Looking into the early Universe with a solid-state device

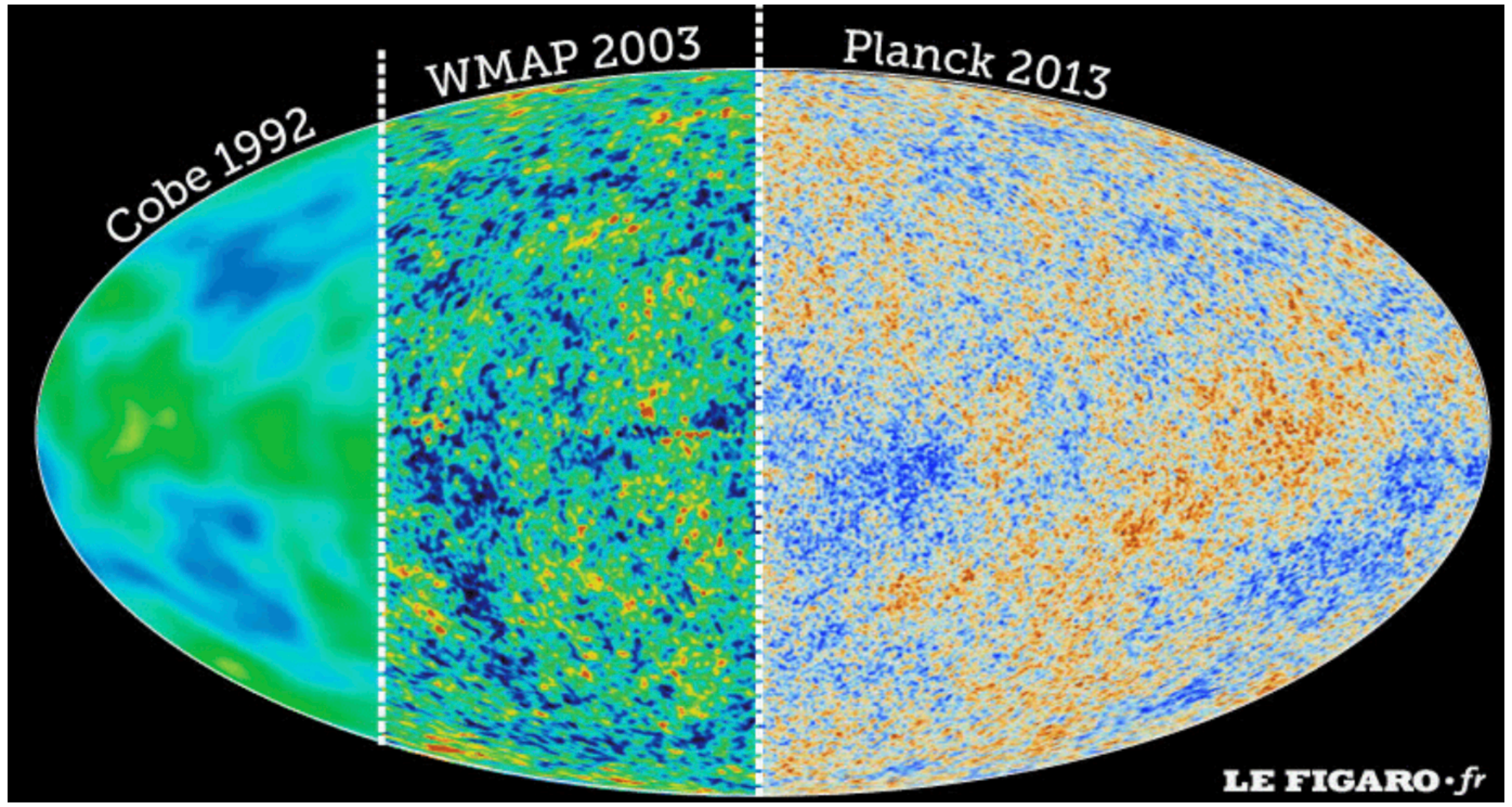
Quantum measurement device
with quantum impurities
for particle physics
and physics of the early universe

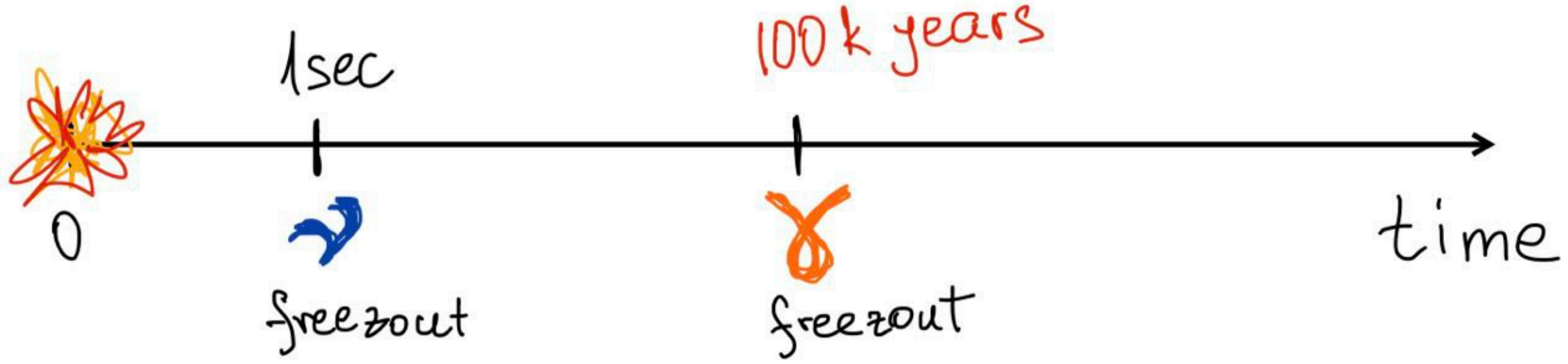



Oleksiy Boyarsky, Yevheniia Cheipesh, Oleksiy Mikulenko, Zhiyang Tan, Vadim Cheianov

How to probe the early Universe? CνB and CMB

- **Gamov:** Early Universe is radiation dominated.
  $\rho_{rad}/\rho_{matter} \sim 10^{10}$
- For cosmology, any relativistic particle is “radiation” !
- In fact, early Universe has equal populations of ν/γ.
- As Universe expands, ν/γ decouple, relic backgrounds (CMB /CvB), keep a **“frozen” pictures** of the Universe.
- Right now, in your room, there are **411 relic photons** and **339 relic neutrinos** in every cm^3 !
- The **“ν - freezout”** is much earlier than photons
- CvB: one of the few **yet untested predictions of the SM**
- **Detecting CvB is a strategic goal for fundamental physics.** [Weinberg , 1962]





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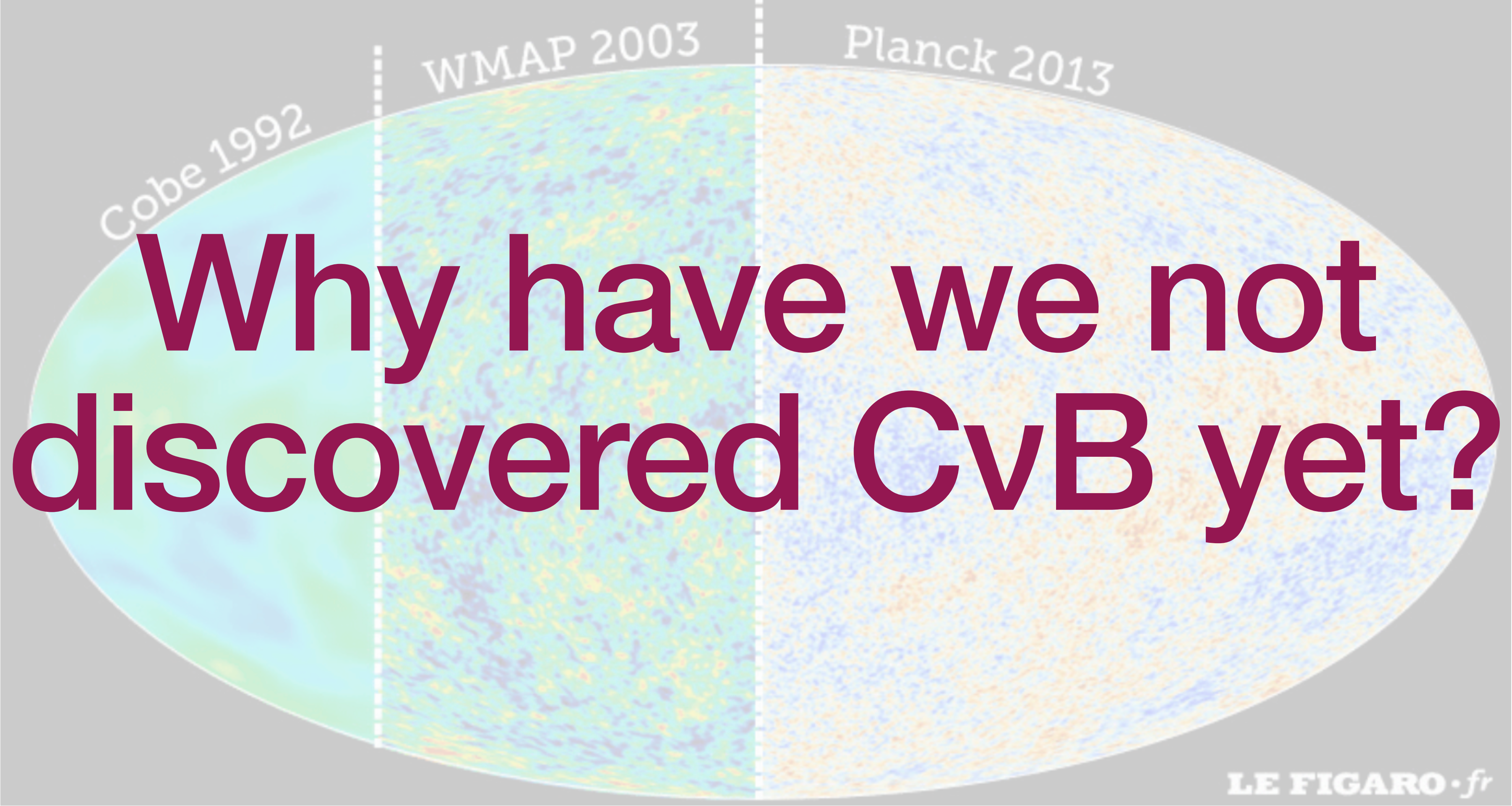
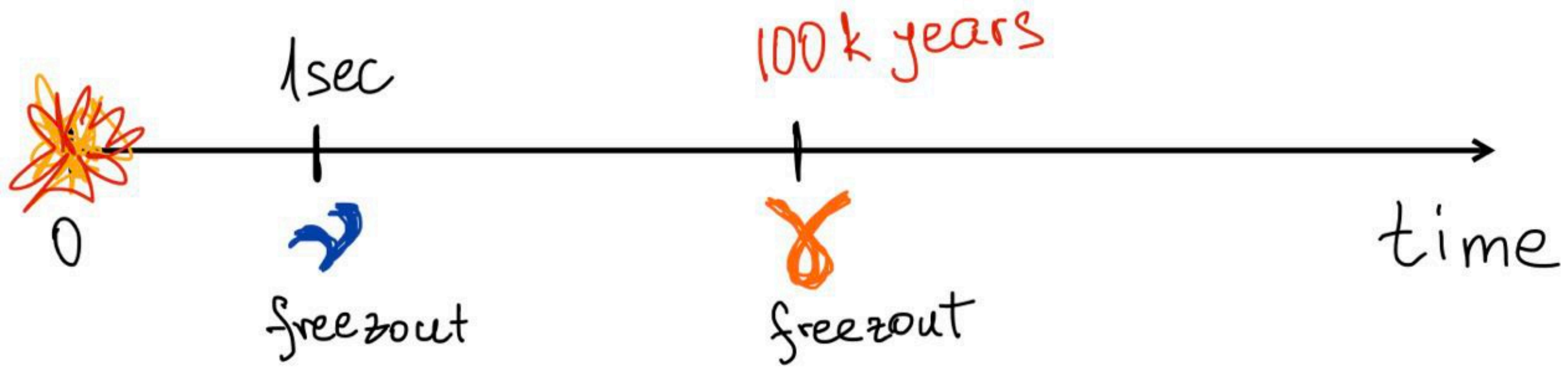
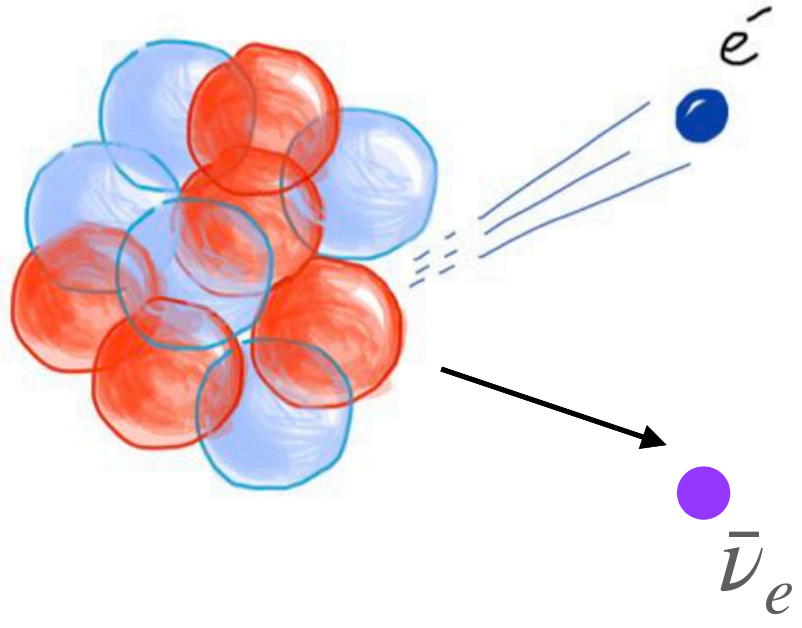




