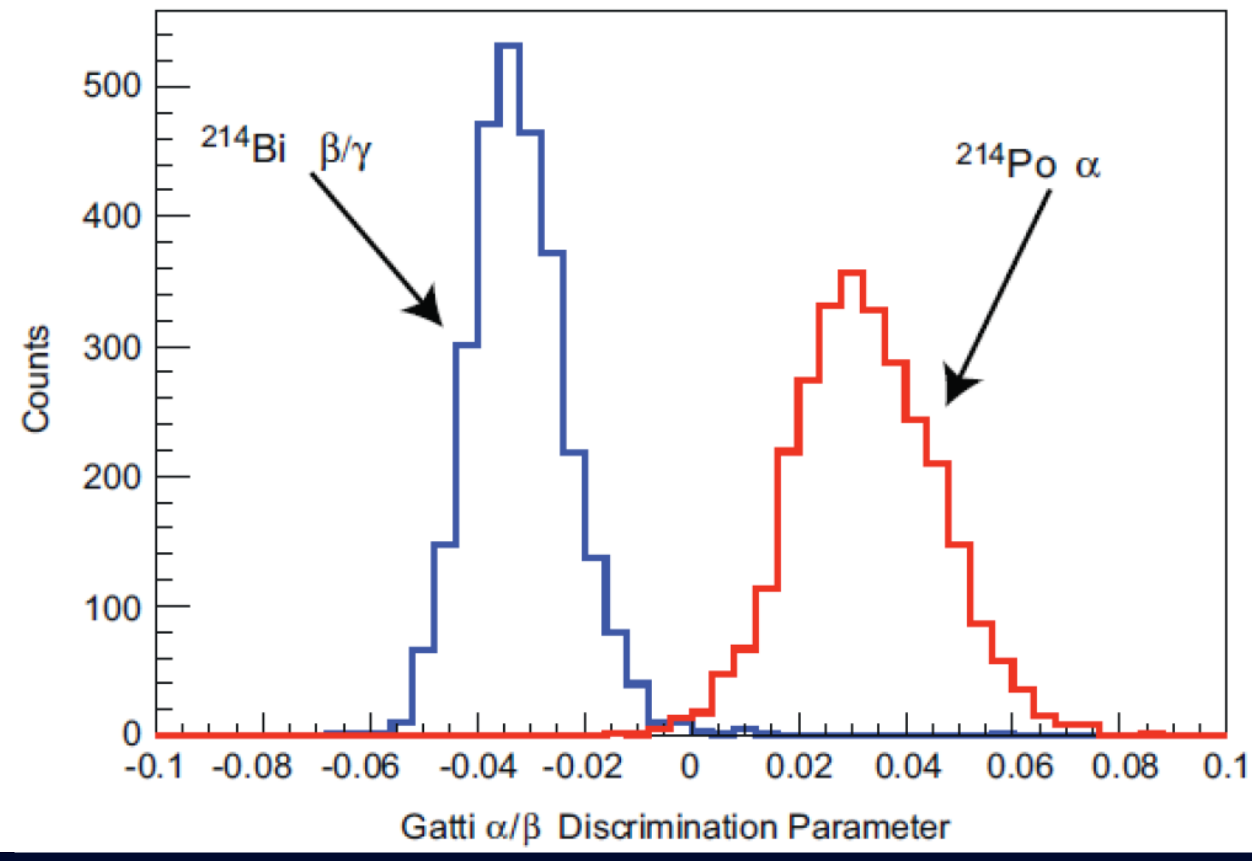
Energy: γ sources



Position: ^{214}Po



α/β: ^{214}Bi - ^{214}Po



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

EXTERNAL

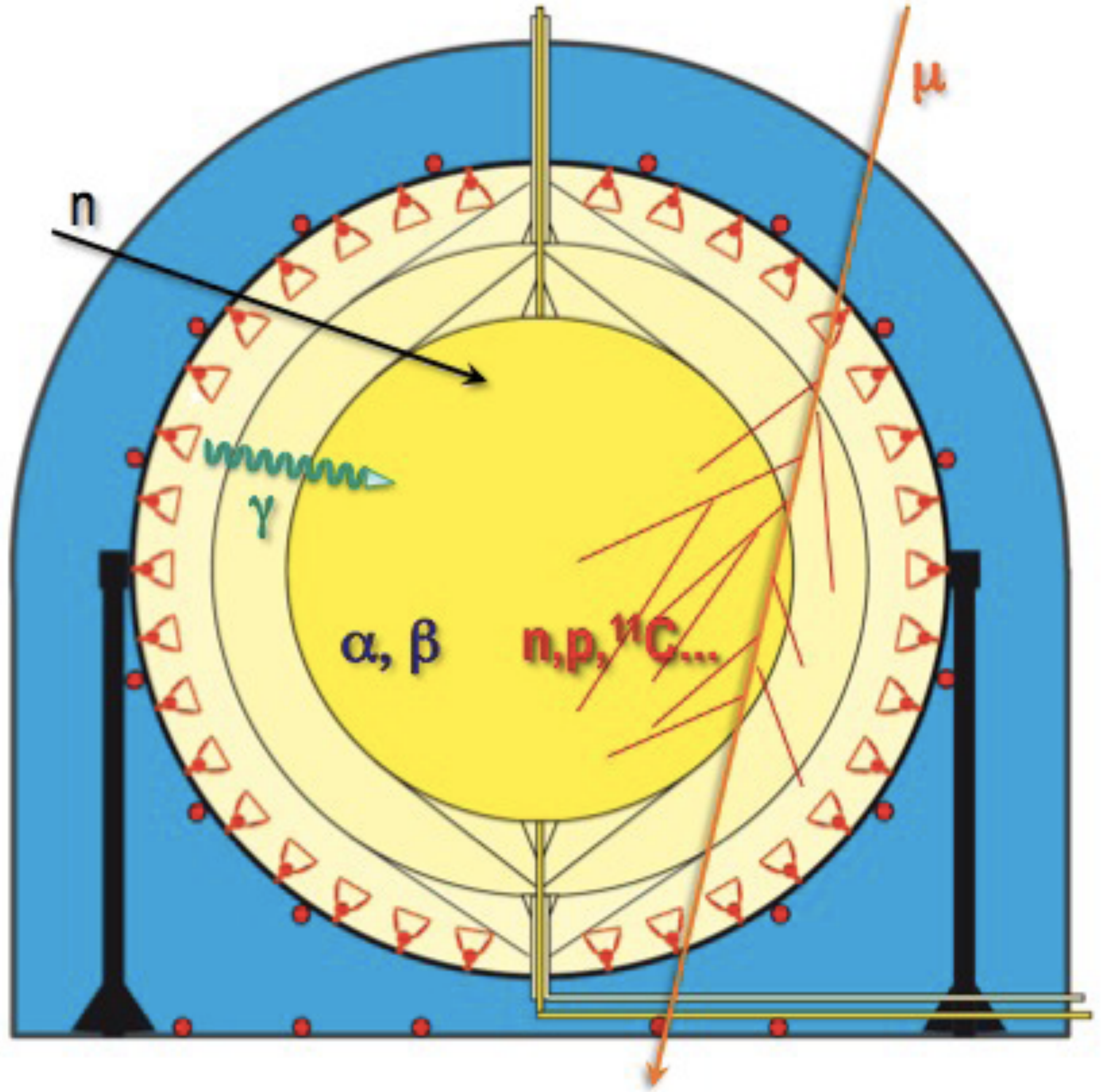
- γs (and n) from environment and detector materials (PMTs and SSS, mostly)

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

Fighting backgrounds

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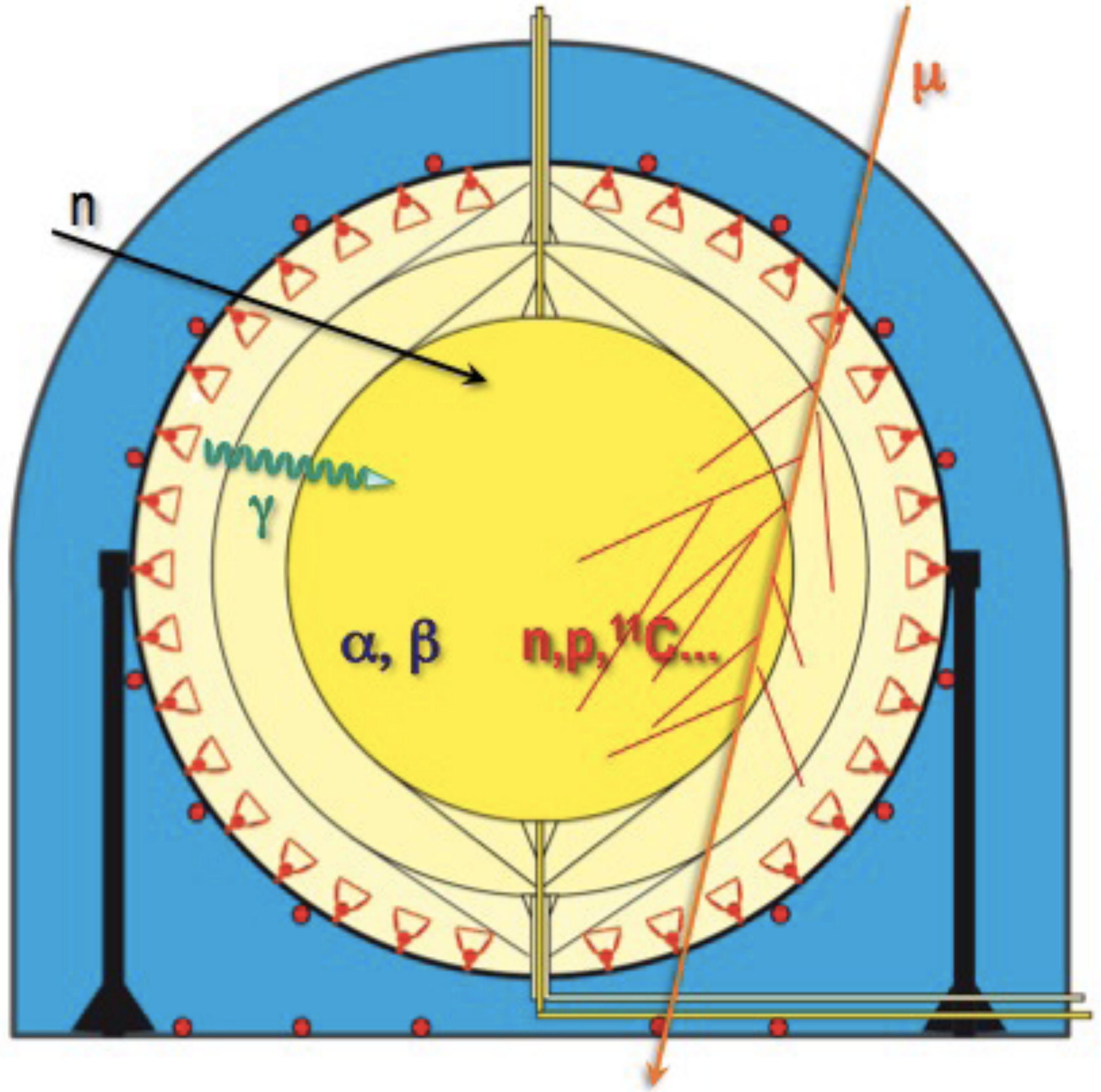

