Neutrino Experiments

Lecture 2

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8th IDPASC School, Valencia (Spain), May 2018

Plan for these lectures

Monday: neutrino experiments basics

- Neutrino open questions ✓
- How to measure neutrino oscillation parameters ✓
- Neutrino sources ✓
- Neutrino interactions with matter ✓
- Neutrino detector technologies ✓

Today: neutrino experiments specifics

- Selected current and future ν oscillation experiments
- Neutrinoless double beta decay experiments
- Experiments for direct neutrino mass measurements

How to experimentally address neutrino questions

Identity	Neutrinoless double beta decay
Mass scale	Direct neutrino mass measurements, neutrino cosmology, neutrinoless double beta decay
Mass ordering	Neutrino oscillations, neutrino cosmology
Mixing	Neutrino oscillations
Species	Neutrino oscillations, neutrino cosmology

Selected current and future ν osc. experiments

Short-baseline

MicroBooNE

Started in 2015

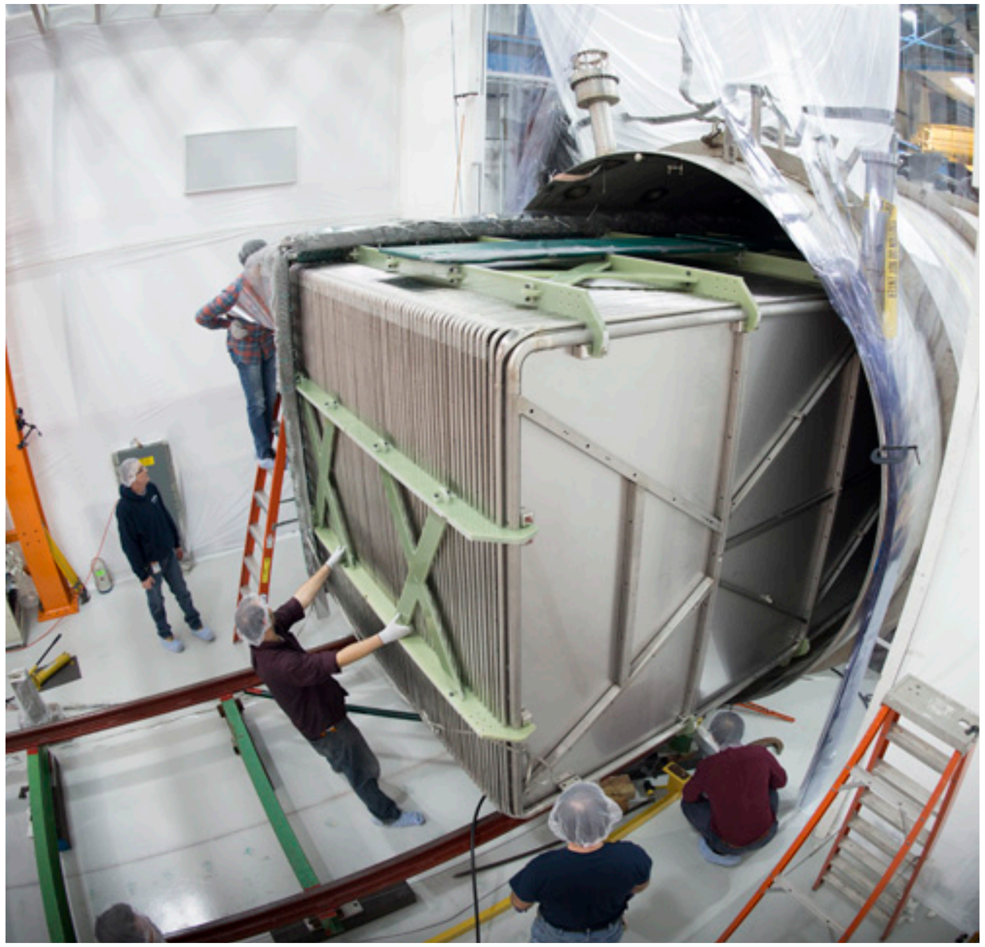
- 170 ton LAr TPC in Booster Neutrino Beamline at Fermilab

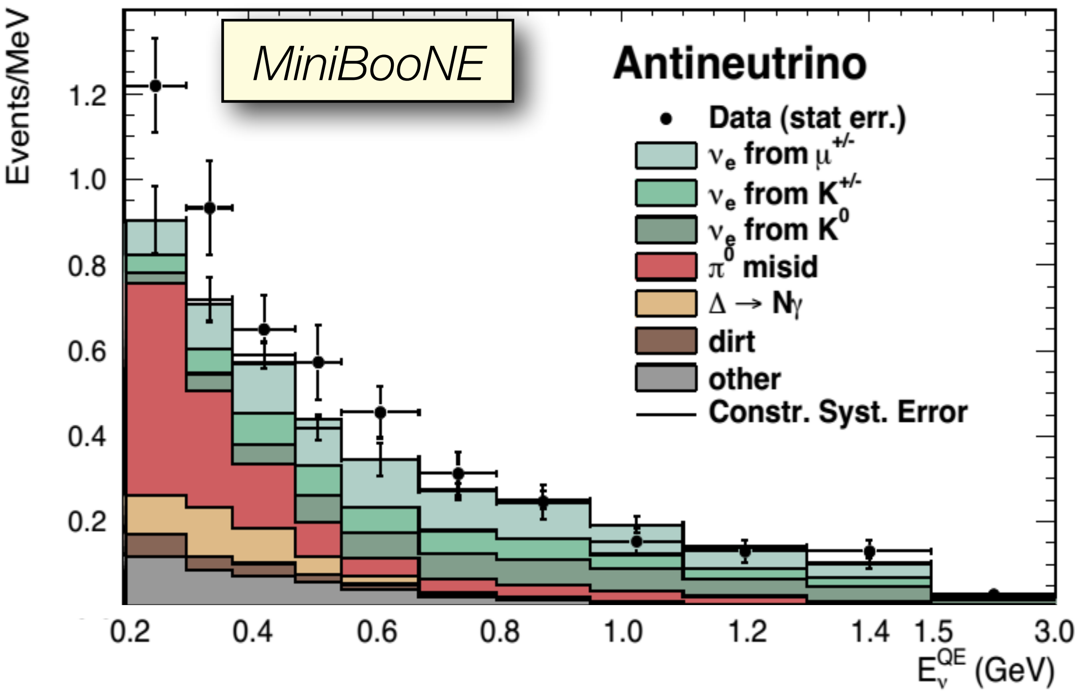
Physics goals:

- MiniBooNE low-energy excess: electrons (oscillation signal) or gammas (background)?
- Neutrino cross sections on argon

R&D goals toward DUNE:

- Long drift (2.5 m)
- Cold electronics (preamplifiers in liquid)
- Purity without evacuation

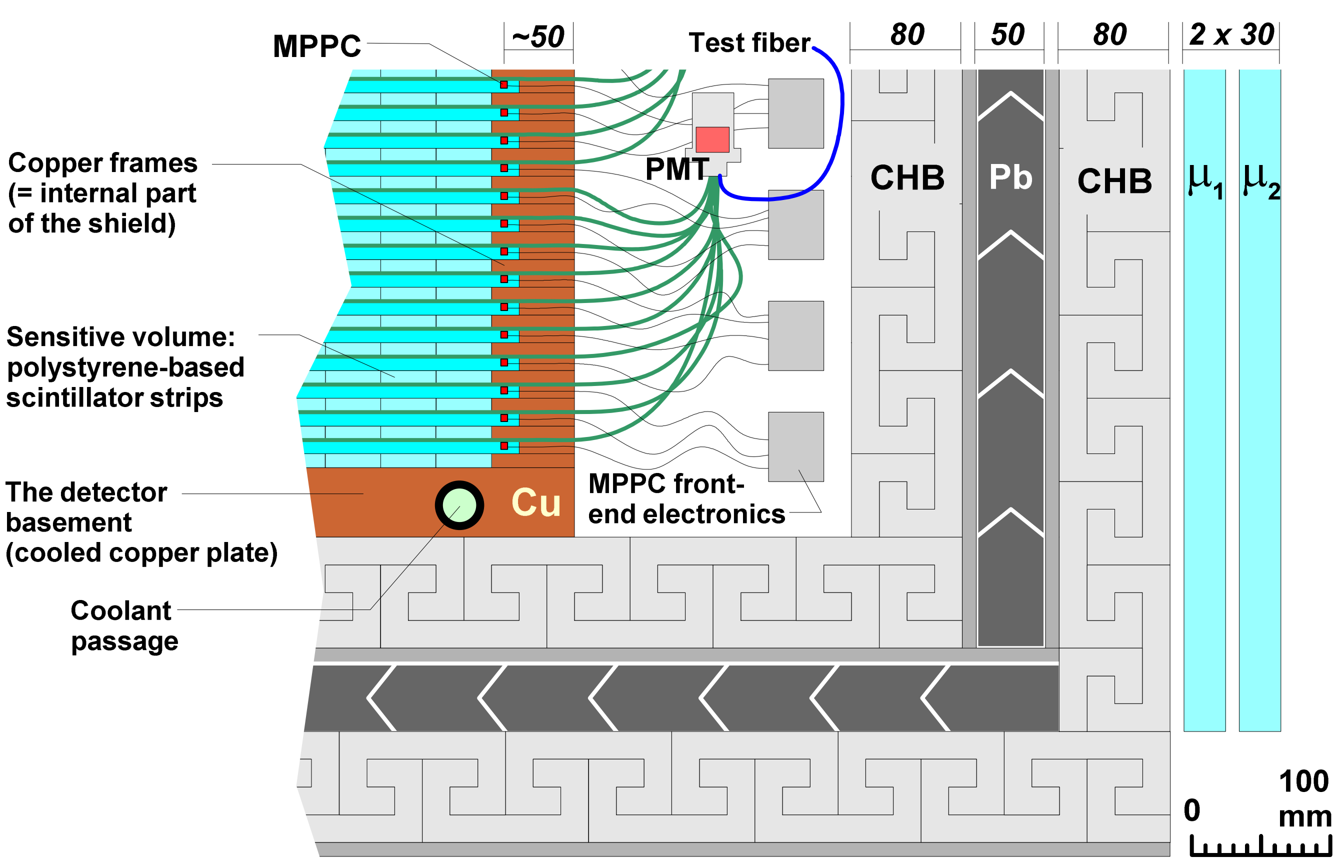


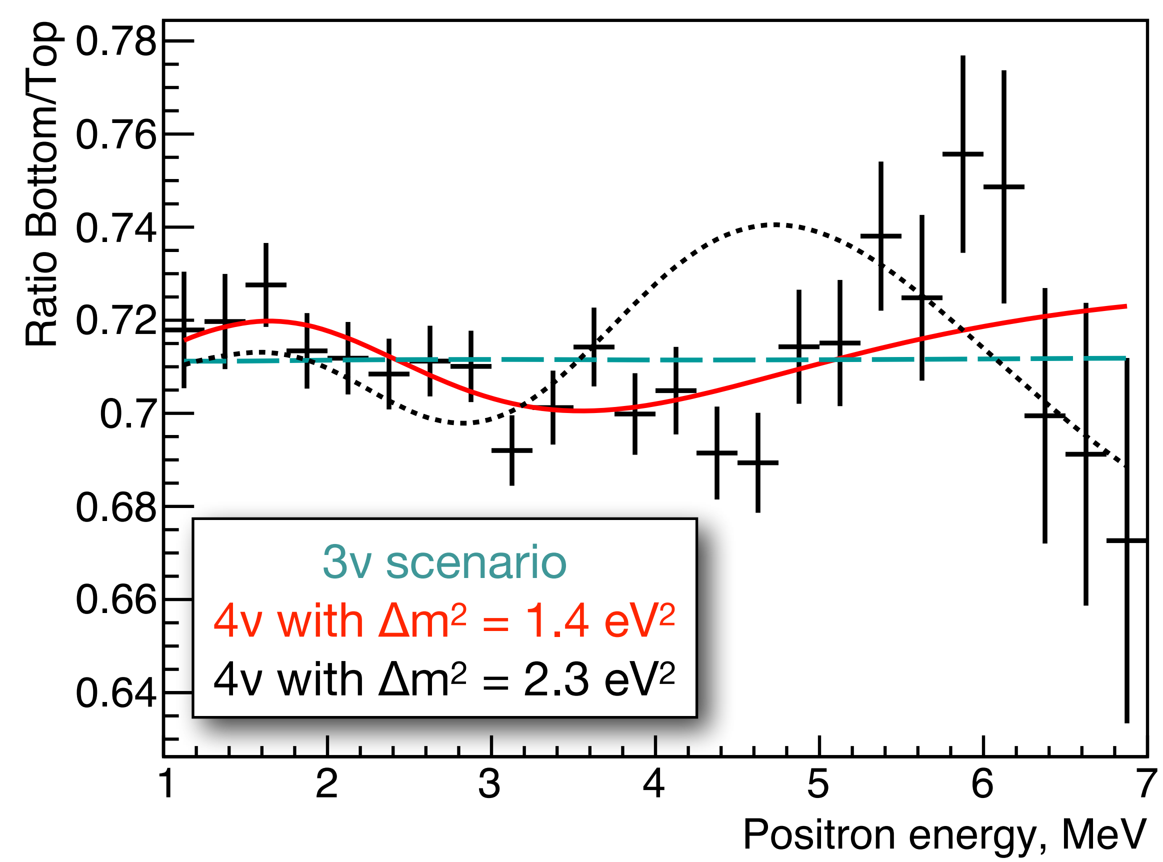


DANSS

Started in 2016

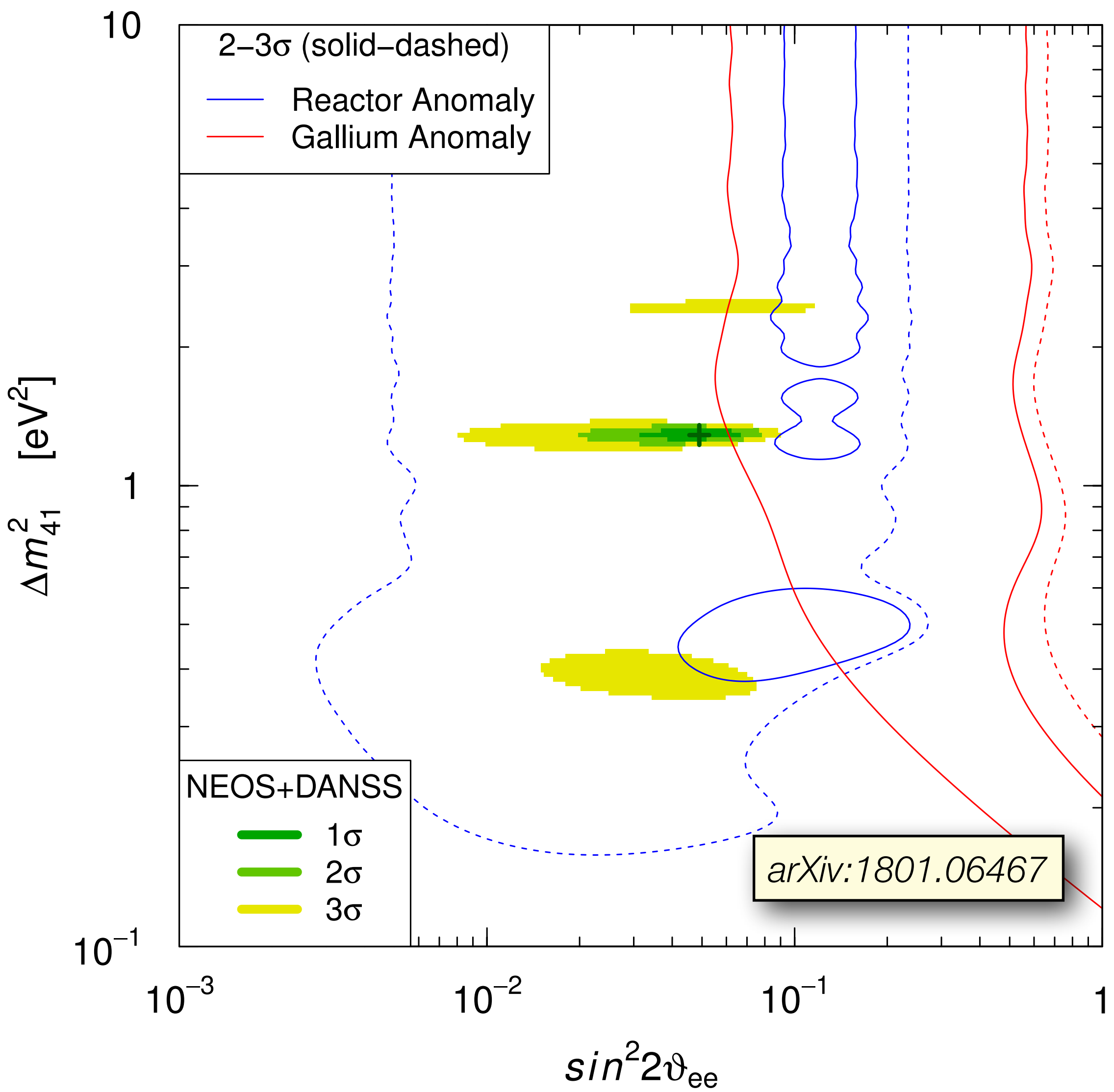
- Highly segmented 1 m³ plastic scintillator detector near 3.1 GW reactor in Russia
- Signal: delayed e^+-n coincidence from $\overline{\nu}_e + p \rightarrow e^+ + n$
- Suppression of high backgrounds: shielding, detector segmentation
- Unique feature: movable! Distance to reactor core: 10.7 - 12.7 m



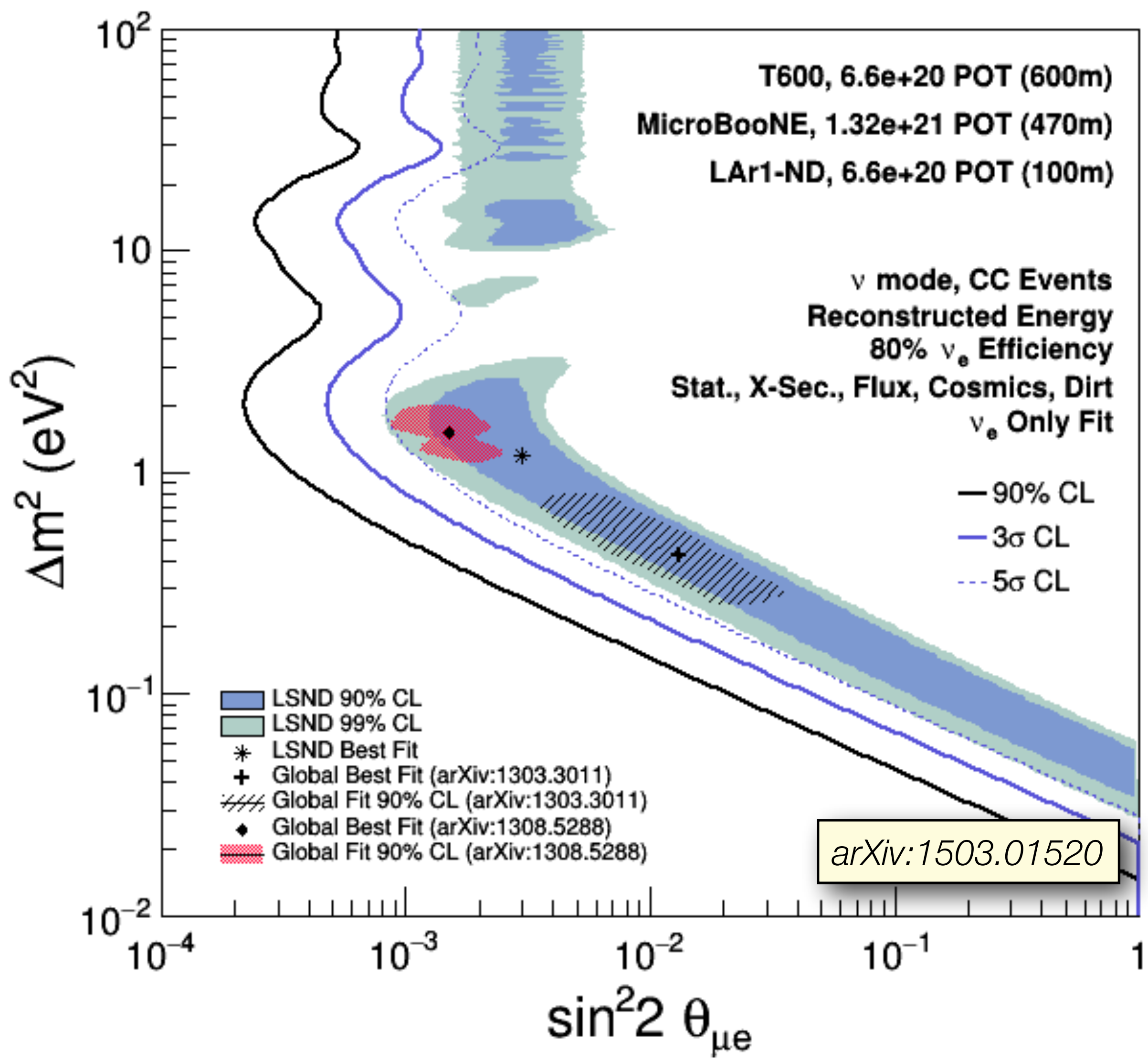


Prospects to discover light sterile neutrinos

- Reactor-based (and source-based) proposals sensitive to reactor+gallium anomaly:



- Accelerator-based proposals sensitive to LSND+MiniBooNE anomaly:



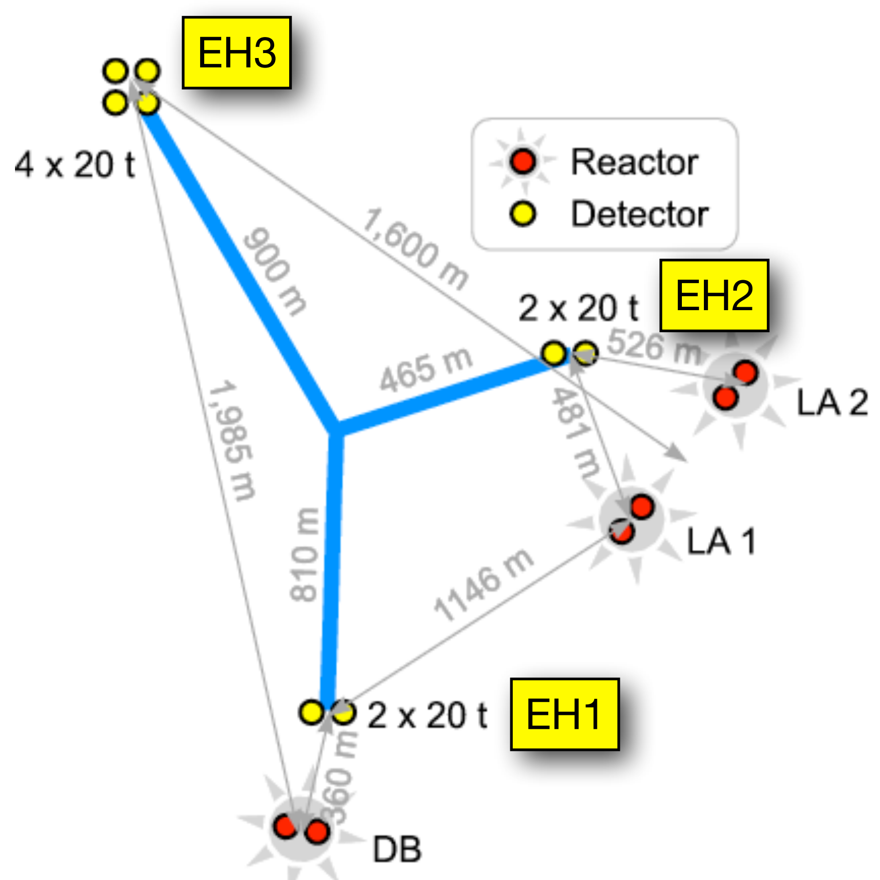
Selected current and future ν osc. experiments

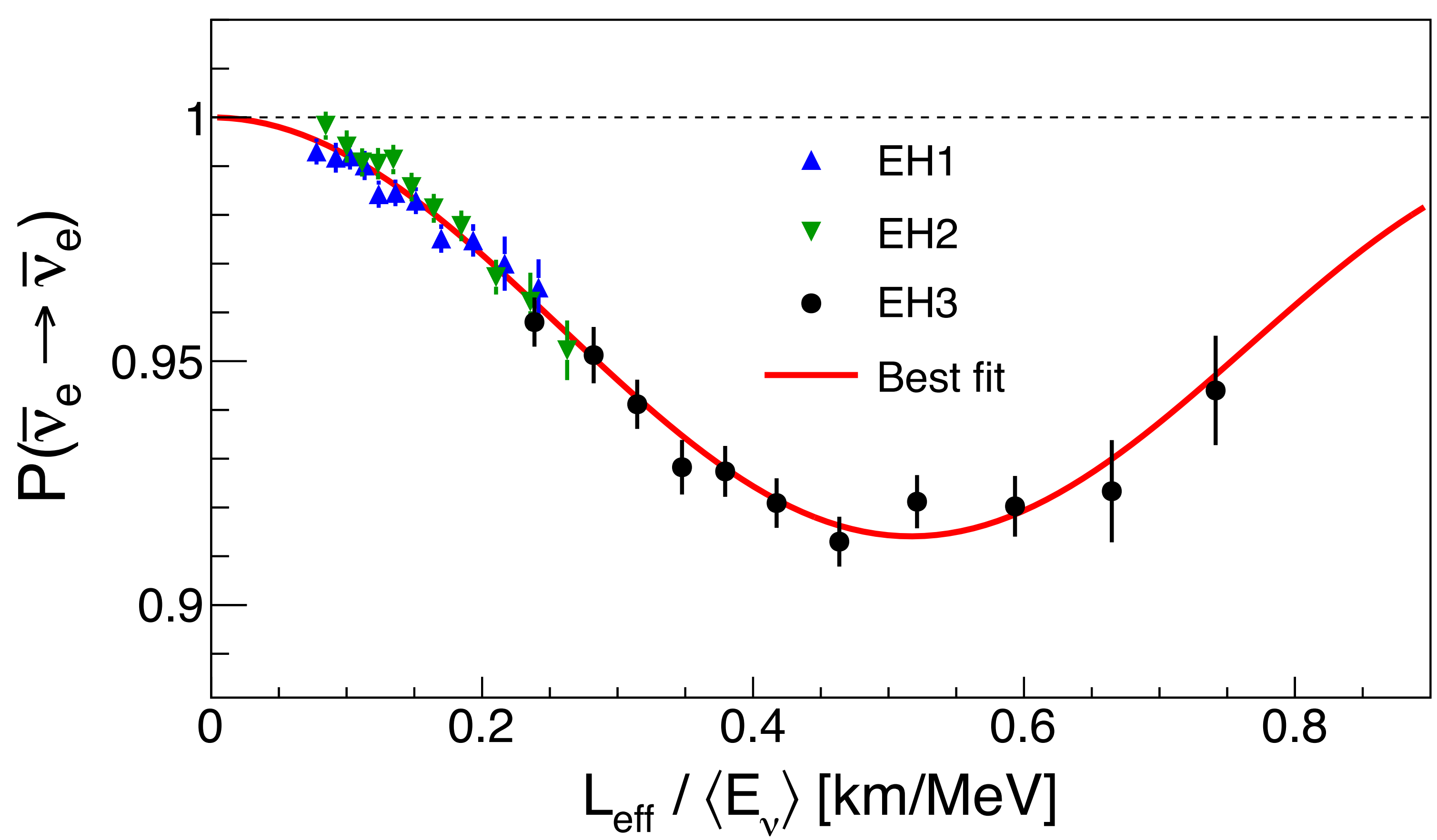
Medium- and long-baseline

Daya Bay

Started in 2011

- Liquid scintillators measuring reactor $\overline{\nu}_e$ disappearance over km-long baselines
- Most precise measurement of $\sin^2 2\vartheta_{13}$ to date
- Consistent results from RENO and Double Chooz

