Probing the Nature of Neutrino Mass

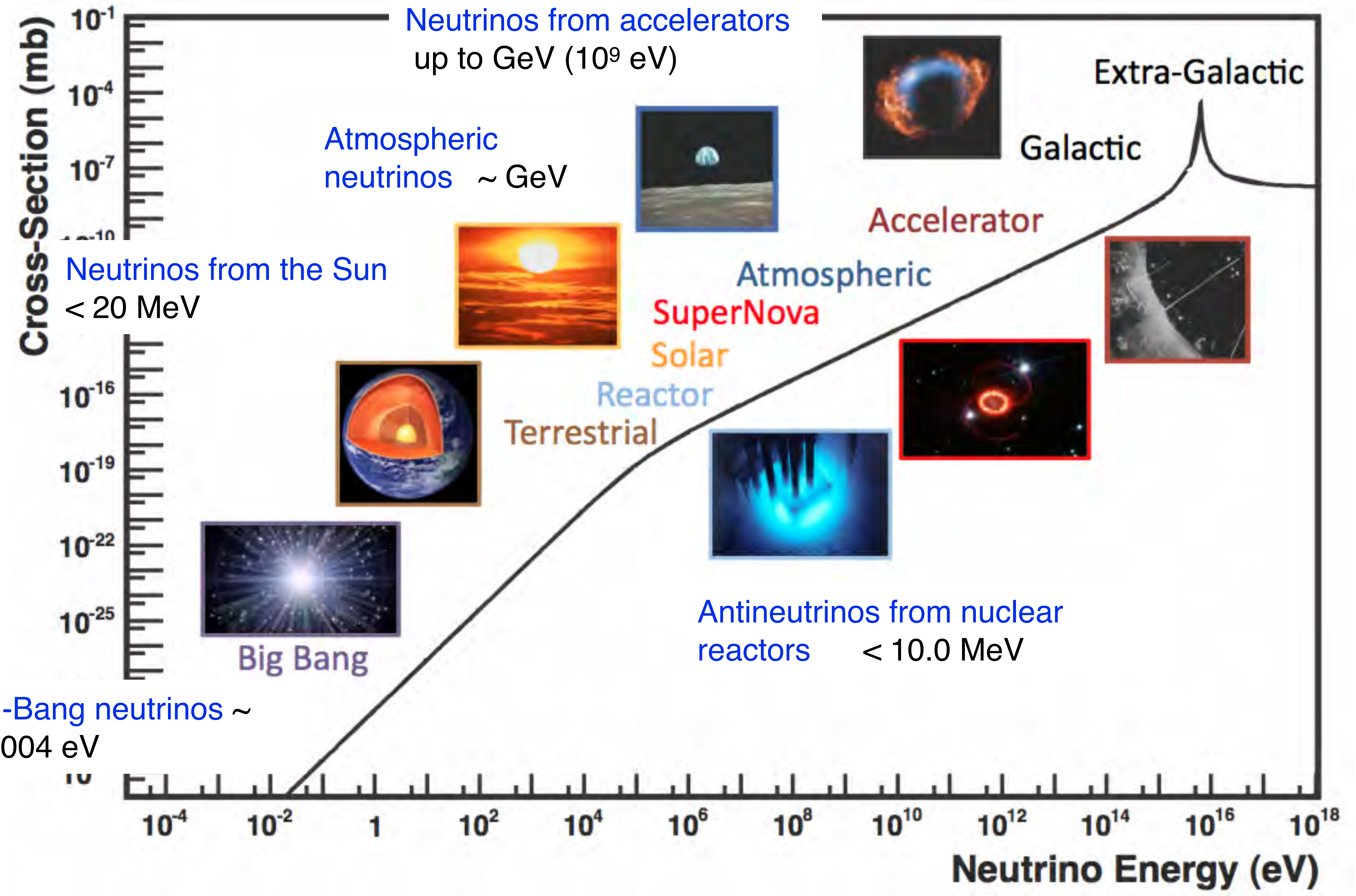
Karsten Heeger
Yale University

August 9, 2023

Yale

Wright
Laboratory

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

Early Days of Neutrinos

1930, Pauli

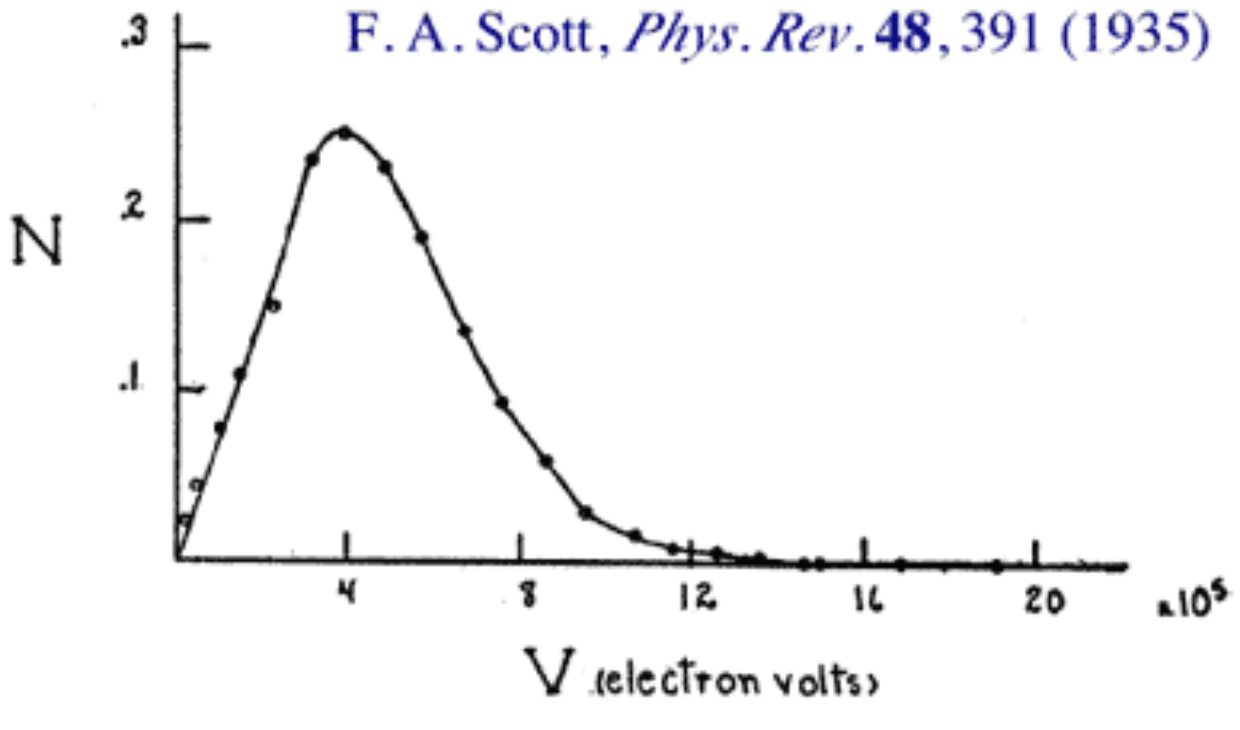
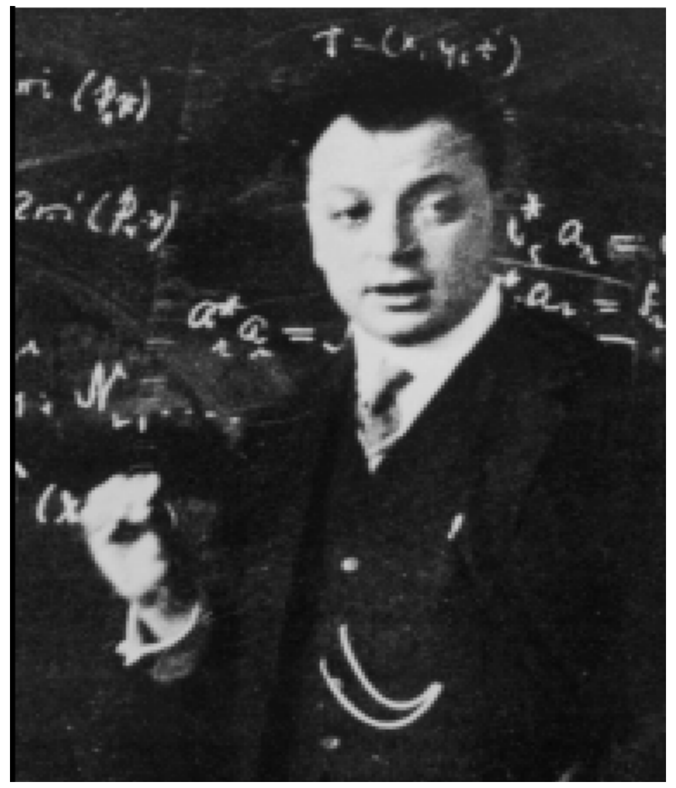
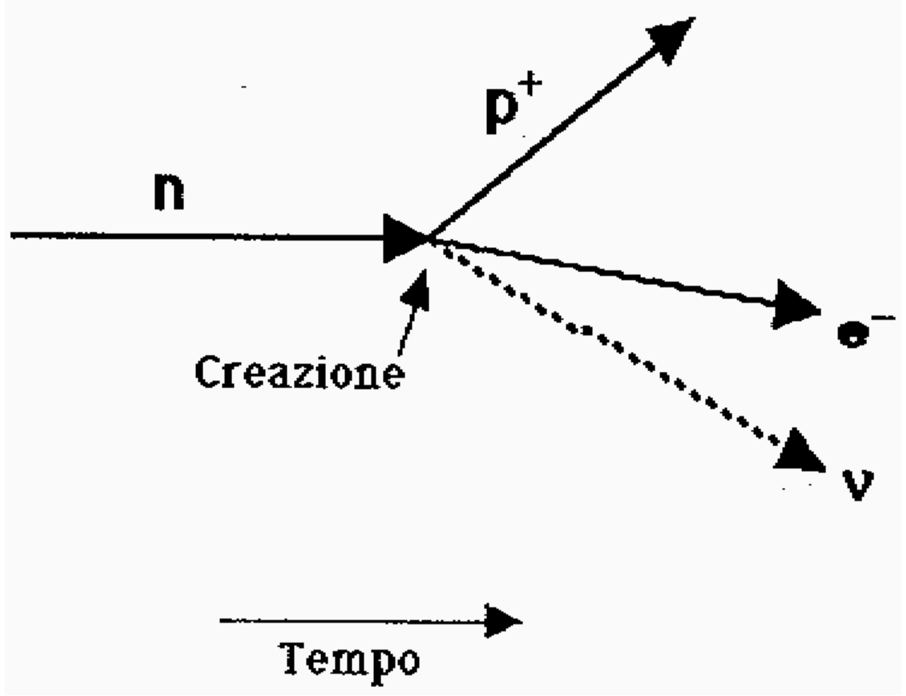
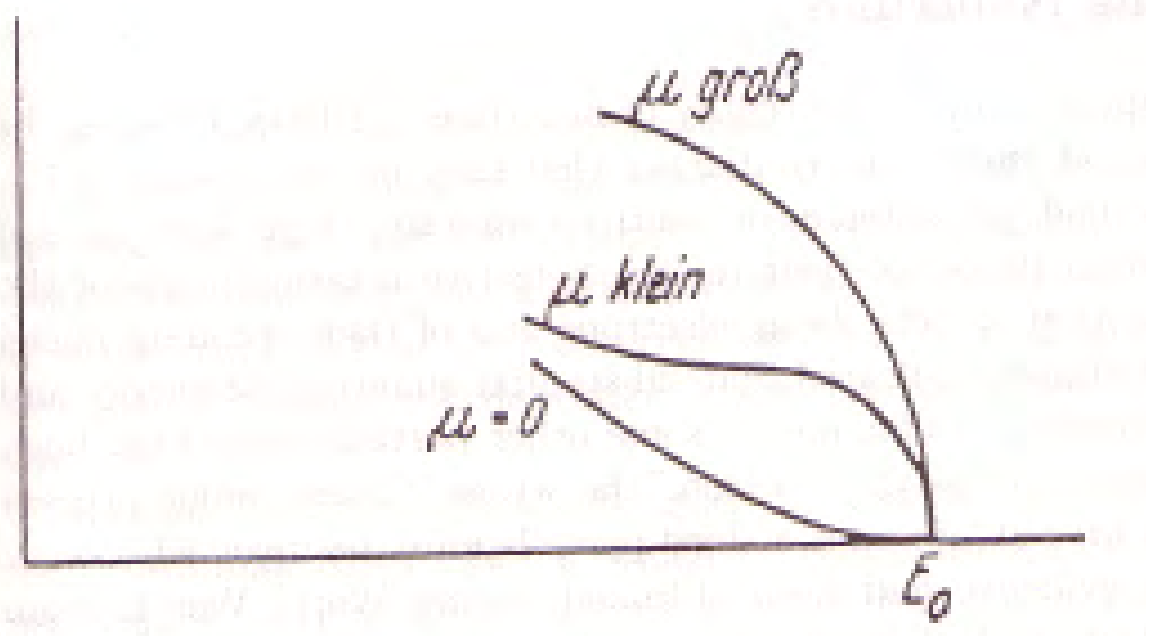


FIG. 5. Energy distribution curve of the beta-rays.

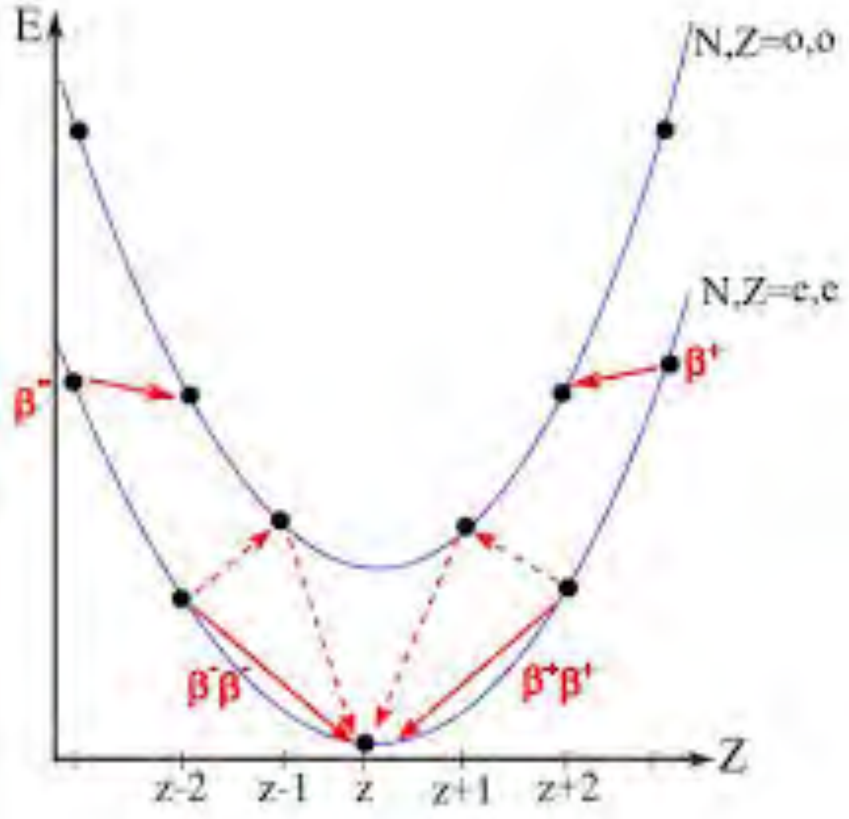


1932, Fermi



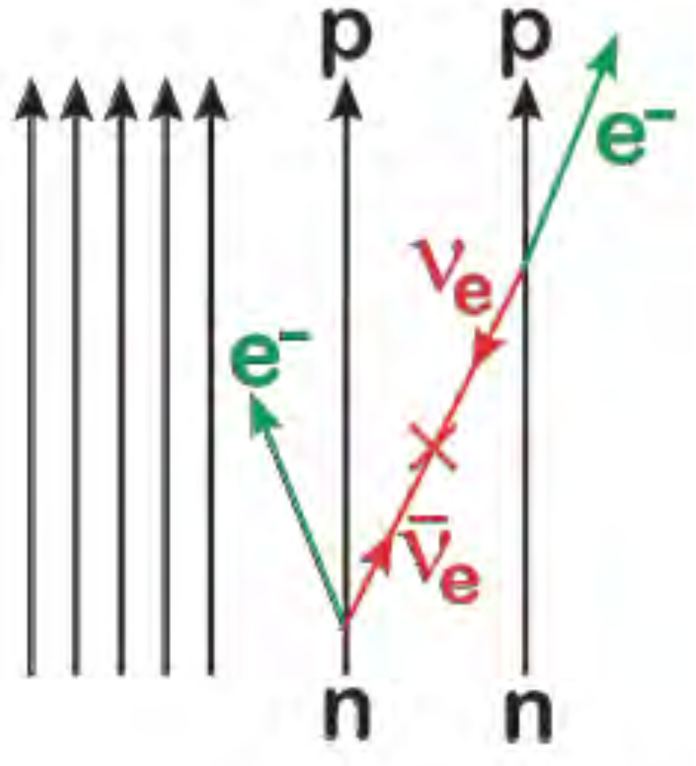


1935, Goeppert Mayer

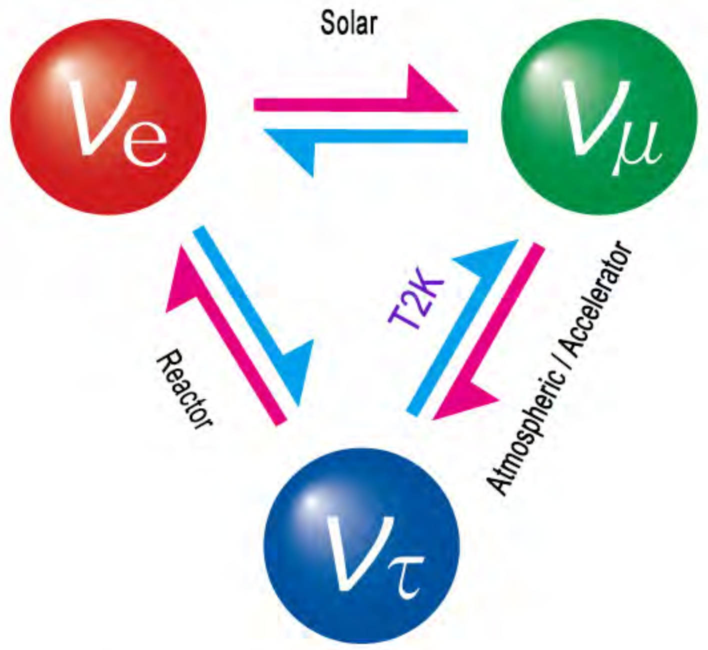


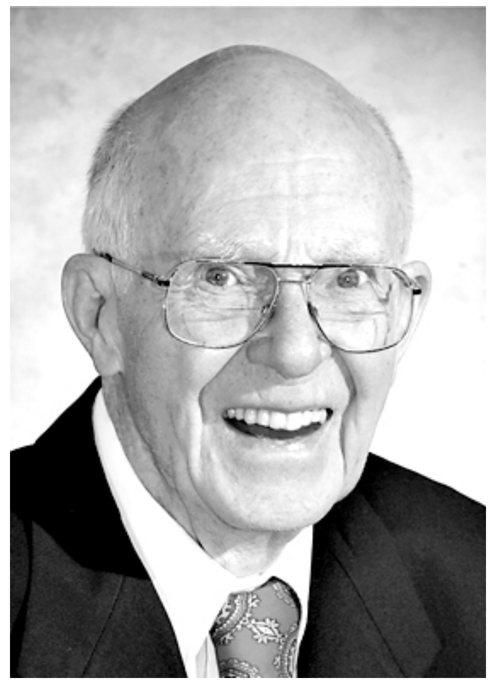
1937, Majorana

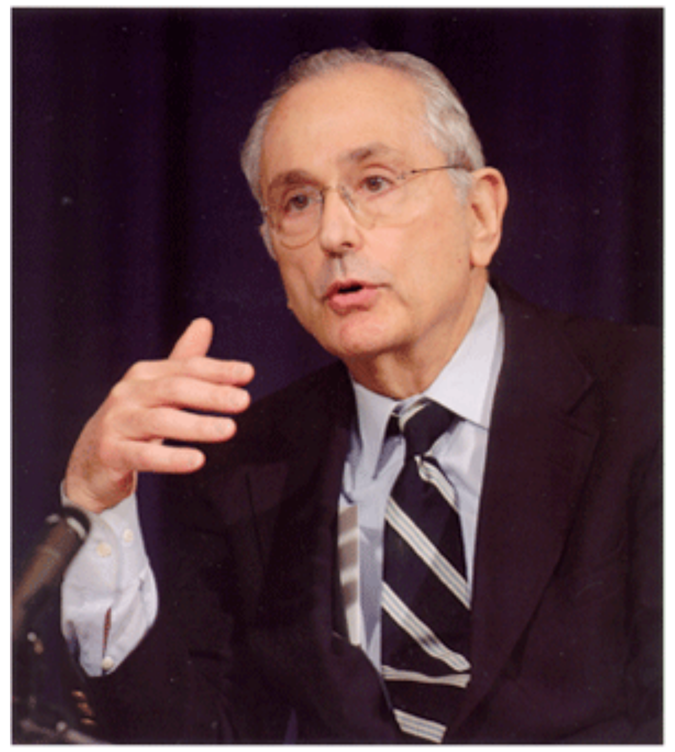
?



From Anomalies to Precision Oscillation Physics

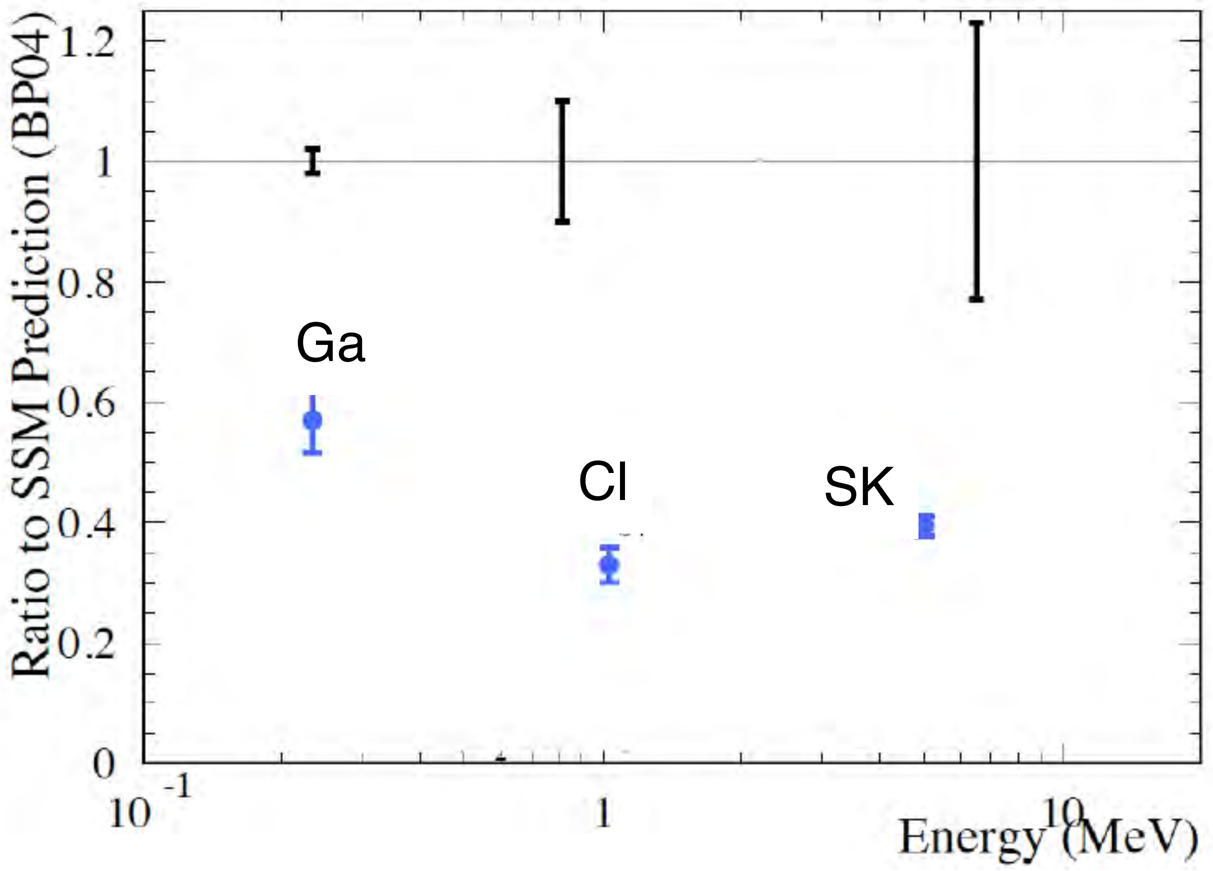






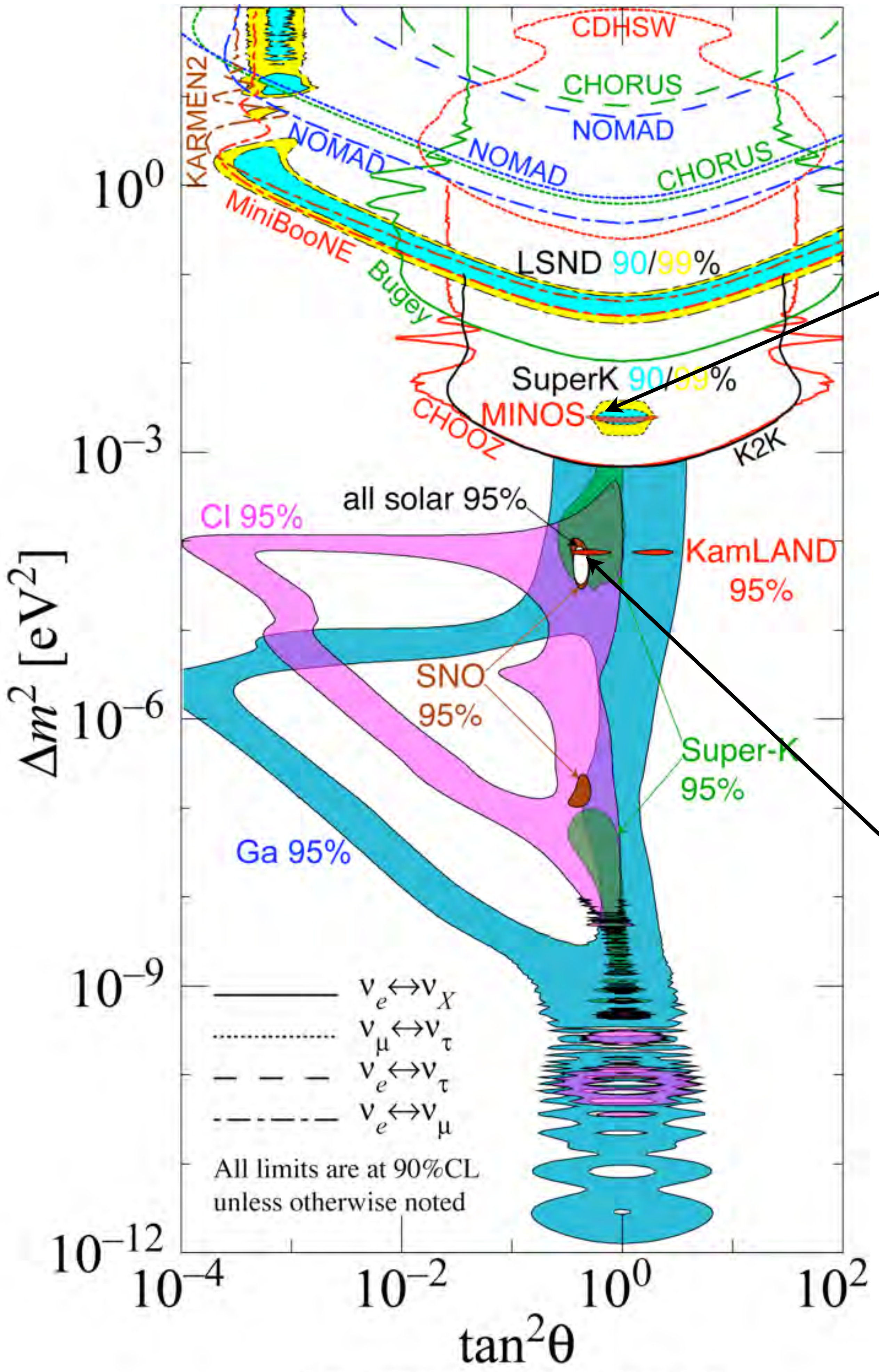
1960 -1990

solar neutrino problem



1990 - 2000

oscillation searches



http://hitoshi.berkeley.edu/neutrino

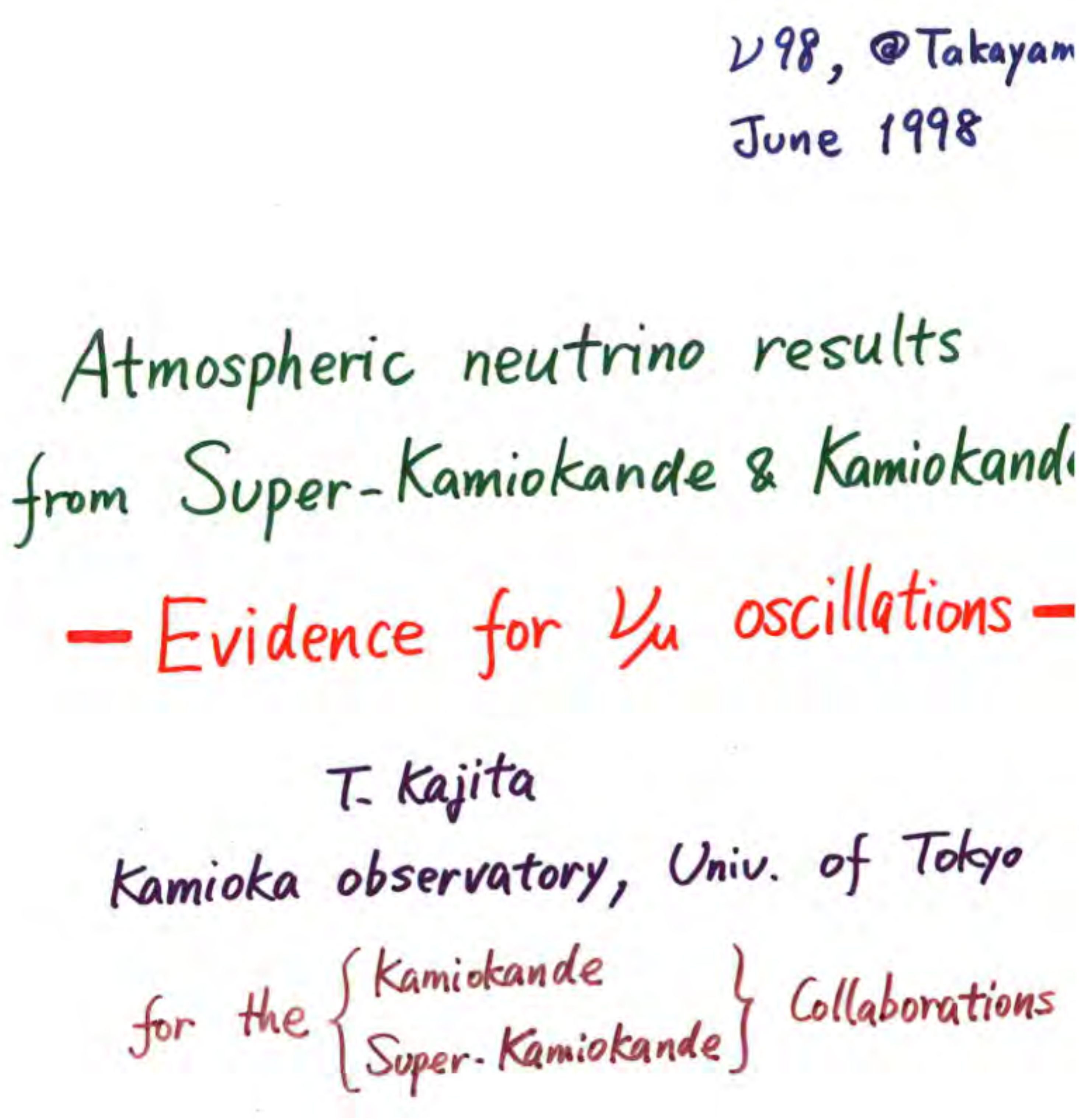
atmospheric/beam neutrinos

θ_{23}, Δm^2_{23}

solar/reactor neutrinos

θ_{12}, Δm^2_{12}

25 Years Ago - Discovery of Atmospheric Neutrino Oscillations



ν98, @Takayam

June 1998

Atmospheric neutrino results

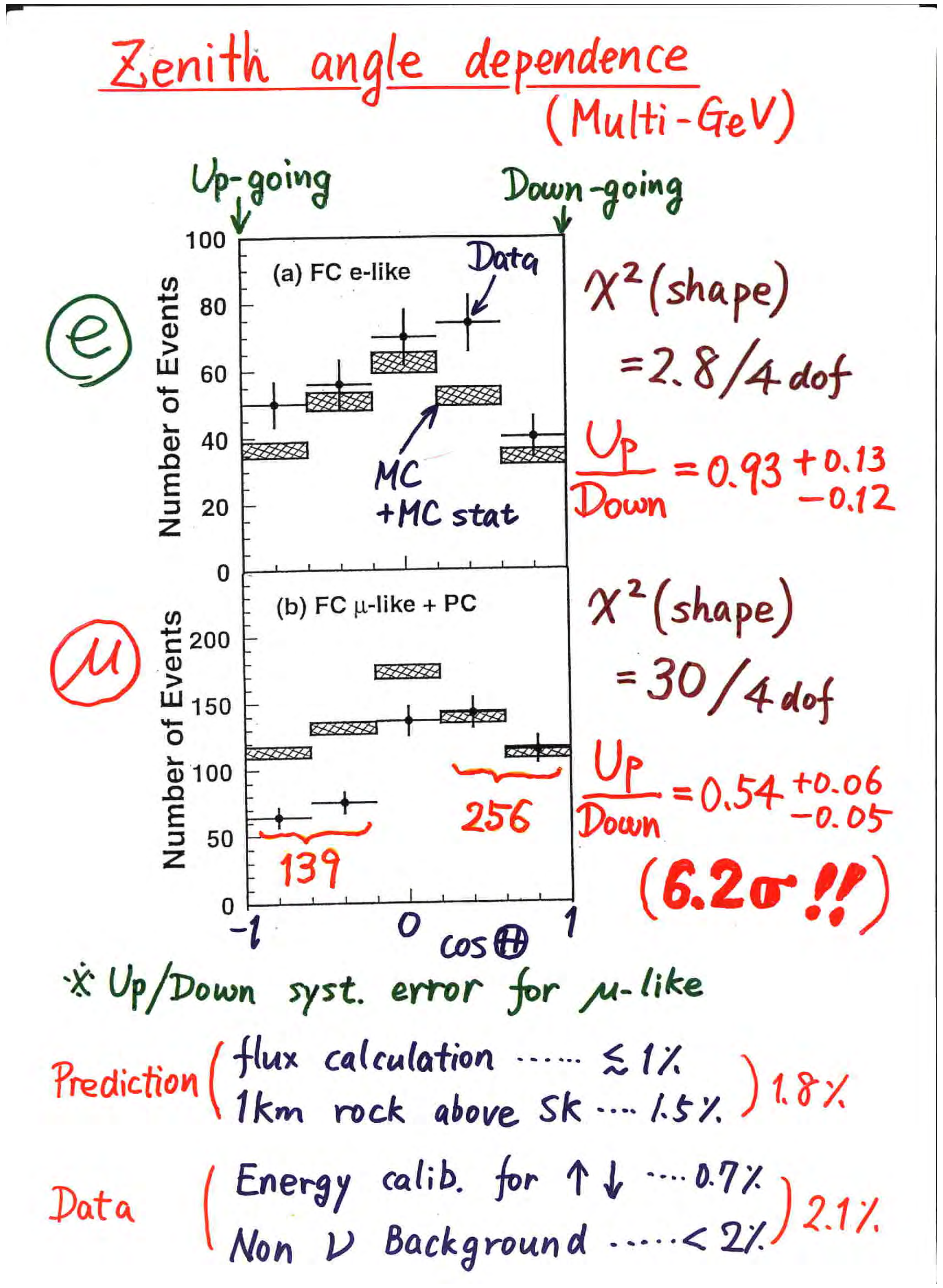
from Super-Kamiokande & Kamiokand

— Evidence for ν_μ oscillations —

T. Kajita

Kamioka observatory, Univ. of Tokyo

for the {Kamiokande / Super-Kamiokande} Collaborations



Zenith angle dependence

(Multi-GeV)

χ^2(shape) $= 2.8/4$ dof

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

χ^2(shape) $= 30/4$ dof

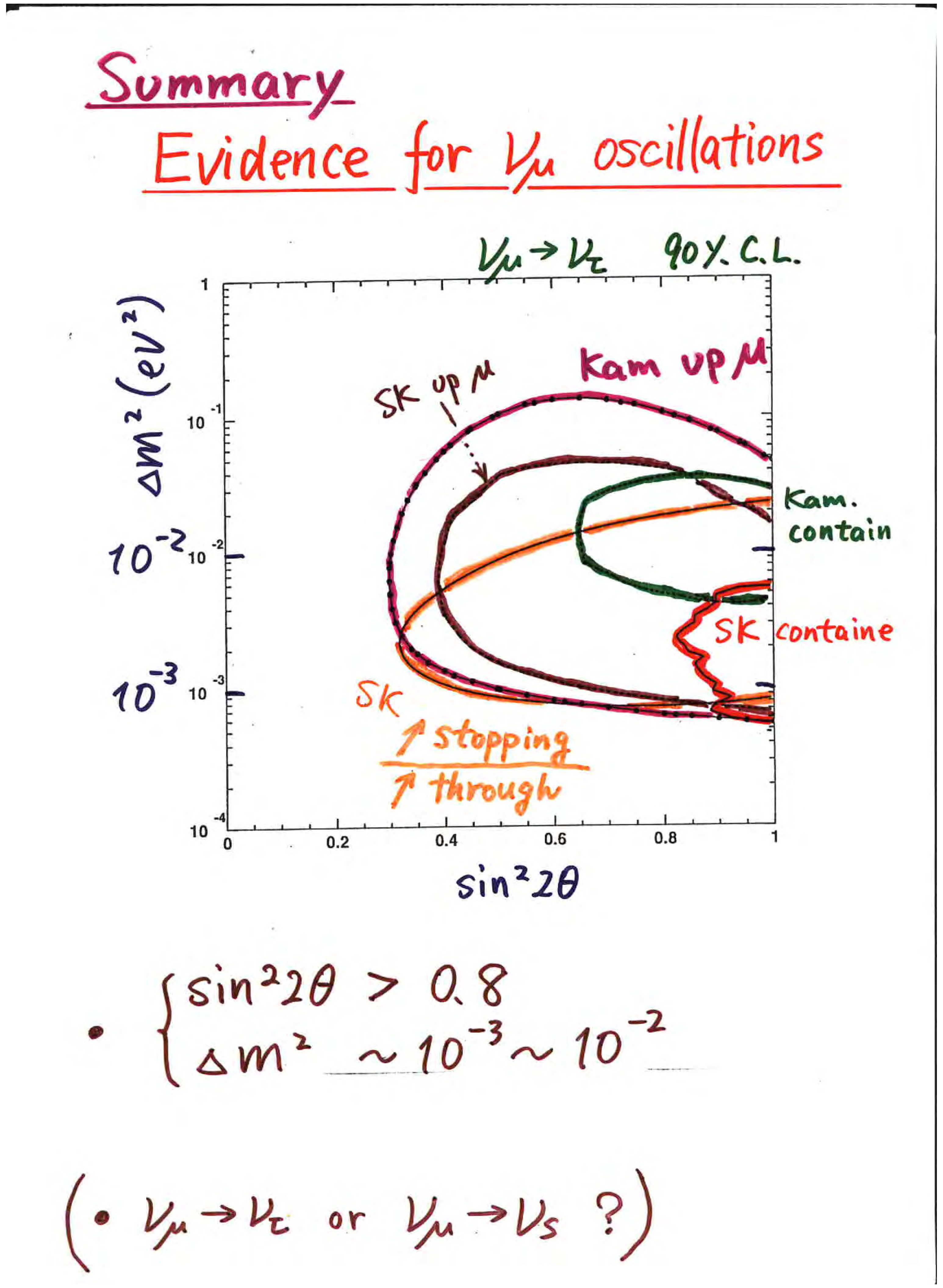
$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ!!)

※ Up/Down syst. error for μ-like

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

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



Summary

Evidence for ν_μ oscillations

- { $\sin^2 2\theta > 0.8$; $\Delta m^2 \sim 10^{-3} \sim 10^{-2}$ }

(• $\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_s$?)

Neutrino 98

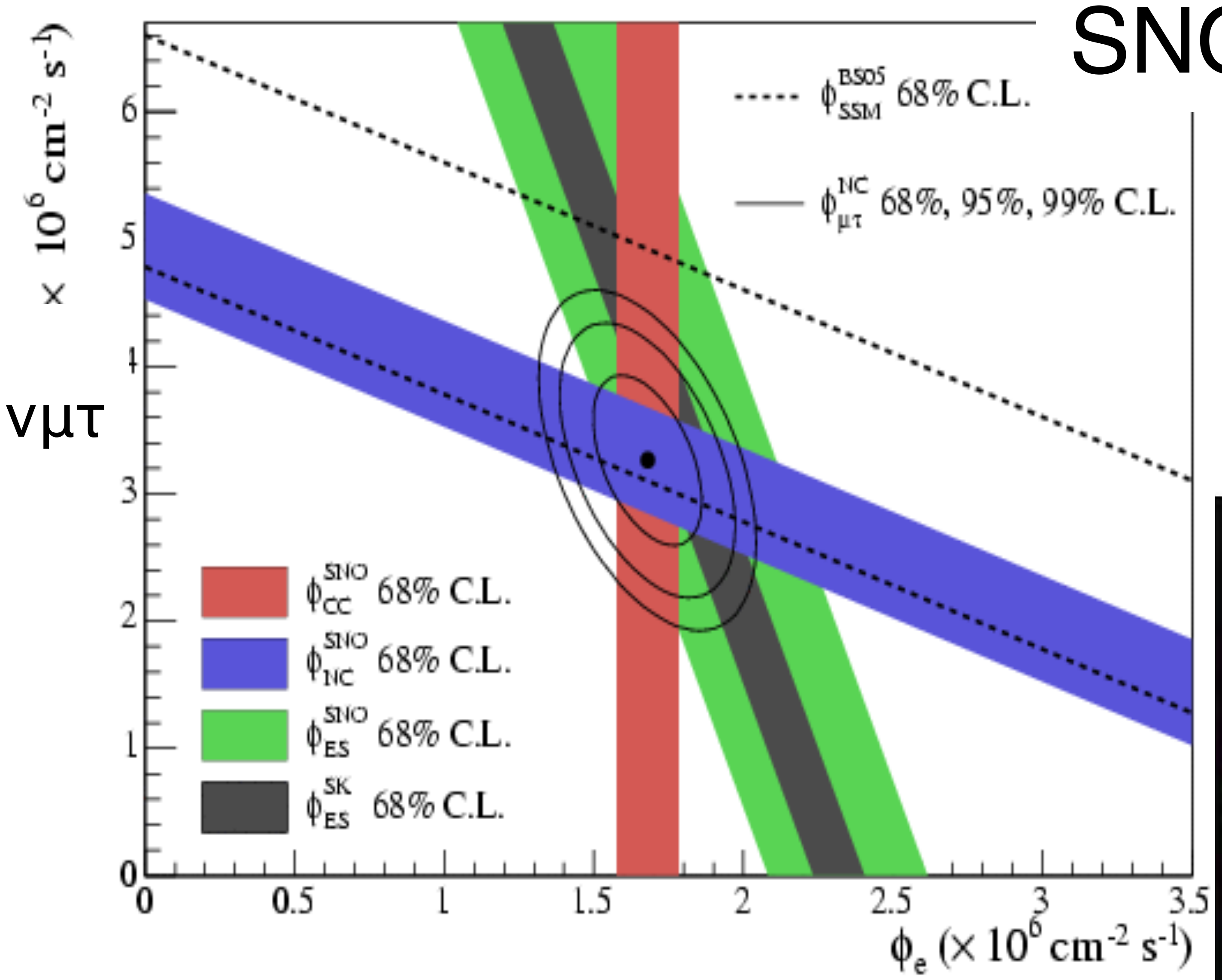
Discovery of Neutrino Flavor Change and Oscillation

Solar ν_e

Reactor $\overline{\nu}_e$

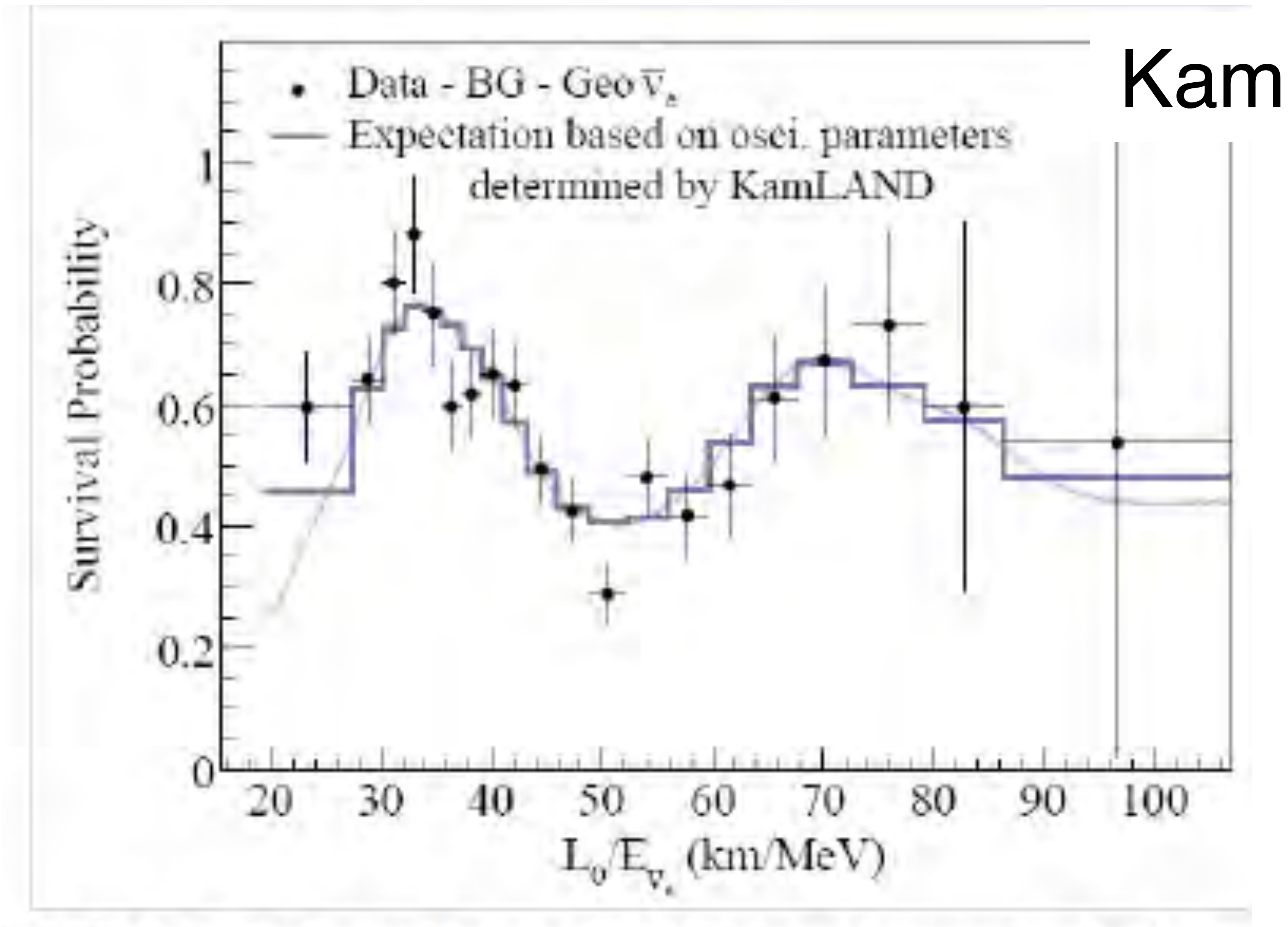
SNO

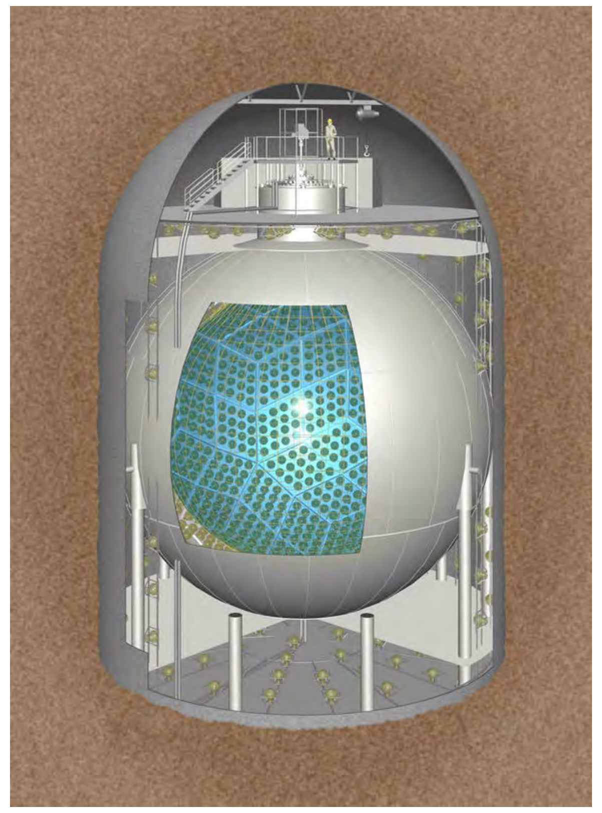
$\Phi_{\nu\mu\tau}$



$\Phi_{\nu e}$

KamLAND





L/E

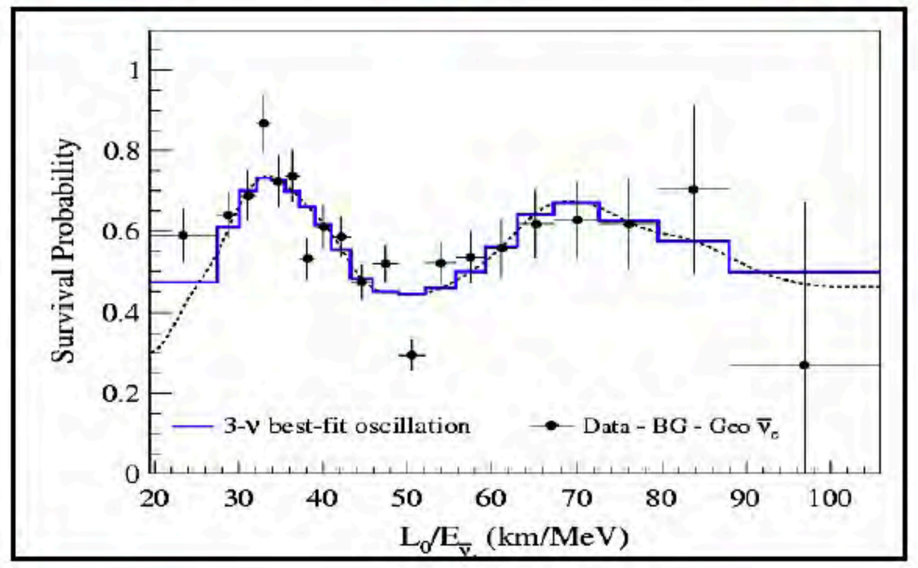
Neutrino oscillations imply that neutrinos have mass and mix.