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MIGRATING

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^{210}Po, ^{222}Rn

FIGHTING STRATEGY

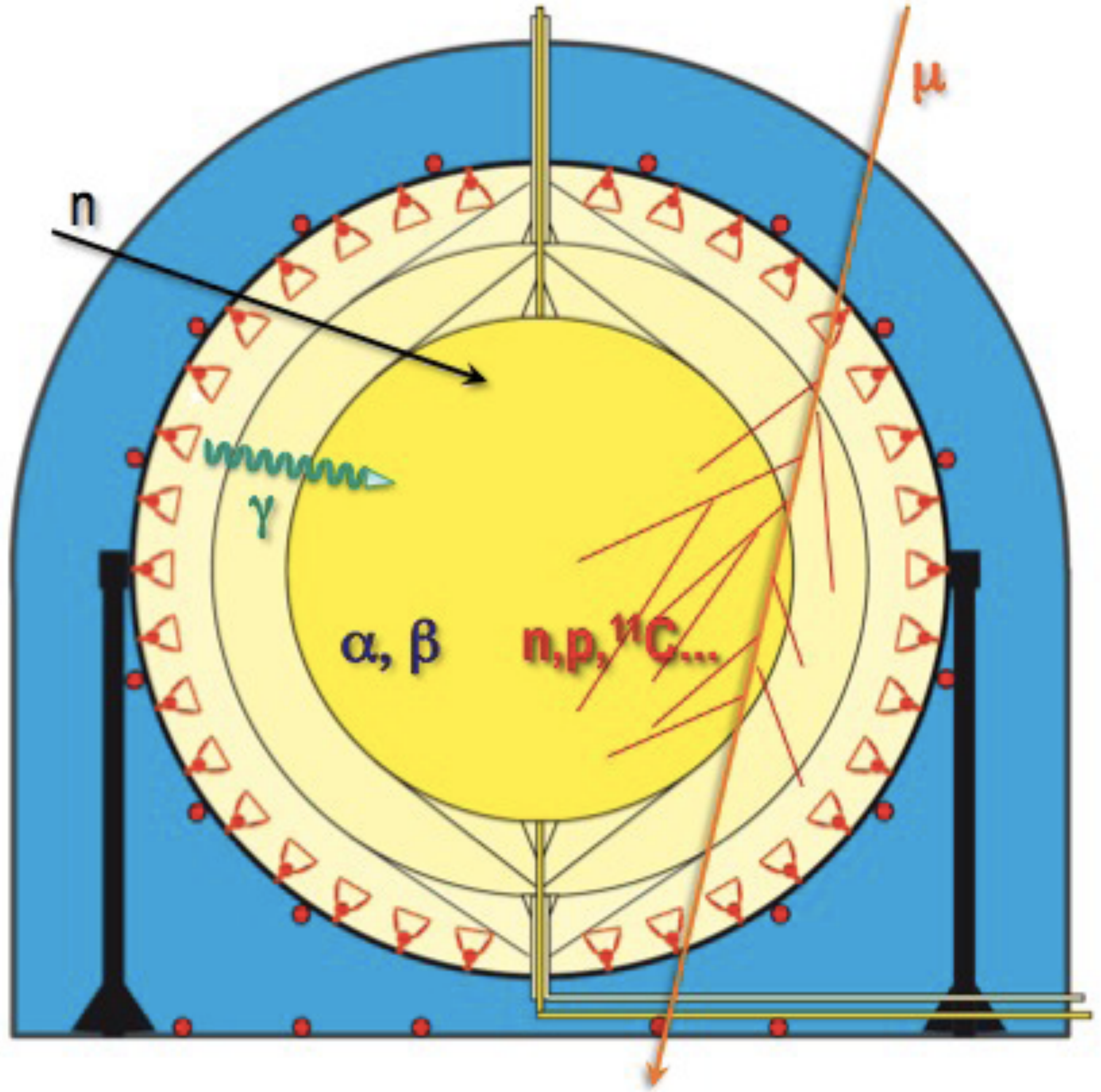
- Shielding, muon tagging and tracking
- Material selection (steel, PMTs, nylon)
- Nylon vessel (material selection, clean construction, no air exposure)

- **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



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^{85}Kr, ^{210}Pb, ^{210}Po

MIGRATING

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

^{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!

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

EXTERNAL

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  A tiny amount reaches FV

INTERNAL

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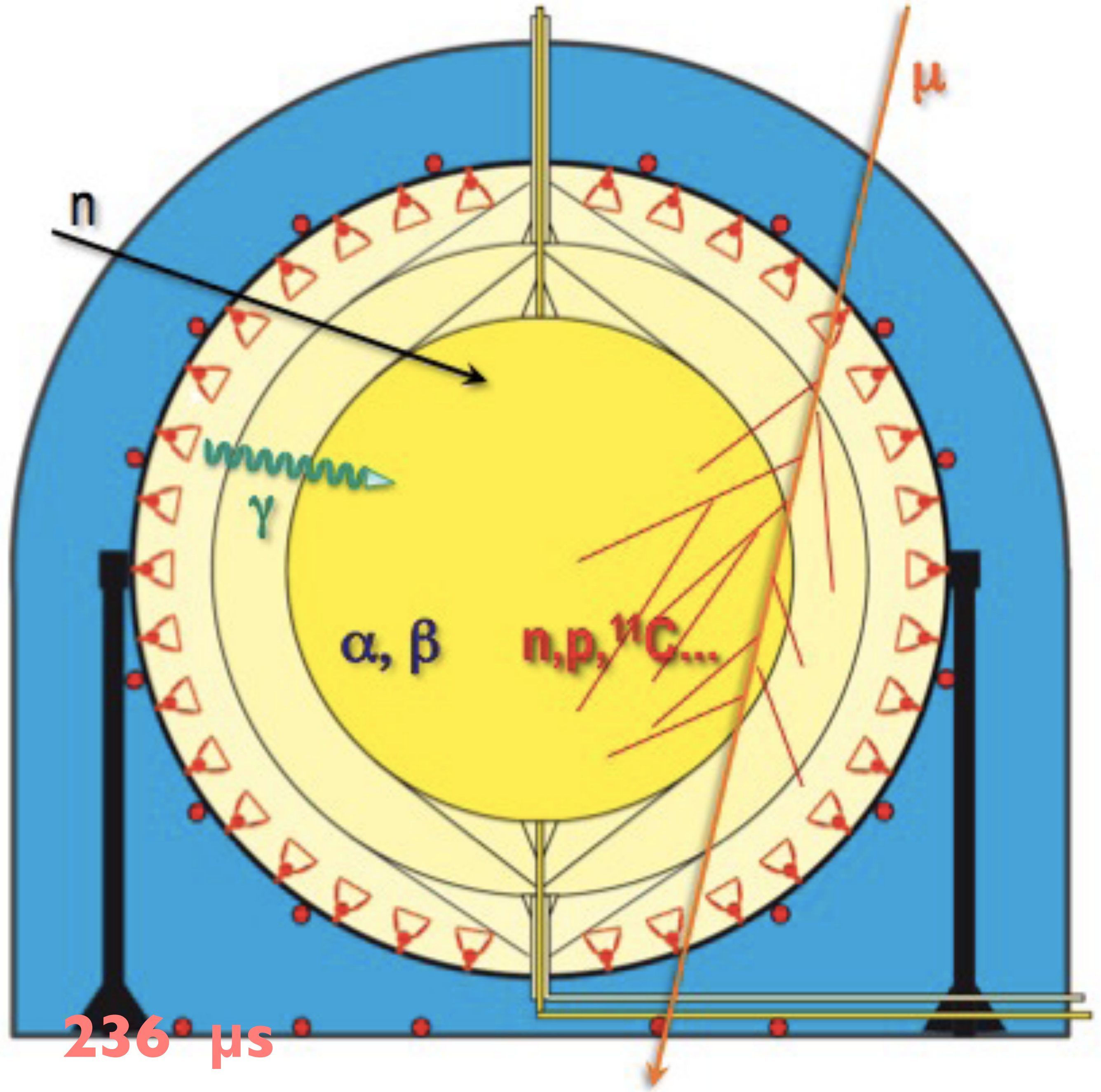

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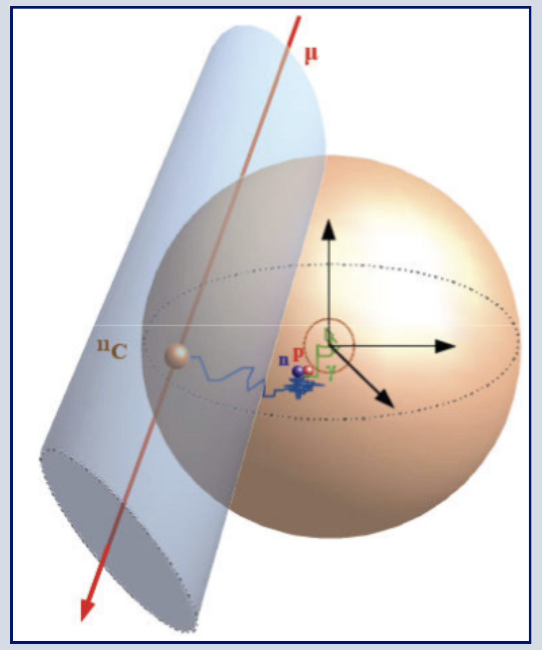
FIGHTING STRATEGY



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

29.4 min

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

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

236 µs

Other isotopes: removed by "after muon" veto cuts

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, …
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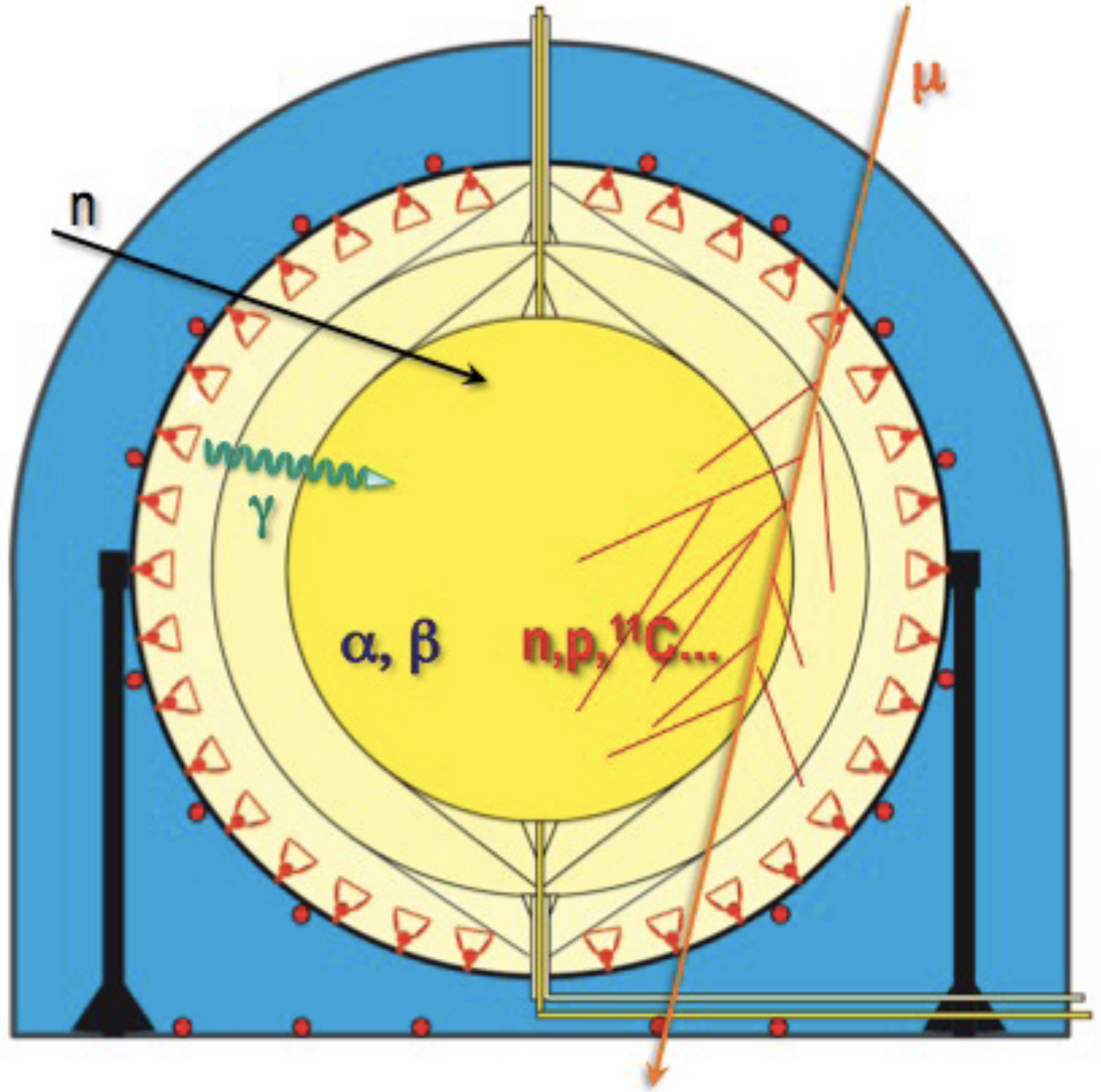


COSMOGENIC

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

^{11}C, ^{8}He, ^{9}C, ^{9}Li, ….

