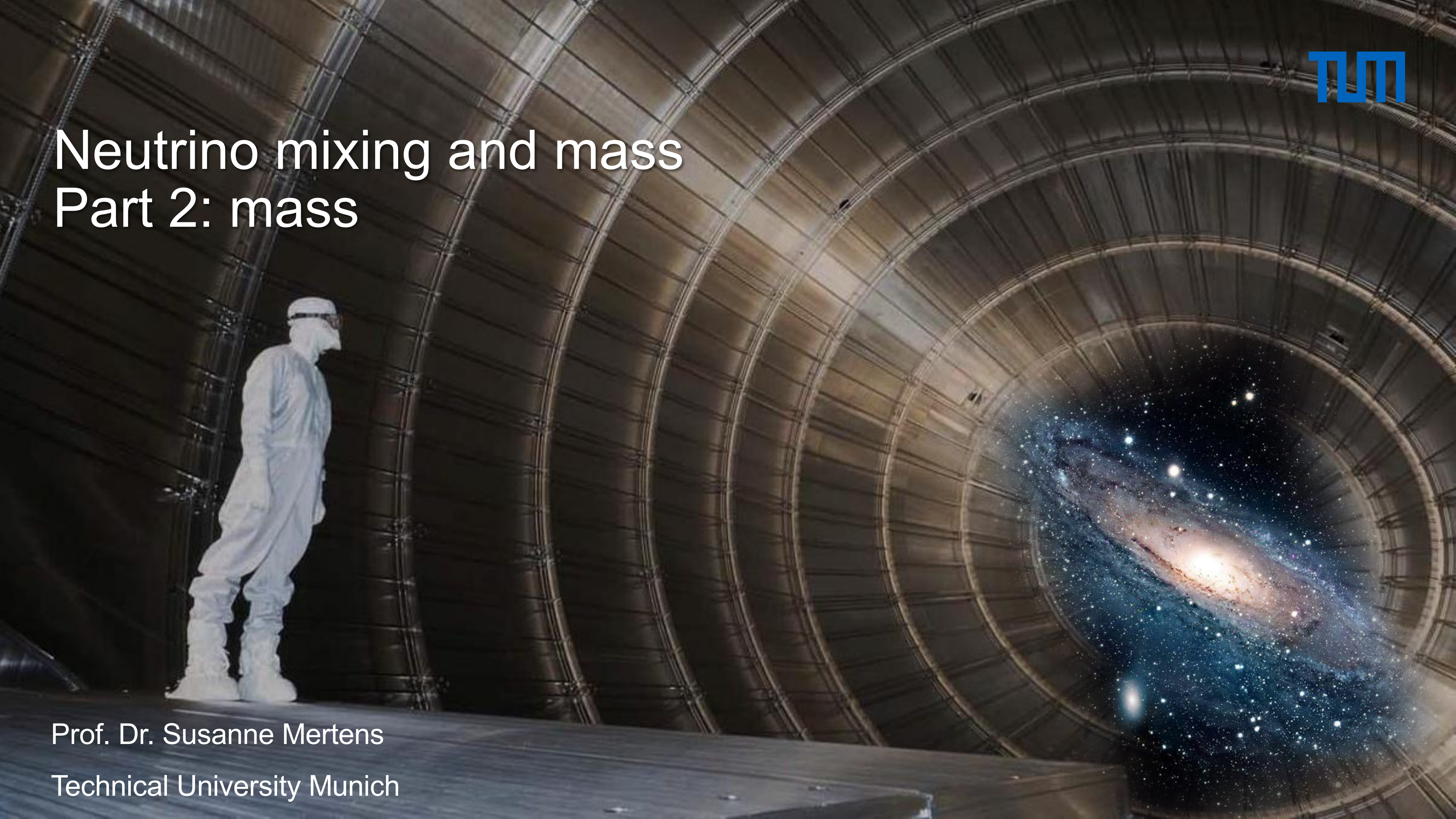
Neutrino mixing and mass
Part 2: mass

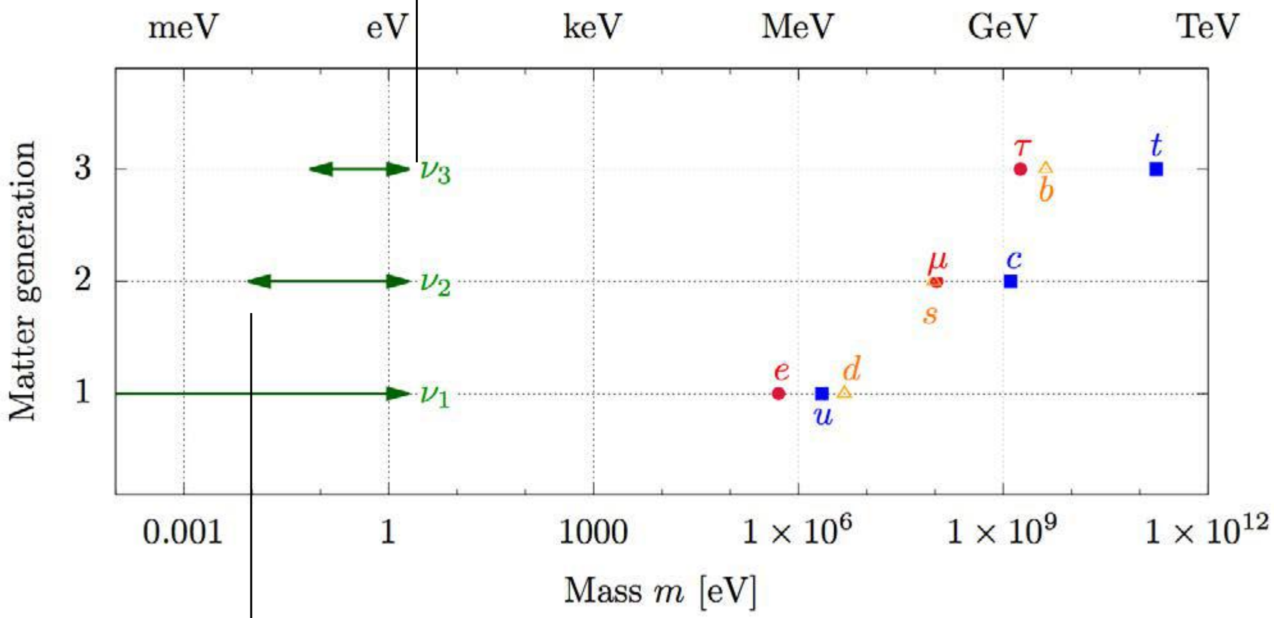


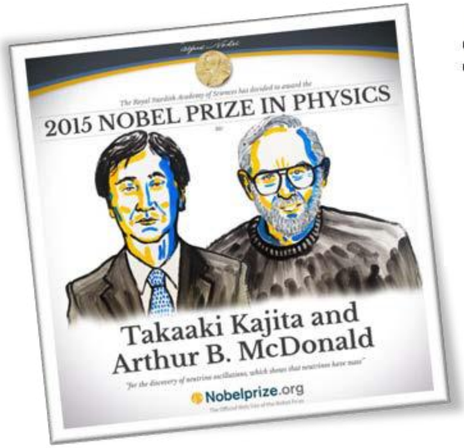
Prof. Dr. Susanne Mertens

Technical University Munich

Neutrino mass

Upper bound
from direct measurements





Lower bound
from oscillation experiments

Neutrino mass

Cosmology

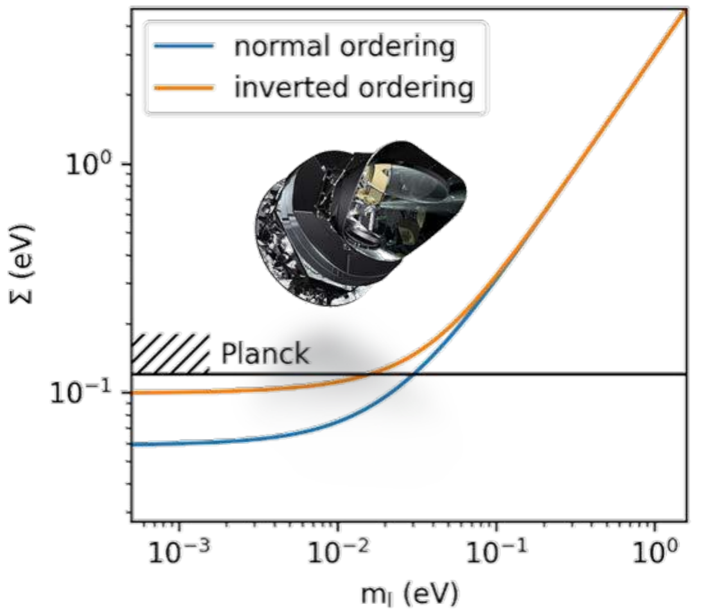
$$\Sigma = \sum_i m_i$$

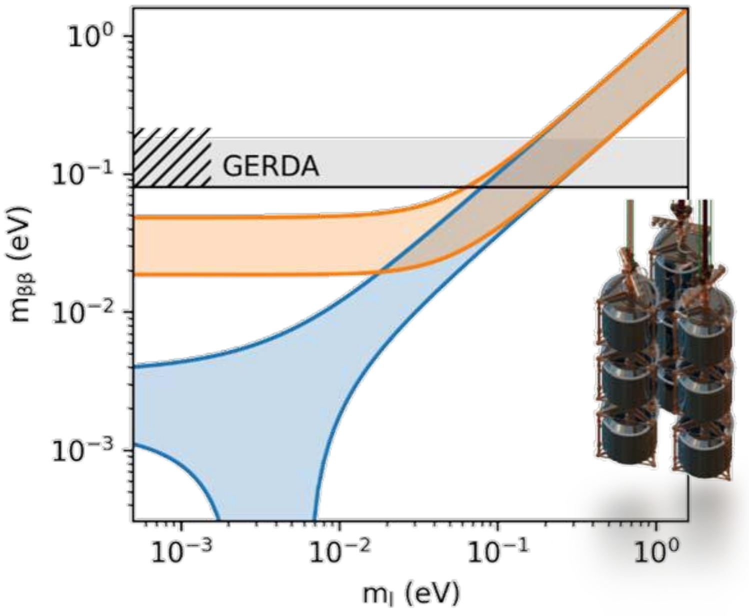
Neutrinoless ßß decay

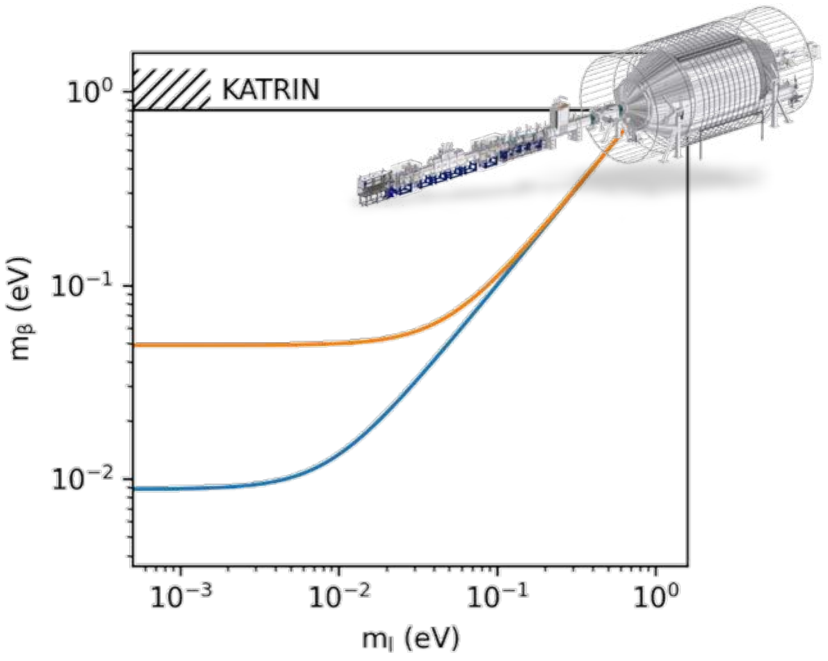
$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$

ß-decay kinematics

$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$







Questions for today

- How to measure the neutrino mass from cosmology
- …and from $0\nu\beta\beta$?
- …and directly ?
- What can we learn if we measure nothing?

Neutrino mass

Cosmology

$$\Sigma = \sum_i m_i$$

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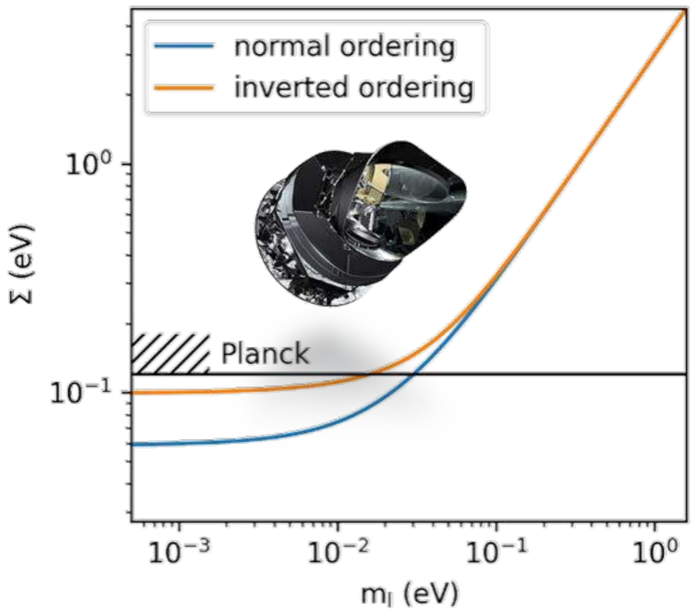
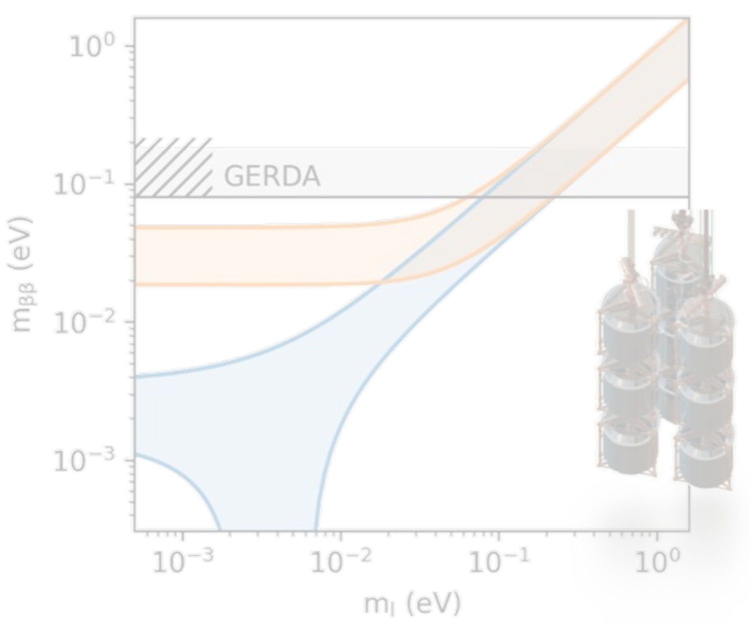
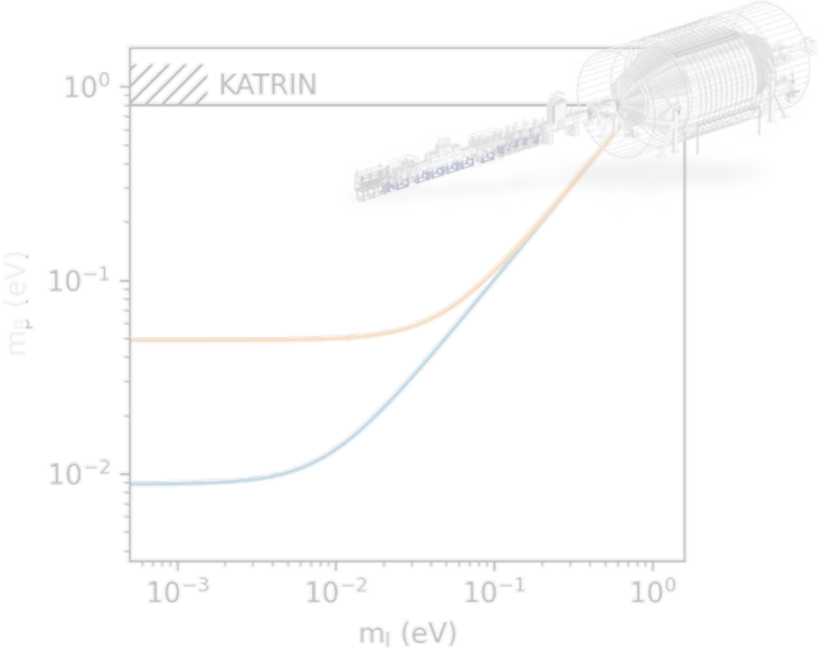


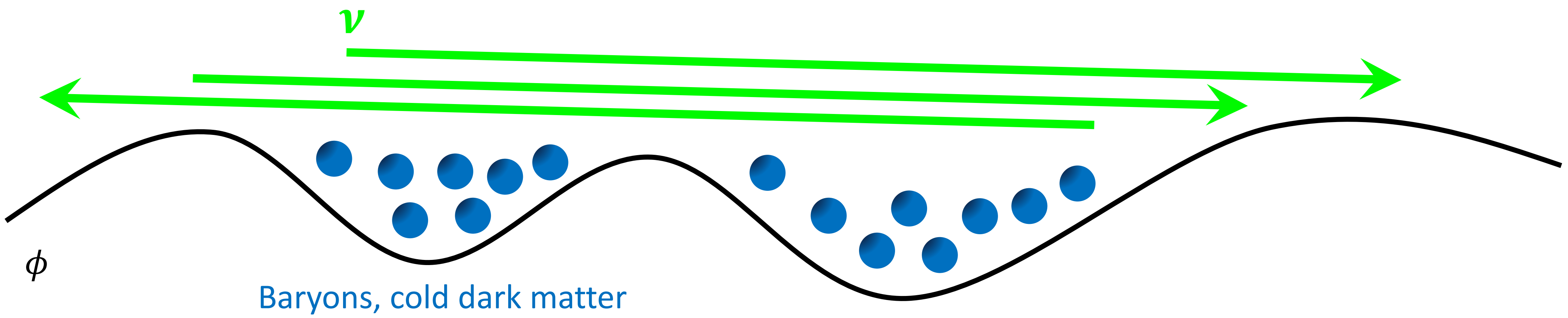




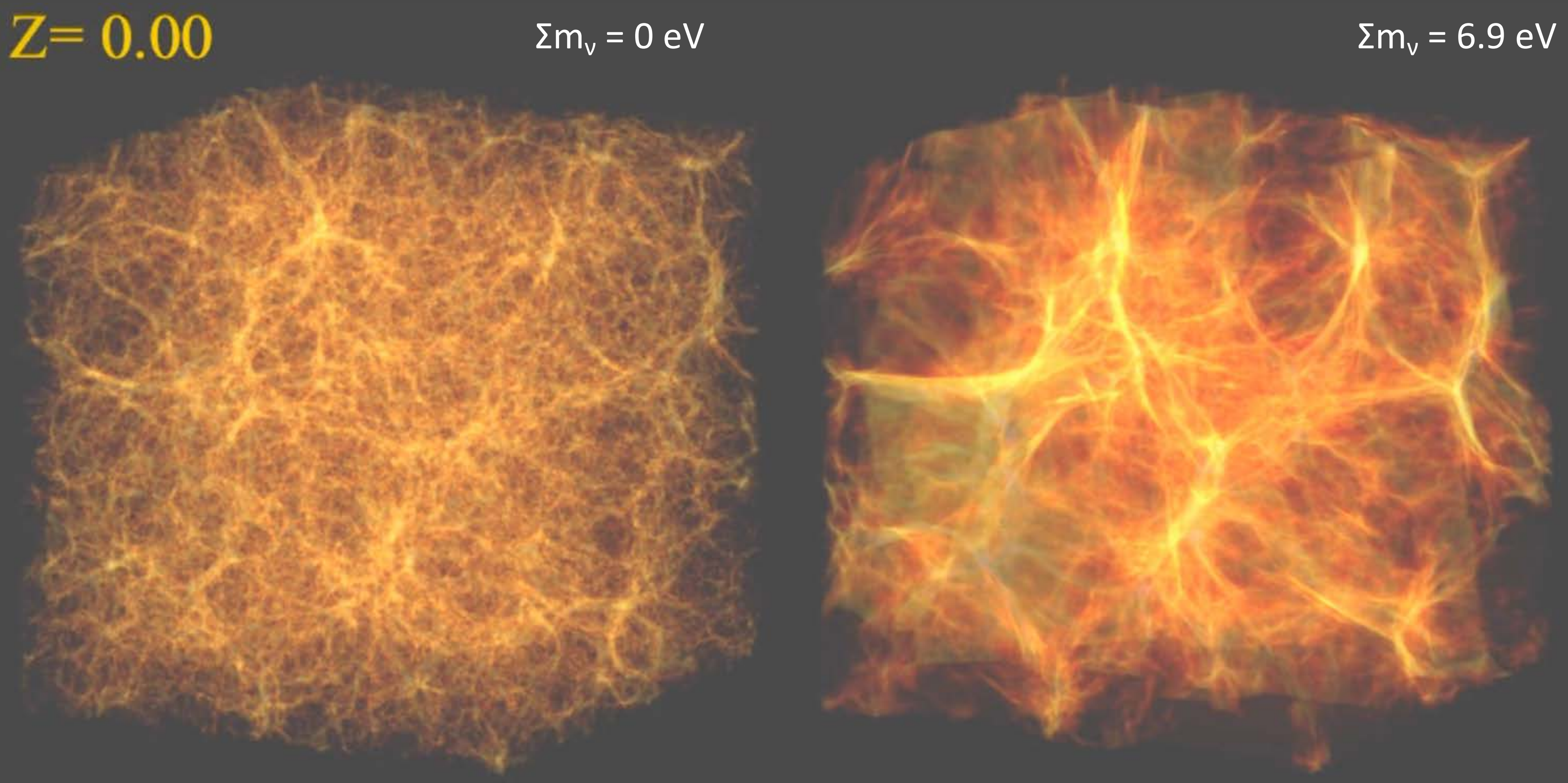
Neutrinos in the universe

- Freeze-out of ν's 1 s after big bang
- Neutrinos are the most abundant matter particle in the universe
- Today 300 neutrinos per cubic centimeter from the Big Bang
- Even if light they can impact the structure formation

Neutrinos as cosmic arcitects



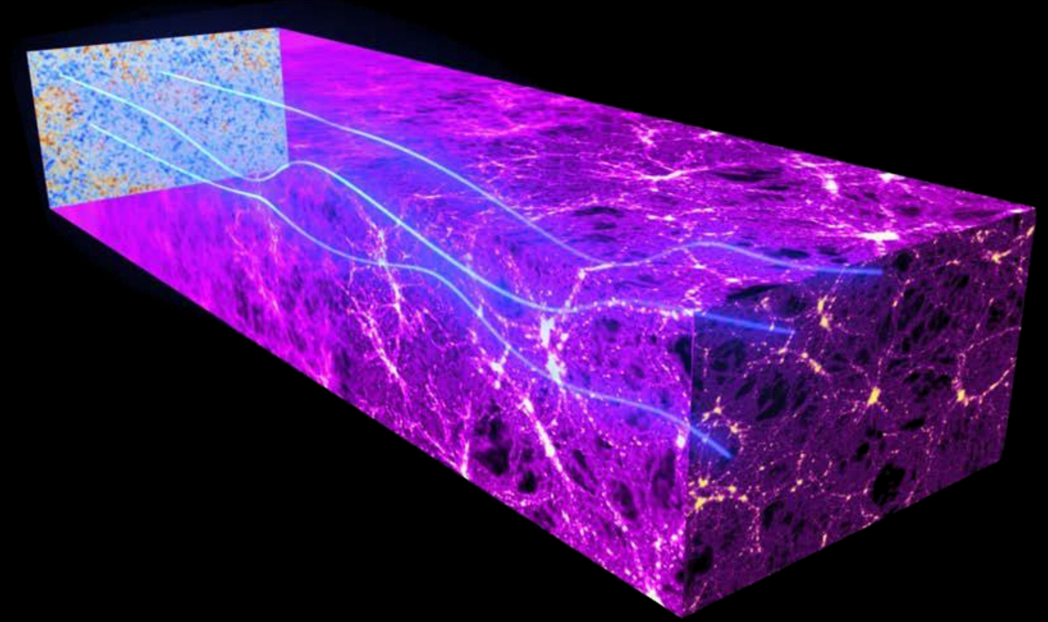
Neutrinos as cosmic arcitects

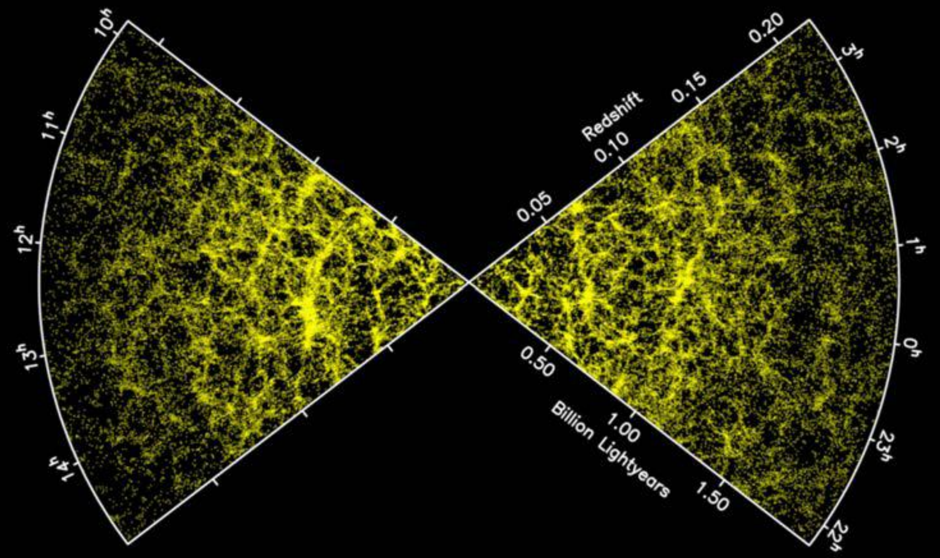


Cosmological probes

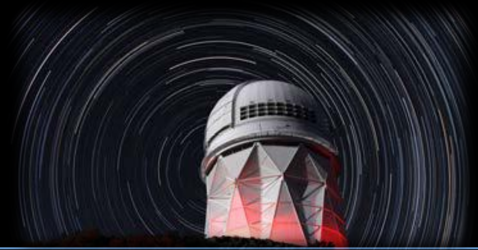
Cosmic microwave background
- CMB temperature anisotropy
- CMB polarization
- CMB lensing

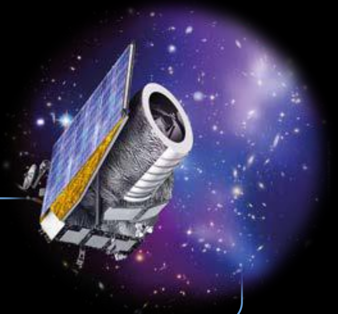
Galaxy surveys
- 3-d galaxy distribution
- weak lensing at different redshift
- Lyman-α forest





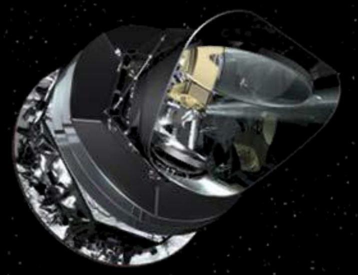
Missions





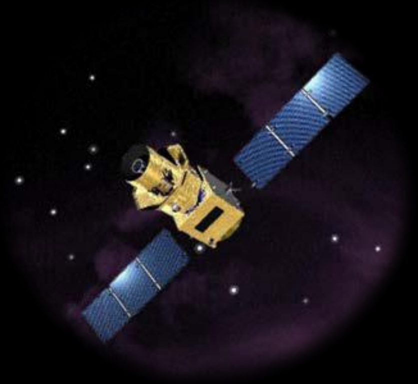
Cosmic microwave background

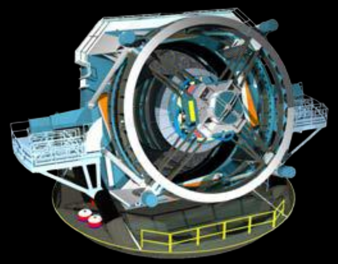
- Planck satellite
- Simons Observatory (1808.07445)
- CMB-S4 (1610.02743)
- LiteBIRD (1801.06987)

