Looking into the early Universe with a solid-state device

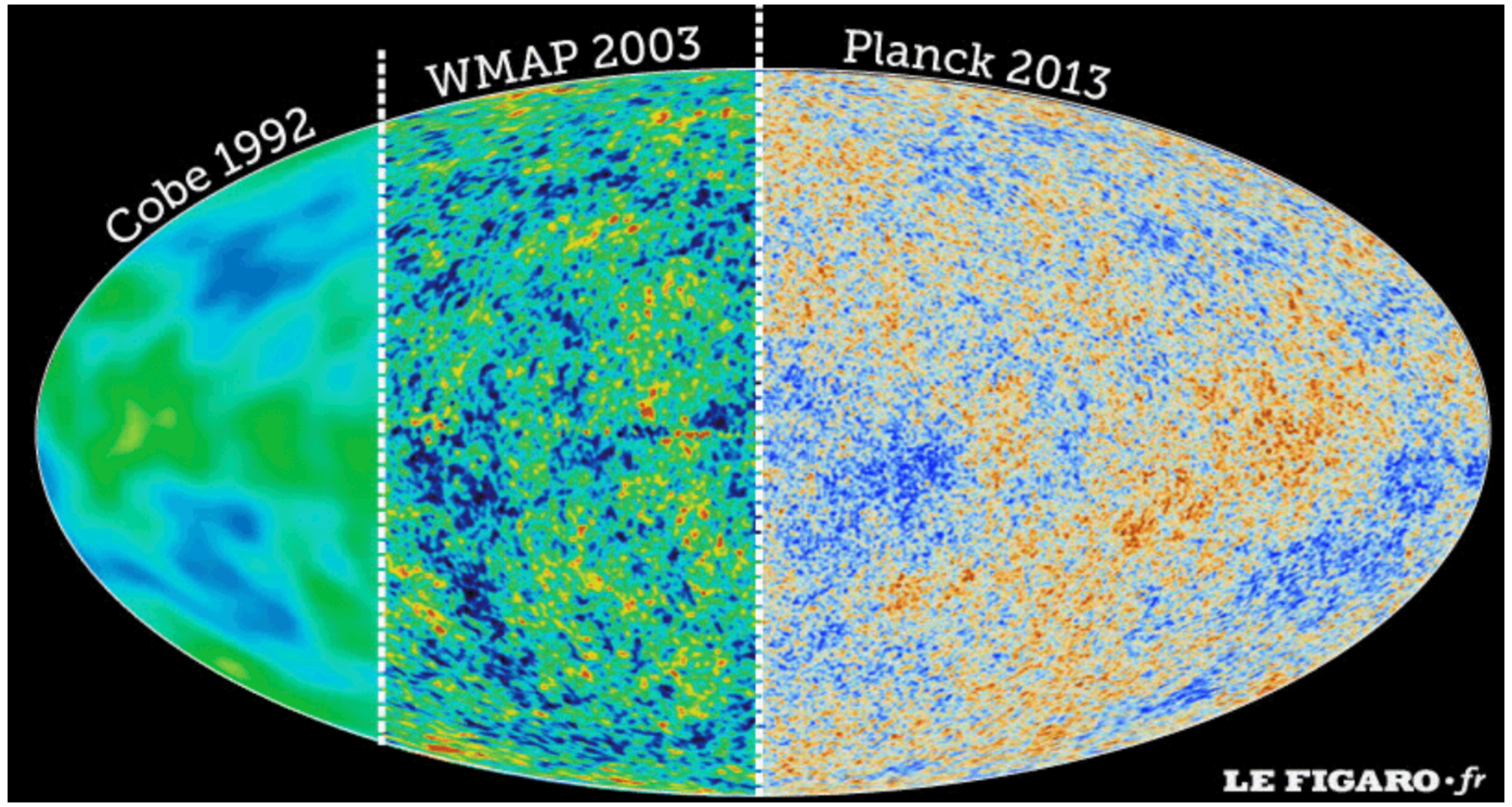
Quantum measurement device
with quantum impurities
for particle physics
and physics of the early universe

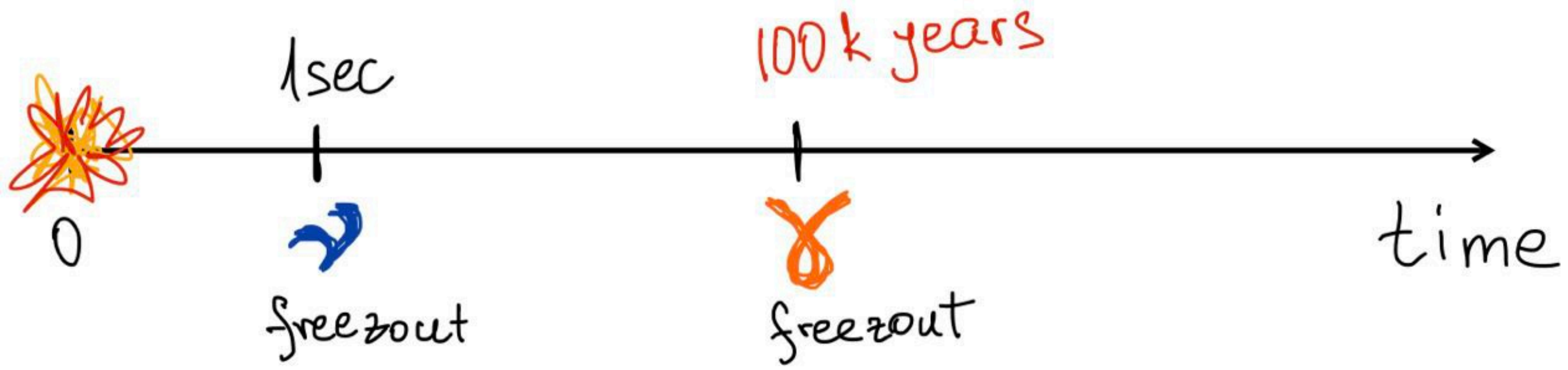



Oleksiy Boyarsky, Yevheniia Cheipesh, Oleksiy Mikulenko, Zhiyang Tan, Vadim Cheianov

How to probe the early Universe? CνB and CMB

- **Gamov:** Early Universe is radiation dominated.
  $\rho_{\text{rad}}/\rho_{\text{matter}} \sim 10^{10}$
- 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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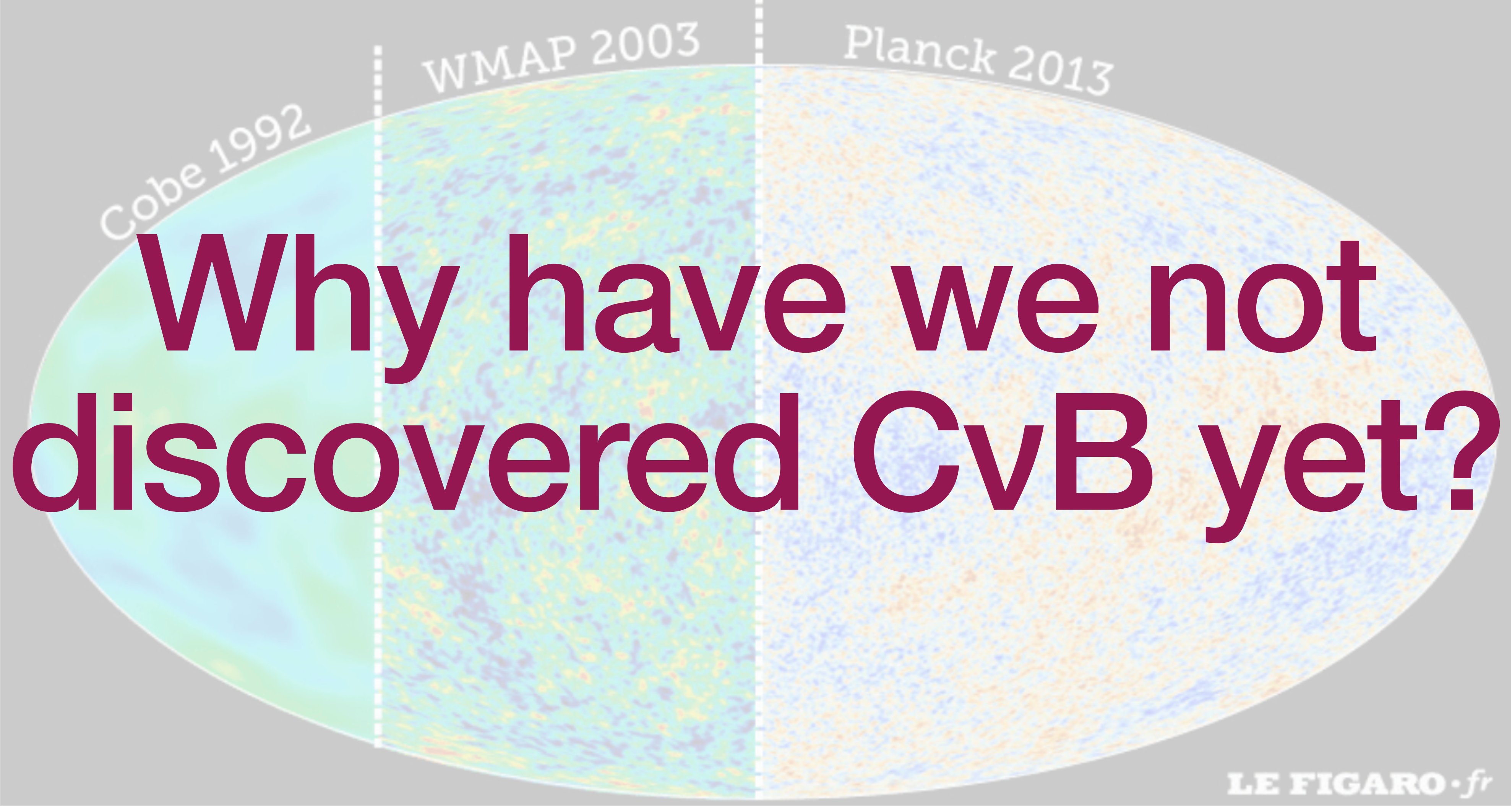

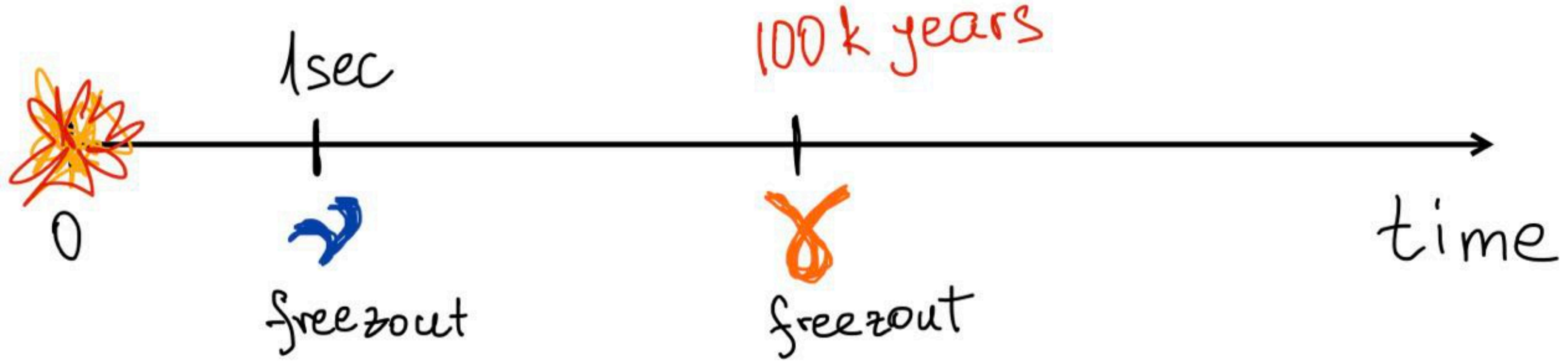

Observation of the cosmological neutrinos would then provide a window into the 1st second of creation

