Effects of General Neutrino Interactions on Cosmic Neutrino Background

(Based on arXiv:2304.02505, I. K. Banerjee, UKD, N. Nath, S. S. Shariff)

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Outline

* Introduction
* Standard Big Bang Cosmology and CNB
* Detection Methods @ PTOLEMY
* GNI & their effects
* Results
* Summary

Outline

* Introduction

- 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)

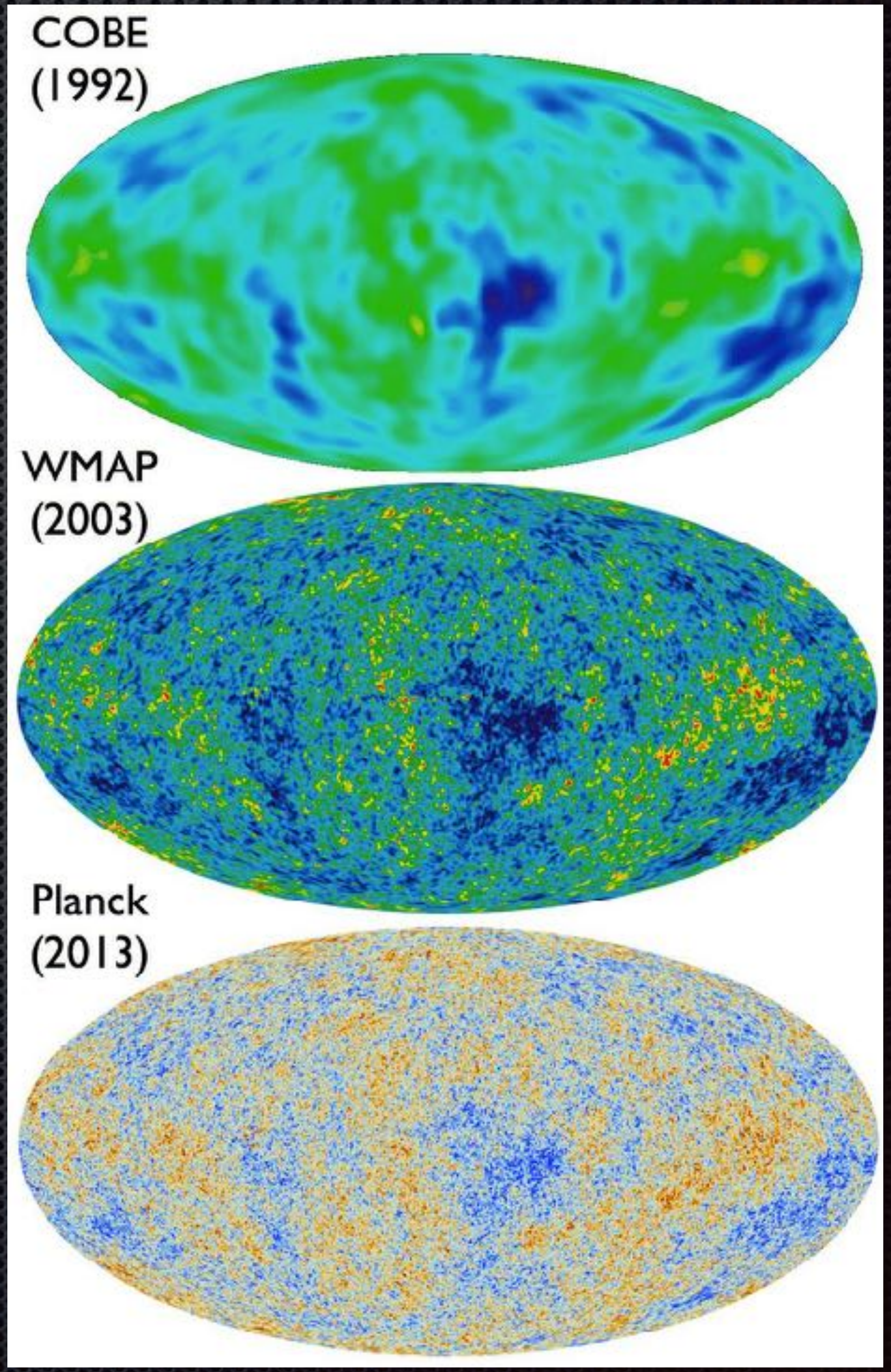
- CNB: a relic radiation that decoupled from matter when the Universe was merely a second old

- 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 ($N_{\rm eff} = 2.99 \pm 0.17$)

