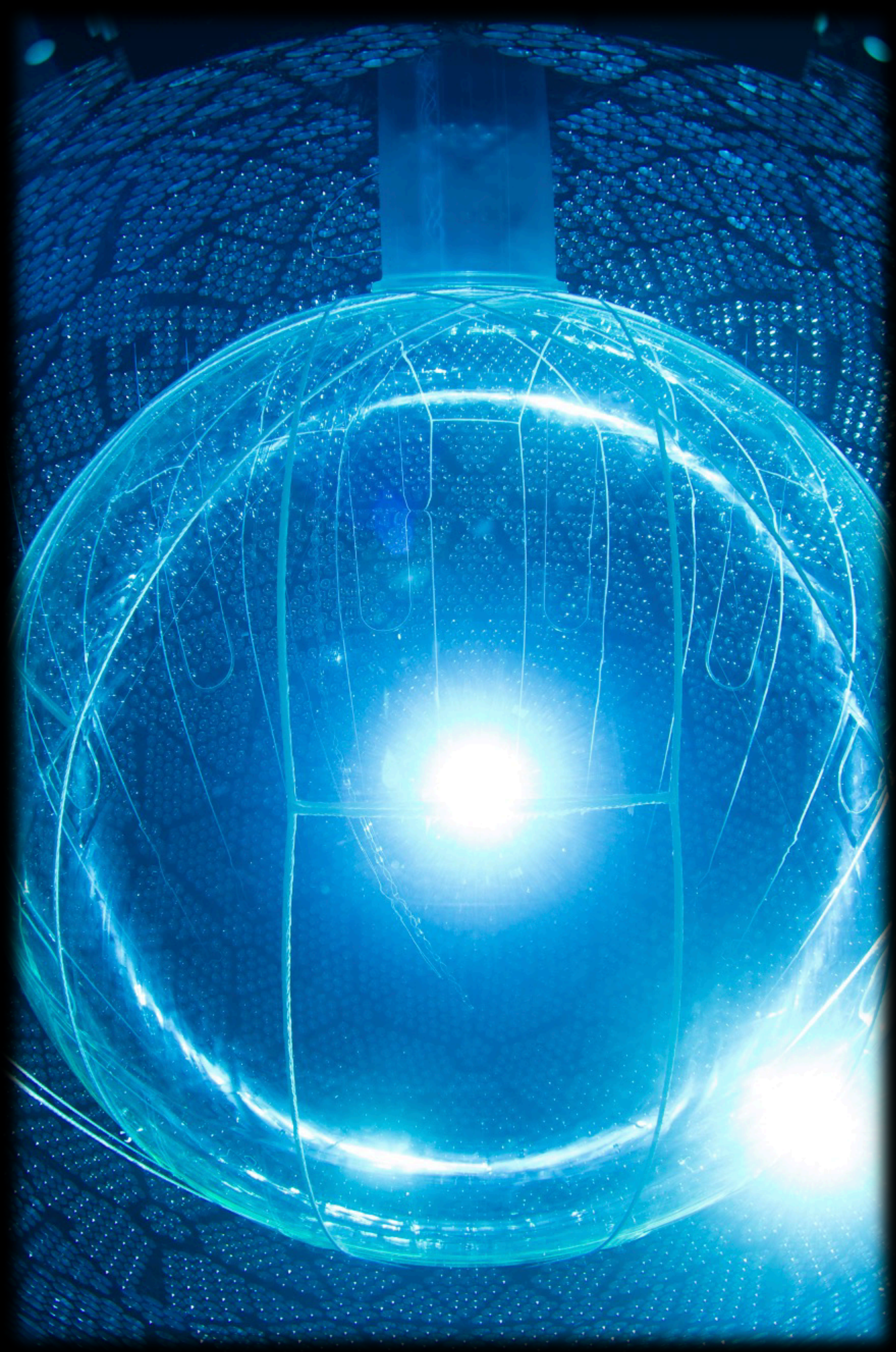

NEUTRINO SCIENCE 5

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OVERALL PLAN OF THE 5 LECTURES

1. Neutrinos in the Standard Model.
2. Neutrino interactions, detectors. Solar and atmospheric neutrino problems.
3. Neutrino oscillations in 2 flavors. SNO and SK.
4. Neutrino oscillations in 3 flavors. Future experiments.
5. Theory and search for neutrino masses. Neutrinoless double-beta decay. Neutrinos in Cosmology and Astrophysics.

- Theory and experiment will be strongly mingled.
- Every lecture will have some of both.

PLAN FOR LECTURE 5

- Theory of neutrino masses
  - Lagrangians in Quantum Field Theory
  - Electroweak symmetry breaking - the Higgs mechanism
  - Yukawa interactions and fermion masses
  - Charge conjugation of Dirac and Weyl fields
  - Types of possible neutrino mass terms
  - See-saw mechanism
- Experimental searches for Dirac and Majorana neutrino masses
  - From cosmology
  - Single beta decay: Katrin
  - Neutrinoless double-beta decay

THEORY OF NEUTRINO MASSES

LAGRANGIANS IN CLASSICAL MECHANICS

- Conservative forces are the gradient of a scalar potential

$$\vec{F} = -\vec{\nabla} U$$

- So Newton's law $\vec{F} = m\vec{a}$ is also

$$m\frac{d\vec{v}}{dt} = -\vec{\nabla} U$$

- Define the Lagrangian

$$L = T - U$$

  - T is the kinetic (e.g. $T=1/2mv^2$) and U the potential energy
  - L is a function of coordinates q_i and their time derivatives $\dot{q}_i$

- Laws of motion given by the Euler - Lagrange equation

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i} = \frac{\partial L}{\partial q_i}$$

Example

$$\frac{\partial L}{\partial \dot{q}_i} = \frac{\partial T}{\partial v_x} = mv_x$$

$$\frac{\partial L}{\partial q_i} = -\frac{\partial U}{\partial x} = F_x$$

- In order to respect Lorentz-invariance, need spatial and time coordinates to be in equal footing
- Replace q_i and $\dot{q}_i$ by fields $\Phi_i(t,x,y,z)$ and field derivatives $\partial_\mu \Phi_i = \frac{\partial \Phi_i}{\partial x^\mu}$
- Replace L by lagrangian density $\mathscr{L}$ such that $L = \int \mathscr{L} d^3x$
- Replace the Euler-Lagrange equation by

$$\partial_\mu \left(\frac{\partial \mathscr{L}}{\partial(\partial_\mu \Phi_i)} \right) - \frac{\partial \mathscr{L}}{\partial \Phi_i} = 0$$

EXAMPLES

Field	Lagrangian	Equation of motion	
Scalar	$\mathscr{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m^2\phi^2$	$\partial_\mu \phi \partial^\mu \phi + m^2\phi = 0$	Klein-Gordon
Spinor	$\mathscr{L} = i\bar{\psi}\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi$	$i\gamma^\mu(\partial_\mu \psi) - m\psi = 0$	Dirac
Vector	$\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - j^\mu A_\mu$	$\partial_\mu F^{\mu\nu} = j^\nu$	Maxwell (w/ source)
Vector	$\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2 A^\mu A_\mu$	$\partial_\mu F^{\mu\nu} + m^2 A^\nu = 0$	Proca (massive boson)

charge density and current

$j^\mu = (\rho, \vec{J}) = e\bar{\psi}\gamma^\mu \psi$

$A^\mu = (\phi, \overrightarrow{A})$

EM potential and vector potential

$F^{\mu\nu} = \partial^\mu A^\nu - \partial_\nu A_\mu$

(all in covariant form)

FULL QED LAGRANGIAN

Fermions: dynamic term ↓ ... mass term ↓ ... Interaction term ↙

$$\mathscr{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - m_f\bar{\psi}\psi - e\bar{\psi}Q_f\gamma^{\mu}\psi A_{\mu}$$

Photons: dynamic term ↑ (under $-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$)

m_f, Q_f : mass and charge of fermion

- Interaction term comes from requiring lagrangian to be invariant to $U(1)_Q$ symmetry
- Example of mass term:

$$m_e\bar{\psi}\psi = m_e\left(\bar{e}_R e_L + \bar{e}_L e_R\right)$$

- But this violates the weak interaction gauge invariance!

WEAK INTERACTION GAUGE GROUP

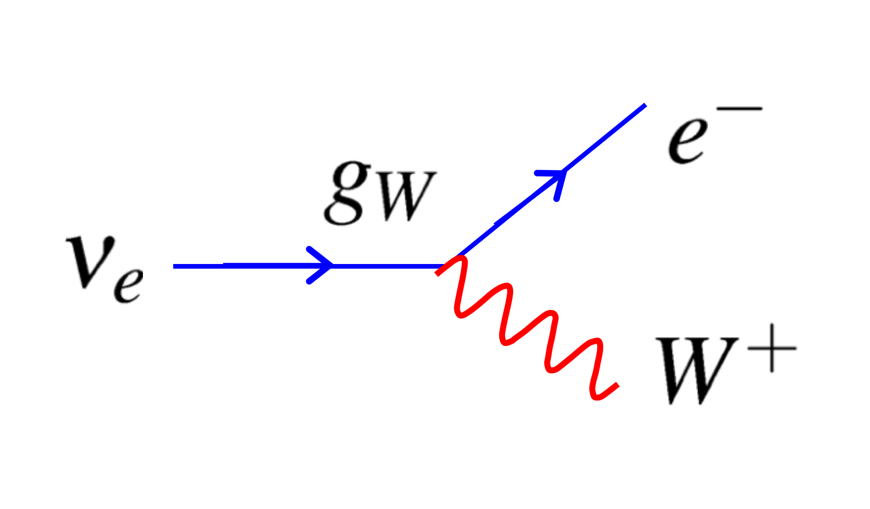
- Mixing between Weak Isospin $SU(2)_L$ and Hypercharge $U(1)_Y$.
- Isospin follows a typical spin algebra. Total isopin I_W, projection I_3^W.
  - Why "L"? L fields are doublets ($I_W = \frac{1}{2}$), while R fields are singlets ($I_W = 0$)
- Hypercharge a function of charge and weak isospin $Y = 2Q - 2I_3^W$

Fermion (f)	I	I_3	Q	Y
$\begin{pmatrix}\nu_{eL}\\ e_L\end{pmatrix}, \begin{pmatrix}\nu_{\mu L}\\ \mu_L\end{pmatrix}, \begin{pmatrix}\nu_{\tau L}\\ \tau_L\end{pmatrix}$	$\frac{1}{2}$	$+\frac{1}{2}$	0	-1
		$-\frac{1}{2}$	-1	-1
$\nu_{eR}, \nu_{\mu R}, \nu_{\tau R}$	0	0	0	0
e_R, μ_R, τ_R	0	0	-1	-2

Fermion (f)	I	I_3	Q	Y
$\begin{pmatrix}u_L\\ d'_L\end{pmatrix}, \begin{pmatrix}c_L\\ s'_L\end{pmatrix}, \begin{pmatrix}t_L\\ b'_L\end{pmatrix}$	$\frac{1}{2}$	$+\frac{1}{2}$	$+\frac{2}{3}$	$+\frac{1}{3}$
		$-\frac{1}{2}$	$-\frac{1}{3}$	$+\frac{1}{3}$
u_R, c_R, t_R	0	0	$+\frac{2}{3}$	$+\frac{4}{3}$
d_R, s_R, b_R	0	0	$-\frac{1}{3}$	$-\frac{2}{3}$

- So, $m_e\left(\bar{e}_R e_L + \bar{e}_L e_R\right)$ is clearly not an isospin singlet

- Example: lepton interaction with W+
- L fermions are doublets, but whole current is singlet -> gauge invariant in SU(2) !
- Equivalent to the familiar formulation:



$$\chi_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$$

$$j_+^\mu = \frac{g_W}{\sqrt{2}} \overline{\chi}_L \gamma^\mu \sigma_+ \chi_L$$

$$j_+^\mu = \frac{g_W}{\sqrt{2}} \overline{\chi}_L \gamma^\mu \sigma_+ \chi_L = \frac{g_W}{\sqrt{2}} (\overline{\nu}_L, \overline{e}_L) \gamma^\mu \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \nu \\ e \end{pmatrix}_L = \frac{g_W}{\sqrt{2}} \overline{\nu}_L \gamma^\mu e_L = \frac{g_W}{\sqrt{2}} \overline{\nu} \gamma^\mu \tfrac{1}{2}(1-\gamma^5) e$$

- Higgs is introduced as an isospin doublet too.
  - Conjugate ϕ_C for the up-quarks
- Yukawa terms (Higgs-fermion interaction) then become gauge invariant as well!

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

$$\phi_c = -i\sigma_2 \phi^* = \begin{pmatrix} -\phi^{0*} \\ \phi^- \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} -\phi_3 + i\phi_4 \\ \phi_1 - i\phi_2 \end{pmatrix}.$$

$$\mathcal{L}_e = -g_e \left[\begin{pmatrix} \overline{\nu}_e & \overline{e} \end{pmatrix}_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} e_R + \overline{e}_R \begin{pmatrix} \phi^{+*} & \phi^{0*} \end{pmatrix} \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \right]$$

$$\mathcal{L}_u = g_u \begin{pmatrix} \overline{u} & \overline{d} \end{pmatrix}_L \begin{pmatrix} -\phi^{0*} \\ \phi^- \end{pmatrix} u_R + \text{ Hermitian conjugate,}$$

DIRAC MASS TERMS

- After "gauging-away" 3 Goldstone fields, after symmetry-breaking and expressing fields around the vaccum expectation value

$$\langle 0|\phi|0\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix} \qquad \phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

v=246 GeV

MASS TERM

$$\mathcal{L}_e = -\frac{g_e}{\sqrt{2}} v\left(\bar{e}_L e_R + \bar{e}_R e_L\right) - \frac{g_e}{\sqrt{2}} h\left(\bar{e}_L e_R + \bar{e}_R e_L\right)$$

INTERACTION WITH HIGGS

$$g_e = \sqrt{2}\frac{m_e}{v} \qquad \mathcal{L}_e = -m_e \bar{e}e - \frac{m_e}{v}\bar{e}eh$$

- Can we do something similar for neutrinos?
  - Introduce new ν_R fields
  - $I_3^W(\nu_L) = +1/2$, so mass terms involve Higgs conjugate field ϕ_C (like up-quarks)
  - Mass terms and Higgs coupling just like for any other fermion
  - Physical neutrino is $\nu_1 = \nu_L + \nu_R$, then

$$\mathcal{L}_D = g_D \left(\overline{\nu_L} \quad \overline{e_L}\right)\begin{pmatrix} -\phi^{0*} \\ \phi^- \end{pmatrix} \nu_R + h.c.$$

$$\mathcal{L}_D = -m_D\left(\overline{\nu_R}\nu_L + \overline{\nu_L}\nu_R\right)$$

$$\mathcal{L}_D = -m_D \overline{\nu_1}\nu_1$$

  - Problems: ν_R appears nowhere else; does not explain small neutrino masses

MAJORANA MASS TERMS

LIP

- Can we build mass terms without ν_R? Yes, for Majorana particles.
  - Charge conjugation is the discrete operation that turns particles into antiparticles
  - for fermion fields $$\psi^C = C\psi^* = i\gamma_2\gamma^0\psi^* = i\gamma_2\gamma^0\bar{\psi}^T$$
  - A Majorana field is $\phi = \psi + \psi^C$, so that $\phi = \phi^C$, i.e. particle = antiparticle!
  - As neutral particles, neutrinos can be Majorana
  - Mass terms can be built only with ψ_L and ψ_L^C, not involving any R fields

$$\mathcal{L}_L^M = -\frac{1}{2} m_L \overline{\nu_L^C} \nu_L$$

- Problem… and solution
  - Since $I_3\left(\overline{\nu_L^C}\right) = I_3\left(\nu_L\right) = 1/2$, the term with Higgs doublet not gauge-invariant (need $I_3 = -1$)
  - So, let's try having both ψ_L^C and new N_R fields
  - Two Majorana fields $\nu_L + \nu_L^C$ and $N_R^C + N_R$
  - Four possible mass terms $m_D \overline{N_R} \nu_L$ $\quad m_D \overline{\nu_L^C} N_R^C$ $\quad m_L \overline{\nu_L^C} \nu_L$ $\quad m_R \overline{N_R} N_R^C$

SEE-SAW MECHANISM

- The general mass term, involving Dirac and Majorana fields, is:
- We can diagonalise the matrix

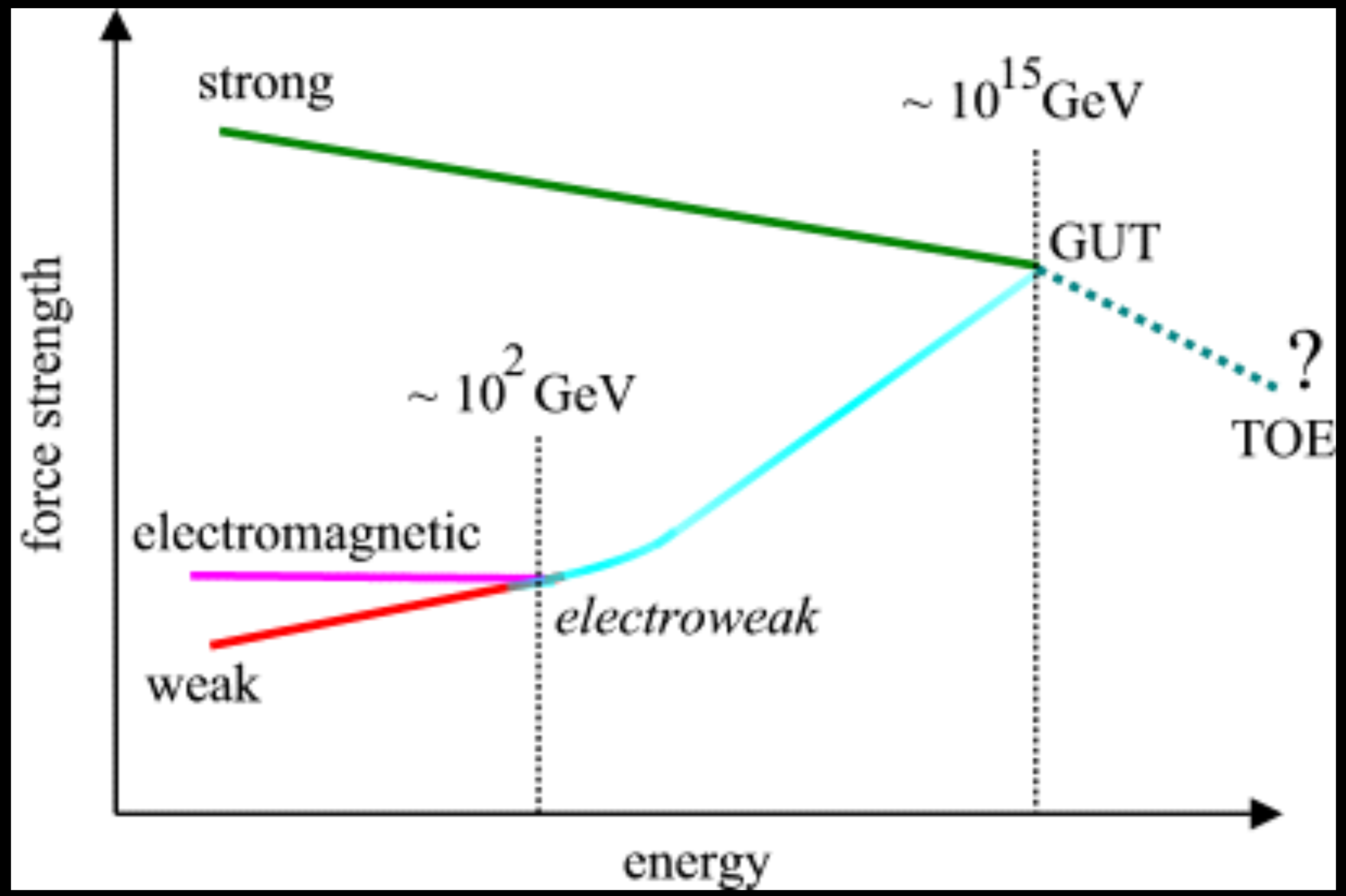
$$\mathcal{L}^{mass} = \begin{bmatrix} \overline{\nu_L^C} & \overline{N_R} \end{bmatrix} \begin{bmatrix} m_L & m_D \\ m_D & m_R \end{bmatrix} \begin{bmatrix} \nu_L \\ N_R^C \end{bmatrix} + h.c.$$

$$m_{1,2} = \frac{1}{2}\left[(m_L + m_R) \pm \sqrt{(m_L - m_R)^2 + 4m_D^2}\right]$$

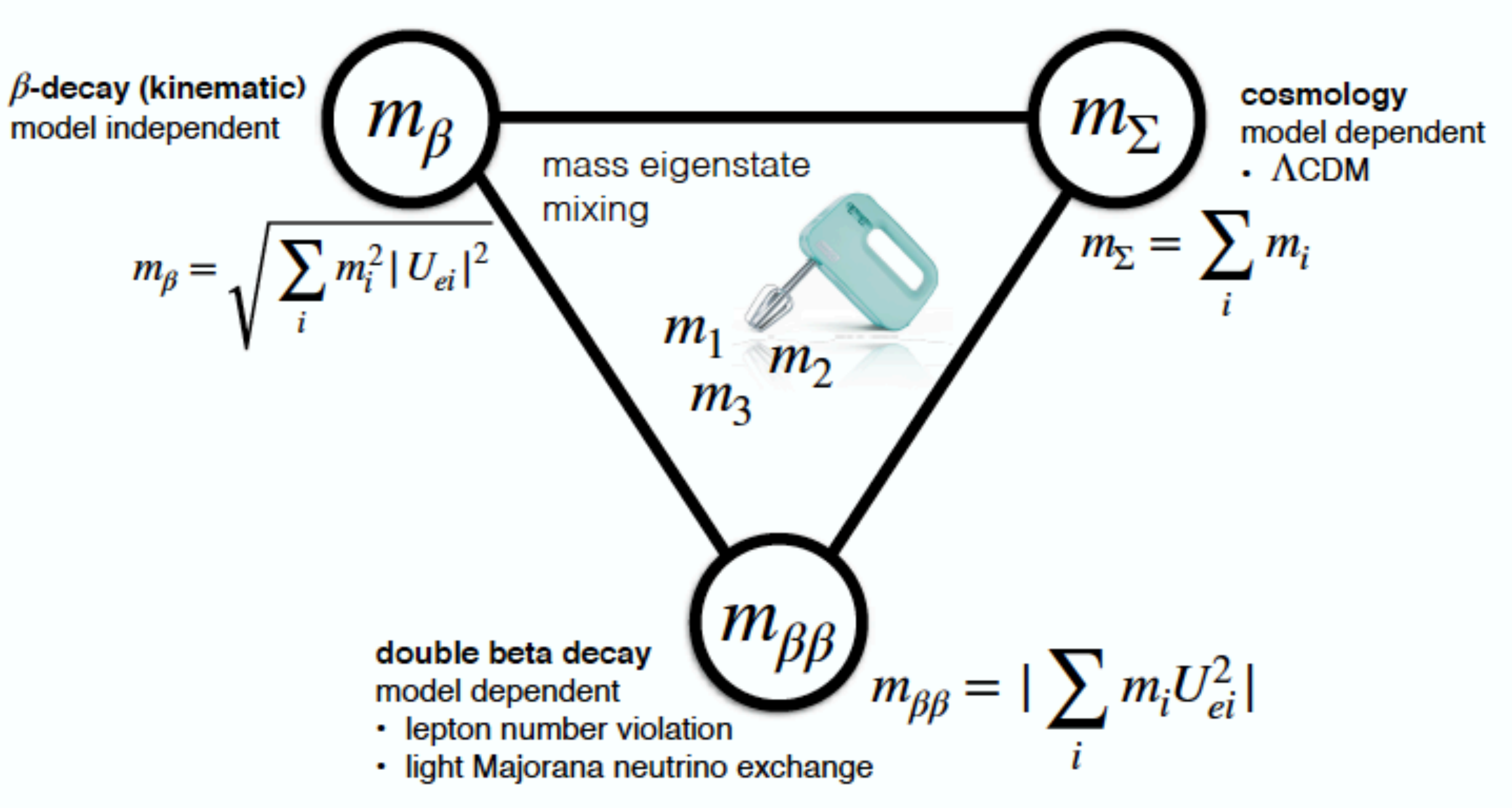
- Interesting special case:
  - $m_L = 0$ (eliminates gauge-breaking term) and $m_R \gg m_D$

$$m_1 = -\frac{m_D^2}{m_R} \qquad m_2 = m_R\left(1 + \frac{m_D^2}{m_R^2}\right) \approx m_R$$

  - If $m_D \approx 10^2 GeV$ (electroweak scale) and $m_R \approx 10^{15} GeV$ (GUT scale), then $m_1 \approx 10\ meV$ (scale of ν masses)
  - Mass eigenstates (both Majorana, i.e. $\phi = \phi^C$)
    - Light: $\nu_1 \approx \nu_L + \nu_L^C$, is the weak interaction active one
    - Heavy: $\nu_2 \approx N_R^C + N_R$, is the weakly inactive one

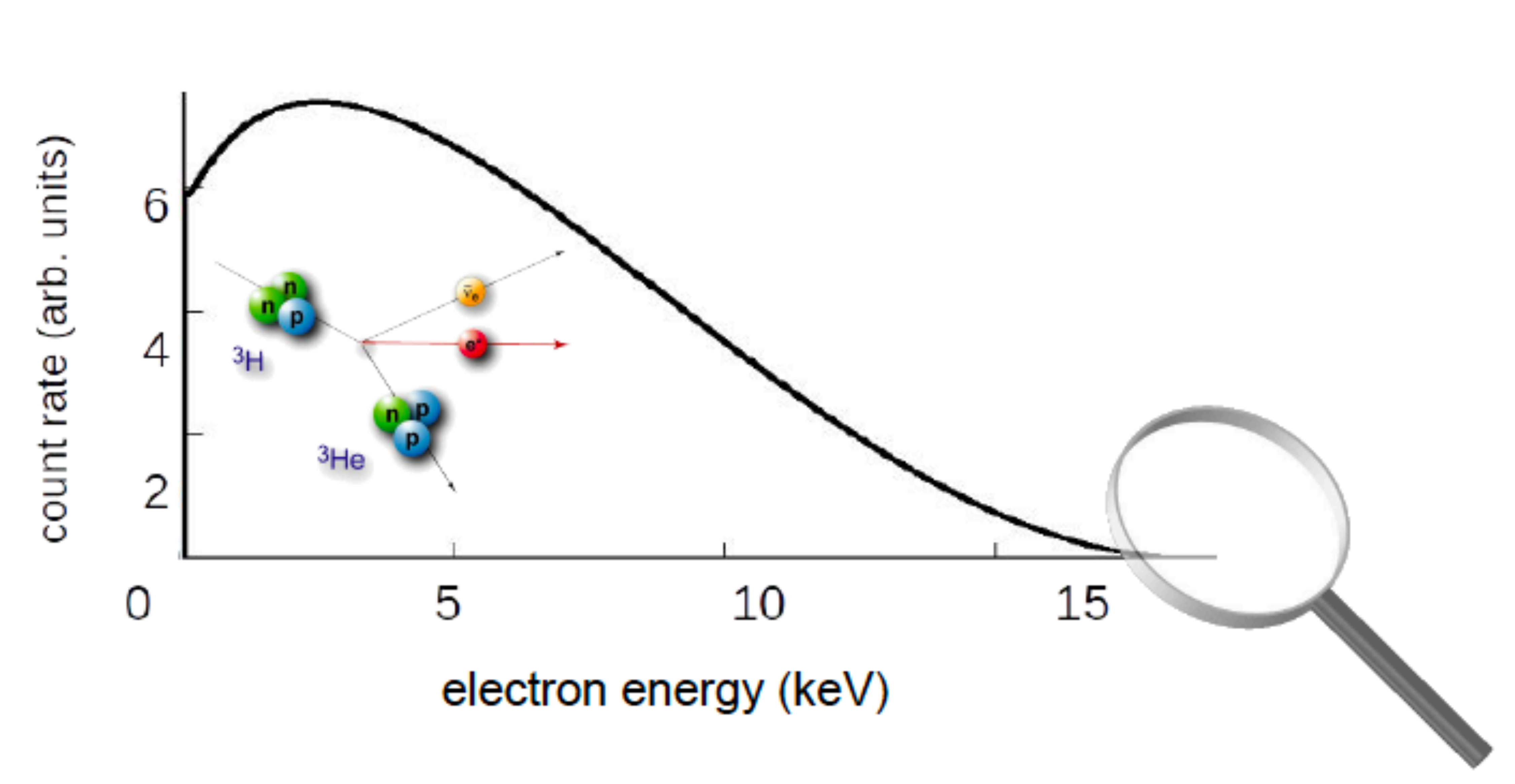


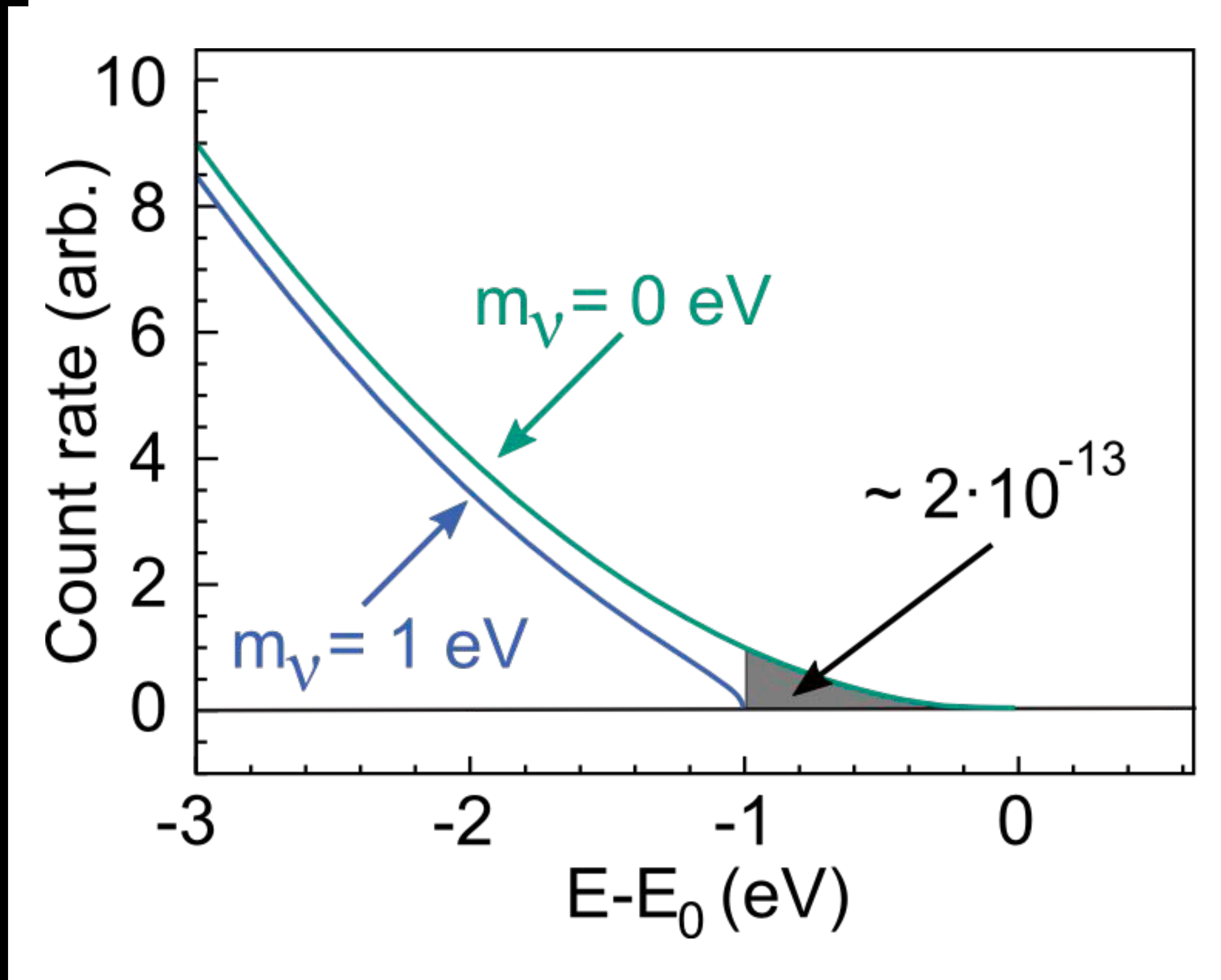
SMALLNESS OF NEUTRINO MASSES EXPLAINED BY EXISTENCE OF VERY HEAVY NEUTRINOS


β-decay (kinematic)
model independent
m_β
$m_\beta = \sqrt{\sum_i m_i^2 |U_{ei}|^2}$
mass eigenstate
mixing
m_1
m_2
m_3
cosmology
model dependent
• ΛCDM
m_Σ
$m_\Sigma = \sum_i m_i$
$m_{\beta\beta}$
double beta decay
model dependent
• lepton number violation
• light Majorana neutrino exchange
$m_{\beta\beta} = |\sum_i m_i U_{ei}^2|$

SEARCH FOR NEUTRINO MASS IN BETA DECAY

TRITIUM BETA DECAY





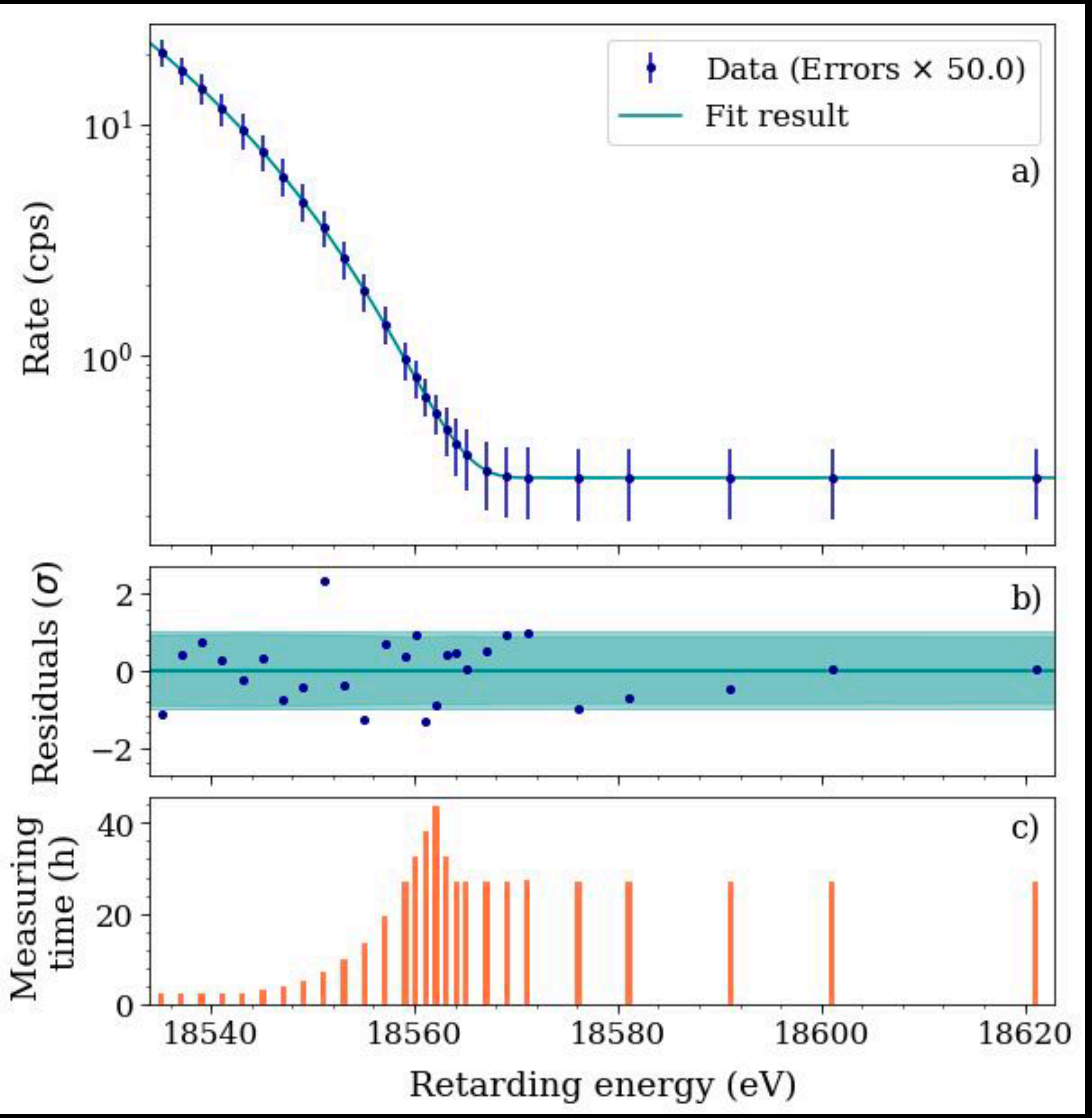
- With massive neutrinos, the endpoint of beta decay should be slightly distorted with respect to the decay's Q value
- Most sensitive search for those distortions are with tritium decay
- E = 18.6 keV, $T_{1/2}$ = 12 yr

- Effective "electron" neutrino mass

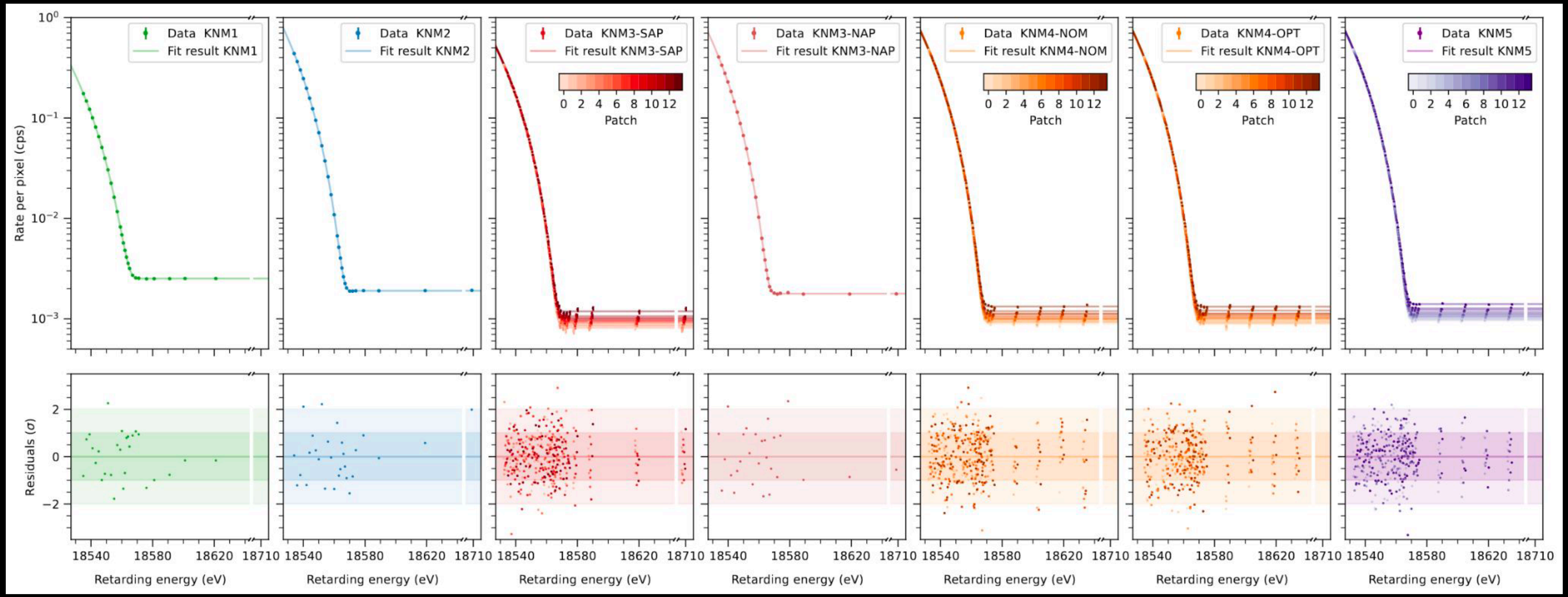
$$m_\nu \stackrel{\text{def}}{=} \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

KATRIN EXPERIMENT

KATRIN RESULTS

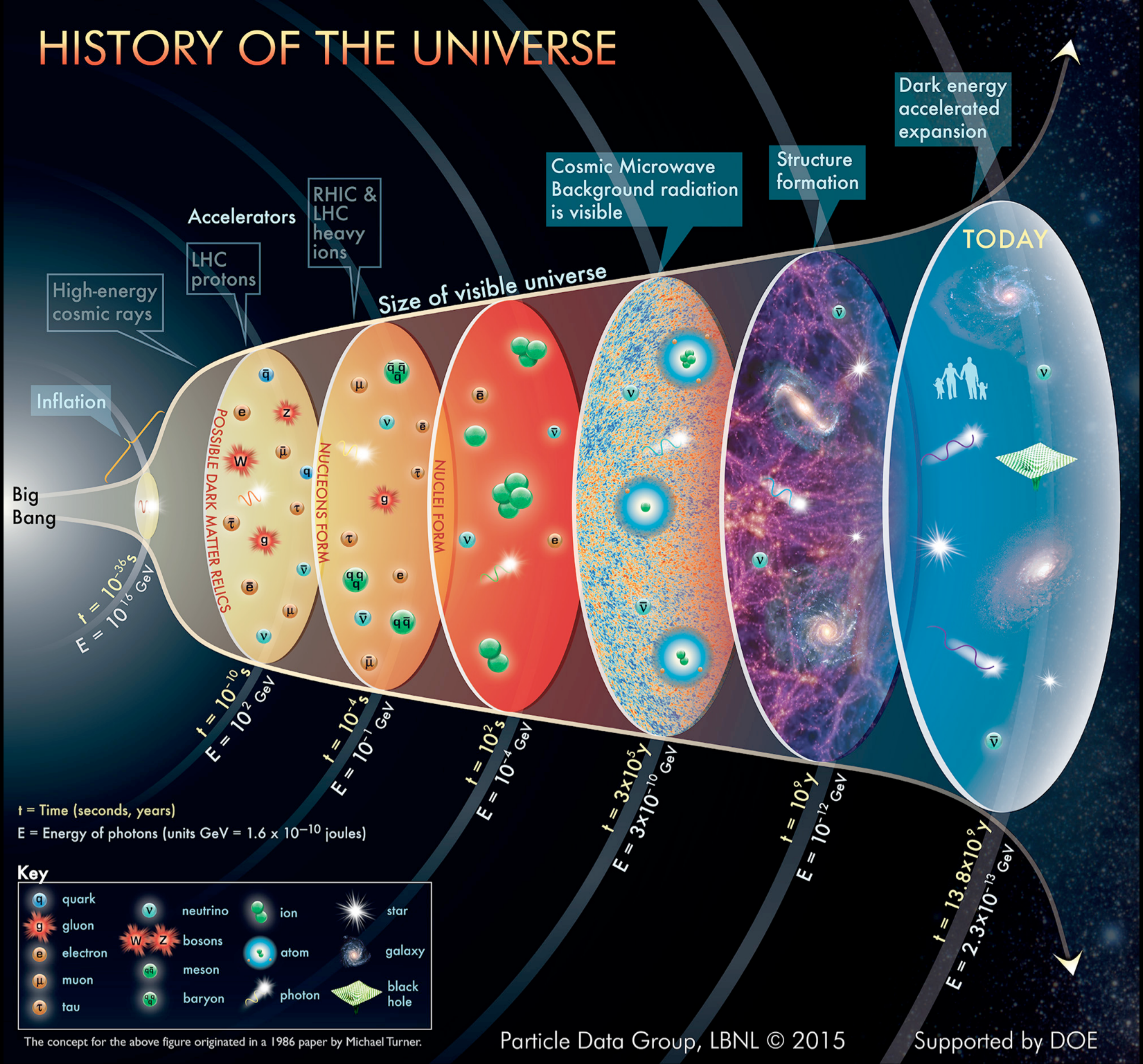


- Data is collected at various retarding energies to describe the endpoint



$$m_\nu < 0.45\,\mathrm{eV}\ \ (90\,\%\ \mathrm{CL})$$

NEUTRINOS IN COSMOLOGY


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Size of visible universe
Inflation
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
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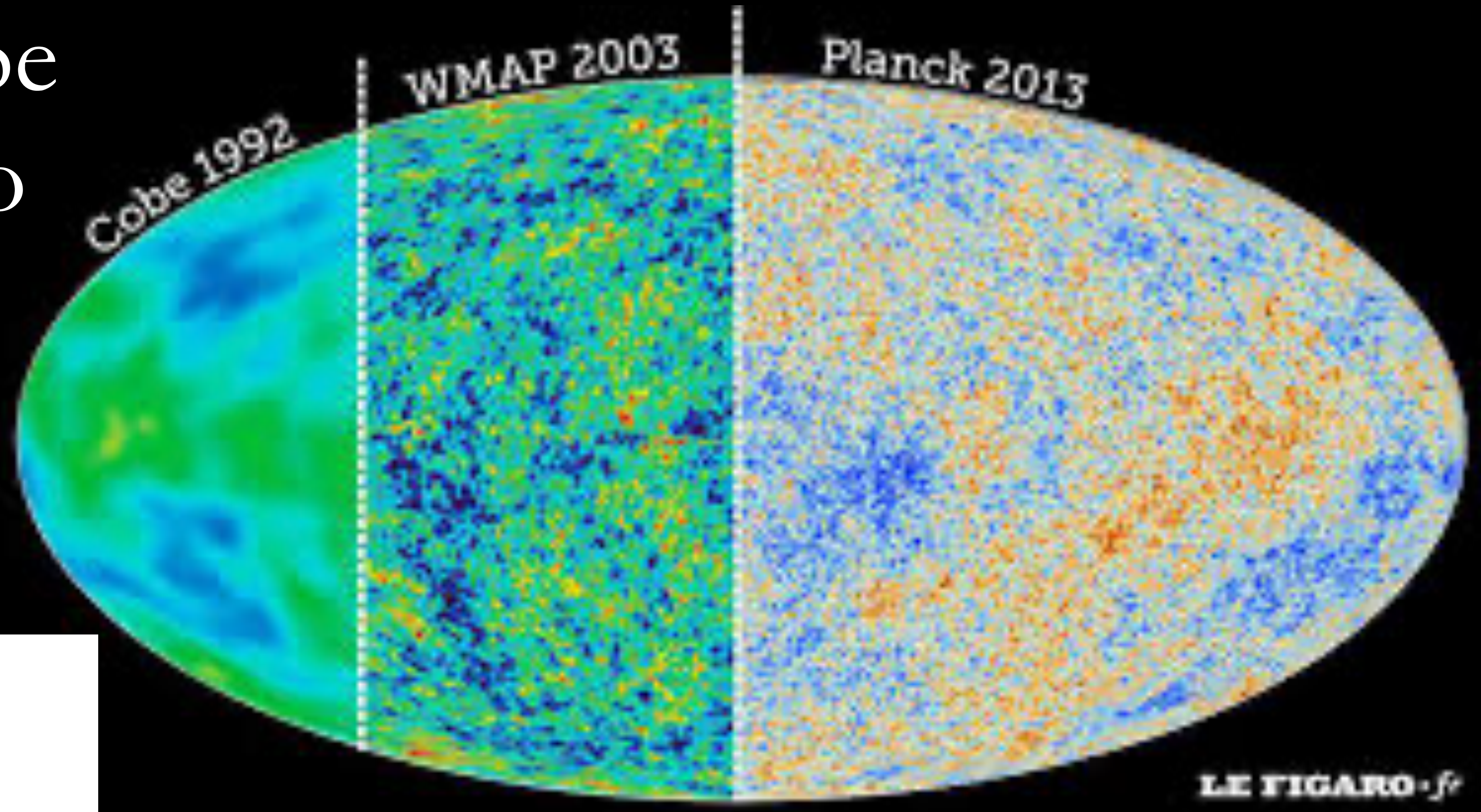
COSMIC BACKGROUND RADIATION

- Primordial Universe: temperature so high that there were no neutral atoms, but a soup of particles that light could not cross or escape
- Only after 300,000 years it cools enough for light to escape: the cosmic background radiation (CMB)
  - Very uniform, local differences about 10^{-5}. A lot of information in those fluctuations!