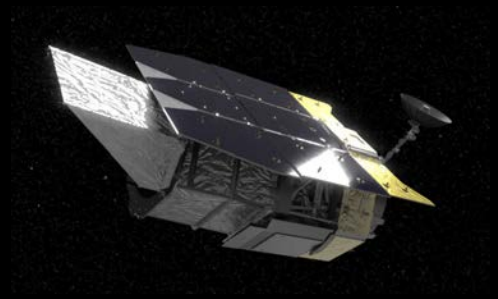


Galaxy surveys

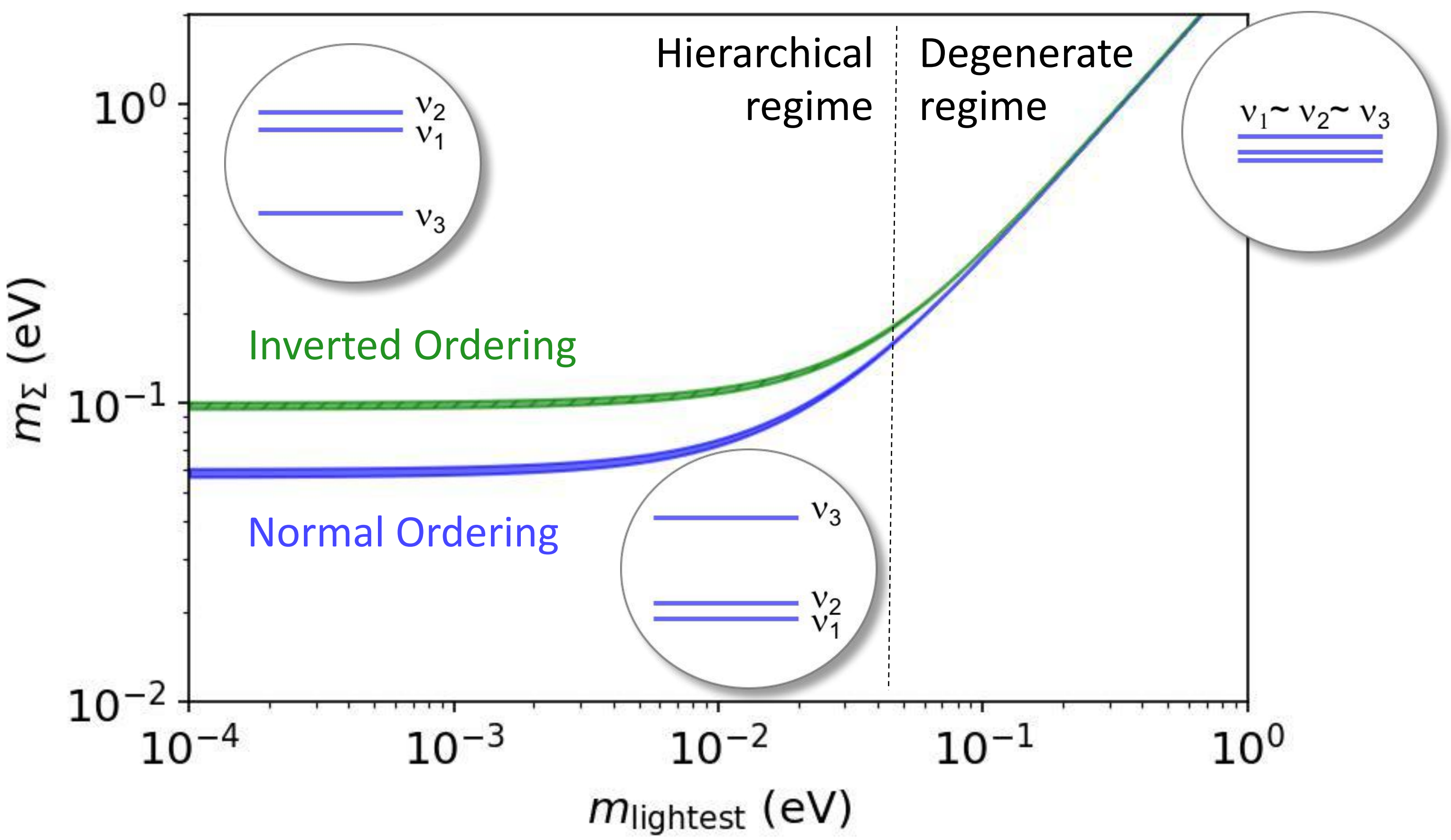
- Dark Energy Spectroscopic Instrument (DESI)
- EUCLID (1110.3193)
- LSST (Vera Rubin Obs.) (0912.0201)
- WFIRST (now: NGRST) (1208.4012)



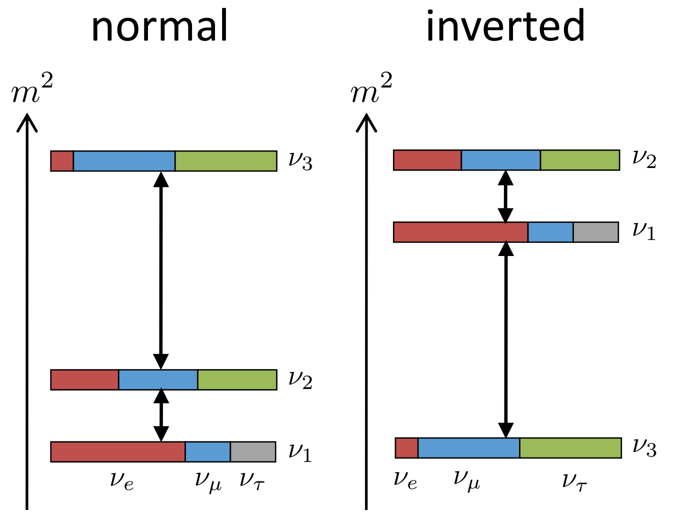




Where do we stand?



- Observable: sum of neutrino mass eigenstates: $m_\Sigma = \sum_i m_i$



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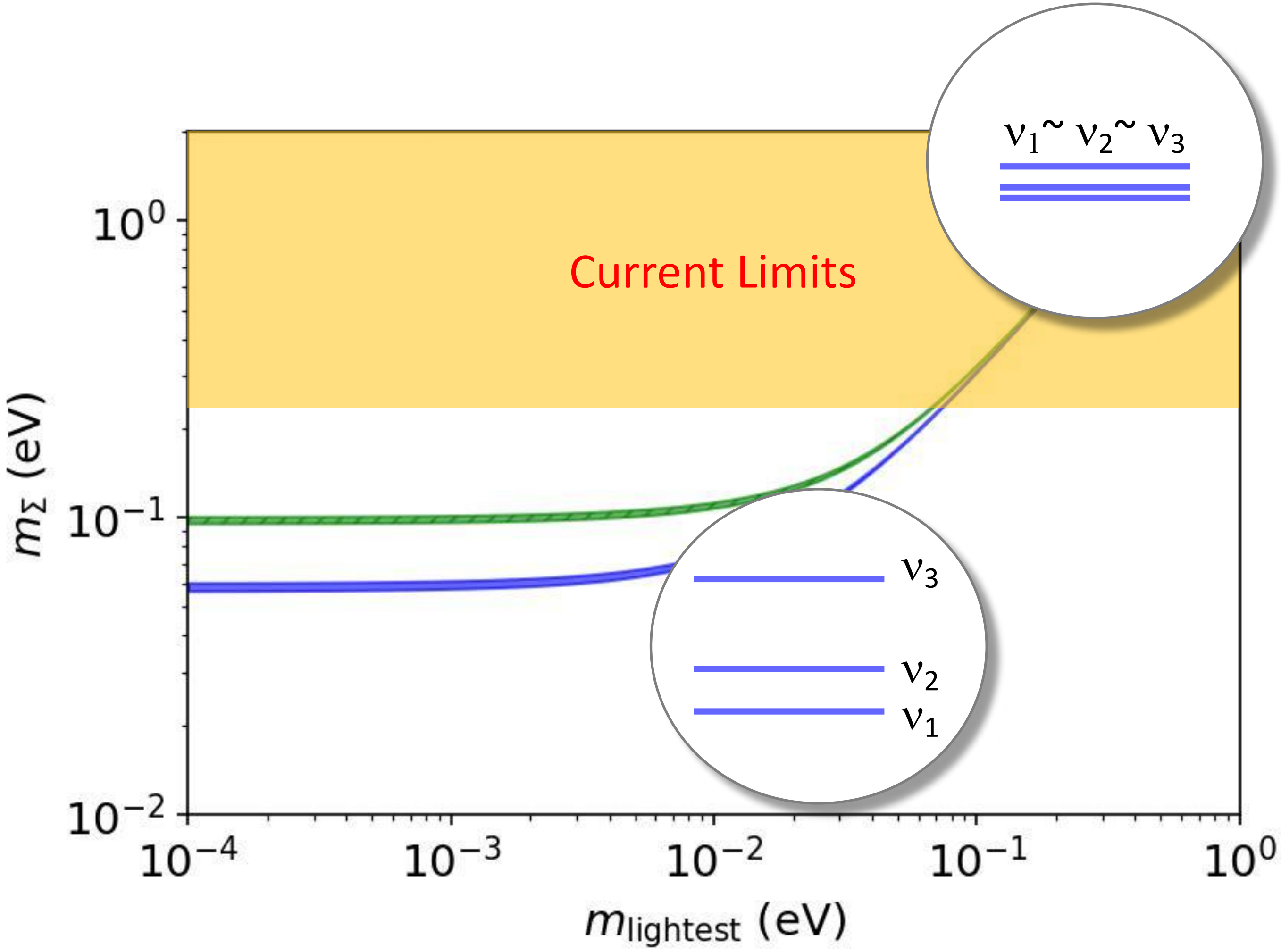
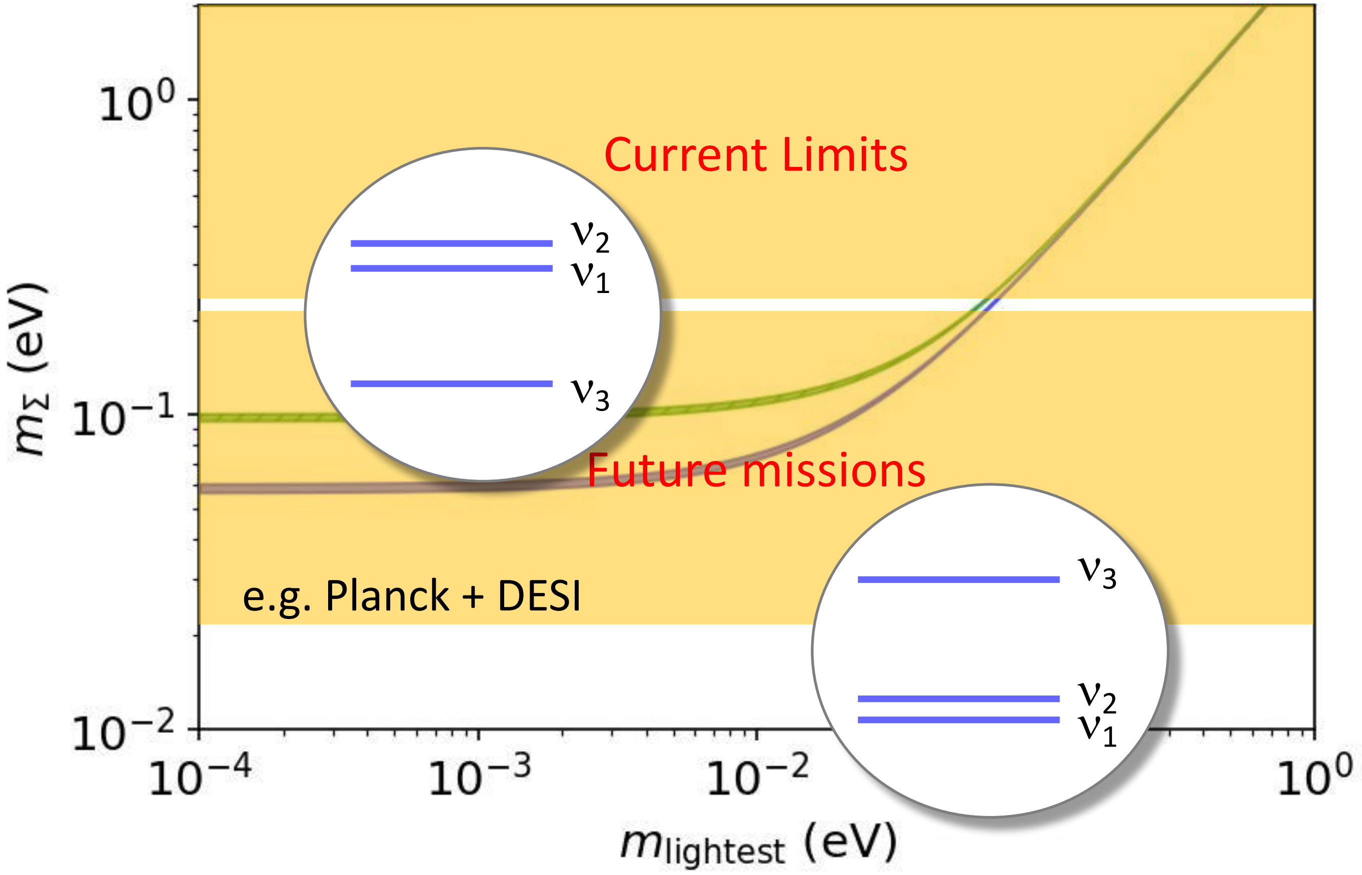


Current best limits:

Planck 2018: arXiv:1807.06209v1

- $\sum m_\nu < 540$ meV (TT + lowE)
- $\sum m_\nu < 260$ meV (TTTEEE + lowE)
- $\sum m_\nu < 240$ meV (TTTEEE + lowE + lensing)
- $\sum m_\nu < 120$ meV (TTTEEE + lowE + lensing + BAO)

Where do we go?



Current best limits:

Planck 2018: arXiv:1807.06209v1

- $\sum m_\nu <$ 120 - 540 meV

Future missions:

- $\sigma(\sum m_\nu) \sim 50$ meV (CMB)
- $\sigma(\sum m_\nu) \sim 20$ meV (CMB + BAO)
- $\sigma(\sum m_\nu) \sim 10$ meV (CMB + BAO + LSS)

Careful:
cosmology sees the amount of hot dark matter
not a direct neutrino mass measurement
= model-dependent

Questions for today

How to measure the neutrino mass from cosmology

...and from $0\nu\beta\beta$?

...and directly ?

What can we learn if we measure nothing?

- Neutrinos are hot dark matter and wash out small scale structure
- Imprint in CMB and LSS
- Sensitivity at $\sum m_{\nu}$ < 0.2 eV

Neutrino mass

Cosmology

$$\Sigma = \sum_i m_i$$

Neutrinoless ßß decay

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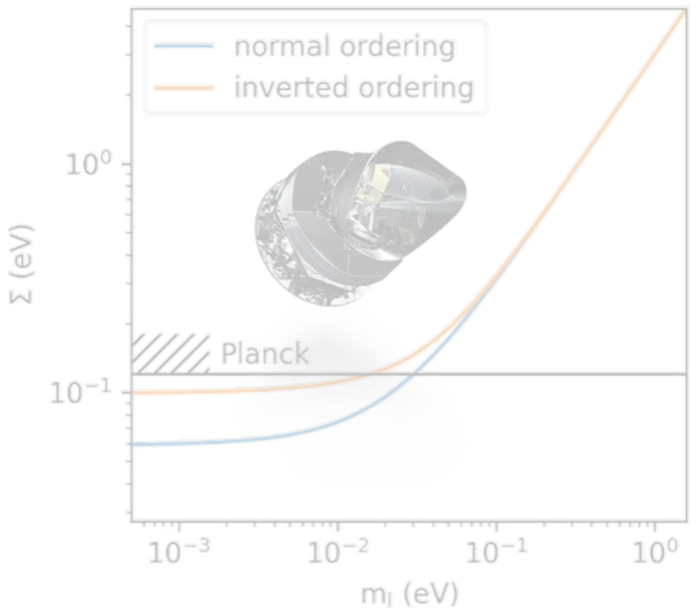
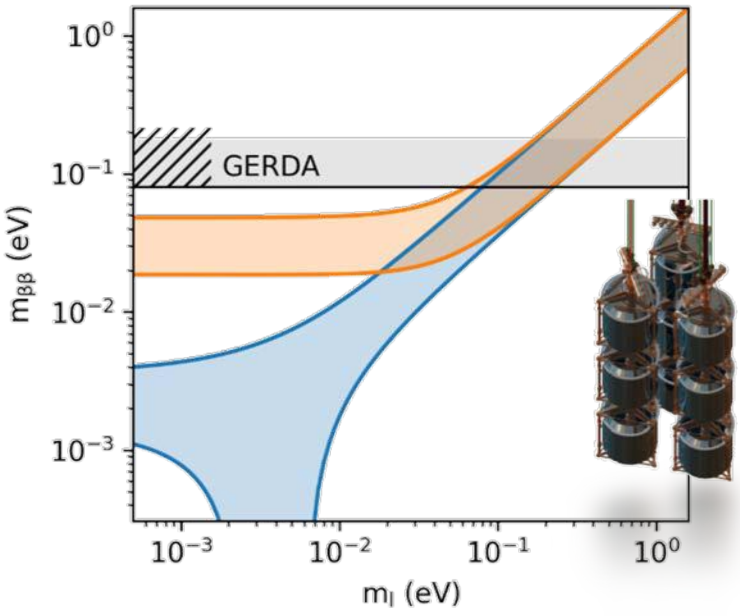
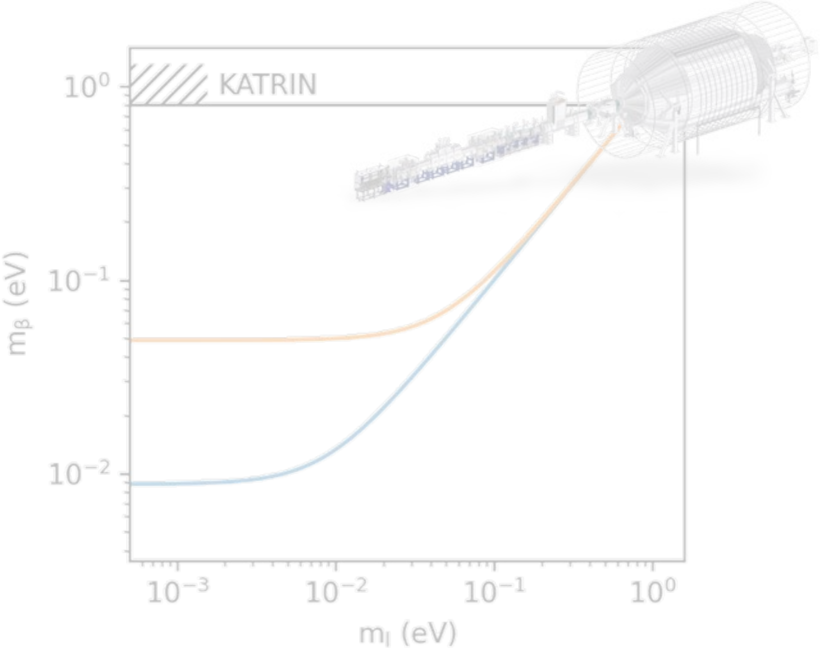






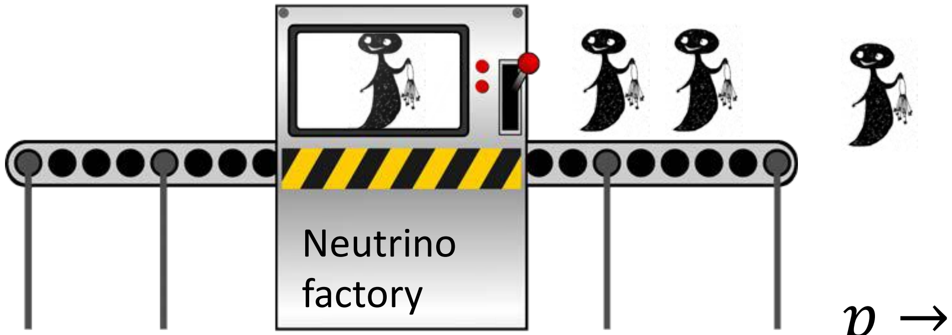
The nature of neutrinos

Dirac:
„Neutrinos and antineutrinos are different“

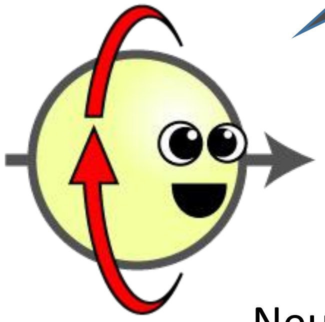
Majorana:
„Neutrinos are their own antiparticle“

Helicity of Neutrinos

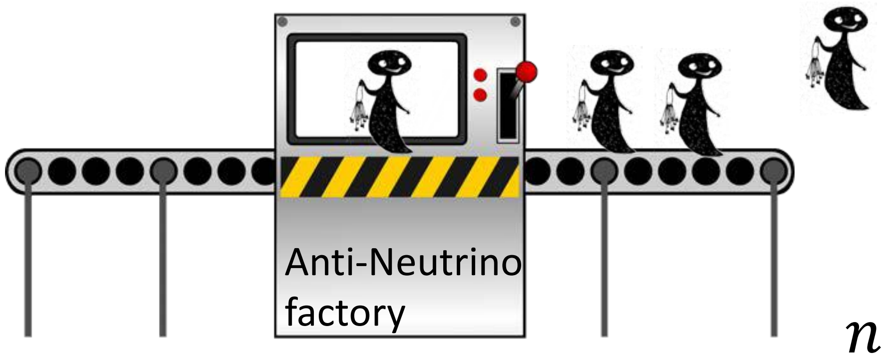
helicity: projection of spin onto momentum



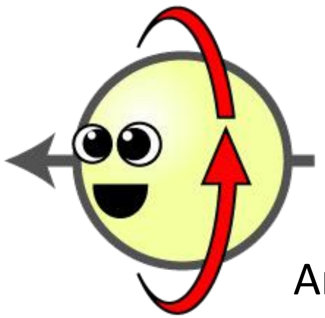
$$p \rightarrow n + e^{+} + \nu_e$$



Neutrinos are left-handed

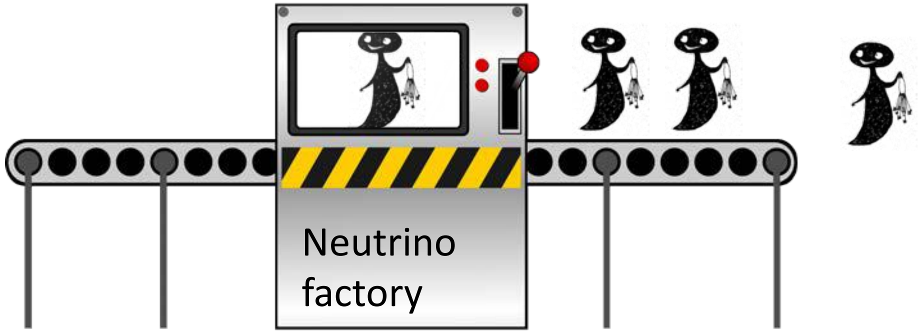


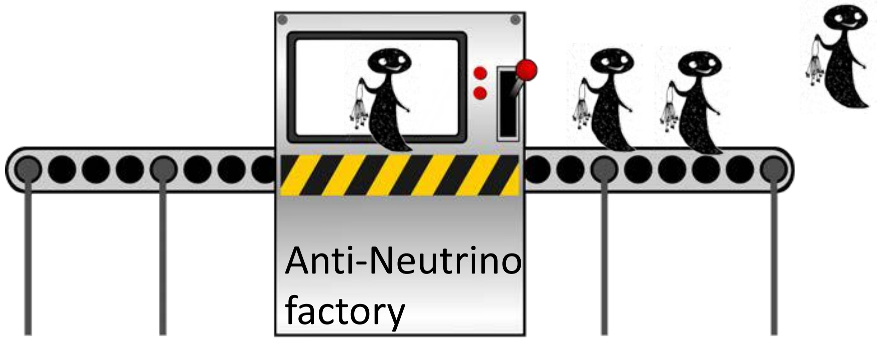
$$n \rightarrow p + e^{-} + \bar{\nu}_e$$



Antineutrinos are right-handed

Helicity of Neutrinos

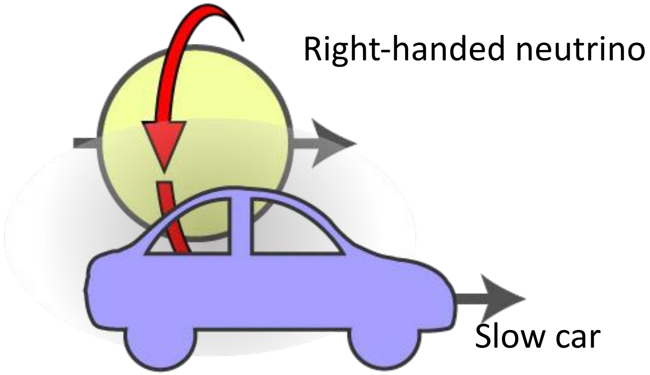


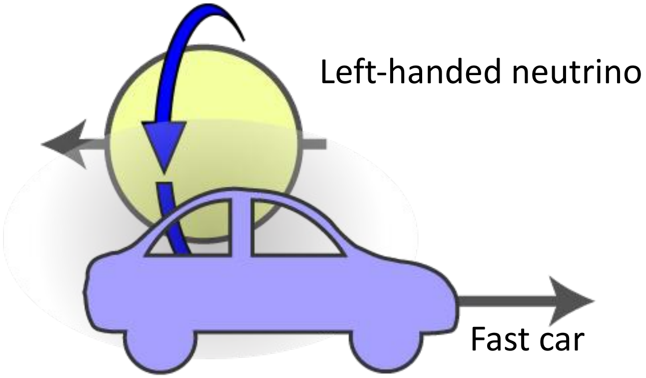


Majorana:
"That's the only difference"

Dirac:
"There is a more fundamental difference between the two"

How can we test who is right?

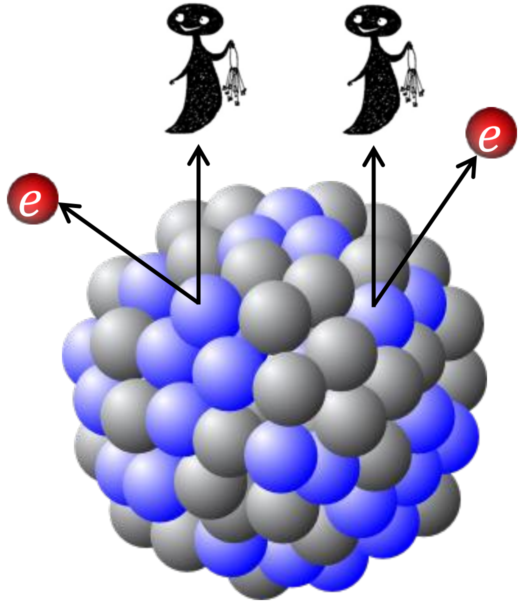




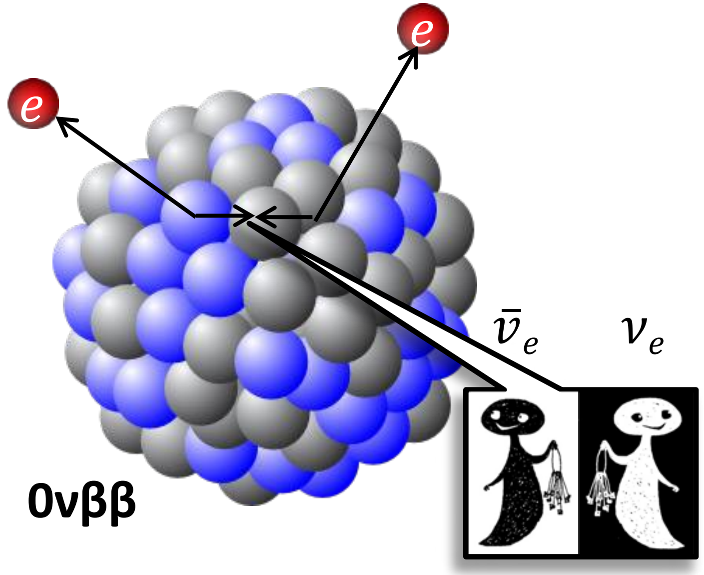
Dirac:
*"The neutrino is **not** **identical** to the known antineutrino"*

Majorana:
*"The neutrino is **identical** to the known antineutrino"*

How can we test who is right?