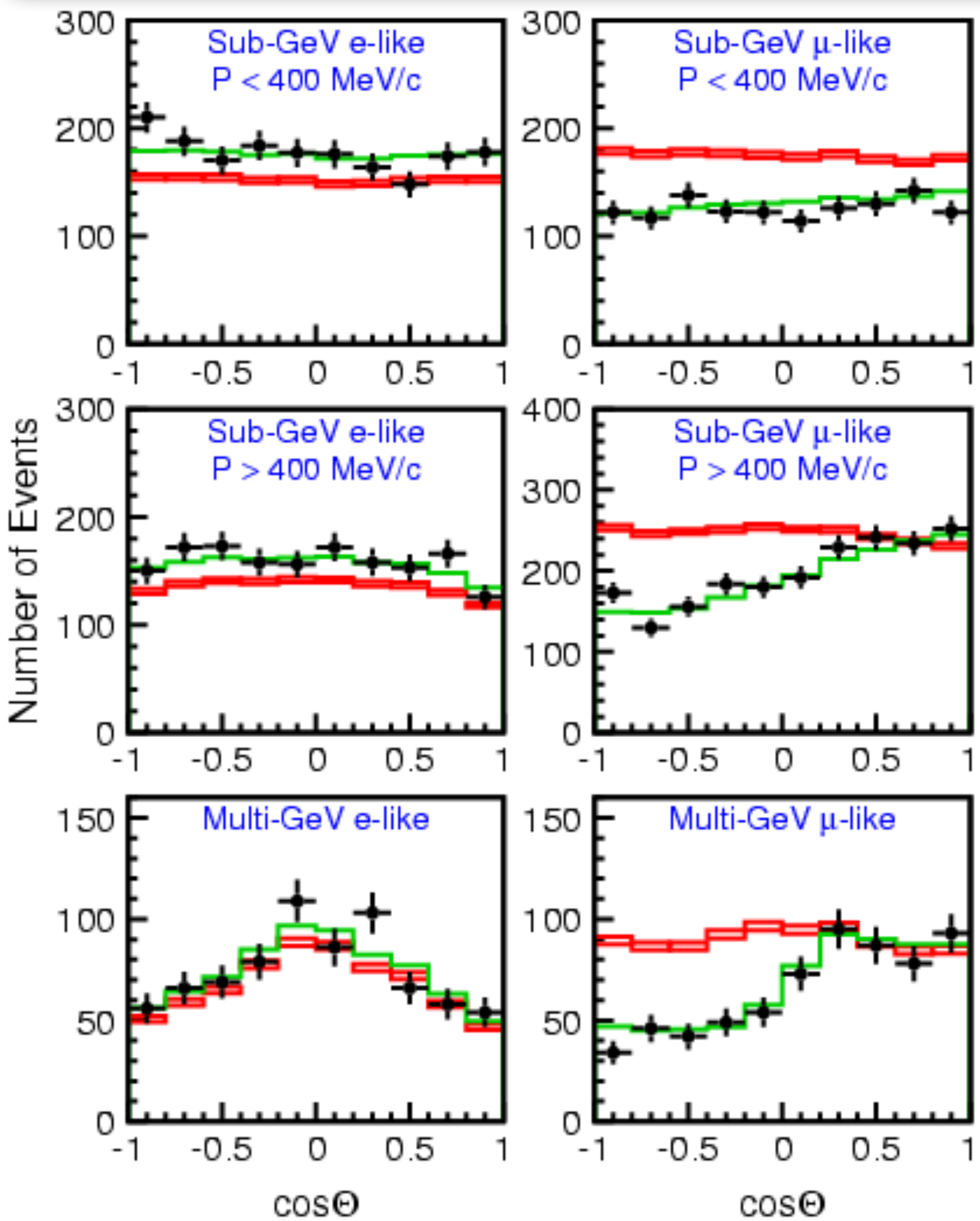




Super-Kamiokande atmospheric

Started in 1996

- Water Cherenkov detector measuring atmospheric neutrinos (both ν_μ and ν_e)
- First conclusive evidence for oscillations, from zenith angle-dependent deficit of ν_μ's!
- Same detector also sensitive to solar neutrino interactions



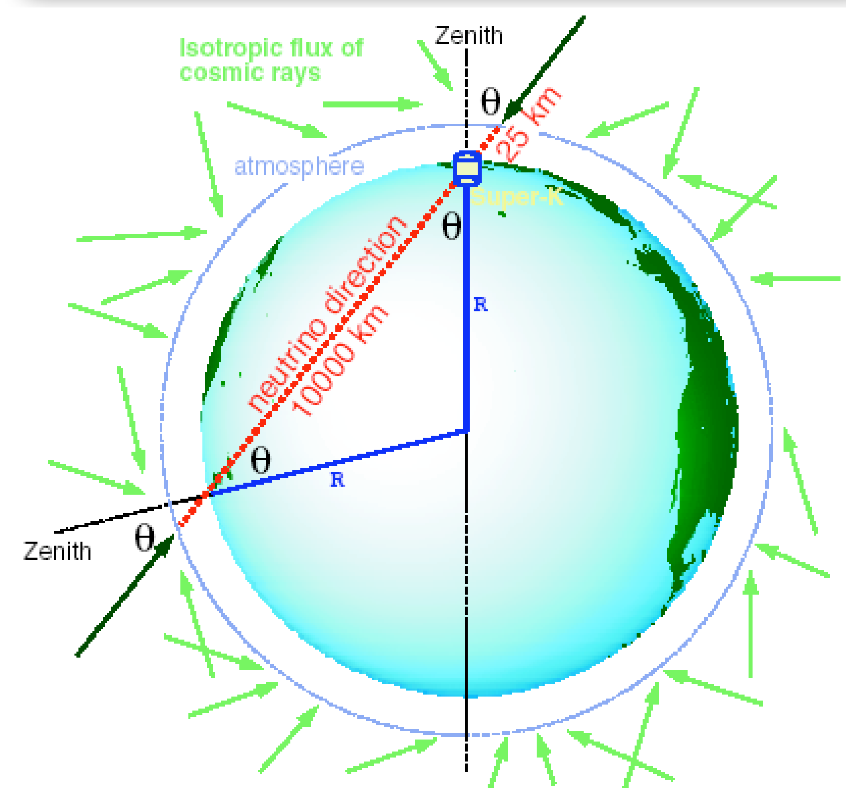
– expected without oscillations

– expected with oscillations

+ observed

$\cos\vartheta = +1 \Leftrightarrow$ travel length ~ 20 km

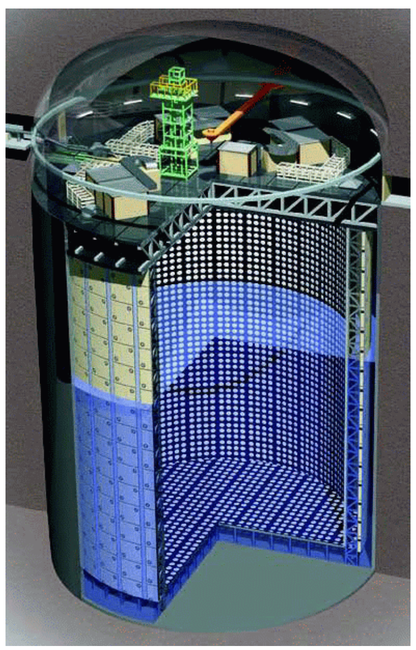
$\cos\vartheta = -1 \Leftrightarrow$ travel length ~ 13000 km

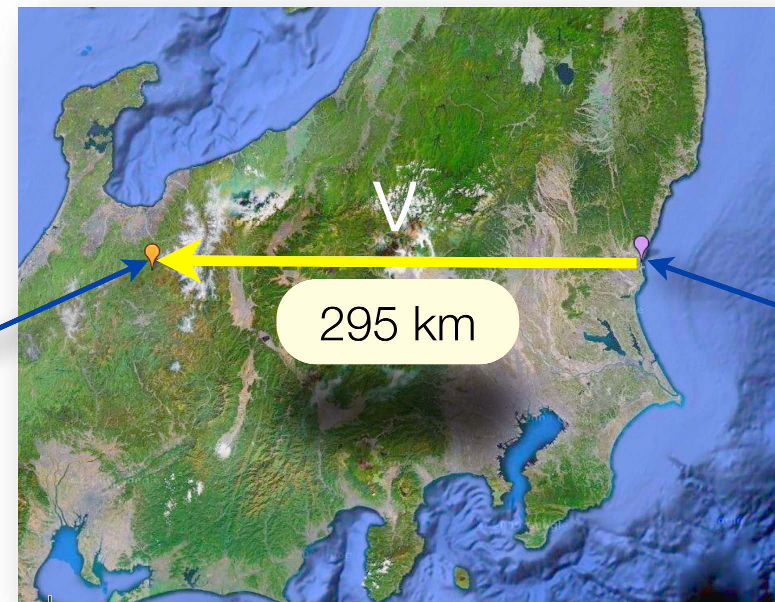


T2K

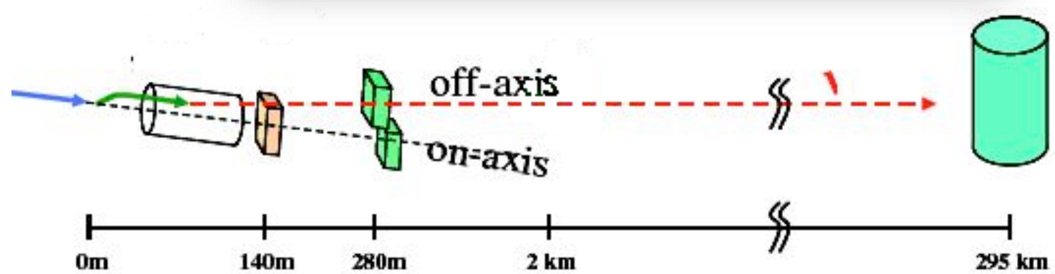
Started in 2010

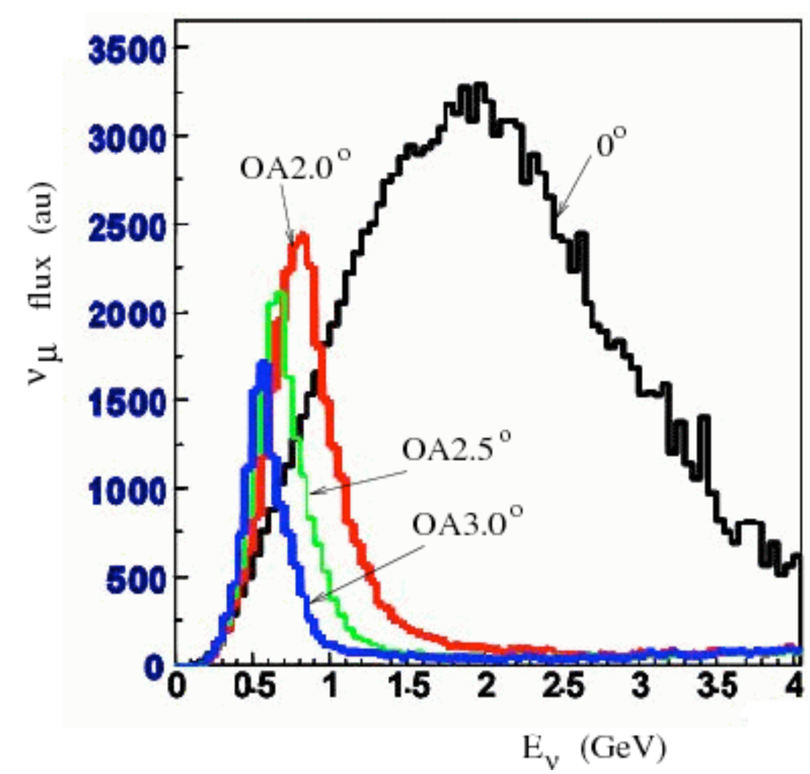
Super-K Detector





J-PARC Accelerator and
Near Detectors (ND280, INGRID)



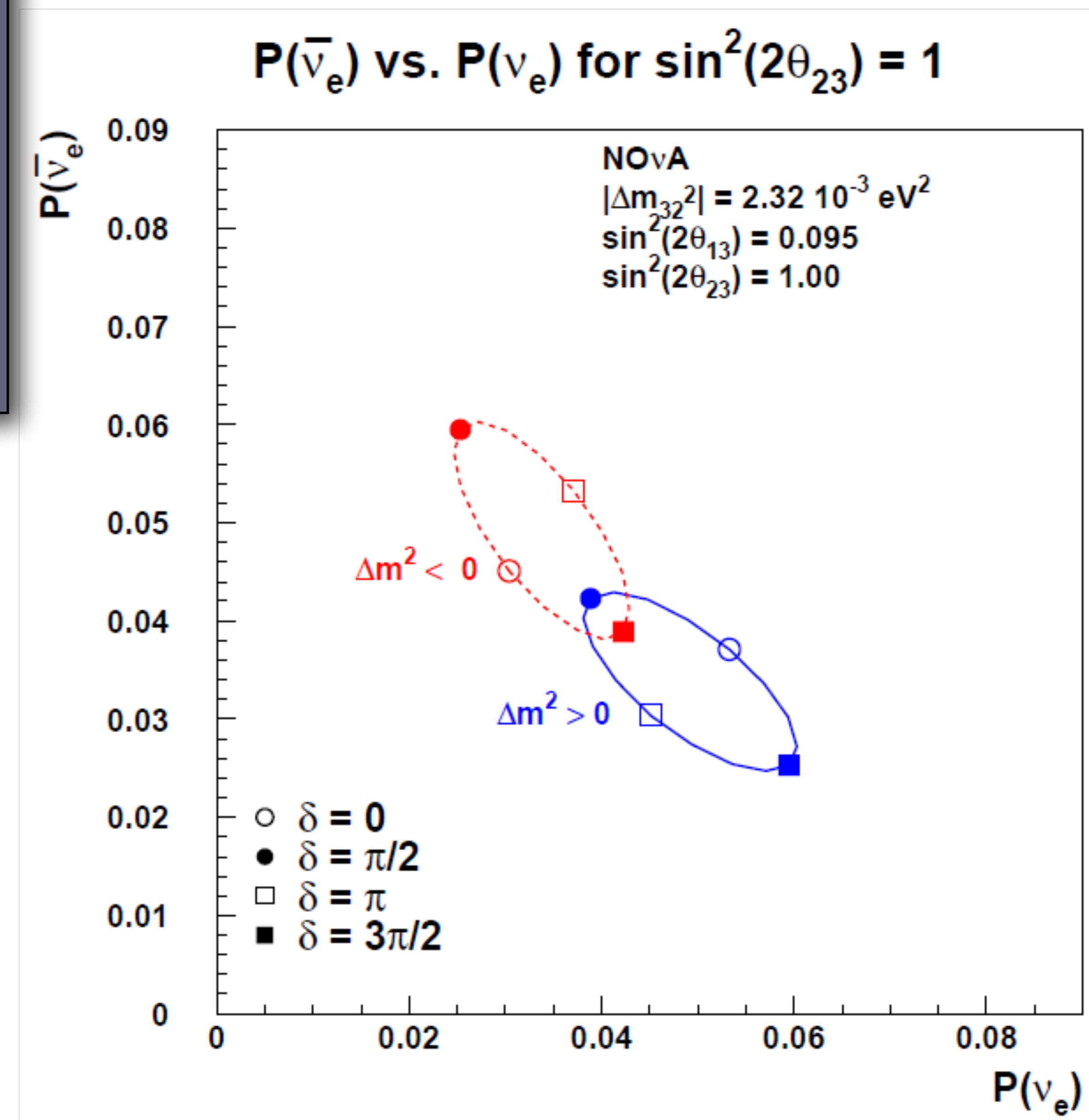


- Super-K also sees JPARC off-axis neutrino beam
- T2K has conclusively shown that ν_μ transform into ν_e
  - T2K + reactors prefer maximal CP violation ($\delta=-\pi/2$)!
- Data until 2026, up to 3σ significance to CP violation

NOvA

Started in 2014

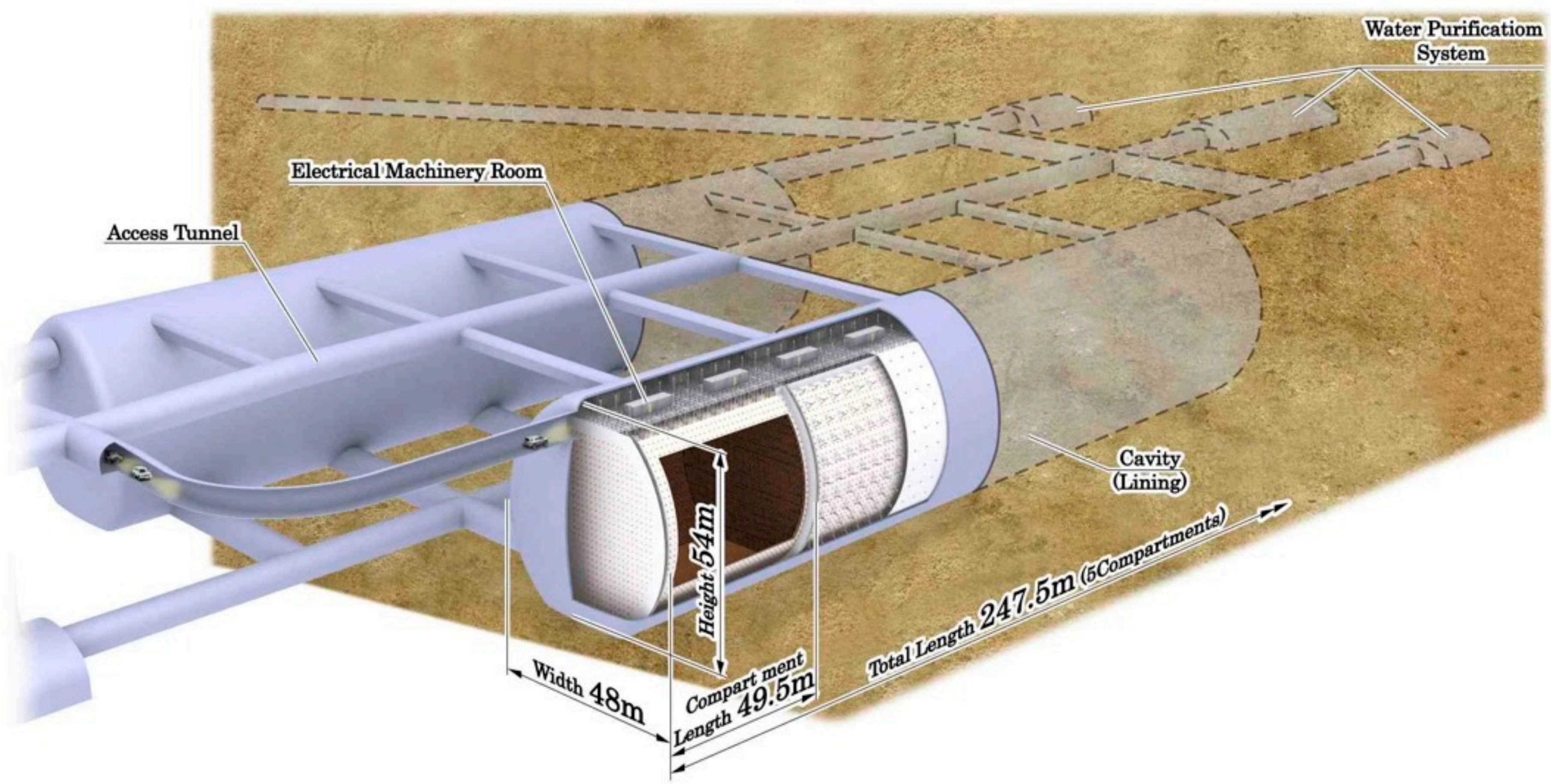
- As T2K, long-baseline and off-axis
- Separately measure $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ to extract CP violation and mass hierarchy
- Compared to T2K:
  - Longer baseline (810 km), better for hierarchy
  - Segmented tracker rather than water Cherenkov



Hyper-Kamiokande (T2HK)

Starting in 2026?

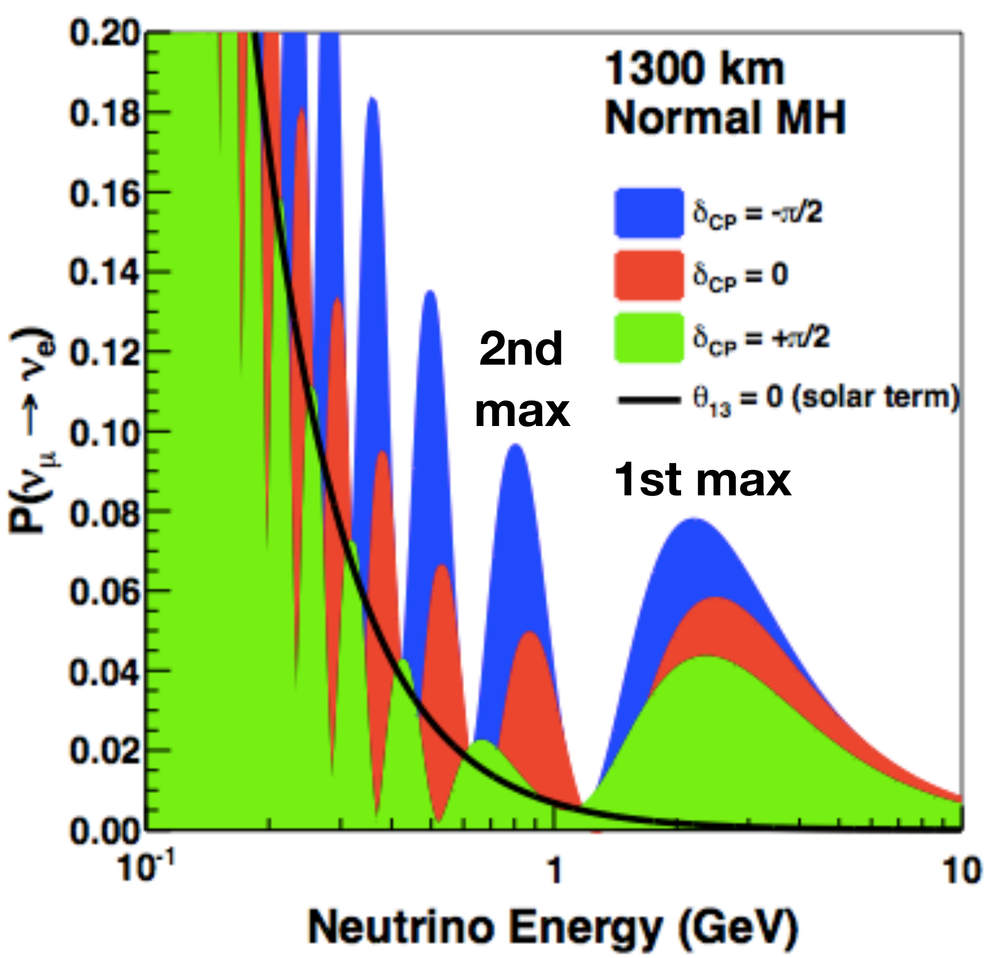
- Same concept as T2K (and NOvA): separately measure $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ off-axis, but:
  - More powerful beam: 1-2 MW! (**x2** T2K)
  - More massive detector: 1 Mton! (**x20** Super-Kamiokande)
- Mostly "counting" experiment at low (< 1 GeV) energies → water Cherenkov detector
- Mass hierarchy from atmospheric neutrinos

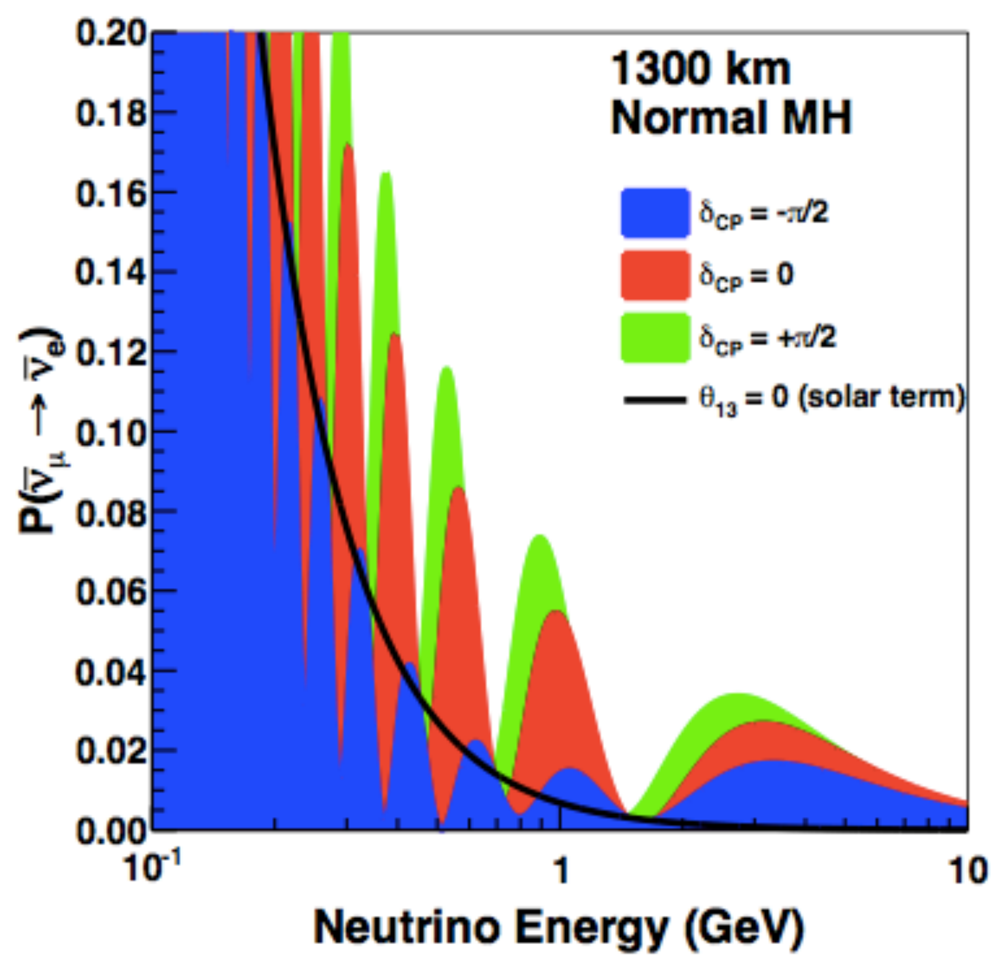


DUNE

Starting in 2024?

