THE PTOLEMY PROJECT

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on behalf of the PTOLEMY collaboration

IAS | INSTITUTE FOR ADVANCED STUDY

PTOLEMY

33rd Rencontres de Blois, May 2022

OUTLINE

- Goal and idea behind PTOLEMY
- Effects of quantum uncertainty
- Conclusion

INTRO

- What we do know about neutrinos:

they are massive

well measured Δm_i^2

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- What we don't know about neutrinos:

absolute mass scale $(m_\nu < 0.8\ \text{eV})$

[KATRIN — Nature Phys. 2022, 2105.08533]

mass ordering $(m_{\text{light}} \simeq m_e$ or $m_\tau)$

cosmic neutrino background yet to be seen

DECAY AND CAPTURE

- Tritium has the largest product of lifetime and capture cross section

$$^3\text{H} \to {}^3\text{He}^+ + e^- + \bar{\nu}_e \qquad \left(Q \simeq 18.6\ \text{keV}\right)$$
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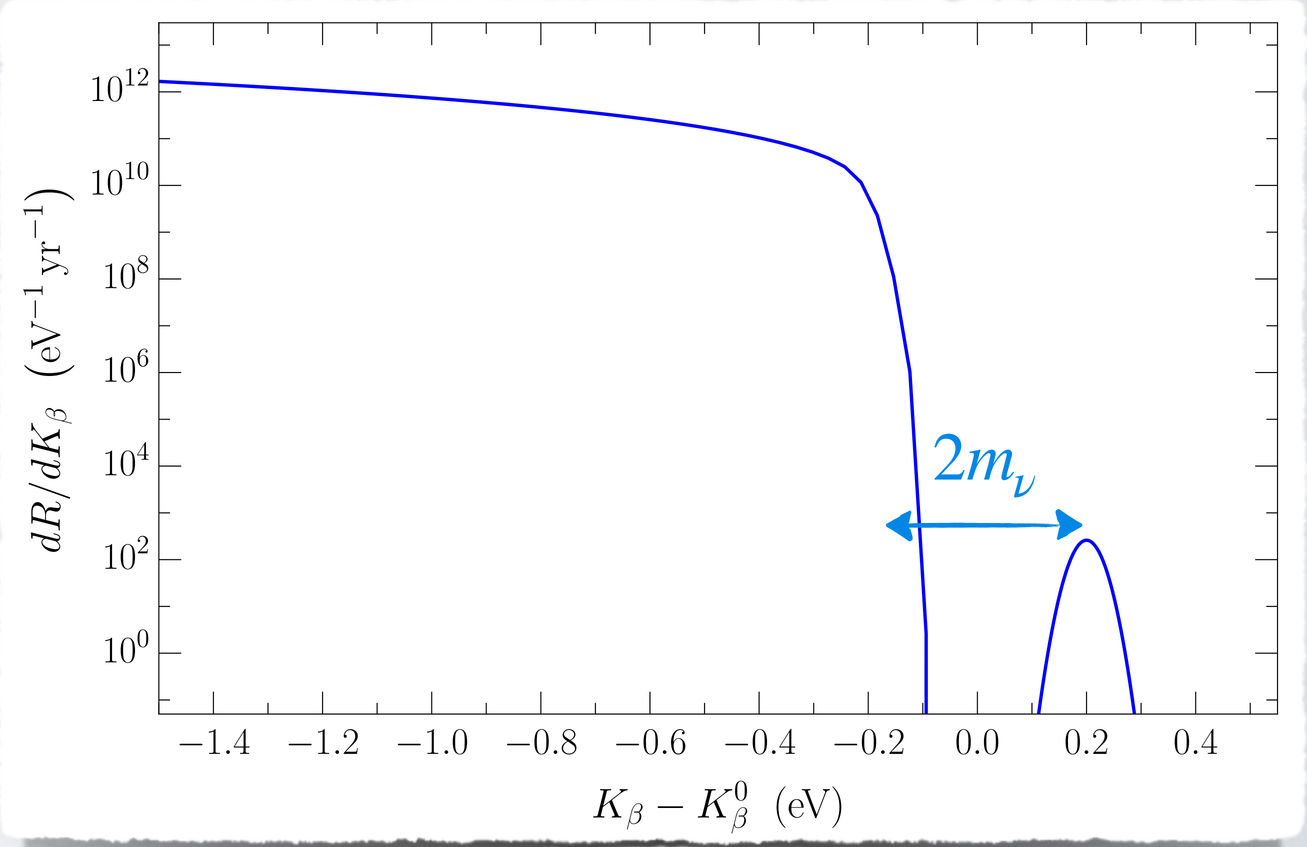

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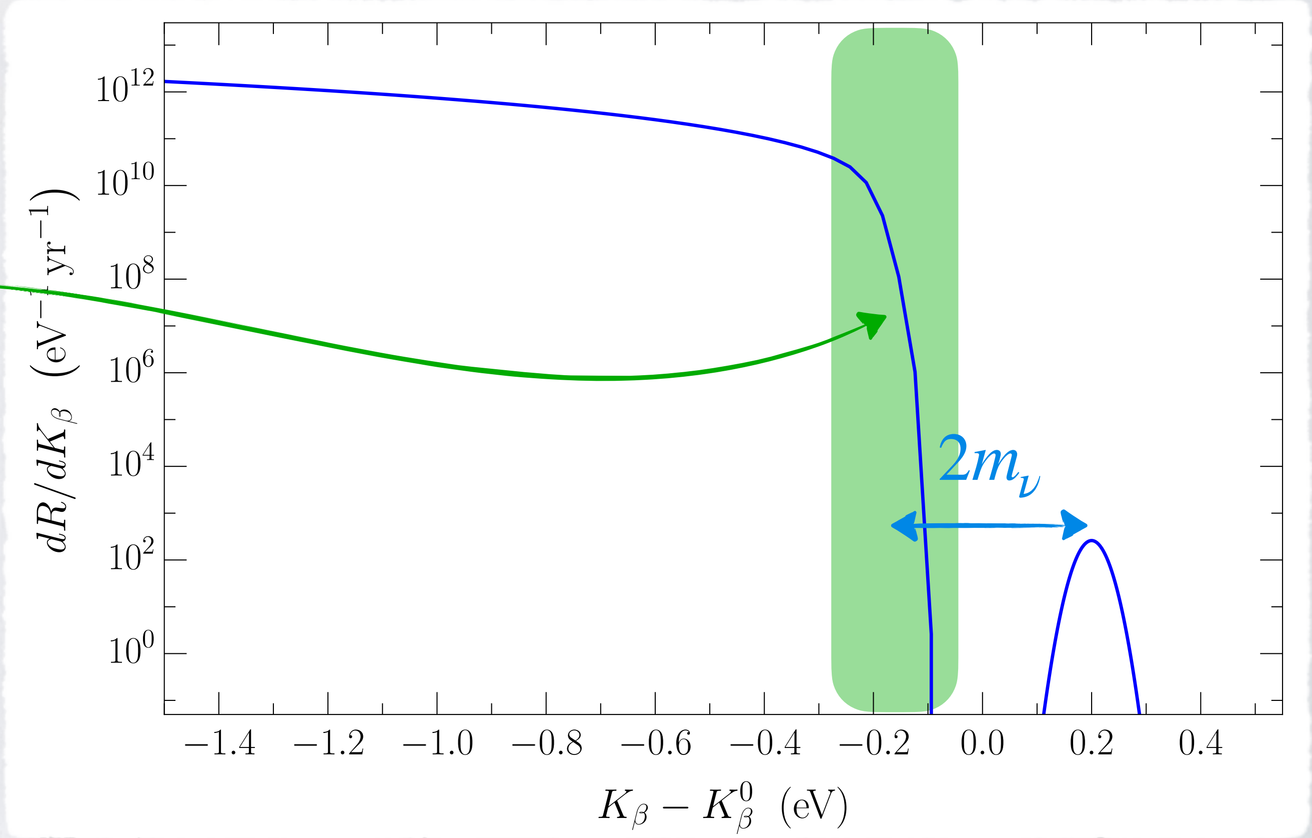