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

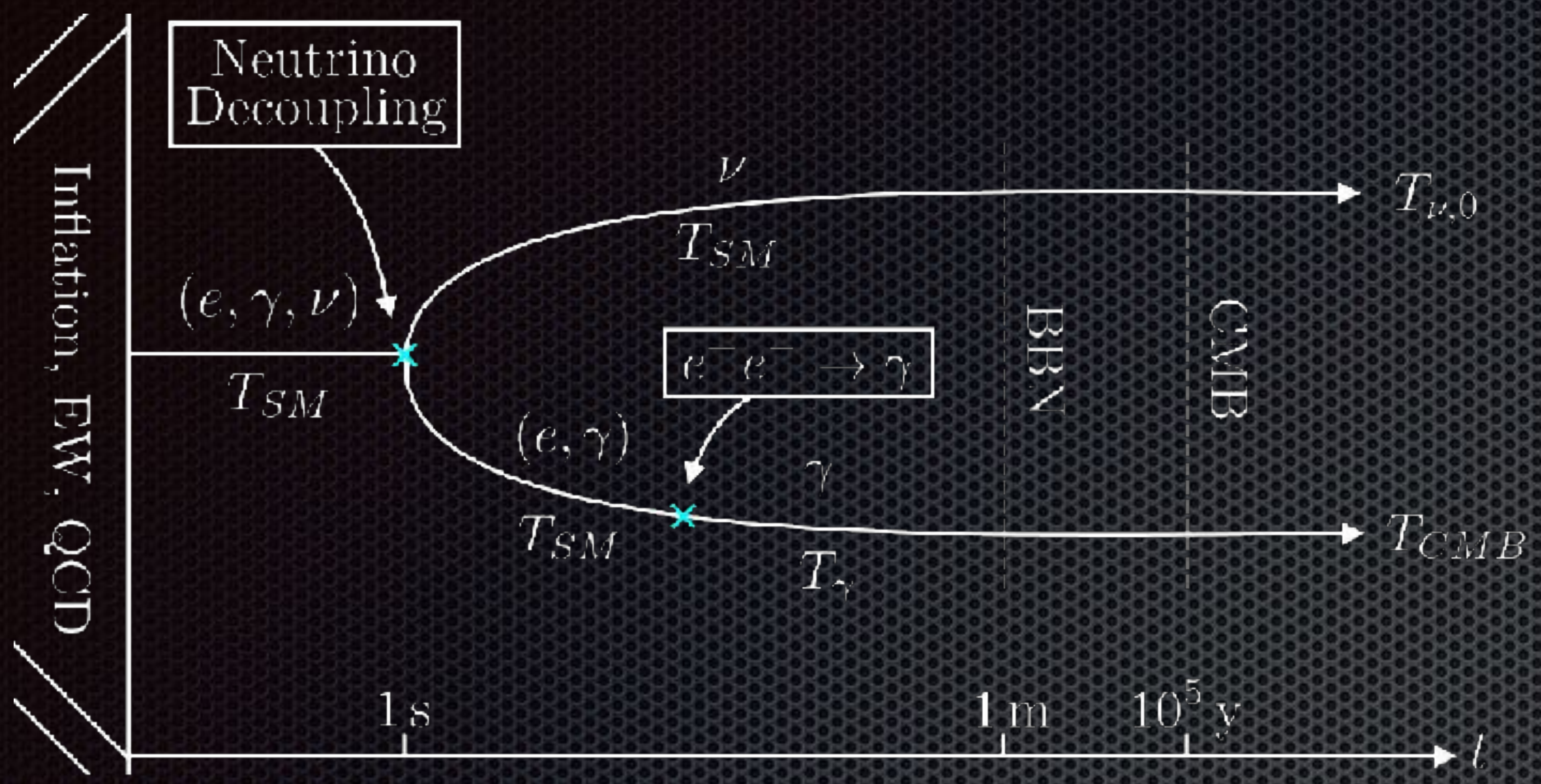


(Source: ESA/Planck Collaboration)

Outline

* Standard Big Bang Cosmology and CNB

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

- 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

- Since 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, $T_{\nu,0} = (4/11)^{1/3} T_{\rm CMB} \sim 1.9\ {\rm K} \sim 1.7 \times 10^{-4}\ {\rm eV}$

- 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

Outline

* Detection Methods @ PTOLEMY

Difficulties

- Low cross-sections:

  Usual weak interaction cross section for neutrinos,

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

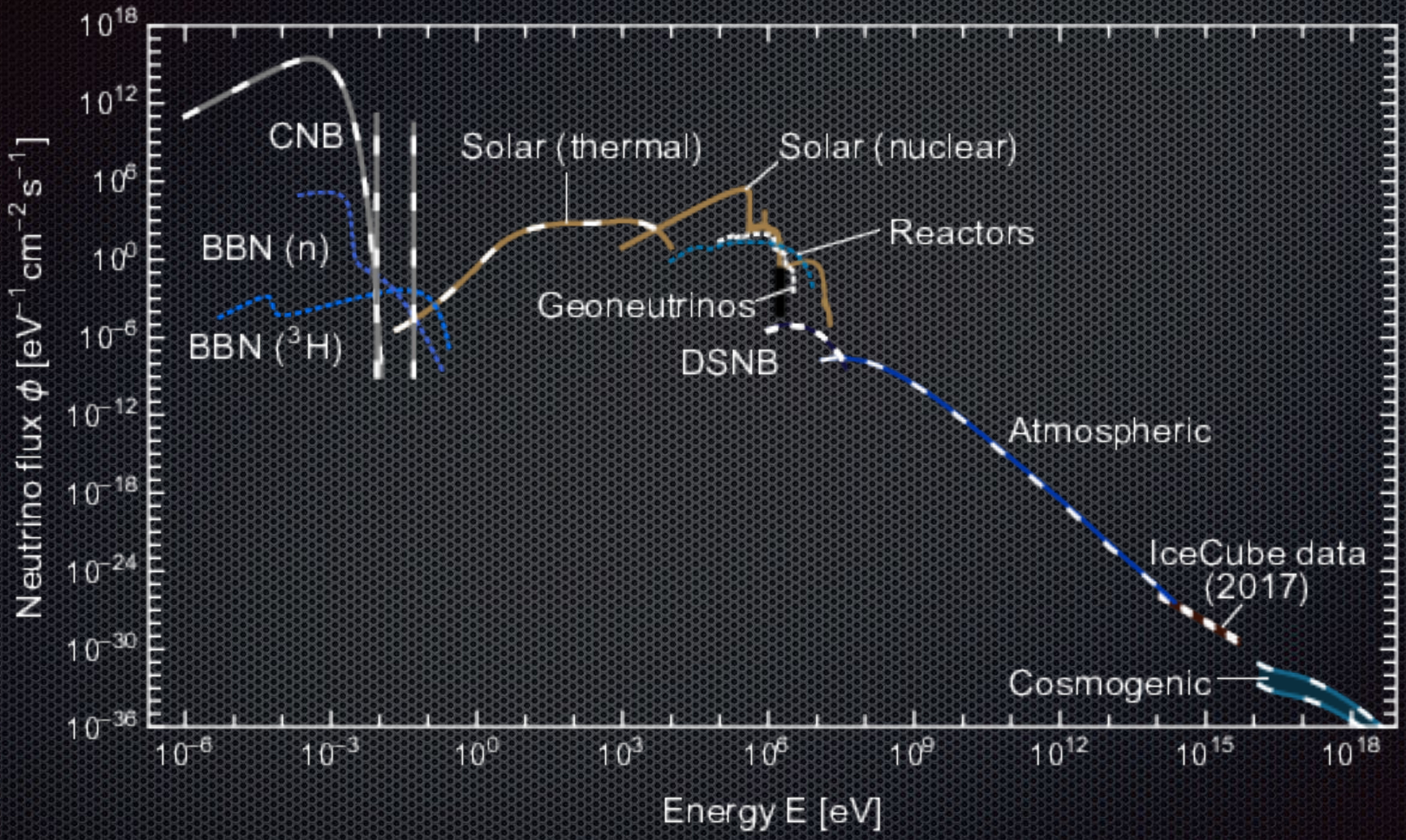
  For typical electromagnetic process, e.g.,

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

- 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

Green shoots:



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

- 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 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))

