Probing the Nature of Neutrinos

Opportunities for Discovery

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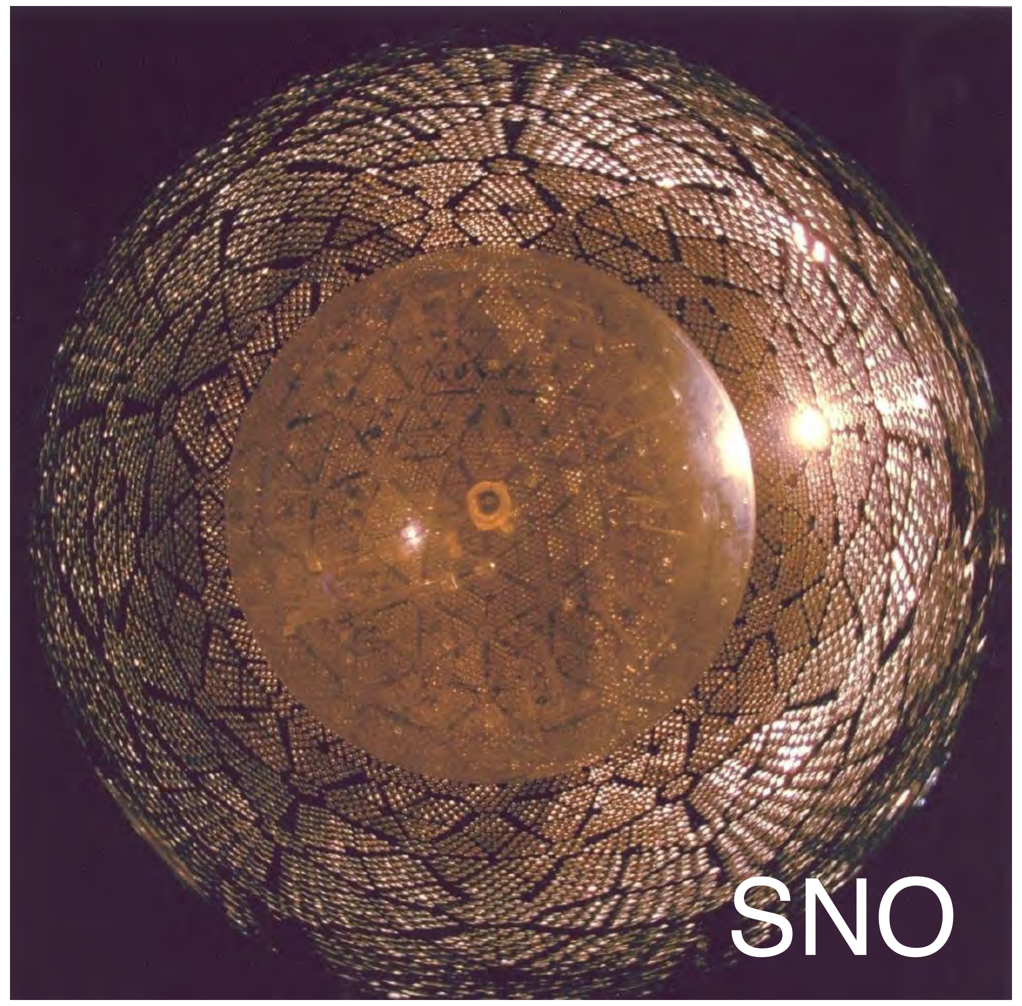
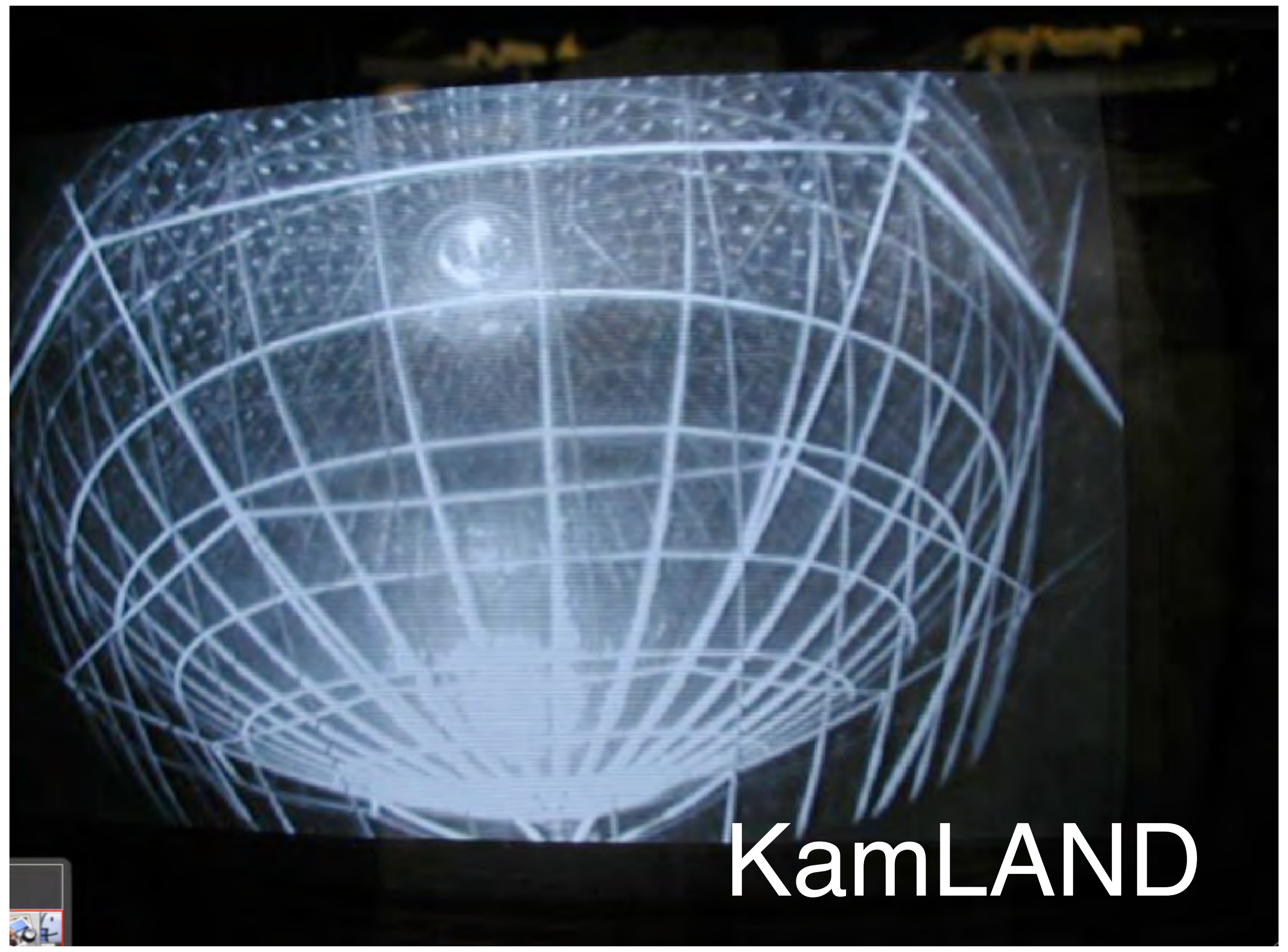
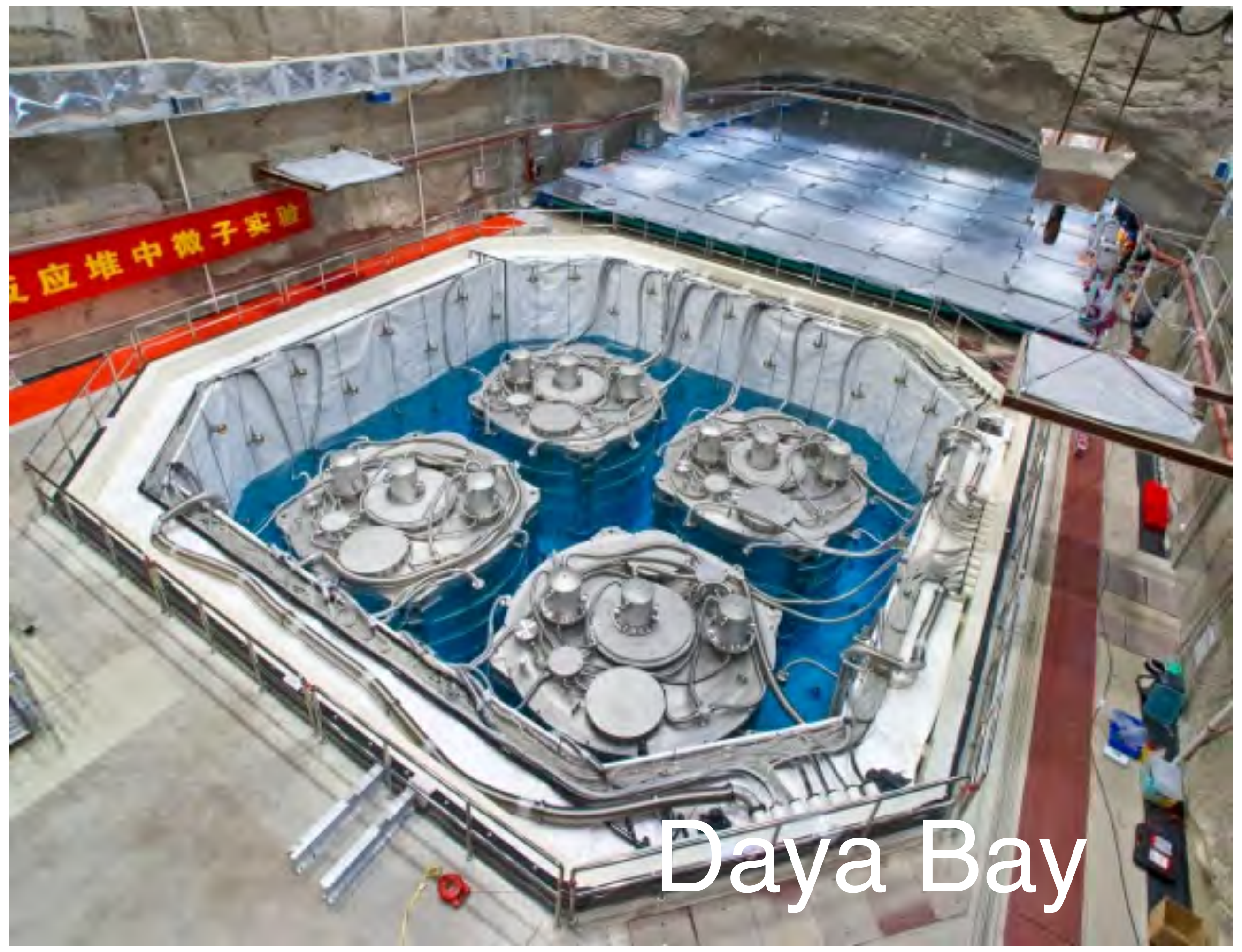
Wright Laboratory

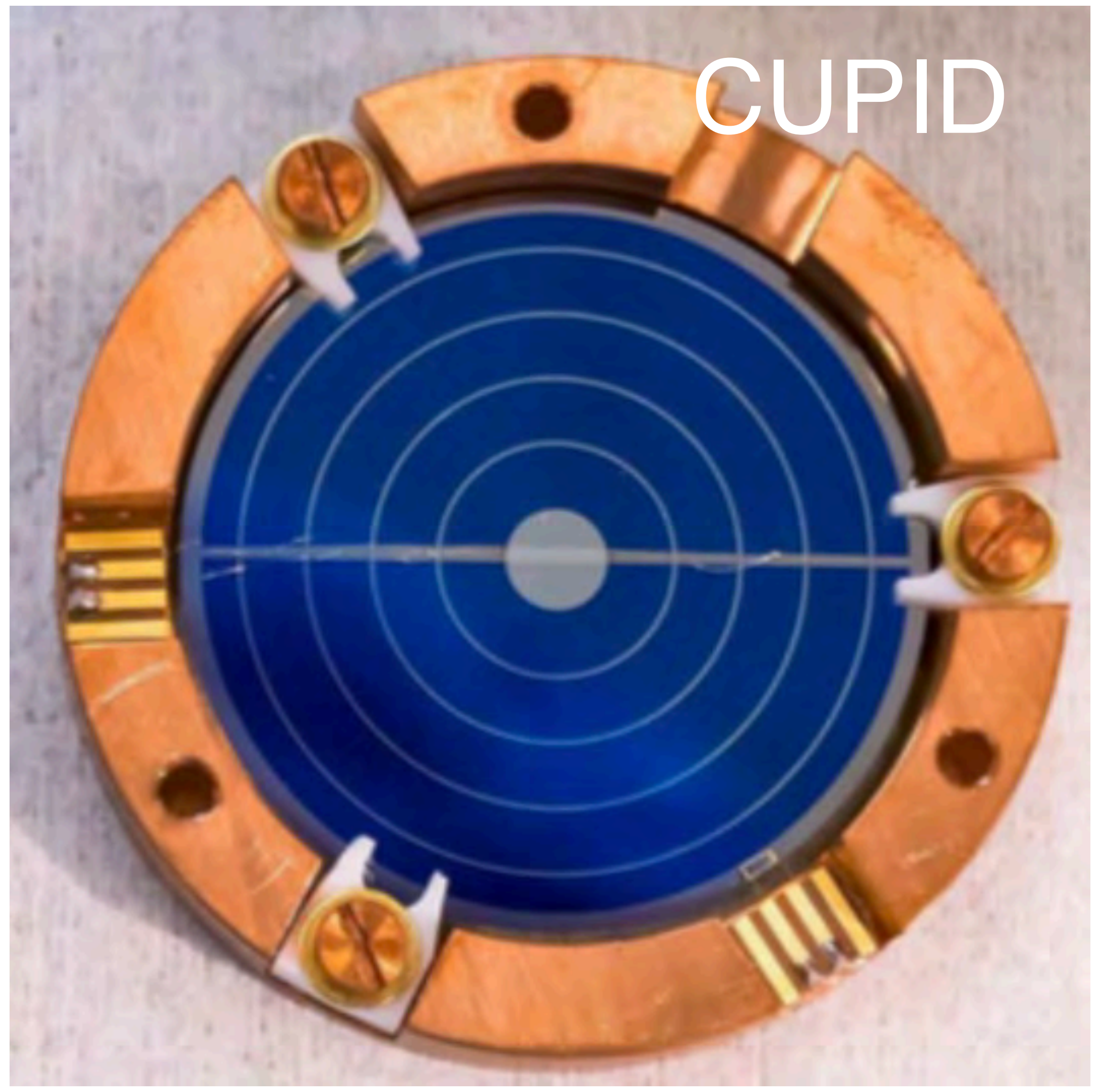
July 3, 2024

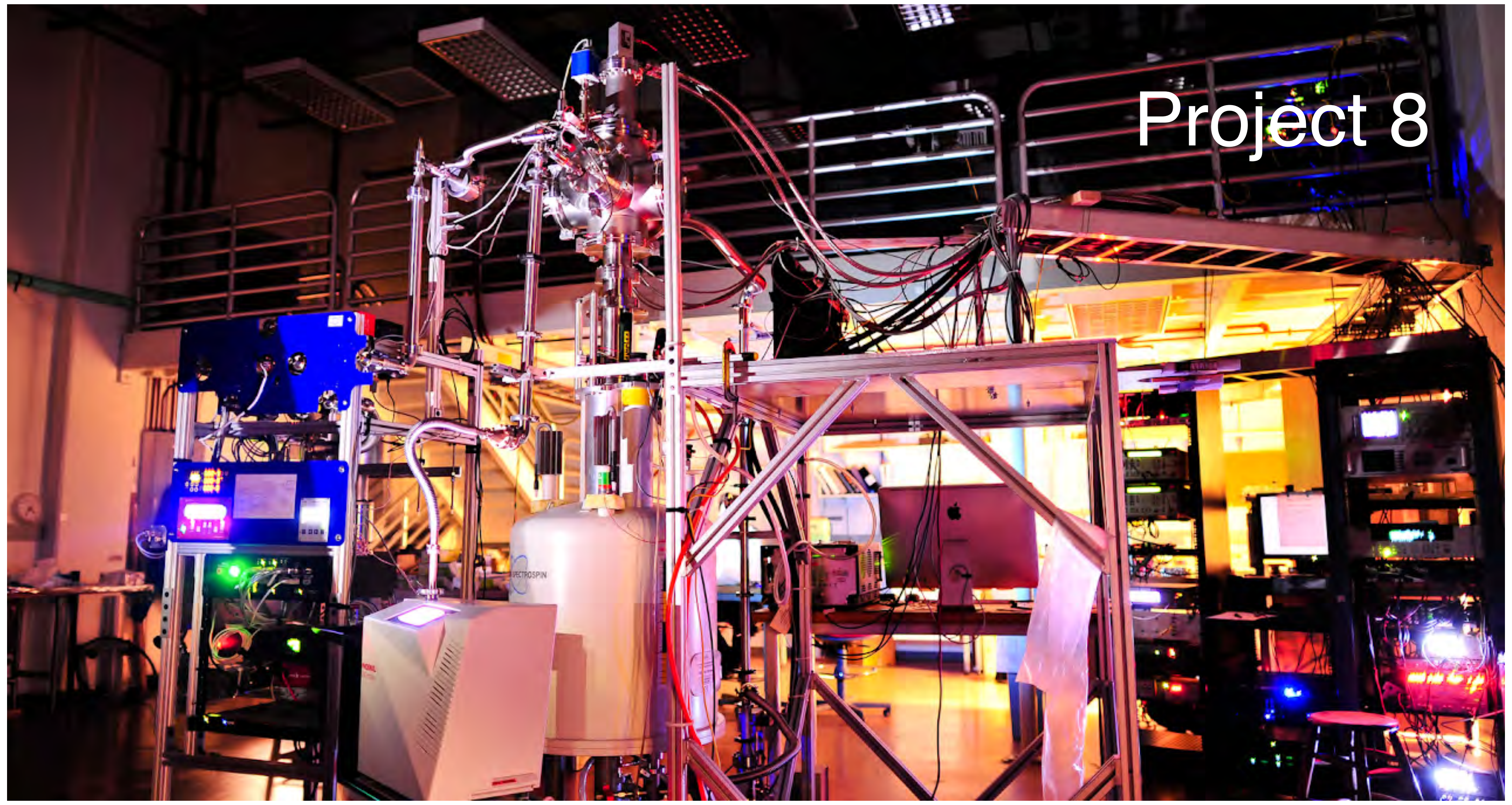
Probing the Nature of Neutrinos





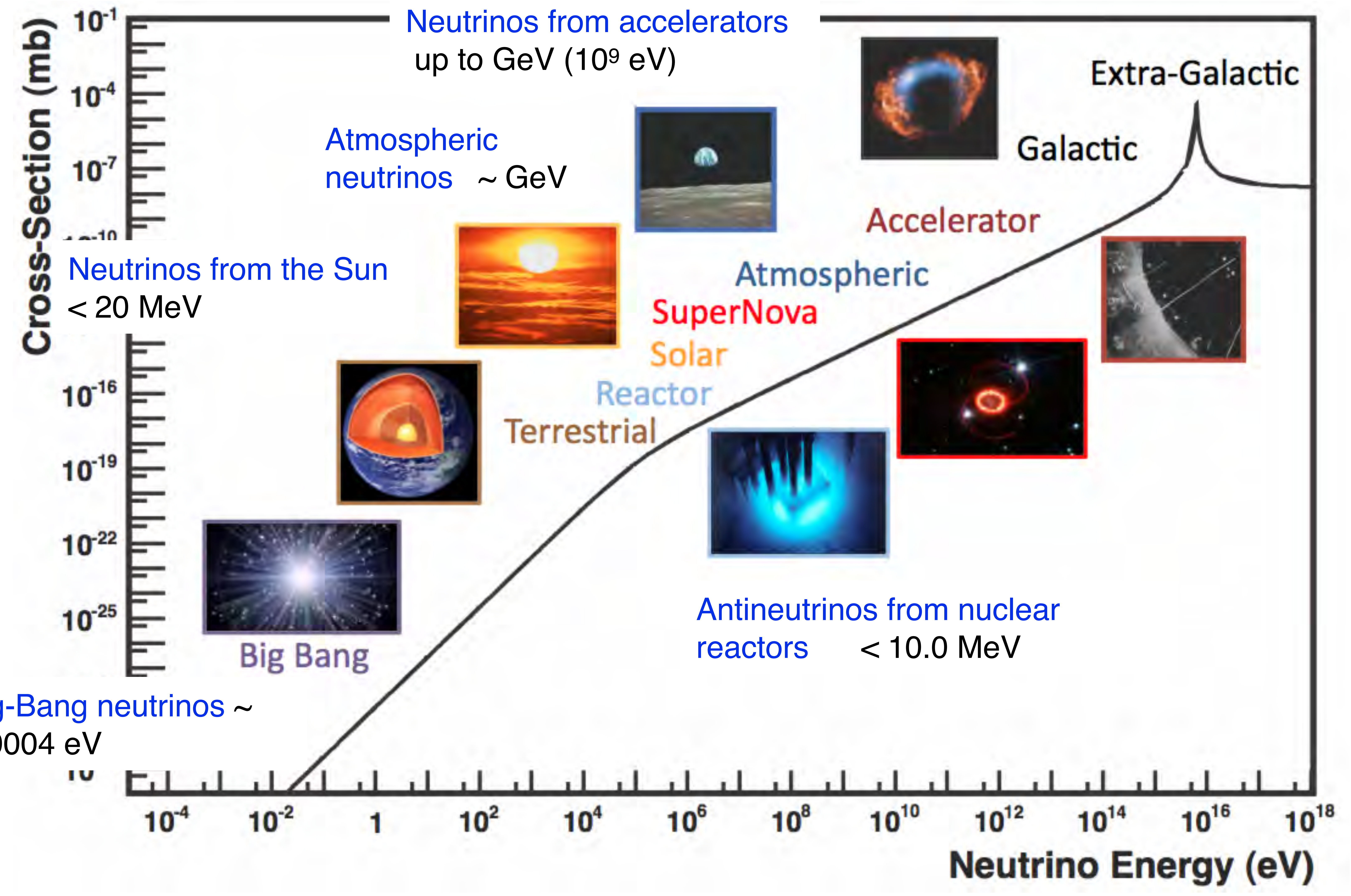






Opportunities for Discovery

Neutrinos in the Universe



Neutrinos from accelerators
up to GeV (10^9 eV)

Atmospheric neutrinos ~ GeV

Neutrinos from the Sun
< 20 MeV

Antineutrinos from nuclear reactors < 10.0 MeV

Big-Bang neutrinos ~ 0.0004 eV

nuclear decays
~ MeV energies

Beta Decays, Neutrinos, and Majorana

1930, Pauli

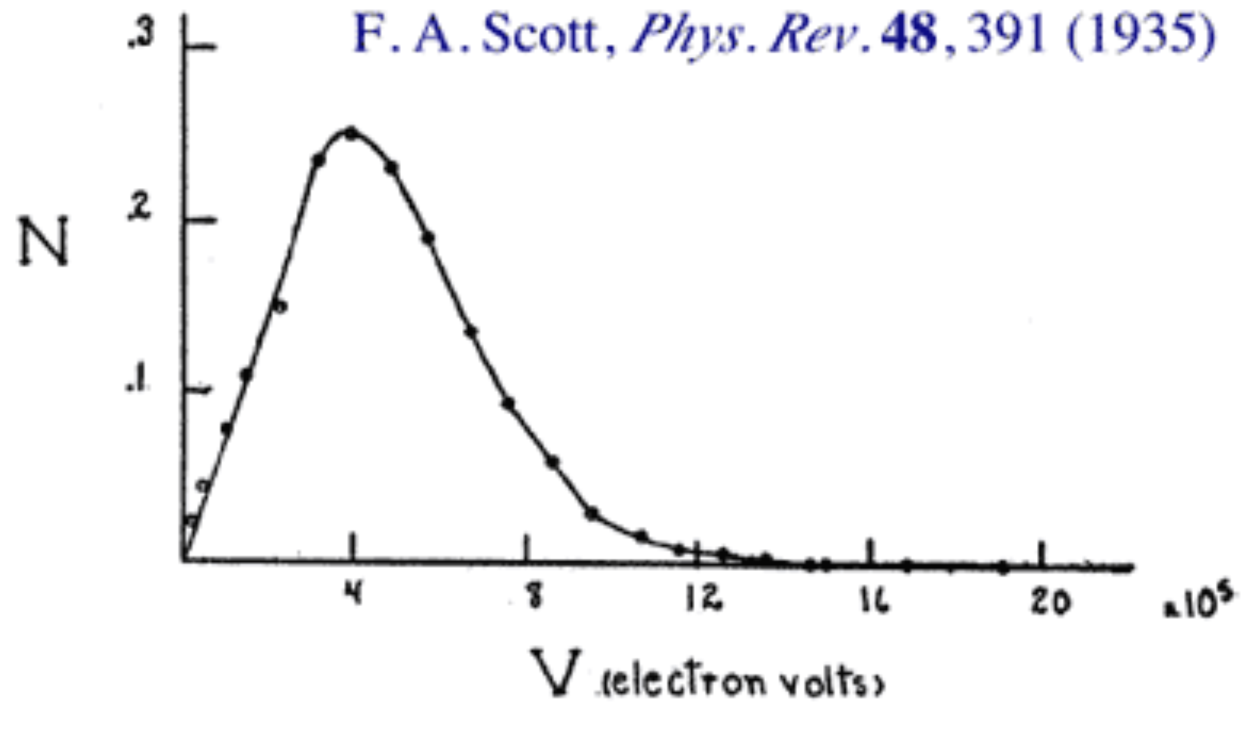
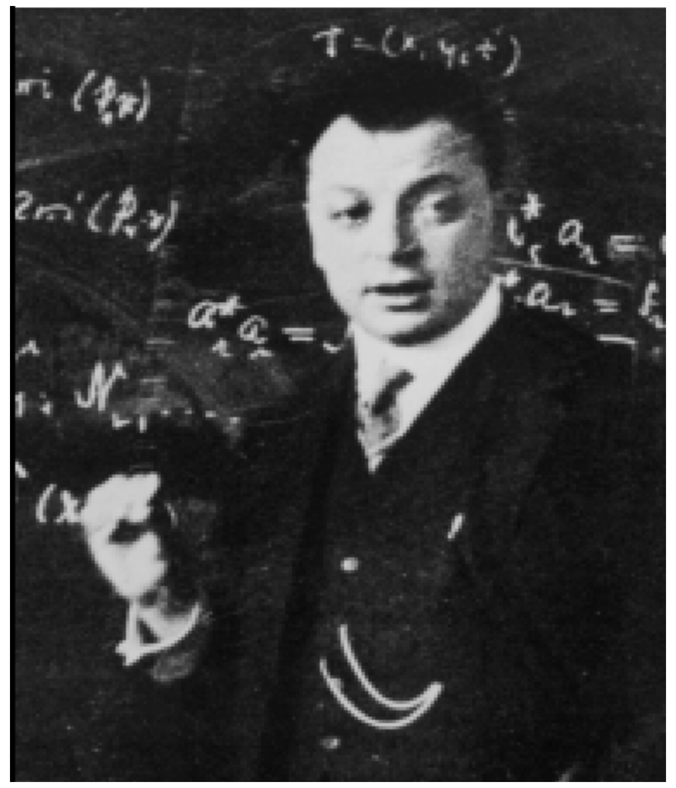
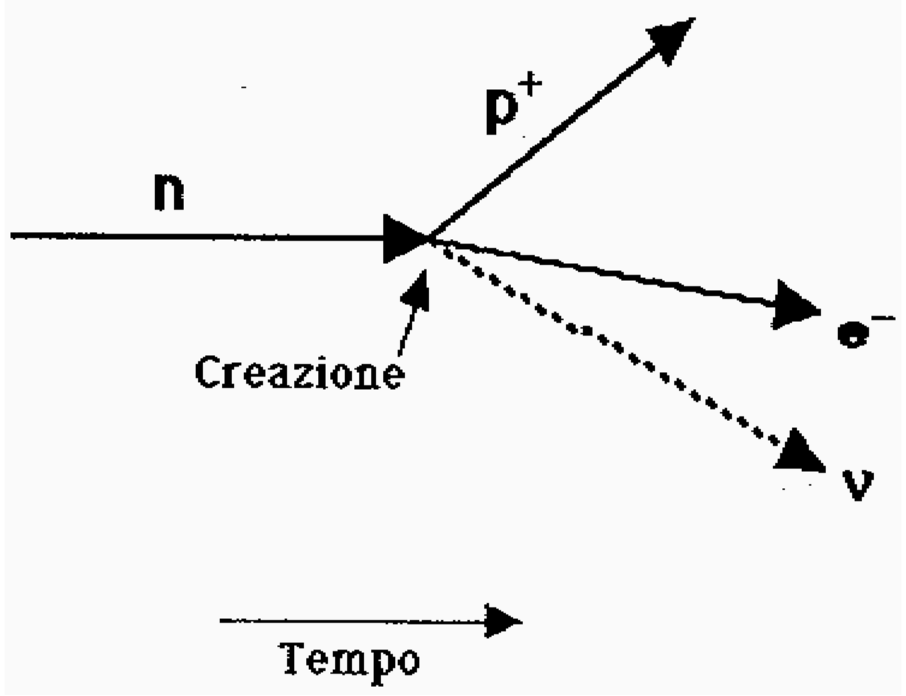
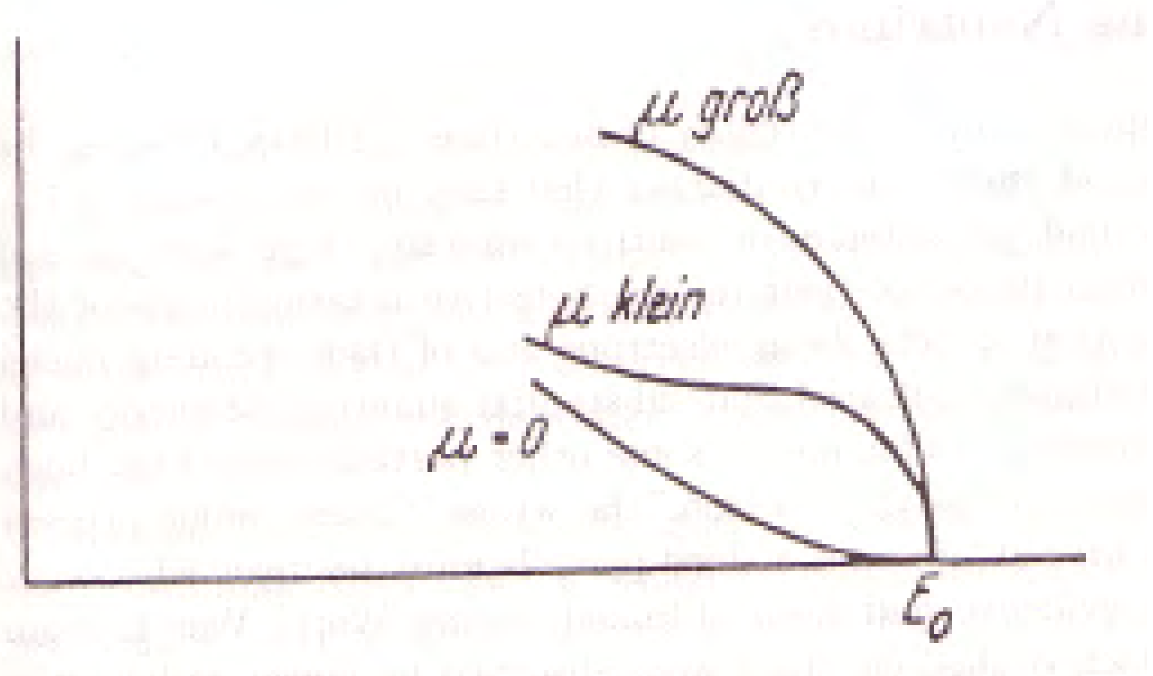


FIG. 5. Energy distribution curve of the beta-rays.

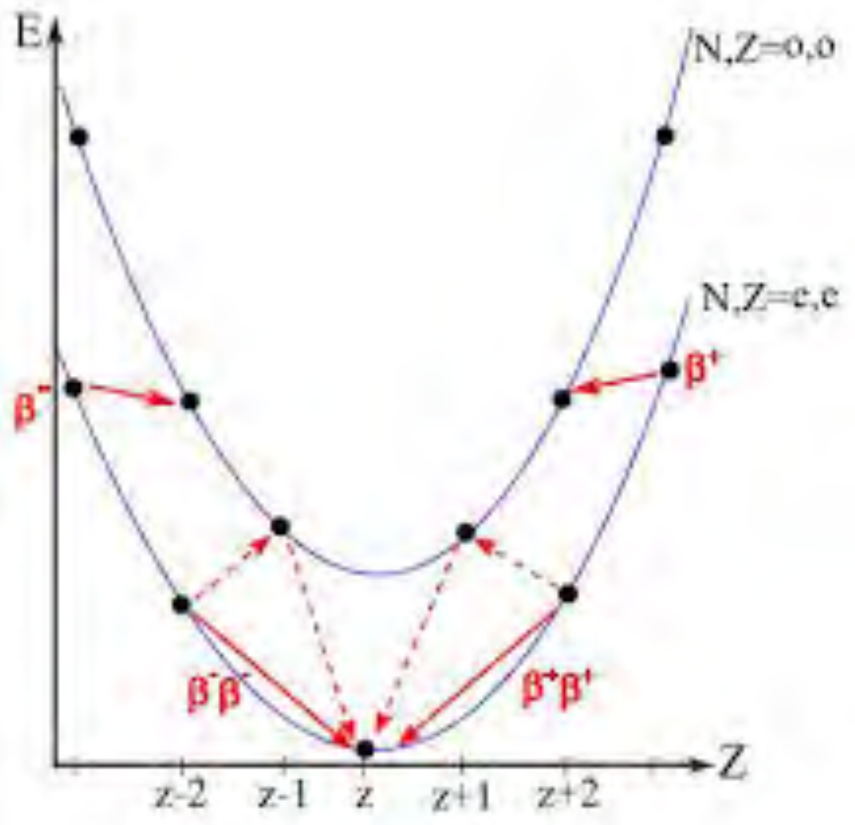


1932, Fermi

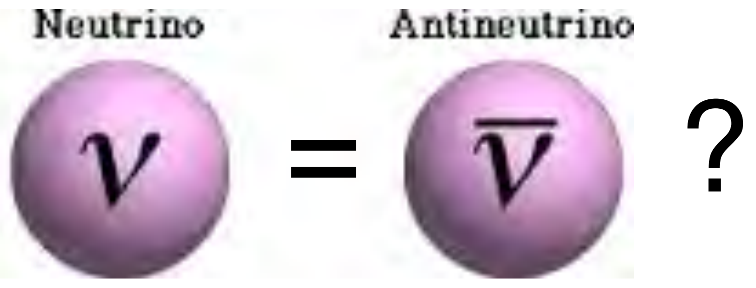


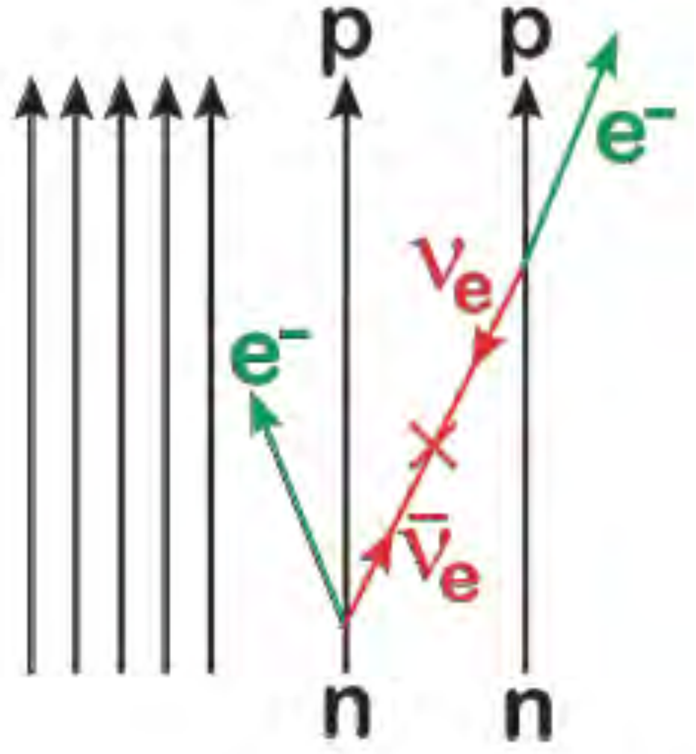


1935, Goeppert Mayer

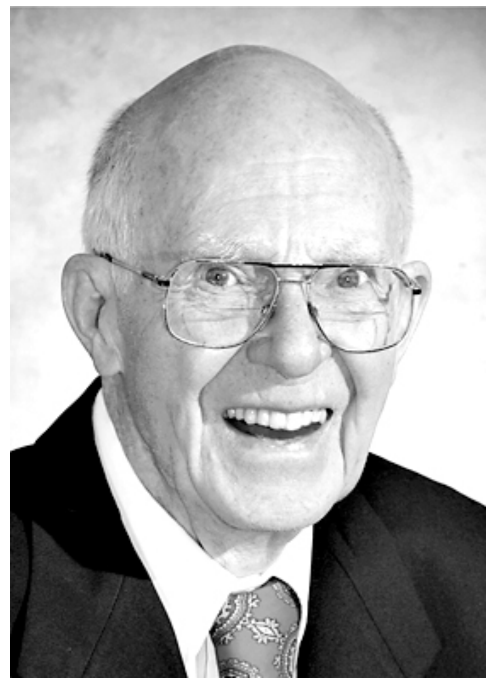


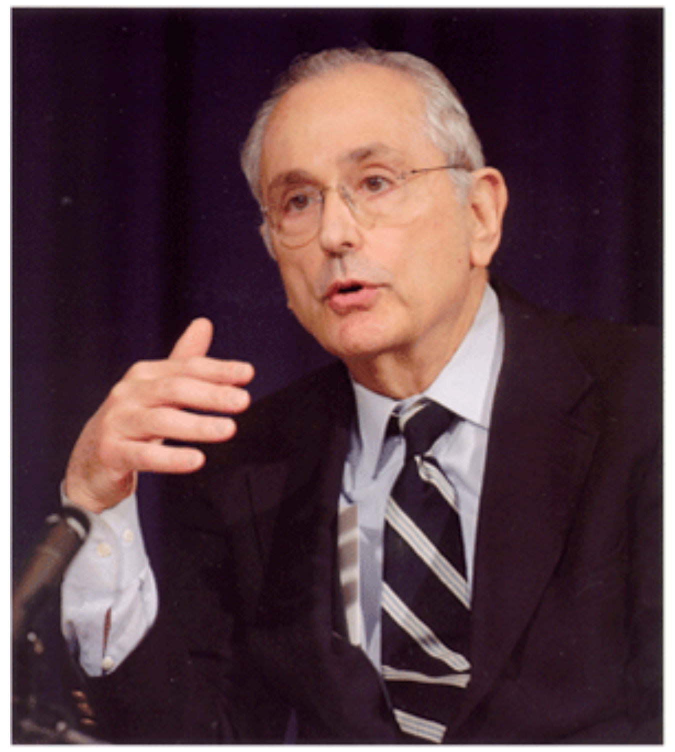
1937, Majorana





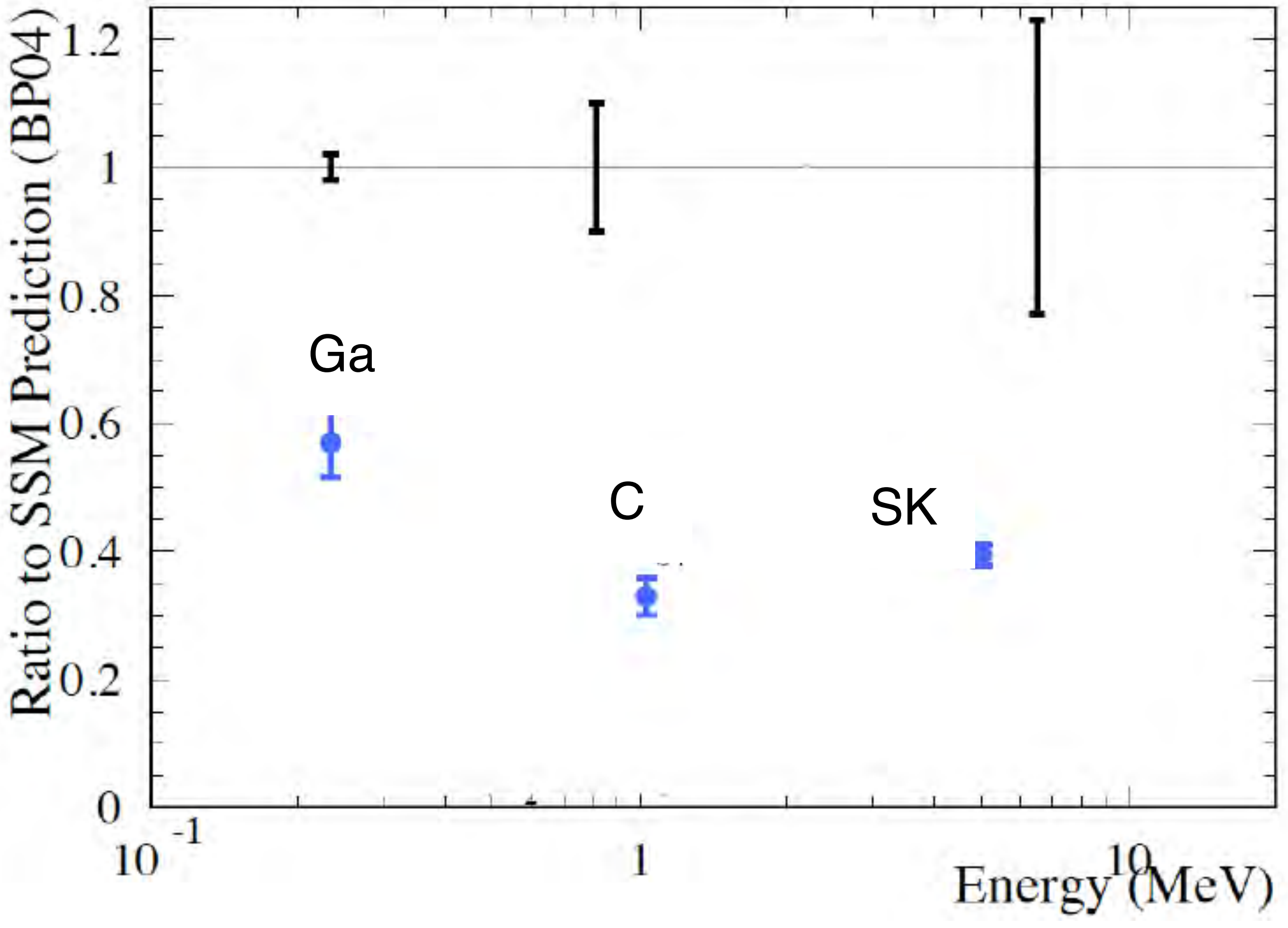
Neutrinos: From Anomalies to Precision Oscillation Physics





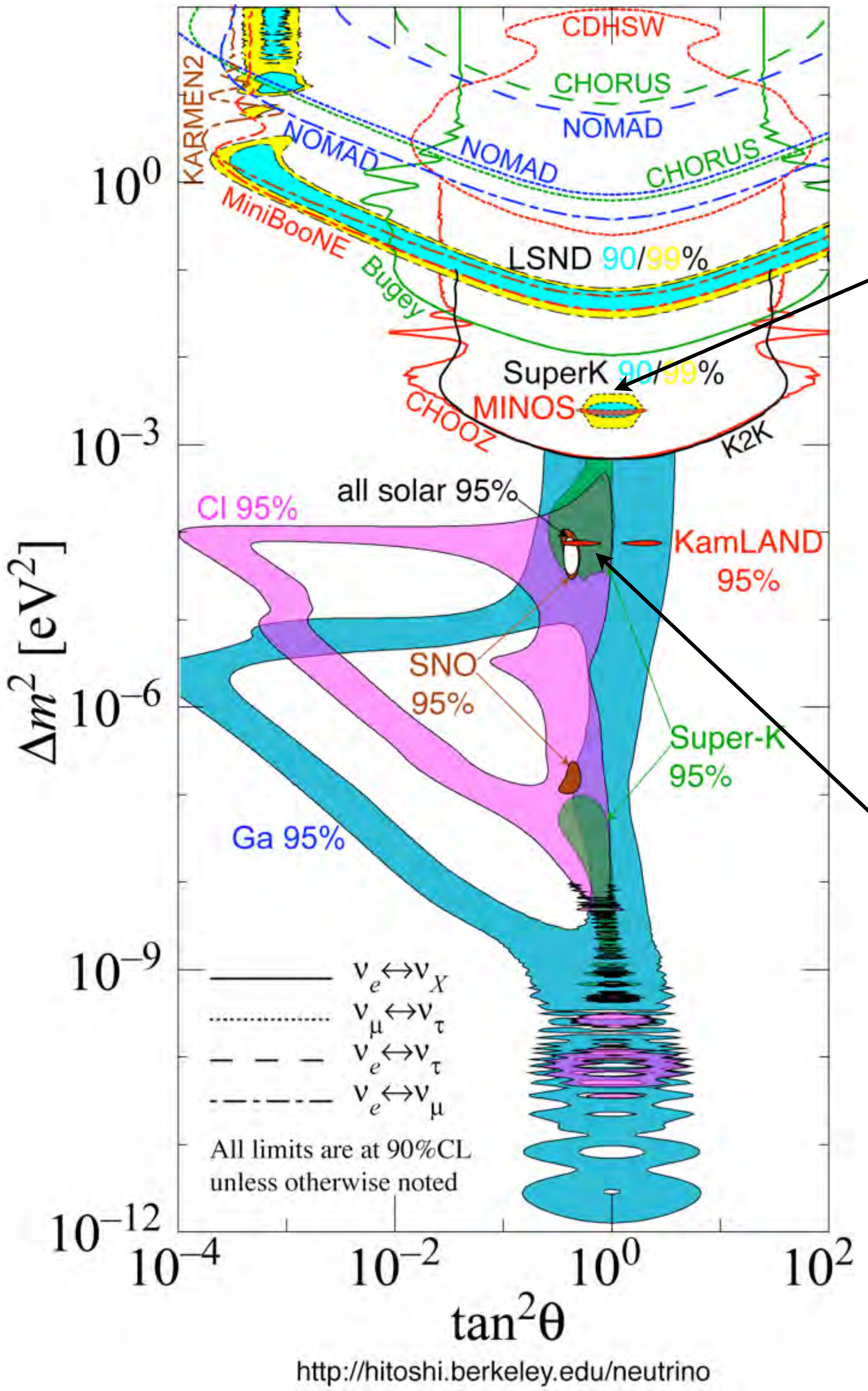
1960 -1990

solar neutrino problem



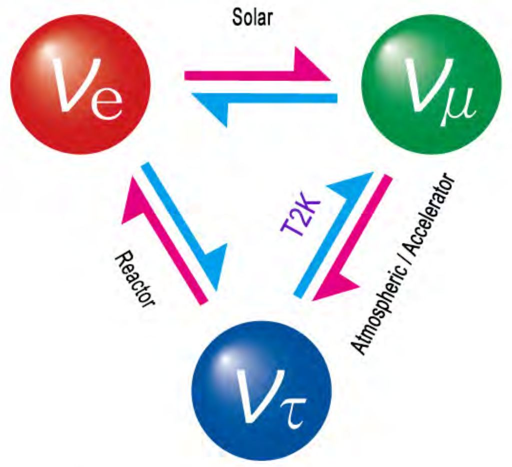
1990 - 2000

oscillation searches



atmospheric/beam neutrinos

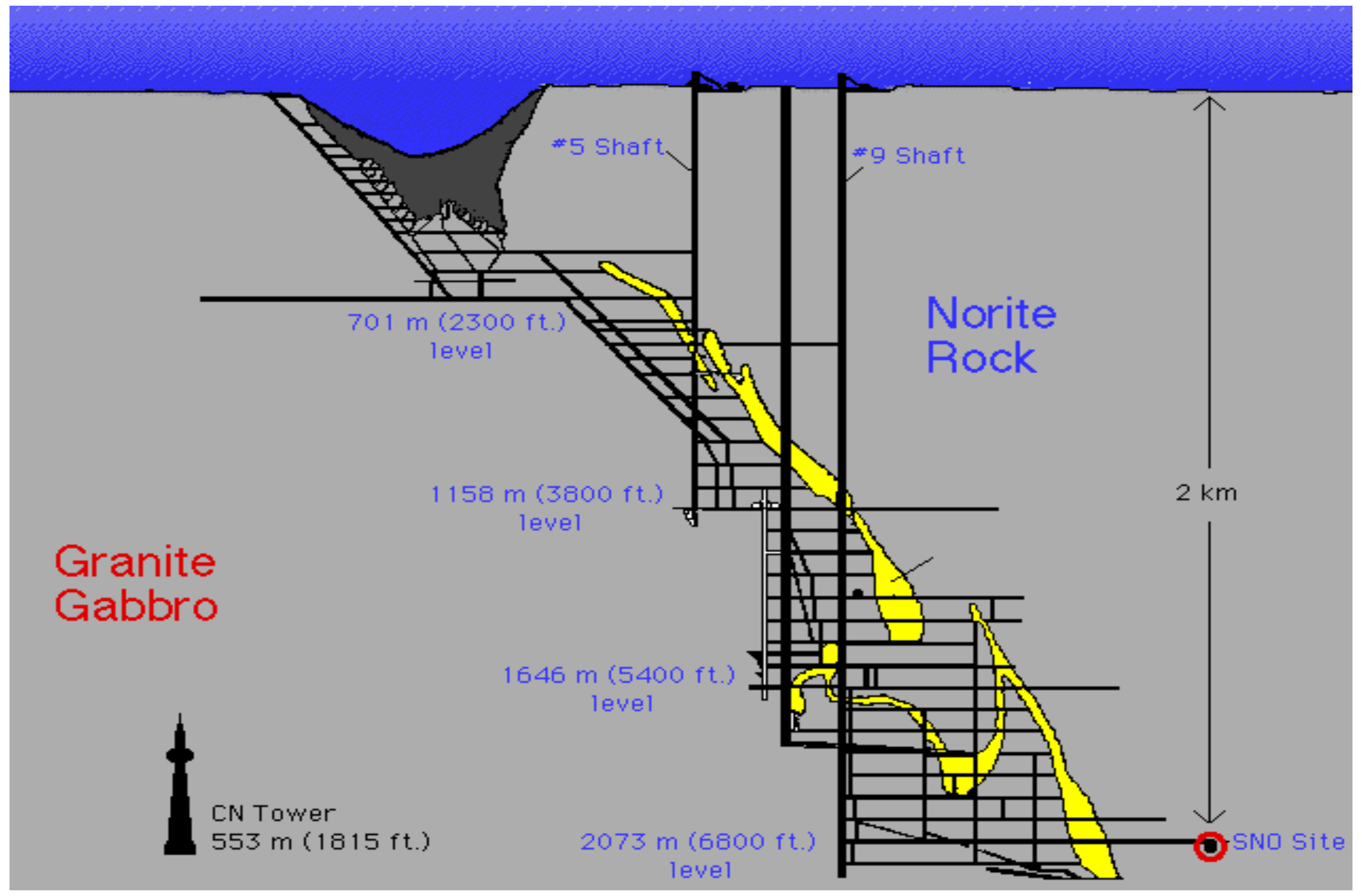
θ_{23}, Δm^2_{23}



solar/reactor neutrinos

θ_{12}, Δm^2_{12}

Sudbury Neutrino Observatory



1000 tonnes D_2O

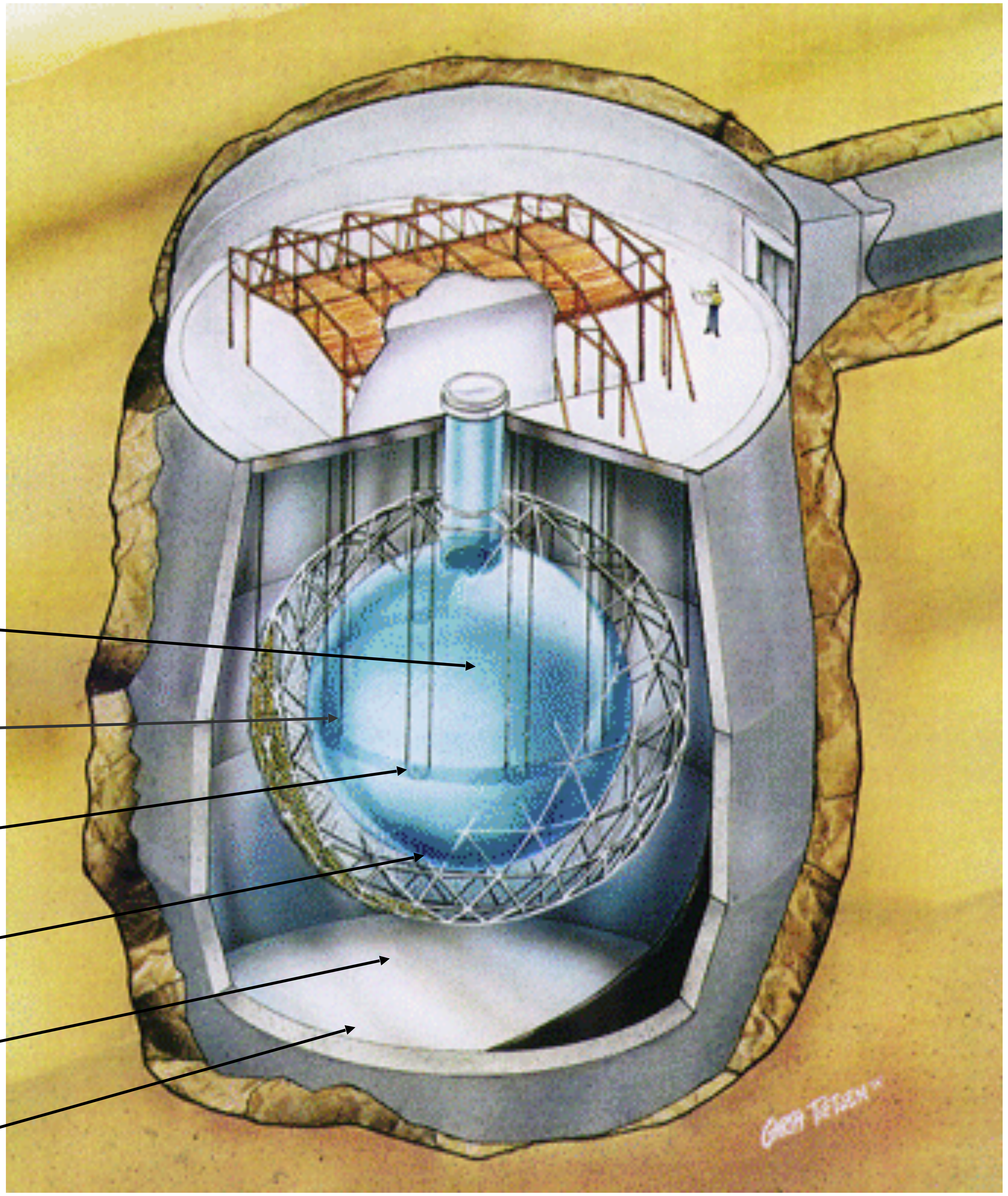
Support Structure for 9456 PMTs, 60% coverage

12 m Diameter Acrylic Vessel

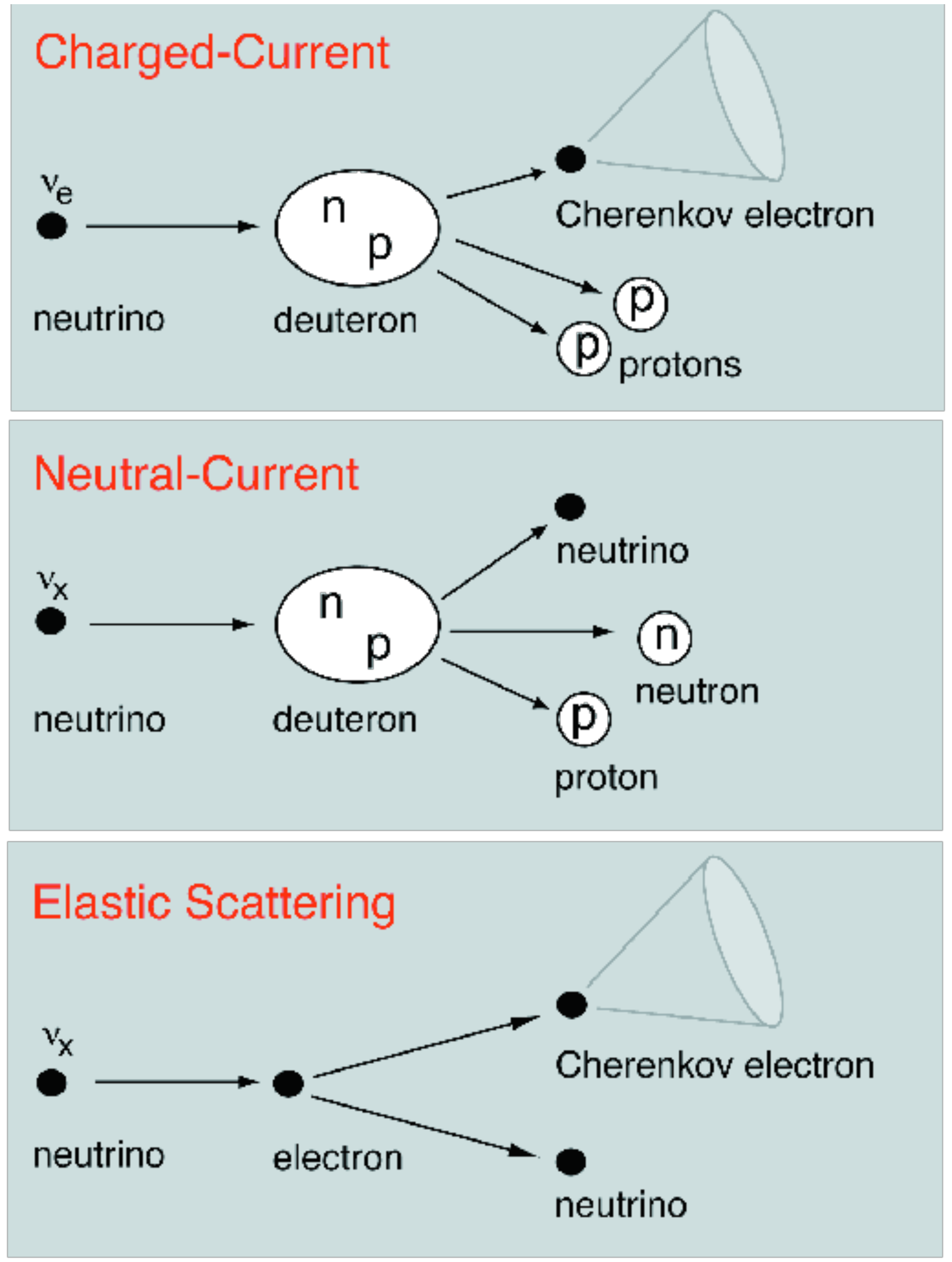
1700 tonnes Inner Shielding H_2O

5300 tonnes Outer Shield H_2O

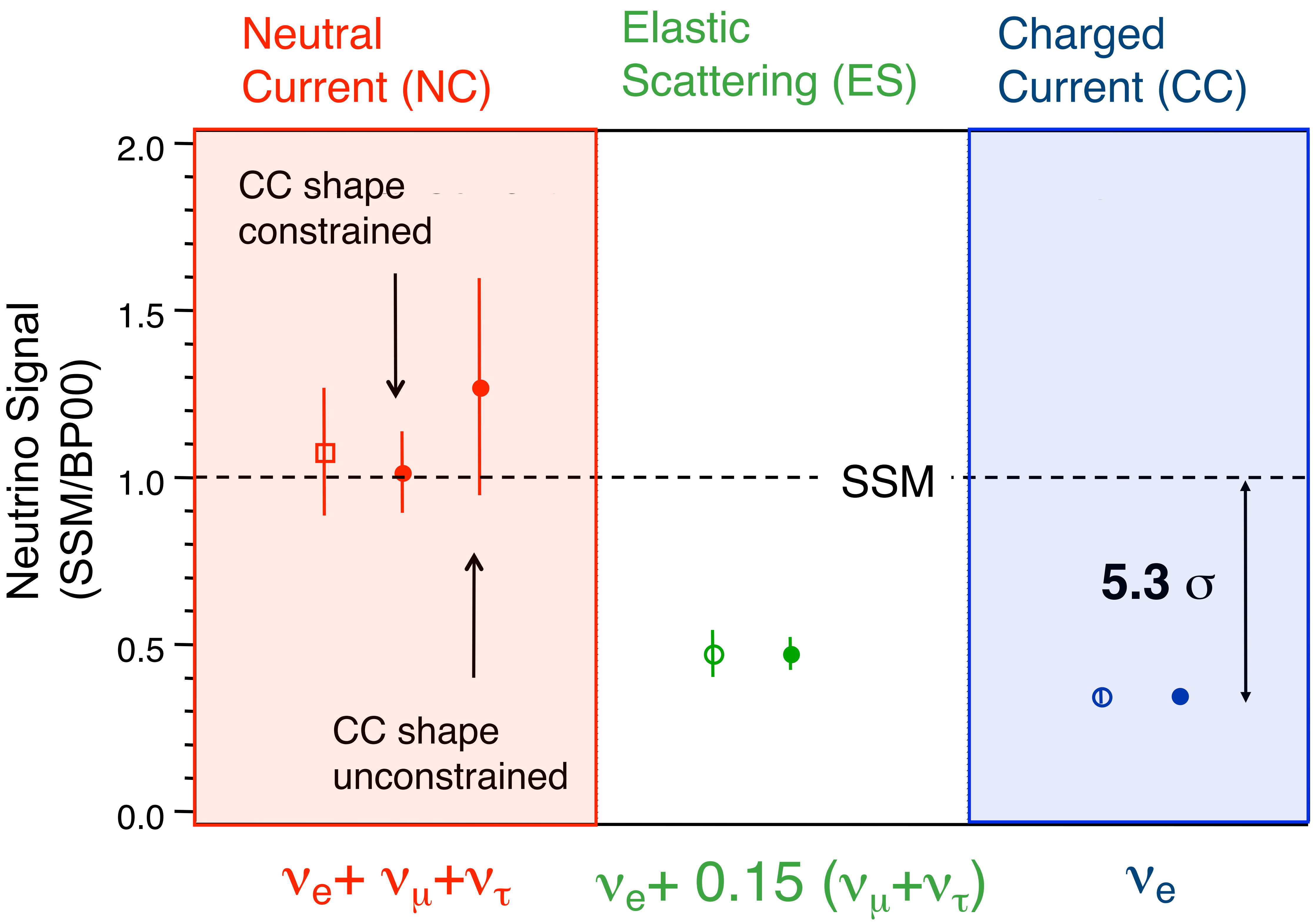
Urylon Liner and Radon Seal



Nucl. Inst. and Meth. A449, p172 (2000)



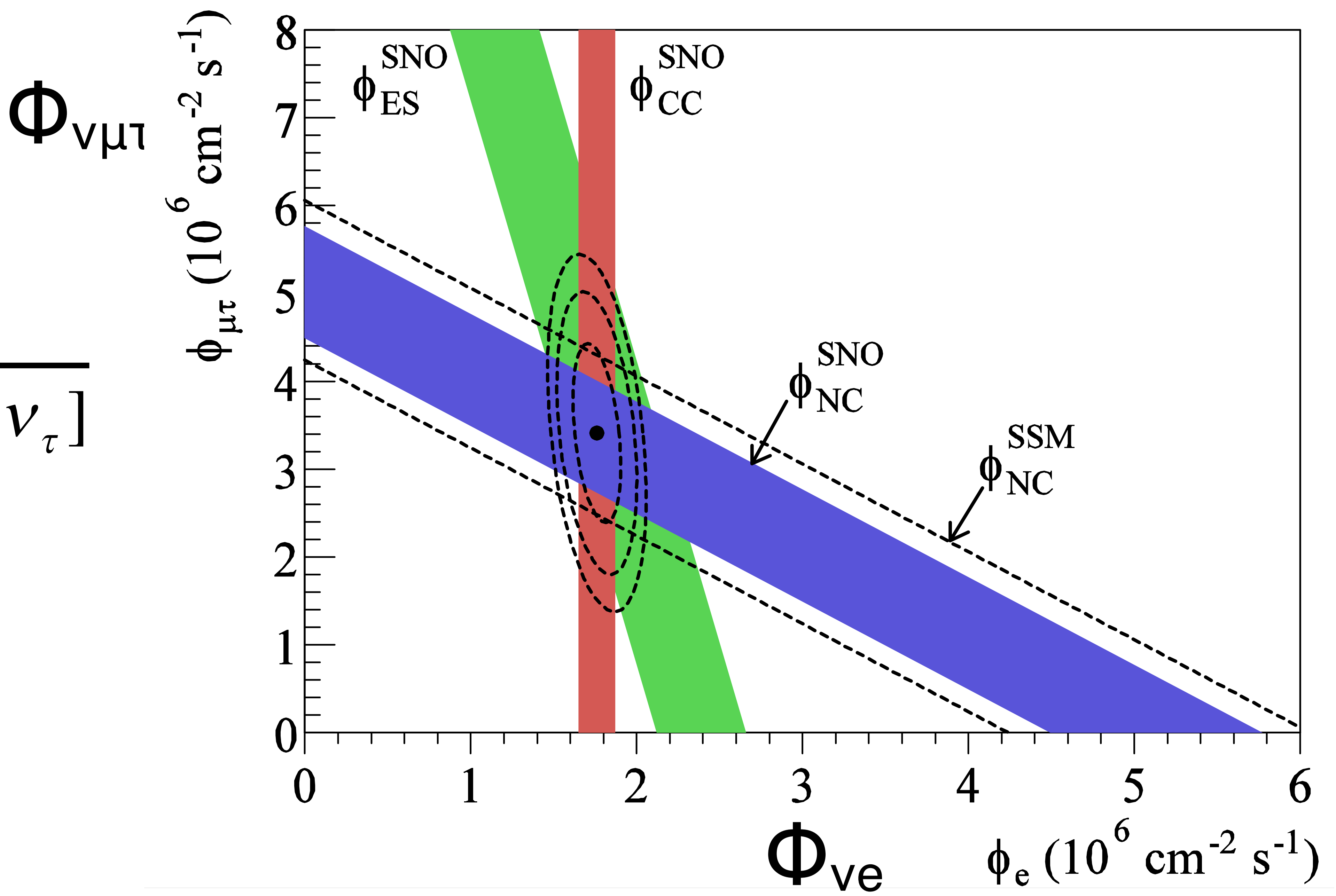
Resolution of the Solar Neutrino Problem with SNO