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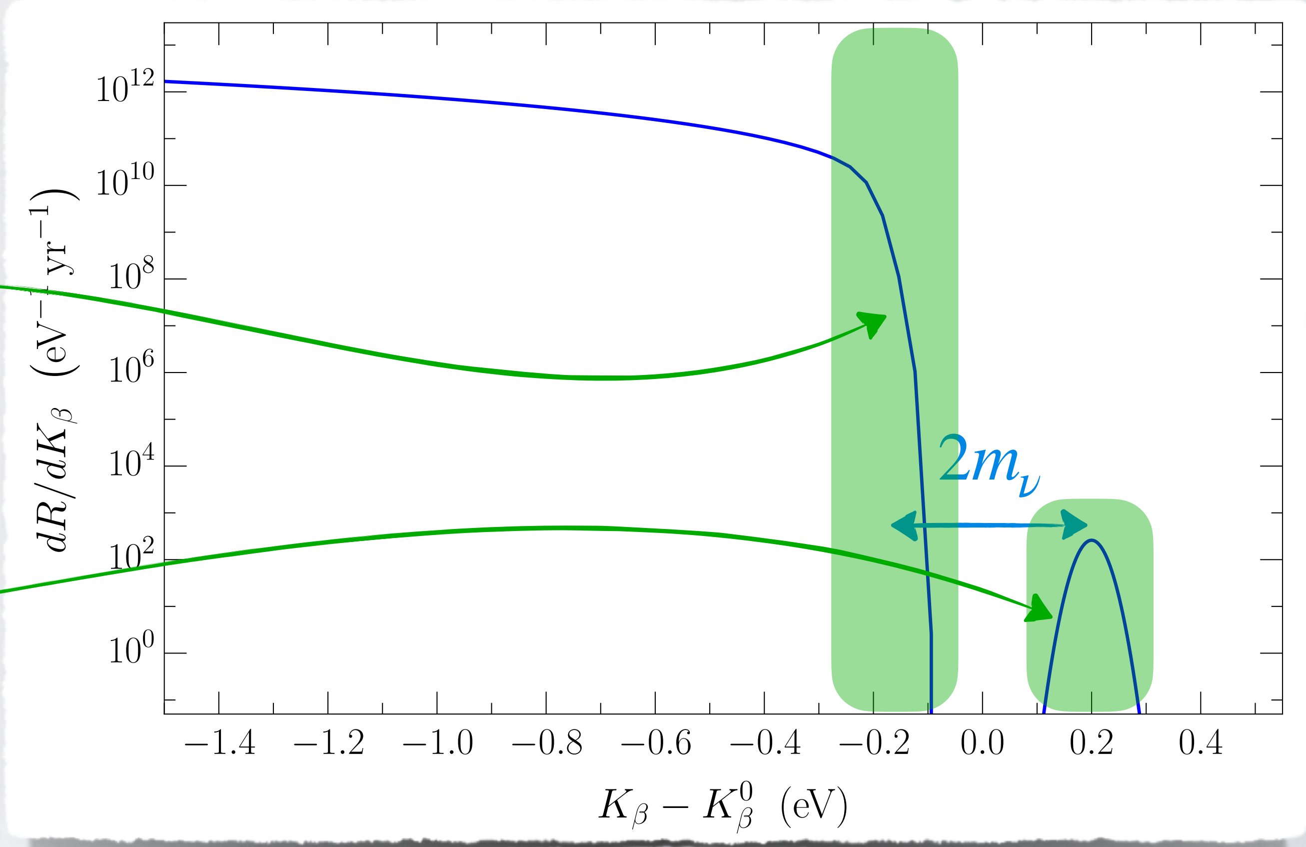
smoking gun for cosmic neutrino background
(need high energy resolution)



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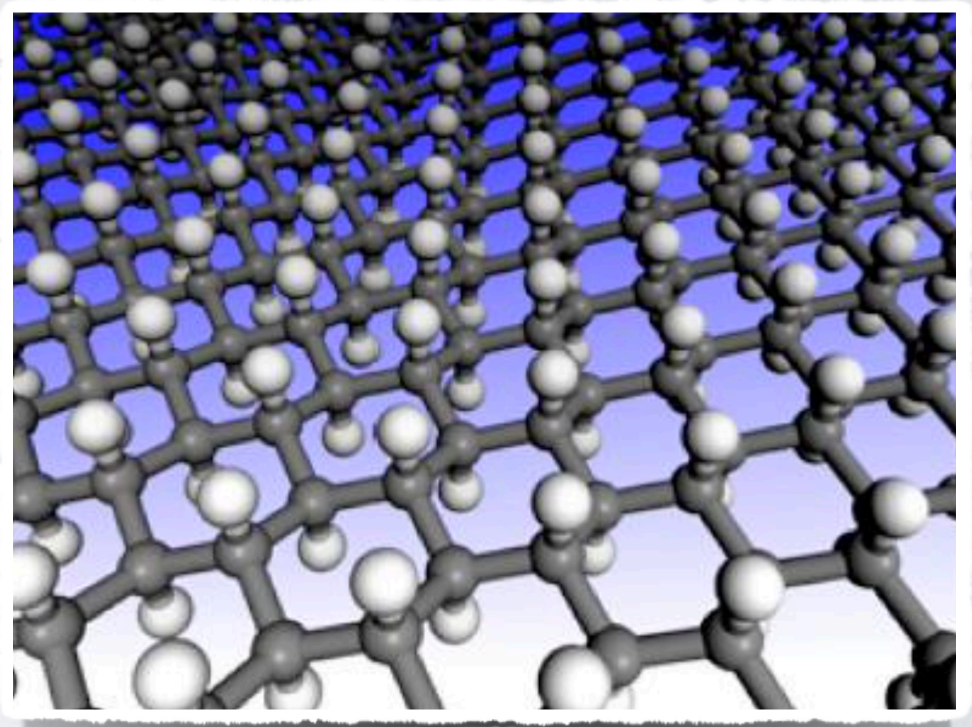
High event rate

- Distribute the tritium on a solid state substrate (e.g. graphene)



[see Betti et al. — Nano Lett. 2022]

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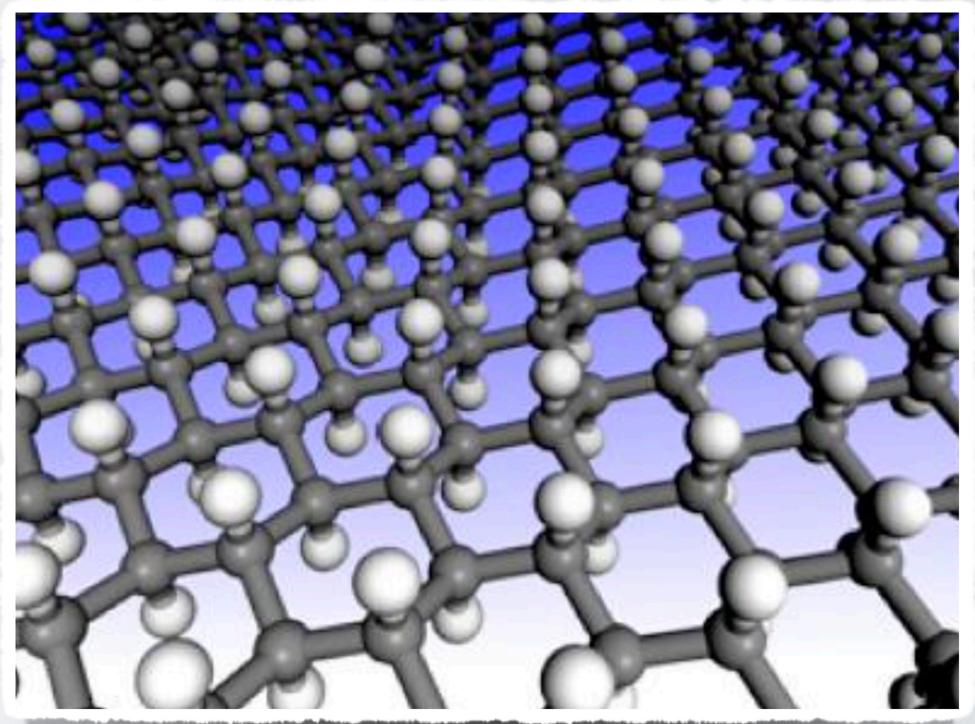
- Prevents formation of T_2 molecules