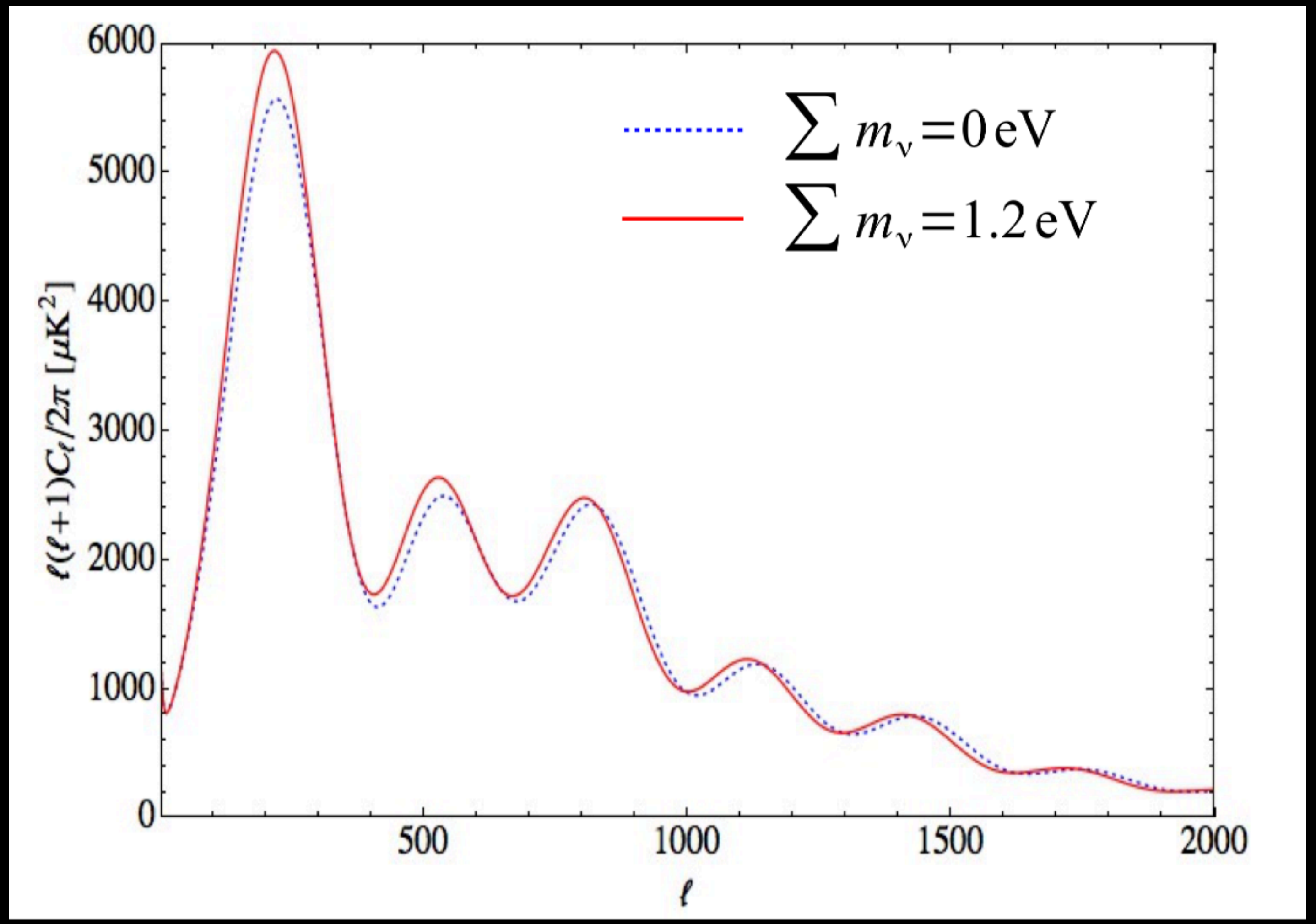


- Something similar with neutrinos
  - Example of reactions cycle
  - But their interaction is much weaker, they decouple much earlier: only one second after the Big Bang
  - Very high number density of neutrinos, similar to photons
  - Numerous enough influence the large scale structure of the Universe

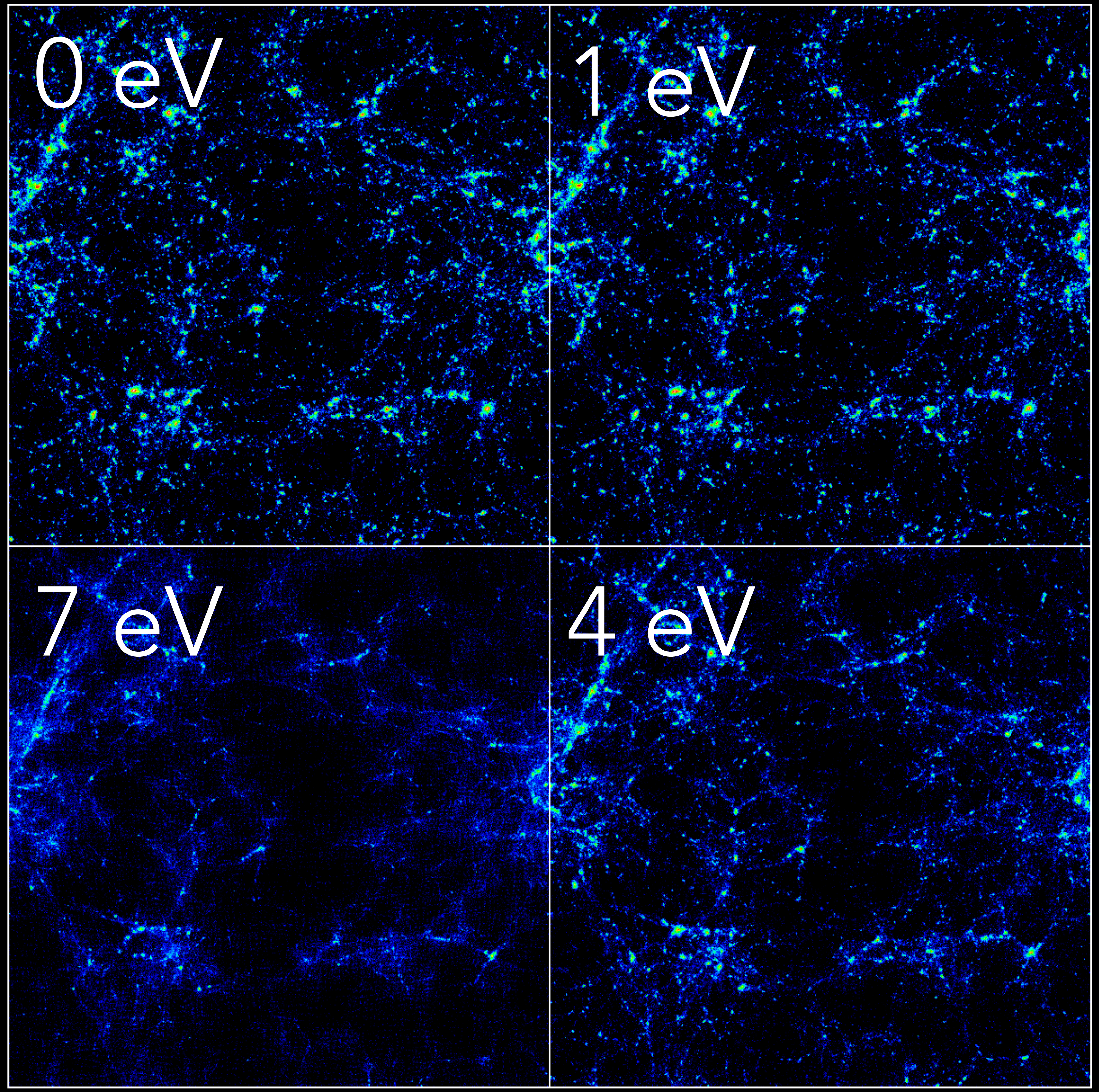
$$\nu_e + n \leftrightarrow e^- + p$$
$$e^+ + n \leftrightarrow \bar{\nu}_e + p$$
$$n \leftrightarrow e^- + p + \bar{\nu}_e$$

CONSTRAINTS ON NEUTRINO MASS

- CMB fluctuations sensitive to ν mass

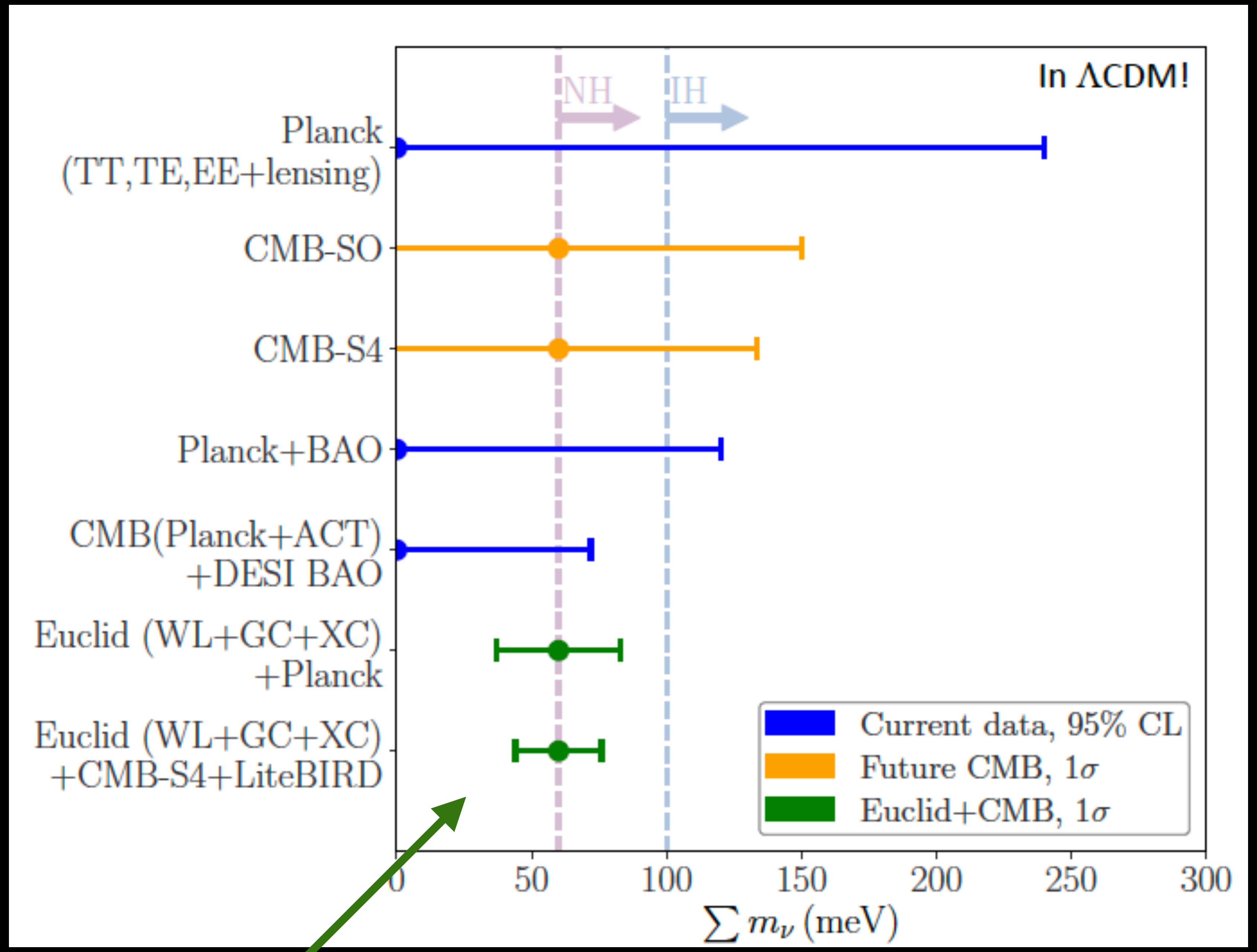


- Large scale structure simulations for different neutrinomasses



- Current best limit from cosmology

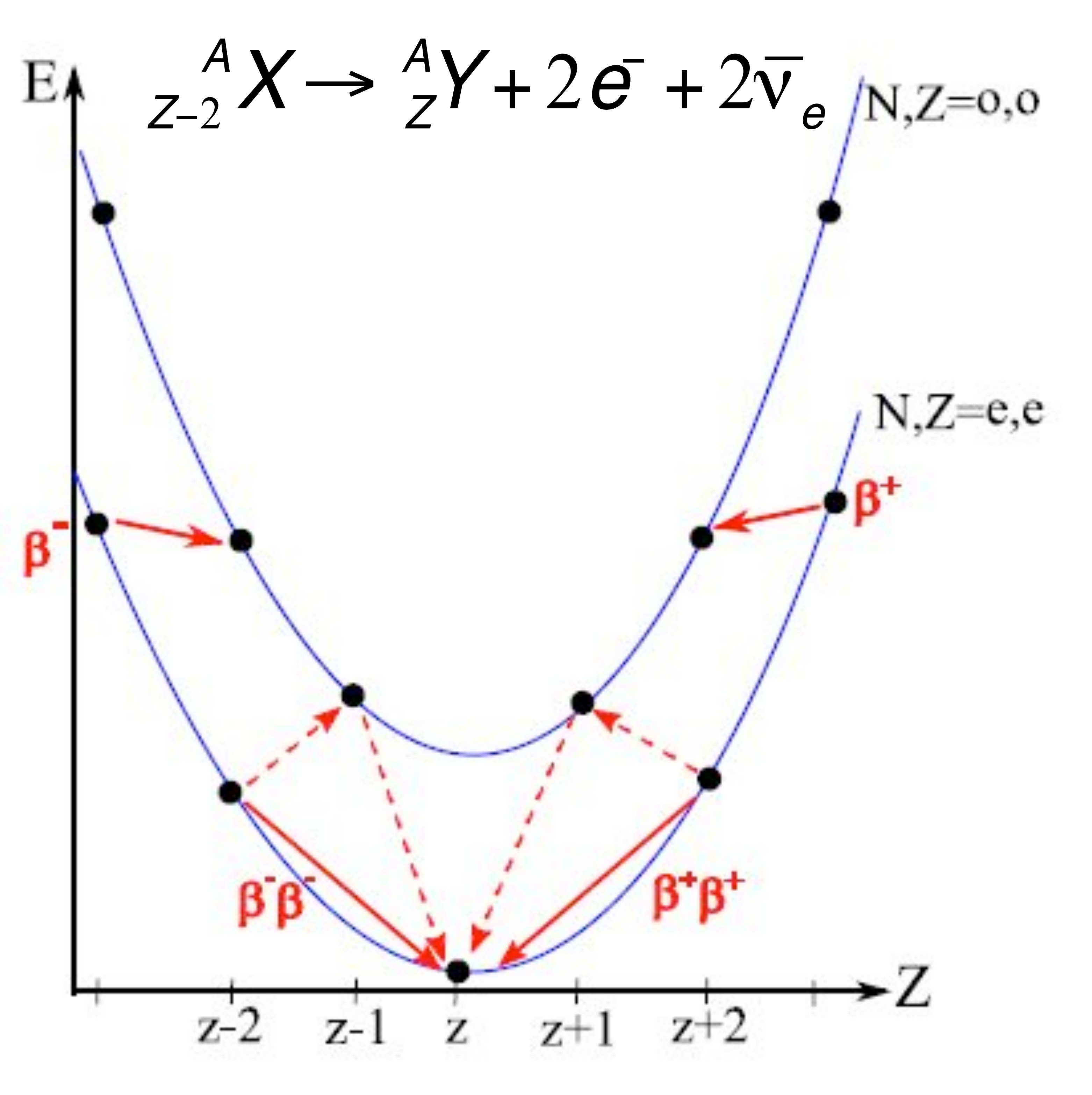
$$\sum m_{\nu_i} < 72\ meV\,!$$



Future missions may give actual measurement

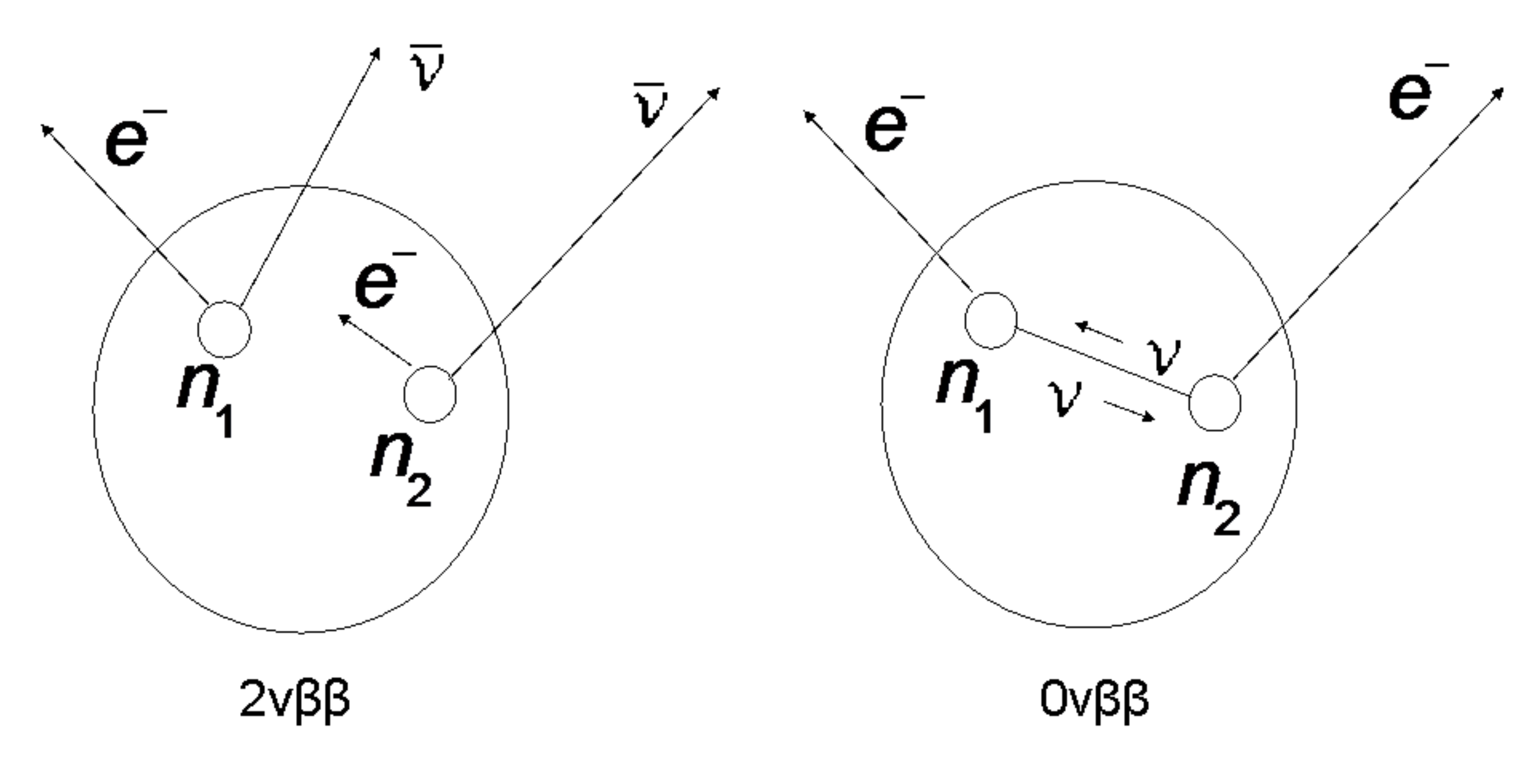
NEUTRINOLESS DOUBLE BETA DECAY

DOUBLE BETA DECAY

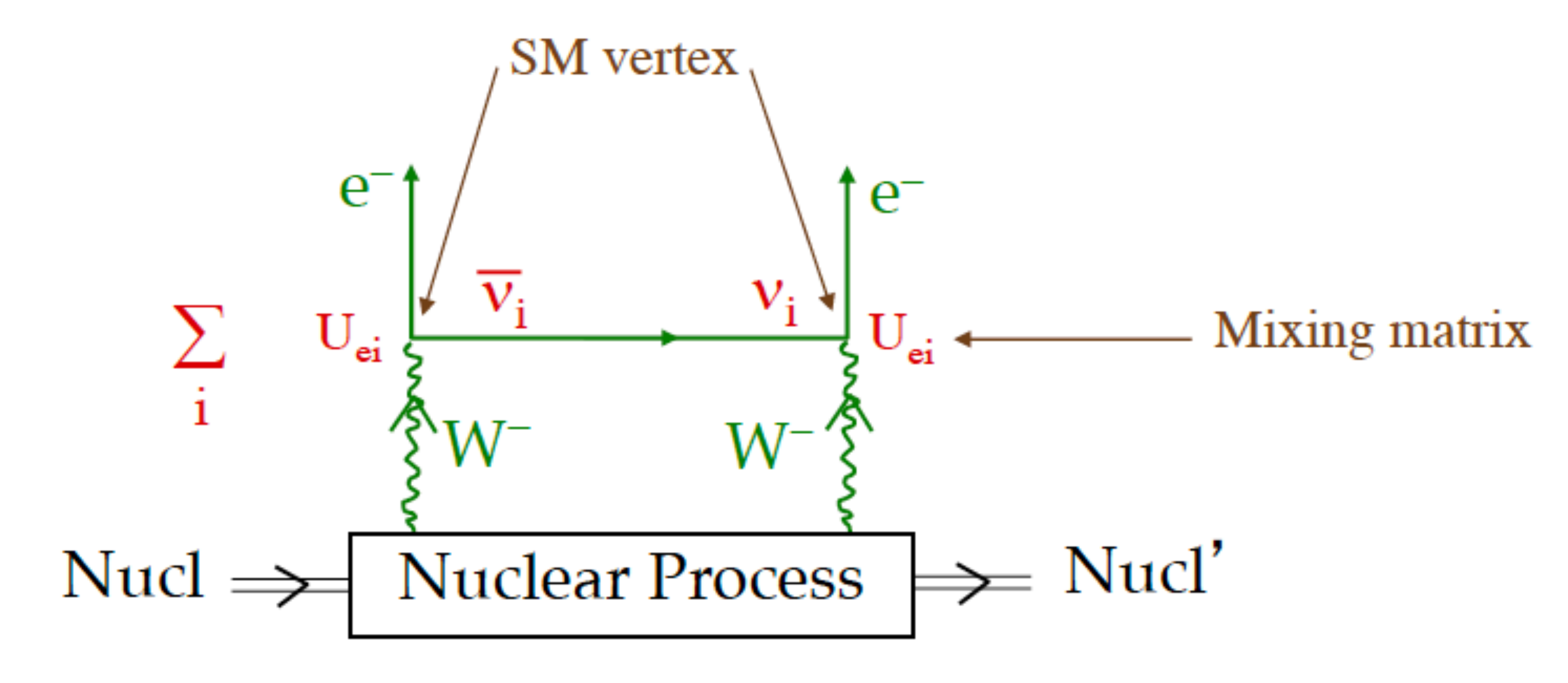


- Double beta decay (DBD) may occur in some even-even nuclei with when beta decay not energetically possible
  - 35 natural isotopes (observed in 11)
- Very rare process: Typical $T^{1/2} \sim 10^{18}$ - 10^{21} yr
- Neutrinoless double decay involves “internal” neutrino annihilation and lepton number violation, possible only if there is a Majorana mass term

$$2\nu\beta\beta\ mode: \ {}_{Z}^{A}X_{N} \rightarrow {}_{Z+2}^{A}X_{N-2} + 2e^{-} + 2\overline{\nu_e}$$
$$0\nu\beta\beta\ mode: \ {}_{Z}^{A}X_{N} \rightarrow {}_{Z+2}^{A}X_{N-2} + 2e^{-}$$



NLDBD RATE AND NUCLEAR PHYSICS

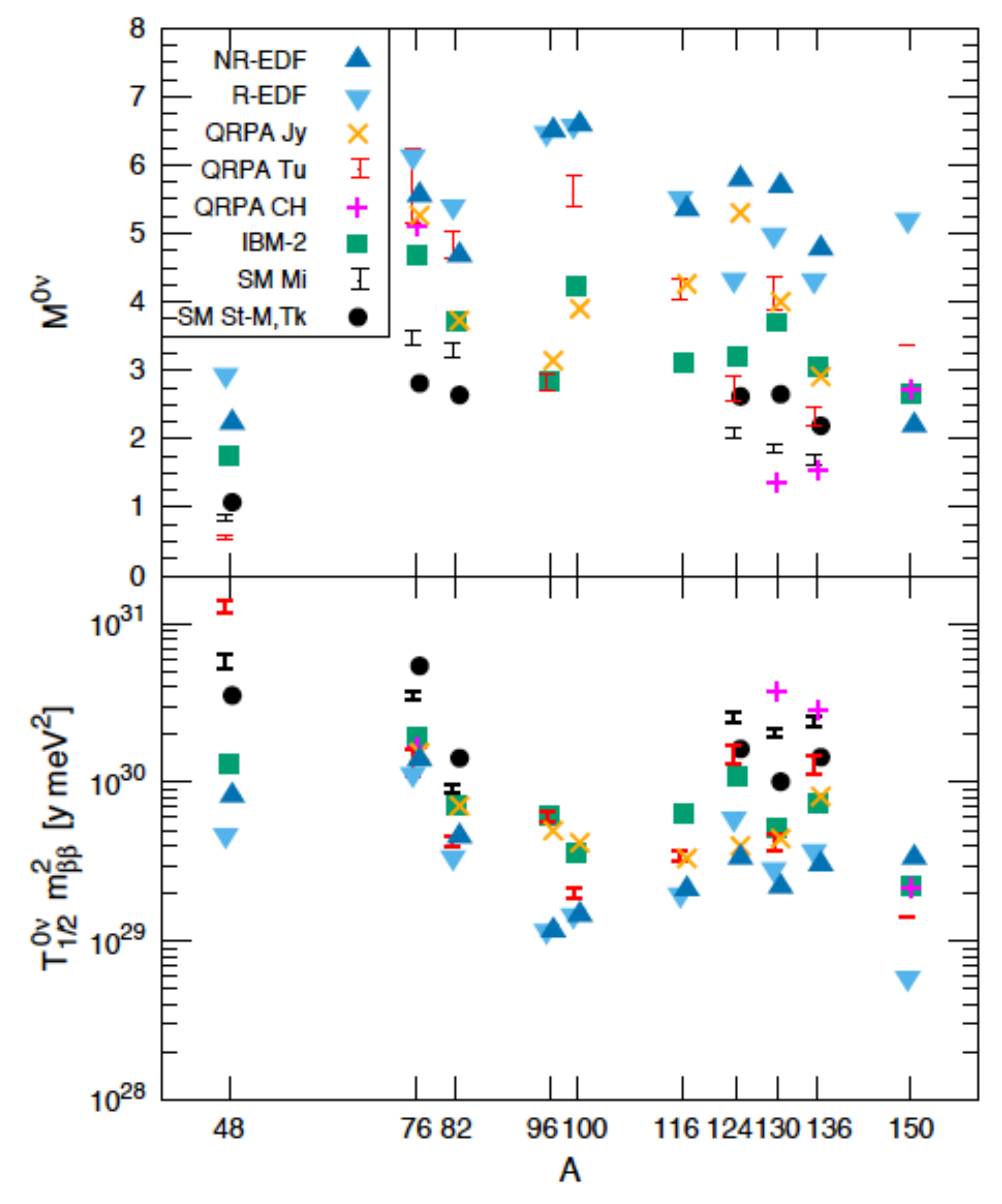


Phase space

Nuclear matrix element

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Particle Physics term



- Phase space depends on Q-value, the higher the better
- Nuclear matrix element calculations are very hard because of the high number of nucleons
  - discrepancies of factors of 3 between models are common
  - more recent ab-initio models are considered more reliable
- Measurement of NLDBD with various isotopes is essential!

NLDBD - PARTICLE PHYSICS TERM

Phase space

Nuclear matrix element

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}|M^{0\nu}|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

Particle Physics term
Effective Majorana mass
Depends on masses m1, m2, m3
also on neutrino mixing parameters

$$m_{\beta\beta} = \left|\sum_{k=1}^{3} m_k U_{ek}^2\right| = \left|m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i(\alpha_2-\alpha_1)} + m_3 s_{13}^2 e^{i(\alpha_1-2\delta_{CP})}\right|$$

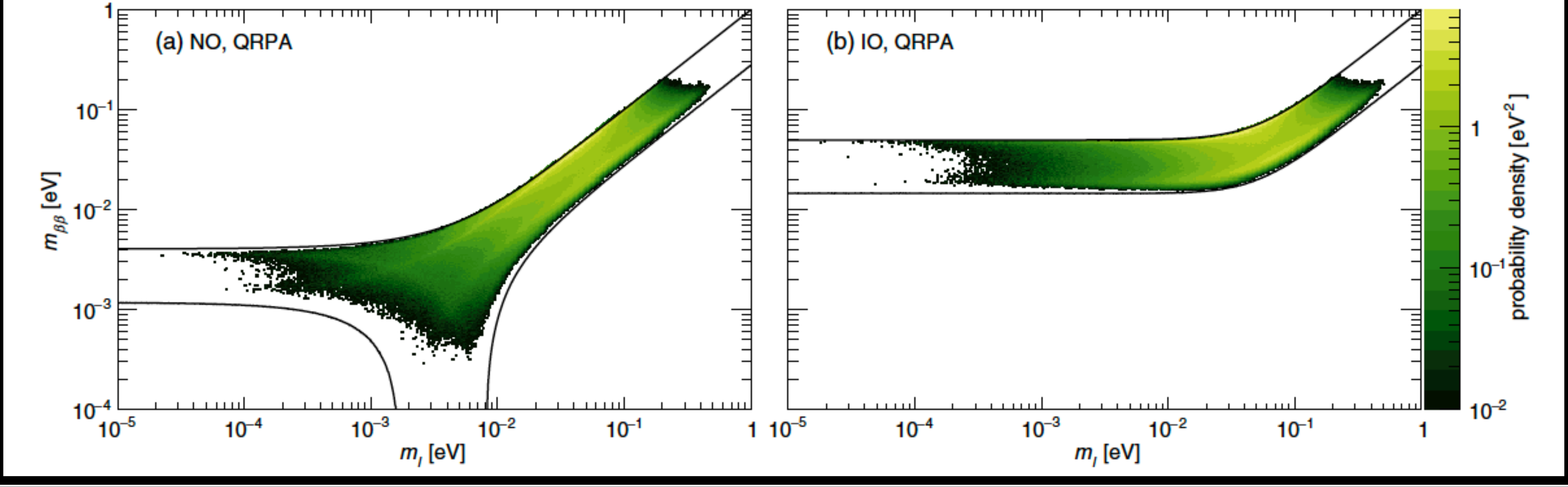
- Many non-SM physics processes can cause NLDBD, we focus here on the simplest possibility, the exchange of light Majorana neutrinos
- Requires a flip of the neutrino's chirality. Possible because for massive neutrinos, chirality is not a good quantum number
- Recall from lecture 1:

$$u_\uparrow \propto \frac{1}{2}(1+k)u_R + \frac{1}{2}(1-k)u_L$$

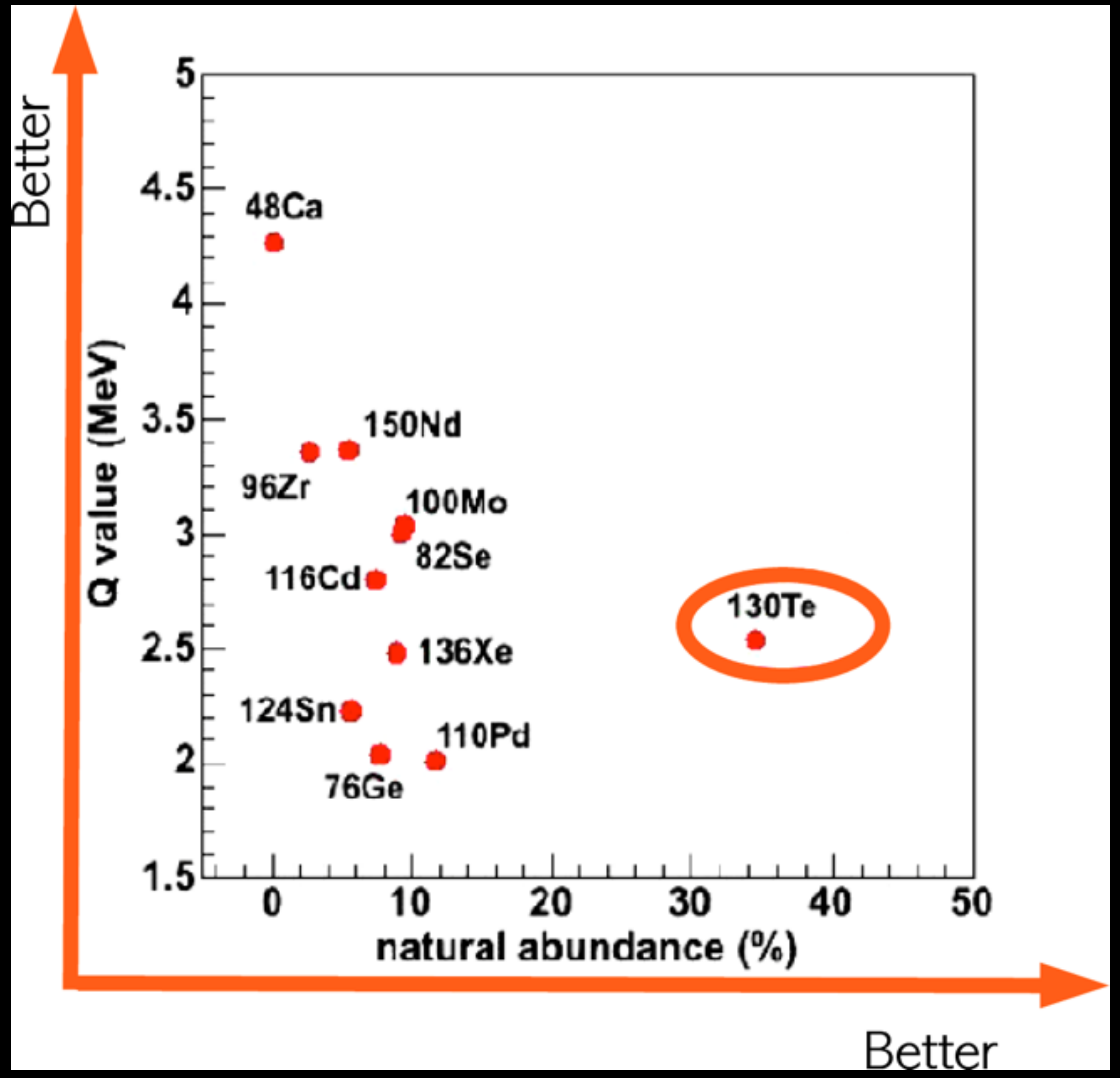
MAJORANA MASS GOALS

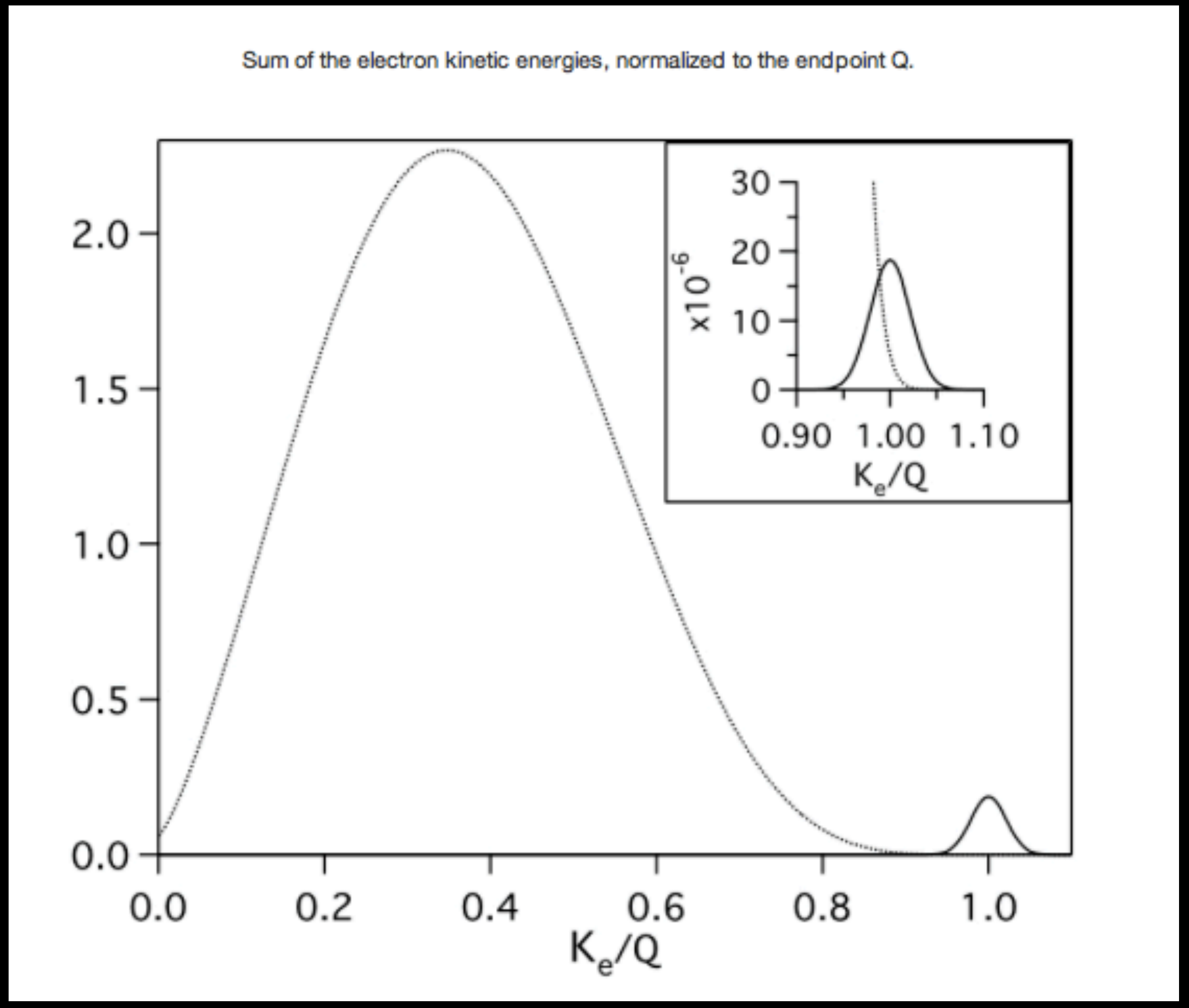
$$m_{\beta\beta} = \left| \sum_{k=1}^{3} m_k U_{ek}^2 \right| = \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i(\alpha_2-\alpha_1)} + m_3 s_{13}^2 e^{i(\alpha_1 - 2\delta_{CP})} \right|$$

- Existing neutrino oscillation measurements put constraints on $m_{\beta\beta}$
  - But in addition, depends on Majorana phases
  - Inverted ordering $m_{\beta\beta}$ > 20 meV, normal ordering $m_{\beta\beta}$ >~ 1 meV



- Choose a suitable isotope
  - High energy, high isotopic abundance (or enrich)
- Observe large quantities for a long time
- Detect electron energy sum, reject backgrounds
- Look for a peak, in addition to the continuum for DBD





$$S^{0\nu} = \frac{ln\ 2}{n_\sigma} T \cdot n \cdot \epsilon \frac{1}{\sqrt{B}}.$$

- Often an optimization of a given parameter leads to a compromise in others
  - Example: large mass, low backgrounds typically means low energy resolution (needed to reject backgrounds)

MAIN TYPES OF EXPERIMENTS

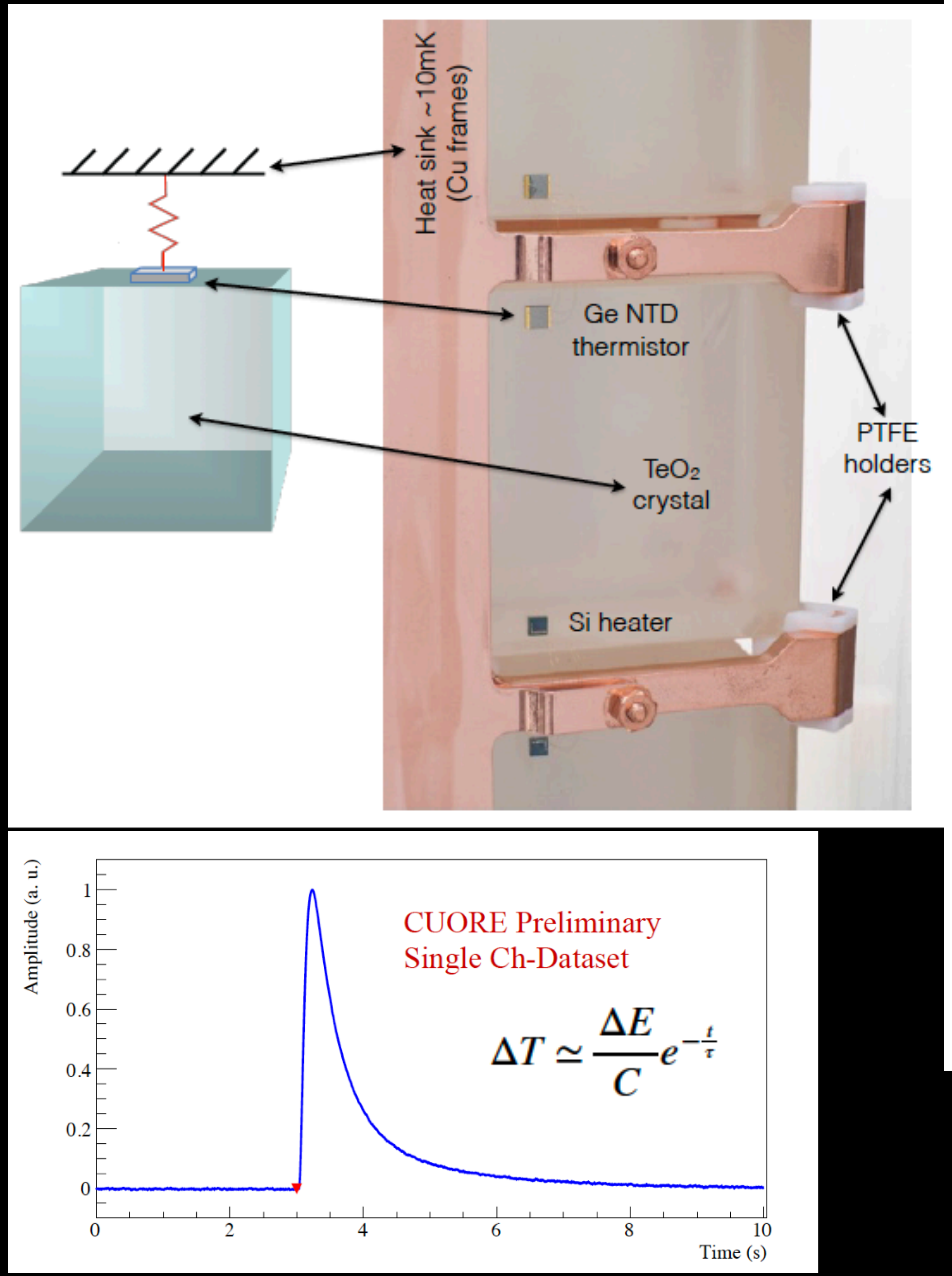
1. **Calorimeters with high energy resolution and low mass:** Germanium semiconductor experiments, like GERDA, or tellurium cryogenic bolometers, like CUORE;
2. **Calorimeters with high mass and low energy resolution:** Large isotope-loaded liquid scintillator detectors, like KamLAND-Zen or SNO+;
3. **Detectors with tracking or topology capabilities:** Gas or liquid-phase time projection chambers (TPCs) with some degree of tracking or topology measurement to complement the calorimetry.

