Detecting the Cosmic Neutrino Background

Jack Shergold

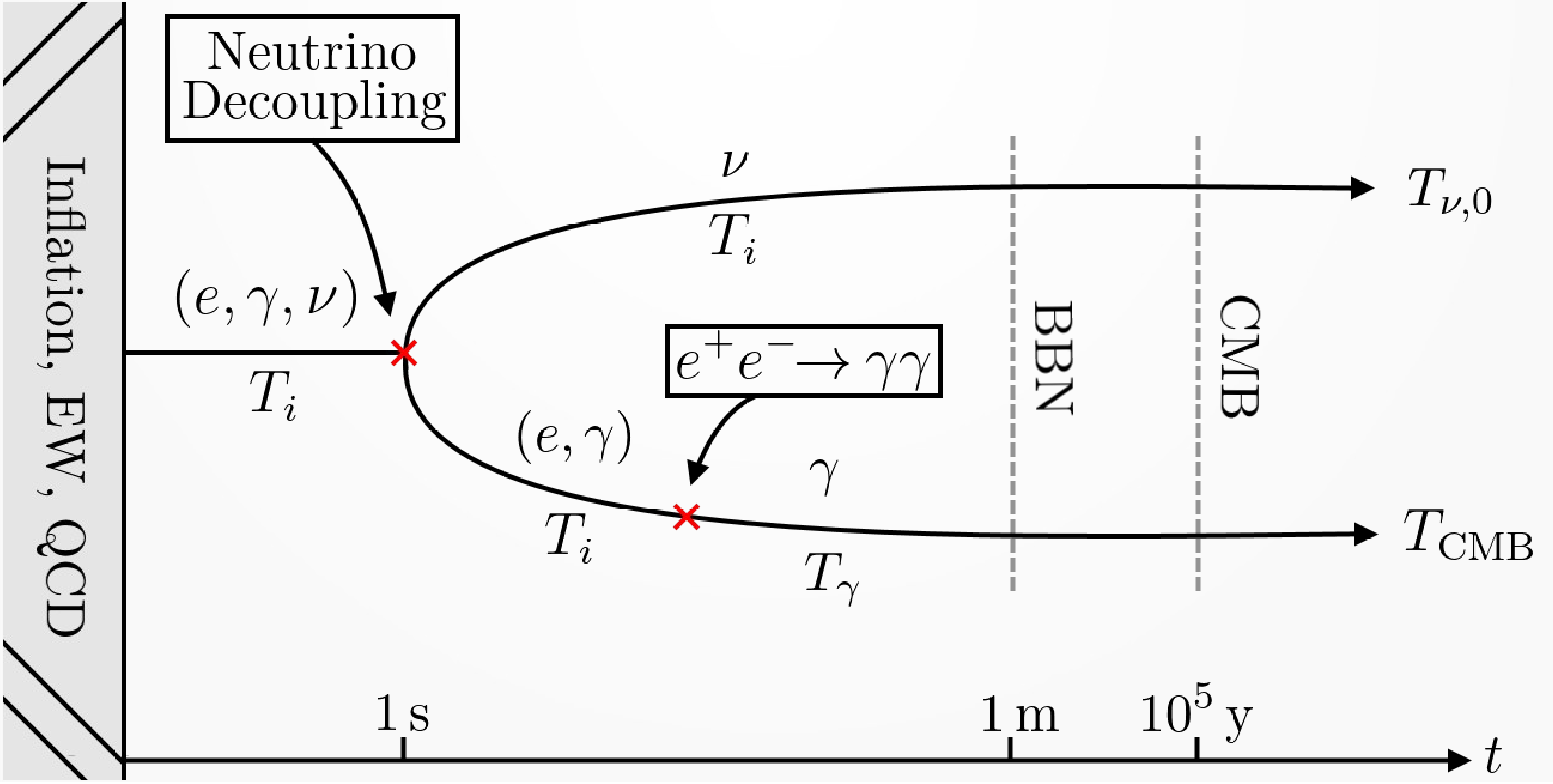
What we will cover

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

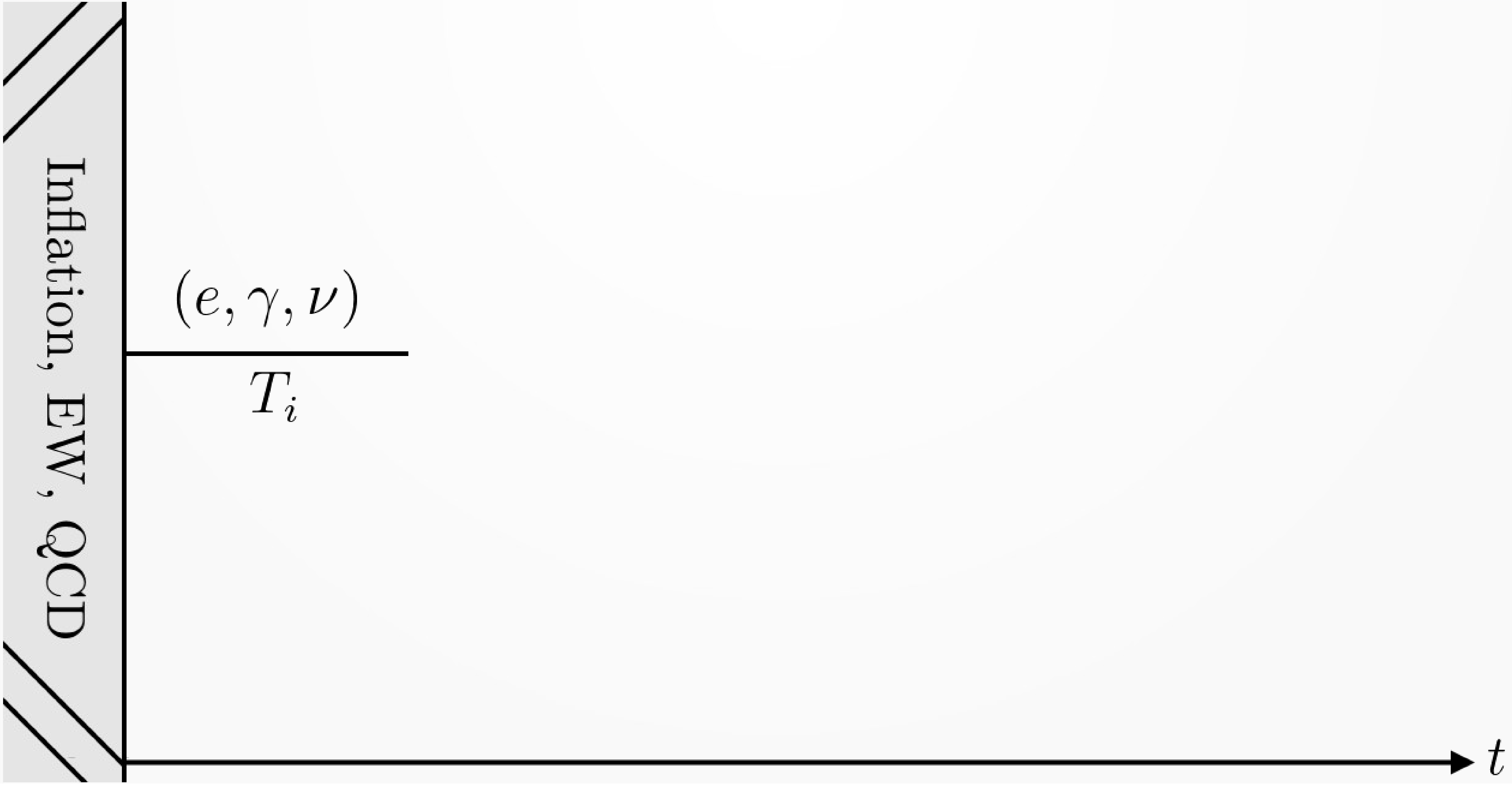
Contents

- What is the CνB?
- The CνB today
- Why are we interested in its detection?
- How to detect the CνB

What is the CνB?



What is the CνB?



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- Neutrinos and electrons are kept in equilibrium through weak interactions:

$$\nu e^{\pm} \leftrightarrow \nu e^{\pm} \qquad\qquad \nu\bar{\nu} \leftrightarrow e^{+}e^{-}$$

What is the CνB?

- At equilibrium, massless species distributed according to:

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- Important quantities:

$$n \propto T^3 \qquad\qquad \rho \propto T^4$$

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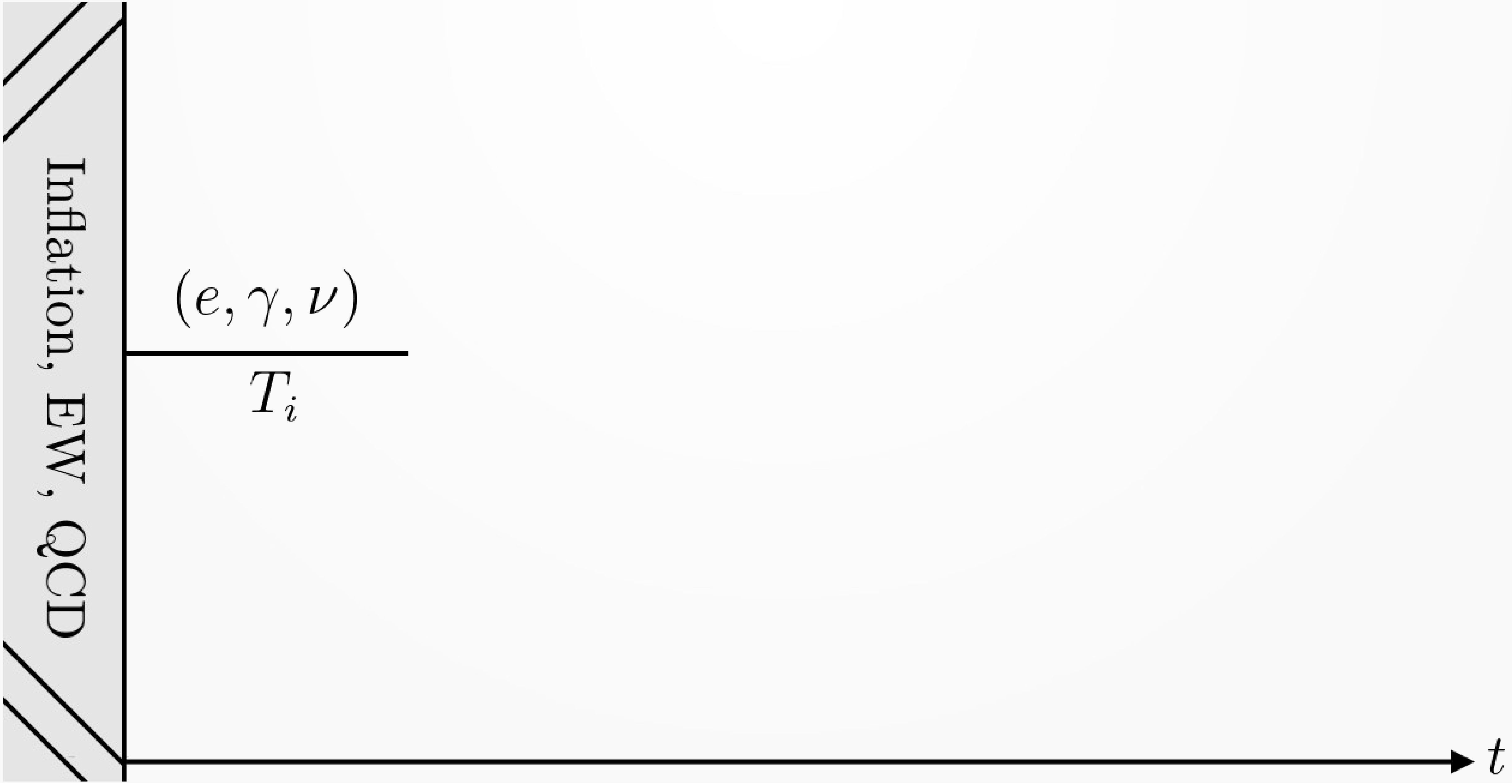

