Detecting the Cosmic Neutrino Background

Jack Shergold

What we will cover

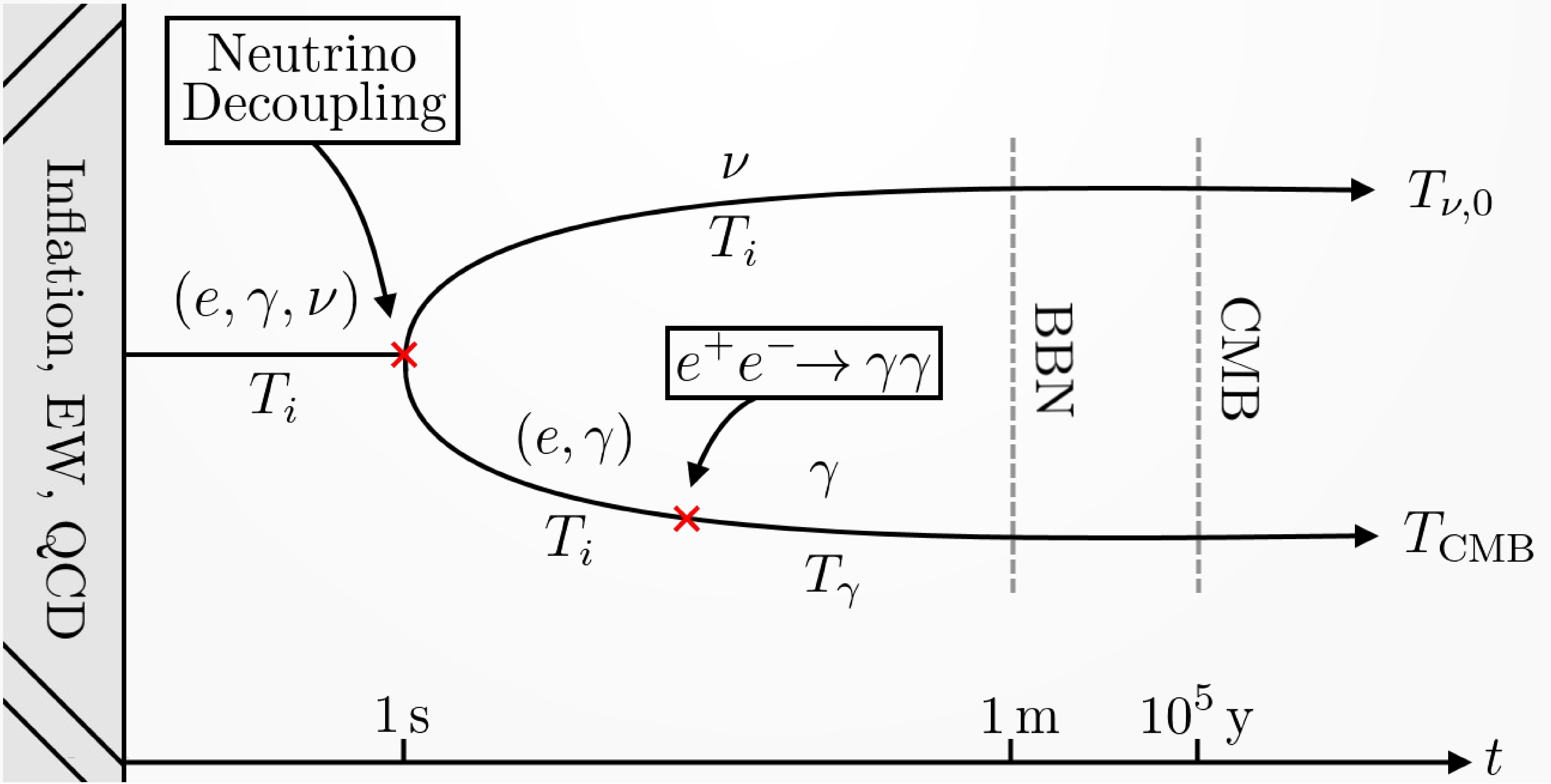
- Lecture 1: Introduction to the CνB
- Lecture 2: Direct detection proposals ⇦
- Lecture 3: Indirect detection, constraints and future prospects

Contents

- Recap ⇦

- Direct detection proposals:
  - PTOLEMY
  - Coherent scattering
  - Stodolsky effect
  - Accelerator

Recap



Inflation, EW, QCD
Neutrino Decoupling
(e, γ, ν)
T_i
ν
T_i
$T_{\nu,0}$
$e^+e^- \to \gamma\gamma$
(e, γ)
T_i
γ
T_γ
$T_{\rm CMB}$
BBN
CMB
1 s
1 m
10^5 y
t

Recap

- Key properties:

$$T_{\nu,0} = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_{\text{CMB}}$$

Recap

- Key properties:

$$T_{\nu,0} = 0.168\,\mathrm{meV}$$

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$$T_{\nu,0} = 0.168\,\mathrm{meV} \qquad |\nu_\alpha\rangle \to |U_{\alpha i}|^2 |\nu_i\rangle$$

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- All left helicity (right helicity antineutrinos)

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- Key properties:

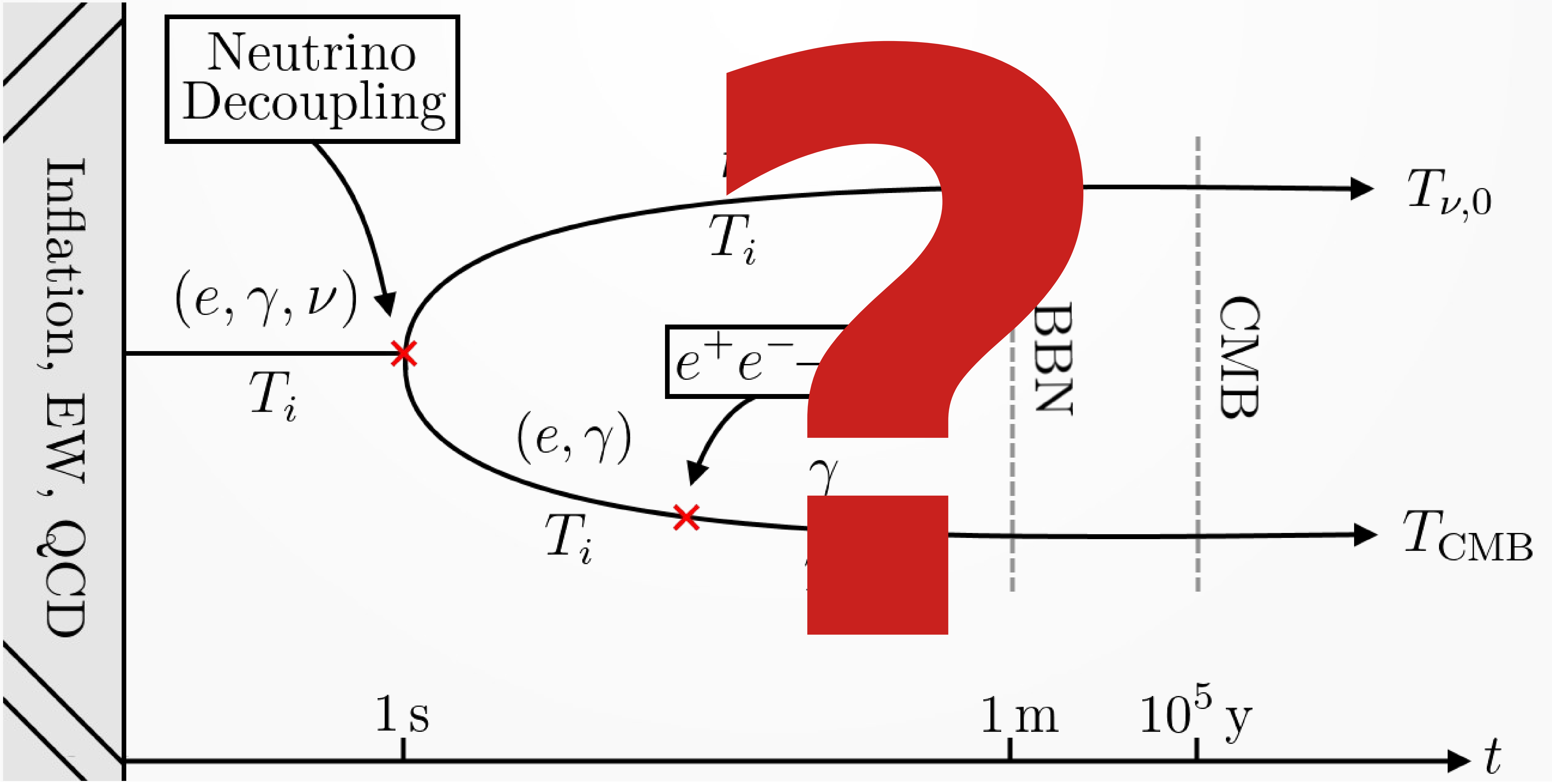
$$T_{\nu,0} = 0.168\,\mathrm{meV} \qquad\qquad |\nu_\alpha\rangle \rightarrow |U_{\alpha i}|^2 |\nu_i\rangle$$

- All left helicity (right helicity antineutrinos)

- Follow massless Fermi-Dirac distribution:

$$f(p) = \frac{1}{\exp\left(\frac{p}{T}\right) + 1}$$

Recap



Neutrino Decoupling
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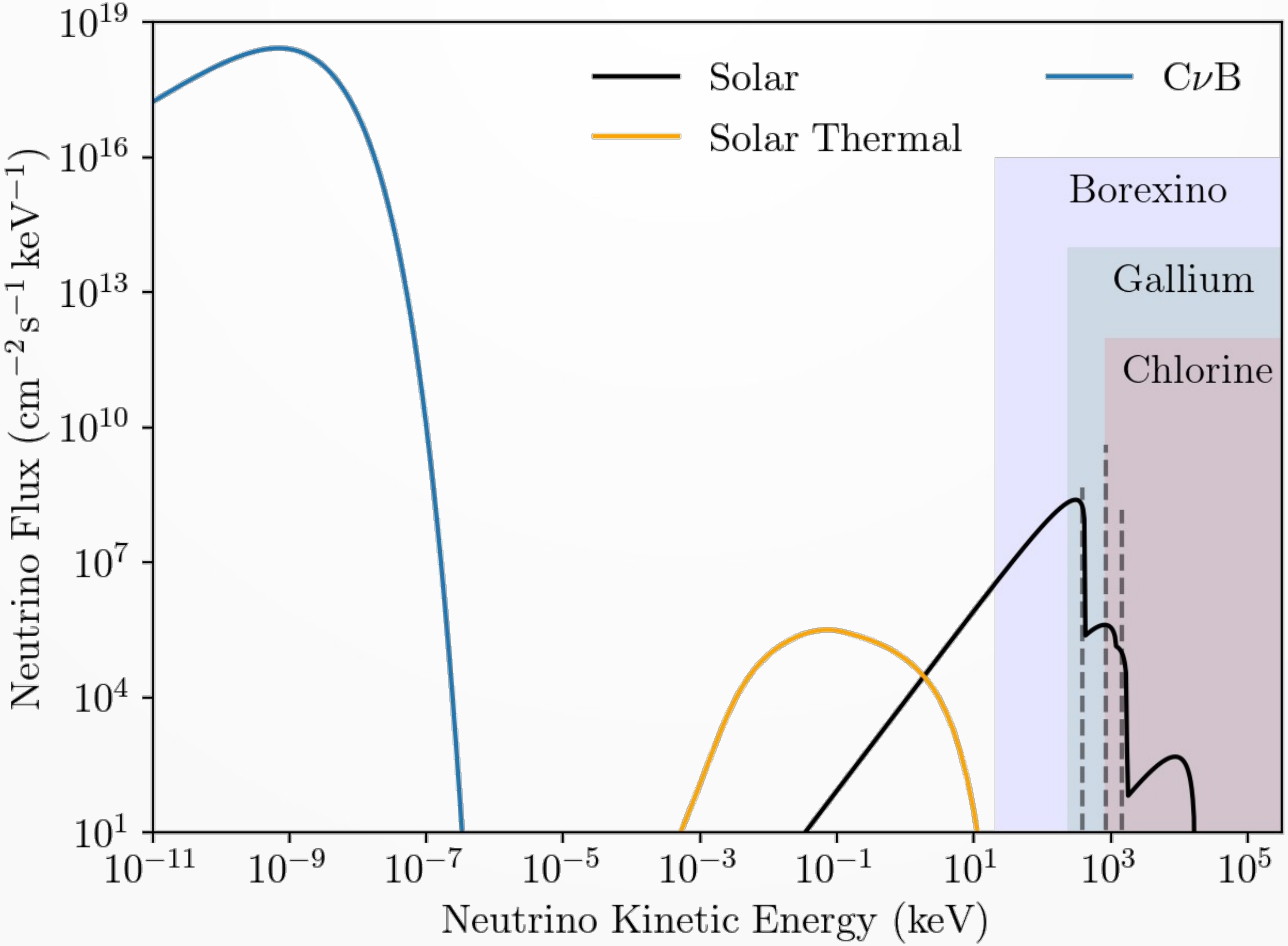
Recap



Solar
Solar Thermal
CνB
Borexino
Gallium
Chlorine
Neutrino Flux (cm^{-2}s^{-1} keV^{-1})
10^{19}
10^{16}
10^{13}
10^{10}
10^{7}
10^{4}
10^{1}
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
Neutrino Kinetic Energy (keV)

How to detect the CνB

Direct	*Indirect*
• Unstable nuclei	• Cosmic ray attenuation
• Coherent scattering	• Pauli blocking
• Stodolsky effect	• Neutron star cooling
• …	• …

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The PTOLEMY experiment

- Proposed by Weinberg in 1962 [1]:

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

[1] S. Weinberg, Phys. Rev. **128**, 1457 (1962)

The PTOLEMY experiment

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[1] S. Weinberg, Phys. Rev. **128**, 1457 (1962) c

