Hunting for the Cosmic Neutrino Background

Jack Shergold

& Martin Bauer; 2207.12413

JCAP 01 (2023), 003

Contents

- What is the CνB?

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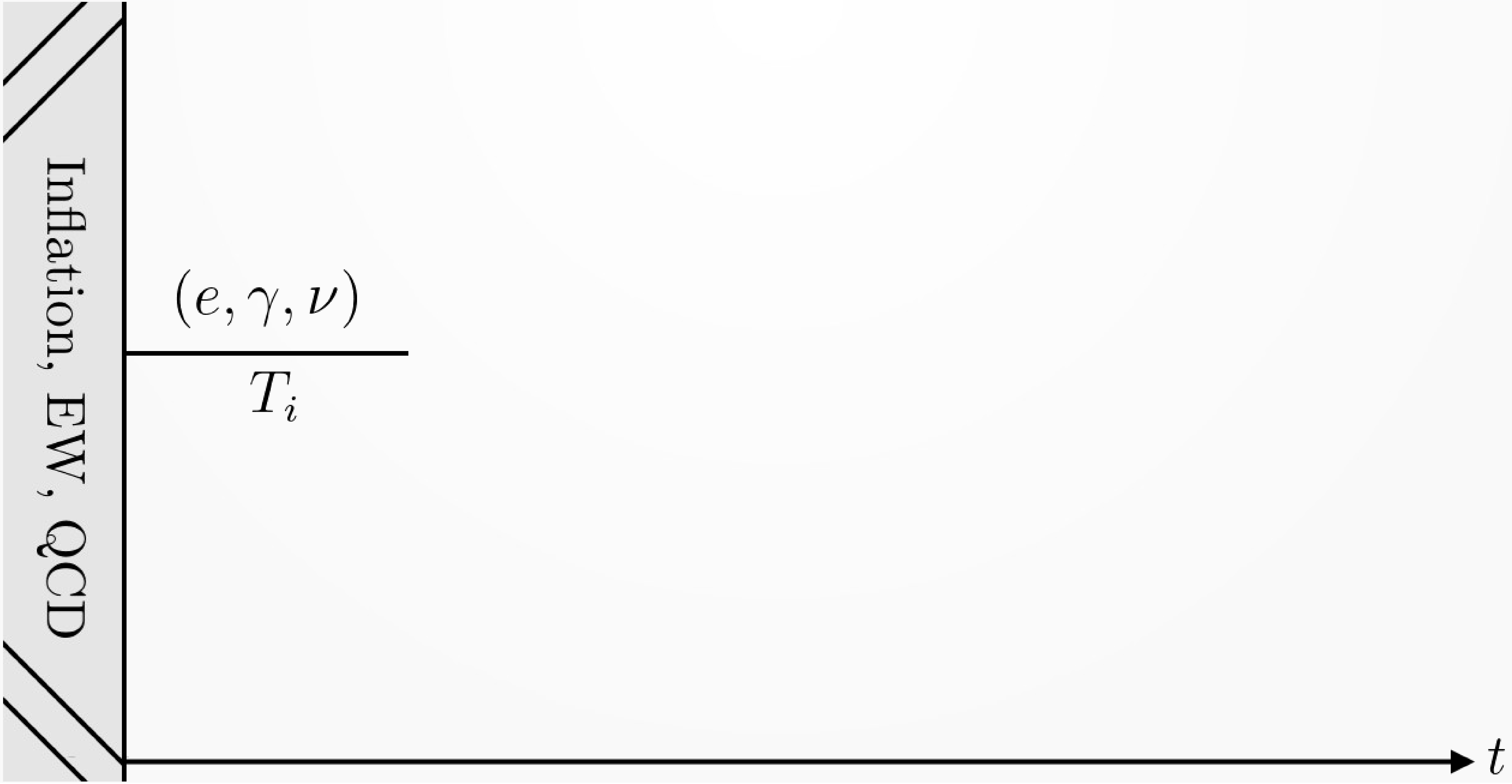
What is the CνB?



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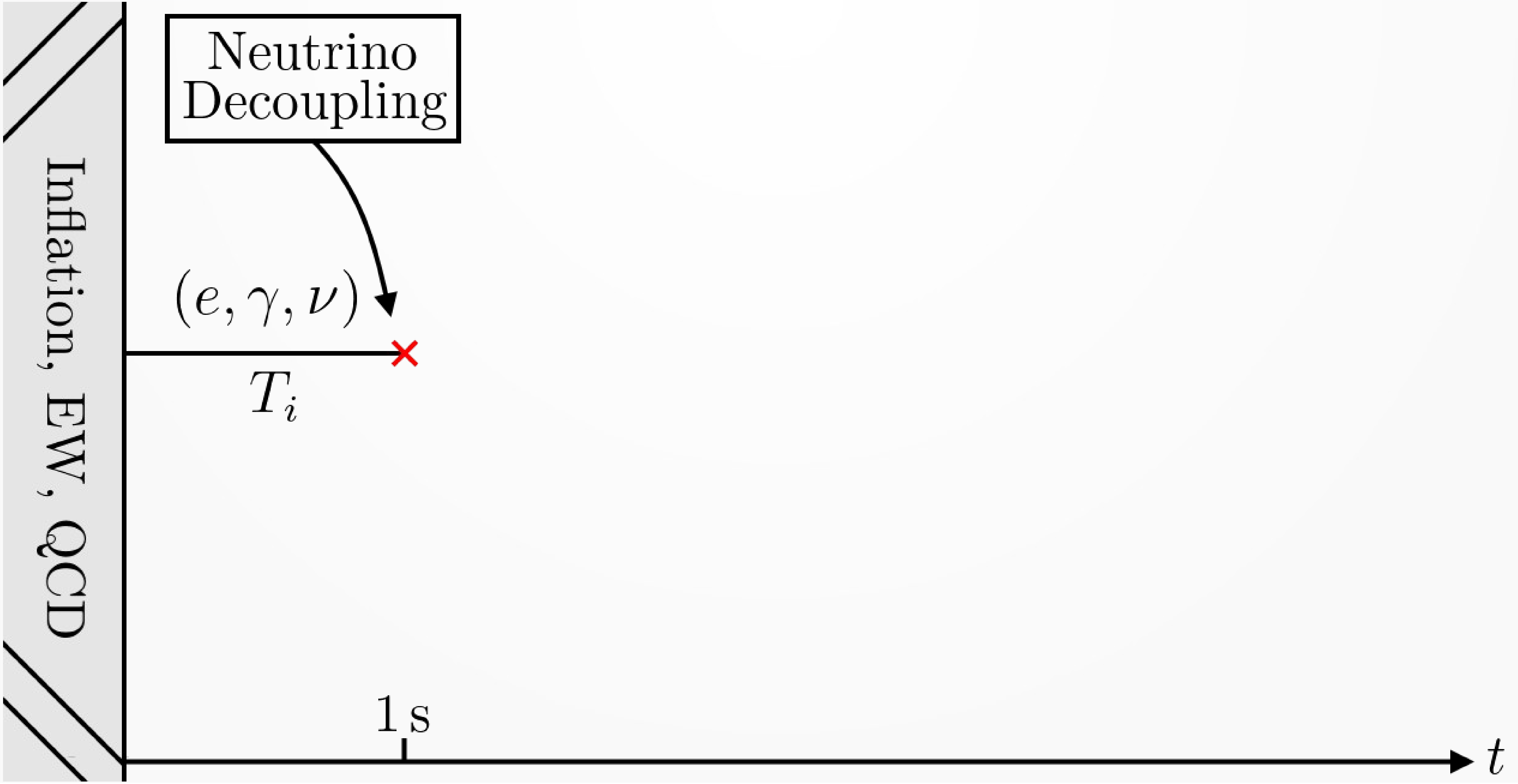

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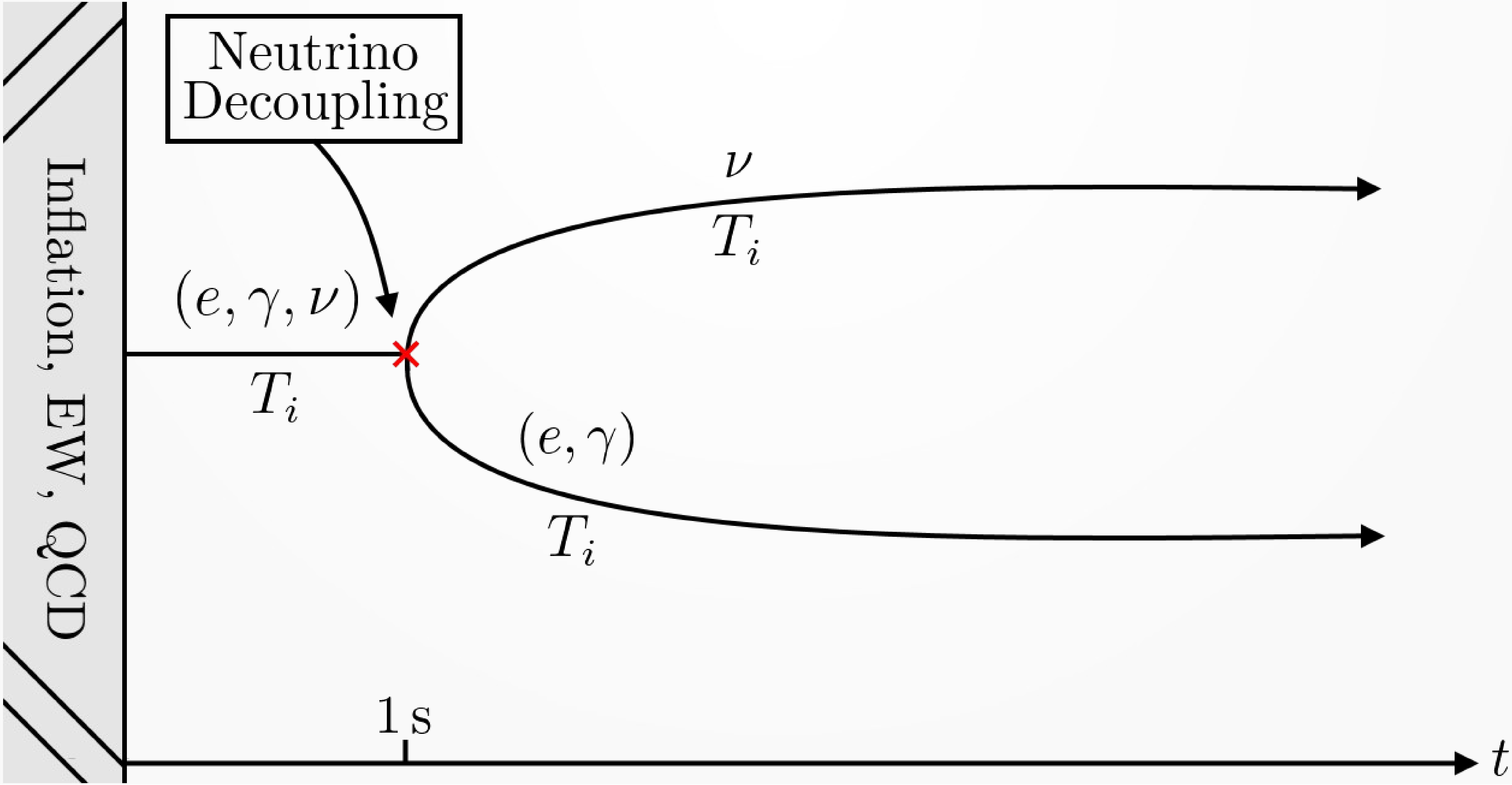

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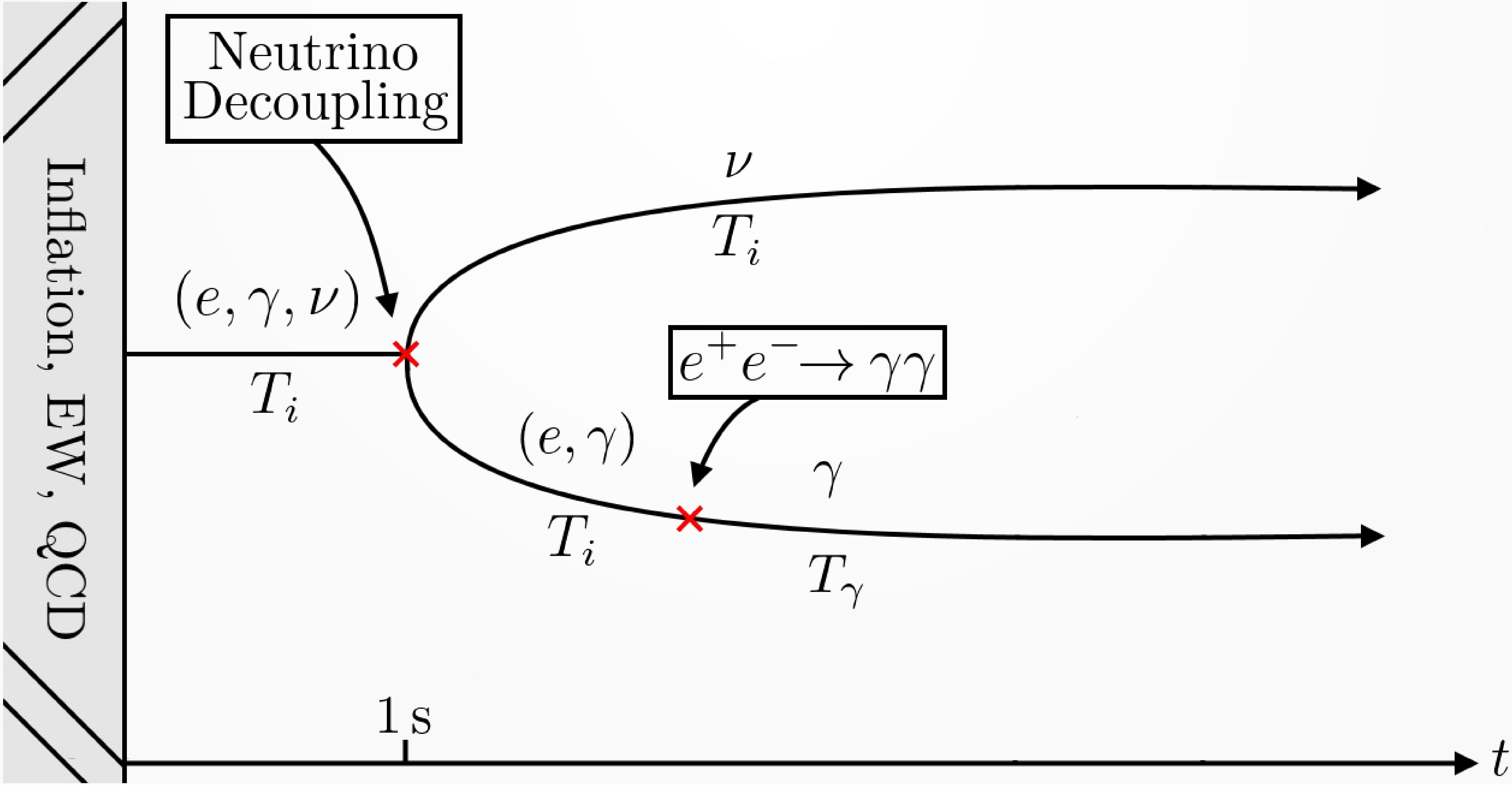