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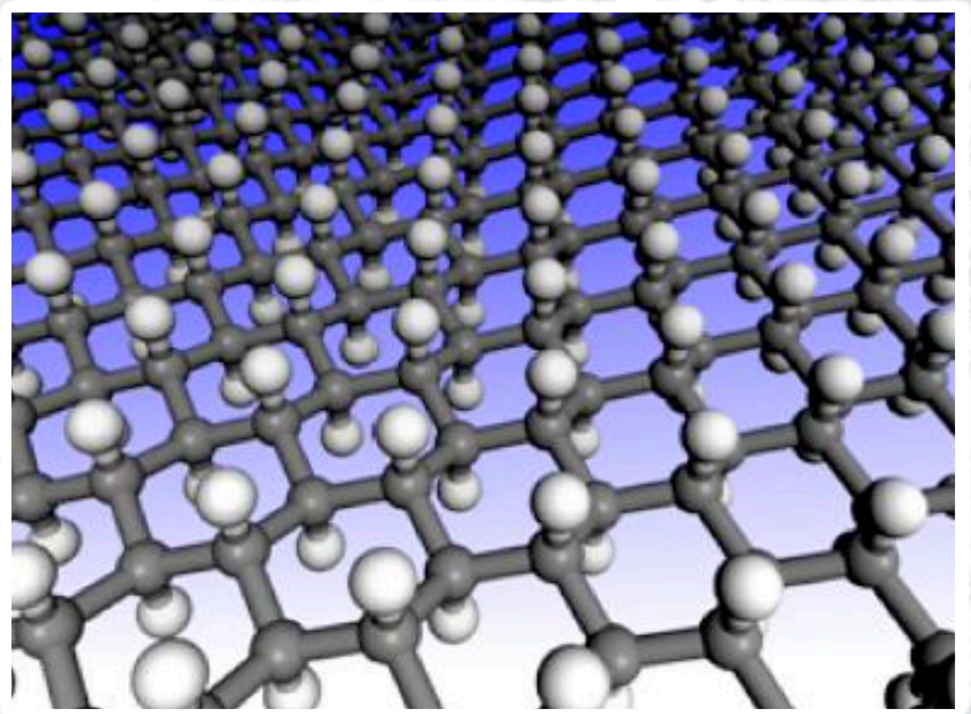
High event rate

- Distribute the tritium on a solid state substrate (e.g. graphene)
- Prevents formation of T_2 molecules
- Allows storage of large quantities of tritium on a small surface

$$\sigma_T \sim 0.5 \text{ mg/cm}^2$$

(desired $m_T \sim 10$ mg at the early stages)



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Small energy resolution

- PTOLEMY aims at using TES detectors with an envisaged resolution of $\Delta E \simeq 0.05$ eV [see e.g. Lolli et al. — Appl. Phys. Lett. 2013]

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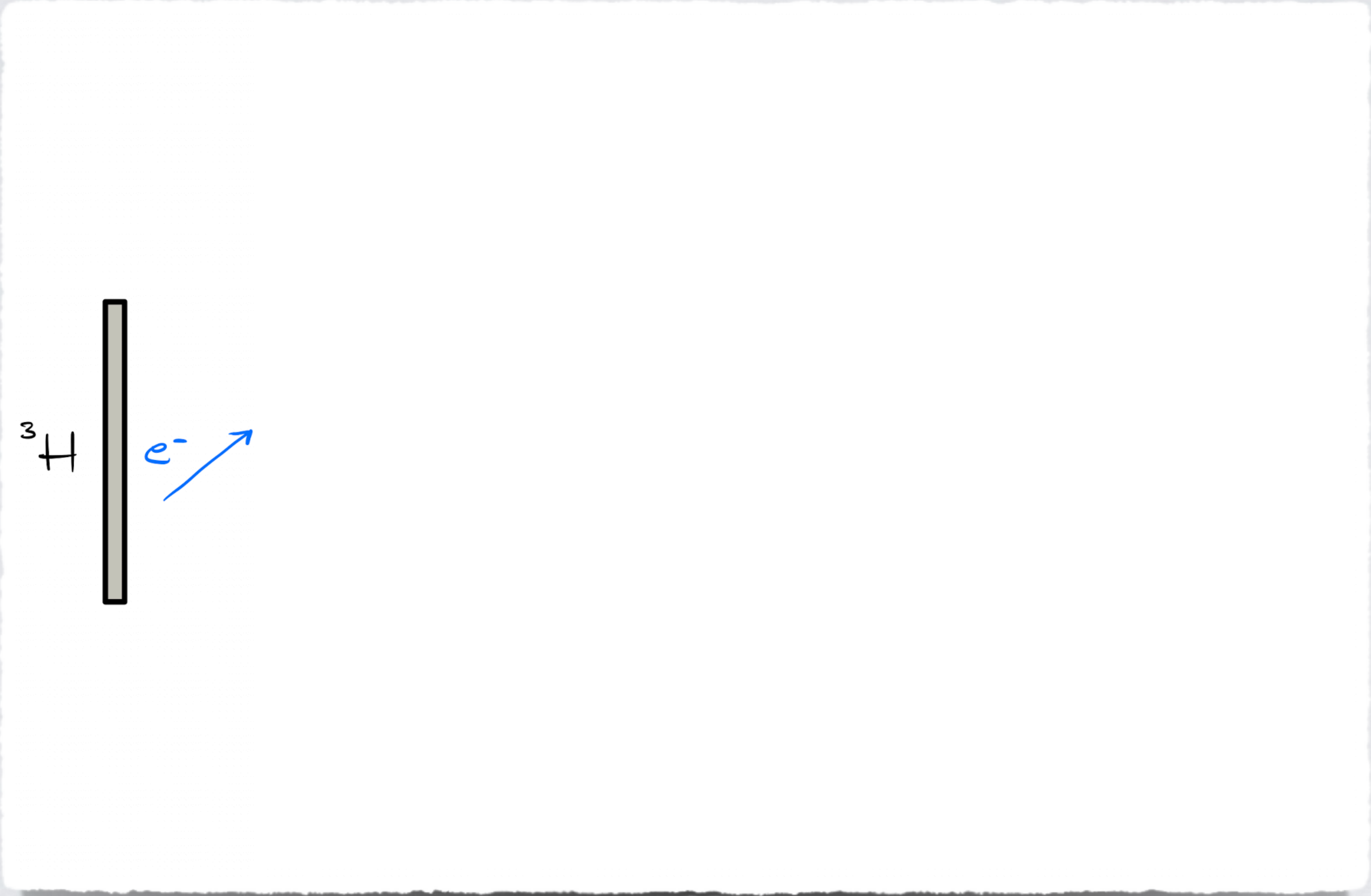
  2. TES' are slow response detectors → need to reduce the number of electrons coming from β-decay

PTOLEMY: THE IDEA

- Both requirements are achieved with a new electromagnetic filter

[see PTOLEMY — 1810.06703; PTOLEMY — JINST 2022, 2108.10388]



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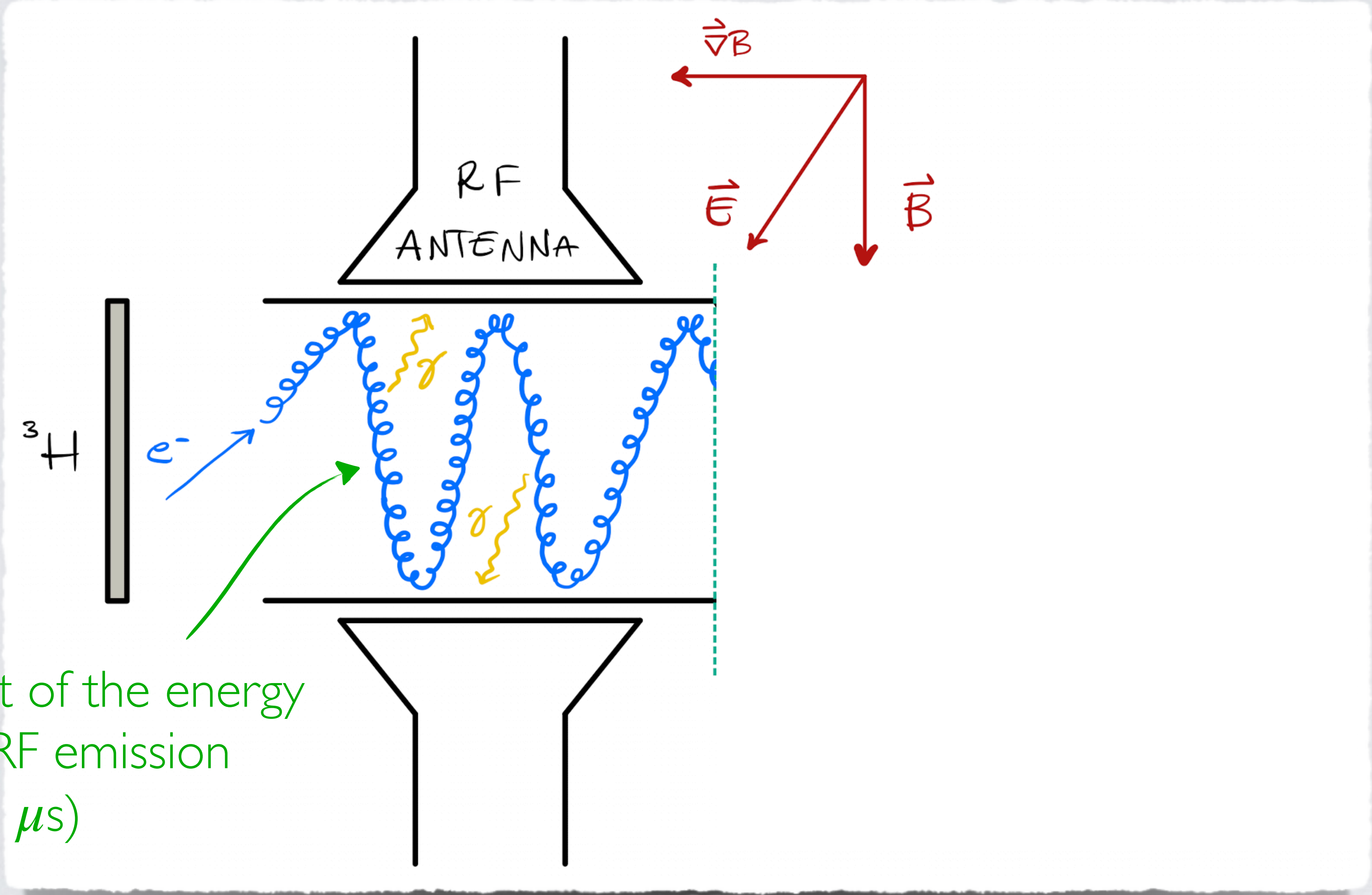