- Other next-generation long-baseline (1300 km) oscillation experiment
- On-axis 0.5-6 GeV ν + $\bar{\nu}$ beam covering 1st and 2nd oscillation maximum to disentangle mass ordering and CP effects
- Requires detector for high-energy neutrinos → LAr TPC as Far Detector (FD)





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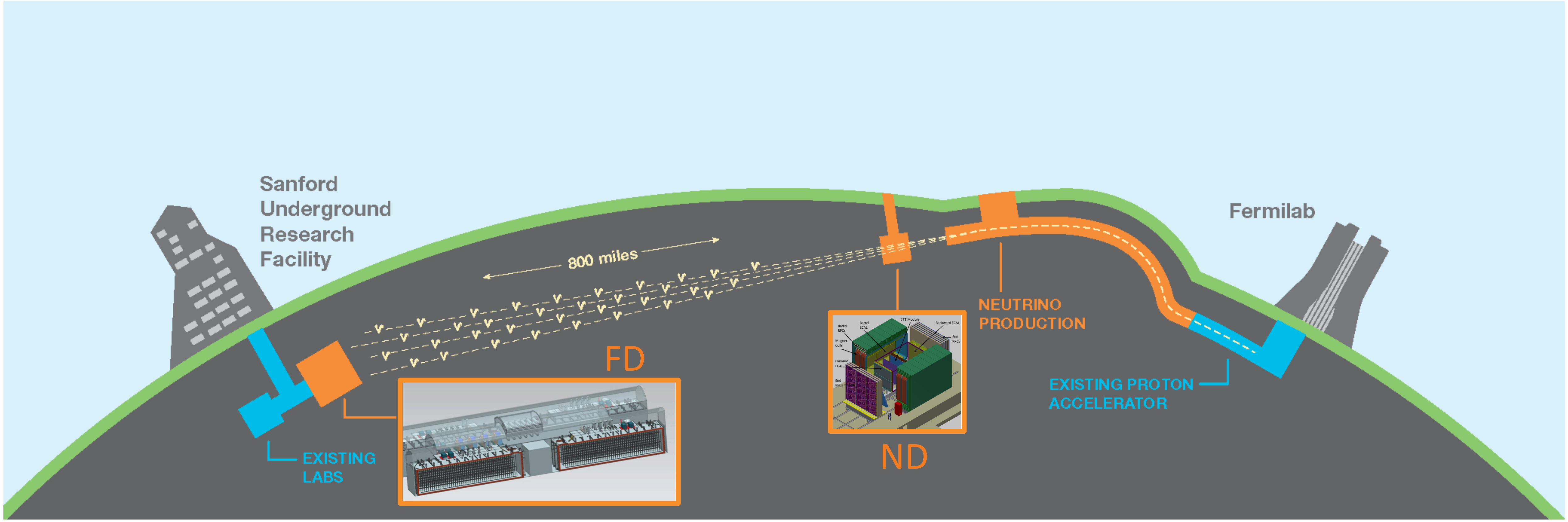
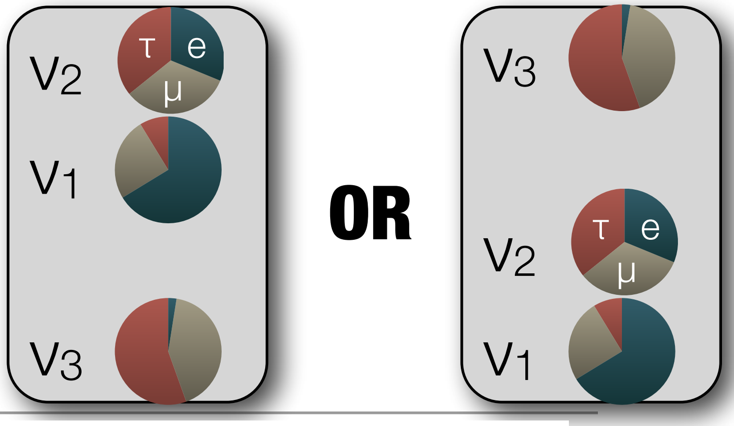
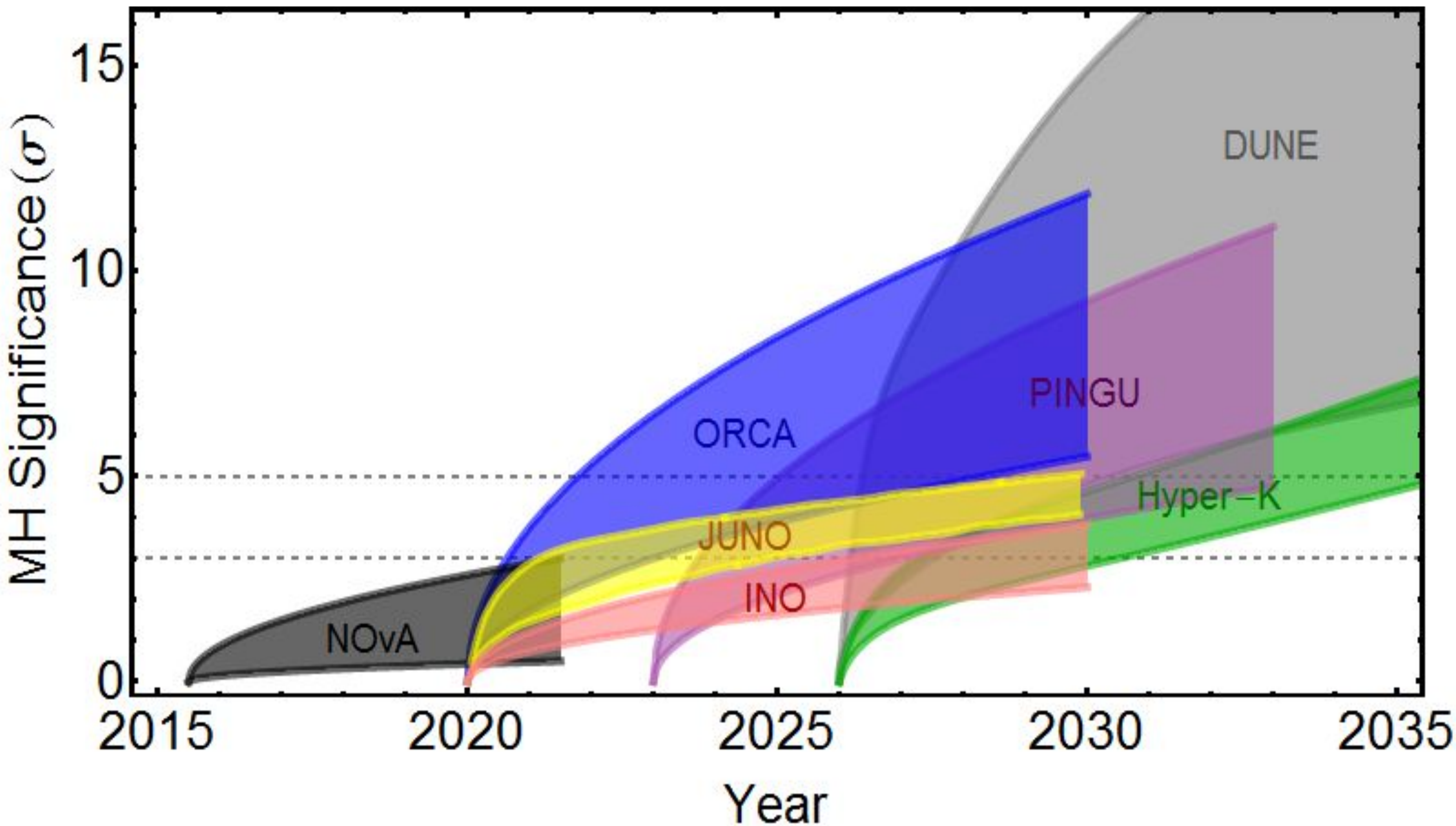


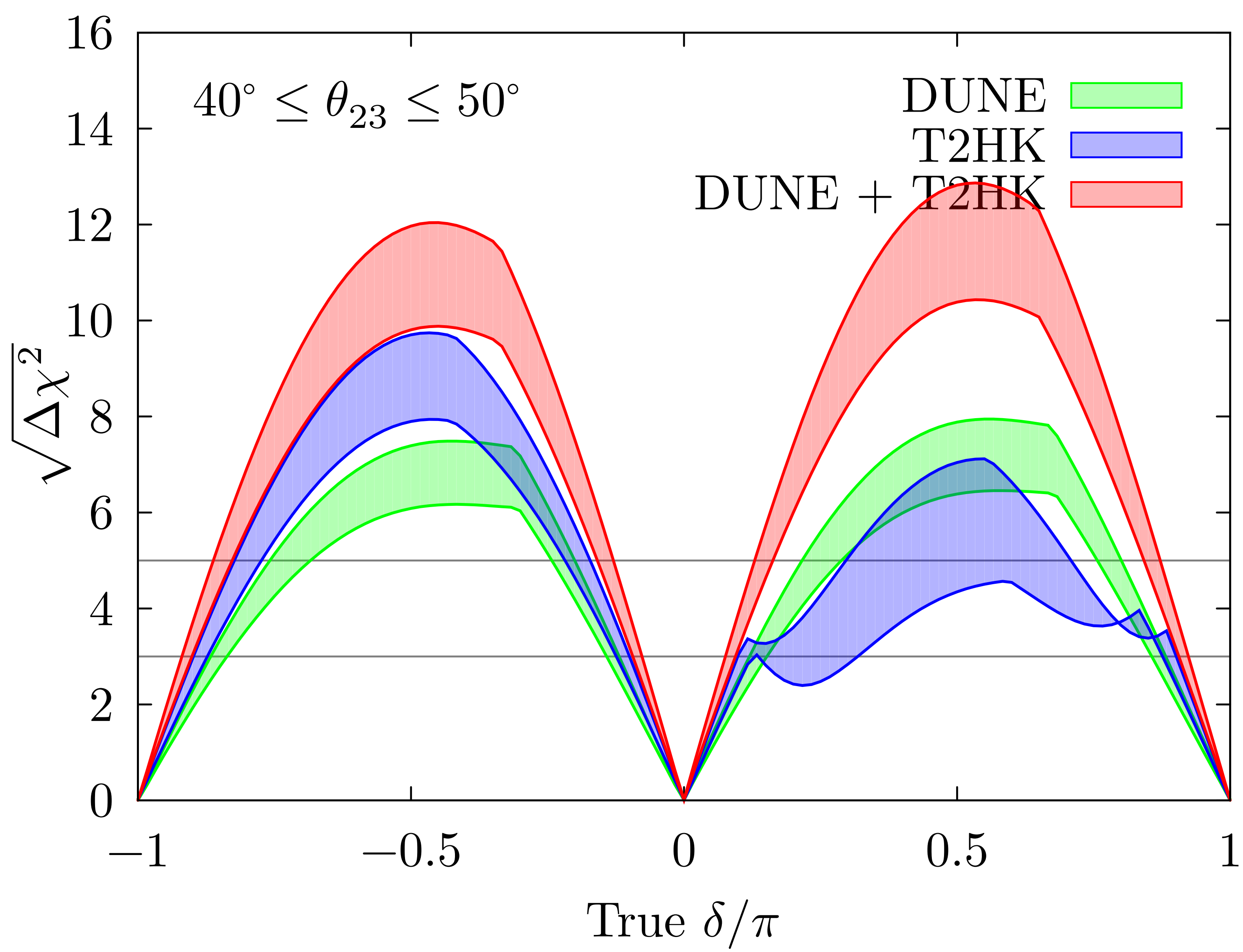
Prospects to measure the neutrino mass ordering





- The neutrino mass ordering will be measured in the next few years!

Prospects to measure leptonic CP violating phase $\delta_{CP} \neq 0, \pi$



- Unambiguous CPV measurement by late 2020's, provided CPV close to maximal
- Hints already here! Maximal CPV at δ_{CP} = -π/2 favoured by current data! (M. Tortola)

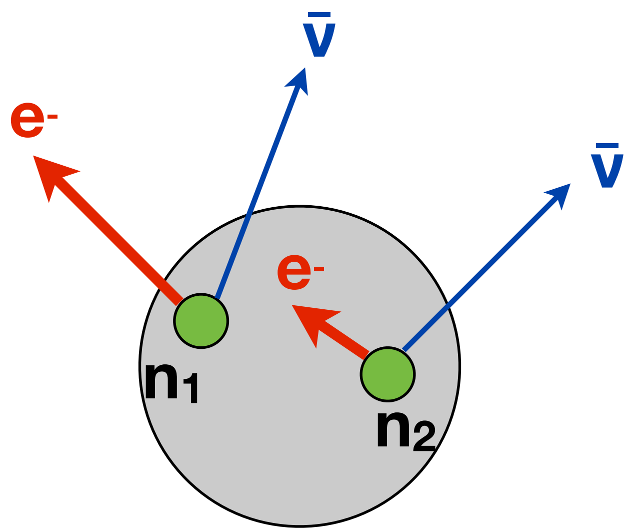
Neutrinoless double beta decay

Generalities

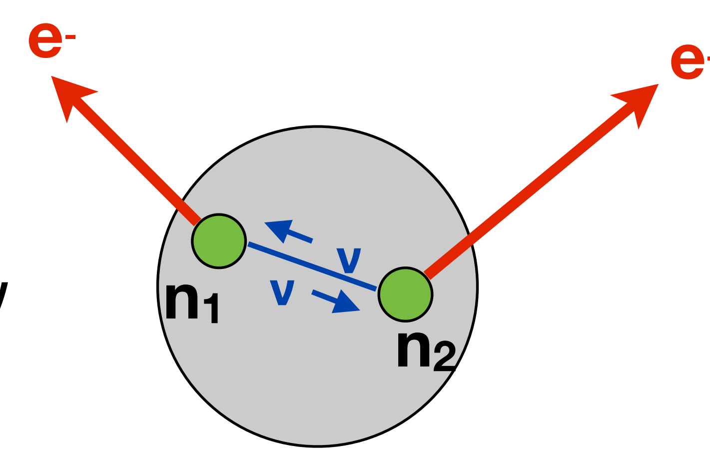
Double beta decay

- Rare (Z,A)→(Z+2,A) nuclear transition, with emission of two electrons
- Two basic decay modes

ββ2ν



ββ0ν



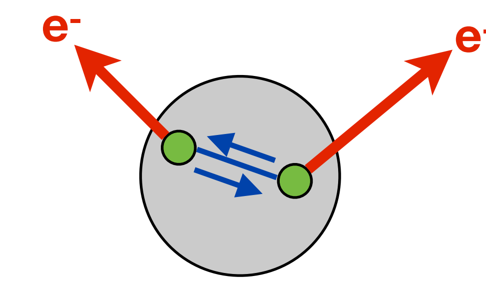
Two neutrino mode

- Observed in several nuclei
- 10^{19}-10^{21} yr half-lives
- Standard Model allowed

Neutrinoless mode

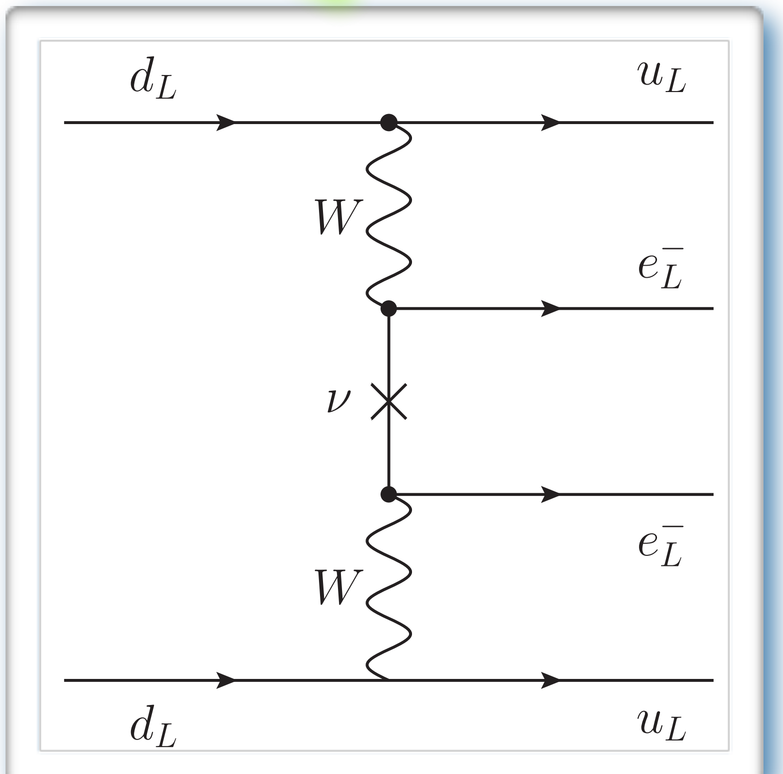
- Not observed yet in Nature
- >10^{26} yr half-lives
- Would signal Beyond-SM physics

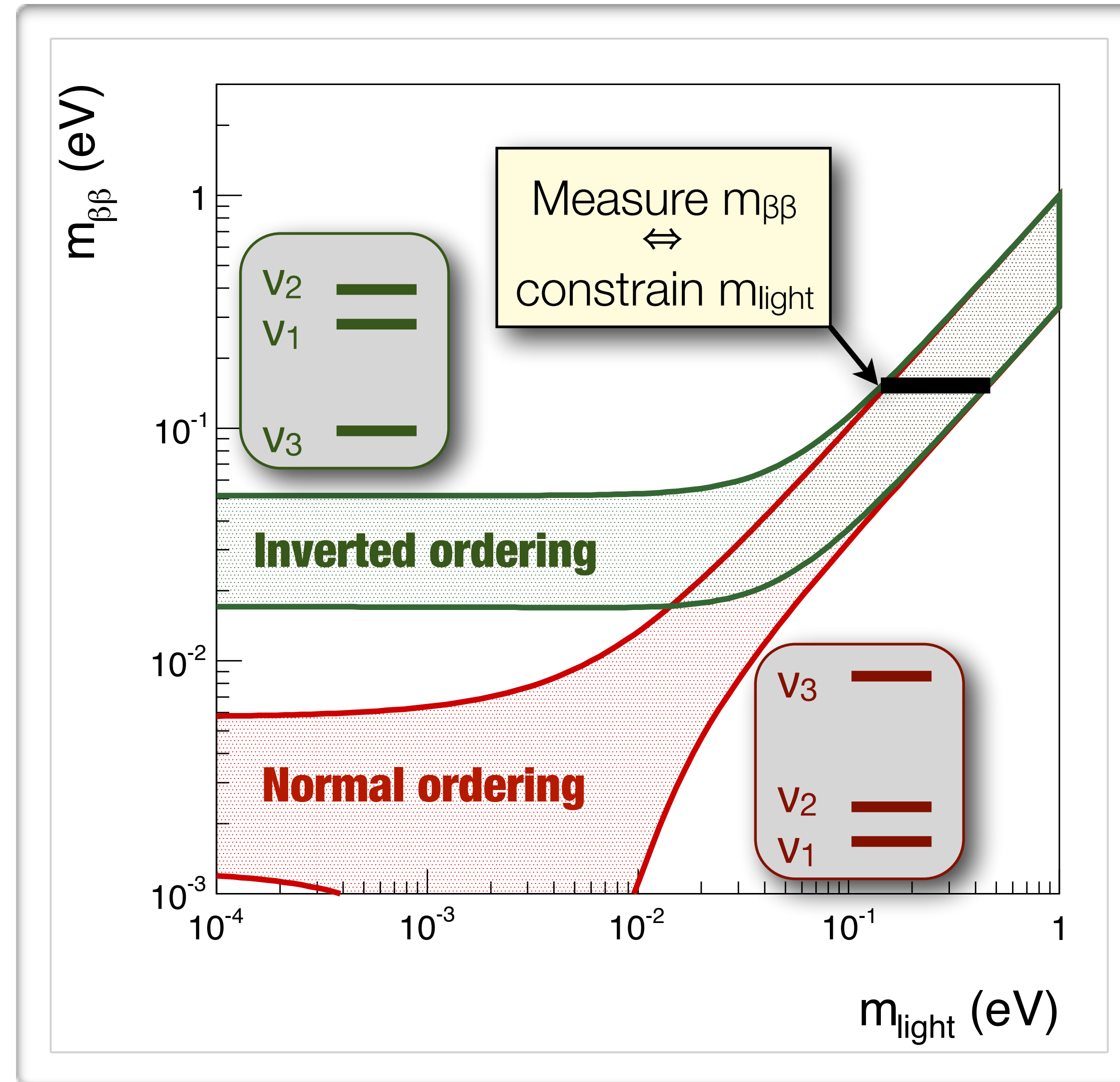
Neutrinoless double beta decay and the neutrino questions



Lepton number violating process implying massive Majorana neutrinos

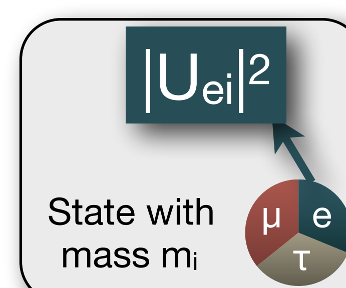
- Identity
- Mass scale
- Mass ordering
- Mixing
- Species





$$(\text{Rate})_{\beta\beta0\nu} = 1/T_{1/2} = G^{0\nu}\cdot|M^{0\nu}|^2\cdot m_{\beta\beta}^2$$

$$\text{Majorana } \nu \text{ mass: } m_{\beta\beta} \equiv \left| \sum_i m_i U_{ei}^2 \right|$$



Facts life of the double beta decay experimentalist

- Total number of ββ0v decays that can be observed in a detector is (exercise: derive!)

$$N_{\beta\beta 0\nu} = \log 2 \cdot \frac{M_{\beta\beta} \cdot N_A}{W_{\beta\beta}} \cdot \varepsilon \cdot \frac{t}{T^{0\nu}_{1/2}}$$

mass of ββ isotope ($M_{\beta\beta}$)

Avogadro's constant (N_A)

Exposure time (t)

ββ0v half-life ($T^{0\nu}_{1/2}$)

Molar mass of ββ isotope ($W_{\beta\beta}$)

Efficiency (ε)

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- N_A: Avogadro's constant
- t: Exposure time
- $T^{0\nu}_{1/2}$: ββ0ν half-life
- $W_{\beta\beta}$: Molar mass of ββ isotope
- ε: Efficiency

- **Question**: for a ^{136}Xe experiment with 100% efficiency and 1 year exposure time, what is the mass $M_{\beta\beta}$ required to observe **only one** ββ0ν decay?

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Avogadro's constant

Exposure time

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ββ0ν half-life

Molar mass of ββ isotope

Efficiency

- **Question**: for a ^{136}Xe experiment with 100% efficiency and 1 year exposure time, what is the mass $M_{\beta\beta}$ required to observe **<u>only one</u>** ββ0ν decay?

- Assuming that the (unknown) ββ0ν half-life of ^{136}Xe is $\mathbf{T_{1/2} = 10^{27}}$ **years**, get:

$$M_{\beta\beta} = 326 \text{ kg!}$$

Facts life of the double beta decay experimentalist

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- $M_{\beta\beta}$: mass of ββ isotope
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$$M_{\beta\beta} = 326\ \text{kg!}$$

- Life is harder than this: non-perfect efficiencies and **backgrounds**

Experimental sensitivity to ββ0ν

- Experiment with no background:

detector efficiency

$$T^{0\nu}_{1/2} \propto \varepsilon \cdot M_{\beta\beta} \cdot t$$

exposure
(mass×time)

Experimental sensitivity to ββ0ν

- Experiment with no background:

detector efficiency

$$T^{0\nu}_{1/2} \propto \varepsilon \cdot M_{\beta\beta} \cdot t$$

exposure (mass×time)

- Experiment with background:

detector efficiency

$$T^{0\nu}_{1/2} \propto \varepsilon \cdot \sqrt{\frac{M_{\beta\beta} \cdot t}{c \cdot \Delta E}}$$

exposure (mass×time)

energy resolution

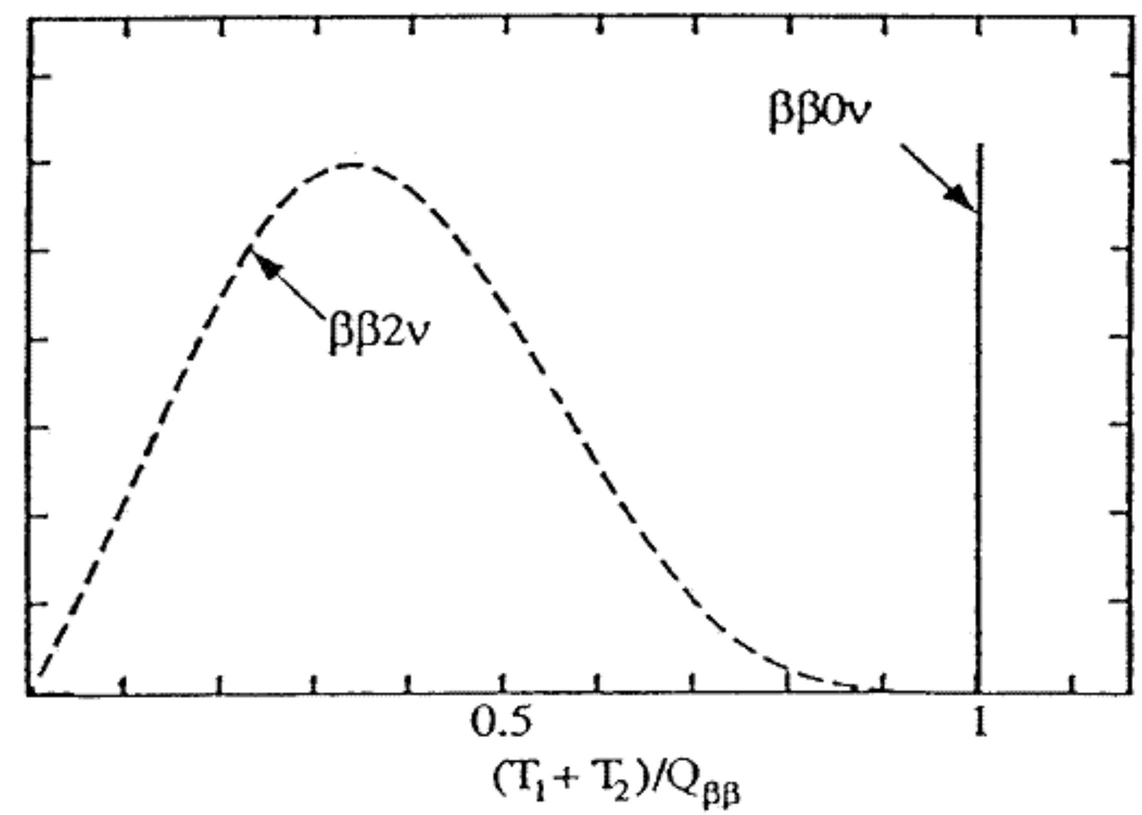
background rate (per unit energy, mass and time)

ββ0ν experimental signature

Rare process to be isolated in radio-pure detector underground

1.Calorimetry *(A MUST)*:

- *2ν mode:* continuous spectrum for sum electron kinetic energy T_1+T_2
- *0ν mode:* mono-energetic line at $Q_{\beta\beta}$ for T_1+T_2 spectrum



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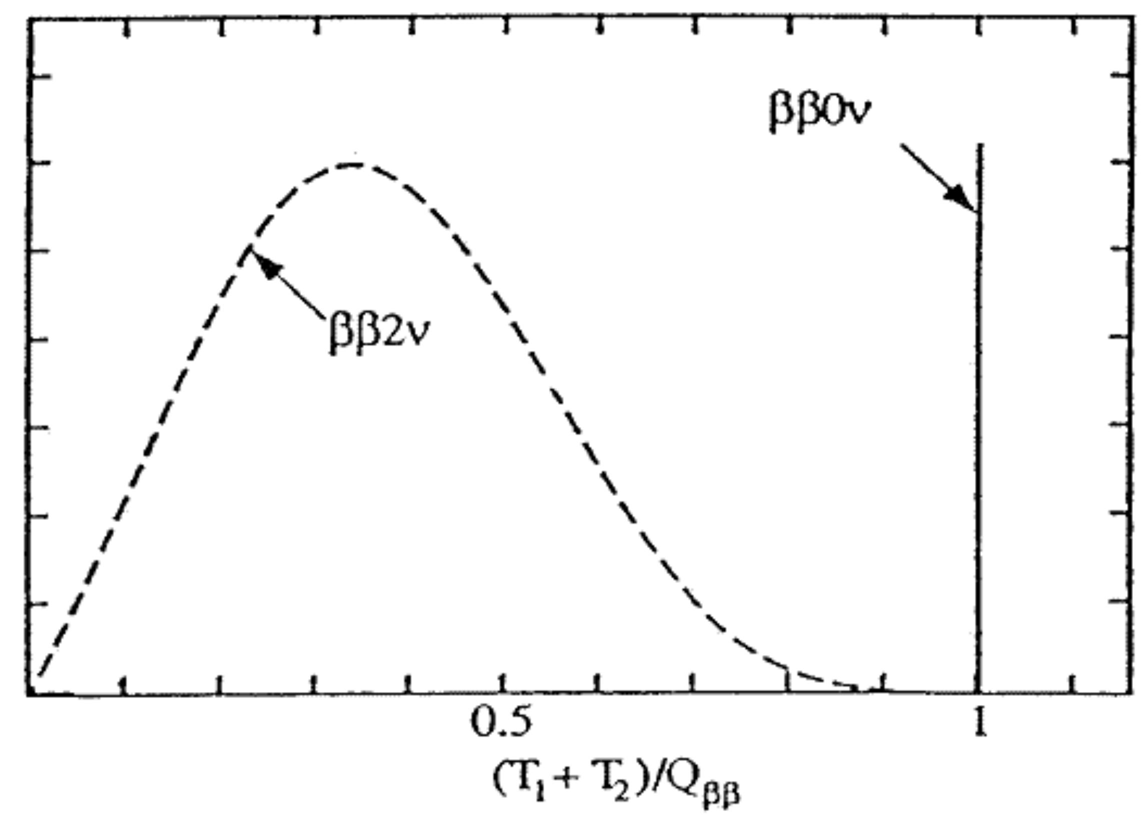

2.Topology of decay electrons *(AN ADDITIONAL HANDLE)*:

- Two electrons from common vertex

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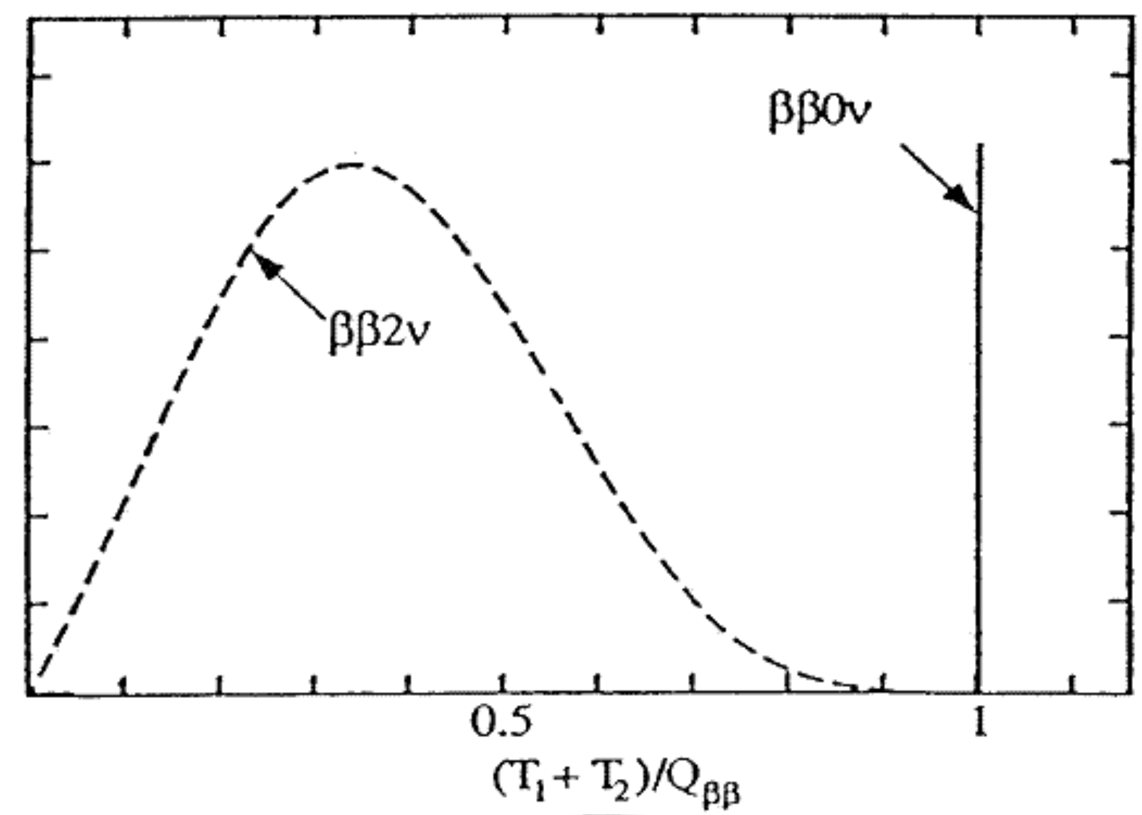


2.Topology of decay electrons *(AN ADDITIONAL HANDLE)*:

- Two electrons from common vertex

3.Daughter ion tagging *(A DREAM)*:

- Observe ion produced in the decay

Comparison of ββ isotopes

- ββ isotope choice affects relationship (ββ0ν rate ↔ Majorana mass):

atomic, nuclear, particle physics

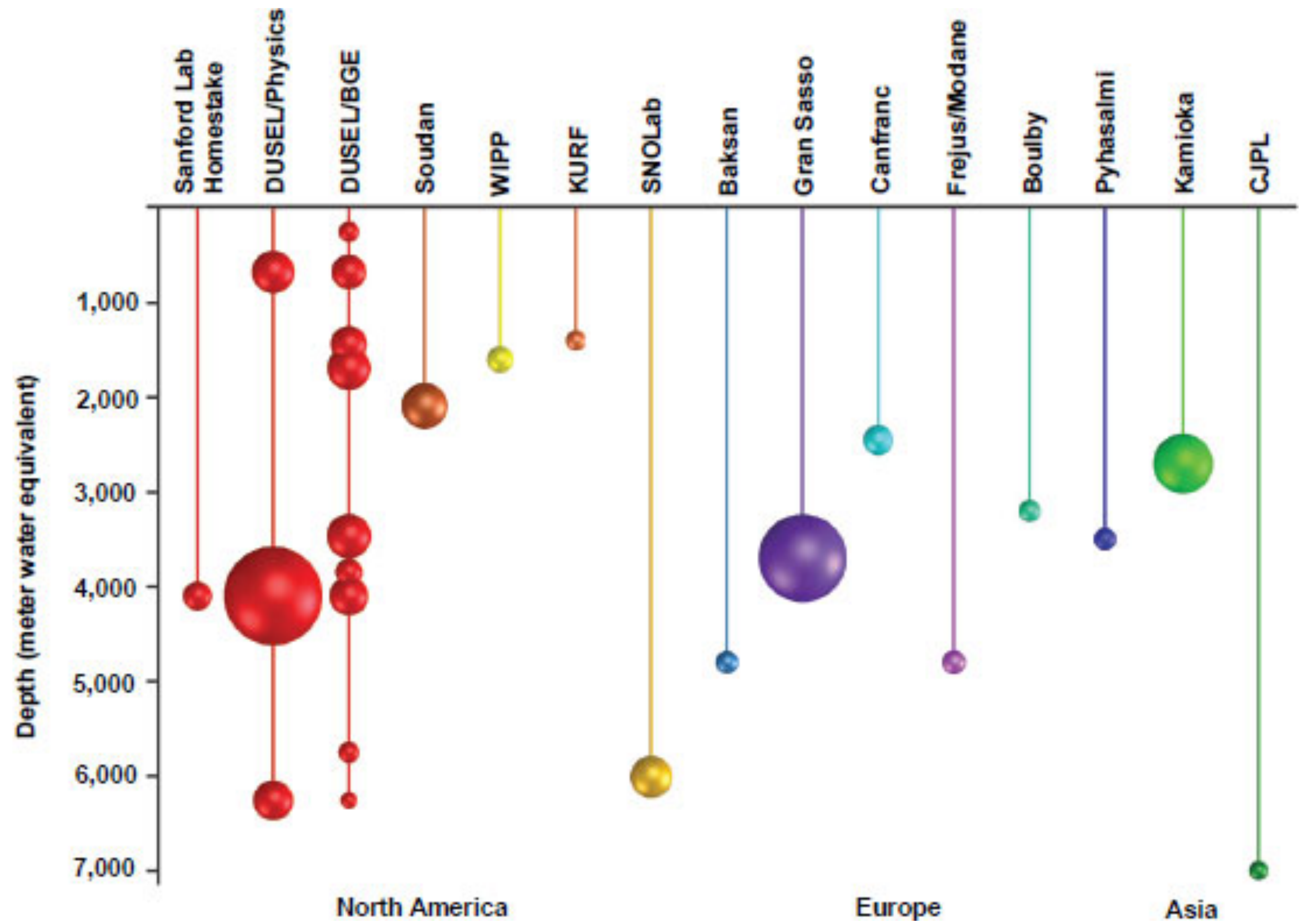
$$1/T_{1/2}^{0\nu} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot m_{\beta\beta}^2$$

Isotope	Q-value (MeV)	Phase space $G^{0\nu}$ (yr^{-1} eV^{-2})	Matrix element $\|M^{0\nu}\|$	Isotopic abundance (%)	Cost (normalized to ^{76}Ge)	Current experiments
^{76}Ge	2.04	3.0×10^{-26}	≈4.1	7.8	1	GERDA, Majorana
^{130}Te	2.53	2.1×10^{-25}	≈3.6	33.8	0.2	CUORE, SNO+
^{136}Xe	2.46	2.3×10^{-25}	≈2.8	8.9	0.1	EXO, KamLAND-Zen, NEXT

The higher, the better

The lower, the better

Underground detectors

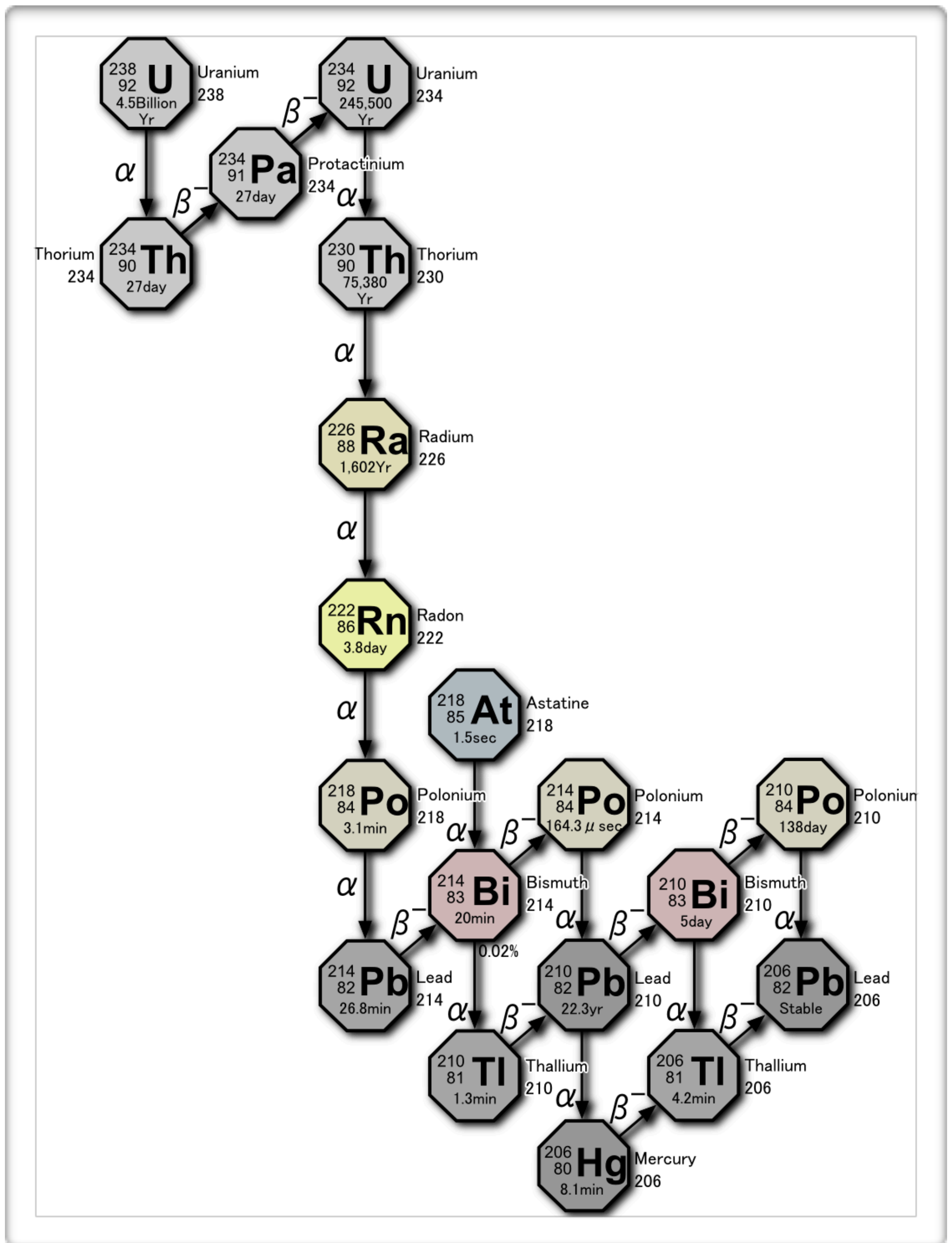


- Some backgrounds originated outside detector by cosmic-ray interactions
- All ββ0ν experiments located deep underground, using rock as shield

Laboratorio Subterraneo de Canfranc

Radiopure detectors

- Minimise contamination from natural radioactivity in all detector components

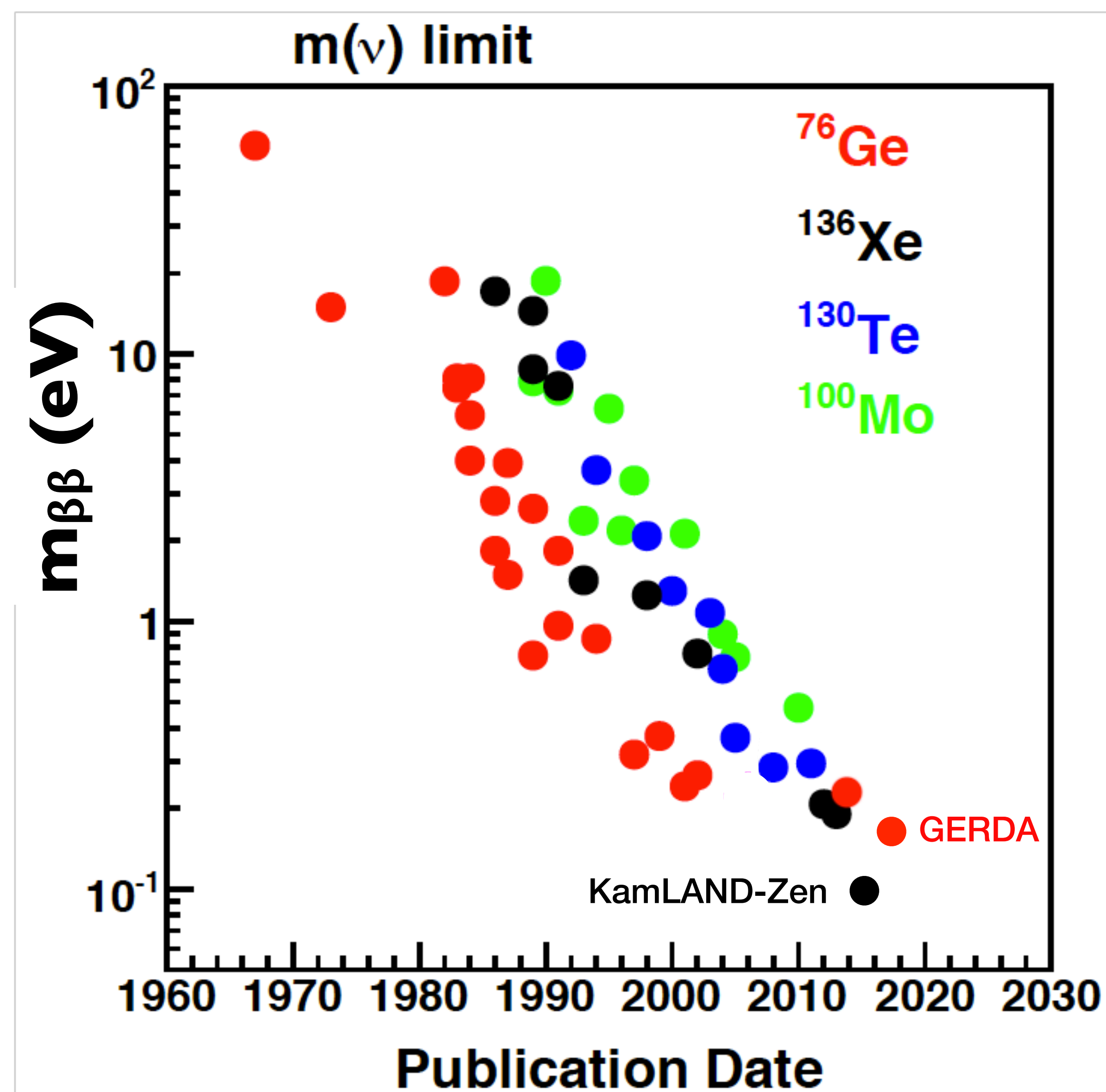


ββ0ν experimental status

Main experiments, current generation:

- No convincing evidence for ββ0ν
- Best limits:

Experiment	$T_{1/2}^{0\nu}$ limit (yr)	$m_{\beta\beta}$ limit (meV)
KamLAND-Zen	$> 1.07\times10^{26}$	< 61-165
GERDA	$> 5.3\times10^{25}$	< 150-330



Neutrinoless double beta decay

A selection of experiments

GERDA experiment

Started in 2011

- High-purity germanium diodes enriched in ^{76}Ge immersed in LAr
- **Advantages**: energy resolution, radiopurity → background-free!

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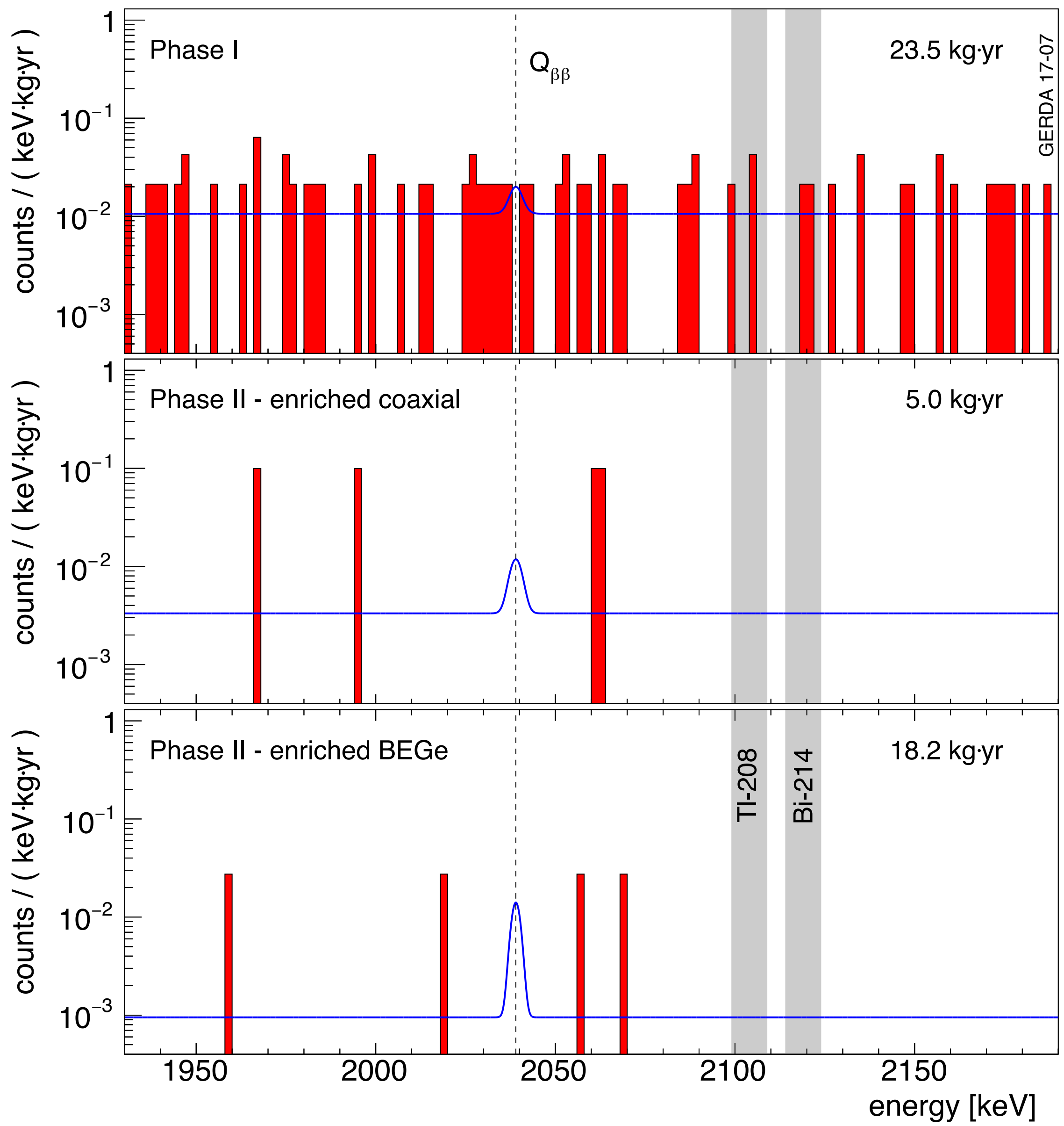
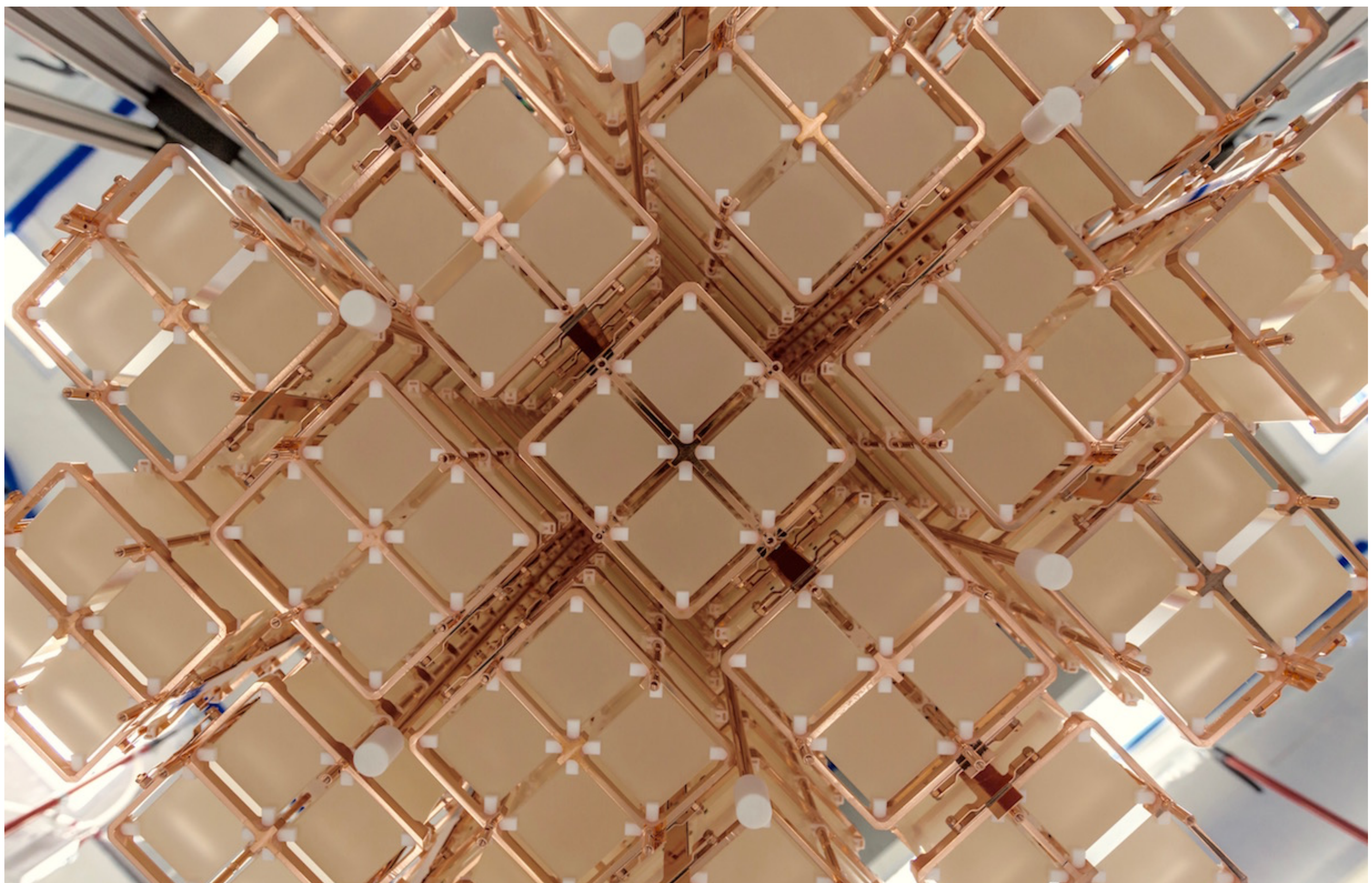


CUORE experiment

Started in 2013

- Towers of TeO_2 crystals. ββ energy measured as temperature increase
- **Advantages**: energy resolution, mass scalability



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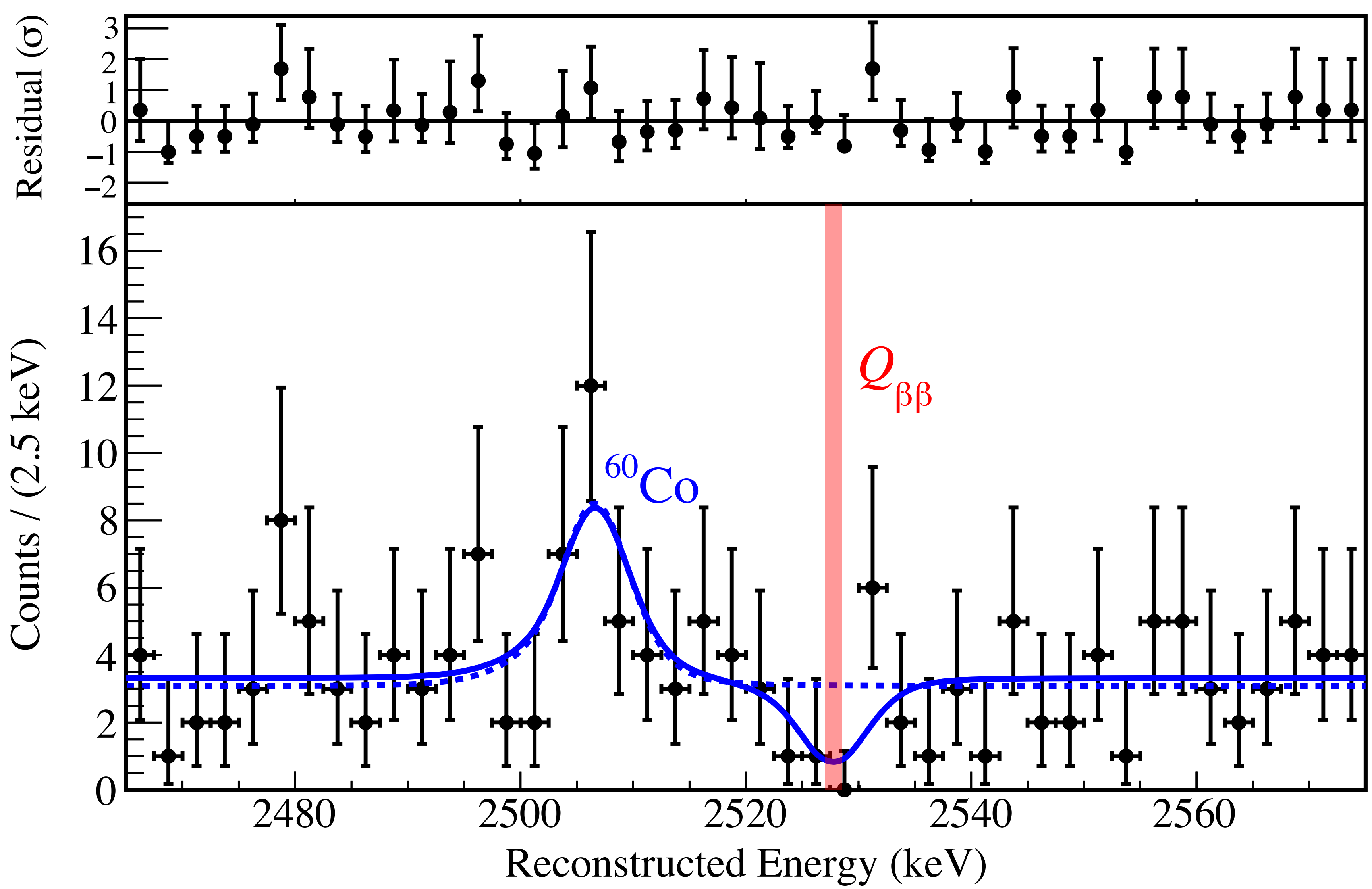
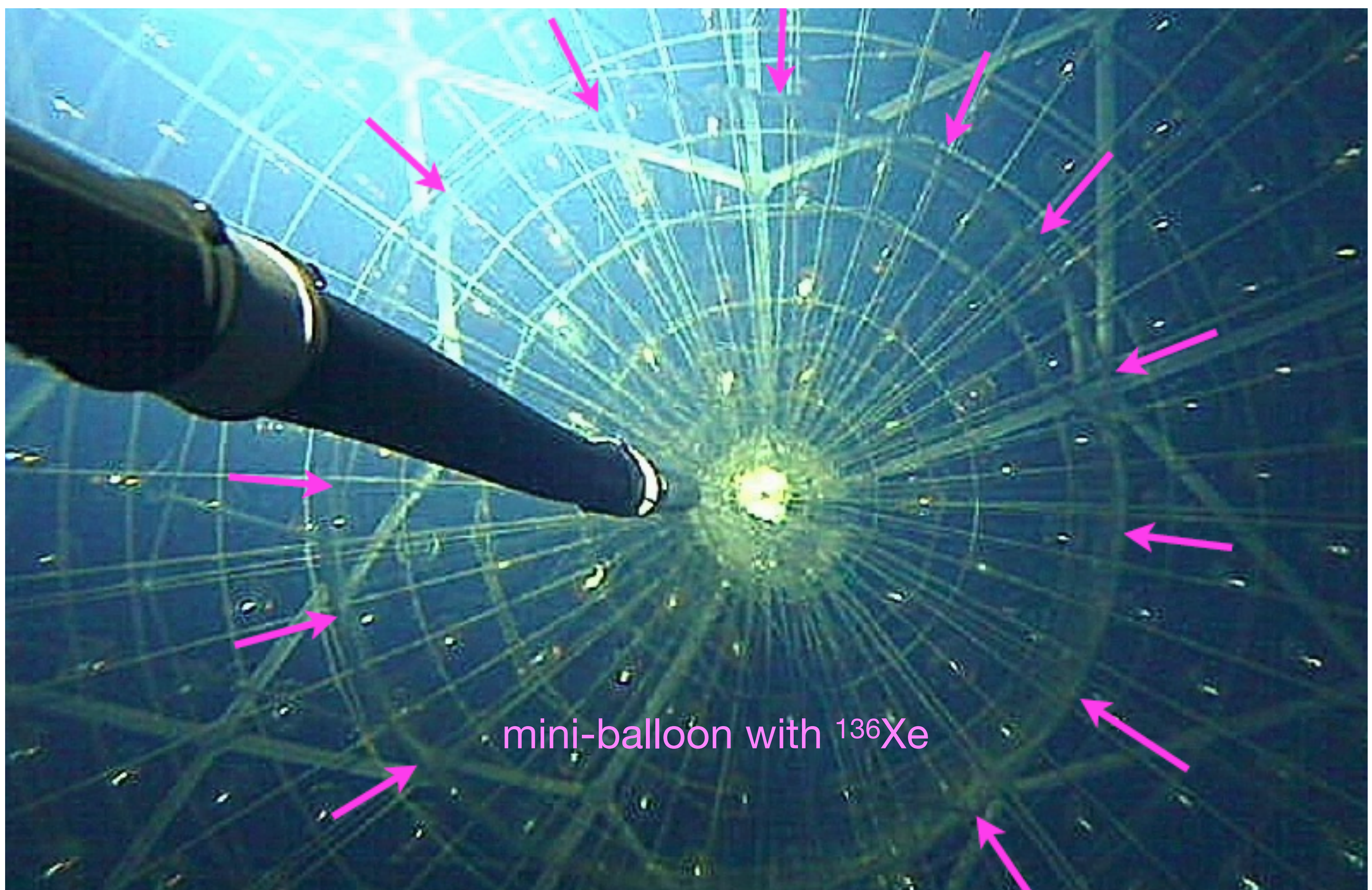