Total Neutrino flux ***Electron Neutrino flux*** 2002

$$\frac{[CC]}{[NC]} = \frac{[\nu_e]}{[\nu_e + \nu_\mu + \nu_\tau]}$$

^{8}B Solar Neutrino Flux

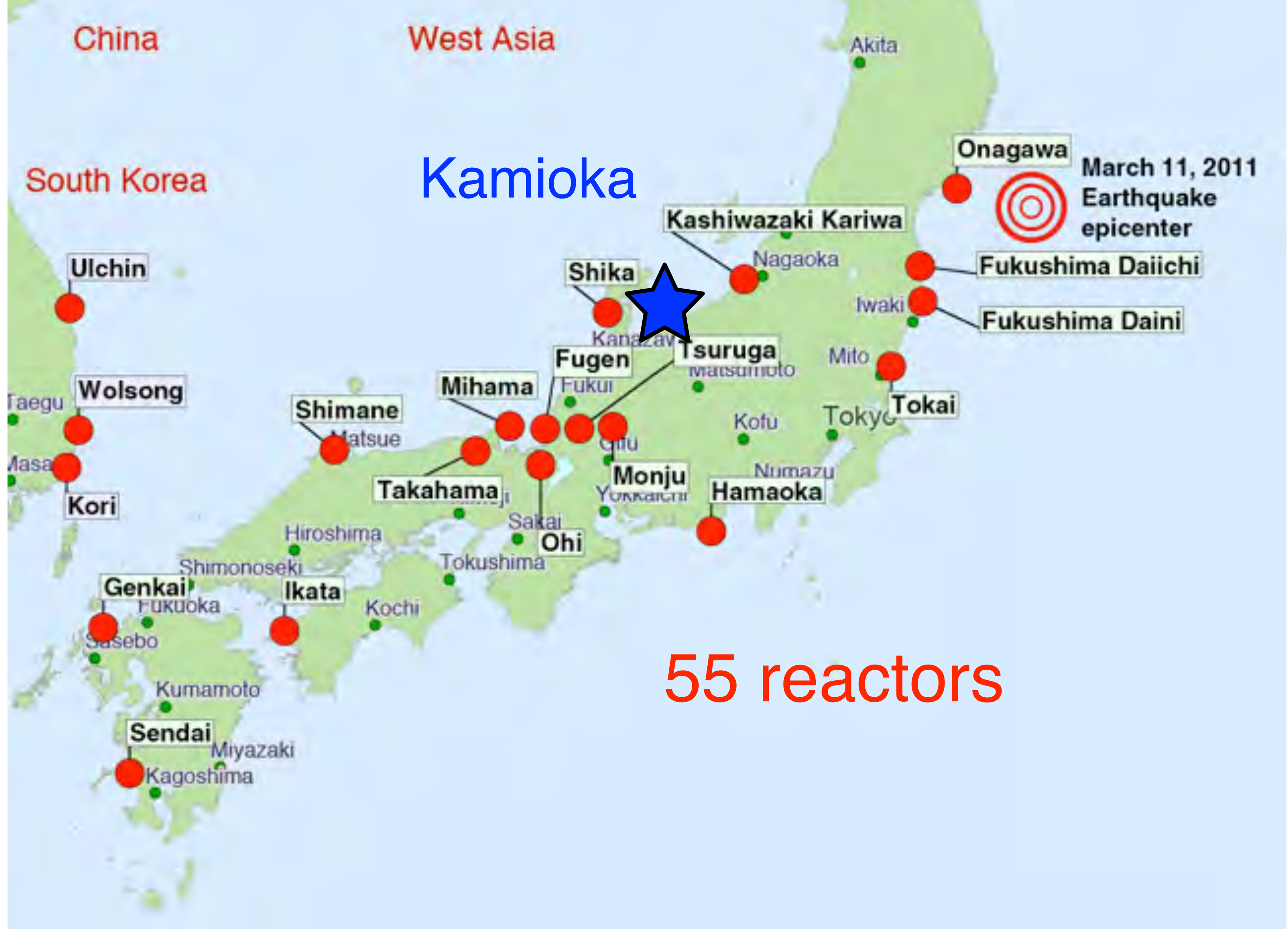


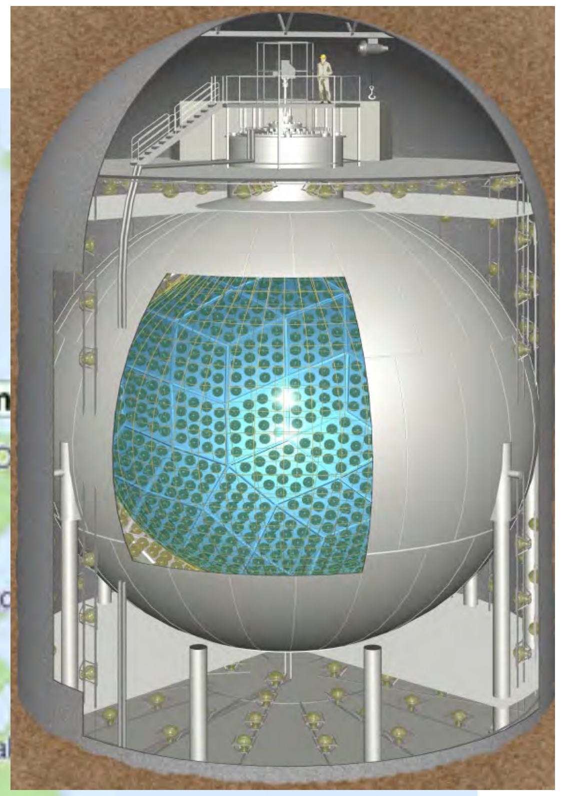
total flux of active solar neutrinos agrees with solar models

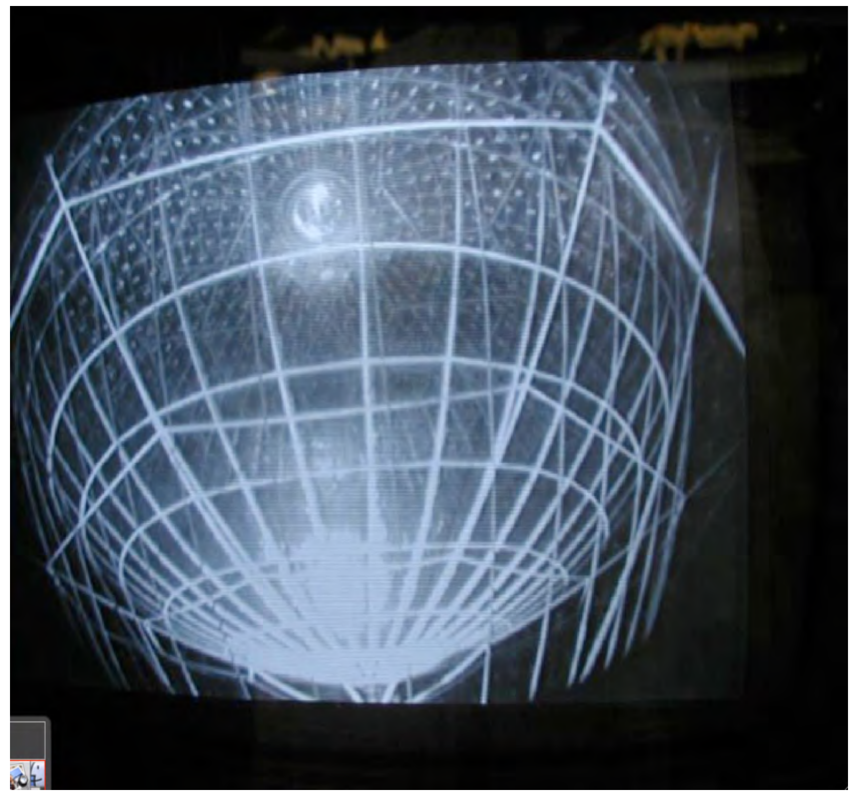
~2/3 of initial solar ν_e are observed at SNO to be $\nu_{\mu,\tau}$
total flux of active solar neutrinos agrees with solar models

Observation of Reactor $\bar{\nu}_e$ Disappearance

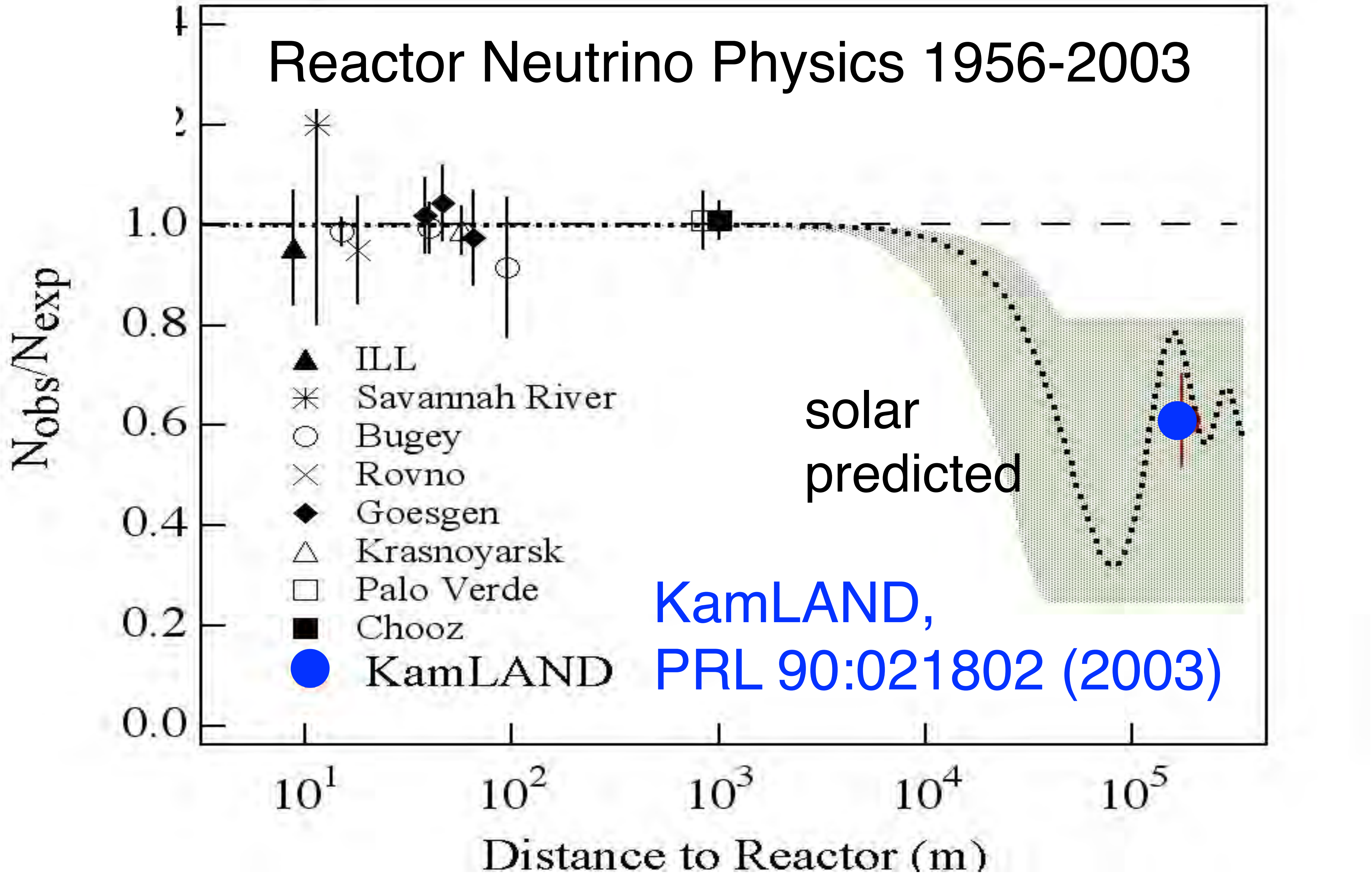
KamLAND 2003





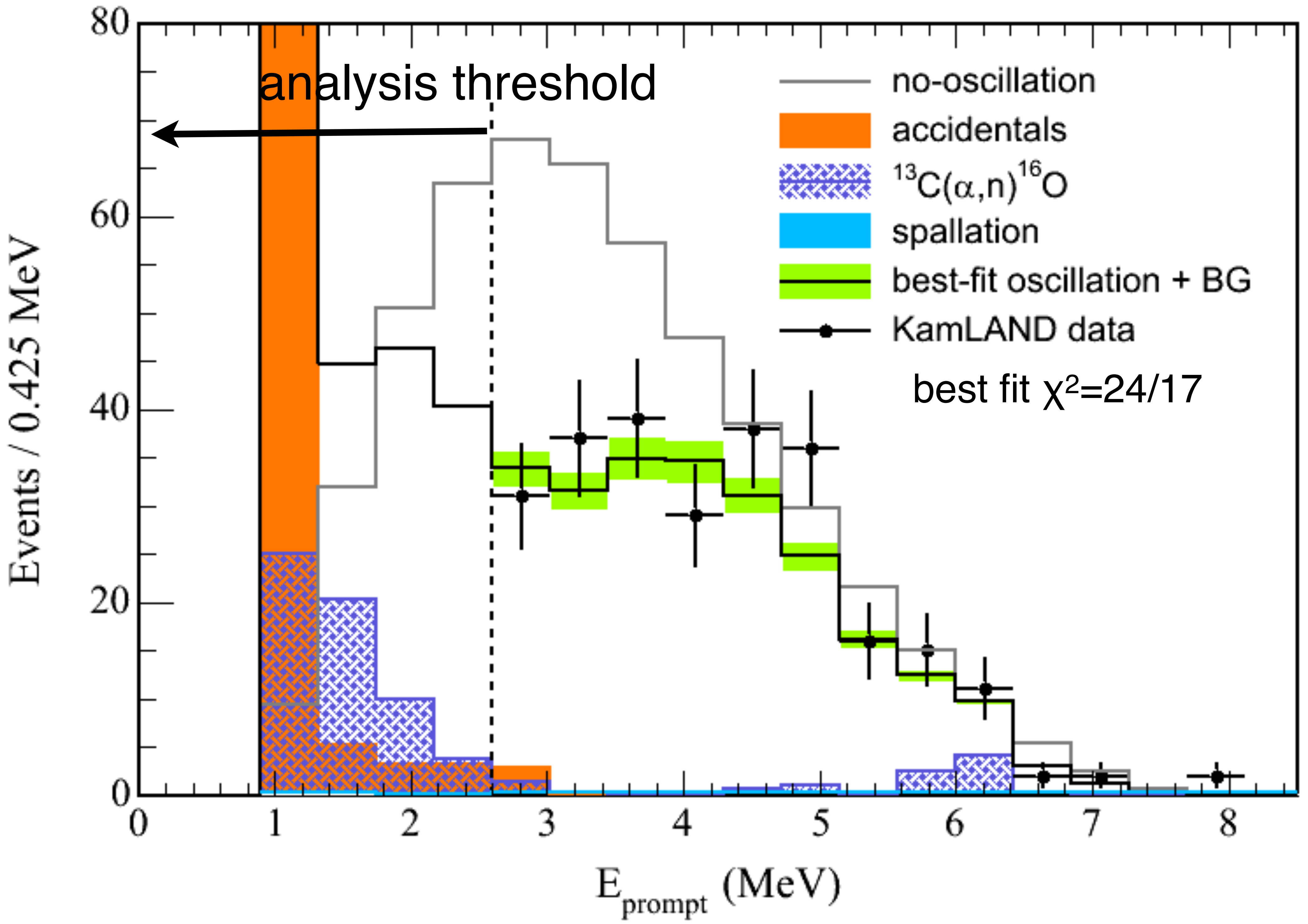


1kt liquid scintillator detector



mean, flux-weighted reactor distance ~ 180km

Evidence of Spectral Distortion with KamLAND



Observed ν_e	258 events
No-Oscillation	365.2 ± 23.7 (syst.)
Background	17.8 ± 7.3 events
Livetime:	766.3 ton-yr

fiducial volume syst.: 4.7%

total systematics = 6.5%

^{210}Pb → ^{210}Bi → ^{210}Po —(138d, α)→ ^{206}Pb

→ ^{13}C(α,n)^{16}O (~10^{-7})

^{222}Rn decay chain introduced in the LS during assembly

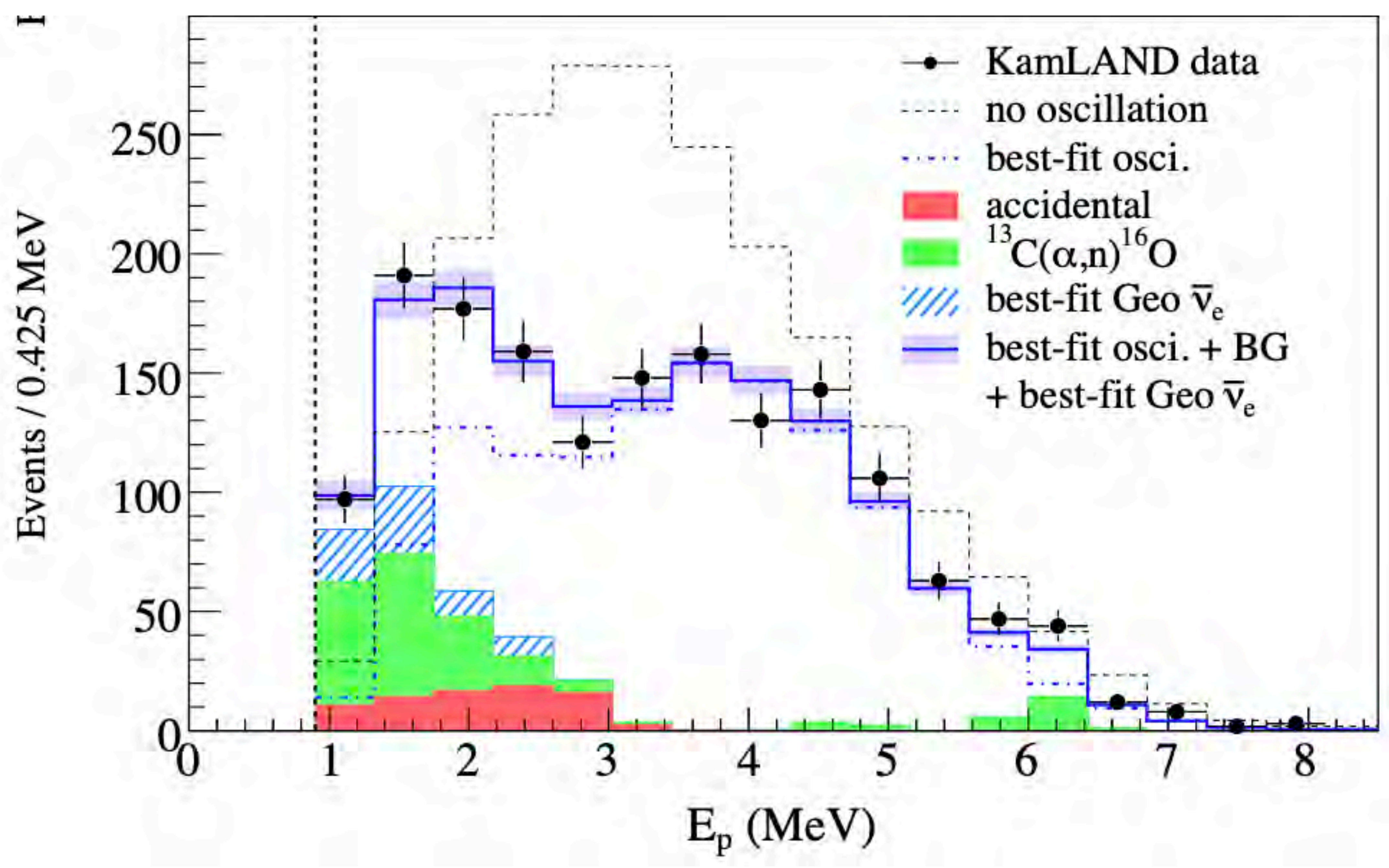
Spectral Distortions: A unique signature of neutrino oscillation!

Simple, rescaled reactor spectrum is excluded at 99.6% CL(χ^2=37.3/18)

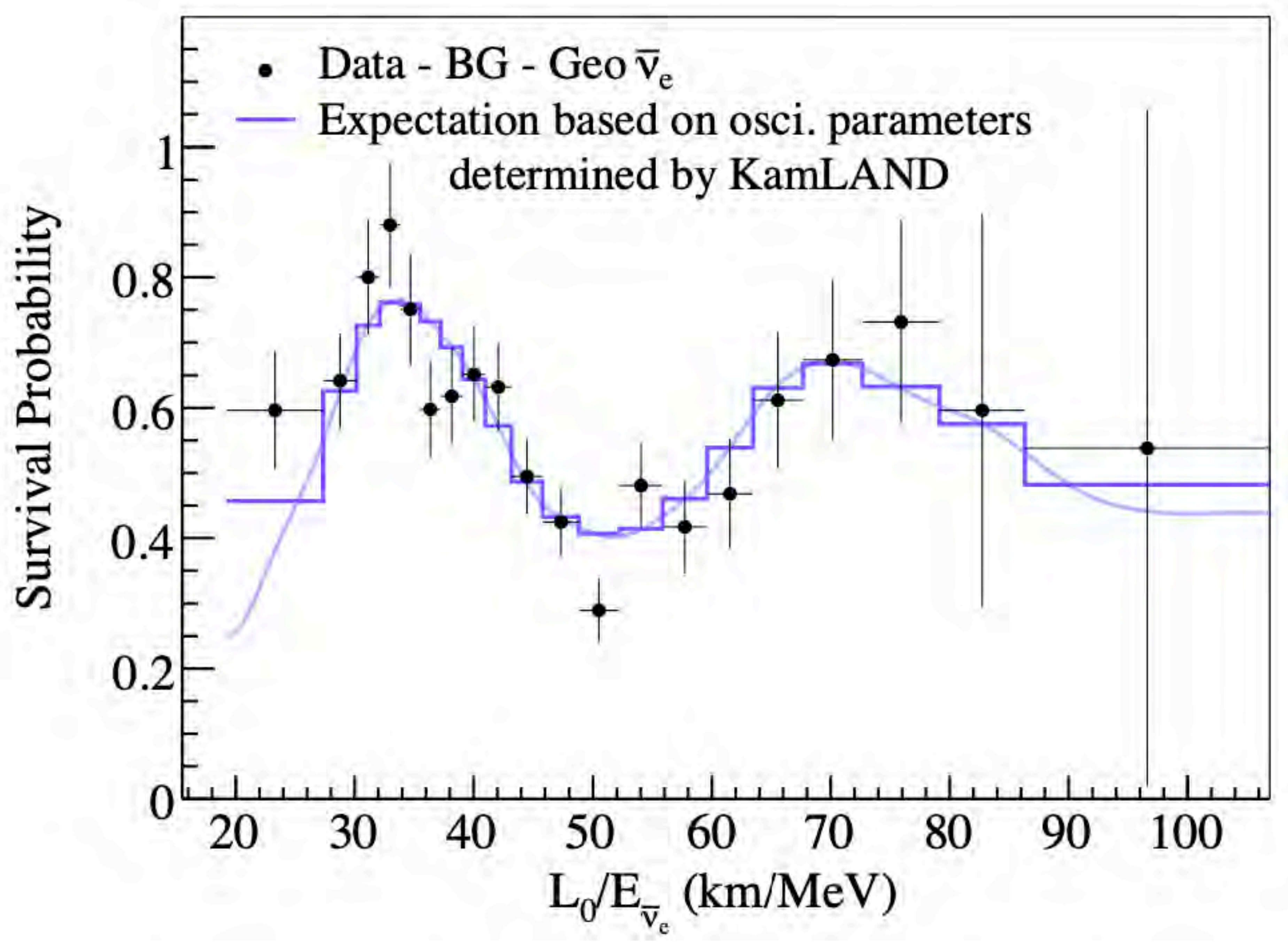
2004

Direct Evidence for Neutrino Oscillation

Reactor $\bar{\nu}_e$ Disappearance



Evidence for Oscillation



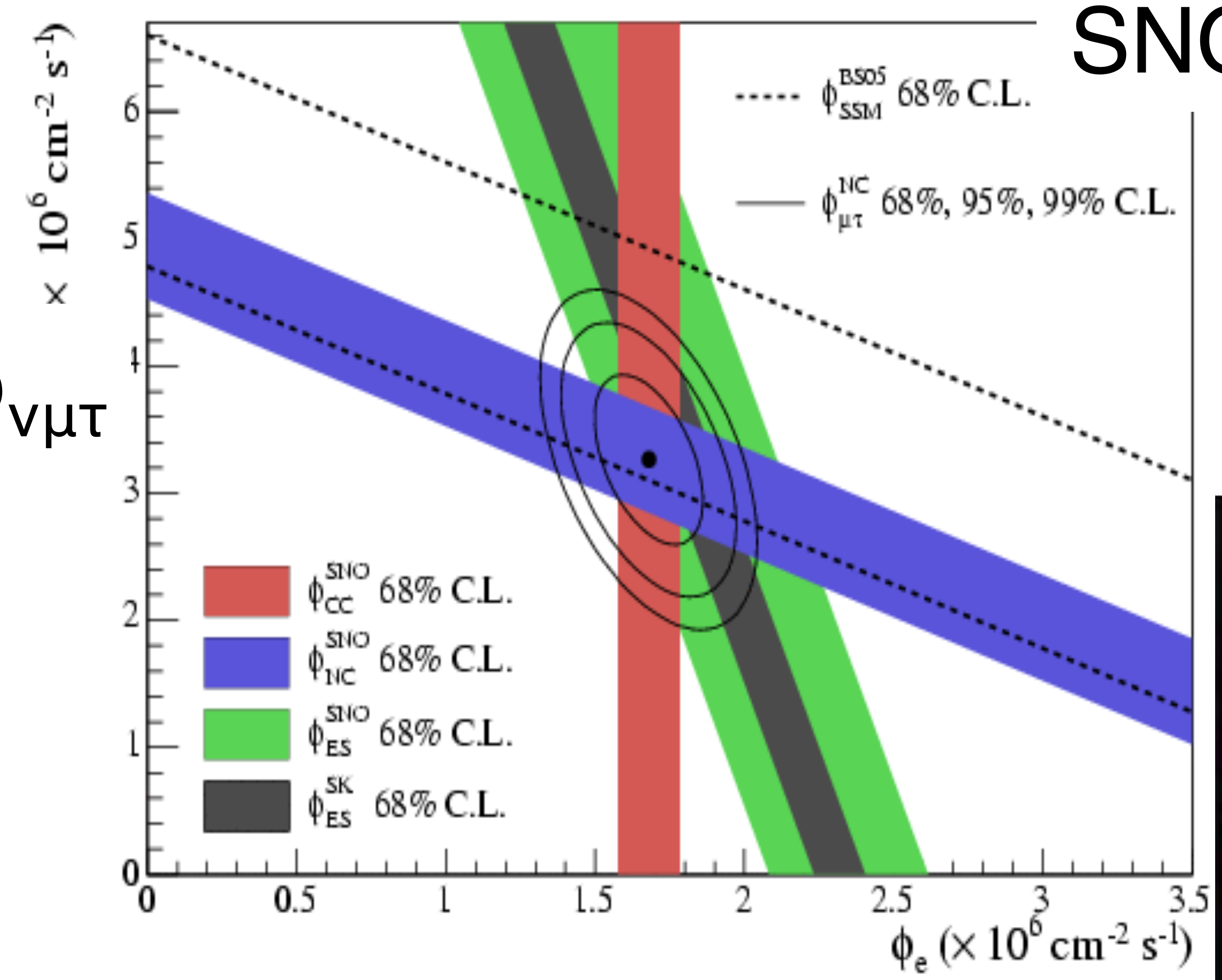
KamLAND Collaboration
Phys.Rev.Lett.100:221803,2008

Discovery of Neutrino Flavor Change and Oscillation

Solar ν_e

SNO

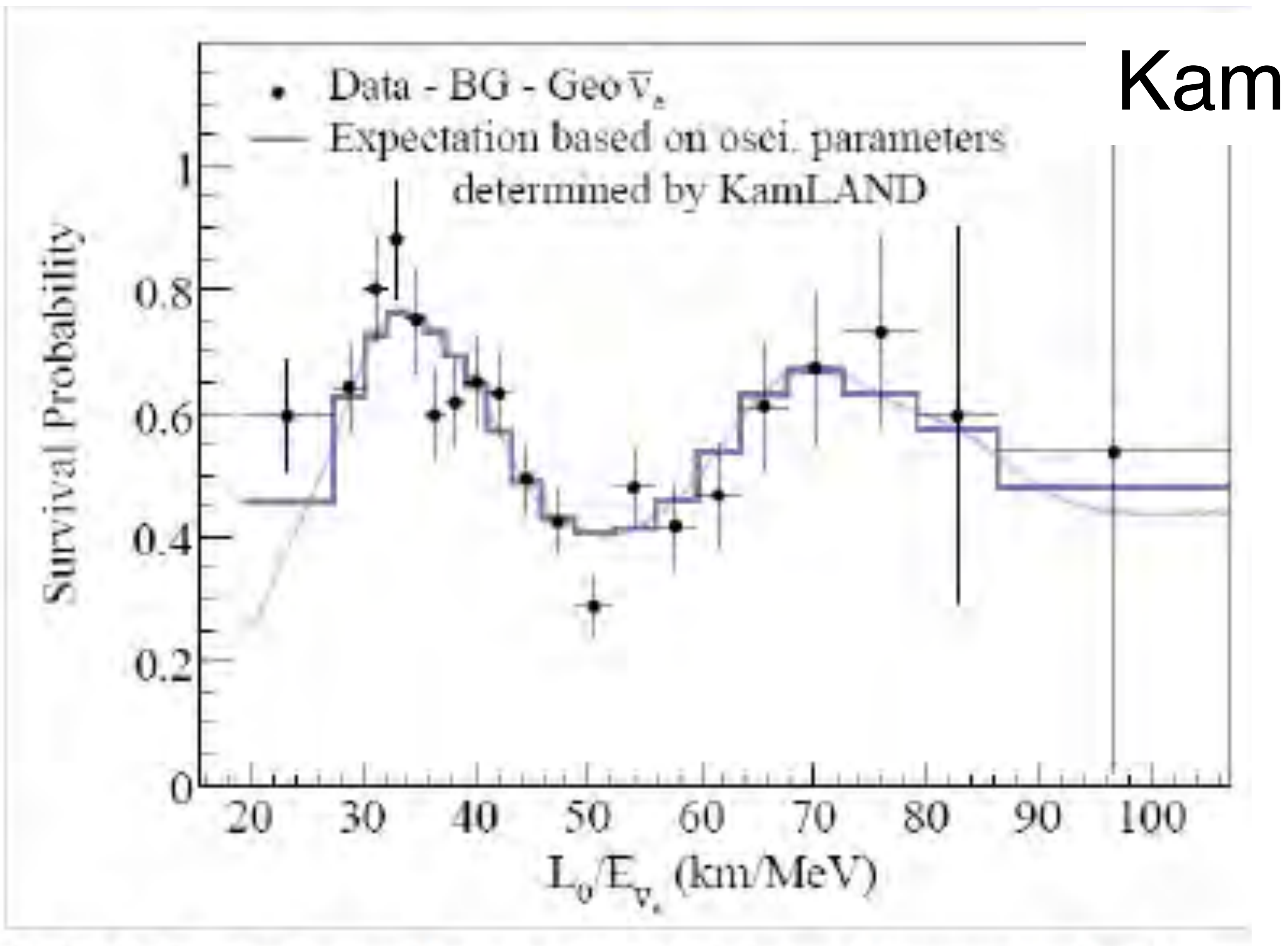
$\Phi_{\nu\mu\tau}$

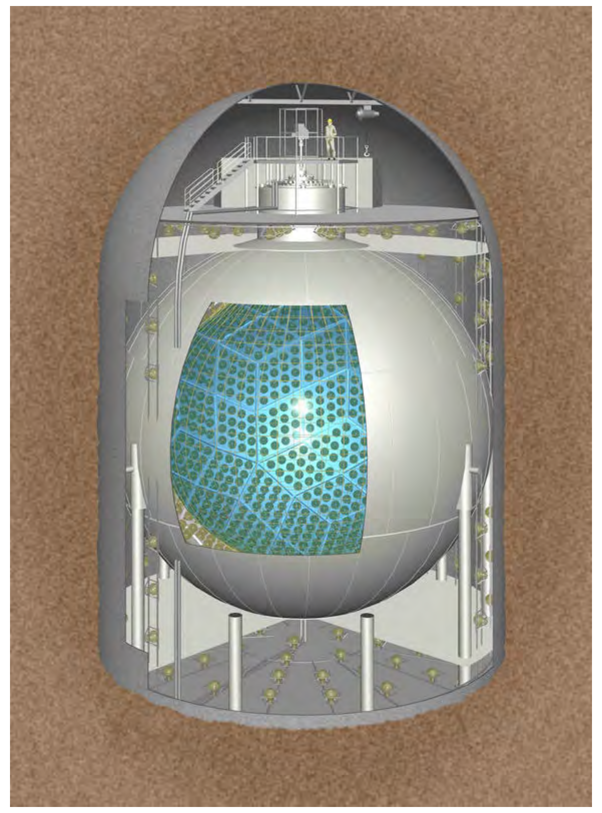


$\Phi_{\nu e}$

Reactor $\bar{\nu}_e$

KamLAND





L/E

Neutrino oscillations imply that neutrinos have mass and mix.

The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. MacFarlane. Queen's University /SNOLAB

Arthur B. McDonald

Prize share: 1/2

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

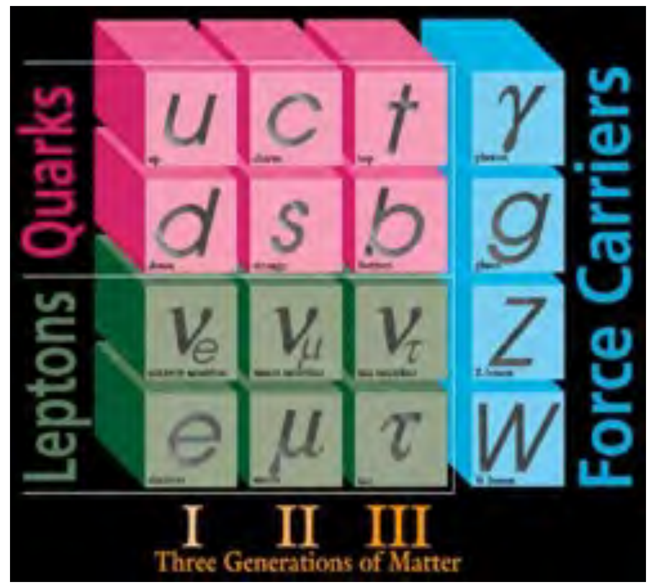
Breakthrough Prize in Fundamental Physics 2016

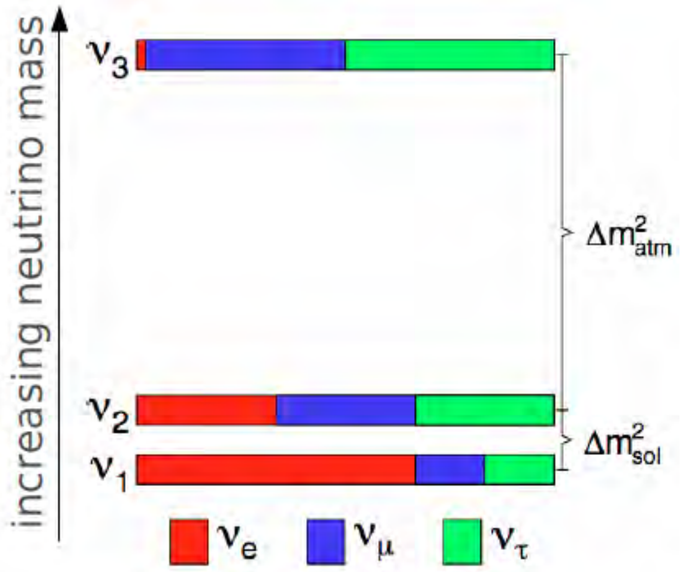
For the fundamental discovery and exploration of neutrino oscillations, revealing a new frontier beyond, and possibly far beyond, the standard model of particle physics.

Daya Bay Collaboration
SNO Collaboration
Super-K Collaboration
KamLAND
K2K and T2K Collaboration

Neutrino Mixing

Mixing Angles





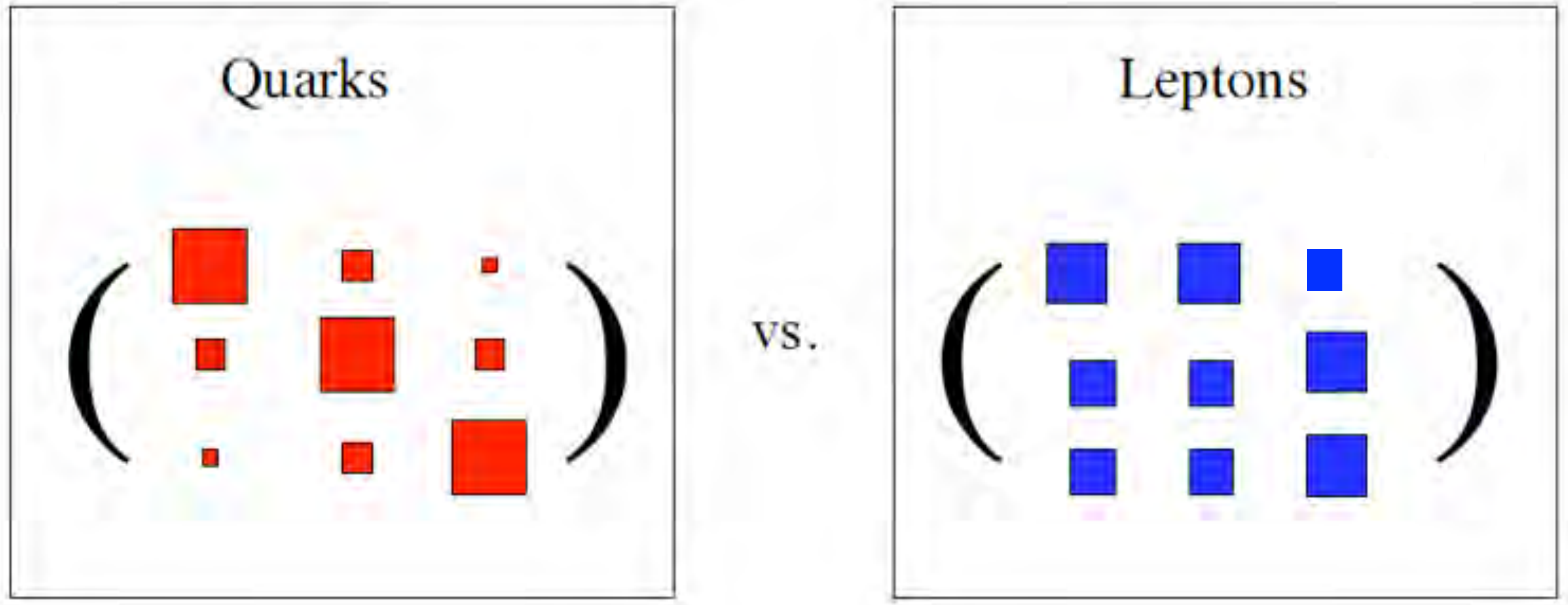
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

U_{MNSP} Matrix

Maki, Nakagawa, Sakata, Pontecorvo

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric, K2K}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{reactor and accelerator}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

atmospheric, K2K   reactor and accelerator   SNO, solar SK, KamLAND $0\nu\beta\beta$



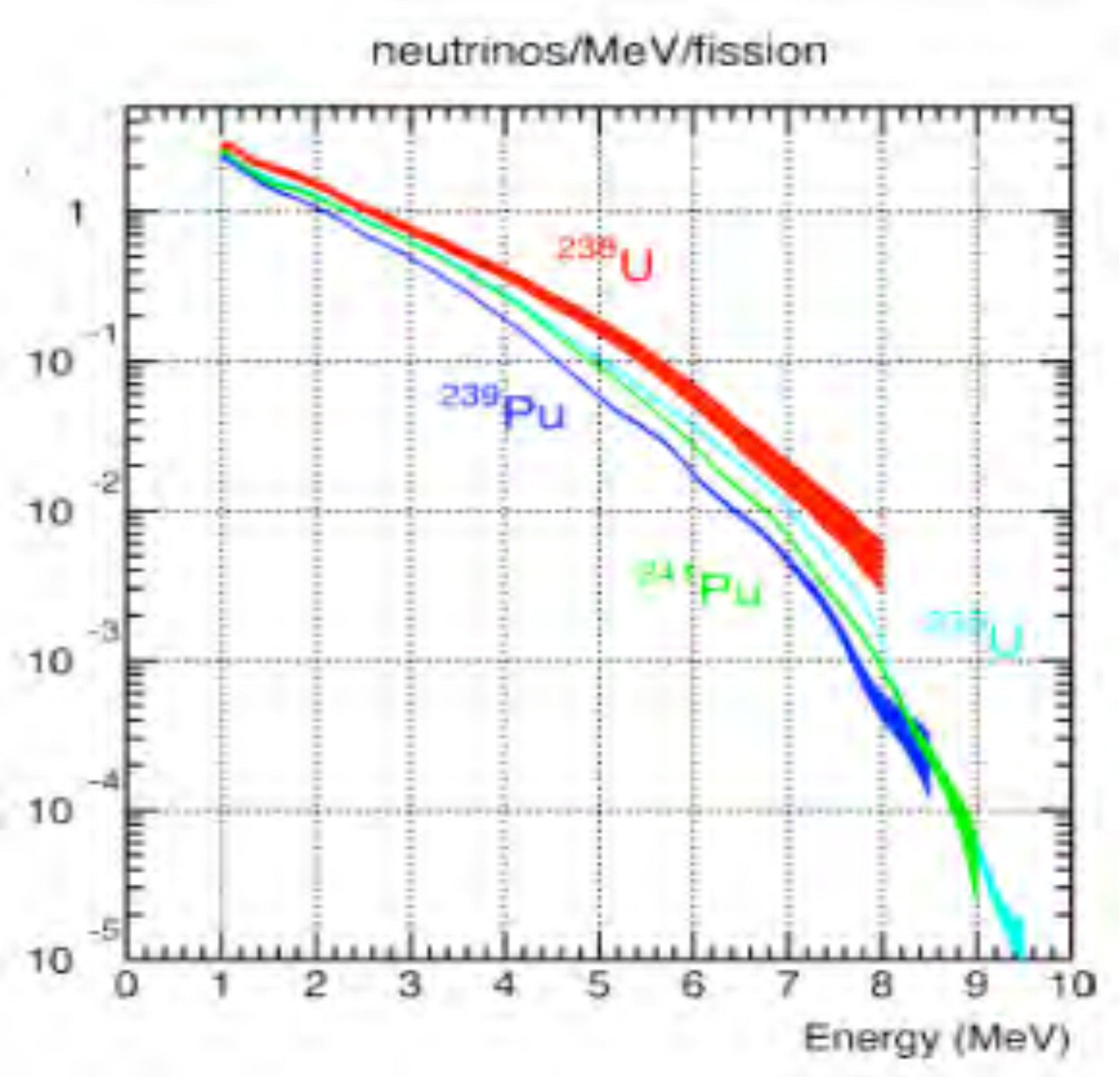
Reactor Antineutrinos

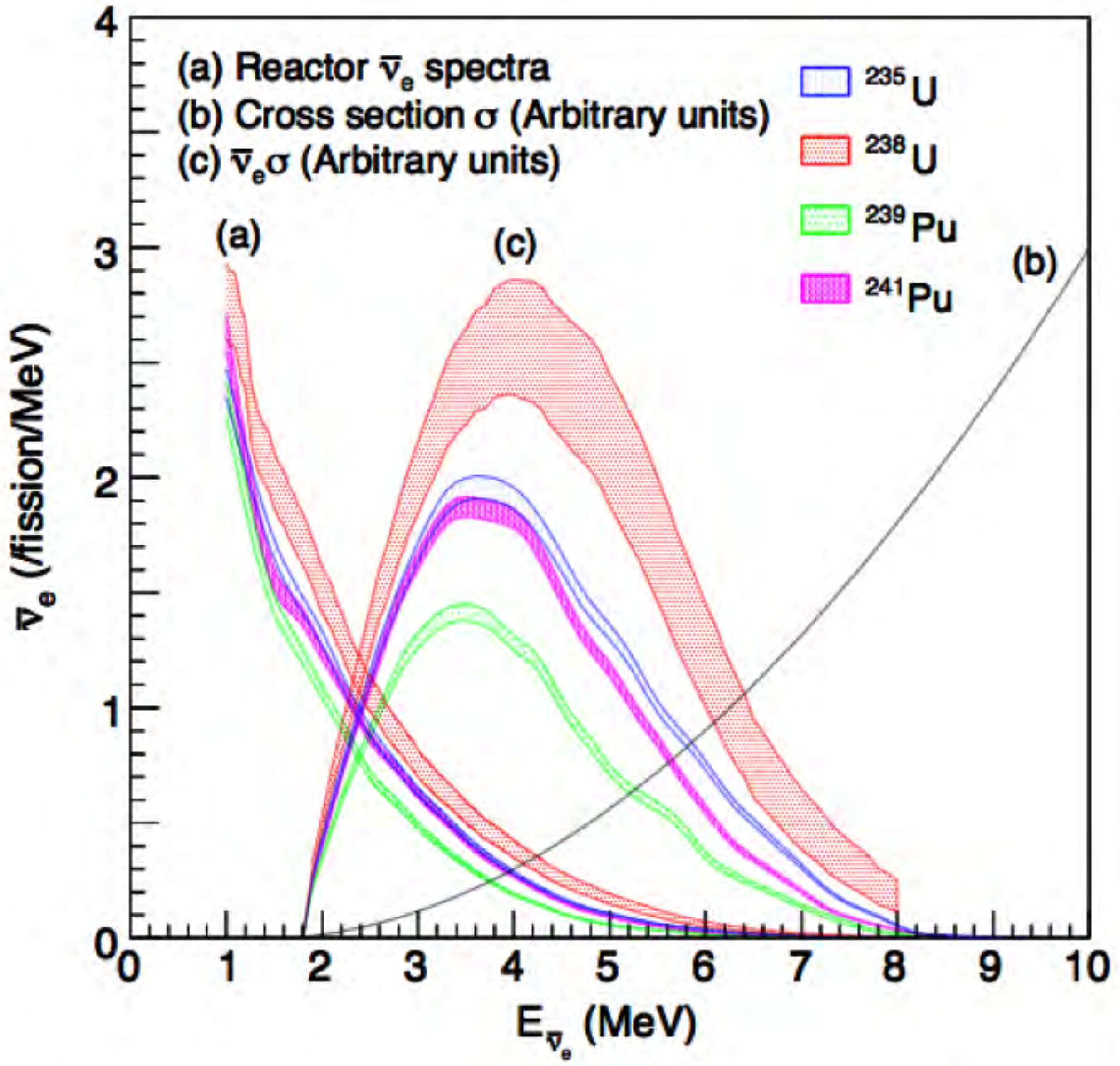
$\bar{\nu}_e$ from β-decays, pure $\bar{\nu}_e$ source

of n-rich fission products

on average ~6 beta decays until stable

threshold: neutrinos with E < 1.8 MeV are not detected



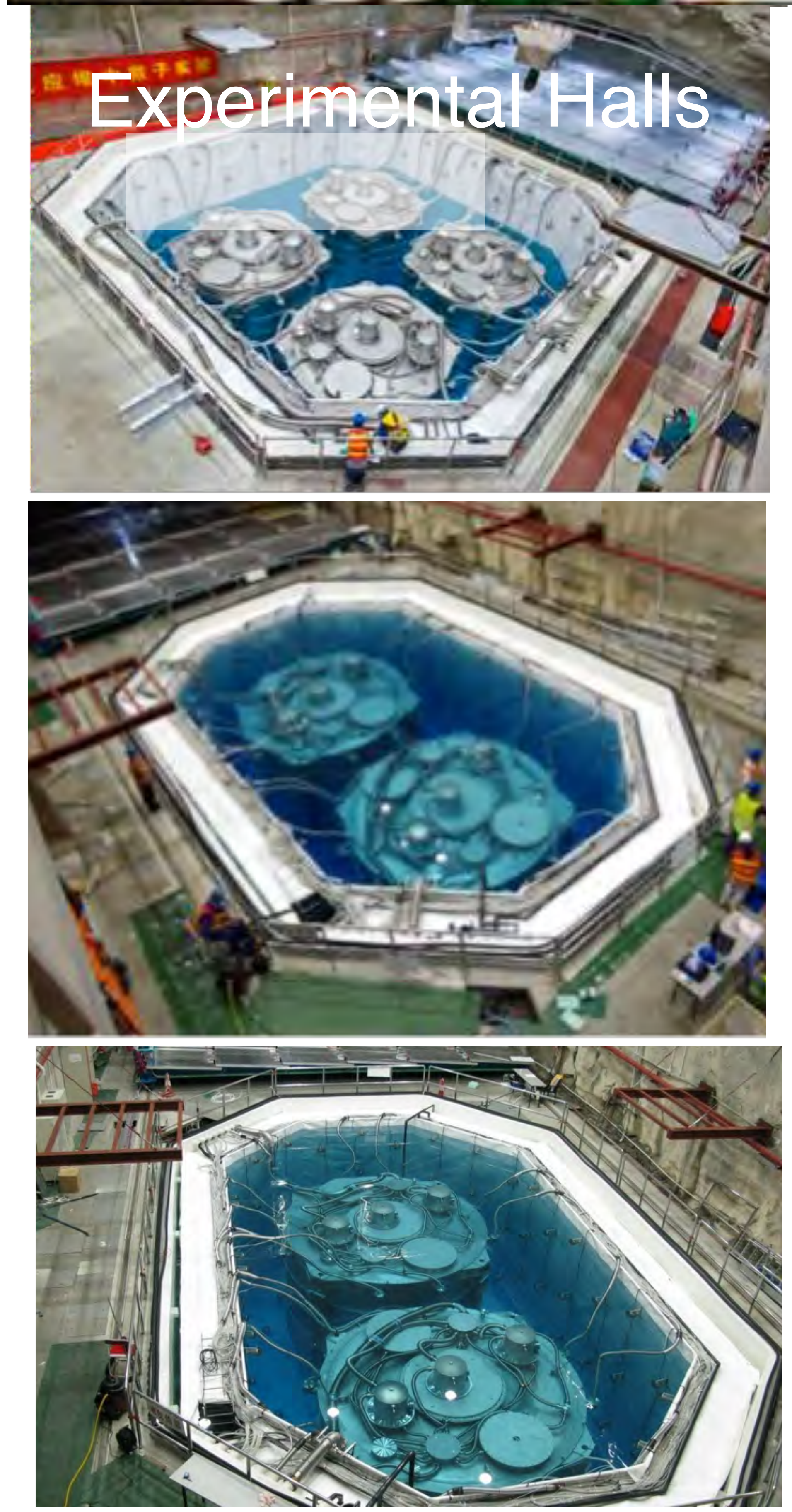


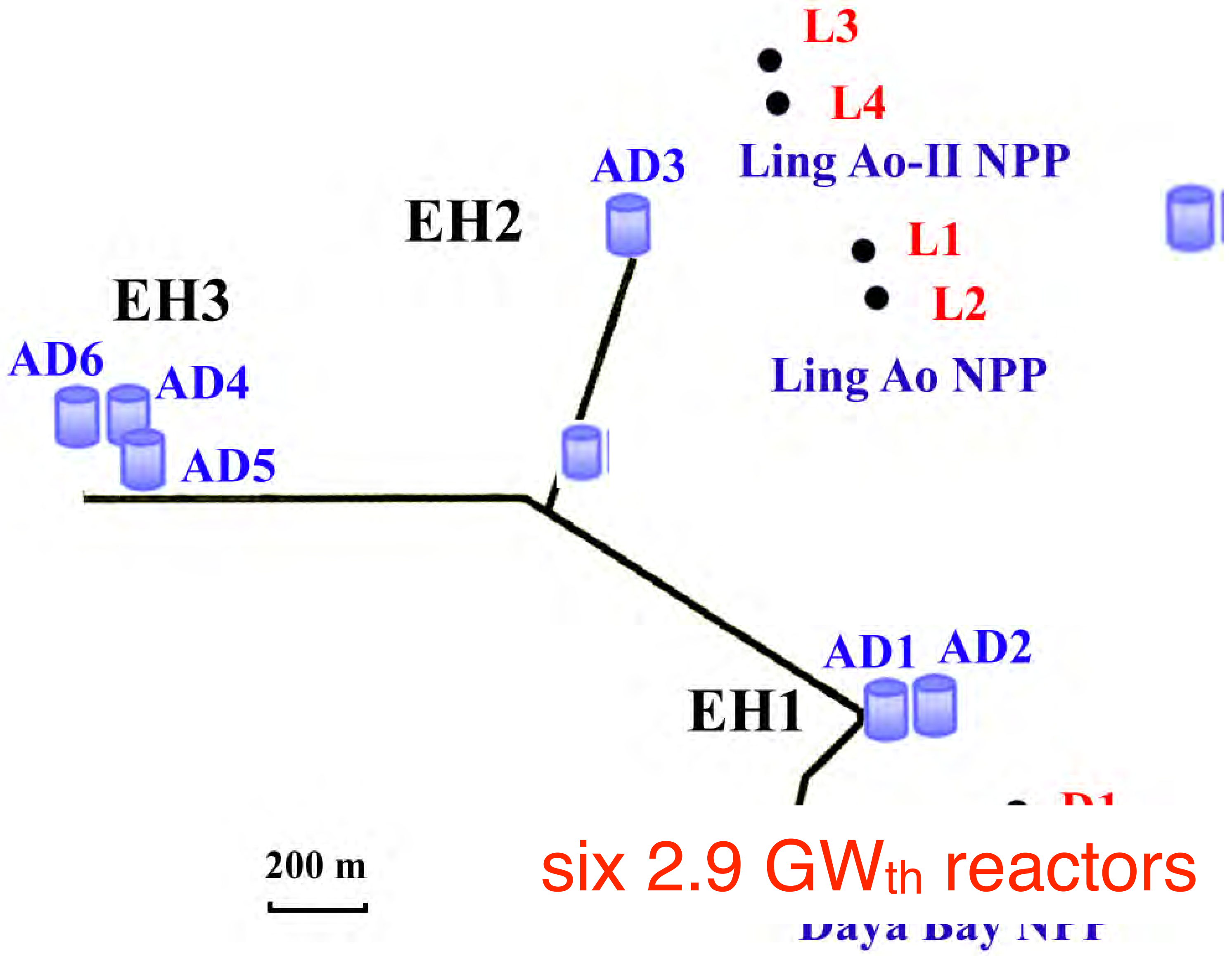
> 99.9% of $\bar{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

mean energy of $\bar{\nu}_e$: 3.6 MeV

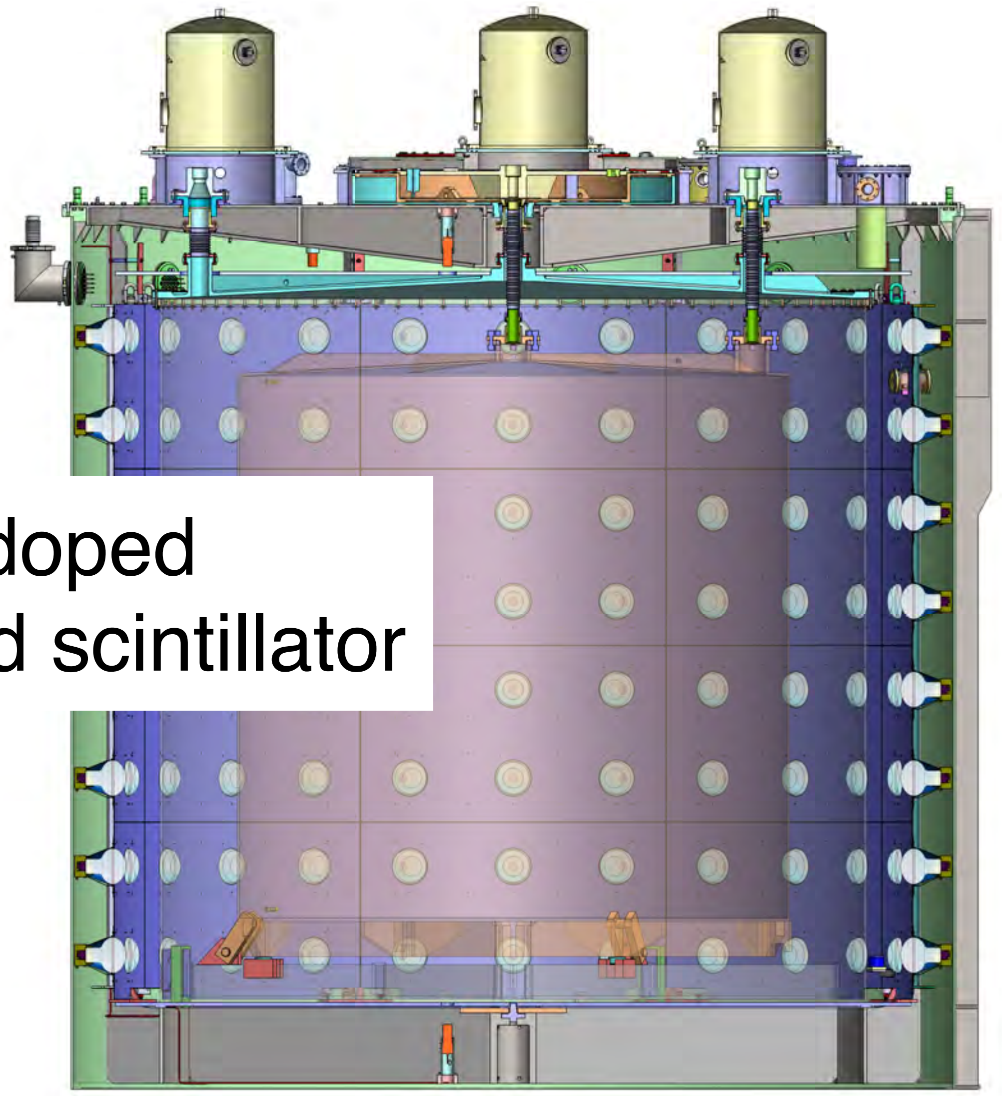
only disappearance experiments possible

Daya Bay Reactor Experiment



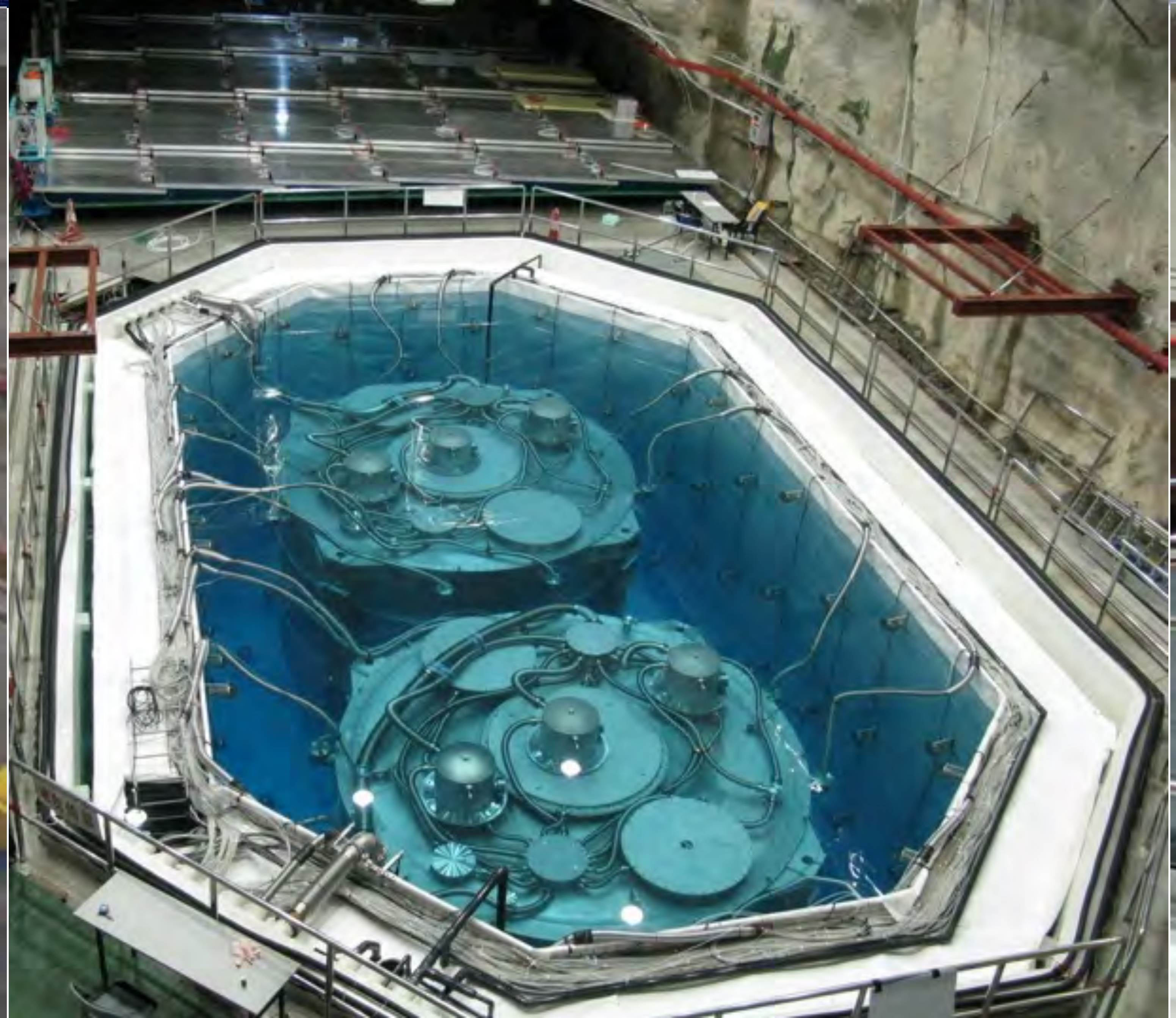


6 detectors, Dec 2011- Jul 2012
then 8 detectors



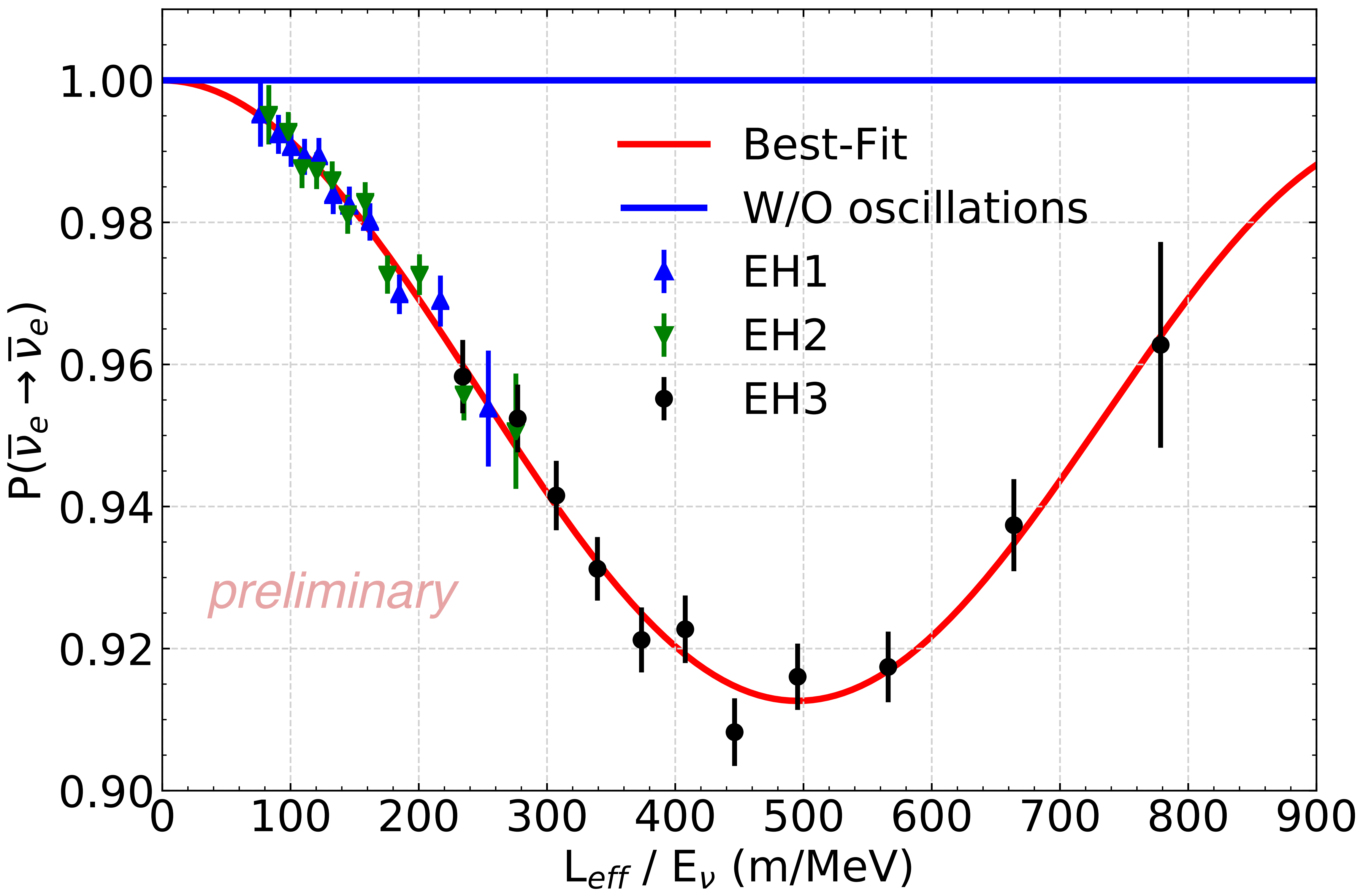
target mass: 20 ton per AD
photosensors: 192 8”-PMTs
energy resolution: $(7.5 / \sqrt{E} + 0.9)\%$