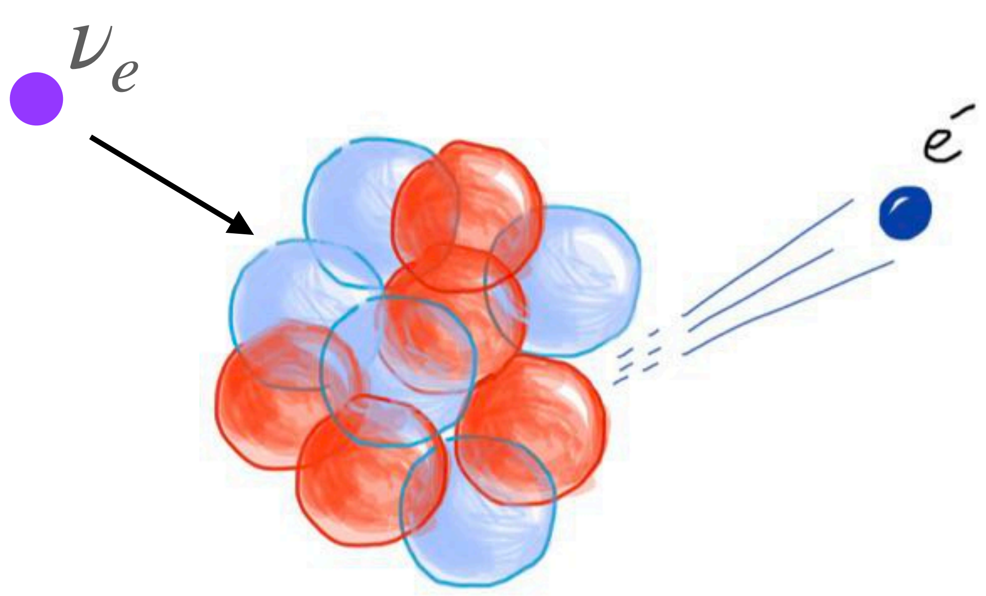
Observation of the cosmological neutrinos would then provide a window into the 1st second of creation

Detecting relic neutrinos via β decay

- Neutrino capture is **threshold-less** – soft relic neutrino detection [Weinberg, 1962]



β decay



Neutrino capture

Detecting relic neutrinos via β decay

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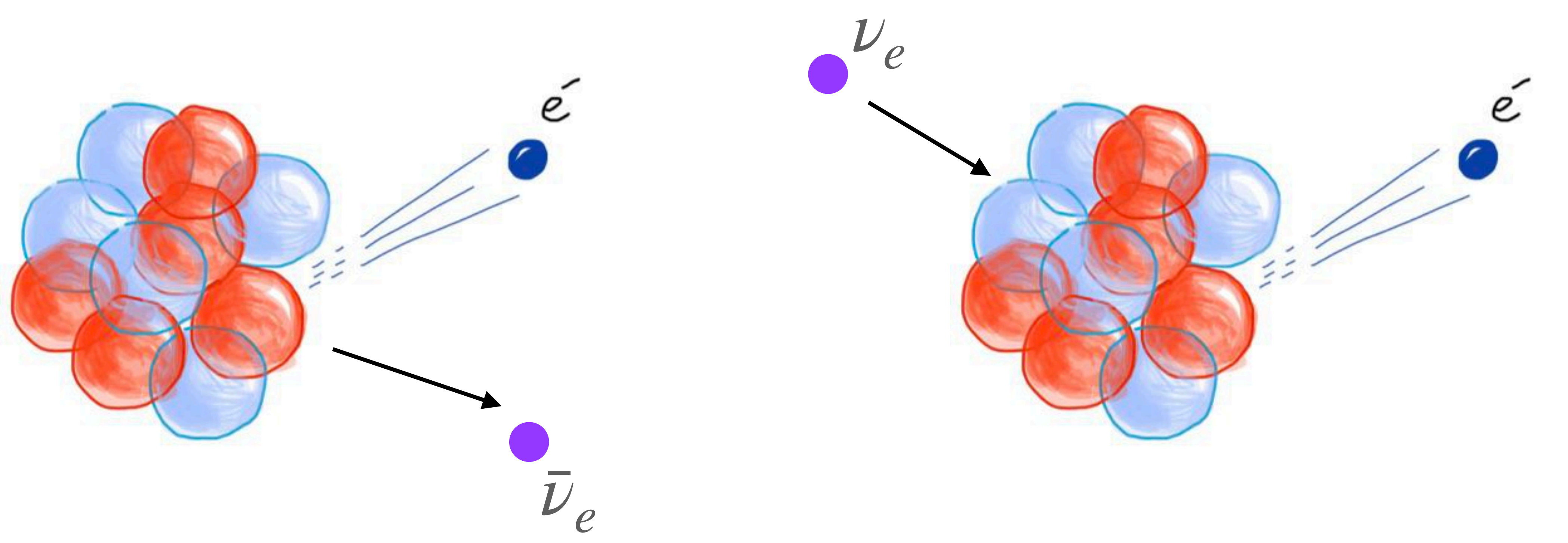
- The **2 parts of the spectrum** are separated by $2m_\nu$



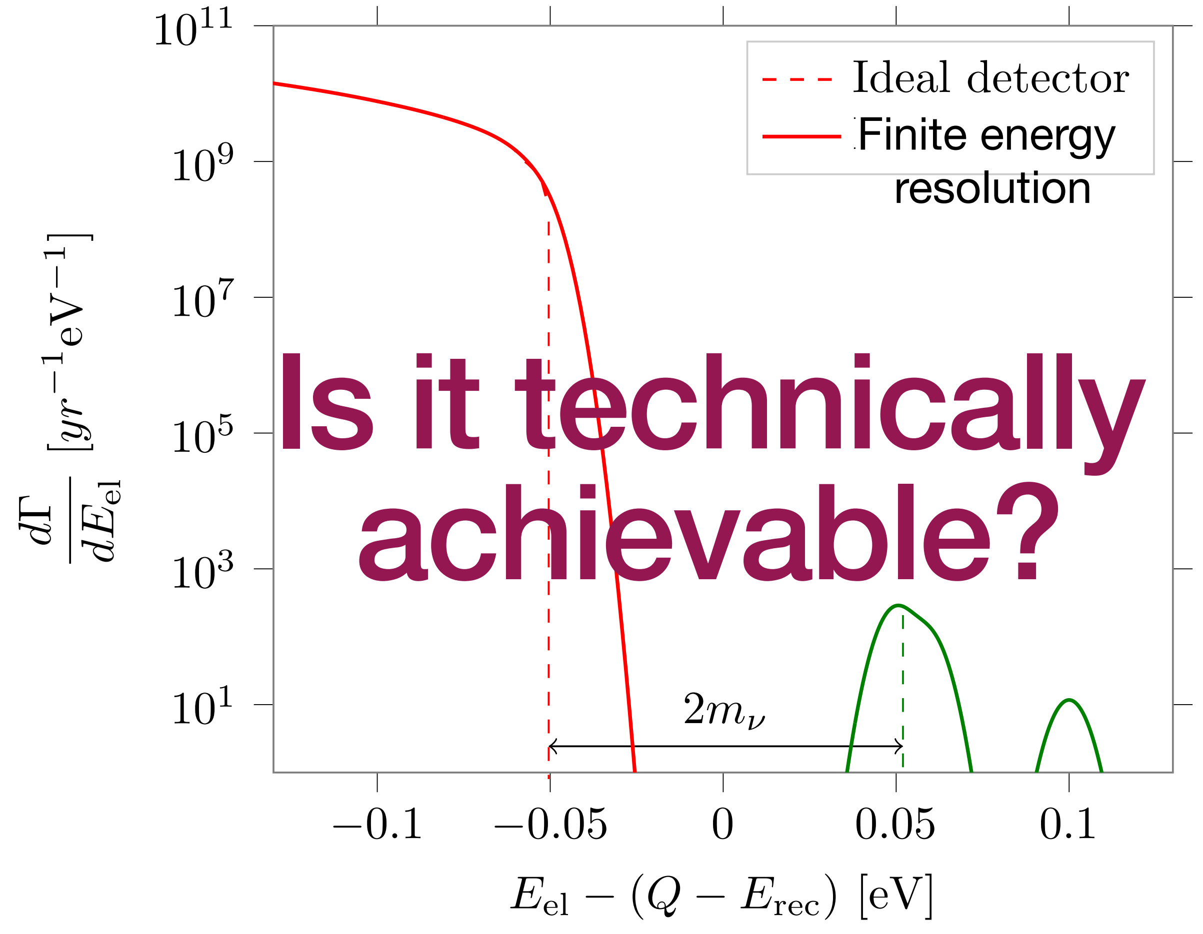
β decay

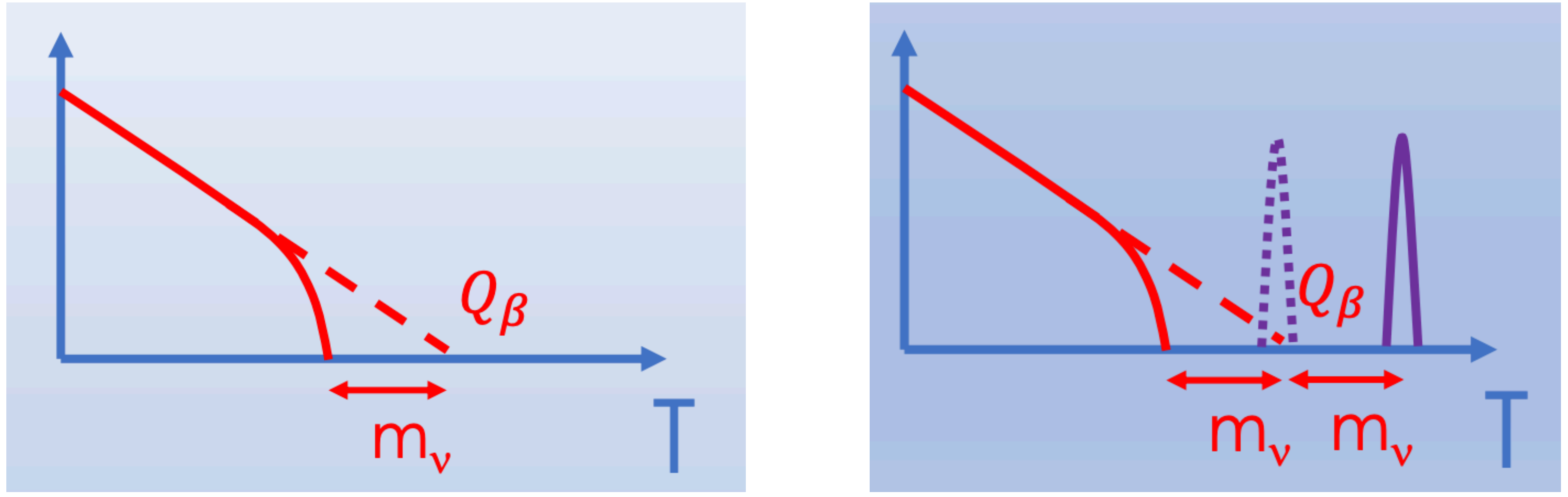
Neutrino capture

Challenges

- High **energy precision** (order of $m_\nu \sim 10$ meV)
- Sufficient **activity rate** (several events per year)

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





Requirements to the experiment

High enough activity

- Low emitter **Q-value** [Cocco et.al., 2007]
- **Lifetime of emitter:** small enough to have a high decay rate, but large enough not to decay instantly

$\left.\right\}$ ^{3}H

$$\sigma_\nu \sim \frac{1}{\tau Q^3}$$

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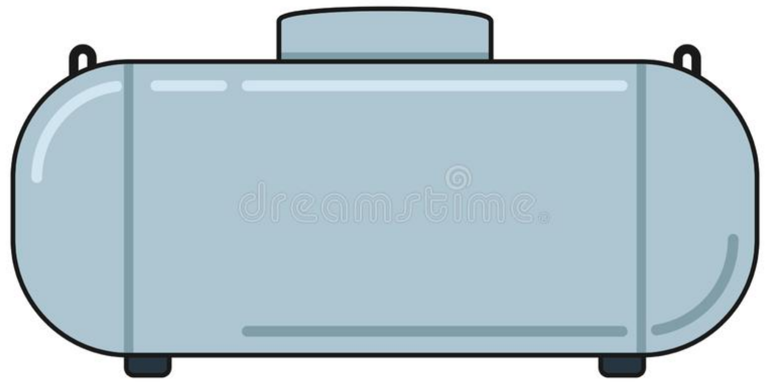

In gaseous form?

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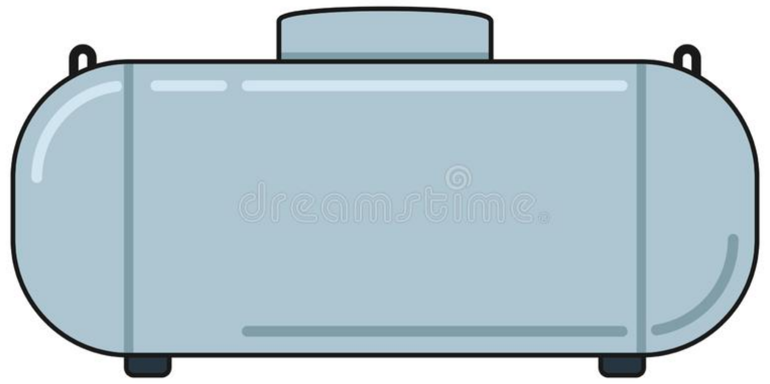

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High energy precision

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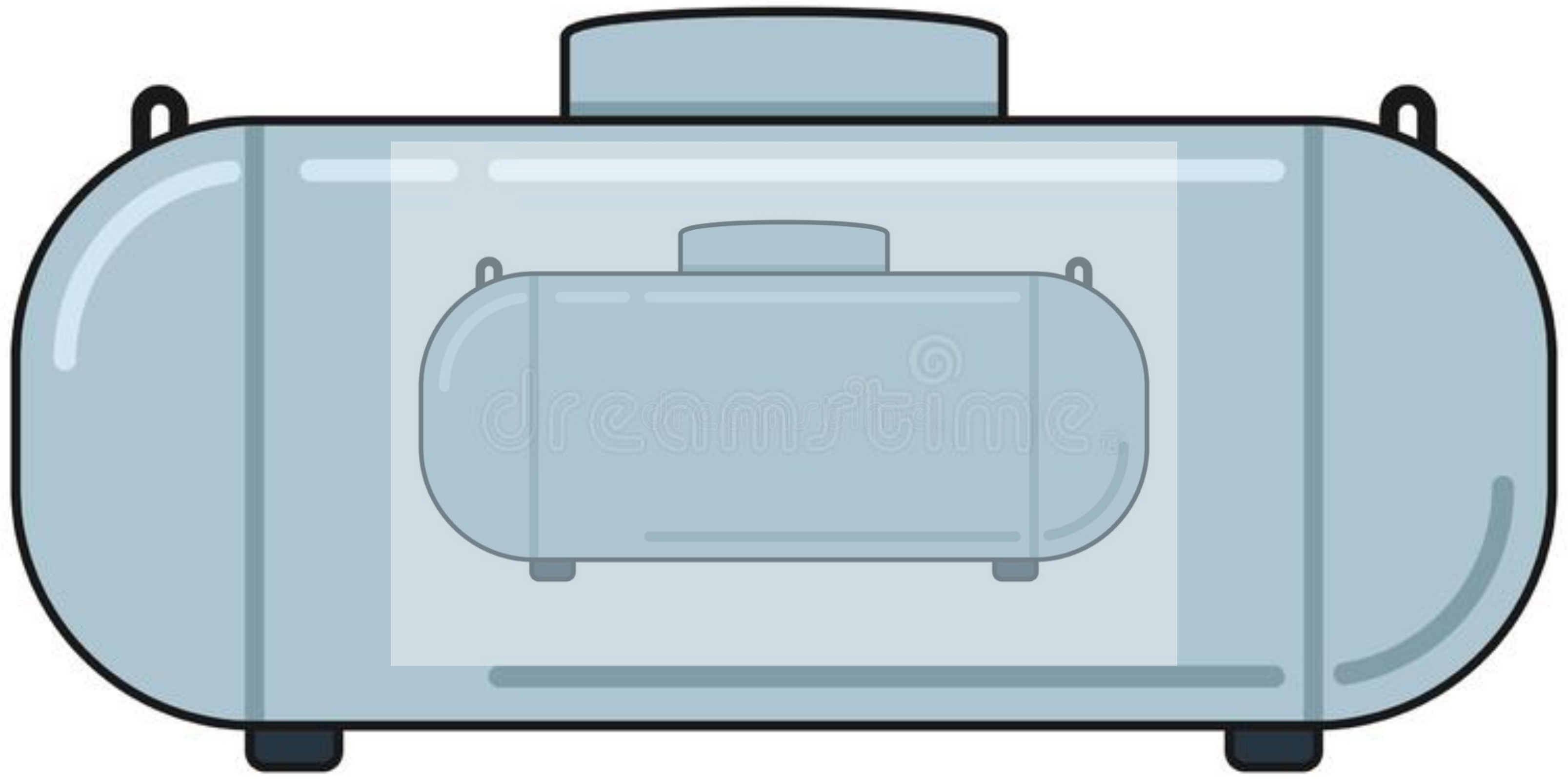
- Low **emitter densities** electron free path bigger than the system size