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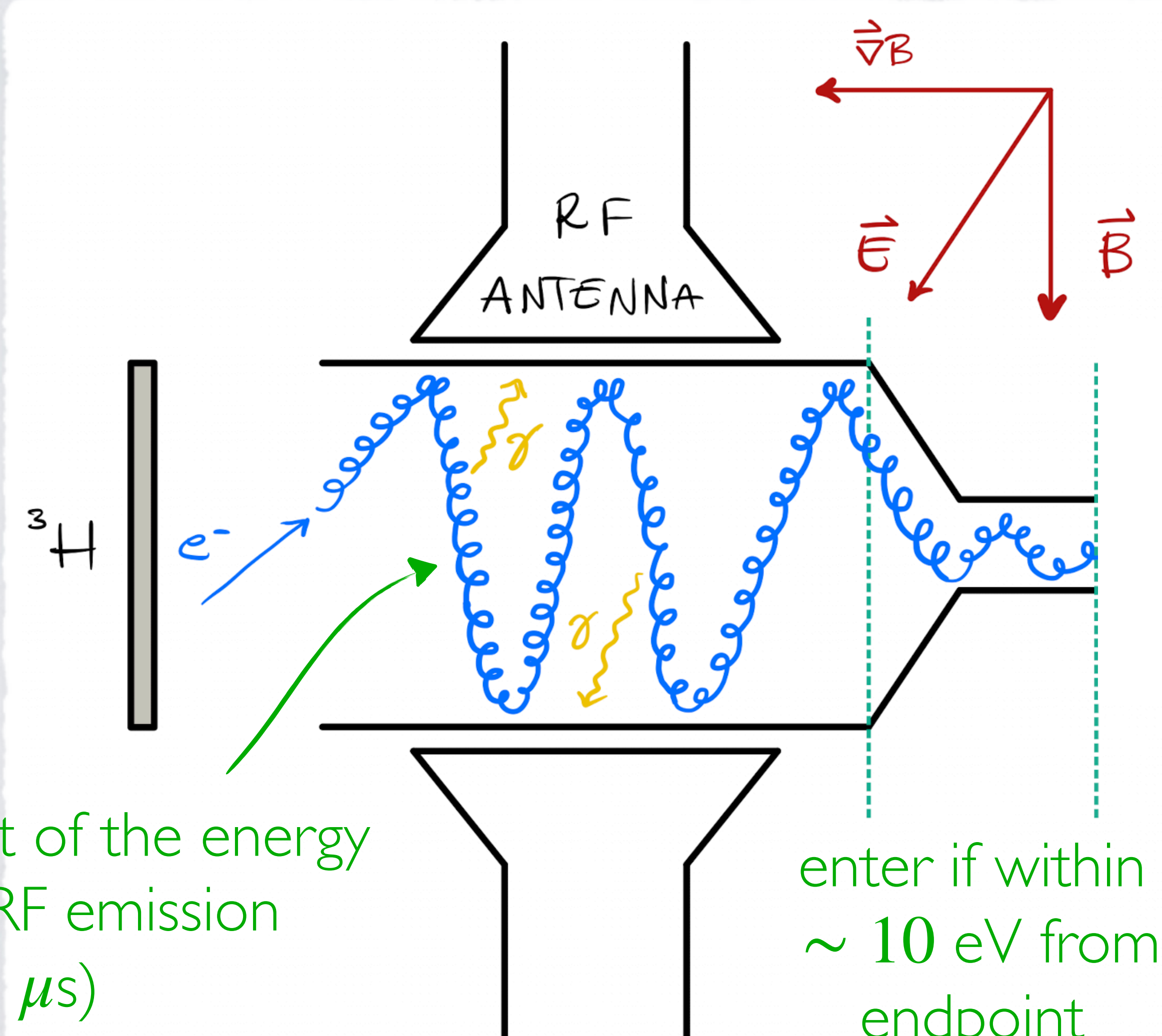

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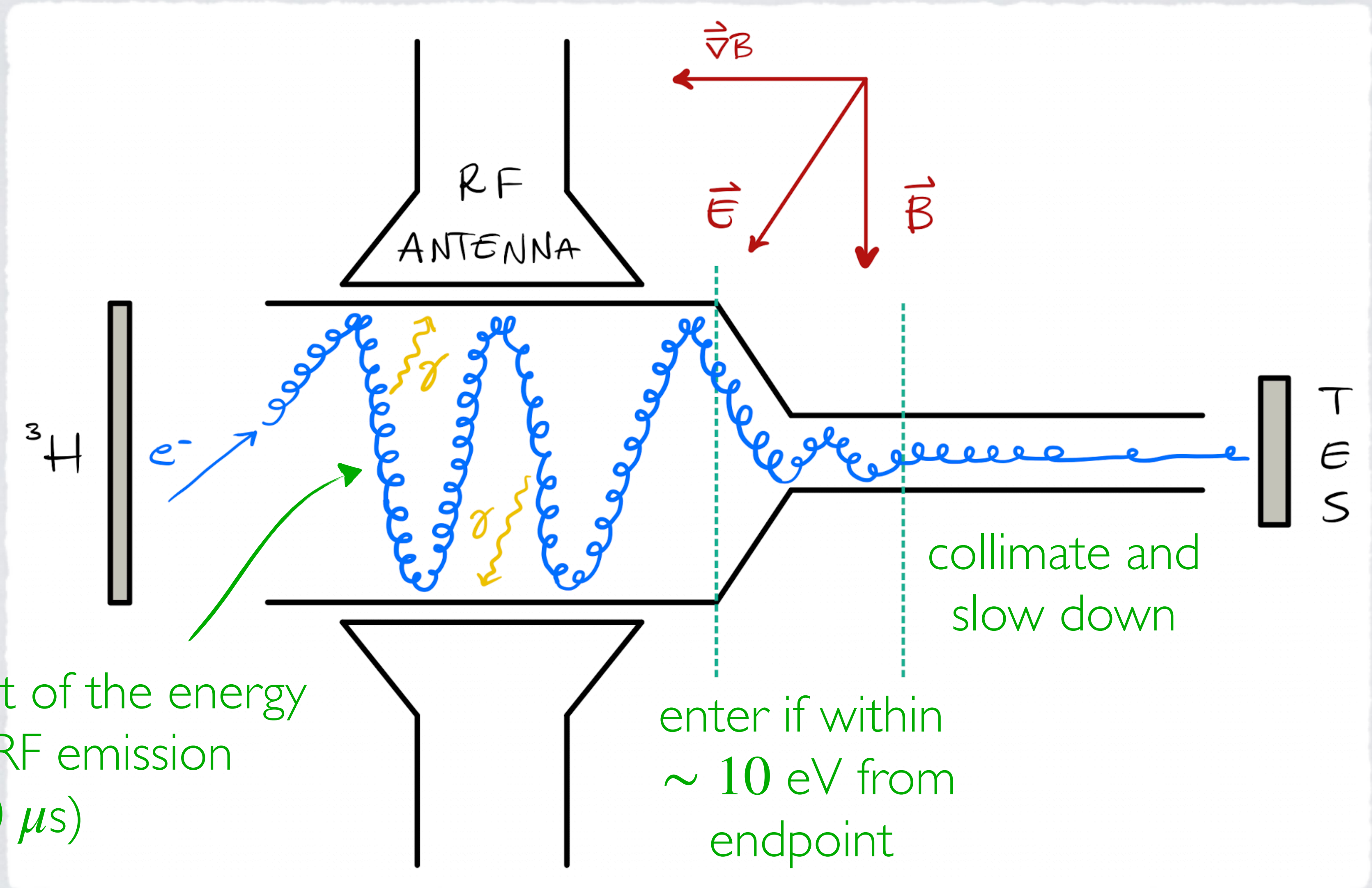