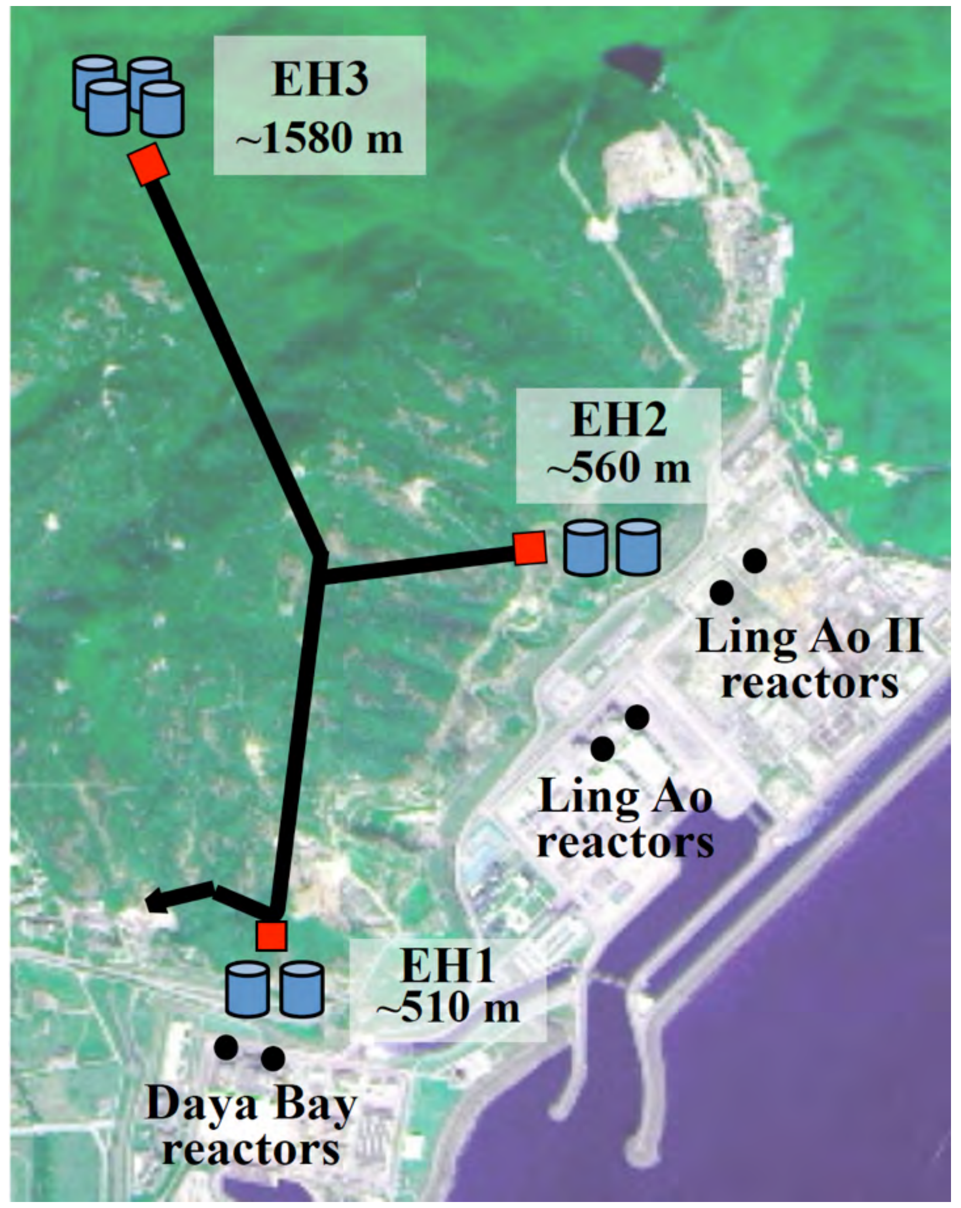
Daya Bay Detector Installation

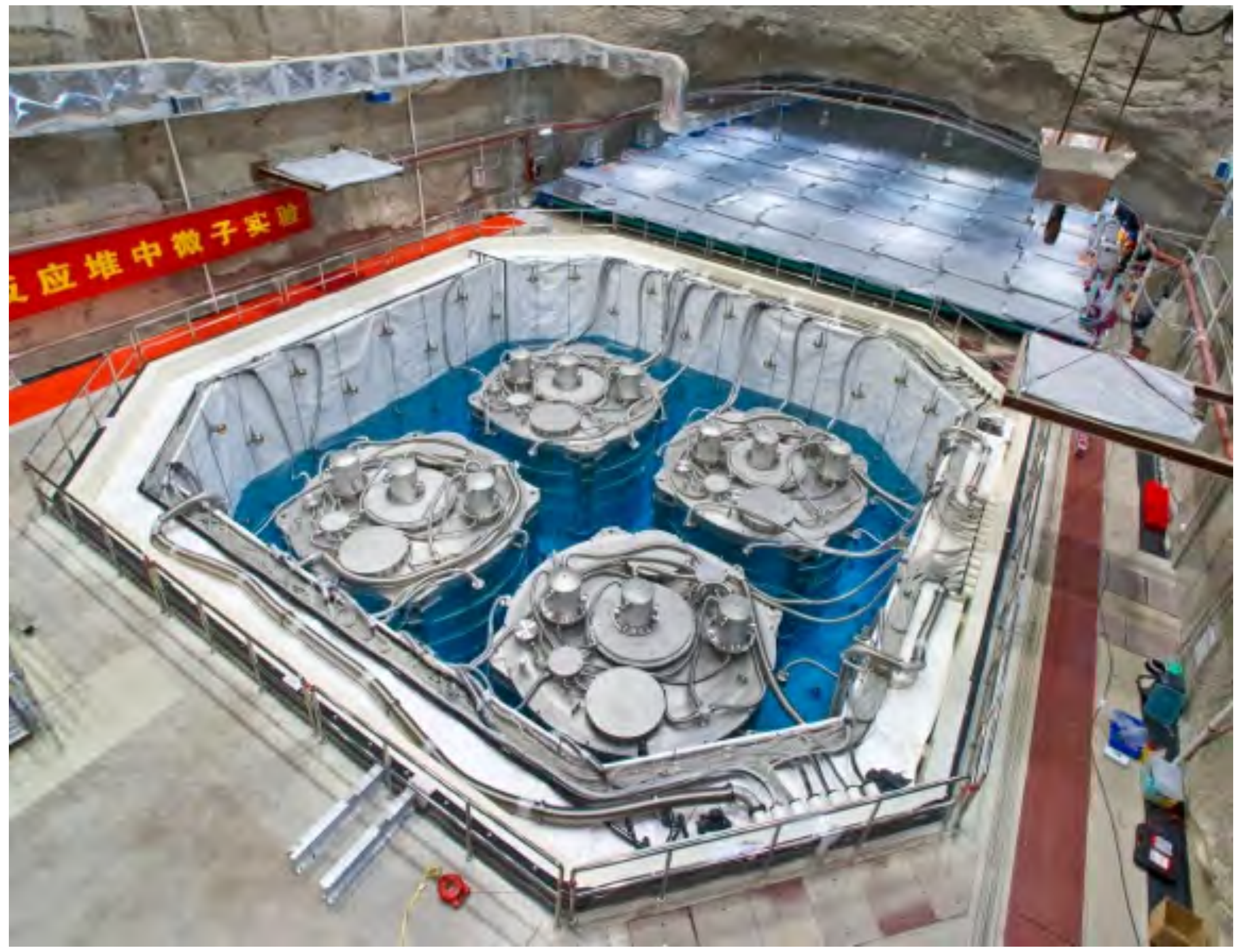


Daya Bay Far Detectors

Daya Bay Neutrino Oscillation (1958 Days)







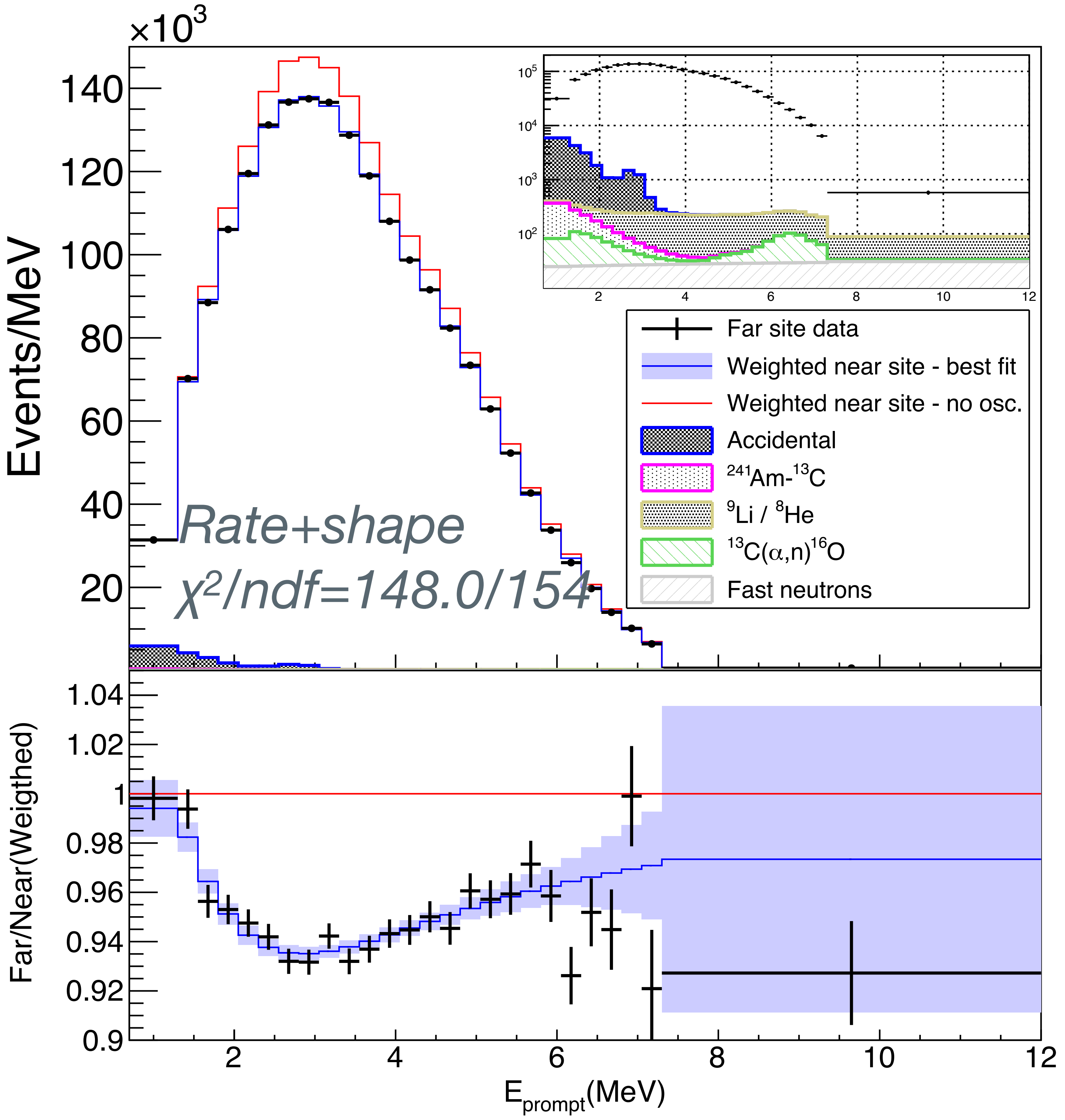
$$P_{i \rightarrow i} = \sin^2 2\theta \sin^2\left(1.27 \Delta m^2 \frac{L}{E}\right)$$

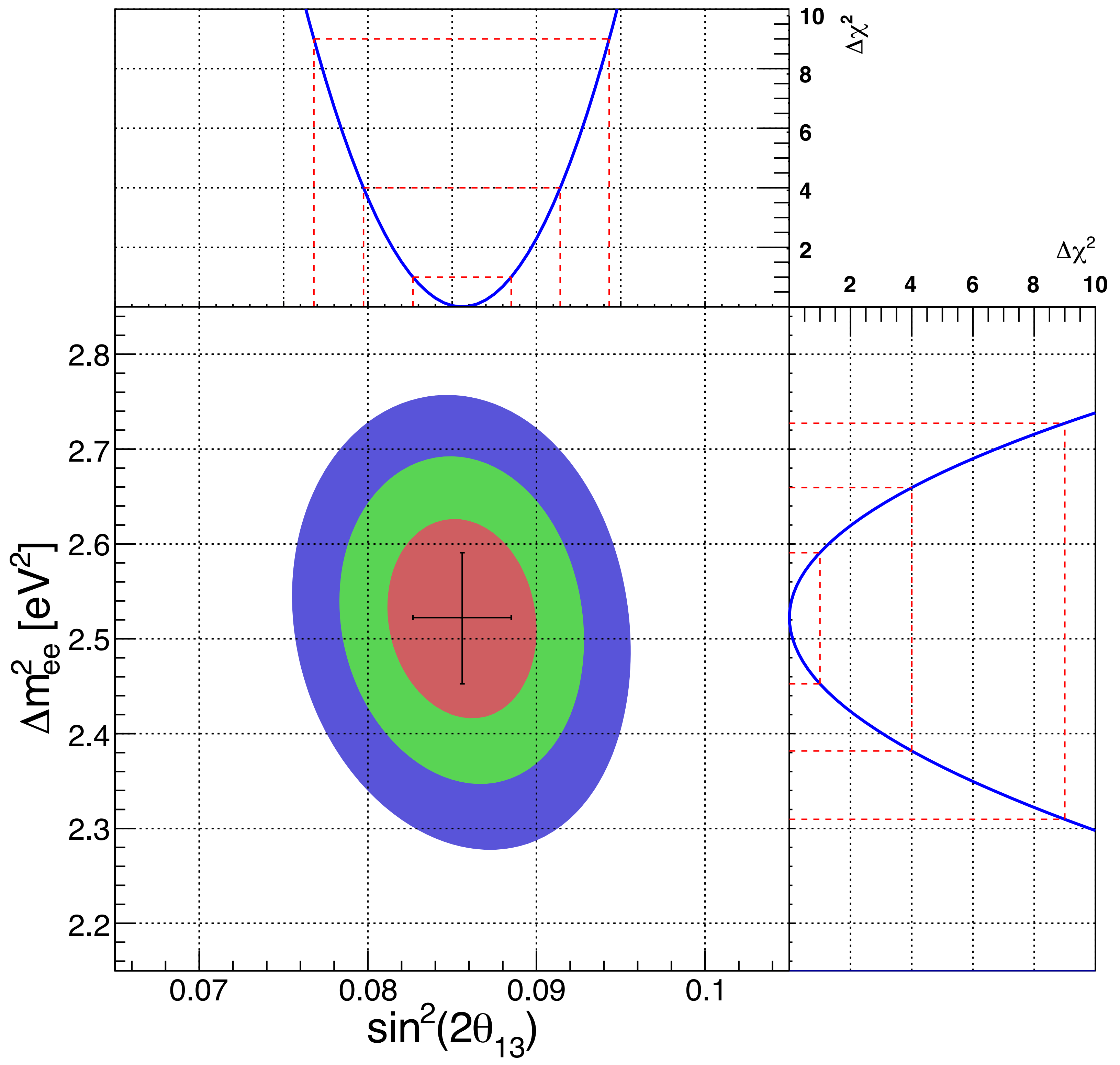
Neutrino oscillation is energy and baseline dependent

Phys. Rev D 95, 072006 (2017).
Daya Bay

Daya Bay Neutrino Oscillation (1958 Days)

nGd Analysis





Daya Bay
Phys.Rev.Lett. 121 (2018) no.24, 241805

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\ \text{eV}^2$$

$\sin^2 2\theta_{13}$ uncertainty: 3.4%
$|\Delta m^2_{32}|$ uncertainty: 2.8%

At Daya Bay:
$|\Delta m^2_{ee}| \approx |\Delta m^2_{32}| \pm 0.05 \times 10^{-3}$ eV^2

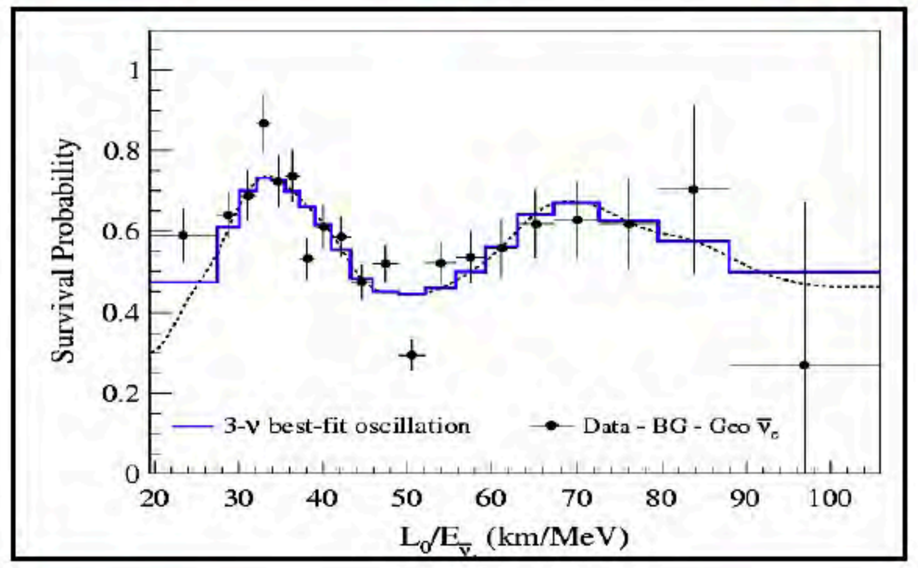
NH: Δm^2_{32} = [2.45 ± 0.08] × 10^{-3} eV^2
IH: Δm^2_{32} = [-2.55 ± 0.08] × 10^{-3} eV^2

Neutrino Mixing

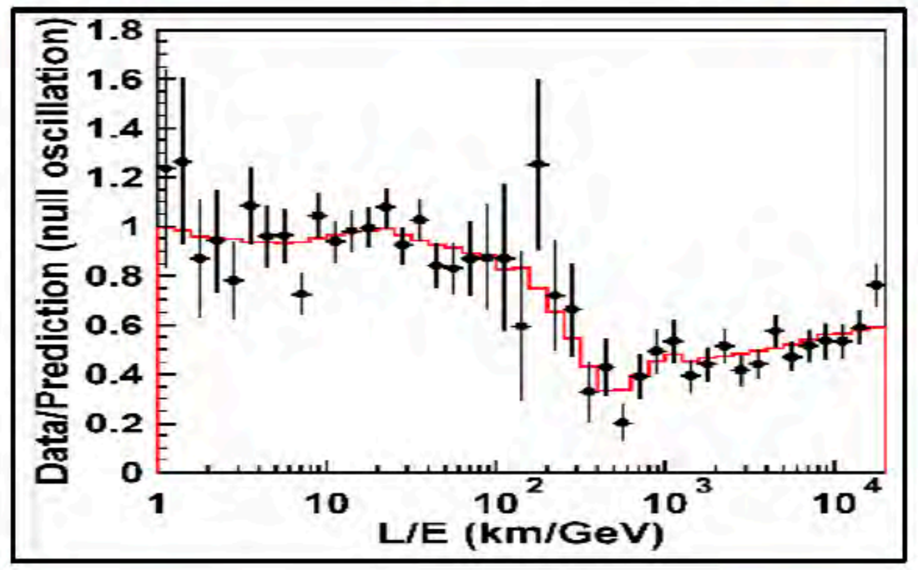
evidence for neutrino oscillations in many sources

reactor
solar
long baseline
atmospheric

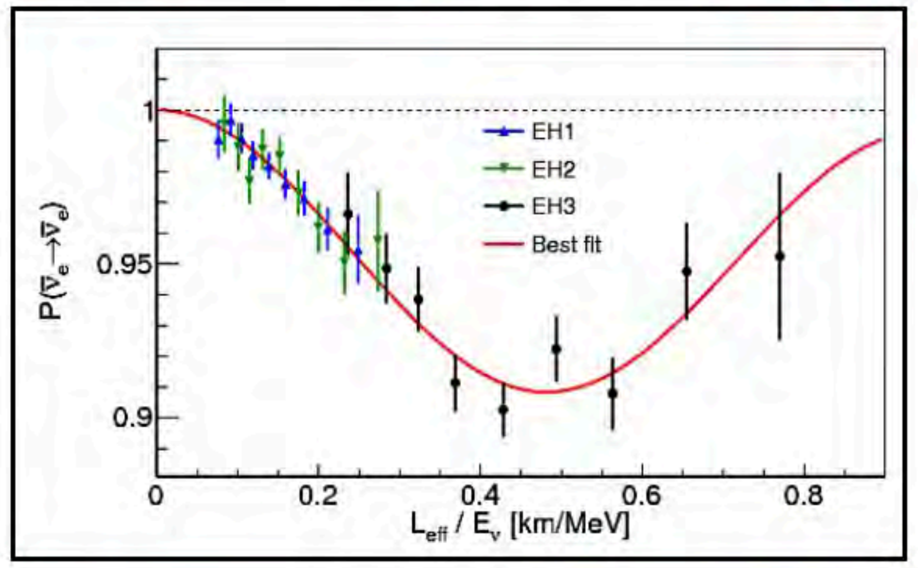
e→e (δm^2 , θ_{12})



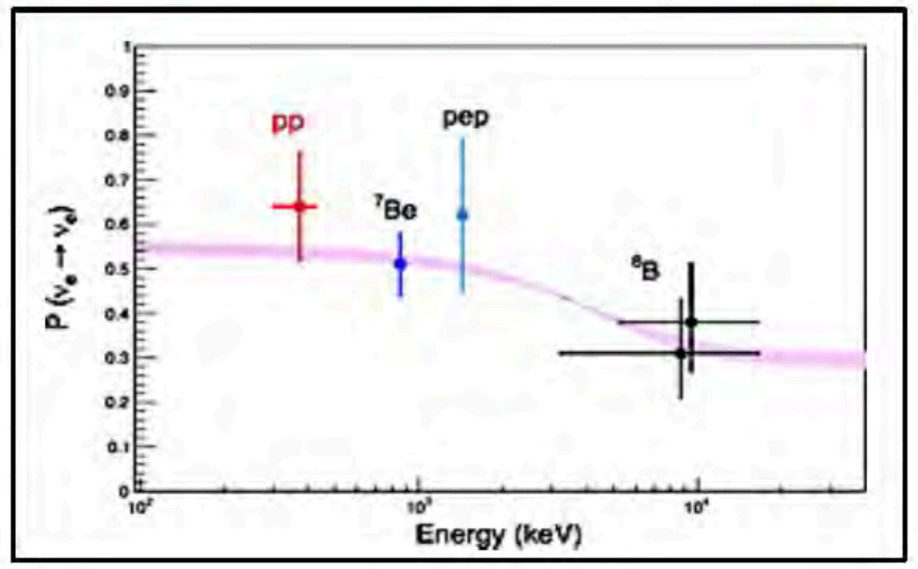
μ→μ (Δm^2 , θ_{23})



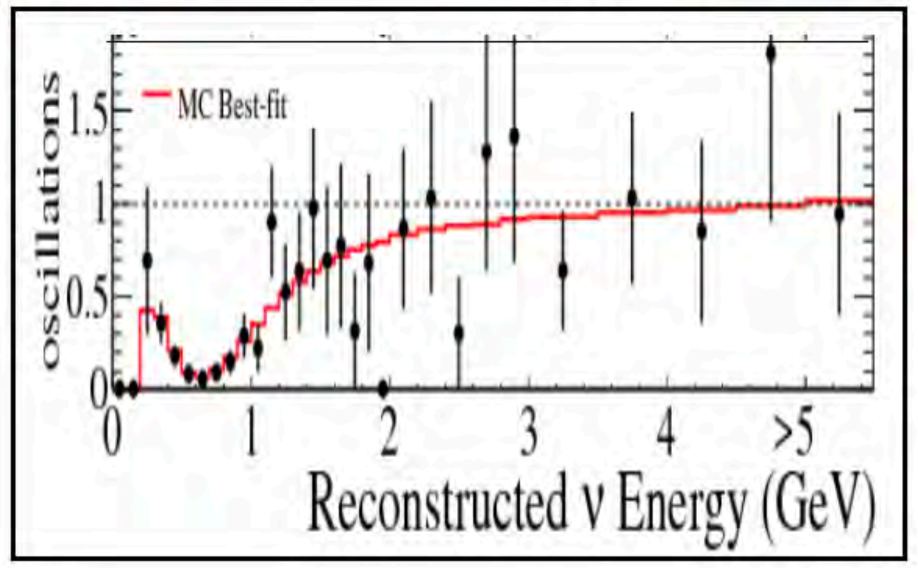
e→e (Δm^2 , θ_{13})



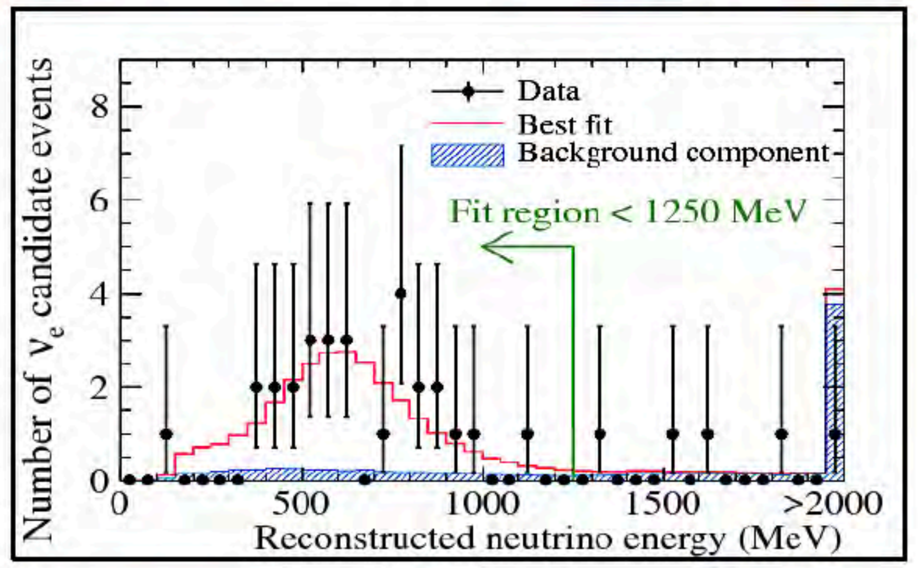
e→e (δm^2 , θ_{12})



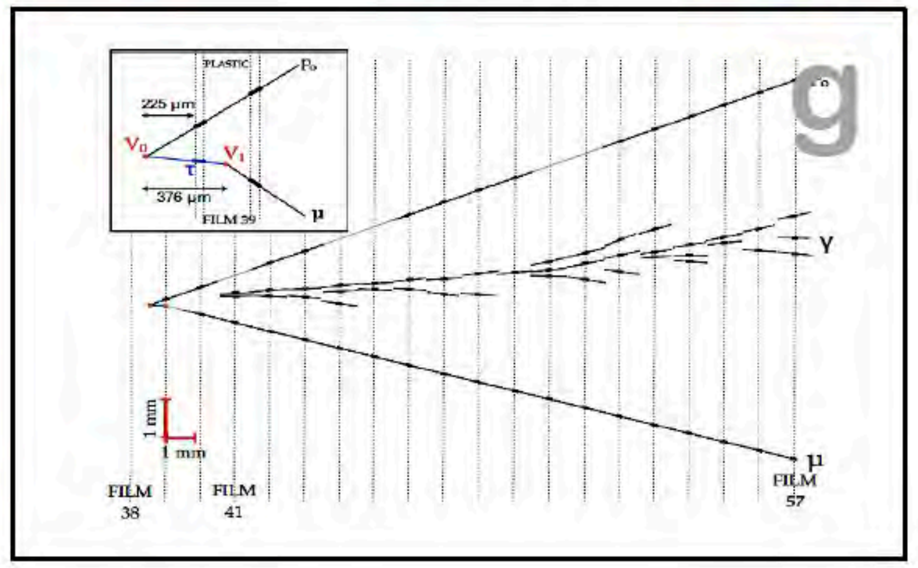
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



3 flavor picture fits data well

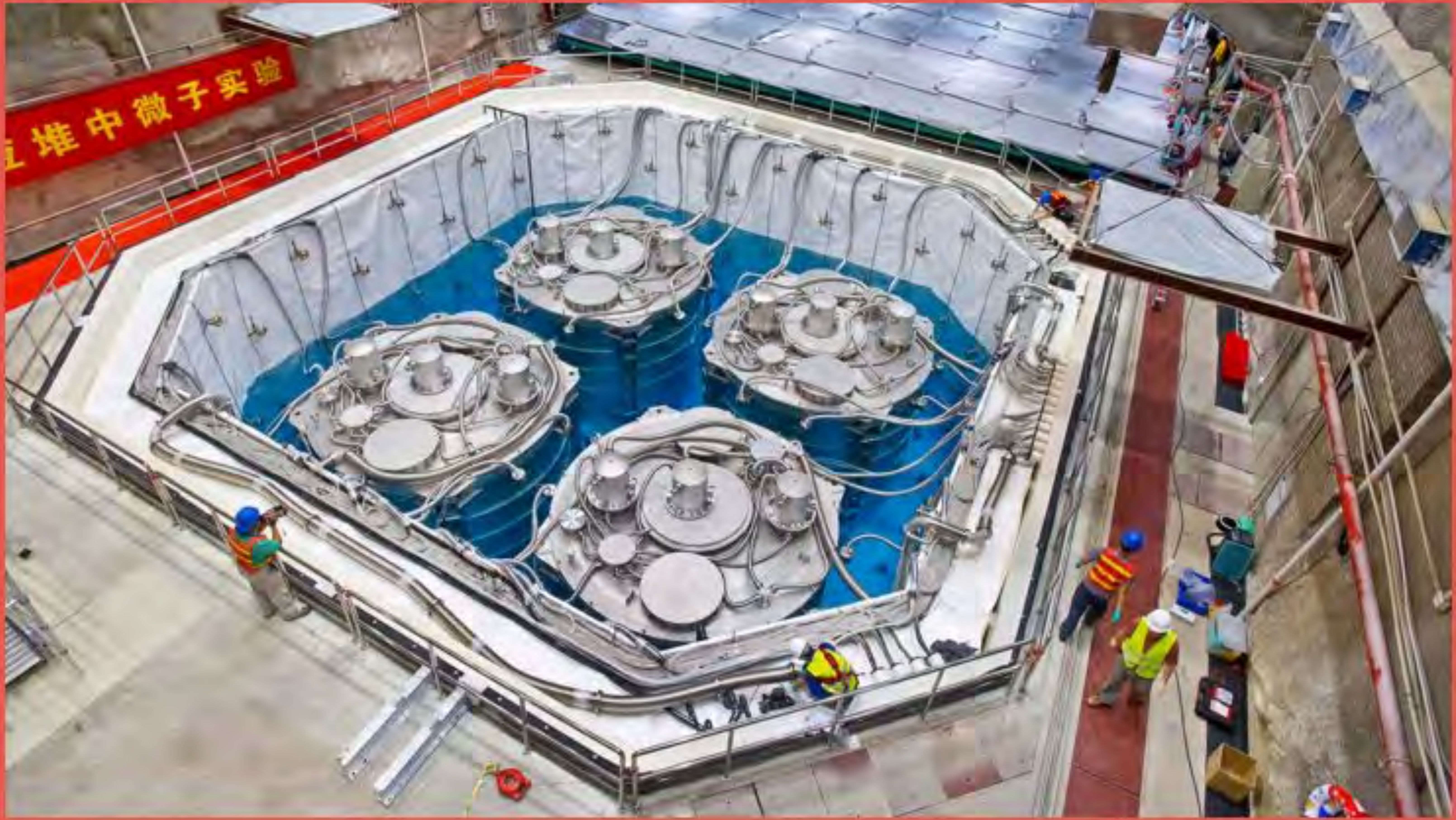


Photo courtesy of Brookhaven National Laboratory

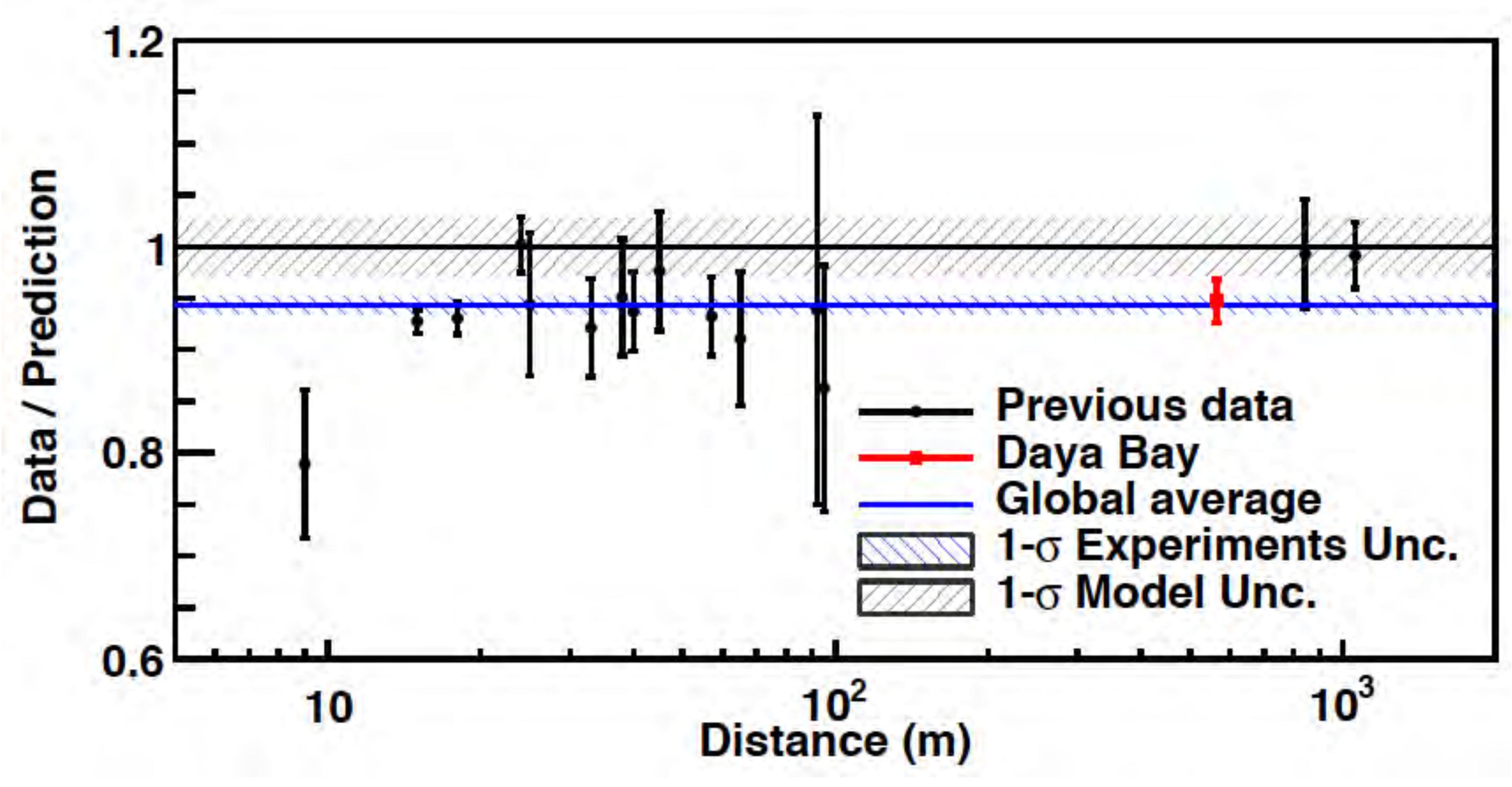
Daya Bay discovers a mismatch

02/12/16 | By Kathryn Jepsen

The latest measurements from the Daya Bay neutrino experiment in China don't align with predictions from nuclear theory.

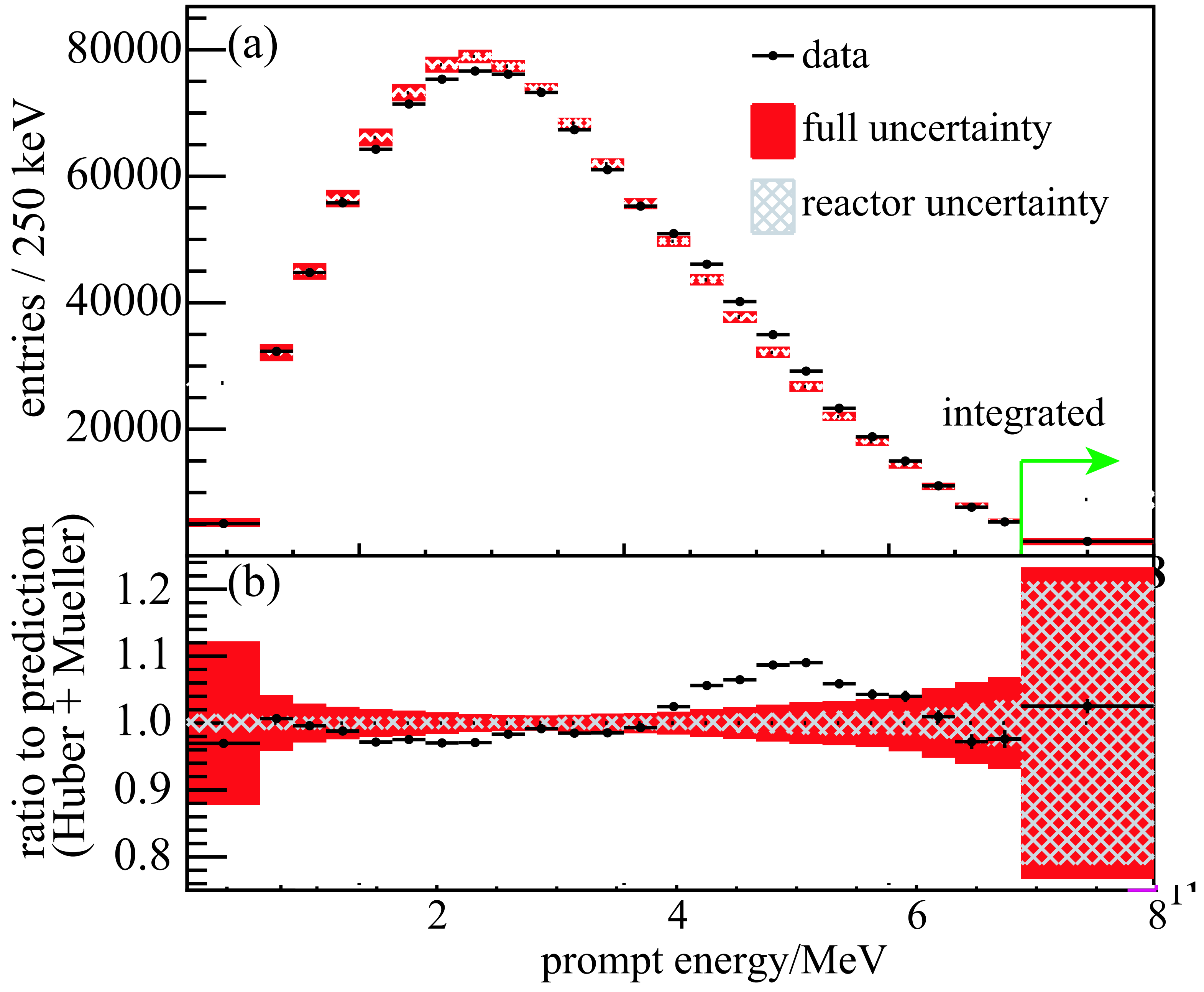
Reactor Antineutrino “Anomalies” (RAA)

Flux Deficit



Deficit due to extra (sterile) neutrino oscillations or artifact of flux predictions?

Spectral Deviation

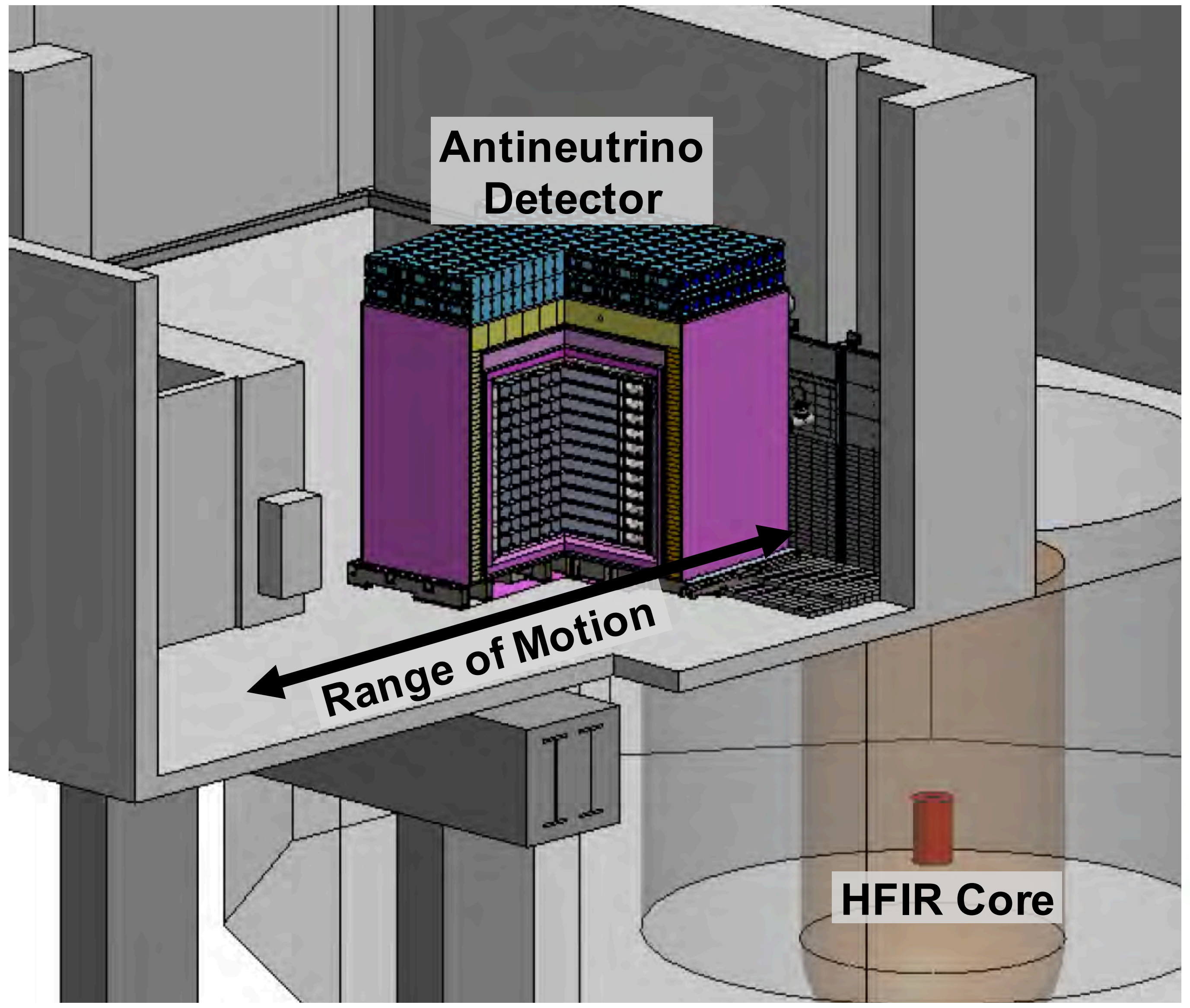


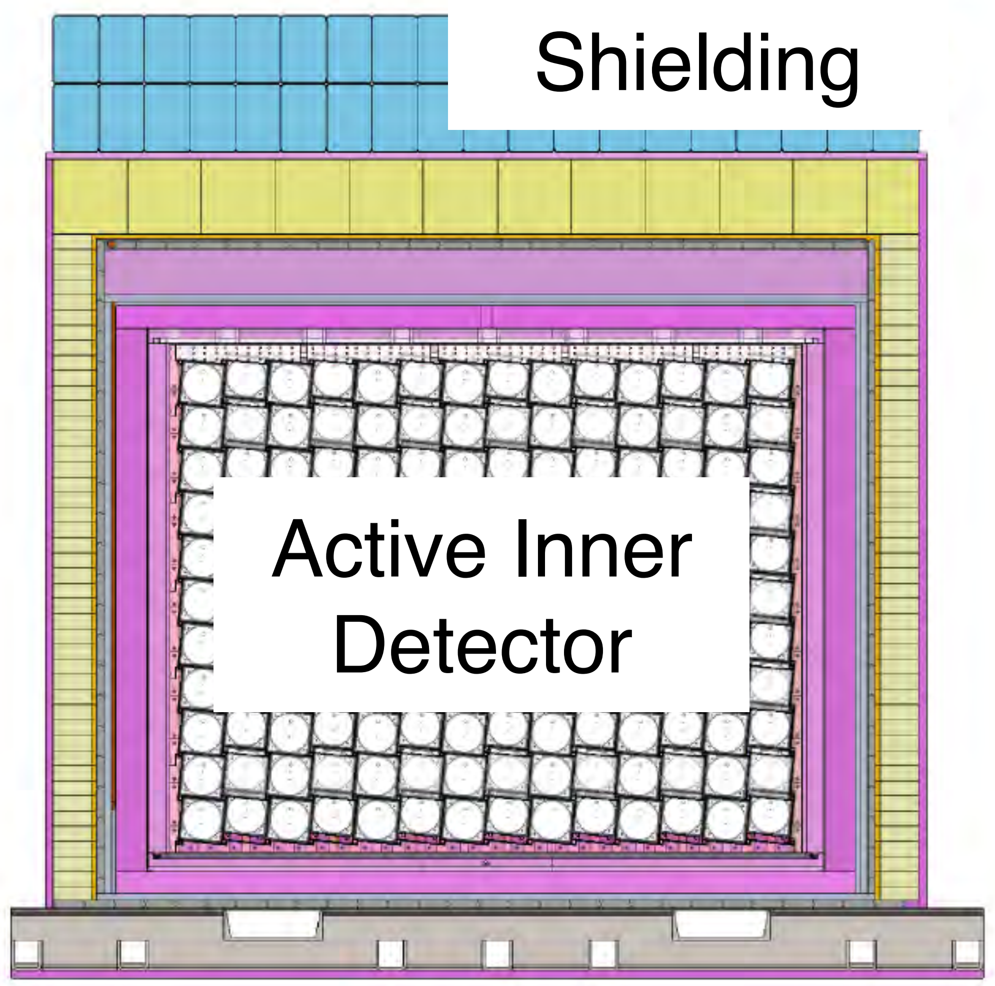
Measured spectrum does not agree with predictions.

Daya Bay,
CPC 41, No. 1 (2017)

Understanding reactor flux and spectrum anomalies requires additional data

PROSPECT: Precision Oscillation and Spectrum Experiment

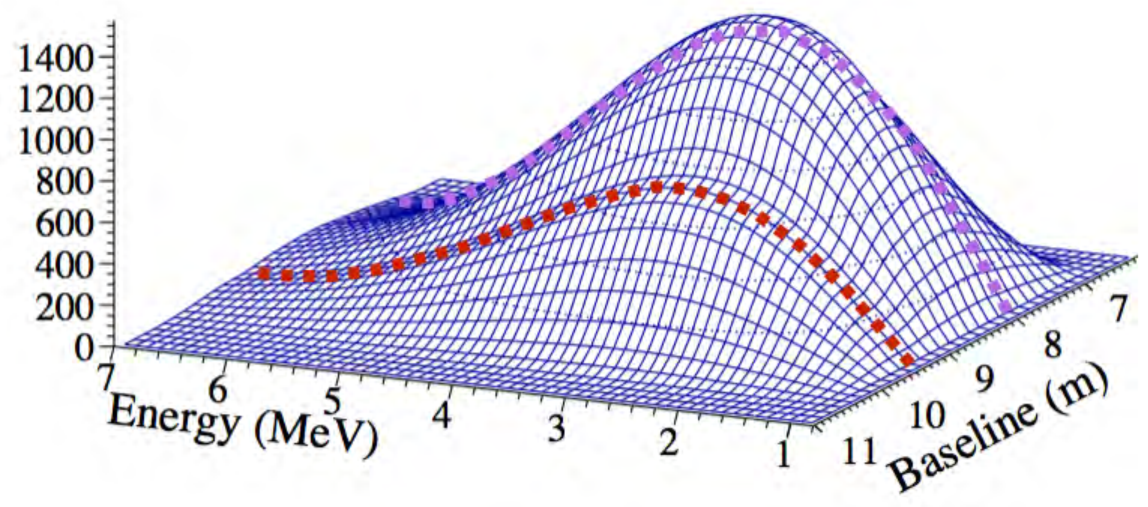




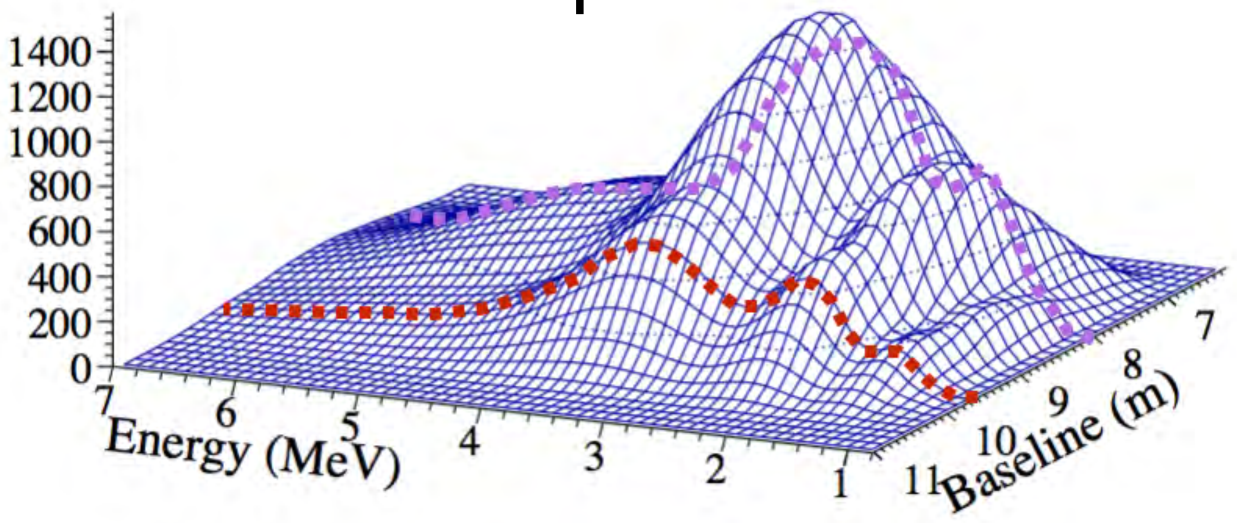
Objectives — **Search for short-baseline oscillation at <10m**
Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum

Relative Spectrum Measurement
relative measurement of L/E and spectral shape distortions

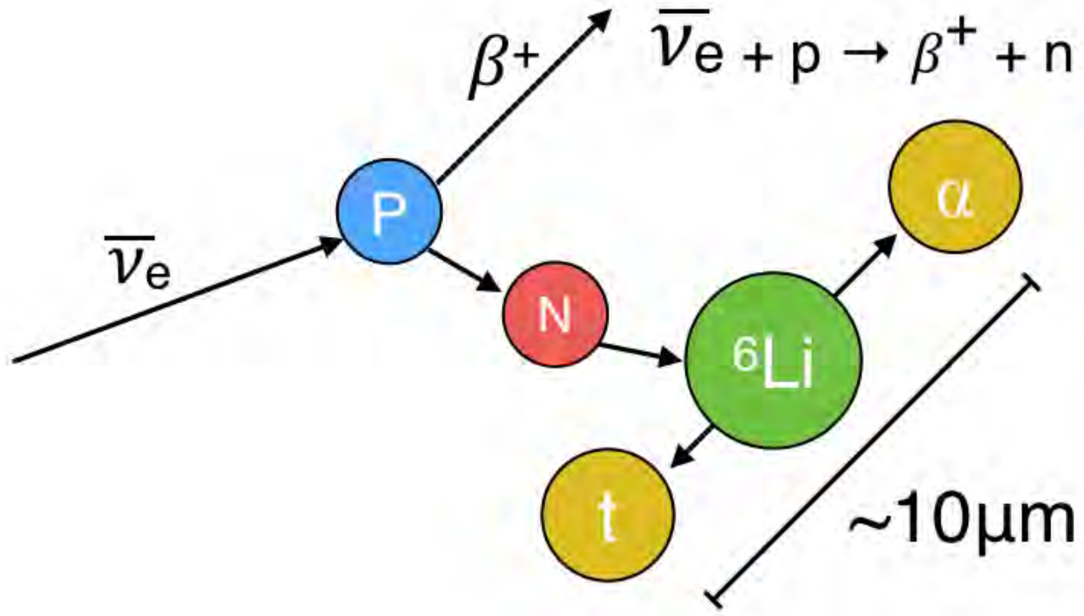
unoscillated spectrum



oscillated spectrum



Segmented, ^{6}Li-loaded Detector



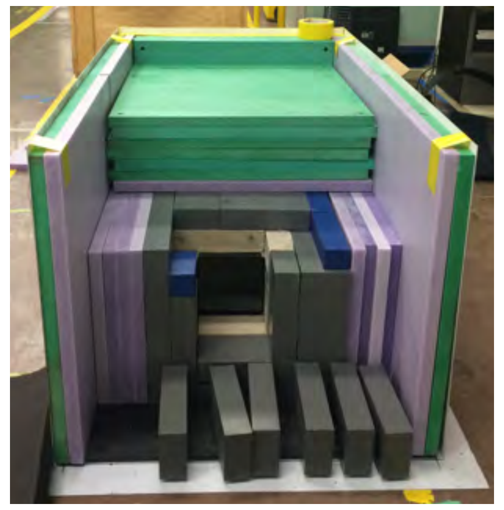
PROSPECT Detector Development

PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

5cm length
0.1 liters
LS, ^{6}LiLS

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

12.5 cm length
1.7 liters
^{6}LiLS



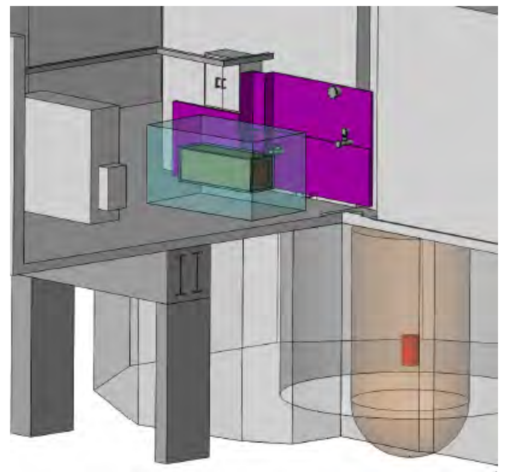
multi-layer shielding

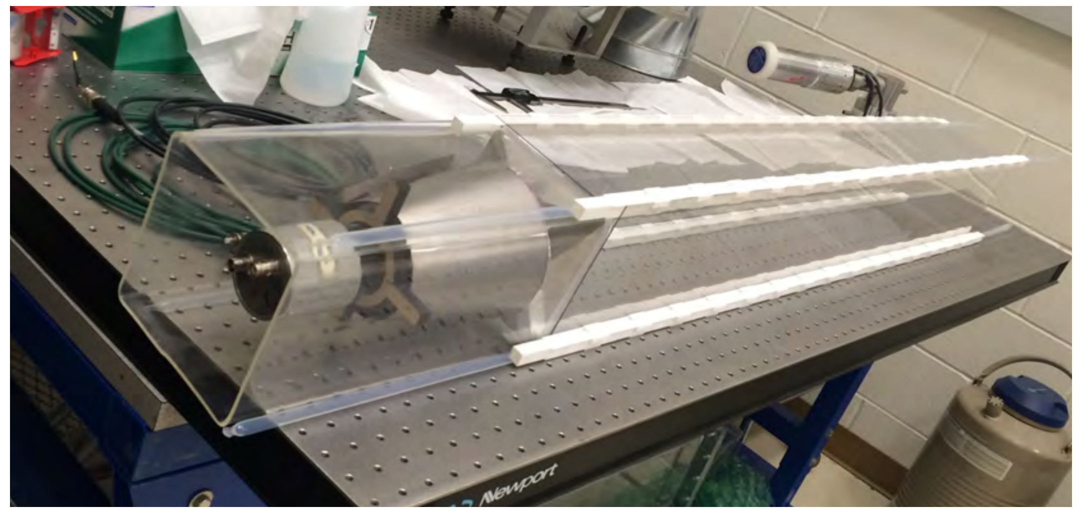
PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015

1m length
23 liters
LS, ^{6}LiLS

PROSPECT-50
Baseline design prototype
Winter 2015

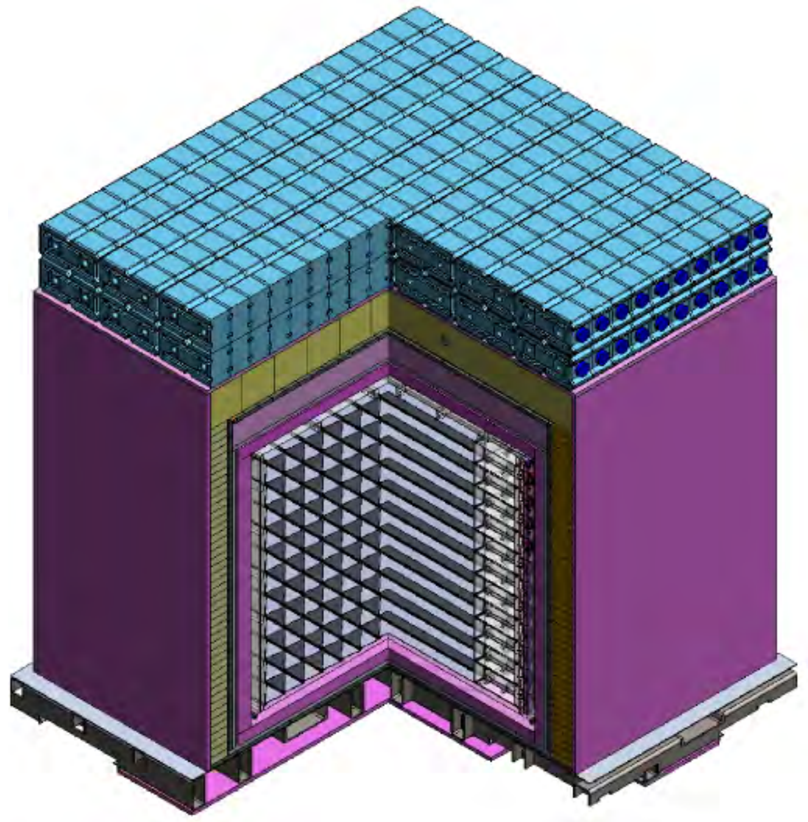
1x2 segments
1.2m length
50 liters
^{6}LiLS

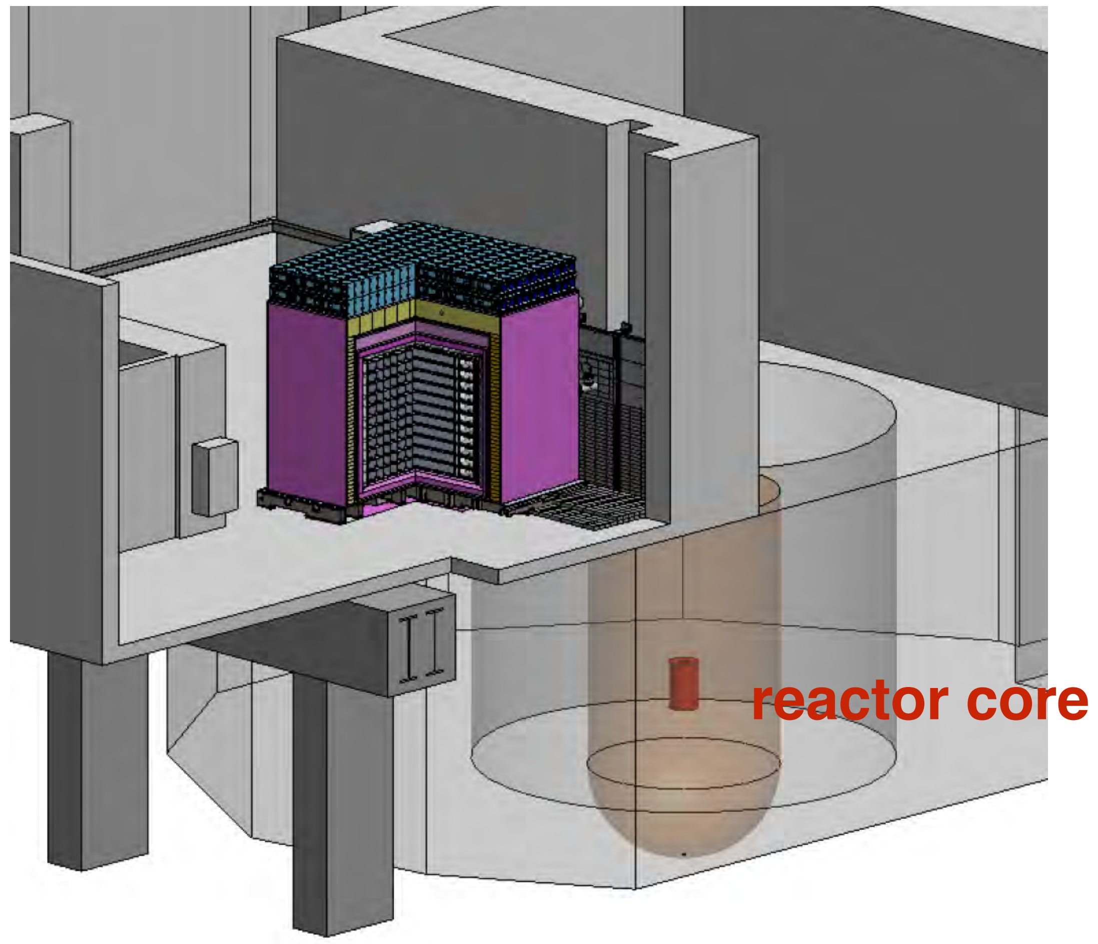




PROSPECT

11x14 segments
1.2m length
~4 tons
^{6}LiLS





PROSPECT Assembly

PROSPECT

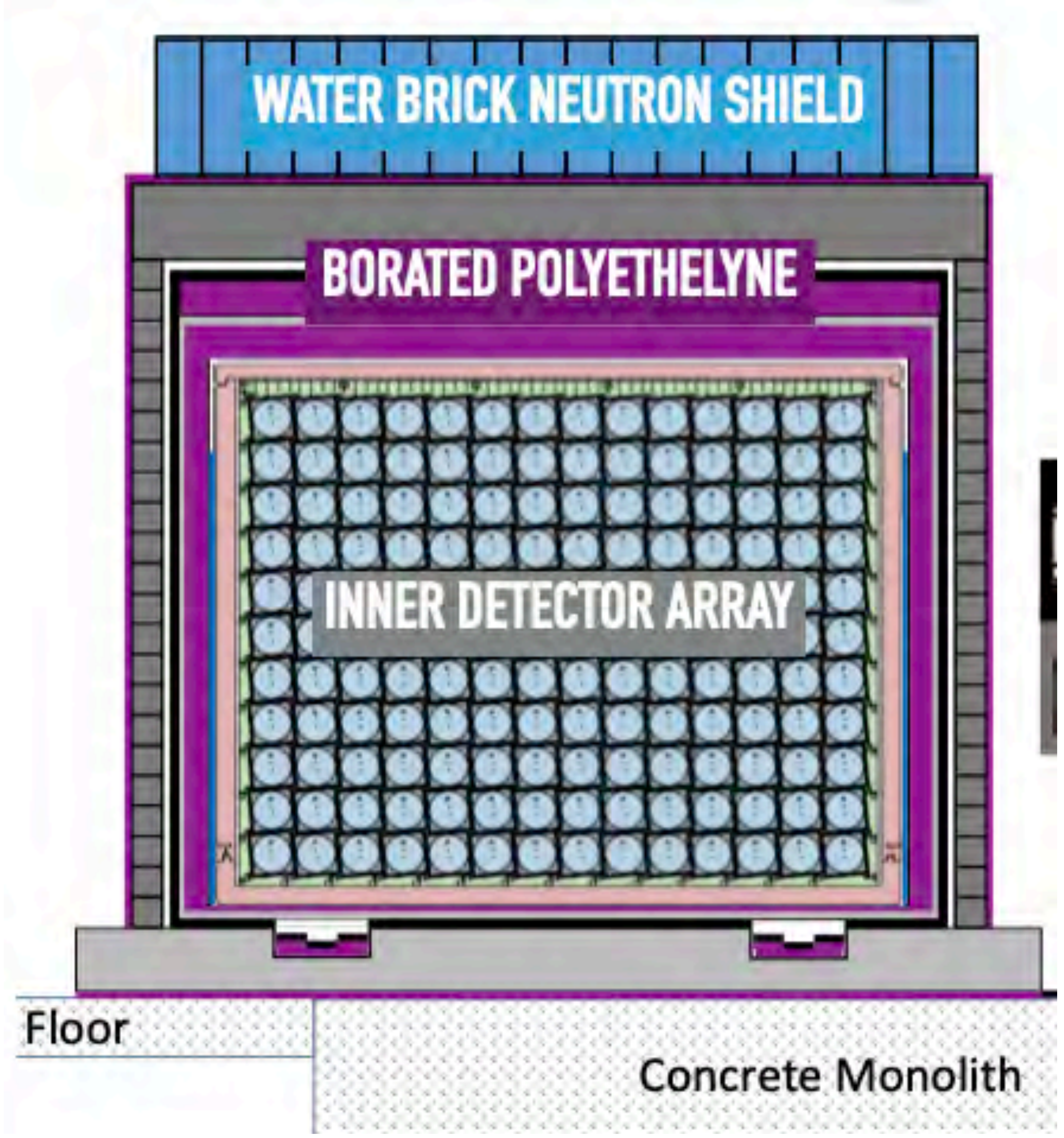
Yale

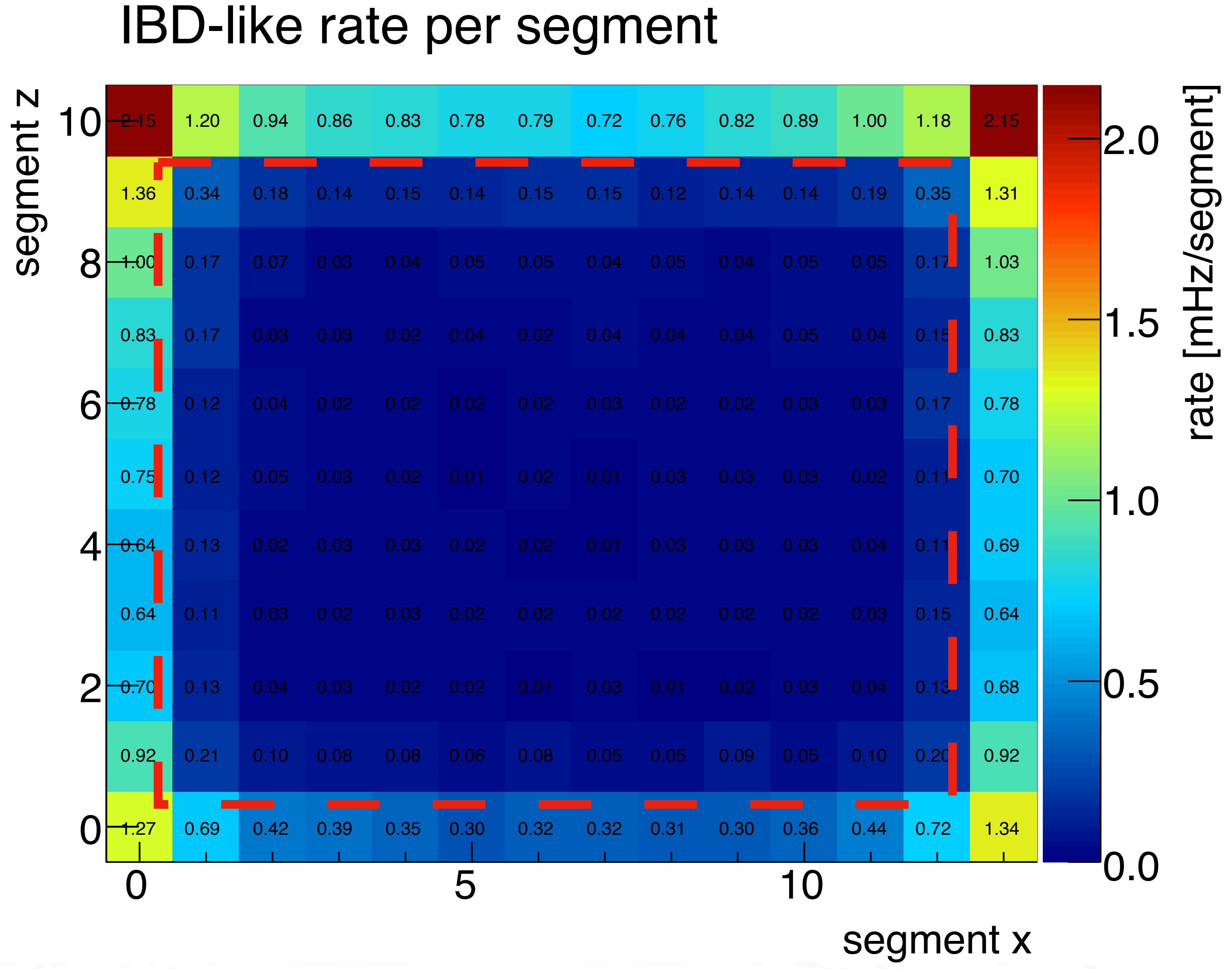
Wright Laboratory

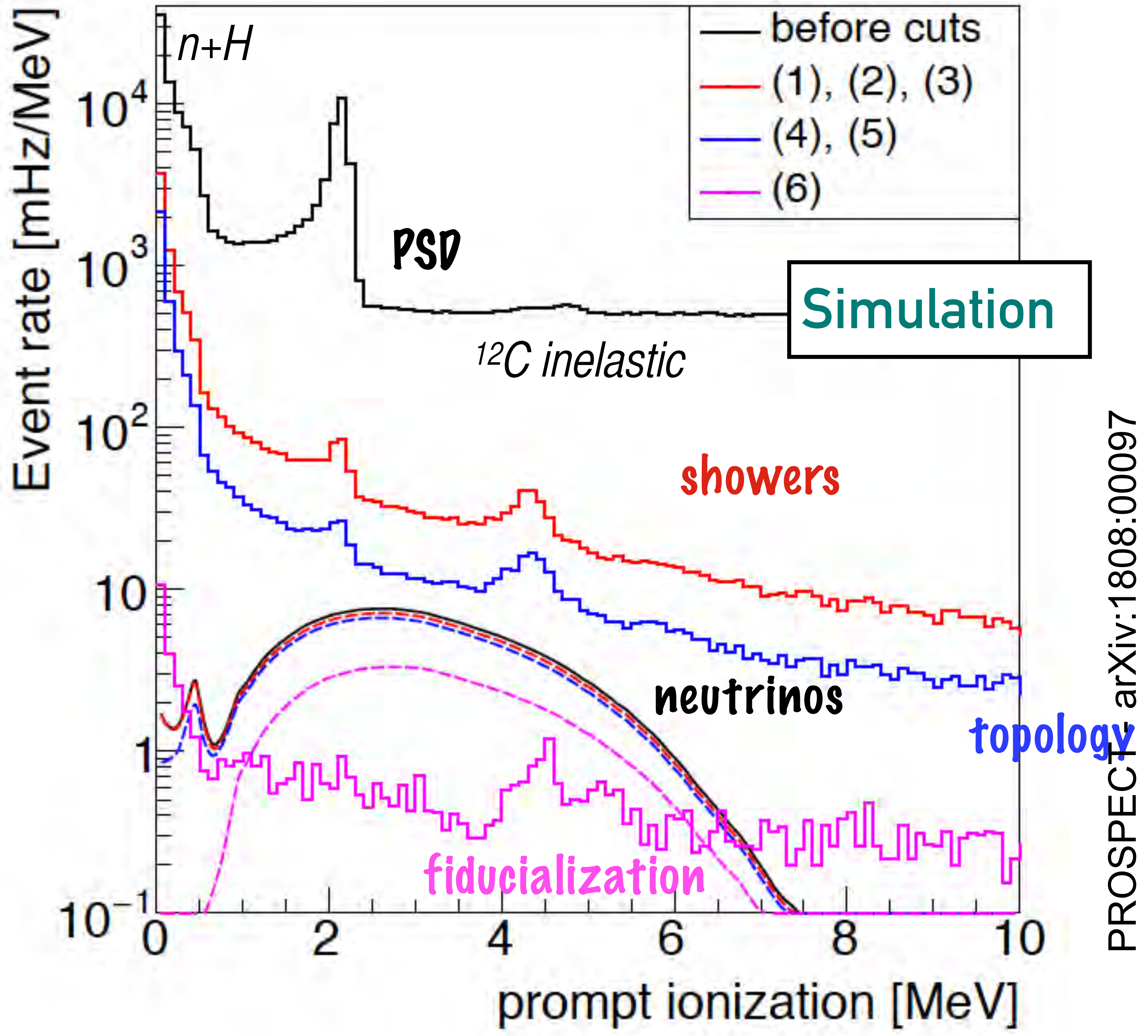
PROSPECT Detector Design

Single 4,000 L **^{6}Li-loaded liquid scintillator** (3,000 L fiducial volume)