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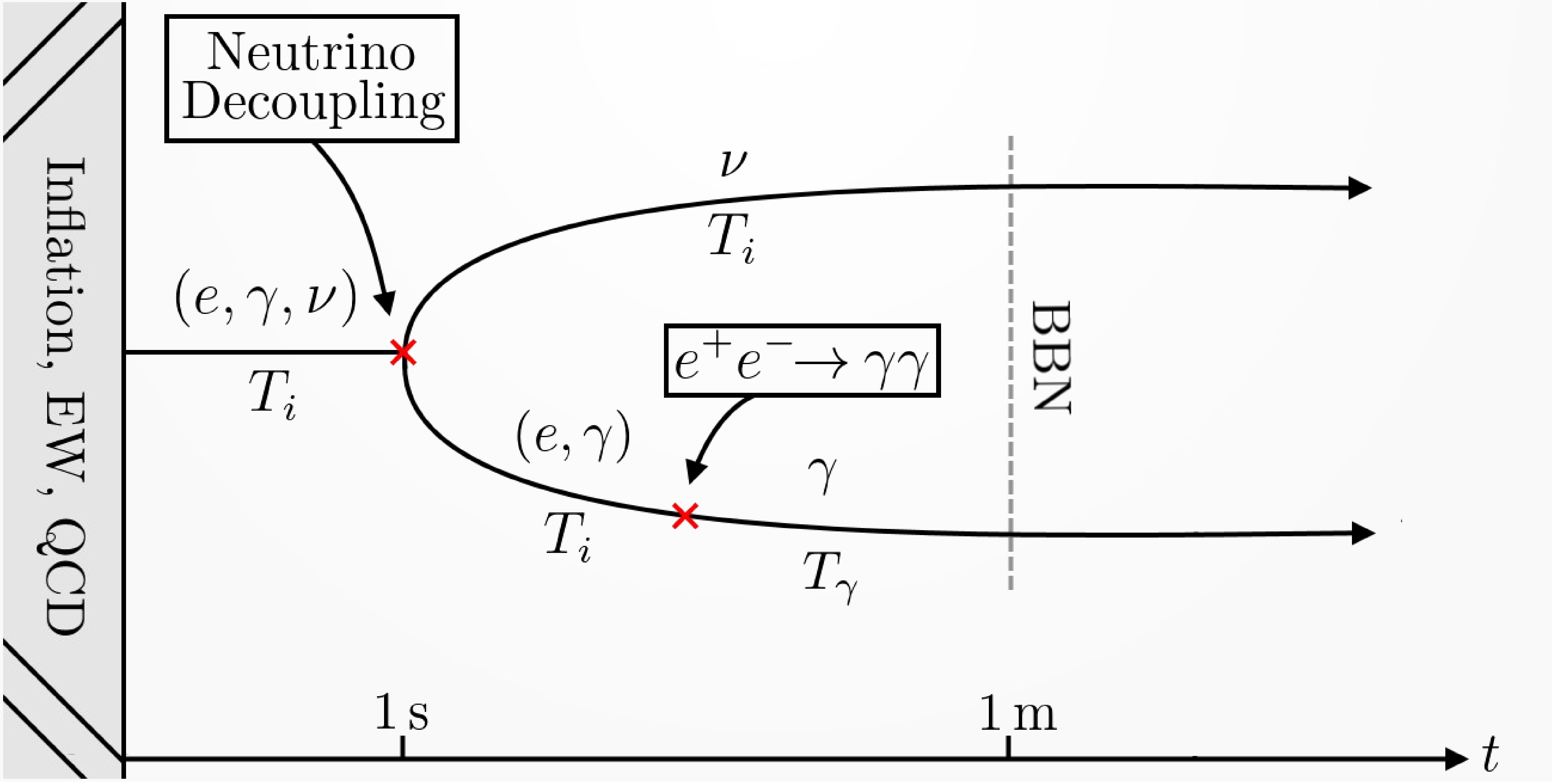

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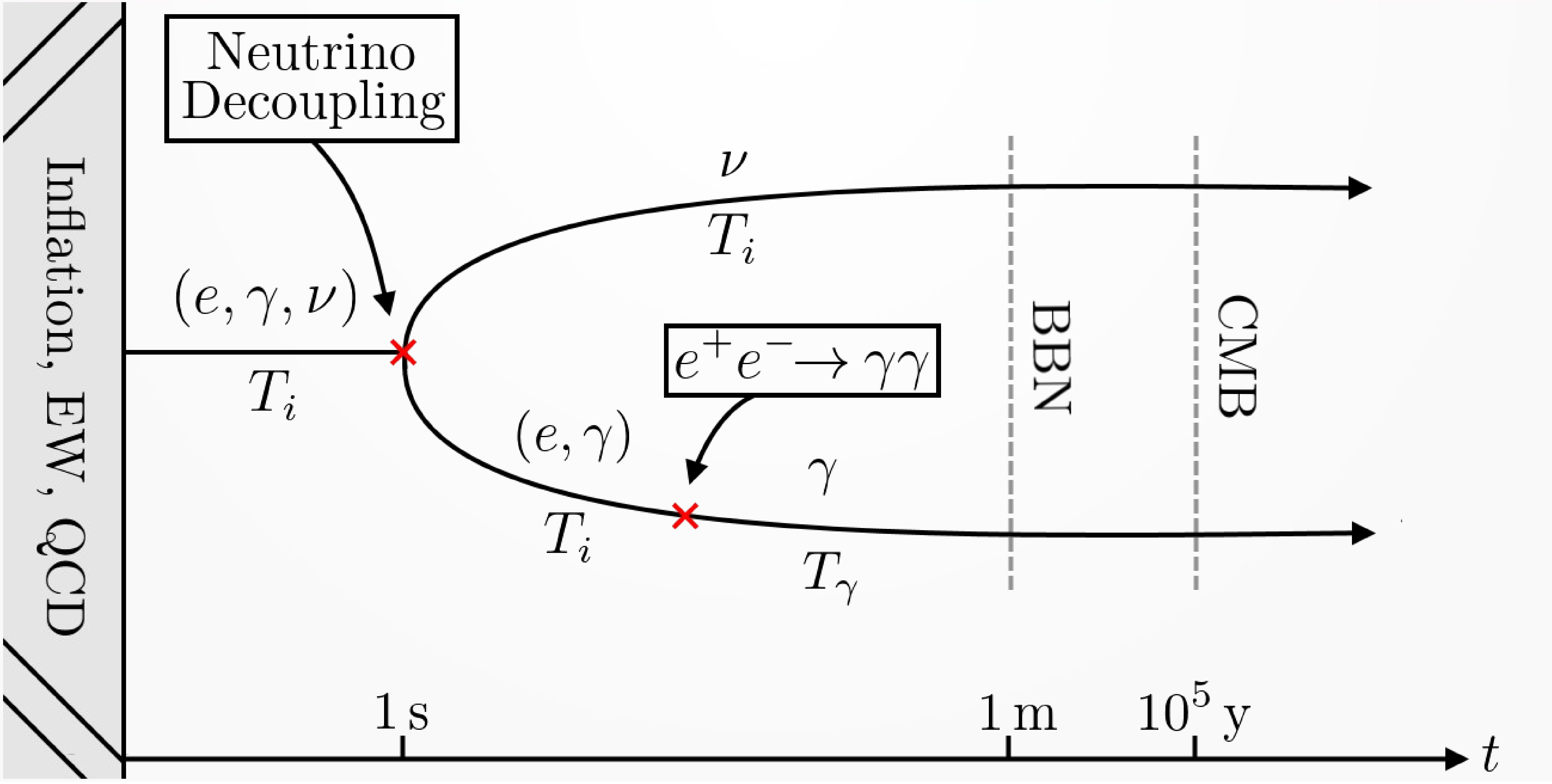

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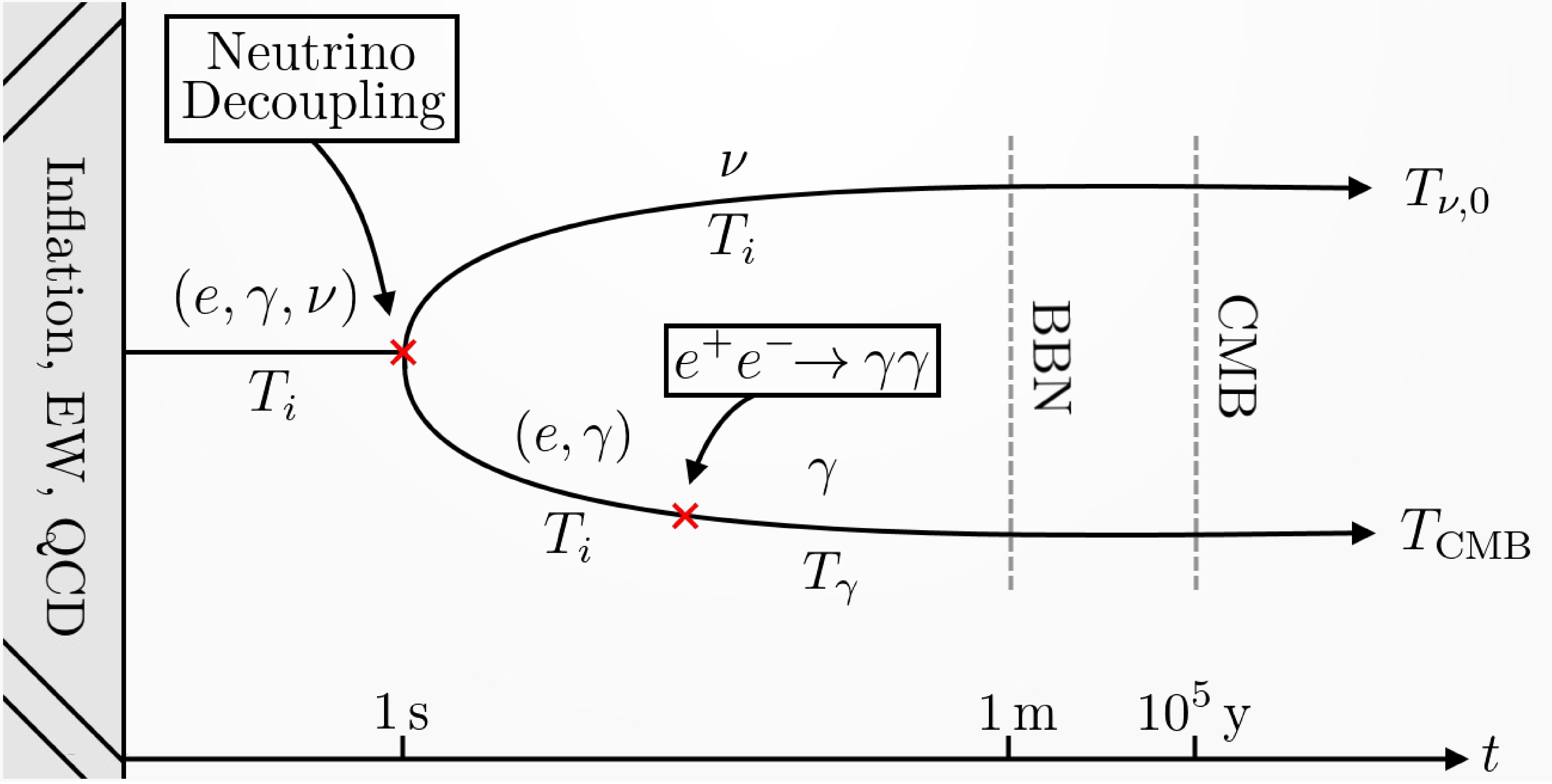

The CνB today

- Redshifted to temperature:

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

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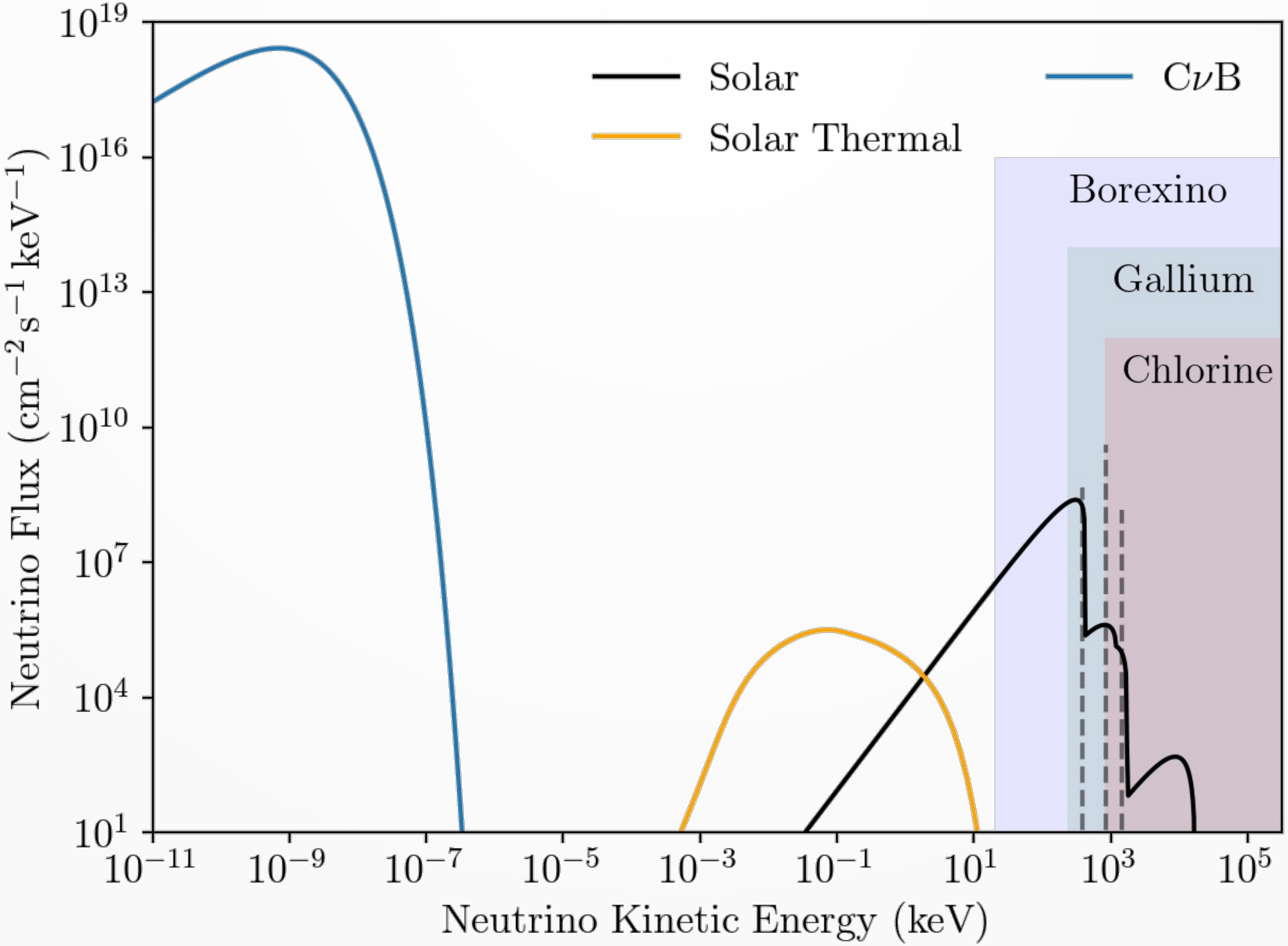
- May be overdense, *e.g.* clustering, decays to neutrinos

The CνB today



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How to detect the CνB

- Threshold:
  -
  -
- Event rate:
  -
  -

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  - Look for thresholdless process
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  - Use a huge number of targets
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- Threshold:
  - Look for thresholdless process
  - Find some way to bridge it

- Event rate:
  - Use a huge number of targets
  - Increase the cross section

The PTOLEMY experiment

- Proposed by Weinberg in 1962 [1]:

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

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

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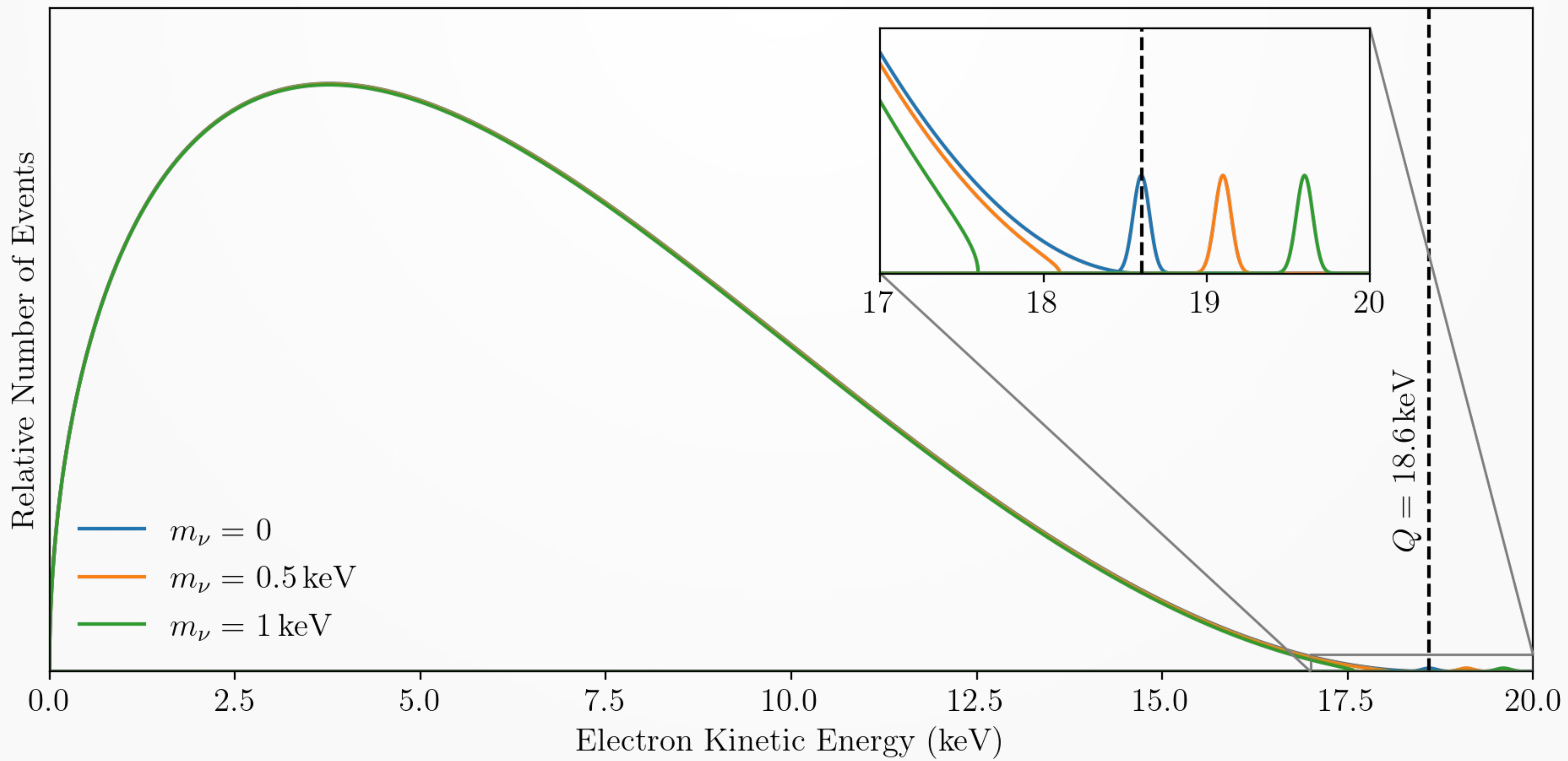
- This process has no threshold

- Tritium already well understood from neutrino mass experiments

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

PTOLEMY



Relative Number of Events
Electron Kinetic Energy (keV)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
17
18
19
20
$Q = 18.6\,\mathrm{keV}$
$m_\nu = 0$
$m_\nu = 0.5\,\mathrm{keV}$
$m_\nu = 1\,\mathrm{keV}$

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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- Giving an event rate for 100g of tritium:

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

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- This event rate is doubled for Majorana neutrinos

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What's the catch?

- Extreme sensitivity required to detect signal:

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

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- Obtaining and storing 100g of tritium
- 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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$$\boxed{\Delta < 2m_{\nu_h}}$$

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- PTOLEMY should at least see something!

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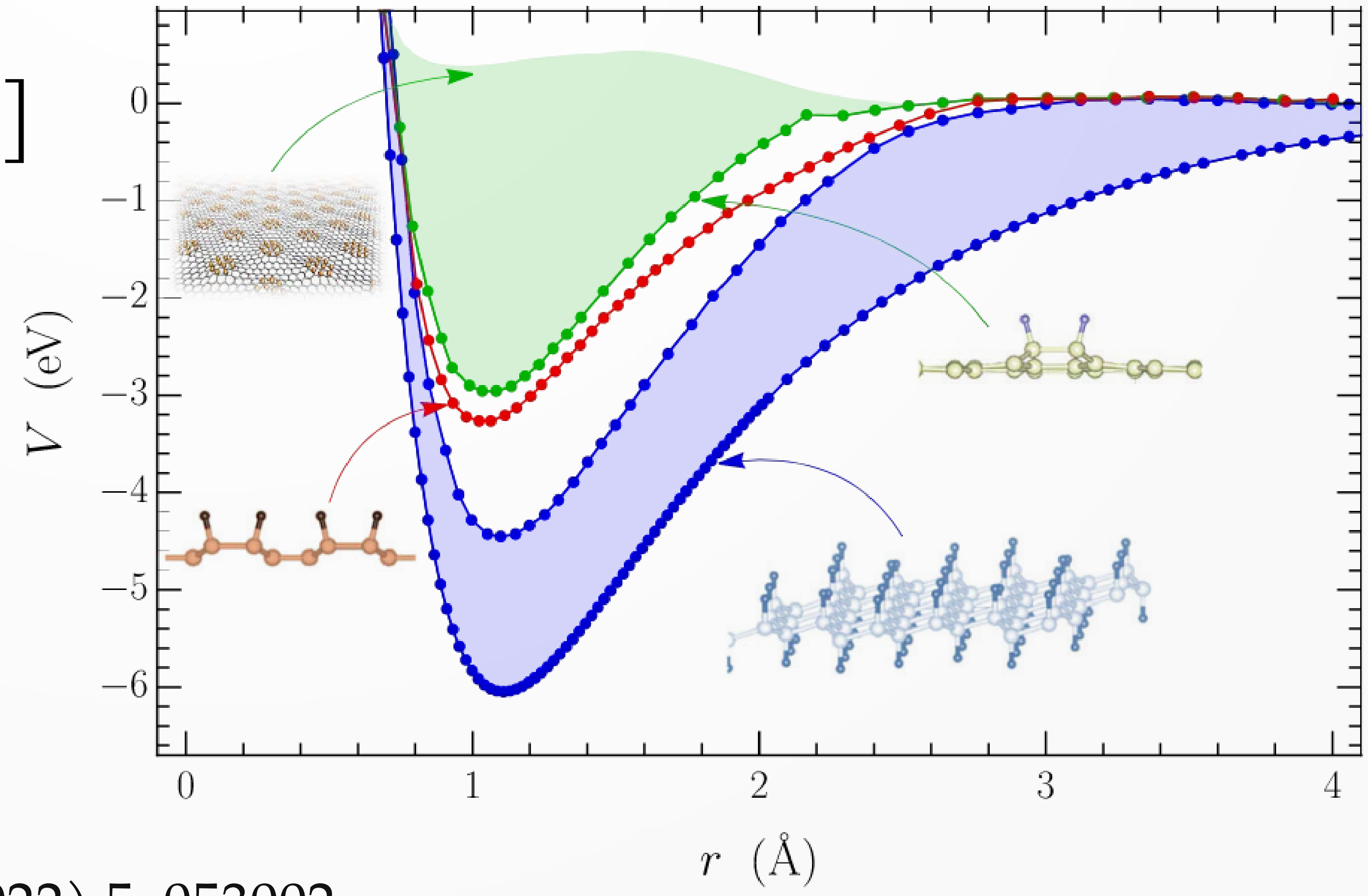
What's the catch?

- Obtaining and storing 100g of tritium
- Graphene substrate [4]



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

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$$\Delta x \Delta p \simeq \frac{1}{2} \implies \Delta v \simeq \frac{1}{2m_T \Delta x}$$

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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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- Uncertainty principle:

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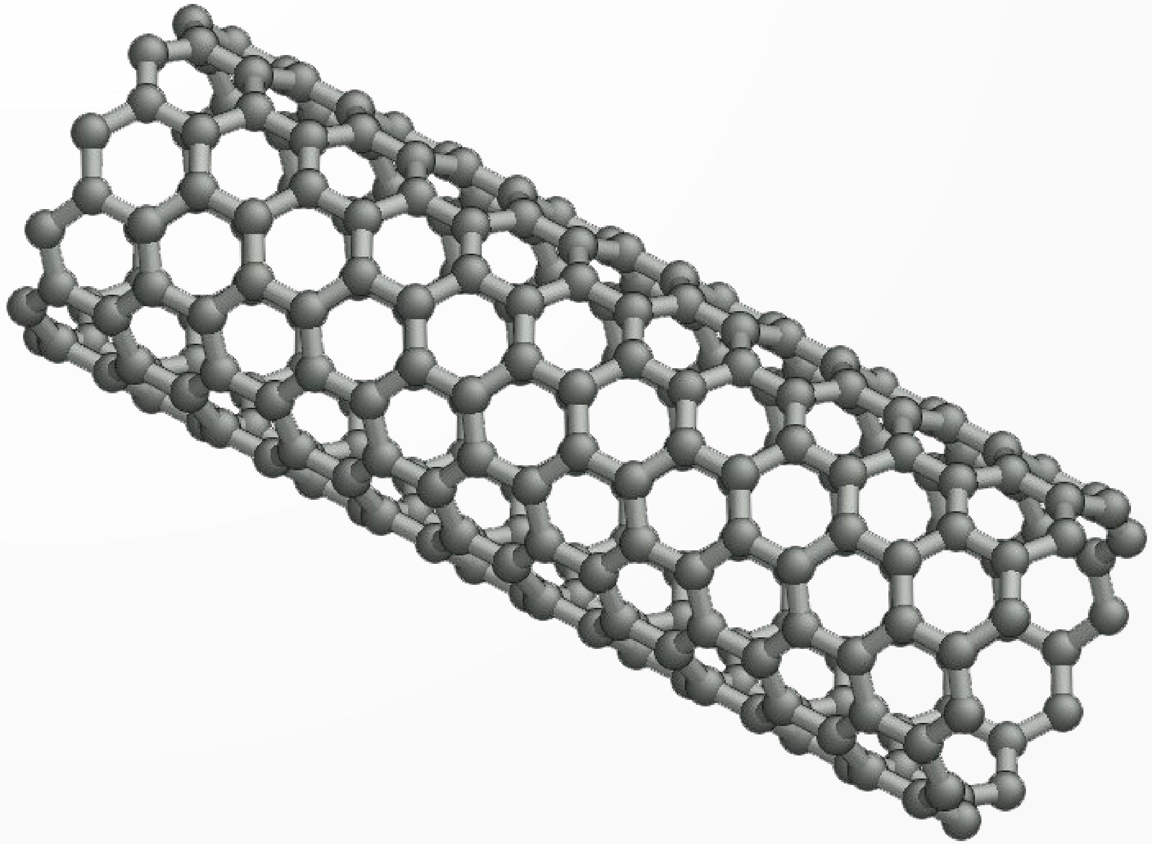
$$\boxed{\Delta E_e \gg 2m_{\nu_h}}$$

- No longer guaranteed to see anything!

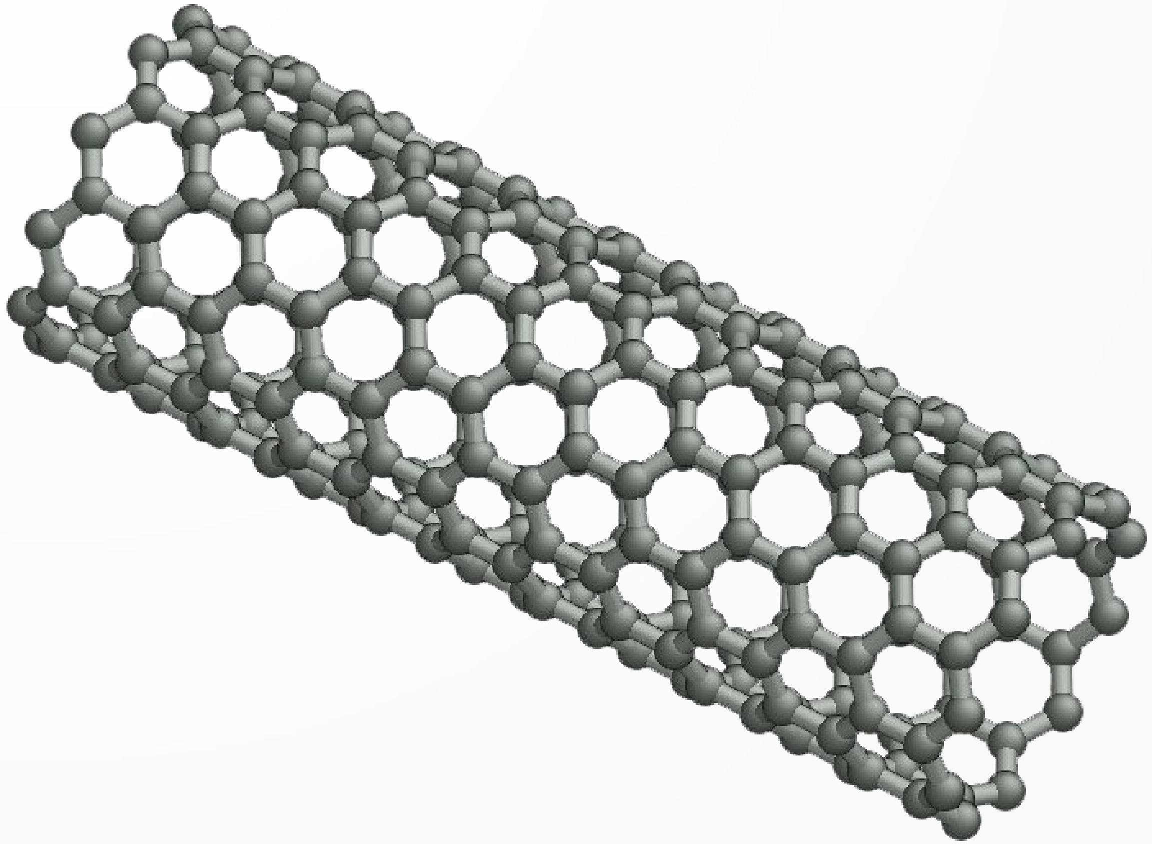
So now what?

- Carbon nanotubes?