2νββ



0νββ

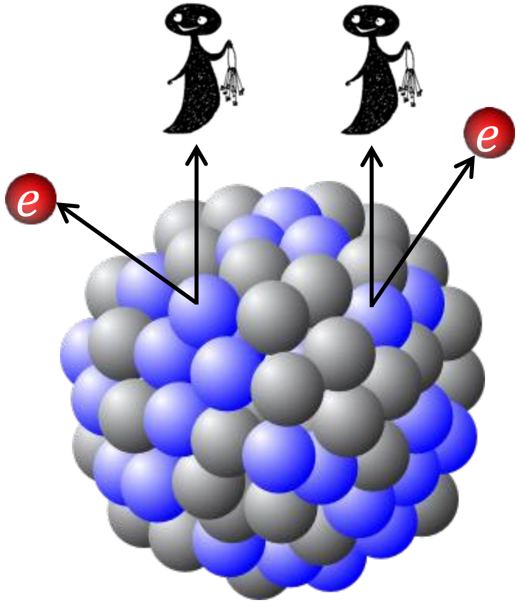
$$n \rightarrow p + e^- + \bar{\nu}_e$$

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

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

$$n + \nu_e \rightarrow p + e^-$$

How can we test who is right?



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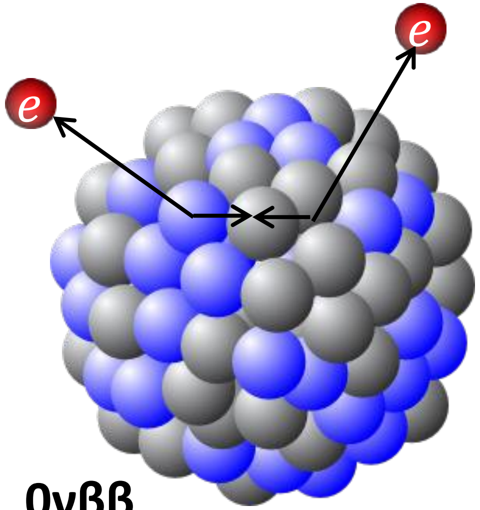


0νββ

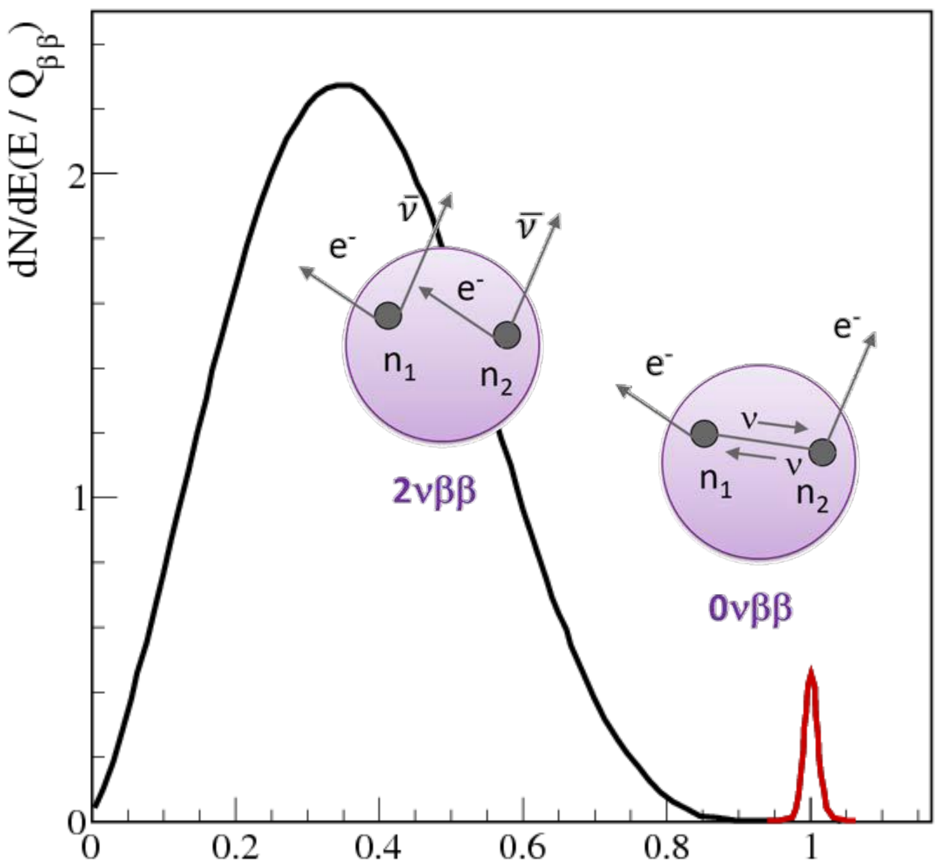
$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$n + \nu_e \rightarrow p + e^-$$

Dirac: *"The reaction is not possible"*

Majorana: *"This reaction should be possible."*

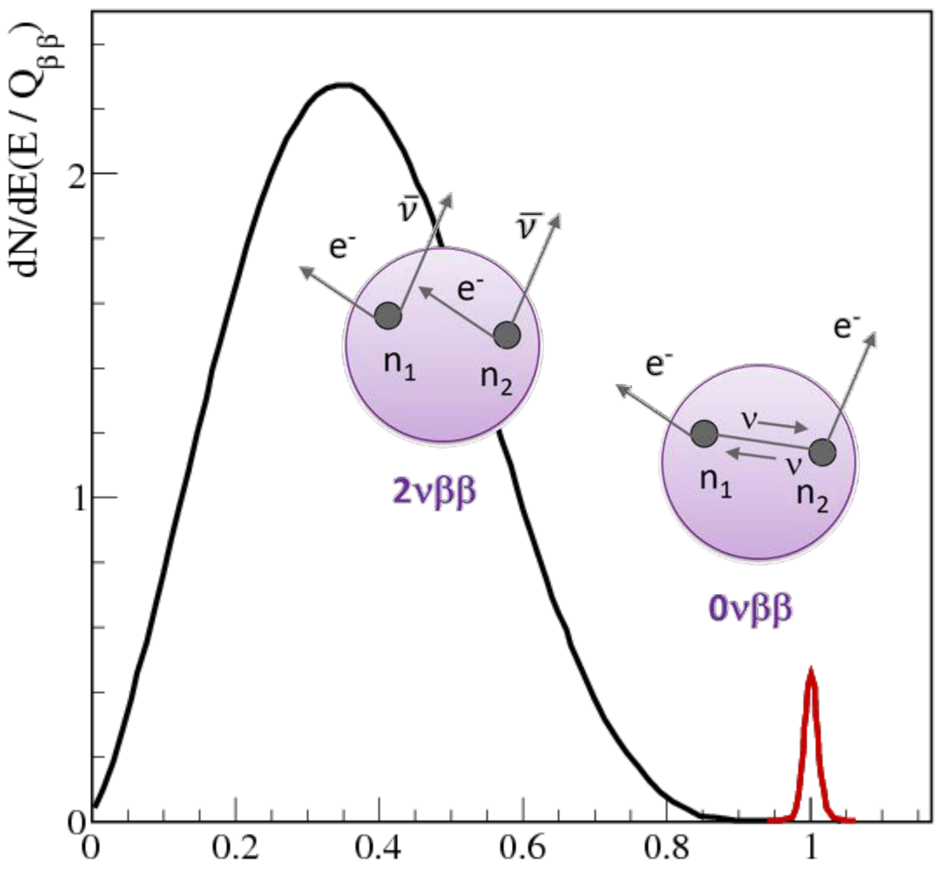
Neutrinoless double beta decay: signature



Energy of the two beta electrons

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{110}Pd, ^{116}Cd, ^{124}Sn, ^{130}Te, ^{136}Xe, ^{150}Nd

Neutrinoless double beta decay



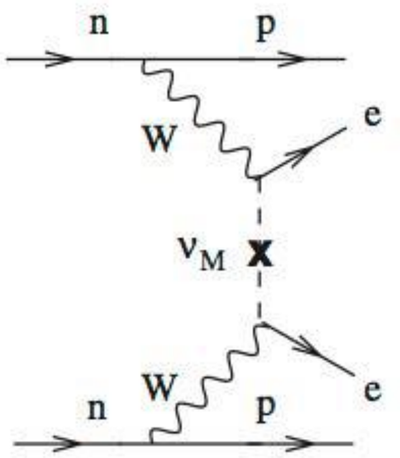
Energy of the two beta electrons

<u>If 0νββ was discovered:</u>

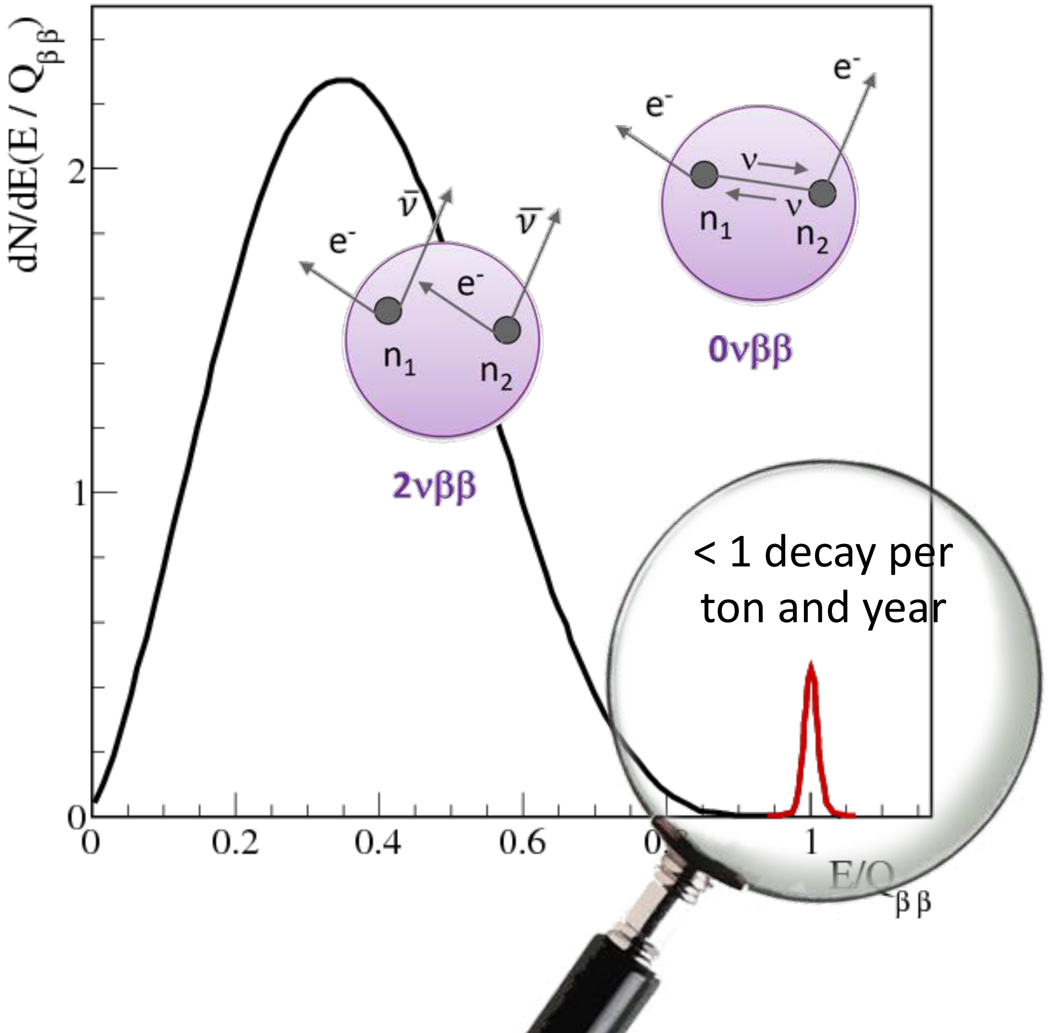
- Proof that Majorana is right
- **Discovery of matter-creating process**
  → shed light on matter-anti-matter asymmetry
- Lepton number is violated

- Half life reveals neutrino mass

$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu}(Q,Z)\cdot|M^{0\nu}|^2\cdot \boldsymbol{m_{\beta\beta}^2}$$

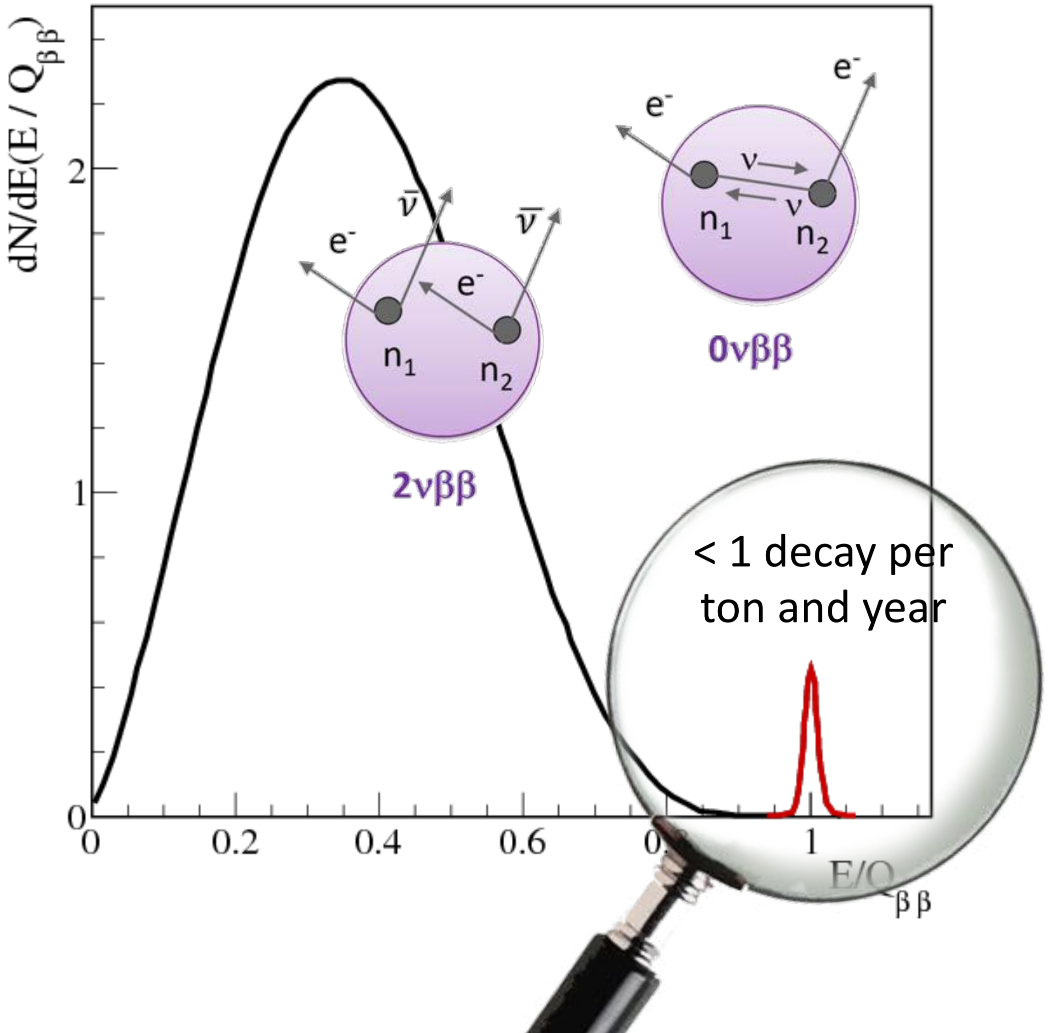


The Challenge



- What do we need to realize an experiment?

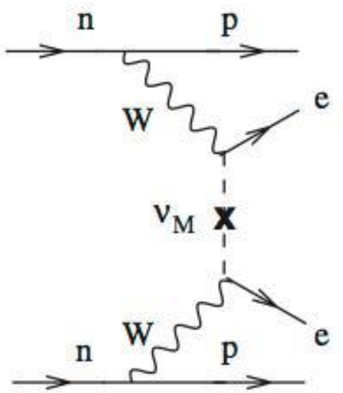
The Challenge

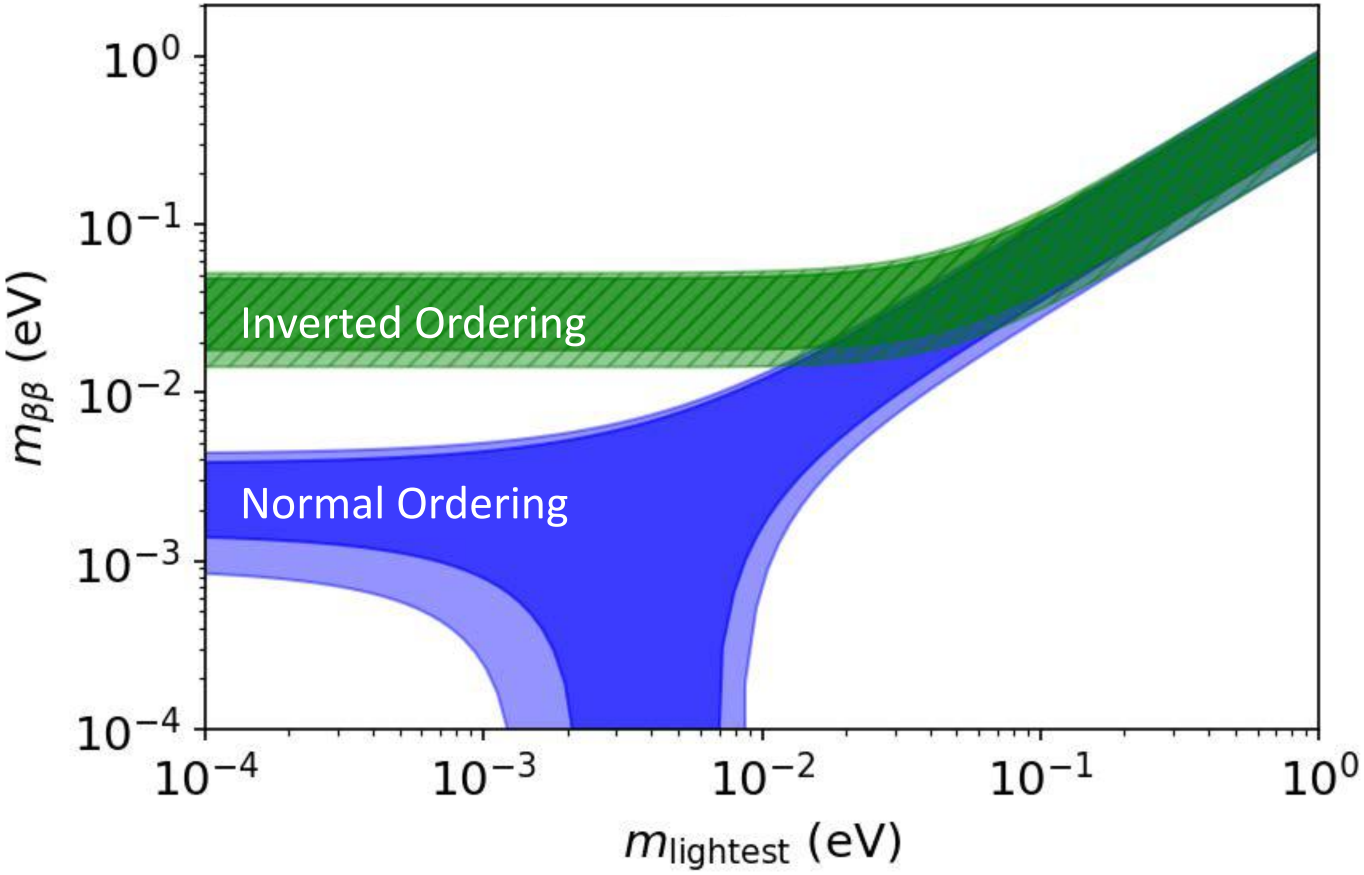


Key requirements:

- Large exposure (tonne-scale)
- Excellent energy resolution (~ 1% @ $Q_{\beta\beta}$)
- Low background (< 1 cts/year/t/ROI)

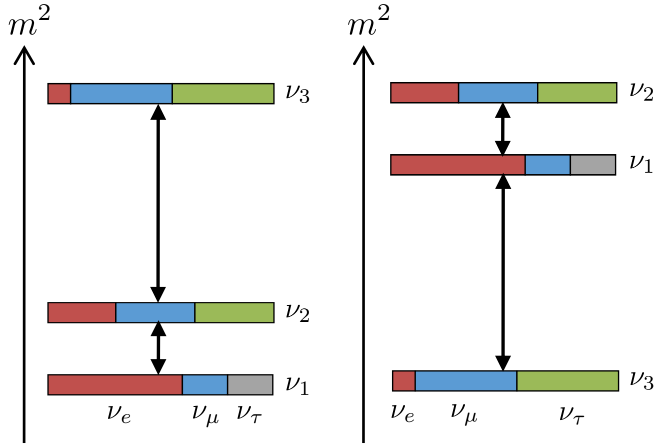
Where do we stand?





- Observable: Coherent sum of neutrino mass eigenstates:

$$m_{\beta\beta} = \left| \sum_i U_{ei}{}^2 m_{\nu i} \right|$$



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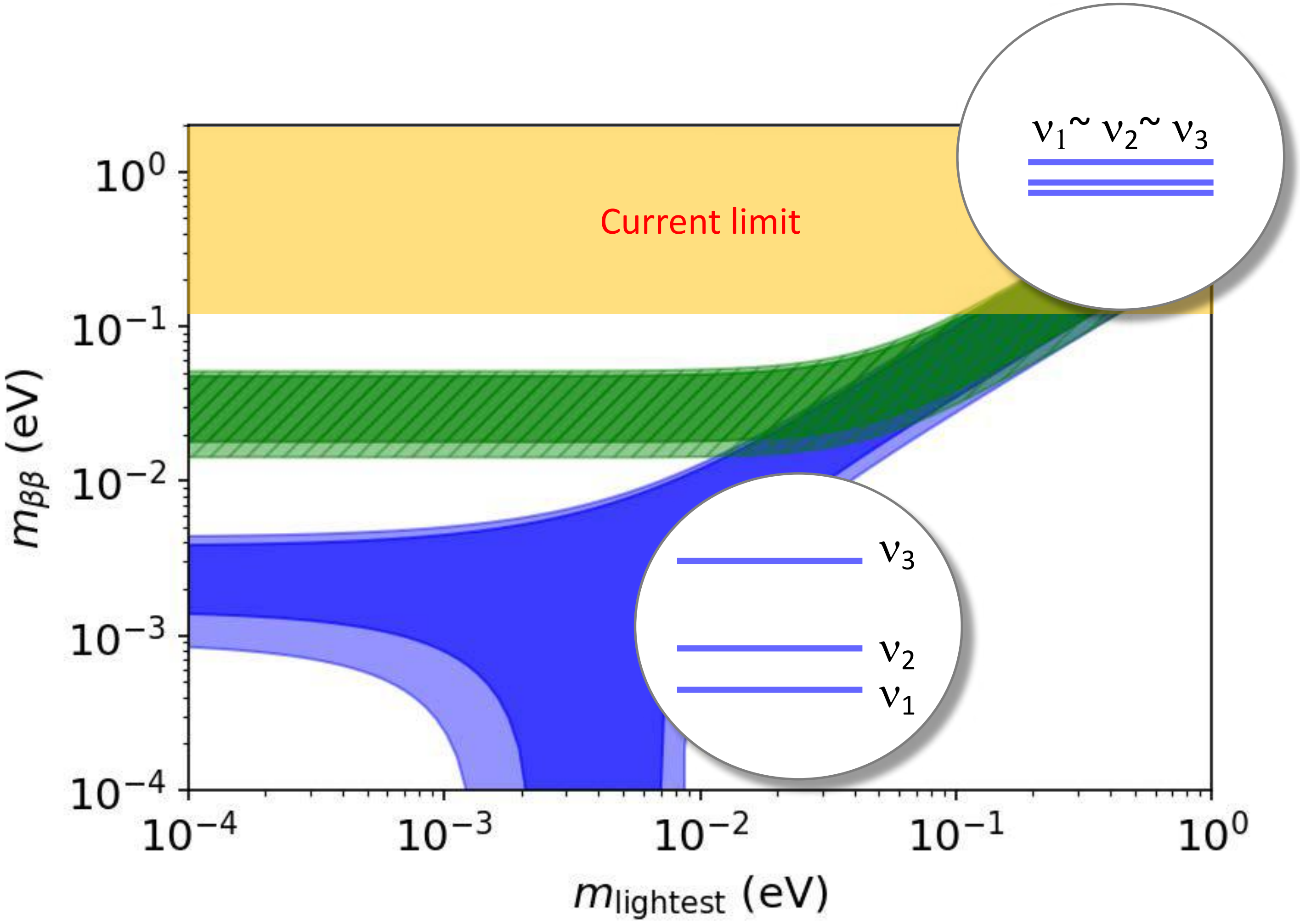
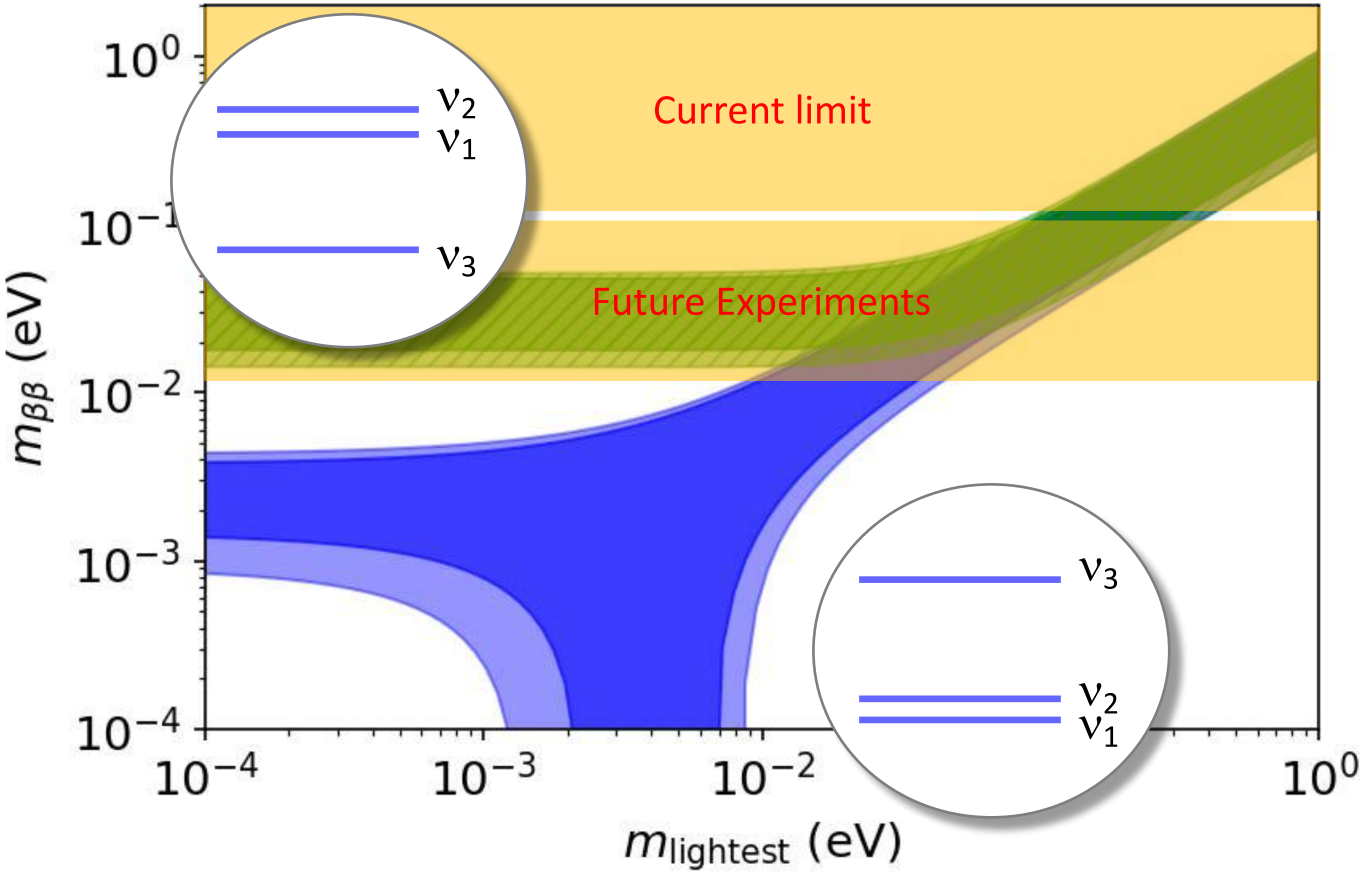


- Current limits (GERDA): $T_{1/2} > \mathcal{O}(10^{26}$ y) (90% CL) $m_{\beta\beta} < \mathcal{O}(100)$ meV
  Phys. Rev. Lett. 117 (2016), 082503
  Phys. Rev. Lett. 120 (2018) 132503

Where do we stand?



