Relic neutrinos at accelerator experiments

Jack Shergold

& Martin Bauer; 2104.12784

Phys. Rev. D 104 (2021), 083039

IP3

Durham University

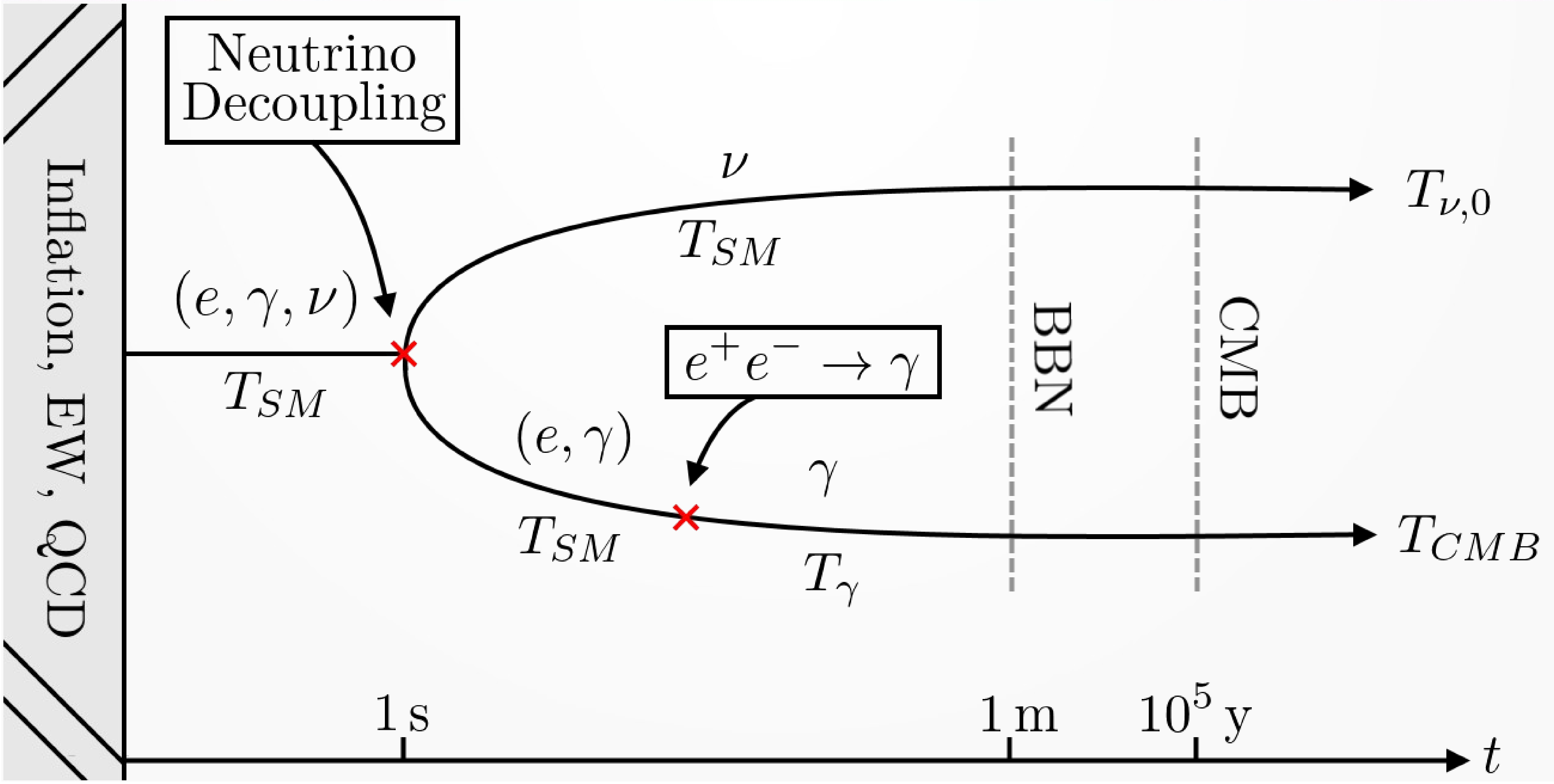
Contents

- What is the CνB?
- PTOLEMY(-on-a-beam)
- Resonant neutrino capture
- Experimental challenges

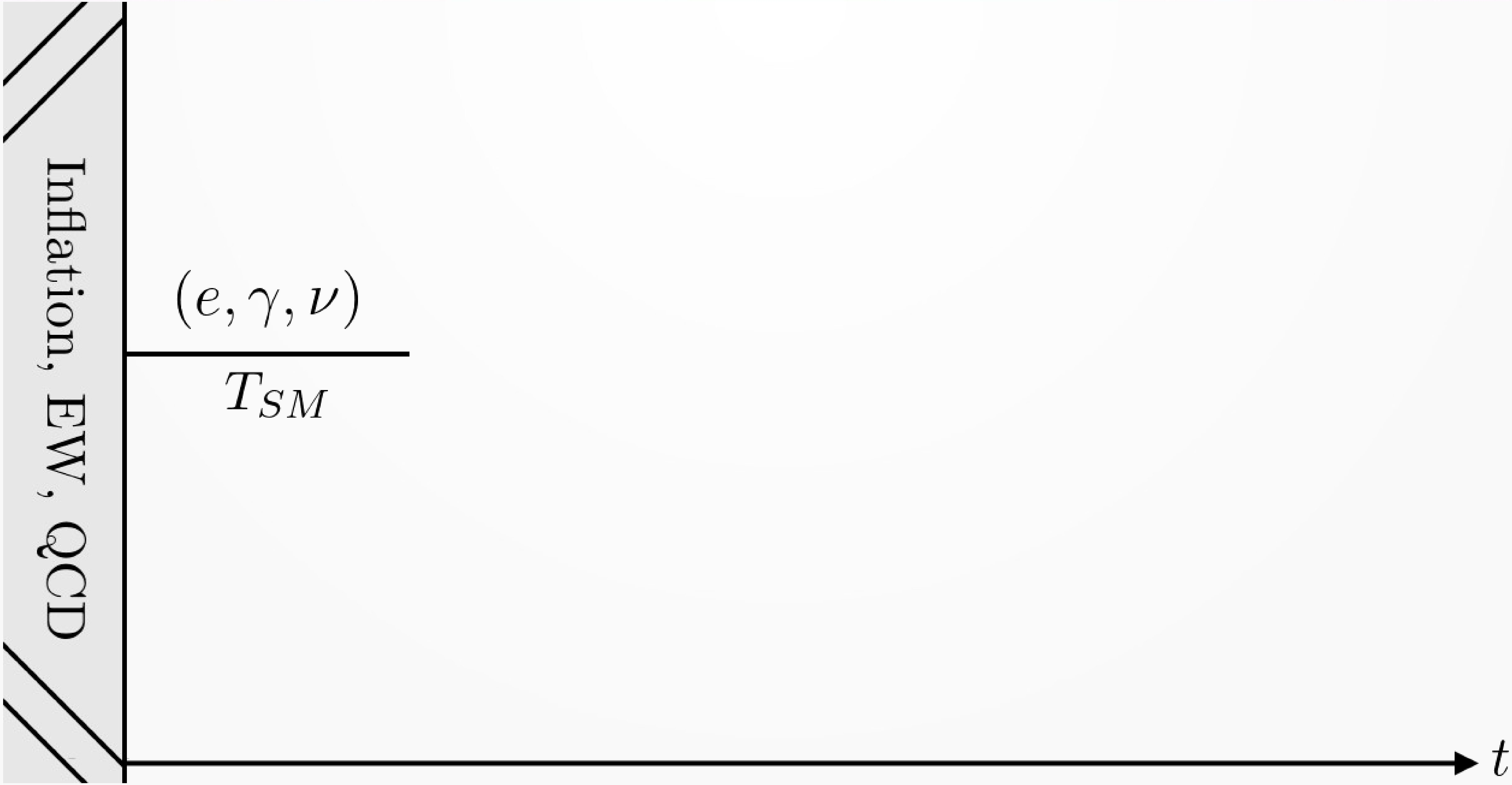
Contents

- What is the CνB? ⇦
- PTOLEMY(-on-a-beam)
- Resonant neutrino capture
- Experimental challenges

What is the CνB?



What is the CνB?



What is the CνB?

- Electrons and photons are kept in equilibrium through EM interactions:

$$e + \gamma \rightarrow e + \gamma \qquad e^+ + e^- \leftrightarrow \gamma$$

What is the CνB?

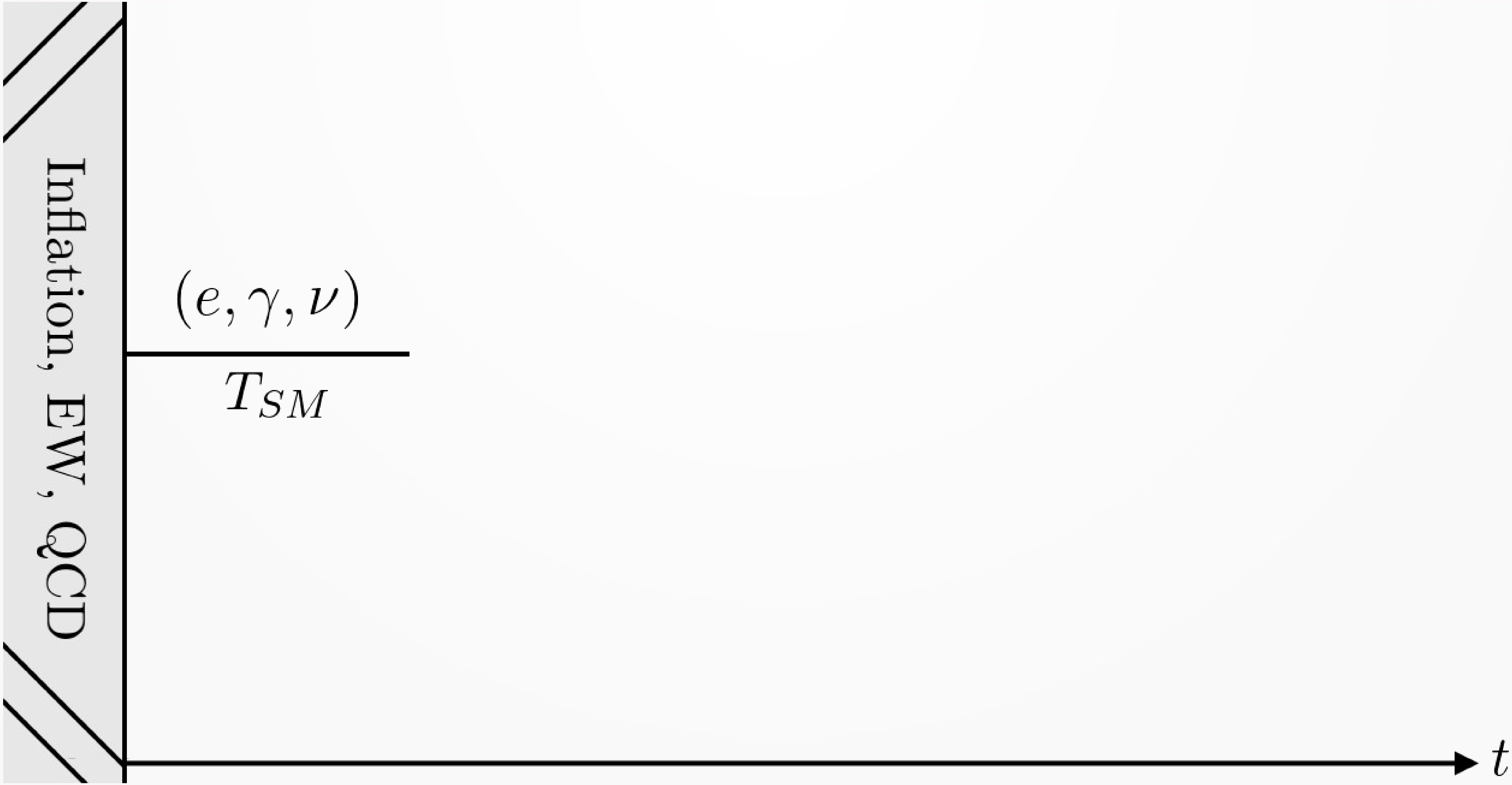
- Electrons and photons are kept in equilibrium through EM interactions:

$$e + \gamma \rightarrow e + \gamma \qquad e^+ + e^- \leftrightarrow \gamma$$

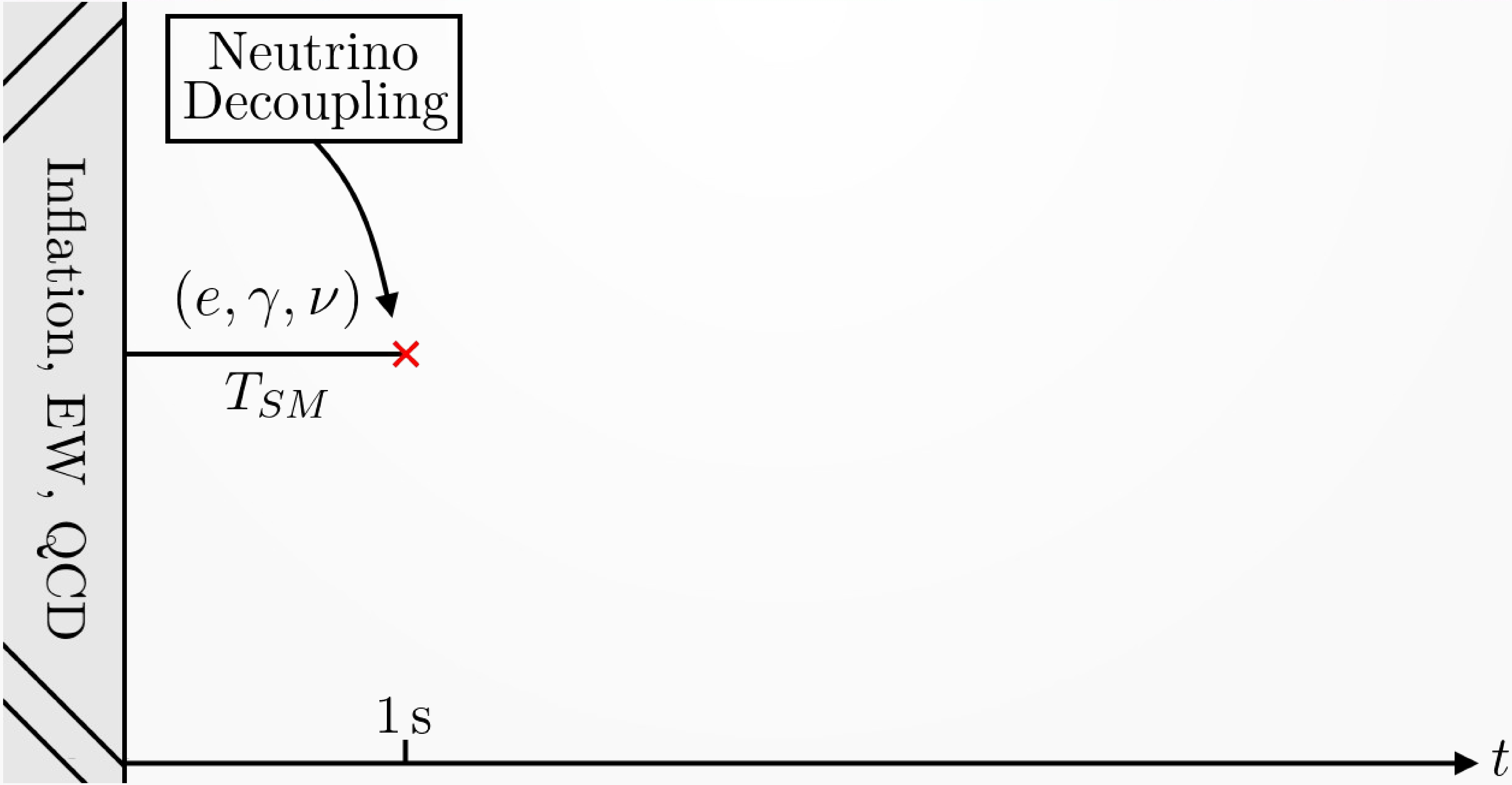
- Neutrinos and electrons are kept in equilibrium through weak interactions:

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

What is the CνB?



What is the CνB?



What is the CνB?

- Freeze-out happens when:

$$\Gamma_\nu = H$$

What is the CνB?

- Freeze-out happens when:

$$\Gamma_\nu = H$$

- Neutrino interaction rate is $\Gamma_\nu \propto \sigma_\nu n_\nu$

What is the CνB?

- Freeze-out happens when:

$$\Gamma_\nu = H$$

- Neutrino interaction rate is $\Gamma_\nu \propto \sigma_\nu n_\nu$

$$\sigma_\nu \propto G_F^2 T_{SM}^2$$

What is the CνB?

- Freeze-out happens when:

$$\Gamma_\nu = H$$

- Neutrino interaction rate is $\Gamma_\nu \propto \sigma_\nu n_\nu$

$$\sigma_\nu \propto G_F^2 T_{SM}^2 \qquad\qquad n_\nu \propto \int \frac{d^3 p_\nu}{e^{\frac{p_\nu}{T_\nu}} + 1} \propto T_{SM}^3$$

What is the CνB?