Cross section

$$\lambda = \left(R^2_{atom} \frac{N}{L^3} \right)^{-1} > L$$

$$L \sim 1\text{km}$$

Very naive! In reality much bigger



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High energy precision

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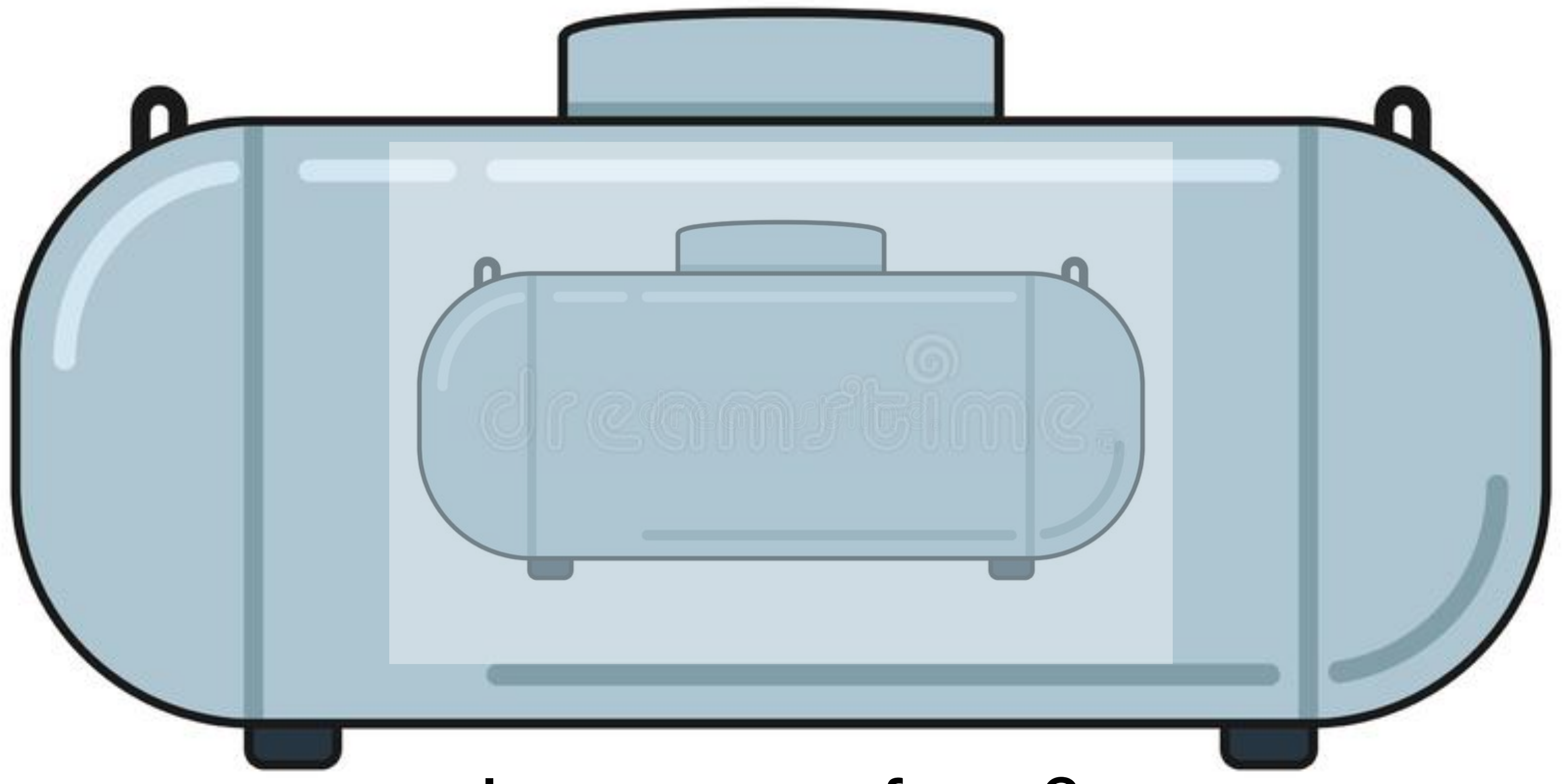
- Low **volume**

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



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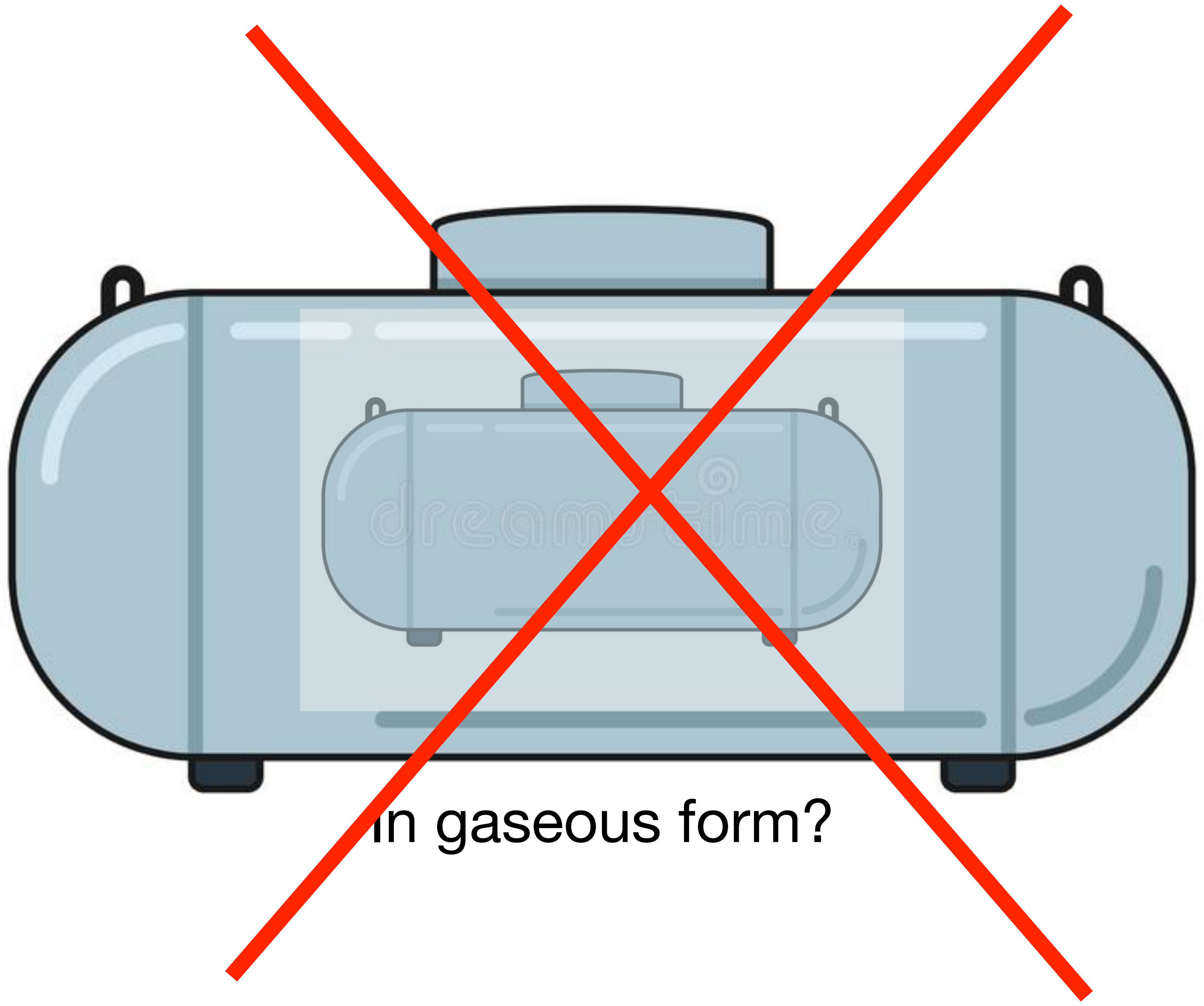

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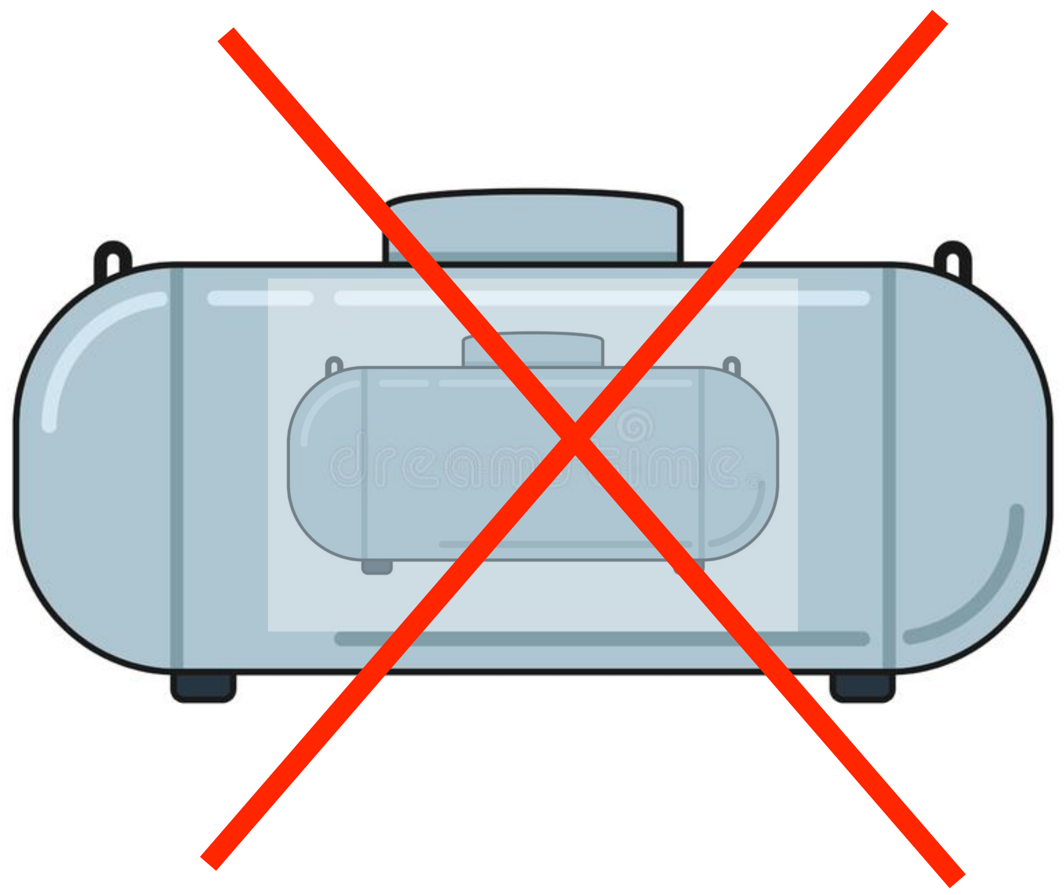
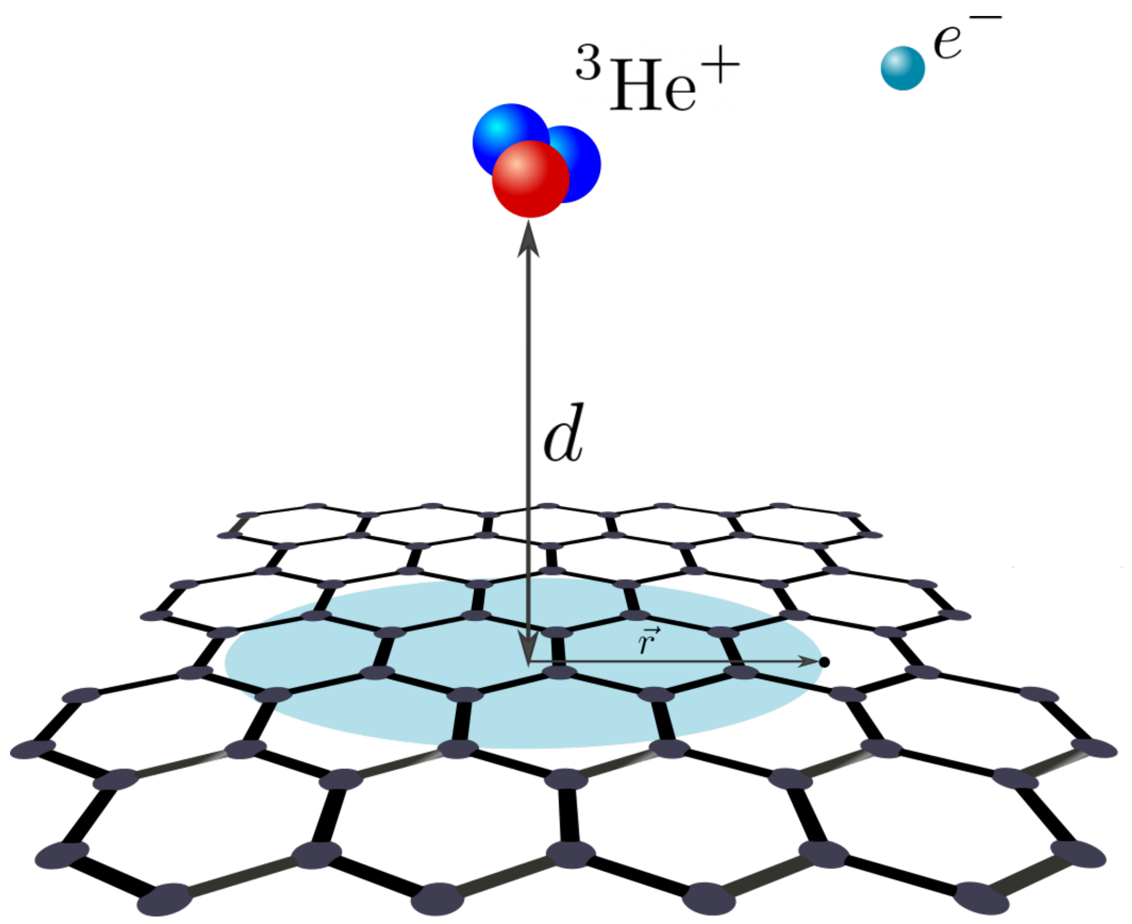