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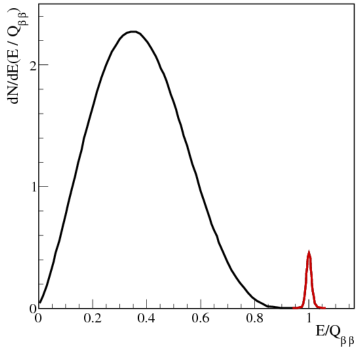
  Phys. Rev. Lett. 117 (2016), 082503
  Phys. Rev. Lett. 120 (2018) 132503

- Goal of future experiments:
  Probe inverted mass ordering

Experimental efforts

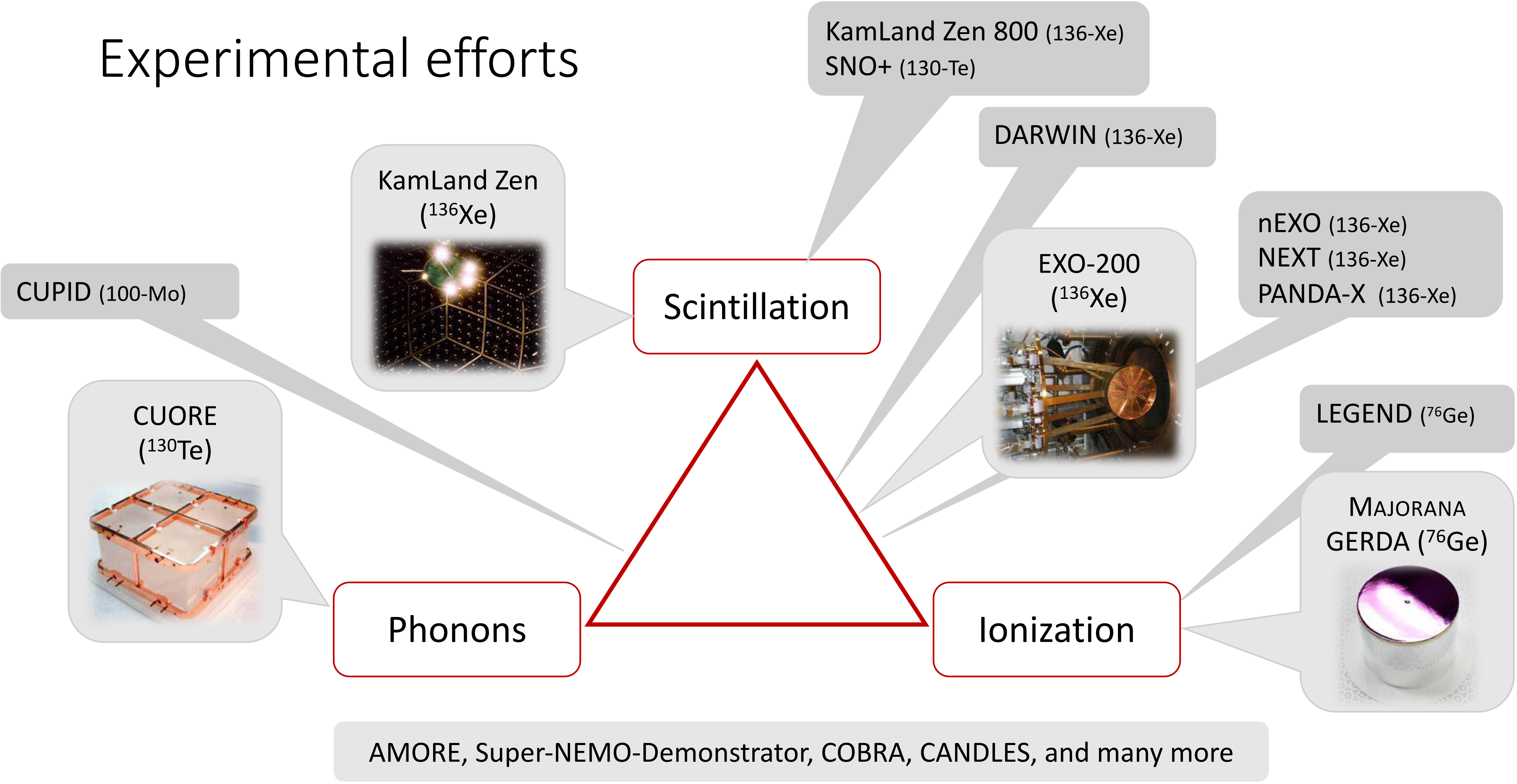


Scintillation

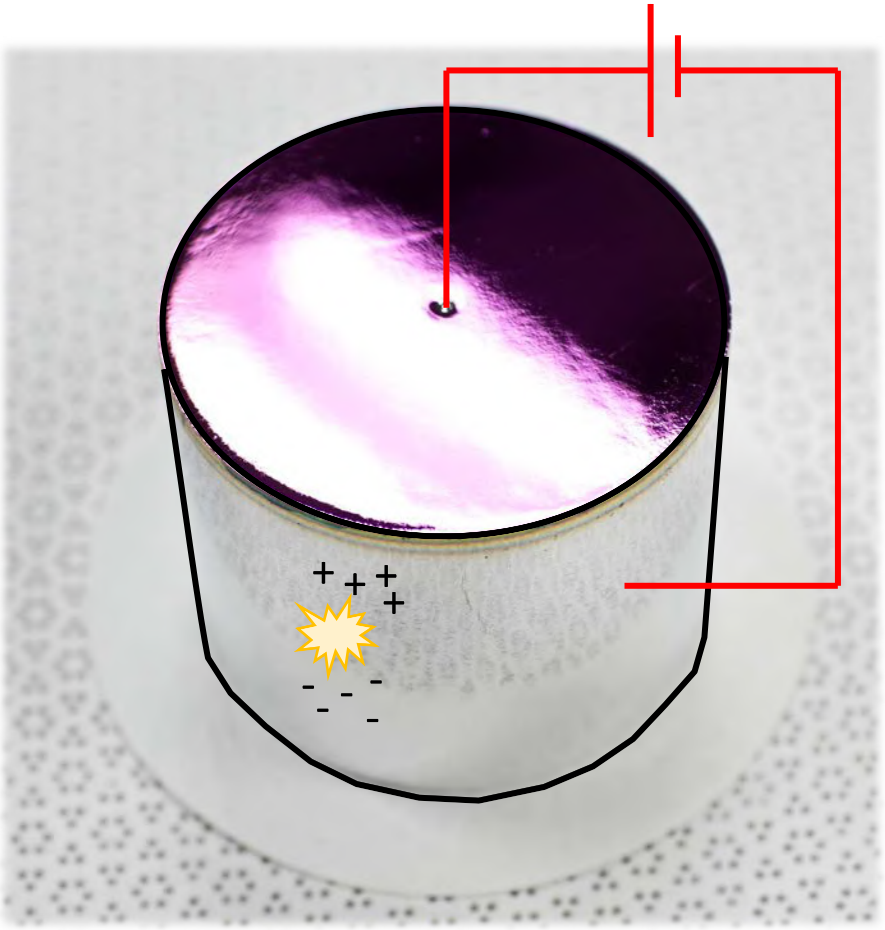
Phonons

Ionization

Experimental efforts



Experimental efforts



Germanium Semiconductors

- ✓ Enrichment to 87% in ^{76}Ge ($Q_{\beta\beta}$=2039 keV)
- ✓ Excellent energy resolution (0.12% FWHM @ $Q_{\beta\beta}$)
- ✓ Pulse-shape-discrimination against background

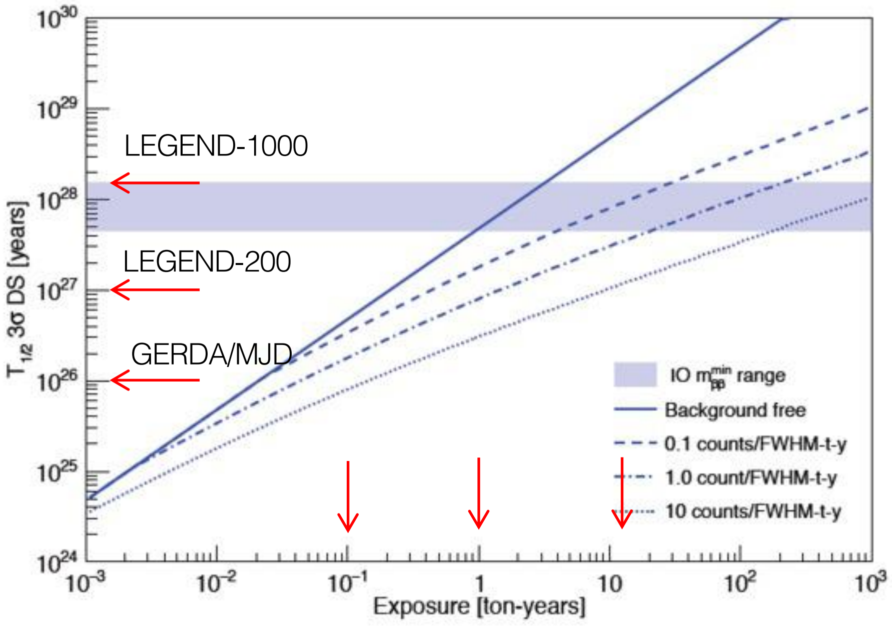
LEGEND (^{76}Ge)

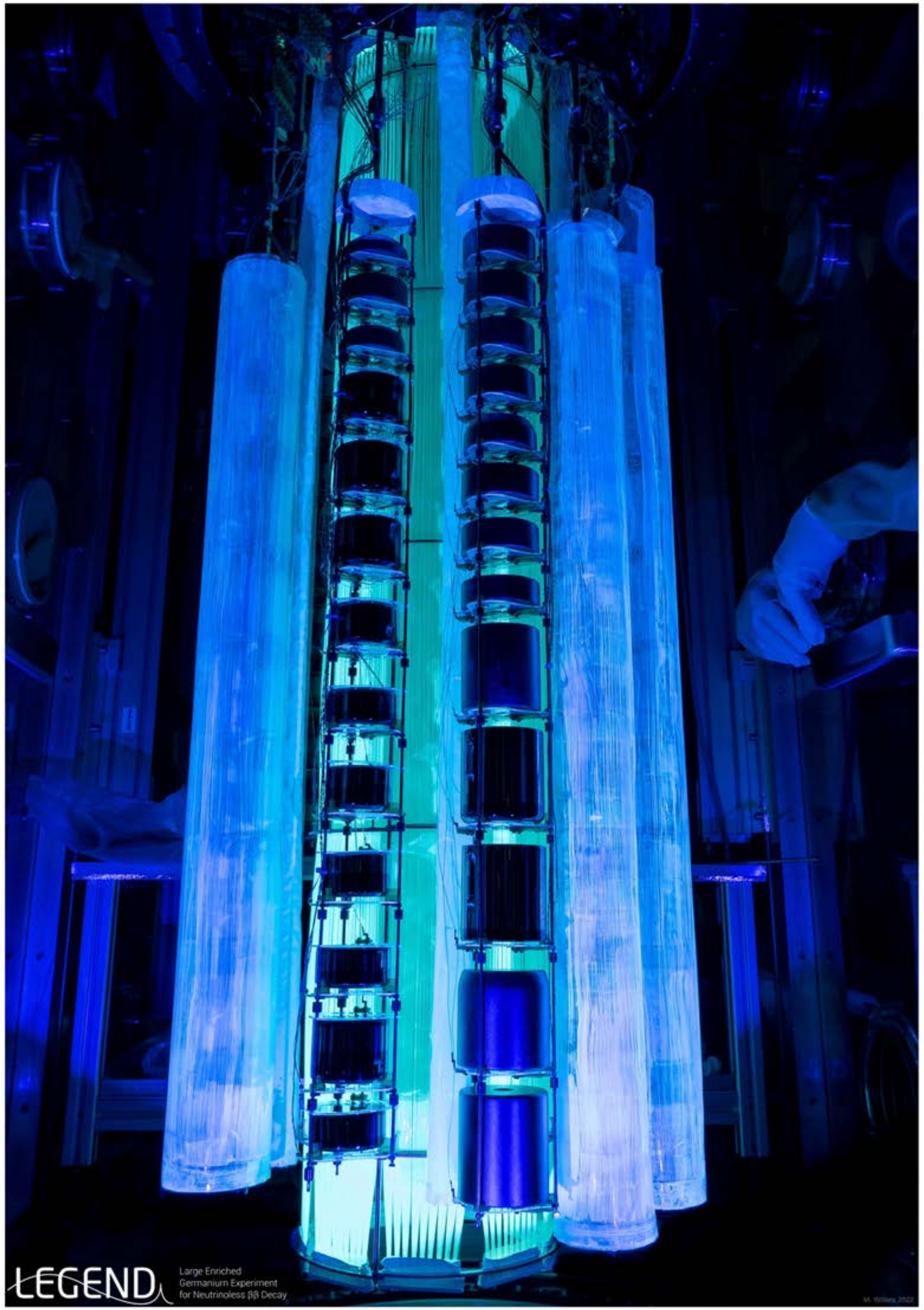
MAJORANA
GERDA (^{76}Ge)

Ionization

LEGEND

- **LEGEND-200:** running with ~100 detectors
- **LEGEND-1000:** 1000 kg of Ge (staged)
- $T_{1/2}$ (3σ DS) > 10^{28} yr, $m_{\beta\beta}$ < 10 - 17 meV





Questions for today

How to measure the neutrino mass from cosmology

- Neutrinos are hot dark matter and wash out small scale structure
- Imprint in CMB and LSS
- Sensitivity at $\sum m_\nu$ < 0.2 eV

…and from $0\nu\beta\beta$?

- Half life of the $0\nu\beta\beta$ decay depends on mass of neutrino
- Signal = peak at $Q_{\beta\beta}$
- Sensitivity at $m_{\beta\beta}$ < 0.2 eV

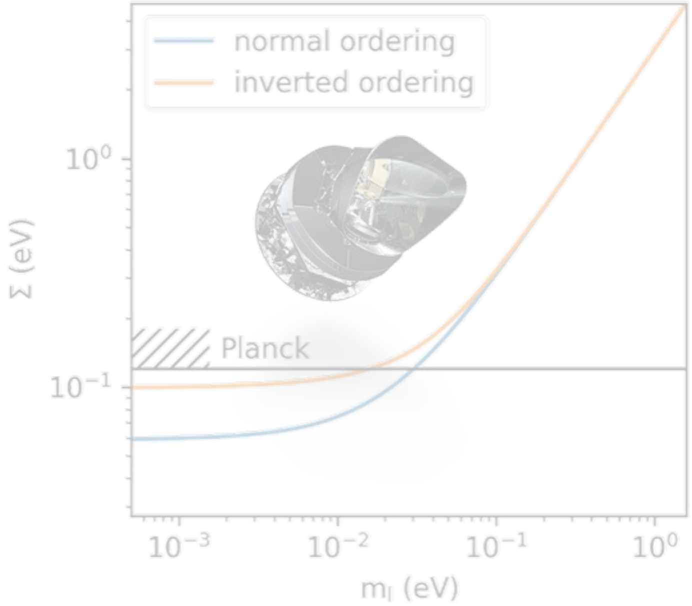
…and directly ?

What can we learn if we measure nothing?

