Detecting the Cosmic Neutrino Background

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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 ⇦
- Indirect detection proposals:
  - Cosmic ray attentuation
  - Exclusion principle
- Constraints and sensitivities
- What's next?

Recap

- PTOLEMY:

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

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- Event rate:

$$\Gamma \sim 4\,\mathrm{y}^{-1} \qquad\qquad \Delta \leq 2m_\nu$$

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- Event rate:

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- Uncertainty principle causes issues

Recap

- Coherent scattering:

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

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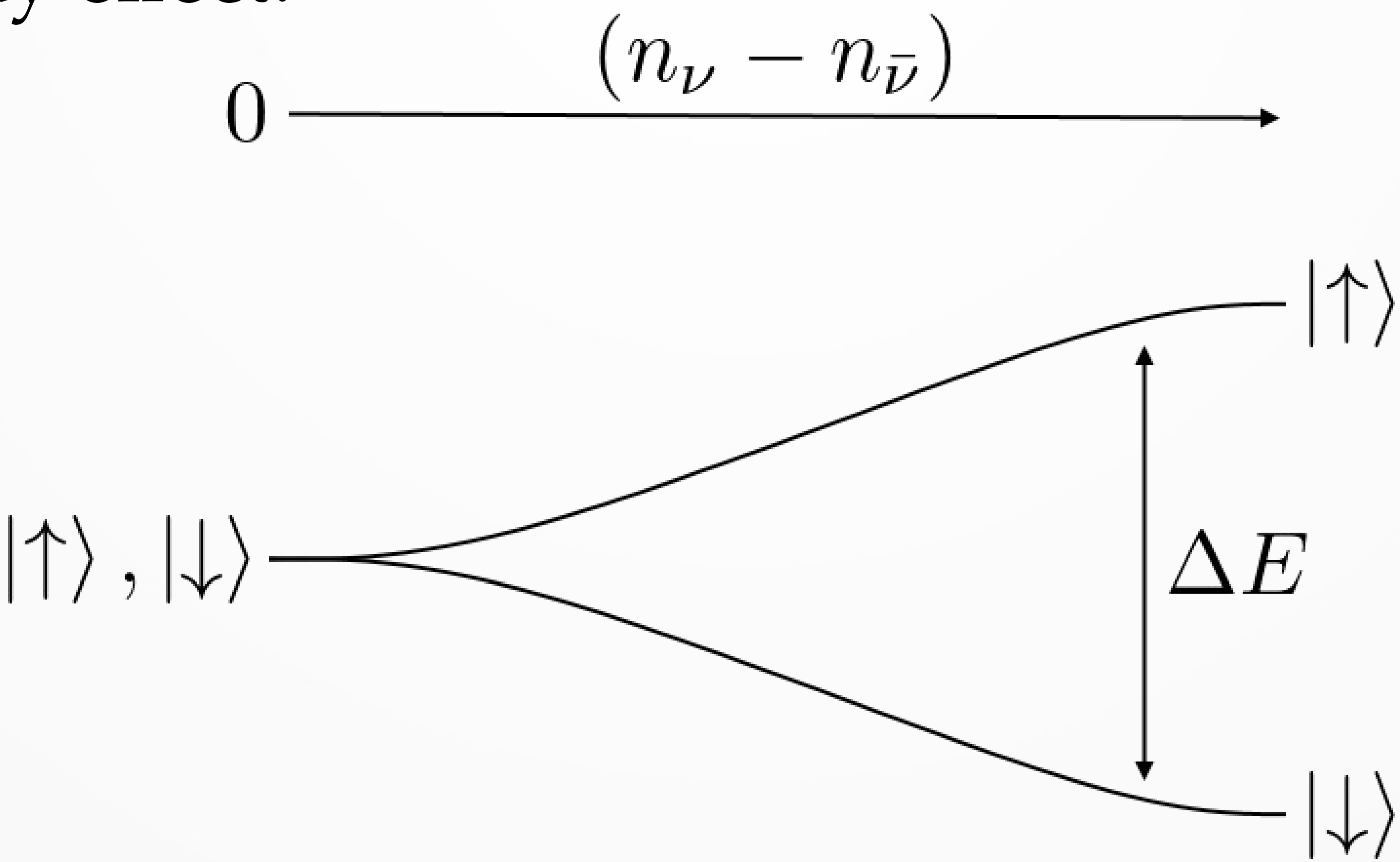
- Future techniques could significantly improve this

Recap

- Stodolsky effect:



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

Recap

- Energy shift giving rise to magnetic field (larger helicity term):

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

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Recap

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

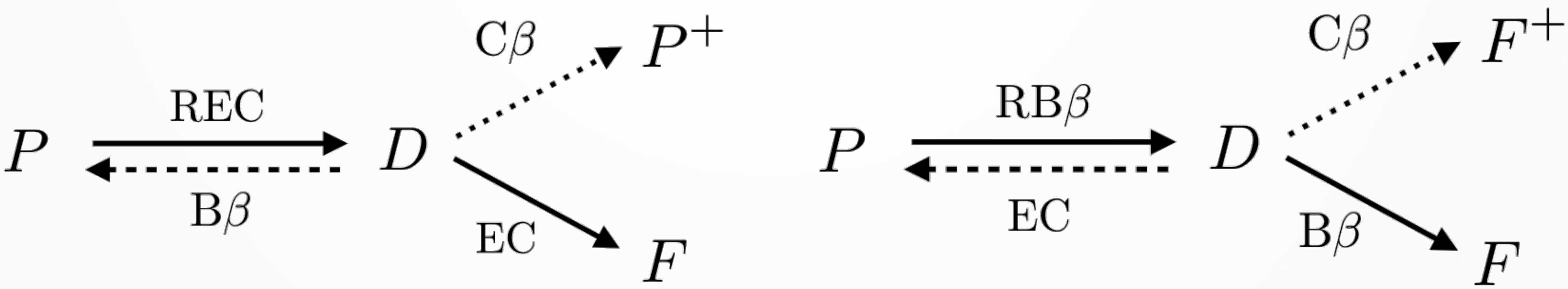
$$B_{\mathrm{ref}} \simeq 10^{-16}\,\mathrm{T}$$

- Asymmetry constrained by BBN:

$$B_\perp \lesssim 10^{-24}\,\mathrm{T}$$

Recap

- Accelerator:



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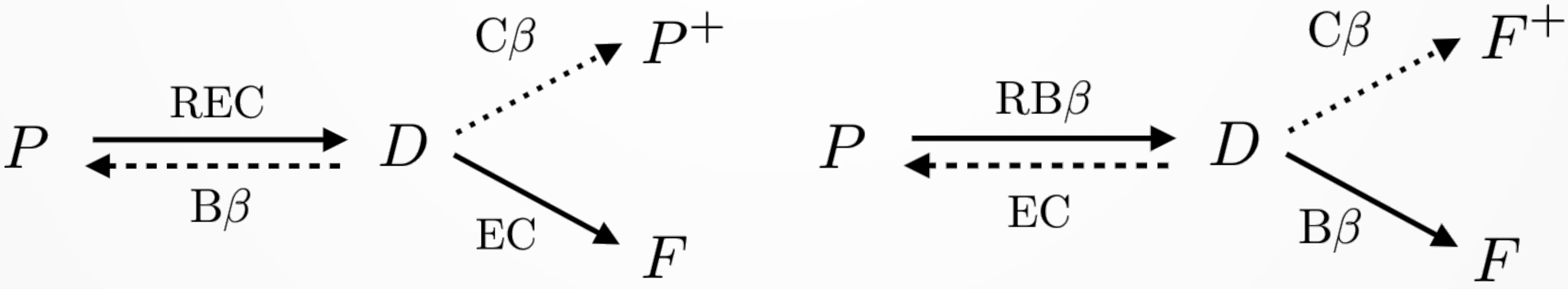
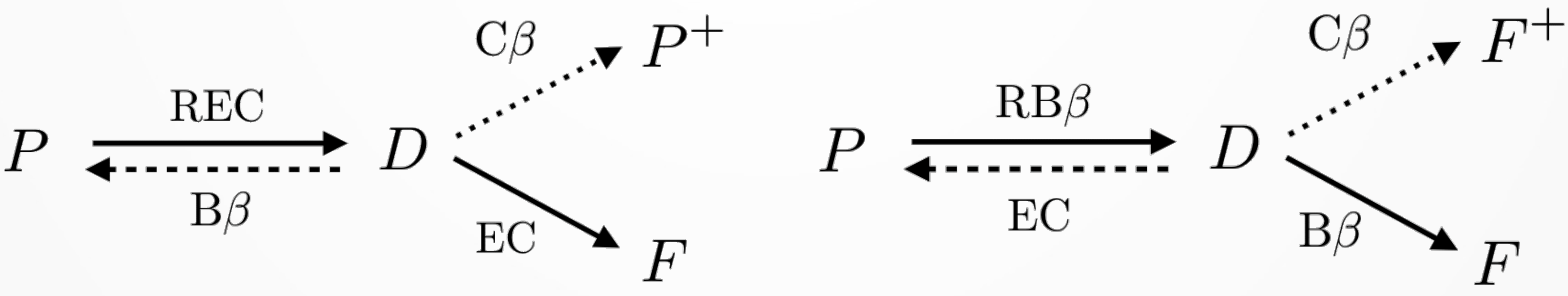


- Need target with small gap

Recap

- Accelerator:



- Need target with small gap
- No suitable targets discovered (yet)

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Cosmic ray attentuation

- The GZK limit:

$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow \ldots$$

Cosmic ray attentuation

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$$E_p \simeq \frac{m_\Delta^2}{2E_{\mathrm{CMB}}}$$

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Cosmic ray attentuation

- The GZK limit:

$$p + \gamma_{\mathrm{CMB}} \to \Delta^+ \to \ldots$$

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$$E_p \simeq 10^{21}\,\mathrm{eV}$$

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Cosmic ray attentuation

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$$p + \gamma_{\text{CMB}} \rightarrow \Delta^{+} \rightarrow \ldots$$

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$$E_p \simeq 10^{19}\,\text{eV}$$

Cosmic ray attentuation

- The GZK limit:

$$p + \gamma_{\rm CMB} \to \Delta^+ \to \ldots$$

- Occurs at energy:

$$E_p \simeq 10^{19}\,{\rm eV}$$

- Limits the proton flux above these energies (see Mauricio's lectures)

Cosmic ray attentuation

- Similar principle for neutrinos:

$$\bar{\nu}_{\mathrm{CR}} + \nu_{\mathrm{C\nu B}} \rightarrow Z \rightarrow \ldots$$

Cosmic ray attentuation

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Cosmic ray attentuation

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- Occurs at energy:

$$E_\nu \simeq 4 \cdot 10^{22}\,\mathrm{eV}\left(\frac{0.1\,\mathrm{eV}}{m_\nu}\right)$$

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- No neutrinos observed at these energies

Cosmic ray attentuation

- Other processes? [1]

$$\bar{\nu}_{\mathrm{CR}} + \nu_{\mathrm{C}\nu\mathrm{B}} \to X \to \ldots$$

[1] V. Brdar, P. S. B. Dev, R. Plestid, A. Soni, Phys. Lett. B **833**, 137358 (2022)

Cosmic ray attentuation

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- Meson resonances much lighter than EW bosons

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Cosmic ray attentuation

- Issues?

$$\sigma(\bar{\nu}\nu \to X) \propto \mathrm{Br}(X \to \bar{\nu}\nu)$$

Cosmic ray attentuation

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$$\sigma(\bar{\nu}\nu \to X) \propto \mathrm{Br}(X \to \bar{\nu}\nu)$$

- For EW bosons:

$$\mathrm{Br}(Z \to \bar{\nu}\nu) \simeq 0.07$$

Cosmic ray attentuation

- Issues?

$$\sigma(\bar{\nu}\nu \to X) \propto \mathrm{Br}(X \to \bar{\nu}\nu)$$

- For mesons:

$$\mathrm{Br}(X \to \bar{\nu}\nu) \lesssim 10^{-11}$$

Cosmic ray attentuation

- Issues?

$$\sigma(\bar{\nu}\nu \to X) \propto \mathrm{Br}(X \to \bar{\nu}\nu)$$

- For mesons:

$$\mathrm{Br}(X \to \bar{\nu}\nu) \lesssim 10^{-11}$$

- Need huge density of neutrinos

Cosmic ray attentuation

- What about the final states?

$$X \to \dots$$

[2] IceCube, Nature **591** (2021) 7849, 220-224

Cosmic ray attentuation

- What about the final states?

