The target for relic neutrino detection. An overview.

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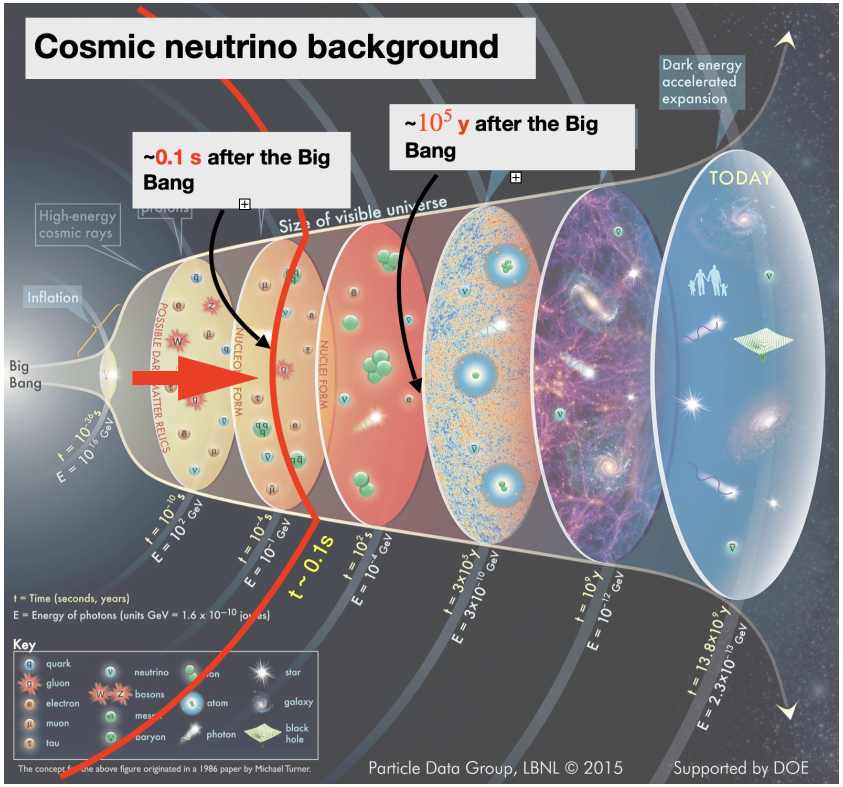
CνB and CMB

- Gamov: Early Universe is **radiation dominated** $\rho_{\text{rad}}/\rho_{\text{matter}} \sim 10^{10}$.
- Early Universe has equal populations of γ/ν.
- As Universe expands, γ/ν decouple, relic backgrounds (CMB /CνB), keep a **"frozen" pictures of the Universe**.
- Right now, in your room, there are 411 relic photons and 339 relic neutrinos in every $1\,\text{cm}^3$.
- The "ν - freezout" is much **earlier** than photons.
- CνB: one of the few yet **untested predictions of the SM**.



Detecting CνB is a strategic goal for fundamental physics.
[Weinberg , 1962]

Why have we not discovered CνB yet?

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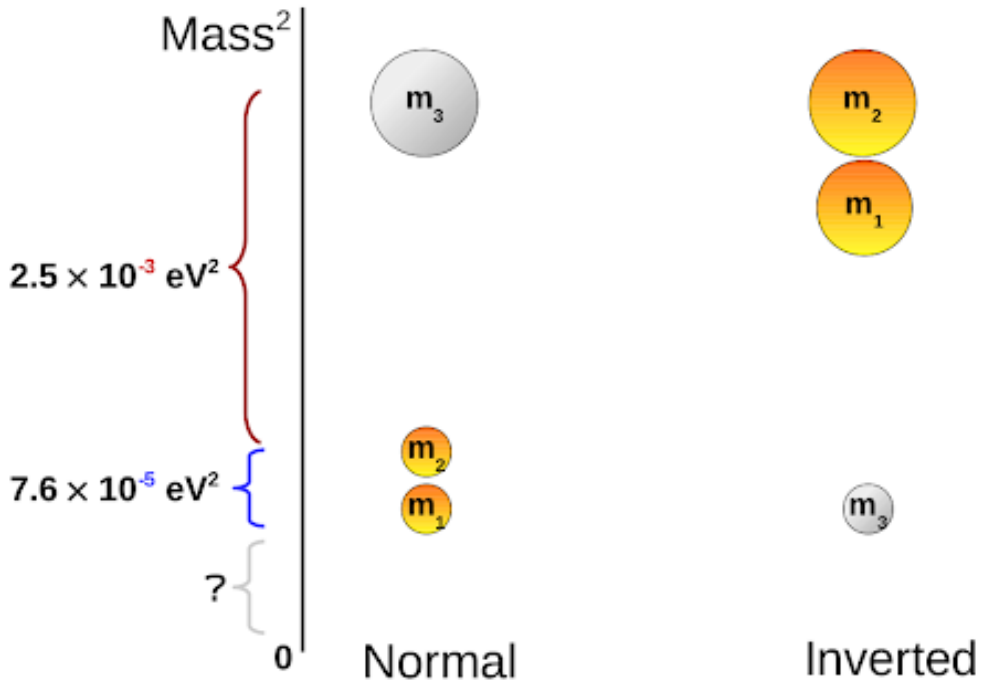
Bethe and Peierls in 1934 estimated

$$\sigma \sim 10^{-44}\ \text{cm}^2$$
$$\sigma_{\text{Thomson}} \sim 10^{-25}\ \text{cm}^2$$
$$\sigma_{\text{nuclear}} \sim 10^{-26}\ \text{cm}^2$$

''I have done a terrible thing. I have postulated a particle that cannot be detected.'' (W. Pauli)

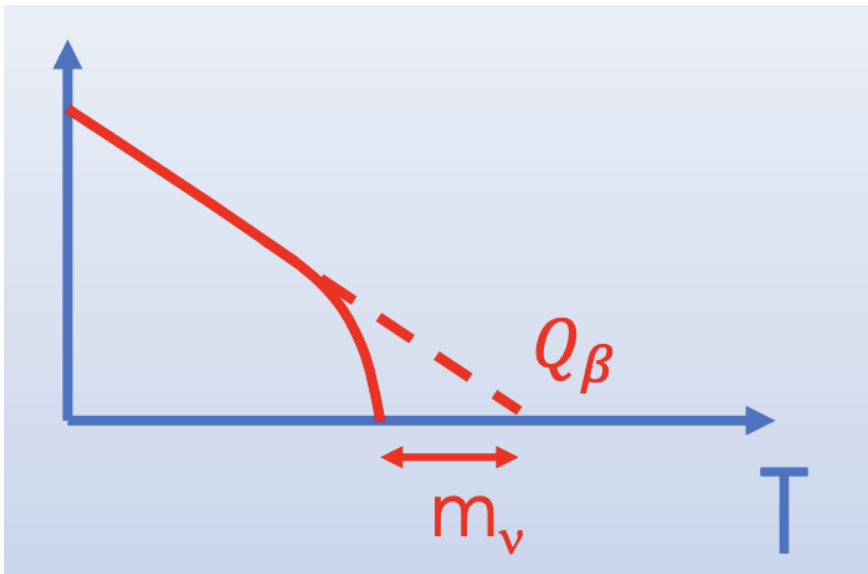
Neutrinos are massive

- In the last few decades neutrino flavor oscillations where convincingly observed, meaning that neutrinos are **massive**
- Neutrino oscillations can only measure Δm and hierarchy.



β-decay and neutrino capture

$$(A, Z) \rightarrow (A, Z+1) + e^- + \bar{\nu}_e$$



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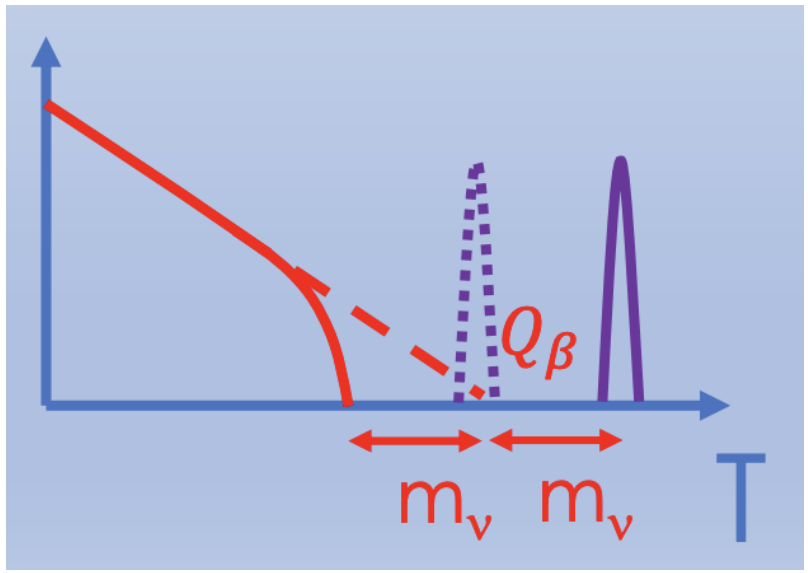


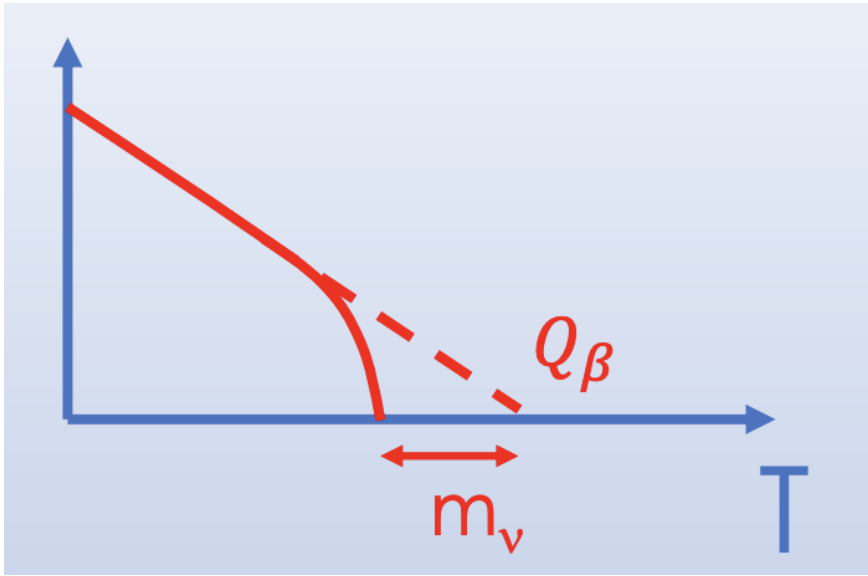
- Neutrino capture is **threshold-less** – soft relic neutrino detection [Weinberg, 1962].
- The 2 parts of the spectrum are separated by $2m_\nu$ [1]
- Before the relic neutrino detection one would be able to measure the neutrino mass m_ν

