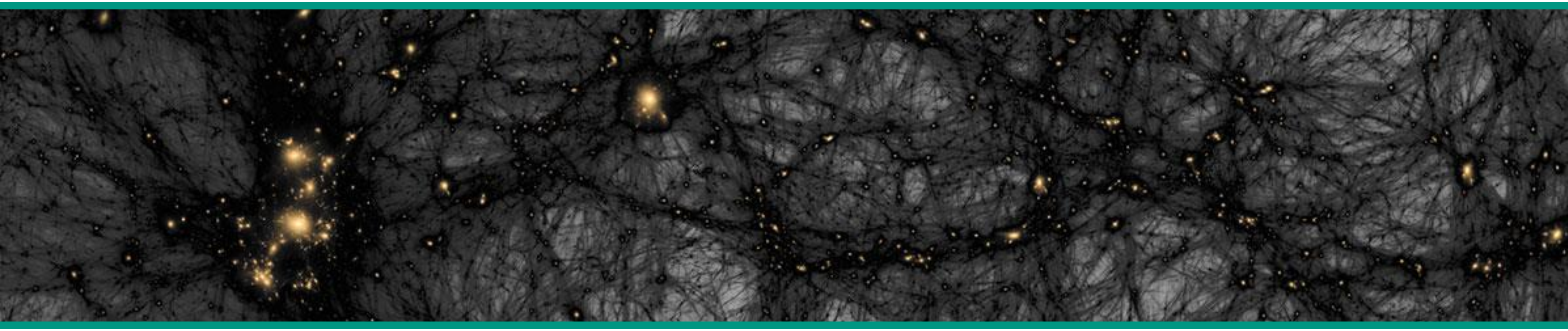
Astroparticle physics I – Dark Matter

Winter term 23/24 Lecture 11 Dec. 7, 2023



Recap of Lecture 10

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- **Shielding against background and origin of background processes**

  - reduction of $\mu -$ induced processes via underground lab ($LNGS$,...)

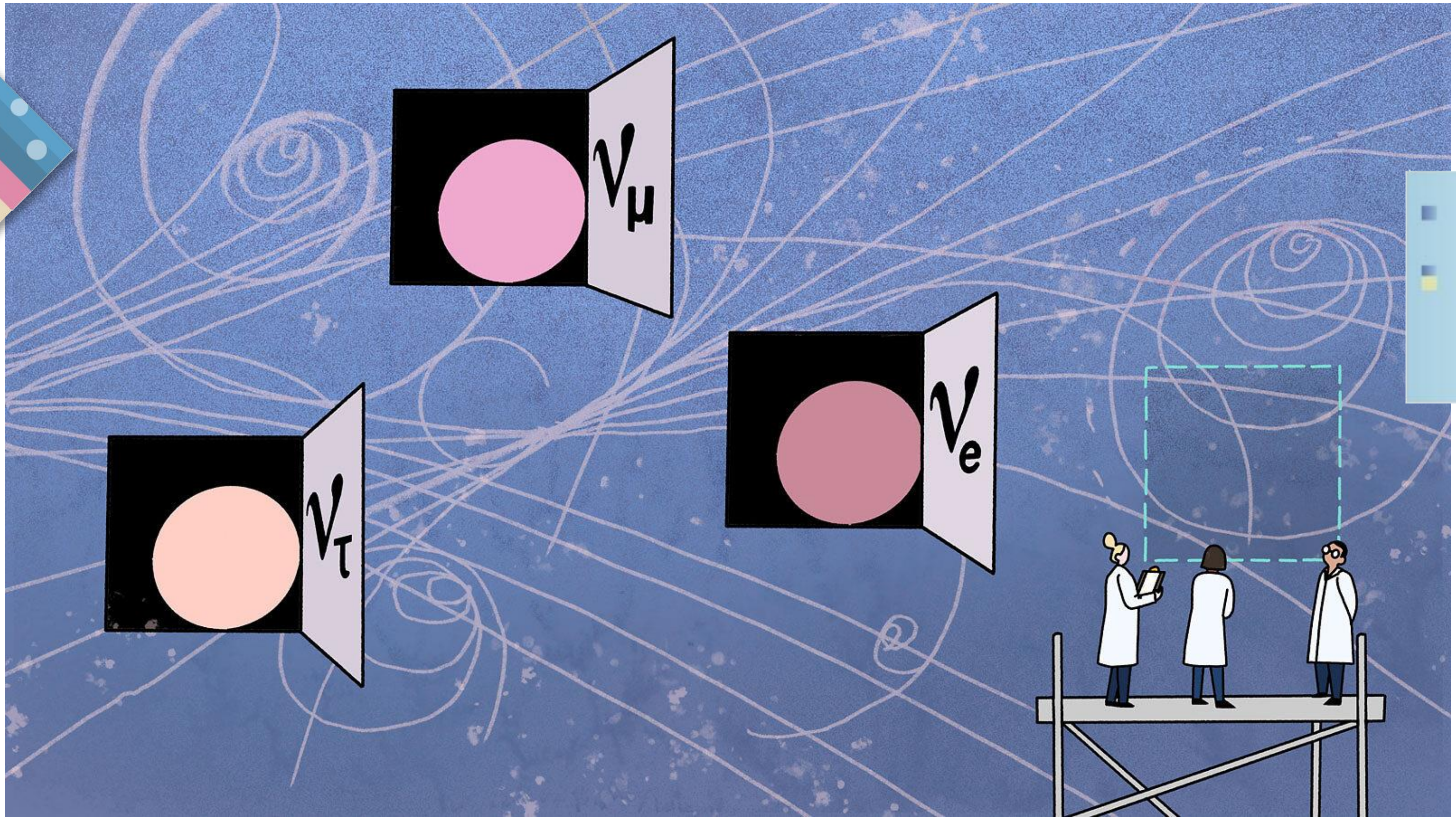
  - **shielding** against **gammas** from rock: veto, $Pb -$ bricks, PE, high$-$purity Cu

  - $\mathbf{4}$ primordial decay chains: ^{232}Th, ^{235}U, ^{237}Np, ^{238}U

  - usually the entire chain is in **secular equilibrium** (all A_j identical)

  - important isotope: ^{210}Pb (thus use Roman$-Pb$ or electro$-$formed Cu)

  - **radon**: ^{222}Rn ^{220}Rn especially dangerous due to emanation in closed spaces



CHAPTER 3 – NEUTRINOS

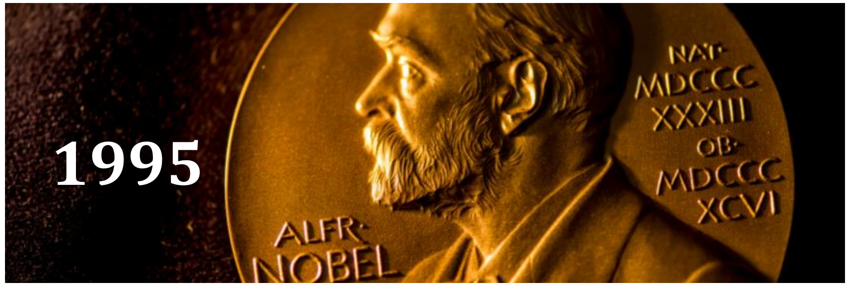
3. 1 Introduction

- **Experimental starting point: *Fred Reines* on the track of neutrinos**

  \- **project ´*Poltergeist*´:** first detection of neutrinos (Savannah River reactor)

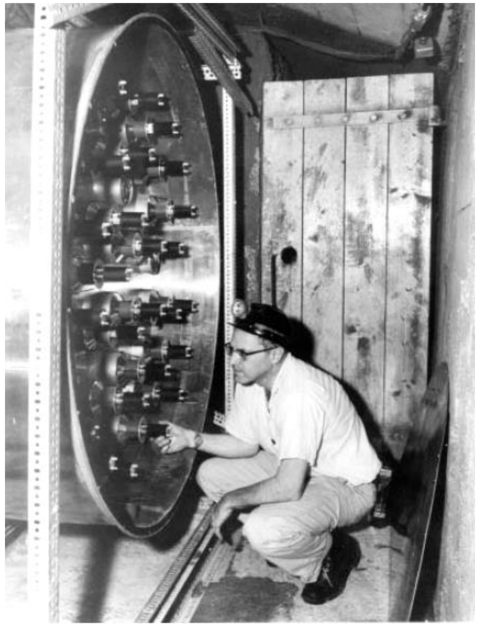
  Hanford **1954**: first (unsuccessful) neutrino detector ´***Herr Auge***´

  300 ℓ liquid scintillator with 90 $PMTs$!



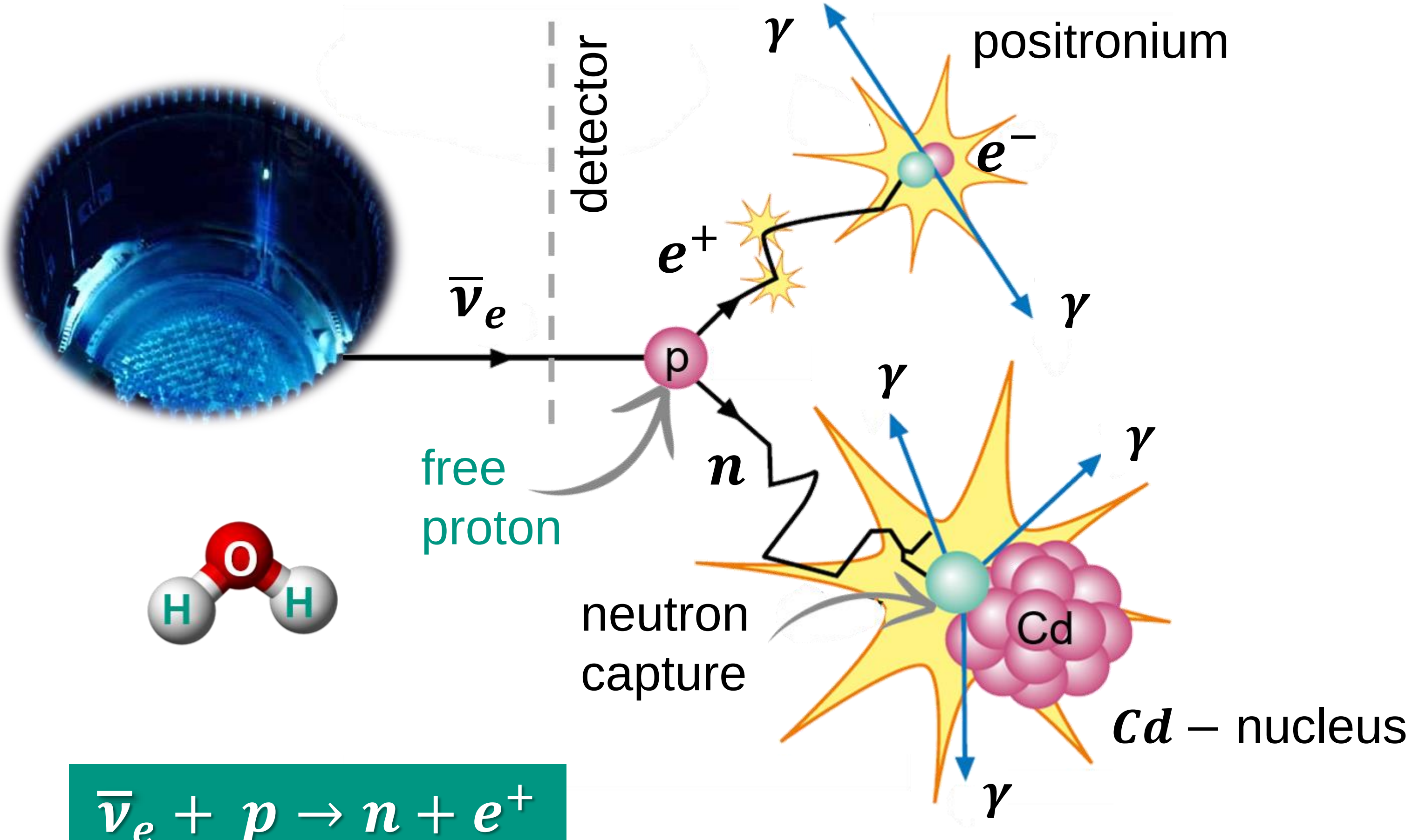
*"for the detection of the **neutrino**"*

Fred Reines
1918 – 1998



Inverse β – decay: ´classical´ detection reaction

- **A unique ´delayed coincidence´ signature: prompt e^+ & delayed (n,γ)**



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

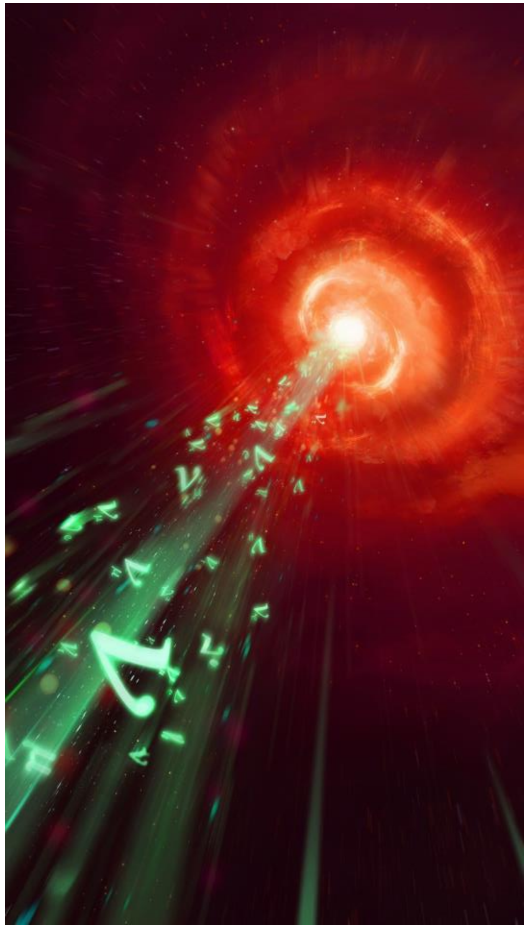
positronium:
annihilation of e^+ and e^- into two γ´s $(2 \times 511\ keV)$

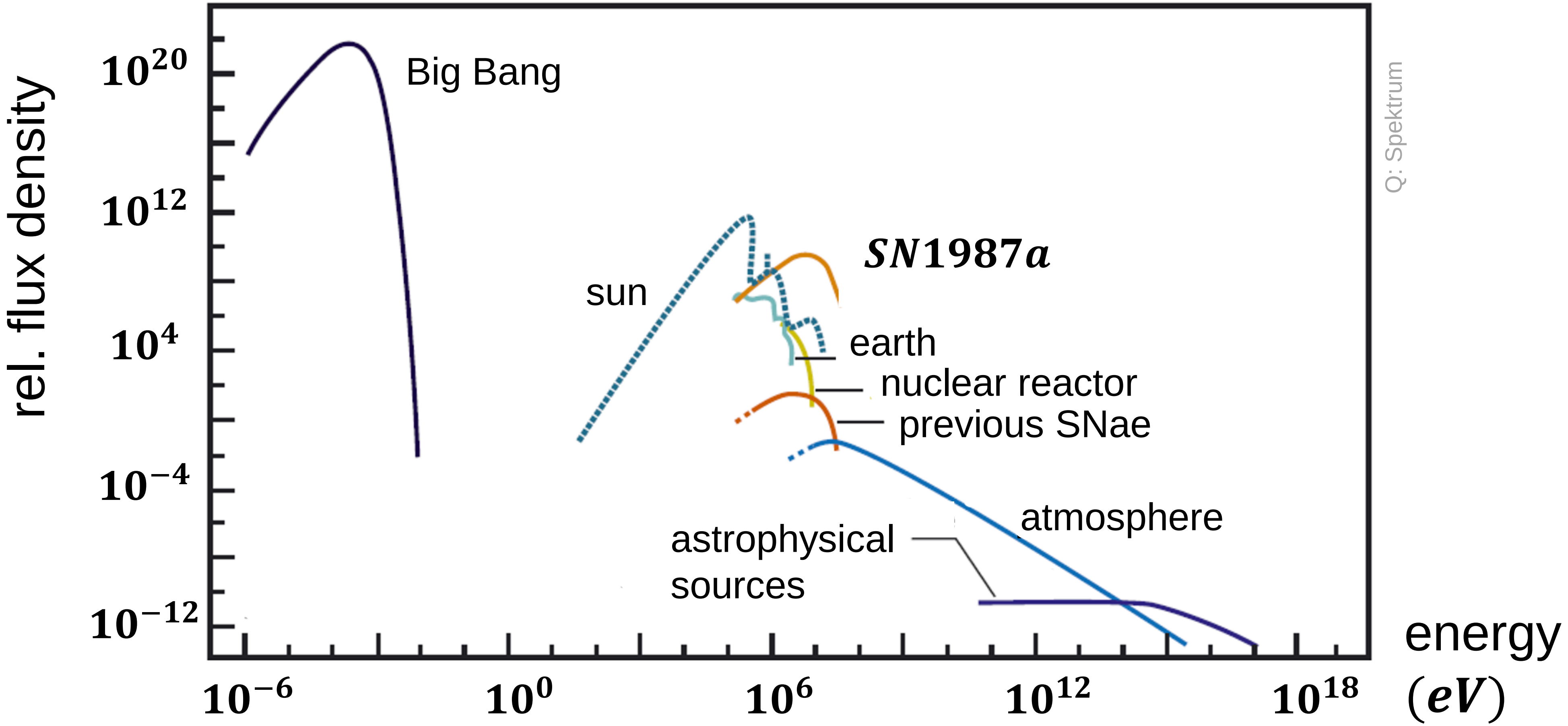
coincidence of the 2 signals

neutron–capture (nucleus):
several γ´s, release of the n – binding energy $(\Sigma E_\gamma \sim 7 \dots 8\ MeV)$

Neutrino sources: an overview from μeV ... PeV

- sources: from primordial ν´s to astrophysical ν´s emitted by $AGNs$ ...