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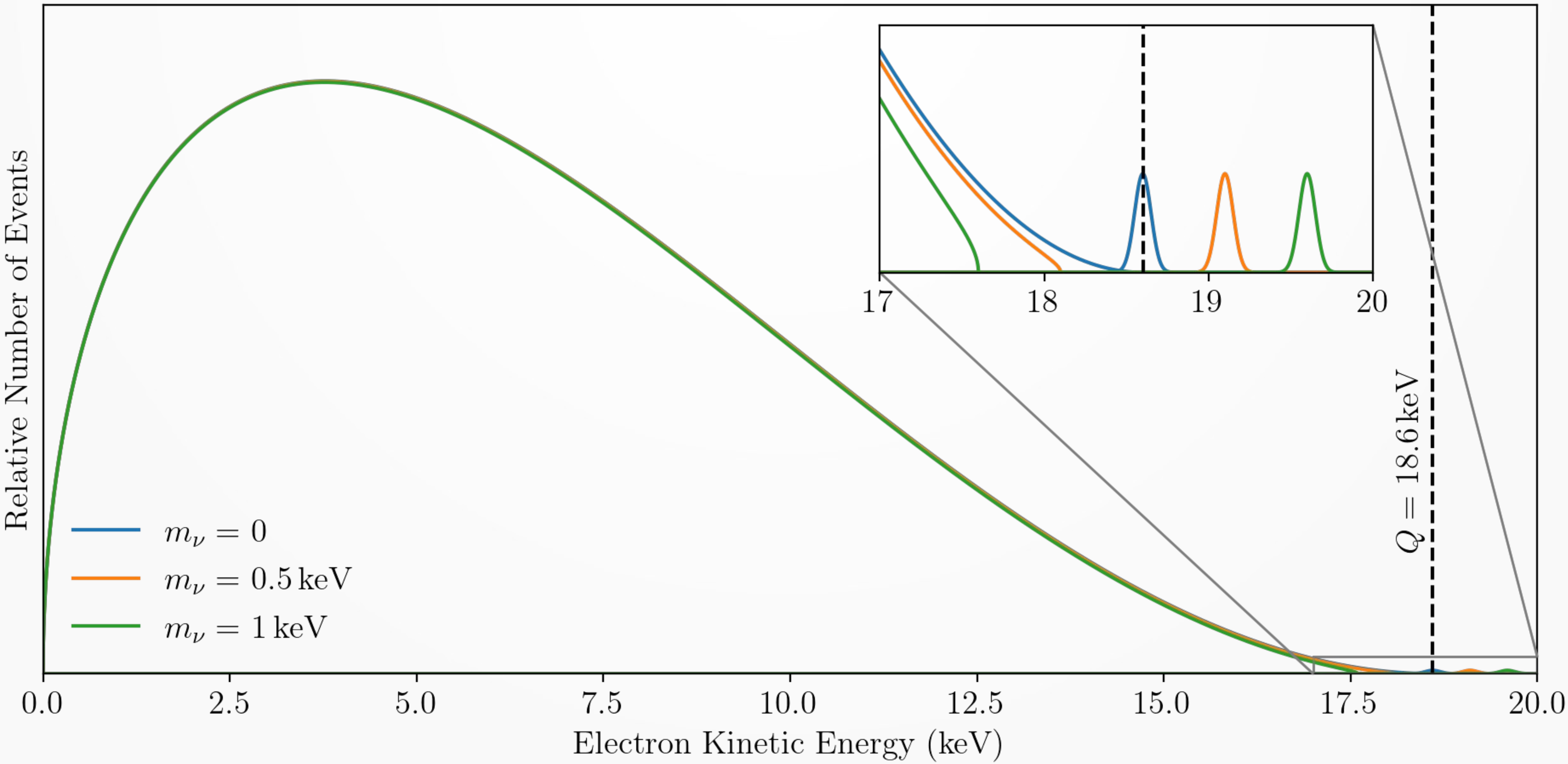
- Beta decay releases 18.6 keV

[1] S. Weinberg, Phys. Rev. **128**, 1457 (1962)

The PTOLEMY experiment



The PTOLEMY experiment

- Neutrino capture cross section [2]:

$$\langle \sigma \beta_\nu \rangle \propto G_F^2 E_e p_e \sim 10^{-45}\,\mathrm{cm}^2$$

[2] A. Long, C. Lunardini and E. Sabancilar, JCAP **08**, 038 (2014)

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$$\Gamma = N_T n_\nu \langle \sigma \beta_\nu \rangle \sim 4\,\mathrm{y}^{-1}$$

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- This event rate is doubled for Majorana neutrinos

[2] A. Long, C. Lunardini and E. Sabancilar, JCAP **08**, 038 (2014)

What's the catch?

- Extreme sensitivity required to detect signal:

$$\Delta \leq 2m_\nu$$

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- cf. KATRIN, uses ~300μg of tritium [3]

[3] L. Kuckert *et al.*, Vacuum **158**, 195-205 (2018)

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$$\Delta \simeq 50\,\mathrm{meV}$$

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$$m_{\nu_h} \gtrsim 50\,\mathrm{meV}$$

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- Extreme sensitivity required to detect signal:

$$\boxed{\Delta < 2m_{\nu_h}}$$

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- PTOLEMY should at least see something!

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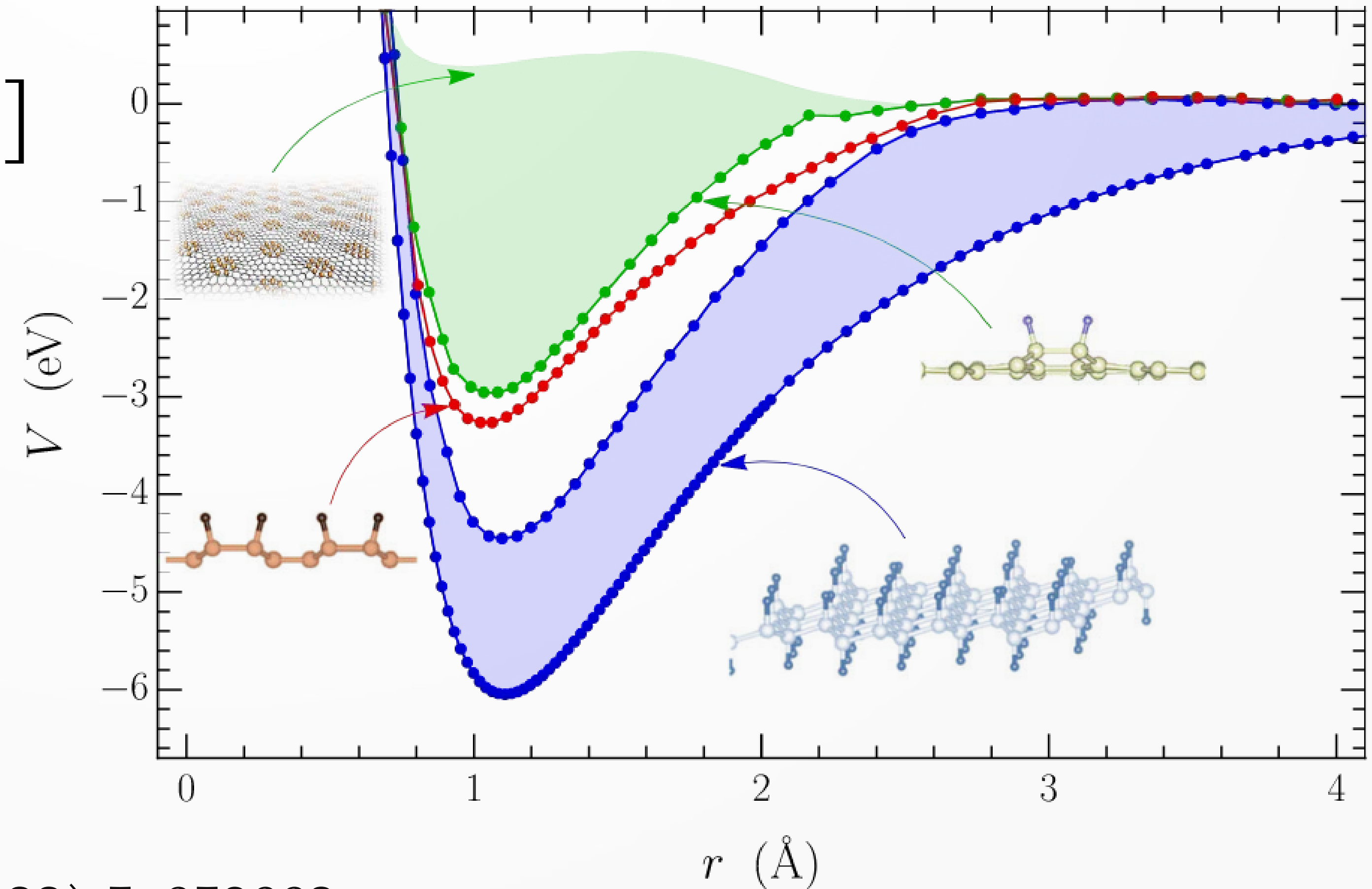
What's the catch?

- Obtaining and storing 100g of tritium

- Graphene substrate [4]



[4] PTOLEMY, Phys. Rev. D **106** (2022) 5, 053002

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$$\Delta E_e \simeq p_e \Delta v$$

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$$\Delta x \simeq 0.1\,\text{Å}$$

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What's the catch?

- Uncertainty principle:

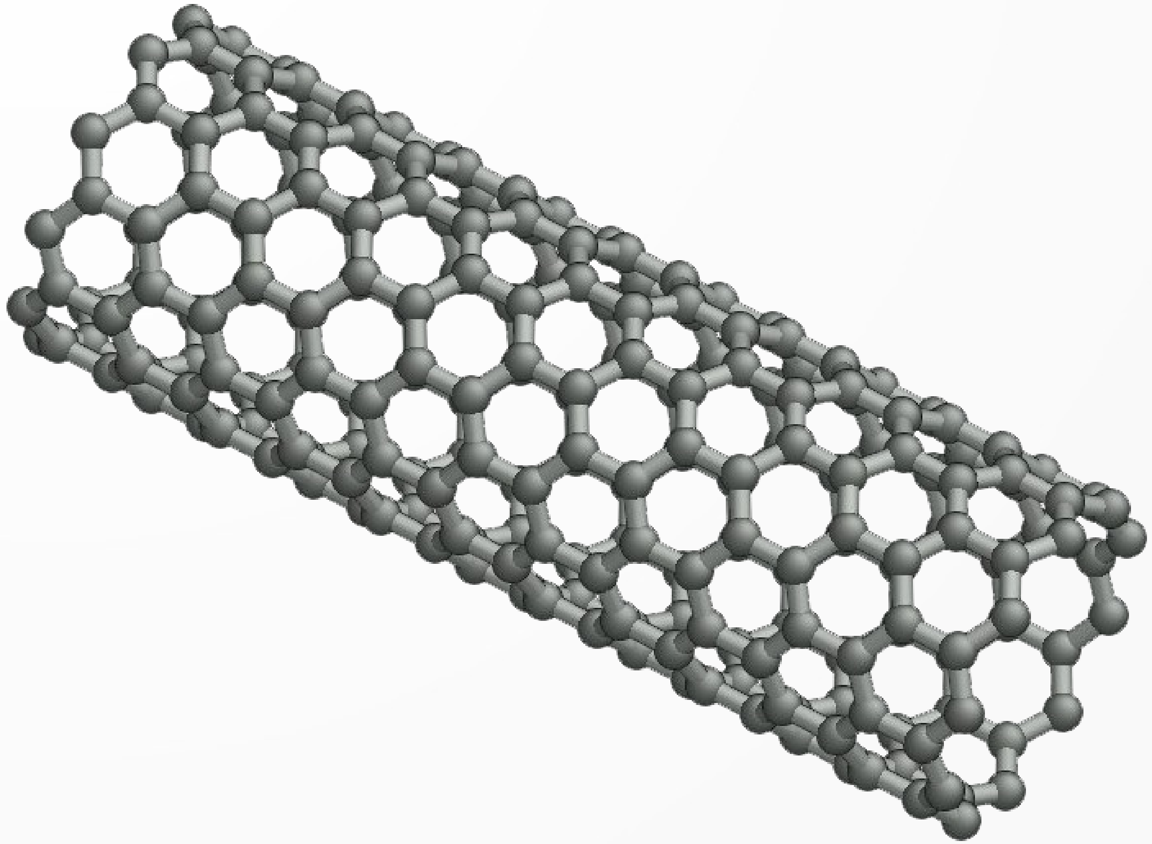
$$\Delta E_e \simeq 480\,\mathrm{meV}$$

$$\boxed{\Delta E_e \gg 2m_{\nu_h}}$$

- No longer guaranteed to see anything!

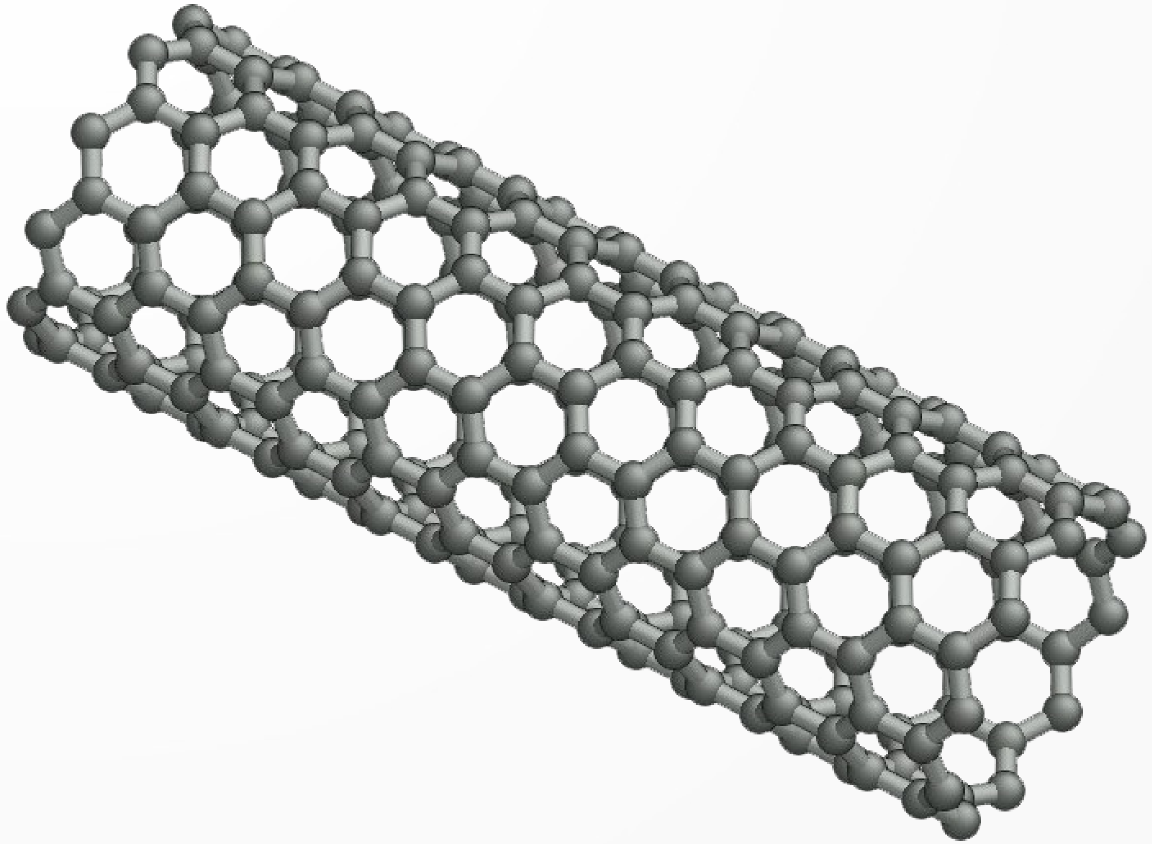
So now what?