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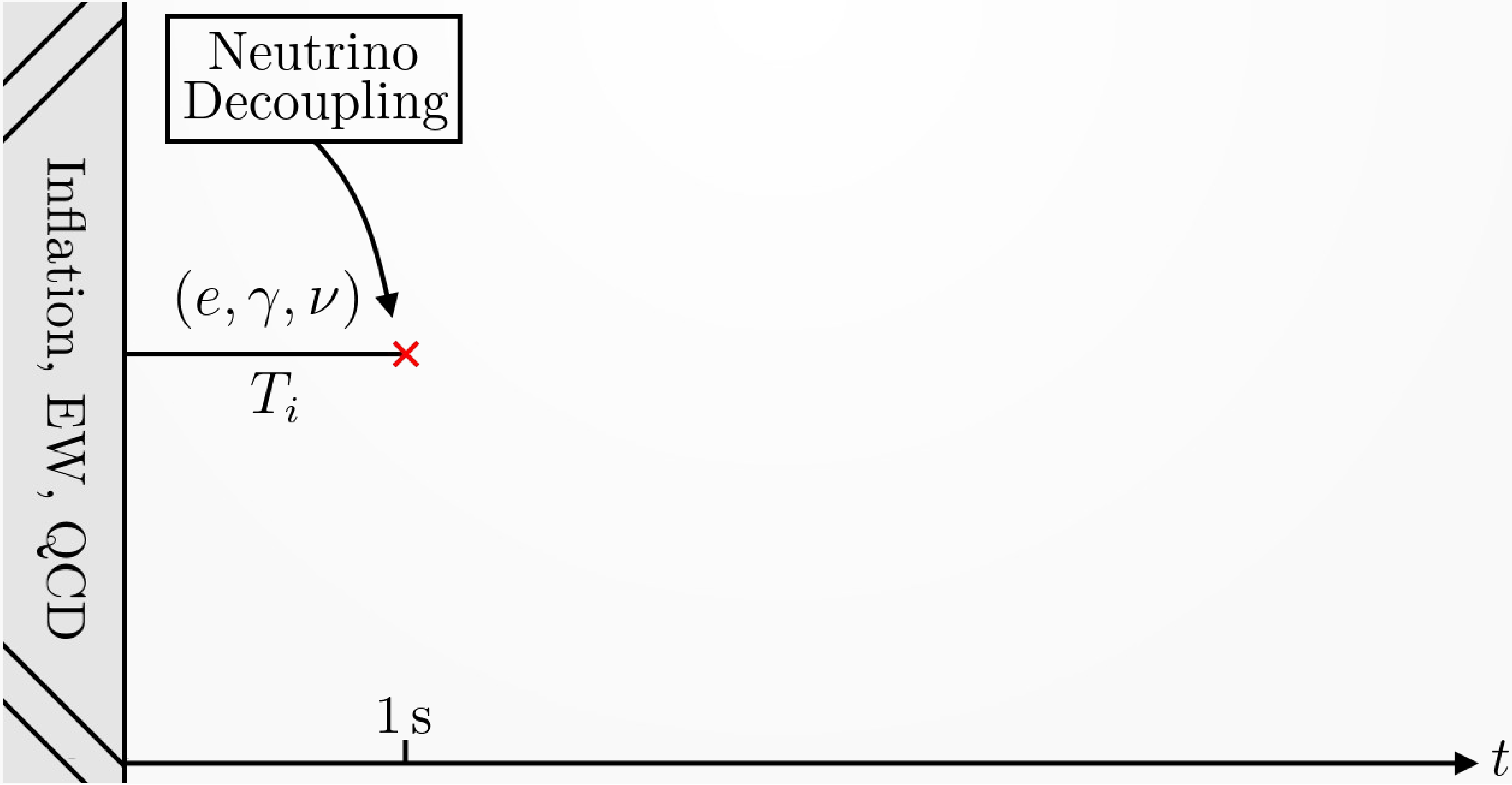

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$$t_{\rm dec} = \frac{1}{2H} \sim 1\,{\rm s}$$

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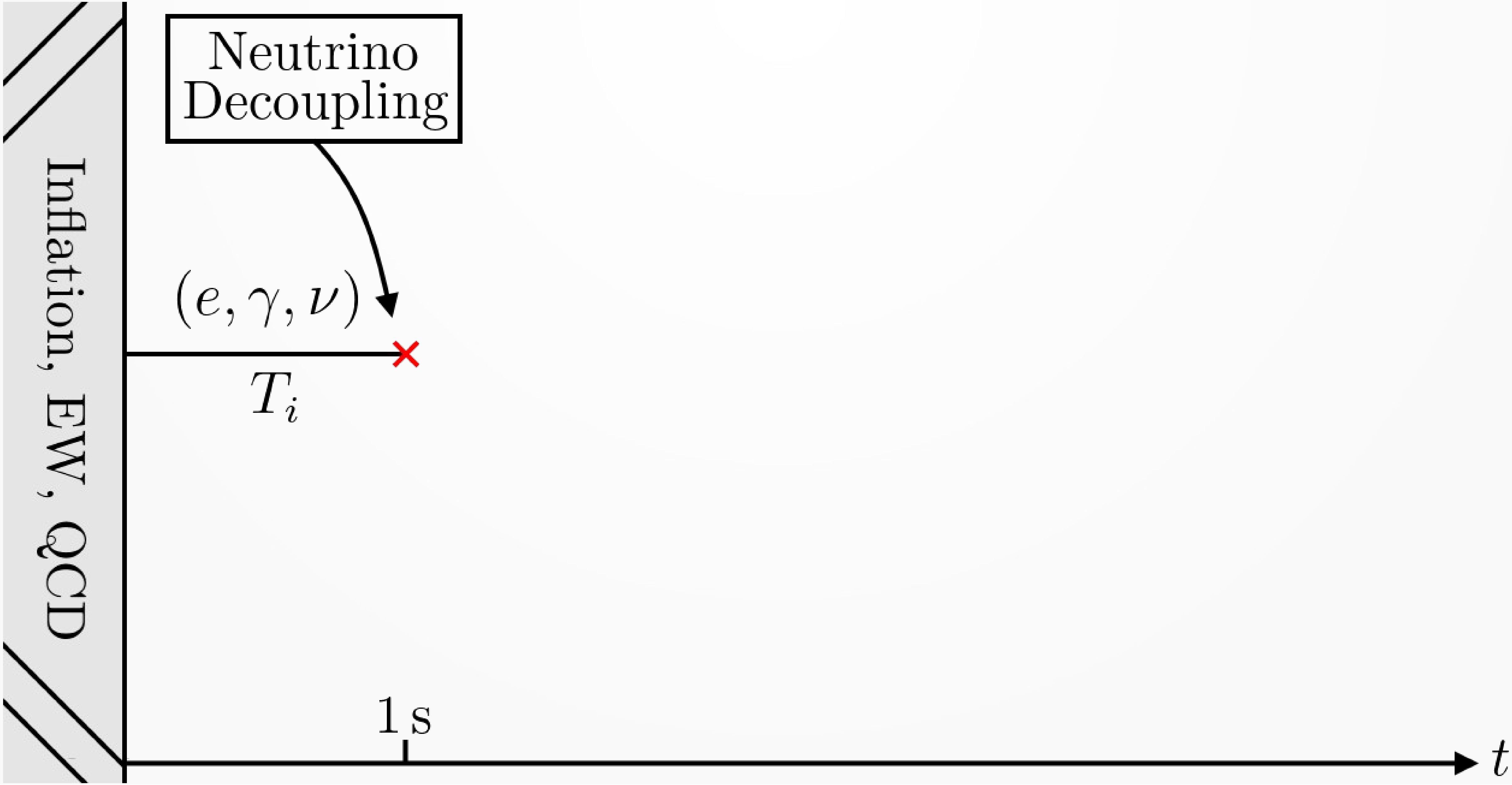

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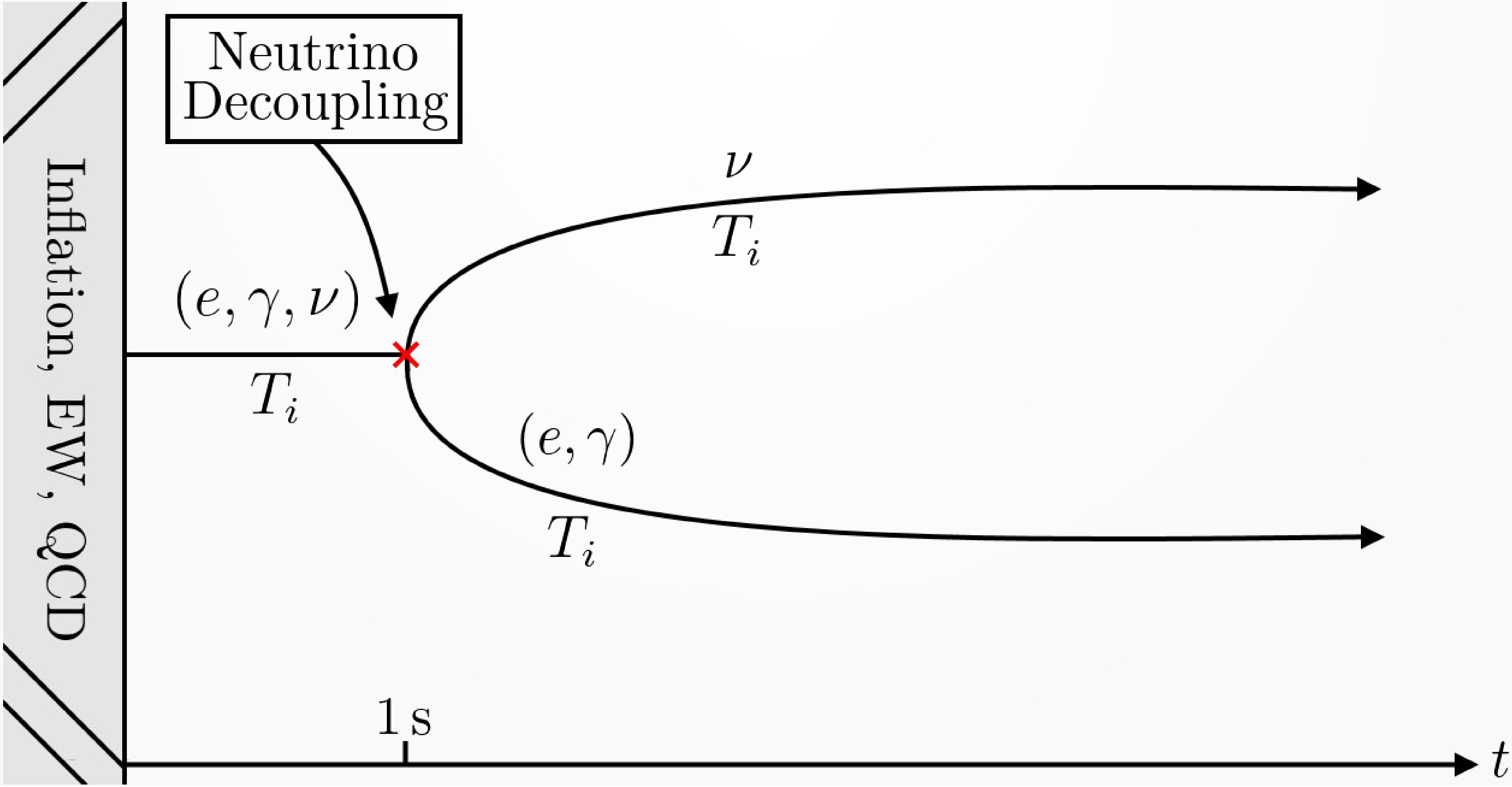