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collimate and slow down

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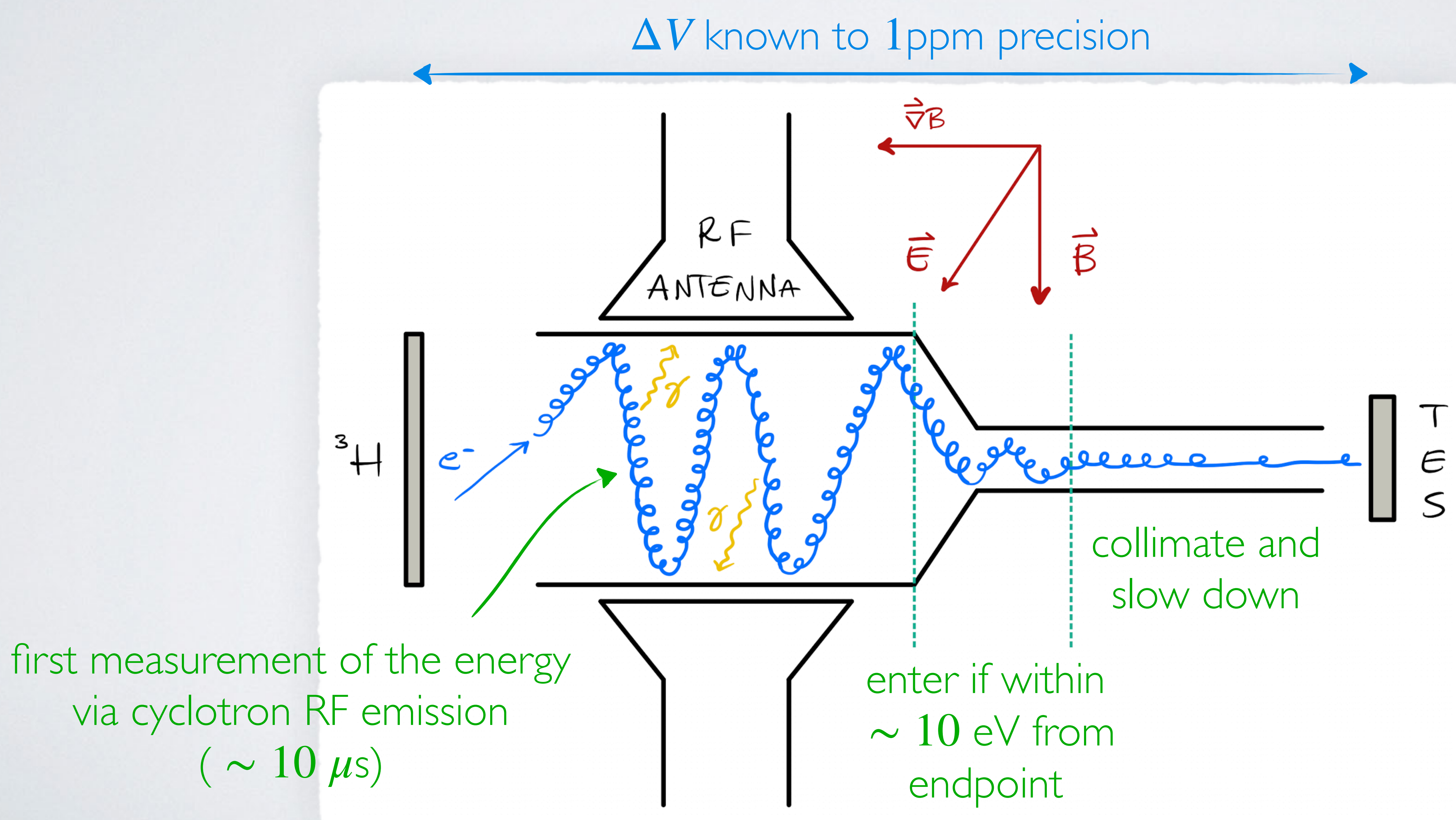

QUANTUM SPREAD

- Distributing tritium on flat graphene has one drawback

spatially localized tritium ⇨ uncertainty on tritium's momentum ⇨ spread in final electron energy

[Cheipesh, Cheianov, Boyarsky — PRD 2021, 2101.10069]

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$$\Delta K_\beta = \left| \frac{\mathbf{p}_e \cdot \Delta \mathbf{p}_T}{E_{He}} \right| \sim \frac{p_e}{m_{He}} \frac{1}{\Delta x_T}$$

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spread of initial tritium wave function

an order of magnitude larger than the wanted energy accuracy

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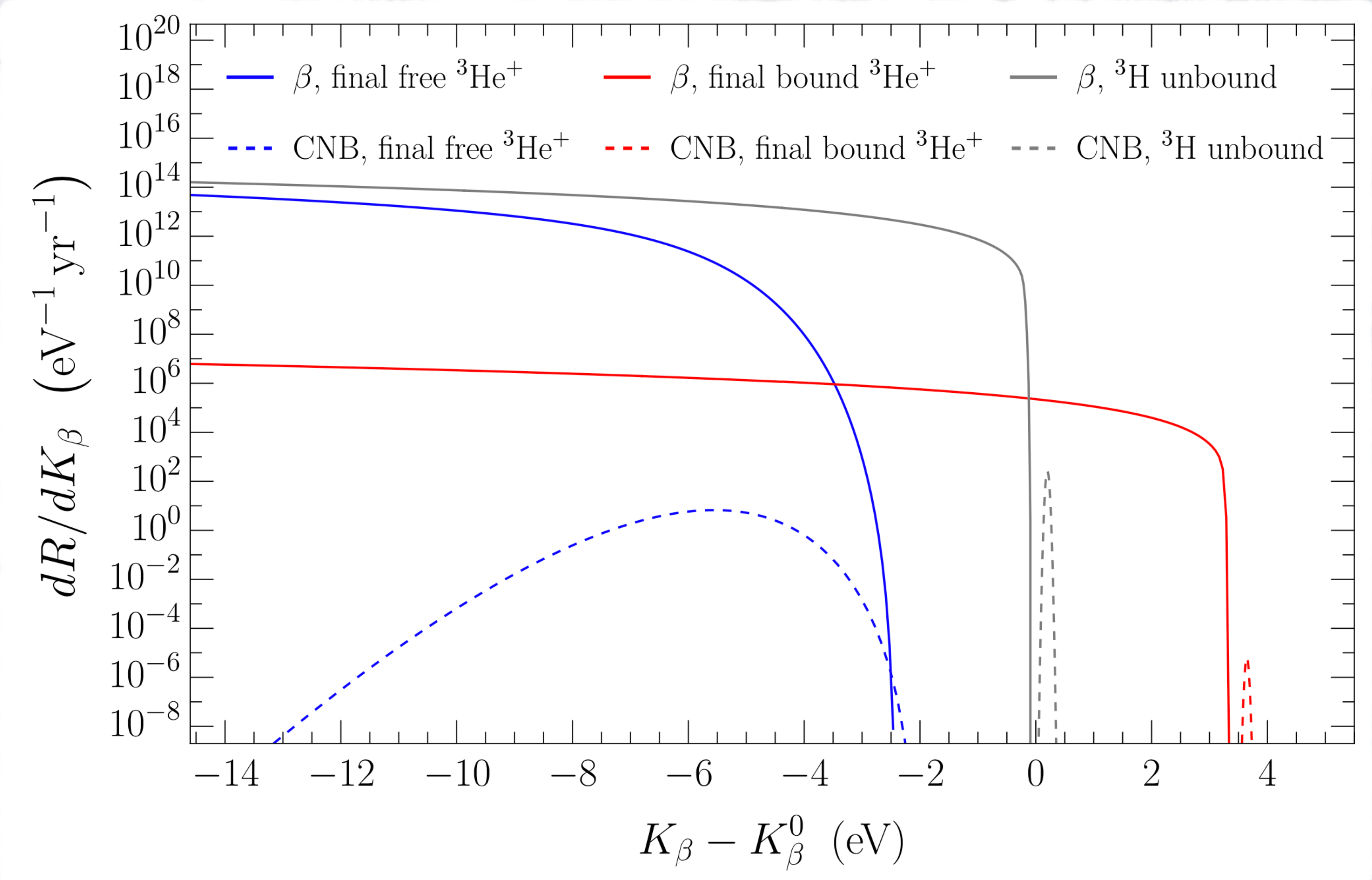

[PTOLEMY — 2203.11228]

