Helicity Property of Relic Neutrinos and Implications on Their Detection

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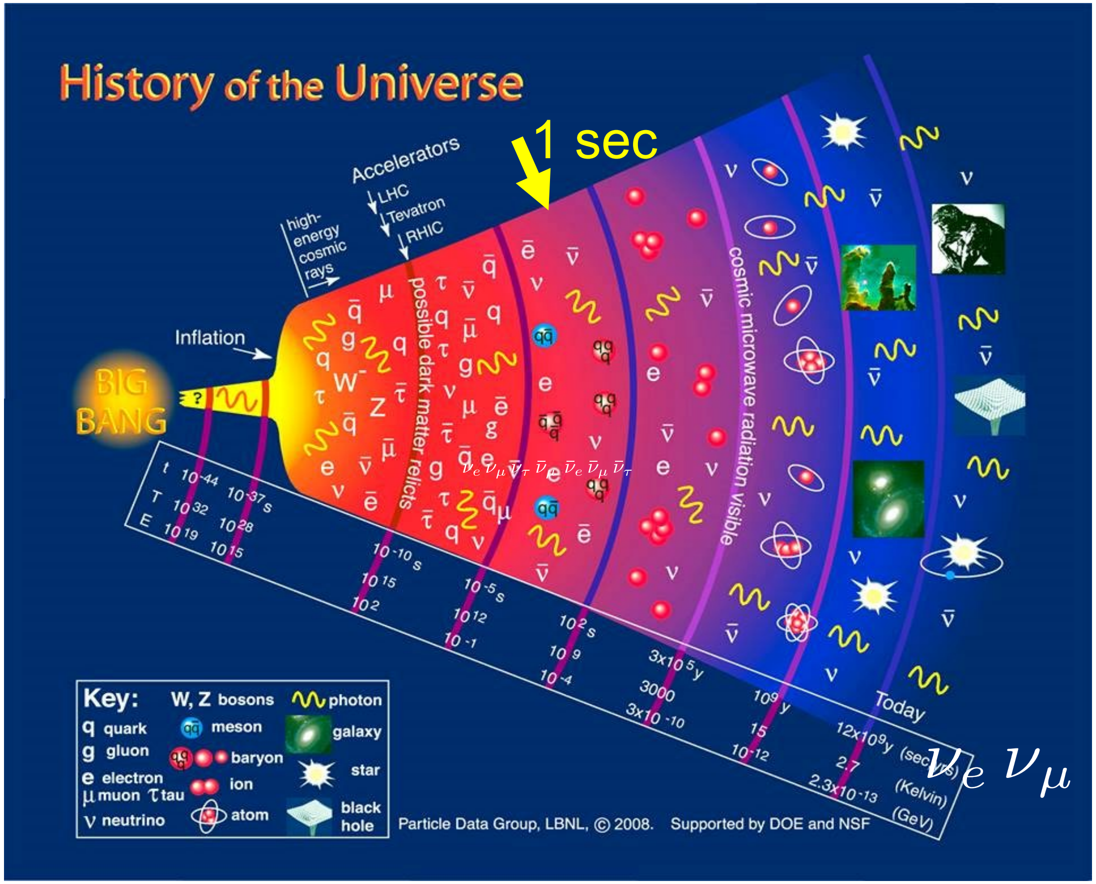
25th International Spin Symposium
Durham, North Carolina
September 24-29, 2023

Based on three papers in collaboration with Gordon Baym

Phys. Rev. Letts. 126, 191803 (2021);
Phys. Rev. D 103, 123019 (2021);
Phys. Rev. D 106, 063018 (2022)

Relic neutrinos from the Big Bang forming the cosmic neutrino background (CνB)



Decoupling occurs at t ~1 sec, T ~1 MeV

CνB has never been observed !

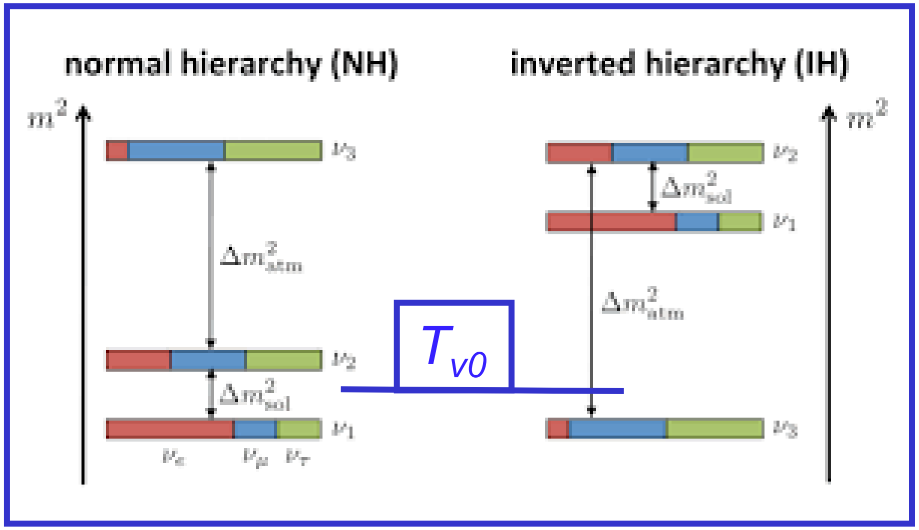
Cosmic neutrino background (CνB) versus cosmic microwave background (CMB)