Neutrino Mixing

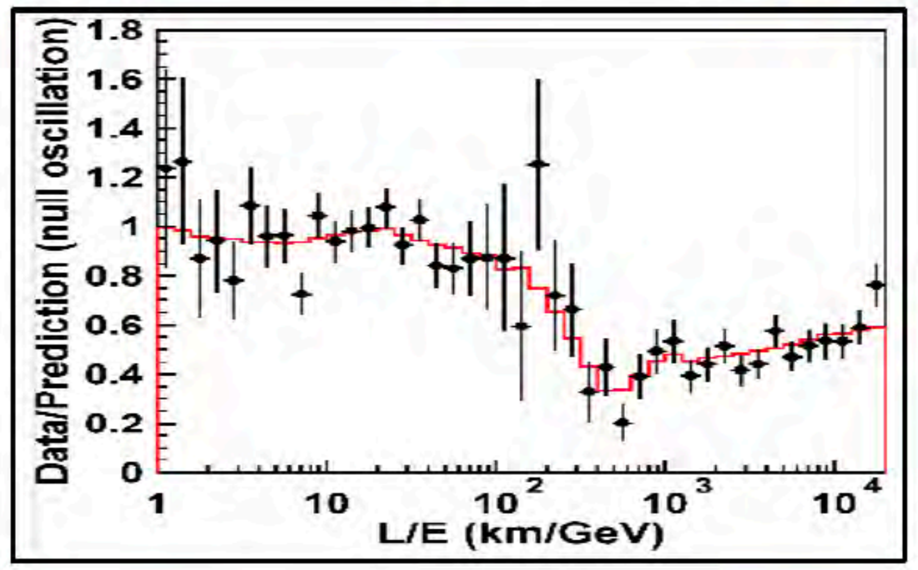
evidence for neutrino oscillations in many sources

reactor
solar
long baseline
atmospheric

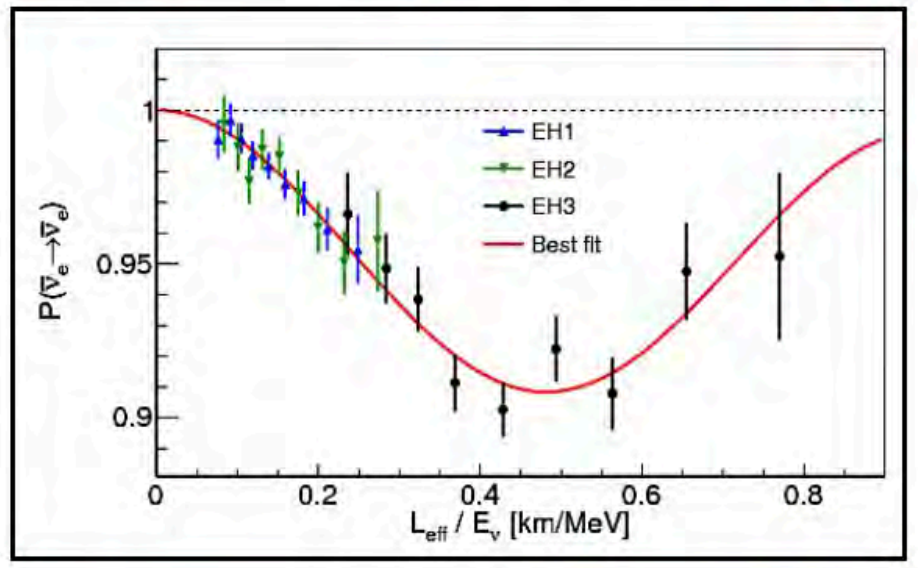
$e \rightarrow e \quad (\delta m^2, \theta_{12})$



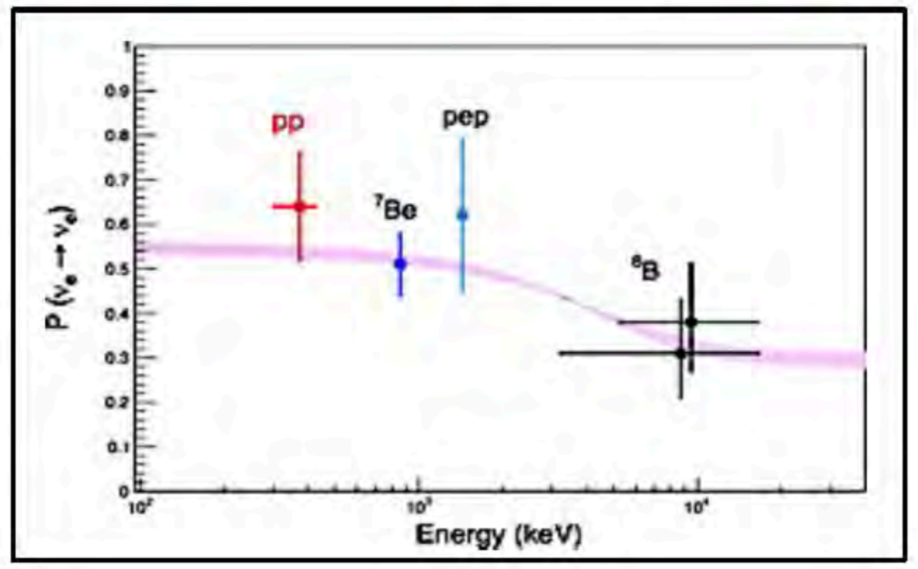
$\mu \rightarrow \mu \quad (\Delta m^2, \theta_{23})$



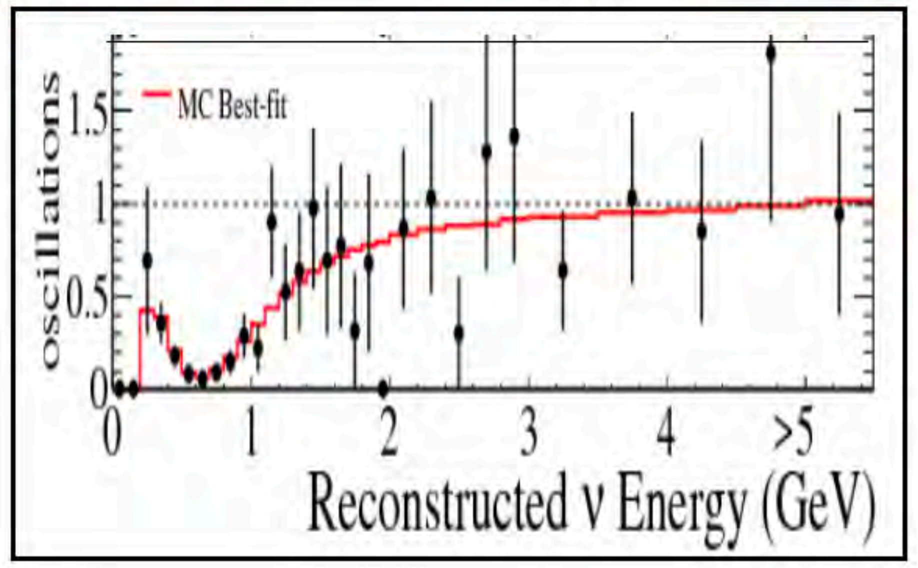
$e \rightarrow e \quad (\Delta m^2, \theta_{13})$



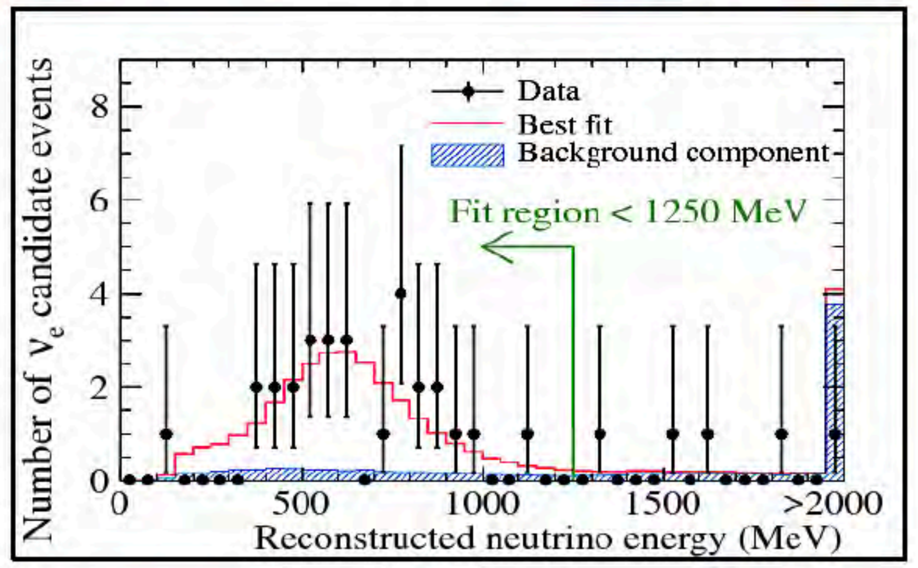
$e \rightarrow e \quad (\delta m^2, \theta_{12})$



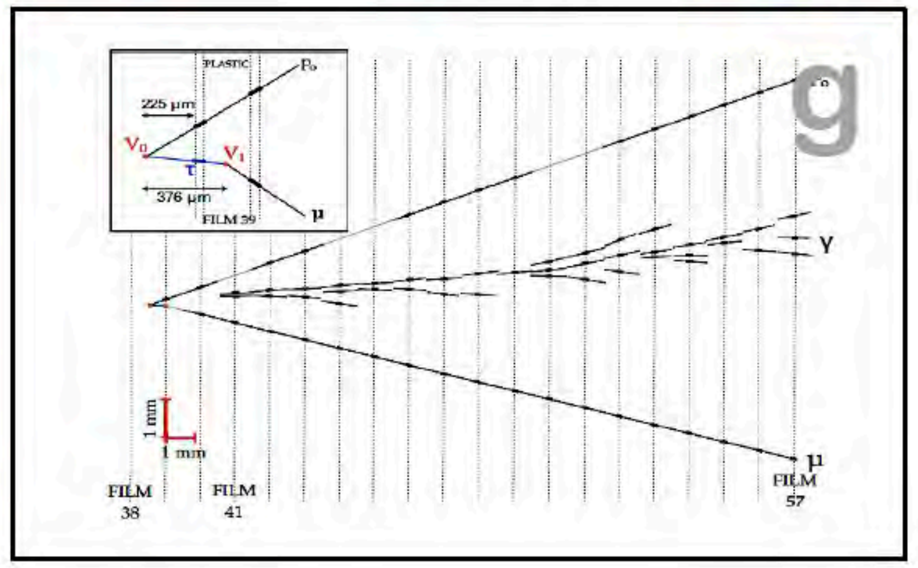
$\mu \rightarrow \mu \quad (\Delta m^2, \theta_{23})$



$\mu \rightarrow e \quad (\Delta m^2, \theta_{13}, \theta_{23})$



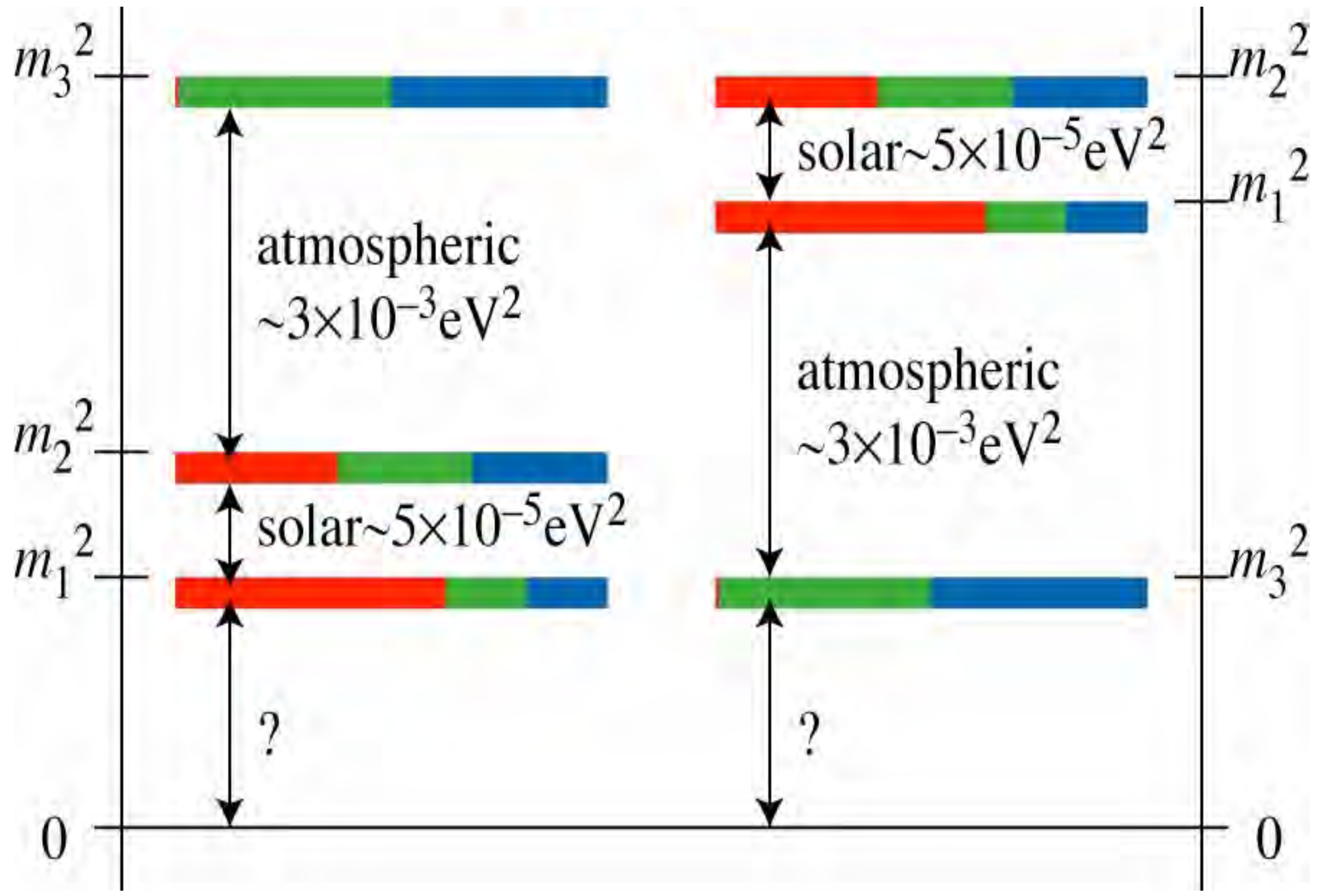
$\mu \rightarrow \tau \quad (\Delta m^2, \theta_{23})$

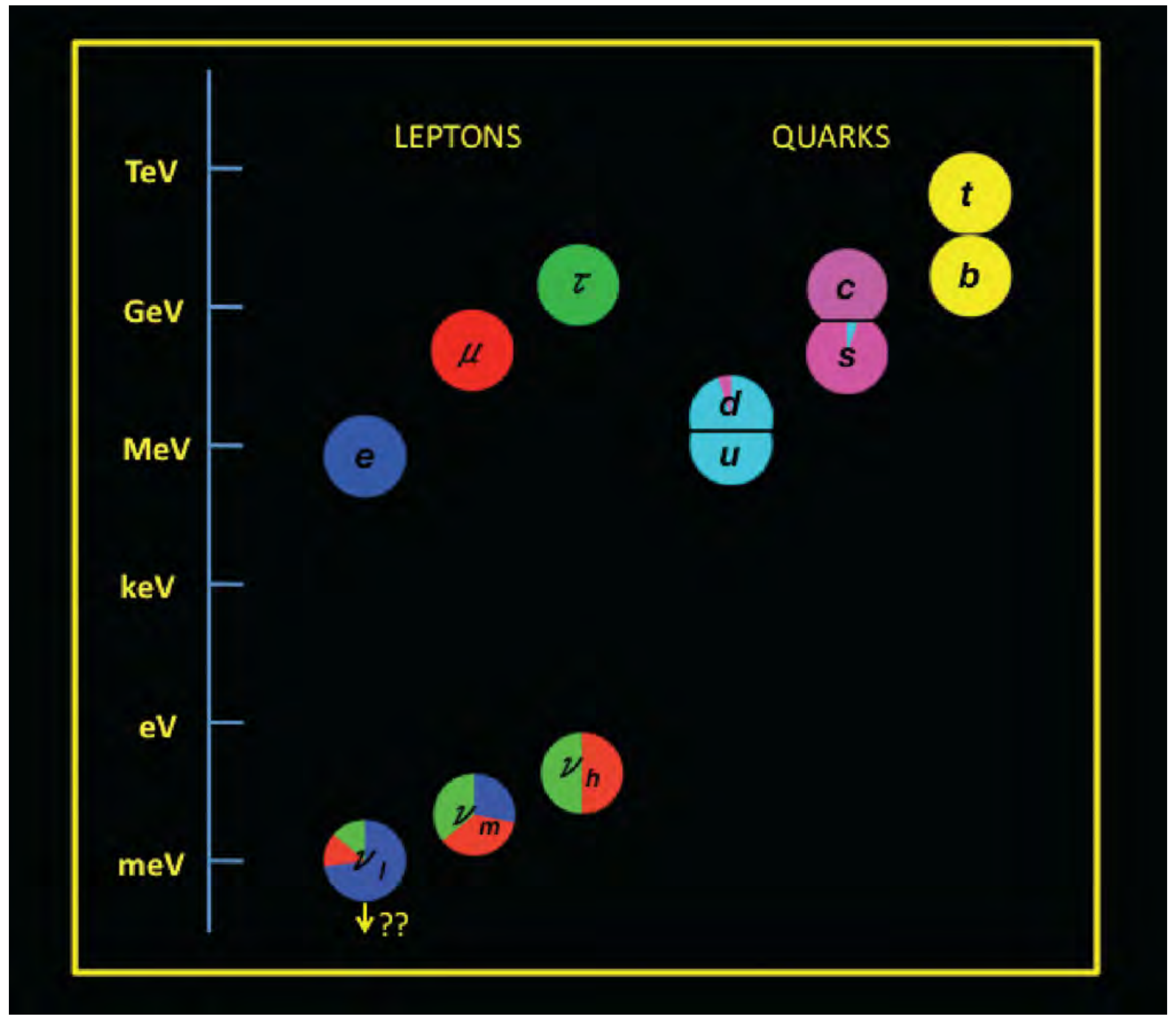


3 flavor picture fits data well

E. Lisi

Open Questions

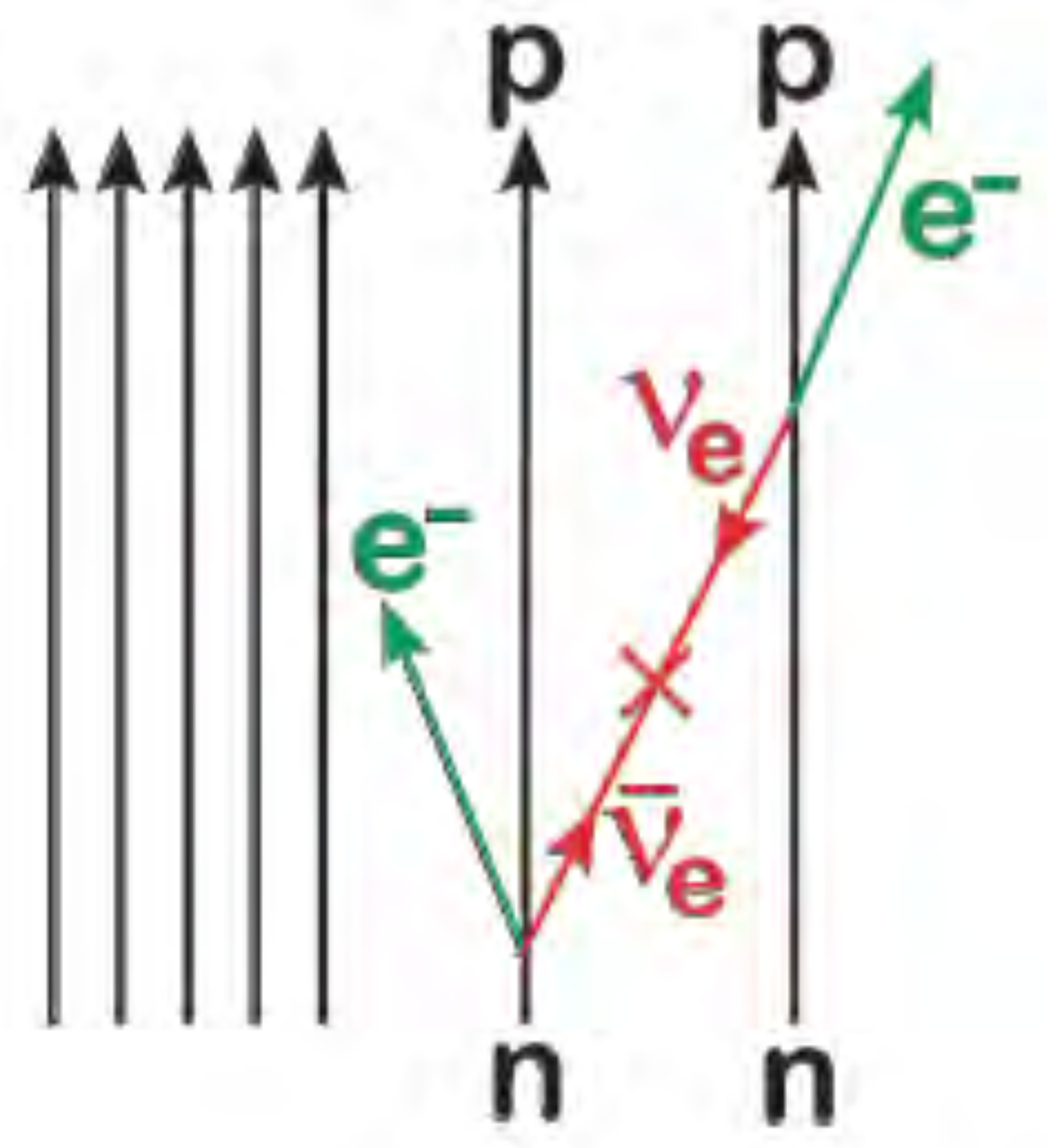




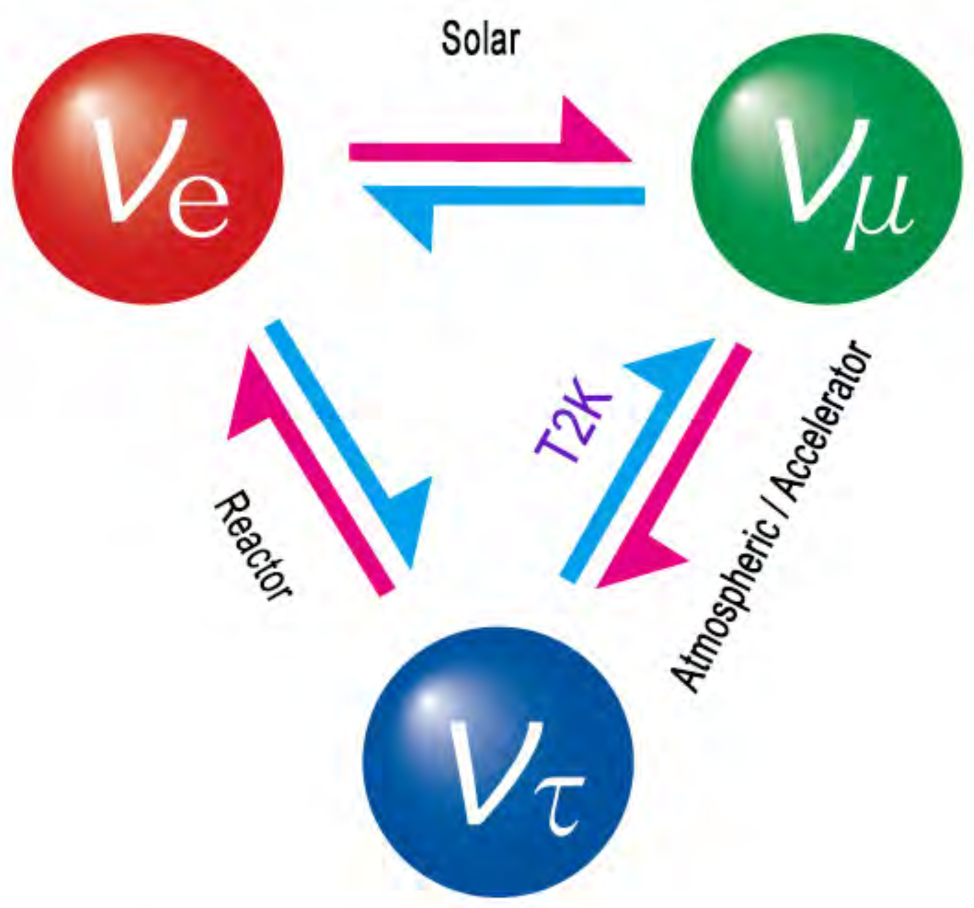
Where do neutrino masses come from?

What is the origin of leptonic mixing?

Are neutrinos their own antiparticles?

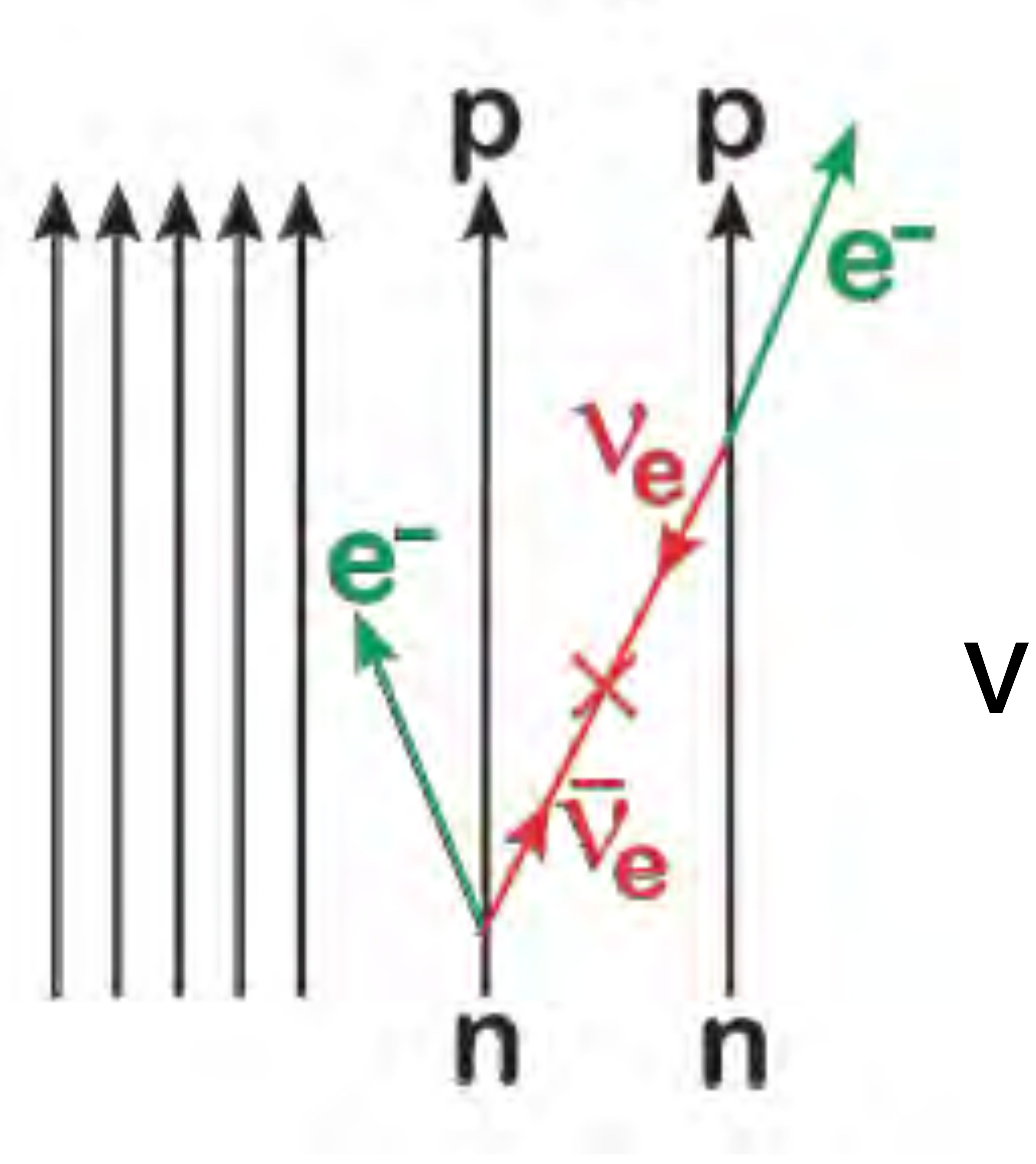


$V=\overline{V}$?



Major discoveries ahead

What is the nature of neutrino mass?



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

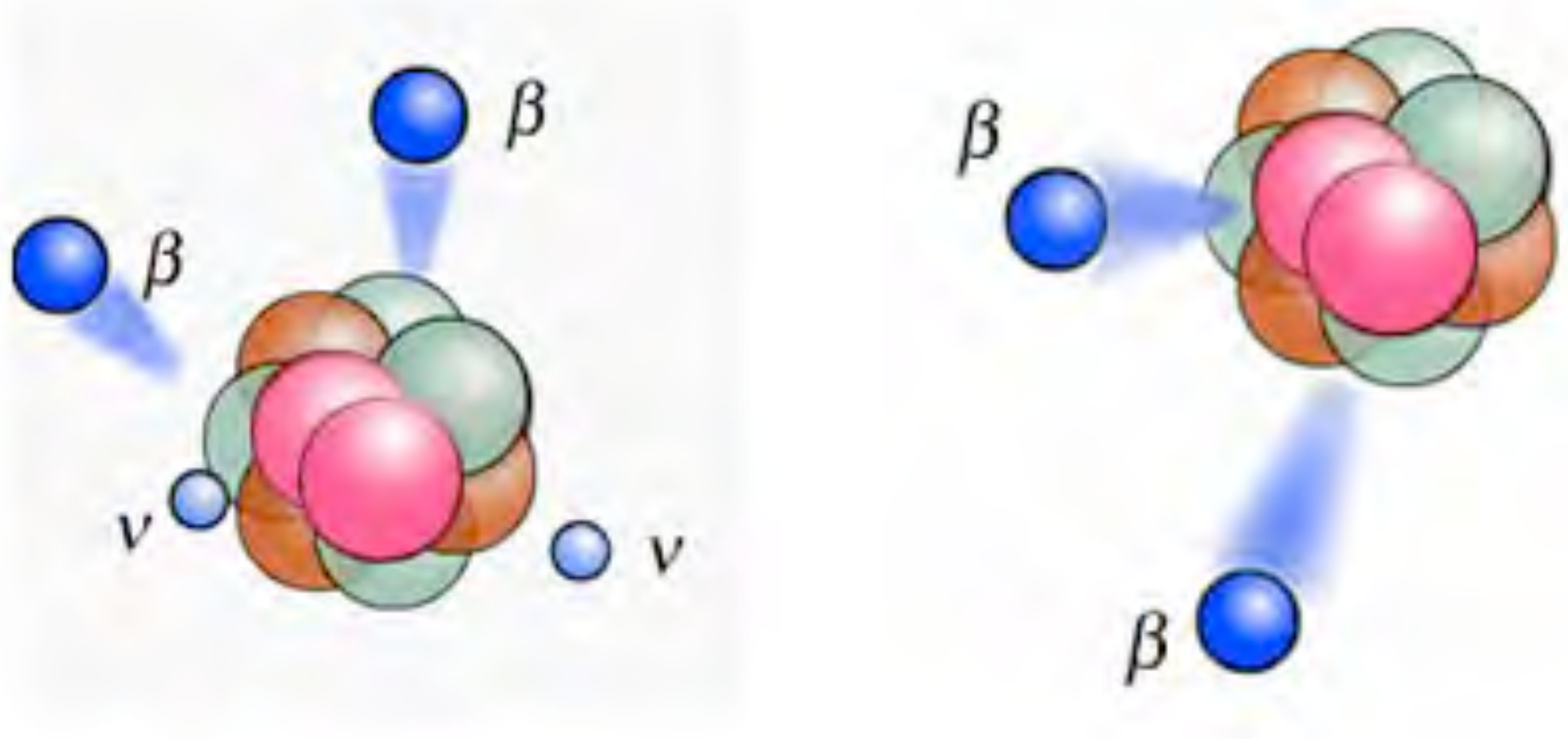
Understanding Neutrino Mass from Beta Decay

Single Beta Decay

Understanding Neutrino Mass from Beta Decay

Single Beta Decay

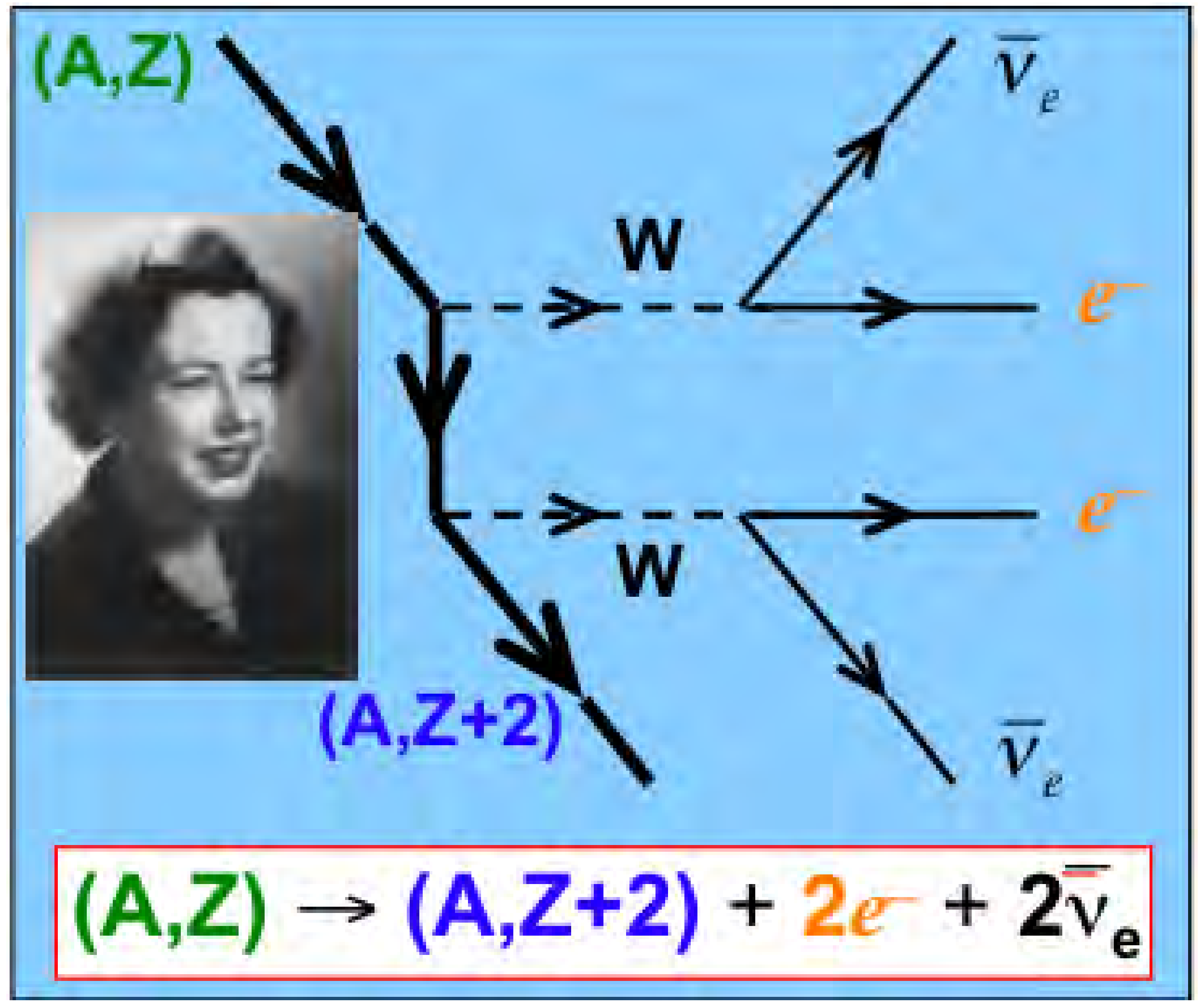
Double Beta Decay



Understanding Neutrino Mass from Double Beta Decay

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

$2\nu\beta\beta$



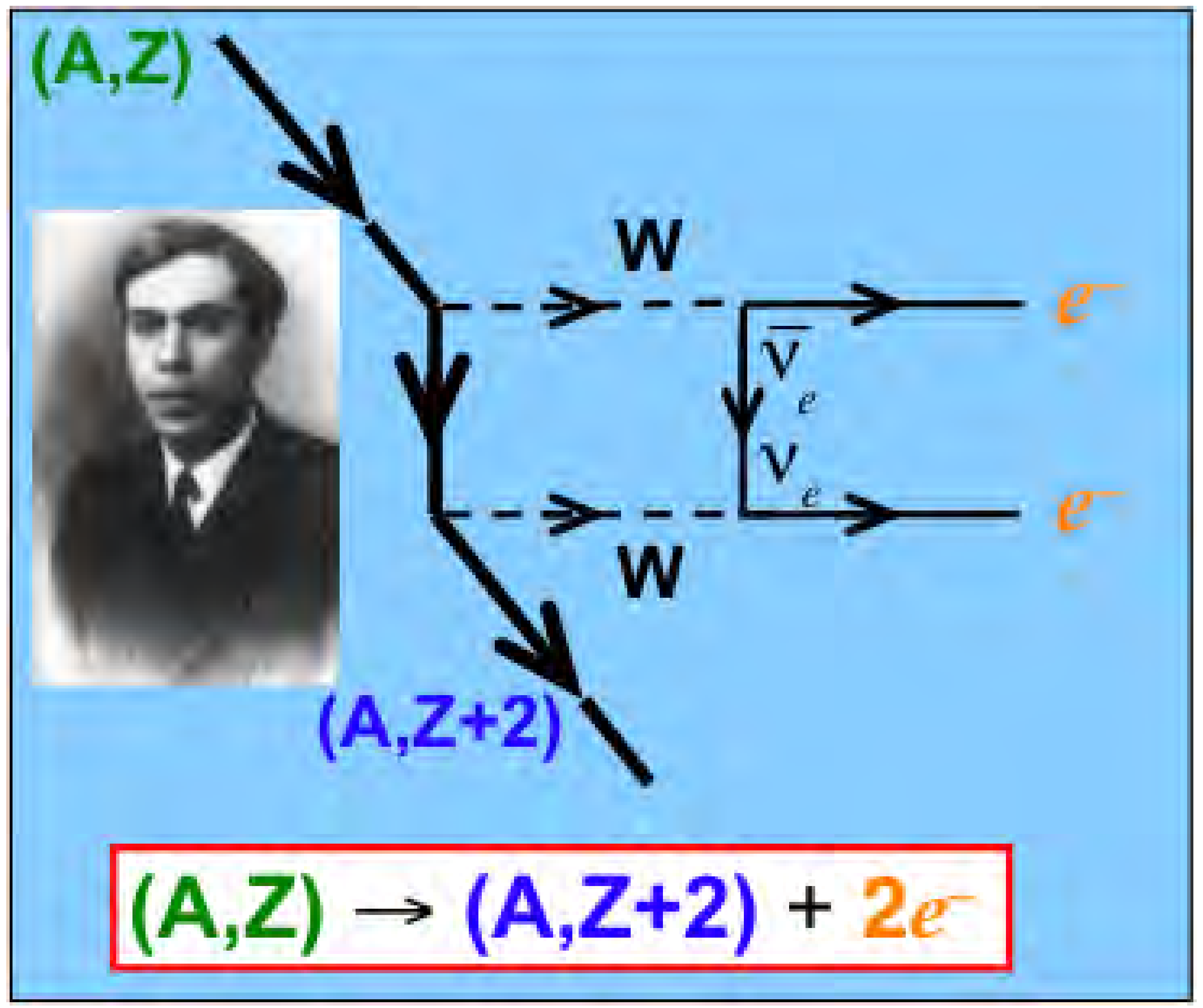
Proposed in 1935 by Maria Goeppert-Mayer

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

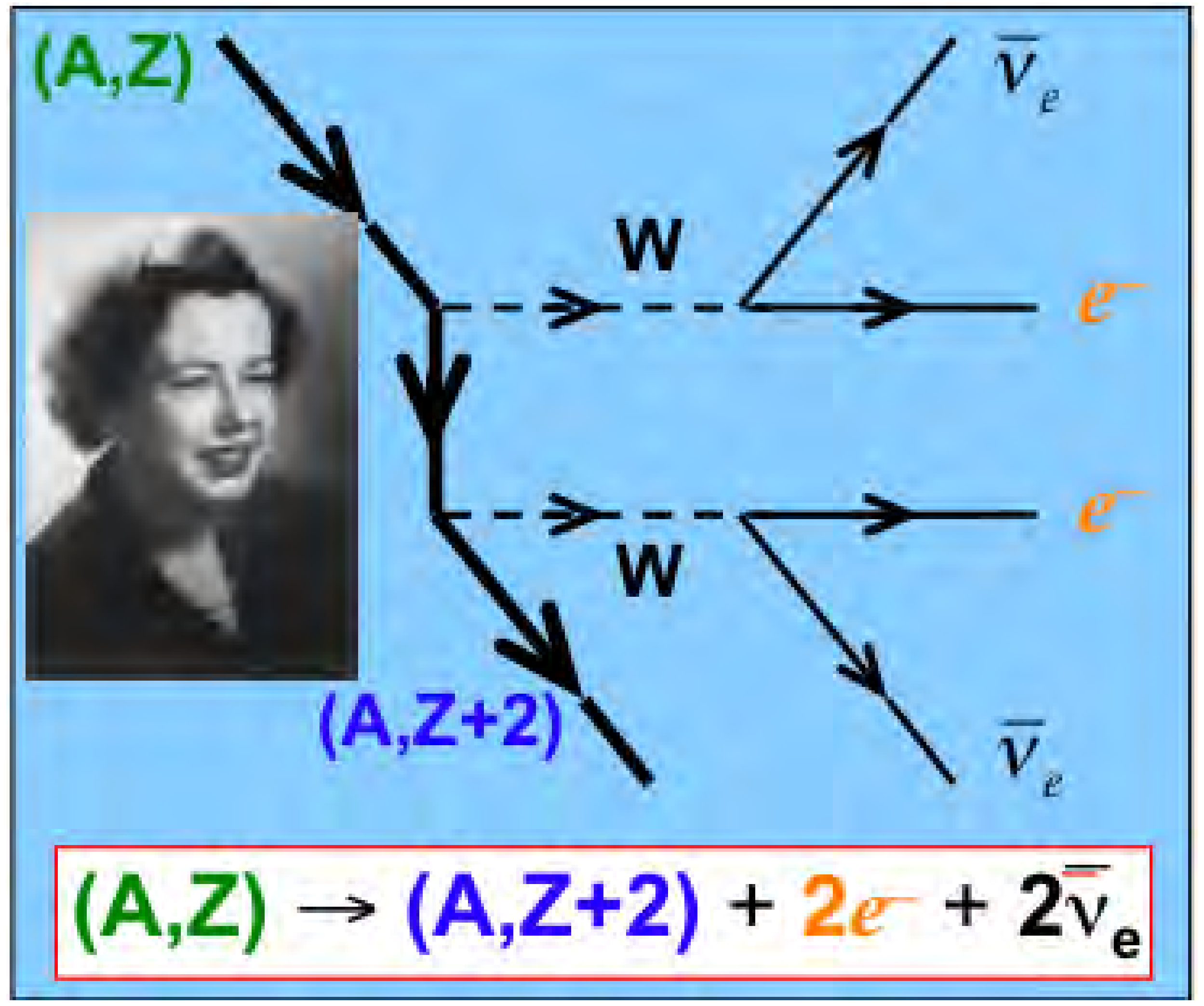
$T_{1/2} \geq 10^{25}$ y

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

Understanding Neutrino Mass from Double Beta Decay

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

$2\nu\beta\beta$



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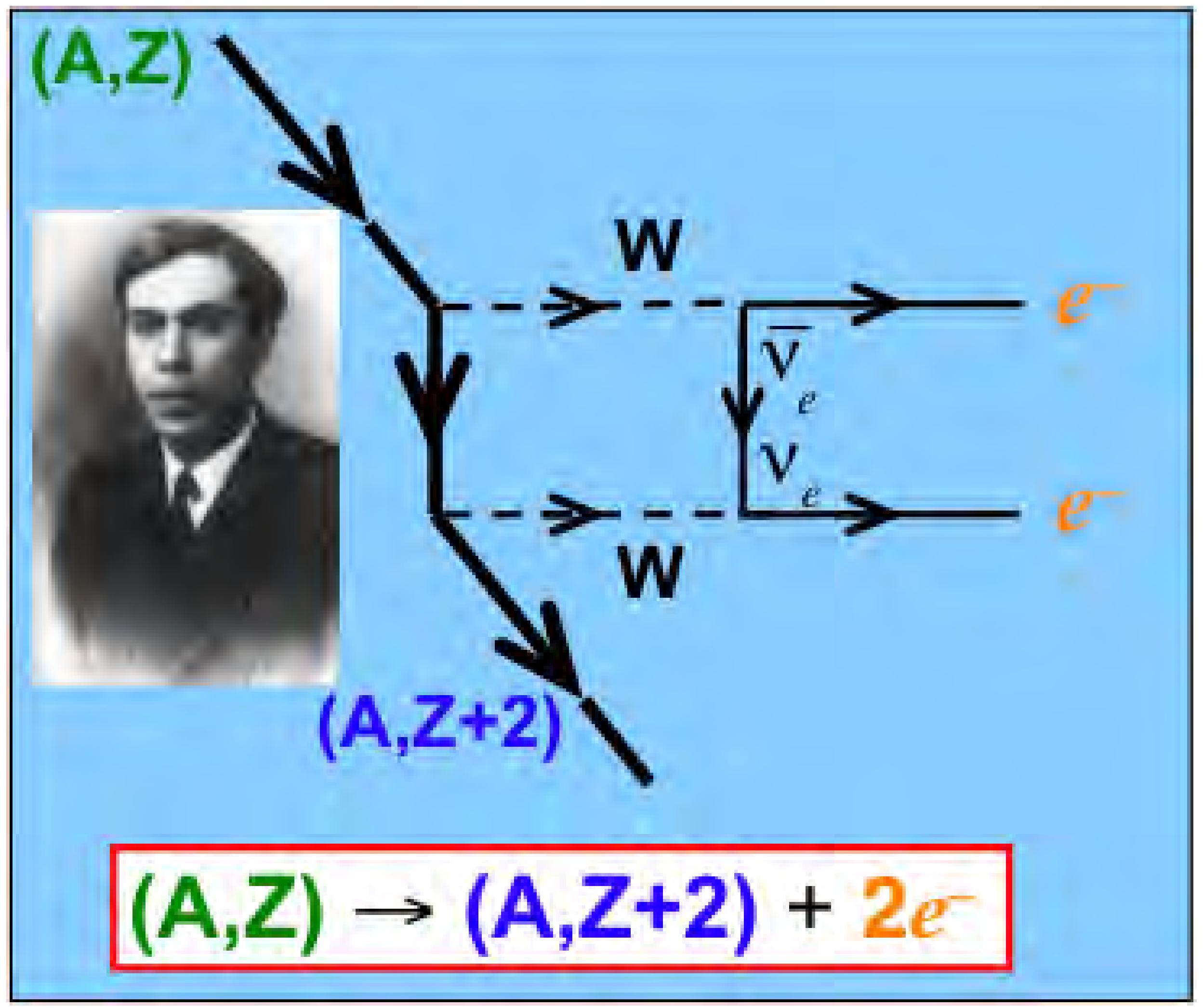


Proposed in 1937 by Ettore Majorana

Not observed yet

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

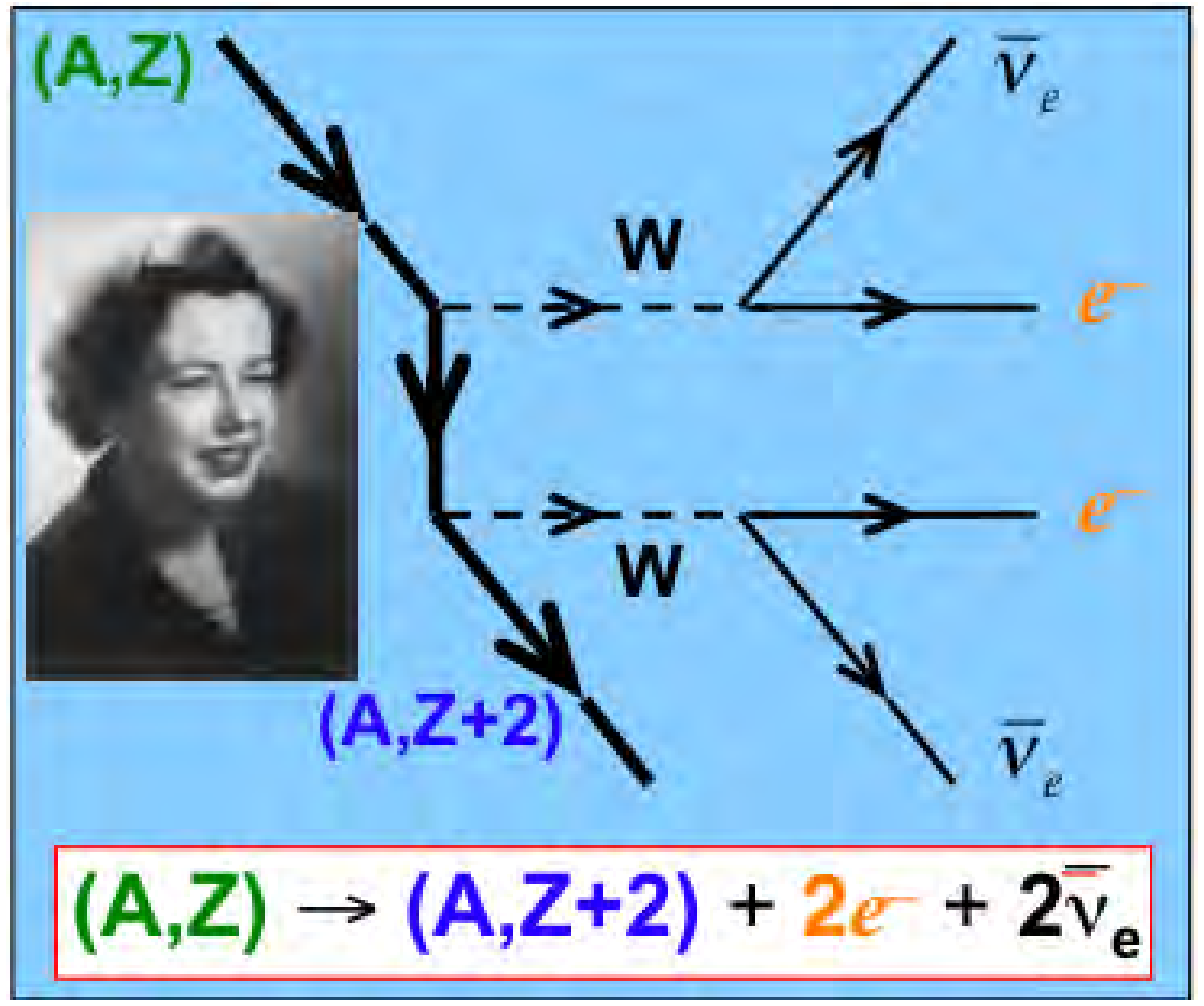
$$\Gamma_{0\nu} = G_{0\nu} \, | M_{0\nu} |^2 \left\langle m_{\beta\beta} \right\rangle^2$$

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

Understanding Neutrino Mass from Double Beta Decay

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

2νββ



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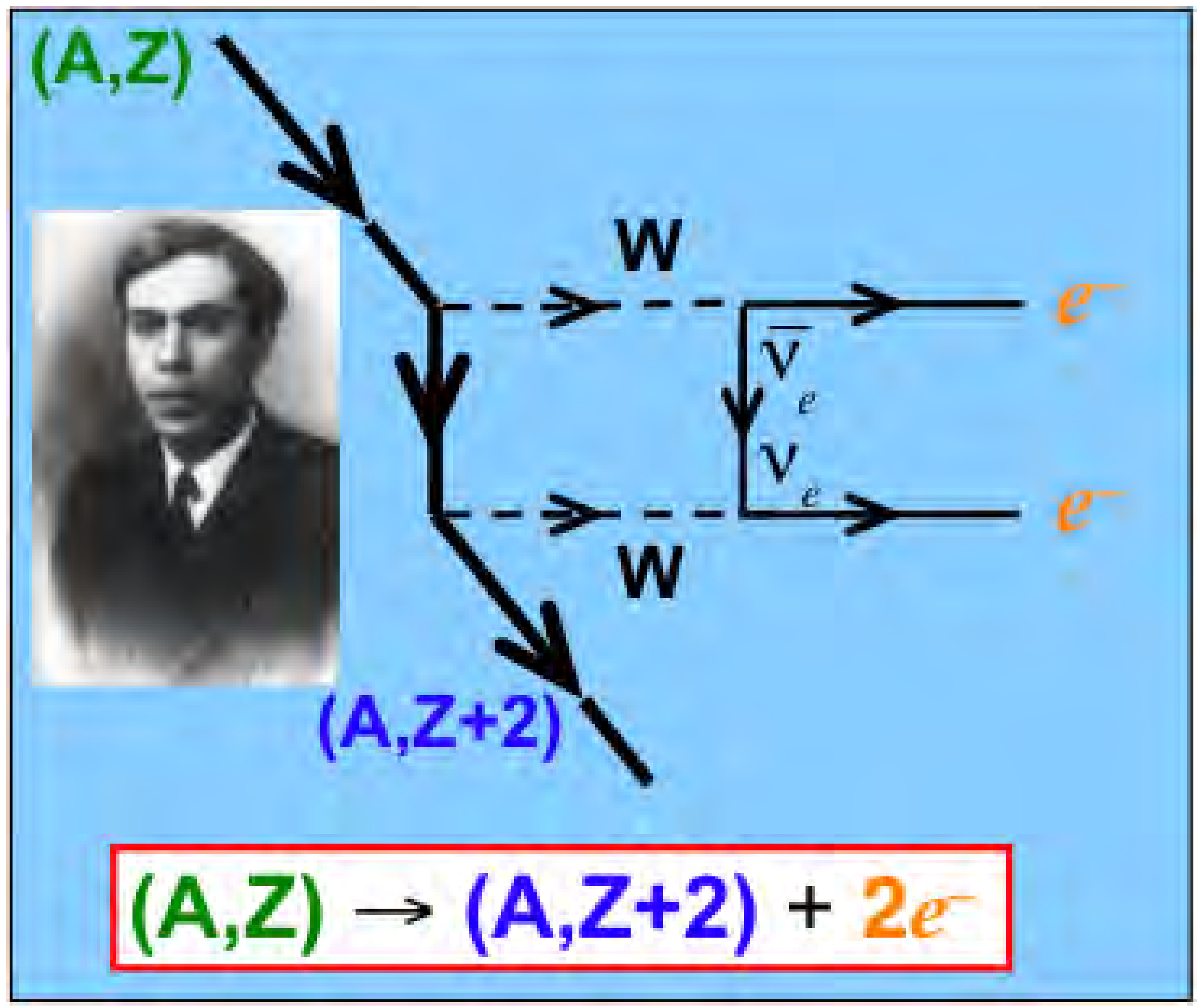
0νββ