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- Glashow resonance observed by IceCube [2]:

$$e^- + \bar{\nu}_e \to W^- \to e^- + \bar{\nu}_e$$

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Cosmic ray attentuation

- What about the final states?

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- Glashow resonance observed by IceCube [2]:

$$e^- + \bar{\nu}_e \to W^- \to e^- + \bar{\nu}_e$$

- Perhaps we can do the same for CνB

[2] IceCube, Nature **591** (2021) 7849, 220-224

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Exclusion principle

- Neutrinos are fermions

Exclusion principle

- Neutrino emitting process:

$$A \rightarrow B + \nu$$

Exclusion principle

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$$A \to B + \nu$$

- Exclusion principle:

$$\int d^3 p_\nu \to \int d^3 p_\nu \left(1 - f(p_\nu)\right)$$

Exclusion principle

Follow a Fermi-Dirac distribution:

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

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- At very small momenta:

$$f(p) \to \frac{1}{2}$$

Exclusion principle

- Atomic and nuclear transitions [3]:

$$|e\rangle \to |g\rangle + \gamma + \nu + \bar{\nu}$$

[3] M. Yoshimura, N. Sasao, M. Tanaka, Phys. Rev. D **91**, 063516 (2015)

Exclusion principle

- Atomic and nuclear transitions [3]:

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- Maximum photon energy → minimum neutrino energy

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Exclusion principle

- Atomic and nuclear transitions [3]:

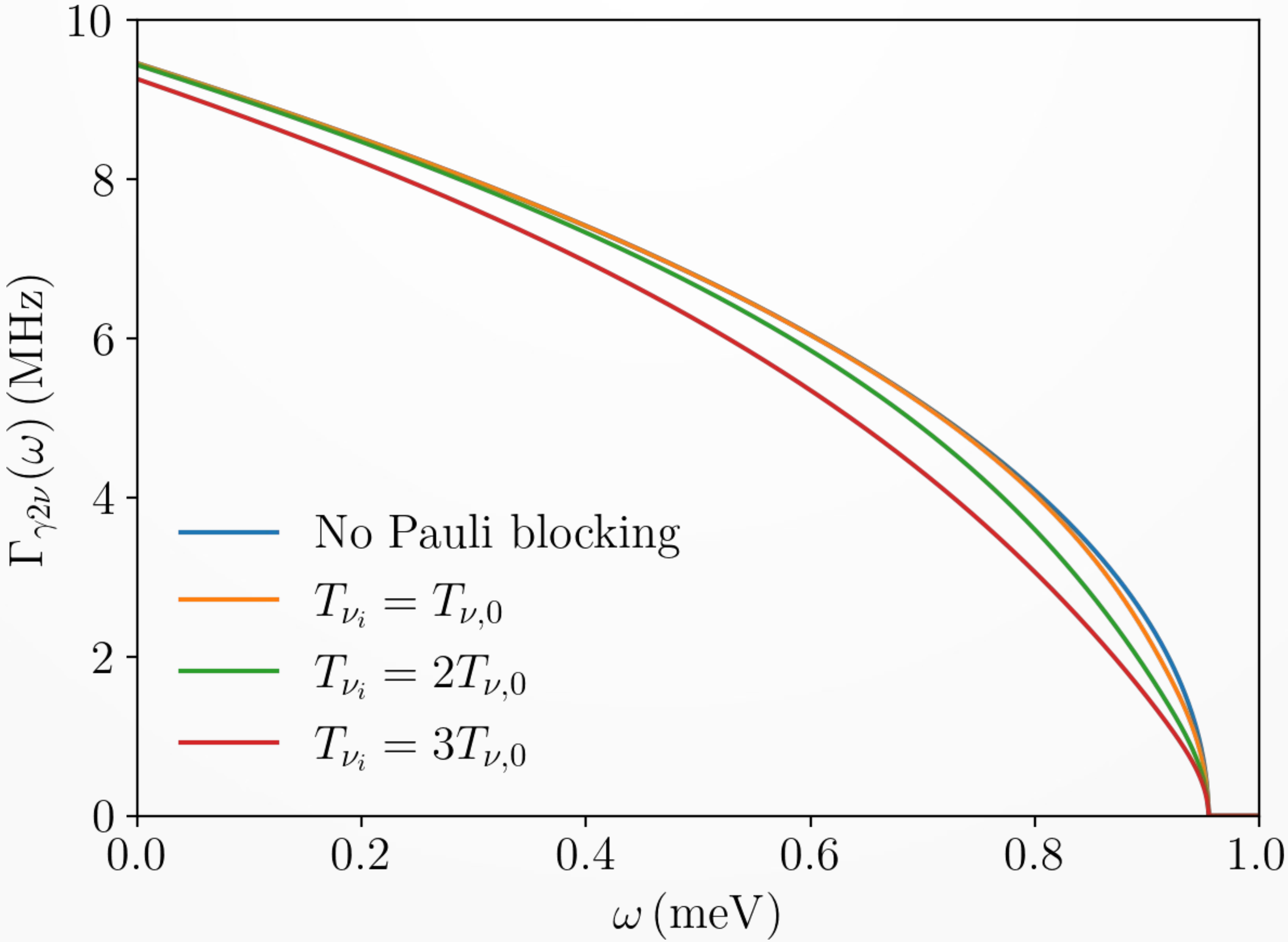
$$|e\rangle \to |g\rangle + \gamma + \nu + \bar{\nu}$$

- Maximum photon energy → minimum neutrino energy

- Look for suppression at the tail end

[3] M. Yoshimura, N. Sasao, M. Tanaka, Phys. Rev. D **91**, 063516 (2015)

Exclusion principle



Exclusion principle

- Realistically?

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- For a given photon energy, lots of combinations of momenta

Exclusion principle

- Realistically?
- For a given photon energy, lots of combinations of momenta
- Neutrinos are cold:

$$1 - f(p_\nu) \to 1$$

Exclusion principle

- So what now?

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- Need a restricted phase space, e.g. 2-body decay

$$X \to Y + \nu \qquad\qquad E_\nu = E_X - E_Y$$

Exclusion principle

- So what now?