- Freeze-out happens when:

$$\Gamma_\nu = H$$

- Neutrino interaction rate is $\Gamma_\nu \propto G_F^2 T_{SM}^5$

What is the CνB?

- Freeze-out happens when:

$$\Gamma_\nu = H$$

- Neutrino interaction rate is $\Gamma_\nu \propto G_F^2 T_{SM}^5$

- Hubble parameter scales as $H^2 \propto G_N \rho$

What is the CνB?

- Freeze-out happens when:

$$\Gamma_\nu = H$$

- Neutrino interaction rate is $\Gamma_\nu \propto G_F^2 T_{SM}^5$

- Hubble parameter scales as $H^2 \propto G_N \rho$

$$\rho \propto \sum_{e,\gamma,\nu} \int \frac{p_i \, d^3 p_i}{e^{\frac{p_i}{T_i}} \pm 1} \propto T_{SM}^4$$

What is the CνB?

- Freeze-out happens when:

$$\Gamma_\nu = H$$

- Neutrino interaction rate is $\Gamma_\nu \propto G_F^2 T_{SM}^5$

- Hubble parameter scales as $H^2 \propto G_N T_{SM}^4$

What is the CνB?

- Freeze-out happens when:

$$G_F^2\, T_{\rm dec}^5 \simeq \sqrt{G_N}\, T_{\rm dec}^2$$

What is the CνB?

- Freeze-out happens when:

$$G_F^2\, T_{\rm dec}^5 \simeq \sqrt{G_N}\, T_{\rm dec}^2$$

$$\implies \quad T_{\rm dec} \sim \left(\frac{\sqrt{G_N}}{G_F^2}\right)^{\frac{1}{3}} \sim 1\,\mathrm{MeV}$$

What is the CνB?

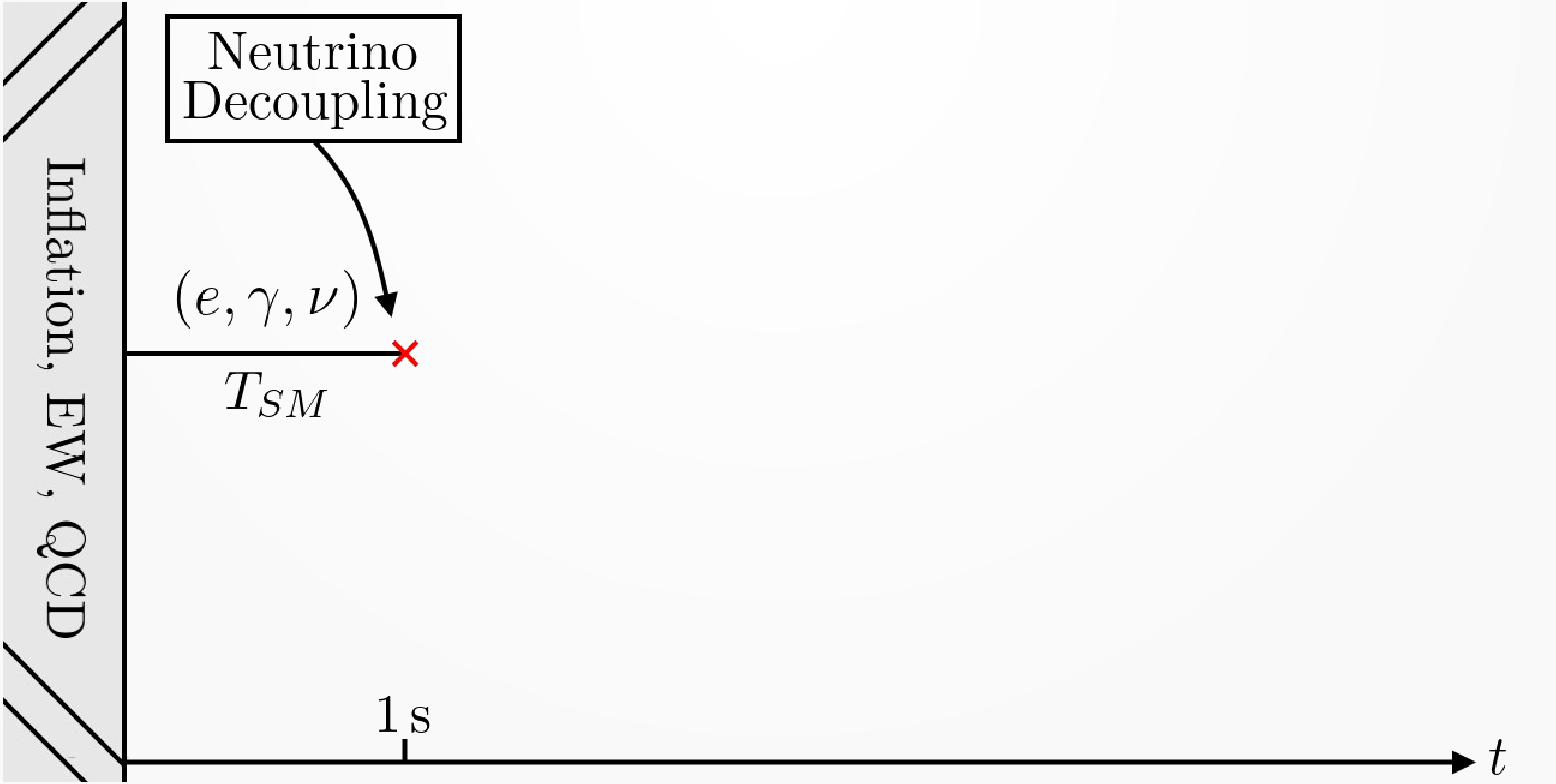
- Freeze-out happens when:

$$G_F^2\, T_{\rm dec}^5 \simeq \sqrt{G_N}\, T_{\rm dec}^2$$

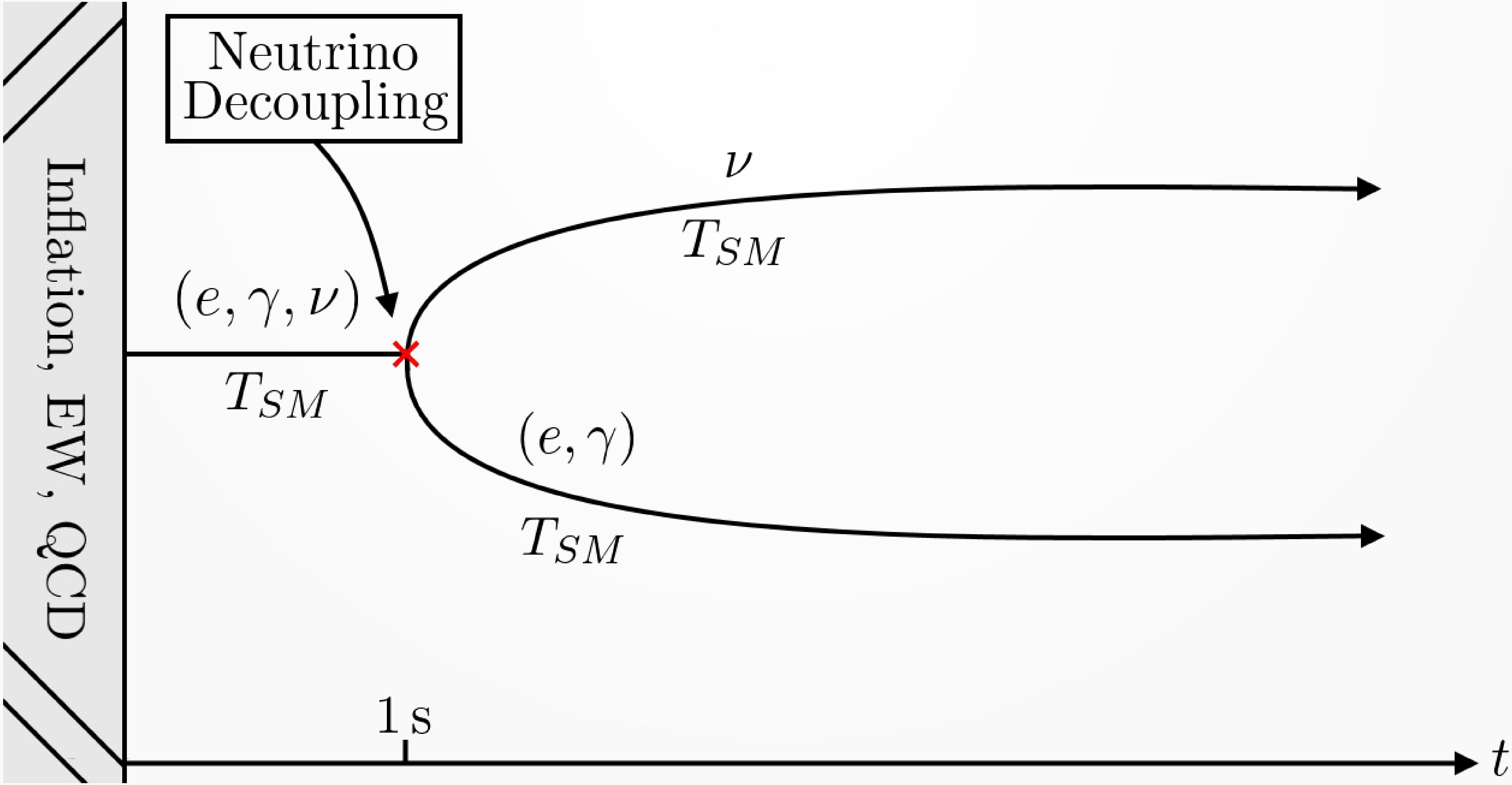
$$\implies \quad T_{\rm dec} \sim \left(\frac{\sqrt{G_N}}{G_F^2} \right)^{\frac{1}{3}} \sim 1\,{\rm MeV}$$

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

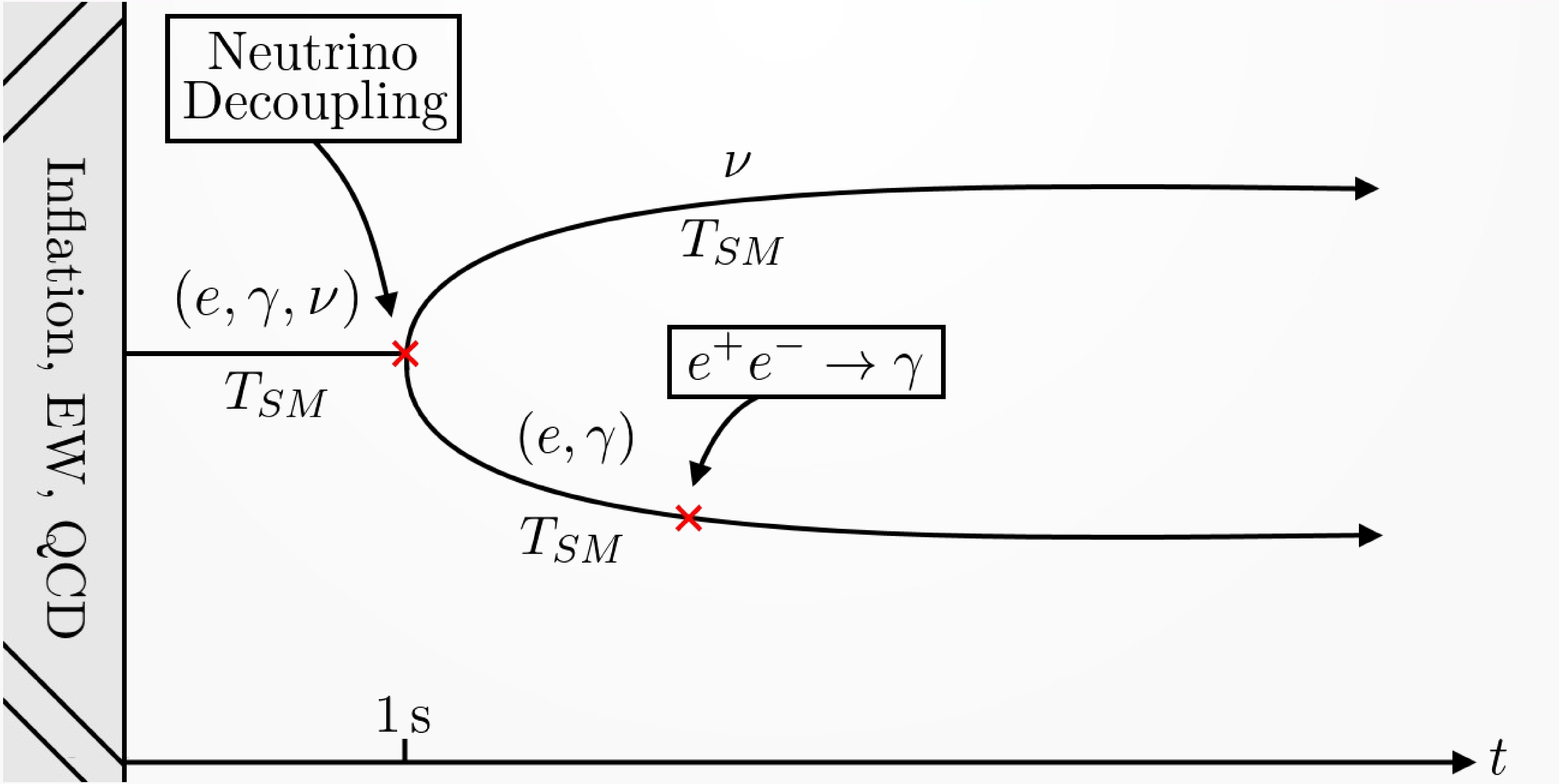
What is the CνB?



What is the CνB?



What is the CνB?



What is the CνB?

- $E_\gamma \geq 1.02\,\mathrm{MeV}$:

$$e^+ + e^- \leftrightarrow \gamma$$

What is the CνB?

- $E_\gamma \geq 1.02\,\mathrm{MeV}$:

$$e^+ + e^- \leftrightarrow \gamma$$

- $E_\gamma < 1.02\,\mathrm{MeV}$:

$$e^+ + e^- \rightarrow \gamma$$

What is the CνB?

- $E_\gamma \geq 1.02\,\mathrm{MeV}$:

$$e^+ + e^- \leftrightarrow \gamma$$

- $E_\gamma < 1.02\,\mathrm{MeV}$:

$$e^+ + e^- \rightarrow \gamma$$

- This process changes the photon temperature!

What is the CνB?

- In a comoving volume, total entropy is conserved:

$$\frac{dS}{dt} = 0$$

What is the CνB?

- In a comoving volume, total entropy is conserved:

$$\frac{dS}{dt} = 0$$

- Entropy before and after annihilation needs to be the same:

What is the CνB?

- In a comoving volume, total entropy is conserved:

$$\frac{dS}{dt} = 0$$

- Entropy before and after annihilation needs to be the same:

$$g_s^*(T_{SM})\,T_{SM}^3 = g_s^*(T_\gamma)\,T_\gamma^3$$

What is the CνB?

- In a comoving volume, total entropy is conserved:

$$\frac{dS}{dt} = 0$$

- Entropy before and after annihilation needs to be the same:

$$g_s^*(T_{SM})\,T_{SM}^3 = g_s^*(T_\gamma)\,T_\gamma^3$$

- In general:

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

What is the CνB?

- Before annihilation:

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

What is the CνB?

- Before annihilation:

$$g_s^*(T_{SM}) = \frac{11}{2}$$

What is the CνB?

- Before annihilation:

$$g_s^*(T_{SM}) = \frac{11}{2}$$

- After annihilation:

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

What is the CνB?

- Photon temperature satisfies:

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

What is the CνB?

- Photon temperature satisfies:

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

- Recalling that the neutrinos are still at T_{SM}:

What is the CνB?