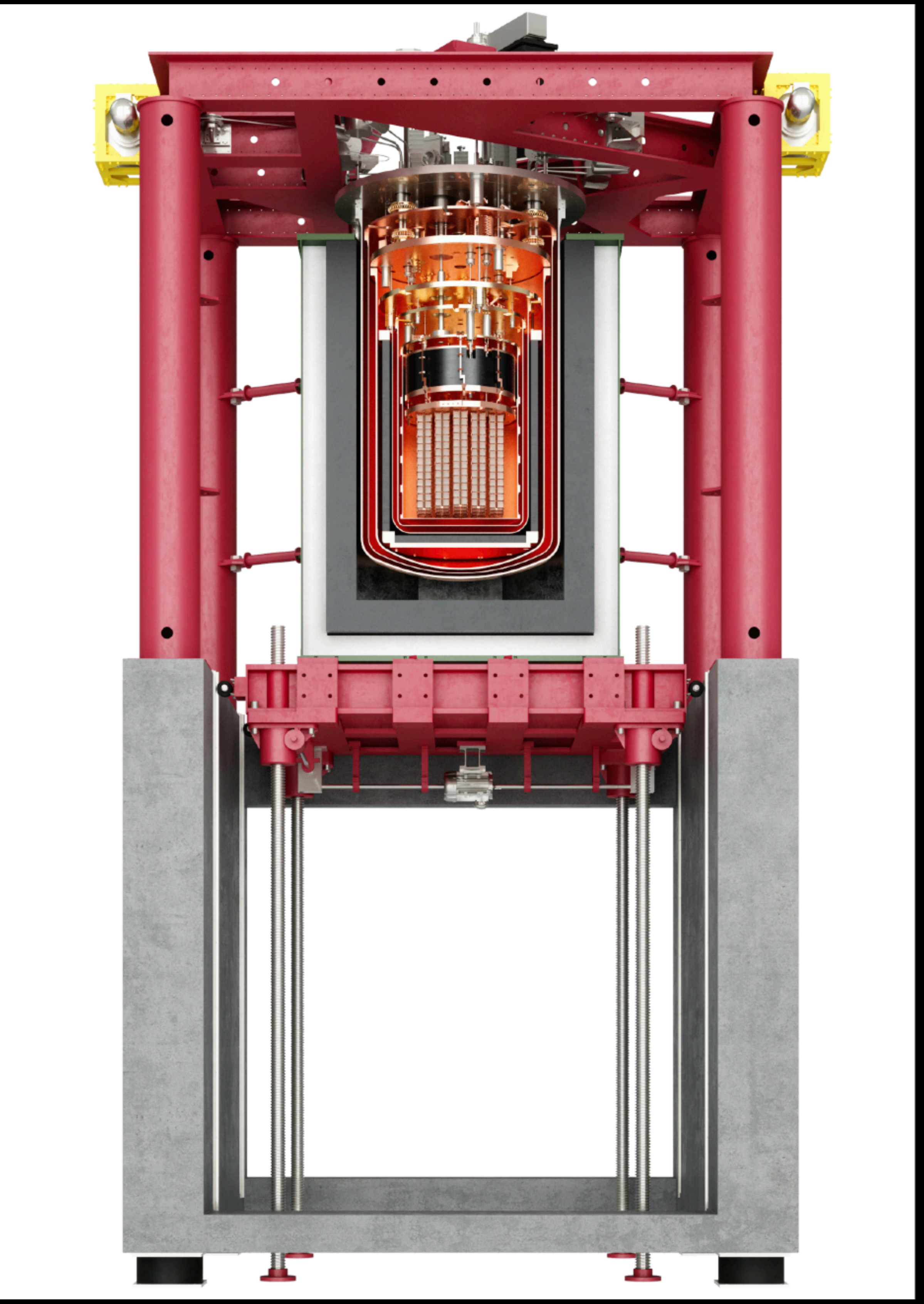
- Leading sensitivity: type 1 and 2

Experiment	Isotope	Resolution keV	Exposure kg.yr	Bg. Idx. $(keV.kg.yr)^{-1}$	$T_{1/2}$, yr (90% C.L.)	$m_{\beta\beta}$ meV
CUORE	^{130}Te	7.8	289	1.5×10^{-2}	2.2×10^{25}	90-305
GERDA	^{76}Ge	2.6–4.9	98	5.2×10^{-4}	1.8×10^{26}	79-180
KLZ	^{136}Xe	247	510	1.3×10^{-4}	2.3×10^{26}	36-156

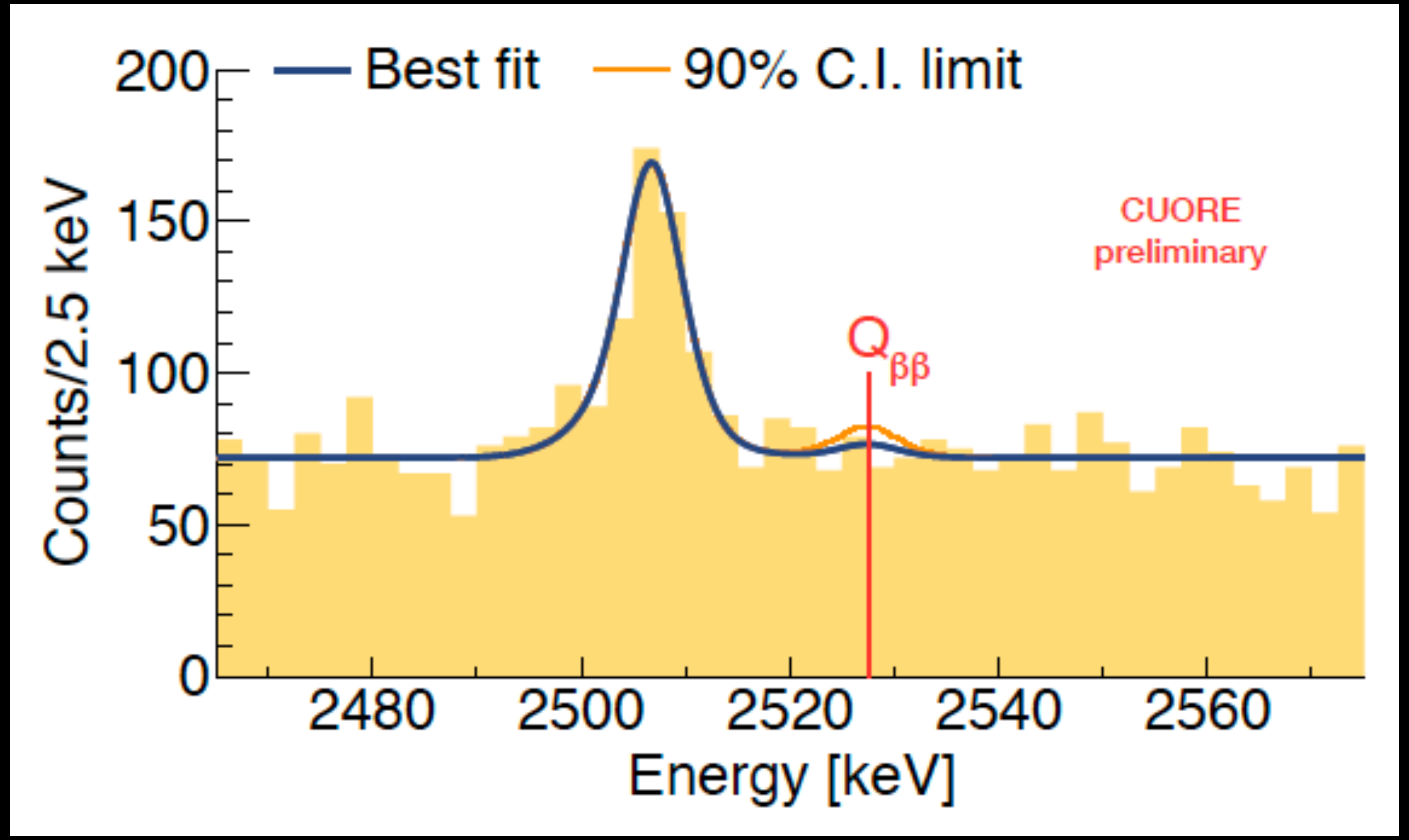
NLDBD CURRENT EXPERIMENTS

CUORE





- Cryogenic bolometers, TeO_2
- Temperature: 10 mK
- ~206 kg of 130Te

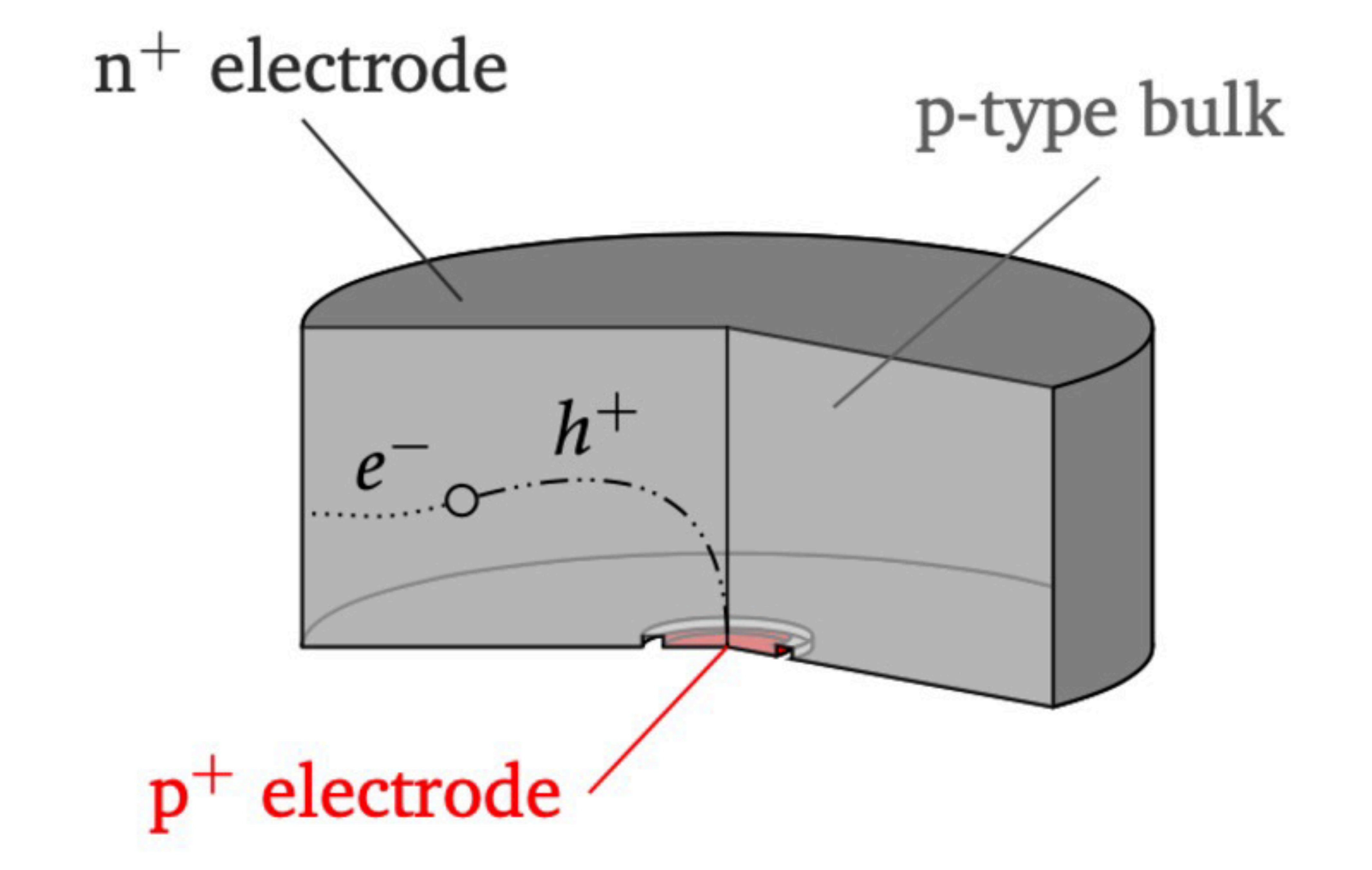


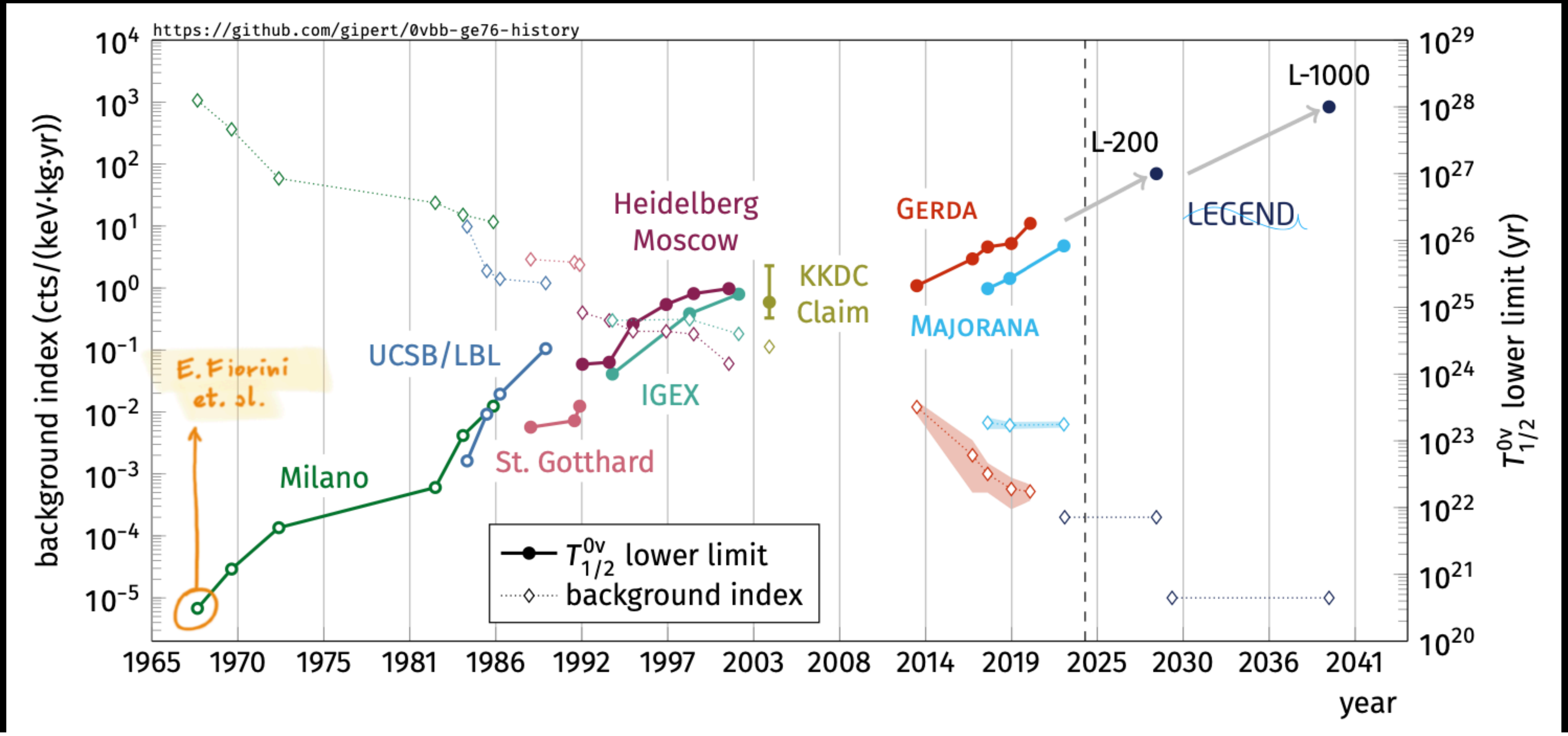
- External backgrounds prevent reaching a better sensitivity

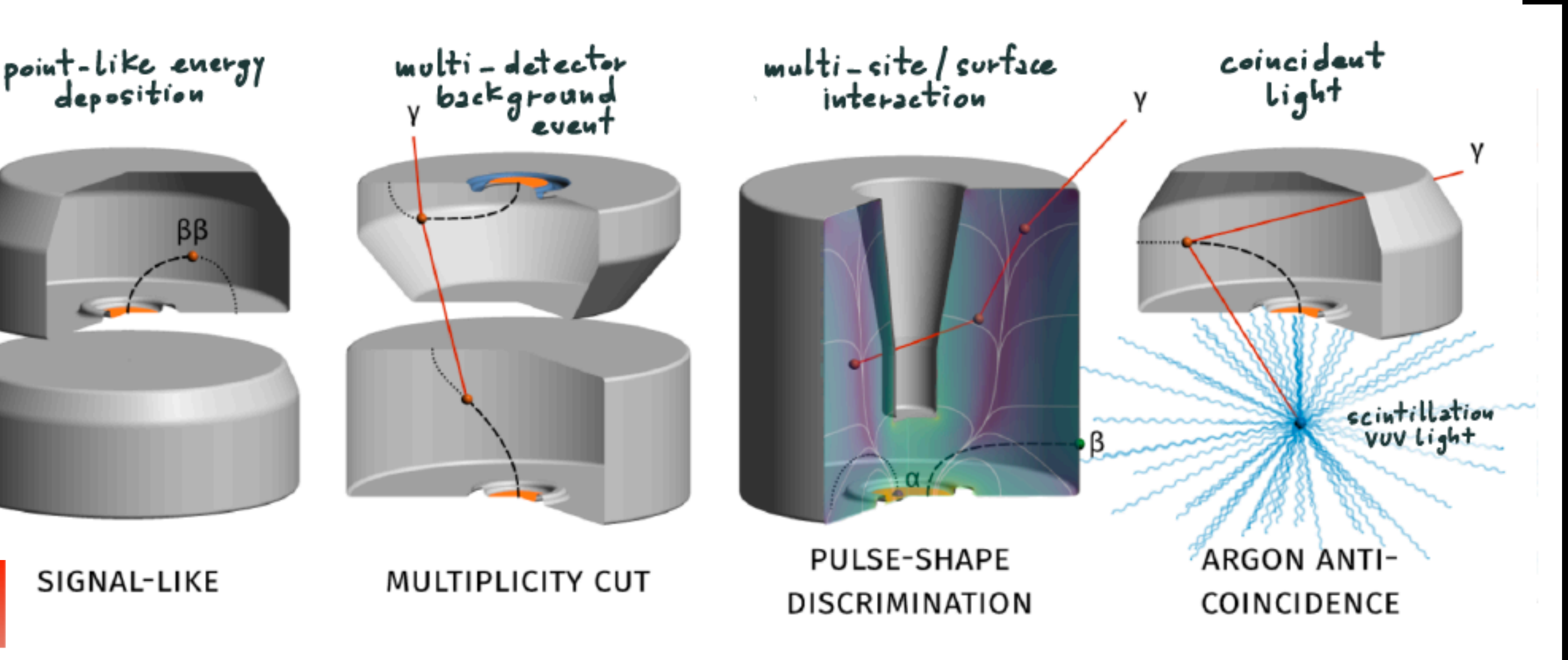
Half-life limit: $T^{0\nu}_{1/2} > 3.8 \times 10^{25}$ yr (90% C.I.)

$m_{\beta\beta} < 70 - 240$ meV

GERMANIUM DETECTORS



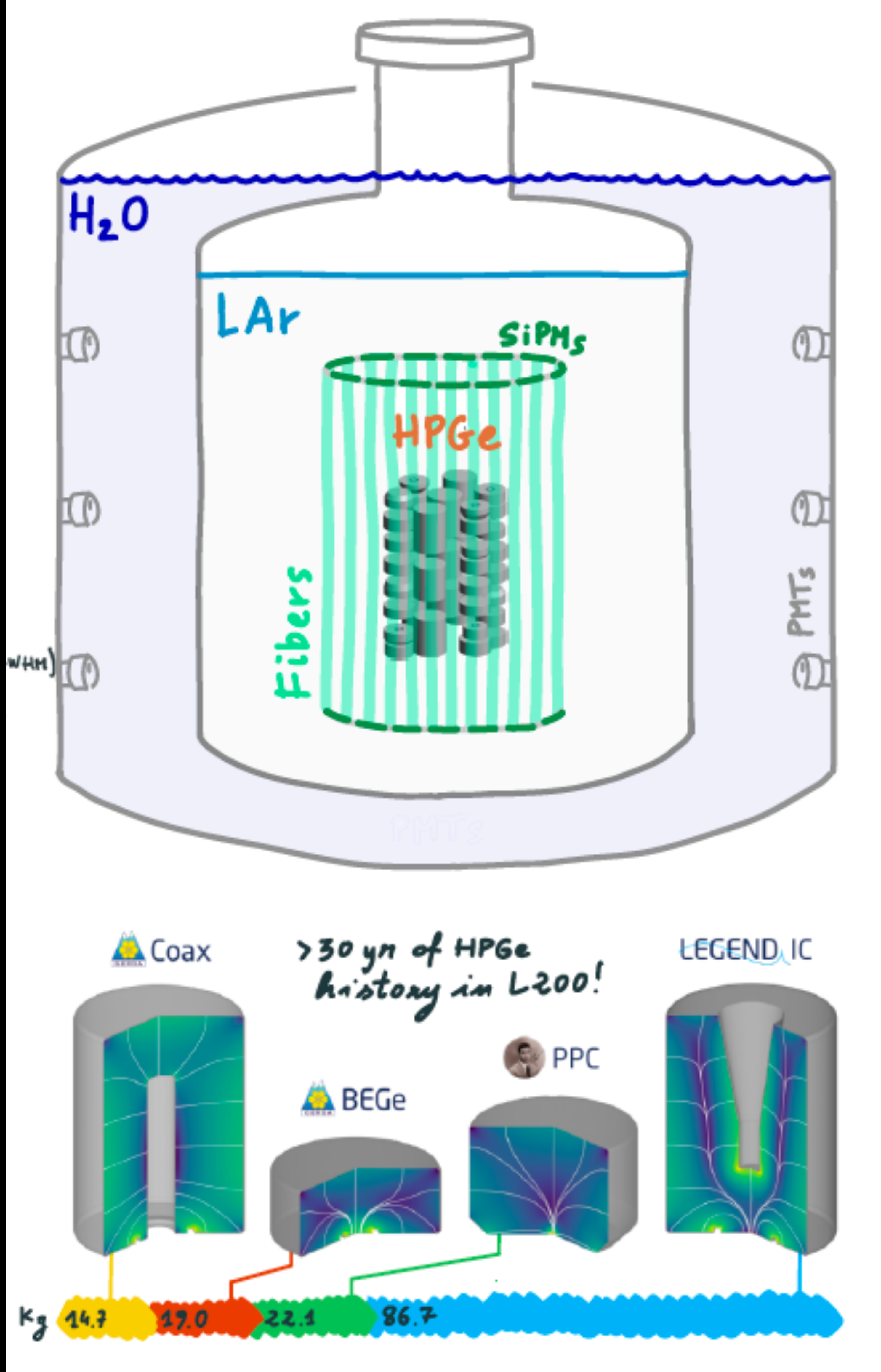


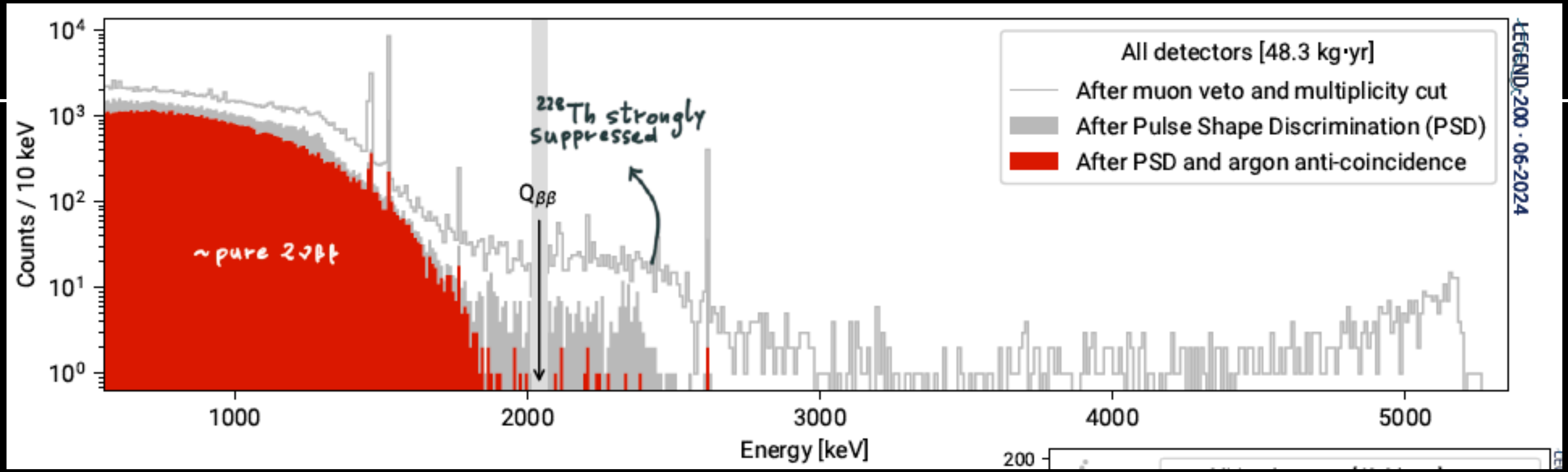


- long history of developments
- capable of reducing multuple types of backgrounds
- leading energy resolution 0.1% (FWHM)

L. PERTOLDI, NEUTRINO 2024

LEGEND





- LEGEND-200 uses 142 kg of enriched Ge crystals
- Preliminary data combined with other Ge experiments (GERDA, MAJORANA) yields limit of $1.9 \times 10^{26} yr$
- LEGEND-1000 aims for $10^{28} yr$ (next decade)

- 7 events surviving. Background index BI = $5.3 \pm 2.2 \cdot 10^{-4}$ cts / (keV kg yr)

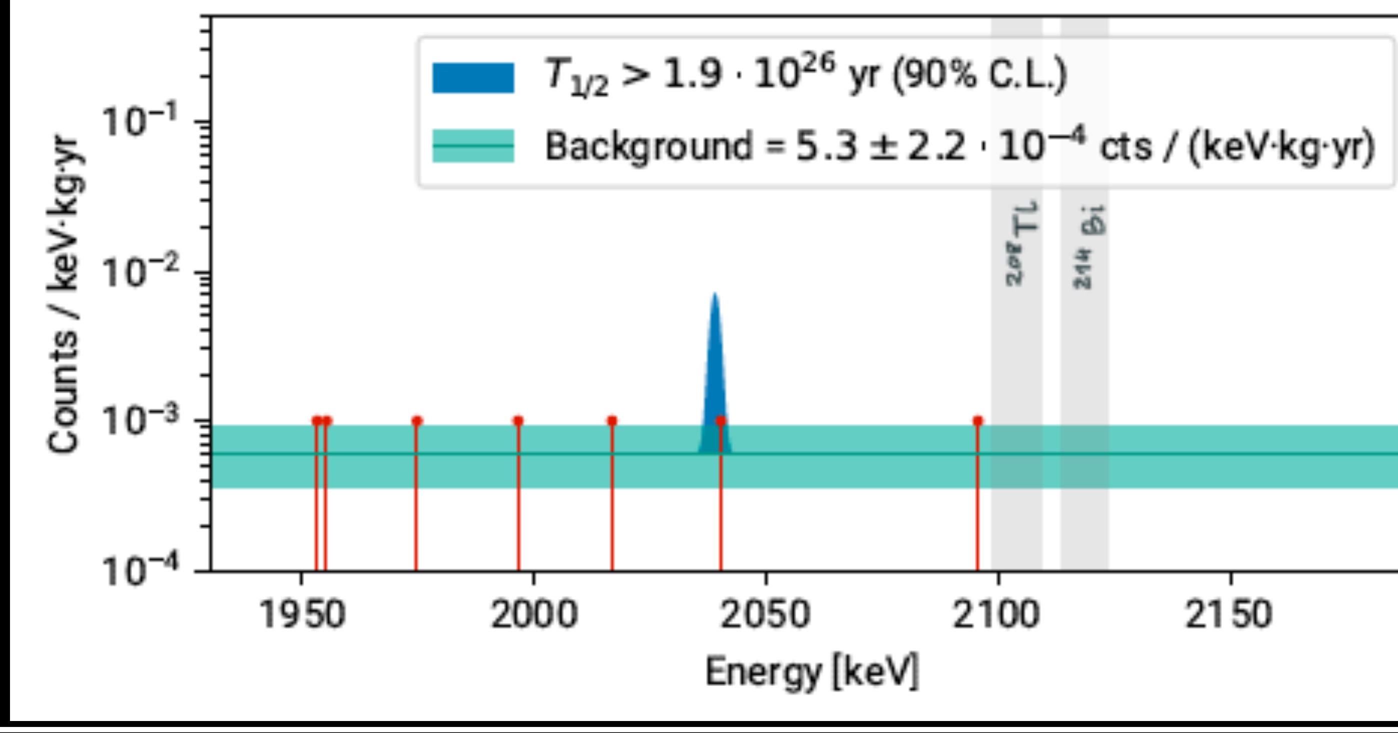
PRELIMINARY!

GERDA, MAJORANA and LEGEND combined fit

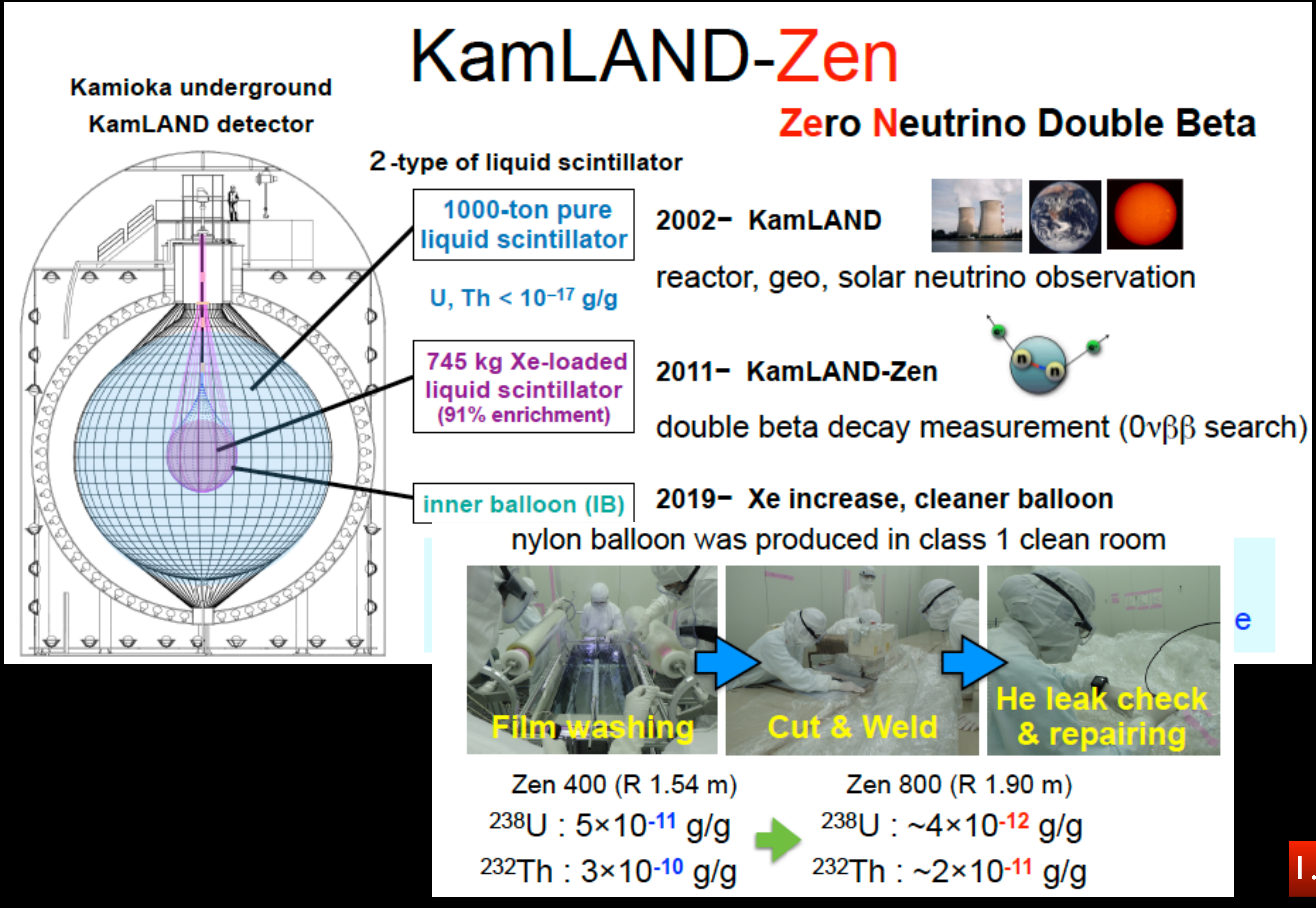
- p-value of background-only = 26%
- $T^{0\nu}_{1/2}$ lower limits (90% frequentist C.L.)

Observed	Sensitivity
$> 1.9 \cdot 10^{26}$ yr	$2.8 \cdot 10^{26}$ yr

L. PERTOLDI, NEUTRINO 2024



KAMLAND-ZEN



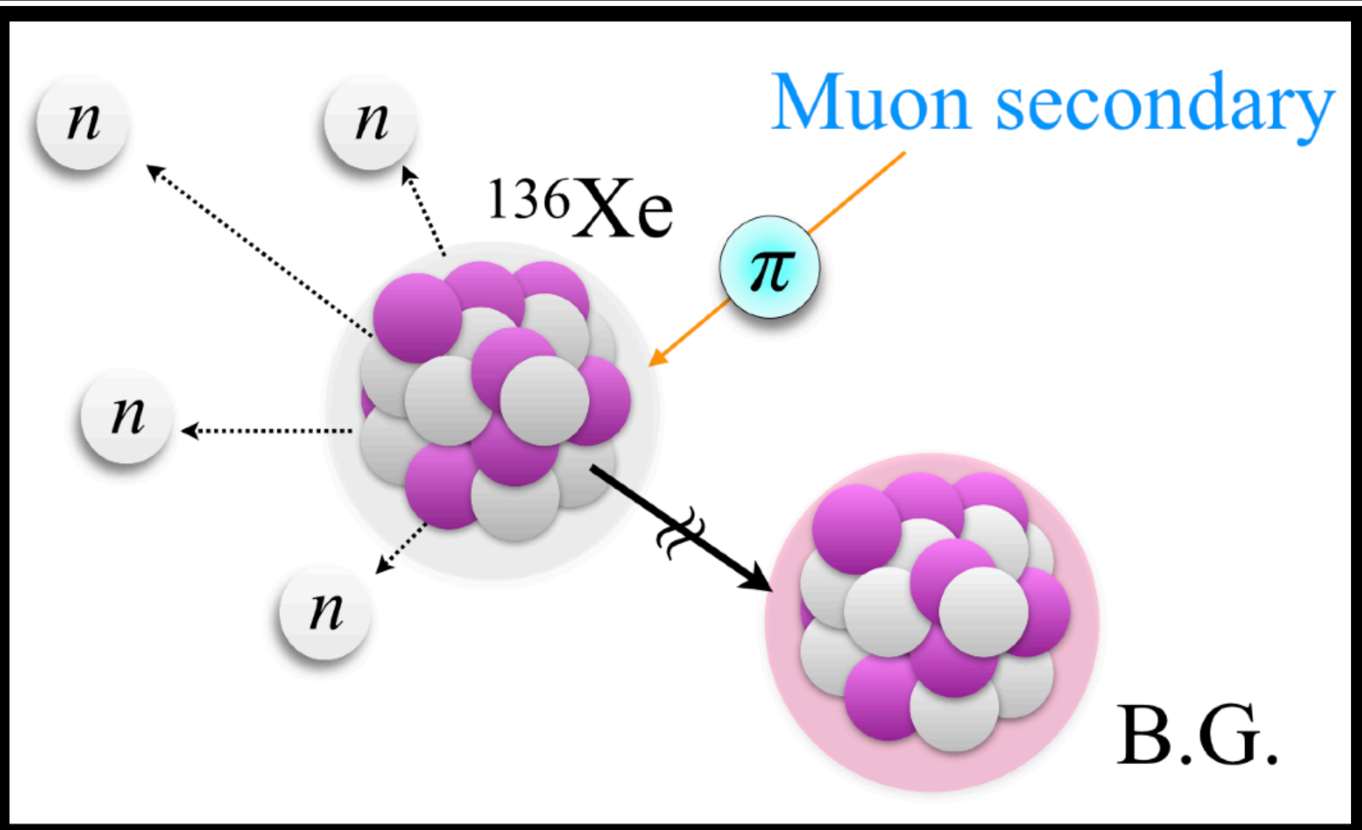
Xenon is a gas, it's soluble in liquid scintillator!

KamLAND-ZEN has 745 kg of enriched Xe dissolved in the LS

Highest mass of isotope of any experiment!