- Need a restricted phase space, e.g. 2-body decay

$$X \to Y + \nu \qquad E_\nu = E_X - E_Y$$

- Chemical potentials?

$$f(p_\nu) > \frac{1}{2}$$

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Constraints: mass

- KATRIN:

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

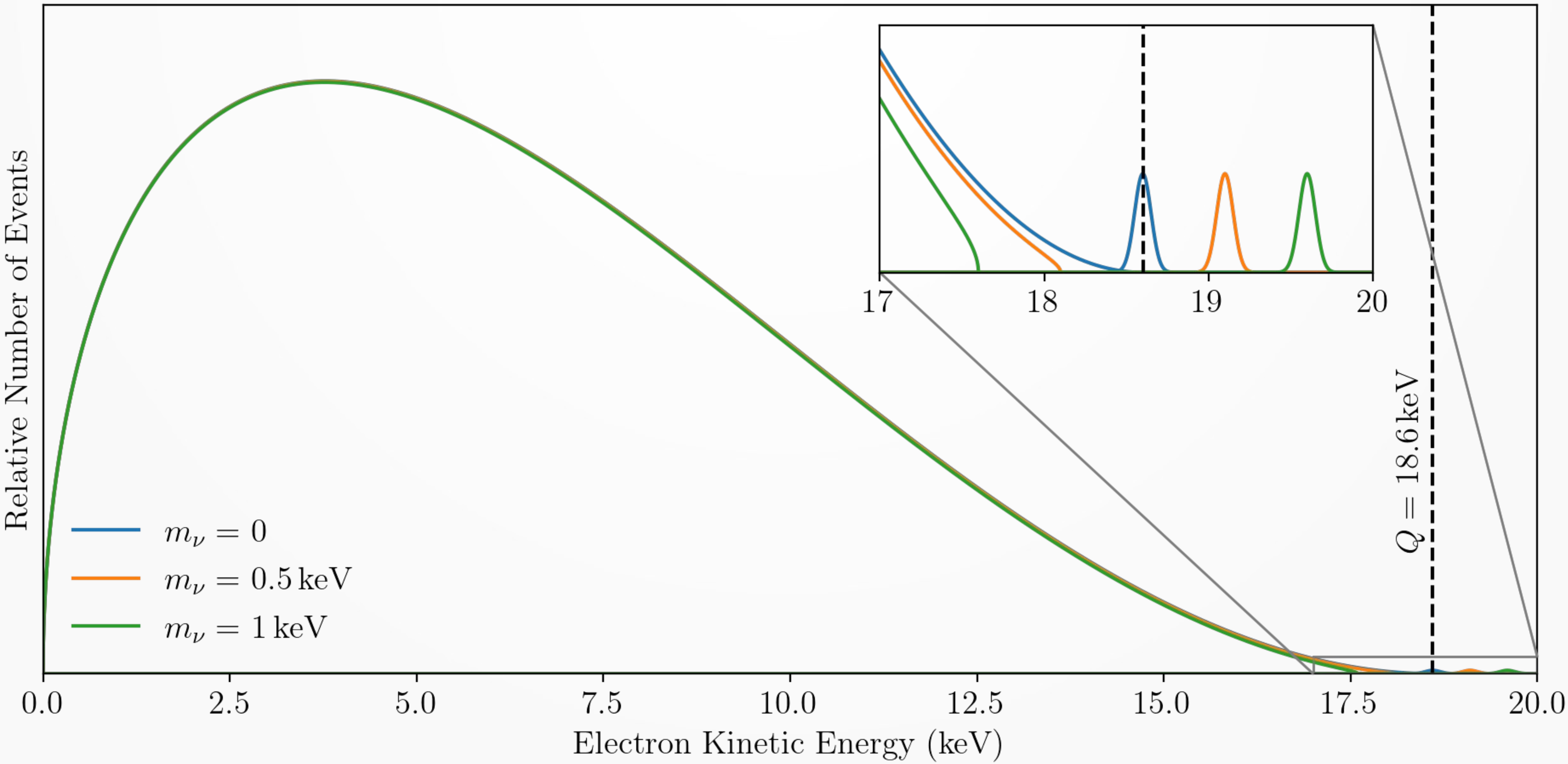
Constraints: mass

- KATRIN:

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

- Analogous to PTOLEMY

Constraints: mass



Constraints: mass

- Current constraints:

$$\sqrt{\sum_i |U_{ei}|^2 m_{\nu_i}^2} < 0.45\,\mathrm{eV}$$

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- Quasi-degenerate regime:

$$m_{\nu_i} \gg \sqrt{\Delta m_{ij}^2}$$

Constraints: mass

- Current constraints:

$$\sqrt{\sum_i |U_{ei}|^2 m_{\nu_i}^2} < 0.45\,\mathrm{eV}$$

- Quasi-degenerate regime:

$$m_{\nu_i} \gg \sqrt{\Delta m_{ij}^2} \implies m_{\nu_i} \simeq m_\nu$$

Constraints: mass

- Current constraints:

$$m_\nu < 0.45\,\mathrm{eV}$$

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- Projection:

$$m_\nu < 0.2\,\mathrm{eV}$$

Constraints: mass

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$$m_\nu < 0.45\,\mathrm{eV}$$

- Projection:

$$m_\nu < 0.2\,\mathrm{eV}$$

- Also weakly sensitive to density

Constraints: mass

- DESI [4]:

$$\sum_i m_{\nu_i} < 0.07\,\mathrm{eV}$$

[4] DESI, arXiv:2404.03002

Constraints: mass

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$$\sum_i m_{\nu_i} < 0.07\,\mathrm{eV}$$

- Heavily disfavours inverted hierarchy!

[4] DESI, arXiv:2404.03002

Constraints: mass

- What if neutrinos are unstable? [5]

$$\sum_i m_{\nu_i} < 1\,\mathrm{eV}$$

[5] M. Escudero, J. Lopez-Pavon, N. Rius, S. Sandner, JHEP **12** (2020) 119

Constraints: mass

- What if neutrinos are unstable? [5]

$$\sum_i m_{\nu_i} < 1\,\mathrm{eV}$$

- Stronger KamLAND bound exists for Majorana neutrinos [6]:

$$\sum_i |U_{ei}|^2 m_{\nu_i} < 0.12\,\mathrm{eV}$$

[5] M. Escudero, J. Lopez-Pavon, N. Rius, S. Sandner, JHEP **12** (2020) 119

[6] KamLAND-ZEN, arXiv: 2406.11438

Constraints: exclusion principle

- Also heavily constrains the CνB

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- CνB has two components – clustered + free streaming:

$$n_\nu = n_{\nu,\mathrm{C}} + n_{\nu,\mathrm{FS}}$$

Constraints: exclusion principle

- Also heavily constrains the CνB

- CνB has two components – clustered + free streaming:

$$n_\nu = n_{\nu,\mathrm{C}} + n_{\nu,\mathrm{FS}}$$

- Ratio set by mass and temperature

Constraints: exclusion principle

- Clustered component:

$$n_{\nu,\mathrm{C}} \leq \underbrace{\frac{1}{(2\pi)^3}}_{V_\nu} \underbrace{\left(\frac{4}{3}\pi p_f^3\right)}_{V_{\mathrm{tot}}}$$