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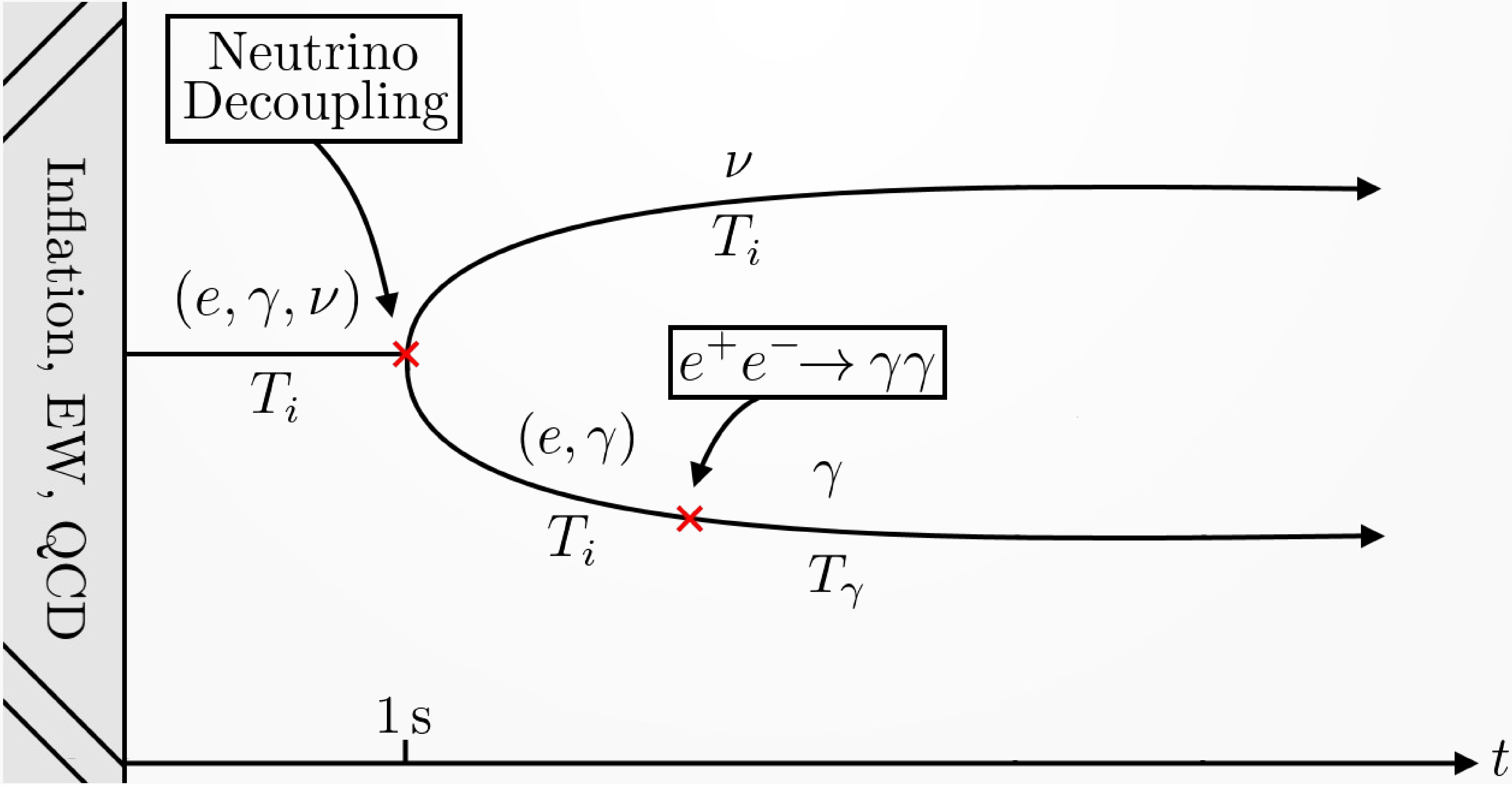

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- This process changes the photon temperature!

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$$g_s^*(T_i)T_i^3 = g_s^*(T_\gamma)T_\gamma^3$$

- In general:

$$g_s^*(T) = \sum_{\text{bosons}} g_i + \frac{7}{8}\sum_{\text{fermions}} g_i$$

What is the CνB?

- Before annihilation:

$$g_s^*(T_i) = \underbrace{2}_{\gamma} + \frac{7}{8}(\underbrace{2 \times 2}_{e})$$

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- After annihilation:

$$g_s^*(T_\gamma) = 2$$

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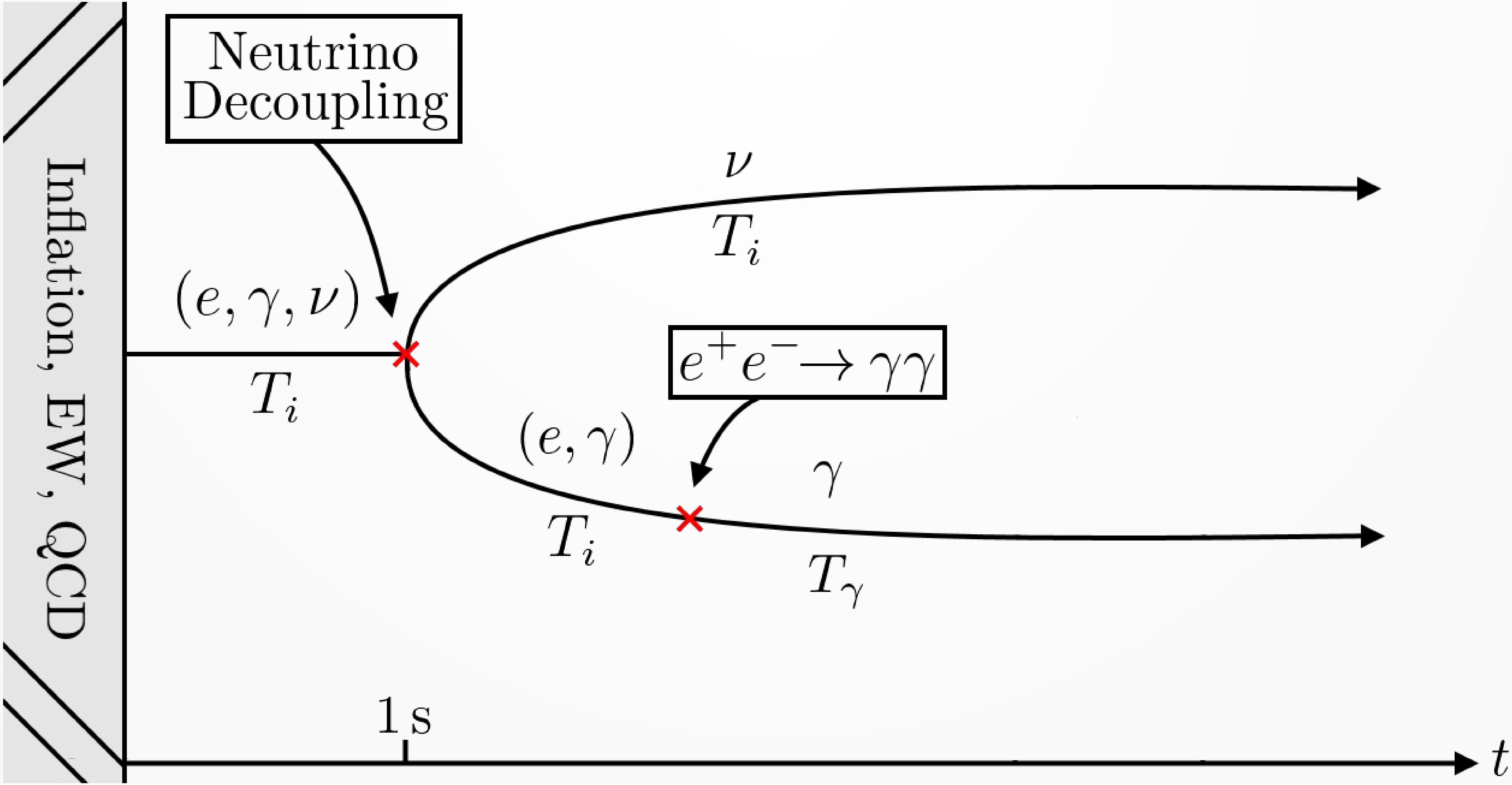
$$\frac{11}{2} T_i^3 = 2\, T_\gamma^3$$

- Recalling that the neutrinos are still at T_i :

$$\boxed{T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma}$$

What is the CνB?



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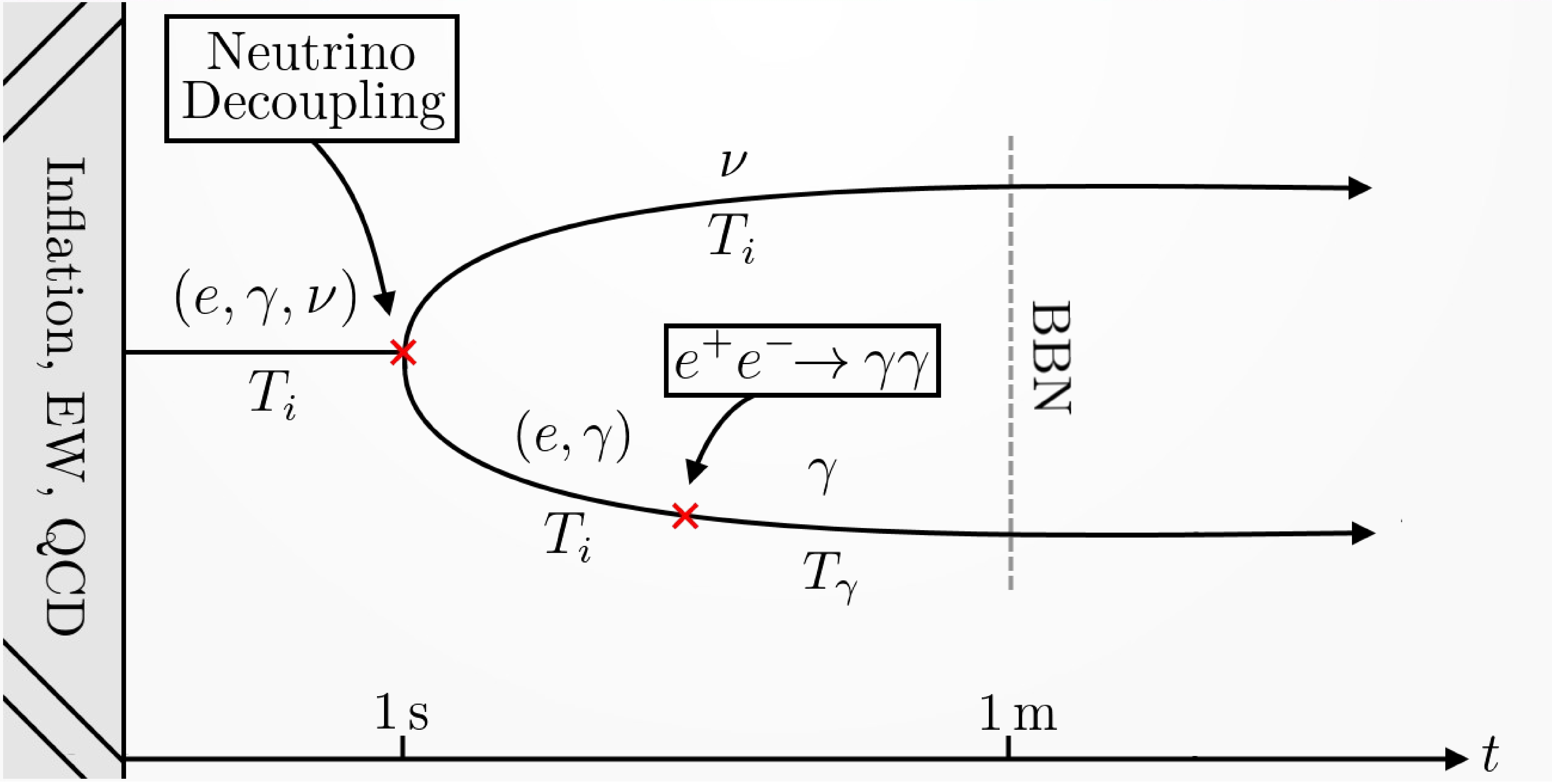