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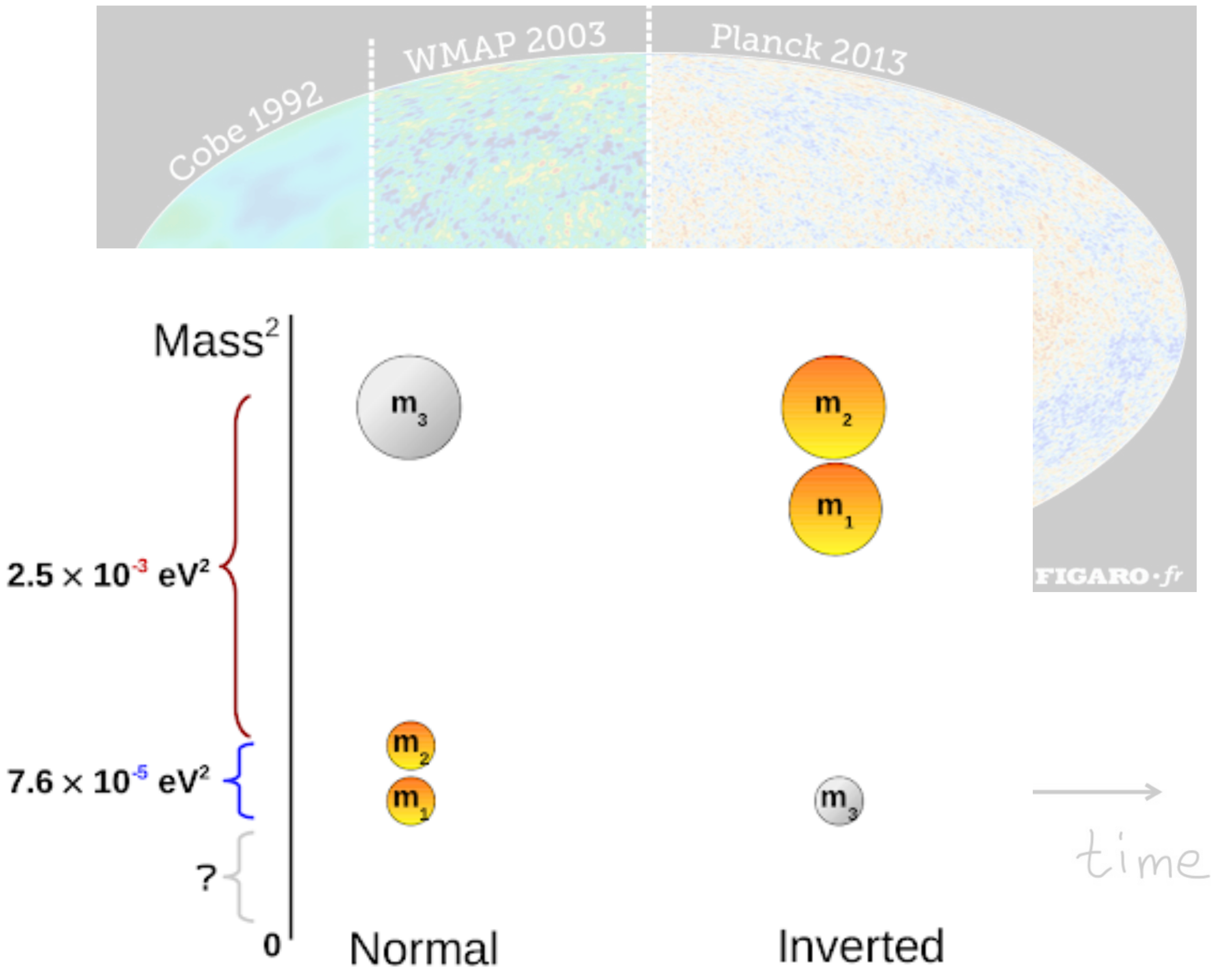
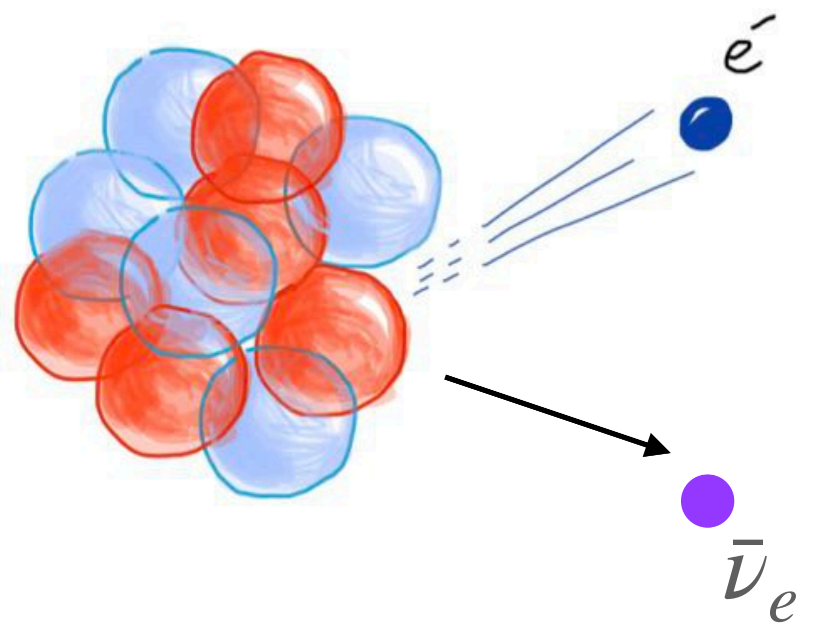
- Neutrino oscillations can only measure Δm and hierarchy

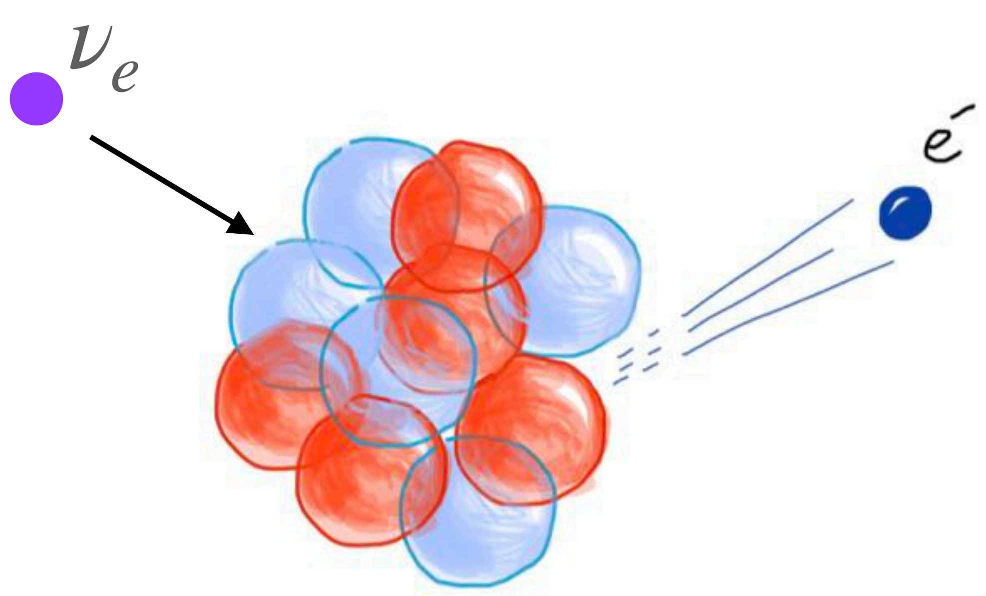


Detecting relic neutrinos via β decay

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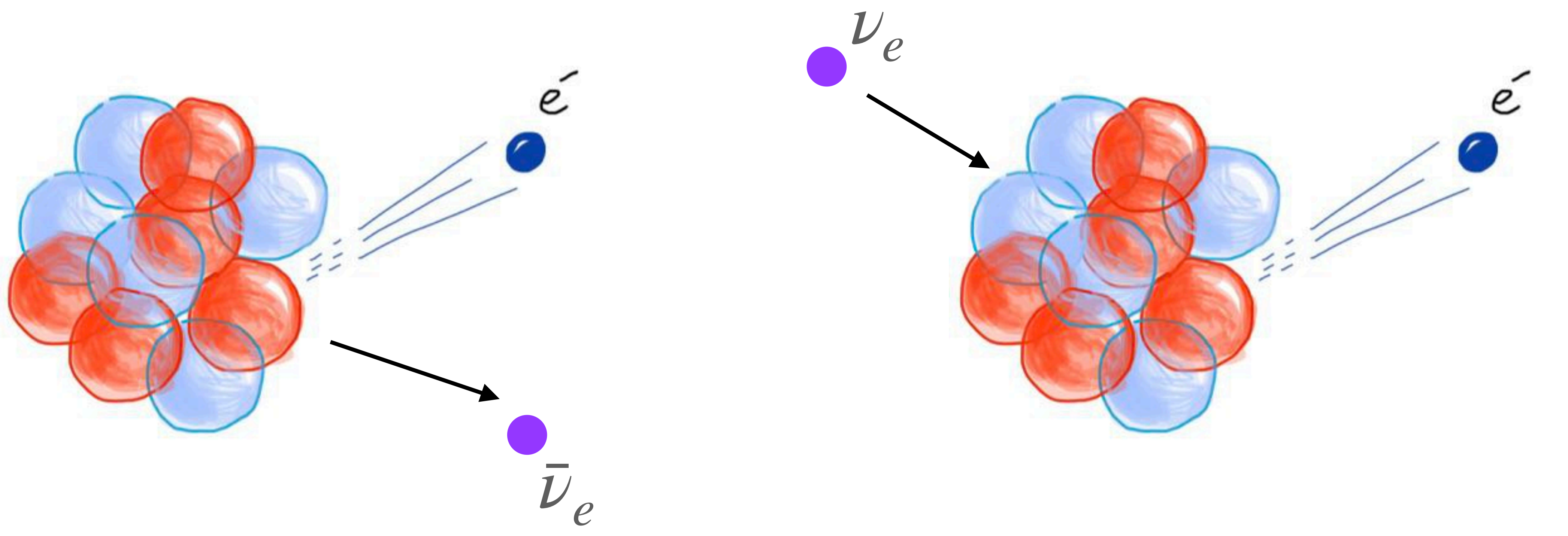
- The **2 parts of the spectrum** are separated by $2m_\nu$