Constraints: exclusion principle

- Clustered component:

$$n_{\nu,\mathrm{C}} \leq \underbrace{\frac{1}{(2\pi)^3}}_{V_\nu} \underbrace{\left(\frac{4}{3}\pi p_f^3\right)}_{V_{\mathrm{tot}}}$$

- Fermi momentum set by escape velocity:

$$p_f \simeq \beta_{\mathrm{esc}} m_\nu$$

Constraints: exclusion principle

- Clustered component:

$$n_{\nu,\mathrm{C}} \leq 12.8\,\mathrm{cm}^{-3}\left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)^3$$

Constraints: exclusion principle

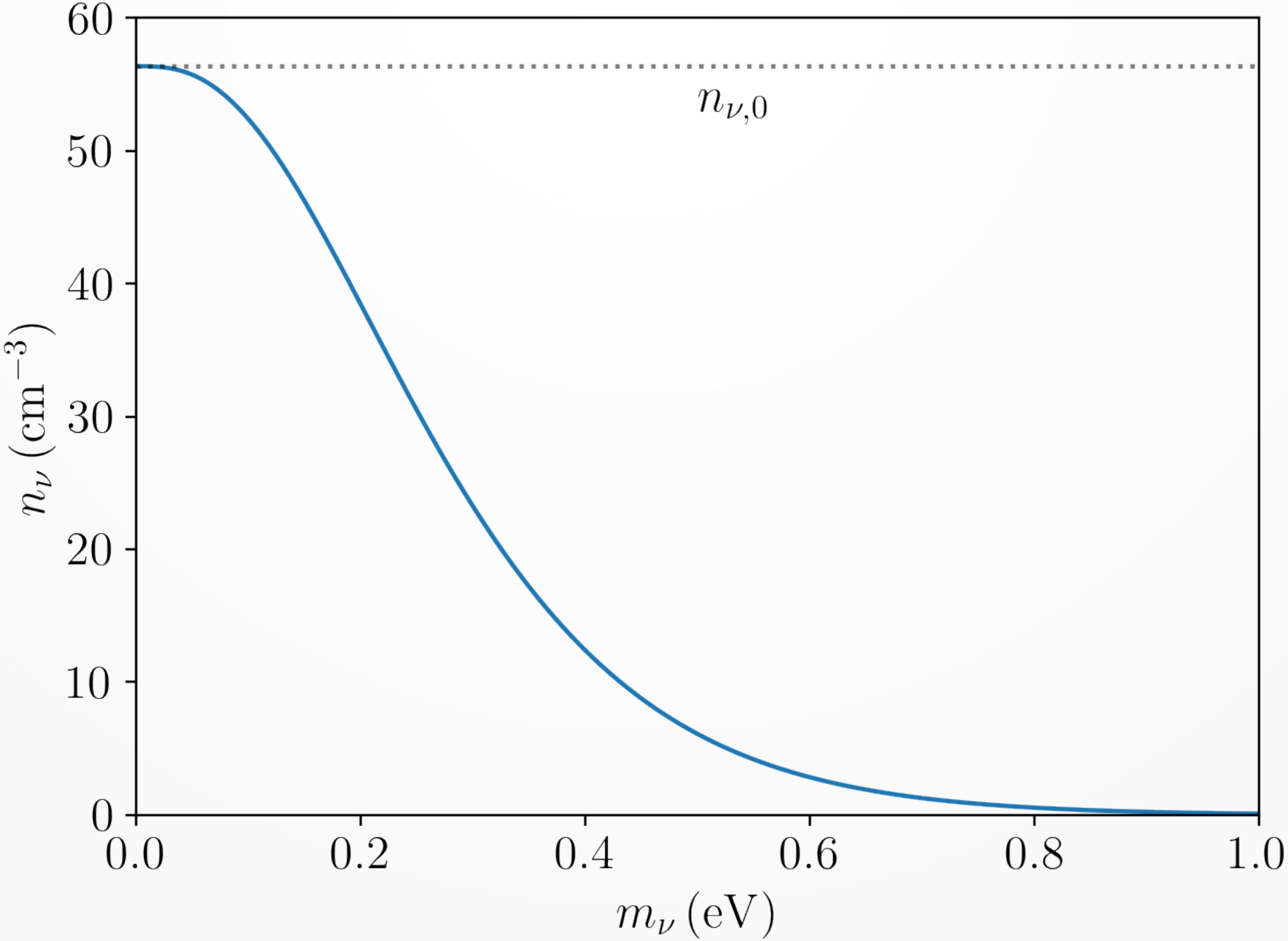
- Clustered component:

$$n_{\nu,\mathrm{C}} \leq 12.8\,\mathrm{cm}^{-3}\left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)^3$$

- Unclustered component:

$$n_{\nu,\mathrm{FD}} = \frac{1}{2\pi^2}\int_{p_f}^{\infty}\frac{p^2}{\exp\left(\frac{p}{T}+1\right)}$$