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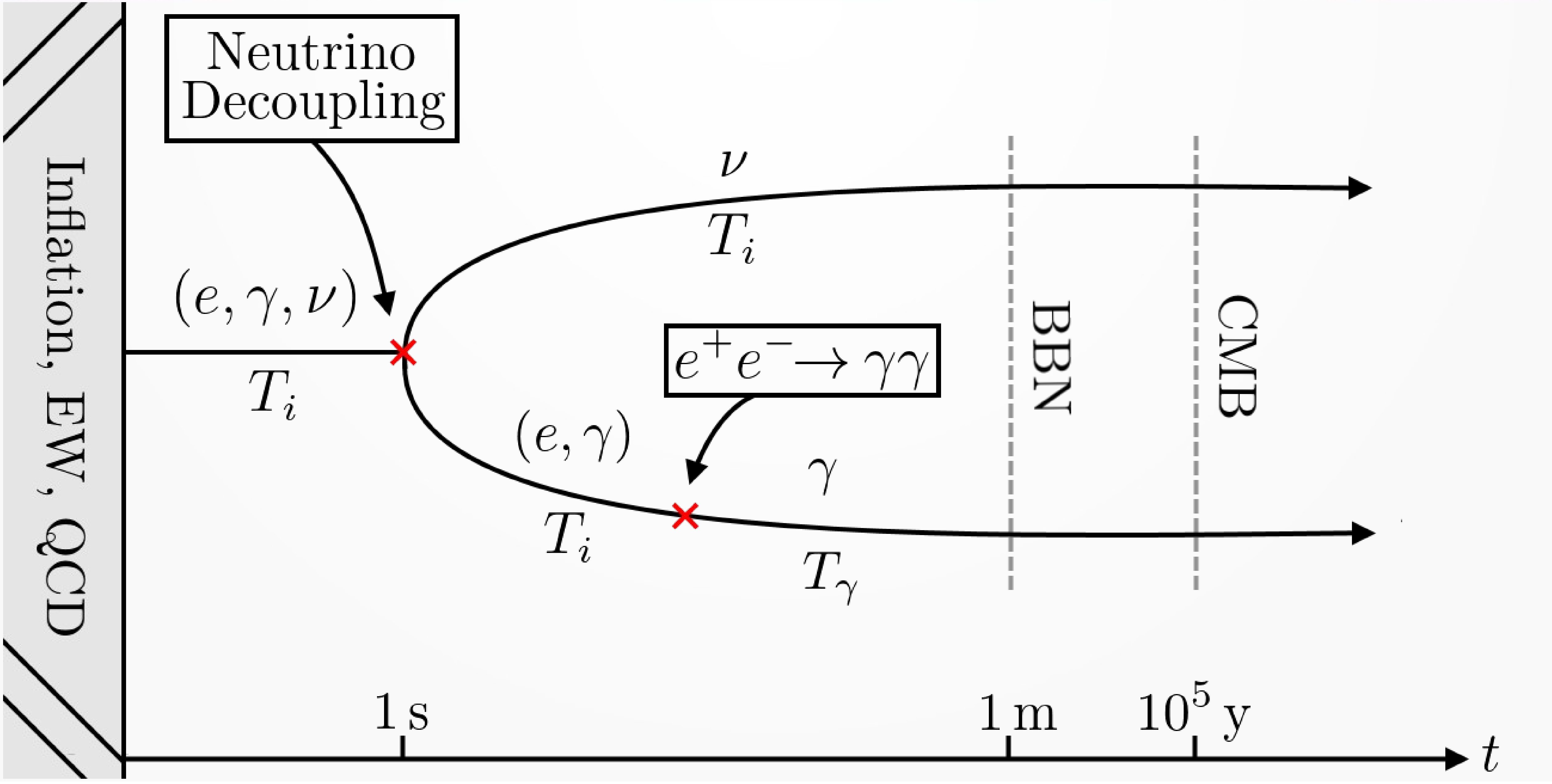

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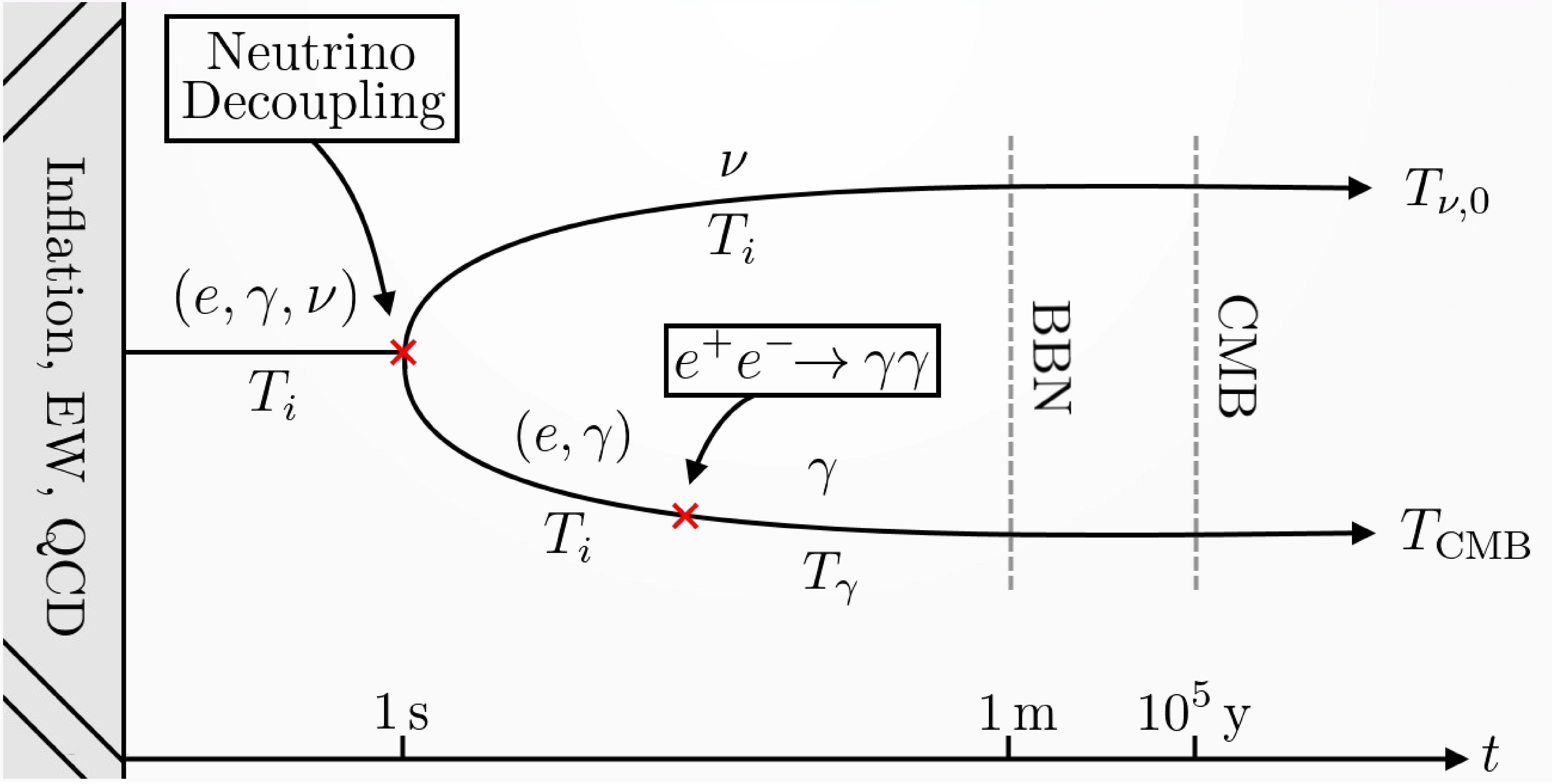

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The CνB today

- Redshifted to temperature:

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

The CνB today

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$$m_{\nu_h} \geq \begin{cases} \sqrt{\Delta m^2_{21}}, & \mathrm{NH} \\ \sqrt{\Delta m^2_{31}}, & \mathrm{IH} \end{cases}$$

The CνB today

- Redshifted to temperature:

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

- At least two neutrinos states are non-relativistic!

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The CνB today

- Redshifted to temperature:

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The CνB today

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$$|\nu_\alpha\rangle \rightarrow |U_{\alpha i}|^2 |\nu_i\rangle$$

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- These exist today as mass eigenstates:

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- Expect these to follow a massless Fermi-Dirac distribution with:

$$n_\nu = 56\,\mathrm{cm}^{-3}$$

The CνB today

- These should all be left helicity states:

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- ...but neutrinos have mass!

- This may lead to different profile, overdensities, helicity mixing etc.

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Why detect the CνB?

- Why not?

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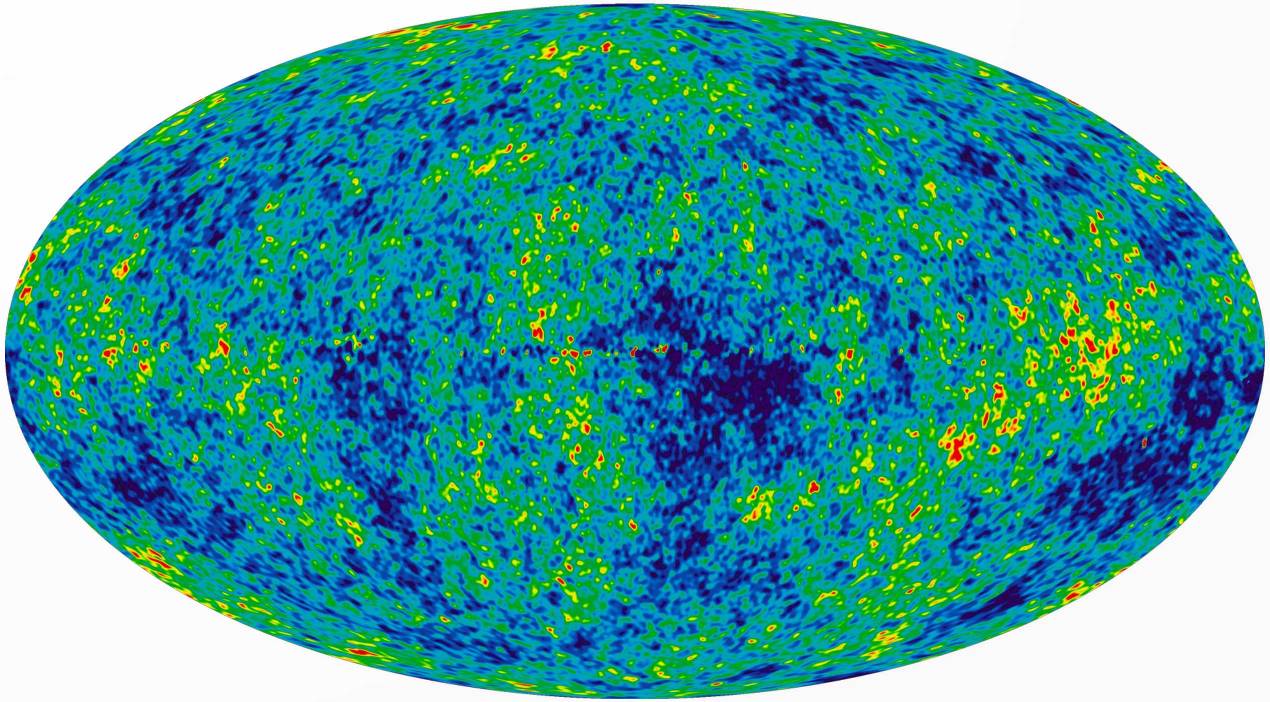
- Why not?
- Firm prediction of ΛCDM

Why detect the CνB?