KamLAND-Zen experiment

Started in 2011

- Liquid scintillator with 300-750 kg of ^{136}Xe gas dissolved in it
- **Advantages**: mass scalability, radiopure, veto region → leading the field



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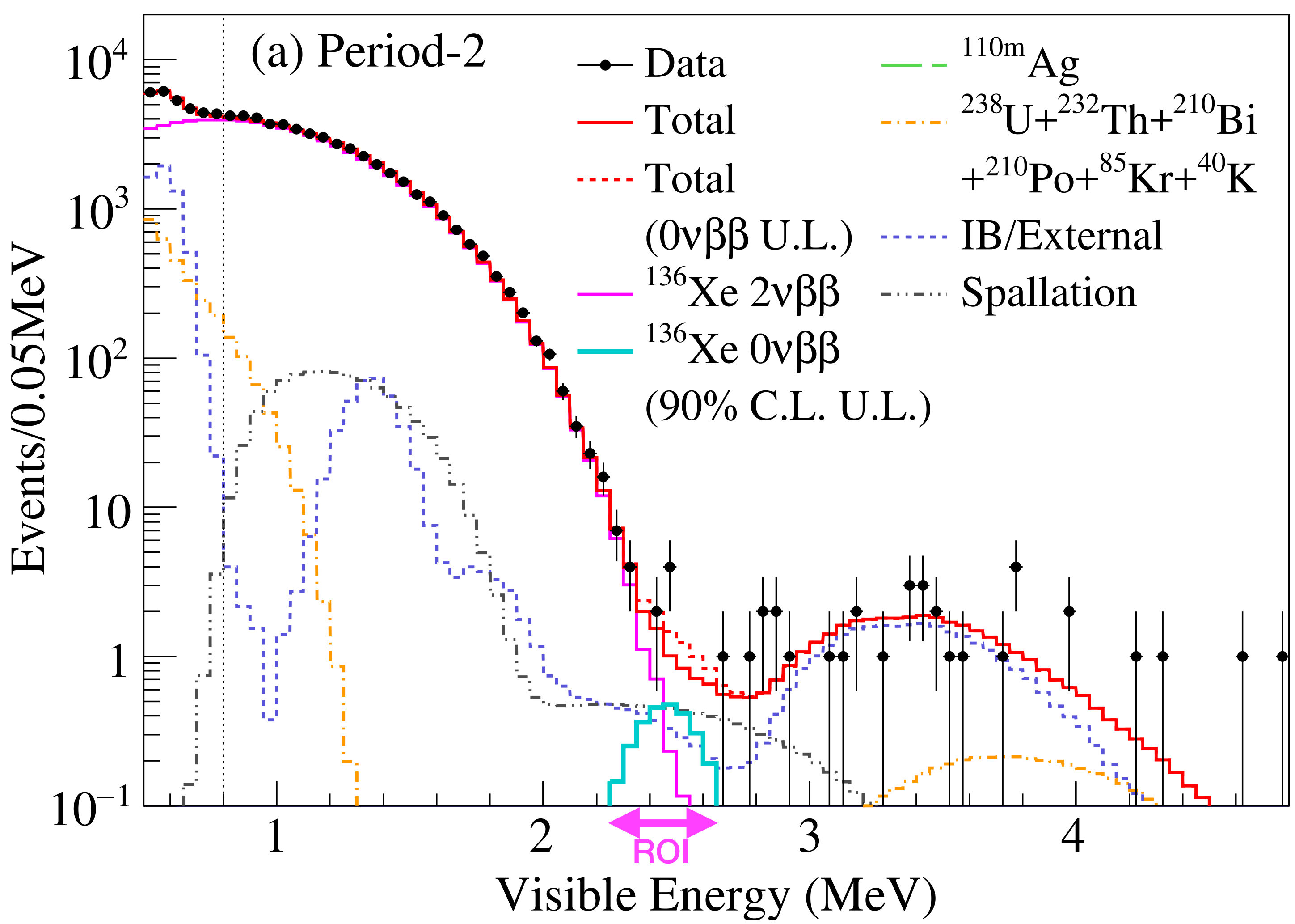

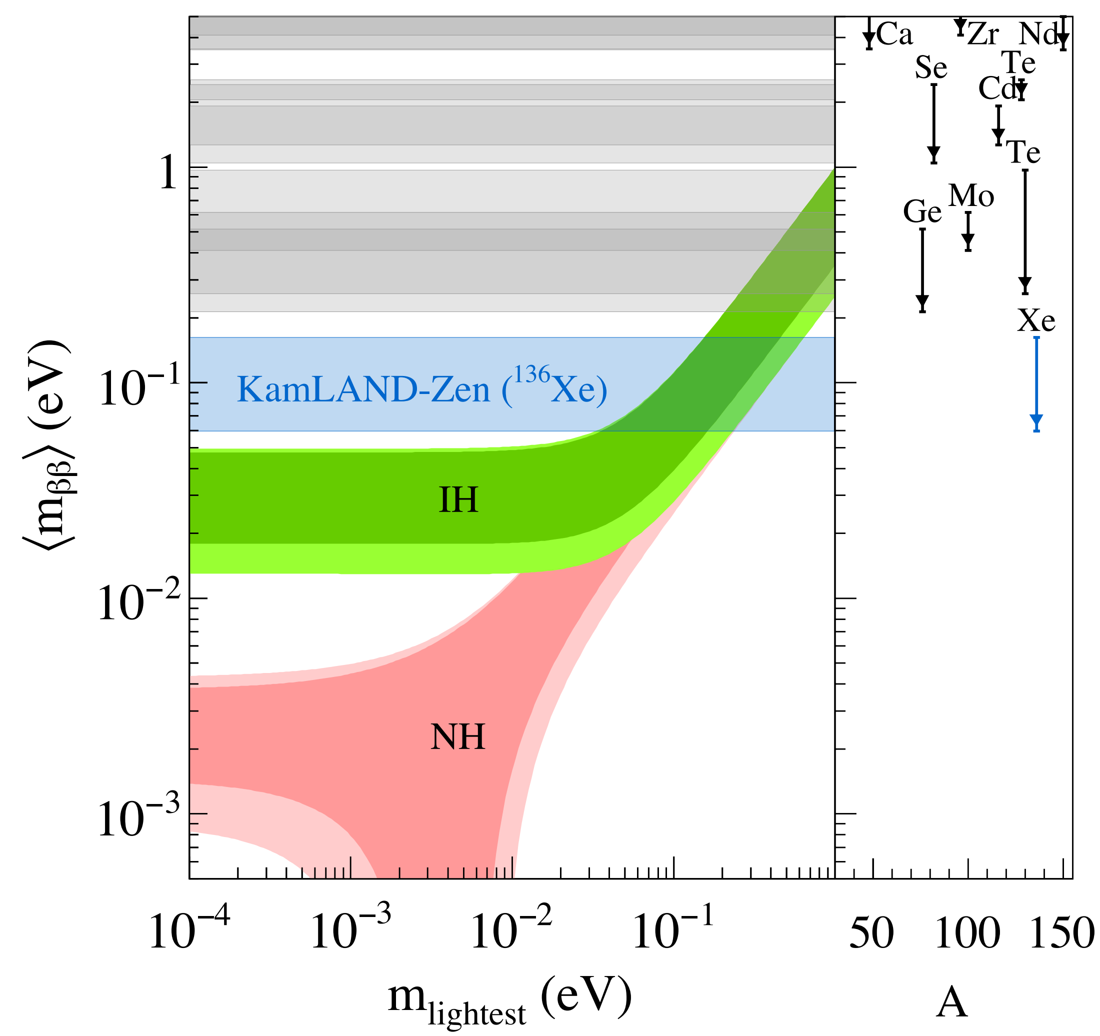

NEXT experiment

Started in 2016

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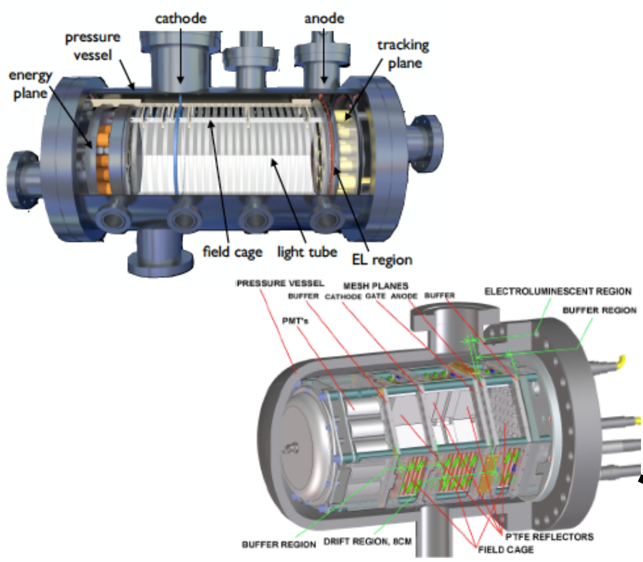
next

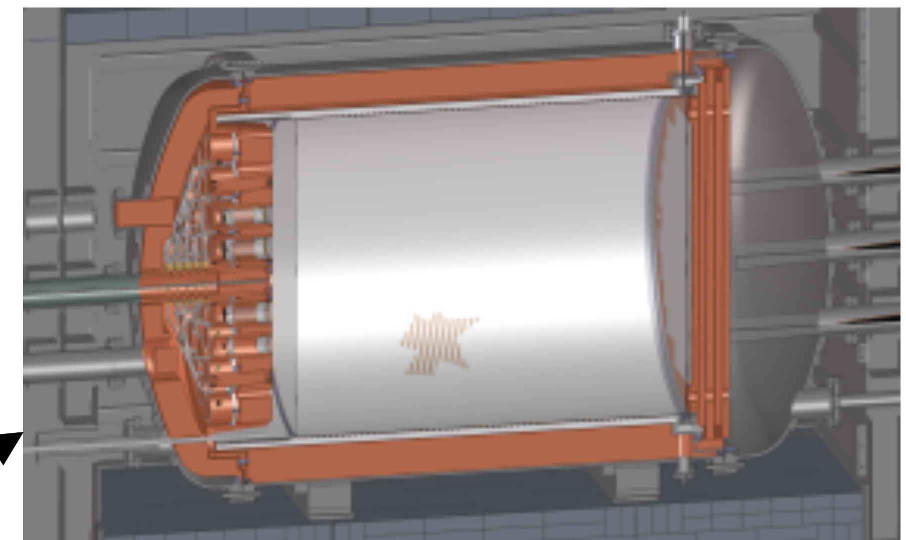
- Time projection chamber filled with high-pressure (10-15 bar) ^{136}Xe gas
- **Advantages**: energy resolution, image electron tracks

NEXT phases



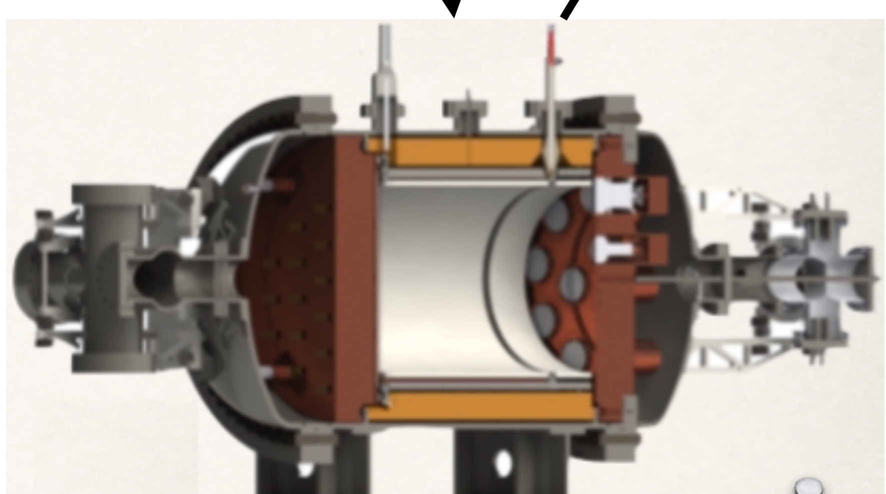
Prototypes (~1 kg)
[2009 - 2014]

Demonstration of detector concept



NEXT-100 (~100 kg)
[2018 - 2020's]

Neutrinoless double beta decay search

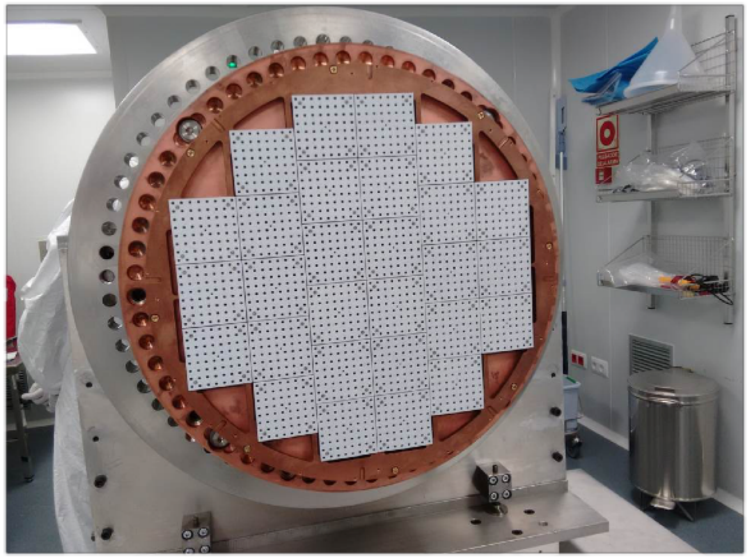


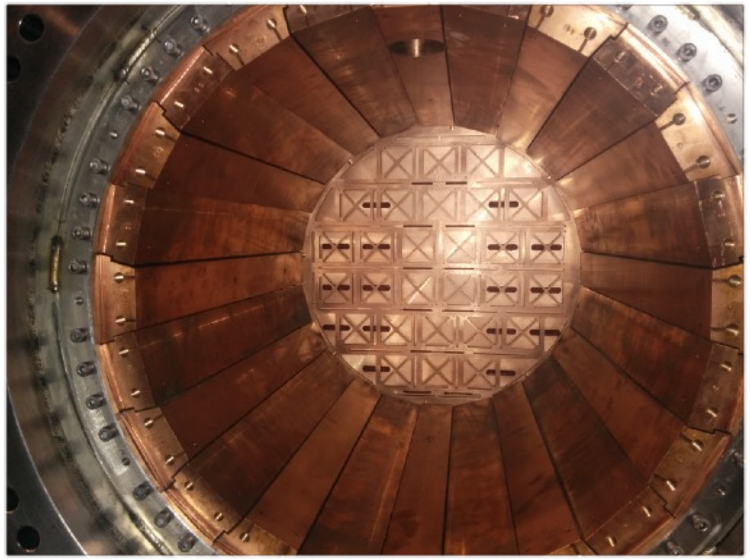
NEXT-White (~5 kg)
[2015 - 2018]

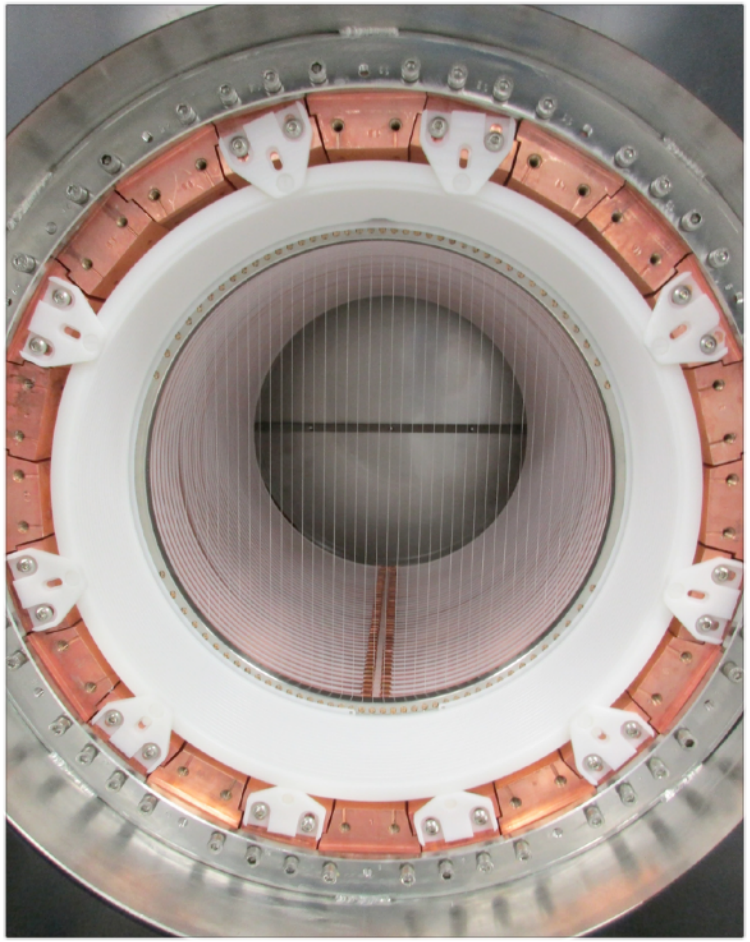
Underground and radio-pure operations, background, ββ2v

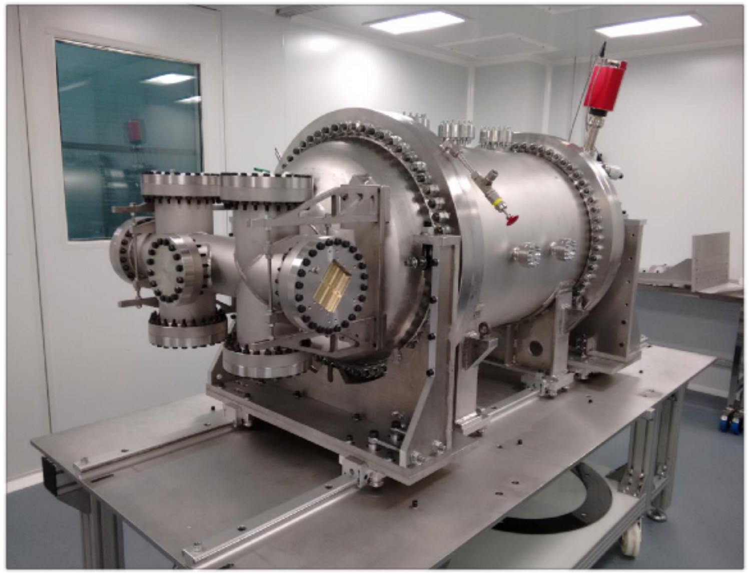
NEXT-tonne (~1000 kg)
[future generation]

NEXT-White construction

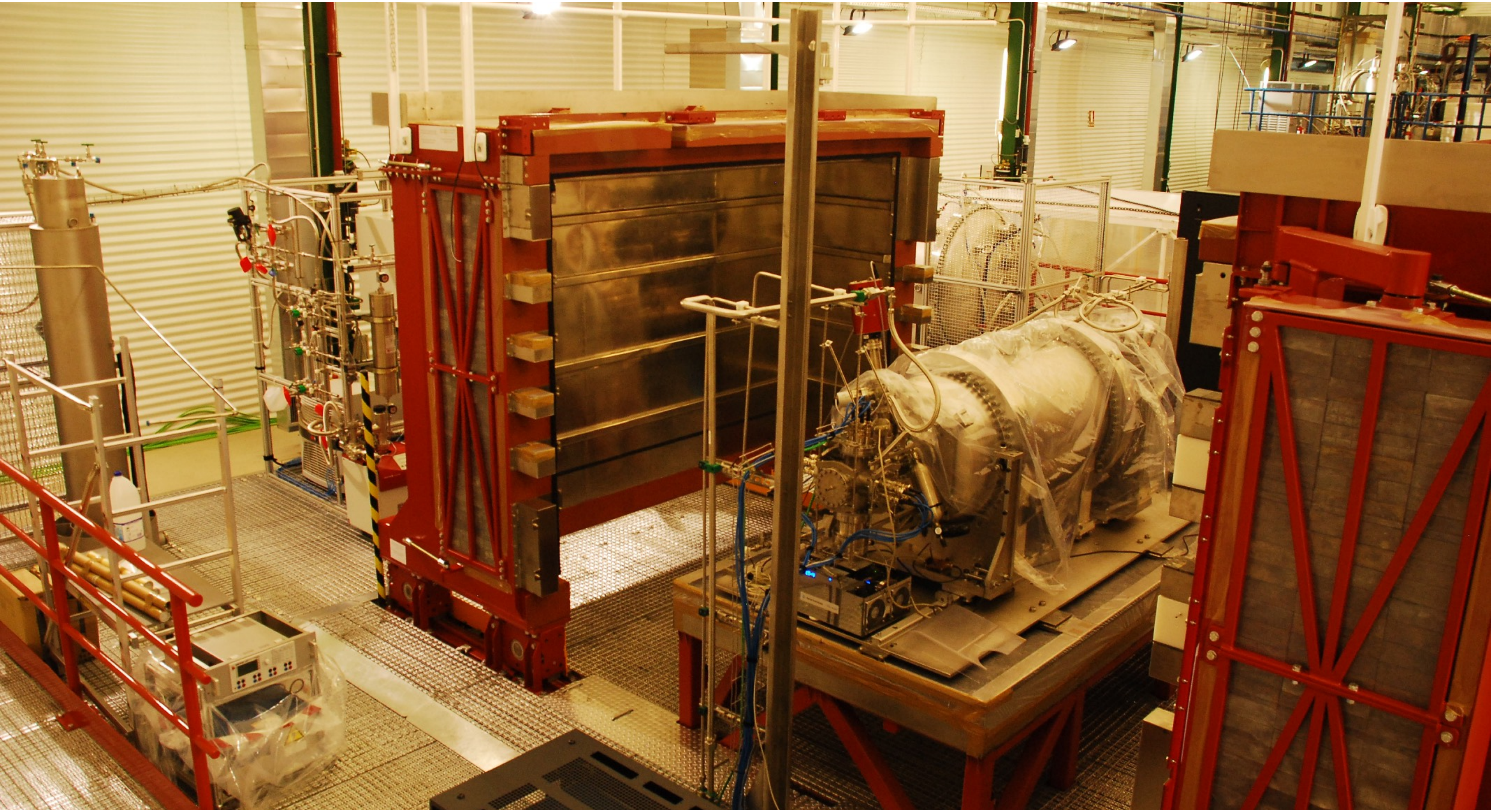




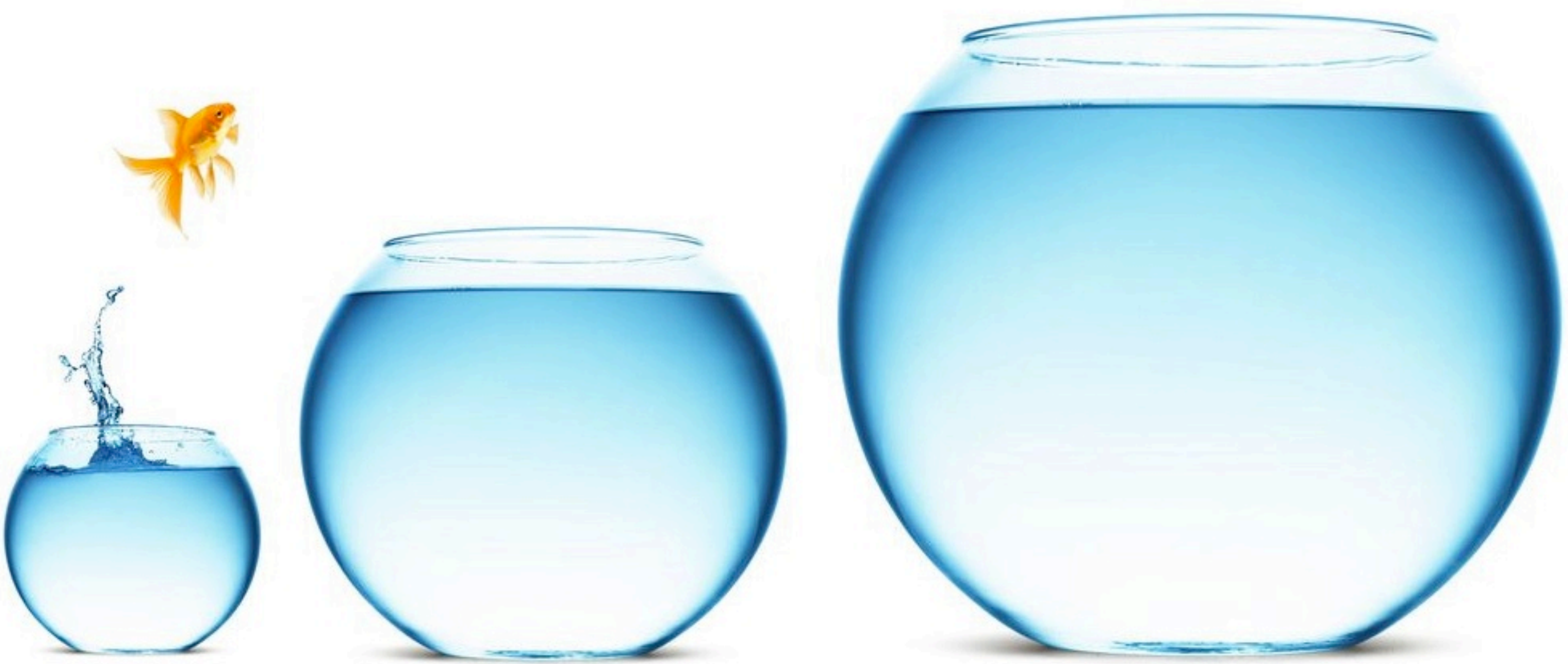




NEXT-White installation at the LSC



How to move forward?