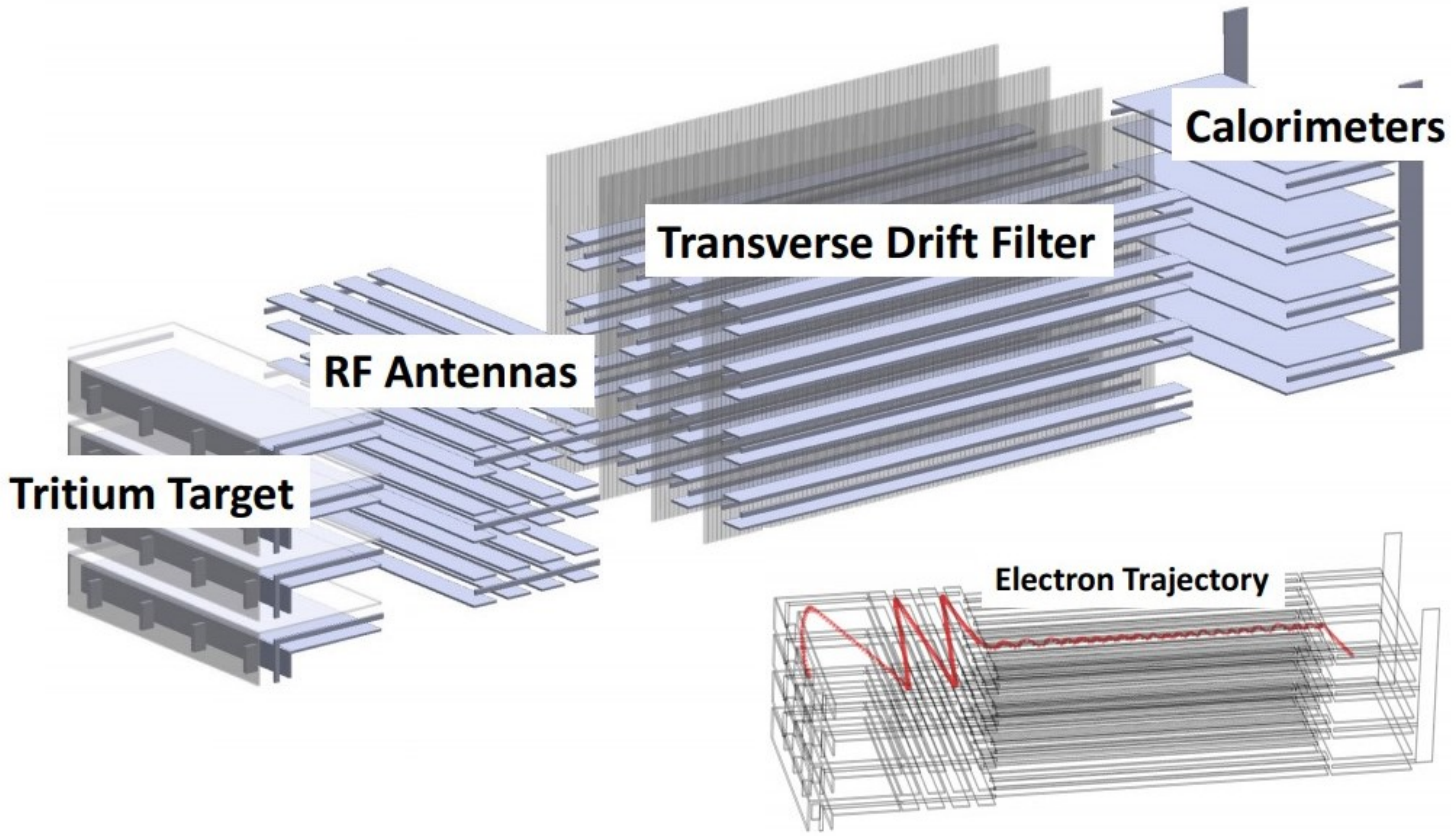
- Radioactive material in gaseous form does not suit
- Need in the **solid-state based experiment**



PTOLEMY project

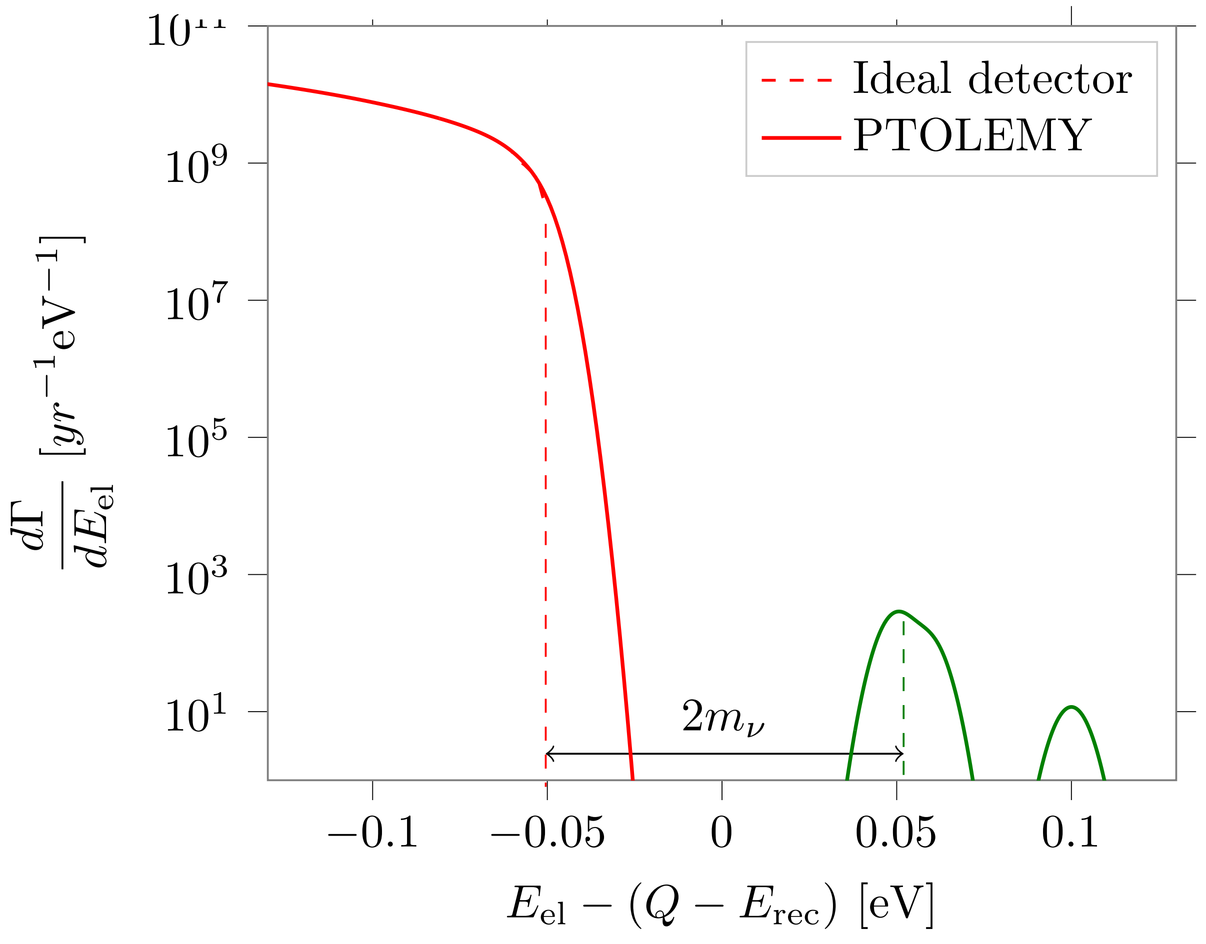
State of the art

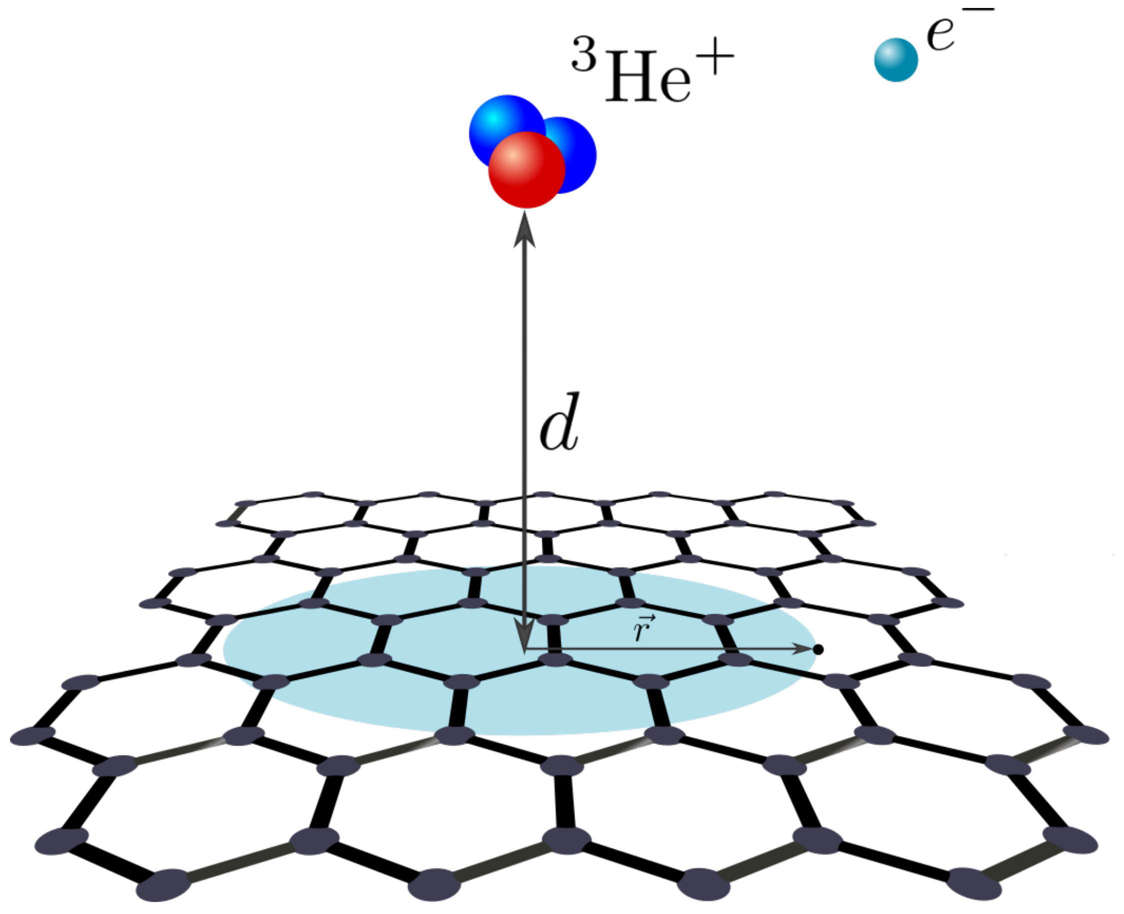
- **Tritium** as a β-decay emitter.
- Tritium is deposed on **graphene** sheets
- $\approx$ 4 CvB **events** per year.
- Outstanding **energy resolution** of the apparatus $\approx$ 10 meV.