11 x 14 (154) **array of optically separated segments**



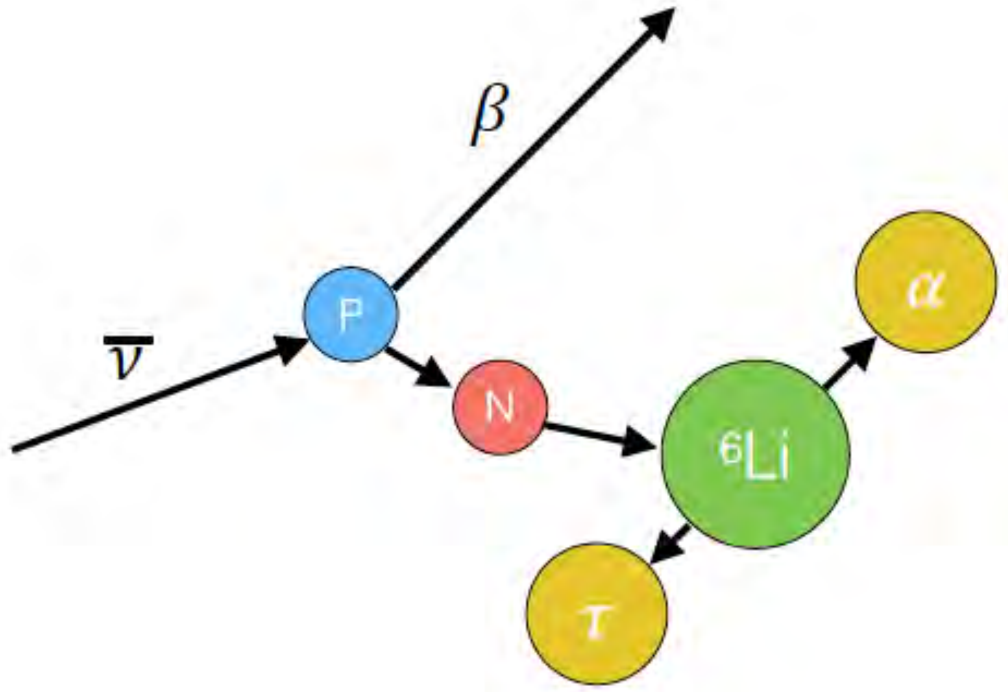




Karsten Heeger, Yale

Antineutrino Event Identification with ^{6}Li

Inverse Beta Decay



Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

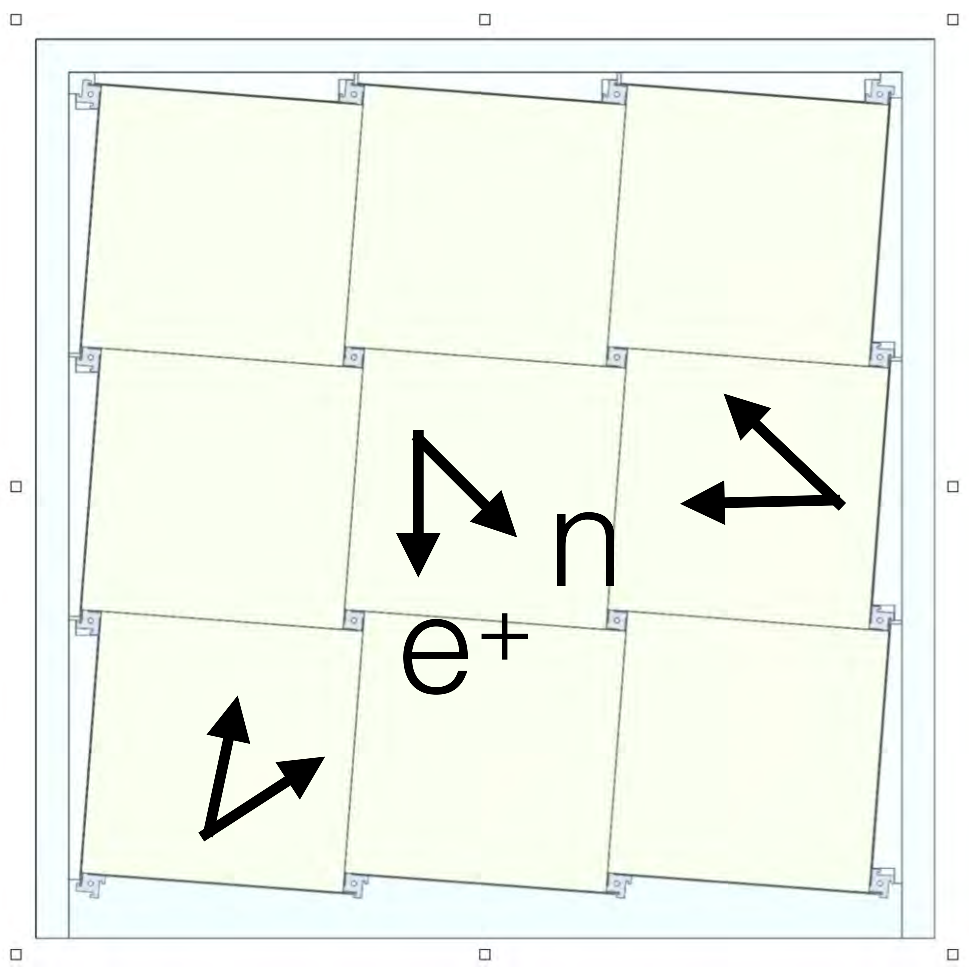
Delay signal: ~0.5 MeV signal from neutron capture on ^{6}Li

40μs delayed n capture

Background Reduction

detector design & fiducialization

IBD event in segmented ^{6}LiLS detector



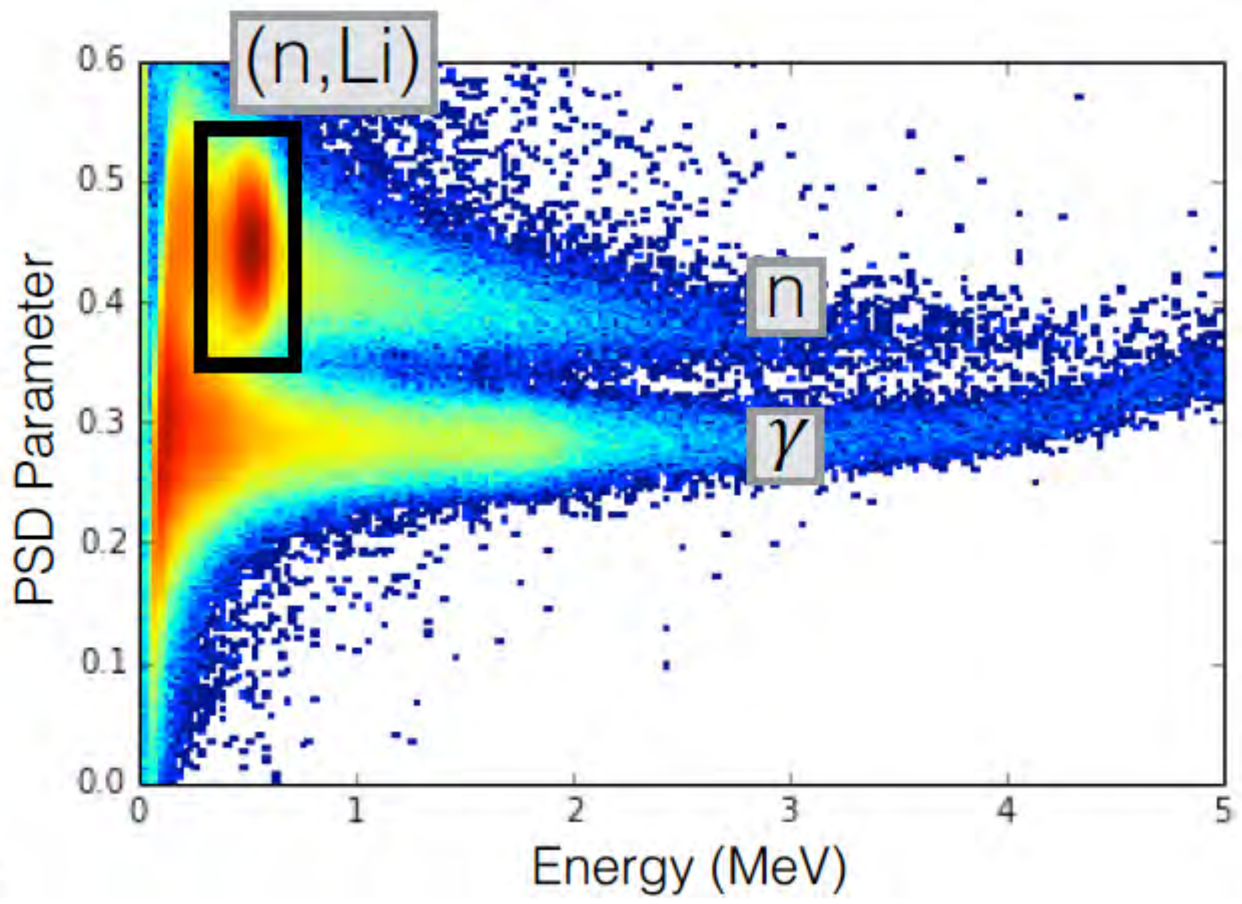
signal — inverse beta decay (IBD)
γ-like prompt, n-like delay

backgrounds — fast neutron
n-like prompt, n-like delay

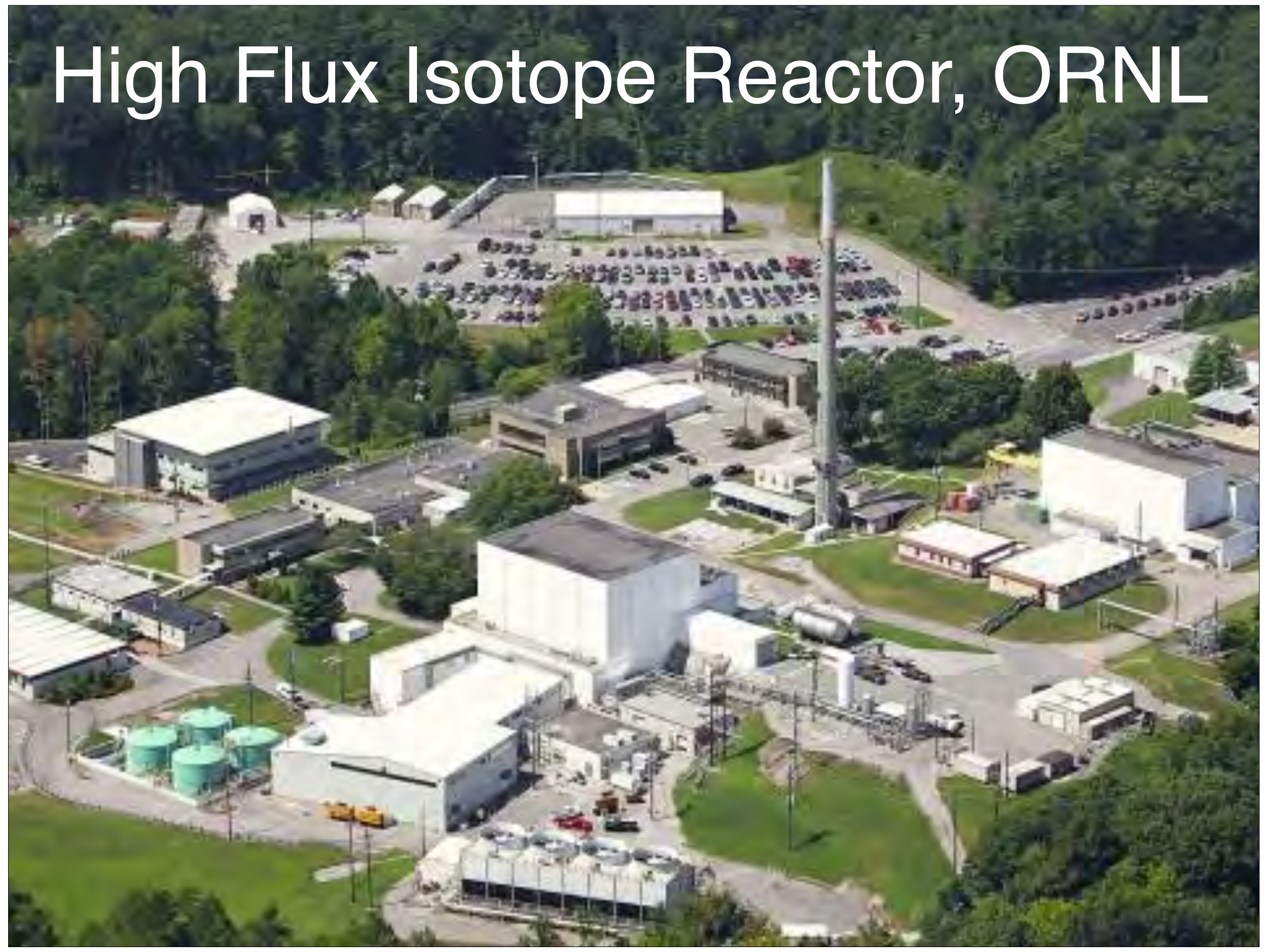
accidental gamma
γ-like prompt, γ-like delay

Background reduction is key challenge

Pulse Shape Discrimination



PROSPECT at HIFR Reactor



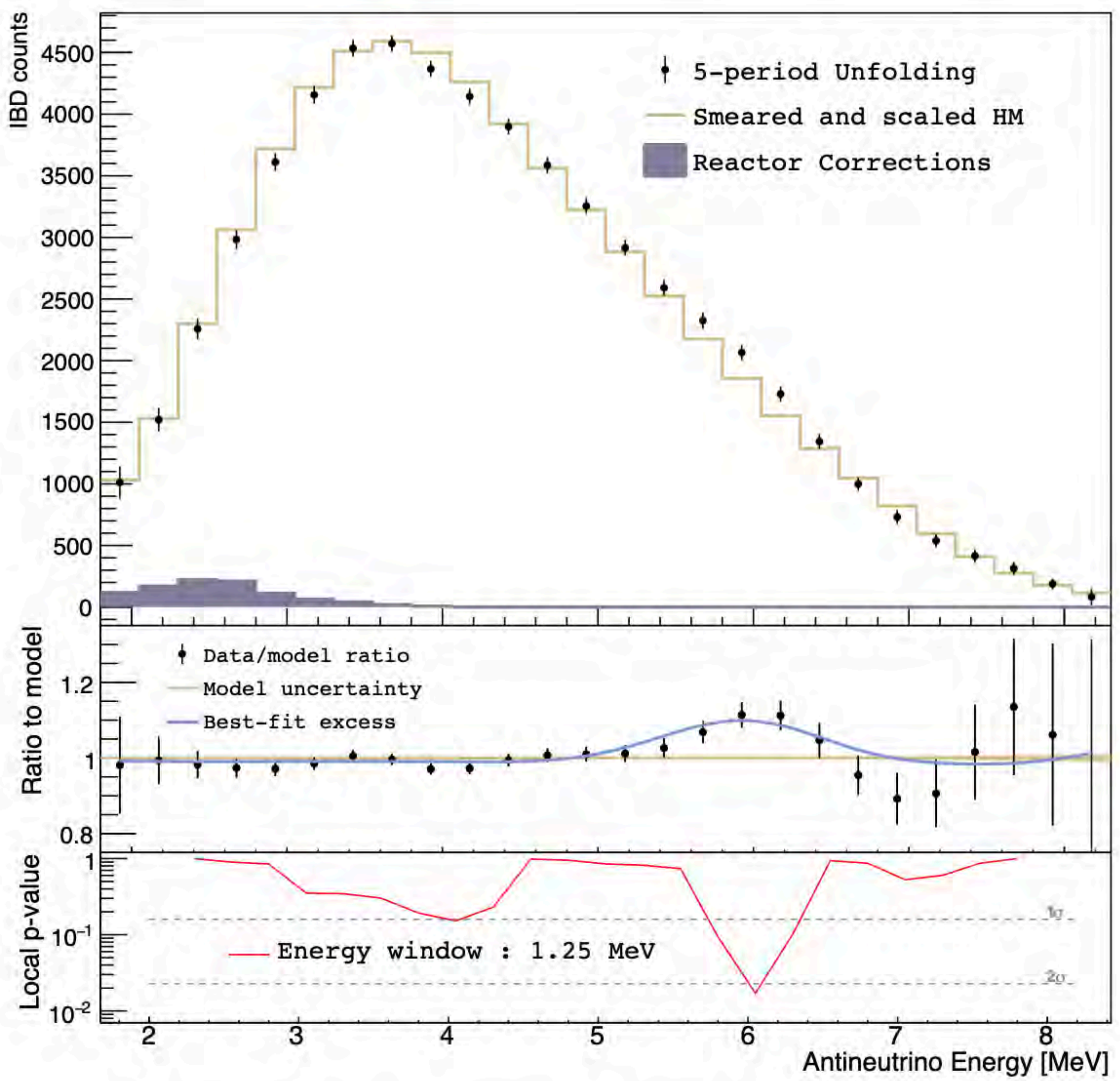
Reactor Core

Power: 85 MW
Core shape: cylindrical
Size: h=0.5m r=0.2m
Duty-cycle: 46%, 7 cycles/yr, 24 days
Fuel: HEU (^{235}U)

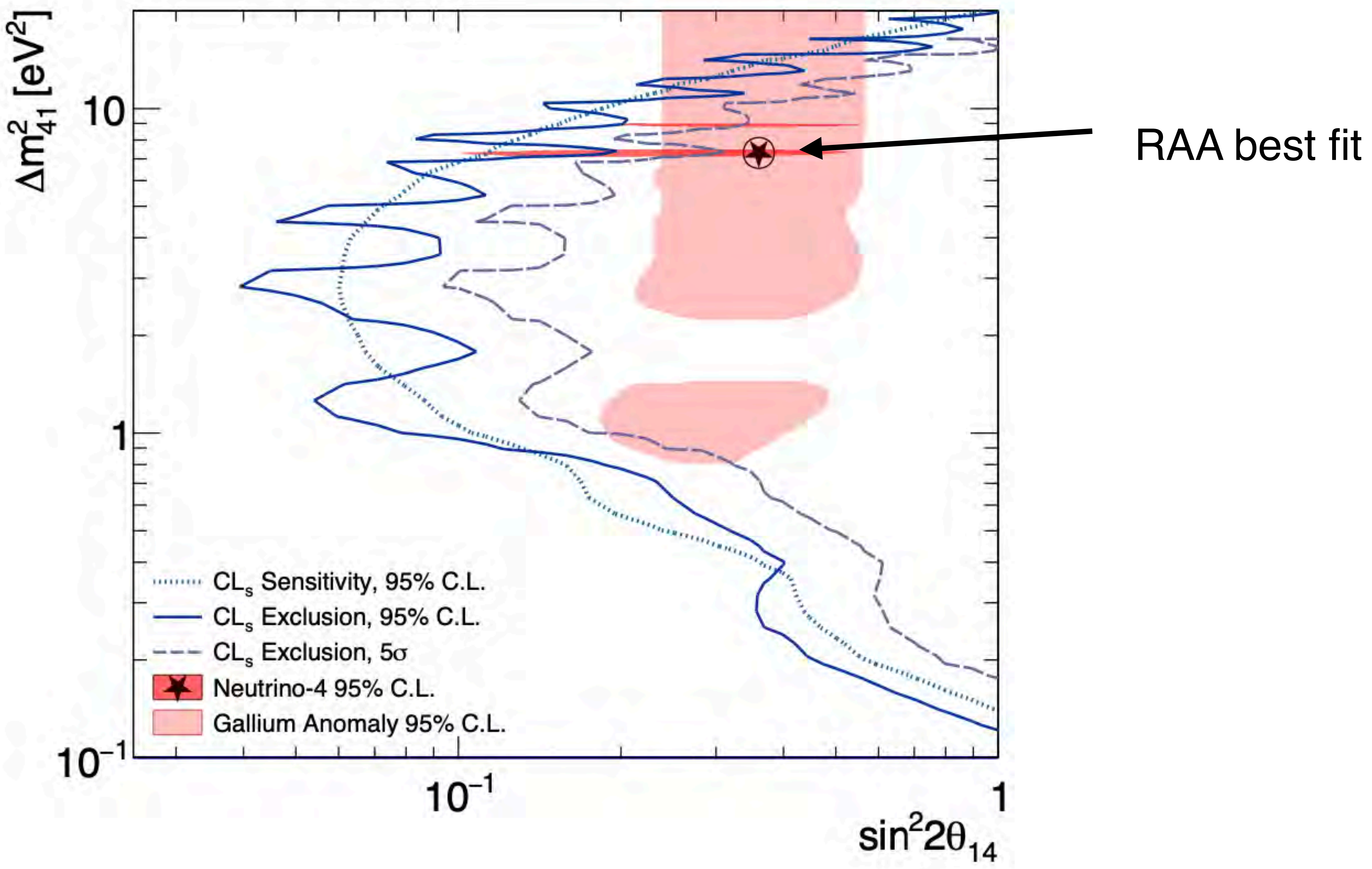
compact reactor core,
detector near surface,
little overburden

highly-enriched (HEU): >99% of $\overline{\nu}_e$ flux from ^{235}U fission

PROSPECT Results



Phys.Rev.Lett. 131 (2023) 2, 021802
PROSPECT Collaboration



https://arxiv.org/pdf/2406.10408
PROSPECT Collaboration

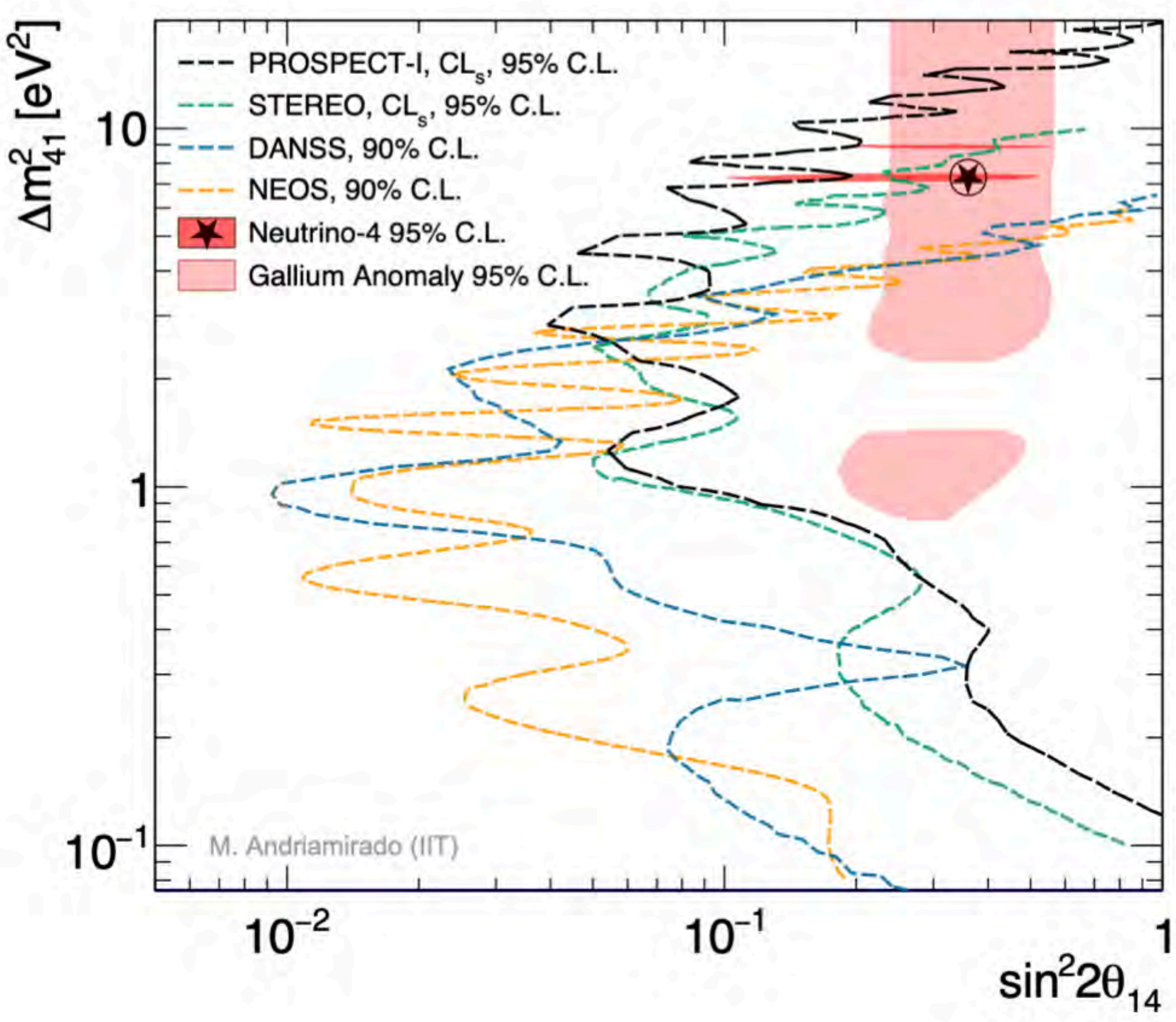
New world-leading limits on sterile neutrino oscillations

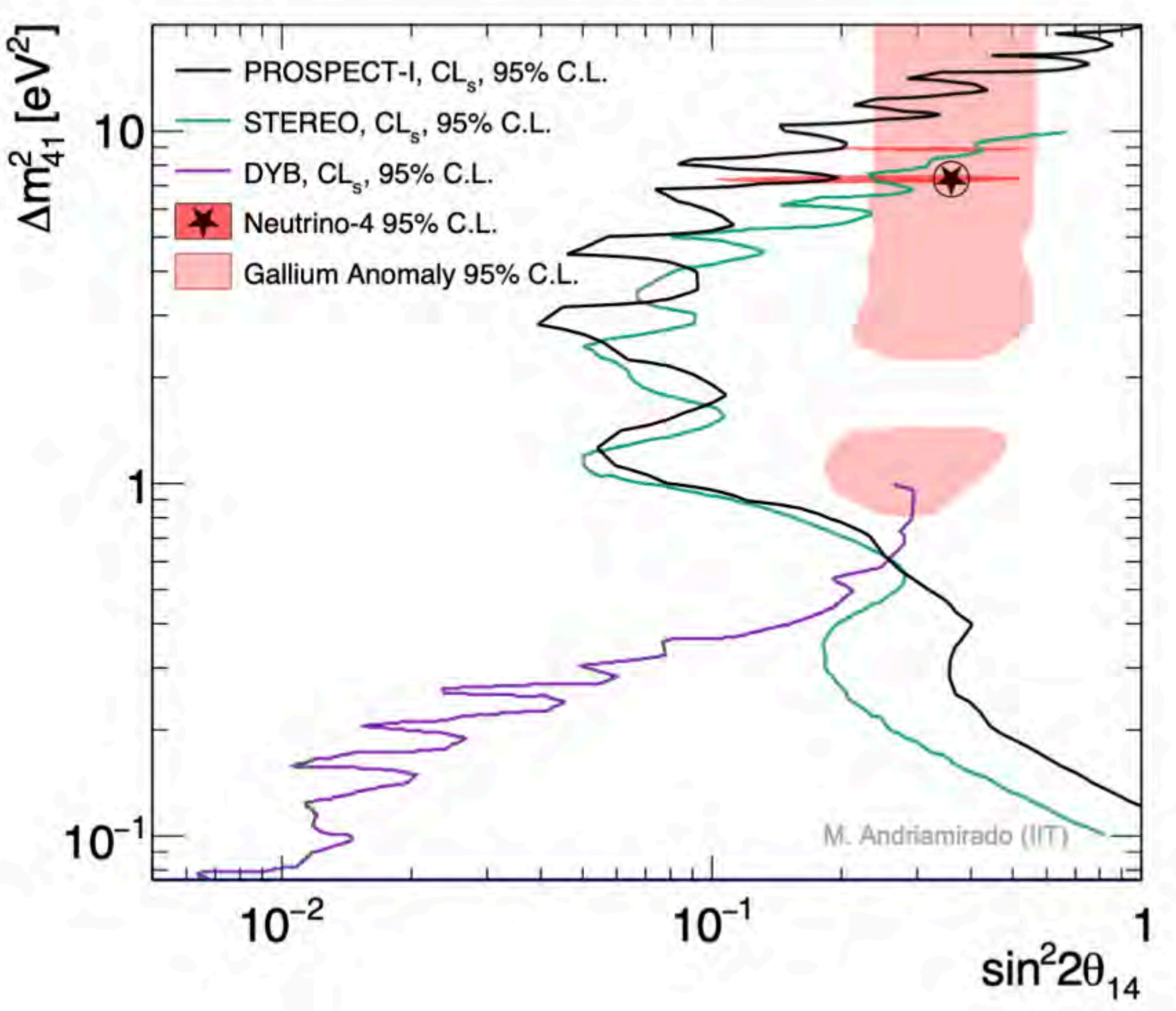
Data are compatible with the null-oscillation prediction

Excludes space below 10 eV^2 suggested by BEST at >95% CL

Neutrino-4 best-fit is ruled out at >5σ CL

PROSPECT + Other Experiments





Joint analysis started between PROSPECT, STEREO and Daya Bay

Strong limits from complementary measurements.

The sterile neutrino hypothesis is rejected over most of the RAA phase space.

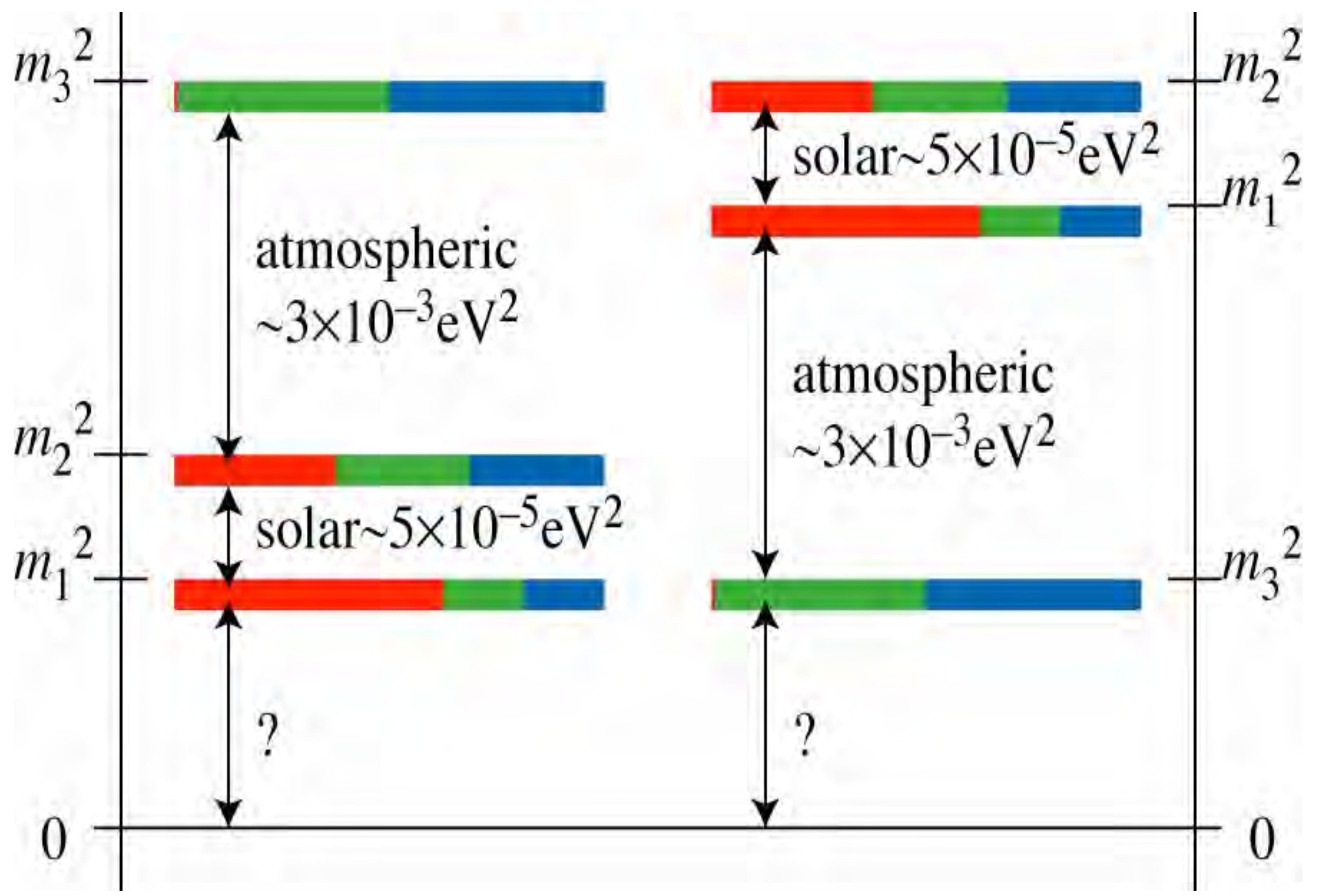
Open Questions

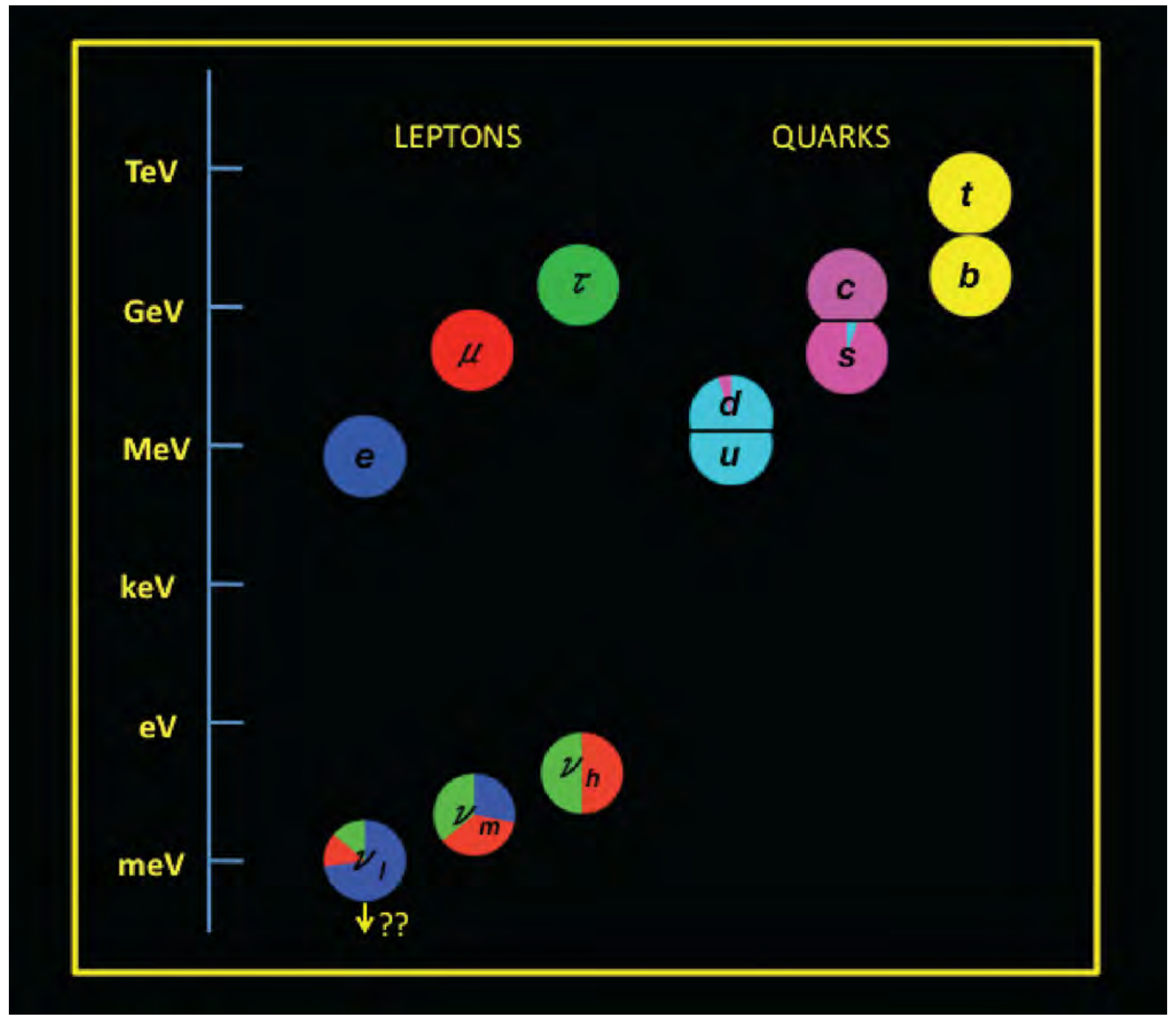
Where do neutrino masses come from?

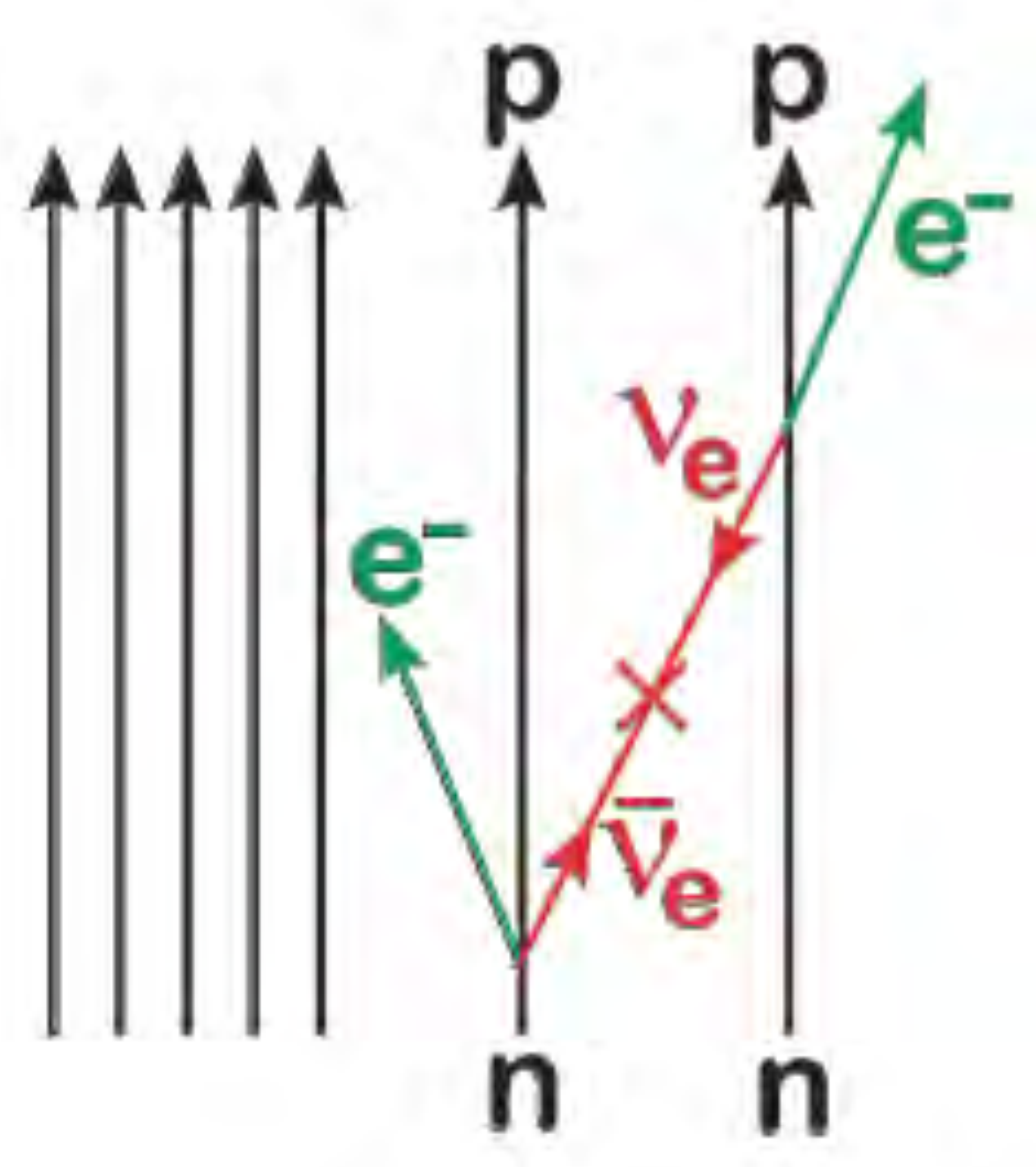
What is the origin of leptonic mixing?

Are neutrinos their own antiparticles?

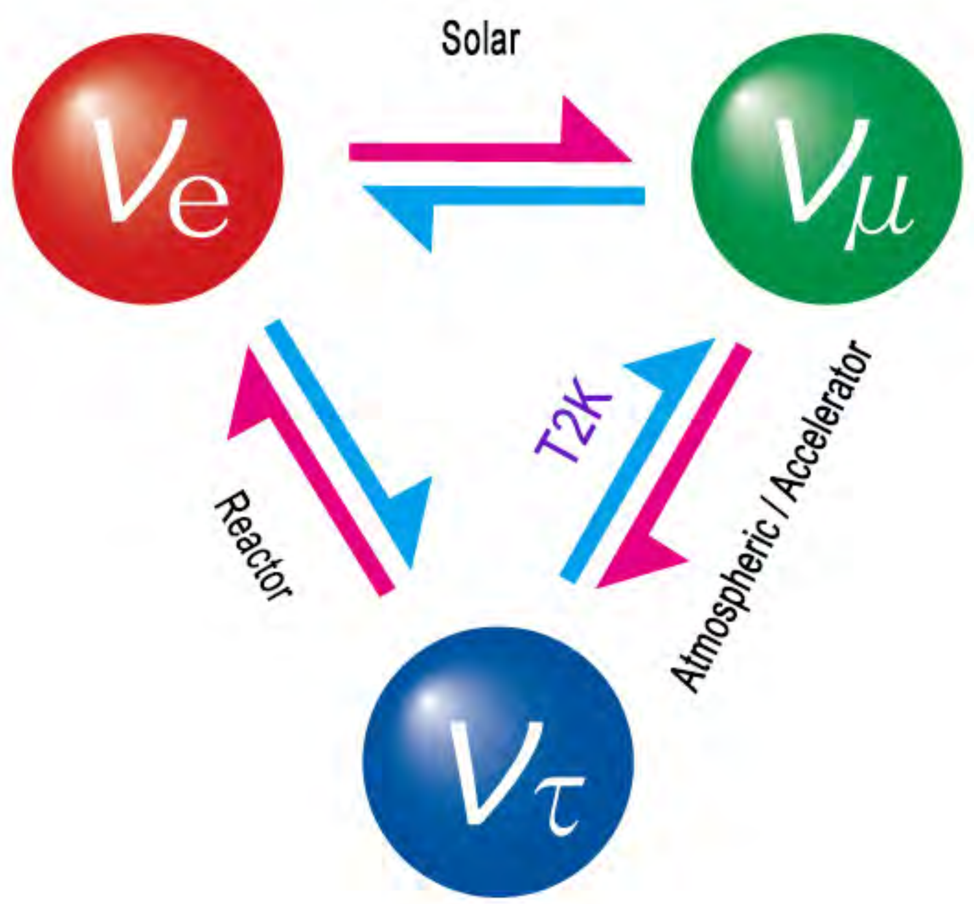
Major discoveries ahead



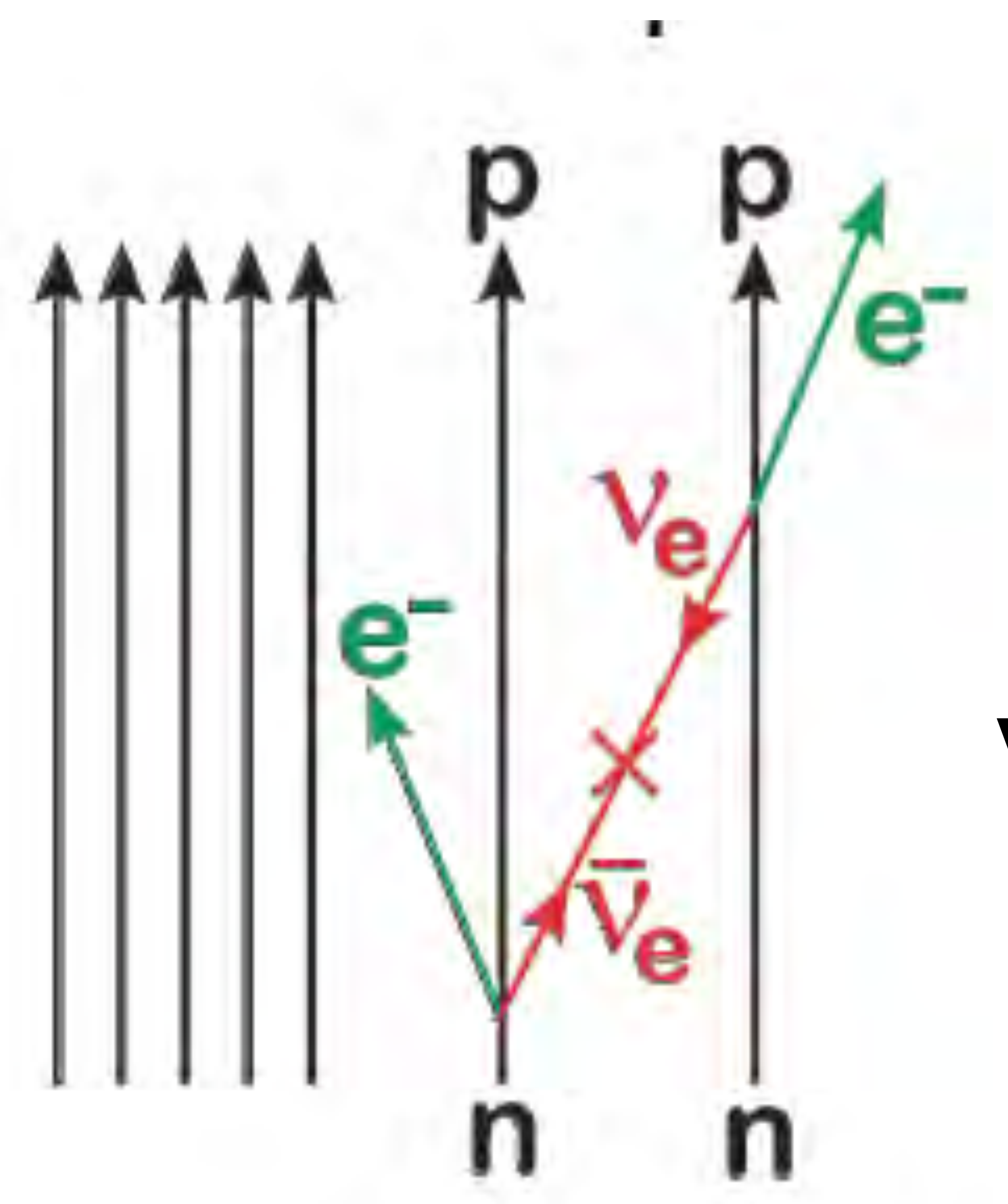




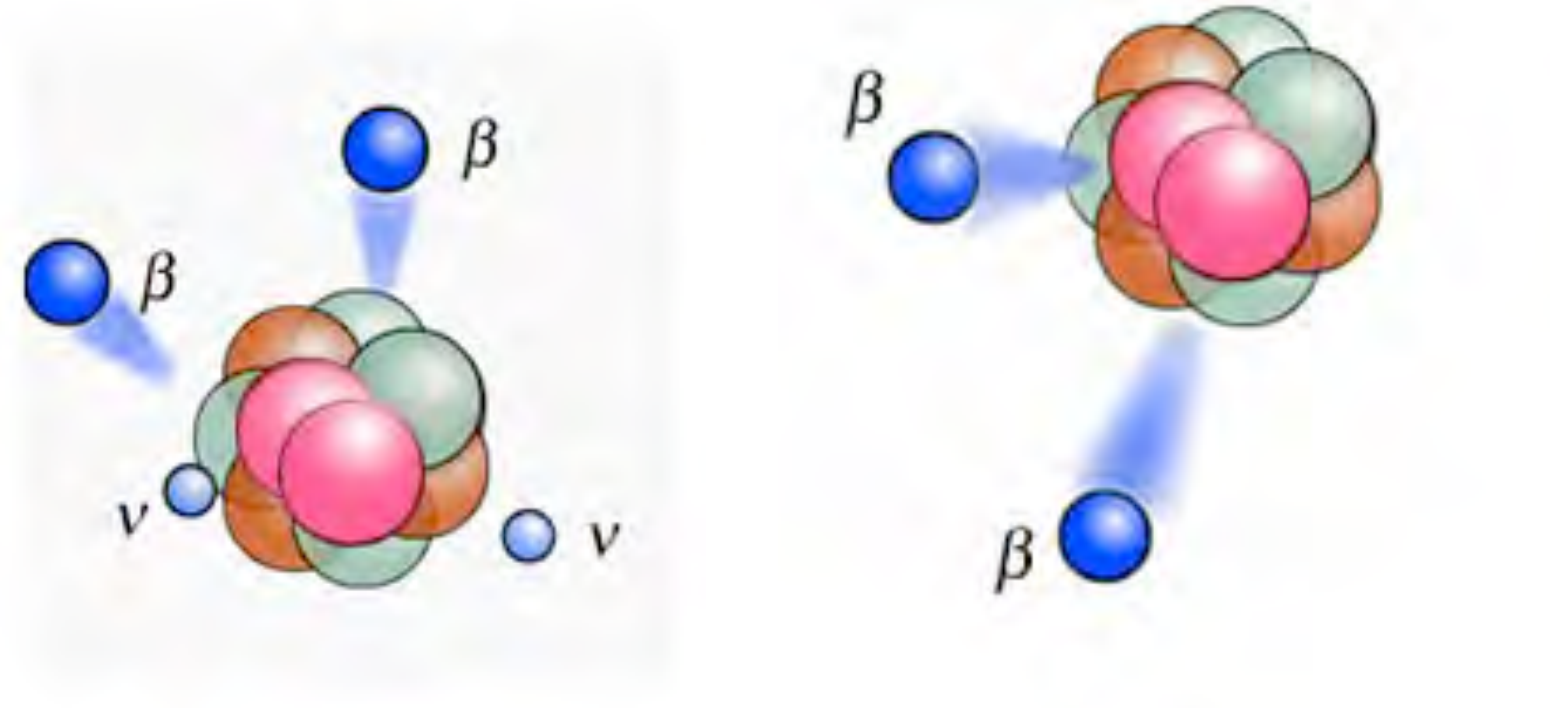
$\nu = \overline{\nu}$?



What is the nature of neutrino mass?



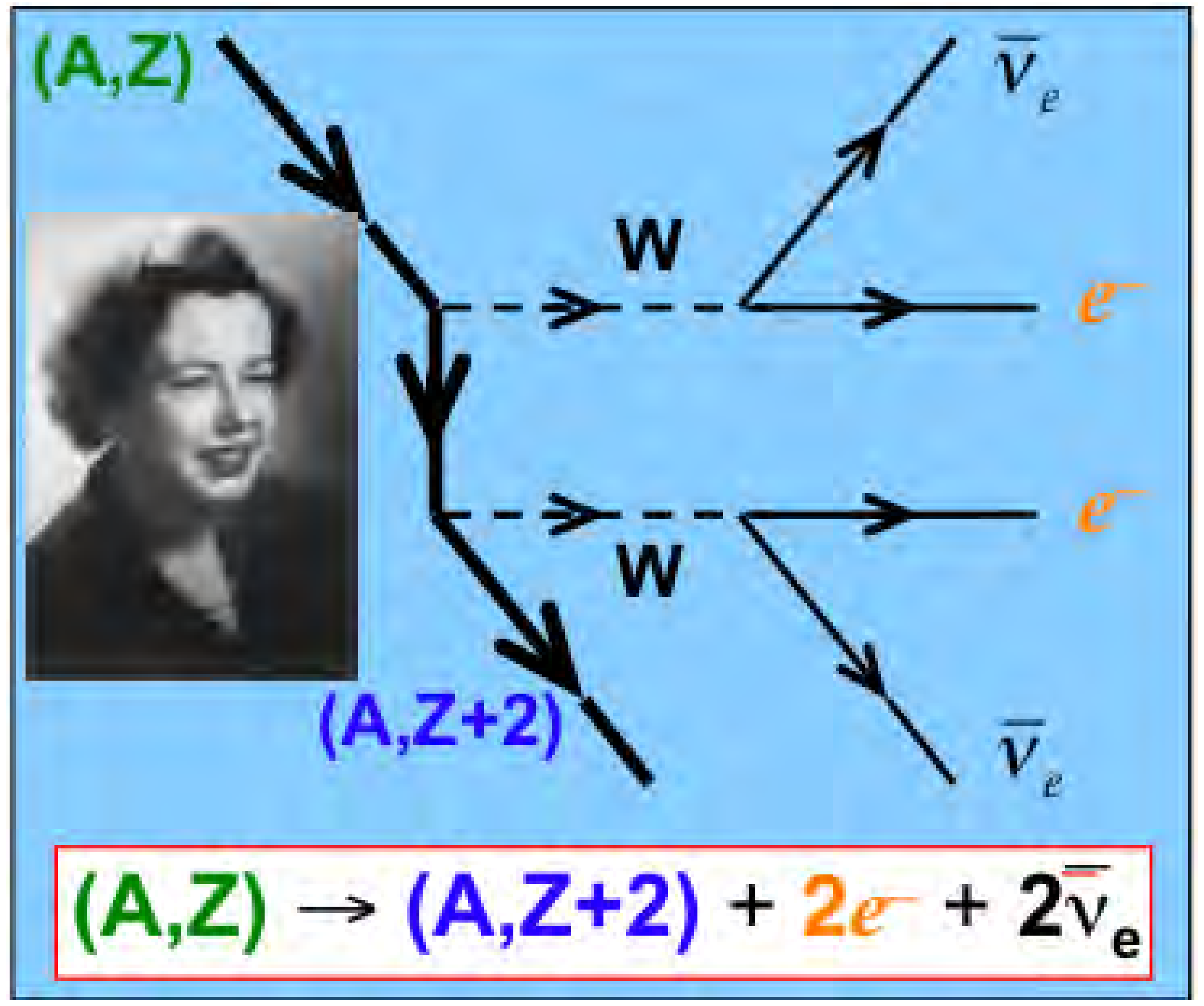
$\nu = \bar{\nu}$?