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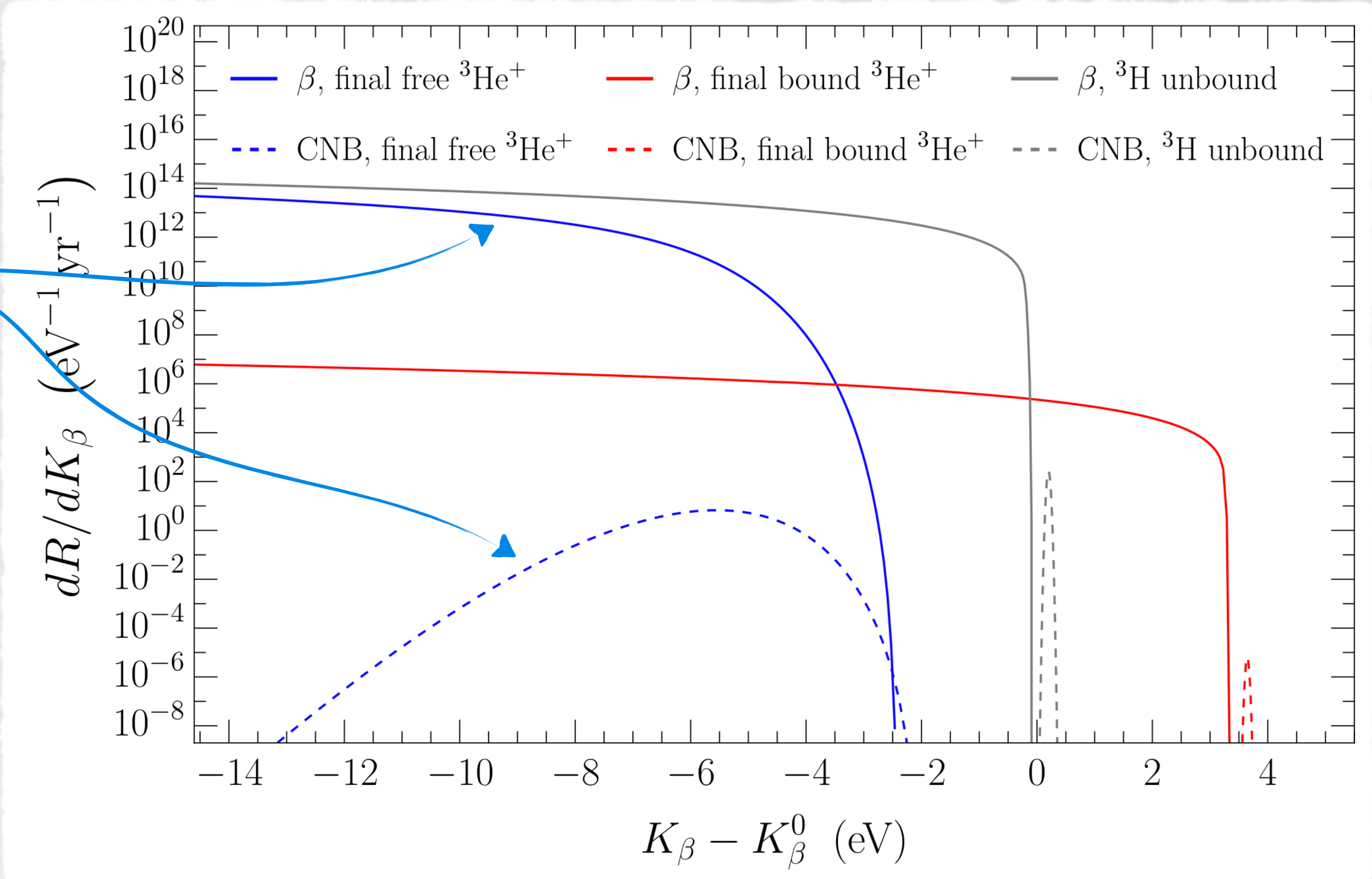
$^3He^+$ **is mostly freed** from the graphene → the **cosmic neutrino peak disappears** under the decay spectrum



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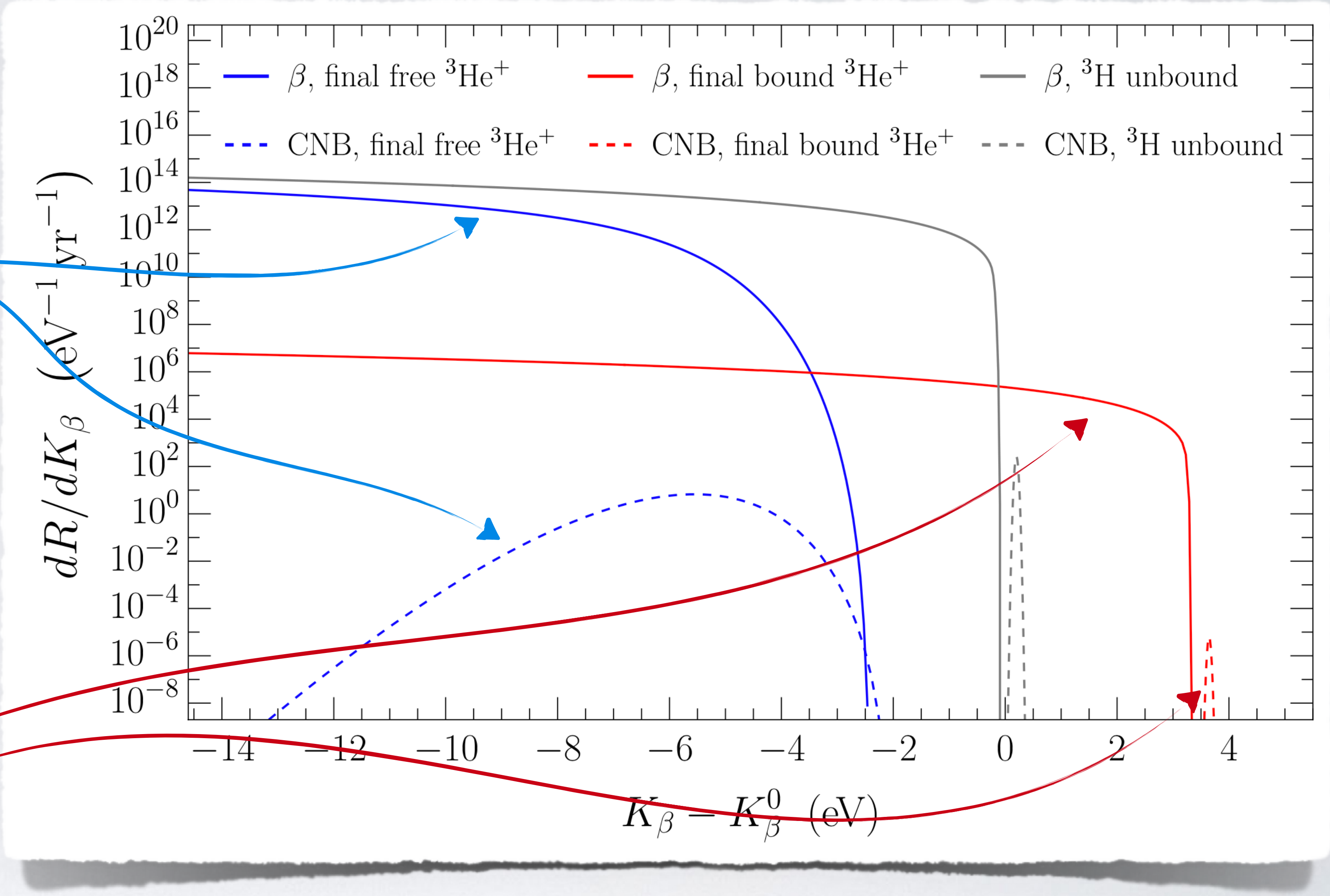

When the $^3He^+$ **remains bound in the ground state** the peak is well separated → it is however **exponentially unlikely**

[PTOLEMY — 2203.11228]