MIGRATING

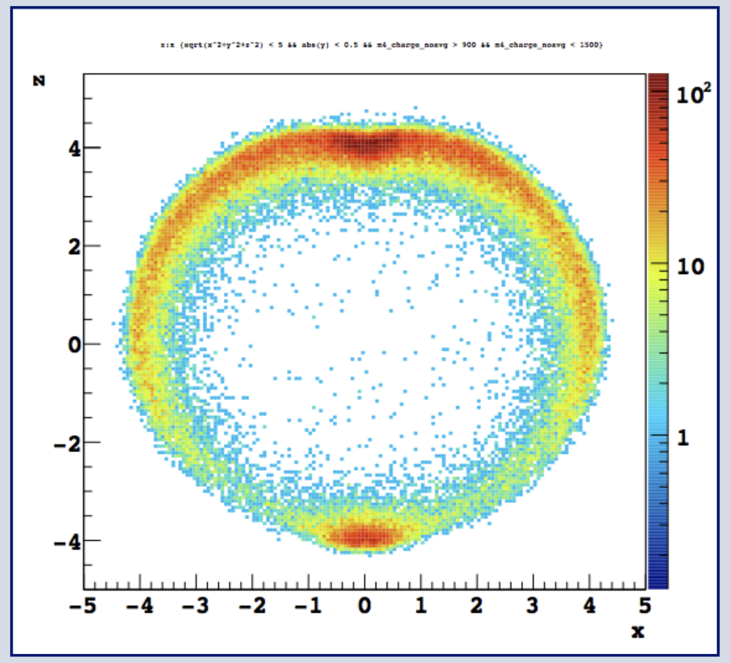
- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po, ^{222}Rn

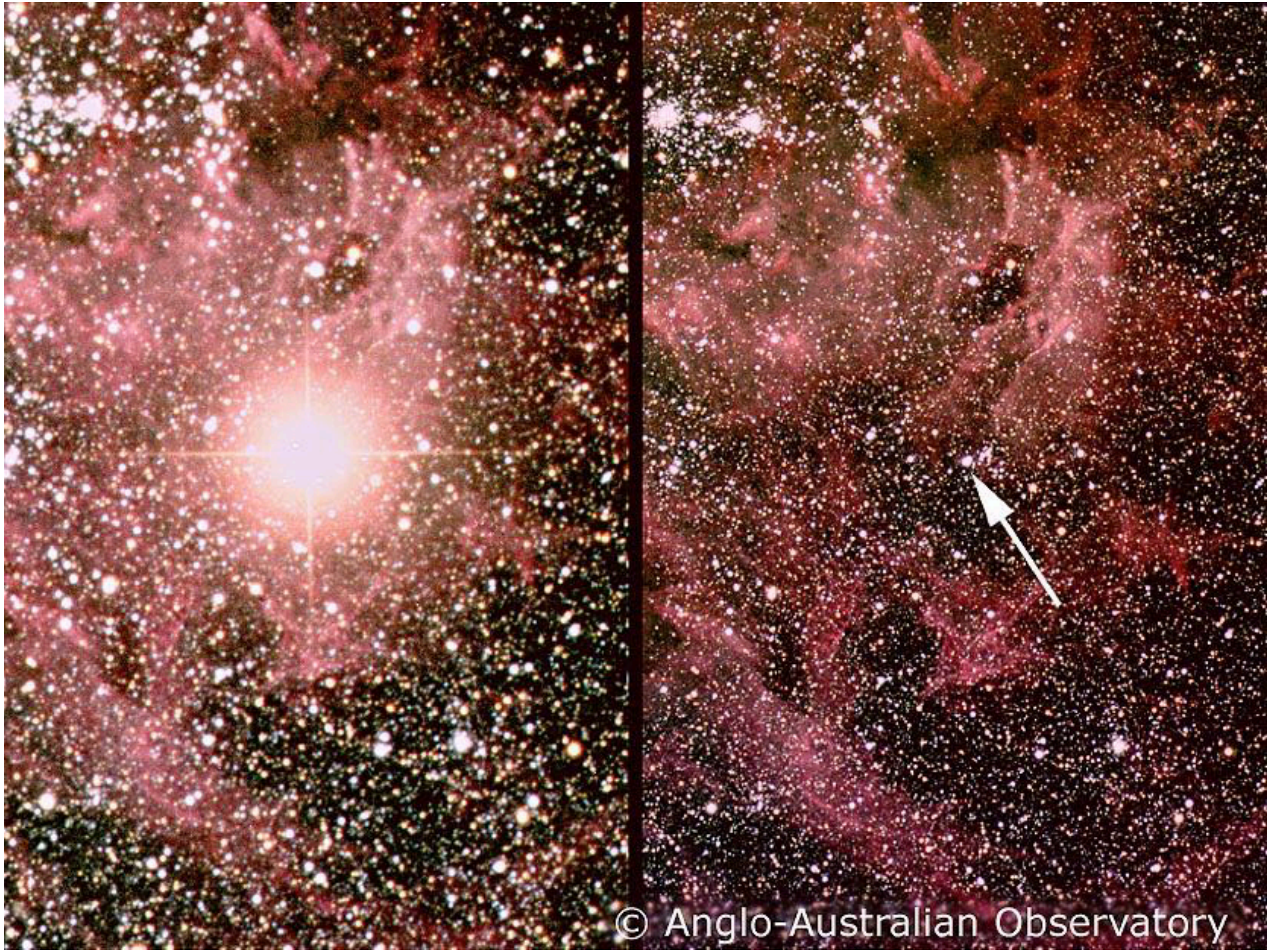
FIGHTING STRATEGY

- 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

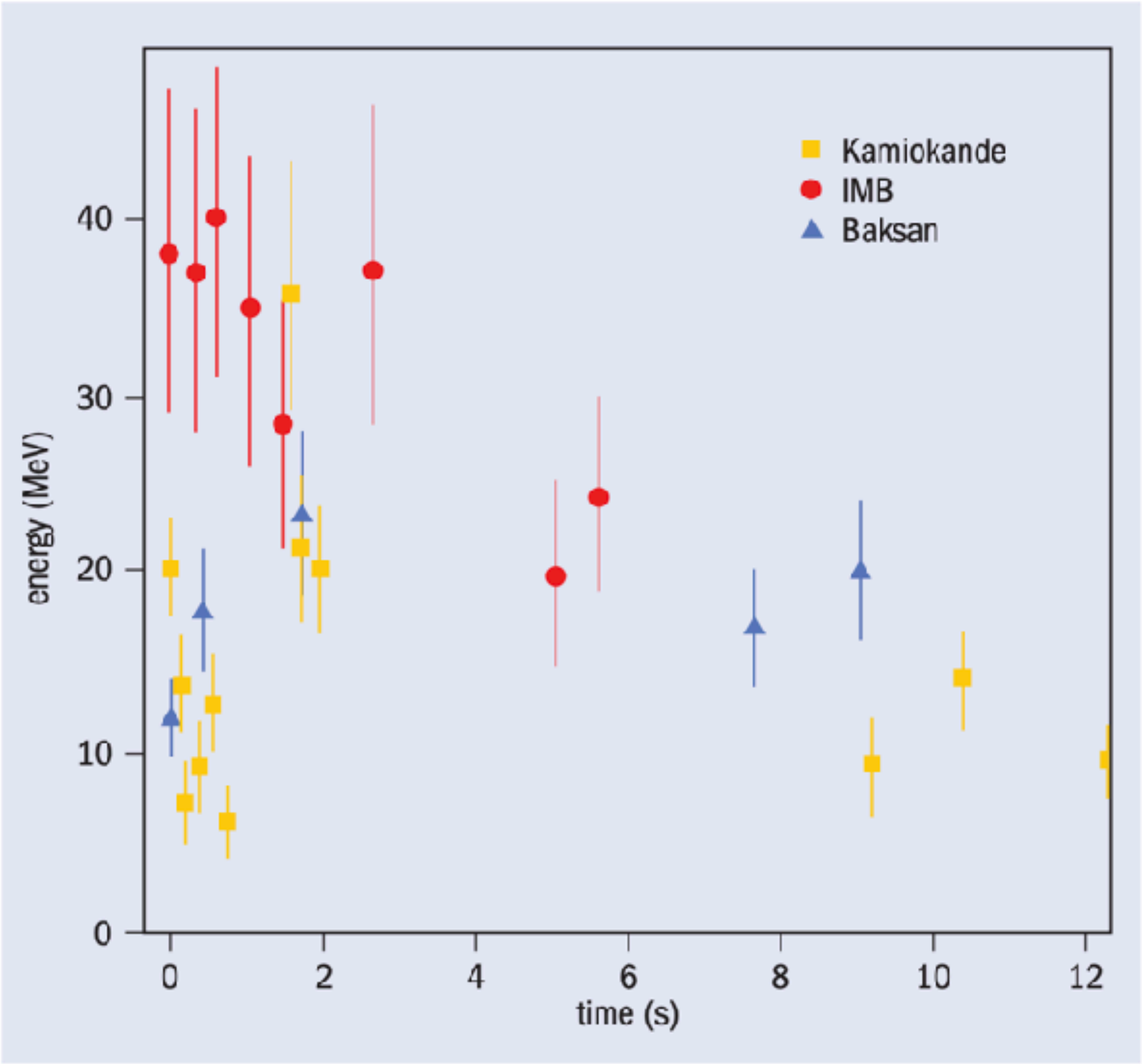
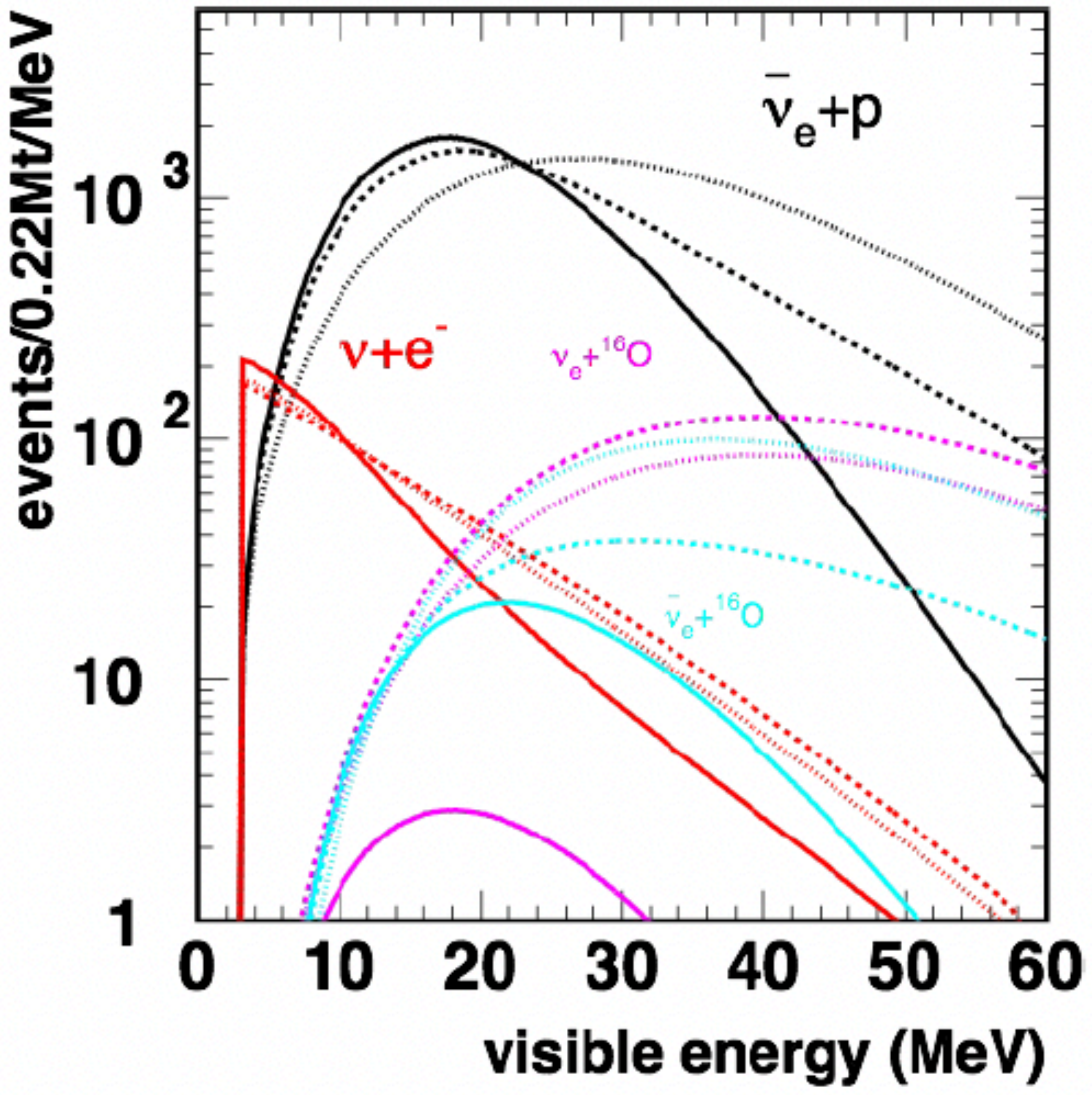
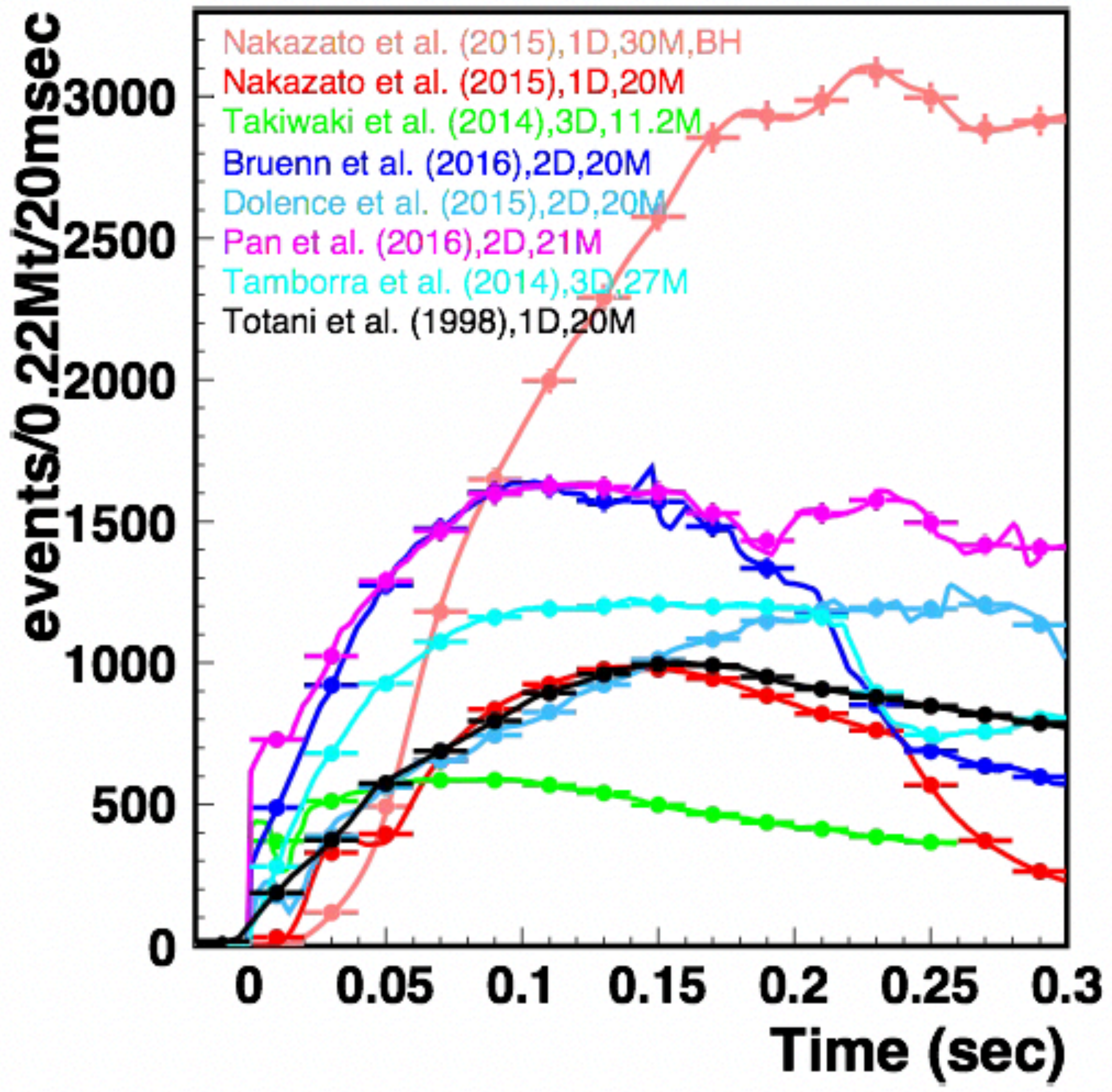