Understanding Neutrino Mass from Double Beta Decay

Nuclei as a laboratory to study lepton number violation at low energies

$2\nu\beta\beta$



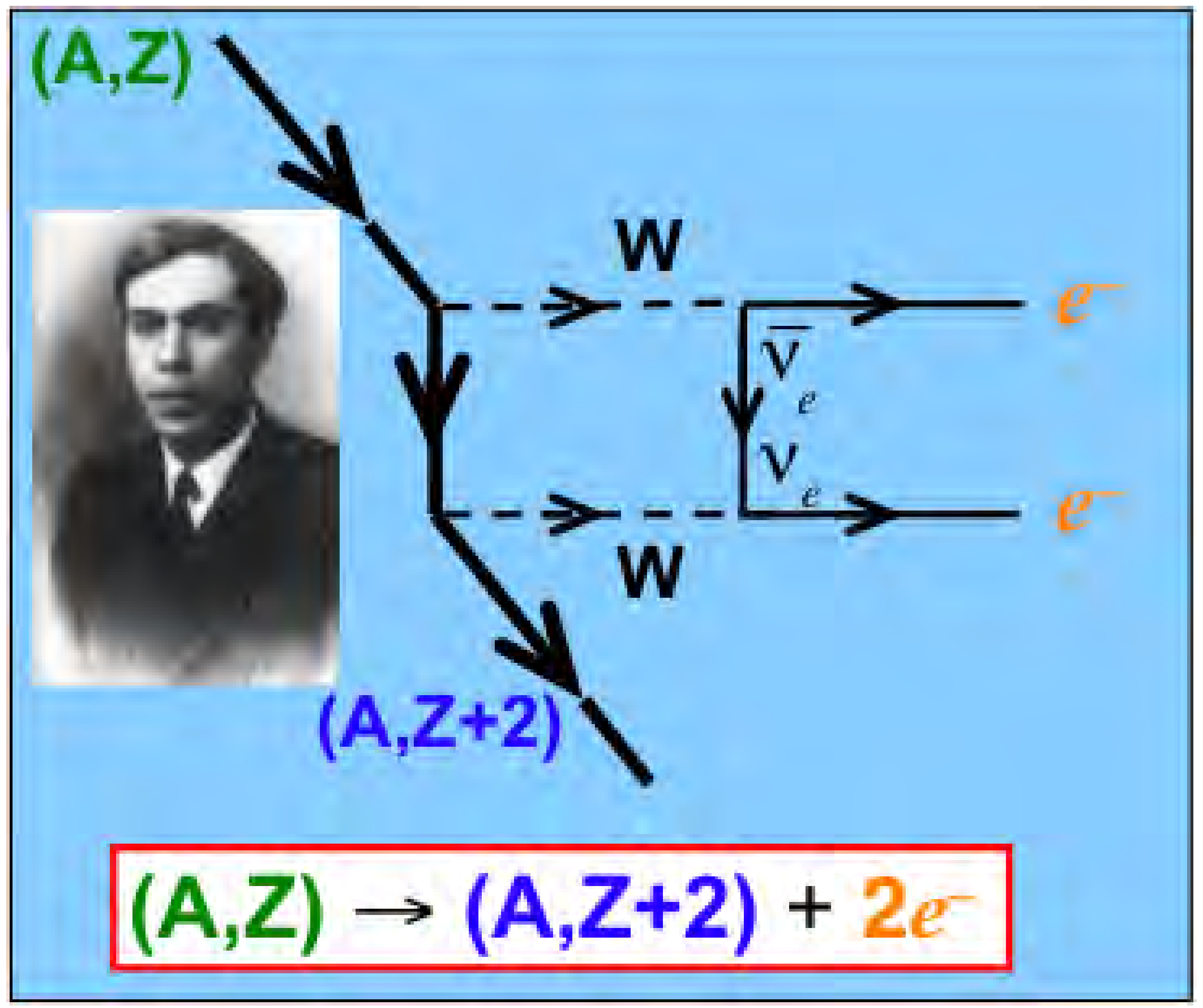
Proposed in 1935 by Maria Goeppert-Mayer

Observed in several nuclei

$T_{1/2} \sim 10^{19} - 10^{21}$ yrs

$$\Gamma_{2\nu} = G_{2\nu} \, | M_{2\nu} |^2$$

$0\nu\beta\beta$



Proposed in 1937 by Ettore Majorana

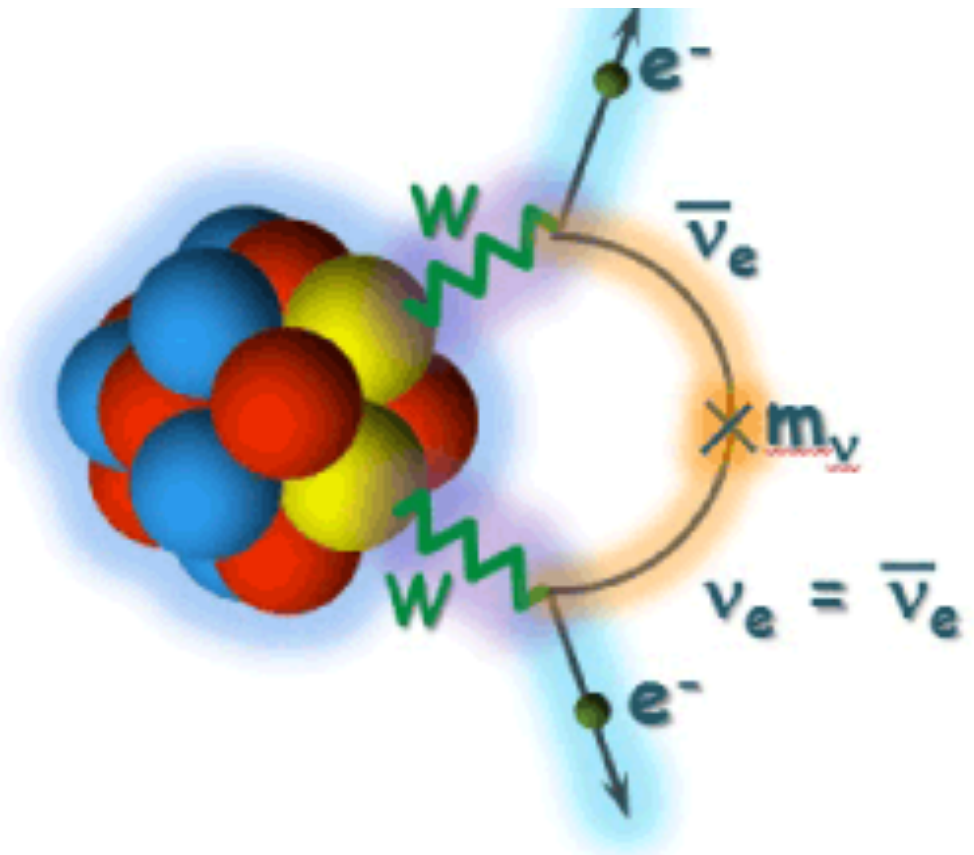
Not observed yet

$T_{1/2} \geq 10^{25}$ y

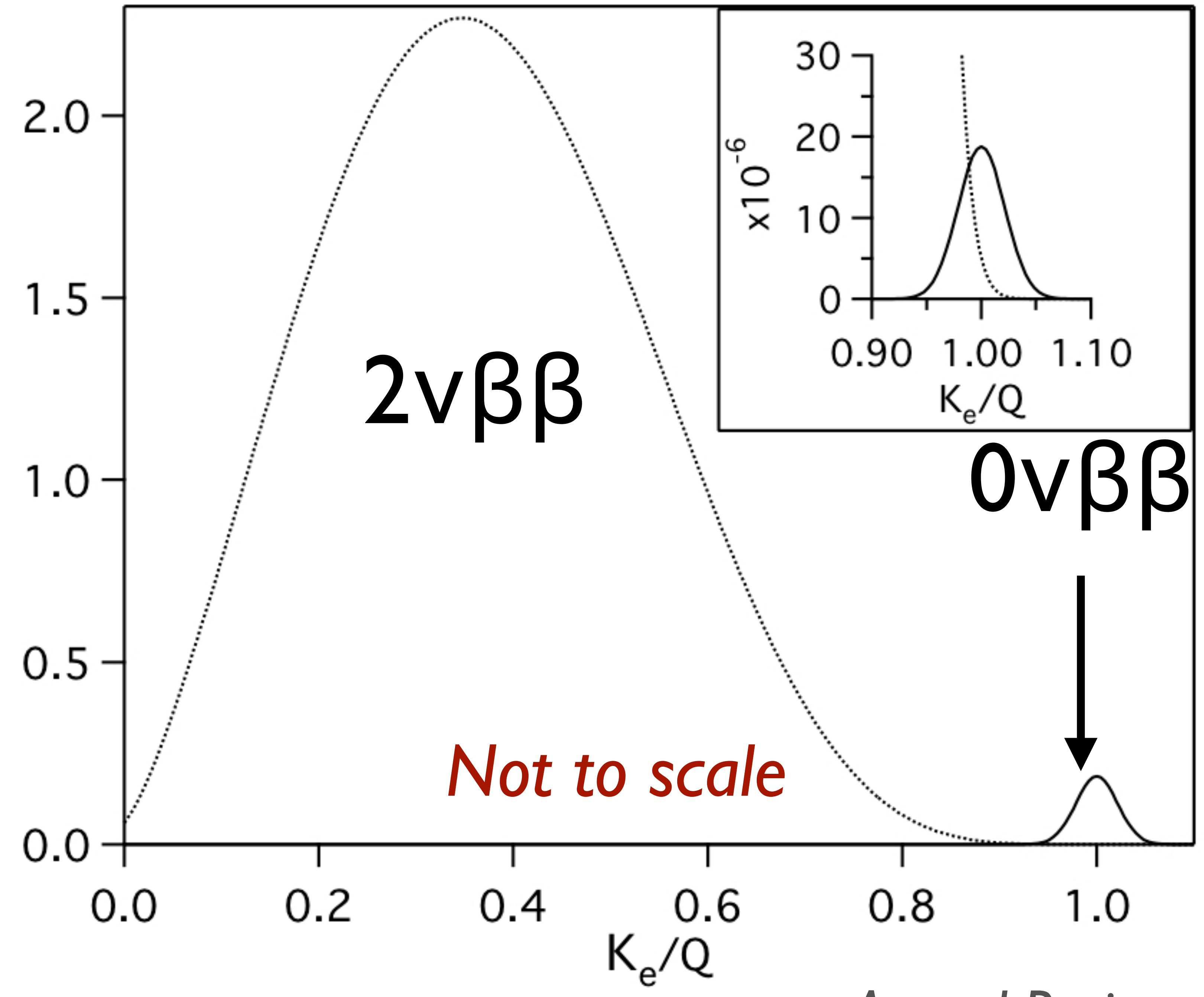
$$\Gamma_{0\nu} = G_{0\nu} \, | M_{0\nu} |^2 \left\langle m_{\beta\beta} \right\rangle^2$$

$0\nu\beta\beta$ would imply
- lepton number non-conservation
- Majorana nature of neutrinos

Neutrinoless Double Beta Decay (0νββ)

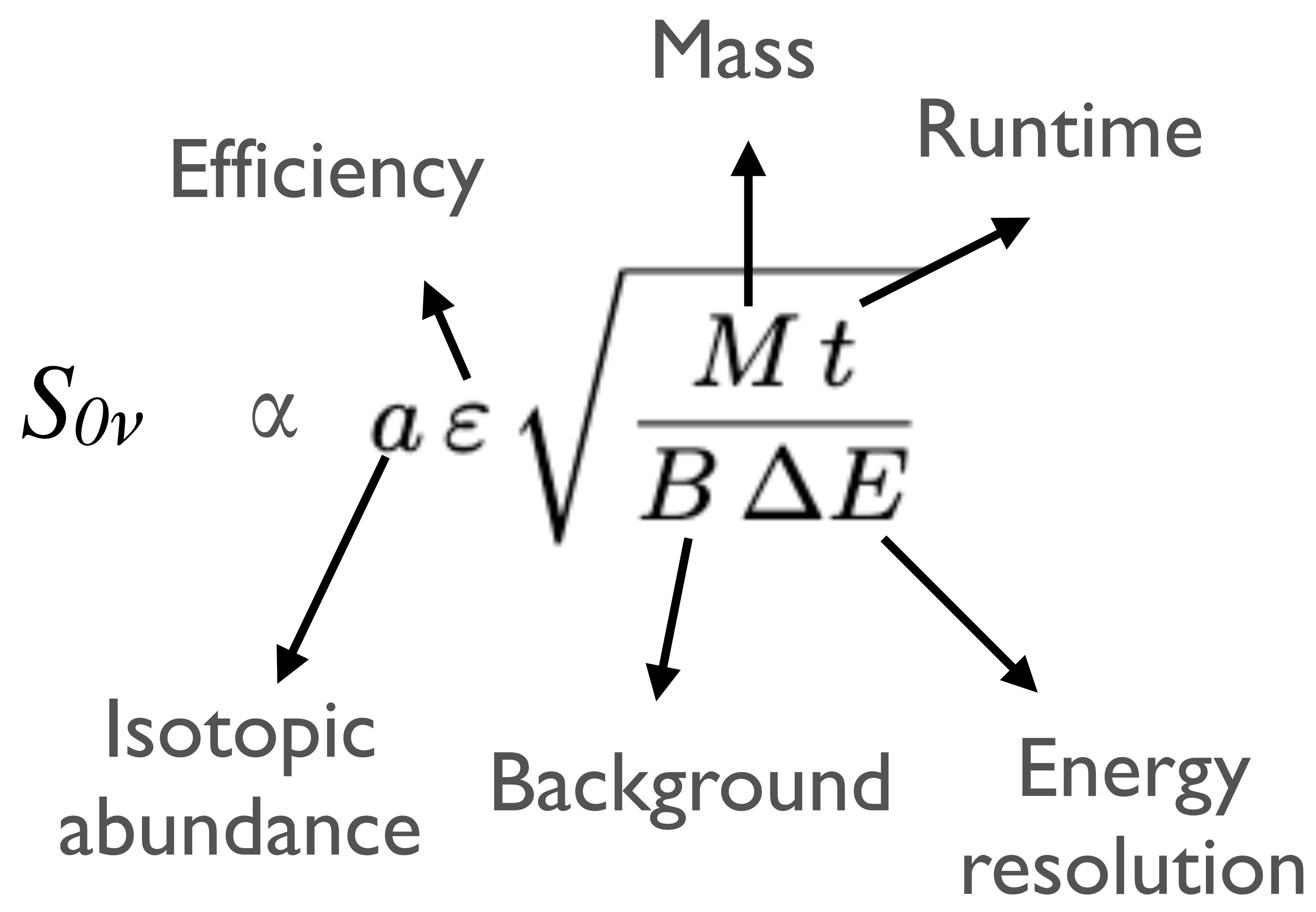


Neutrinoless
double beta decay



Annual Reviews: 52:115-151

Sensitivity



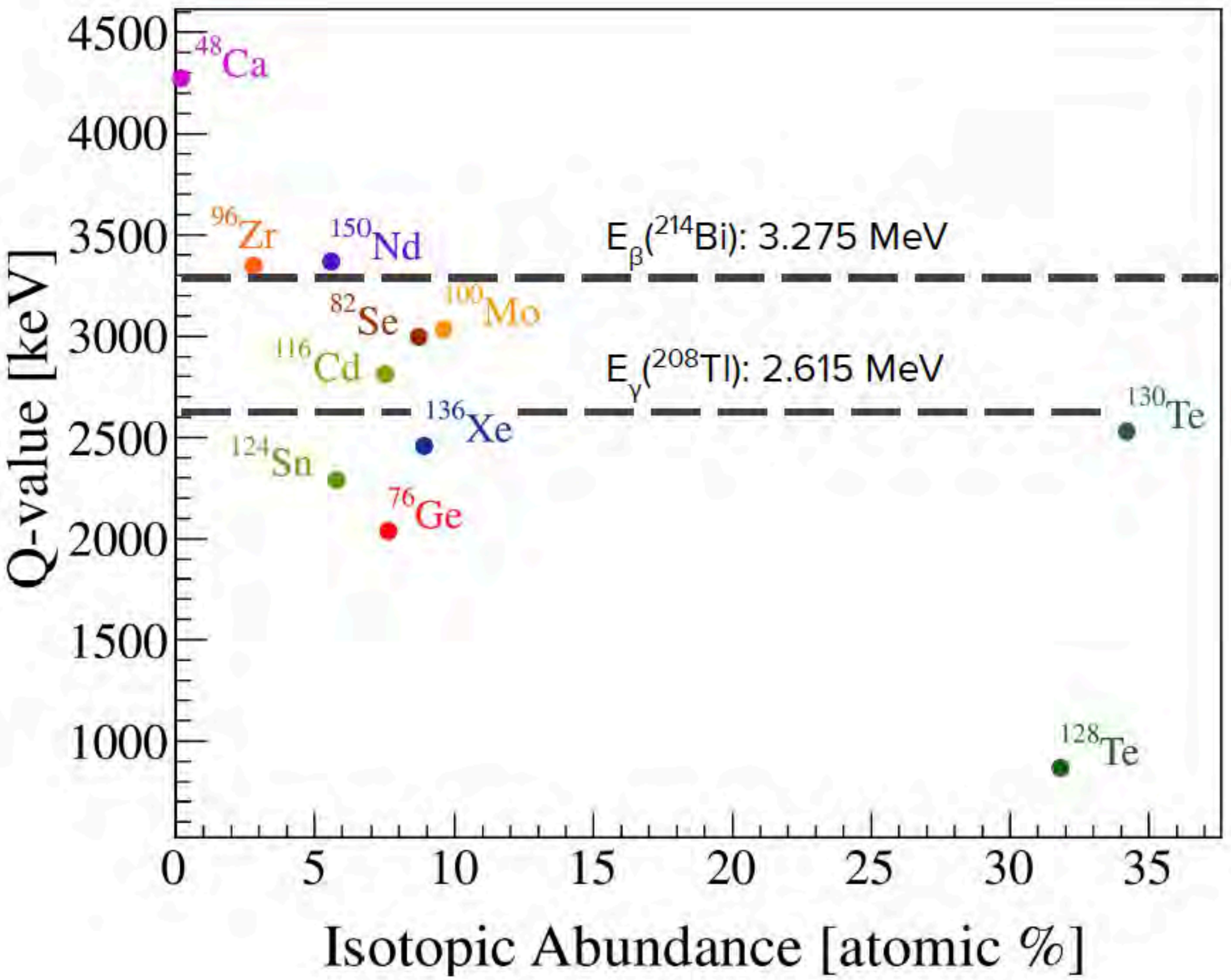
Search for peak search at the Q value of the decay

Energy peak is necessary and sufficient signature to claim a discovery.
Additional signatures from signal topology etc

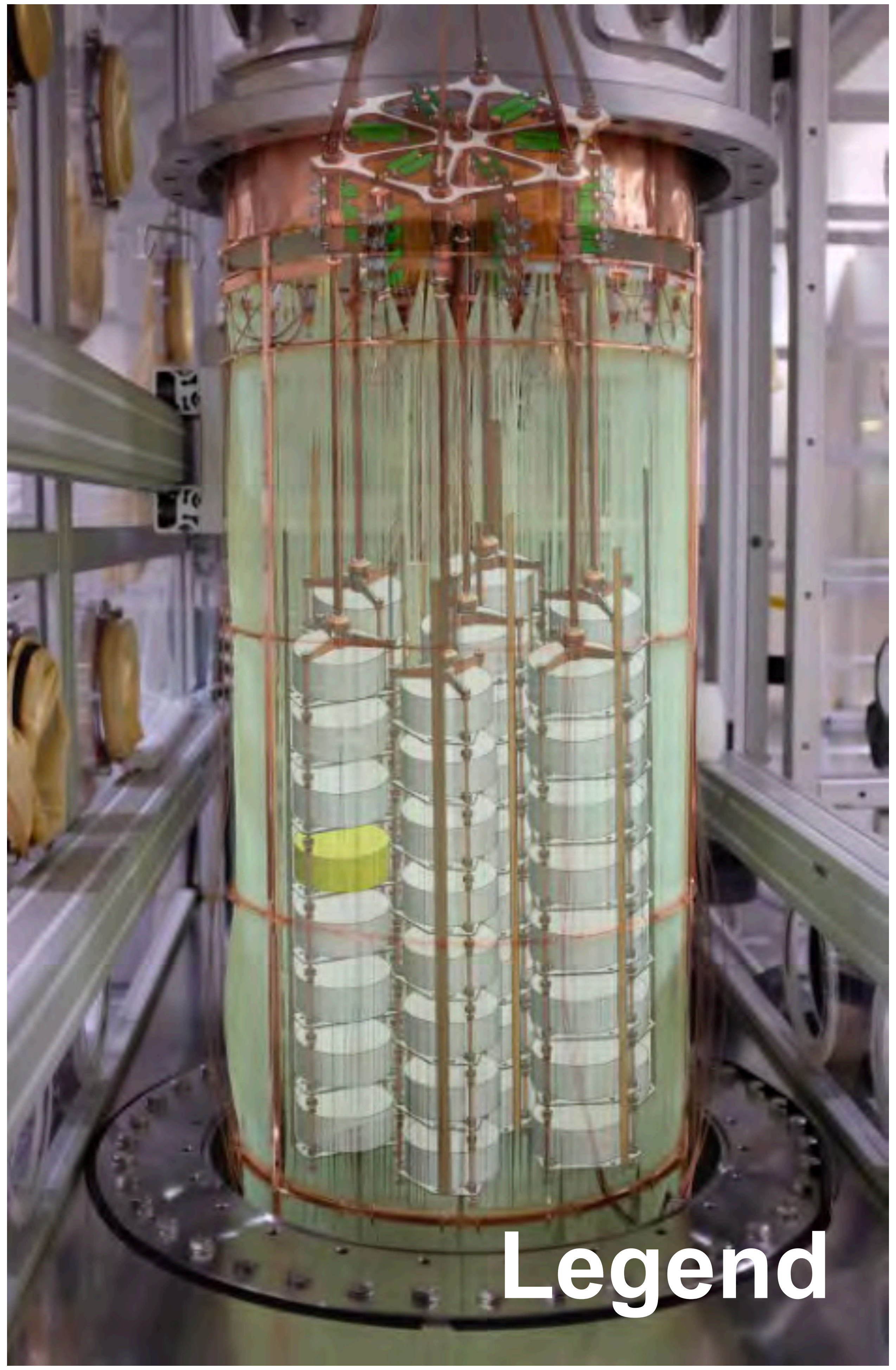
Isotope Choice

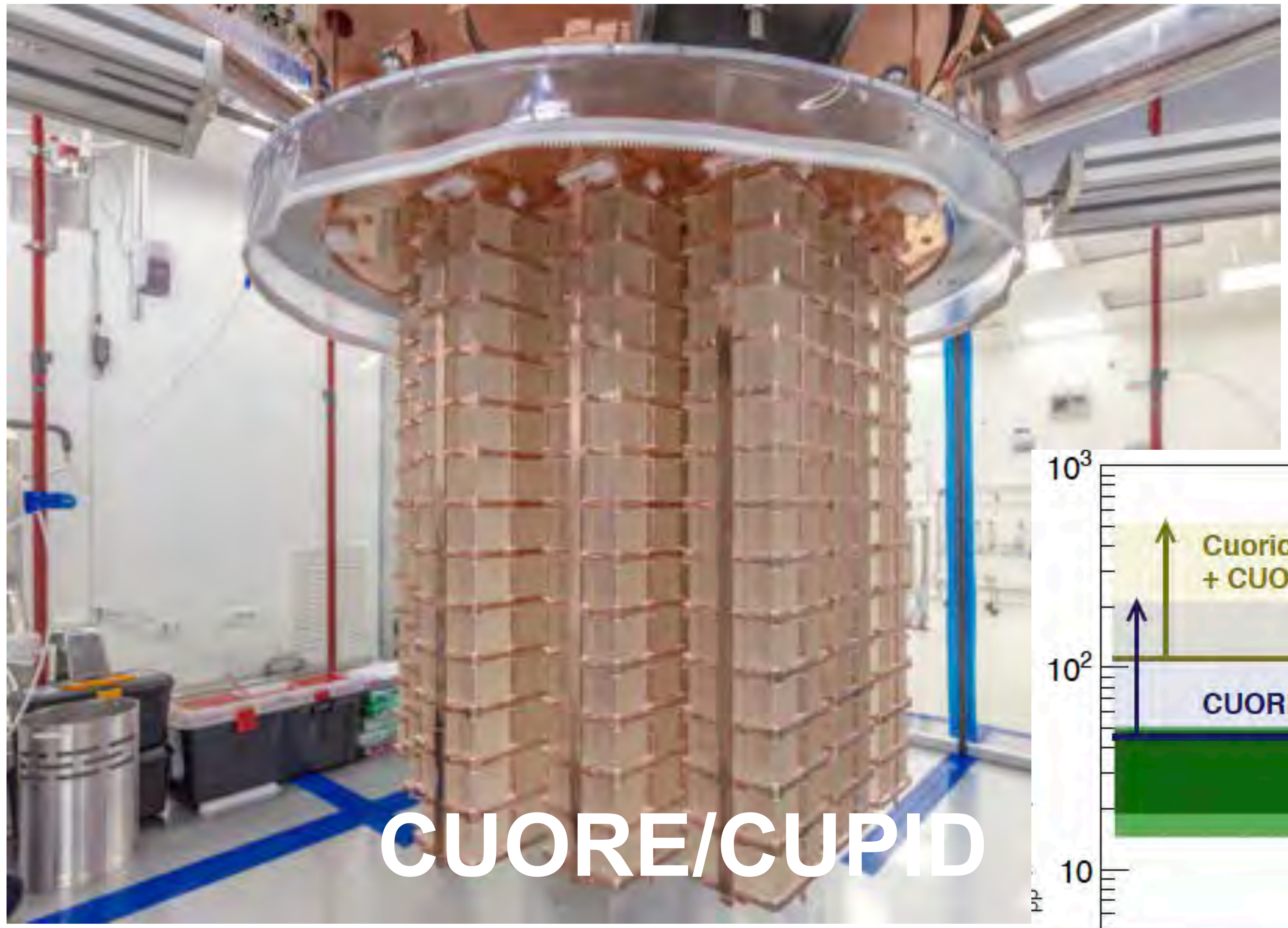
Desired Characteristics

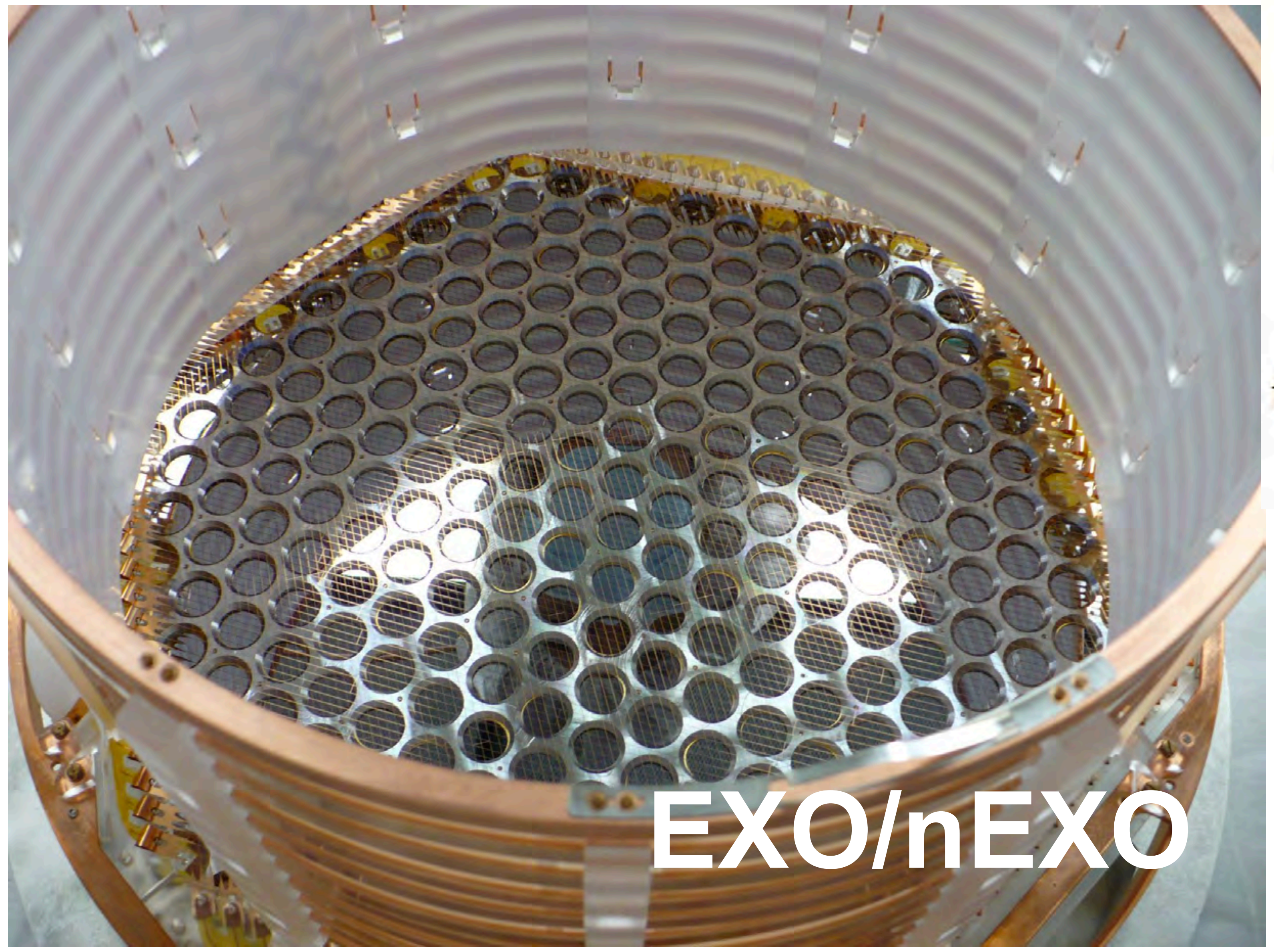
- High isotopic abundance
- Enrichment possible
- Qββ above end point of β or γ radiation
- Large scale production possible

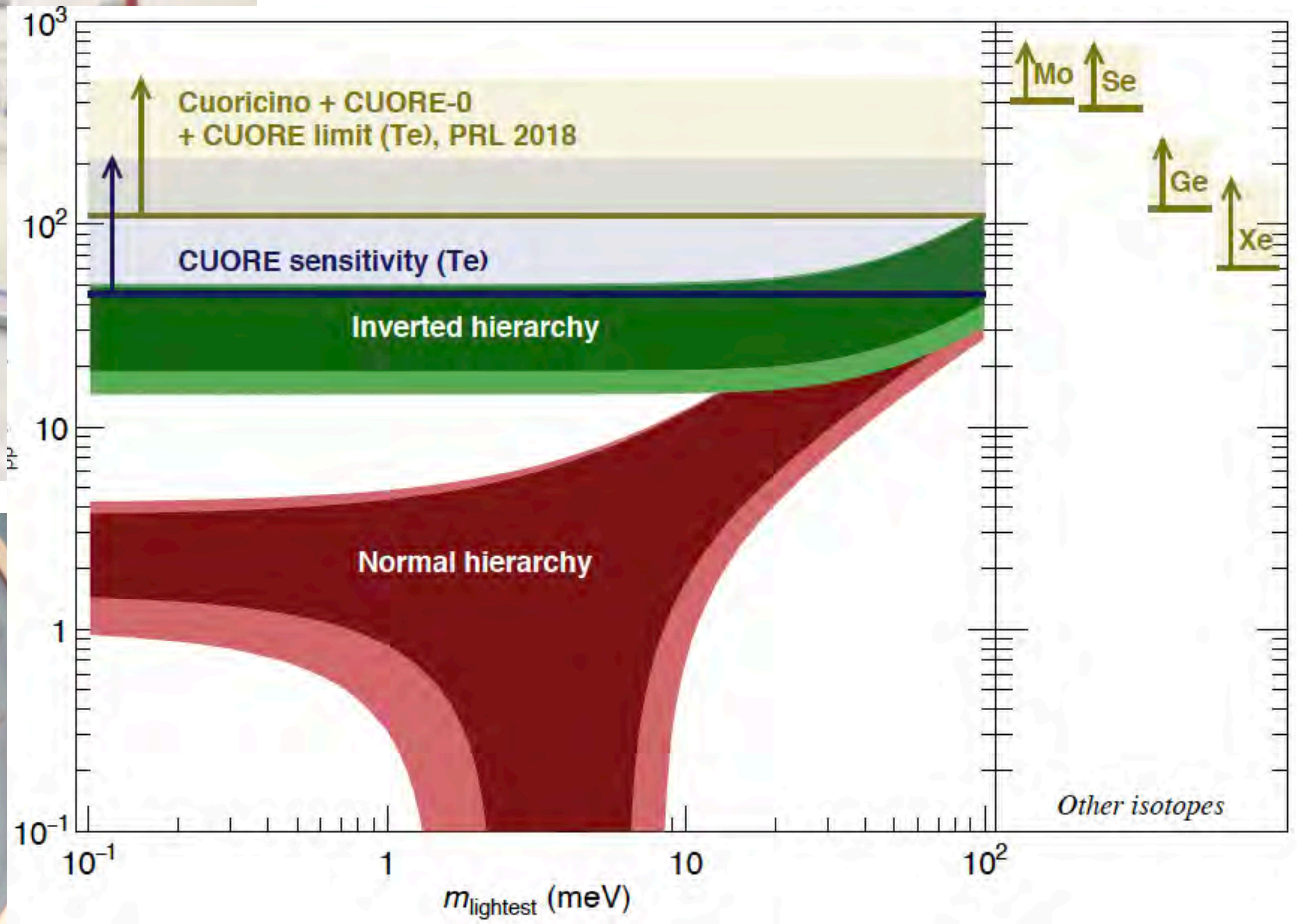


0νββ Searches









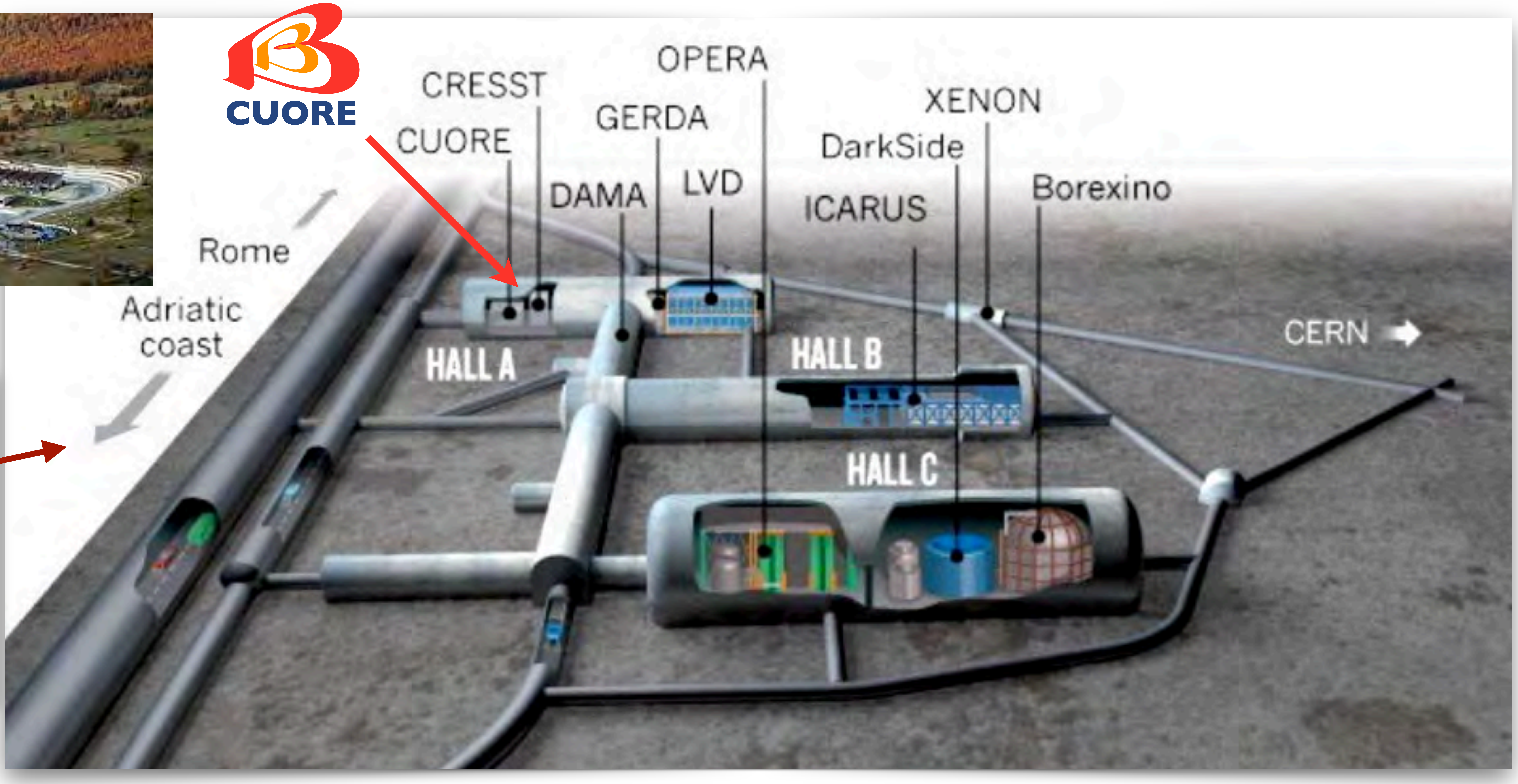
pushing limits towards inverted hierarchy

LNGS: Laboratori Nazionali del Gran Sasso

Natural shielding from cosmic rays by the mountain of Gran Sasso

3600 meter water equivalent overburden

Well-established support for experiments and user access

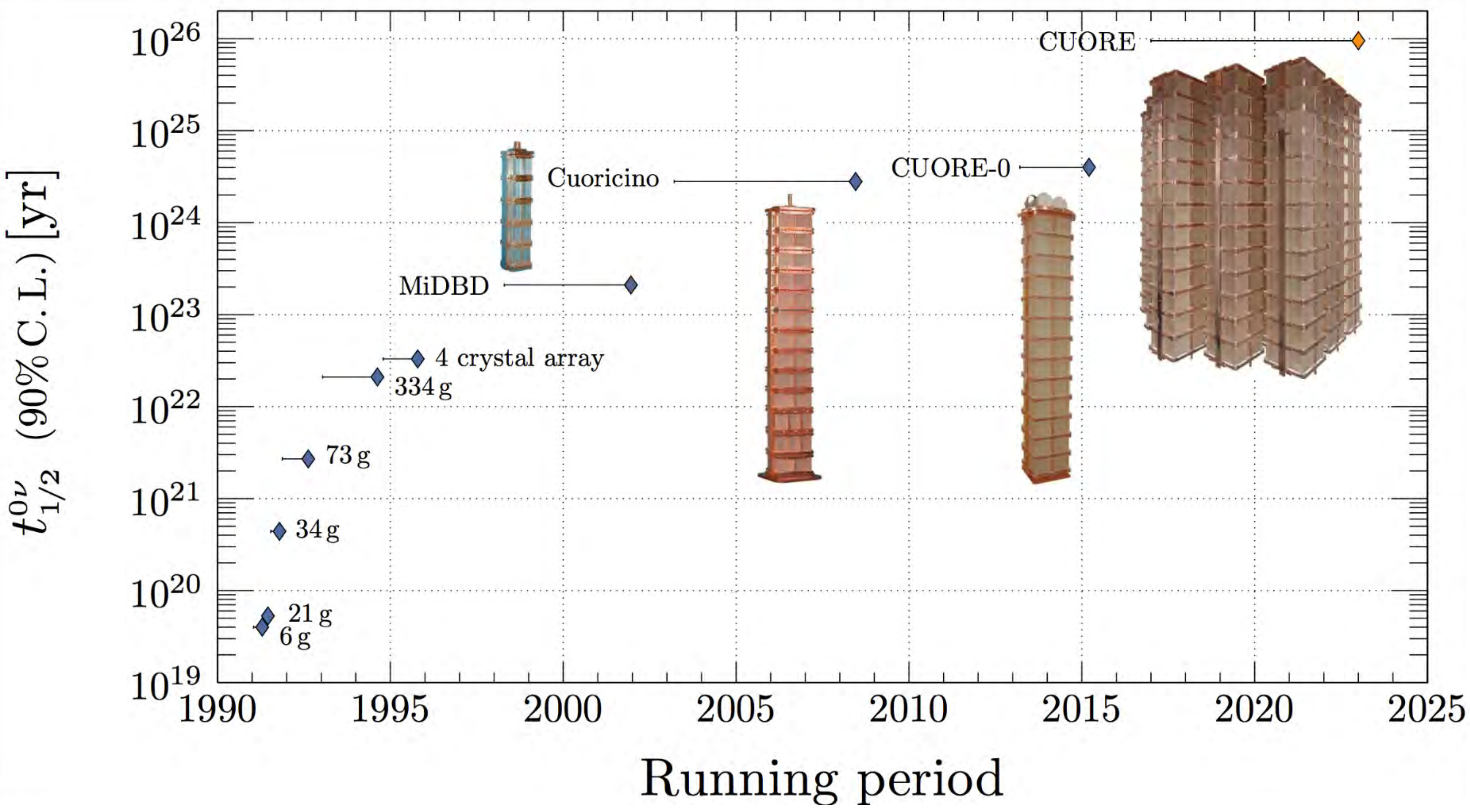


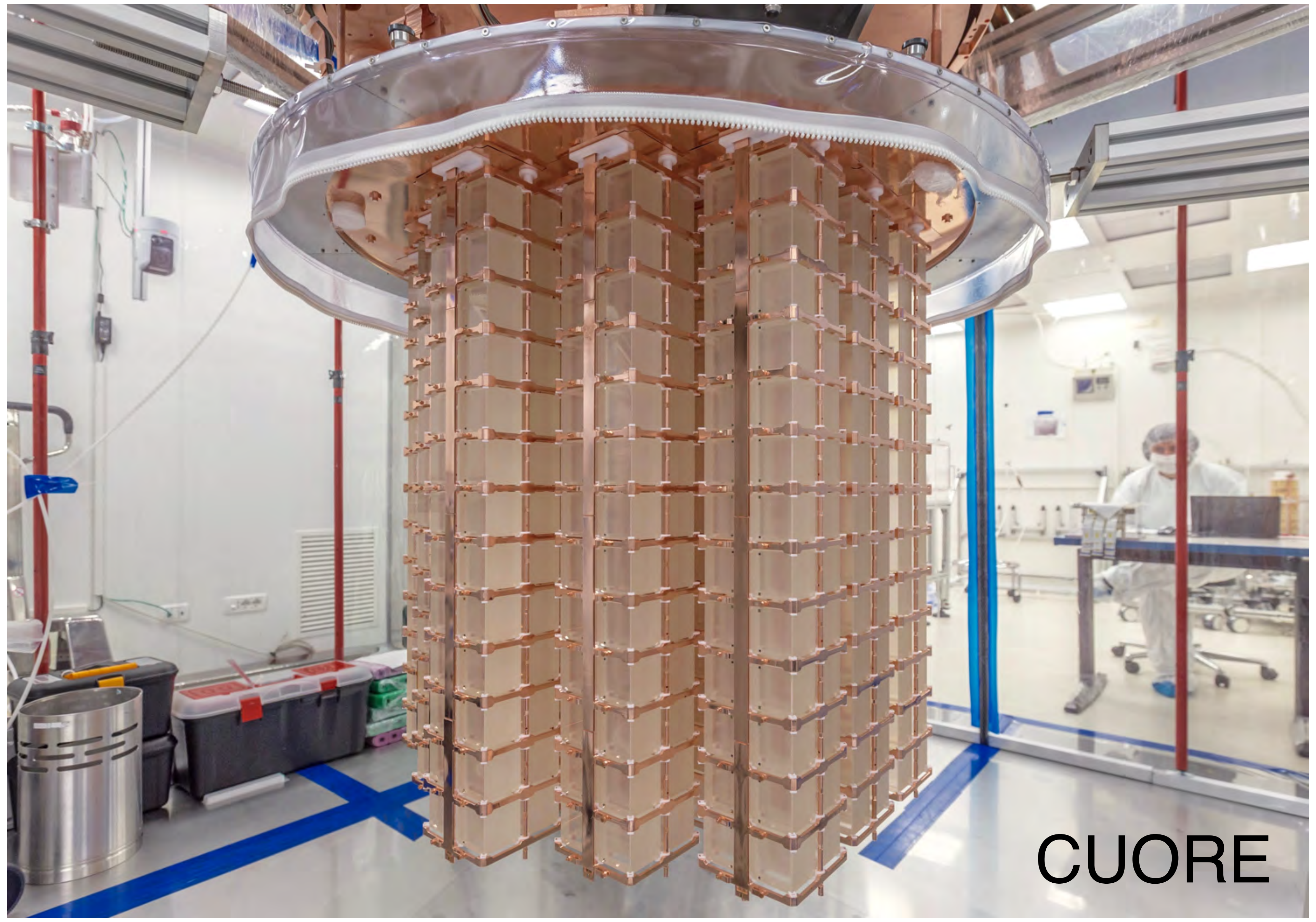
History of Bolometer Experiments

30 years of experience in searching for 0νββ with cryogenic bolometers

CUORE is in a long series of experiments, from few grams to 742 kg of detector material

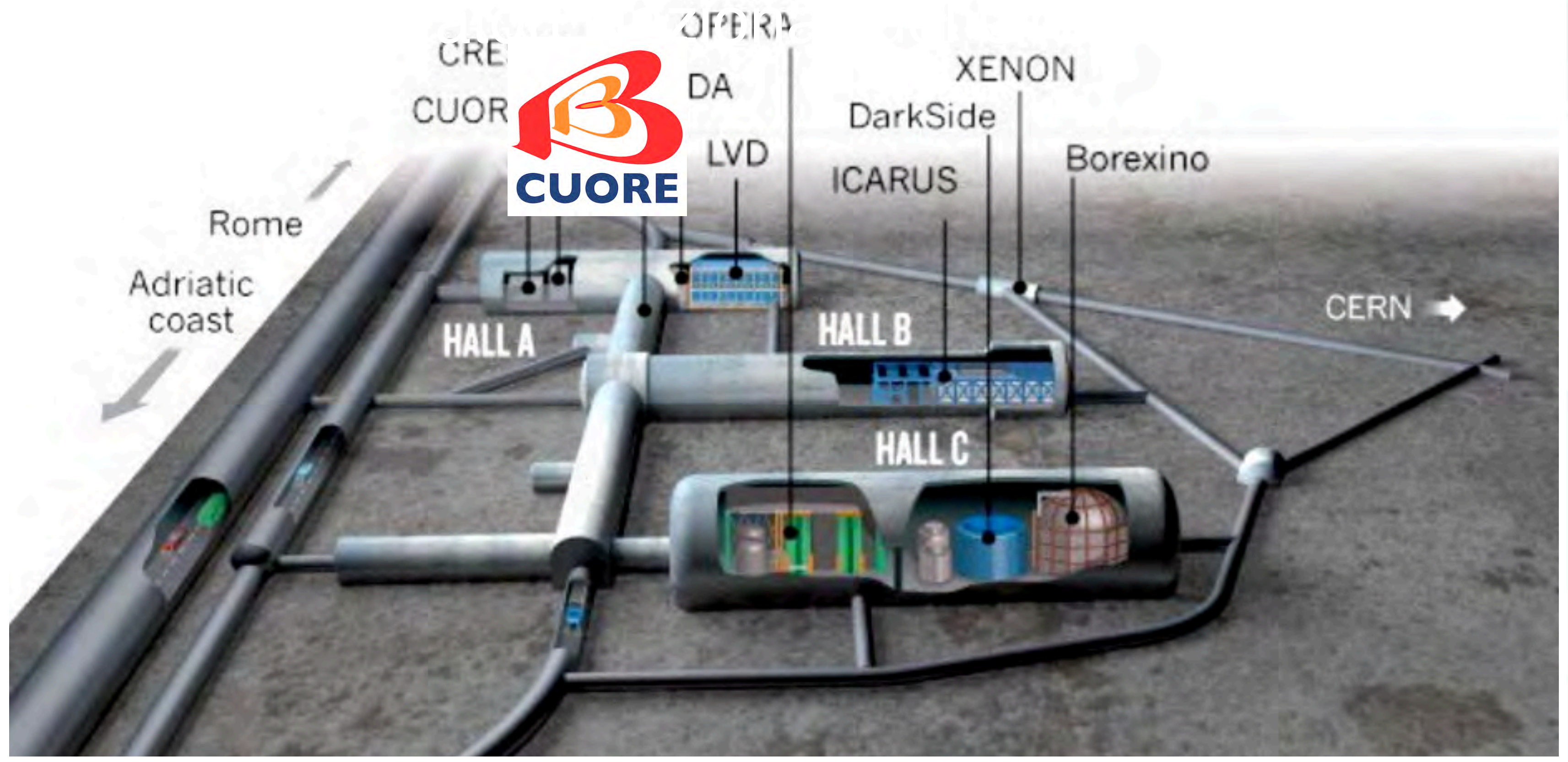
First tonne-scale bolometric experiment in the world

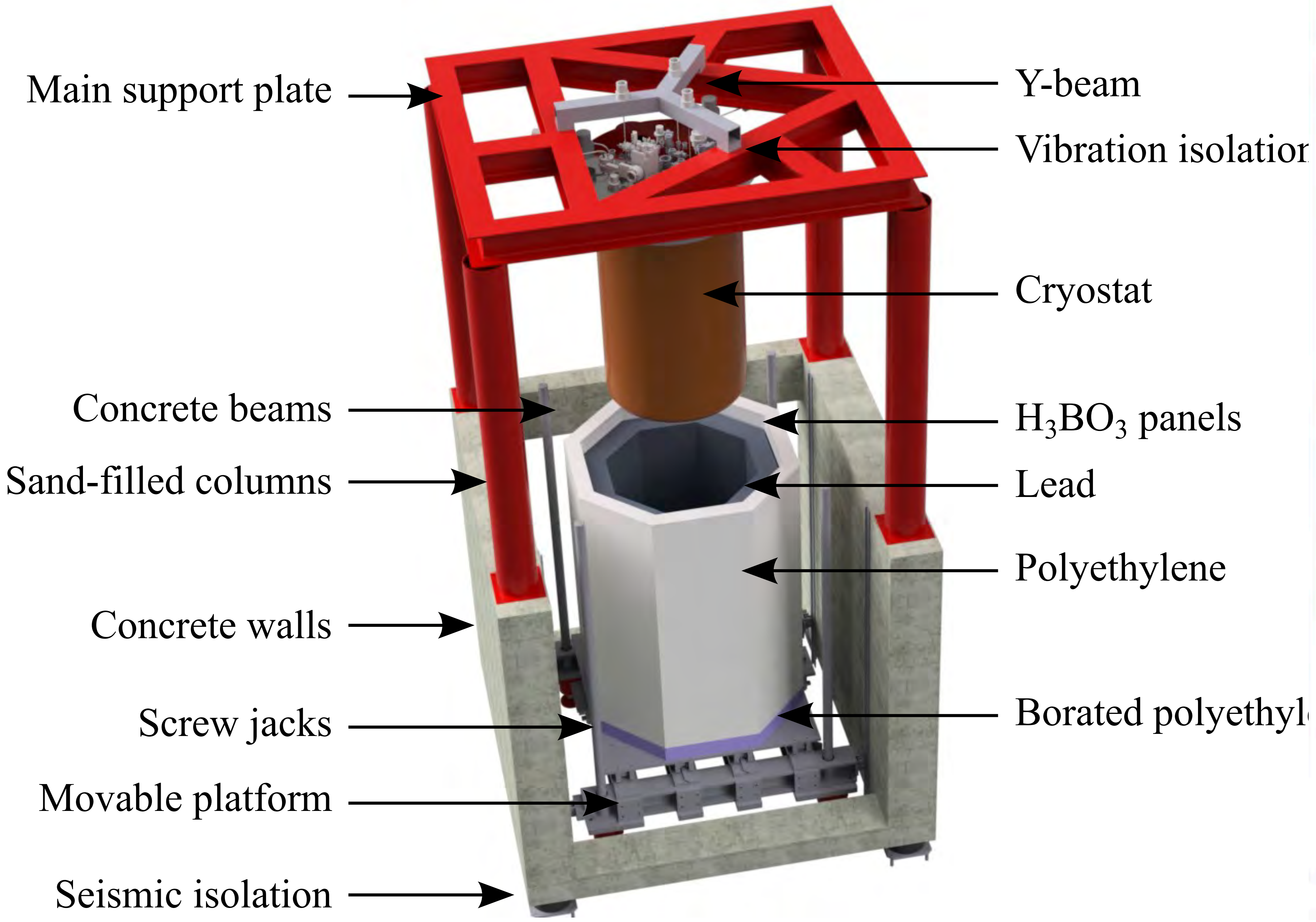


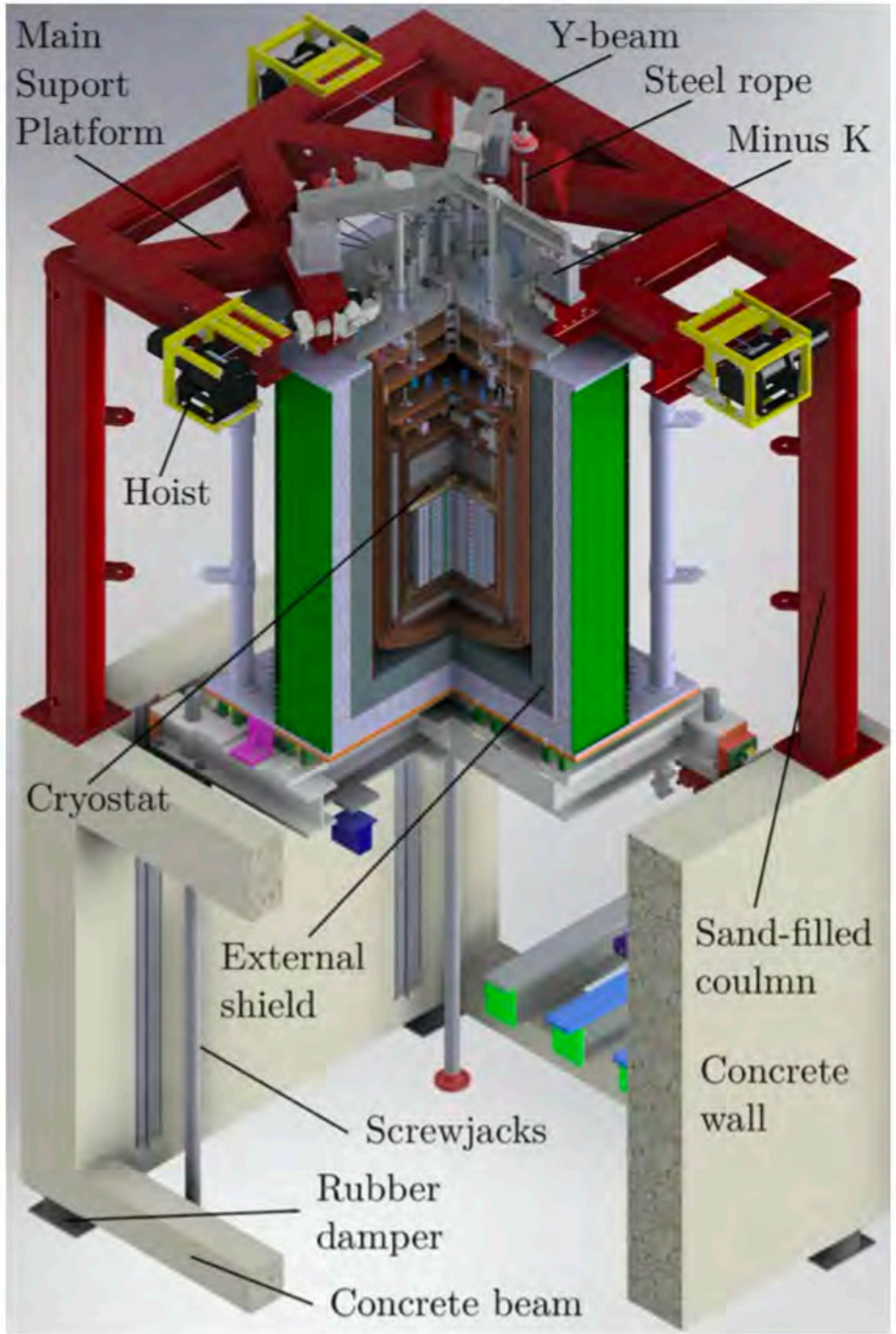


Brofferio, C. and Dell'Oro, S., Rev. Sci. Inst. 89, 121501 (2018)

Experimental Site







Unique cryogenic infrastructure.

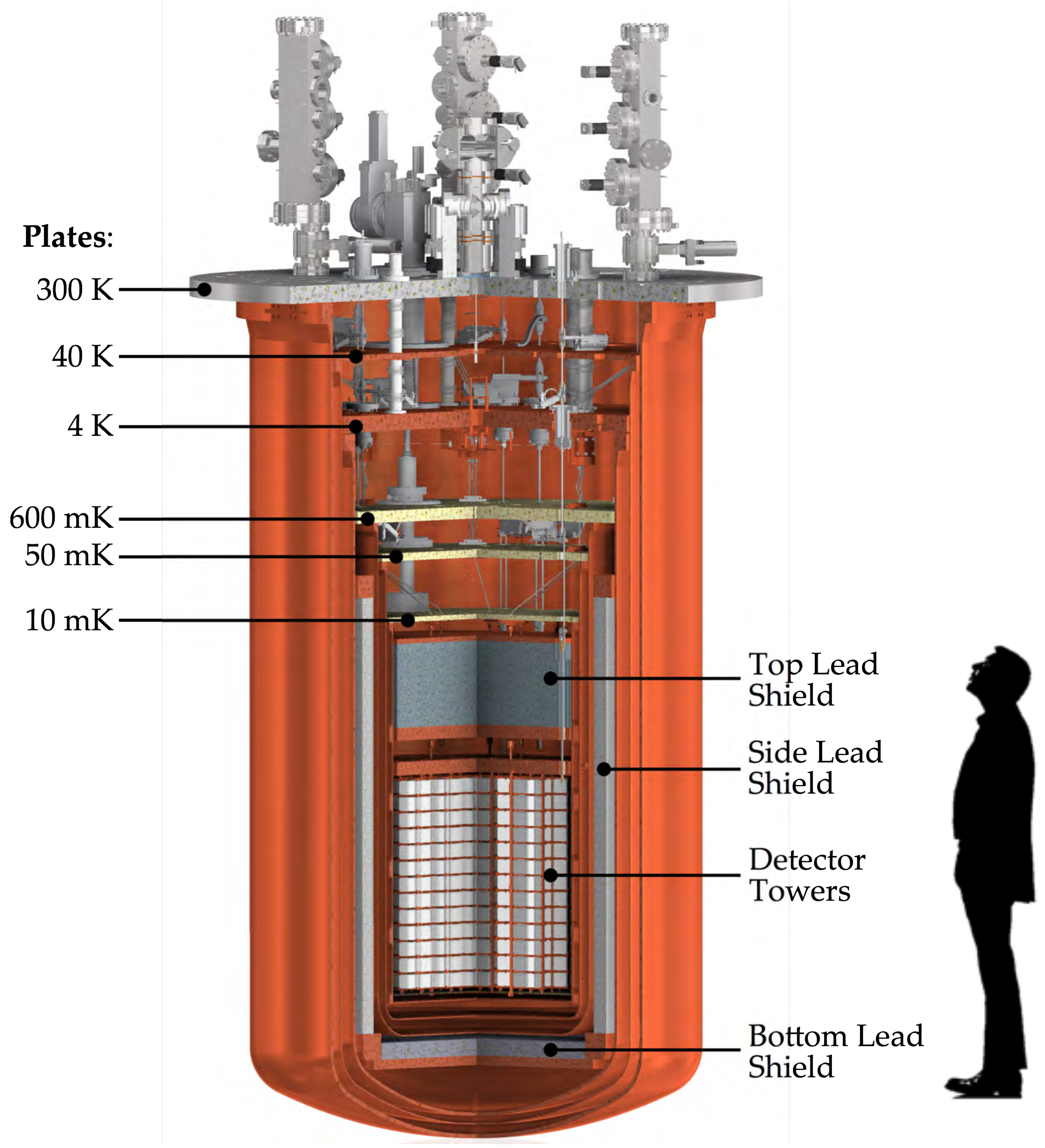
CUORE - *Coldest Cubic Meter in the Known Universe*

CUORE cryostat

- Multistage cryogen-free
- cryostat
- Cooling systems: fast cooling
- system, Pulse Tubes (PTs), and
- Dilution Unit (DU)
- ~15 tons @ < 4 K
- ~ 3 tons @ < 50 mK
- Mechanical vibration isolation
- Active noise cancelling

CUORE (passive) shielding

- Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels + polyethylene

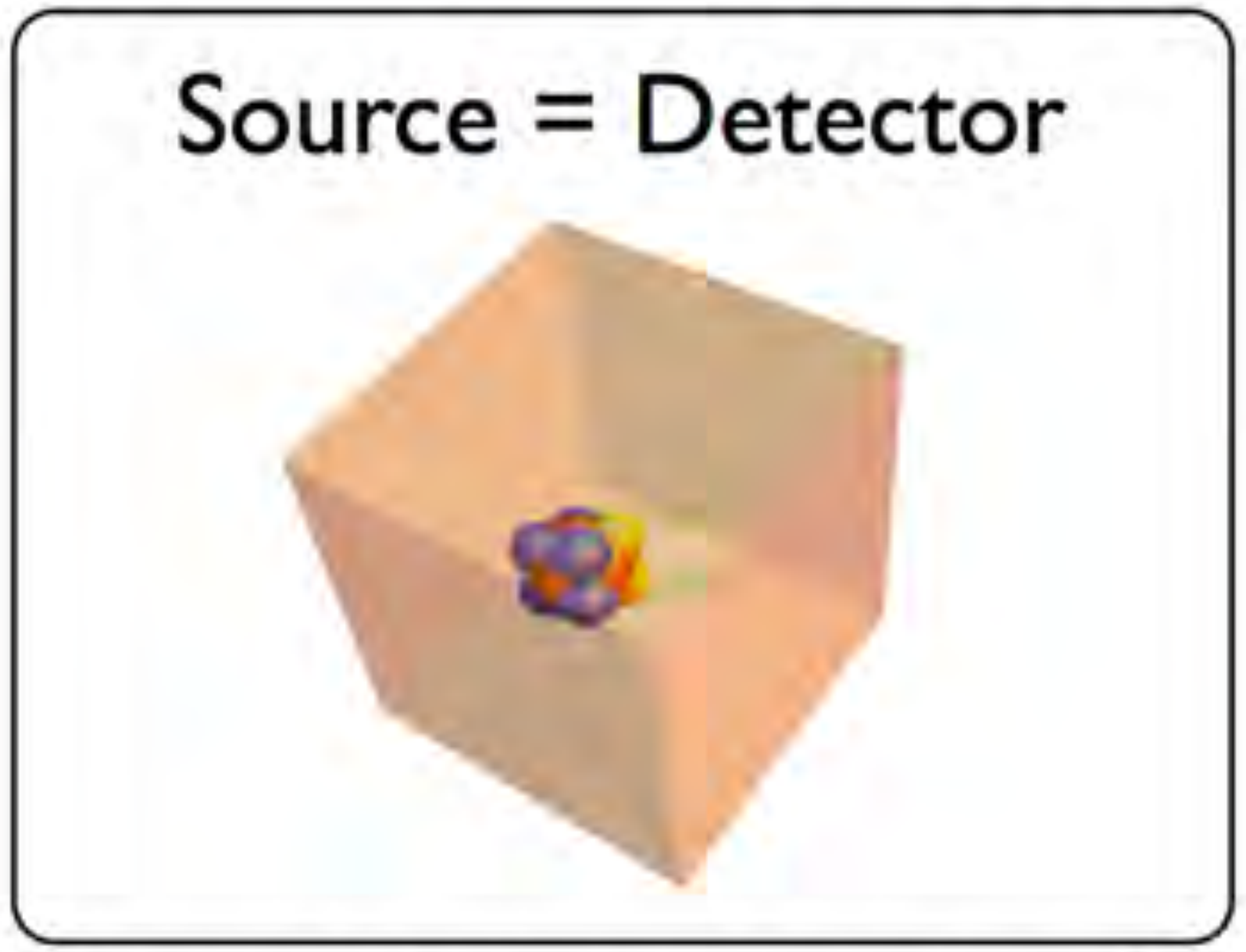


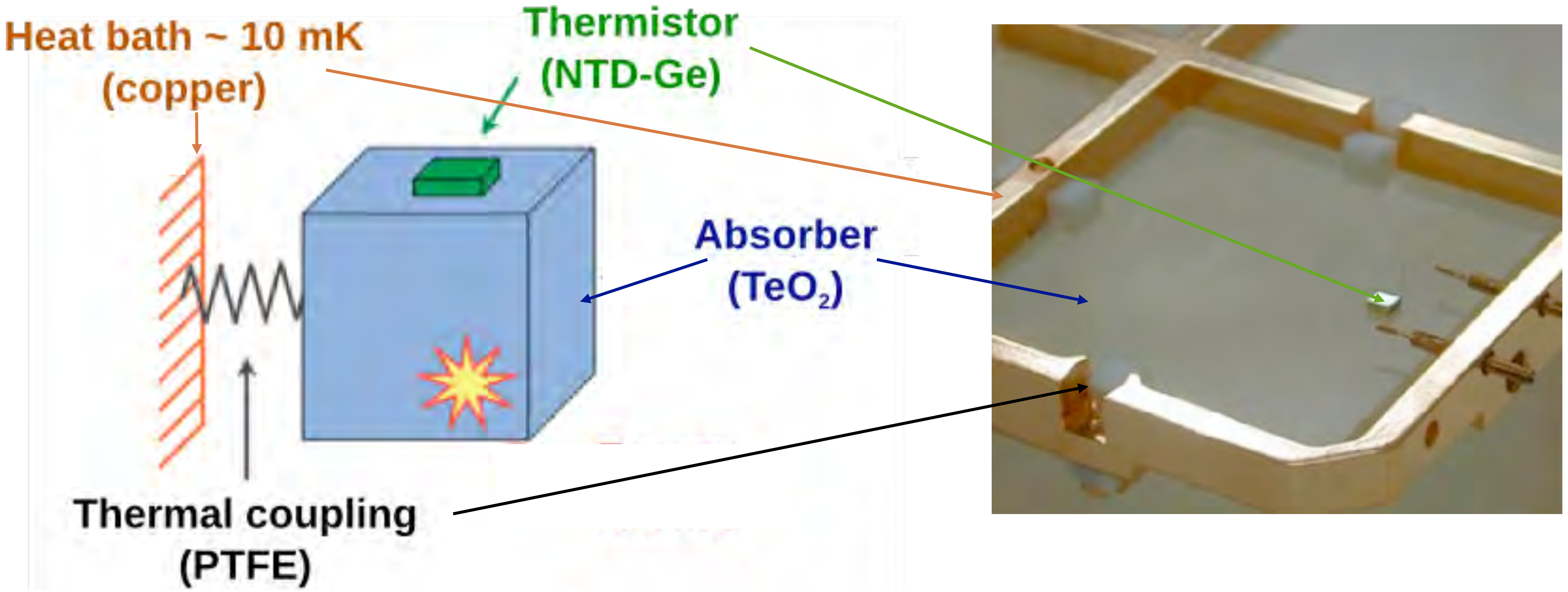
Roman lead ingots

70 tonne of lead, 7 tonne of cold lead

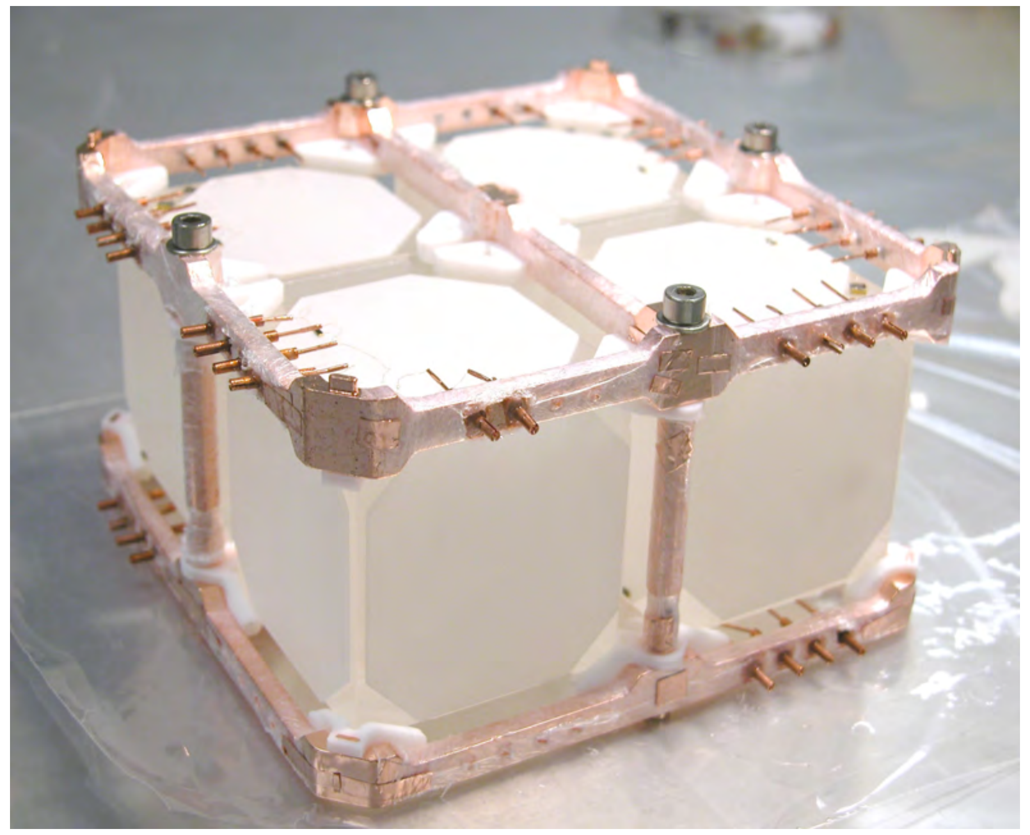
Careful material selection: Ancient Lead and low radioactive copper