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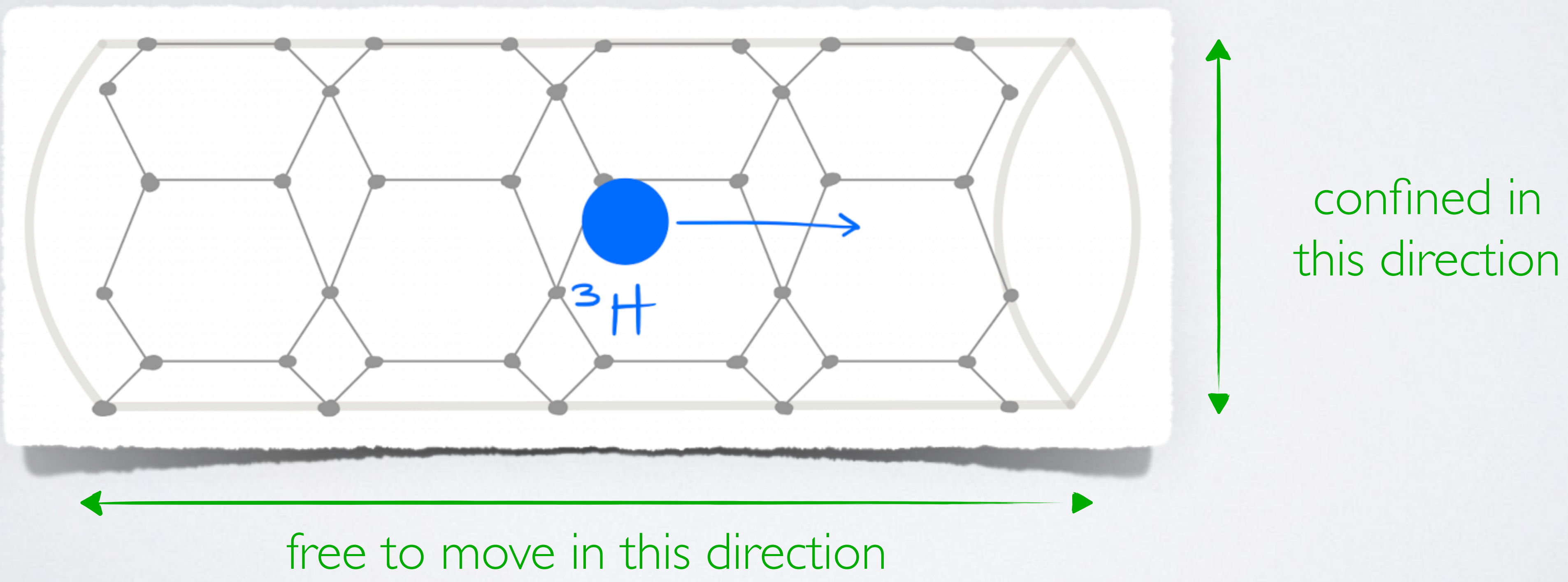
- One proposal: hydrogenated carbon nanotubes [PTOLEMY – 2203.11228]



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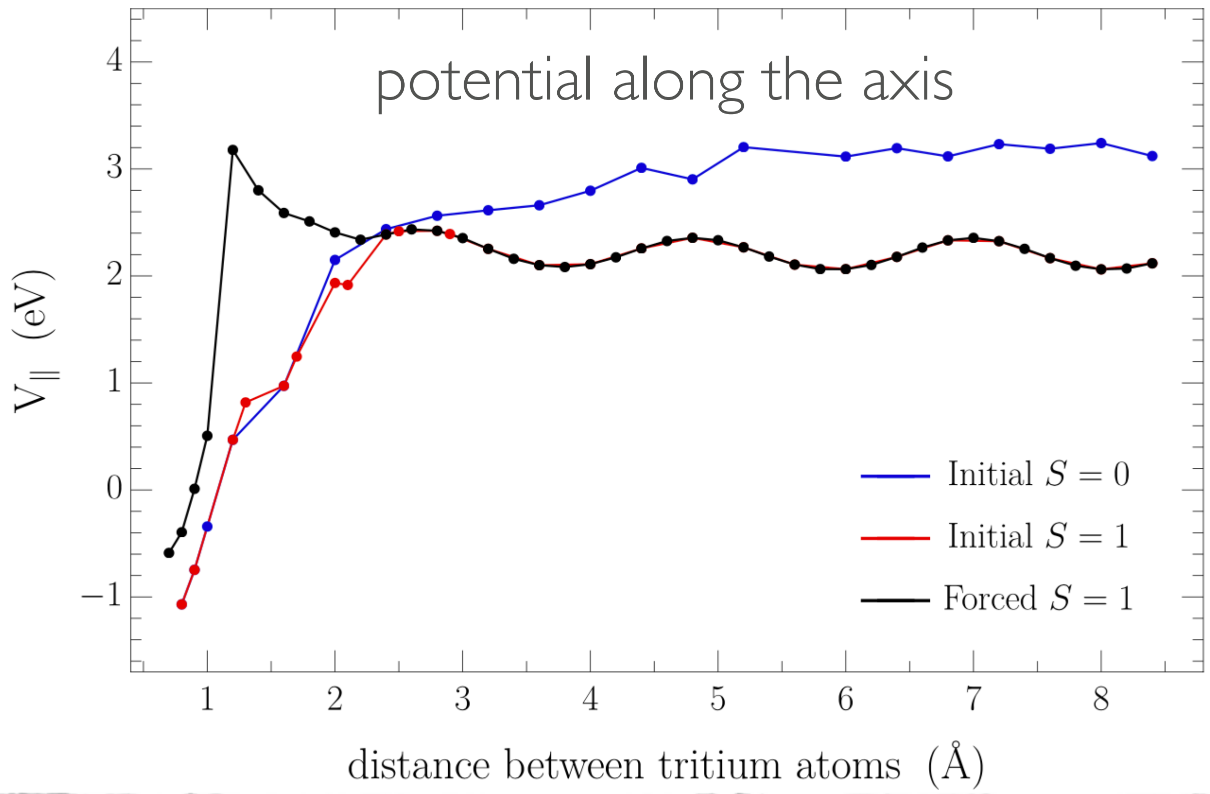
- Preliminary studies show that this is a feasible solution
- When passivated with hydrogen, the nanotube potential looks like



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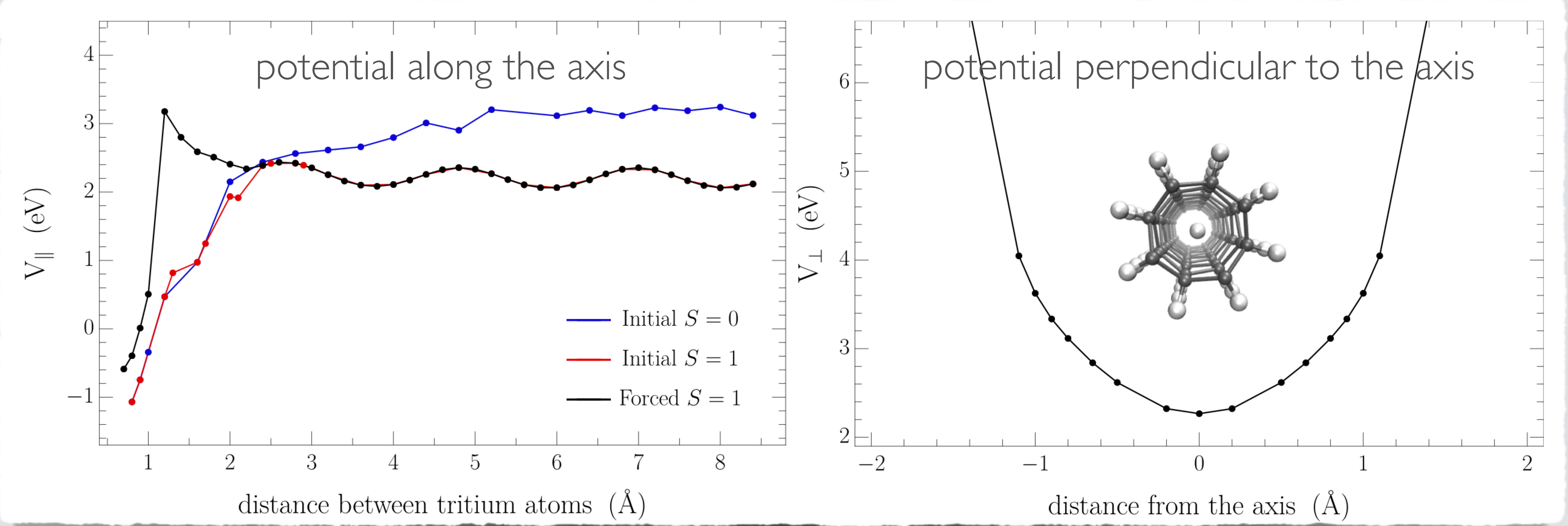

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- More things to investigate: Final state effects? Other emitters?