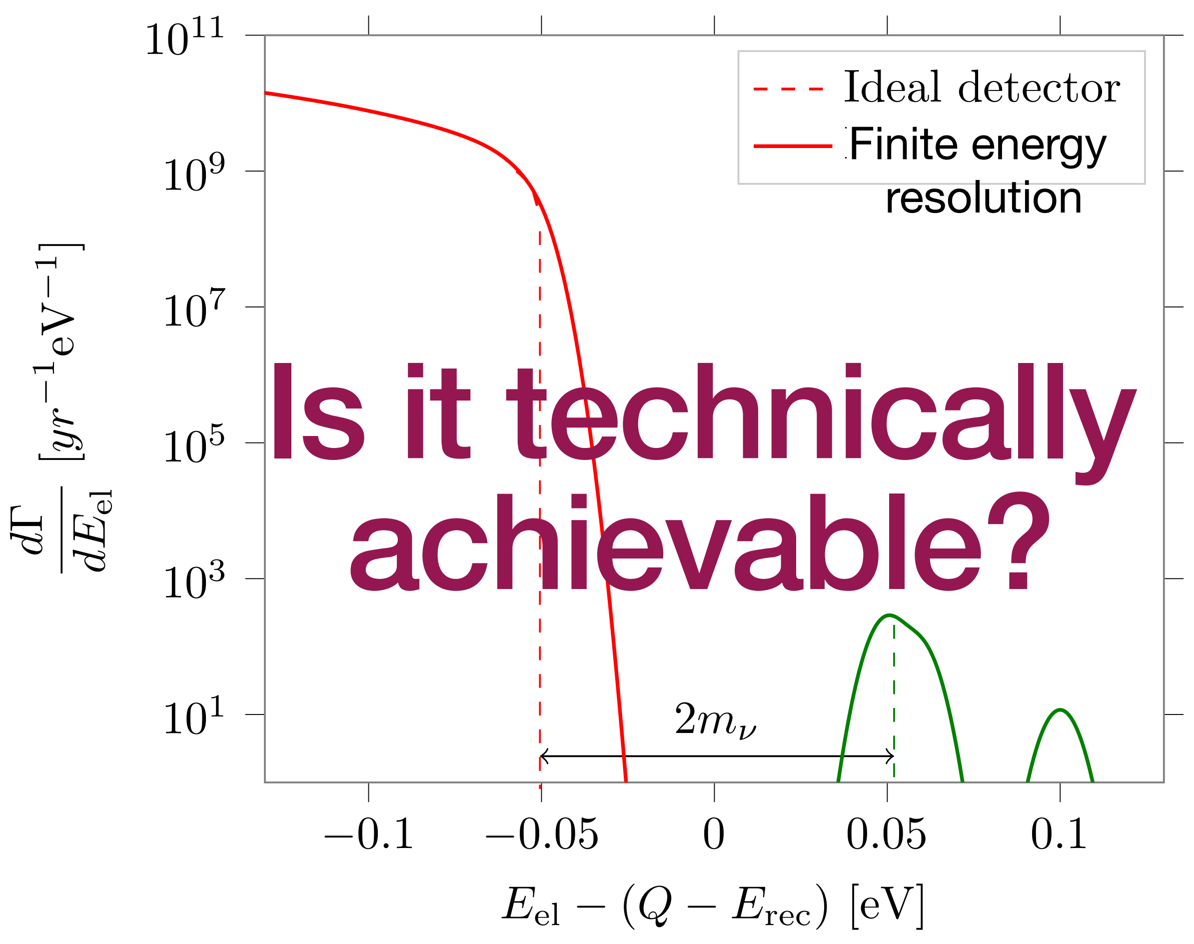


β decay

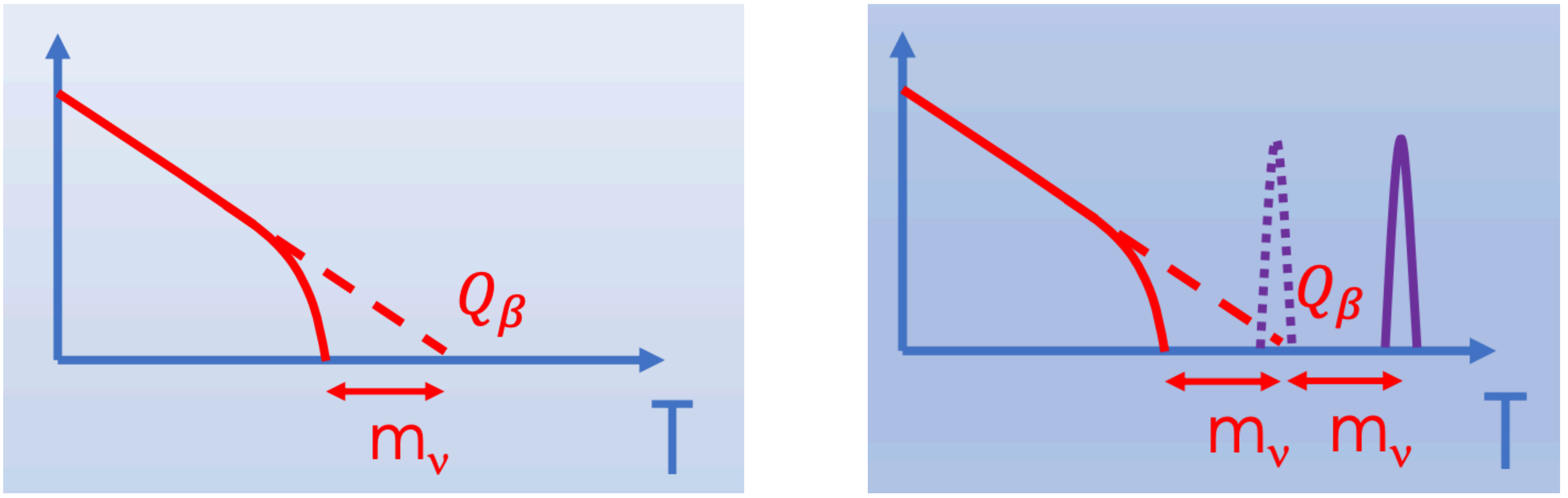
Neutrino capture

Challenges

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



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



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

} ^{3}H

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

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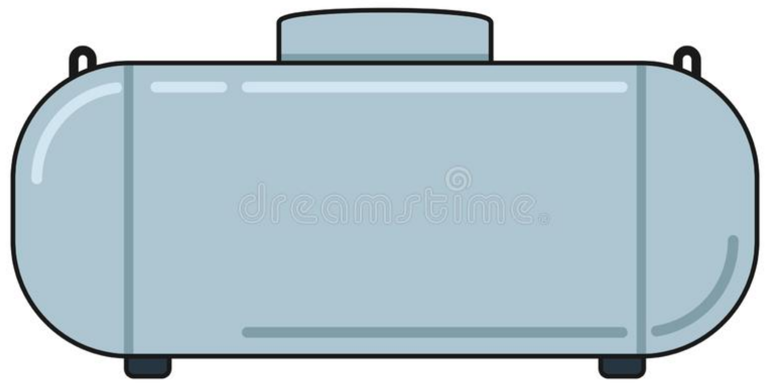

In gaseous form?

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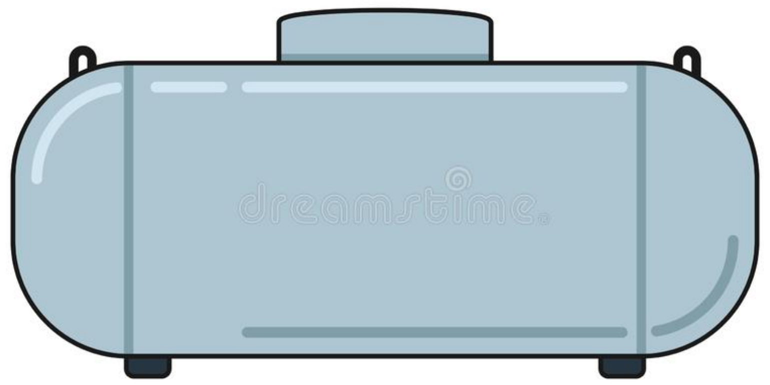

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High energy precision

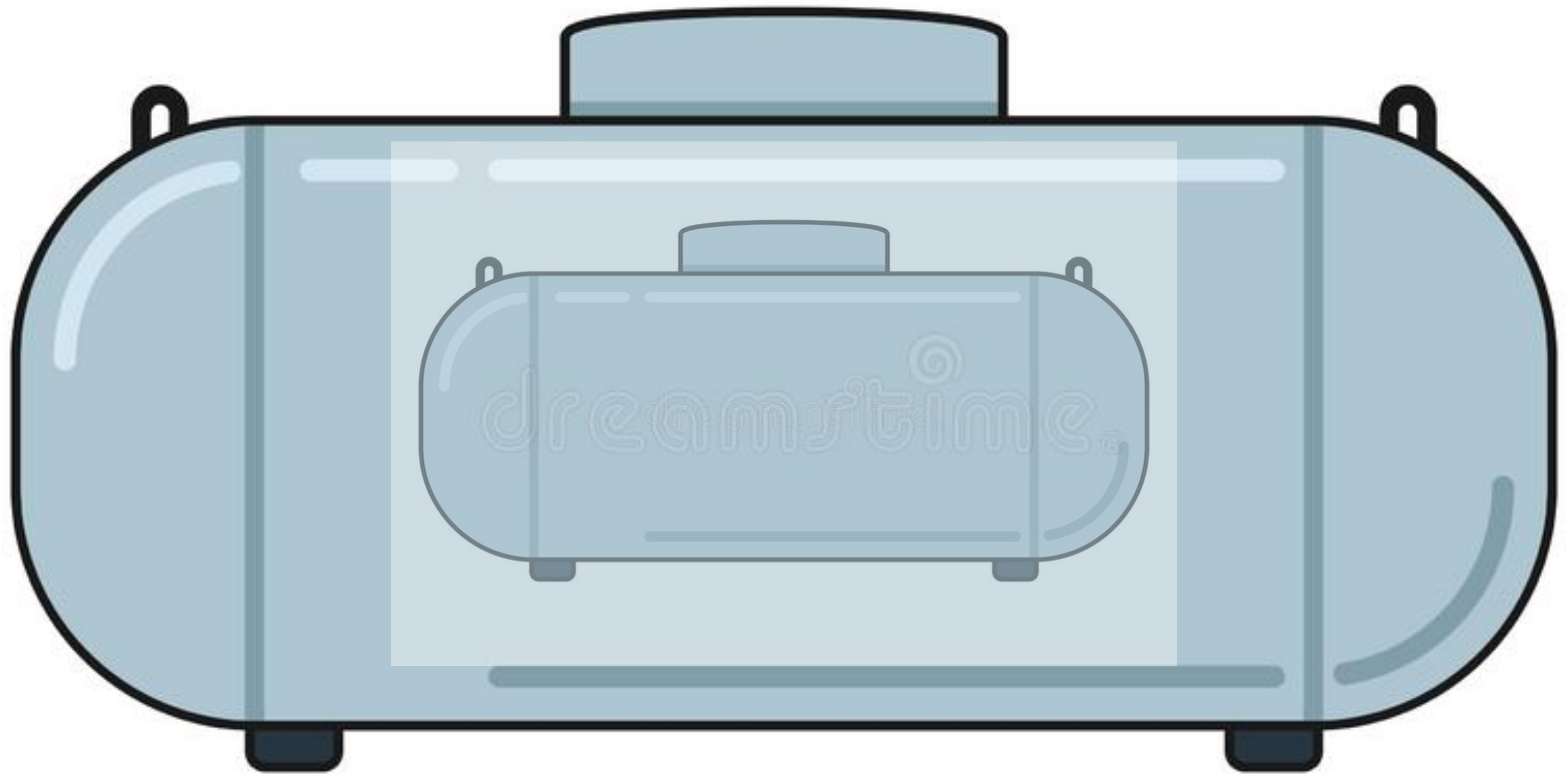
- Low emitter **Q-value**
- Low **emitter densities** electron free path bigger than the system size

Cross section

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

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

Very naive! In reality much bigger



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

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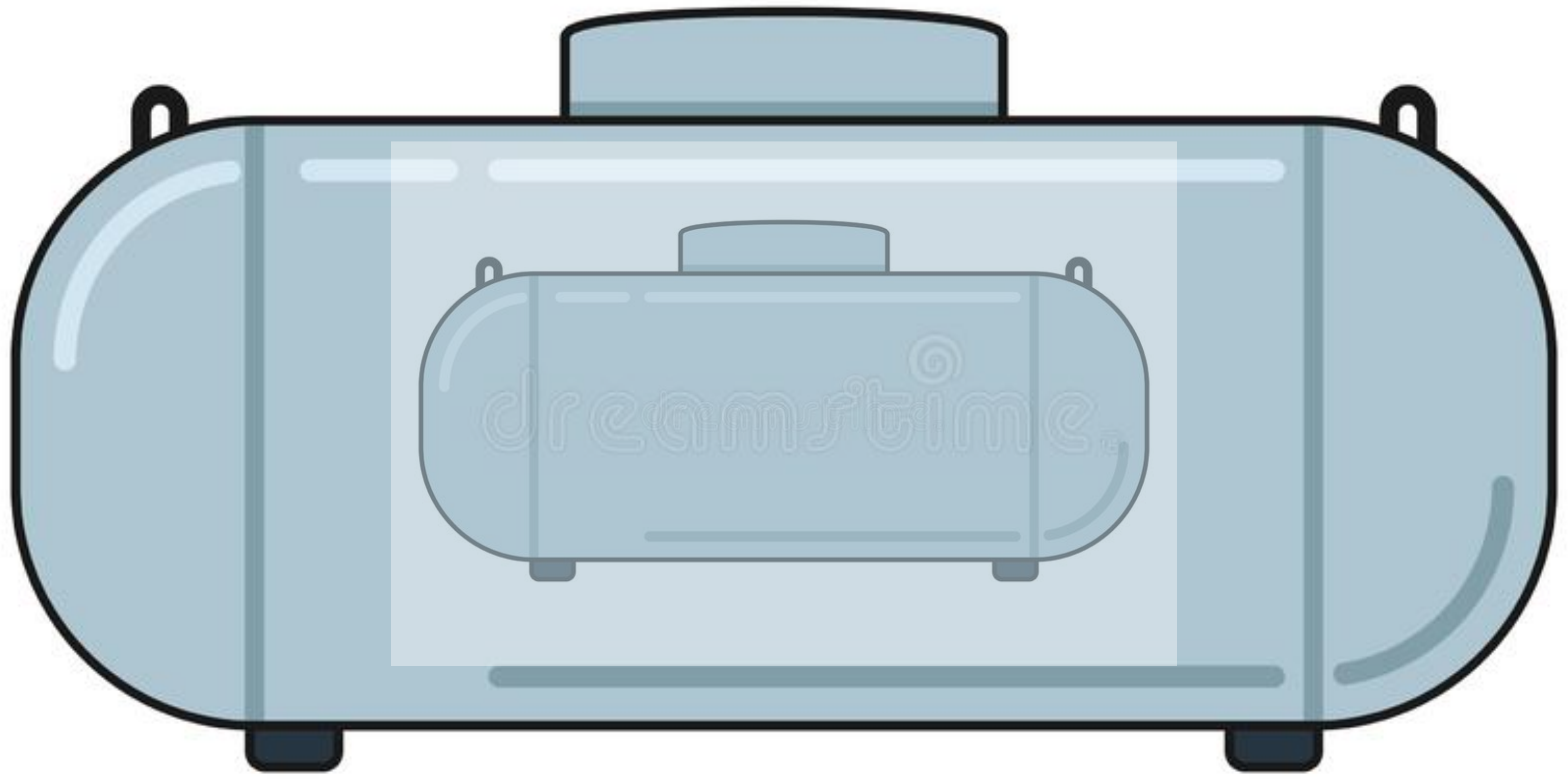

In gaseous form?