Bolometric Search for 0νββ

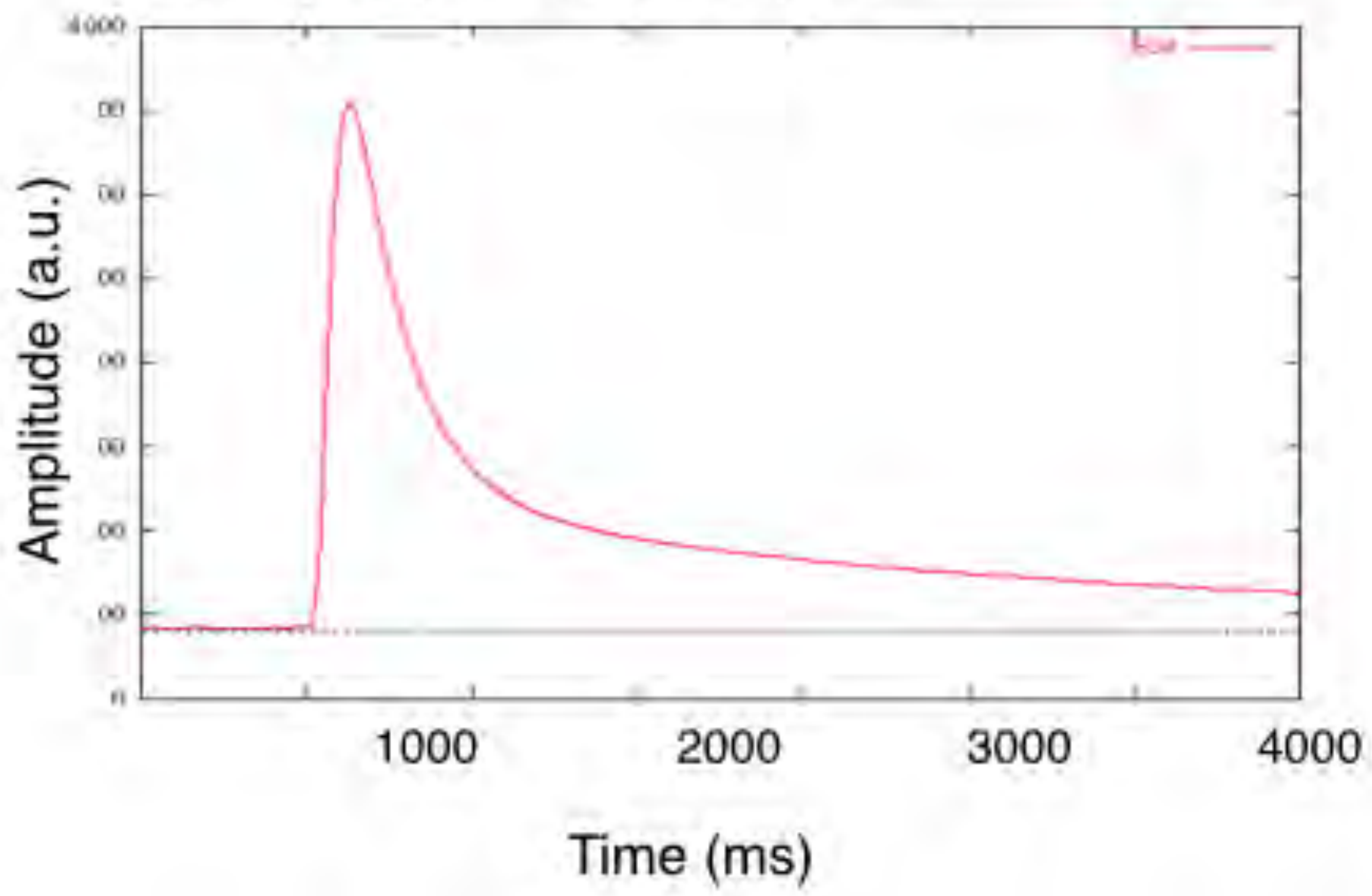


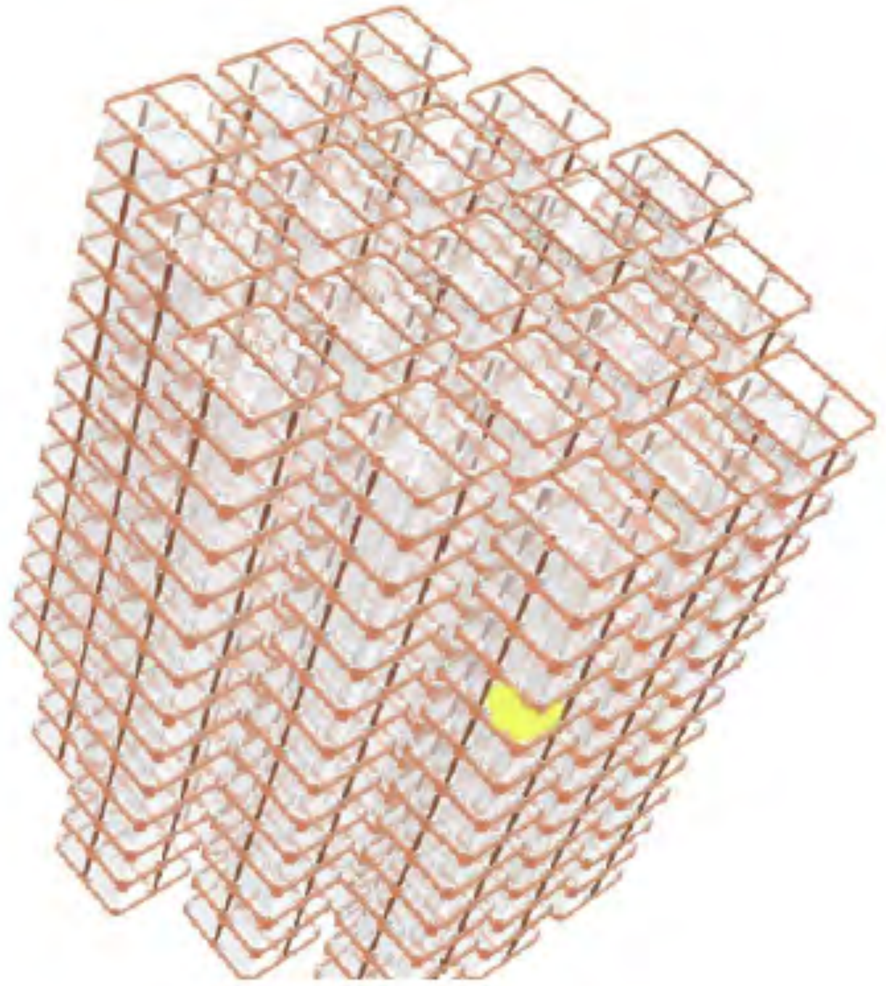


$^{130}Te \rightarrow {}^{130}Xe + 2e^-$ Q = (2527.518 +/- 0.013) keV



Single pulse example



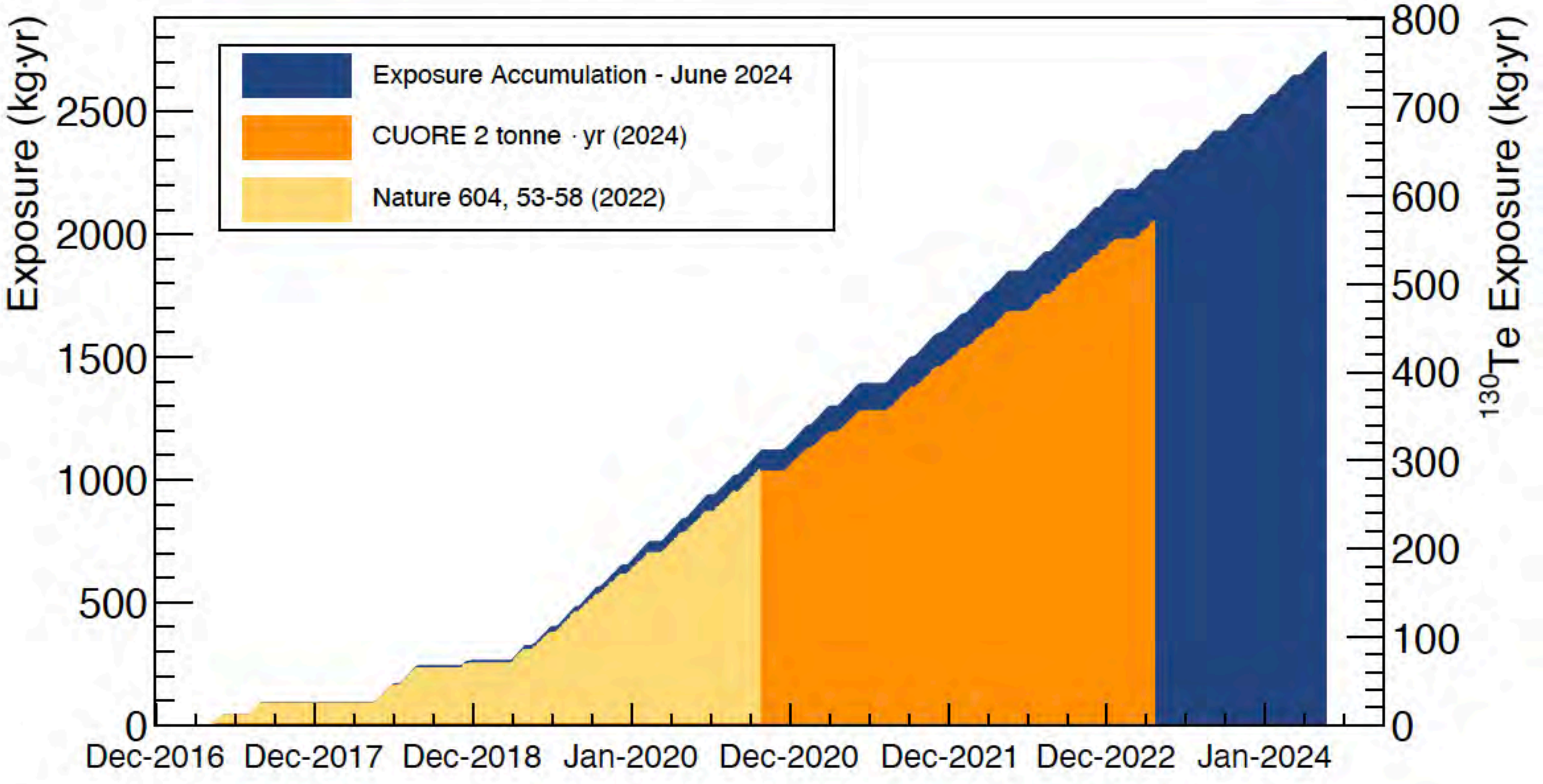


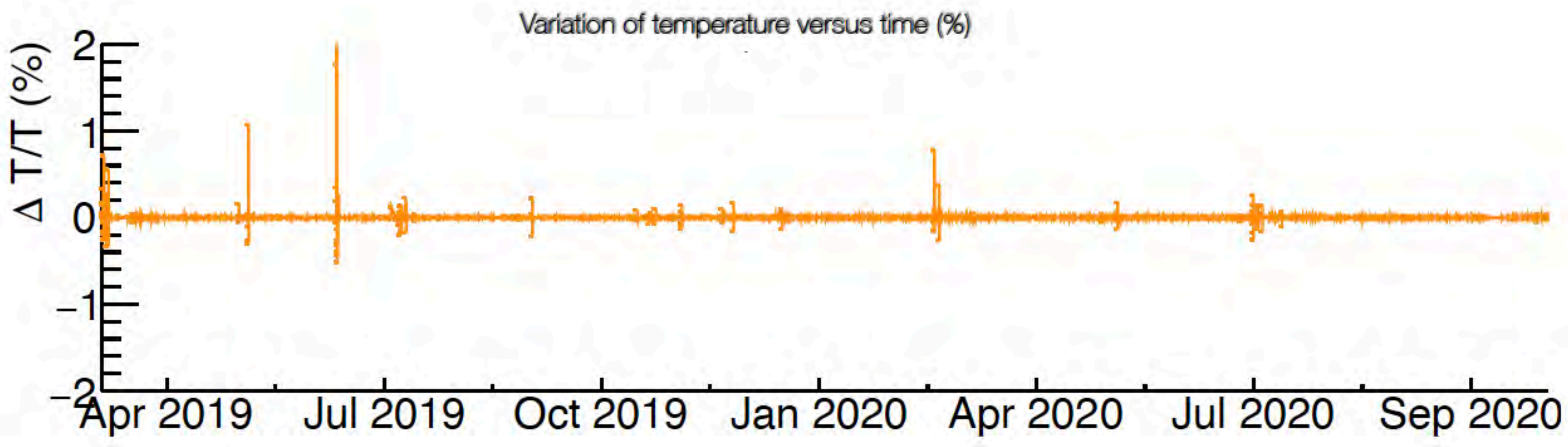
single hit, monochromatic event

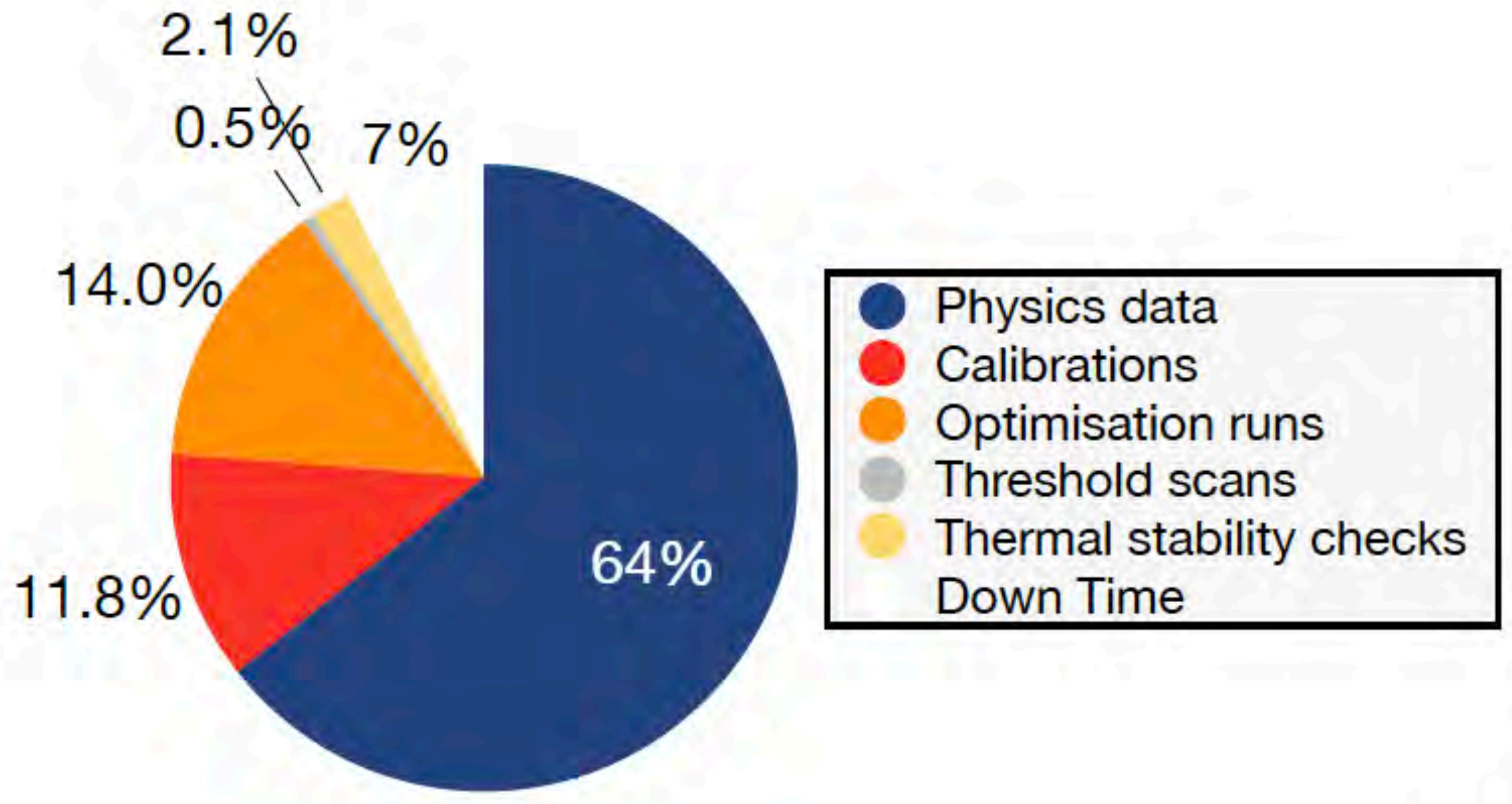
CUORE Detector

CUORE Data Taking

- Data taking started in Spring 2017
  - In the first two years we learned how to operate the cryogenic system at its best and optimised the performances
  - Datasets (~ 2 months long) interleaved by routine maintenances
- Continuous physics data taking at mK temperature since March 2019
  - Uptime > 90%
  - Data taking rate ~ 50 kg·yr/month





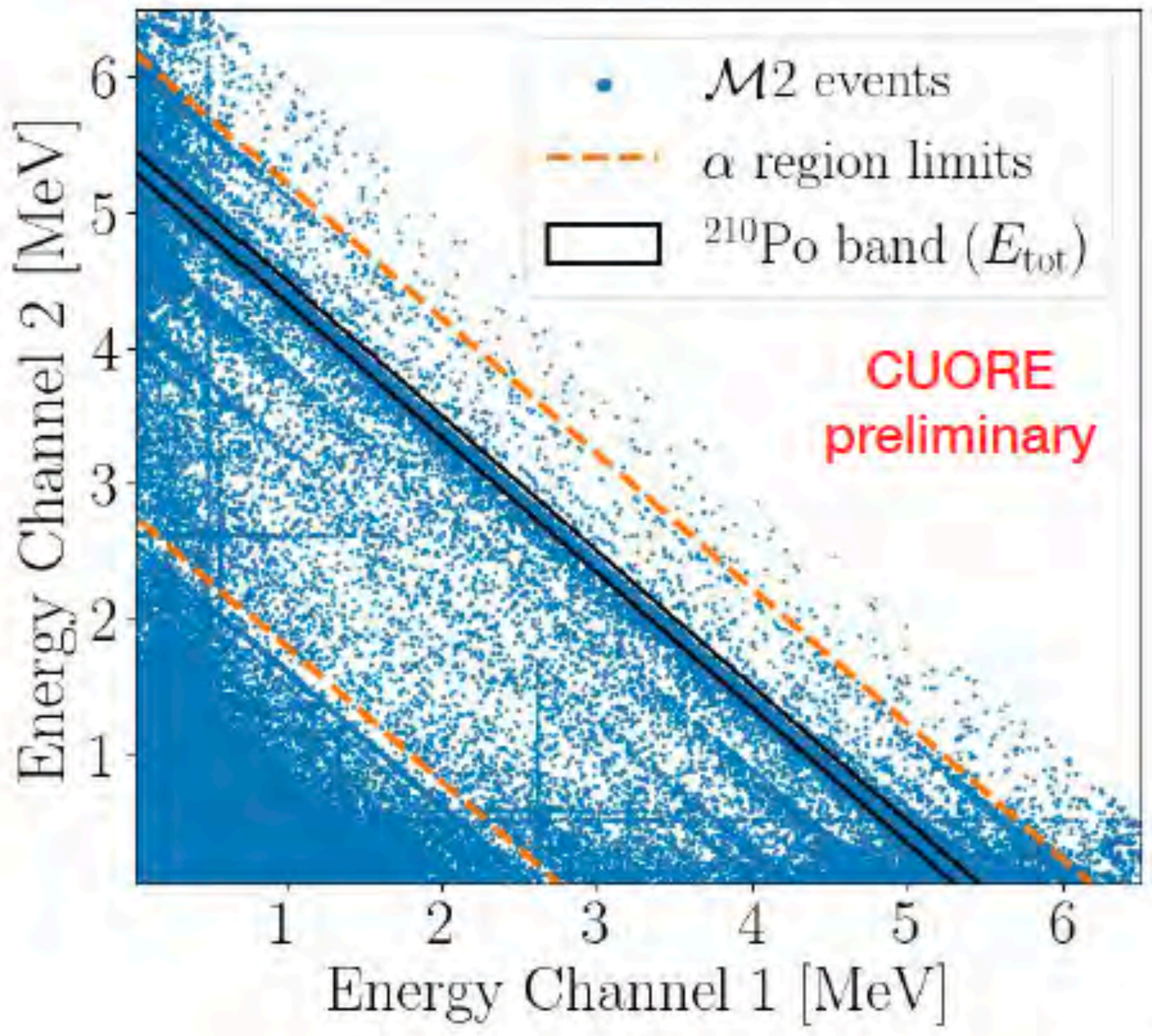


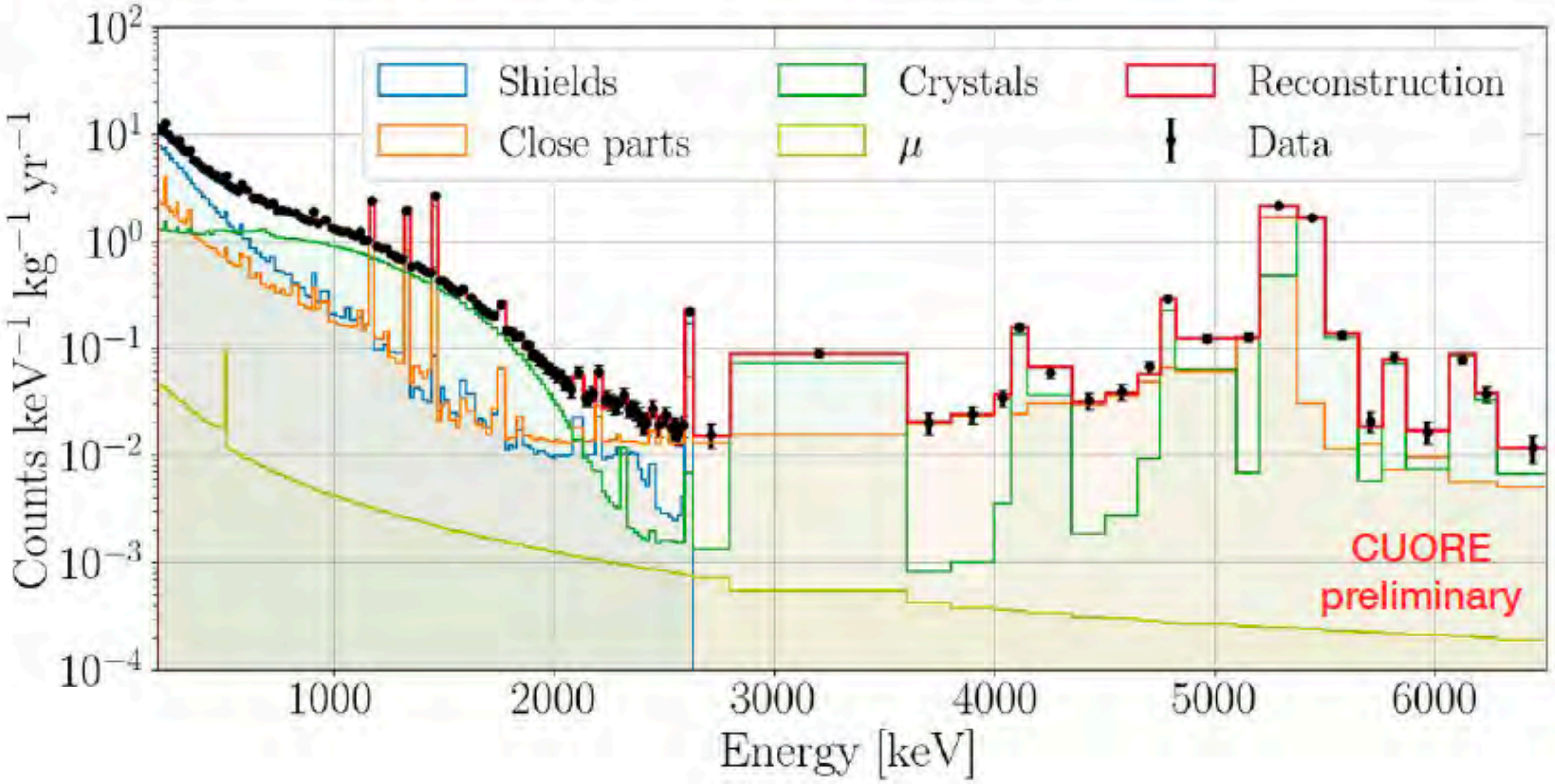
11

CUORE Background Model

Accurate Geant4-based background model

- Detailed geometry
- Simulation of ~80 different sources
- Takes advantage of the high granularity of the detector
- Bayesian simultaneous fit of M1 and M2 spectra with a linear combination of the background sources
- Priors given by radioassays and previous experiments





ArXiv:2405.17937

CUORE Noise Reduction

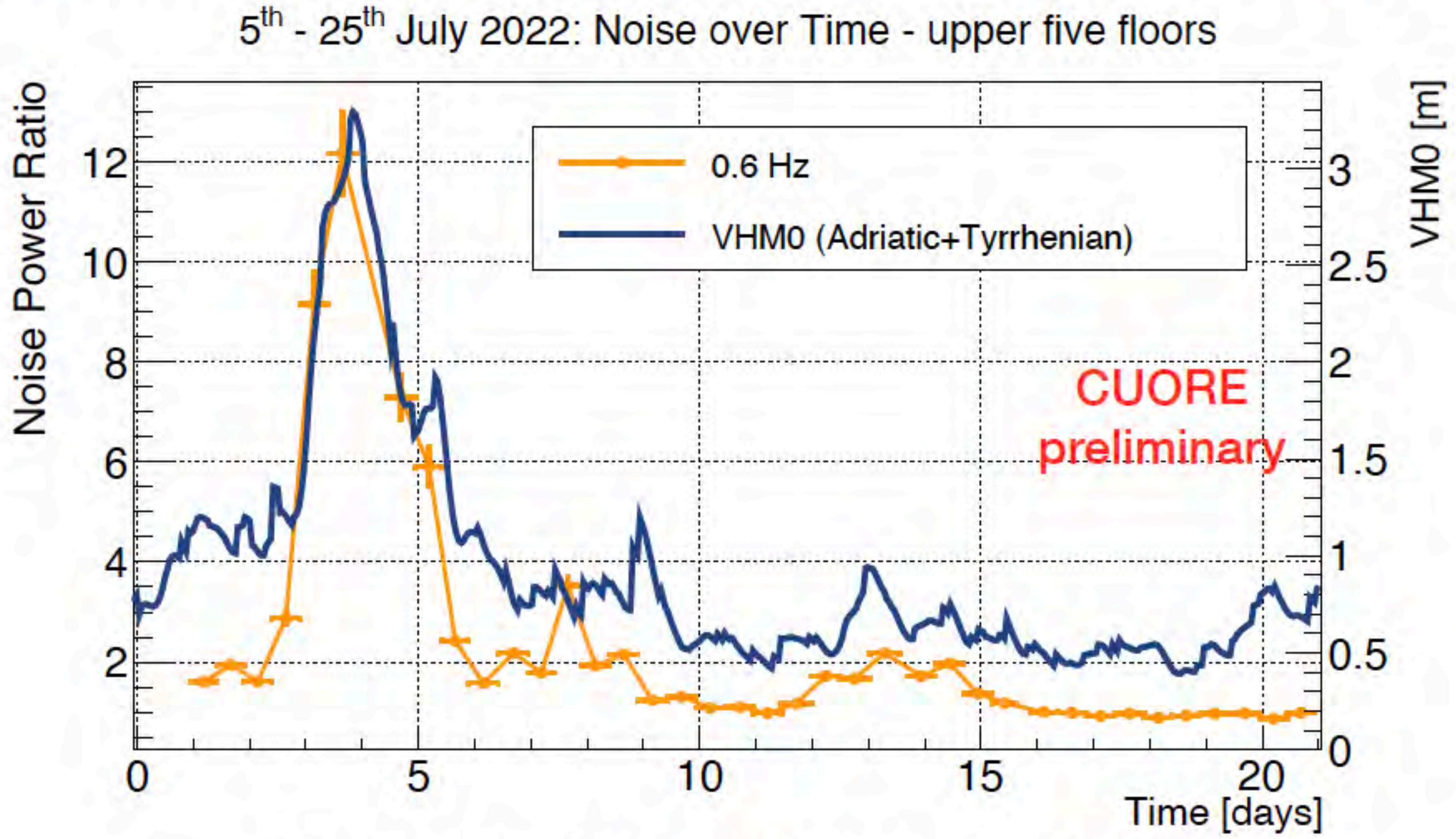
Quite unexpectedly we discovered that CUORE is sensitive to the faint microseismic activity induced by the sea waves

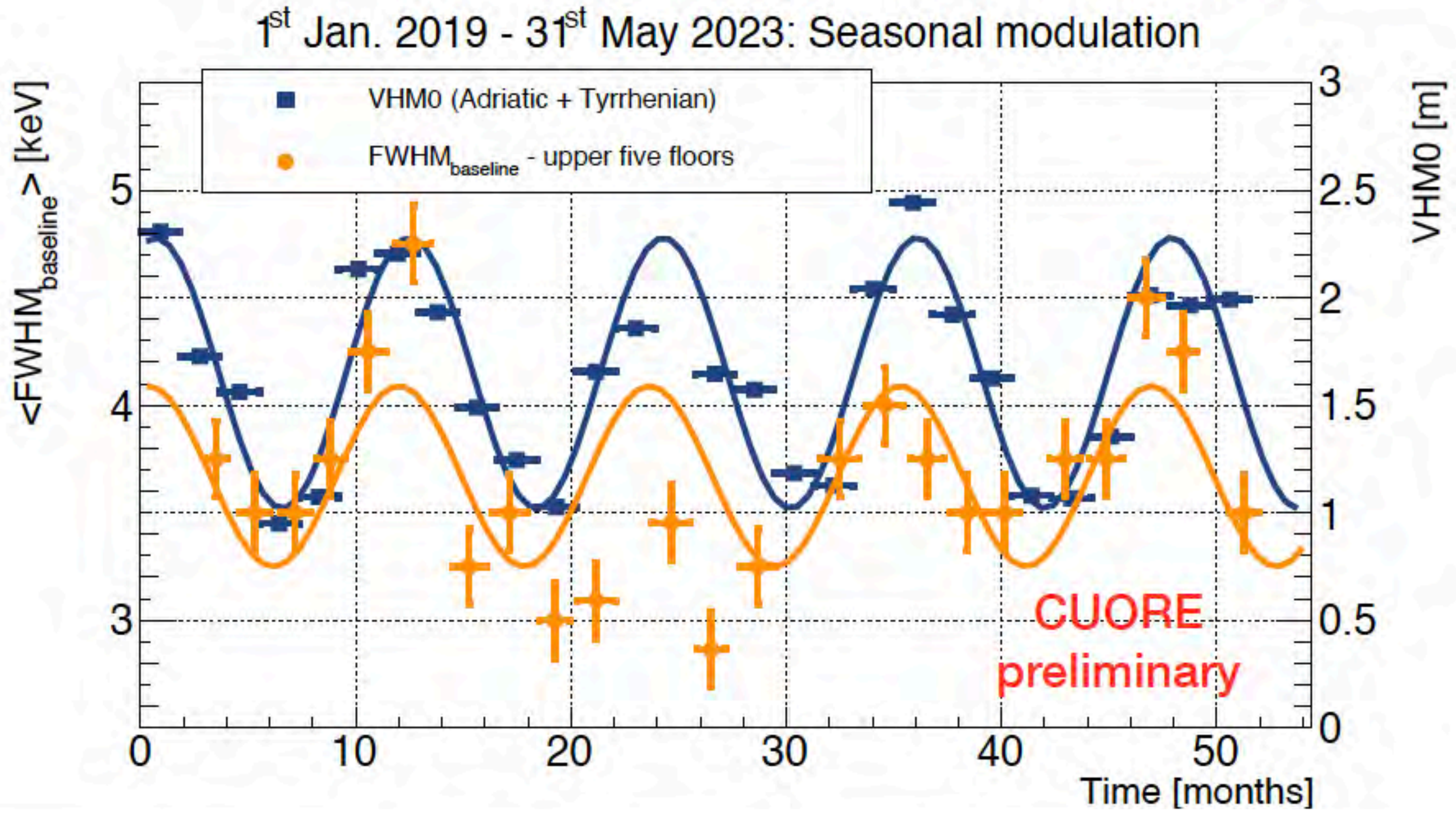
- Strong correlation between storms and low frequency noise in CUORE
- Sea waves characteristic frequency: 0.2 - 0.3 Hz
- Resonance frequency in the cryogenic apparatus

Copernicus
Europe's eyes on Earth

- Seasonal modulation of detectors energy resolution
- Solutions under study to improve cryostat seismic decoupling

ArXiv:2404.13602





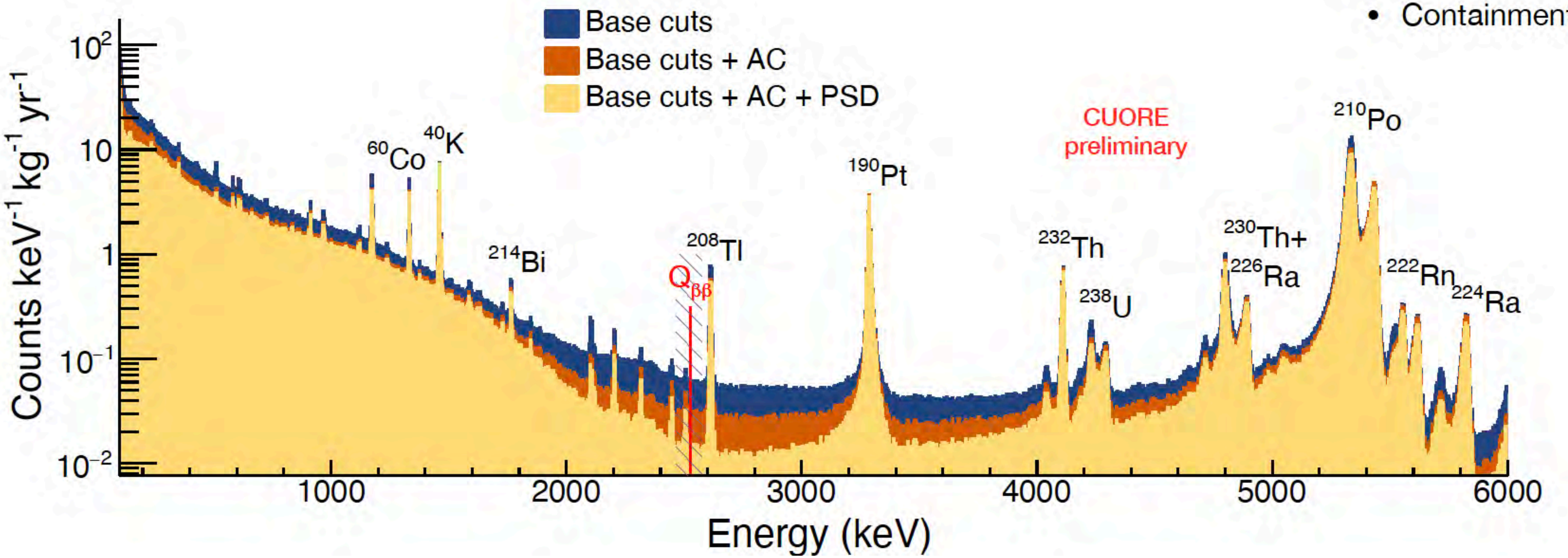
CUORE 2-tonne Year Spectrum

Latest results on the ^{130}Te $0\nu\beta\beta$ search

- 28 datasets analyzed from May 2017 to April 2023
- Total analysed exposure: 2039.0 kg·yr TeO_2 (567.0 kg·yr ^{130}Te)

Efficiencies

- Total analysis efficiency 93.4 %
  - Reconstruction: 95.6 %
  - Anti-coincidence (M1): 99.8 %
  - PSD: 97.9 %
- Containment efficiency: 88.4 %

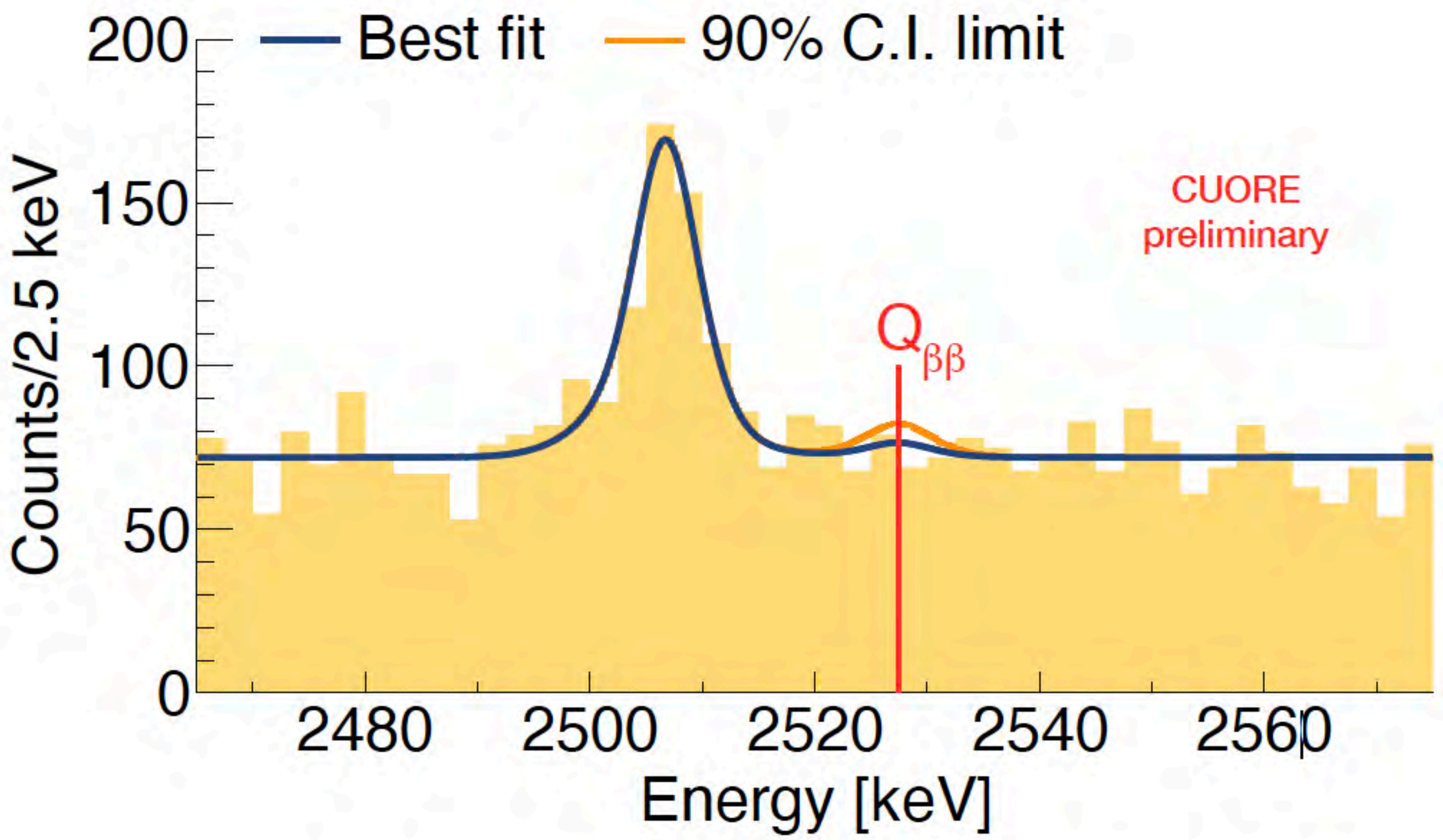


CUORE 2-tonne Year Spectrum

Bayesian and Frequentist Analysis

- Unbinned fit in ROI: [2465, 2575] keV
- Flat-background dataset-dependent
- 0νββ posited peak
- time-dependent ^{60}Co-sum peak
- Energy resolution channel and dataset dependent

Average background index: $1.42(2) \times 10^{-2}$ count/ keV kg yr



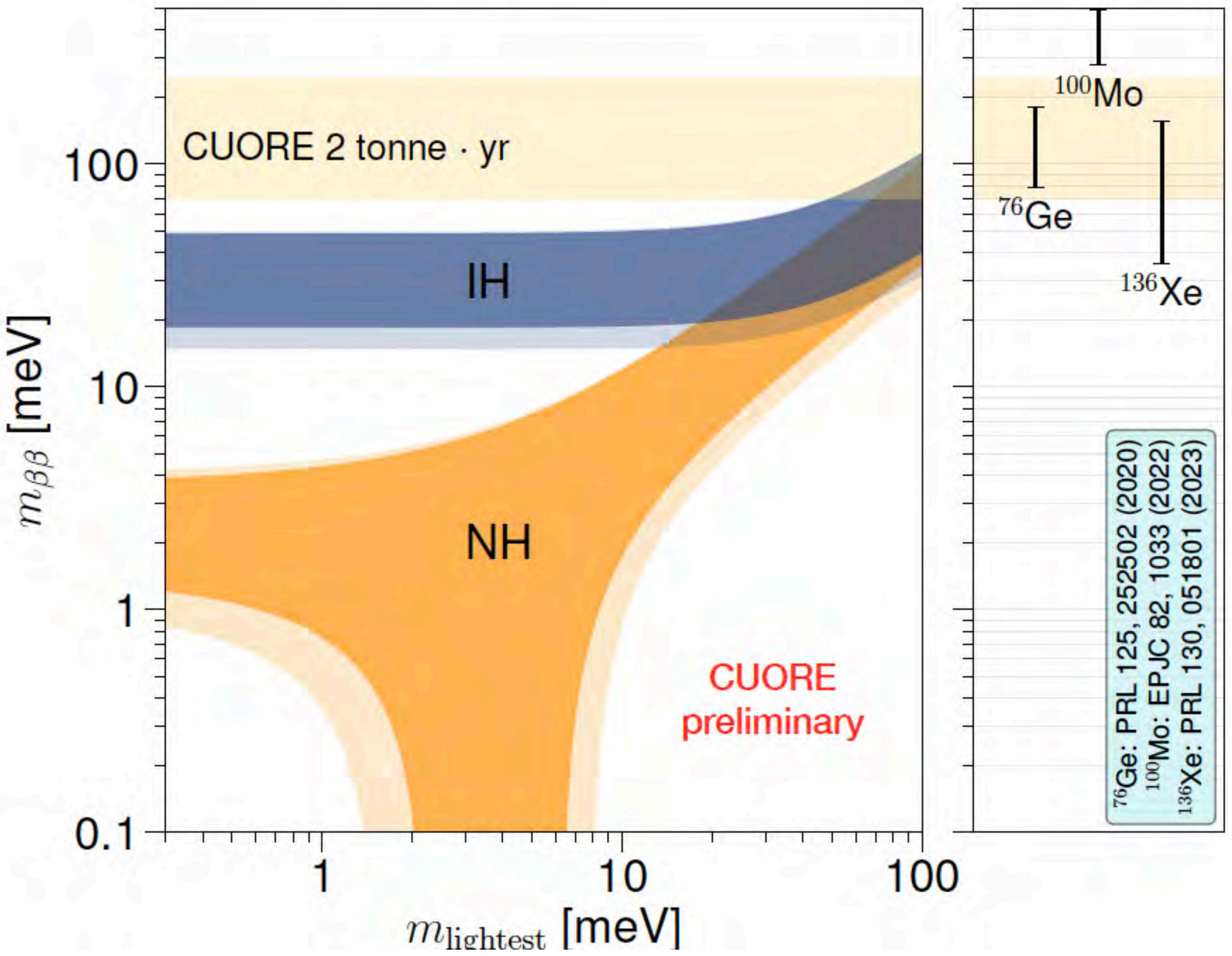
Half-life limit: $T^{0\nu}_{1/2} > 3.8 \times 10^{25}$ yr (90% C.I.)

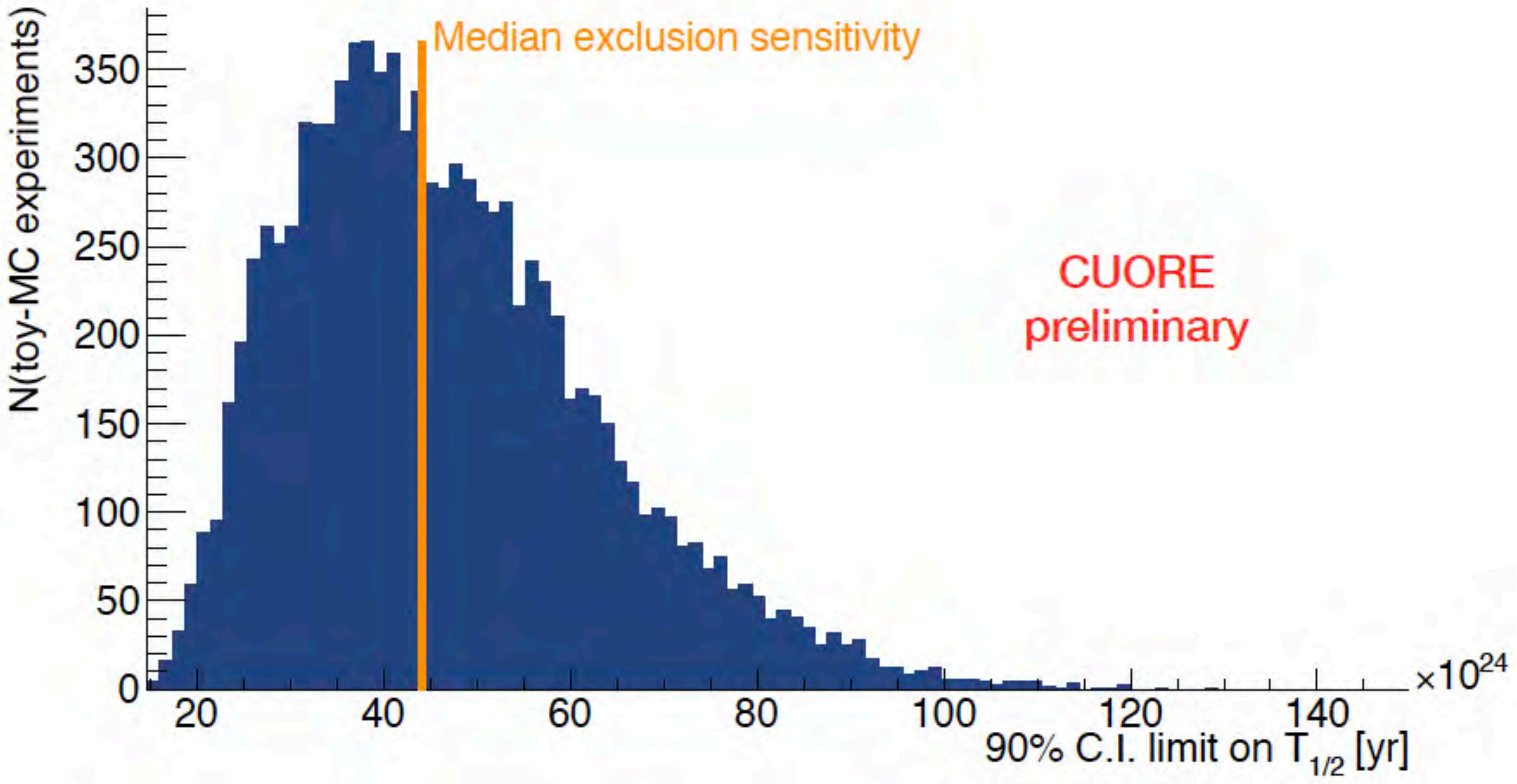
Frequentist limit: $T^{0\nu}_{1/2} > 3.7 \times 10^{25}$ yr (90% C.L.)

CUORE 2-tonne Year Spectrum

Median exclusion sensitivity: 4.4×10^{25} yr (90% C.I.)

- 67% probability to get a more stringent limit given the current sensitivity





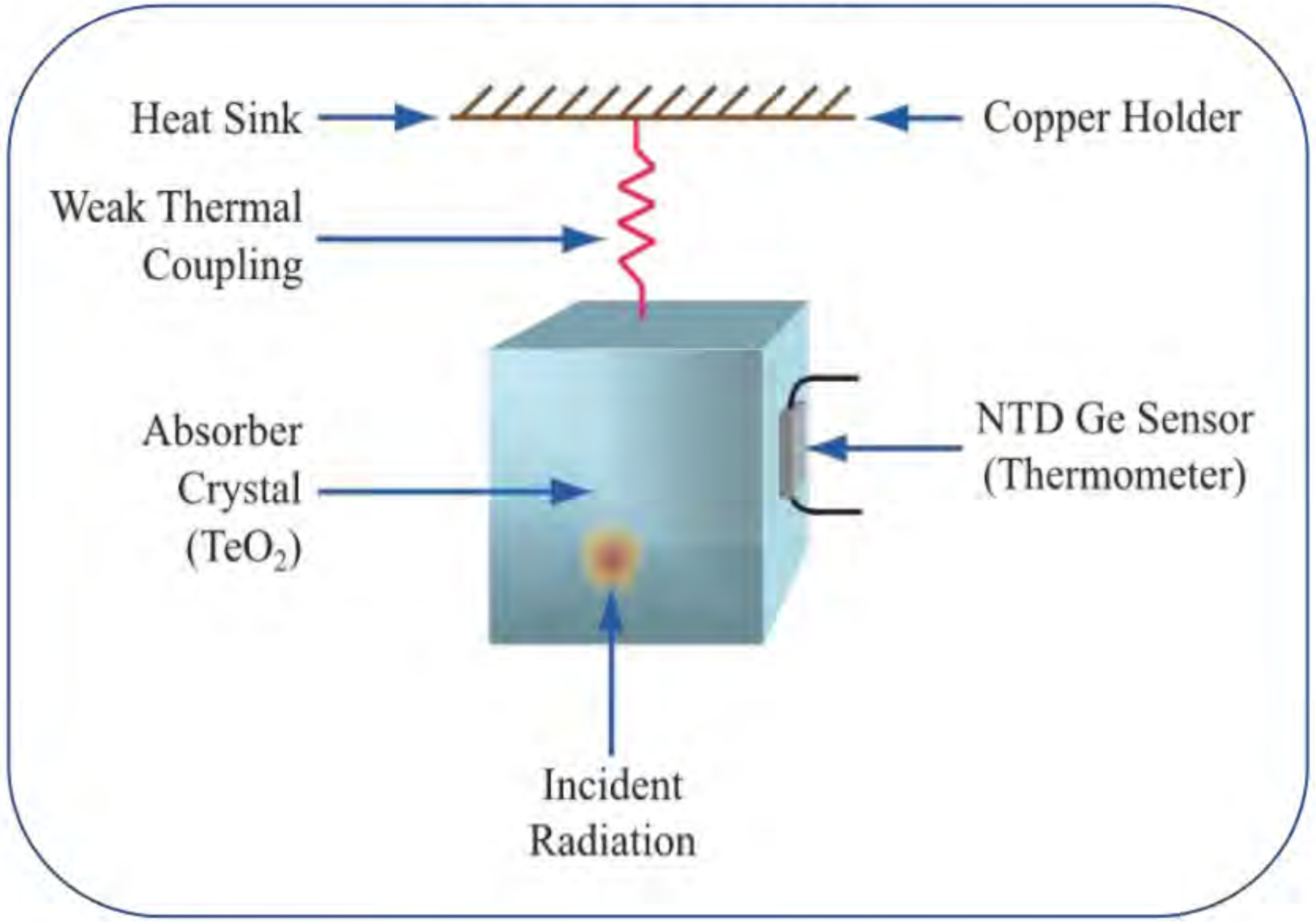
Limit on the effective Majorana mass (assuming light Majorana neutrino exchange)

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

<u>*ArXiv:2404.04453*</u>

CUPID: CUORE Upgrade with Particle Identification

CUORE ^{130}Te
pure thermal detector
(bolometer)

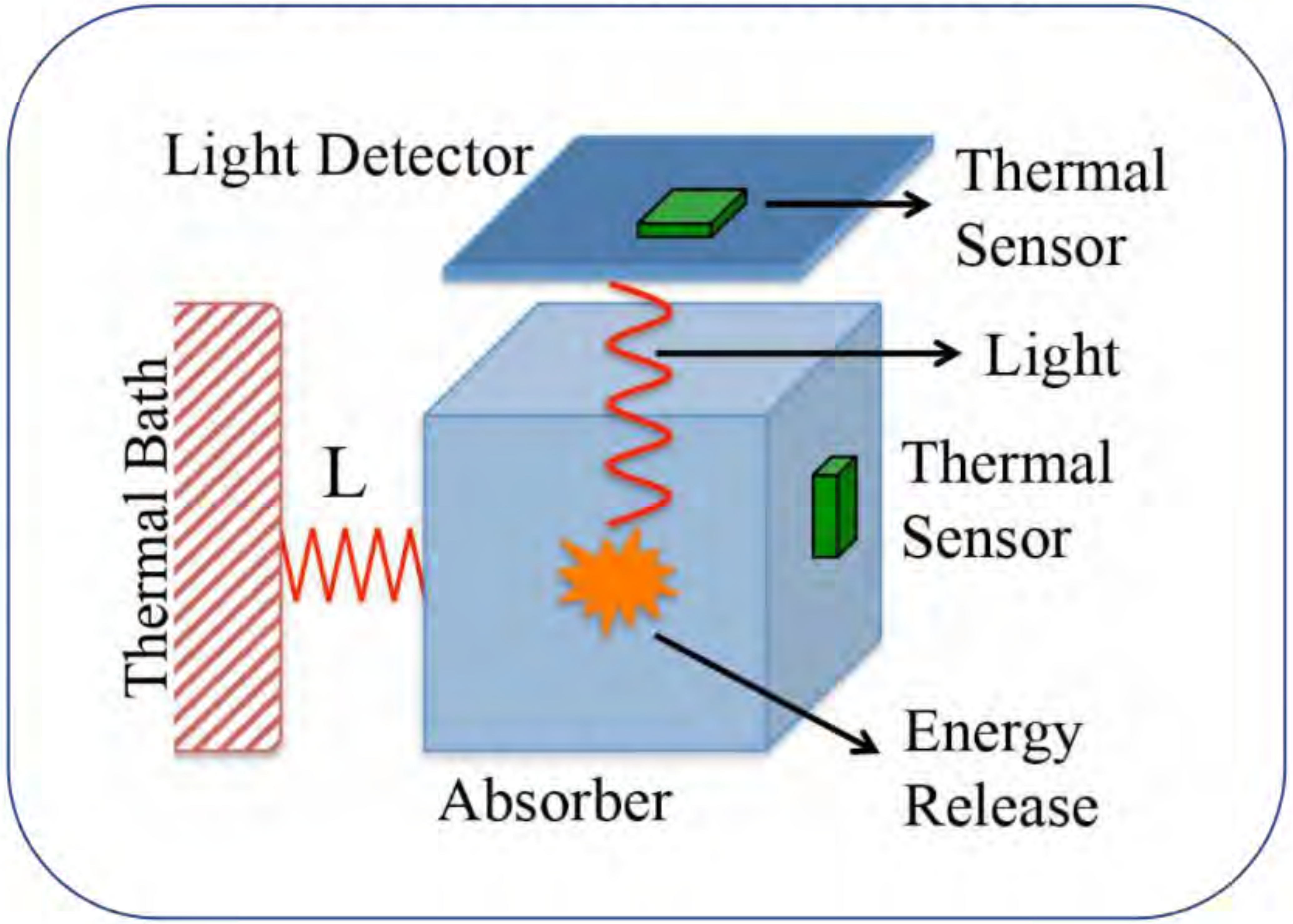


No PID
Q = 2527 keV **< 2615 keV**

PID → remove α

high Q → remove γ

CUPID ^{100}Mo
heat + light
(scintillating bolometer)



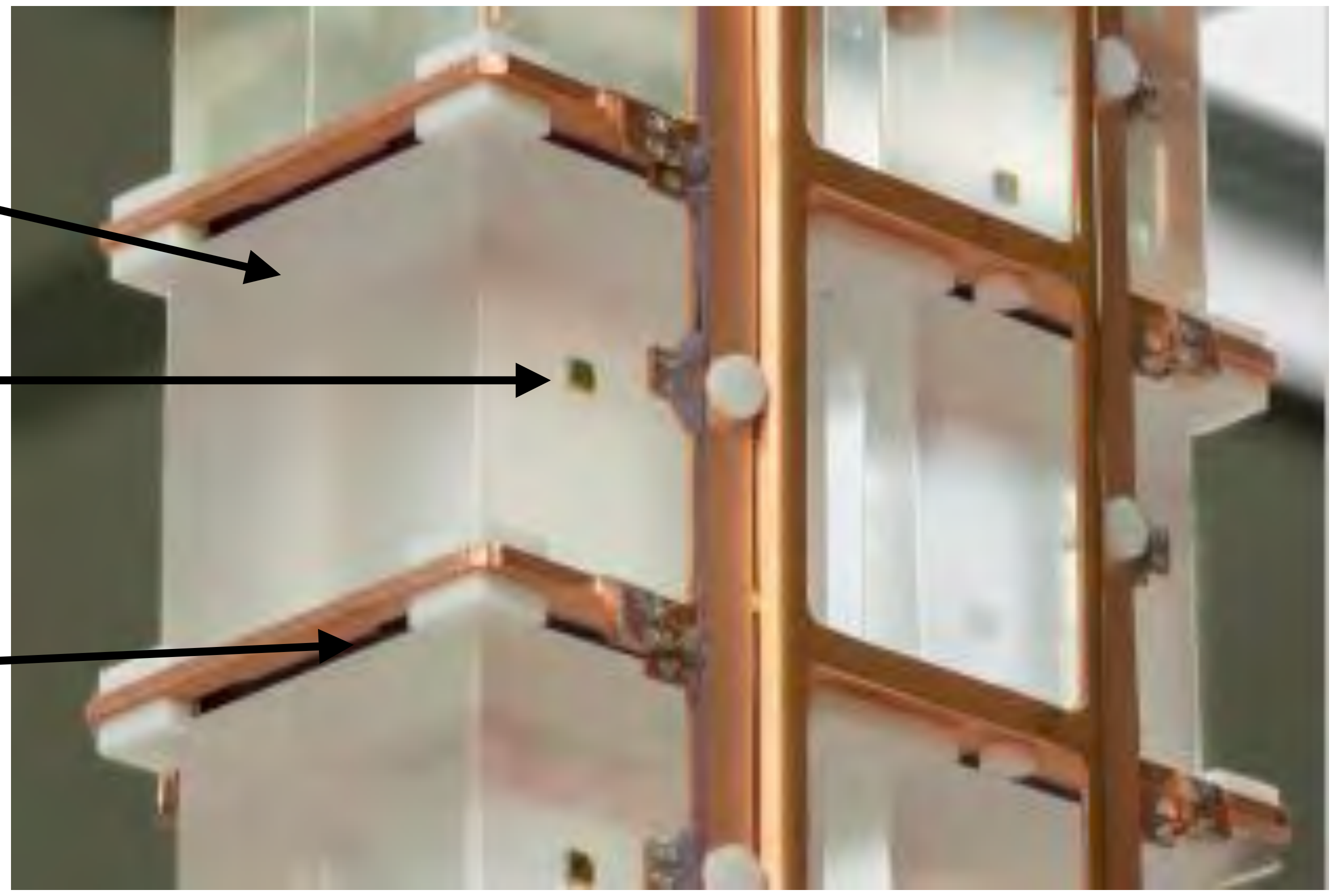
^{100}Mo **Q-value: 3034 keV**: β/γ background significantly reduced

CUPID: CUORE Upgrade with Particle Identification

Single Detector

$Li_2{}^{100}MoO4$, 45x45x45 mm, 280 g

Ge light detector as in CUPID-Mo, CUPID-0

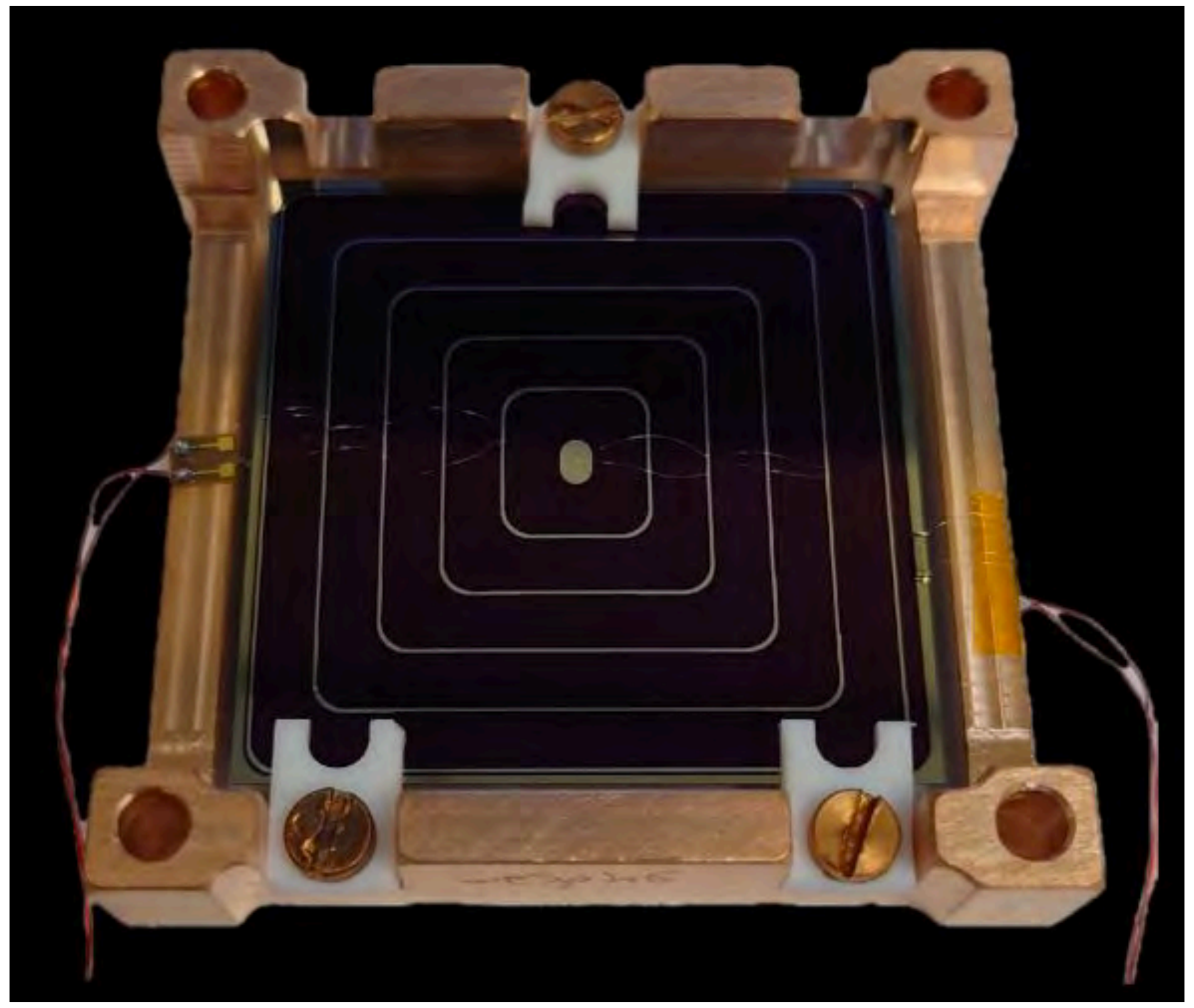


Detector Array

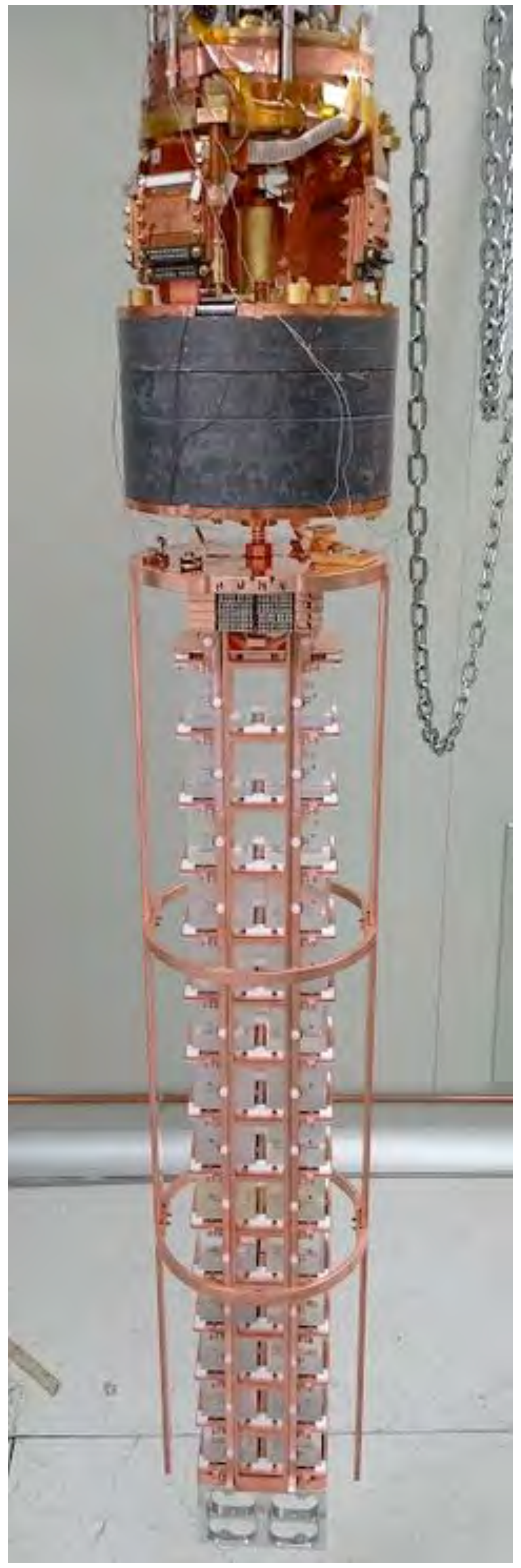
~240 kg of ^{100}Mo with >95% enrichment

