Reviewing Cosmic Neutrino Background

Ujjal Kumar Dey
Dept. of Physical Sciences
IISER Berhampur

Vikram Discussions on Neutrino Astrophysics
Physical Research Laboratory, Ahmedabad

Mar 20, 2025

Outline

- Introduction
- Detection possibilities
  - Difficulties
  - Direct Methods
  - Indirect Methods
- Prospects
- Summary and Conclusion

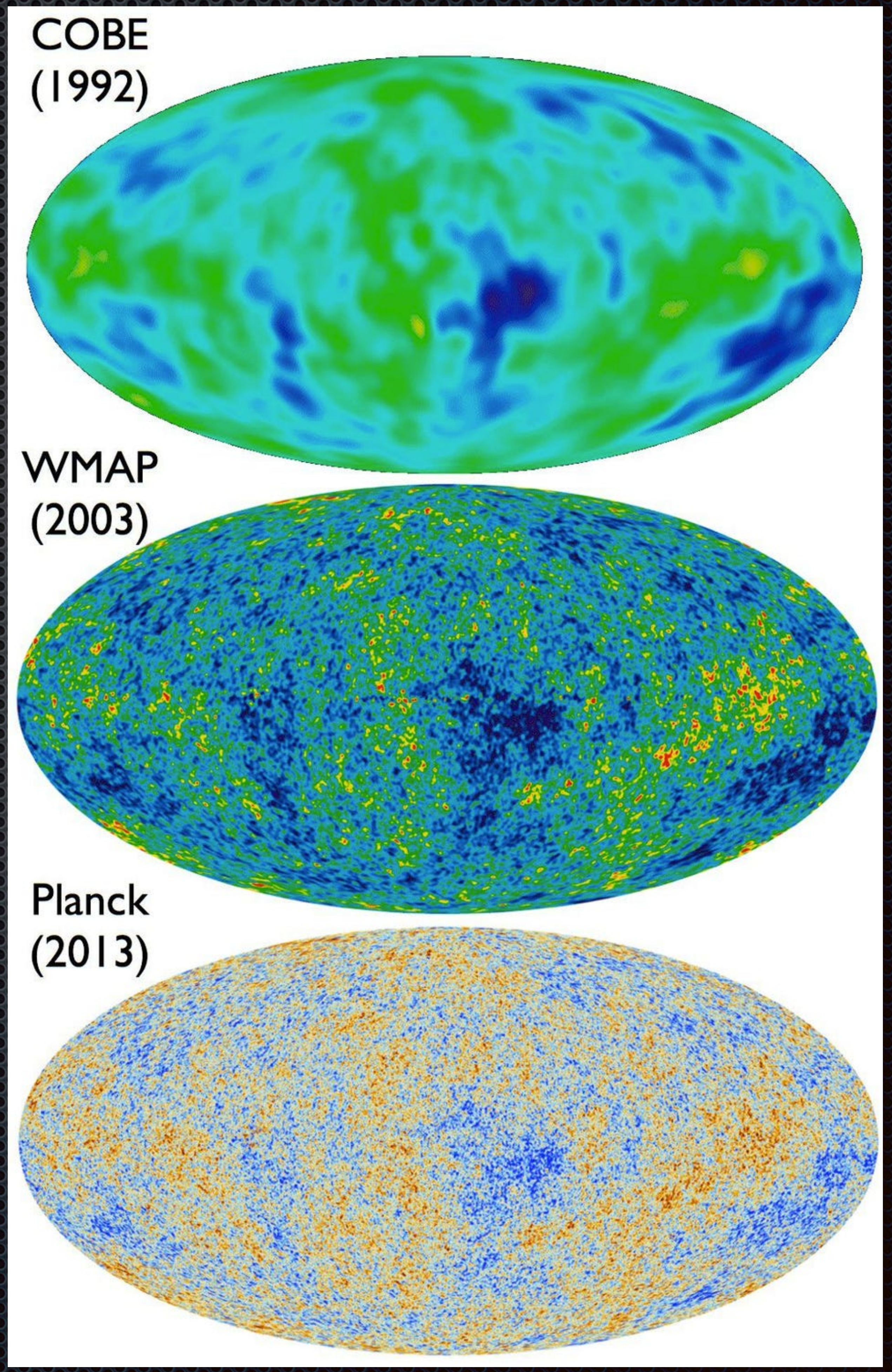
Outline

- Introduction
- Detection possibilities
    - Difficulties
    - Direct Methods
    - Indirect Methods
- Prospects
- Summary and Conclusion

- CMB is the oldest directly observed radiation in the Universe, dating from the epoch of recombination
- Establishes the SM of cosmology, the Big Bang Theory (BBT) which along with CMB, predicts the existence of cosmic neutrino background (CNB)
- CNB: a relic radiation that decoupled from matter when the Universe was merely a second old
- Played a crucial role in primordial nucleosynthesis and in large scale structure formation
- CMB anisotropies → an indirect imprint of the CNB ⇒ two crucial constraints pertaining to particle physics

    (i) limit on the sum of neutrino masses ($\Sigma m_\nu < 0.12$ eV)

    (ii) effective number of neutrino species ($N_{\rm eff} = 2.99 \pm 0.17$)