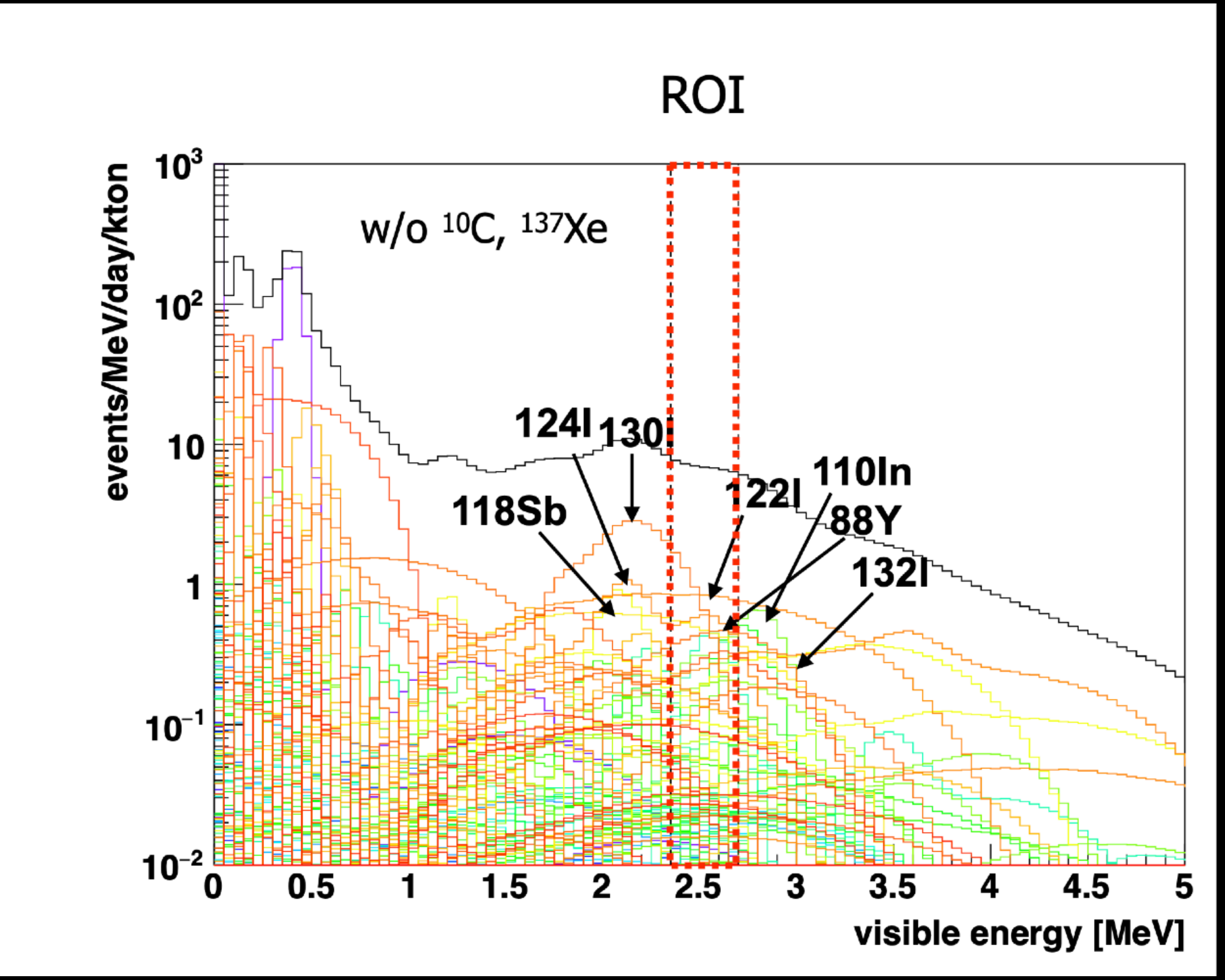
I. SHIMIZU, NEUTRINO 2024

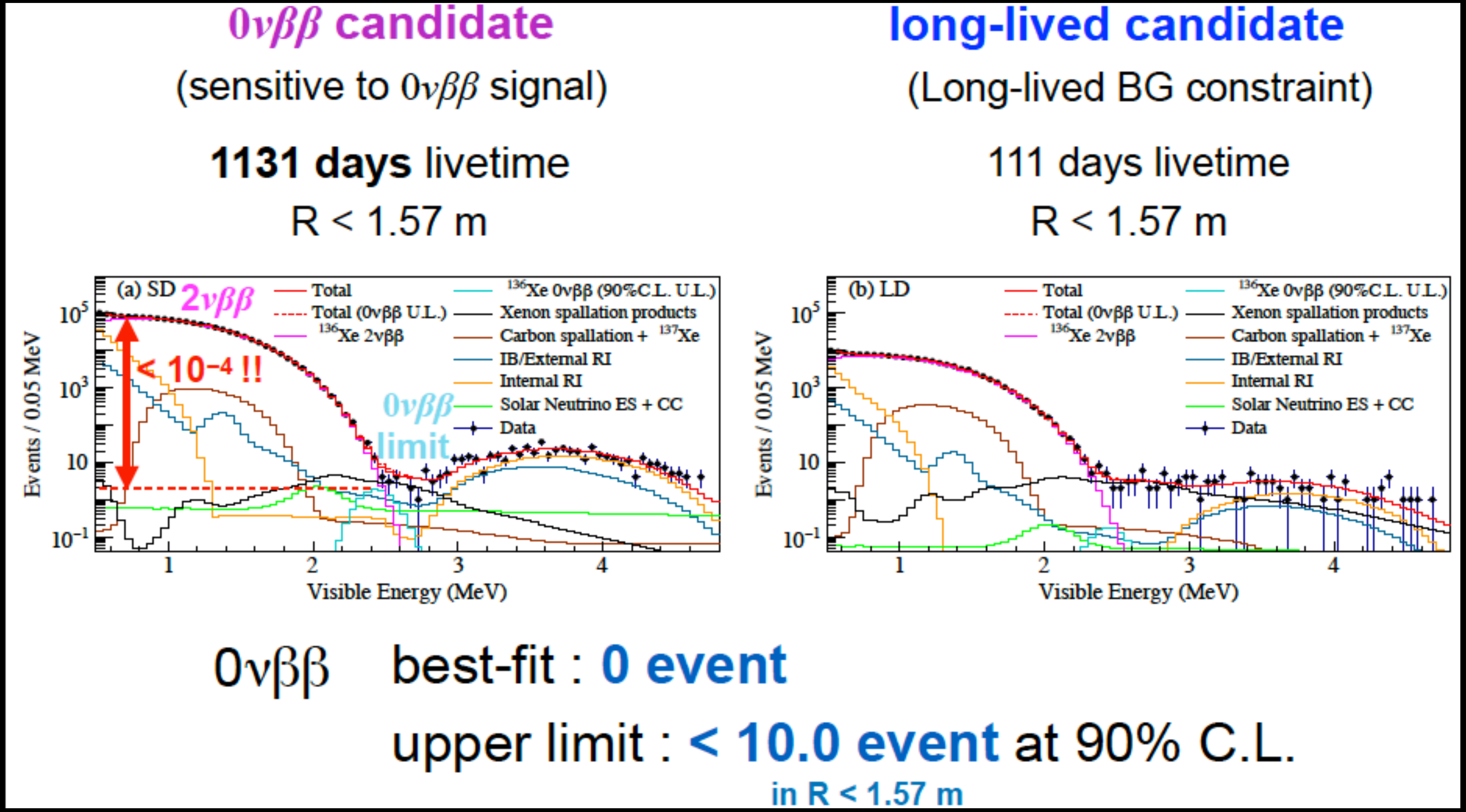
KAMLAND-ZEN RESULTS



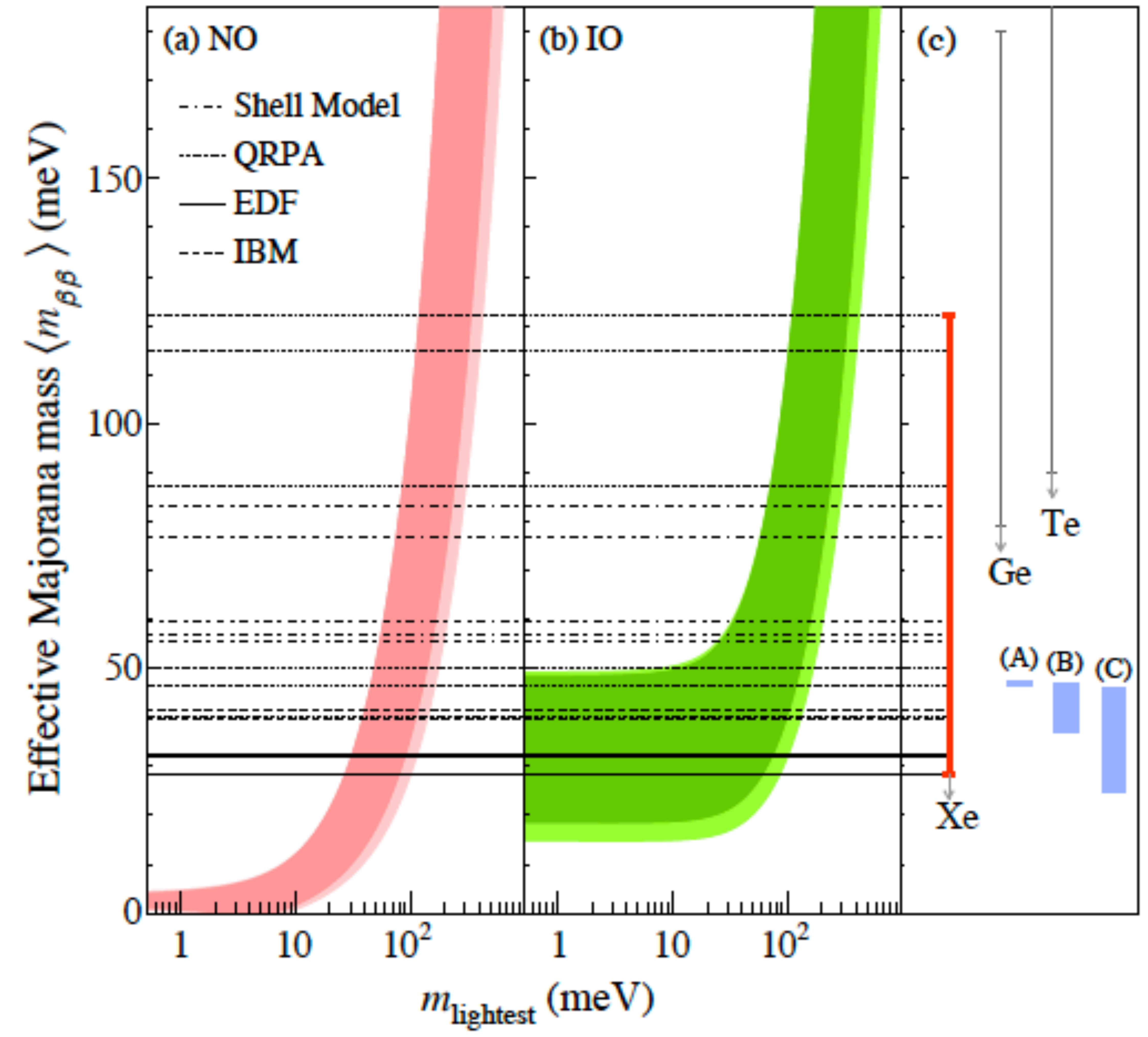
- Kamioka not so deep, very large backgrounds from cosmic muon activation of Xenon nuclei
- Cosmigenic tagging not perfect: fit both tagged and untagged spectra

rate in ROI : 30.0 events/Xe-ton/yr





KAMLAND-ZEN RESULTS



Combined $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ yr

KamLAND-Zen (^{136}Xe)

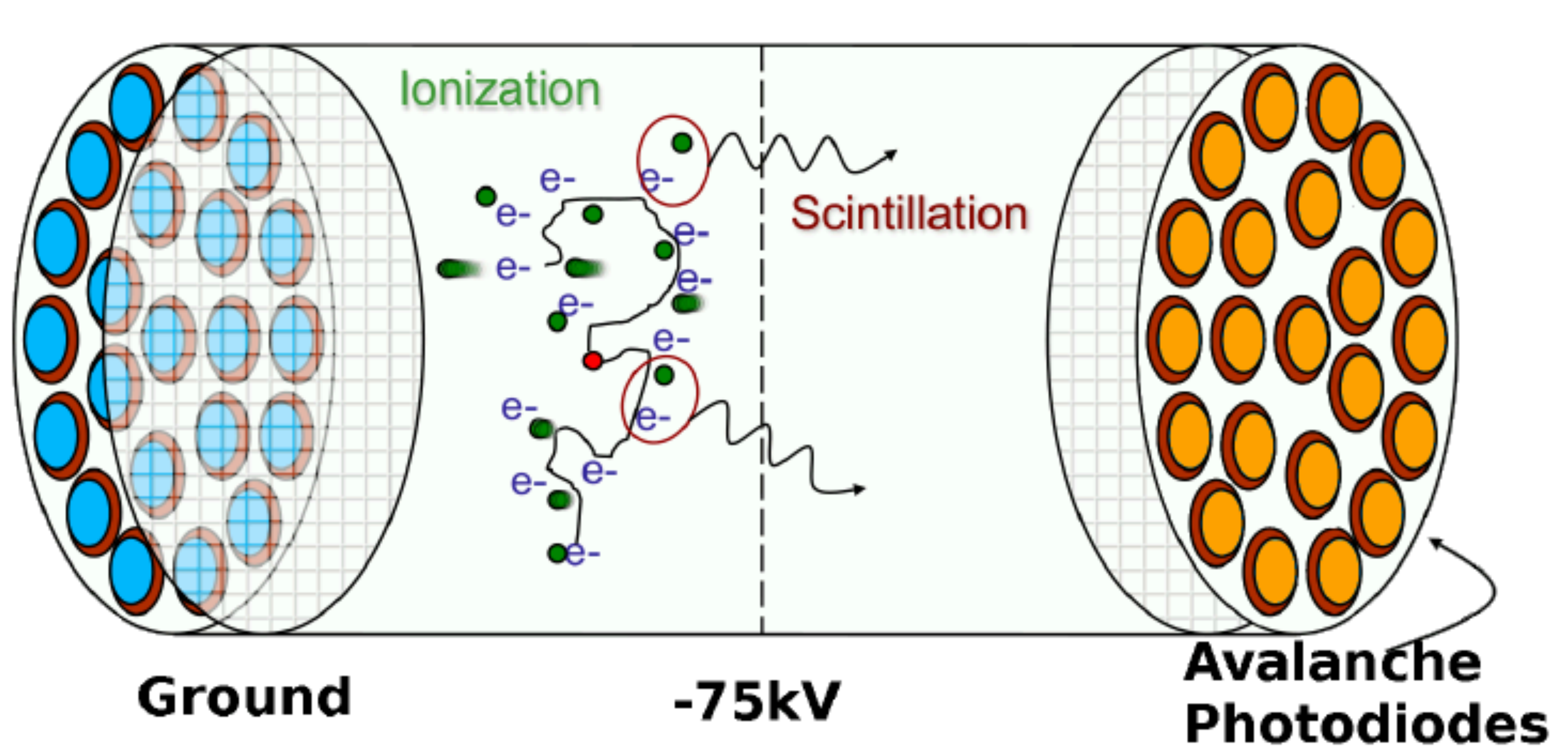
$\langle m_{\beta\beta} \rangle < 28\text{–}122$ meV

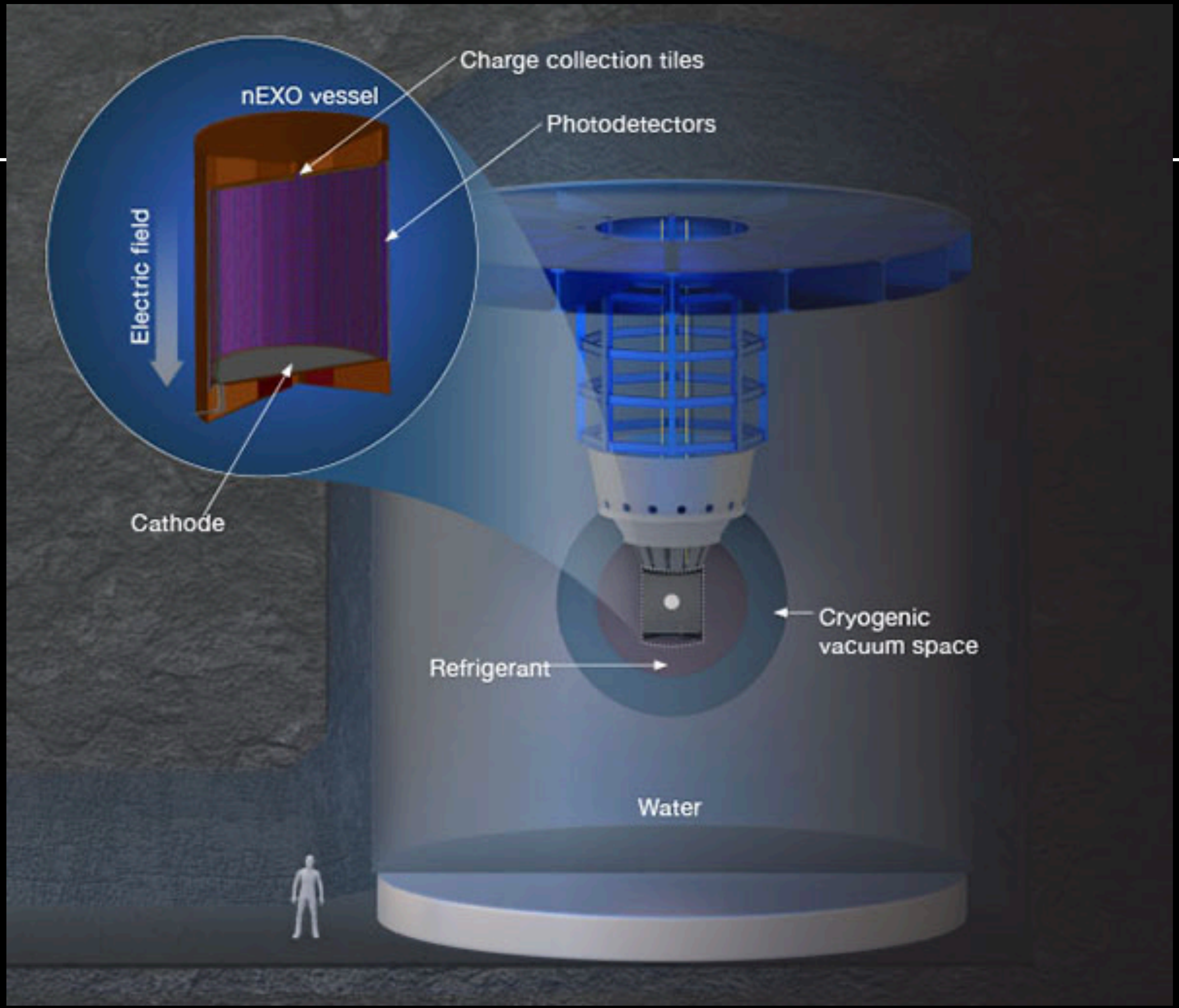
$m_{lightest} < 84\text{–}353$ meV

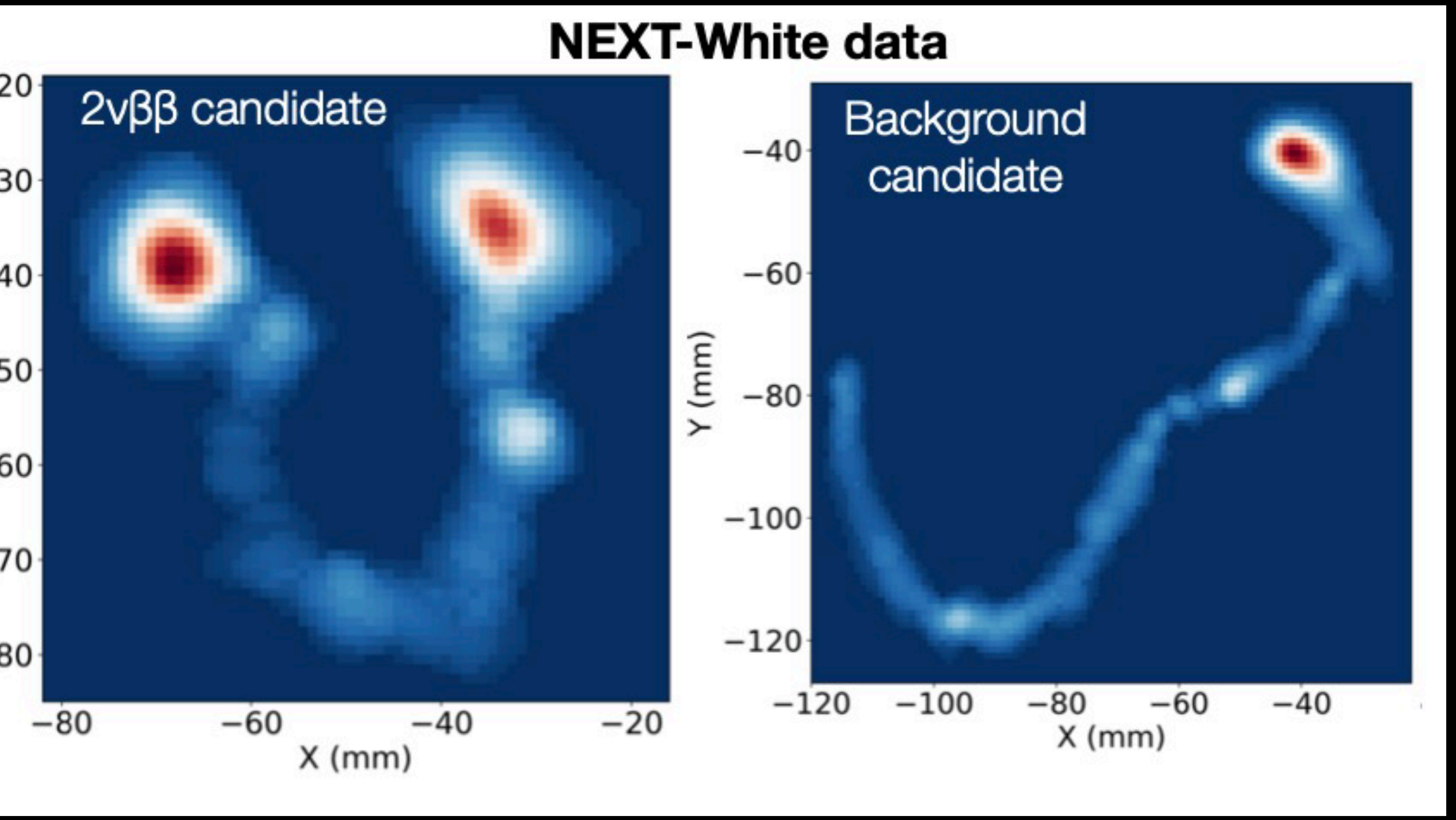
- Leading result from KamLAND-Zen due to high mass
- Probing well into the IO region, depending on nuclear matrix elements

NLDBD FUTURE EXPERIMENTS

XENON TPCS







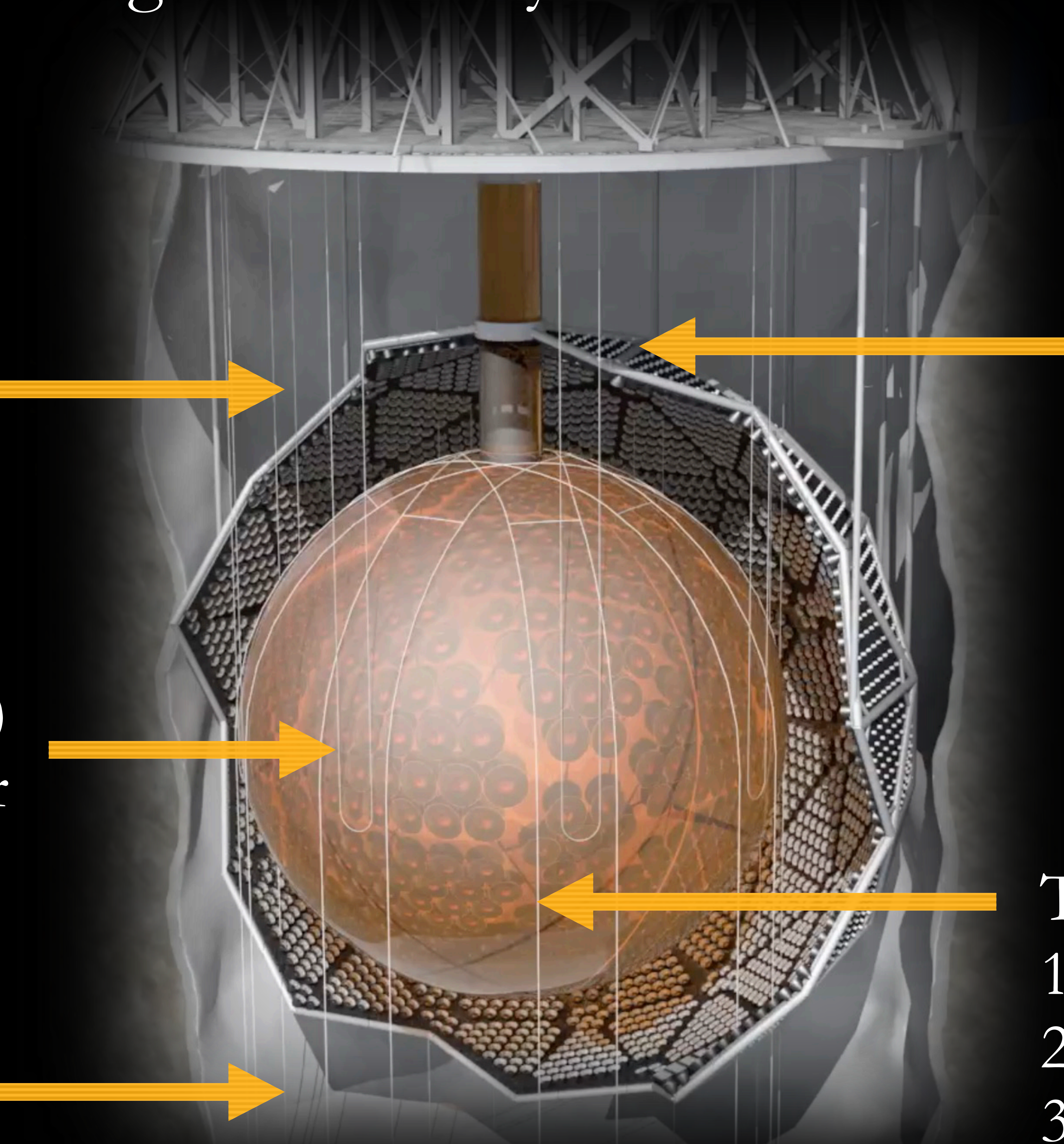
- Future projects
  - Nexo: 5 tons liquid Xenon, enriched
    - based on EXO-200 design (200 kg, 80% enriched). T1/2> 3.5x1025 y (90% C.L.)
  - Next: High Pressure gas TPC
    - topological separation

THE SNO+ EXPERIMENT

Repurposing the Sudbury Neutrino Observatory (SNO) detector

2 km underground
~70 muons/day

Rope system
Hold-up and -down
Low Radioactivity



~9300 PMTs

Acrylic Vessel (AV)
12 m diameter

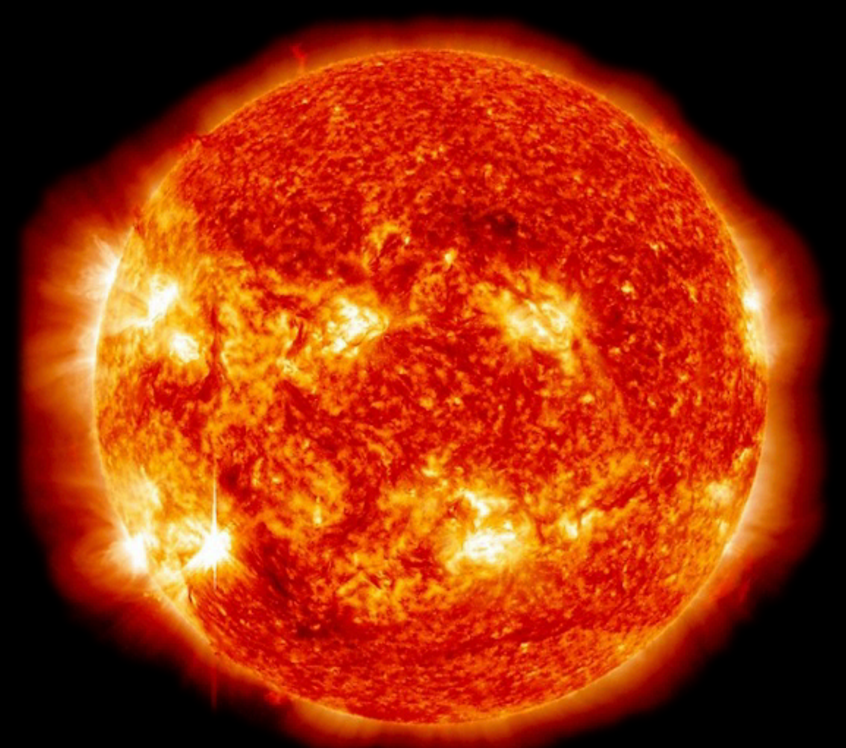
Purification plant

Ultra-Pure
Water

Target Material

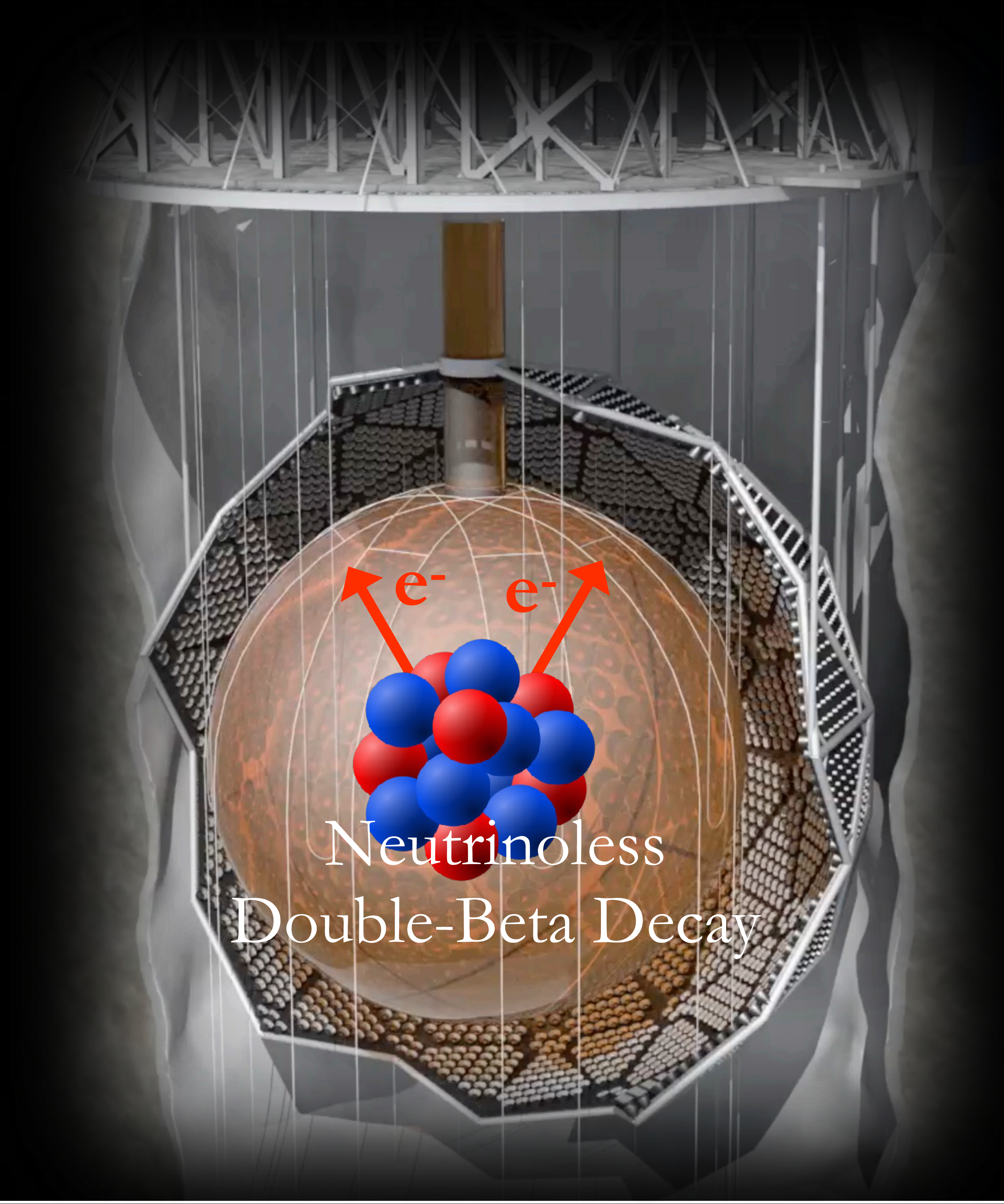
1. Water: 905 tonnes
2. LAB Scintillator: 780 tonnes
3. Tellurium loading: +3.9 tonnes

THE SNO+ EXPERIMENT



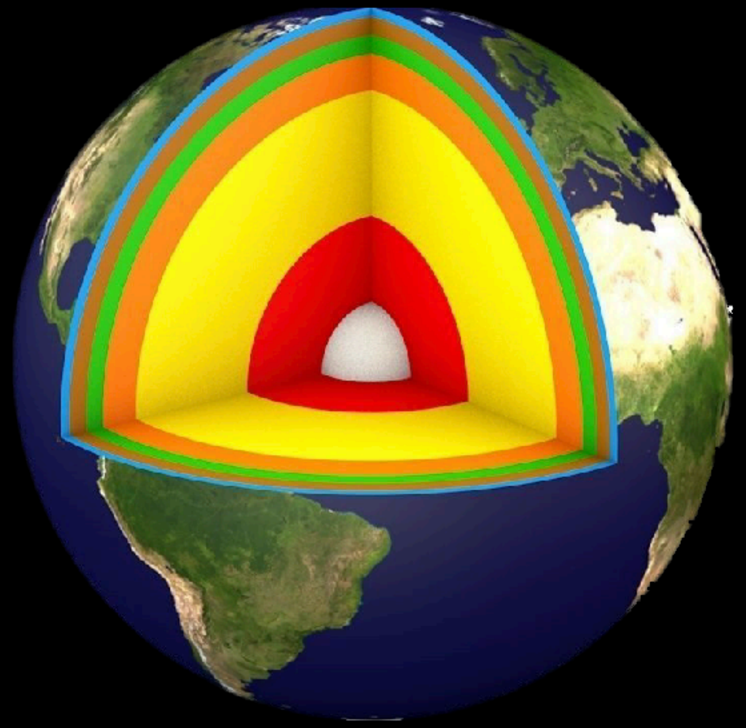
Solar Neutrinos

Reactor Neutrinos



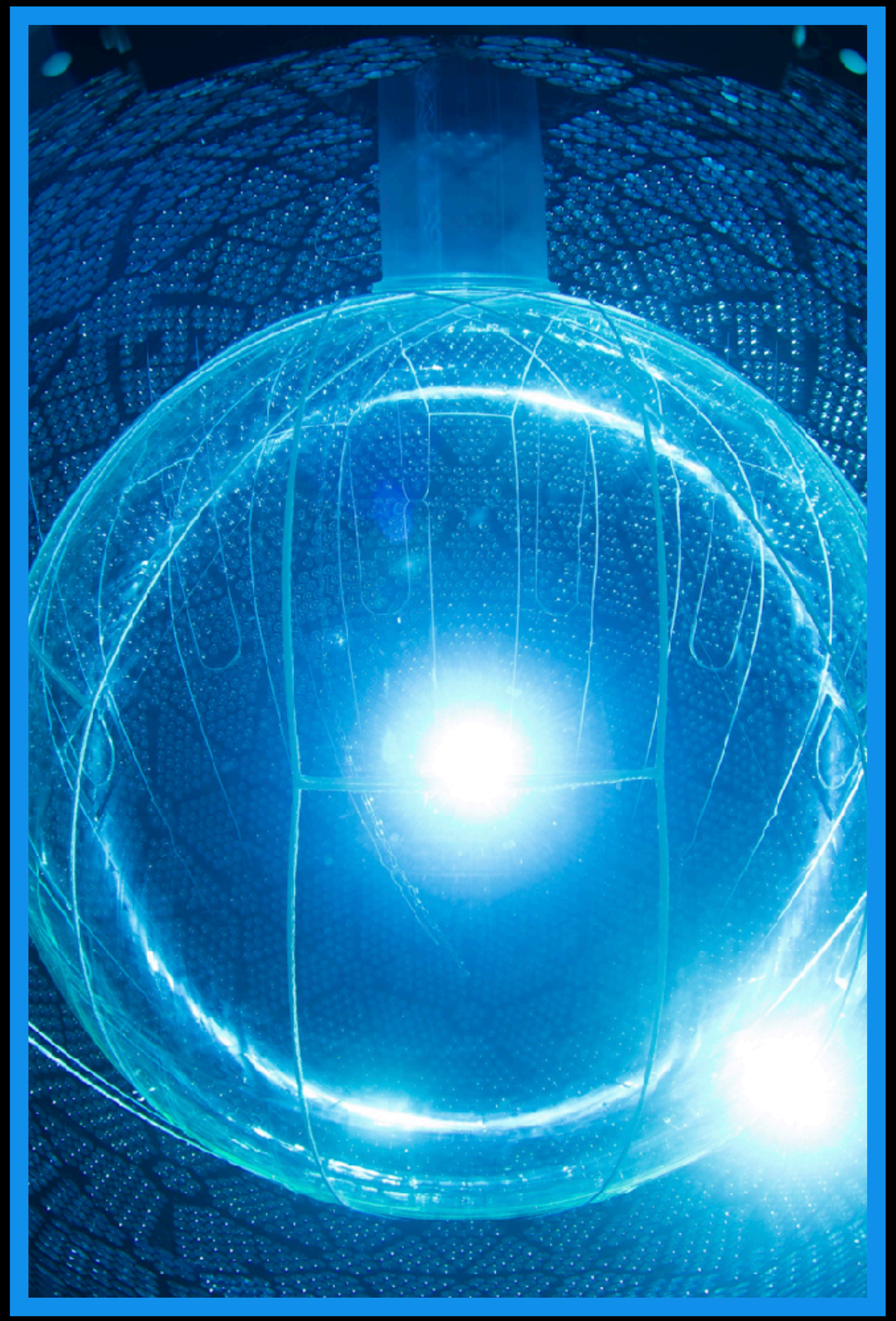
Supernova Neutrinos
+ exotics

Geo-Neutrinos

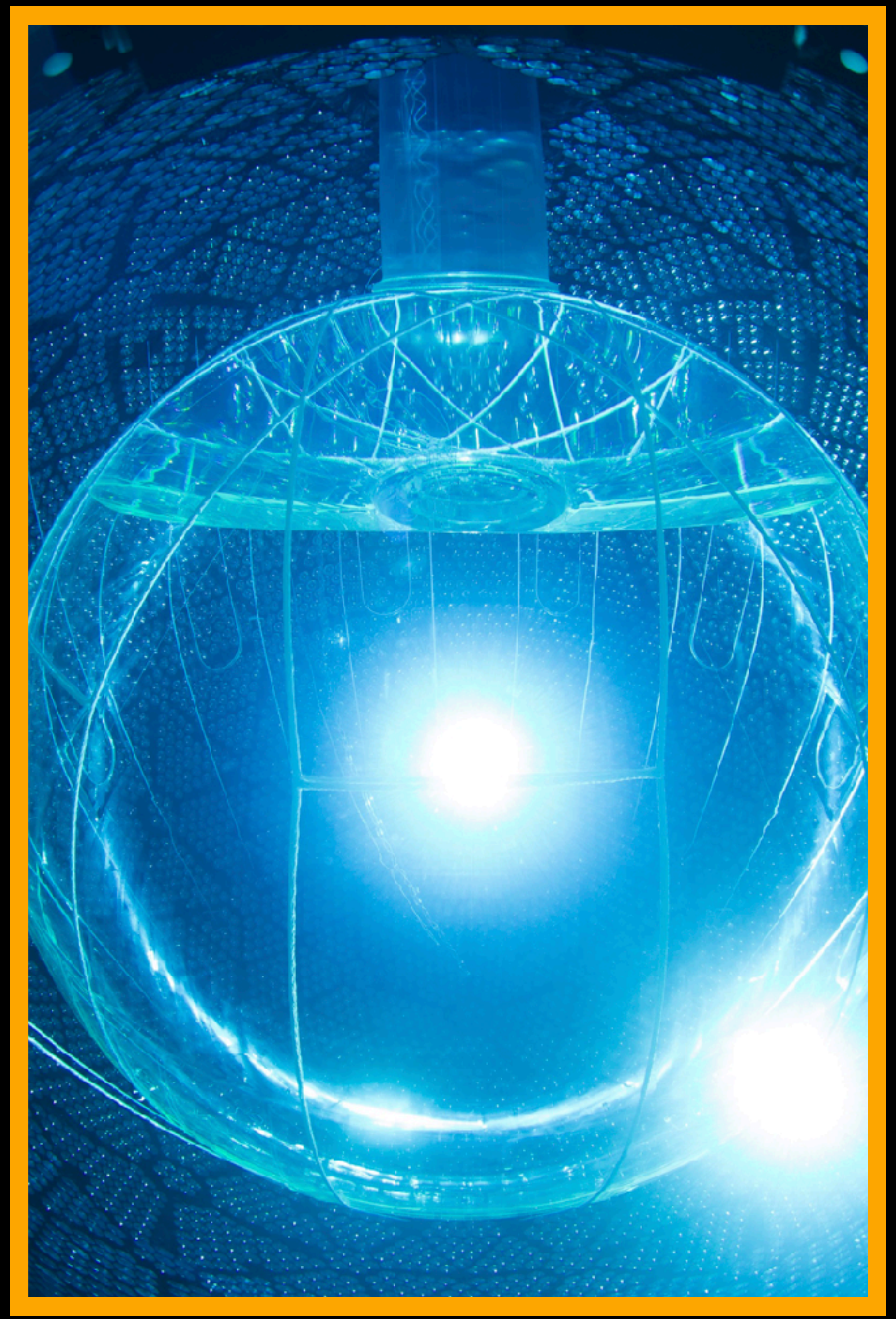


SNO+ TIMELINE

2017 2018 2019 2020 2021 2022 2023 2024 2025



Water phase
- High Rn
- Low Rn



Partial fill phase

Scintillator over water.

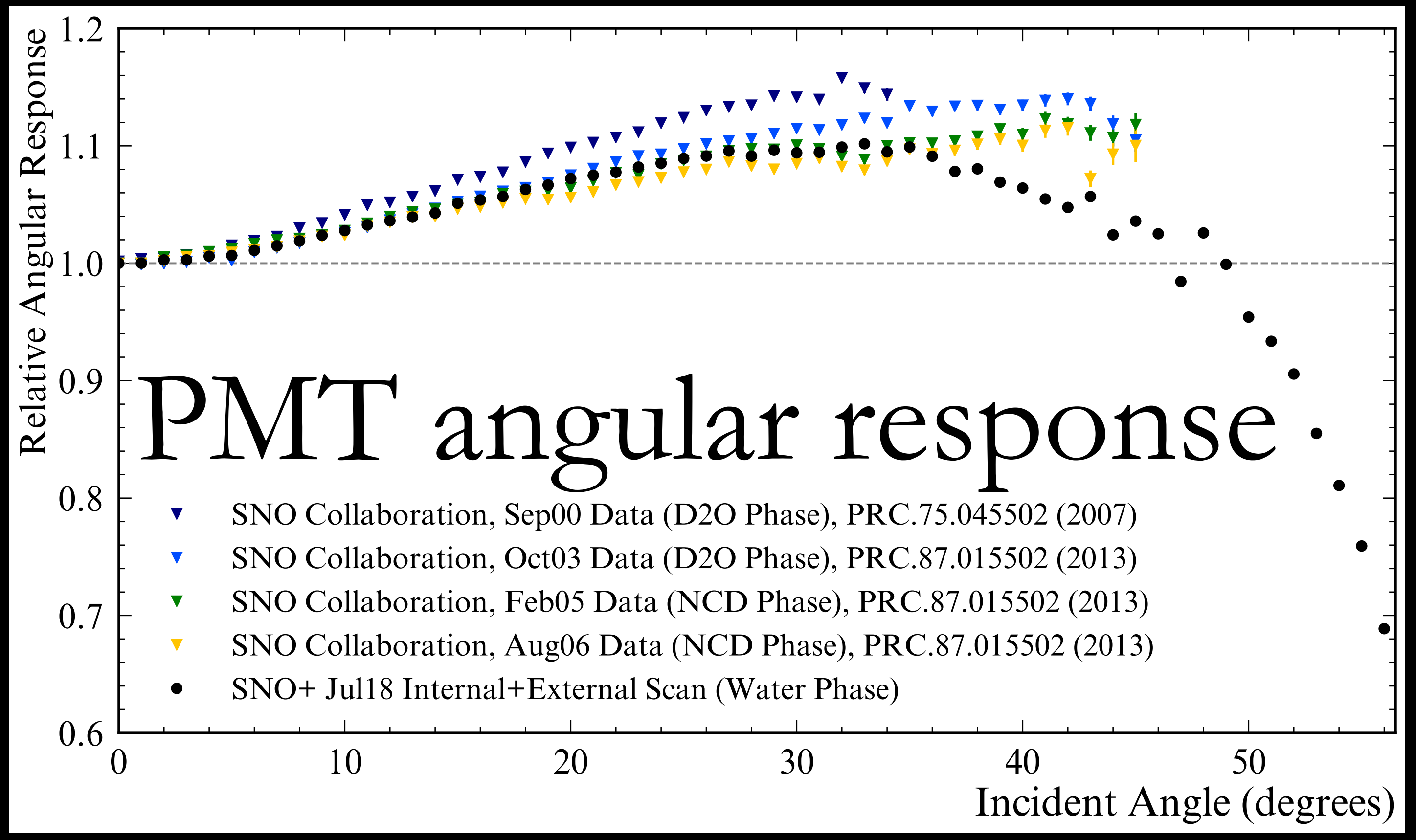
Stop in fill due to Covid.