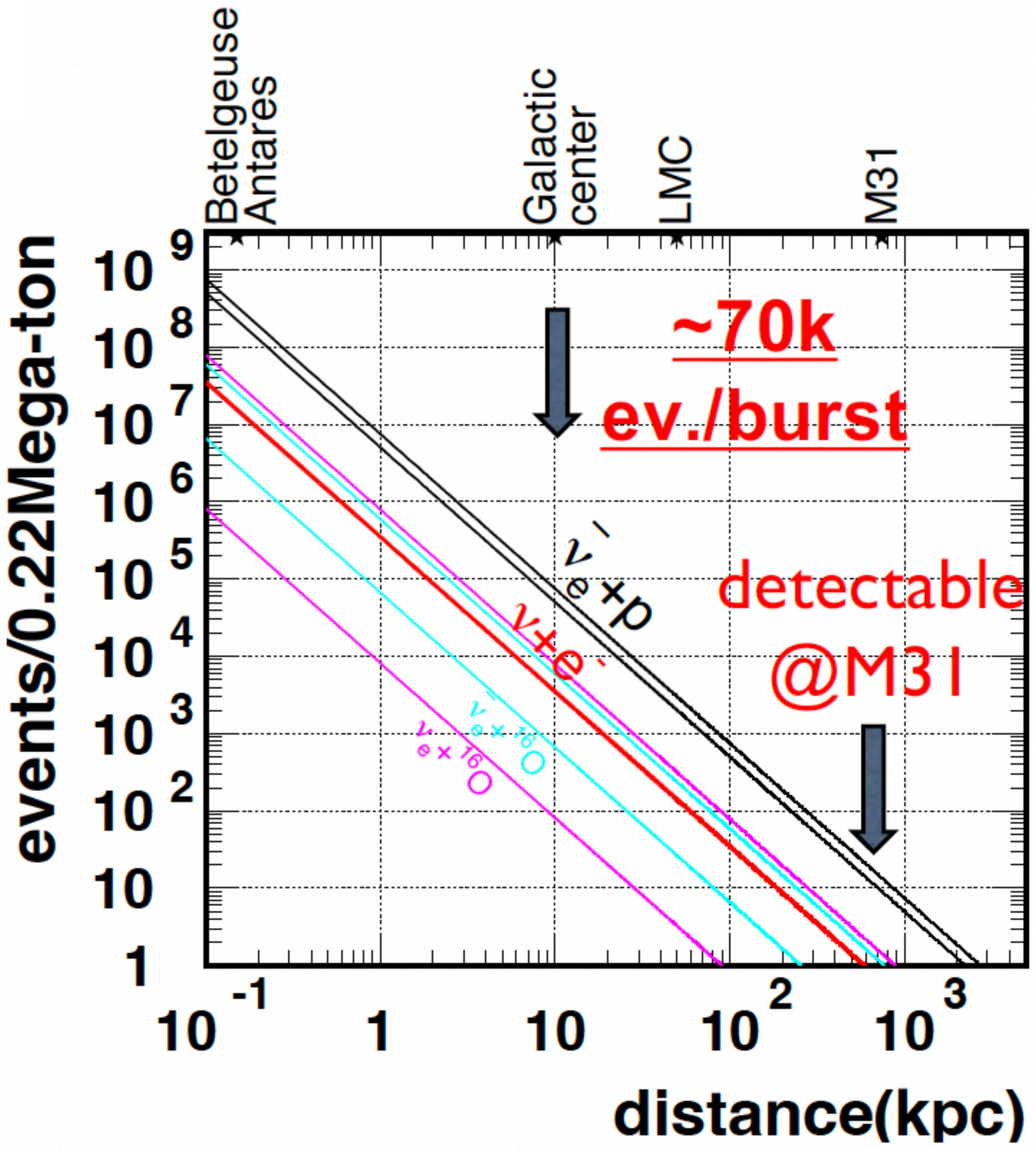
Fig. 3. SN1987A neutrino events observed by Kamiokande, IMB and Baksan showed that the neutrino burst lasted about 13 s.