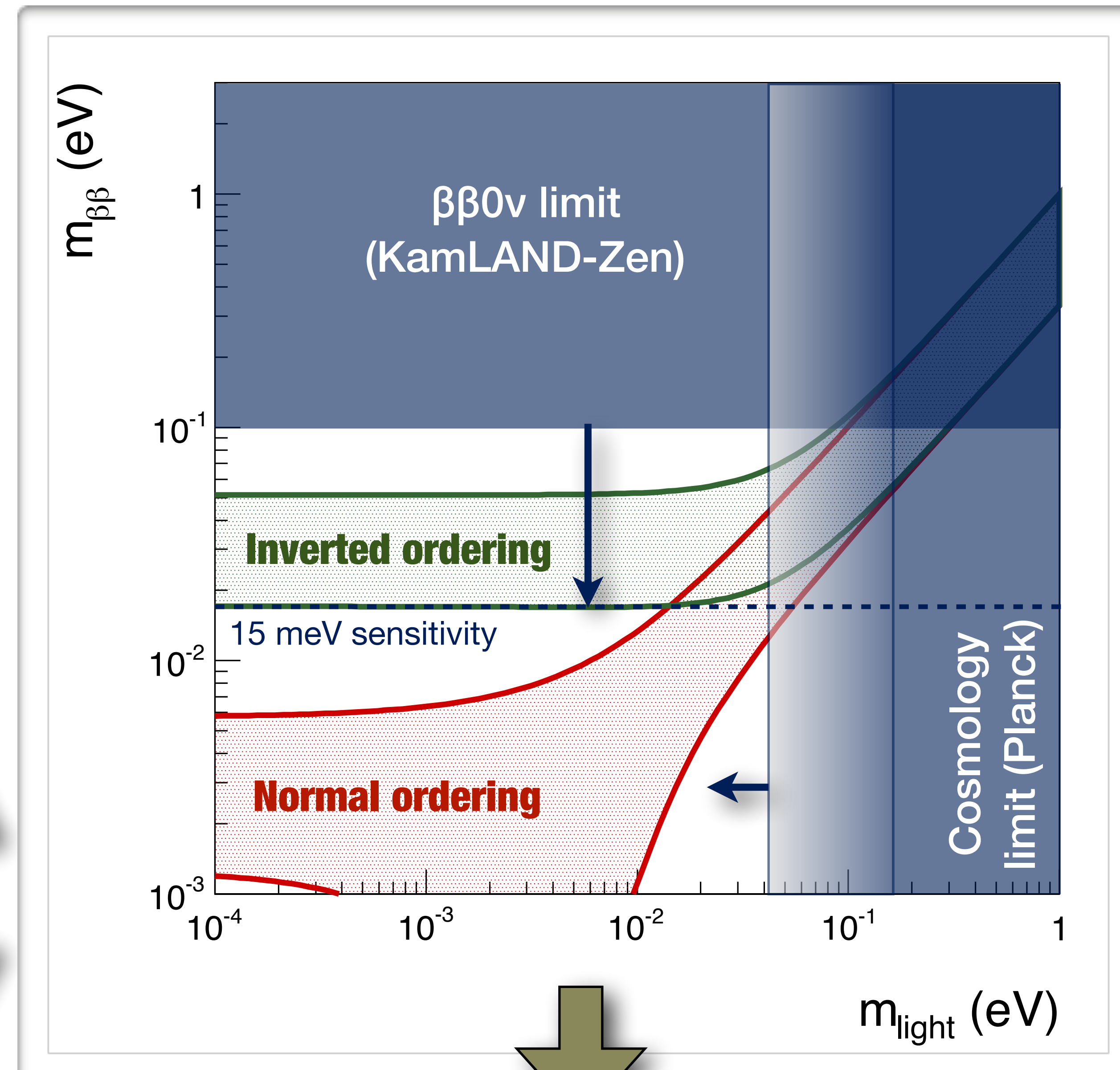


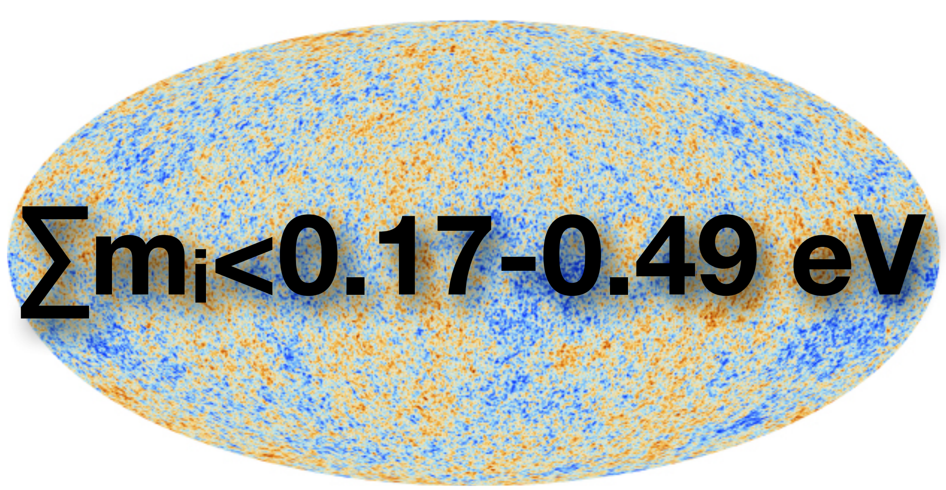
- Support to build 2-3 next-generation $\beta\beta0\nu$ experiments. Which ones?

Goal for next-generation experiments

15 meV Majorana neutrino mass sensitivity

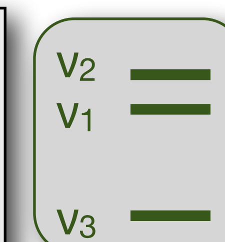
$m_{\beta\beta}$<0.06-0.16 eV





$\sum m_i$<0.17-0.49 eV

Guaranteed ββ0ν discovery if neutrinos are Majorana and have "inverted" mass ordering



Recipe for next-generation experiments

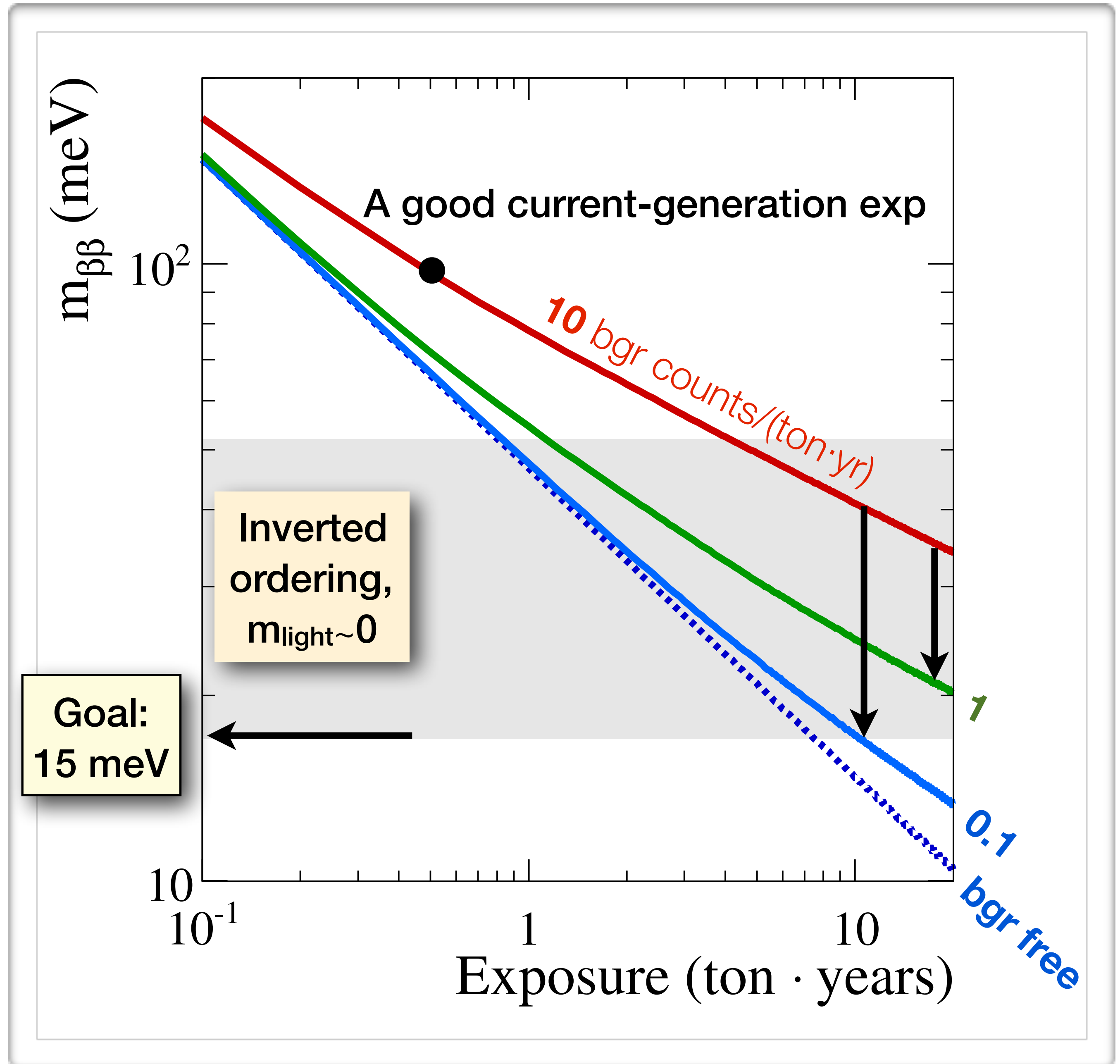
Favour ββ isotopes that can be extrapolated to large masses (~ton)

+

Favour low background rate experimental techniques

Ton-scale detector and need for background R&D

- Ton-scale detector necessary but not sufficient requirement
- Need at least 1-2 orders of magnitude background reduction with respect to current-generation
- R&D on active background reduction techniques

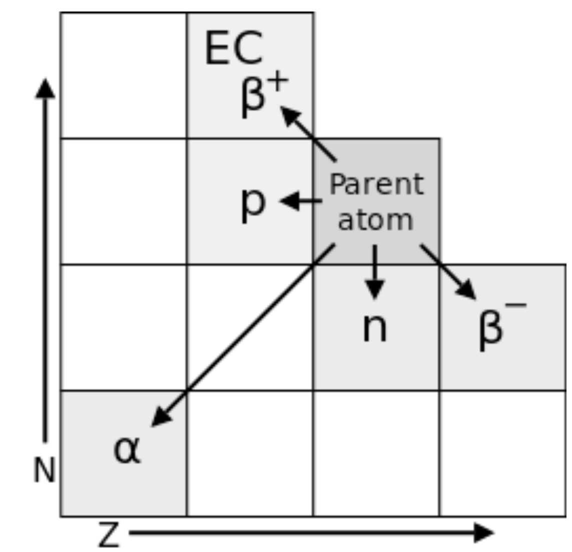


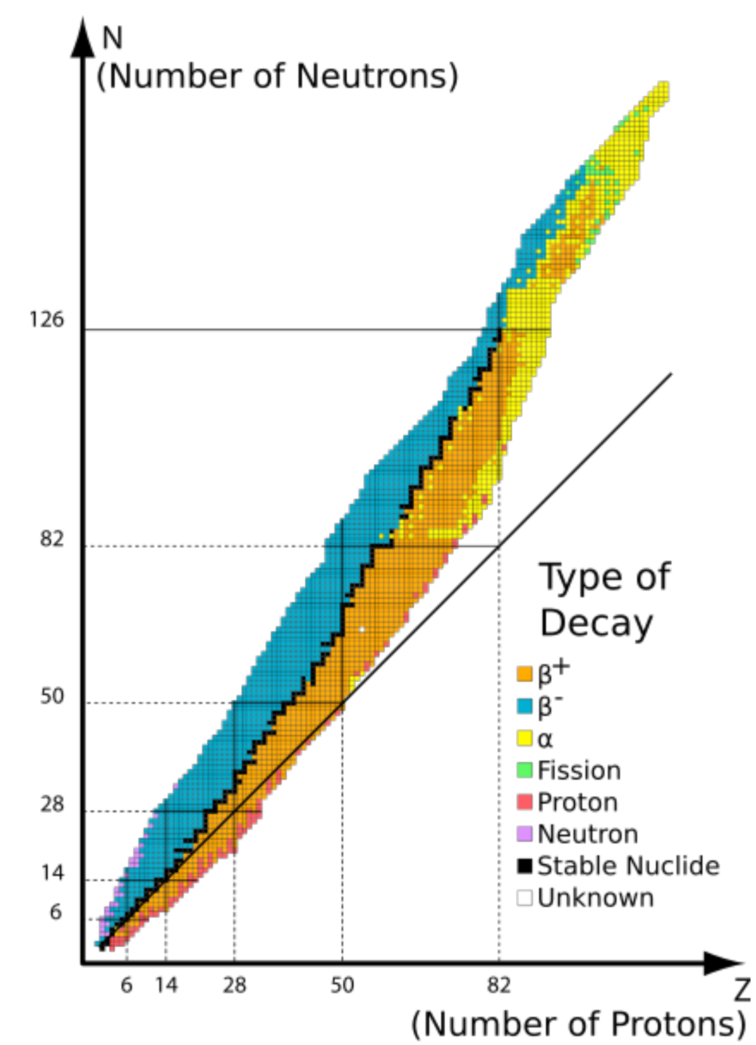
Direct neutrino mass measurements

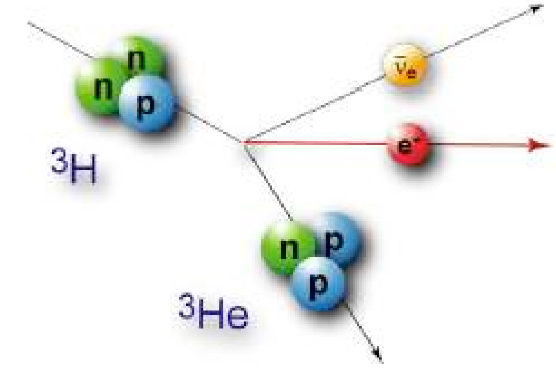
Radioactive decays

A reminder

- Three types of (1st order) nuclear transitions producing neutrinos or antineutrinos:
  - β^- decay: (Z,A) → (Z+1,A) + e^- + $\overline{\nu}_e$
  - β^+ decay: (Z,A) → (Z-1,A) + e^+ + ν_e
  - Electron Capture (EC): (Z,A) + e^- → $(Z\text{-}1,A)^*$ + ν_e → (Z-1,A) + γ/e^- + ν_e
- Information on neutrino mass from kinematics of emitted electrons (and photons)







Beta-decay energy spectrum

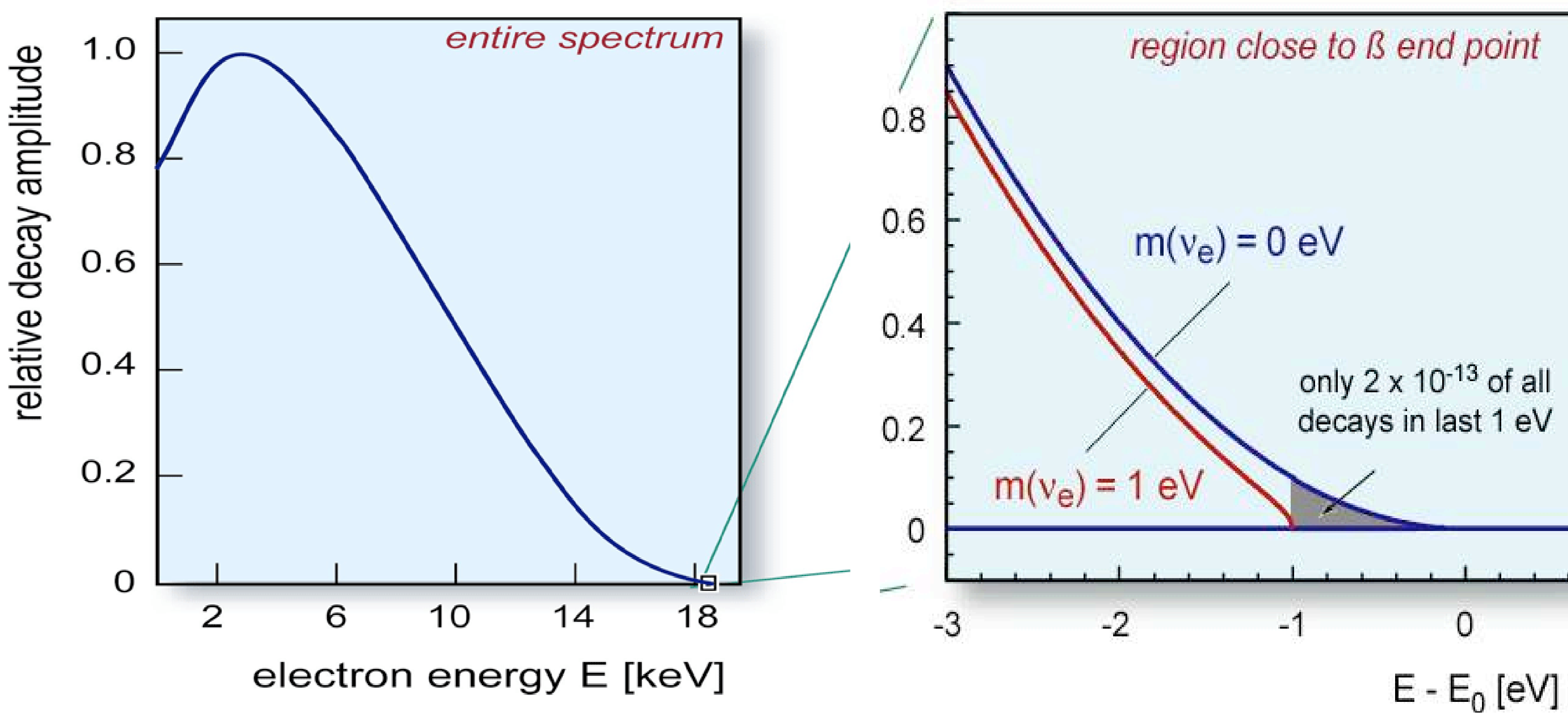
- Phase space determines electron energy spectrum
- Massive neutrinos distort the end-point spectrum:

$$dN/dK_e \propto F(K_e,Z) \cdot p_e \cdot (K_e+m_e) \cdot (E_0-K_e) \cdot [(E_0-K_e)^2-m_\beta^2]^{1/2}$$

Endpoint energy (Q-value): $E_0 = K_e + E_\nu$

Observable: β decay neutrino mass

$$m_\beta = (\textstyle\sum_i |U_{ei}^2| \cdot m_i^2)^{1/2}$$



Experimental requirements

$$dN/dK_e \propto F(K_e,Z) \cdot p_e \cdot (K_e+m_e) \cdot (E_0-K_e) \cdot [(E_0-K_e)^2-m_\beta^2]^{1/2}$$

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- Low endpoint energy E_0 → ^3H, ^{187}Re, ^{163}Ho

Isotope	Q_β-value (keV)
^3H	18.6
^{163}Ho	2.3-2.8
^{187}Re	2.5

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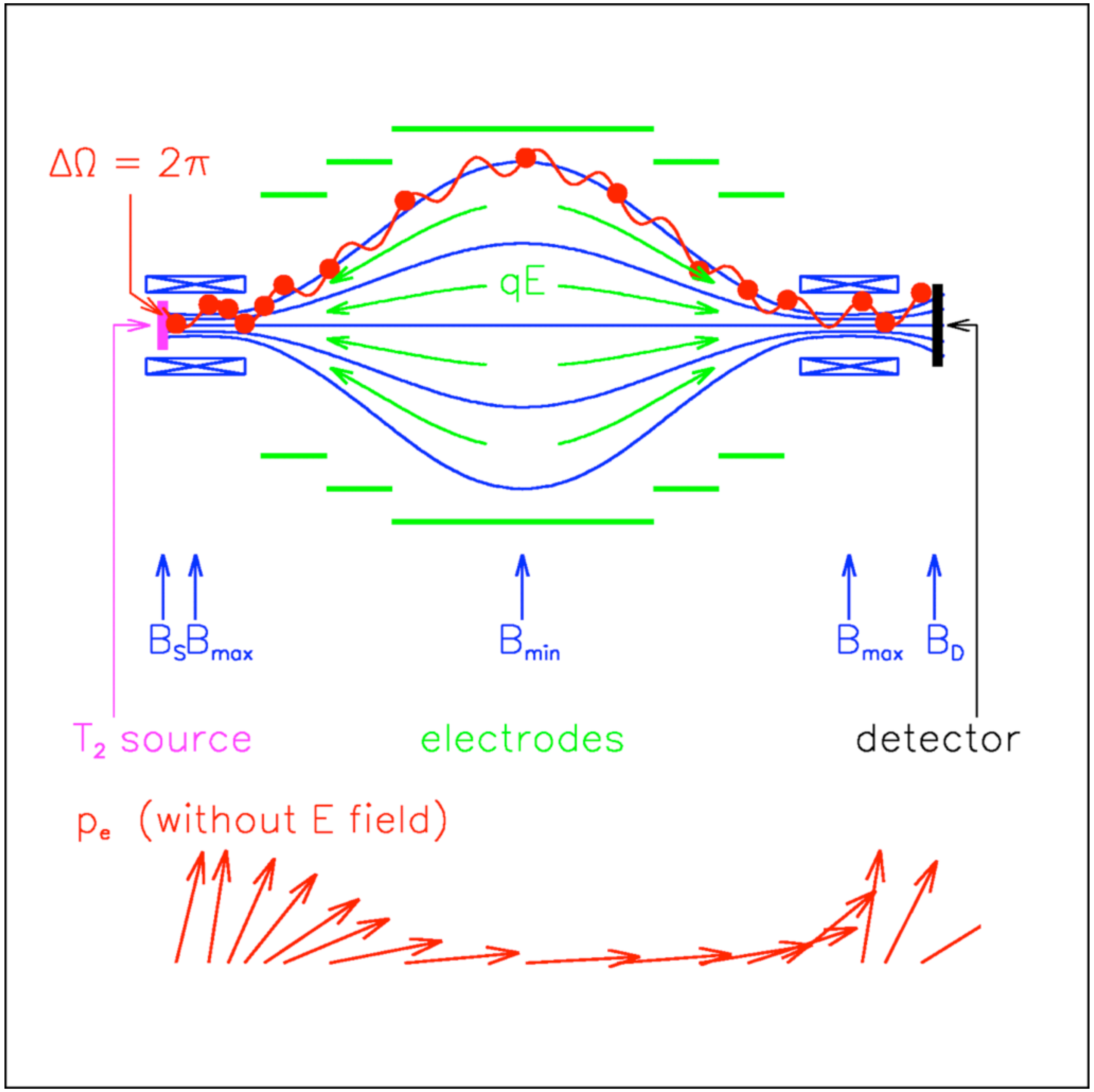
- High energy resolution
- High luminosity
- Low background

} → MAC-E-Filters or Bolometers

MAC-E-Filter technique

***M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter*



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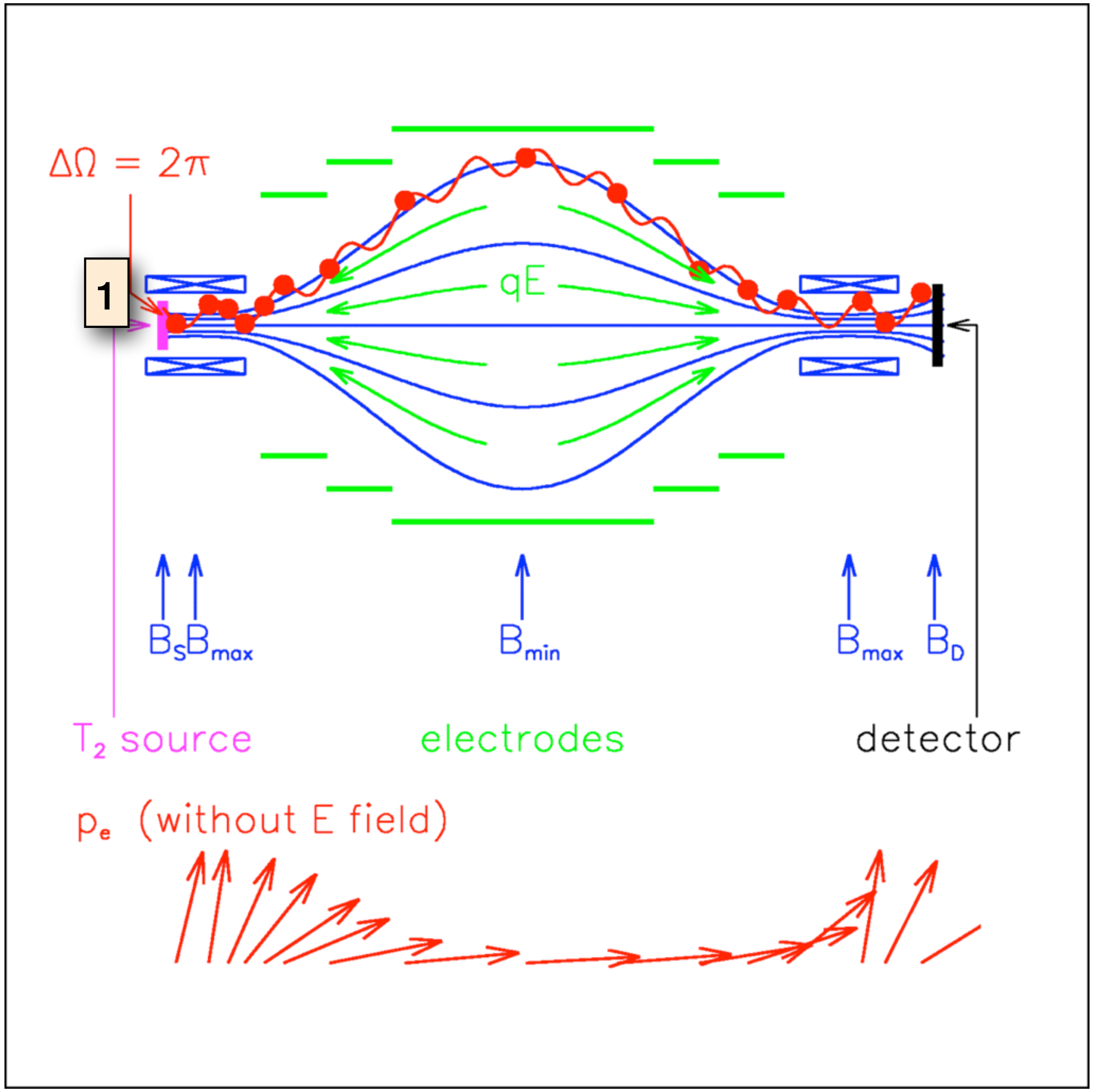

1. Electrons emitted isotropically at T_2 source

MAC-E-Filter technique

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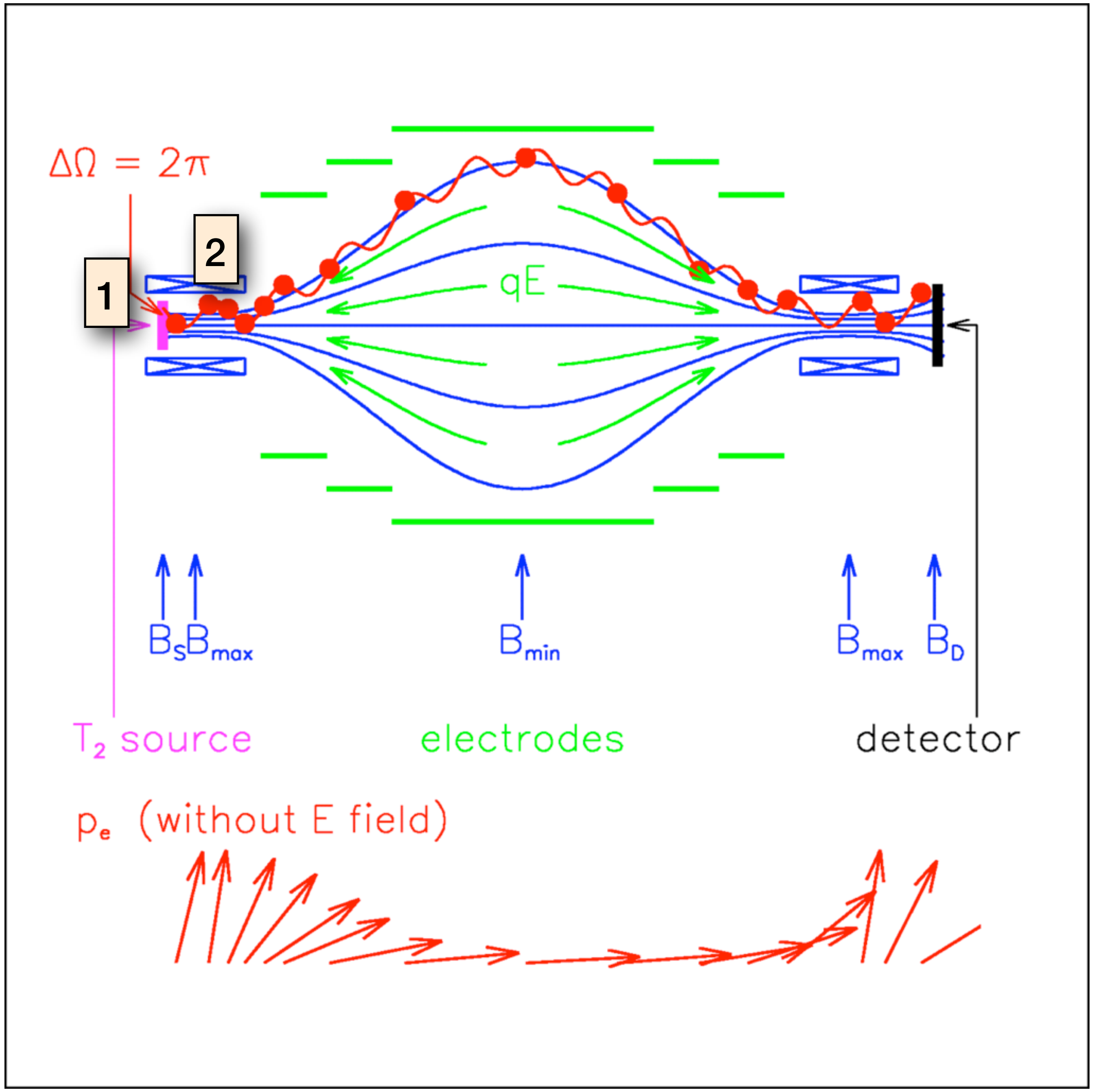