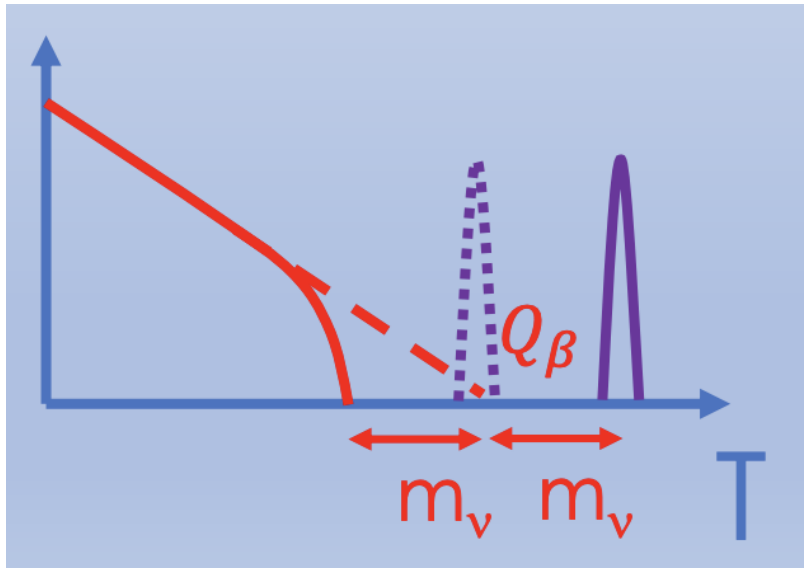
[1] Schematic picture that assumes only one neutrino flavour.

Relic neutrinos leave a signature in the spectrum of a radioactive atom

Is this goal technically achievable?

Challenges

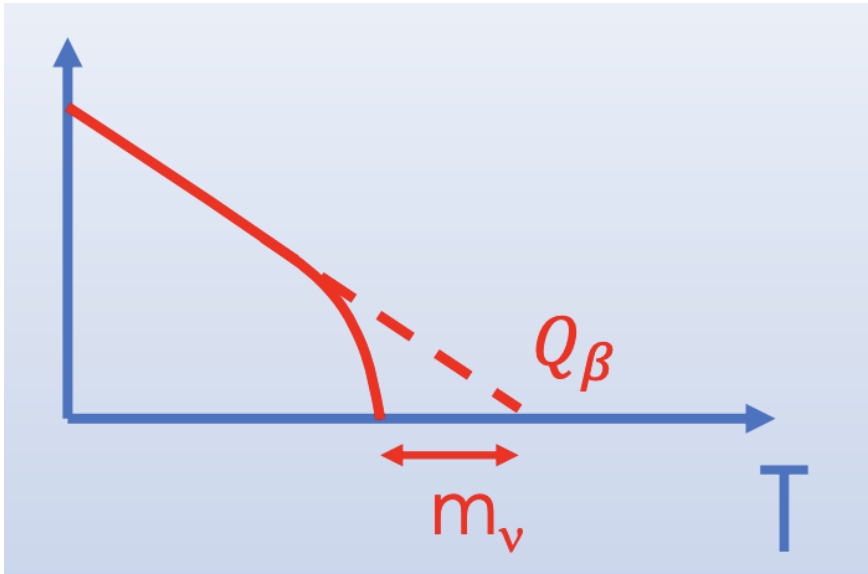


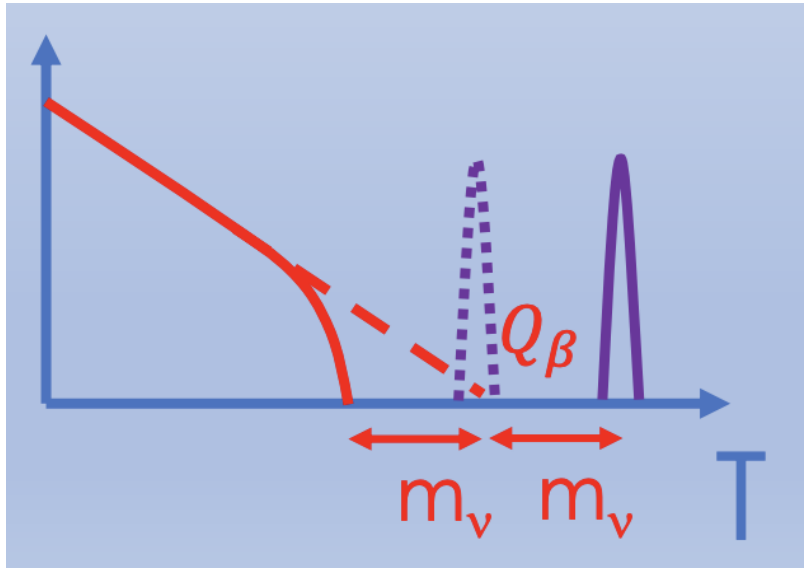


Requirements:

- High energy precision (order of $m_\nu \sim \mathrm{meV}$)
- Sufficient activity rate (several events per year)

Challenges





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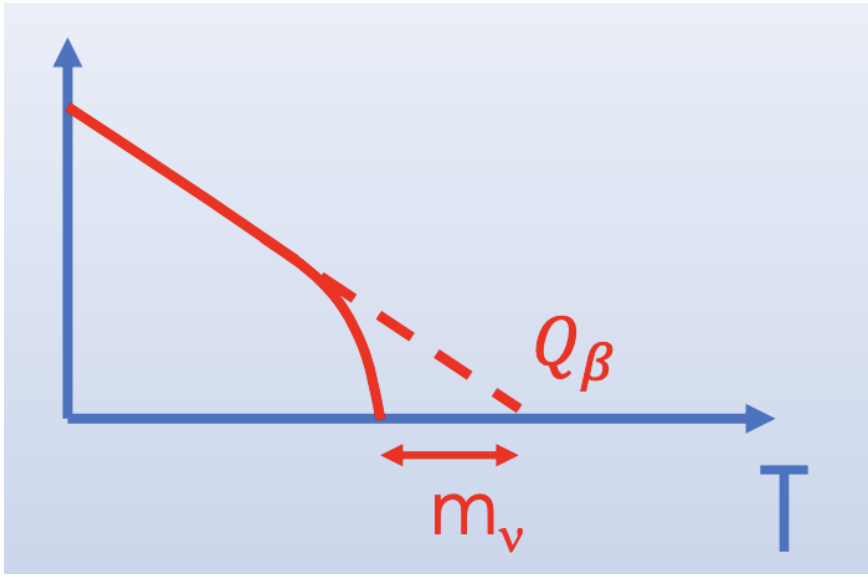

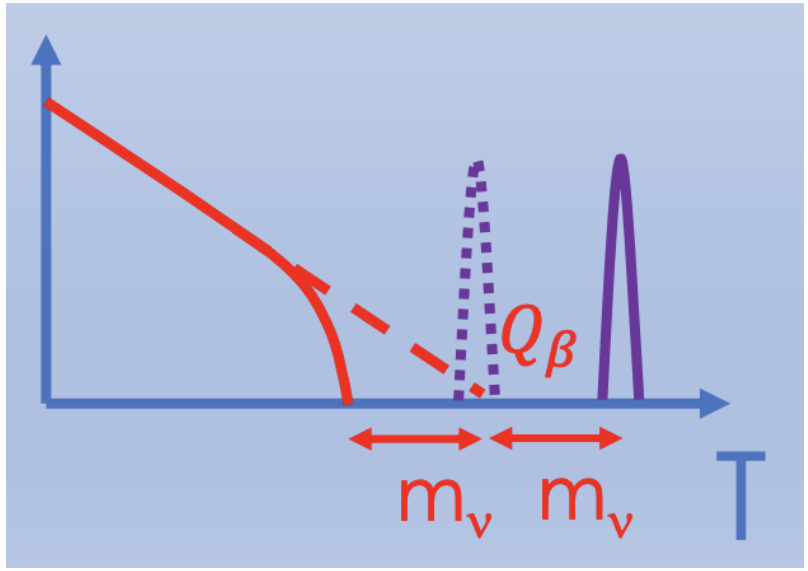

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$$(\sigma v)_\nu \propto \frac{1}{\tau Q^{\frac{-}{3}}}$$

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$$\lambda = (\sigma n)^{-1} = \left(R_{\text{atom}}^2 \frac{N}{L^3} \right)^{-1} > L$$

$$L > R_{\text{atom}} \sqrt{N} \sim 1\,\text{km}$$

Very naive estimate! In reality much bigger

Requirements to the experiment

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$$\Delta E \sim \frac{V_{\text{source}}}{V_{\text{detector}}}$$

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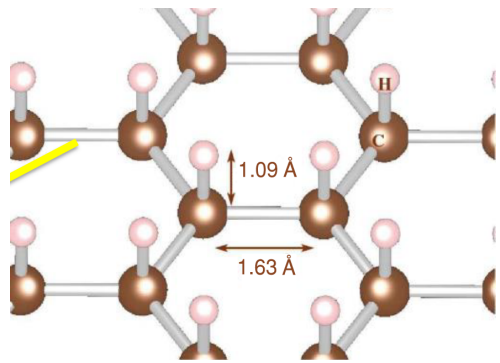
- Radioactive material in gaseous form does not suit ($0.93\,\mathrm{eV}$ resolution)
- Need in the solid-state based experiment



PTOLEMY[2] - state of the art

CνB detection experiment challemge:

- High energy resolution combined with sufficient number of events.

- **Tritium** as a β-decay emitter.
- Tritium is **deposed on graphene sheets** (vdW forces).
- ≈ 4 CνB **events per year**.
- Outstanding **energy resolution** of the apparatus $\approx 10\,\mathrm{meV}$.