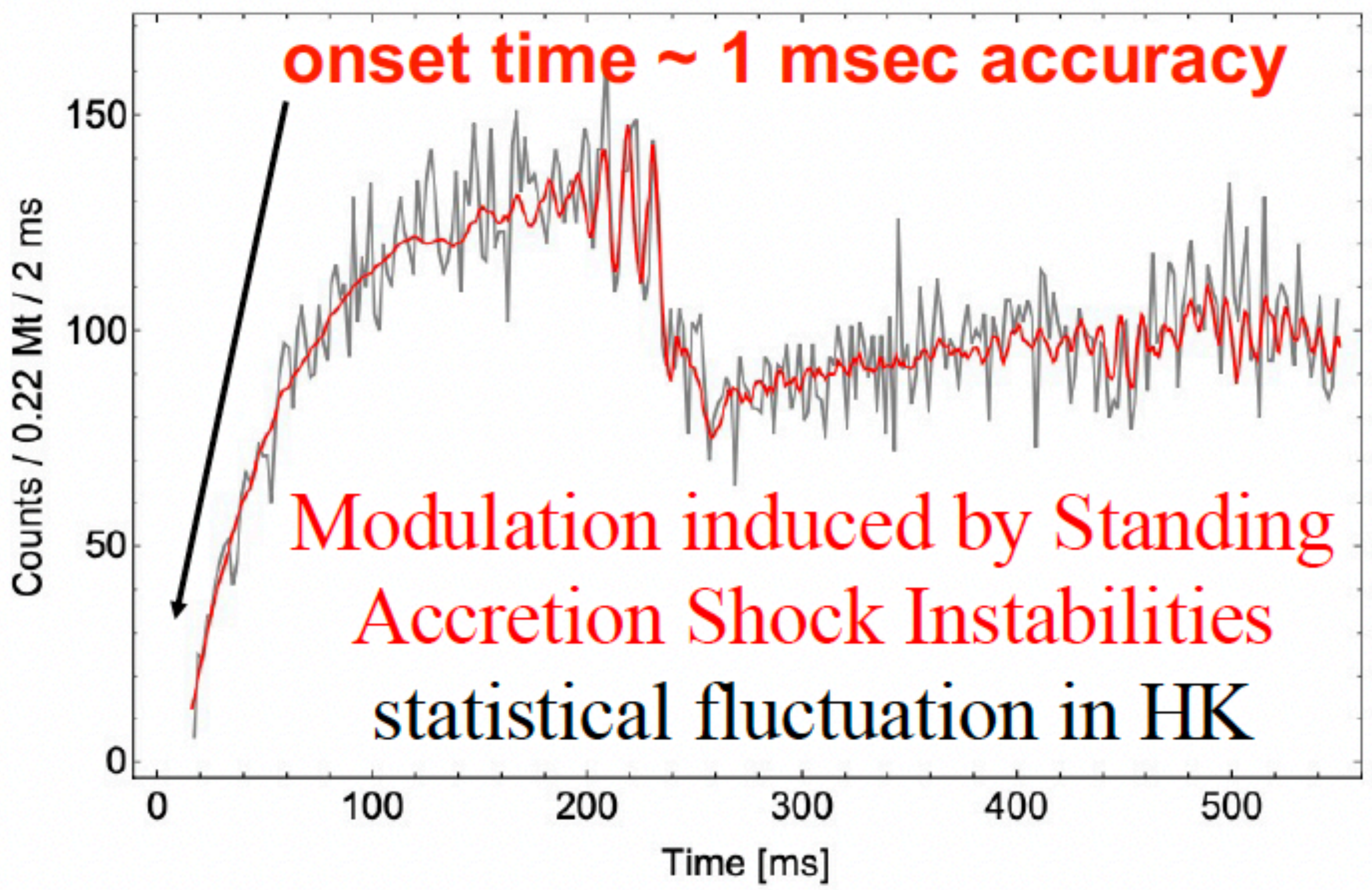
SN neutrino burst in HK

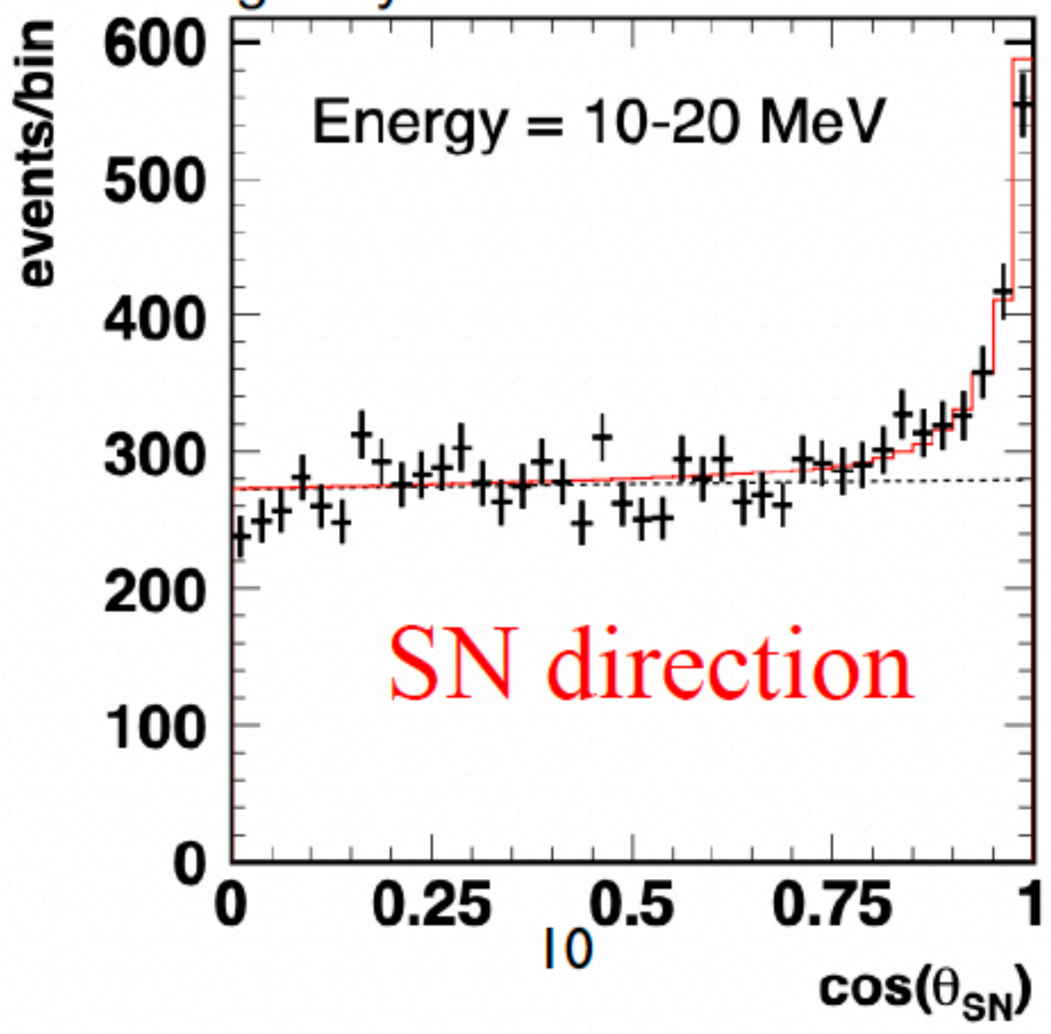




galactic supernova at 10 kpc (our r_{galaxy}= 8 kpc)