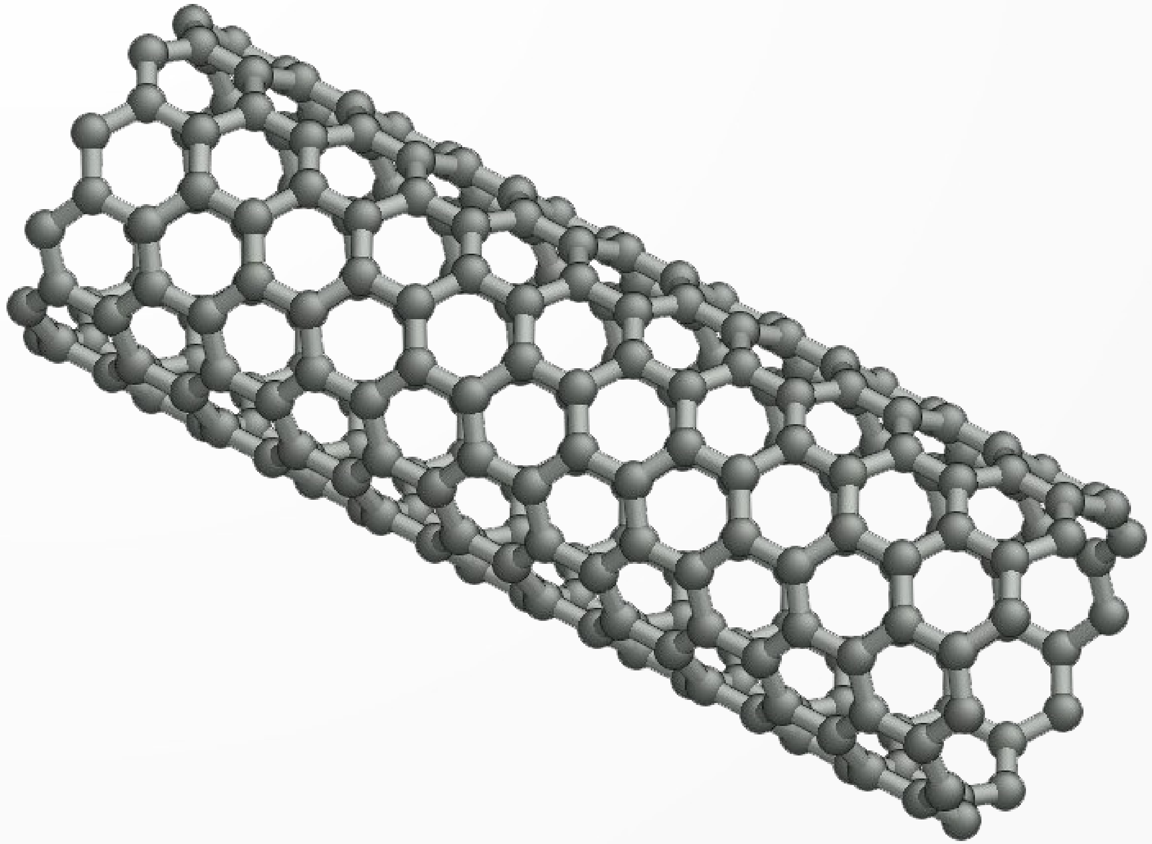
So now what?

- Carbon nanotubes?
- Allow tritium to *slide*



So now what?

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



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Coherent scattering

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

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

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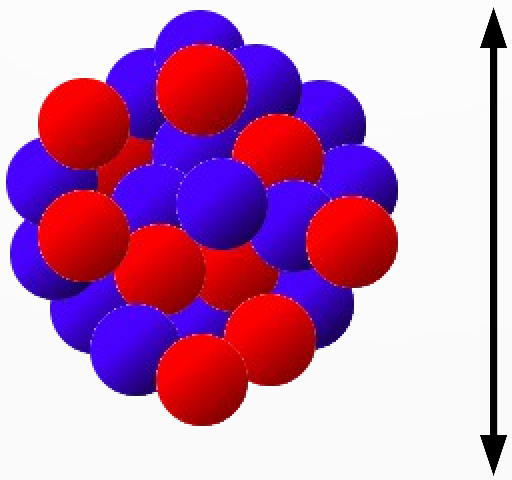
- Wavelength of order target size:



$$\sim \lambda$$

Coherent scattering

- Neutrino "sees" a larger charge:

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

Coherent scattering

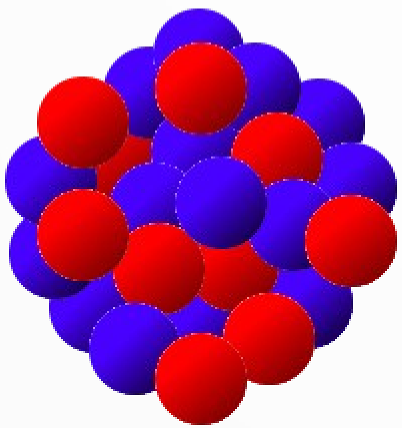
- Neutrino "sees" a larger charge:

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

- Significantly enhanced event rates:

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

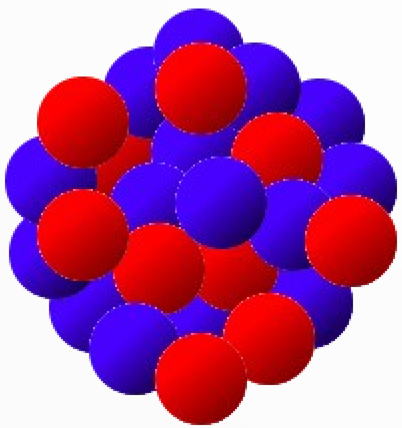
Coherent scattering

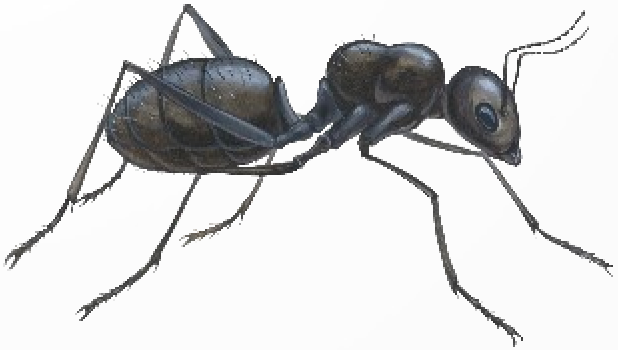


$$\lambda \sim \text{fm}$$

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

Coherent scattering





$\lambda \sim \mathrm{fm}$

$\lambda \sim \mathrm{mm}$

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

$\Gamma \sim N_A^2$

Coherent scattering

- Neutrino scattering rate:

$$\frac{\Gamma}{N_T} \simeq G_F^2 m_\nu^2 T_{\nu,0}^3$$

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- So why don't we see anything?

Coherent scattering

- Relic neutrinos are cold and light:

$$\Delta p_\nu \sim \mathcal{O}(\mathrm{meV})$$

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

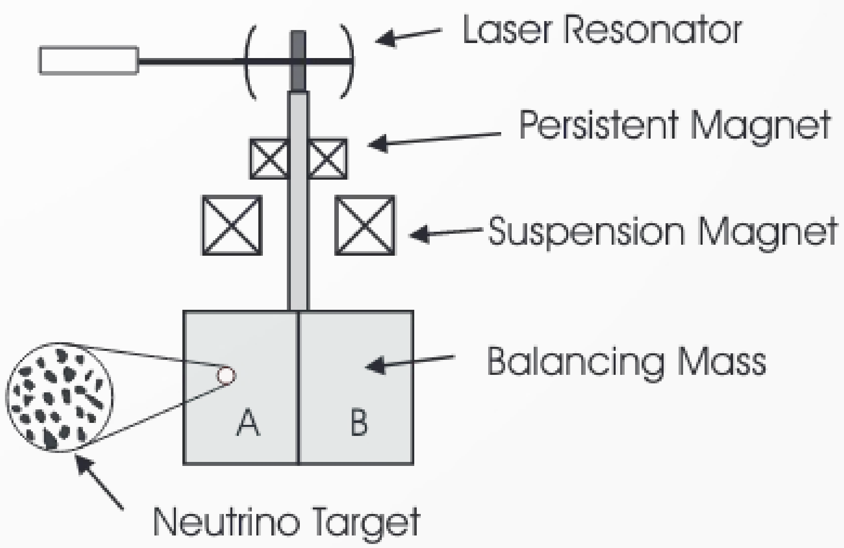

Fig: C. Hagmann, arXiv:astro-ph/9905258

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

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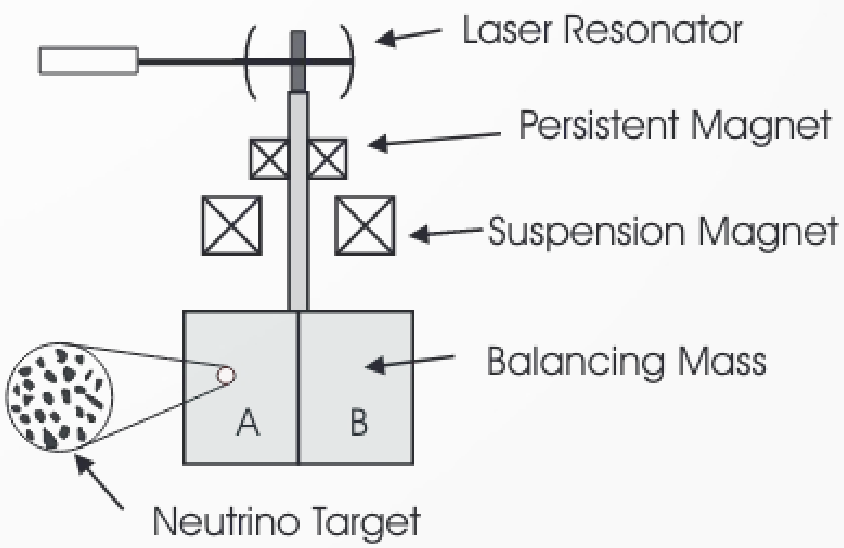

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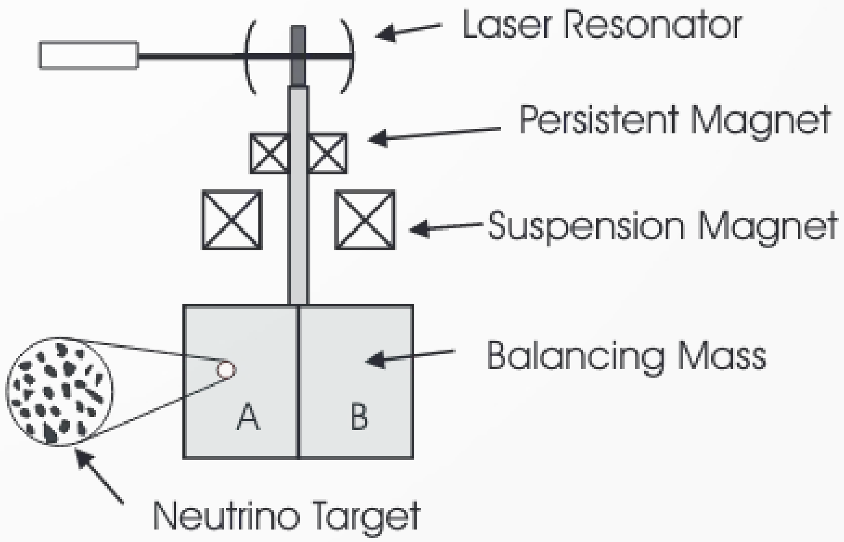

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Stodolsky effect

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

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Stodolsky effect

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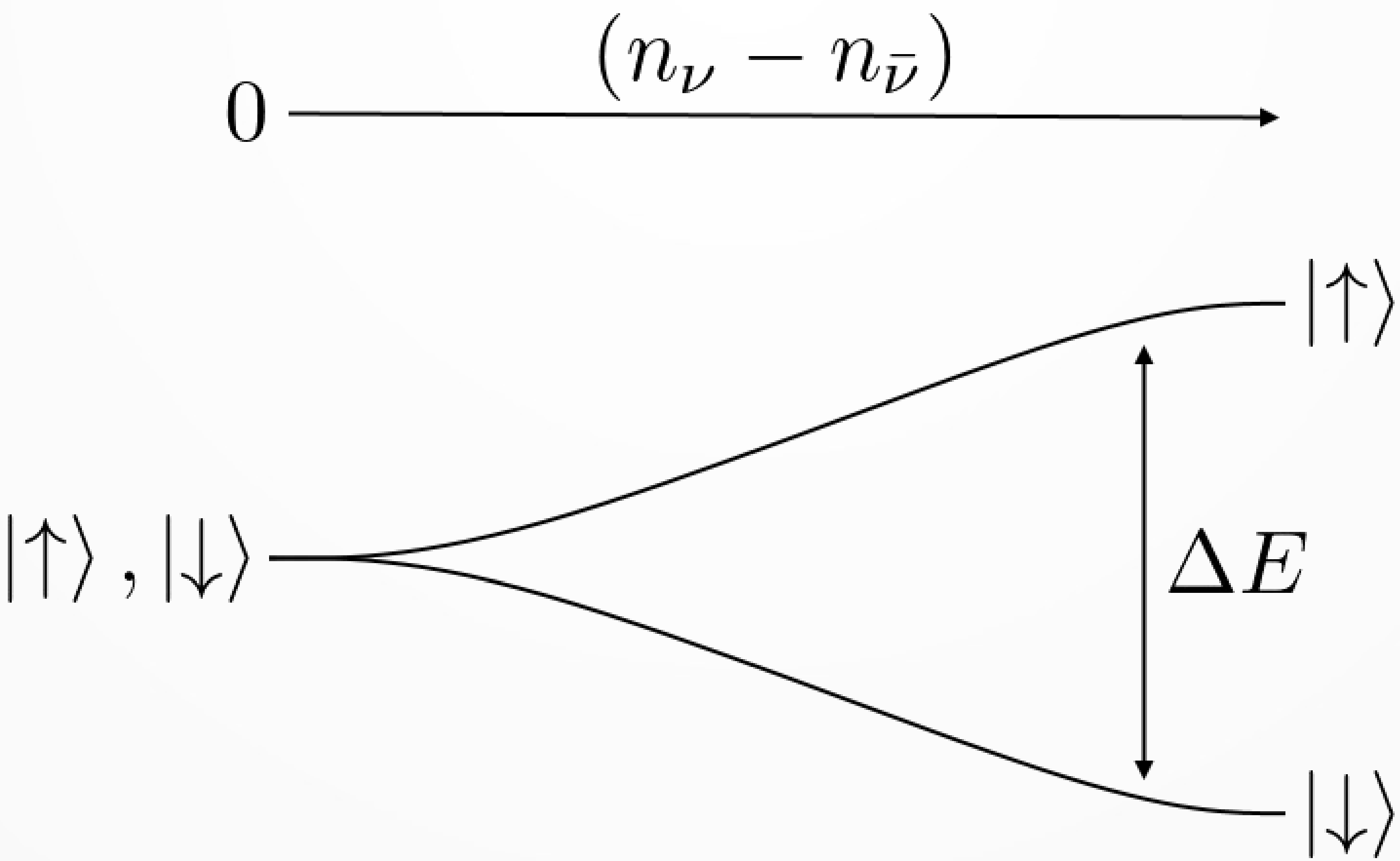
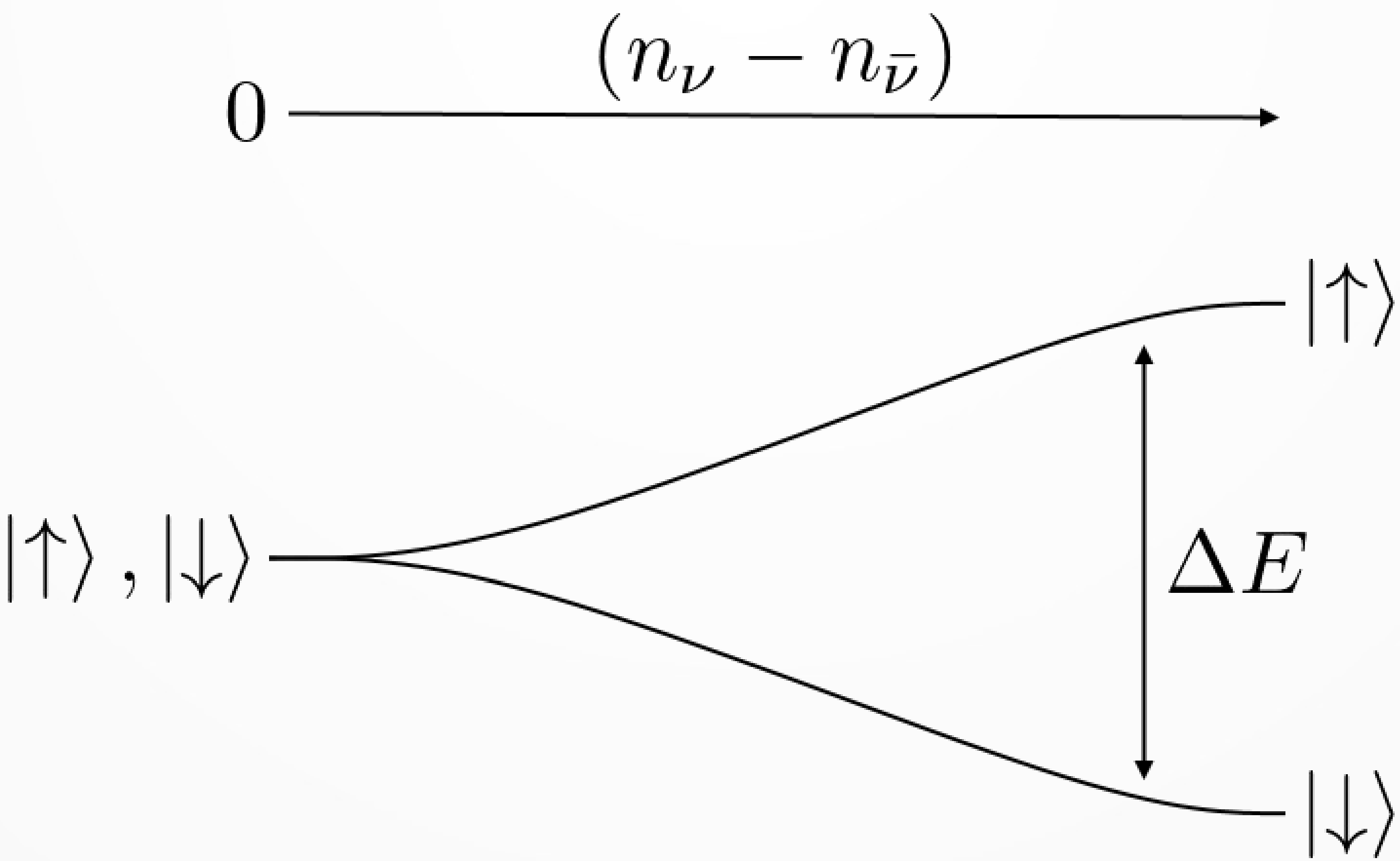
- Analogous to the Zeeman effect
- Only* effect linear in G_F (Cabibbo '82, Langacker '83)