Proposed in 1937 by Ettore Majorana

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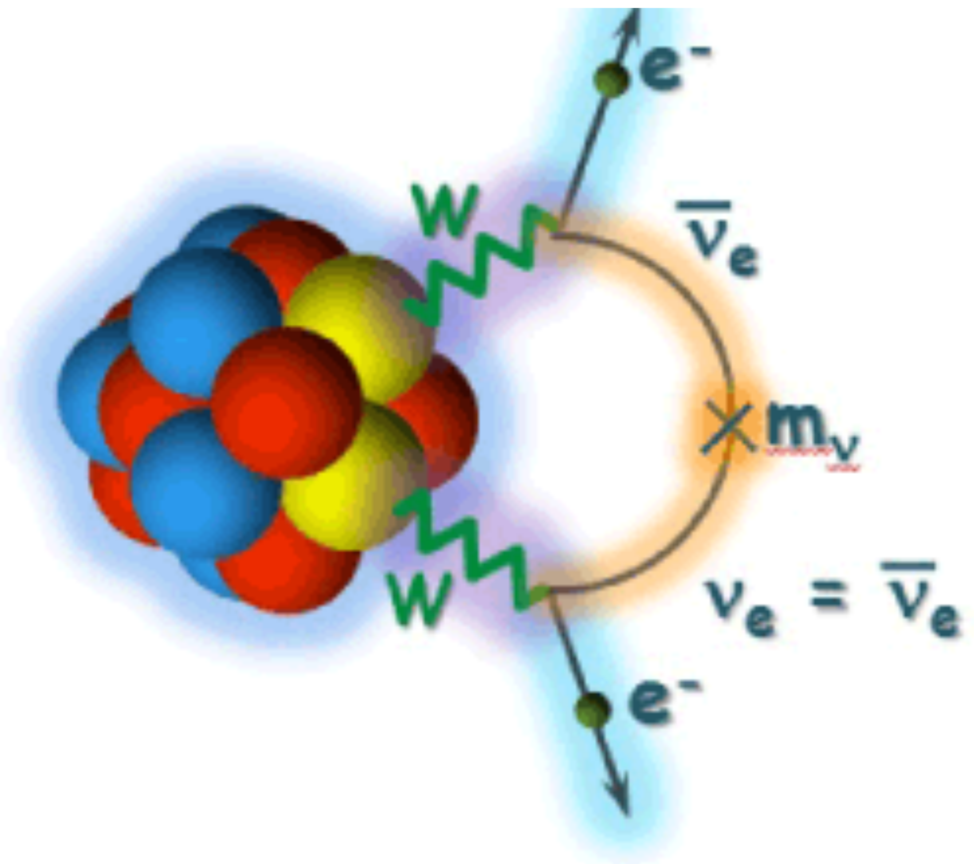
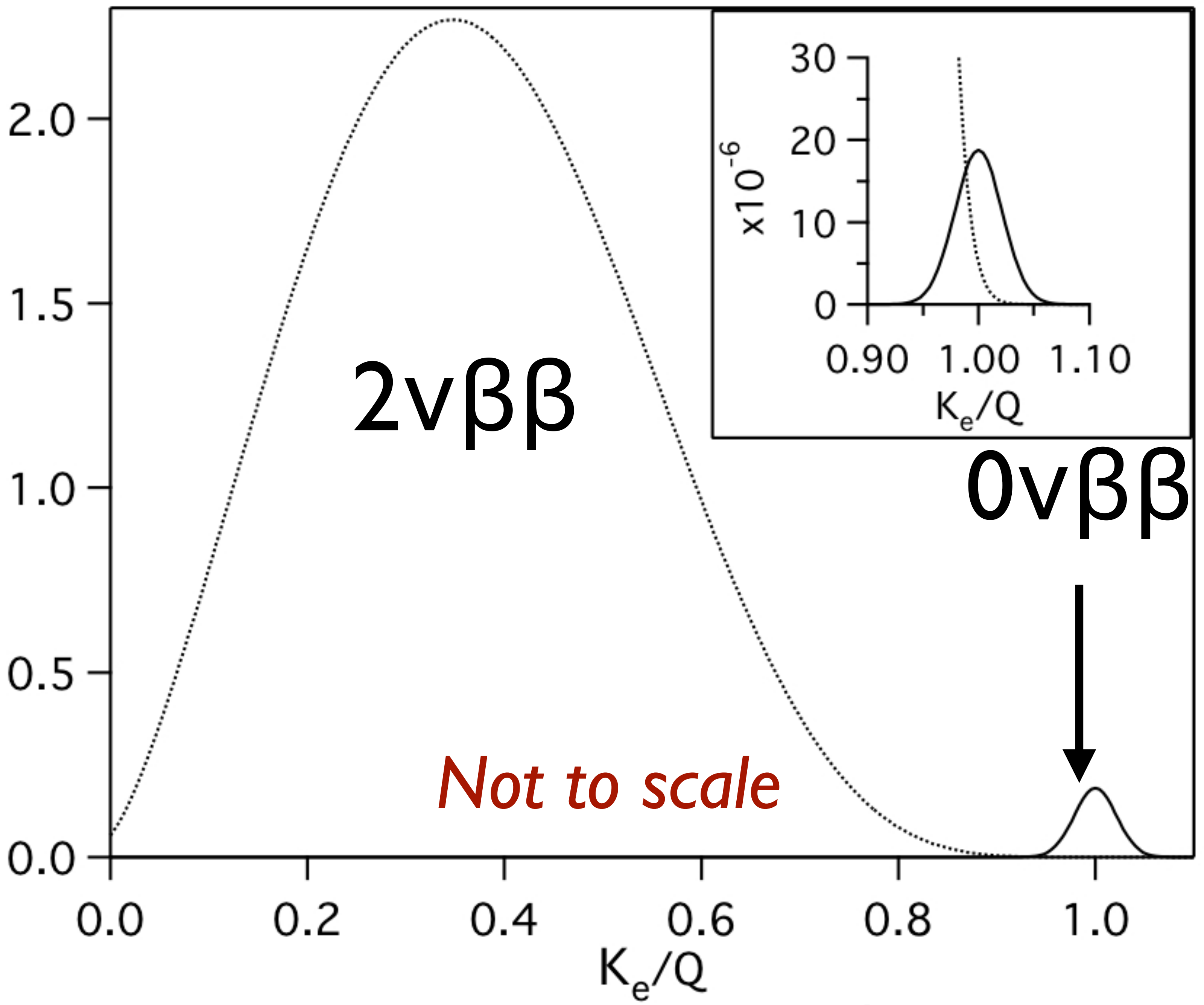
$$\Gamma_{0\nu} = G_{0\nu} \, | M_{0\nu} |^2 \left\langle m_{\beta\beta} \right\rangle^2$$

0νββ may allow us to determine
- effective neutrino mass

Neutrinoless Double Beta Decay (0vββ)



Neutrinoless
double beta decay

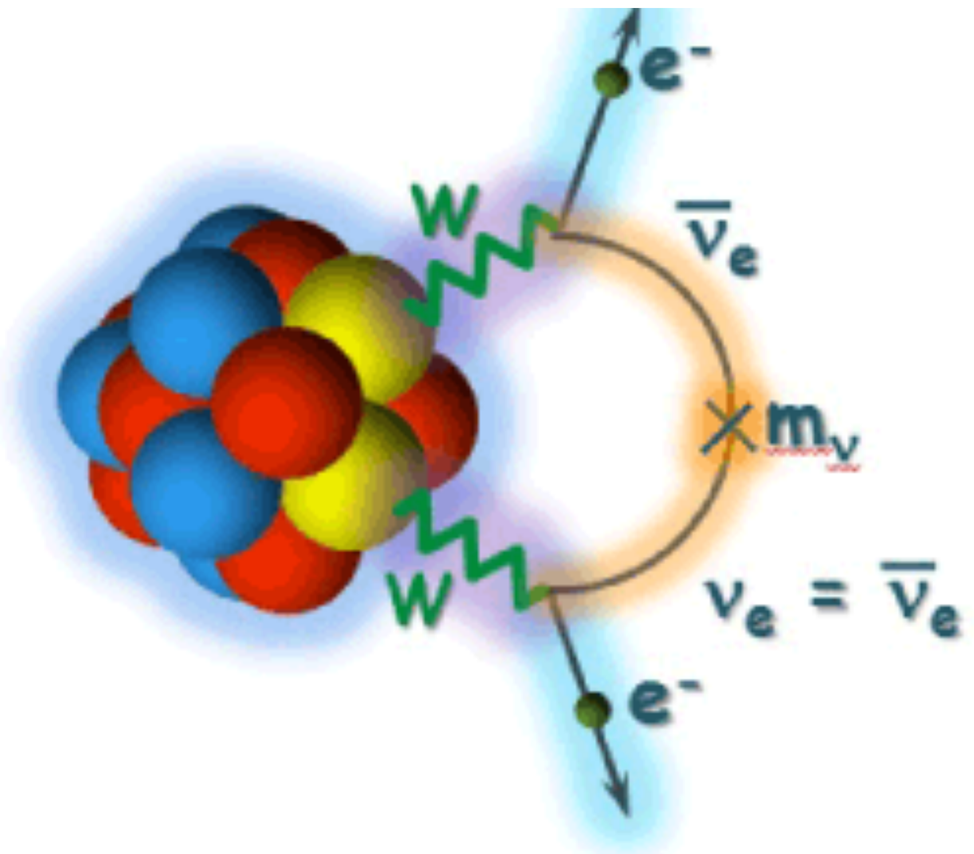


Annual Reviews: 52:115-151

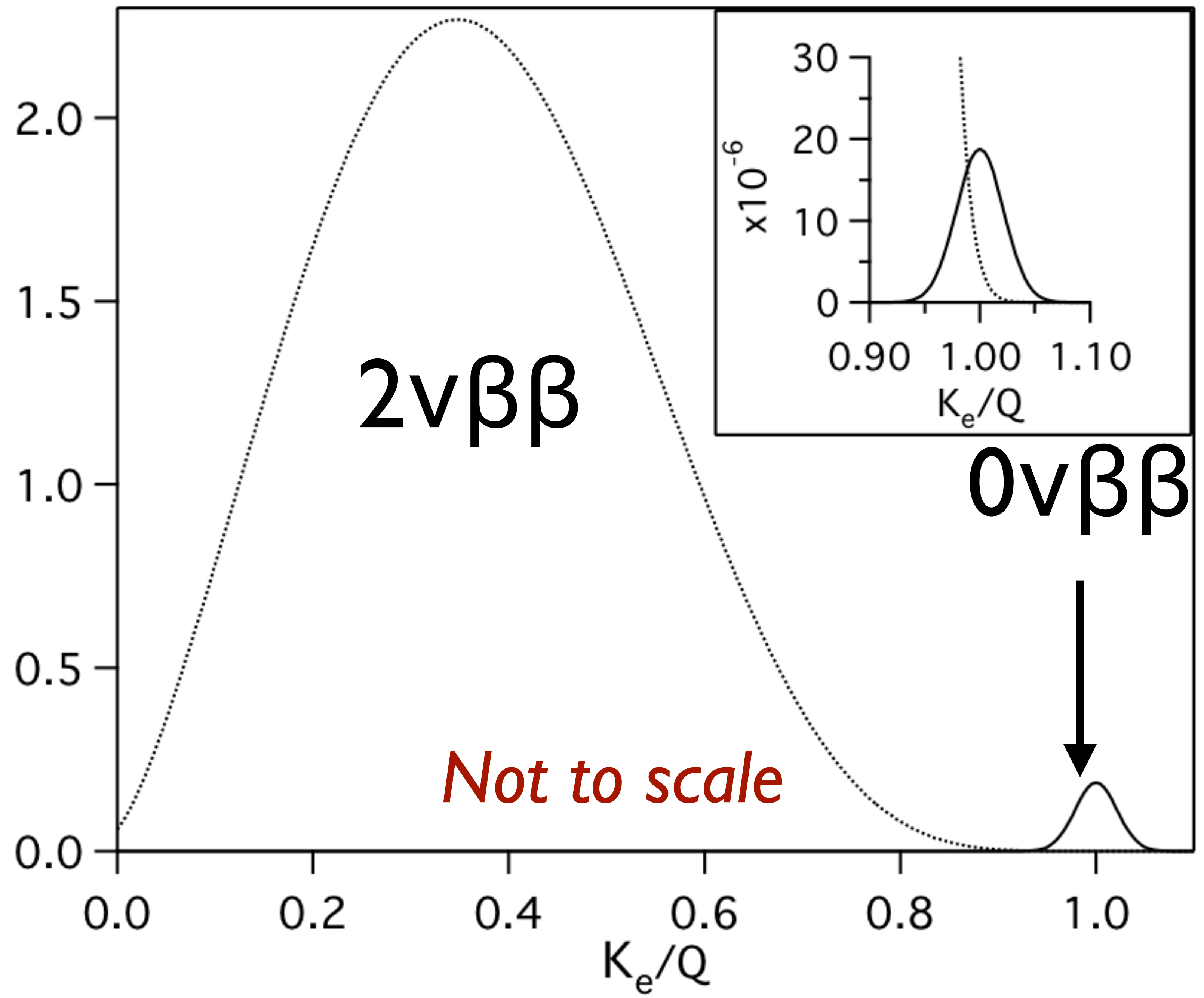
Search for peak search at the Q value of the decay

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

Neutrinoless Double Beta Decay (0νββ)

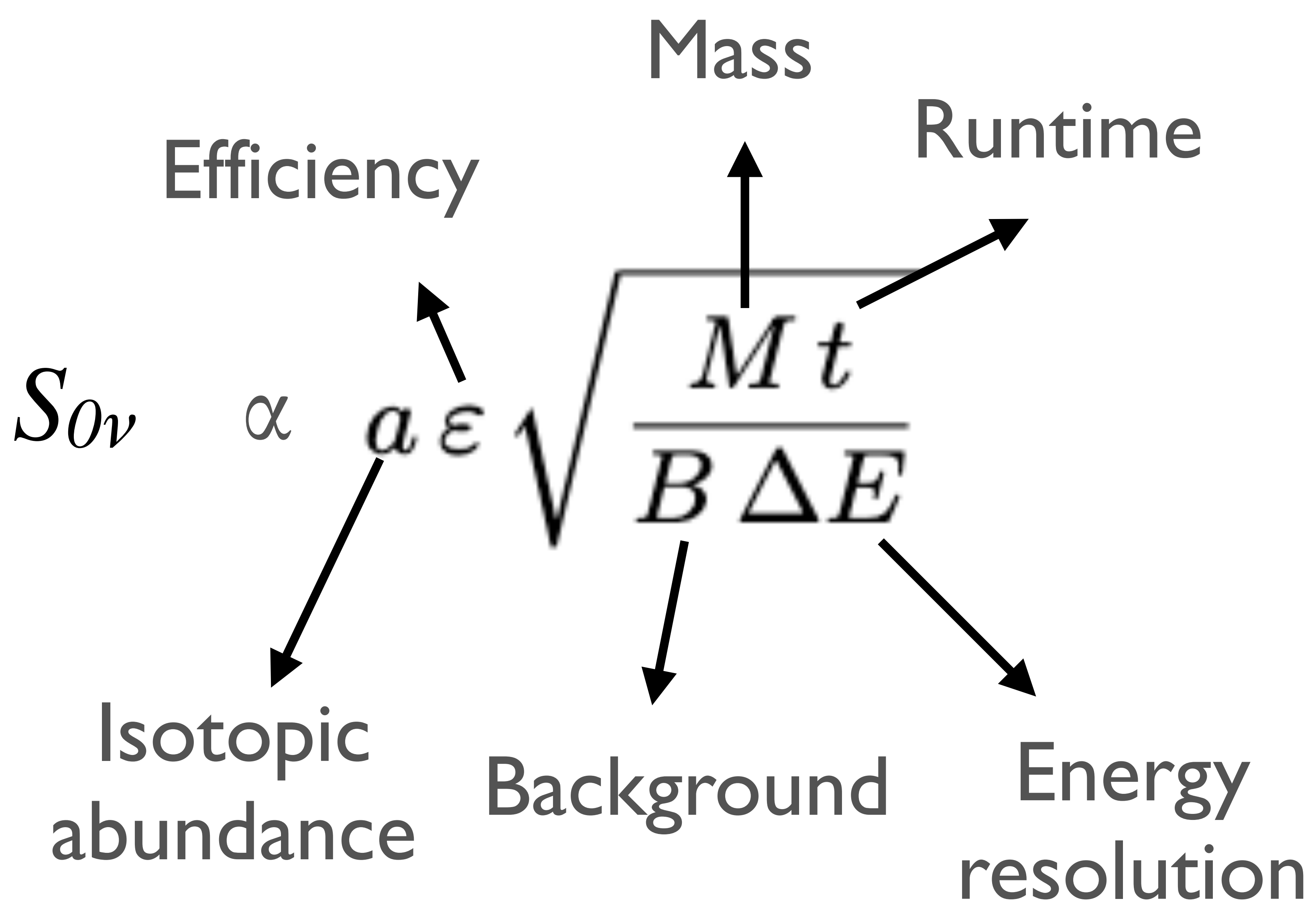


Neutrinoless double beta decay



Annual Reviews: 52:115-151

Sensitivity



$$S_{0\nu} \propto a\,\varepsilon \sqrt{\frac{M\,t}{B\,\Delta E}}$$

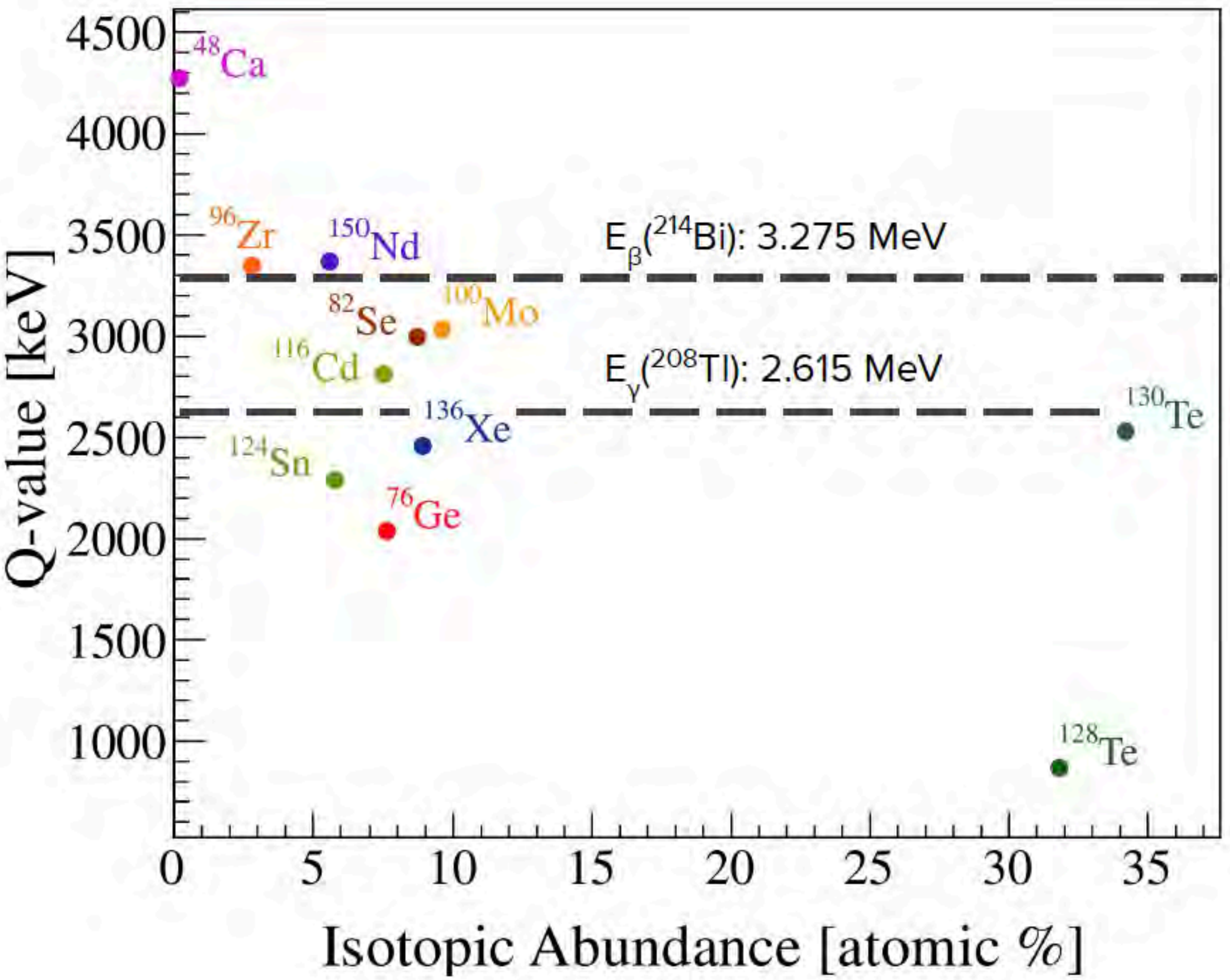
Search for peak search at the Q value of the decay

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

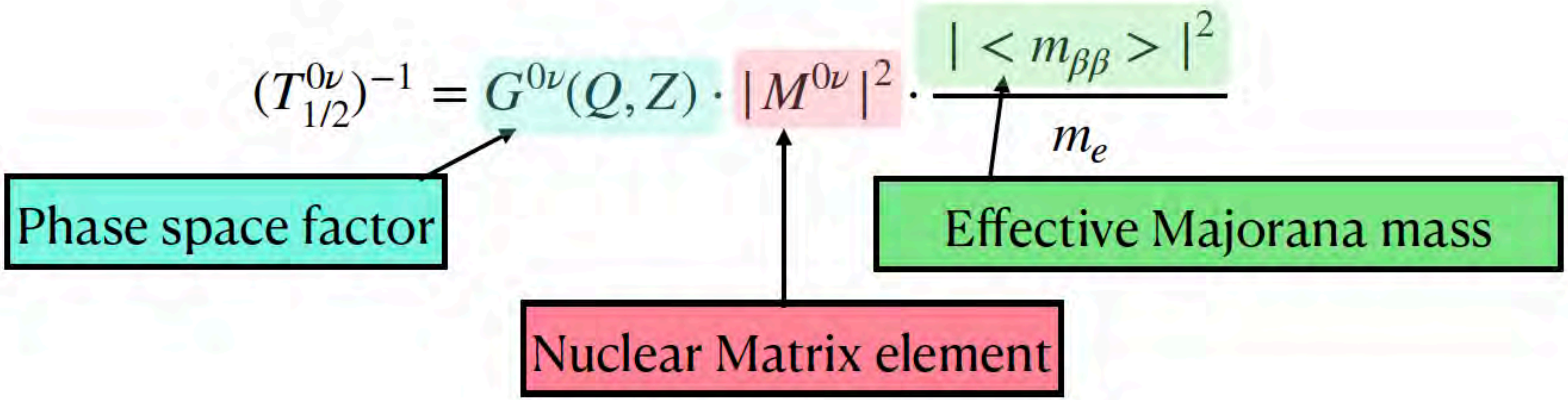
Isotope Choice

Desired Characteristics

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



0vββ Half Life



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\cdot|M^{0\nu}|^2\cdot\frac{|<m_{\beta\beta}>|^2}{m_e}$$

Phase space factor

Nuclear Matrix element

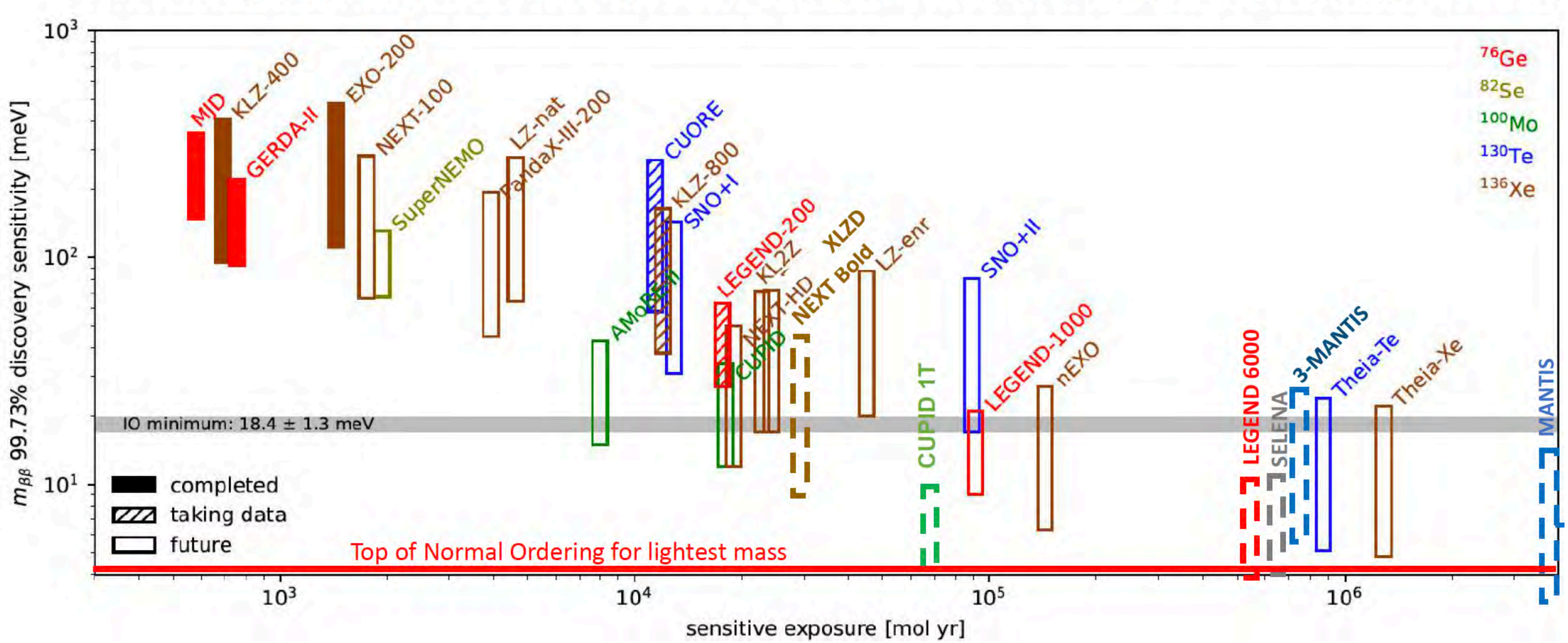
Effective Majorana mass

$$m^2_{\beta\beta} = |\sum_i U^2_{ei} m_{\nu_i}|^2$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\text{PMNS}\\ \text{matrix}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

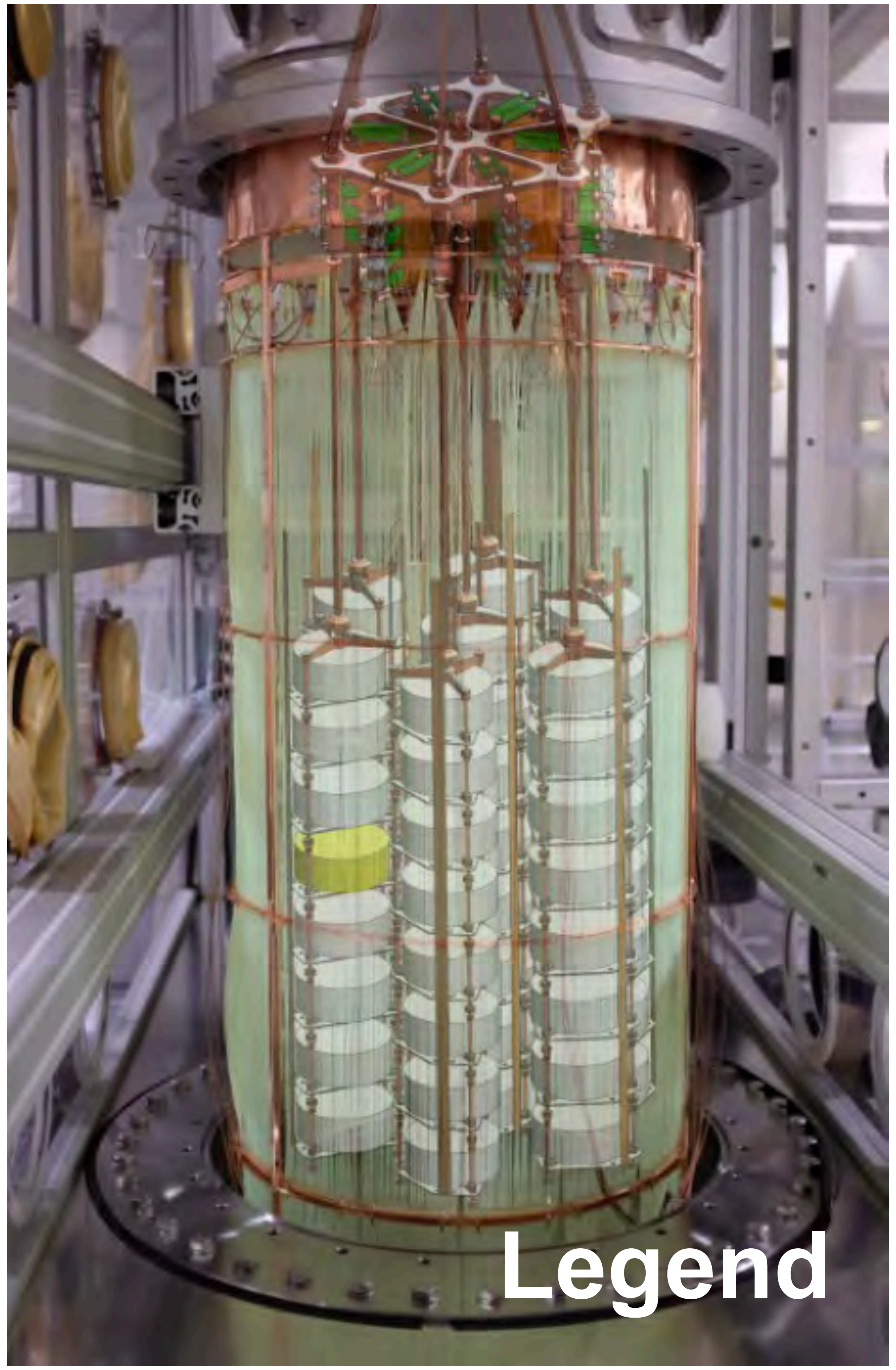
https://www.particlebites.com/?m=201609

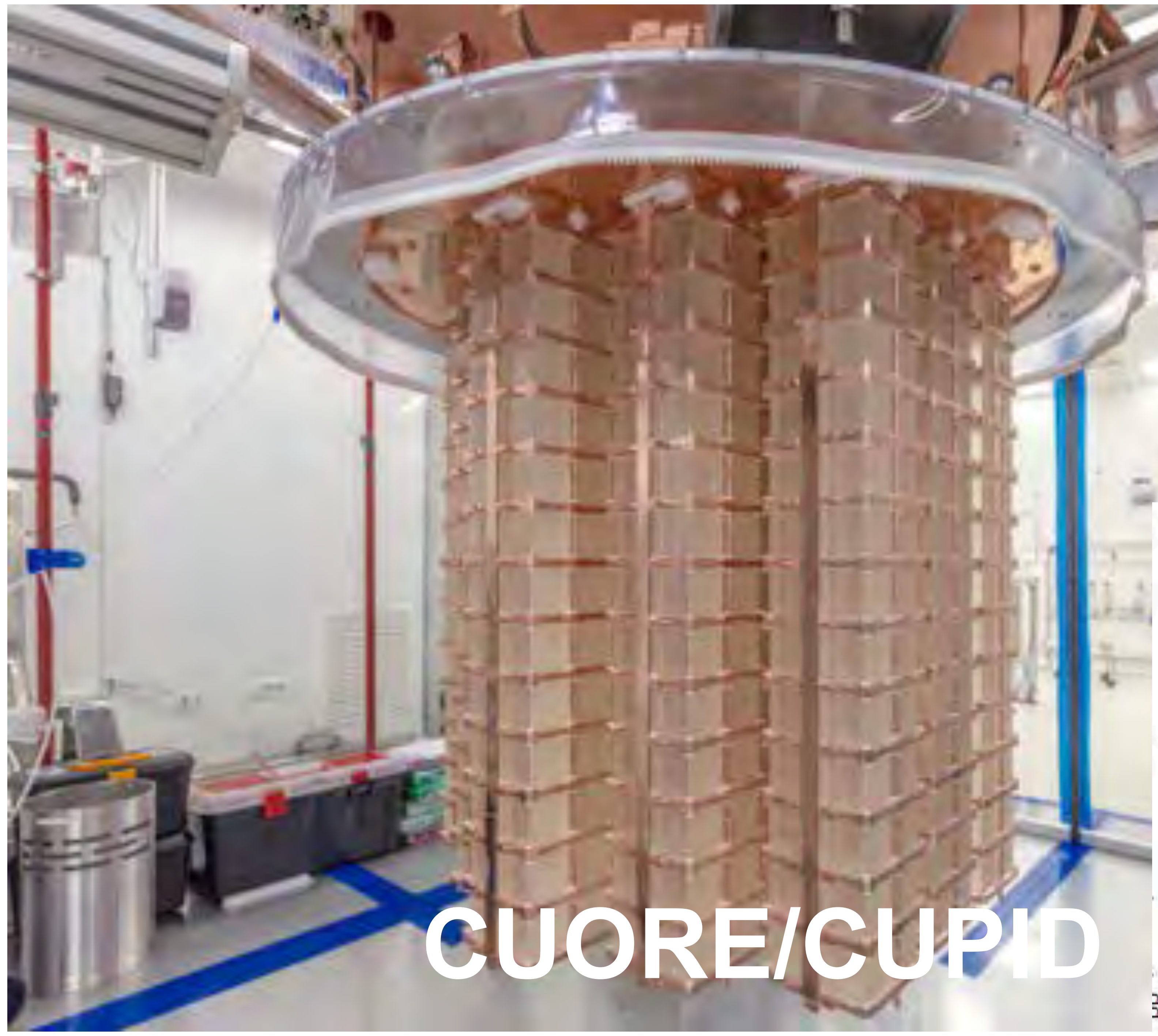
Isotope Choice

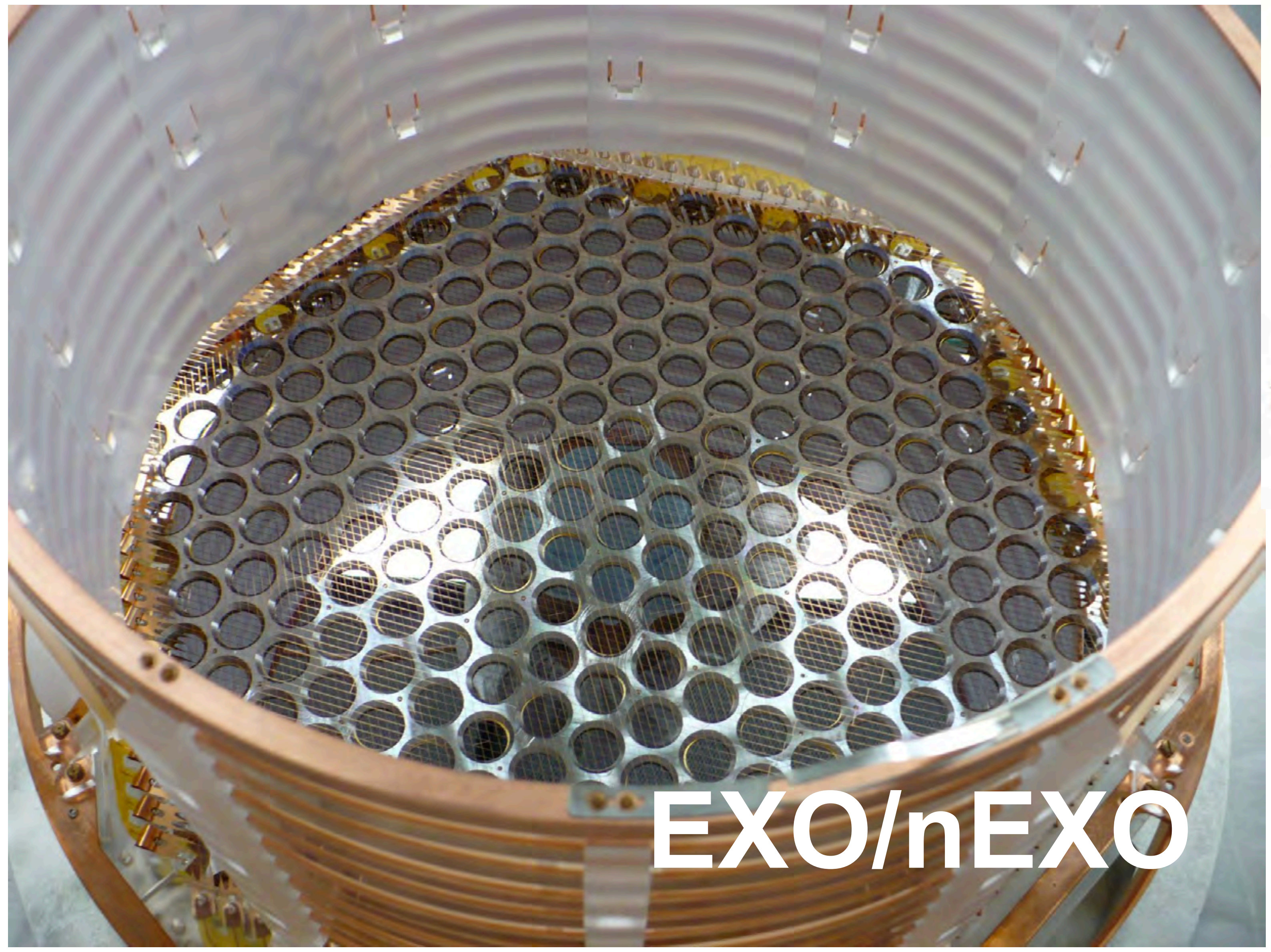


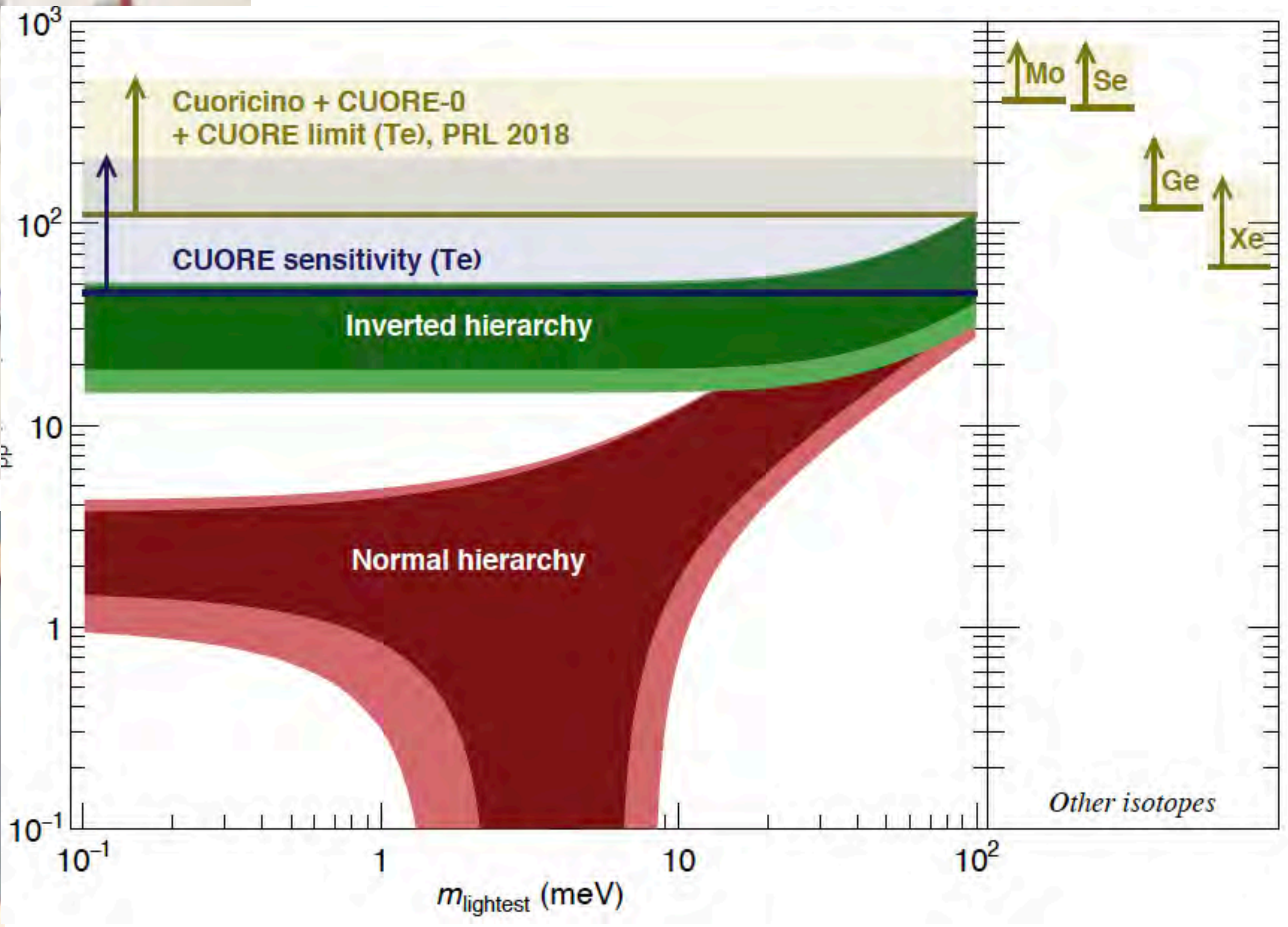
From: Fundamental Symmetries, Neutrons, and Neutrinos (FSNN):
Whitepaper for the 2023 Nuclear Science Advisory Committee Long Range
Plan: arXiv:2304.03451iv:2304.03451

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

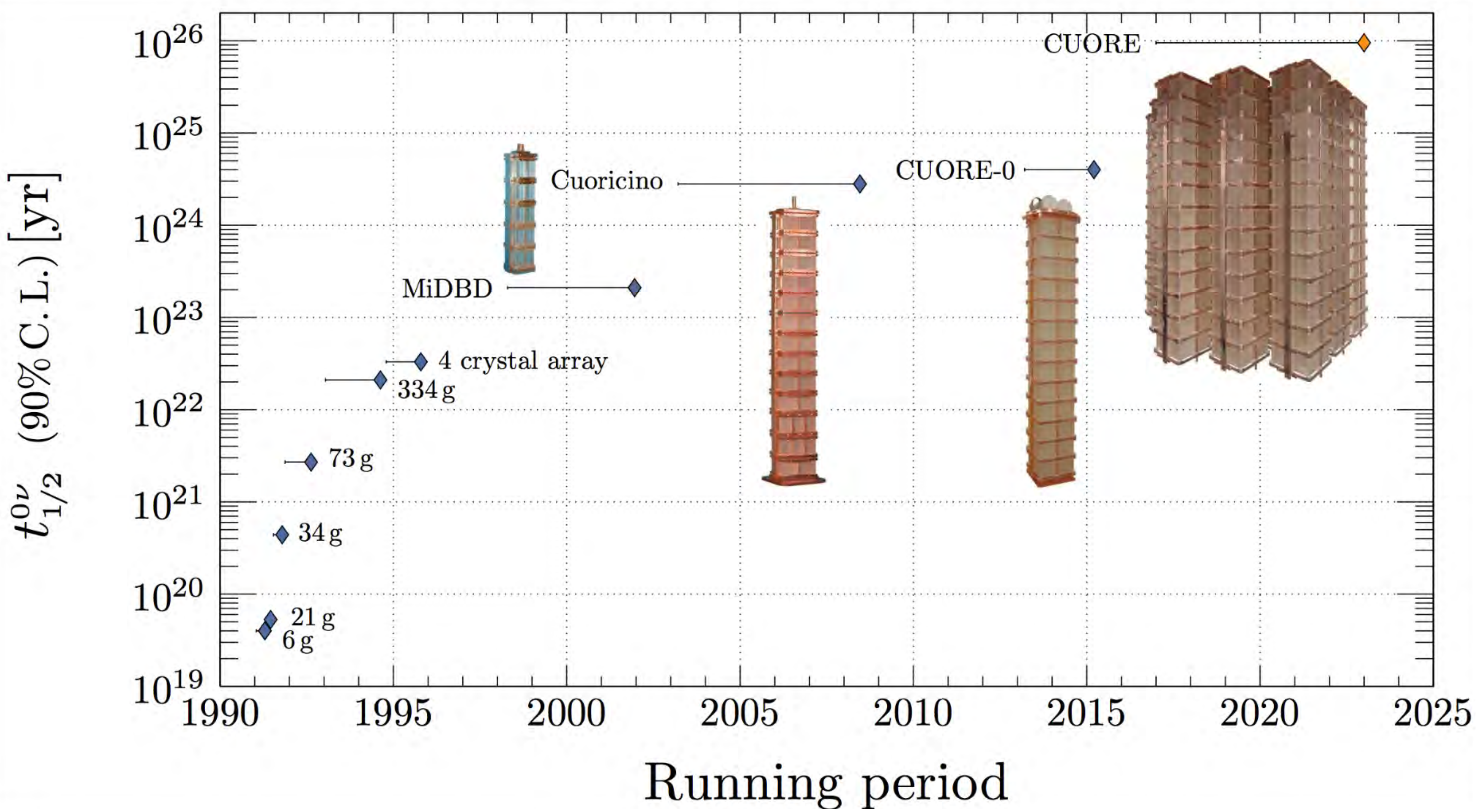
Well-established support for experiments and user access

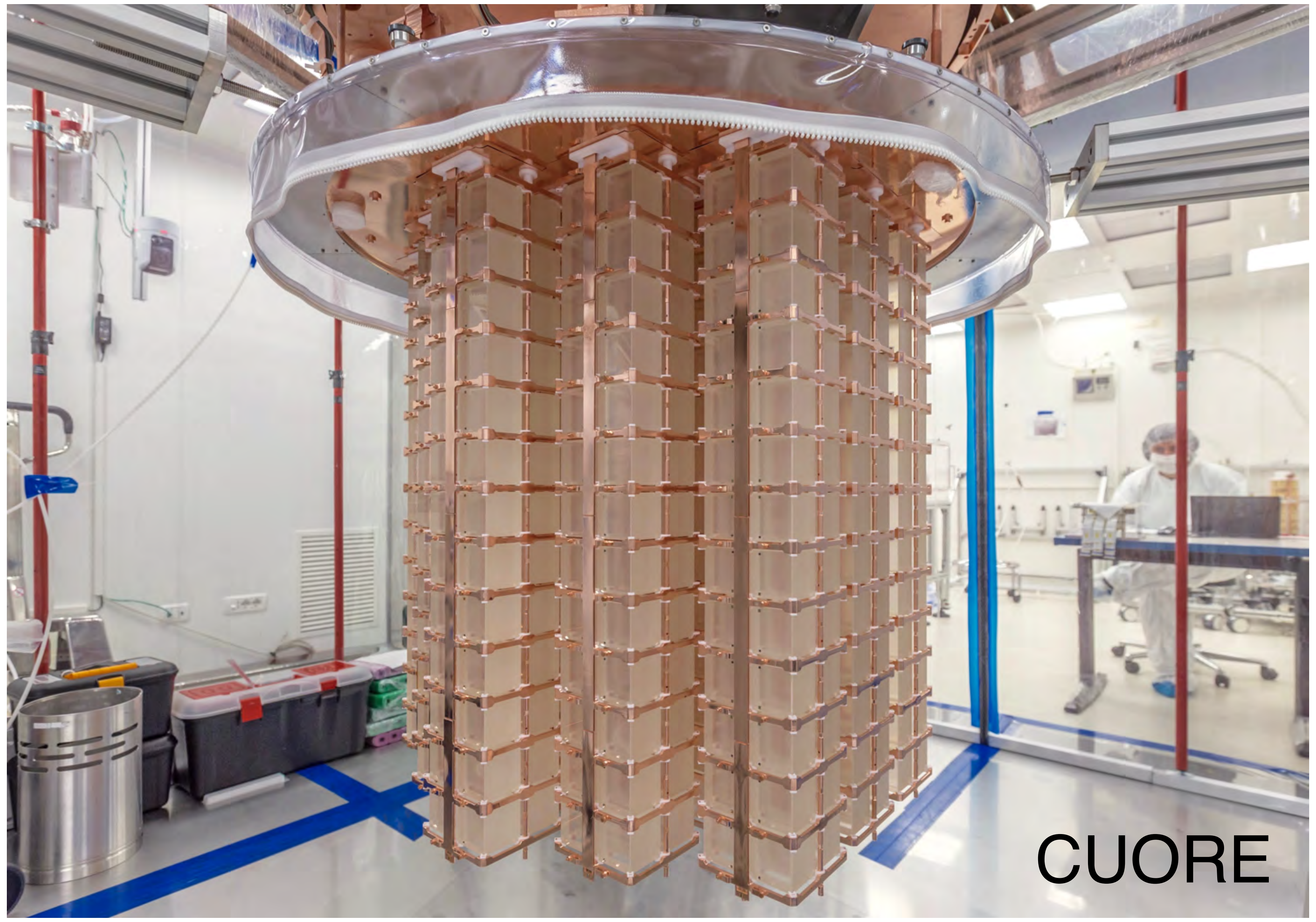
History of Bolometer Experiments

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

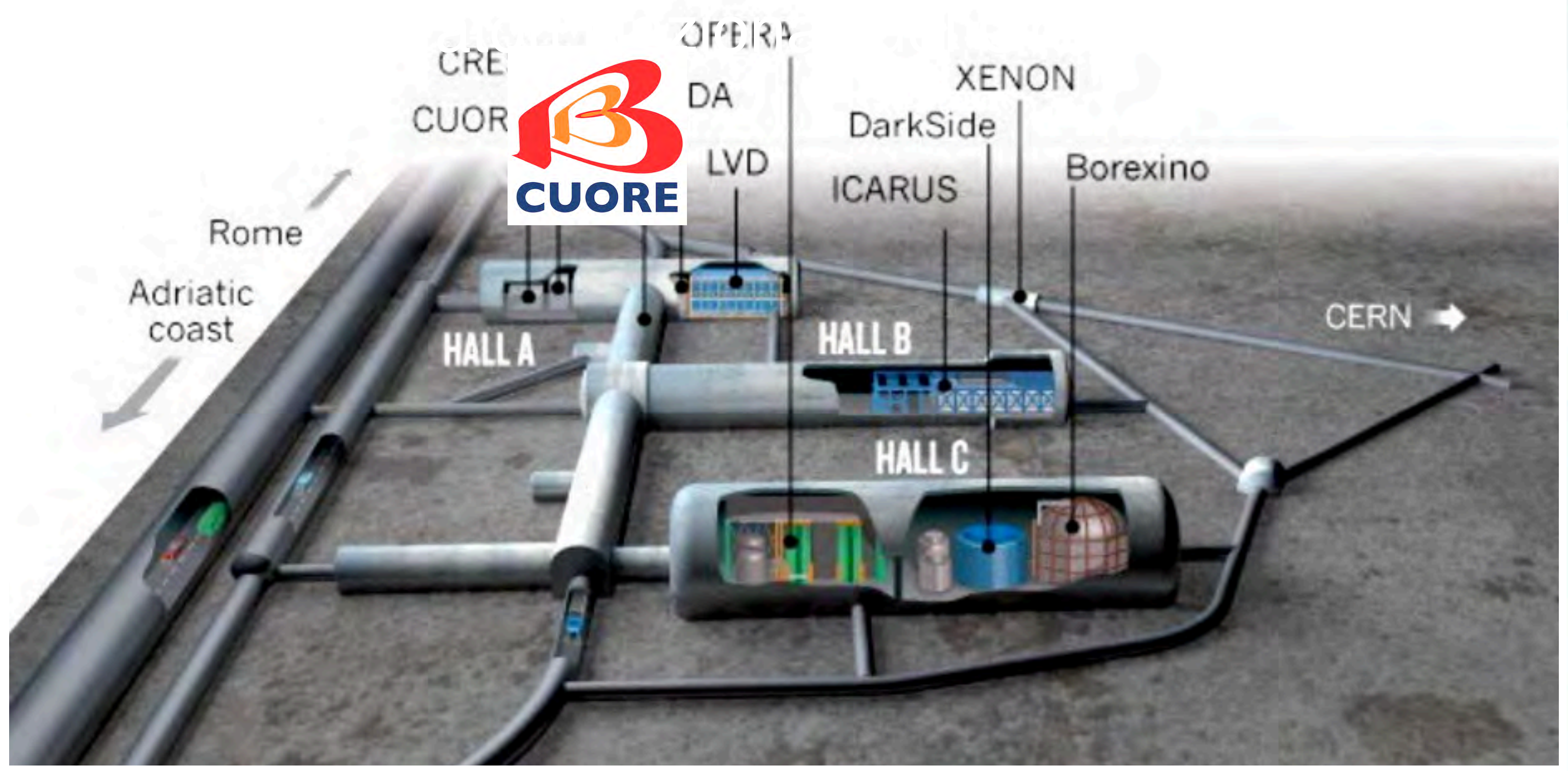
First tonne-scale bolometric experiment in the world

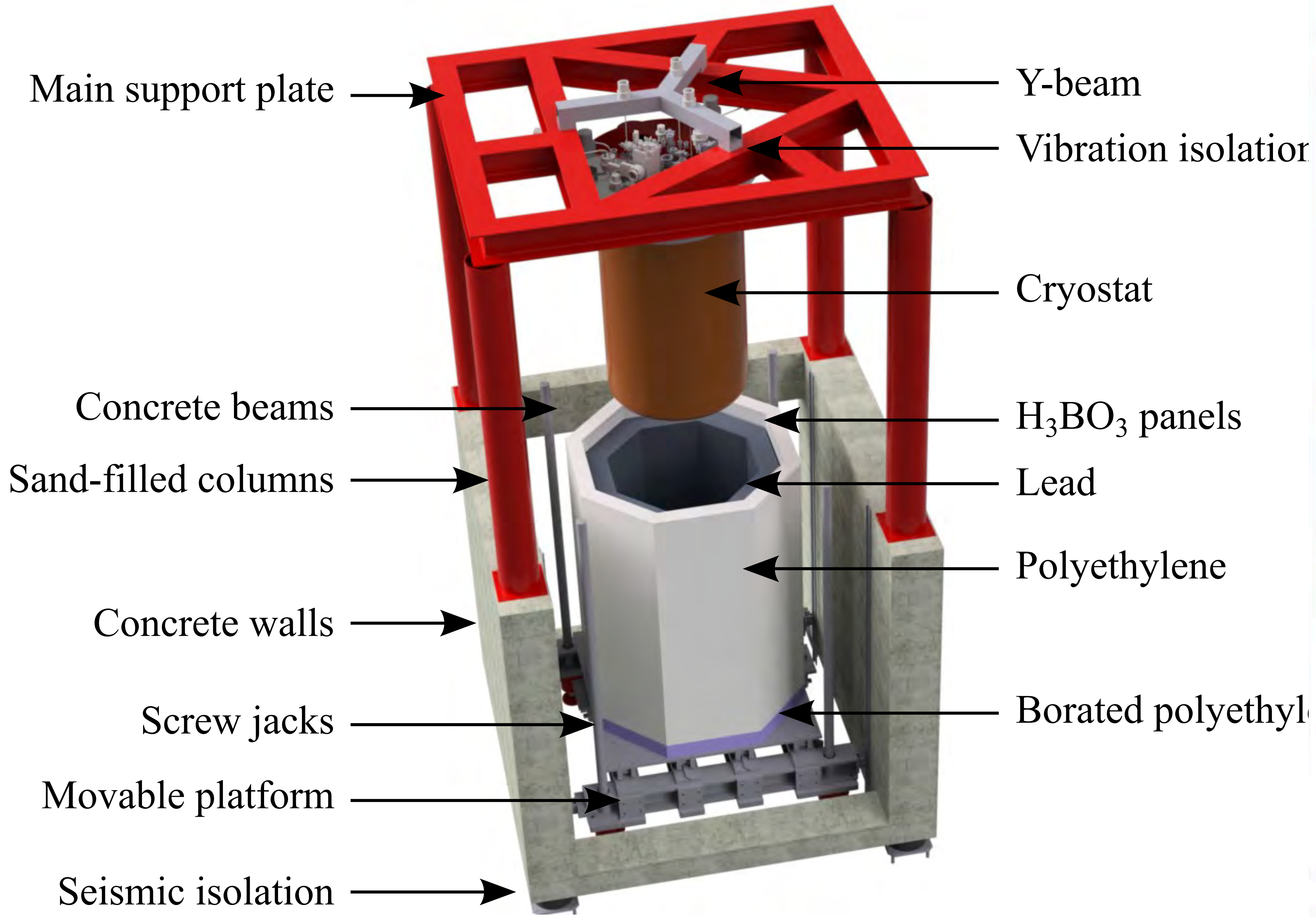


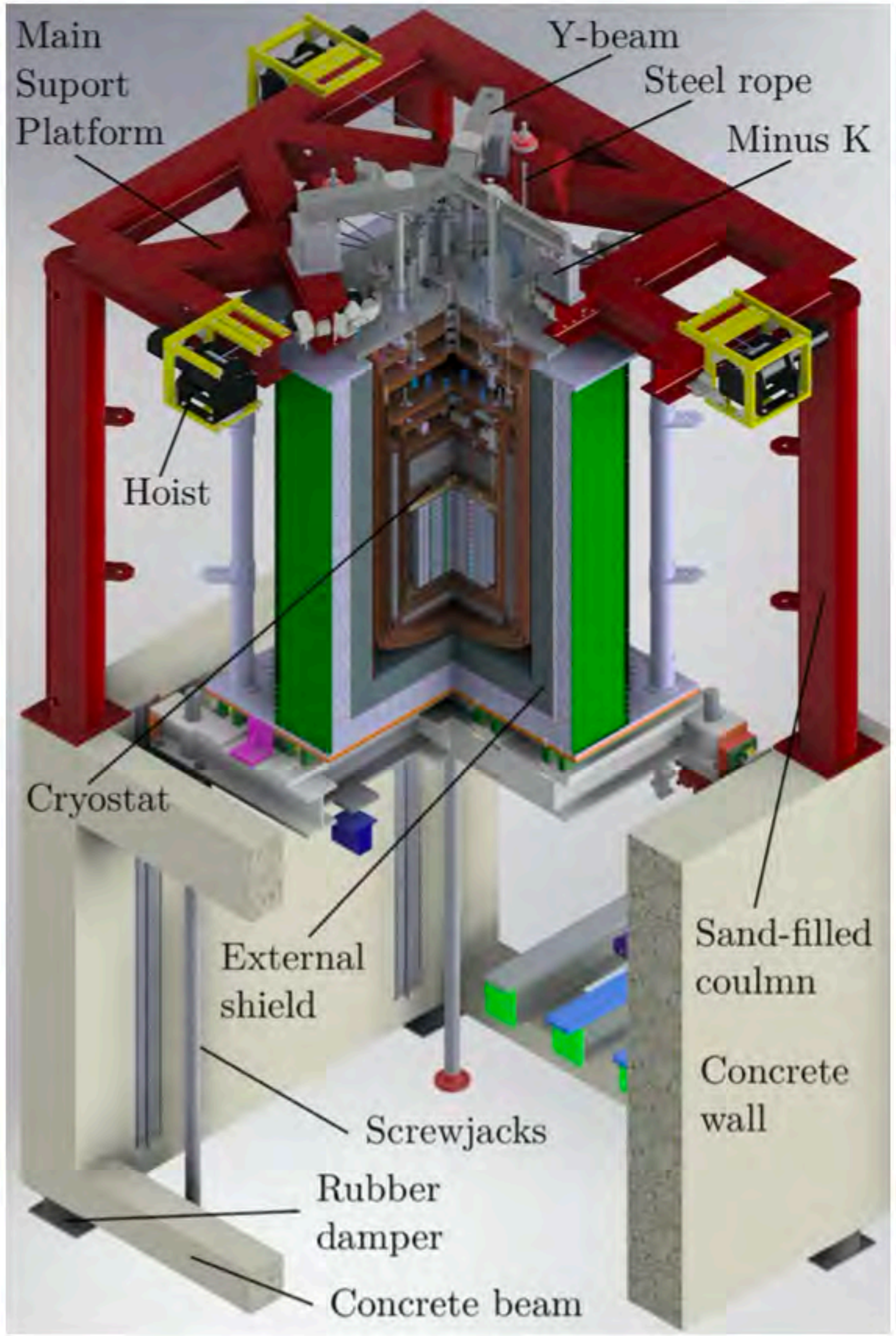


Brofferio, C. and Dell'Oro, S., Rev. Sci. Inst. 89, 121501 (2018)

Experimental Site







Unique cryogenic infrastructure.