1. Electrons emitted isotropically at T_2 source

2. Guided magnetically on a cyclotron motion

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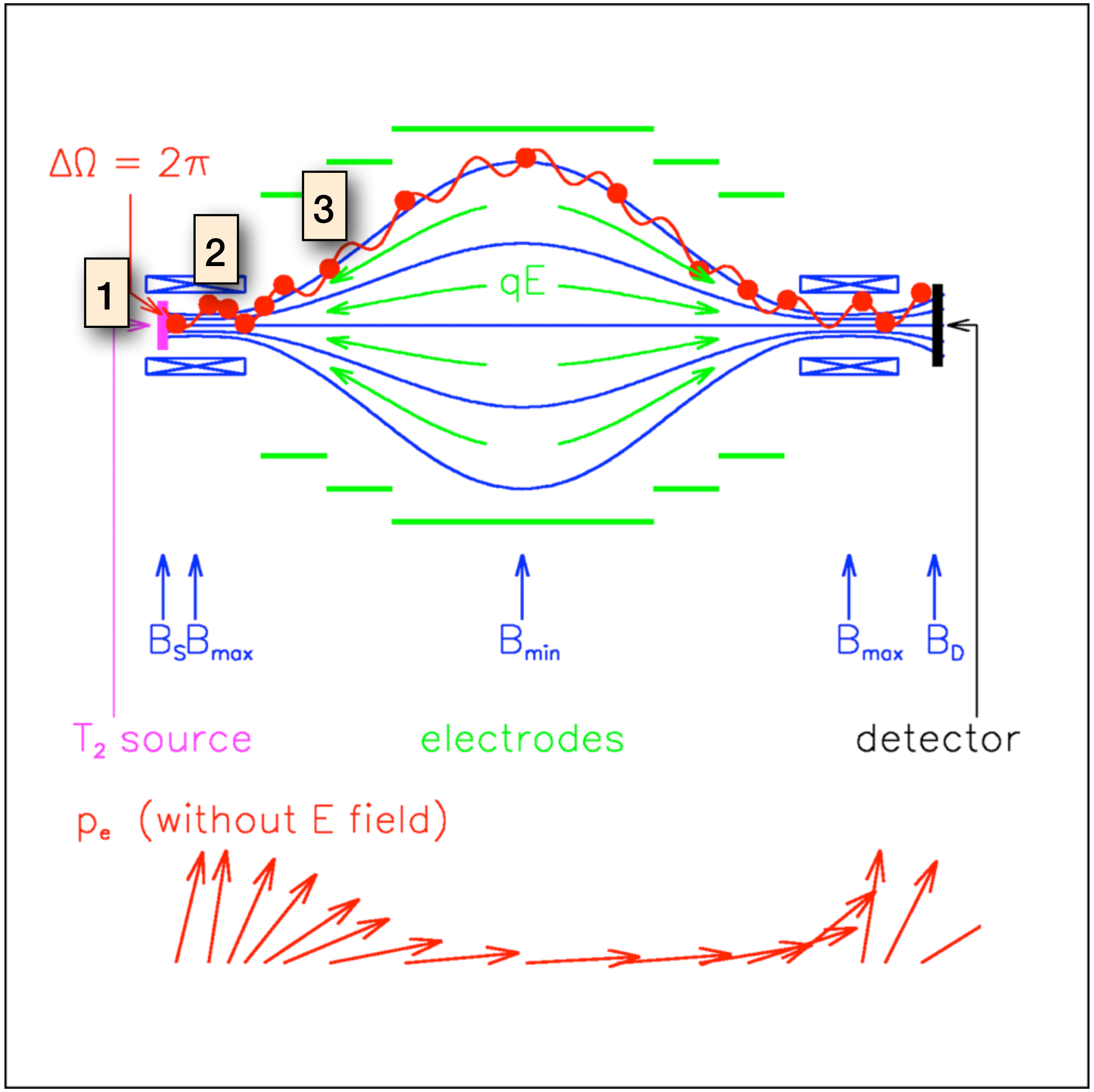

1. Electrons emitted isotropically at T_2 source

2. Guided magnetically on a cyclotron motion

3. Transform cyclotron motion into long. motion
→ Broad beam almost parallel to B field lines

MAC-E-Filter technique

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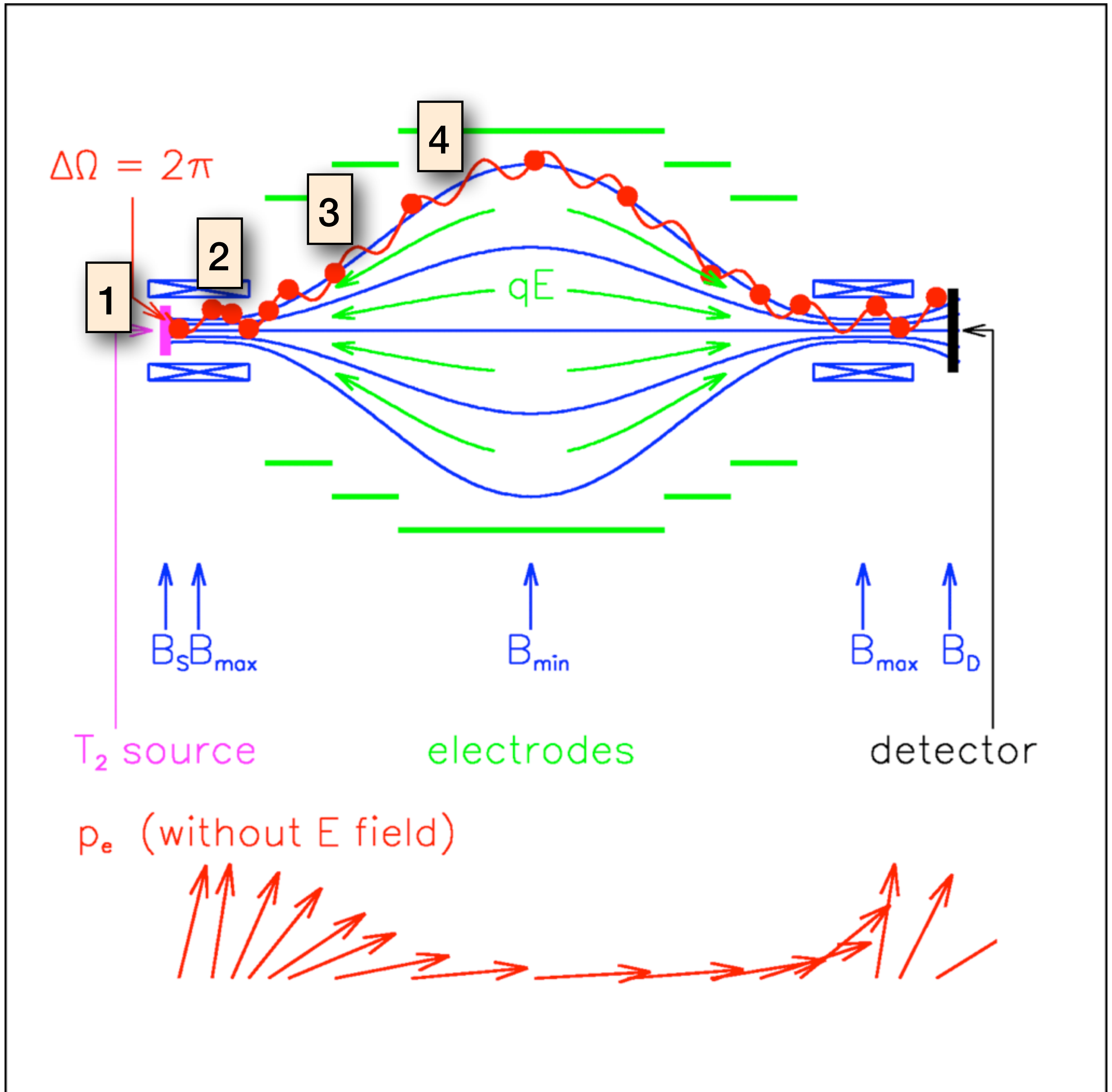

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4. Beam running against electrostatic potential formed by cylindrical electrodes

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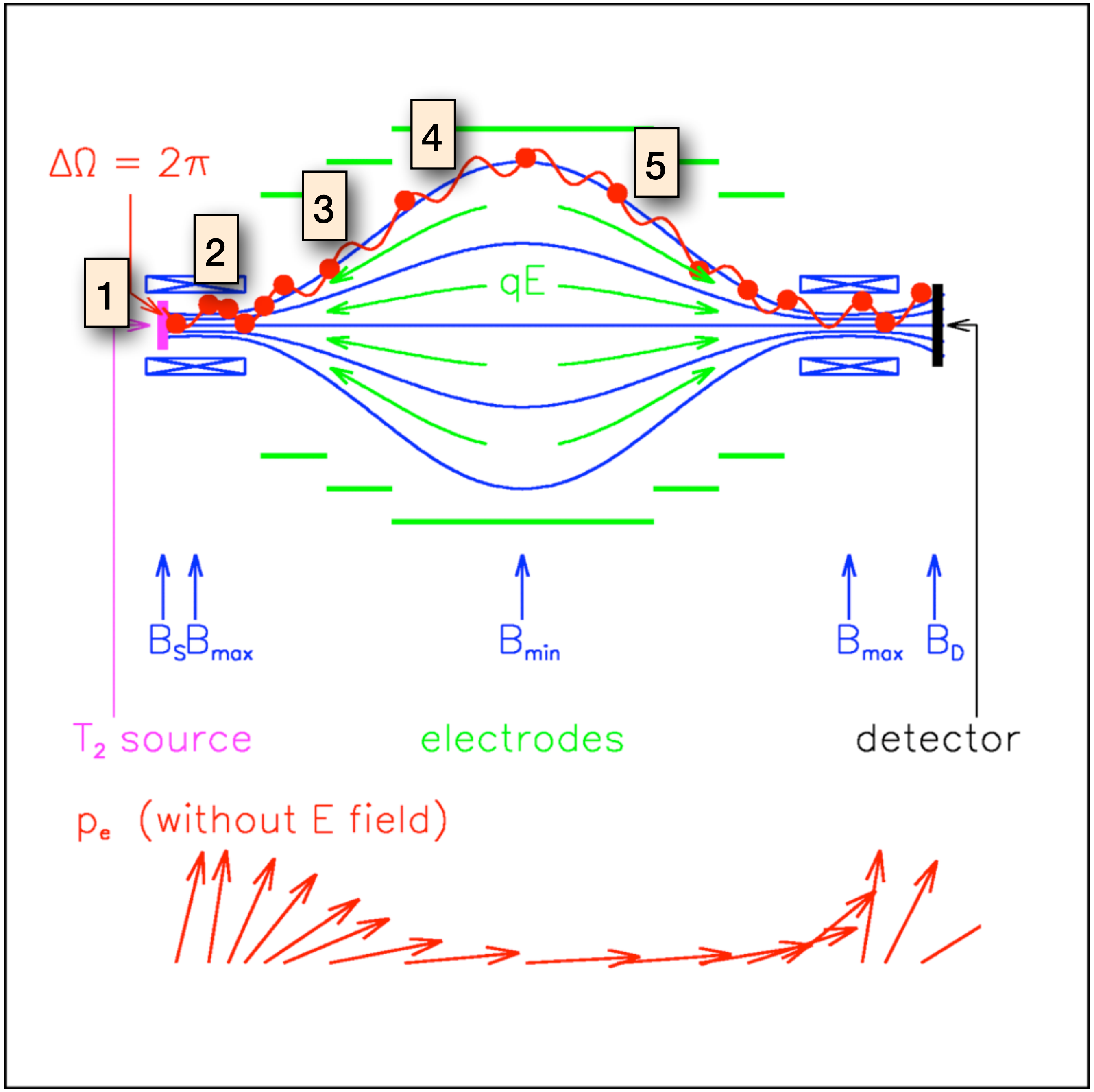

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→ Integrating high-energy pass filter

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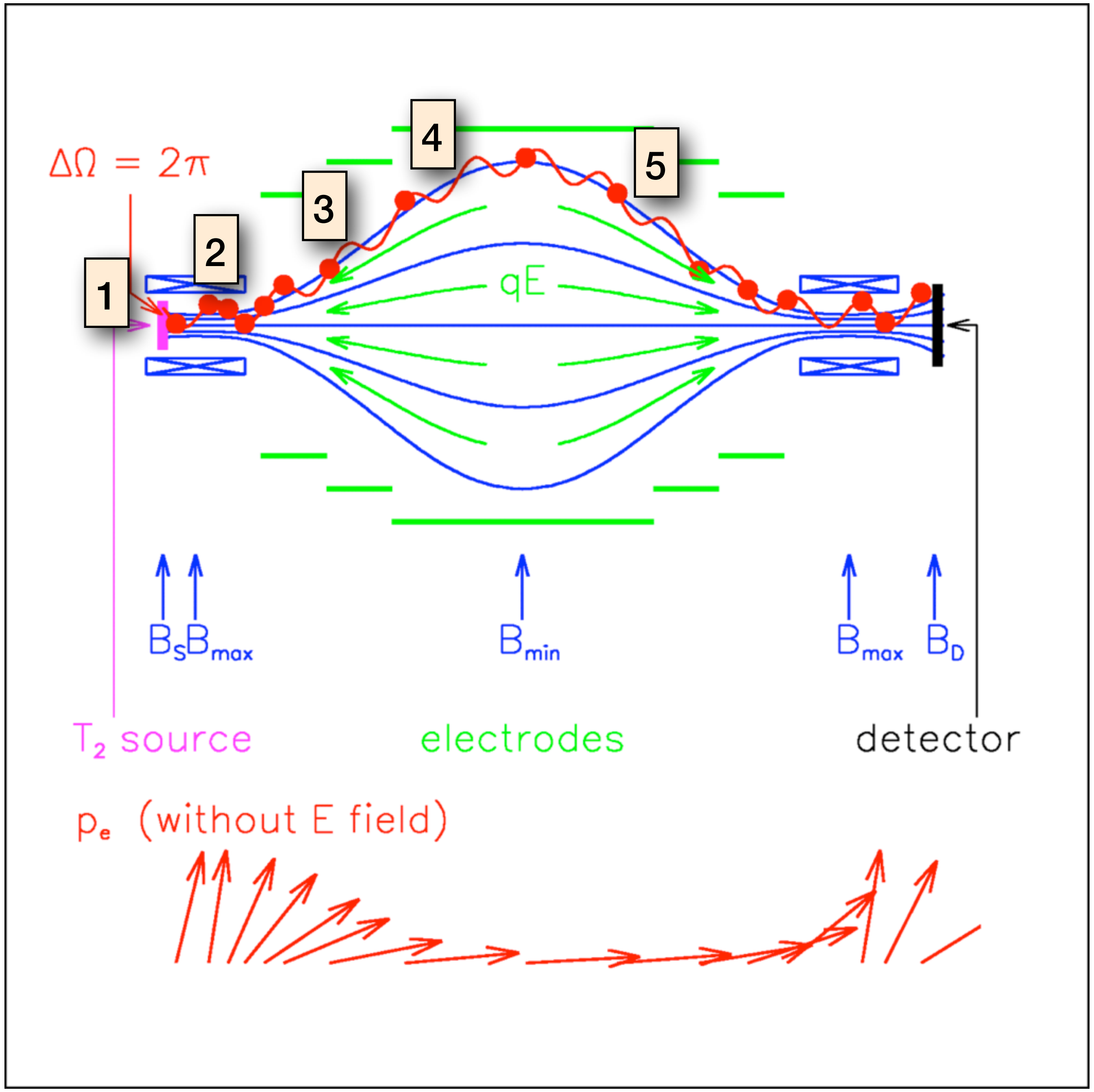

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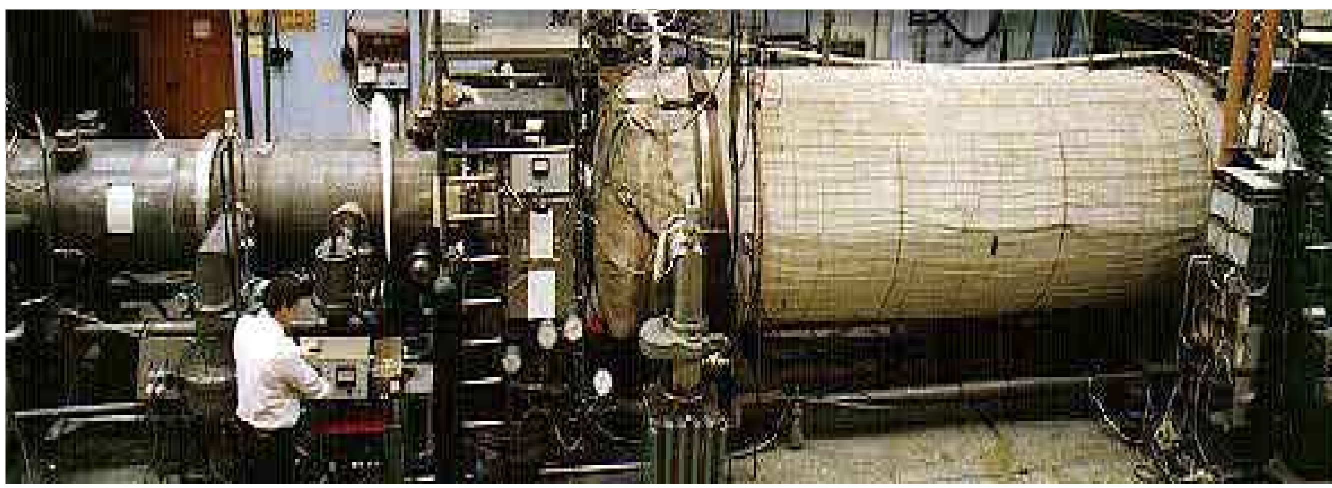
Measure β spectrum endpoint by varying electrostatic potential close to Q-value

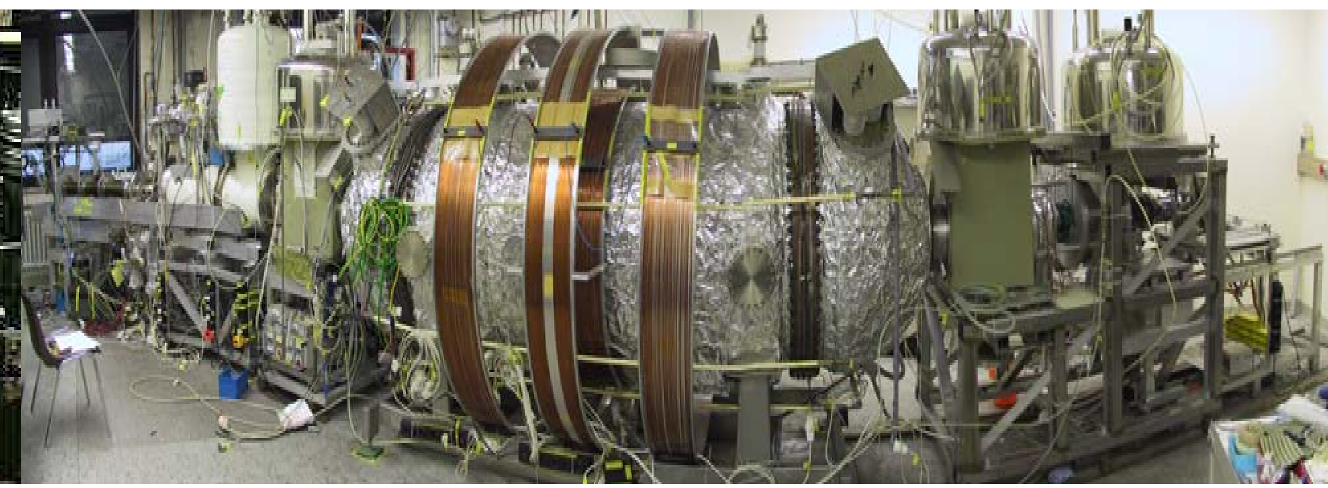
Mainz and Troitsk experiments

No evidence for non-zero neutrino mass from β decay experiments

Troitsk



Mainz



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$m_\beta^2 = -2.3 \pm 2.5 \pm 2.0\ \mathrm{eV}^2$

$m_\beta < 2.1$ eV (95% CL)

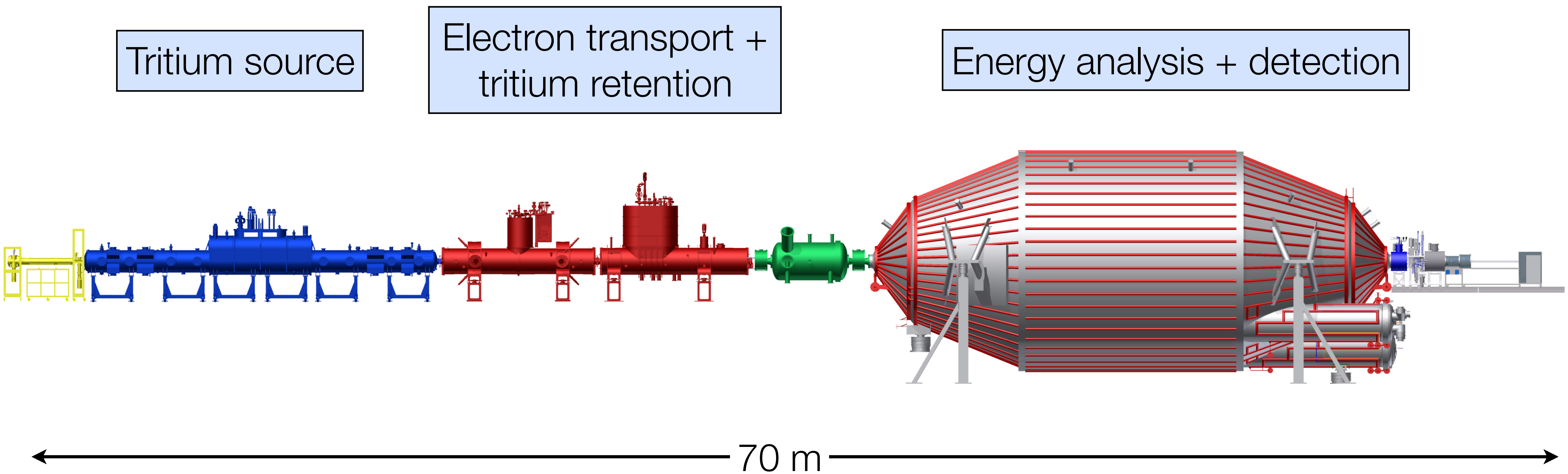
$m_\beta^2 = -0.6 \pm 2.2 \pm 2.1\ \mathrm{eV}^2$

$m_\beta < 2.3$ eV (95% CL)

KATRIN experiment

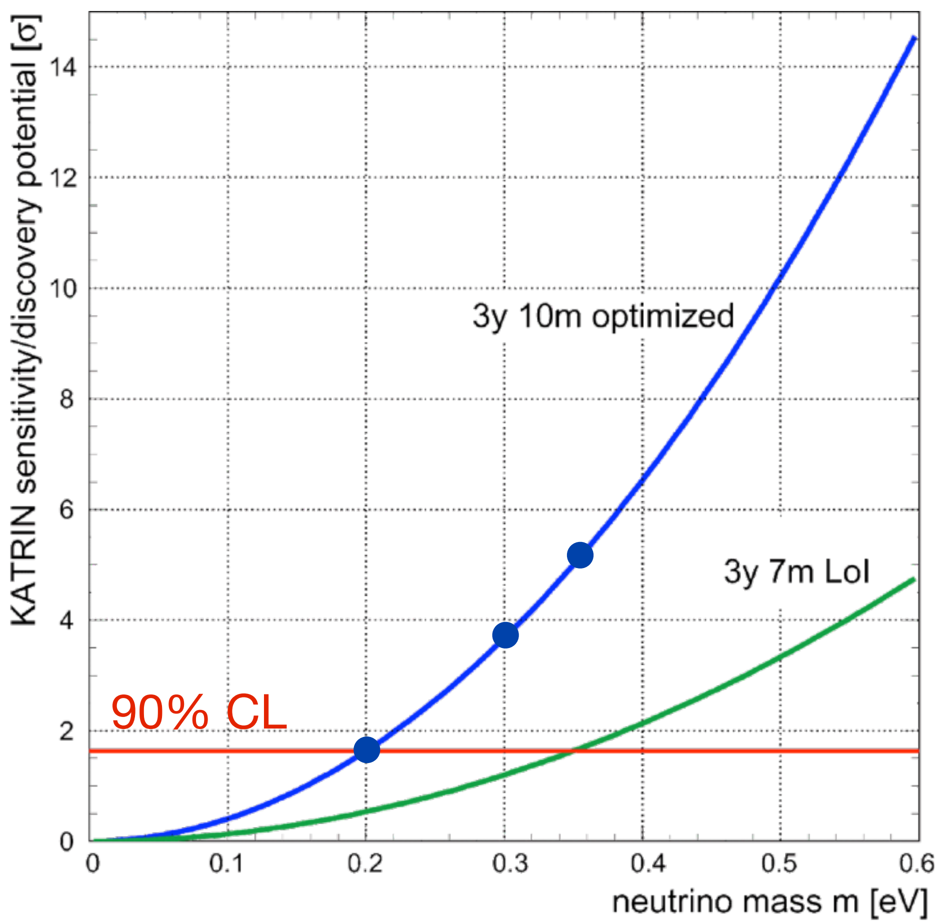
Starting in 2018

- Tritium source
  - Low end-point (18.6 keV), intense (10^{11} β decays/sec))
- Electron energy analysis + detection
  - MAC-E-Filter technique with largest spectrometer to date!