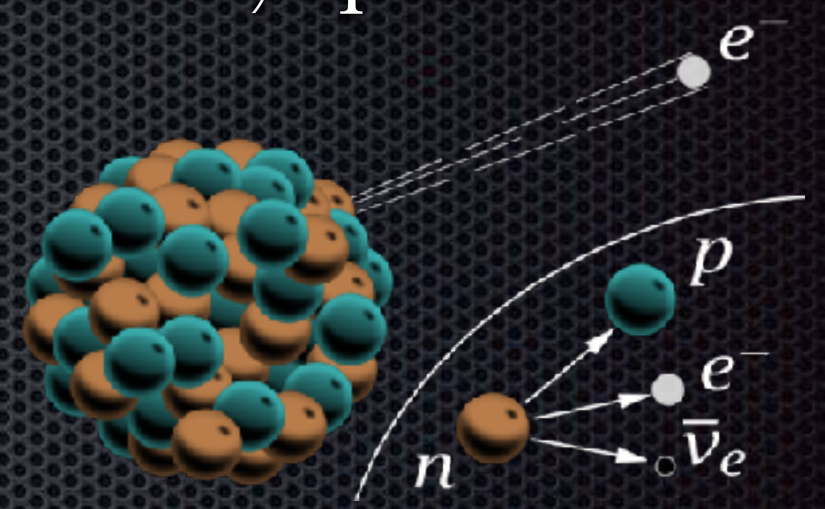
  (ii) direct detection by neutrino capture on β-decaying nuclei

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

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,

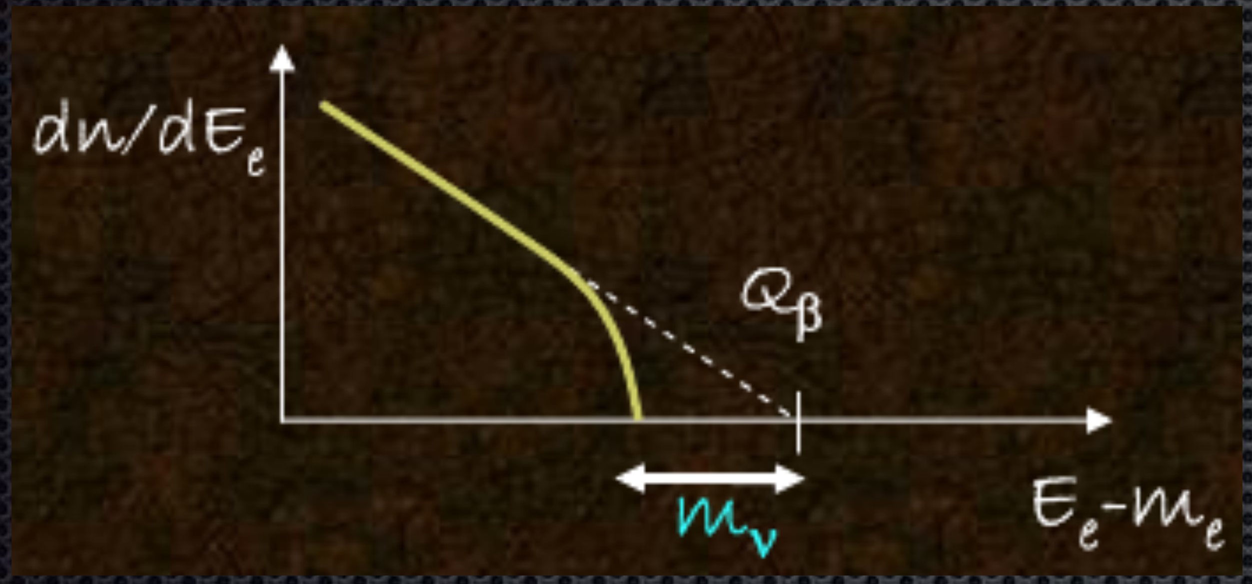
$$(A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$$



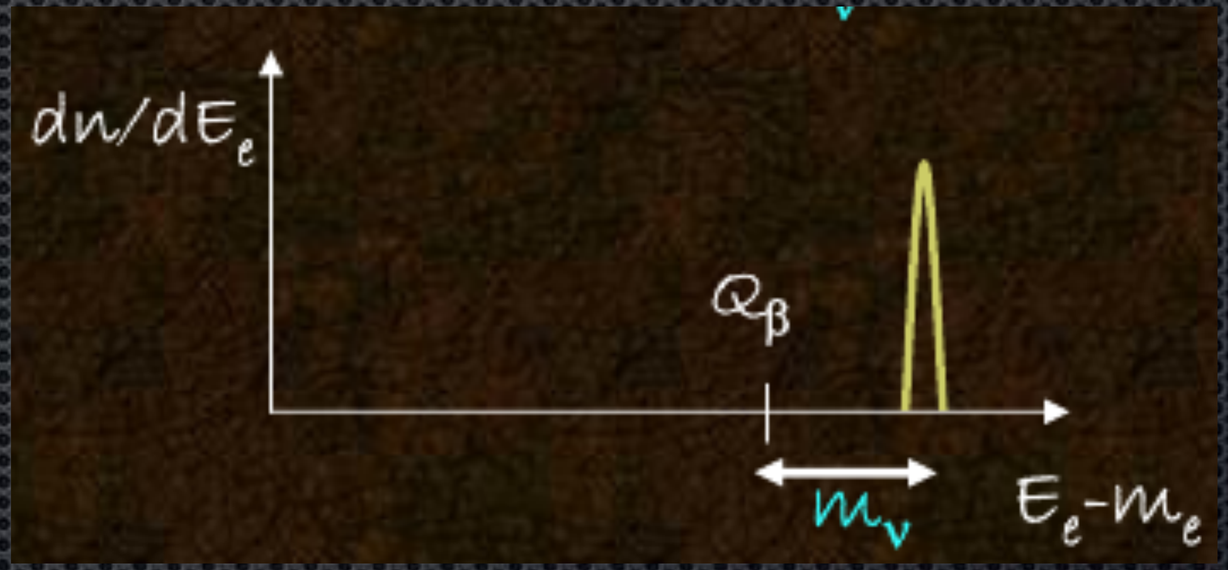
- In this case there exists a threshold-less reaction of neutrino capture

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

- 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) large cross section of neutrino capture $\sim 3.7 \times 10^{-45}\mathrm{cm}^2$
- One of the drawbacks is that it is insensitive to other neutrino flavours, $\nu_{\mu,\tau}$