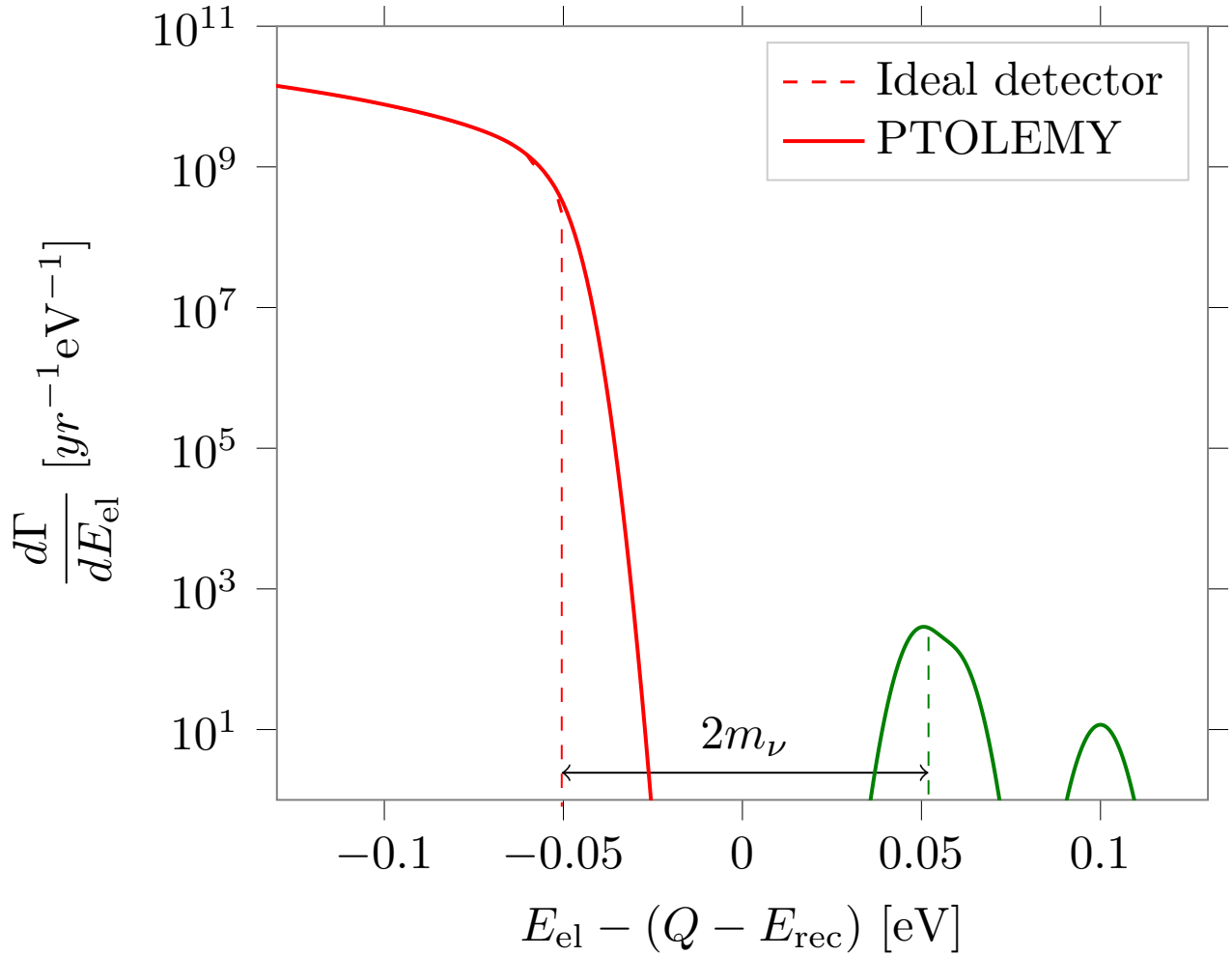
P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

[2] *PTOLEMY collaboration "Neutrino physics with the PTOLEMY project", (2019)*

β-decay in Tritium [3]

$$\nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e$$

$${}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e + \bar{\nu}_e$$



[3] Mind the log scale

So that is it?

So that is it?

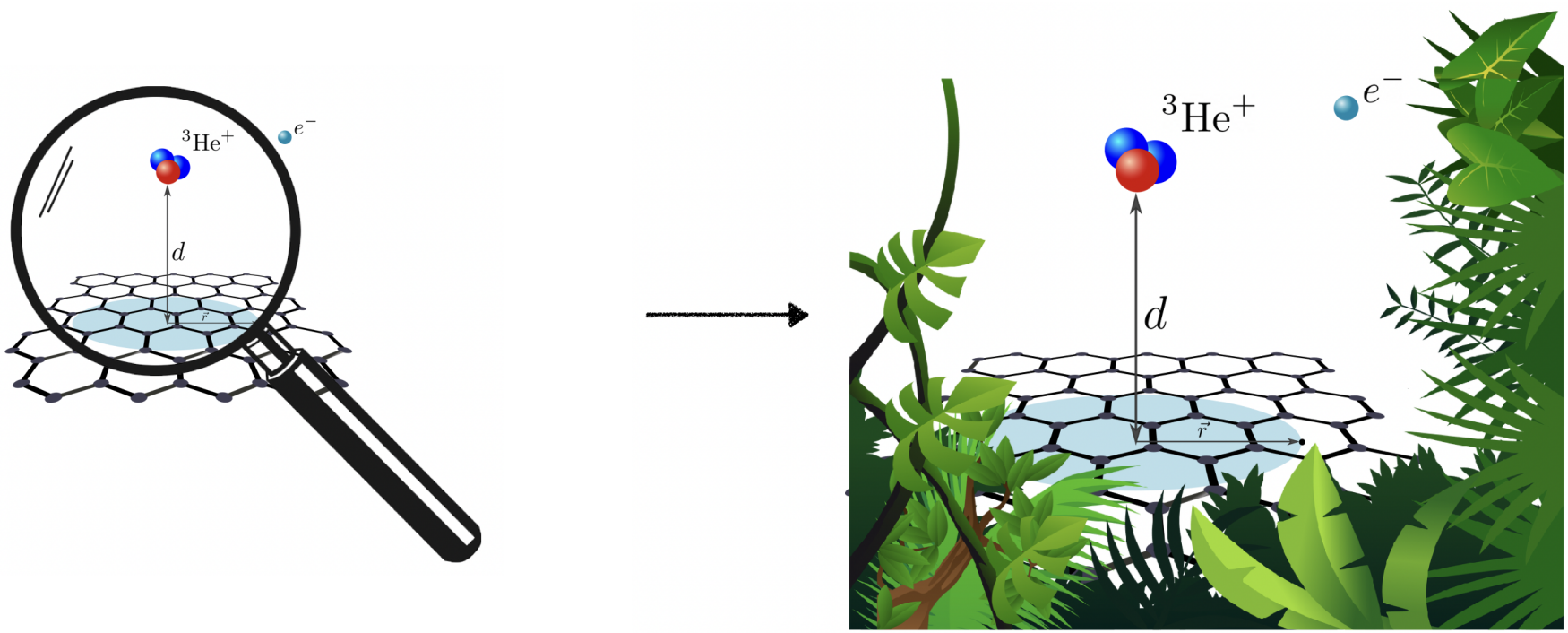
No

Jungle of many-body and chemical effects

The **width of the peak** (signature of CνB) is defined by

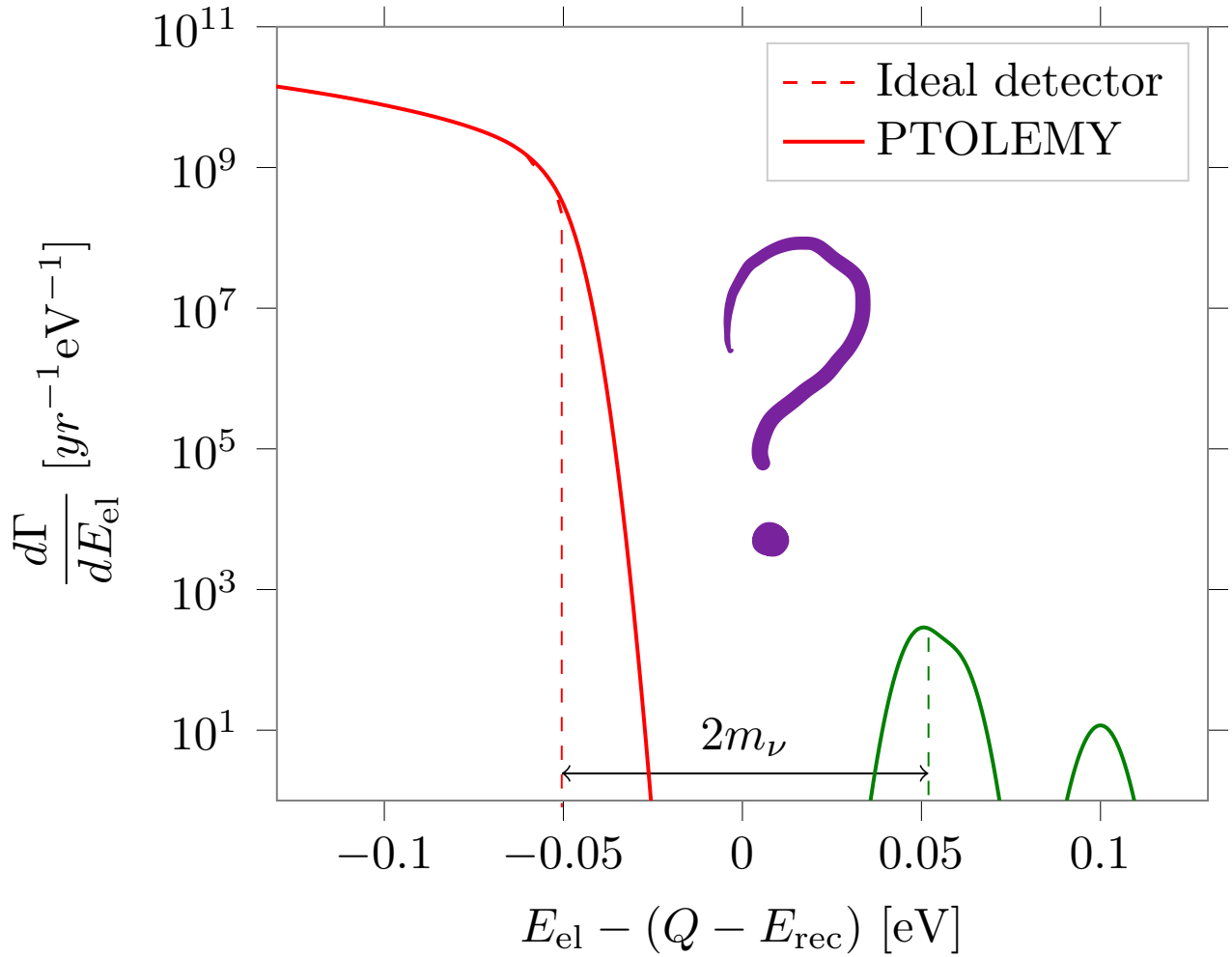
- *energy resolution* of the measurement
- physical *smearing* of the energies of individual electrons