Stodolsky effect



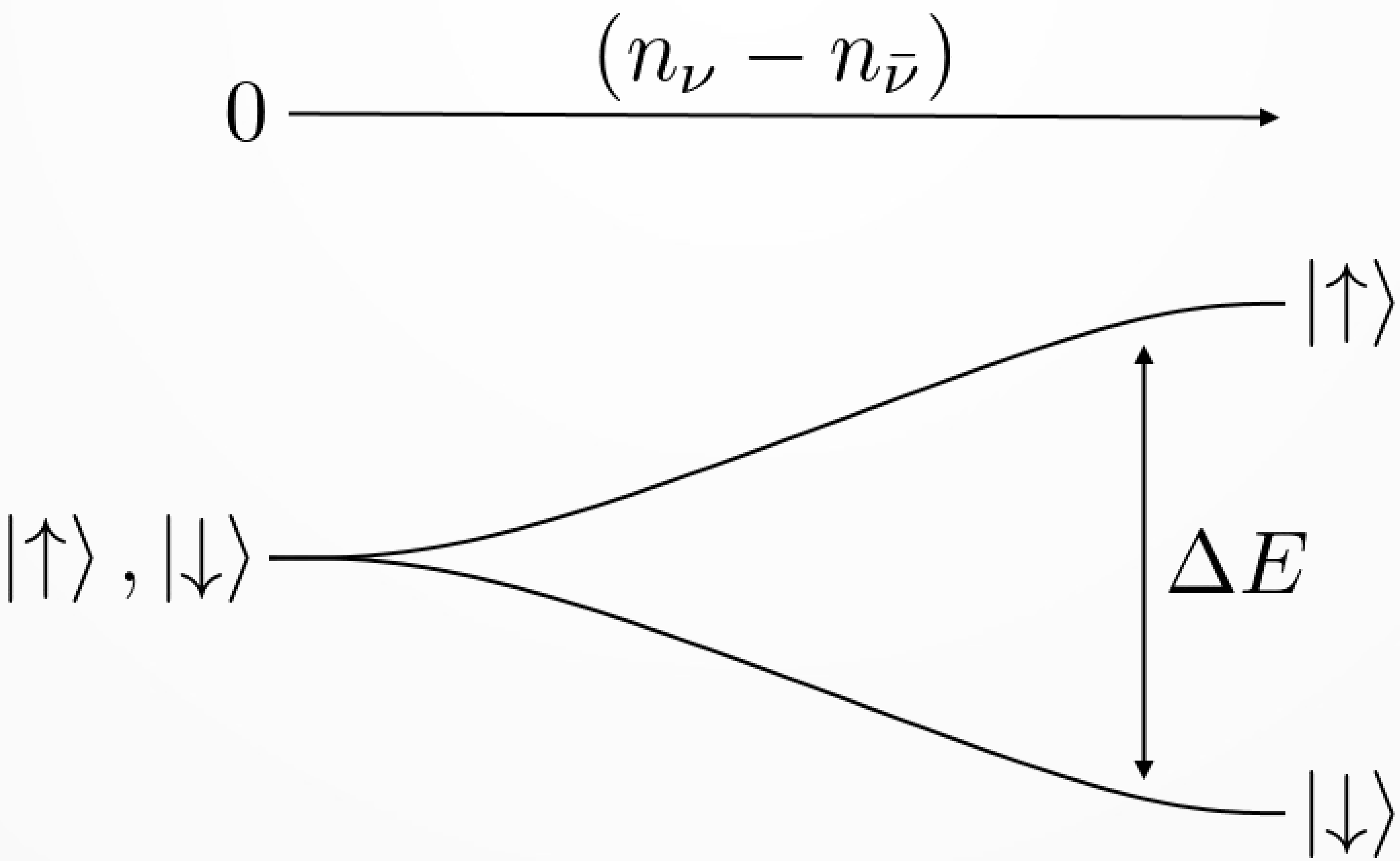
$$\Delta E \sim G_F \beta_\oplus (n_\nu - n_{\bar{\nu}})$$

Stodolsky effect



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

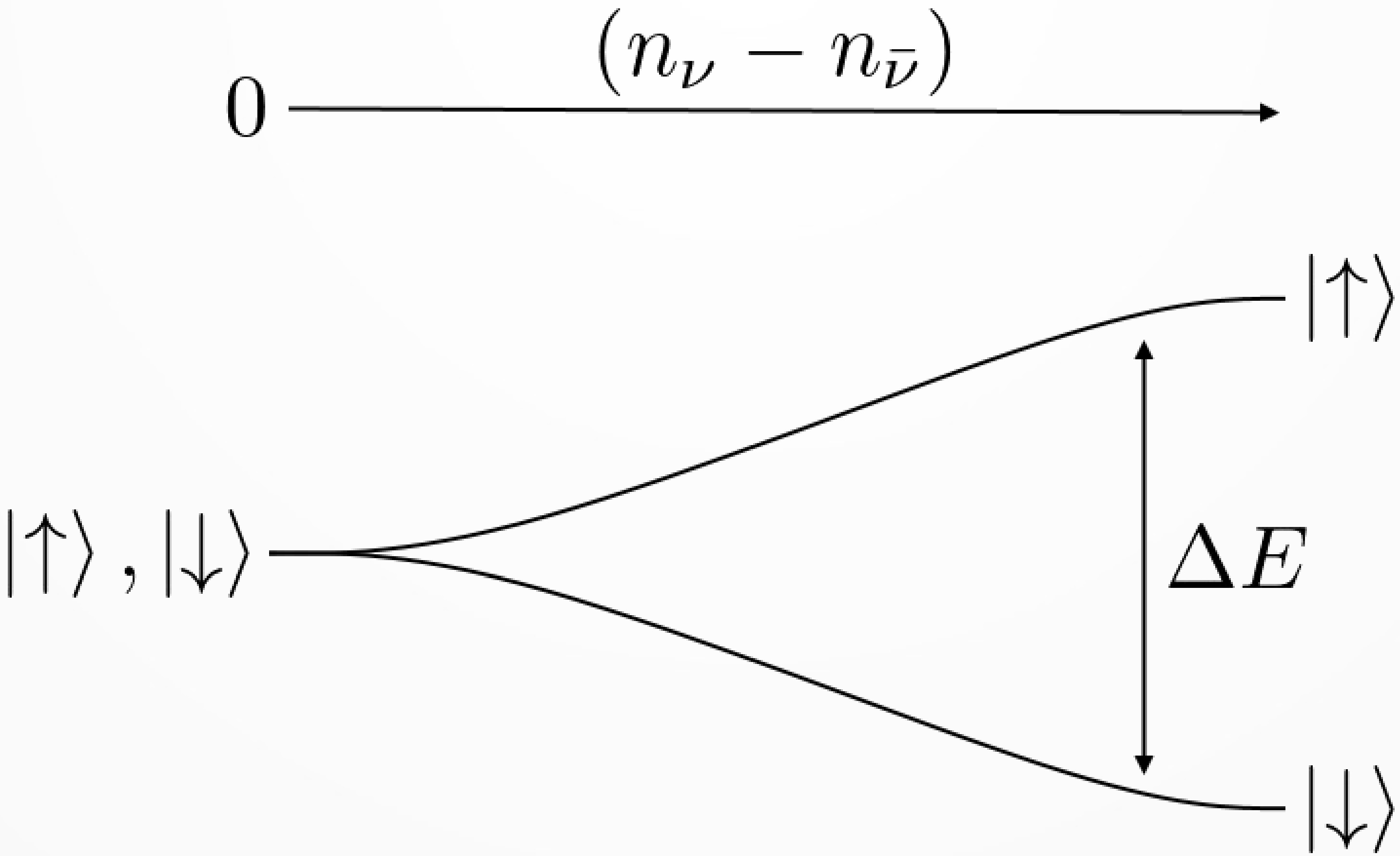
Stodolsky effect



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

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

Stodolsky effect



- Also an effect that depends on helicity asymmetry

Stodolsky effect

- So how do we see it?

Stodolsky effect

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- Spin precession:

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

Stodolsky effect

- Two observables:

- Torque [6]:

$$\tau \simeq \Delta E$$

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

Stodolsky effect

- Two observables:

- Torque [6]:

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

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

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

Stodolsky effect

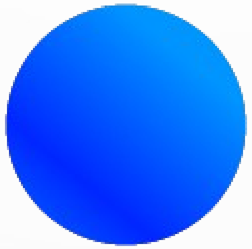
- Two observables:

- Magnetisation [6]:

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

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

Stodolsky effect



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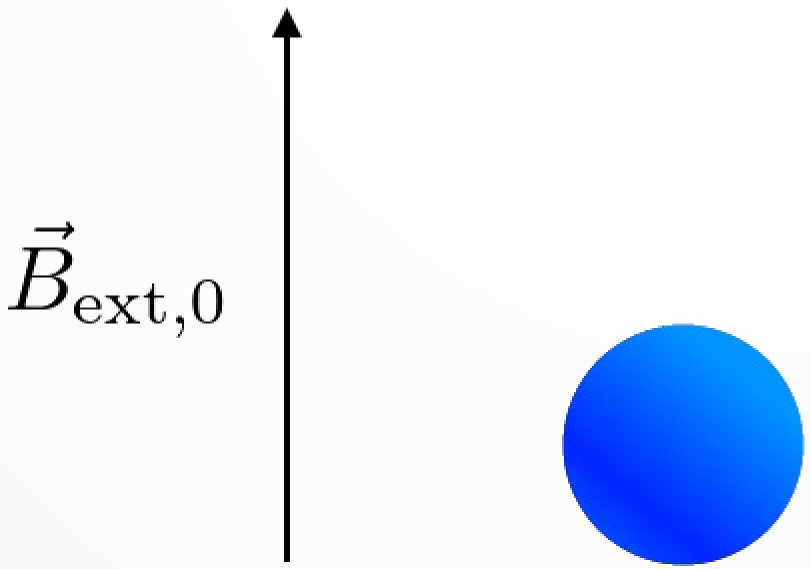

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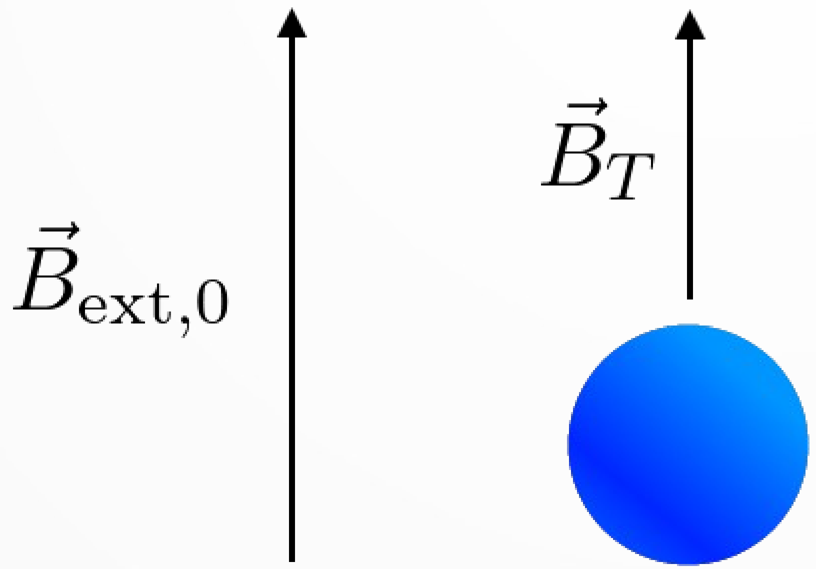