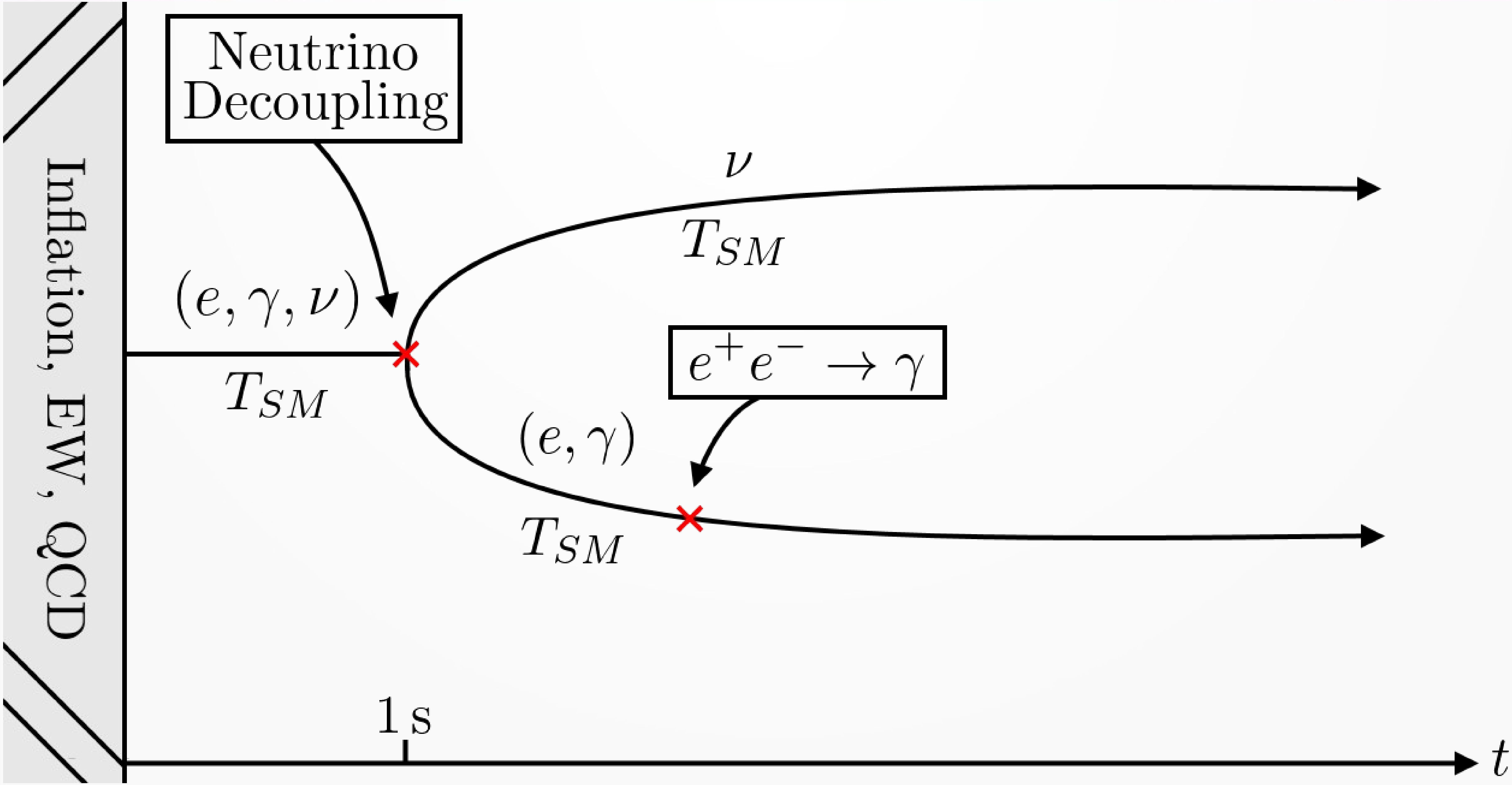
- Photon temperature satisfies:

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

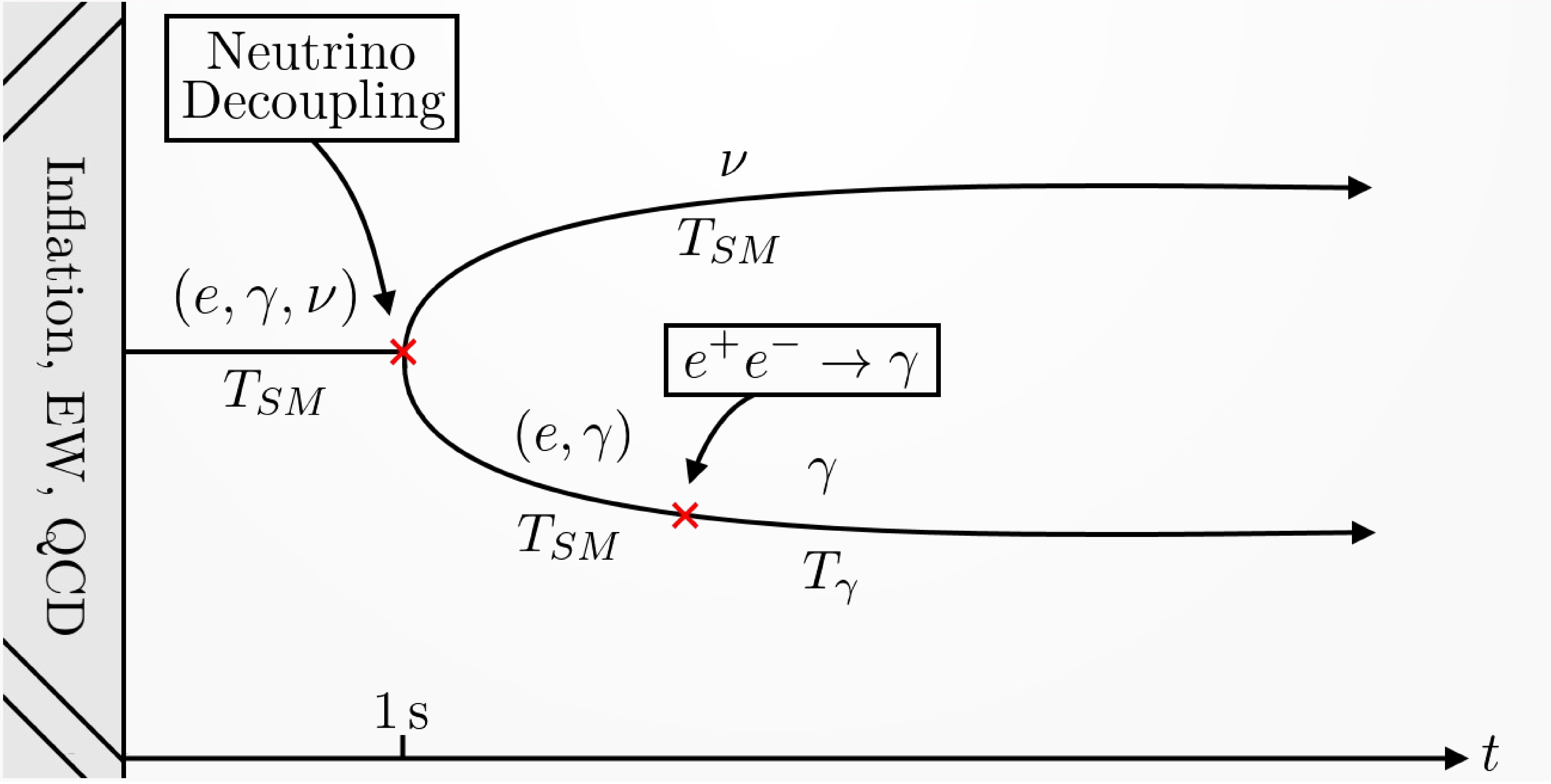
- Recalling that the neutrinos are still at T_{SM}:

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

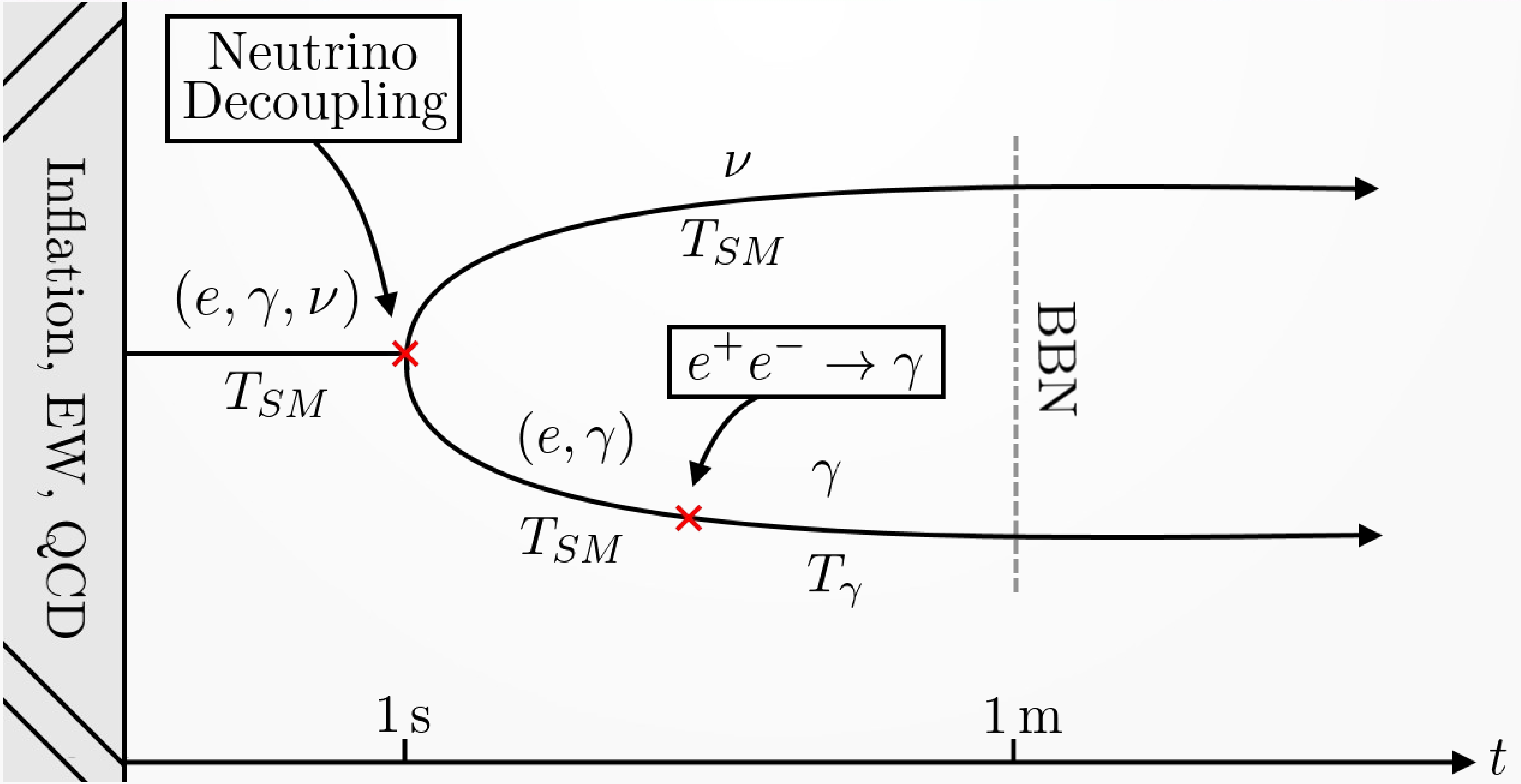
What is the CνB?



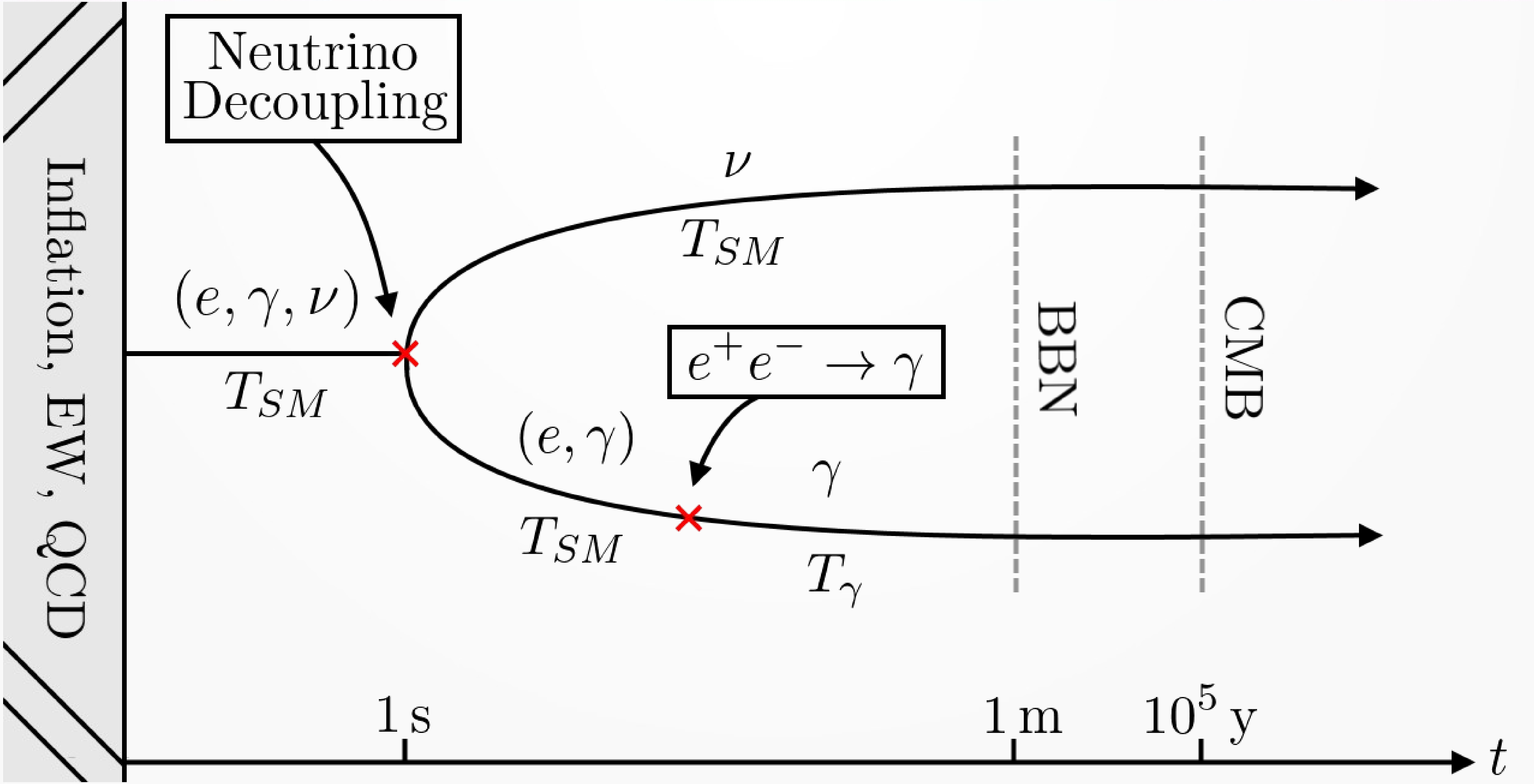
What is the CνB?



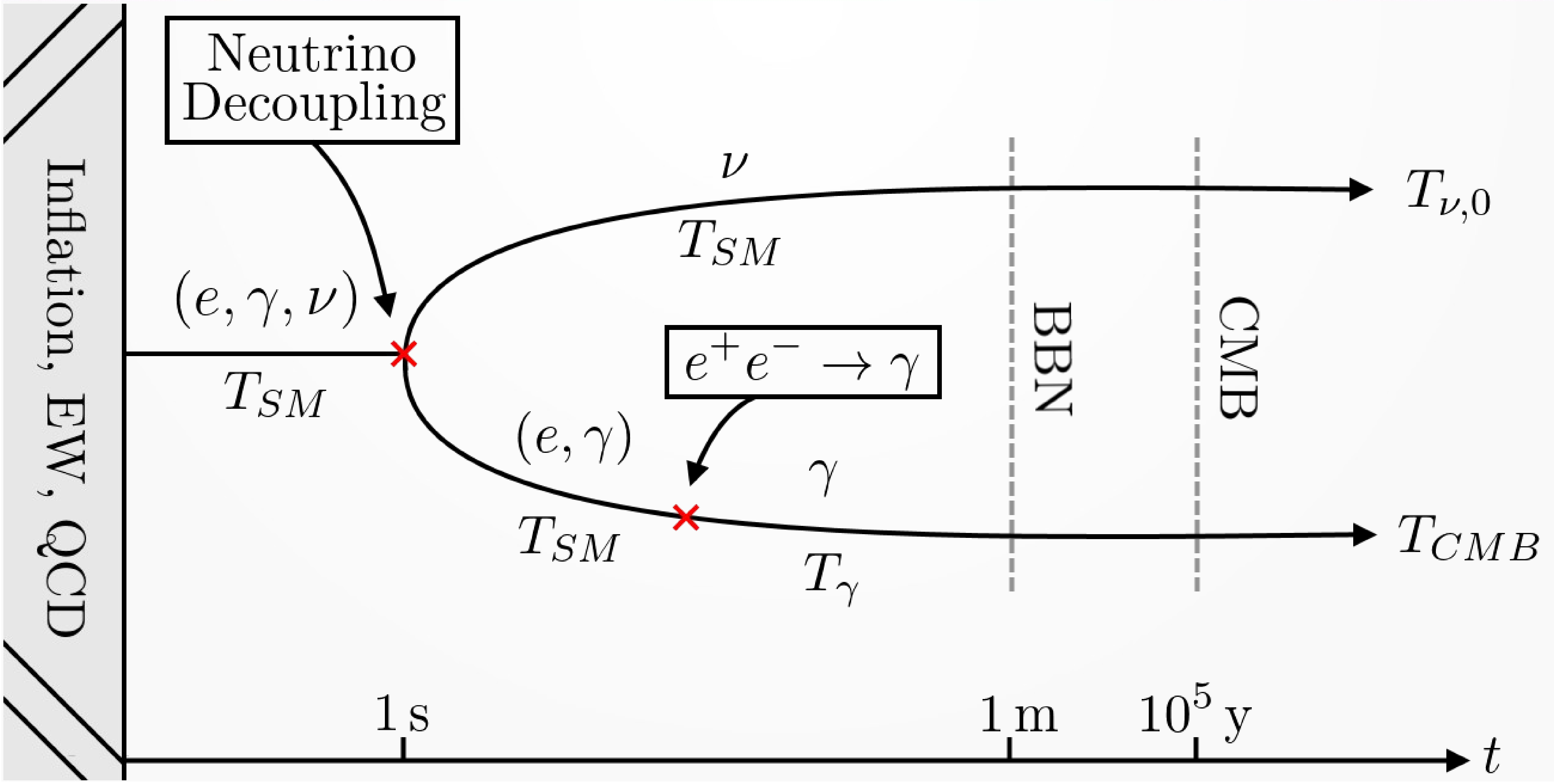
What is the CνB?