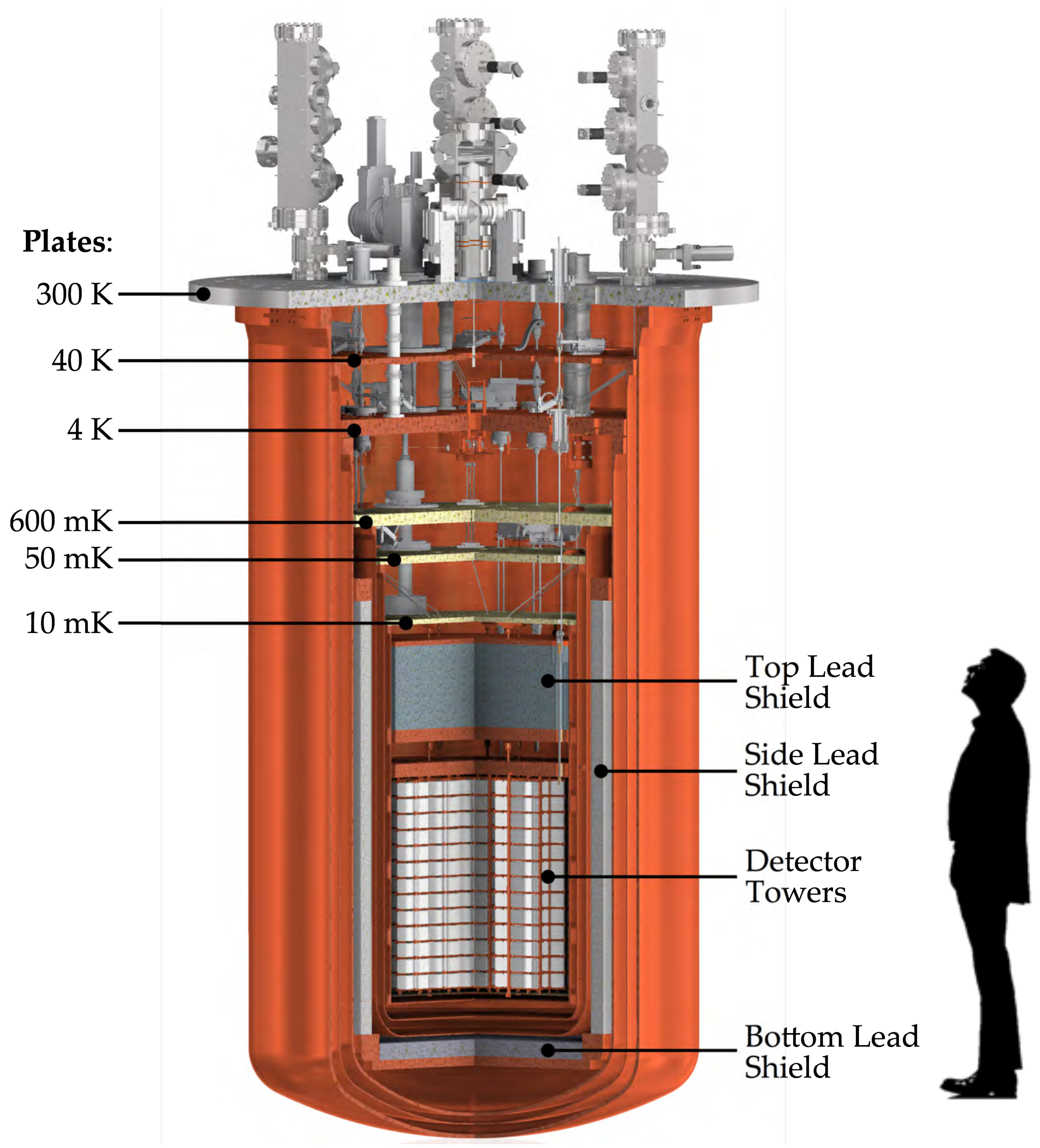
CUORE - *Coldest Cubic Meter in the Known Universe*

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

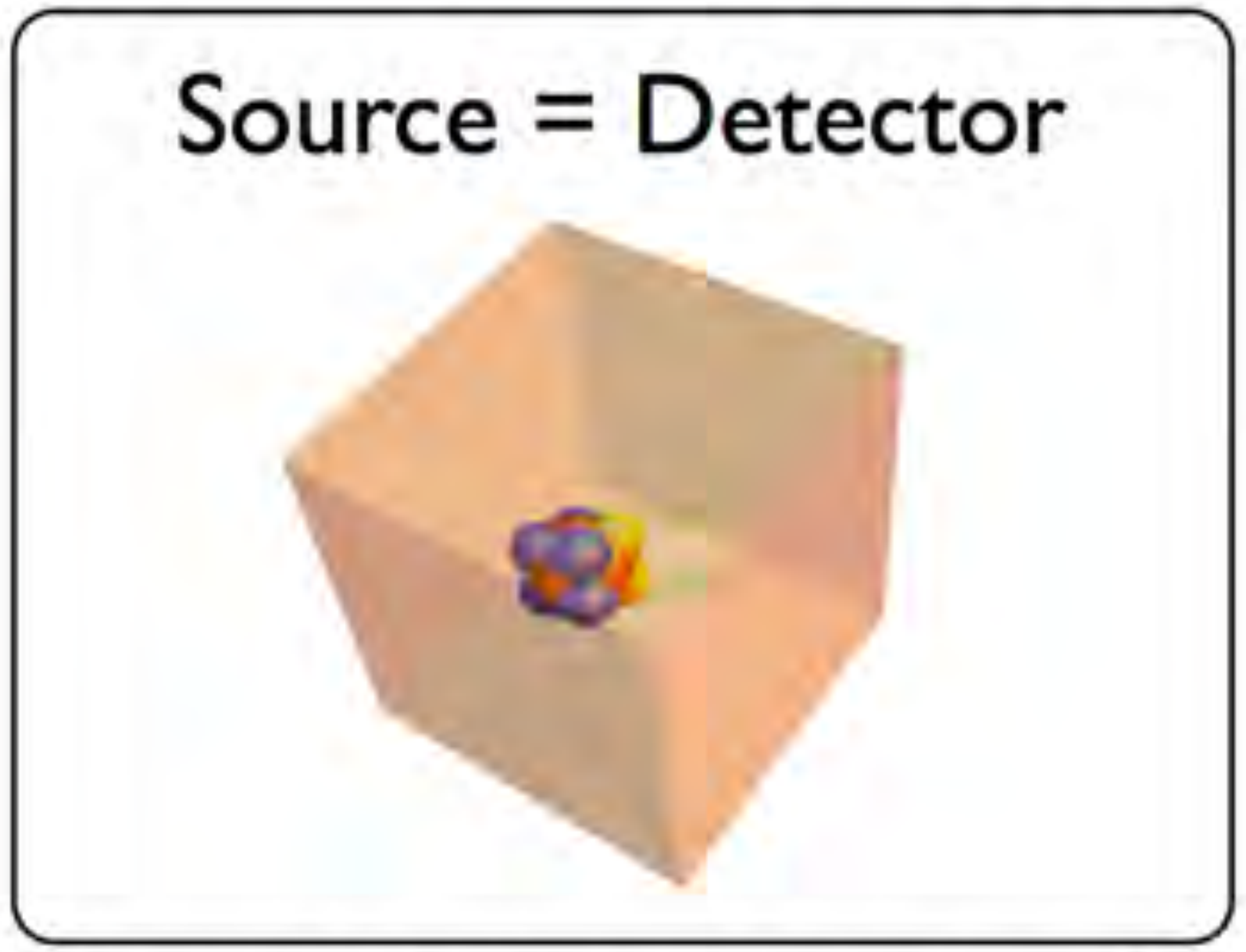
- Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels + polyethylene

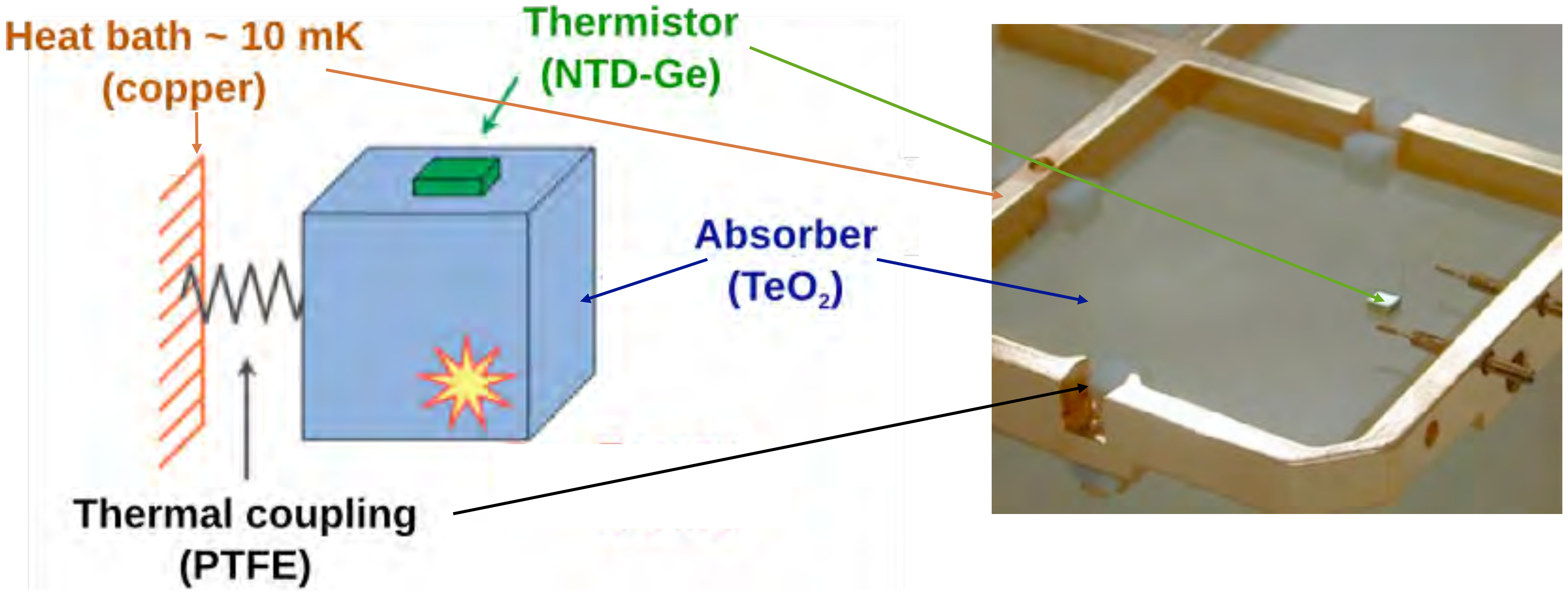


70 tonne of lead, 7 tonne of cold lead

Careful material selection: Ancient Lead and low radioactive copper

Bolometric Search for 0νββ





Heat bath ~ 10 mK (copper)

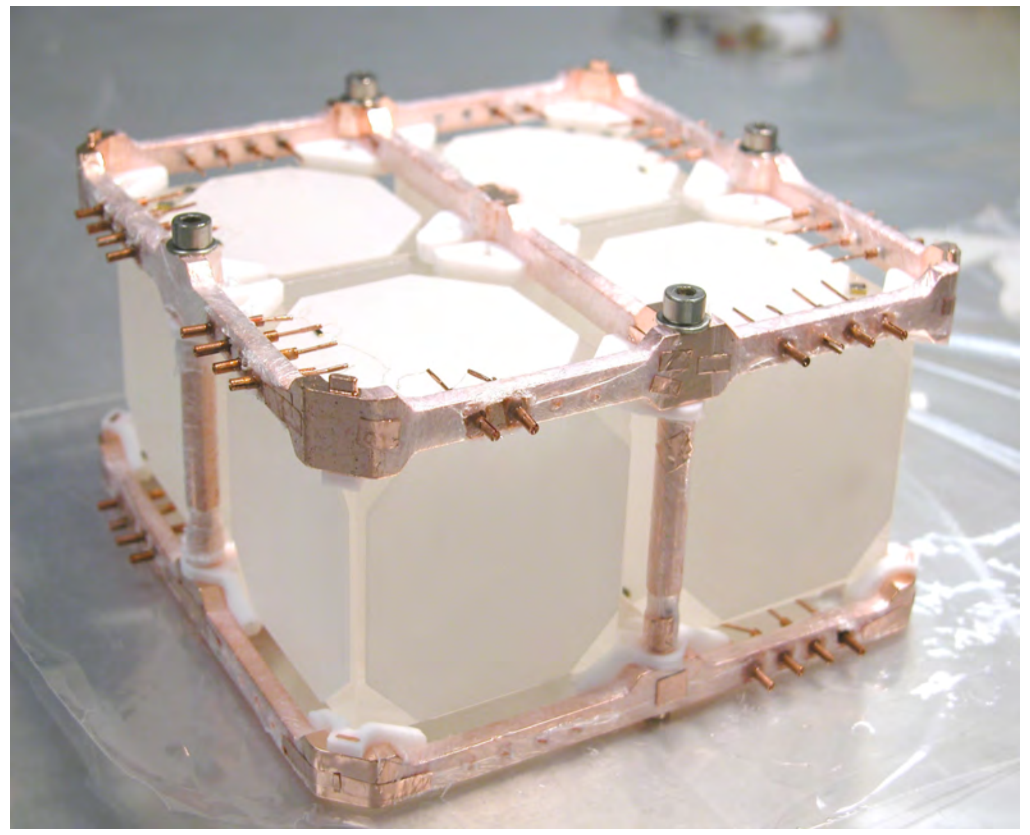
Thermistor (NTD-Ge)

Absorber (TeO_2)

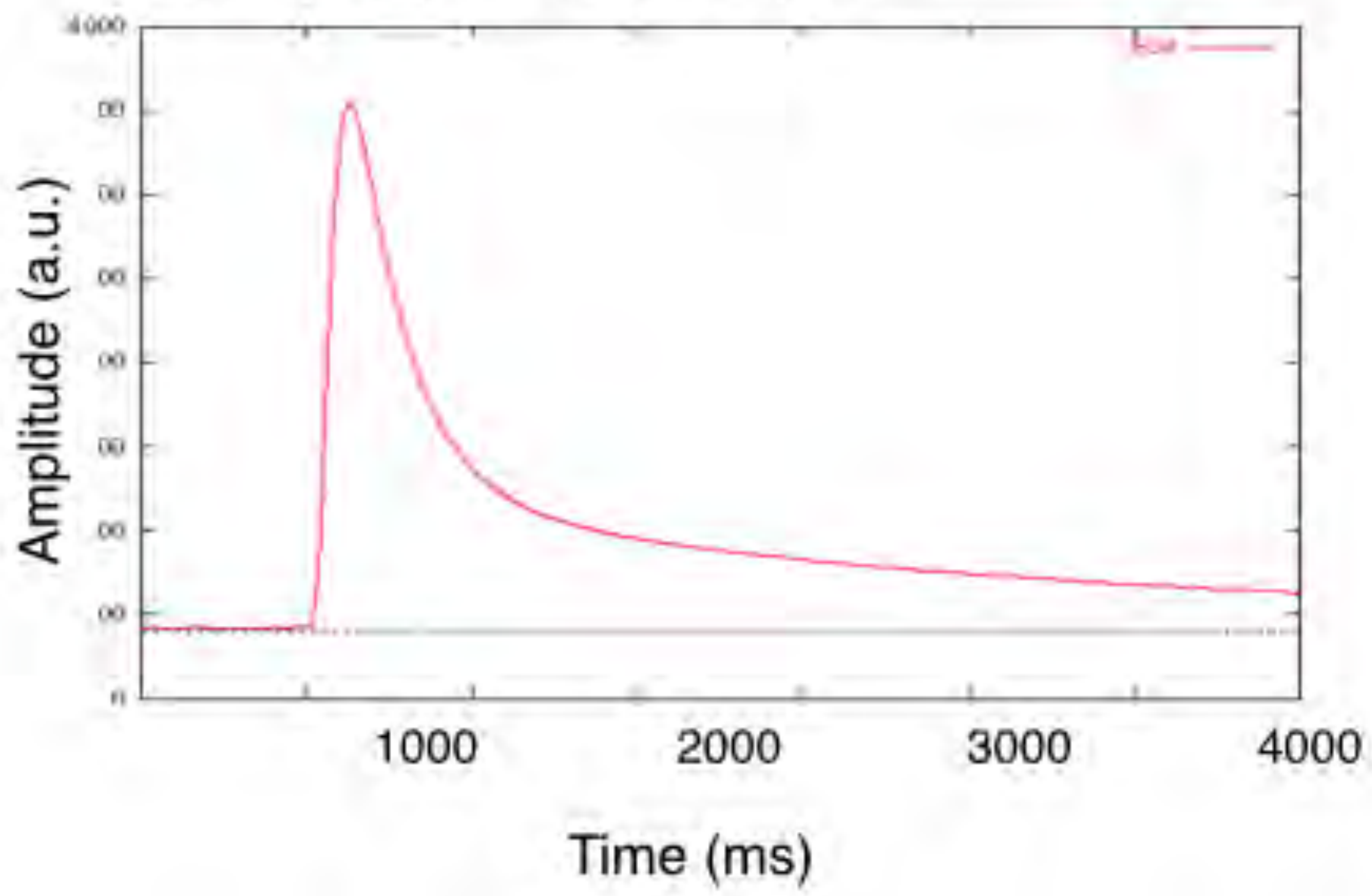
Thermal coupling (PTFE)

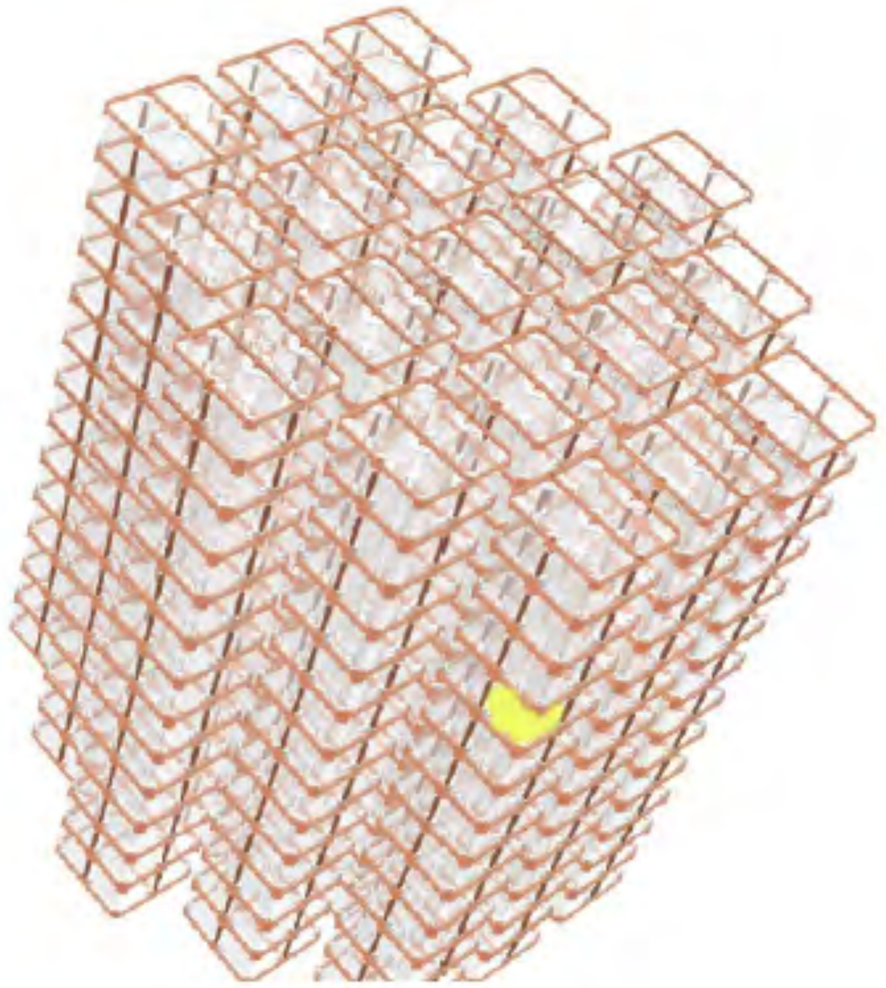
$^{130}Te \rightarrow {}^{130}Xe + 2e^-$

Q = (2527.518 +/- 0.013) keV



Single pulse example





single hit, monochromatic event

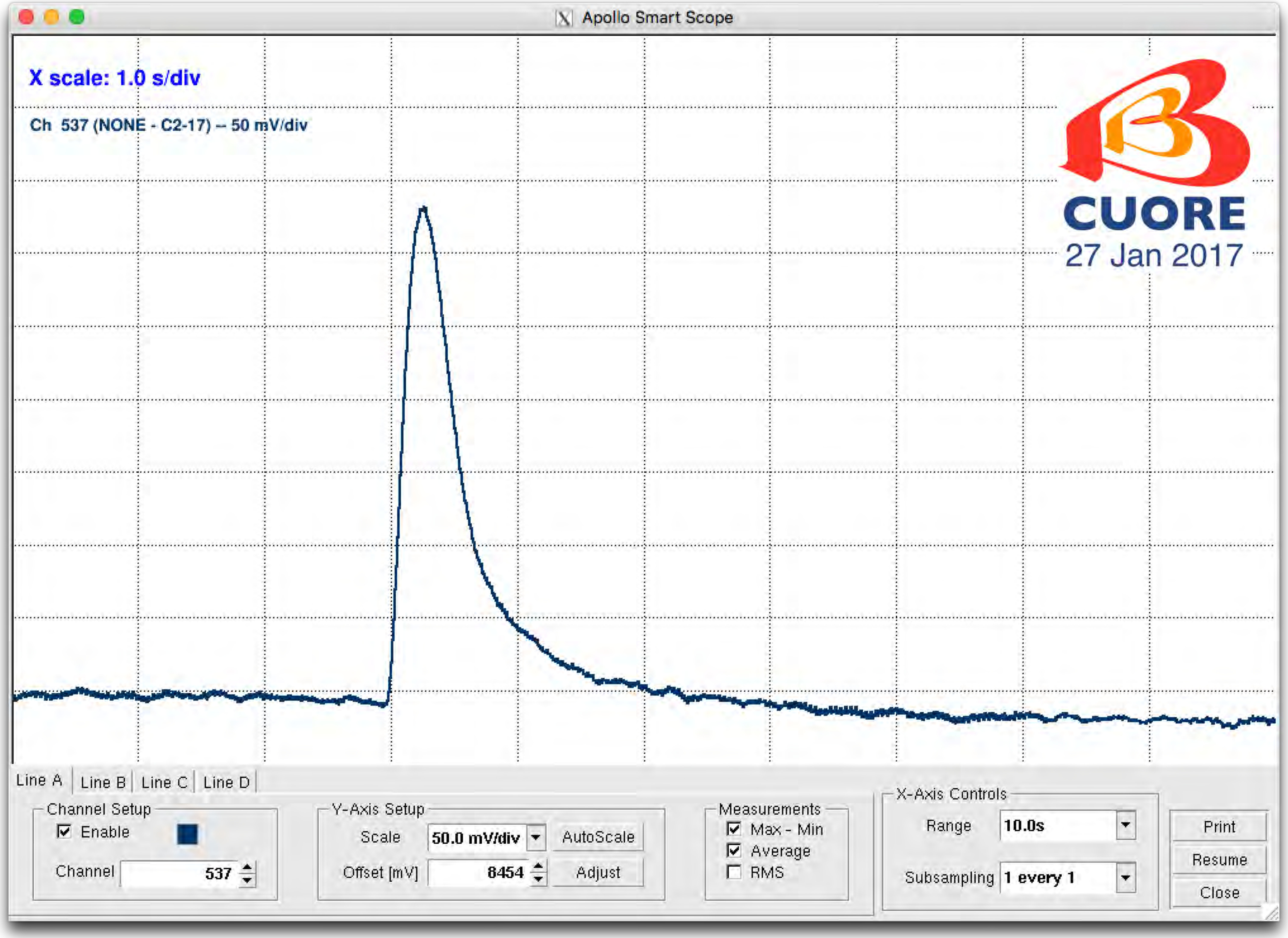
CUORE Detector

Bolometer Event

Cooldown: Started in Dec 2016

1 month cool down

First data in Jan 2017



Apollo Smart Scope

X scale: 1.0 s/div

Ch 537 (NONE - C2-17) -- 50 mV/div

CUORE
27 Jan 2017

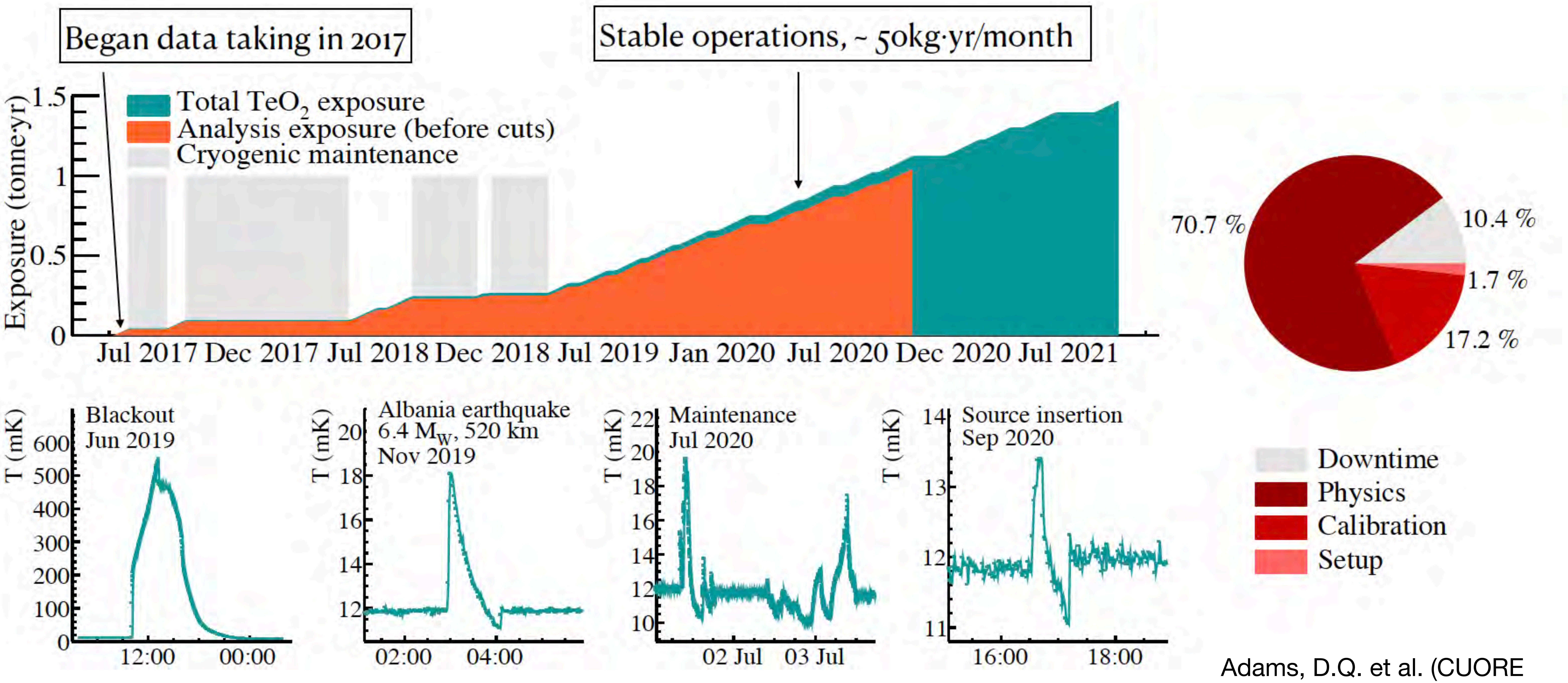
Channel Setup
☑ Enable
Channel 537

Y-Axis Setup
Scale 50.0 mV/div
Offset [mV] 8454

Measurements
☑ Max - Min
☑ Average
☐ RMS

X-Axis Controls
Range 10.0s
Subsampling 1 every 1

CUORE Data Taking

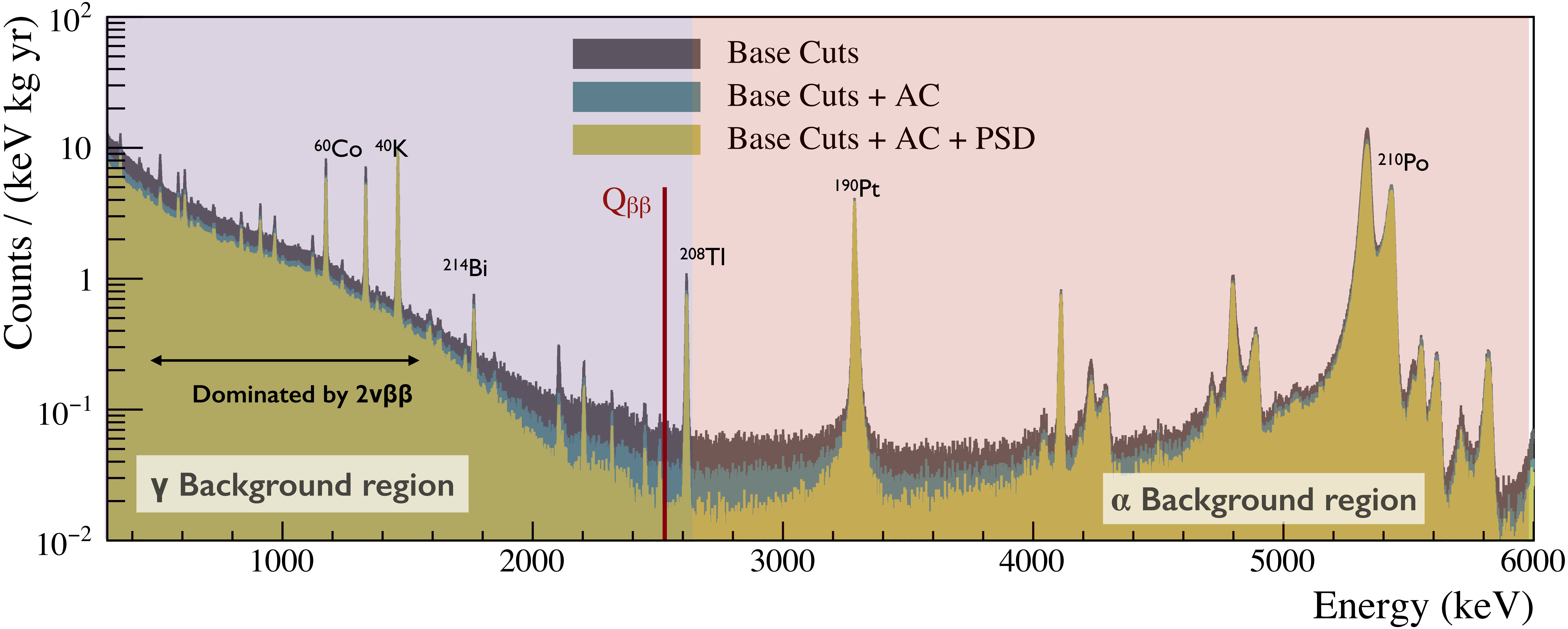


Began data taking in 2017

Stable operations, ~ 50kg·yr/month

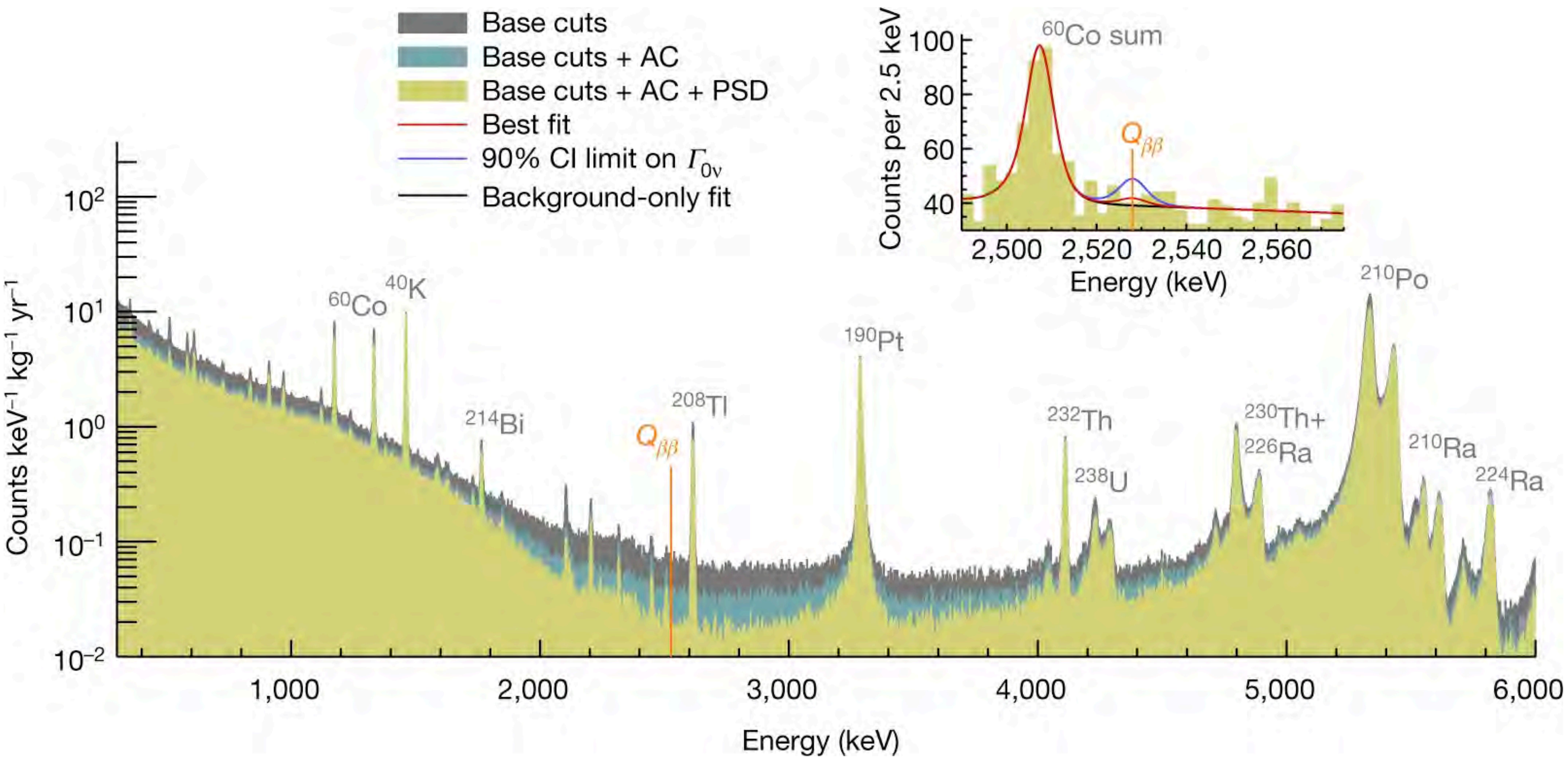
Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

CUORE 1-tonne Year Spectrum



Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

CUORE 1-tonne Year Spectrum



Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

Background in Region of Interest (ROI)

α region

fit flat background in [2650,3100] keV
1.40(2) 10^{-2} counts/(keV kg yr)

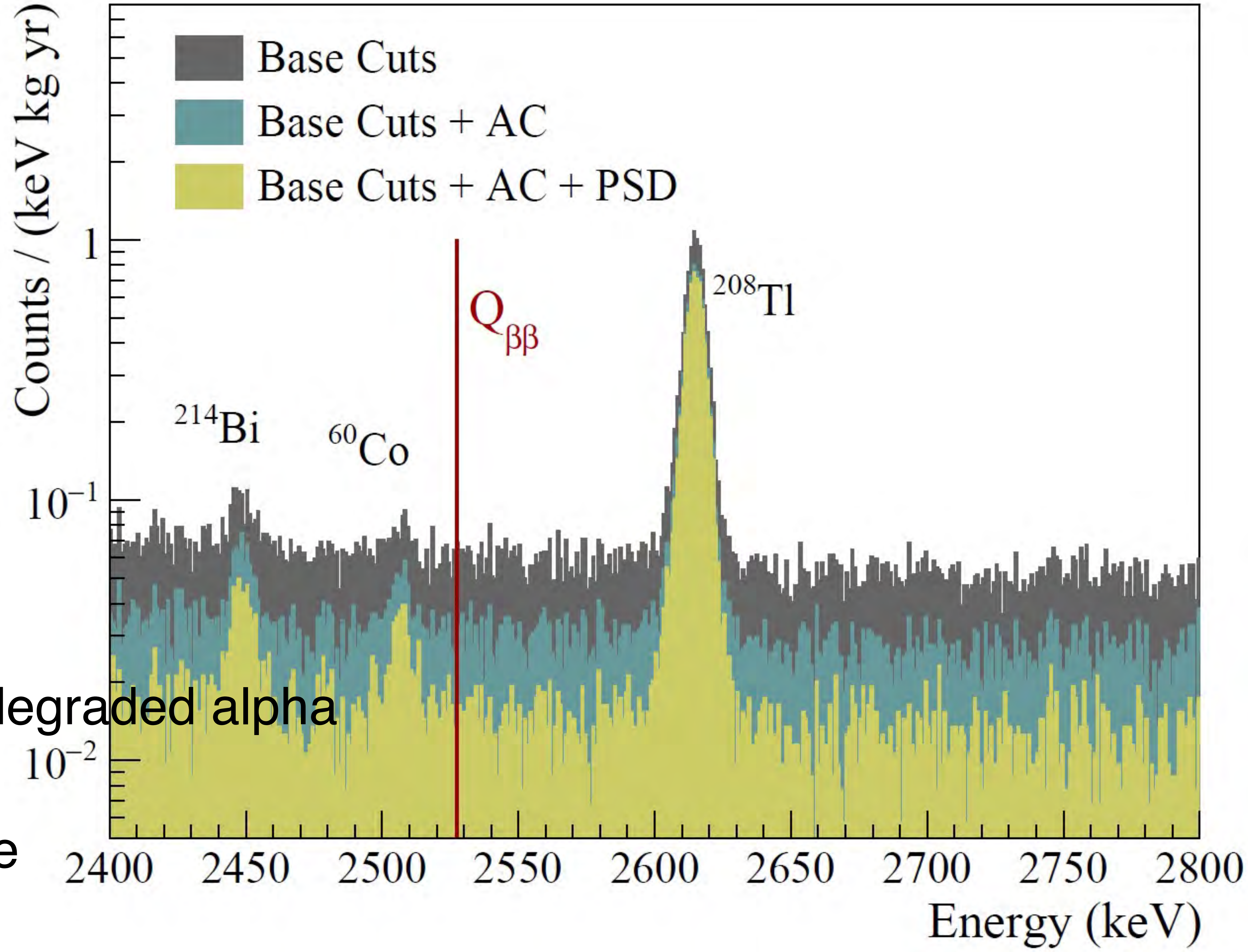
$Q_{\beta\beta}$ region

fit background + ^{60}Co peak in [2490,2575] keV
1.49(4) 10^{-2} counts/(keV kg yr)

source

~90% of the background in the ROI is given by degraded alpha interactions

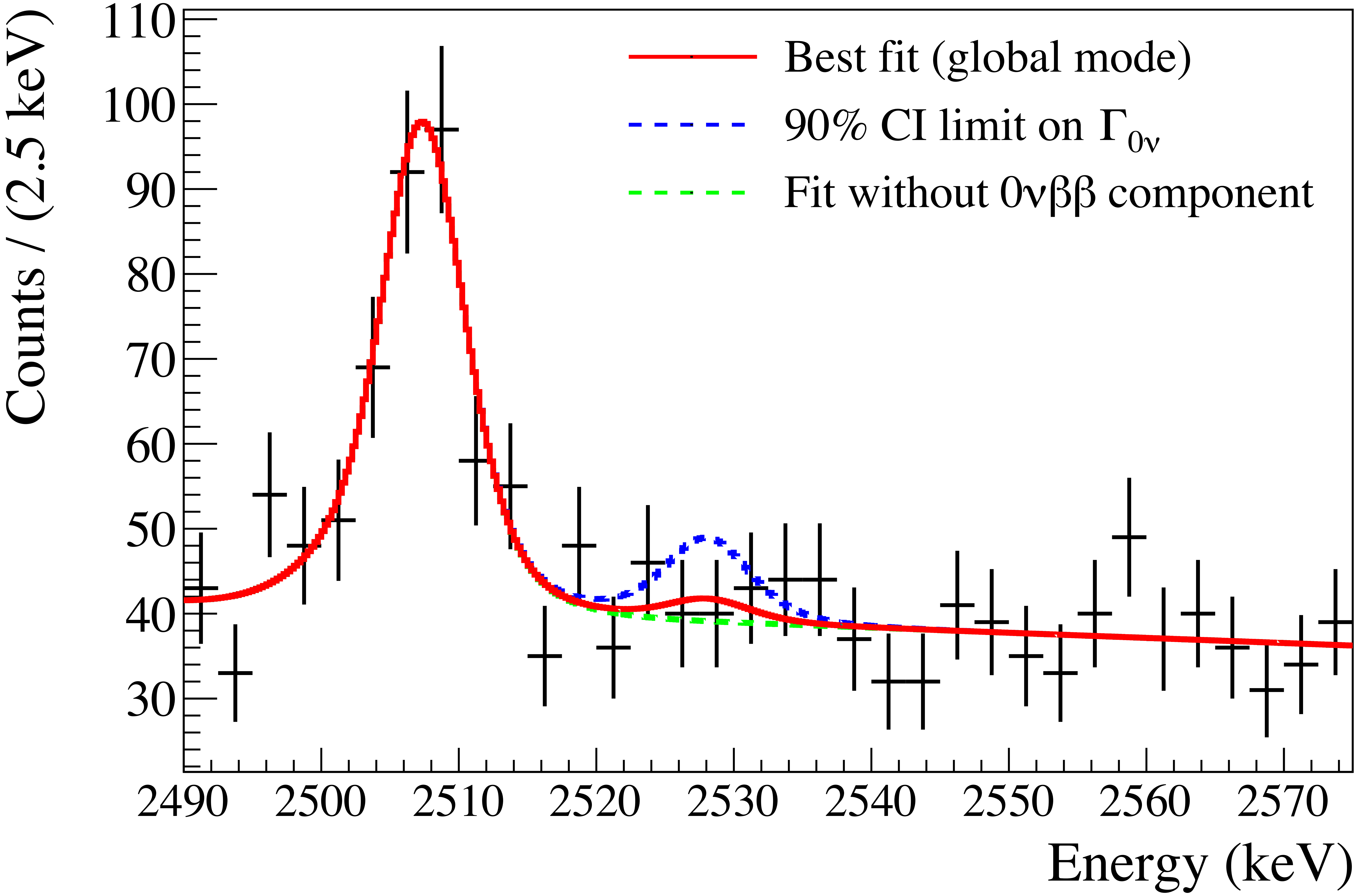
Muons are the next dominant background source



CUORE uses ^{130}Te with 34% natural isotopic abundance, $Q_{\beta\beta}$ (2528 keV)

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

CUORE Fit



Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

No evidence of 0νββ

Best fit rate: **$(0.9 \pm 1.4)\times10^{-26}$** yr

Background index = **$1.49(4)\times10^{-2}$** cts/keV/kg/yr

$T^{0\nu}_{1/2}$ > **$2.2\ \times10^{25}$** yr at 90% C.L.