- Carbon nanotubes?



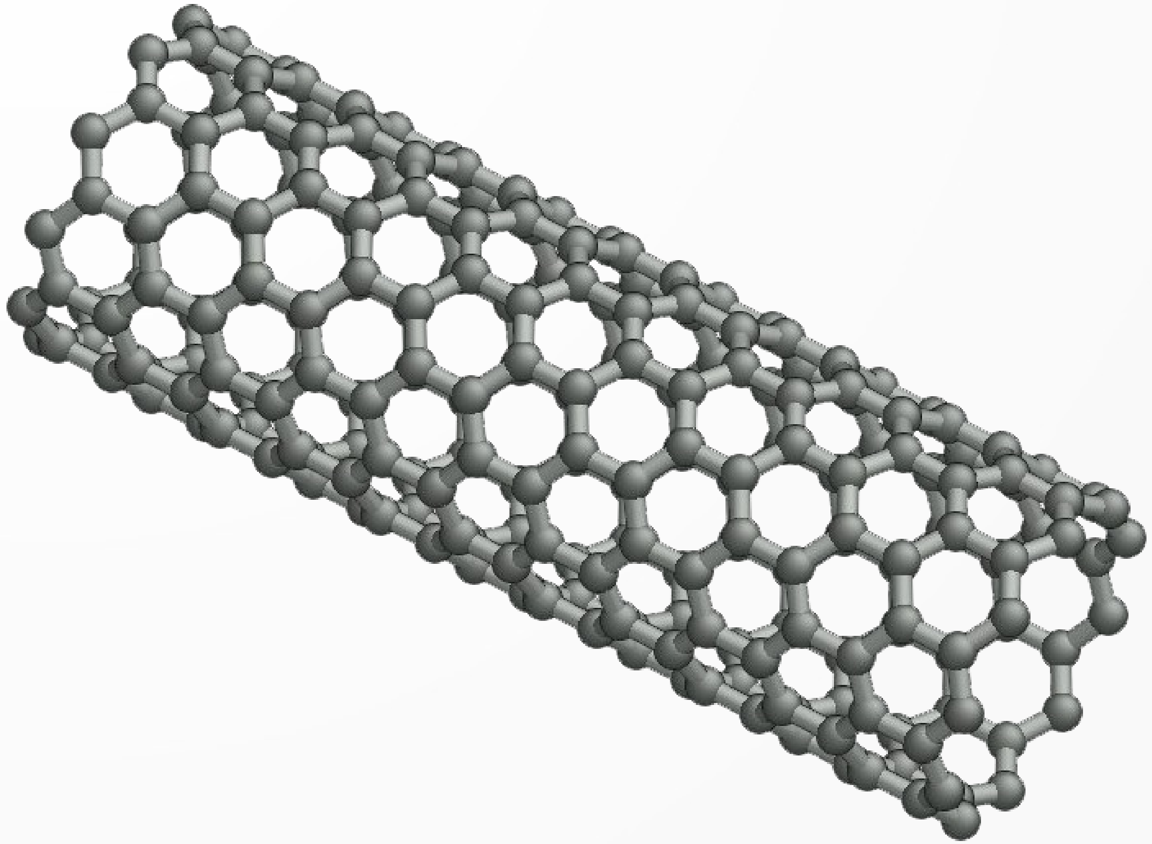
So now what?

- Carbon nanotubes?
- Allow tritium to *slide*



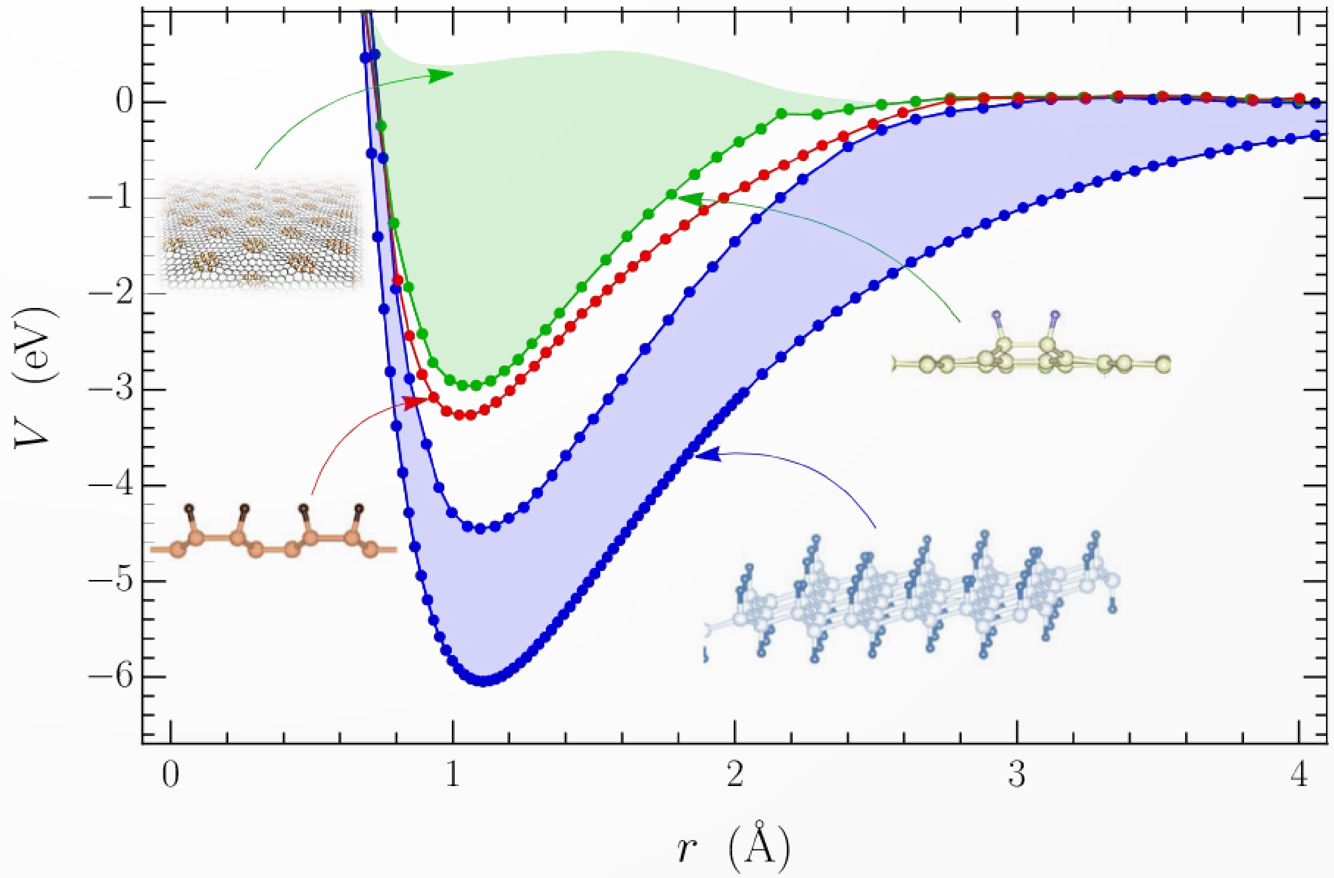
So now what?

- Carbon nanotubes?
- Allow tritium to *slide*
- Increases Δx!



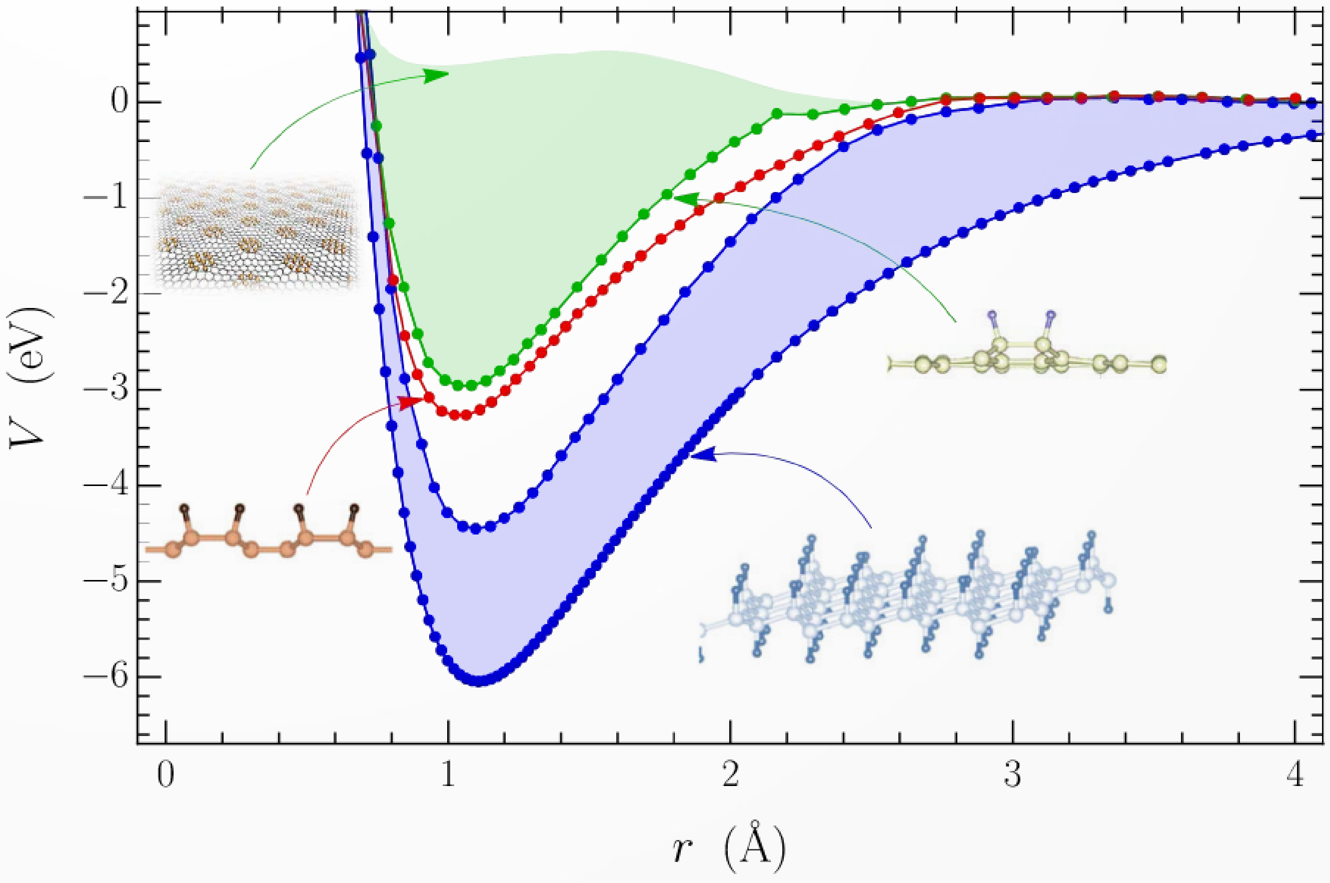
So now what?

- Other ideas:



So now what?

- Other ideas:
- Modified potentials?



So now what?

- Time-dependent signal [5]:

$$\langle \vec{\beta}_\nu \rangle \neq \vec{0}$$

[5] E. Akhmedov, JCAP **09** (2019) 031

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- Time-dependent signal [5]:

$$\langle \vec{\beta}_\nu \rangle \neq \vec{0} \implies \Gamma_\nu = \Gamma_\nu(t)$$

- Variation of around 0.1%

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- Allows for worse energy resolution!

[5] E. Akhmedov, JCAP **09** (2019) 031

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Coherent scattering

- Coherent scattering (Opher '74, … , JS '21):

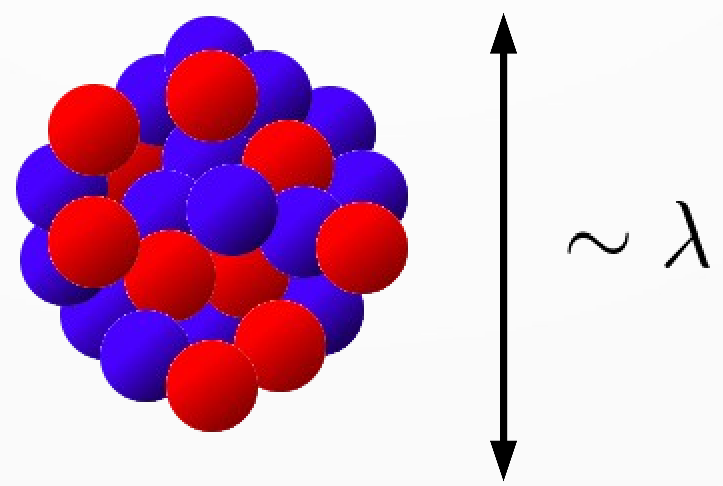
$$\nu + X \rightarrow \nu + X$$

Coherent scattering

- Coherent scattering (Opher '74, … , JS '21):

$$\nu + X \to \nu + X$$

- Wavelength of order target size:



Coherent scattering

- Neutrino "sees" a larger charge:

$$\mathcal{M} \sim Q_T \qquad\qquad Q_T \sim N_T$$

Coherent scattering

- Neutrino "sees" a larger charge:

$$\mathcal{M} \sim Q_T \qquad\qquad Q_T \sim N_T$$

- Significantly enhanced event rates:

$$\Gamma \sim N_T \longrightarrow \Gamma_{\rm coh} \sim N_T^2$$

Coherent scattering

- More rigorously [6]:

$$\mathcal{M}_i \propto e^{-i(\vec{q}\cdot\vec{x}_i)}$$

[6] M. Bauer, JS, JCAP **01** (2023), 003

Coherent scattering

- More rigorously [6]:

$$|\mathcal{M}|^2 \propto \left| \sum_i e^{-i(\vec{q}\cdot\vec{x}_i)} \right|^2$$

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Coherent scattering

- More rigorously [6]:

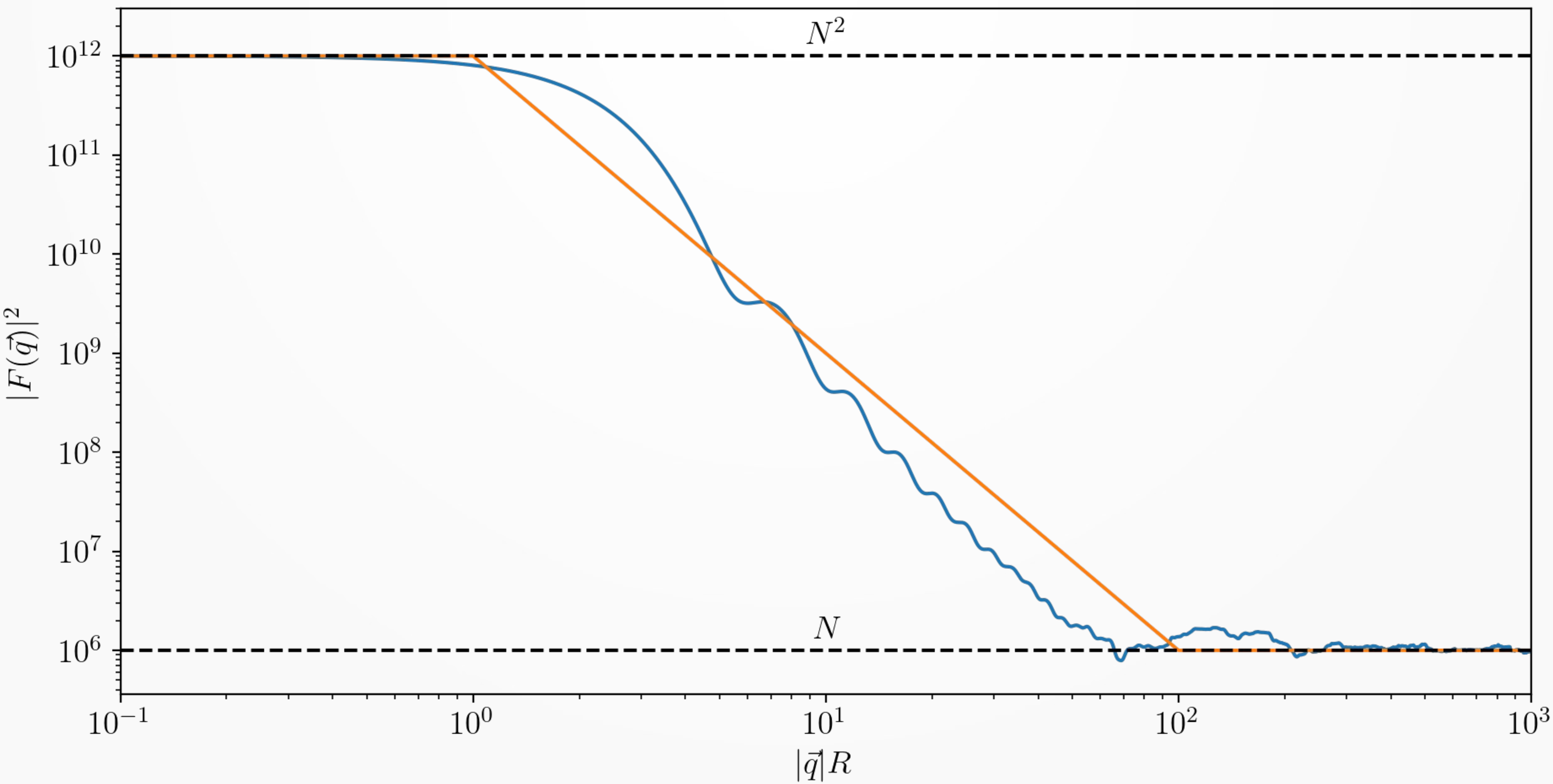
$$|\mathcal{M}|^2 \propto \left| \sum_i e^{-i(\vec{q}\cdot\vec{x}_i)} \right|^2$$

- Small momentum transfer, $\langle q \rangle^{-1} \ll \langle x_i \rangle$:

$$\left| \sum_i e^{-i(\vec{q}\cdot\vec{x}_i)} \right|^2 \to N_T^2$$

[6] M. Bauer, JS, JCAP **01** (2023), 003

Coherent scattering



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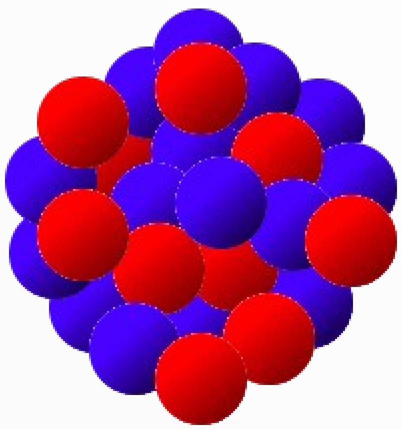
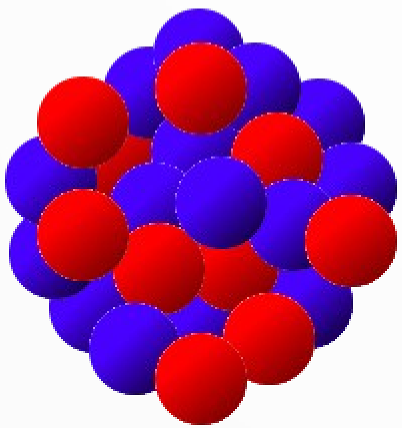
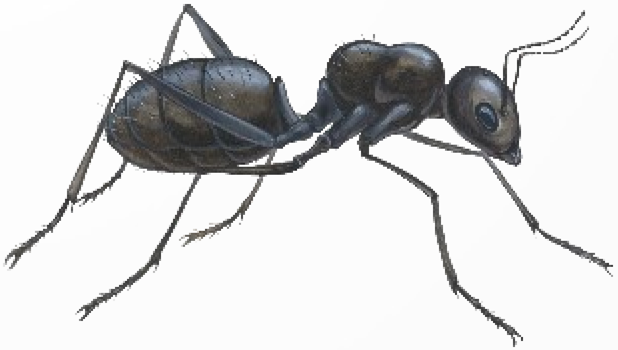


$$\lambda \sim \mathrm{fm}$$

$$\Gamma \sim (A - Z)^2$$

Coherent scattering





$\lambda \sim \text{fm}$

$\lambda \sim \text{mm}$

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$\Gamma \sim N_A^2$

Coherent scattering

- Recall from last lecture:

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Coherent scattering

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- Per mole of target:

$$\Gamma_{\mathrm{incoh}} \simeq 10^{-16}\,\mathrm{y}^{-1} \qquad \Gamma_{\mathrm{coh}} \simeq 10^{7}\,\mathrm{y}^{-1}$$

Coherent scattering

- Recall from last lecture:

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- For a typical setup:

$$\Gamma_{\mathrm{coh}} \sim \mathcal{O}(\mathrm{kHz})$$

Coherent scattering

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$$\frac{\Gamma}{N_T} \simeq 10^{-39}\,\mathrm{y}^{-1}$$

- For a typical setup:

$$\Gamma_{\mathrm{coh}} \sim \mathcal{O}(\mathrm{kHz})$$

- So why don't we see anything?

Coherent scattering

- Relic neutrinos are cold and light:

$$\langle p_\nu \rangle \simeq 0.5\,\mathrm{meV}$$

Coherent scattering

- Relic neutrinos are cold and light:

$$\Delta p_\nu \sim \beta_\oplus E_\nu$$

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Coherent scattering

- Relic neutrinos are cold and light:

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- Torsion balance [7]:

$$a_\nu \simeq 10^{-28} \left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)^2 \mathrm{cm\,s^{-2}}$$

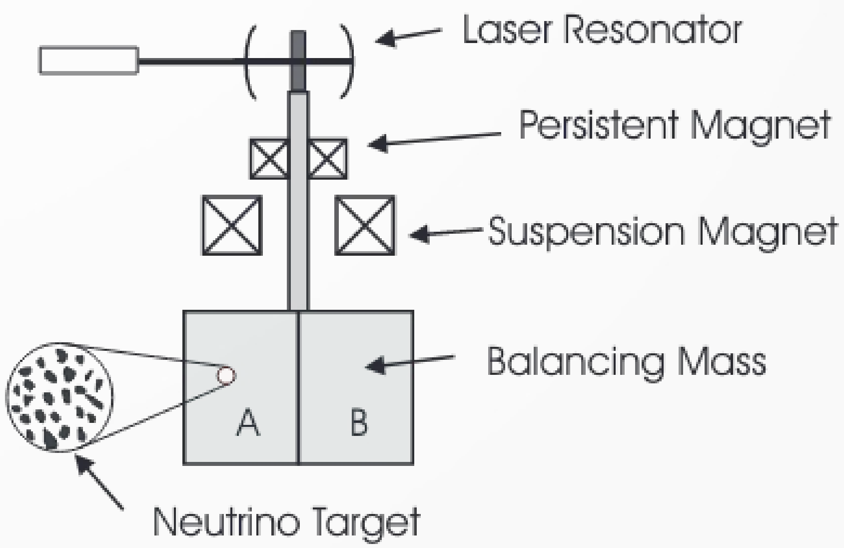

Fig: C. Hagmann, arXiv:astro-ph/9905258

[7] JS, JCAP **11** (2021), 052

Coherent scattering

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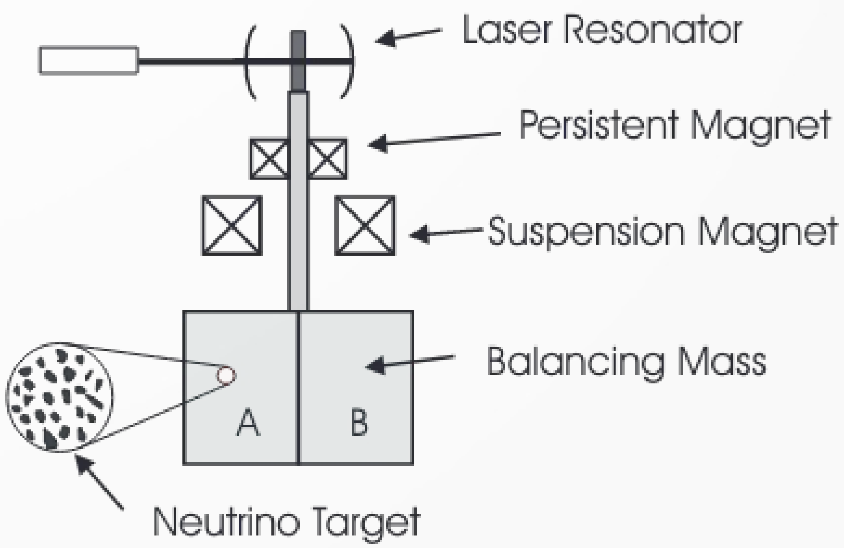

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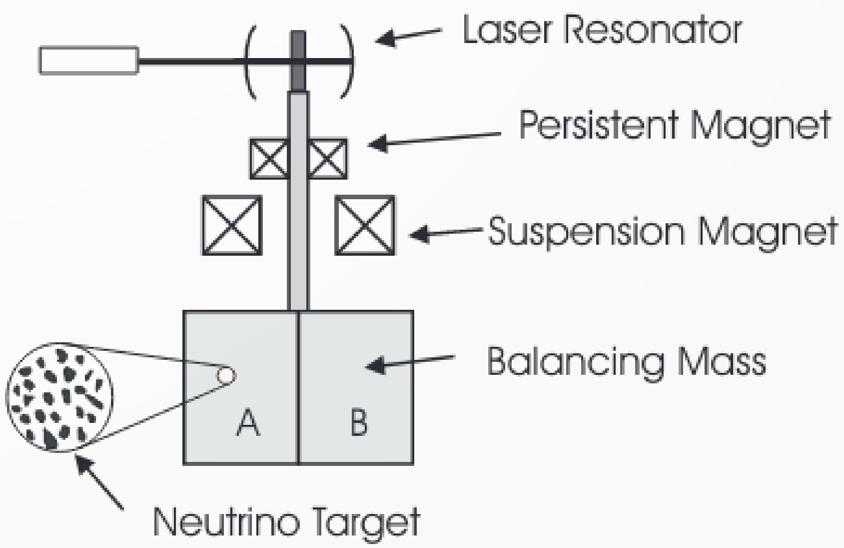

Fig: C. Hagmann, arXiv:astro-ph/9905258

[7] JS, JCAP **11** (2021), 052

Coherent scattering

- Majorana neutrinos:

$$\sigma_M \sim (2 - \beta_\nu^2)\sigma_D$$

Coherent scattering

- Majorana neutrinos:

$$\sigma_M \sim (2 - \beta_\nu^2)\sigma_D$$

- Should be sensitive to Majorana neutrinos!

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Stodolsky effect

- Stodolsky effect (Stodolsky '75, Duda '01, JS '23)

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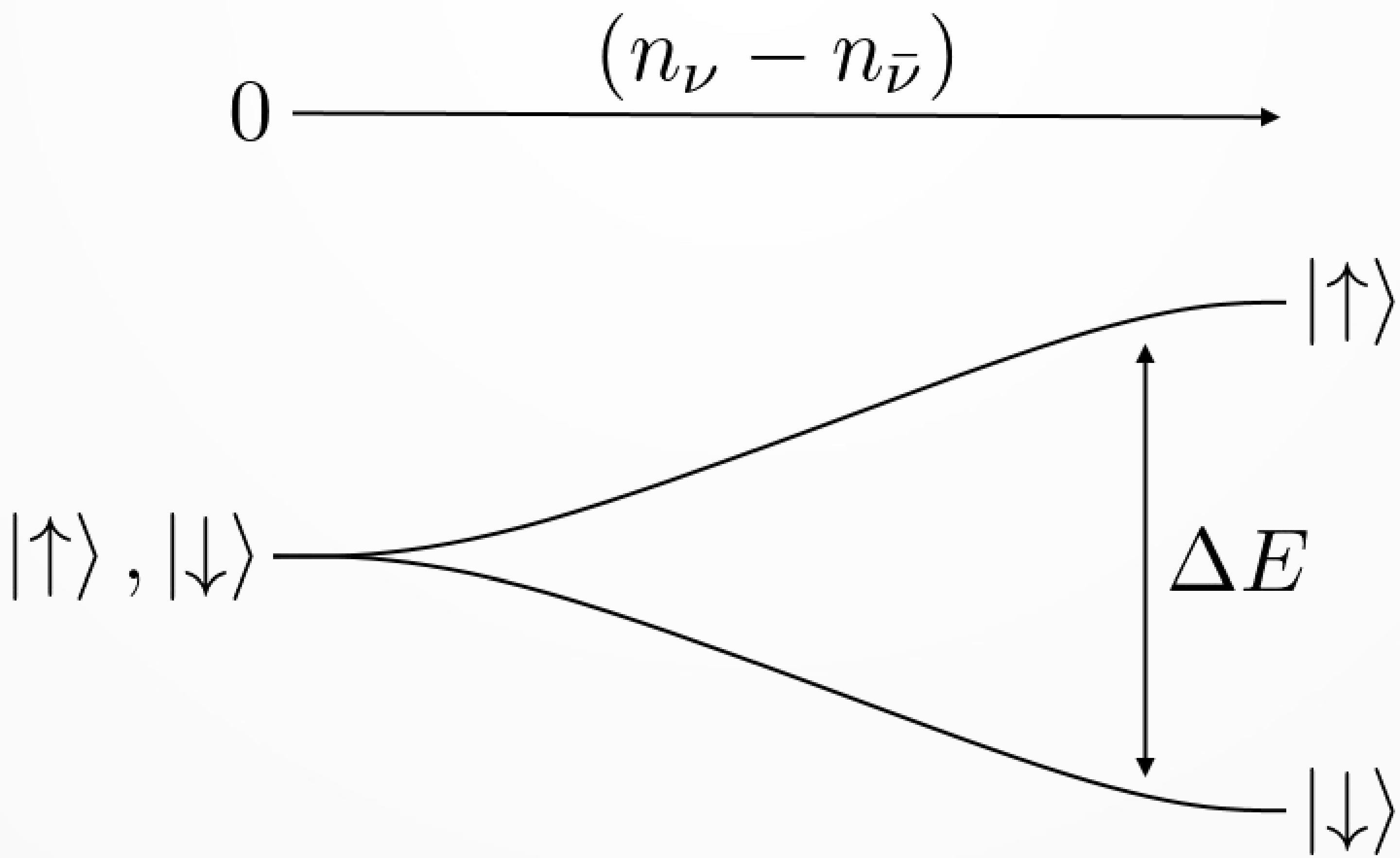
- Analogous to the Zeeman effect