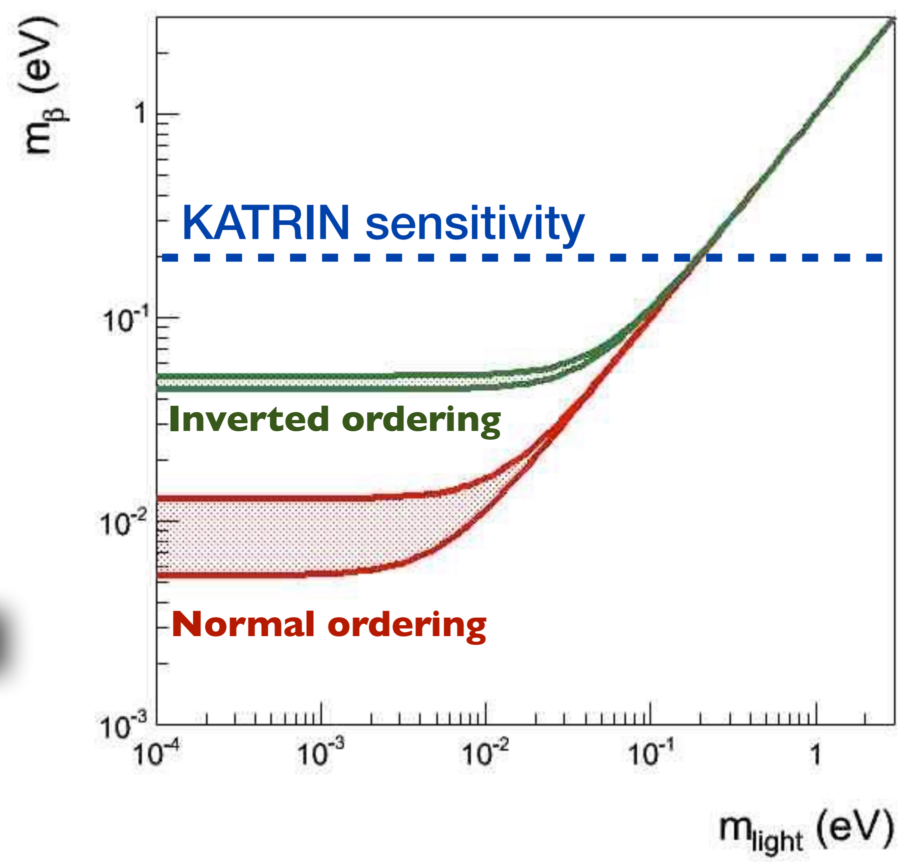


KATRIN design sensitivity

Assuming 3 years exposure



- Sensitivity down to m_β = 0.2 eV at 90% CL
    - One order of magnitude improvement over Mainz and Troitsk
- Discovery potential:
    - 3.5σ if m_β = 0.3 eV
    - 5σ if m_β = 0.35 eV

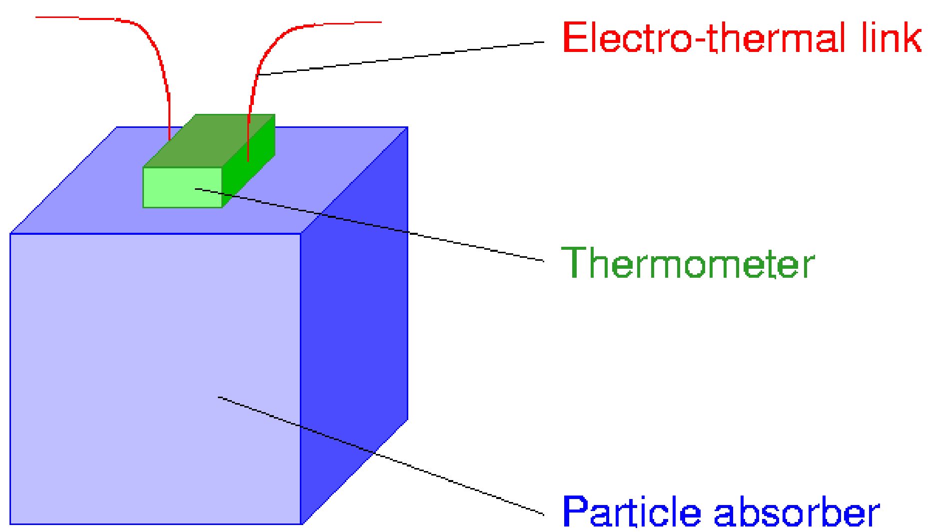


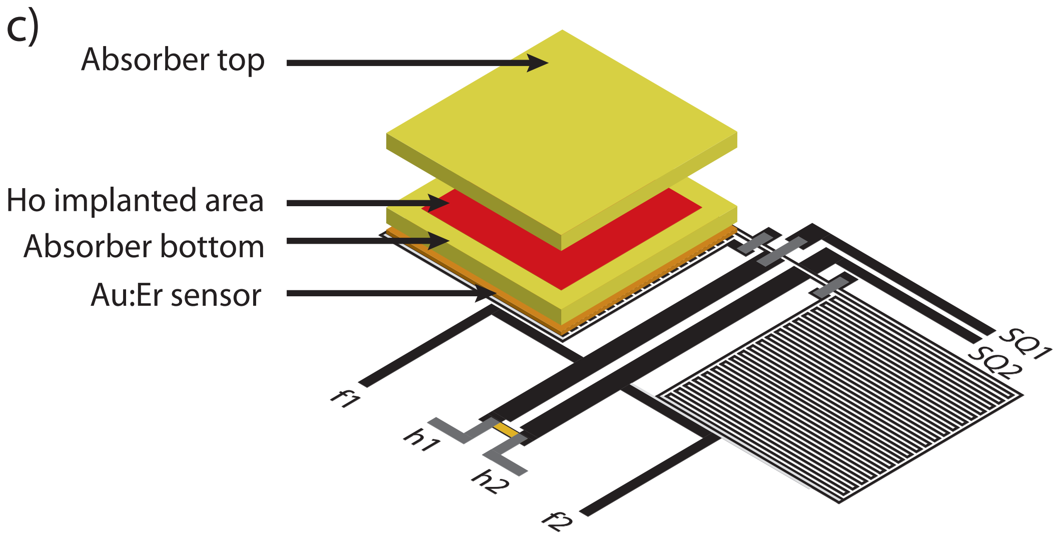
- Sensitive to ~ mass-degenerate neutrinos only (no sensitivity to mass ordering)
- KATRIN inauguration: June 11th, 2018!

Cryogenic bolometers

Electron capture of ^{163}Ho: ECHo, HOLMES

- Detectors with small heat capacity $\mathbf{C_{tot}}$
  → operate at ultra-low temperatures: T < 100 mK
- Small deposited energy ΔE results in large temperature increase: $\mathbf{\Delta T = \Delta E / C_{tot}}$
- Only detectors capable of measuring <3 keV energy with high precision





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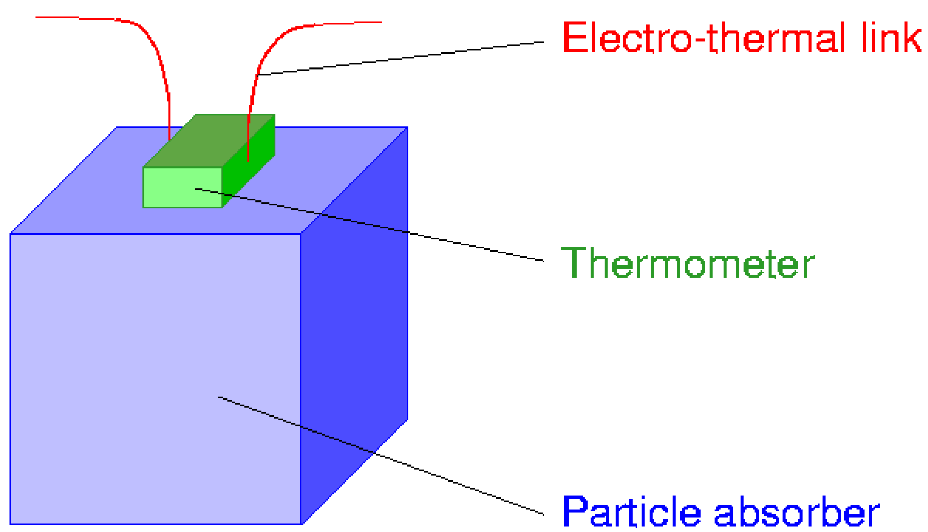
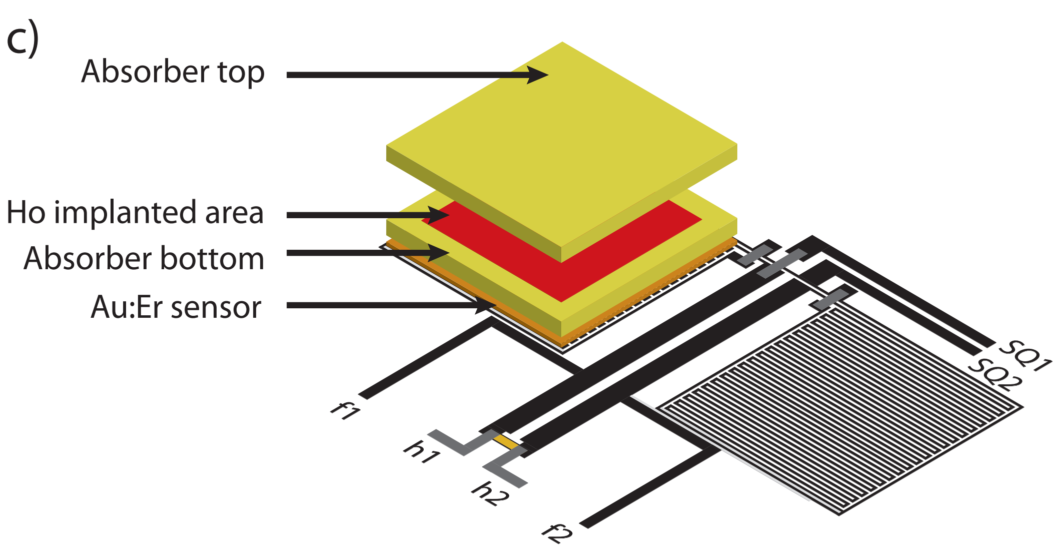
Advantage:
- Measures all released energy except that of the neutrino, no final atomic/molecular states involved





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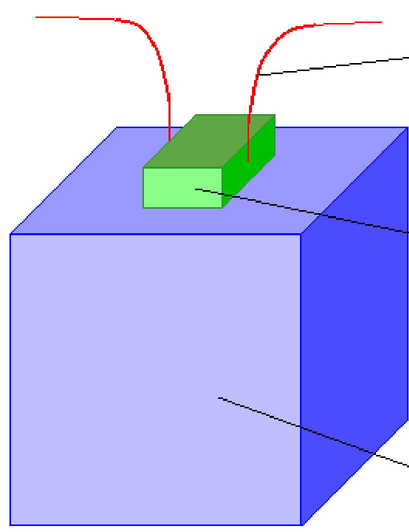

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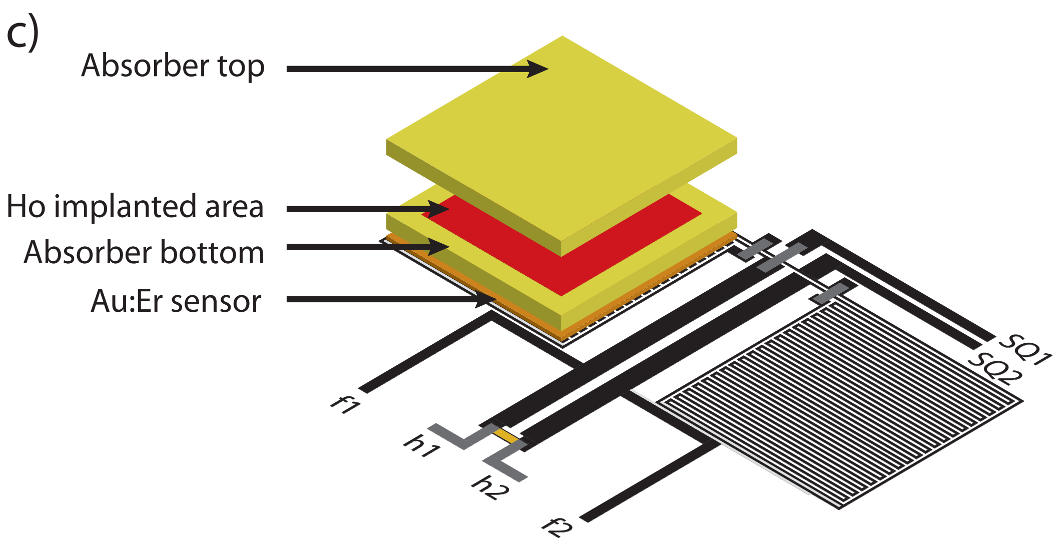
Disadvantage:

- Relatively low time response → measured energy spectrum suffers from pile-up → segment detector into many pixels → hard to scale to large masses!

c)



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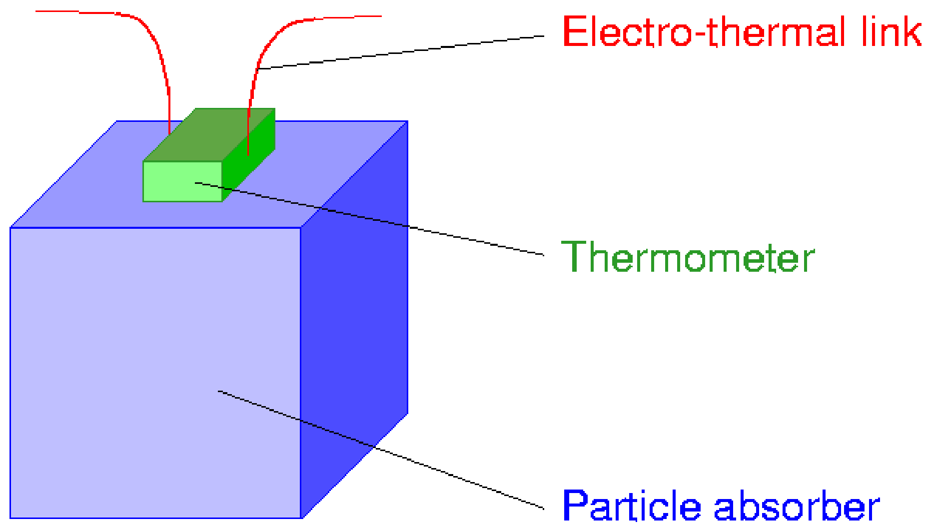

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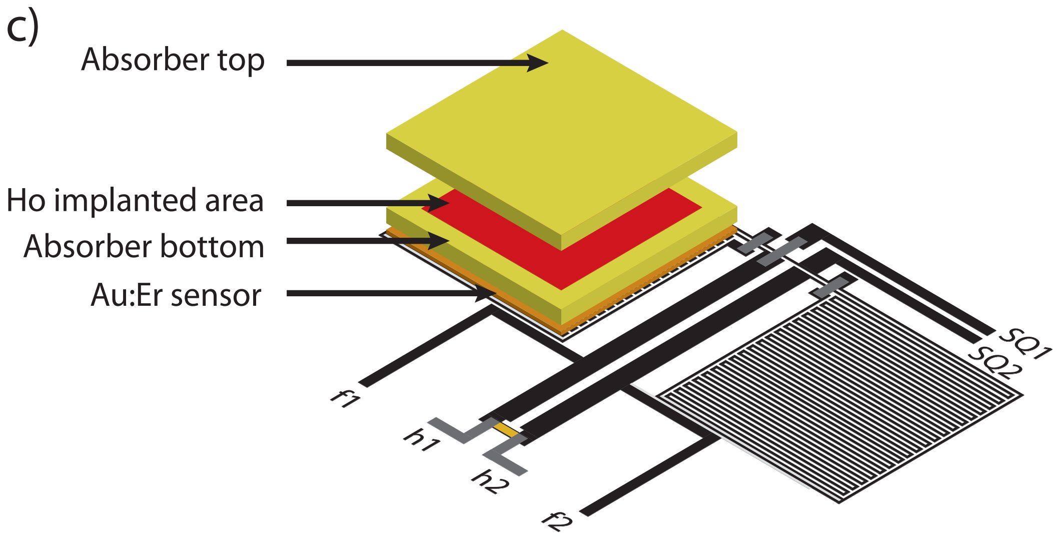

- Sub-eV neutrino mass sensitivity within reach?

Neutrino mass scale summary

What is the best experimental strategy?

β decay	ββ0ν decay	Cosmology
$m_\beta^2 \equiv \sum_i m_i^2 \mid U_{ei} \mid^2$	$m_{\beta\beta} \equiv \mid \sum_i m_i U_{ei}^2 \mid$	$m_{cosmo} \equiv \sum_i m_i$

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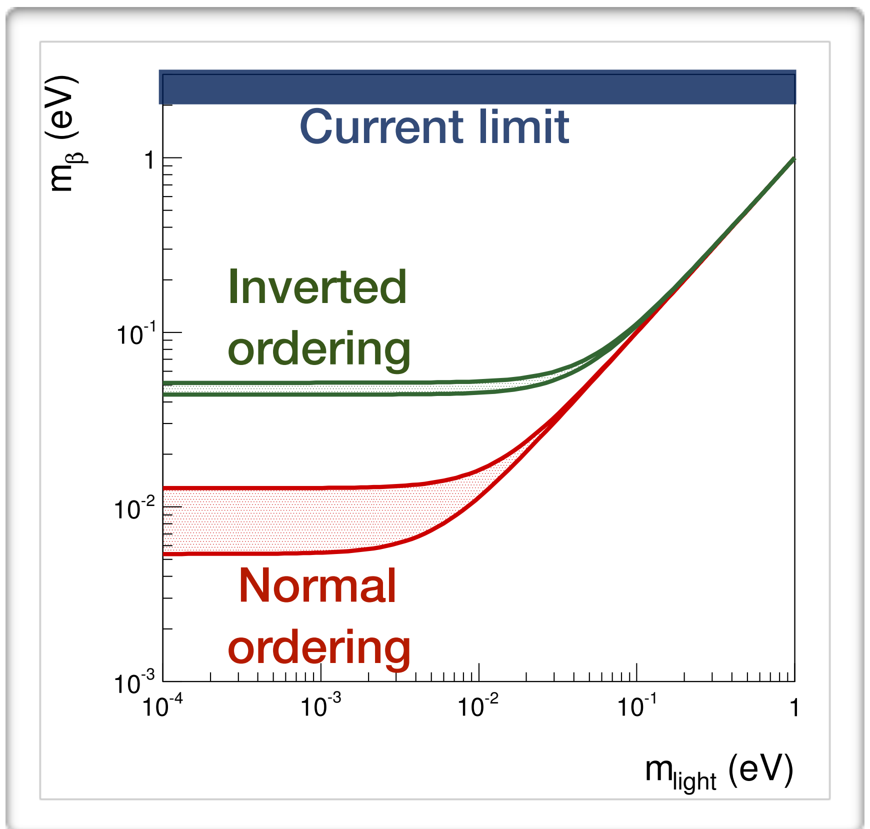
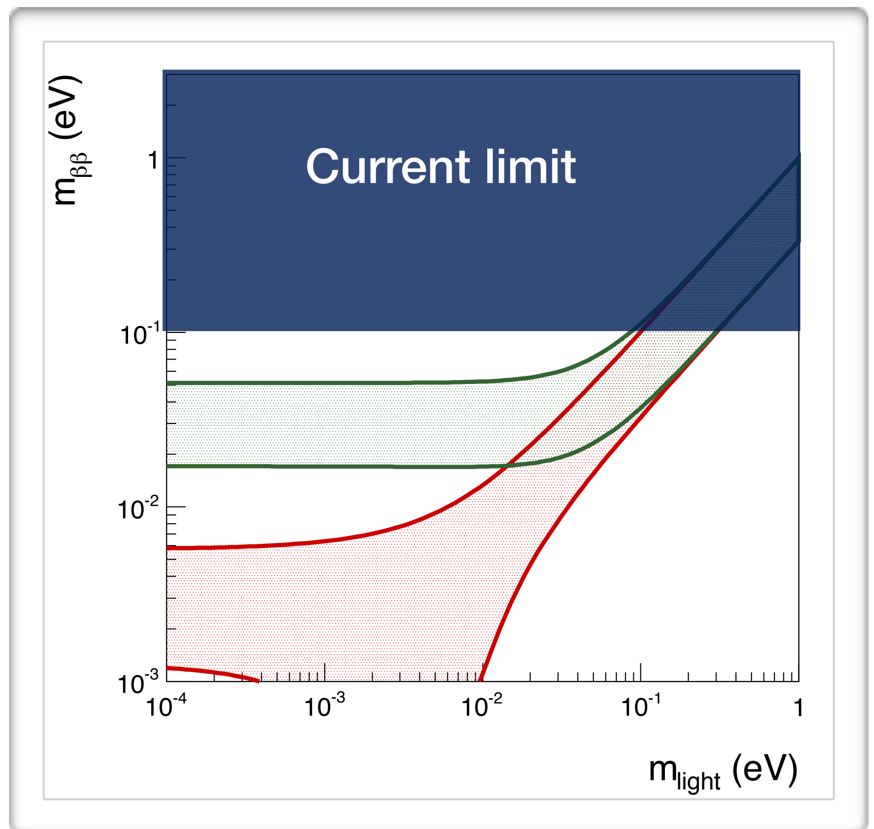
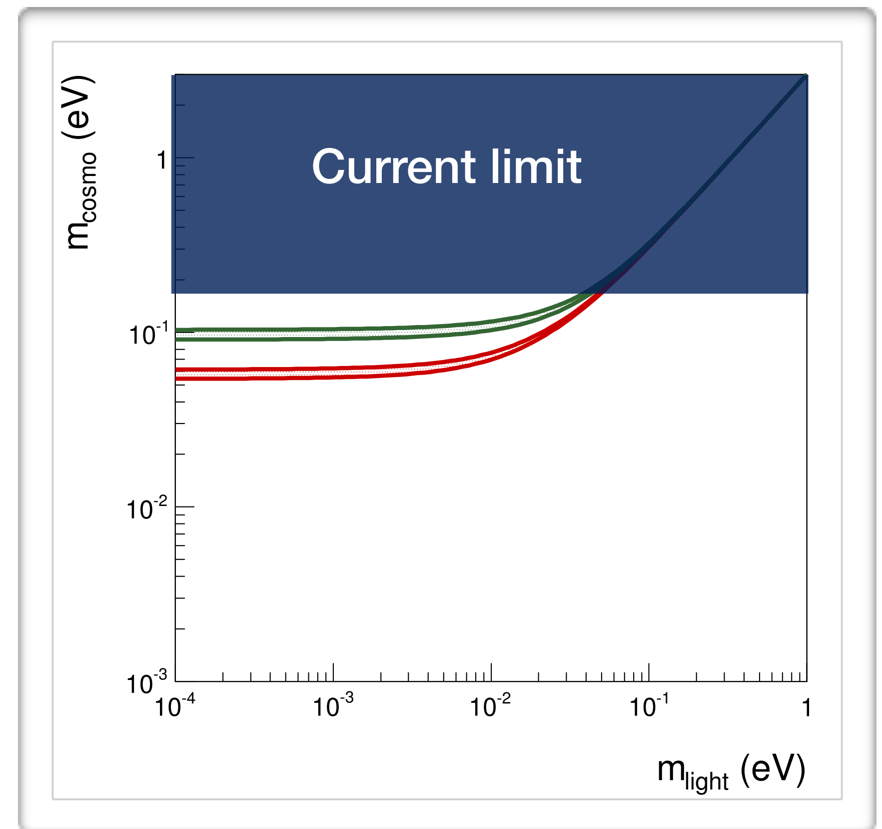






Less stringent, but less model-dependent → More stringent, but more model-dependent

Concluding remarks

A wealth of neutrino experiments!

Experiments to be presented at Neutrino 2018 Conference

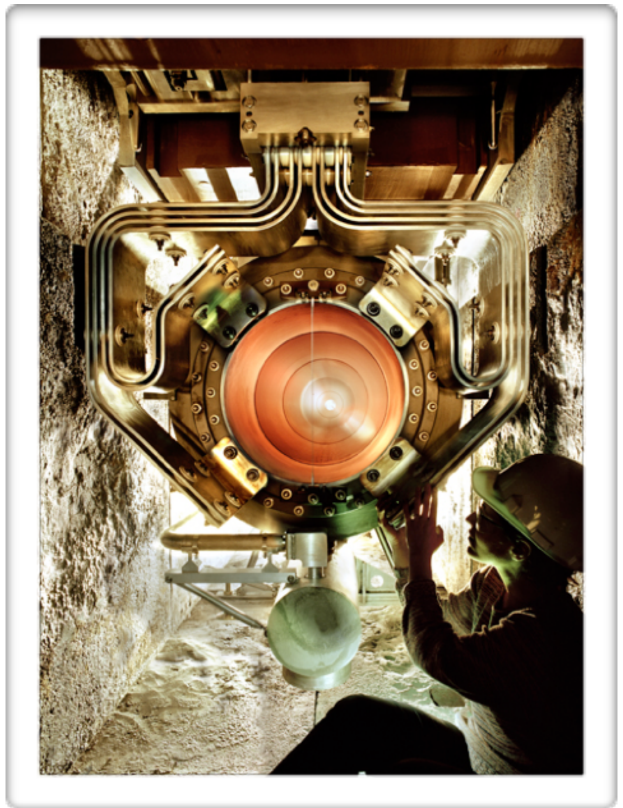
Concluding remarks

The life of a neutrino experimentalist

Concluding remarks

The life of a neutrino experimentalist

- Build powerful neutrino sources...



Concluding remarks

The life of a neutrino experimentalist

- Build powerful neutrino sources...

- and massive neutrino detectors...

Concluding remarks

The life of a neutrino experimentalist

- Build powerful neutrino sources...

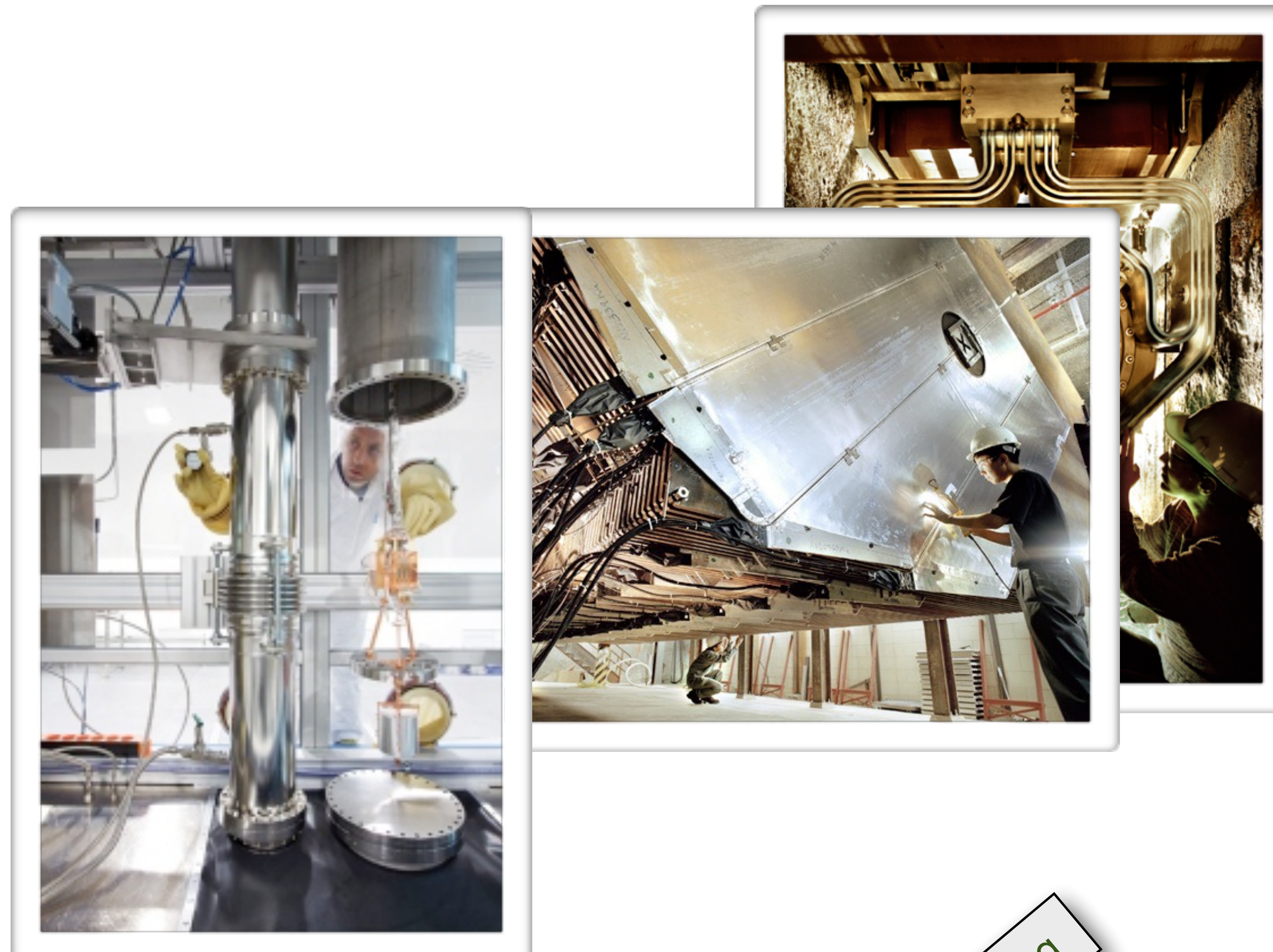
- and massive neutrino detectors...

- in a low-background environment...

Concluding remarks

The life of a neutrino experimentalist

- Build powerful neutrino sources...



- and massive neutrino detectors...
- in a low-background environment...
- to answer known neutrino questions and be prepared for the unexpected!

Identity

Mixing

Mass ordering

?

Mass scale

Species