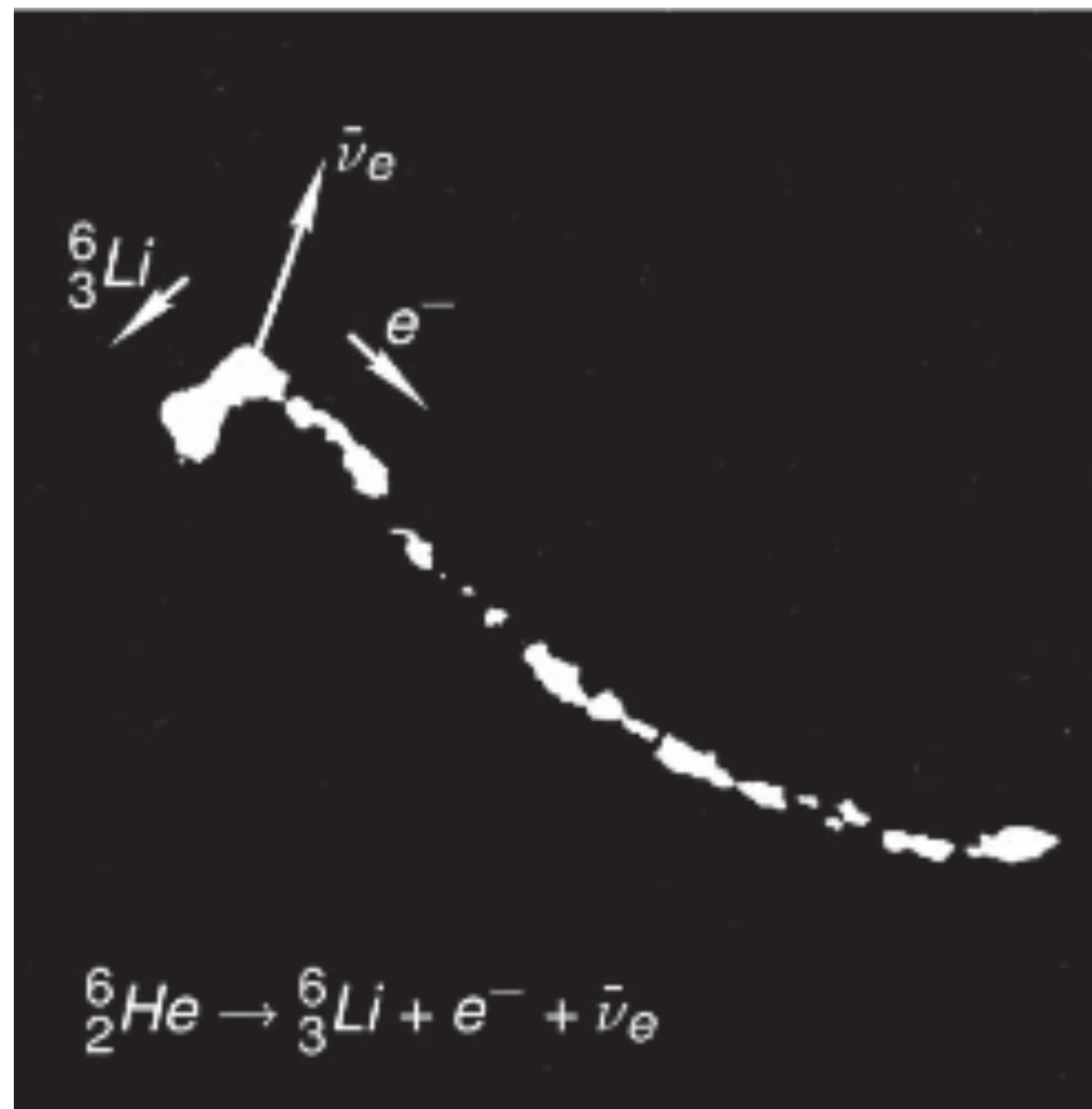


First cloud chamber image of β decay

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



Overview of neutrino experiments

Hands-On 2025 Summer School

LNGS, Sep. 10th, 2025

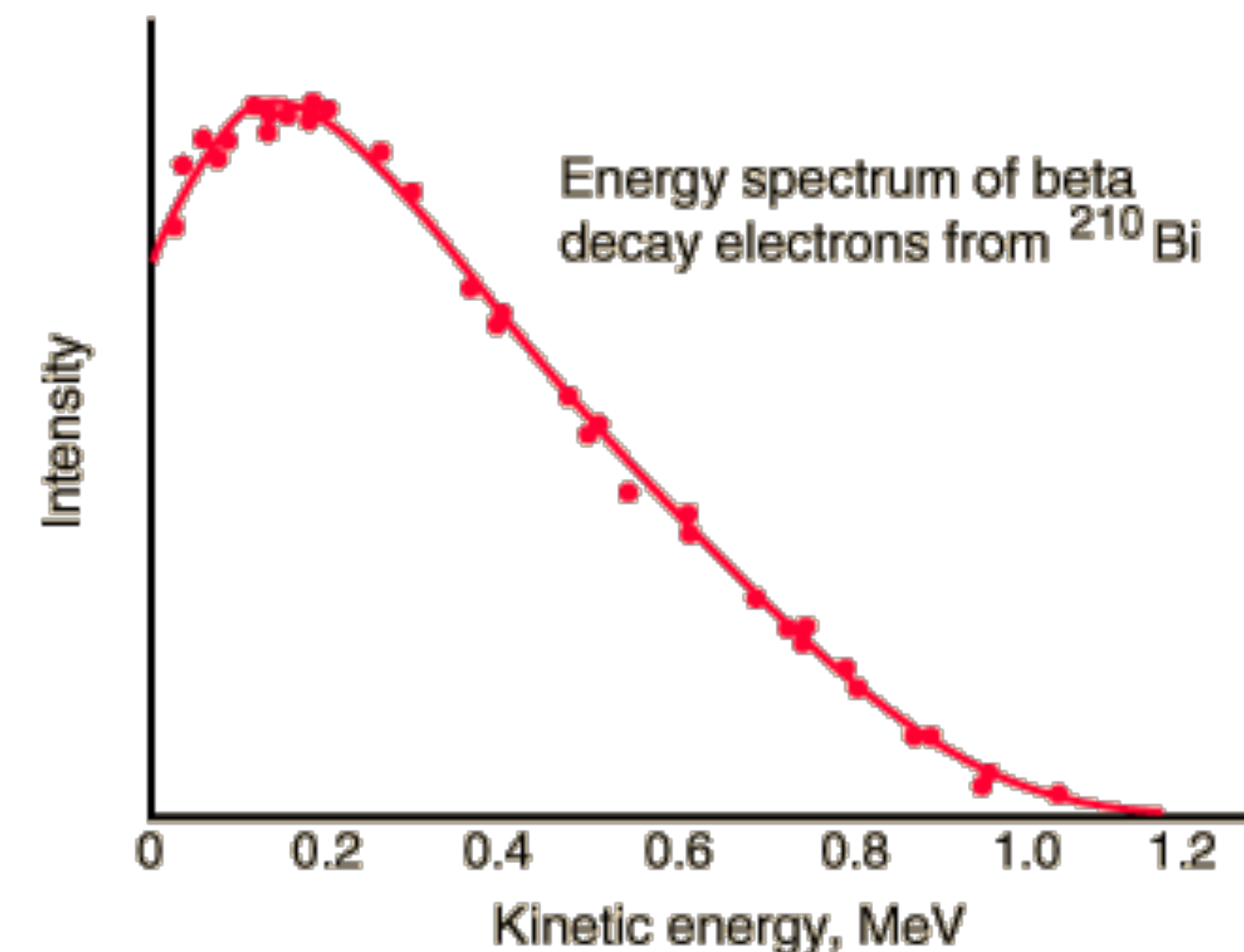
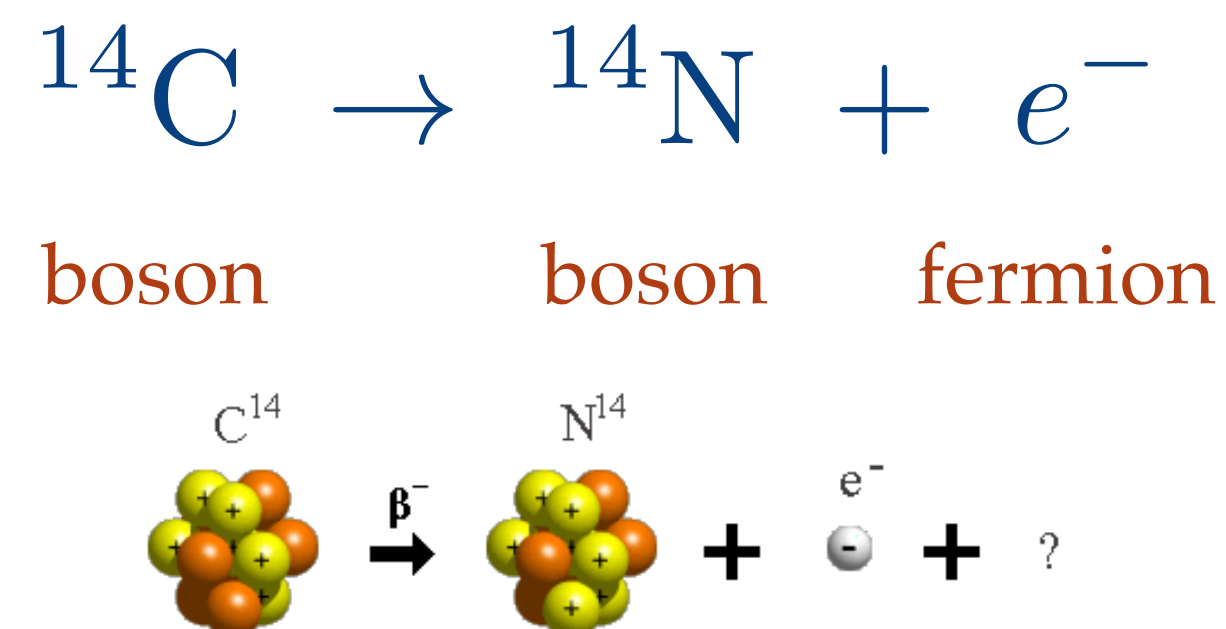
Marco Pallavicini

Università di Genova and INFN

- **Quick review of relevant neutrino physics**
 - See F. Vissani's lecture.
- **Experimental techniques**
 - Radiochemistry
 - Water/Ice (and D₂O) Cherenkov detectors
 - Organic scintillators
 - Sampling calorimeters
 - LAr
 - Accelerator experiments
- **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

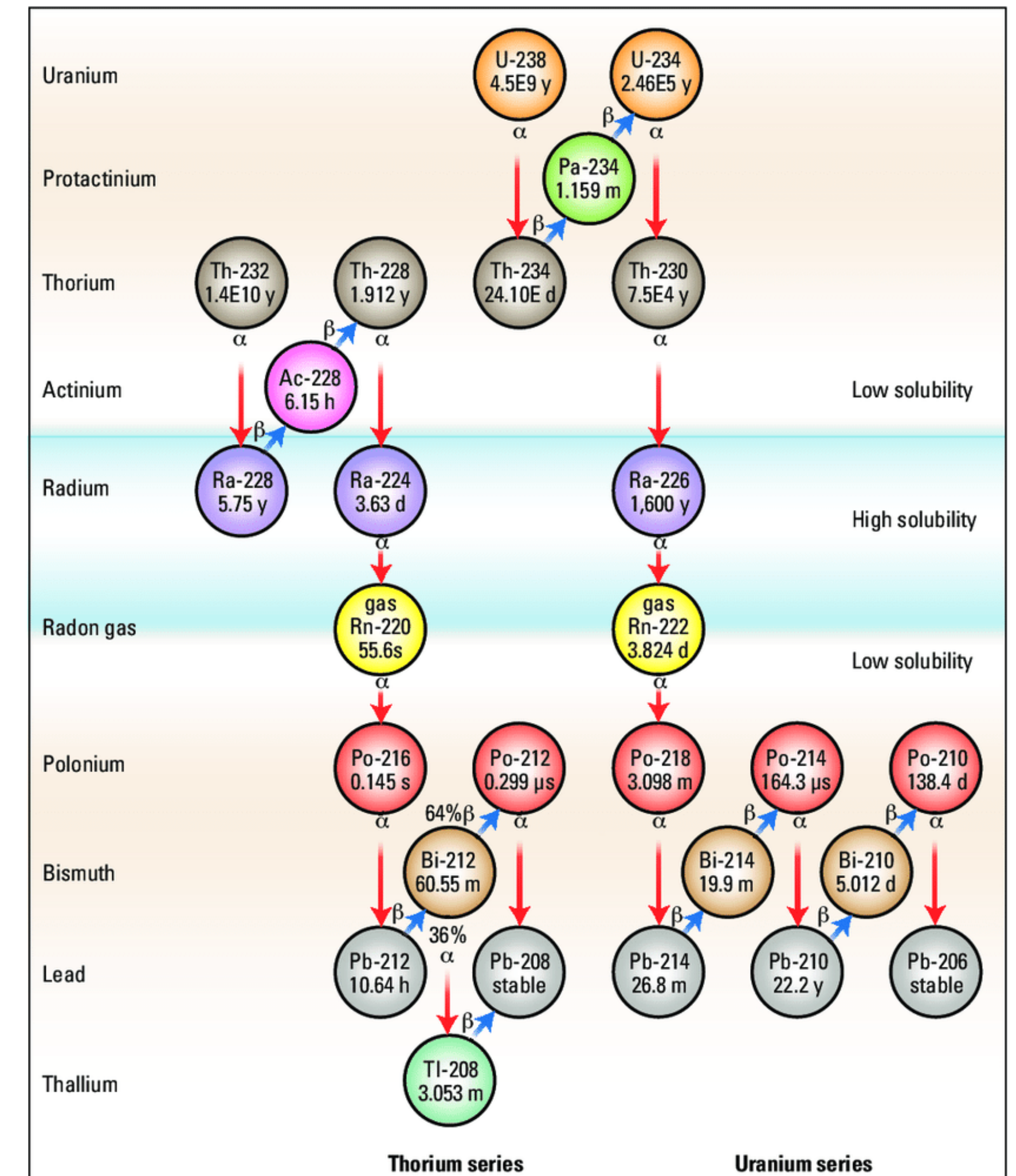
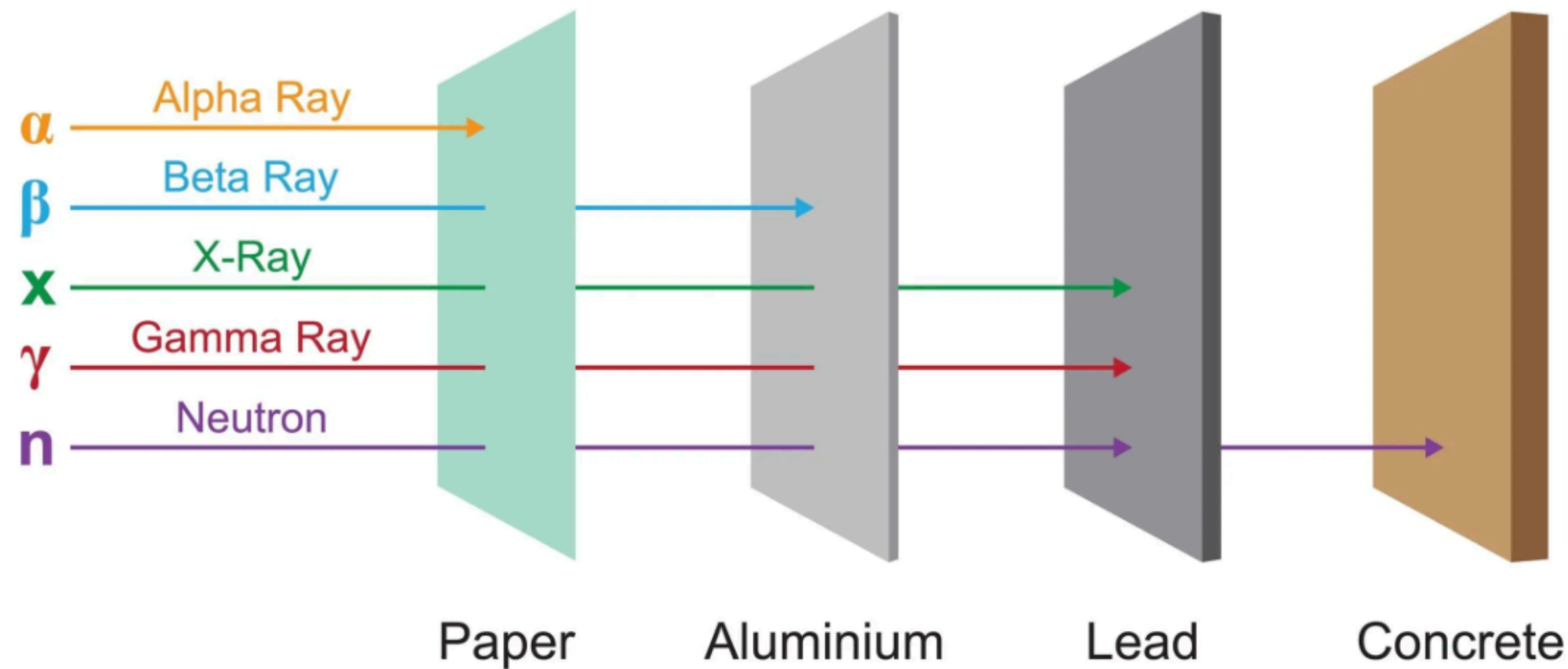
- The list **exceeds** what may be discussed thoroughly in only 2 **hours**.
- Therefore:
 - I assume you are somewhat familiar with basic neutrino physics and the basics of the Standard Model.
 - I will focus on key points or on some points often mis-understood
 - **I will fly quickly over some of the 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
- **DISCLAIMER**
 - I mention 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 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^-



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

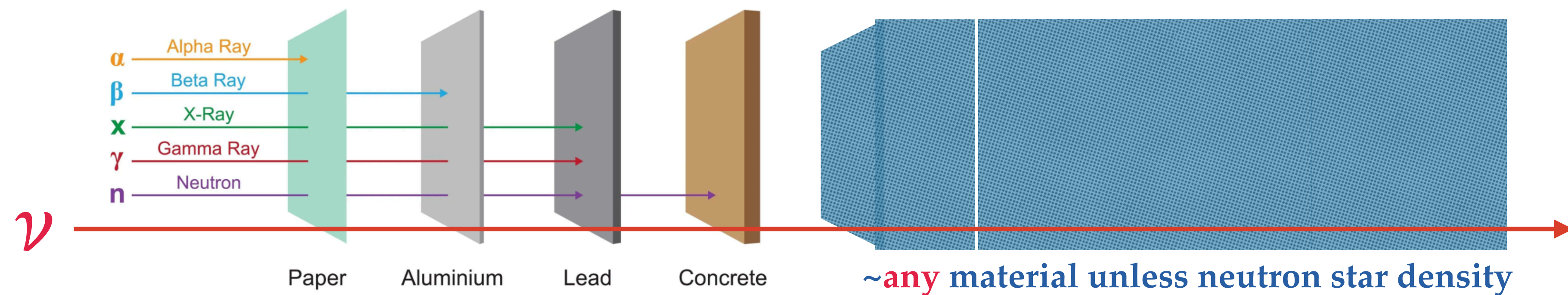


Fermi theory

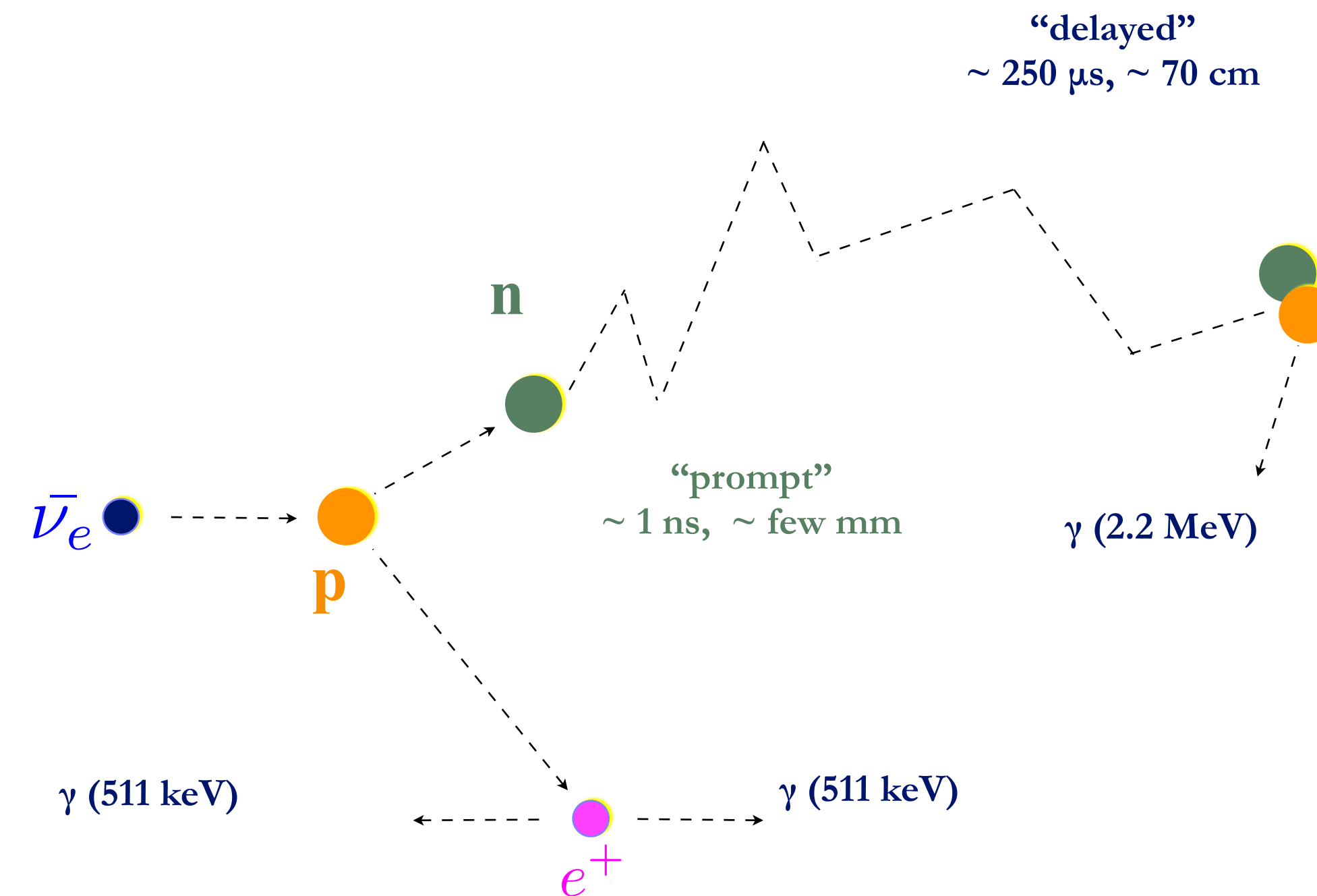
- Fermi theory is a blessing which gives the “desperate remedy” a convincing theoretical framework
 - But it almost killed neutrino physics at its infancy
 - Bethe and others (1934) compute the neutrino-matter cross sections and the result is despairing
 - $\sim 10^{-42} - 10^{-44} \text{ cm}^2 @ 1 \text{ MeV}$

MEAN FREE PATH IN WATER

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



- Historically and physically, is a key process for neutrino physics still today (e.g. JUNO)
 - “The golden channel” for anti-neutrino detection at low energy
 - Large cross section, clean signature of final state
- First detection by Reines and Cowan (1956) was done using this technique



Prompt event

Visible in Water ($E_p > \sim 3$ MeV) or Liquid Scintillators

First detection of (anti)-neutrinos (I)

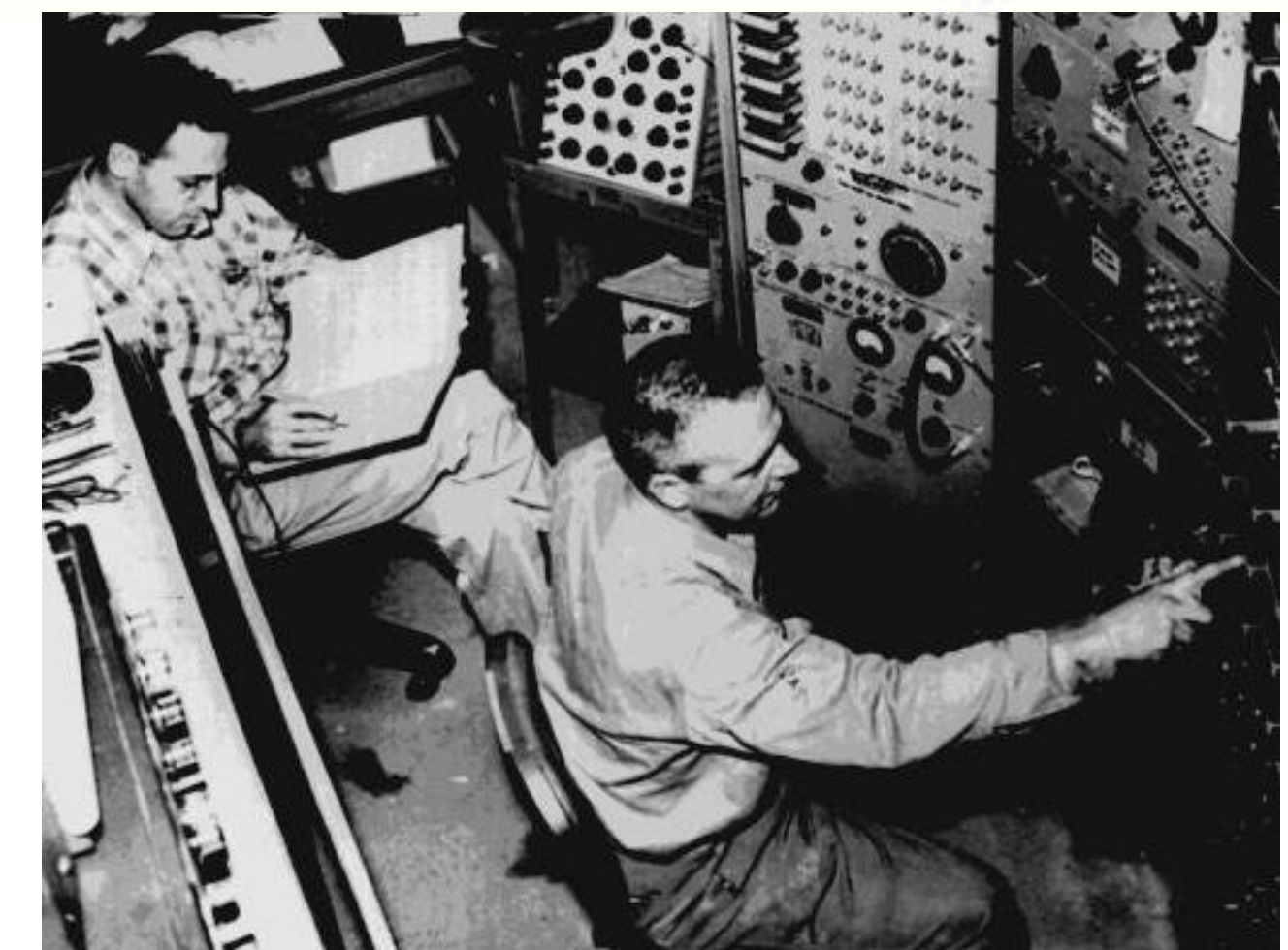
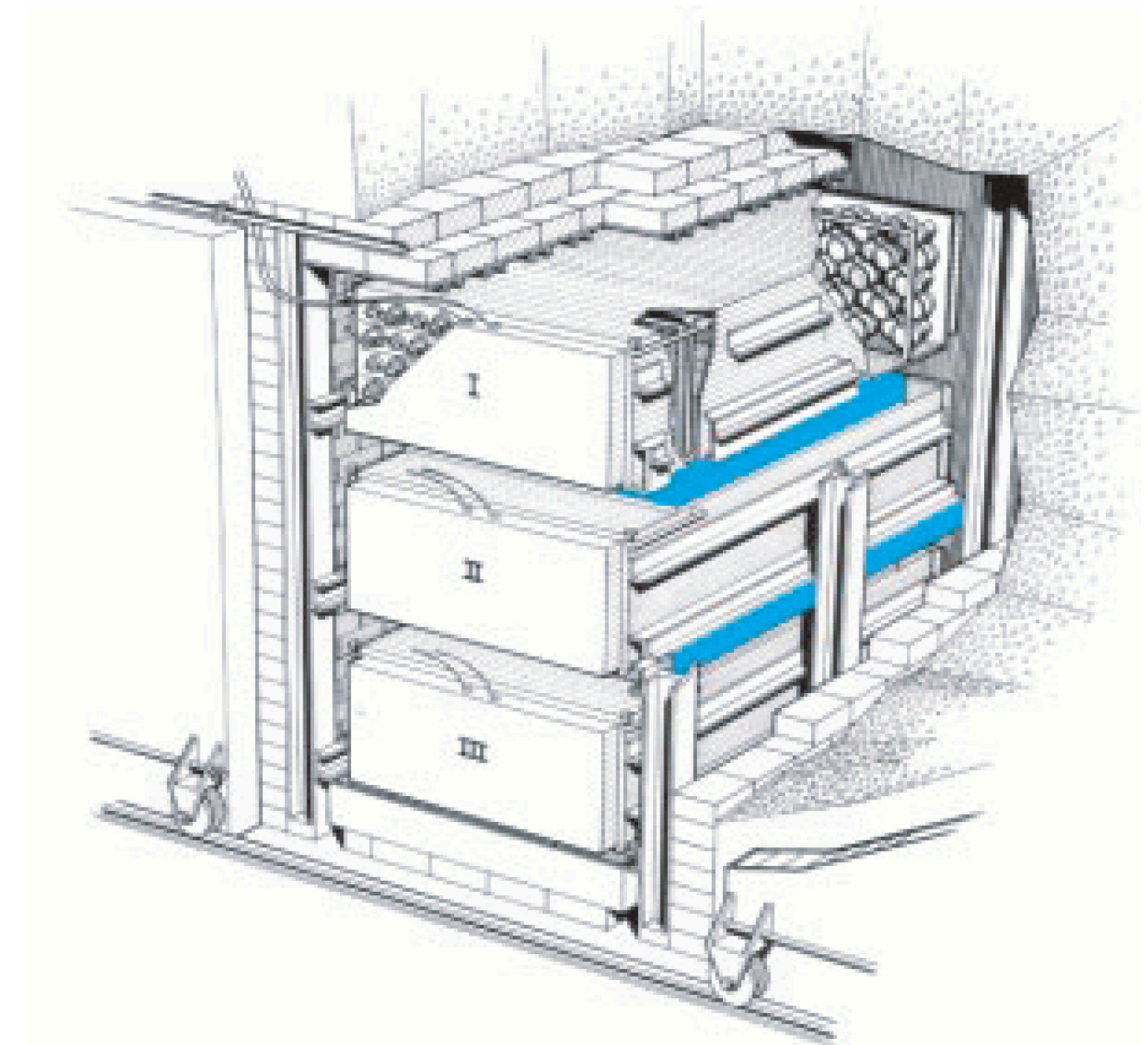
- Key point: ν -matter cross sections are (always) small
 - To detect some ν s you need a **huge integrated luminosity**, which is obtained with large **detector masses**, very large ν fluxes, and **patience**.
- ν detection was at first made possible by the development of **fission reactors**
- **Reines and Cowan, 1956** (after several attempts, including the “idea” to use atomic bombs explosions!)
- Each U fission yields 200 MeV on average, and **6 ν_e**
 - Flux: $\sim 2 \cdot 10^{20} \text{ s}^{-1} \text{ GW}^{-1}$, isotropic, $\langle E_\nu \rangle \approx 0.5 \text{ MeV}$
 - About $\sim 4 \cdot 10^{12} \text{ s}^{-1} \text{ cm}^{-2}$ for 1 GW reactor at **20 m from the core**
 - For comparison **solar neutrinos: $\sim 6.5 \cdot 10^{10} \text{ s}^{-1} \text{ cm}^{-2}$ 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 court.”*
- **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)

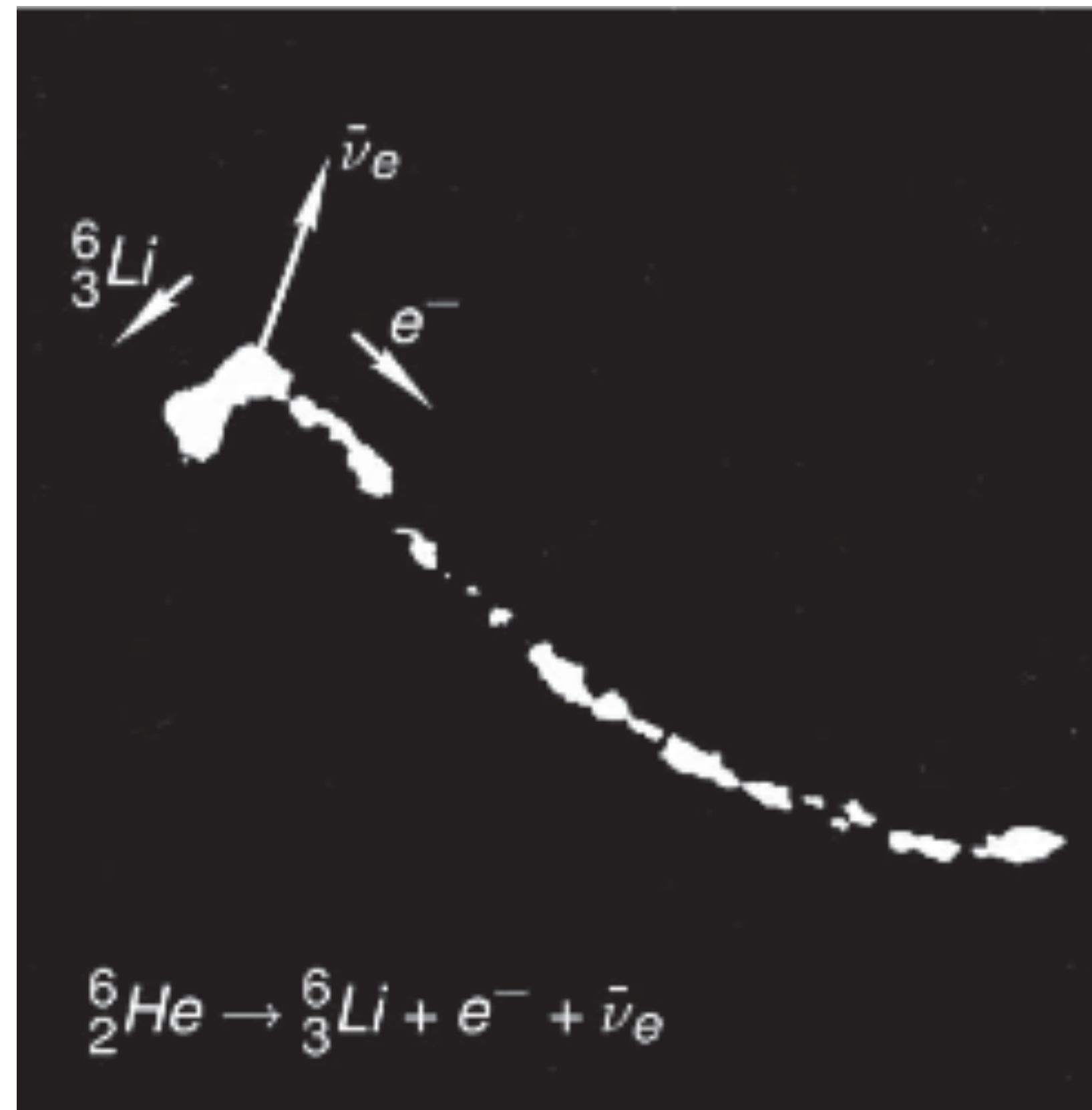
- Conclusive result at Savannah River in 1956
 - Two plastic tanks filled with water (blue)
 - $\Rightarrow \nu$ target (protons)
 - Cadmium dissolved in water
 - $\Rightarrow$ Cd has a **huge neutron capture cross section** and emits high energy γ
 - Between the water tanks, 3 large liquid scintillators 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 γ s $\Rightarrow$ fast coincidence in tanks I and II.
 - A neutron, captured by Cd $\Rightarrow$ again signals in tanks I or II, delayed by 3-10 μ s.
 - No signal in tank III because Tank II is a good shield



- First visual image of a β decay (${}^6\text{He}$ 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

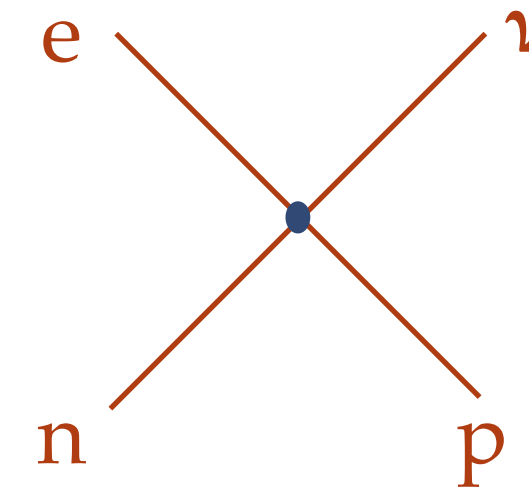
J. Csikai
A. Szalay

C. Budapest, fall 1956



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

$$H_W = \frac{G_F}{\sqrt{2}} \hat{j}_\mu^\dagger \hat{j}^\mu$$



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**.

- 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

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

$$\tau = \frac{1}{\Gamma} = \frac{G_F^2 m_\mu^5}{192 \pi^3} \quad \mu \rightarrow \begin{matrix} e \\ \nu_\mu \\ \nu_e \end{matrix} \quad \tau = \frac{1}{\Gamma} = \frac{G_F^2 m_\mu^5}{192 \pi^3} \left[1 - \frac{\alpha}{2\pi} \left(\pi^2 - \frac{25}{4} \right) \right] \quad \text{WITH LEADING QED CORRECTIONS}$$

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

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

$$K^+ \rightarrow \pi^+ \pi^0 \quad \text{BR } 20.7\%$$

- The **V-A structure** of weak interactions is based on solid experimental evidence

- For example a scalar or pseudo-scalar interaction terms would yield:

$$\frac{\Gamma(\pi^+ \rightarrow e^+ \nu_e)}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu)} = 5.5 \quad \text{WRONG!}$$

- V-A predicts:**

THEORY (tree level)

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

EXPERIMENT PDG 2020

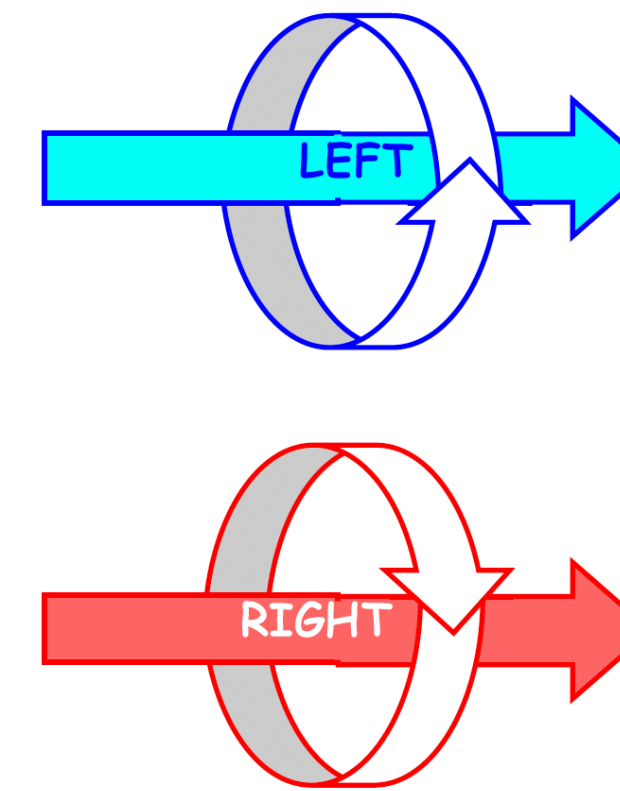
$$\frac{\Gamma(\pi^+ \rightarrow e^+ \nu_e)}{\Gamma(\pi^+ \rightarrow \mu^+ \nu_\mu)} = 1.230 \pm 0.004 \cdot 10^{-4}$$

- 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:
 - $\rho = 0.74977 \pm 0.00012(\text{stat.}) \pm 0.00023(\text{syst.})$
 - $\delta = 0.75049 \pm 0.00021(\text{stat.}) \pm 0.00027(\text{syst.})$

Phys. Rev. D 85, 092013 (2012)

- **NEUTRINOS**
 - Are (always) created left-handed
- (So called) **ANTI-NEUTRINOS**
 - Are (always) created right-handed
- If $m=0$, helicity is conserved. No problem.
- If $m \neq 0$, 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**



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

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

- Universal Fermi Interaction (1949)**

$$\mu^{-} + p \longrightarrow n + \nu \quad 1947 \text{ CONVERSI, PANCINI, PICCIONI}$$

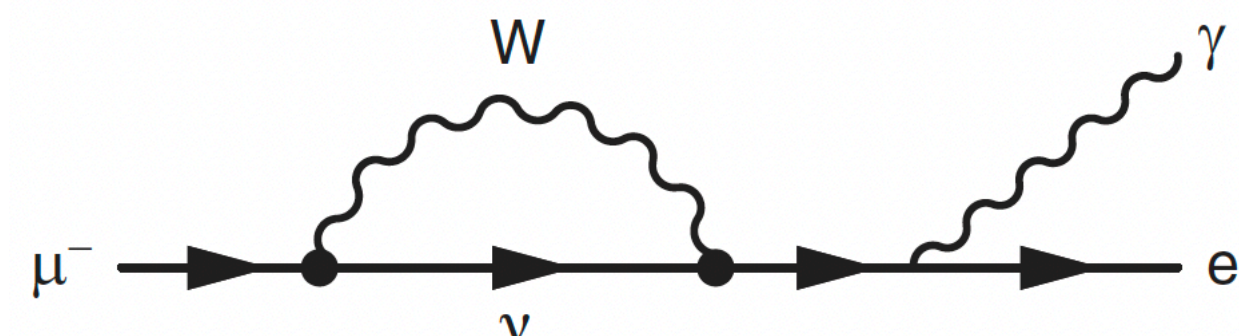
$$\mu \longrightarrow e + \nu + \bar{\nu} \quad 1948 \text{ J. STEINBERGER, PhD THESIS}$$

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

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

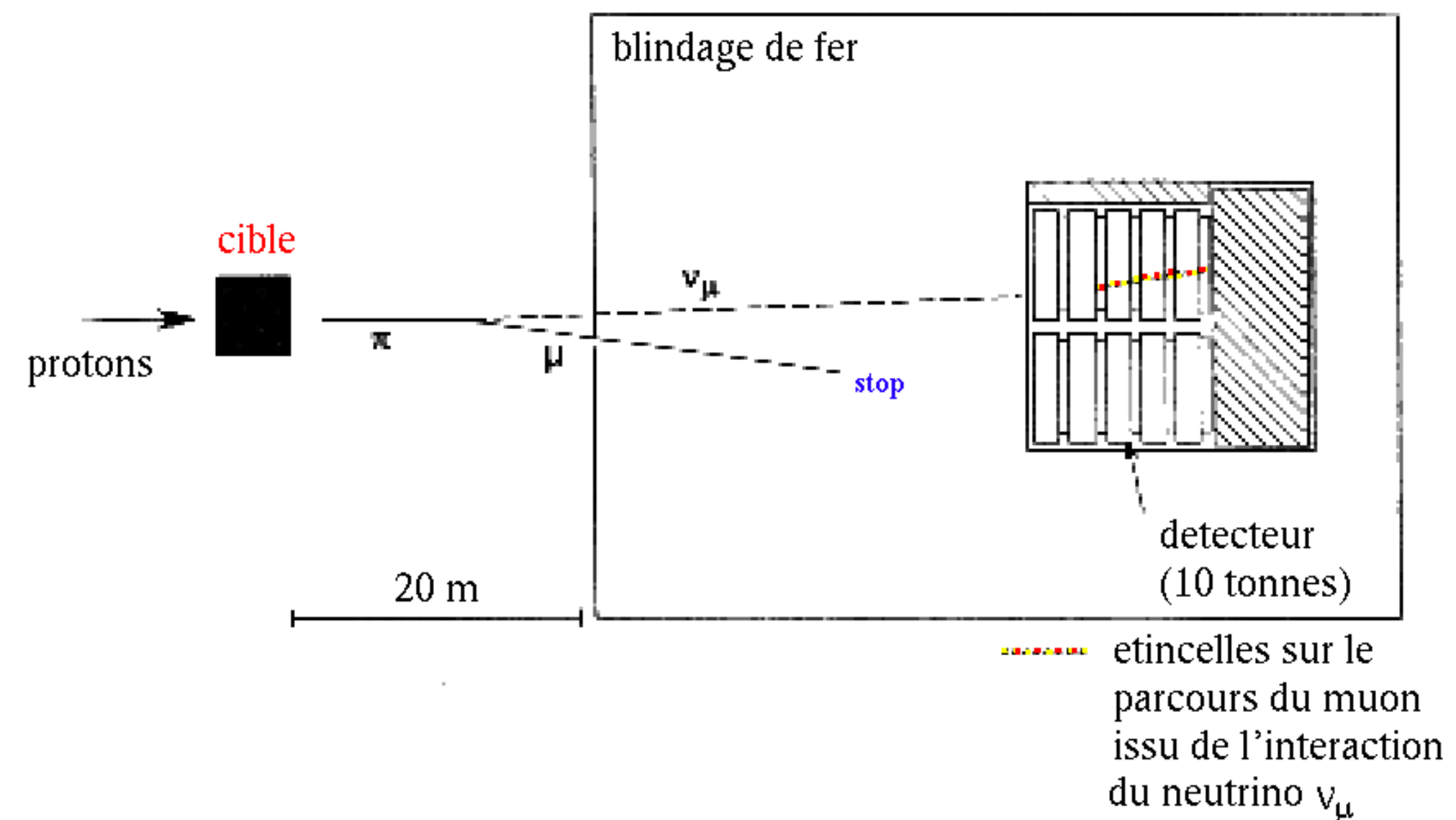


With modern eyes, why this diagram does not work ?



- 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

- 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



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)

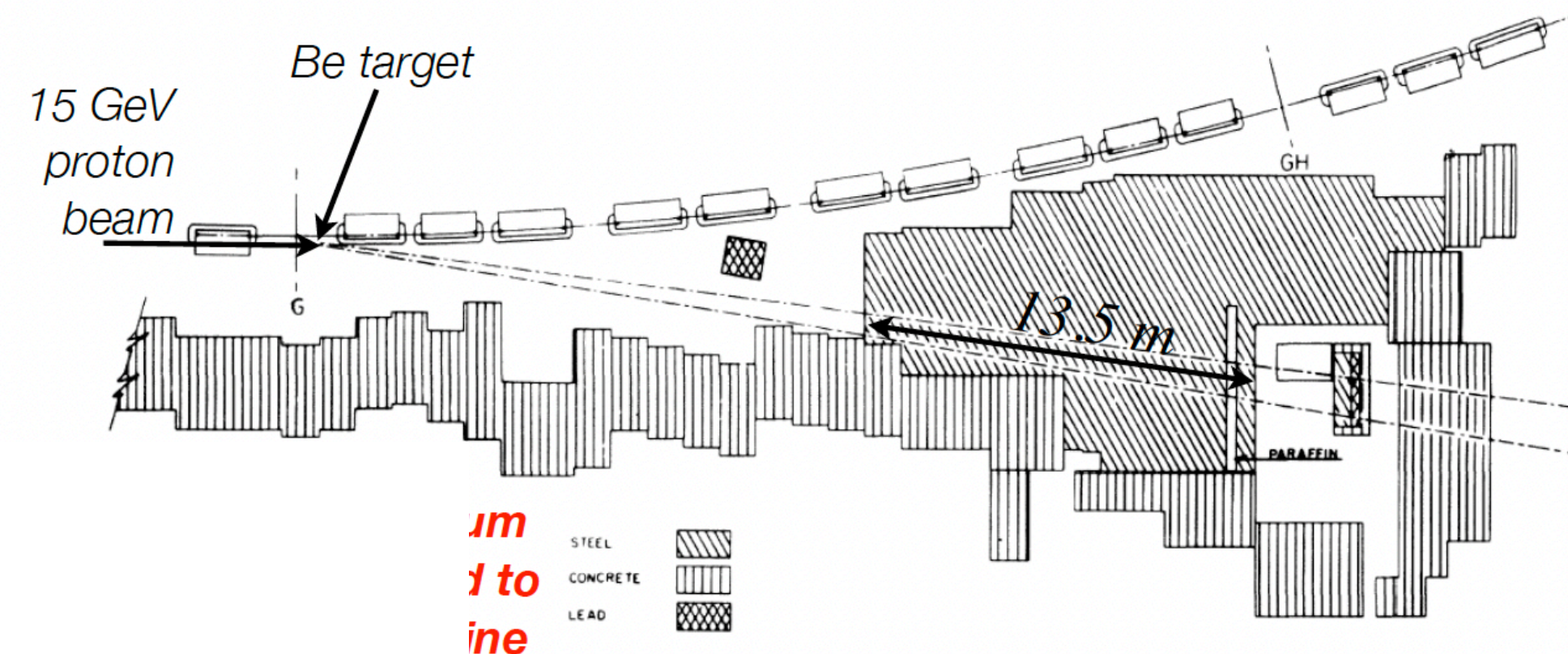


FIG. 1. Plan view of AGS neutrino experiment.

to the detector?

B,C,D vetos
against entering
tracks

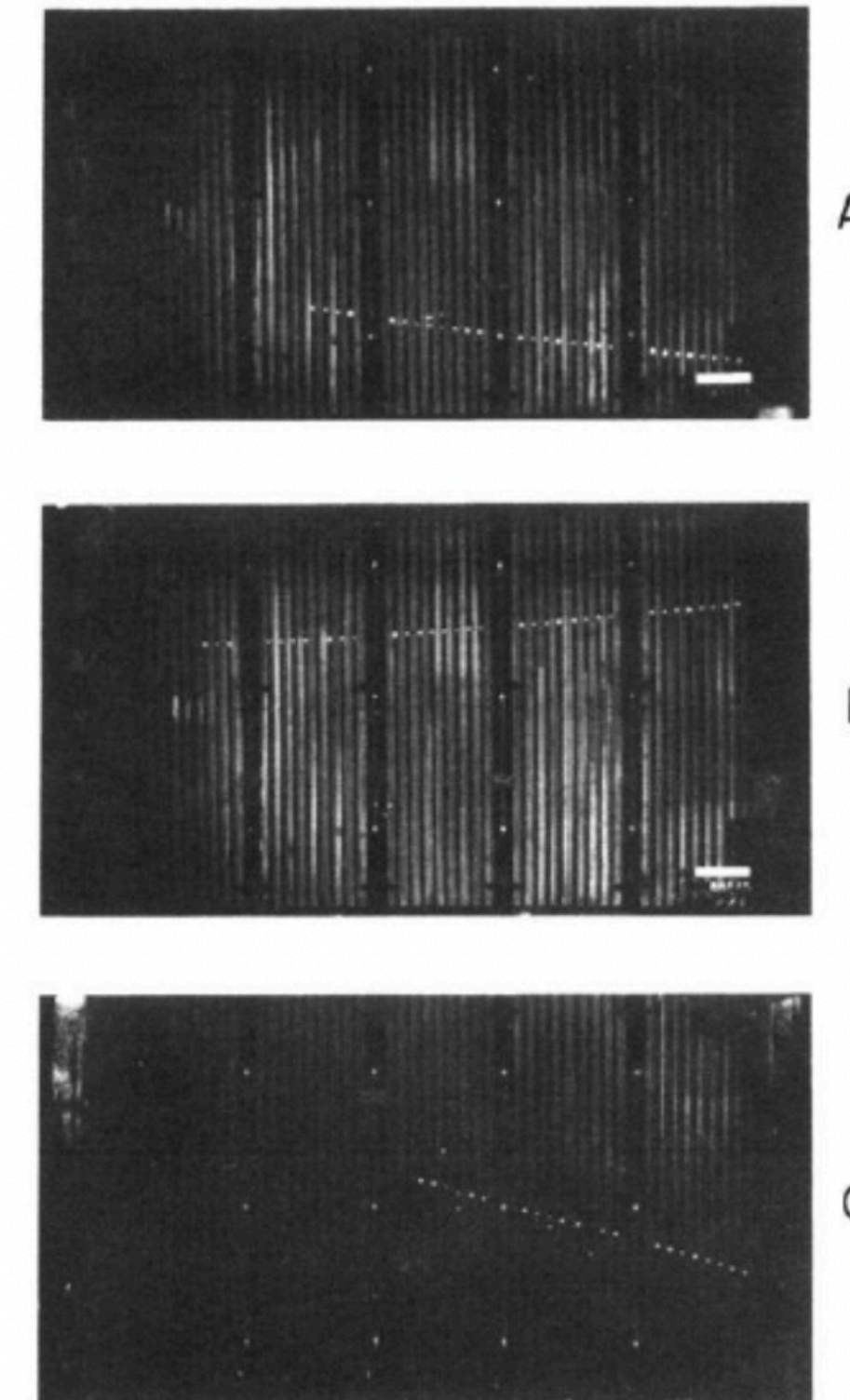
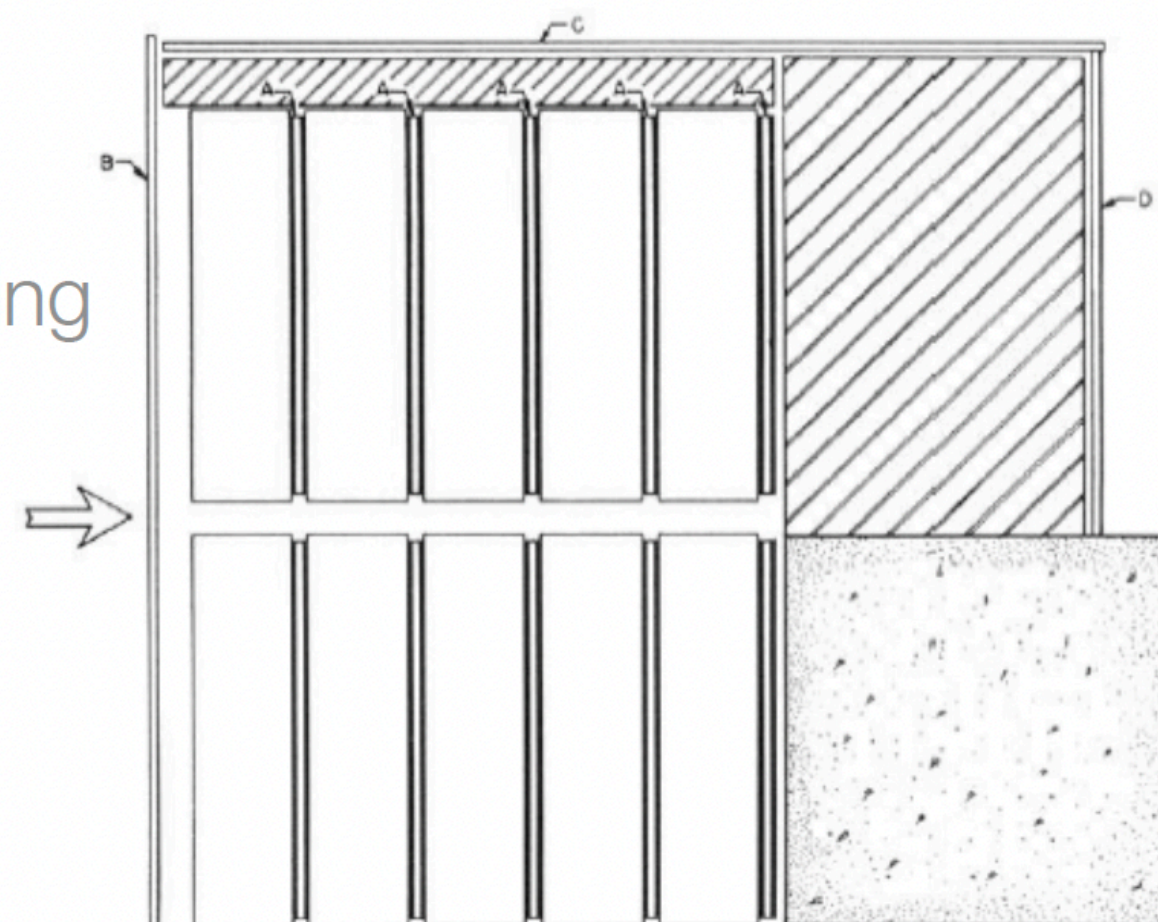
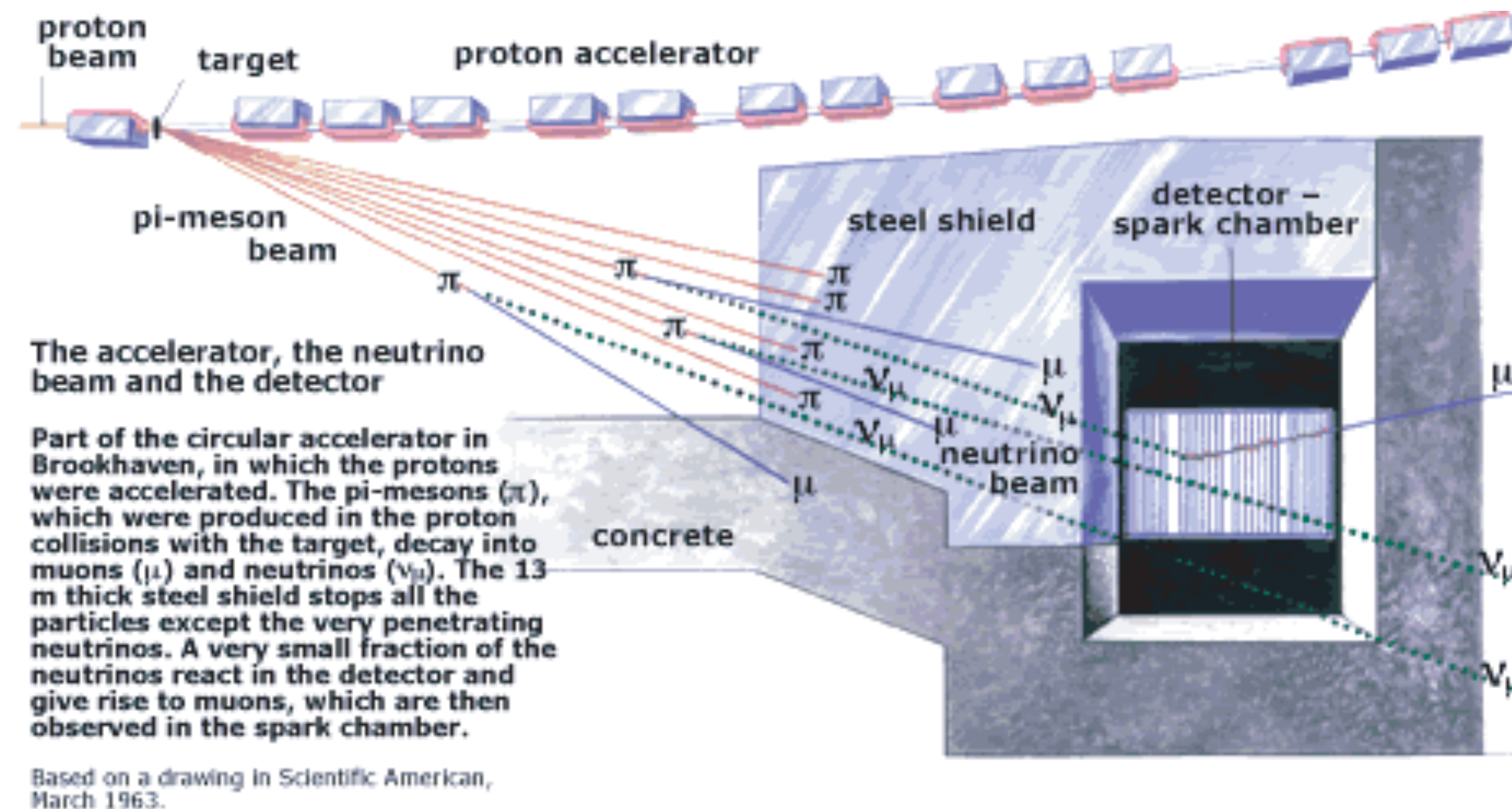


FIG. 5. Single muon events. (A) $p_\mu > 540$ MeV and δ ray indicating direction of motion (neutrino beam incident from left); (B) $p_\mu > 700$ MeV/c; (C) $p_\mu > 440$ with δ ray.



- 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

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

- 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:

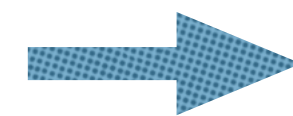
- for $\nu_e e^-$ scattering: $c_V = 1 + \rho g_V$ $c_A = 1 + \rho g_A$
- for $\nu_\ell e^-$ scattering: $c_V = \rho g_V$ $c_A = \rho g_A$

Neutrino - electron interaction

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

$$\frac{d\sigma}{dT'_e} = \frac{2G_F^2 m_e}{\pi} \left[c_L^2 + c_R^2 \left(\frac{E'_\nu}{E_\nu} \right)^2 - c_L c_R \frac{m_e}{E_\nu} \frac{E_\nu - E'_\nu}{E_\nu} \right] \quad T'_e = E'_e - m_e = E'_\nu - E_\nu$$

- 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

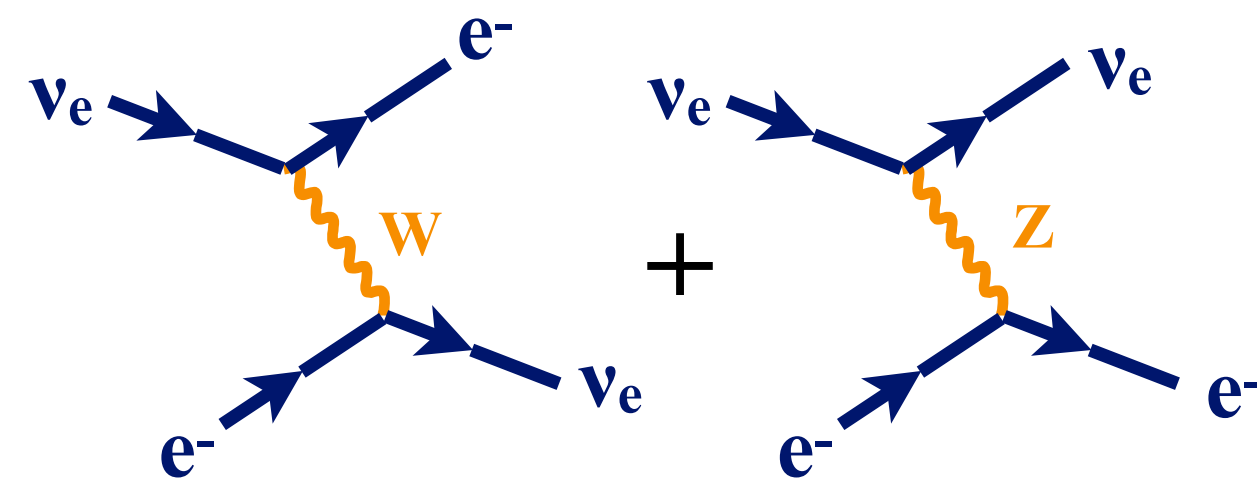
$$\sin^2 \theta_W = 0.2312 \quad \overline{\text{MS}}$$

	c_L	c_R	$\sigma [10^{-44} \text{ cm}^2]$
$\nu_e e^-$	$\frac{1}{2} + \sin^2 \theta_W$	$\sin^2 \theta_W$	$0.95 E_\nu [\text{MeV}]$
$\nu_\mu e^-$	$-\frac{1}{2} + \sin^2 \theta_W$	$\sin^2 \theta_W$	$0.16 E_\nu [\text{MeV}]$
$\bar{\nu}_e e^-$	$\sin^2 \theta_W$	$\frac{1}{2} + \sin^2 \theta_W$	$0.23 E_\nu [\text{MeV}]$
$\bar{\nu}_\mu e^-$	$\sin^2 \theta_W$	$-\frac{1}{2} + \sin^2 \theta_W$	$0.078 E_\nu [\text{MeV}]$

- **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 (or JUNO for solar neutrinos)

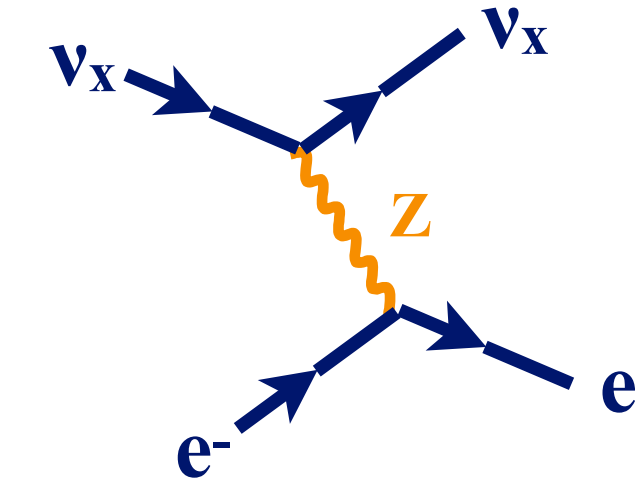
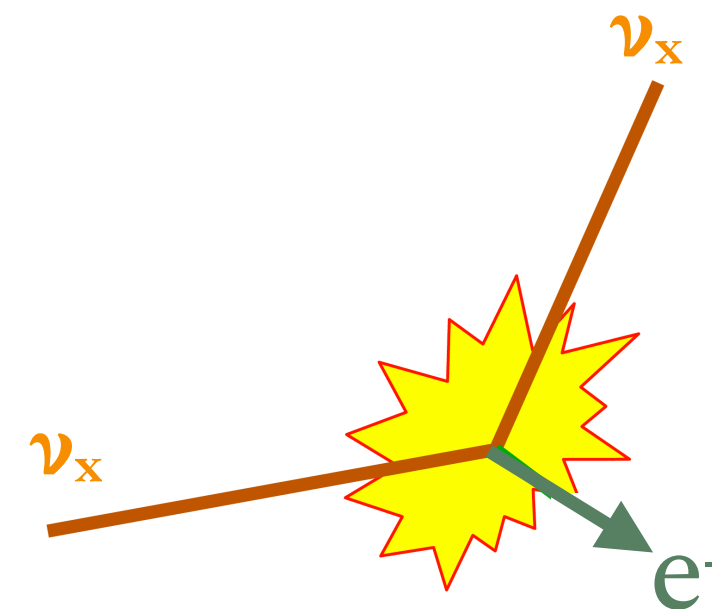
- Elastic scattering on e^- : detects **all** ν flavours, with a **larger cross-section for ν_e**



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

$$9.5 \cdot 10^{-45} \text{ cm}^2 \text{ @ } 1 \text{ MeV}$$

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



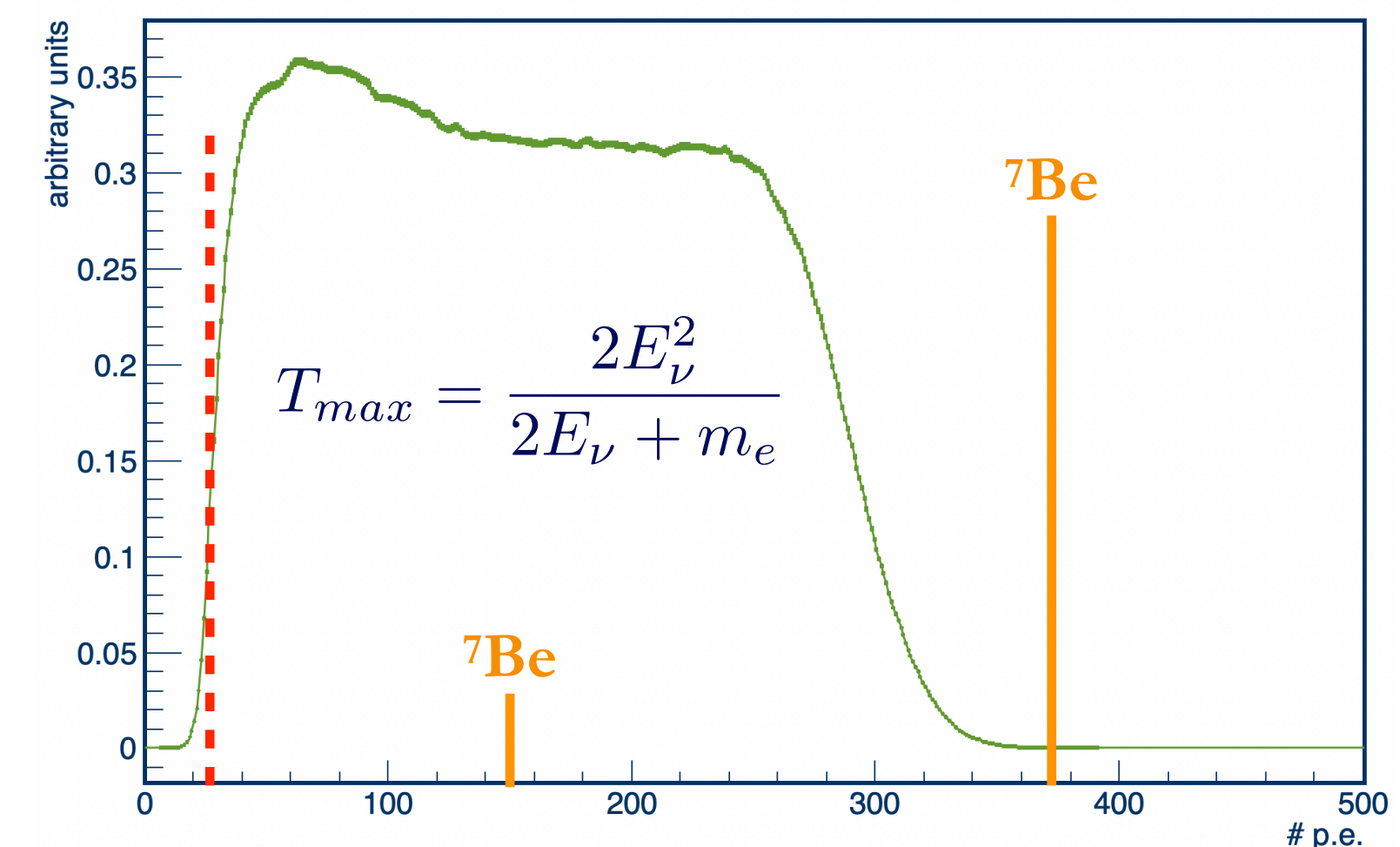
$$\sigma(\nu_x e^-) = \frac{G_F^2 s}{\pi} \left[\left(\frac{1}{2} - \xi \right)^2 + \frac{\xi^2}{3} \right]$$

$$1.6 \cdot 10^{-45} \text{ cm}^2 \text{ @ } 1 \text{ MeV}$$

- 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)

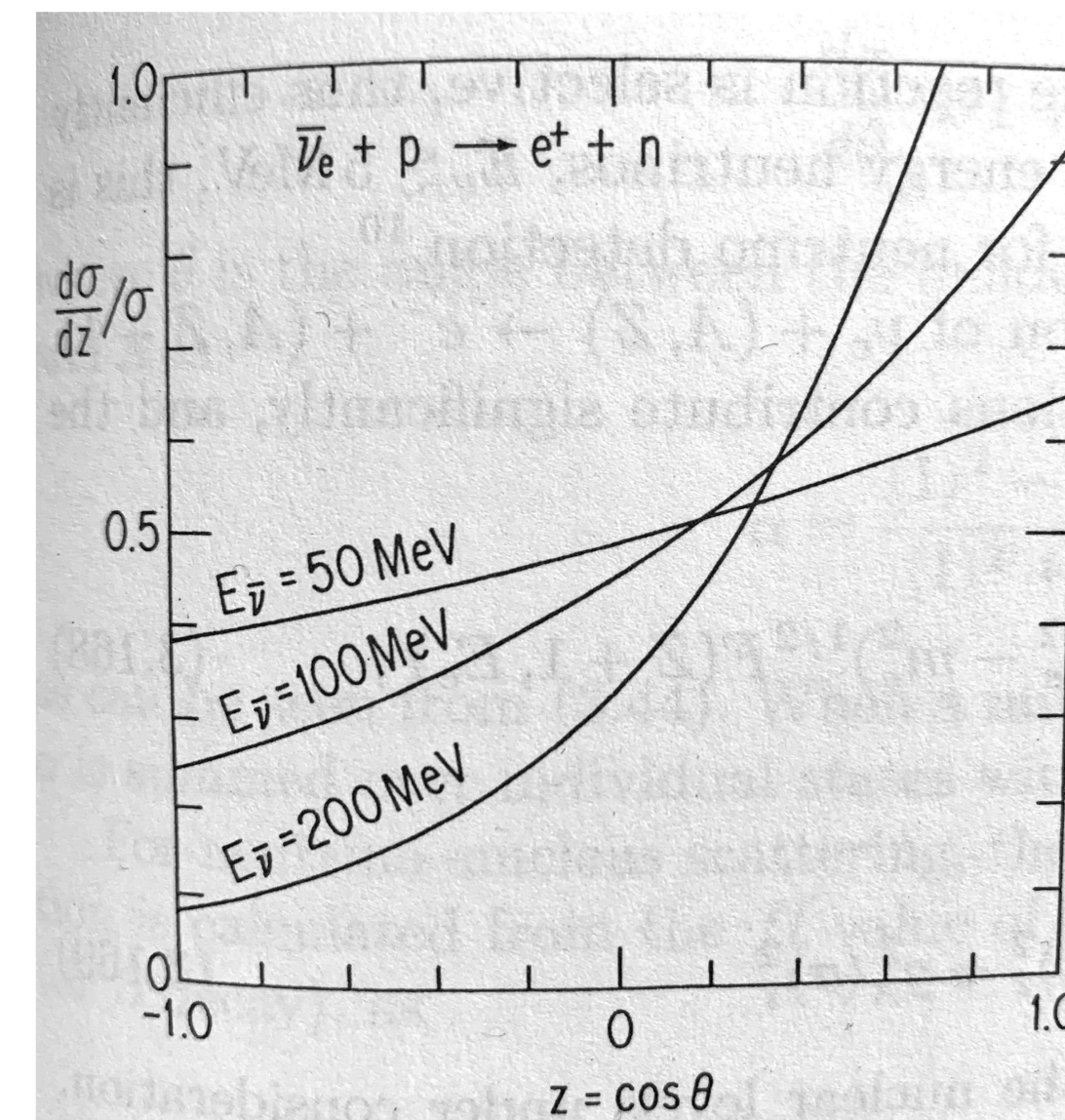
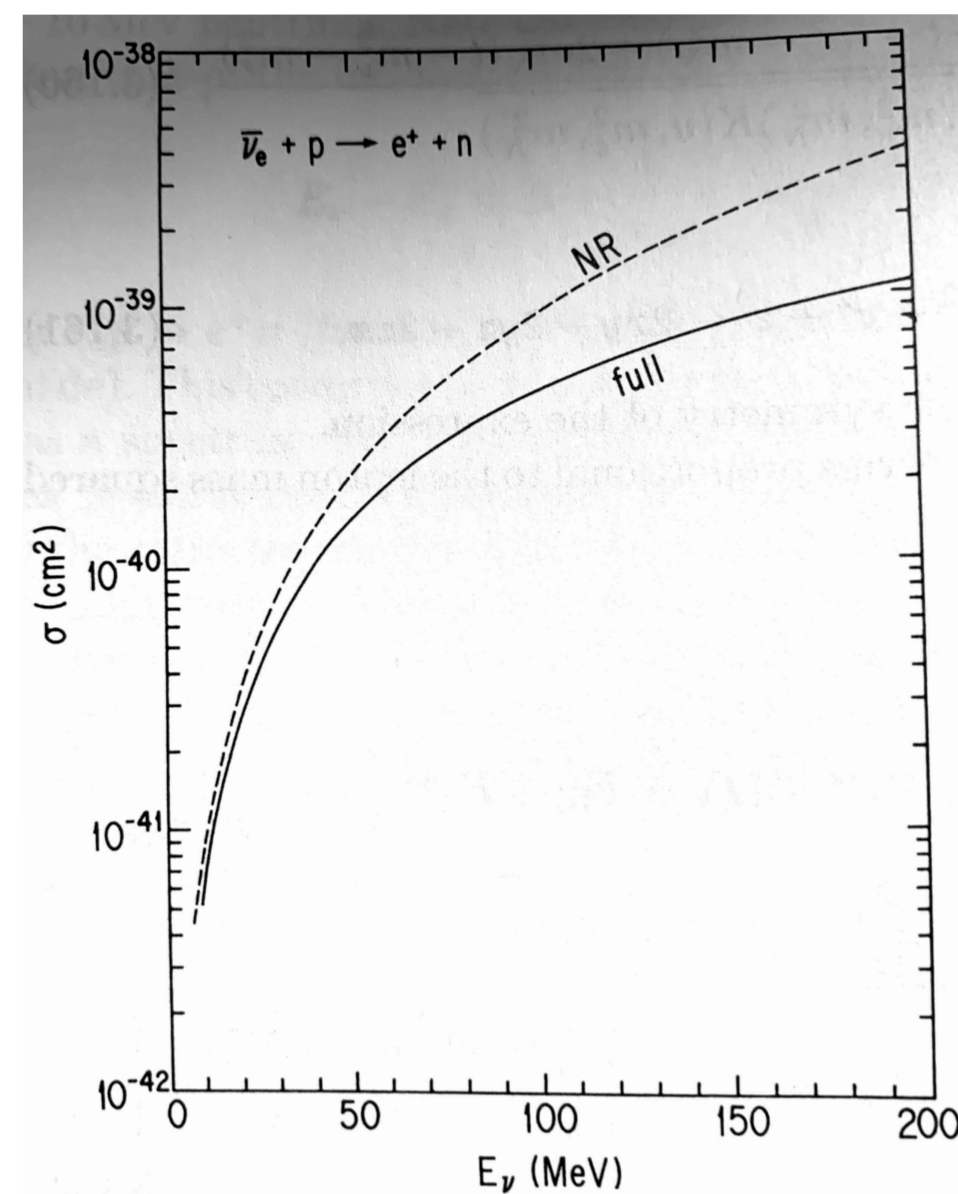
- At low E_ν (≈ 100 MeV), only ν_e are active, being μ and τ too heavy



- At very low E_ν (≈ 30 MeV), the cross section is well reproduced by:

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

- While in the region $E_\nu \sim 30 - 100$ 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....)