CUORE 0νββ Limit and Sensitivity

$$(T^{0\nu}_{1/2})^{-1} = \boxed{G^{0\nu}(Q,Z)}\,\boxed{|M^{0\nu}|^2}\,\frac{\boxed{|\langle m_{\beta\beta}\rangle|^2}}{m_e^2}$$

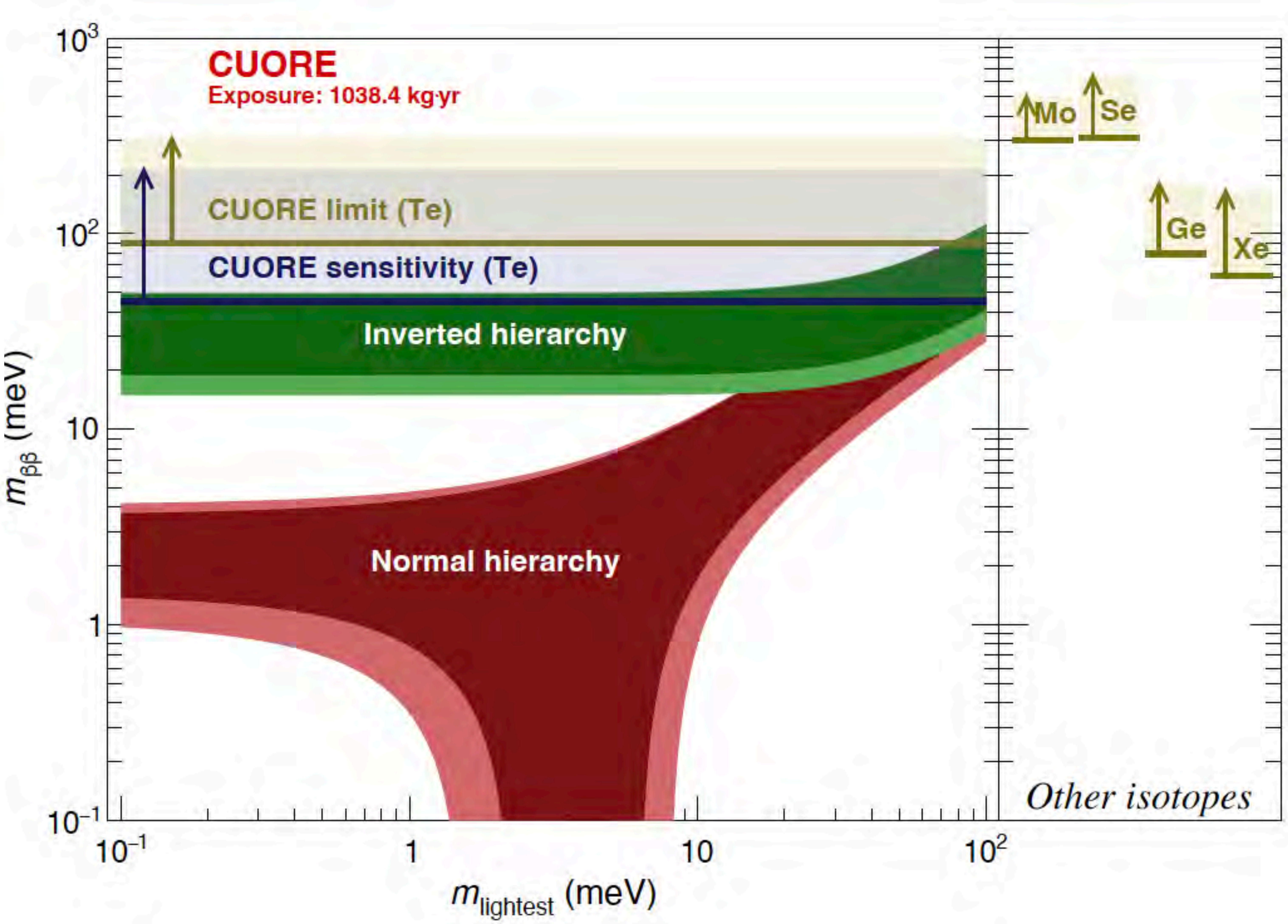
- Phase Space Factor
- Nuclear Matrix element
- Effective Majorona mass: a weighted sum of different ν flavors masses

CUORE 1 Tonne Limit:

$m_{\beta\beta} <$ 90-305 meV

CUORE Sensitivity (5 yrs)

$m_{\beta\beta} <$ 50 - 130 meV

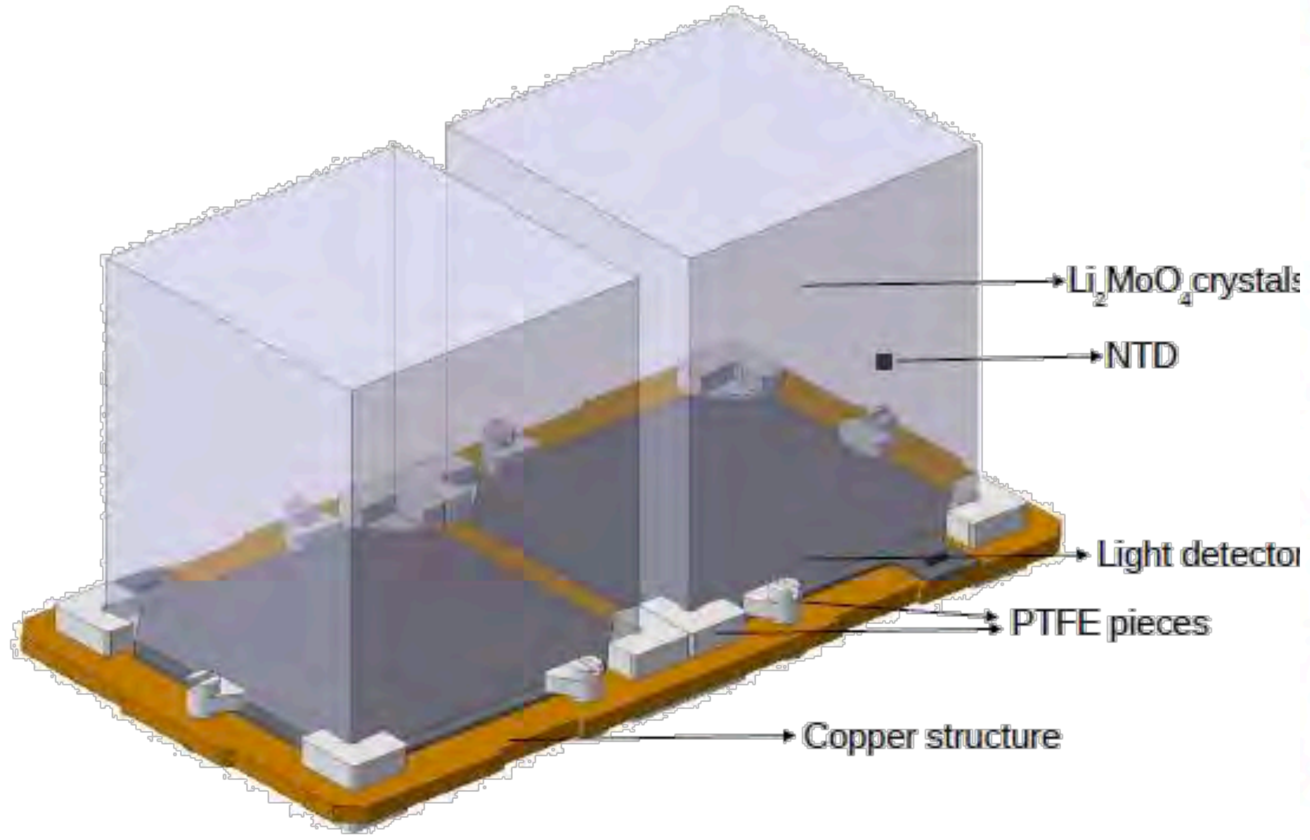


CUPID Detector

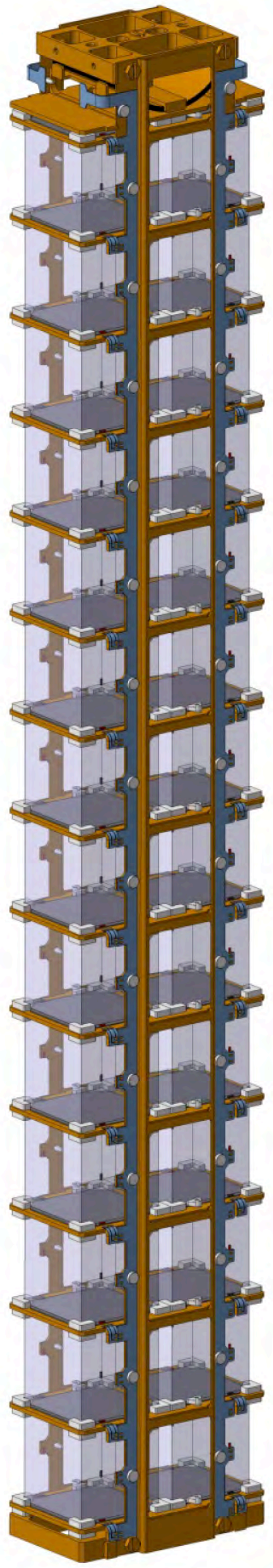
Single Detector

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

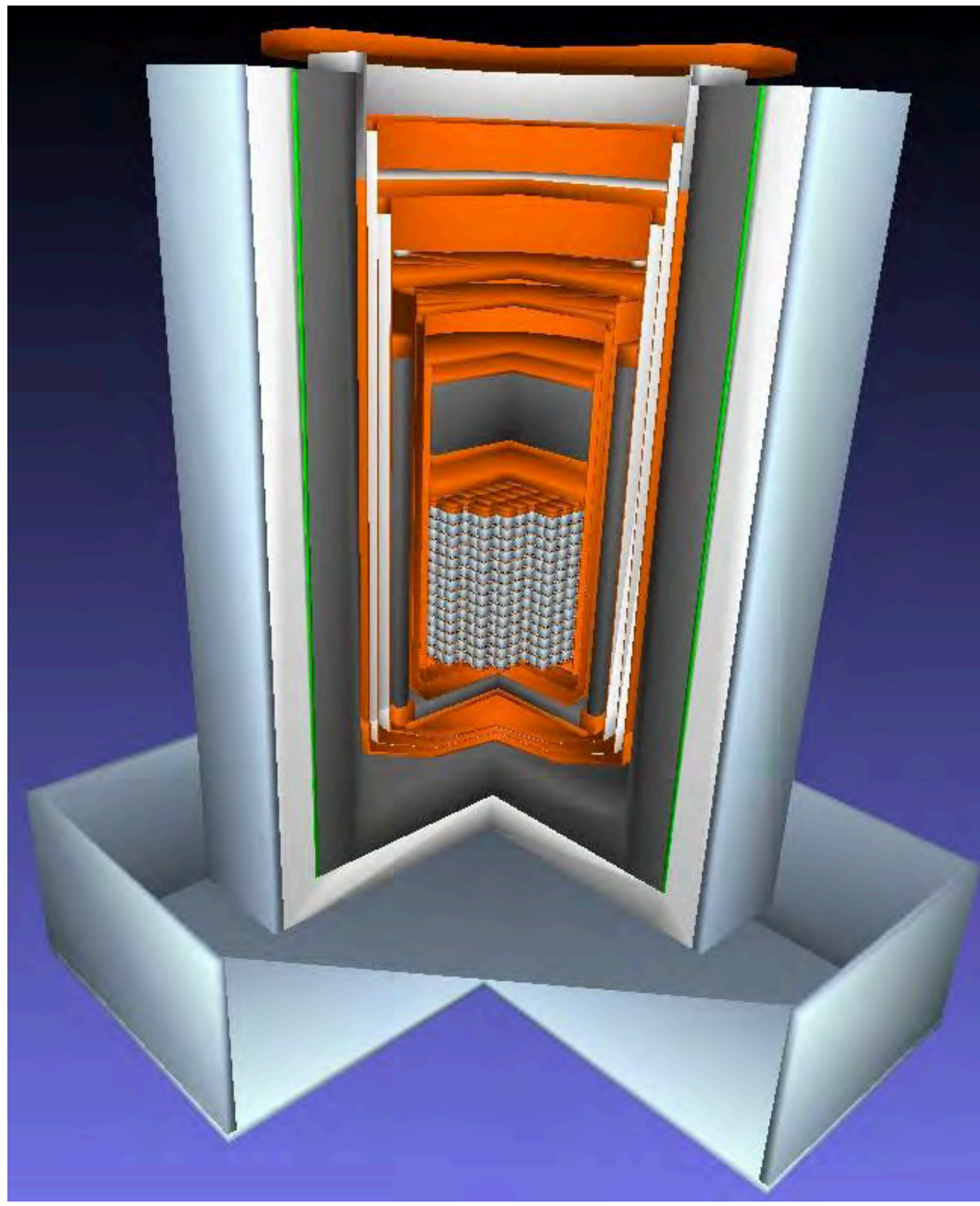
Ge light detector as in CUPID-Mo, CUPID-0



Gravity stacked structure
Crystals thermally interconnected



Tower



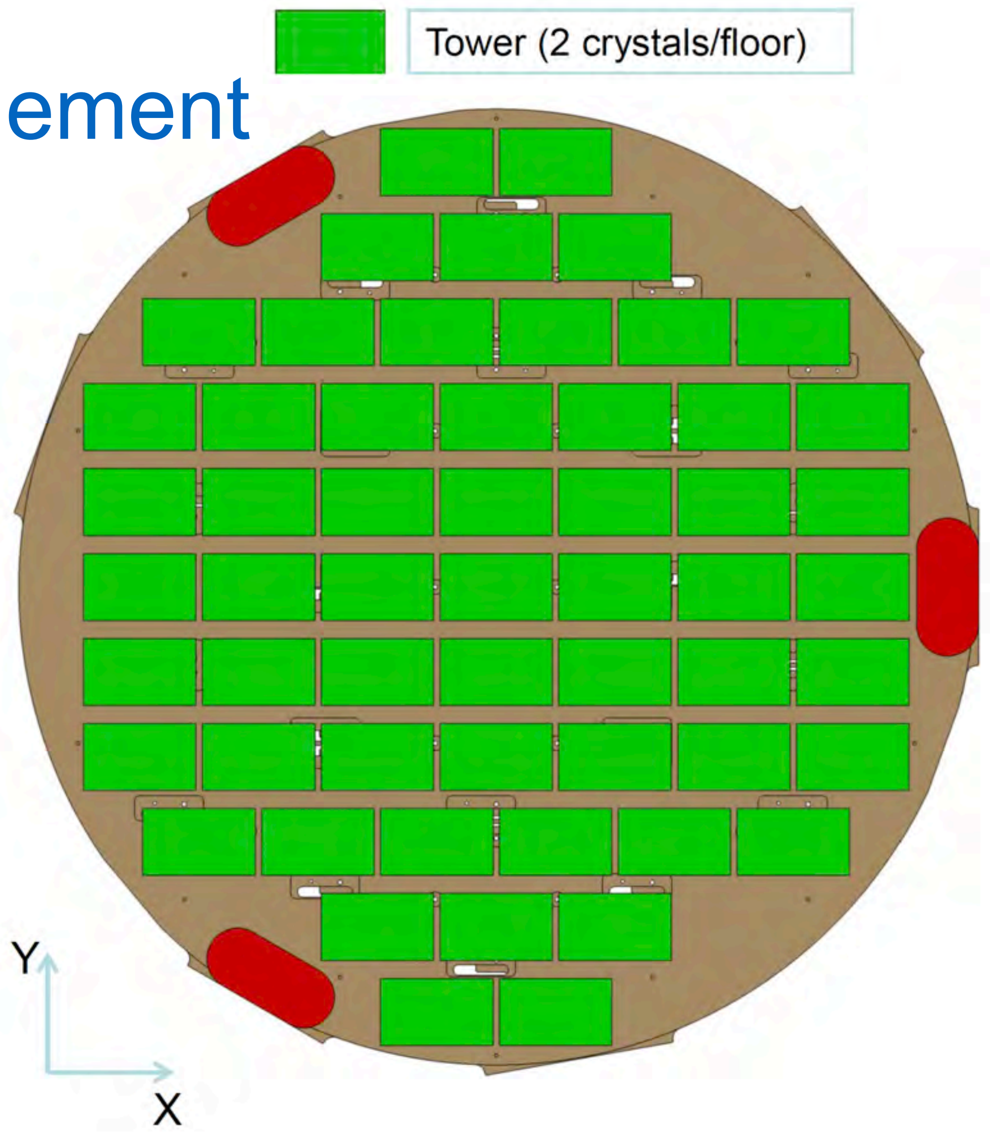
Detector Array

~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

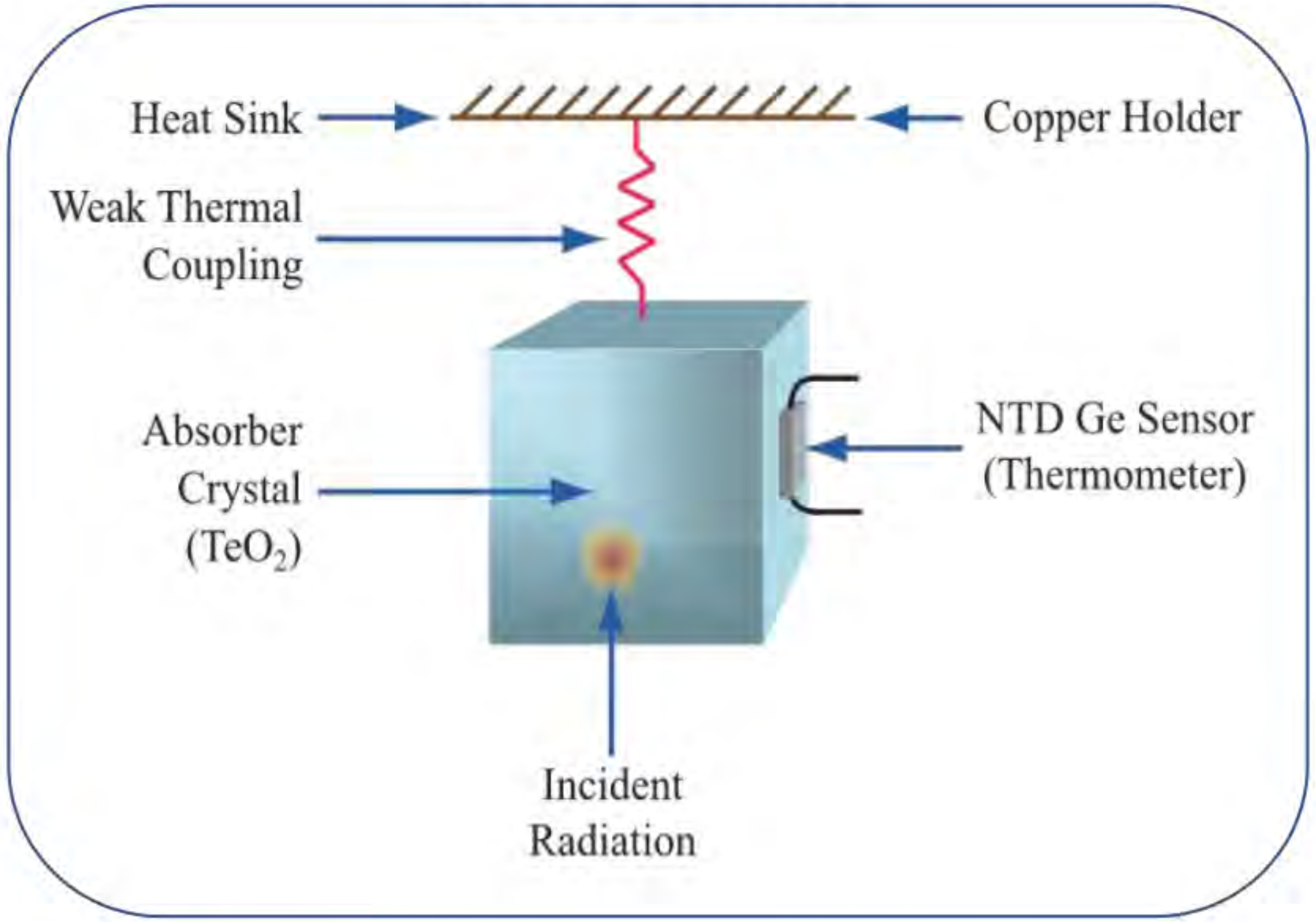
Tower Arrangement



Opportunity to deploy multiple isotopes, phased deployment

CUPID detector technology

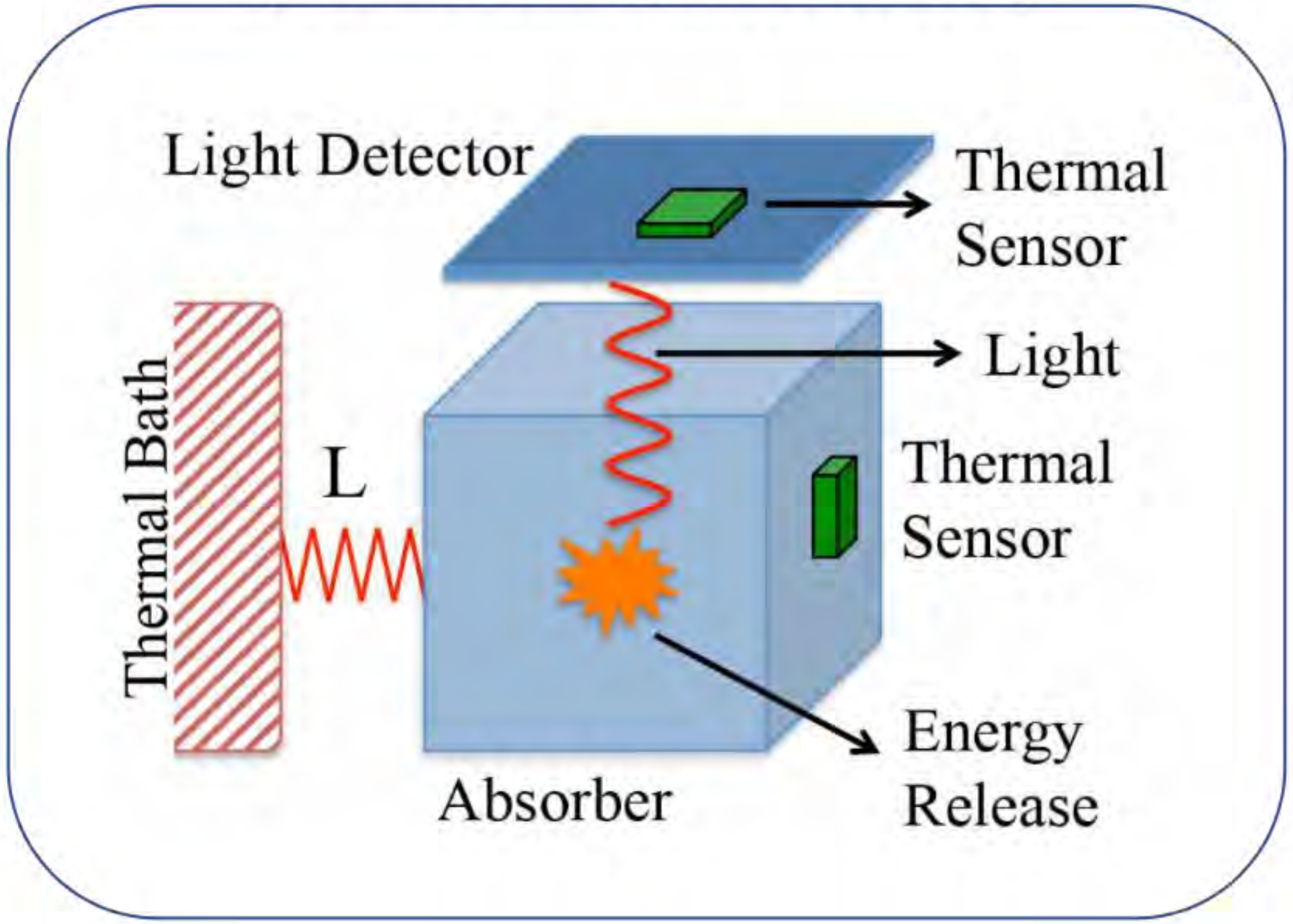
CUORE ^{130}Te
pure thermal detector
(bolometer)



PID → remove α

high Q → remove γ

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

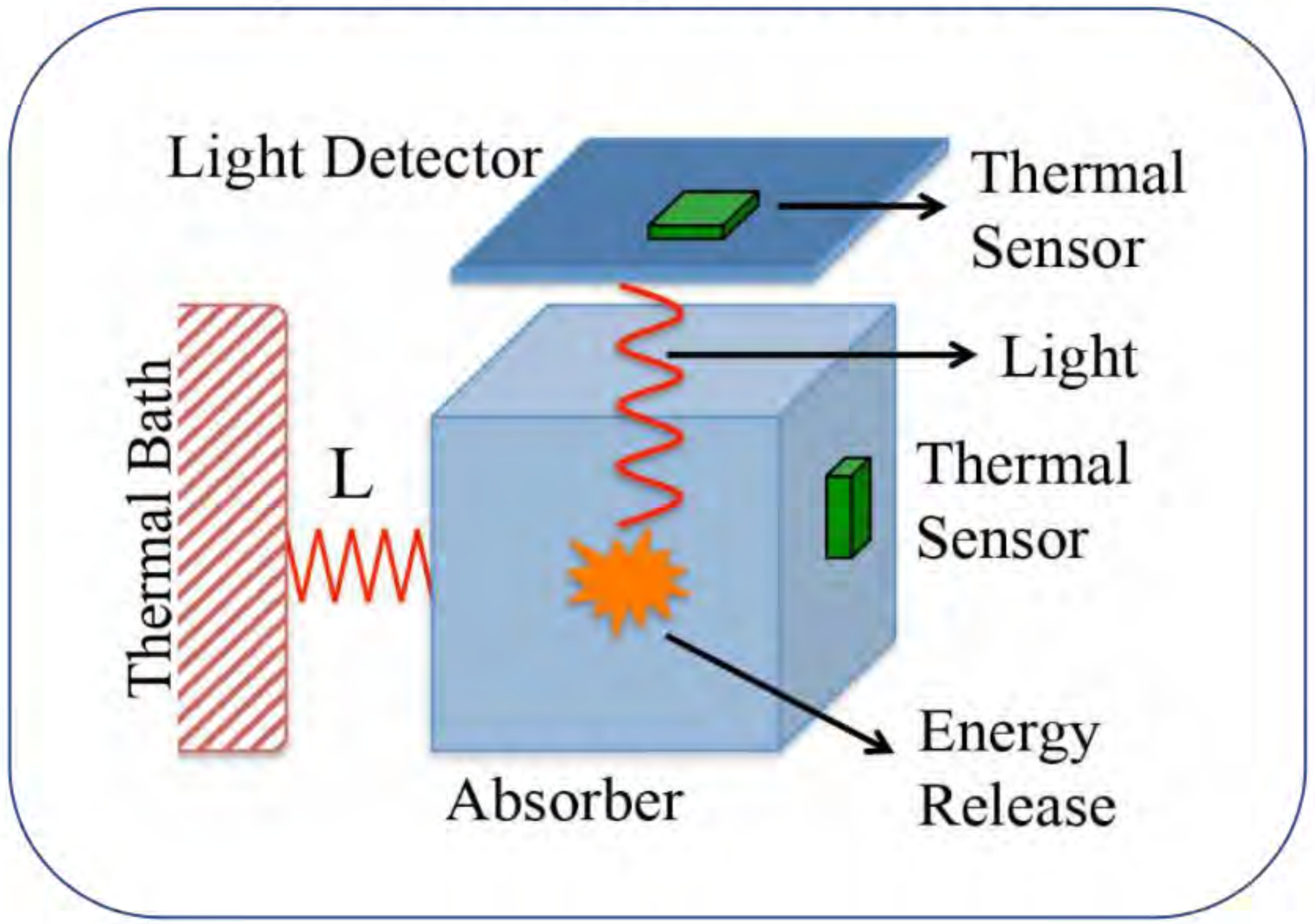


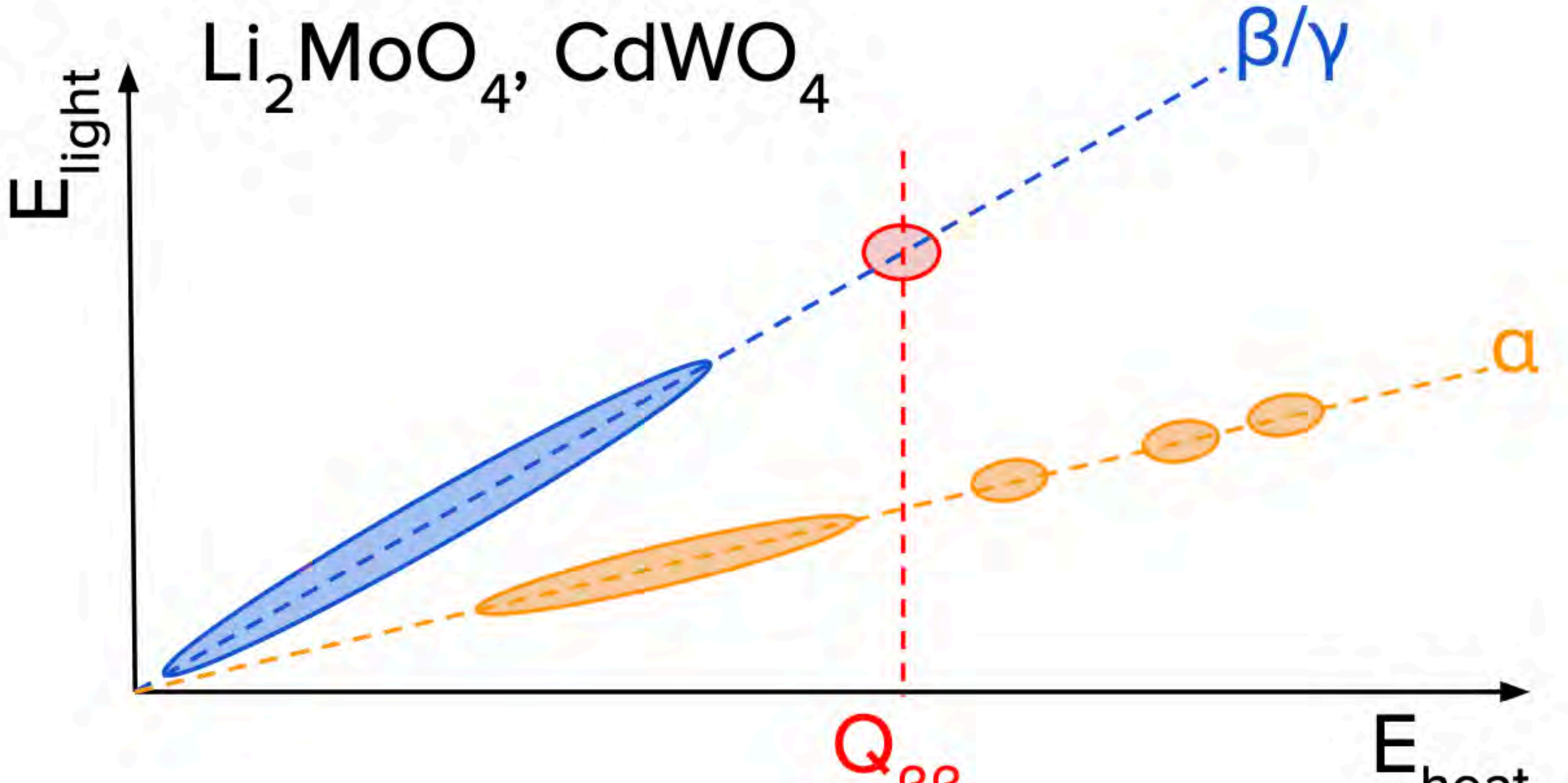
No PID
Q = 2527 keV **< 2615 keV**

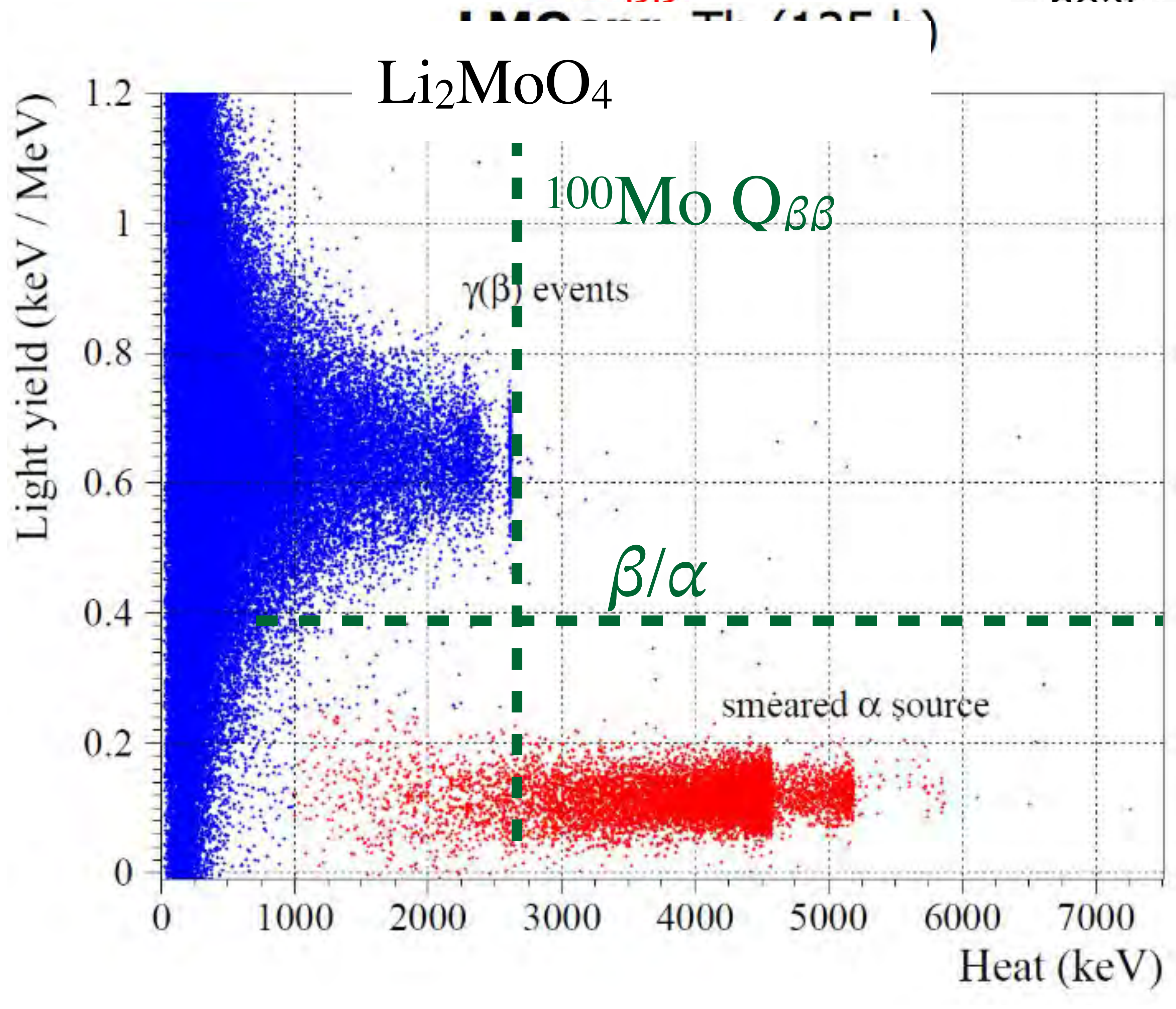
^{100}Mo **Q-value: 3034 keV**: β/γ background significantly reduced

CUPID Concept

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







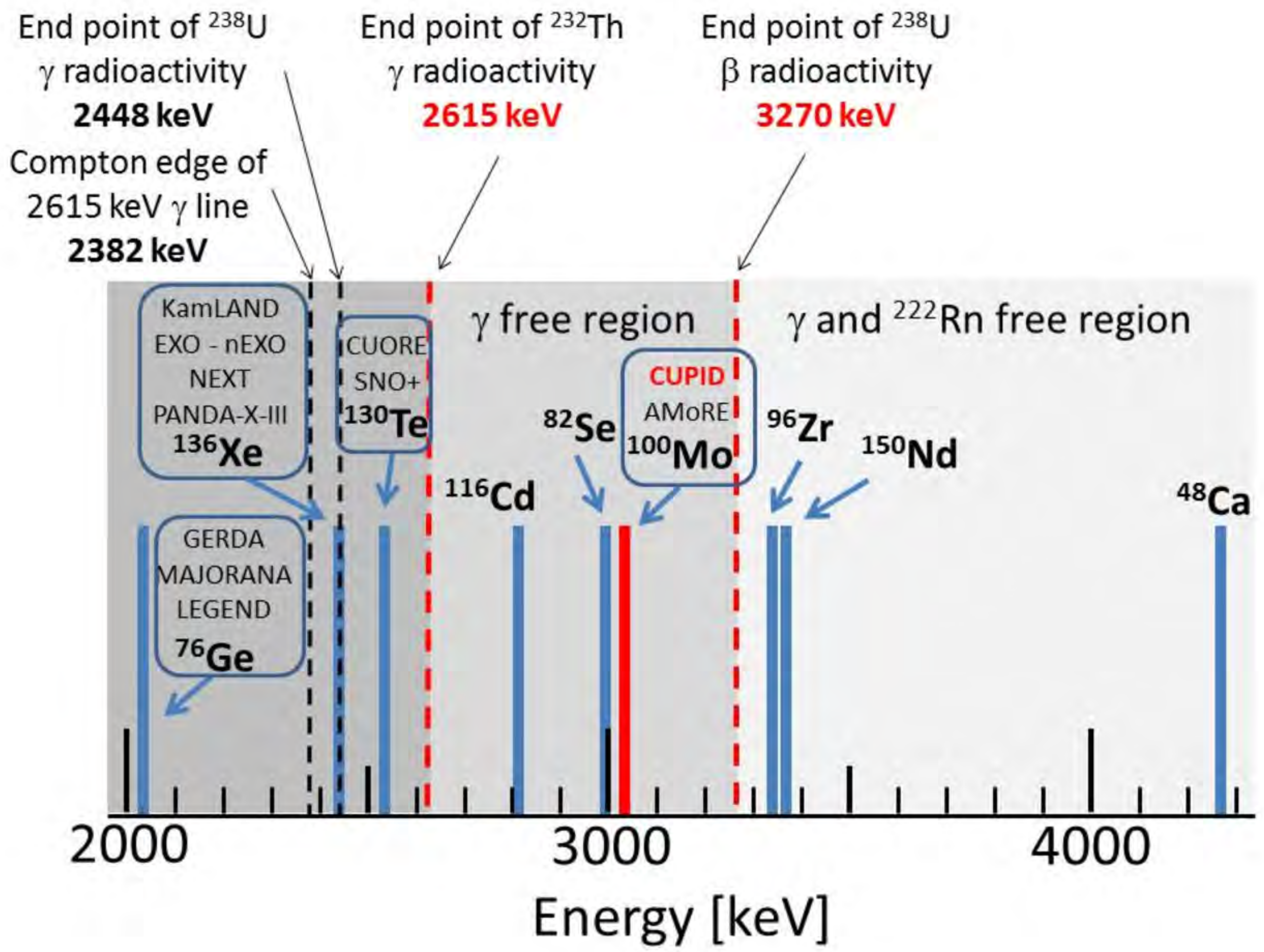
Measure heat and light from energy deposition

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

Actively discriminate α using measured light yield

Isotope choice

Balance between **performance** (background reduction, NME, detector performance) and **cost** (isotope enrichment, crystal growth). **Higher Q-value translates into smaller background**



^{100}Mo

- Q-value above most of natural radioactivity
- good quality scintillating crystals for α-β discrimination
- existing enrichment technology and interest for medical applications
- CUPID requires producing ~280 kg of ^{100}Mo

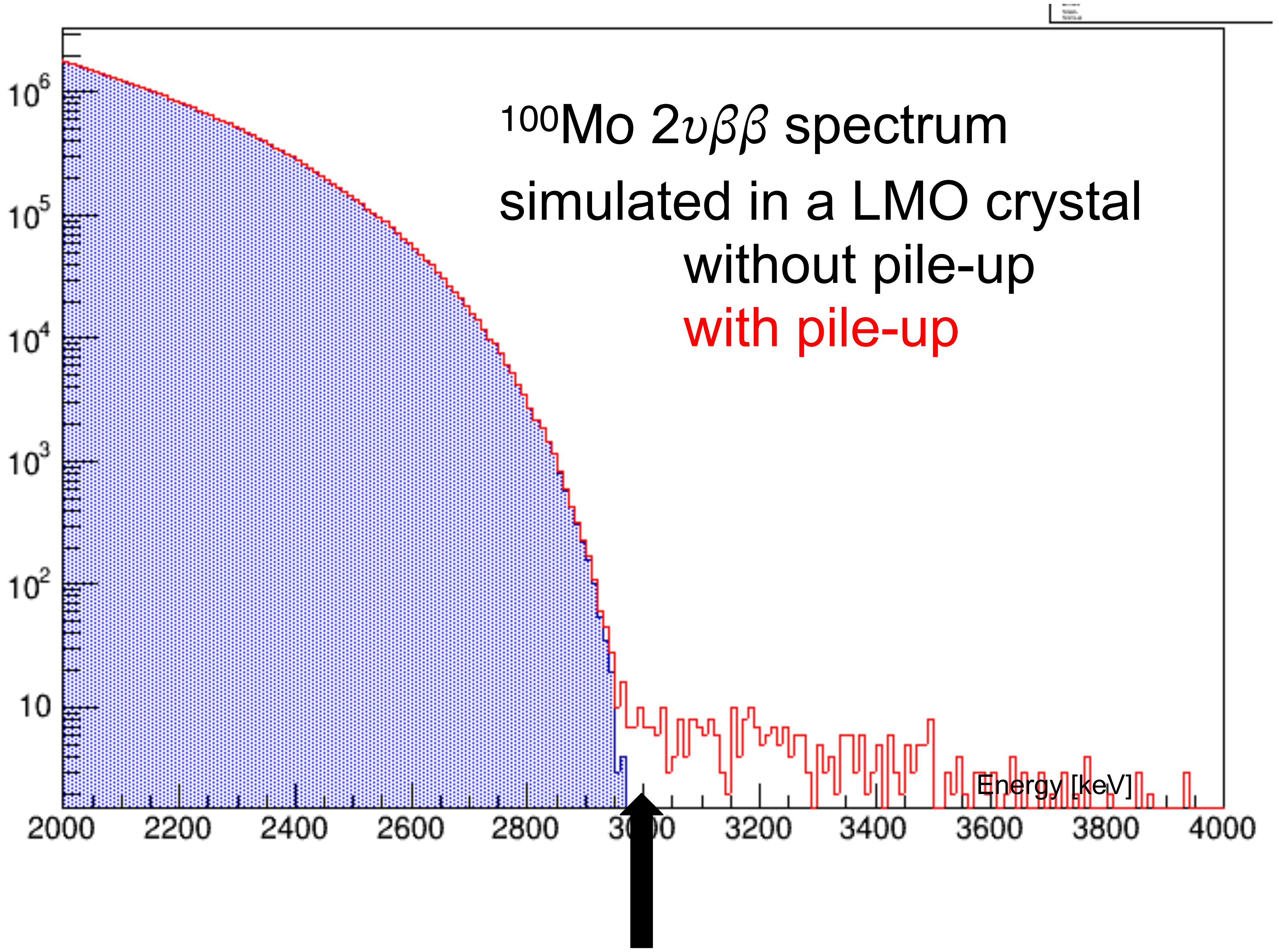
Karsten Heeger, Yale University

Background from ^{100}Mo 2vββ Pileup

^{100}Mo $2\upsilon\beta\beta$ half-life ~ 7 x 10^{18} yr

rate ~ 3 mHz/crystal

pile-up events may populate the 0vββ ROI



$Q_{\beta\beta}$ ~3034 keV

Pile-up discrimination depends

LMO and light detector risetime and S/N

read-out & DAQ band-width

noise (vibration reduction)

analysis algorithms

demonstrated	**$< 1\times10^{-4}$ counts/(keV·kg·yr)**
goal (test on-going)	$< 0.5 \times10^{-4}$ counts/(keV·kg·yr)

CUPID Sensitivity to 0νββ

Baseline

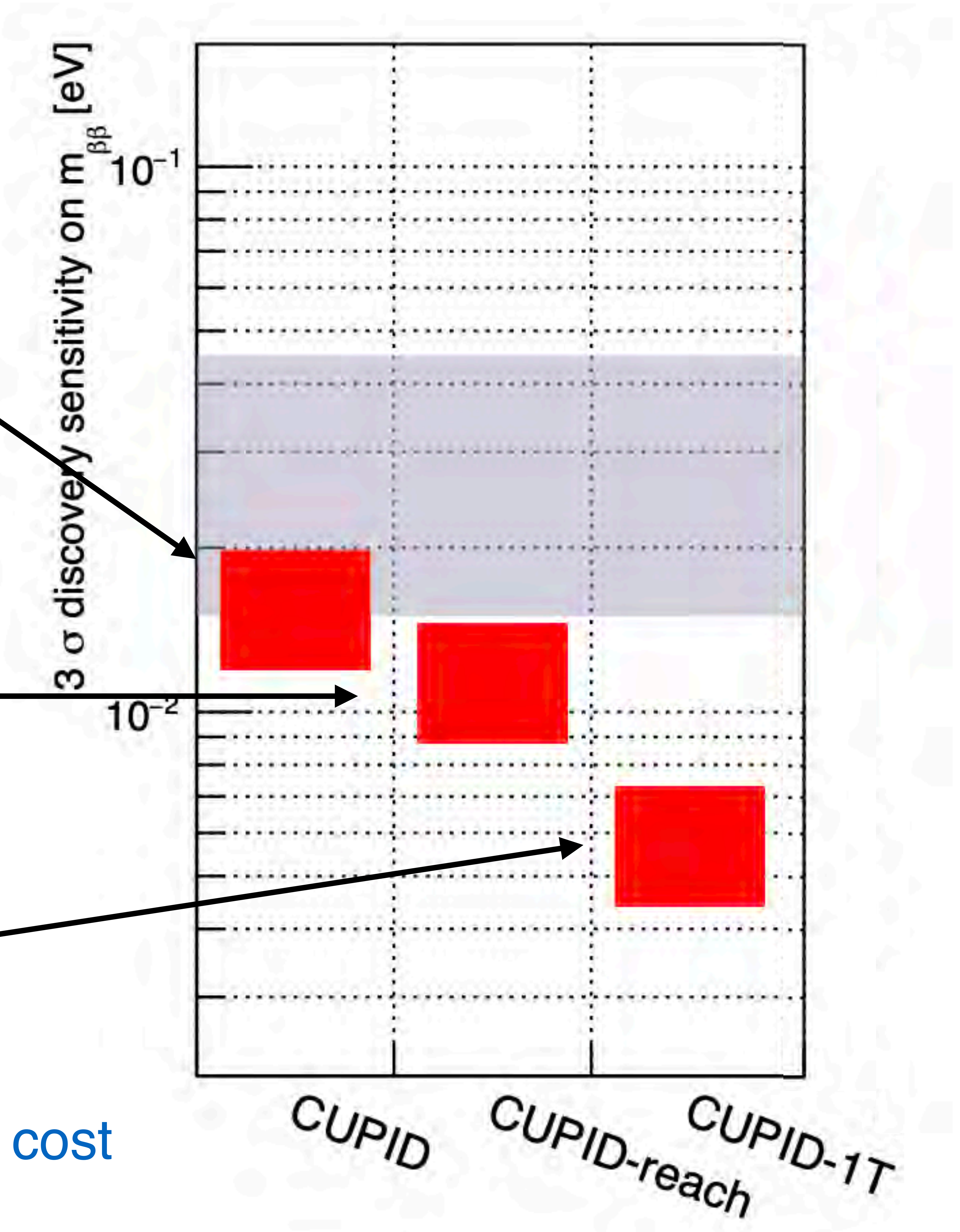
- Mass: 450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr
- Discovery sensitivity **$T_{1/2} > 1.1\times10^{27}$ yr (3σ)**
- Conservative, limited R&D

Reach

- R&D for further background reduction by radio purity and reduce pileup background
- Discovery sensitivity **$T_{1/2} > 2\times10^{27}$ yr (3σ)**

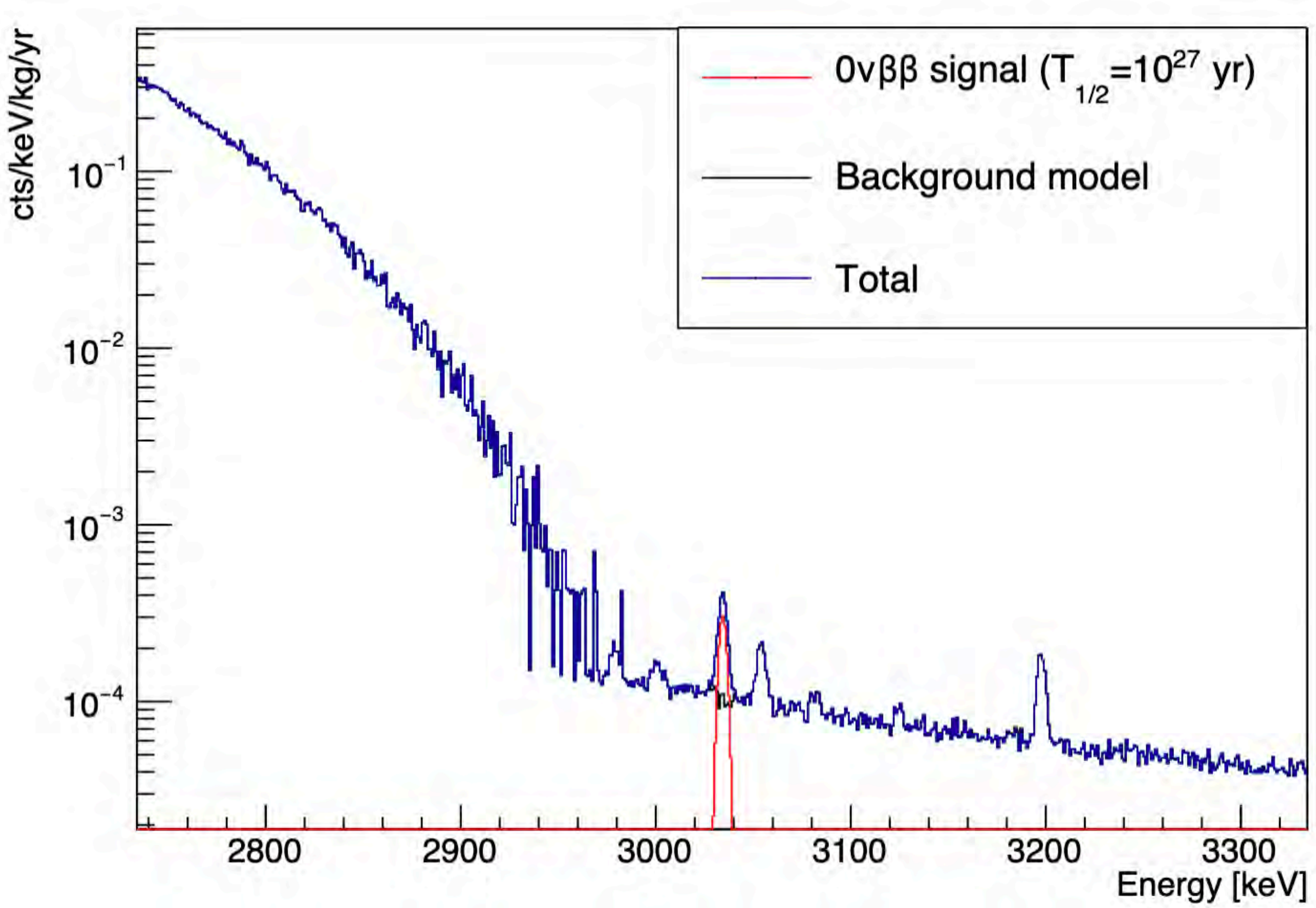
1-Ton

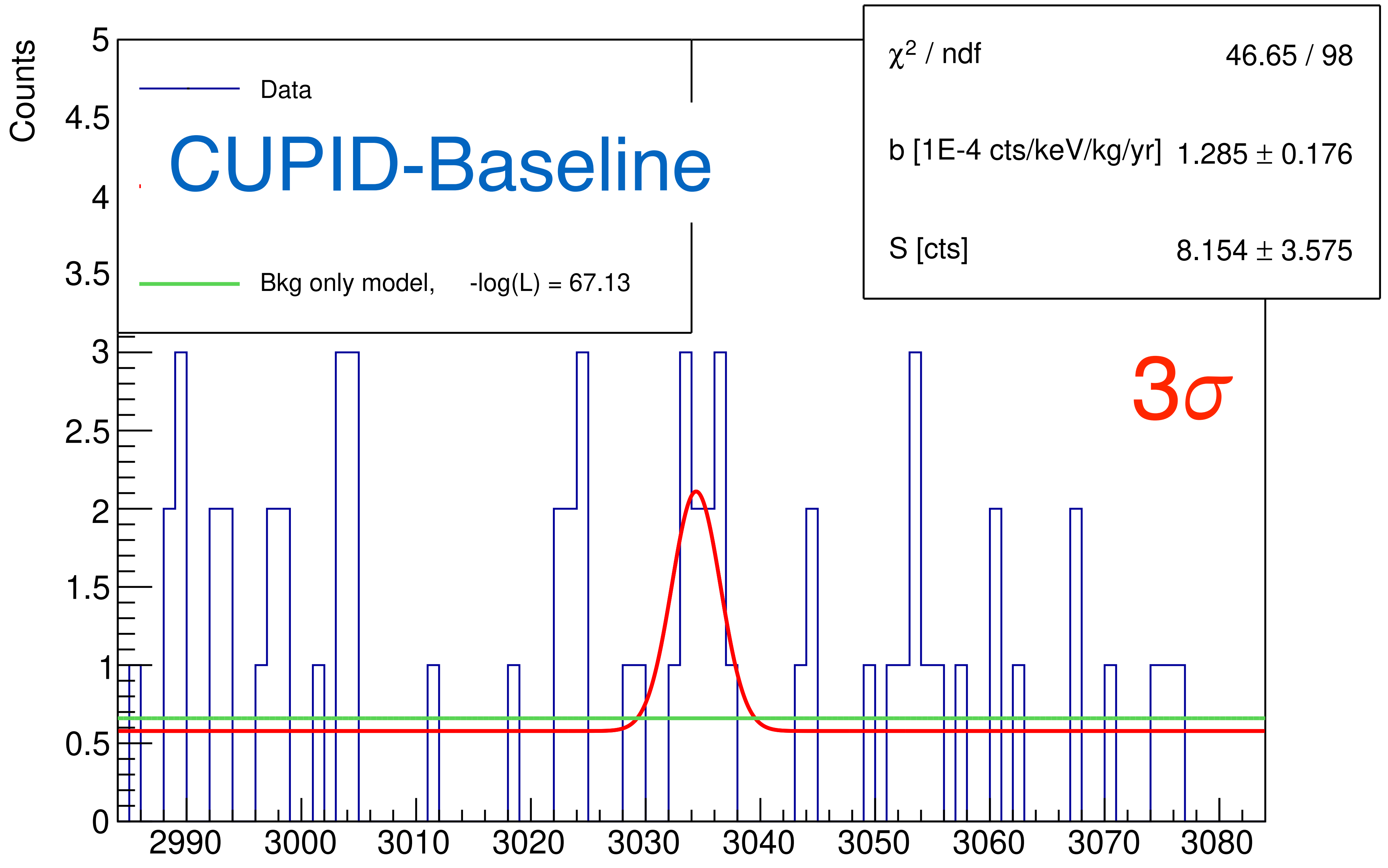
- 1000 kg of ^{100}Mo
- Discovery sensitivity **$T_{1/2} > 8\times10^{27}$ yr (3σ)**

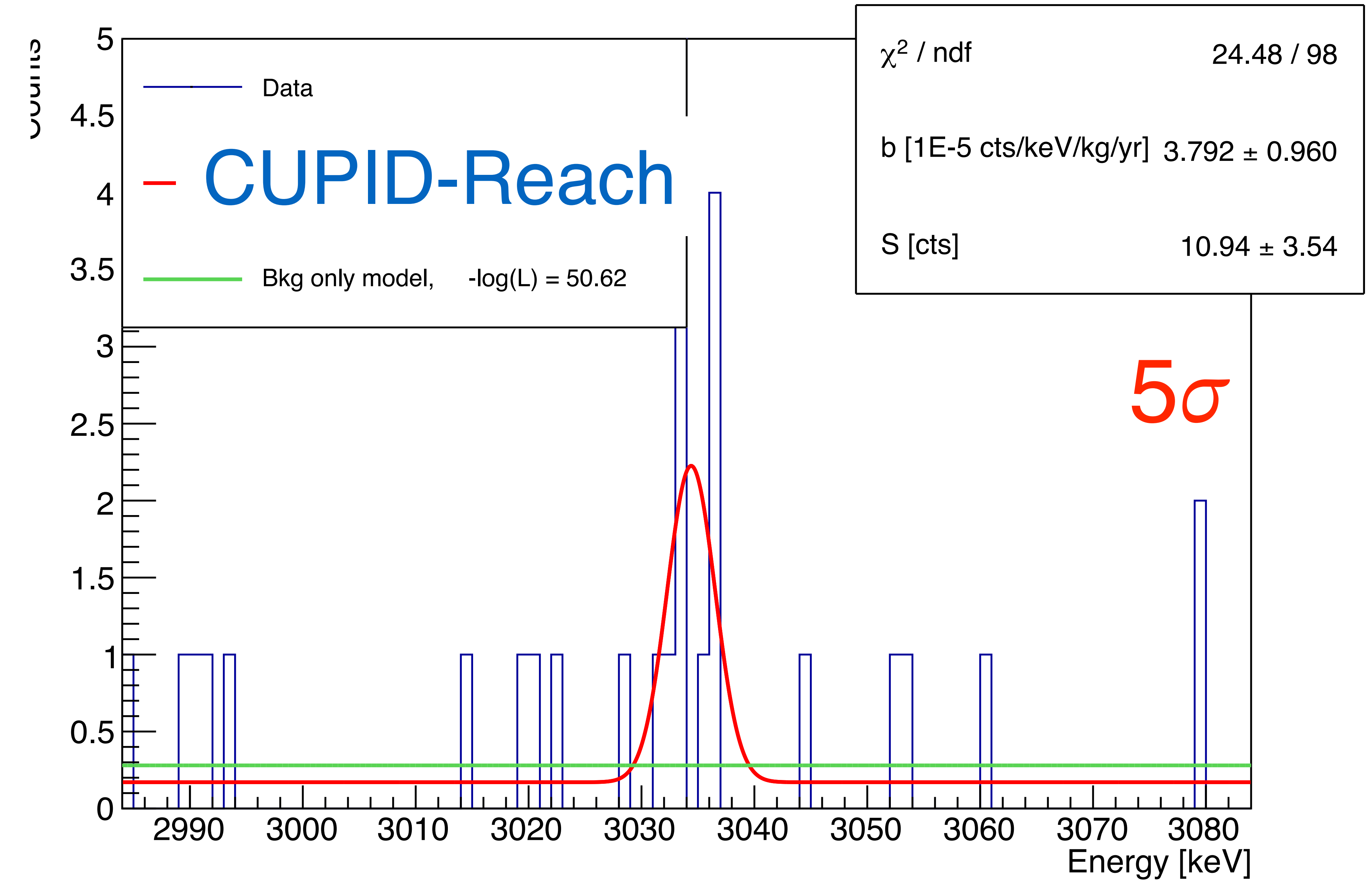


CUPID-1T is within technical reach, limited by timeline and cost

CUPID Signal: Preparing for Discovery







Example of toy experiments simulated for 10-year exposure and $T_{1/2}(^{100}\mathrm{Mo})=10^{27}$ years.