We are interested in effects on $m_\nu \sim 10\,\mathrm{meV}$ scale



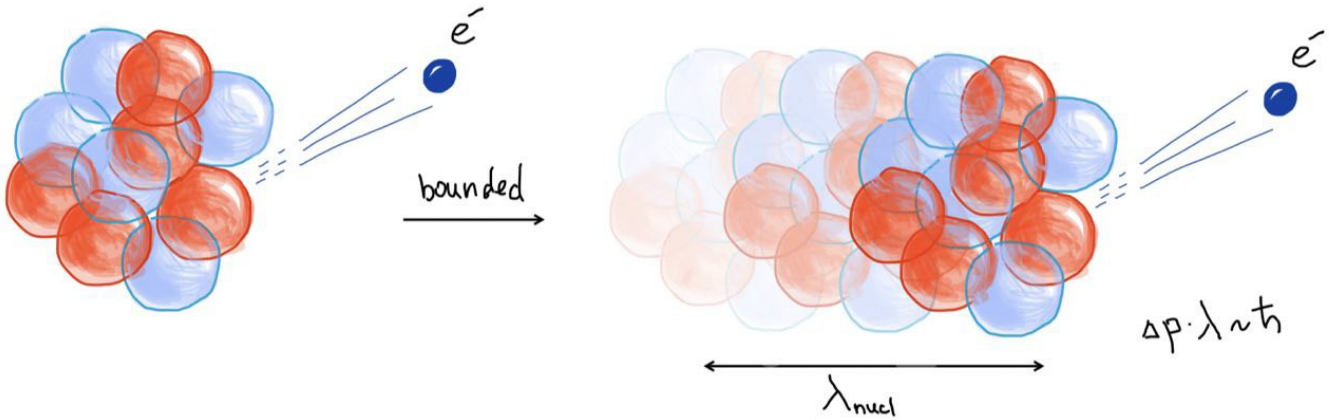
Real spectrum

Energy resolution is defined *not only by the resolution of the measurement device*, but also by **the interaction between the decaying nucleus and the substrate** that affects the energies of individual electrons.



Chemical bonding of the atom to the substrate

General mechanism of the broadening



- For a bonded system, recoil energy of the nucleus is not fixed by the kinematics but has some distribution.
- Uncertainty[4] in the velocity of the centre of mass of the nucleus

$$\Delta u \approx \frac{\hbar}{m_{\text{nucl}} \lambda_{\text{nucl}}}.$$

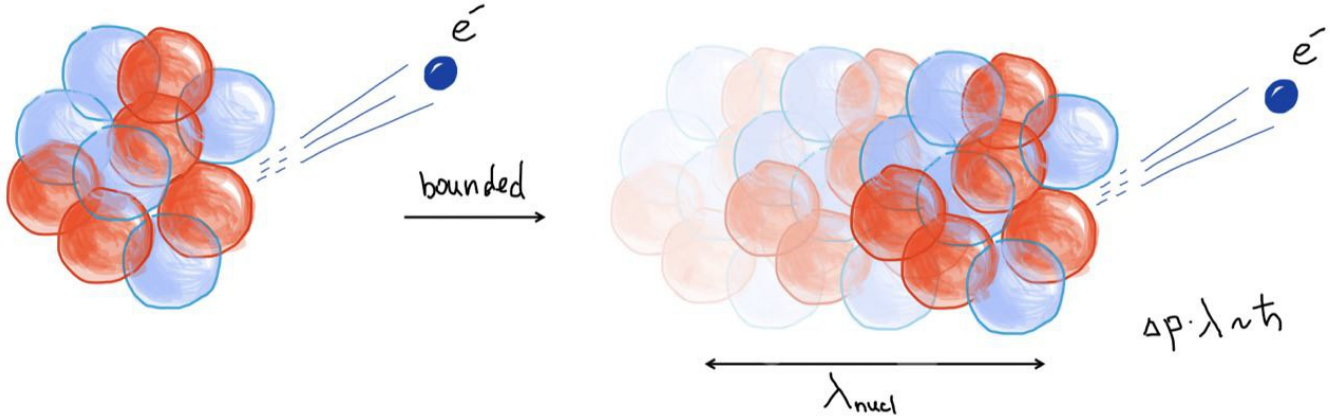
- The energy of the electron is measured in the laboratory frame of reference, where it acquires an uncertainty[5]

$$\Delta E \approx m_e v_e \Delta u.$$

[4] from the Heisenberg uncertainty principle.

[5] ΔE has the same distribution as Δu.

General mechanism of the broadening

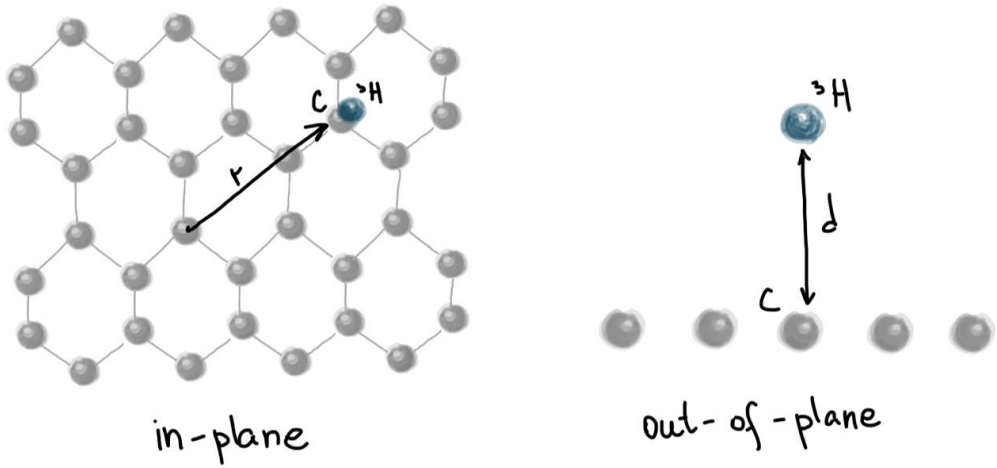


$$\Delta E \approx \hbar \frac{m_e v_e}{m_{\text{nucl}} \lambda_{\text{nucl}}},$$

- λ_{nucl} is the spread of the ground state of the nucleus that is defined by the stiffness of the bonding potential $\varkappa$.

$$\lambda_{\text{nucl}}^2 = \frac{\hbar}{\sqrt{m_{\text{nucl}} \varkappa}}$$

Bonding potential



For the heavy atom one can expand the potential near its minimum

$$U = \frac{1}{2}\varkappa_{i,j} r_i r_j + U_0$$

The energy uncertainty very weakly depends on the binding potential

$$\Delta E \propto \lambda_{\text{nucl}}^{-1} \propto \varkappa^{1/4}$$

Energy broadening for the β-decay of the Tritium on graphene

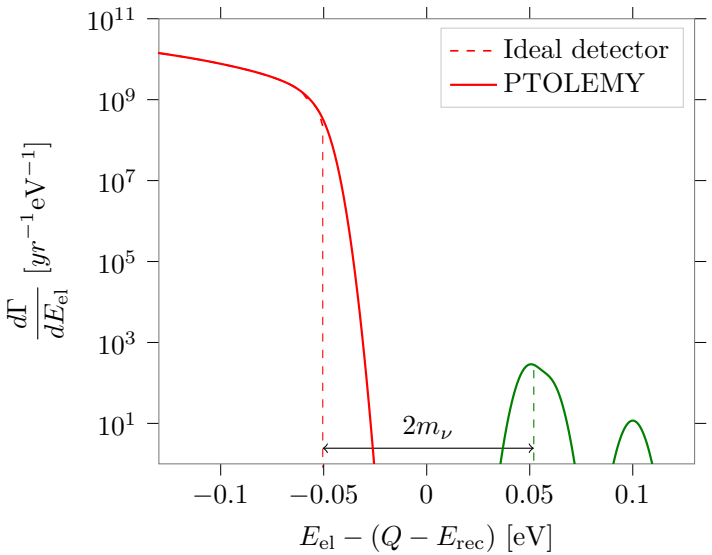
$$\frac{\Delta E}{\sqrt{\hbar m_e}} \approx \underbrace{\varkappa^{1/4}}_{\text{potential}} \underbrace{\sqrt{\frac{Q}{m_{\text{nucl}}^{3/2}}}}_{\text{nucleus}}$$

The uncertainty in the electron energy ΔE:

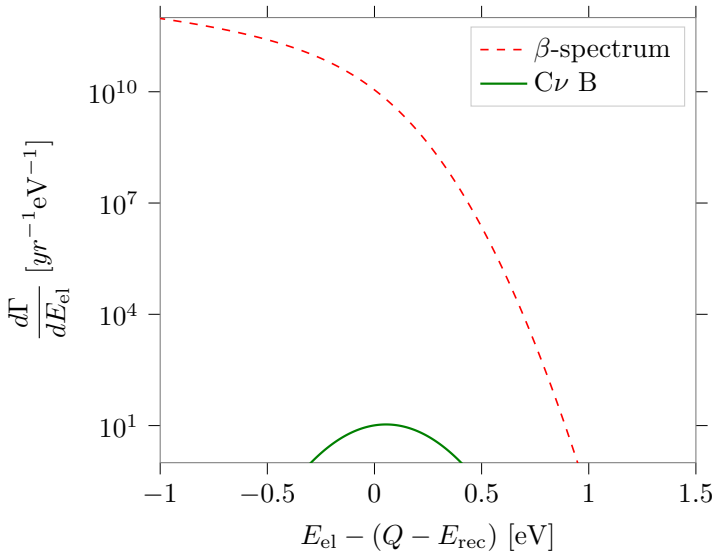
- Is of the order of $0.5\,\text{eV}$.
- Is 2 orders of magnitude greater than the resolution needed to see the CνB signal.
- Weakly depends on the potential stiffness.
- For molecular tritium the estimate is of the same order.
- Strongly depends on the radioactive nucleus.
- Agrees with the the fully quantum calculation[6]

[6] Fermi Golden Rule.

Shape of the spectrum for the β-decay of the Tritium on graphene[7]



smearing



$$\tilde{\mathcal{G}}(\mathbf{v}) = \int du \mathcal{F}(\mathbf{u})\mathcal{G}(\mathbf{v}+\mathbf{u}).$$

- $\mathcal{G}$ - distr. of the electron velocity in the centre of mass ref. frame.
- $\mathcal{F}$ - distr. of the velocity of the centre of mass.
- $\tilde{\mathcal{G}}$ - distr. of the electron velocity in the laboratory ref. frame.

[7] $\Delta E \approx mu\Delta u$, therefore ΔE has the same distribution as Δu.