PTOLEMY: Detection Rate

- Since flavour eigenstates are a composition of mass eigenstates with different masses, while propagating, relic neutrinos quickly decohere into those, in a time scale less than one Hubble time. So, the capture rate of relic neutrinos by tritium nuclei

$$\Gamma_{\rm CNB} = \sum_j \Gamma_j = N_H \sum_j |U_{ej}|^2 \int \frac{d^3p_j}{(2\pi)^3} \sigma(p_j) v_j f_j(p_j) \approx N_H \sum_j |U_{ej}|^2 \bar{\sigma} v_j f_{c,j} n_{\nu,0}$$

  where $N_H = M_T/m_{^3H} \sim 2 \times 10^{25}$ is the number of tritium nuclei for $M_T = 100$ g,

  $\bar{\sigma} v_j \sim 3.7 \times 10^{-45} \mathrm{cm}^2$, $n_{\nu,0} \approx 56$ $\Rightarrow$ total rate, $\Gamma_{\rm CNB} \approx 3.9\ \mathrm{yr}^{-1} \sum_j |U_{ej}|^2 f_{c,j}$, where the factor after the summation is $\gtrsim 1$

- An important observation is that the capture rate in the Majorana case is twice as that of the Dirac case, i.e., $\Gamma^{\rm M}_{\rm CNB} = 2\Gamma^{\rm D}_{\rm CNB}$ [Long et. al, JCAP 2014]

- This assertion changes in the presence of additional particles, interactions etc. [Arteaga et. al, JHEP 2017]

Outline

* GNI & their effects

Generalised Neutrino Interactions (GNI)

- GNI: general class of neutrino interactions of *scalar*, *pseudoscalar*, *vector*, *axial-vector* and *tensor* type

- We are interested in the effect of GNIs in relic neutrino capture on β-decaying tritium; the relevant Lagrangian can be written as

$$\mathscr{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{ud} U_{ej} \left\{ [\bar{e}\gamma^{\mu}(1-\gamma^5)\nu_j][\bar{u}\gamma_{\mu}(1-\gamma^5)d] + \sum_{l,q} \epsilon_{lq} [\bar{e}\mathcal{O}_l \nu_j][\bar{u}\mathcal{O}_q d] \right\} + \text{h.c.}$$

- The dimensionless ϵ_{lq} are the GNI parameters, V_{ud} and U_{ej} are the CKM and PMNS matrix elements, respectively

- The operators $\mathcal{O}_l$ and $\mathcal{O}_q$ are the relevant lepton and quark currents, which are given as

ϵ_{lq}	$\mathcal{O}_l$	$\mathcal{O}_q$
ϵ_{LL}	$\gamma^\mu(1-\gamma^5)$	$\gamma_\mu(1-\gamma^5)$
ϵ_{LR}	$\gamma^\mu(1-\gamma^5)$	$\gamma_\mu(1+\gamma^5)$
ϵ_{RL}	$\gamma^\mu(1+\gamma^5)$	$\gamma_\mu(1-\gamma^5)$
ϵ_{RR}	$\gamma^\mu(1+\gamma^5)$	$\gamma_\mu(1+\gamma^5)$
ϵ_{LS}	$1-\gamma^5$	1
ϵ_{RS}	$1+\gamma^5$	1
ϵ_{LT}	$\sigma^{\mu\nu}(1-\gamma^5)$	$\sigma_{\mu\nu}(1-\gamma^5)$
ϵ_{RT}	$\sigma^{\mu\nu}(1+\gamma^5)$	$\sigma_{\mu\nu}(1+\gamma^5)$

* Relevant hadronic matrix elements can be represented by form factors,

$$\left\langle p\left(p_p\right)|\bar{u}d|n\left(p_n\right)\right\rangle = g_S\left(q^2\right)\overline{u_p}\left(p_p\right)u_n\left(p_n\right) ,$$

$$\left\langle p\left(p_p\right)\left|\bar{u}\sigma^{\mu\nu}\left(1\pm\gamma^5\right)d\right|n\left(p_n\right)\right\rangle = g_T\left(q^2\right)\overline{u_p}\left(p_p\right)\sigma^{\mu\nu}\left(1\pm\gamma^5\right)u_n\left(p_n\right) ,$$

$$\left\langle p\left(p_p\right)\left|\bar{u}\gamma^\mu\left(1\pm\gamma^5\right)d\right|n\left(p_n\right)\right\rangle = \overline{u_p}\left(p_p\right)\gamma^\mu\left[g_V\left(q^2\right)\pm g_A\left(q^2\right)\gamma^5\right]u_n\left(p_n\right)$$

* The relic neutrino capture cross-section in the presence of GNI for a neutrino mass eigenstate j can be given as,

$$\sigma_j^{\rm BSM}\left(h_j\right)v_j = \frac{G_F^2}{2\pi}\left|V_{ud}\right|^2\left|U_{ej}\right|^2 F_Z\left(E_e\right)\frac{m_{\rm He}}{m_{\rm H}}E_e p_e \mathscr{M}_j\left(\epsilon_{lq}\right)$$

* Not all GNI parameters can be relevant though; vector and axial-vector GNIs come along with SM couplings and hence can be absorbed in the CKM matrix elements V_{ud} and the axial-vector charge g_A, as

$$\left|\tilde{V}_{ud}\right|^2 \approx \left|V_{ud}\right|^2(1+\epsilon_{LL}+\epsilon_{LR}+\epsilon_{RL}+\epsilon_{RR})^2$$

$$\tilde{g}_A \approx g_A\frac{1+\epsilon_{LL}-\epsilon_{LR}+\epsilon_{RR}-\epsilon_{RL}}{1+\epsilon_{LL}+\epsilon_{LR}+\epsilon_{RR}+\epsilon_{RL}}$$

ϵ_{lq}	$\mathcal{O}_l$	$\mathcal{O}_q$
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ϵ_{LS}	$1-\gamma^5$	1
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$$\left|\tilde{V}_{ud}\right|^2 \approx \left|V_{ud}\right|^2(1+\epsilon_{LL}+\epsilon_{LR}+\epsilon_{RL}+\epsilon_{RR})^2$$

$$\tilde{g}_A \approx g_A\frac{1+\epsilon_{LL}-\epsilon_{LR}+\epsilon_{RR}-\epsilon_{RL}}{1+\epsilon_{LL}+\epsilon_{LR}+\epsilon_{RR}+\epsilon_{RL}}$$