If signal is seen, modular detector allows data taking with different isotopes.

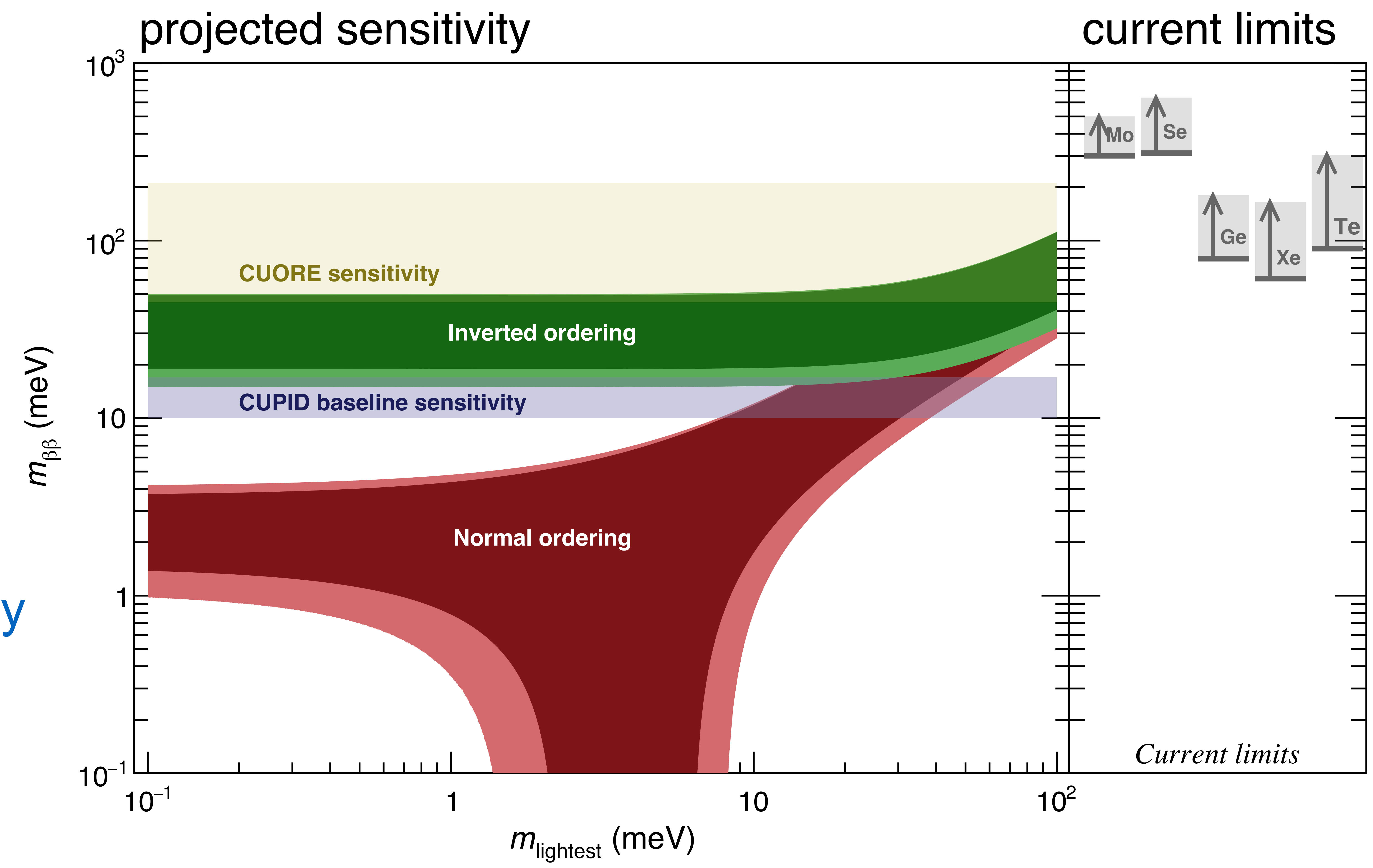
Envision CUPID to be part of a world-wide suite of experiments to discover 0νββ.

Multiple experiments will be needed to establish discovery.

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



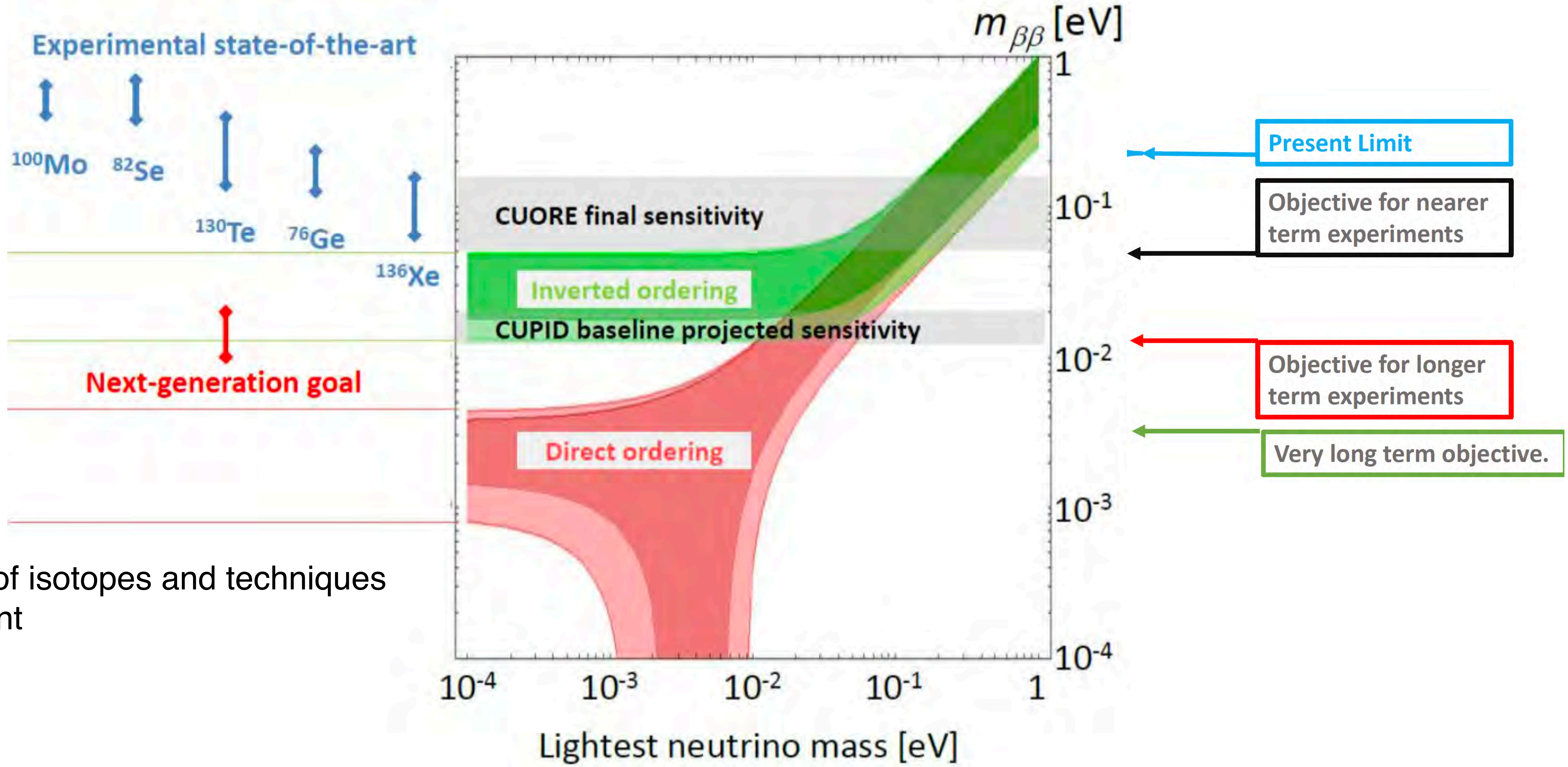
CUPID Baseline Discovery Sensitivity

$T_{1/2}$ > **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

Sensitivity of Future 0νββ Searches



Present Limit

Objective for nearer term experiments

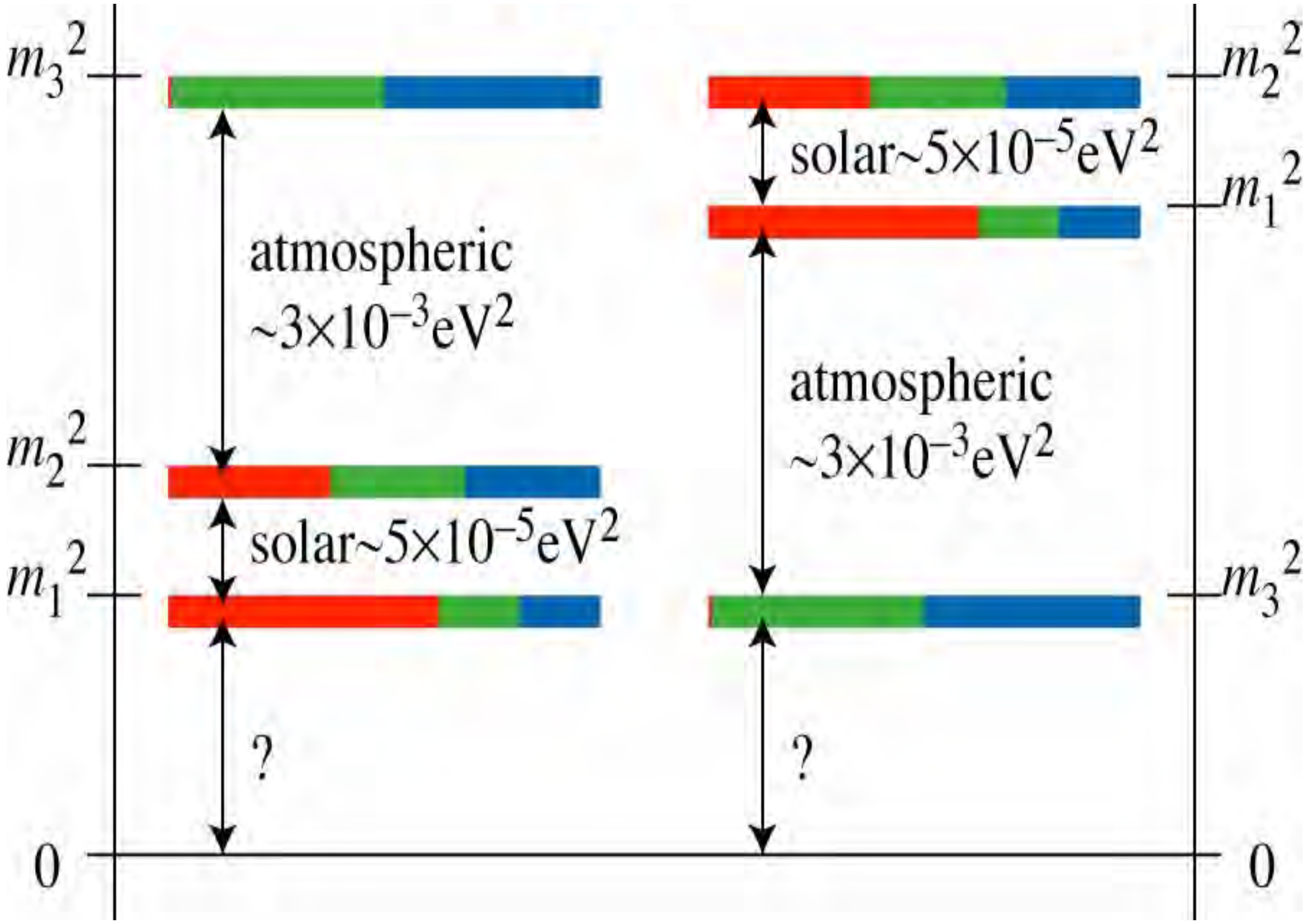
Objective for longer term experiments

Very long term objective.

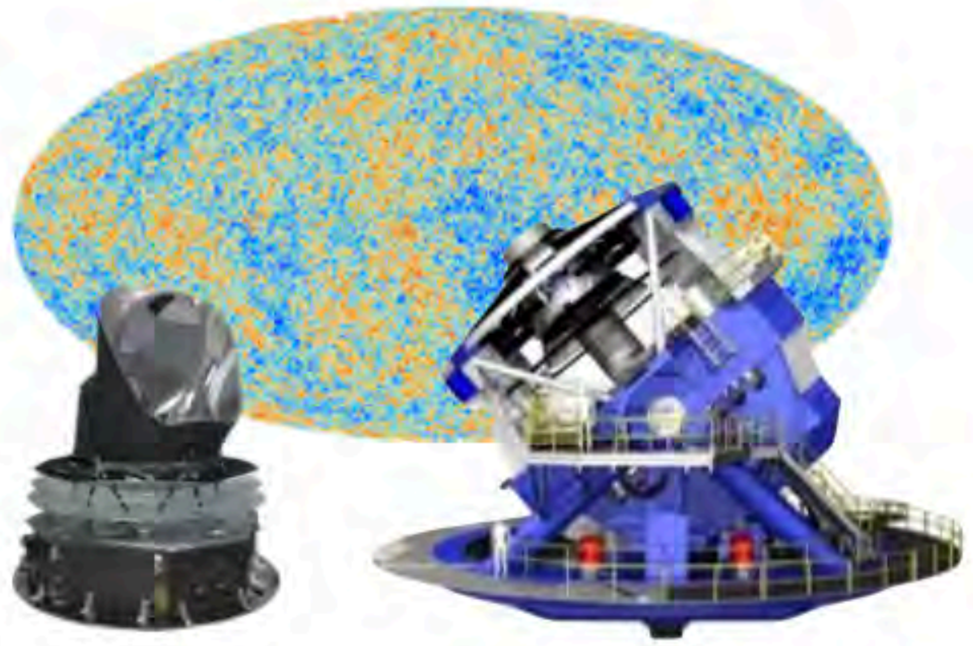
variety of isotopes and techniques important

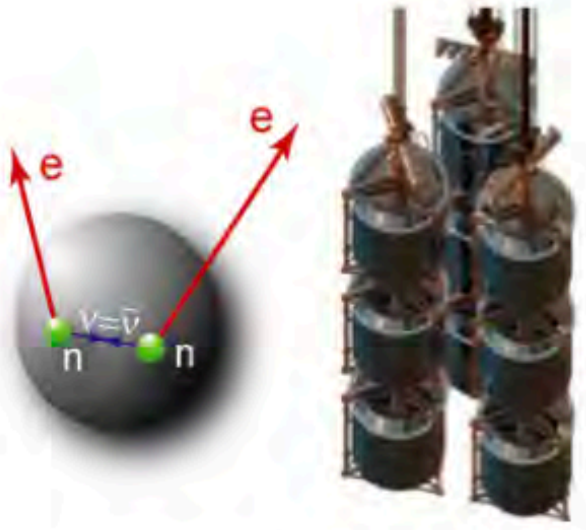
Designing for discovery experiments
A discovery in the next 10-15 years possible

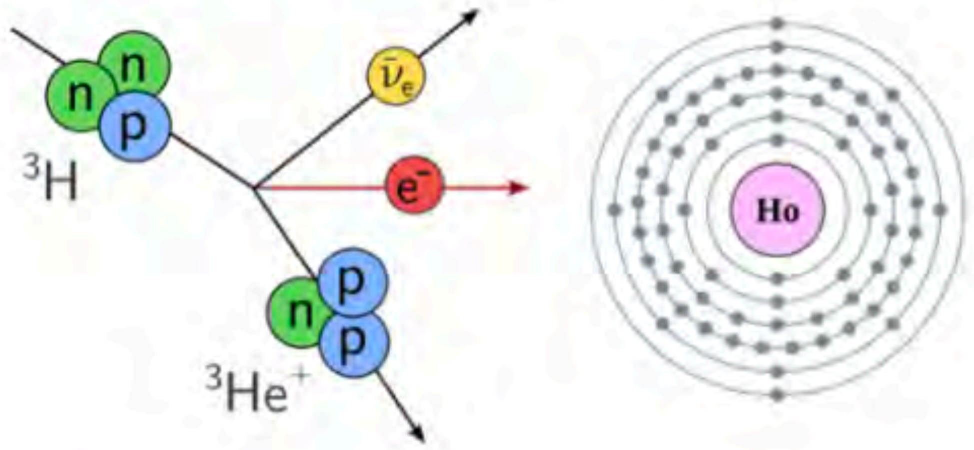
What is the mass scale?



Paths to the Neutrino Mass Scale



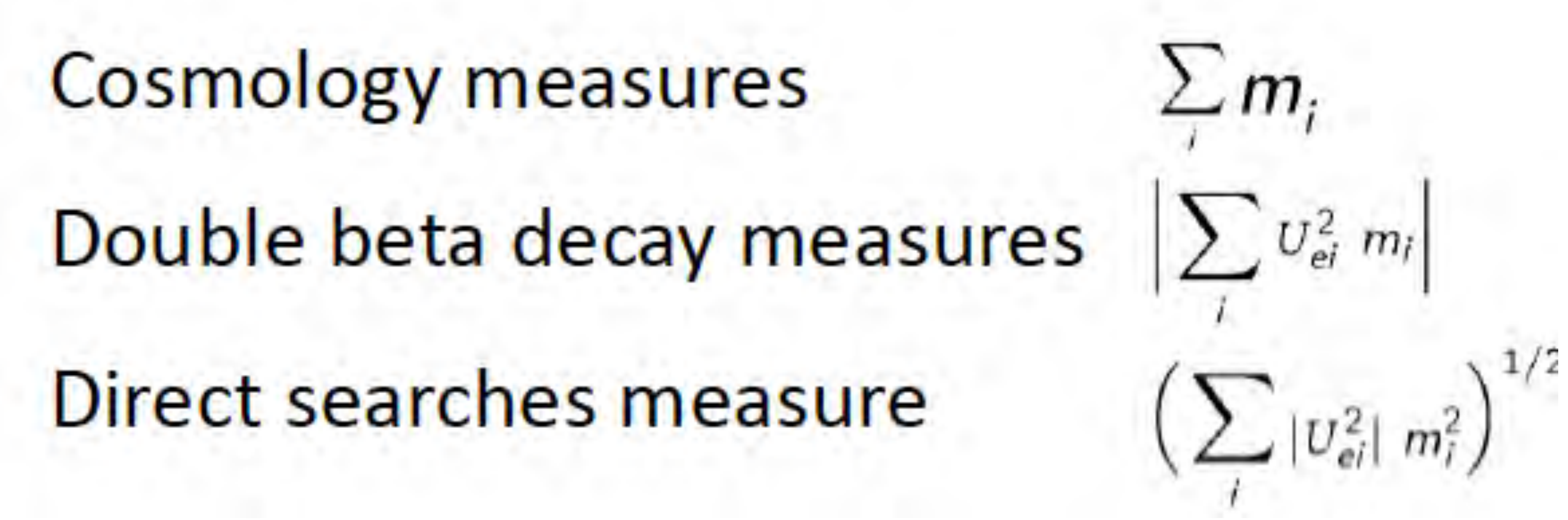




	Cosmology	Search for 0νββ	β-decay & electron capture
Observable	$M_\nu = \sum_i m_i$	$m_{\beta\beta}^2 = \left\|\sum_i U_{ei}^2 m_i\right\|^2$	$m_\beta^2 = \sum_i \|U_{ei}\|^2 m_i^2$
Present upper limit	~0.1 – 0.6 eV	~0.1 – 0.4 eV	~~2 eV~~ **0.8 eV**
Potential: near-term (long-term)	60 meV (15 meV)	50 – 200 meV (20 – 40 meV)	200 meV (40 – 100 meV)
Model dependence	Multi-parameter cosmological model	- Majorana nature of ν, lepton number violation - BSM contributions other than m(ν)? - Nuclear matrix elements	**Direct,** only kinematics; no cancellations in incoherent sum

K. Valerius

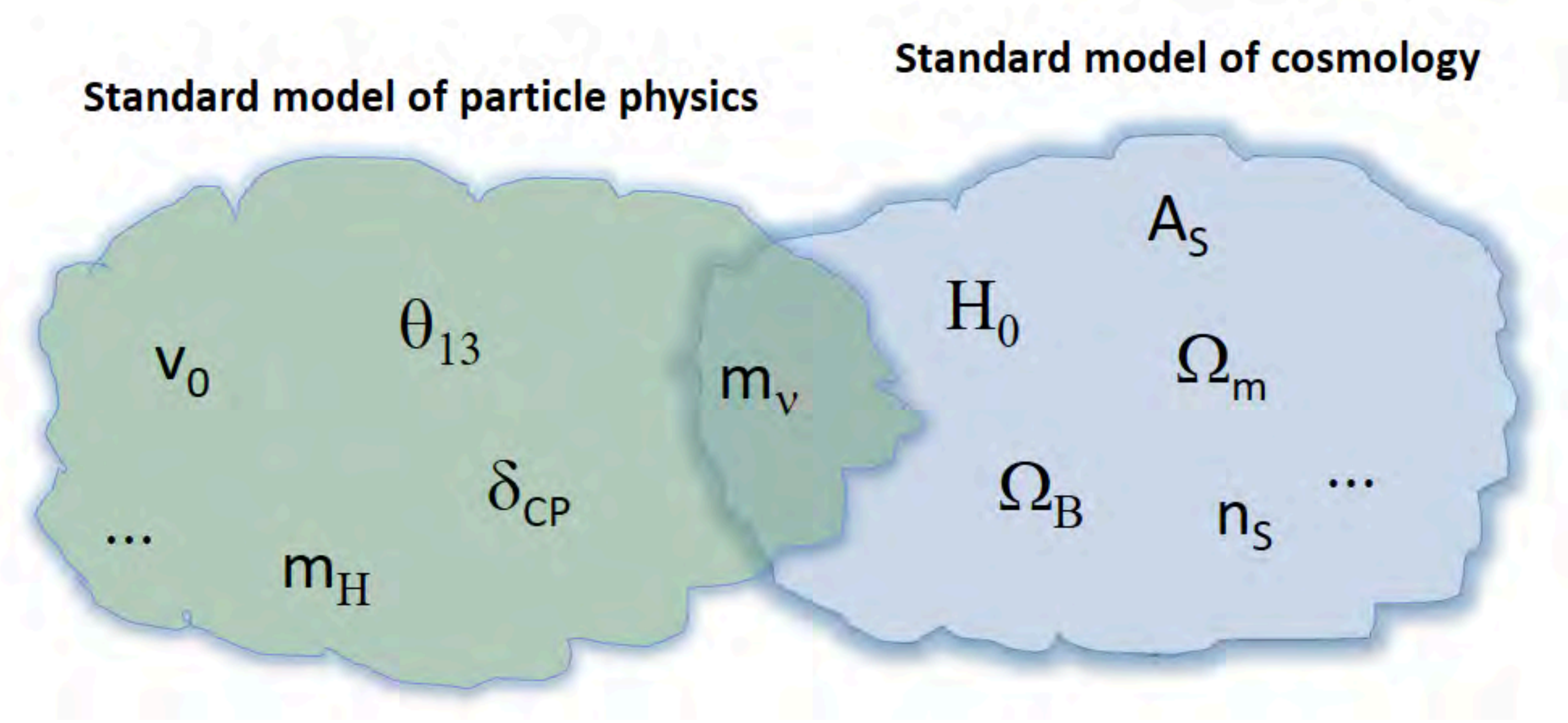
Neutrino Mass Constraints

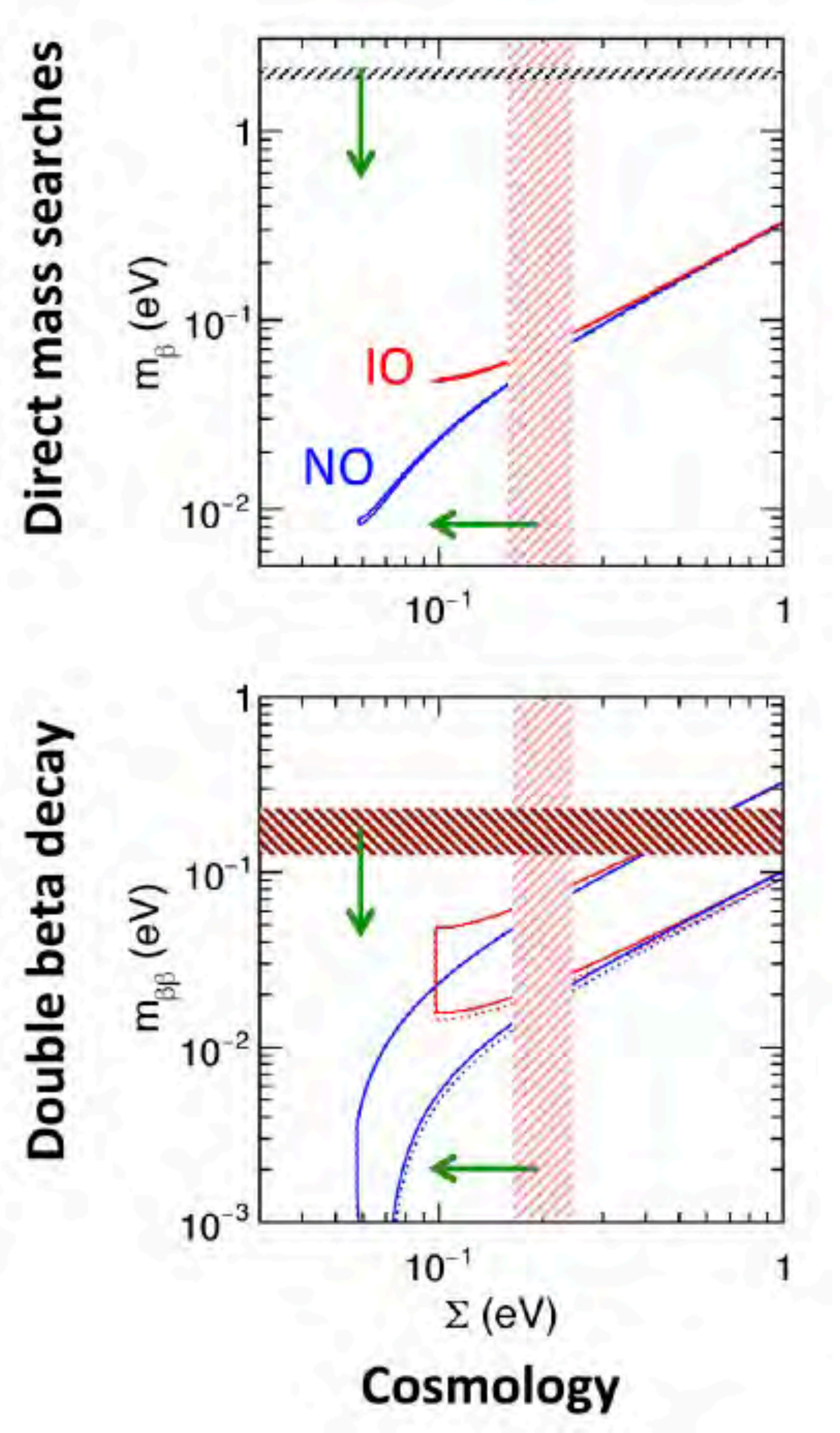


Cosmology measures	$\sum_i m_i$
Double beta decay measures	$\left\lvert\sum_i U_{ei}^2\, m_i\right\rvert$
Direct searches measure	$\left(\sum_i \lvert U_{ei}^2\rvert\, m_i^2\right)^{1/2}$

m_ν measurable both by laboratory experiments and cosmology

a critical test of consistency





Mezetto

Neutrino Mass Constraints

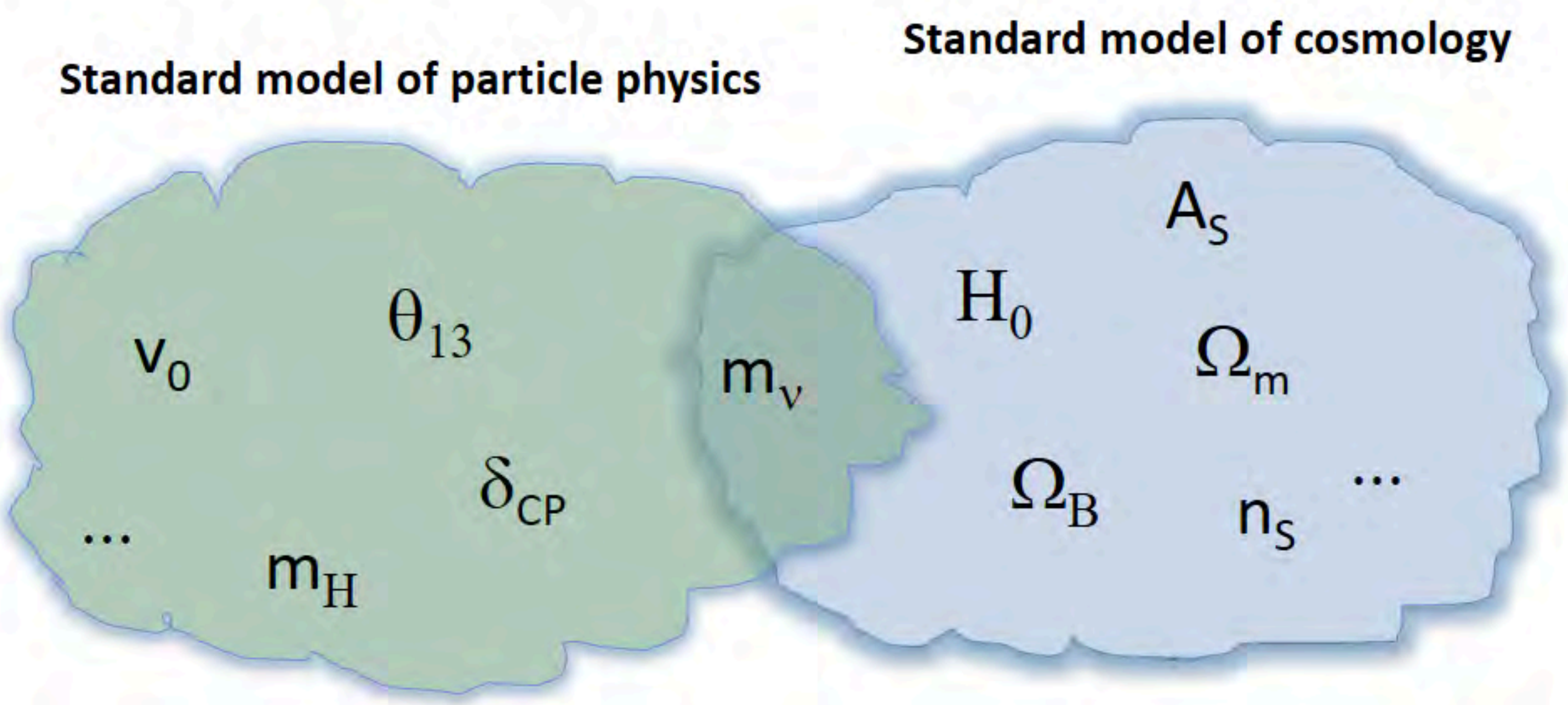
Cosmology measures $\sum_i m_i$

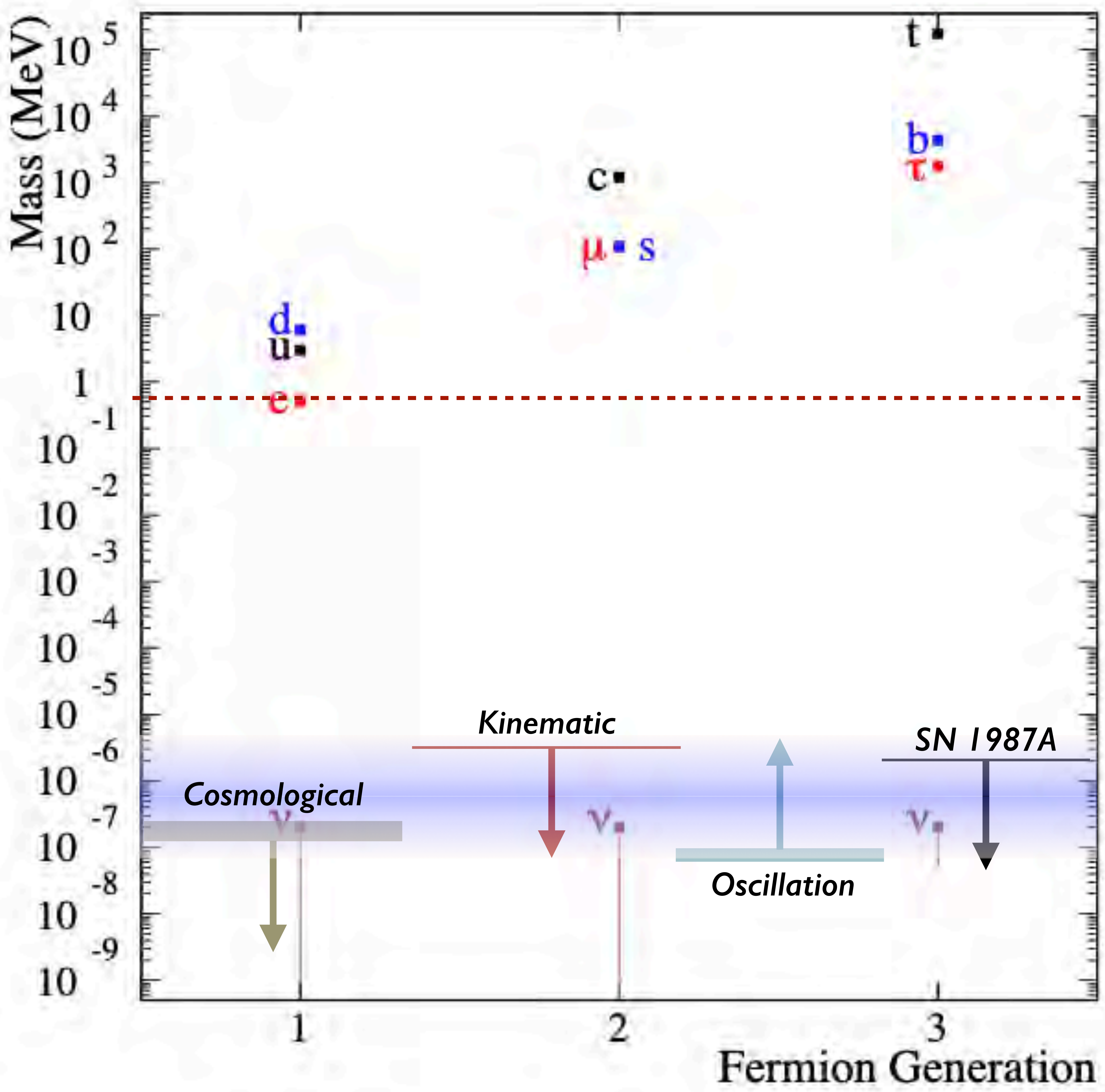
Double beta decay measures $\left|\sum_i U_{ei}^2\, m_i\right|$

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

m_ν measurable both by laboratory experiments and cosmology

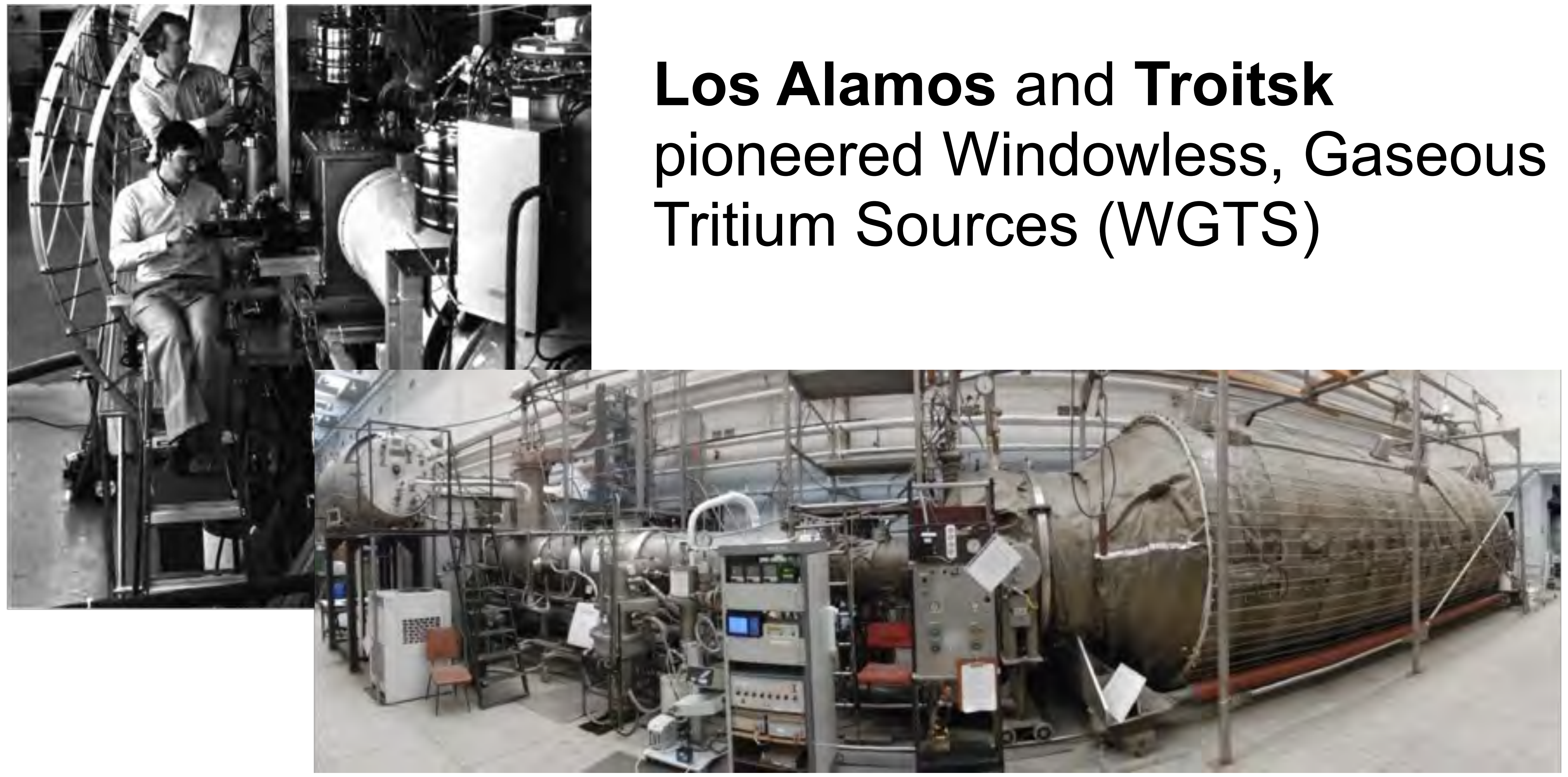
a critical test of consistency





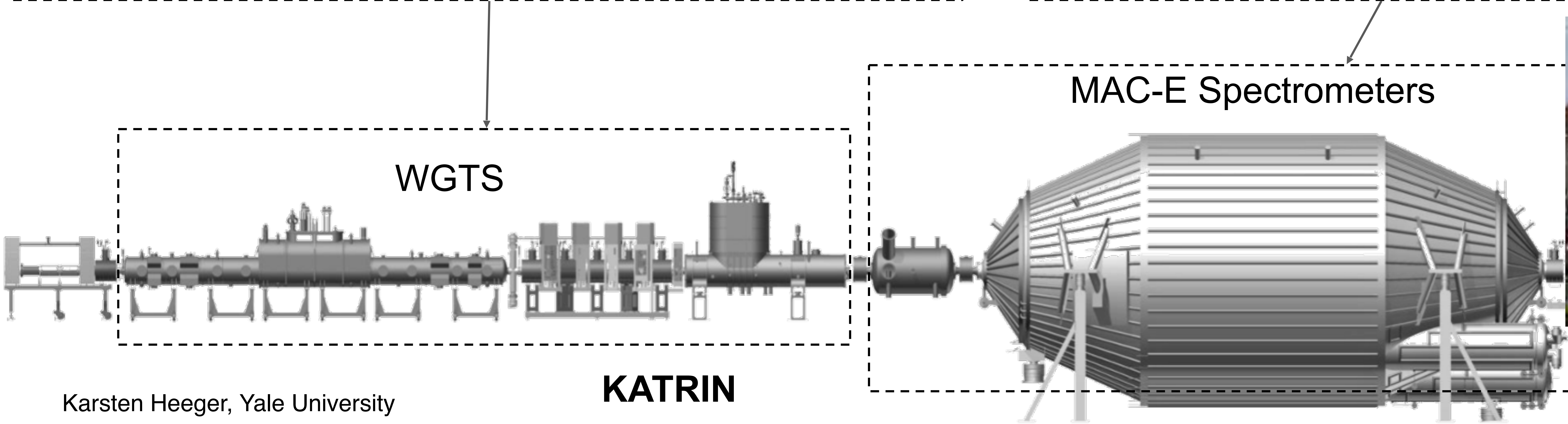
Adapted from arXiv:0604021

Direct Neutrino Mass Measurements



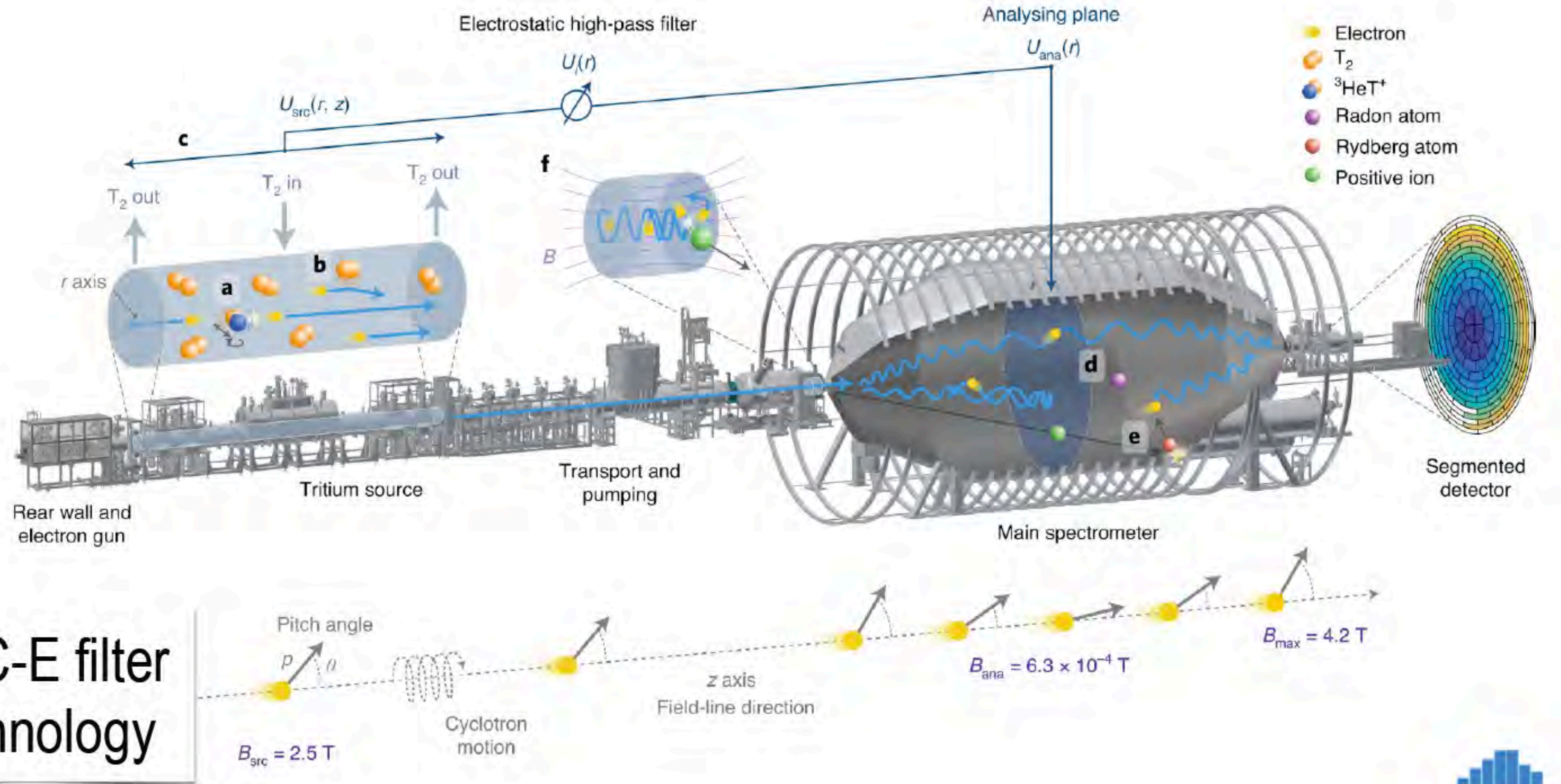
Los Alamos and **Troitsk** pioneered Windowless, Gaseous Tritium Sources (WGTS)

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



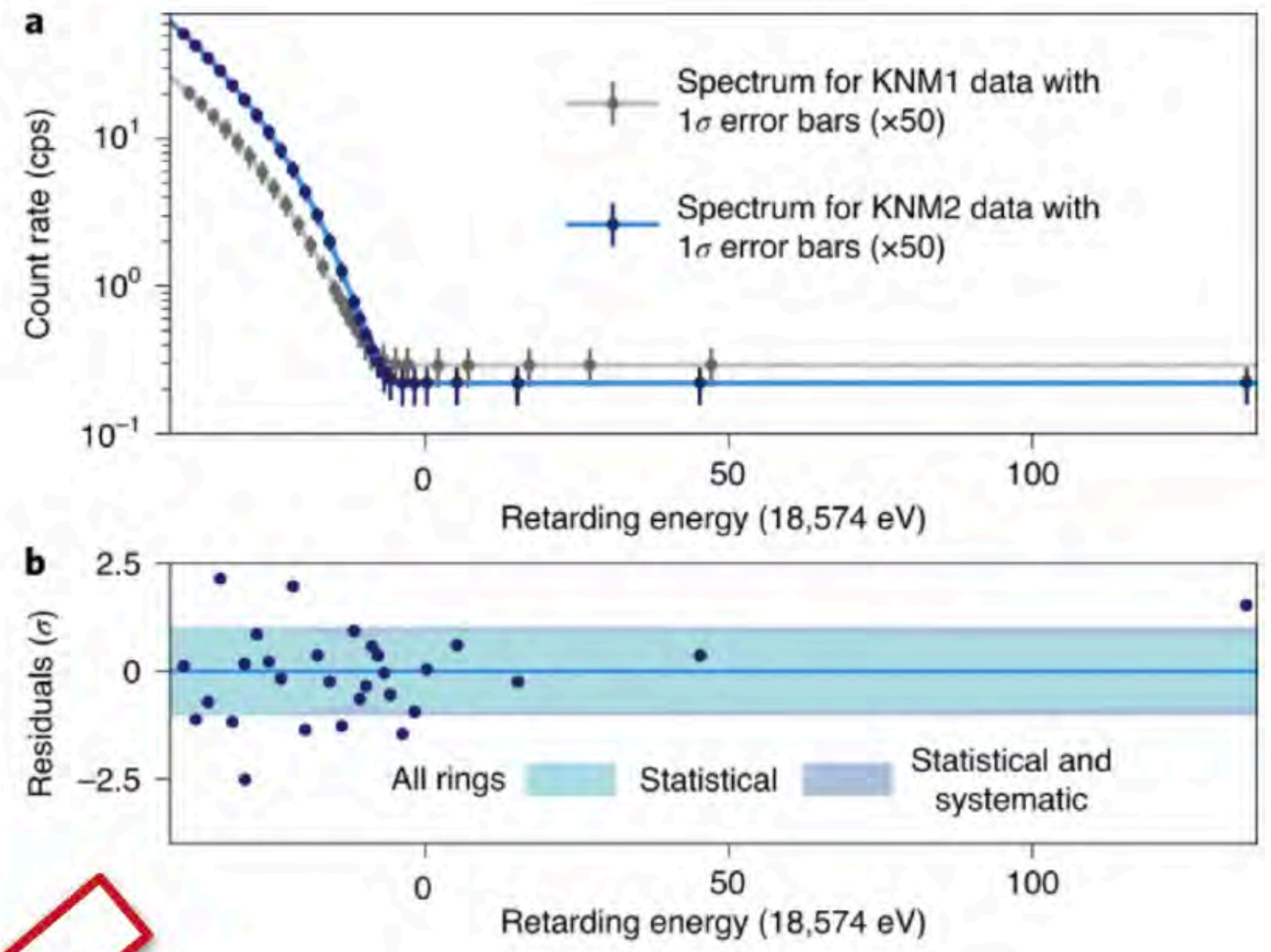
KATRIN

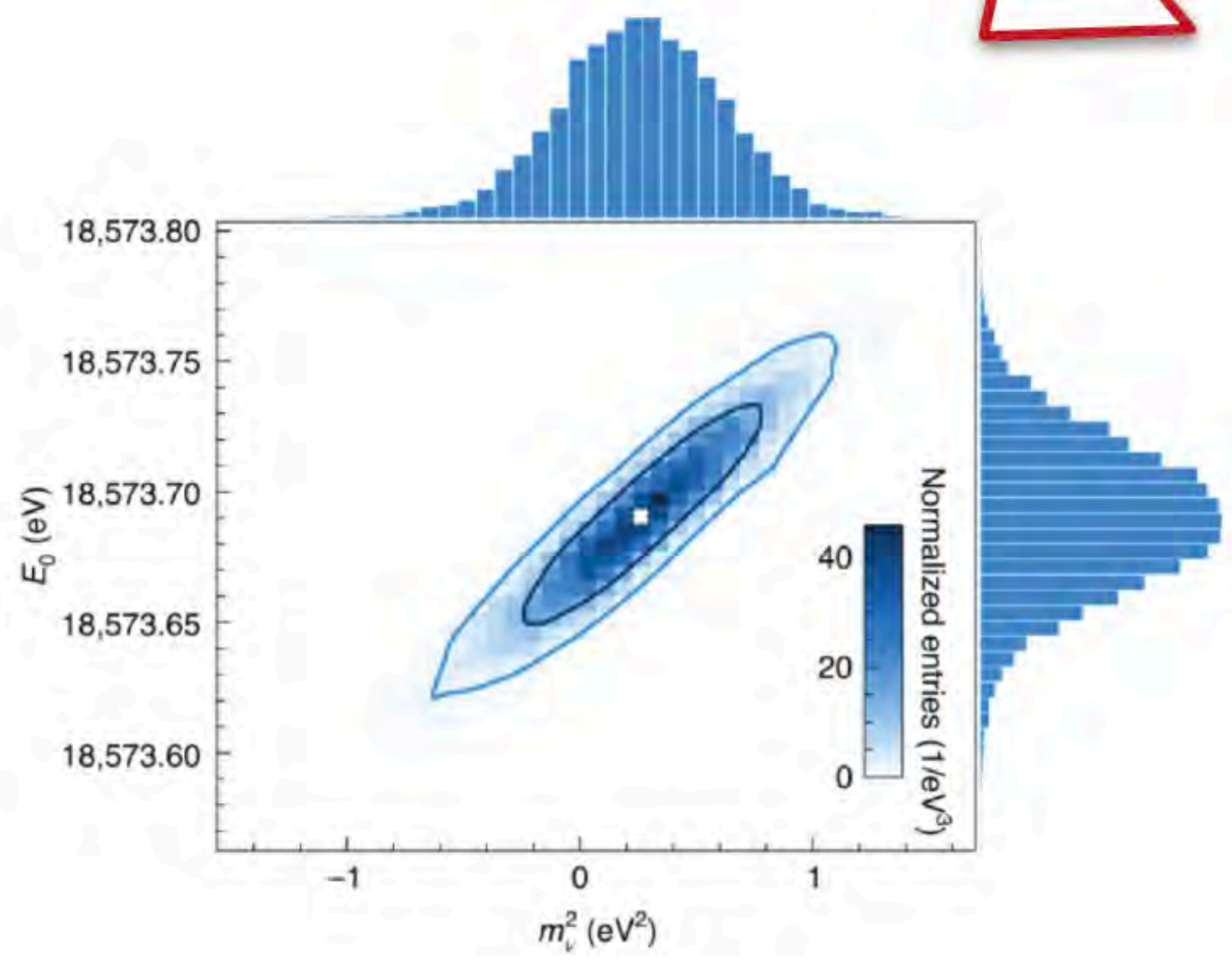
KATRIN



MAC-E filter technology

- Source decay rate > 10^{11} Bq
- Tritium suppression > 10^{12}
- MAC-E filter width: 0.93 eV @ 18.6 keV
- Main spectrometer at < 10^{-10} mbar
- Exquisite MC model of experiment





Best upper limit on neutrino mass

$m_\nu < 0.8\,\mathrm{eV/c^2}$ at 90 % CL

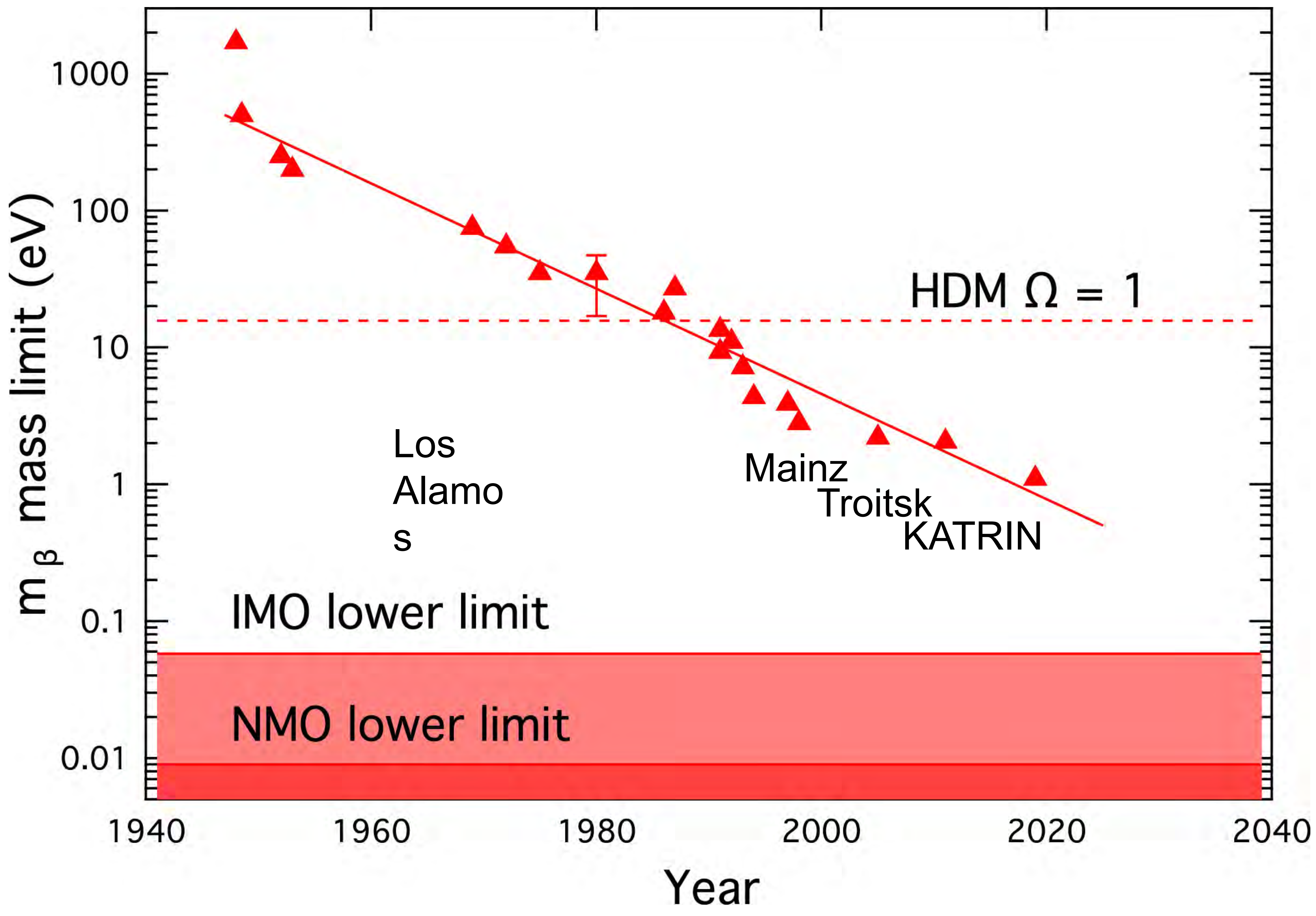
Anticipated sensitivity:

$m_\nu < 0.2\,\mathrm{eV/c^2}$ at 90 % CL

Direct Neutrino Mass Measurements

Experiment	**Operations**	**Final Results**
Los Alamos	1980–1987	$m_\beta < 9.3$ eV, 1991 [1]
Mainz	1997–2001	$m_\beta < 2.3$ eV, 2005 [2]
Troitsk	1994–2004	$m_\beta < 2.05$ eV, 2011 [3]
KATRIN	2019–2023*	$m_\beta < 0.8$ eV, 2022* [4]

[1] Robertson *et al.*, Phys. Rev. Lett. **67** 957, 1991
[2] Kraus *et al.*, Eur. Phys. J C **40** 447, 2005.
[3] Aseev *et al.*, Phys. Rev. D **84** 112003, 2011.
[4] Aker *et al.*, Nature Physics **18** 160, 2022.
* KATRIN is not yet complete



Formaggio, de Gouvea, Robertson, Physics Reports **914** 1, 2021.