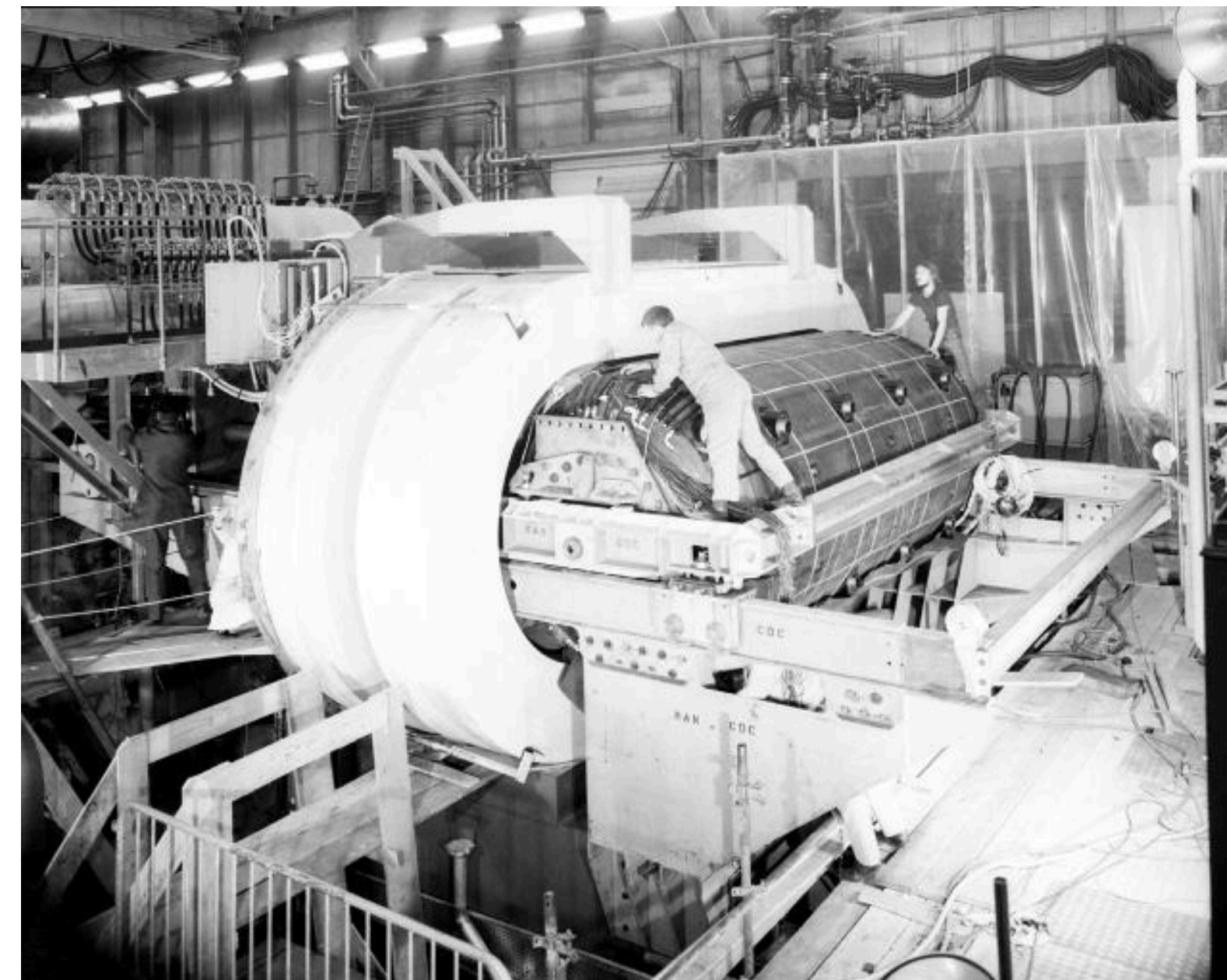
- **Neutral currents must exist**, and their coupling is fixed by theory

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

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

- 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)**

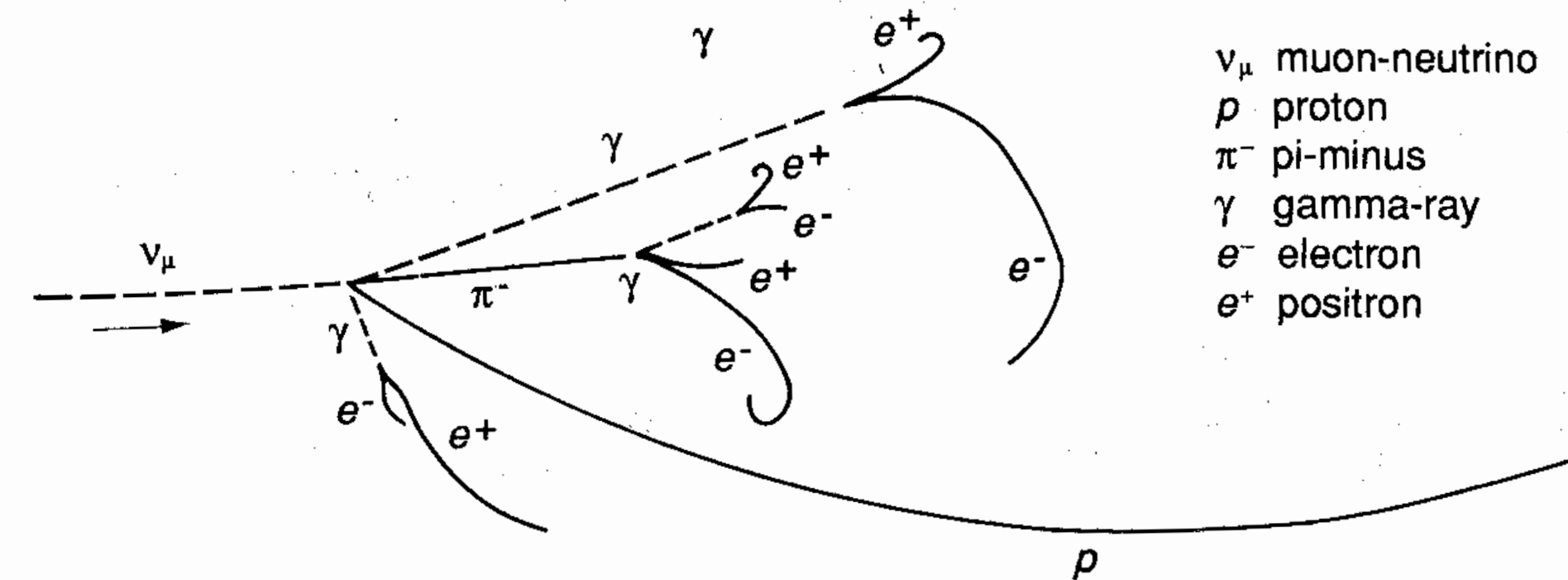
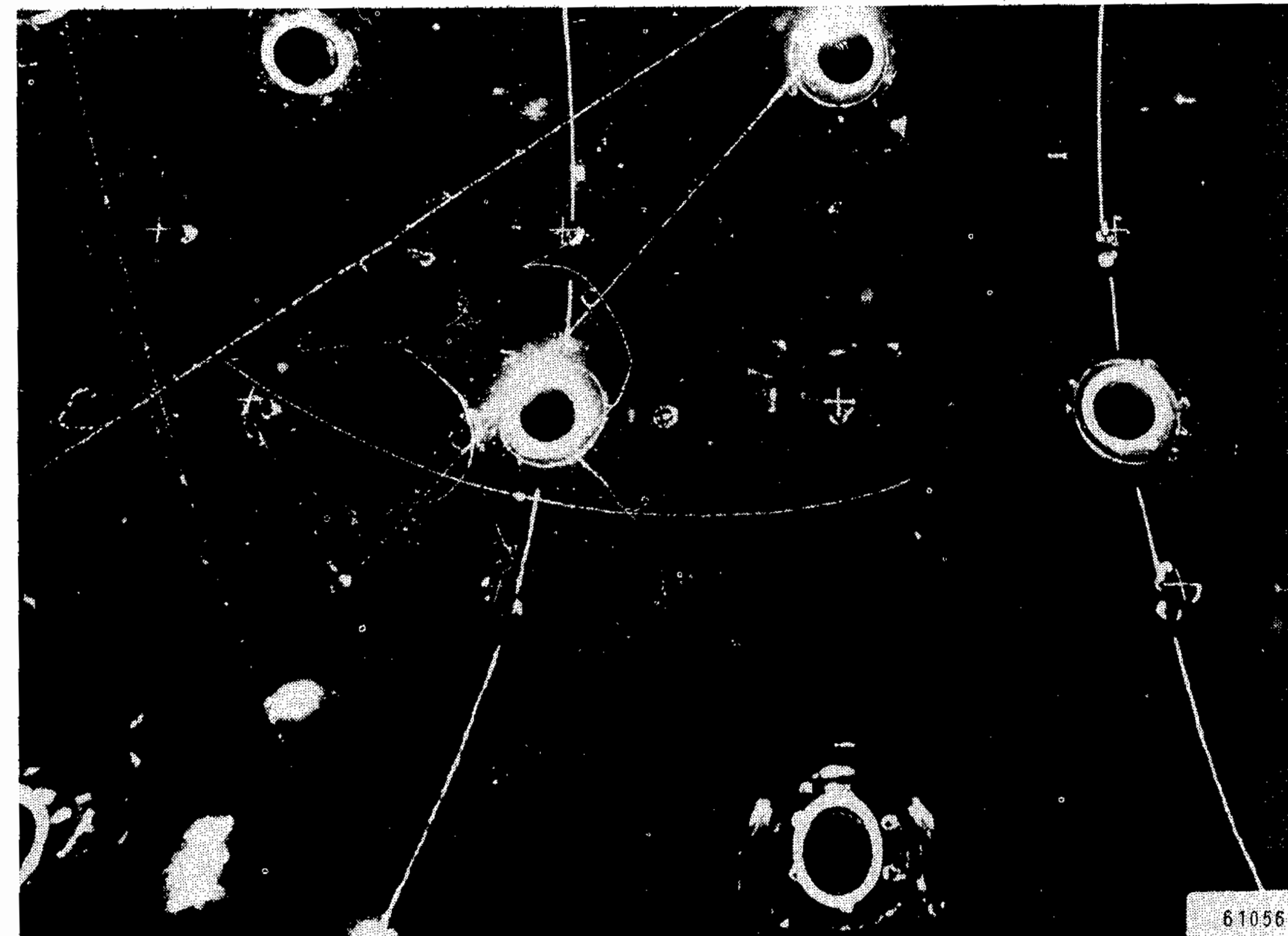
- The successful detection of neutral currents depends on two crucial technological improvements/achievements
 - **The magnetic horn**, which allows more intense and purer beams
 - It focalise mesons of one size and delocalise the other ones
 - The fast, high volume, and high density **bubble chamber**, to visualise events
 - **6.2 m³** of liquid freon (**CF₃Br**) with a **density of 1.5 g/cm³**
- Ideas that are **still the key of more modern efforts** such as SBN at Fermilab, DUNE, T2K, HK



Magnetic horn to focalise the beam



Neutral current event in the bubble chamber



Results of Gargamelle

- Run with both neutrinos and anti-neutrinos
 - ν run: 102 NC, 428 CC, 15 neutrons
 - $\bar{\nu}$ run: 64 NC, 178 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."*
 - **$(NC/CC) = 0.21 \pm 0.03$**
 - **$(NC/CC) = 0.45 \pm 0.09$**
 - **$\sin\theta_w$ in range 0.3 - 0.4**

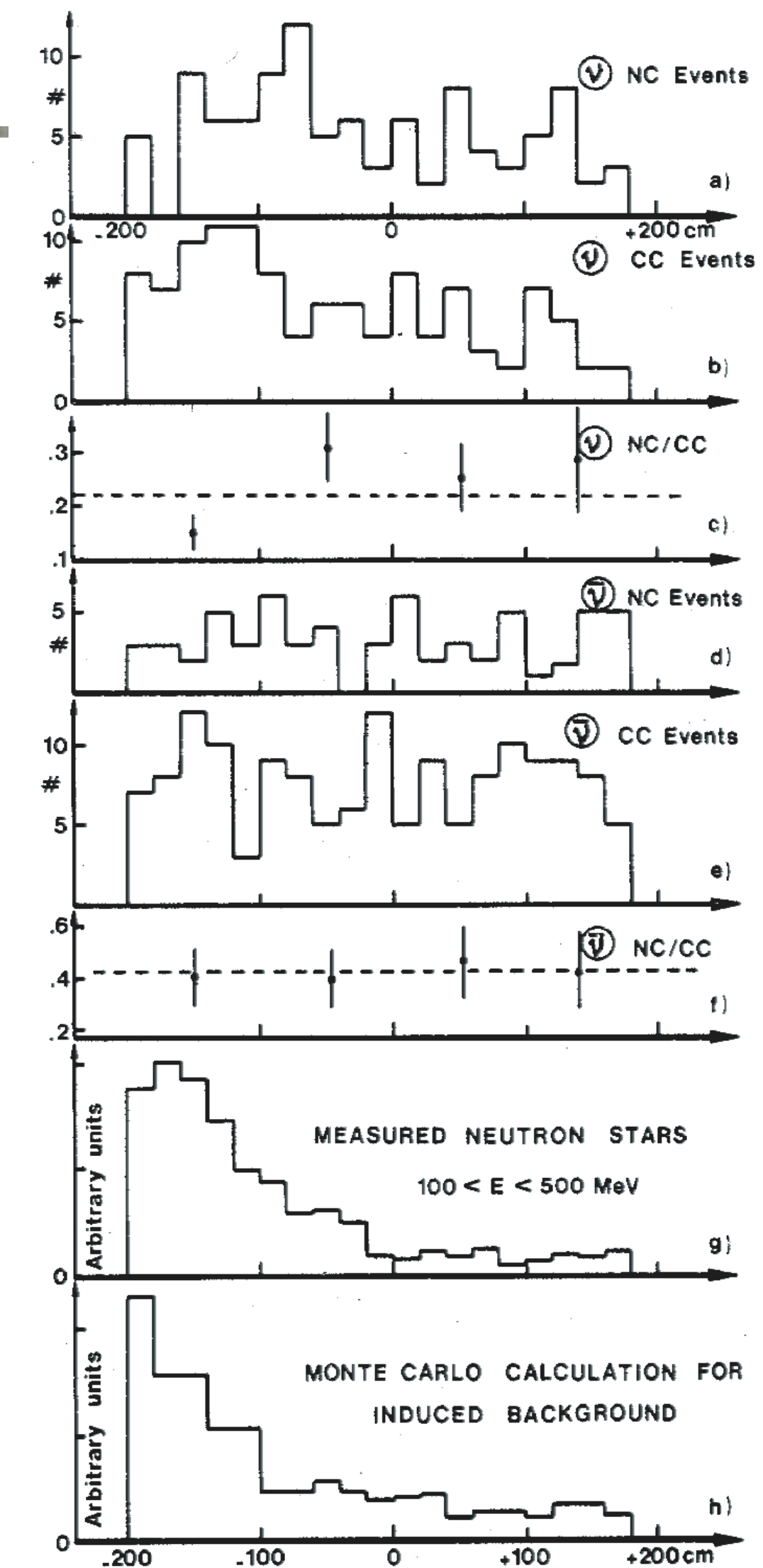


Fig. 1. Distributions along the ν -beam axis. a) NC events in ν . b) CC events in ν (this distribution is based on a reference sample of $\sim 1/4$ of the total ν film). c) Ratio NC/CC in ν (normalized). d) NC in $\bar{\nu}$. e) CC events in $\bar{\nu}$. f) Ratio NC/CC in $\bar{\nu}$. g) Measured neutron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

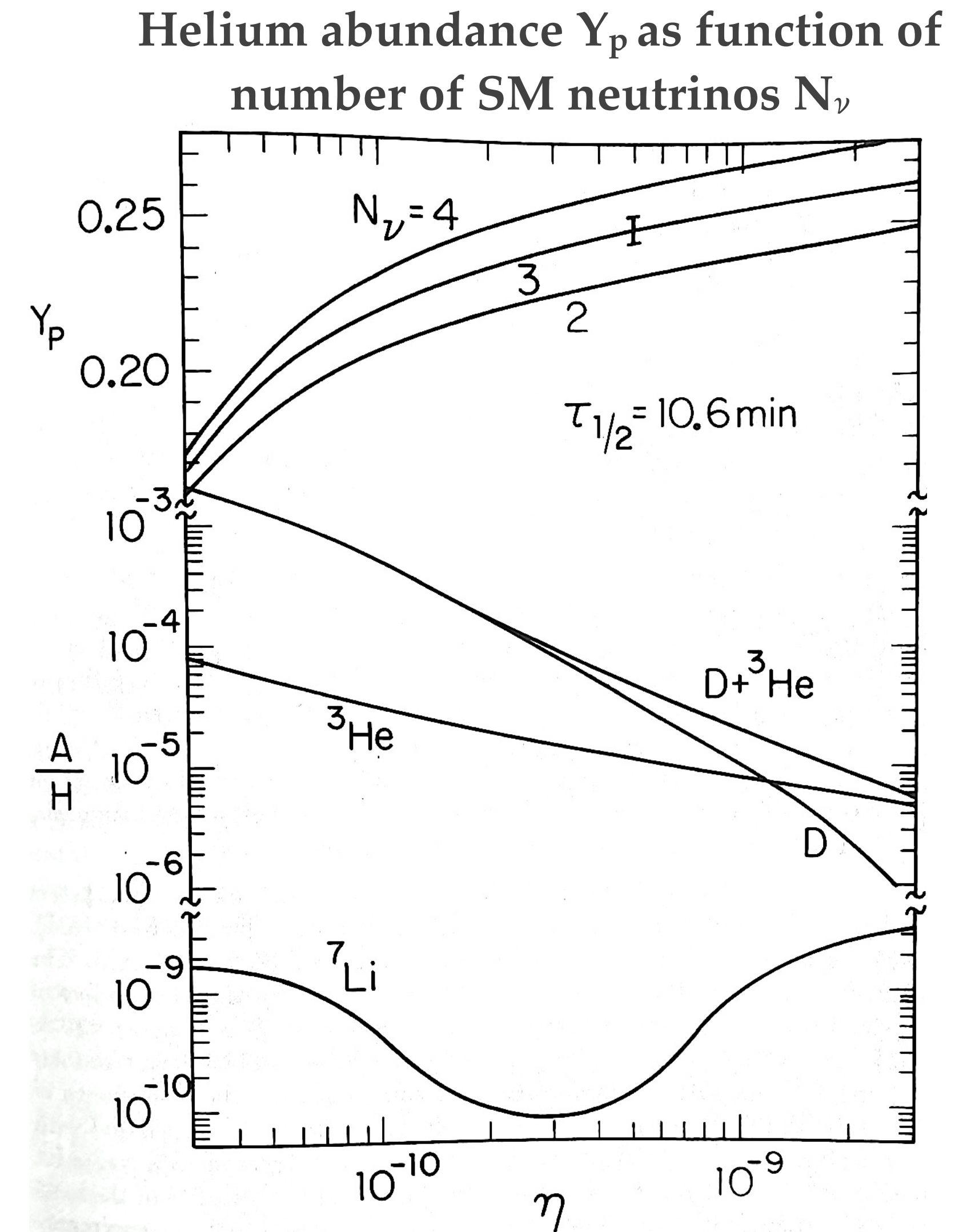
Three neutrinos: from cosmology

- 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 $N_\nu = 3$**

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

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

- 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 after disfavoured**



Klob-Turner, 1990

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

- The precise measurement of **Z⁰ “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

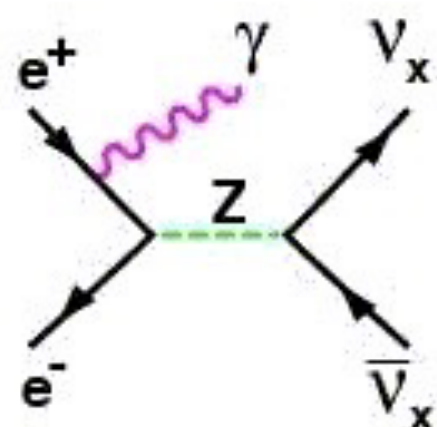
$$\Gamma_Z = \Gamma_{e\bar{e}} + \Gamma_{\mu\bar{\mu}} + \Gamma_{\tau\bar{\tau}} + \Gamma_{had} + N_\nu \Gamma_{\nu\bar{\nu}}$$

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

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

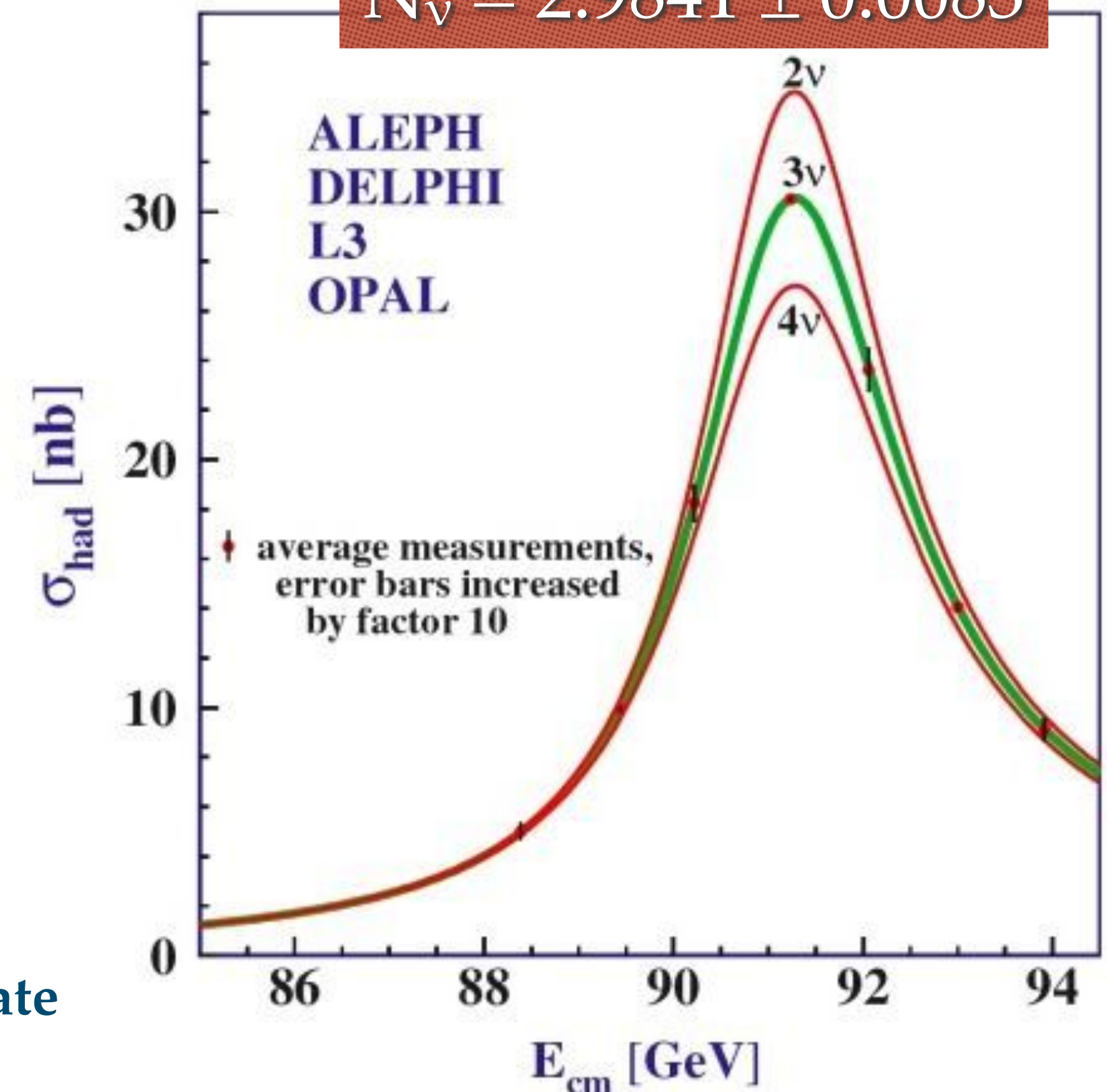
Γ_{had} **measured adding up all events with hadrons in the final state**

- 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

$$N_\nu = 2.9841 \pm 0.0083$$

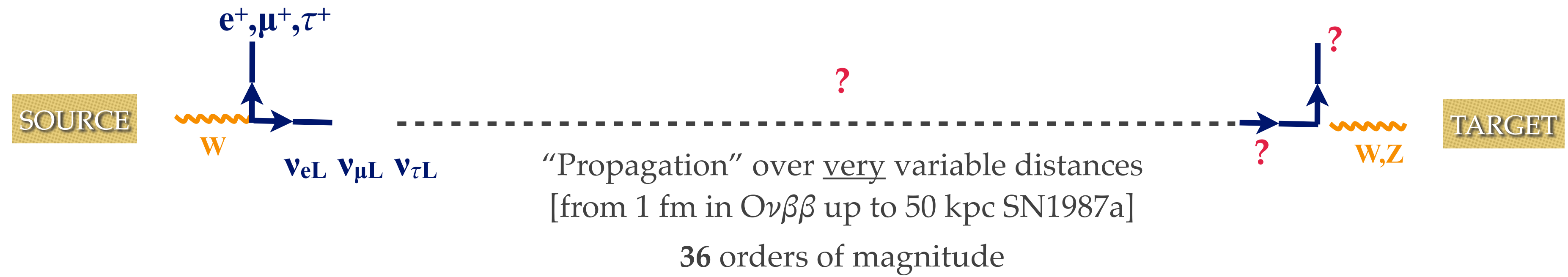


$$N_\nu = 2.98 \pm 0.10 \text{ [L3]}$$

Neutrino propagation

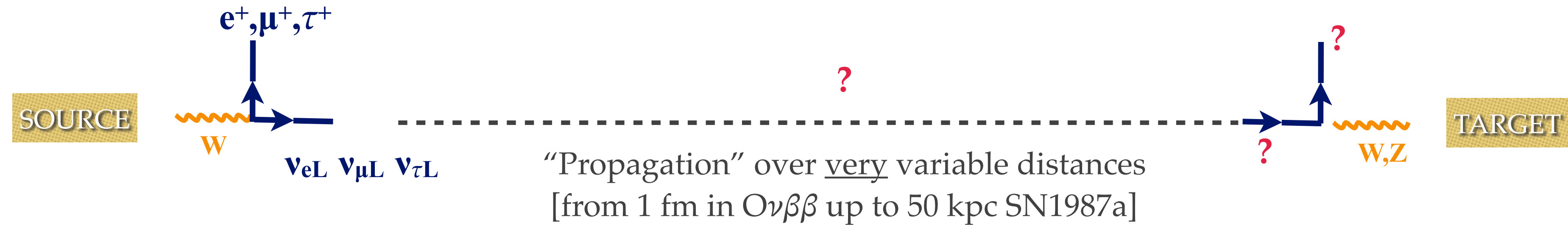


CHIEFLY:
nuclear $\beta^\pm$ decay
 e^-, μ^- nuclear capture
 $\mu^\pm, \tau^\pm, \pi^\pm$ decay



CHIEFLY:

nuclear $\beta^\pm$ decay
 e^-, μ^- nuclear capture
 $\mu^\pm, \tau^\pm, \pi^\pm$ decay



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 $m \ll E$
 - The wrong handed-ness component can be observed only for Majorana neutrinos
 - For Dirac neutrinos is sterile
 - MIXING induce flavour transitions $O(m^2 L / E)$
 - Observed with the right L and m^2/E values
 - Propagation in matter (Earth, Sun, neutron star cores) may amplify oscillations
 - 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:

$$\nu_e + p \rightarrow e^+ + n \quad \text{X (not seen)}$$

$$m/E \sim 10^{-7}!$$

Neutrino Oscillations

- Massive neutrinos are mixed: $\Rightarrow |\nu_\alpha\rangle = \sum_{i=1}^n U_{\alpha i}^* |\nu_i\rangle$
- 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:

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

- 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**:

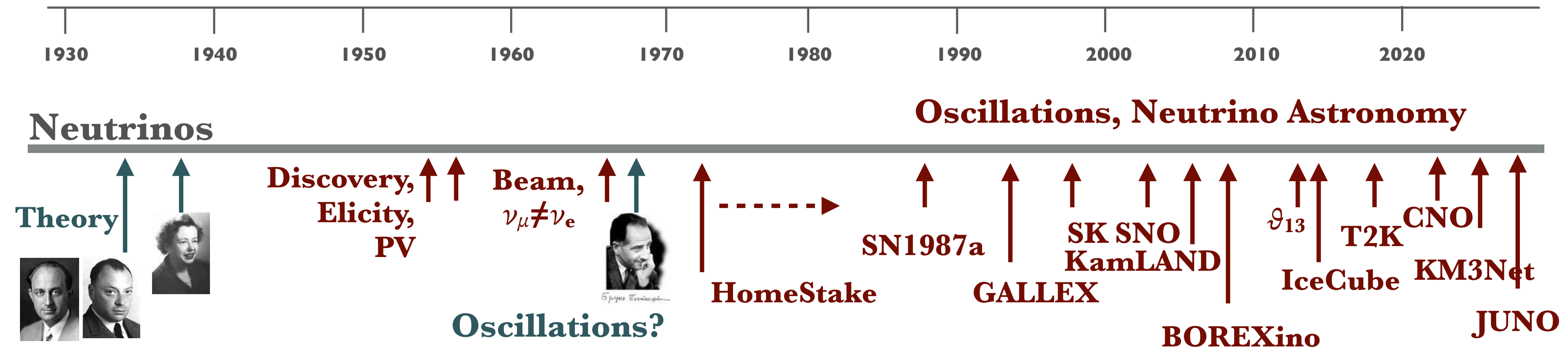
$$\xi_i^{\alpha\beta} = U_{\alpha i}^* U_{\beta i}; \quad \epsilon_i = \frac{m_i^2}{2E}.$$

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

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

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

Experimental neutrino physics: state of the art



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

$$\theta_{23} = 47.5 \pm 3.2^\circ$$

$$\delta_D = ? (-\pi/2 ?)$$

$$\theta_{13} = 8.56 \pm 0.15^\circ$$

$$\delta m^2 = 7.40 \pm 0.21 \cdot 10^{-5} \text{ eV}^2$$

$$\theta_{12} = 33.6 \pm 0.77^\circ$$

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

Atmospheric

Accelerators LBL

L ~ 700 km

Reactors L ~ 1 km

LBL L ~ 200 km

Solar

Reactors

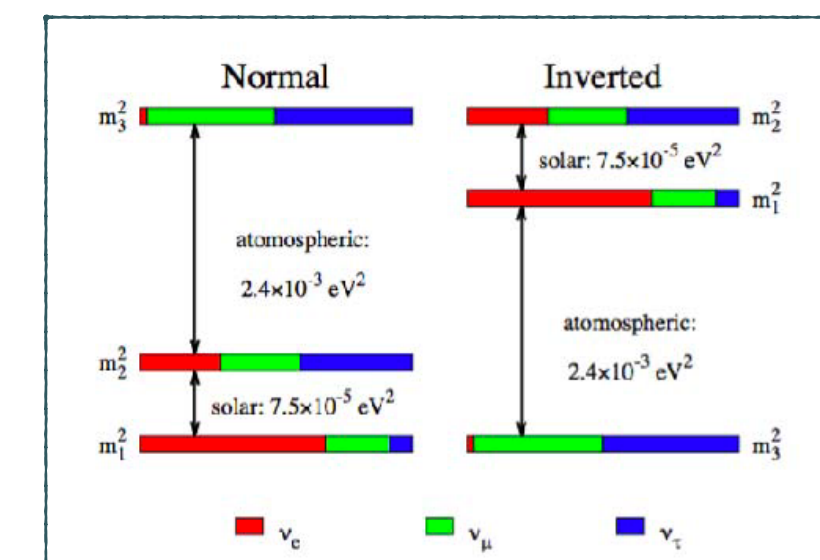
L ~ 200 km

$0\nu\beta\beta$

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

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

$$V \neq \bar{V} ?$$



Dirac vs Majorana ($\nu \neq \bar{\nu}$?) $0\nu\beta\beta$

U_{PMNS} unitary?

$\delta_{\text{CP}} \neq 0$?

$\Delta m^2 > 0$?

ϑ_{23} maximal? Octant ?

OSCILLATIONS

Absolute Mass scale

Spectrometers, μ Bolometers, EUCLID

Astrophysics

IceCUBE, KM3Net

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

$C\nu B$

R&D for PTolemy, Euclid, CMB fits

SN (pulse and relics)

(LVD), JUNO, SK, HK, DUNE

- **Artificial**

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

- **Natural**

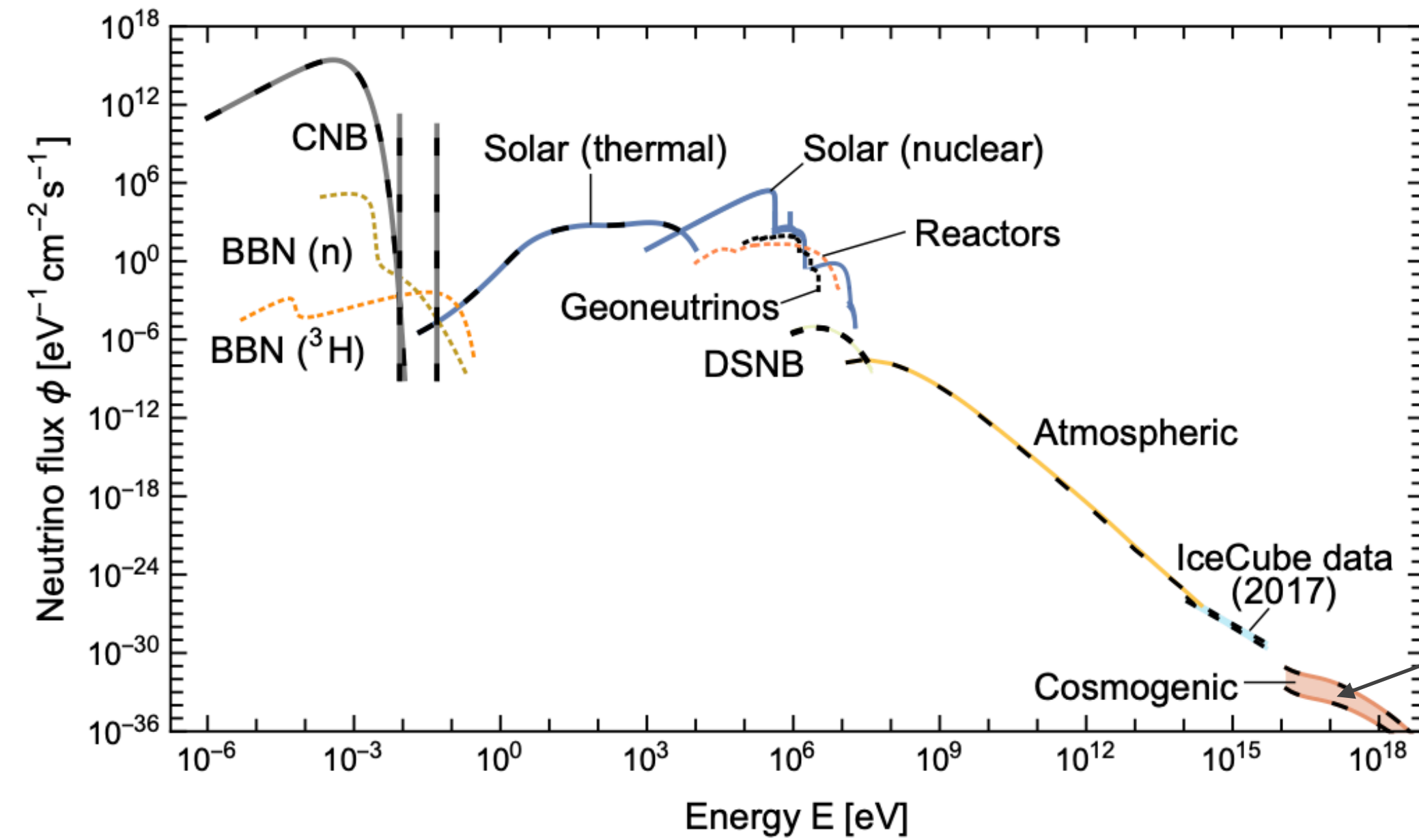
- Sun
- Atmospheric
 - secondary from cosmic rays interaction in atmosphere
- Cosmic
 - coming from outside Earth
- Geo-neutrinos
 - from Earth bulk and crust radioactivity
- Diffuse SN (statistical sum of many past SN events)
- SN
 - only once so far, **SN1987a**
- Relic (from big bang)

Natural neutrino sources

Neutrinos

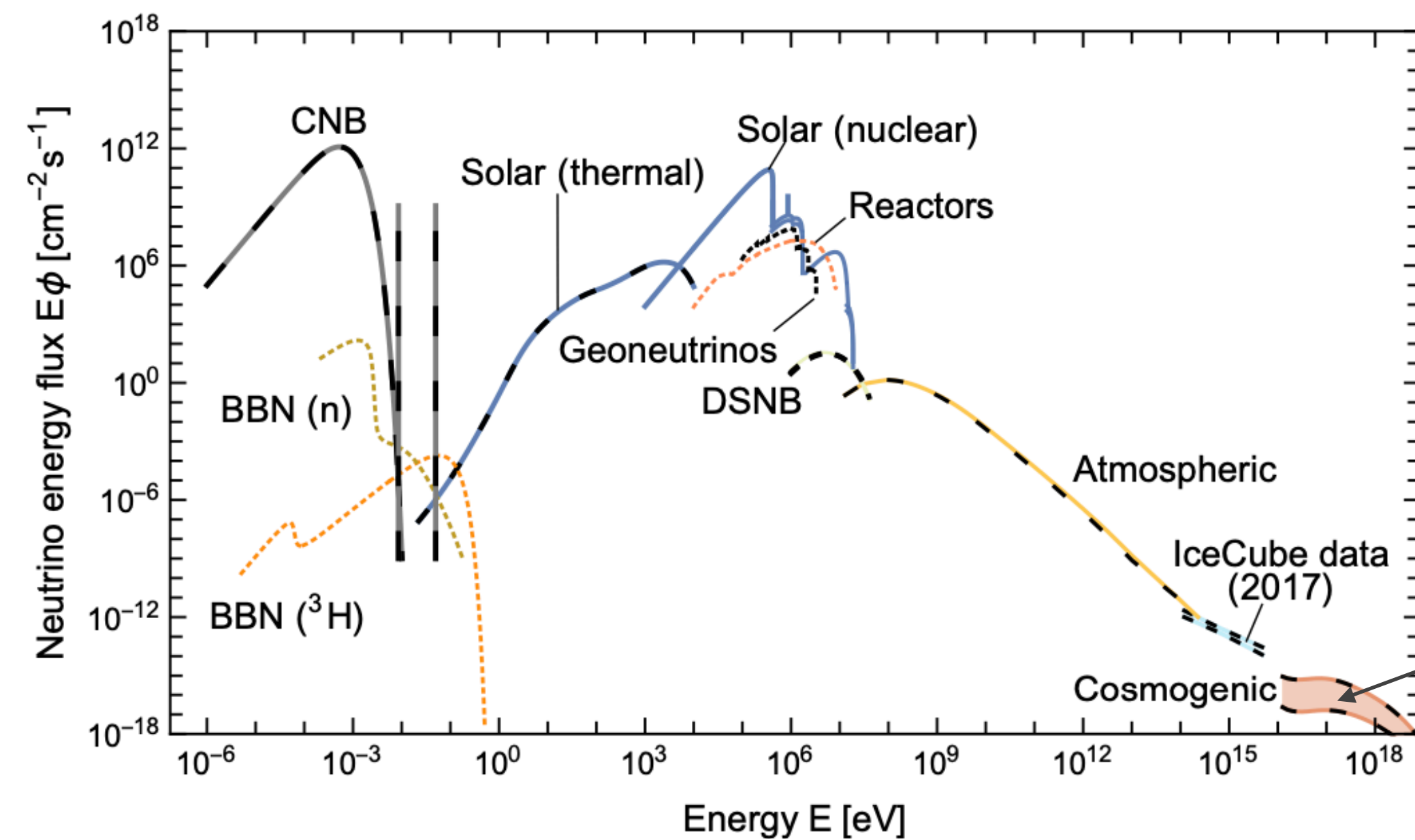
Anti-Neutrinos

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



Flux

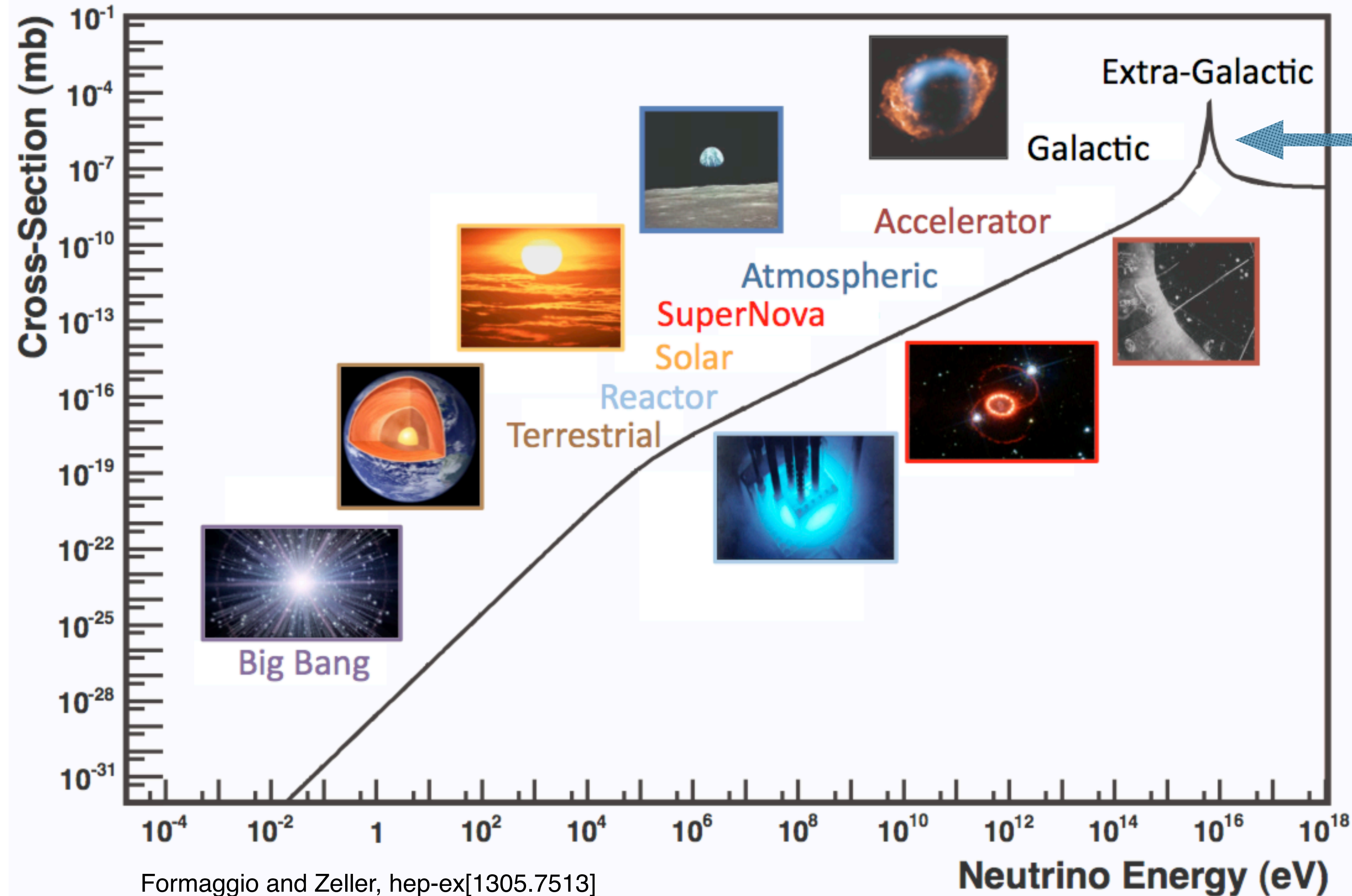
KM3Net event ?
2024



Flux × Energy = Rate

KM3Net event ?
2024

Neutrino detection cross section vs energy



Earth is **not** anymore transparent at $\sim 10^{15} - 10^{16}$ eV

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

Detecting neutrinos: key parameters and processes

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

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.

- **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 $N_{targ} \sim 6 \cdot 10^{26} \text{ kg}^{-1}$ (e⁻ or p)
- **T**: exposure time (2.7 10⁷ s / y typical up-time)
- **φ**: neutrino flux
 - **Sun**: $\sim 10^6 - 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$ at Earth; **Reactors**: $\sim 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ @ 20 m; **Accelerators**: $\sim 1 \text{ cm}^{-2} \text{ s}^{-1}$ @ 1000 km
- **σ**: cross section (total for the specific FS)
- **ε**: efficiency/acceptance; usually large, but not always
- TWO SIGNIFICANT EXAMPLES:

- **SOLAR (Borexino, elastic scattering on electrons)**

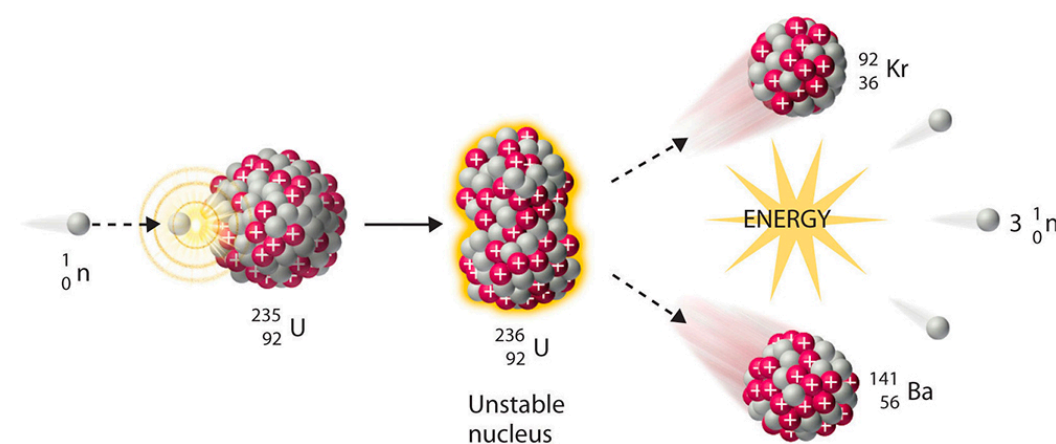
$$\begin{array}{c} \rightarrow \\ N_{obs} = \underbrace{[3. \cdot 10^{31} e^-]}_{100 \text{ t}} \times \underbrace{[86400 \text{ s}]}_{1 \text{ day}} \times \underbrace{[6 \cdot 10^9 \text{ cm}^{-2} \text{ s}^{-1}]}_{\text{flux}} \left[\frac{0.7 \cdot 10^{-45} \text{ cm}^2}{(\text{MeV})} \right]_{\text{cross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

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

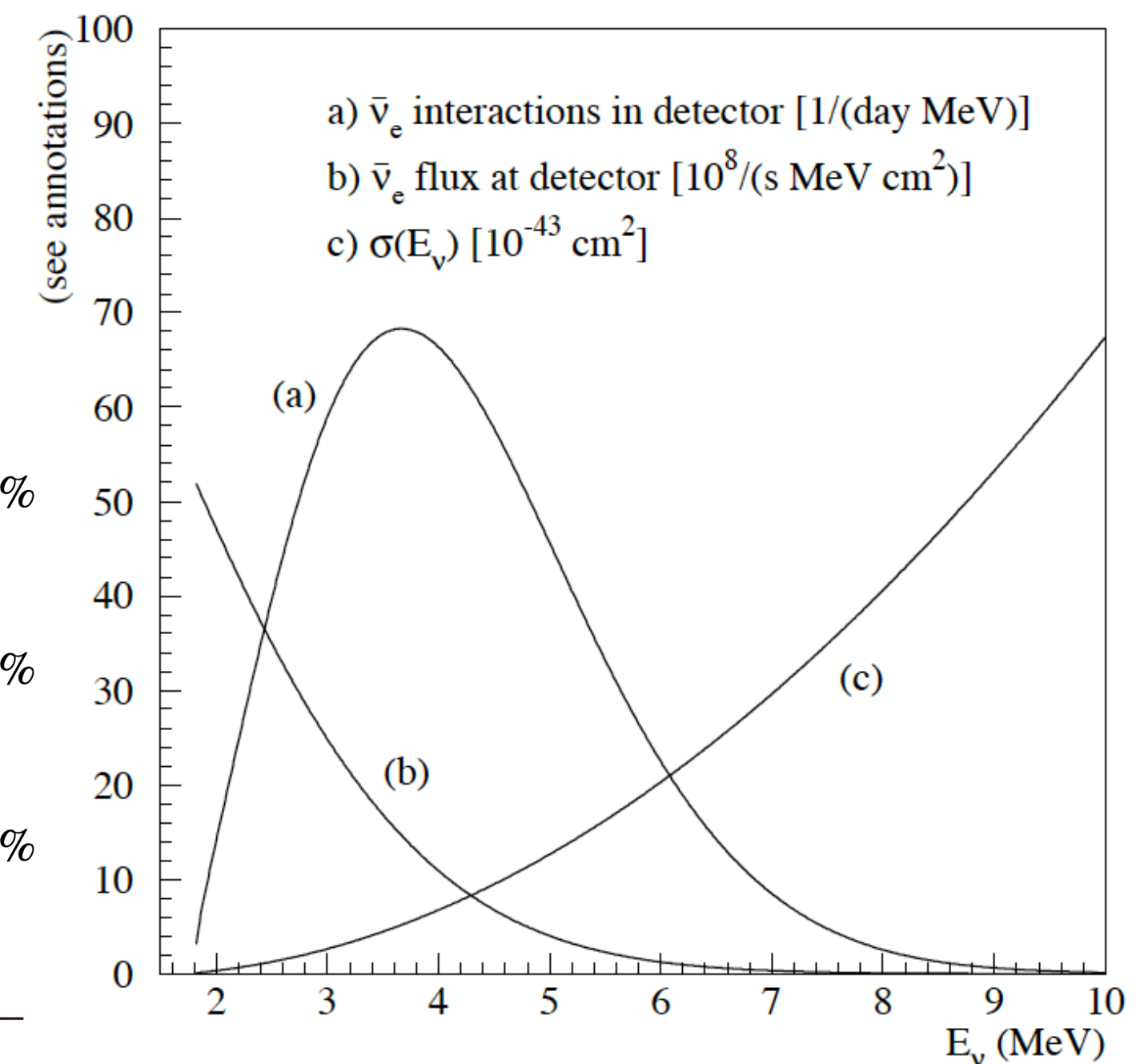
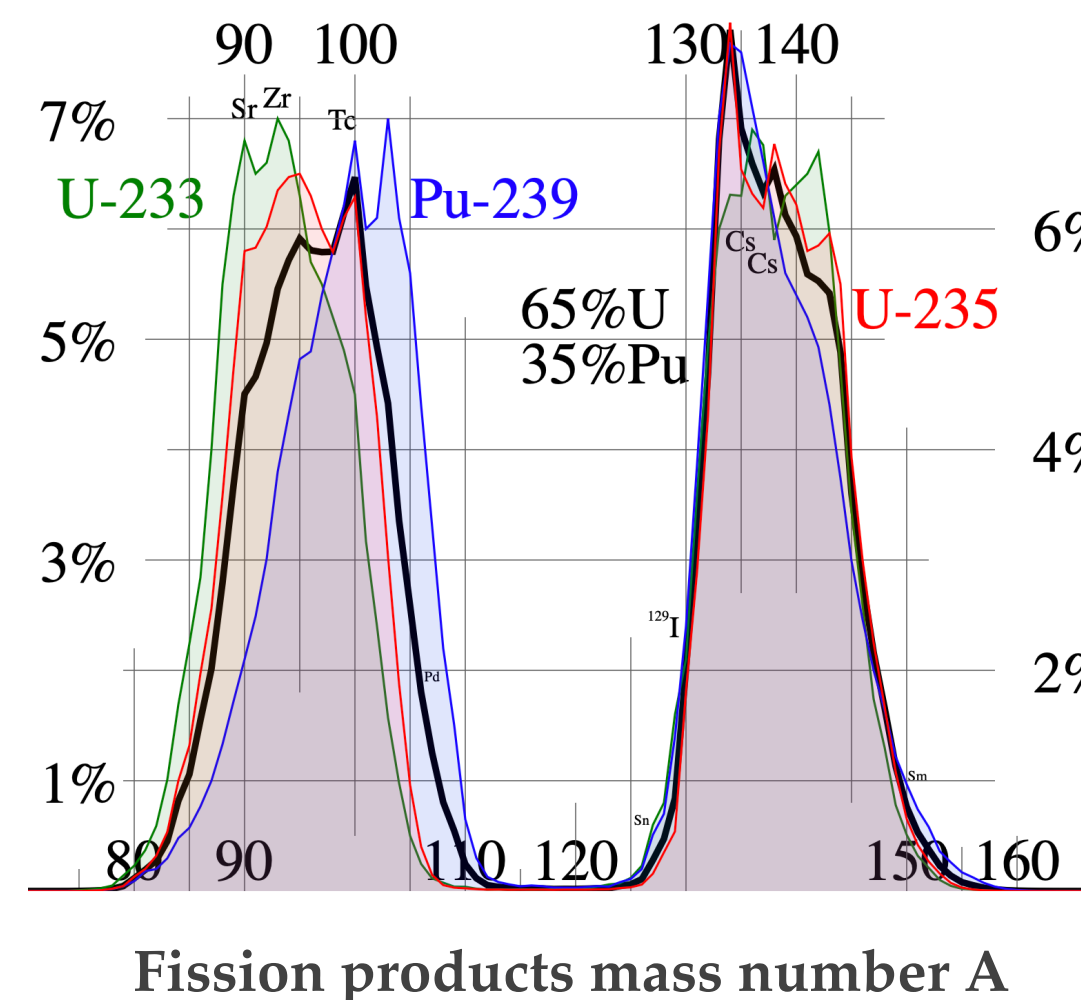
$$\begin{array}{c} \rightarrow \\ N_{obs} = \underbrace{\left[\frac{M}{1.67 \cdot 10^{-27} \text{ kg}} \right]}_{\text{Number of nucleons}} \cdot \underbrace{[2. \cdot 10^7 \text{ s}]}_{\text{Effective year}} \cdot \underbrace{[1 \text{ cm}^{-2} \text{ s}^{-1}]}_{\text{Strong beam @ 1000 km}} \cdot \epsilon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

Nuclear reactors

- A reactor is a powerful source of **anti-neutrinos**
 - Each U fission yields 200 MeV on average, and **6 ν_e**
 - Flux: $\sim 2 \cdot 10^{20} \text{ s}^{-1} \text{ GW}^{-1}$, isotropic, $\langle E_\nu \rangle \simeq 0.5 \text{ MeV}$
 - About $\sim 4 \cdot 10^{12} \text{ s}^{-1} \text{ cm}^{-2}$ 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**)

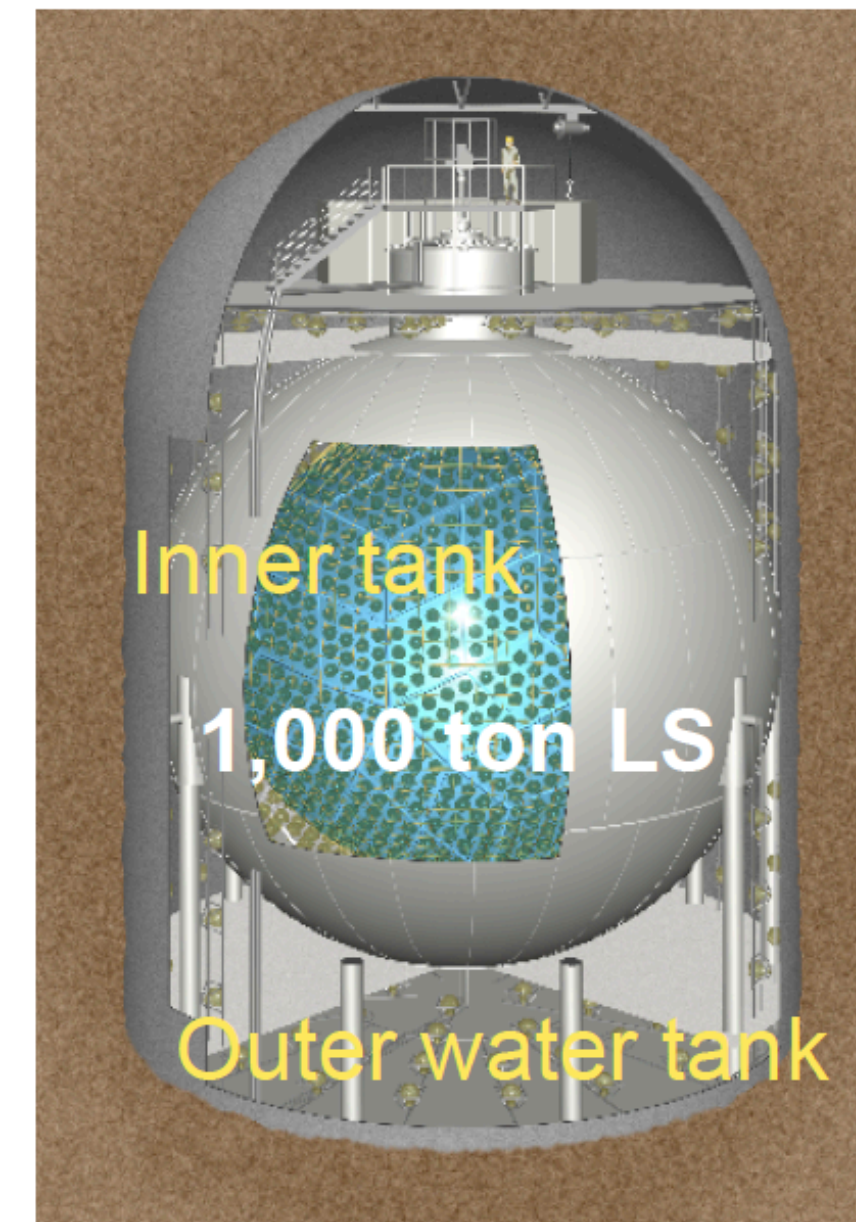
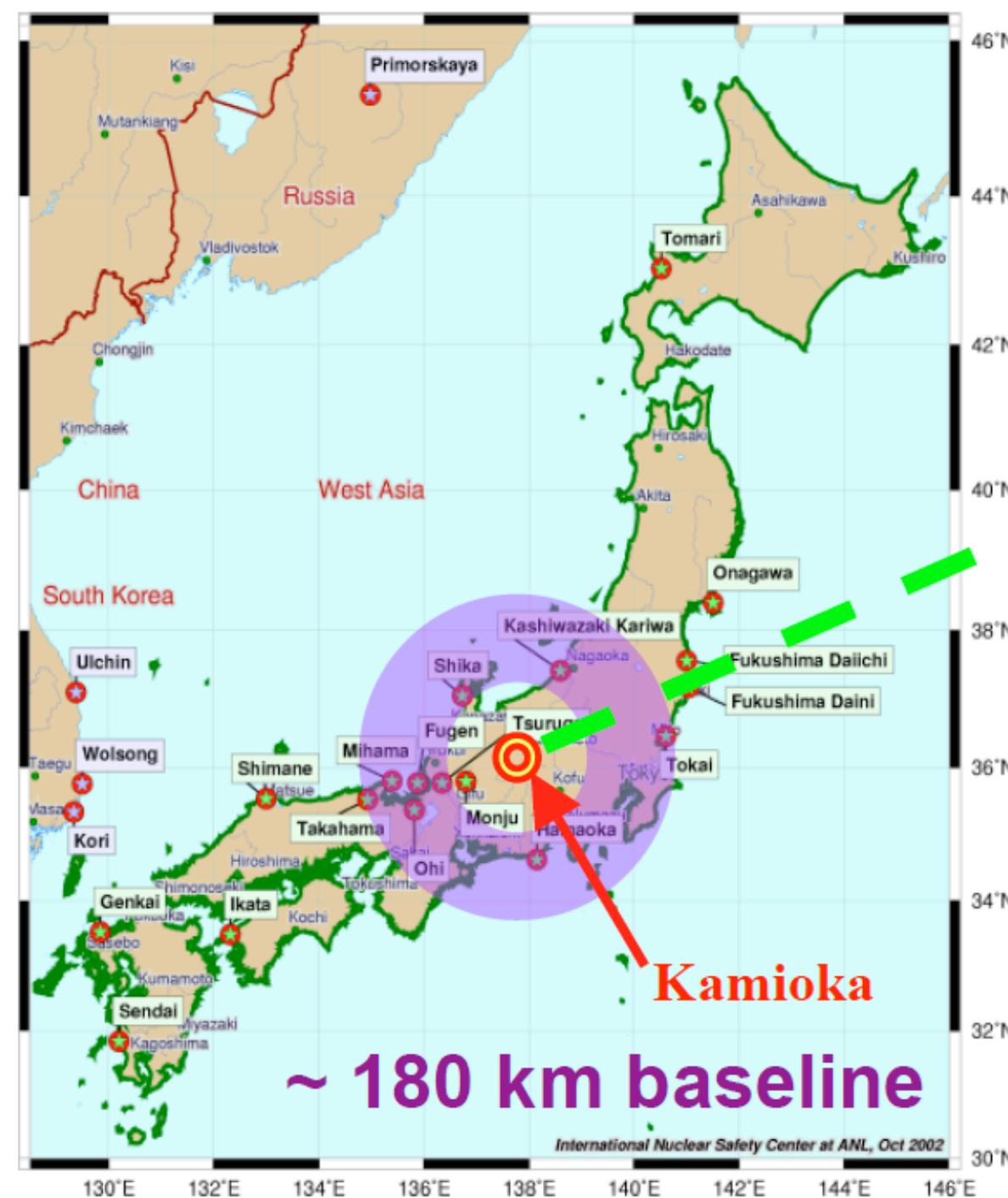


- The flux depends on **reactor type** and also on **time** because **fuel composition evolves**



Example: KamLAND experiment

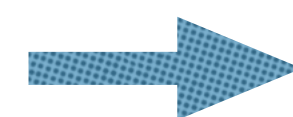
- Kamioka Liquid Scintillator Anti-Neutrino Detector



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

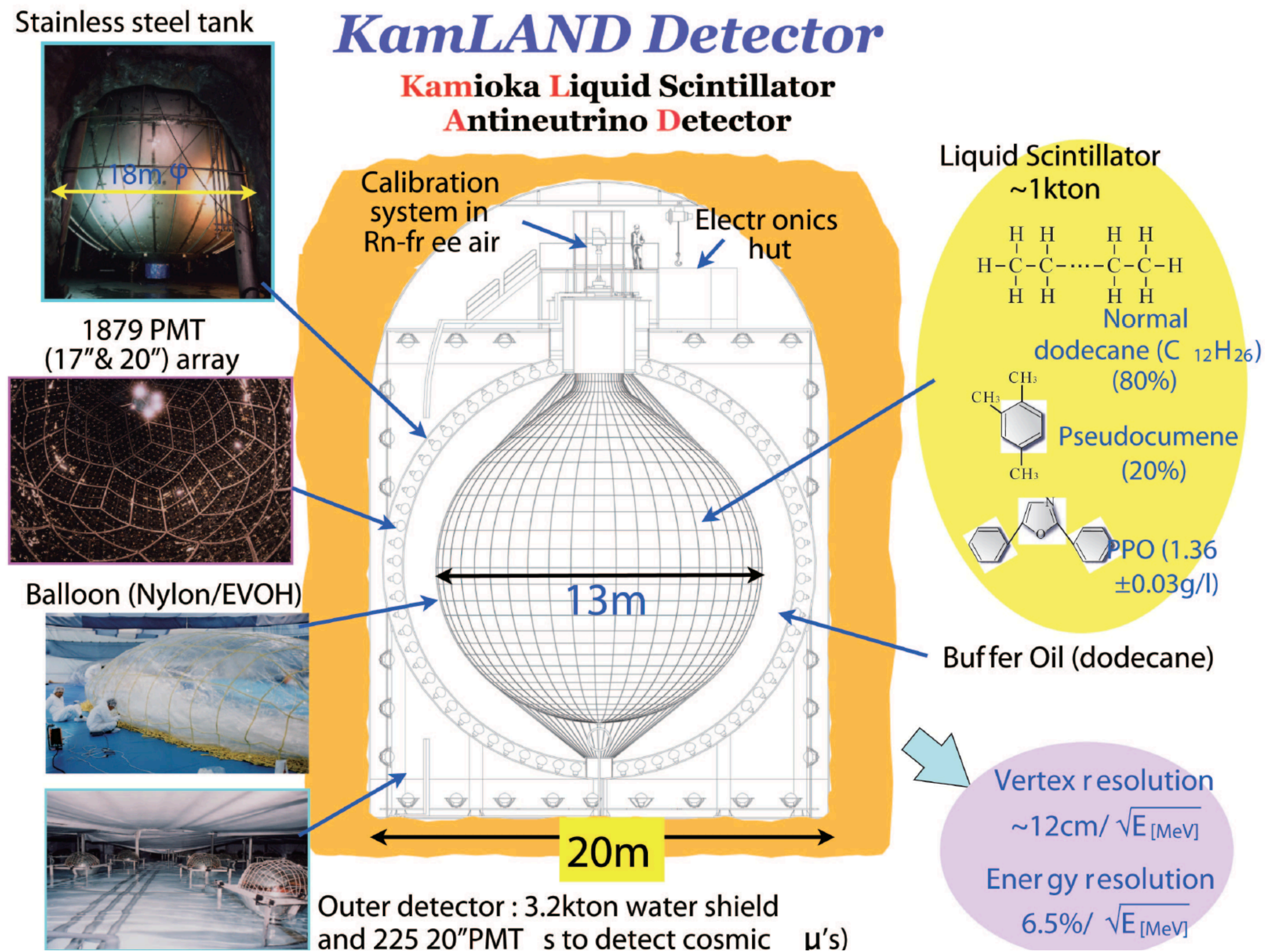
2 flavor neutrino oscillation

most sensitive region

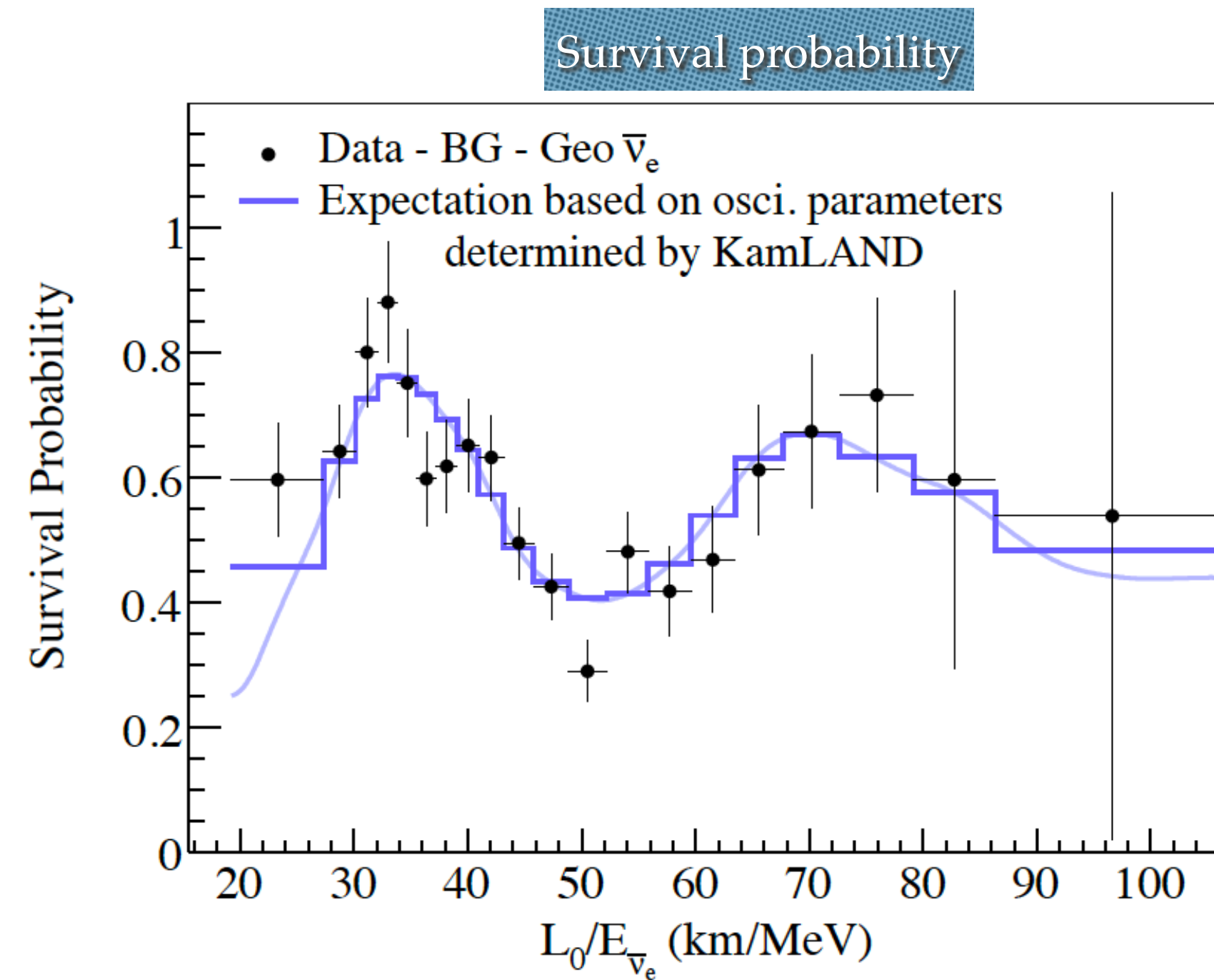
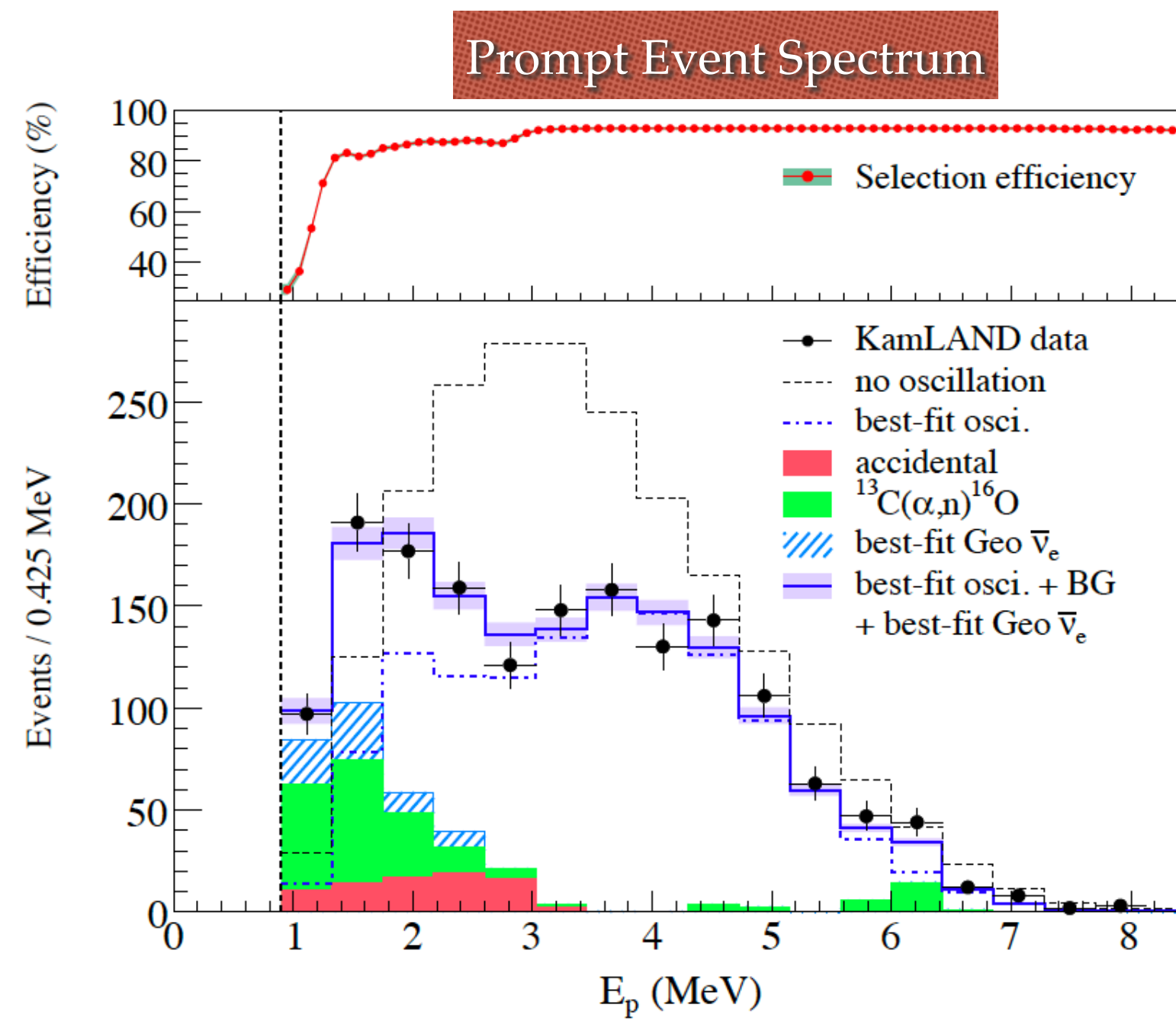