~1.6.10^{27} ^{100}Mo atoms

57 towers of 14 floors with 2 crystals each, 1596 crystals

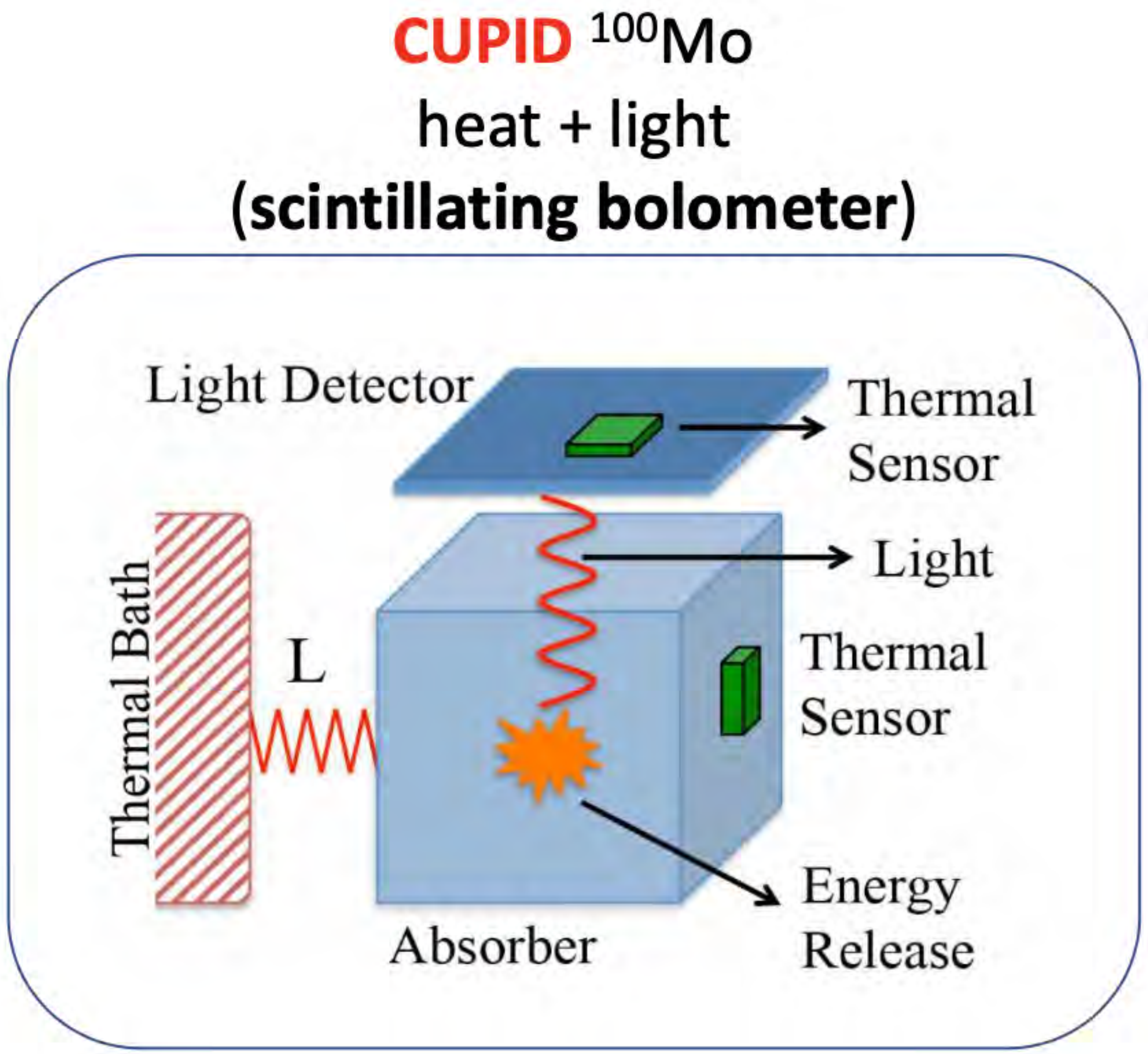


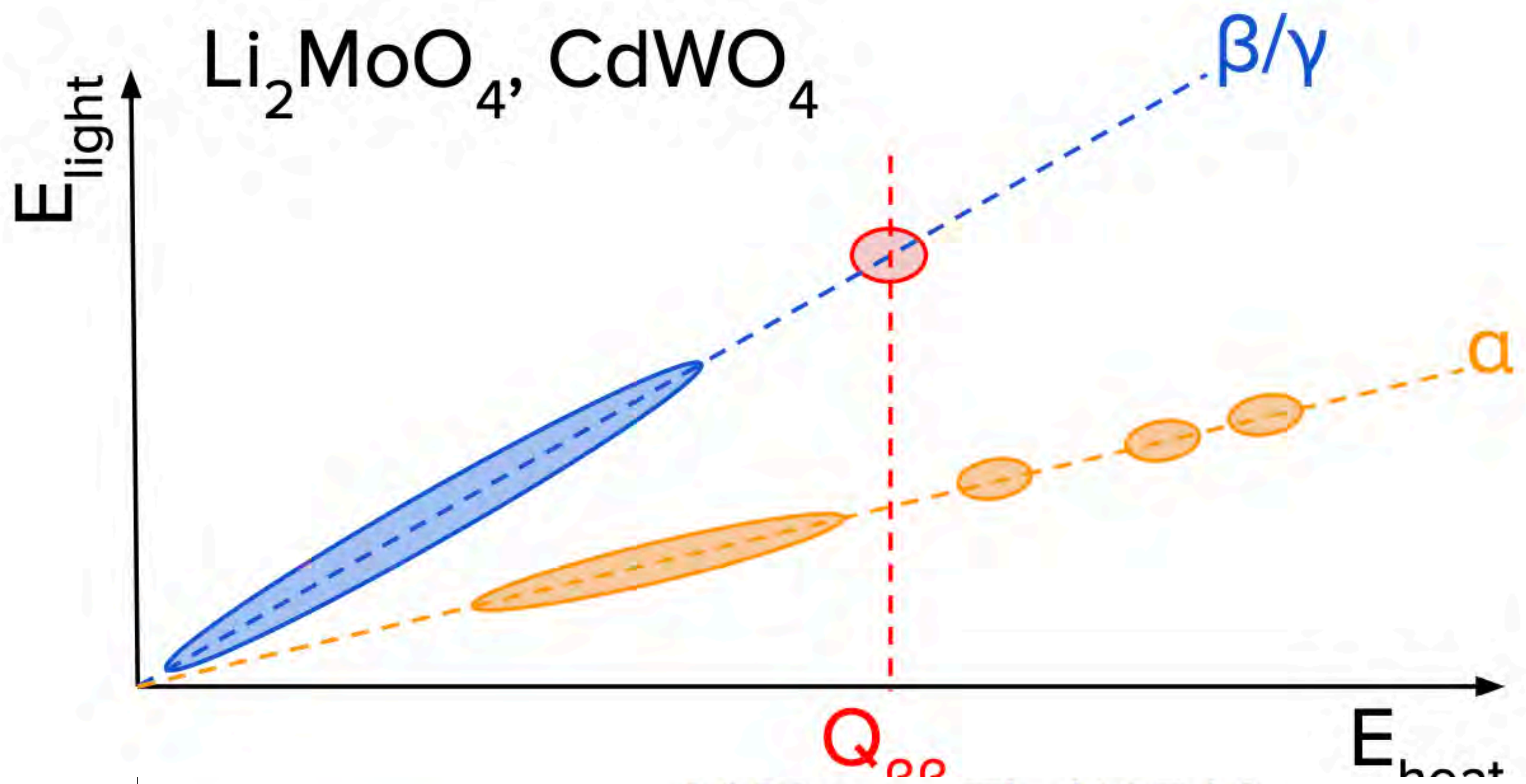
single tower

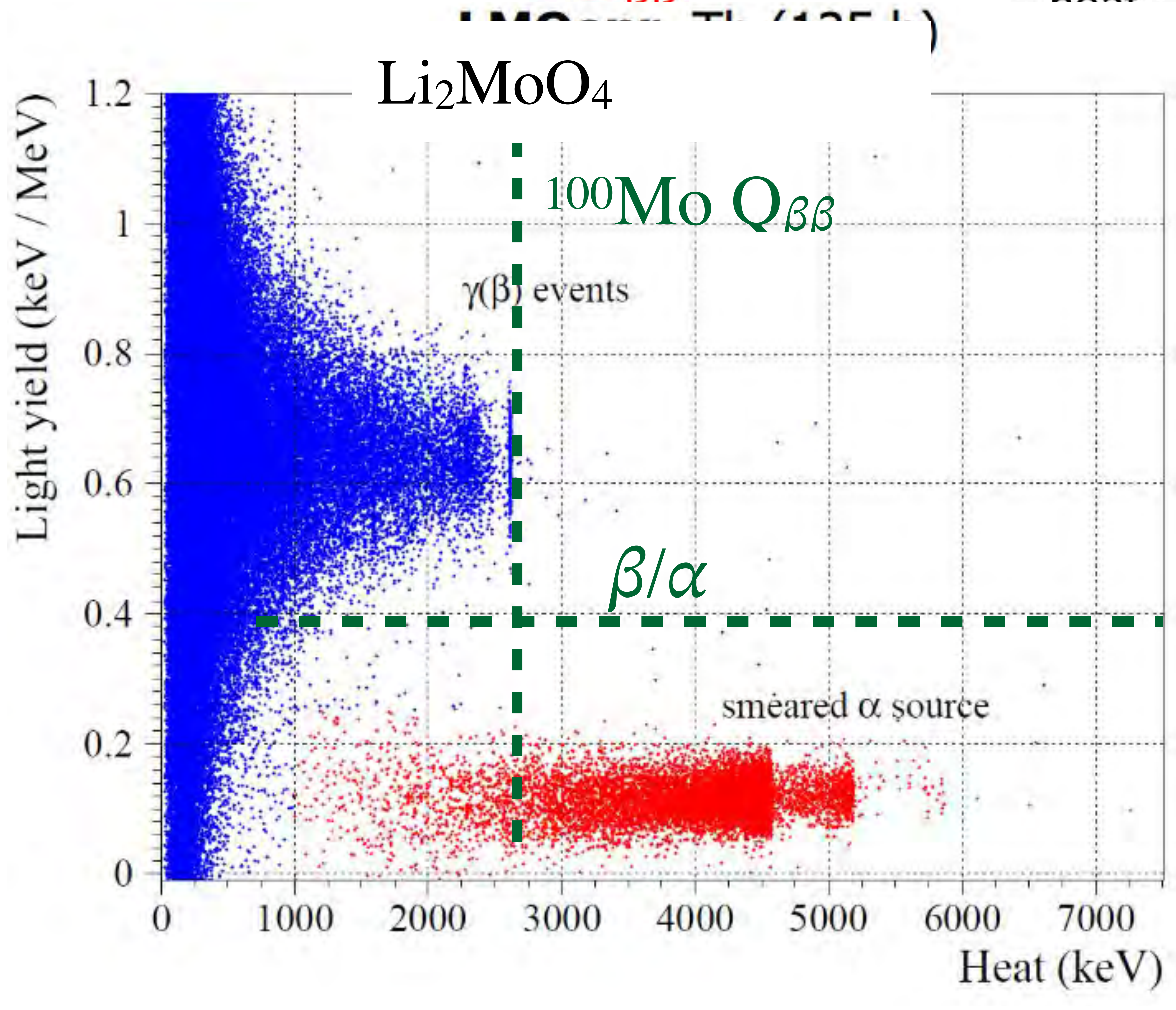


Opportunity to deploy multiple isotopes, phased deployment

CUPID Concept







Measure heat and light from energy deposition

Heat is particle independent, but light yield depends on particle type

Actively discriminate α using measured light yield

CUPID Sensitivity to 0νββ

Baseline

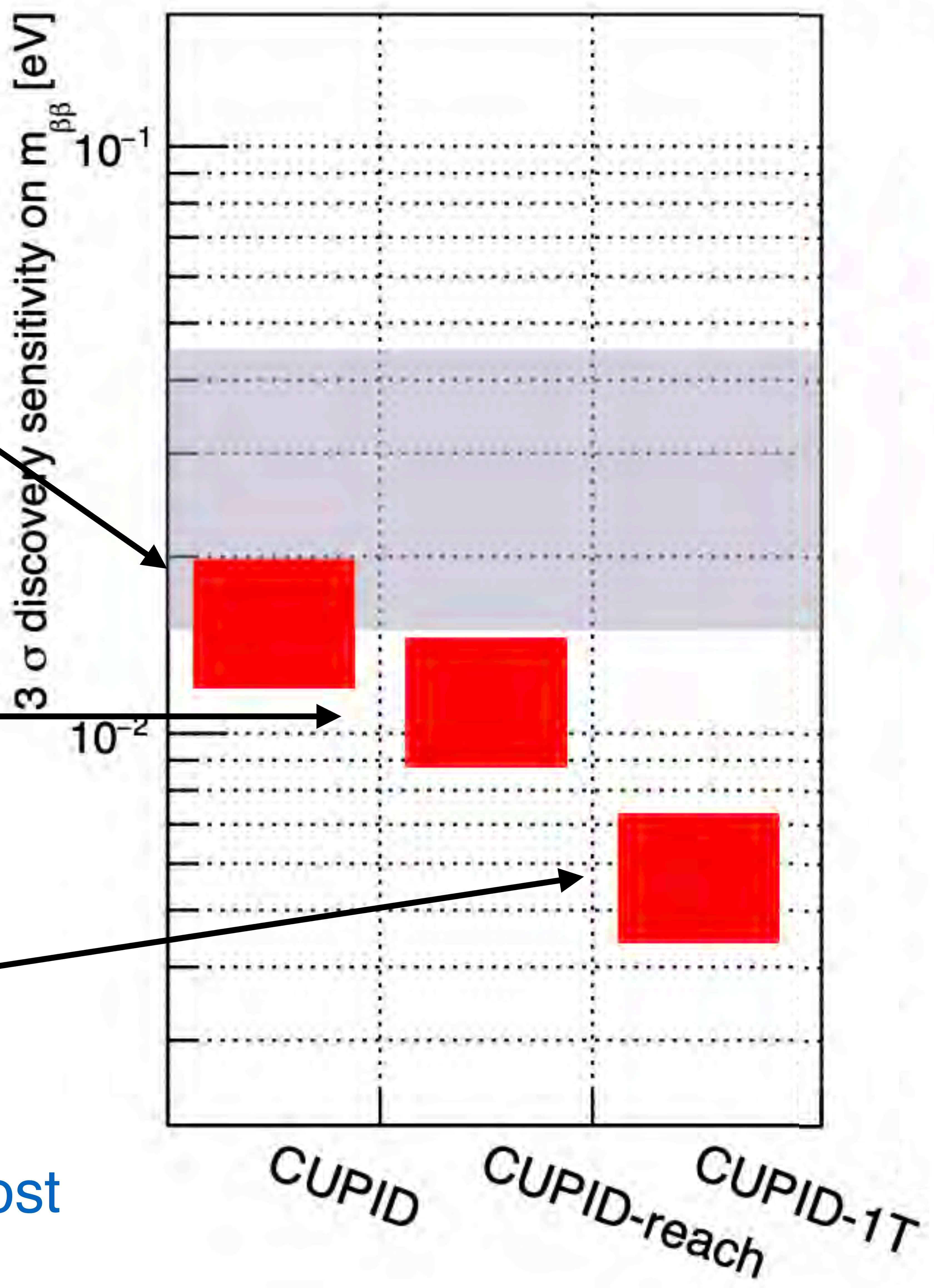
- Mass: 450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr
- Discovery sensitivity **$T_{1/2}$ > 1.1×10^{27} yr (3σ)**
- Conservative, limited R&D

Reach

- R&D for further background reduction by radio purity and reduce pileup background
- Discovery sensitivity **$T_{1/2}$ > 2×10^{27} yr (3σ)**

1-Ton

- 1000 kg of ^{100}Mo
- Discovery sensitivity **$T_{1/2}$ > 8×10^{27} yr (3σ)**



CUPID-1T is within technical reach, limited by timeline and cost

CUPID Sensitivity to 0νββ

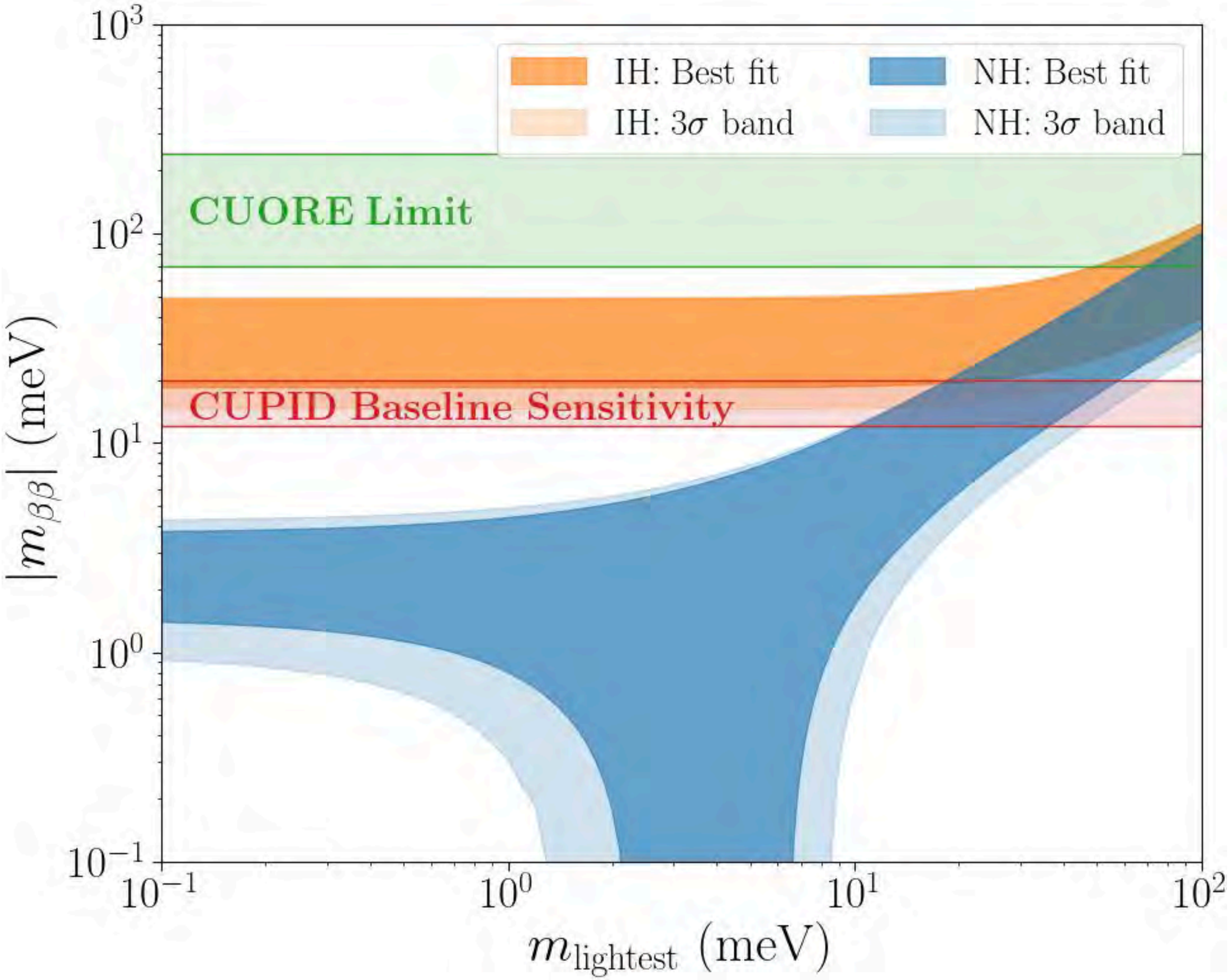
CUPID Baseline

- Mass: 472 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo)
- **10** yr runtime
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr

CUPID Baseline Discovery Sensitivity

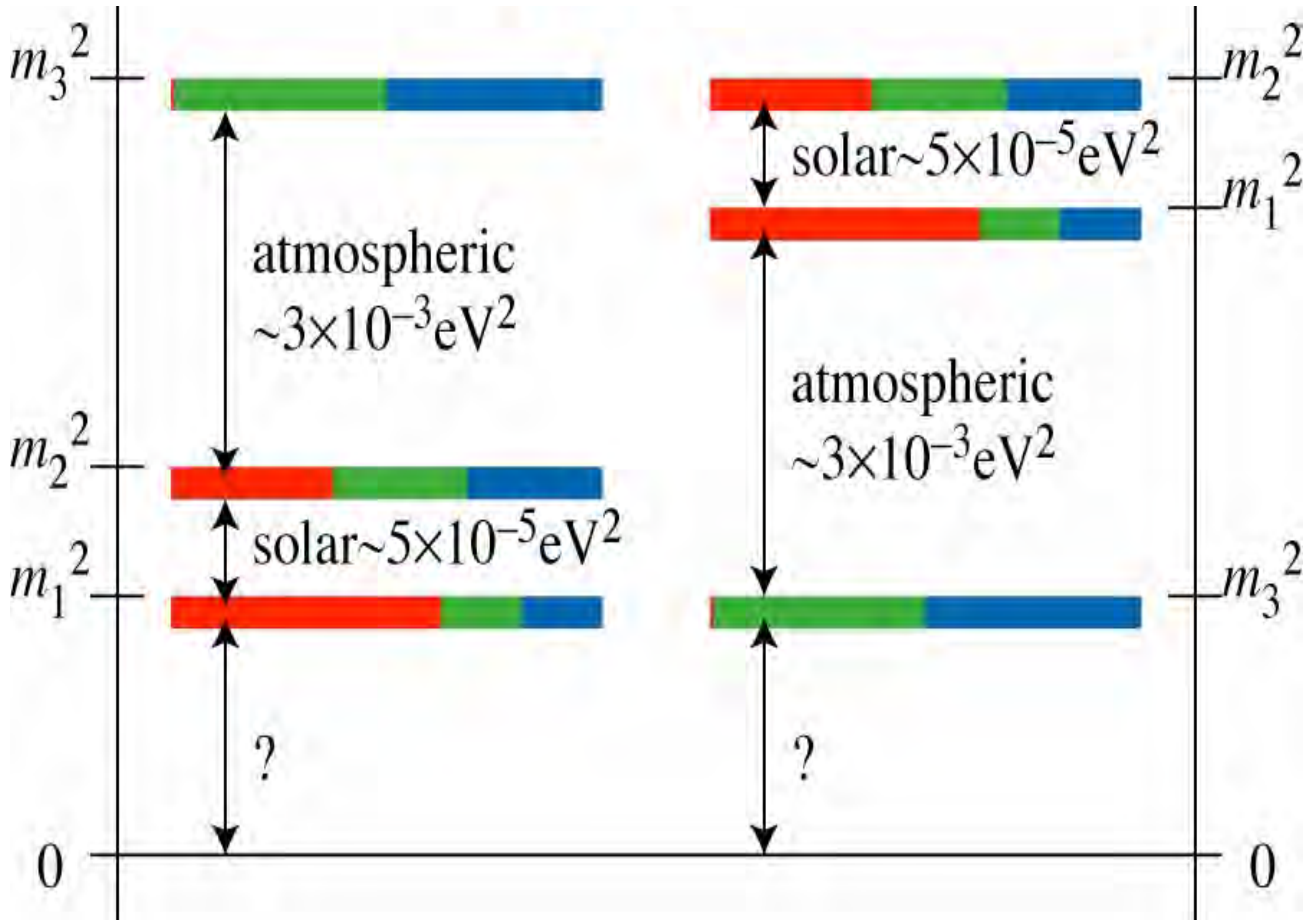
$T_{1/2}$ > **1.1×10^{27} yrs (3σ)**

$m_{\beta\beta}$ ~ **12-20 meV**



CUPID aims to cover the inverted hierarchy and a fraction of normal ordering

What is the mass of neutrinos?



Neutrino Mass Constraints

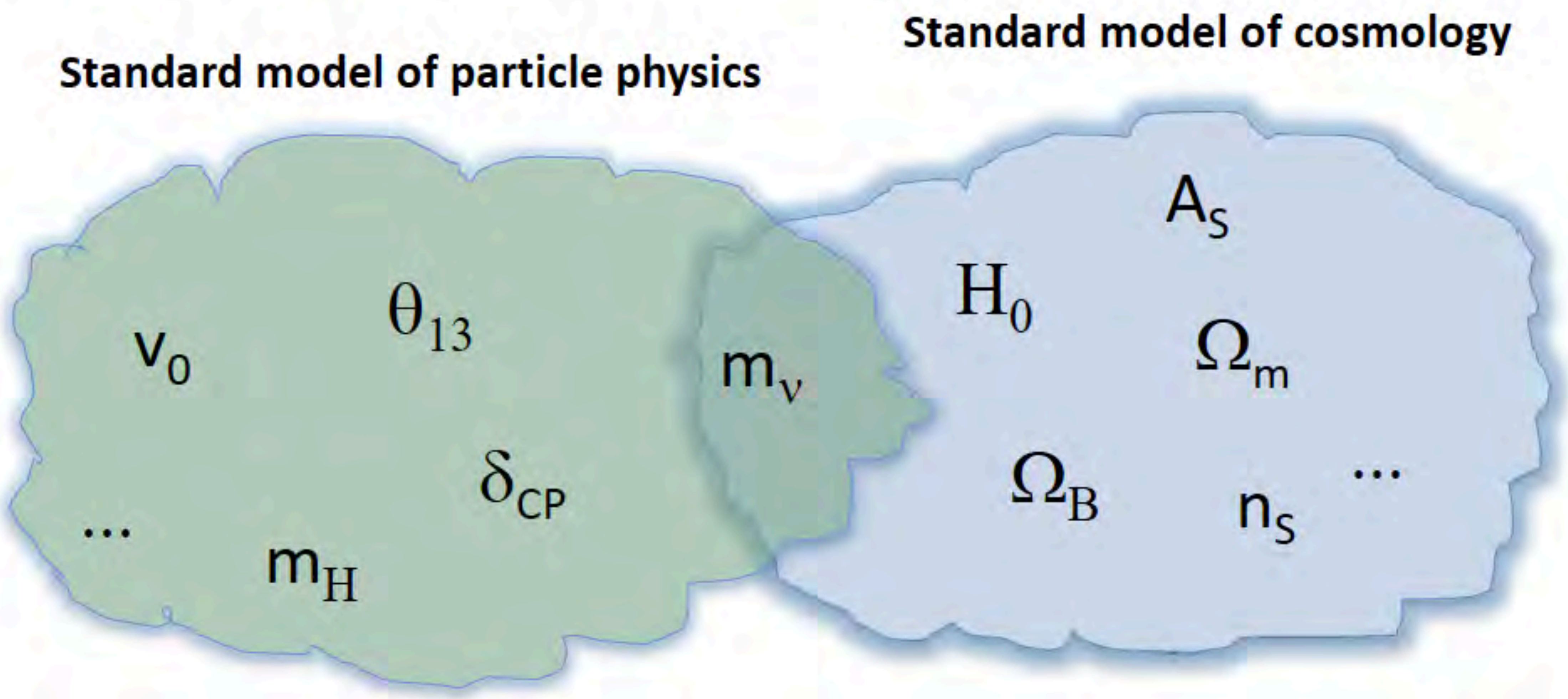
Cosmology measures $\sum_i m_i$

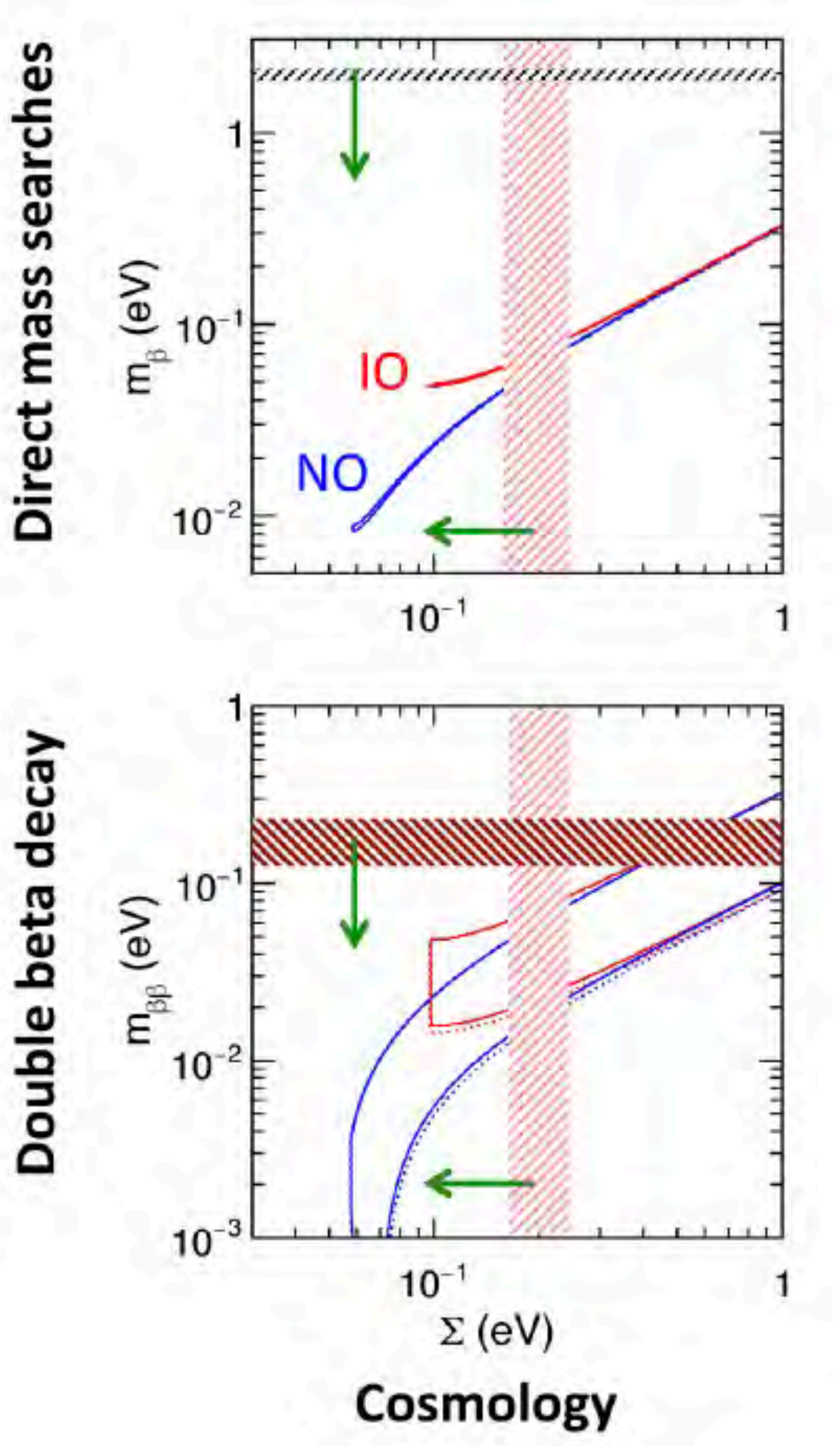
Double beta decay measures $\left|\sum_i U_{ei}^2 \, m_i\right|$

Direct searches measure $\left(\sum_i |U_{ei}^2| \, m_i^2\right)^{1/2}$

m_ν measurable both by laboratory experiments and cosmology

a critical test of consistency





Mezetto

Neutrino Mass Constraints

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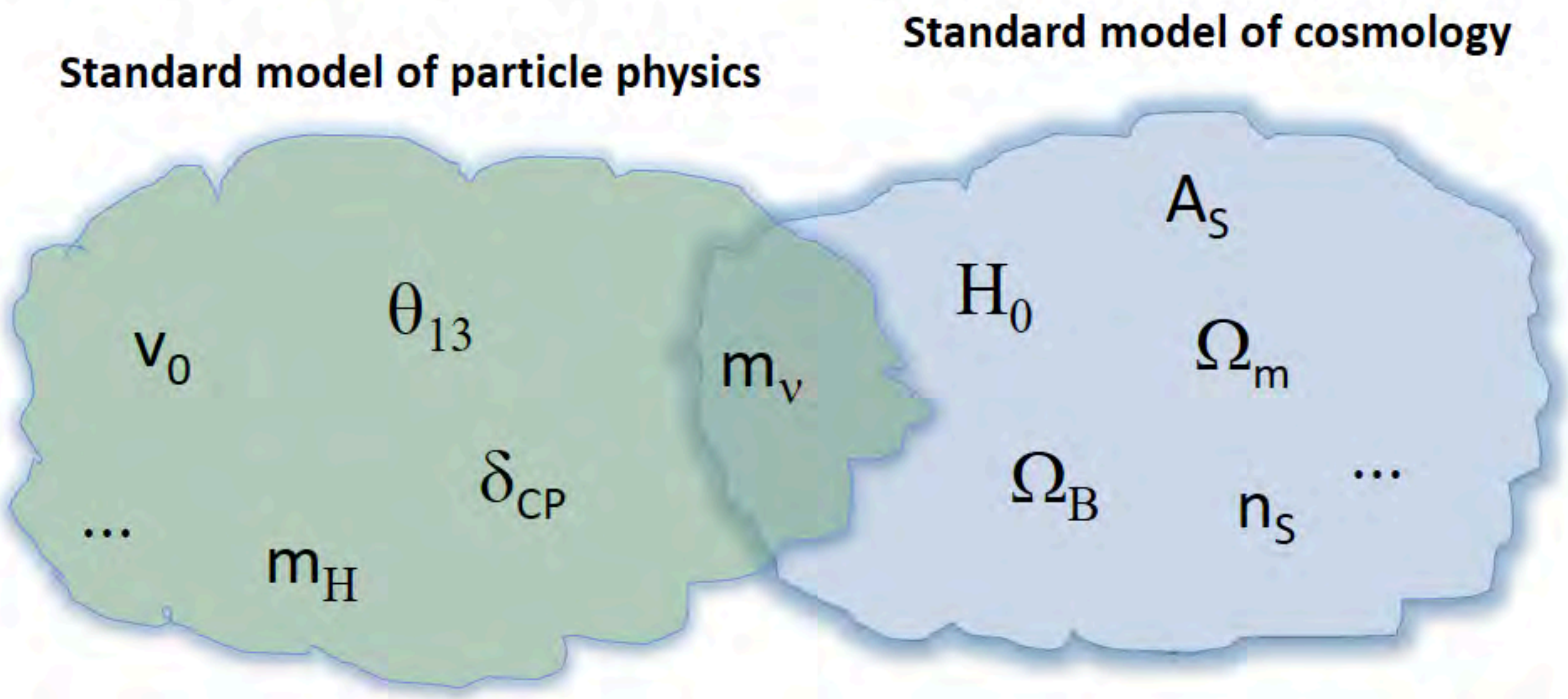
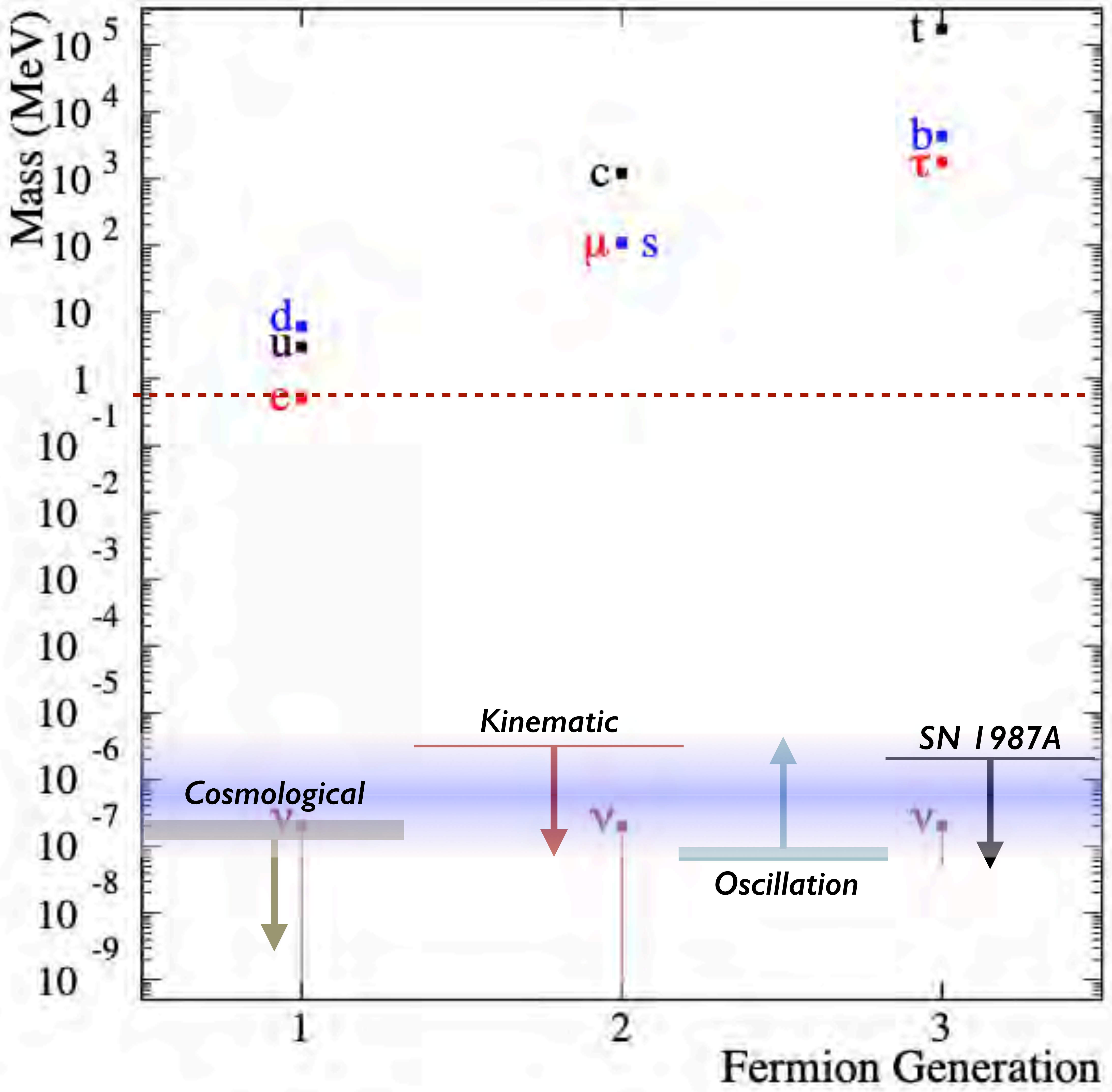
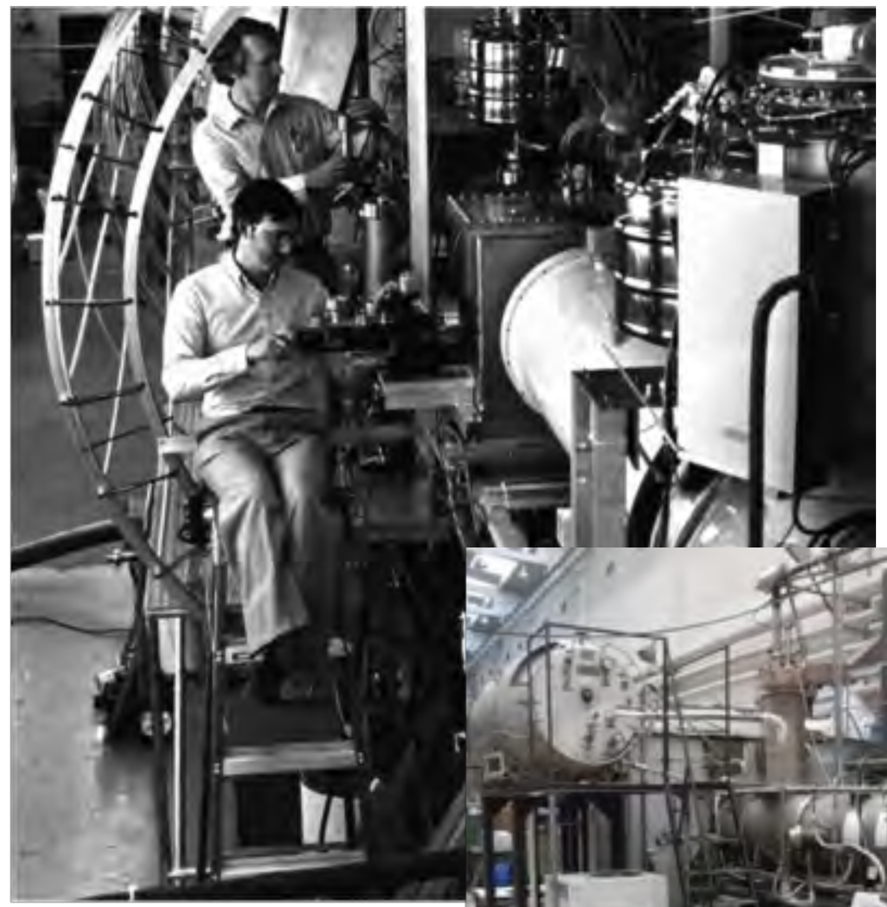




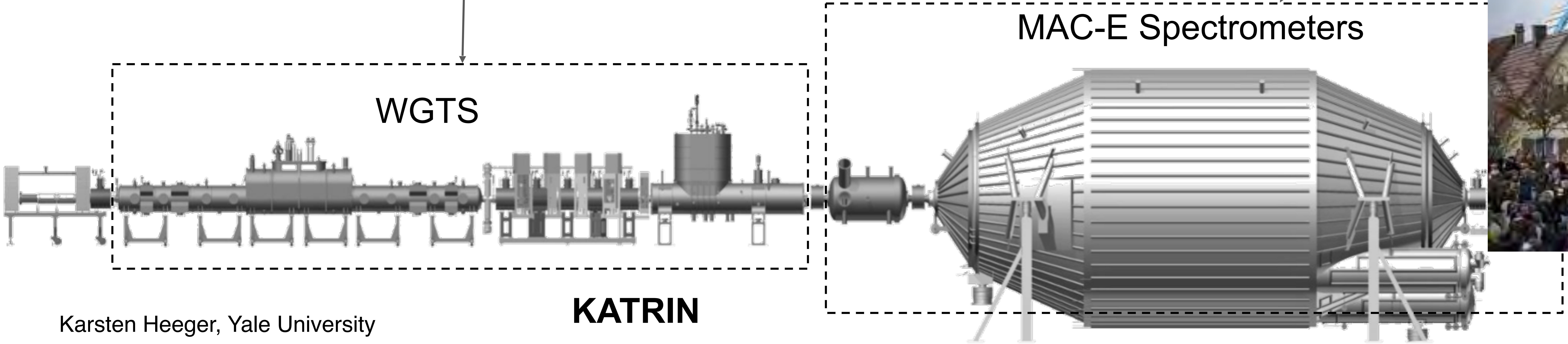
Adapted from arXiv:0604021

Direct Neutrino Mass Measurements



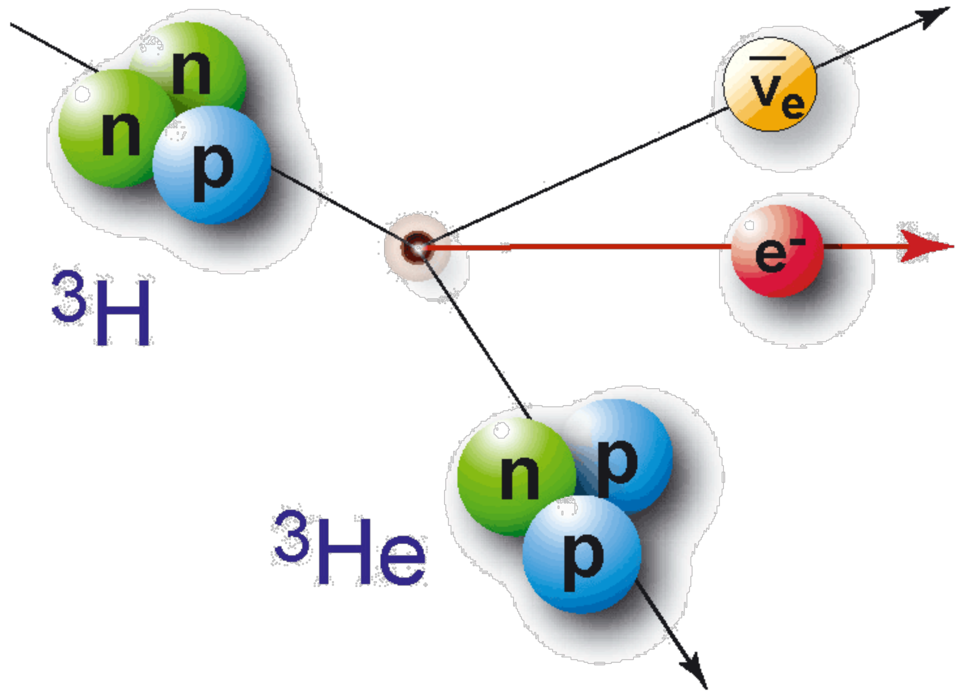
Los Alamos and **Troitsk** pioneered Windowless, Gaseous Tritium Sources (WGTS)

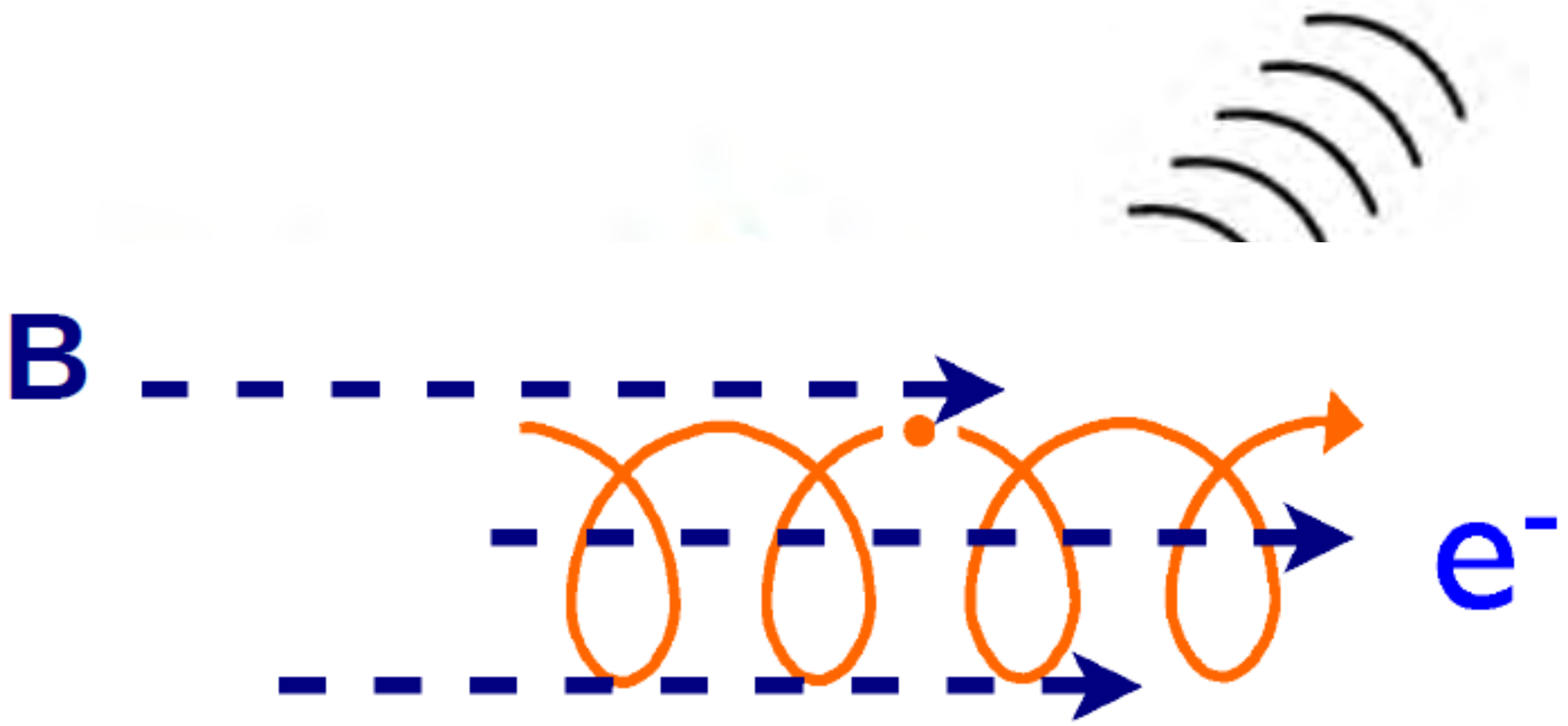
Mainz and **Troitsk** pioneered MAC-E spectrometry



KATRIN

Project 8 - A New Approach to Measuring Neutrino Mass



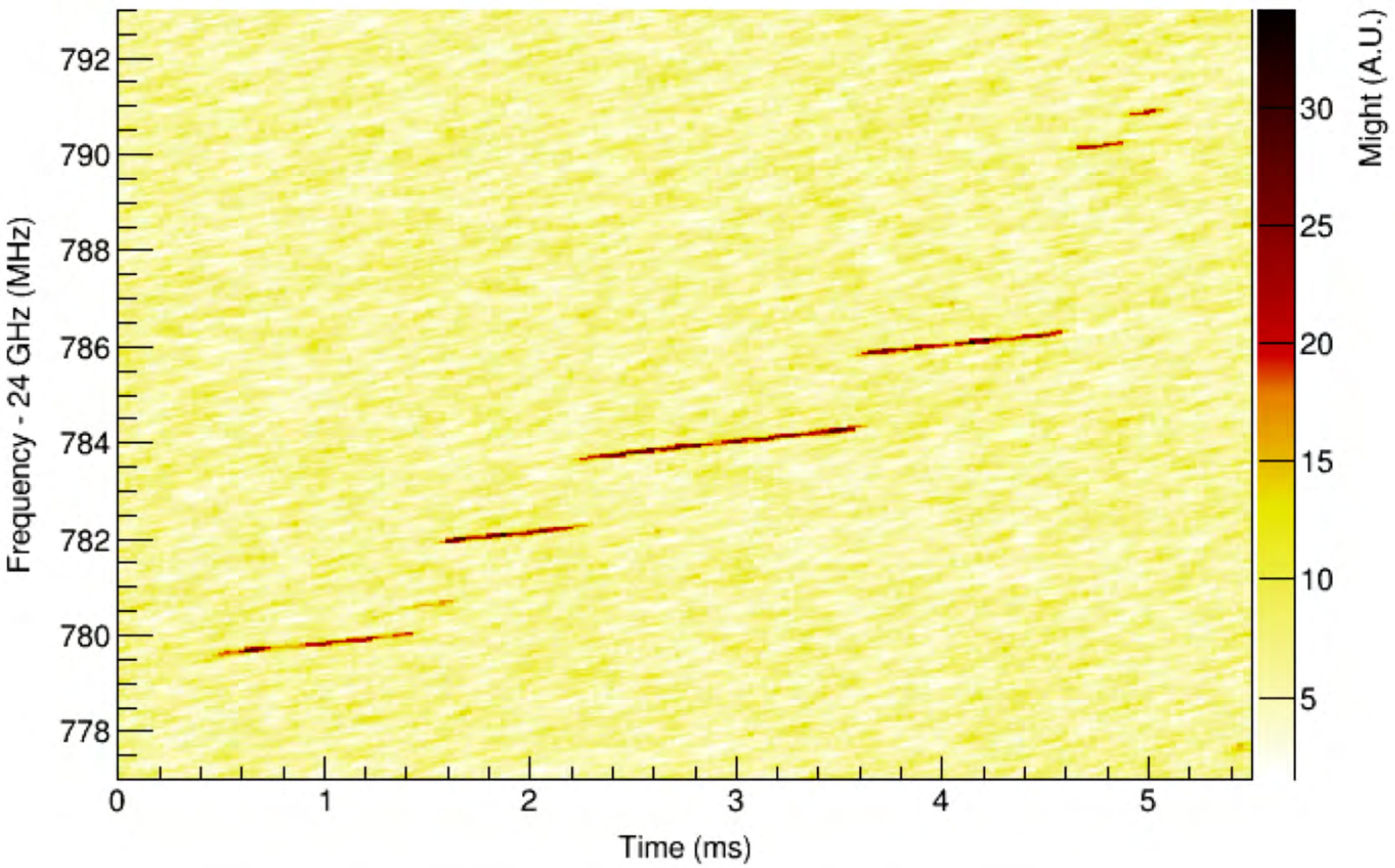


Cyclotron Radiation Emission Spectroscopy (CRES)

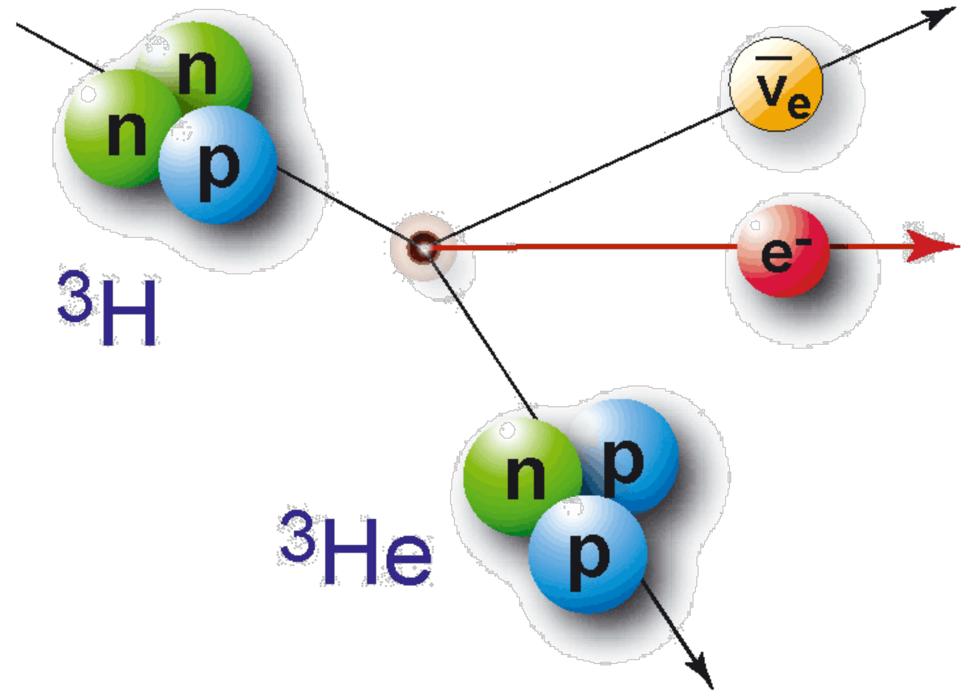
In uniform magnetic field, a charged particle will have a helical trajectory

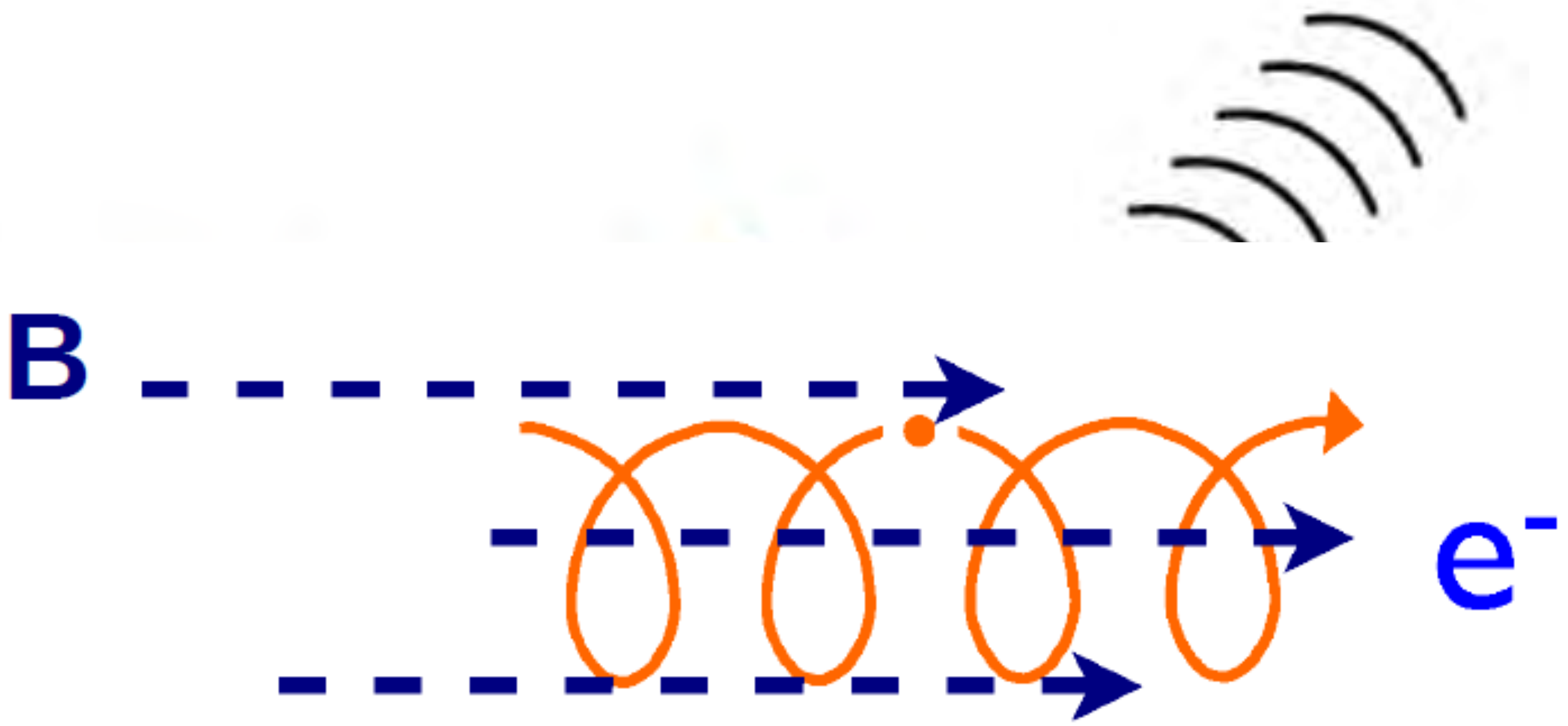
Accelerating electron will radiate EM waves at frequency:

$$f_{Cyc} = \frac{1}{2\pi}\frac{qB}{m\gamma} = \frac{1}{2\pi}\frac{qB}{m_e + E_e}$$



Project 8 - A New Approach to Measuring Neutrino Mass





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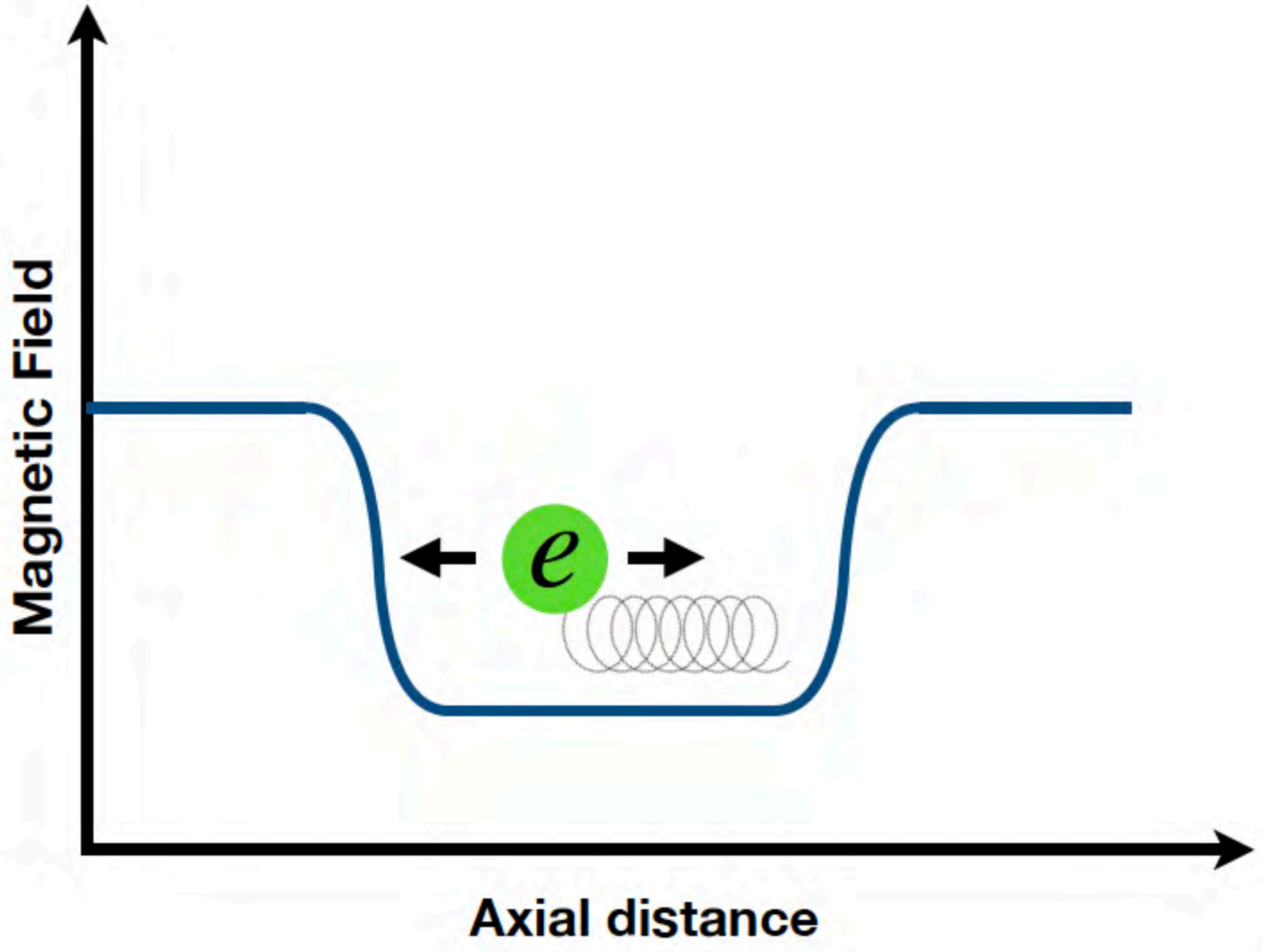
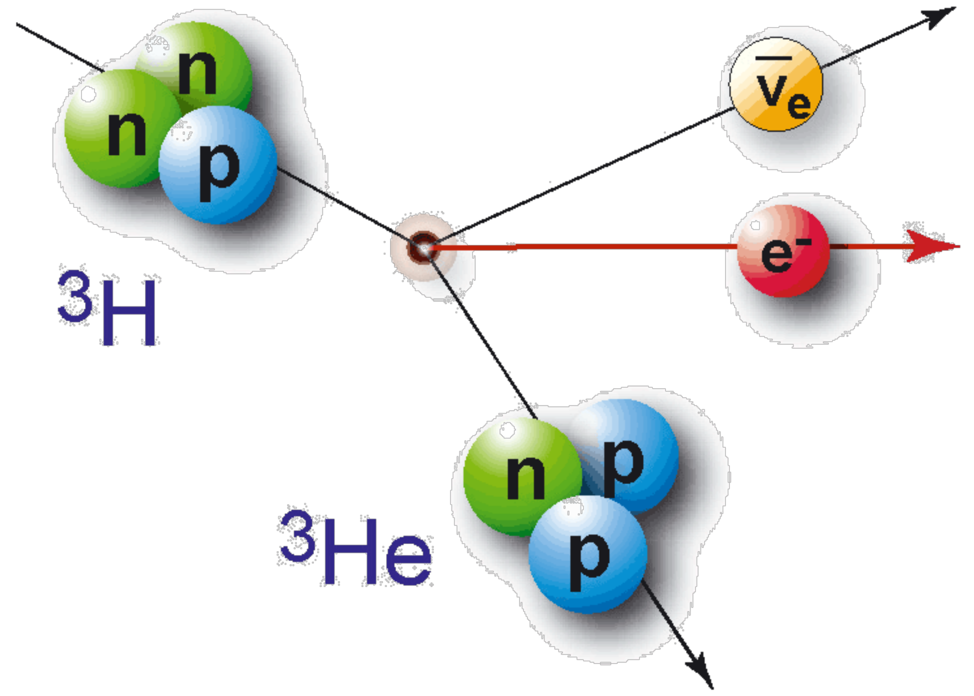