Direct Neutrino Mass Measurements

Experiment	Operations	Final Results
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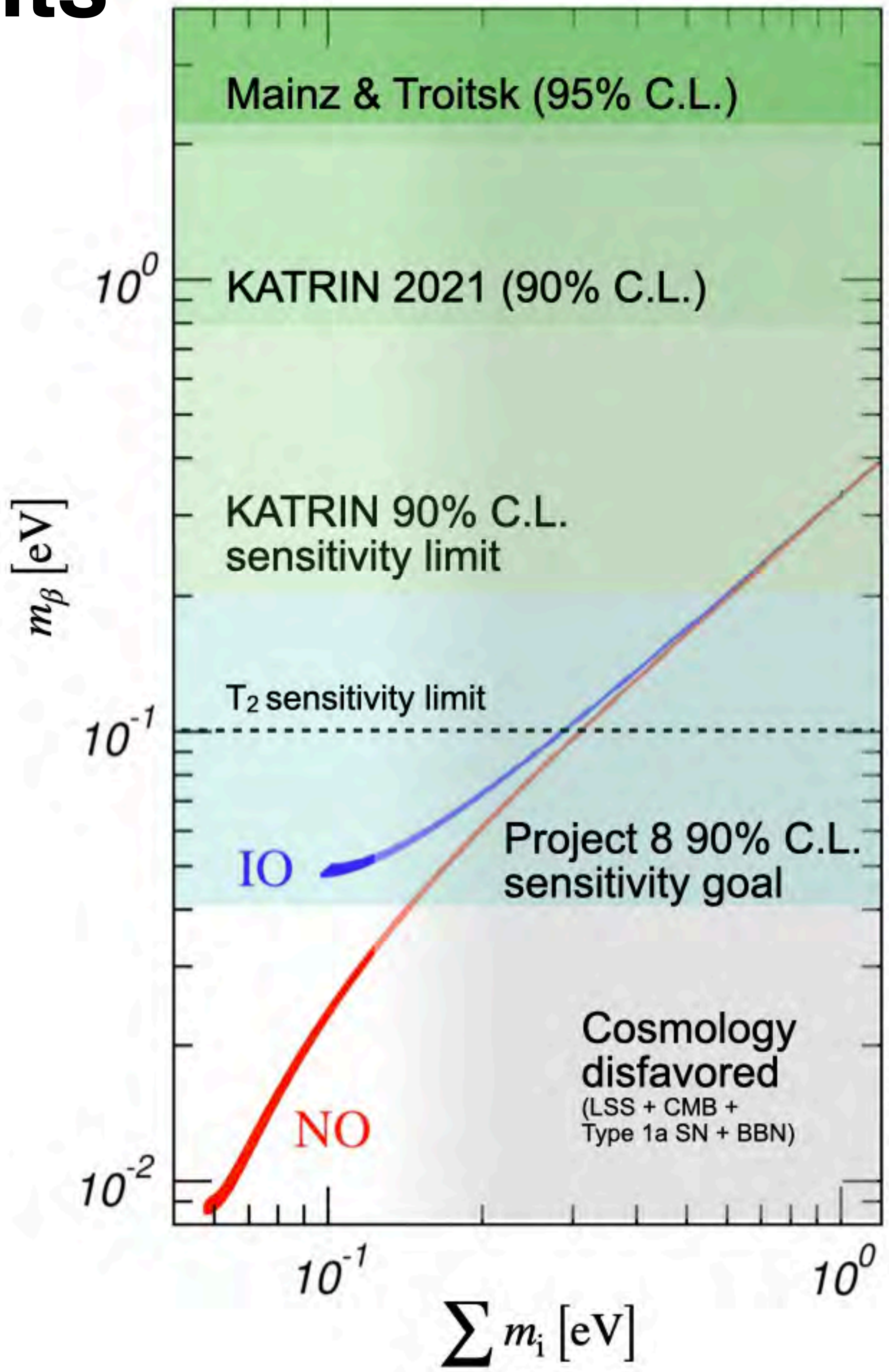
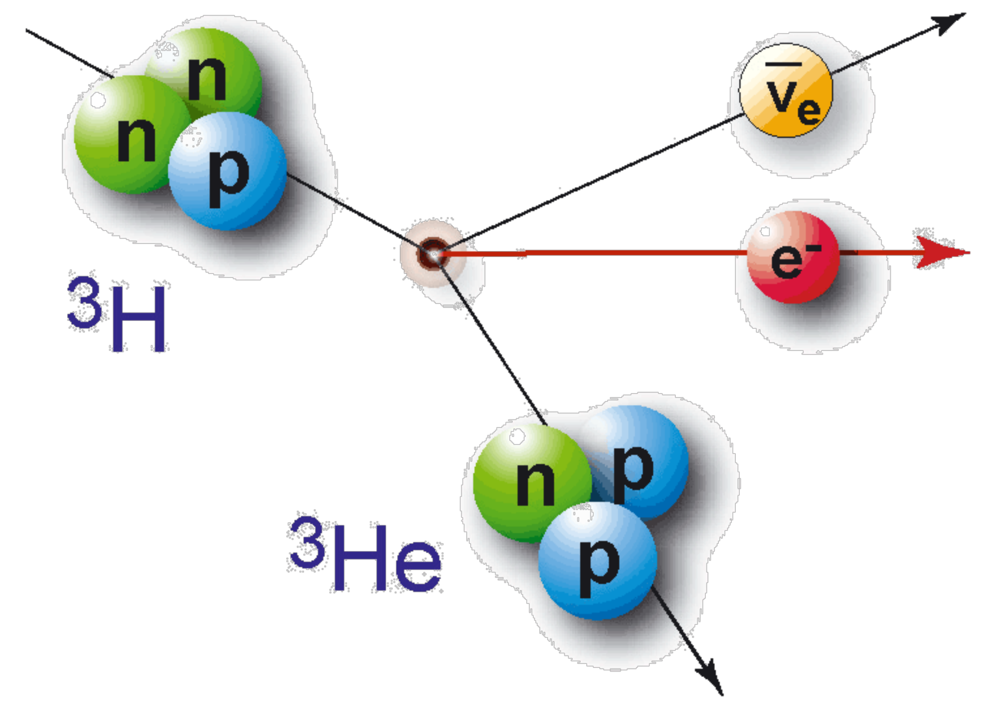
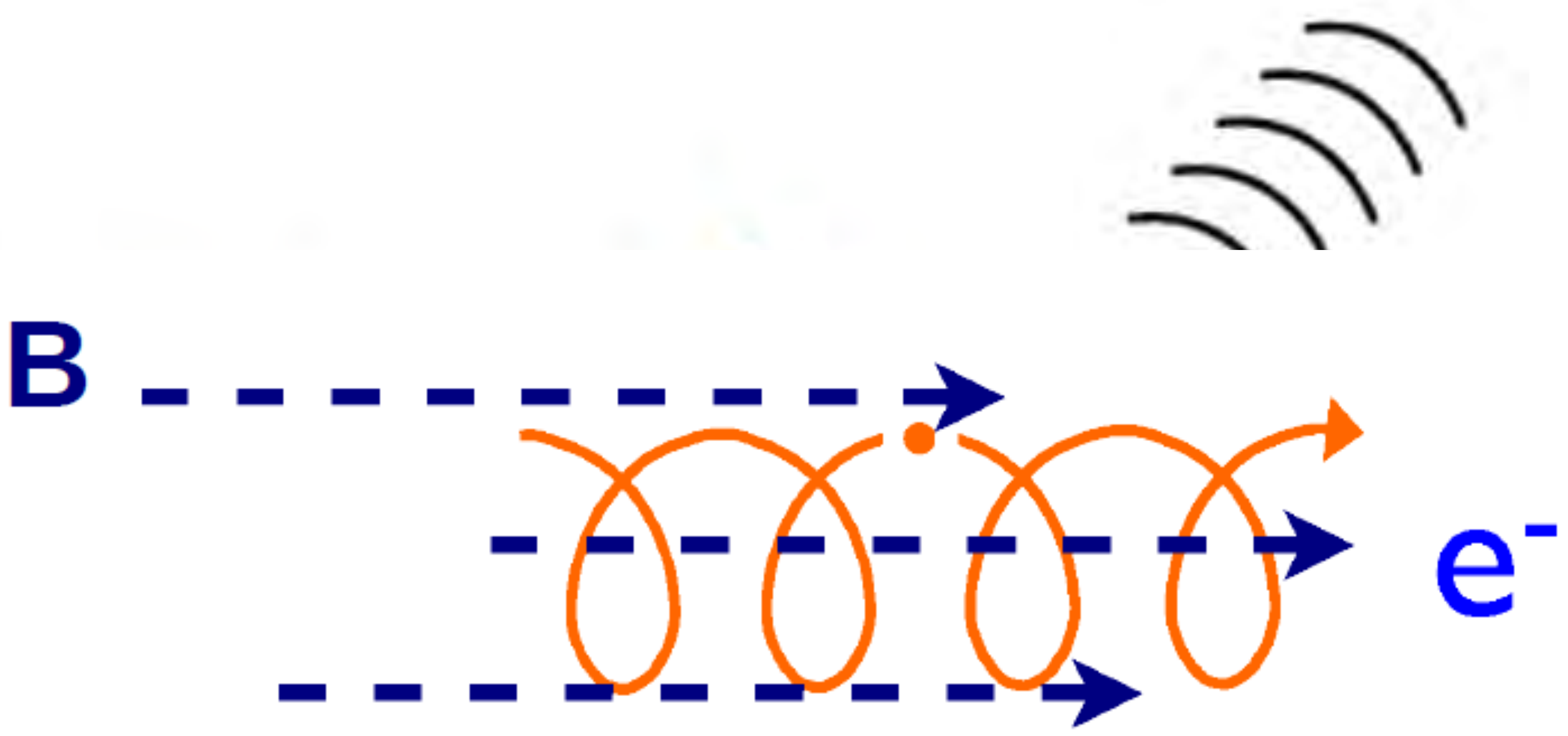
[1] Robertson *et al.*, Phys. Rev. Lett. **67** 957, 1991
[2] Kraus *et al.*, Eur. Phys. J C **40** 447, 2005.
[3] Aseev *et al.*, Phys. Rev. D **84** 112003, 2011.
[4] Aker *et al.*, Nature Physics **18** 160, 2022.
* KATRIN is not yet complete



Plot based on JHEP 09 (2020) 178 [arXiv:2007.14792] as well as NuFIT 5.0 (2020), www.nu-fit.org, modified by M. Fertl

Project 8 - A New Approach to Measuring Neutrino Mass





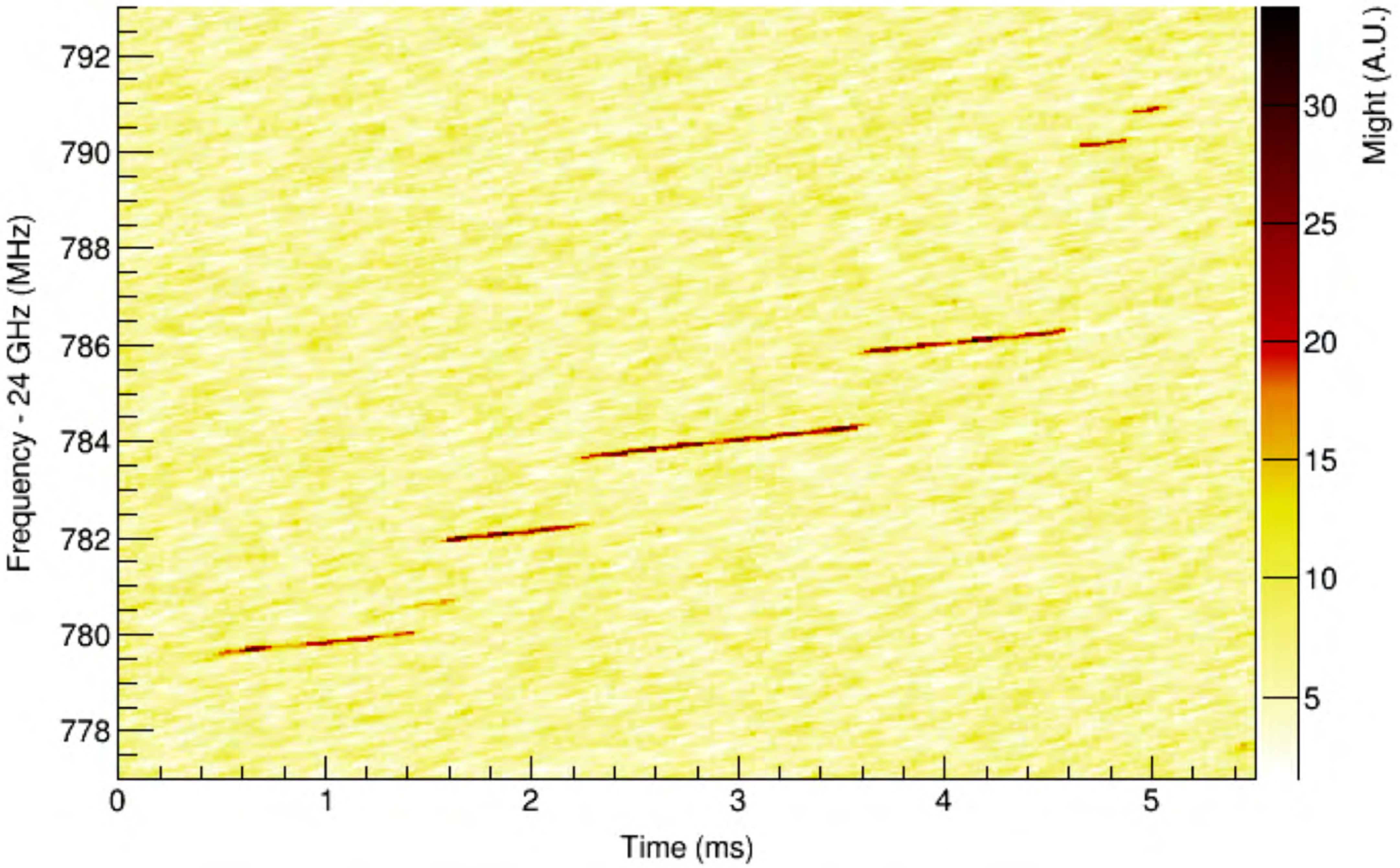
PROJECT 8

Cyclotron Radiation Emission Spectroscopy (CRES)

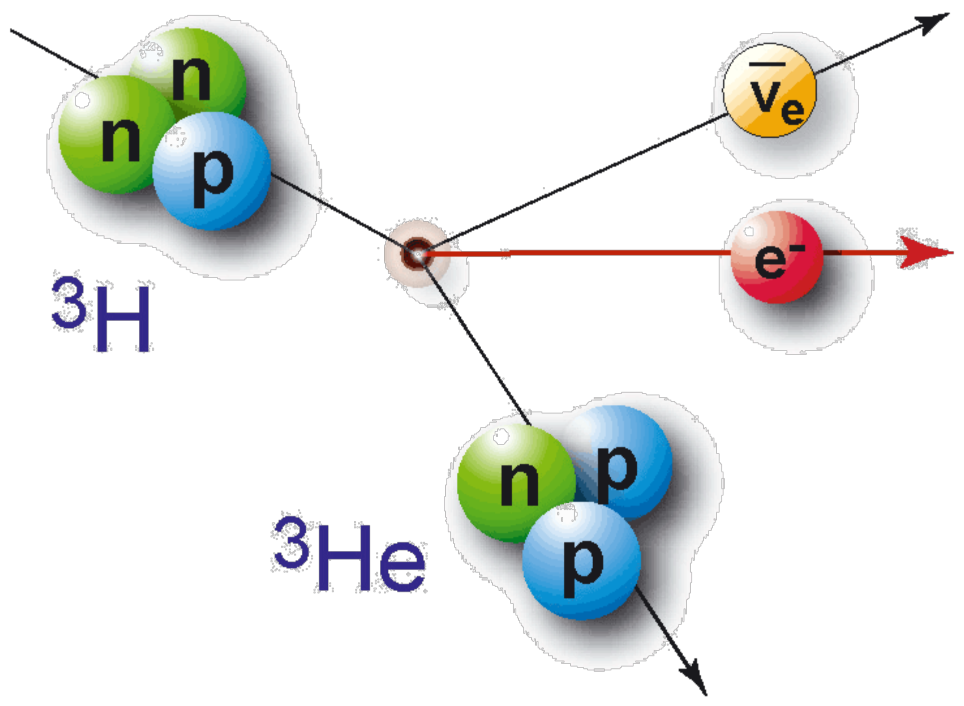
In uniform magnetic field, a charged particle will have a helical trajectory

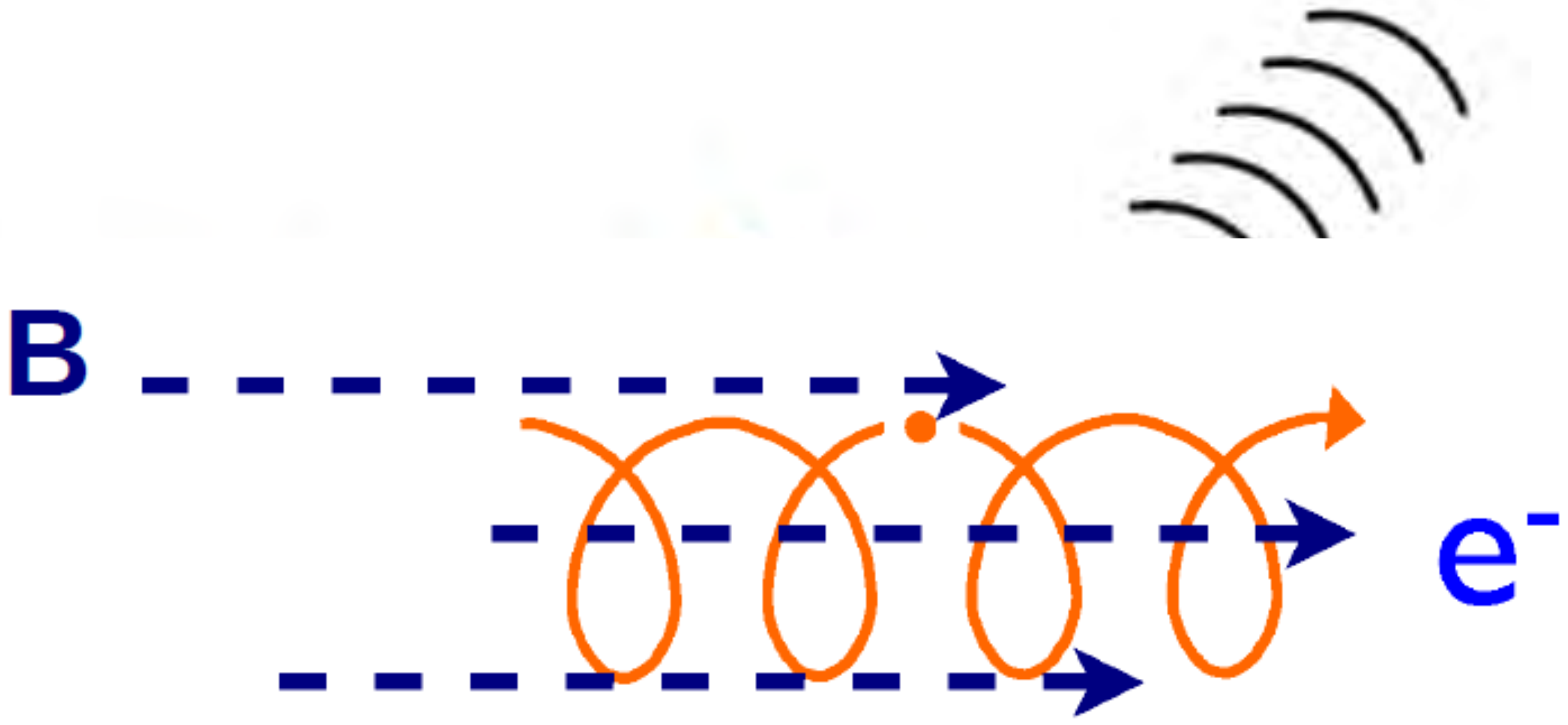
Accelerating electron will radiate EM waves at frequency:

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



Project 8 - A New Approach to Measuring Neutrino Mass





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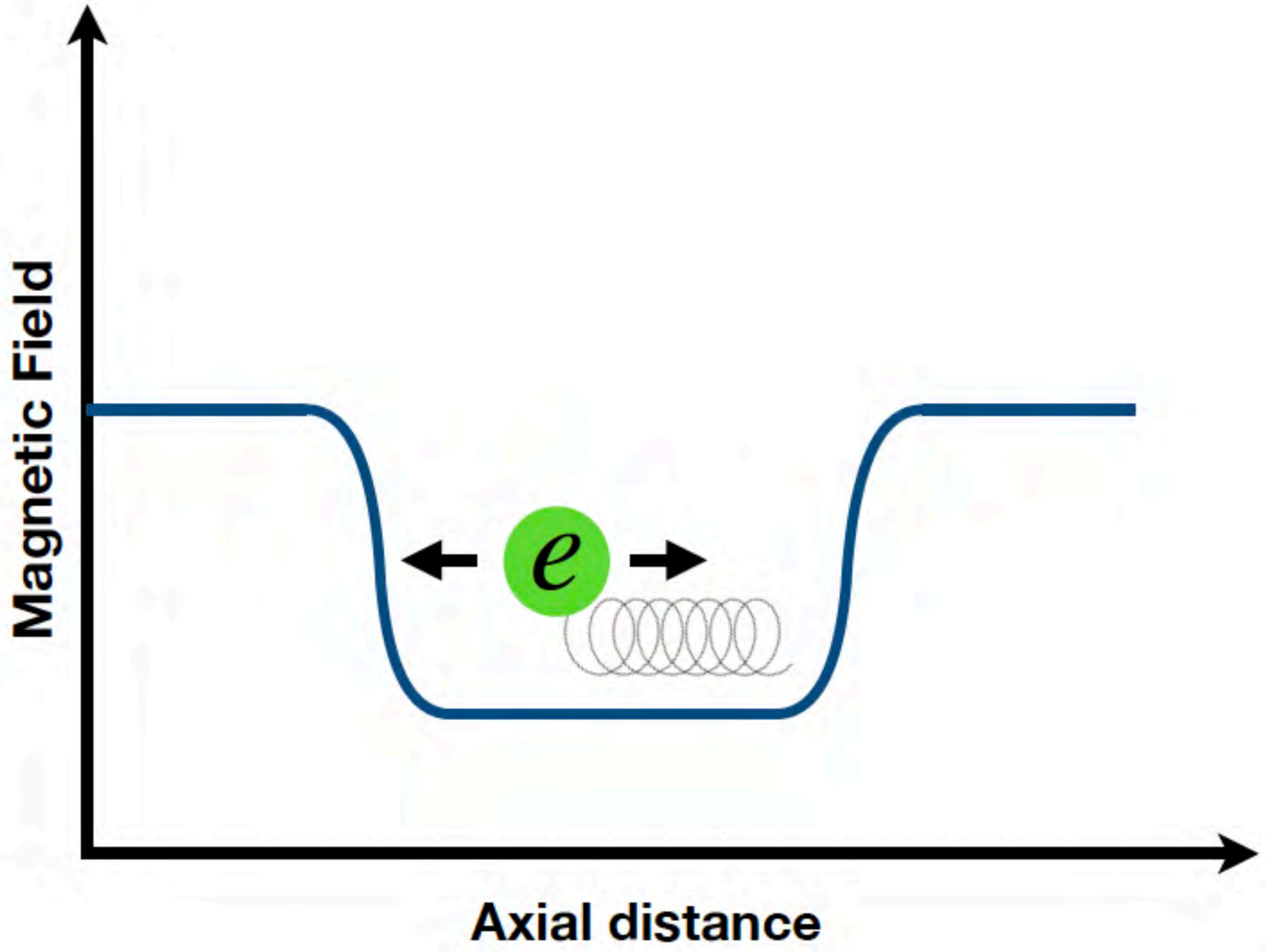
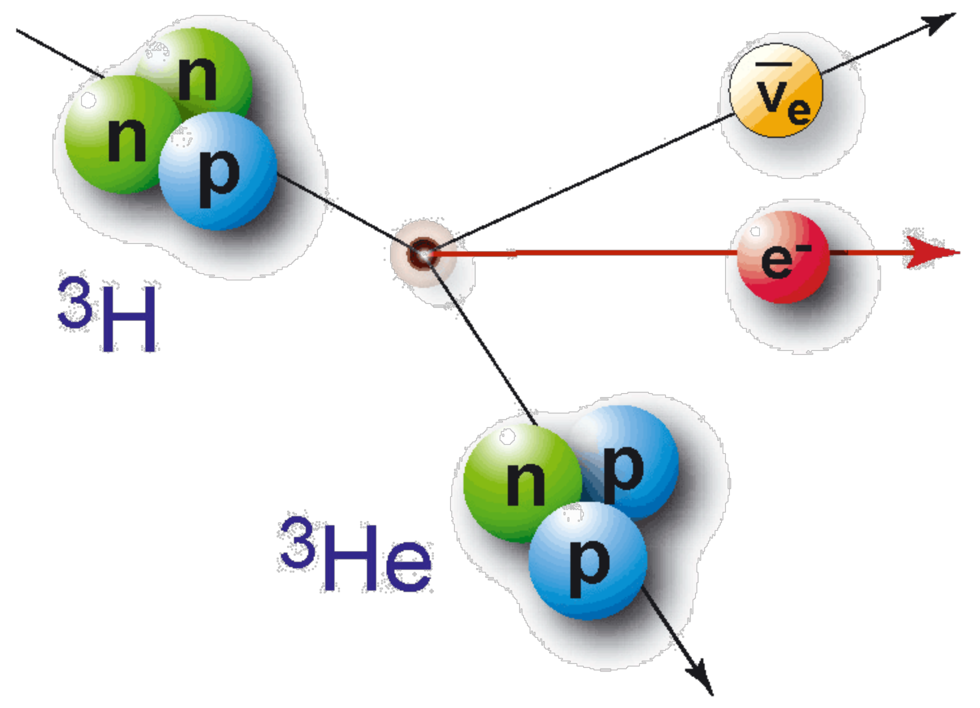


- Magnetic trap (no energy change)
- Extends observation time of electron (*time)
- Knowledge of B places limit on energy resolution

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

Project 8 - A New Approach to Measuring Neutrino Mass



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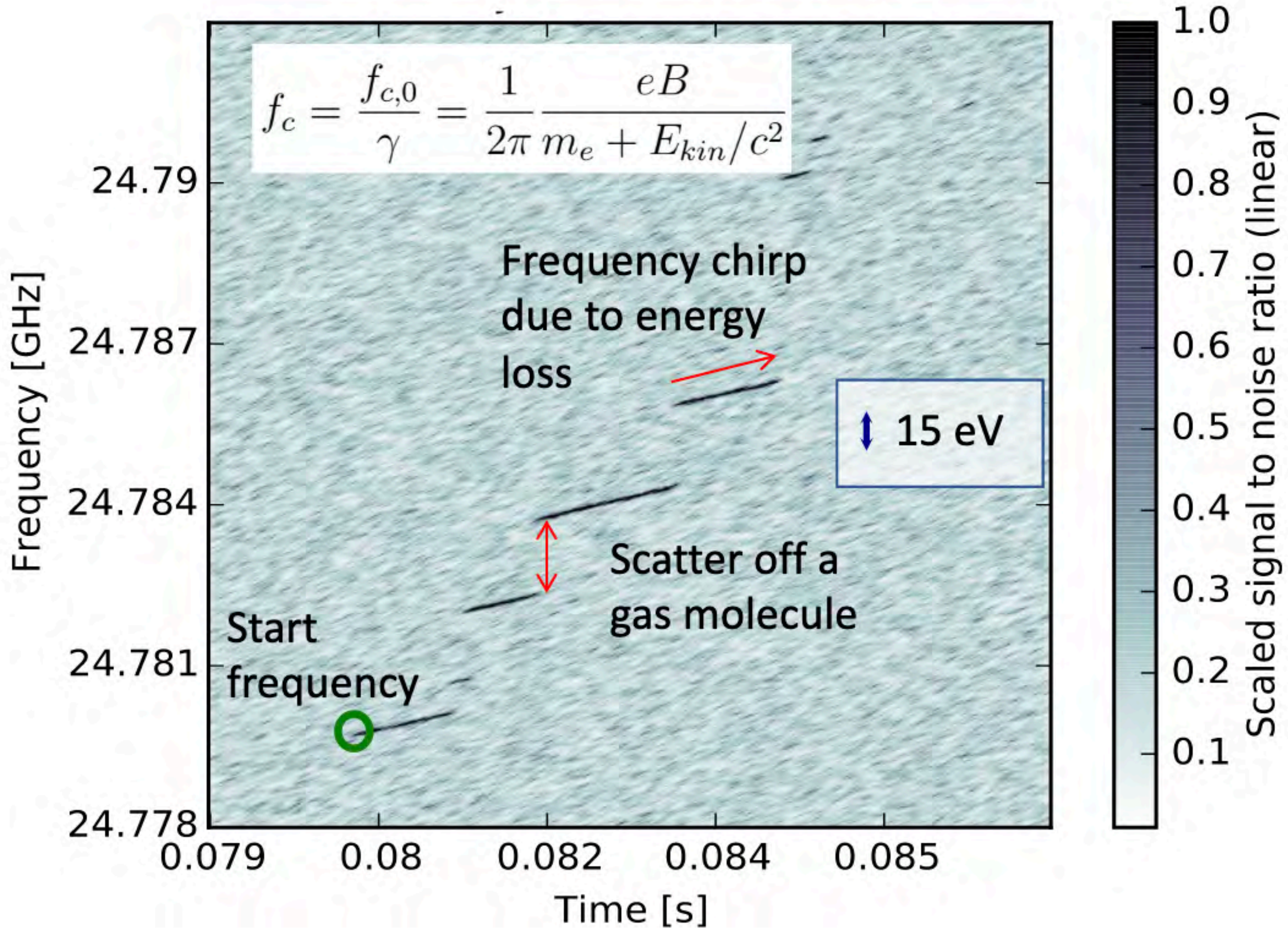
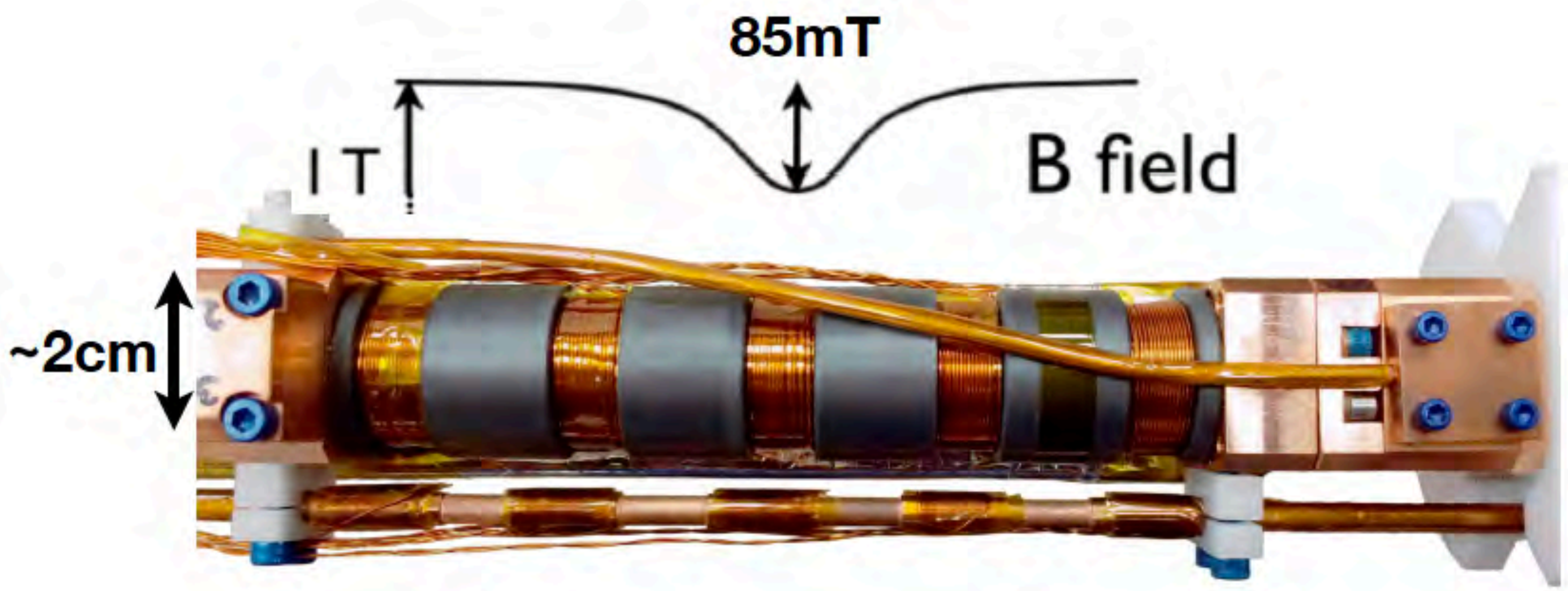
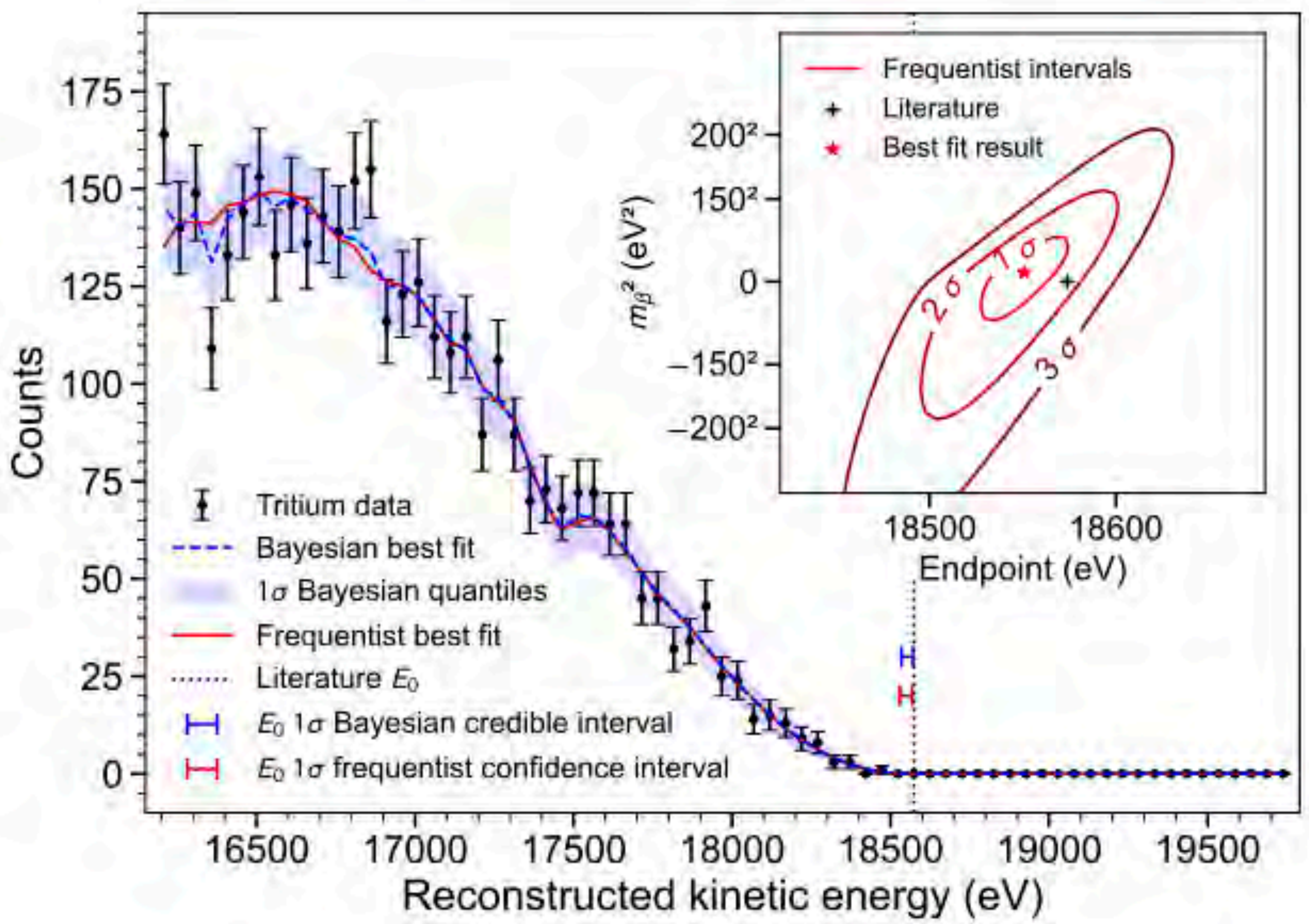


Project 8 - A New Approach to Measuring Neutrino Mass



- 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

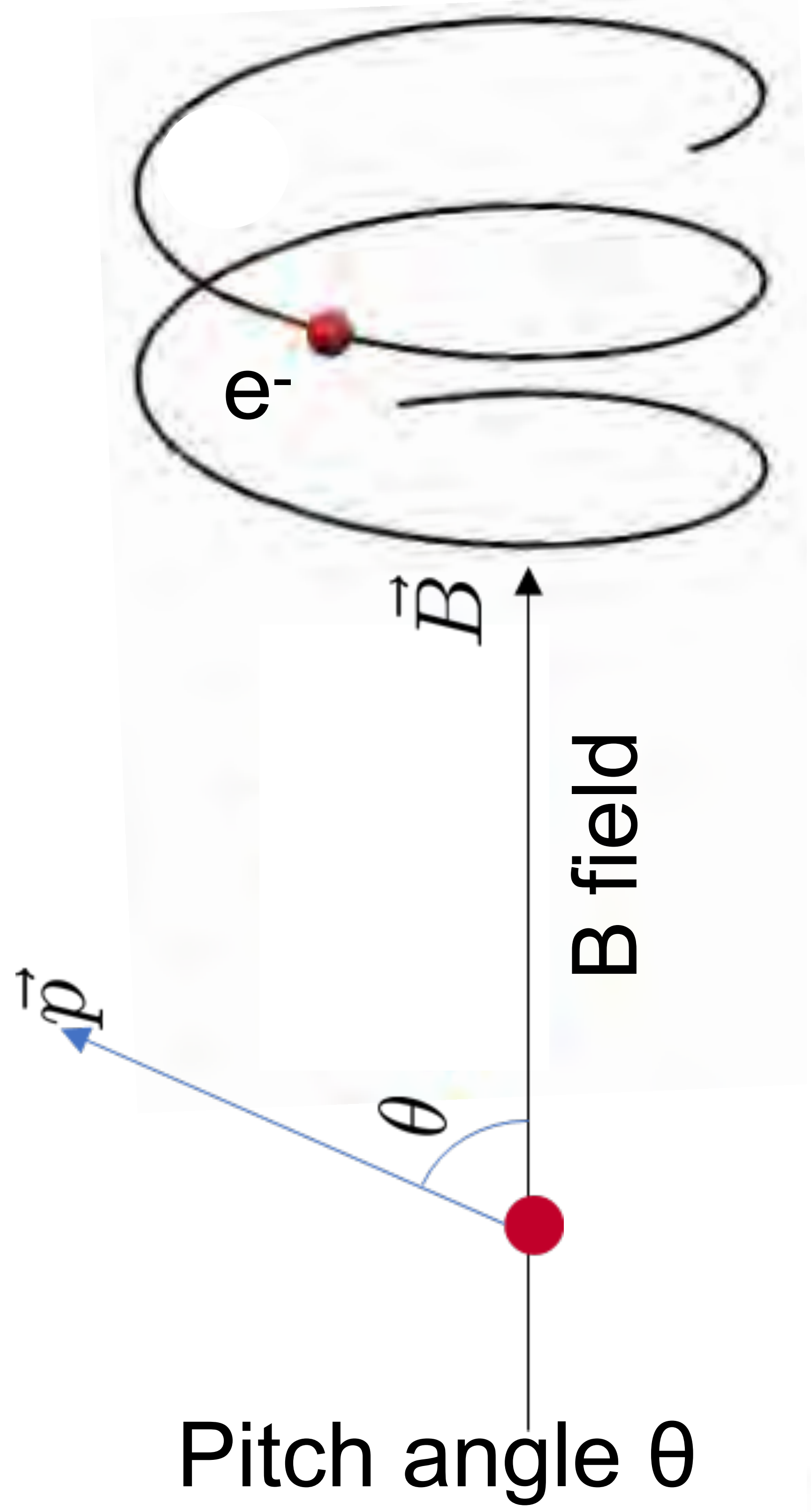
First measurement of the T_2 endpoint with CRES, Placed limit on the neutrino mass of m_β<155 eV

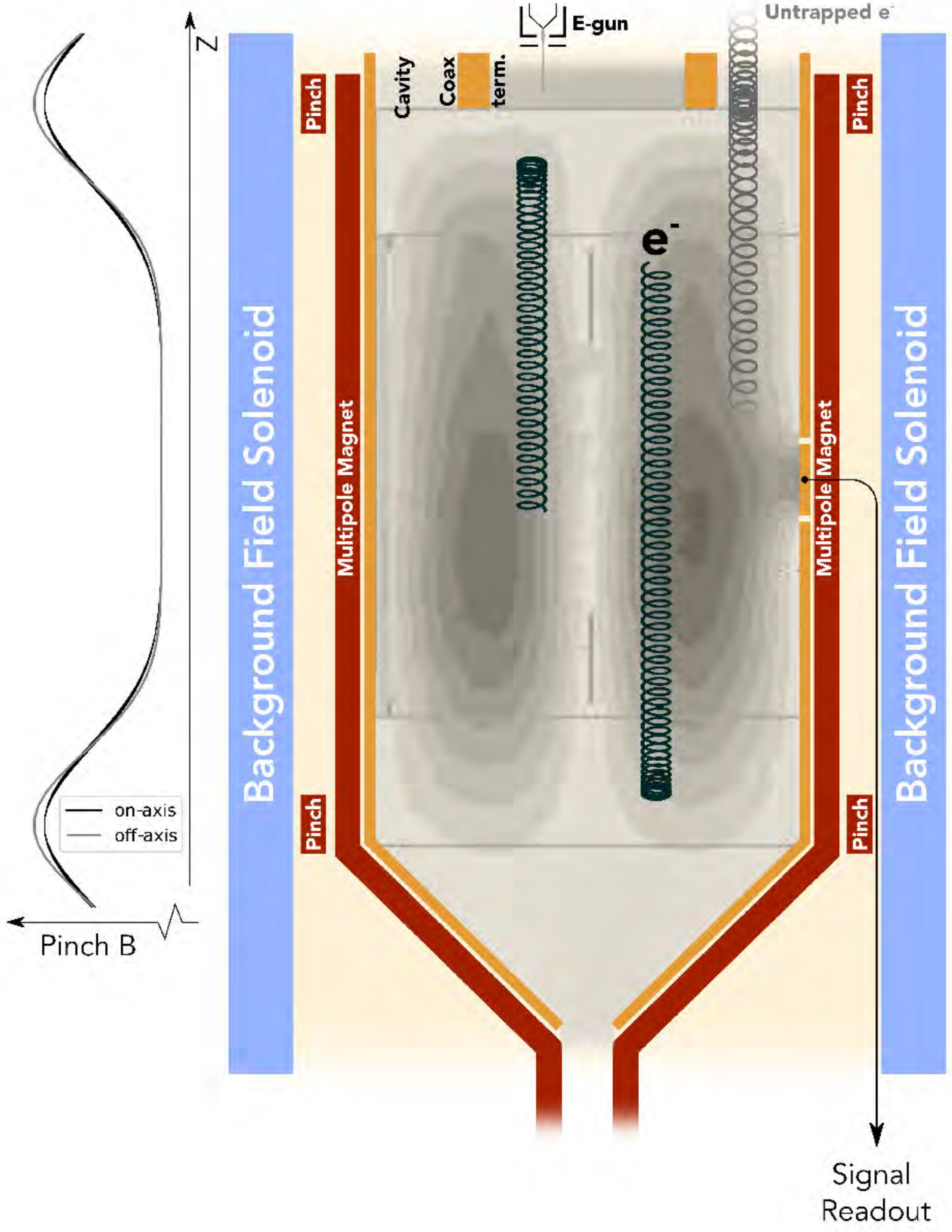
Project 8 - A New Approach to Measuring Neutrino Mass

Cavity CRES in Project 8

The elements of CRES:

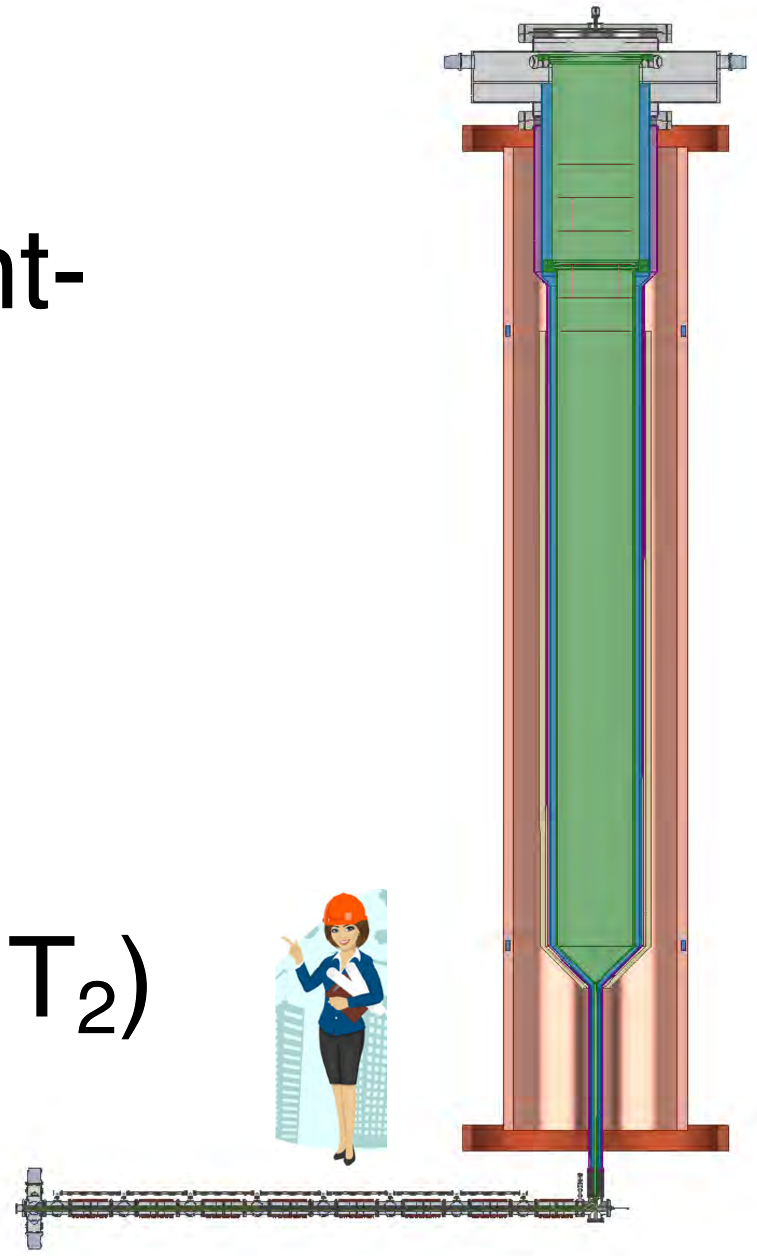
- Uniform magnetic field
- Magnetic trap for e^-
- Antenna or cavity
- Sensitive receiver
- Tritium
- Atomic source
- Magnetic trap for atoms





Why use CRES to measure neutrino mass?

- Source is transparent at radio frequency. Scales with volume instead of area. (10 m^3 is roughly comparable to KATRIN's 1200 m^3.)
- Whole spectrum is recorded at once, not point-by-point.
- Low backgrounds obtainable.
- Excellent resolution obtainable.
- An atomic source of T (rather than molecular T_2) is compatible. Eliminates the molecular broadening.