The are two possible solutions

Two possible solutions

$$\frac{\Delta E}{\sqrt{\hbar m_e}} \approx \varkappa^{1/4} \sqrt{\frac{Q}{m_{\text{nucl}}^{3/2}}} \equiv \varkappa^{1/4} \gamma$$

Changing the binding potential
[Apponi et.al., 2022]

- Making it very **soft**
  This will reduce the energy smearing
- Making it very **stiff**
  Recoil-less part of the spectrum at the very end does not get smeared, but is suppressed as

$$\mathcal{M} = \mathcal{M}_0 e^{-\lambda^2 k_\beta^2/4}$$

- ω_{vibr} of H-based molecules vary within one order of magnitude.

Changing the β-emitter
[Mikulenko et.al., 2021]

- Finding a heavier β-emitter with low Q
  This will reduce the energy smearing
- However, one needs to double-check the capture rate

$$(\sigma v)_\nu = \frac{p_e^{\max} E_e^{\max}}{\pi} \times \frac{1}{2} \sum |\mathcal{M}_{\mathcal{H}}|^2$$

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  Naive estimate for $\mathcal{M}_{\mathcal{H}} = \text{const}$

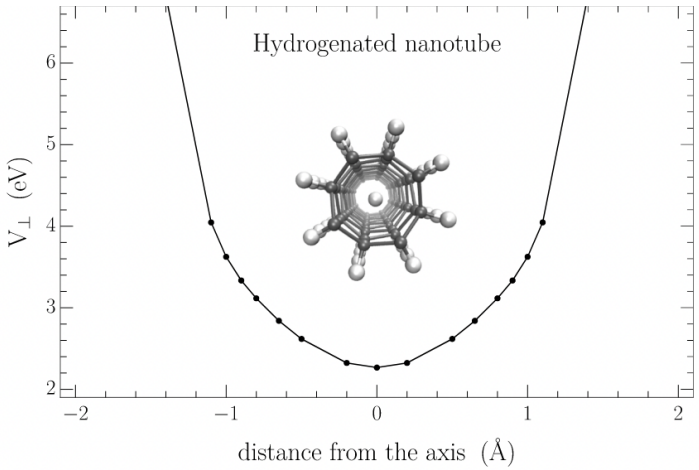
$$(\sigma v)_\nu = 5.3 \cdot 10^{-46}\,\text{cm}^2 \times \frac{1\,\text{year}}{\tau} \times \left(\frac{100\,\text{keV}}{Q}\right)^3$$

First solution: Changing the binding potential

Changing the binding potential: soft potential

- One way is to use **carbon nanotubes** [Apponi et.al., 2022] - **full mobility** along the axis of the nanotube.
- Bound on the emission angle

$$\theta_{\max} = \arcsin\left(\Delta E_{\text{allowed}} / \Delta E_{\text{existing}}\right)$$



- **Reduced event rate** by $\sim \theta_{\max}^{-2}$ times.
  - Free Tritium tends to **form molecules**.
  - Non-zero **recombination rate** [Mehta et.al., 2007]

$$\frac{d\lambda}{dt} = -K_{1D}\lambda^3,$$

where λ is a linear density, K_{1D} recombination rate.

- For Tritium, with lifetime of $\tau \sim 100\,\mathrm{d}$, we get $\lambda \sim 300\,\mathrm{cm}^{-1}$.
- With $5\,\text{Å}$ nanotubes spacing we get surface density of $\sim 10^{10}\mathrm{cm}^{-2}$ - five orders of magnitude lower than fully loaded graphene.

Second solution: Changing the β-emitter

Changing the β-emitter

- From the requirements of low γ and meaningfull $\tau_{1/2}$ by searching **all existing transitions of all energy levels** (not only ground states).

Parent	$\tau_{1/2}$, [yr]	Daughter	Q, [keV]	$\gamma/\gamma_{^3\mathrm{H}}$
$^{171}\mathrm{Tm}$	1.92	$^{171}\mathrm{Yb}$	96.5	0.110
$^{63}\mathrm{Ni}$	101.	$^{63}\mathrm{Cu}$	66.9	0.193
$^{147}\mathrm{Pm}$	2.62	$^{147}\mathrm{Sm}$	225.	0.188
$^{151}\mathrm{Sm}$	90.0	$^{151}\mathrm{Eu}$	75.9	0.107

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- The **daughter** nucleus should be β - **stable** or have **lower** Q than parent.
- This is **not the case** for $^{151}\mathrm{Sm}$.
- $^{151}\mathrm{Eu}$ α-decays into $^{147}\mathrm{Pm}$ which is β unstable with $\tau_{1/2} = 2.62$ years and with $Q_{^{147}\mathrm{Pm}} > Q_{^{151}\mathrm{Sm}}$.
- The lifetime of $^{151}\mathrm{Eu}$ is $\tau_{1/2} = 10^{18}$ years, but we also need to have order of 10^{27} atoms of $^{151}\mathrm{Sm}$.
- $^{147}\mathrm{Sm}$ α-decays with $\tau_{1/2} \sim 10^{11}$ years and $Q = 2311\,\mathrm{keV}$ which can scatter on β-electrons.

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We need to know precise **capture rates**. **Spoiler:**

- For $^{63}\mathrm{Ni}$ we can calculate it pretty precise theoretically

$$^{63}\mathrm{Ni}: \qquad \Gamma_{\text{capt}} = 7 \cdot 10^{-28}\mathrm{y}^{-1} \frac{\eta_\nu}{\langle \eta_\nu \rangle} \text{ per atom}$$

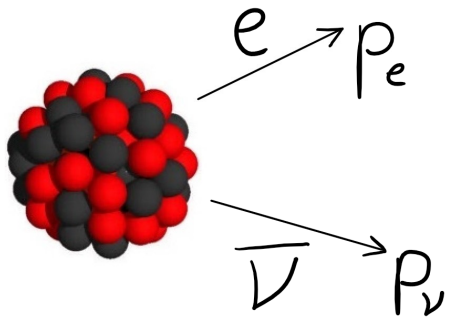
- Typical size of the setup is $31\,\mathrm{m} \times 31\,\mathrm{m} \times 31\,\mathrm{m}$.
- For $^{171}\mathrm{Tm}$ it is much more tricky.

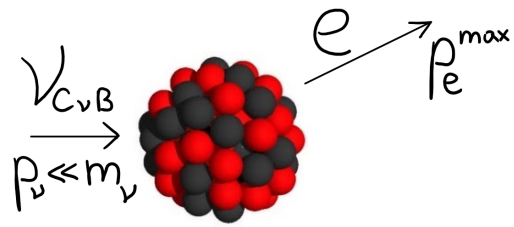
Let us discuss how we calculate capture rates

Calculating neutrino capture rate

- Both neutrino capture and β-decay are governed by the same weak interaction:

$$\mathcal{H} \propto \bar{e}\gamma_\mu(1-\gamma_5)\nu \times \bar{p}\gamma^\mu(g_V - g_A\gamma_5)n$$





$$\frac{d\Gamma}{dE_e} = \frac{p_\nu E_\nu p_e E_e}{2\pi^3} \times \sum |\mathcal{M}_\mathcal{H}|^2 \qquad (\sigma v)_\nu = \frac{p_e^{\max} E_e^{\max}}{\pi} \times \frac{1}{2} \sum |\mathcal{M}_\mathcal{H}|^2$$

Neutrino capture rate for $^{171}\mathrm{Tm}$

- In some cases (such as for $^{3}\mathrm{H}$ and $^{63}\mathrm{Ni}$), $\sum |\mathcal{M}_{\mathcal{H}}|^2 = \text{const}$, hence:

$$(\sigma v)_\nu = 5.3 \cdot 10^{-46}\,\mathrm{cm}^2 \times \frac{1\,\mathrm{year}}{\tau} \times \left(\frac{100\,\mathrm{keV}}{Q}\right)^3$$

neglecting Coulomb field and assuming $Q \ll m_e$

- For $^{171}\mathrm{Tm}$ this **not the case**.
- The reason is that for $^{171}\mathrm{Tm}$ $\quad \sum |\mathcal{M}_{\mathcal{H}}|^2 \neq \text{const}$

Unique

$$\sum |\mathcal{M}_{\mathcal{H}}|^2 = C \cdot f(p_e, p_\nu)$$

- one final state
- C - single nuclear constant
- f - known function of p_e, p_ν

Nonunique

$$\sum |\mathcal{M}_{\mathcal{H}}|^2 = c_1 \cdot f_1(p_e, p_\nu) + \ldots$$

- *several* possible final states
- c_i - *several* nuclear constants
- f_i - known functions of p_e, p_ν

Naive estimate

- In some cases (such as for $^{3}\mathrm{H}$ and $^{63}\mathrm{Ni}$), $\sum |\mathcal{M}_{\mathcal{H}}|^2 = \text{const}$, hence:

$$(\sigma v)_\nu = 5.3 \cdot 10^{-46}\,\mathrm{cm}^2 \times \frac{1\,\mathrm{year}}{\tau} \times \left(\frac{100\,\mathrm{keV}}{Q}\right)^3$$

  neglecting Coulomb field and assuming $Q \ll m_e$

- For $^{171}\mathrm{Tm}$ this **not the case**.
- One can still **make the crude estimate** using $(\sigma v)_\nu \sim \left(Q^3 \tau\right)^{-1}$ gives

$$\Gamma^{^{171}\mathrm{Tm}}_{\text{capture}} = 0.05 \times \Gamma^{^{3}\mathrm{H}}_{\text{capture}}$$

- But we do not know **how reliable it is**.

Naive estimate. How reliable?

- In some cases (such as for $^{3}\mathrm{H}$ and $^{63}\mathrm{Ni}$), $\sum |\mathcal{M}_{\mathcal{H}}|^2 = \text{const}$, hence:

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neglecting Coulomb field and assuming $Q \ll m_e$

- For some isotopes this **not the case**, but we can write

$$(\sigma v)_\nu = \delta \times (\sigma v)_{\text{est.}}$$

Isotope	Q, keV	τ, year	$(\sigma v)_\nu$, $10^{-46}\,\mathrm{cm}^2$	δ
$^{3}\mathrm{H}$	18.591	17.8	39.2	0.86
$^{63}\mathrm{Ni}$	66.945	145	$6.9 \cdot 10^{-2}$	0.57
$^{93}\mathrm{Zr}$	60.63	$2.27 \cdot 10^{6}$	$1.20 \cdot 10^{-5}$	1.15
$^{106}\mathrm{Ru}$	39.4	1.48	29.4	0.51
$^{107}\mathrm{Pd}$	33	$9.38 \cdot 10^{6}$	$1.29 \cdot 10^{-5}$	0.83
$^{187}\mathrm{Re}$	2.646	$6.28 \cdot 10^{10}$	$2.16 \cdot 10^{-6}$	0.48

- For many isotopes, $\delta \sim 1$, but **we can not be sure** about $^{171}\mathrm{Tm}$.