Scintillator phase
- Low PPO
- Nominal PPO
- Added bis-MSB

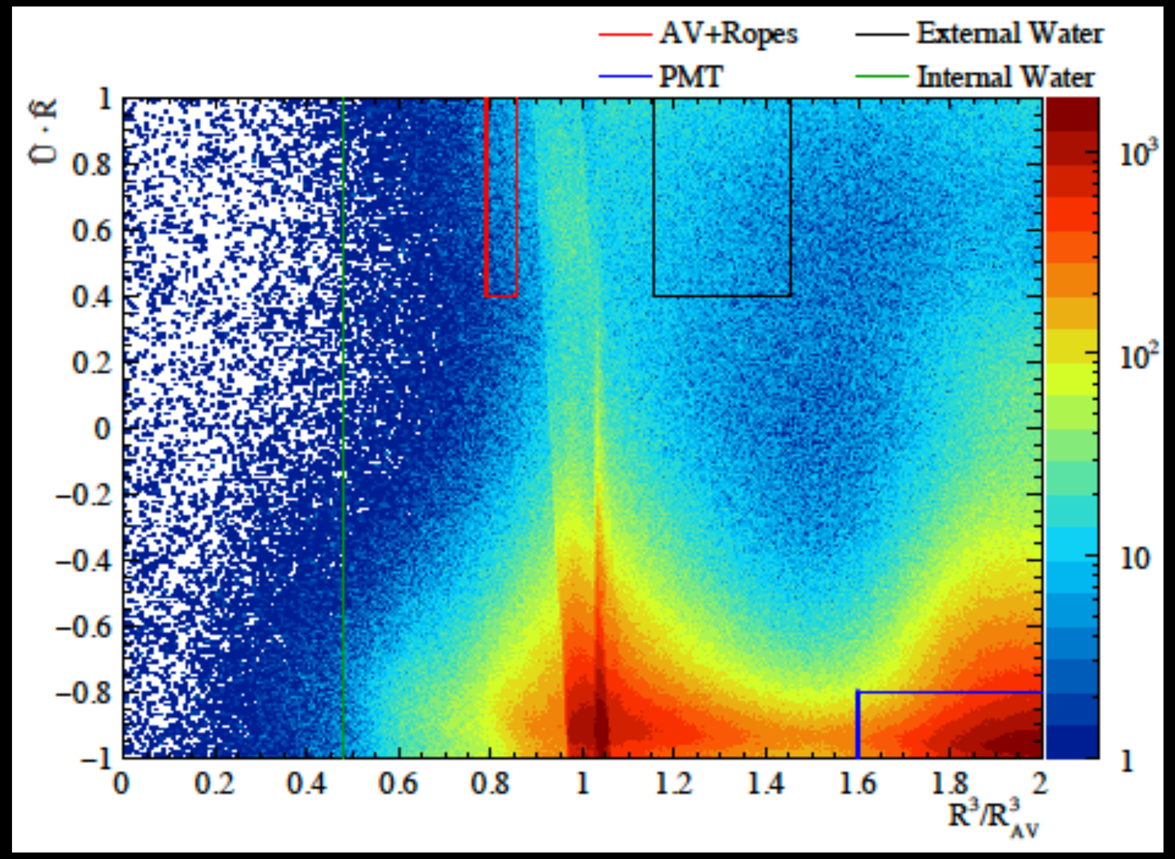
Next: Tellurium-loaded phase

SNO+ PERFORMANCE

- Water Phase
  - Extensive calibrations: well-tuned detector model
  - Constraints on external backgrounds: smaller than nominal

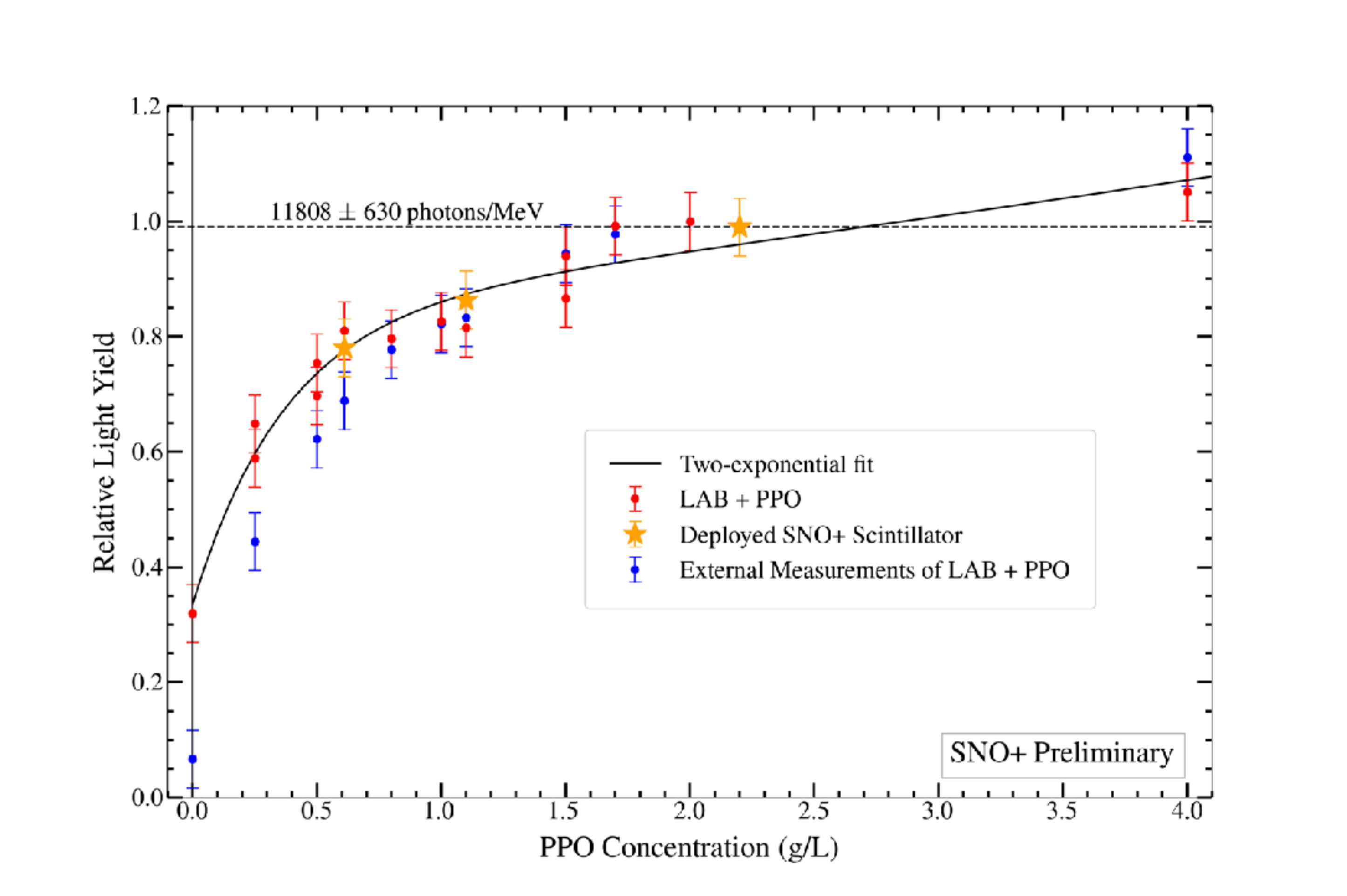


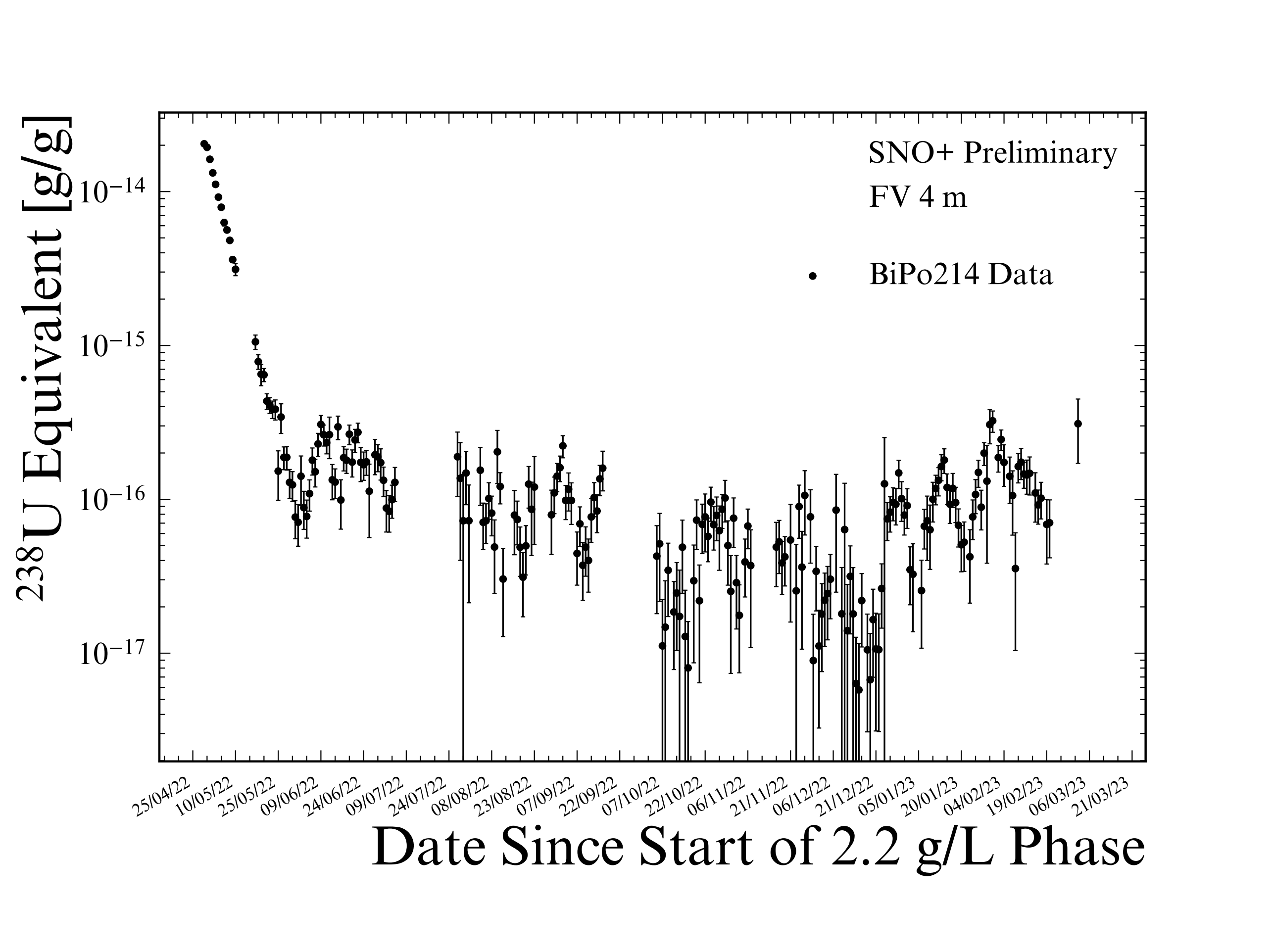
In/Out Direction



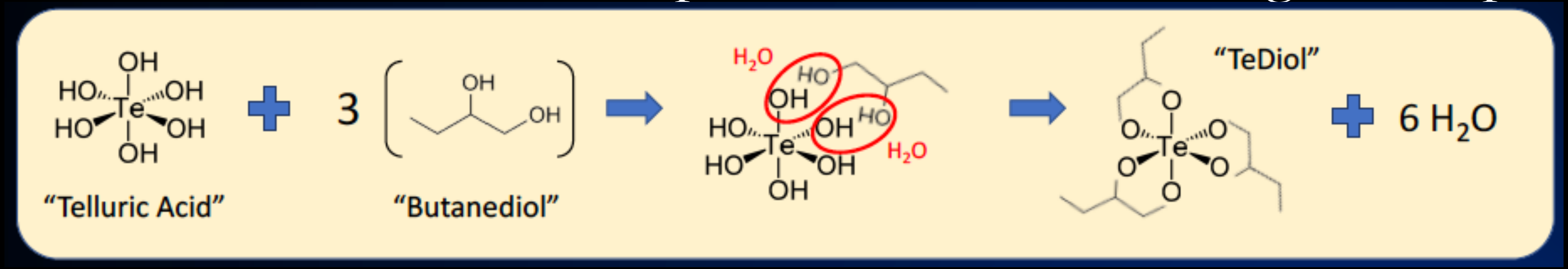
Radial Position

- Scintillator Phase
  - Tracking background and light levels throughout operations
  - High but decreasing level of Po210
  - BiPo214/212 segments of Uranium and Thorium chains at low level:
    - Eq. ^{238}U ~4.3×10^{-17} g/g
    - Eq. ^{232}Th ~5.3×10^{-17} g/g

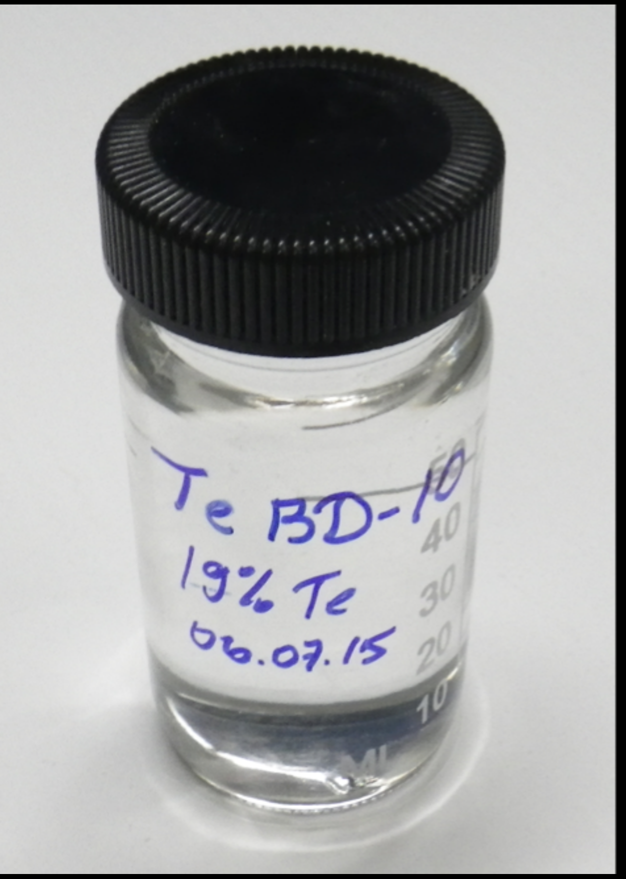




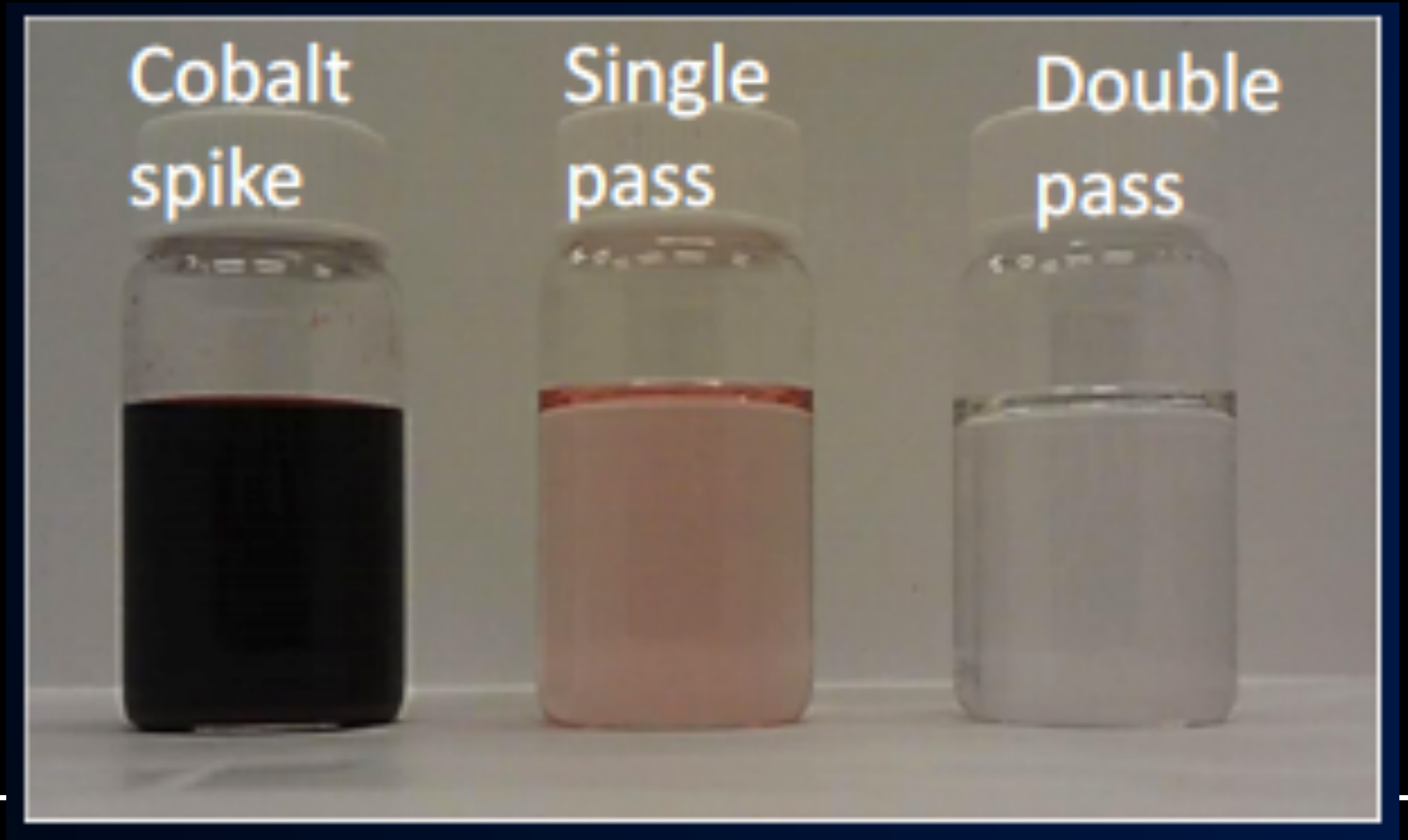
- Overall approach
  - Develop a way to load Tellurium in a large liquid scintillator detector
  - Highest abundance isotope -> high mass (1333kg of ^{130}Te at 0.5% loading)
  - Scintillator purifiable, detector is large and can use fiducial volume -> low backgrounds!
- Chemical methods for purification and loading developed by SNO+



Tellurium-butanediol complex (TeBD)+ water (evaporate after synthesis)

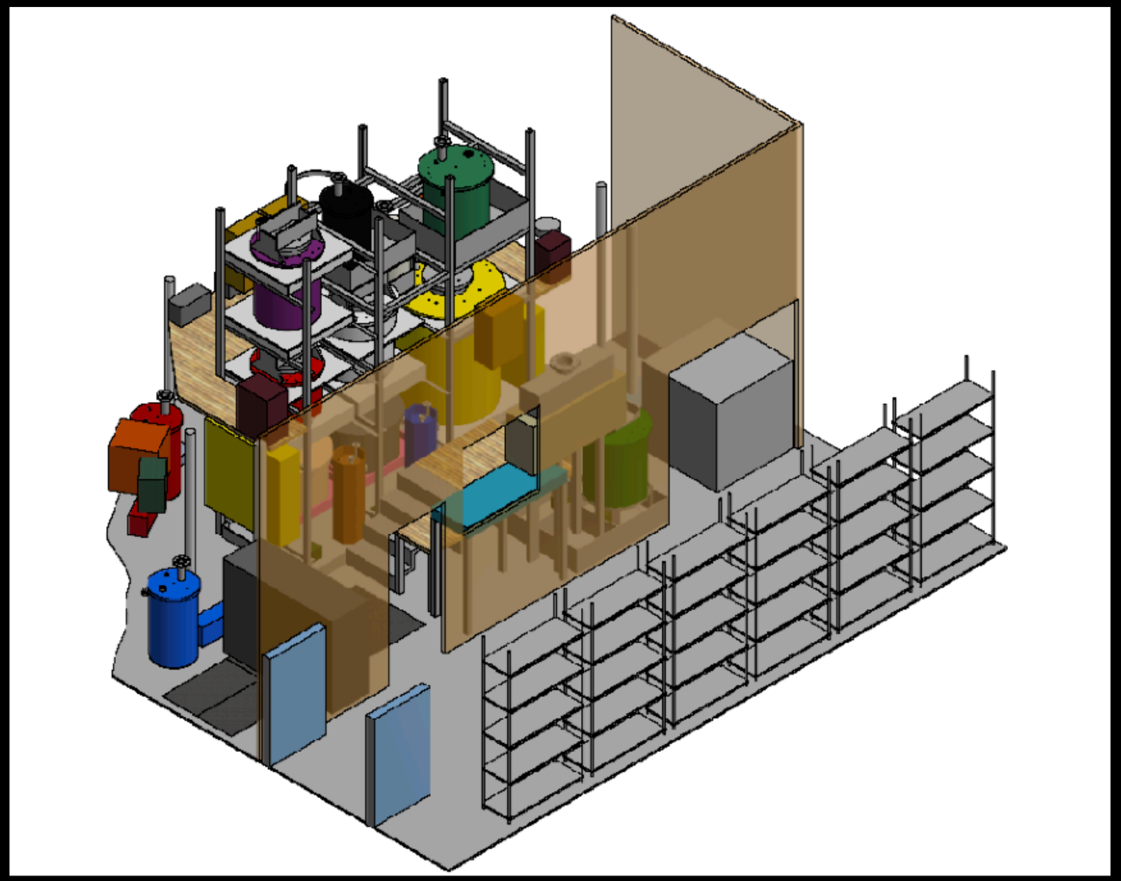


- TeBD very transparent and soluble in liquid scintillator. Expect 400 p.e./MeV
- Purification by dissolving Te acid in water and force recrystalization. Impurities stay in water.

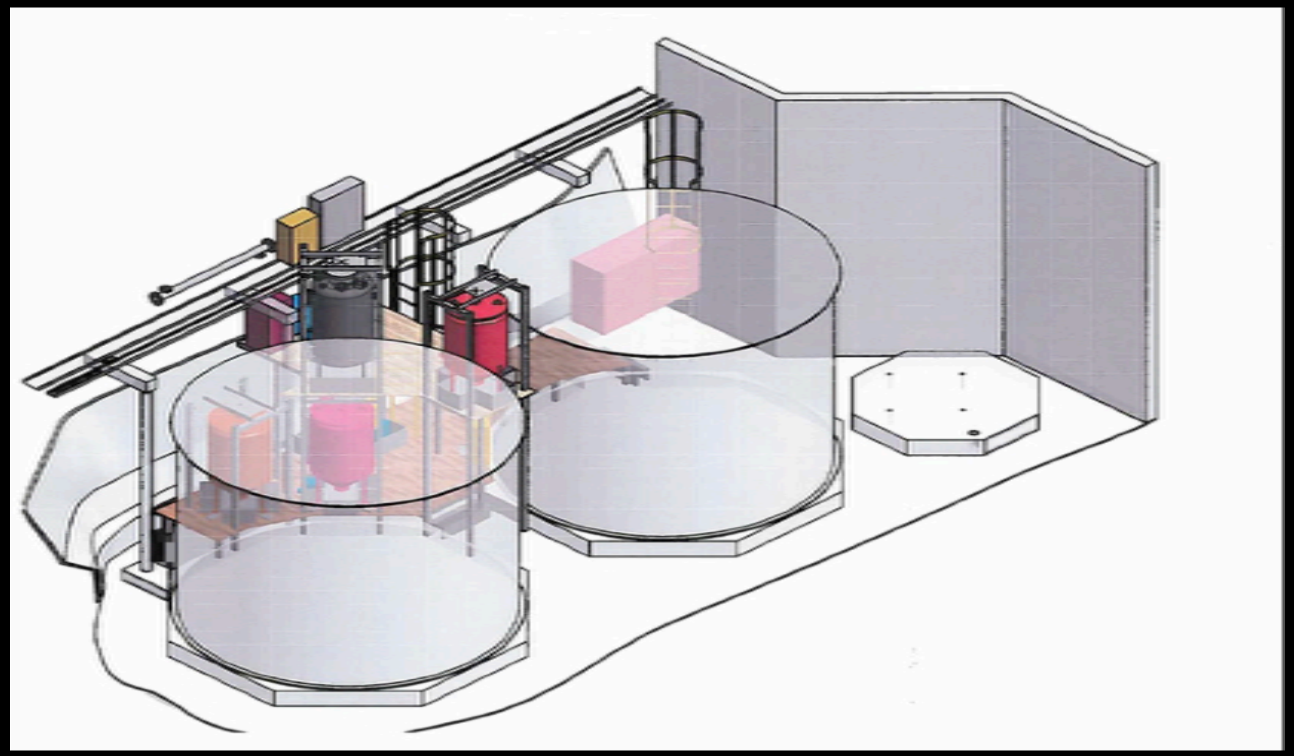


TELLURIUM SYSTEMS

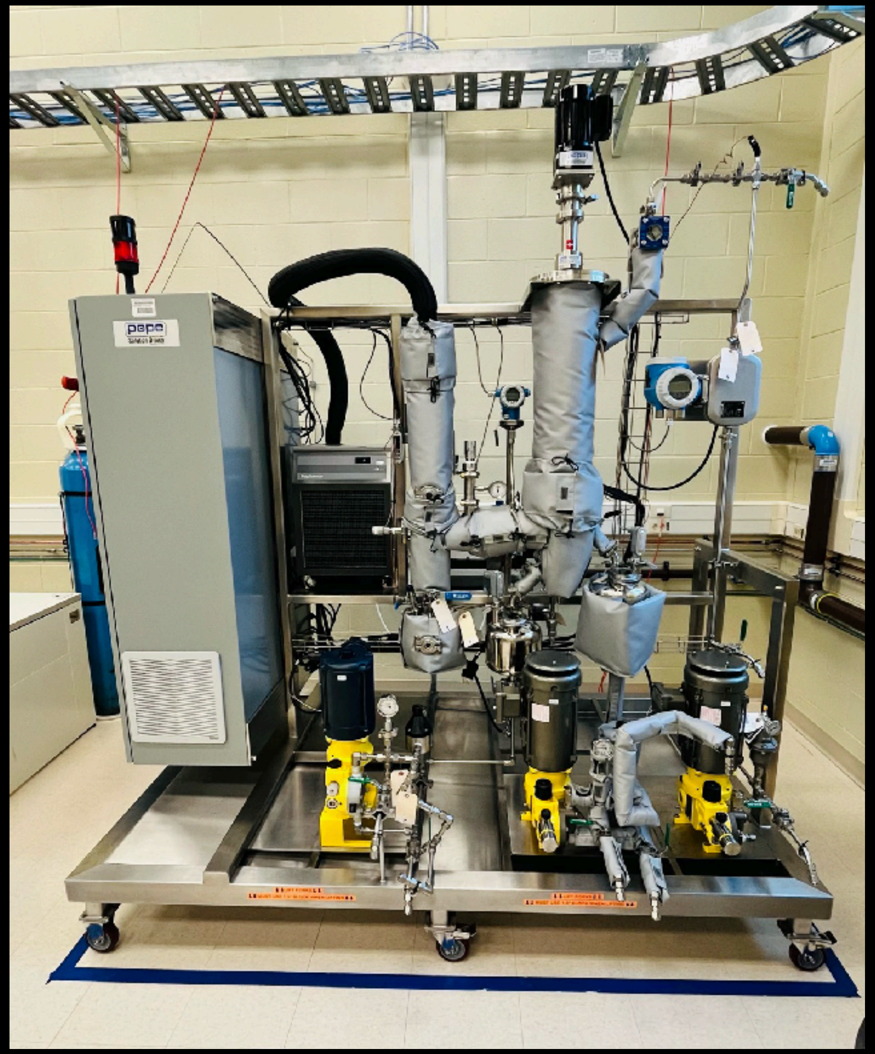
Te acid purification (UG)



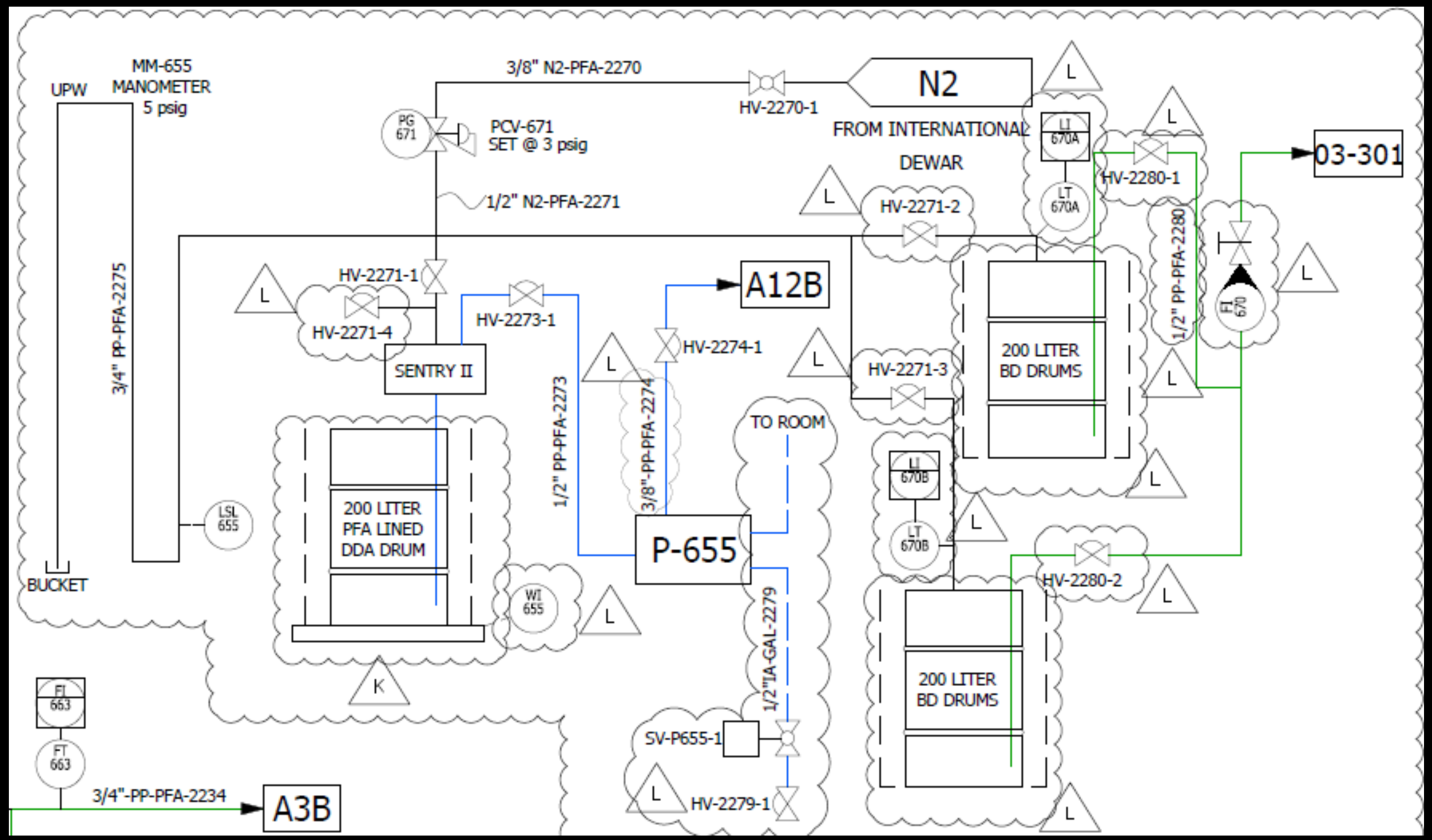
Te diol synthesis (UG)



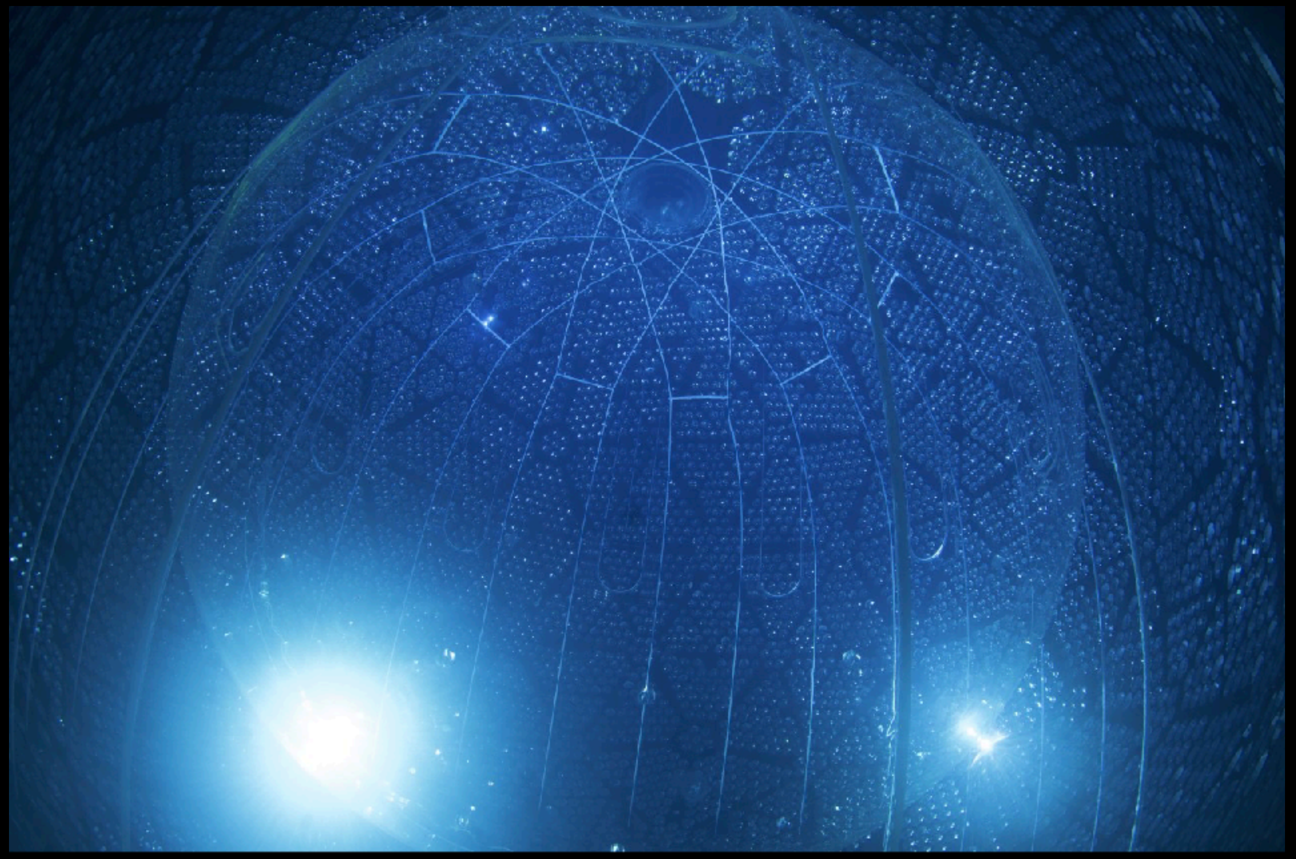
DDA distillation (surface)



DDA surface to UG transfer



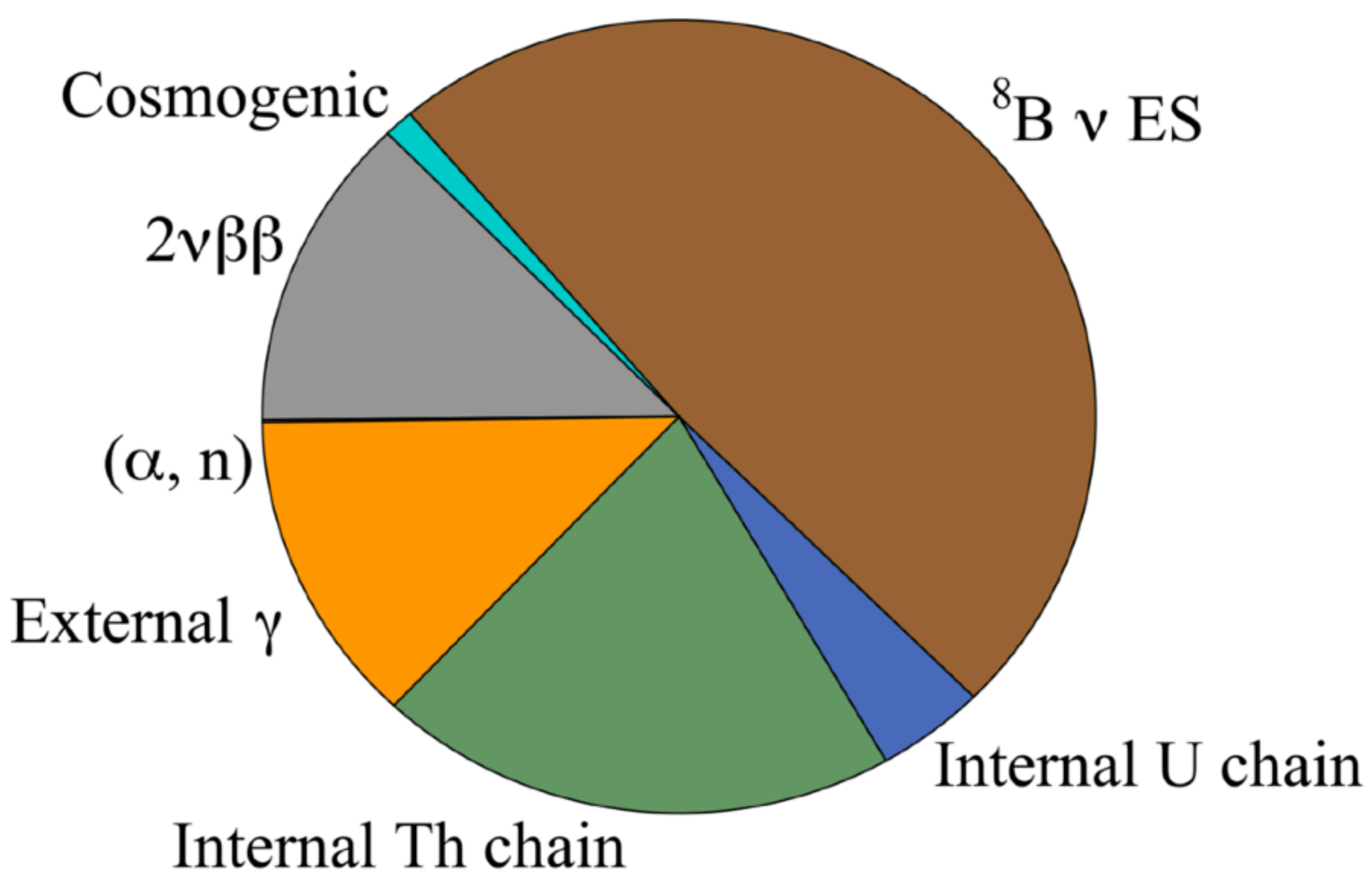
AV

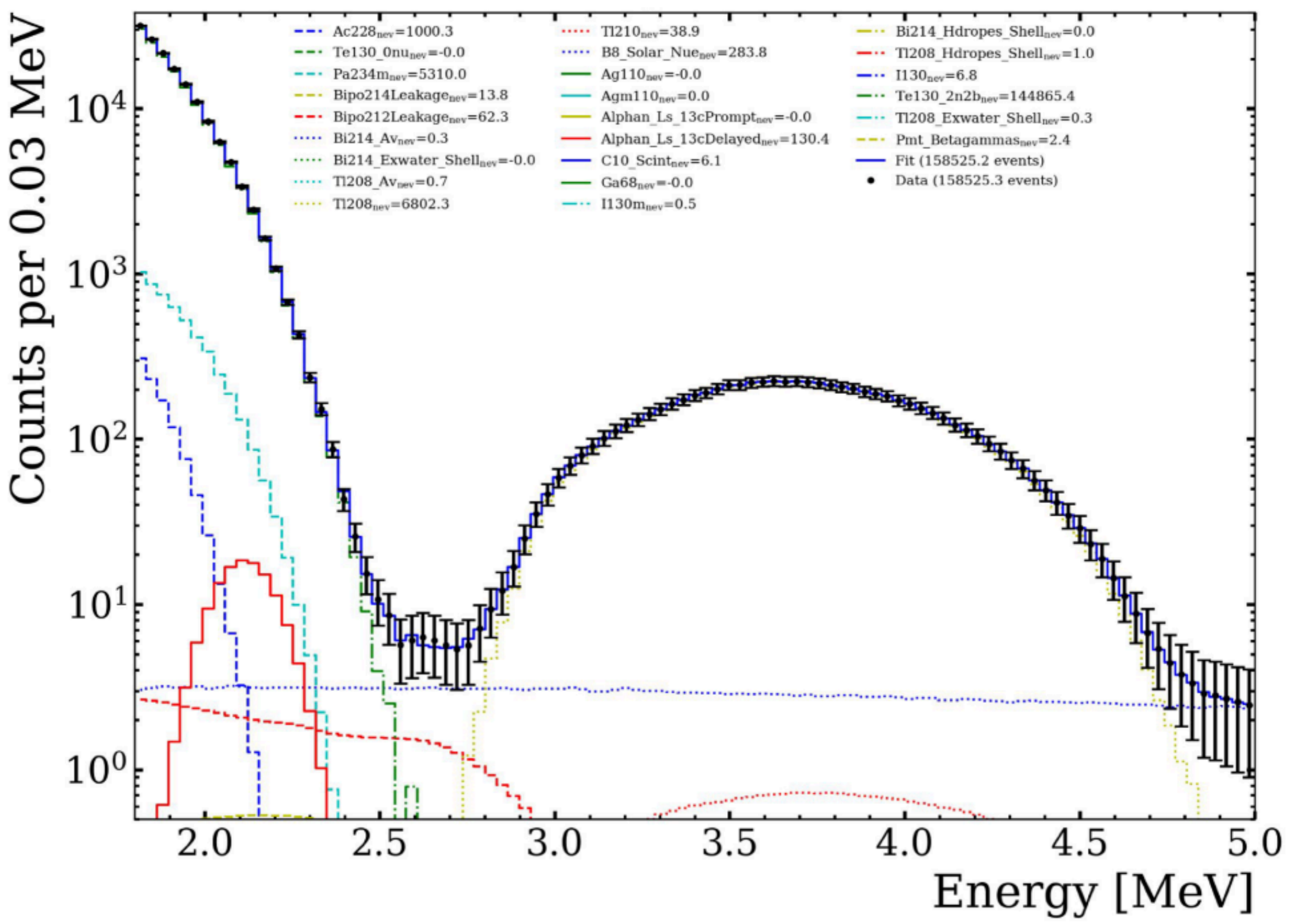


SNO+ DBD SENSITIVITY

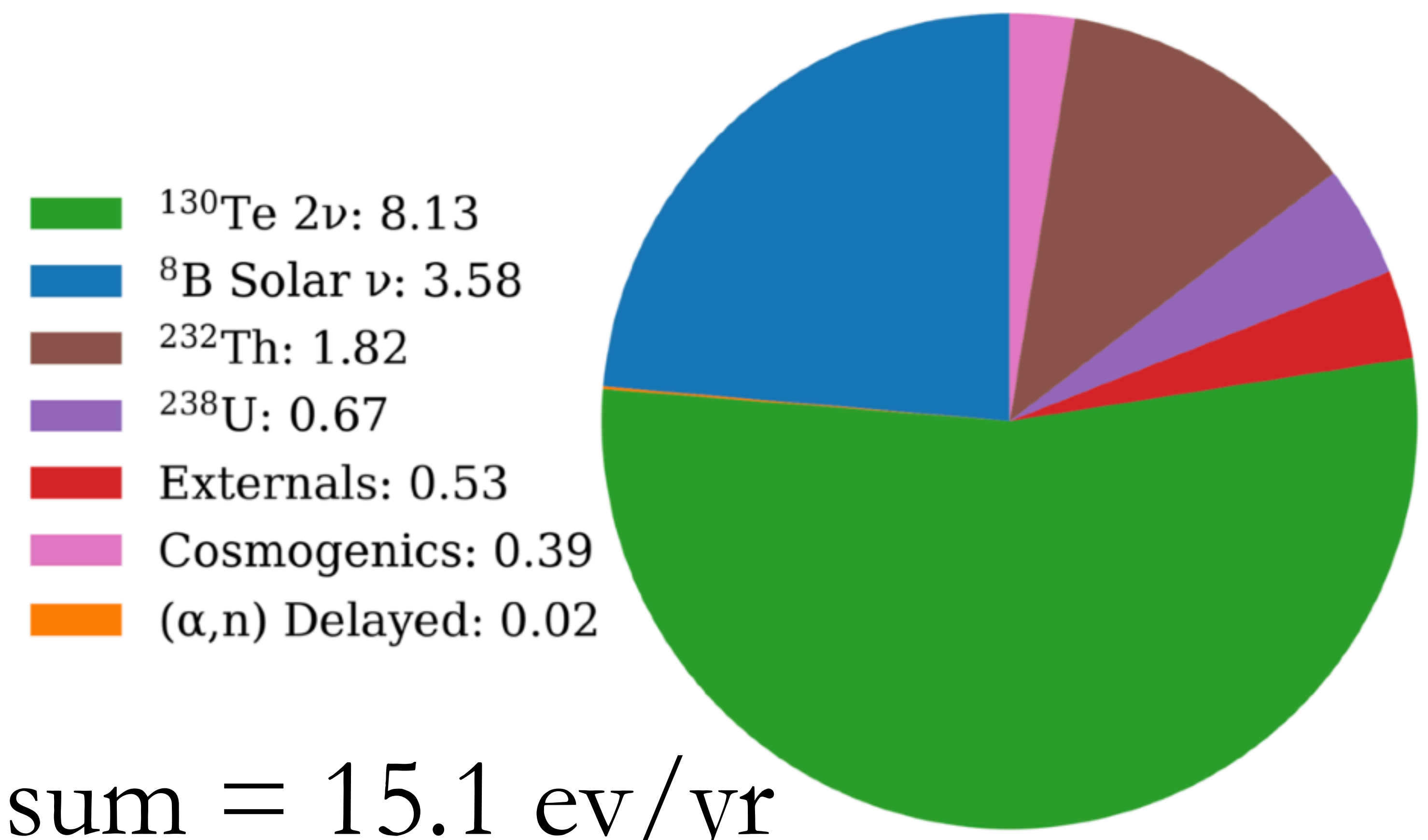
- Water phase constrained external backgrounds
- Scintillator phase constrained several internal backgrounds
- Other expectations based **conservatively** on raw purity and purification factors