Stodolsky effect

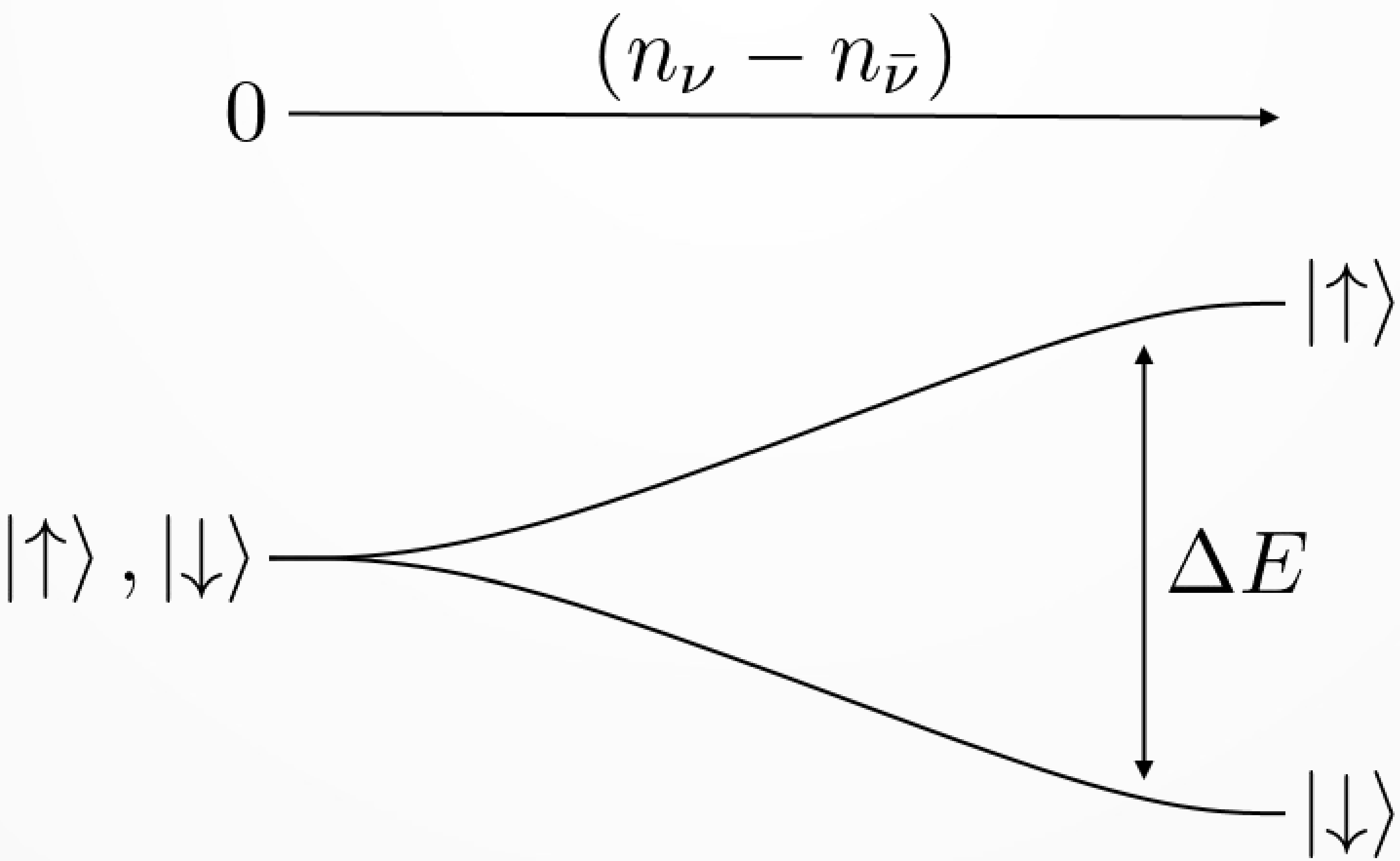
- Stodolsky effect (Stodolsky ‘75, Duda ‘01, JS ‘23)
- Analogous to the Zeeman effect
- Only* effect linear in G_F (Cabibbo ‘82, Langacker ‘83)

Stodolsky effect



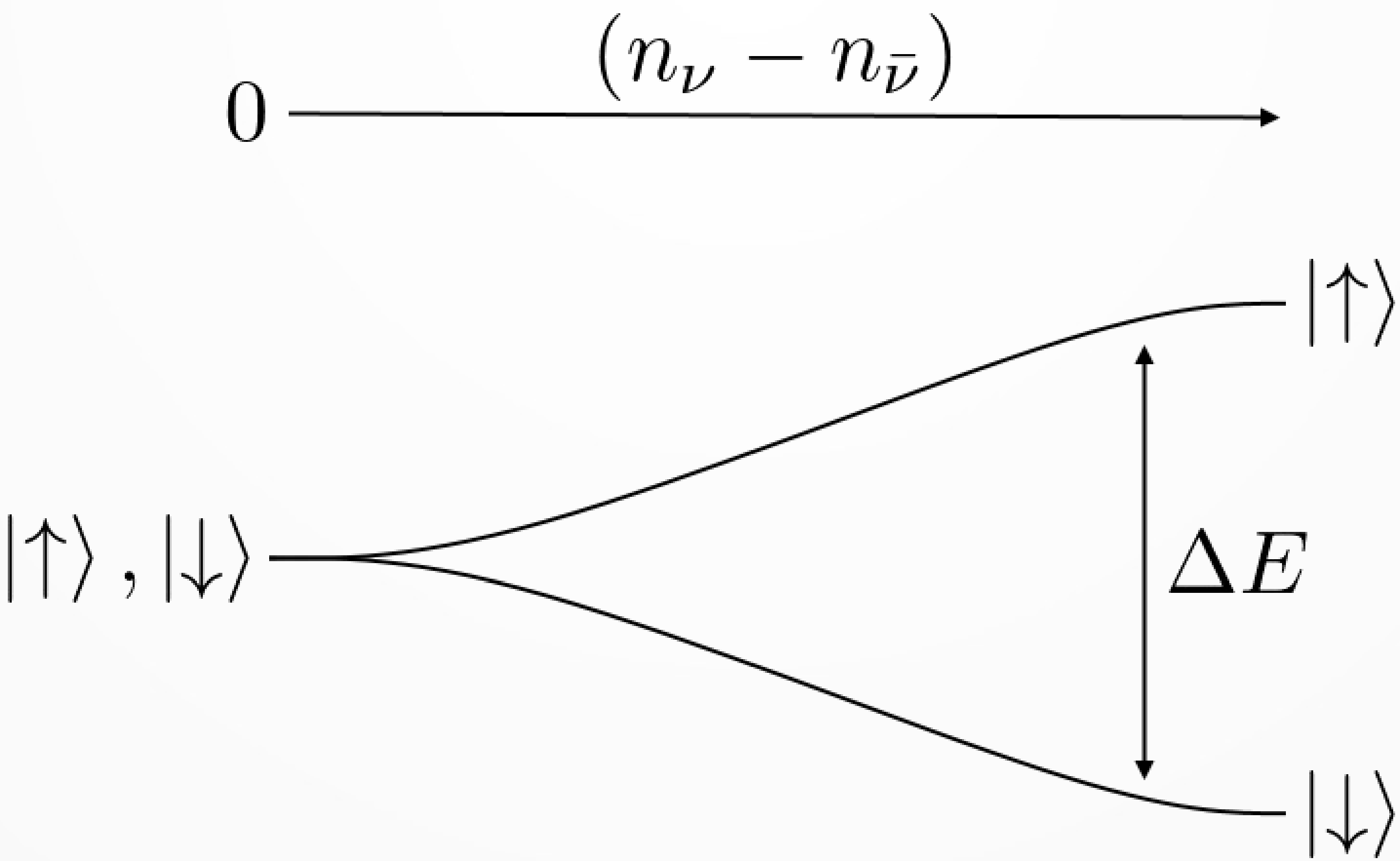
$$\Delta E \sim G_F \beta_\oplus (n_\nu - n_{\bar{\nu}})$$

Stodolsky effect



$$\Delta E \sim 10^{-38} \delta_\nu \, \mathrm{eV}$$

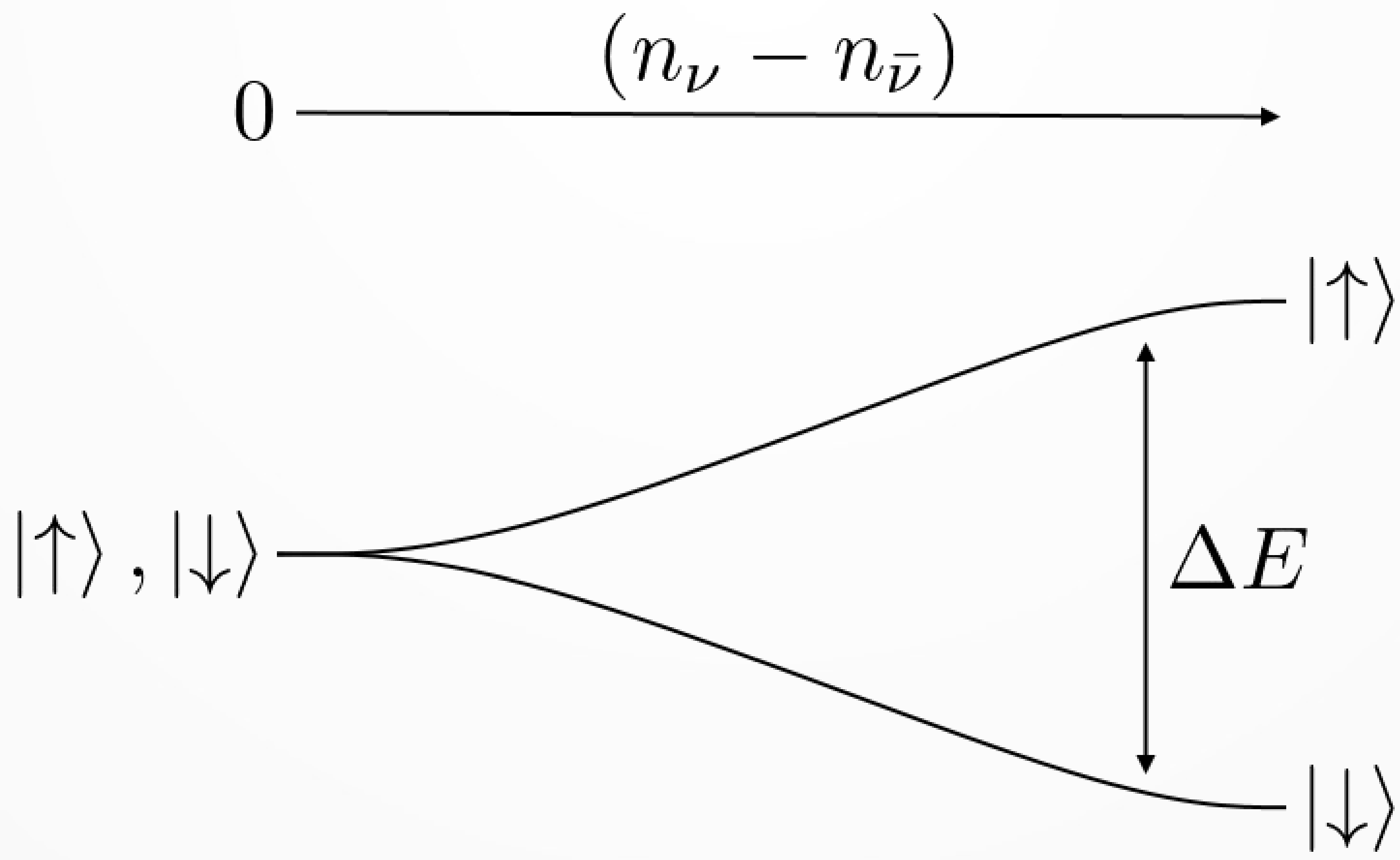
Stodolsky effect



$\Delta E \sim 10^{-38} \delta_\nu \, \mathrm{eV}$

$\Delta E_B \sim 10^{-4} \, \mathrm{eV}$

Stodolsky effect



- Also an effect that depends on helicity asymmetry

Stodolsky effect

- So how do we see it?