Neutrino capture rate from experimental spectrum

- $\sum |\mathcal{M}_{\mathcal{H}}(p_e^{\max}, p_\nu \to 0)|^2 \propto (\sigma v)_\nu$ cannot be predicted from lifetime τ for nonunique transitions
- **Measure it directly** from the spectrum!

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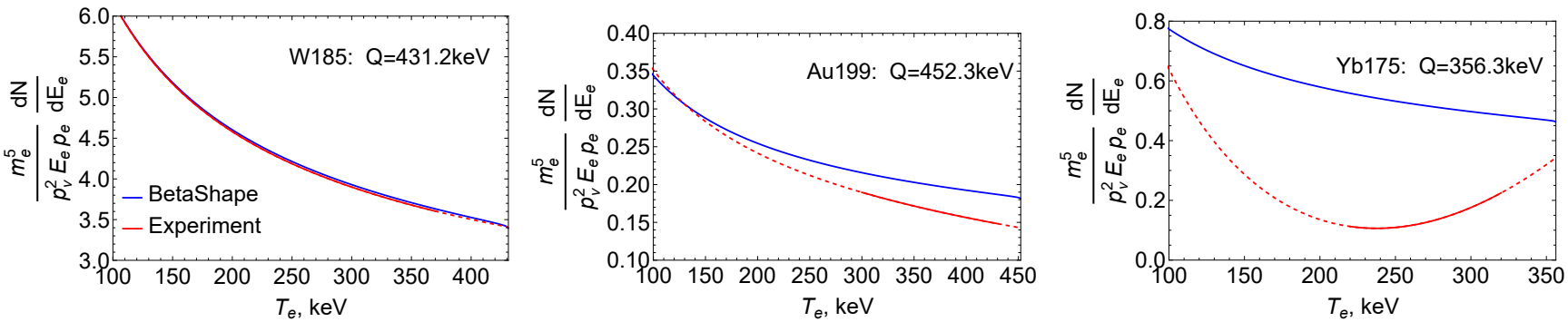
- **Measure it directly** from the spectrum!

$$(\sigma v)_\nu = \frac{7.0 \cdot 10^{-37}\,\mathrm{cm}^2}{(T_\mathrm{m} \text{ in hours})(\Delta E \text{ in keV})} \times \frac{1}{N_\mathrm{at}} \left(\frac{N(\varepsilon)}{(\varepsilon \text{ in keV})^2} \right) \Bigg|_{\varepsilon \to 0}$$

- Measure the number of electrons in energy bins $T_e^n \in [Q - \Delta E n, Q - \Delta E(n-1)]$ with width ΔE (say, $1\,\mathrm{keV}$)
- $\varepsilon_n = \Delta E(n + 1/2)$
- $N(\varepsilon_n)$ - number of events in the n-th bin.
- N_at - number of β-emitters
- T_m - time of the measurement

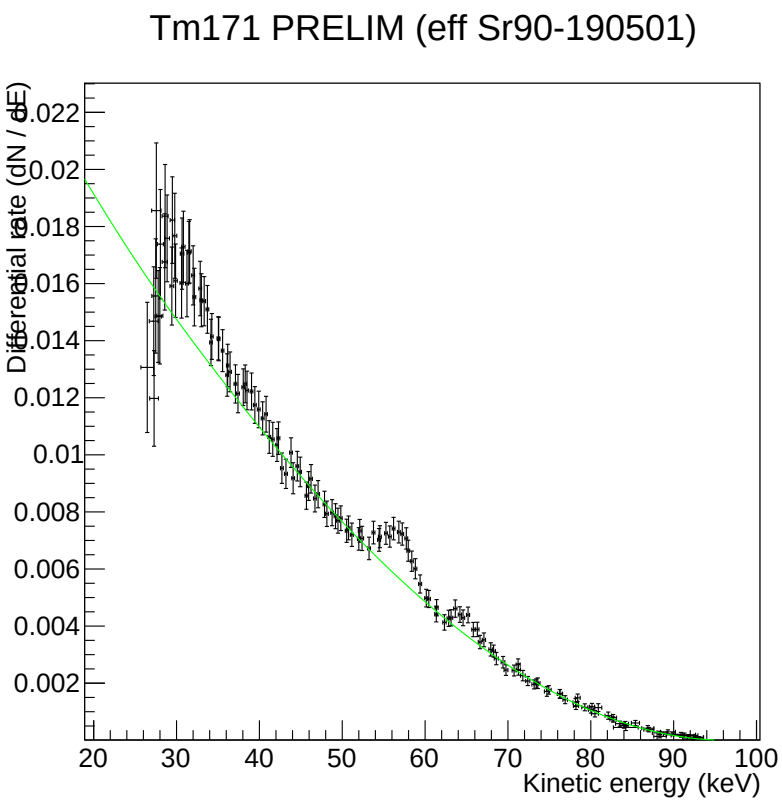
Neutrino capture rate for $^{171}\mathrm{Tm}$

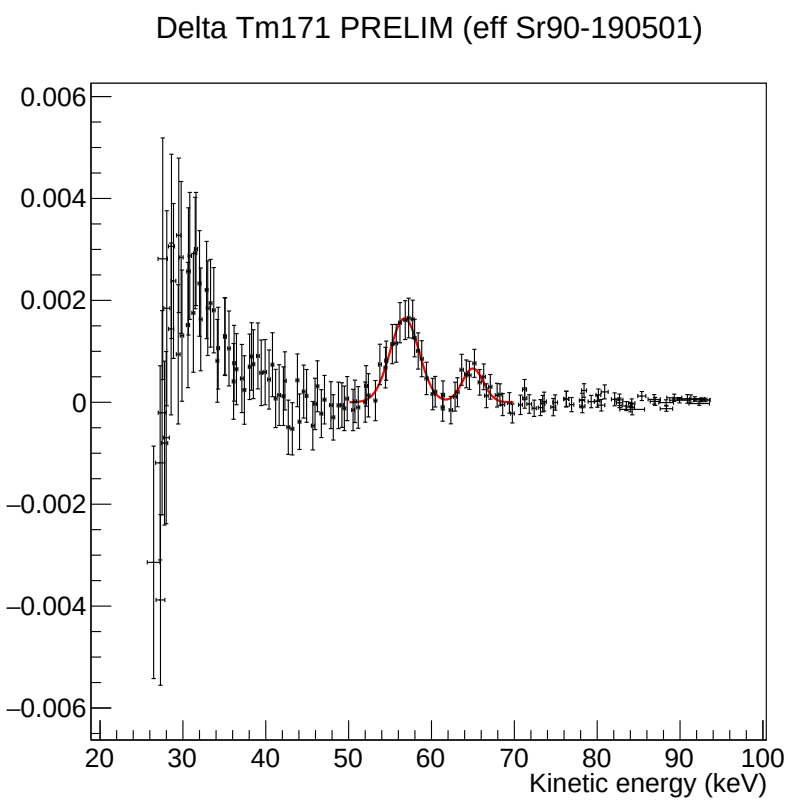
- For $^{171}\mathrm{Tm}$ no experimental spectrum is available
- To make an estimate of neutrino capture rate, we used **BetaShape** to compute the spectrum
- BetaShape calculates electromagnetic corrections to the spectrum. Still, it cannot compute nuclear constants and predict the spectrum – *treats nonunique as unique*



The results from BetaShape need to be verified by an experiment

Was experimentally tested at EPFL





Results

- With the BetaShape spectra, the capture rate for $^{171}\mathrm{Tm}$ is

$$\Gamma_{\text{capture}}^{^{171}\mathrm{Tm}} = 3 \cdot 10^{-2} \Gamma_{\text{capture}}$$

  — consistent with the crude estimate up to a factor of two
- Assuming local relic neutrino concentration $\eta_\nu = 56\,\mathrm{cm}^{-3}$ and Majorana nature, we need

$$N_{\text{atoms for event/year}} = \begin{cases} 2 \cdot 10^{24}, & ^{3}\mathrm{H} \\ 10^{26}, & ^{171}\mathrm{Tm} \\ 1.3 \cdot 10^{27}, & ^{63}\mathrm{Ni} \end{cases}$$

- With atom density on a graphene sheet $3.8 \cdot 10^{15}\mathrm{cm}^{-2}$ and separation of mm between sheets, event/year target would have the volume

$$\begin{aligned} ^{3}\mathrm{H}: &\quad V \approx 1\,\mathrm{m} \times 8\,\mathrm{m} \times 8\,\mathrm{m} \\ ^{171}\mathrm{Tm}: &\quad V \approx 10\,\mathrm{m} \times 15\,\mathrm{m} \times 15\,\mathrm{m} \\ ^{63}\mathrm{Ni}: &\quad V \approx 31\,\mathrm{m} \times 31\,\mathrm{m} \times 31\,\mathrm{m}. \end{aligned}$$

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Our next main roadblock is...

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finite lifetime of the ion

Finite lifetime of the daughter ion

- The daughter ion will **not be in the ground state**. Hence it will have **finite lifetime** τ.
- We will have Lorentz profile in energy distribution which is **very slowly decaying at tails**

$$\delta\left(E_f - E_i\right) \to \frac{4\tau}{1 + (4\pi\tau(E_f - E_i))^2}$$

- This would introduce **additional energy smearing** to the β-spectrum.
- From requirement $\Delta E \leq 10\,\mathrm{meV}$ for $^{171}\mathrm{Tm}$ we need to have the lifetime of the ion $\tau \geq 10^{-7}\mathrm{s}$.
- The estimate of the lifetime of the $^{171}\mathrm{Tm}$ is $\tau_{^{171}\mathrm{Tm}} \sim 10^{-15}\mathrm{s}$.
- For $^{3}\mathrm{H}$ the situation is **even worse**. Its daughter, $^{3}\mathrm{He}^{+}$ is an inert gas, so its ionization energy is extremely big.
- From this perspective, transition metals are profitable.

Is that it?

Is that it?

No, it is only beginning...

Mechanisms of the intrinsic energy broadening

- Chemical bonding of the atom to the substrate.
- Impurity screening by charges in the substrate.
- X-ray edge singularity.
- Lattice vibrations
- Emission of plasmons and surface polaritons
- Creation of shock wave emission due to the motion of the emitted electron at grazing angles at speeds exceeding the Fermi velocity
- Inhomogeneous broadening
- ...

Conclusions

- Fundamental questions of particle physics and the origin of our Universe could realistically be accessed only through the understanding of the condensed matter effects
- Limitations due to zero point motion bring us to the nessecity of changing the experimental design.
- There are 2 solutions to it: changing the binding potential and changing the emitter.
- Among the possible candidates for new β-emitters are $^{171}\mathrm{Tm}$ and $^{63}\mathrm{Ni}$.
- Zoo of effects appear in the $E \sim 10\,\mathrm{meV}$ which needs a much better understanding than usually in CM.