initial 0.5% loading





1.5% loading

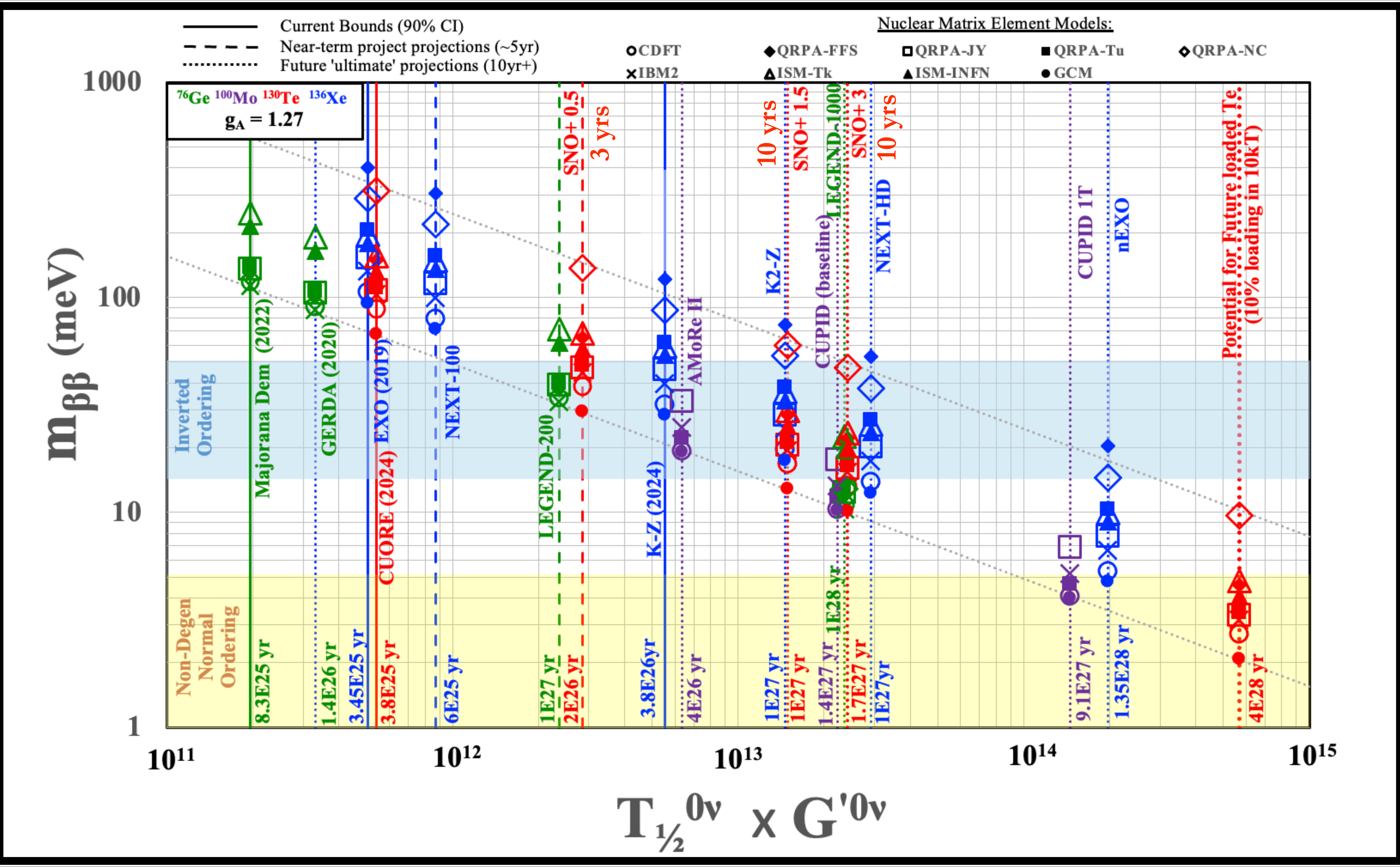


sum = 15.1 ev/yr

$T_{1/2} > 2 \cdot 10^{26}$ yrs, 90% C.L. 3 yrs

$T_{1/2} > 5 \cdot 10^{26}$ yrs, 90%C.L., 5 yrs

SNO+ IN CONTEXT

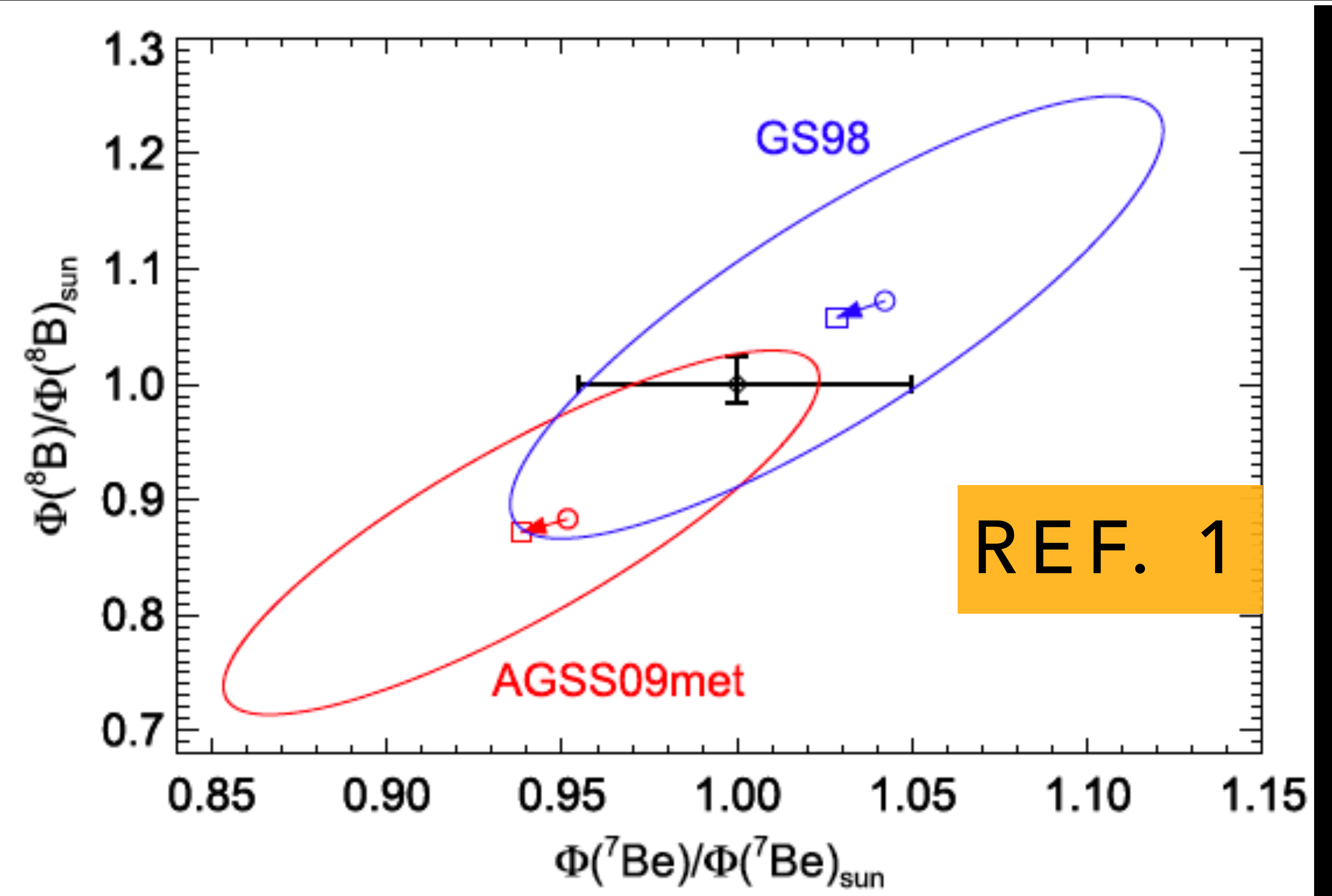


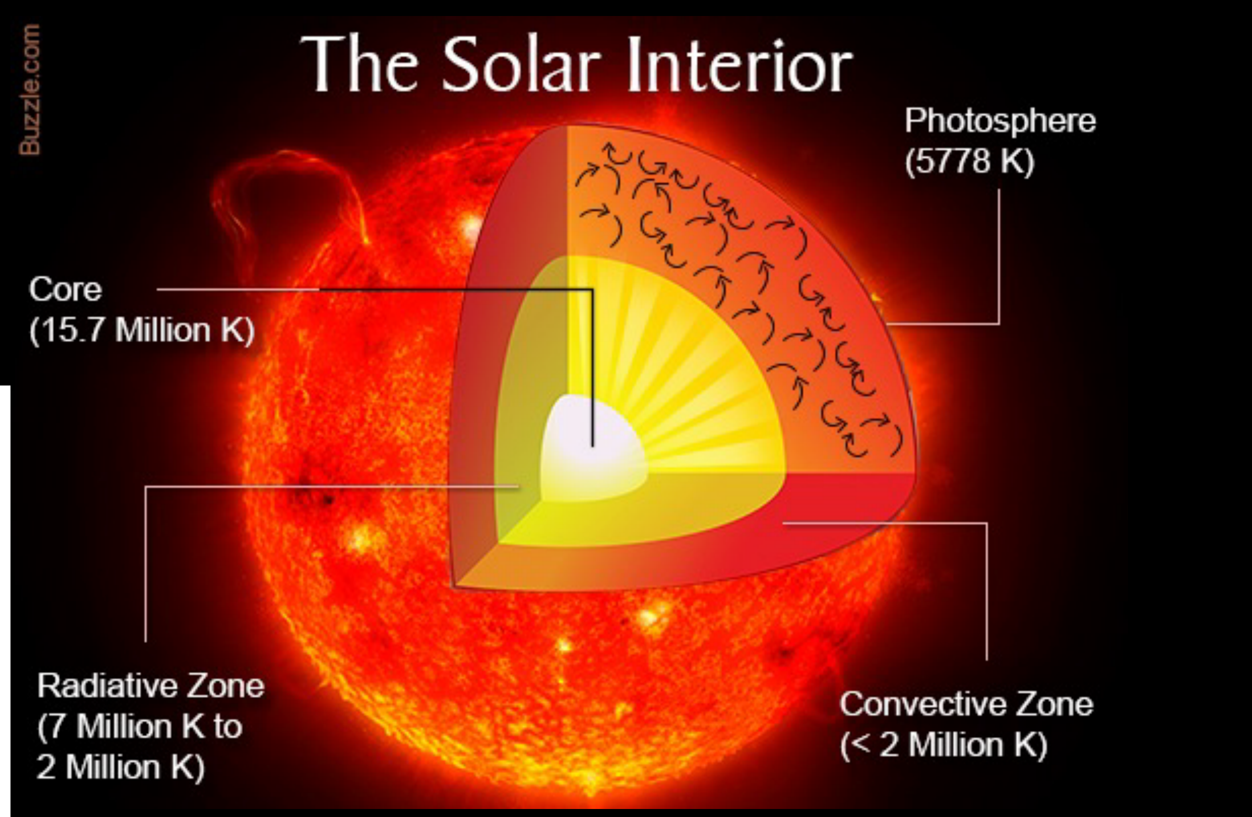
NEUTRINOS IN ASTROPHYSICS

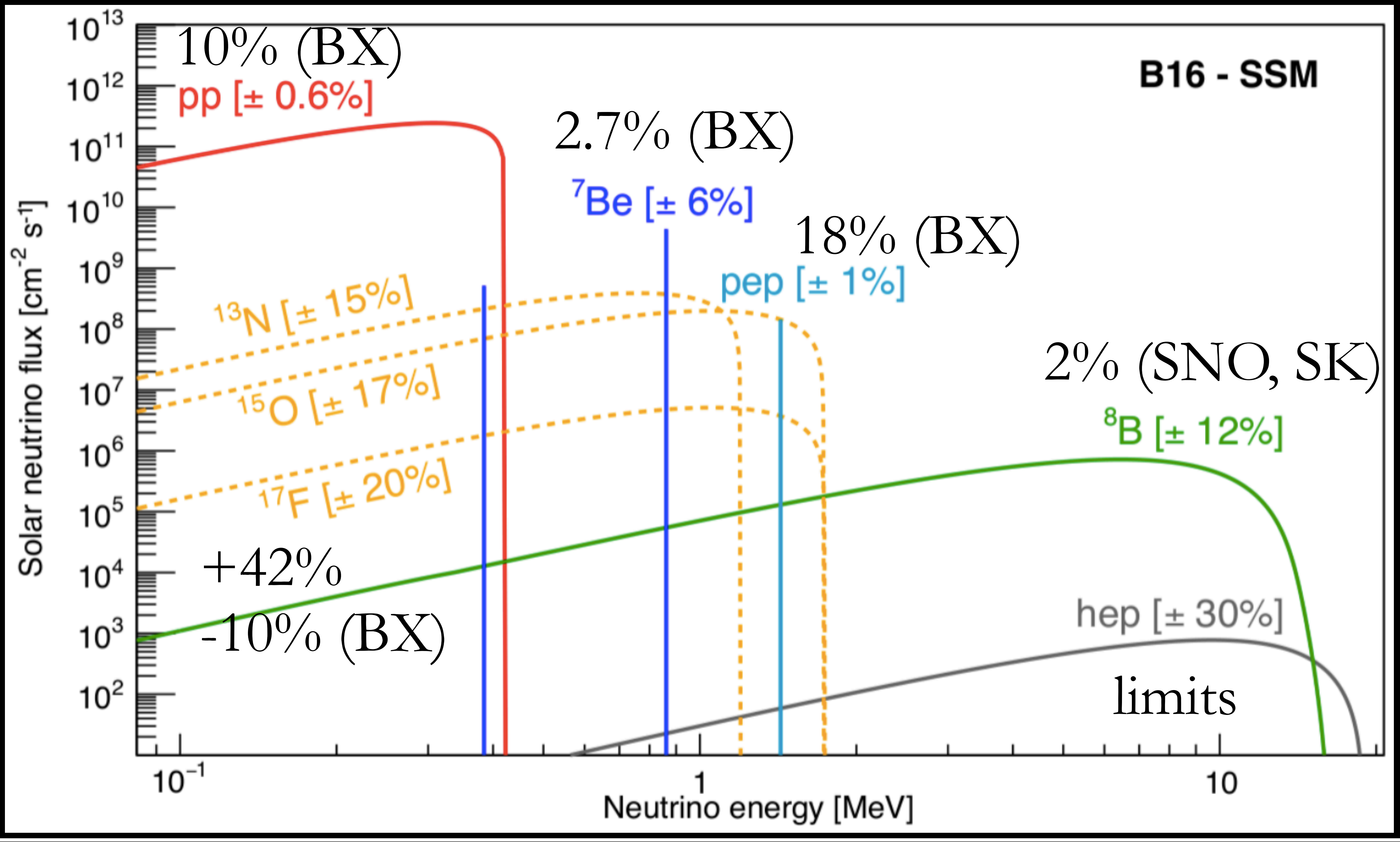
SOLAR NEUTRINOS

NEUTRINOS AS A PROBE OF THE SUN

- Solar neutrino observations
  - Sun burns via pp chain (99%), CNO cycle (1%) ✓
- Sun's composition still uncertain. Two classes of solar models high or low metallicity Z [abundances X: H, Y: He, Z: Li, …]
  - HighZ favored by helioseismology

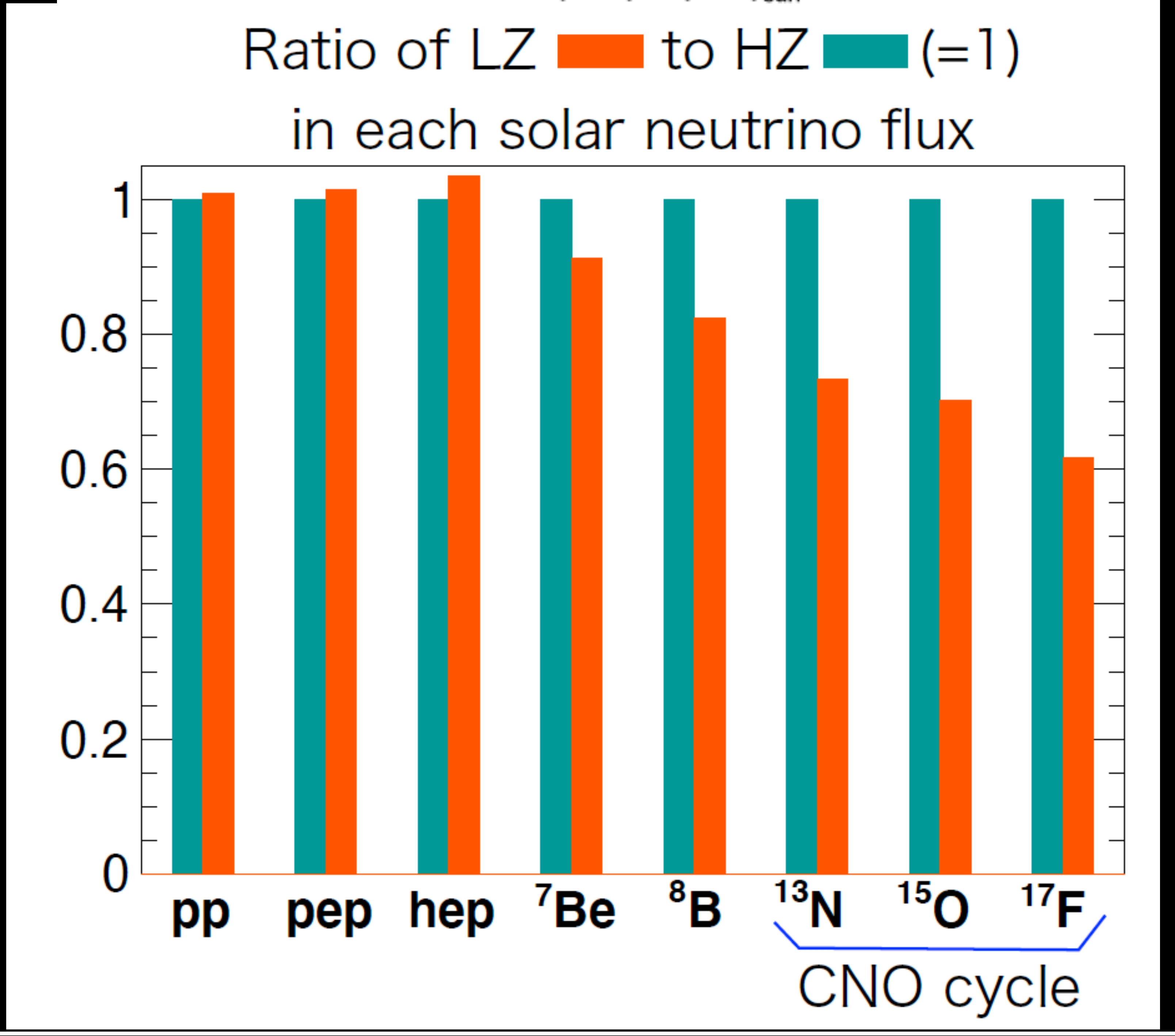




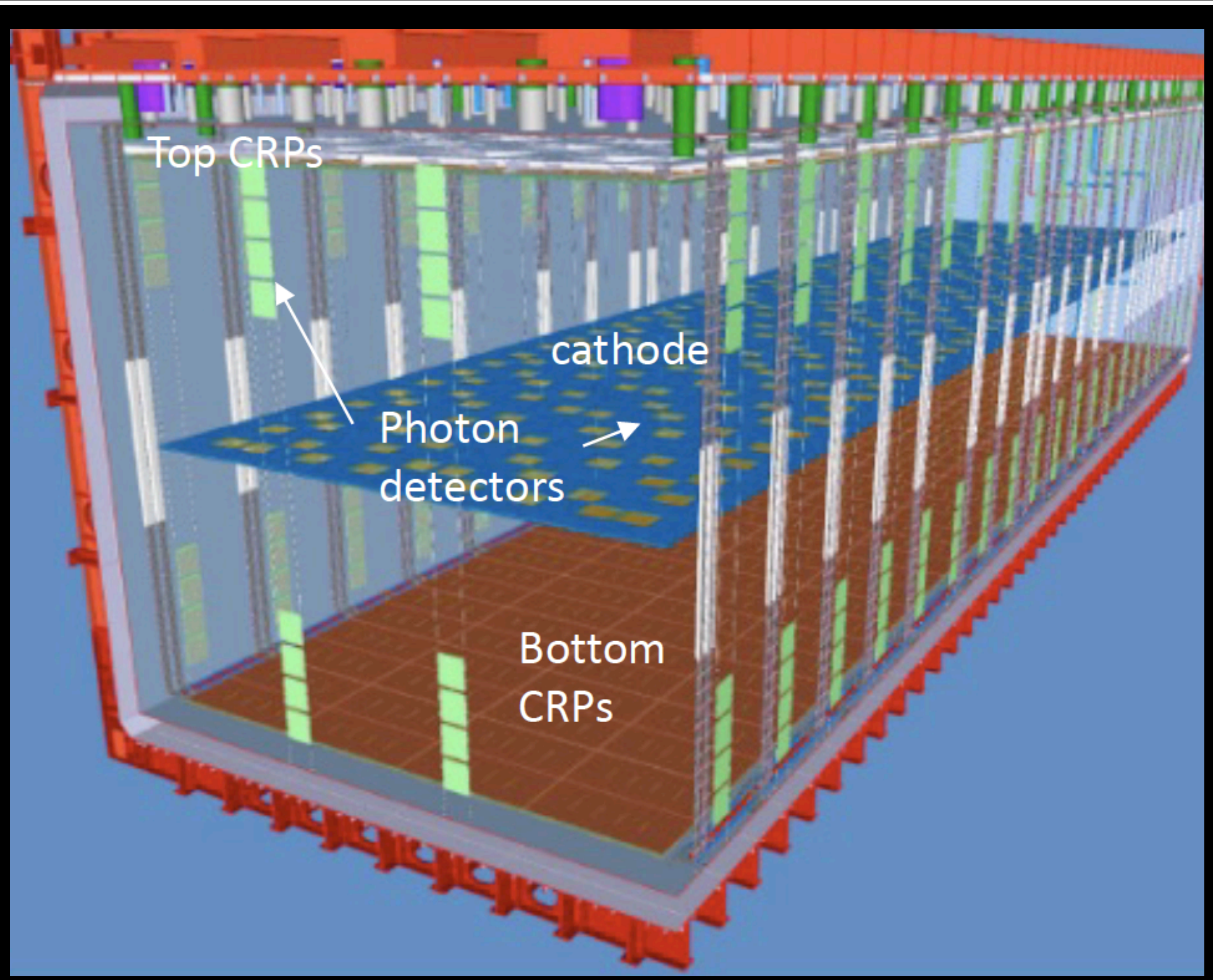


Questions ?

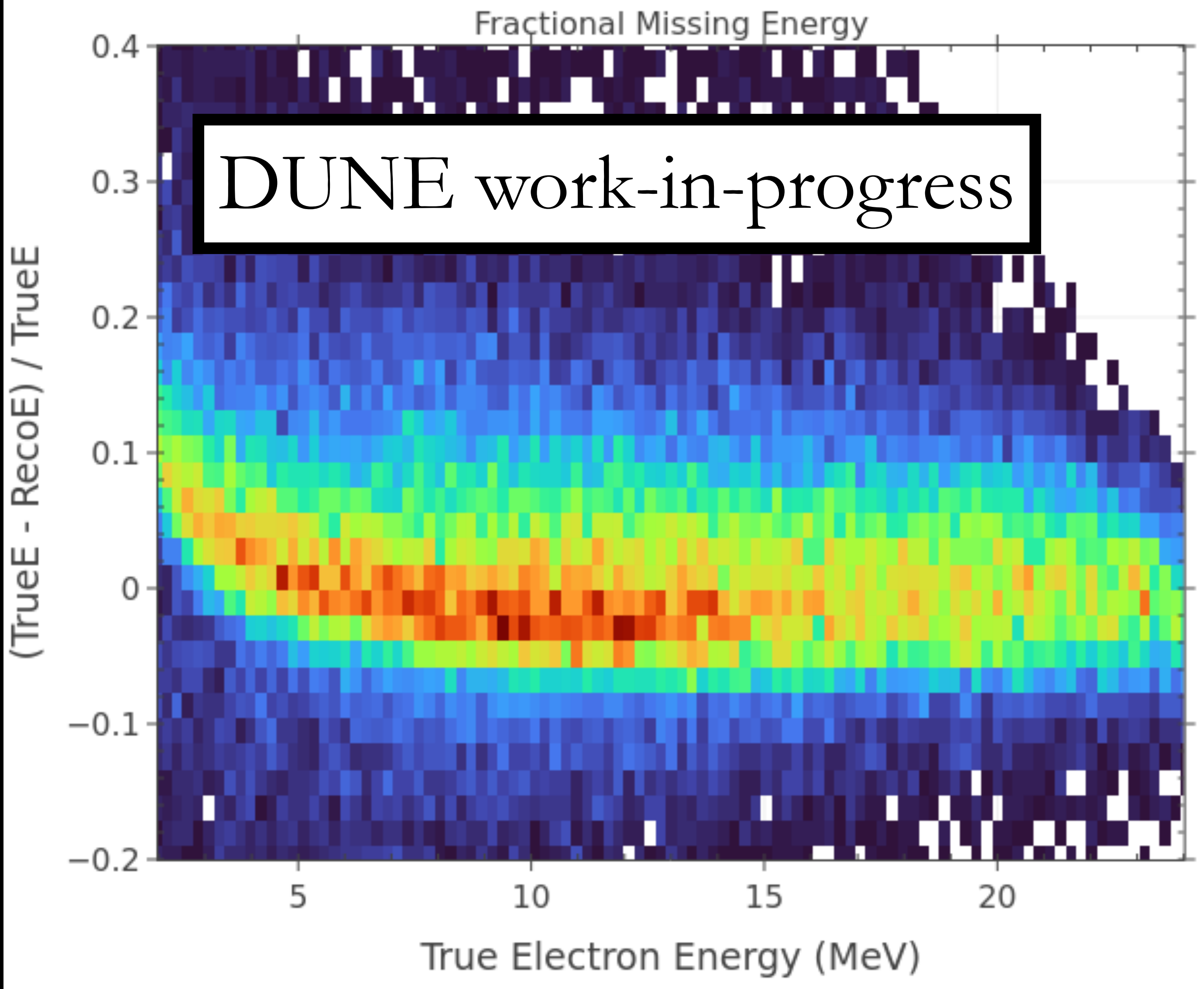
- HZ or LZ ?
- time variations/ correlations with solar events ?
- still missing hep flux

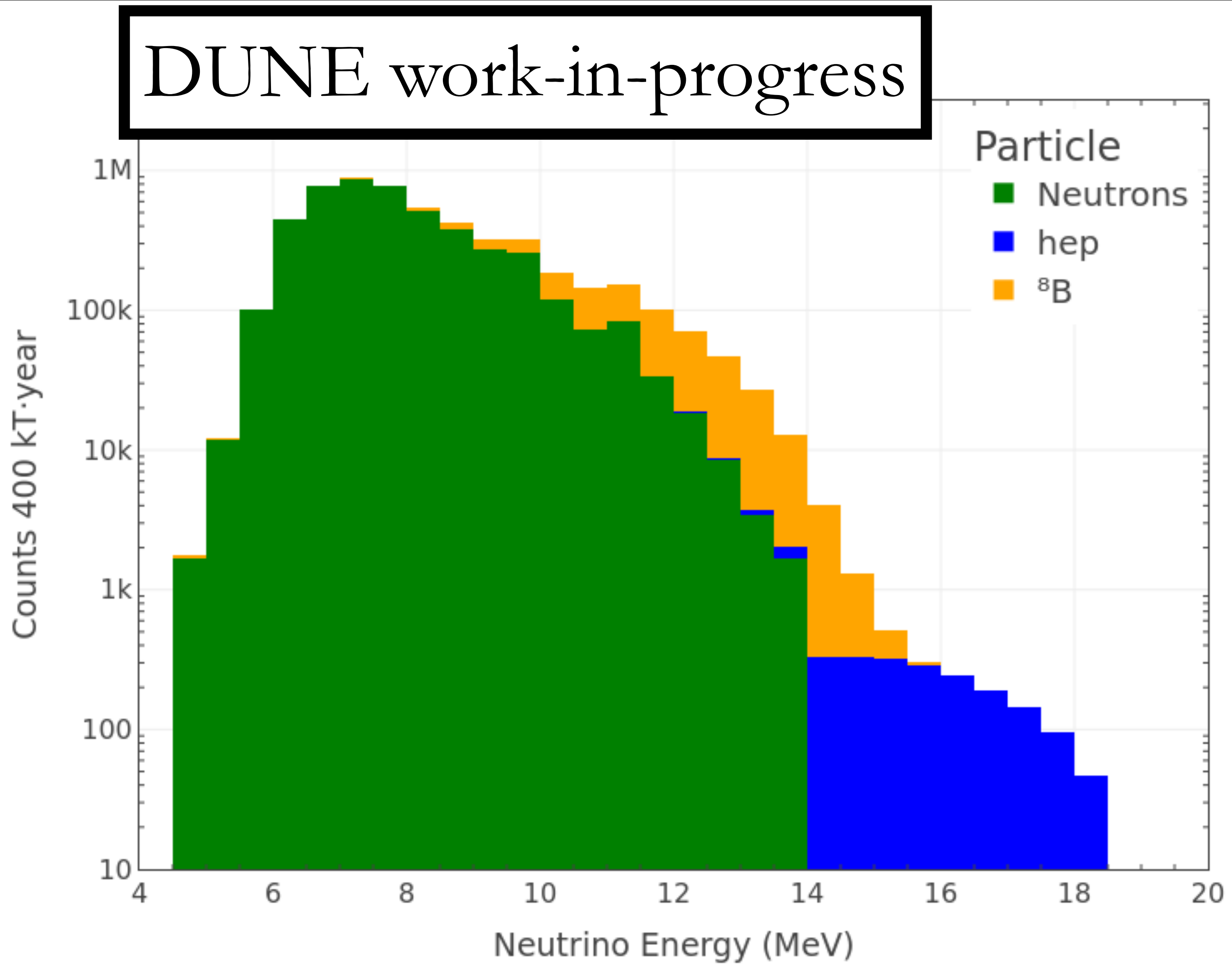


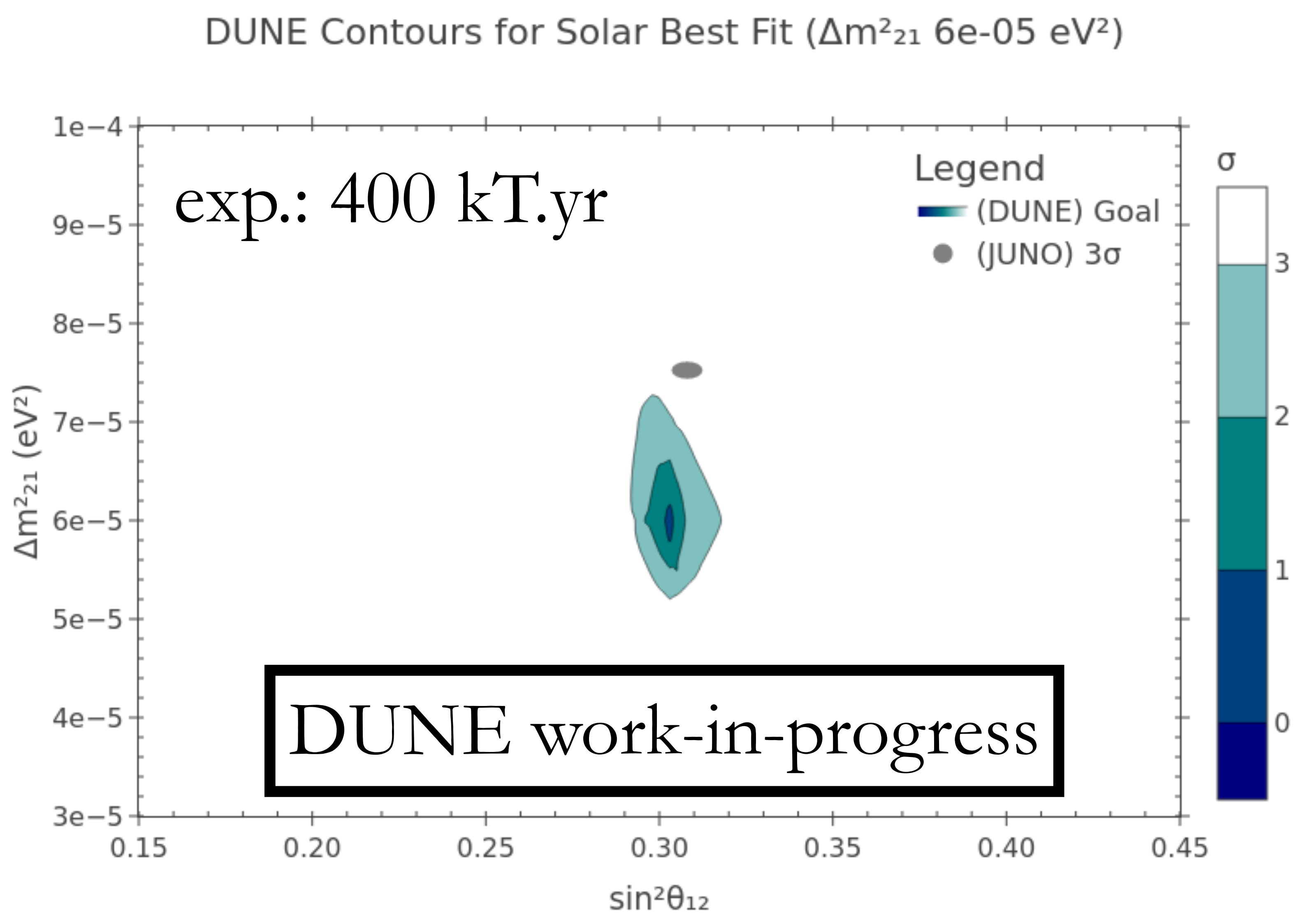
DUNE



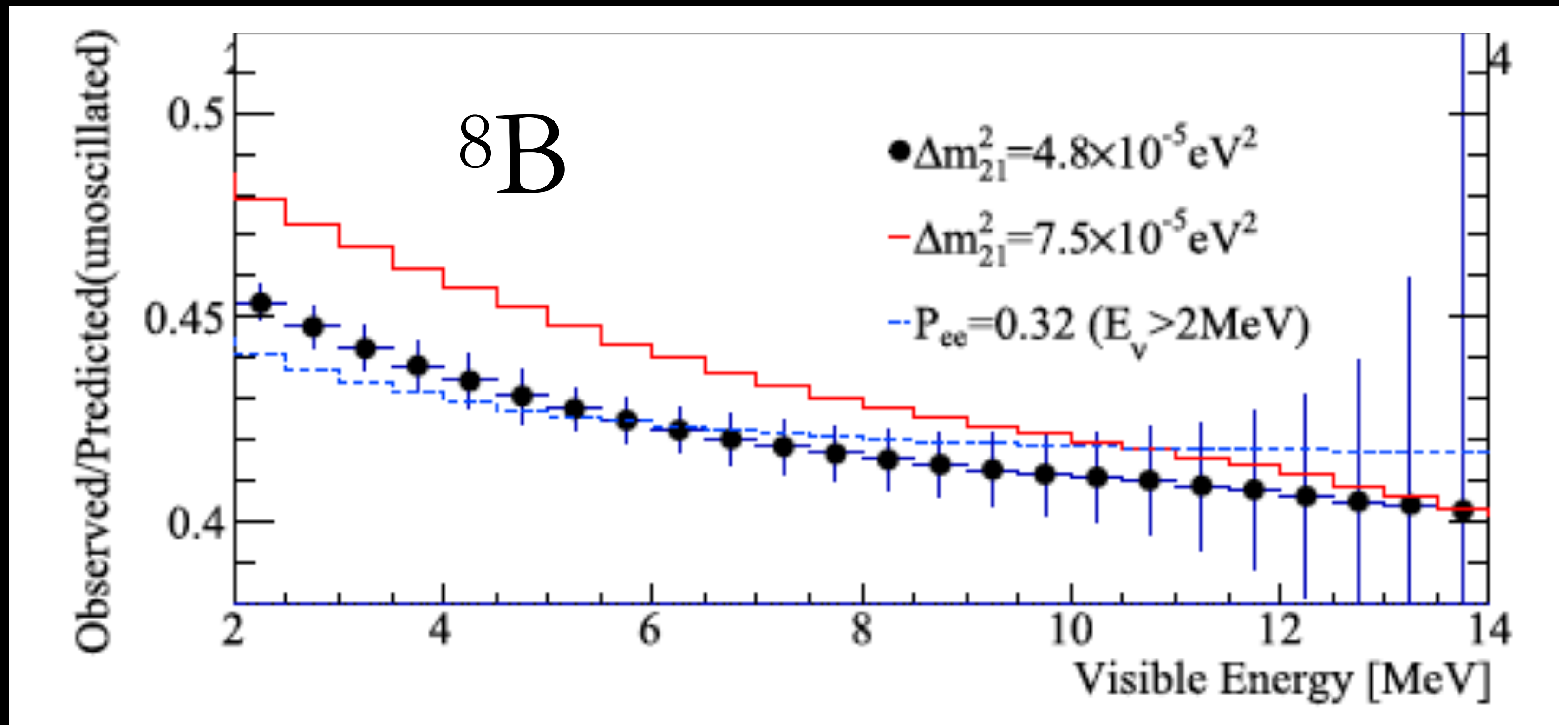
- Phase-I, starting 2029
  - Two largest LAr TPCs ever built: ~27 kton active vol. (comb.)
  - Recent progress in low energy reconstruction: ~16% resolution
  - High ^{8}B stats → 3 σ solar/reactor Δm^2_{21} discrimination
  - High x-section on Ar, kinematics favorable for **hep discovery**
- Phase-II
  - very active R&D to improve LE performance