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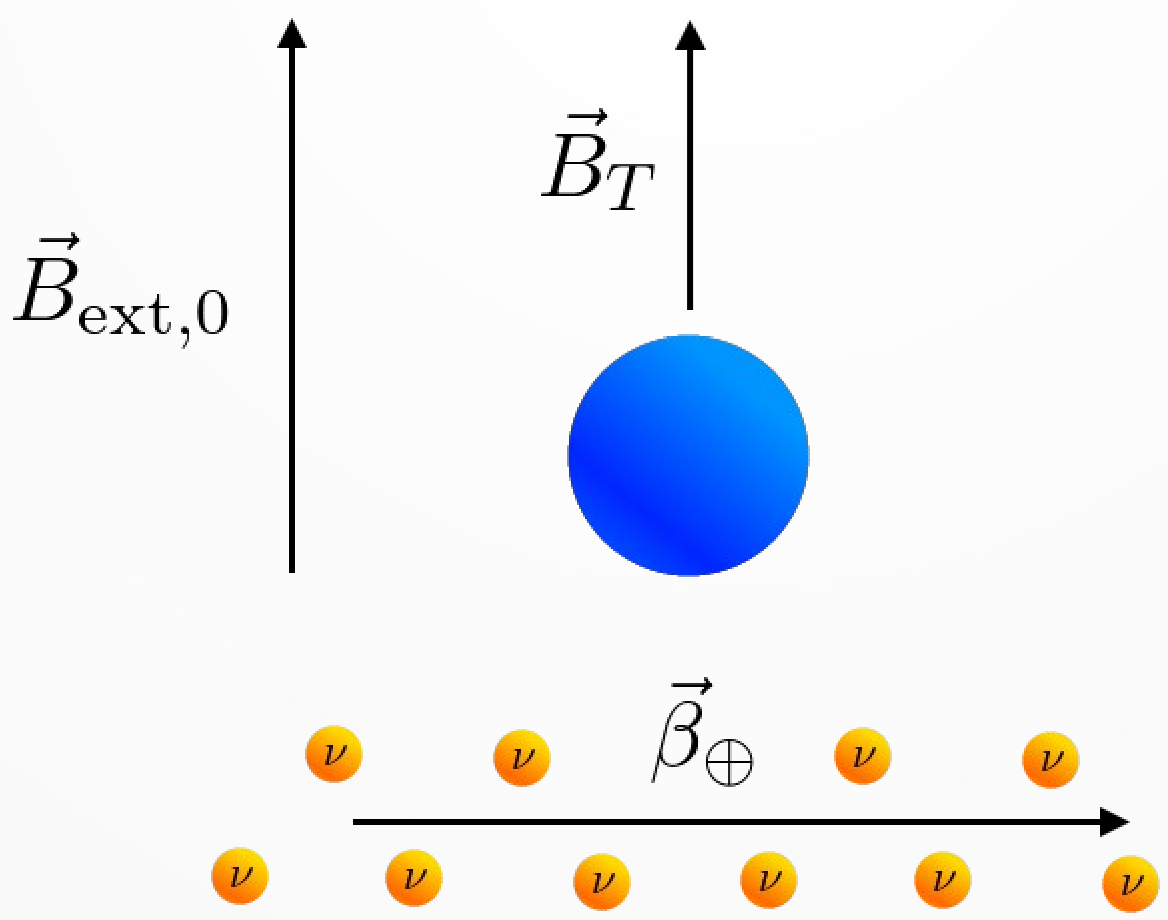

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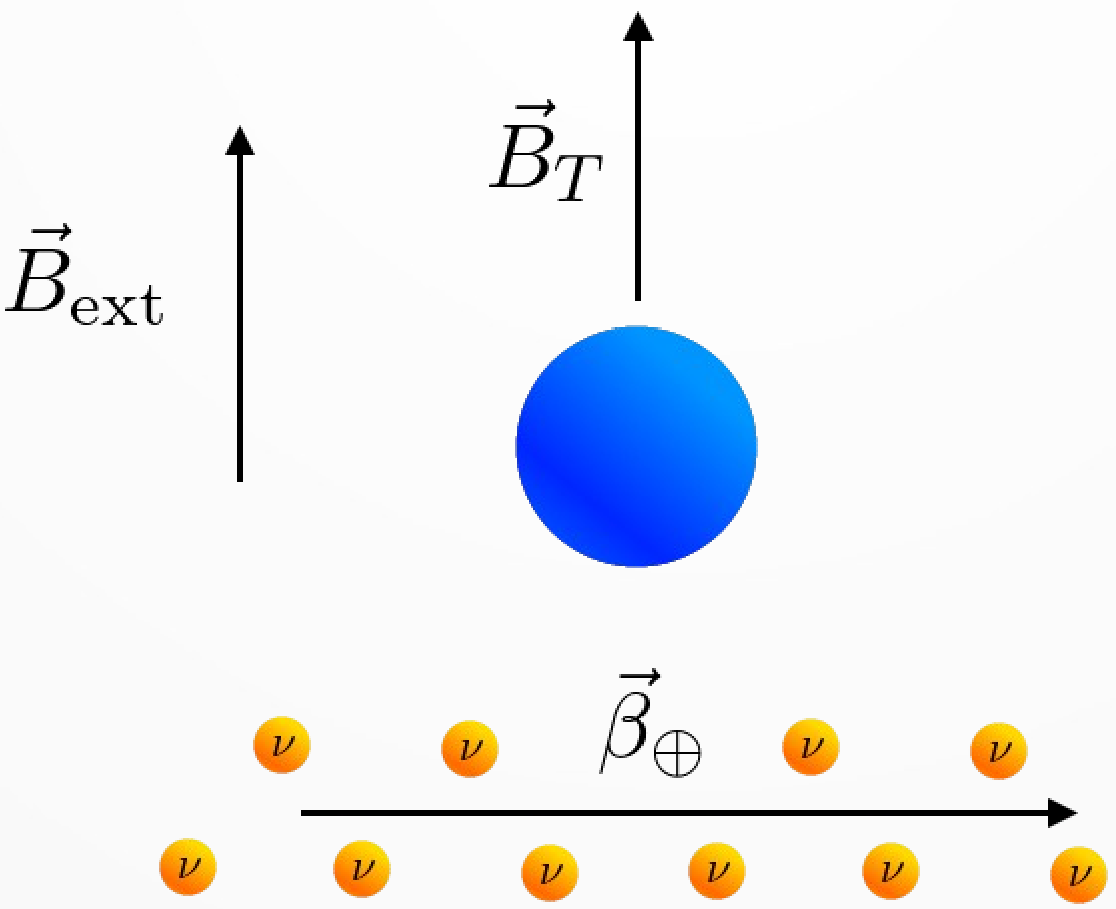

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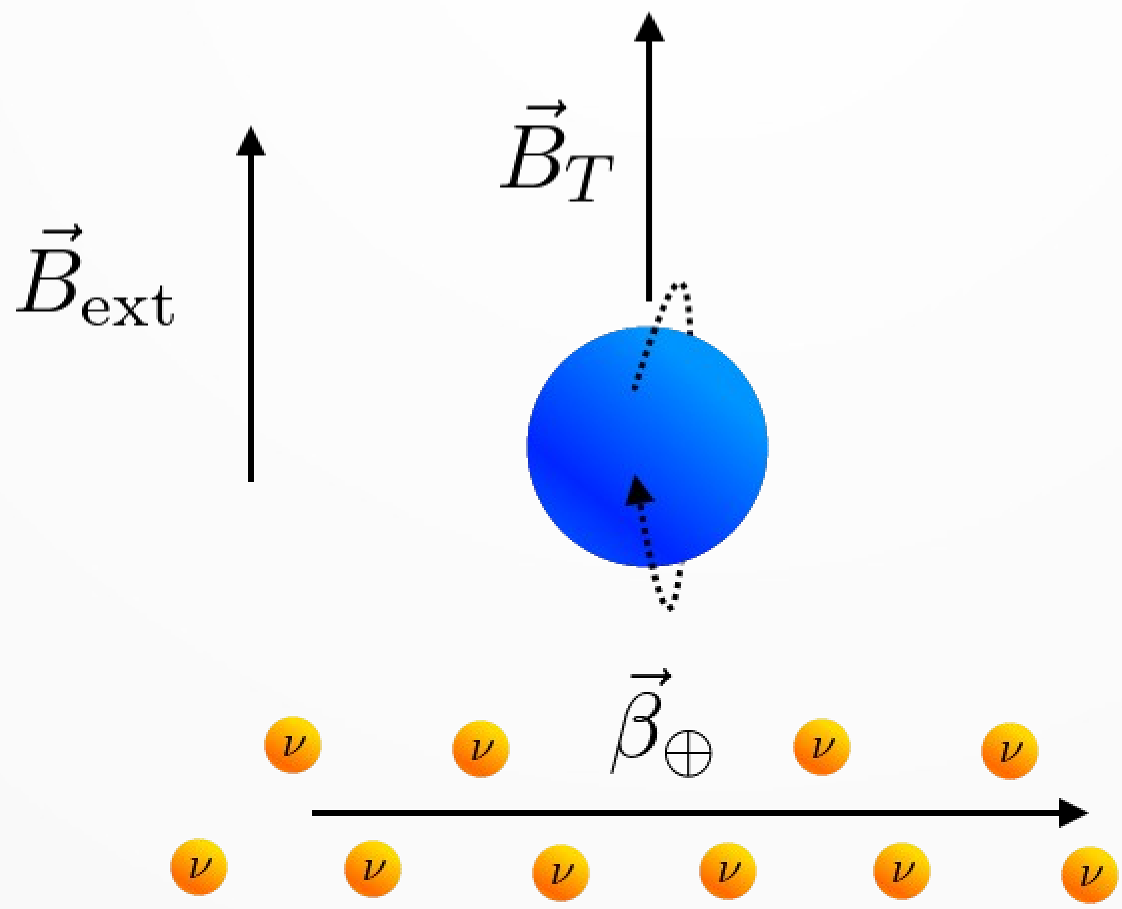

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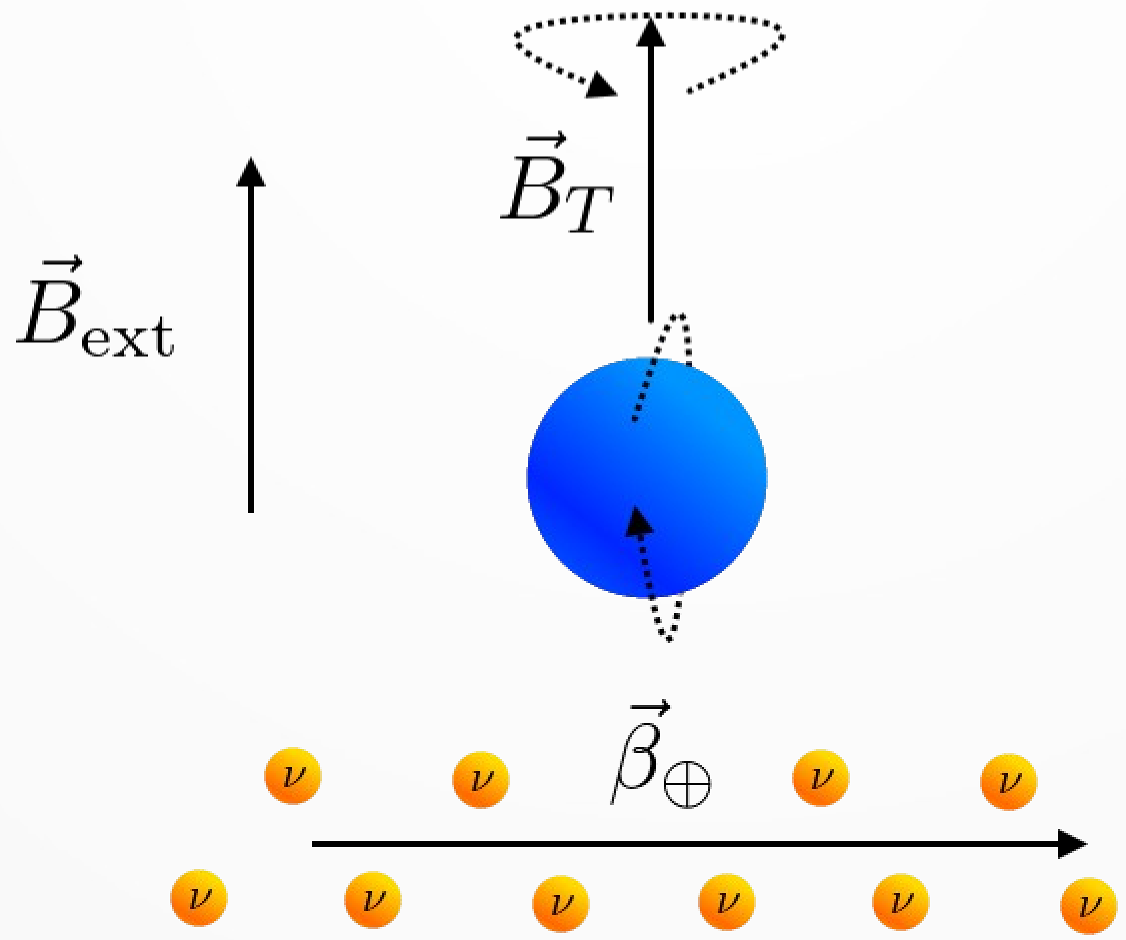

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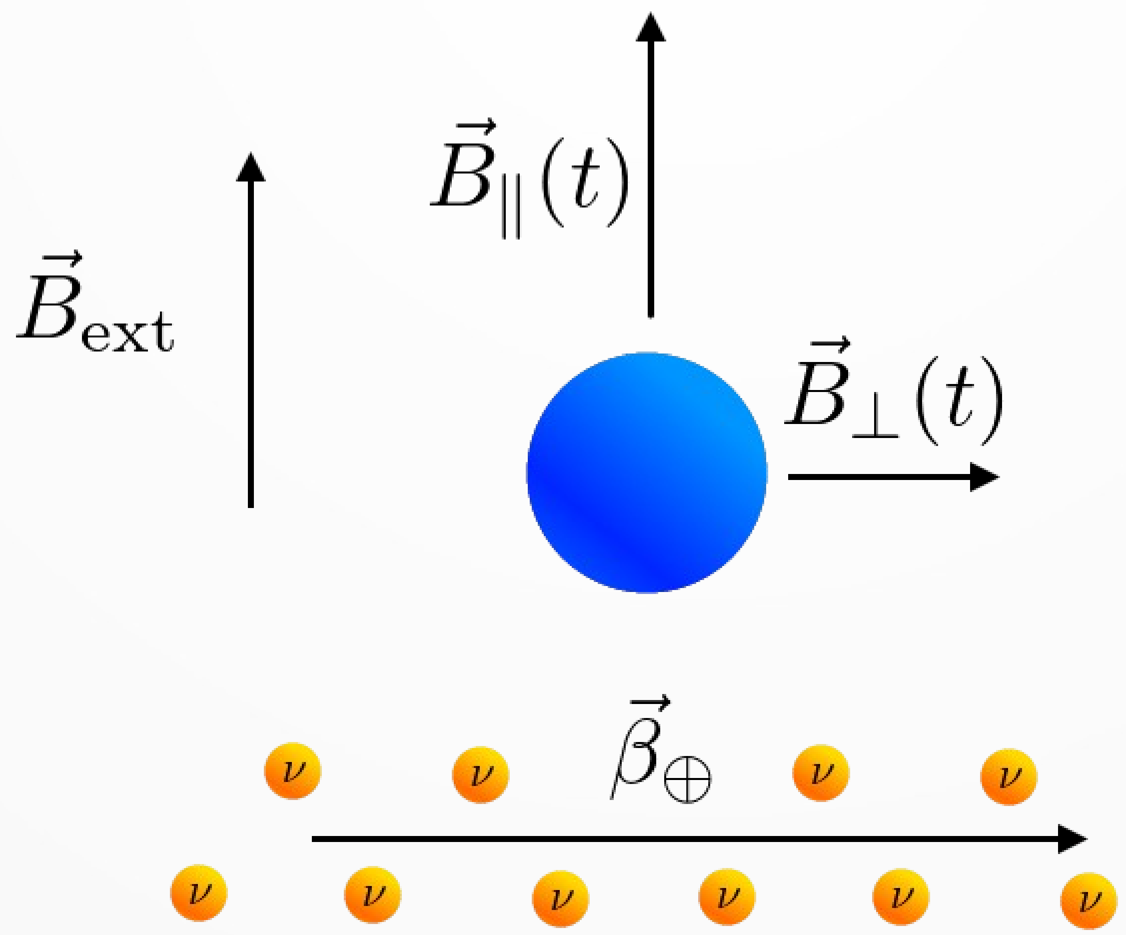