Backup slides

Isotope production

Typically, heavy isotopes are produced in two ways:

- From **nuclear waste** ($^{147}\mathrm{Pm}$).
- From lighter stable isotopes by **neutron irradiation** ($^{171}\mathrm{Tm}, ^{63}\mathrm{Ni}, ^{147}\mathrm{Pm}$).

During both processes there is a substantial **contamination by isotopes**.

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Isotope	^{171}**Tm**	^{170}**Tm**	^{169}**Tm**
Atoms	1.23×10^{19}	7.4×10^{15}[b]	2.59×10^{17}[b]
Activity (Bq)	1.40×10^{11}[a]	4.6×10^{8}	–
Mass (µg)	3480	1.9	72.7
Uncertainty (%)	2.4	20	3

Figure: [Heinitz et.al., 2017]

- $Q_{^{170}\mathrm{Tm}} \approx 968\,\mathrm{keV}$ bigger then $Q_{^{171}\mathrm{Tm}} \approx 97\,\mathrm{keV}$ with $\tau_{1/2} = 130$ days which **will completely cover the CνB peak**

.

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Radio-isotope	Half-life	Radioactivity at processing time (127 d post-EOB)	
		(MBq/mg of ^{146}Nd target)	(%)
^{147}Nd	10.98 d	0.83	3.13
^{147}Pm	2.62 y	2.55×10^{1}	95.3
^{148m}Pm	41.3 d	1.72×10^{-1}	0.64
^{148g}Pm[b]	5.37 d	8.6×10^{-2}	3.2×10^{-2}
^{146}Pm	5.53 y	$\leq 1 \times 10^{-6}$[c]	$\leq 4 \times 10^{-6}$[c]

Figure: [Broderick et.al., 2019]

.

- Same holds for $^{147}\mathrm{Pm}$

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^{146}Pm	5.53 y	$\leq 1 \times 10^{-6}$[c]	$\leq 4 \times 10^{-6}$[c]

Figure: [Williams et.al., 1993]

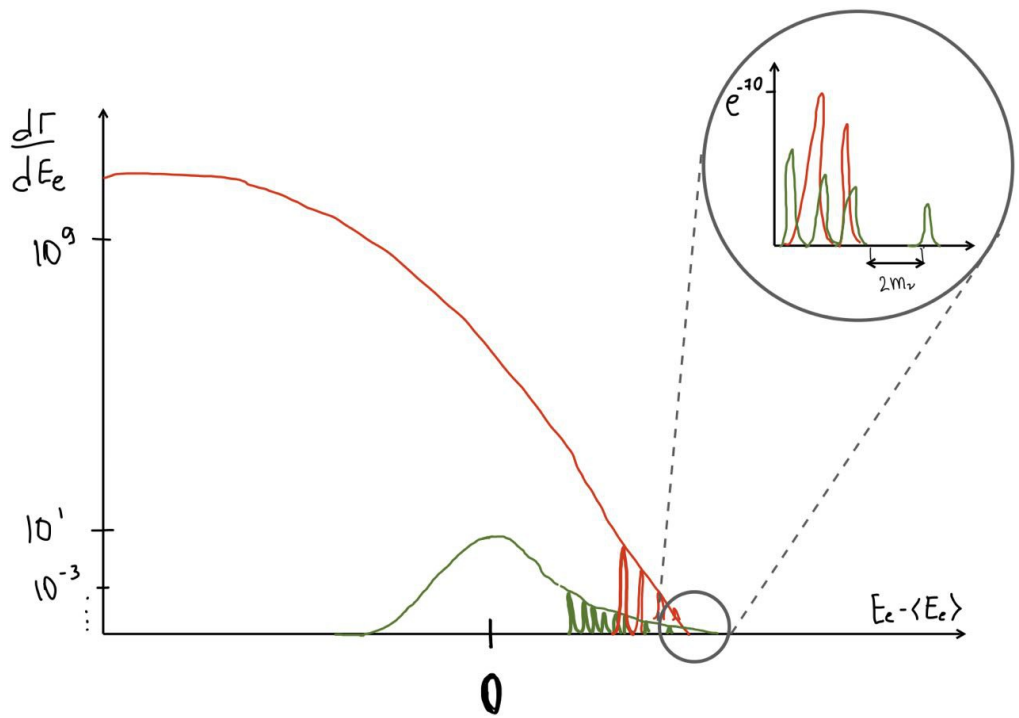
.

- All isotopes of $^{63}\mathrm{Ni}$ are stable.

General shape of the spectrum

In case when the bonding potential is harmonic, the spectrum is

- Discrete near the edge.
- Continuous further from the edge.
- The envelope has a gaussian distribution.
- The distance between the discrete lines[8] is $\varepsilon = \hbar\sqrt{\frac{\varkappa}{m_{\text{nucl}}}}$.
- Biggest part of the CνB channel overlaps with the continuum.



[8] $10\,\text{meV}$ for the Tritium on graphene and $0.5\,\text{eV}$ for the molecular tritium.

Comparison with molecular Tritium

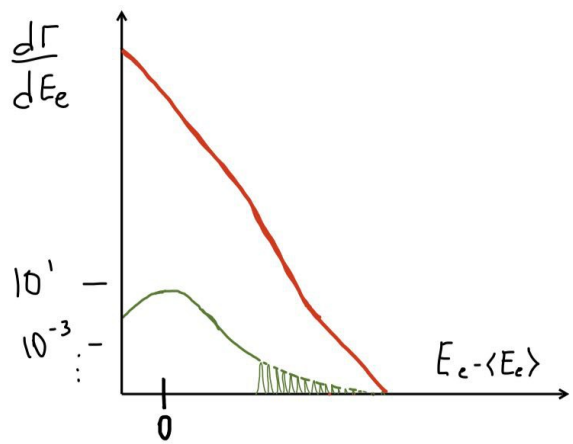
Similarities:

- Bonded by a harmonic potential ($\varkappa_{\text{graphene}} \approx 0.1, \varkappa_{\text{mol}} \approx 75$).
- Localized and therefore are subjects to Heisenberg's uncertainty principle $m\Delta v\Delta x \sim \hbar$.

Differences:

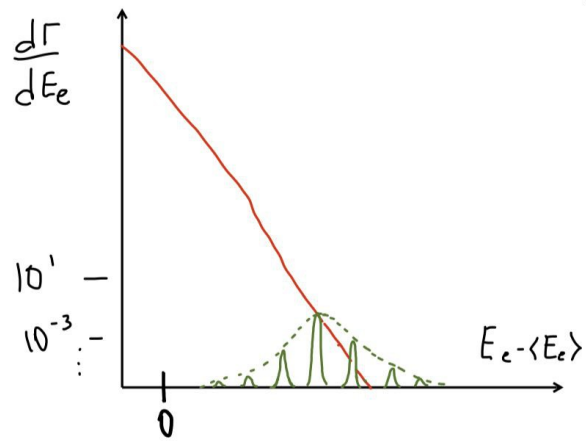
Atomic Tritium on graphene:

- All of the recoil energy goes to the harmonic modes.
- May break the bound after the recoil.

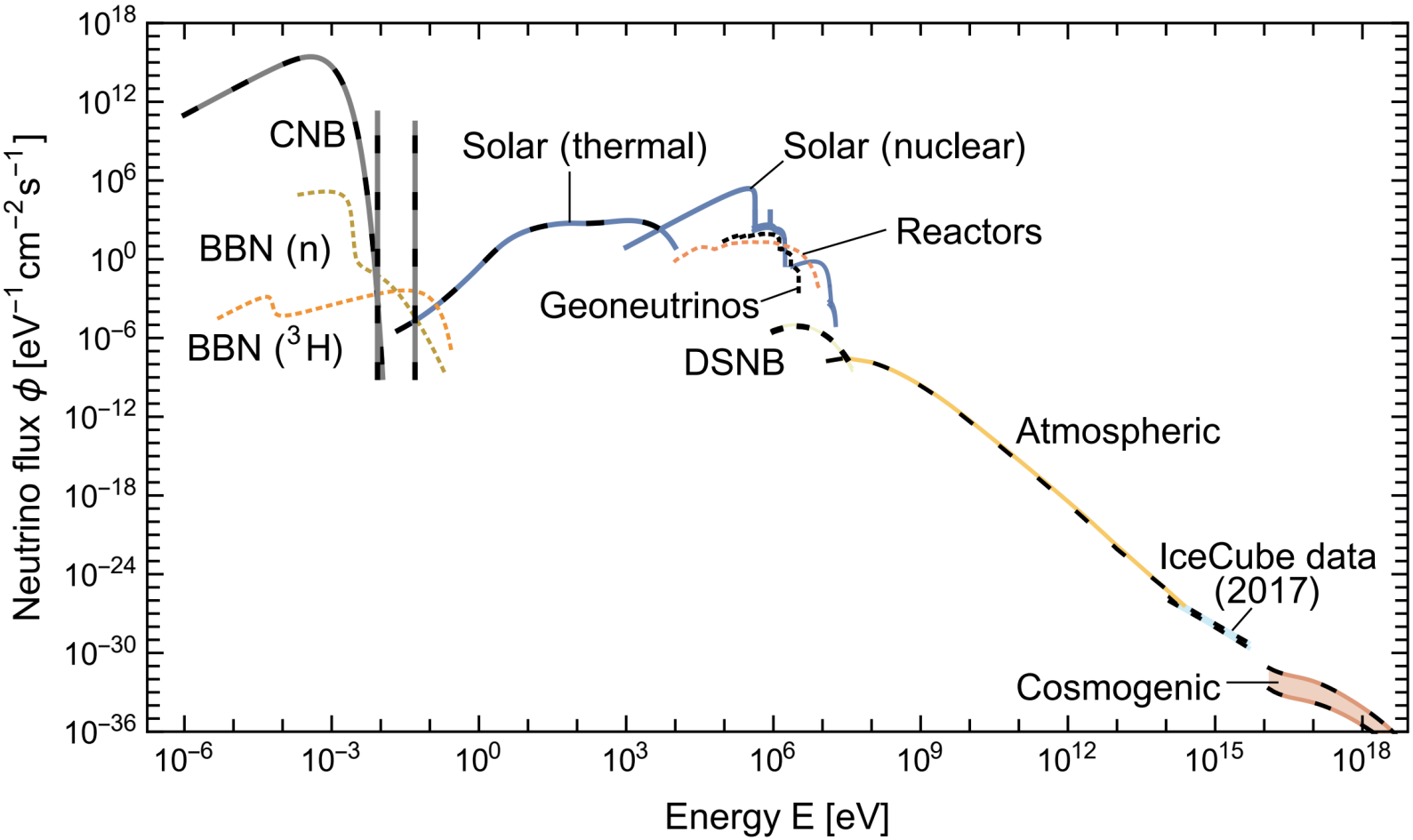


Gaseous molecular Tritium:

- Half of the recoil energy goes to the transnational motion.
- Remains bound after the recoil.