- The CMB is the furthest we can currently look back through time



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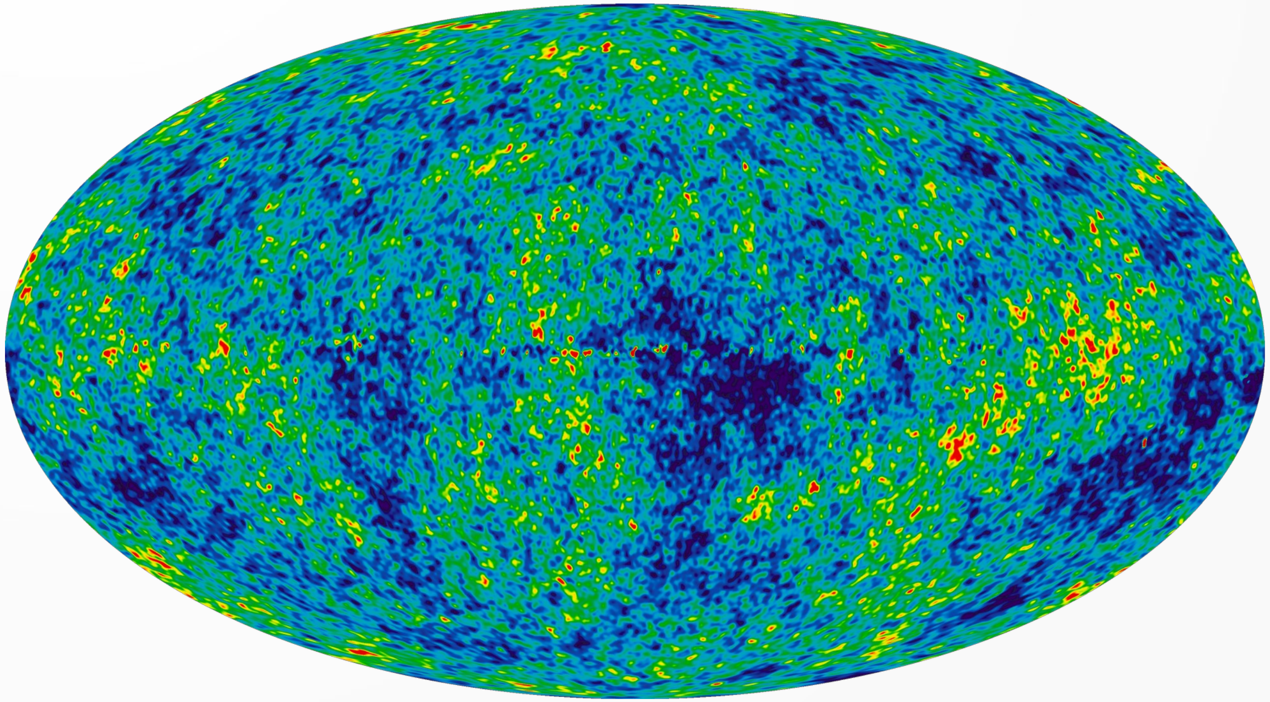

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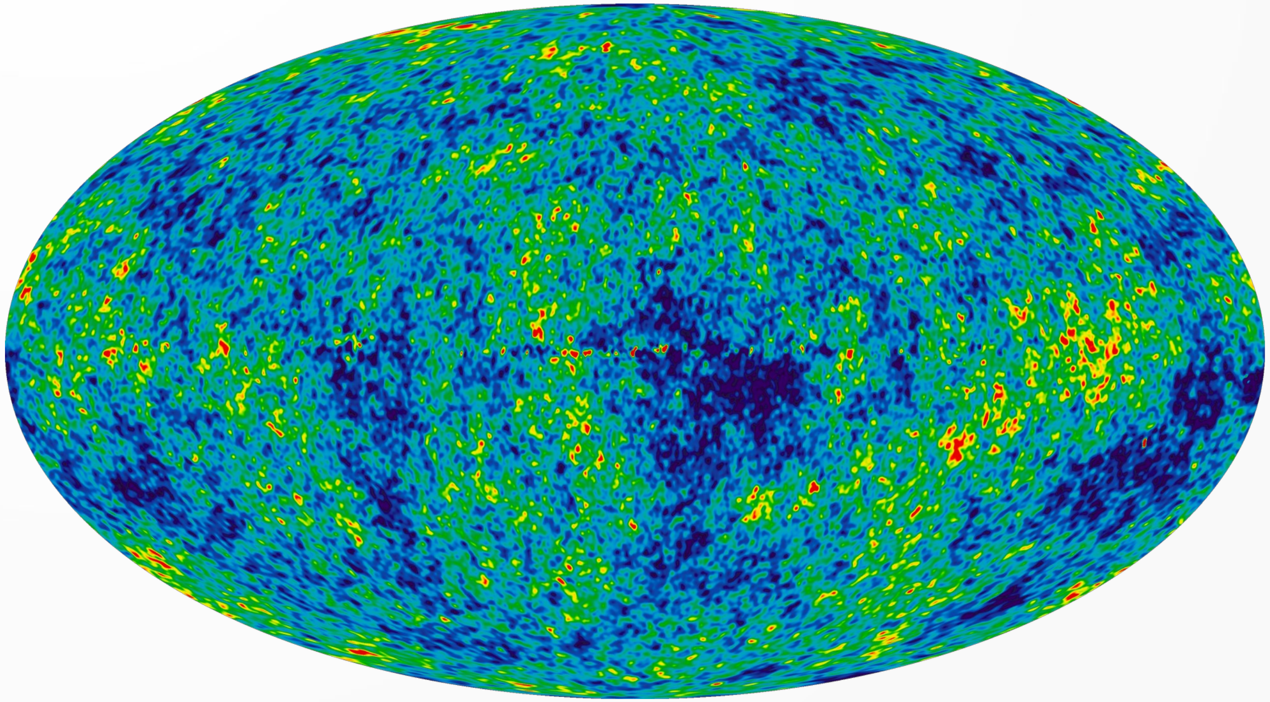
- Gain insight into BBN
- Measure lepton asymmetries



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- A rare source of non-relativistic neutrinos!
- Perhaps sensitive to the neutrino mass
- As a result, also sensitive to Dirac/Majorana nature!

$$\mathcal{L}_{\text{mass}} = -Y_{\alpha i} \overline{L}_{\alpha} \widetilde{H} \nu_{i,R} + \frac{1}{2} \overline{(\nu_{i,R})^c} (M_R^*)_{ij} \nu_{j,R} + \text{h.c.}$$

Why detect the CνB?

- Modified backgrounds

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- Neutrinos could be unstable on cosmological timeframes

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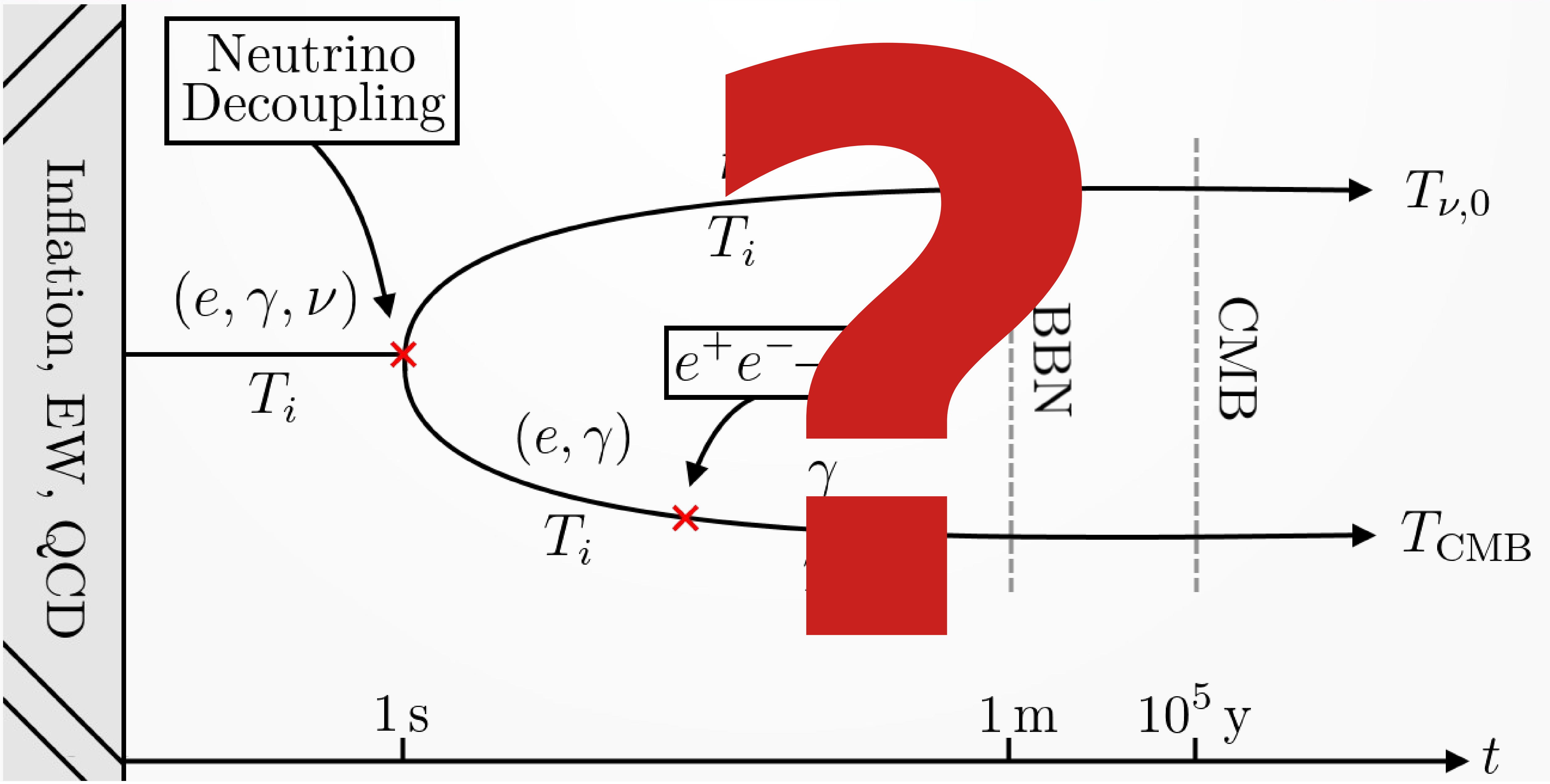
- Modified backgrounds

- Neutrinos could be unstable on cosmological timeframes

- Invisble decays to neutrinos could augment the CνB [1]

[1] Z. Chacko, P. Du, M. Geller, Phys. Rev. D **100** (2019) 1, 015050

Why detect the CνB?