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

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

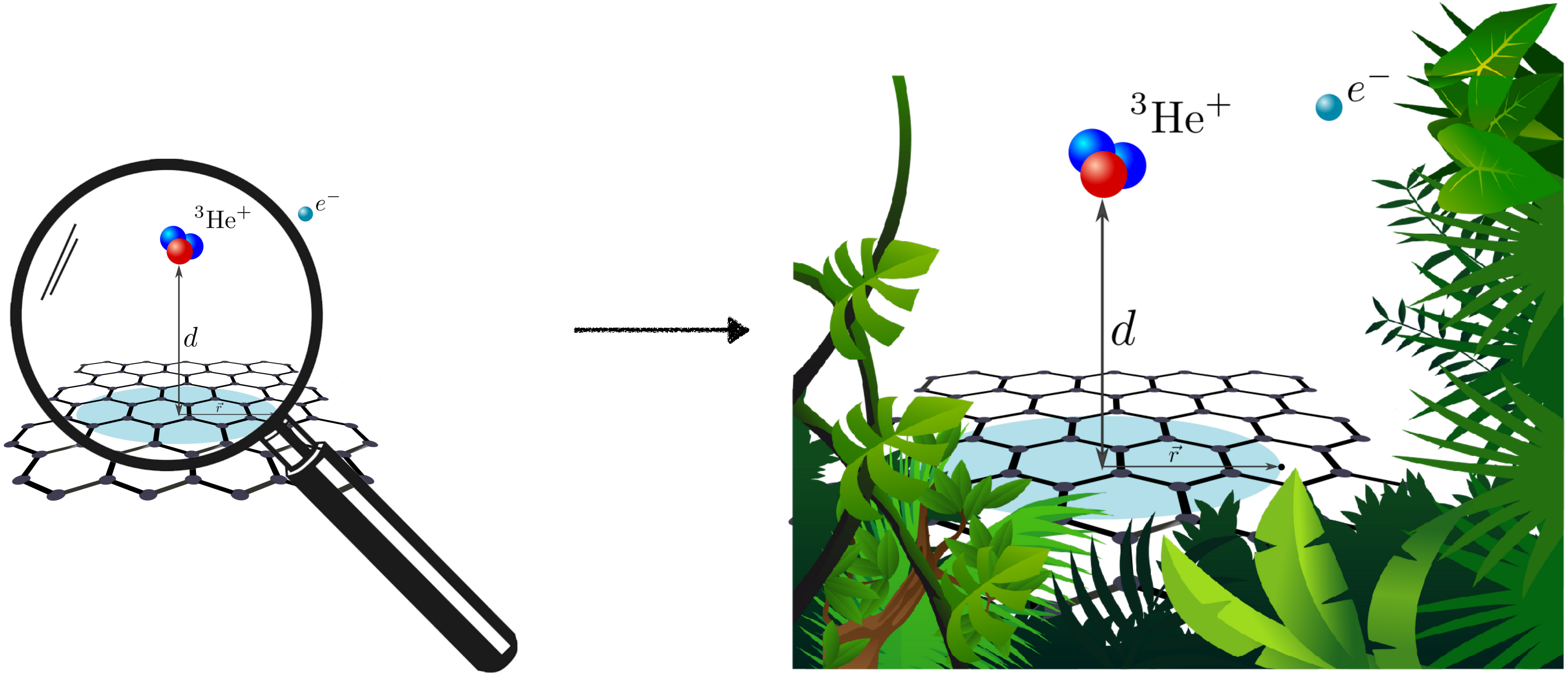




P on-
T ecorvo
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield

Jungle of many-body and chemical effects

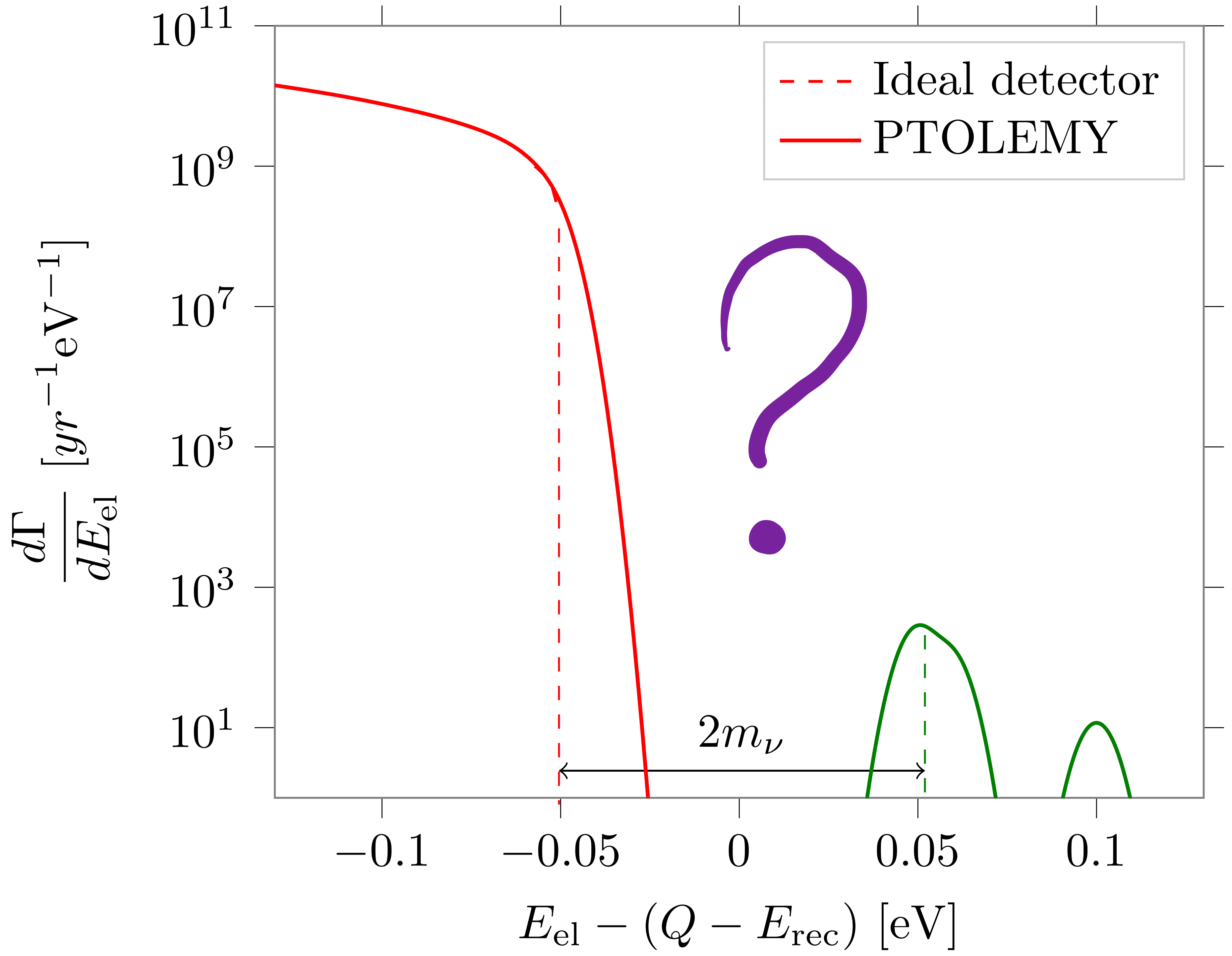
We need **energy resolution** $> m_\nu \sim 10$ meV