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

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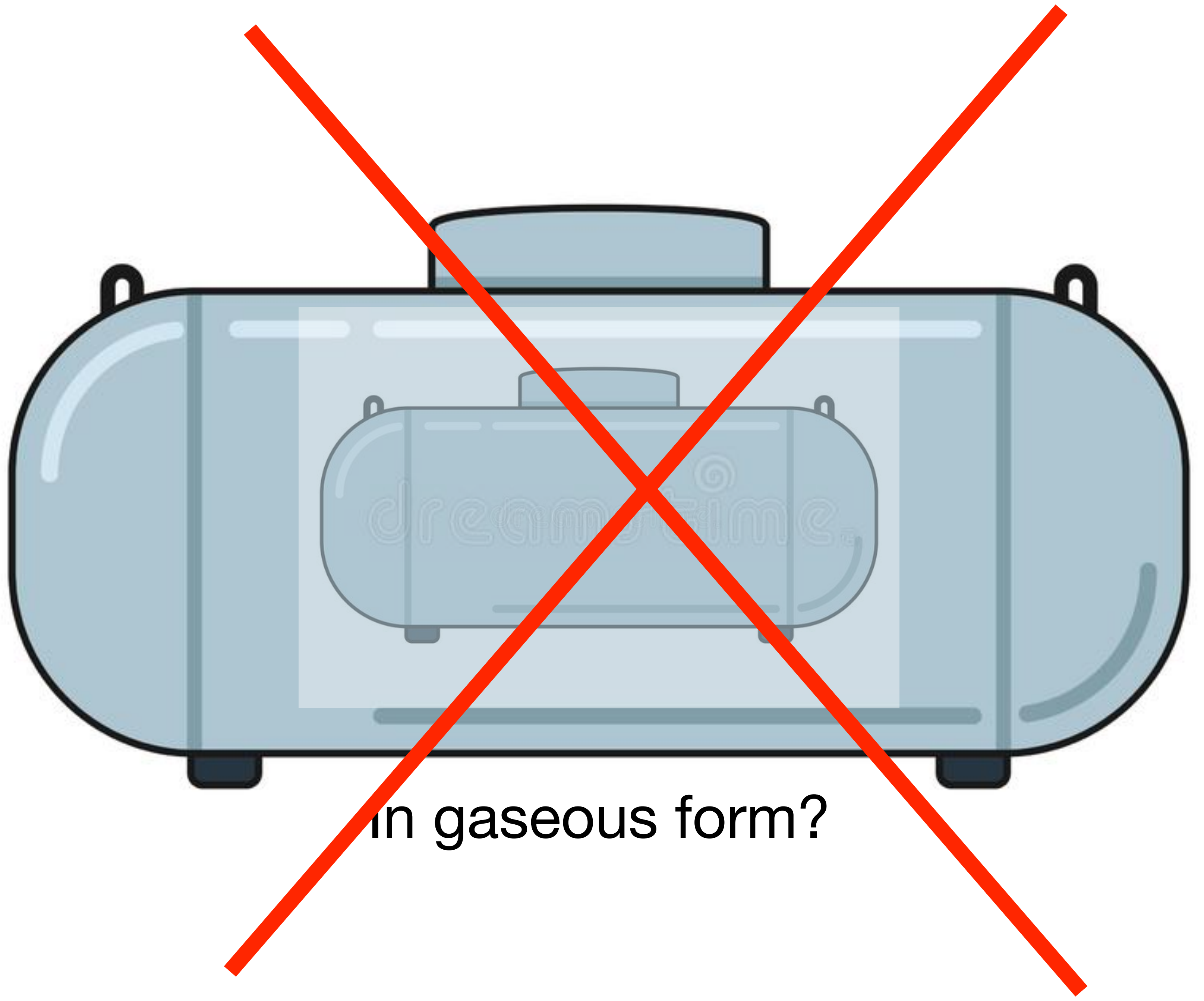

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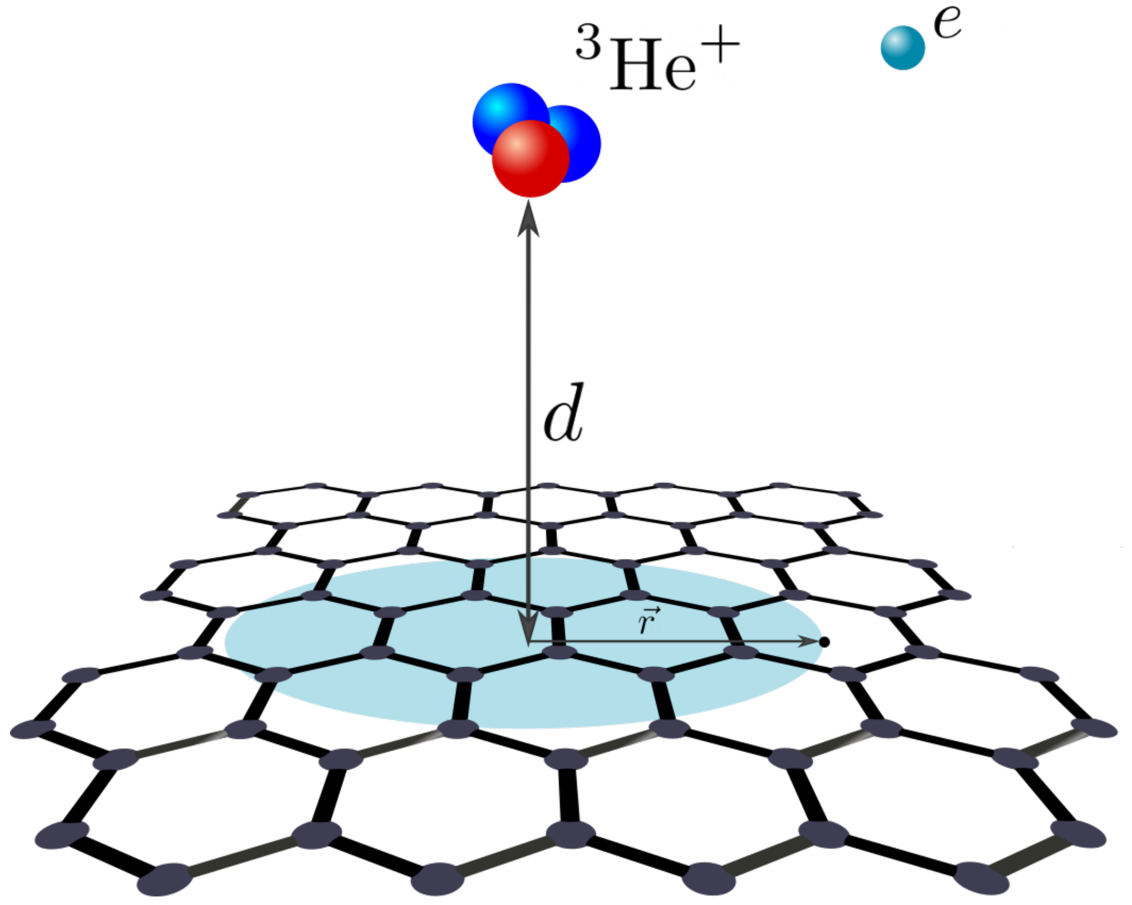
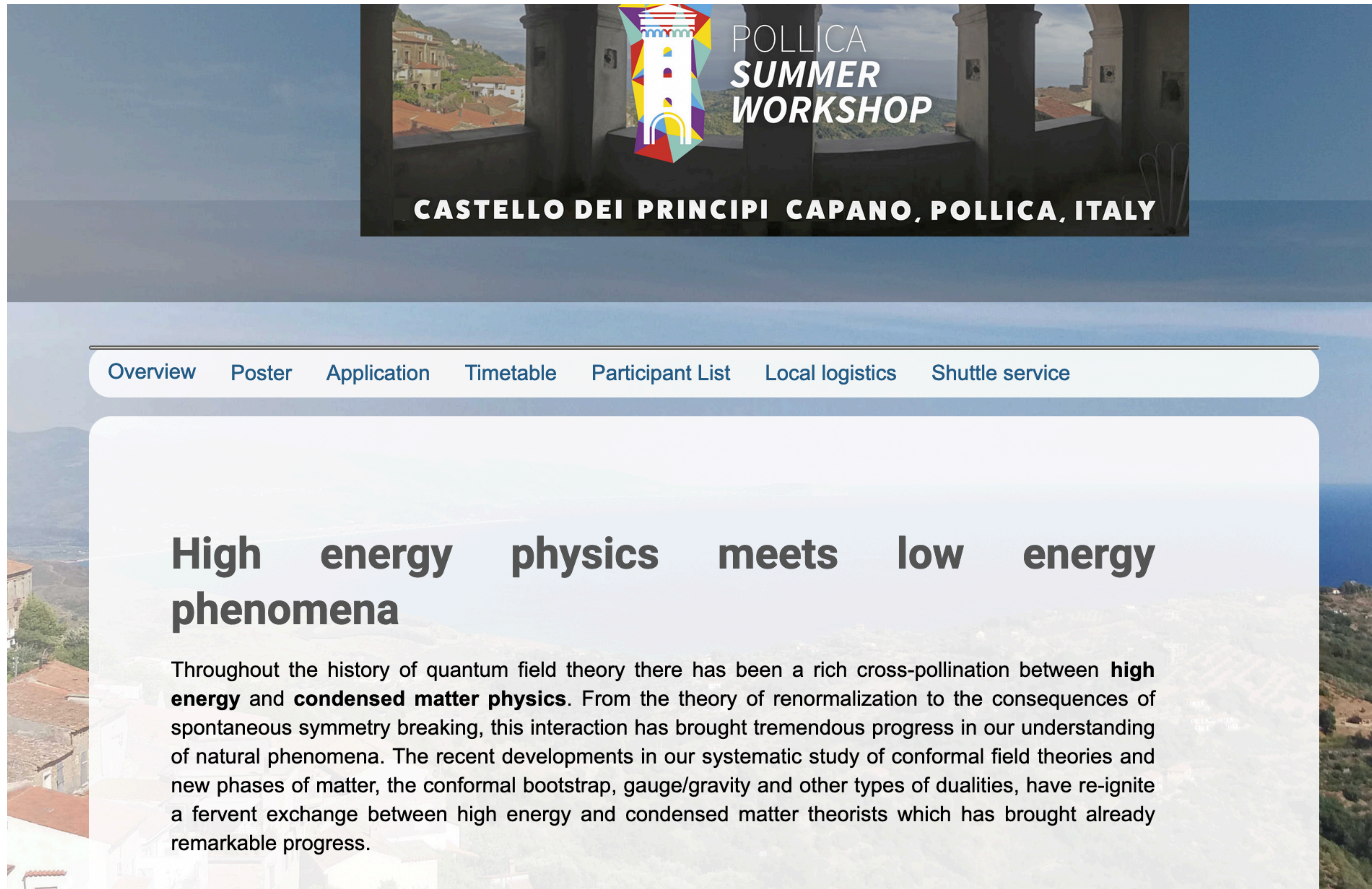
- Radioactive material in gaseous form does not suit
- Need in the **solid-state based experiment**