What is the CνB?



What is the CνB?



The CνB today

- Redshifted to temperature:

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

The CνB today

- Redshifted to temperature:

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

The CνB today

- Redshifted to temperature:

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

- At least two neutrinos states are non-relativistic!

The CνB today

- Redshifted to temperature:

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

- At least two neutrinos states are non-relativistic!

- Exist today as freely propagating mass eigenstates

The CνB today

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

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

The CνB today

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

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

- These should all be left helicity states

The CνB today

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

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

- These should all be left helicity states

- ...but neutrinos have mass!

The CνB today

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

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

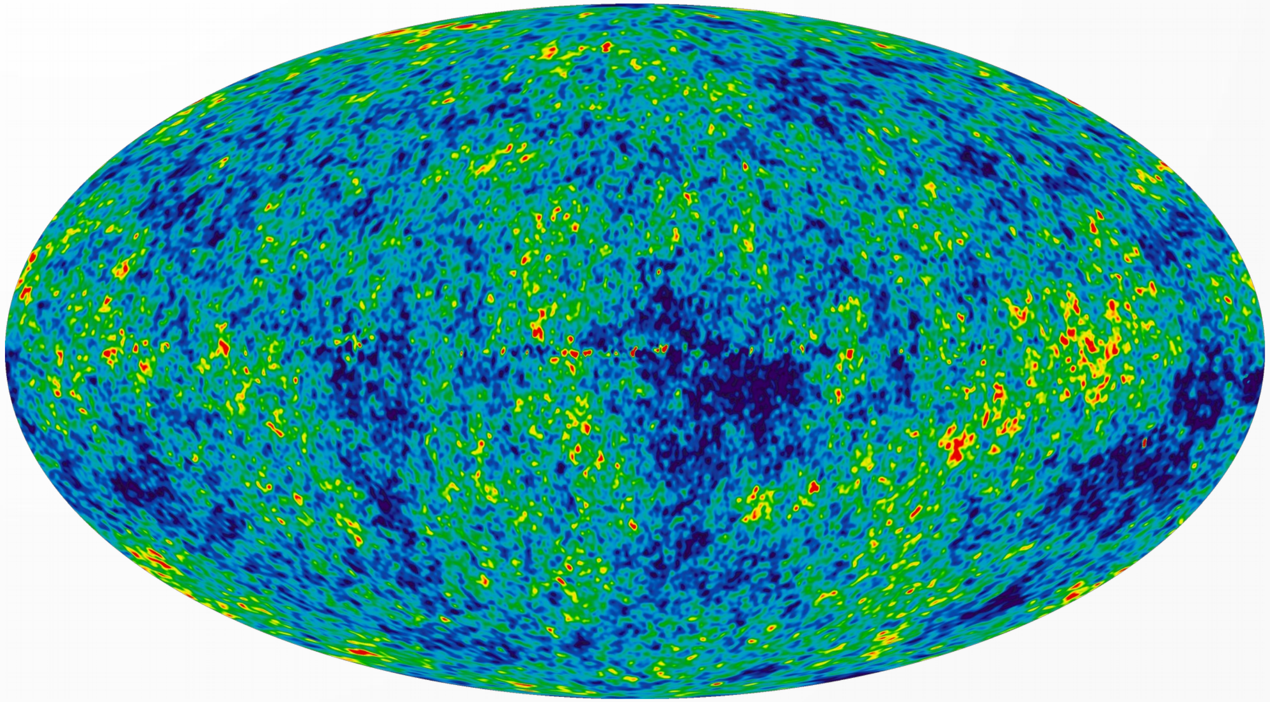
- These should all be left helicity states

- ...but neutrinos have mass!

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

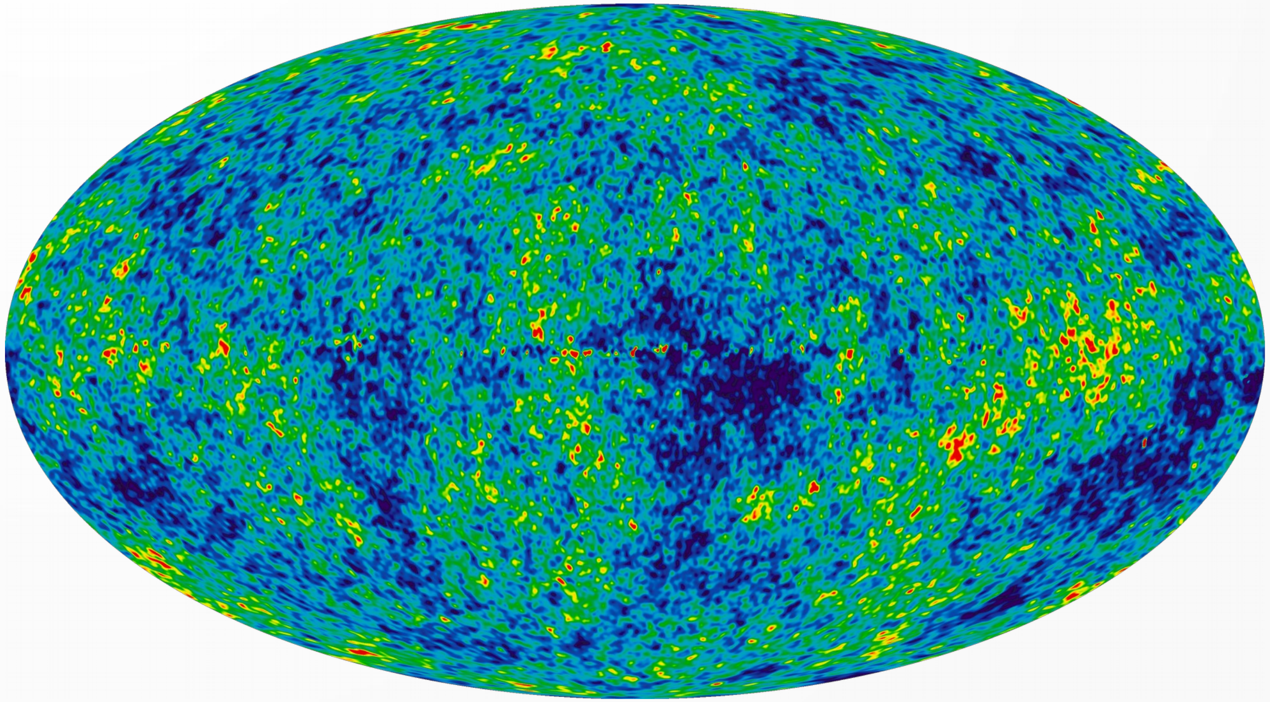
Why detect the CνB?

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



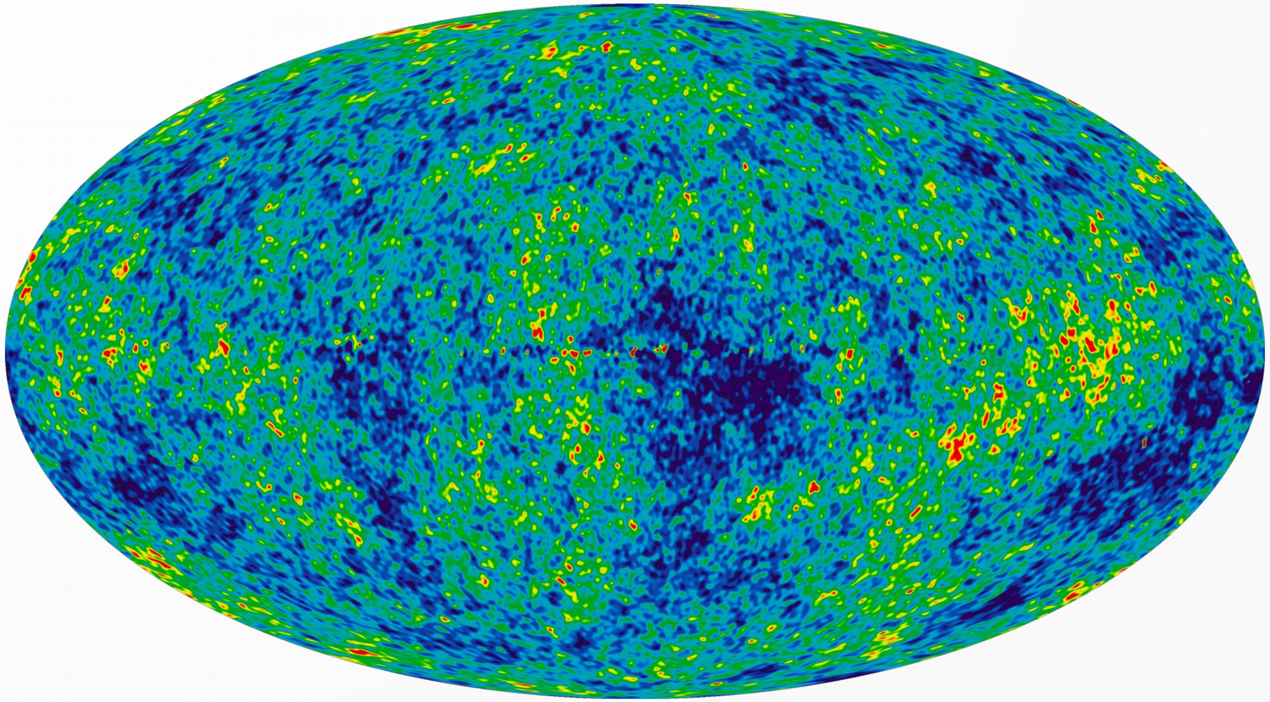
Why detect the CνB?

- The CMB is the furthest we can currently look back through time
- A rare source of non-relativistic neutrinos!

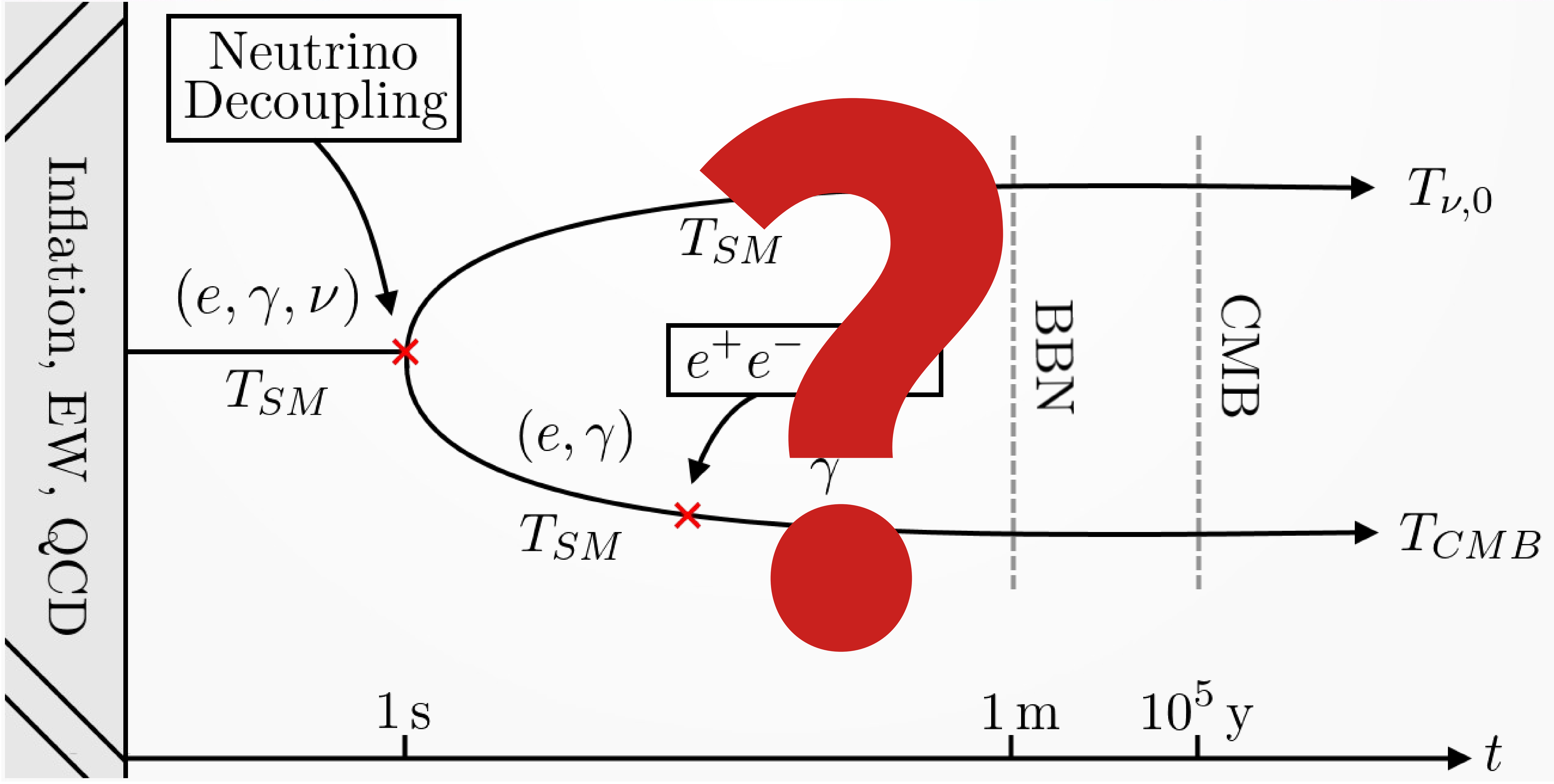


Why detect the CνB?

- The CMB is the furthest we can currently look back through time
- A rare source of non-relativistic neutrinos!
- Perhaps they're not there at all



Why detect the CνB?



So…why haven't we detected them yet?

- Neutrinos are notoriously hard to look for…

$$\sigma_\nu \sim G_F^2 E_\nu^2 \sim 5 \cdot 10^{-50} \left(\frac{E_\nu}{1\,\mathrm{keV}} \right)^2 \mathrm{cm}^2$$

So...why haven't we detected them yet?

- Neutrinos are notoriously hard to look for...

$$\sigma_\nu \sim G_F^2 E_\nu^2 \sim 5 \cdot 10^{-50} \left(\frac{E_\nu}{1\,\mathrm{keV}} \right)^2 \mathrm{cm}^2$$

- Compare this to a typical EM process:

$$\sigma_{e\mu} = \frac{4\pi\alpha^2}{3s} \sim 10^{-25} \left(\frac{1\,\mathrm{MeV}}{E_e} \right)^2 \mathrm{cm}^2$$

So...why haven't we detected them yet?