Numerical analysis

- For this first we define the β-decay spectrum,

$$\frac{d\bar{\Gamma}_\beta}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}(\Delta/\sqrt{8\ln 2})}\int_{-\infty}^{+\infty} dE' \frac{d\Gamma_\beta}{dE_e}(E')\exp\left[-\frac{(E_e - E')^2}{2(\Delta/\sqrt{8\ln 2})^2}\right]$$

- and the CNB neutrino capture rate,

$$\frac{d\bar{\Gamma}_{\rm CNB}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}(\Delta/\sqrt{8\ln 2})}\sum_{j=1}^{3}\Gamma_j \exp\left[-\frac{[E_e - (E_{\rm end} + m_j + m_{\rm lightest})]^2}{2(\Delta/\sqrt{8\ln 2})^2}\right]$$

- These help us defining the respective number of events as,

$$N^i_\beta(E_{\rm end}, m_j, U_{ej}) = T\int_{E_i-\delta/2}^{E_i+\delta/2} \frac{d\bar{\Gamma}_\beta}{dE_e} dE_e$$

$$N^i_{\rm CNB}(E_{\rm end}, m_j, U_{ej}) = T\int_{E_i-\delta/2}^{E_i+\delta/2} \frac{d\bar{\Gamma}_{\rm CNB}}{dE_e} dE_e$$

Numerical analysis (some more definitions)

- We define the χ^2 as follows,

$$\chi^2 = \sum_i \left(\frac{N^i_{\rm exp}(E_{\rm end}, m_j, U_{ej}) - N^i_{\text{GNI-th}}(E_{\rm end}, m_j, U_{ej}, \epsilon_{lq})}{\sqrt{N^i_{\rm tot}}} \right)^2$$

where $N^i_{\text{GNI-th}}(E_{\rm end}, m_j, U_{ej}, \epsilon_{lq}) = N^i_\beta(E_{\rm end}, m_j, U_{ej}) + N^i_{\text{GNI-CNB}}(E_{\rm end}, m_j, U_{ej}, \epsilon_{lq}) + N_{\rm Bkg}$

and $N^i_{\rm exp}(E_{\rm end}, m_j, U_{ej}) = N^i_{\rm tot}(E_{\rm end}, m_j, U_{ej}) \pm \sqrt{N^i_{\rm tot}(E_{\rm end}, m_j, U_{ej})}$

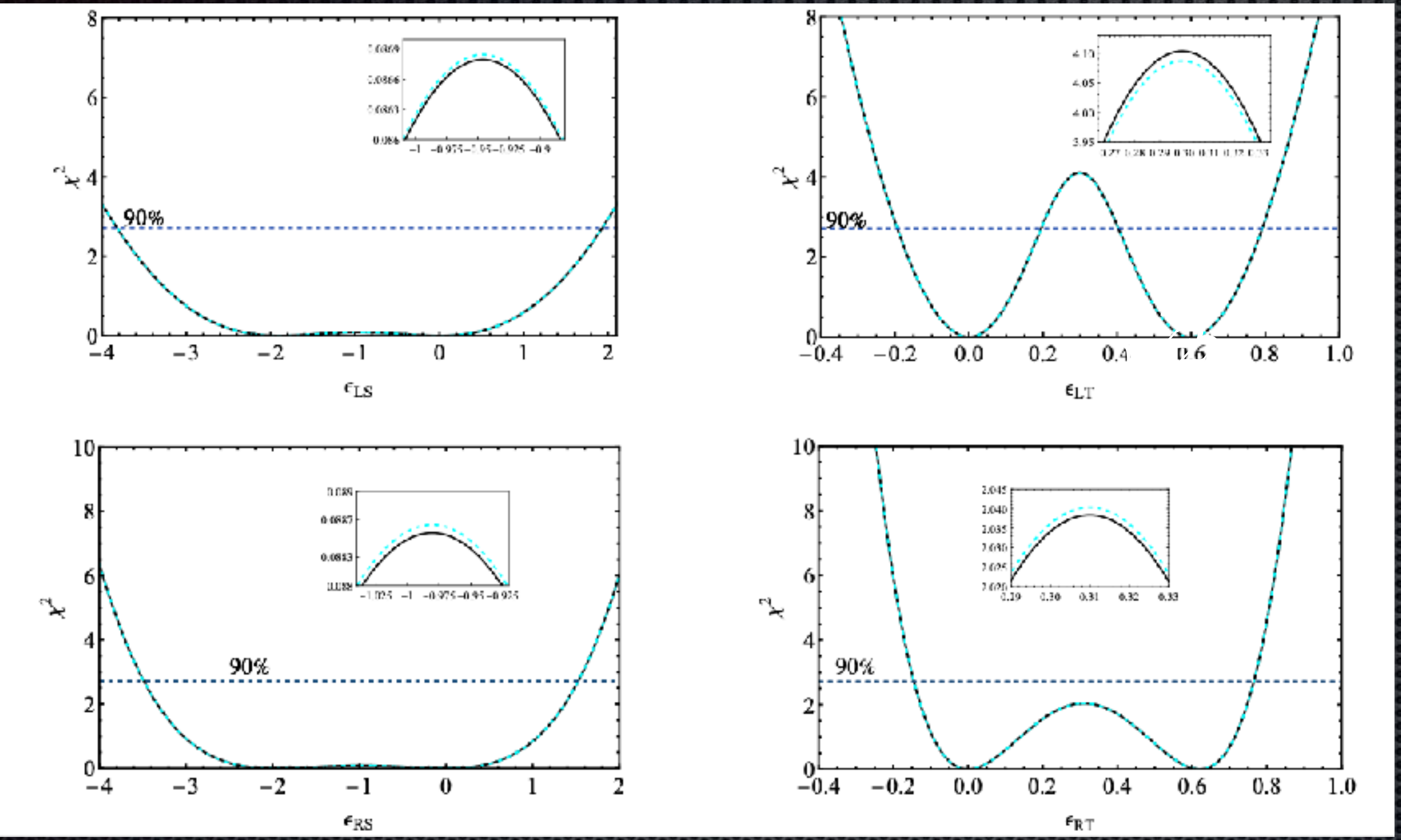
with $N^i_{\rm tot}(E_{\rm end}, m_j, U_{ej}) = N^i_\beta(E_{\rm end}, m_j, U_{ej}) + N^i_{\rm CNB}(E_{\rm end}, m_j, U_{ej}) + N_{\rm Bkg}$