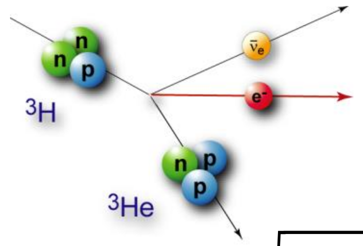


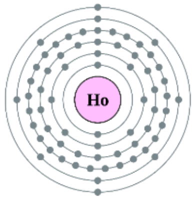
3.2 kinematic determination of the ν – mass

- **three complementary approaches: laboratory–based & cosmology**

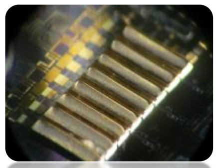
kinematics of weak decays

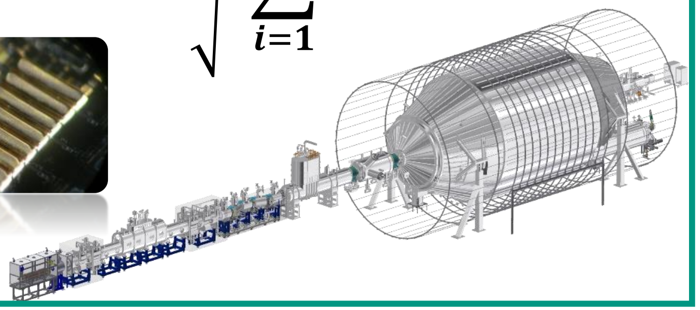
- β – decay: ^3H, EC: ^{163}Ho
- **model–independent**





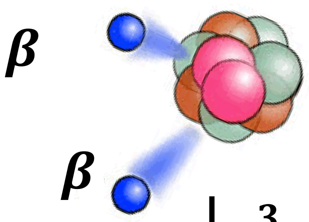
$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$



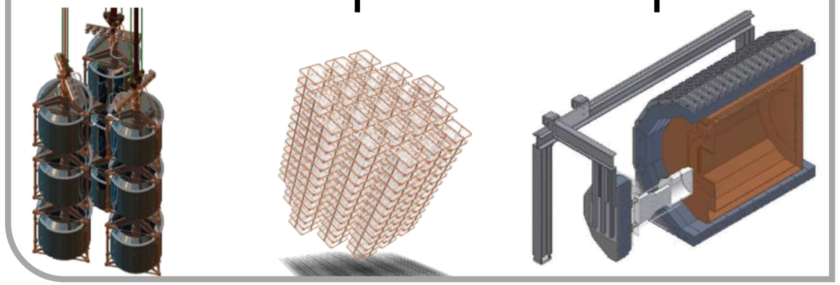


search for $0\nu\beta\beta$ – decay

- $\beta\beta$ – decay: ^{76}Ge, ^{136}Xe,...
- **model–dependent** (α_i)

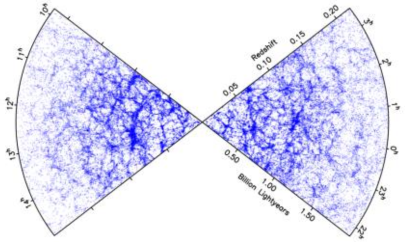


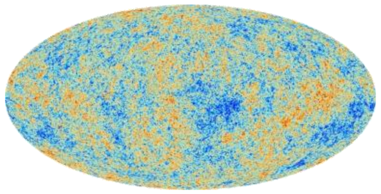
$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 \cdot m_i \right|$$



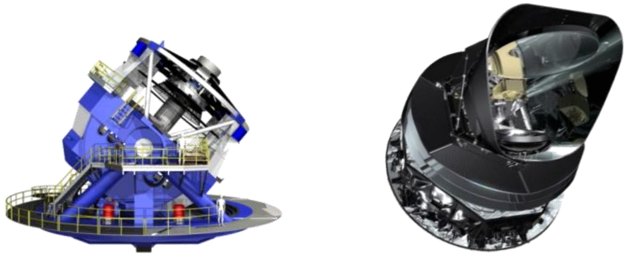
large–scale structures*

- CMB, galaxy surveys,...
- **model–dependent** (H_0)





$$m_{tot} = \sum_{i=1}^{3} m_i$$



*see lectures on cosmology

Neutrinos – intrinsic properties

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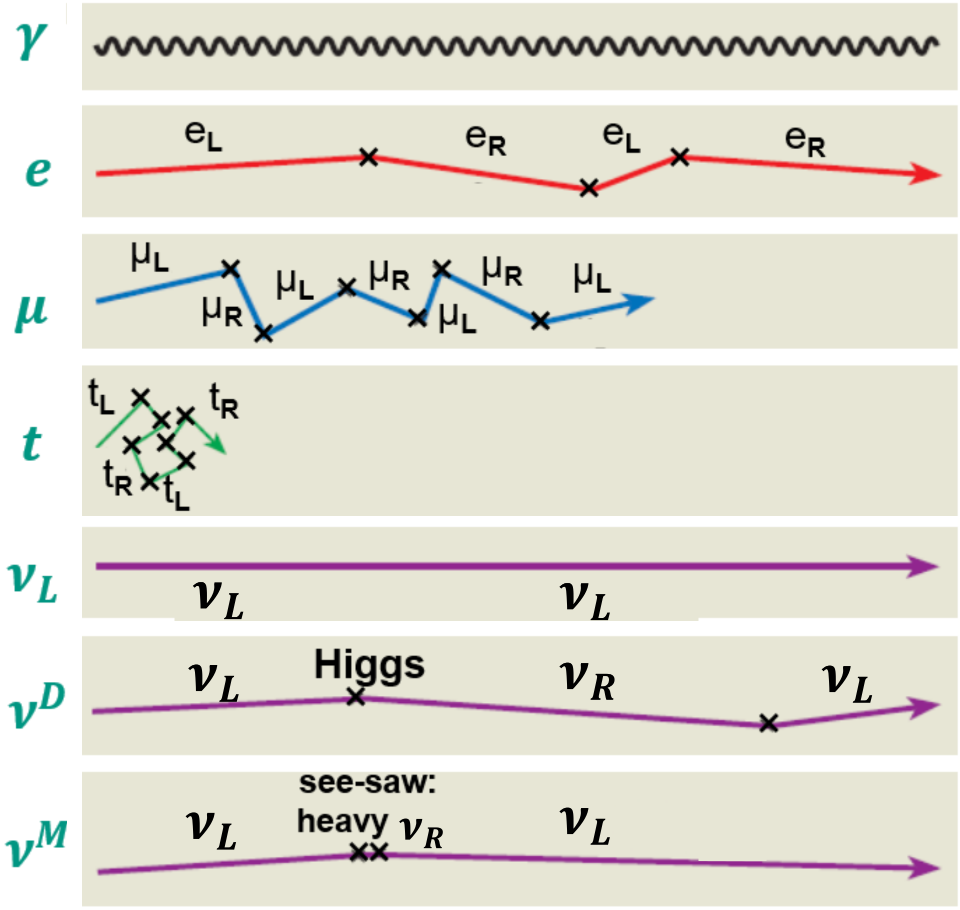
- **Higgs vs.** $\boldsymbol{see-saw}$*** mechansim**

masses $\boldsymbol{m_i}$ via **Higgs–coupling**: it involves a change of the **handedness**

chiral $\boldsymbol{LH}$ ↔ chiral $\boldsymbol{RH}$



particle	scale	$m(MeV)$
photon γ	massless	0
electron e	light	0.511
muon μ	medium	105.6
top quark t	heavy	$1.71 \cdot 10^5$
SM neutrino ν_L	massless	0
Dirac-ν ν^D	very light	$10^{-8} \ldots 10^{-6}$
Majorana-ν ν^M	very light	$10^{-8} \ldots 10^{-6}$

*theory model with super–heavy $\boldsymbol{RH\ \nu's}$

Neutrinos: Dirac– or Majorana– type?

Dirac Neutrino

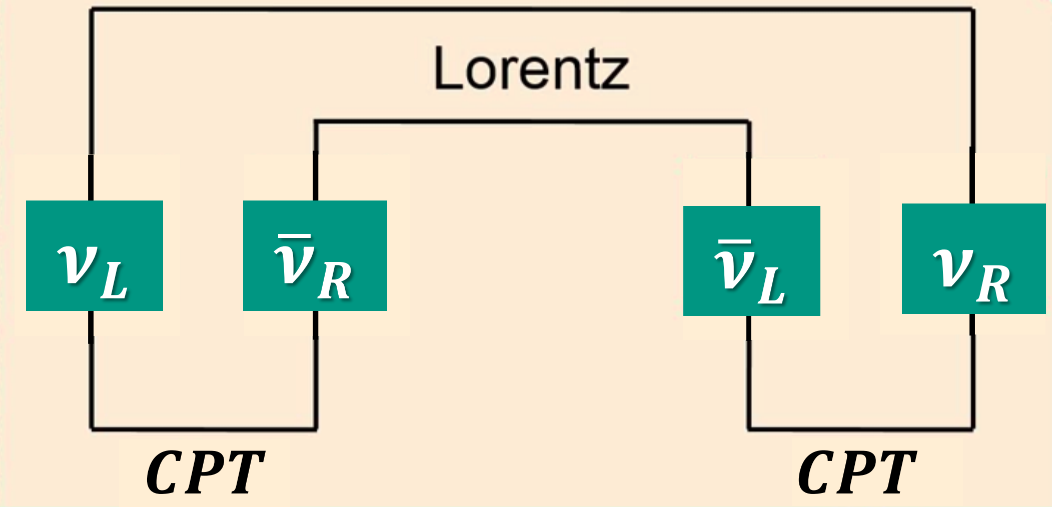
4ν – states

Lepton number conservation

$\Delta L = 0$

neutrino ≠ anti-neutrino

ν^D



Majorana Neutrino

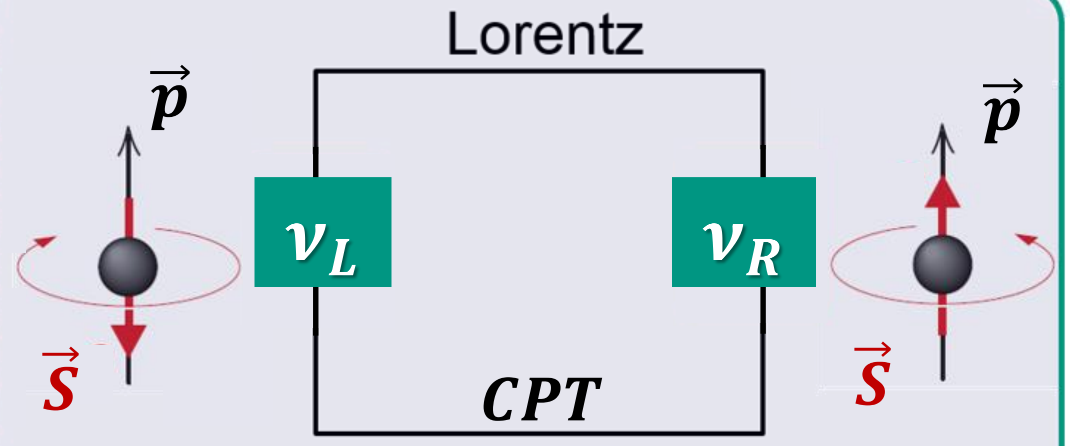
2ν – states

Lepton number violation

$\Delta L = 2$

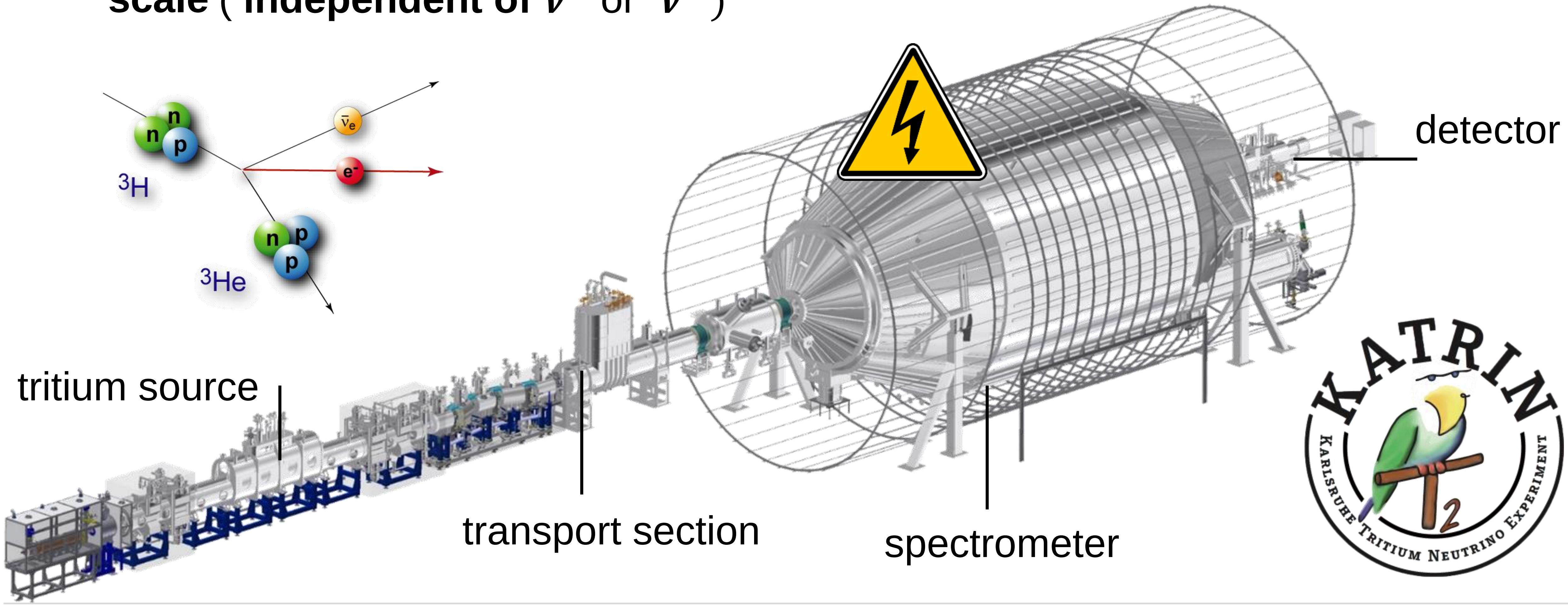
´neutrino = anti–neutrino´

ν^M



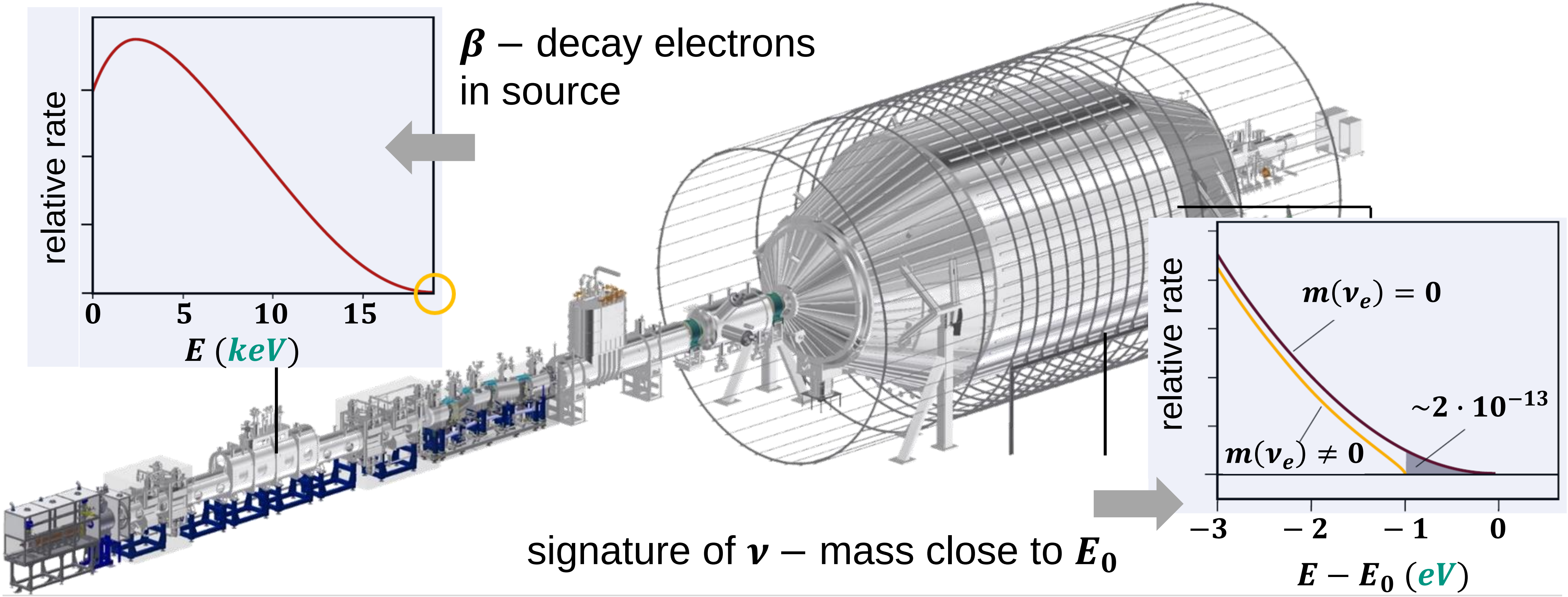
$KATRIN$ neutrino mass experiment

- **direct, model−independent measurement of the fundamental ν − mass scale** (**independent of ν^D** or ν^M)



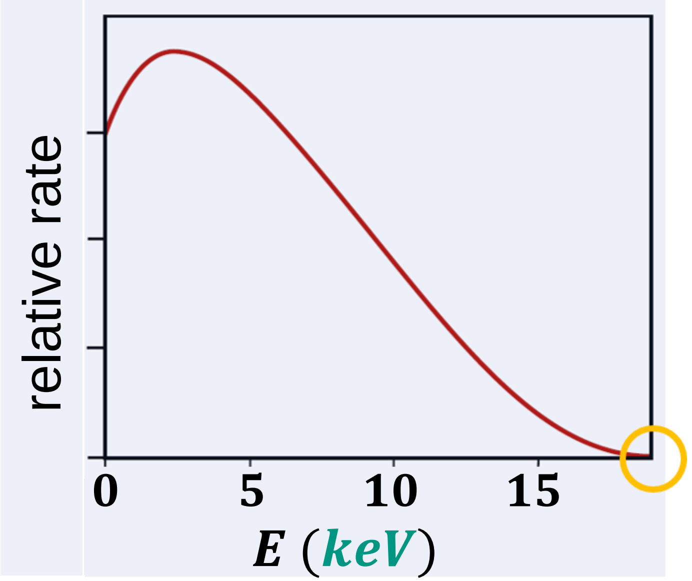
$KATRIN$ neutrino mass experiment

- 10^{11} $\beta-$ decays from a molecular, gaseous T_2 source at cryogenic $T \sim 80\ K$