- Neutrinos are notoriously hard to look for...

$$\sigma_\nu \sim G_F^2 E_\nu^2 \sim 5 \cdot 10^{-50} \left(\frac{E_\nu}{1\,\mathrm{keV}} \right)^2 \mathrm{cm}^2$$

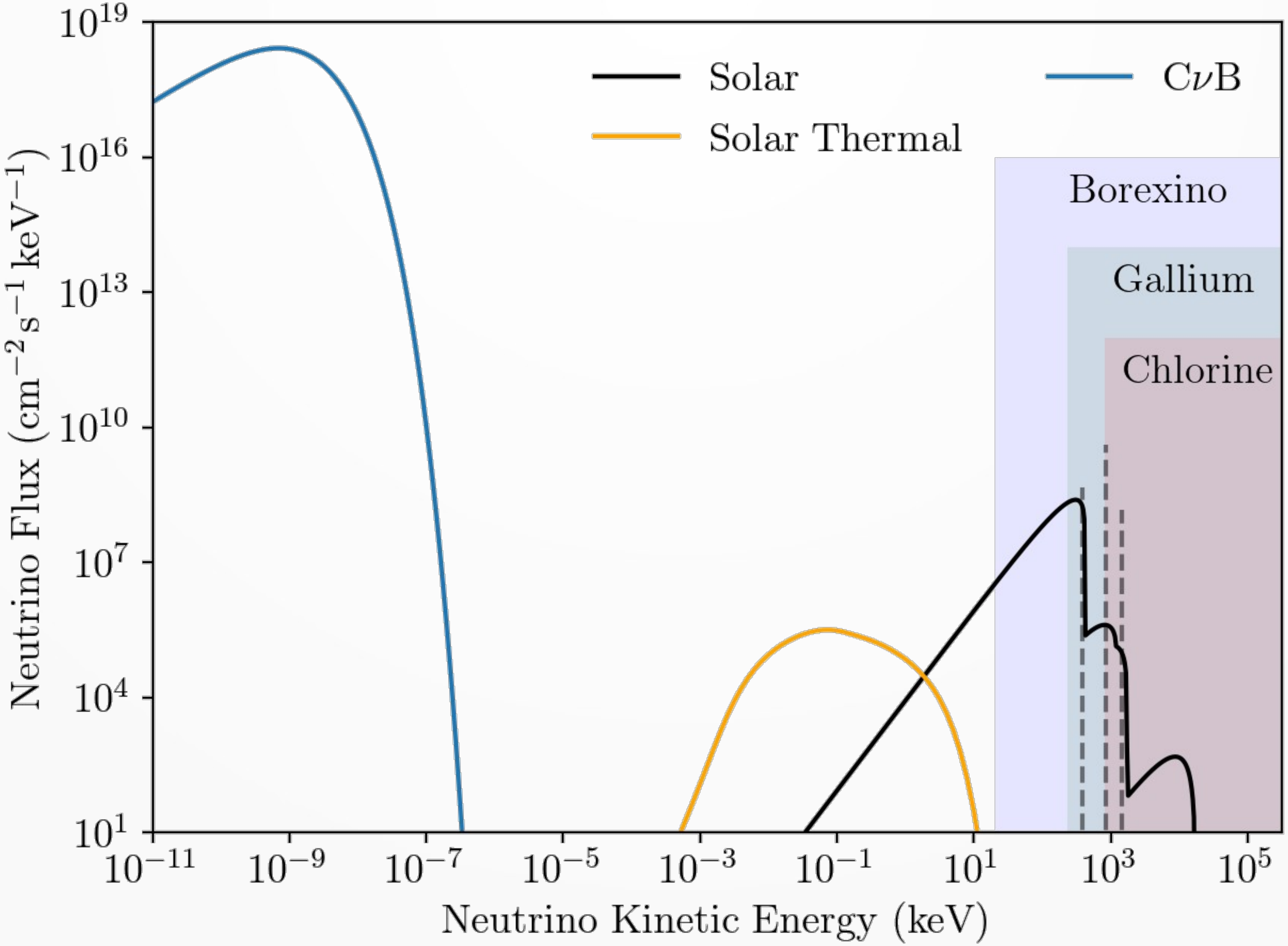
- Compare this to a typical EM process:

$$\sigma_{e\mu} = \frac{4\pi\alpha^2}{3s} \sim 10^{-25} \left(\frac{1\,\mathrm{MeV}}{E_e} \right)^2 \mathrm{cm}^2$$

- Existing neutrino detection experiments have thresholds:

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

But...there is hope!



How might we detect the CνB?

- Threshold:
  - Remove it completely!
  - Find some way to bridge it

How might we detect the CνB?

- Threshold:
  - Remove it completely!
  - Find some way to bridge it
- Event rate:
  - Use a huge number of targets
  - Increase the cross section

How might we detect the CνB?

- Threshold:
  - Remove it completely!
  - Find some way to bridge it ⇦
- Event rate:
  - Use a huge number of targets
  - Increase the cross section ⇦

Contents

- What is the CνB?
- PTOLEMY(-on-a-beam) ⇦
- Resonant neutrino capture
- Experimental challenges

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)

The PTOLEMY experiment

- Proposed by Weinberg in 1962 [1]:

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

- This process has no threshold

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

The PTOLEMY experiment

- Proposed by Weinberg in 1962 [1]:

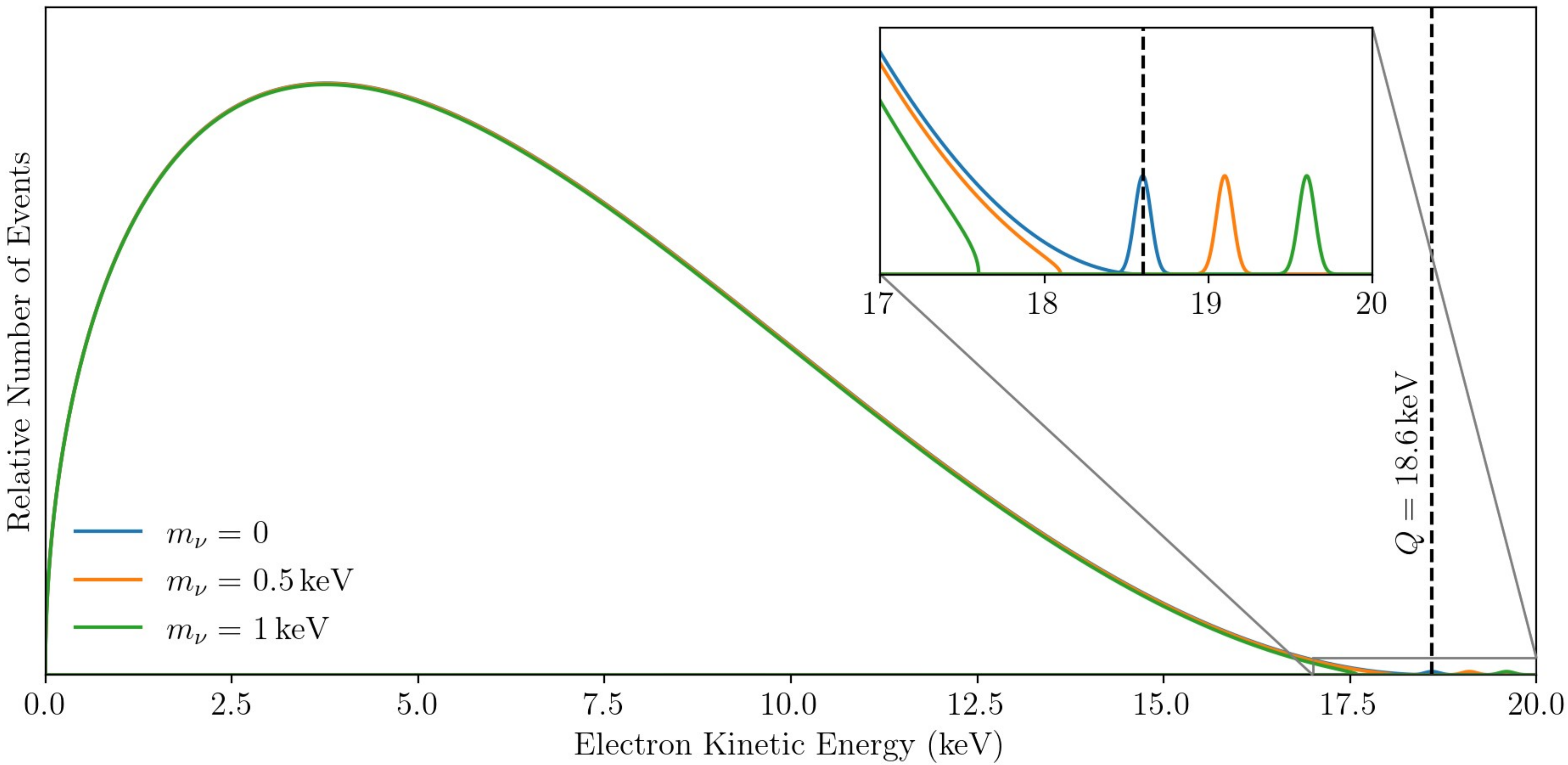
$$\nu_e + {}^3\mathrm{H} \to e^- + {}^3\mathrm{He}^+$$

- This process has no threshold

- Tritium already well understood from neutrino mass experiments

[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)

The PTOLEMY experiment

- Neutrino capture cross section [2]:

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

- Giving an event rate for 100g of tritium:

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

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

The PTOLEMY experiment

- Neutrino capture cross section [2]:

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

- Giving an event rate for 100g of tritium:

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

- 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:

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

What's the catch?

- Extreme sensitivity required to detect signal:

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

- Obtaining and storing 100g of tritium

What's the catch?

- Extreme sensitivity required to detect signal:

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

- Obtaining and storing 100g of tritium

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

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

Can we do better?

- Recall the cross section:

$$\langle \sigma \beta_\nu \rangle \propto G_F^2 E_e p_e$$

Can we do better?

- Recall the cross section:

$$\langle \sigma \beta_\nu \rangle \propto G_F^2 E_e p_e$$

- This scales quadratically with energy!

$$E_e = m_e + |Q_{\mathrm{H}}| + E_\nu$$

$$p_e = \sqrt{(E_\nu + |Q_{\mathrm{H}}|)(E_\nu + 2m_e + |Q_{\mathrm{H}}|)}$$

Can we do better?

- Recall the cross section:

$$\langle \sigma \beta_\nu \rangle \propto G_F^2 E_e p_e$$

- This scales quadratically with energy!

$$E_e = m_e + |Q_{\mathrm{H}}| + E_\nu$$

$$p_e = \sqrt{(E_\nu + |Q_{\mathrm{H}}|)(E_\nu + 2m_e + |Q_{\mathrm{H}}|)}$$

- We can increase our neutrino energy by using a beam

Setup

- Accelerate (tritium) ions on a beam

Setup

- Accelerate (tritium) ions on a beam
- Treat neutrinos as at rest in lab frame:

$$E_\nu \simeq m_\nu$$

Setup

- Accelerate (tritium) ions on a beam
- Treat neutrinos as at rest in lab frame:

$$E_\nu \simeq m_\nu$$

- Relevant beam rest frame quantities:

$$\widetilde{E}_\nu \simeq \frac{m_\nu}{M} E \qquad \widetilde{\phi} = \gamma \phi \qquad \widetilde{t} = \frac{t}{\gamma} \qquad \widetilde{R} = \gamma R$$

Setup

- In the beam rest frame:

$$\langle \sigma \widetilde{\beta}_\nu \rangle \propto G_F^2 \widetilde{E}_e \widetilde{p}_e$$

$$\widetilde{E}_e = m_e + |Q_{\rm H}| + \widetilde{E}_\nu$$

$$\widetilde{p}_e = \sqrt{(\widetilde{E}_\nu + |Q_{\rm H}|)(\widetilde{E}_\nu + 2m_e + |Q_{\rm H}|)}$$

Setup

- In the beam rest frame:

$$\langle \sigma \widetilde{\beta}_\nu \rangle \propto G_F^2 \widetilde{E}_e \widetilde{p}_e$$

$$\widetilde{E}_e = m_e + |Q_{\mathrm{H}}| + \widetilde{E}_\nu$$

$$\widetilde{p}_e = \sqrt{(\widetilde{E}_\nu + |Q_{\mathrm{H}}|)(\widetilde{E}_\nu + 2m_e + |Q_{\mathrm{H}}|)}$$

- Quadratic enhancement begins when:

$$\widetilde{E}_\nu > 2m_e \implies E \gtrsim 3\,\mathrm{PeV}$$

Difficulties

- Huge energy requirements

Difficulties

- Huge energy requirements
- Still need a large amount of tritium

Difficulties

- Huge energy requirements
- Still need a large amount of tritium
- Almost no way to recover a signal

Difficulties

- Huge energy requirements
- Still need a large amount of tritium
- Almost no way to recover a signal
- ...but, large energy presents an opportunity!

"Inverse PTOLEMY-on-a-beam"

- Large energy allows us to use the inverse process:

$$^3\mathrm{He}^{++} + \bar{\nu}_e \to {}^3\mathrm{H}^{+} + e^{+}$$

“Inverse PTOLEMY-on-a-beam”

- Large energy allows us to use the inverse process:

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

- Positron energy given by:

$$\widetilde{E}_e = m_e - Q_{\text{He}} + \widetilde{E}_\nu$$

$$\widetilde{p}_e = \sqrt{(\widetilde{E}_\nu - Q_{\text{He}})(\widetilde{E}_\nu + 2m_e - Q_{\text{He}})}$$

"Inverse PTOLEMY-on-a-beam"

- Large energy allows us to use the inverse process:

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

- Positron energy given by:

$$\widetilde{E}_e = m_e - Q_{\text{He}} + \widetilde{E}_\nu$$

$$\widetilde{p}_e = \sqrt{(\widetilde{E}_\nu - Q_{\text{He}})(\widetilde{E}_\nu + 2m_e - Q_{\text{He}})}$$

- This process has a 'unique' signal

“Inverse PTOLEMY-on-a-beam”

- Large energy allows us to use the inverse process:

$$^3\mathrm{He}^{++} + \bar{\nu}_e \to {}^3\mathrm{H}^+ + e^+$$

- Positron energy given by:

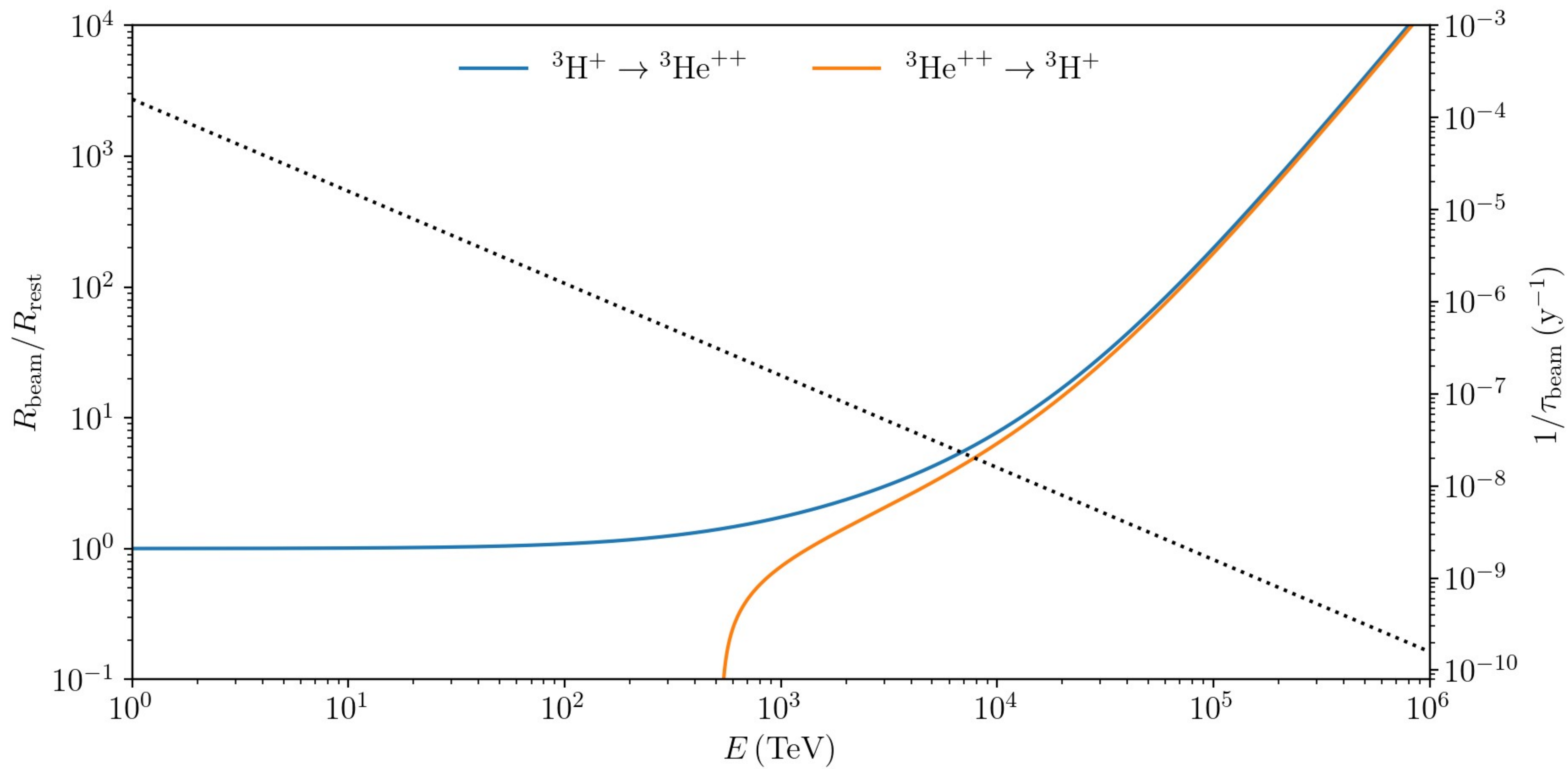
$$\widetilde{E}_e = m_e - Q_{\mathrm{He}} + \widetilde{E}_\nu$$

$$\widetilde{p}_e = \sqrt{(\widetilde{E}_\nu - Q_{\mathrm{He}})(\widetilde{E}_\nu + 2m_e - Q_{\mathrm{He}})}$$

- This process has a ‘unique’ signal

- Signal is now unstable

“Inverse PTOLEMY-on-a-beam”



Can we do better?

- Not really...

Can we do better?

- Not really...

- Cross section still tiny at huge energies:

$$\langle \sigma \widetilde{\beta}_\nu \rangle \propto G_F^2 E_e p_e$$

Can we do better?

- Not really...
- Cross section still tiny at huge energies:

$$\langle \sigma \widetilde{\beta}_\nu \rangle \propto G_F^2 E_e p_e$$

- But we have learnt some lessons!

Contents

- What is the CνB?
- PTOLEMY(-on-a-beam)
- Resonant neutrino capture ⇦
- Experimental challenges

Resonant neutrino capture

- Tiny cross sections → use a resonance!