- Magnetic trap (no energy change)
- Extends observation time of electron (*time)
- Knowledge of B places limit on energy resolution

$$\triangle E = \frac{\triangle B}{B}(m_e c^2 + E_{kin})$$

Project 8 - A New Approach to Measuring Neutrino Mass



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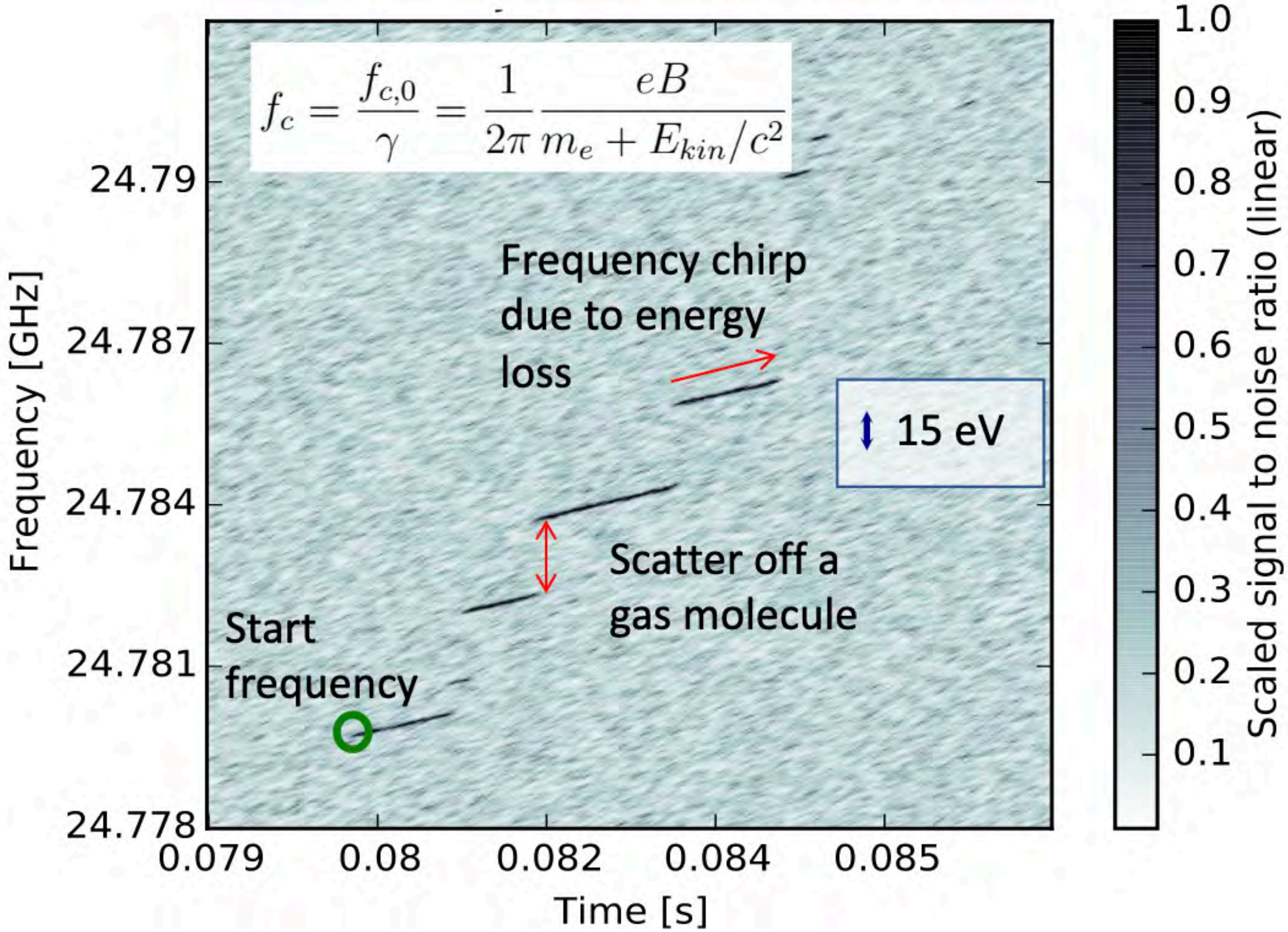
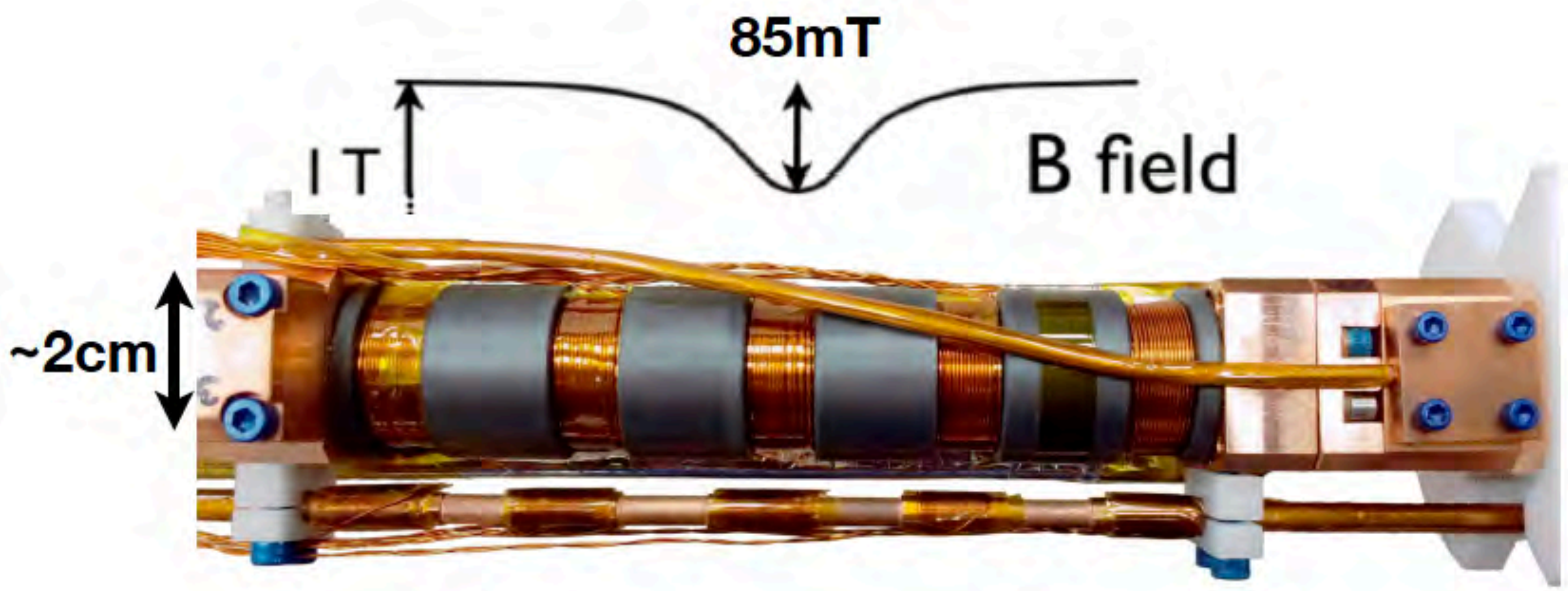
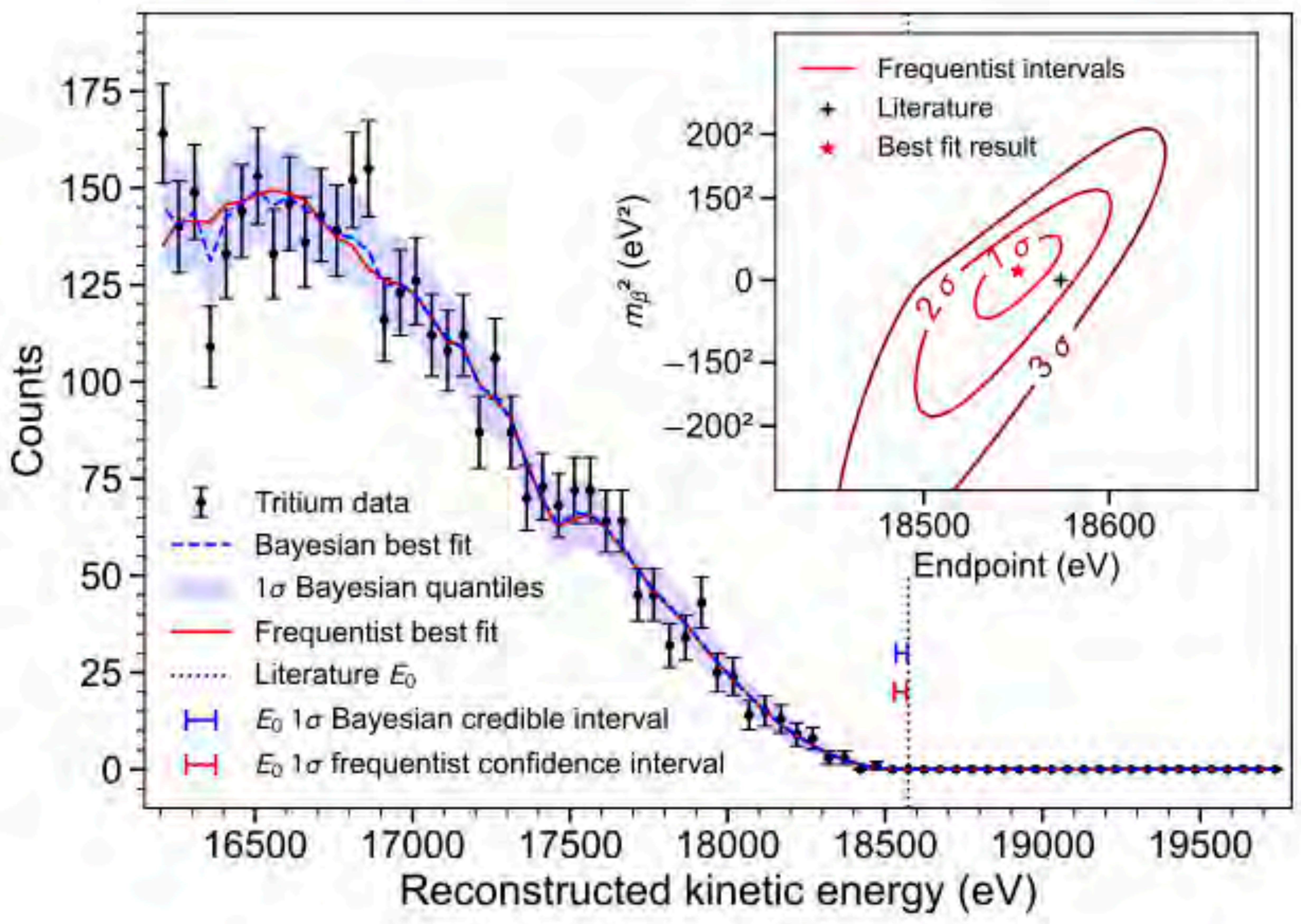


Project 8 - A New Approach to Measuring Neutrino Mass



- Mass limit: 170 eV (Bayesian) 180 eV (Frequentist)
- Count rate: 3770 events over 82 days. T_2 at 10^{-6} mbar
- Resolution: 54.3 eV (FWHM)
- Effective volume: 1.20 ± 0.09 mm^3



arXiv: 2212.05048, to be submitted to PRL

First measurement of the T_2 endpoint with CRES, Placed limit on the neutrino mass of m_β<155 eV

Project 8 - A New Approach to Measuring Neutrino Mass

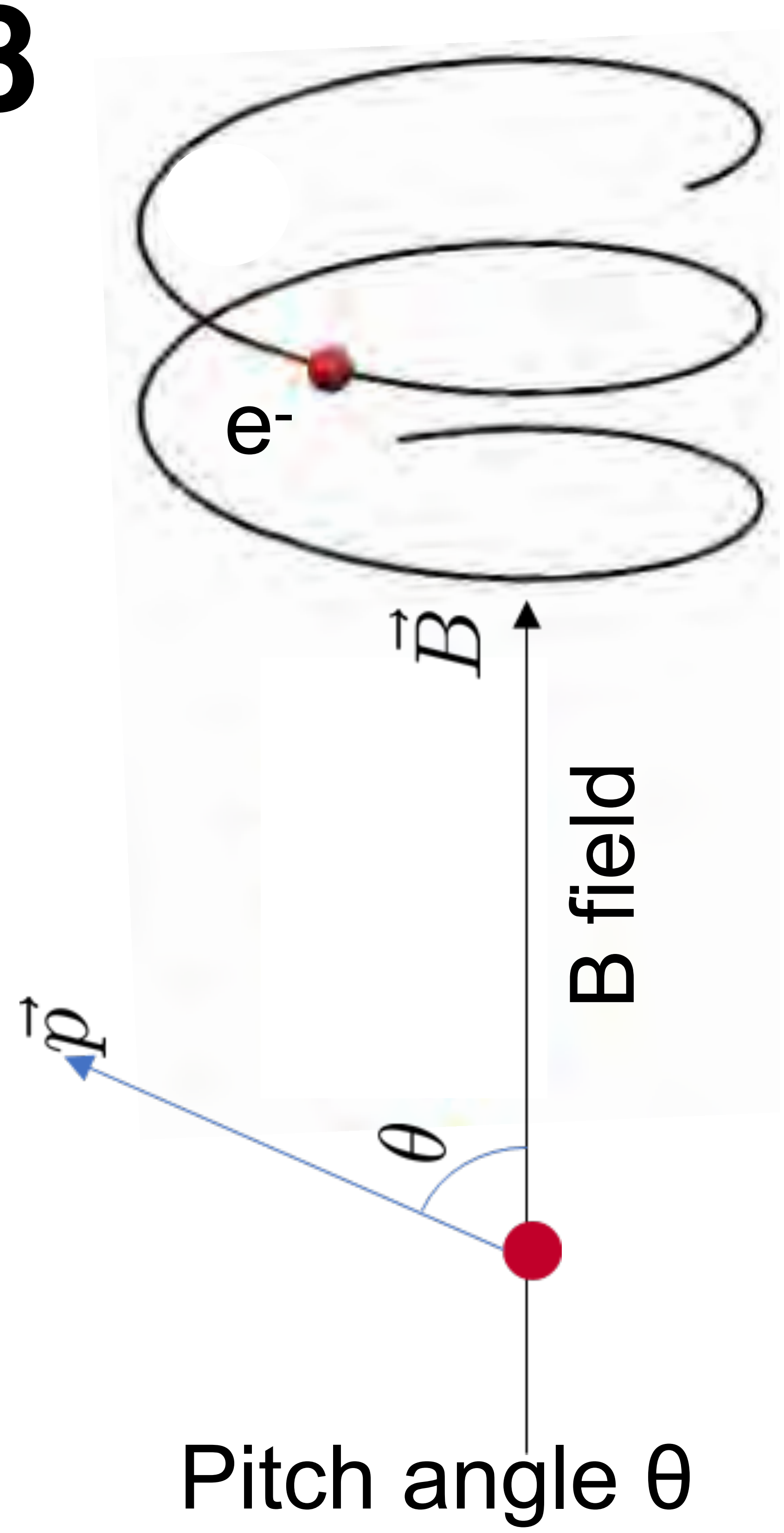
Cavity CRES in Project 8

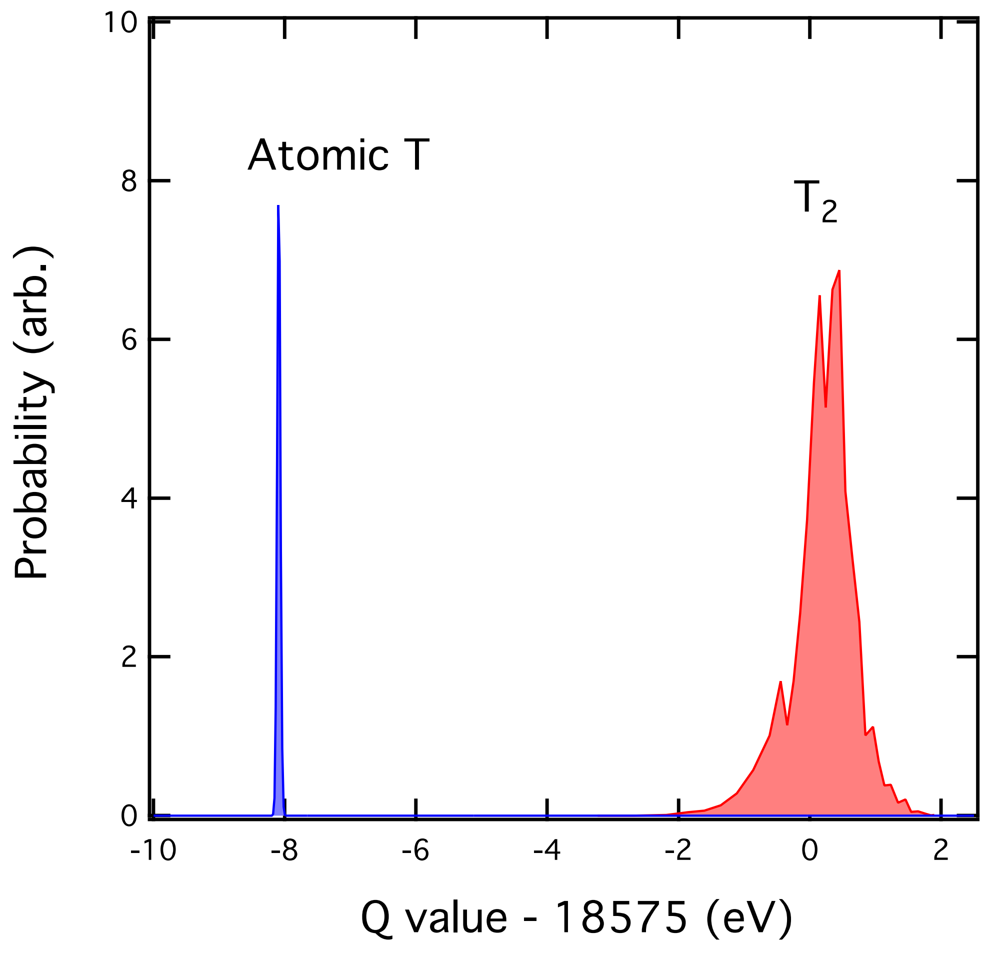
The elements of CRES:

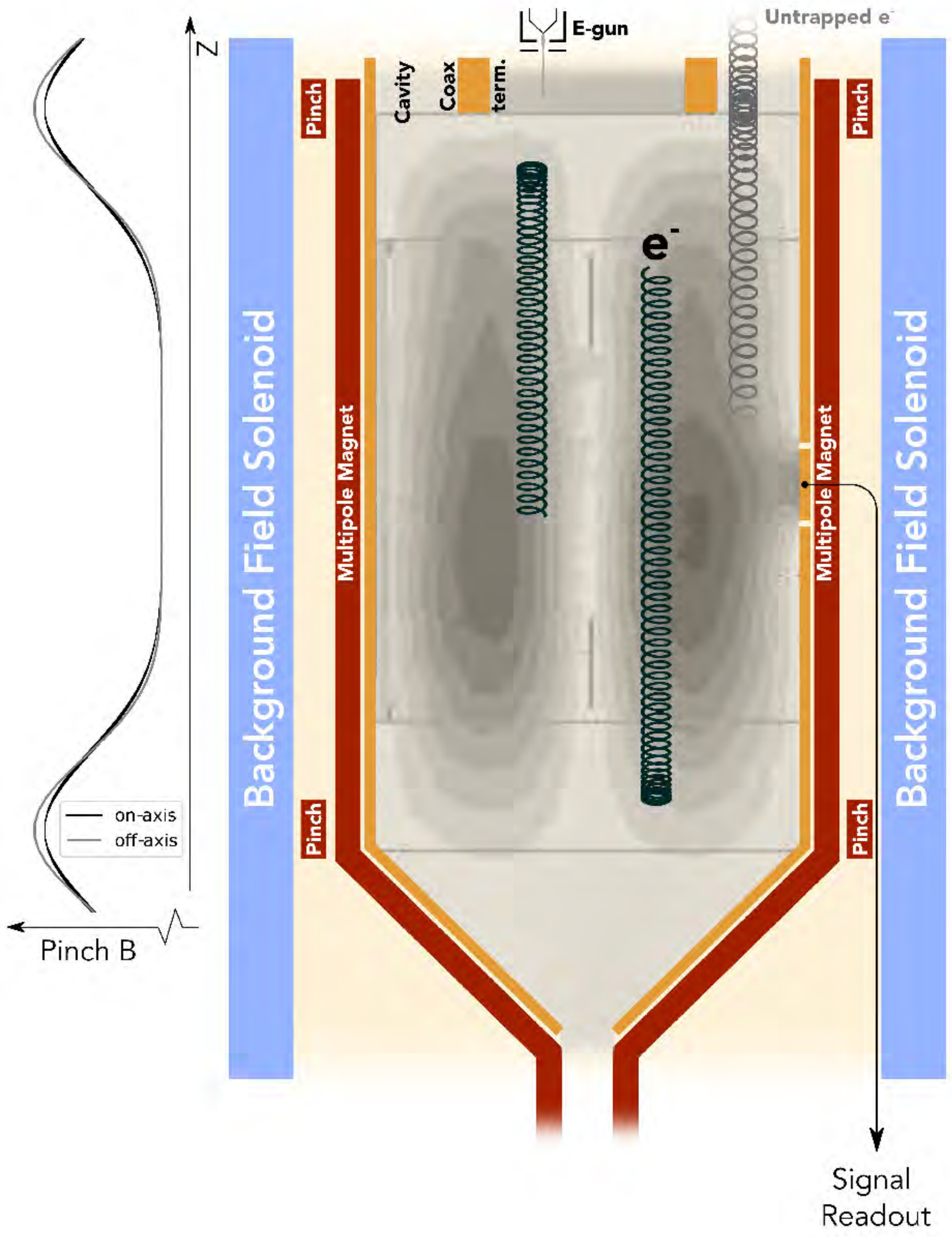
- Uniform magnetic field
- Magnetic trap for e-
- Antenna or cavity
- Sensitive receiver
- Tritium
- Atomic source
- Magnetic trap for atoms

Key features

- Low backgrounds obtainable.
- Excellent resolution obtainable.
- An atomic source of T (rather than molecular T_2) is compatible.



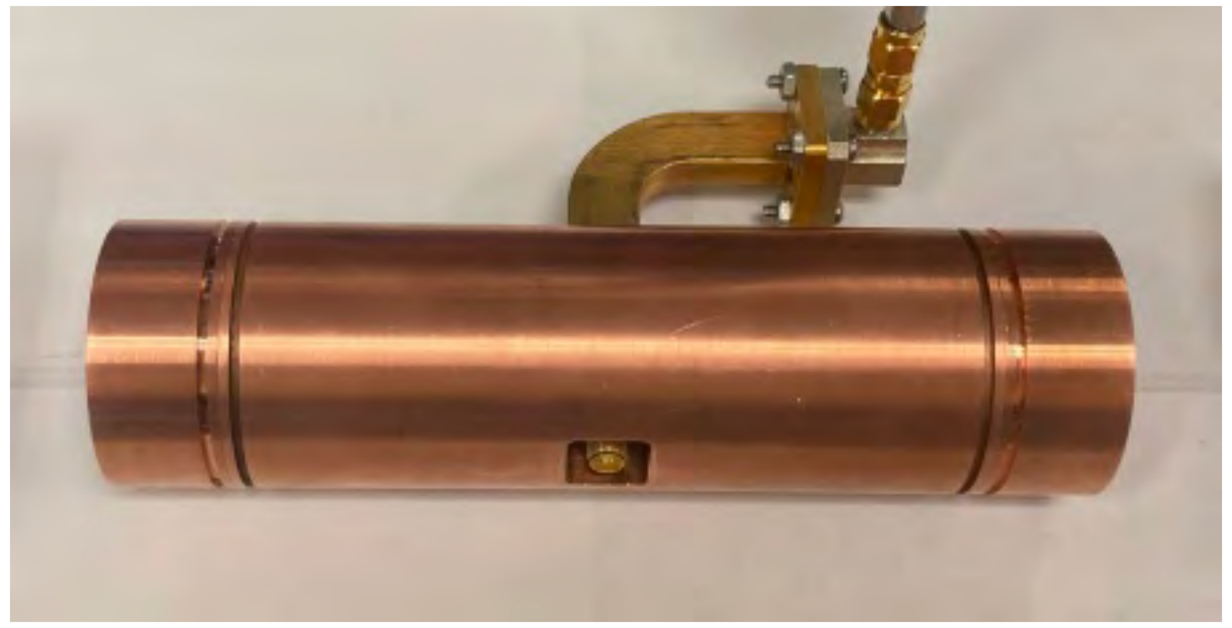




Project 8 - Next Steps

Cavity CRES prototype

Under construction



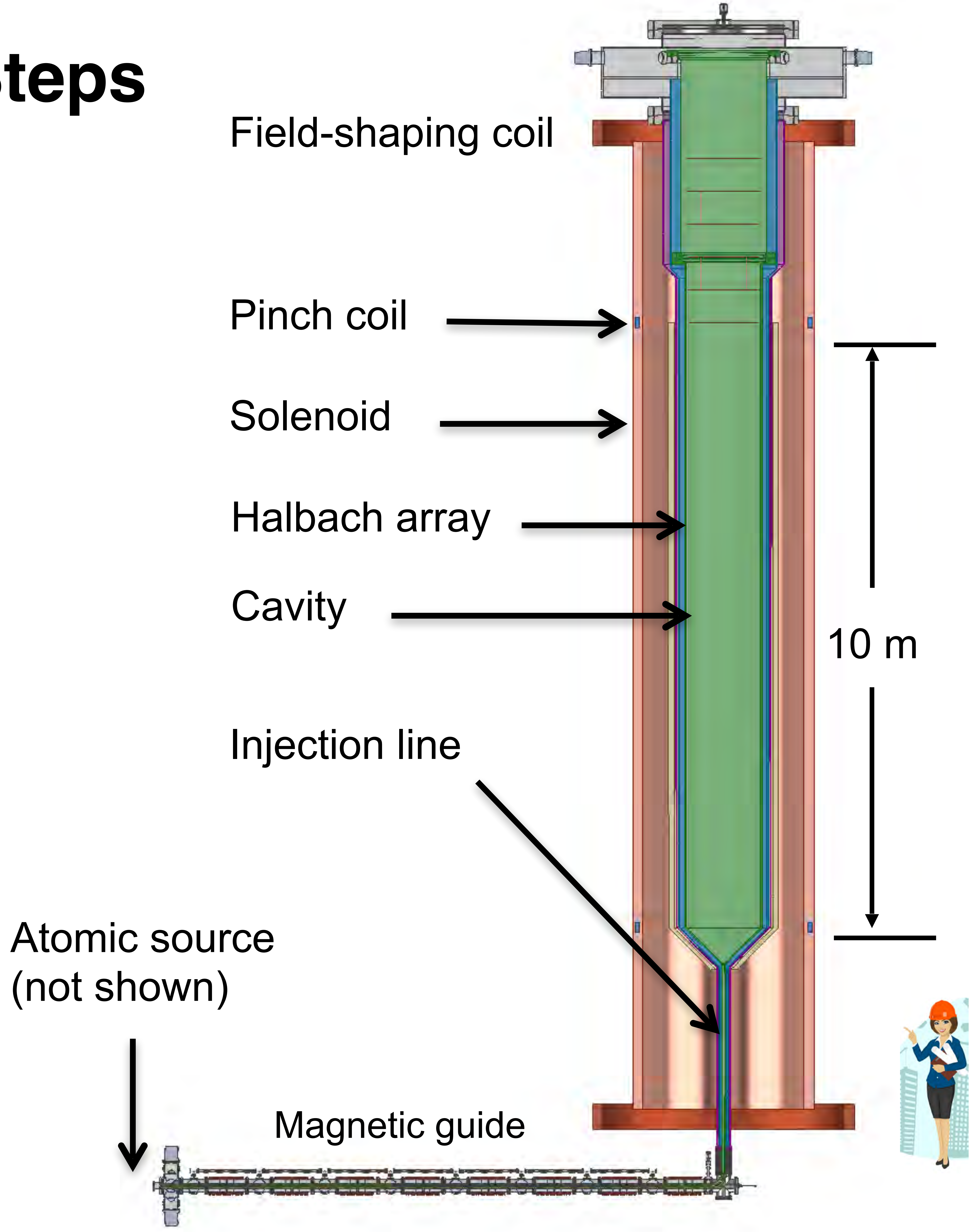
Phase III

CRES with T2 or magnetogravitationally trapped T atoms

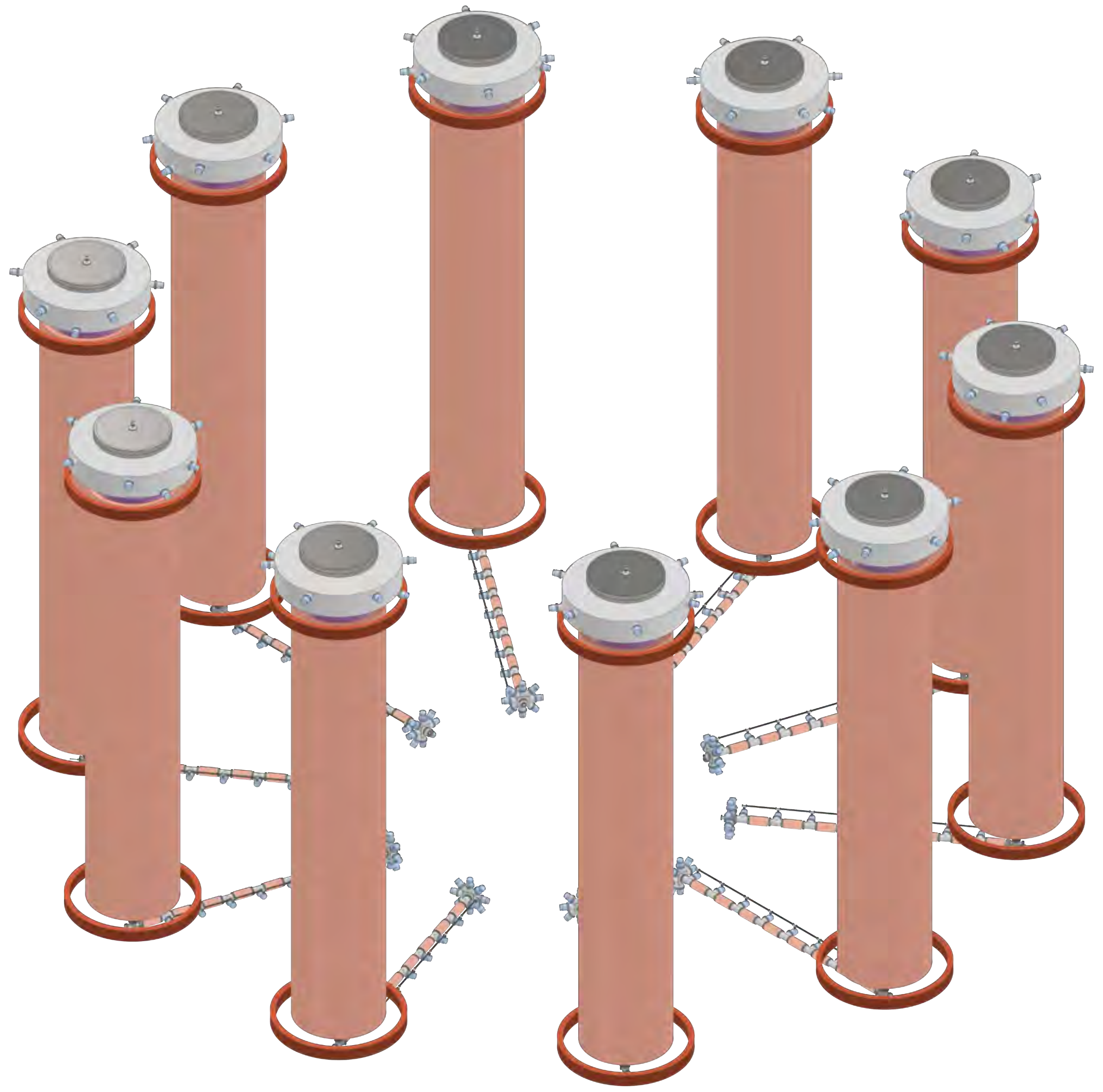
R&D on atomic Tritium source

R&D on cavity RF readout (*fc* <1GHz for T trapping)

goal $m_\nu < 0.2$ eV (with T_2)



Phase IV



With 10 of these

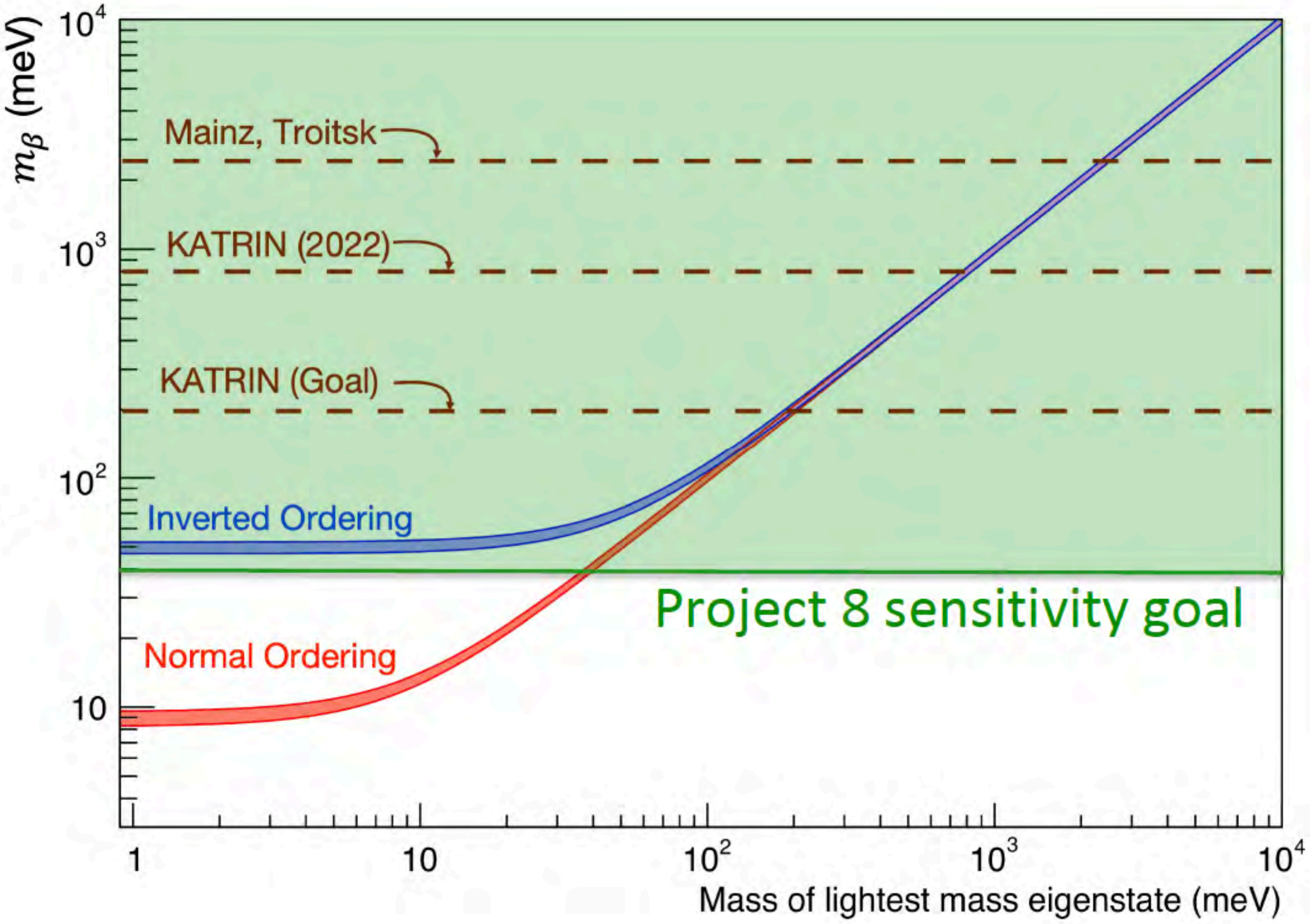
goal $m_\nu < 0.04$ eV

Project 8 Sensitivity

Probing the neutrino mass hierarchy at 40meV

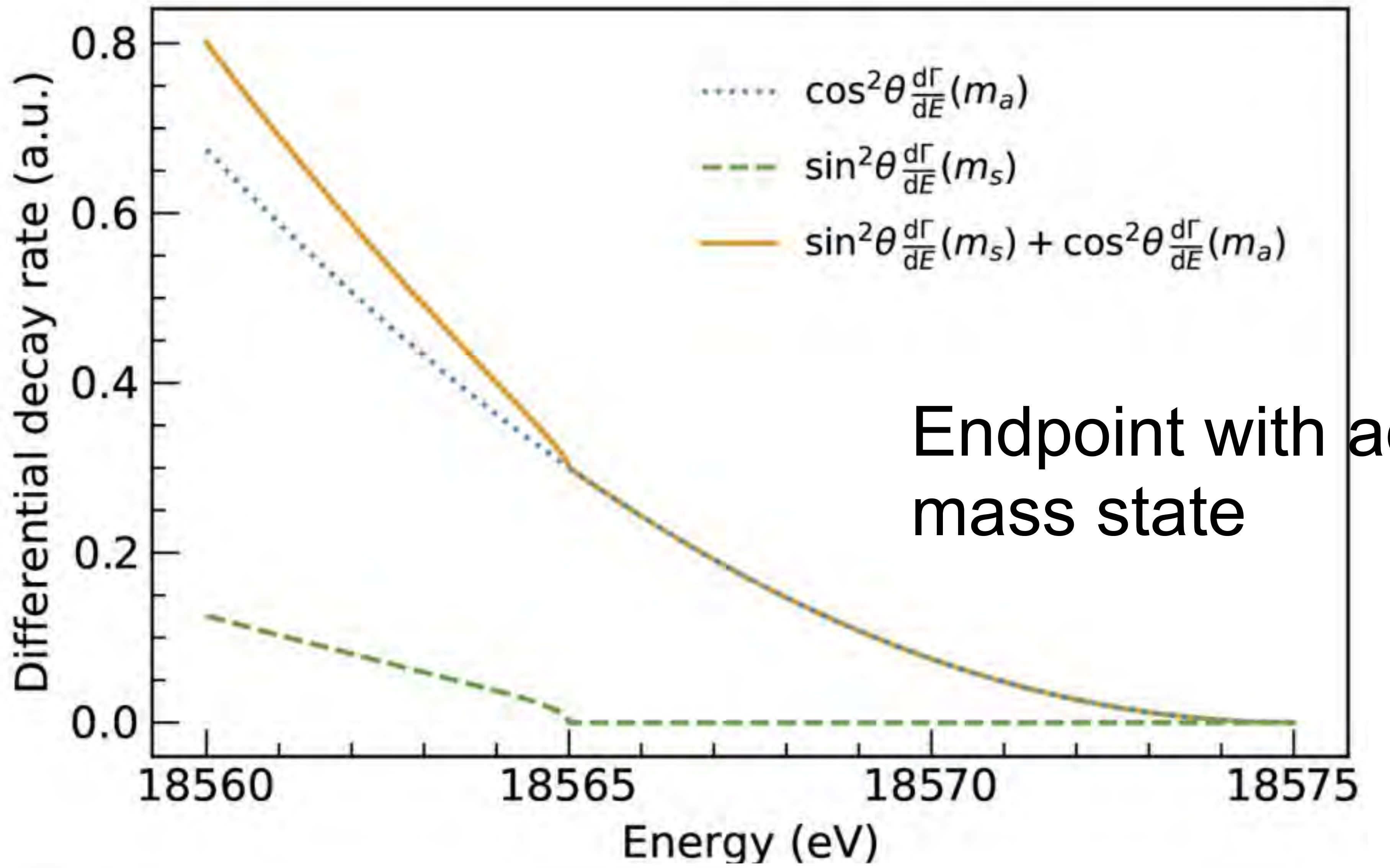
Sensitivity below inverted mass ordering

New technologies required
- atomic tritium
- CRES

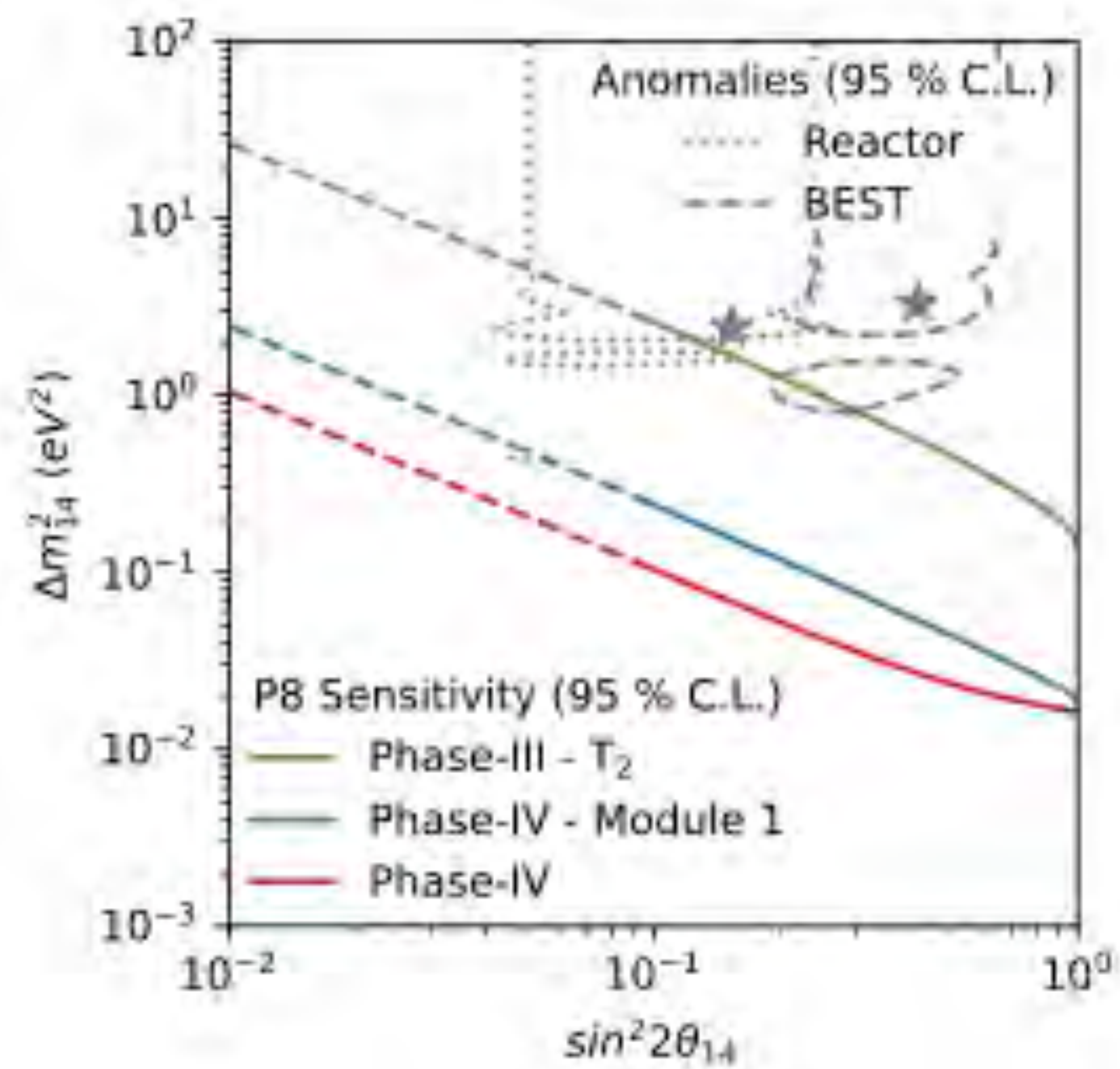


Project 8 - Sterile Neutrinos

- Tritium spectrum = sum of individual spectra from each mass state
- With fine enough resolution, Project 8 could potentially resolve the individual mass-state contributions — Phase IV
- In Phase III we could have sensitivity to higher-mass sterile neutrino mass states, if they exist
- An O(eV) sterile neutrino would put a kink in the spectrum



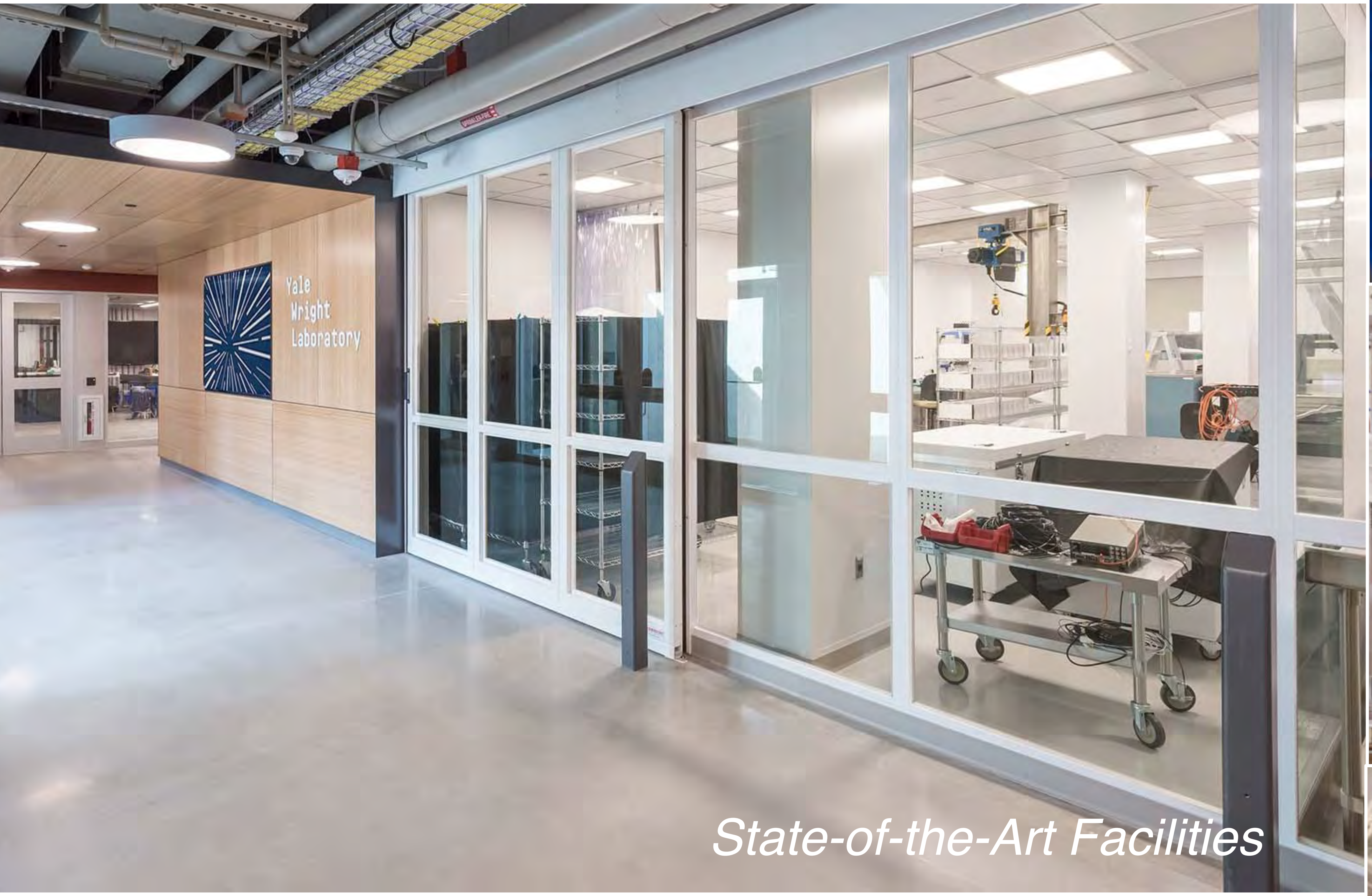
Endpoint with added sterile mass state



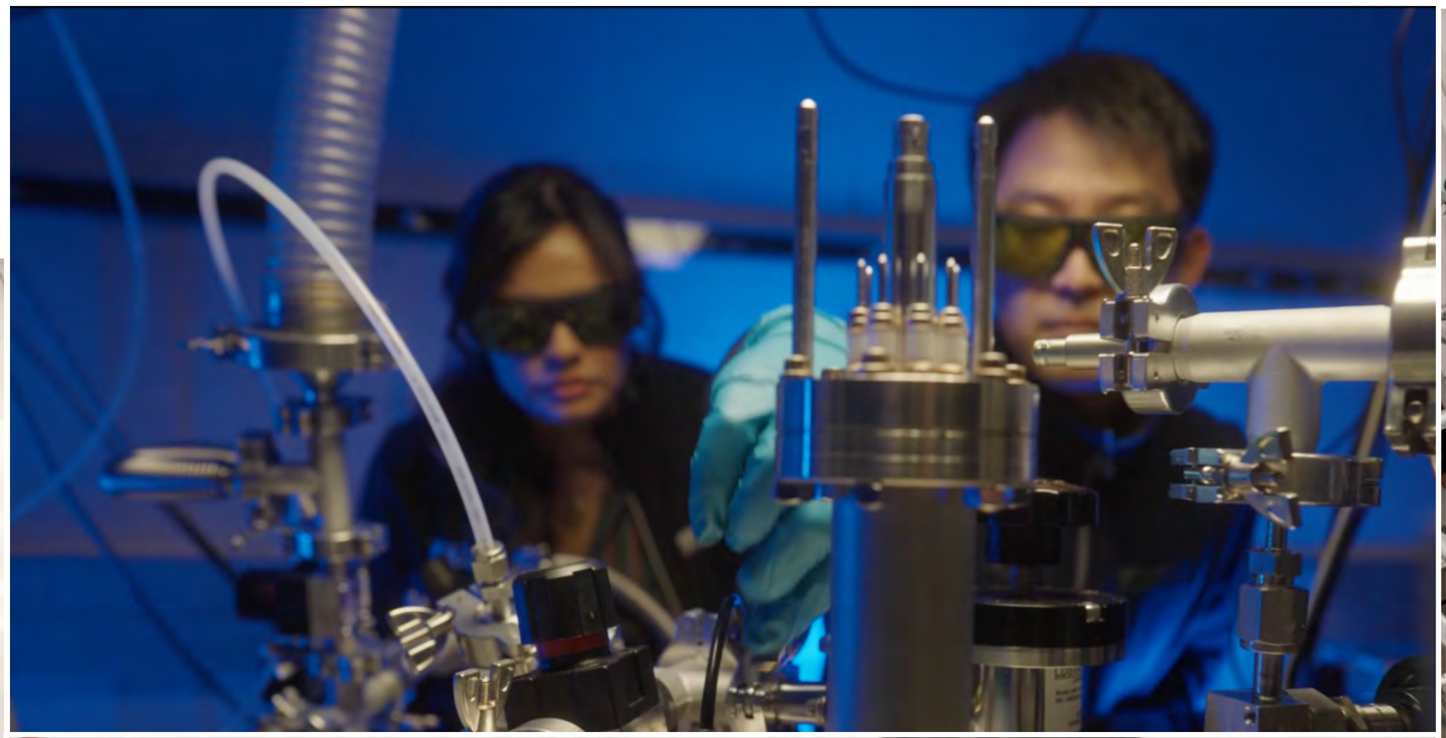
Yale Wright Laboratory

Developing Tools for Discoveries

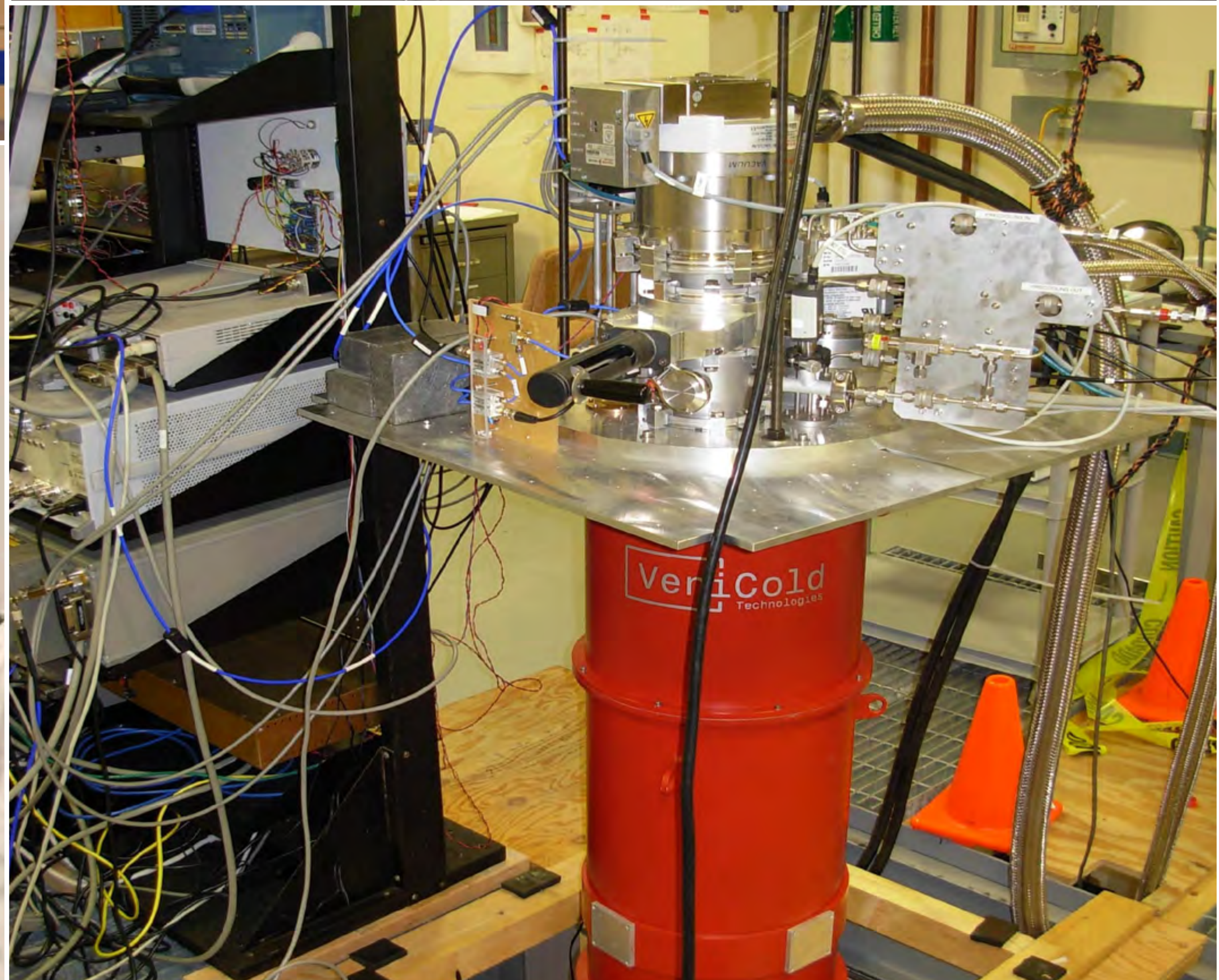
Exploring the Invisible Universe



State-of-the-Art Facilities




Training Future Scientists



Advancing frontiers of nuclear, particle, and astrophysics including studies of **neutrinos**; searches for **dark matter**; understanding **matter**; exploration of **quantum science** and observations of **the early Universe**.

https://wlab.yale.edu

Yale Wright Laboratory

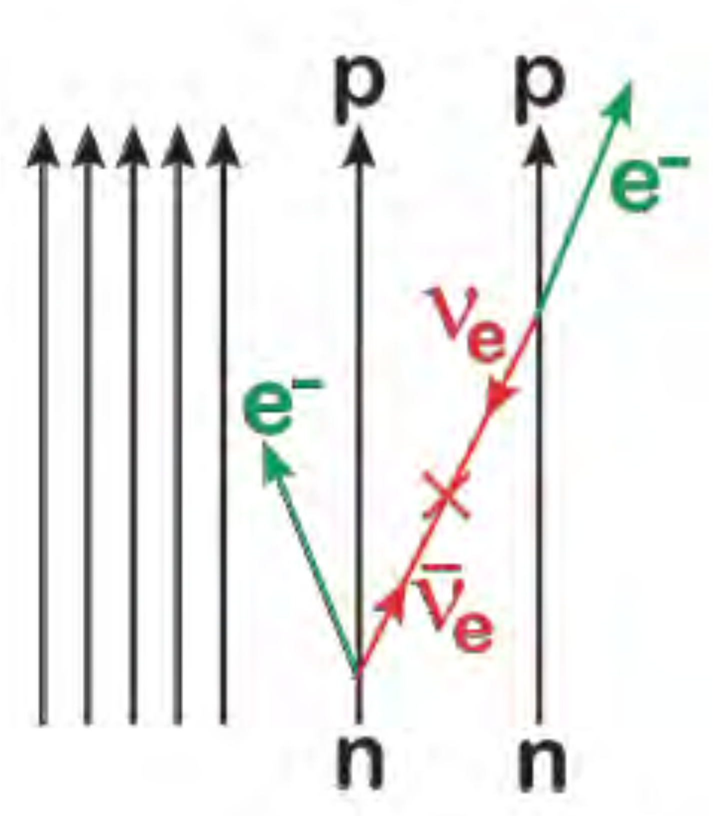
Research Worldwide

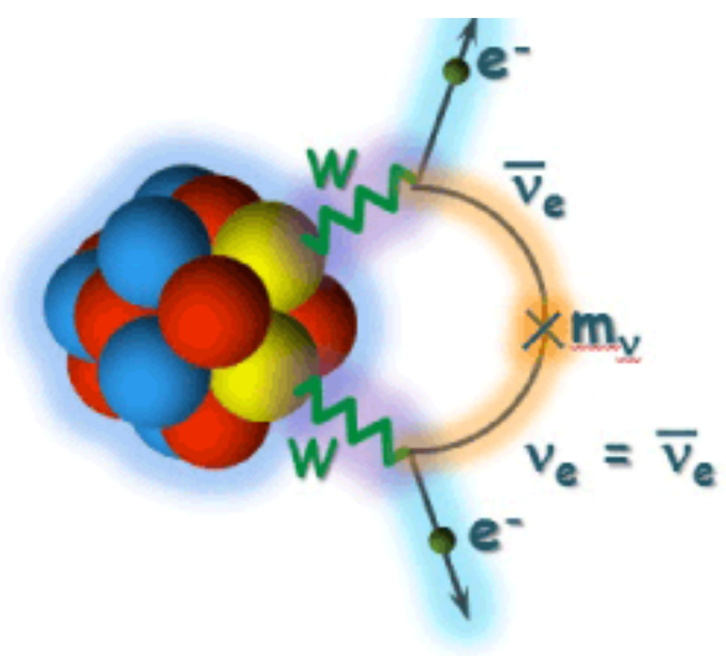
Exploring the Invisible Universe

Summary and Outlook

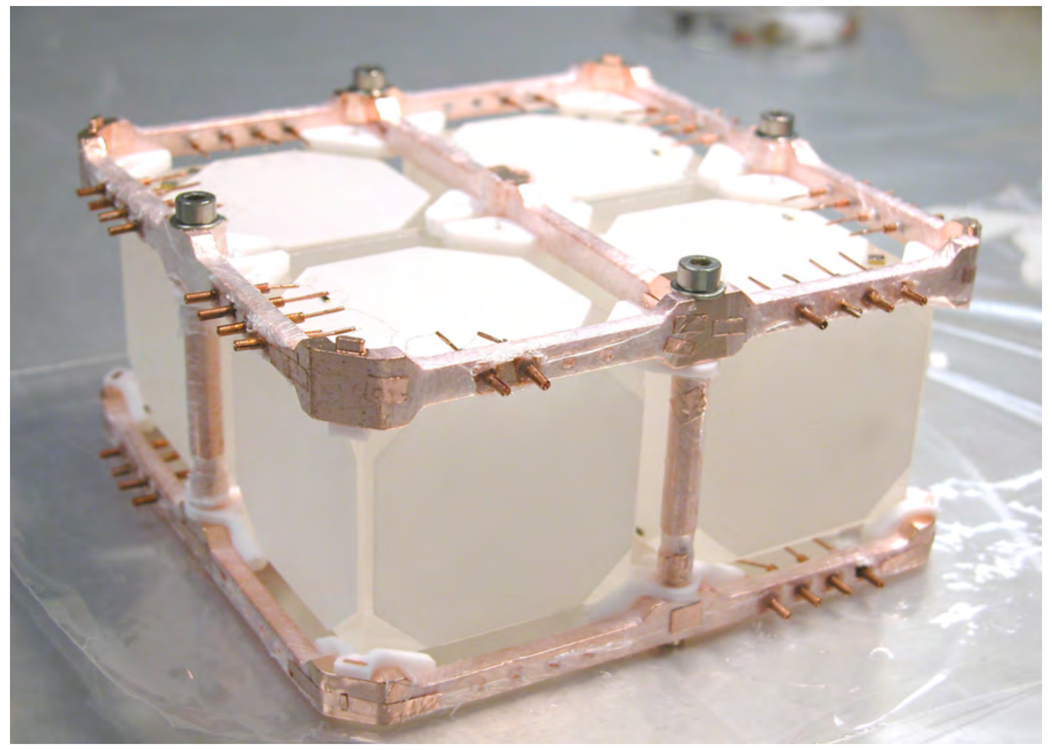
Low-energy ν experiments provide key insight into the nature of neutrinos, synergies with dark matter experiments. Instrumentation development and novel detectors open new frontiers.

Neutrinoless double beta (0νββ) most powerful and comprehensive probe of lepton number violation (ΔL=2).

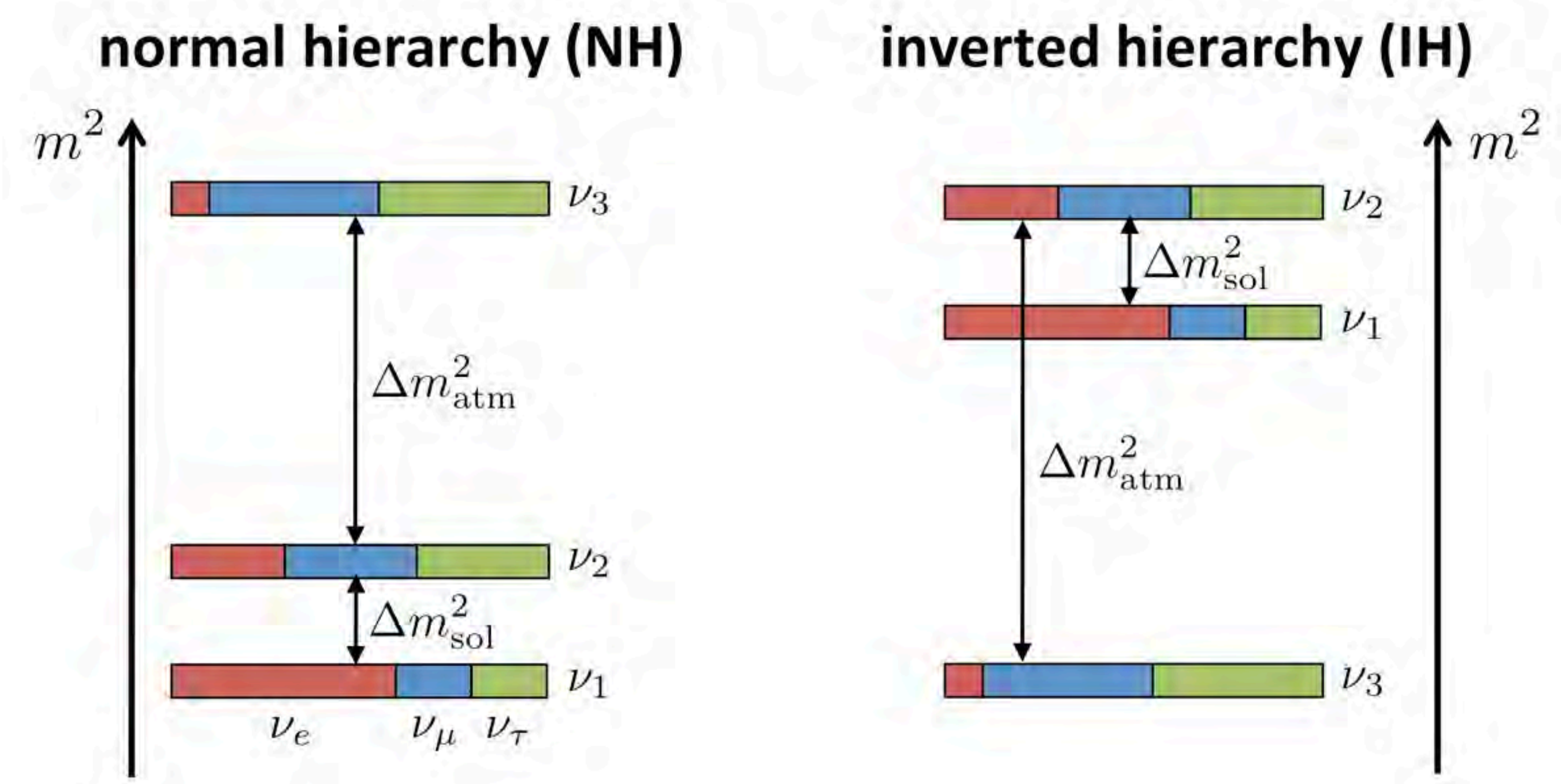




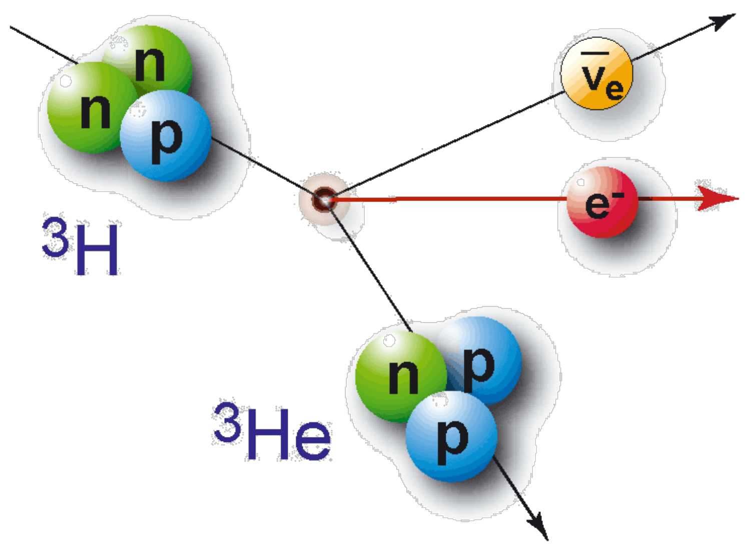
Neutrinoless double beta decay

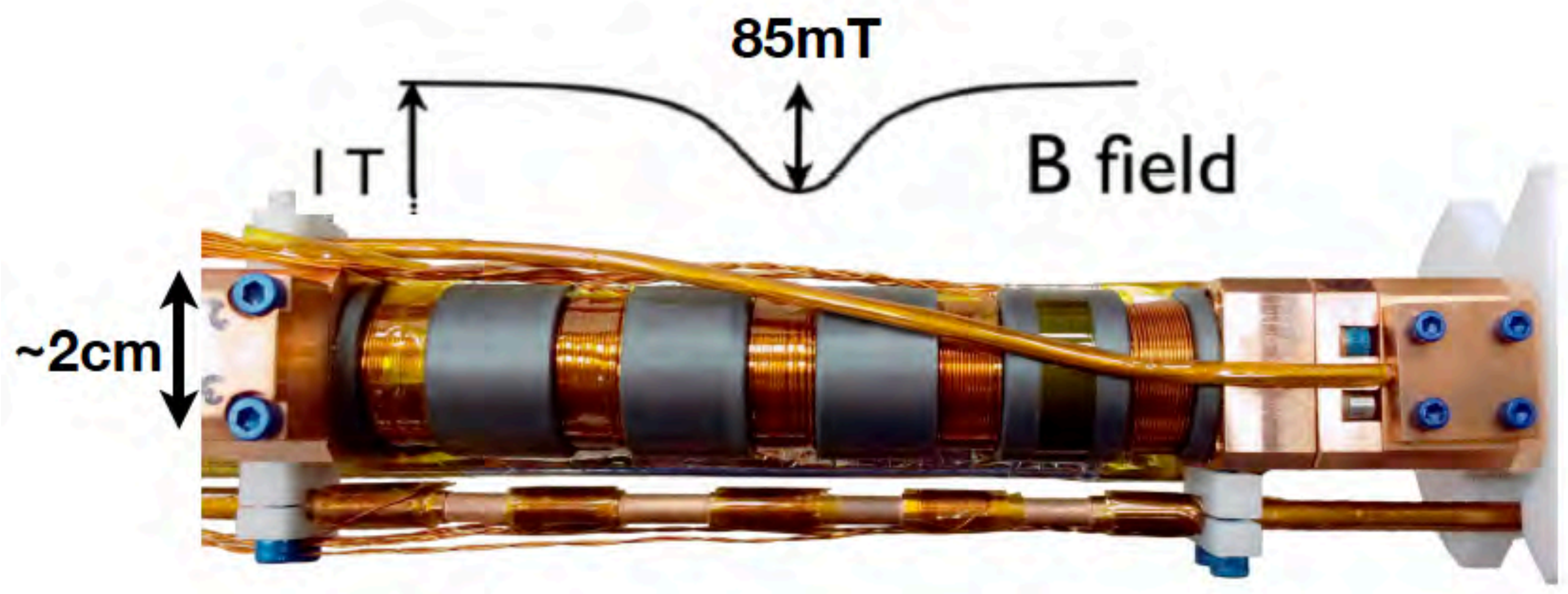


Reactor and accelerator experiments will determine mass ordering and probe CP violation, and test the three flavor paradigm



Beta decay allows **direct neutrino mass measurements**





Project 8 aims to reach m_ν <0.04 eV

Exciting years lie ahead!