Constraints: exclusion principle



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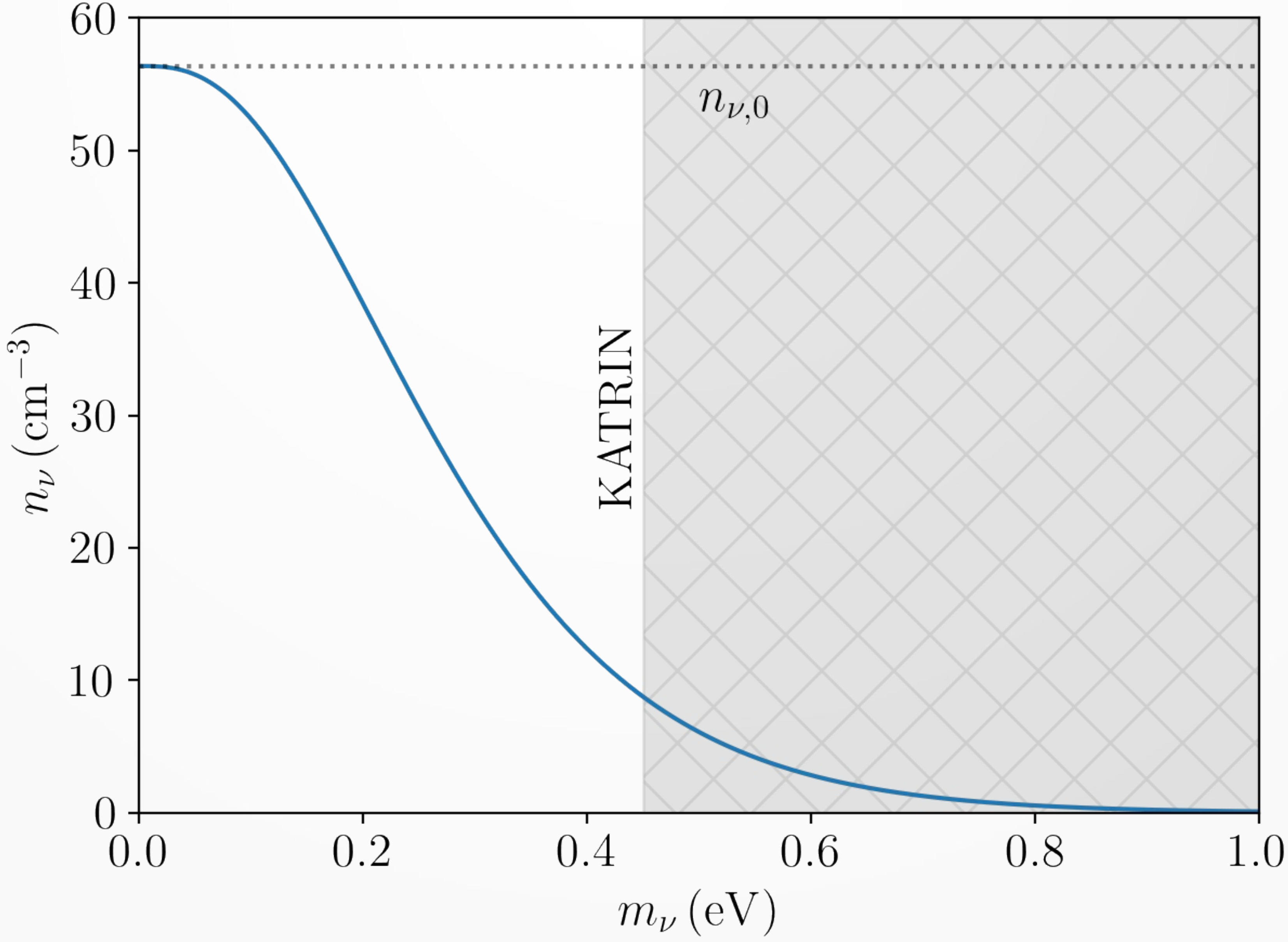

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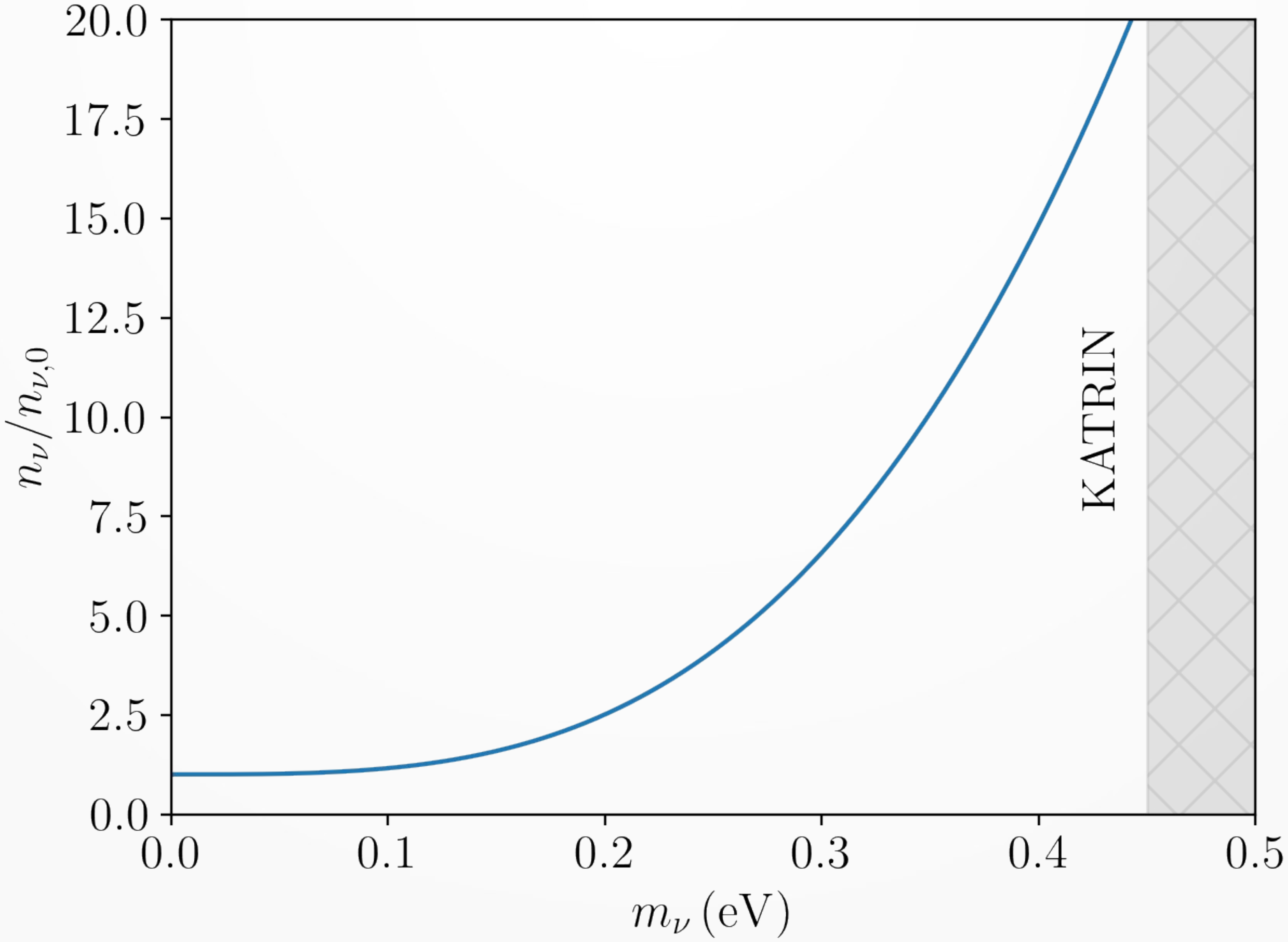