  [Nussinov, Nussinov — PRD 2022, 2108.03659; Tan, Cheianov — 2202.07406; Mikulenko, Cheipesh, Cheianov, Boyarsky — 2111.09292]

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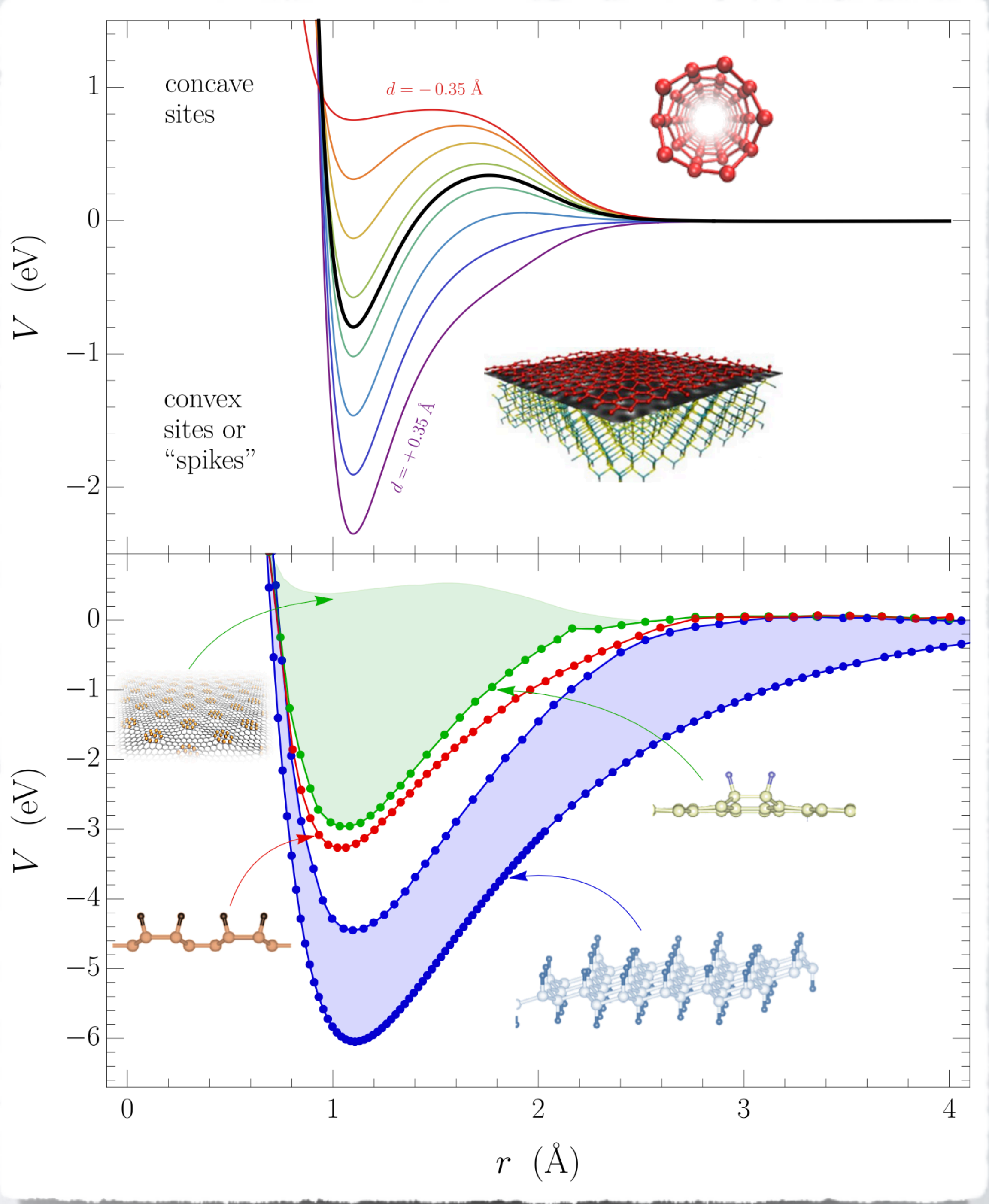
Thank you for your attention!

BACK UP

TRITIUM-GRAPHENE POTENTIAL

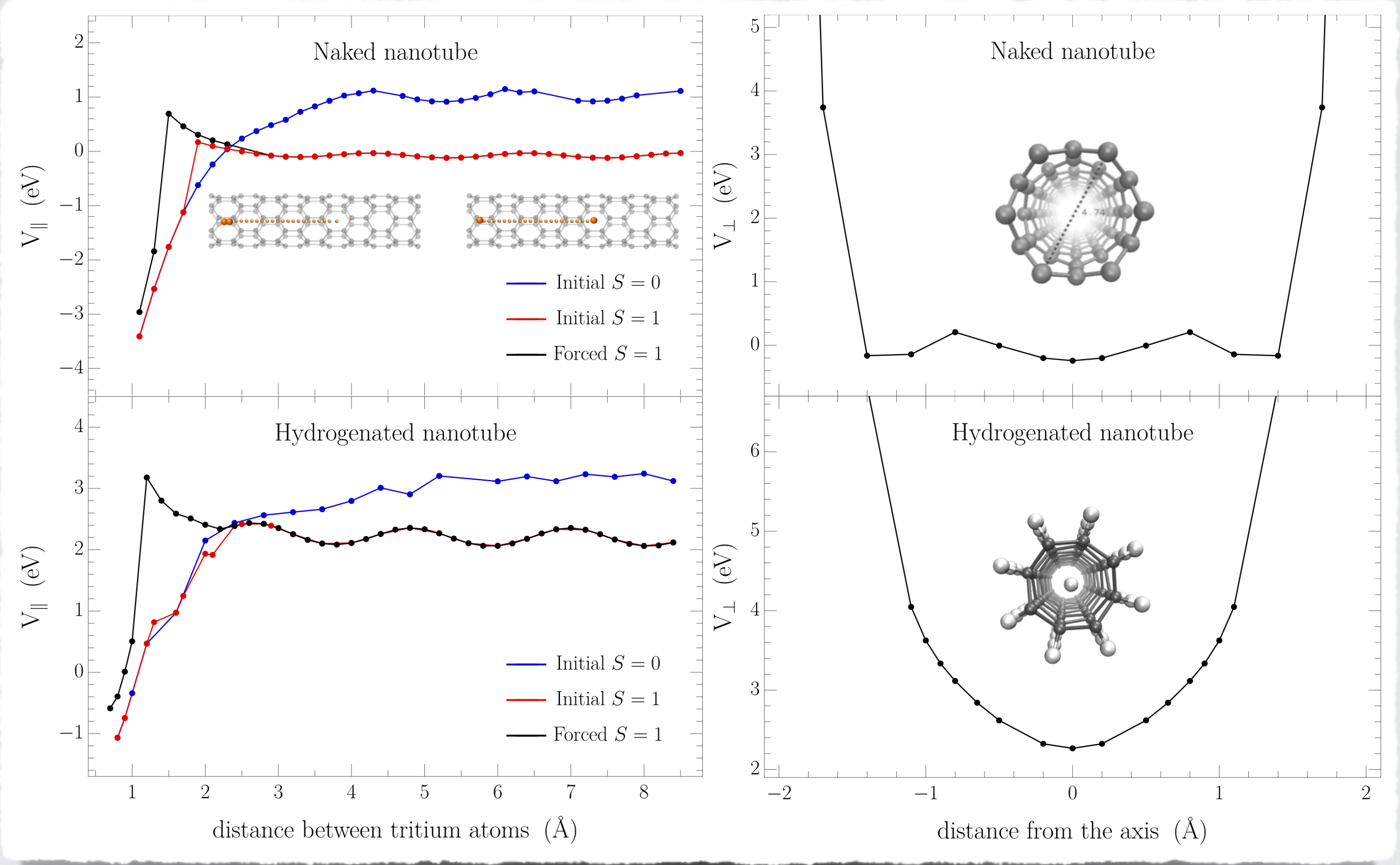
- The tritium-graphene potential is strongly dependent on coverage and curvature of the sheet
- For very concave sheets (nanotube) the potential is essentially not binding anymore
- The highest the coverage the deeper is the potential



[PTOLEMY — 2203.11228]

WHY HYDROGENATED NANOTUBES?

- The reason to passivate the nanotubes with hydrogen is to prevent the tritium from sticking to the walls



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MORE DETAILS ON THE ELECTRON SPECTRUM

- Two extreme cases for the $^3He^+$ wave function (near the endpoint)
- Free helium:

$$\psi_{He}(\mathbf{x}) \sim e^{i\mathbf{k}_{He}\cdot\mathbf{x}} \quad \Longrightarrow \quad \mathcal{M}_{fi} \sim \exp\left(-\Delta x_T^2 |\mathbf{k}_{He} + \mathbf{k}_e|^2\right)$$

- maximize the probability when $\mathbf{k}_{He} \simeq -\mathbf{k}_e$ ➜ probability is maximum in a region $\Delta k_{He} \sim 1/\Delta x_T$ ➜ large quantum spread
- Bound helium:

$$\psi_{He}(\mathbf{x}) \simeq \psi_T(\mathbf{x}) \quad \Longrightarrow \quad \mathcal{M}_{fi} \sim \exp\left(-\Delta x_T^2 k_e^2\right) \ll 1$$

- no spread ➜ but the event is exponentially unlikely

[PTOLEMY — 2203.11228]