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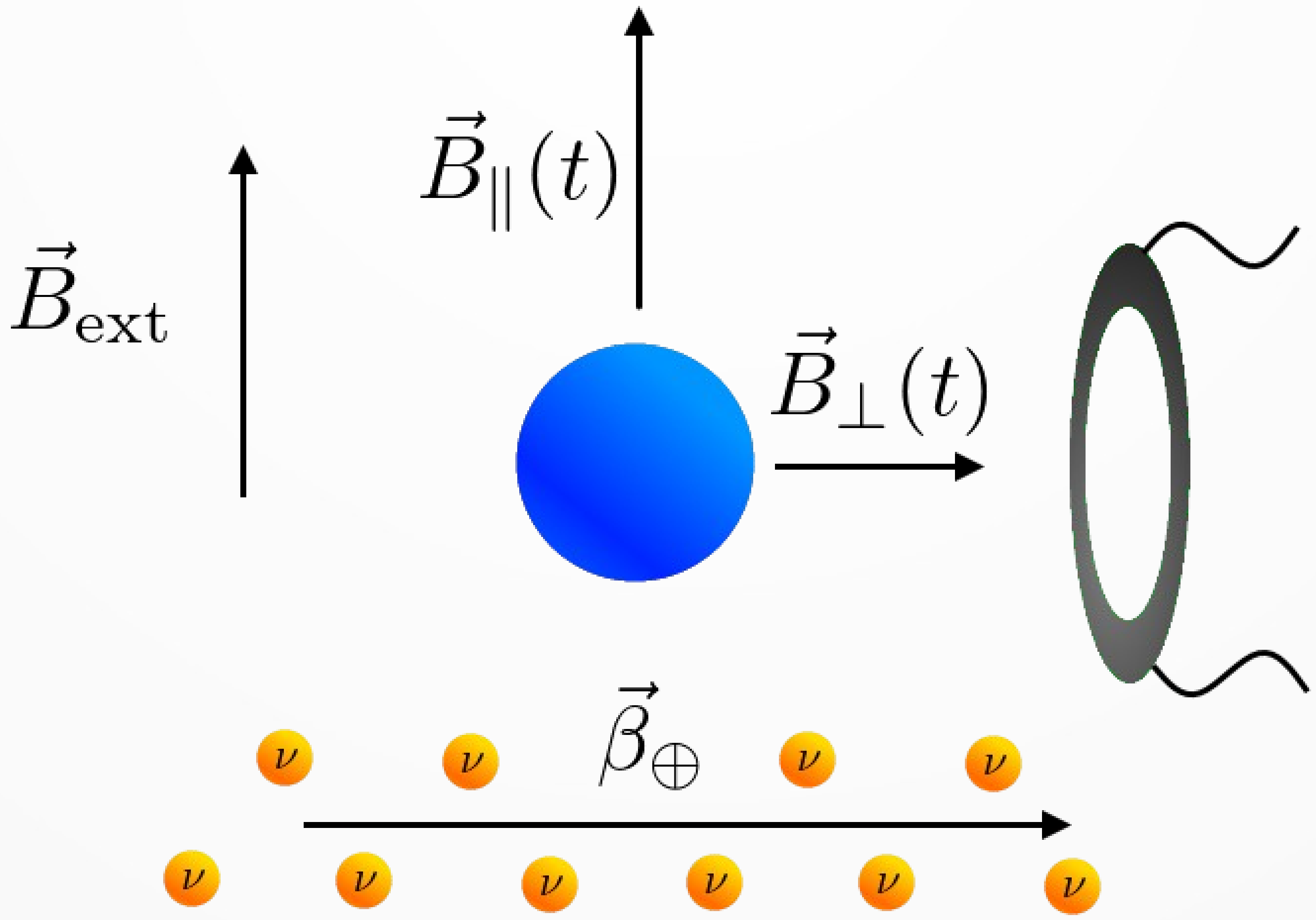

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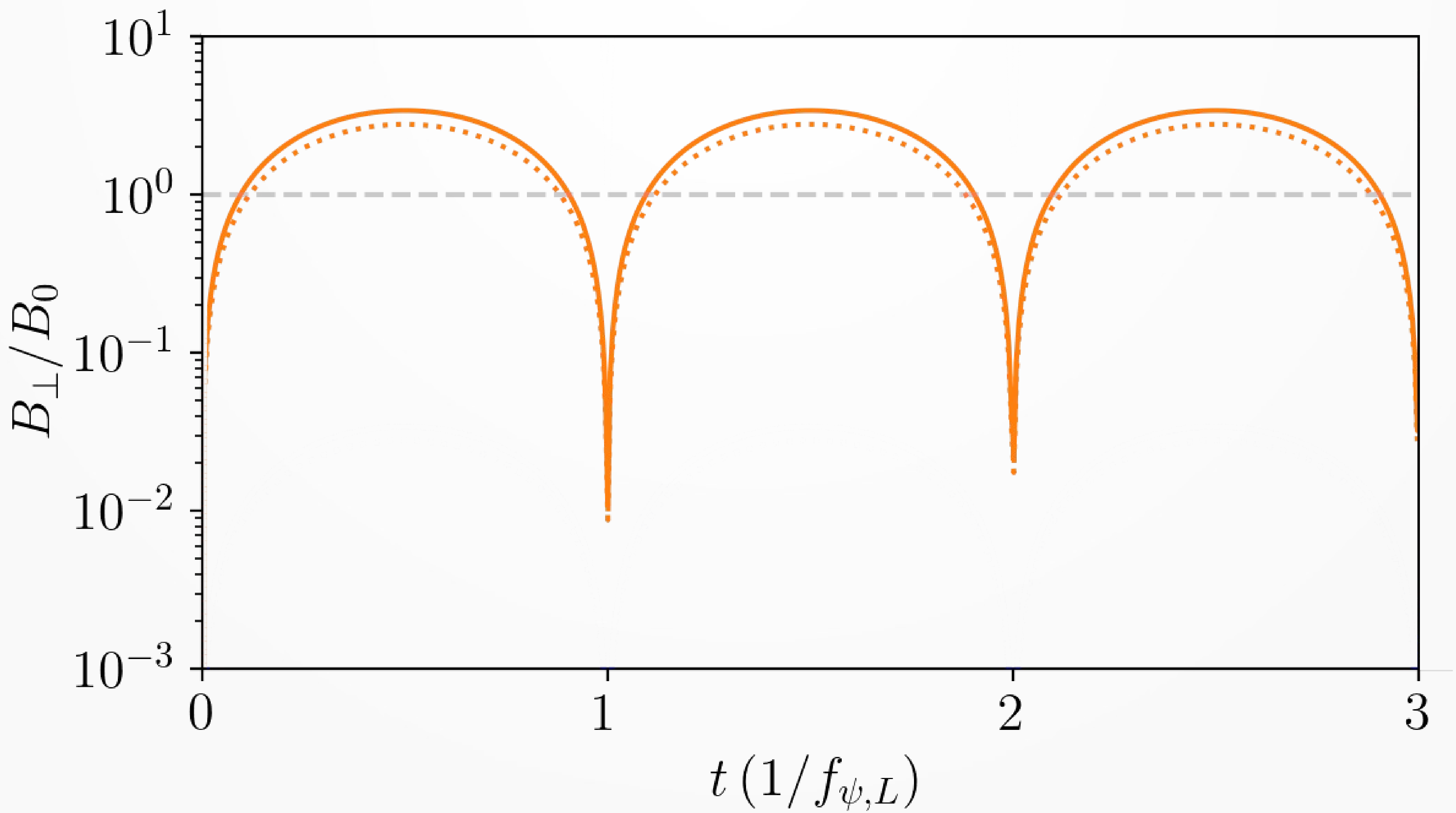

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- Helicity asymmetry term? 3 orders of magnitude larger!

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

Stodolsky effect

- Asymmetry?

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- BBN constraint:

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- Still a way off, but better than coherent

Contents

- What is the CνB?

- How might we go about detecting it?
  - PTOLEMY
  - Coherent scattering
  - Stodolsky effect
  - Accelerator ⇐

Accelerator

- PTOLEMY-on-a-beam?

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Accelerator

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

Accelerator

- Accelerator experiment [7]:

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

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

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

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

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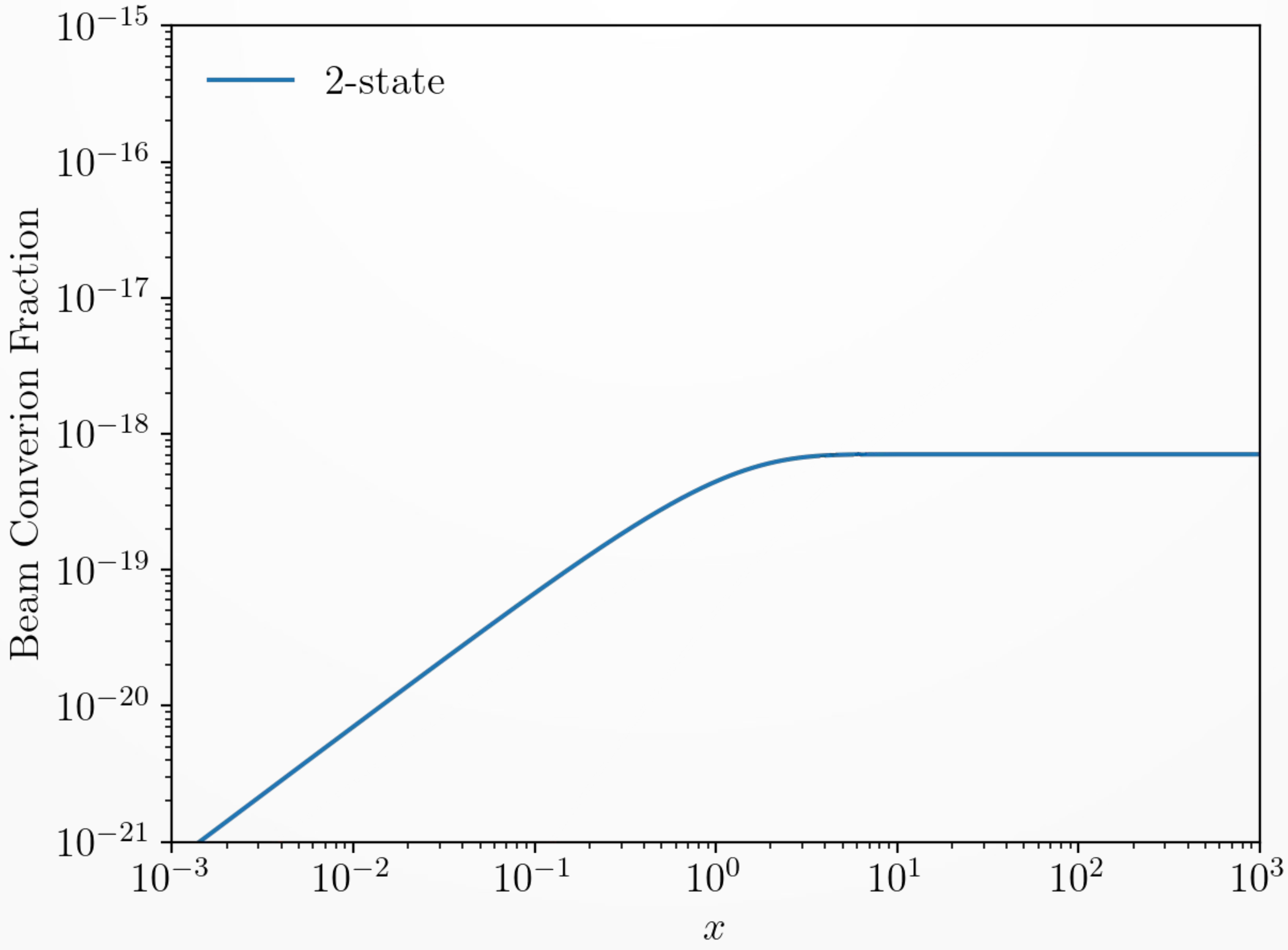
Accelerator



Accelerator

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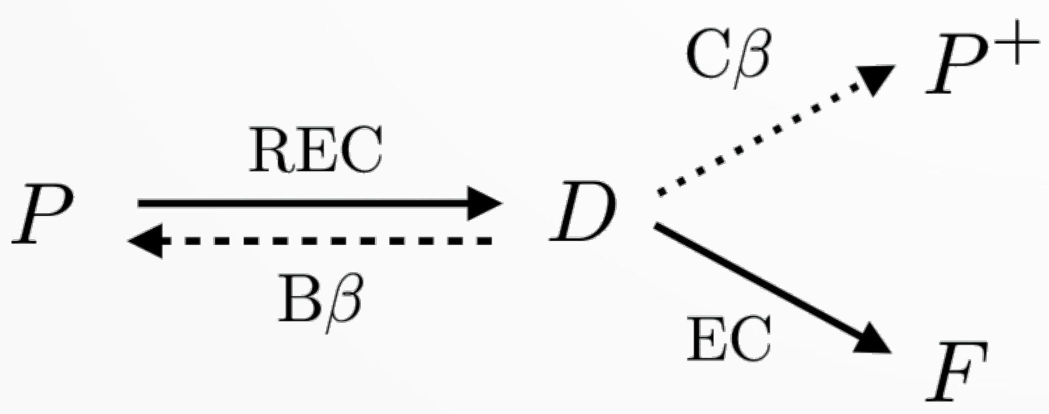

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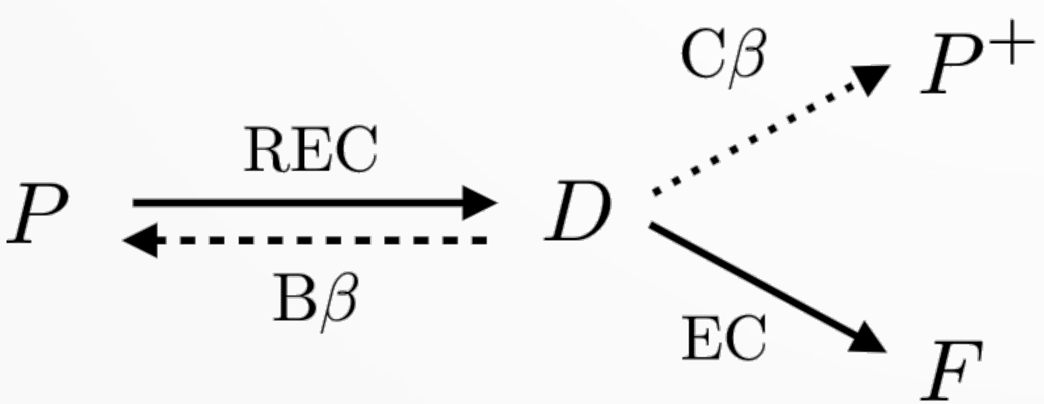