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How (not) to detect the CνB

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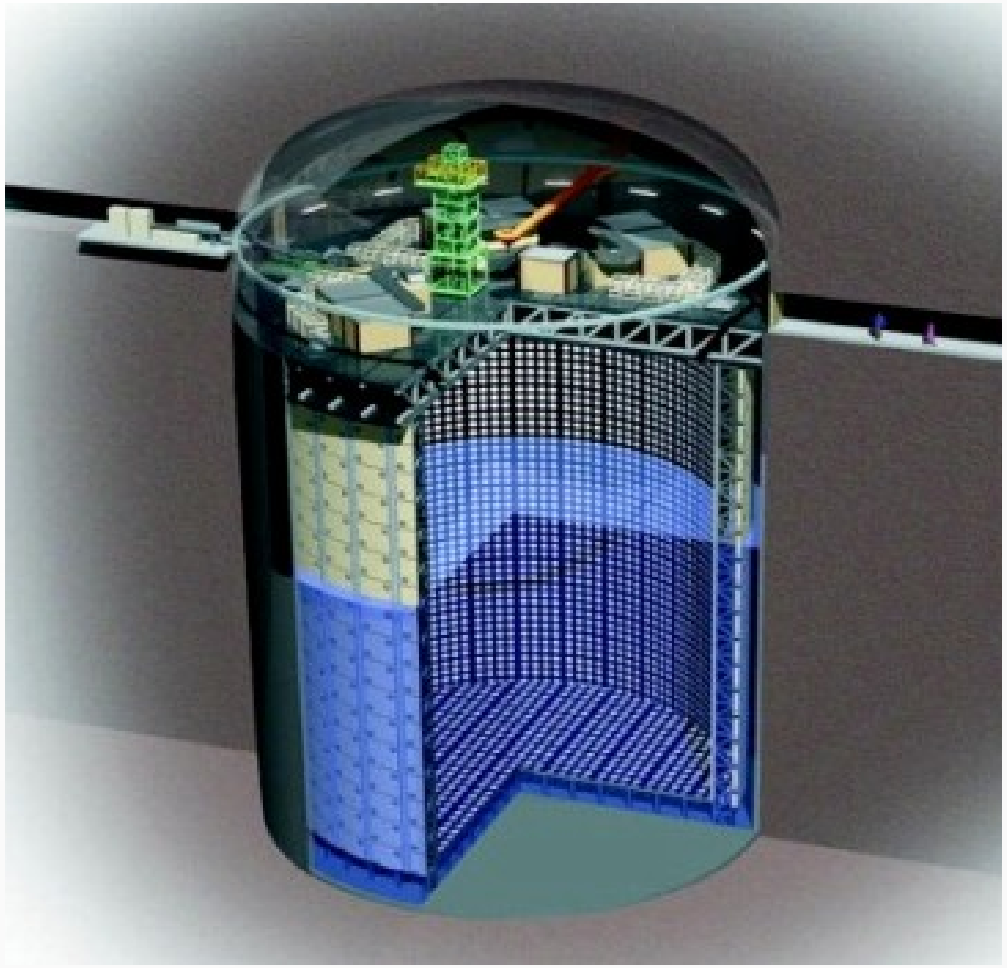
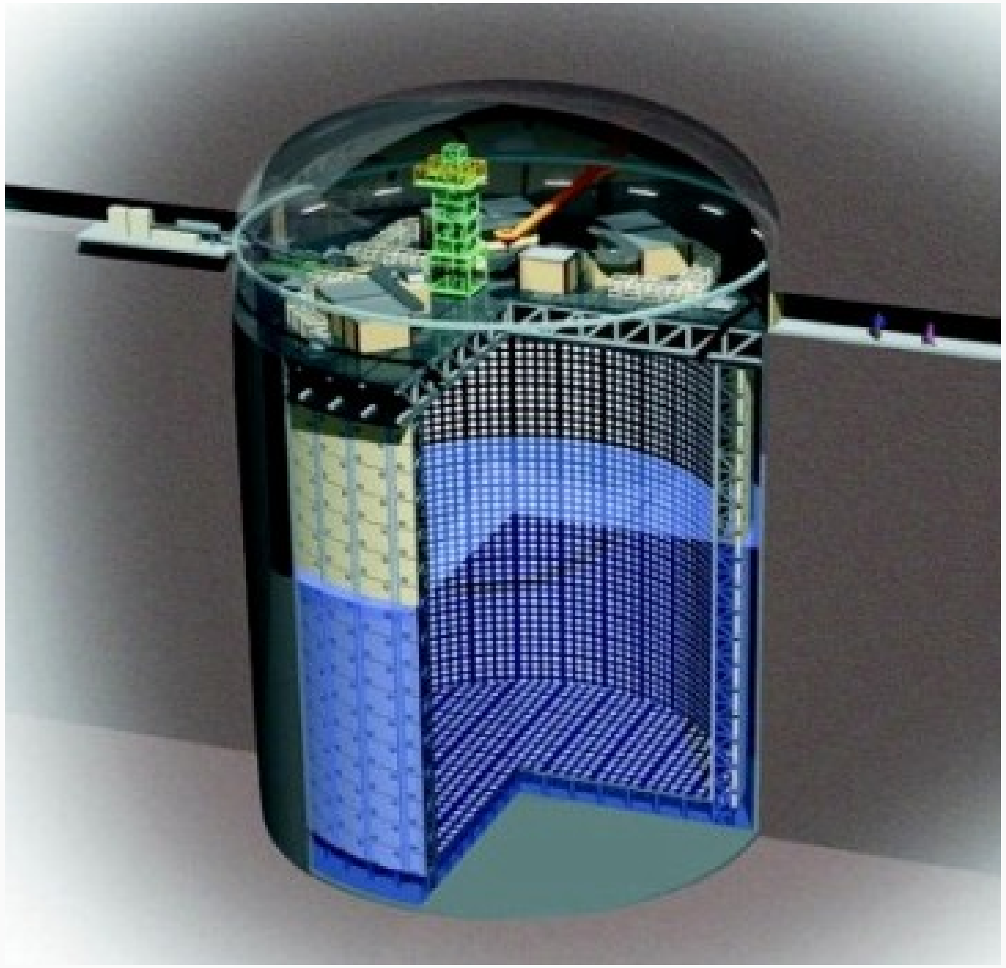


How (not) to detect the CνB

- Existing techniques:

- Inverse β-decay



How (not) to detect the CνB

- Existing techniques:
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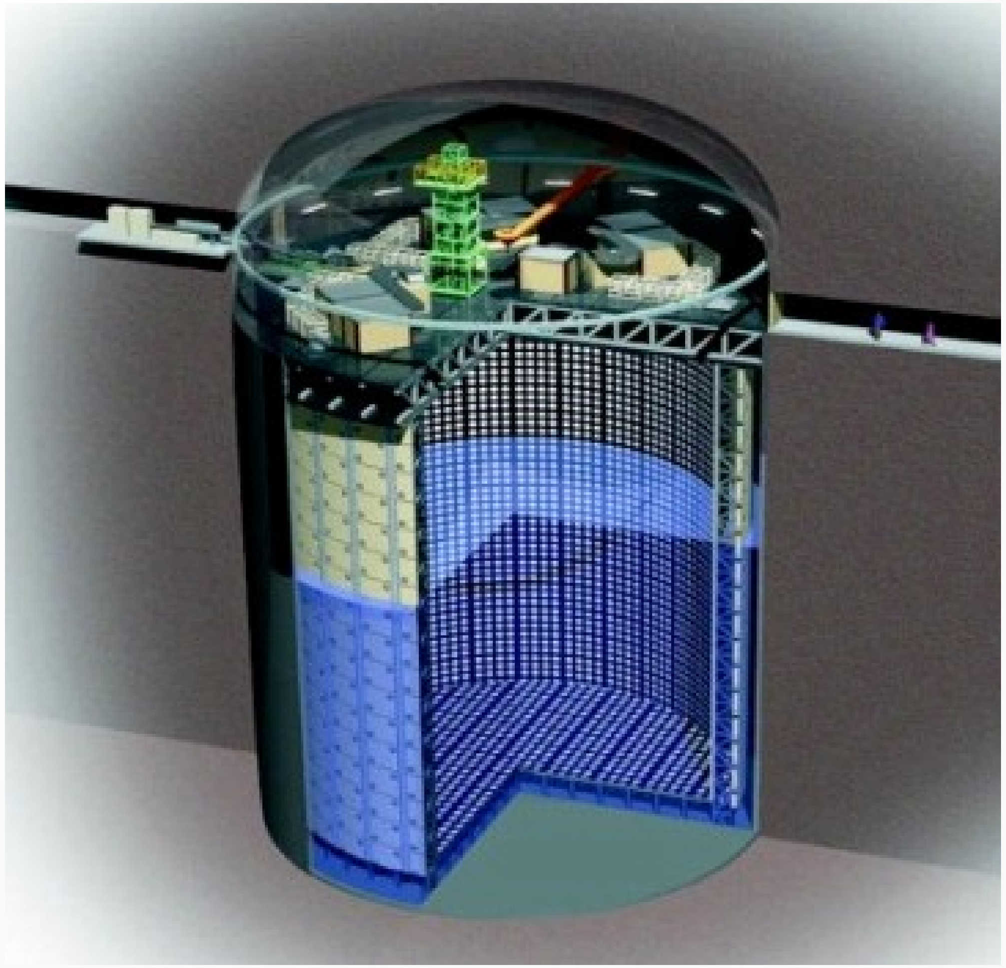

How (not) to detect the CνB

- Existing techniques:
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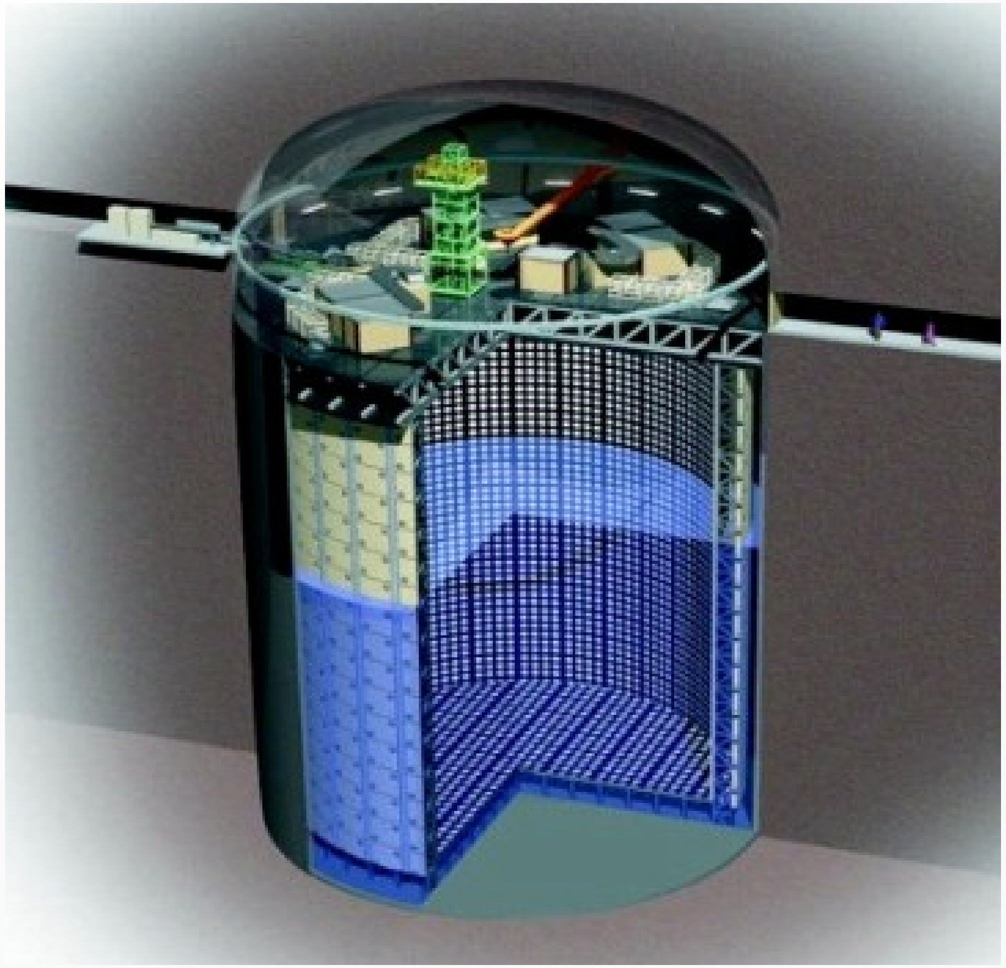