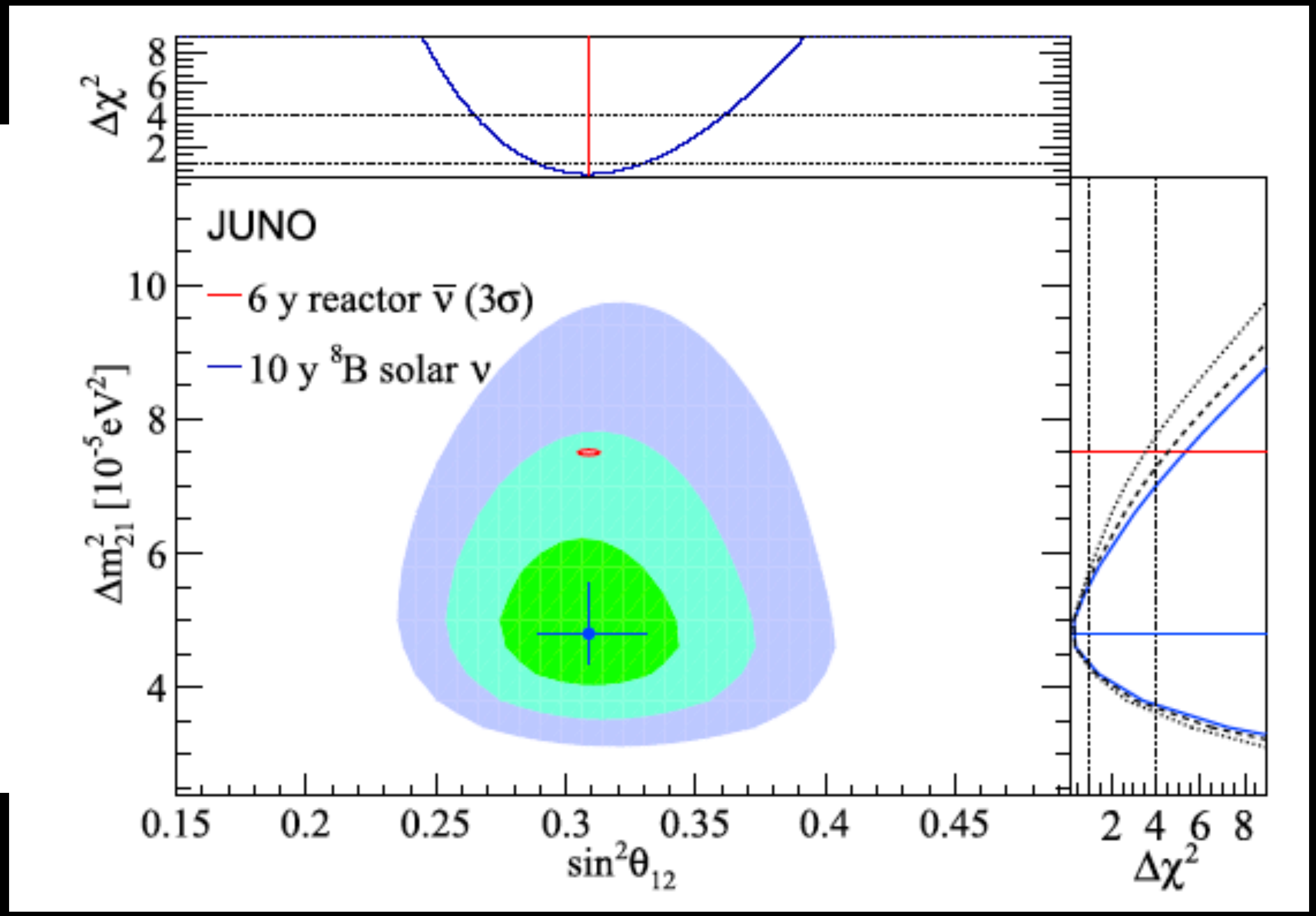


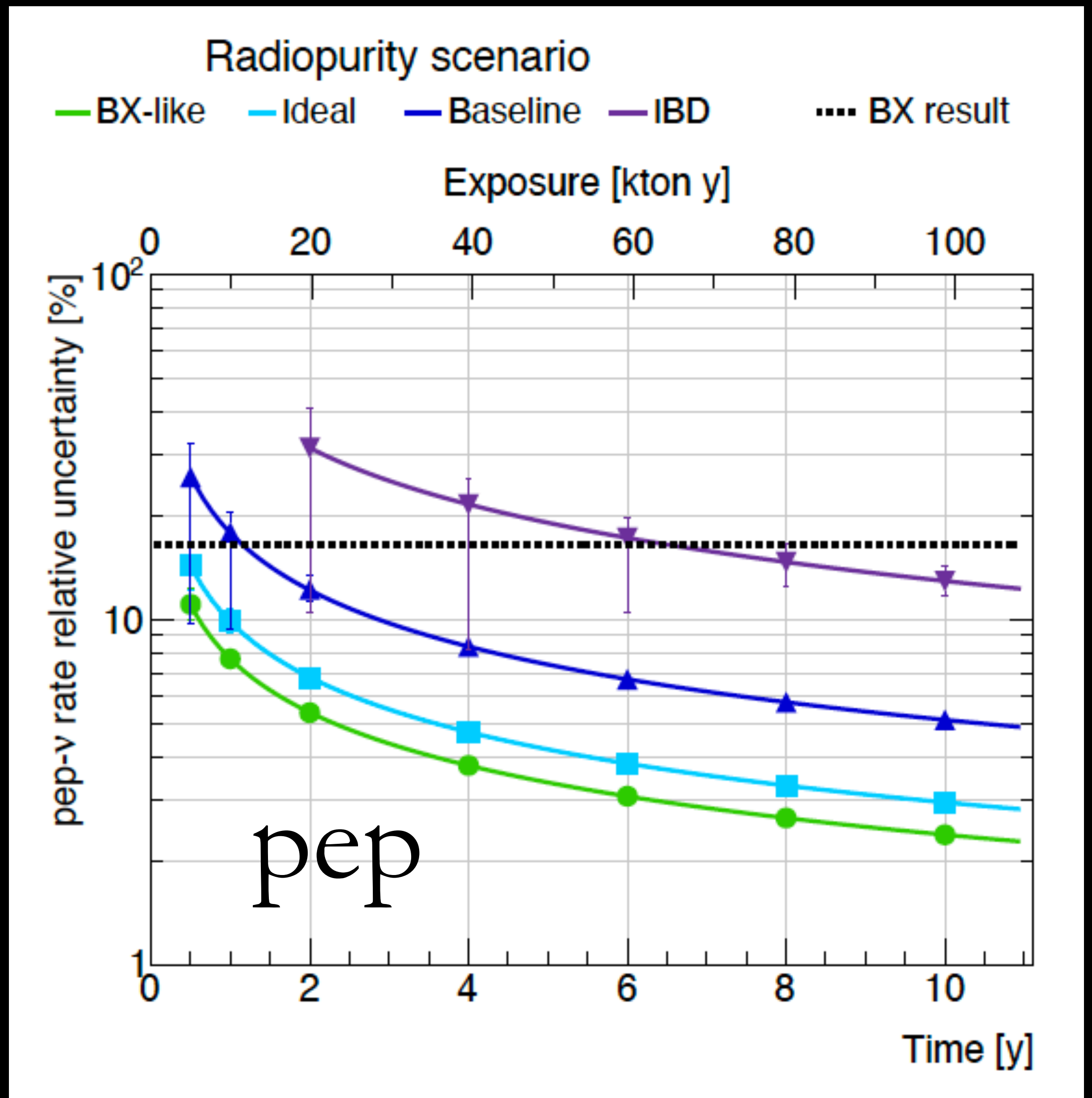


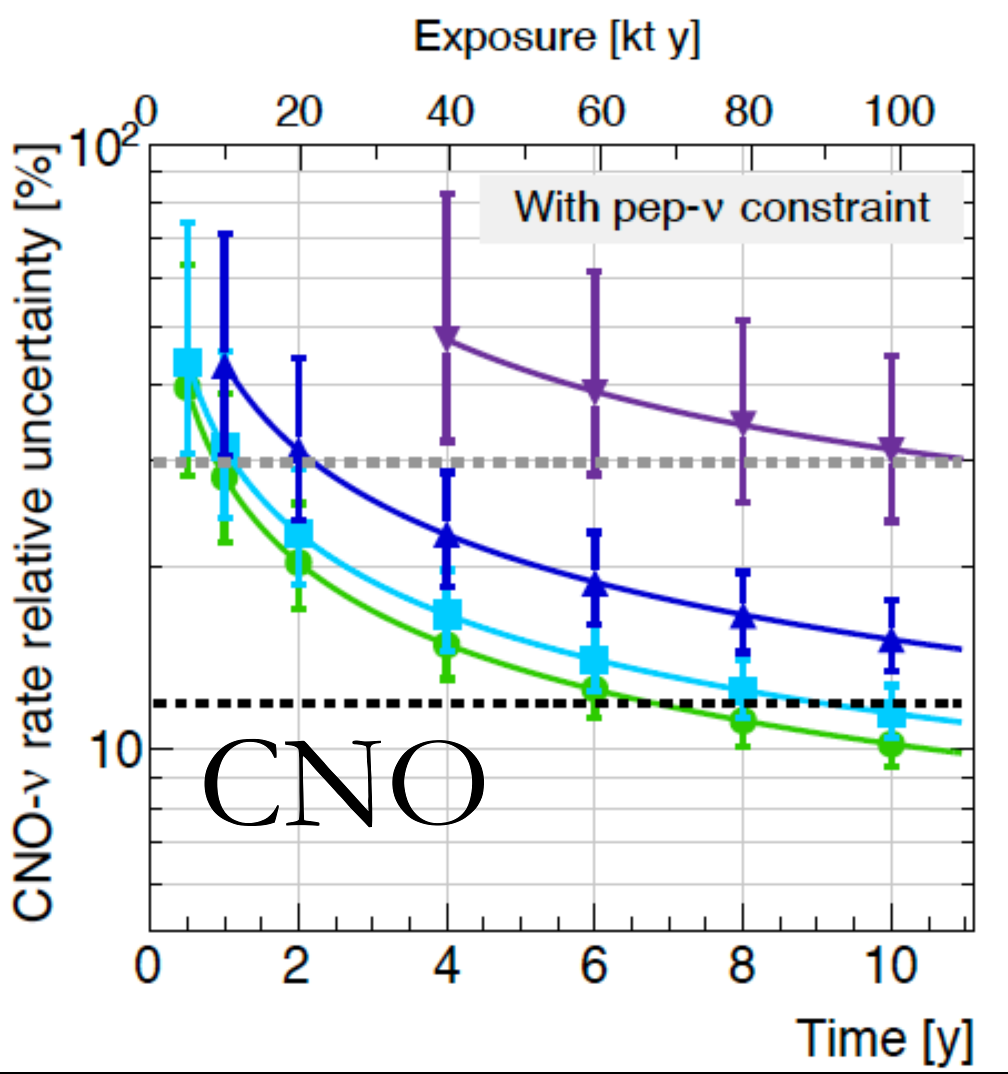


- Low energy ^8B spectral measurement (+ day-night), constraining upturn and oscillation parameters
- ^7Be rate < 1%
- pep rate < 10%
- CNO similar to Borexino (not accurate enough for metallicity)

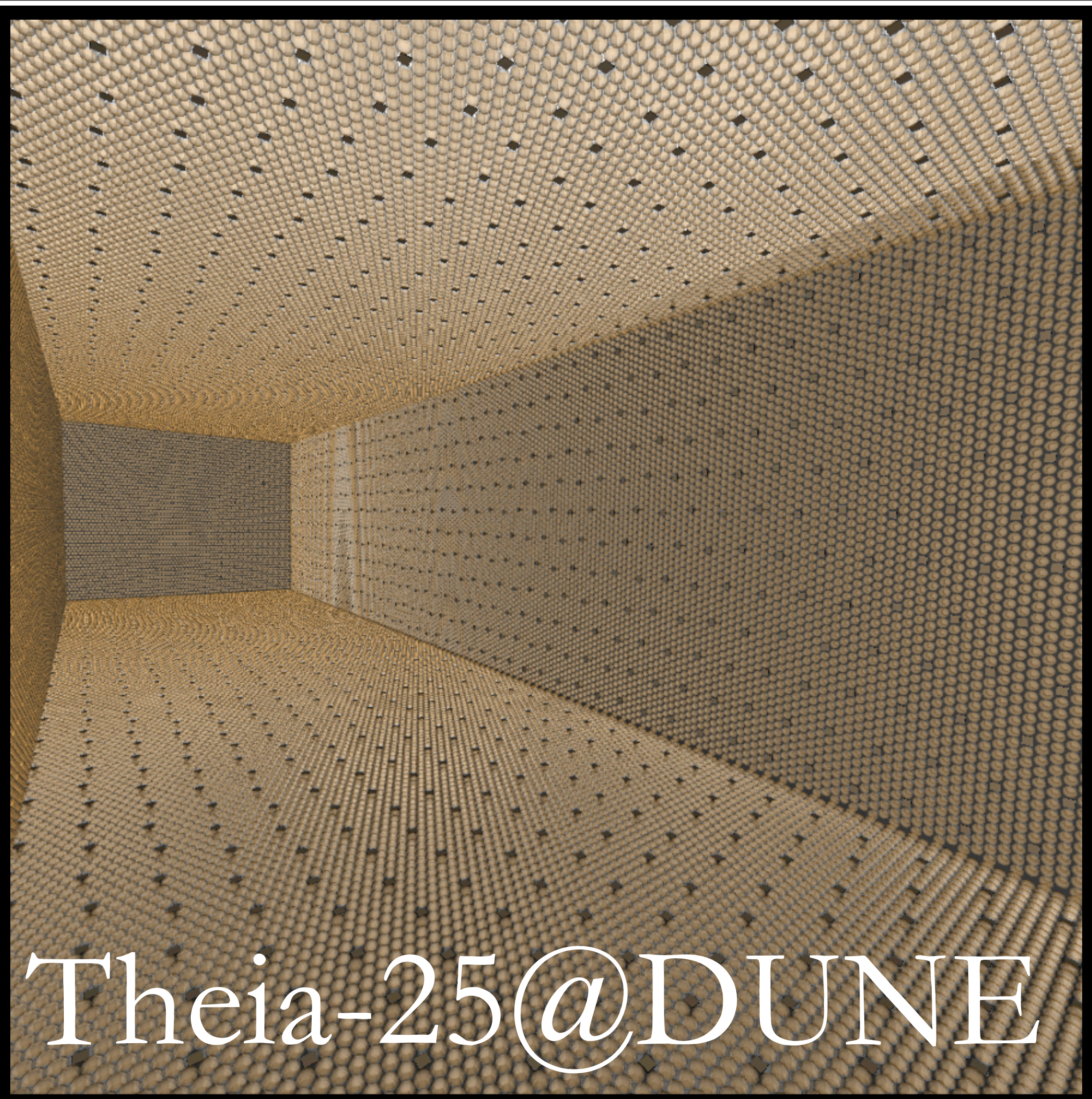




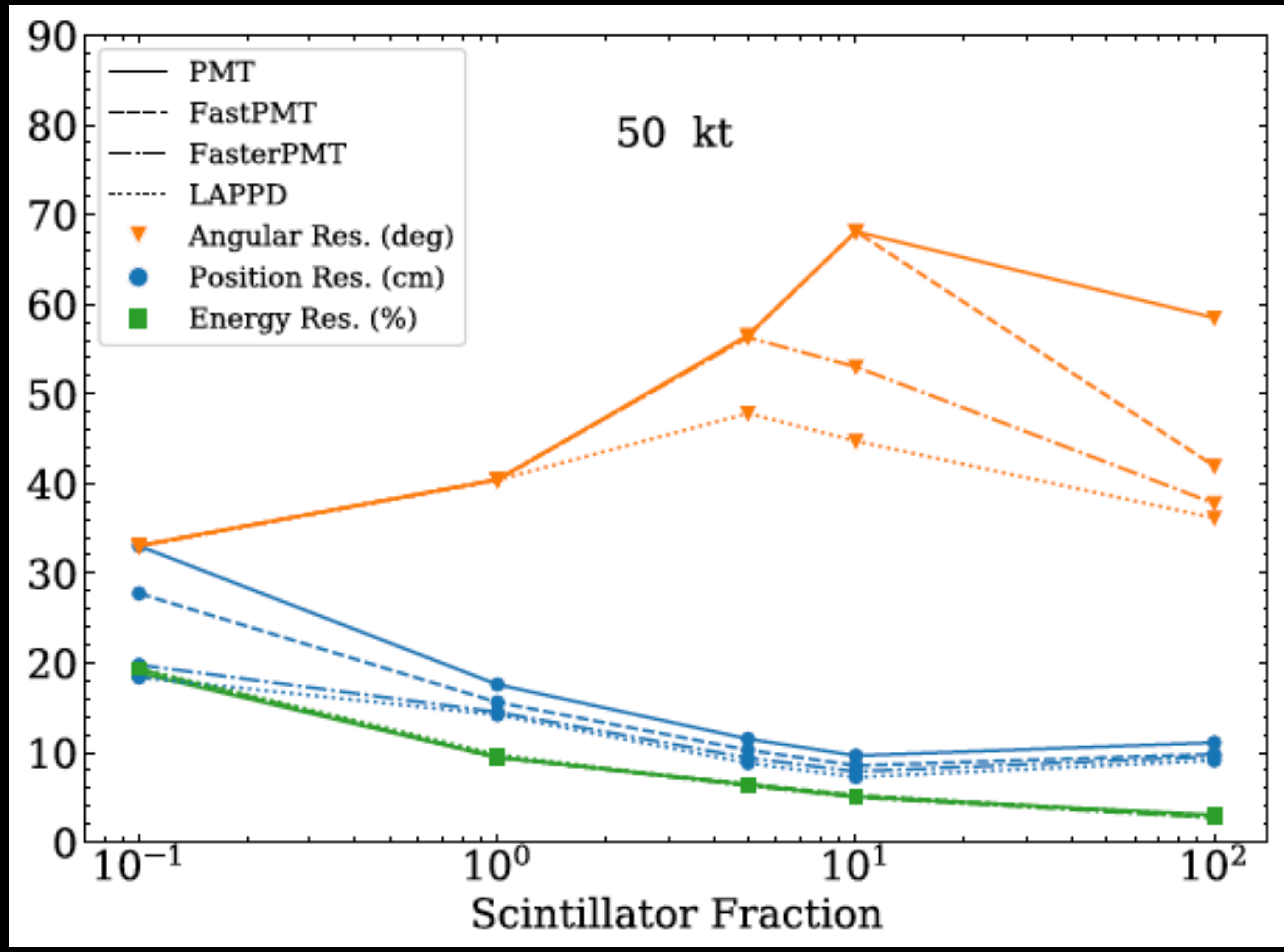




THEIA

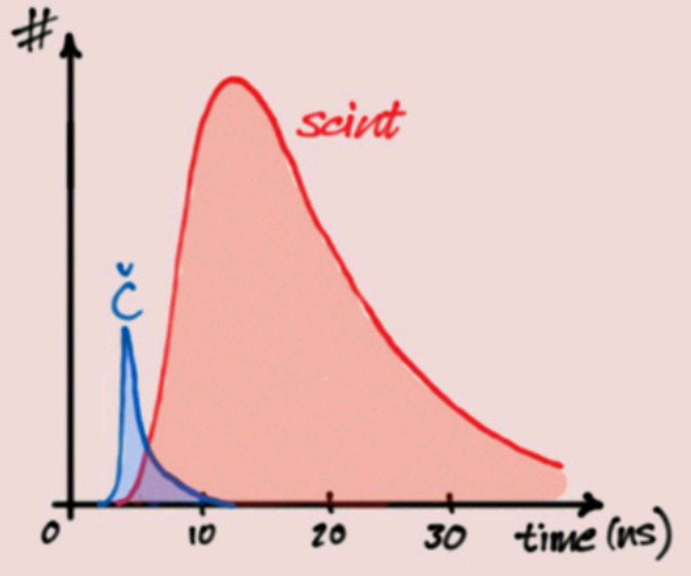


- Hybrid Cherenkov+scintilation detection combines high light yield and directionality
- R&D on Cherenkov/scintillation separation: fast sensors, slow scintillator, dichroicon (ANNIE, EOS, BUTTON)
- Targeting precision CNO and sensitive probe of vacuum/matter transition region.
  Directionality provides powerful discriminant



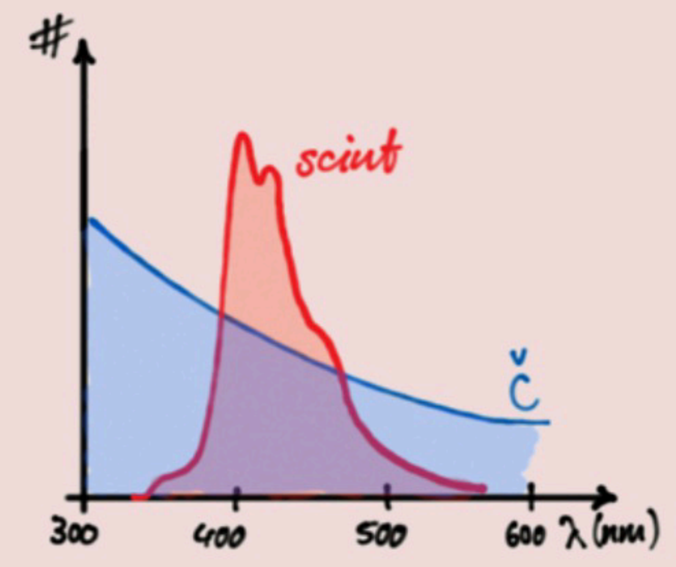
Timing

"instantaneous chertons" vs. delayed "scintons"
→ ns resolution or better



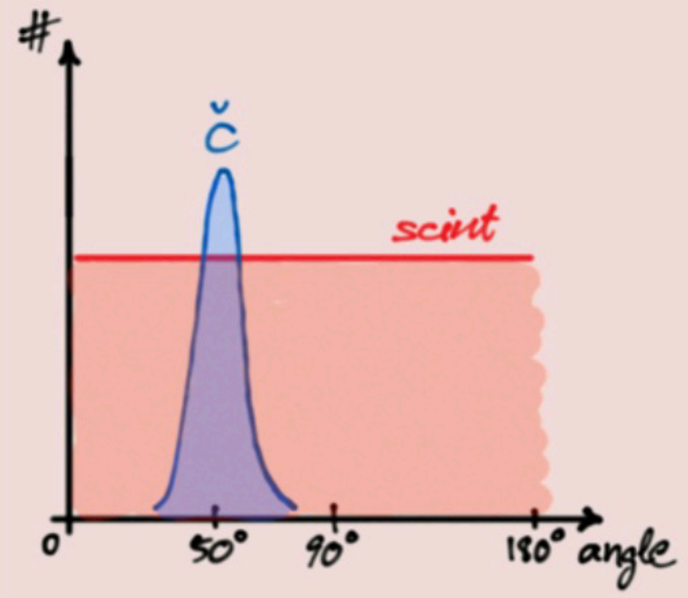
Spectrum

UV/blue scintillation vs. blue/green Cherenkov
→ wavelength-sensitivity

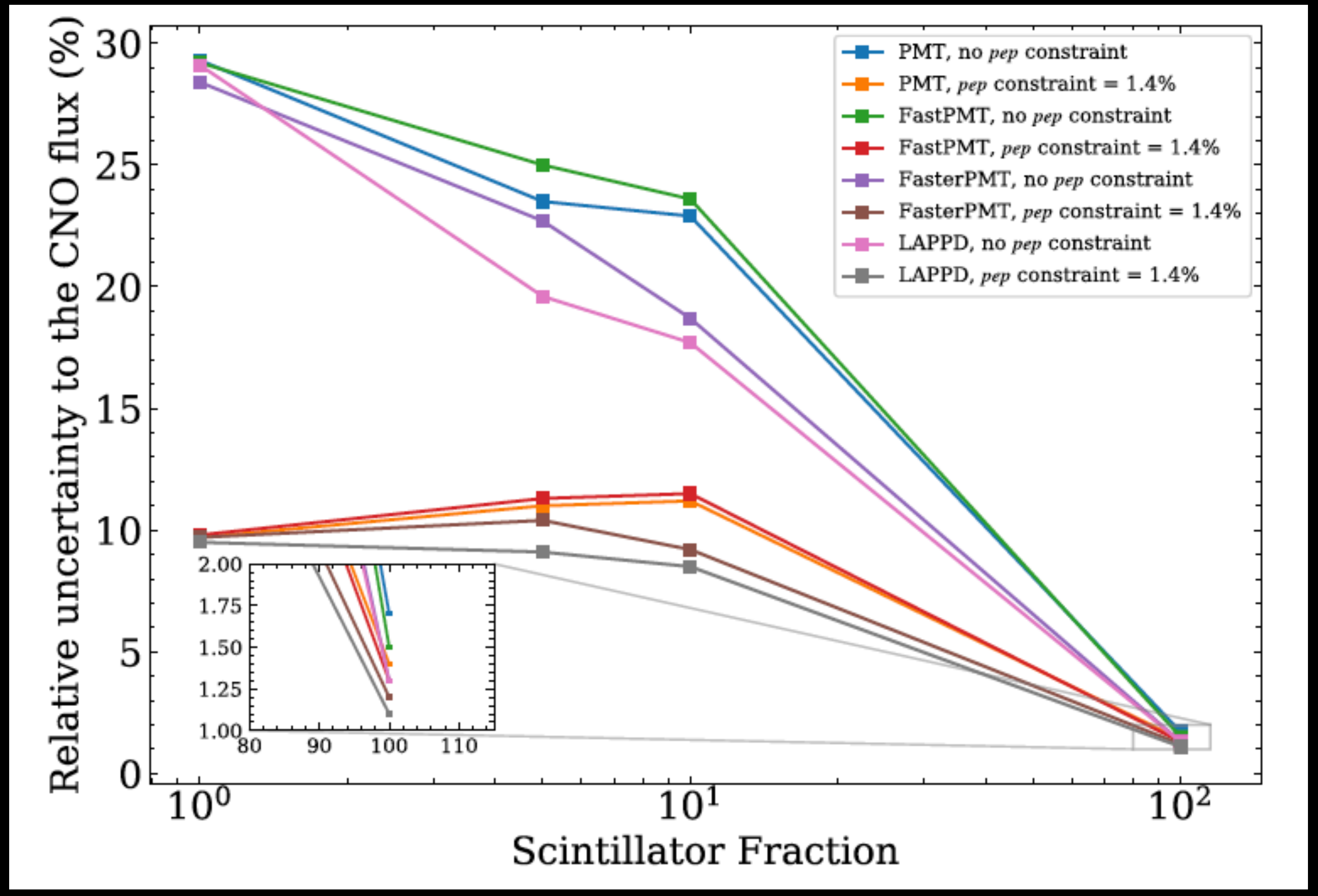


Angular distribution

increased PMT hit density under Cherenkov angle
→ sufficient granularity

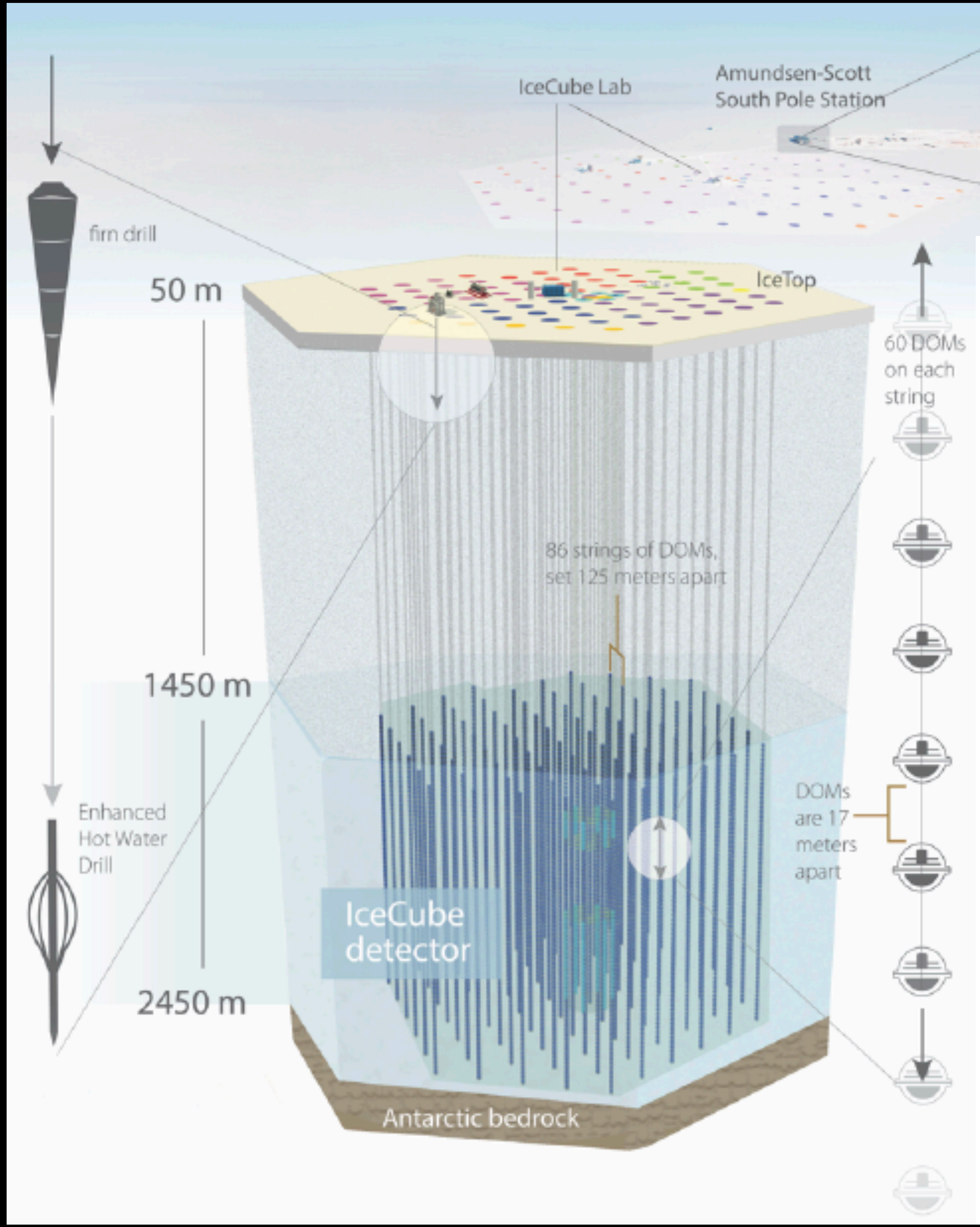


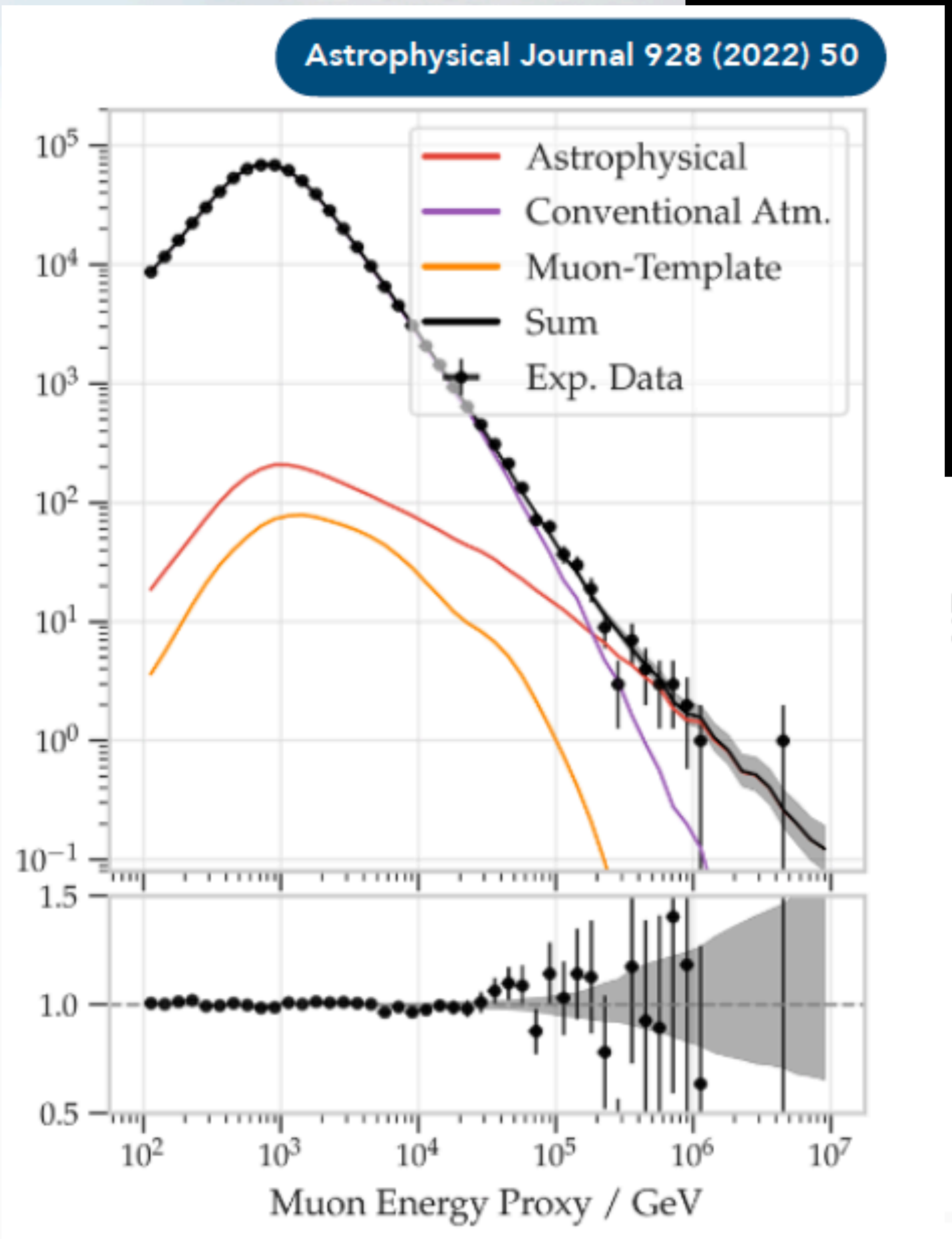
CNO precision well below 10%



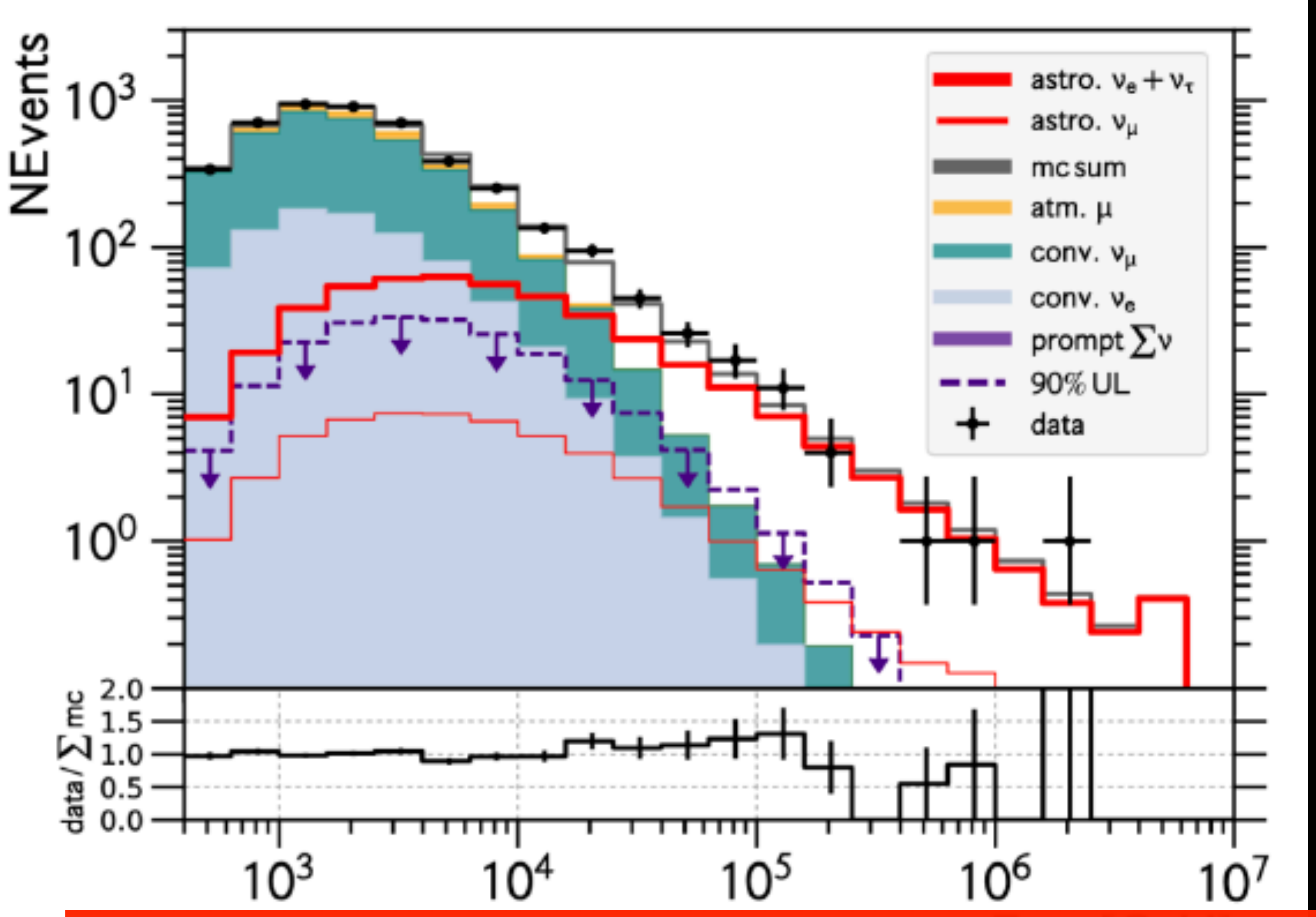
HIGH ENERGY NEUTRINOS

ICECUBE AND HIGH ENERGY NEUTRINOS



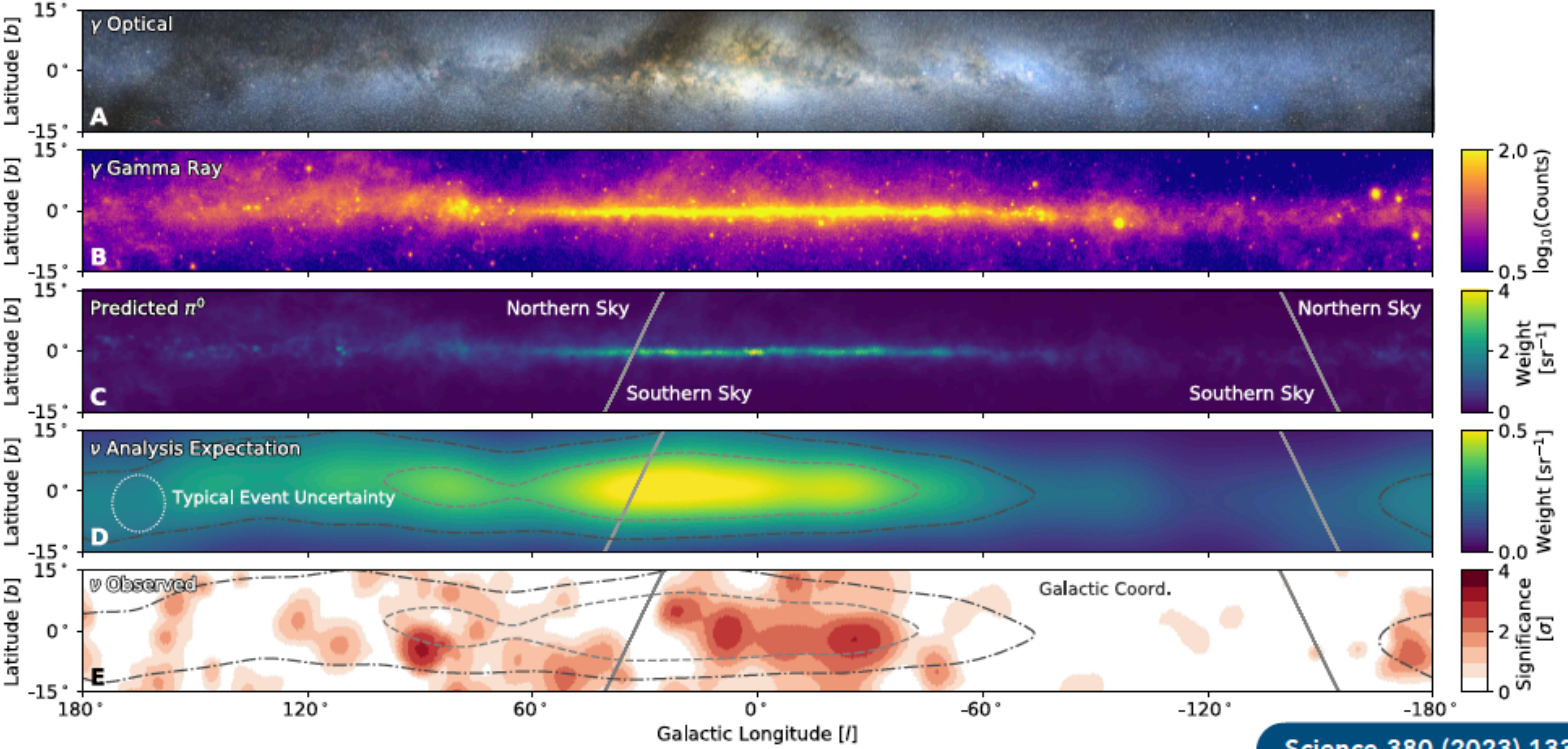


- Ice Cherenkov detector in the South Pole! km^3
- Highest energy neutrinos observed
- Astrophysical origin proven



J.A. AGUILAR, NEUTRINO 2024

The Galaxy with Neutrinos



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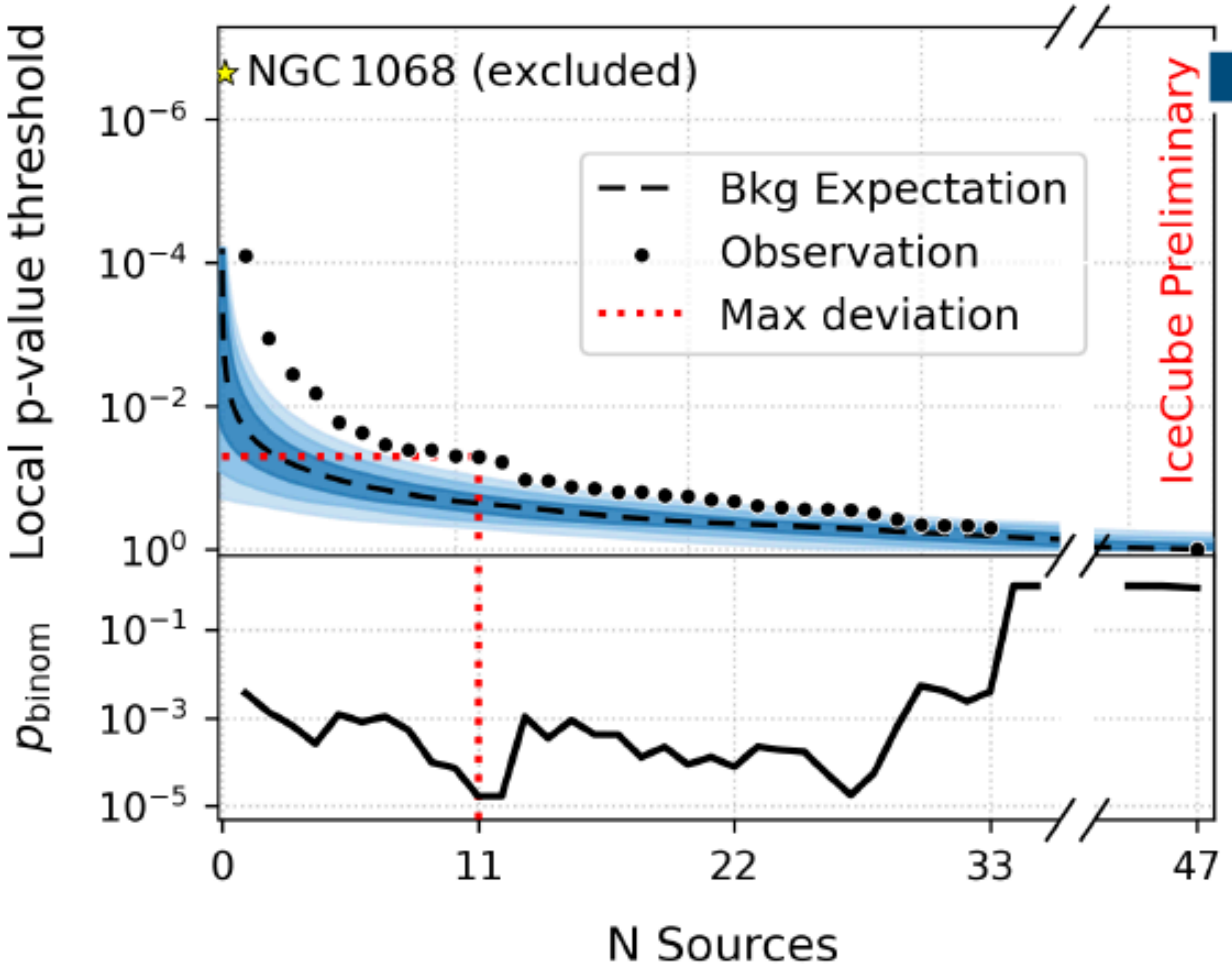
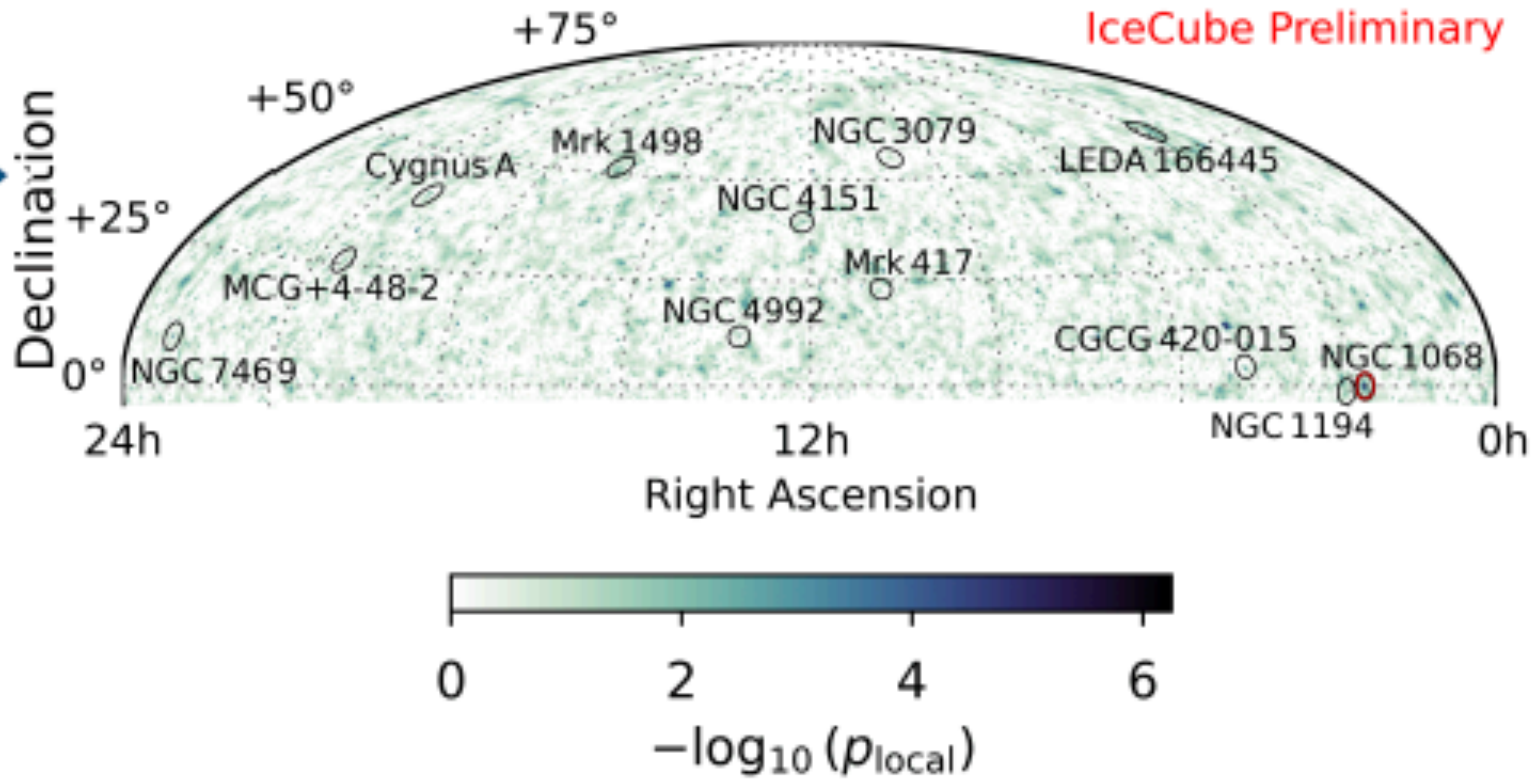
Searches for Neutrinos from Seyfert Galaxies