Resonant neutrino capture

- Tiny cross sections → use a resonance!
- Tunable beam energy naturally invites resonances

Resonant neutrino capture

- Tiny cross sections → use a resonance!
- Tunable beam energy naturally invites resonances
- e.g. Z-resonance: $\nu + \bar{\nu}_{\mathrm{C}\nu\mathrm{B}} \to Z \to\ ?$

Resonant neutrino capture

- Tiny cross sections → use a resonance!
- Tunable beam energy naturally invites resonances
- e.g. Z-resonance: $\nu + \bar{\nu}_{\mathrm{C}\nu\mathrm{B}} \to Z \to \,?$
- Vastly larger cross section: $\sigma \propto \frac{1}{M_Z^2} \propto G_F$

Resonant neutrino capture

- Resonant electron capture (REC):

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

Resonant neutrino capture

- Resonant electron capture (REC):

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

- Resonant bound beta decay (RBβ):

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

Resonant neutrino capture

- Resonant electron capture (REC):

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

- Resonant bound beta decay (RBβ):

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

- Parent ionised down to one s-shell electron (REC) or completely ionised (RBβ)

Resonant neutrino capture

- Cross section for resonant neutrino capture [4]:

$$\sigma \propto \frac{1}{\widetilde{E}_\nu^2} \left[\frac{\Gamma^2/4}{(\widetilde{E}_\nu - Q)^2 - \Gamma^2/4} \right] \mathrm{Br}(D \to P)$$

[4] R. G. C. Oldeman, M. Meloni and B. Saitta, Eur. Phys. J. C **65**, 81-87 (2010)

Resonant neutrino capture

- Cross section for resonant neutrino capture [4]:

$$\sigma \propto \frac{1}{\widetilde{E}_\nu^2} \underbrace{\left[\frac{\Gamma^2/4}{(\widetilde{E}_\nu - Q)^2 - \Gamma^2/4} \right]}_{1,\, \widetilde{E}_\nu = Q} \mathrm{Br}(D \to P)$$

[4] R. G. C. Oldeman, M. Meloni and B. Saitta, Eur. Phys. J. C **65**, 81-87 (2010)

Resonant neutrino capture

- Cross section for resonant neutrino capture [4]:

$$\sigma \propto \frac{1}{\widetilde{E}_\nu^2}\left[\frac{\Gamma^2/4}{(\widetilde{E}_\nu - Q)^2 - \Gamma^2/4}\right] \mathrm{Br}(D \to P)$$

$$\sigma_{\mathrm{peak}} \propto \frac{1}{Q^2} \mathrm{Br}(D \to P)$$

[4] R. G. C. Oldeman, M. Meloni and B. Saitta, Eur. Phys. J. C **65**, 81-87 (2010)

Resonant neutrino capture

- Cross section for resonant neutrino capture [4]:

$$\sigma \propto \frac{1}{\widetilde{E}_\nu^2}\left[\frac{\Gamma^2/4}{(\widetilde{E}_\nu - Q)^2 - \Gamma^2/4}\right]\underbrace{\mathrm{Br}(D \to P)}_{\mathcal{O}(1)}$$

$$\sigma_{\mathrm{peak}} \propto \frac{1}{Q^2}\,\mathrm{Br}(D \to P)$$

[4] R. G. C. Oldeman, M. Meloni and B. Saitta, Eur. Phys. J. C **65**, 81-87 (2010)

Resonant neutrino capture

- Cross section for resonant neutrino capture [4]:

$$\sigma \propto \frac{1}{\widetilde{E}_\nu^2}\left[\frac{\Gamma^2/4}{(\widetilde{E}_\nu - Q)^2 - \Gamma^2/4}\right]\mathrm{Br}(D \to P)$$

$$\sigma_{\mathrm{peak}} \propto \frac{1}{Q^2}\mathrm{Br}(D \to P)$$

- Peak cross section is independent of G_F!

[4] R. G. C. Oldeman, M. Meloni and B. Saitta, Eur. Phys. J. C **65**, 81-87 (2010)

Resonant neutrino capture

- Cross section for resonant neutrino capture [4]:

$$\sigma \propto \frac{1}{\widetilde{E}_\nu^2} \left[\frac{\Gamma^2/4}{(\widetilde{E}_\nu - Q)^2 - \Gamma^2/4} \right] \mathrm{Br}(D \to P)$$

$$\sigma_{\mathrm{peak}} = 2.5 \cdot 10^{-15} \left(\frac{1\,\mathrm{keV}}{Q} \right)^2 \mathrm{Br}(D \to P)\,\mathrm{cm}^2$$

- Peak cross section is independent of G_F!

[4] R. G. C. Oldeman, M. Meloni and B. Saitta, Eur. Phys. J. C **65**, 81-87 (2010)

Resonant neutrino capture

- Capture rate per target given by:

$$\frac{R}{N_T} = \int_Q^\infty d\widetilde{E}_\nu \, \sigma(\widetilde{E}_\nu) \frac{d\phi}{d\widetilde{E}_\nu}$$

Resonant neutrino capture

- Capture rate per target given by:

$$\frac{R}{N_T} = \int_Q^\infty d\widetilde{E}_\nu \, \sigma(\widetilde{E}_\nu) \frac{d\phi}{d\widetilde{E}_\nu}$$

- For narrow resonances:

$$\left[\frac{\Gamma^2/4}{(\widetilde{E}_\nu - Q)^2 - \Gamma^2/4} \right] \to \pi\Gamma \, \delta(\widetilde{E}_\nu - Q)$$

Resonant neutrino capture

- Capture rate per target given by:

$$\frac{R}{N_T} = \frac{\pi}{2}\sigma_{\mathrm{peak}}\Gamma\frac{d\phi}{d\widetilde{E}_\nu}\Big|_{\widetilde{E}_\nu=Q}$$

Resonant neutrino capture

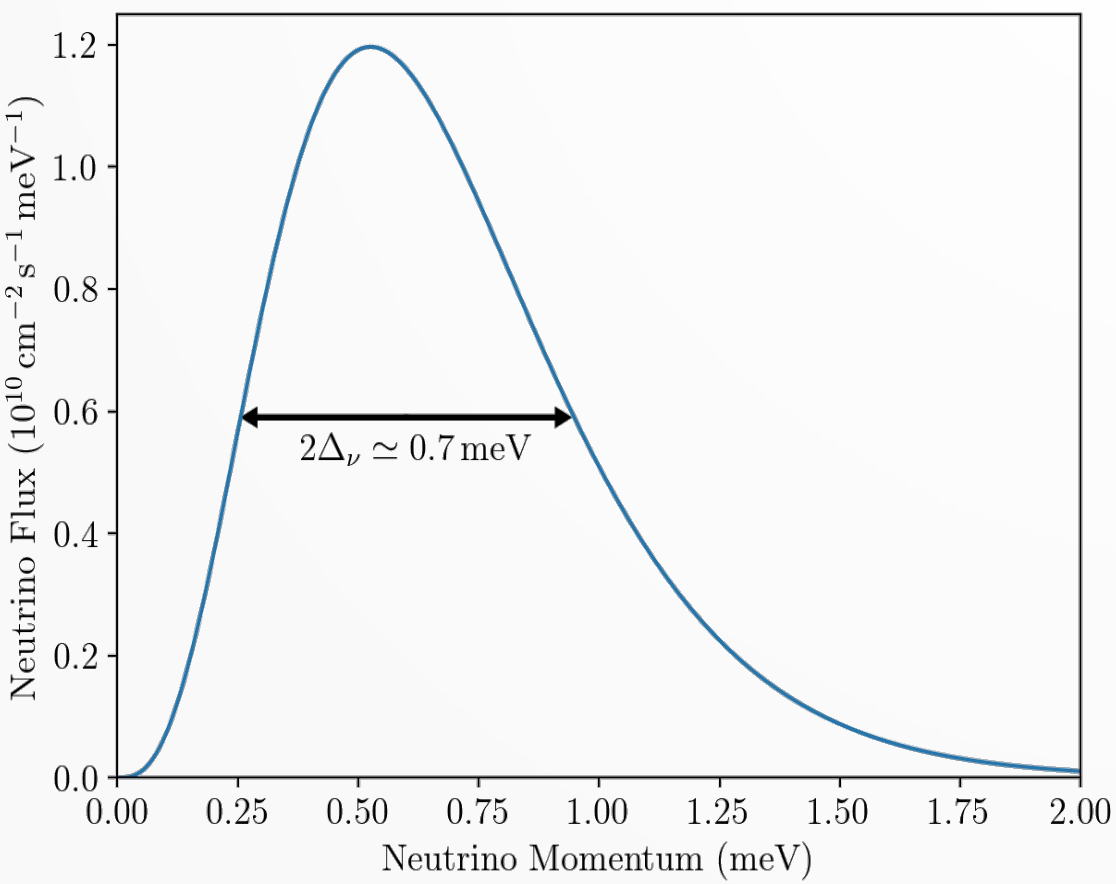
- Capture rate per target given by:

$$\frac{R}{N_T} = \frac{\pi}{2}\sigma_{\text{peak}}\Gamma\frac{d\phi}{d\widetilde{E}_\nu}\Big|_{\widetilde{E}_\nu=Q}$$

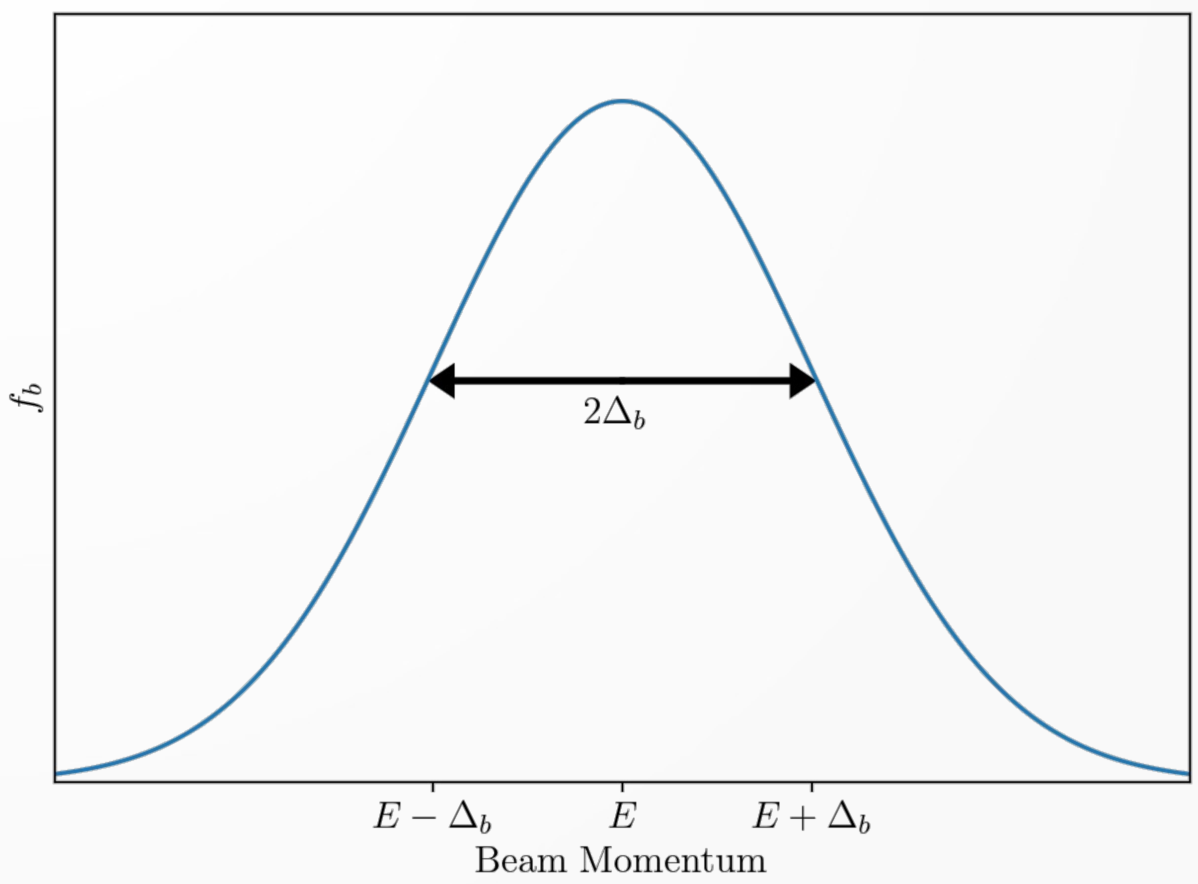
- Assuming Gaussian distribution:

$$\frac{R}{N_T} \propto \frac{\Gamma}{Q^2}\frac{\phi}{\widetilde{\Delta}_E}\text{Br}(D \to P)$$

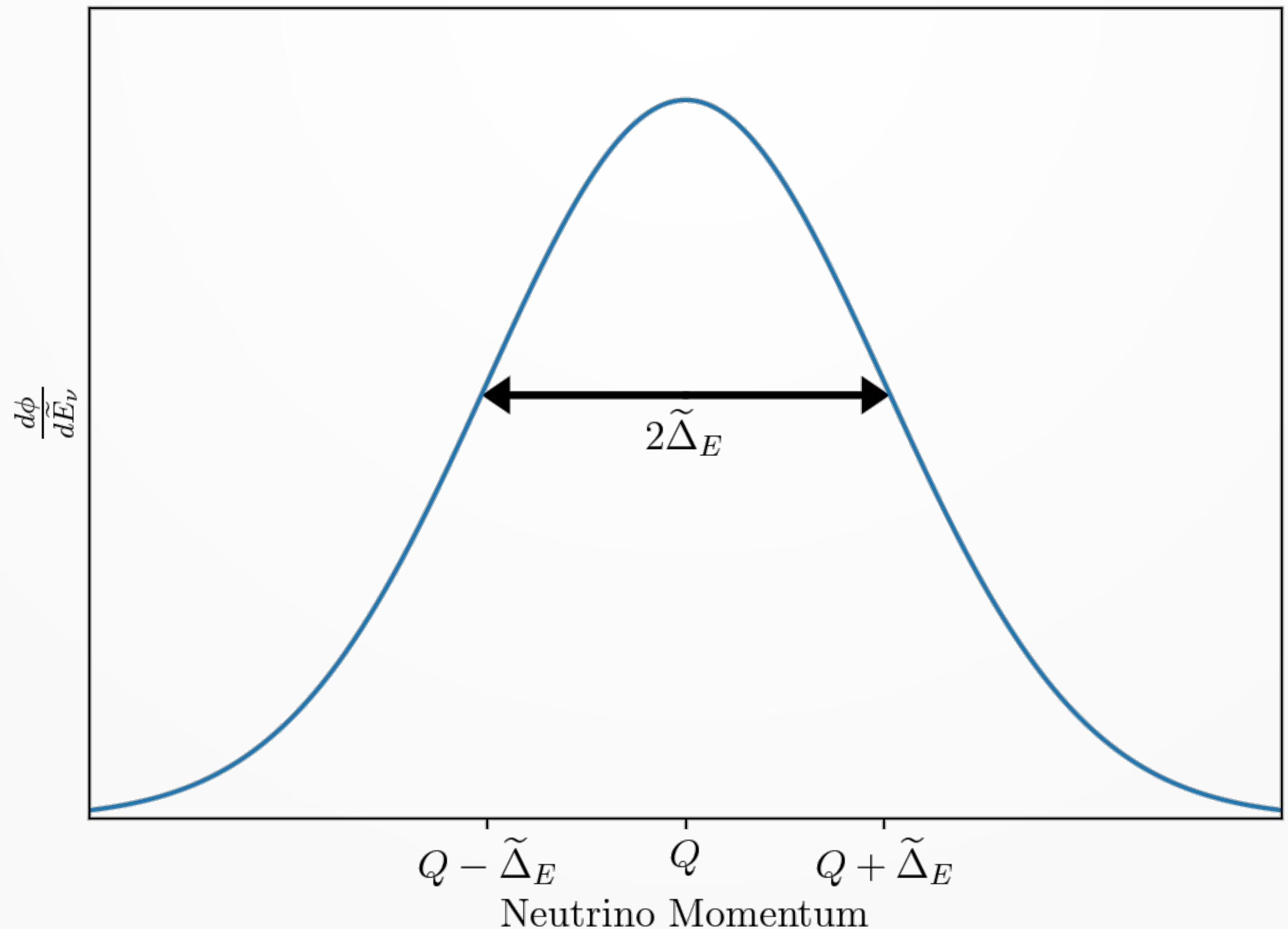
Accounting for the finite width of the CνB



+



Accounting for the finite width of the CνB



Accounting for the finite width of the CνB

- Treating widths of distributions as uncertainty:

$$\widetilde{\Delta}_E = \sqrt{\left(\Delta_\nu \frac{\partial \widetilde{E}_\nu}{\partial p_\nu}\right)^2 + \left(\Delta_b \frac{\partial \widetilde{E}_\nu}{\partial p}\right)^2}$$

Accounting for the finite width of the CνB

- Treating widths of distributions as uncertainty:

$$\widetilde{\Delta}_E = \sqrt{\left(\Delta_\nu \frac{\partial \widetilde{E}_\nu}{\partial p_\nu}\right)^2 + \left(\Delta_b \frac{\partial \widetilde{E}_\nu}{\partial p}\right)^2}$$