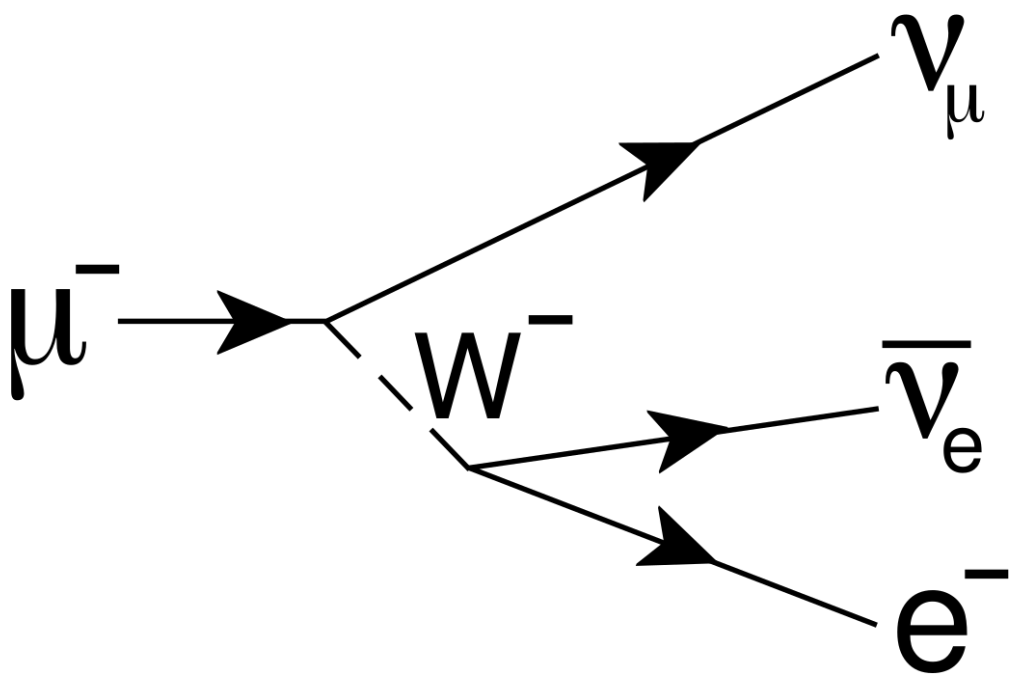


Neutrino flux[9]

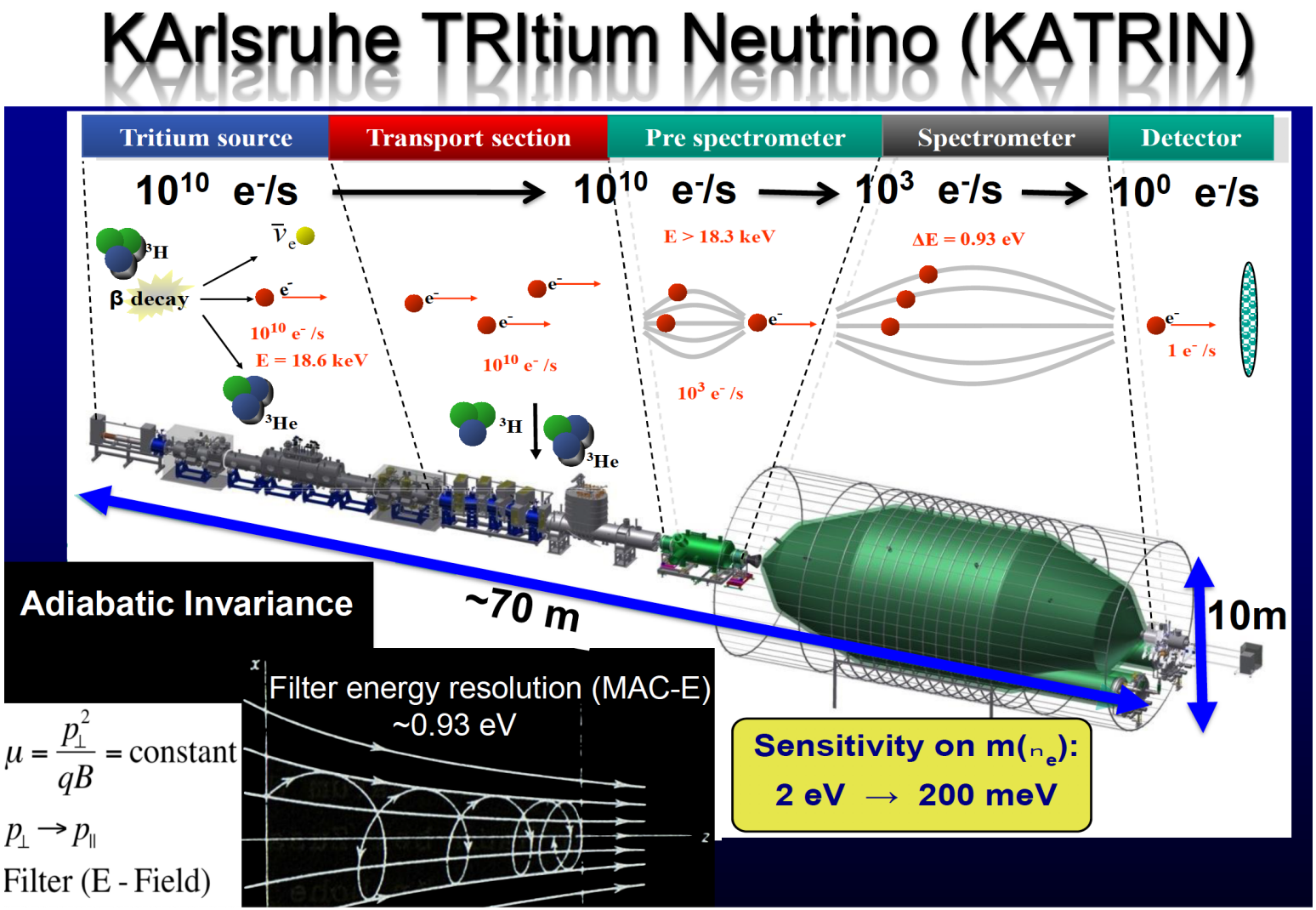


[9] *E. Vitagliano et.al. "Grand Unified Neutrino Spectrum at Earth: Sources and Spectral Components", (2020)*

Neutrino flavours



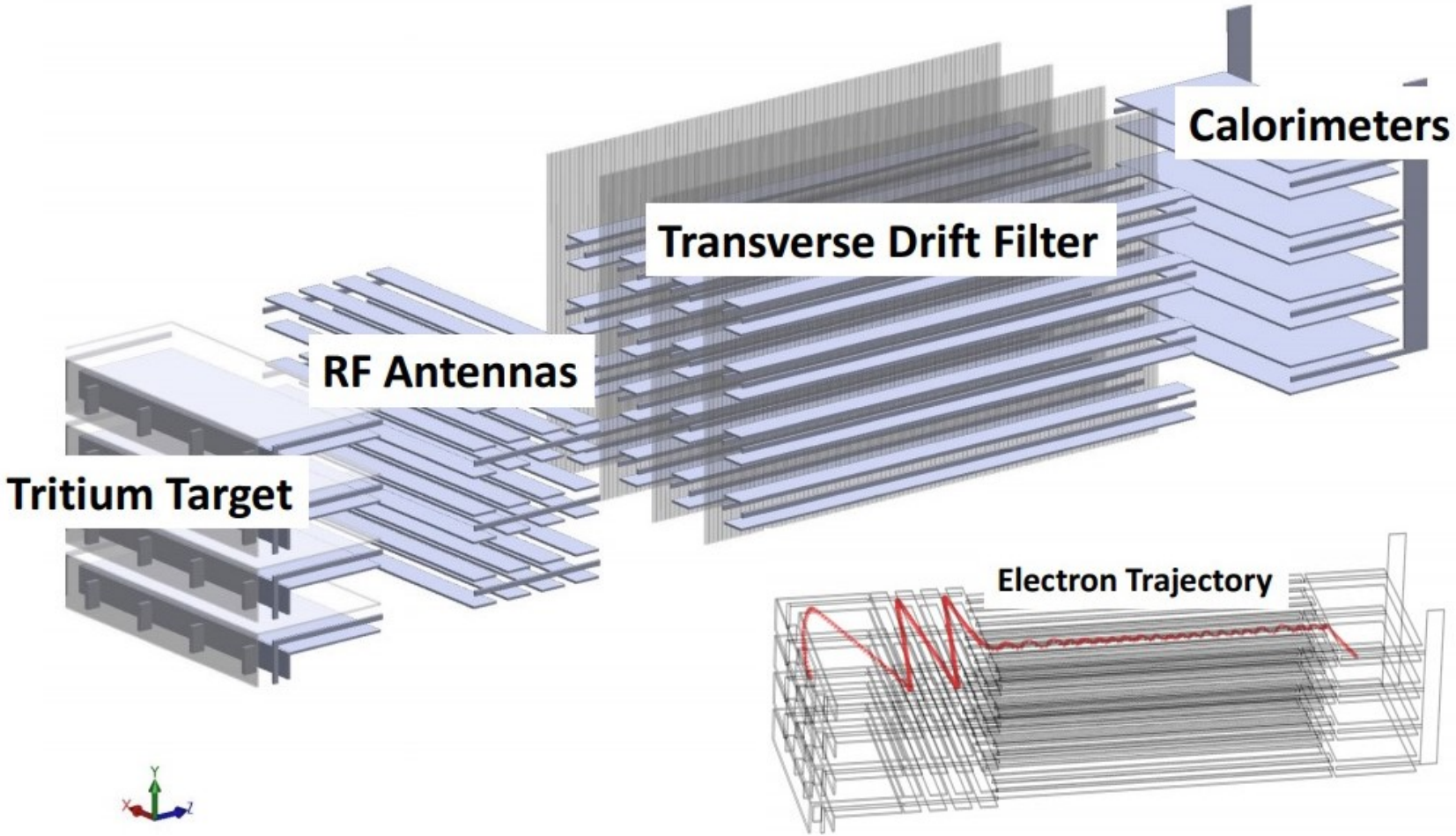
KATRIN



$$\mu = \frac{p_\perp^2}{qB} = \text{constant}$$

$$p_\perp \rightarrow p_\parallel$$

PTOLEMY


Calorimeters
Transverse Drift Filter
RF Antennas
Tritium Target
Electron Trajectory