$KATRIN$ neutrino mass experiment

- **Fermi theory of $\beta -$ decay: kinematic variables only to describe spectrum**



electron:
momentum p, energy E, mass m_e

neutrino:
3 mass eigenstates m_i

phase space:
maximum energy E_0

final state interaction:
Fermi function $F(E,Z)$

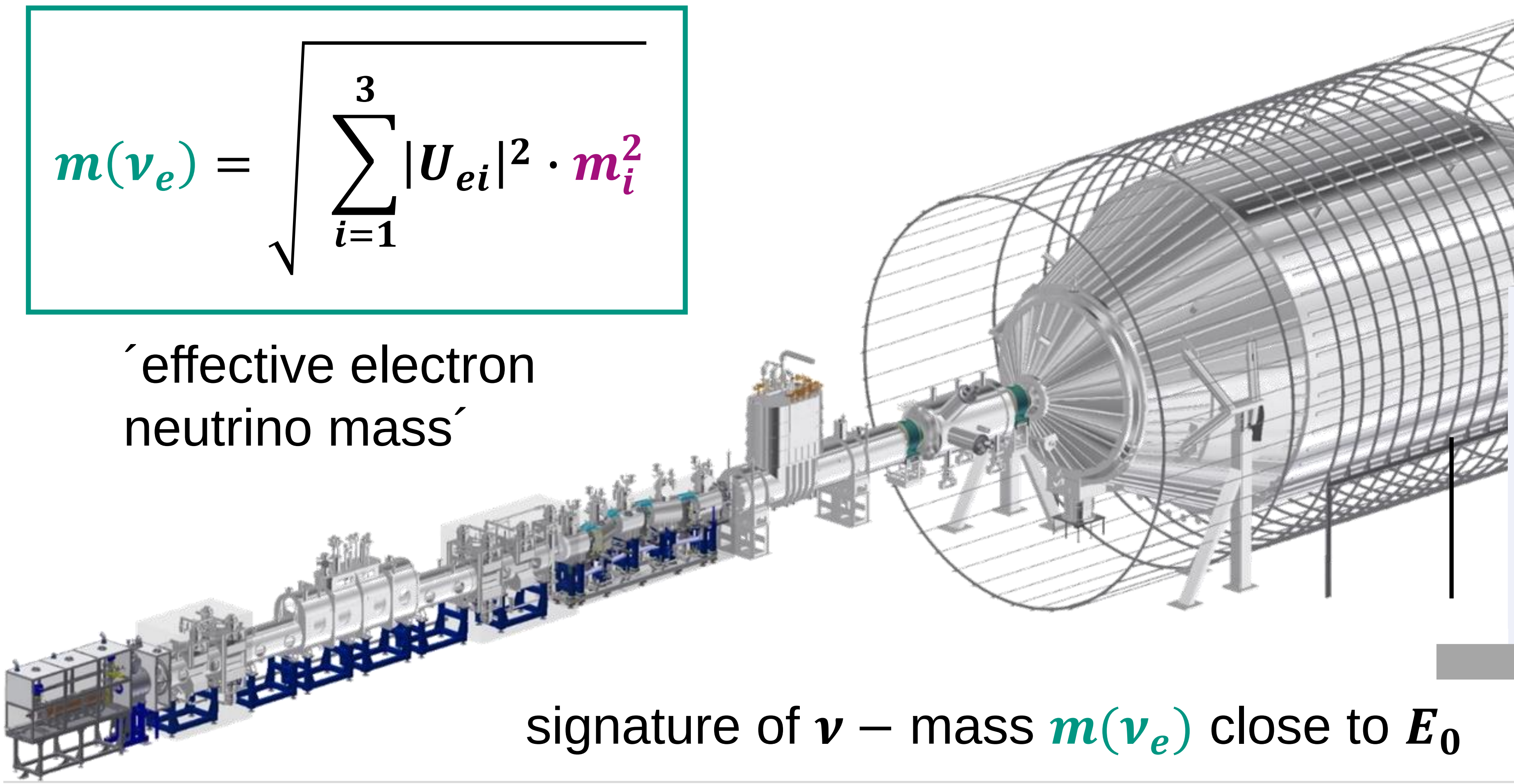
$$dN_i/dE \sim p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(Z,E) \cdot \theta(E_0 - E - m_i)$$

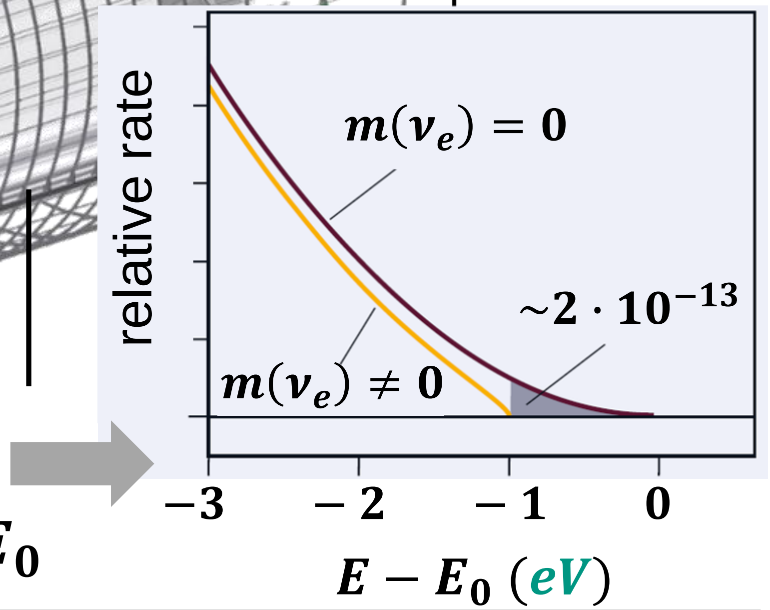
$KATRIN$ neutrino mass experiment

- ´effective mass´ of the electron neutrino ν_e: incoherent sum of masses m_i

$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2}$$

´effective electron neutrino mass´

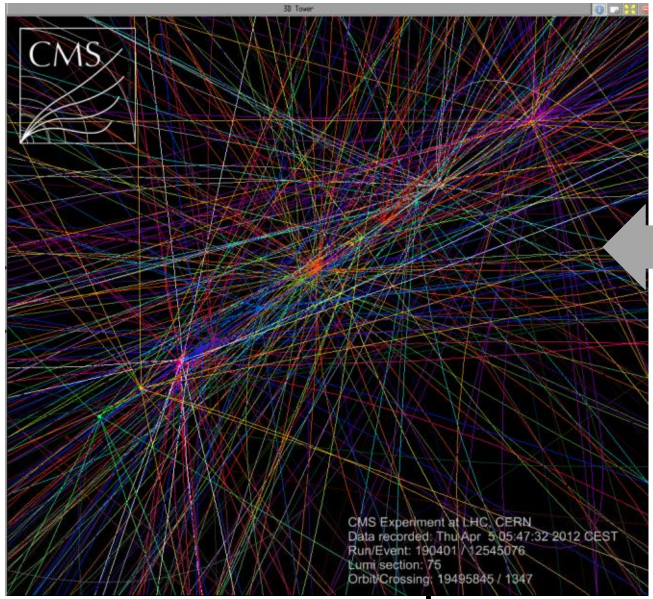




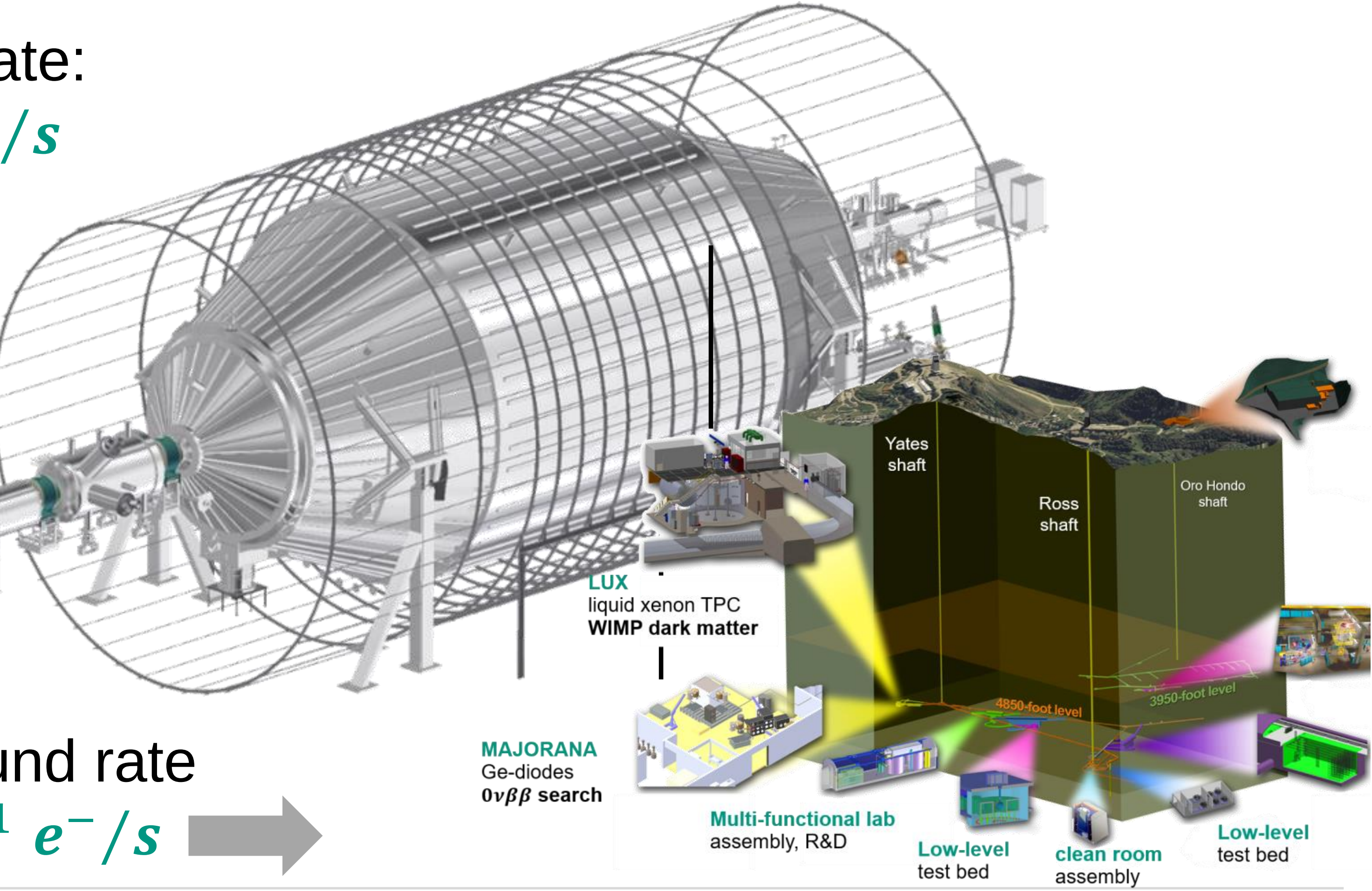
signature of ν – mass $m(\nu_e)$ close to E_0

$KATRIN$ neutrino mass experiment

- **challenges: combining a huge rate (LHC) with low−level technologies**



$\boldsymbol{\beta}$ – decay rate:
$\sim \mathbf{10^{11}}\ \boldsymbol{e^-/s}$



background rate
$\sim \mathbf{10^{-1}}\ \boldsymbol{e^-/s}$

$KATRIN$ neutrino mass experiment – challenges

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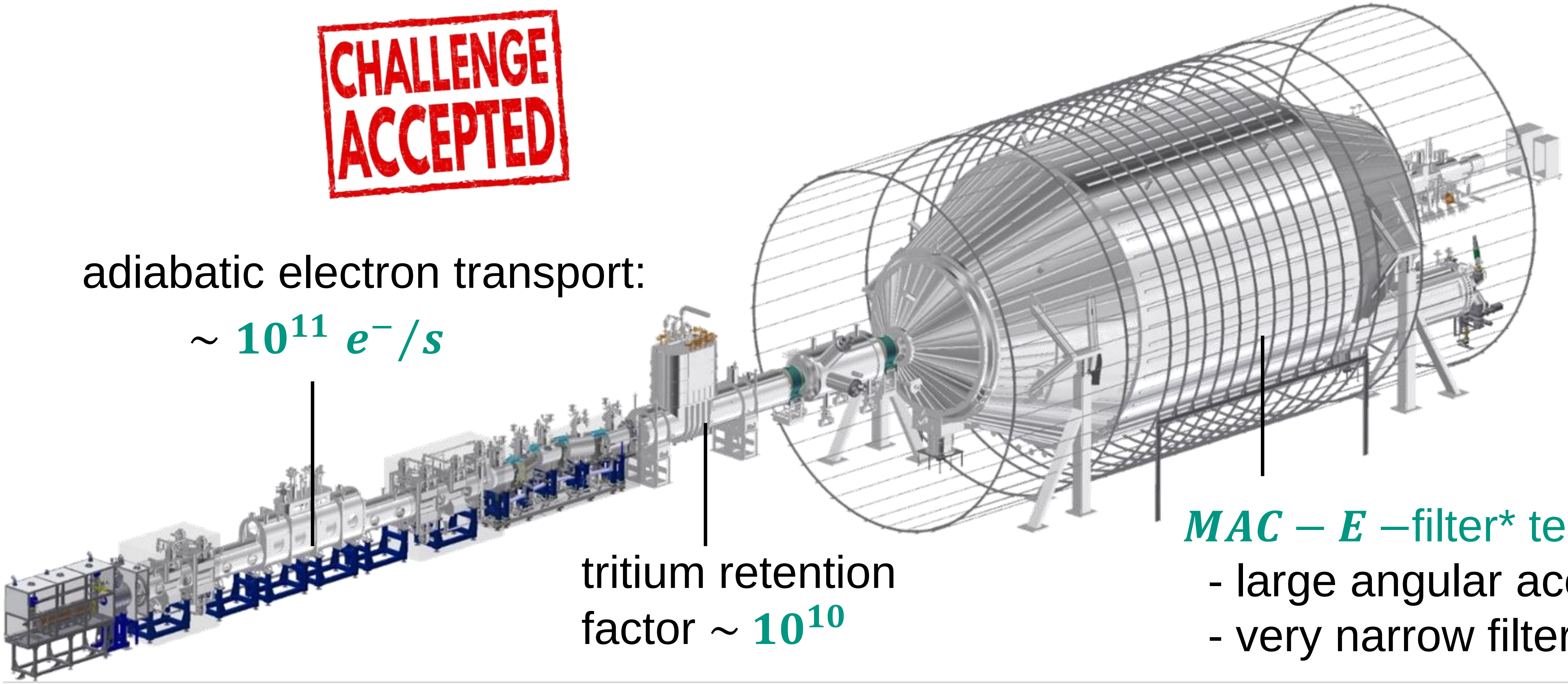
- precision spectroscopy $(sub-eV)$ of $\beta-$ decay electrons $(keV-scale)$



adiabatic electron transport:

$\sim 10^{11}\ e^-/s$

tritium retention factor $\sim 10^{10}$

$MAC-E$ –filter* technology:
- large angular acceptance
- very narrow filter width