- For non-relativistic neutrinos, relativistic beam:

$$\widetilde{\Delta}_E = Q\sqrt{\delta_\nu^2 + \delta_b^2}$$

Accounting for the finite width of the CνB

- Total capture rate per target:

$$\frac{R}{N_T} \propto \frac{\Gamma}{Q^3} \frac{\phi}{\sqrt{\delta_\nu^2 + \delta_b^2}} \mathrm{Br}(D \to P)$$

Accounting for the finite width of the CνB

- Total capture rate per target:

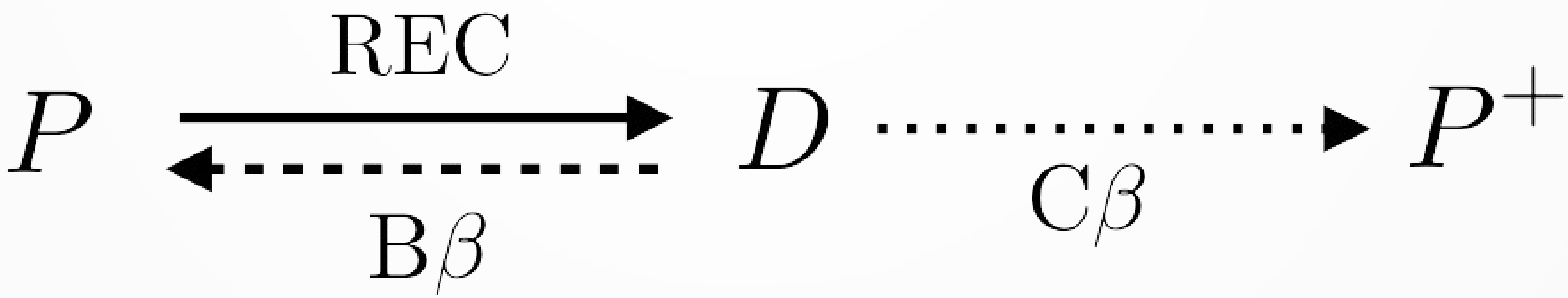
$$\frac{R}{N_T} \propto \frac{\Gamma}{Q^3} \frac{\phi}{\sqrt{\delta_\nu^2 + \delta_b^2}} \mathrm{Br}(D \to P)$$

- More convenient to introduce *quality factor*:

$$\boxed{R_\tau = \frac{\gamma}{\Gamma} \frac{R}{N_T} = 1.7 \cdot 10^{-17} \frac{\mathrm{Br}(D \to P)}{\sqrt{\delta_\nu^2 + \delta_b^2}} \left[\frac{0.1\,\mathrm{eV}}{m_\nu}\right] \left[\frac{1\,\mathrm{keV}}{Q}\right]^2}$$

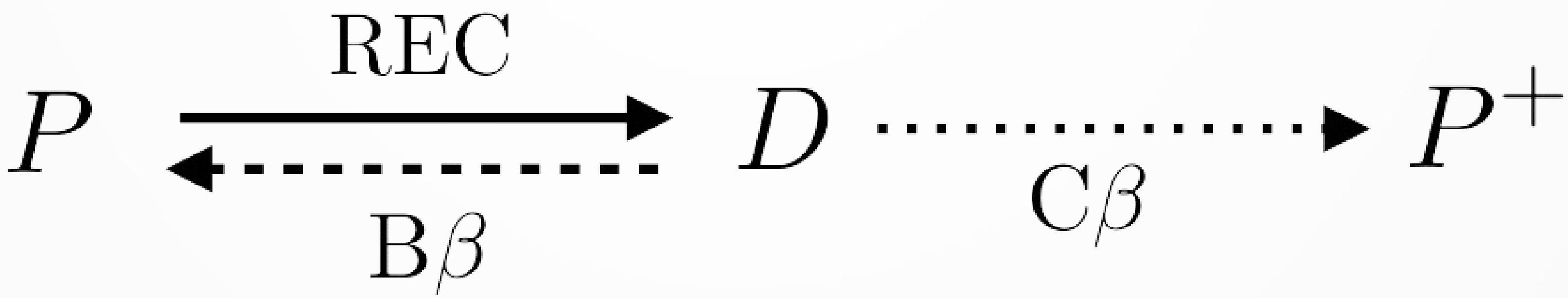
2-state systems

- Resonant electron capture:

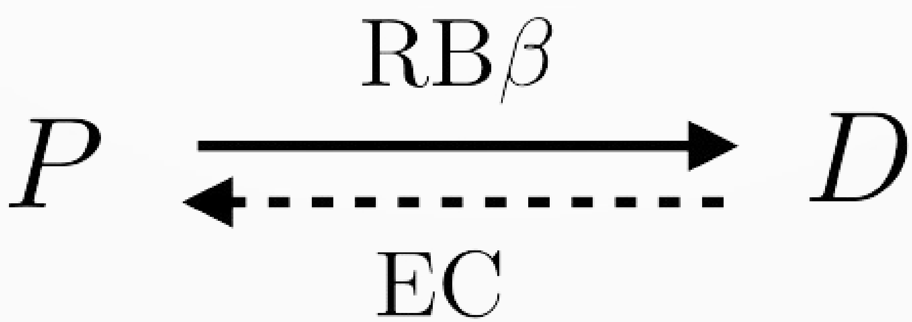


2-state systems

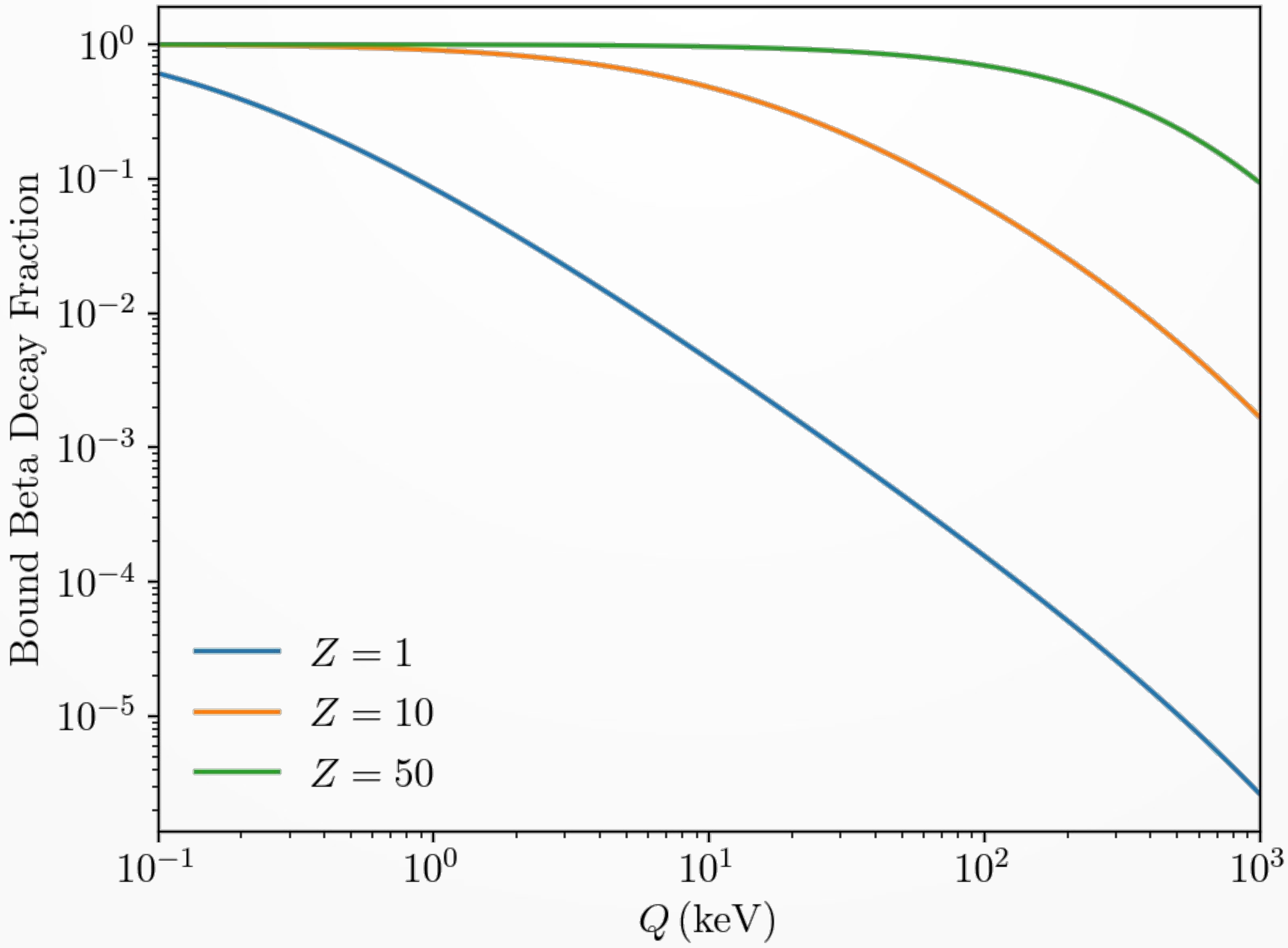
- Resonant electron capture:



- Resonant bound beta decay:



2-state systems



2-state systems

- Number of states on the beam:

$$\frac{dN_P}{d\tilde{t}} = -\gamma \frac{R}{N_T} N_P(\tilde{t}) + \frac{\mathrm{Br}(D \to P)}{\tau_D} N_D(\tilde{t})$$

2-state systems

- Number of states on the beam:

$$\frac{dN_P}{d\tilde{t}} = -\gamma \frac{R}{N_T} N_P(\tilde{t}) + \frac{\mathrm{Br}(D \to P)}{\tau_D} N_D(\tilde{t})$$

- Working in terms of dimensionless variables:

$$x = \frac{t}{\gamma \tau_D} = \frac{m_\nu}{Q} \frac{t}{\tau_D} \qquad R_\tau = \frac{\gamma}{\Gamma} \frac{R}{N_T} = \gamma \tau_D \frac{R}{N_T}$$

2-state systems

- Number of states on the beam:

$$\frac{dN_P}{dx} = -R_\tau N_P(x) + \mathrm{Br}(D \to P) N_D(x)$$

2-state systems

- Number of states on the beam:

$$\frac{dN_P}{dx} = -R_\tau N_P(x) + \mathrm{Br}(D \to P) N_D(x)$$

$$\frac{dN_D}{dx} = R_\tau N_P(x) - N_D(x)$$

2-state systems

- Number of states on the beam:

$$\frac{dN_P}{dx} = -R_\tau N_P(x) + \mathrm{Br}(D \to P) N_D(x)$$

$$\frac{dN_D}{dx} = R_\tau N_P(x) - N_D(x)$$

- Number of daughter states reaches an equilibrium value!

2-state systems

- Number of states on the beam:

$$N_D(x) = N_0 R_\tau (1 - e^{-x}) + \mathcal{O}(R_\tau^2)$$

2-state systems

- Number of states on the beam:

$$N_D(x) = N_0 R_\tau (1 - e^{-x}) + \mathcal{O}(R_\tau^2)$$

- 2-state systems are limited to converting small fraction of the beam

2-state systems

- Number of states on the beam:

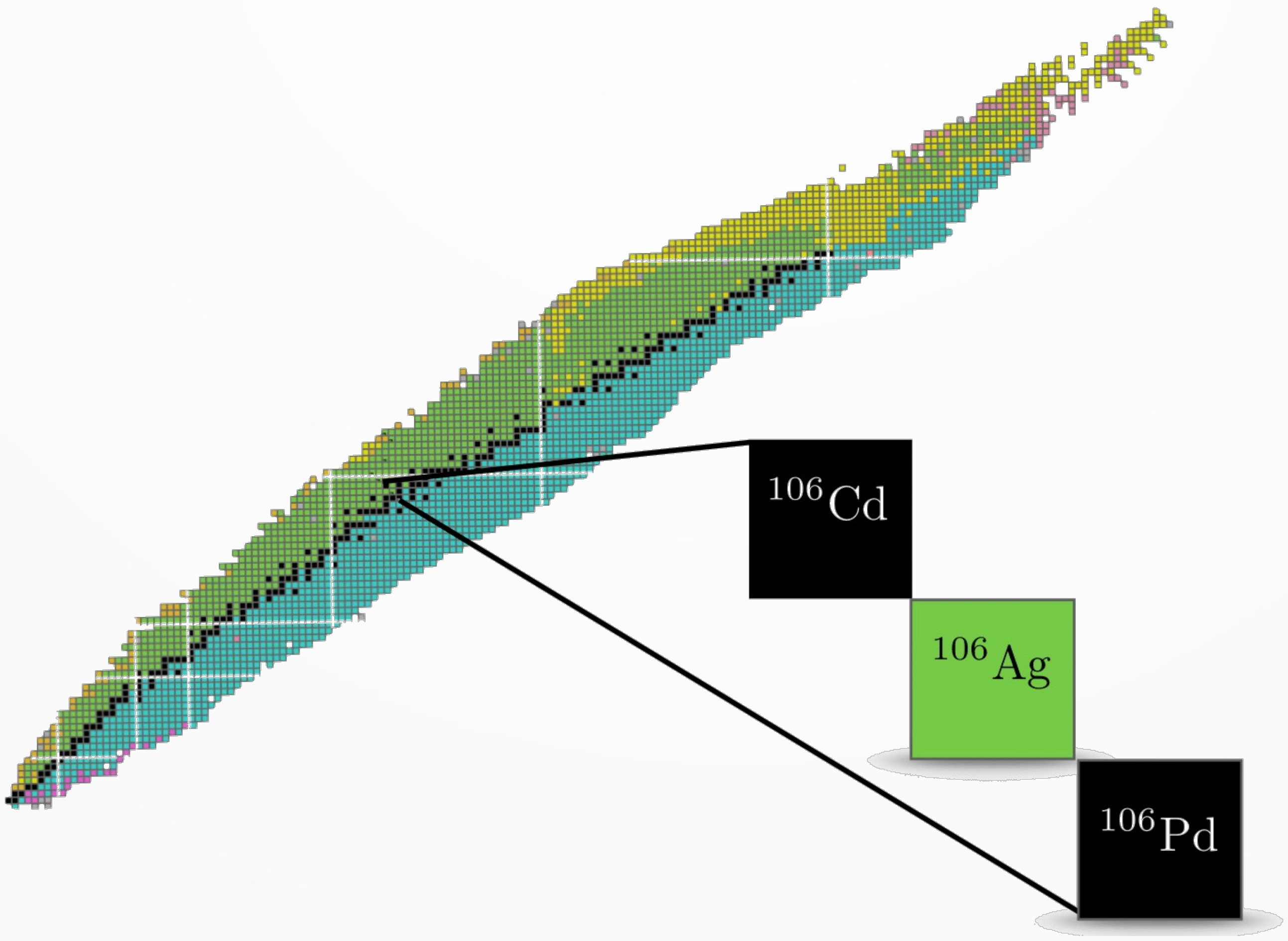
$$N_D(x) = N_0 R_\tau (1 - e^{-x}) + \mathcal{O}(R_\tau^2)$$

- 2-state systems are limited to converting small fraction of the beam

- Can we do better?