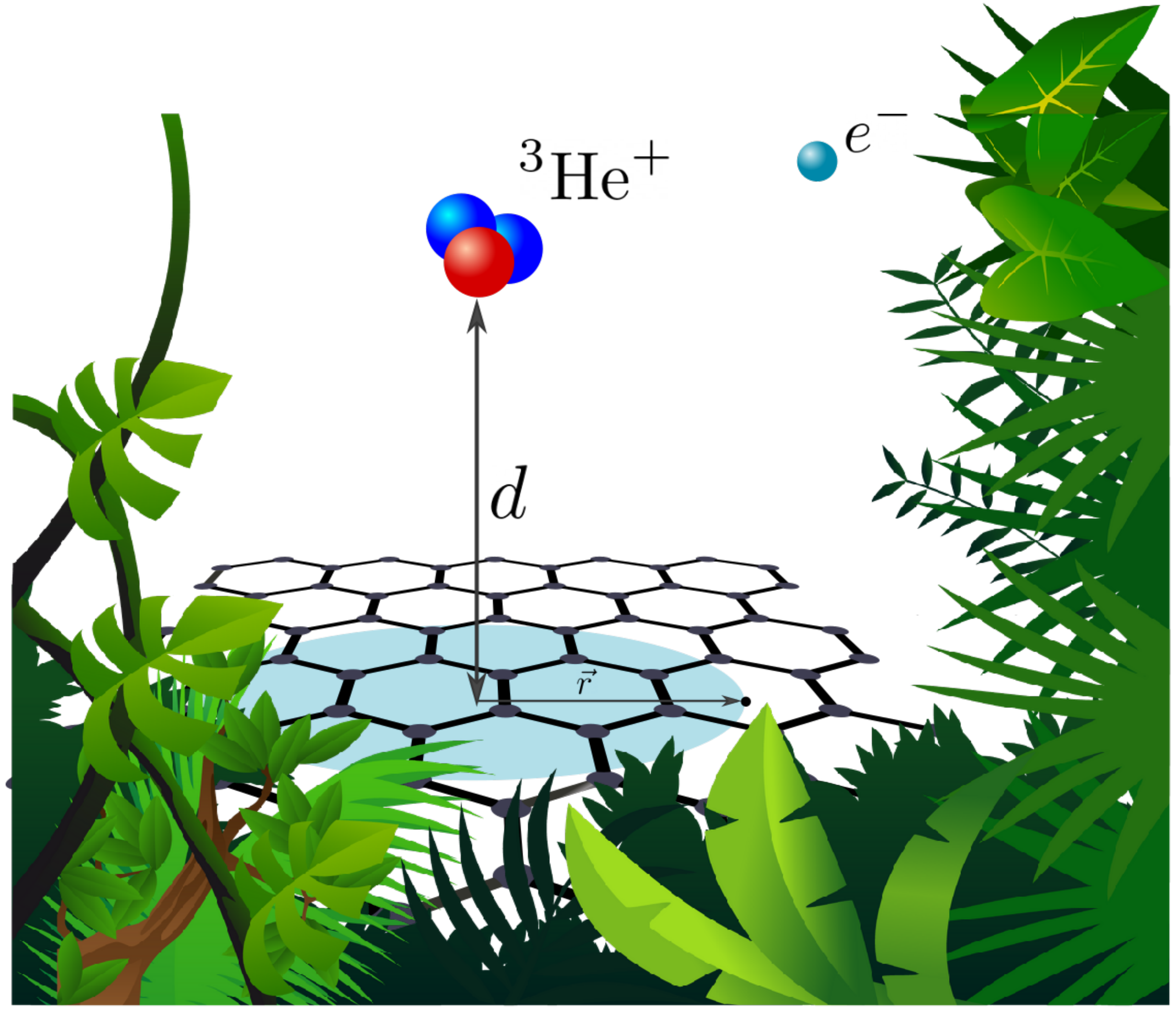


Jungle of many-body and chemical effects

The **width of the peak** that serves as a signature of CνB is defined by

- The energy **resolution of the apparatus**
- **Intrinsic** physical effects

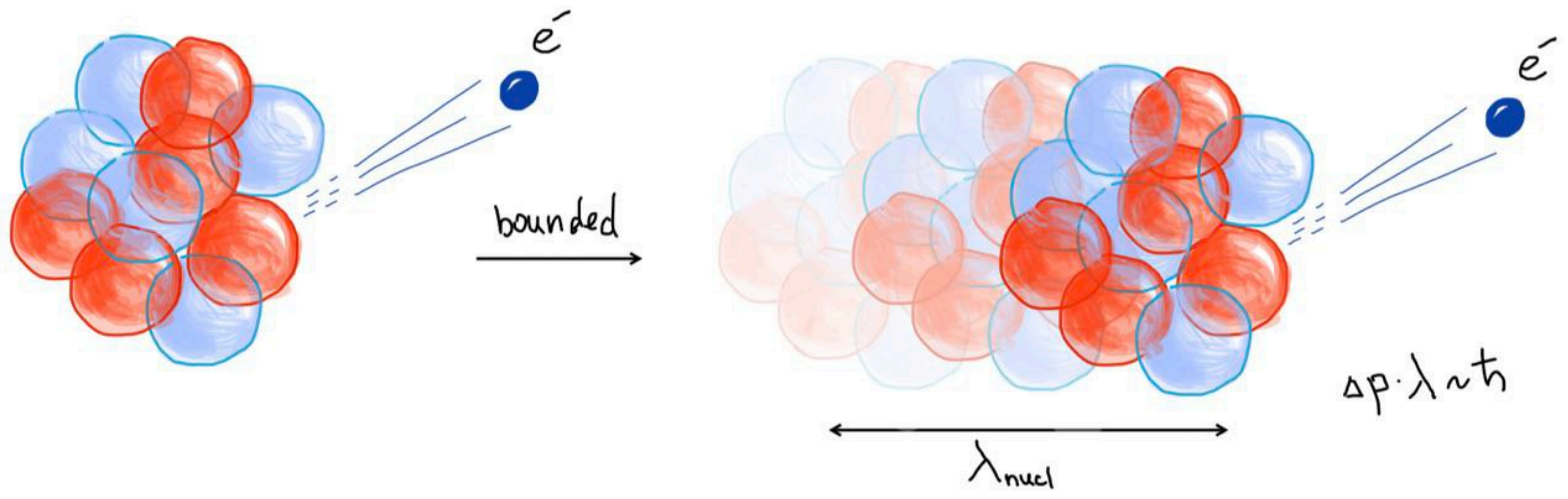




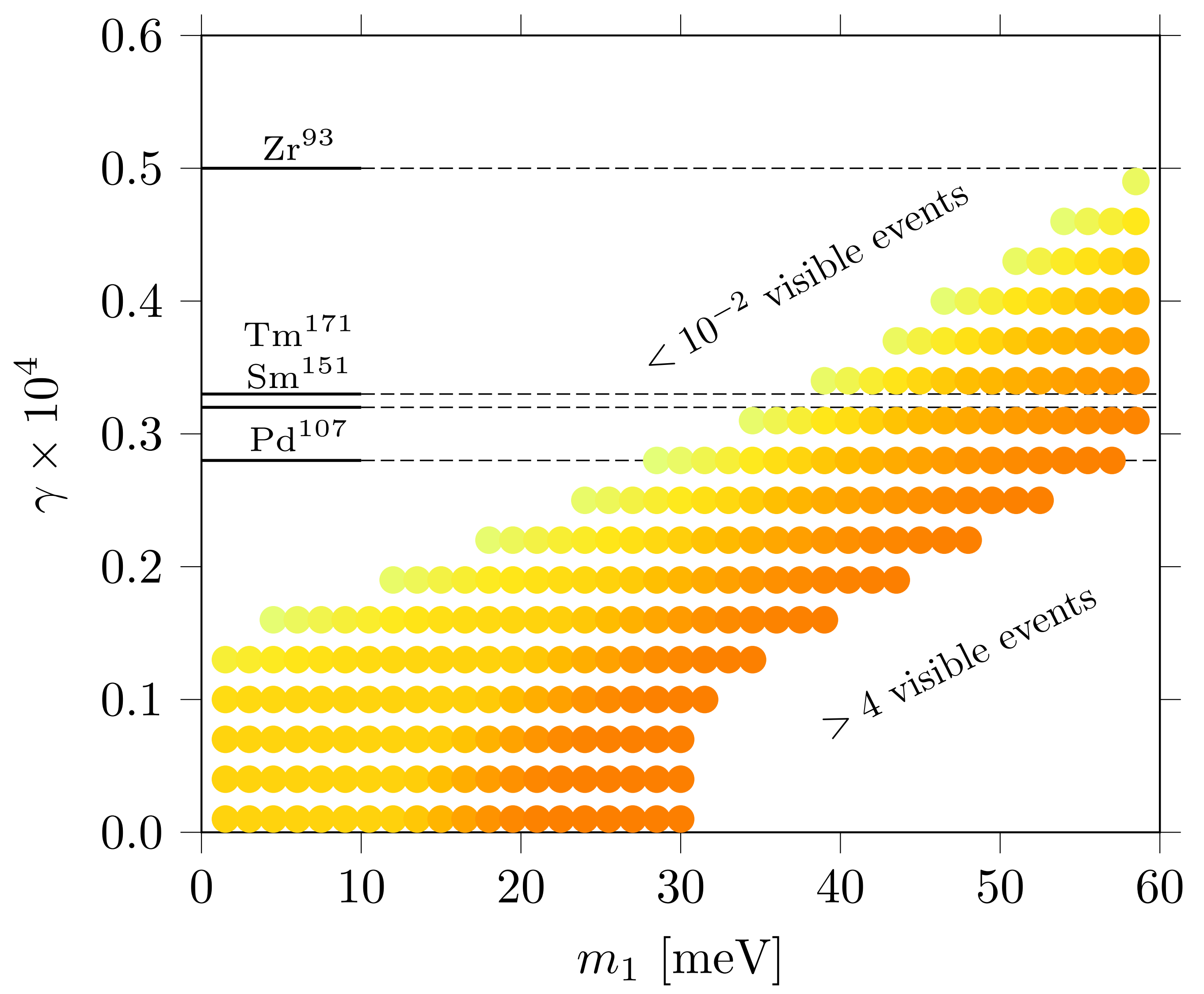
Heisenberg uncertainty

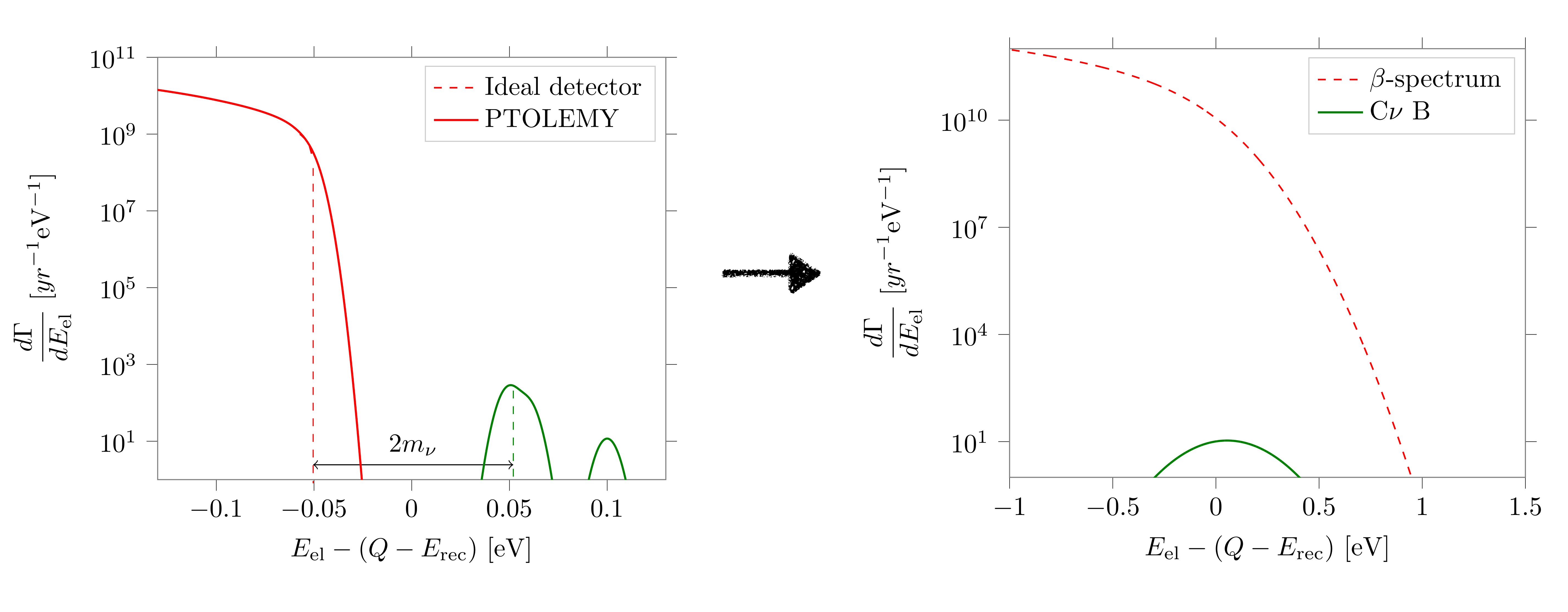
The uncertainty in energy of the emitted electron ΔE

- Is of the **order of 0.5 eV**
- Is 2 orders of magnitude greater than the resolution needed
- Weakly depends on the potential stiffness.
- Strongly depends on the radioactive nucleus.



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





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- By **making the bonding potential softer** one reduces ΔE
- In order to reduce ΔE by an order, one has to make the bonding potential **4 orders of magnitude softer**

[Apponi et. al., Phys. Rev. D, 2022]

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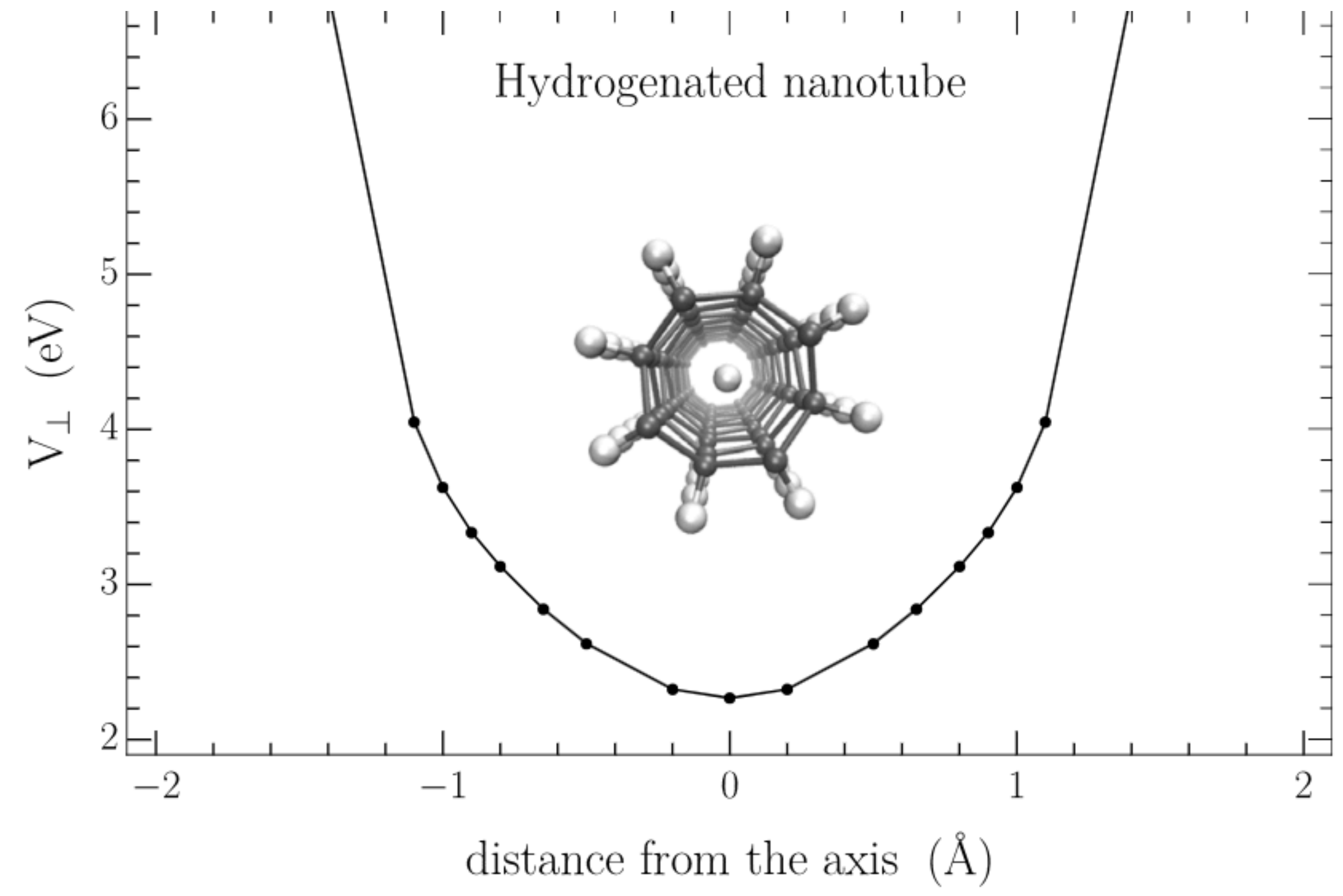
- Binding Tritium inside array of carbon nanotubes [Apponi et. al., Phys. Rev. D, 2022]



- Tritium will form molecules, in 1D the rate defined by

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

- For experiment time $\Delta t \sim 100$ days at $T = 0.1$K it gives a **surface density five orders of magnitude lower then fully loaded graphene**

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- What if we **make the bonding potential harder, not softer**
- Heavy bounded nucleus is sitting in the harmonic potential, therefore its **low energy excitation spectrum is discrete**
- In such an atom, the **end of the total** β **decay spectrum** (including chemical interaction of the atom with the substrate) will be **discrete**

- The last discrete level that corresponds to maximal electron energy corresponds to the process where atom stays in its ground state (**recoil-less** β **decay**)
- Such a level is **not smeared** by the background
- the matrix element of it $\mathscr{M}$ is suppressed as compared to the one of the unbounded ^3H ($\mathscr{M}_0$) as

$$\mathscr{M} = \mathscr{M}_0 \exp\left(-\frac{k_\beta^2}{4\sqrt{m_{nucl}\kappa}}\right)$$

Where k_β is the momentum of emitted electron

- For ^3H adsorbed on graphene one has $\mathscr{M} \approx 10^{-4}\mathscr{M}_0$
- For other types of binding κ can be bigger, but not sufficiently.

[Cheipesh et. al., arXiv:2111.09292, 2021]

[Mikulenko et. al., arXiv:2111.09292, 2021]

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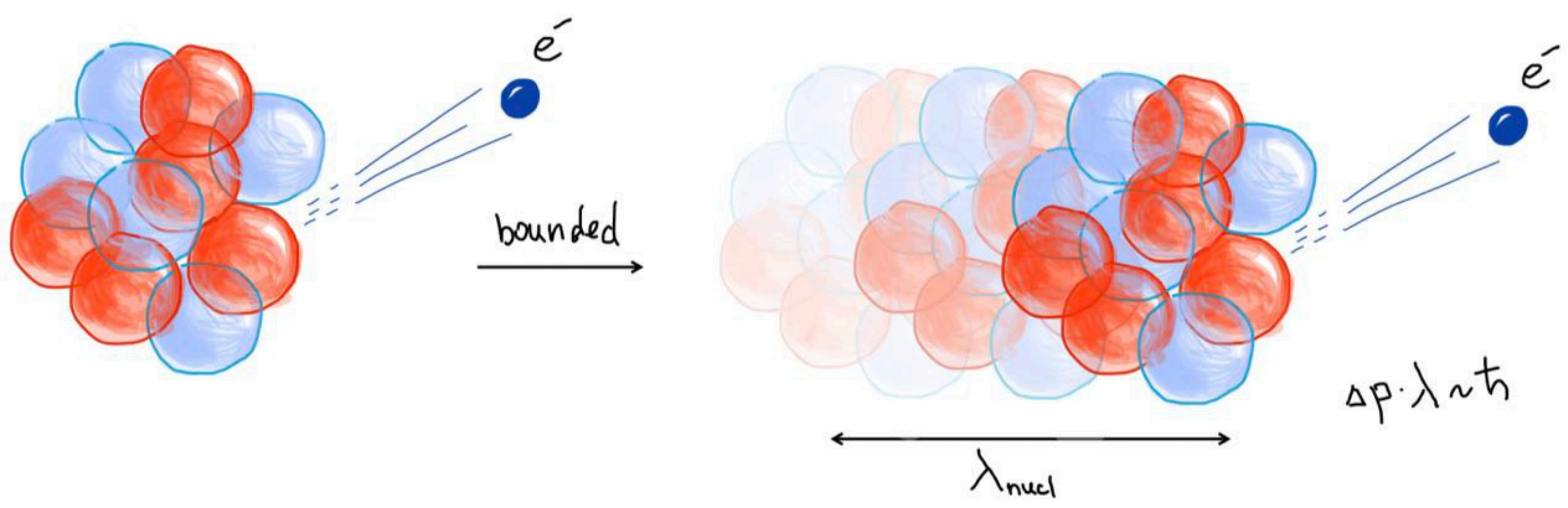

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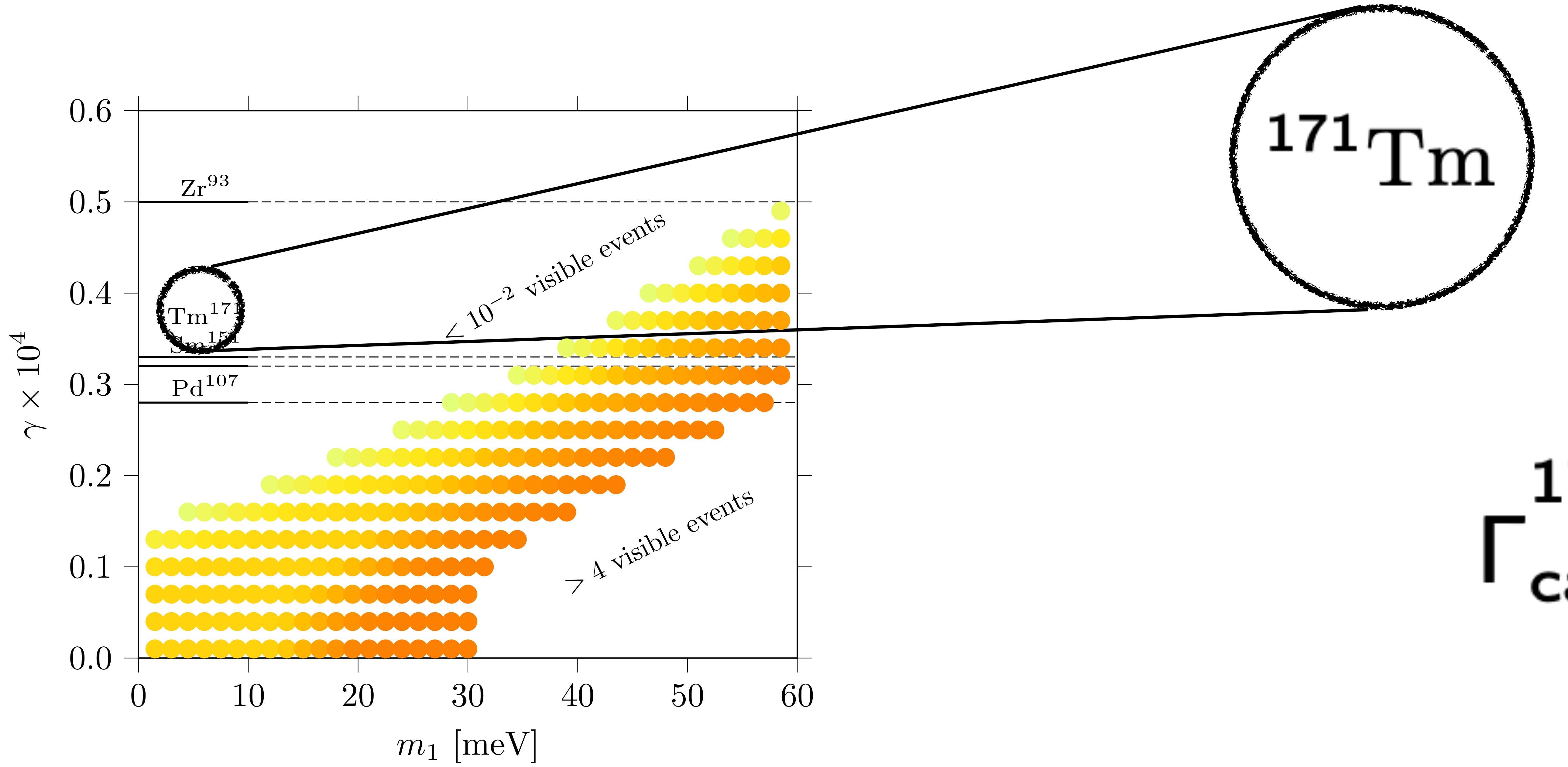


$$\Gamma^{^{171}\mathrm{Tm}}_{\text{capture}} = 3 \cdot 10^{-2} \Gamma^{^{3}\mathrm{H}}_{\text{capture}},$$

[Mikulenko et. al., arXiv:2111.09292, 2021]