*see next slide

KATRIN neutrino mass experiment – principle

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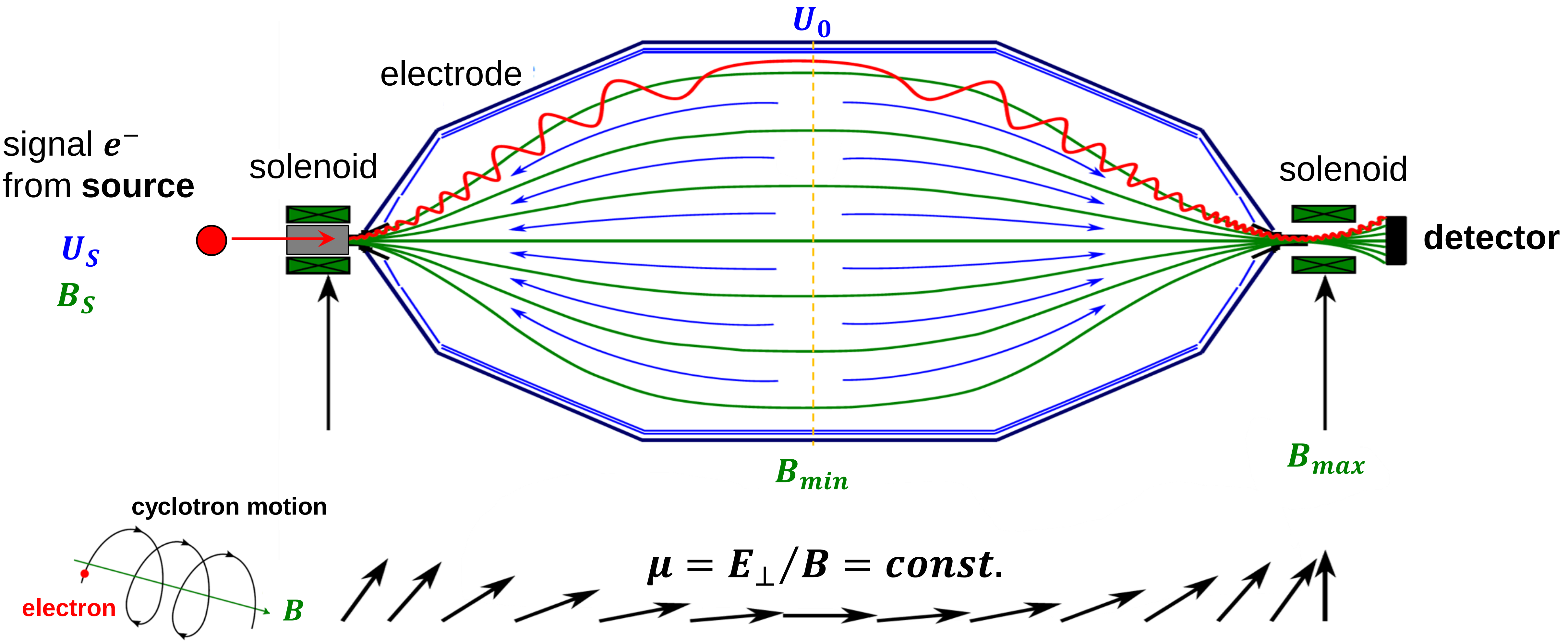
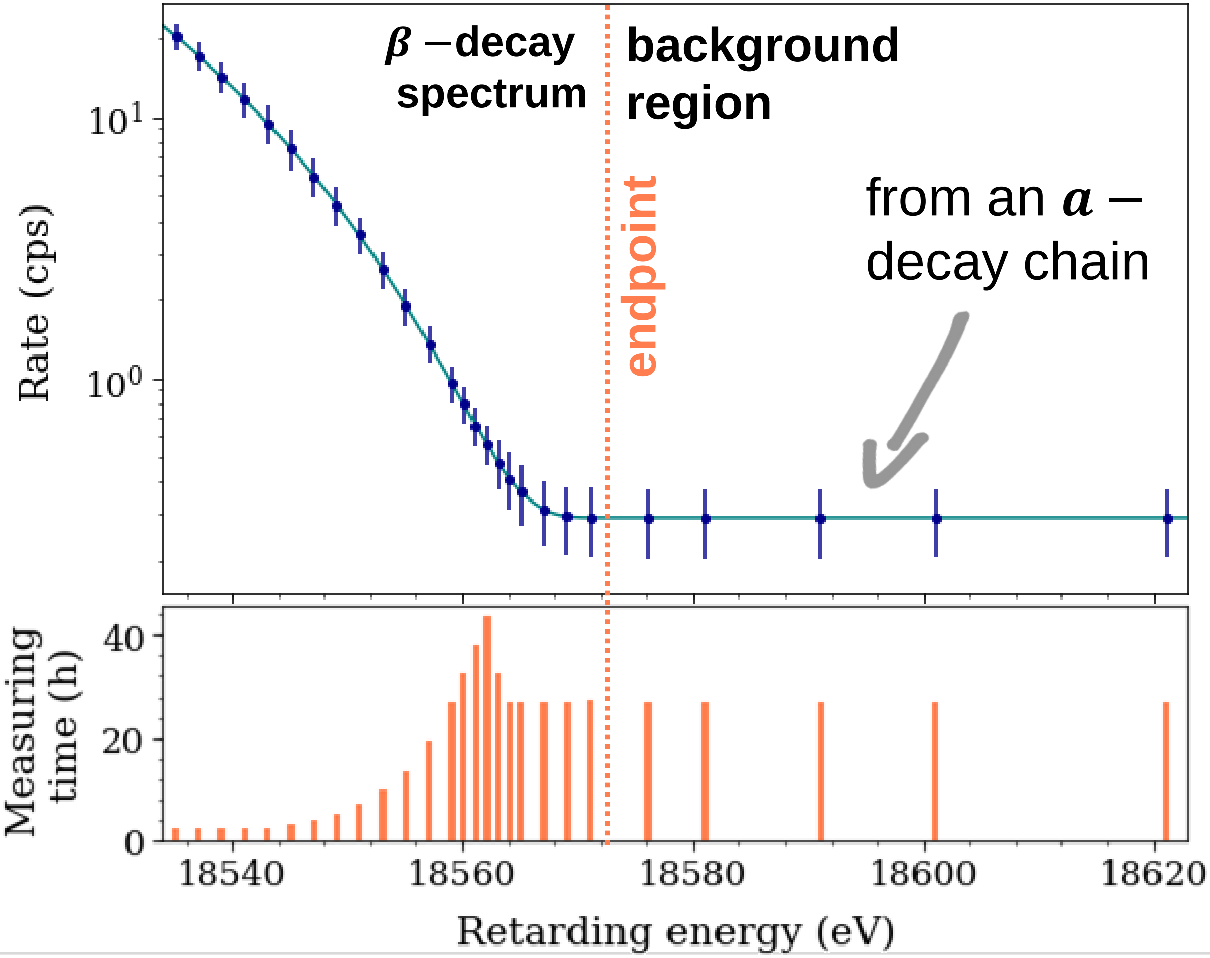
- ***MAC – E*** **filter: *M*agnetic *A*diabatic *C*ollimation with *E*nergy filter**



$KATRIN$ – measurement principle & strategy

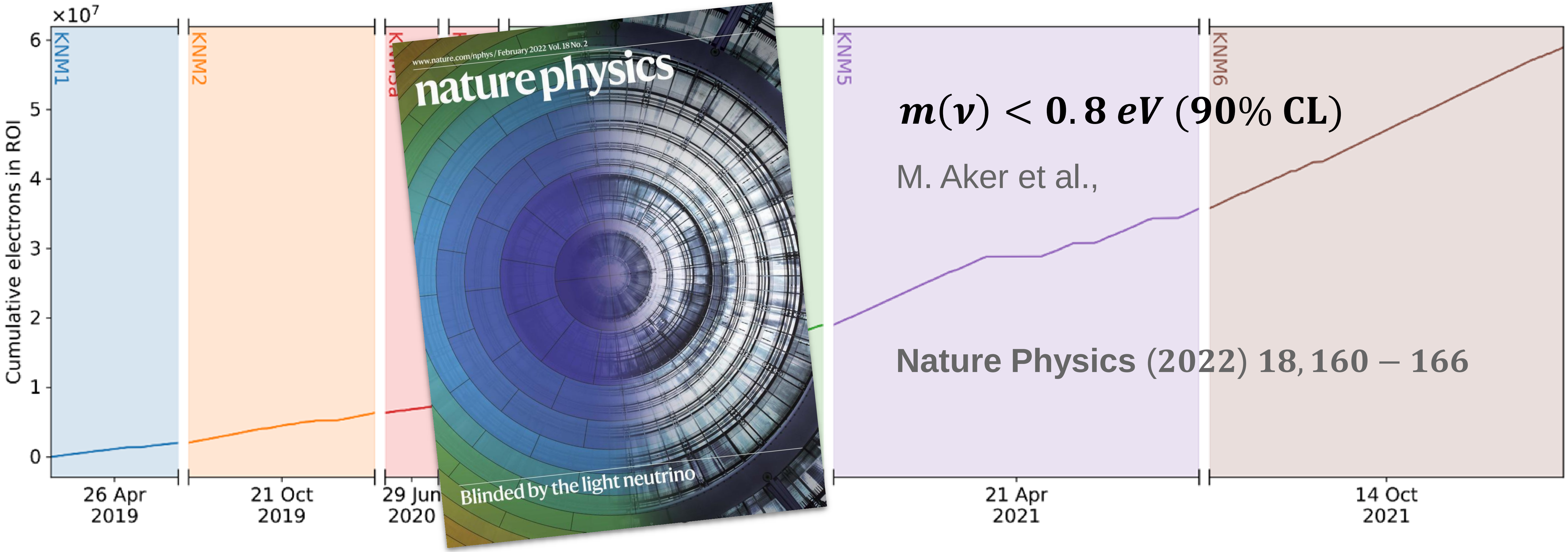
- **measurement: integrated rate above spectrometer retarding potential U_0**

- **calendar year**:
  several measurement campaigns ($KNMx$), typically $4 - 5$
- **campaign**:
  several (up to 8) weeks
  hundreds of β – scans (up–down mode)
- β – **scan**:
  typical scan time: $2\ h$
  $30\ HV$ set points with specific holding time & U_0 distribution interval $[E_0 - 40\ eV,\ E_0 + 130\ eV]$



$KATRIN$ data taking: first 2 campaigns $KNM1+2$

- 2019: initial 91 days of β – scanning (spring & autumn)



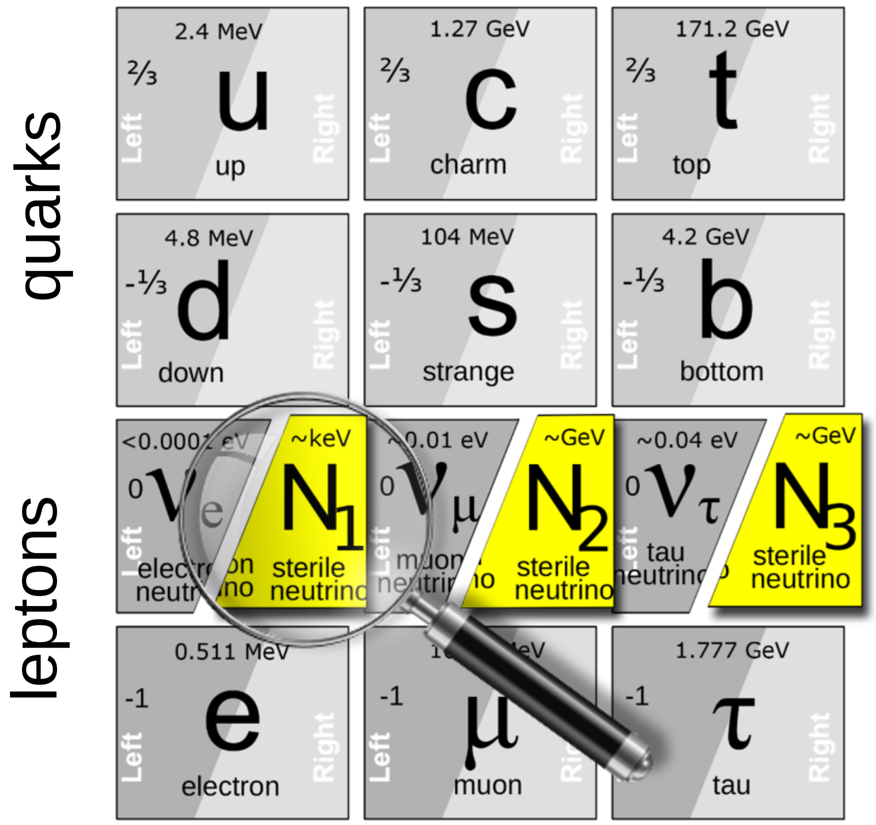
$m(\nu) < 0.8\ eV$ (90% CL)

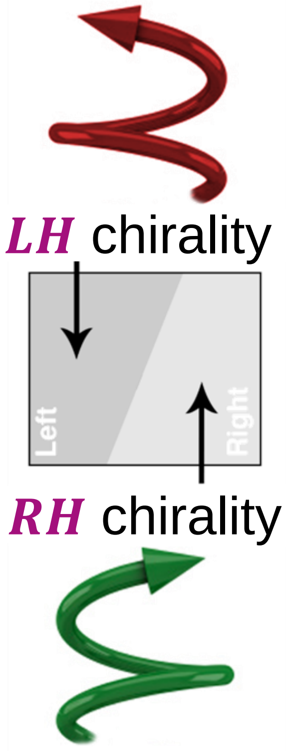
M. Aker et al.,

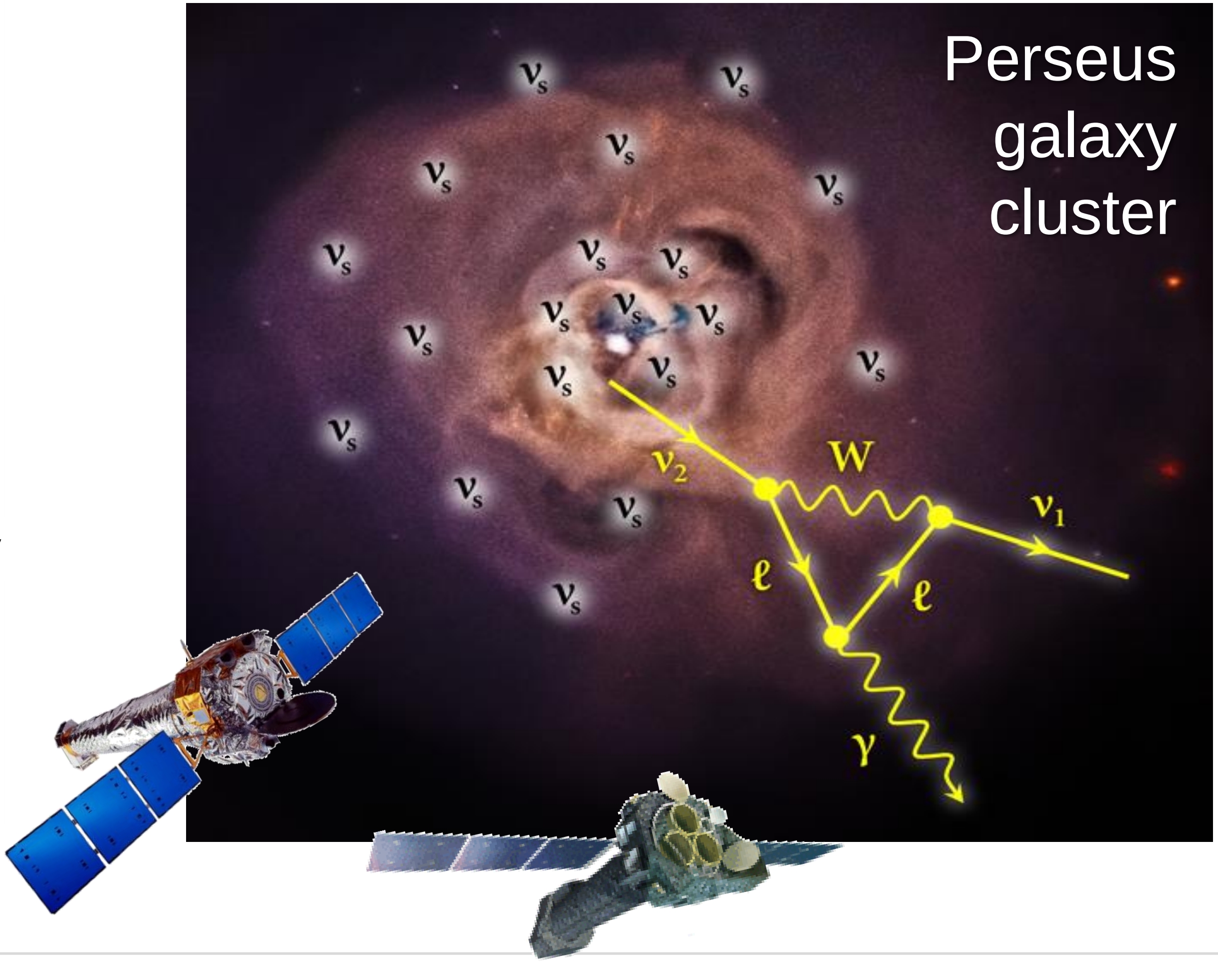
Nature Physics (2022) 18, 160 – 166

KATRIN experiment – future programme

- **Hunting sterile neutrinos at the mass scale m_s of several keV**







νMSM*

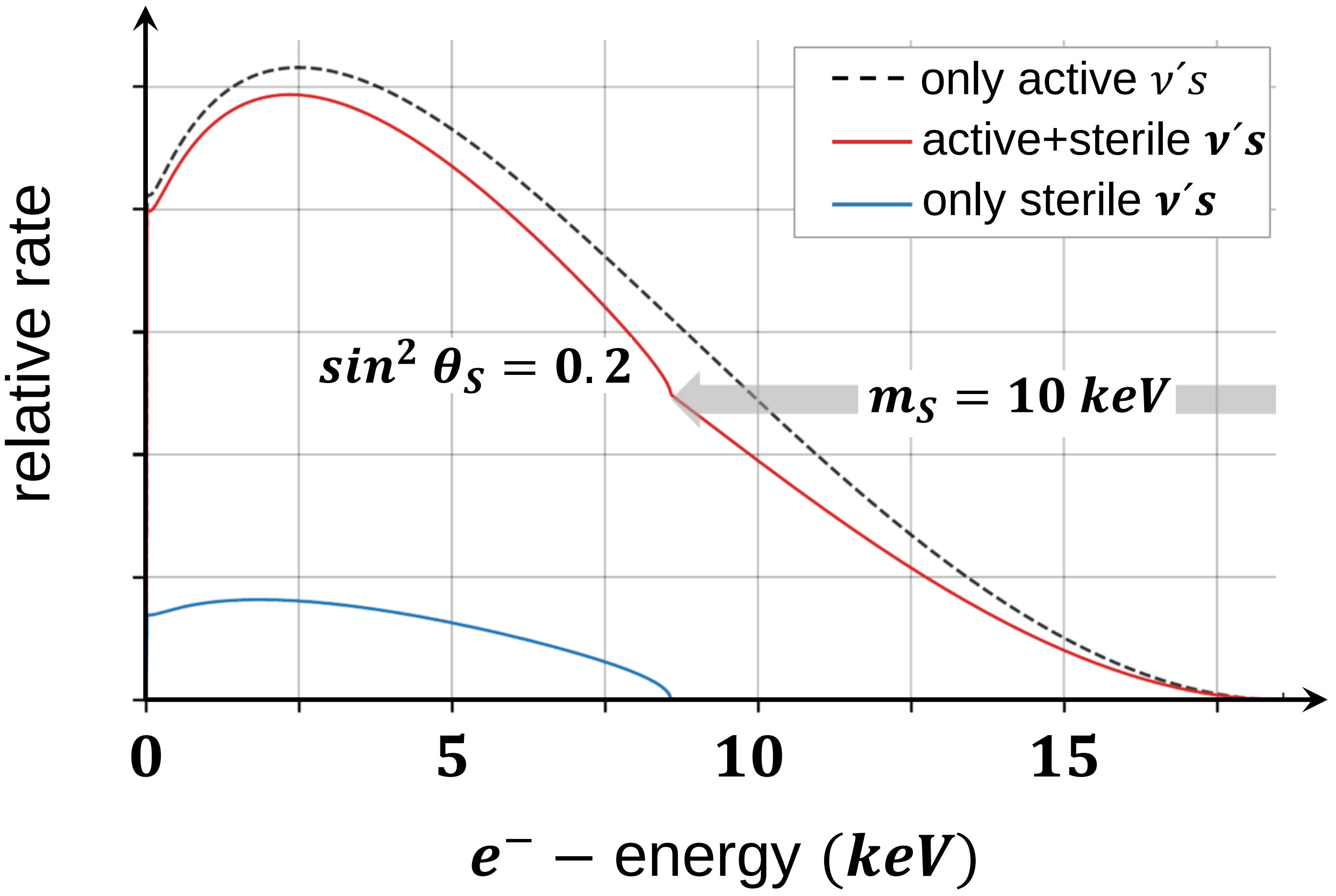
*minimal Standard Model with $keV - \nu$ (RH)