Neutrino mass

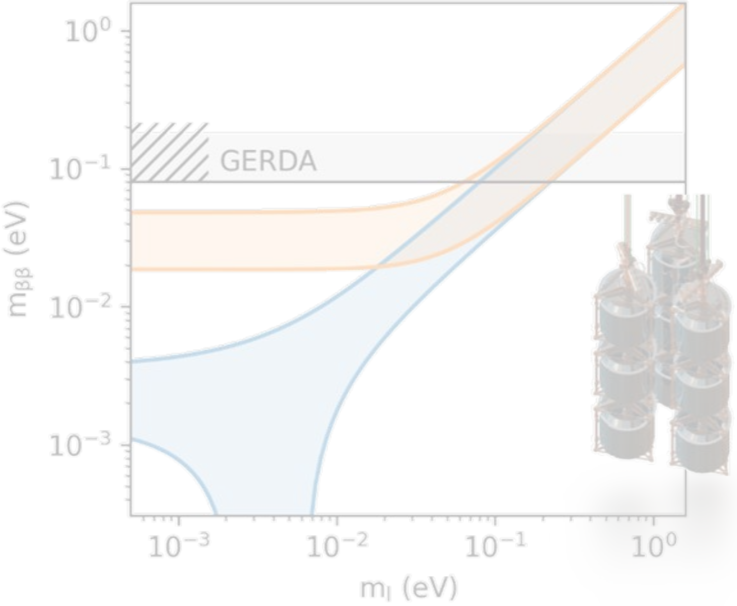
Cosmology

$$\Sigma = \sum_i m_i$$



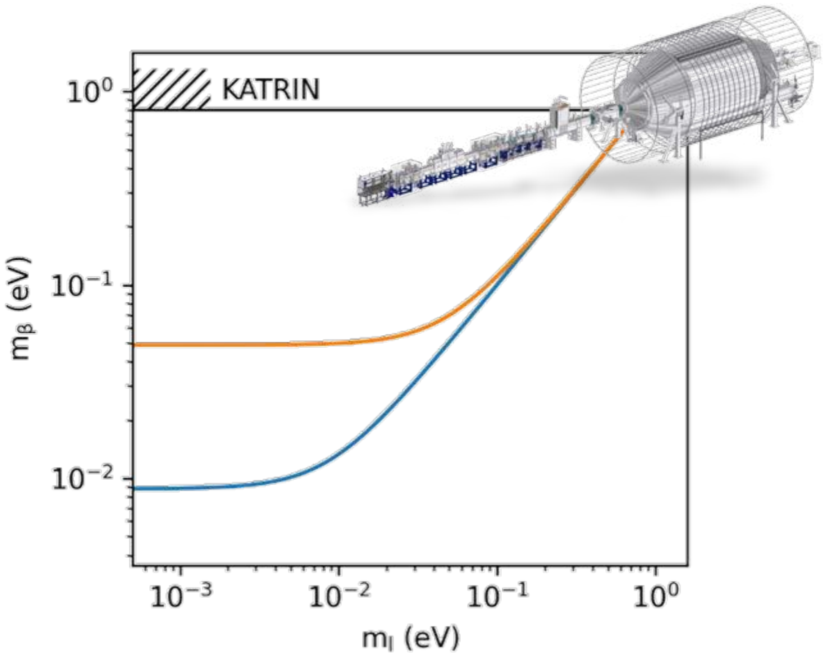
Neutrinoless ßß decay

$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i|$$



ß-decay kinematics

$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

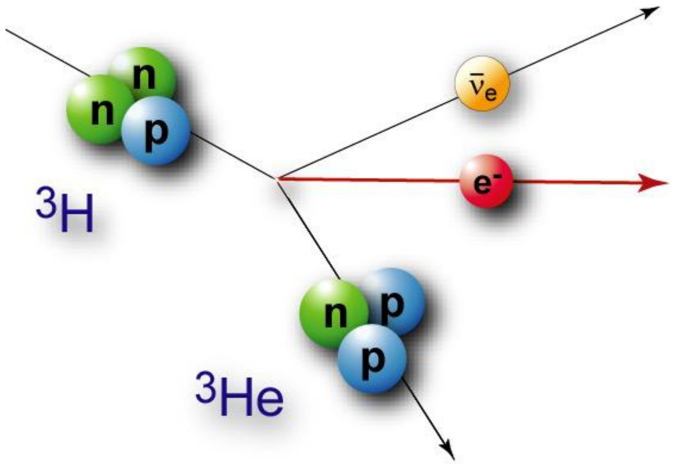


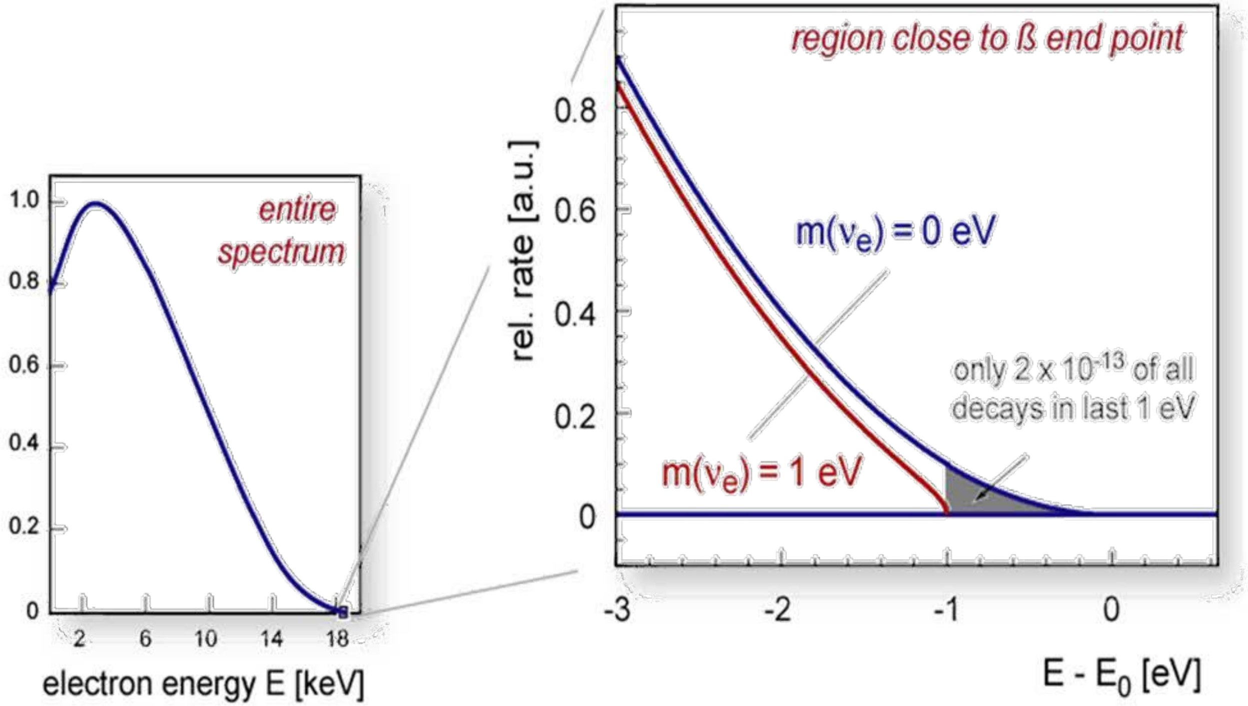
Direct neutrino mass measurement

Non-zero neutrino mass distorts the spectrum close to the endpoint

✓ Independent of cosmology

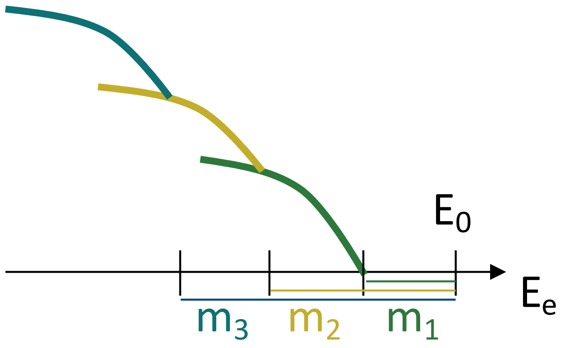
✓ Independent of neutrino nature

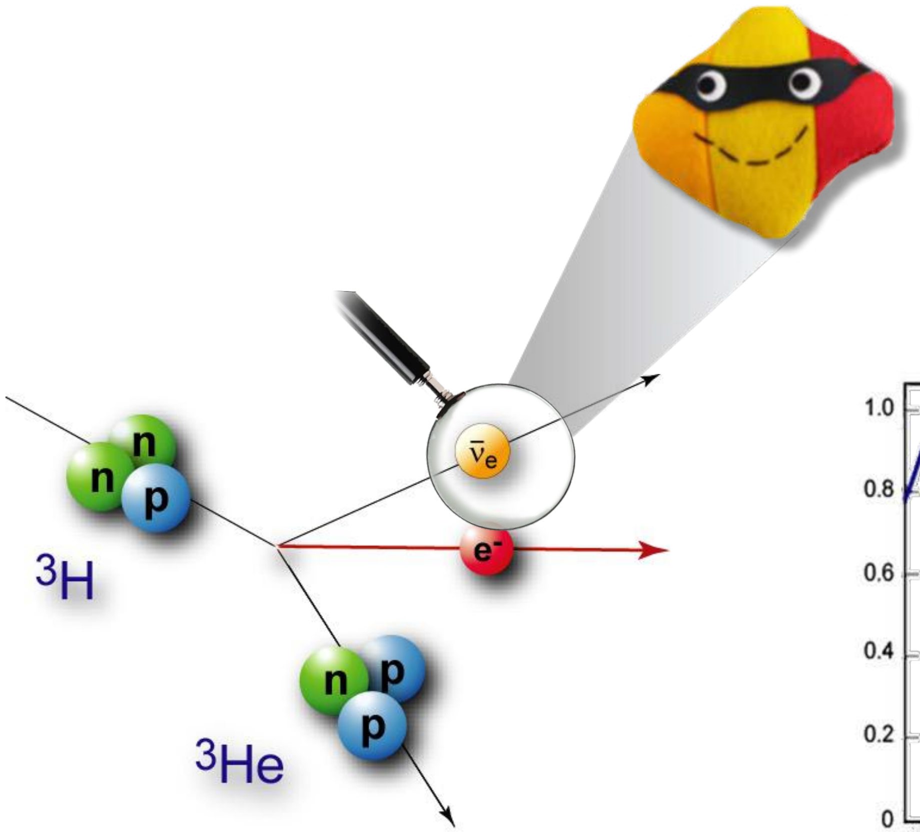


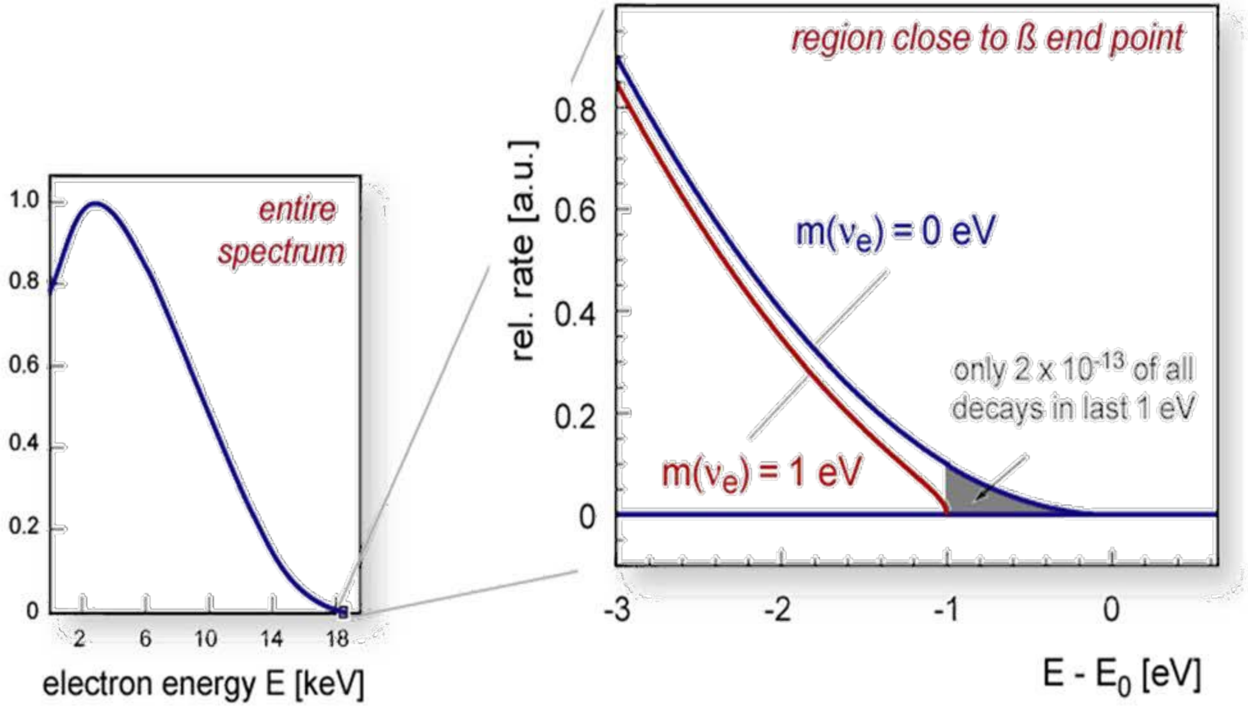


Direct neutrino mass measurement

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$

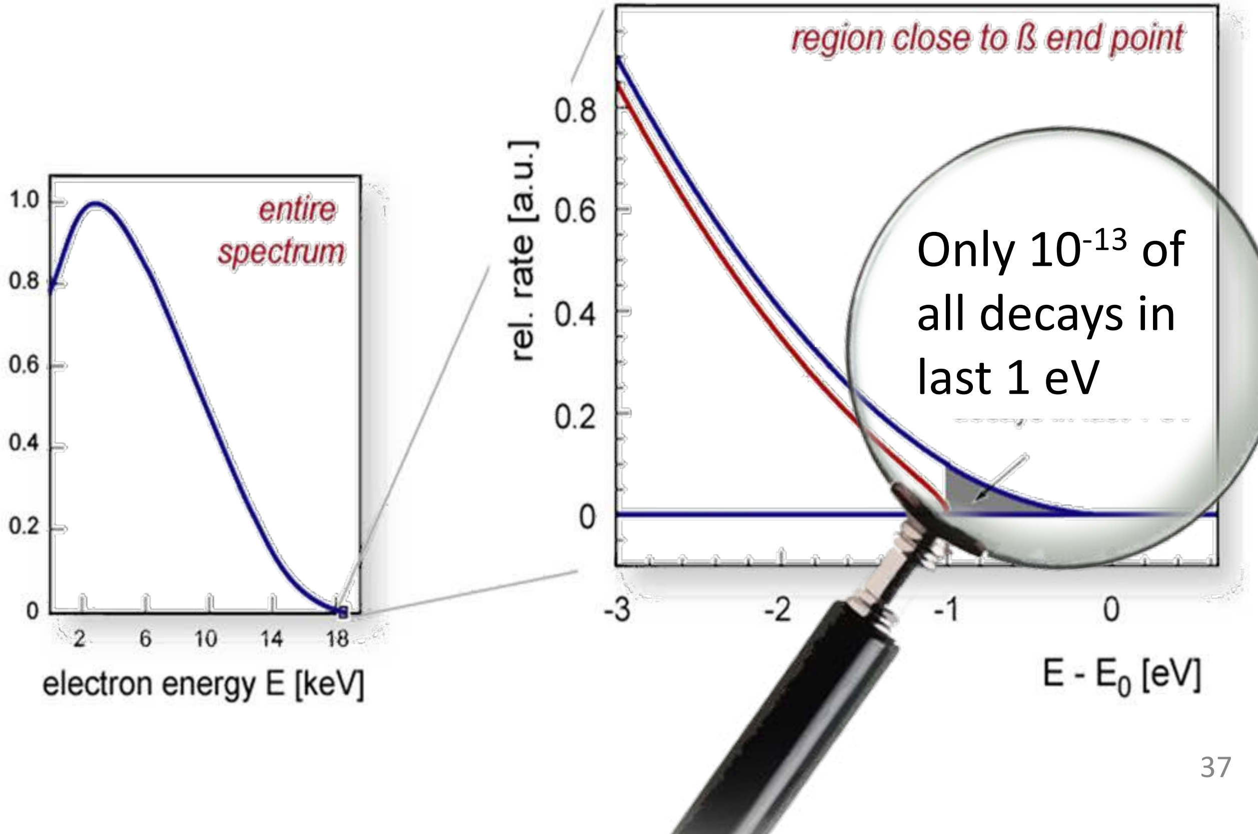






The challenge

- What do we need to realize an experiment?



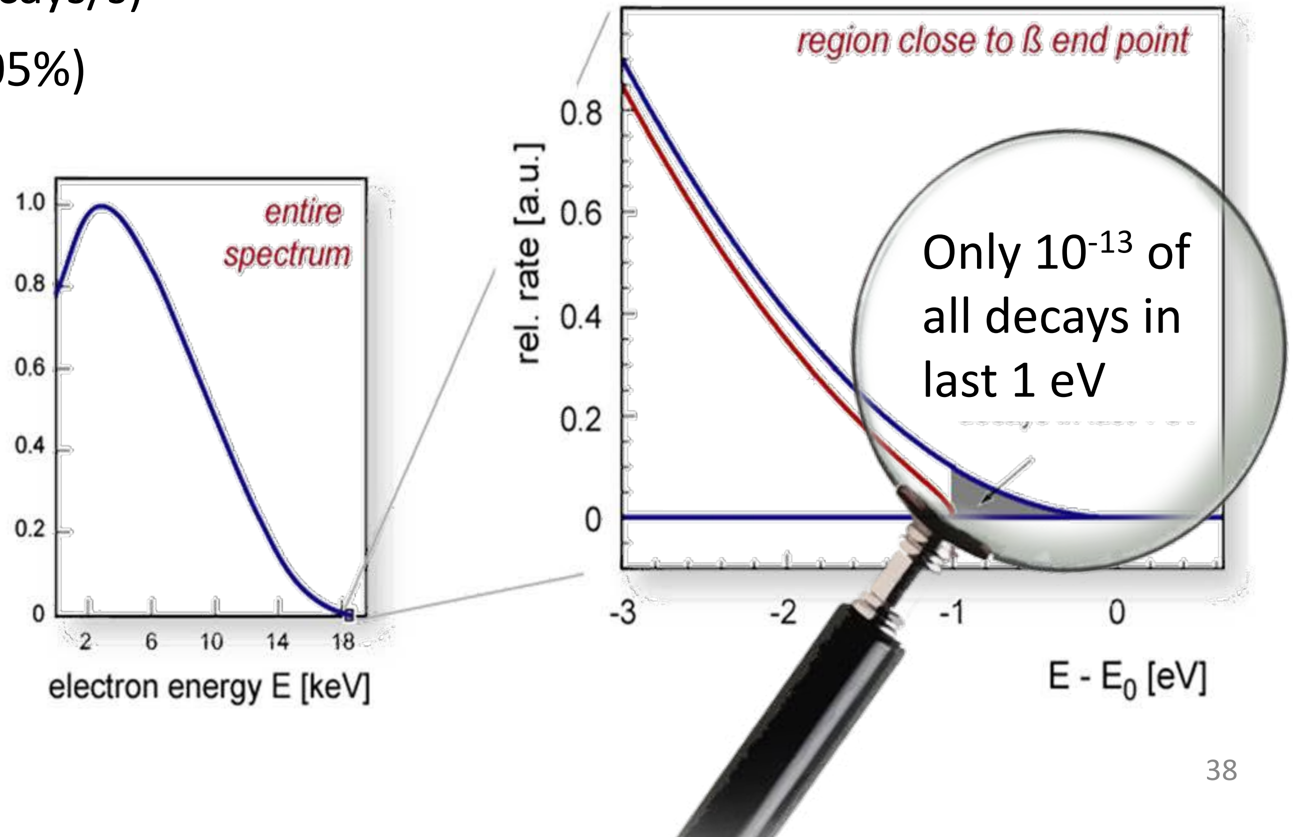
The challenge

- What do we need to realize an experiment?

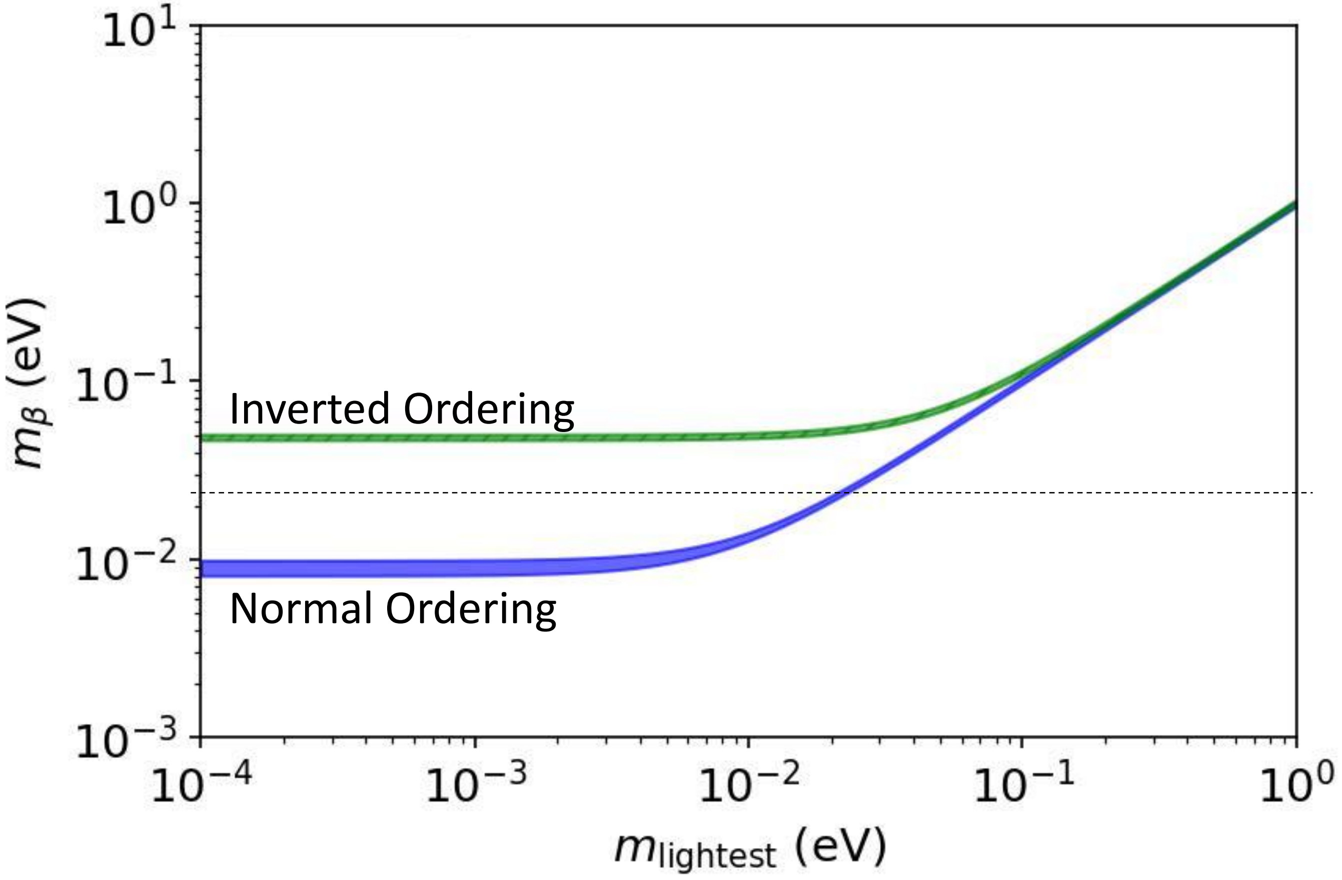
✓ Ultra-strong radioactive source (10^{11} decays/s)

✓ Excellent energy resolution (~ 1 eV, 0.005%)

✓ Low background (< 100 mcps)

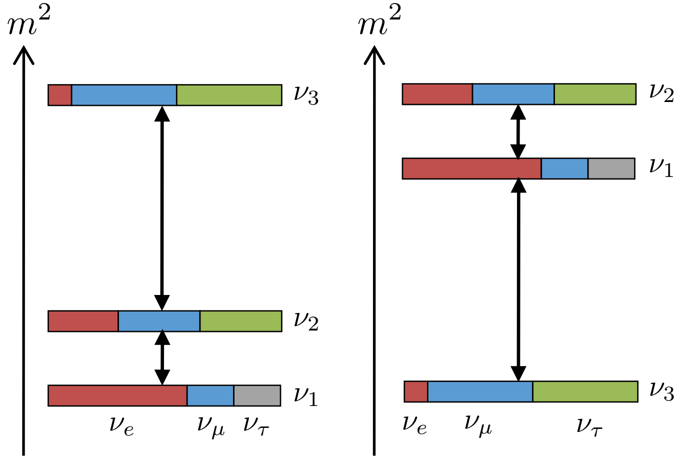


Where do we stand?



Observable:

- $m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$



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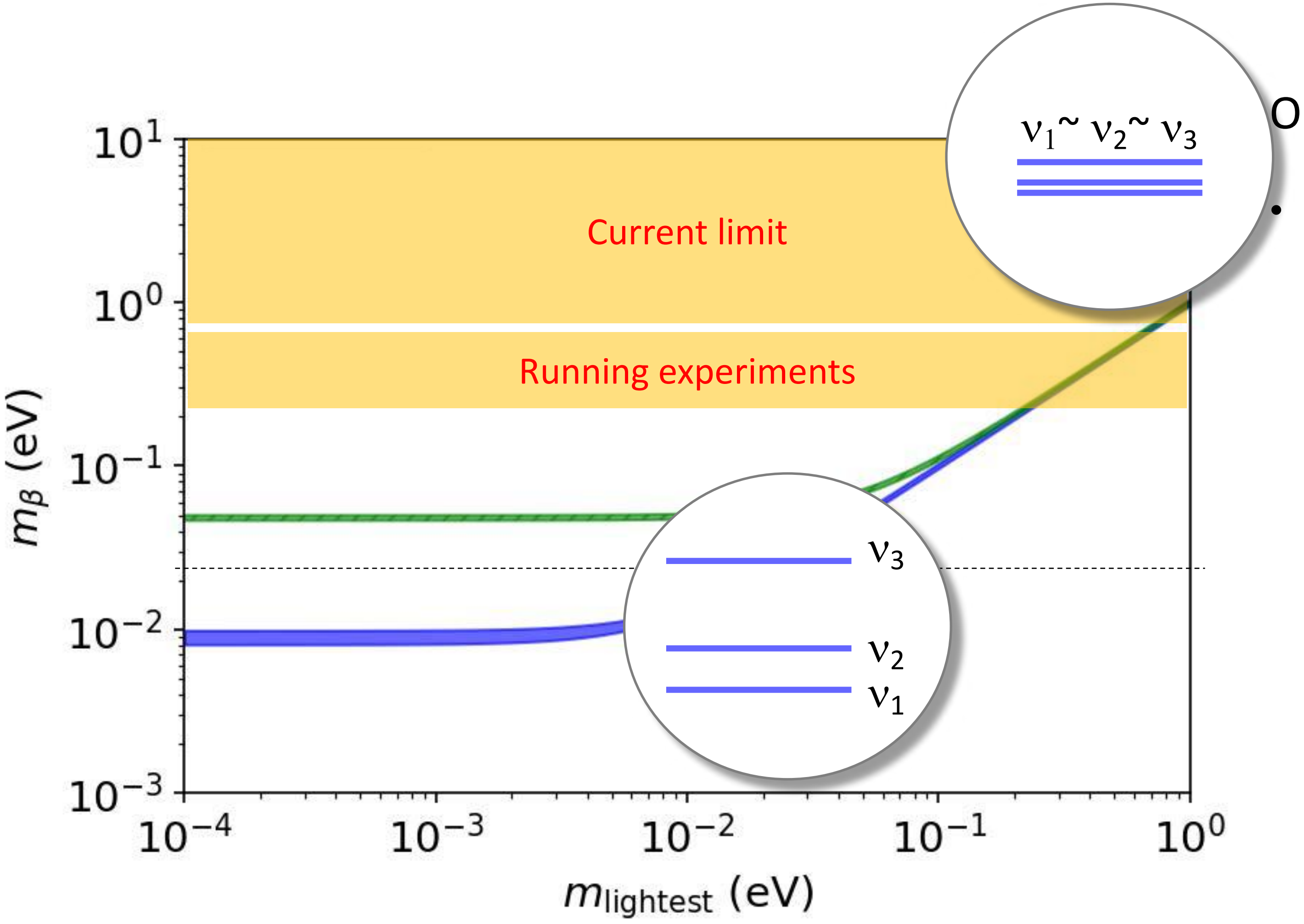

Observable:

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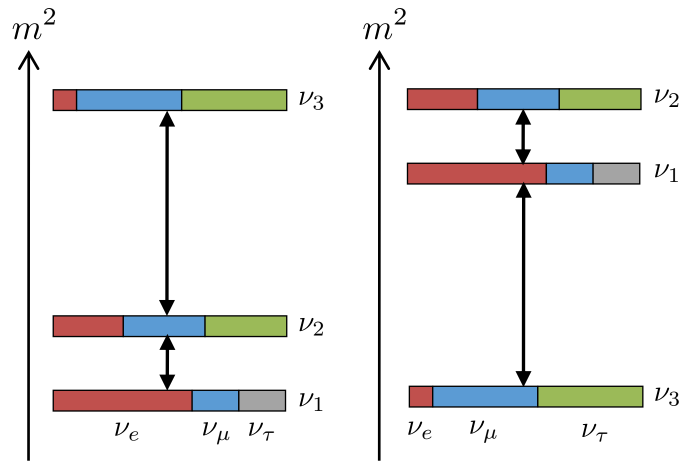

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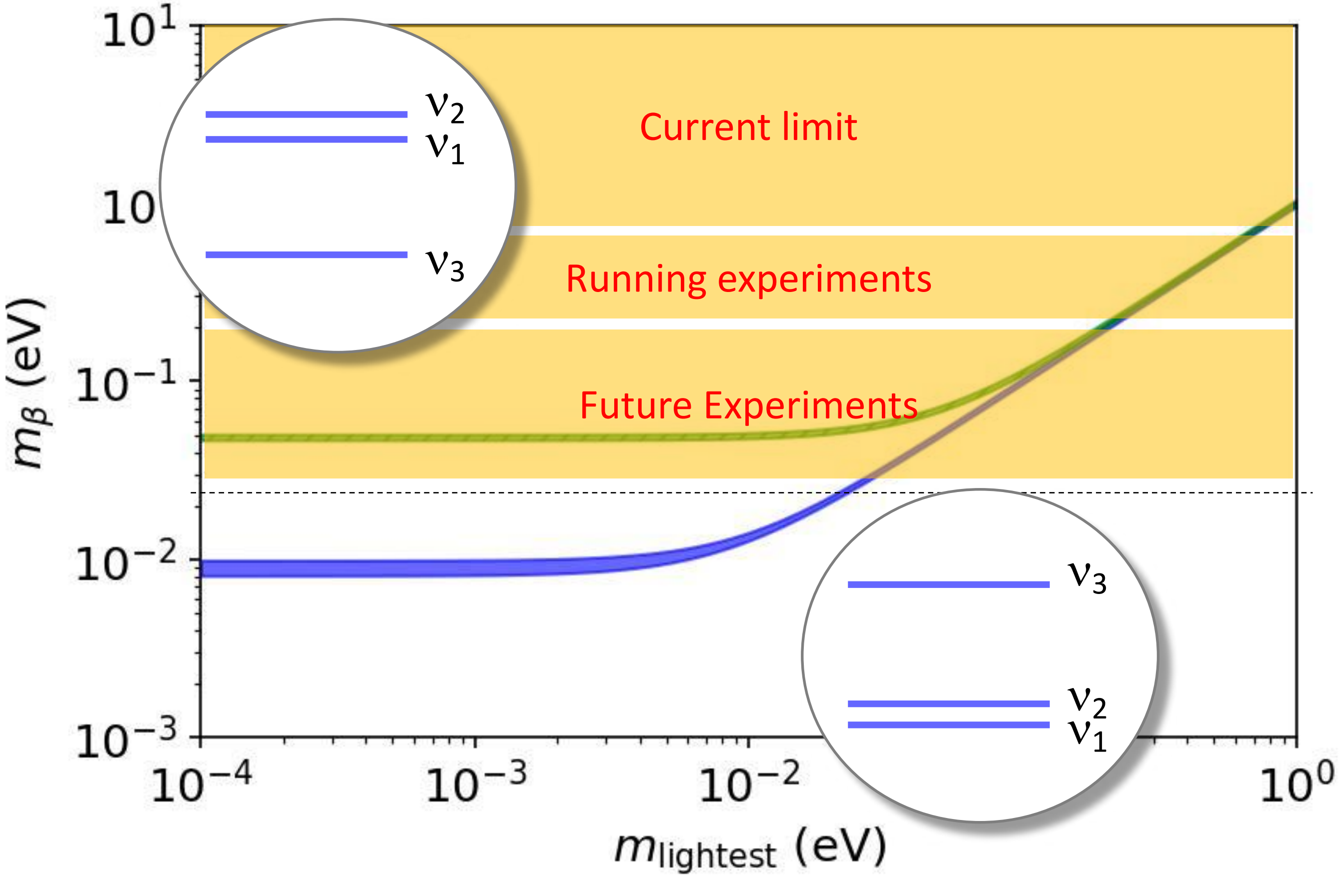

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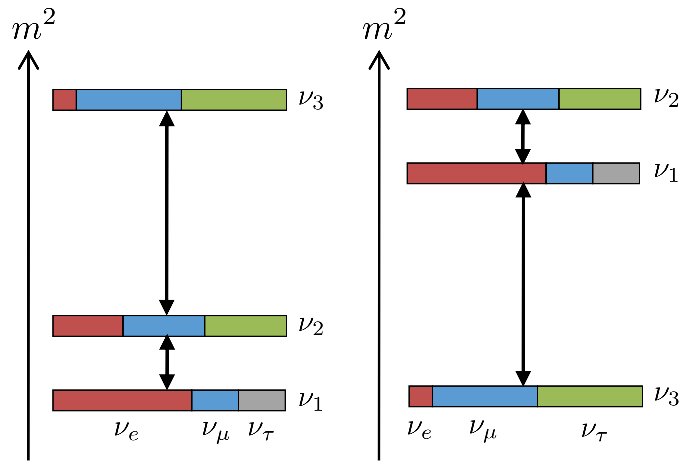
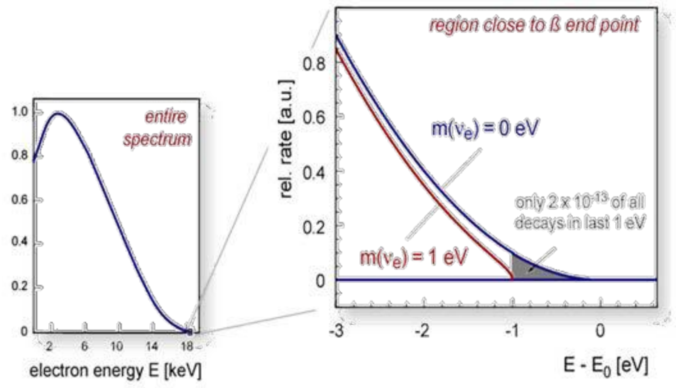
- $m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$



Experimental efforts

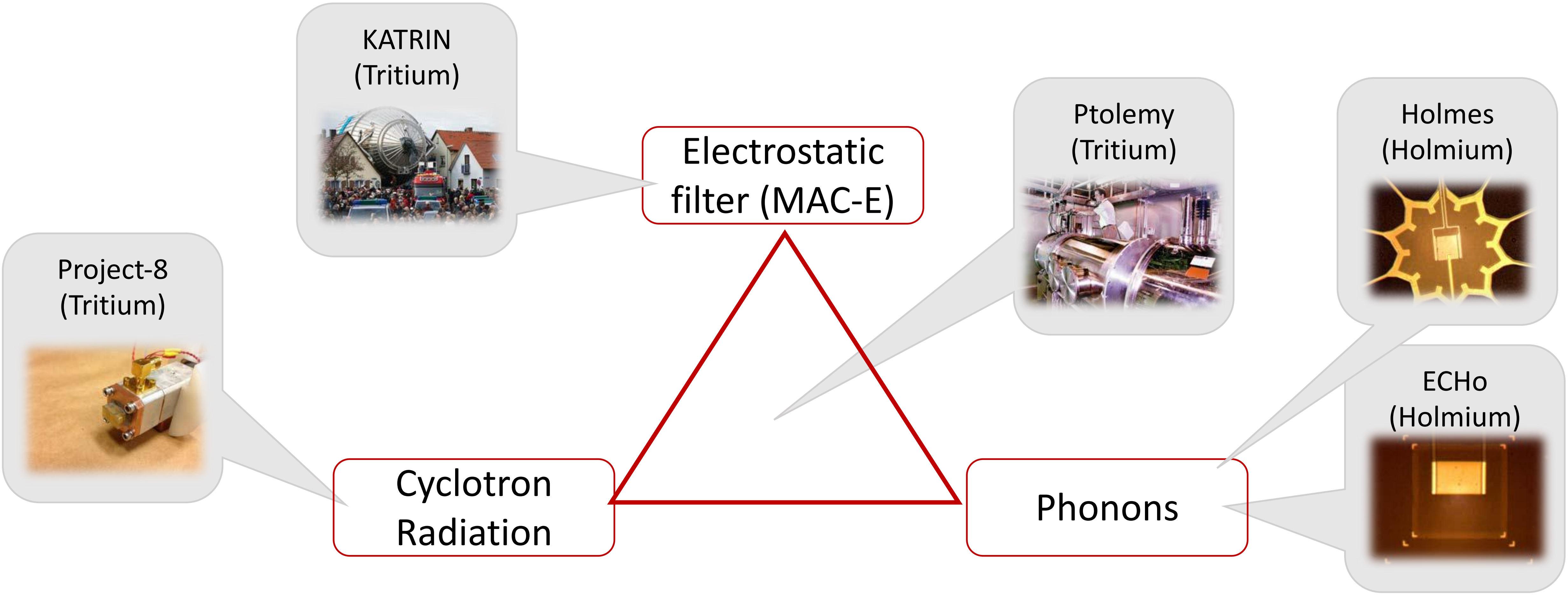


Electrostatic filter (MAC-E)

Cyclotron Radiation

Phonons

Experimental efforts



Experimental efforts

KATRIN
(Tritium)

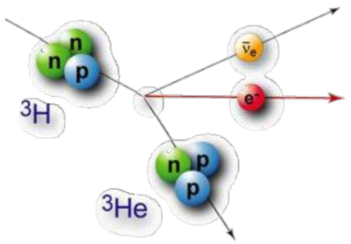
Electrostatic filter (MAC-E)