$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27 \Delta m^2 [\text{eV}^2] l [\text{m}]}{E [\text{MeV}]}\right) \quad \Delta m^2 = (1/1.27) \cdot (E [\text{MeV}] / L [\text{m}]) \cdot (\pi/2)$$

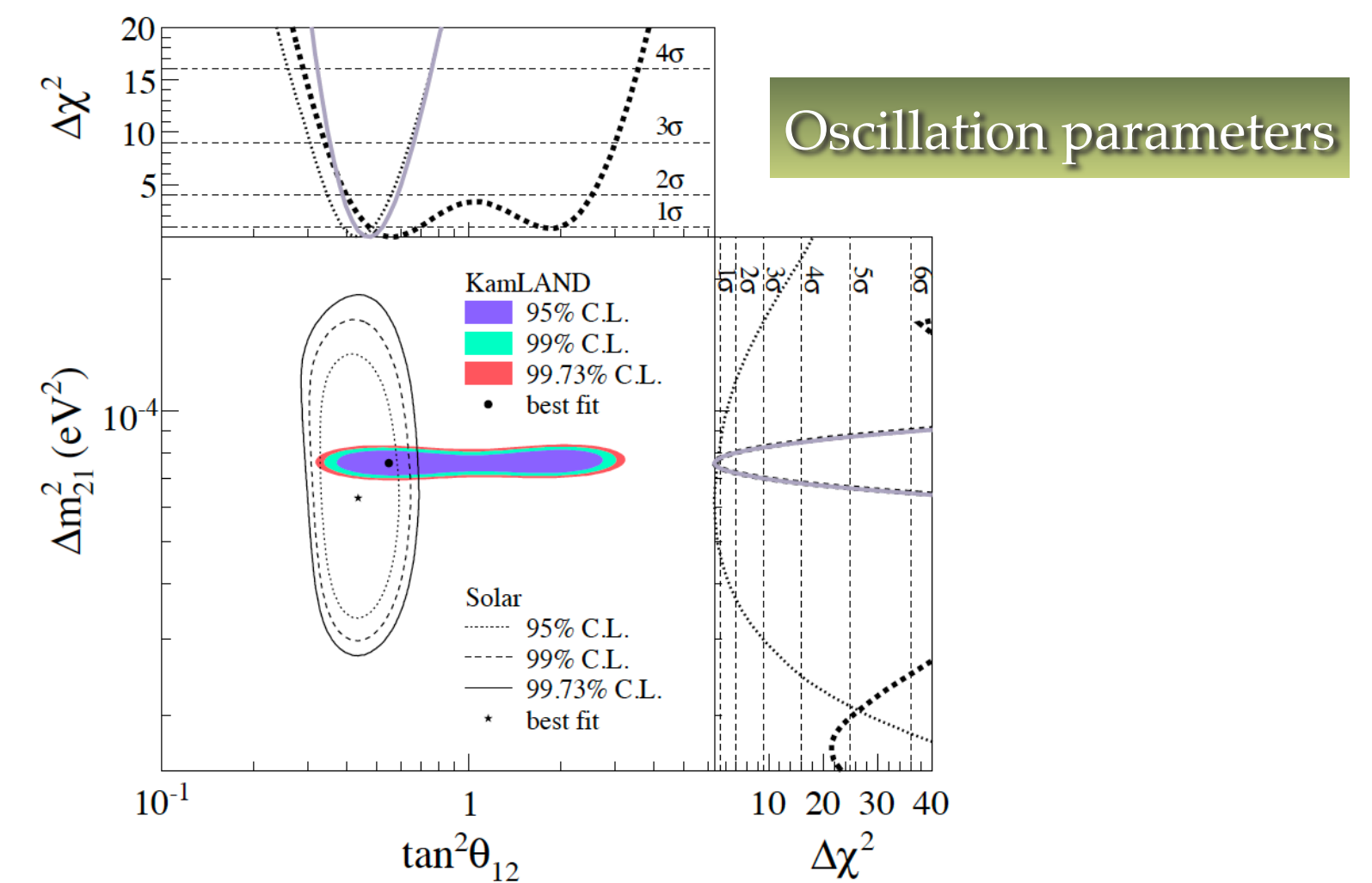
$$\sim 3 \times 10^{-5} \text{eV}^2$$



A neat oscillation experiment



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



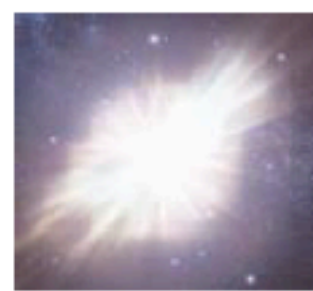
State of the art today: JUNO

- JUNO is a huge liquid scintillator detector now operating in China
 - LS 23231.6 m³



Solar Neutrinos

Examine the dynamics of stellar evolution

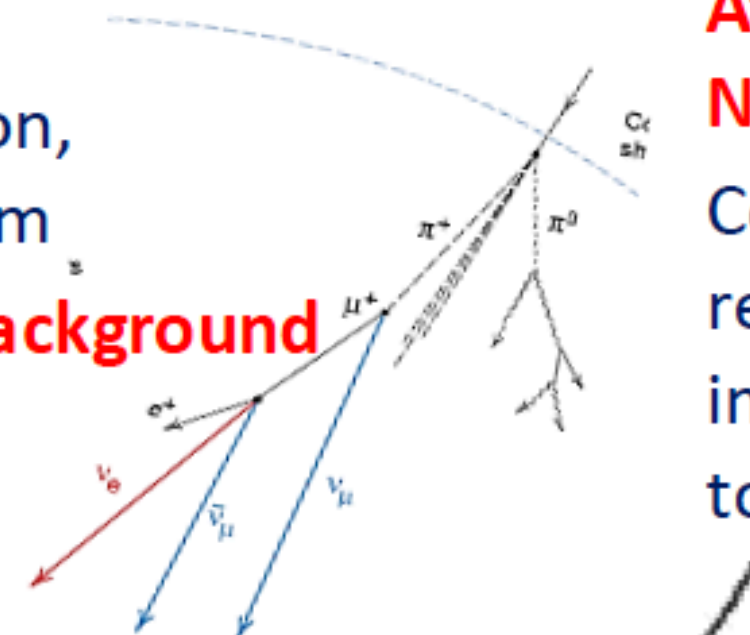


Supernova Neutrinos

Cosmic evolution, star formation, supernova explosion mechanism

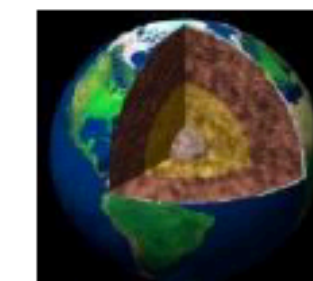
Diffuse Supernova Neutrino Background

Potential to discover DSNB



Atmospheric Neutrinos

Complementary to reactor neutrinos to improve the sensitivity to mass ordering



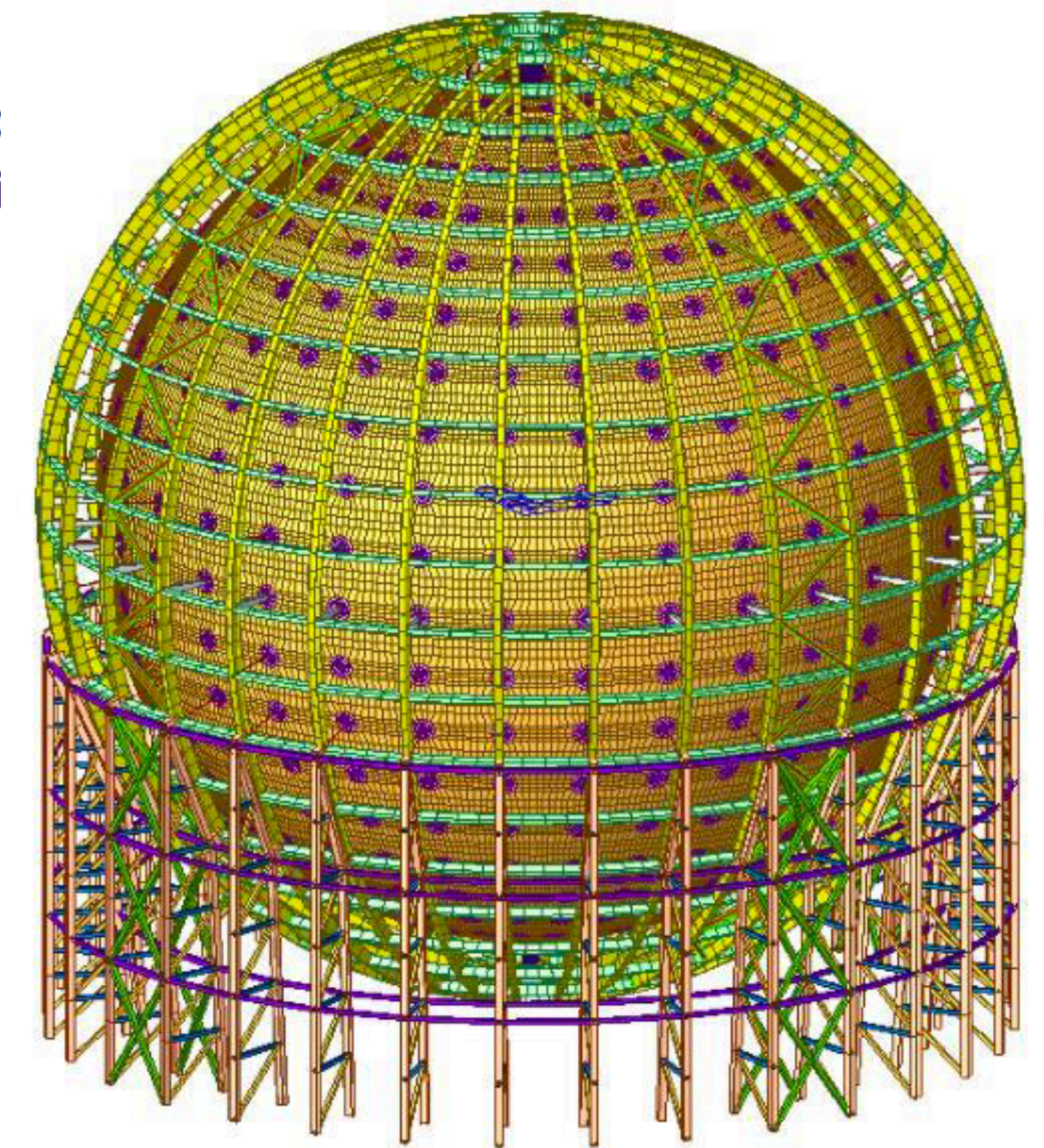
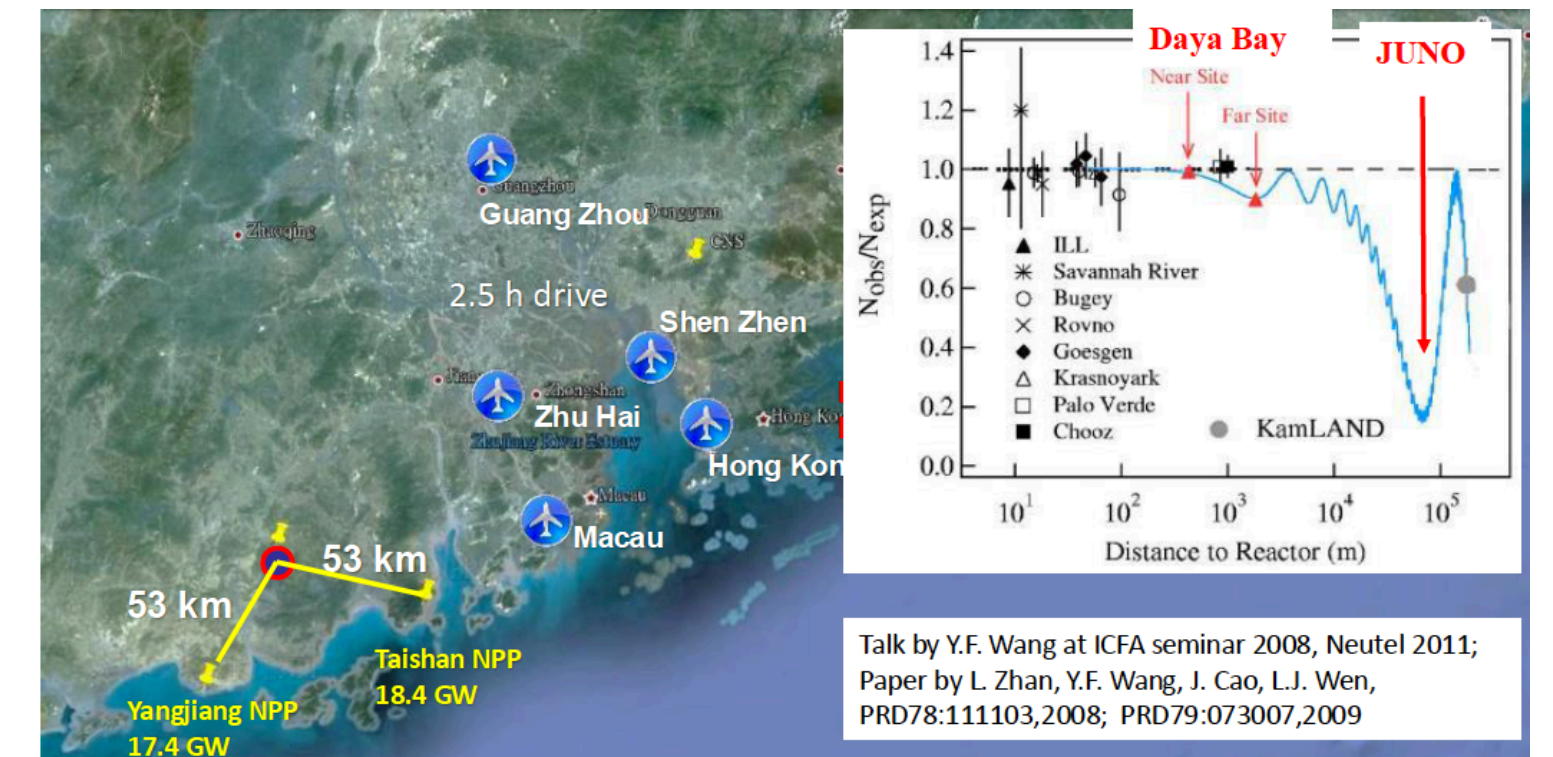
Geoneutrinos

Examine the Earth's geophysical model

New physics searches

e.g., proton decay and sterile neutrinos

J. Phys. G 43 (2016) 030401
Prog. Part. Nucl. Phys. 123(2022), 103927



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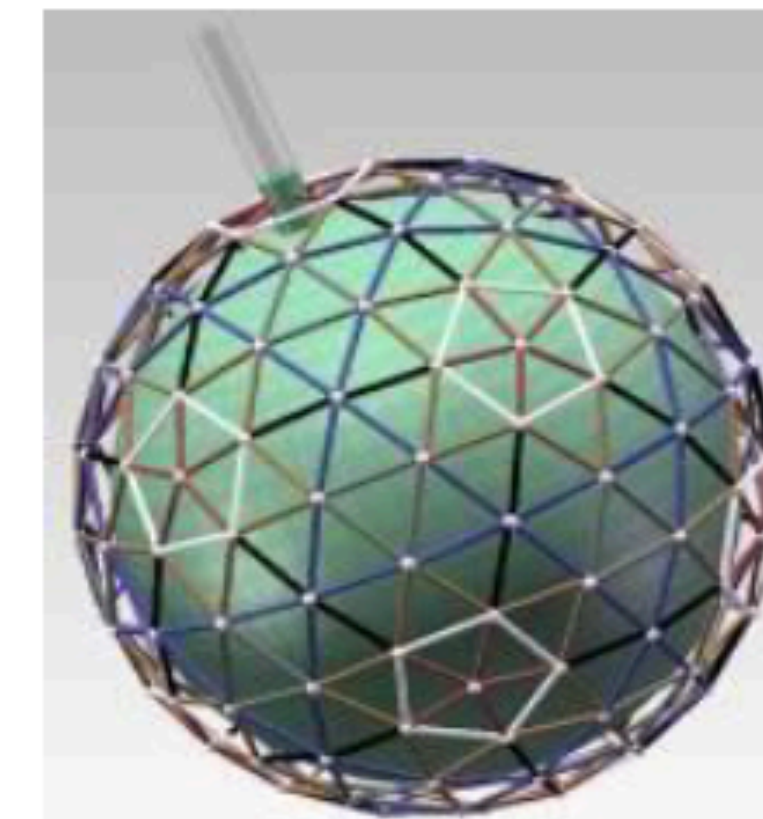
	Current (PDG2020)	JUNO (100 days)	JUNO (6 years)
Δm^2_{31} (Δm^2_{32})	1.3%	0.8%	0.2%
Δm^2_{21}	2.4%	1.0%	0.3%
$\sin^2\theta_{12}$	4.2%	1.9%	0.5%
$\sin^2\theta_{13}$	3.2%	47.9%	12.1%

JUNO Detector concept(s)

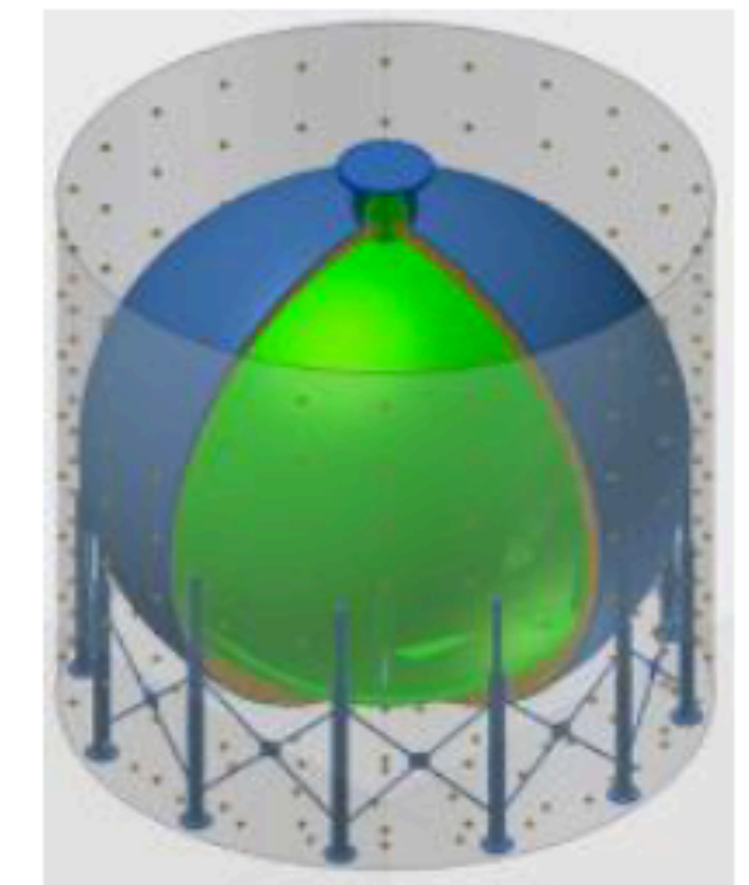
- Target mass of 20 kt liquid scintillator → × 20 KamLAND, × 40 Borexino
- Energy resolution < 3%@ 1MeV → >1200 PE/MeV

	KamLAND	JUNO	PE Ratio
Photon Statistics	250 p.e./MeV	1200 p.e./MeV	5
PMT coverage	34%	75%	2.2
LS transparency	~12 m	> 20 m	~0.9
Light yield(anthracene)	30%	45%	~1.5
Detection Eff.(QE×CE)	~15%	30%	~ 2

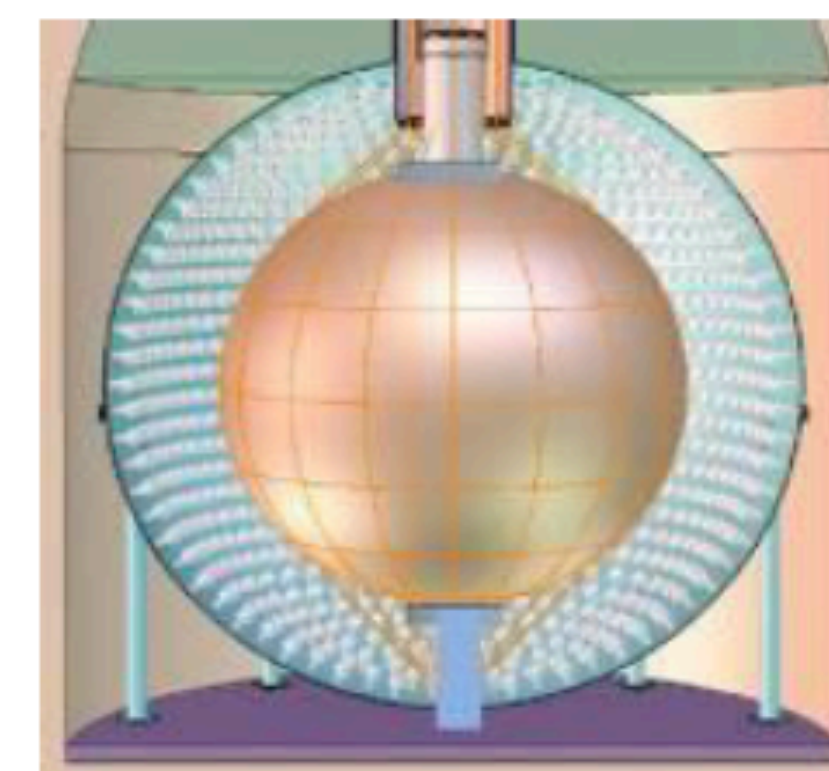
- Key technology R&D since 2009:
 - Transparent & high light yield liquid scintillator
 - High detection efficiency 20" PMTs
 - Radiopurity U/Th/K < 10⁻¹⁷ g/g for 20 kt LS
- Detector Design(more than 10 options):
 - Central target container: acrylic or balloon ?
 - Mechanical structure: steel frame or steel tank ?
 - Buffer layer: Water or Mineral oil ?



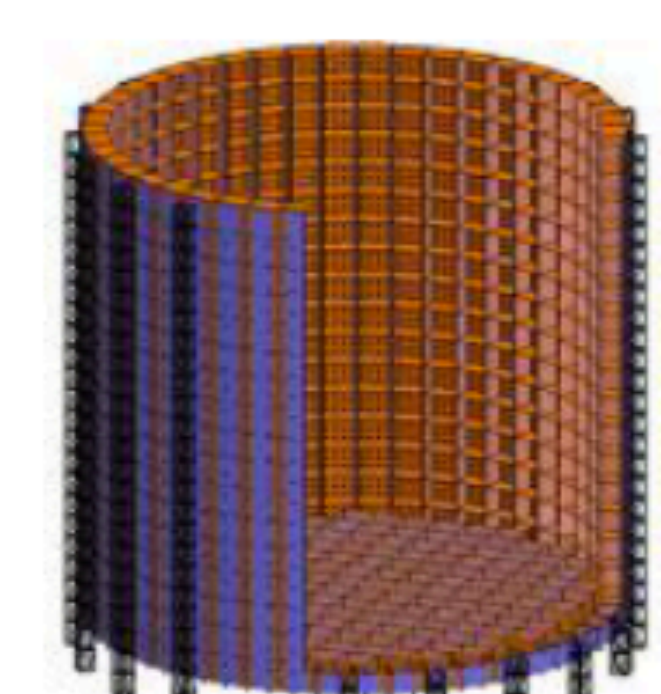
Steel frame+ Acrylic tank



Steel tank+ Acrylic tank



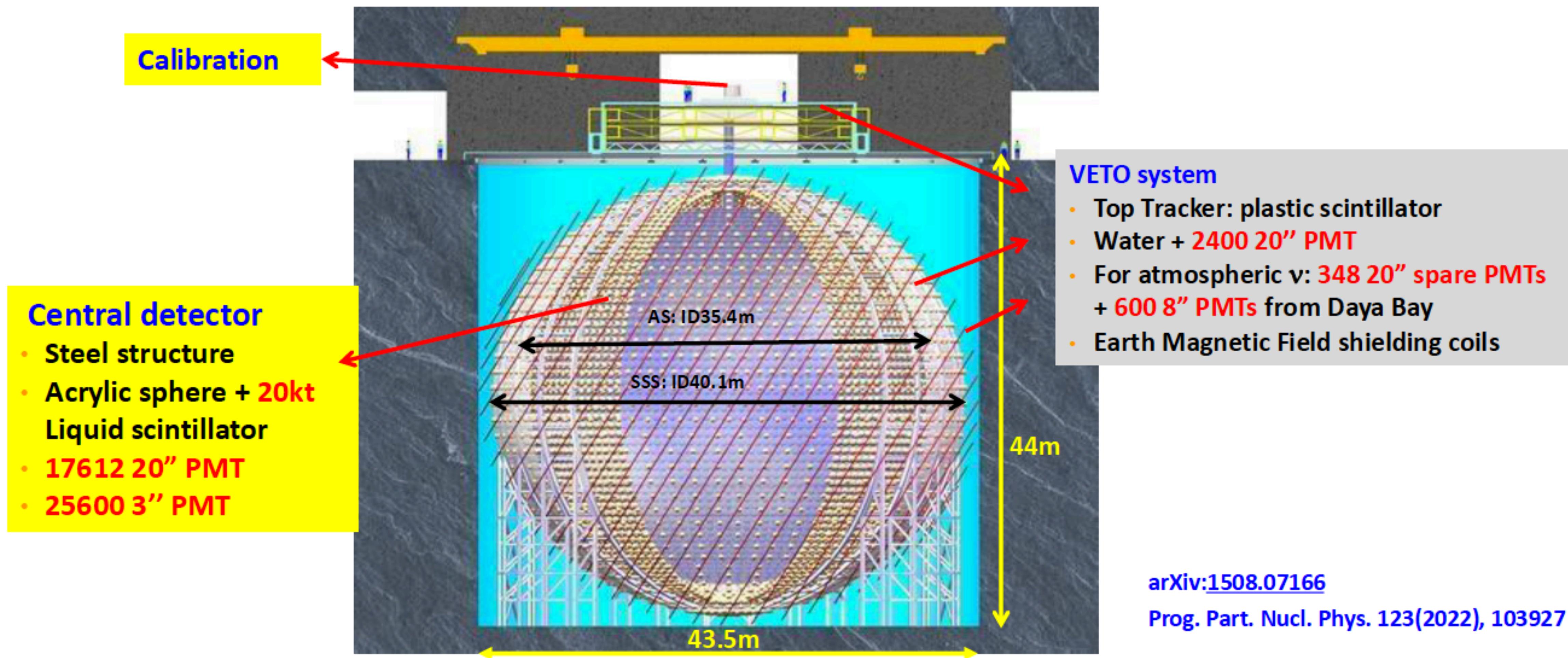
Steel Tank + Balloon



Steel Tank + Acrylic blocks

CREDIT: Y. F. Wang 2025

- Two-layers structure for simplicity and cost: stainless steel frame + Acrylic tank
- Water as VETO and Buffer(instead of oil) → radiopurity control of water

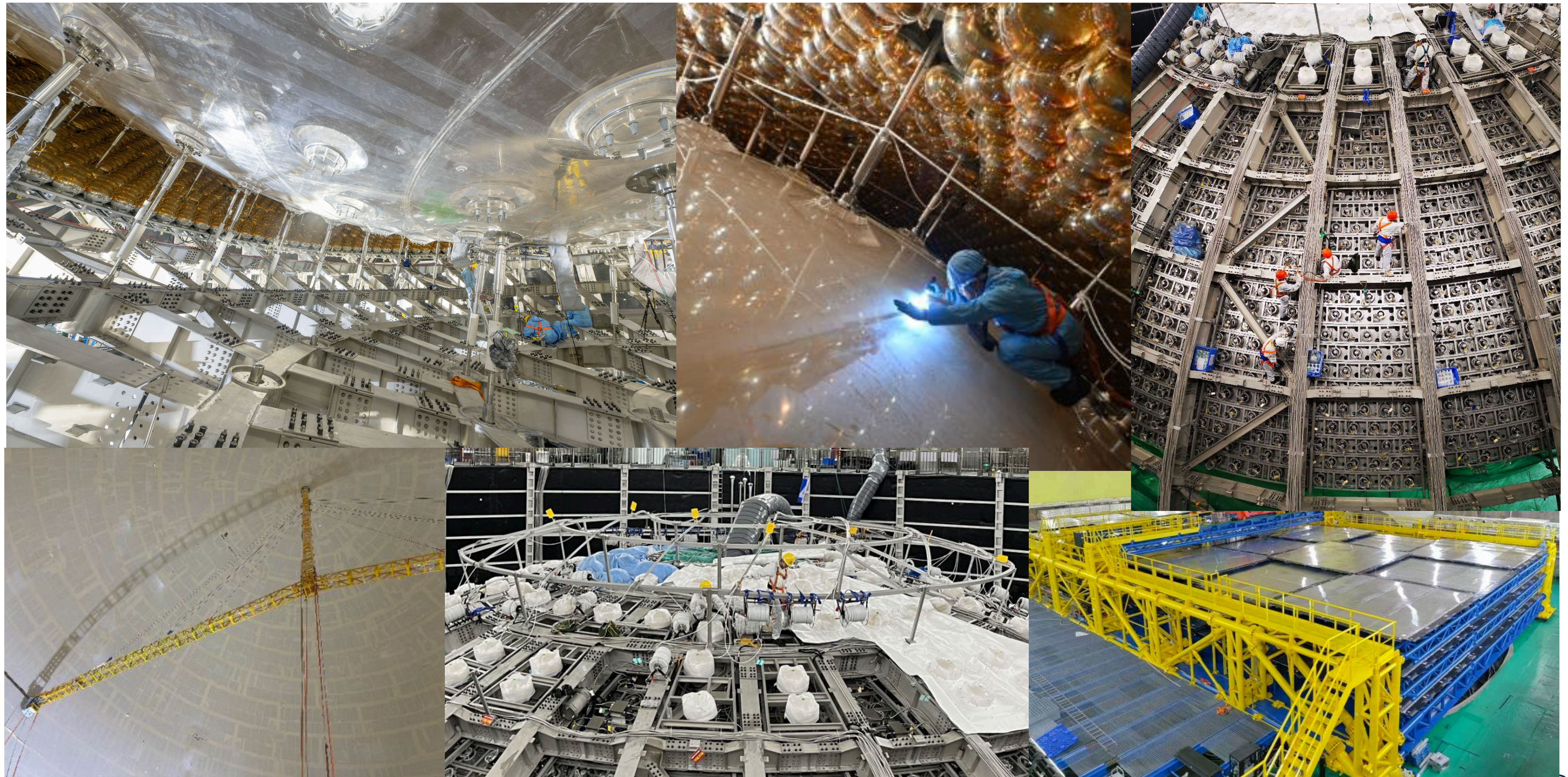


arXiv:1508.07166

Prog. Part. Nucl. Phys. 123(2022), 103927

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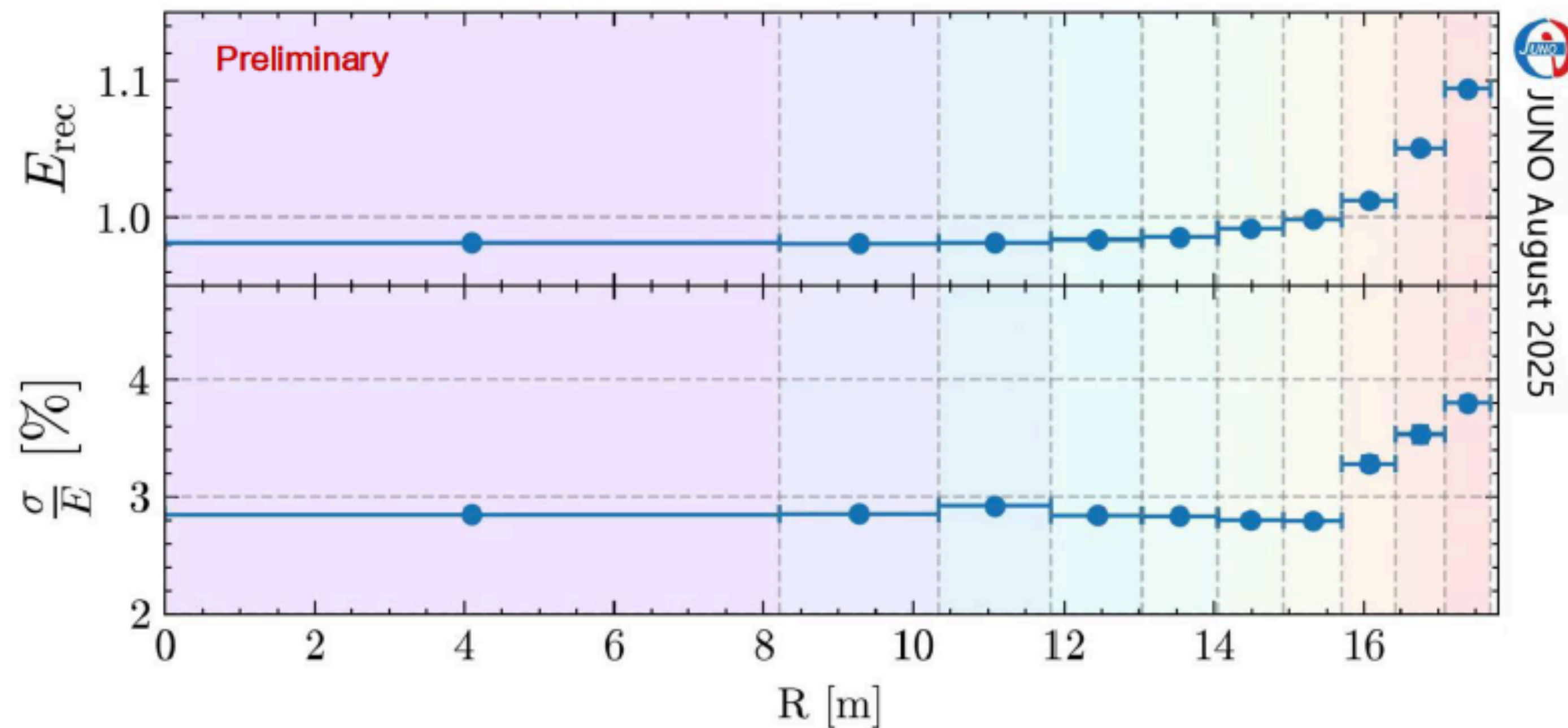
Picture gallery



Preliminary energy resolution

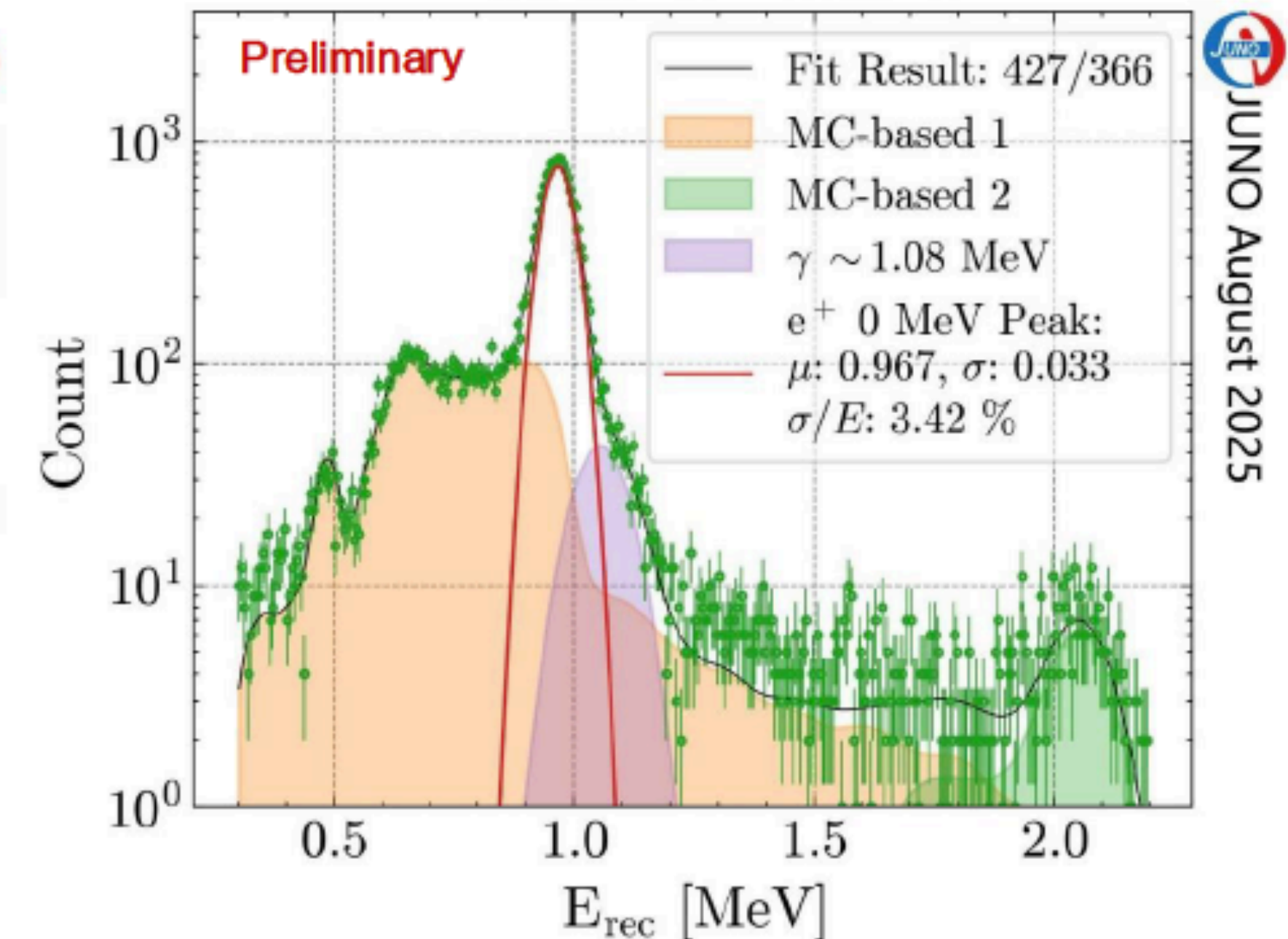
- Energy resolution for alpha from ^{214}Po is $\sim 3\%$ @ 0.92MeV
- Energy resolution for ^{68}Ge is $\sim 3.4\%$ @ $2 \times 0.511\text{ MeV}$, already close to but slightly worse than the expectation of 3.1%
- Further improvement are coming: more calibration data, noise/flasher removal, reconstruction and fit, ...

Energy Non-uniformity and Resolution of ^{214}Po



CREDIT: Y. F. Wang 2025

^{68}Ge at CD Center



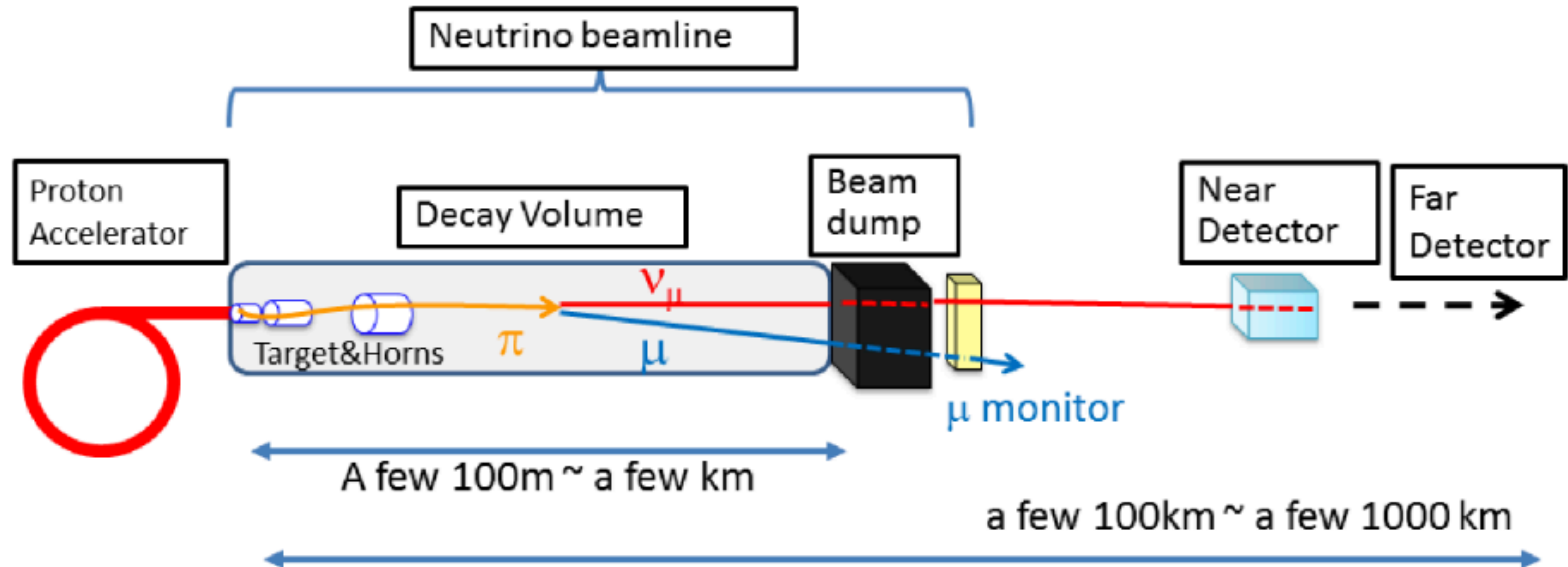
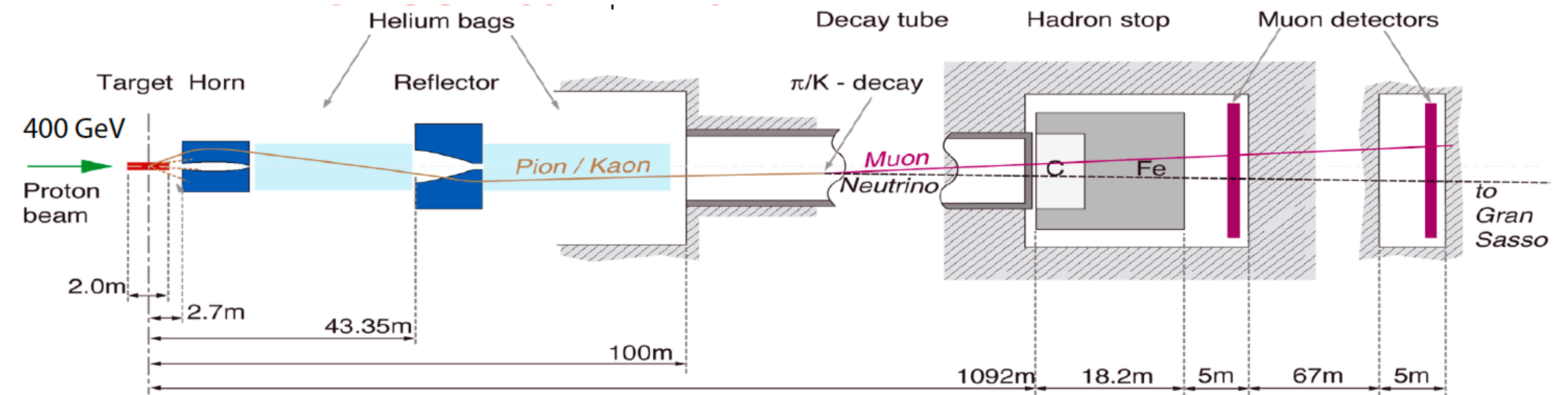


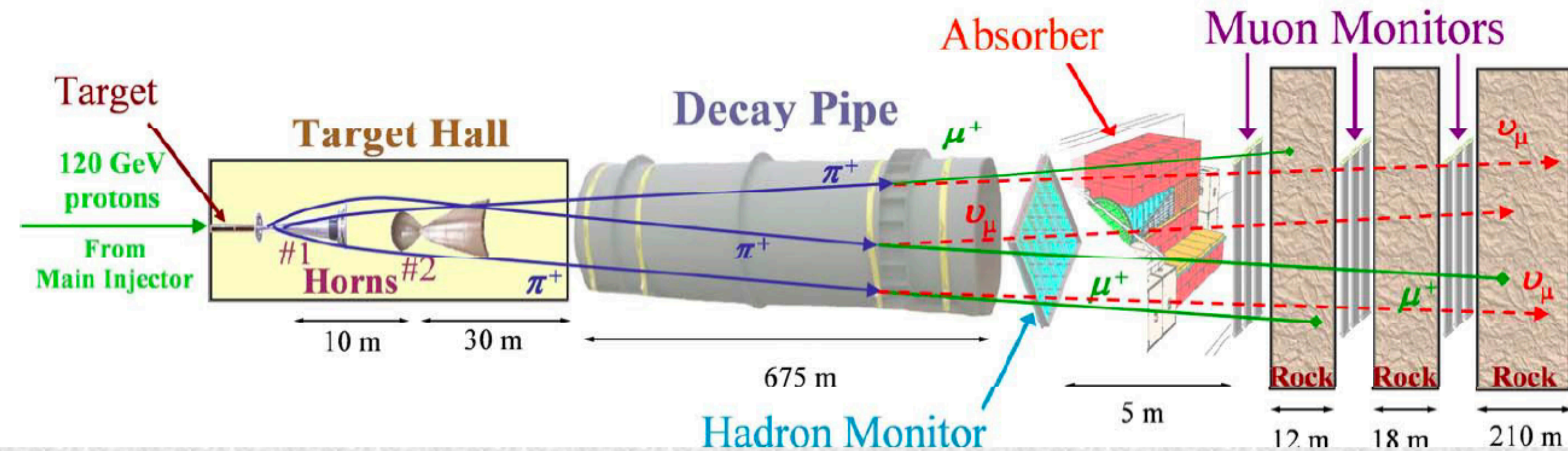
FIGURE 1. Components of the accelerator neutrino experiment

Neutrino beams: examples

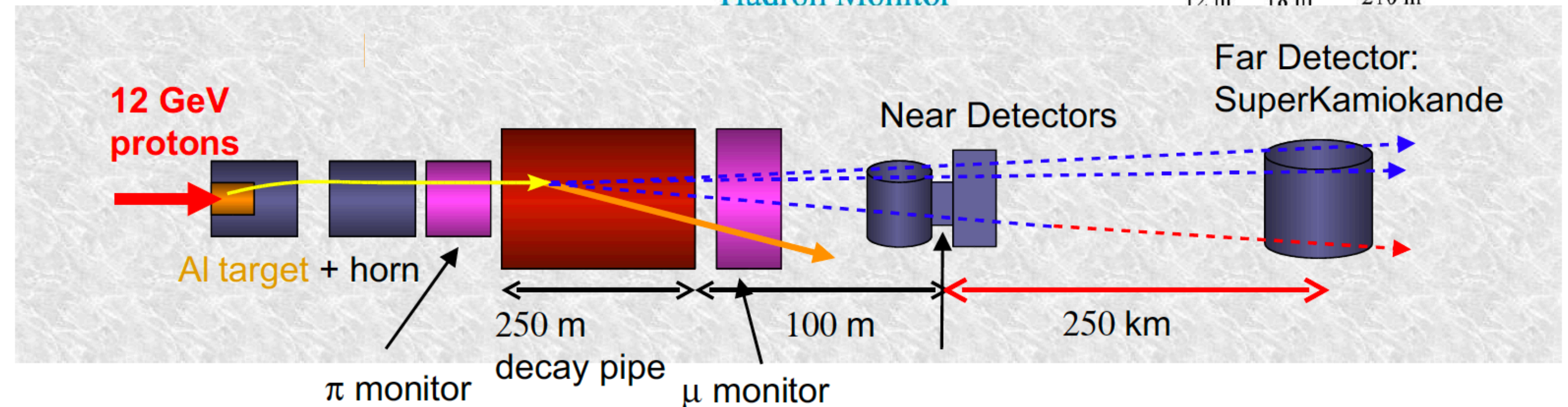
CNGS: CERN -> LNGS

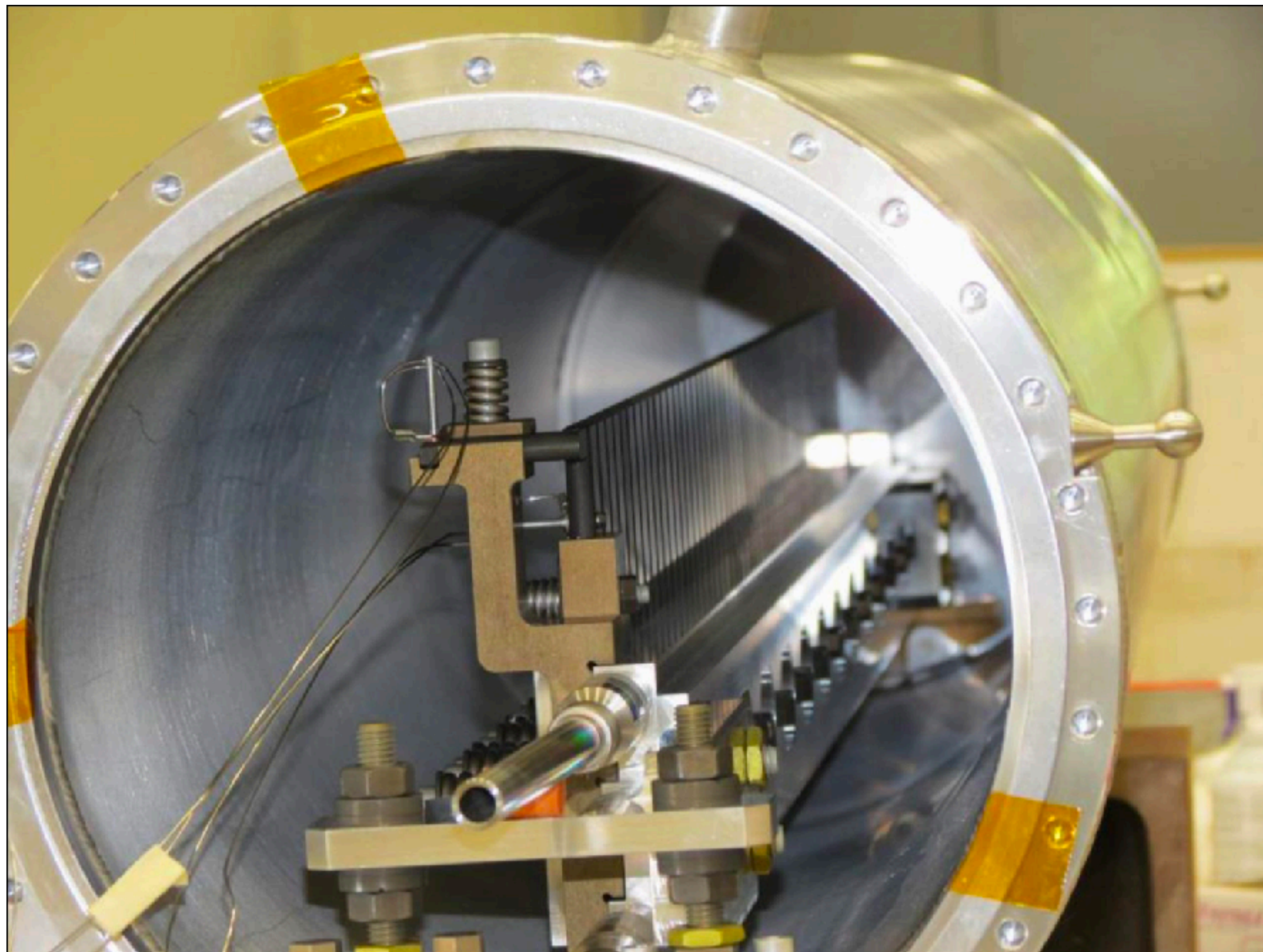


Fermilab: FNAL to MINOS, NuMi

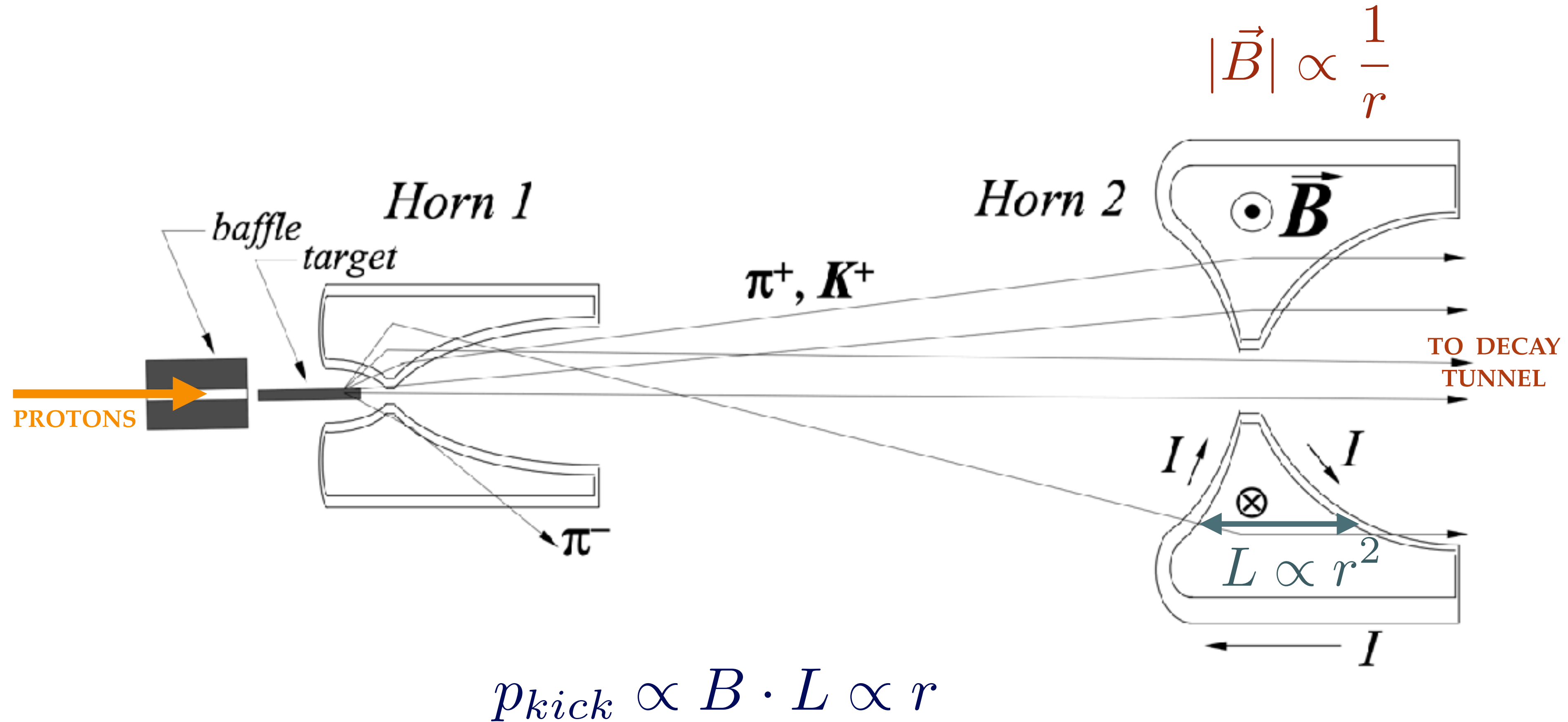


K2K: KEK to Kamioka

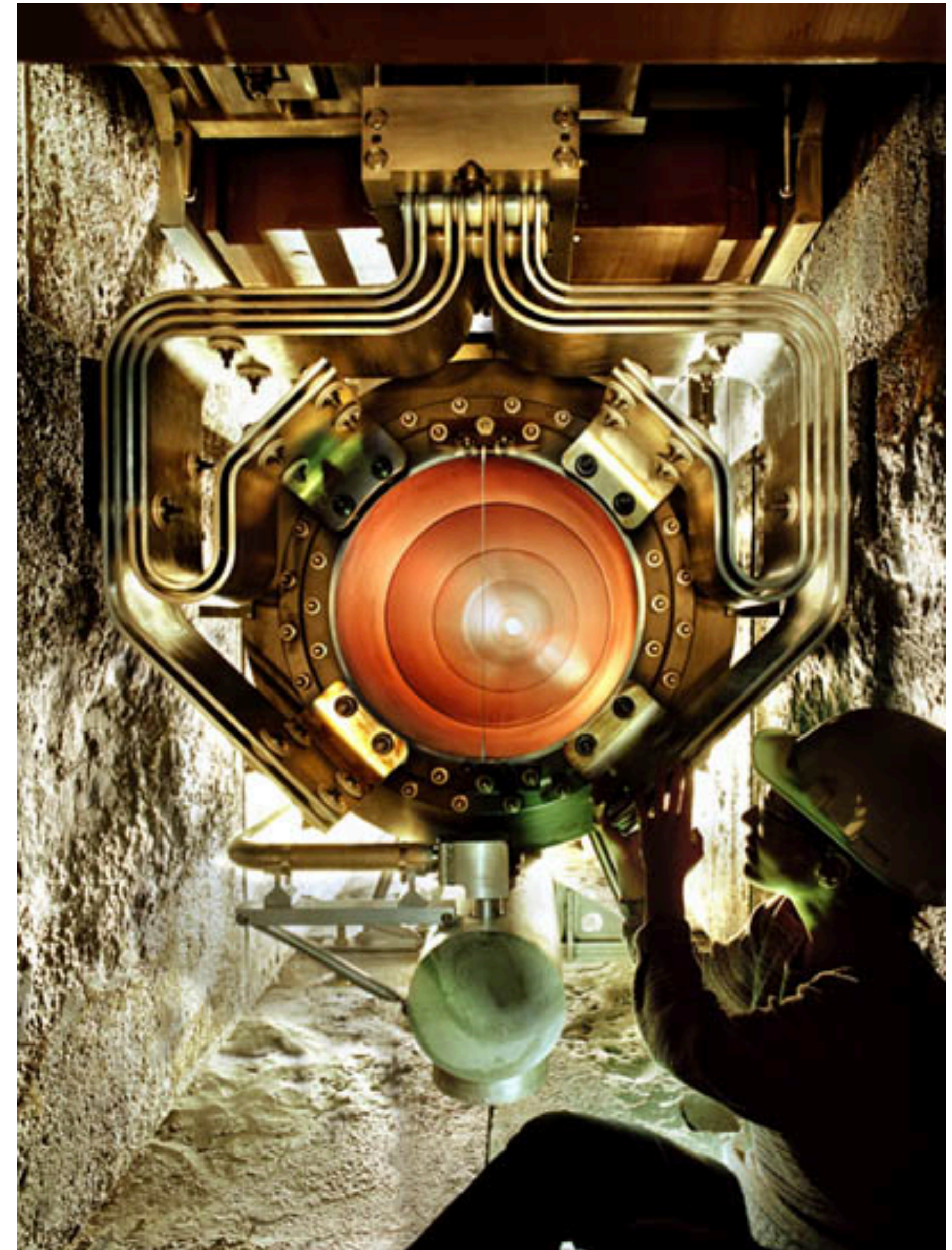




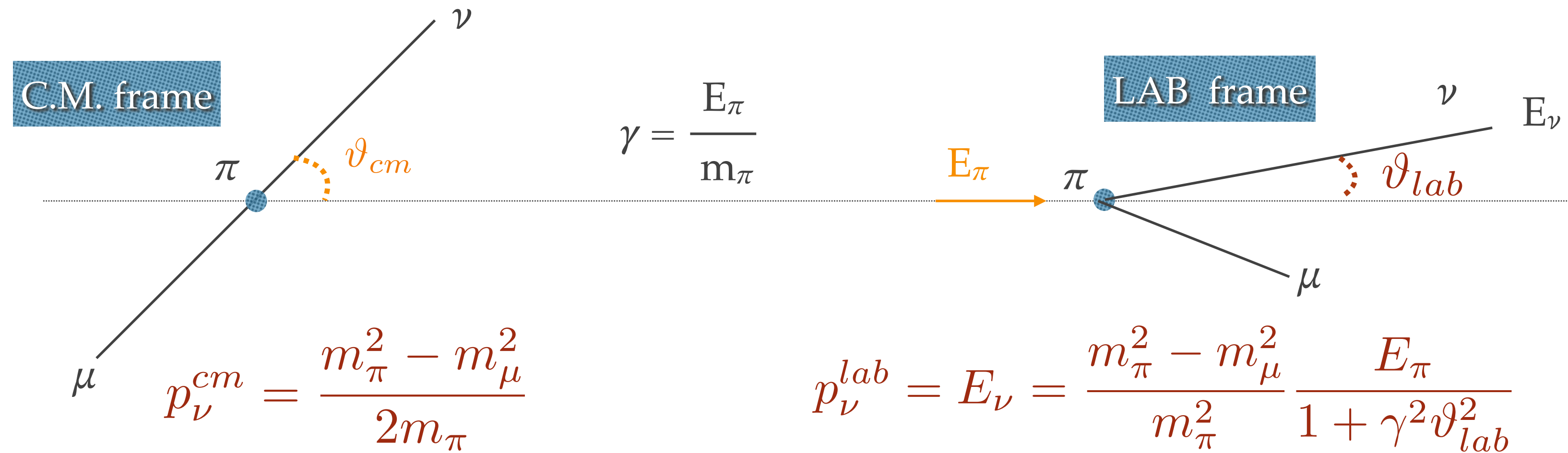
Focussing: conceptual scheme



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

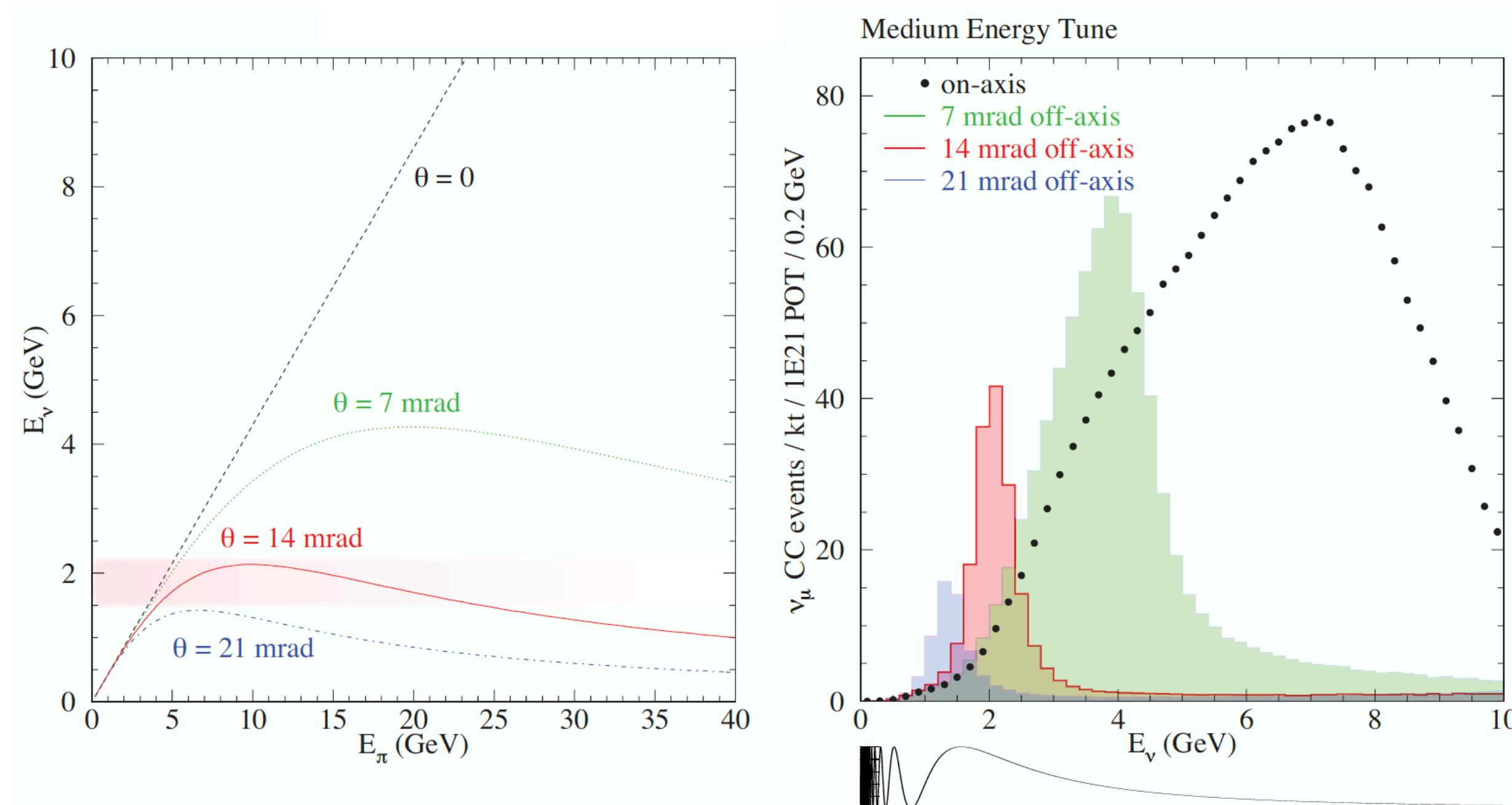


ON-axis vs OFF-axis: narrowing neutrino energy spread



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

NuMi
example

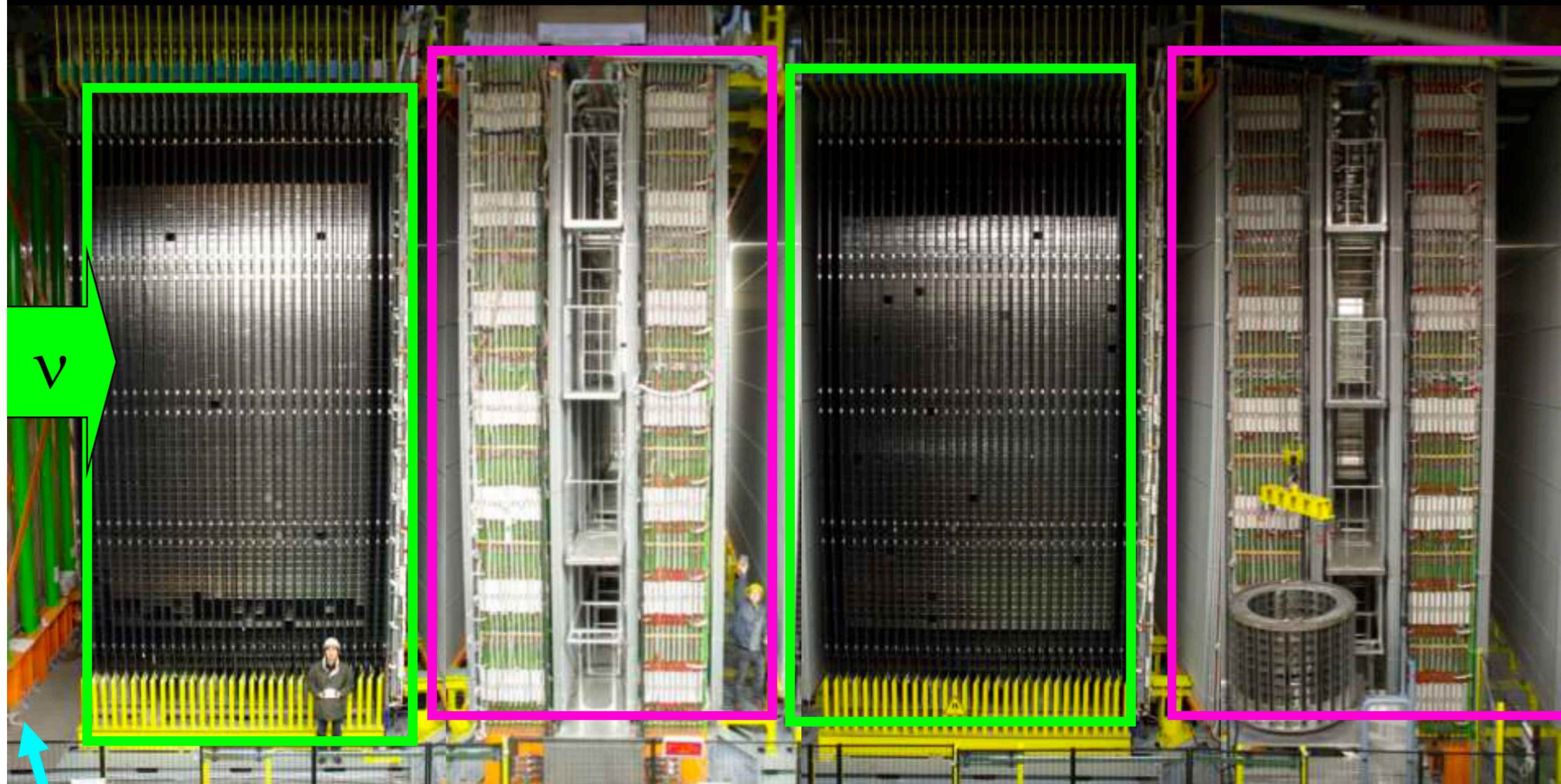


Example: Opera experiment @ LNGS

OPERA Detector

GranSasso Undergroud Lab, Italy

~150000 ECC Bricks = Weight ~1250 ton



ν

Veto

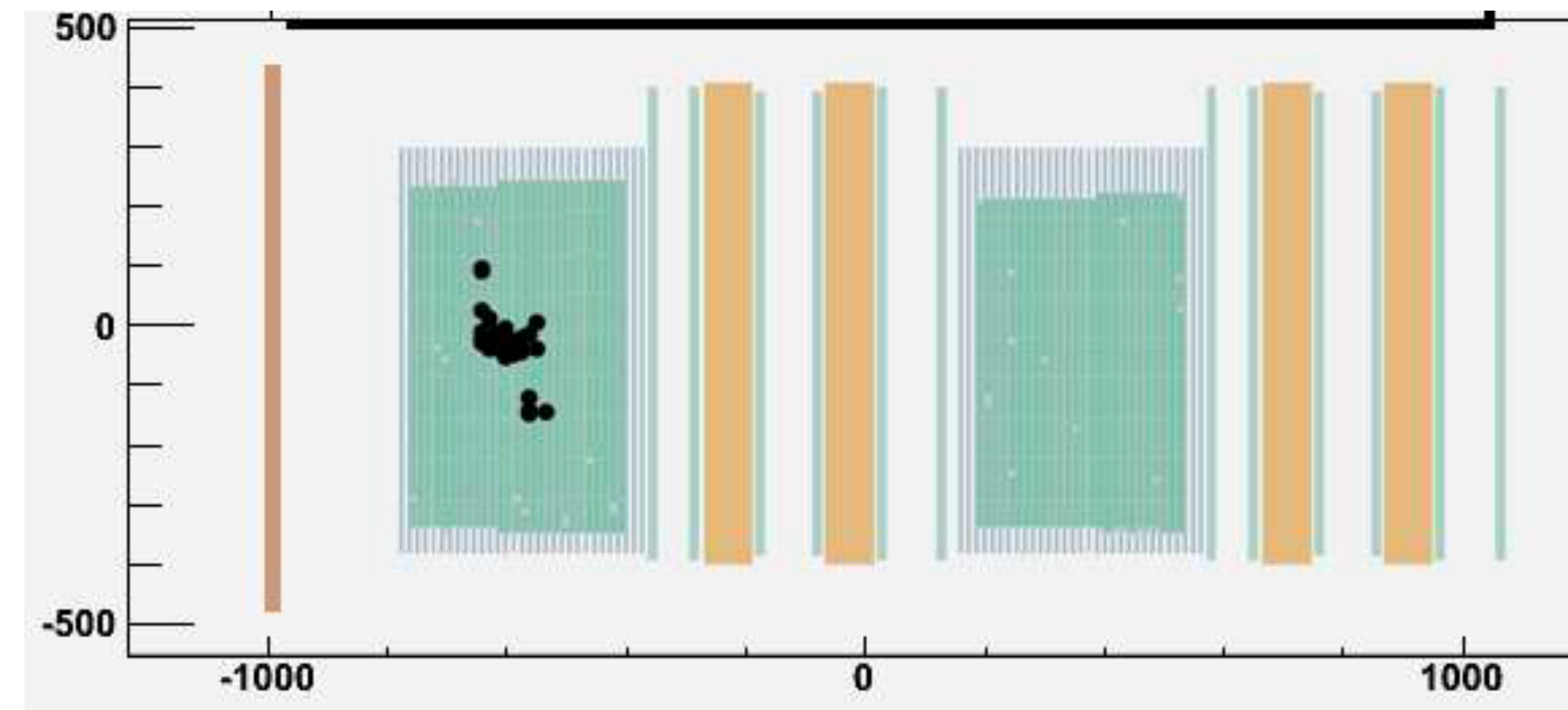
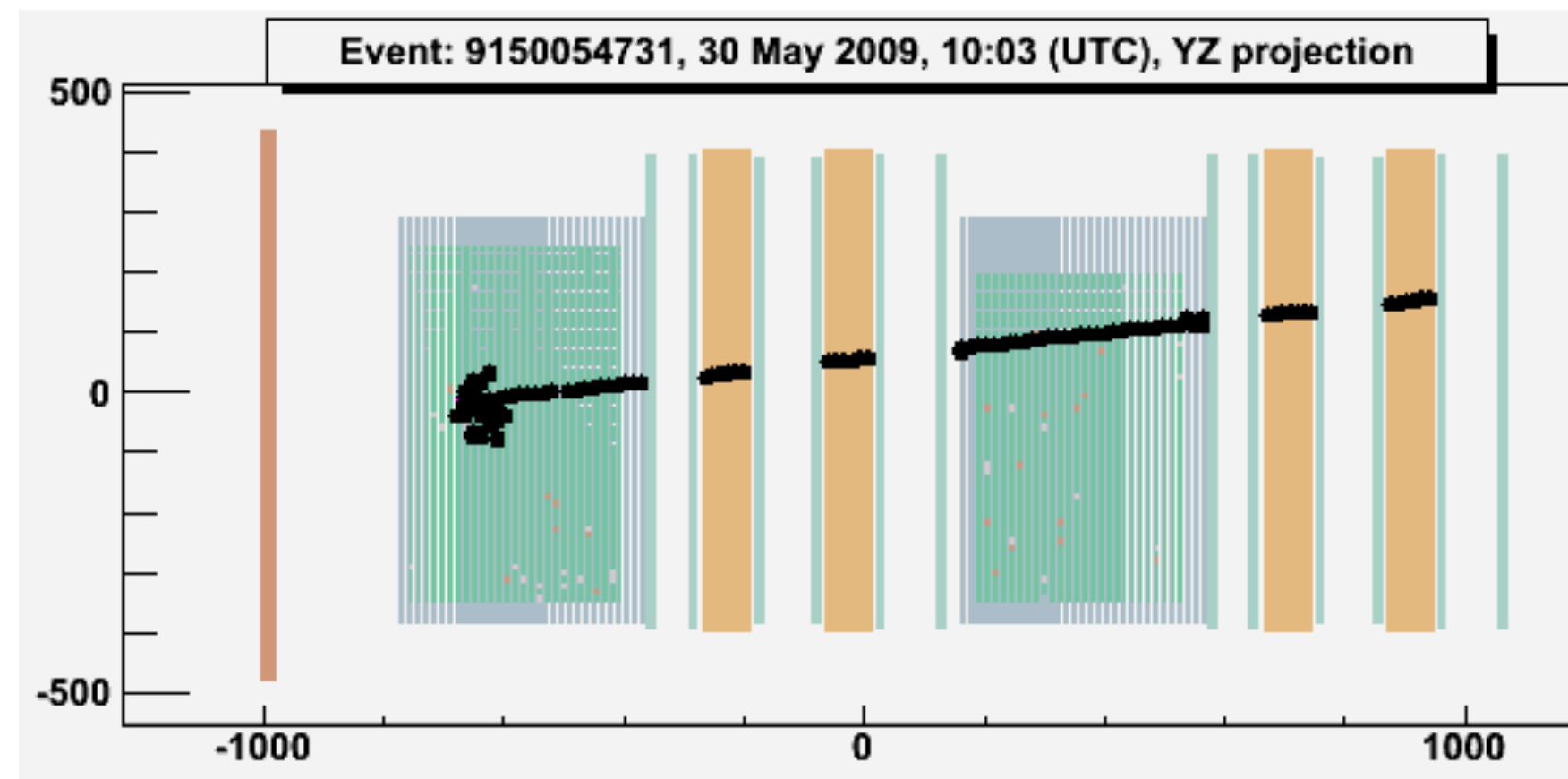
Target area