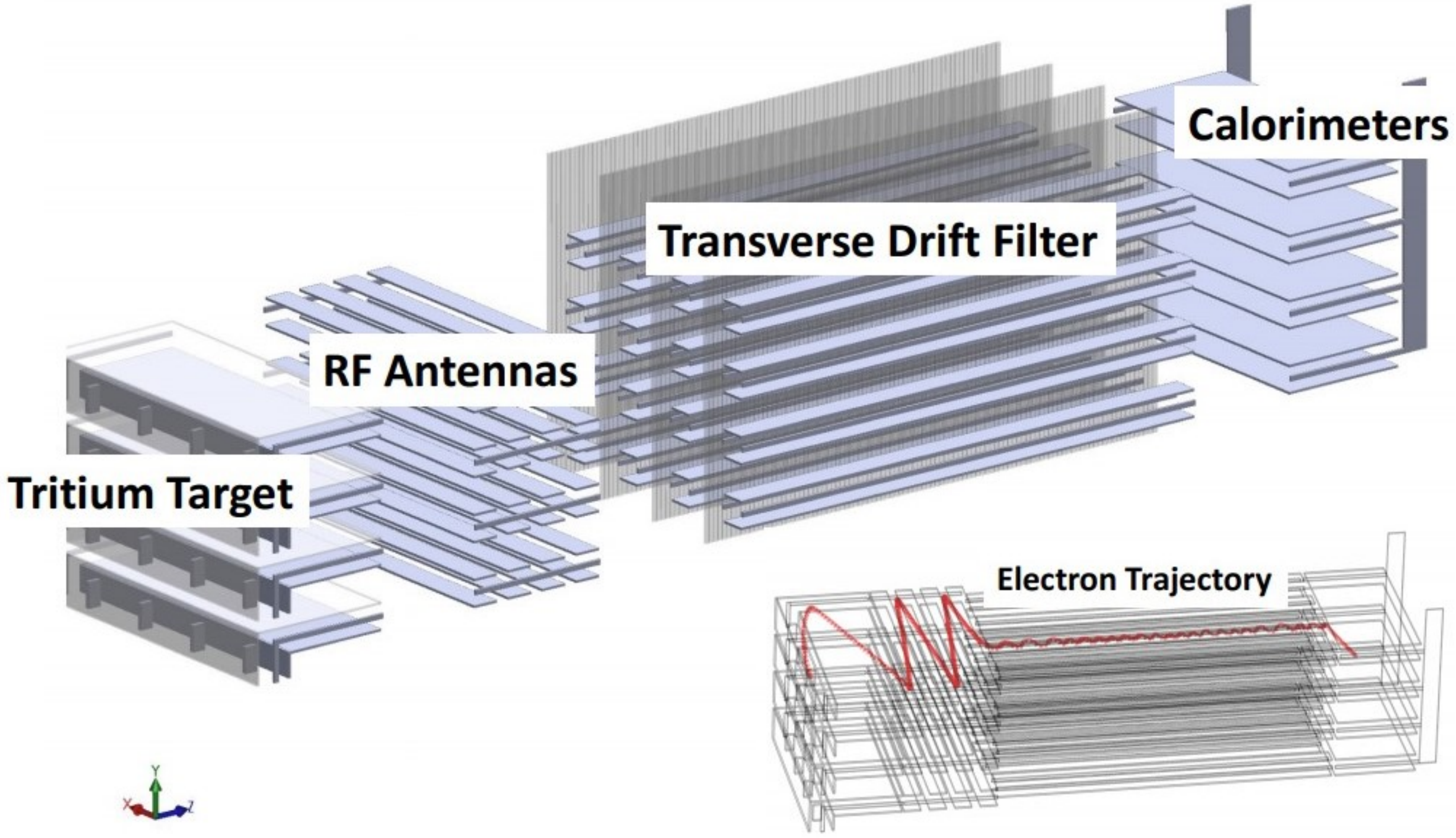


PTOLEMY project

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

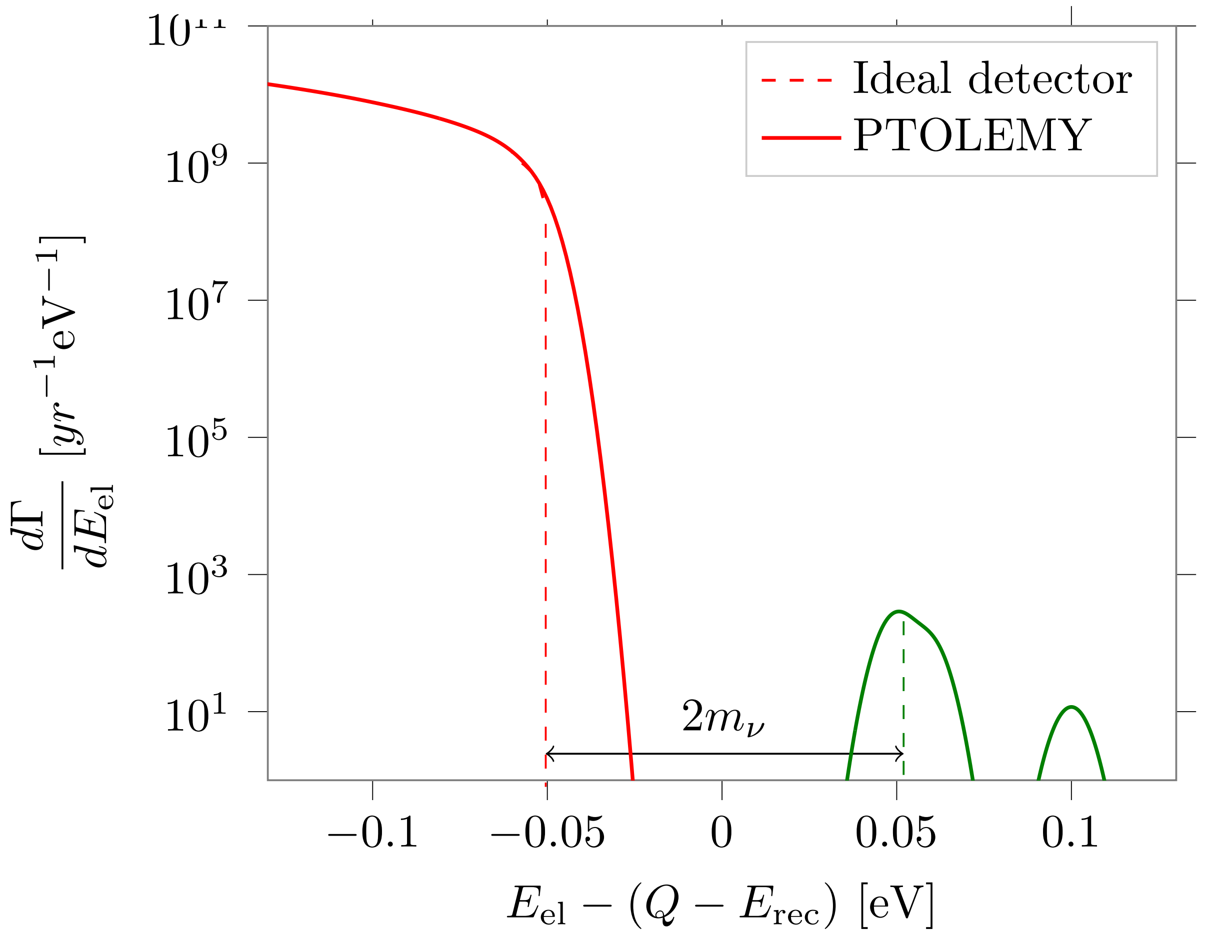
State of the art

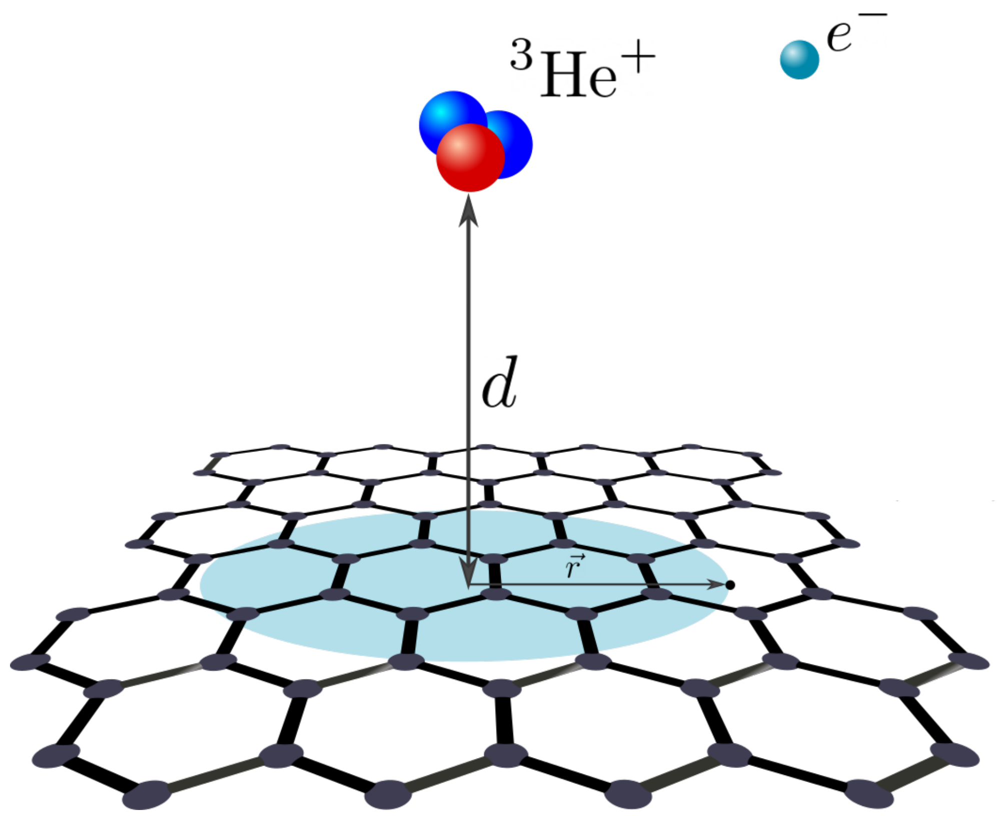
- **Tritium** as a β-decay emitter.
- Tritium is deposed on **graphene** sheets
- $\approx$ 4 CvB **events** per year.
- Outstanding **energy resolution** of the apparatus $\approx$ 10 meV.



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

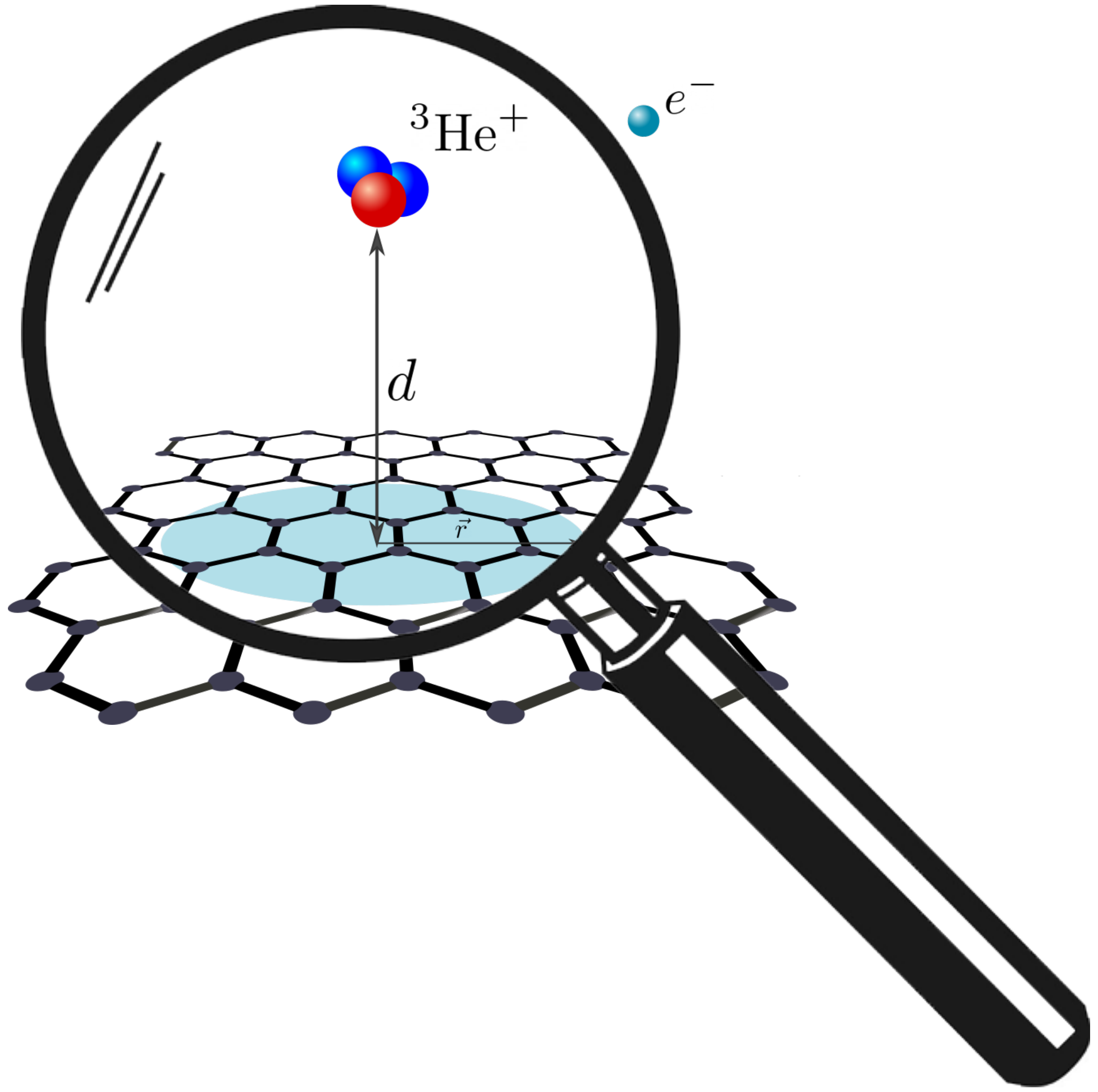
$$ {}^3\text{H} \rightarrow {}^3\text{He} + e + \bar{\nu}_e$$