Cyclotron Radiation

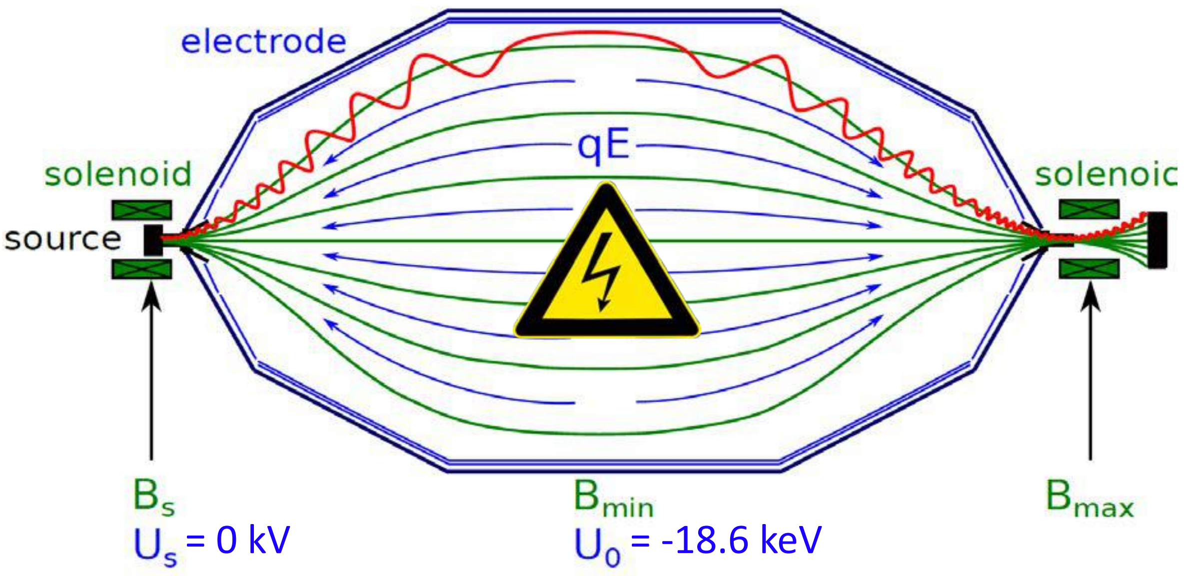
Phonons

MAC-E-Filter

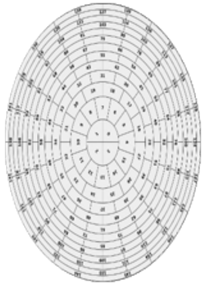
Tritium source

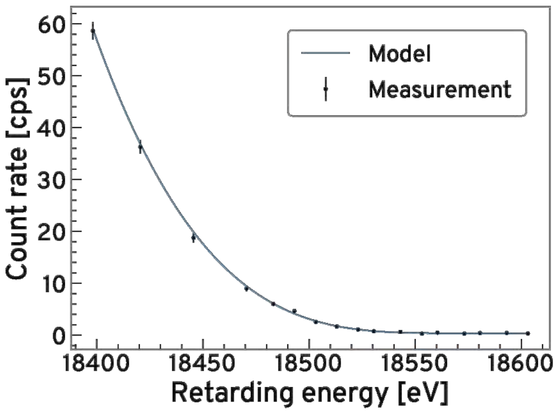


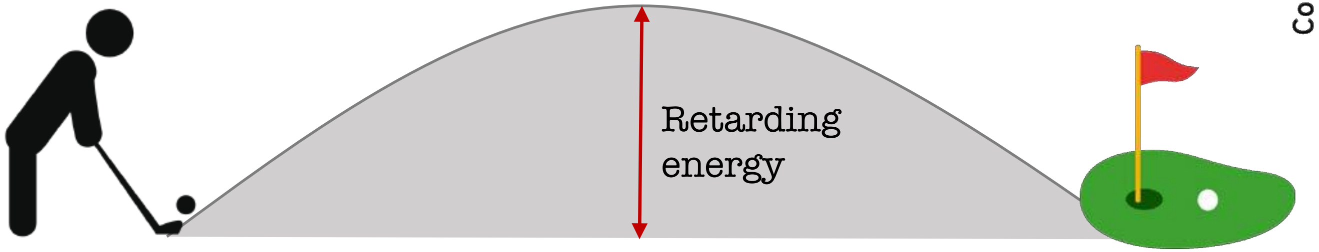
Spectrometer



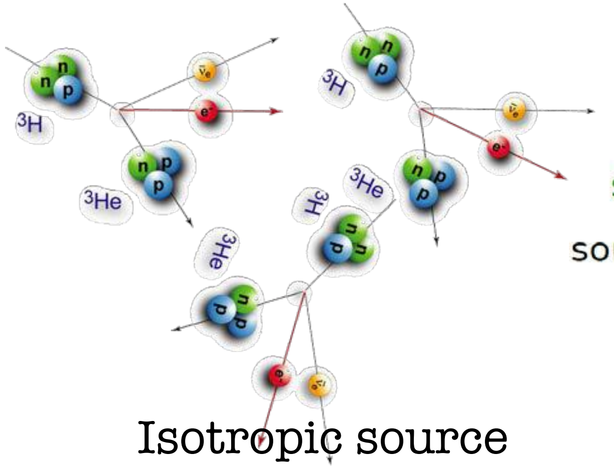
Detector



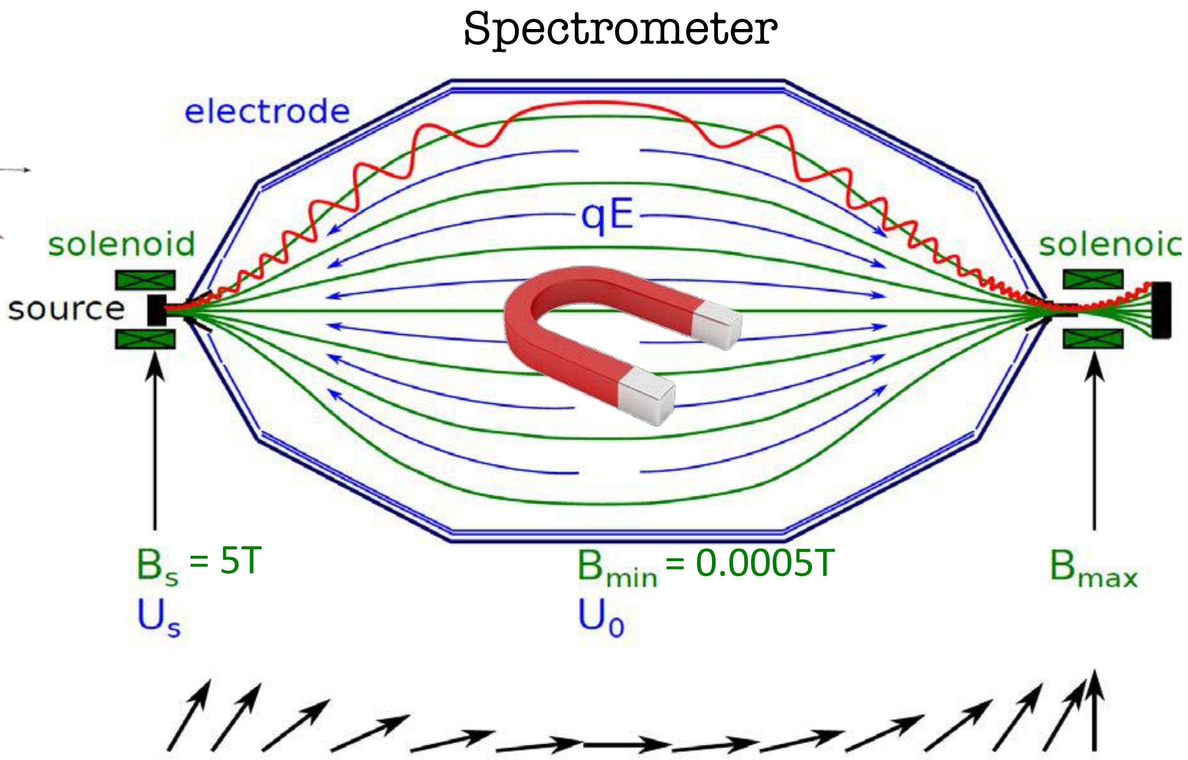


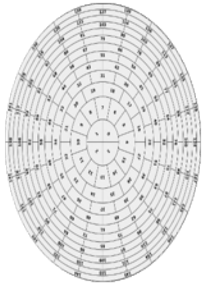


MAC-E-Filter



$$E_{kin} = E_L + E_T$$



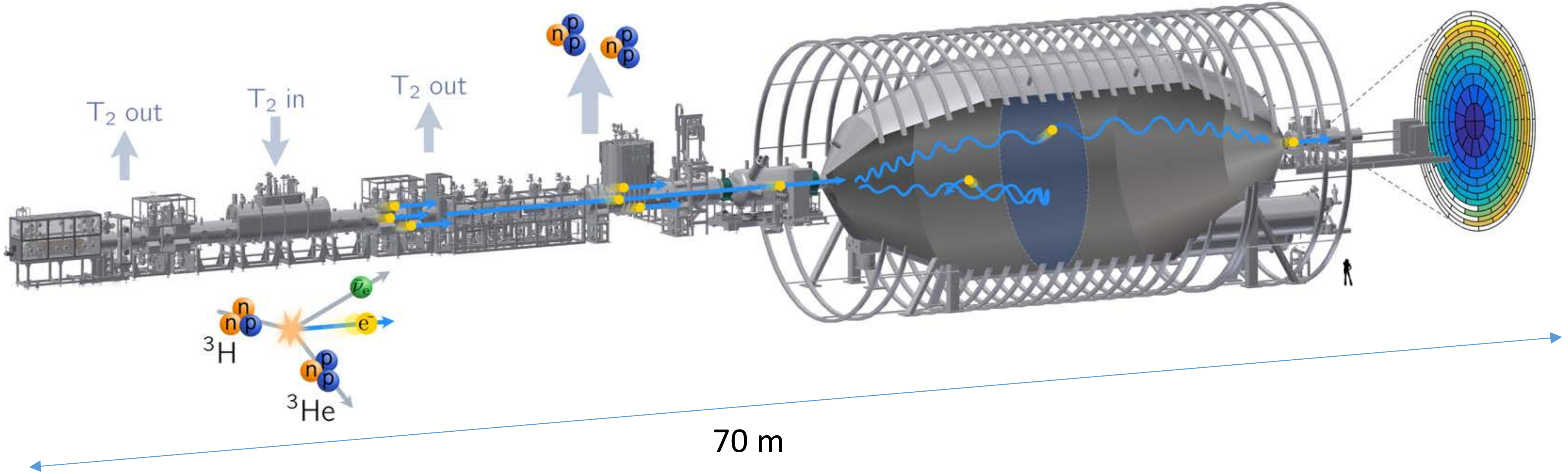


- ✓ Large angle acceptance
- ✓ eV-scale E-resolution

$$E_T^{center} = E_T^{start} \cdot \frac{B^{center}}{B^{start}} \quad \rightarrow \quad E_T^{center,max} = E \cdot \frac{B^{center}}{B^{start}} \approx 2 \text{ eV}$$

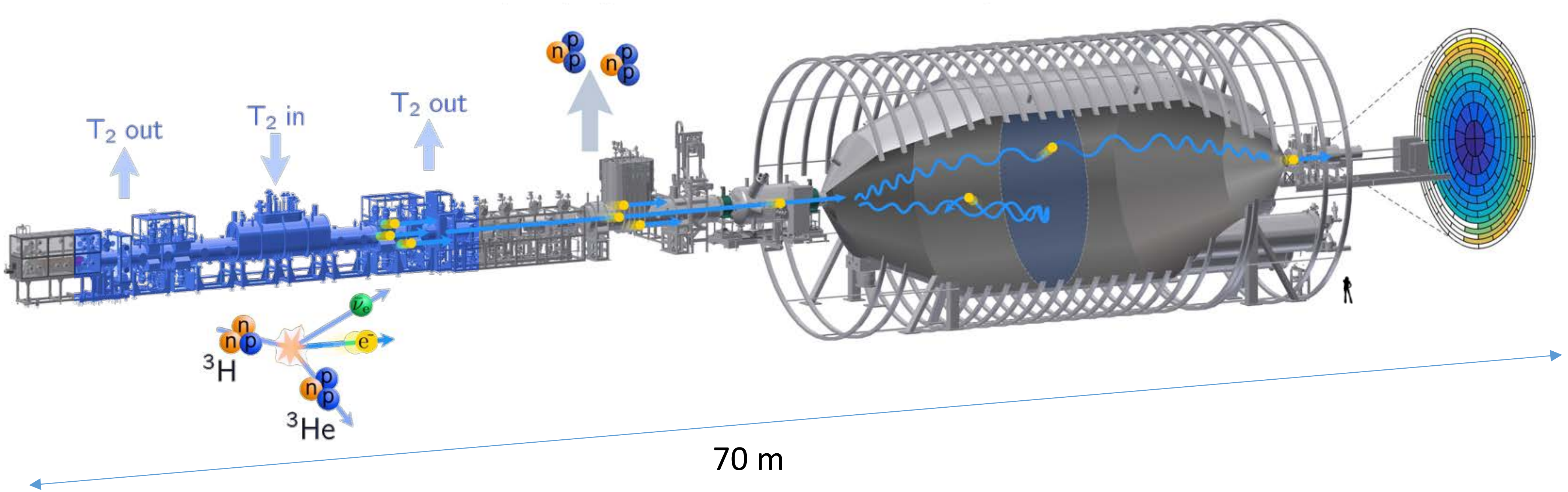
Karlsruhe Tritium Neutrino Experiment

Working Principle



Working Principle

Tritium source
- 100 μg of gaseous T_2
- 10^{11} T_2 decays/s



Working Principle

Tritium source
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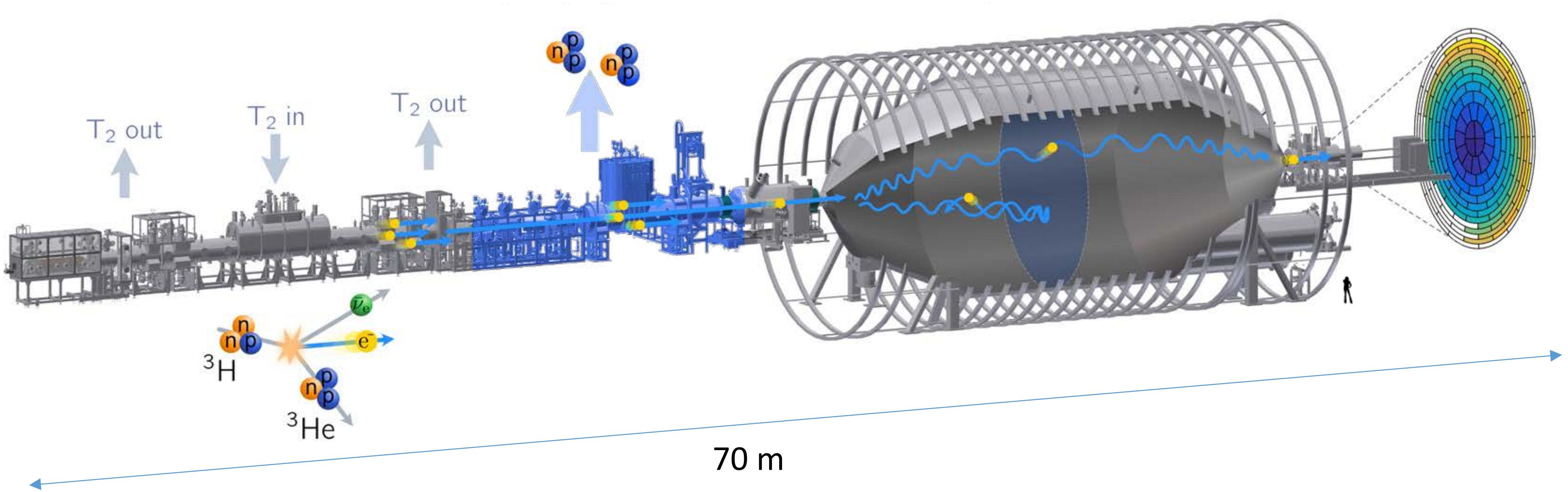
Transport section
- Guidance of electrons
- Removal of tritium



Working Principle

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Transport section
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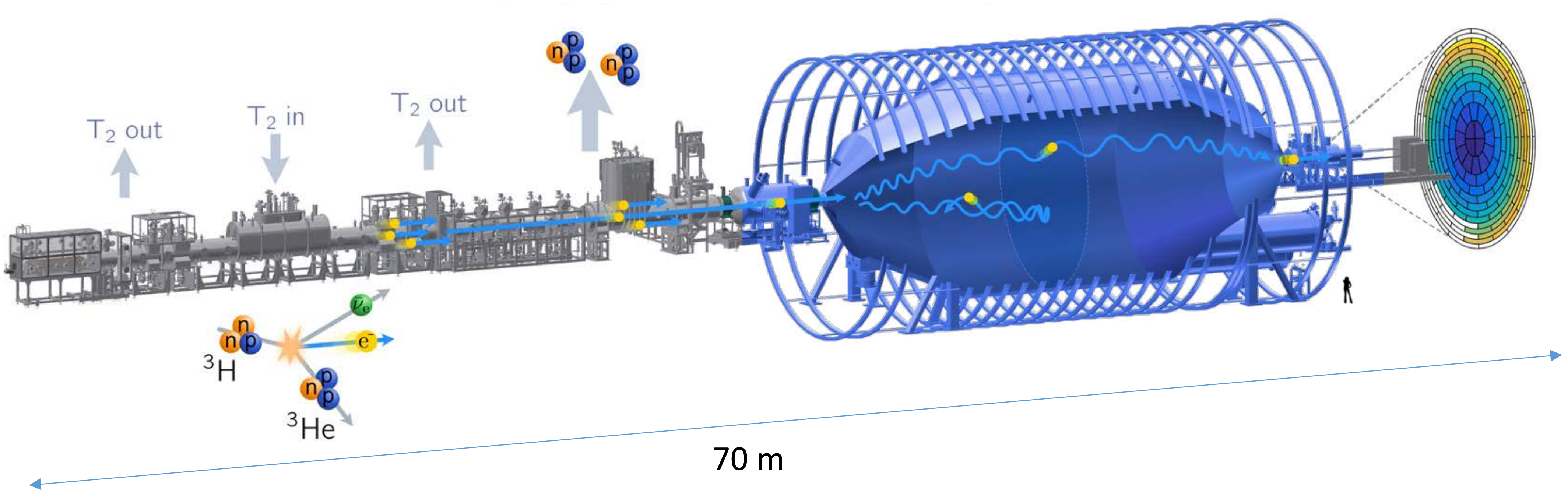
Spectrometer
- Electrostatic filter
- MAC-E filter principle



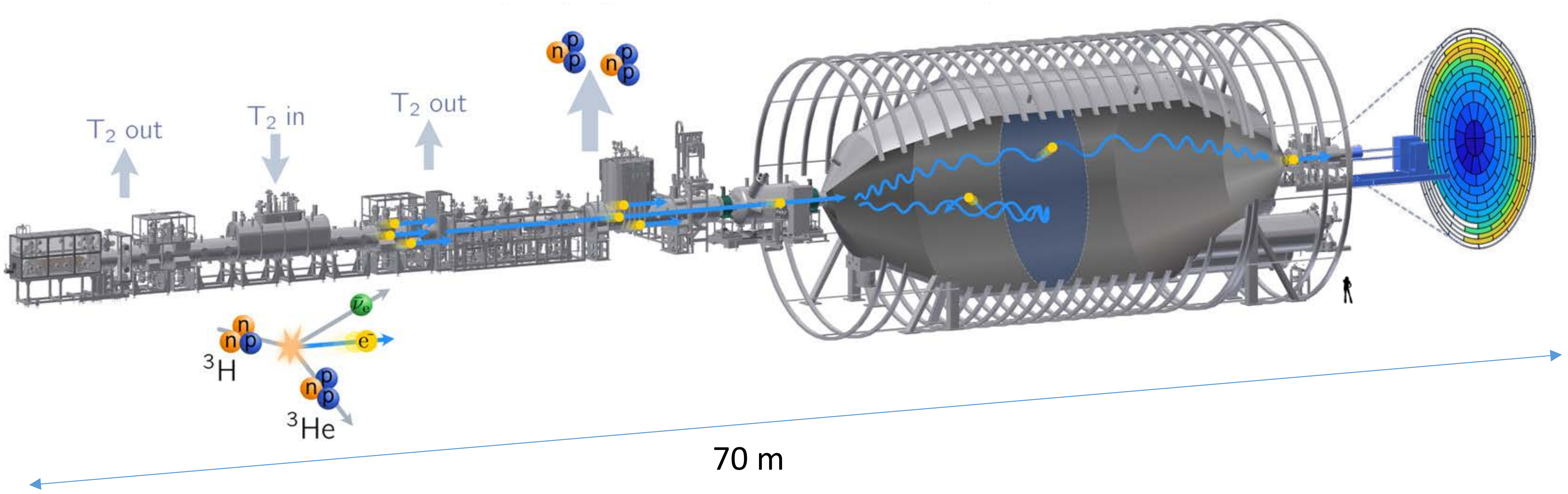
Working Principle

Tritium source
- 100 μg of gaseous T_2
- 10^{11} T_2 decays/s

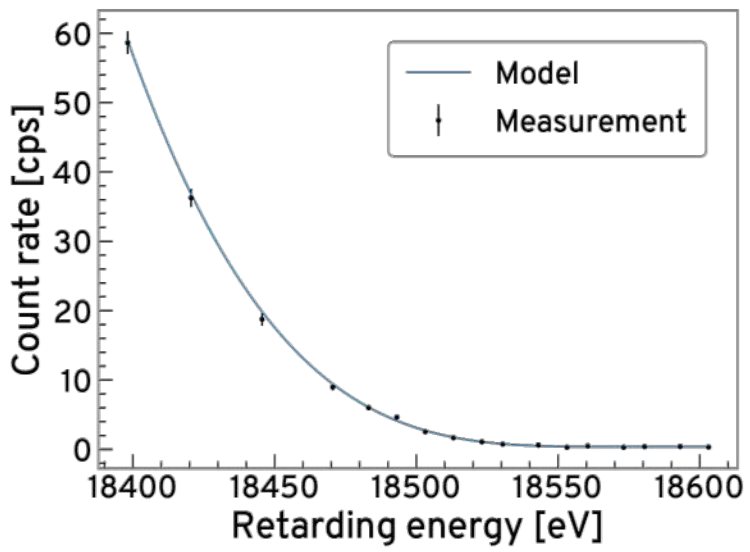
Transport section
- Guidance of electrons
- Removal of tritium

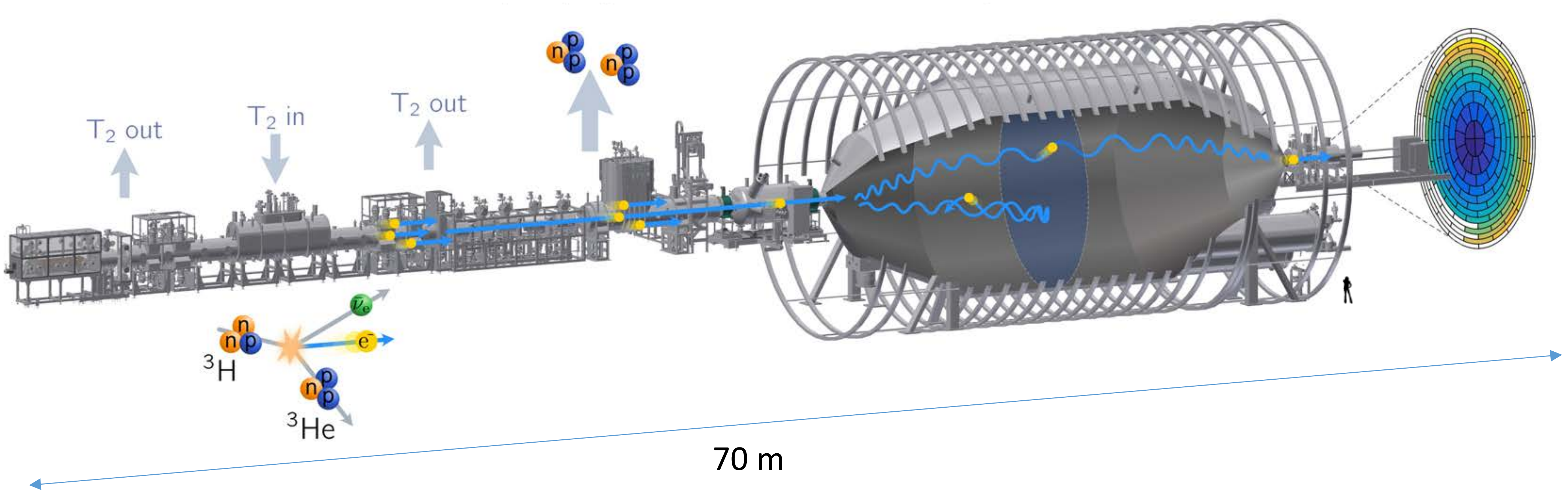
Spectrometer
- Electrostatic filter
- MAC-E filter principle

Detector
- Counts electrons
- Rate vs potential

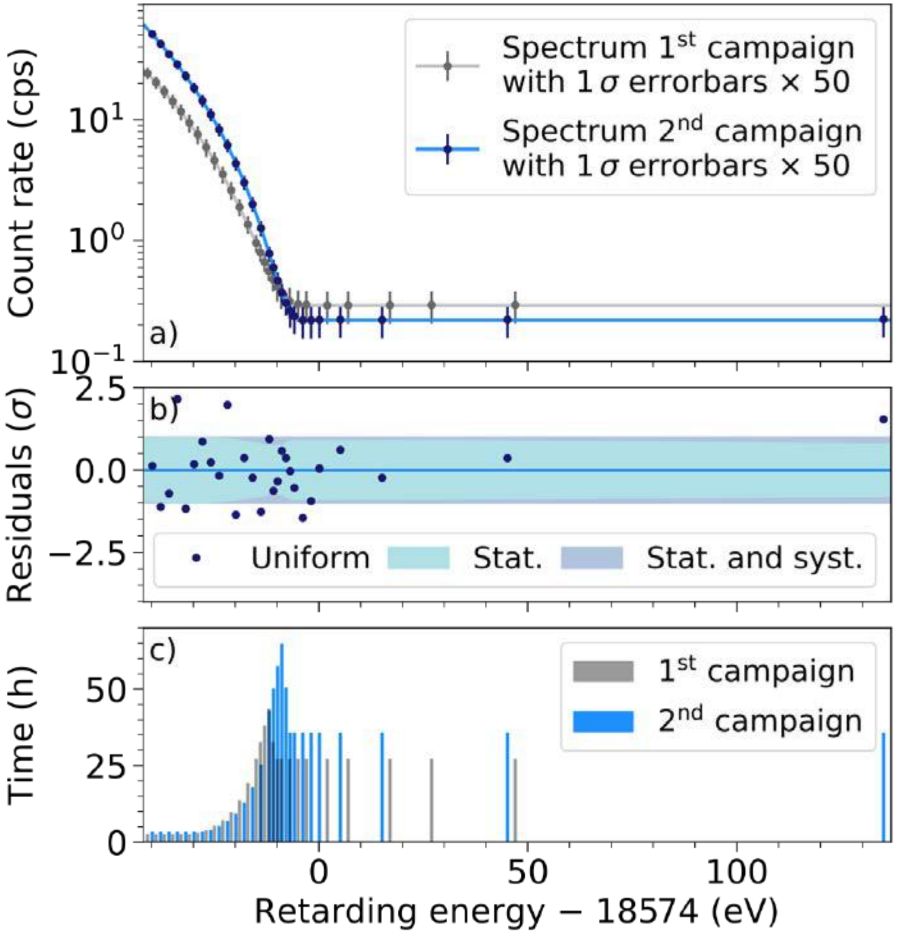


Working Principle





Latest results



First campaign:

- total statistics: 2 million events
- best fit: $m_\nu^2 = \left(-1.0^{+0.9}_{-1.1}\right)$ eV² (stat. dom.)
- limit: $m_\nu < 1.1$ eV (90% CL)

PRL. 123, 221802 (2019)
Phys. Rev. D 104, 012005 (2021)