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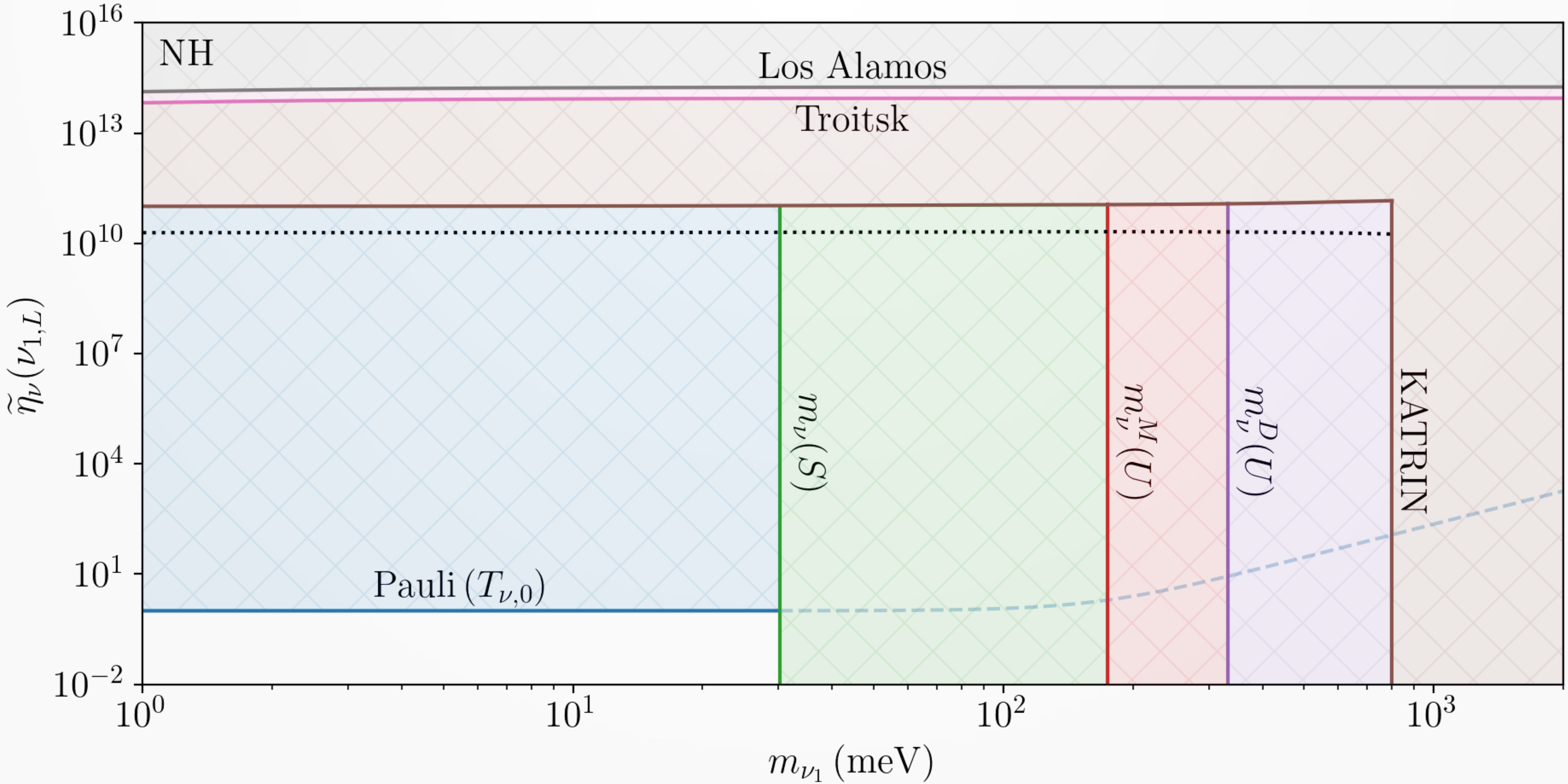
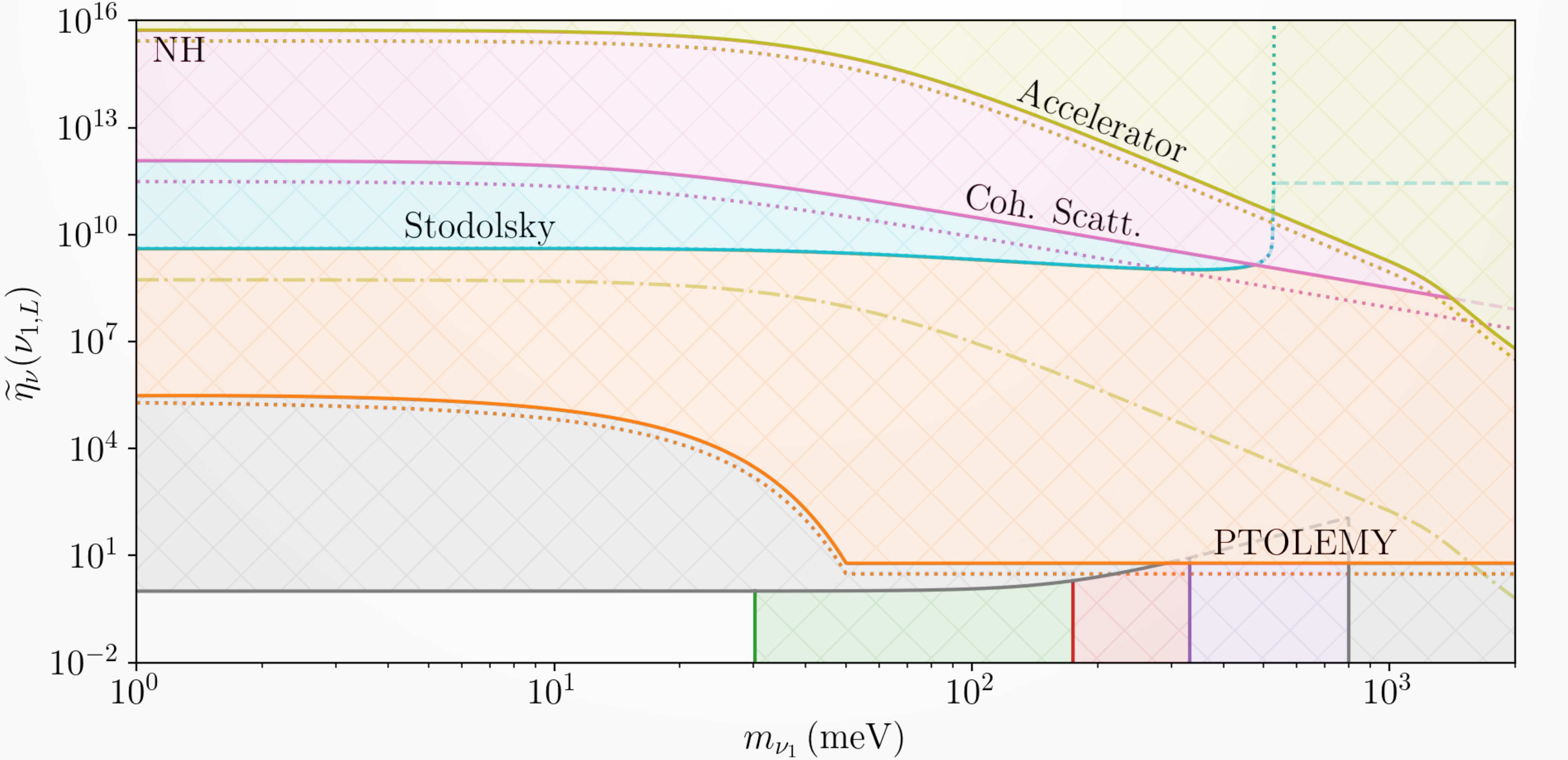