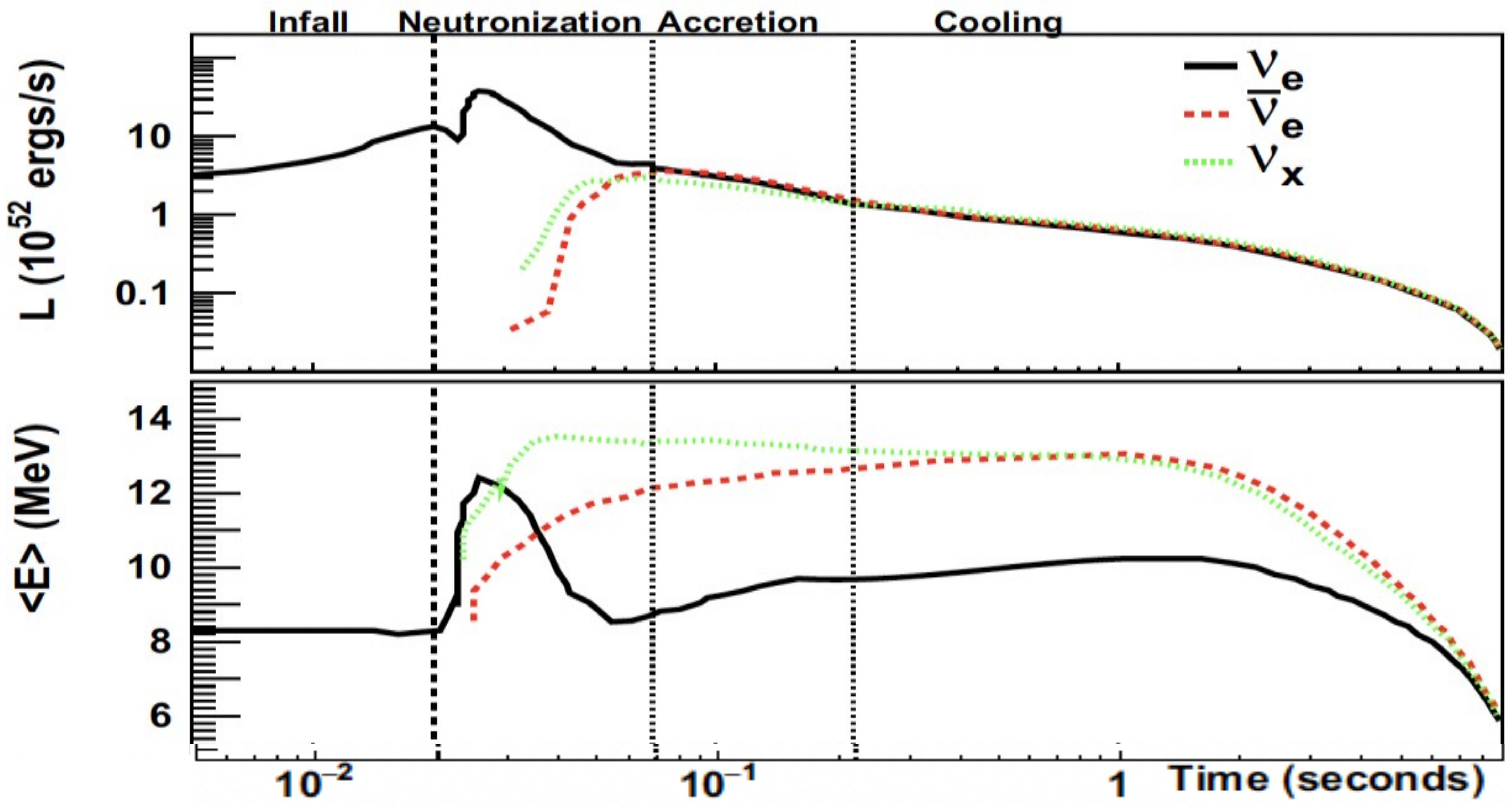


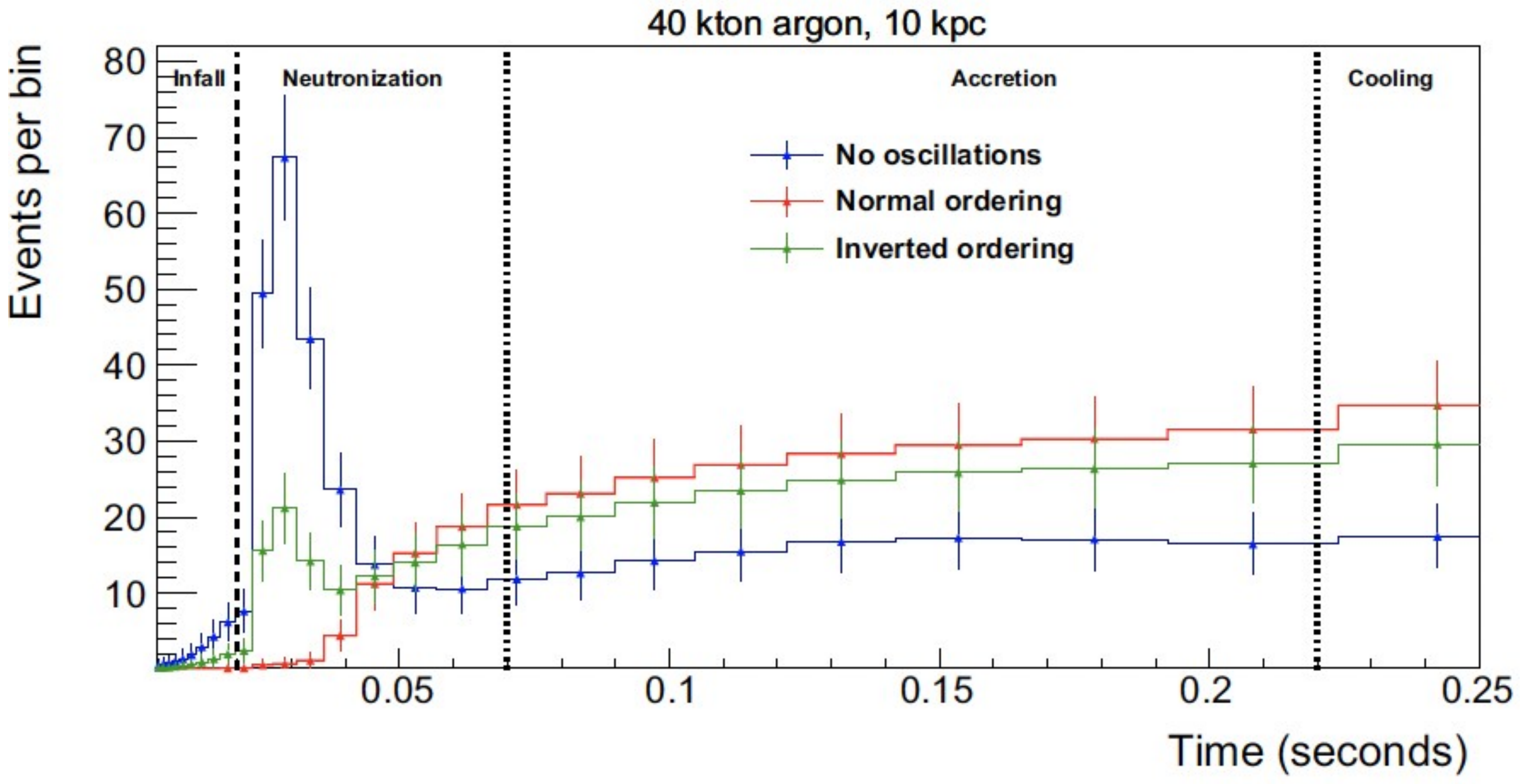
~70k events/burst at 10 kpc

- explosion mechanism,
- BH/NS formation,
- alert with 1° pointing

10

SN neutrino burst in DUNE





DUNE sensitive to ν_e CC events by

$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$

exploiting the Ar target and to ν ES on electrons thanks to its large mass

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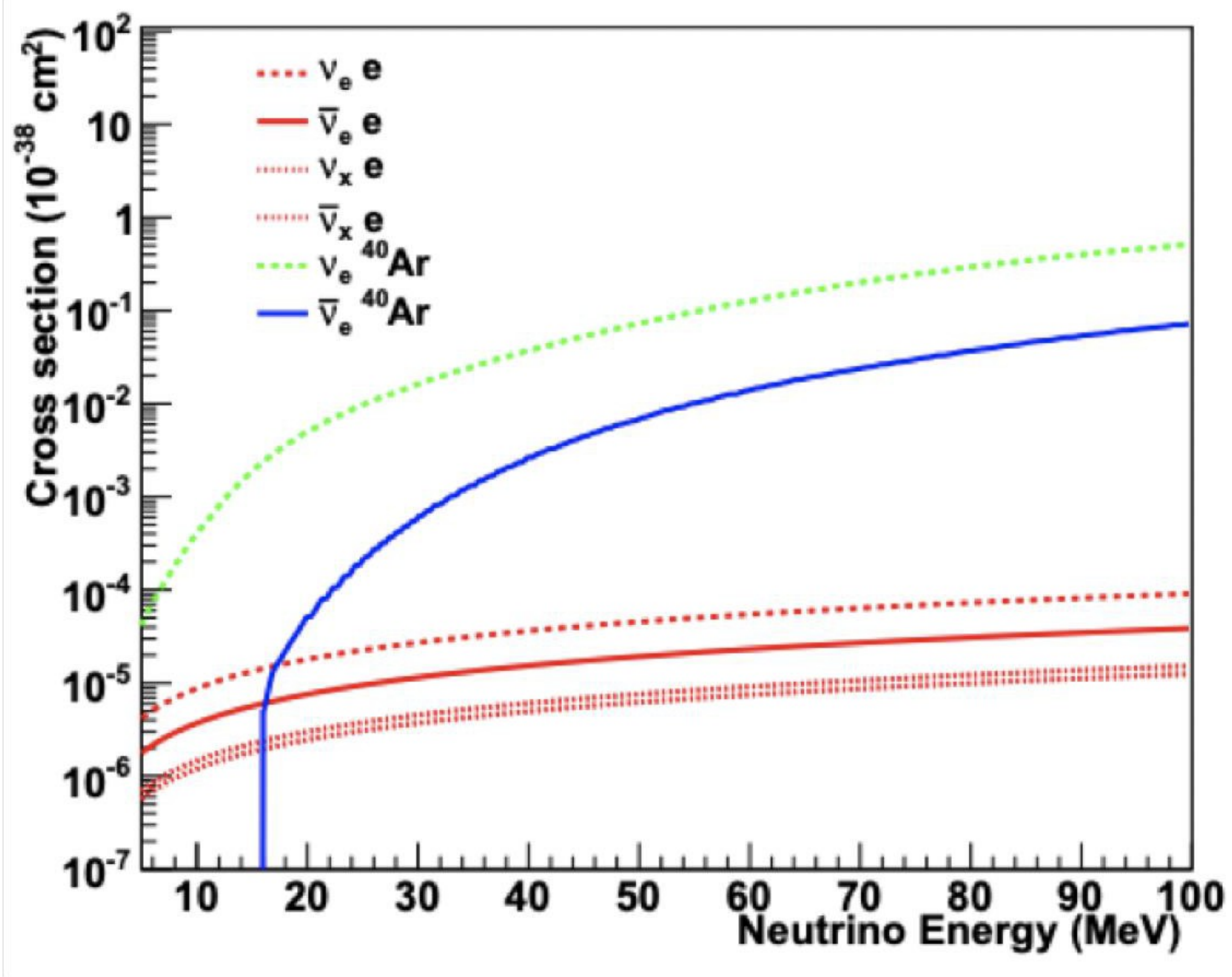


Open problems

- **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)

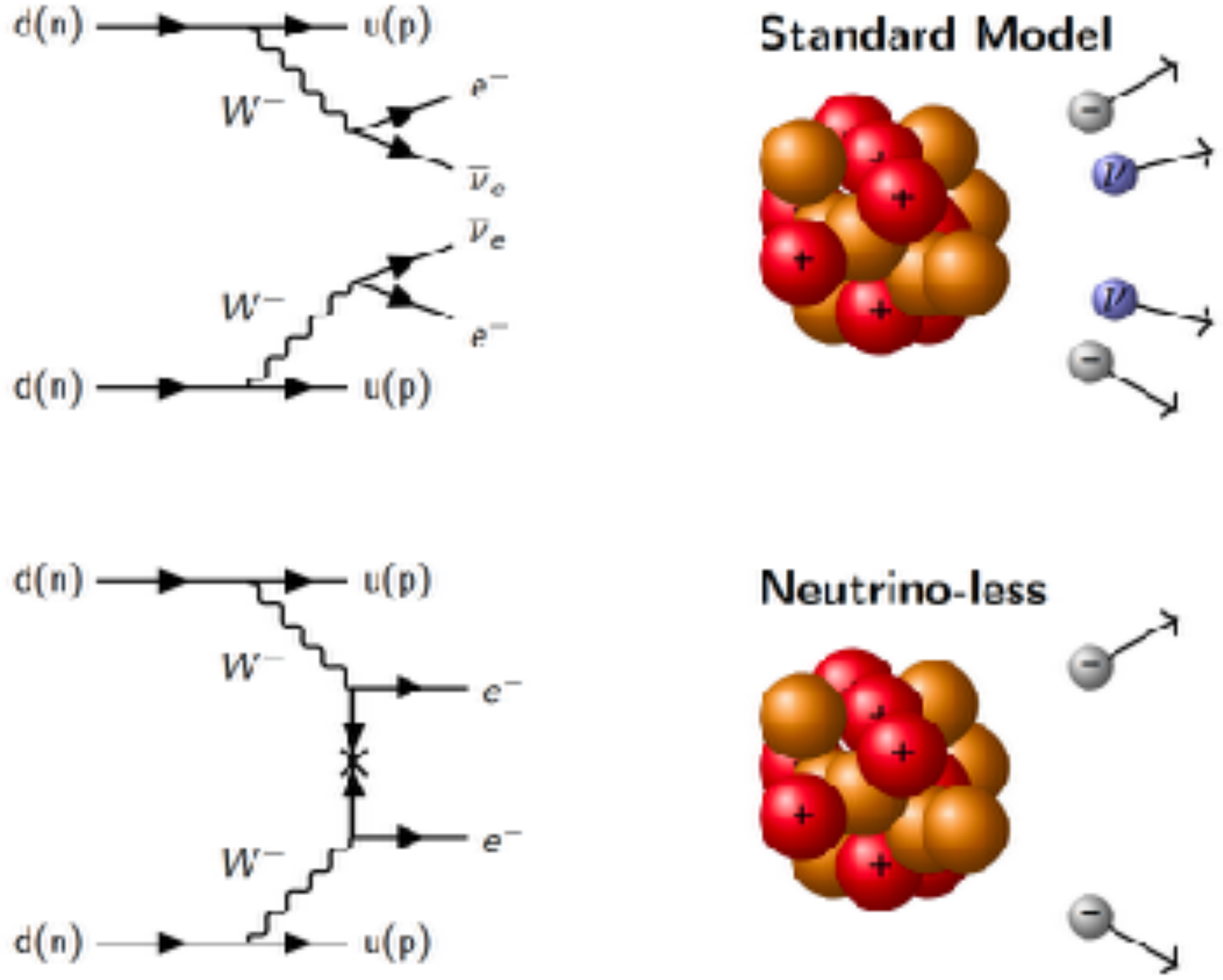
- **Neutrino mass ordering**
  - $m_3>m_1$ or $m_3<m_1$?
    - JUNO, ORCA, DUNE

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

Neutrinoless double beta decay

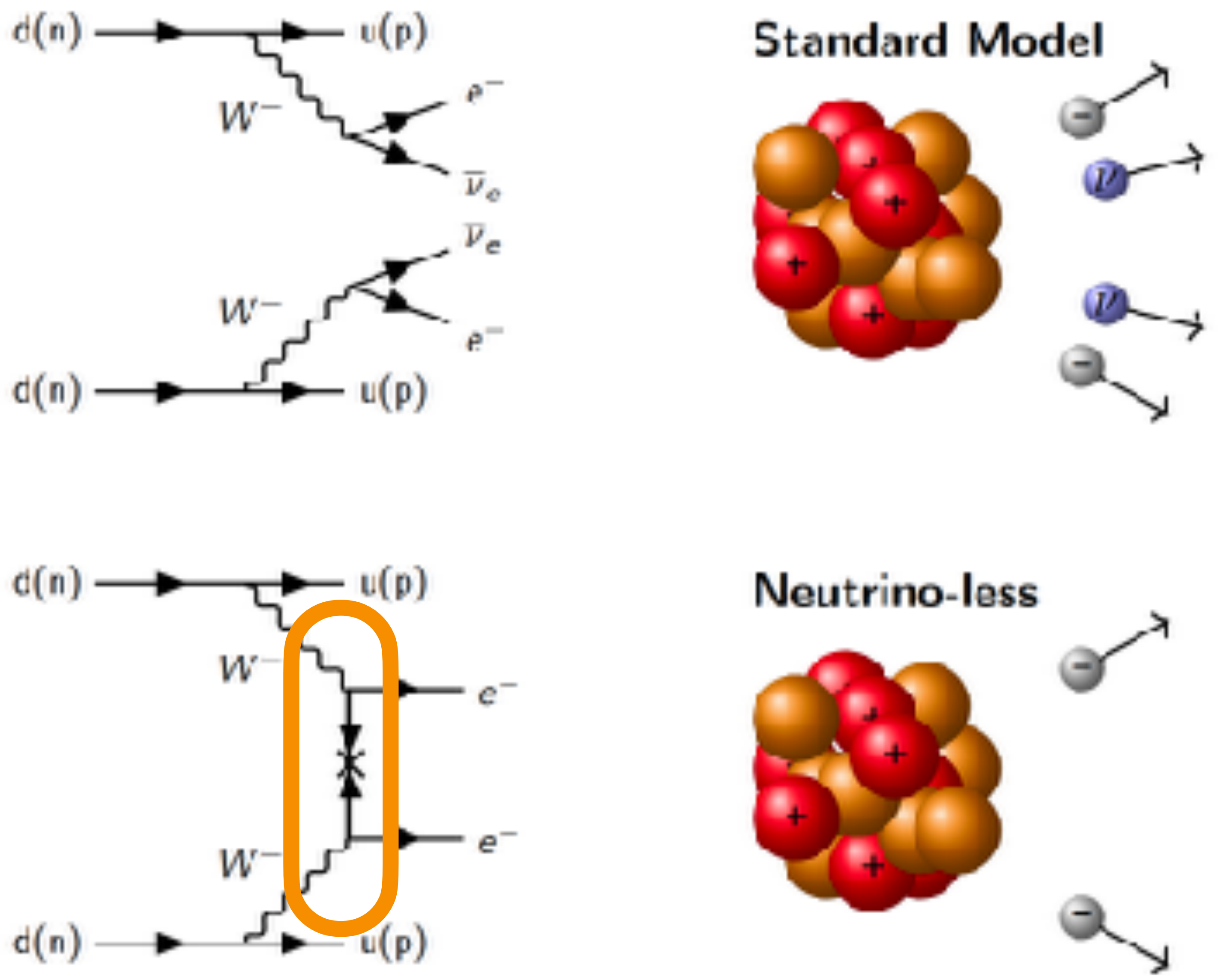
- It is a very rare nuclear process (if it exists) in which a nucleus makes a "double" beta decay **without the emission of neutrinos**
  - The decay with 2 neutrinos exists and has been observed
    - It does not contain new physics
  - **That without neutrinos is super-interesting**
  -