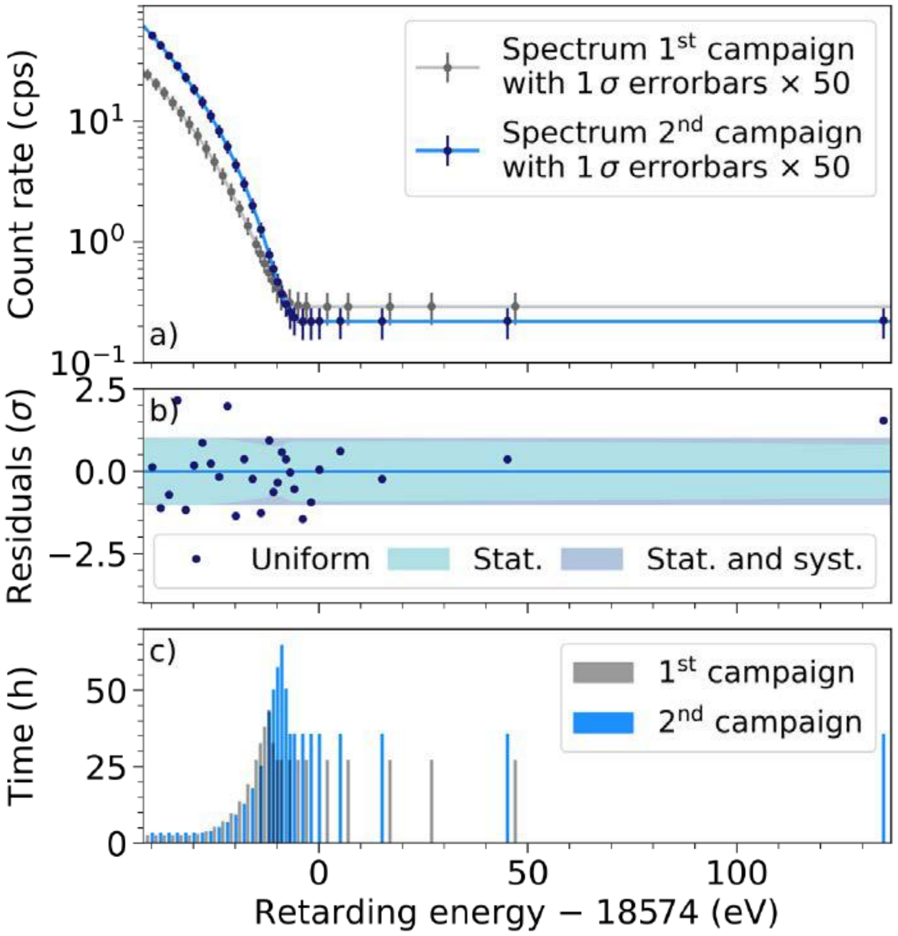
Second campaign:

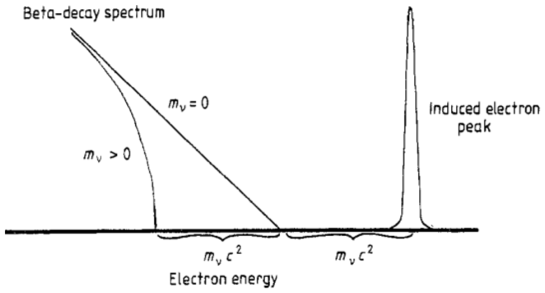
- total statistics: 4 million events
- best fit: $m_\nu^2 = \left(0.26^{+0.34}_{-0.34}\right)$eV² (stat. dom.)
- limit: $m_\nu < 0.9$ eV (90% CL)

Nat. Phys. ***18,*** *160–166 (2022)*

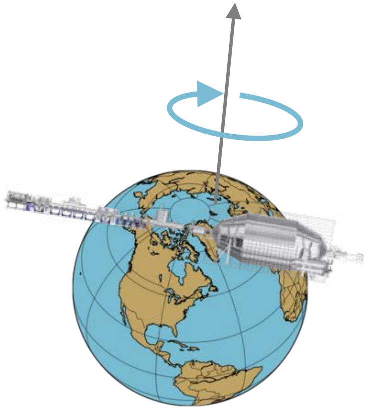
- **Combined result: $m_\nu < 0.8$ eV (90% CL)**

Latest results



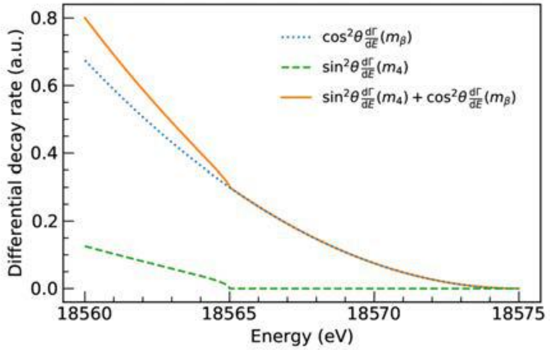


✓ Search for relic big-bang neutrinos
Phys. Rev. Lett. **129**, 011806 (2022)

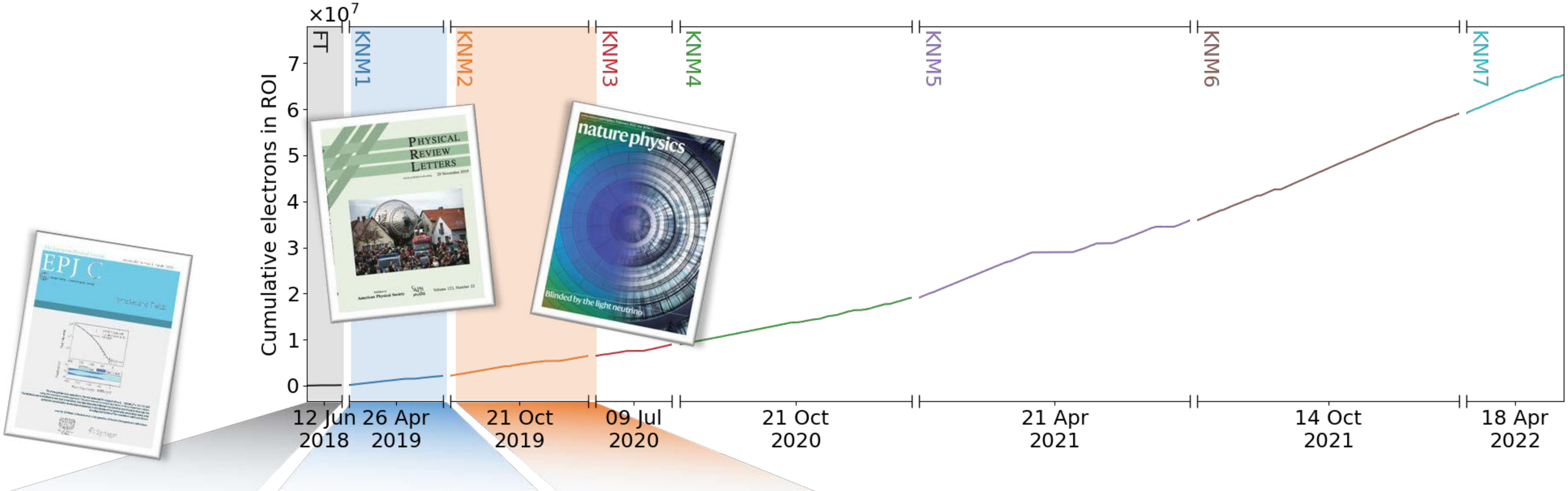


✓ Search for violation of Lorentz invariance
arxiv:2207.06326 (2022)

✓ Search for light sterile neutrinos
Phys. Rev. Lett. **126**, 091803 (2021)
Phys. Rev. D **105**, 072004 (2022)



KATRIN Data Taking Overview



- Commissioning
- Only 0.5% tritium

EPJ C 80, 264 (2020)

- 1^{st} m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

Phys. Rev. D 104, 012005 (2021)

- 2^{nd} m_ν campaign
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

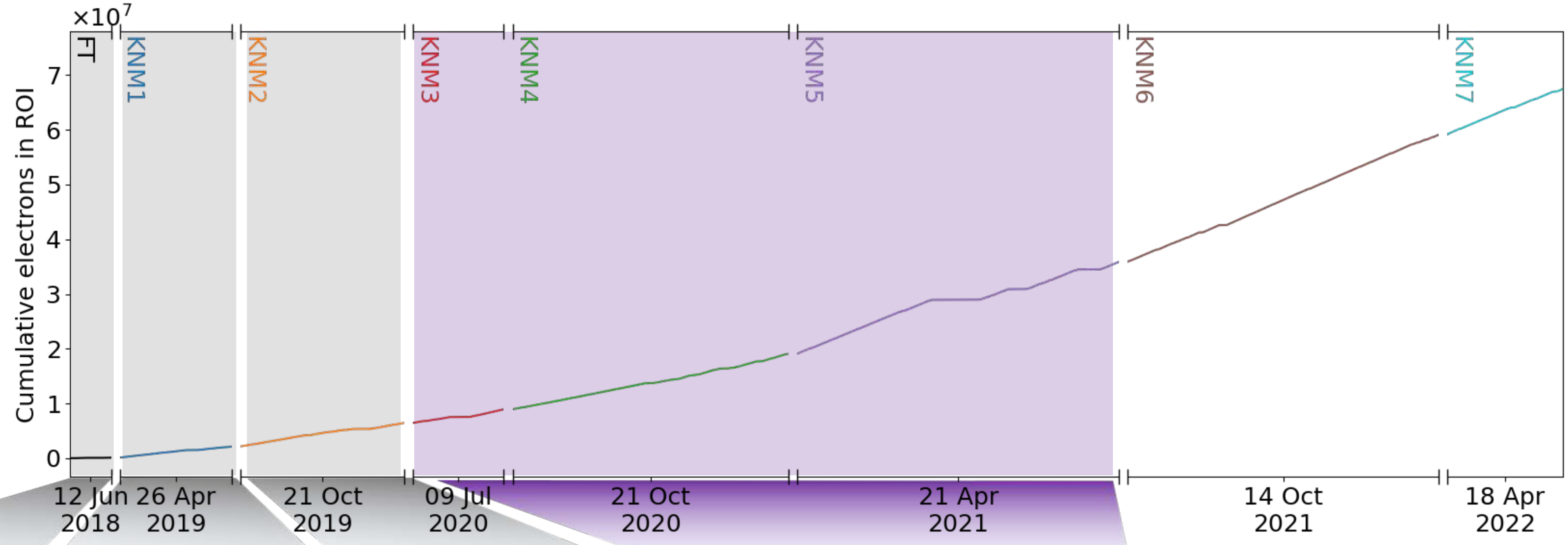
+ sterile and relic neutrino searches:

PRL 126, 091803 (2021)

PRD 105, 072004 (2022)

arXiv:2202.04587 (2022)

What‘s next ?



- Commissioning
- Only 0.5% tritium

EPJ C 80, 264 (2020)

- 1st m_ν campaign
- $m_\nu < 1.1$ eV

PRL. 123, 221802 (2019)

Phys. Rev. D 104, 012005 (2021)

- 2nd m_ν campaign
- $m_\nu < 0.8$ eV

Nat. Phys. **18,** 160–166 (2022)

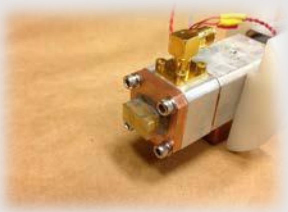
- New result this year

Data taking until 2026

Experimental efforts

Electrostatic filter (MAC-E)

Project-8 (Tritium)



Cyclotron Radiation

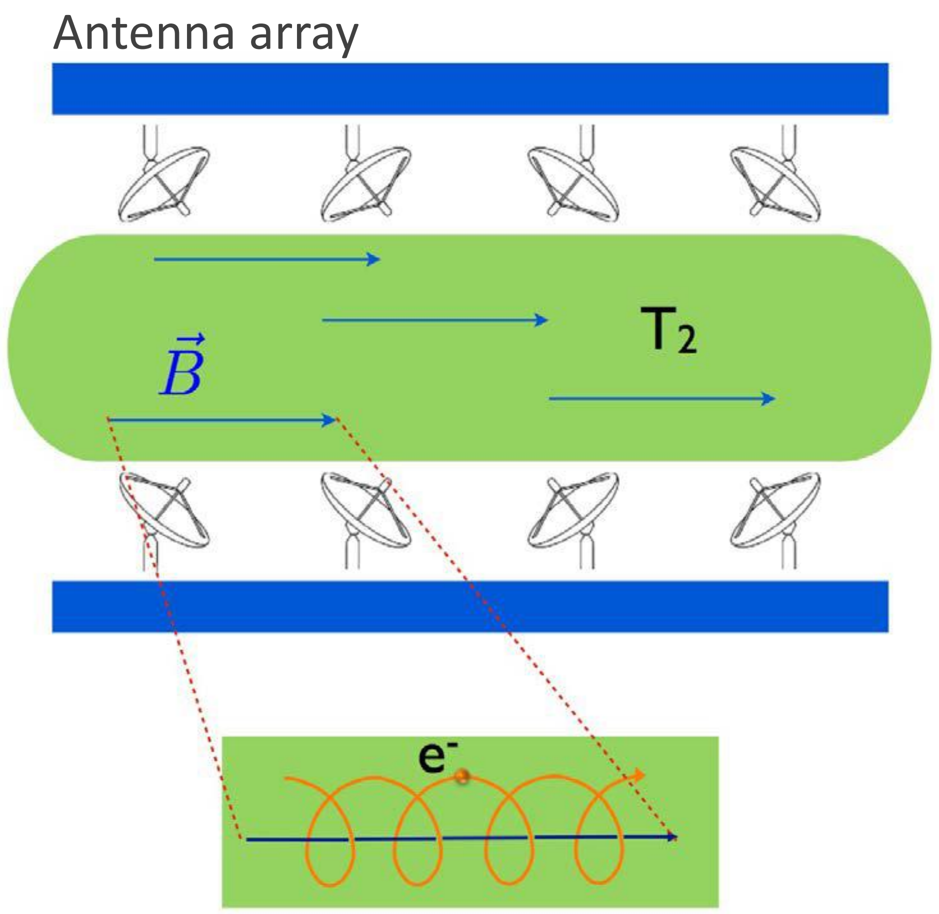
Phonons

Working principle

- **Technology:**
  Cyclotron Radiation Emission Spectroscopy (CRES)

$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{E + m_e}$$

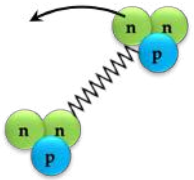
- **Advantage**
  - Differential measurement
  - Source = detector



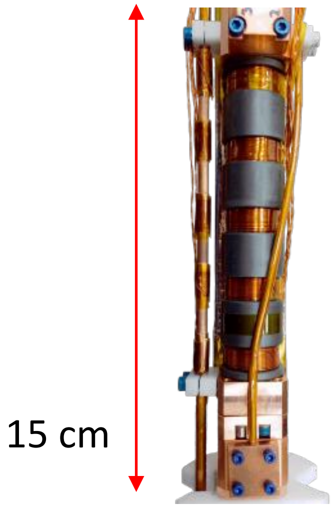
B. Monreal and Joe Formaggio, Phys. Rev D 80:051301

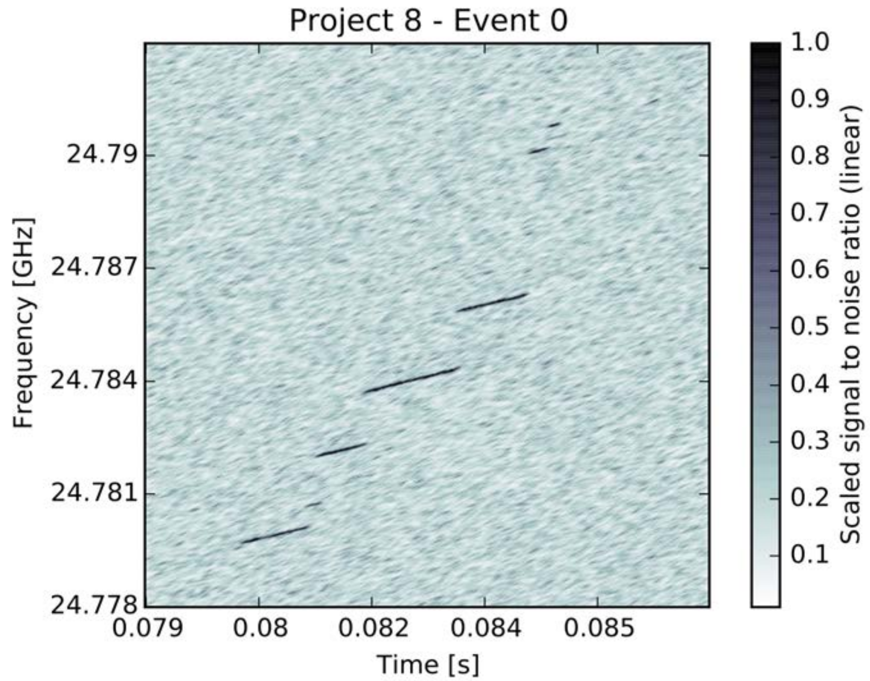
Project 8

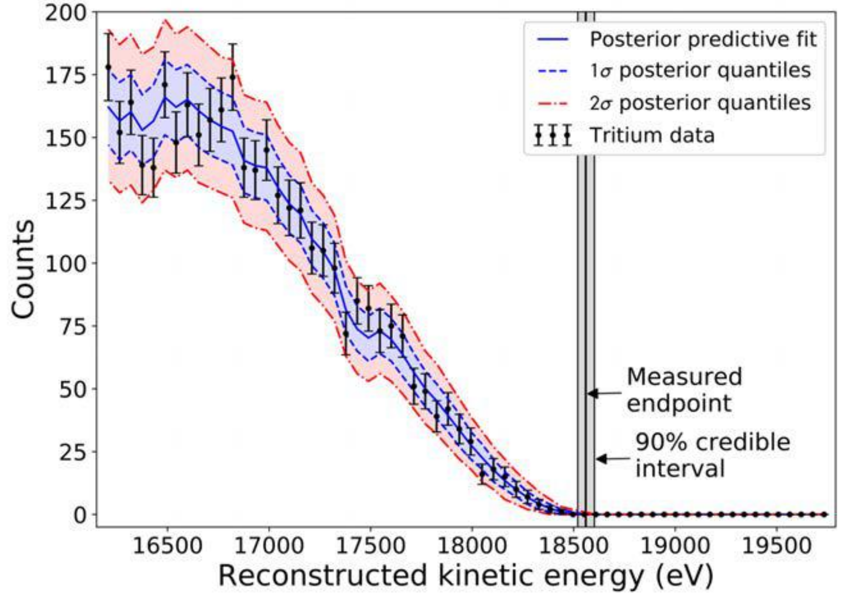
- **Recent Achievements**
  - ✓ Proof of concept
  - ✓ First tritium spectra measured
    ΔE = 2 eV (FWHM), b < 3 x 10^{-11} eV^{-1} s^{-1}
  - ✓ **First neutrino mass limit: m_ν < 185 eV (90% Cl.)**
- **Next steps / challenges:**
  - large-volume traps (m^3) (cavity resonator)
  - develop atomic tritium source



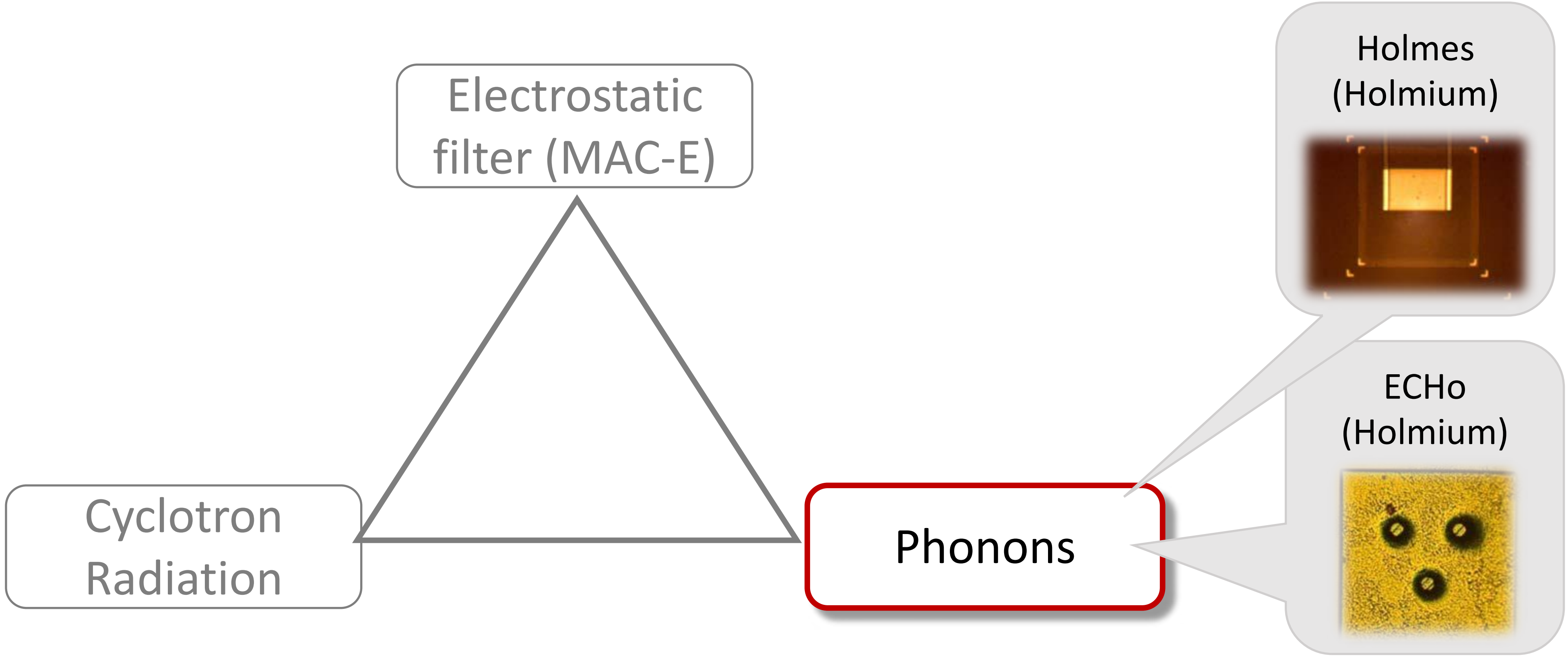
- **Ultimate goal:**
  - 0.04 eV sensitivity (150 meV resolution)
    arXiv:2203.07349 (2022)



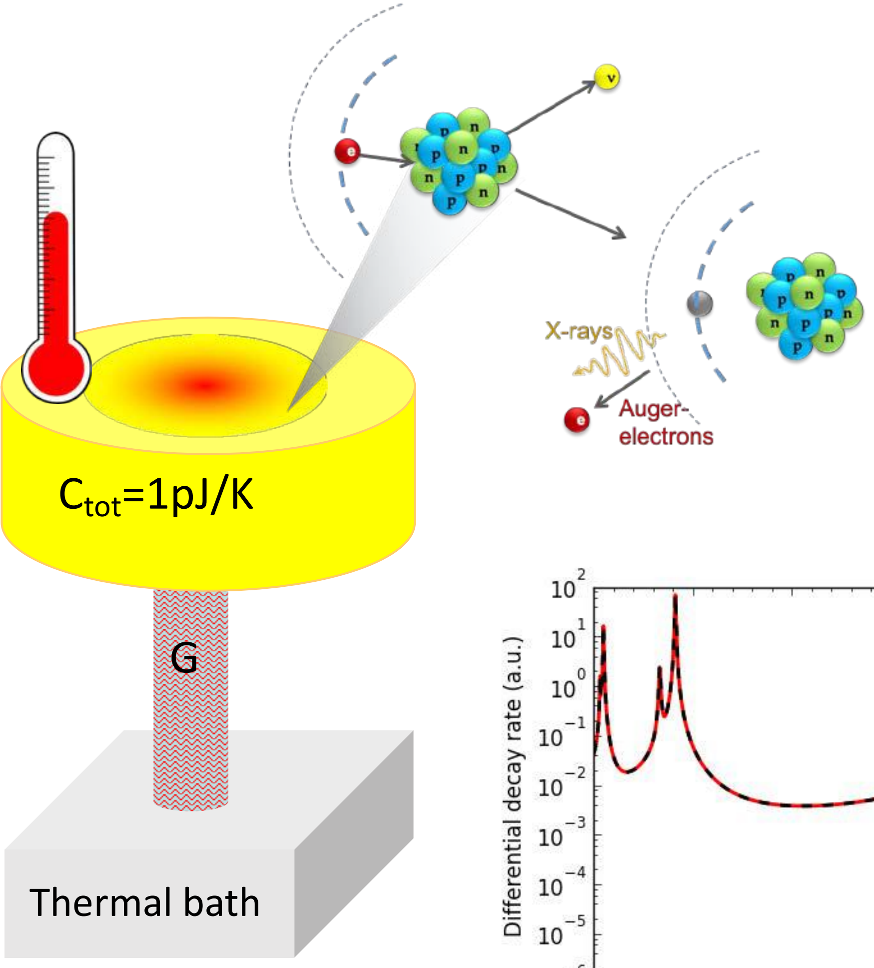


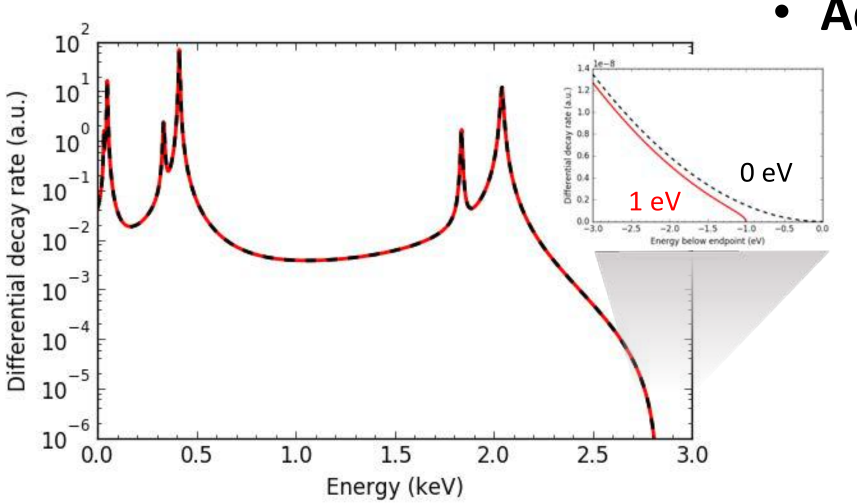


Experimental efforts



Working principle





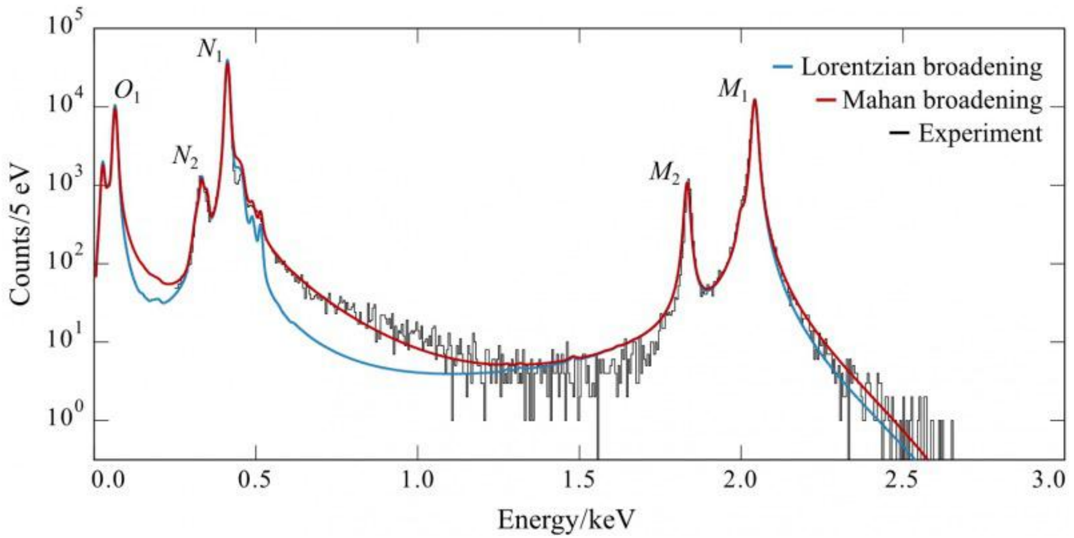
Technology:

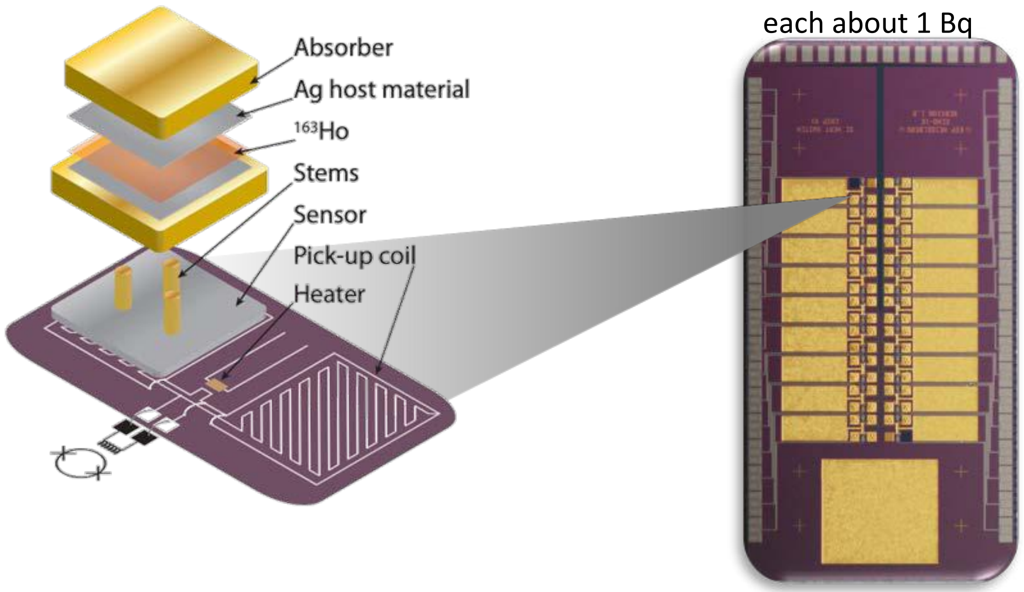
- Low-temperature micro-calorimetry
  A. De Rujula and M. Lusignoli, *Phys. Lett.* **118B** (1982)
- Holmium enclosed in absorber
- Measure decay energy via temperature rise

- **Advantage**
  - Differential measurement
  - Source = detector

ECHo

- **Achievements**
  - ✓ first holmium spectra measured
    ΔE = 5 eV (FWHM), b < 1.6 x 10^{-4} eV^{-1} $pixel^{-1}$ day^{-1}
  - ✓ first neutrino mass limit: m < 150 eV (95% C.L.)
    EPJ-C 79 1026 (2019)
  - ✓ refined theoretical calculations
    Phys.Rev.C 97 (2018) and *New J. Phys.* 22 (2020) 093018
  - ✓ ***ECHo-1k* completed: ~60 Bq (> 10^8 events)**
    EPJ-C 81, 963 (2021)
- **Next steps/challenges**
  - Scaling to higher activity per pixel and more pixels
  - ECHo-100k: m < 1.5 eV
- **Ultimate goal:**
  - low sub-eV sensitivity





Questions for today

How to measure the neutrino mass from cosmology

- Neutrinos are hot dark matter and wash out small scale structure
- Imprint in CMB and LSS
- Sensitivity at $\sum m_{\nu}$ < 0.2 eV

…and from $0\nu\beta\beta$?