$KATRIN$ experiment – future programme

- **Signature of sterile $\nu's$ at the mass scale of keV via characteristic ´kink´**

- investigate **entire phase space** of β – decay of T_2 : sensitive to masses of ν_S with $m_s < 18\ keV$ and mixing angle $sin^2\theta_s \sim 10^{-6}$

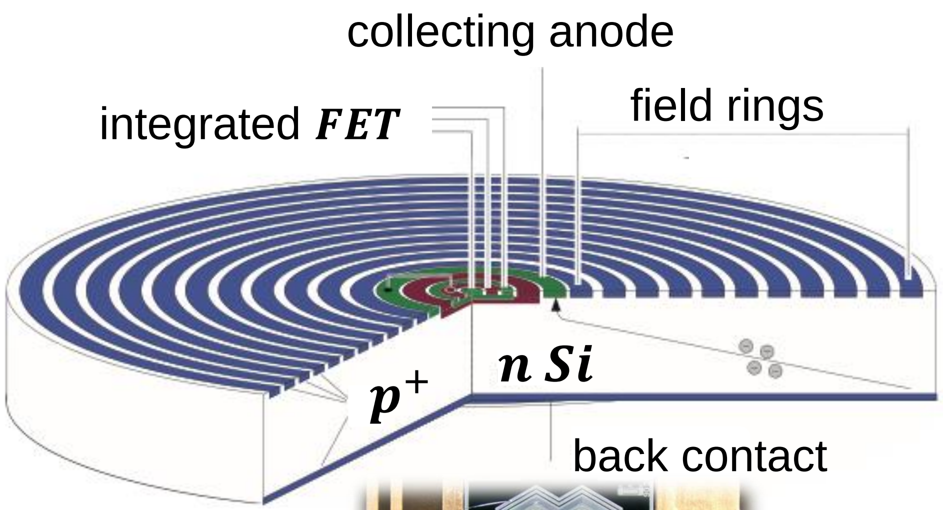
$$dN_i/dE \sim cos^2\theta_s \cdot \frac{dN}{dE} m(\nu_e) + sin^2\theta_s \cdot \frac{dN}{dE}(m_s)$$

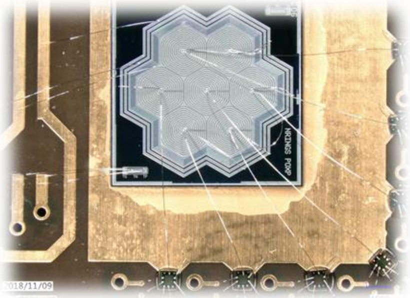


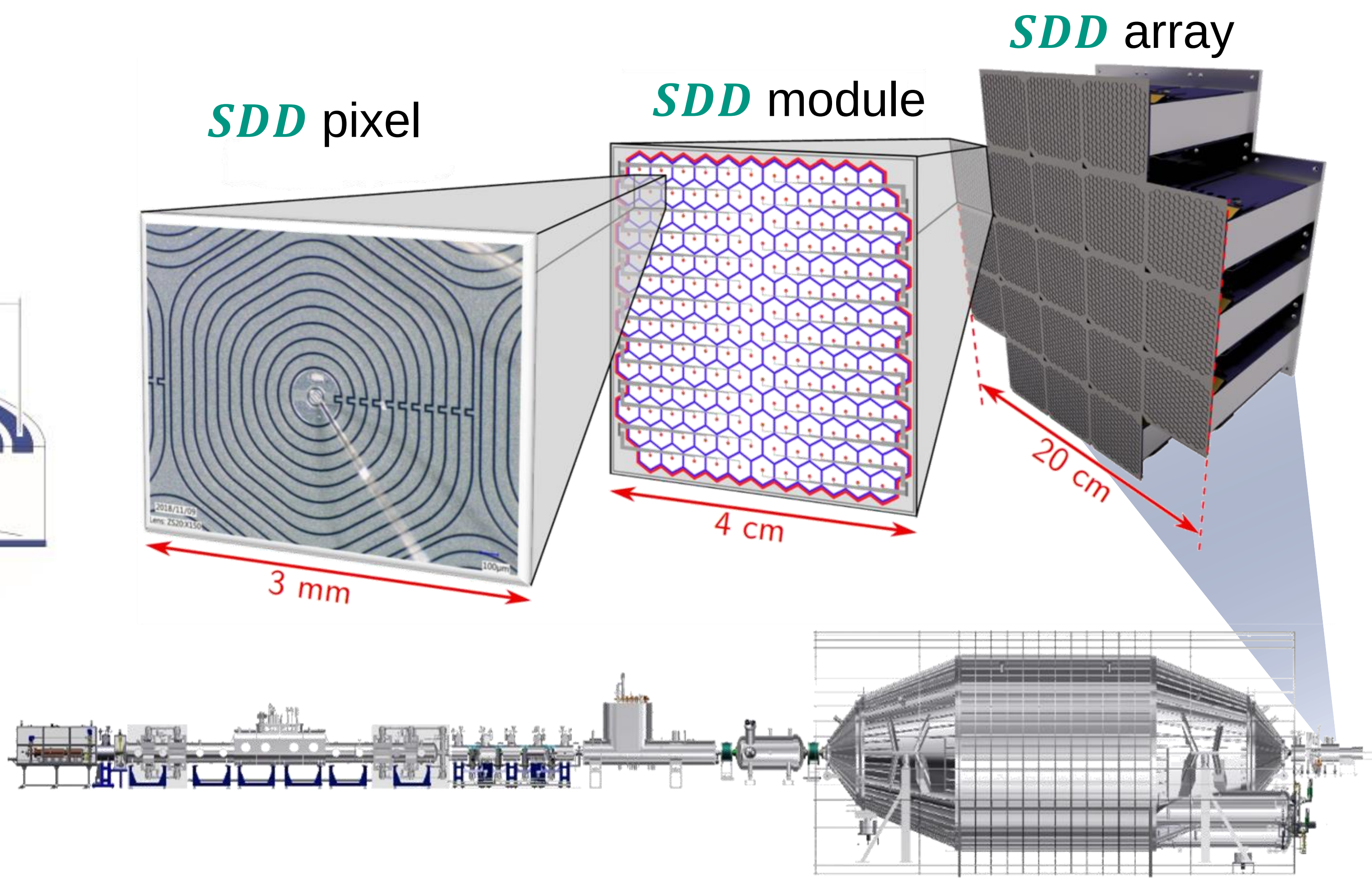
$KATRIN$ experiment – future programme

- **Signature of sterile ν´s requires new detector technology – $SDDs$**

  - novel detector technology:
    ***S**ilicon **D**rift **D**etector*







3.2 Search for $0\nu\beta\beta$ processes

- **Rare event searches: hot on the track of Lepton Number (L) violation**

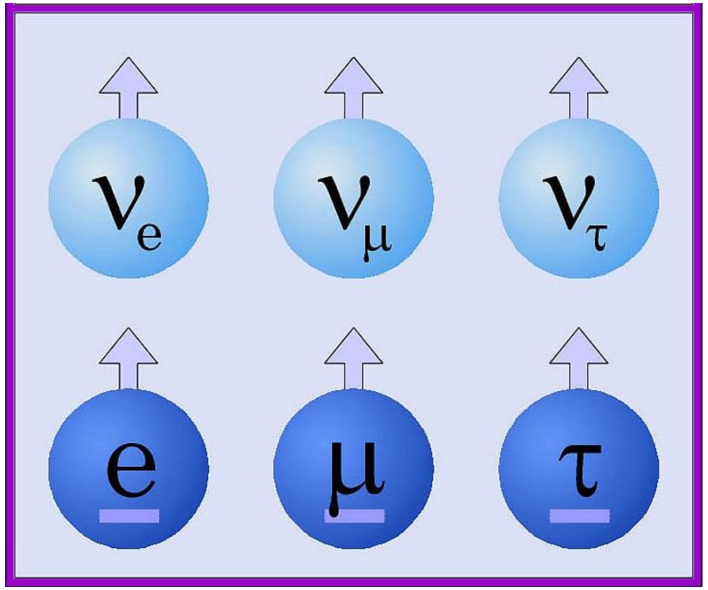
- definition: $L = N(\ell) - N(\bar{\ell})$

ℓ = lepton $\bar{\ell}$ = anti–lepton

- L and L_i : $L = L_e + L_\mu + L_\tau$

- flavour specific L_i: $L_e = +1$ for e^-, ν_e $L_e = -1$ for $e^+, \bar{\nu}_e$

$L_\mu = +1$ for μ^-, ν_μ $L_\mu = -1$ for $\mu^+, \bar{\nu}_\mu$



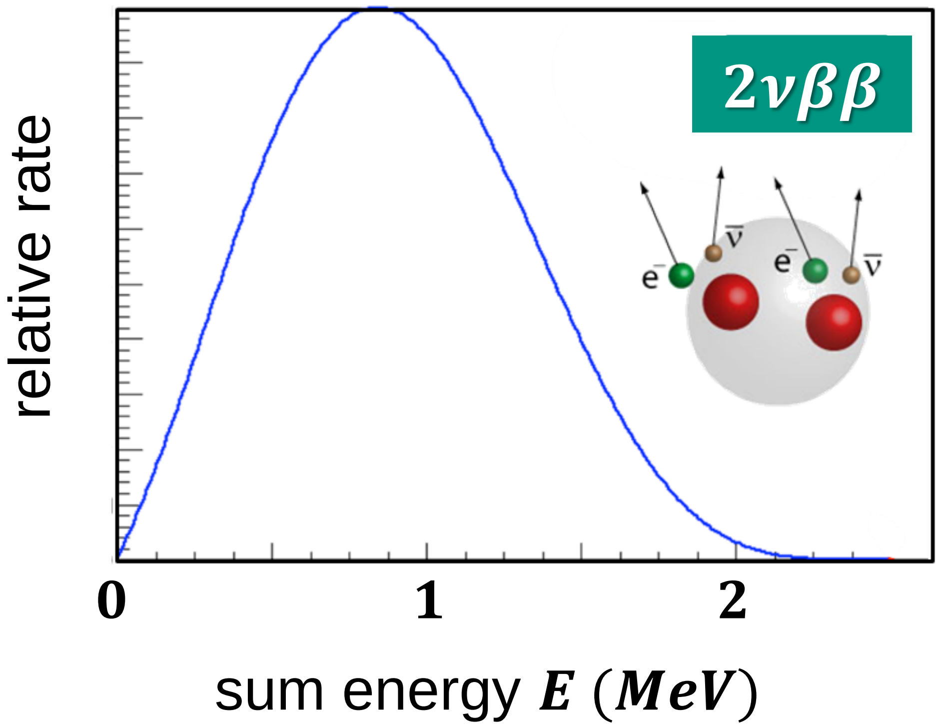
- flavour–specific L_i is ***not*** conserved due to ν – **flavour oscillations*** $(\nu_e \rightarrow \nu_\mu)$, but total lepton number L remains conserved

*see $ATP-2$ summer term 2024

Search for $0\nu\beta\beta$ processes – introduction

- The ´classical´ process $2\nu\beta\beta$: an allowed, second order weak interaction

  - SM – allowed process with **4 particles** in the final state: $2\ e^-$ & $2\ \bar{\nu}_e$
  - small transition rate, as weak interaction process of 2^{nd} order



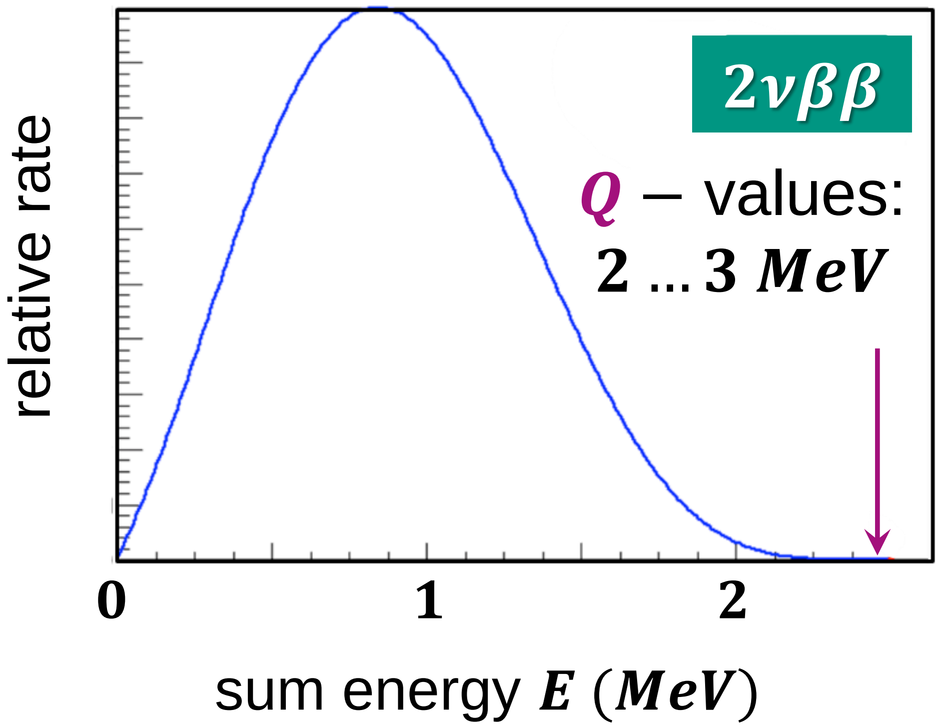
$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^- + \bar{\nu}_{e,1} + \bar{\nu}_{e,2}$$

- $2\nu\beta\beta$: long half–lifes $t_{1/2} \sim 10^{19} \dots 10^{21}\ yr$
- $2\nu\beta\beta$: observed in > 10 isotopes
- similar process: double electron capture $\varepsilon\varepsilon$

Search for $0\nu\beta\beta$ processes – introduction

- **The ´classical´ process $2\nu\beta\beta$: an allowed, second order weak interaction**

  - SM – allowed process with **4 particles** in the final state: $2\ e^-$ & $2\ \bar{\nu}_e$
  - small transition rate, as weak interaction process of 2^{nd} order



- first description of a $2\nu\beta\beta$ – by Maria Goeppert–Mayer (1935)

- first indirect evidence of $2\nu\beta\beta$ – processes (of ^{130}Te) obtained by radiochemical methods already in 1950

Search for $0\nu\beta\beta$ processes – introduction

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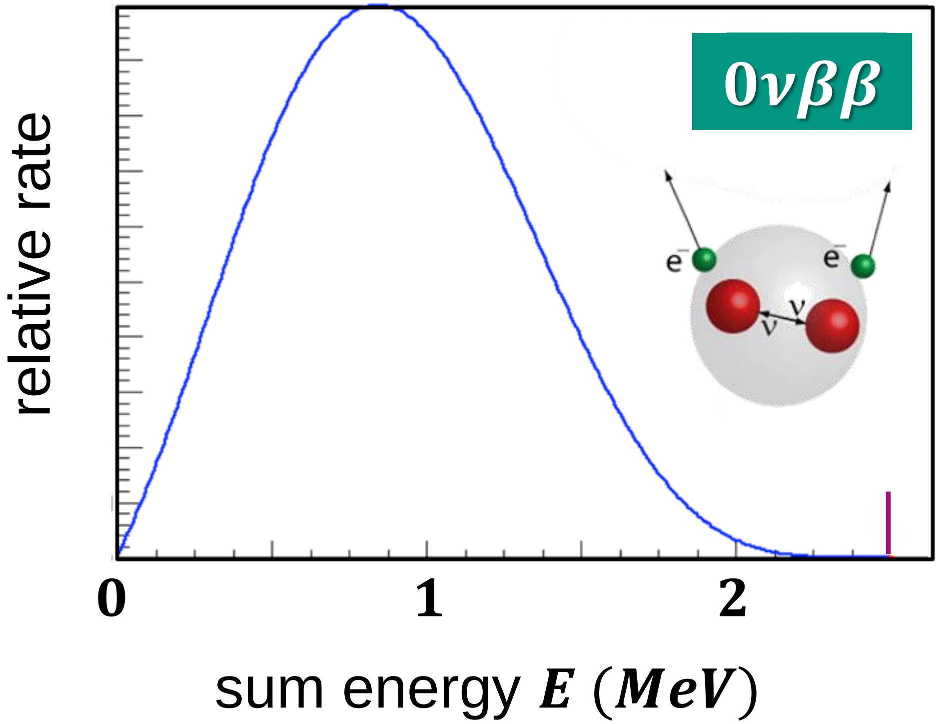
- ´Forbidden´ process $0\nu\beta\beta$: second order weak interaction, no ν – emission

  - SM – forbidden process with 2 particles in the final state: $2\ e^-$
  - extremely small transition rate, allowed only if neutrinos are **Majorana** particles



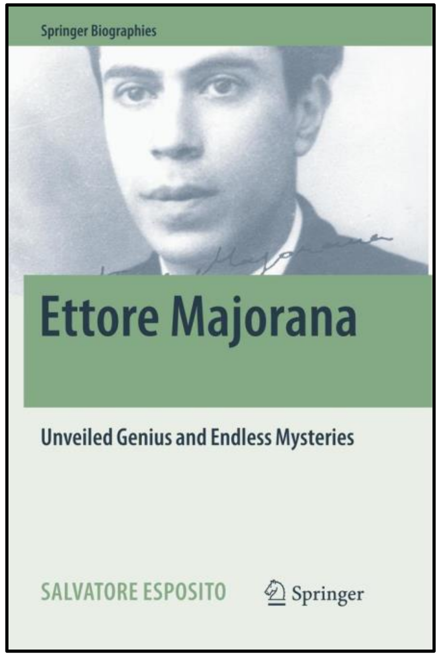
- first description of a $0\nu\beta\beta$ – by George Racah & Ettore Majorana (1937)