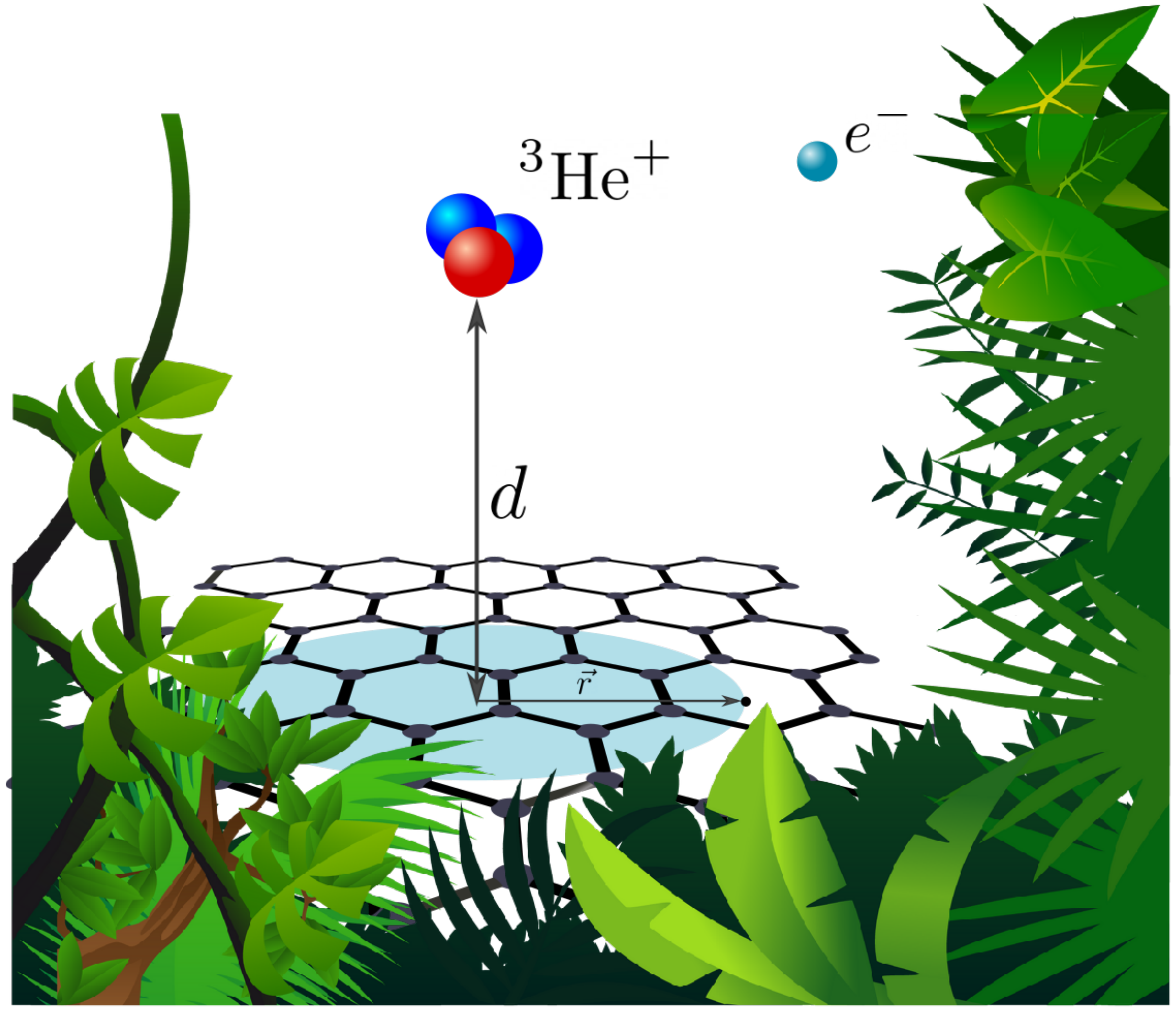




Jungle of many-body and chemical effects

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

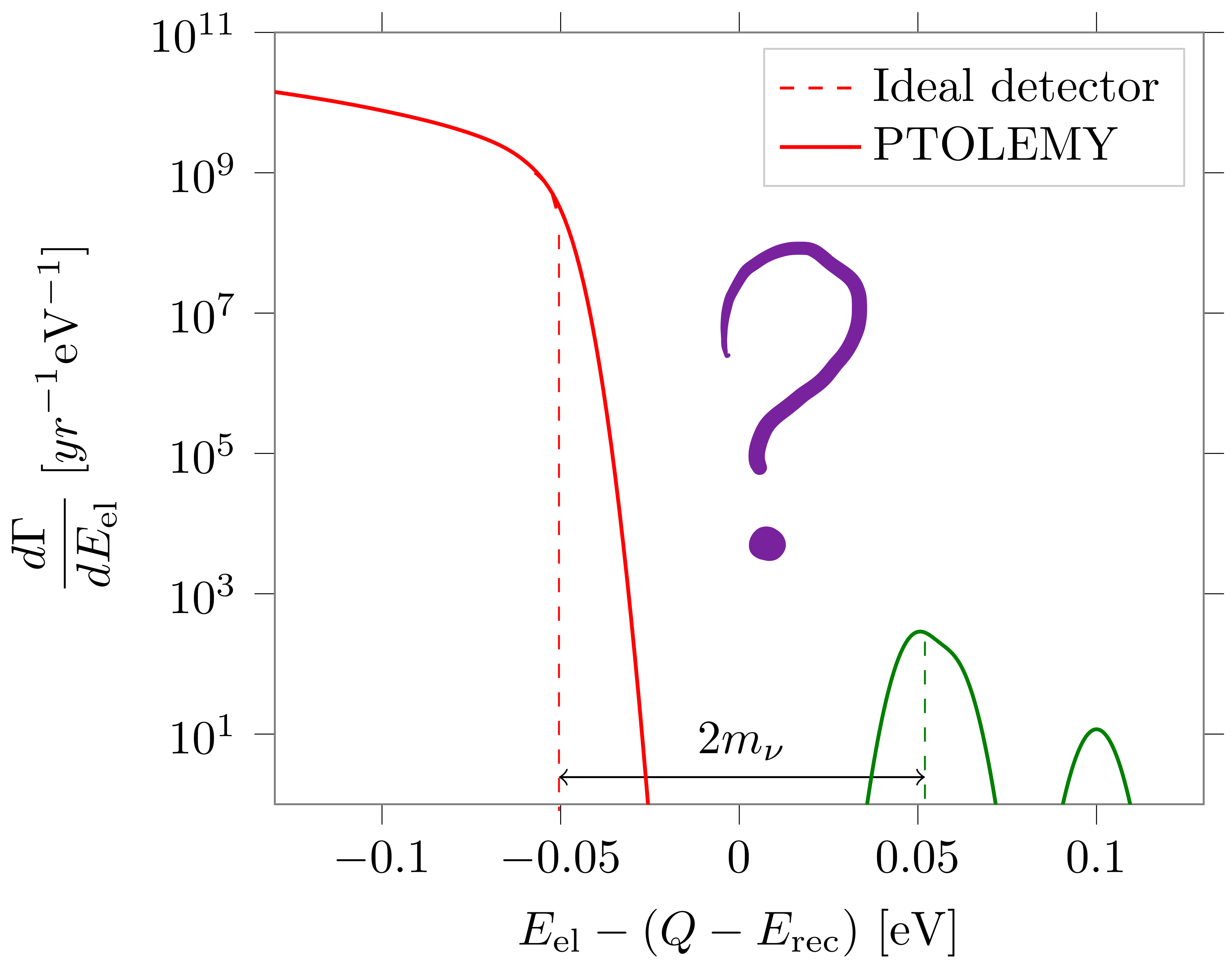


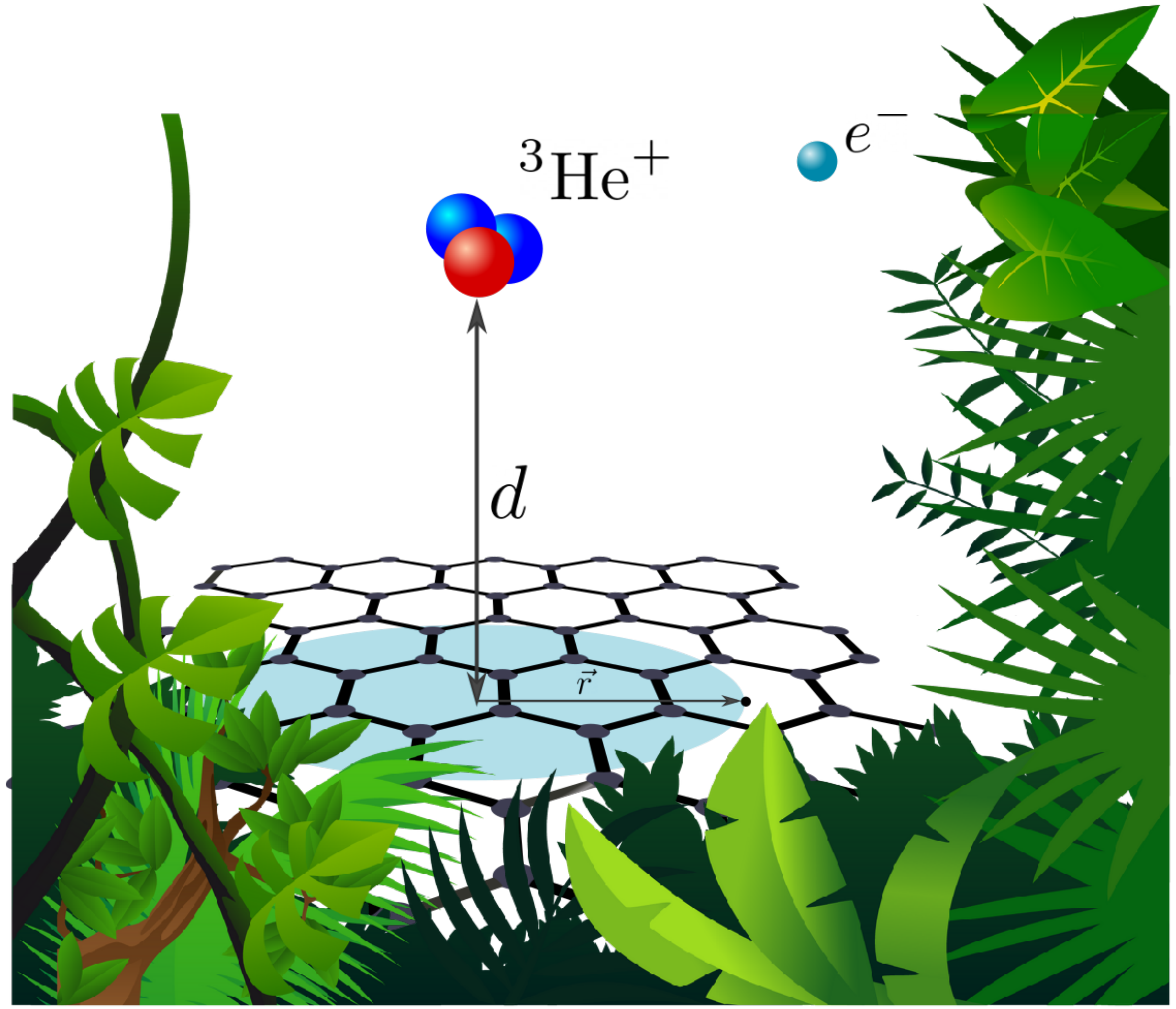


Jungle of many-body and chemical effects

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

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

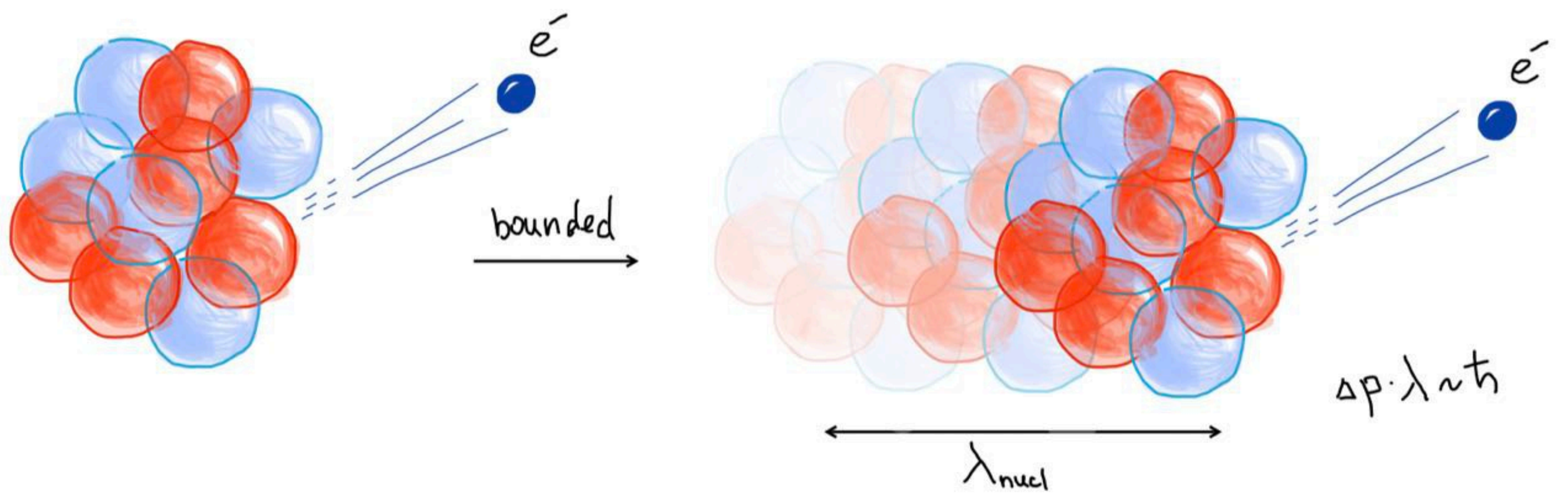