Outline

* Results

One parameter analysis

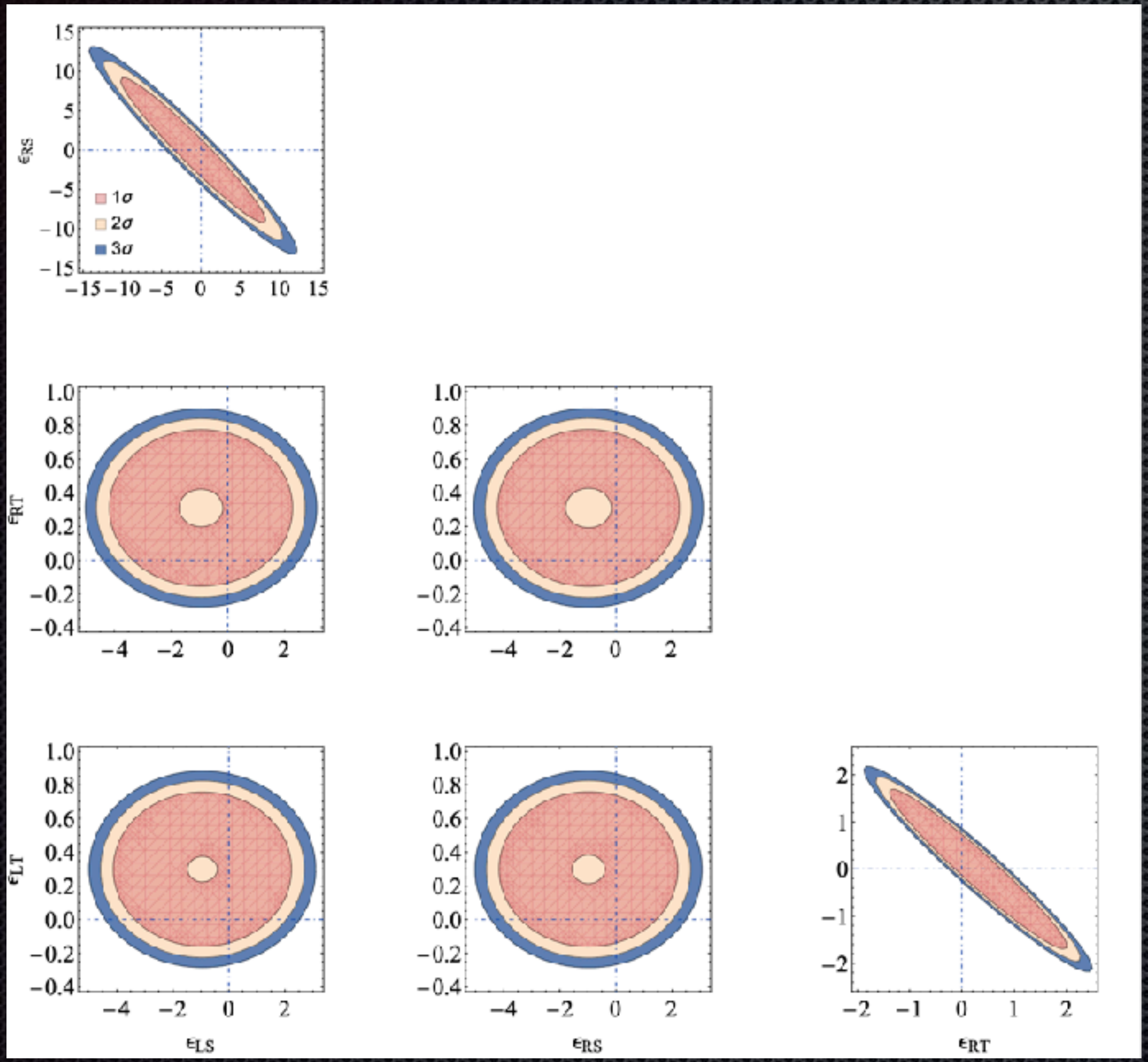
- One parameter χ^2 analysis for the parameters ϵ_{LS}, ϵ_{LT}, ϵ_{RS}, and ϵ_{RT}



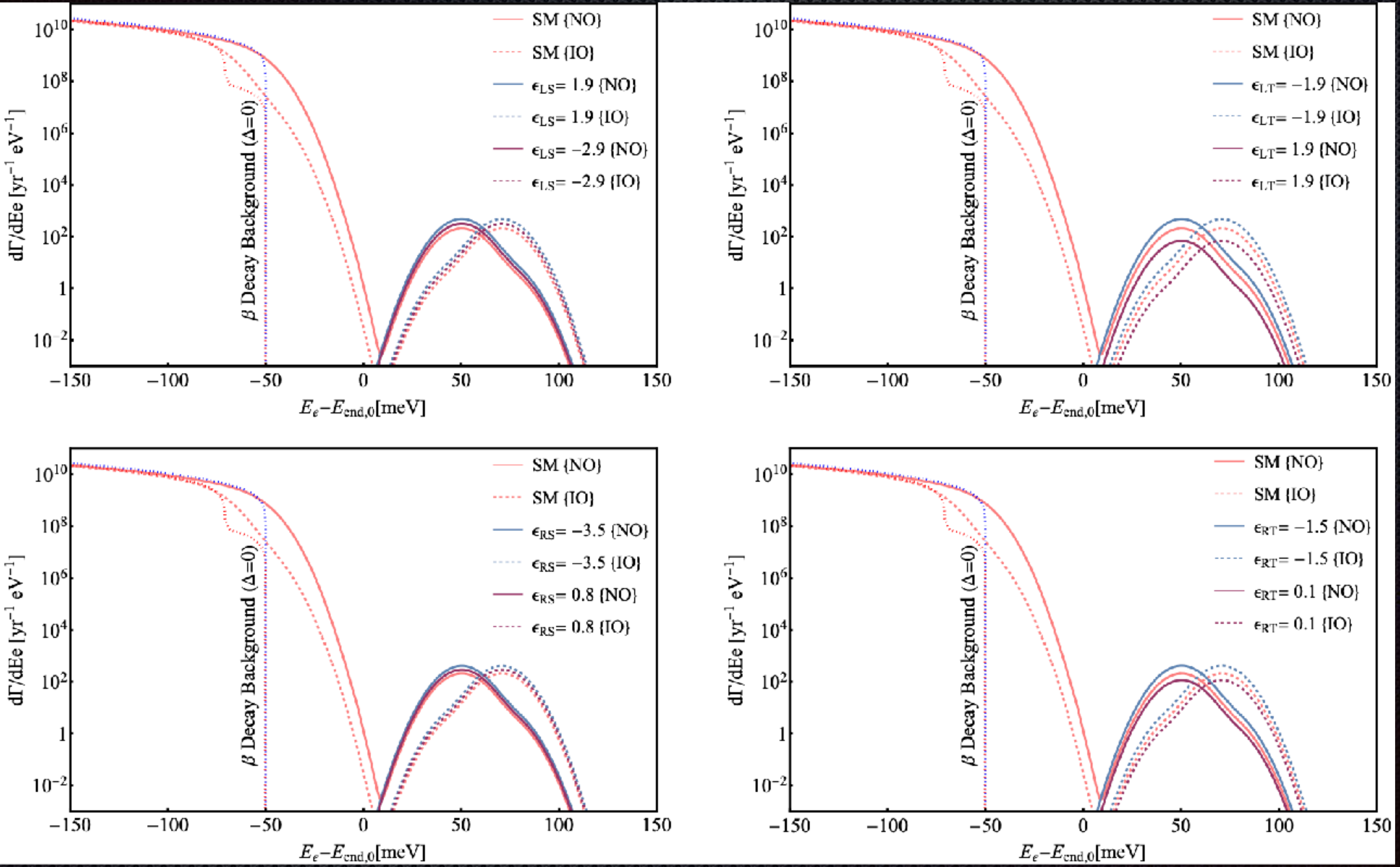
GNI Parameter	χ^2 values at 90% CL
ϵ_{LS}	$[-3.8, 1.9]$
ϵ_{LT}	$[-0.19, 0.19], [0.4, 0.8]$
ϵ_{RS}	$[-3.5, 1.5]$
ϵ_{RT}	$[-0.15, 0.75]$