Stodolsky effect

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- Hamiltonian picks up spin-dependent terms:

$$H = H_0 + H_S$$

Stodolsky effect

- So how do we see it?
- Spin precession:

$$\frac{dS_\perp}{dt} = i[H, S_\perp] \neq 0$$

Stodolsky effect

- Two observables:

- Torque [8]:

$$\tau \simeq \Delta E$$

[8] G. Rostagni, JS, JCAP **07** (2023), 018

Stodolsky effect

- Two observables:

- Torque [8]:

$$\tau \simeq \Delta E \longrightarrow a_\nu \simeq 10^{-27} \delta_\nu \, \mathrm{cm\,s^{-2}}$$

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Stodolsky effect

- Two observables:

- Torque [8]:

$$\tau \simeq \Delta E \longrightarrow a_\nu \simeq 10^{-27} \delta_\nu \, \mathrm{cm\,s^{-2}}$$

$$a_{\mathrm{ref}} \simeq 10^{-15} \, \mathrm{cm\,s^{-2}}$$

$$a_{\mathrm{best}} \simeq 10^{-23} \, \mathrm{cm\,s^{-2}}$$

[8] G. Rostagni, JS, JCAP **07** (2023), 018

Stodolsky effect

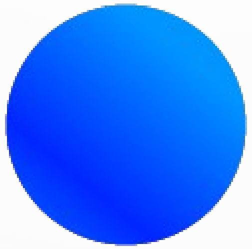
- Two observables:

- Magnetisation [8]:

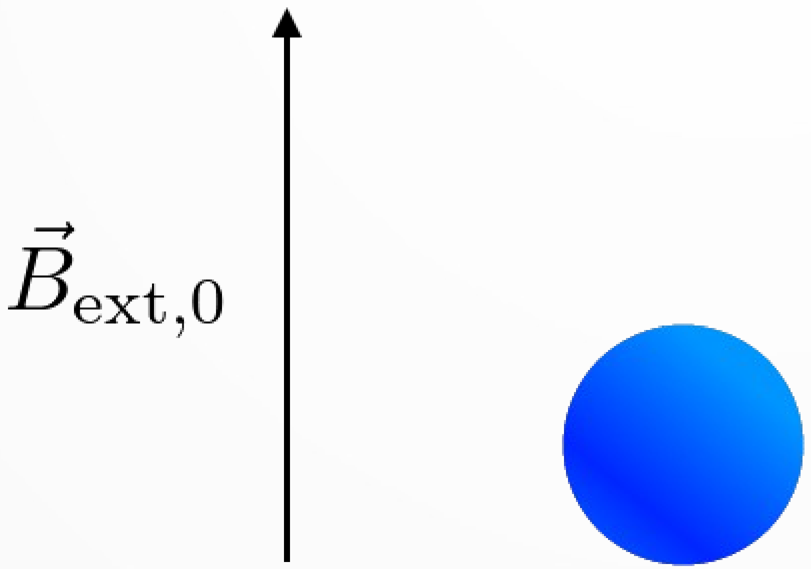
$$\frac{dS_\perp}{dt} \neq 0 \implies \frac{dB_\perp}{dt} \neq 0$$

[8] G. Rostagni, JS, JCAP **07** (2023), 018

Stodolsky effect



Stodolsky effect



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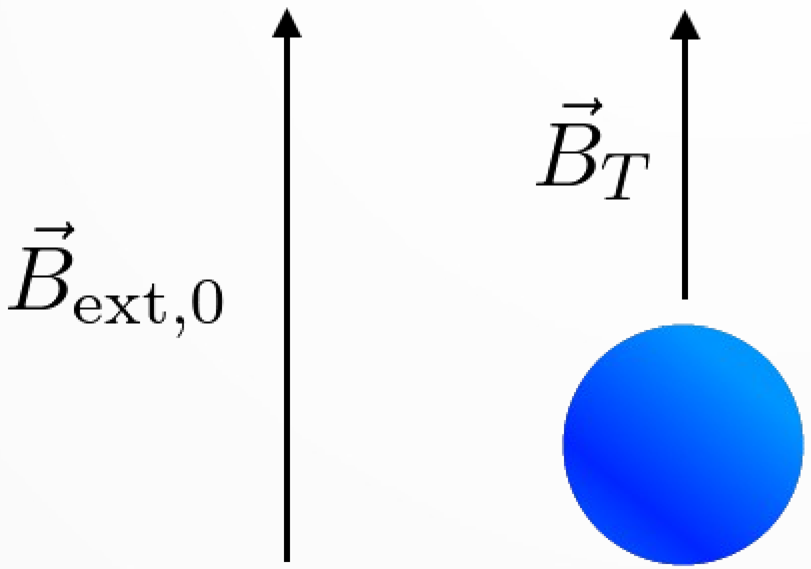

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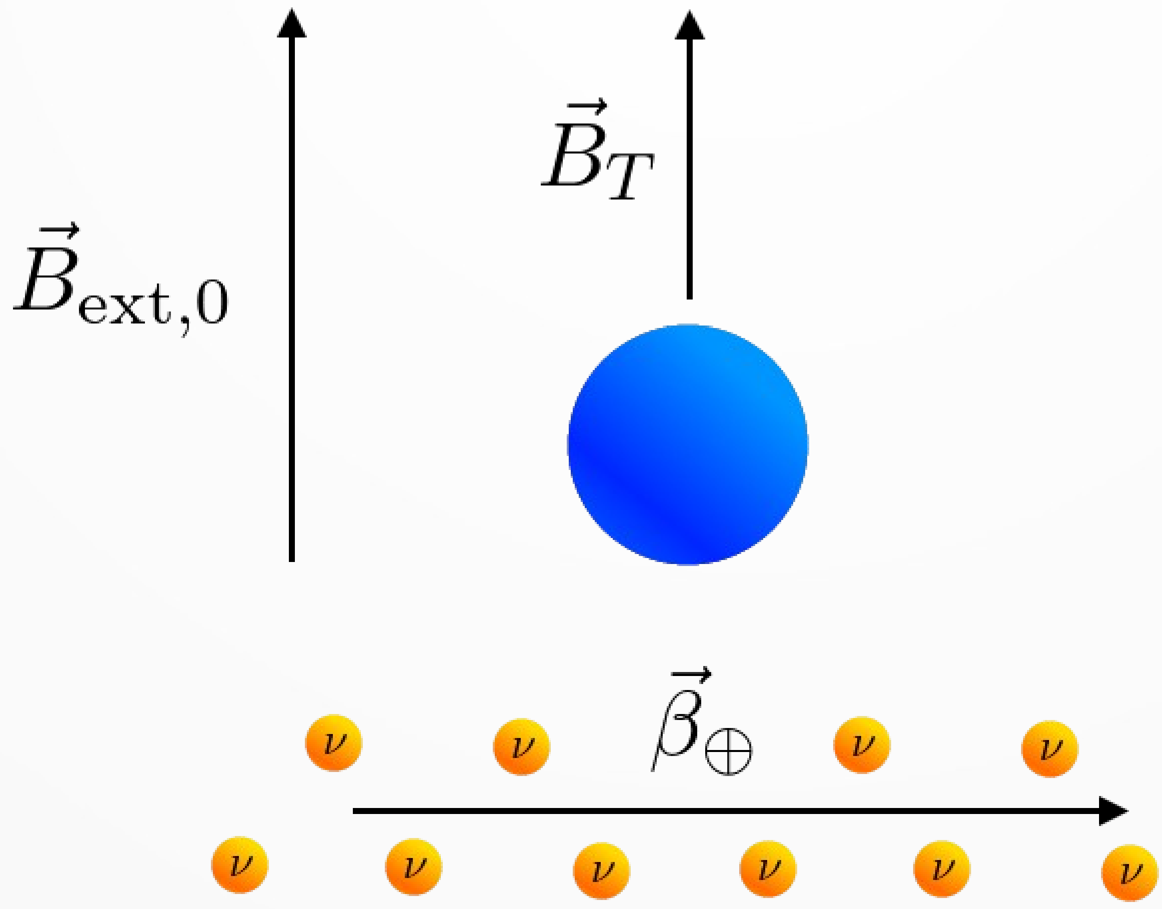

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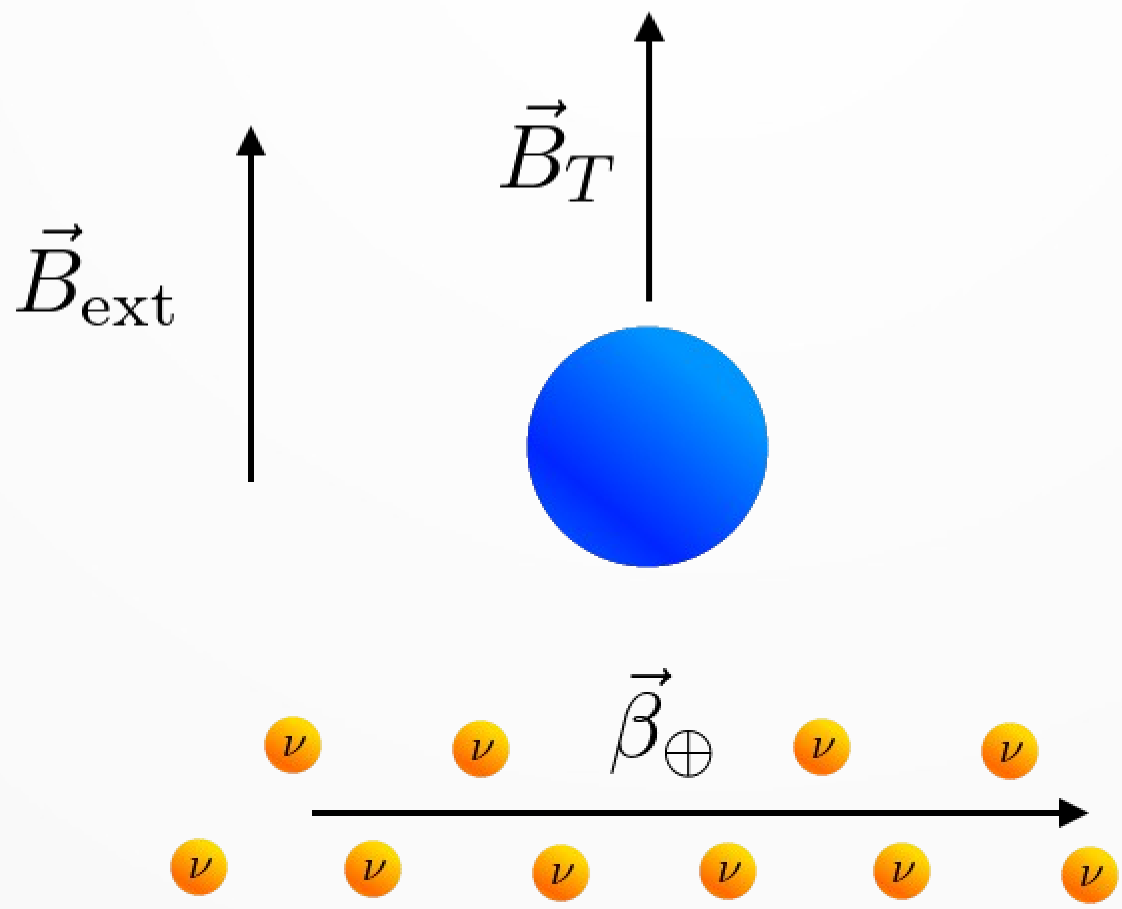
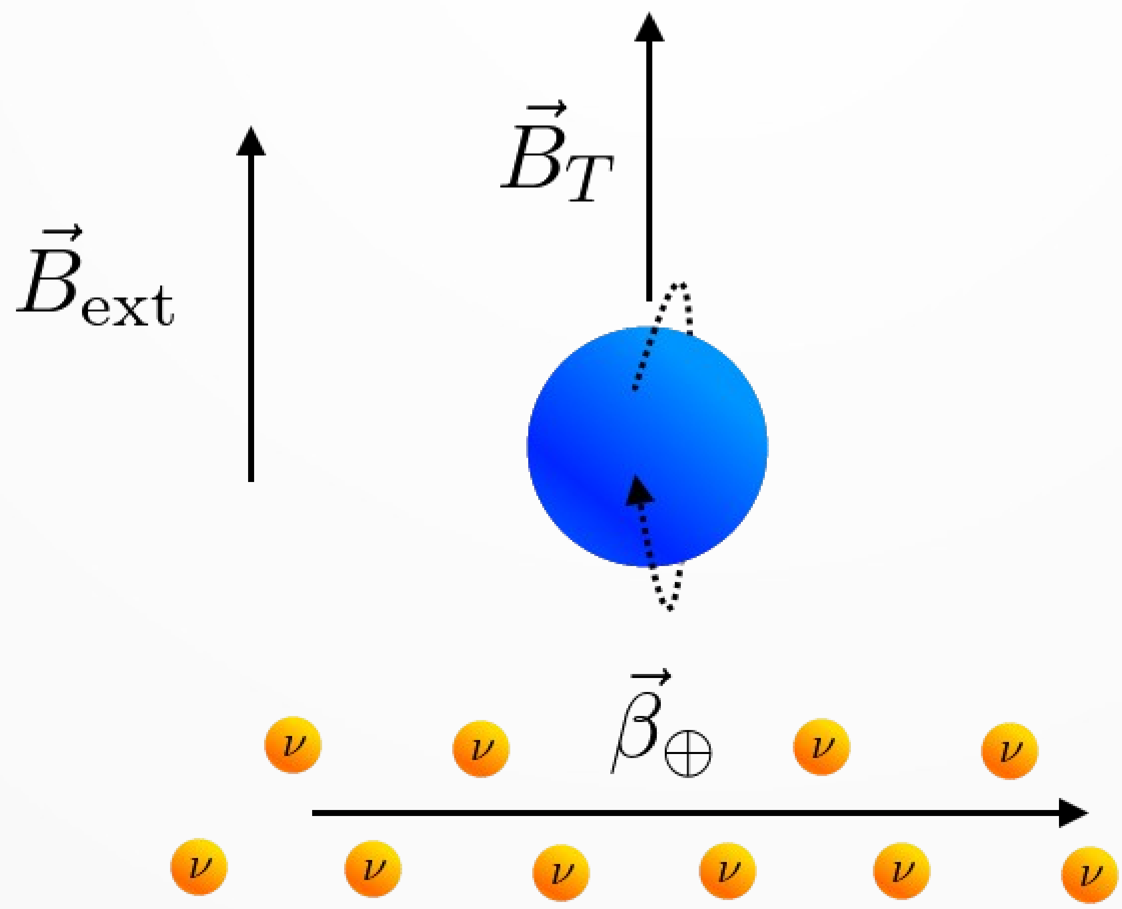


Stodolsky effect



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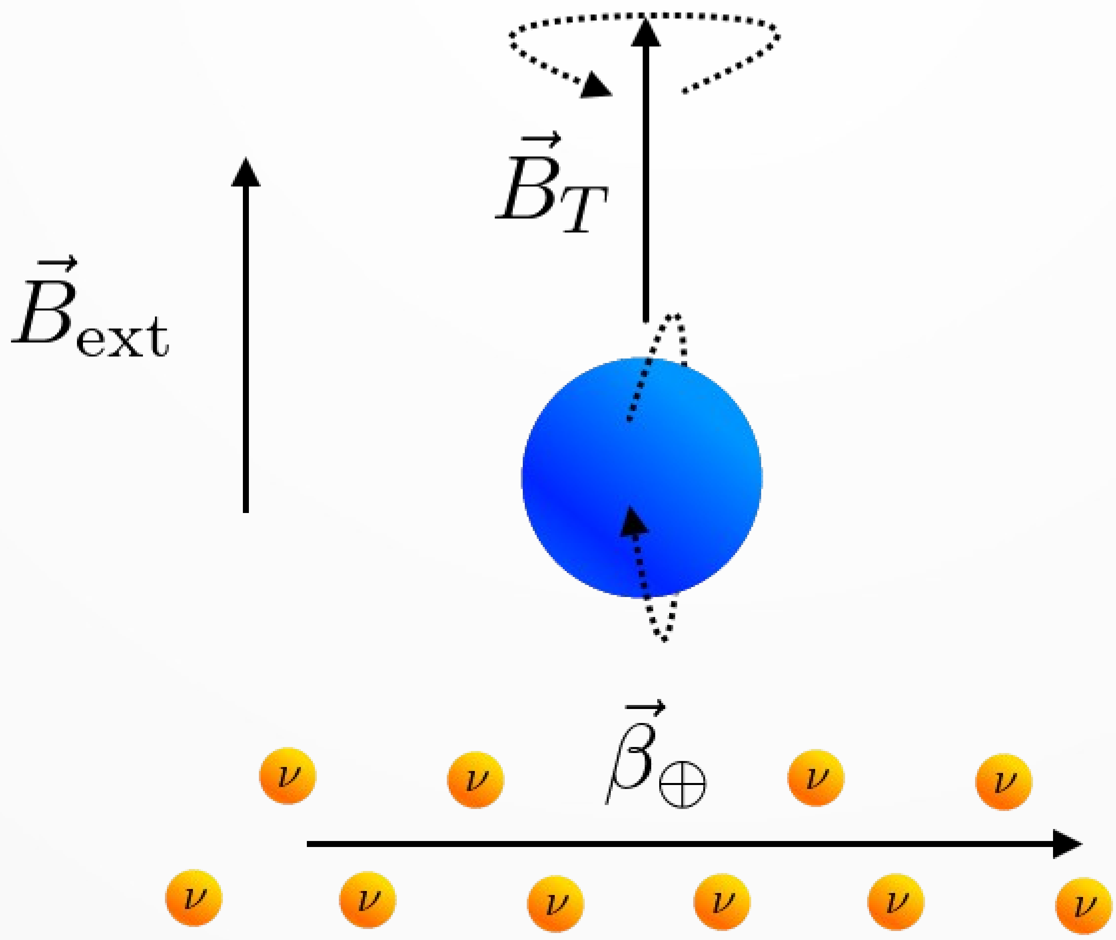