Sensitivity



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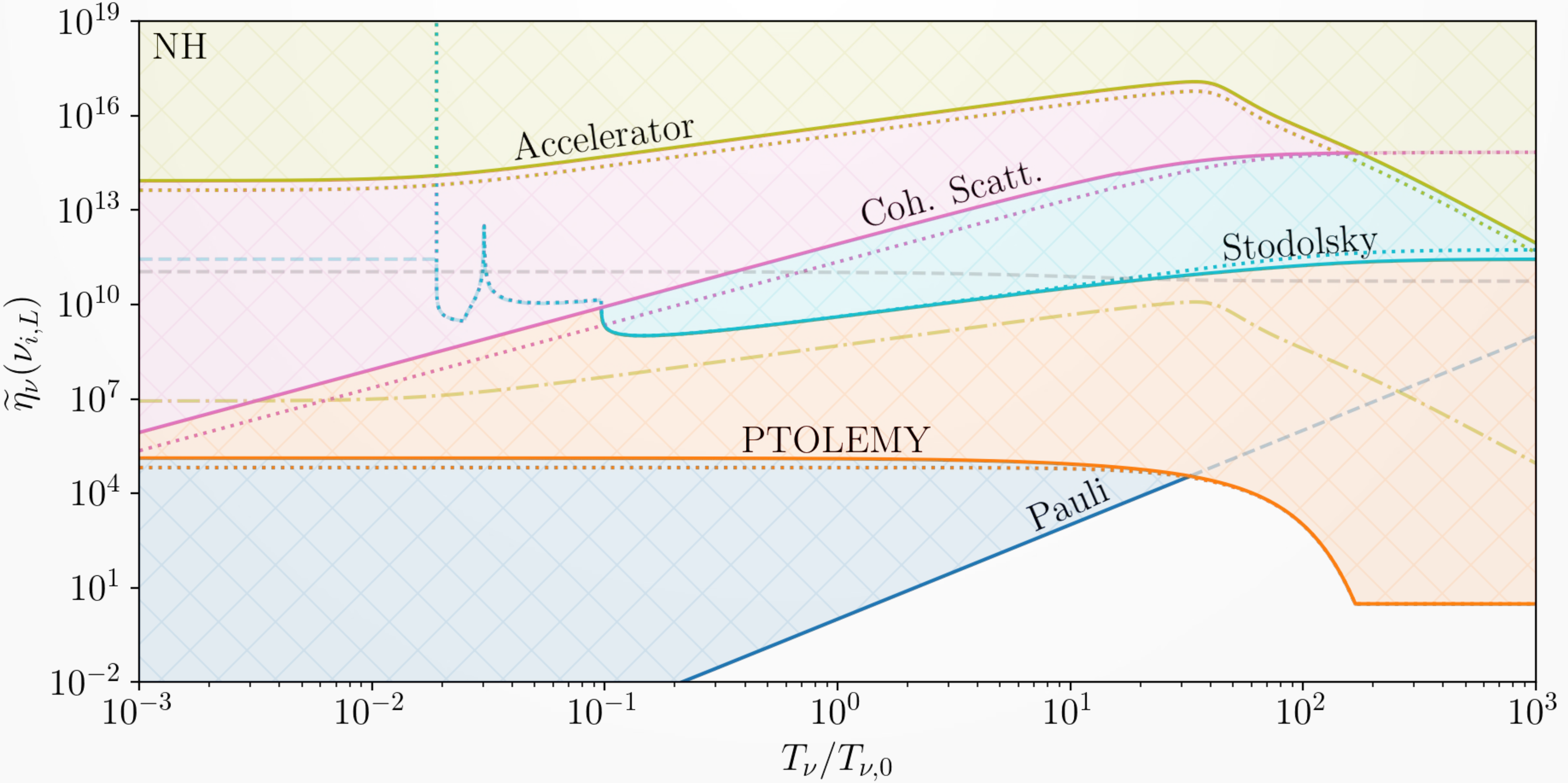

Summary

- $C\nu B$ detection is an almost impossible task:
  - Cold, almost non-interacting neutrinos
- Lots of reasons to look for the $C\nu B$:
  - New interactions, lepton asymmetries, $N_{\rm eff}$
- Lots of ideas to detect the $C\nu B$!
  - None really work…
  - But there are hints!

Thank you!

Děkuju!