Two parameter analysis

- Two parameter χ^2 analysis for the parameters $\epsilon_{LS}, \epsilon_{LT}, \epsilon_{RS}$, and ϵ_{RT}



Electron spectrum in presence of GNI



Number of CNB events

- For illustration here we make a few comments about the exact number of CNB events
- In the presence of GNI the number of CNB events will be different from the SM prediction
- For the SM, e.g., if $m_{\text{lightest}} = 50$ meV and the experimental resolution $\Delta = 20$ meV then the number of CNB capture events per year is approximately 4.5
- In the presence of GNIs, e.g., with the same parameters and 10 yrs of exposure time —

GNI	Values	(Min., Max.) # of evts.
ϵ_{LS}	(-1, -3.8)	(38, 104)
ϵ_{LT}	(0.3, 0.8)	(10, 108)
ϵ_{RS}	(-1, -3.5)	(37, 89)
ϵ_{RT}	(0.31, 0.75)	(7, 90)

Outline

* Summary

Summary

- 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
- We explored the impact of GNIs in the detection of CNB through PTOLEMY
- GNIs arising due to vector and axial couplings can be absorbed in the CKM elements and hence using only (inverse) β-decay processes one cannot test these new physics couplings
- We have confined ourselves to the scalar and tensor couplings for both left- and right-handed neutrinos, i.e., ϵ_{LS}, ϵ_{LT}, ϵ_{RS}, and ϵ_{RT}

Summary

- The 90% confidence level values of the four GNI parameters have been taken from the one-parameter χ^2-analysis
- These sets of values are used to obtain the electron spectrum around the endpoint energy of the β-decay of tritium in the presence of GNIs
- Analyzing this nature we can get an idea regarding the values of the GNI parameters from the experimental data
- These features can be used to confirm the neutrino mass orderings or at least put more stringent bounds on the different orderings from the PTOLEMY data
- In the future, when there will be more insight regarding the experimental resolution, studies of this kind can lead to a deeper understanding of the m_{lightest} and also the ordering of neutrino mass

Thank you

Back-up slides

Utility of detecting CNB

- Currently CMB sets our limit to look back in time, CNB will help see further
- CNB is a rare source of non-relativistic neutrinos
- Detecting it can reveal certain neutrino properties which are otherwise difficult to measure at high momentum
- Caveat: neutrinos are assumed to be stable

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 in the Majorana case

A few technical points

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 cm^{-3} can be enhanced [Mertsch et. al, JCAP 2020]
- This is not at the level that can be measured exactly even with a few years running of the proposed experiments like PTOLEMY

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)

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

- Typically, $\Delta E_e \sim G_F g_A \beta_\oplus n_\nu \Rightarrow$ 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 $N_e \tau_e \sim N_A Z M |\Delta E_e| / A m_A$

- This can induce a linear acceleration on a ferromagnet with some spatial extent, and Cavendish torsion balance can, in principle, be used to measure the effect

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

- 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]

- In the Earth's rest frame the momentum transfer per scattering is:

$$\langle \Delta p \rangle_R \approx \beta_\oplus \frac{E_\nu}{c} \text{ for relativistic } \nu$$

$$\langle \Delta p \rangle_{NC,NR} \approx \beta_\oplus \frac{4T_\nu}{c} \text{ for non-clustering non-relativistic } \nu$$

$$\langle \Delta p \rangle_{C,NR} \approx \beta_\oplus c m_\nu \text{ for clustering non-relativistic } \nu$$

- This induces a small macroscopic acceleration in a target with total mass M,

$$a \sim \frac{1}{M} N_T \beta_\nu \sigma_{\nu N} n_\nu \langle \Delta p \rangle$$

- Applicable when coherence can only be maintained over a single nucleus; relic neutrinos with macroscopic wavelengths $\lambda_\nu \sim \mathcal{O}(\text{mm})$ should be capable of maintaining coherence over many nuclei, leading to vastly enhanced cross sections

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 [Yoshimura et. al, PRD, 2015]