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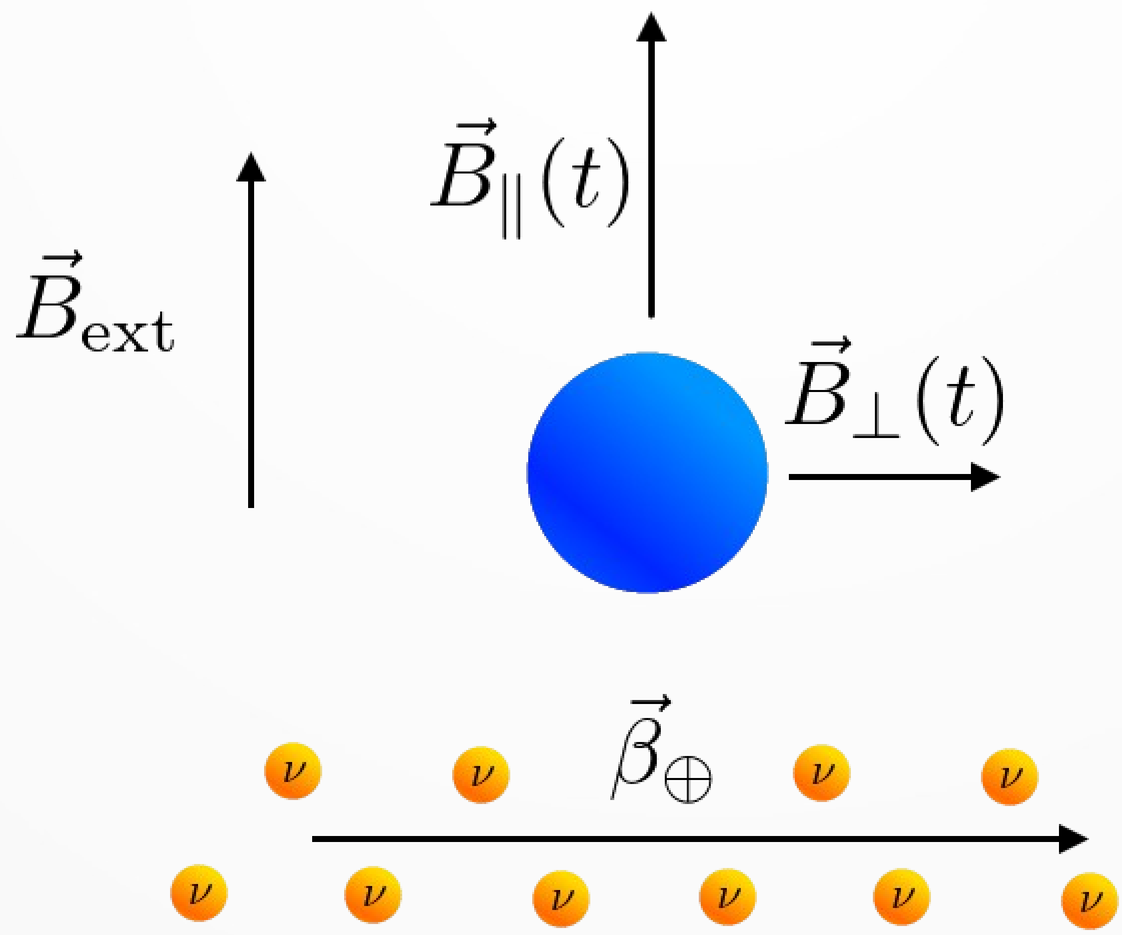

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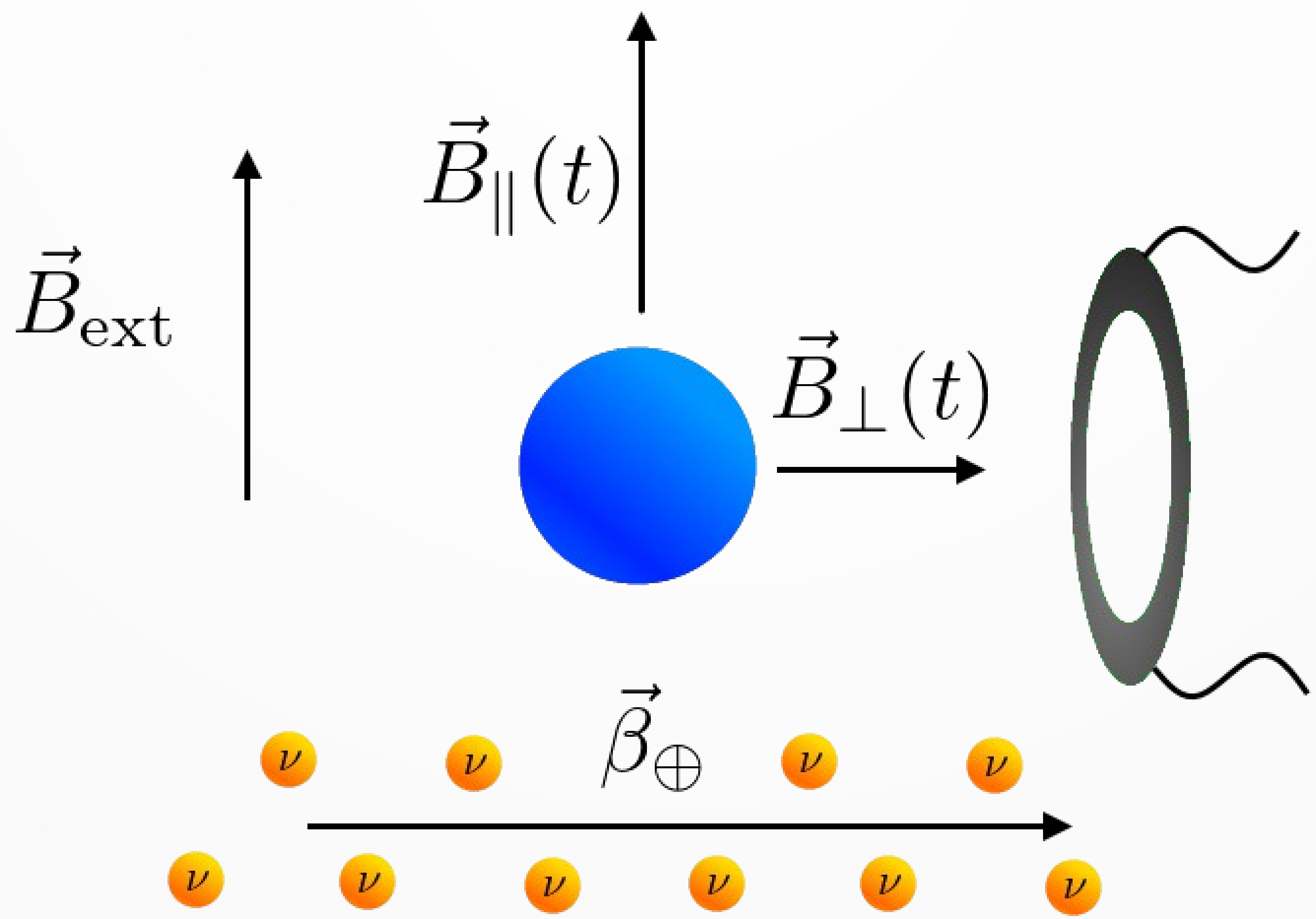

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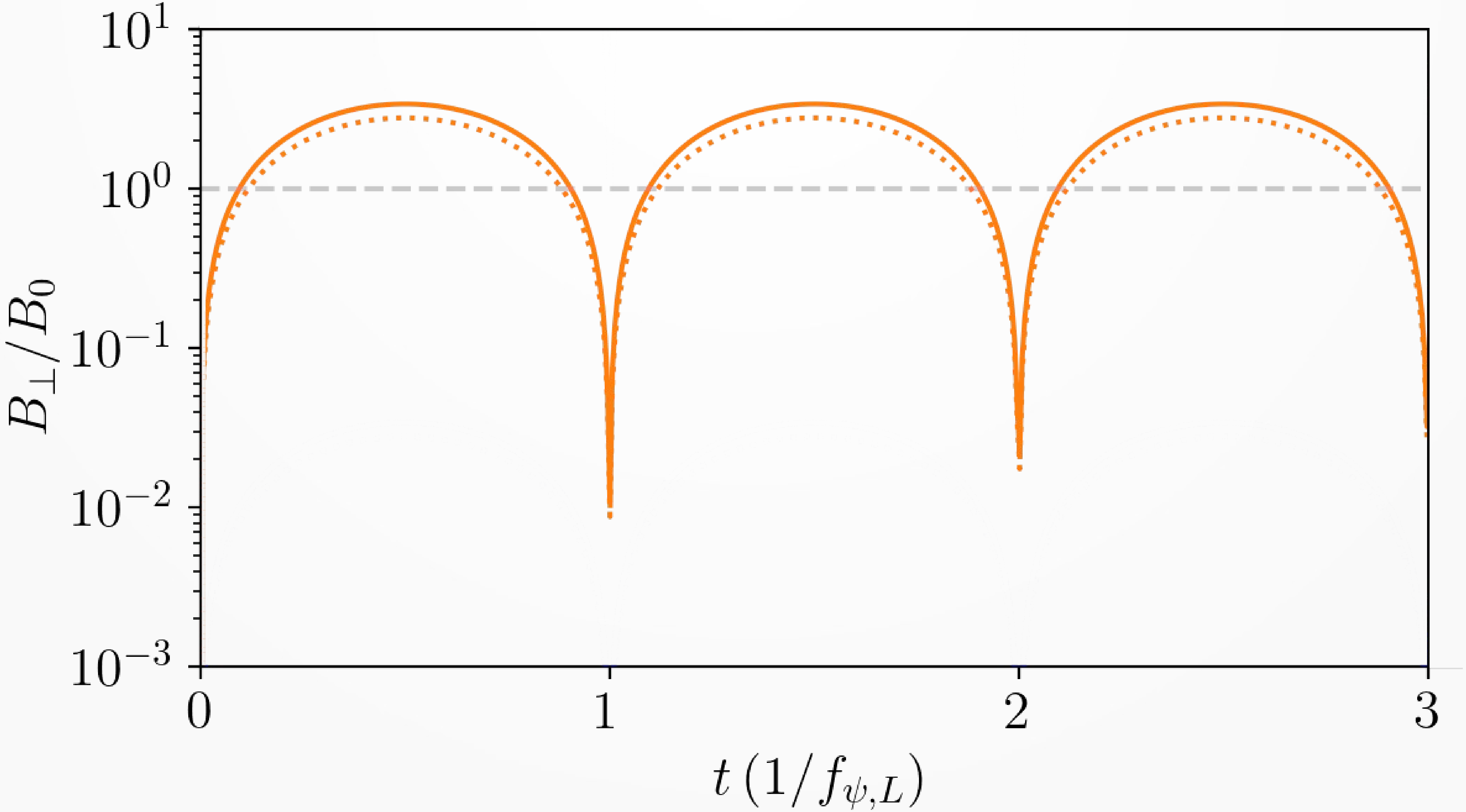

Stodolsky effect

- Two observables:

- Magnetisation [8]:

$$B_\perp \simeq 10^{-25} \delta_\nu \, \mathrm{T}$$

[8] G. Rostagni, JS, JCAP **07** (2023), 018

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- Helicity asymmetry term? 3 orders of magnitude larger!

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Stodolsky effect

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Stodolsky effect

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- Only a problem for very slow neutrinos

Contents

- Recap

- Direct detection proposals:
  - PTOLEMY
  - Coherent scattering
  - Stodolsky effect
  - Accelerator ⇐

Accelerator

- PTOLEMY-on-a-beam?

$$\langle \sigma \beta_\nu \rangle \propto G_F^2 E_e p_e \sim 10^{-45}\,\mathrm{cm}^2$$

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- e.g. Z-resonance: $\nu + \bar{\nu}_{\mathrm{C}\nu\mathrm{B}} \rightarrow Z \rightarrow ?$
- Vastly larger cross section: $\sigma \propto \frac{1}{M_Z^2} \propto G_F$

Accelerator

- Accelerator experiment [9]:

$$^{A}_{Z}P + e^{-}(\text{bound}) + \bar{\nu}_e \rightarrow {}^{A}_{Z-1}D$$

$$^{A}_{Z}P + \nu_e \rightarrow {}^{A}_{Z+1}D + e^{-}(\text{bound})$$

[9] M. Bauer, JS, Phys. Rev. D **104** (2021), 083039

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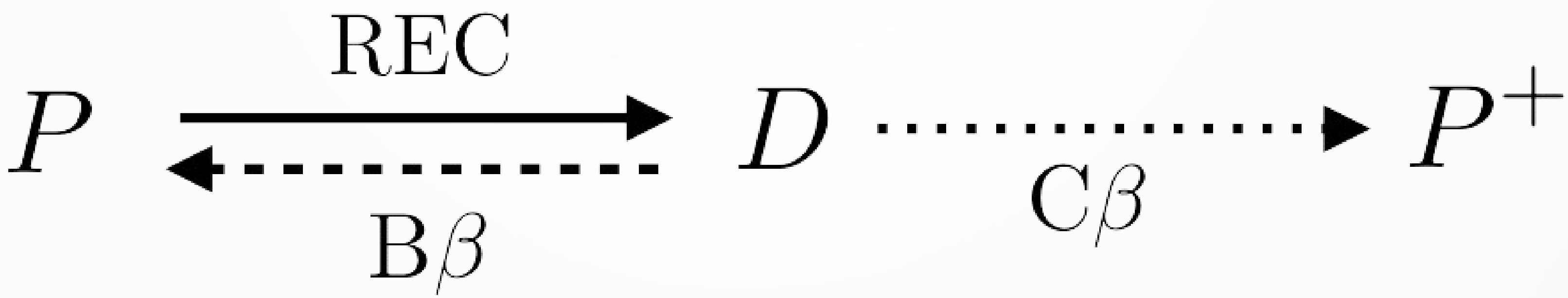
- Resonant electron capture:



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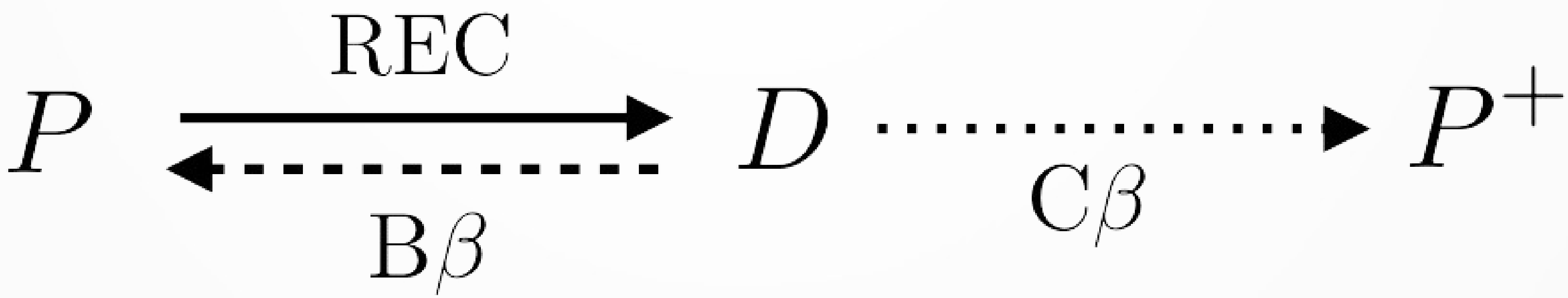
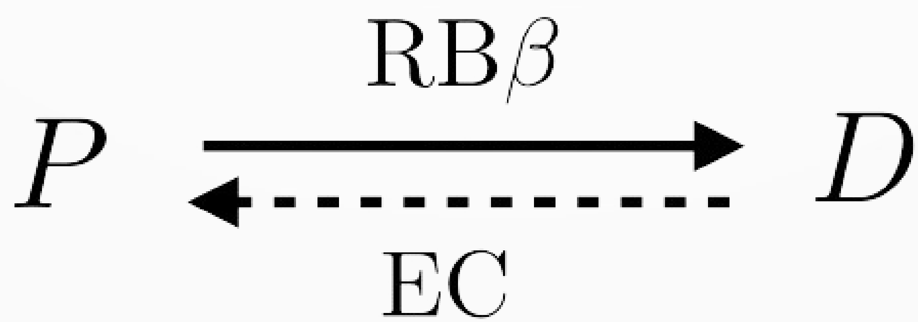


- Resonant bound beta decay:



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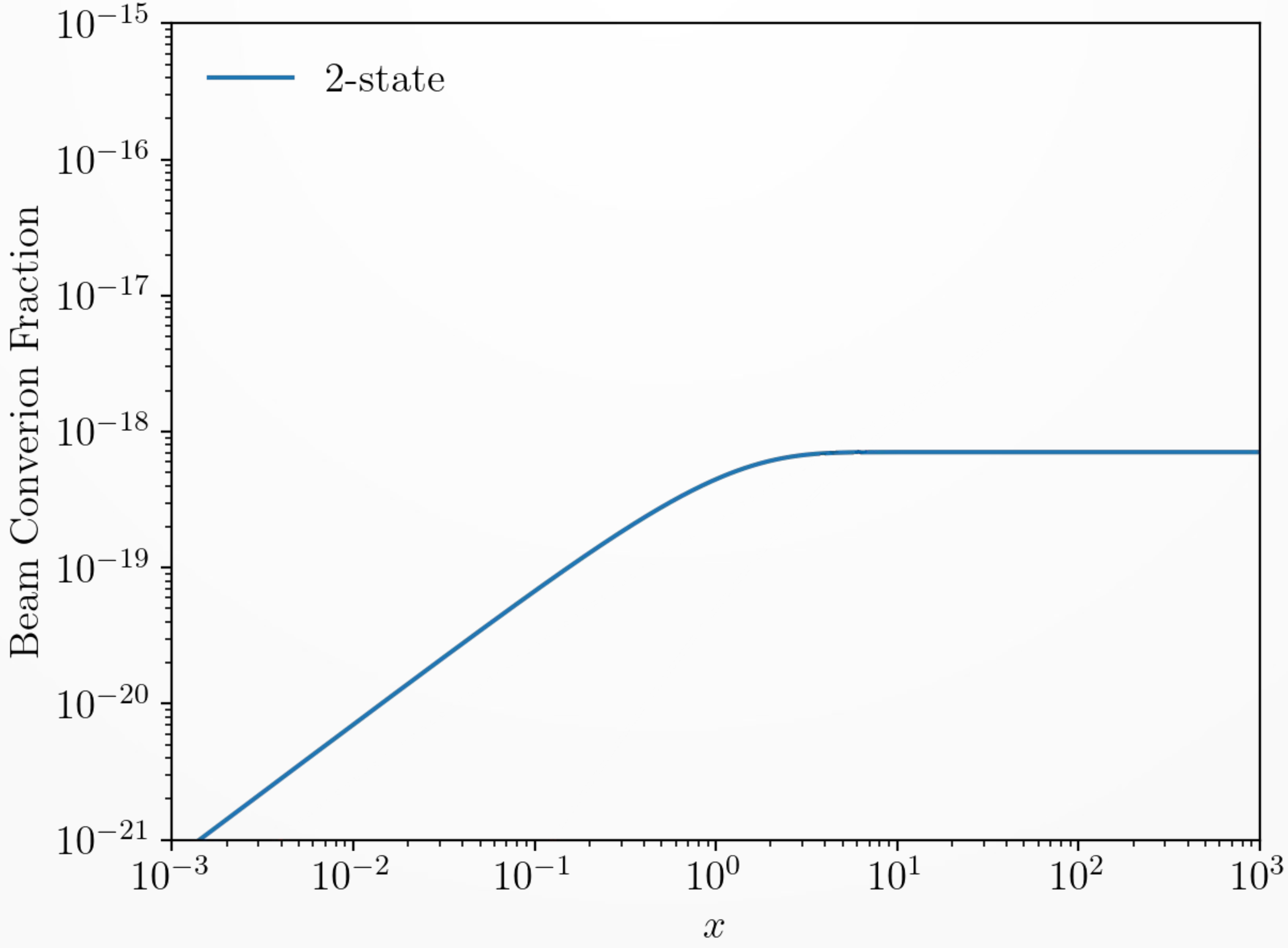

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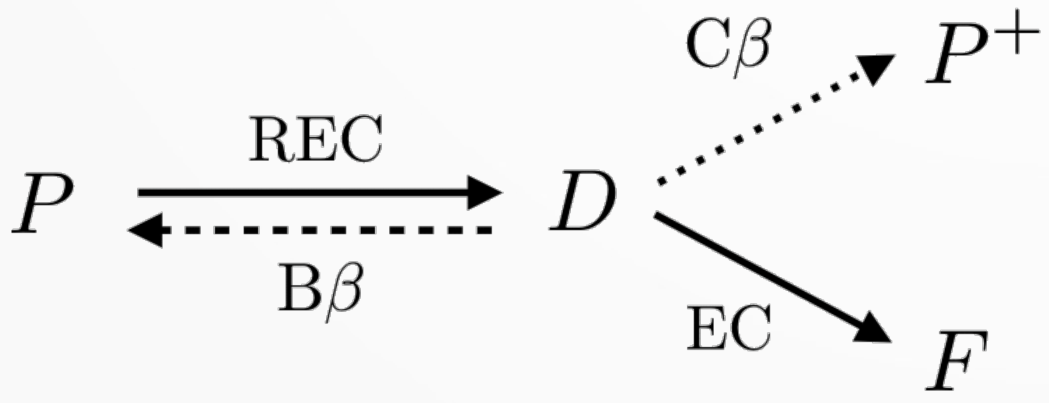

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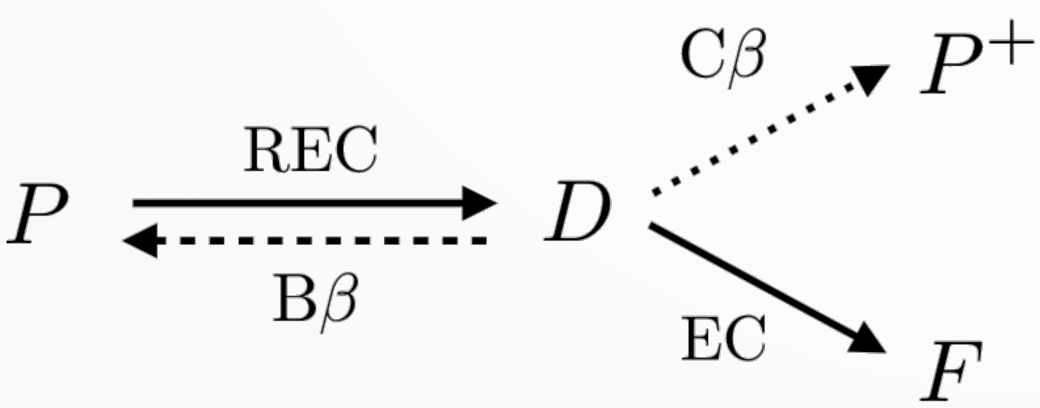

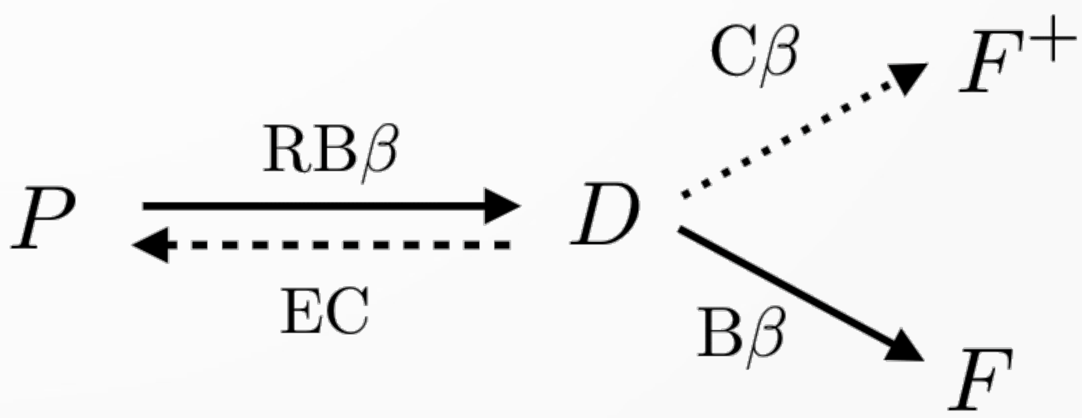

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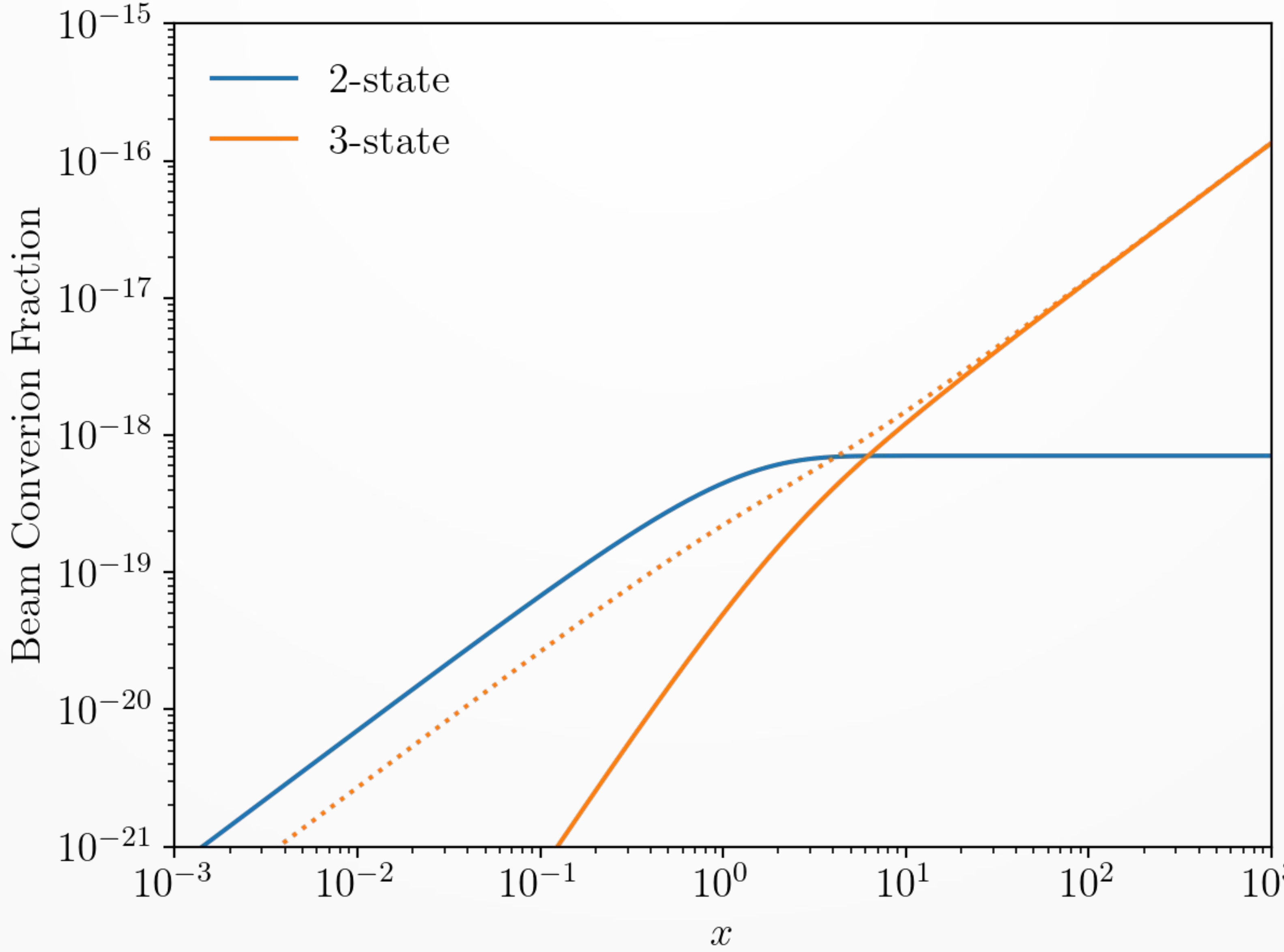

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- In general:

$$N_D \sim \frac{1}{Q^7} \implies Q \sim 0.1\,\mathrm{keV}$$

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Thank you!
Questions?