[Cheipesh et.al., Scipost, 2023]

Choosing heavy nuclei

The candidate should satisfy following conditions:

- Minimize combination $\gamma^4 = Q^2 m_{el}/c^2 m_{nucl}^3$
- Have **sufficient neutrino capture rate** $(\sigma v)_\nu \gtrapprox 10^{-3} \times (\sigma v)_\nu^{^3H}$
- Have **meaningfully big lifetime** $\tau \gtrapprox 1$yr
- The **daughter nucleus** should either be **stable** (with regard to both β and α decays) or have Q-value smaller then the one of a parent nucleus.
- The simple estimate of the capture cross section can be made $(\sigma v)_{est} = (\tau Q^3)^{-1}$
- For ^3H and ^{63}Ni that undergo allowed β decay this estimate is exact
- ^{171}Tm undergoes so-called **1st non-unique forbidden decay**

Parent	$\tau_{1/2}$, [yr]	Daughter	Q, [keV]	$(\sigma v)_{\rm est}/(\sigma v)_{^3\rm H}$ $[10^{-3}]$	$\gamma/\gamma_{^3\rm H}$
^{171}Tm	1.92	^{171}Yb	96.5	45.0	0.110
^{63}Ni	101.	^{63}Cu	66.9	2.6	0.193

Table 1: **List of possible candidates** for suitable β-emitter and their characteristics. The capture rates are calculated using the estimate $(\sigma v)_{\rm est} = (\tau Q^3)^{-1}$.

$$^3H : \quad N \approx 2 \cdot 10^{24}$$

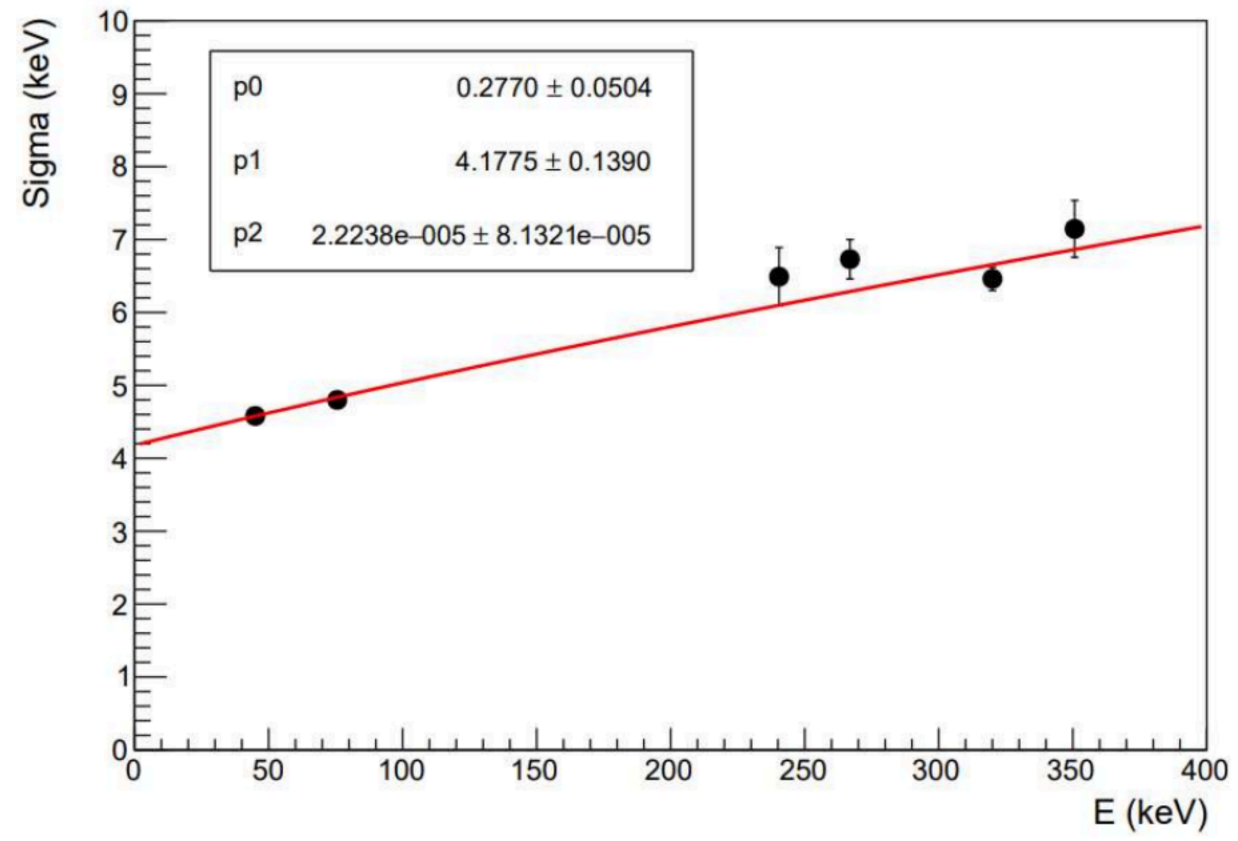
$$^{171}Tm : \quad N \approx 8 \cdot 10^{25}$$

$$^{63}Ni : \quad N \approx 1.1 \cdot 10^{27}$$

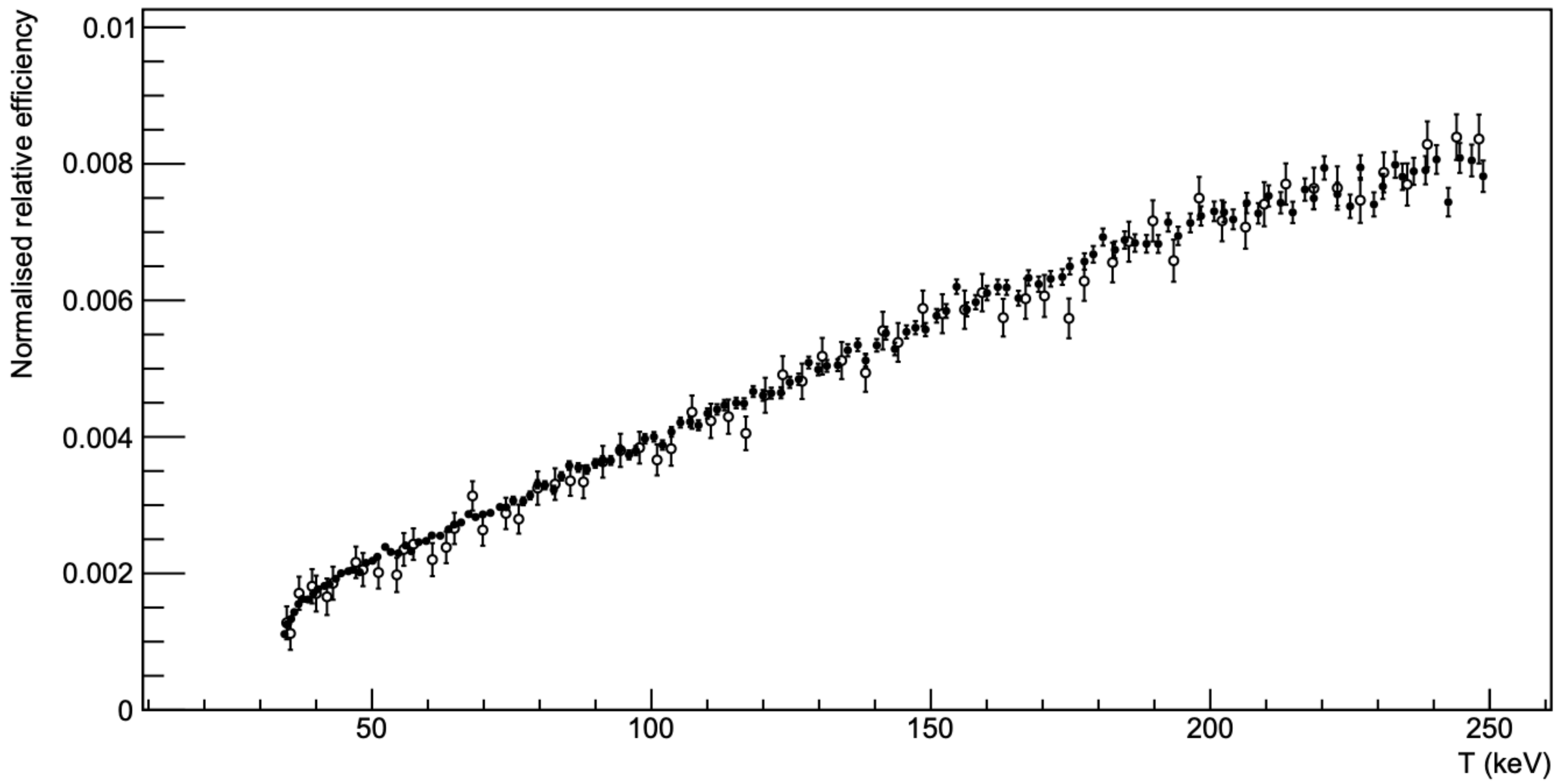
Number of emitters needed for **the single event exposure per year** using the estimate $(\sigma v)_{est} = (\tau Q^3)^{-1}$

Neutrino capture rate for ^{171}Tm

- The ^{171}Tm neutrino capture cross section can be estimated using the **ξ-approximation** [Mikulenko et. al. 2021, Brdar et.al., 2022]. It calculates electromagnetic corrections to the spectrum but treats decay as unique.
- This gives $\Gamma^{171}_{capture}{}^{Tm} = 3 \cdot 10^{-2} \Gamma^{^3H}_{capture}$ **consistent with the crude estimate** $(\sigma v)_{est} = (\tau Q^3)^{-1}$ up to a factor of two [Mikulenko et. al. 2021].
- In order to be sure, one needs to **measure the end of the β decay spectrum.**
- A **precise measurement** of the end point of β spectrum has been performed, using a double focalizing magnetic spectrometer that focuses electrons of specific energy into the detector [Juget et. al., to appear].
- The energy measurement calibration is done using a ^{133}Ba source. The achieved **energy resolution** of the detector is $4 - 5$ keV in the energy range of interest.
- **Detector efficiency** is computed using a ^{60}Co source by comparison with the spectrum computed in BetaShape.



Energy resolution (sigma) measured with ^{133}Ba conversion electrons



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[Juget et. al., to appear]

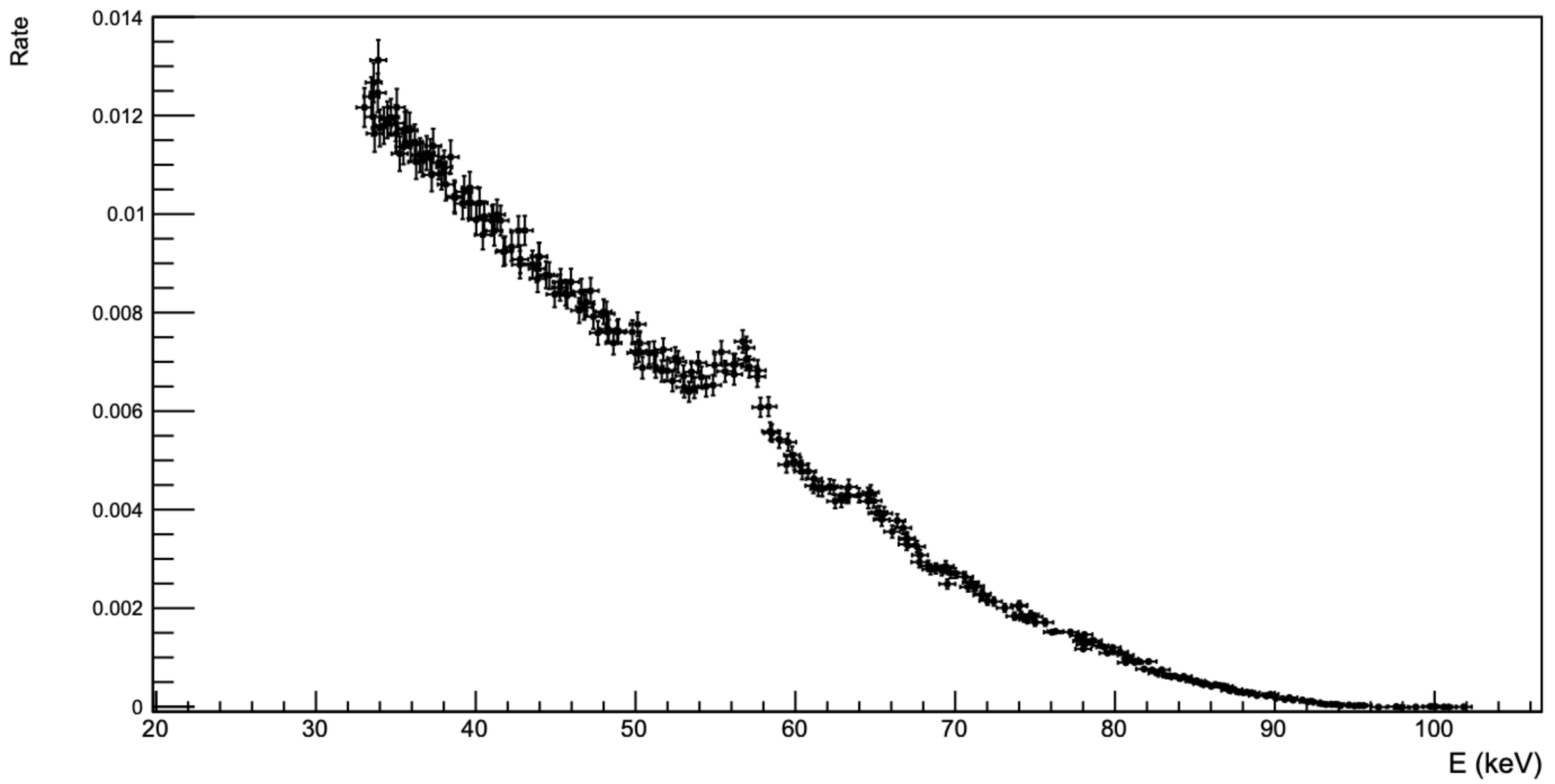
[Smith et.al., 1957]

[Gregers Hansen, 1964]

Neutrino capture rate for ^{171}Tm

- **Pure** ^{171}Tm source with activity 50 kBq was prepared. The spectrum shape is measured from 33 keV to 102 keV with steps of 0.25 keV, and 72 minutes duration.

- The spectrum endpoint is $E_{max} = 97.62(39)$ keV, compatible with the two last measurements [Smith et.al., 1957, Gregers Hansen, 1964].