Muon
spectrometer

Target area

Muon
spectrometer

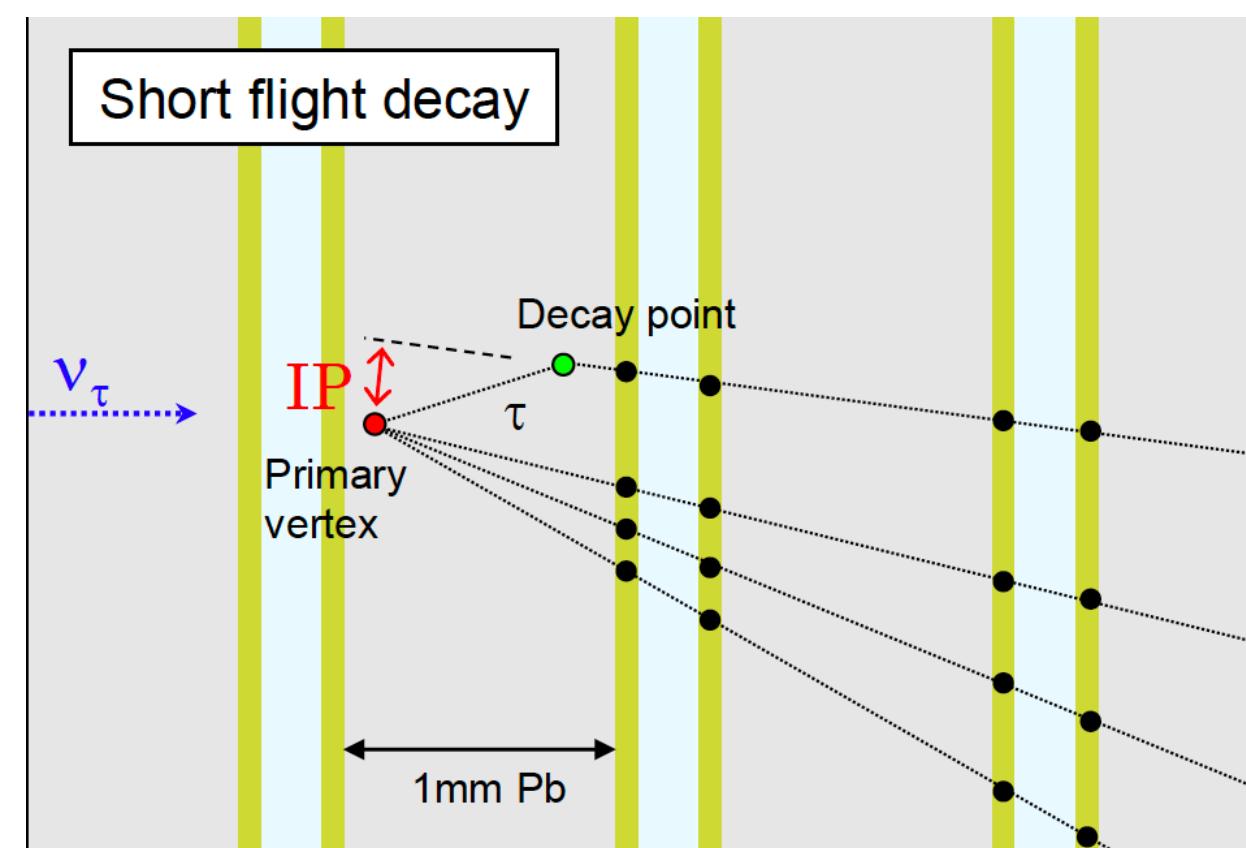
Example: Opera experiment at LNGS



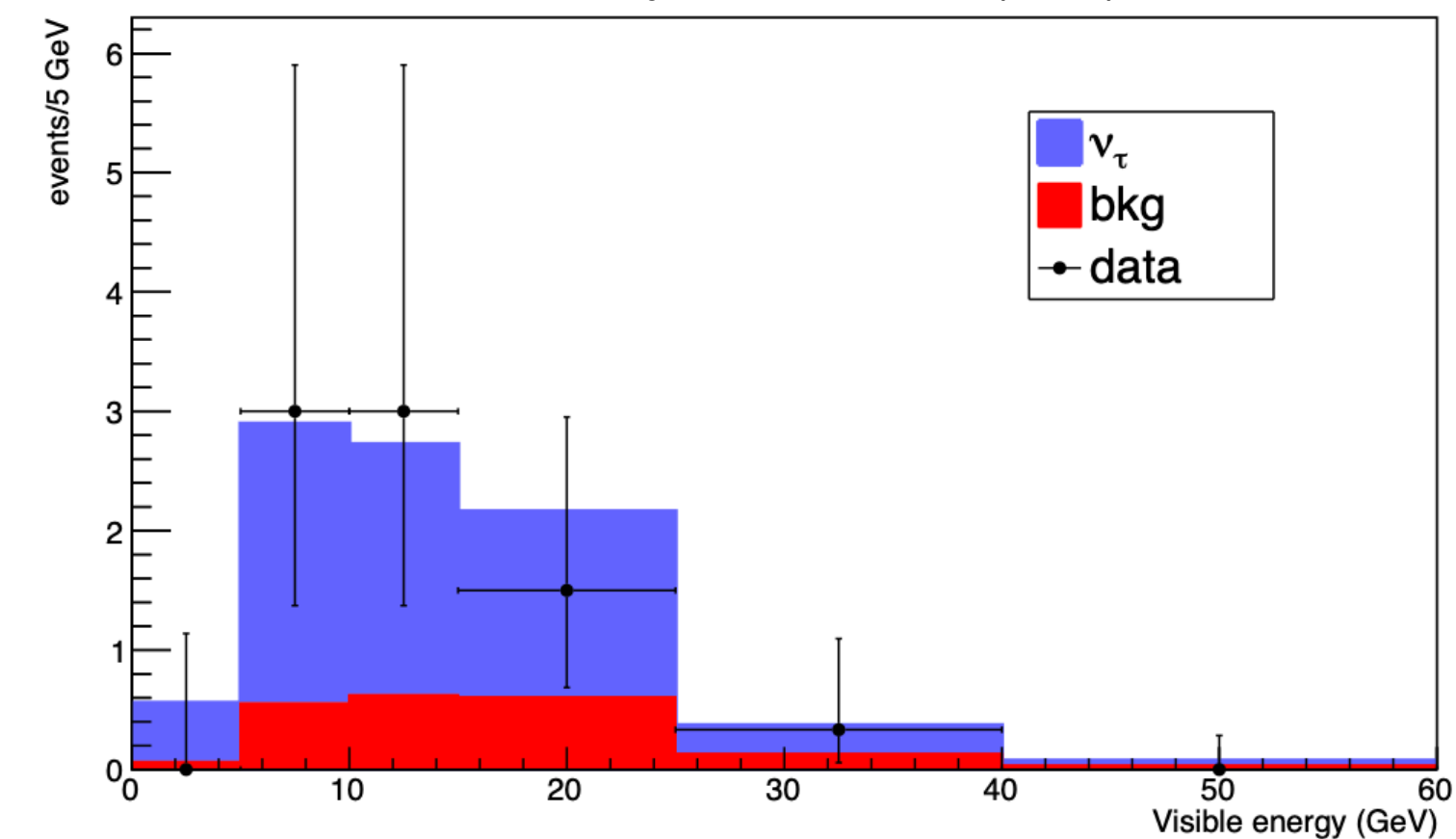
BRICK ID	72693	29570	23543	92217	130577	77152	27972	26670	136759	4838
Channel	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow \mu$	$\tau \rightarrow 1h$	$\tau \rightarrow 1h$	$\tau \rightarrow 1h$	$\tau \rightarrow 1h$	$\tau \rightarrow 1h$	$\tau \rightarrow 3h$	$\tau \rightarrow 3h$
z_{dec}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

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

10 candidates



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



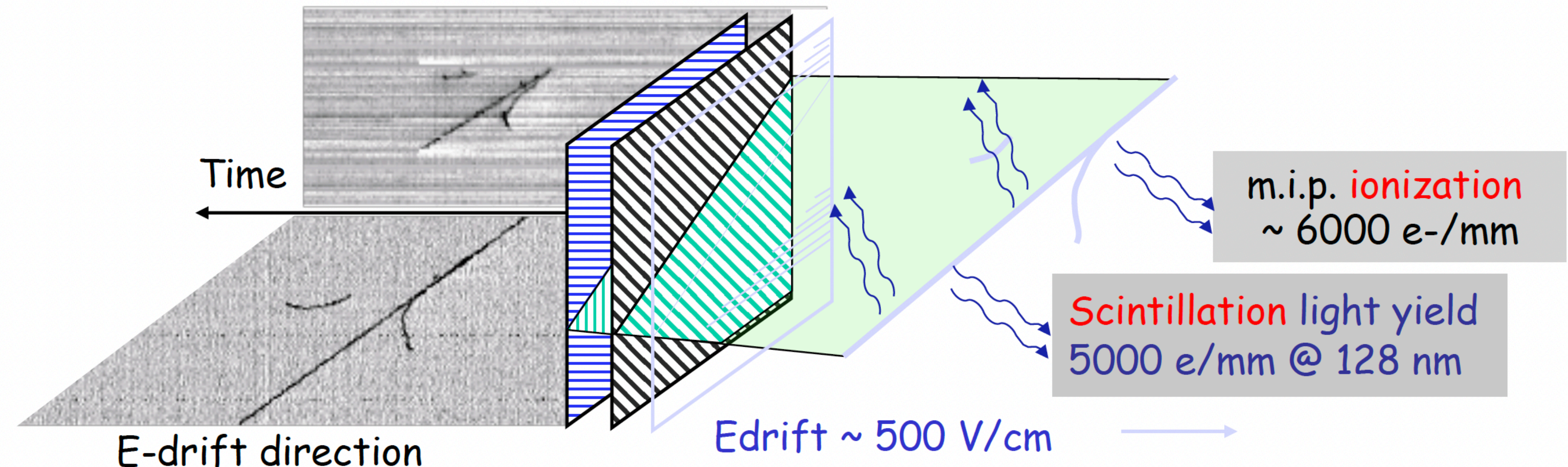
Example: Noble Liquid Detectors

A new, powerful detection technique initiated at CNGS

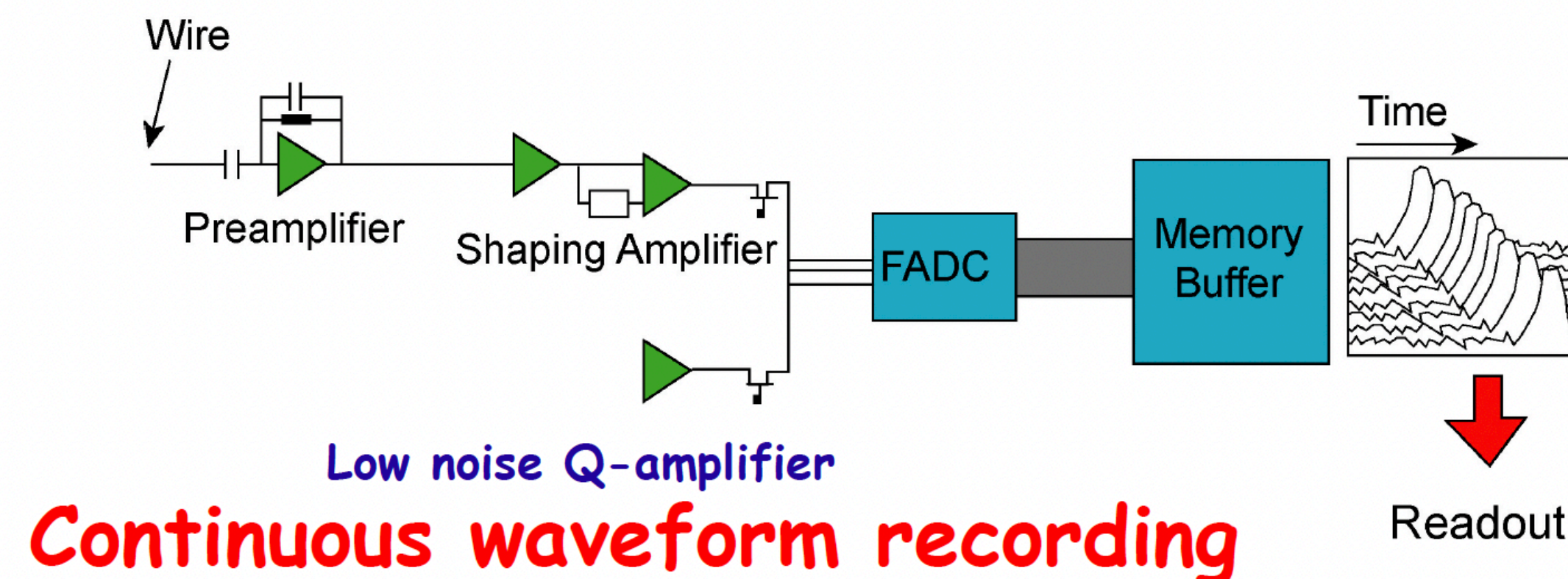
NOTE

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

See DM lectures



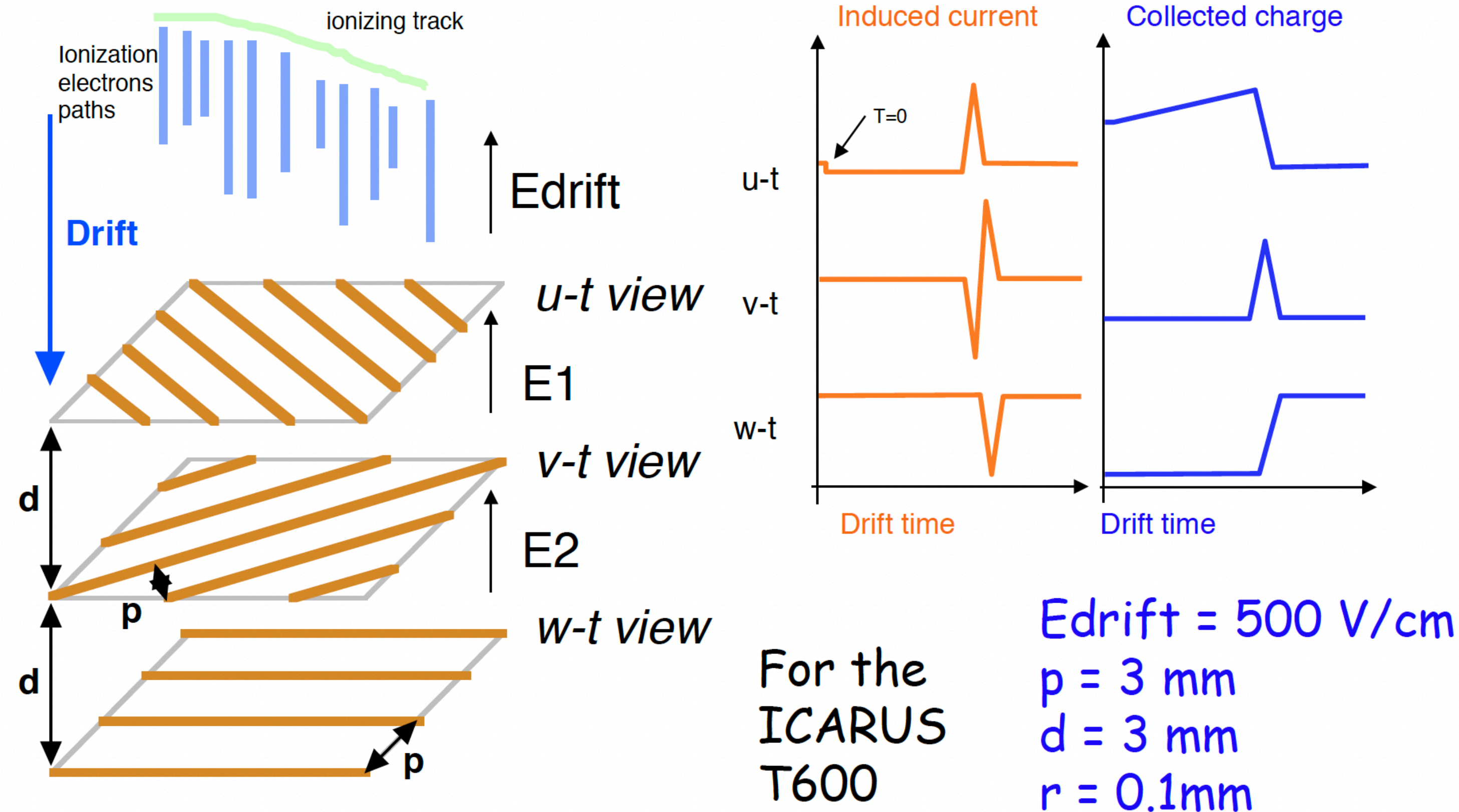
Drifting electrons are moving to transparent wire arrays oriented in different directions, where signals are recorded.



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

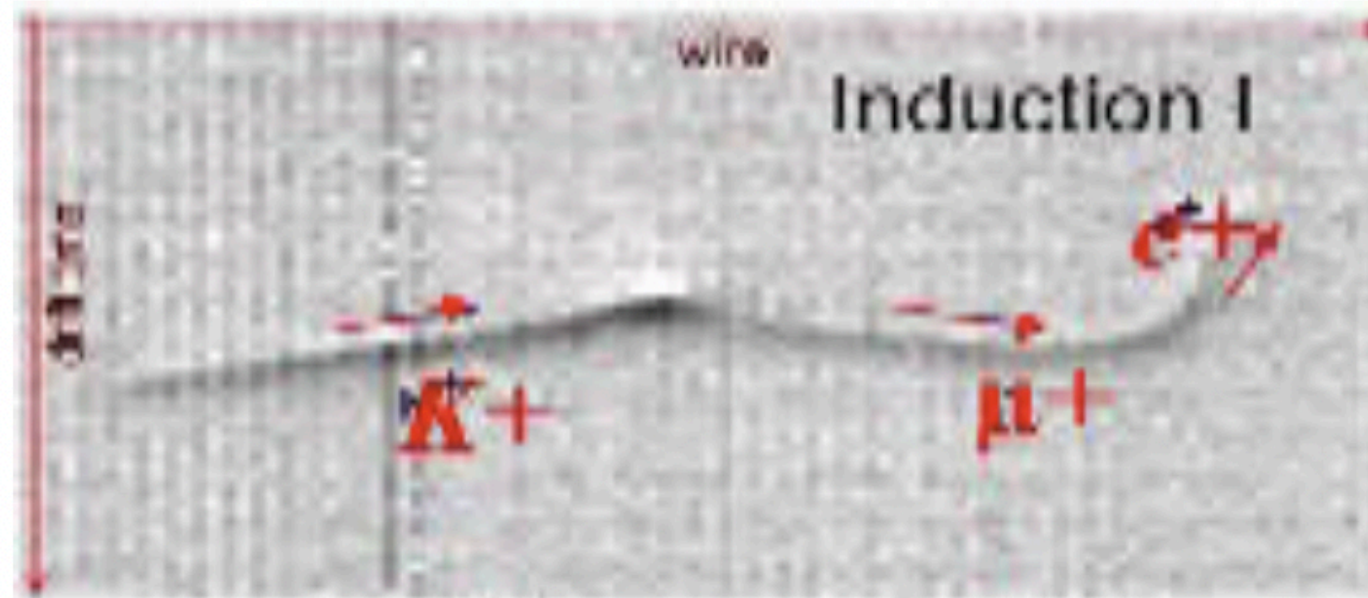
C. Rubbia, 2019

Non destructive multiple charge readout

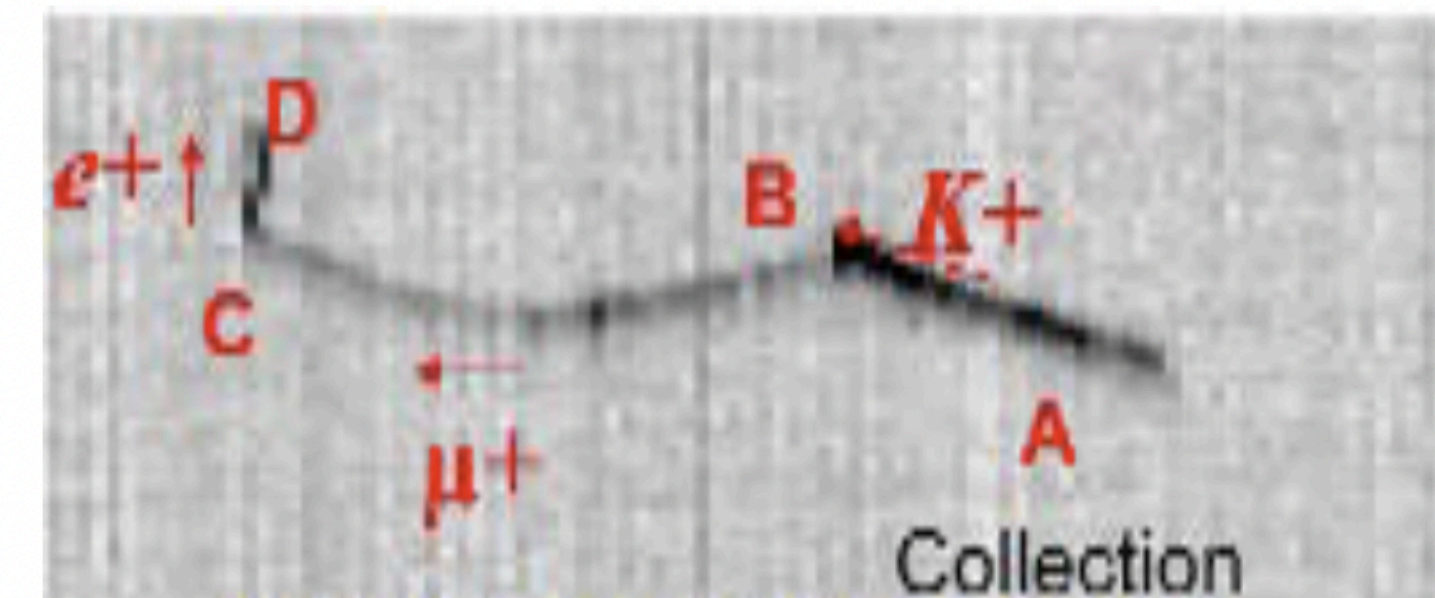


- At FNAL's shallow depth, the T600 will require two additions:
 - 3 m concrete overburden to mitigate the c. rays background,
 - Particles entering the detector must be removed with a Cosmic Rays Tagging (CRT) around the full LAr volume

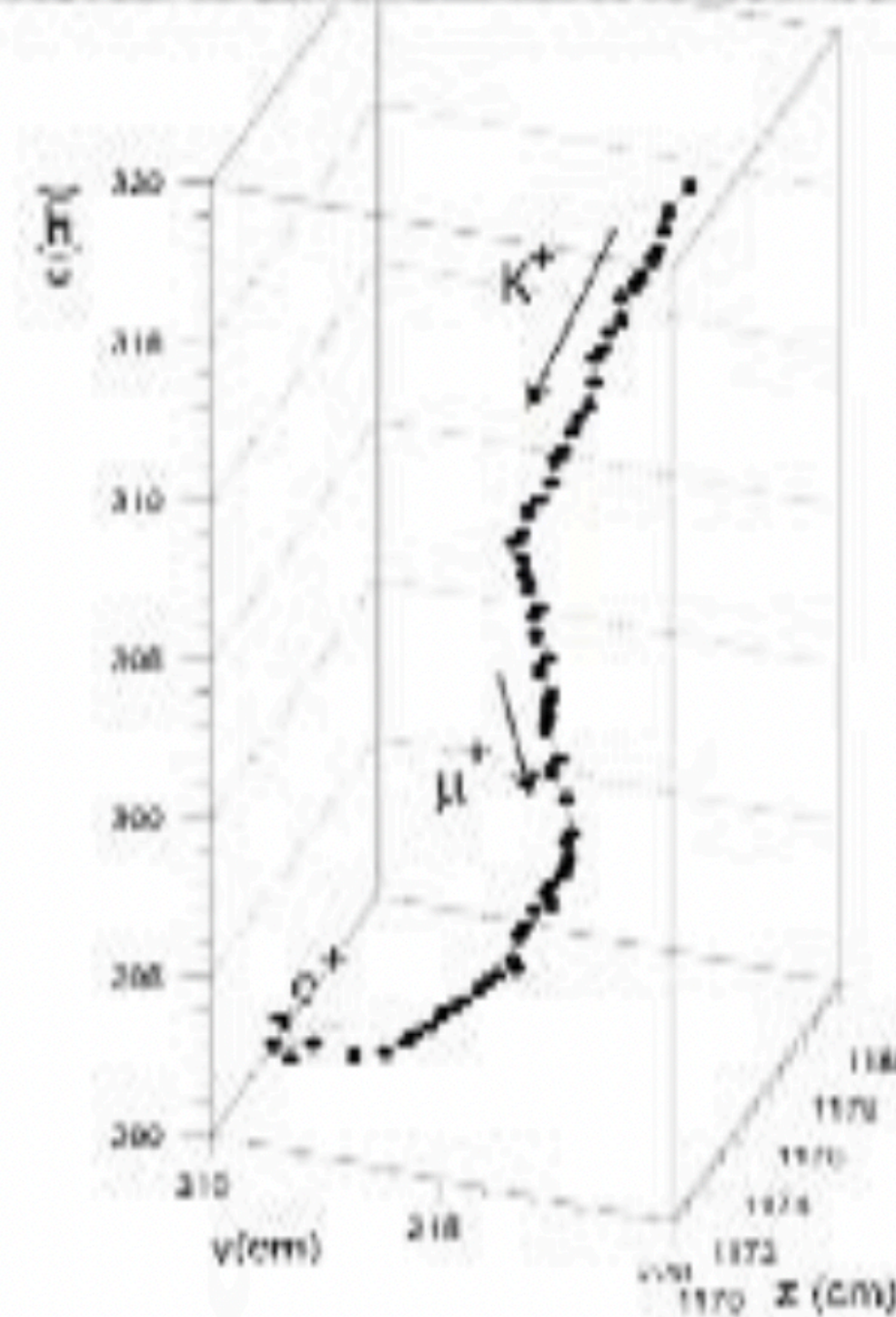
Example: 3 D particle identification : $K^+ \rightarrow \mu^+ \rightarrow e^+$



ICARUS EVENT

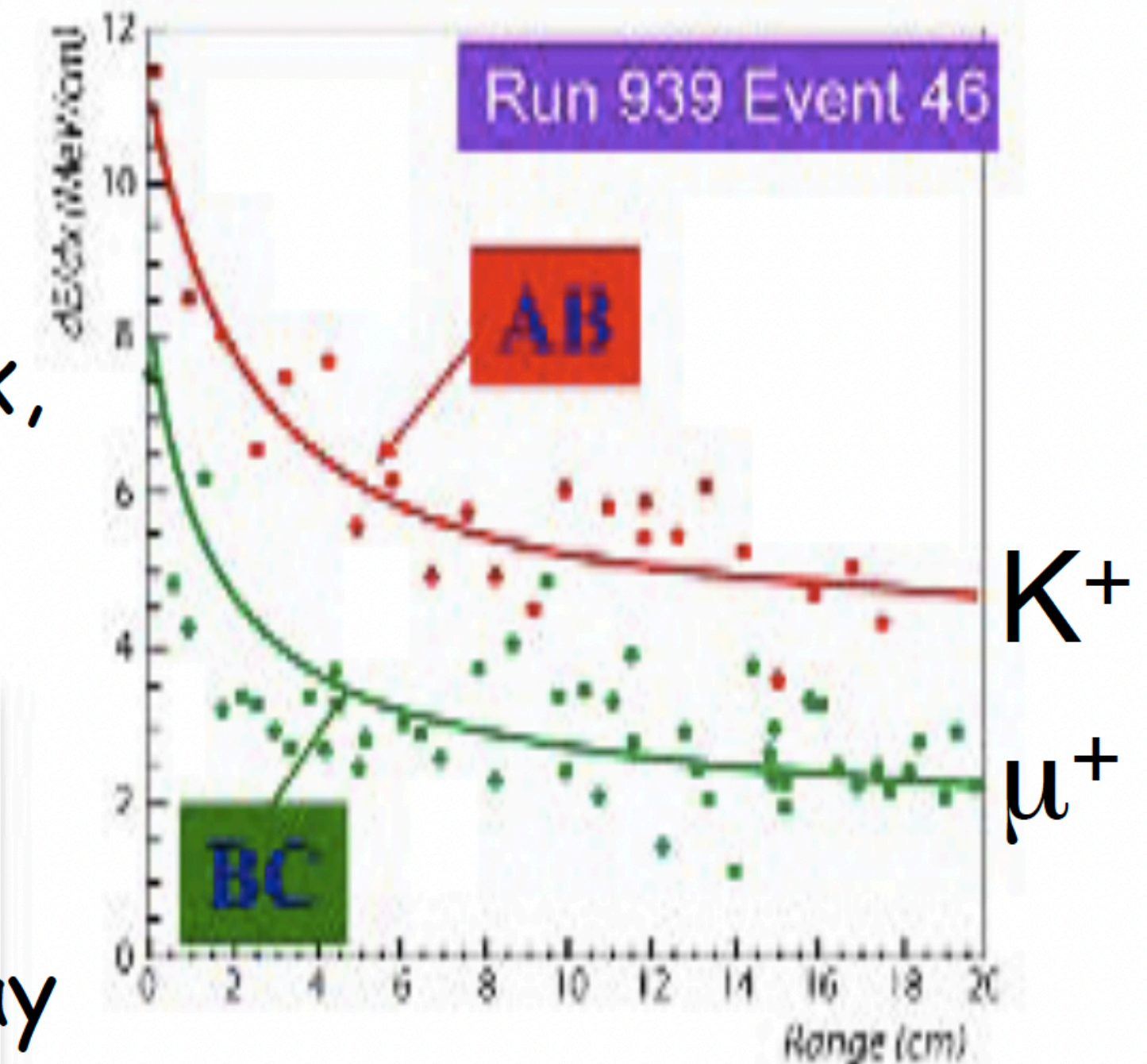


$K^+ [AB] \rightarrow \mu^+ [BC] \rightarrow e^+ [CD]$



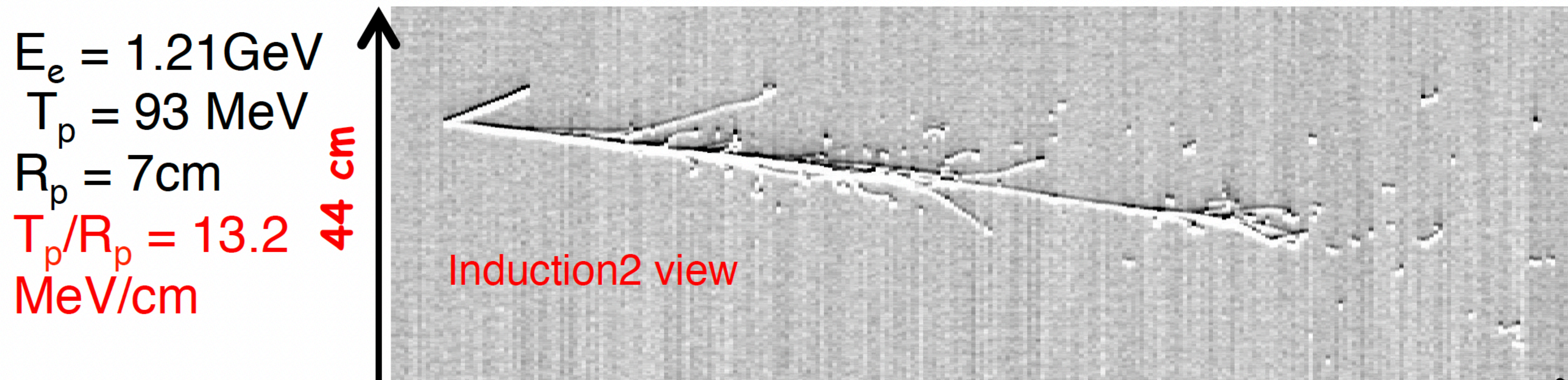
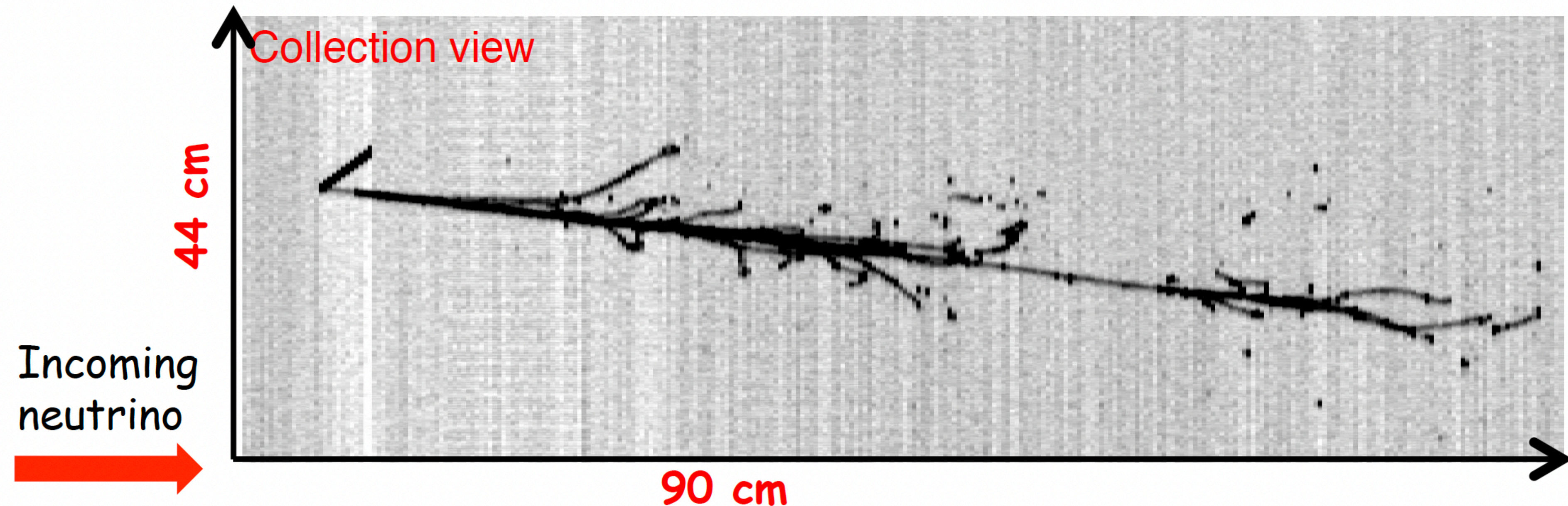
Efficient, low mis-identification, due to precise 3D reconstruction, dE/dx , range measurement

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



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

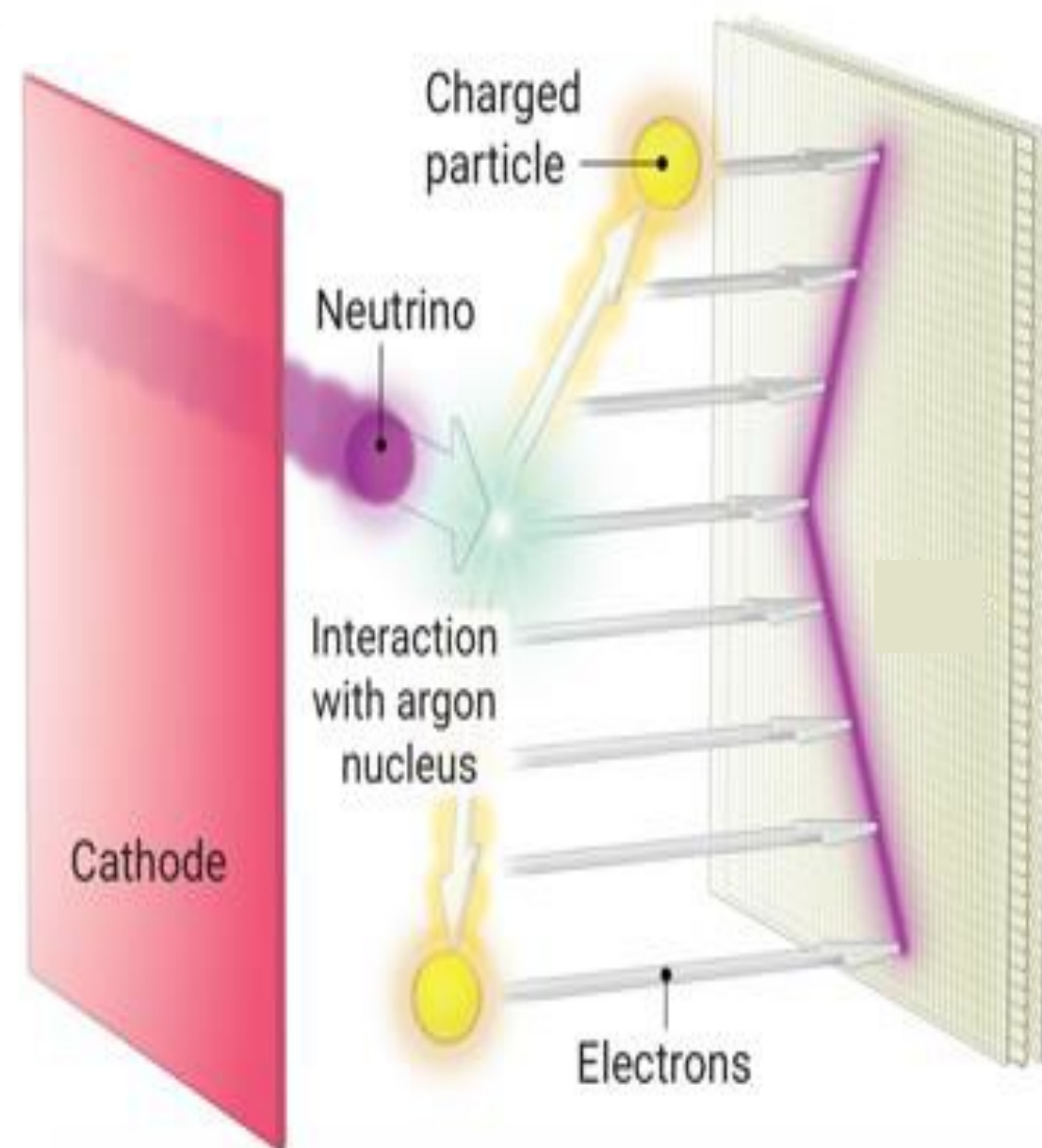
$$E_\nu = 1.34 \text{ GeV} \quad E_{\text{dep}} = 1.29 \text{ GeV}$$



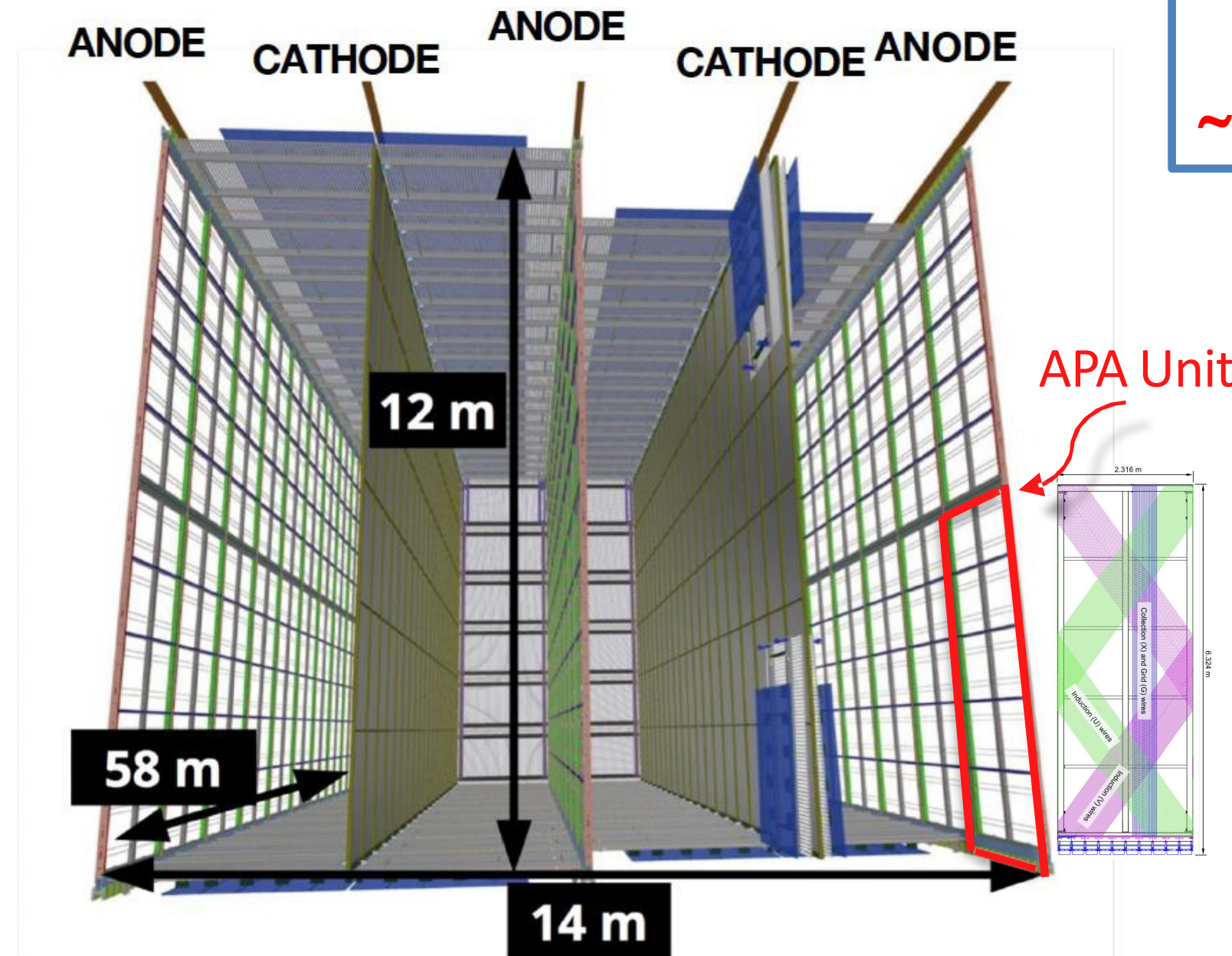
C. RUDDIA, 2019

The future of LAr: DUNE

LAr TPC technology



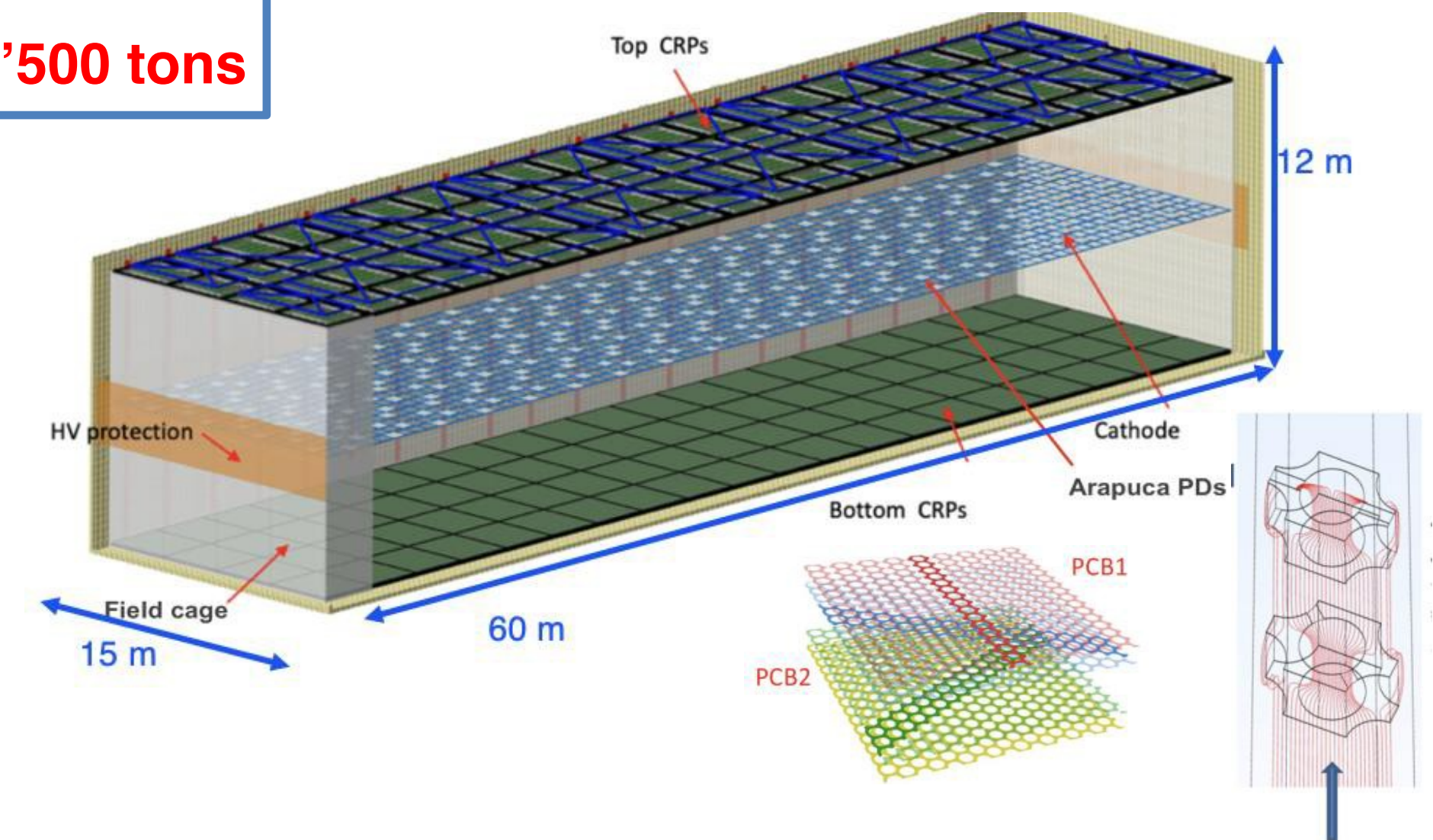
FD1-HD «Horizontal drift» (ICARUS concept, wires)



- 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)

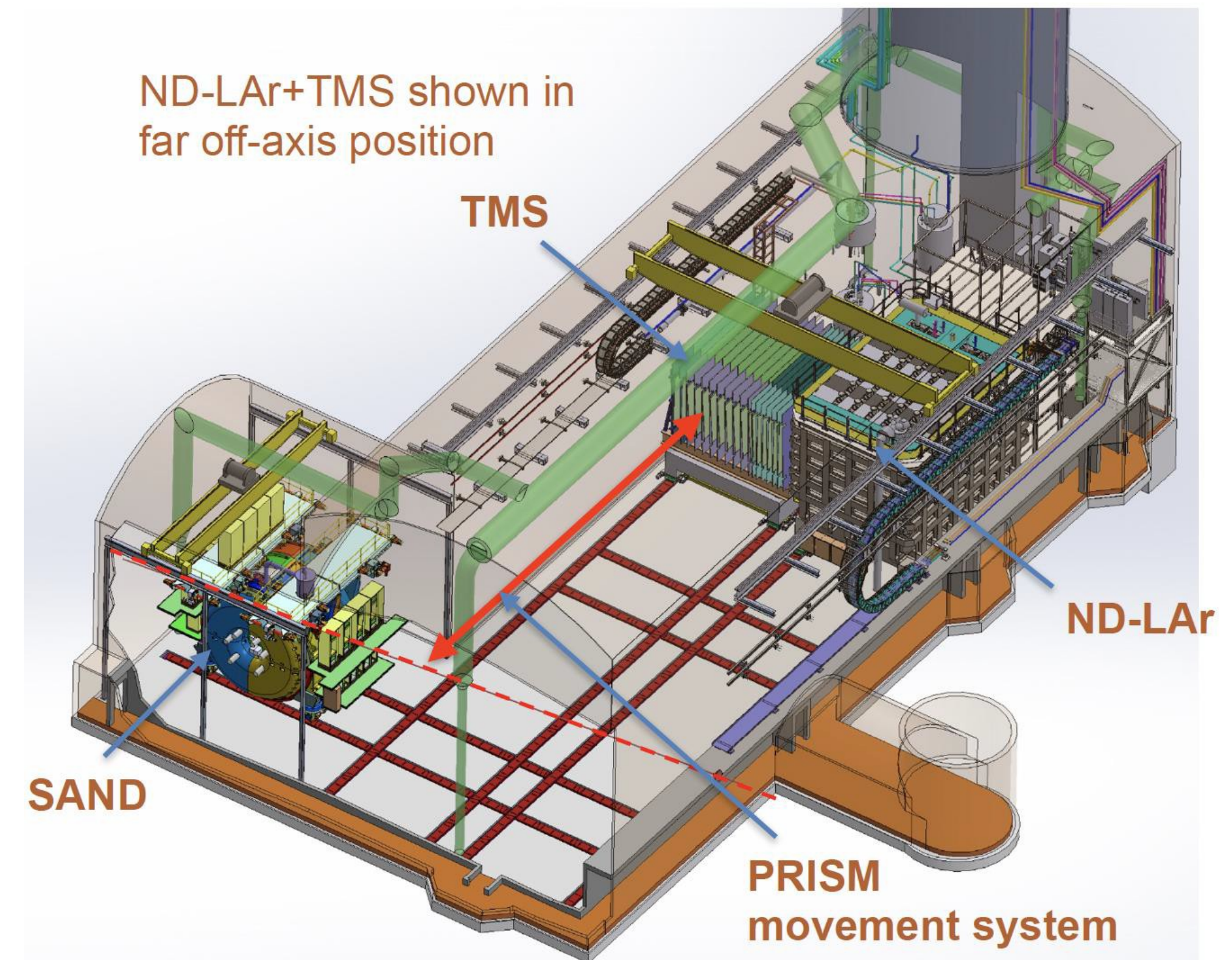


- Charge Readout Planes : perforated PCB's with segmented electrodes (strips)
- CRPs at the top and bottom
- Cathode (-300 kV) in the middle
- two 6.5 m drift chambers 450 V/cm field
- X-Arapuca modules integrated on cathode and on cryostat walls.

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

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

- 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 precision neutrino oscillations

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

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

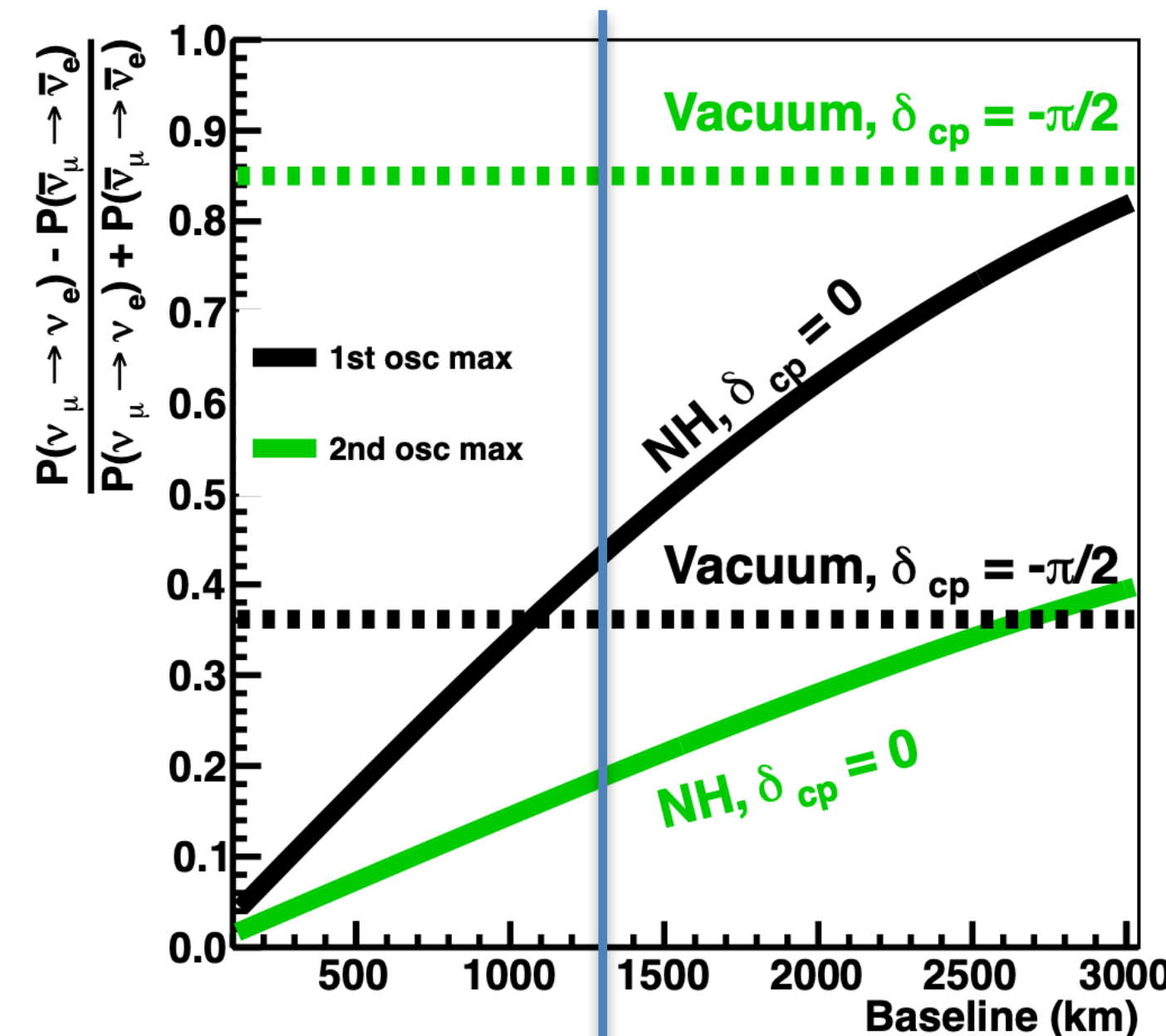
$$+ \cos^2 \theta_{13} \sin^2 2\theta_{12} \left(\frac{\delta m^2}{a} \right)^2 \sin^2 \left(\frac{aL}{4E} \right) - \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \left(\frac{\delta m^2}{a} \right) \left(\frac{\Delta m^2}{a - \Delta m^2} \right) \sin \left(\frac{aL}{4E} \right) \sin \left(\frac{a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

$a \rightarrow -a$
 $\delta \rightarrow -\delta$

Leading order approximation

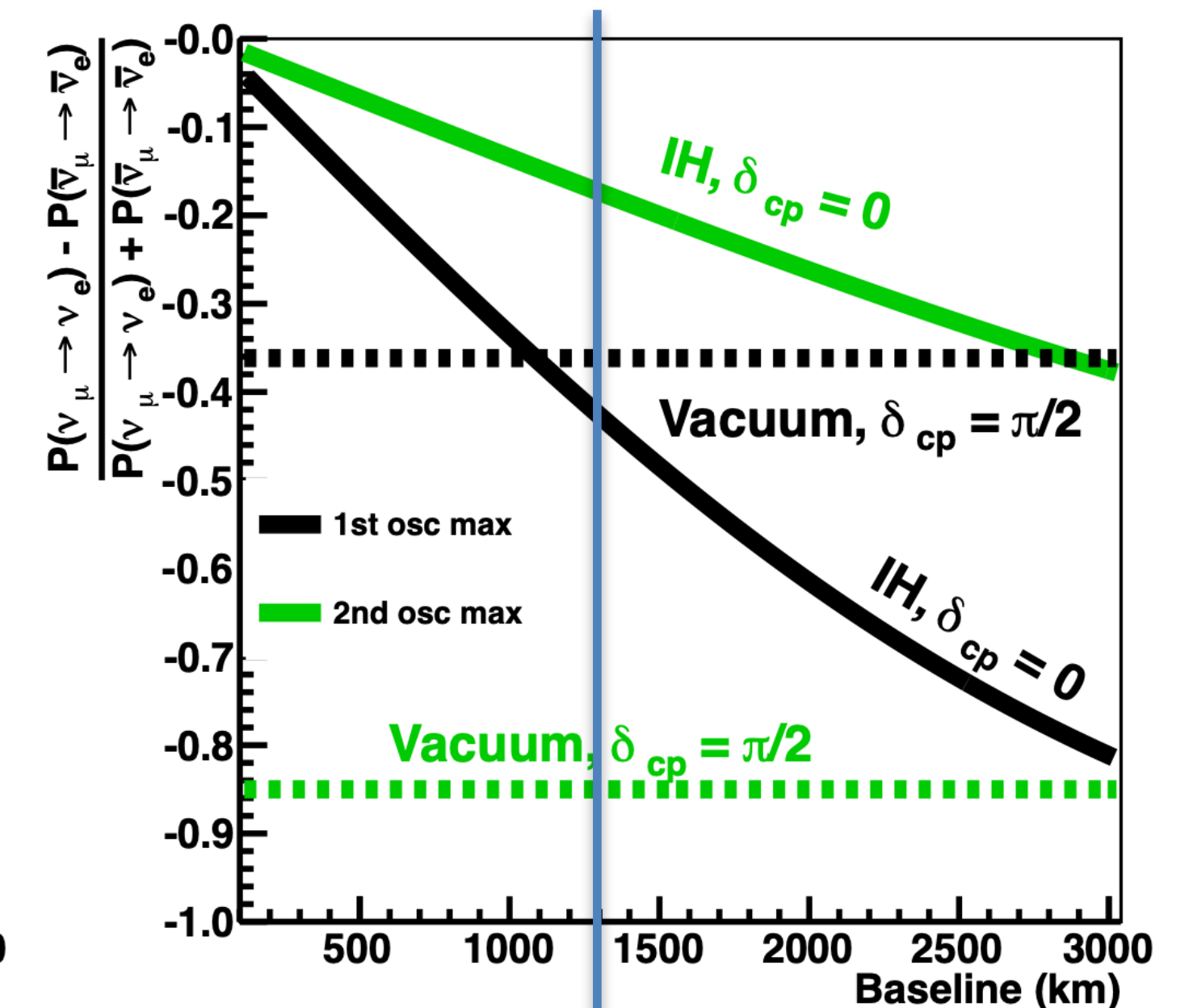
$$\mathcal{A}_{cp}(E_\nu) = \left[\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \right] \approx \frac{\cos \theta_{23} \sin 2\theta_{12} \sin \delta_{CP}}{\sin \theta_{23} \sin \theta_{13}} \left(\frac{\Delta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

- 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



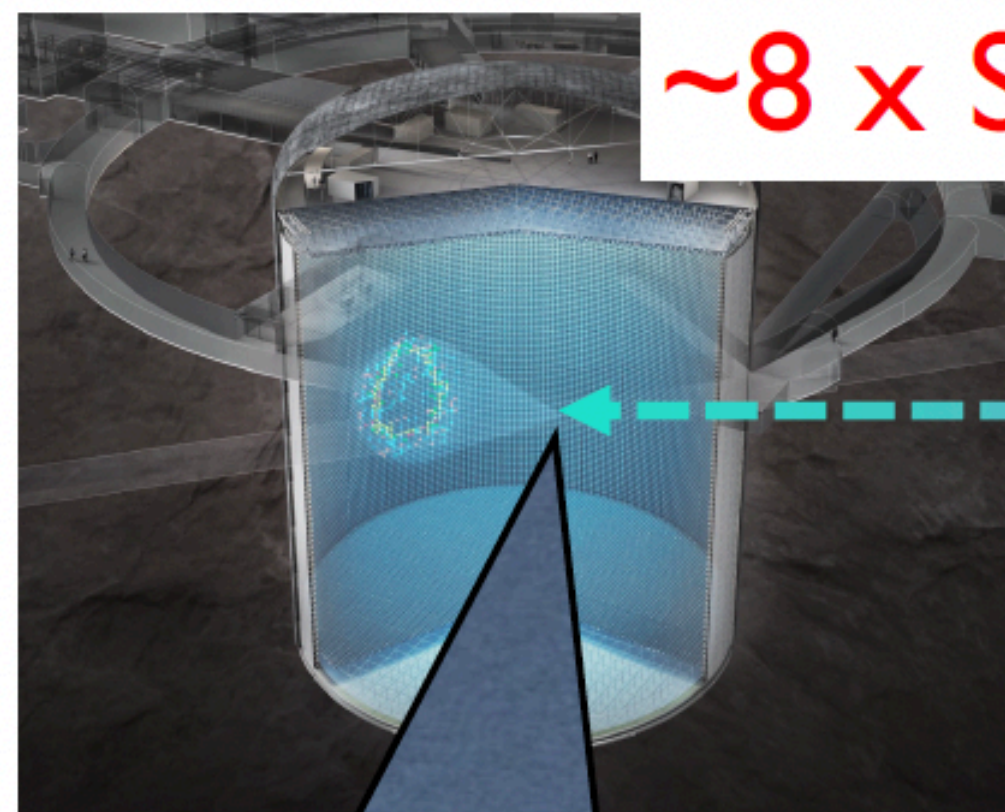
Phys. Rev. D 91 052015 (2015)

DUNE



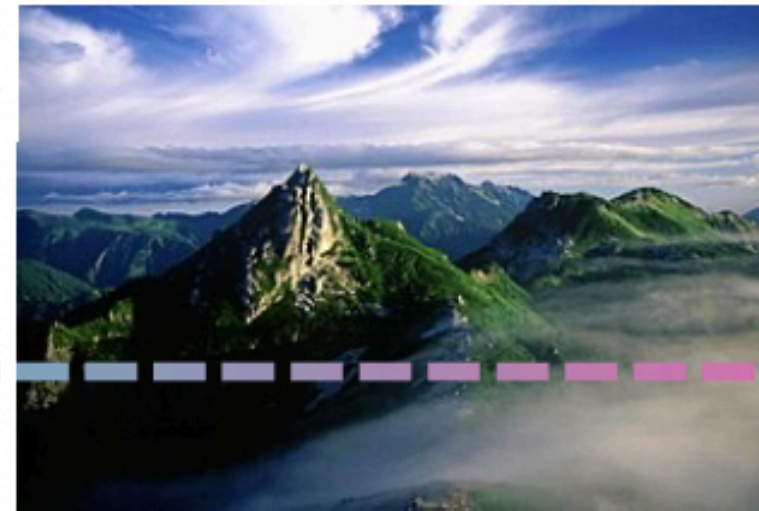
DUNE

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



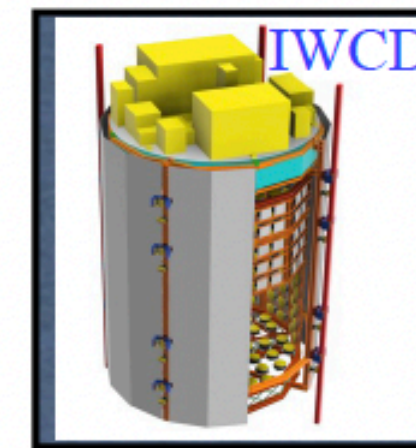
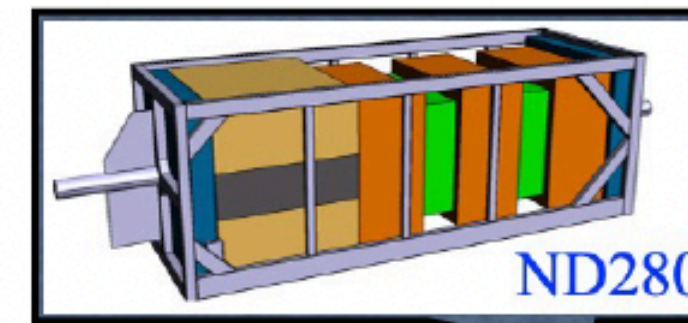
~8 x Super-K