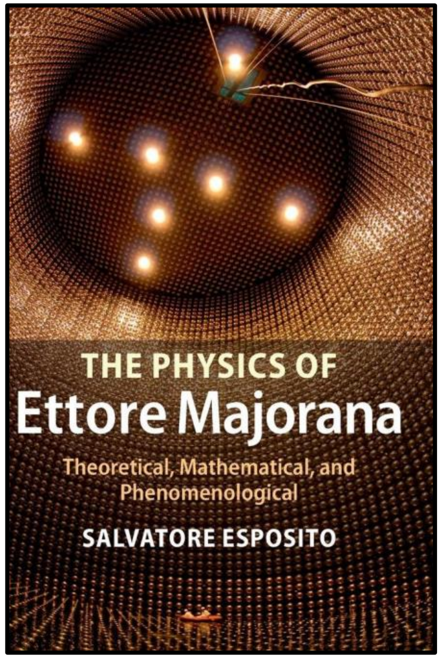
$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^-$$

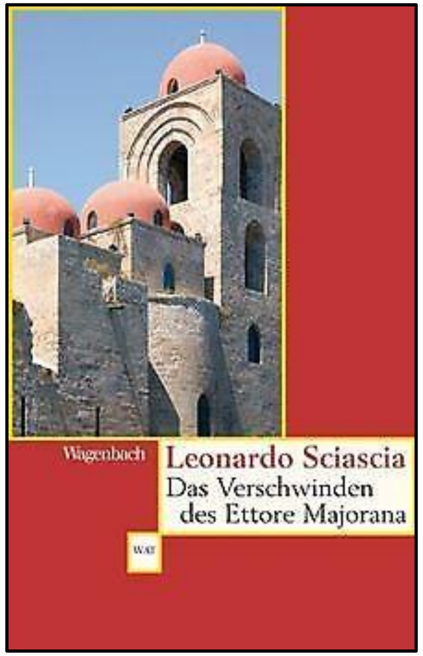
Search for $0\nu\beta\beta$ processes – the search for Ettore

- ´Forbidden´ process $0\nu\beta\beta$: second order weak interaction, no $\nu -$ emission

  “There are several categories of scientists in the world; those of second or third rank do their best but never get very far. Then there is the first rank, those who make important discoveries, fundamental to scientific progress. But then there are the geniuses, like Galilei and Newton. Majorana was one of these.” ***E. Fermi***







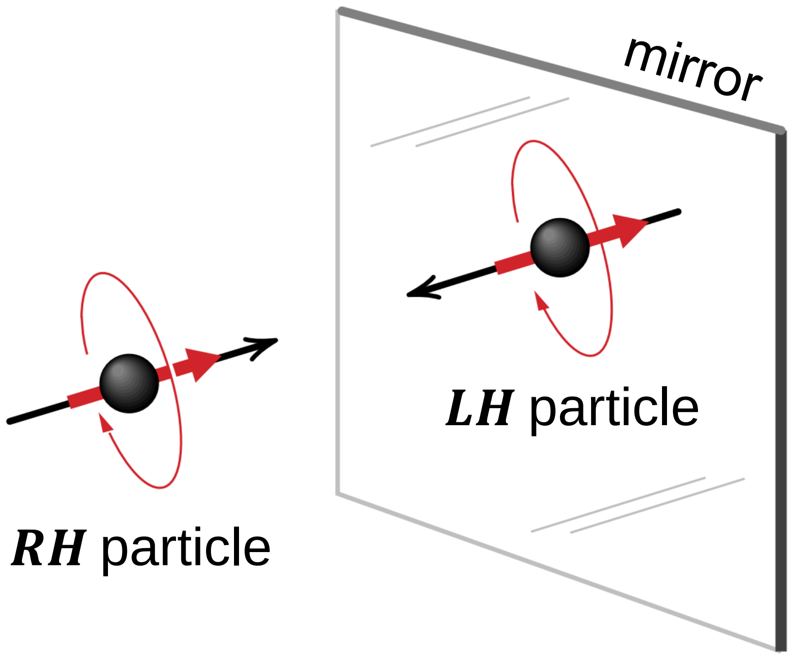
Ettore Majorana (1937)*

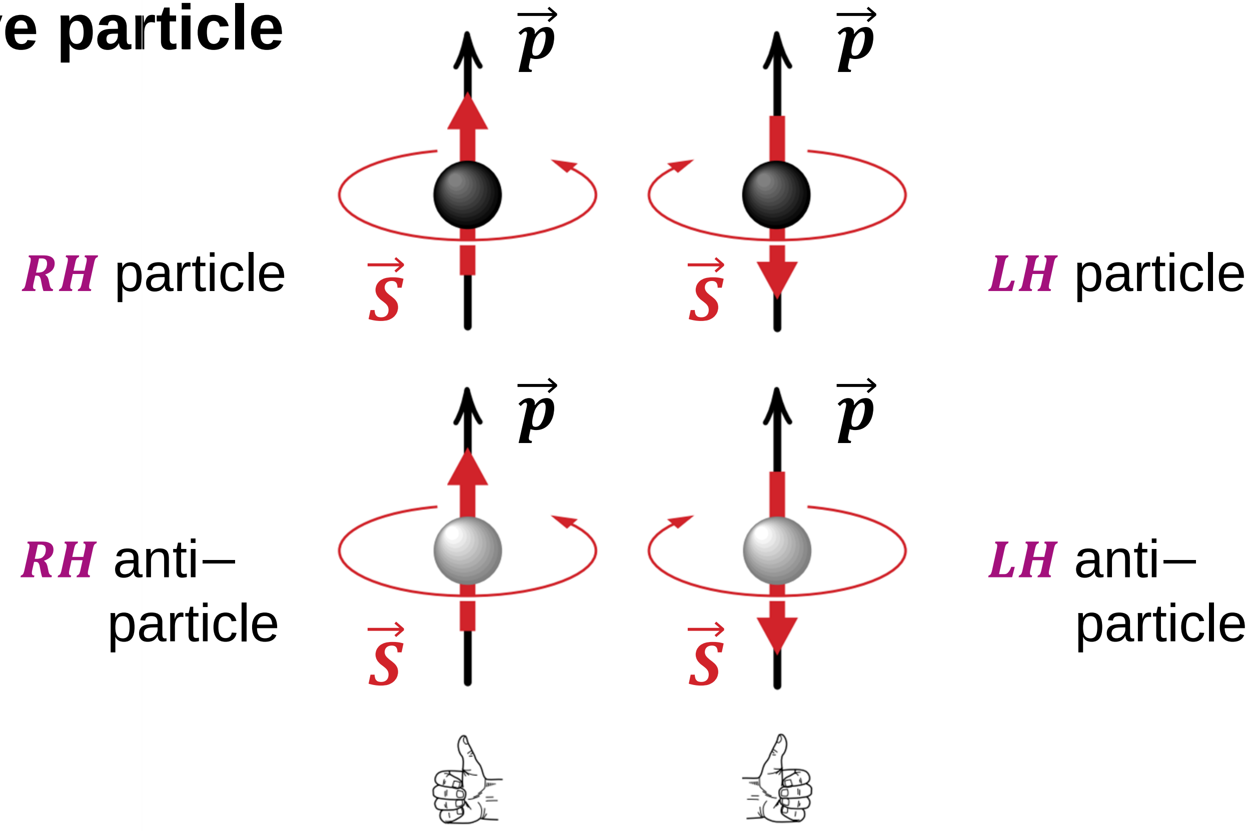
*disappeared on March $25, 1938$

$0\nu\beta\beta$ processes – description via helicity

- **RECAP: helicity states of a massive particle**

- the four states of a spin $s = ½$ particle





- mirror impage of a spin $s = ½$ fermion

$\vec{p}$ (**momentum**) = vector

$\vec{s}$ (**spin**) = pseudo–vector

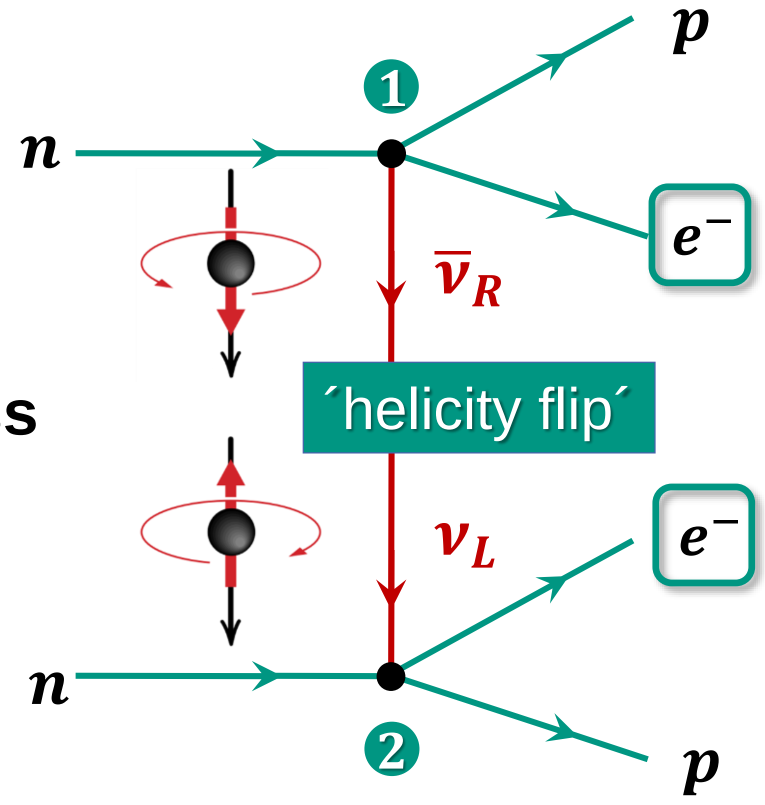
$0\nu\beta\beta$ processes – description

- **Feynman diagram: exchange of a massive Majorana neutrino**

  - the exchanged neutrino undergoes a **helicity flip**

vertex ❶: emission as ***RH*** **state**
from the decay of a $\boldsymbol{n}$

emission



exchange of a **virtual* Majorana−ν with mass**

vertex ❷: absorption as ***LH*** **state**
by a second $\boldsymbol{n}$

absorption

*you cannot observe it!

$0\nu\beta\beta$ processes – description

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- **Feynman diagram: the Racah process**

  - **helicity flip** of the exchanged ν corresponds to a **Majorana mass term**

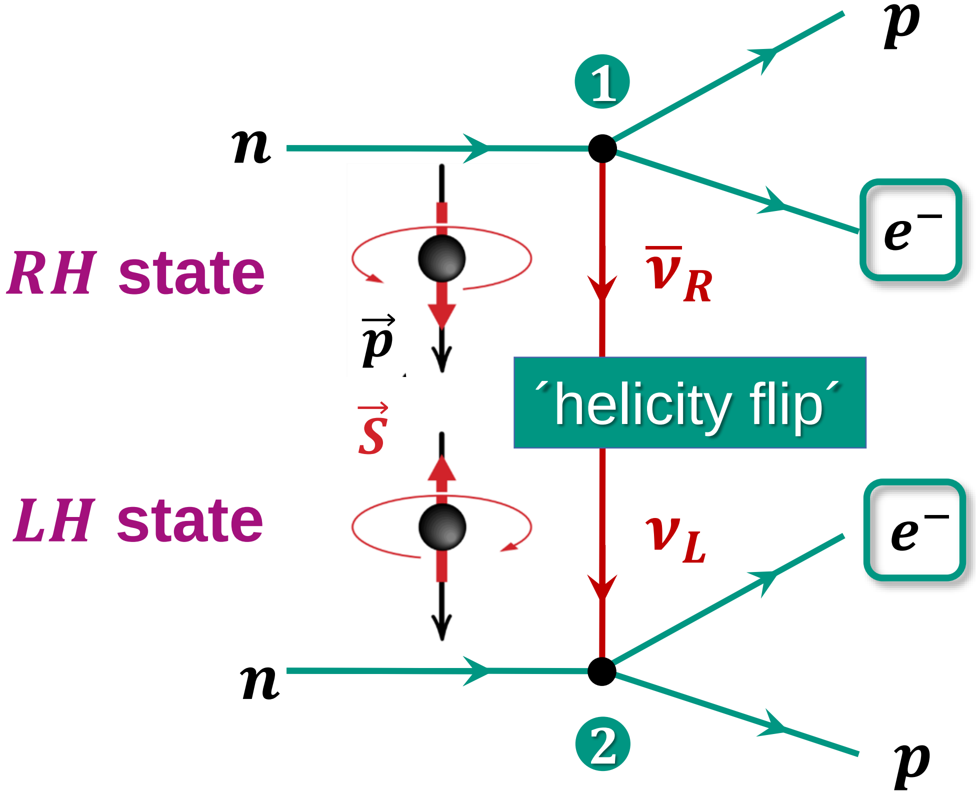
  - intrinsic properties of a Majorana neutrino:

    a) does not carry additive quantum numbers

    - does not carry a **lepton number** L

    - has vanishing electric & magnetic dipole moments $\mu_i = 0$

    b) ´**neutrino is its own antiparticle**´



$0\nu\beta\beta$ processes – kinematics & nuclear size

- nucleons inside nucleus carry a large Fermi momentum $p_F \sim 100\ MeV/c$

  - virtual, light ($m_\nu \sim meV$) Majorana$-\nu$ is **ultra−relativistic** due to

  $$E_\nu \sim p_\nu \sim 100\ MeV$$

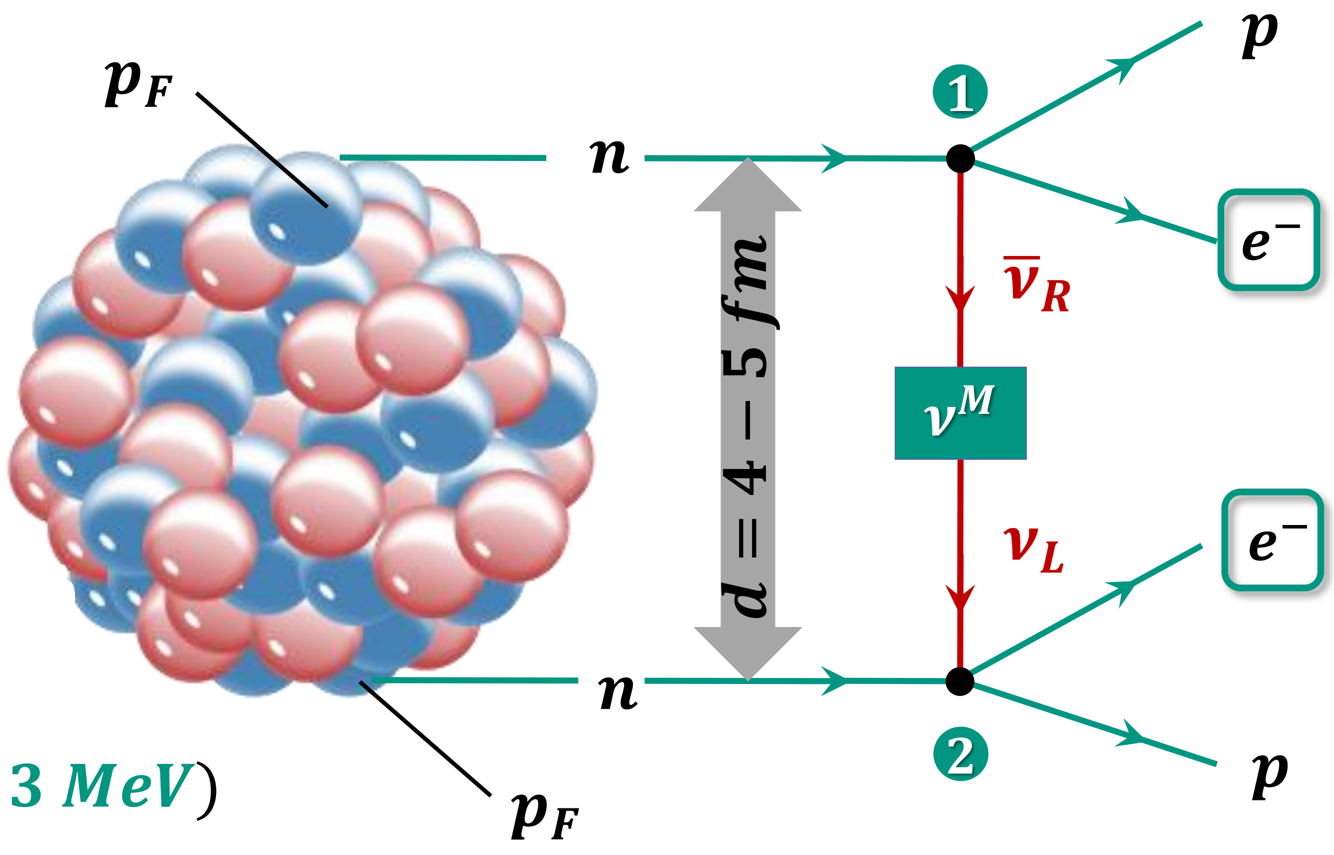
  - travel distance of ν^M between emission & absorption ($2\ n$)

  $$d \sim 4 - 5\ fm$$

  (size of a nucleus)