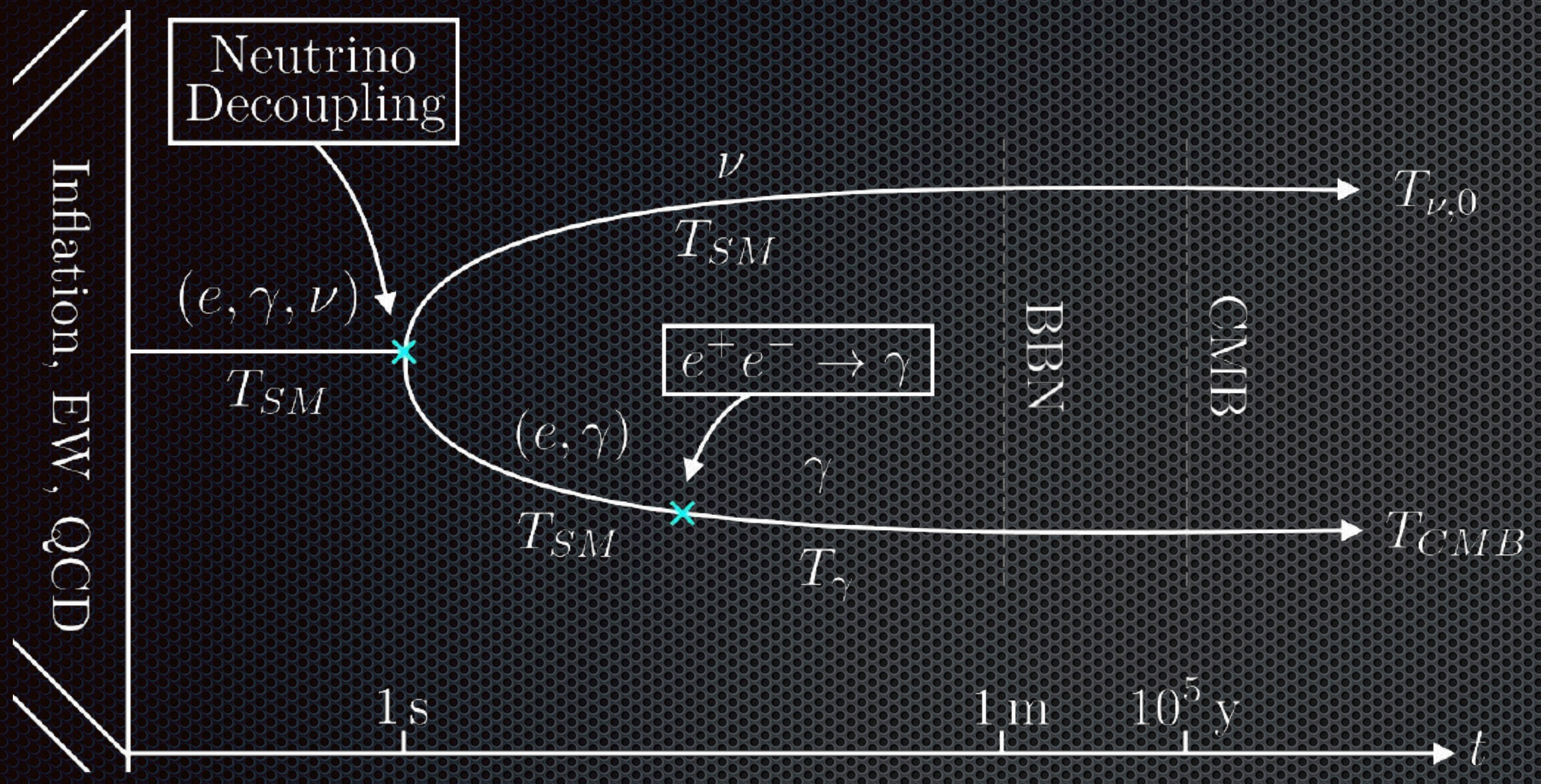


(Source: ESA/Planck Collaboration)

Direct detection of CNB

⇒ further consolidation of BBT, new opportunities in ν (new?) physics

A Brief (thermal) History of ν



(Source: a talk by J. Shergold)

- At the early hot and dense stage of the Universe, equilibrium betweeen
  - electrons and photons are maintained by electromagnetic interactions, $e^\pm\gamma \rightleftharpoons e^\pm\gamma, \quad e^+e^- \rightleftharpoons \gamma\gamma$
  - electrons and neutrinos are maintained by weak interactions, $e^+e^- \rightleftharpoons \nu_j\bar{\nu}_j,\ e^\pm\nu_j \rightleftharpoons e^\pm\nu_j,\ e^\pm\bar{\nu}_j \rightleftharpoons e^\pm\bar{\nu}_j$
- As the Universe expands, particle densities are diluted and temperatures fall, weak interactions become ineffective to keep neutrinos in good thermal contact with the EM thermal bath

An order-of-magnitude estimate

- Decoupling or freeze-out of neutrinos occur when interaction rate becomes less than or equal to the expansion rate of the Universe, i.e., $\Gamma_{\rm int} \lesssim H$

$$\Gamma_{\rm int} = n\langle\sigma v\rangle \sim \left(\frac{g}{(2\pi)^3}\int d^3p f(\vec{p})\right) \times \left(\frac{\alpha^2 E_\nu^2}{m_{W,Z}^2}\right) \sim \left(\frac{3\zeta(3)}{4\pi^2}T^3\right)\left(\frac{\alpha^2}{m_{W,Z}^2}T^2\right) \sim G_F^2 T^5$$

$$H = \sqrt{\frac{8\pi G}{3}\rho} = \sqrt{\frac{8\pi G}{3}\left(\frac{g}{(2\pi)^3}\int d^3p E(\vec{p}) f(\vec{p})\right)} \sim \sqrt{\frac{8\pi G}{3}\left(\frac{\pi^2}{30}g_* T^4\right)} \sim \sqrt{g_*}\frac{T^2}{m_{\rm Pl}}$$

At decoupling $G_F^2 T_{\nu,f}^5 = \sqrt{g_*}\dfrac{T_{\nu,f}^2}{m_{\rm Pl}} \Rightarrow T_{\nu,f} \sim \sqrt[6]{g_*}$ MeV ~ 1.48 MeV

More refined calculations predict $T_{\nu_e,f} = 2.3$ MeV, and $T_{\nu_{\mu,\tau},f} = 3.5$ MeV; this corresponds to a time roughly $\mathcal{O}(1)$ second after the Big Bang, since $t \sim \left(\dfrac{1\ \text{MeV}}{T}\right)^2$ s

- So, neutrinos decouple from $e^{\pm}$ and photons at the temperature $T \sim$ a few MeV, and remain as such until today

- At the time of neutrino decoupling the electromagnetic processes of $e^{\pm}$ and photons were still going on, but as the temperature reduced to $2m_e$ i.e., 1.02 MeV, the reverse process in $e^+e^- \rightleftharpoons \gamma\gamma$ stopped and only $e^+e^- \to \gamma\gamma$ remained active

- This transfer of entropy to photons effectively slows down the rate of decrease in the photon temperature in comparison to the neutrino temperature as the Universe expands

- In a comoving volume total entropy remains conserved; this can be used to connect photon and neutrino temperatures as $T_\nu = (4/11)^{1/3} T_\gamma$

- Redshifted to today, the last relation implies, $T_{\nu,0} = (4/11)^{1/3} T_{\mathrm{CMB}} \sim 1.9\ \mathrm{K} \sim 1.7 \times 10^{-4}\ \mathrm{eV}$