Maria Göppert Mayer



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**
  -



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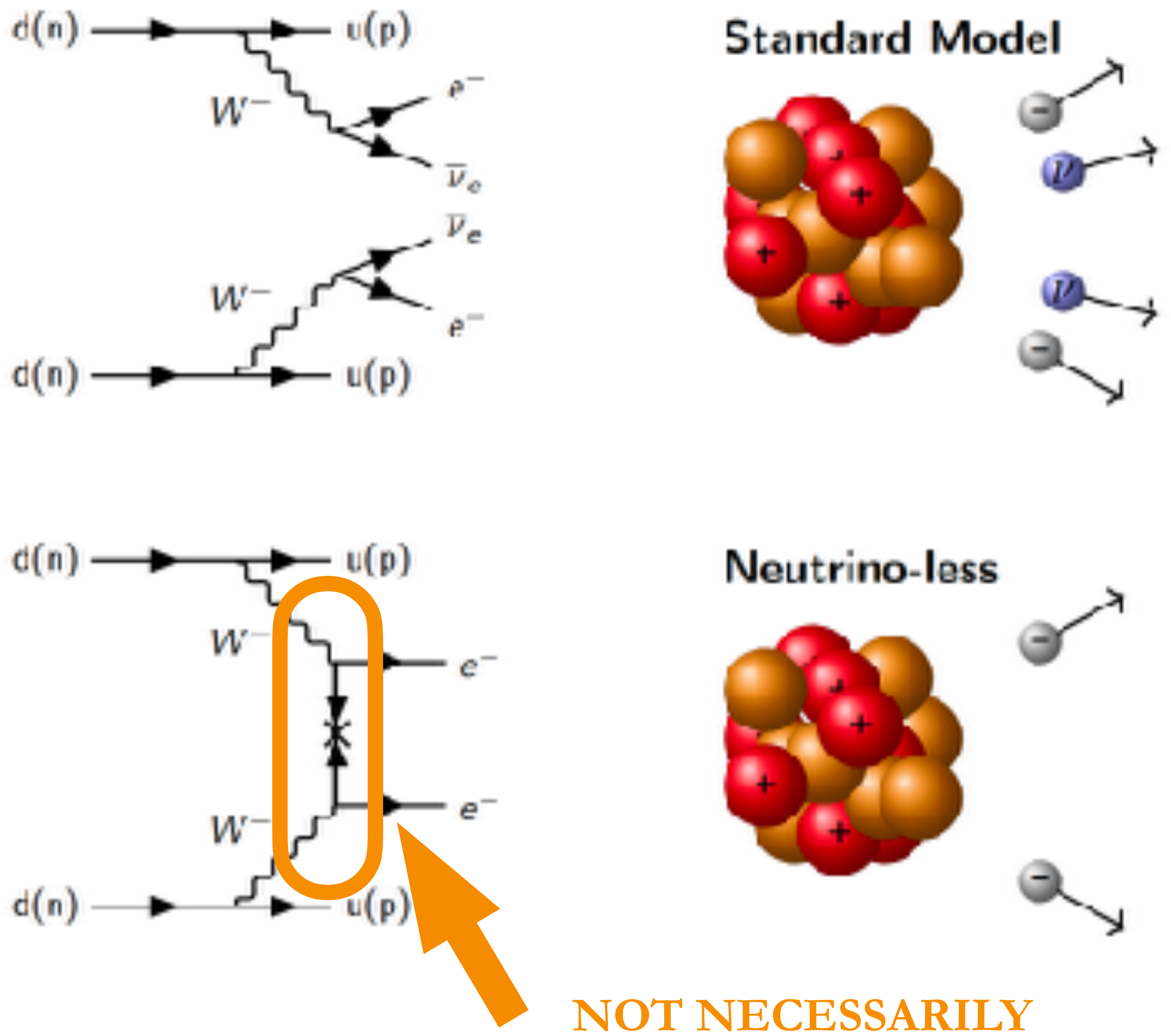
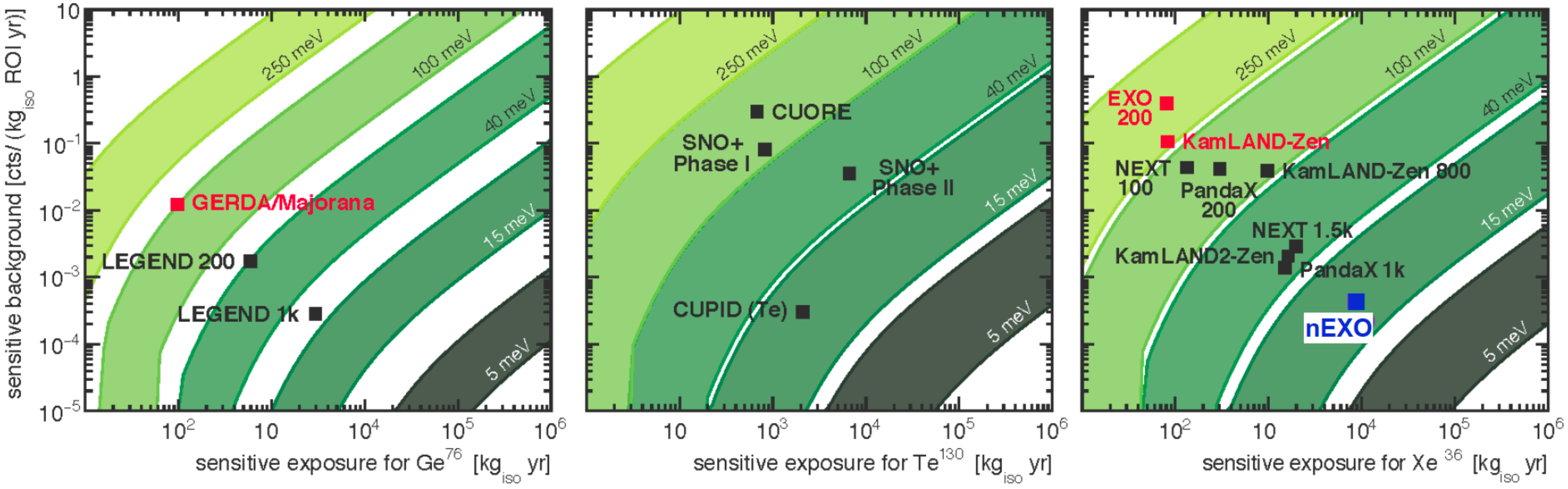
  - i.e. lepton number is violated
  - **In all scenarios $0\nu\beta\beta$ implies new physics**

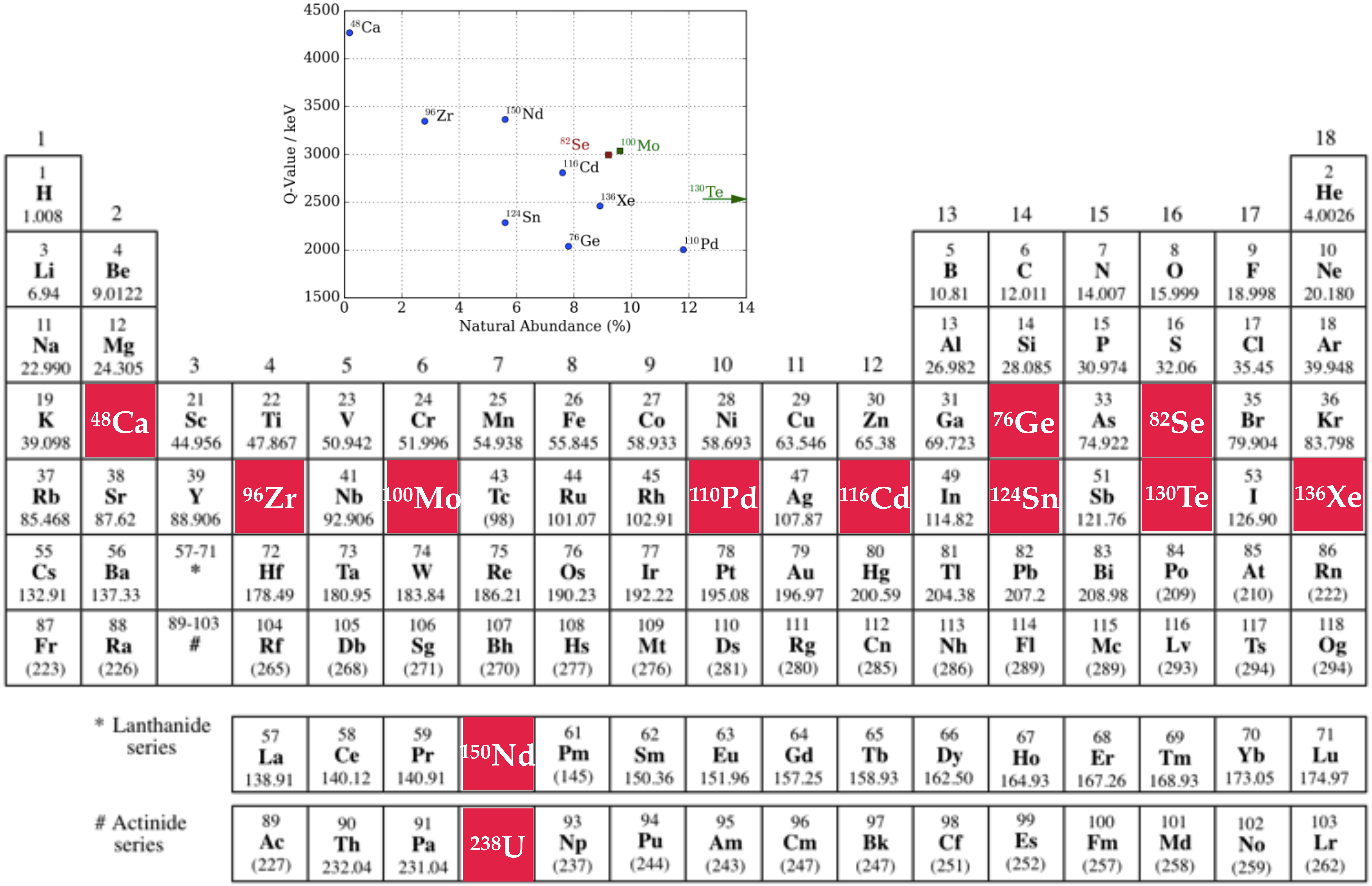


SENSITIVITY OF NEXT GENERATION EXPERIMENTS

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



Only a few elements work



Even less good for detectors

- Best candidates

  - ^{76}**Ge**: excellent because of technology (semiconductor), excellent detectors, good nuclear physics, expensive

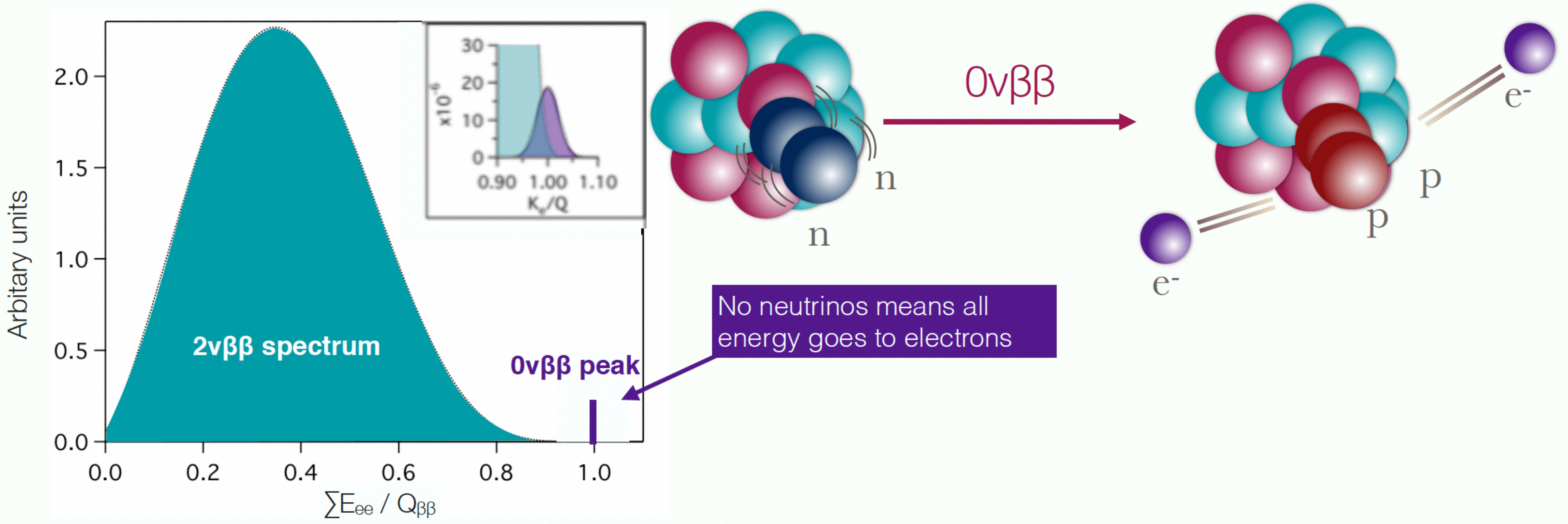
  - ^{136}**Xe**: not as good technologically, cheap, excellent nuclear physics, usable dissolved in scintillators and in liquid phase

  - ^{100}**Mo**: very good, difficult, high electrons energy

  - ^{130}**Te**: abundant, very good

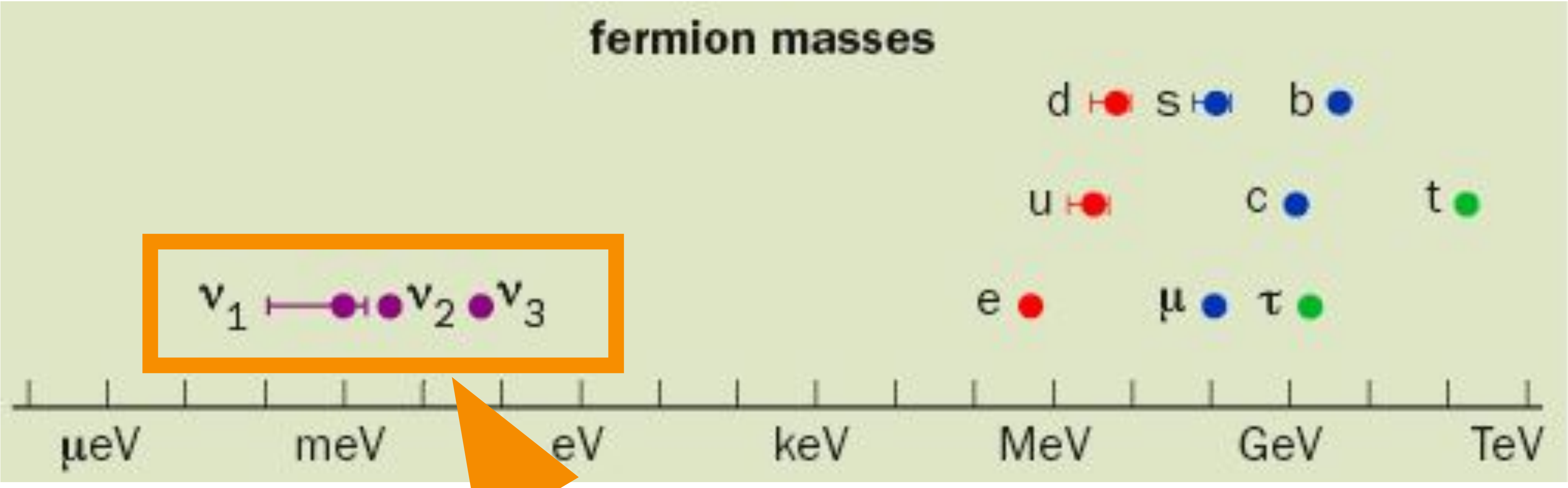
- Globally, none is perfect.
  - Many experiments around the world using all these targets
  - Three key experiments in Italy, at Laboratori Nazionali del Gran Sasso (INFN)