Measured spectrum of ^{171}Tm

[Juget et. al., to appear]
[Smith et.al., 1957]
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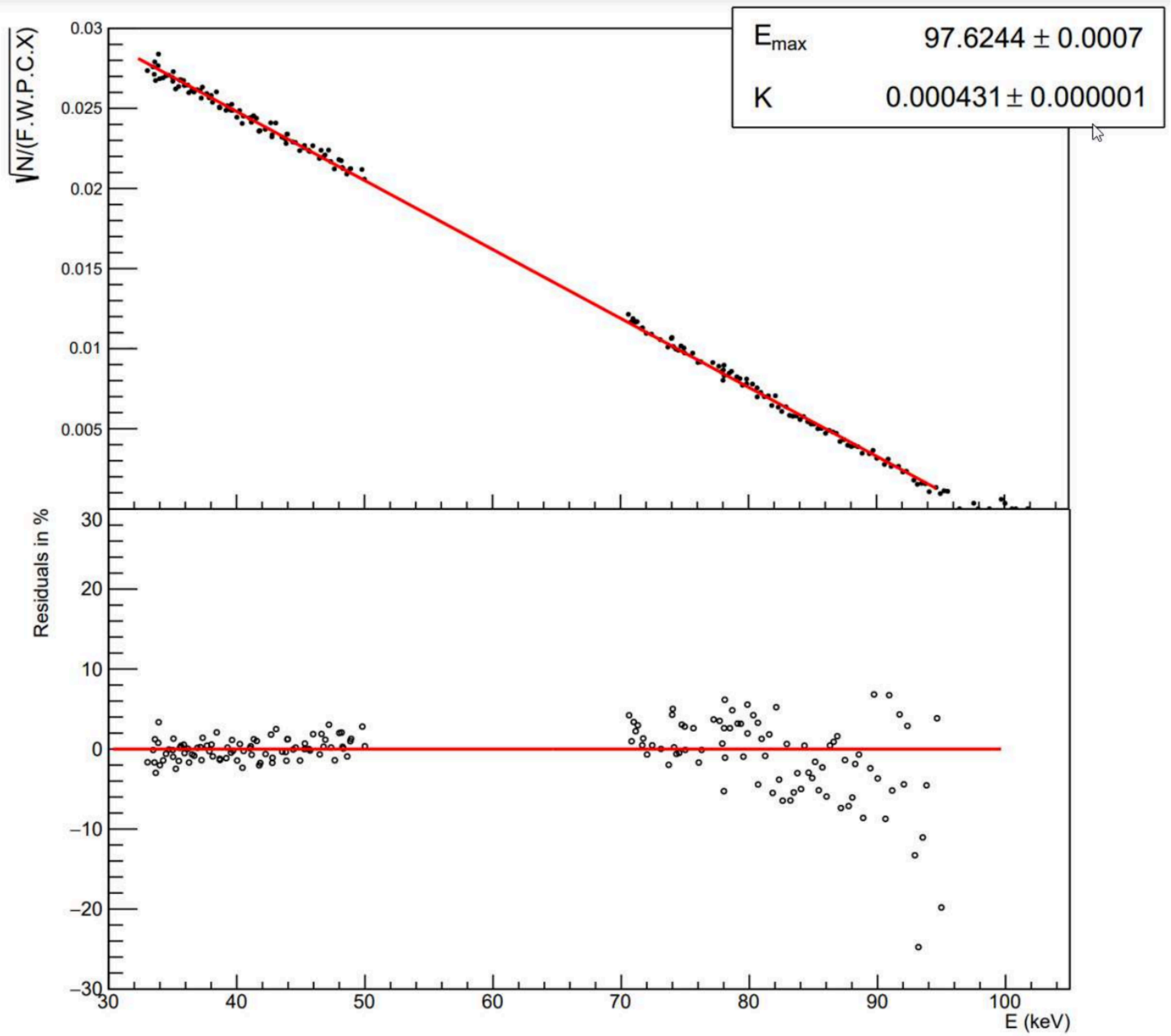
- The spectrum endpoint is $E_{max} = 97.62(39)$ keV, compatible with the two last measurements [Smith et.al., 1957, Gregers Hansen, 1964].
- The deviations from the allowed spectrum do not exceed ~ 10% in the whole energy range up to the endpoint
- To estimate deviations from allowed spectrum, Kurie plot with a fit from 33 keV to 95 keV and residuals of the Kurie plot were calculated. The uncertainty corresponds to the fit only.
- Combined uncertainty is ≈ 0.4 keV.
- The results agree with the ones obtained using **ξ-approximation at 1% level**



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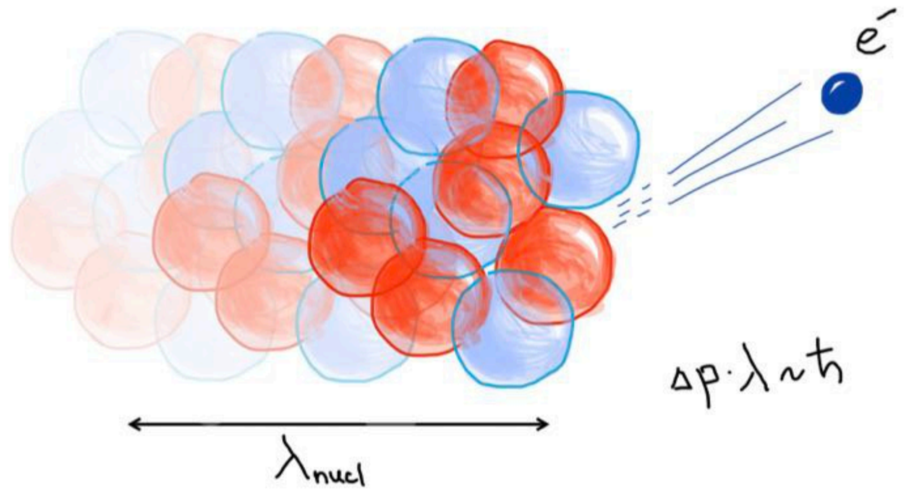
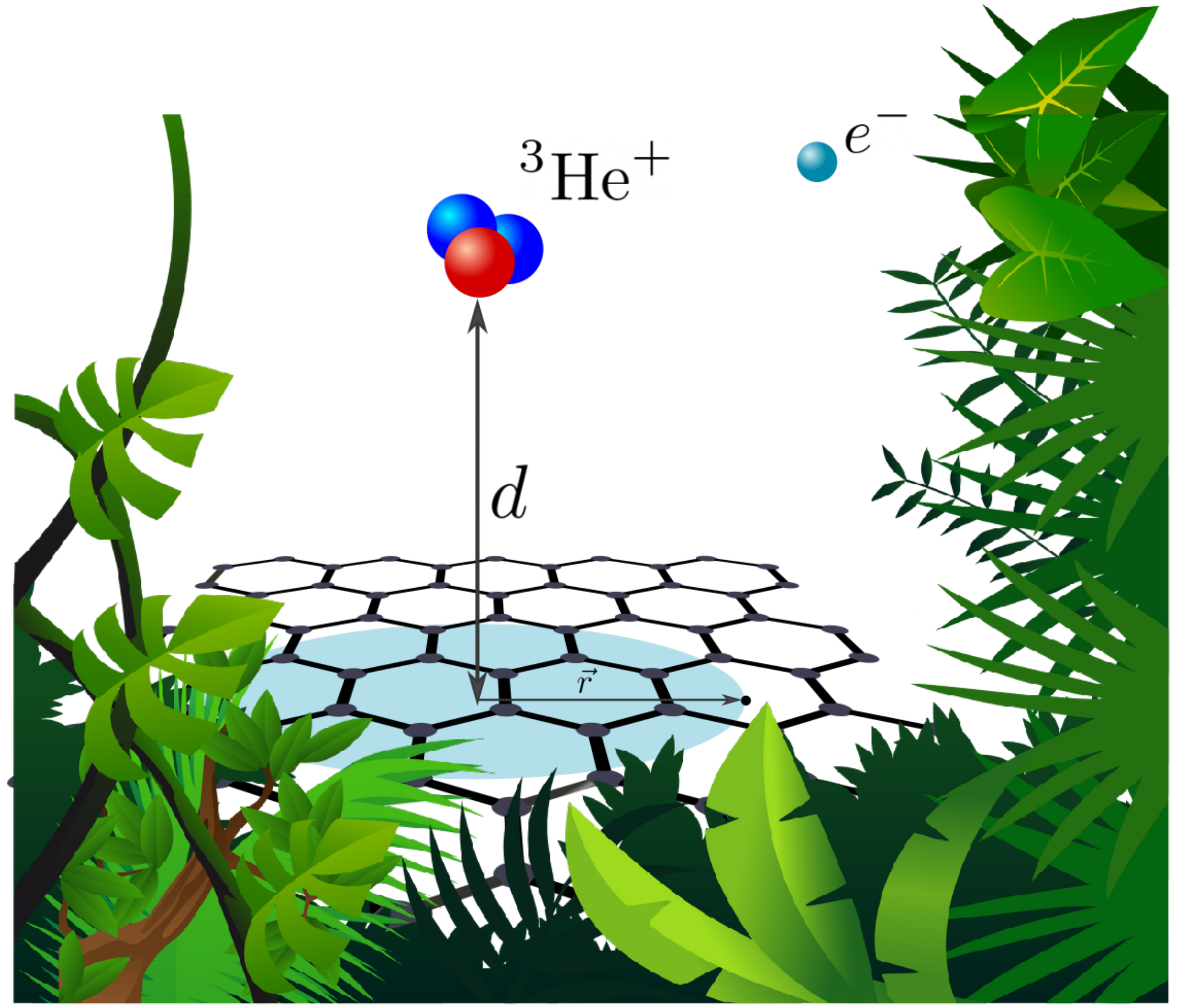
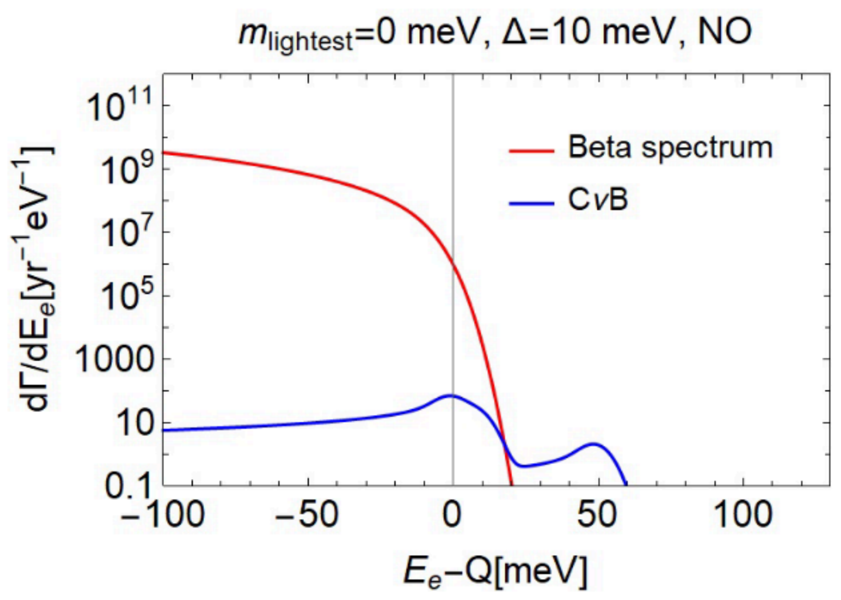


Zero-point motion



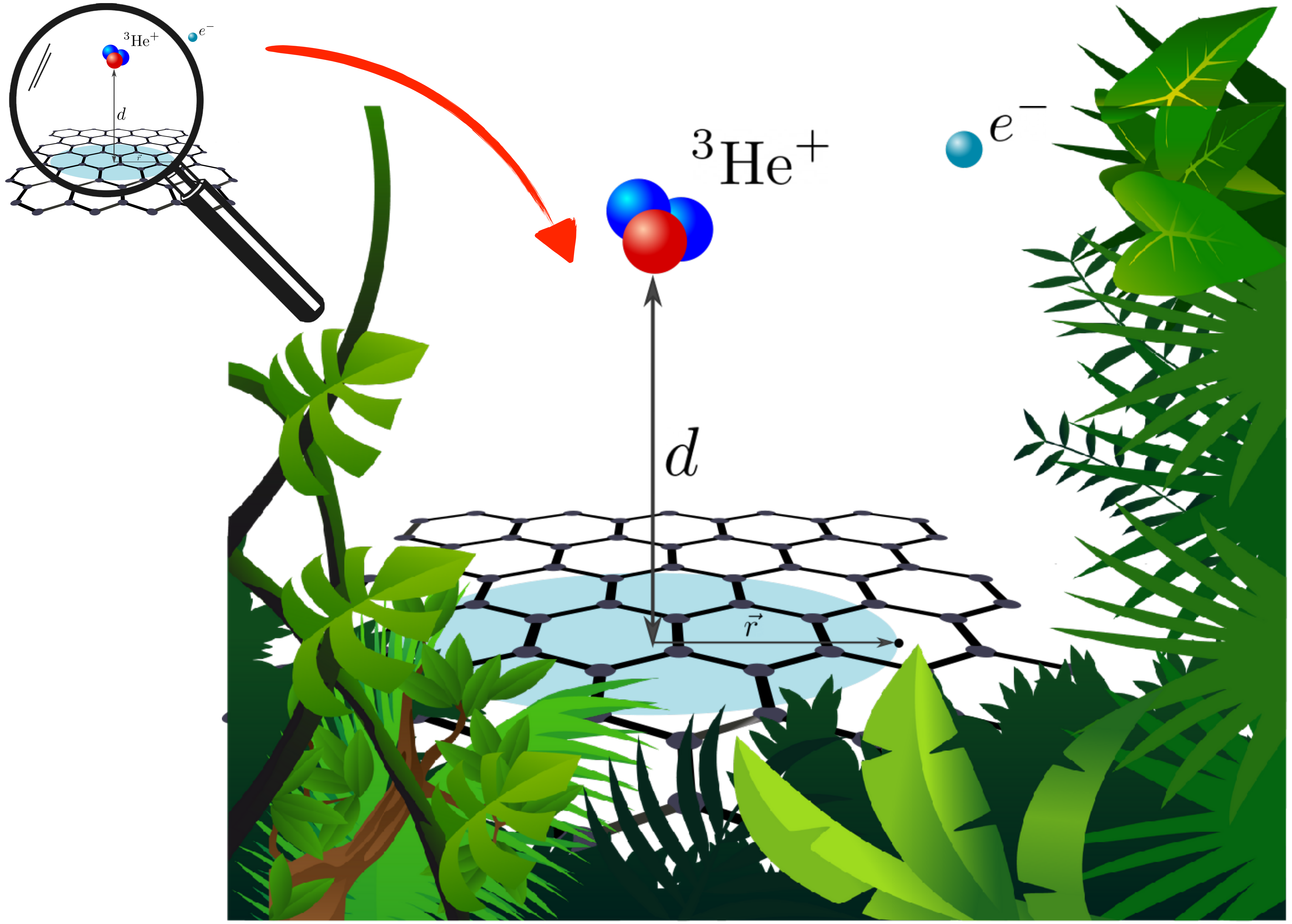
Finite lifetime of the daughter ion

Electric effects



X-ray edge singularity

Etc…



^{3}He$^+$
e^-
d
$\vec{r}$