- The frozen-out neutrinos (at least two states of them) are thus extremely non-relativistic today

- The number density of neutrinos per degree of freedom

$$n_{\nu,0} = \frac{3\zeta(3)}{4\pi^2} T_{\nu,0}^3 \simeq 56 \text{ cm}^{-3}$$

i.e., $6n_{\nu,0} = 336 \text{ cm}^{-3}$ for the entire decoupled neutrinos

- Note that neutrinos are produced as flavour eigenstates which are a coherent superposition of mass eigenstates

- Flavour eigenstate decoupled neutrinos quickly decohere into their mass eigenstates on a timescale much less than one Hubble time [Eberle et. al, PRD 2004]

- Assuming the decoherence do not affect the relative abundance, one can conclude that neutrinos with masses of interest are present in the Universe today as mass eigenstates, populated with an abundance mentioned above ⇒ and this is what constitutes CNB

A few technical points

- Helicity; Chirality; Dirac; Majorana:
  - At the freeze-out neutrinos were ultra-relativistic, so there was no distinction between their helicities and chiralities. As they cool down, they remain no longer ultra-relativistic and helicity and chirality do not coincide, after all neutrinos are not massless. While neutrinos are free-streaming their helicity is conserved but not chirality. If the neutrinos are not completely free-streaming but have some kind of interaction then the helicity can be flipped. This can redistribute relative abundances in Dirac case, but nothing is affected for the Majorana case.

- Clustering:
  - Since neutrinos have some tiny masses they can not escape gravitational effects. They can be trapped in gravitational potential wells of galaxies or cluster of galaxies if the CNB neutrinos have velocities smaller than the escape velocity [Ringwald and Wong, JCAP 2004]. This may lead to a local overdensity of neutrinos and the standard density of $56\ \mathrm{cm}^{-3}$ can be enhanced [Mertsch et. al, JCAP 2020].

Outline

- Introduction
- Detection possibilities
  - Difficulties
  - Direct Methods
  - Indirect Methods
- Prospects
- Summary and Conclusion

Difficulties

- Low cross-sections/event rate:

  Usual weak interaction cross section for neutrinos,

$$\sigma_\nu \sim G_{\mathrm{F}}^2 E_\nu^2 \sim 5 \times 10^{-50} \left(\frac{E_\nu}{1\ \mathrm{keV}} \right)^2 \mathrm{cm}^2$$

  For typical electromagnetic process, e.g.,

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

- Thresholds:

  Traditional neutrino detection methods requires threshold (anti-)neutrino energies to be way higher than CNB neutrino energies, e.g., "inverse beta-decay" interactions with the protons in the water, producing positrons and neutrons requires anti-neutrinos with an energy above the threshold of 1.8 MeV

Possibilities

- The methods of detection will require:

  (i) removing or regulating the threshold

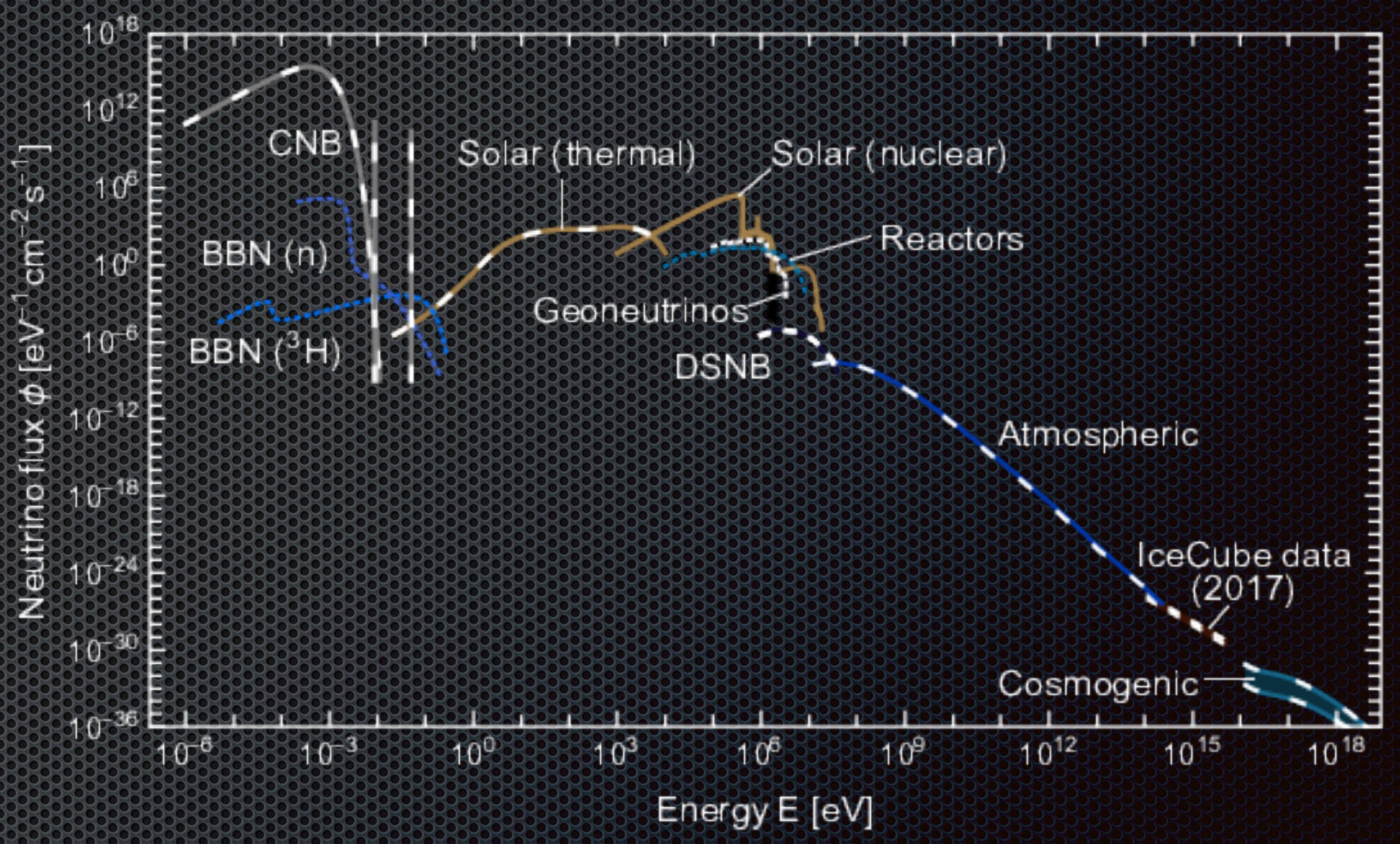
  (ii) enhance the event rate — (a) using exorbitantly large number of targets, (b) increasing the cross-sections