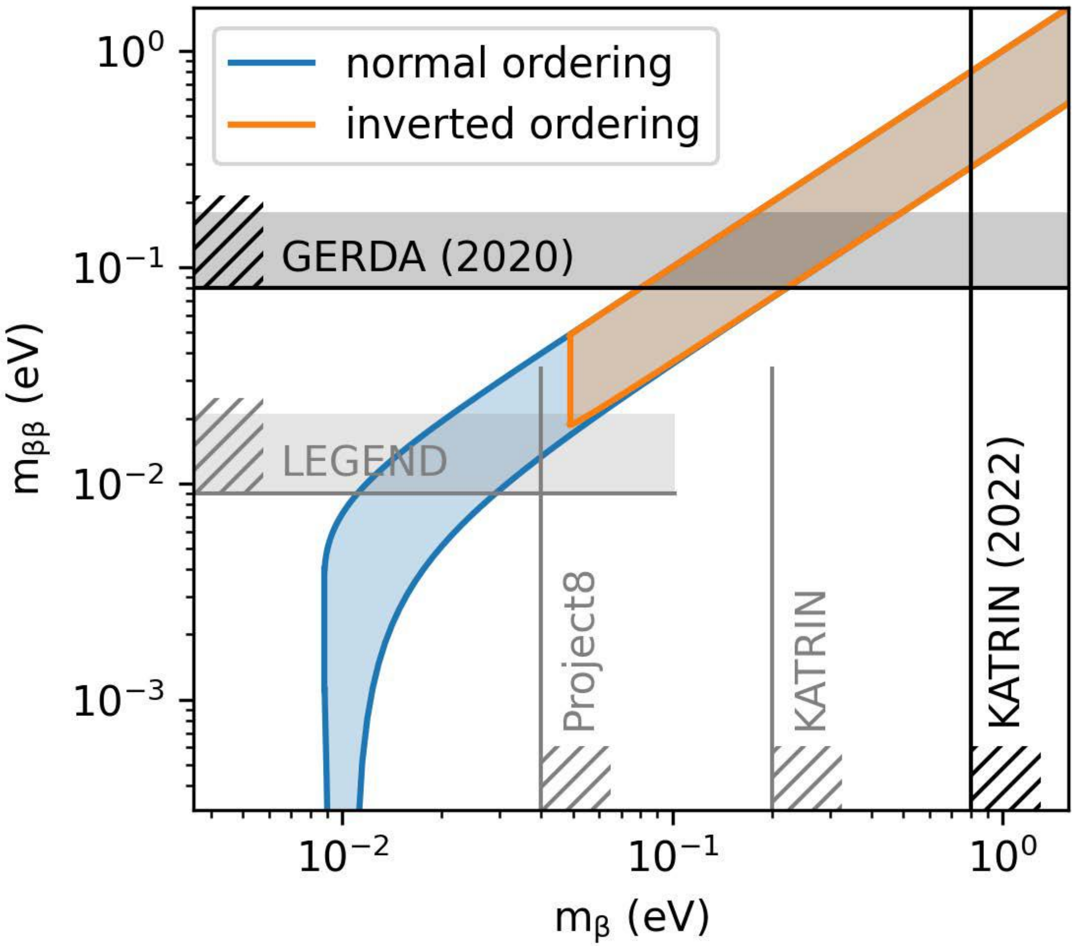
- Half life of the $0\nu\beta\beta$ decay depends on mass of neutrino
- Signal = peak at $Q_{\beta\beta}$
- Sensitivity at $m_{\beta\beta}$ < 0.2 eV

…and directly ?

- Neutrino mass reduces energy of beta
- Distortion of beta spectrum close to endpoint
- Sensitivity at m_{β} < 0.8 eV

What can we learn if we measure nothing?

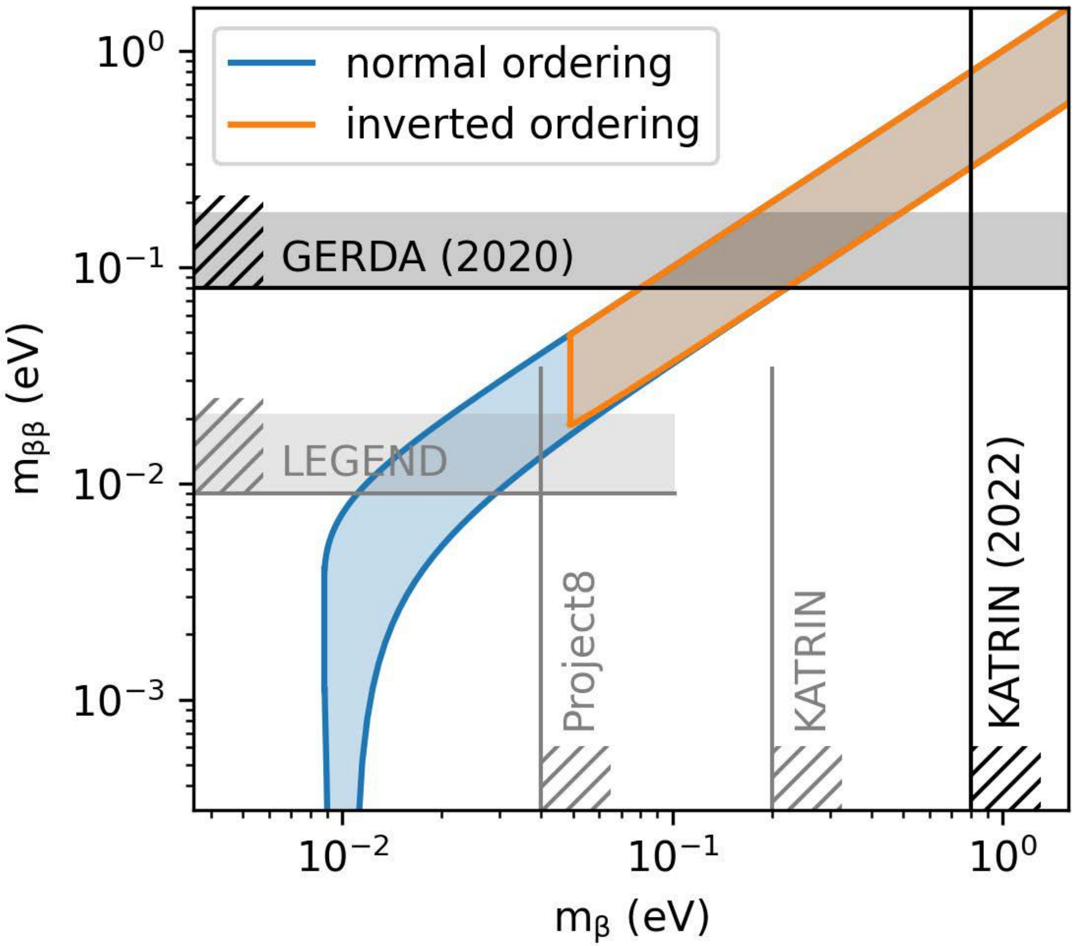
Complementarity



Puzzle 1: If Project-8 would measure a neutrino mass and LEGEND would not observe a signal

Puzzle 2: If LEGEND would see a signal and Project-8 would not measure the neutrino mass…

Complementarity



Puzzle 1: If Project-8 would measure a neutrino mass, **but** LEGEND would not observe a signal

- Neutrino is a Dirac particle
- (Or something is very wrong with our understanding of nuclear/neutrino physics)

Puzzle 2: If LEGEND would see a signal, **but** Project-8 would not measure the neutrino mass…

- different lepton number violating mediator than light Majorana neutrino exchange

Questions for today

How to measure the neutrino mass from cosmology

- Neutrinos are hot dark matter and wash out small scale structure
- Imprint in CMB and LSS
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…and from $0\nu\beta\beta$?

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…and directly ?

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- Sensitivity at $m_{\beta} < 0.8$ eV

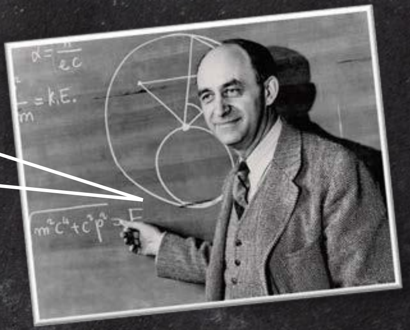
What can we learn if we measure nothing?

- Probes measure different combinations of m_i
- Observables are complementary
- We need all three of them

Back up

Let‘s have a closer look

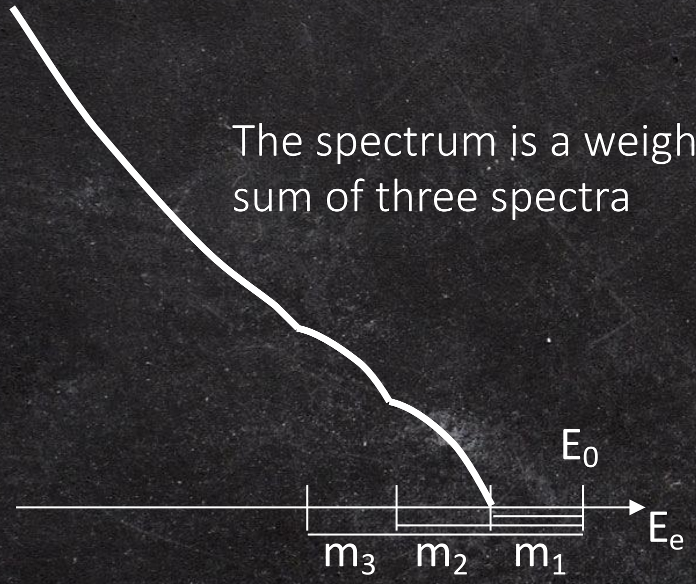
This is the formula for beta-decay



$$\frac{d\Gamma}{dE} = \sum_i |U_{ei}|^2 \, C \cdot F(E,Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E + m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - m_i^2}$$

Electron energy — Neutrino energy — Electron momentum — Neutrino momentum

The spectrum is a weighted sum of three spectra



$m_i < 0.5$ eV

Let‘s have a closer look

We measure „far away“ from the endpoint

$$\frac{d\Gamma}{dE} = \sum_i |U_{ei}|^2 \, C \cdot F(E,Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E + m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - m_i^2}$$

$$\sqrt{1+x} \approx 1 + \frac{1}{2}x + \ldots$$

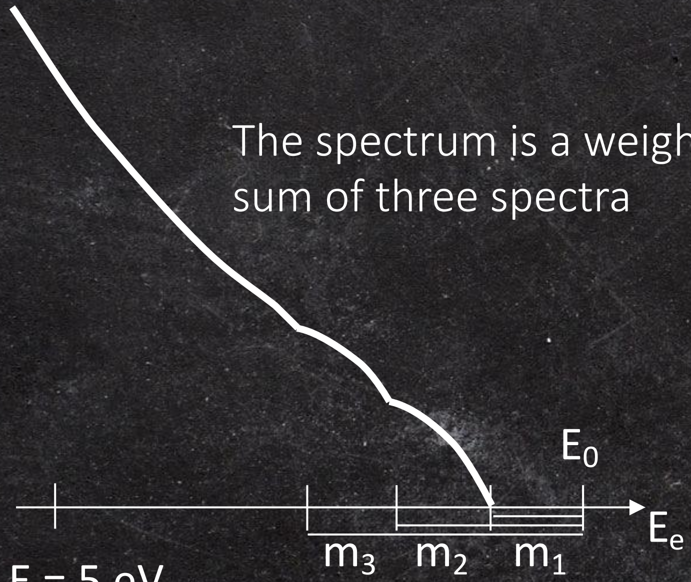
$$\sum_i |U_{ei}|^2 (E_0 - E)\sqrt{1 - \frac{m_i^2}{(E_0 - E)^2}}$$

$$\approx \sum_i |U_{ei}|^2 (E_0 - E)\left(1 - \frac{1}{2}\frac{m_i^2}{(E_0 - E)^2}\right)$$

$$= (E_0 - E)\left(1 - \frac{1}{2}\frac{\sum_i |U_{ei}|^2 m_i^2}{(E_0 - E)^2}\right)$$

$$= \sqrt{(E_0 - E)^2 - \sum_i |U_{ei}|^2 m_i^2}$$

The spectrum is a weighted sum of three spectra



E_0-E = 5 eV

$m_i < 0.5$ eV

Let‘s have a closer look

$$\frac{d\Gamma}{dE} = \sum_i |U_{ei}|^2 \, C \cdot F(E,Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E+m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - m_i^2}$$

$$\frac{d\Gamma}{dE} \approx C \cdot F(E,Z) \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E+m_e)^2 - m_e^2} \cdot \sqrt{(E_0 - E)^2 - \sum_i |U_{ei}|^2 m_i^2}$$

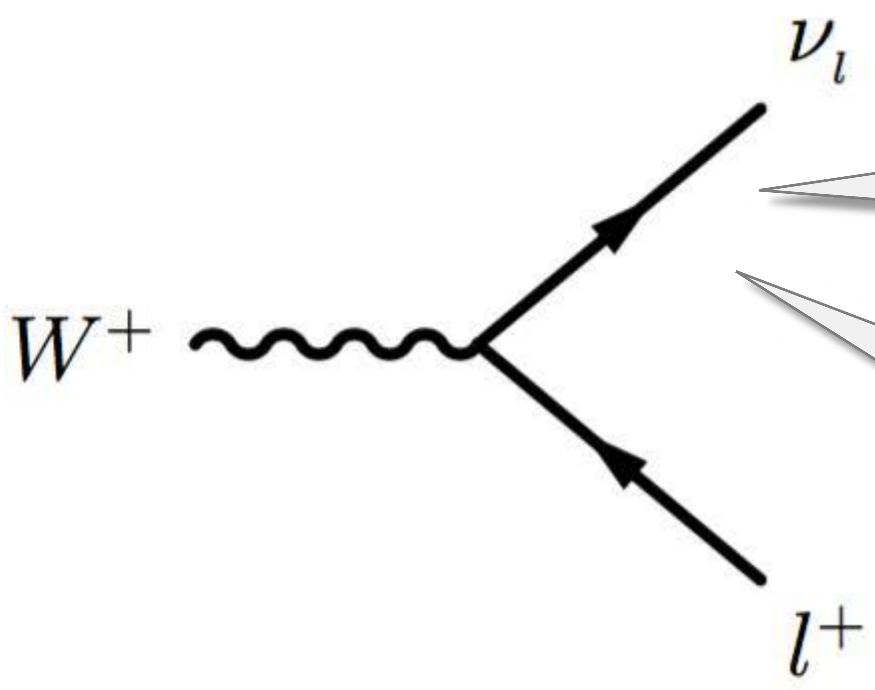
$$m_\nu^2 \equiv \sum_i |U_{ei}|^2 m_i^2$$

incoherent sum of neutrino mass eigentstates

Helicity vs Chirality

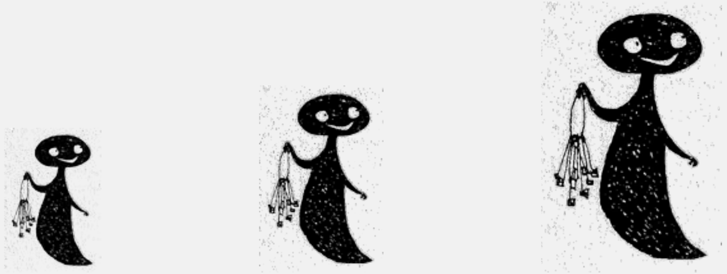
Helicity	Chirality
$$h = \frac{\vec{S} \cdot \vec{p}}{\lvert \vec{p} \rvert}$$	$$P_L = \frac{1-\gamma^5}{2}$$
Weak interaction does not know about helicity	Weak interaction projects out a chiral component of the field
Helicity of massive particle depends on reference frame	Chirality is frame independent
Physical particles occur with a definite helicity in nature	Physical particles have no defined chirality

Chirality vs Helicity



QM superposition of **helicity** eigenstates
(composition determined by m/E)

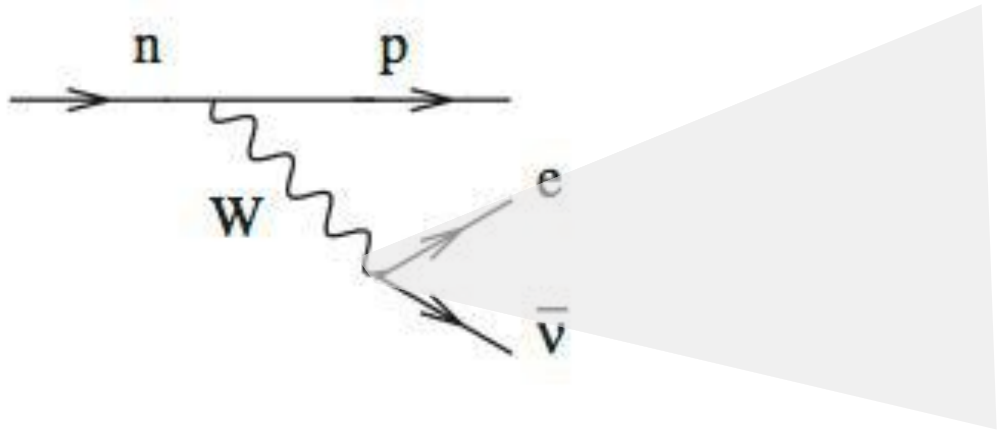
QM superposition of **mass** eigenstates
(composition determined by PMNS matrix)



$$n \rightarrow p + e + \bar{\nu}_e$$

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

Helicity vs Chirality

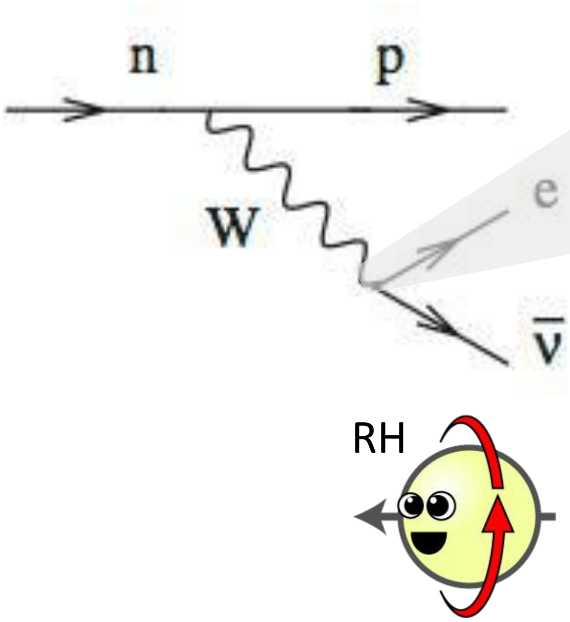


- Projection on electron neutrino flavor = super position of mass eigenstate
- The physical neutrino, is the one that propagates through space, it has a definite mass (and no definite flavor)

Helicity vs Chirality

$$n \to p + e + \bar{\nu}_e$$

$$\nu_e + n \to p + e$$



- Projection on right-chiral component of anti neutrino field

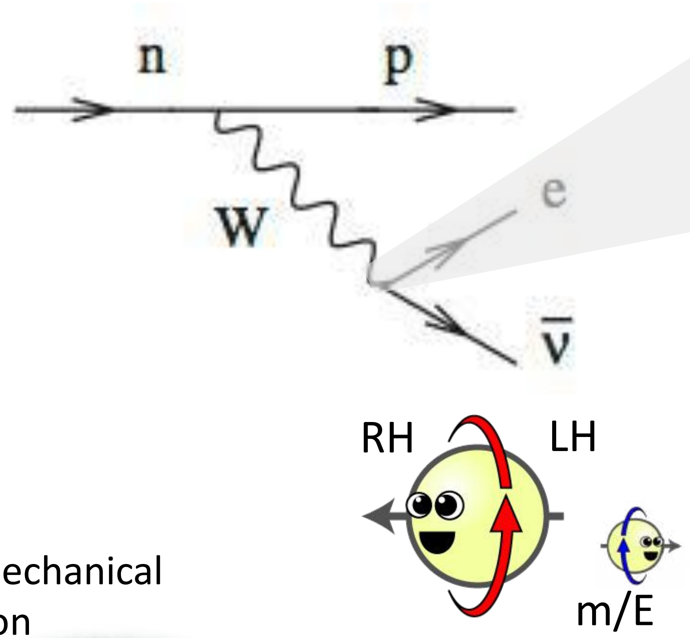
Massless case:

- The physical neutrino appears only with right-handed helicity

Helicity vs Chirality

$$n \to p + e + \bar{\nu}_e$$

$$\nu_e + n \to p + e$$



- Projection on right-chiral component of anti neutrino field

Massive case:

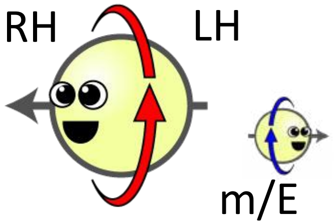
- The physical neutrino appears mostly with right-handed helicity and a bit O(m/E) of left-handed helicity

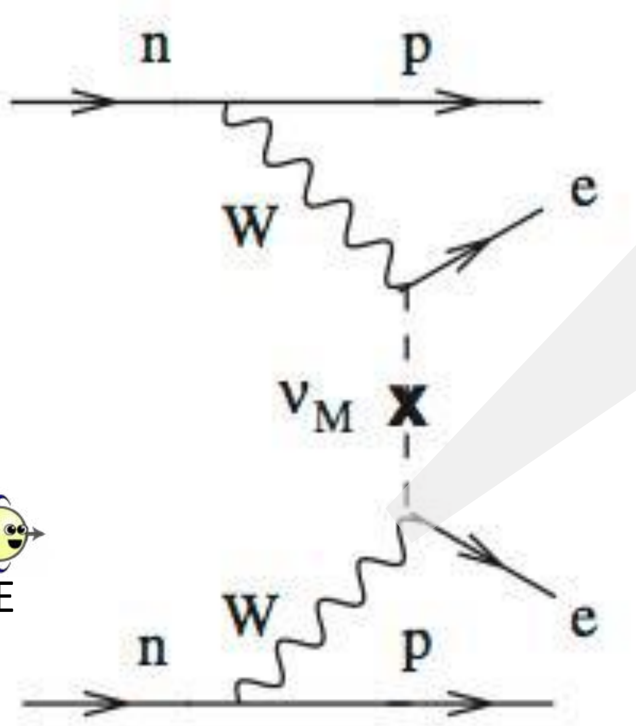
Quantum mechanical superposition

Helicity vs Chirality

$$n \rightarrow p + e + \bar{\nu}_e$$

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





- Projection on right-chiral component of anti neutrino field

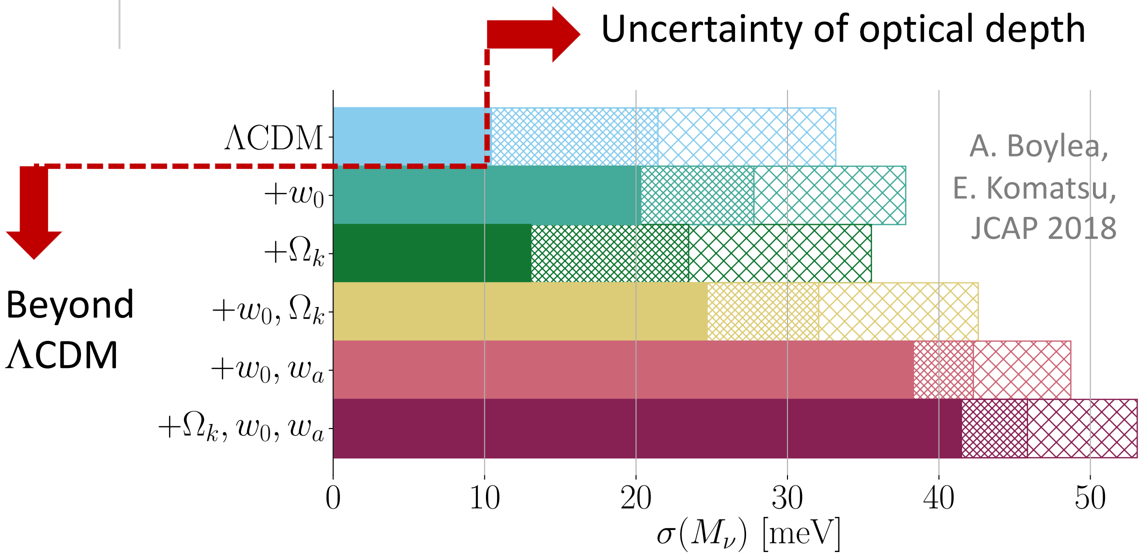
Massive case:

- The physical neutrino appears mostly with right-handed helicity and a bit O(m/E) of left-handed helicity
- The vertex will absorb with almost no suppression the left-handed helicity neutrino and a O(m/E) fraction of the right-handed helicity neutrino
- The decay can occur, but is suppressed with m_ν

LH: will be completely absorbed
RH: A tiny bit ~O(m/E) will be absorbed

Model dependence

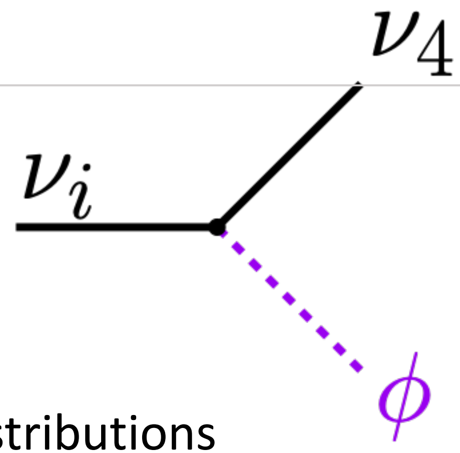
Cosmology



- Beyond ΛCDM

➢ Bounds relaxed up to factor of ~3

Neutrino physics



- Non-standard p or T distributions
  Farzan & Hannestad 1510.02201
  Oldengott et al. 1901.04352
  Alvey, Escudero, Sabti, Schwetz 2111.14870v
- Invisible neutrino decay
  Escudero, López-Pavón, Rius, Sandner 2007.04994
  Chacko et al. 1909.05275, 2112.13862
- Time-dependent neutrino mass
  Dvali & Funcke 1602.03191
  Lorenz et al. 2102.13618

➢ Bounds relaxed up to $\sum m_\nu < 3$ eV