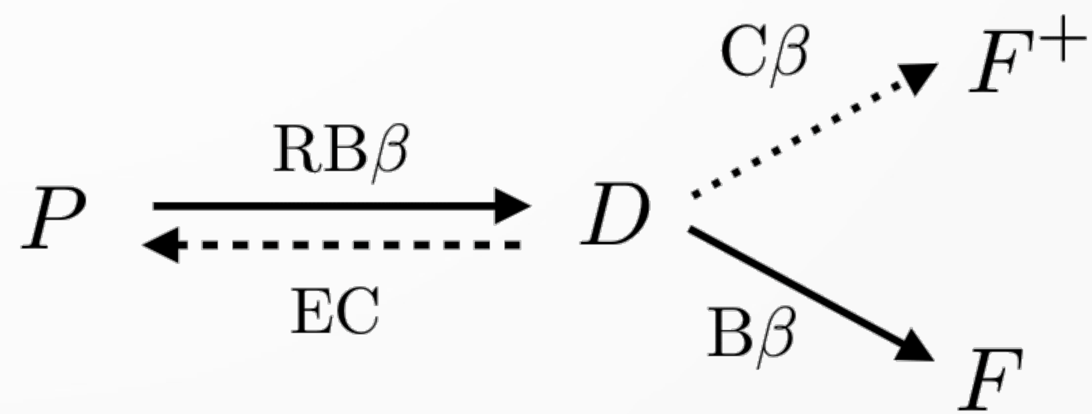

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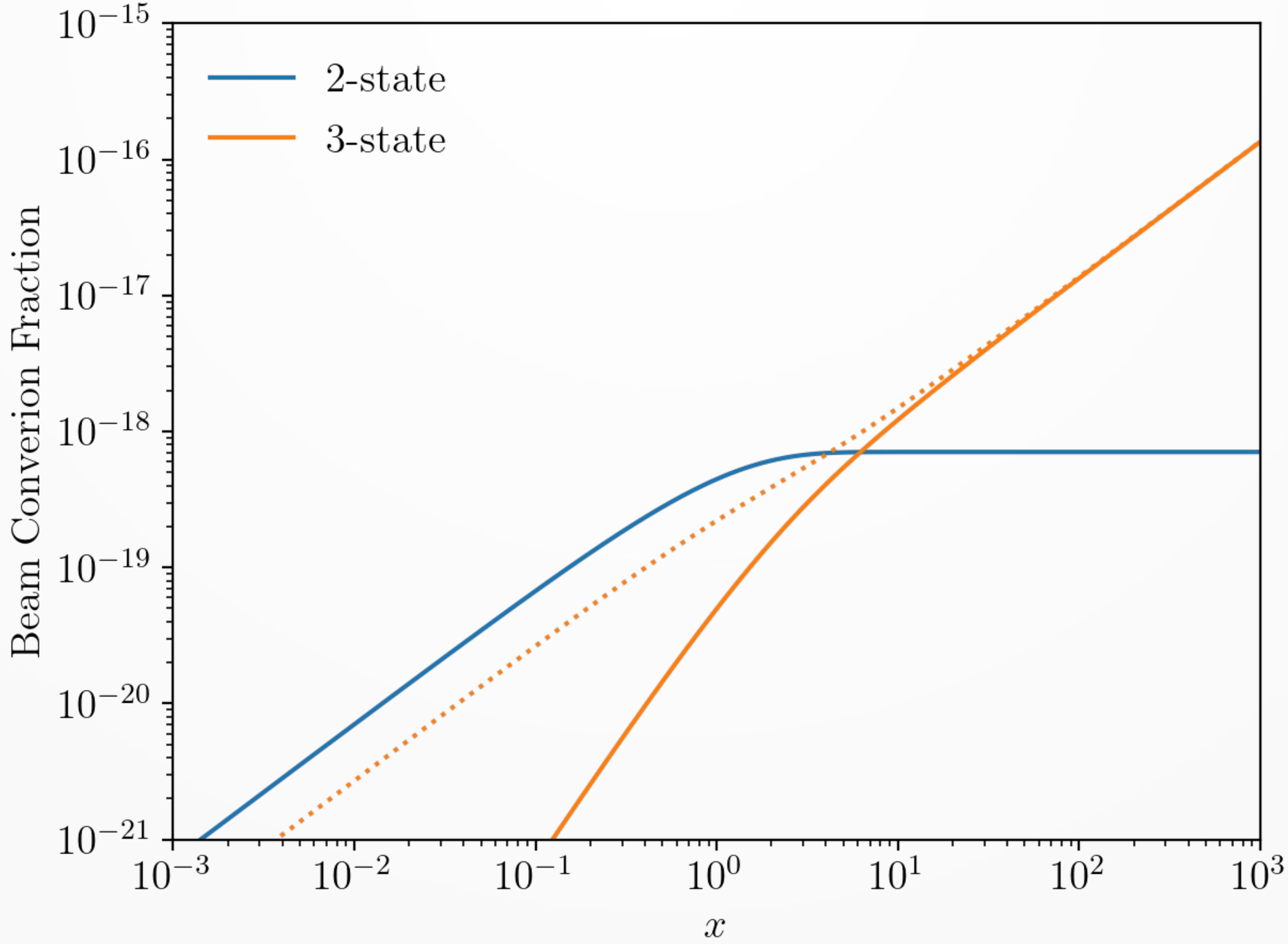

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- In general:

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

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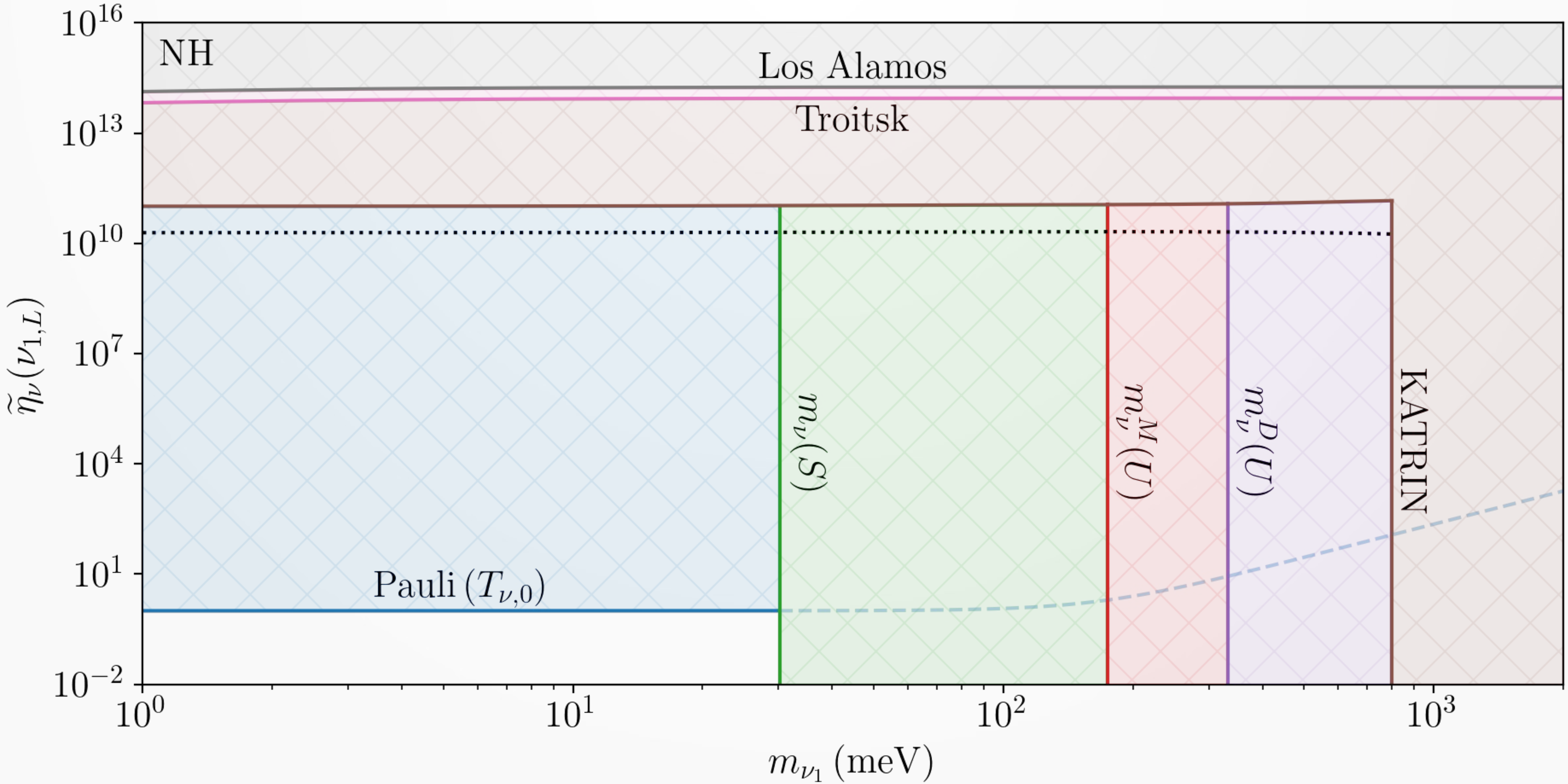
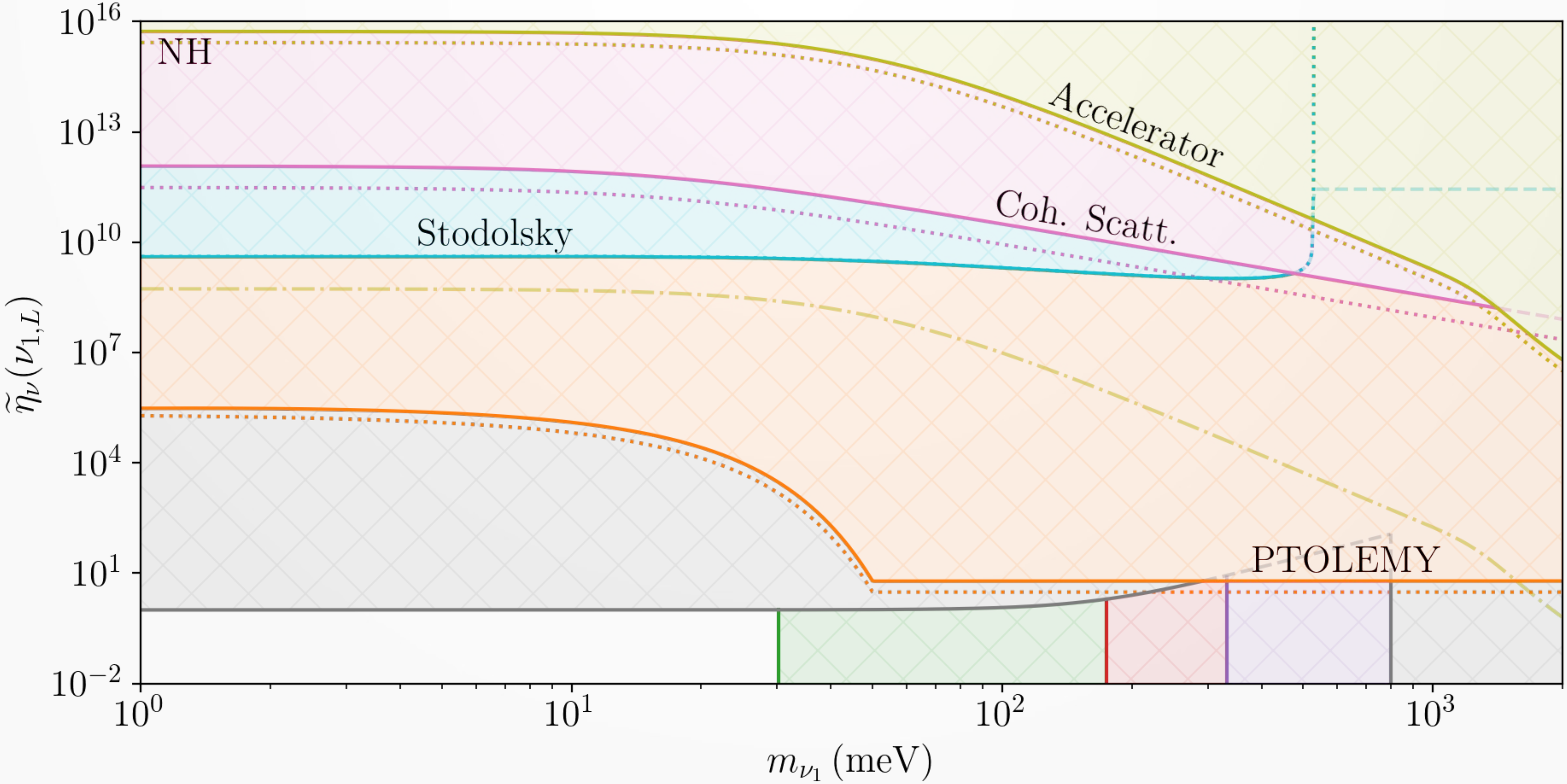
- Mapping out the allowed parameter space lets us find the best detection proposal!

Constraints



Sensitivity



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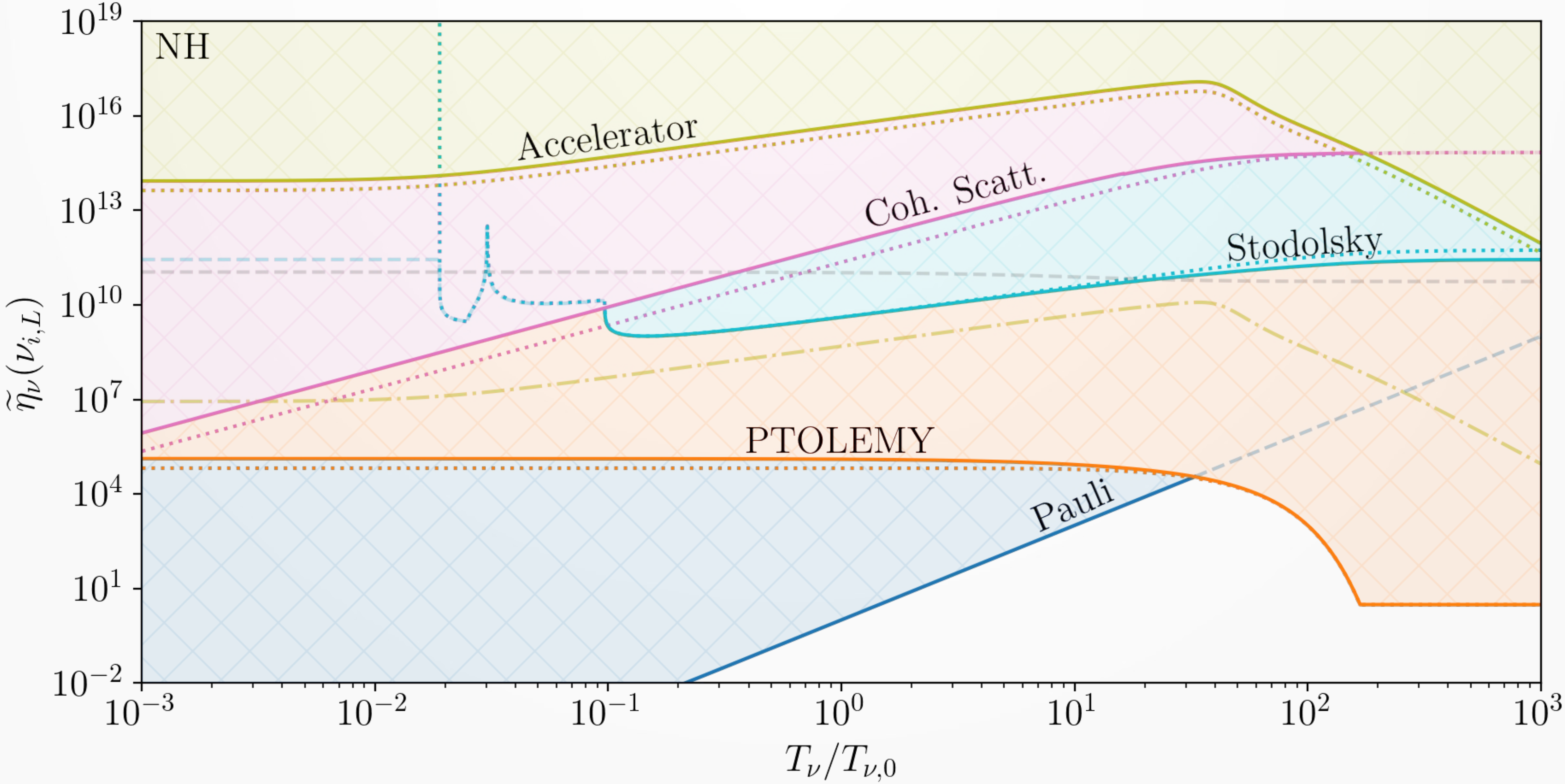

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- Detecting the CνB could reveal a wealth of new physics
- Detection made difficult by neutrino properties
- Many exciting proposals to detect the CνB!

Thank you!
Questions?