- Several methods to detect CNB have been proposed — broadly three main categories:

  (i) direct detection by neutrino capture on β-decaying nuclei

  (ii) direct detection of coherent CNB elastic scattering with target nuclei through momentum transfer [mainly two types — (a) $\mathcal{O}(G_F)$ effect (e.g., Stodolsky effect), (b) $\mathcal{O}(G_F^2)$ effect (e.g., coherent neutral current scattering)]

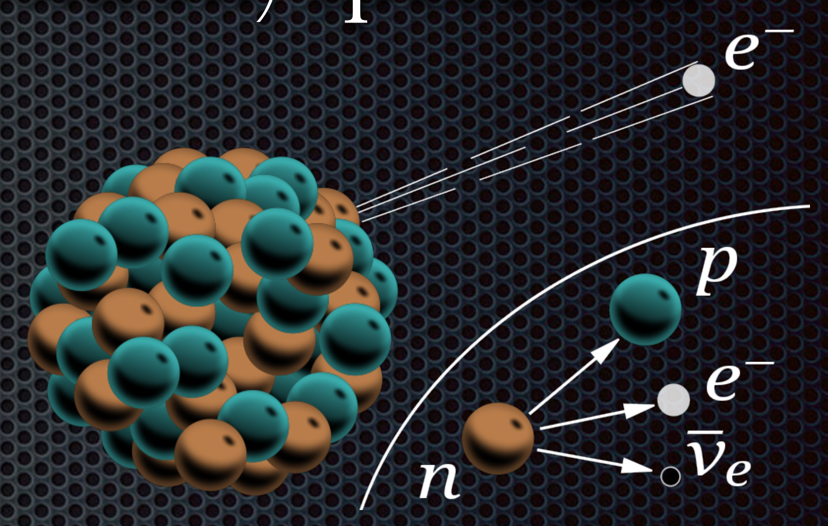
  (iii) indirect detection by finding spectral distortion through CNB interaction with ultra-high energy neutrinos or protons/nuclei from unknown sources



(Source: Vitagliano et. al, Rev. Mod. Phys. 2020)

Neutrino capture by β-decaying nuclei

- Original idea — a large neutrino chemical potential distorts the electron (positron) spectrum near the β-decay endpoint energy [Weinberg, Phys. Rev. 1962]



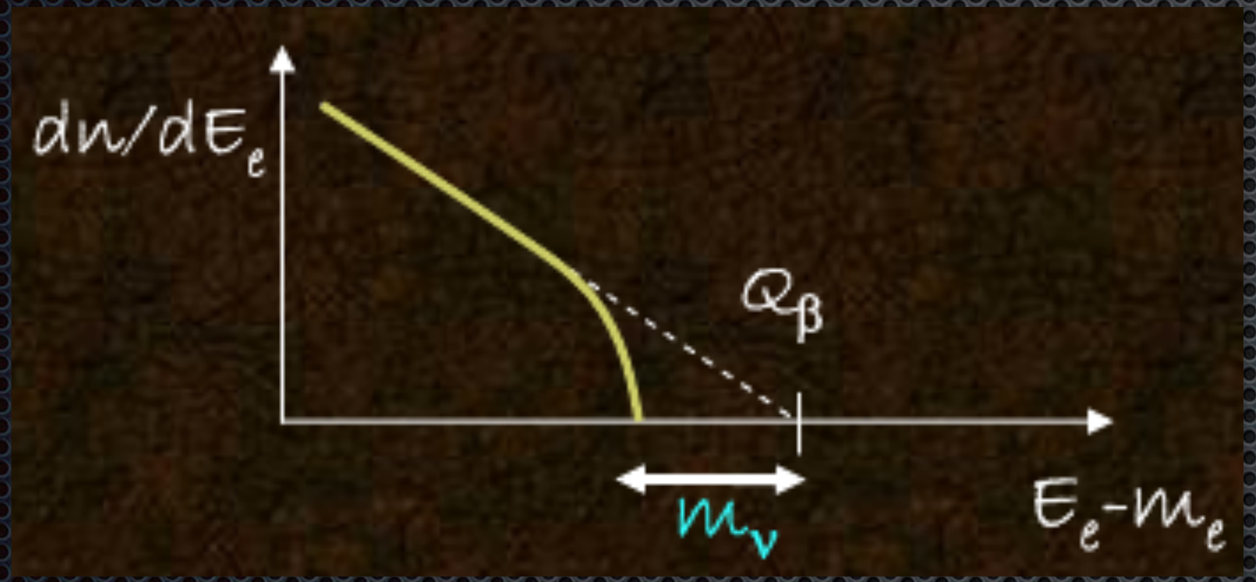
- Usual β-decay of an unstable nucleus,

$$(A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$$

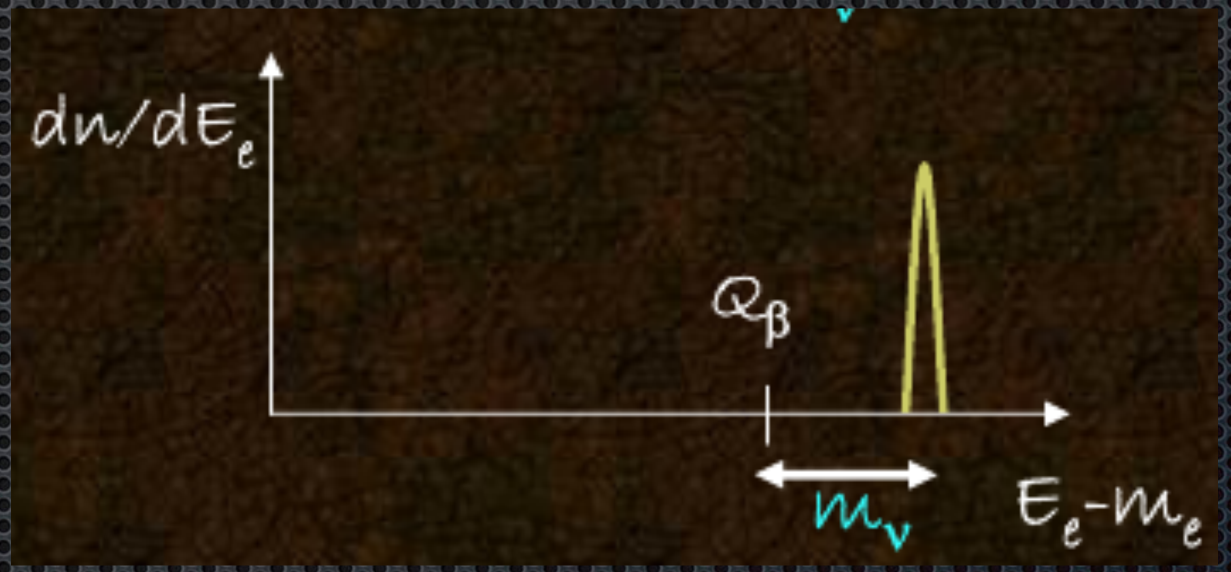
- In this case there exists a threshold-less reaction of neutrino capture