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

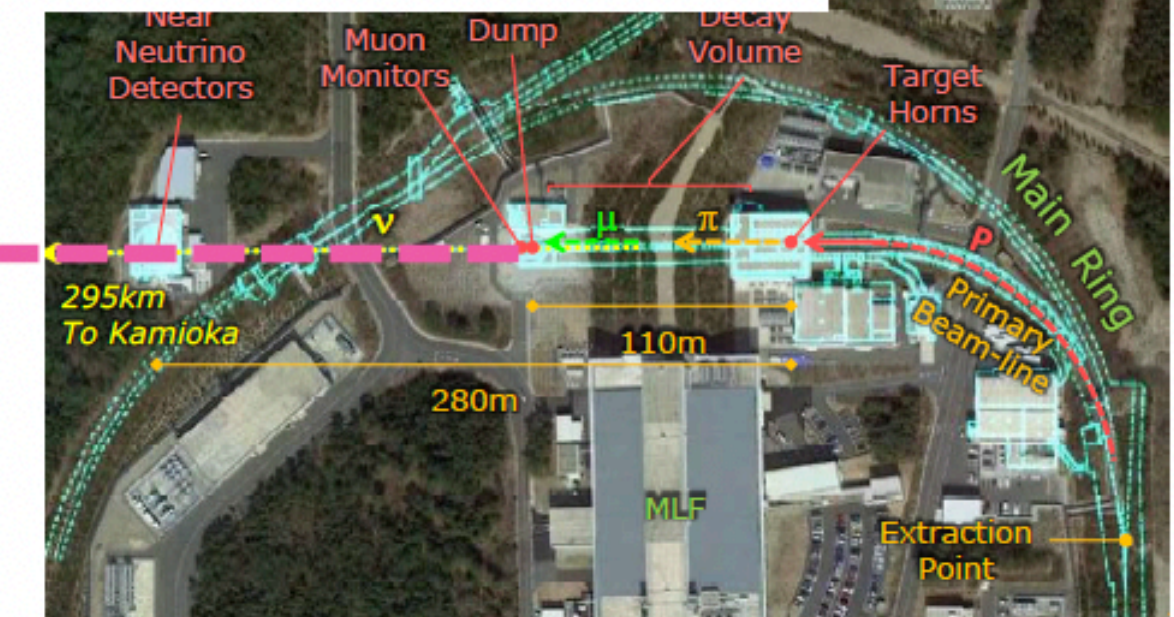


The Japanese Alps

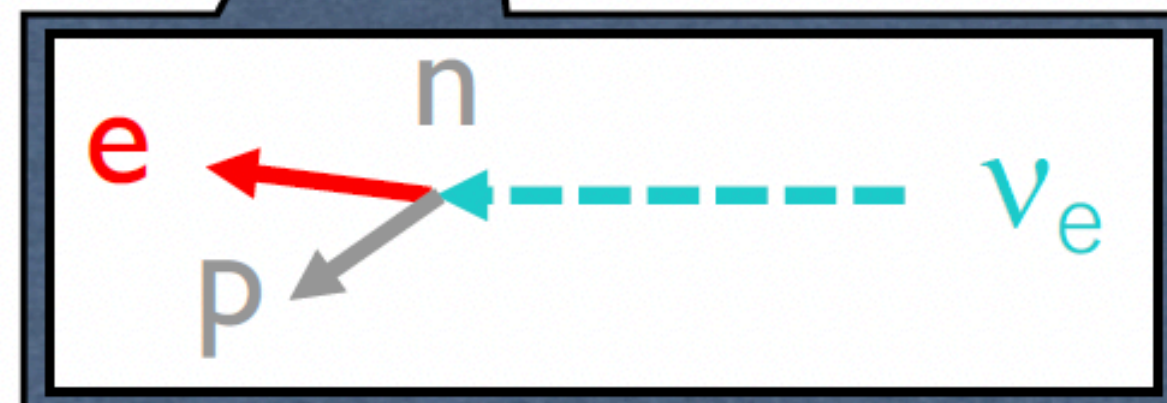
$\nu_\mu / \bar{\nu}_\mu$



0.5 → 1.3 MW



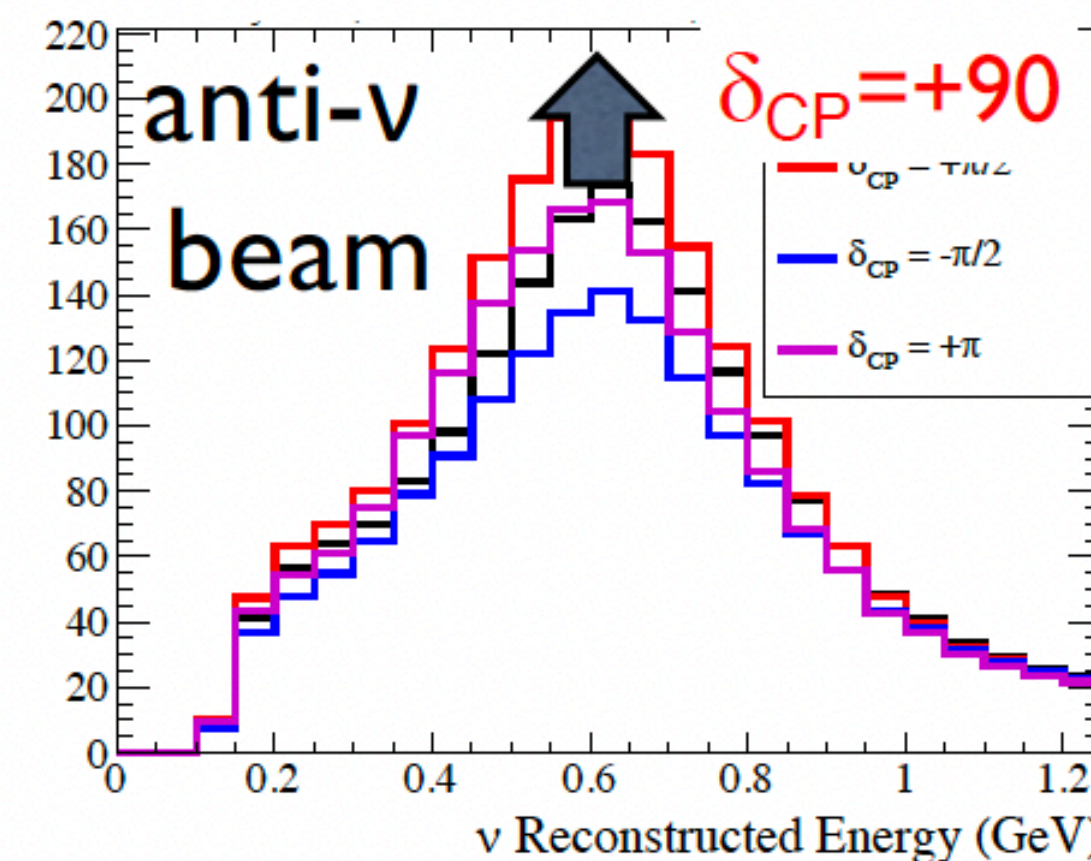
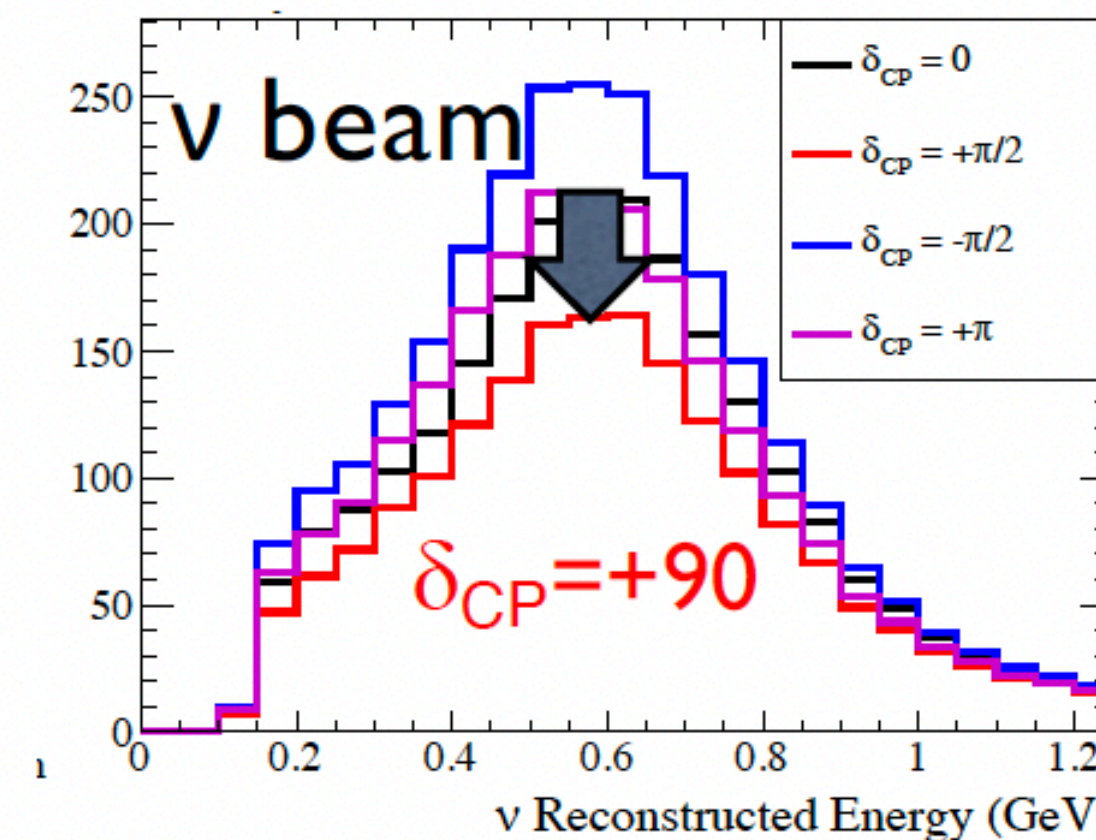
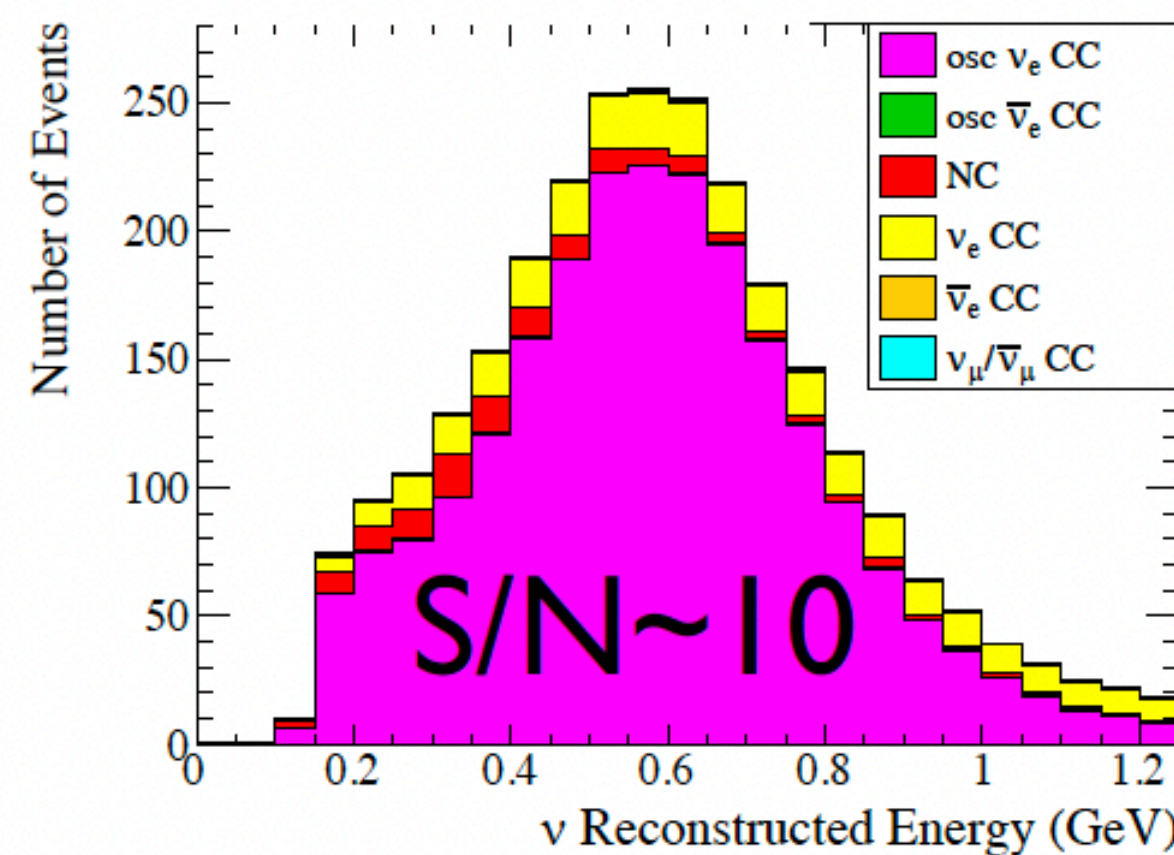
2.5 deg. off-axis



ν_e appearance signal = single e event

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

(dominant process at J-PARC beam energy)

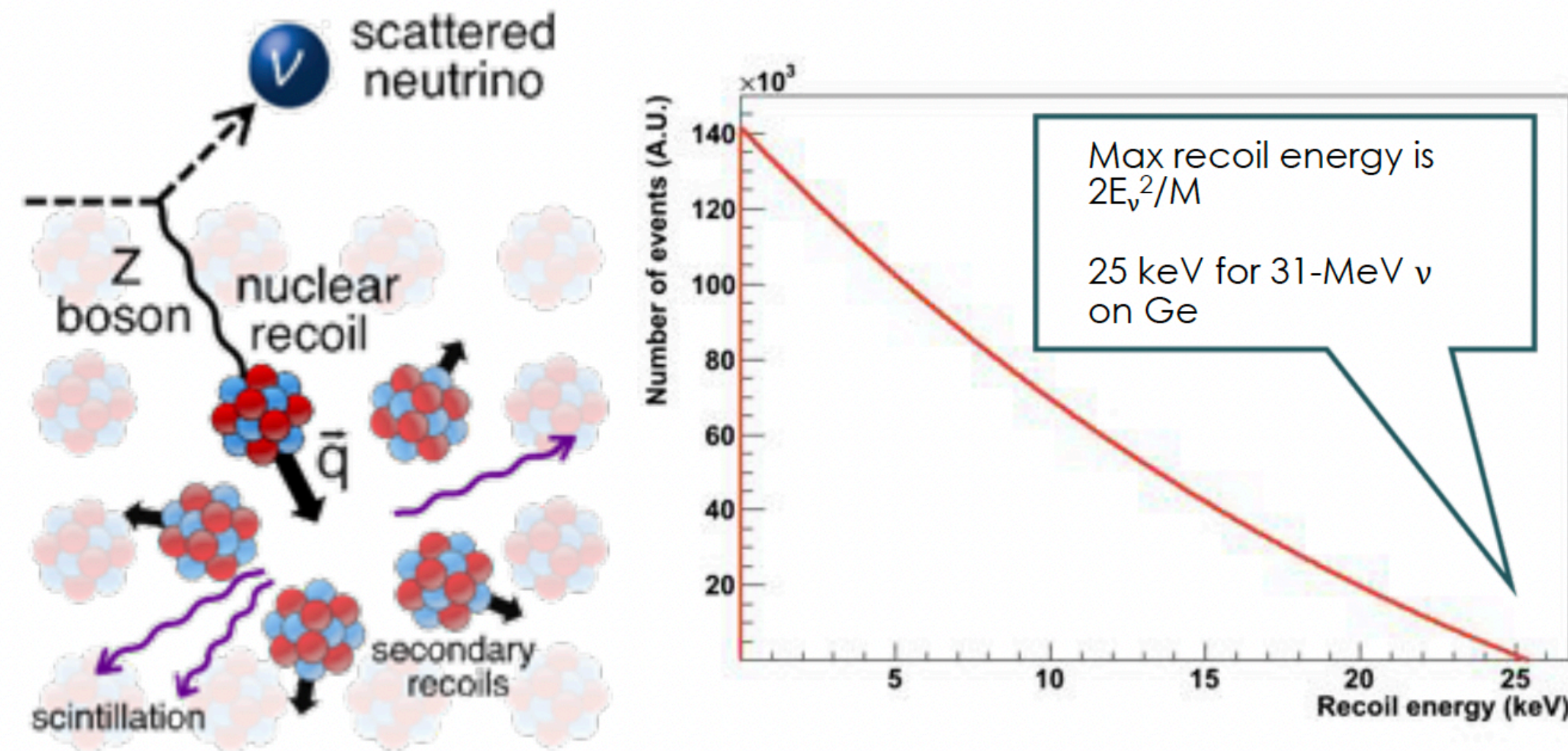


Relatively
Small matter
Effect &
Large CPV
Effect

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

Coherent elastic neutrino-nucleus scattering (CE ν NS)

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



CE ν NS cross section is well calculable in the Standard Model

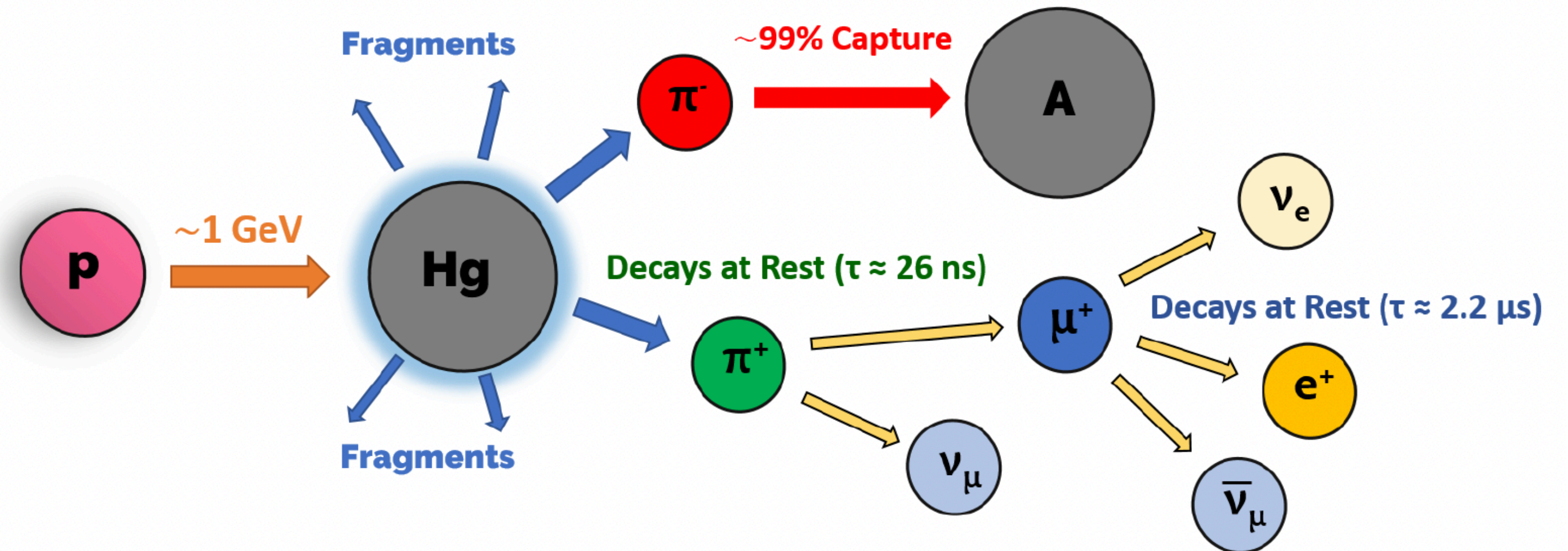
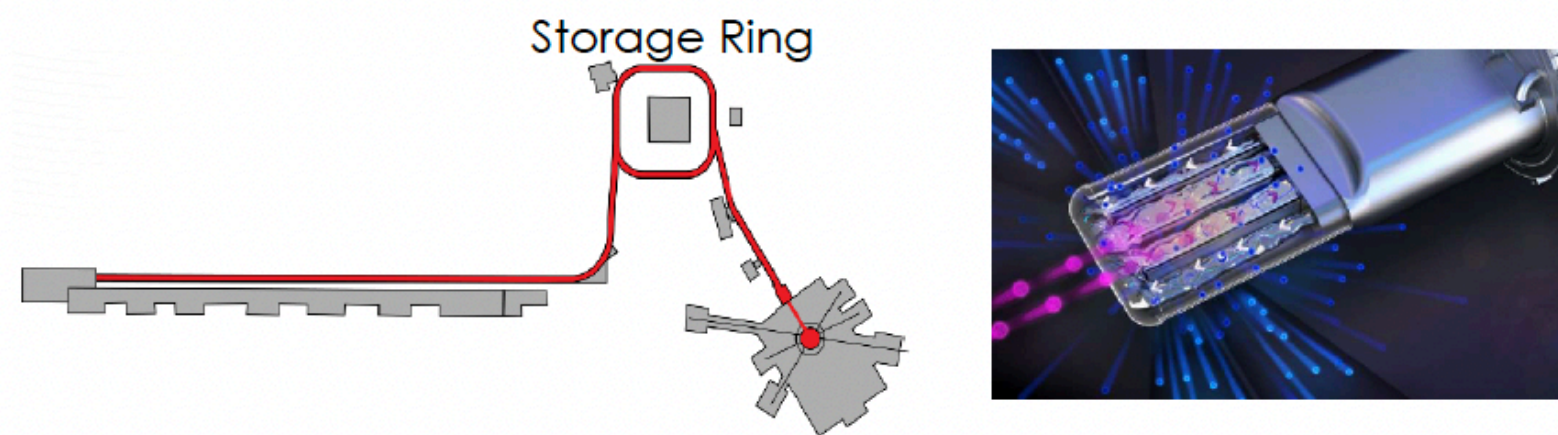
$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1 + \cos \theta) \frac{(N - (1 - 4 \sin^2 \theta_W)Z)^2}{4} F^2(Q^2)$$

CE ν NS cross section is large!

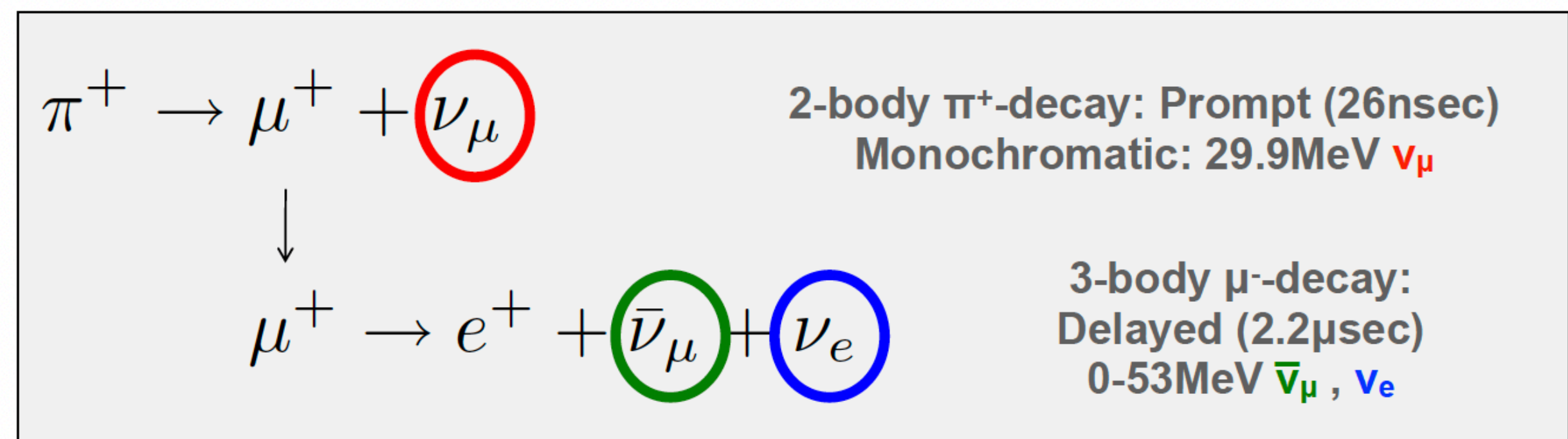
$$\propto N^2$$

- 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

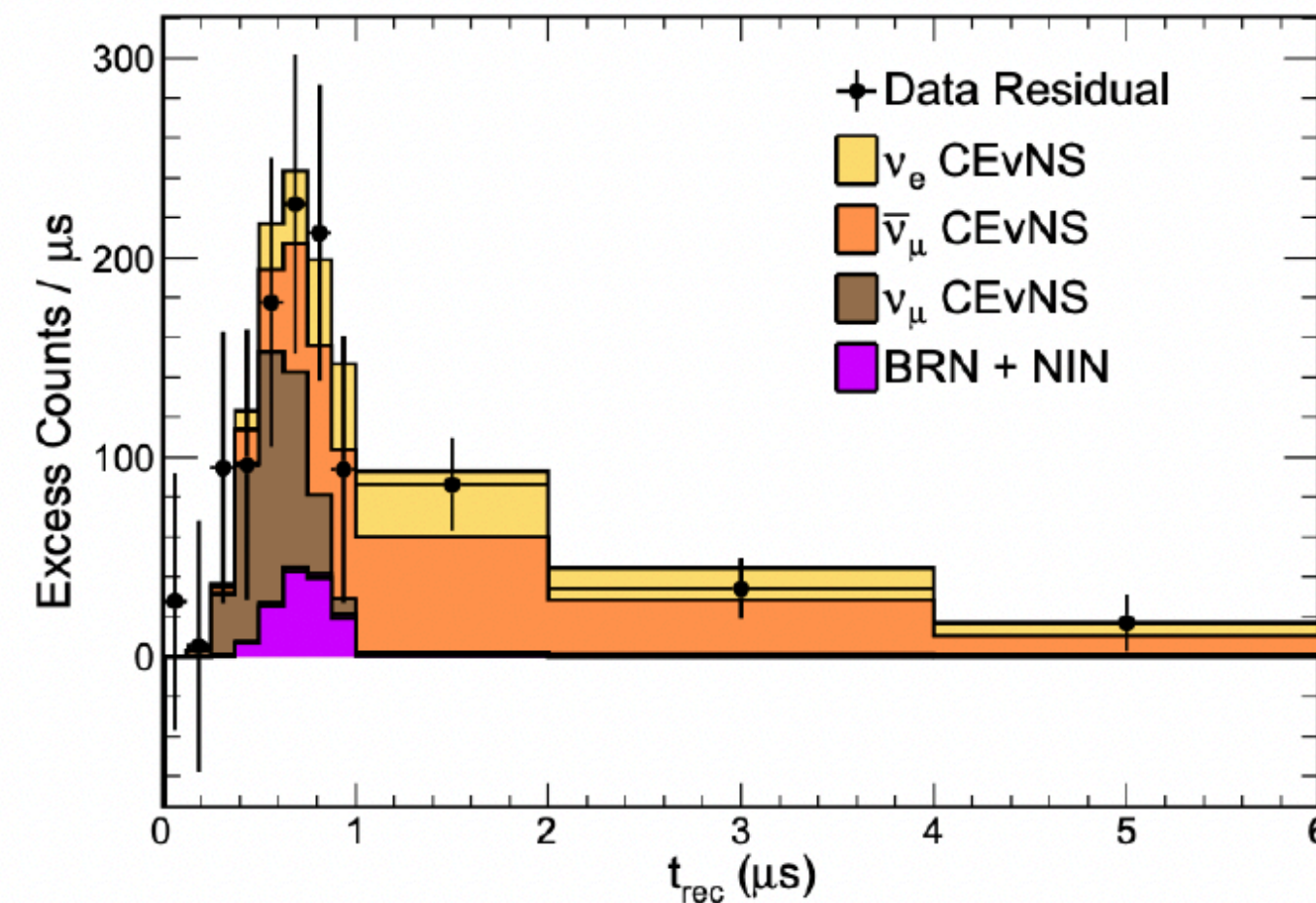
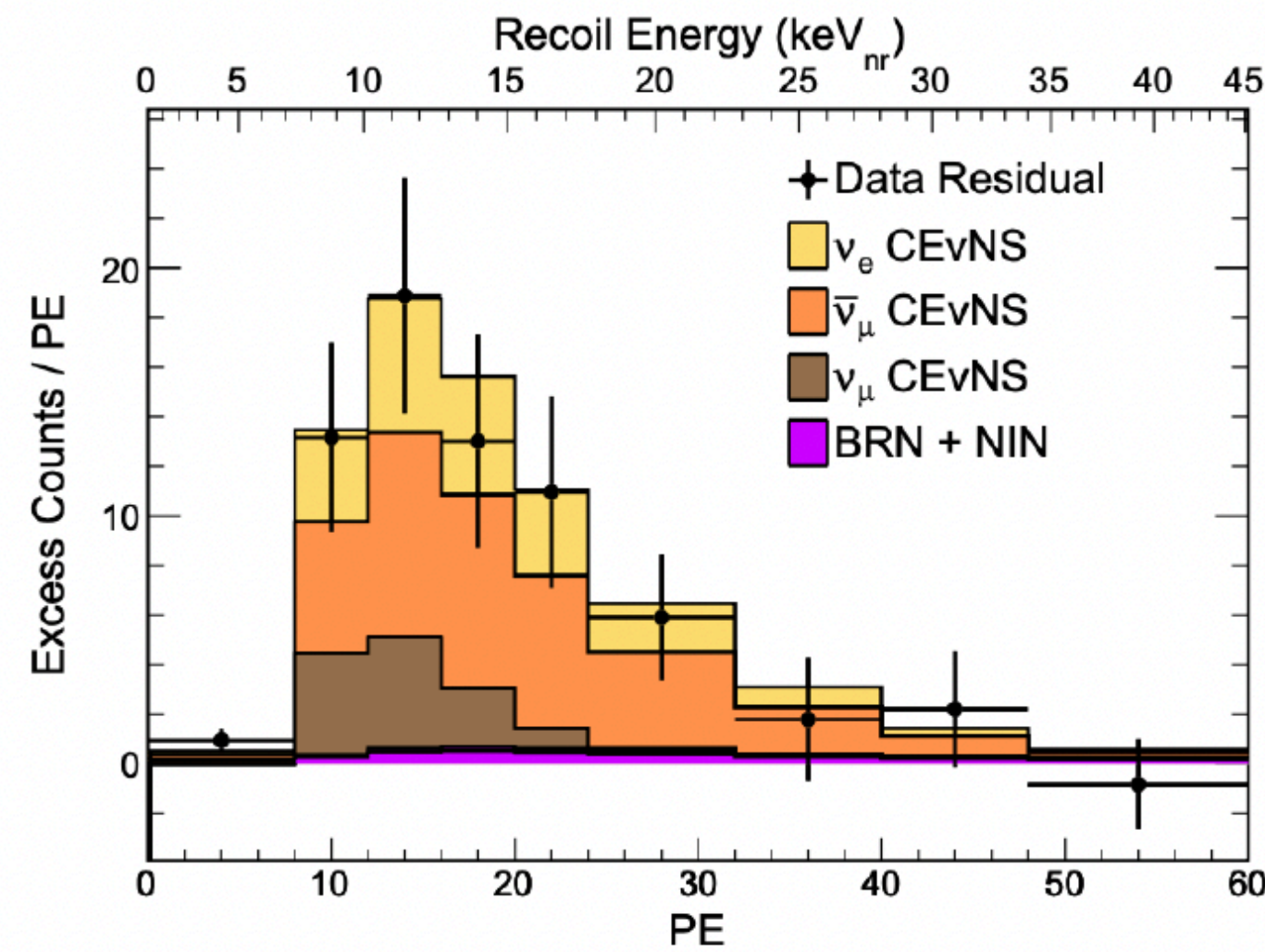


- Proton Beam:
 - 0.9-1.3 GeV
 - 0.9-1.7 MW, **soon 2 MW (PPU)**.
- Total ν flux: $\sim 4.3 \times 10^7$ cm $^{-2}$ s $^{-1}$ at 20m
- Beam timing & duty cycle (60Hz, 380ns FWHM) allow for powerful reduction of steady-state backgrounds ($\sim 10^{-4}$)



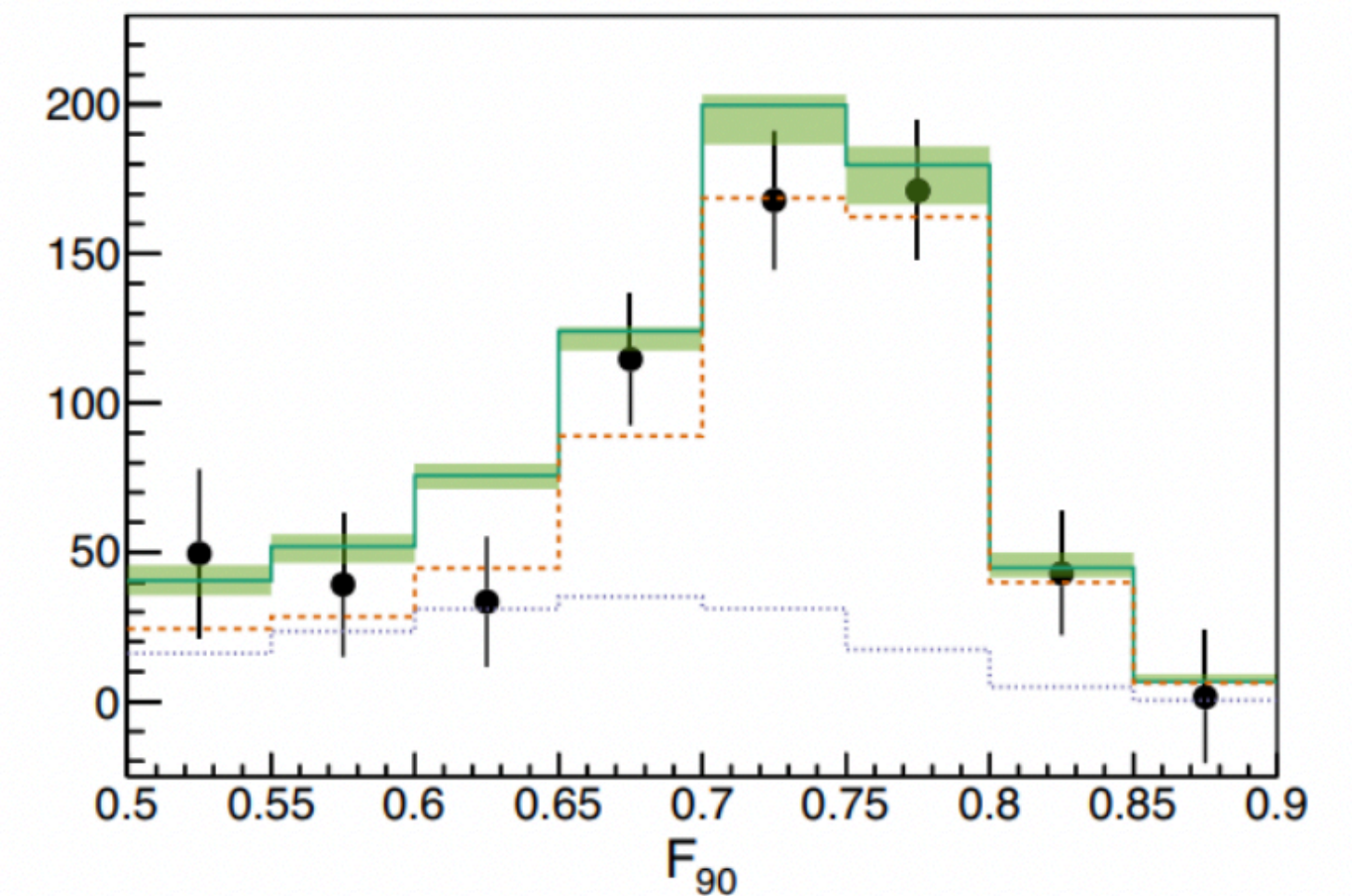
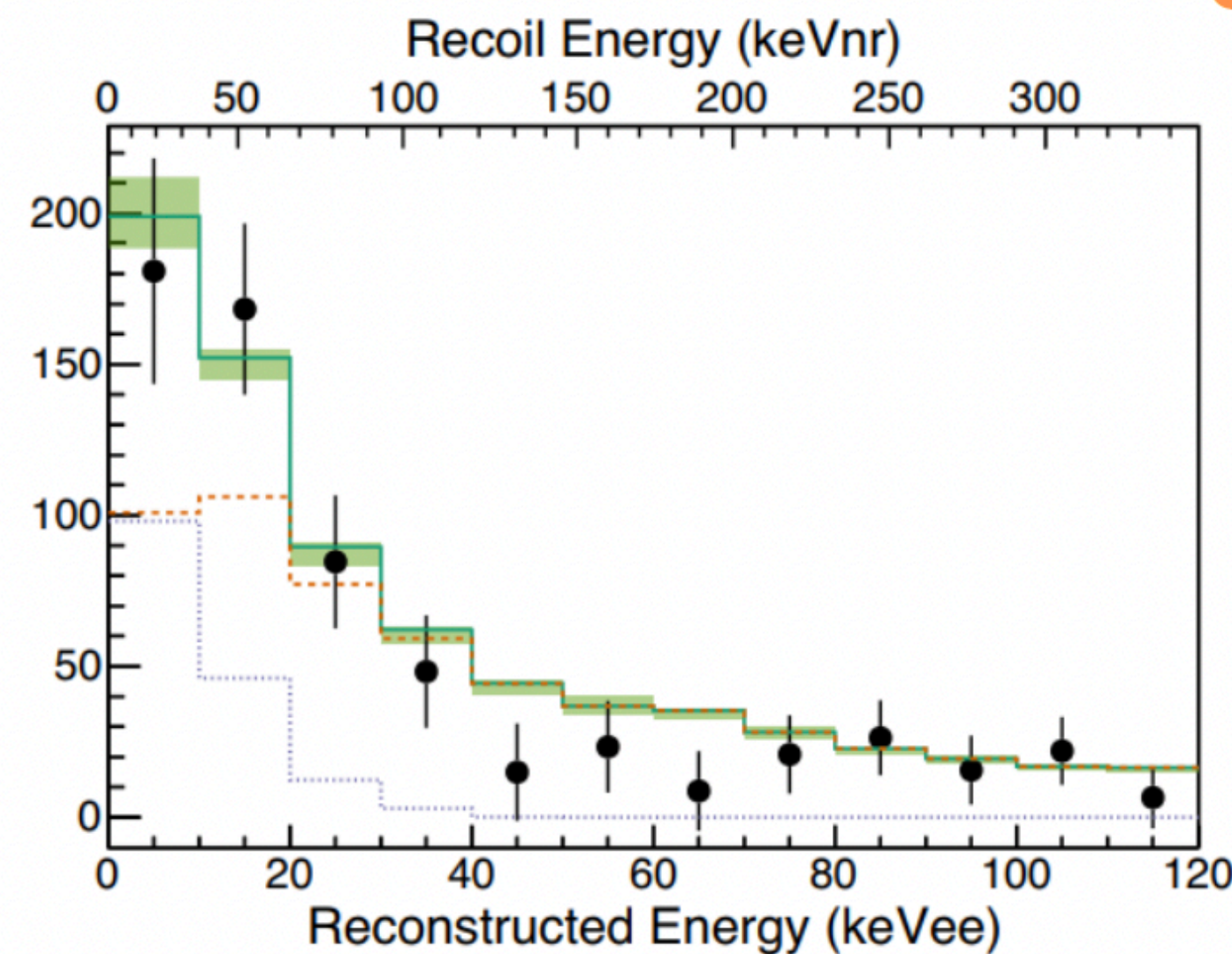
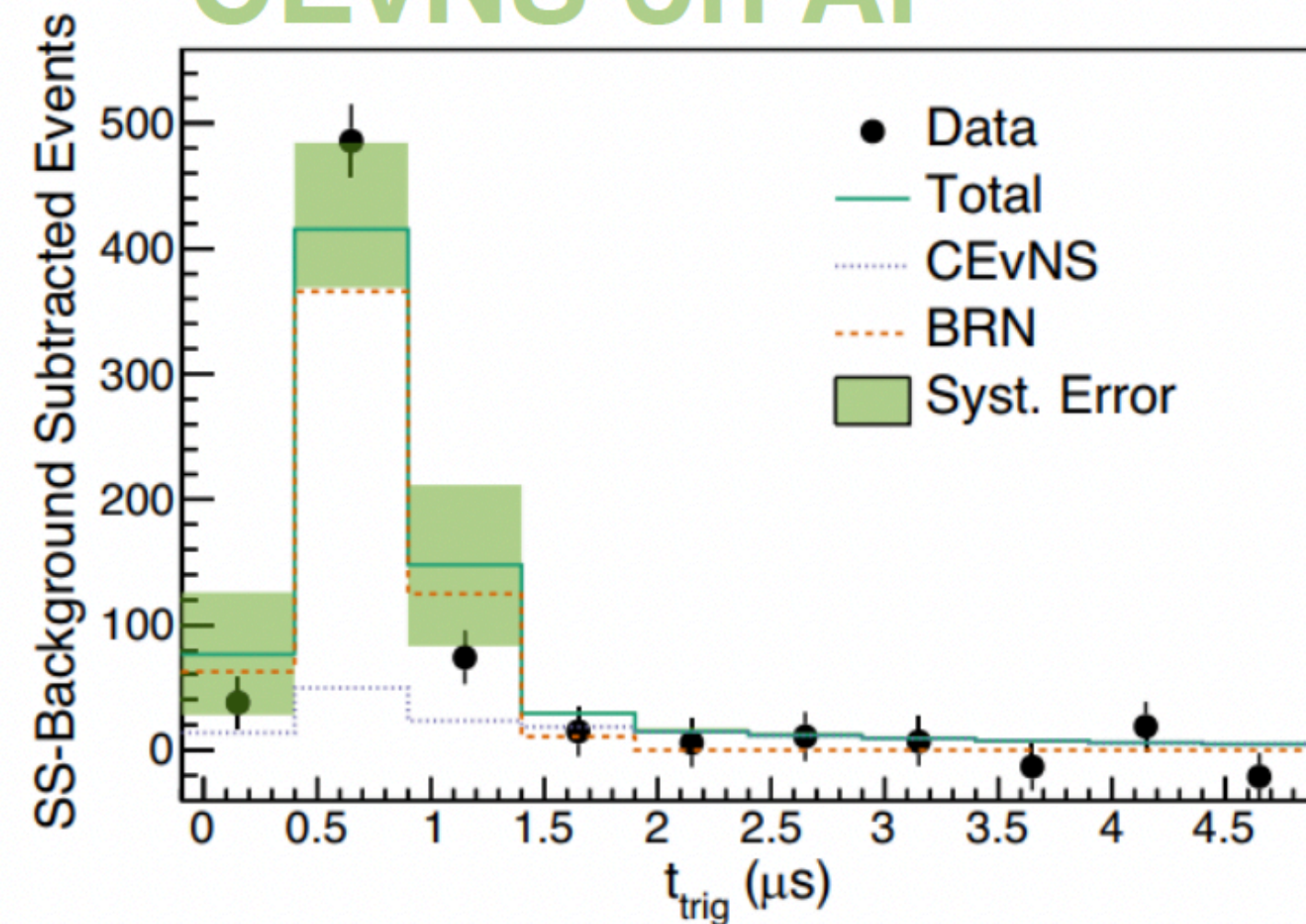
CE ν NS: example of detections (there are more)

CE ν NS on CsI



COHERENT, PRL 129 081801 (2022)

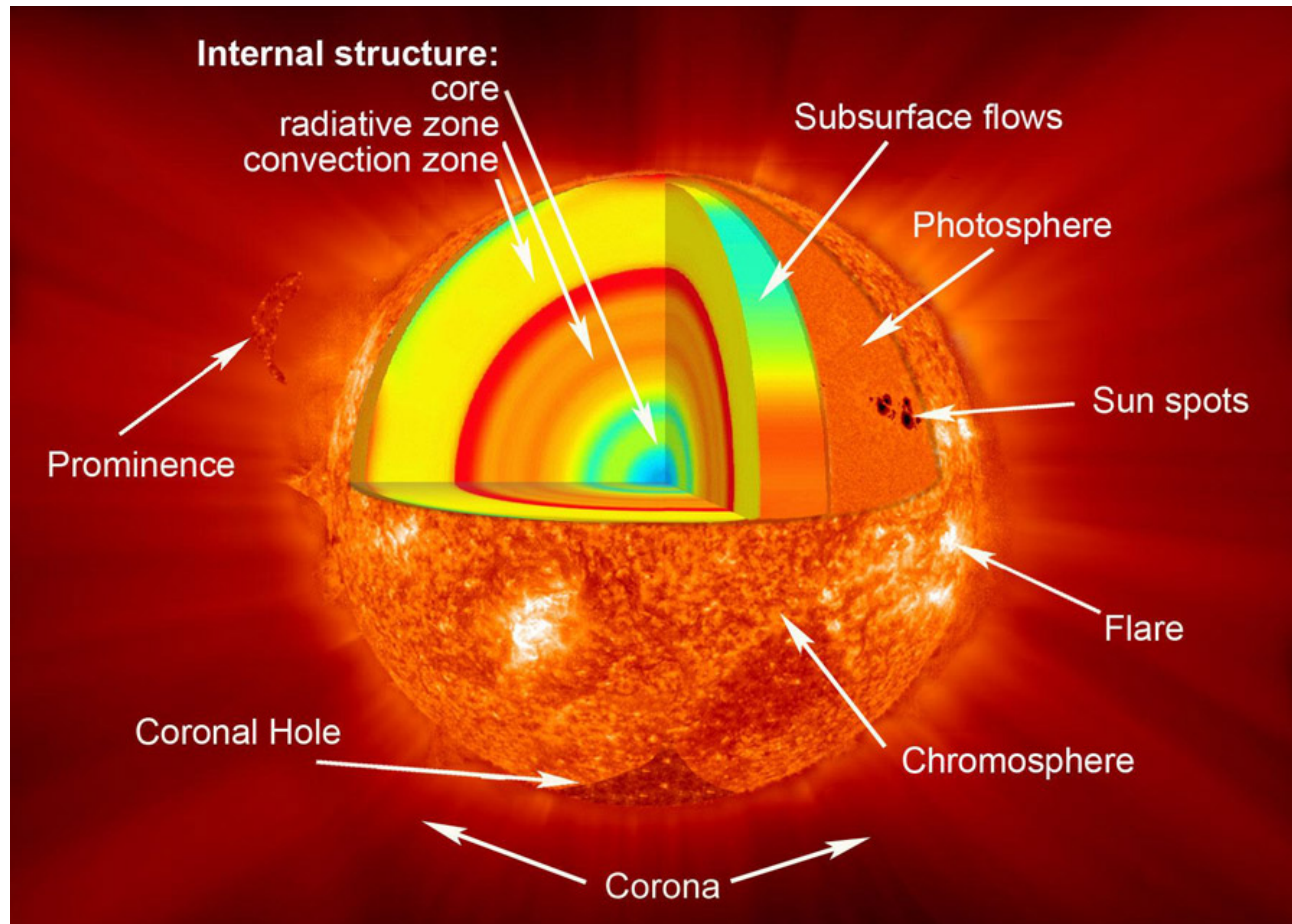
CE ν NS on Ar



COHERENT, PRL 126 012002 (2021)

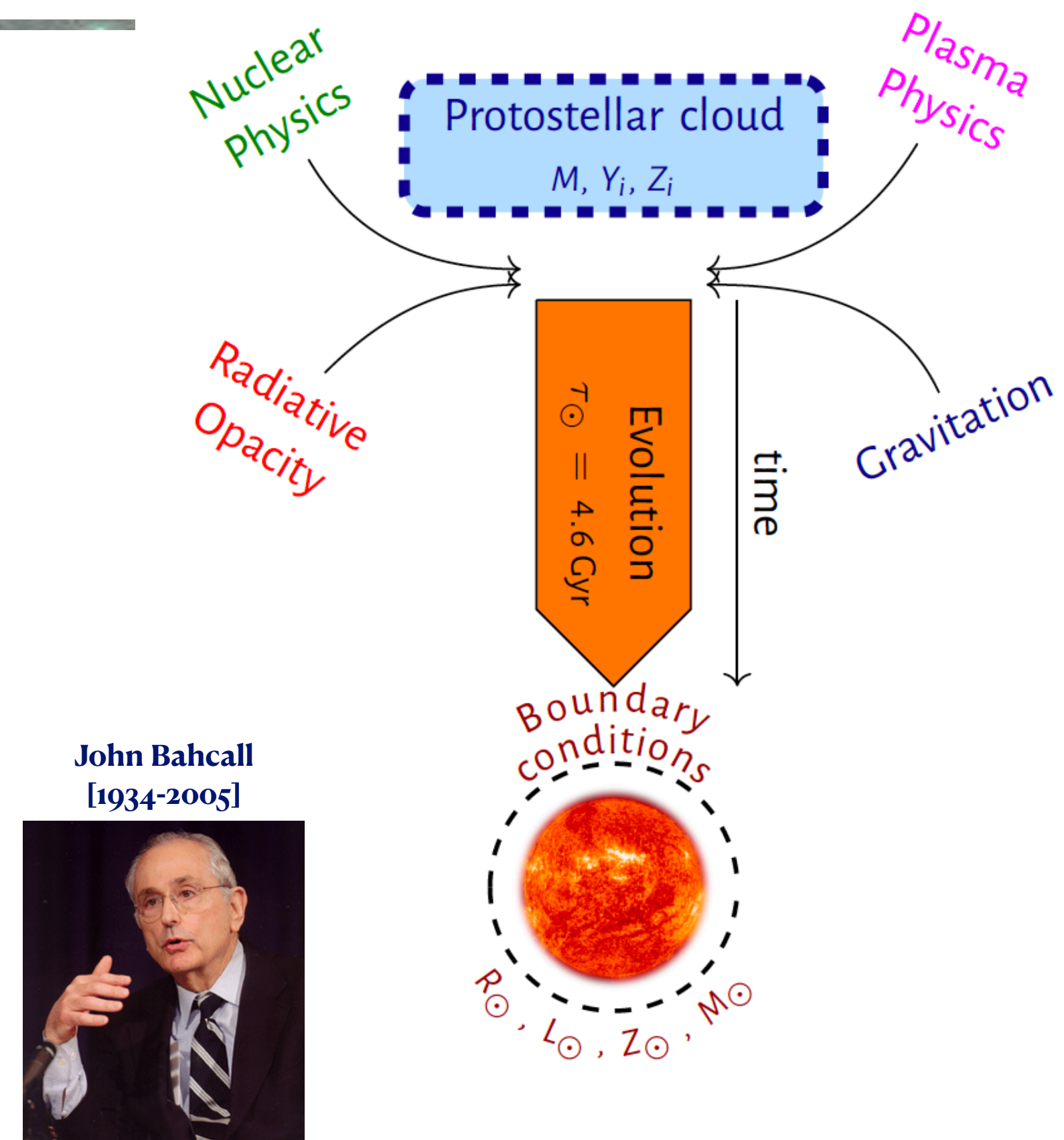


The structure of the Sun



The Standard Solar Model

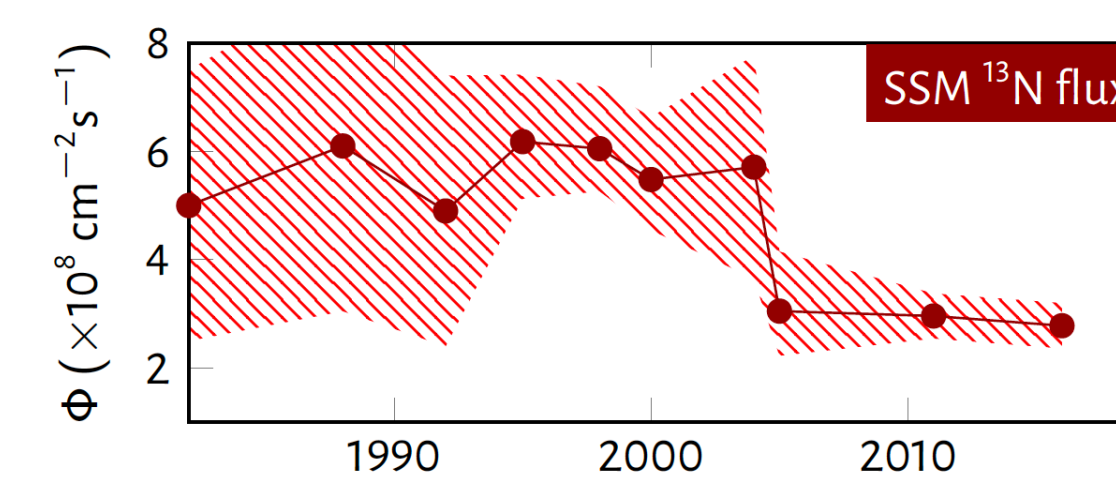
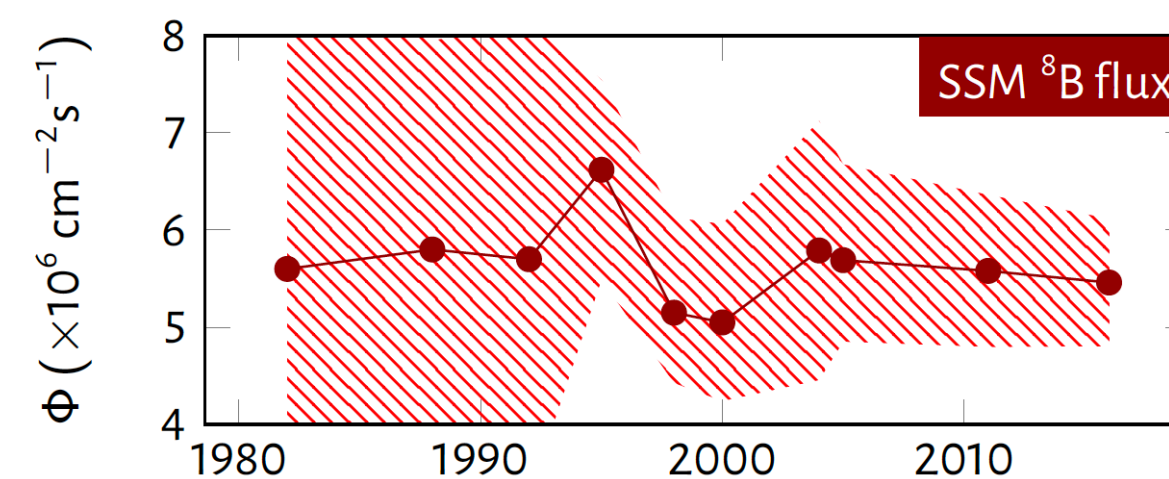
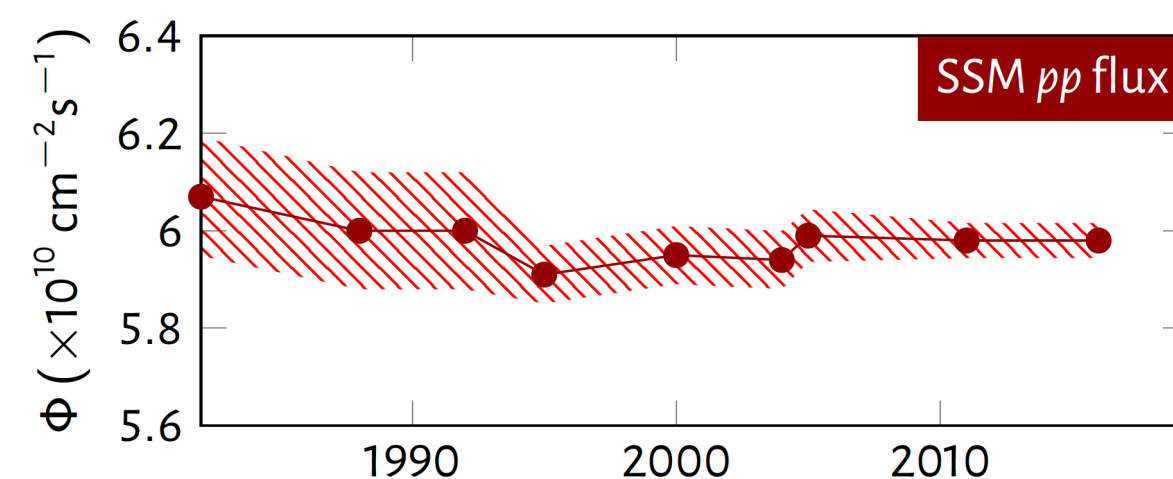
- The observable is the Sun we see now, which depends on a **complex evolution process**
 - Gravity
 - **Composition:** X (hydrogen), Y (helium), , Z (“metals”)
 - Radiative **opacity** and plasma physics
 - Temperature and density profiles
 - Energy transport: radiative until $0.71 R_{\odot}$, then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

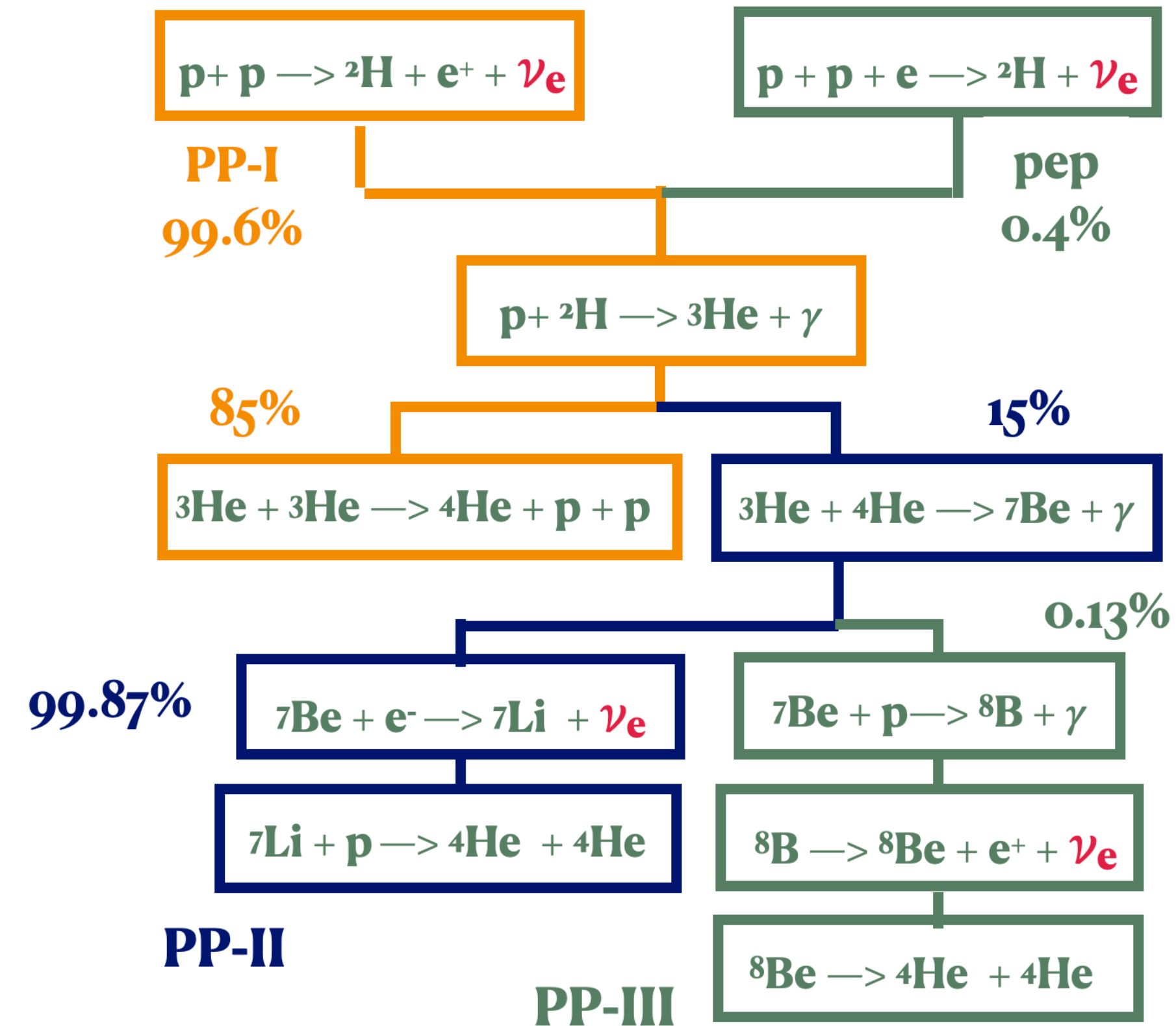


Solar neutrinos from hydrogen burning

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

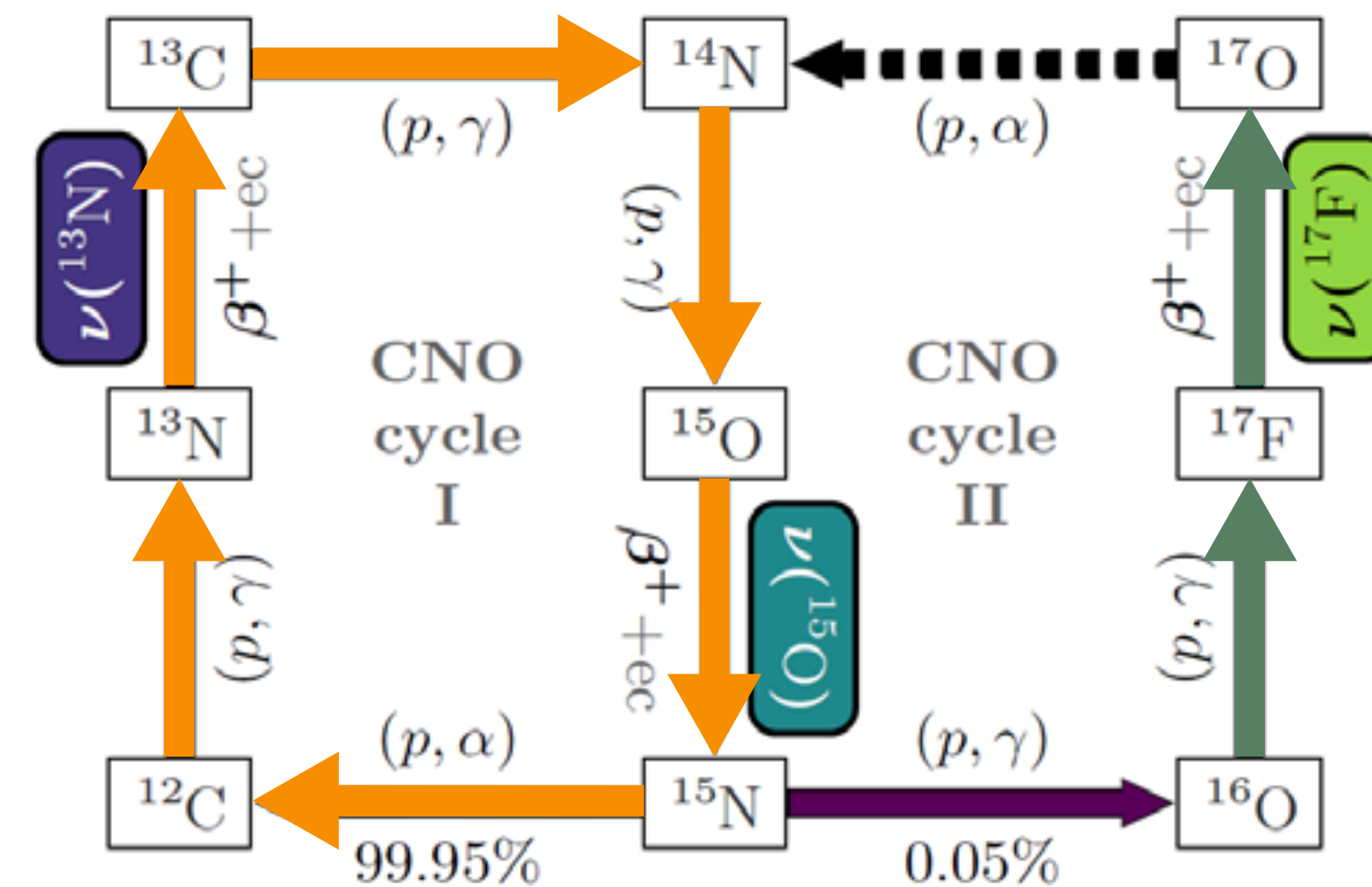
Bethe &
Critchfield 1938

pp chain (99% energy)



CNO cycle (~ 1% energy)

Weizsäcker (1937, 1938)
Bethe (1939)



${}^{12}\text{C}$ is the main catalyst
CNO-II is suppressed in the Sun

REACTION



ENERGY YIELD

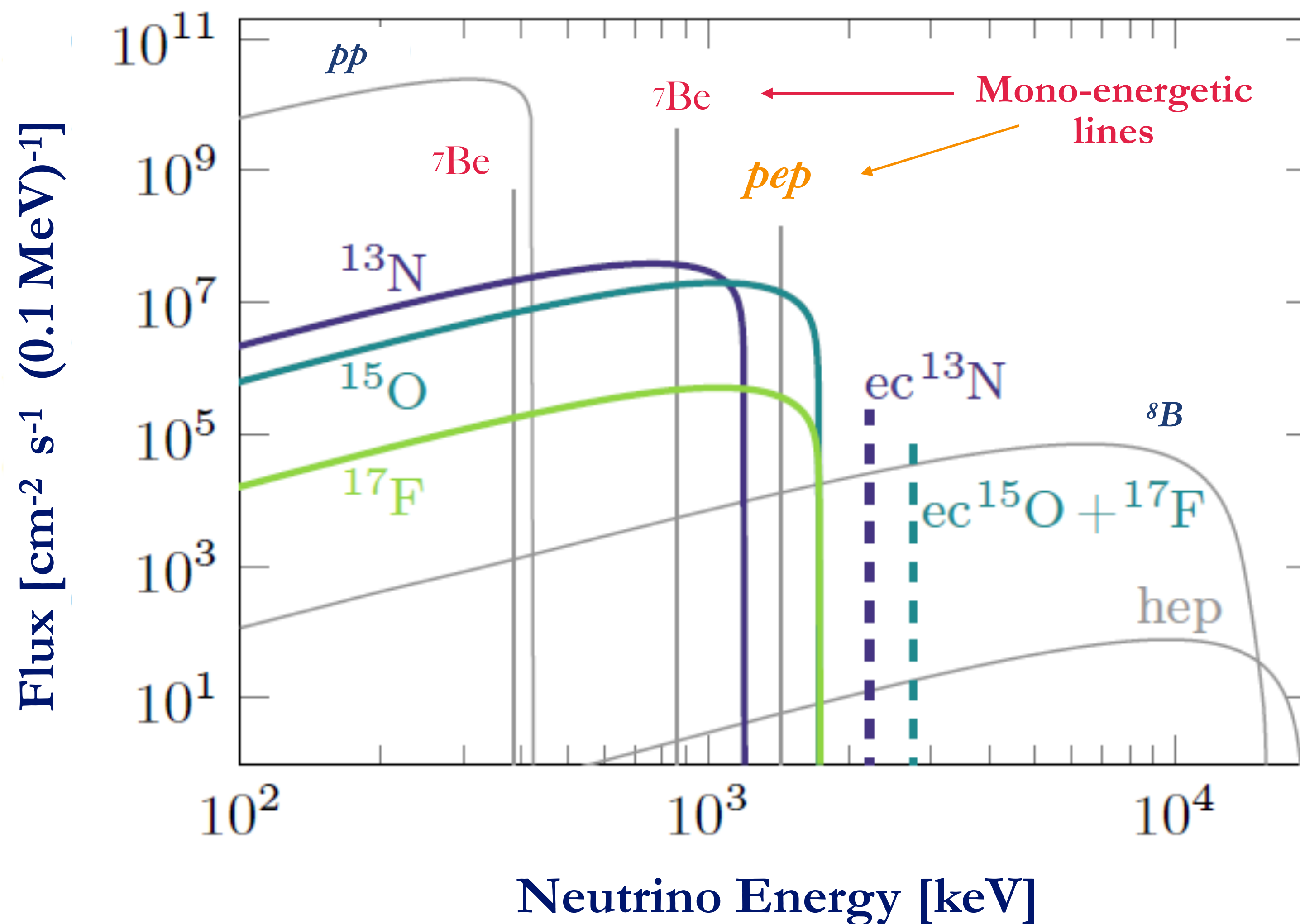
$$24.7 \text{ MeV} + 2m_e c^2$$

2% of E in NEUTRINOS

$$\langle E_\nu \rangle = 0.53 \text{ MeV}$$



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



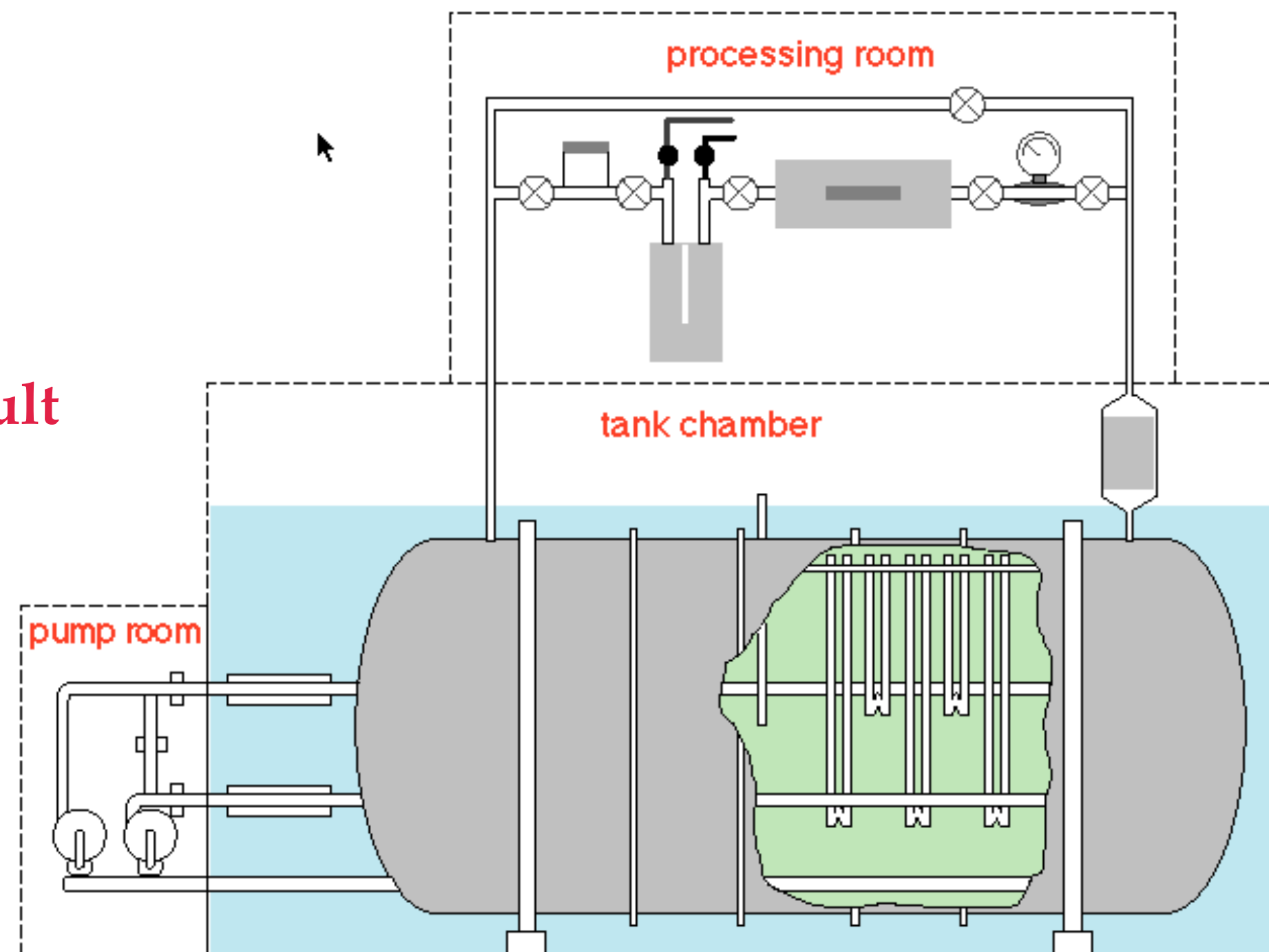
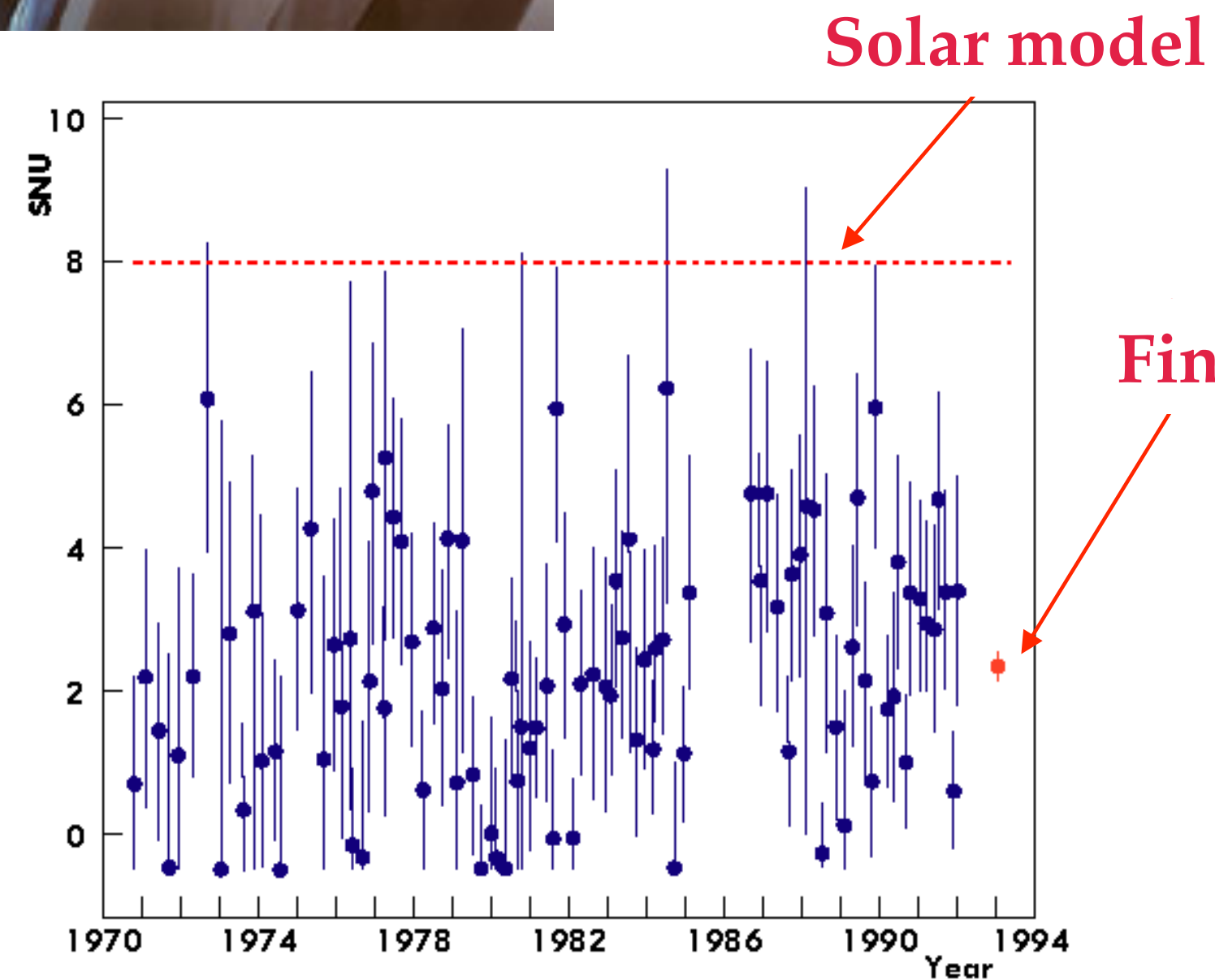
History: counting an atom a day at Homestake



- Extract a single atom out of $\sim 10^{31}$



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

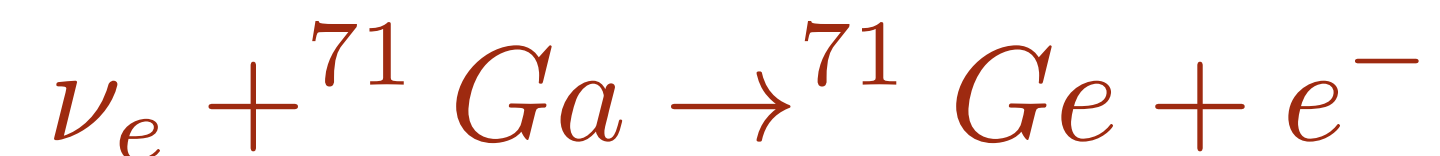


History: Gallex/GNO @ LNGS and SAGE in Russia (Baksan)

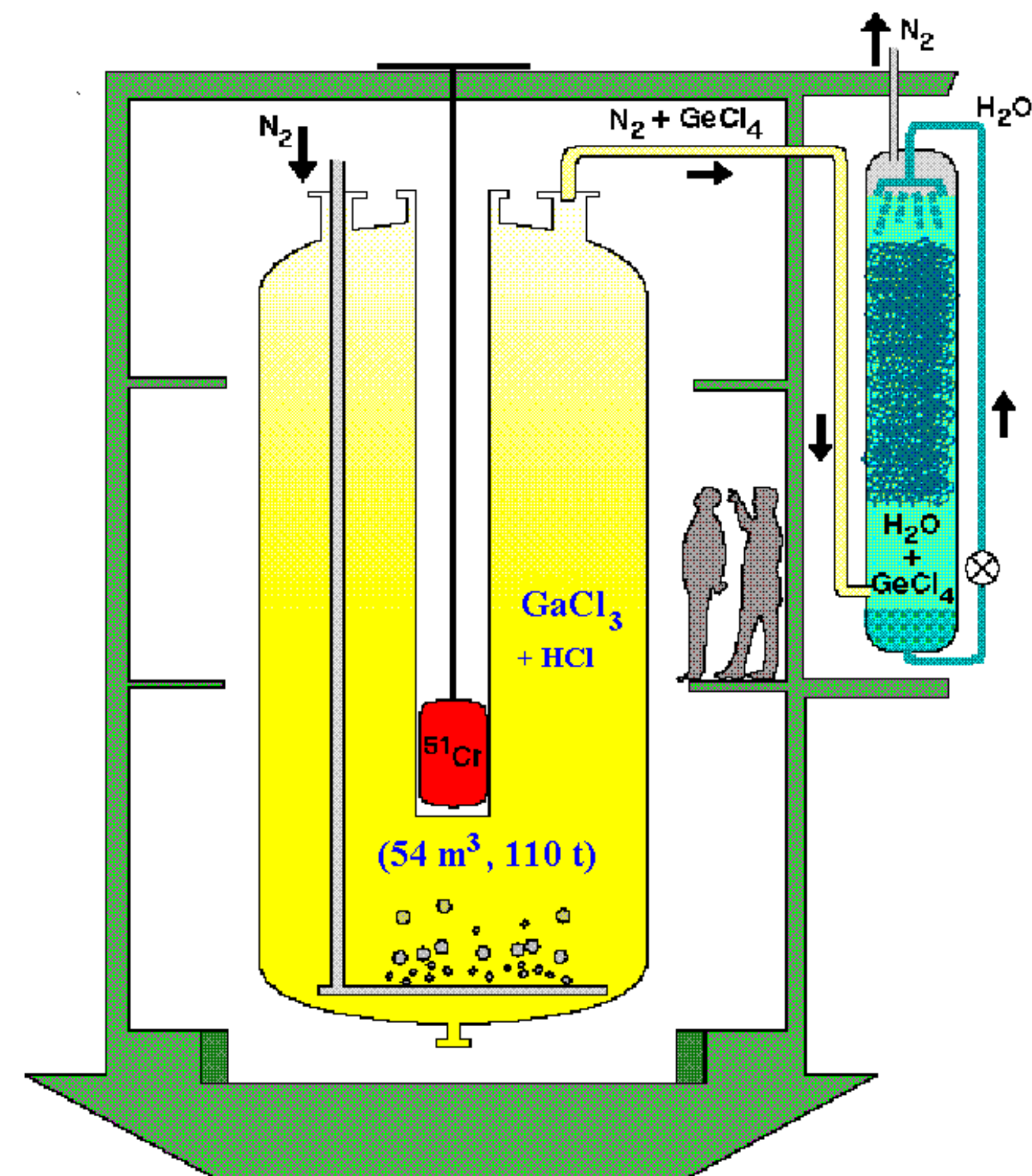
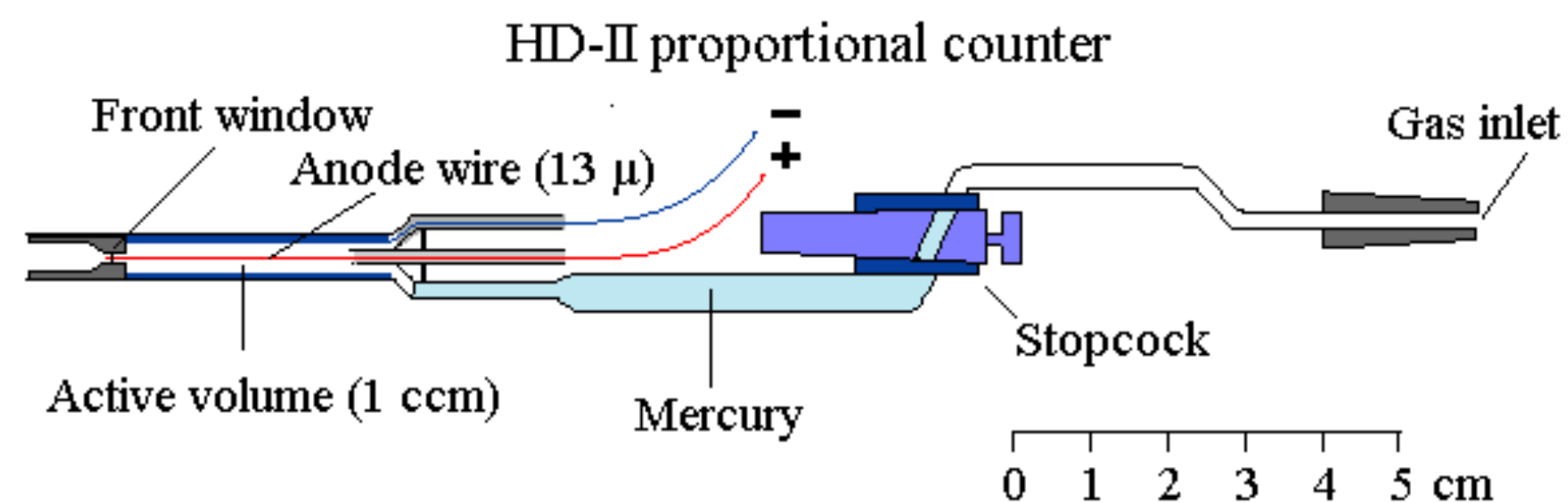
- A key radio-chemical experiment for solar neutrino physics

- The first sensitive to all solar neutrino components (through an **integrated**, energy-weighted spectrum)

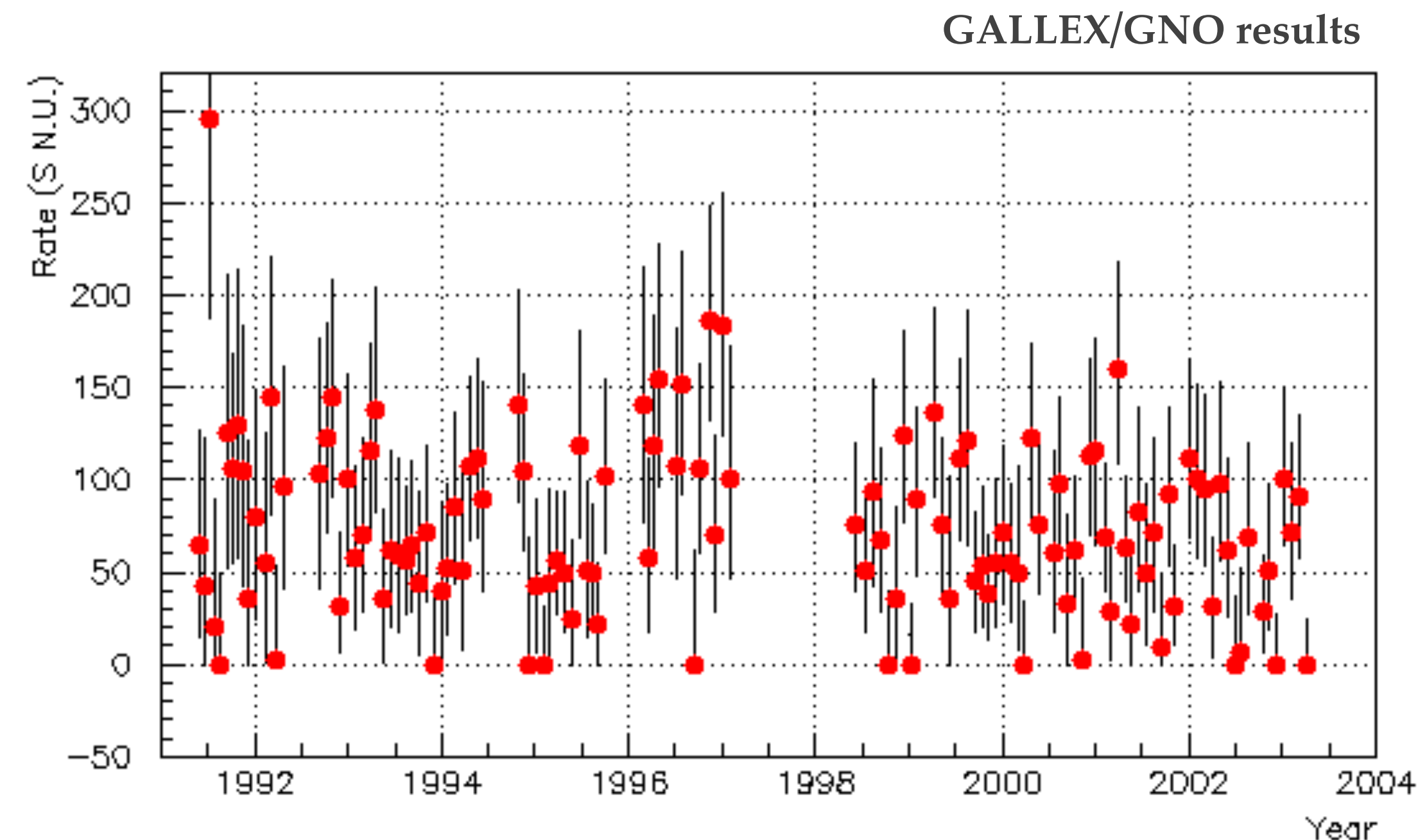
- 30.3 ton of Ga in GaCl_3 – HCl solution.