  - kinematics: compare ν – energy to reaction Q – value:

  $$E_\nu\ (100\ MeV) \gg Q - \text{value}\ (2 \ldots 3\ MeV)$$



$0\nu\beta\beta$ processes – kinematics & nuclear size

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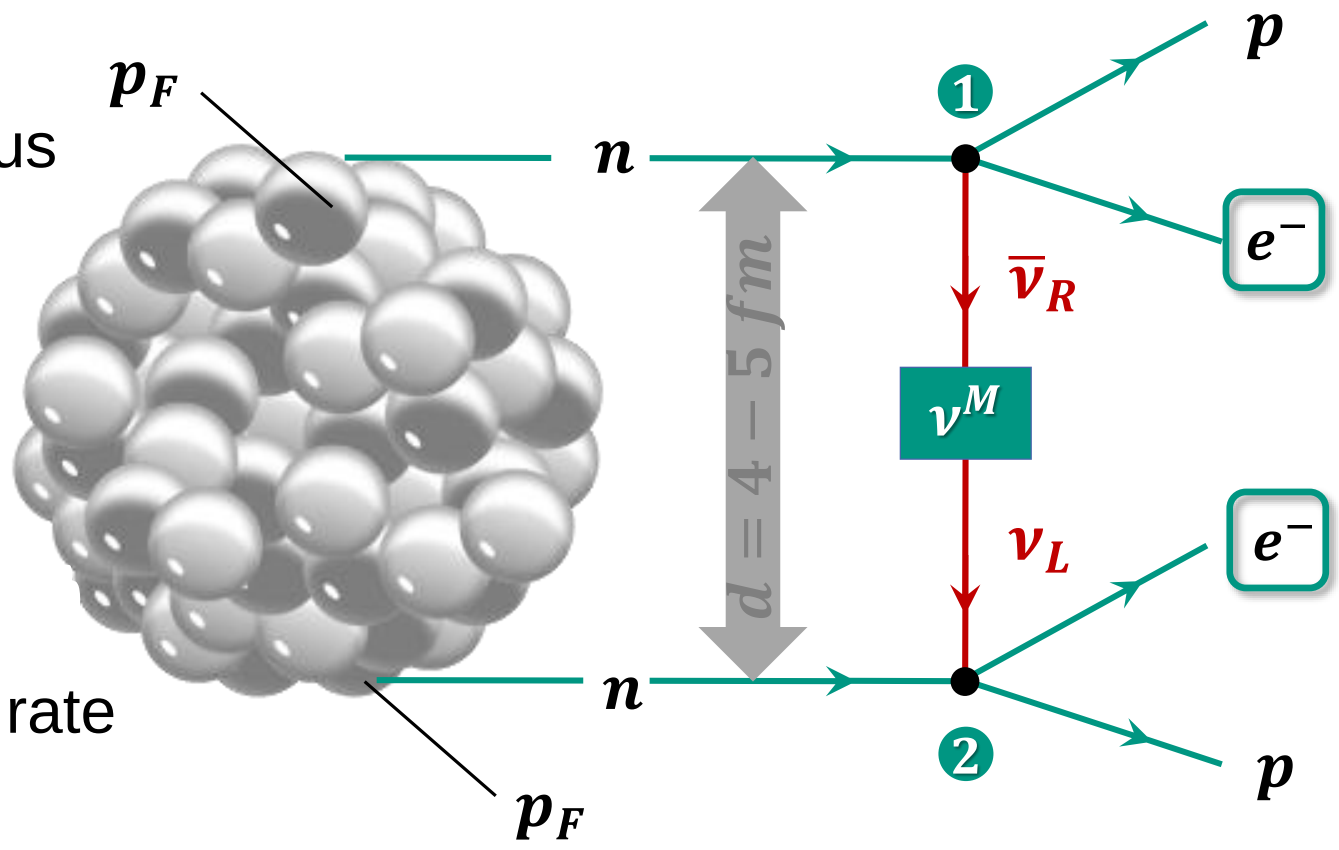
$$E_\nu \sim p_\nu \sim 100\ MeV$$

- expected $0\nu\beta\beta$ – rate should thus be ***larger*** even than β – decay, as it scales as

$$\Gamma \sim (E_\nu/Q)^5 \sim 10^6$$

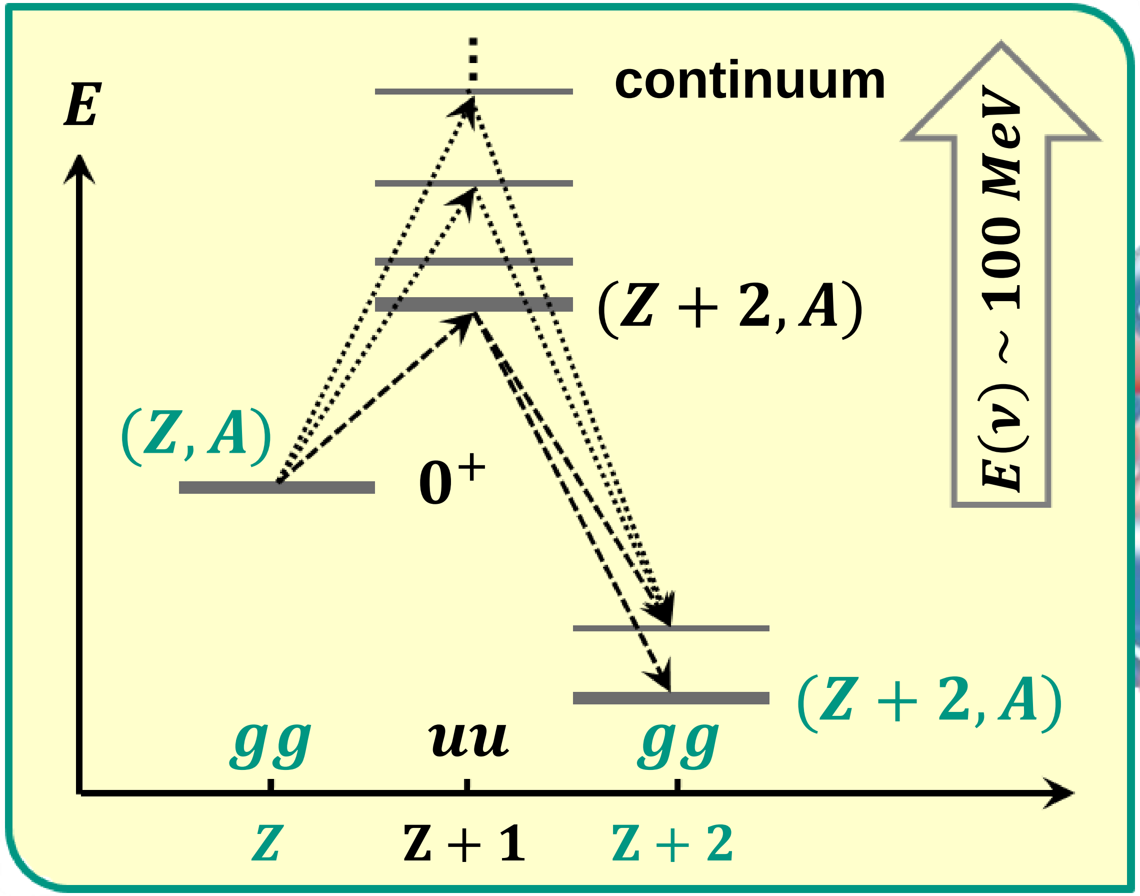
- however, the ultra$-$relativistic nature of neutrinos in $0\nu\beta\beta$ – processes reduces the spin$-$flip rate by many, many, many orders...

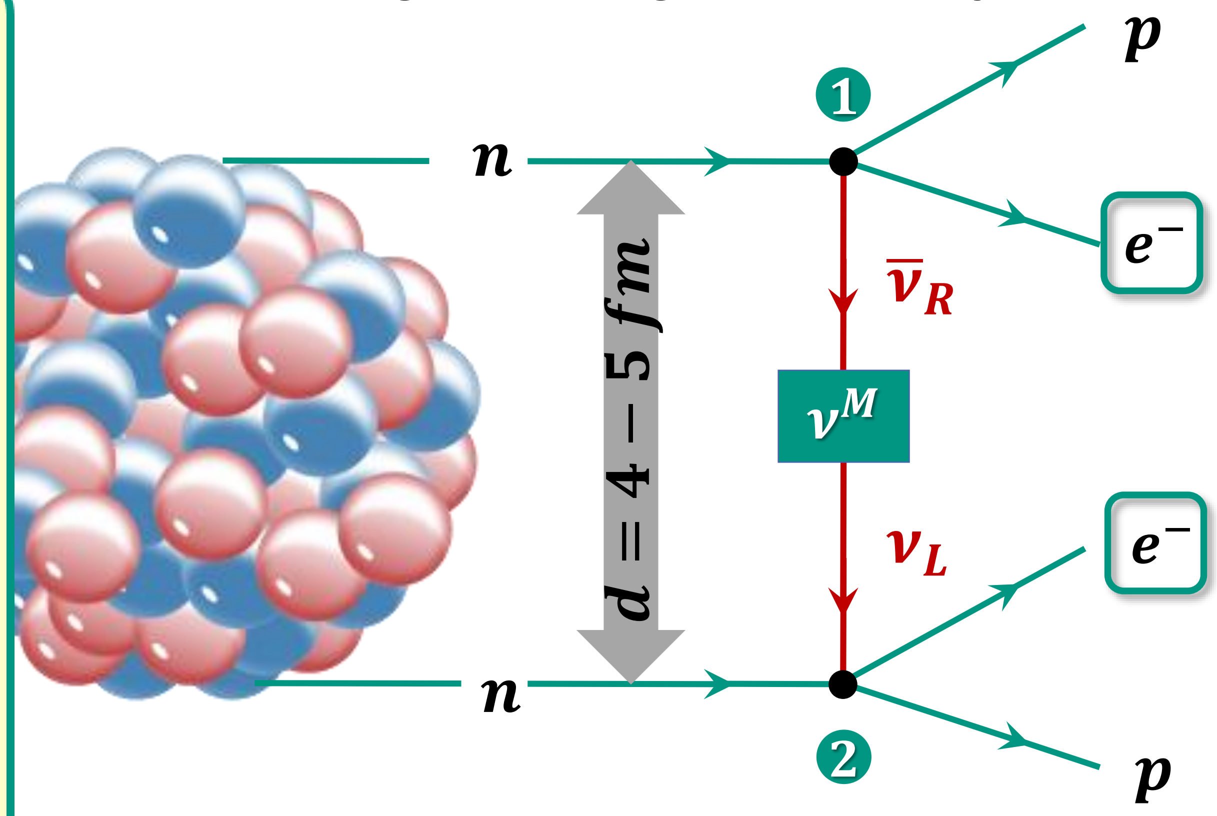


$0\nu\beta\beta$ processes – a ´virtual´ intermediate state

- When going from ^{Z}A nucleus to ^{Z+2}A we form many intermediate states ^{Z+1}A

- this is a big challenge for theory!





$0\nu\beta\beta$ processes – ´virtual´ nature of Majorana – ν

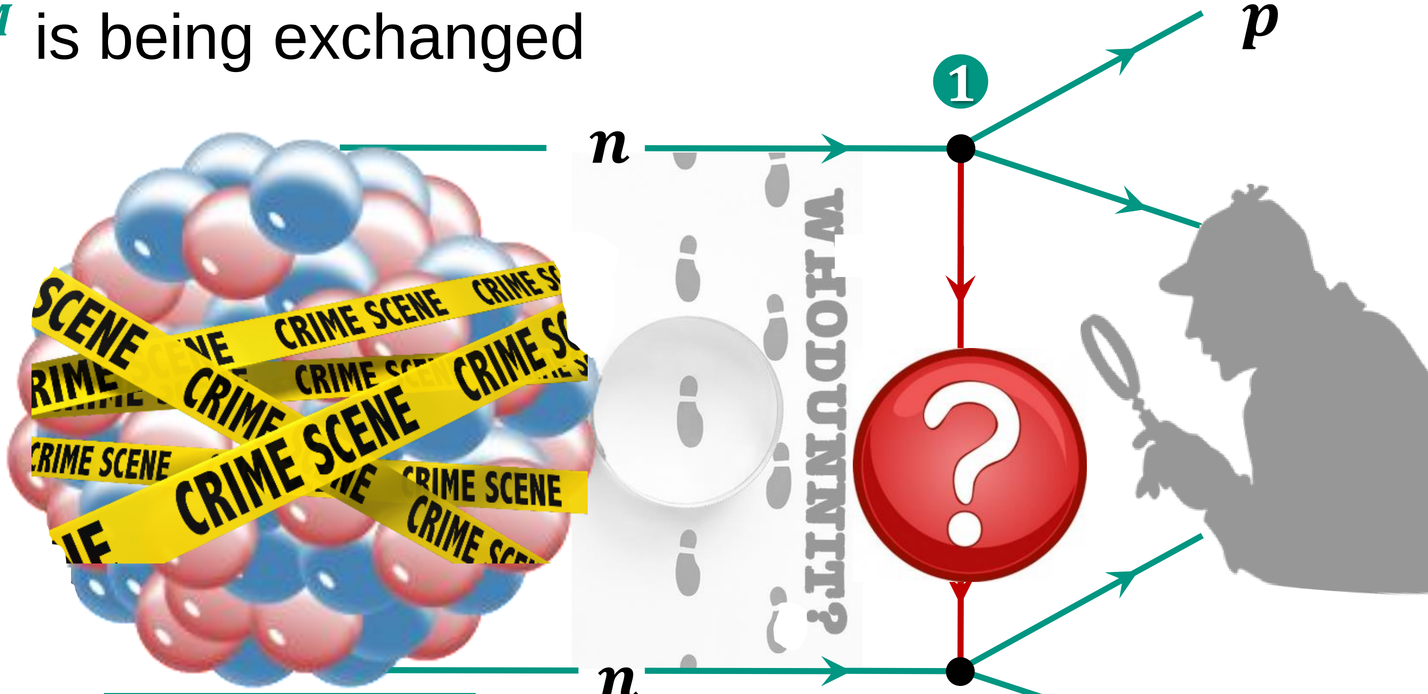
Karlsruhe Institute of Technology

- **Which virtual (!) particle is exchanged between the two neutrons?**

  - expected rate of $\mathbf{0\nu\beta\beta}$ – events is usually calculated under the assumption that **ONLY** a **light ν^M** is being exchanged

  - new particles at the TeV – scale (neutralinos, lepto–quarks) could modify the $\mathbf{0\nu\beta\beta}$ – rate

  - new physics at the TeV – scale (RH weak currents with W_R – bosons) could modify the $\mathbf{0\nu\beta\beta}$ – rate

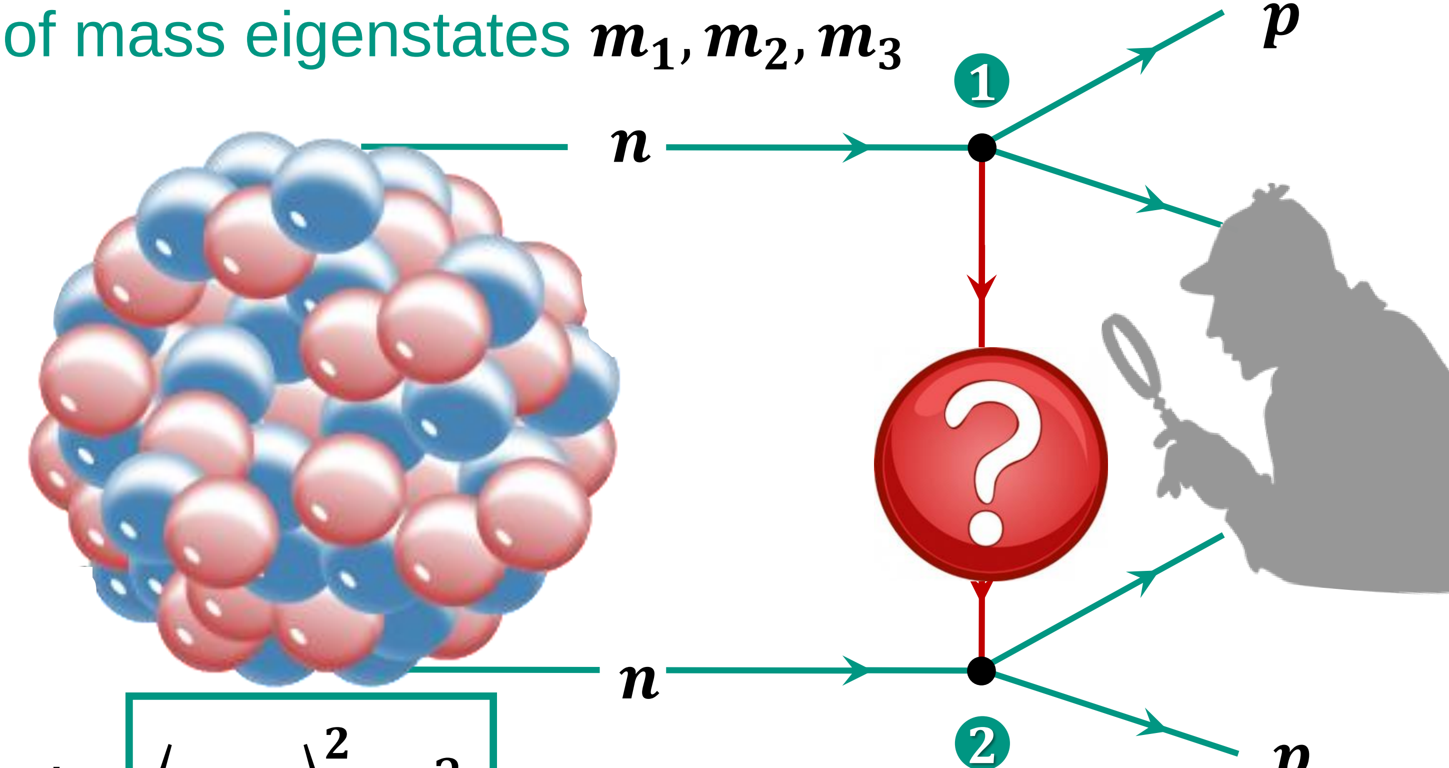


$$\langle m_{\beta\beta}\rangle^2 = ?$$

$0\nu\beta\beta$ processes – ´virtual´ nature of Majorana – ν

- **How do the mass eigenstates m_1, m_2, m_3 interfere in $0\nu\beta\beta$?**

- rate of $0\nu\beta\beta$ – events depends on the effective Majorana ν – mass $m_{\beta\beta}$ which is the ***coherent sum*** of mass eigenstates m_1, m_2, m_3



virtual quantum states **interfere**!