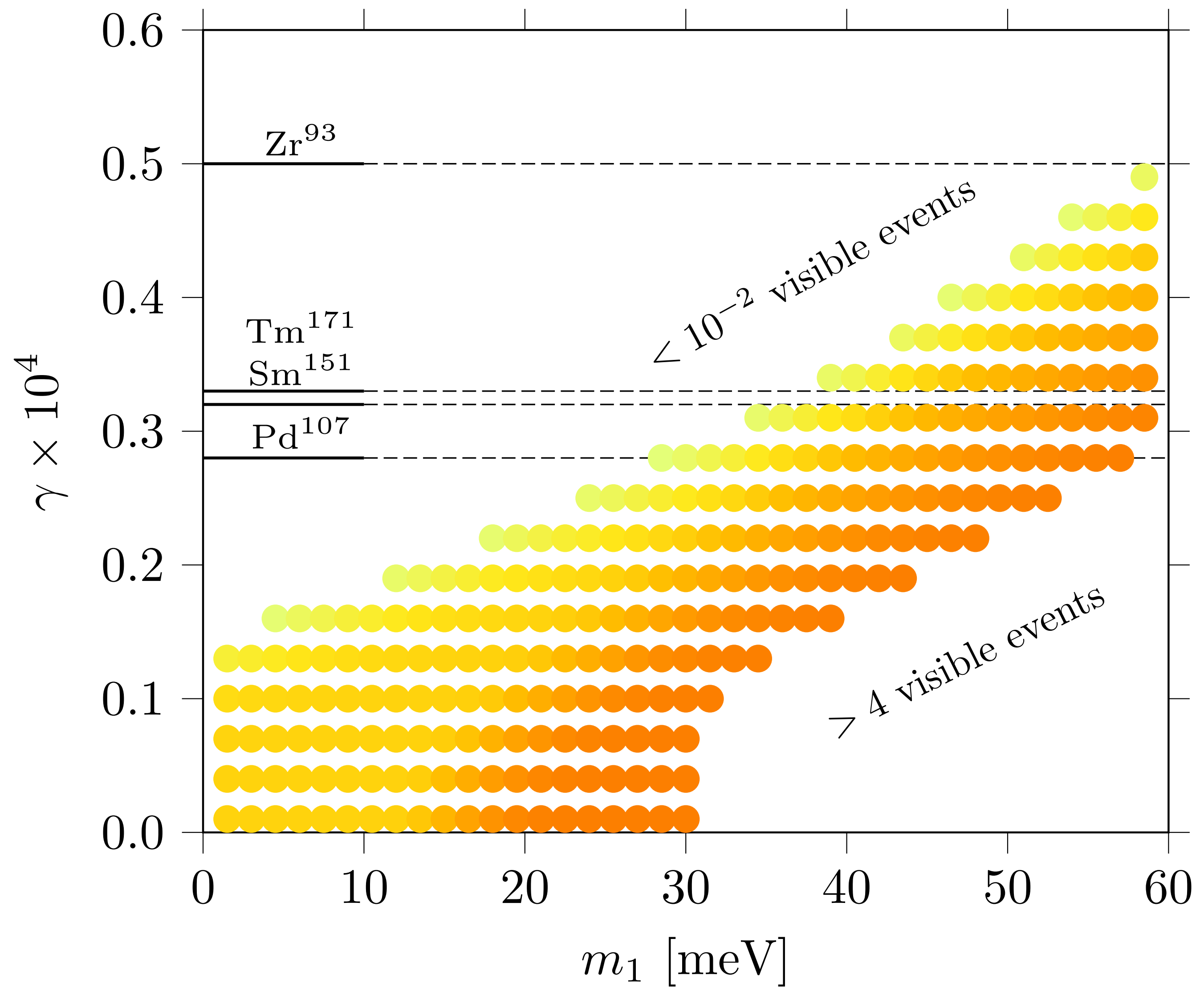
Heisenberg uncertainty

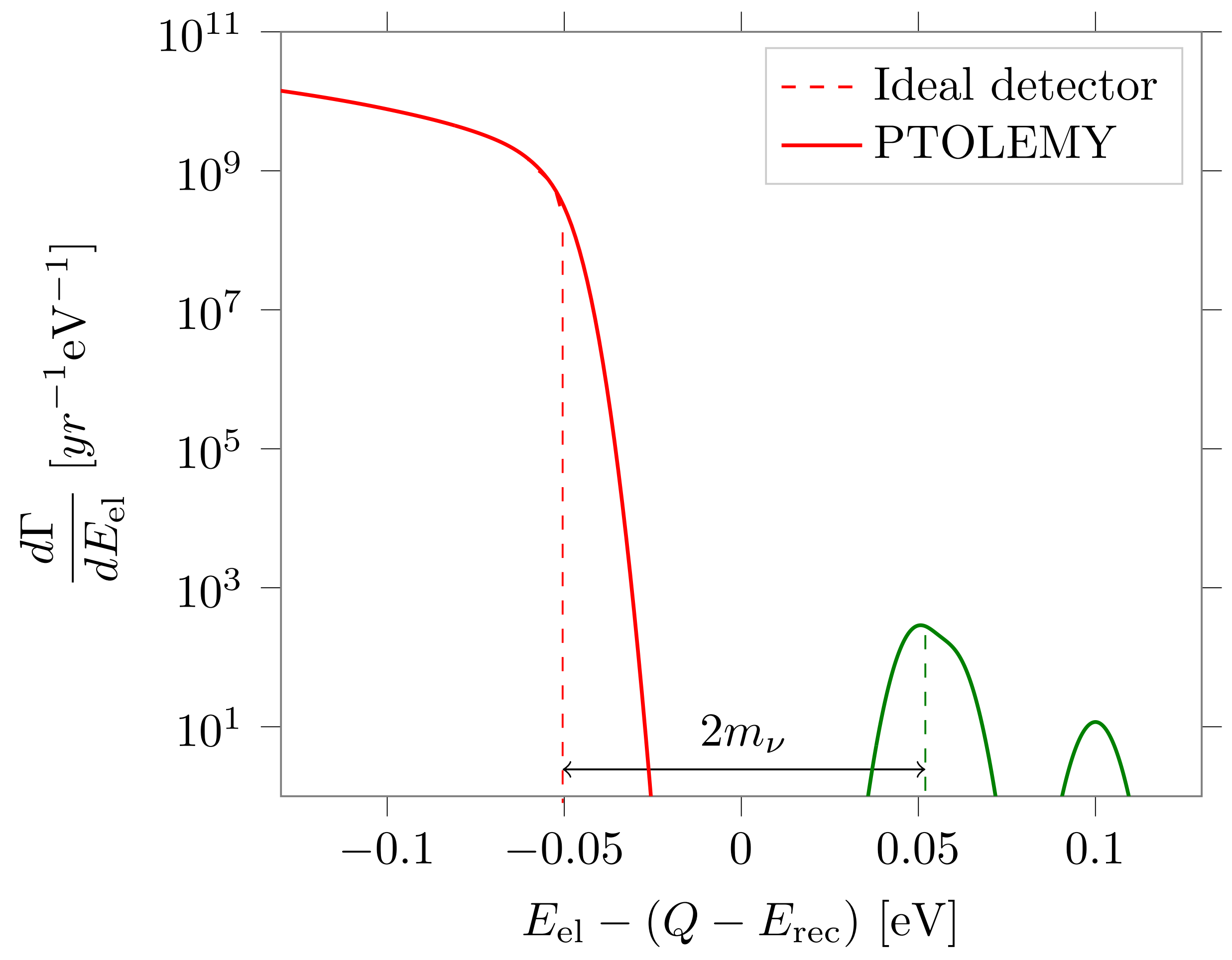
The uncertainty in energy of the emitted electron ΔE

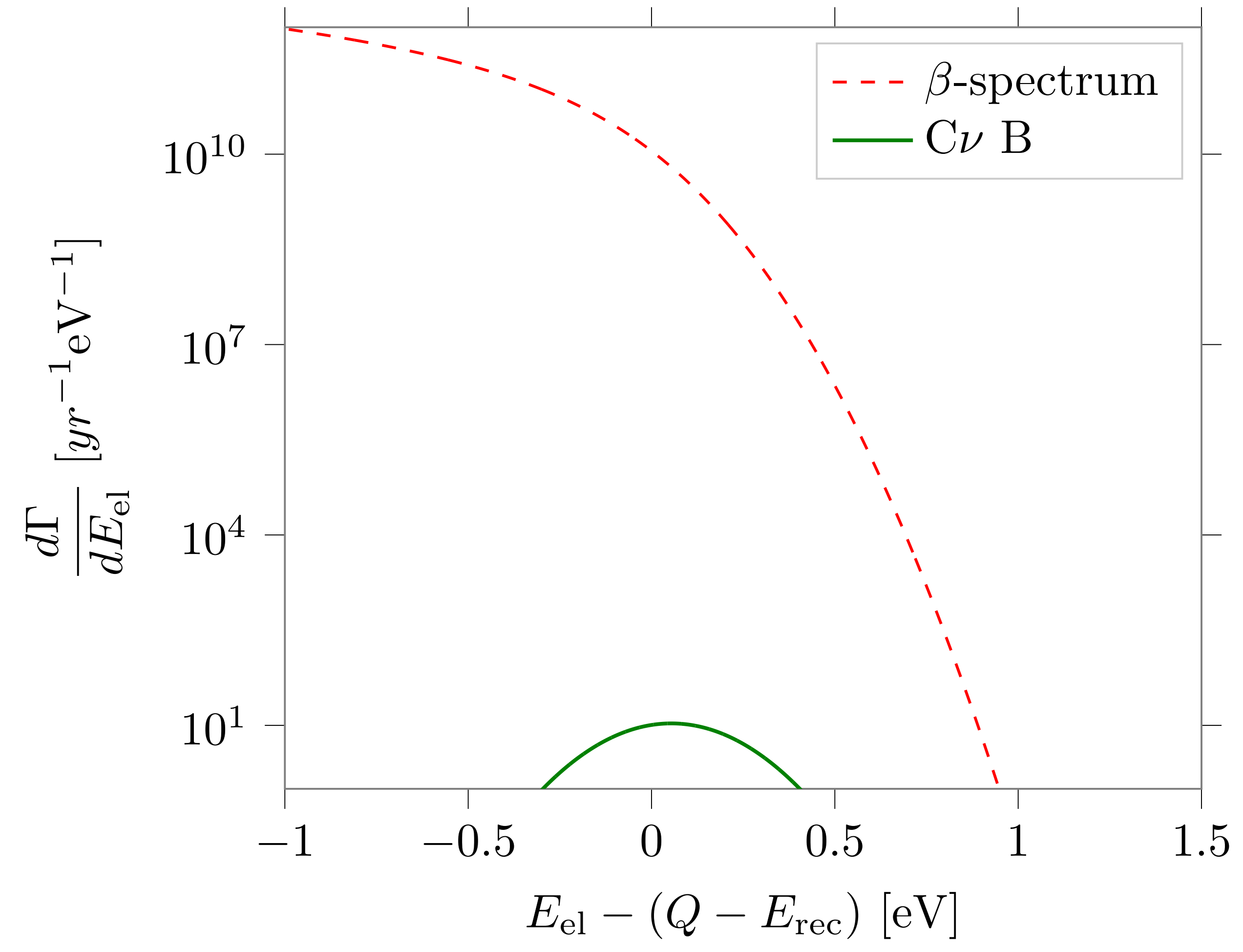
- Is of the **order of 0.5 eV**
- Is 2 orders of magnitude greater than the resolution needed
- Weakly depends on the potential stiffness.
- Strongly depends on the radioactive nucleus.