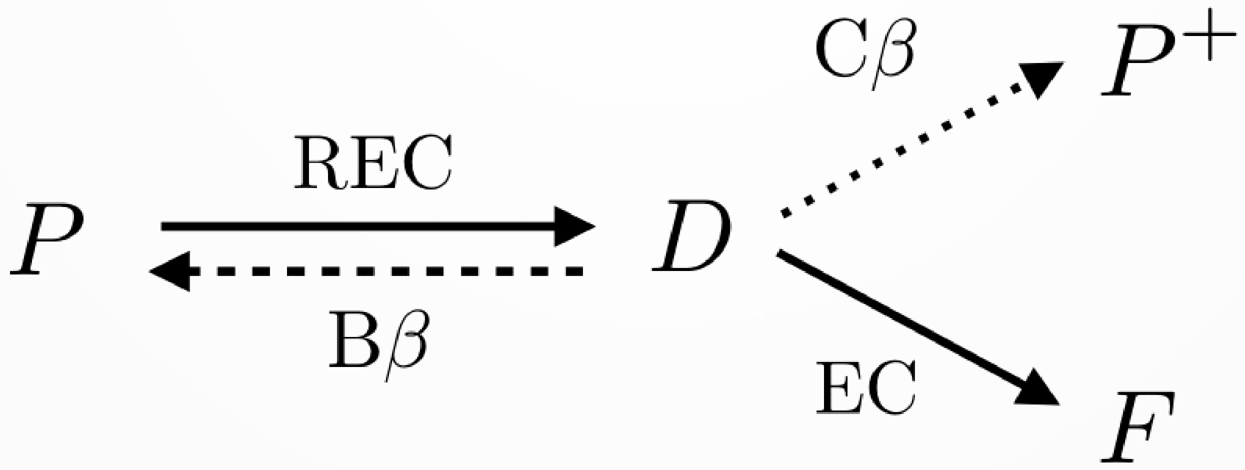
3-state systems

- Introduce a third, stable signal state:



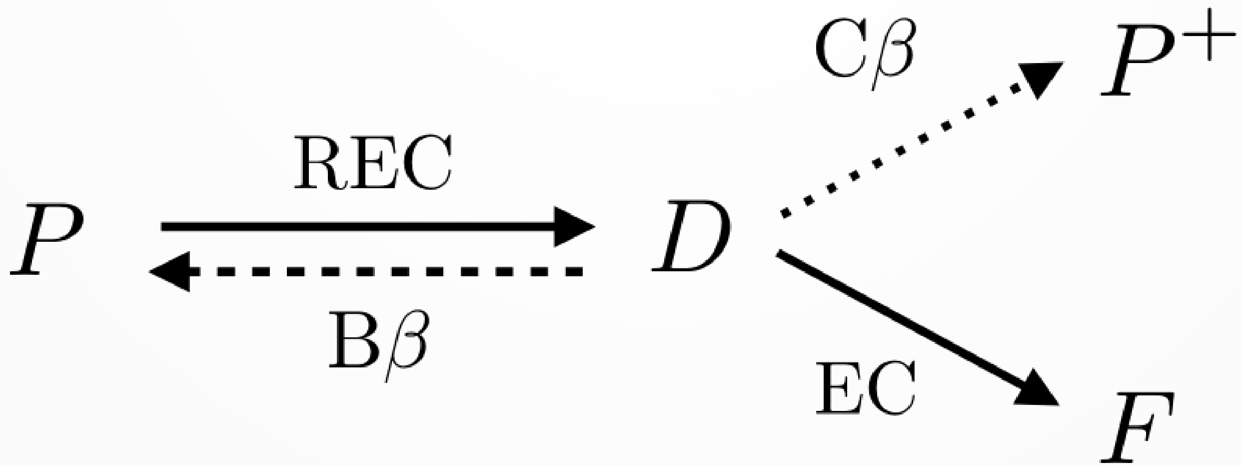
3-state systems

- 3-state resonant electron capture:

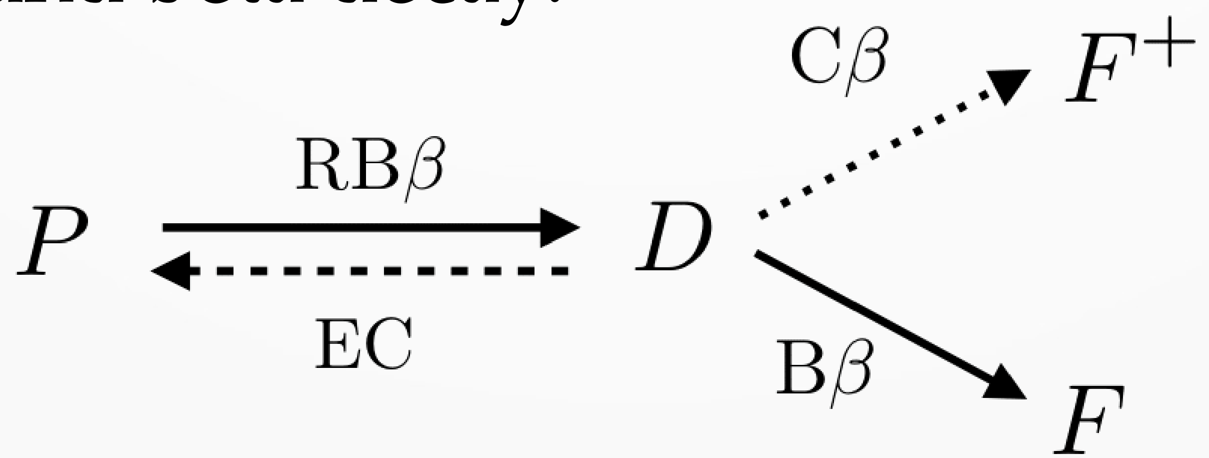


3-state systems

- 3-state resonant electron capture:



- 3-state bound beta decay:



3-state systems

- Number of states on the beam:

$$\frac{dN_P}{dx} = -R_\tau N_P(x) + \mathrm{Br}(D \to P) N_D(x)$$

3-state systems

- Number of states on the beam:

$$\frac{dN_P}{dx} = -R_\tau N_P(x) + \mathrm{Br}(D \to P) N_D(x)$$

$$\frac{dN_D}{dx} = R_\tau N_P(x) - N_D(x)$$

3-state systems

- Number of states on the beam:

$$\frac{dN_P}{dx} = -R_\tau N_P(x) + \mathrm{Br}(D \to P) N_D(x)$$

$$\frac{dN_D}{dx} = R_\tau N_P(x) - N_D(x)$$

$$\frac{dN_F}{dx} = \mathrm{Br}(D \to F) N_D(x)$$

3-state systems

- Number of states on the beam:

$$\frac{dN_P}{dx} = -R_\tau N_P(x) + \mathrm{Br}(D \to P) N_D(x)$$

$$\frac{dN_D}{dx} = R_\tau N_P(x) - N_D(x)$$

$$\frac{dN_F}{dx} = \mathrm{Br}(D \to F) N_D(x)$$

- Number of final (F) states increases monotonically!

3-state systems

- Now able to convert a significant fraction of the beam:

$$\lim_{x\to\infty} N_F(x) = \frac{N_0 \mathrm{Br}(D \to F)}{1 - \mathrm{Br}(D \to P)} \gg N_0 R_\tau$$

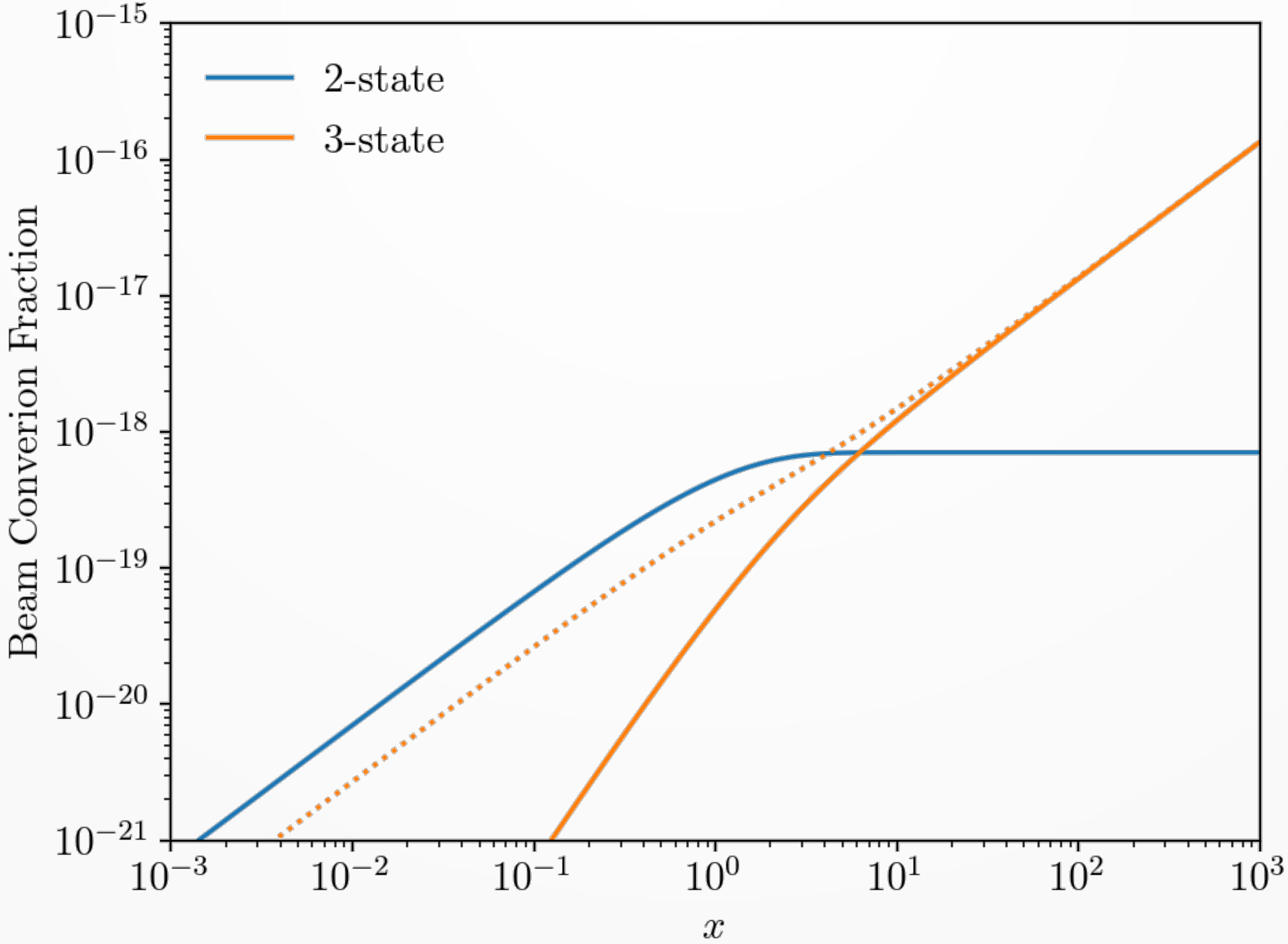
3-state systems

- Now able to convert a significant fraction of the beam:

$$\lim_{x\to\infty} N_F(x) = \frac{N_0 \mathrm{Br}(D \to F)}{1 - \mathrm{Br}(D \to P)} \gg N_0 R_\tau$$

- We now have a ***stable, clean signal*** with a large cross section!

3-state systems



Real world examples

- 2-state system:

$$^{157}\mathrm{Gd} \xrightarrow{\mathrm{RB}\beta} {}^{157}\mathrm{Tb}$$

Real world examples

- 2-state system:

$$^{157}\text{Gd} \xrightarrow{\text{RB}\beta} {}^{157}\text{Tb} \quad \frac{E}{A} \simeq 100\,\text{TeV} \quad \frac{N_D}{N_0} \simeq 10^{-24}$$

Real world examples

- 2-state system:

$$^{157}\mathrm{Gd} \xrightarrow{\mathrm{RB}\beta} {}^{157}\mathrm{Tb} \qquad \frac{E}{A} \simeq 100\,\mathrm{TeV} \qquad \frac{N_D}{N_0} \simeq 10^{-24}$$

- 3-state system:

$$^{106}\mathrm{Cd} \xrightarrow{\mathrm{REC}} {}^{106}\mathrm{Ag} \xrightarrow{\mathrm{EC}} {}^{106}\mathrm{Pd}$$

Real world examples

- 2-state system:

$$^{157}\mathrm{Gd} \xrightarrow{\mathrm{RB}\beta} {}^{157}\mathrm{Tb} \qquad \frac{E}{A} \simeq 100\,\mathrm{TeV} \qquad \frac{N_D}{N_0} \simeq 10^{-24}$$

- 3-state system:

$$^{106}\mathrm{Cd} \xrightarrow{\mathrm{REC}} {}^{106}\mathrm{Ag} \xrightarrow{\mathrm{EC}} {}^{106}\mathrm{Pd}$$

$$\frac{N_D + N_F}{N_0} \simeq 10^{-23} \qquad \frac{E}{A} \simeq 2\,\mathrm{PeV}$$

Contents

- What is the CνB?
- PTOLEMY(-on-a-beam)
- Resonant neutrino capture
- Experimental challenges ⇦

Experimental challenges

- Large energy requirements → appropriate choice of target, use an excited state

Experimental challenges

- Large energy requirements → appropriate choice of target, use an excited state
- Require knowledge of the neutrino mass → KATRIN, beam broadening

Experimental challenges

- Large energy requirements → appropriate choice of target, use an excited state
- Require knowledge of the neutrino mass → KATRIN, beam broadening
- Large number of targets required → reduce threshold, purpose built experiment

Strategy

- Seek processes with small threshold
  - Increased cross section
  - Shorter ‘effective’ resonance lifetime
  - Lower energy requirements

Strategy

- Seek processes with small threshold
  - Increased cross section
  - Shorter ‘effective’ resonance lifetime
  - Lower energy requirements

- Try to find a 3-state system
  - Stable, clean signal
  - Possibility to convert huge fraction of the beam

Summary

- Resonant neutrino capture has huge cross sections

Summary

- Resonant neutrino capture has huge cross sections
- Capture cross section is independent of G_F

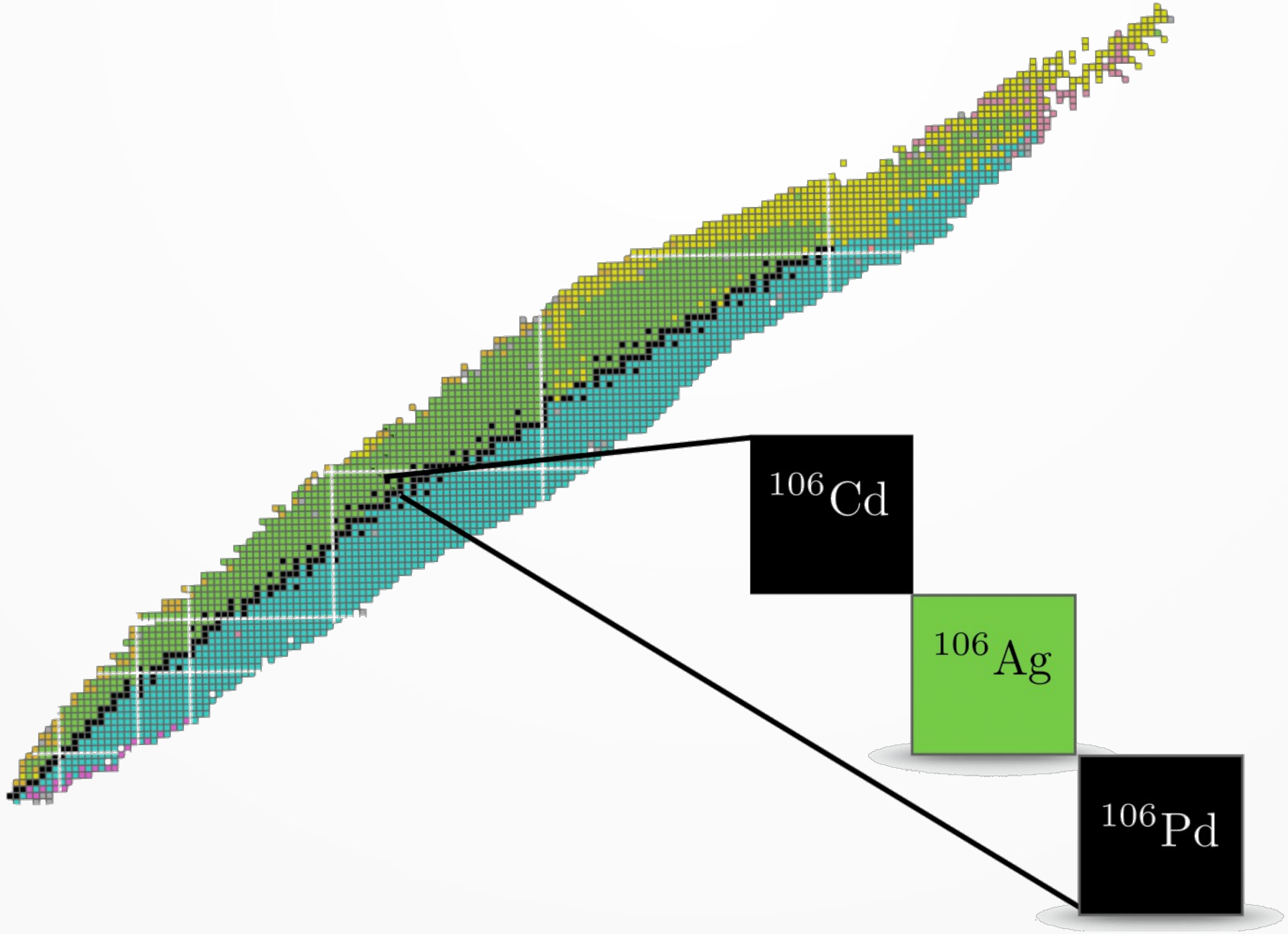
Summary

- Resonant neutrino capture has huge cross sections
- Capture cross section is independent of G_F
- Able to perform this experiment with $\mathcal{O}(\mathrm{TeV})$ energies!

Summary

- Resonant neutrino capture has huge cross sections
- Capture cross section is independent of G_F
- Able to perform this experiment with $\mathcal{O}(\mathrm{TeV})$ energies!
- Great deal of parameter space left to be explored

Summary



Thank you!
Questions?

Neutrino mass uncertainty

- Assuming wrong neutrino mass → incorrectly centred beam energy

$$\delta_m = \frac{m_{\nu,\text{true}} - m_{\nu,\text{pred}}}{m_{\nu,\text{true}}}$$

$$R_{\tau,\text{eff}} = R_\tau (1 - \delta_m)^2 \, e^{-\frac{\delta_m^2}{2(\delta_\nu^2 + \delta_b^2)}}$$

- Only capturing neutrinos from tail end of spectrum

- Partially rectifiable by appropriate choice of δ_b

Neutrino mass uncertainty