Binomial Test



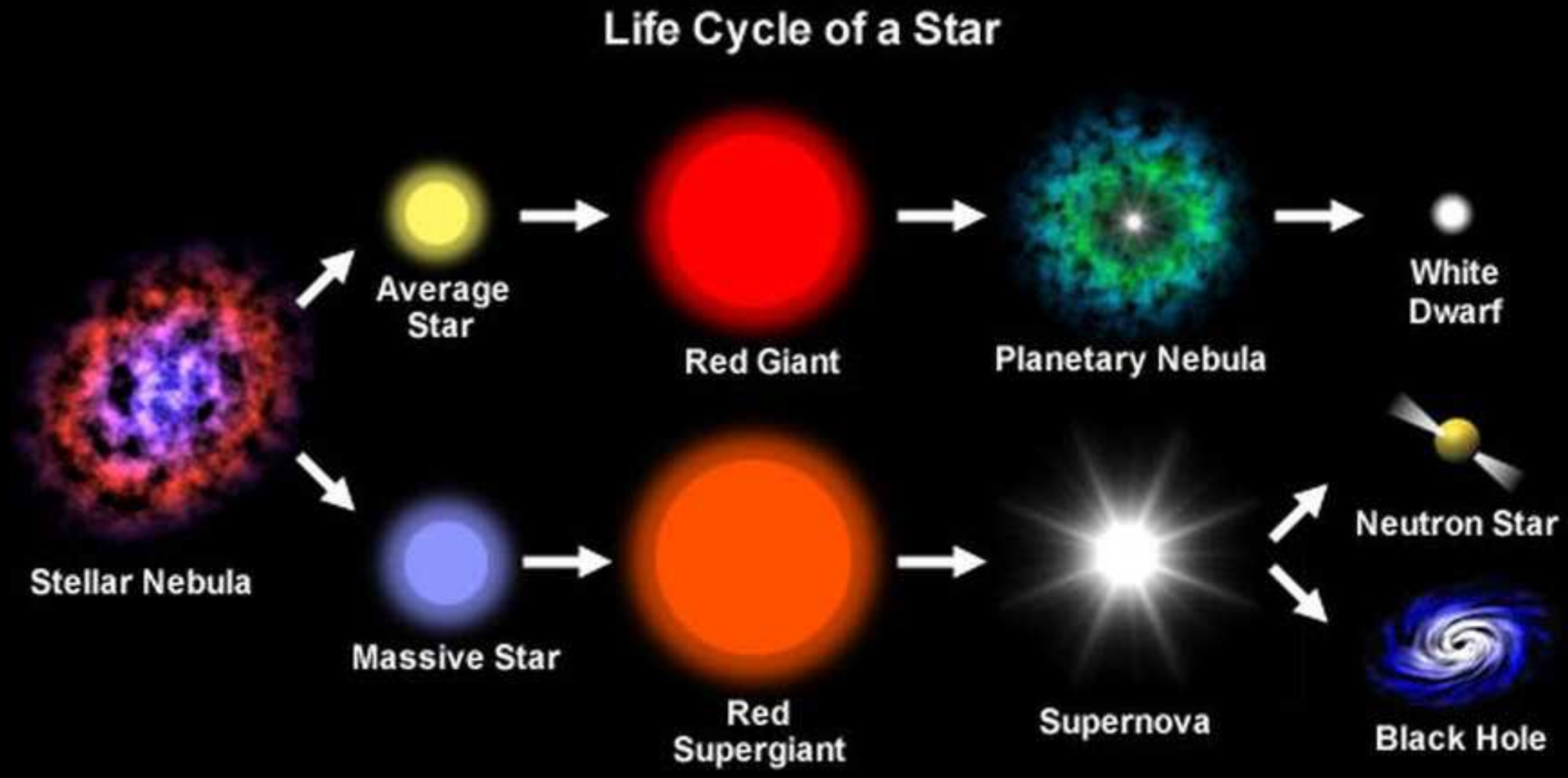


- Binomial Test: Probability of finding a signal from 47 AGNs too weak to be identified individually
- Result: 3.3σ excess for 11 sources (excluding NGC1068)

SUPERNOVA NEUTRINOS

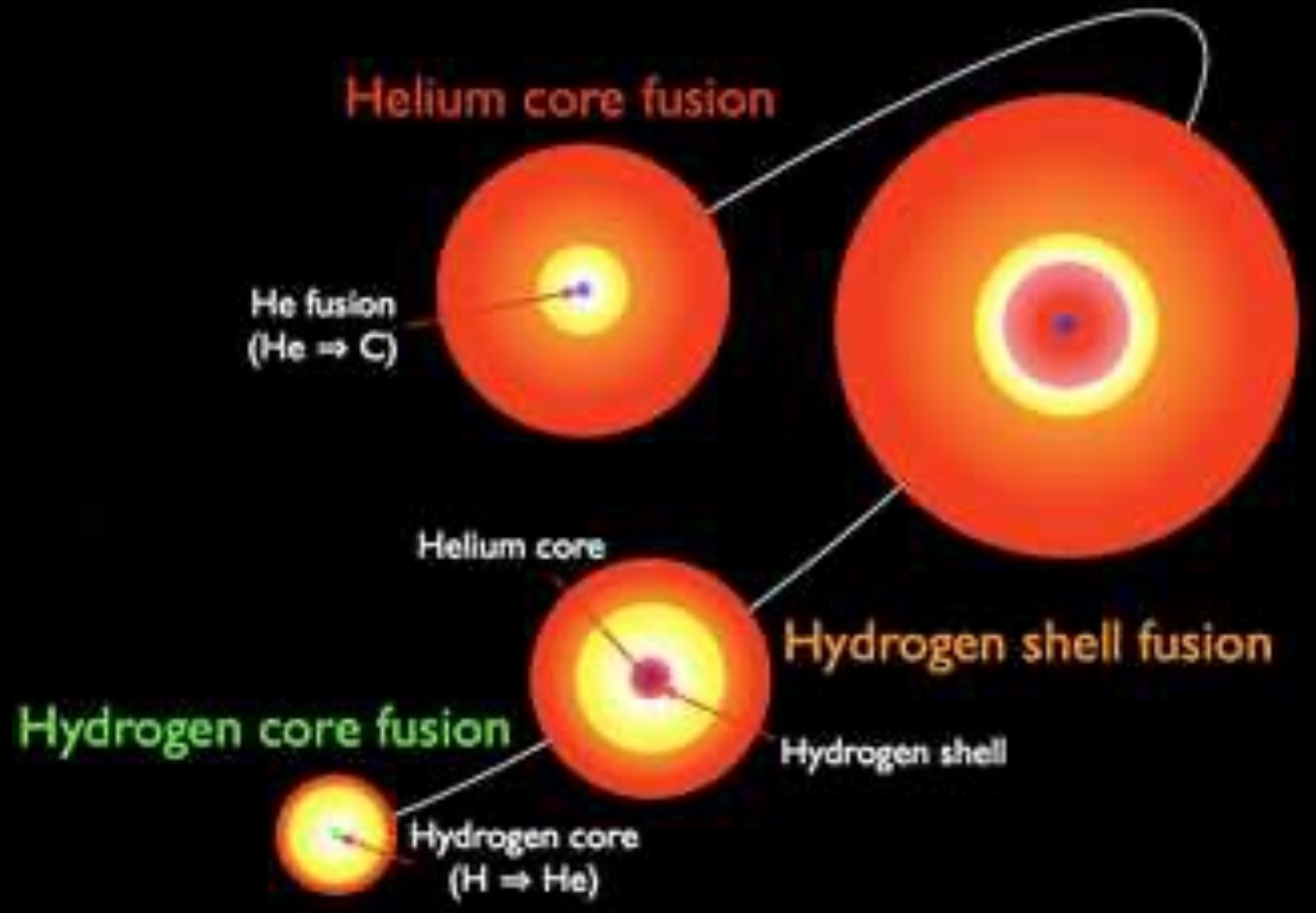
and yet, they are much brighter in neutrinos!

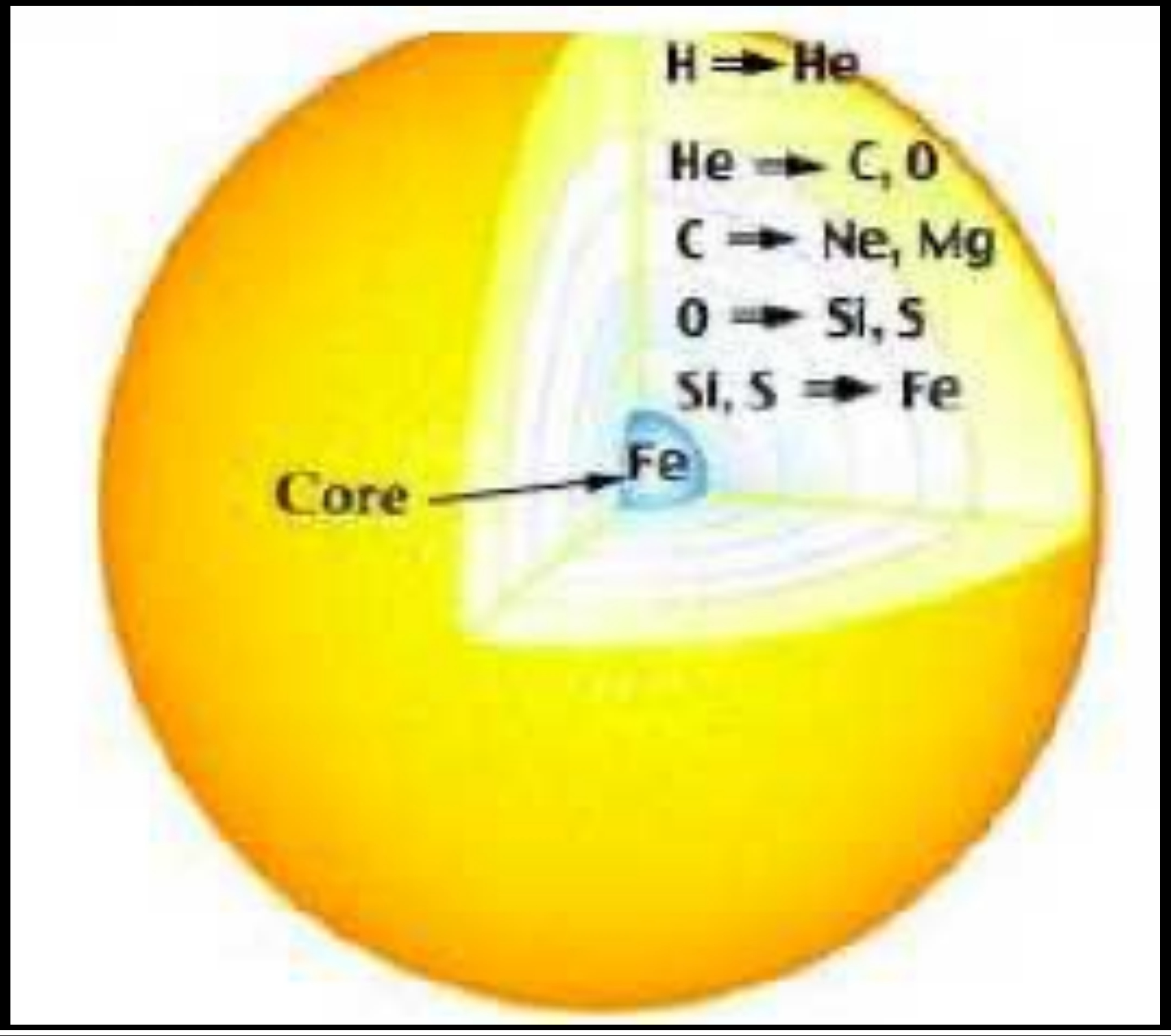
THE LIFE AND DEATH OF STARS



PHASES OF STELLAR EVOLUTION

- Main sequence
  - Hydrogen burning in core
- Red Giant
  - Hydrogen burning in shell
  - Helium burning in core
- Supergiant
  - Helium burning in shell
  - … and so on up to iron
  - M=1.5 Msun in R=8000km
  - ...burning stops
  - gravity not balanced → Collapse!
  - core becomes a neutron star $\rho = 3 \times 10^{14} gcm^{-3}$, R= 50km

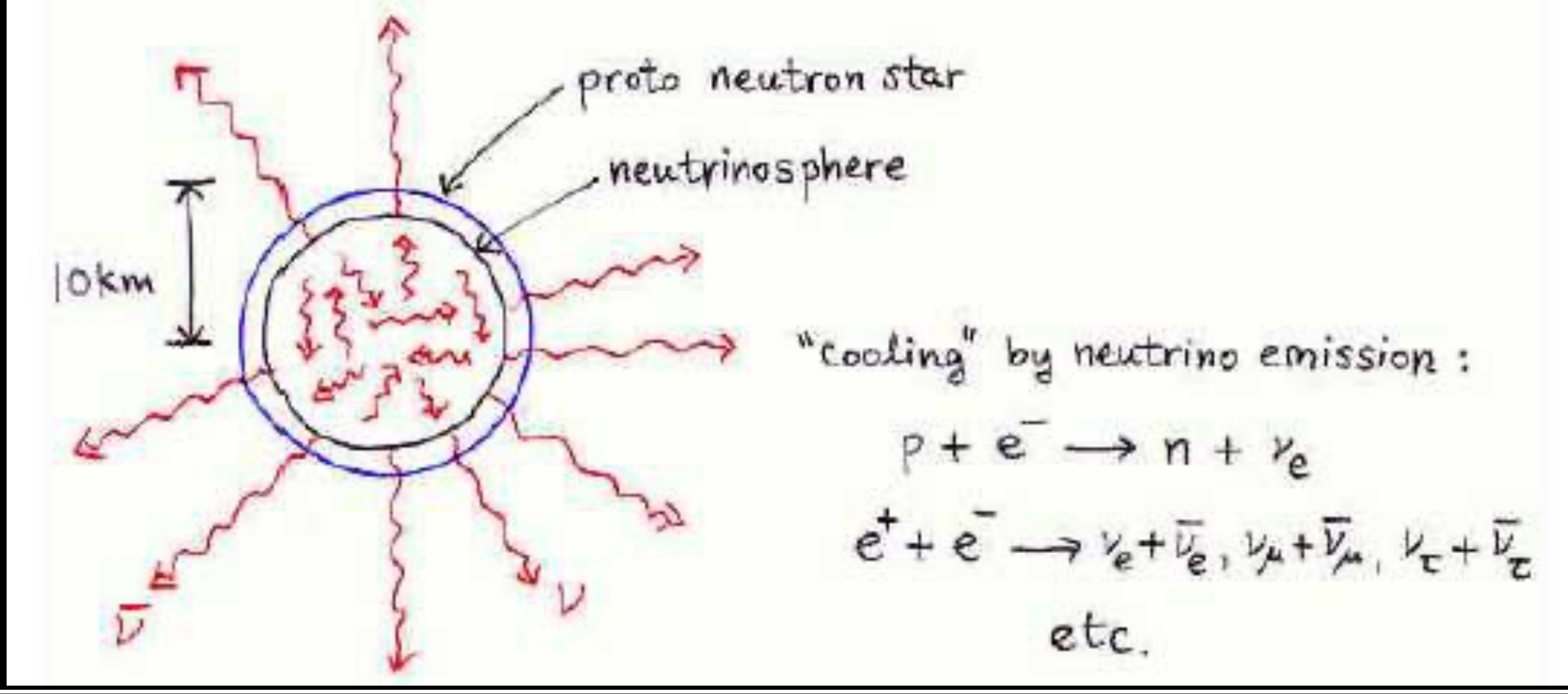




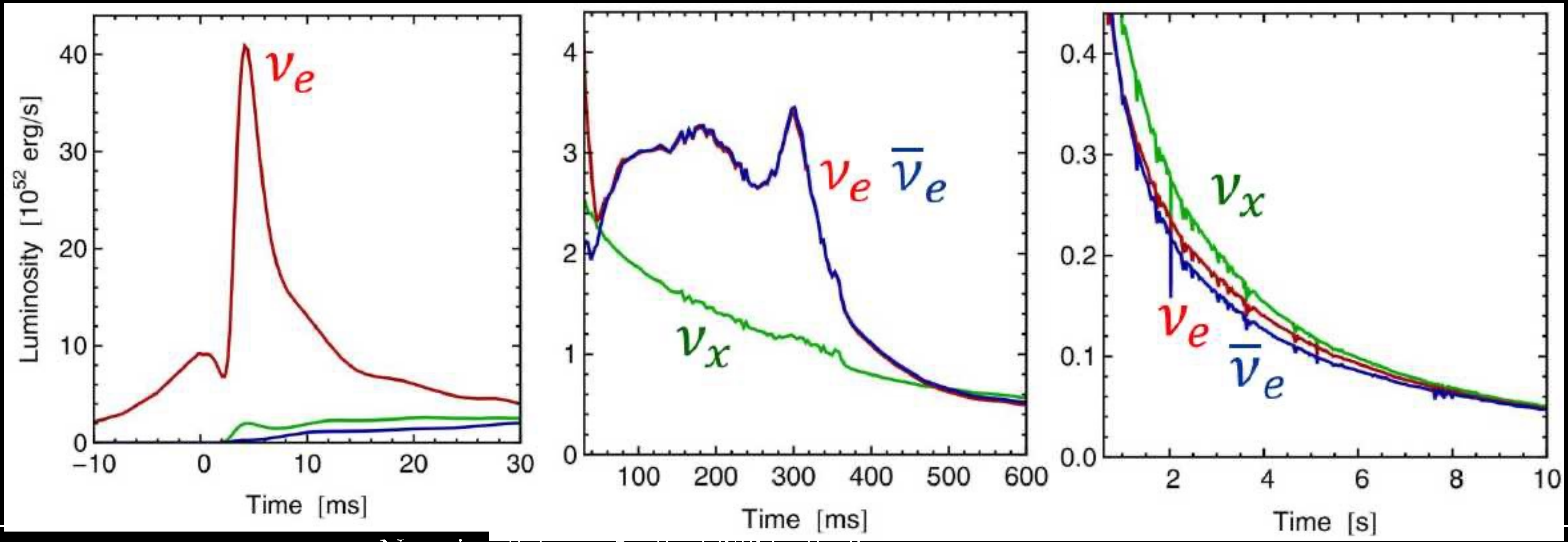
SUPERNOVA EXPLOSION

- Explosion from release of gravitational binding energy
  - $E = 3x\ 10^{53}$ erg ~ 17% Msun c^2
  - 99% neutrinos
  - 1% kinetic energy of ejecta
  - only 0.01% as photons

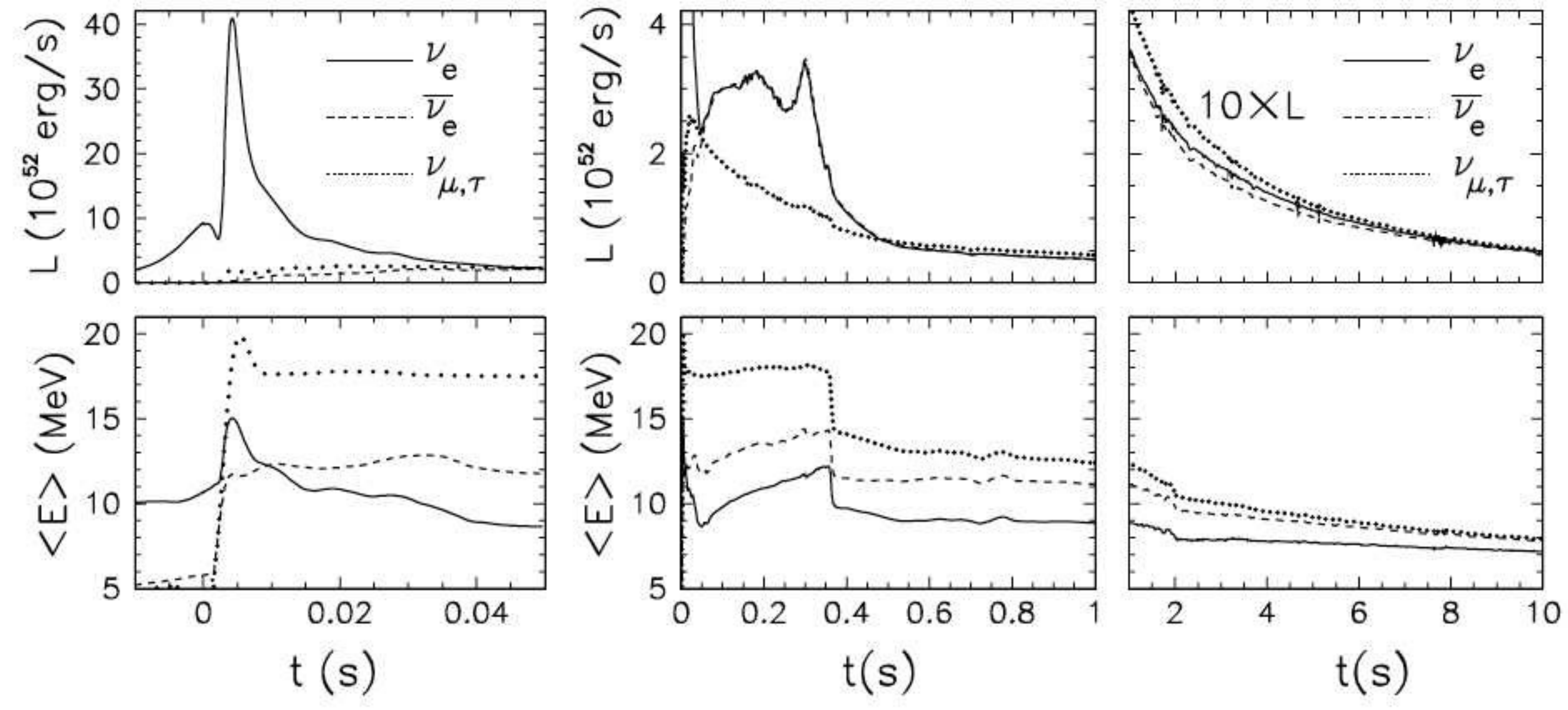
- Neutrino production
  - in formation of neutron star
  - Neutronization: p + e- ↔ n + ν
  - reaction in equilibrium within "neutrinosphere"
  - when shock wave reaches it, intense electron neutrino burst



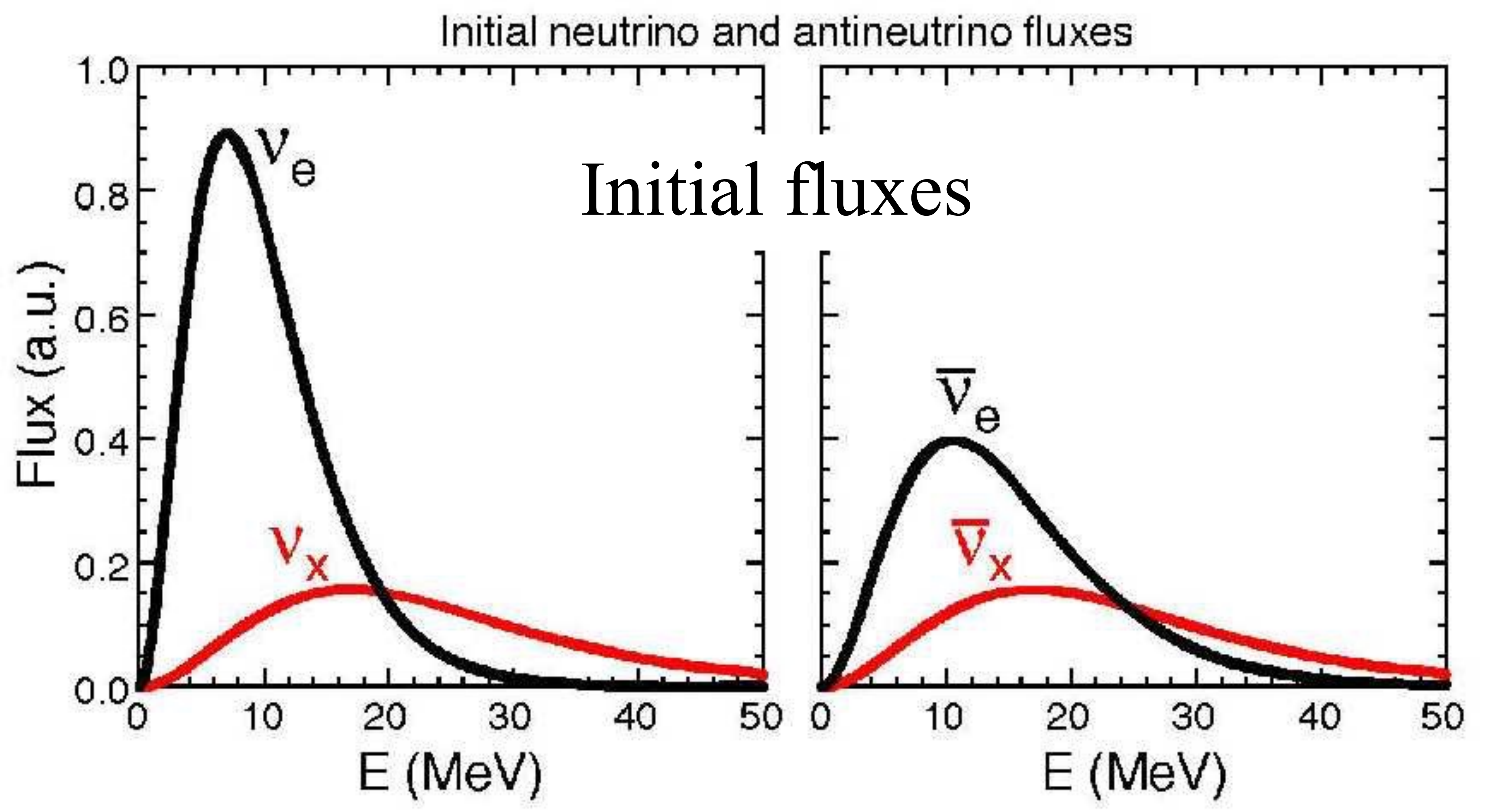
- Prompt νe burst
  - neutronization
  - when shock wave reaches zone with density of 10^{11} gcm^{-3}
  - intense, but very short
- Accretion
  - delayed explosion fueled by neutrino heating of infalling matter
  - all-flavors reaction
- Cooling
  - neutrino diffusion

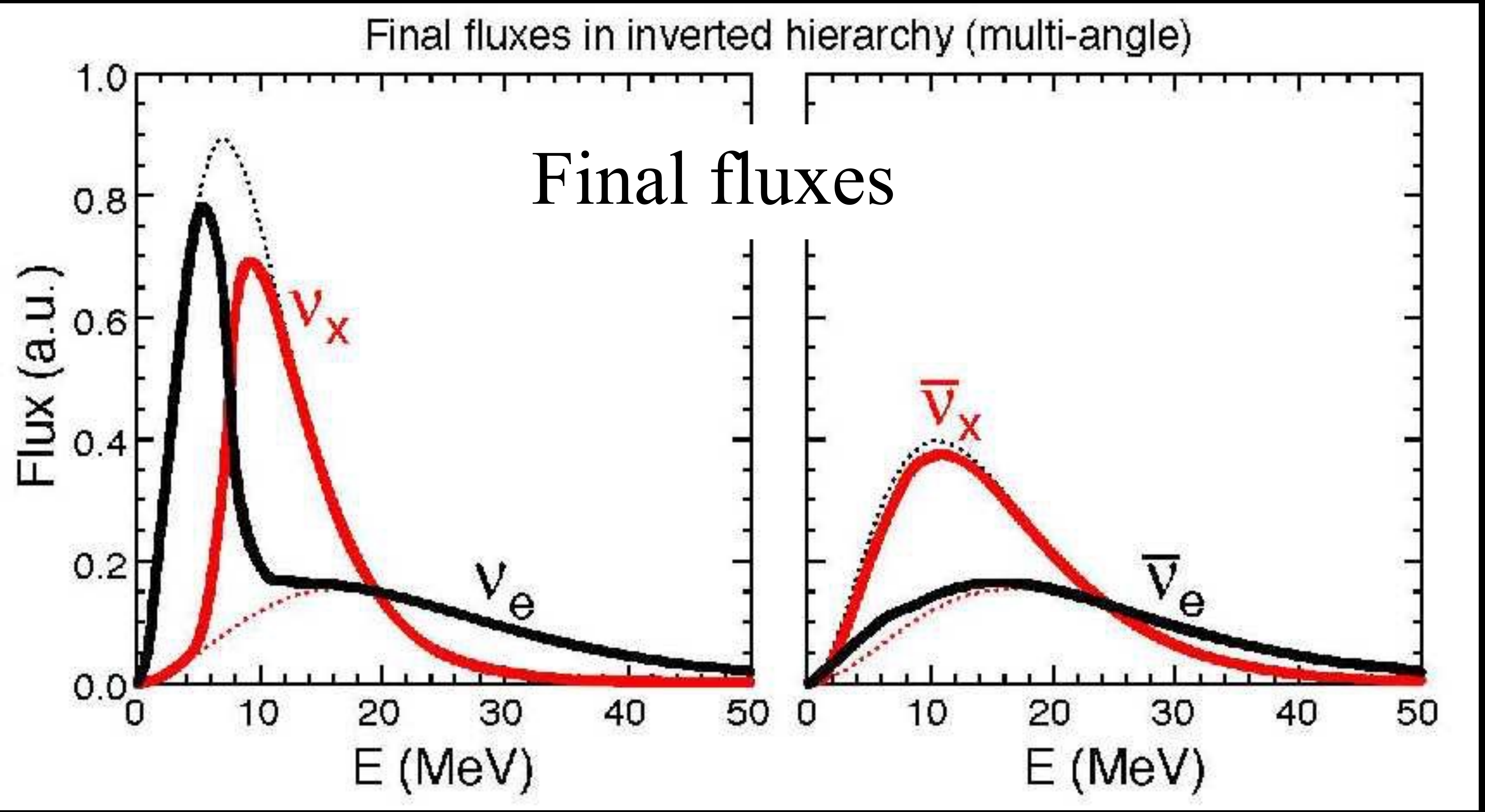


FLUX AND ENERGY VS TIME



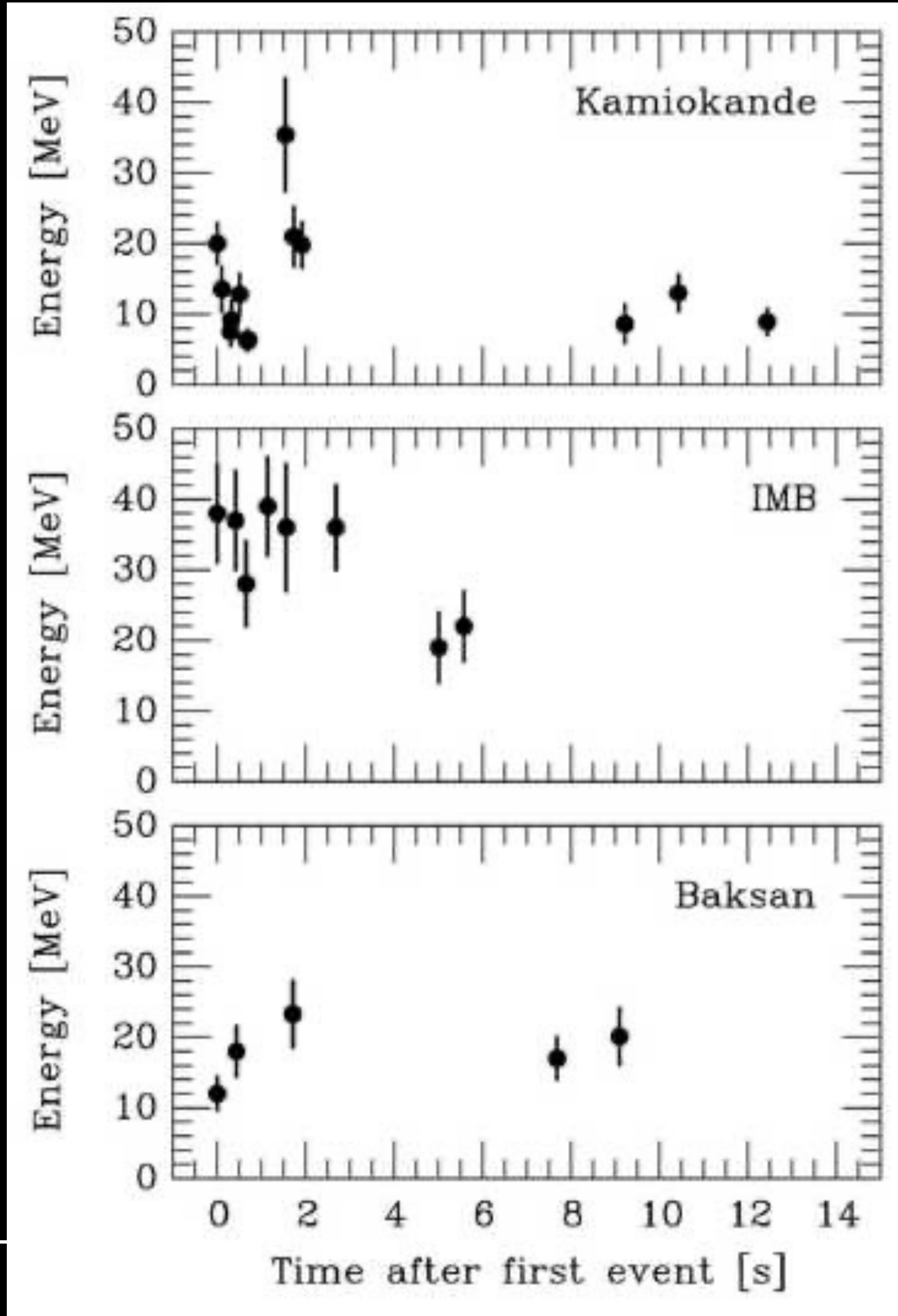
- Oscillations affect flavor composition
- Depend on:
  - density profile
  - mass ordering

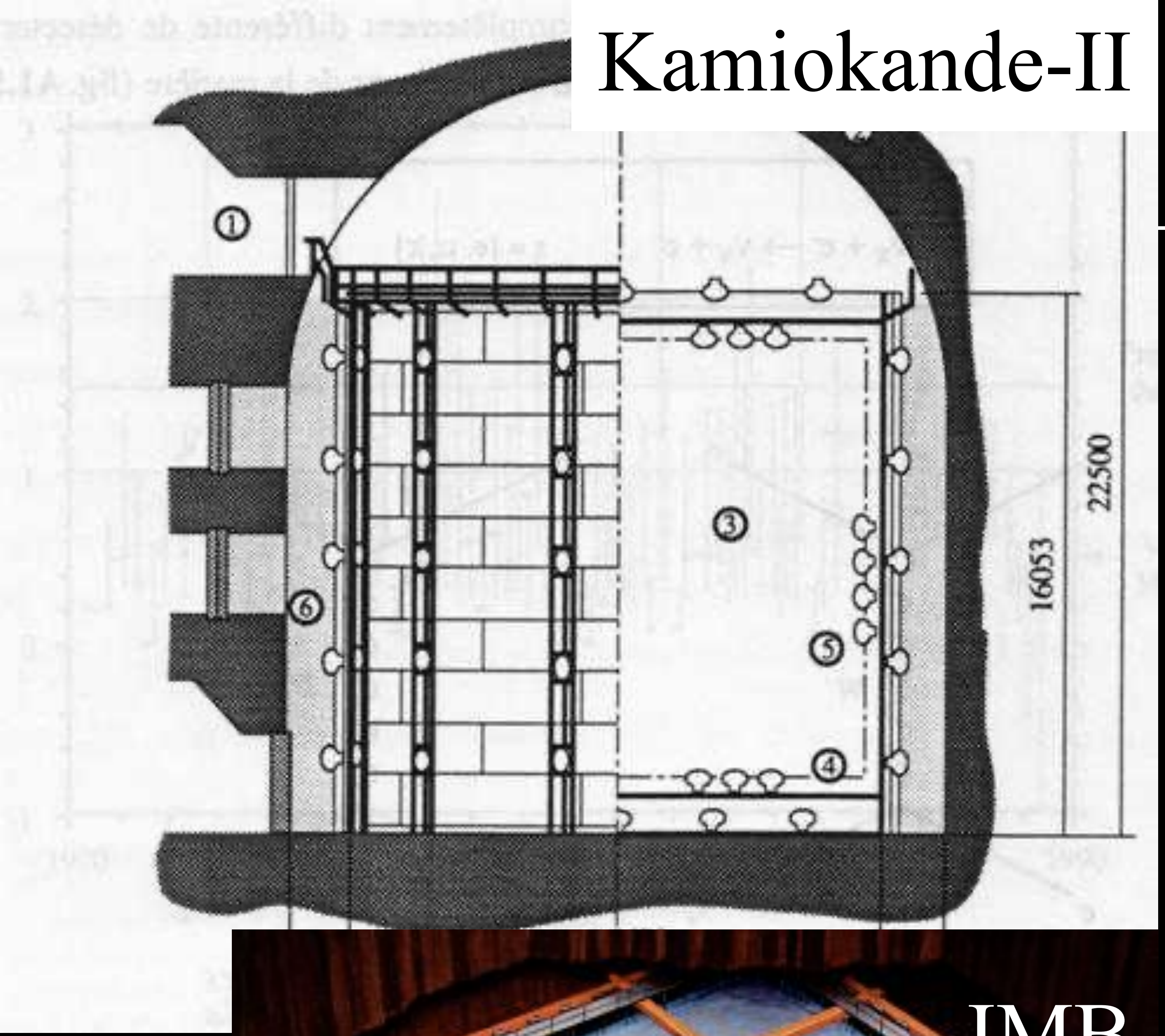


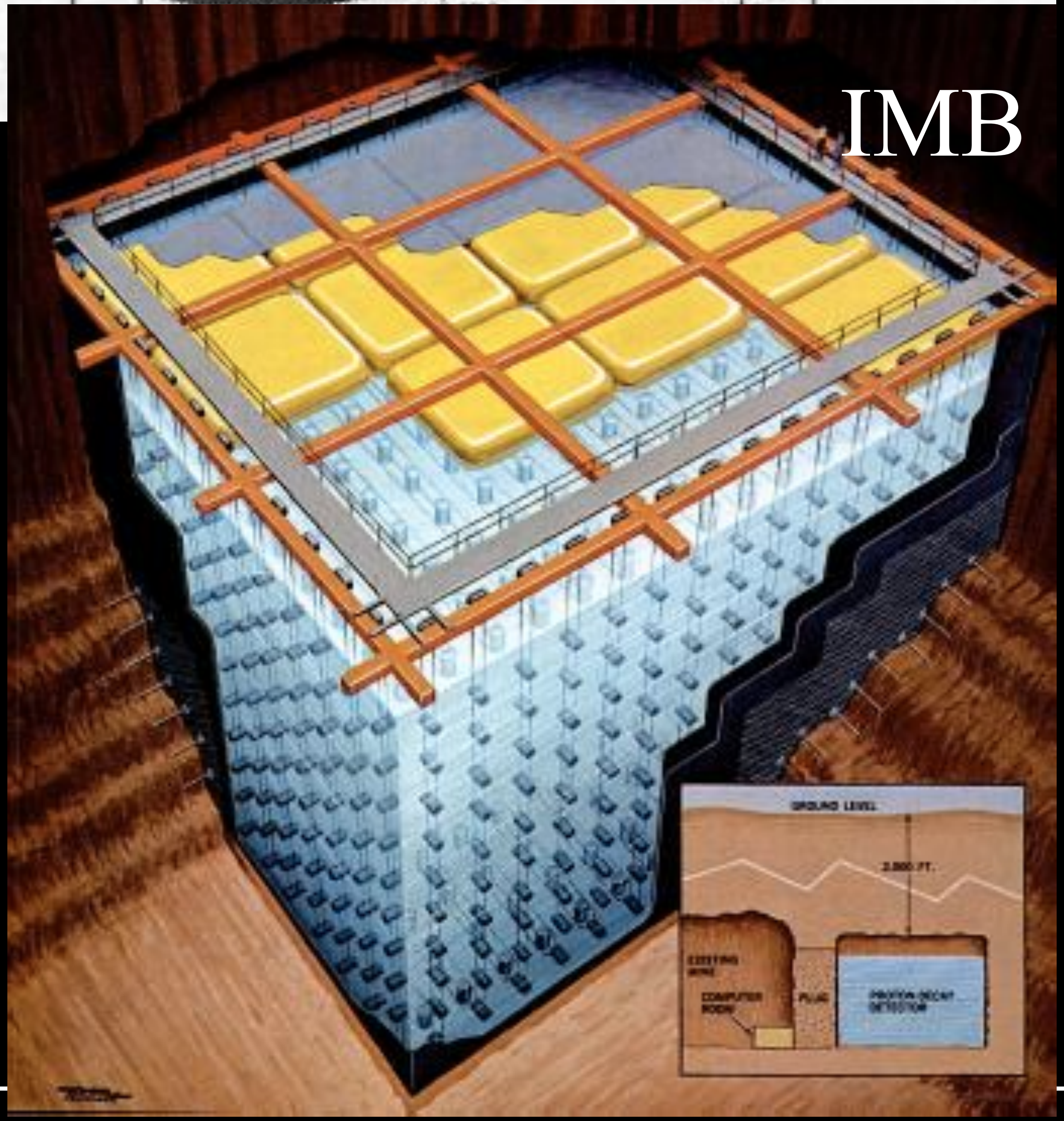


SUPERNOVA 1987A

- 160 light-years (close-by...)
- 10^{58} neutrinos emitted!! 24 were detected







THANK YOU !