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







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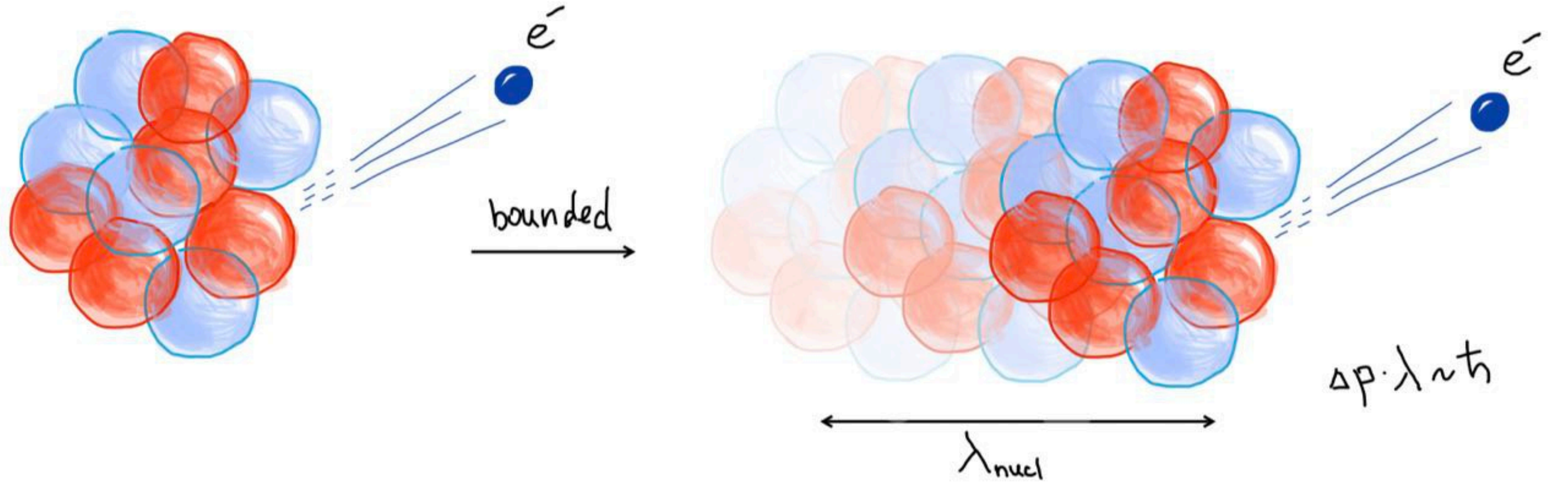

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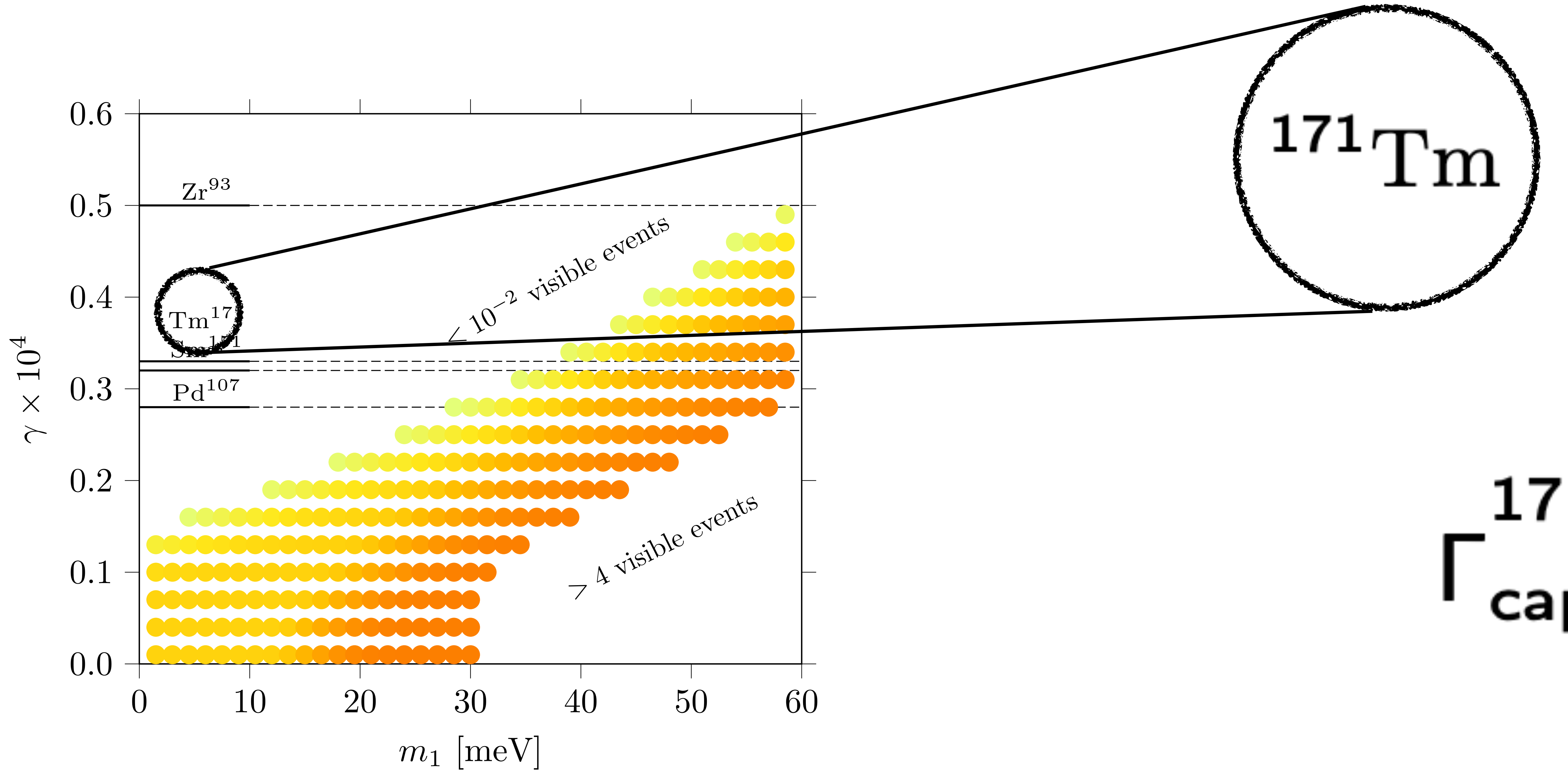
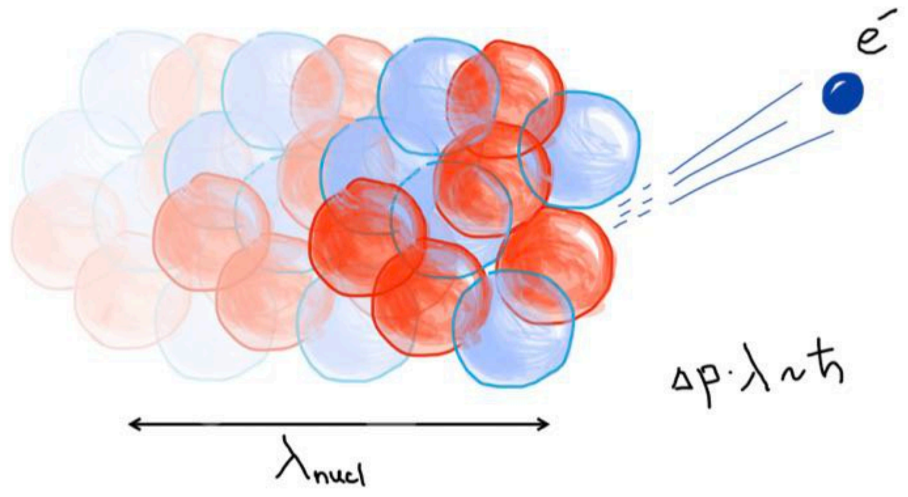
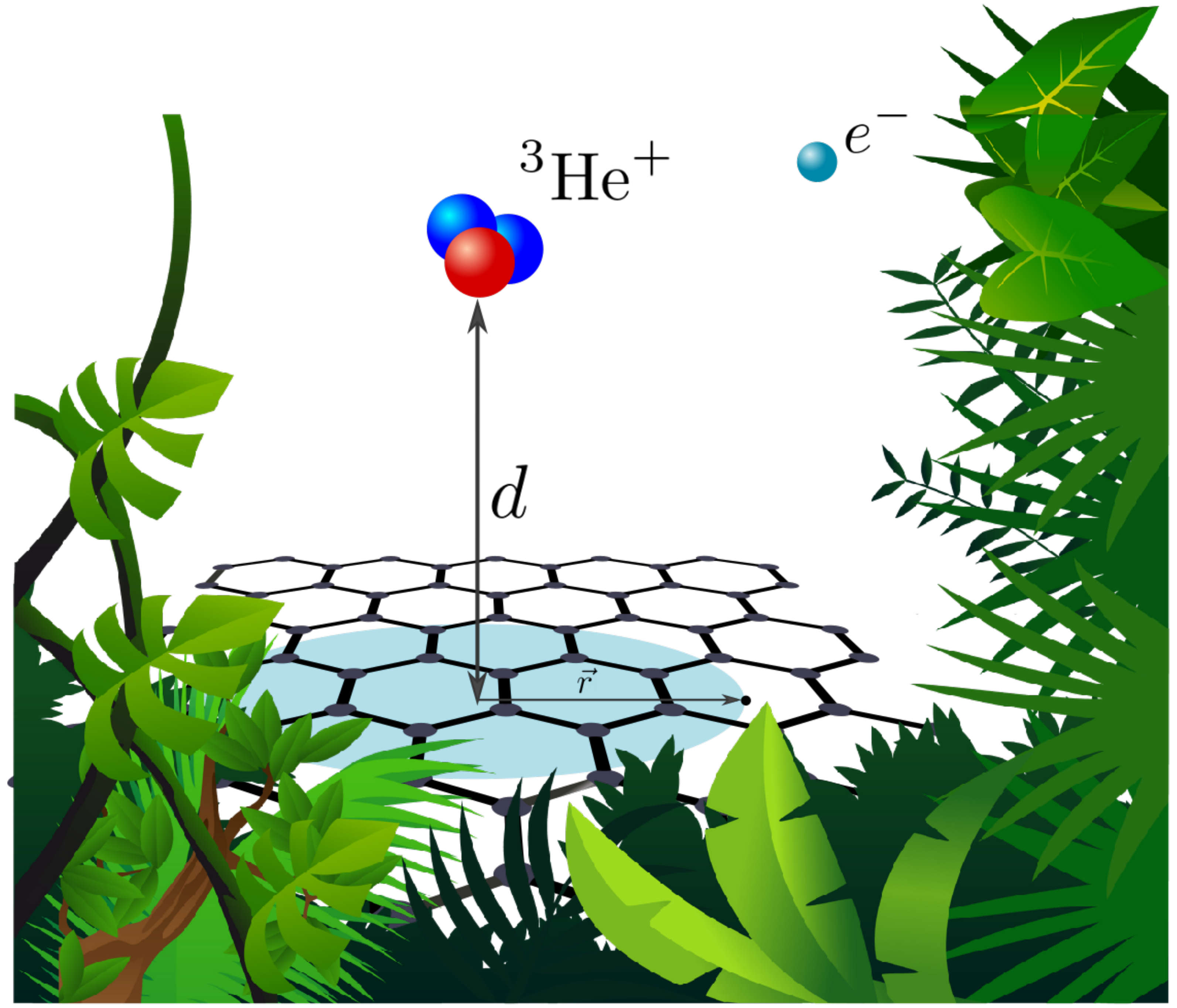


$$\Gamma^{^{171}\mathrm{Tm}}_{\text{capture}} = 3 \cdot 10^{-2} \Gamma^{^{3}\mathrm{H}}_{\text{capture}},$$

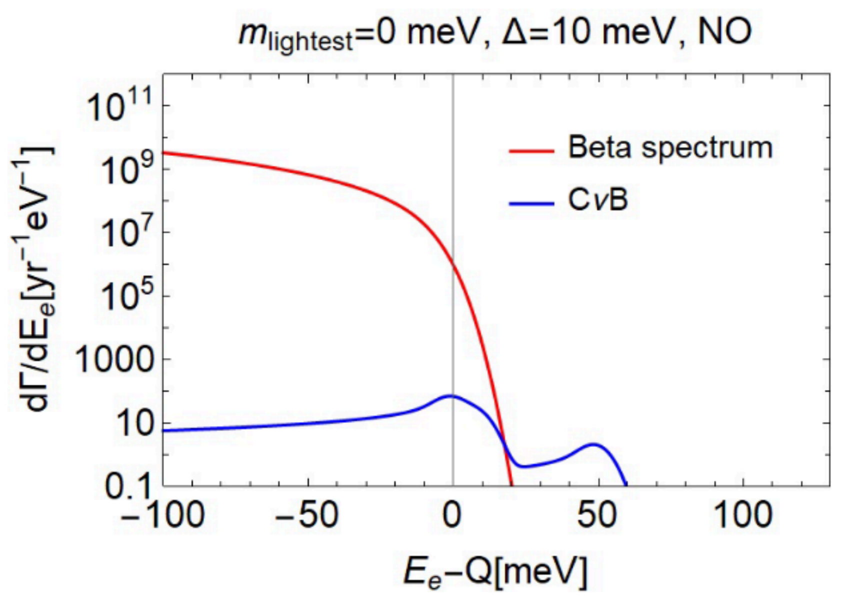
Jungle of many-body and chemical effects



Zero-point motion



Finite lifetime of the daughter ion



Electric effects

X-ray edge singularity

Etc…

Generalised smeared spectrum

The bare spectrum of the β decay

$$\frac{d\Gamma^{(0)}}{dE_e} = \frac{4E_e p(E_e)}{(2\pi)^4\hbar} \int E_\nu k(E_\nu) dE_\nu \left| \int dx j^{\mu}_{\text{lept}}(x, E_e, E_\nu) J^{\text{nucl}}_{\mu}(x) \right|^2 \delta(E_e + E_\nu - E_{\alpha_0}).$$

in the presence of the substrate becomes smeared

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where the correlation function $\mathscr{F}(\omega)$ represents the **finite lifetime** of the system

$$\frac{1}{2\pi} \int d\tau \, \langle \alpha_0, z | \, \hat{\chi} e^{i\tau \hat{H}^{\alpha}_{z+1}} \hat{\chi}^\dagger \, | \alpha_0, z \rangle \, e^{i\tau(E_e + E_\nu - E_{\alpha_0})} = \mathcal{F}(E_e + E_\nu - E_{\alpha_0})$$

and maybe can be probed on the experiment