$$(A, Z) + \nu_e \to (A, Z+1) + e^-$$

- Clearly, β-decays create a background for the neutrino capture, but that can be distinguished using relevant kinematics [Cocco et. al, JCAP 2007]



(β-decay spectrum)



(ν-capture spectrum)

A $2m_\nu$ gap in the electron spectrum centered around Q_β

(Source: a talk by G. Mangano)

PTOLEMY

- PTOLEMY experiment (Princeton Tritium Observatory for Light-Early Universe Massive-neutrino Yield) aims to detect the CNB by capturing electron neutrinos on a 100 g tritium target in the process ${}^3\mathrm{H} + \nu_e \to {}^3\mathrm{He} + e^-$ [Baracchini, arXiv:1808.01892]
- Tritium is the best option, since —
  (i) low $Q_\beta \approx 18.6$ keV $\Rightarrow$ easier to observe an effect of m_ν in the high-energy end of energy distribution of electrons
  (ii) lifetime $\tau \sim 12$ yr $\Rightarrow$ small enough to have a high decay rate, but large enough not to decay instantly
  (iii) typical cross section of neutrino capture $\sim 3.7 \times 10^{-45}\mathrm{cm}^2$
- With 100 g of tritium (PTOLEMY proposal), event rate $\sim 4/\mathrm{yr}$
- The capture rate in the Majorana case is twice as that of the Dirac case, i.e., $\Gamma^{\mathrm{M}}_{\mathrm{CNB}} = 2\Gamma^{\mathrm{D}}_{\mathrm{CNB}}$ [Long et. al, JCAP 2014]. Additional particles, interactions etc. can change this [Arteaga et. al, JHEP 2017].

Drawbacks of PTOLEMY

- Extreme sensitivity requirements, $\Delta \leq 2m_\nu$. PTOLEMY claims a sensitivity of $\Delta \simeq 50$ meV is achievable
- Storage of tritium related issues: diffusion, lifetime etc. PTOLEMY proposes to use graphene substrates
- Uncertainty principle, the killjoy [Chiepesh et. Al, PRD(2021), Nussinov et. Al, PRD (2022)]:

$$\Delta x \Delta p \sim \frac{1}{2} \Rightarrow \Delta v \sim \frac{1}{2m_T \Delta x}$$

$$\Rightarrow \Delta E_e \sim p_e \Delta v = \sqrt{\frac{m_e Q}{2}} \frac{1}{m_T \Delta x} \sim 500 \text{ meV for } \Delta \text{x} \sim 0.1 \text{ Å}$$

- The uncertainty (i.e., the resolution is much larger than $2m_\nu$). PTOLEMY proposes usage of carbon nanotube can fix the problem

Drawbacks of PTOLEMY

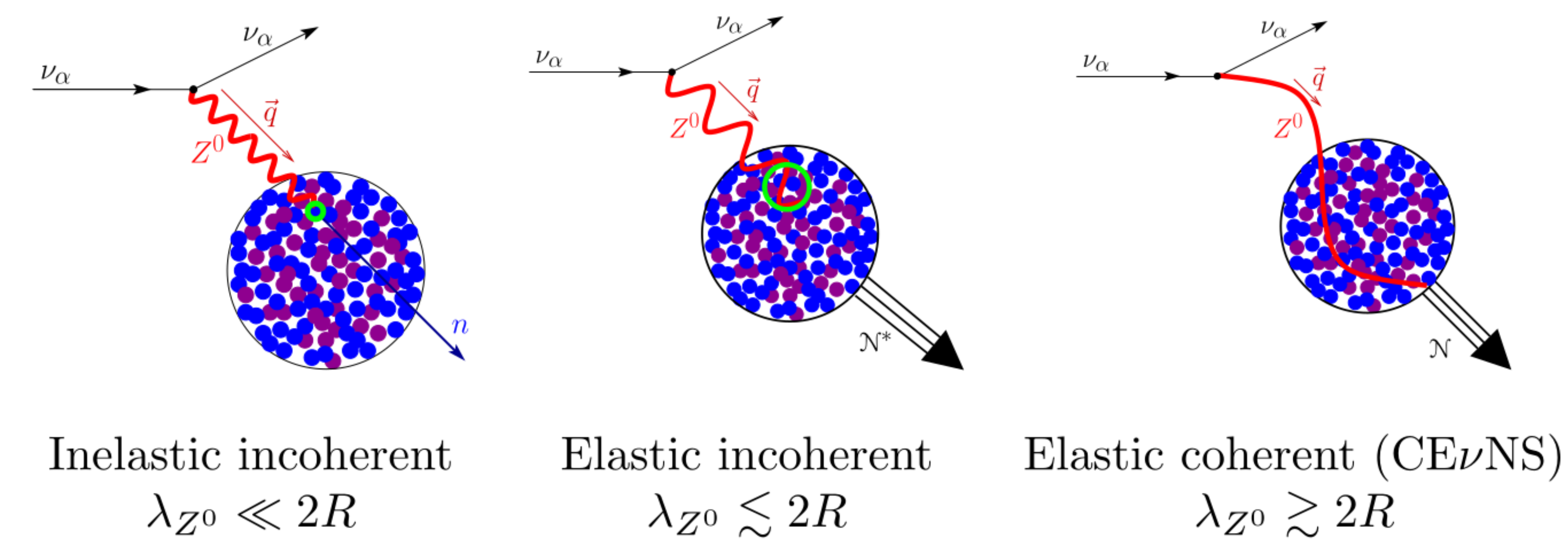
- Extreme sensitivity requirements, $\Delta \leq 2m_\nu$. PTOLEMY claims a sensitivity of $\Delta \simeq 50$ meV is achievable
- Storage of tritium related issues: diffusion, lifetime etc. PTOLEMY proposes to use graphene substrates
- Uncertainty principle, the killjoy [Chiepesh et. Al, PRD(2021), Nussinov et. Al, PRD (2022)]:

$$\Delta x \Delta p \sim \frac{1}{2} \Rightarrow \Delta v \sim \frac{1}{2m_T \Delta x}$$

$$\Rightarrow \Delta E_e \sim p_e \Delta v = \sqrt{\frac{m_e Q}{2}} \frac{1}{m_T \Delta x} \sim 500 \text{ meV for } \Delta \text{x} \sim 0.1 \text{ Å}$$

- The uncertainty (i.e., the resolution is much larger than $2m_\nu$). PTOLEMY proposes usage of carbon nanotube can fix the problem

Coherent scattering ($\mathcal{O}(G_F^2)$ effect)



(Source: Cadeddu et. al, EPL 143 34001)

- As the Earth moves through the sea of CNB neutrinos, a target on Earth experiences, by elastic scattering, momentum transfer from neutrinos [Freedman, PRD 1974; Shergold, JCAP 2021]
- Applicable when coherence can only be maintained over a single nucleus; relic neutrinos with macroscopic wavelengths $\lambda_\nu \sim \mathcal{O}(\mathrm{mm})$ should be capable of maintaining coherence over many nuclei, leading to vastly enhanced cross sections

- Induces a small macroscopic acceleration in a target with total mass M (in Cavendish-type torsion balance), $a \sim \dfrac{1}{M} N_T \beta_\nu \sigma_{\nu N} n_\nu \langle \Delta p \rangle$

- Issue:

$$a_\nu \sim 10^{-28} \left(\frac{m_\nu}{0.1 \text{ eV}} \right)^2 \text{cm s}^{-2}$$ (Shergold, JCAP 2021)

$$a_{\text{ref}} \sim 10^{-15} \text{ cm s}^{-2}$$ (Wagner et. al, Class. Quant. Grav. (2012))

$$a_{\text{H}} \sim 10^{-23} \text{ cm s}^{-2}$$ (Hagmann, astro-ph/9905258)

Stodolsky effect ($\mathcal{O}(G_F)$ effect)

- The presence of a neutrino background acts as a potential that changes the energy of atomic electron spin states, analogous to the Zeeman effect in the presence of a magnetic field [Stodolsky, PRL, 1975; Duda et. al PRD, 2001]

- Requirements to have the energy splitting ΔE_e,

  (i) net neutrino chemical potential (for Dirac case) or net helicity (for Majorana case)

  (ii) breaking of isotropy (Earth velocity)

- Typically, $\Delta E_e \sim G_F g_A \beta_\oplus (n_\nu - n_{\bar{\nu}})$

- Result depend on Dirac/Majorana, relativistic/non-relativistic, clustered/unclustered

- Spectroscopic methods are of no use, $\Delta E_e \sim 10^{-38}\delta_\nu$ eV, whereas usual Zeeman effect it is ~ 10^{-4} eV

Stodolsky effect ($\mathcal{O}(G_F)$ effect)

- Because of the spin-dependence of the Hamiltonian,

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

- A torque $\tau_e \sim |\Delta E_e|$ on each electron, such that a ferromagnet with N_e polarised electrons in the presence of CNB experiences a total torque $N_e \tau_e \sim N_A Z M |\Delta E_e| / A m_A$

- $a_\nu \sim 10^{-27} \delta_\nu$ cm s^{-2}

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

- A time-dependent magnetisation of a ferromagne

- $B_\perp \sim 10^{-25} \delta_\nu$ T

- $B_{\mathrm{ref}} \sim 10^{-18}$ T

Some other proposals:

- Using accelerators: CoM energy requirements for thresholded neutrino capture processes can be met by running an accelerated beam of ions through the CNB. This offers the additional advantage of being able to tune the neutrino energy to hit a resonance, in doing so significantly enhancing capture cross sections [Bauer et. al, PRD, 2021]

- Using neutrino decay: The electromagnetic decay of neutrinos from CNB would result in a background of photons; the spectral lines from relic neutrino decays could be observed using line intensity mapping, which could place competitive bounds on the neutrino lifetime and provide direct evidence for the cosmic neutrino background; neutrino electromagnetic moment plays significant role here [Bernal et. al, PRL, 2021]

- Indirect methods:

  (i) Cosmic ray neutrino attenuation — most pronounced when the incident cosmic ray scatters from a relic neutrino resonantly resulting in a narrow absorption line in the cosmic ray spectrum analogous to the GZK cutoff [Weiler, PRL, 1982]