Phase III pilot experiment

KATRIN

Karsten Heeger, Yale University

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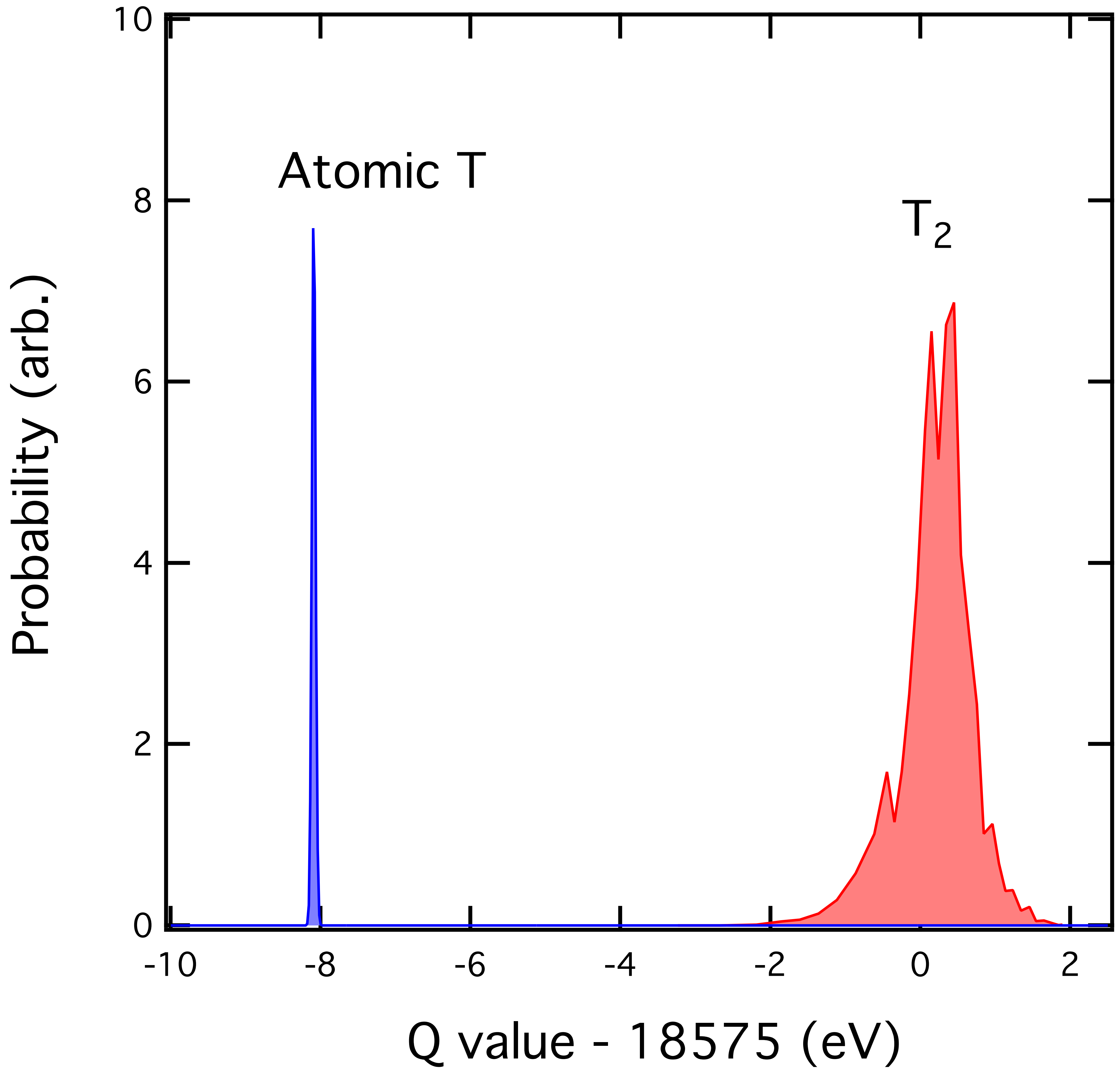
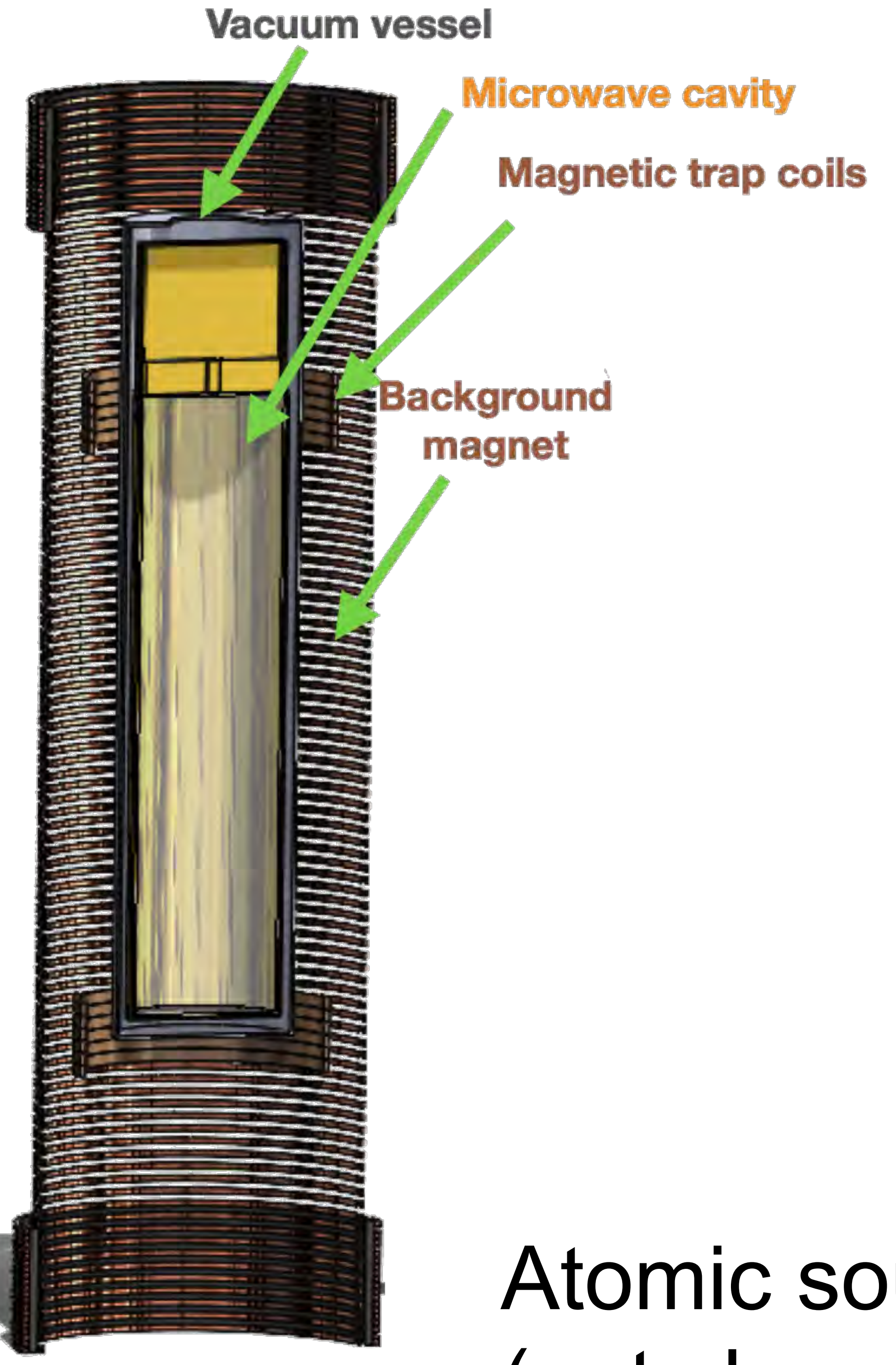
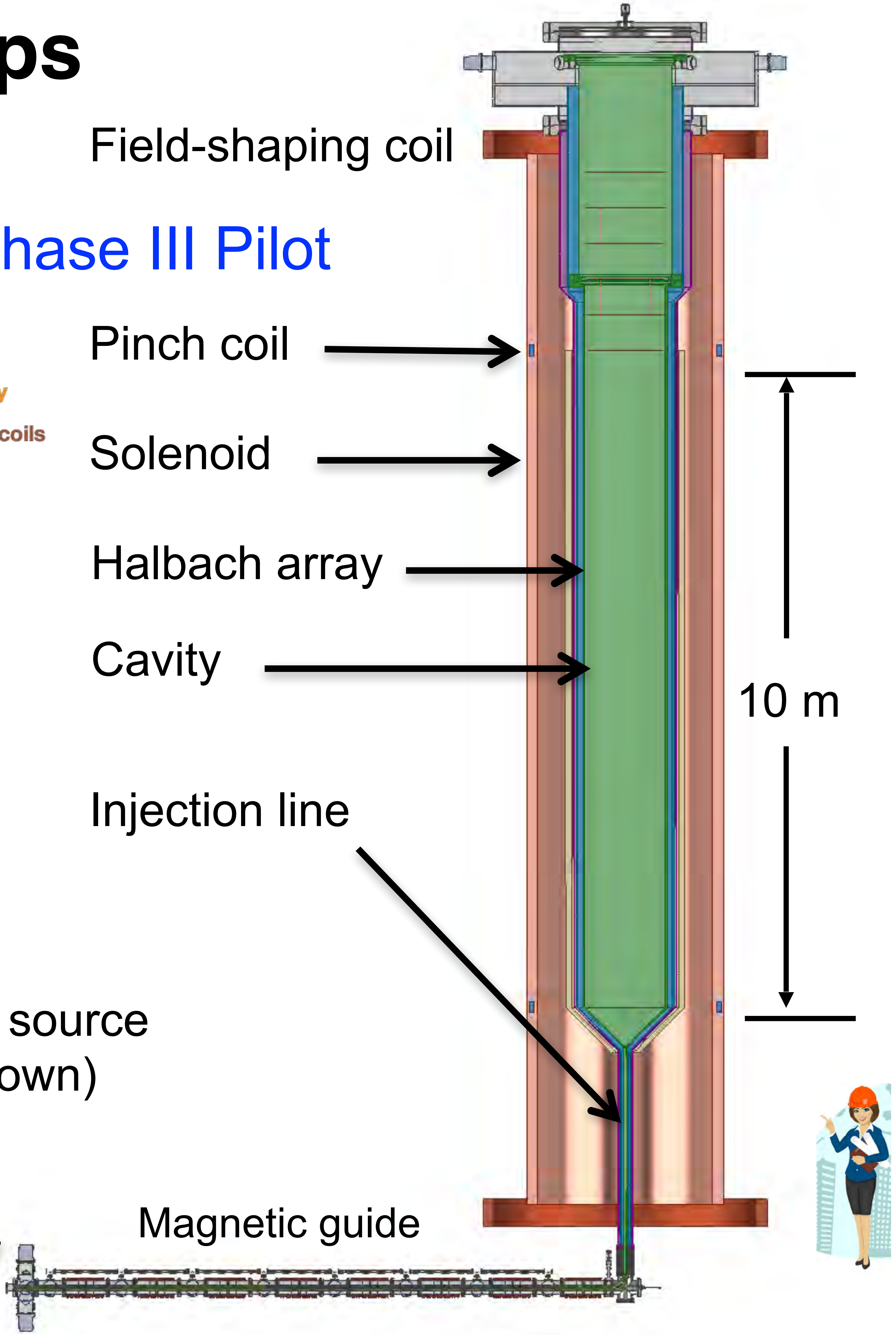


Project 8 - Next Steps

Cavity demonstrators



Phase III Pilot



Field-shaping coil

Pinch coil

Solenoid

Halbach array

Cavity

Injection line

Atomic source
(not shown)

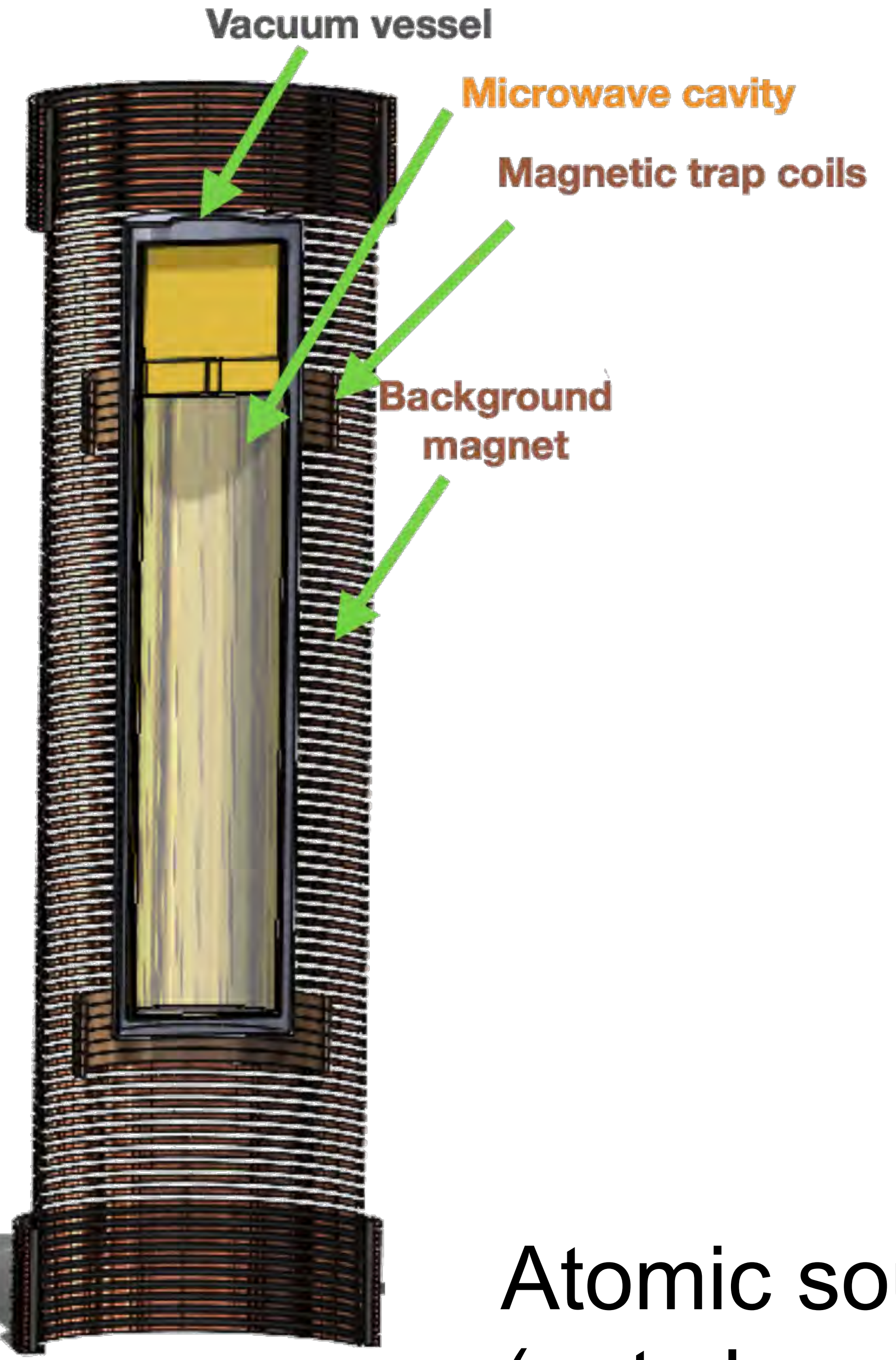
Magnetic guide

Magnetic beamline and
325-MHz cavity

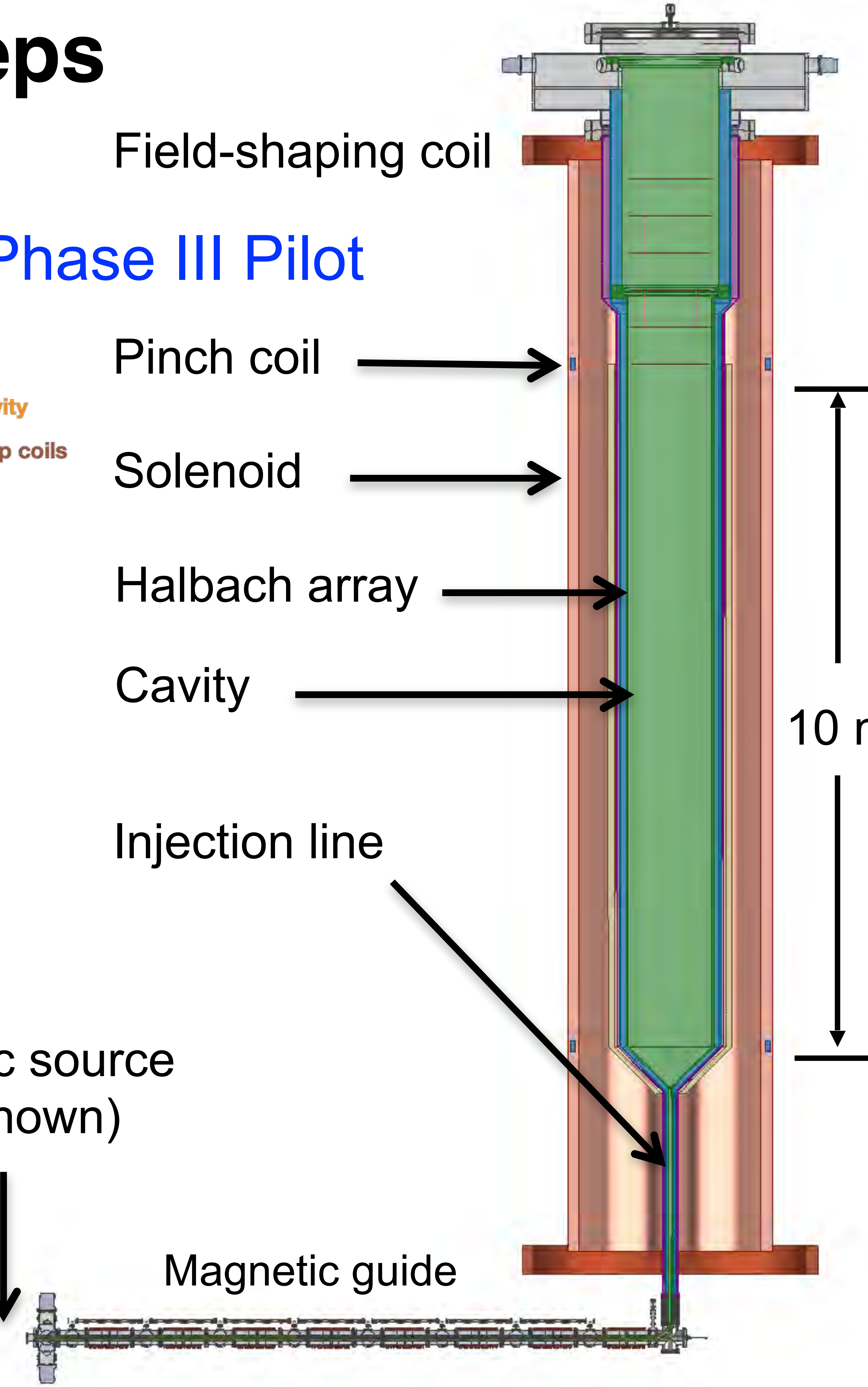
Sensitivity goal
~ 100 - 70 meV in 1 year

Project 8 - Next Steps

Cavity demonstrators



Phase III Pilot



Field-shaping coil

Pinch coil

Solenoid

Halbach array

Cavity

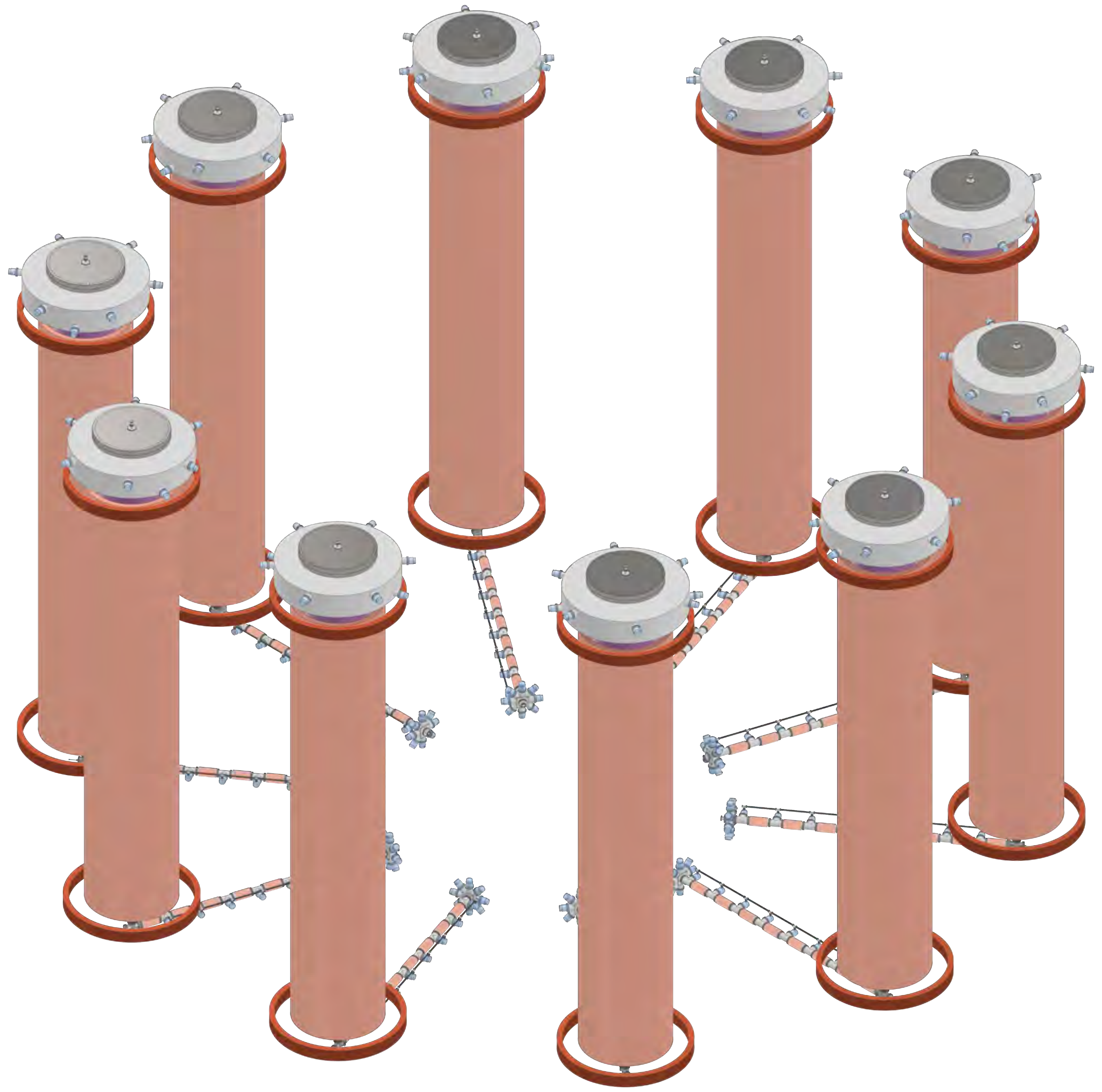
10 m

Injection line

Atomic source (not shown)

Magnetic guide

Phase IV



With 10 of these you get to 40 meV in 3 years

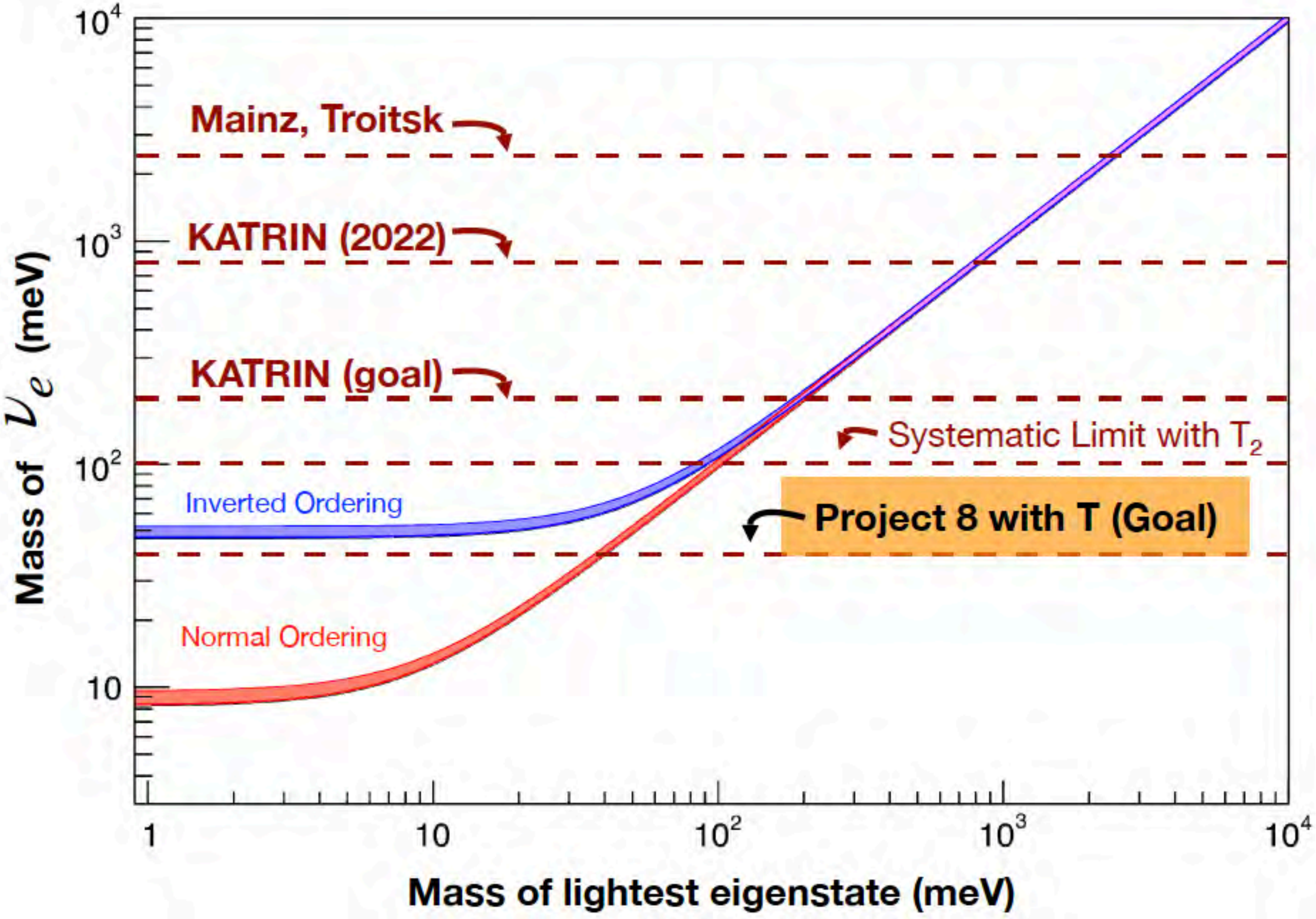
Karsten Heeger, Yale University

Project 8 Sensitivity

Probing the neutrino mass hierarchy at 40meV

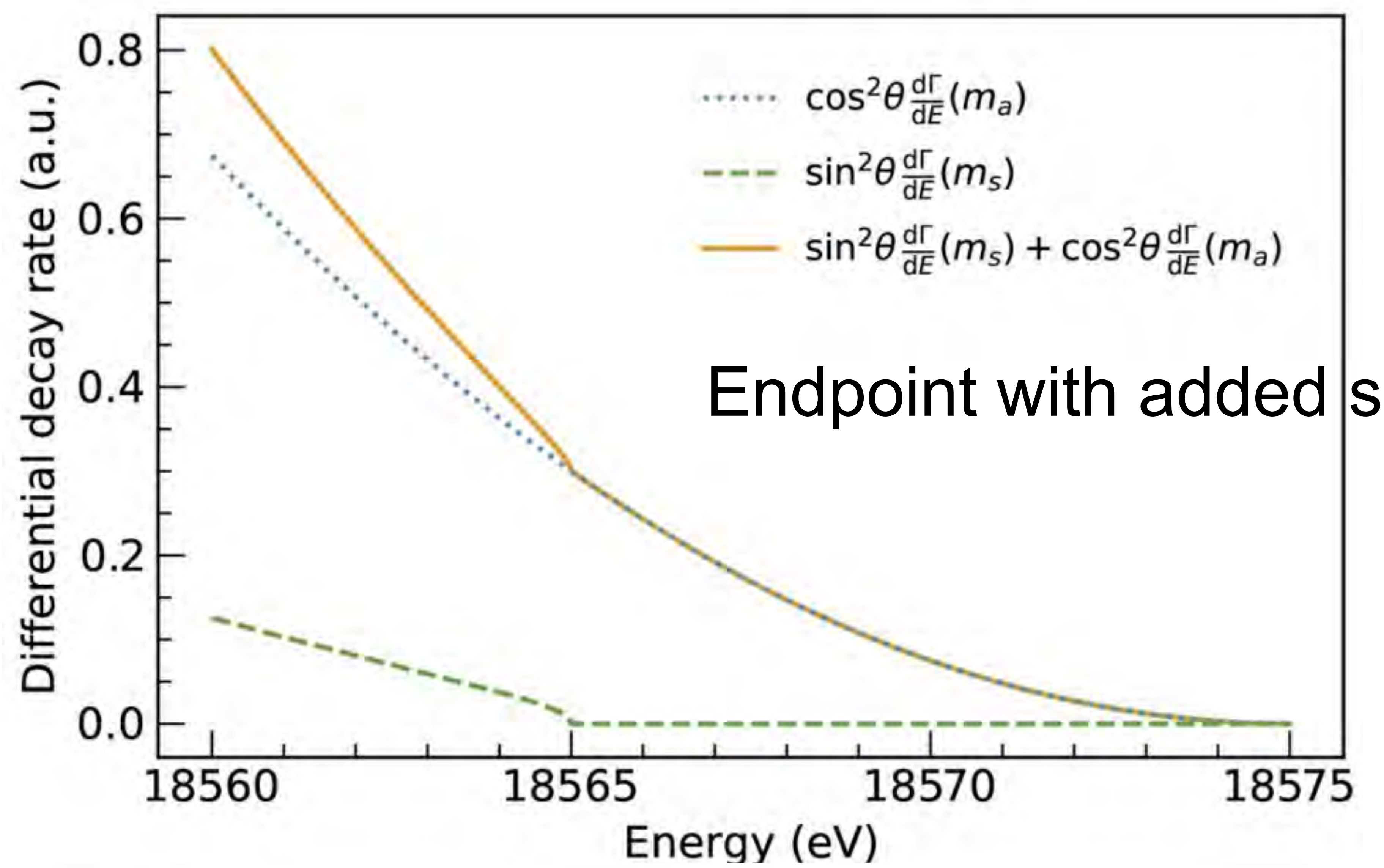
Sensitivity below inverted mass ordering

New technologies required
- atomic tritium
- CRES

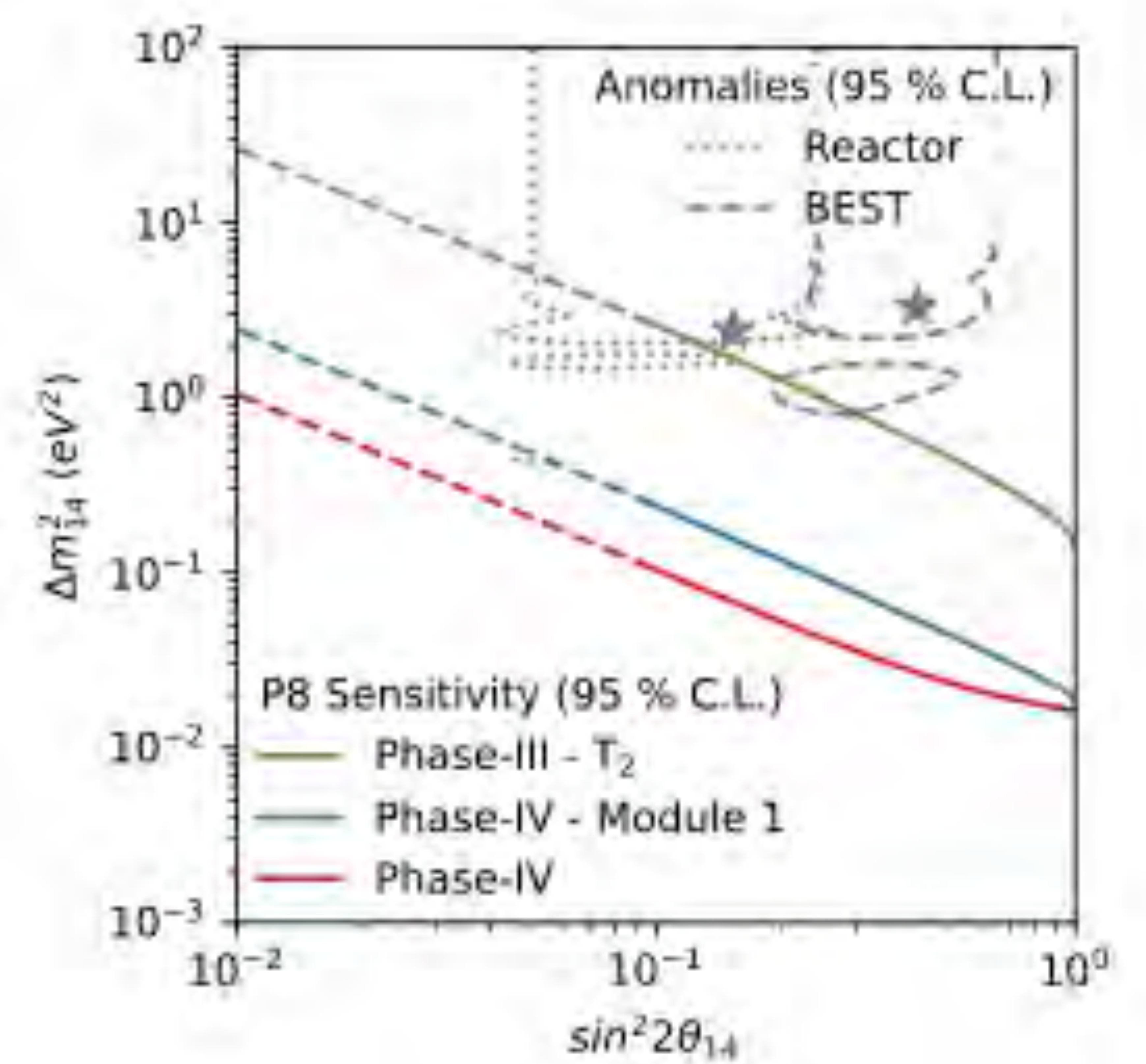


Project 8 - Sterile Neutrinos

- 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

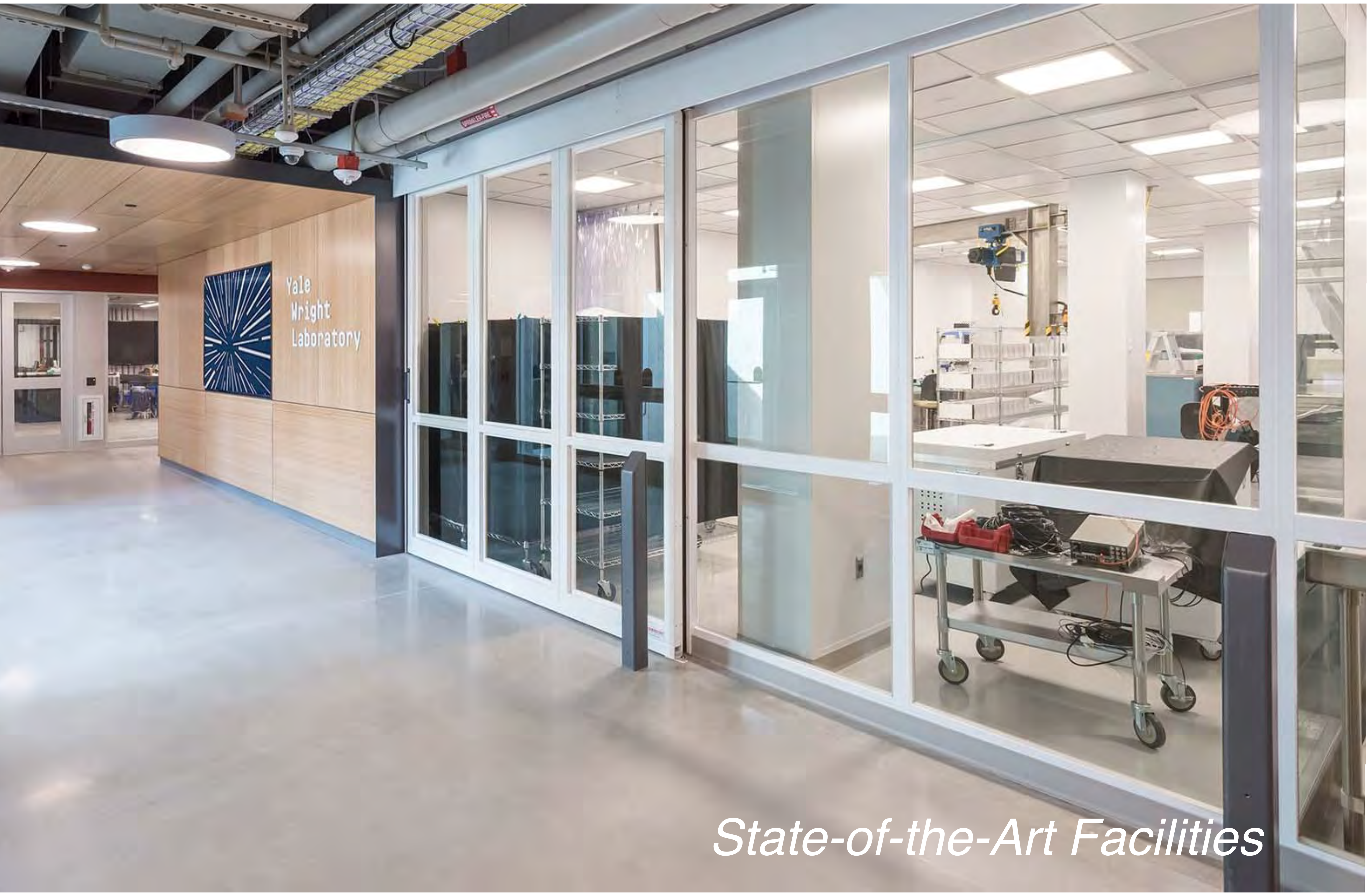


Endpoint with added sterile mass state



Yale Wright Laboratory

Exploring the Invisible Universe

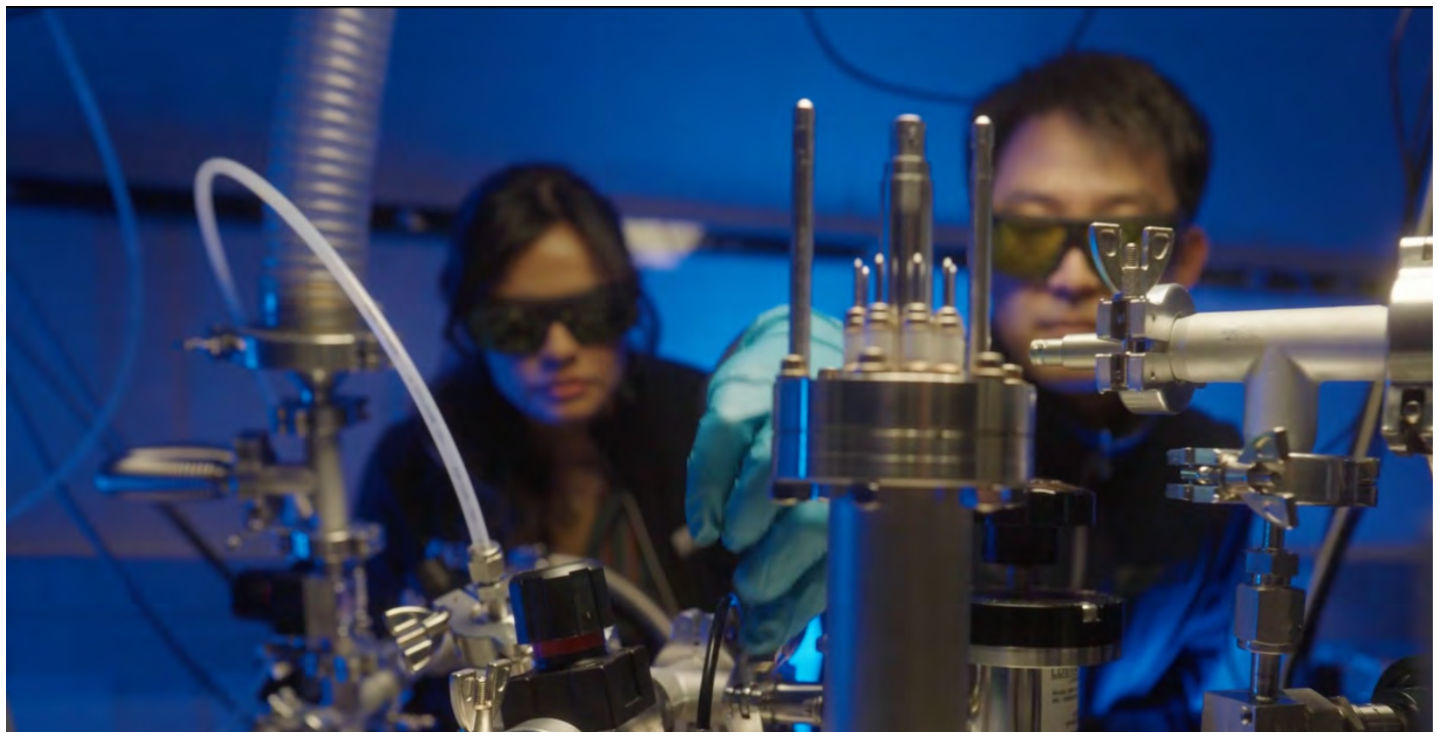


State-of-the-Art Facilities

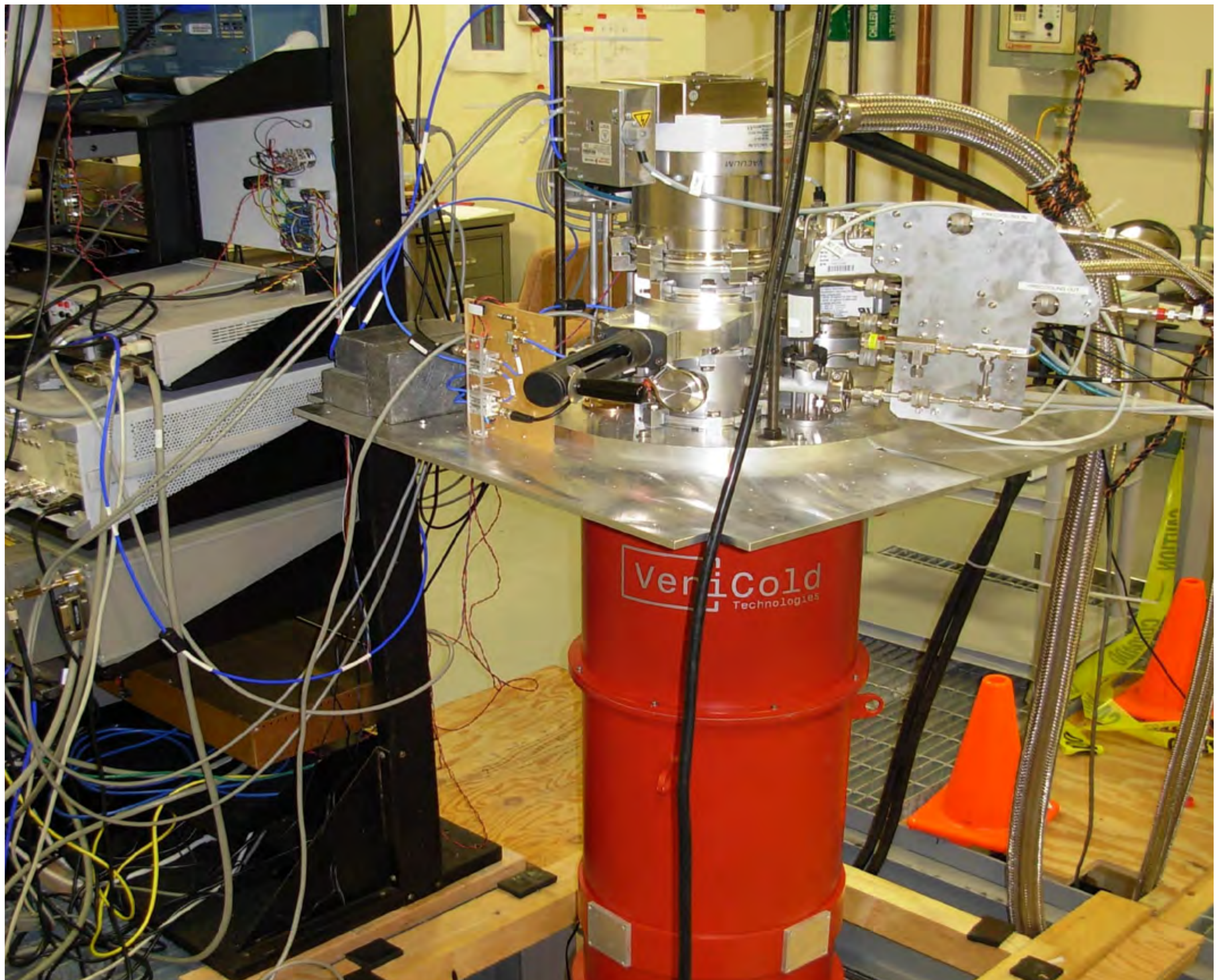
Advancing frontiers of nuclear, particle, and astrophysics including studies of **neutrinos**; searches for **dark matter**; understanding **matter**; exploration of **quantum science** and observations of **the early Universe**.

https://wlab.yale.edu

Developing Tools for Discoveries



Training Future Scientists



Yale Wright Laboratory

Research Worldwide

Exploring the Invisible Universe

Sanford Underground Research Facility
Lead, SD
DUNE

Fermilab
Batavia, IL
DUNE, SBND, LArIAT, ArgoNeuT MicroBooNE

SNOLAB
Ontario, Canada
nEXO

Dominion Radio Astrophysical Obs.
BC, Canada
CHIME

Wright Lab
New Haven, CT
HAYSTAC, SIMPLE

University of Washington
Seattle, WA
Project 8

Brookhaven National Laboratory
Long Island, NY
EIC, STAR

Kitt Peak National Observatory
Tucson, AZ
DESI

NASA Goddard
Greenbelt, MD
Roman Space Telescope

Waste Isolation Pilot Plant
Carlsbad, NM
EXO-200

Oak Ridge National Laboratory
Oak Ridge, TN
PROSPECT

Simons Observatory
Atacama Desert, Chile
Simons Observatory, ACT

La Silla Observatory
Coquimbo, Chile
QUEST

Large Hadron Collider
CERN, Geneva, Switzerland
ATLAS, ALICE

Gran Sasso National Underground Laboratory
L'Aquila, Italy
CUORE, CUPID

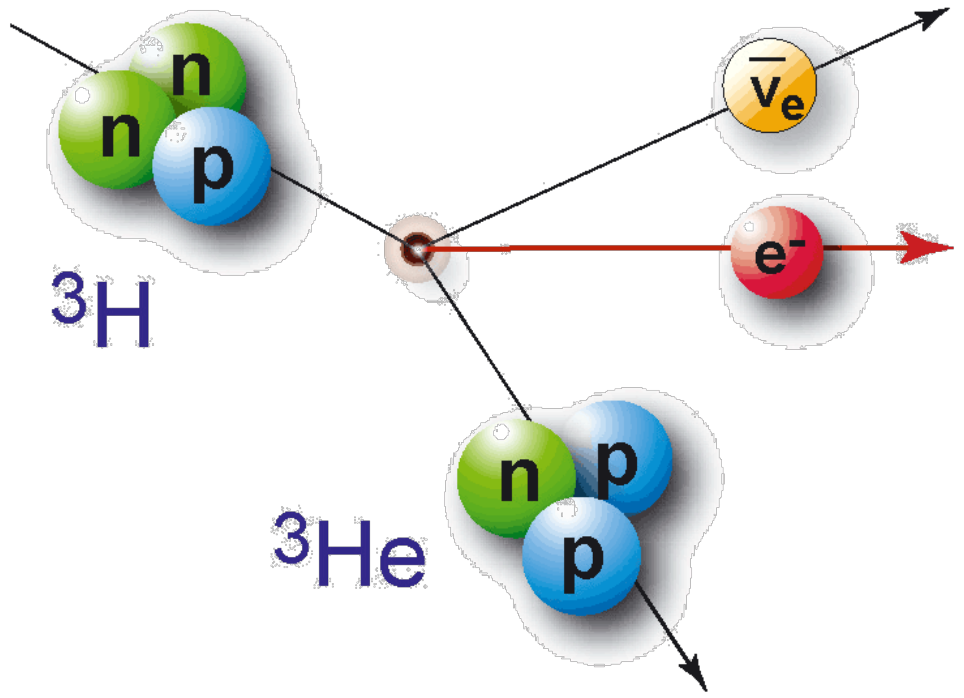
Karoo Desert
South Africa
HIRAX

Daya Bay Nuclear Power Plant
Guangdong, China
DayaBay

Yangyang Underground Laboratory
Yangyang, South Korea
COSINE-100

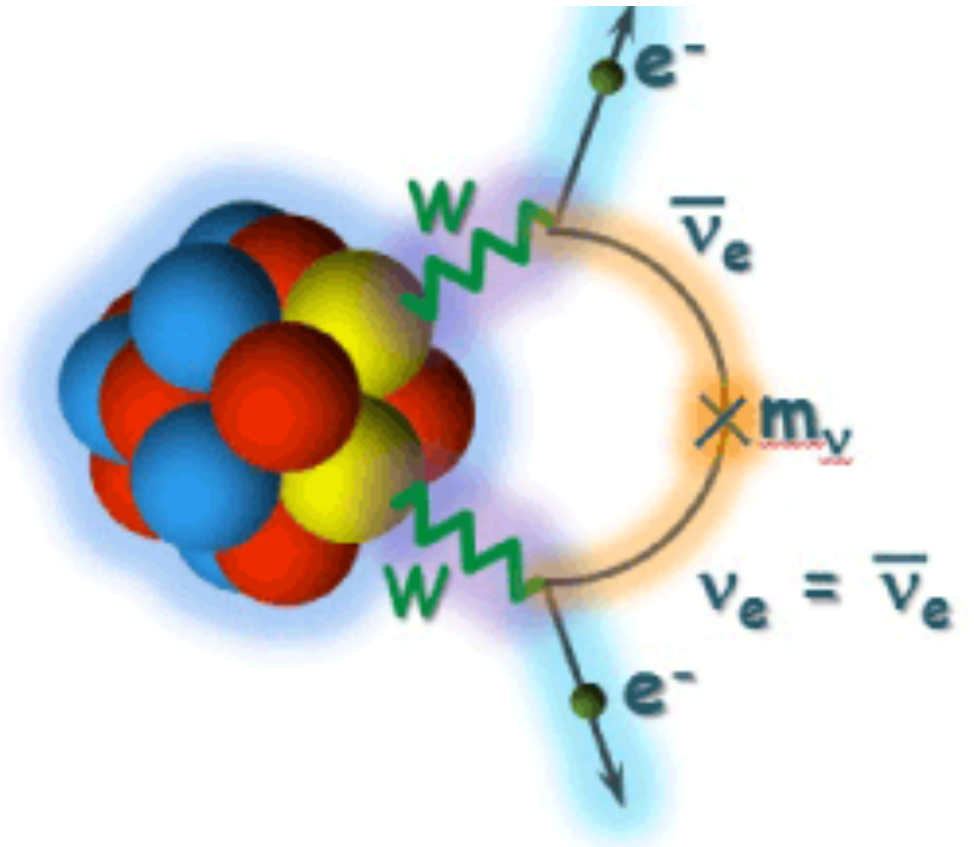
Summary and Outlook

Low-energy ν experiments provide key insight into the nature of neutrinos

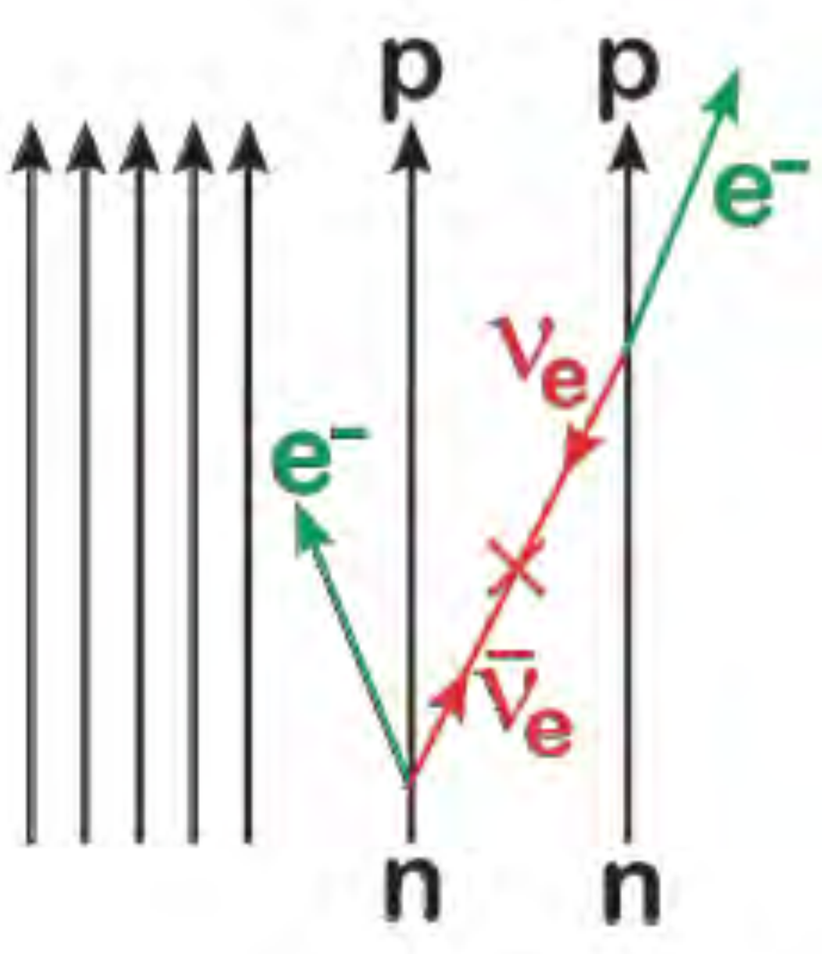


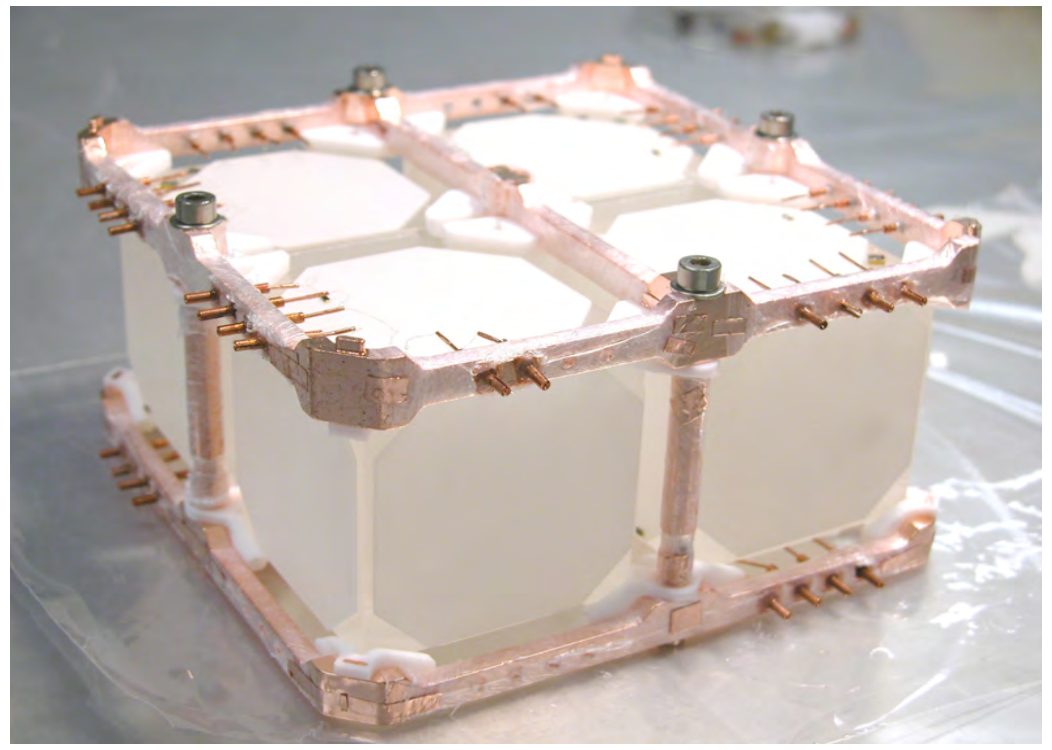
Beta decay allow
direct neutrino mass measurements

Project 8 aima to reach m_ν <0.04 eV



Neutrinoless
double beta decay





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

Would establish lepton number violation and demonstrate that neutrinos are Majorana.

CUPID reaches half lives of 10^{27}-10^{28} years with tonne-scale experiments