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



- 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
 - $\varepsilon = 95 \pm 3 \%$
 - Mono-chromatic ν_e flux, $E_\nu = 0.75 \text{ MeV}$
- At the end only, insertion of ^{71}As
 - $^{71}\text{As} \rightarrow ^{71}\text{Ge} + e^- + \nu_e$
 - $[\tau_{1/2} = 2.72 \text{ d}]$;
 - $\varepsilon = 100 \pm 1 \%$



Experiment	Runs	Result
GALLEX	65	$77.5 \pm 6.2 \text{ (stat)} \pm 6.2 \text{ (sys) SNU}$
GNO	58	$62.9 \pm 5.4 \text{ (stat)} \pm 2.5 \text{ (sys) SNU}$
GALLEX+GNO	123	$69.3 \pm 4.1 \text{ (stat)} \pm 3.6 \text{ (sys) SNU}$

STANDARD SOLAR MODEL prediction: $129 \pm 7 \text{ SNU}$

Neutrino detection in water/ice: Cherenkov light

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

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

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

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

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

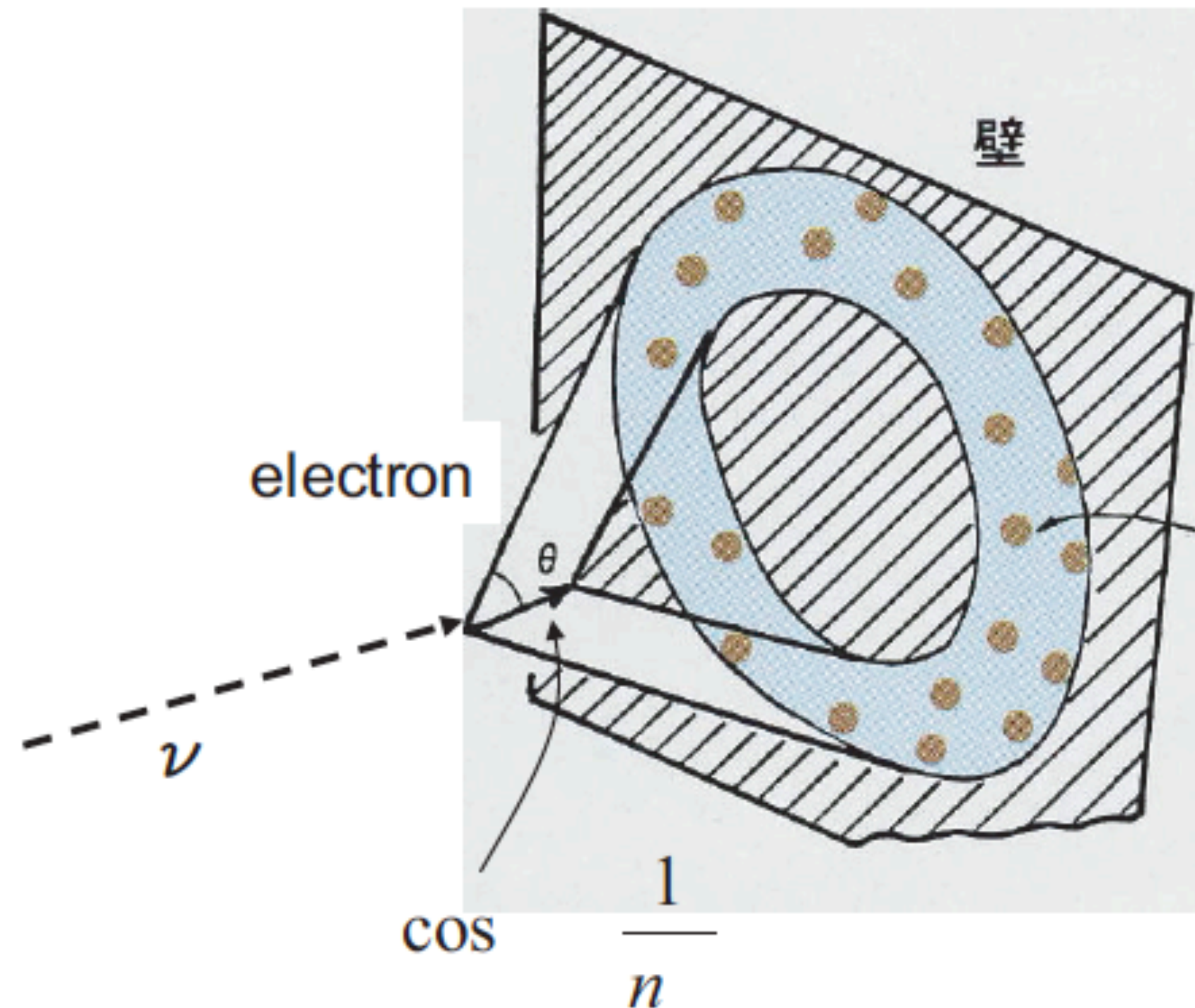
Cerenkov light spectrum as function of wavelength λ :

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

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

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

Detection of light in water



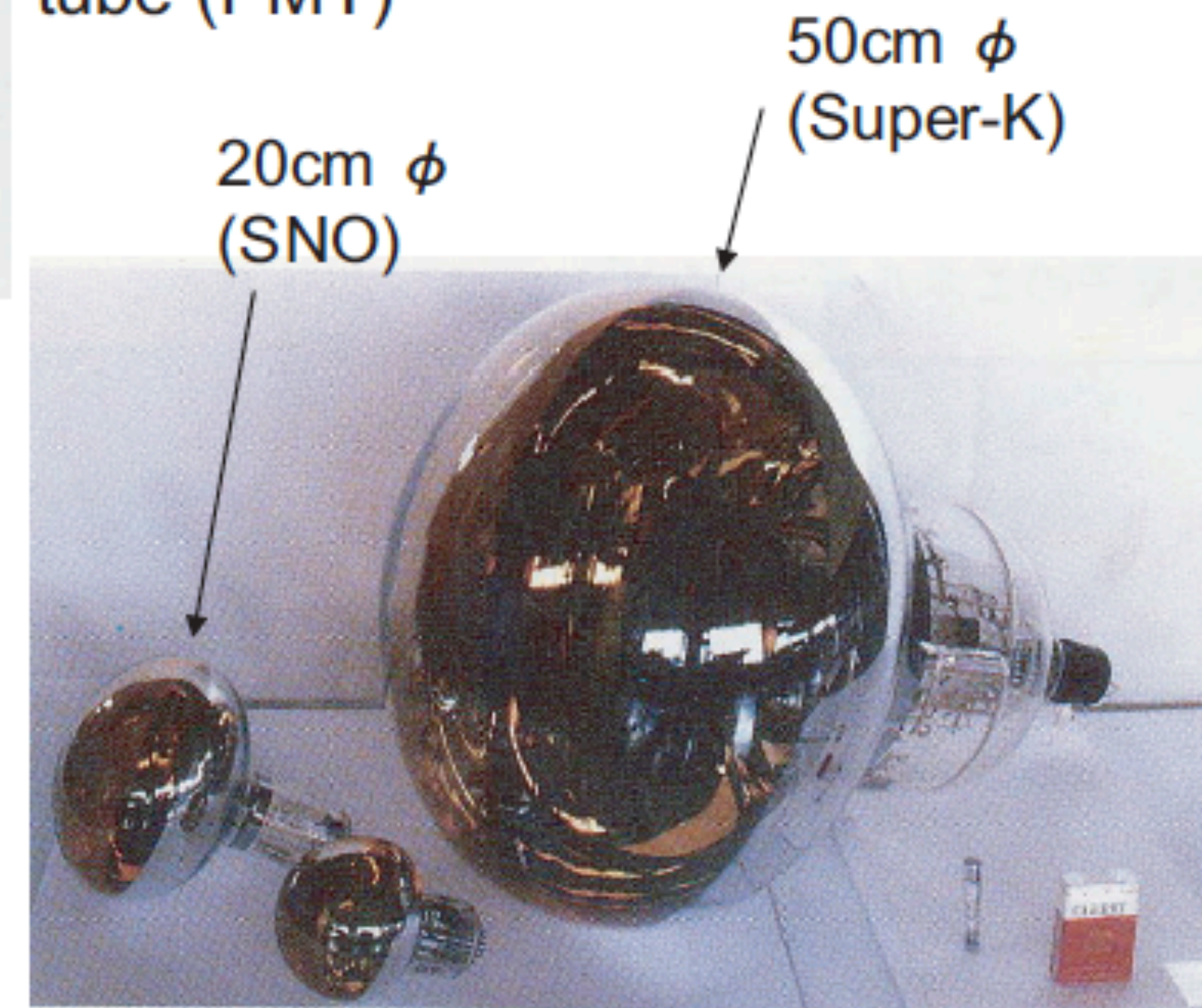
n (refractive index)=1.34
in water

$\Rightarrow \theta = 42^\circ$ for $\beta = 1$

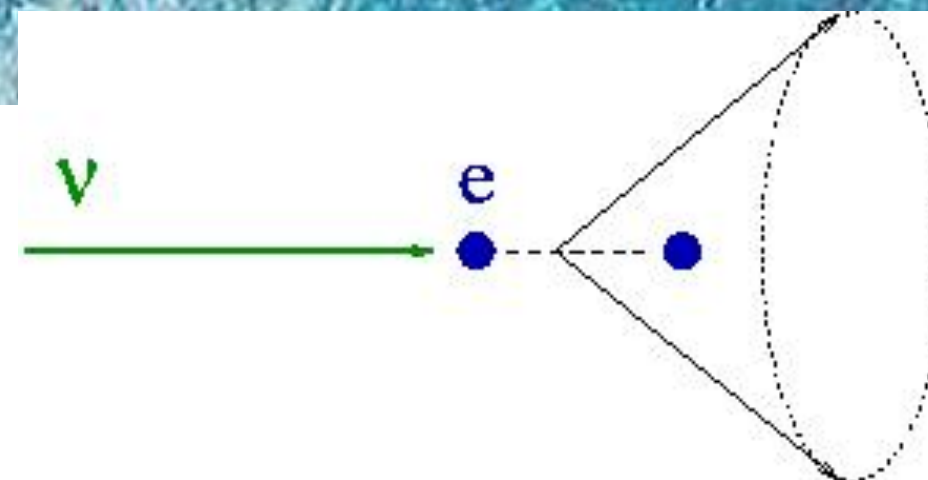
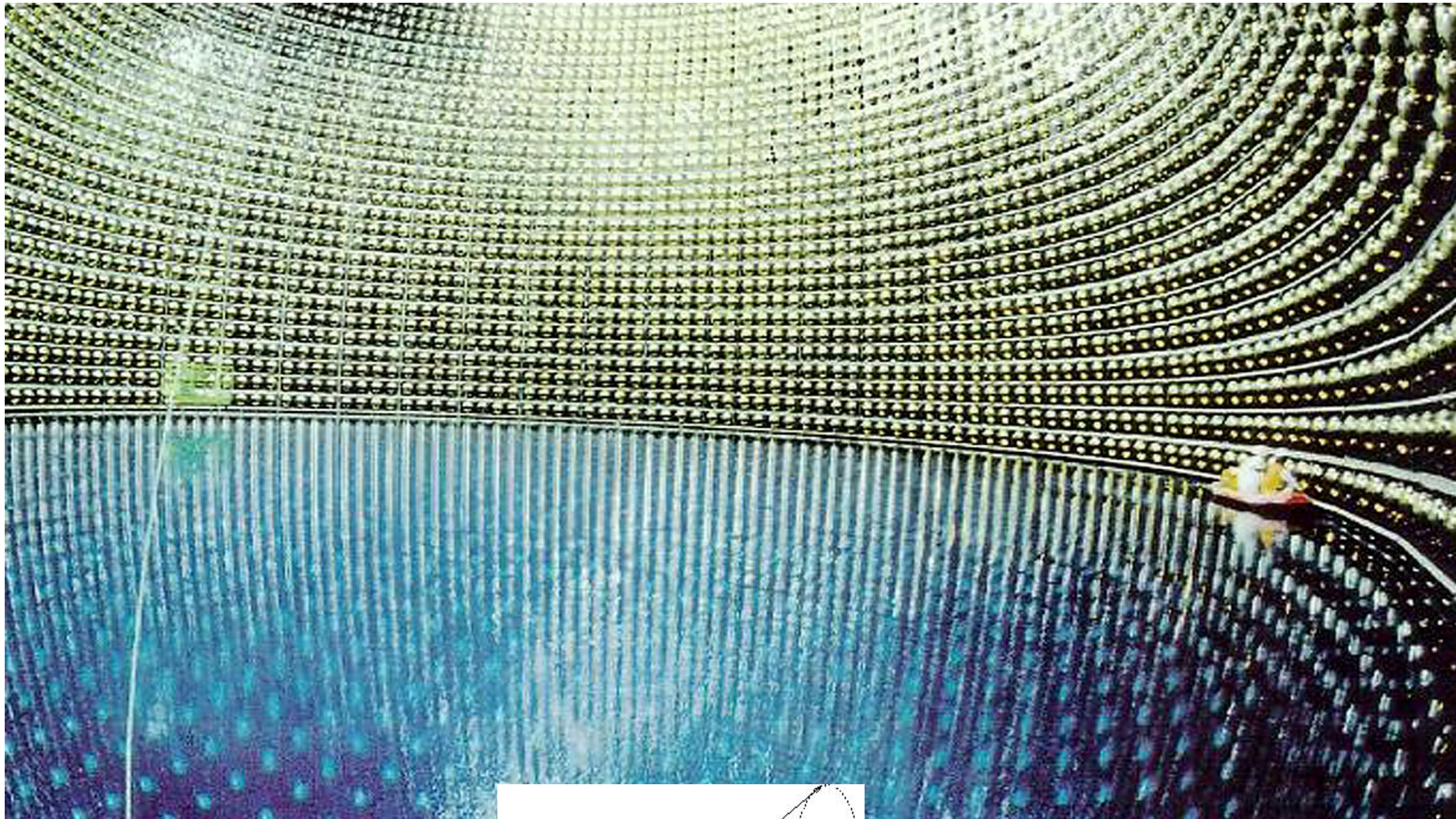
Number of Ch. photons with
 $\lambda = 300-600$ nm emitted by a
relativistic particle per cm = 340.

Need an efficient detection of the
photons. $\Rightarrow$ Large PMTs

Photomultiplier
tube (PMT)

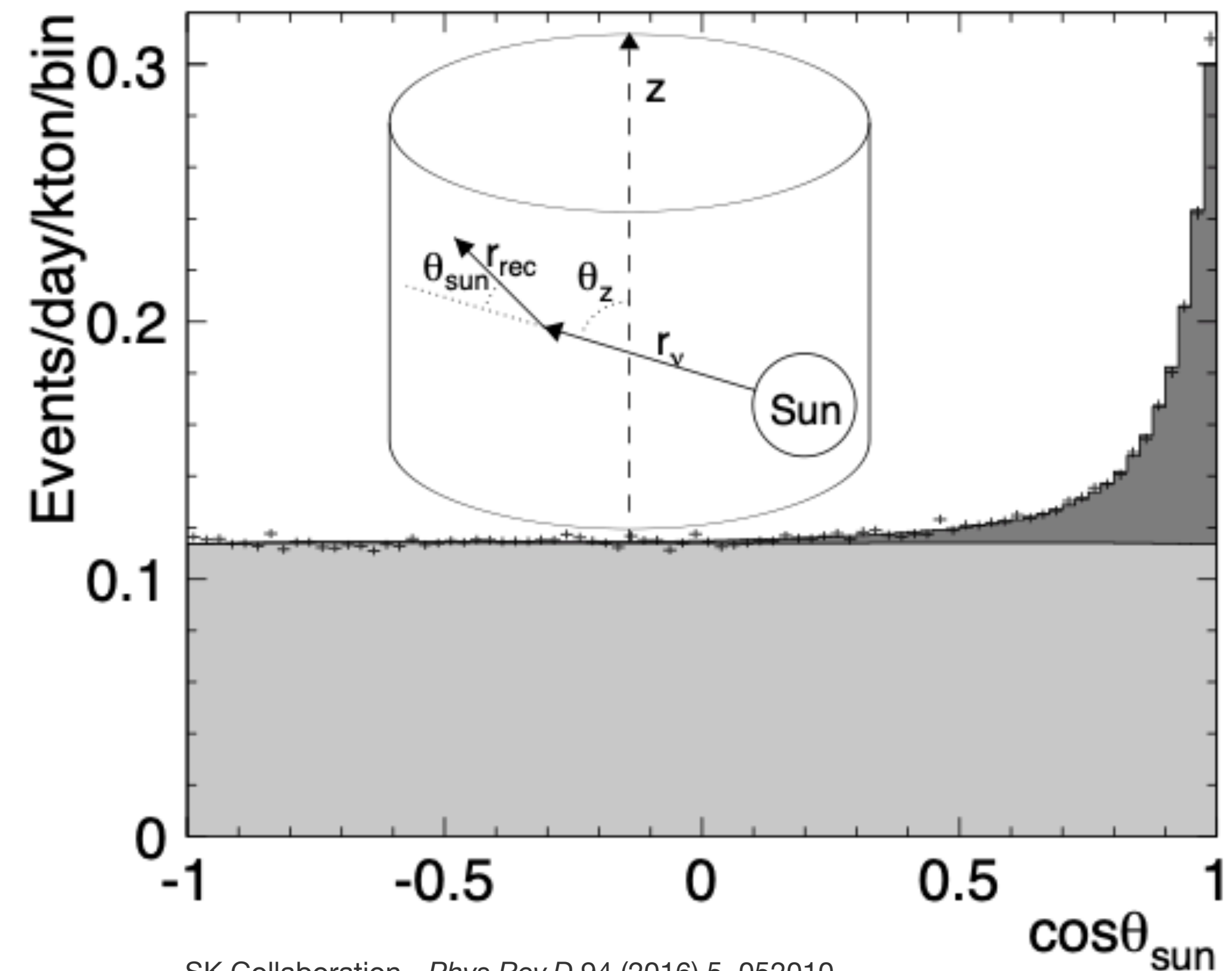
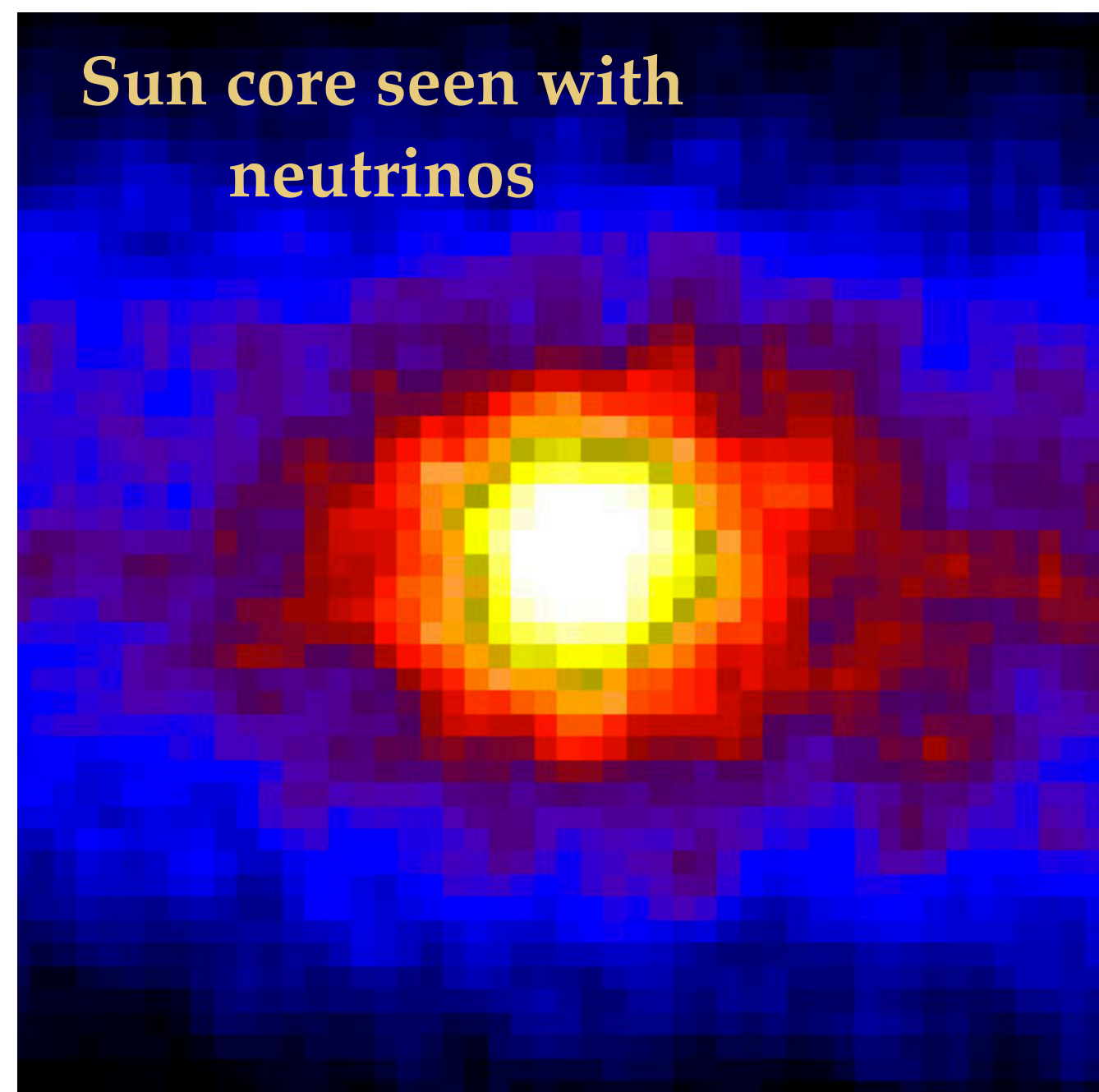


T. Kajita - Nufact 05 School



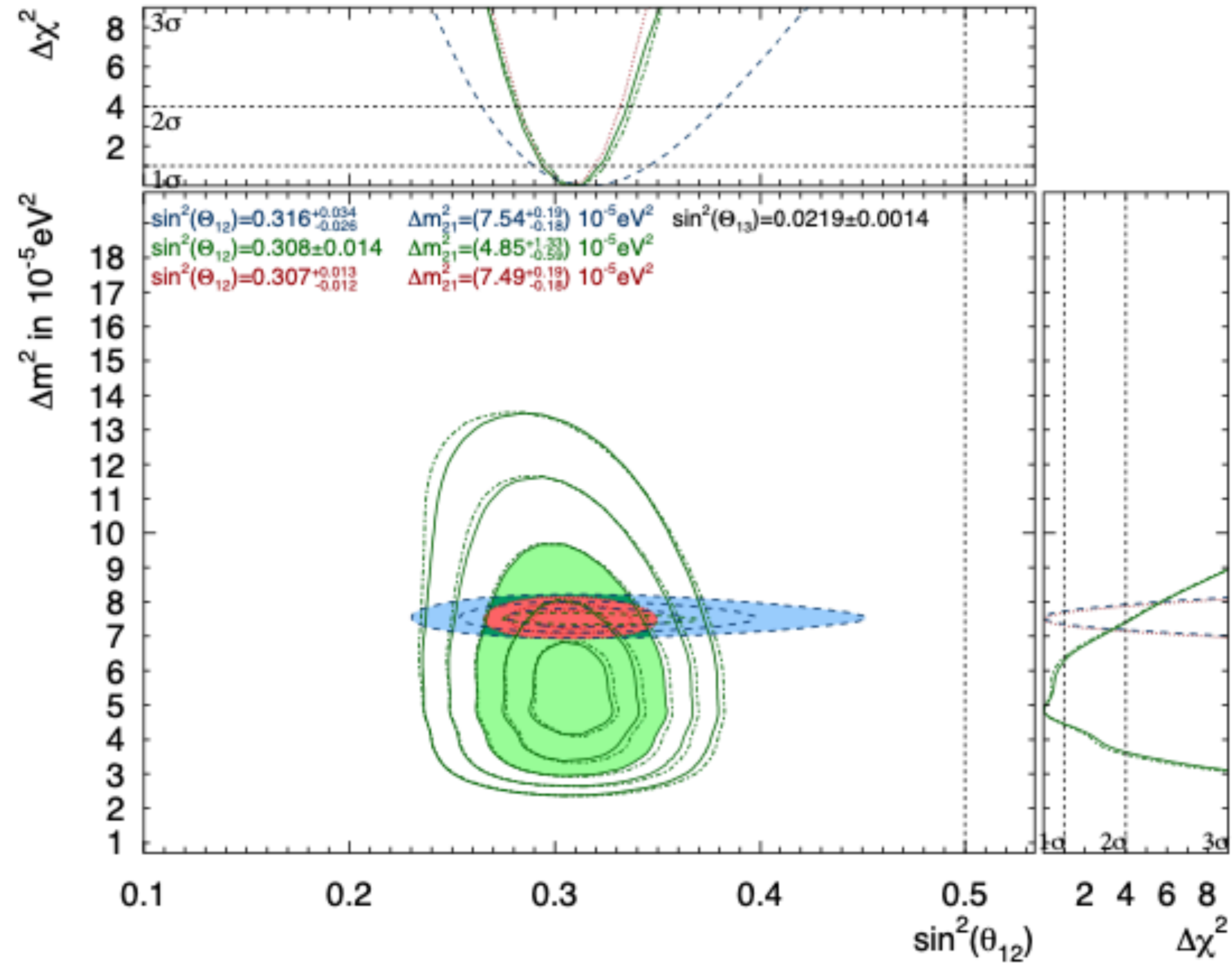
**Cherenkov detector for solar,
accelerator and atmospheric
neutrinos**

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



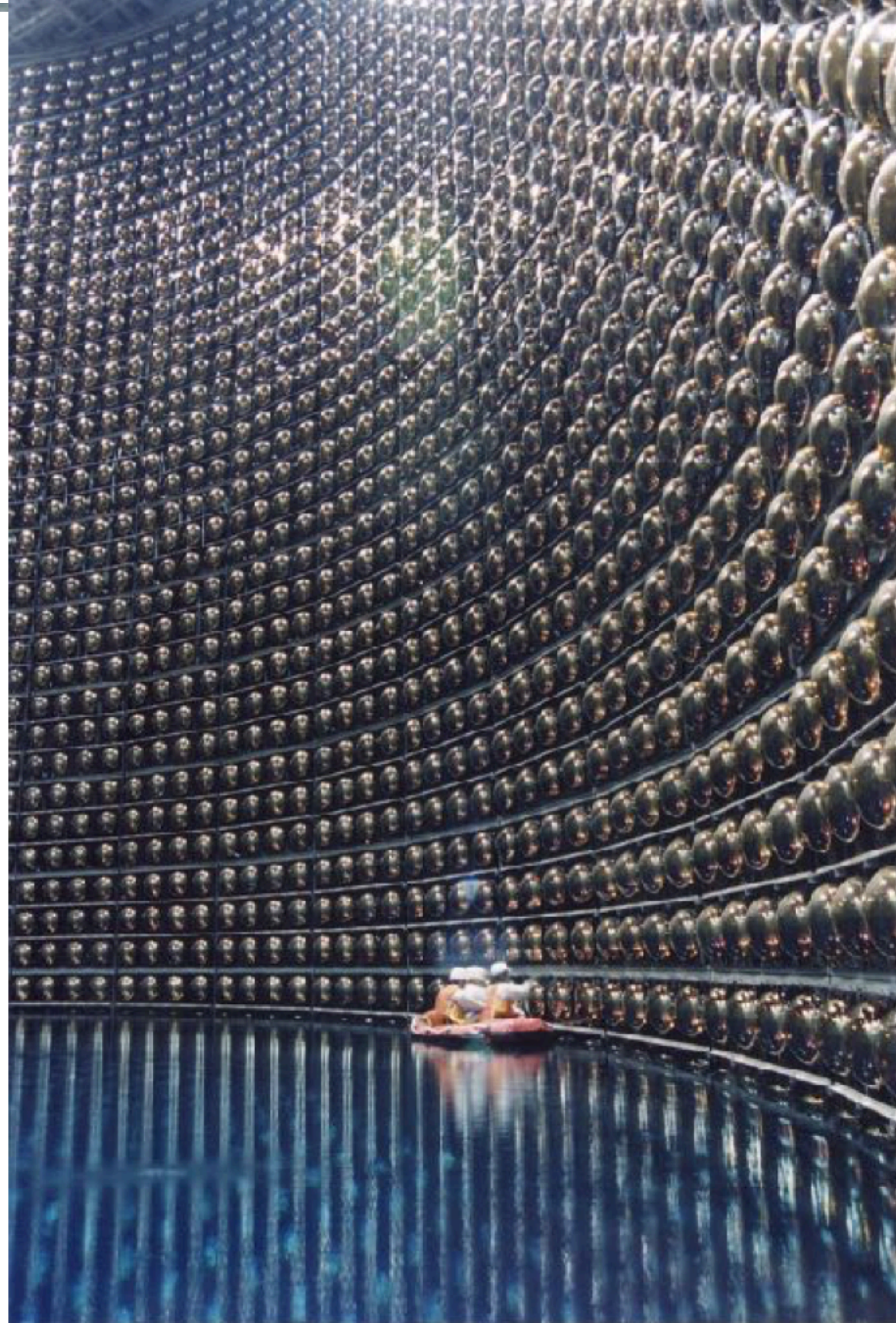
SK Collaboration - *Phys.Rev.D* 94 (2016) 5, 052010

Recent solar neutrino analysis with SK+KamLAND

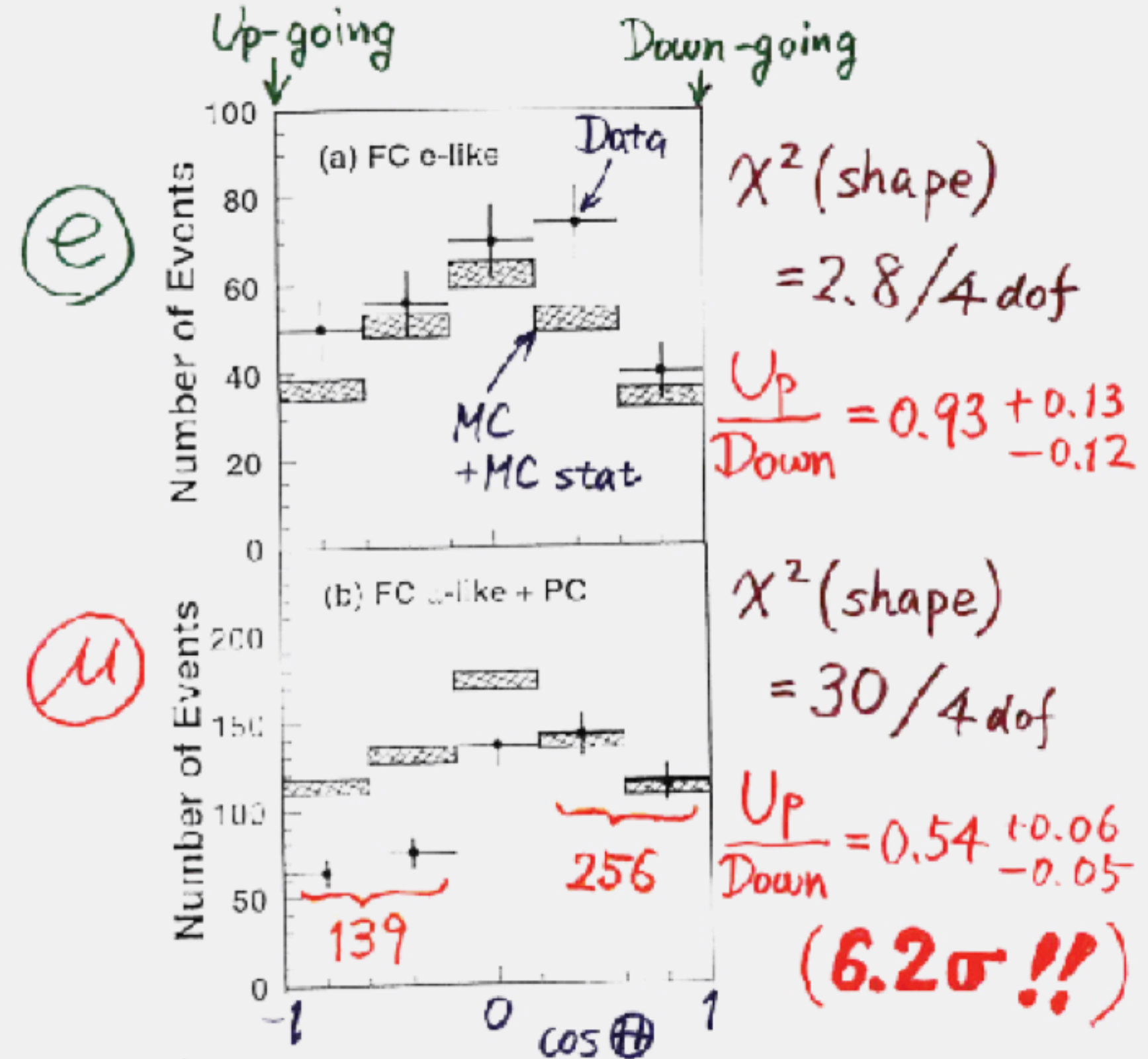


SK Collaboration - *Phys.Rev.D* 94 (2016) 5, 052010

Discovery of atmospheric neutrinos at SK: 1998



Zenith angle dependence (Multi-GeV)

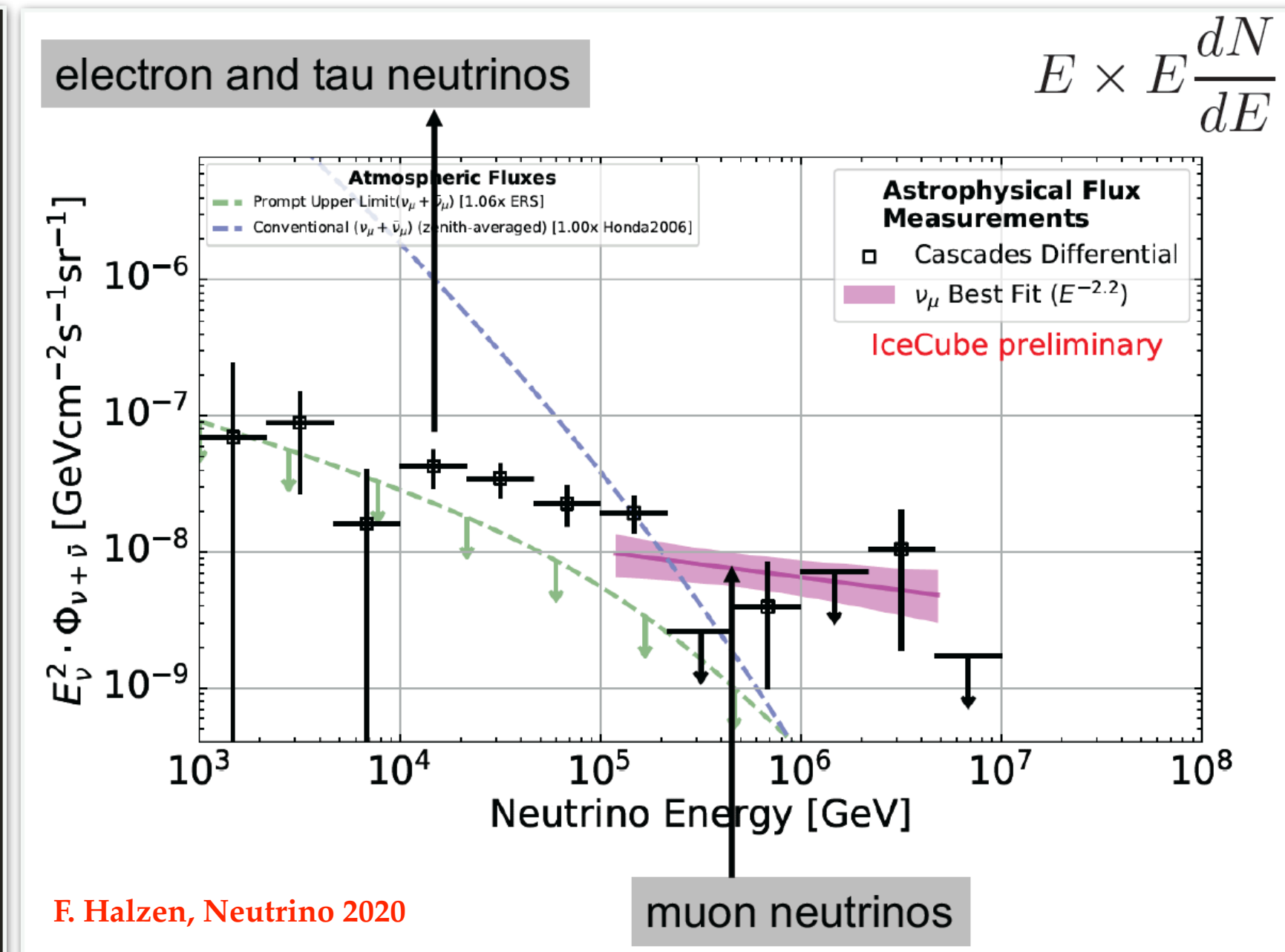
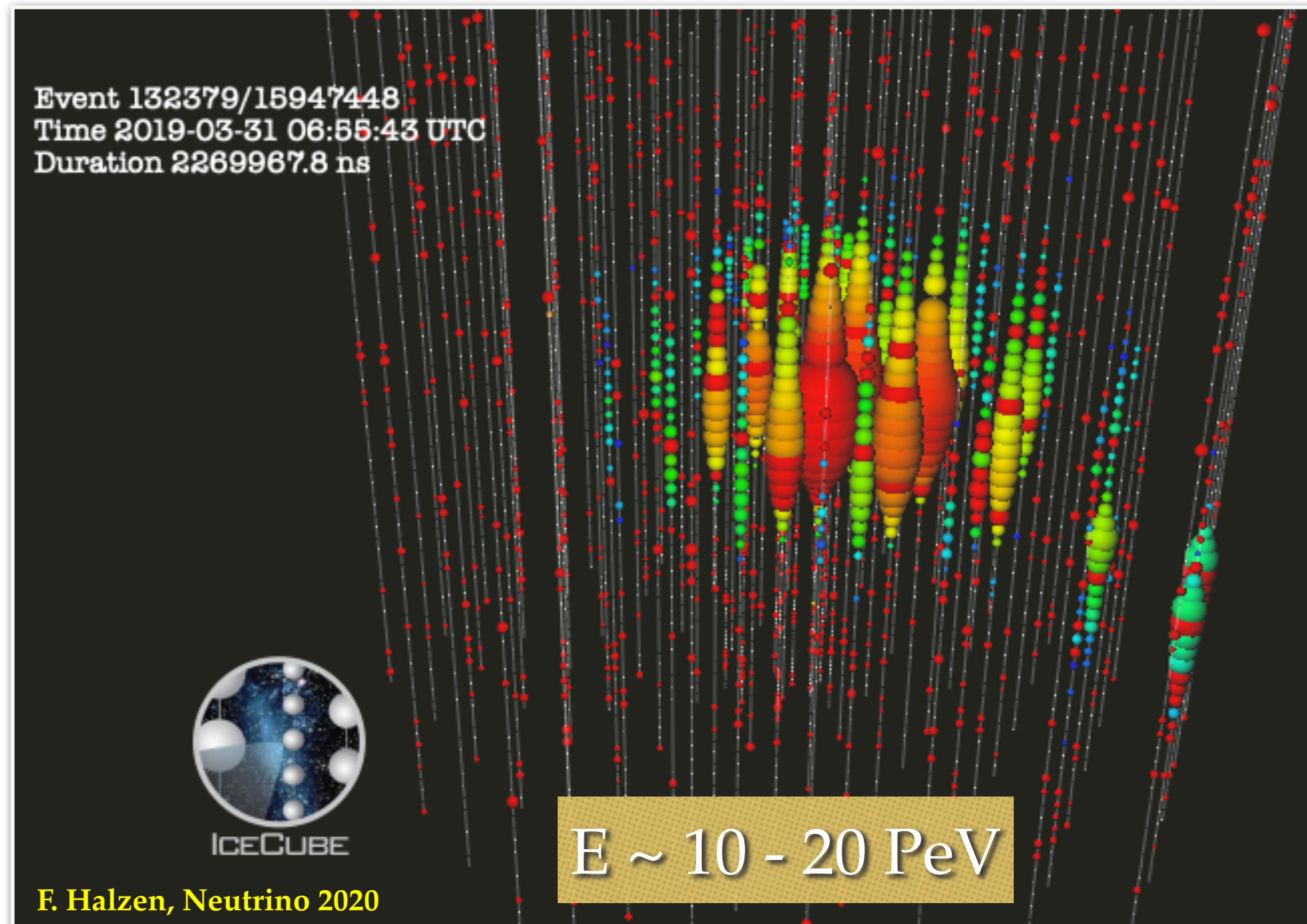
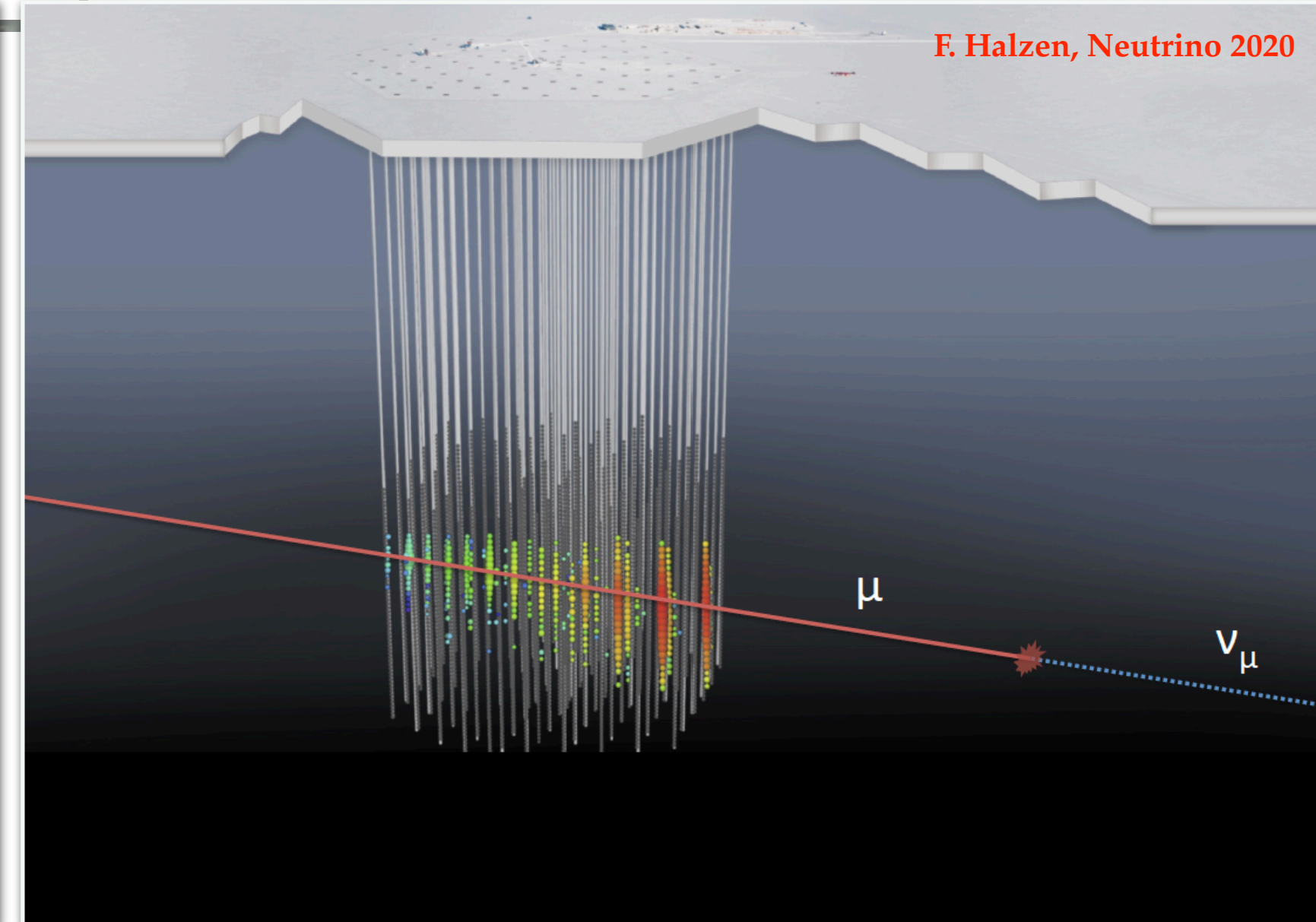
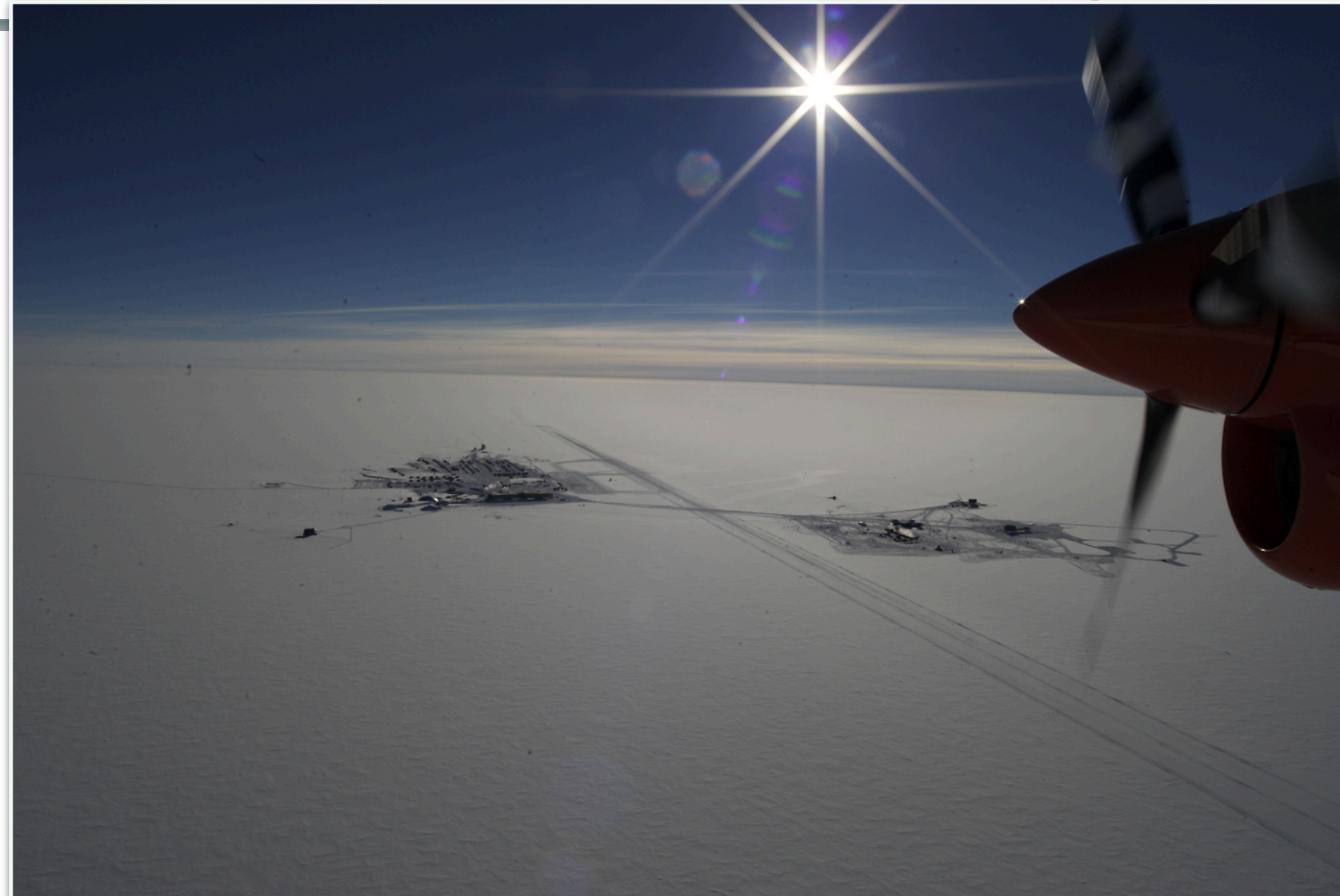


* Up/Down syst. error for μ -like

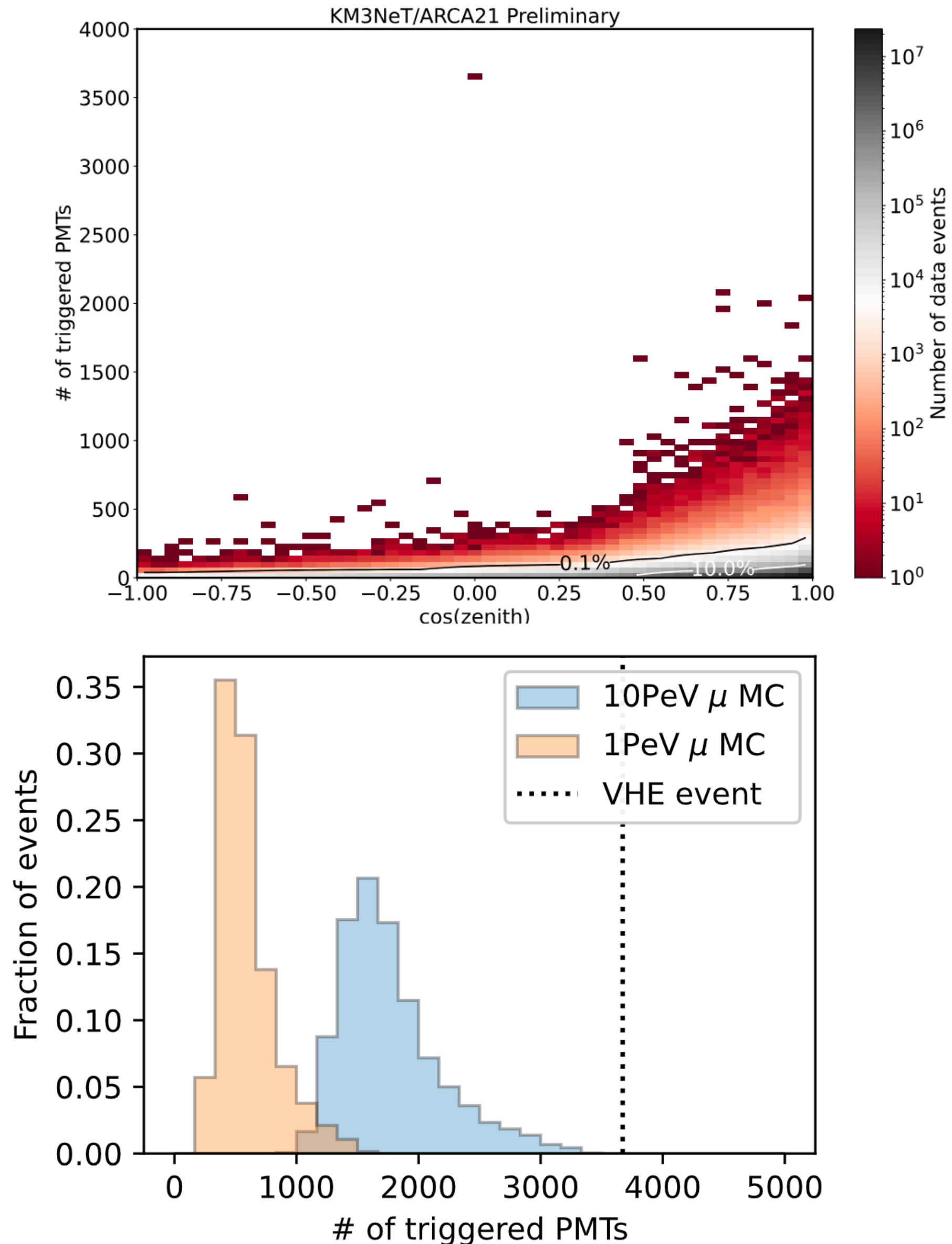
Prediction (flux calculation $\lesssim 1\%$
1km rock above SK 1.5%) 1.8%

Data (Energy calib. for $\uparrow \downarrow$ 0.7%
Non ν Background $< 2\%$) 2.1%

Intermezzo: neutrino detection in ice (Ice-Cube)



Monster beautiful event from KM3Net - 2024



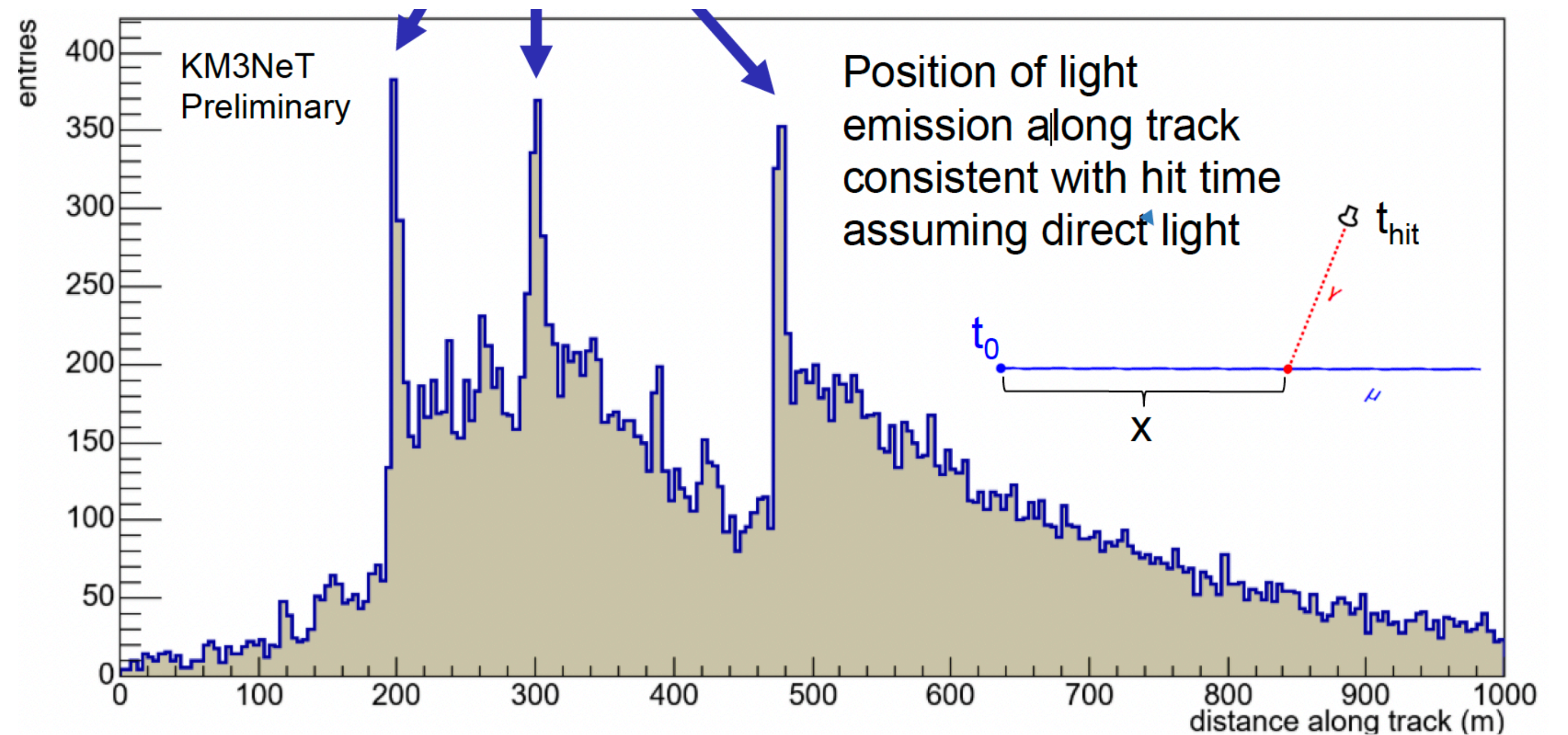
Light profile consistent with at least 3 large energy depositions
along the muon track

Characteristic of stochastic losses from very high energy muons

Estimated energy ~ 100 PeV scale

To be published soon

(Shown at Neutrino 2024 conference)

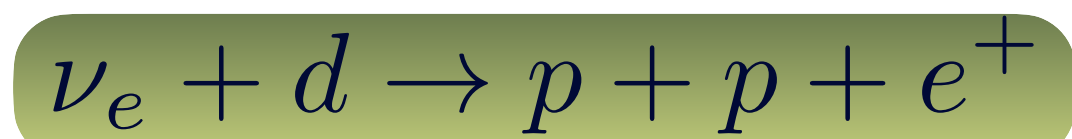


Solution of Solar Neutrino Problem: SNO

- Sudbury Neutrino Observatory
 - Key feature: 1 kt D₂O
 - Ability to identify electron type neutrinos, and measure the others

- Three key reactions:

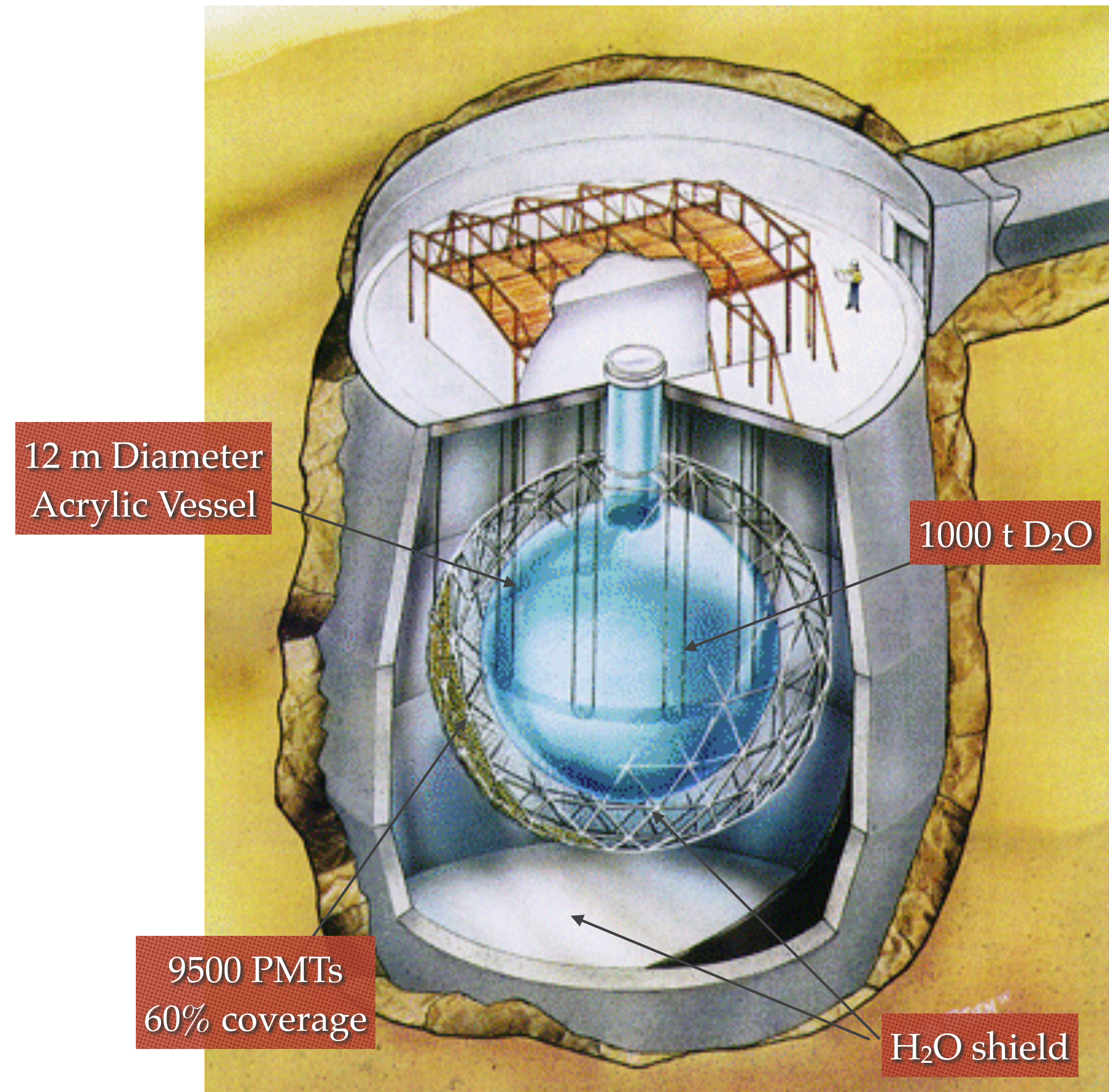
- **CC:** ν_e only



- **NC:** All types, equal



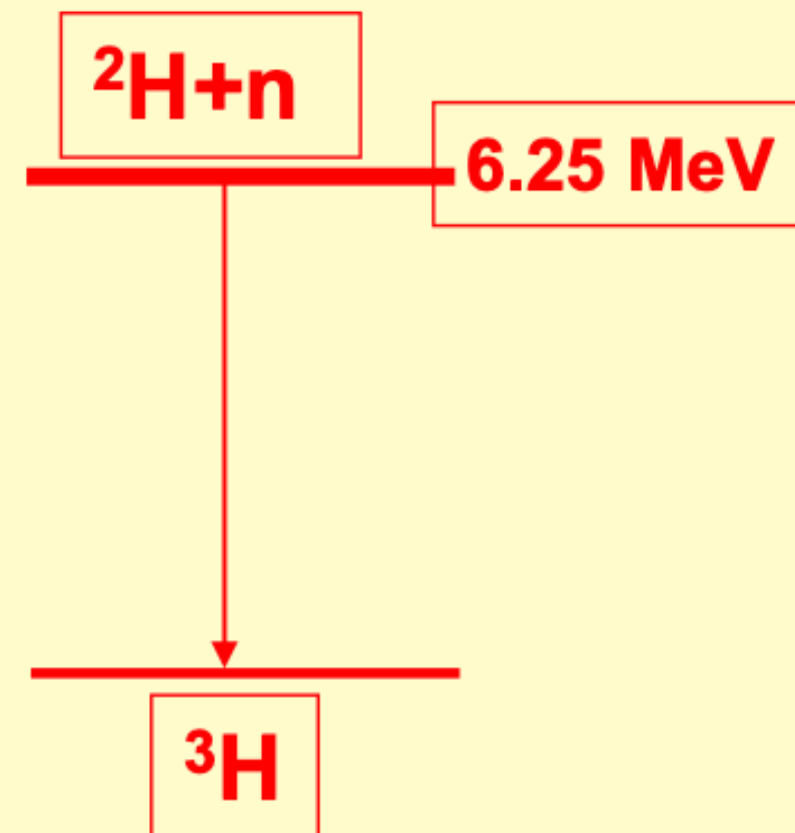
- **ES:** All types, un-equal



3 neutron (NC) detection methods (systematically different)

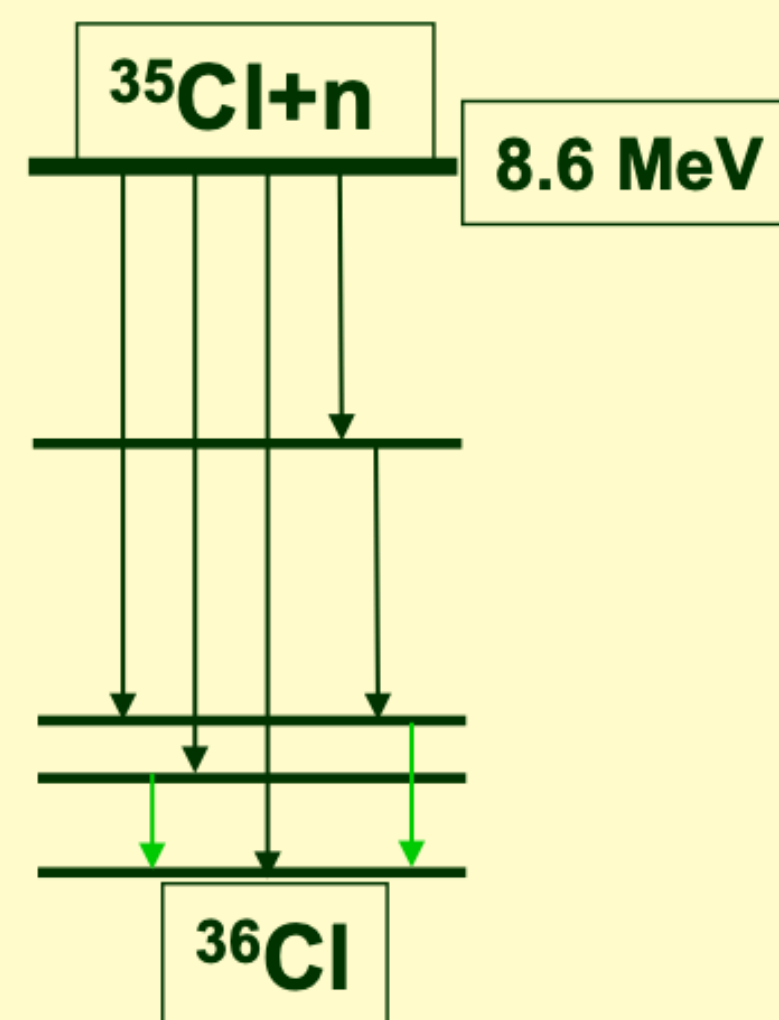
Phase I (D_2O) Nov. 99 - May 01

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



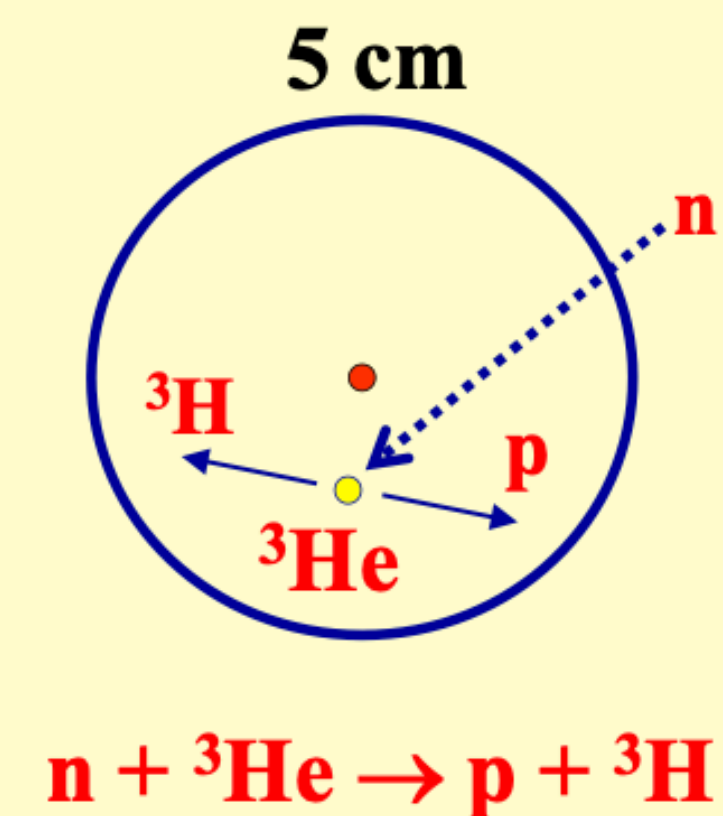
Phase II (salt) July 01 - Sep. 03

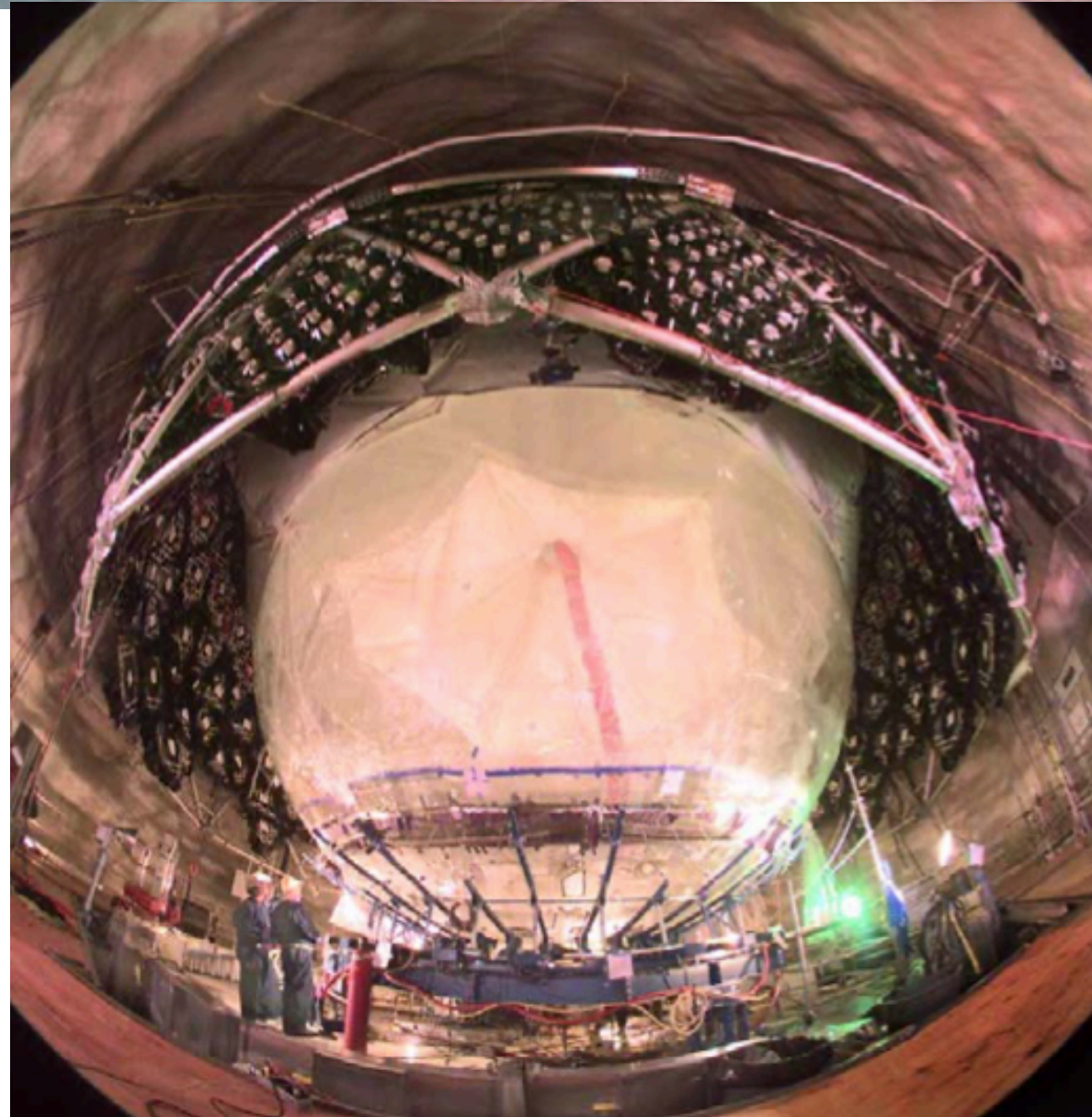
2 tonnes of NaCl
n captures on
 $^{35}Cl(n, \gamma)^{36}Cl$
Effc. $\sim 40\%$
NC and CC separation
by event isotropy



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

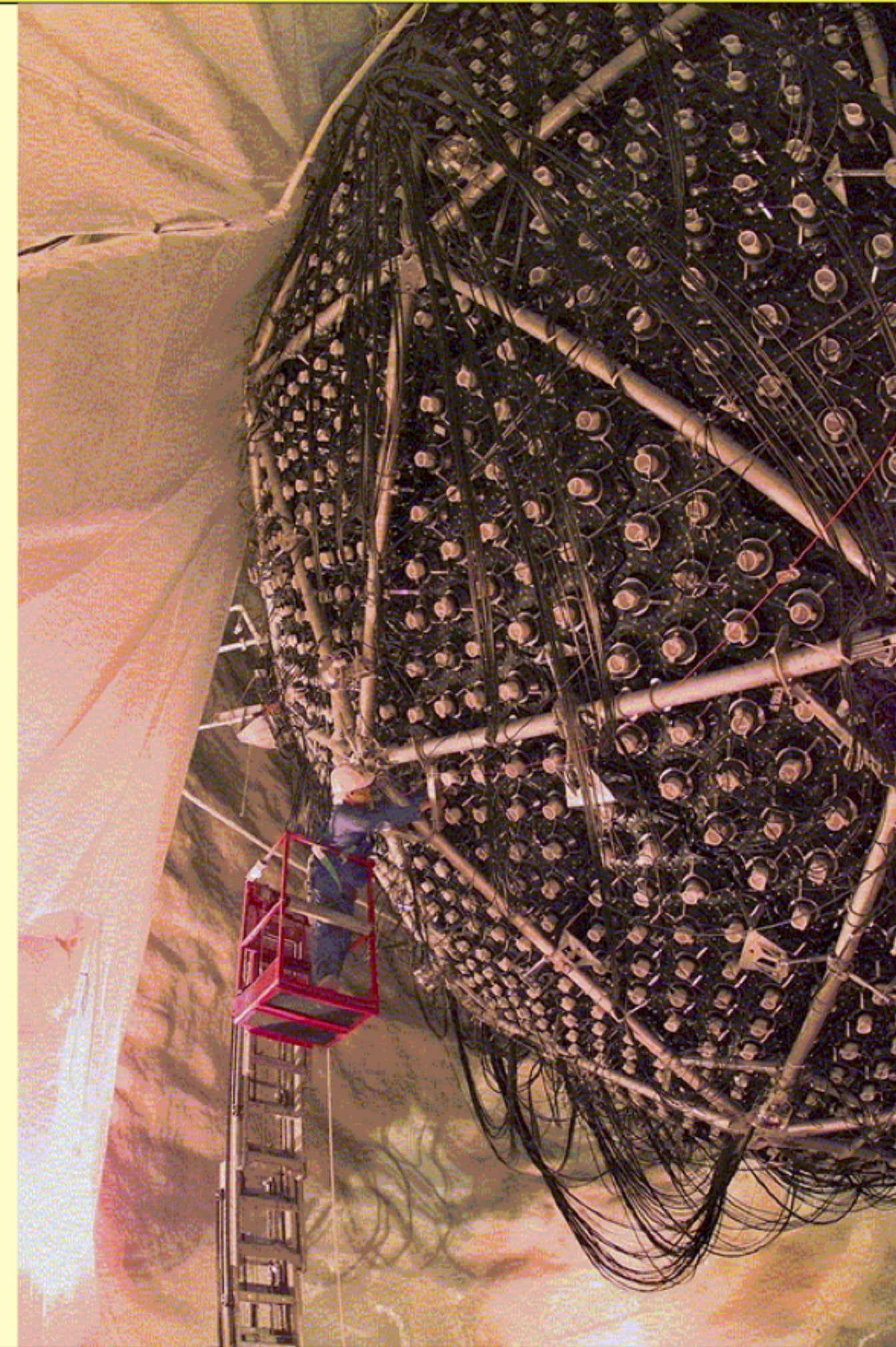
400 m of proportional
counters
 $^3He(n, p)^3H$
Effc. $\sim 30\%$ capture
Measure NC rate with
entirely separate
detection system.