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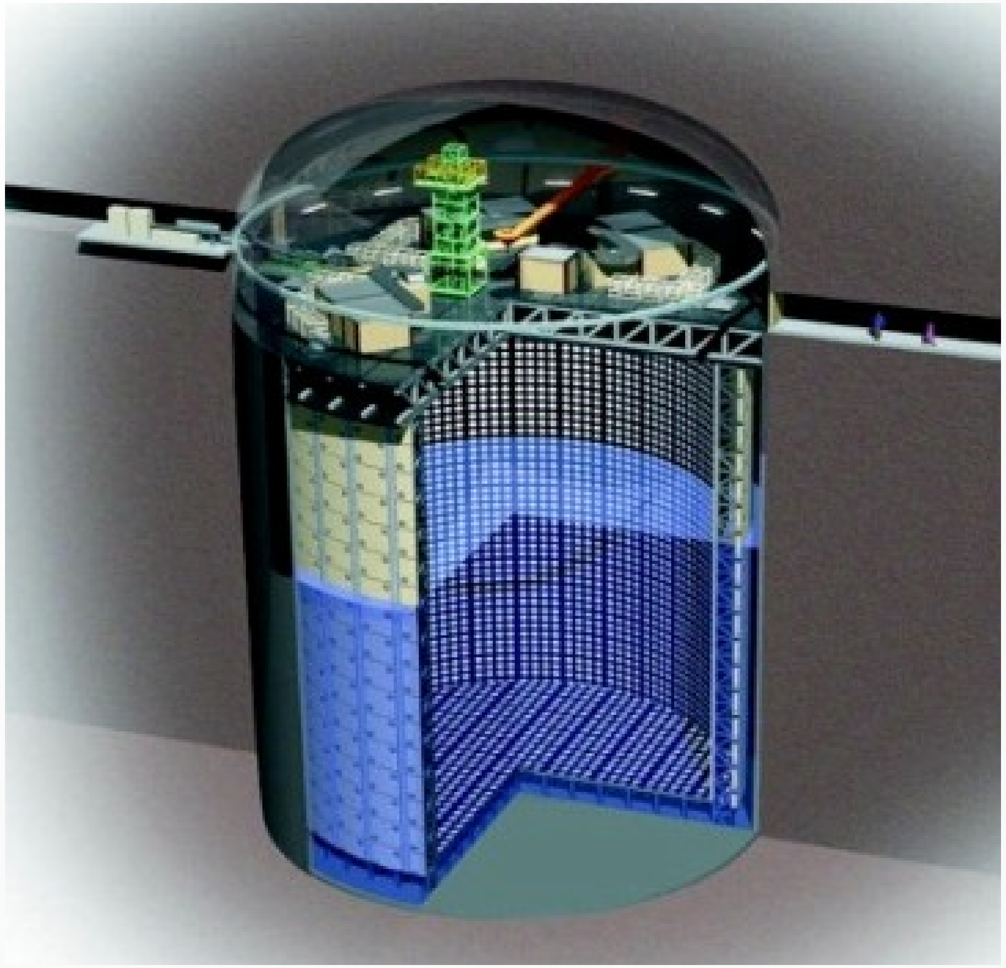

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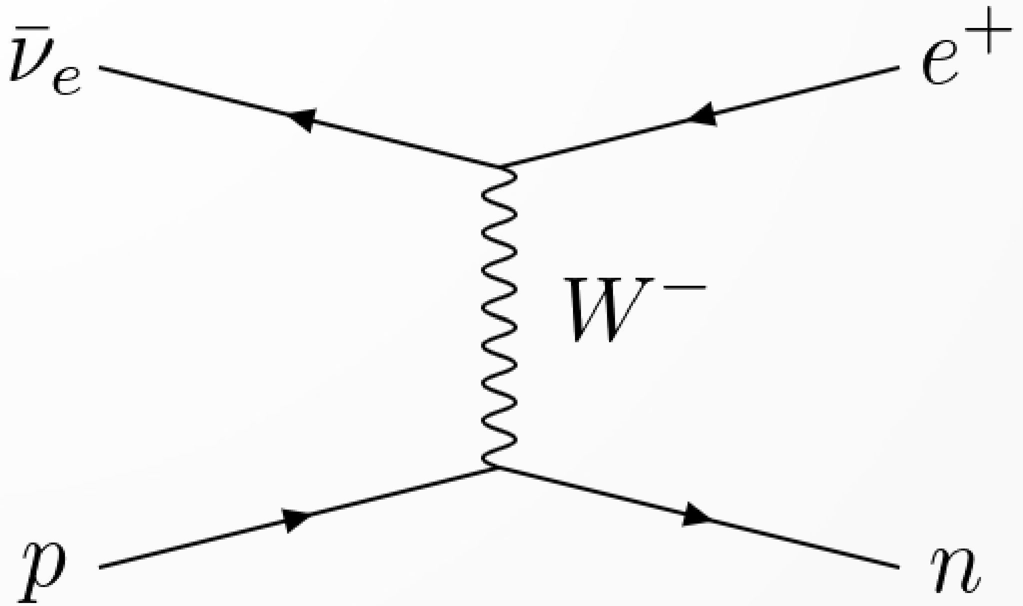
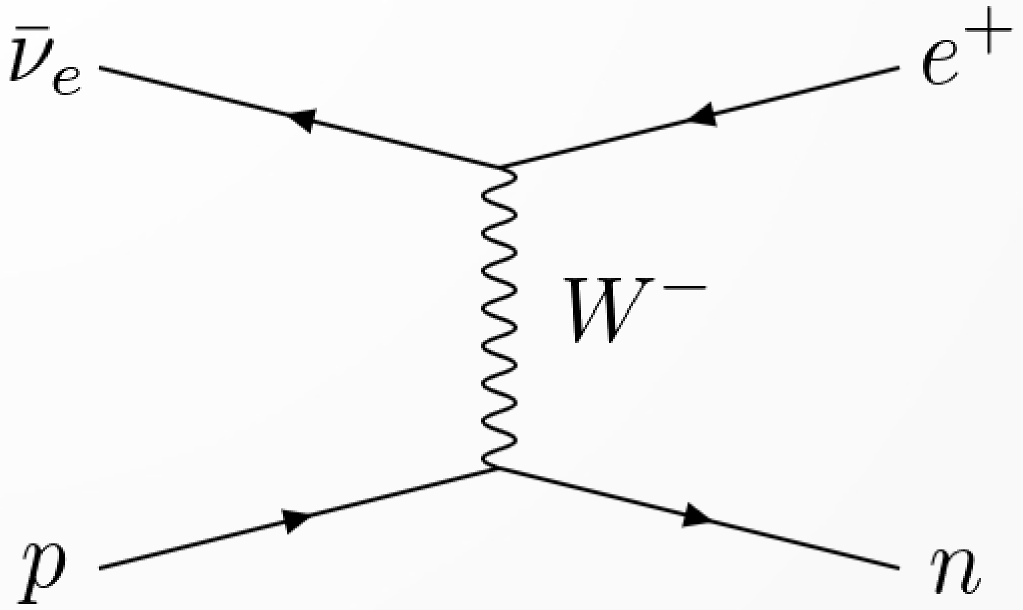


How (not) to detect the CνB

- Inverse β-decay:

$$p + \bar{\nu}_e + (1.8\,\mathrm{MeV}) \to n + e^+$$



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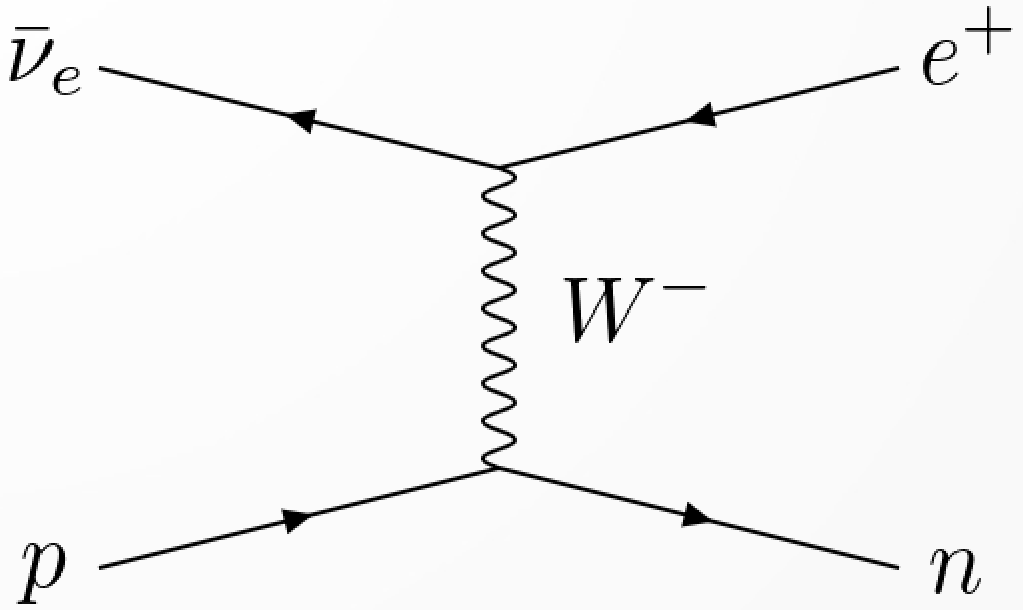

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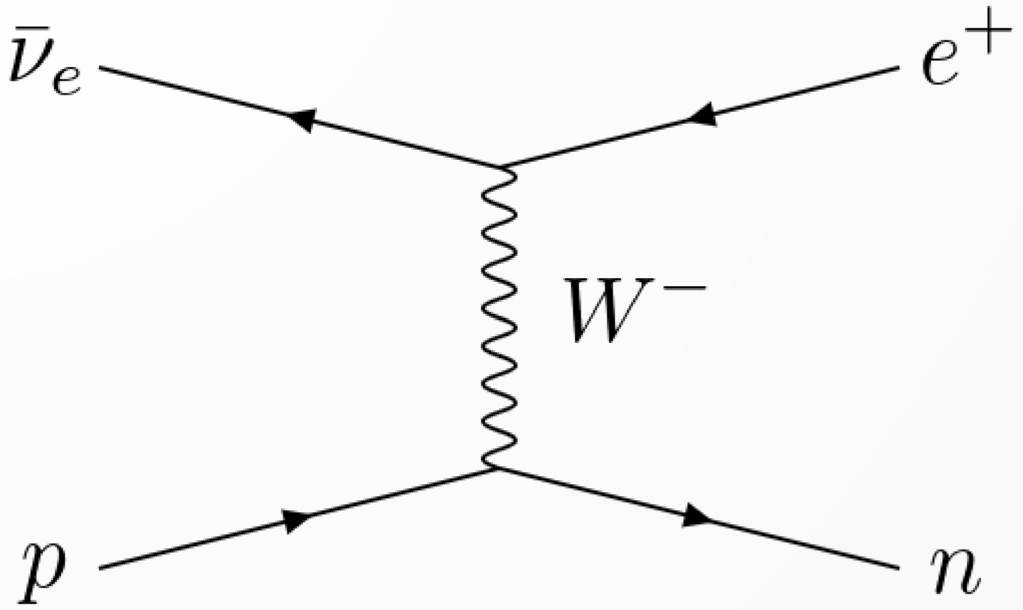
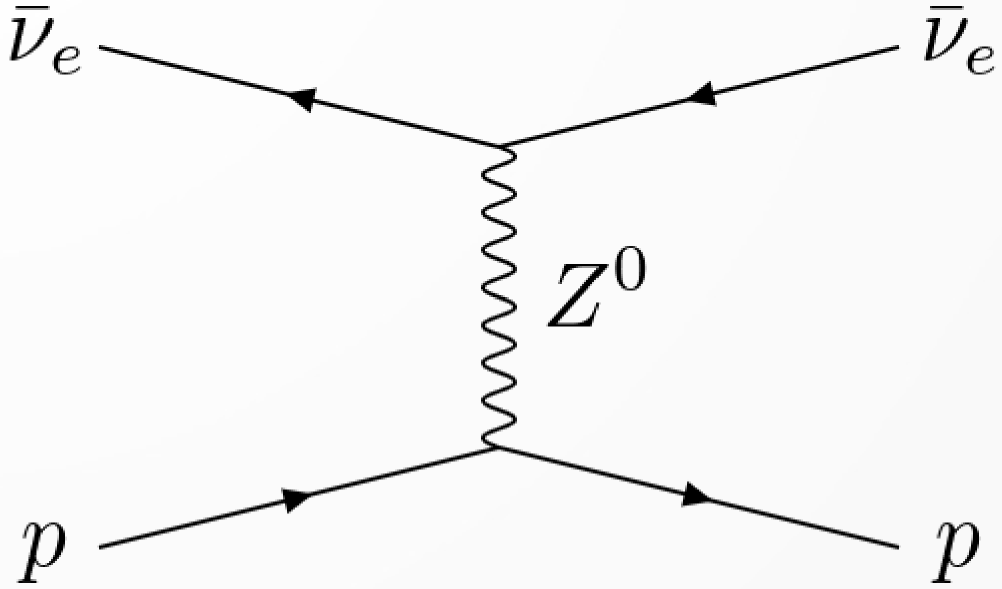