$$\langle m_{\beta\beta} \rangle^2 = ?$$

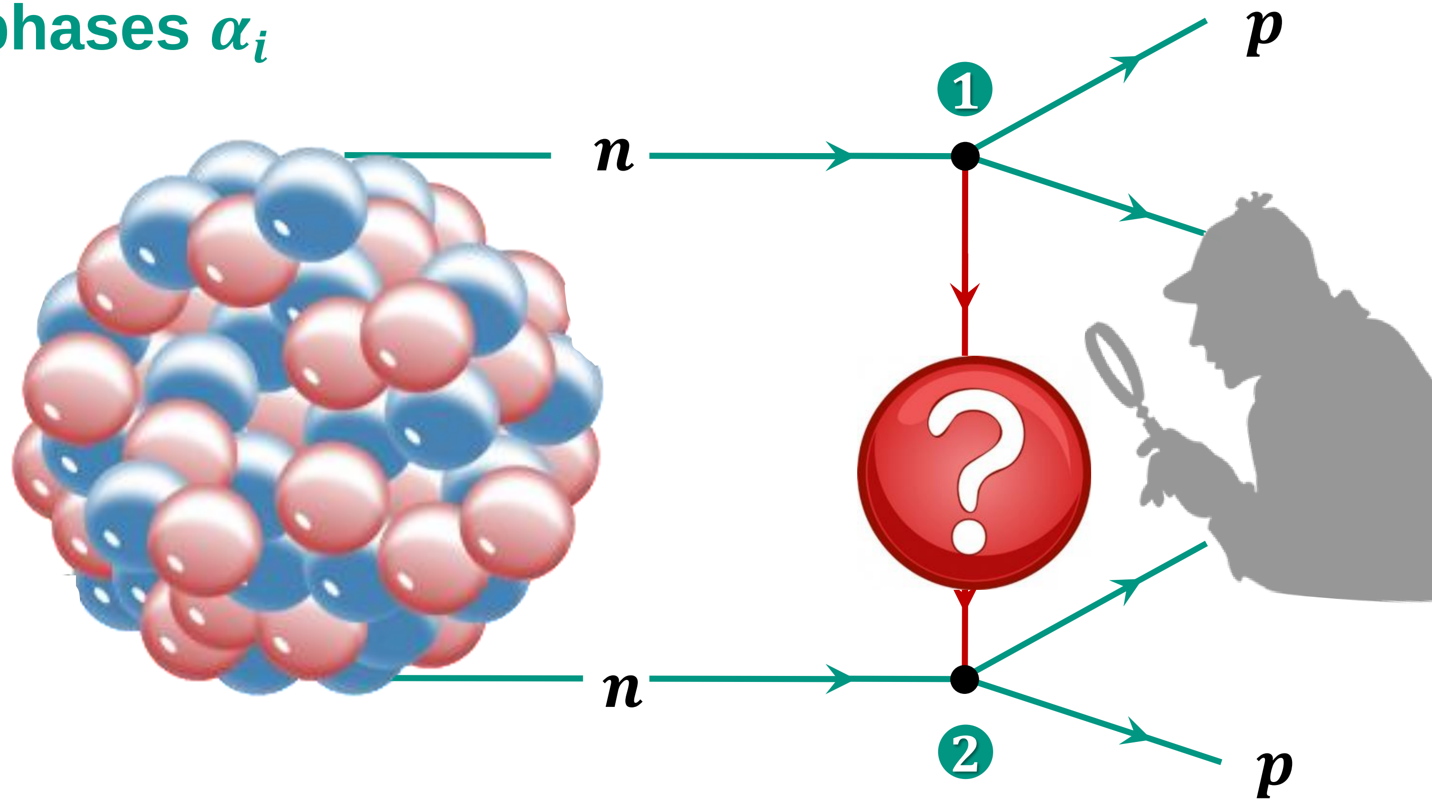
$0\nu\beta\beta$ processes – CP phases of Majorana – ν´s

- **How do the mass eigenstates m_1, m_2, m_3 interfere in $0\nu\beta\beta$?**

  - rate of $0\nu\beta\beta$ – events depends on more unknown parameters: the important **Majorana CP – phases α_i**

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i \cdot e^{i\alpha_i}\right|$$

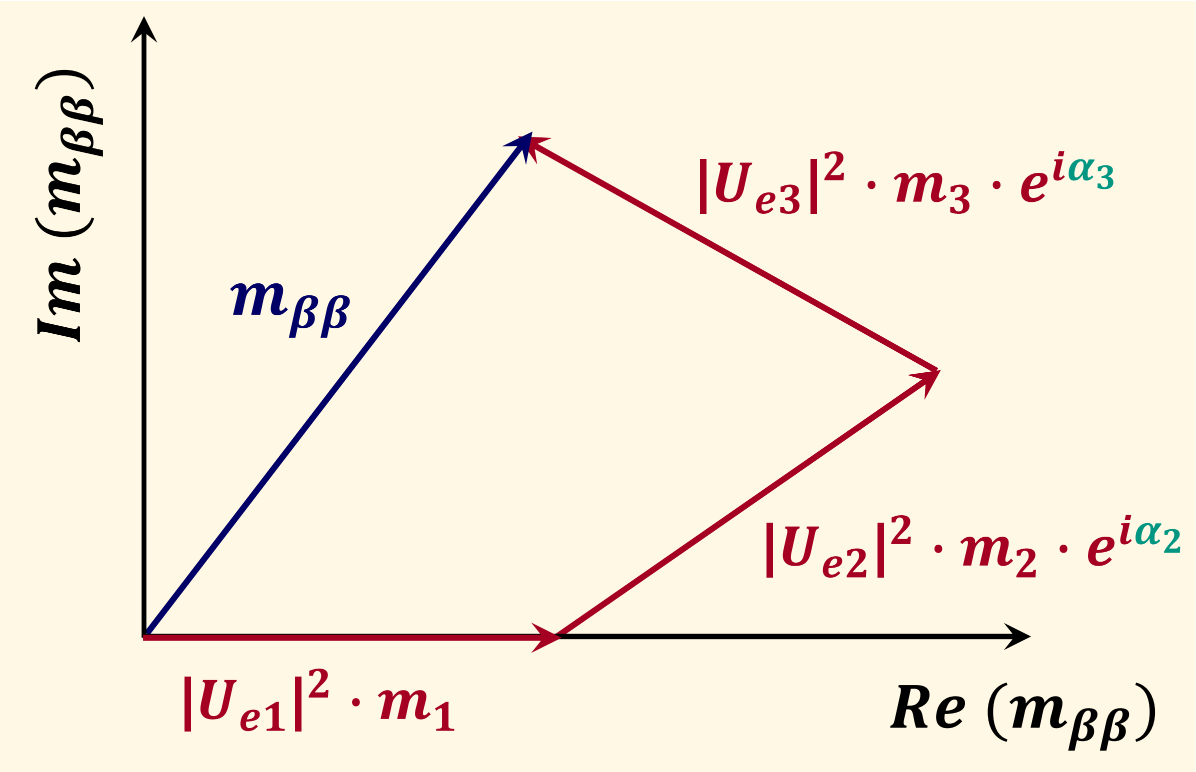
two independent phases:
⇨ can result in **cancellations**

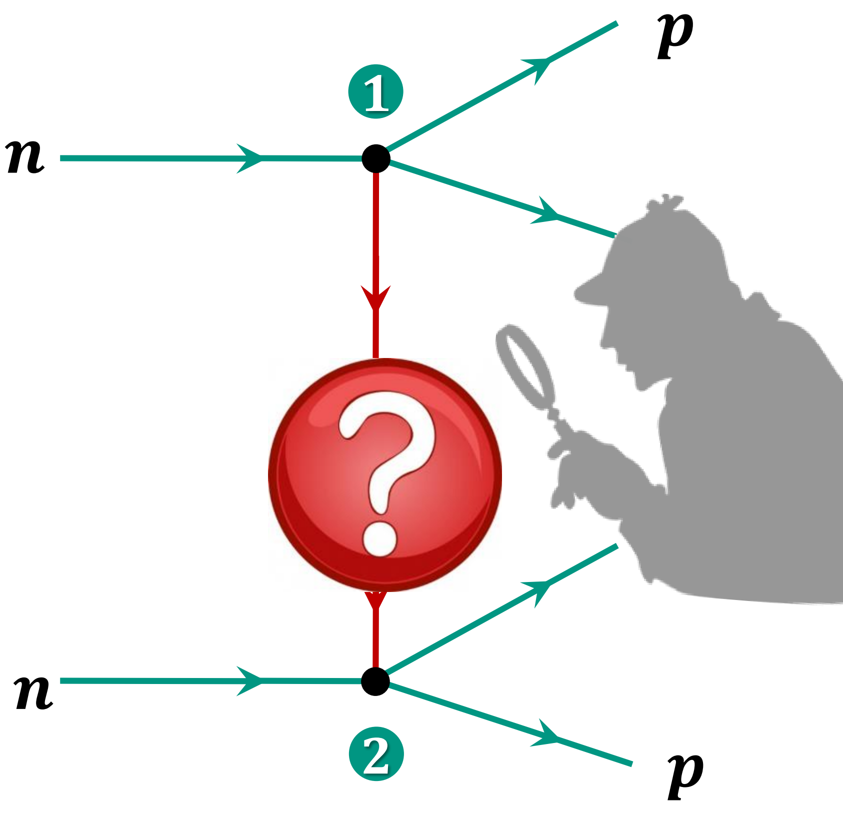


$0\nu\beta\beta$ processes – CP phases of Majorana – ν´s

- **How do the mass eigenstates m_1, m_2, m_3 interfere in $0\nu\beta\beta$?**

  - rate of $0\nu\beta\beta$ – events depends on two* more unknown parameters: the important **Majorana CP – phases α_i**



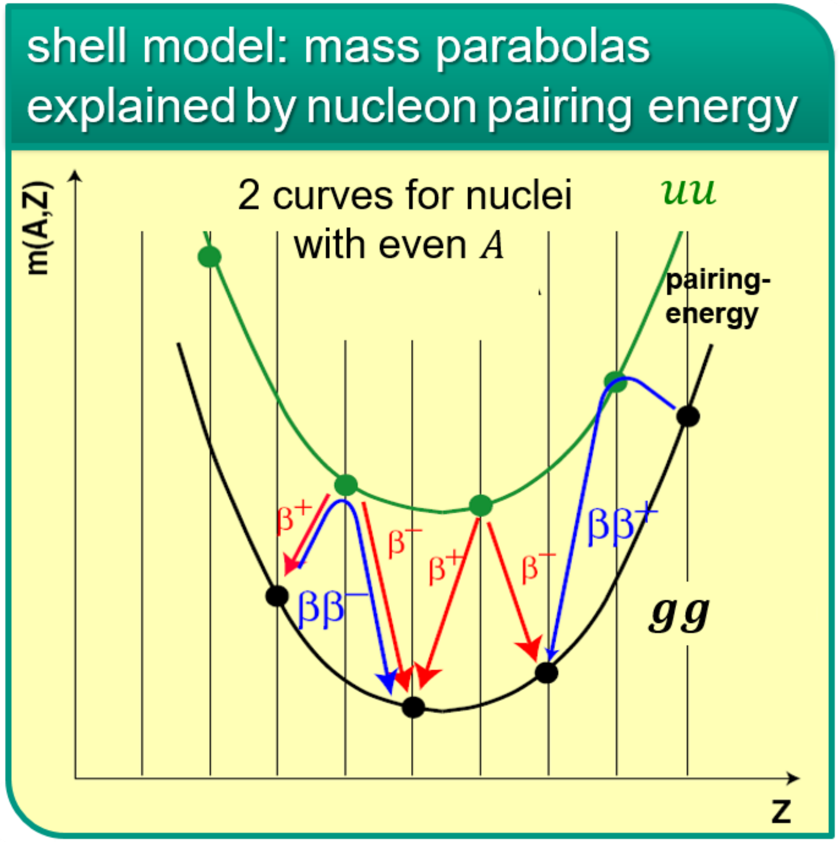


*we can set $\alpha_1 = 0$

$0\nu\beta\beta$ processes: gg – isotopes as target

- **Double beta decay is only possible for gg – nuclei**

  - mass parabolas of gg and uu nuclei



	Q – value	relative abundance %
$^{48}Ca \rightarrow {}^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow {}^{76}Se$	2.040	7.8
$^{82}Se \rightarrow {}^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow {}^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow {}^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow {}^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow {}^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow {}^{124}Te$	2.228	5.64
$^{130}Te \rightarrow {}^{130}Xe$	2.530	**33.8**
$^{136}Xe \rightarrow {}^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow {}^{150}Sm$	**3.367**	5.6

$0\nu\beta\beta$ processes: gg – isotopes as target

- **Double beta decay is only possible for gg – nuclei**

  - **11** isotopes with $Q_{\beta\beta} > 2\ MeV$
  - **3** promising isotopes especially suited to perform a high–sensitivity $0\nu\beta\beta$ search

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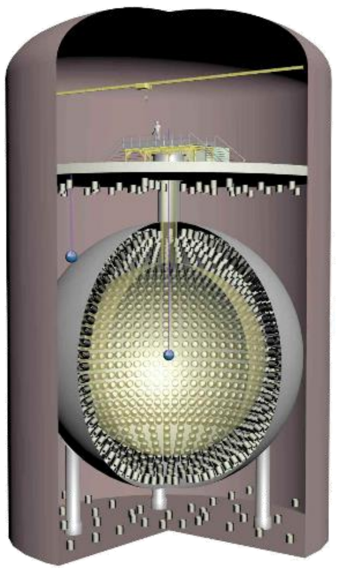
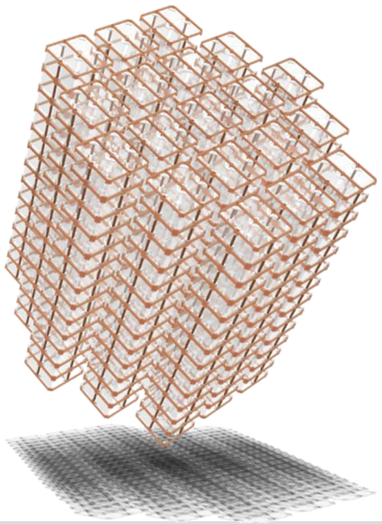
^{76}Ge

^{136}Xe



^{130}Te



$0\nu\beta\beta$ processes: gg – isotopes as target

- Use of gg – isotopes as **active detector target**

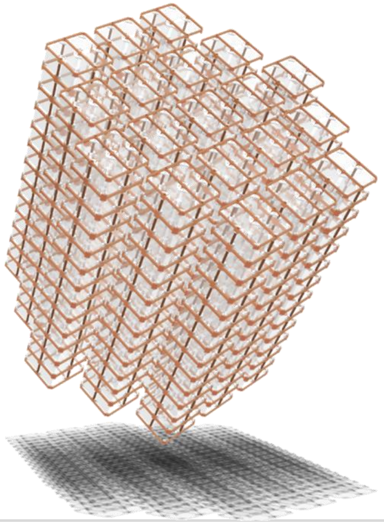
$\beta\beta$ – signal via

ionization of a solid state detector	heat deposit in cryogenic quantum sensor

^{76}Ge

active target = detector

^{130}Te



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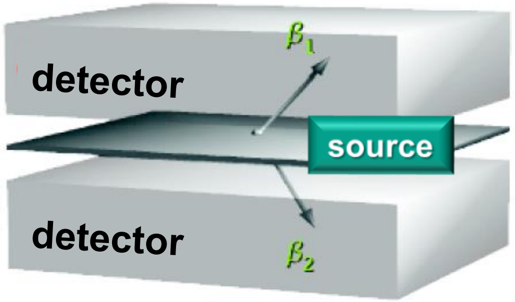
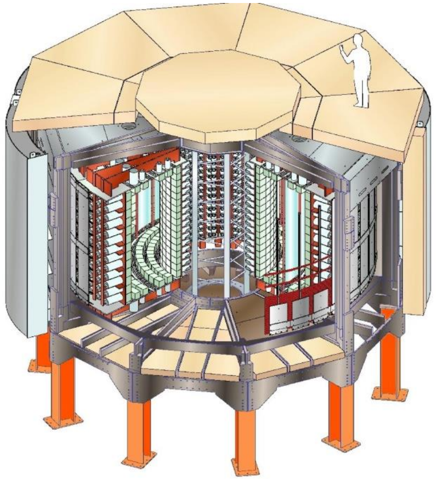
$0\nu\beta\beta$ processes: gg – isotopes as target

- Use of gg – isotopes as **passive target**

^{100}Mo

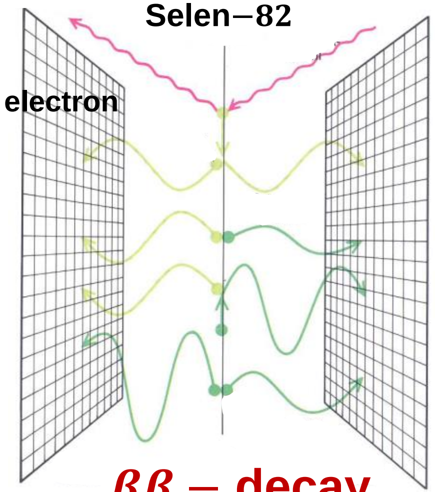


^{82}Se



$NEMO-3$

passive target
=
thin foil, wires, …



$\beta\beta$ – decay

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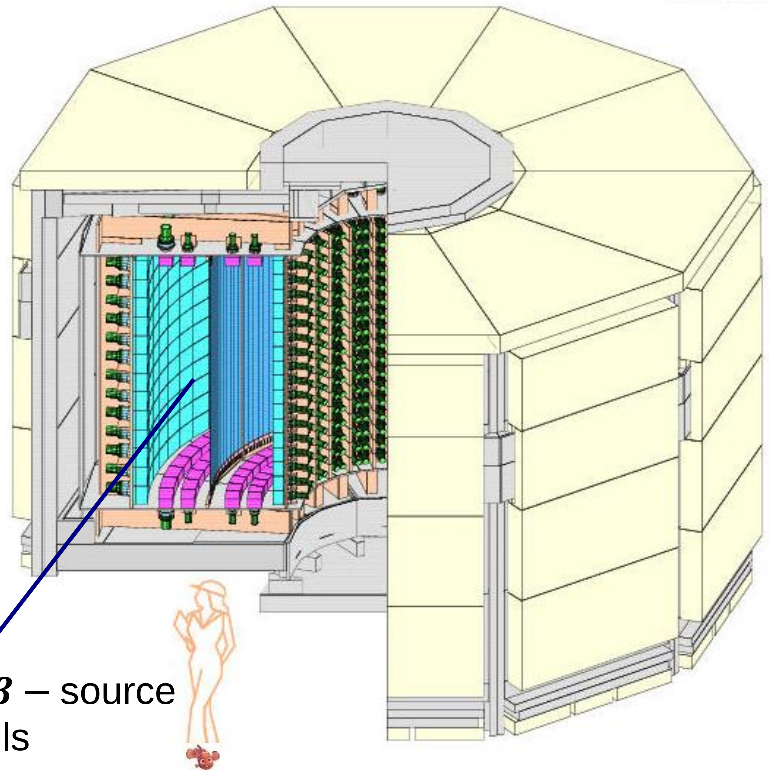
$0\nu\beta\beta$ processes: gg – isotopes as target

- Use of gg – isotopes as **passive target:** example $NEMO$

*N*eutrino *E*ttore *M*ajorana *O*bservatory at ***Modane*** underground laboratory



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