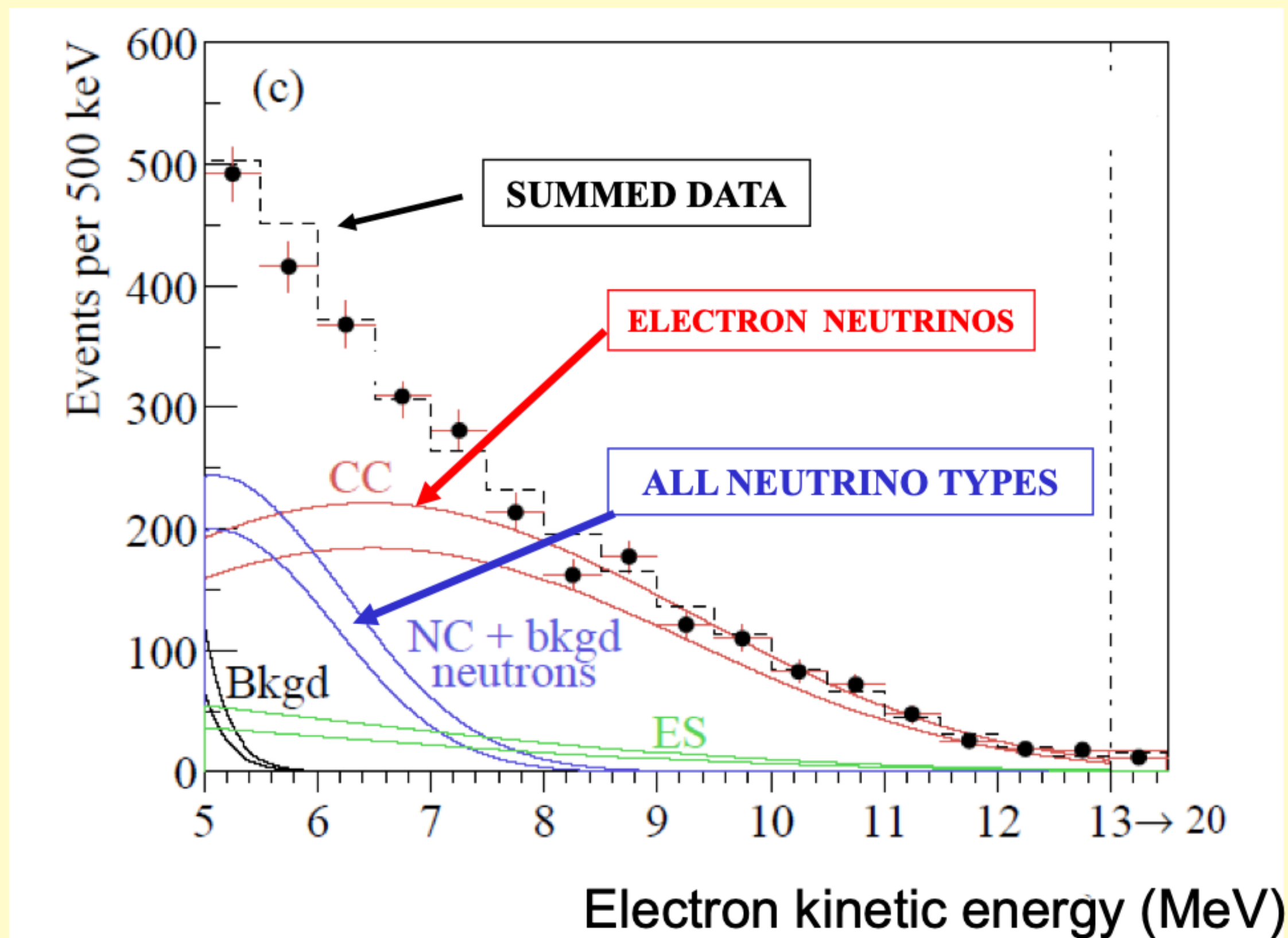
SNO: One million pieces transported down in the 3 m x 3 m x 4 m mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

70,000
showers
during the
course of the
SNO project



Art McDonald: Neutrino 2016

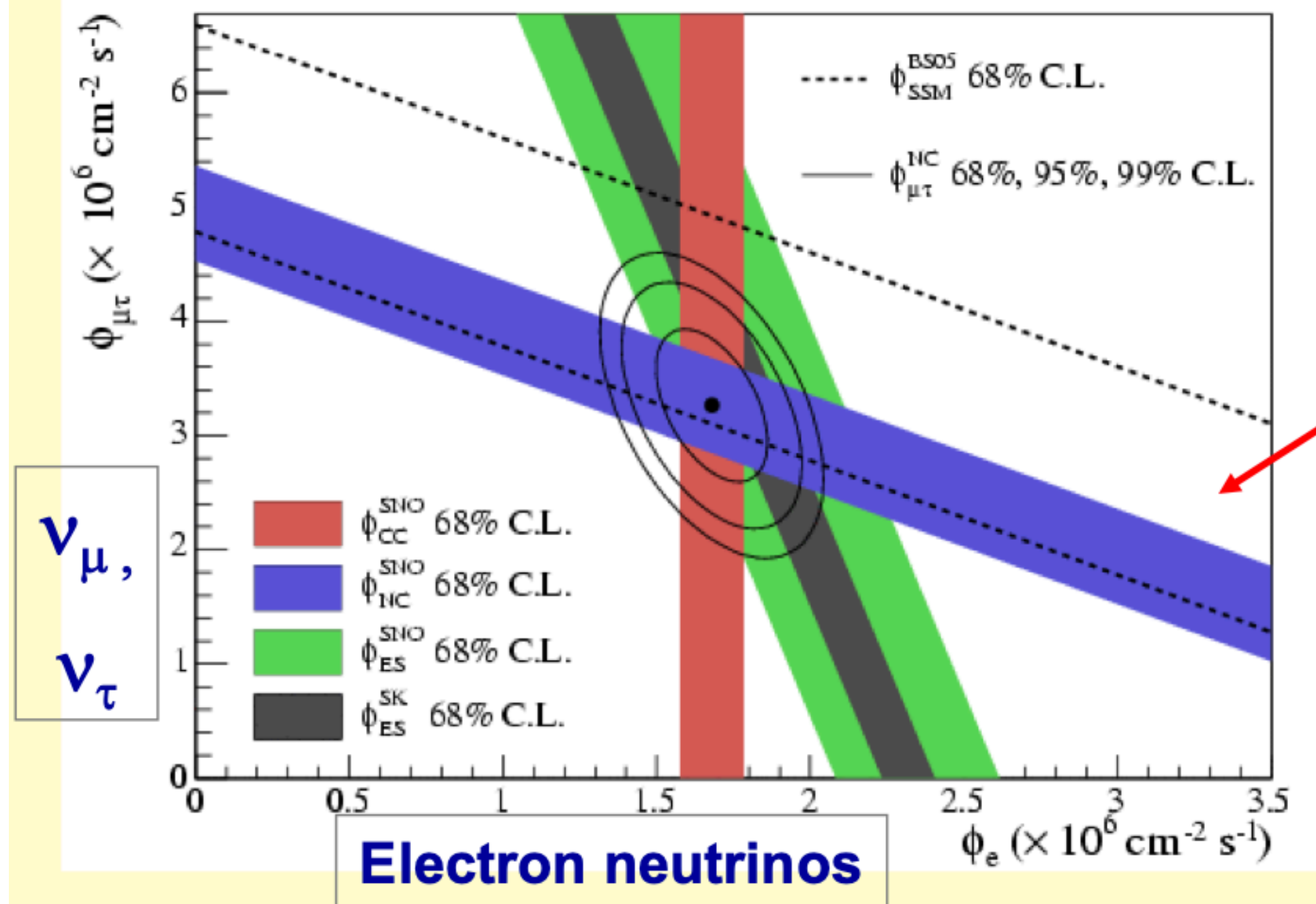
WE OBSERVED NEUTRINOS FROM THE SUN WITH ALMOST NO RADIOACTIVE BACKGROUND



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

Data from Pure Heavy Water Phase in 2002

SNO results



SNO Results for Salt Phase

Flavor change determined by $> 7 \sigma$.

New physics beyond The Standard Model of Elementary Particles!

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

Calculations:

5.82 $\pm$ 1.3 (Bahcall et al),

5.31 $\pm$ 0.6 (Turck-Chieze et al)

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

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

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

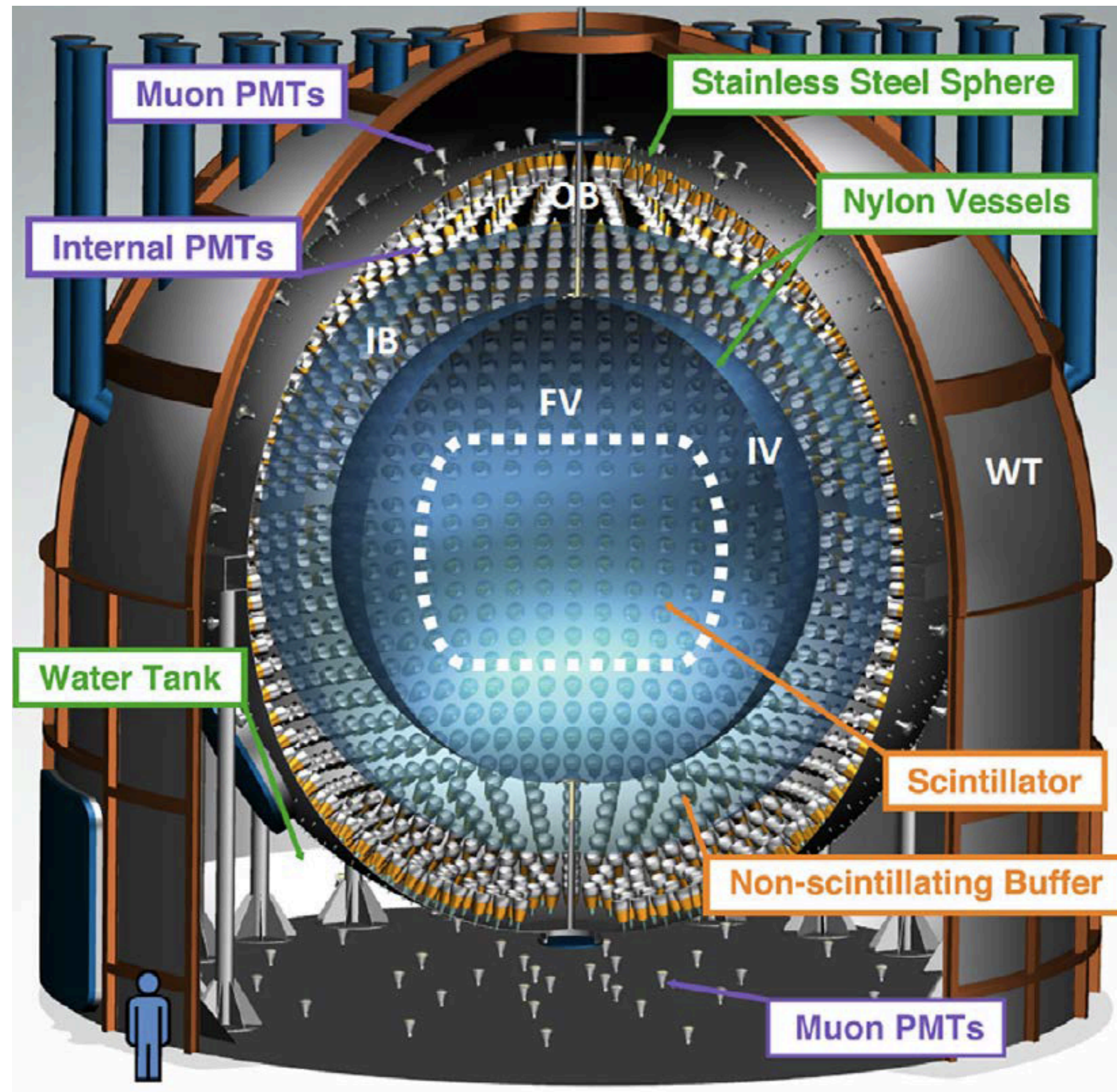
(In units of $10^6 \text{ cm}^{-2} \text{ s}^{-1}$)

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

Electron Neutrinos are only 1/3 of Total

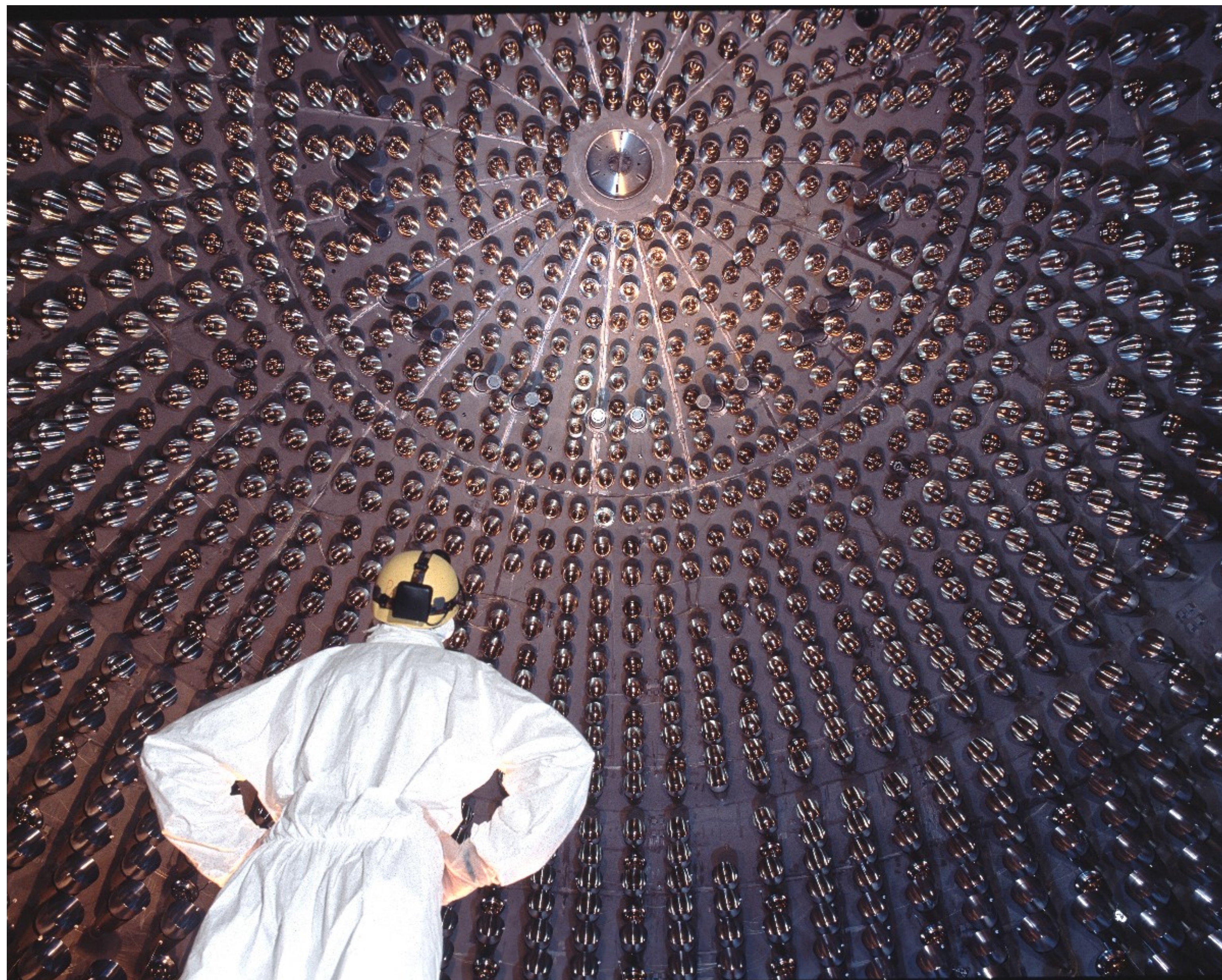


The Borexino detector





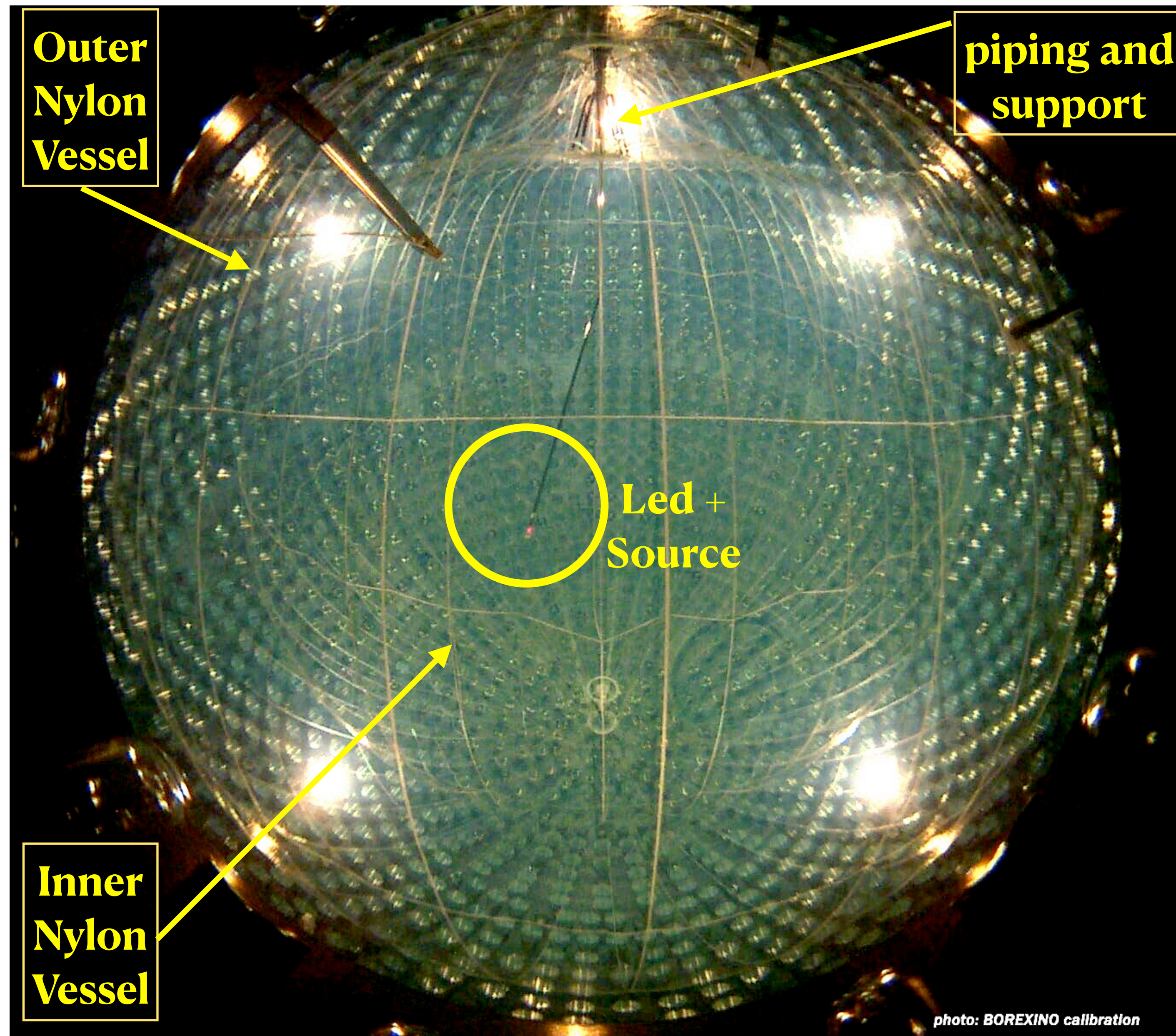
Internal view, empty



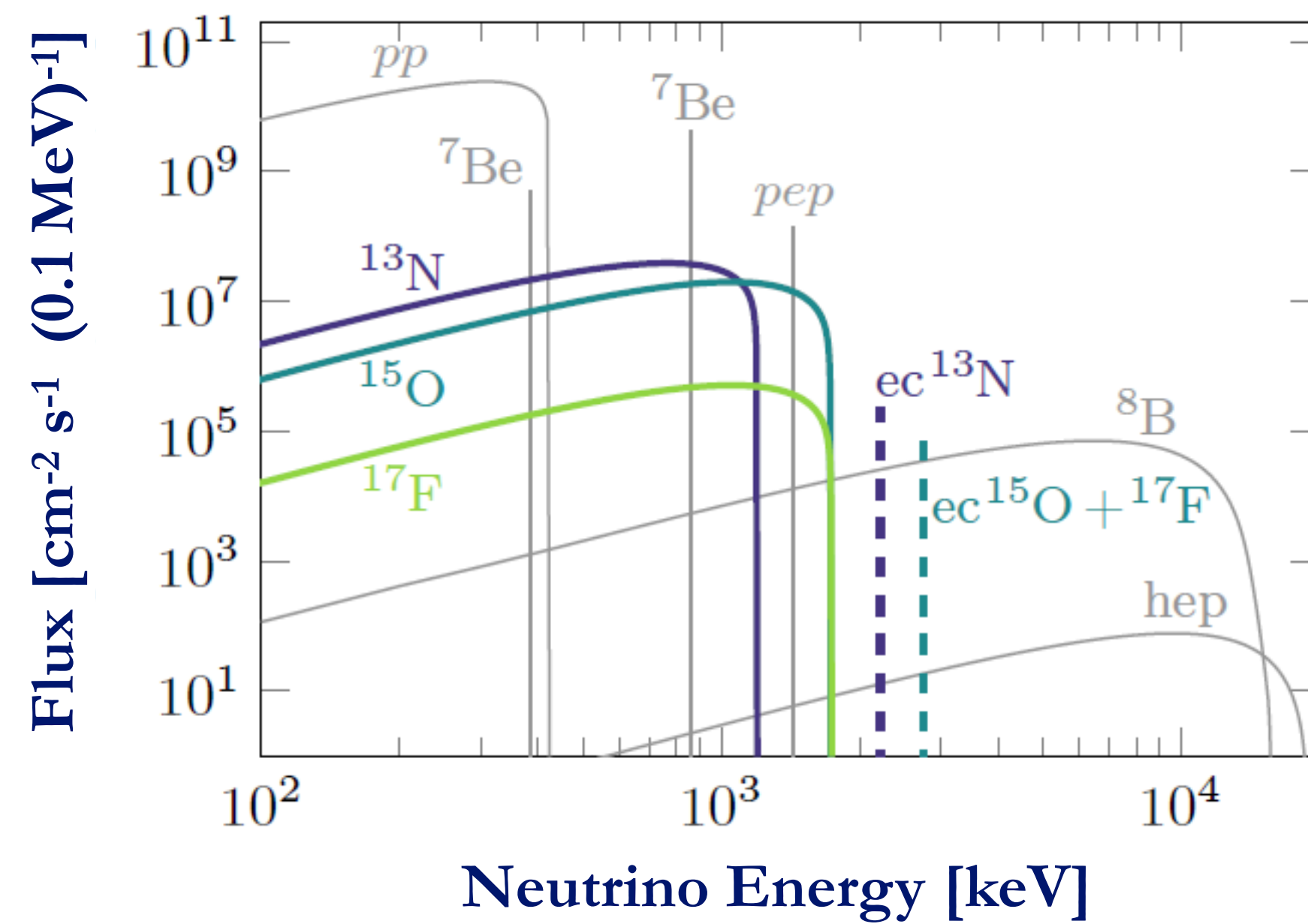
Internal view: inflated vessels (with N₂)



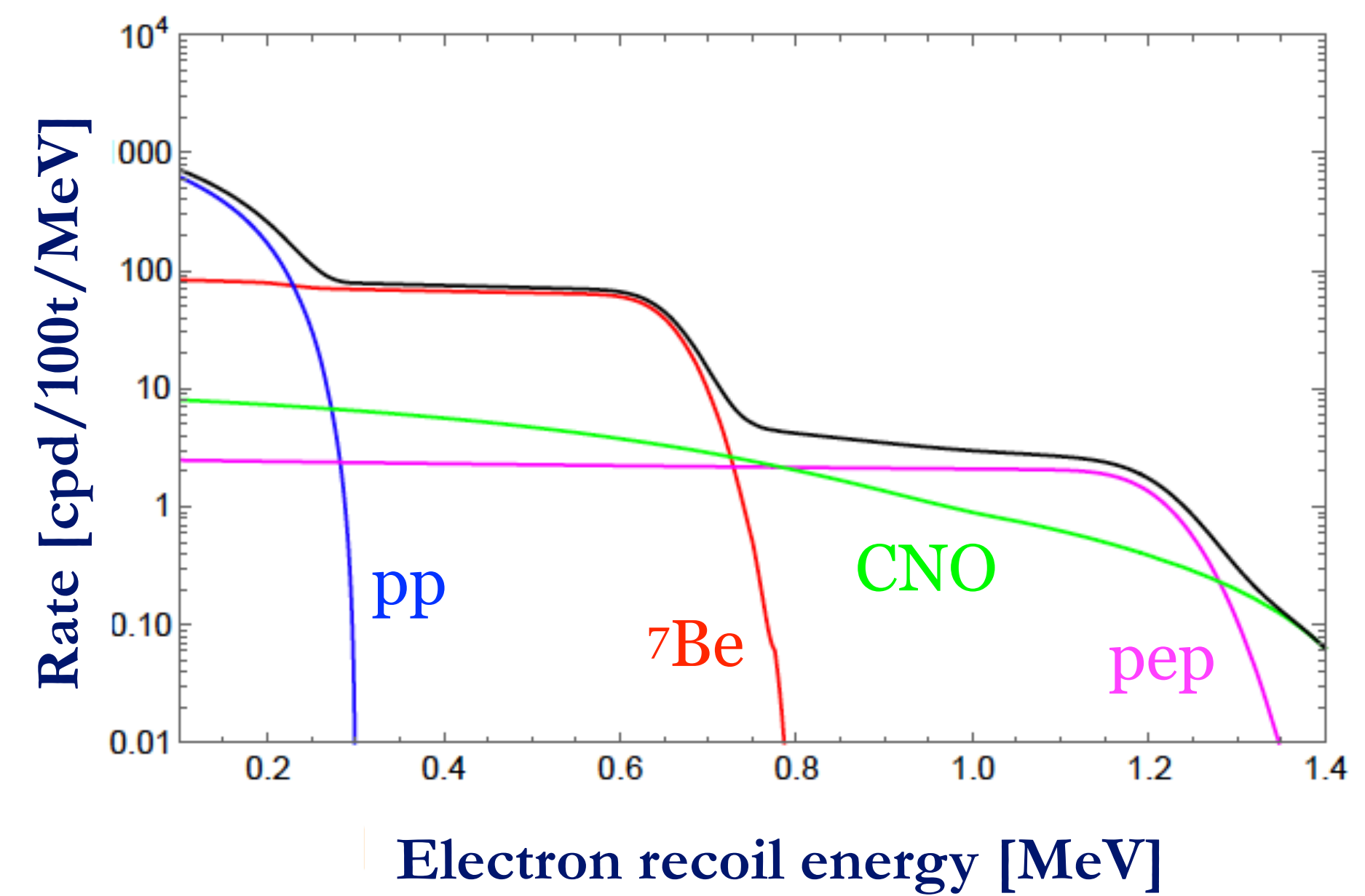
Internal view, filled, during calibration in 2009



SOLAR NEUTRINO SPECTRUM

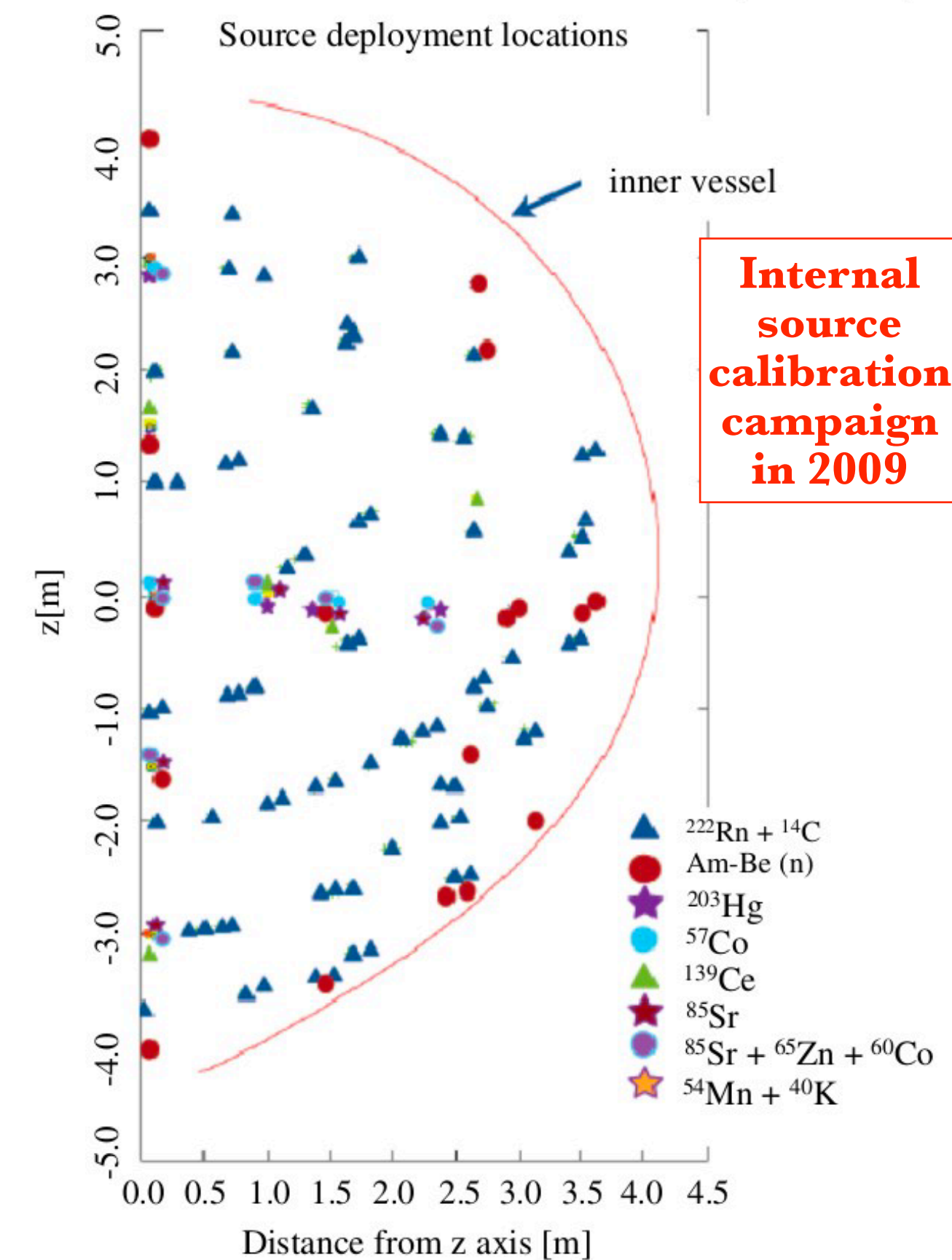


DETECTION RATE IN BOREXINO

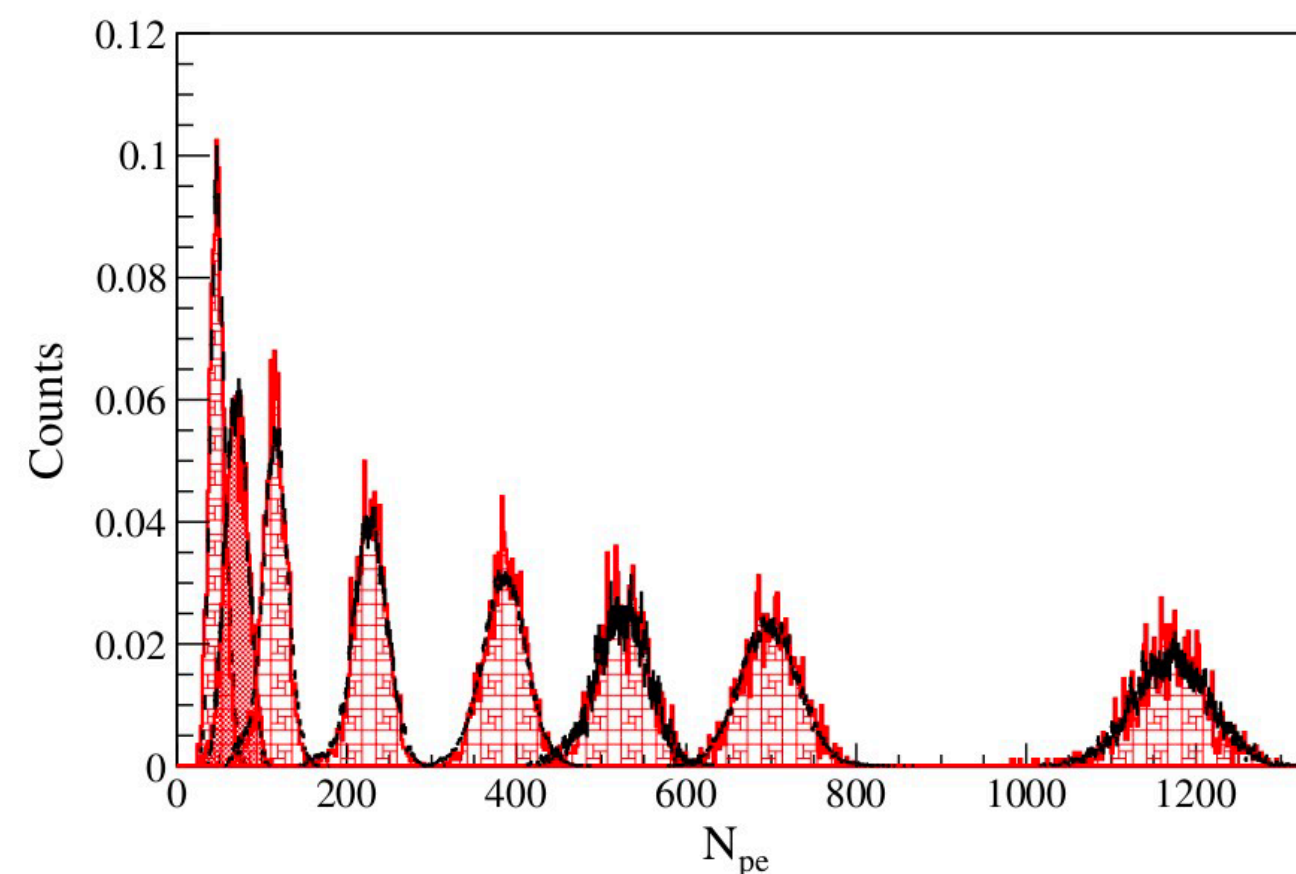


Detector response

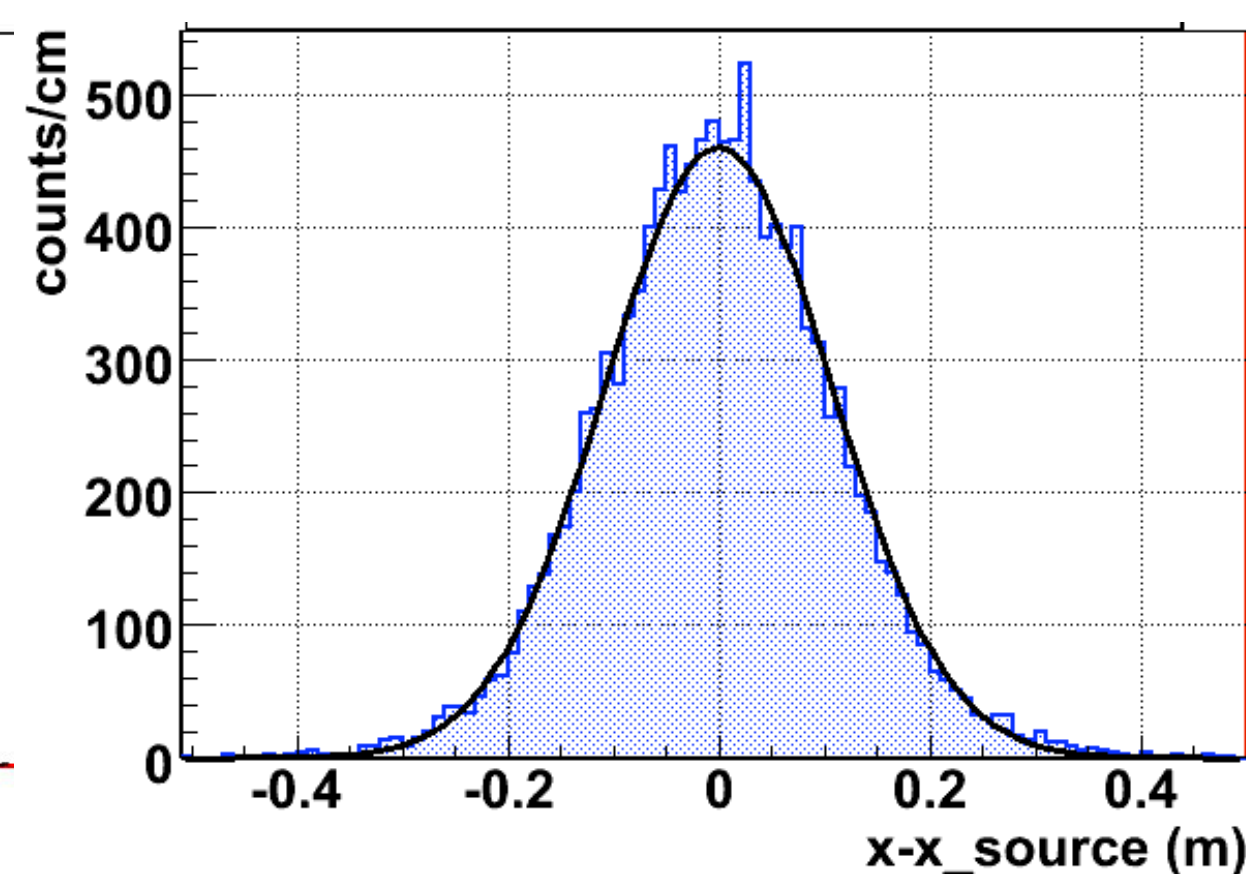
- Large liquid scintillator signal yields:
 - # photo-electrons:
 - energy: **6% @ 1 MeV**
 - time-of-flight:
 - position: **~11 cm @ 1 MeV**
 - pulse shape:
 - very good α/β and (weak) β^+/β^- discrimination



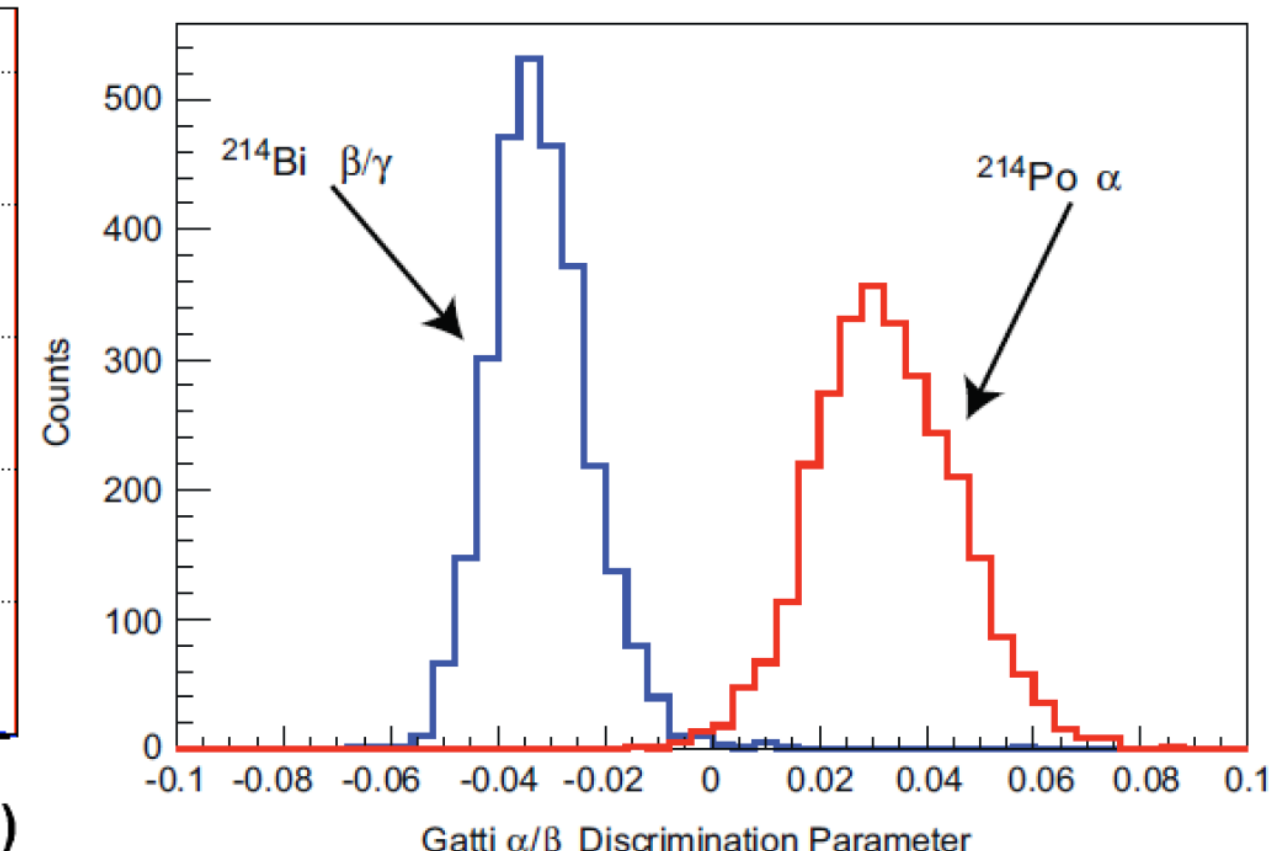
Energy: γ sources



Position: ^{214}Po



α/β : $^{214}\text{Bi} - ^{214}\text{Po}$



• Quasi-point-like energy deposits mimic neutrino events

EXTERNAL

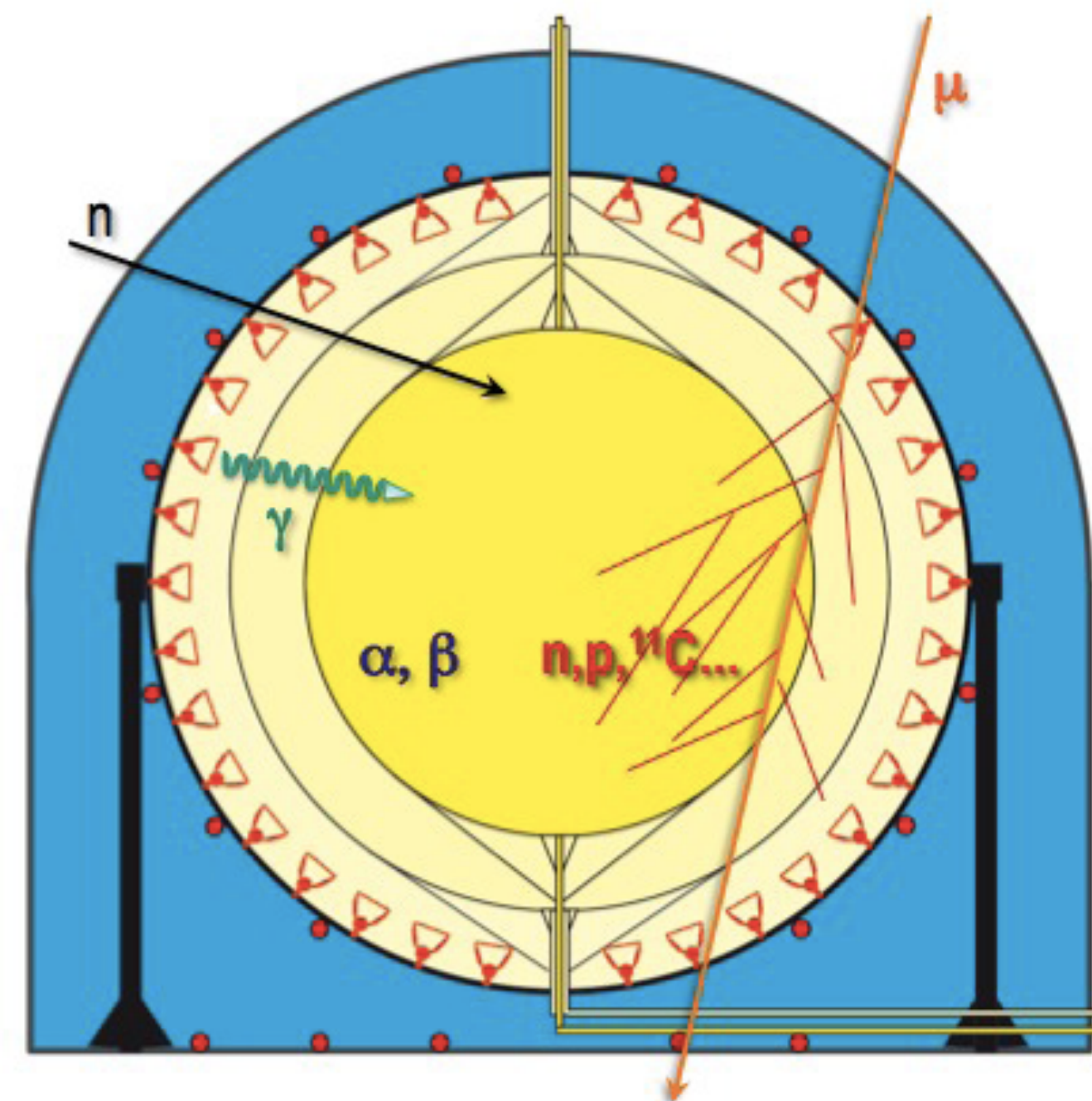
- γ s (and n) from environment and detector materials (PMTs and SSS, mostly)

A tiny amount reaches FV

INTERNAL

- α and β emitters dissolved in the scintillator

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



COSMOGENIC

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

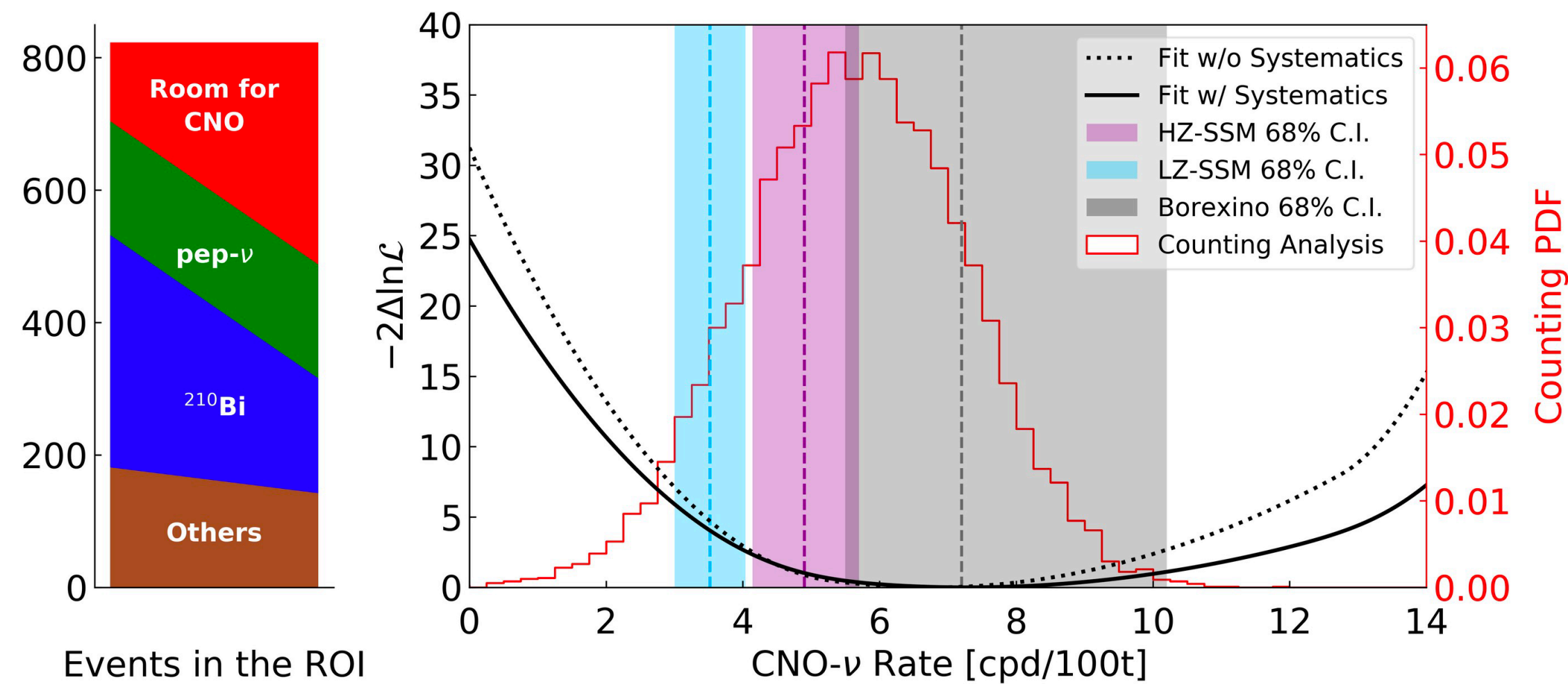
^{11}C , ^8He , ^9C , ^9Li ,

MIGRATING

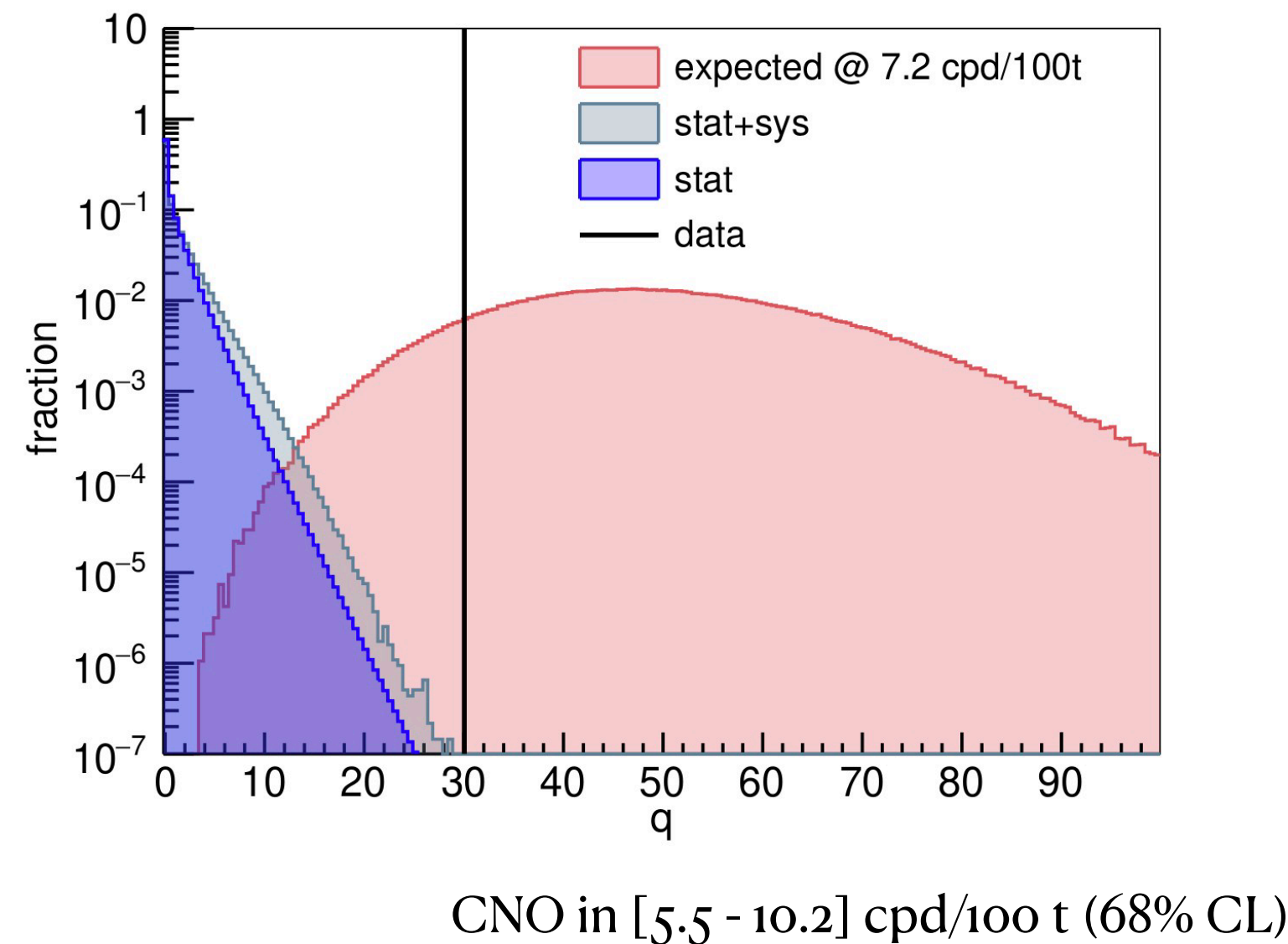
- Detaching from Nylon Vessel and transported by convection into the FV

^{210}Po , ^{222}Rn

Observation of CNO



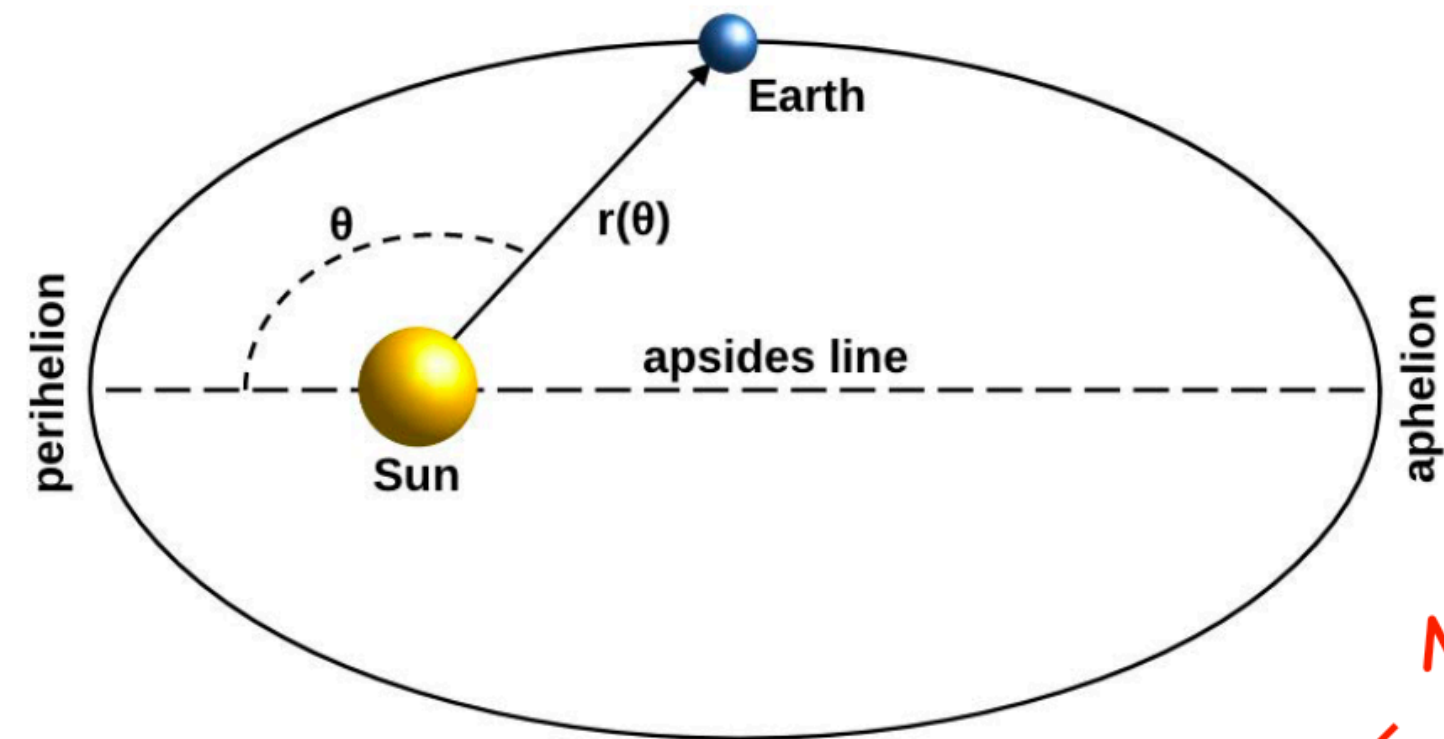
Result (68% CL stat + sys) = $7.2 - 1.7 + 3.0$ cpd/100t



- Systematics:
 - Response, resolution, spectral shapes and
 - LY: $\sigma_L = -0.5$, $\sigma_R +0.6$ (5.1 σ significance)
- Significance
 - Hypothesis test with 13.8×10^6 pseudo-experiments
 - Hypothesis CNO=0 excluded at 5.0 σ (99%CL)
- Model compatibility
 - - 0.5 σ (HZ)
 - - 1.3 σ (LZ)
 - - LZ disfavoured at 2.1 σ including other
- Fluxes from pp-chain (Borexino only)

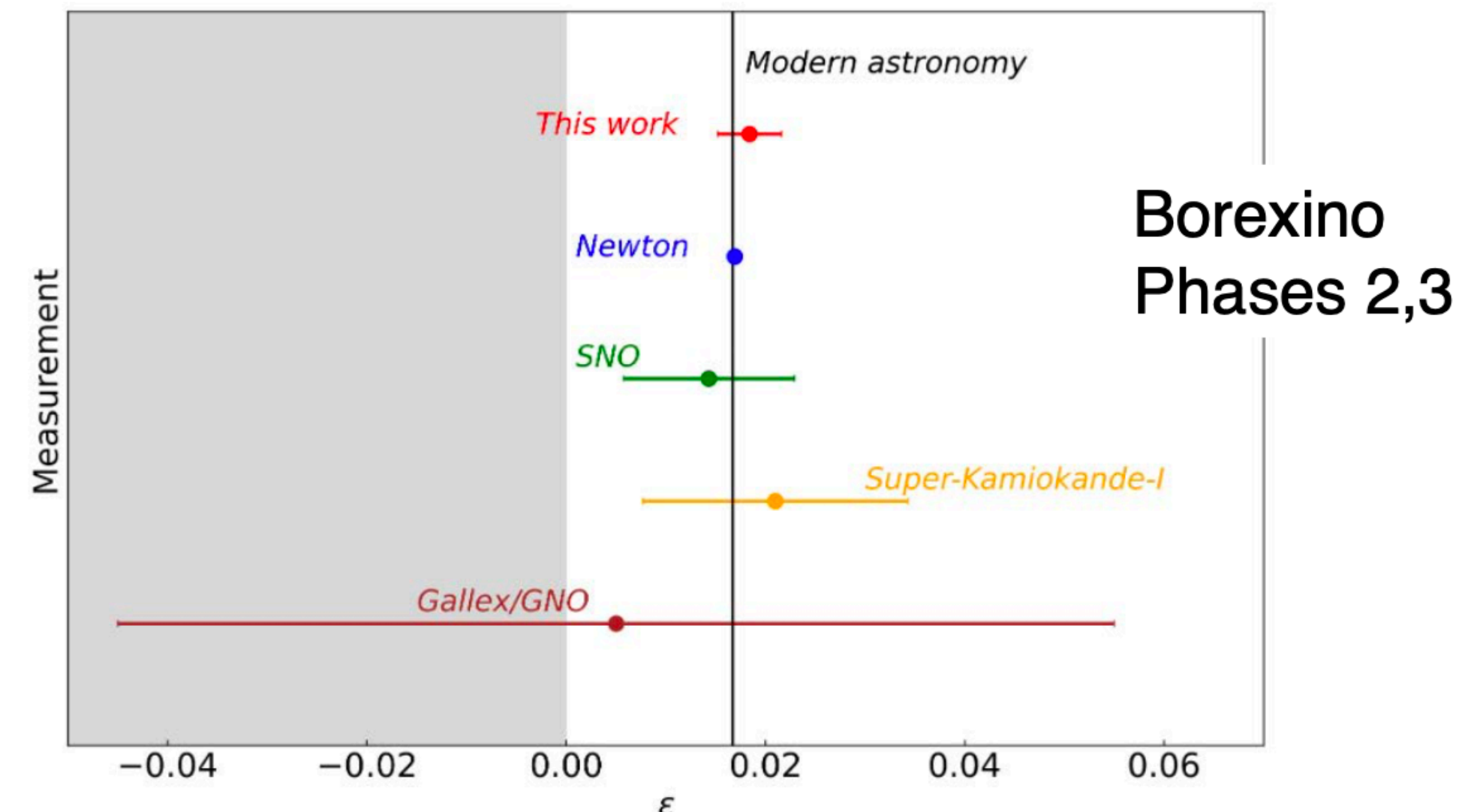
Stability check: Earth orbit with neutrinos

- Check of Borexino stability over 10 years



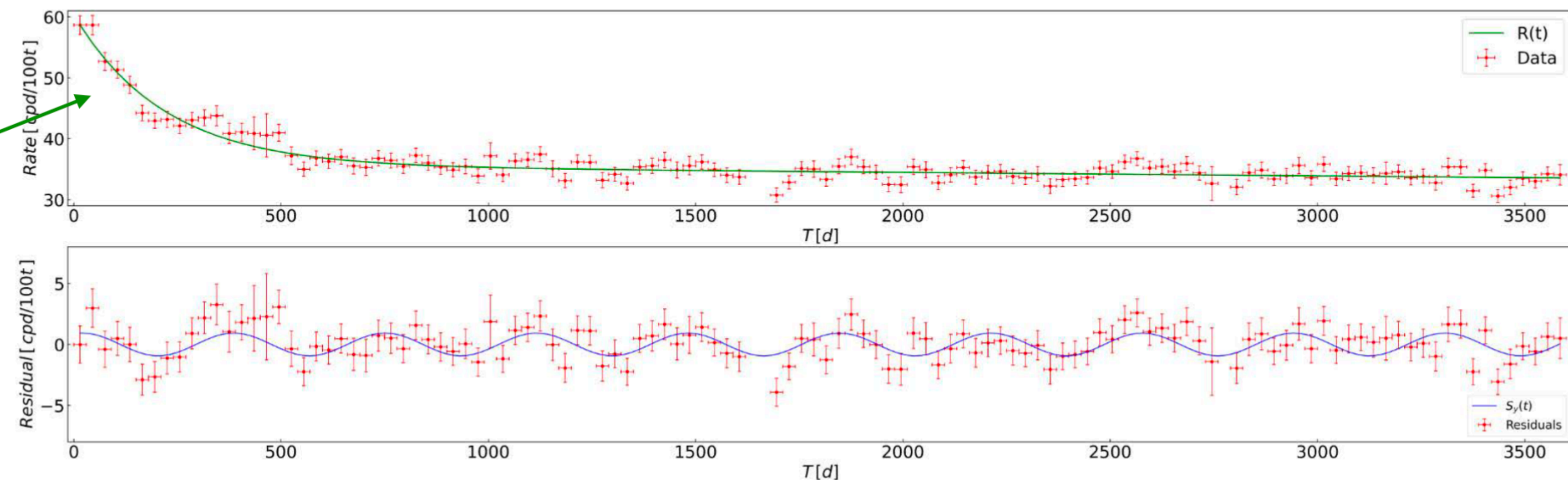
$$r(\theta) = \frac{\bar{r}(1 - \epsilon^2)}{1 + \epsilon \cos(\theta)}$$

$$\Phi(t) \approx \frac{\Phi_0}{\bar{r}^2} \left[1 + 2\epsilon \cos(\omega_y(t - t_0)) \right]$$



Secular (unmodulated) components:

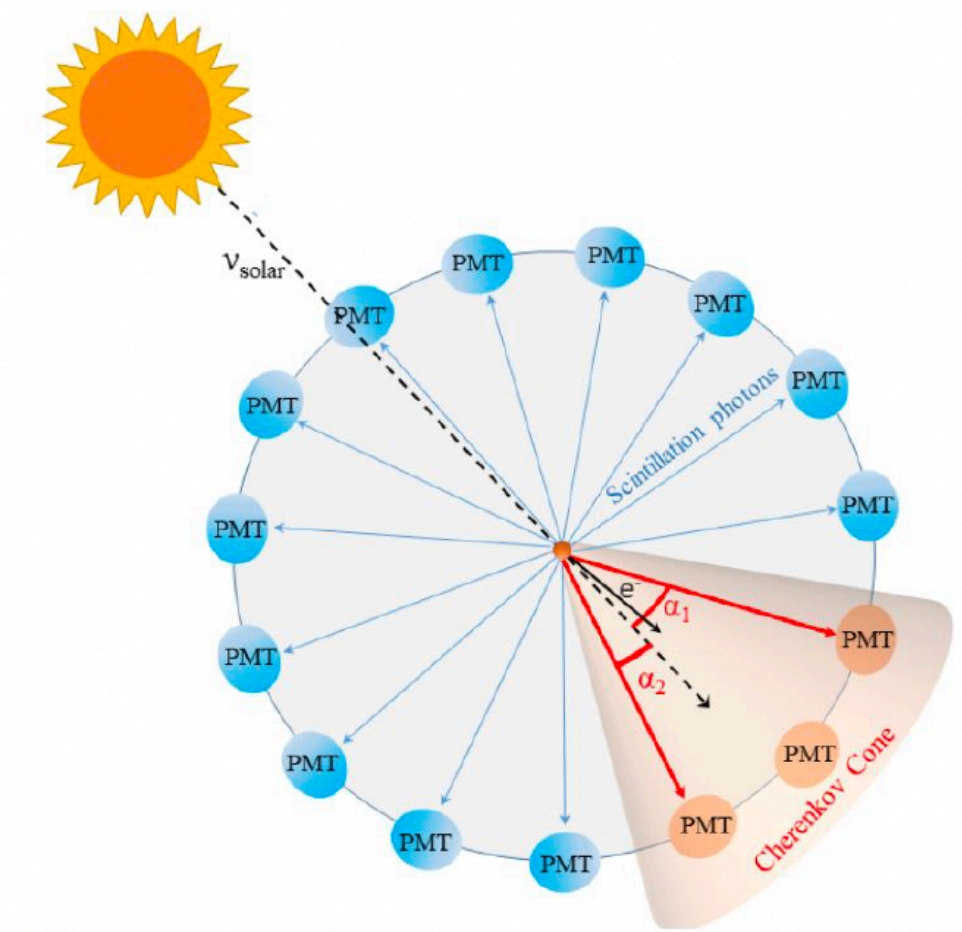
- ^{210}Po leakage
- Bg non-uniform mixing
- External bg leakage from slow vessel deformation
- ^{85}Kr ?



CNO by means of directionality

- Although most light comes from scintillation, a small amount of **Cherenkov light** is emitted too
 - A few early photons keep memory of **neutrino incoming direction**
 - Time-space correlation allows the reconstruction of direction (statistically)

PRL 128, 091803 (2022).