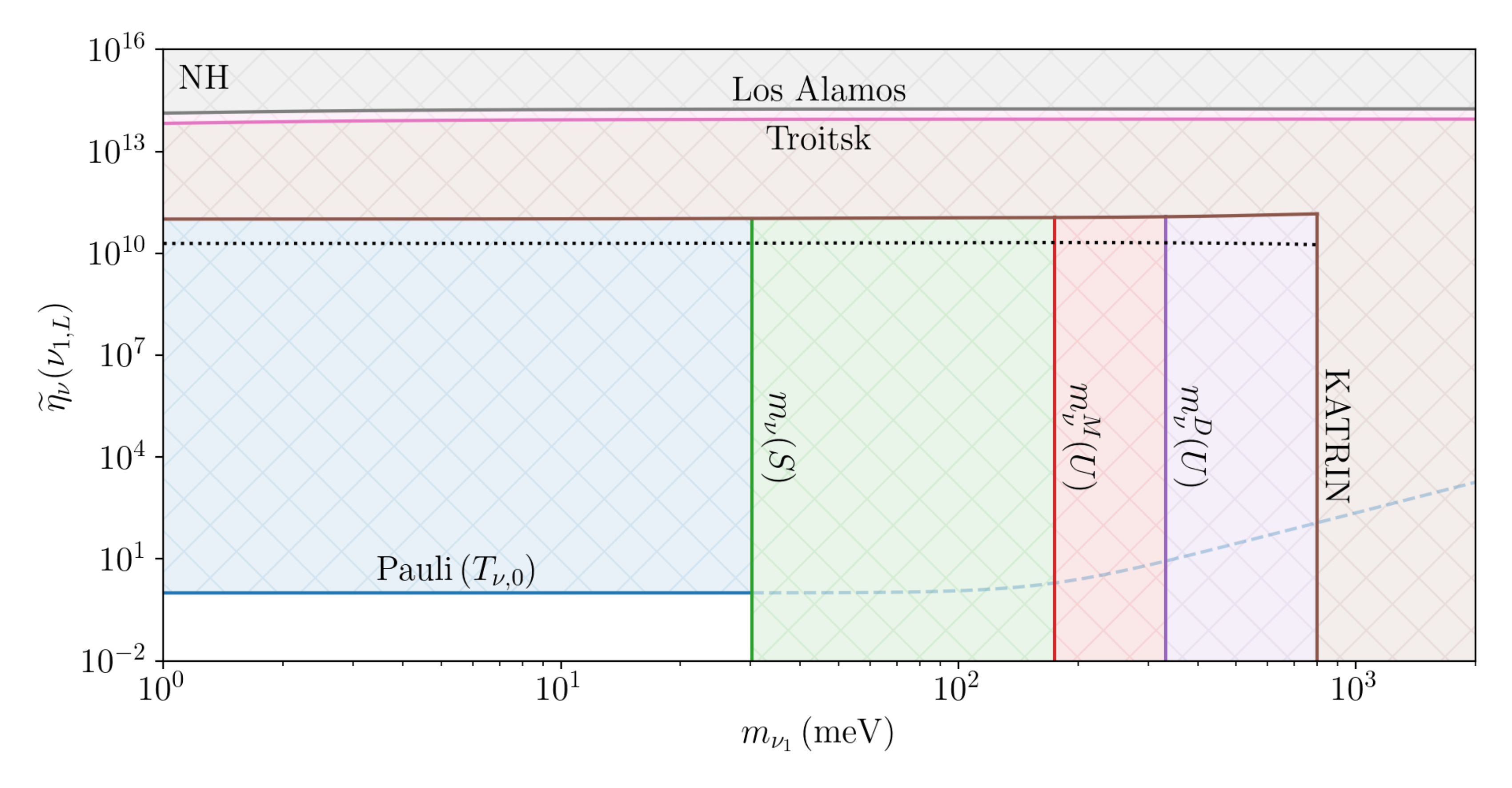
  (ii) Atomic de-excitation — using Pauli exclusion principle. Due to the presence of the CNB, processes emitting neutrinos will have their phase space restricted. For example, in the radiative emission of neutrino pairs (RENP) by de-exciting atomic states, the outgoing photon energy spectrum will be modified [Yoshimura et. al, PRD 2015]

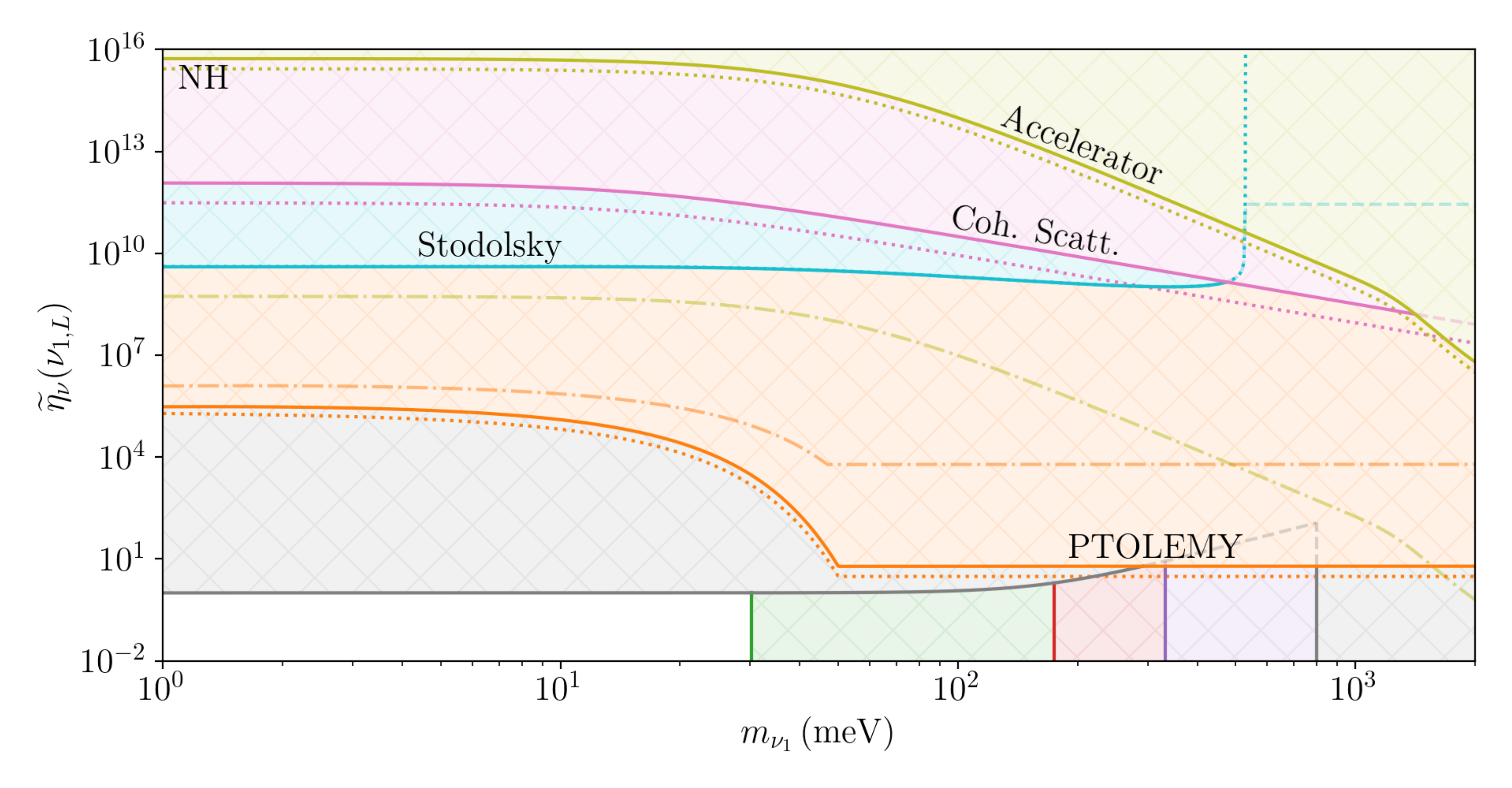
A few more!