How (not) to detect the CνB

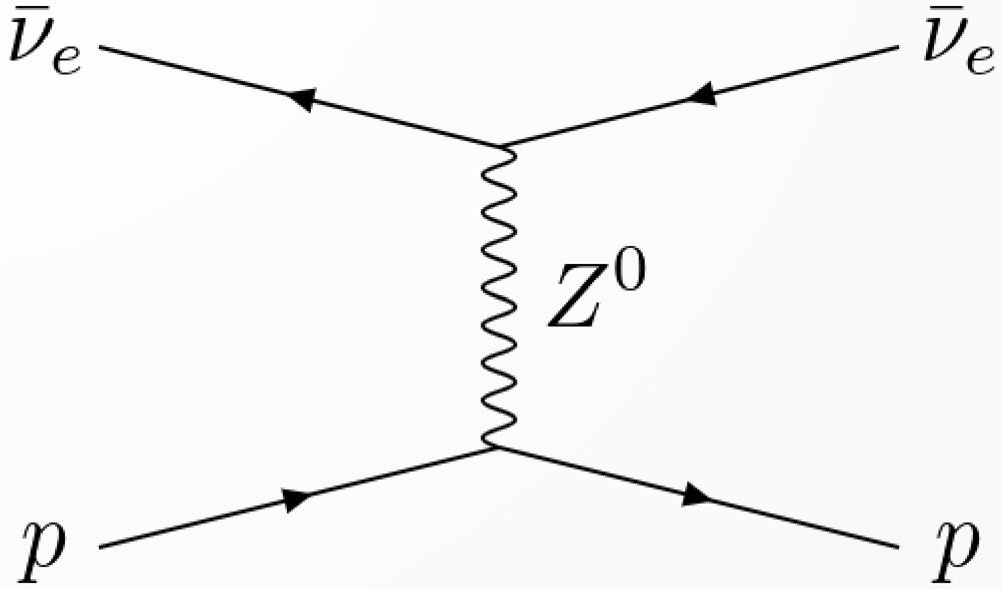
- Neutral current?



How (not) to detect the CνB

- Neutral current?

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



How (not) to detect the CνB

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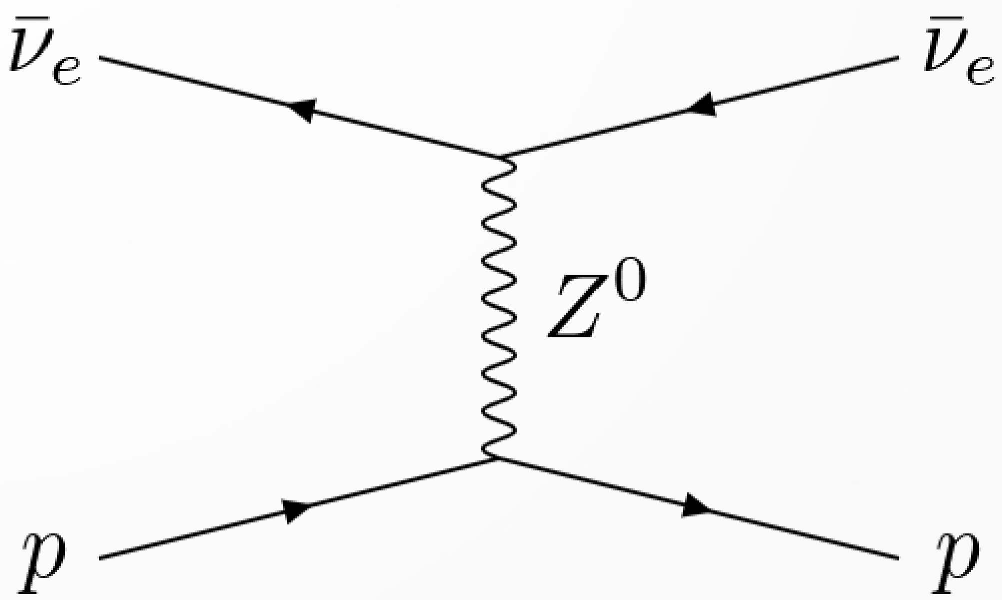
$$\frac{\Gamma}{N_T} \simeq 10^{-39}\,\mathrm{y}^{-1}$$



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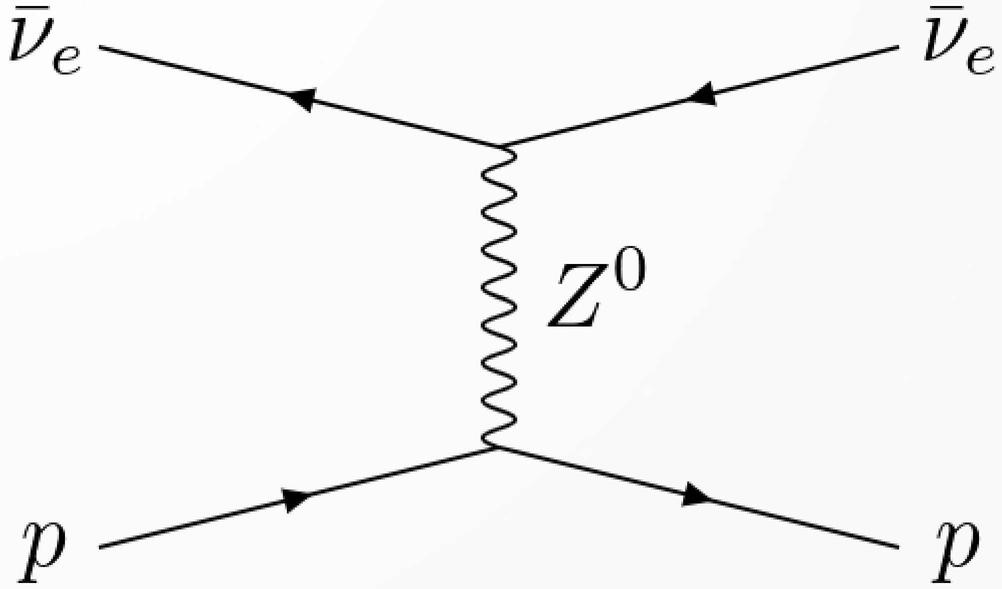
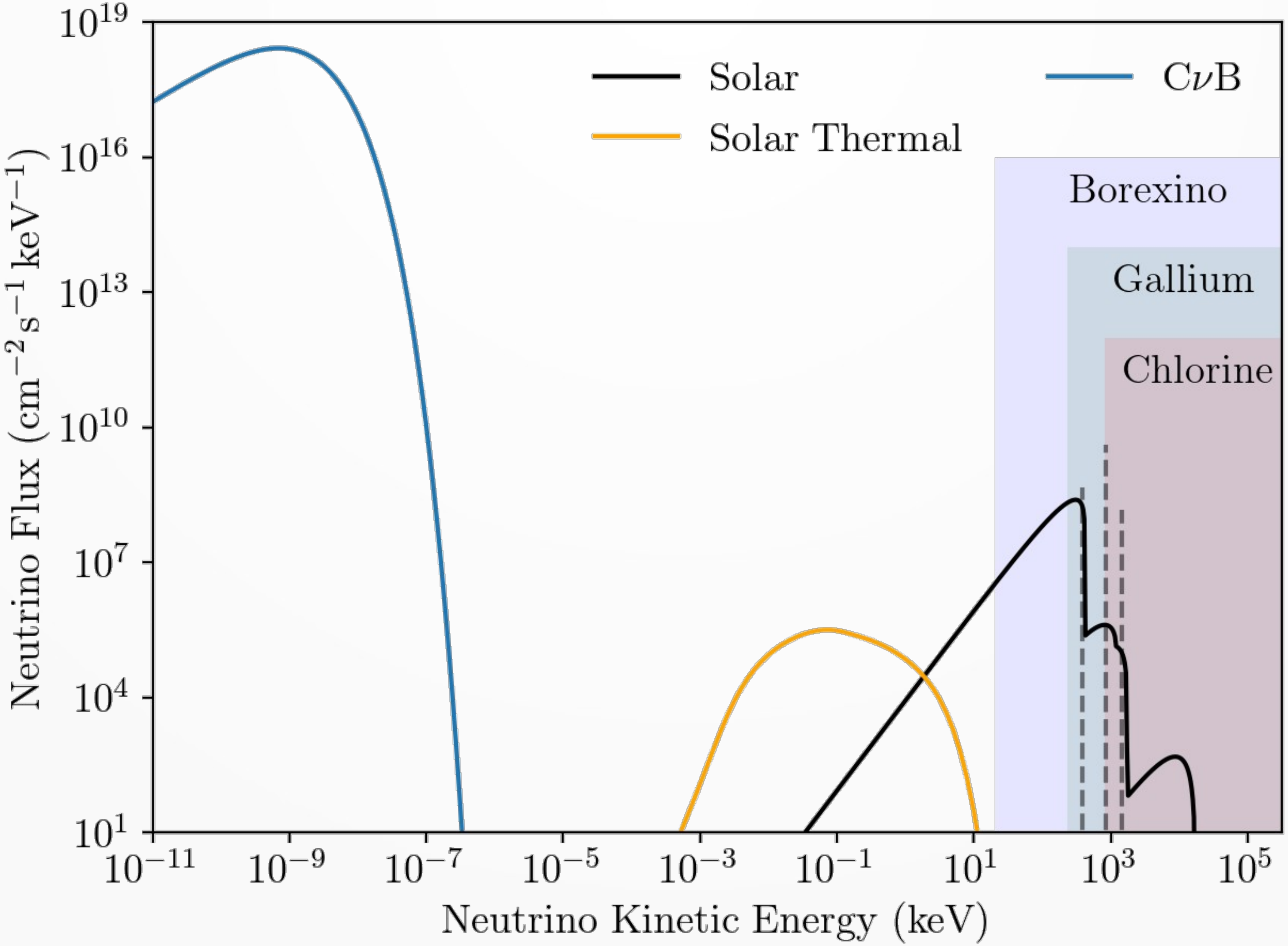


- 10^{14} kg for just one event per year!

How (not) to detect the CνB



How to detect the CνB

- Nobody knows for sure!

How to detect the CνB

- Threshold:
  -
  -
- Event rate:
  -
  -

How to detect the CνB

- Threshold:
  - Look for thresholdless process
  -
- Event rate:
  -
  -

How to detect the CνB

- Threshold:
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  - Find some way to bridge it

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  -
  -

How to detect the CνB

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  - Use a huge number of targets
  -

How to detect the CνB

- Threshold:
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  - Find some way to bridge it

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

How to detect the CνB

Direct

Indirect

How to detect the CνB

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- See the product of a CνB interaction:

Indirect

How to detect the CνB

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- See the product of a CνB interaction:

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- See a consequence of the CνB:

How to detect the CνB

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- May be due to some other effect

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- *Something appearing*

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Indirect

- See a consequence of the CνB:

$$p + \bar{\nu}_e \rightarrow n + e^+$$

- May be due to some other effect

- *Something disappearing*

How to detect the CνB

Direct

Indirect

How to detect the CνB

Direct

- Unstable nuclei

Indirect

How to detect the CνB

Direct

- Unstable nuclei
- Coherent scattering

Indirect

How to detect the CνB

Direct

- Unstable nuclei
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- Stodolsky effect

Indirect

How to detect the CνB

Direct

- Unstable nuclei
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- ...

Indirect

How to detect the CνB

Direct

- Unstable nuclei
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- ...

Indirect

- Cosmic ray attenuation

How to detect the CνB

Direct

- Unstable nuclei
- Coherent scattering
- Stodolsky effect
- ...

Indirect

- Cosmic ray attenuation
- Pauli blocking

How to detect the CνB

Direct

- Unstable nuclei
- Coherent scattering
- Stodolsky effect
- ...

Indirect

- Cosmic ray attenuation
- Pauli blocking
- Neutron star cooling

How to detect the CνB

Direct

- Unstable nuclei
- Coherent scattering
- Stodolsky effect
- ...

Indirect

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Summary

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- Detecting the CνB could reveal a wealth of new physics
- Incredibly challenging to detect
- Many exciting proposals to detect the CνB!

Thank you!
Questions?