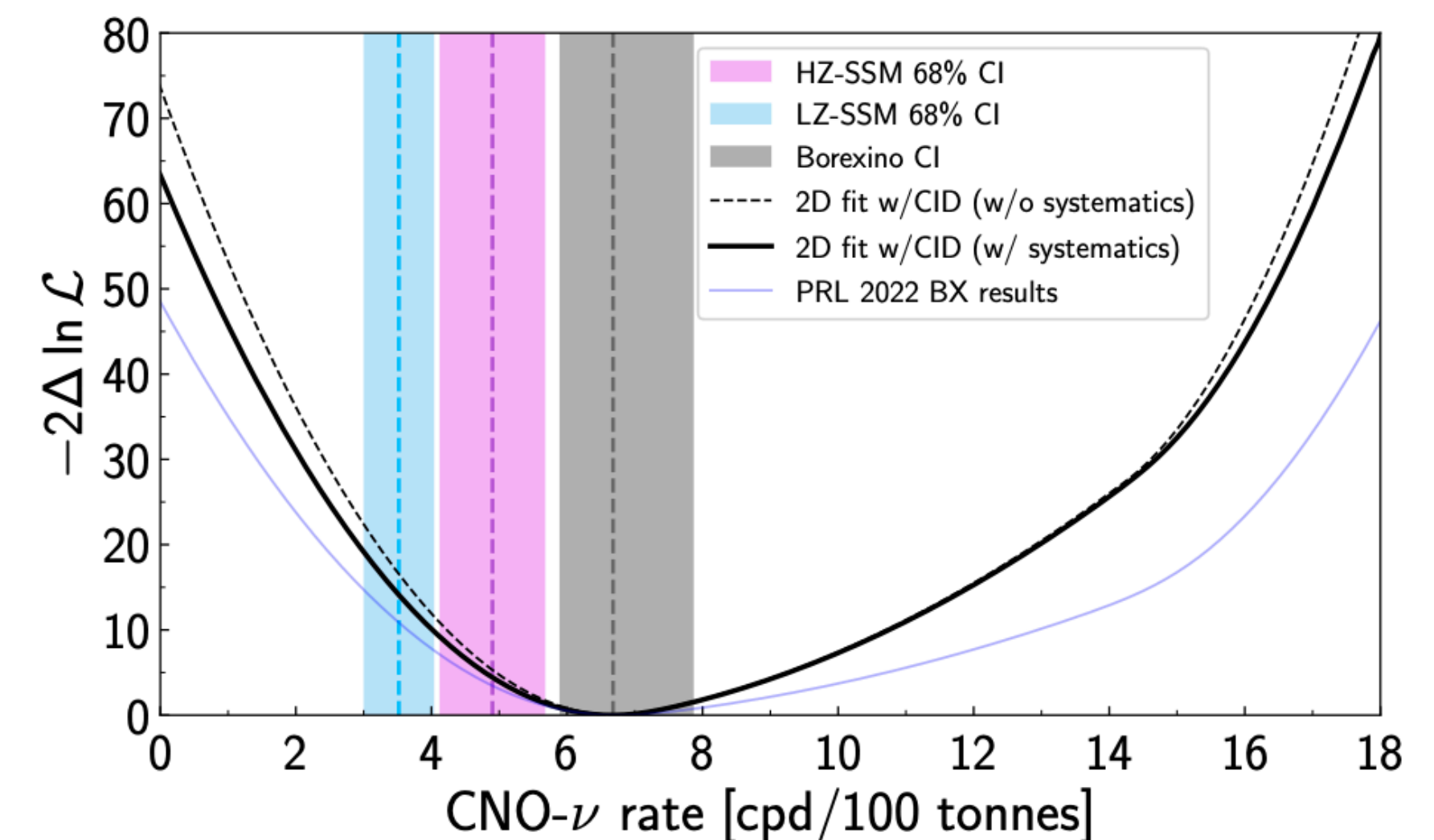
- By means of a Correlated and Integrated Directionality (CID) technique it's been possible to **extract the CNO** signal from the whole data set (all phases, not only Phase III) and:

- Confirm** the CNO result independently
- Improve** the CNO measurement by combining the CID with the Multivariate Fit used for “Nature” paper

Result (68% CL stat + sys) = $6.7 - 0.8 + 1.2$ cpd/100t

- Pave the way for **future experiments** which might improve significantly the technique with more dedicated hardware and/or better scintillators (hybrid)

Phys.Rev.D 108 (2023) 10, 102005





SN1987a: optical image before and after



© Anglo-Australian Observatory

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

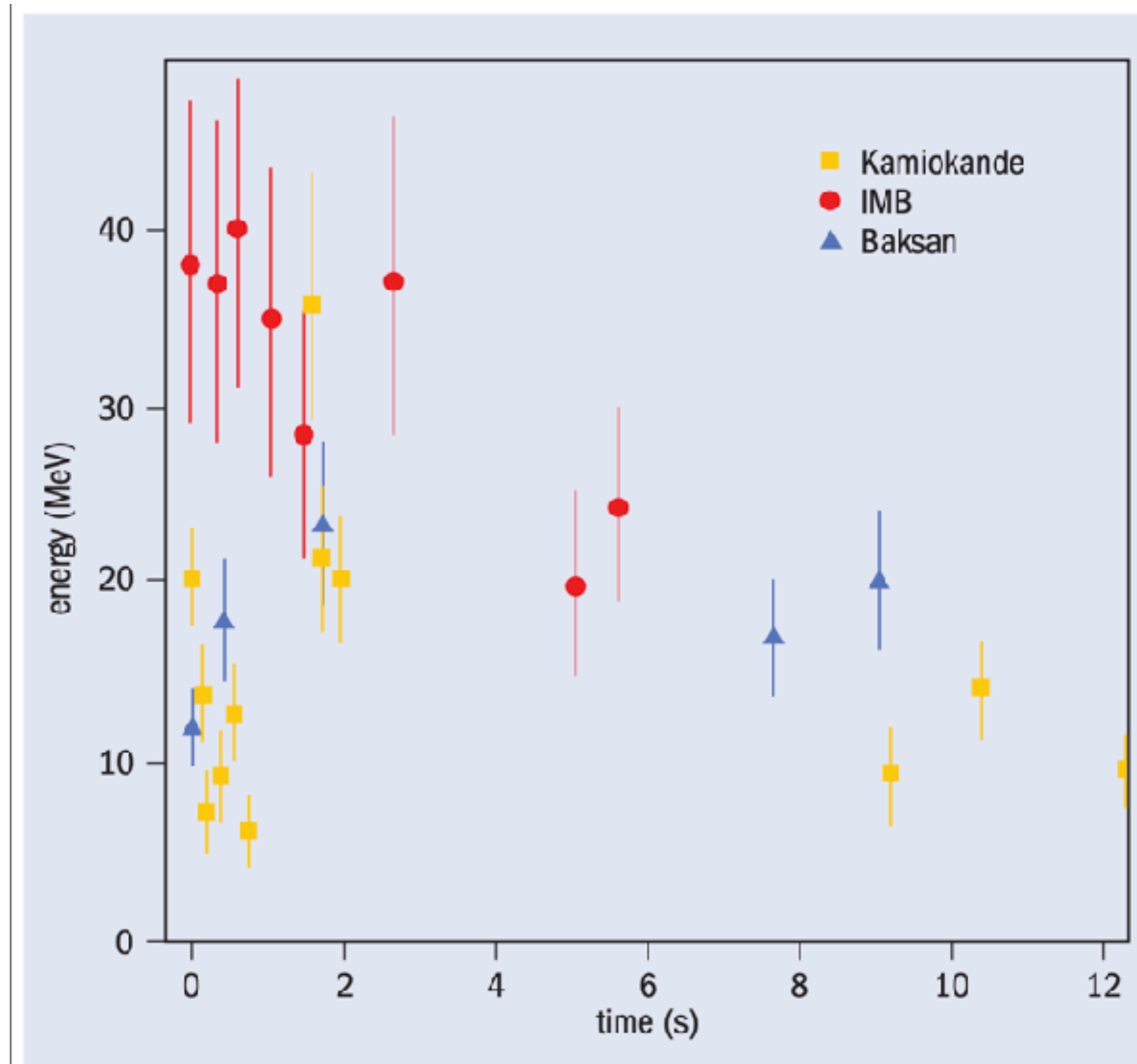
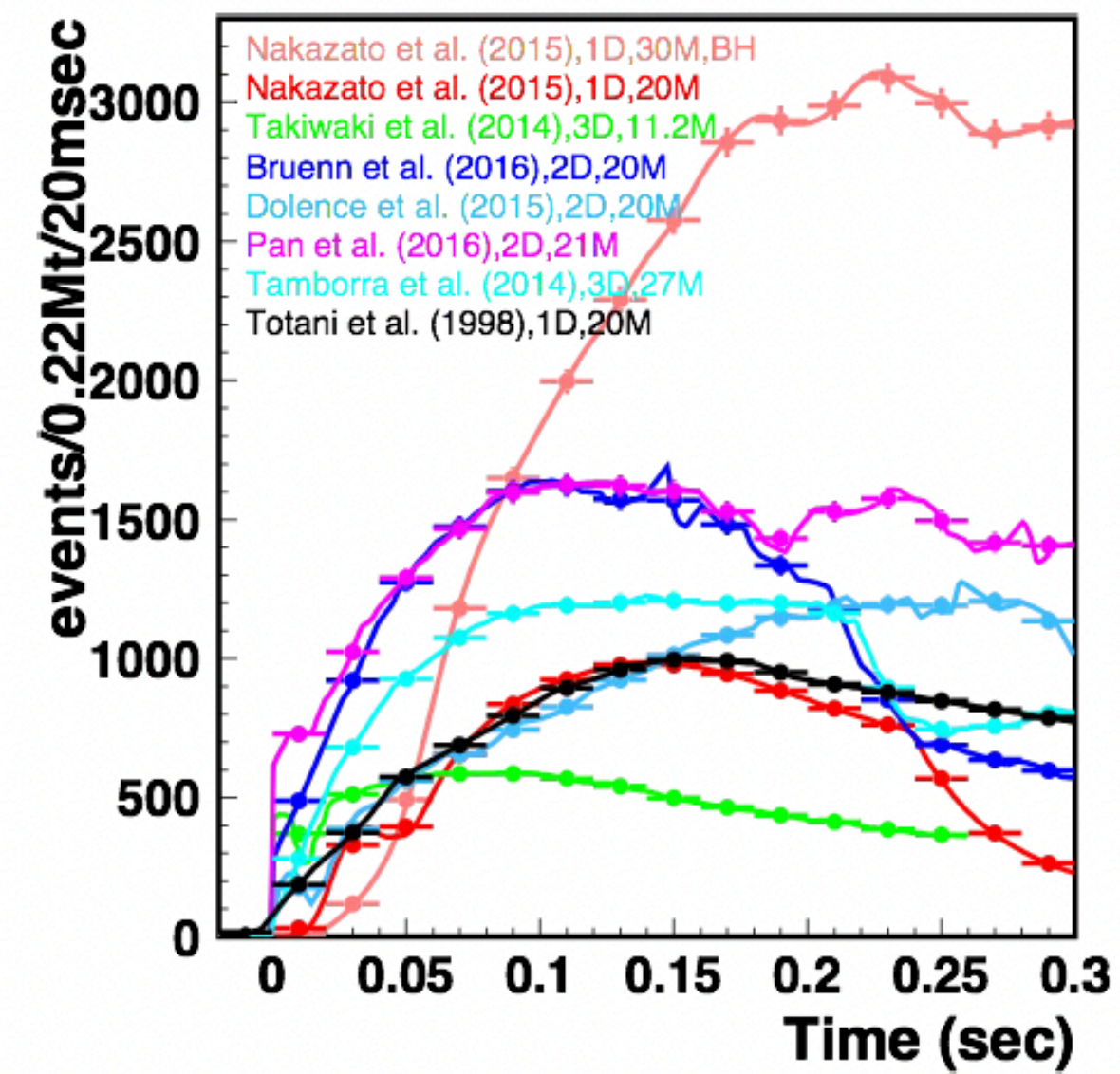
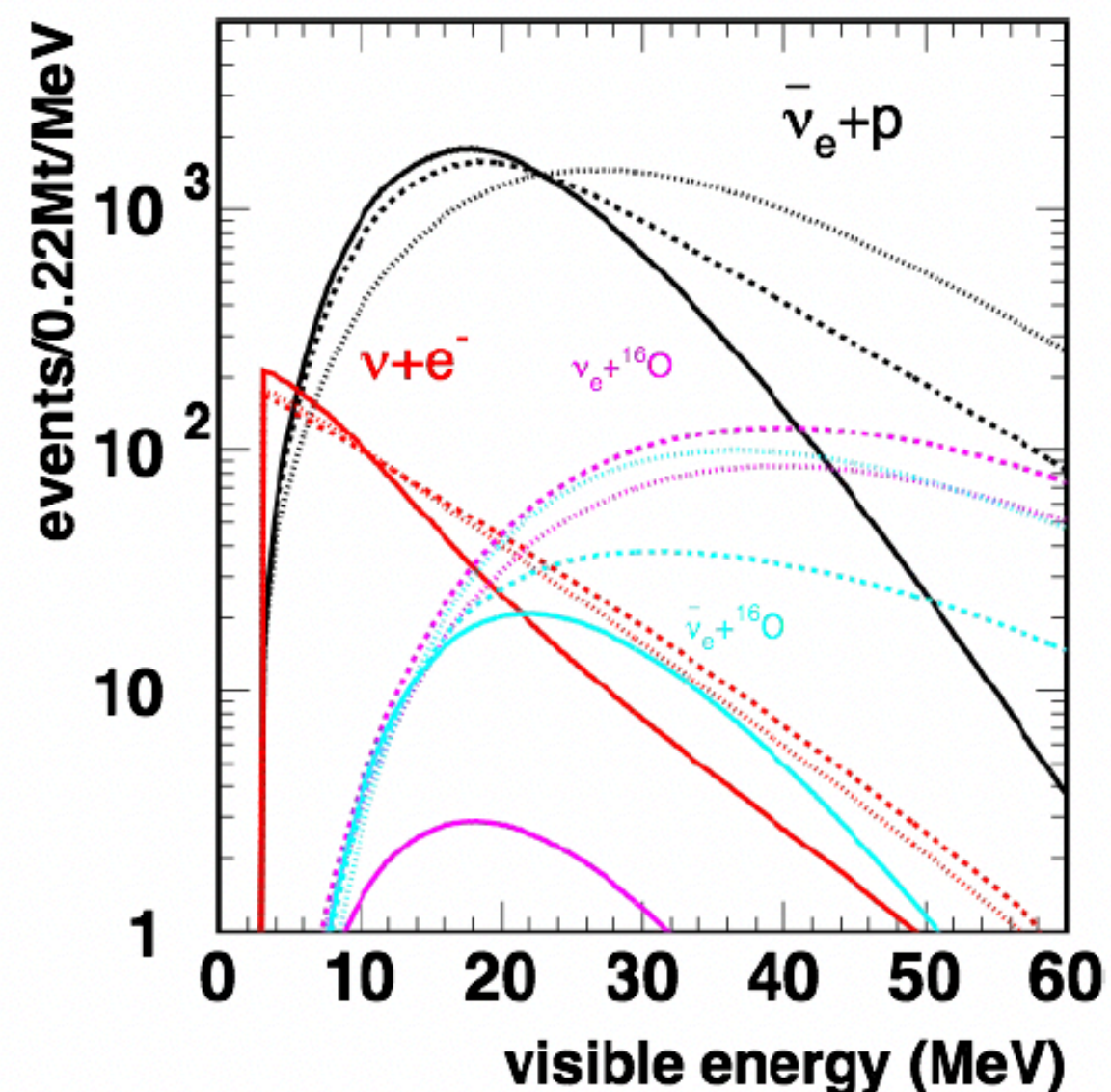
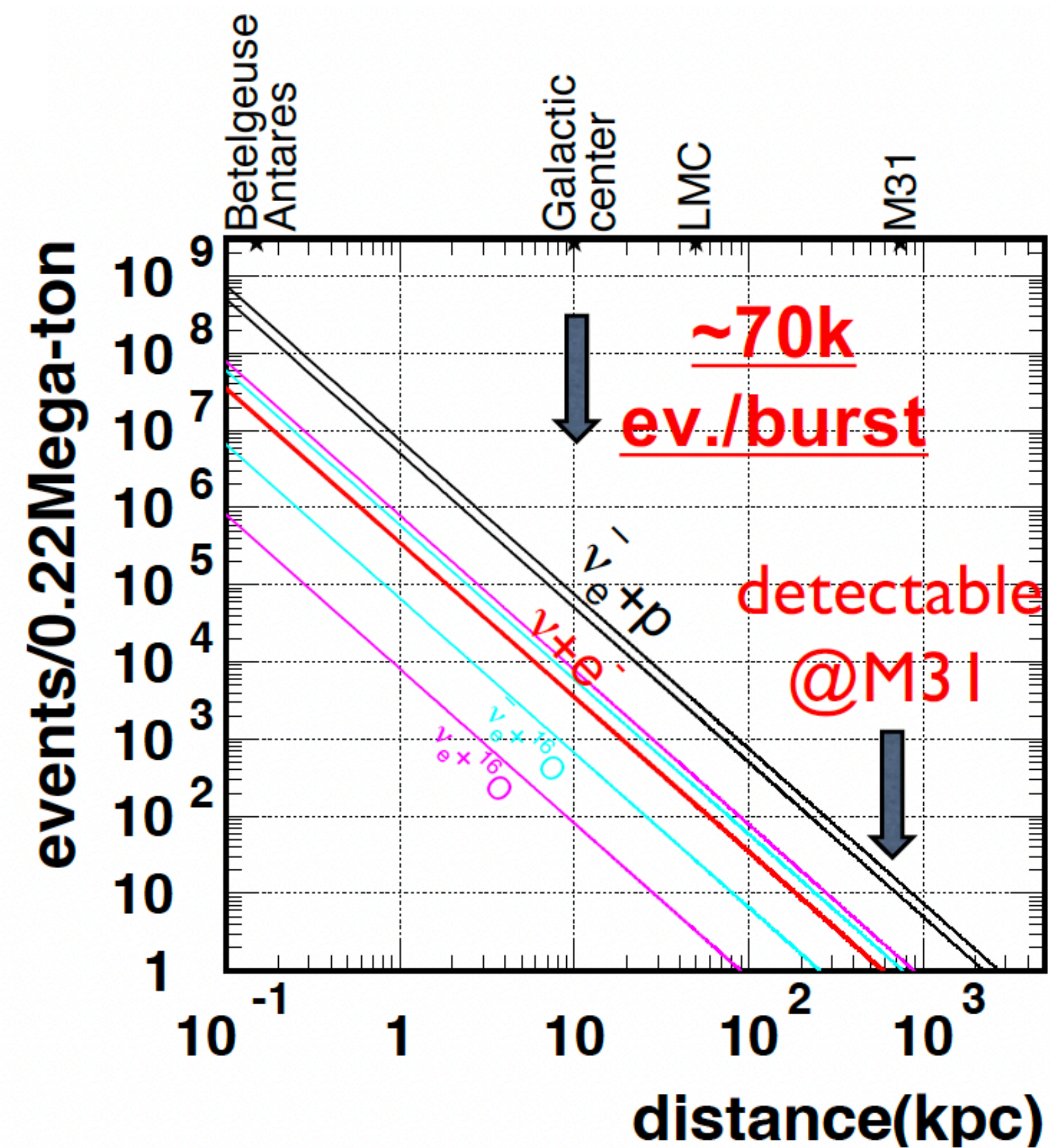
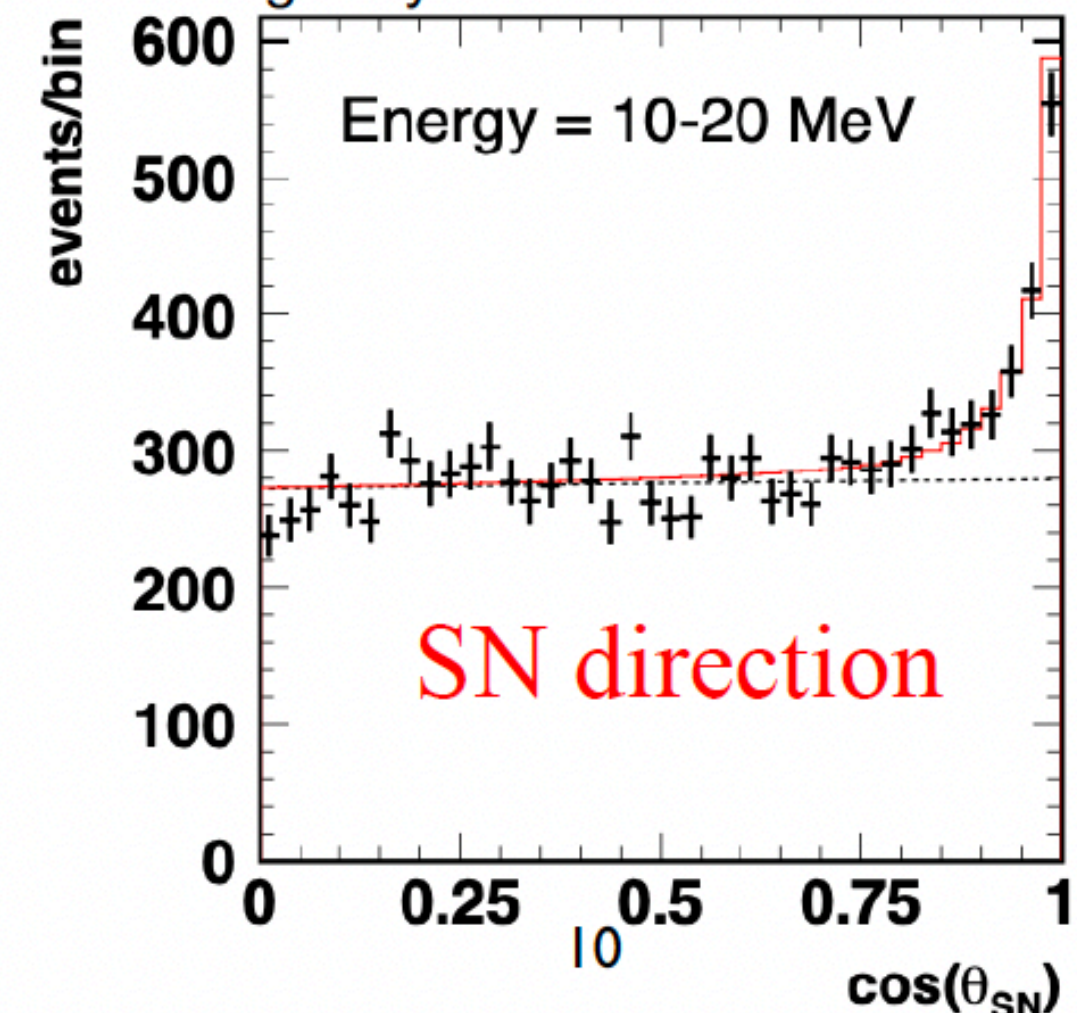
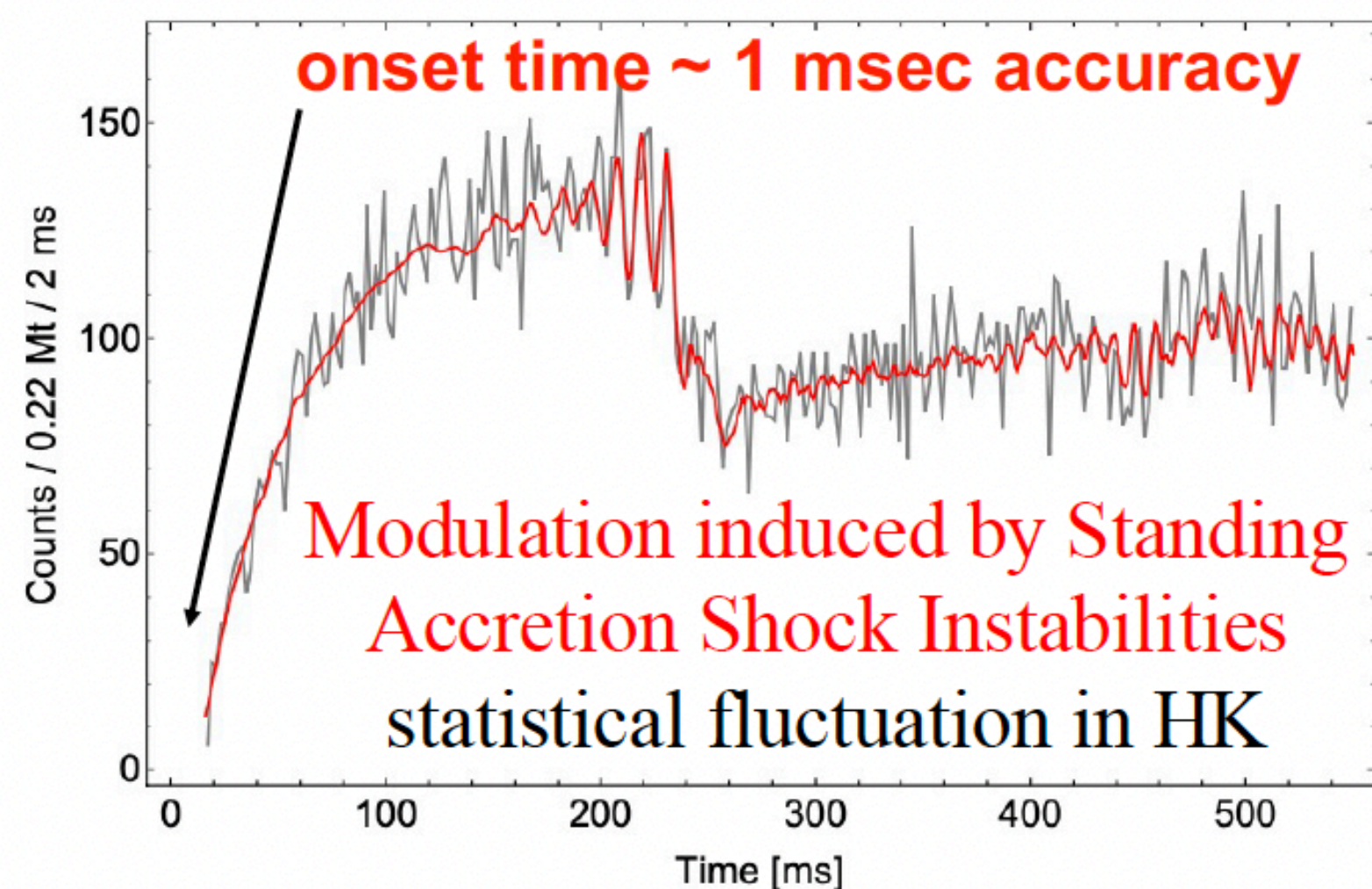


Fig. 3. SN1987A neutrino events observed by Kamiokande, IMB and Baksan showed that the neutrino burst lasted about 13s.



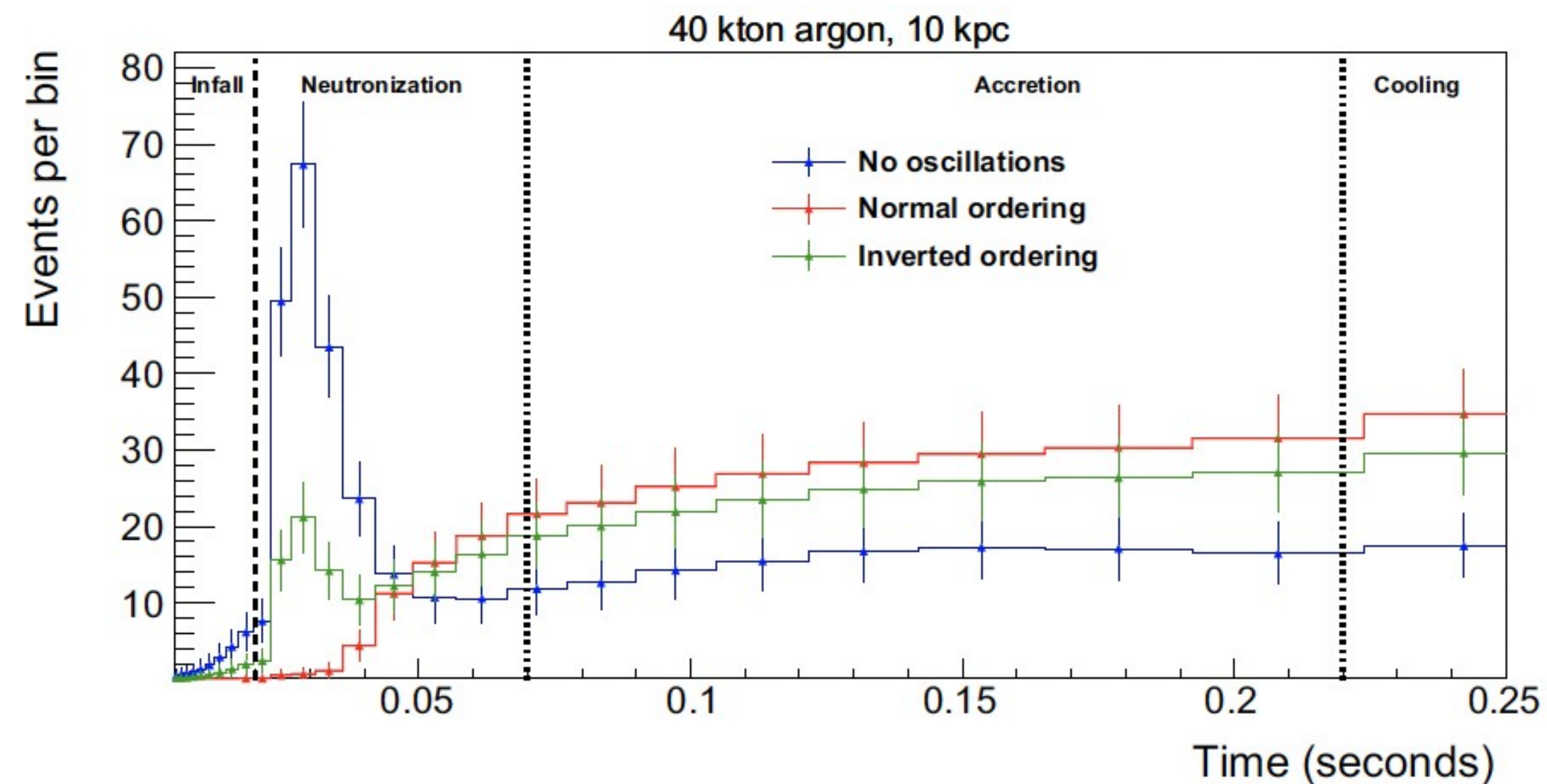
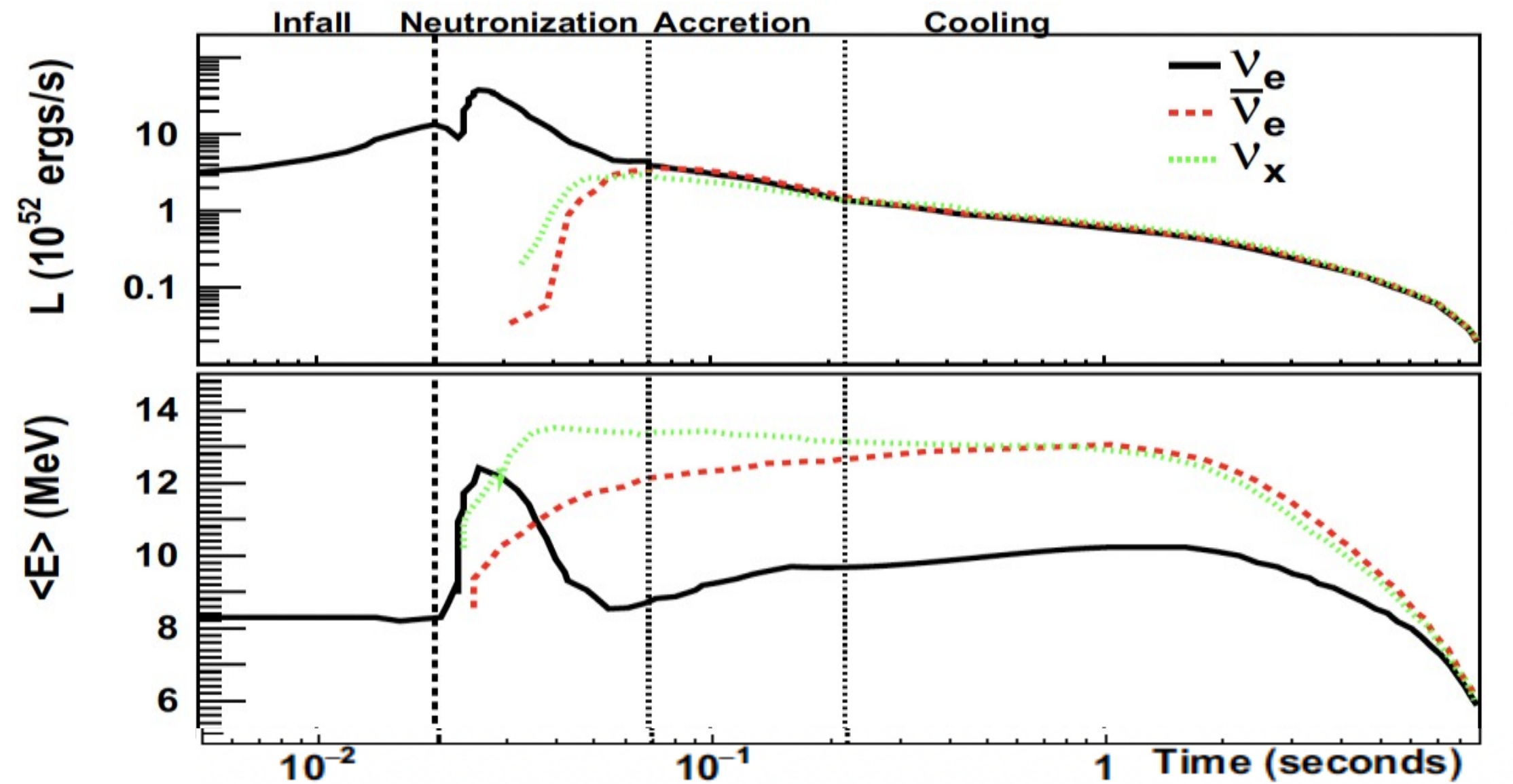
galactic supernova at 10 kpc (our $r_{\text{galaxy}} = 8$ kpc)



~70k events/burst at 10 kpc

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

SN neutrino burst in DUNE

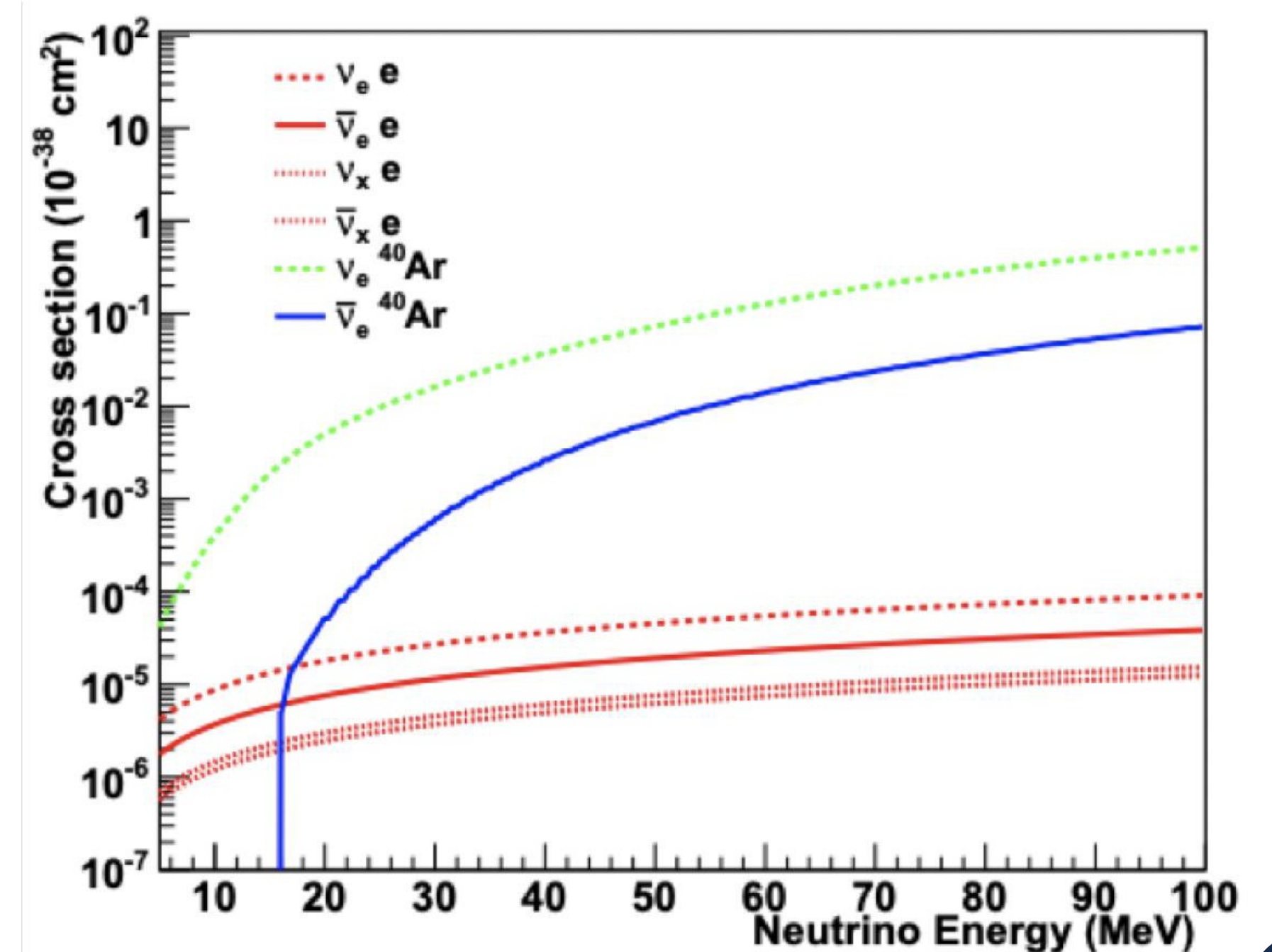


DUNE sensitive to ν_e CC events by



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

Eur. Phys. J. C (2021) 81

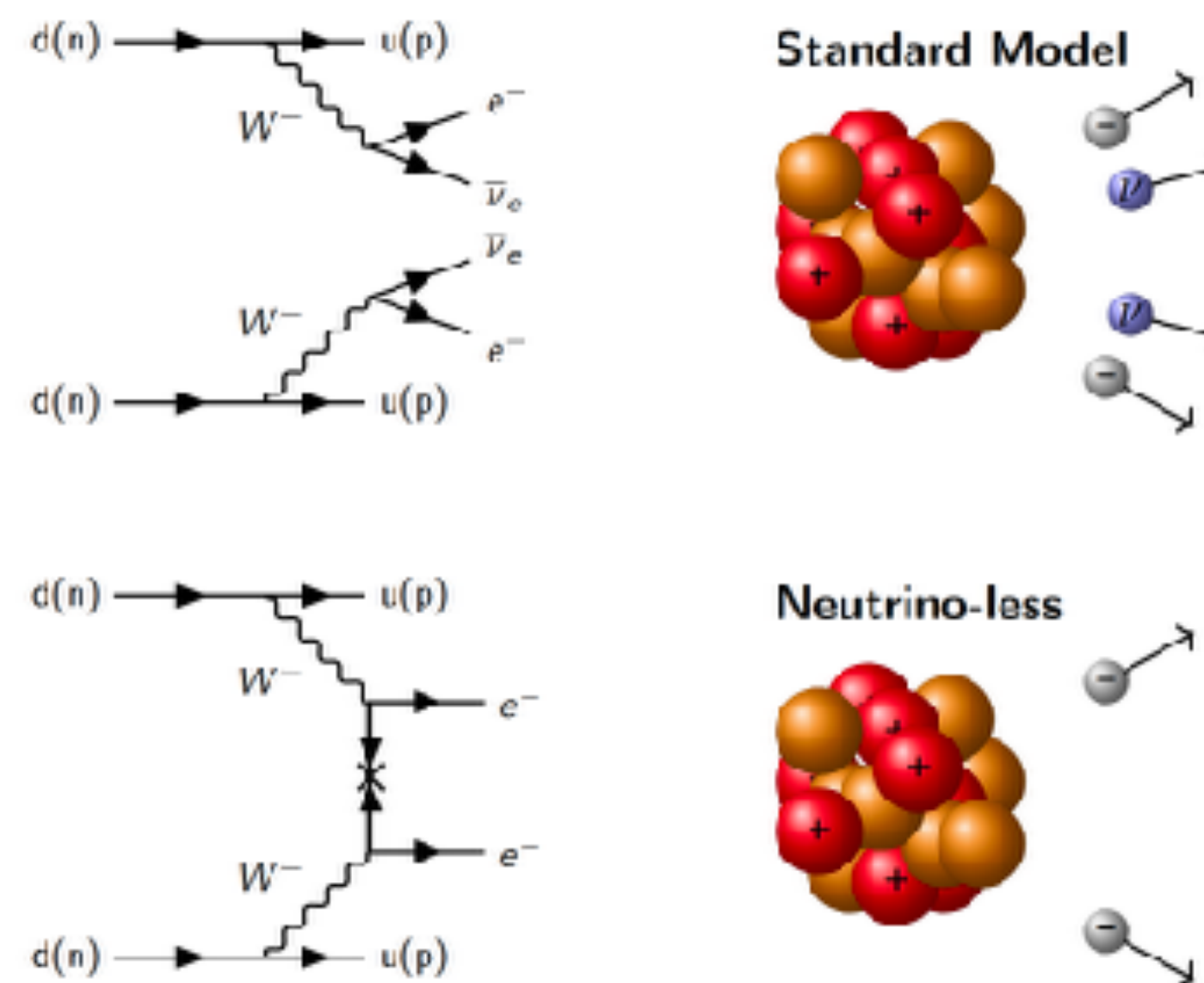


- **Neutrino mass type**
 - Majorana vs Dirac
 - **NEUTRINOLESS DOUBLE BETA DECAY**
- **Neutrino mass scale**
 - What is the value of m_1 ?
 - **DIRECT NEUTRINO MEASUREMENTS** (not covered)
- **Neutrino mass ordering**
 - $m_3 > m_1$ or $m_3 < m_1$?
 - JUNO, ORCA, DUNE
- **CP violation in lepton sector ?**
 - What is the value of δ_{CP} ?
 - T2K and Nova, then (>2028) DUNE and T2HK

- 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



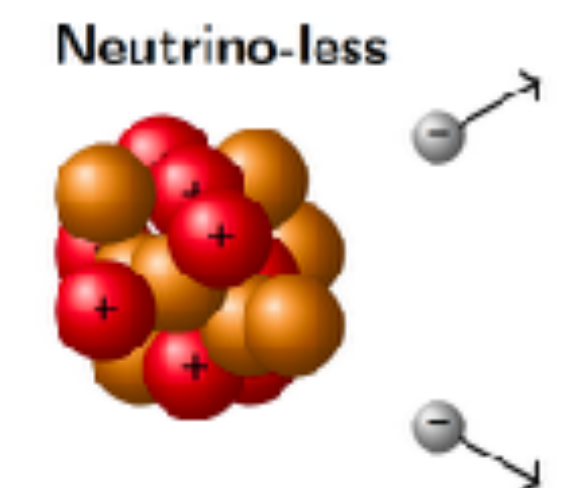
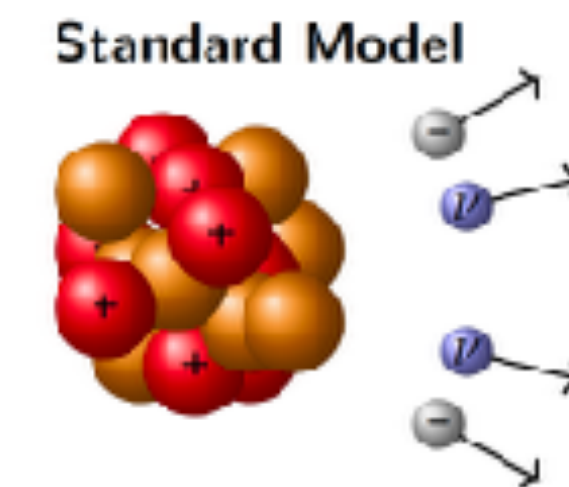
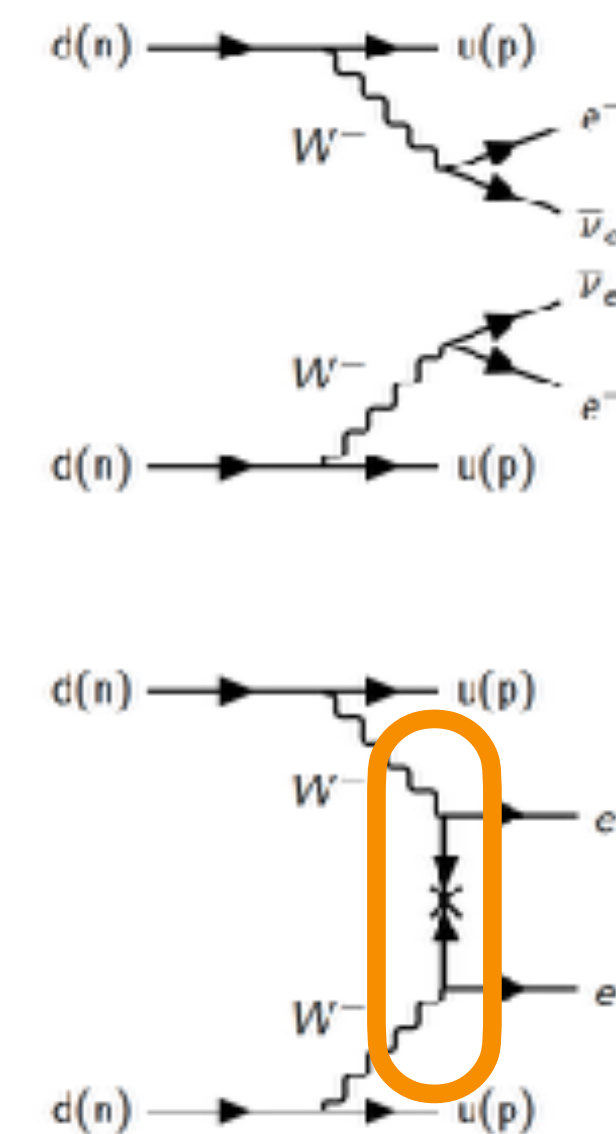
Why $0\nu\beta\beta$ is important ?

- 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)

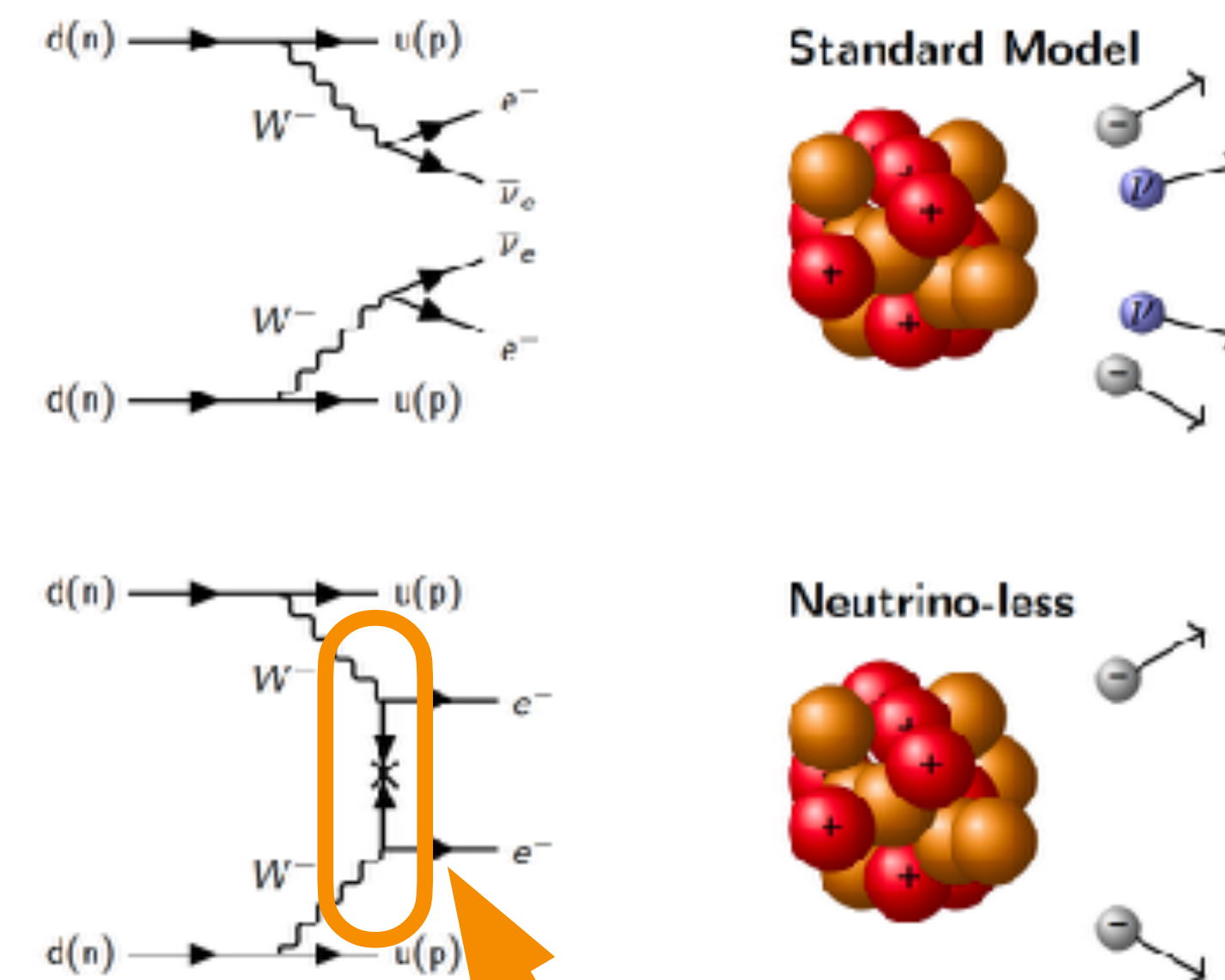
- i.e. lepton number is violated

- In all scenarios $0\nu\beta\beta$ implies new physics



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

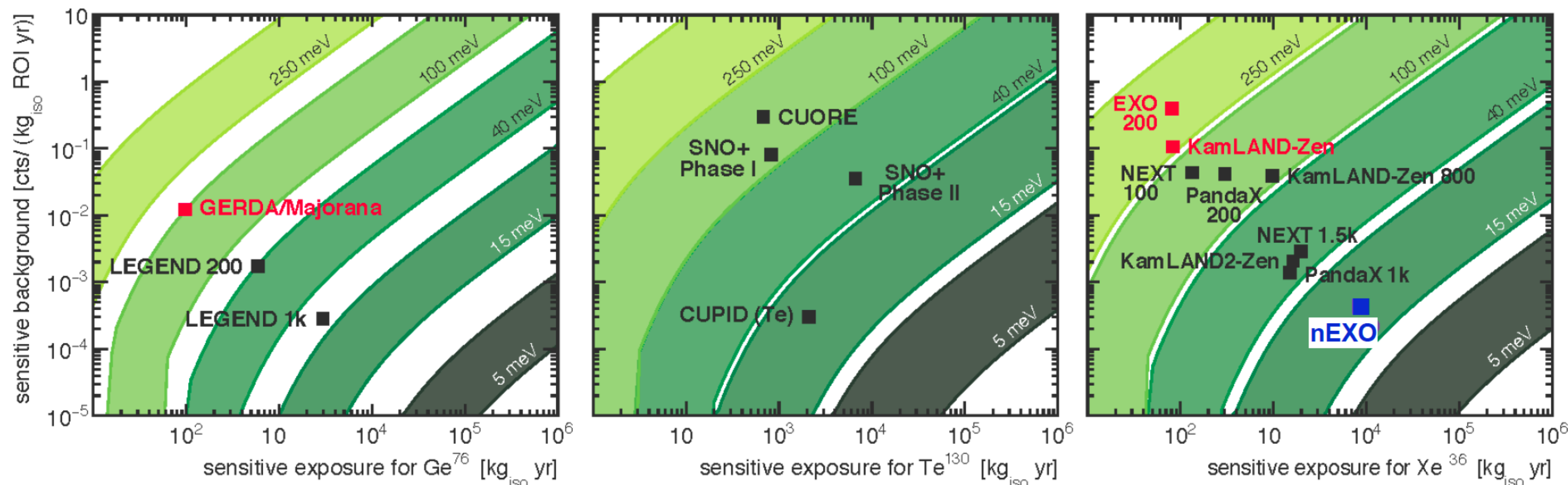
- The only known process that can **distinguish** between **Majorana** and **Dirac** mass terms
 - i.e. $0\nu\beta\beta$ can happen only if neutrinos are their own anti-particle (truly neutral)
 - i.e. lepton number is violated
 - In all scenarios $0\nu\beta\beta$ implies new physics



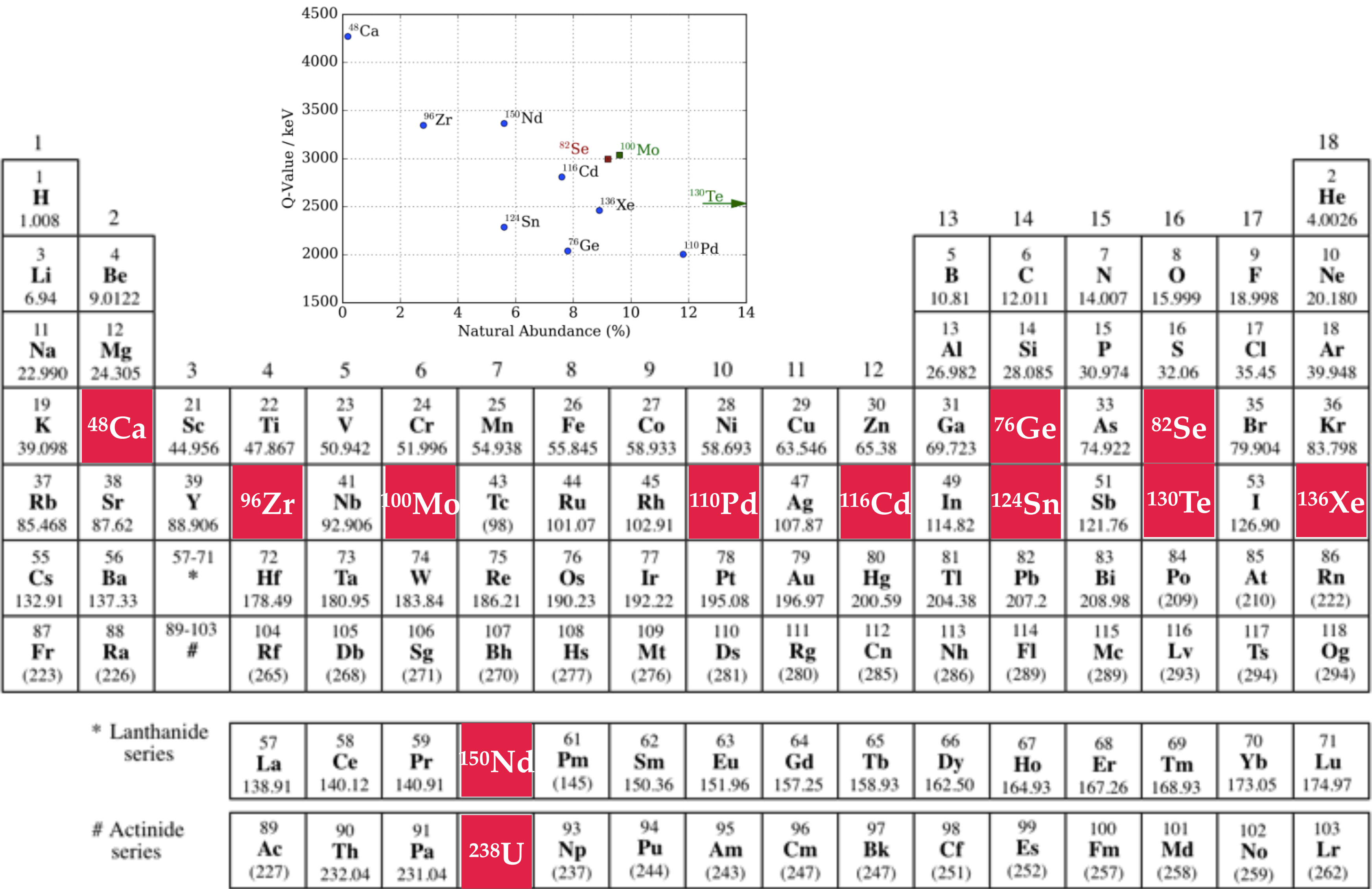
NOT NECESSARILY
MAJORANA NEUTRINOS

SENSITIVITY OF NEXT GENERATION EXPERIMENTS

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PRD 96 (2017) 073001

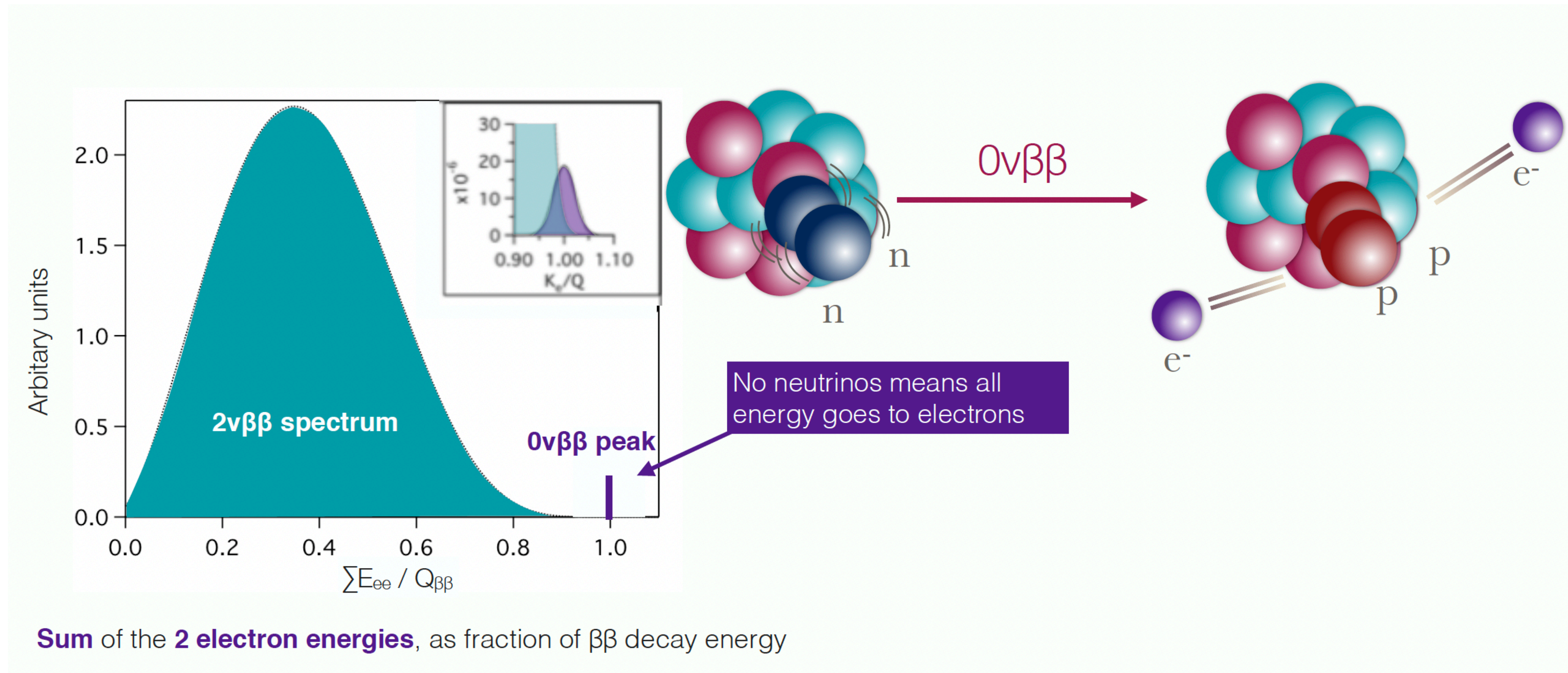


Only a few elements work

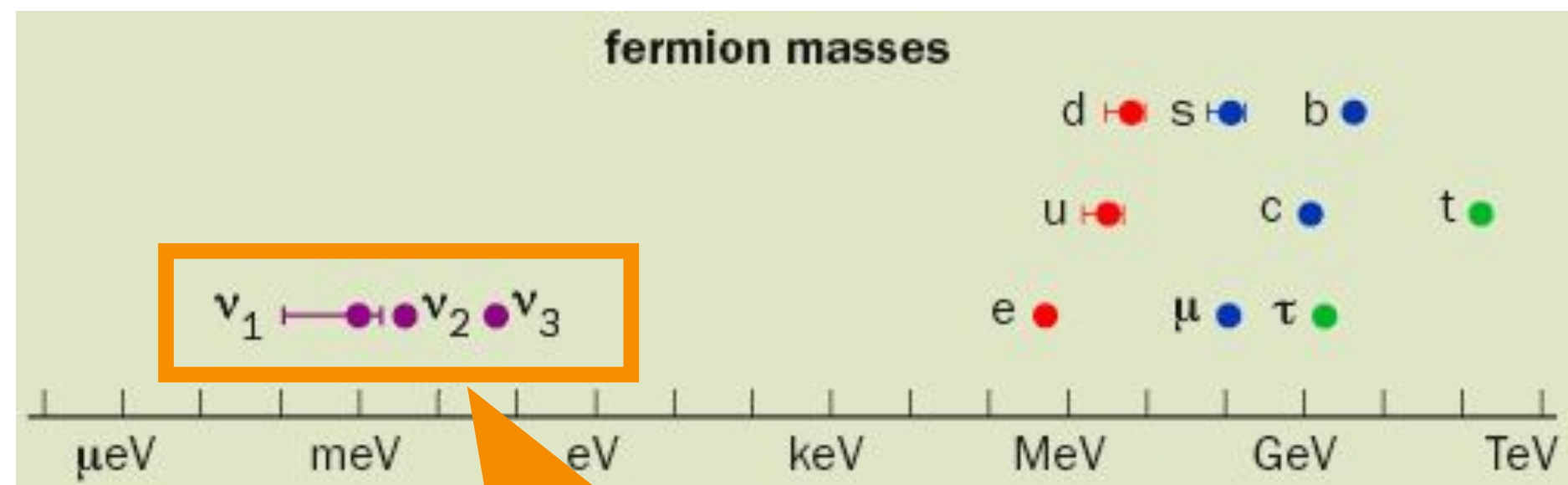


- Best candidates
 - ^{76}Ge : excellent because of technology (semiconductor), excellent detectors, good nuclear physics, expensive
 - ^{136}Xe : not as good technologically, cheap, excellent nuclear physics, usable dissolved in scintillators and in liquid phase
 - ^{100}Mo : very good, difficult, high 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



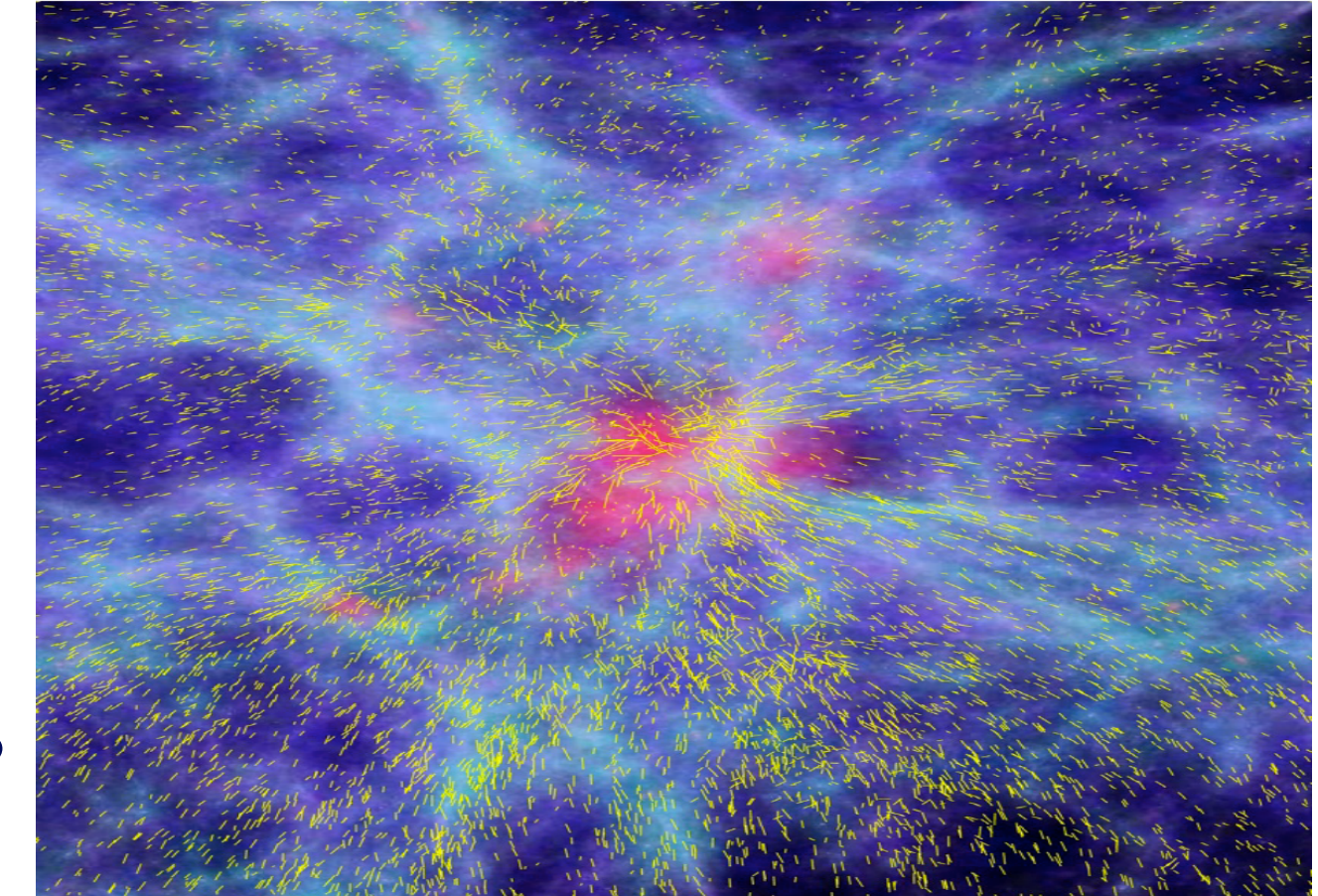
Why mass is important: three ways, three “masses” !



NEUTRINOS
ARE DIFFERENT ?

GRAVITY

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

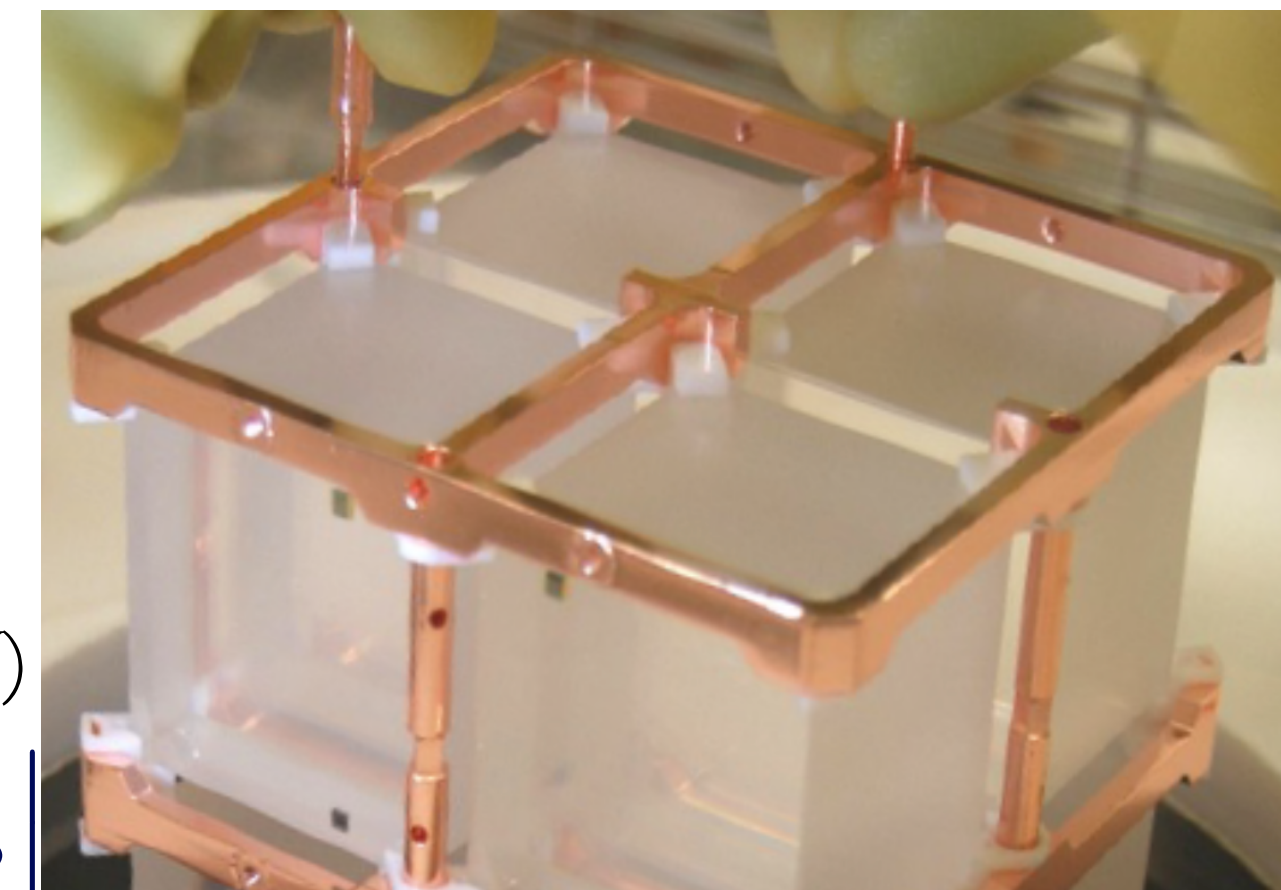


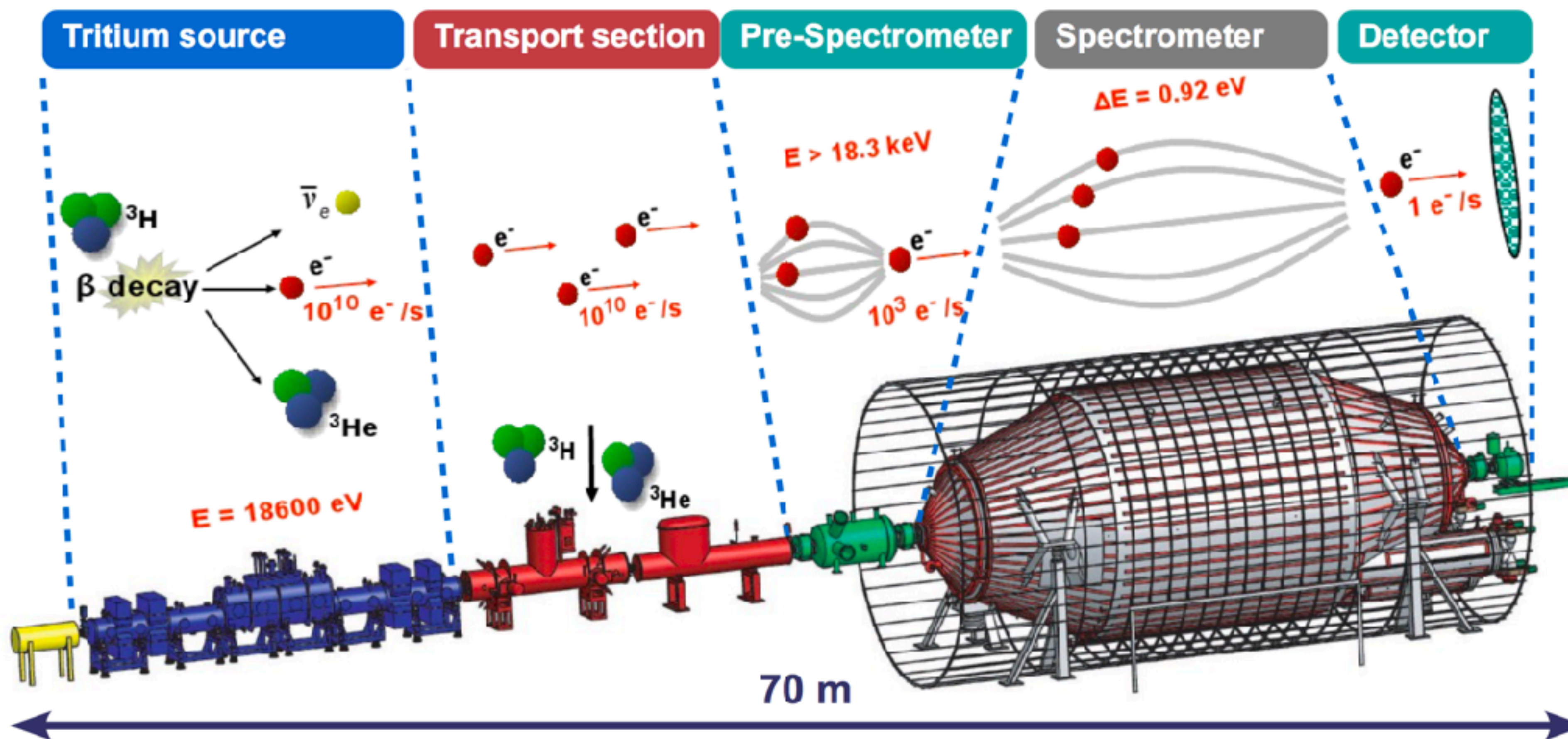
β DECAY KINEMATICS

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

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

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





Potential sensitivity: 0.35 eV (discovery at 5σ , 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