Experimental technique: search for monochromatic events



Sum of the **2 electron energies**, as fraction of ββ decay energy

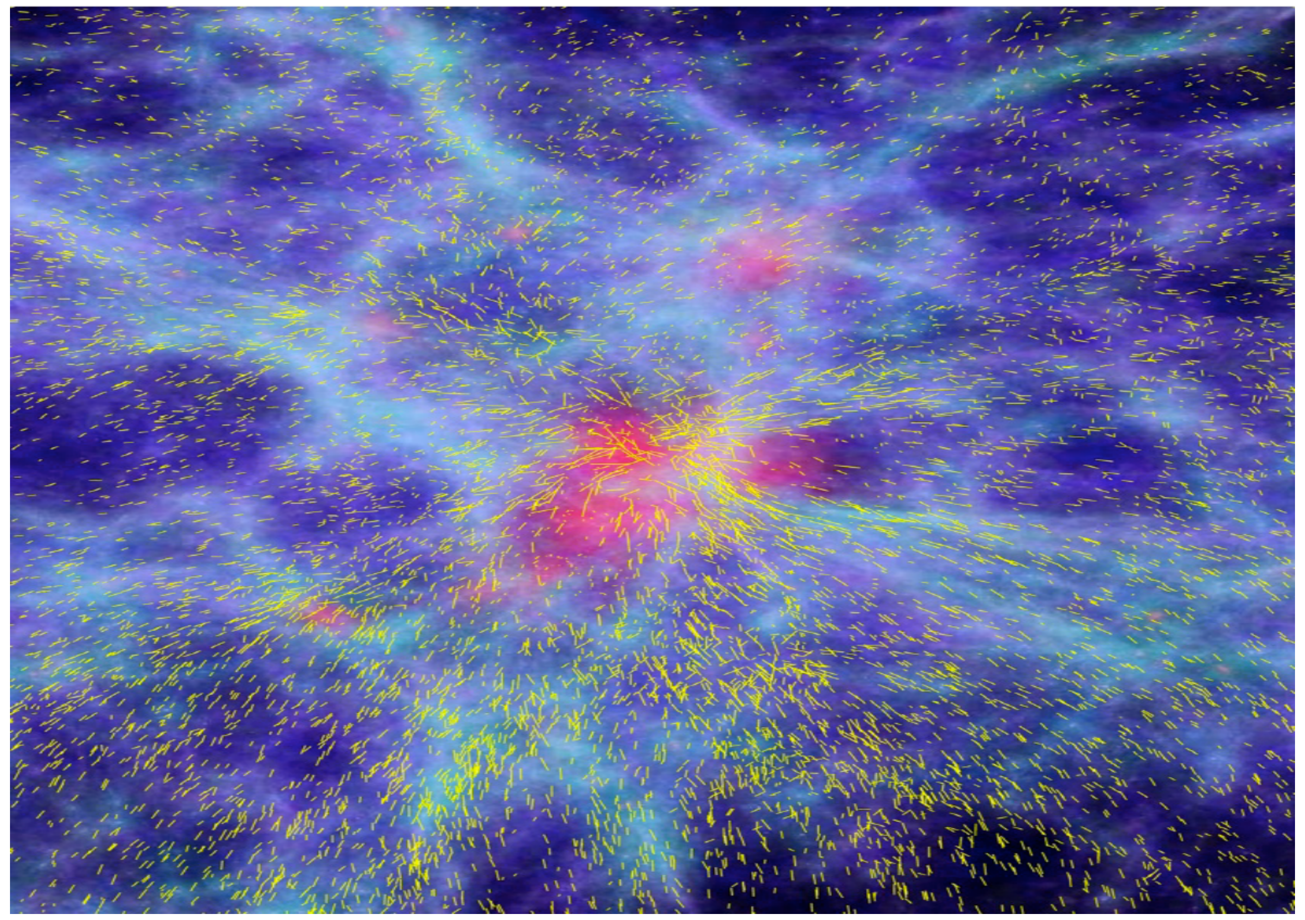
Why mass is important: three ways, three "masses" !



NEUTRINOS
ARE DIFFERENT ?

GRAVITY

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

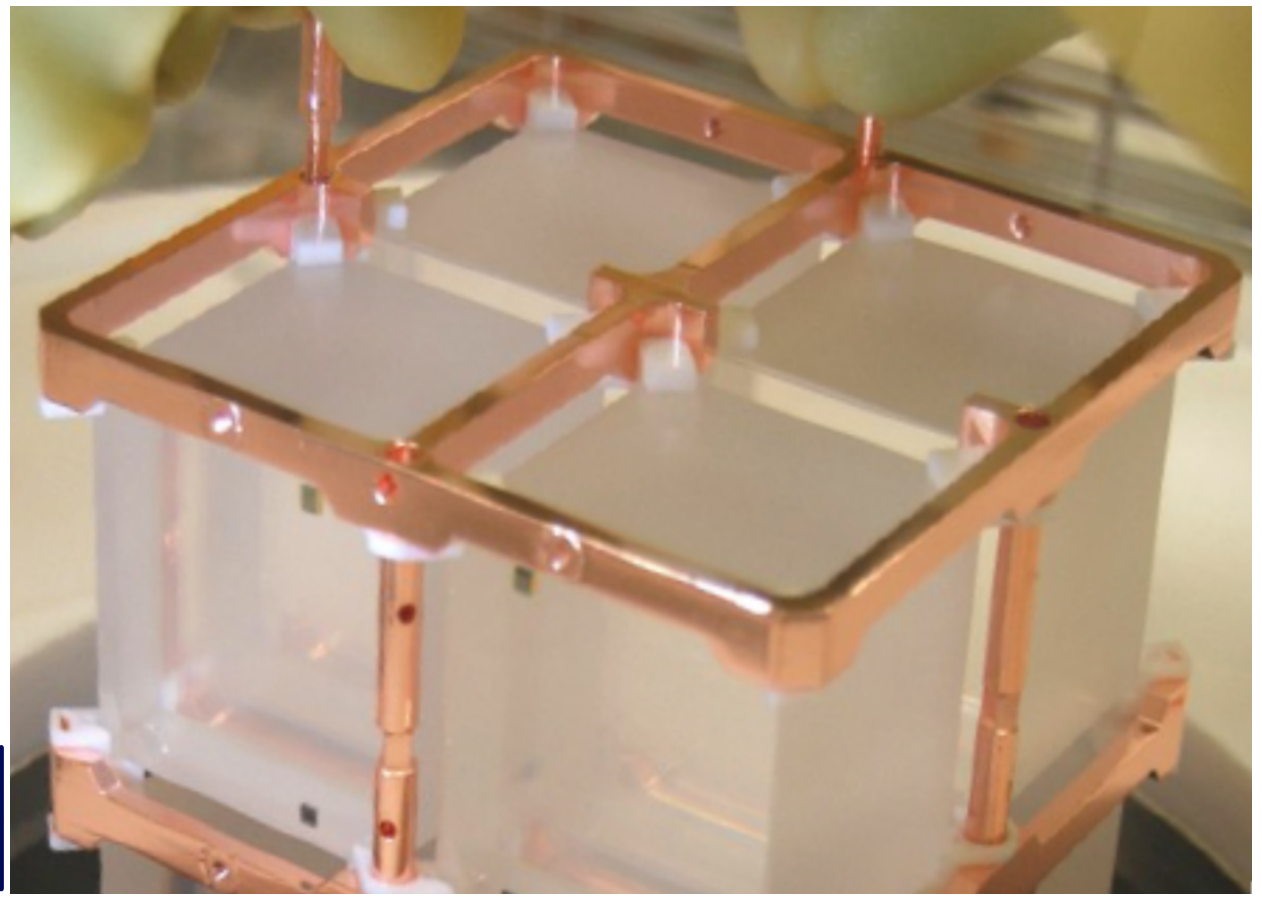


β **DECAY KINEMATICS**

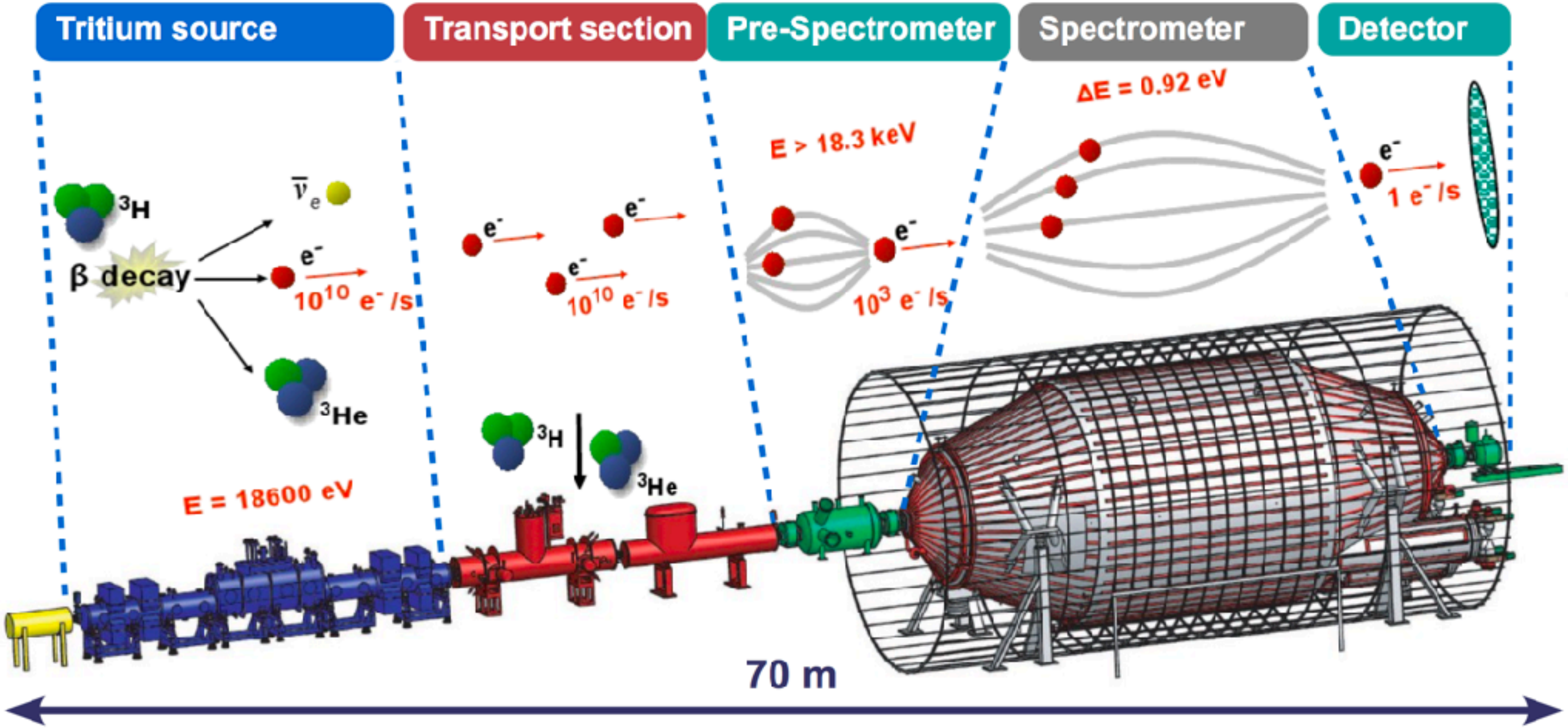
$$m_\beta = \sqrt{|U_{e1}|^2\, m_1^2 + |U_{e2}|^2\, m_2^2 + |U_{e3}|^2\, m_3^2}$$

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 directly to lepton sector

Thank you