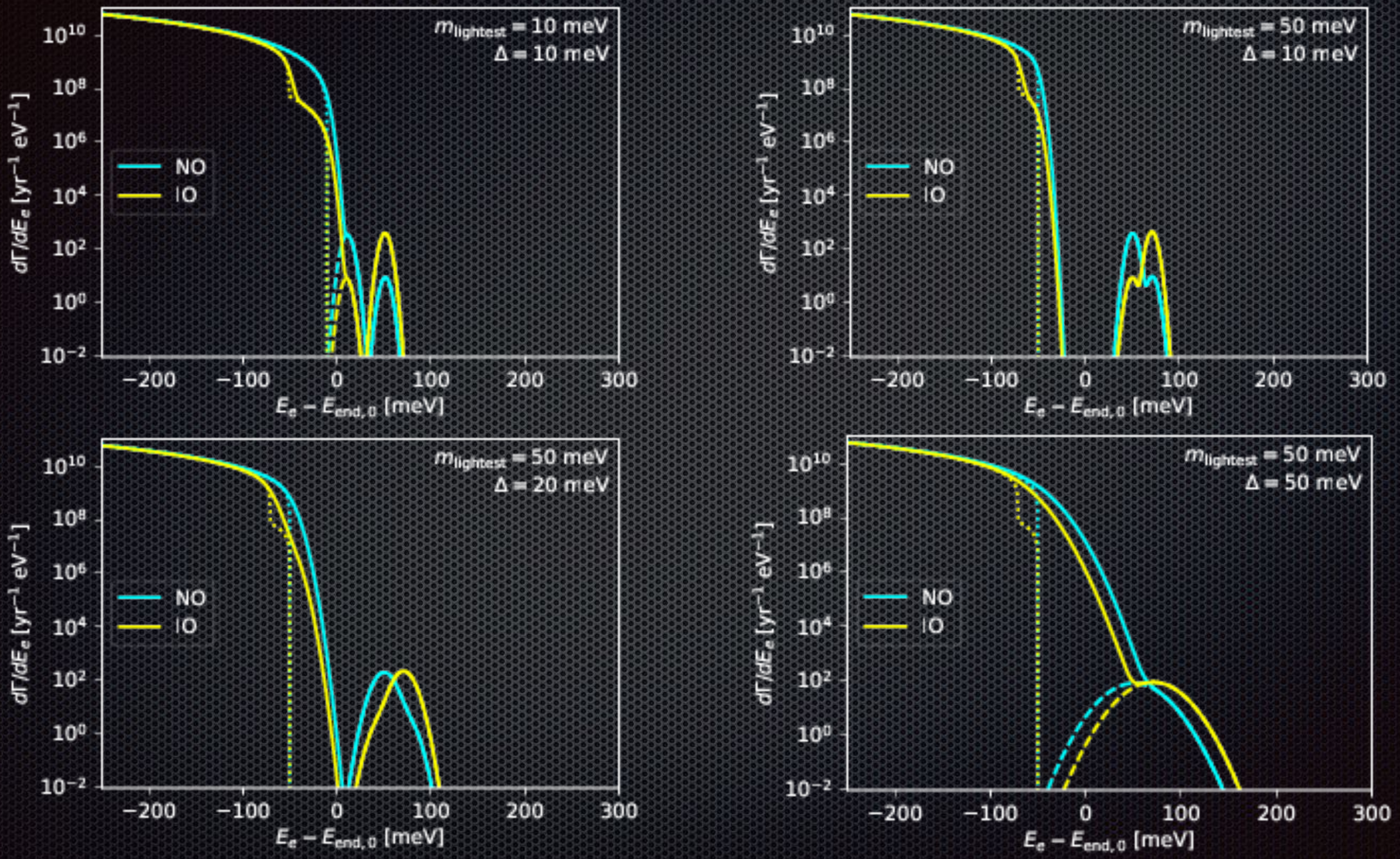
Cross-section (BSM)

- The expression for the cross-section can be given as,

$$\sigma_j^{\mathrm{BSM}}\left(h_j\right)v_j = \frac{G_F^2}{2\pi}\left|\tilde{V}_{ud}\right|^2\left|U_{ej}\right|^2 F_Z\left(E_e\right)\frac{m_{\mathrm{He}}}{m_{\mathrm{H}}}E_e p_e \tilde{\mathscr{M}}_j\left(\epsilon_{lq}\right)$$ where

$$\begin{aligned}
\tilde{\mathscr{M}}_j\left(\epsilon_{lq}\right) = &\frac{g_V^2}{\mathscr{D}_1^2}\left((1+\epsilon_{LL}+\epsilon_{LR})^2+(\epsilon_{RR}+\epsilon_{RL})^2\right)+g_S^2\left(\epsilon_{LS}^2+\epsilon_{RS}^2\right)+48g_T^2\left(\epsilon_{LT}^2+\epsilon_{RT}^2\right)\\
&+\frac{3\tilde{g}_A^2}{\mathscr{D}_2^2}\left((1+\epsilon_{LL}-\epsilon_{LR})^2+(\epsilon_{RR}-\epsilon_{RL})^2\right)\\
&+\frac{2g_Sg_V}{\mathscr{D}_1^2}\left[\frac{m_e}{E_e}\left(\epsilon_{LS}(1+\epsilon_{LL}+\epsilon_{LR})+\epsilon_{RS}(\epsilon_{RR}+\epsilon_{RL})\right)+\left(\epsilon_{RS}(1+\epsilon_{LL}+\epsilon_{LR})+\epsilon_{LS}(\epsilon_{RR}+\epsilon_{RL})\right)\right]\\
&-\frac{24\tilde{g}_Ag_T}{\mathscr{D}_1\mathscr{D}_2}\left[\frac{m_e}{E_e}\left(\epsilon_{LT}(1+\epsilon_{LL}-\epsilon_{LR})+\epsilon_{RT}(\epsilon_{RR}-\epsilon_{RL})\right)+\left(\epsilon_{RT}(1+\epsilon_{LL}-\epsilon_{LR})+\epsilon_{LT}(\epsilon_{RR}-\epsilon_{RL})\right)\right]\\
&+\frac{2m_e}{E_e\mathscr{D}_1^2}\left[g_V^2(1+\epsilon_{LL}+\epsilon_{LR})(\epsilon_{RR}+\epsilon_{RL})+g_S^2\epsilon_{RS}\epsilon_{LS}+48g_T^2\epsilon_{LT}\epsilon_{RT}\right]\\
&+\frac{2m_e}{E_e\mathscr{D}_2^2}3\tilde{g}_A^2(1+\epsilon_{LL}-\epsilon_{LR})(\epsilon_{RR}-\epsilon_{RL})
\end{aligned}$$

PTOLEMY: Detection Rate



(Source: PTOLEMY Collaboration, JCAP 2019)