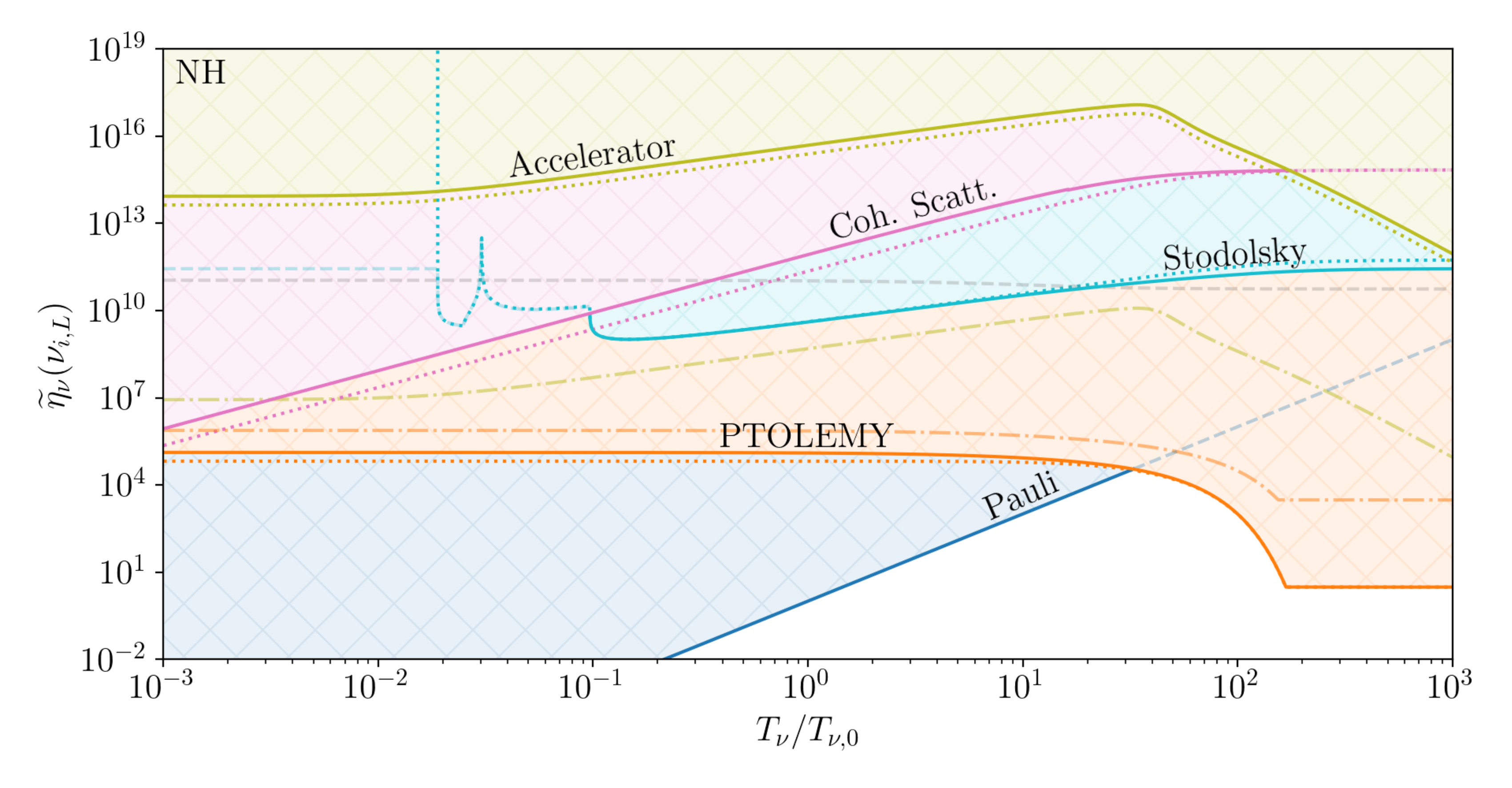
- Angular correlations in neutrino capture on β-decaying nuclei; based on periodic variations (due to the peculiar motion of the Sun with respect to the CνB rest frame and the rotation of the Earth about its axis) of angular correlations in inverse beta decay transitions induced by relic neutrino capture. [Akhmedov, JCAP 2019]
- Using resonant scattering against cosmogenic neutrinos [Brdar et. al, PLB 2022]
- Using laser interferometry [Domcke & Spinrath, JCAP 2017]
- Using neutron stars; not so much of any detection prospects, but can be used to constrain overdensities on short length scales [Garv Chauhan, arXiv:2408.01489]

Constraints and Sensitivity

- There are 3 important parameters: (i) $\eta_\nu = \dfrac{n_\nu}{n_{\nu,0}}$, (ii) m_ν, (iii) T_ν







(Bauer & Shergold, JCAP 2023)

Outline

- Introduction
- Detection possibilities
    - Difficulties
    - Direct Methods
    - Indirect Methods
- Prospects
- Summary and Conclusion

Prospects

- Not much as far as direct methods are concerned unless there is significant technological advancement
- Indirect methods: possibilities are innumerable provided observational feasibilities can be addressed properly; various cosmological observation, GW astronomy (?)
- If neutrinos have hitherto unknown (long range) interactions then the conclusions of many of the aforementioned scenarios can change significantly

Outline

- Introduction
- Detection possibilities
    - Difficulties
    - Direct Methods
    - Indirect Methods
- Prospects
- Summary and Conclusion

Summary and Conclusion

- Detecting relic neutrinos is an overwhelmingly difficult challenge due to their low energy and weakly interacting nature
- A successful detection of the CNB can help us look back deeper than CMB
- Many of the as yet unmeasured parameters such as the temperature and number density of the CNB can be predicted from theory, extended scenarios could result in significantly different values
- Success of many detection proposals depends heavily on these parameters
- As always, *BSM* (particle physics and/or cosmology) can be probed or constrained by the successful detection of CNB

Thank you