	CMB	CνB	Relation
Temperature	2.73K	1.9 K (1.7 x 10^{-4} eV)	$T_\nu/T_\gamma = (4/11)^{1/3}$ =0.714
Decoupling at	3.8 x 10^5 years	~ 1 sec	
Density	~ 411 / cm^3	~ 336 / cm^3	$n_\nu = (9/11)\ n_\gamma$

- CνB took a snapshot of the Universe at a much earlier epoch than CMB
- At least two of the three neutrinos are non-relativistic
- ~20,000,000 of CνB inside you at this moment
- Density of CνB is ~100 times of solar neutrinos
- Decoupled as flavor eigenstates, now in mass eigenstates

At least 2 relic neutrino mass states are non-relativistic

(Current temperature: $T_{\nu 0} = 1.945\,\mathrm{K} = 1.676\times 10^{-4}\,\mathrm{eV}$)



$$\Delta m^2_{21} = 7.50\times 10^{-5}\,\mathrm{eV}^2$$

$$\Delta m^2_{31,N} = 2.52\times 10^{-3}\,\mathrm{eV}^2$$

$$\Delta m^2_{31,I} = -2.51\times 10^{-3}\,\mathrm{eV}^2$$

$$T_{\nu 0} = 1.945\,\mathrm{K} = 1.676\times 10^{-4}\,\mathrm{eV}$$

At least two neutrino masses are larger than 100 K with $m_i \gg T_{\nu 0} = 1.945\ \mathrm{K} = 1.676\ \times\ 10^{-4}\ \mathrm{eV}$

Normal Hierarchy: If $m_1 = 0$, $\beta_1 = 1,\ \beta_2 \sim 1/50,\ \beta_3 \sim 1/300$

Inverted Hierarchy: If $m_3 = 0$, $\beta_3 = 1,\ \beta_1 \sim \beta_2 \sim 1/300$

Capture of CνB on radioactive nuclei (positive Q value)

(S. Weinberg, 1962)

Tritium beta decay:

$$a)\ {}^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_{e}$$

3-body β-decay with Q-value of

$$Q_{a} = M({}^{3}\mathrm{H}) - M({}^{3}\mathrm{He}) - M(e^{-}) - M(\bar{\nu}_{e})$$

Inverse tritium beta decay (ITBD):

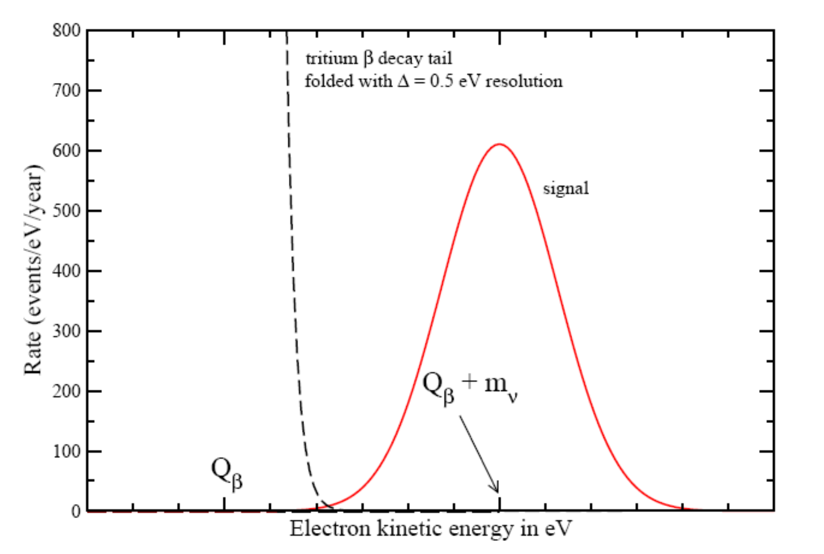
$$b)\ \nu_{e} + {}^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-}$$

2-body reaction with the Q-value of

$$Q_{b} = M({}^{3}\mathrm{H}) - M({}^{3}\mathrm{He}) - M(e^{-}) + M(\bar{\nu}_{e})$$

Therefore, $Q_{b} = Q_{a} + 2M(\bar{\nu}_{e})$

Positive Q value implies low-energy relic neutrinos can be captured !



Look for a mono-energetic peak beyond the endpoint of tritium beta decay

PTOLEMY experiment for this search

Helicity dependence of the ITBD

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

- ITBD for neutrino in mass eigenstate i and helicity h:

$$\sigma_i^h = \frac{G_F^2}{2\pi v_i} |V_{ud}|^2 |U_{ei}|^2 \, F(Z, E_e) \frac{m({}^3He)}{m({}^3H)} E_e p_e A_i^h (\overline{f}^2 + 3\overline{g}^2)$$

- The helicity-dependent factor, A_i^h, is given as

$$A_i^{\pm} = 1 \mp \beta_i; \quad \text{where } \beta_i = v_i / c$$

- For relativistic neutrinos, $\beta_i \rightarrow 1$, we have

$$A_i^+ \rightarrow 0 \quad \text{and} \quad A_i^- \rightarrow 2$$

- For non-relativistic neutrinos, $\beta_i \rightarrow 0$, we have

$$A_i^+ \rightarrow 1 \quad \text{and} \quad A_i^- \rightarrow 1$$

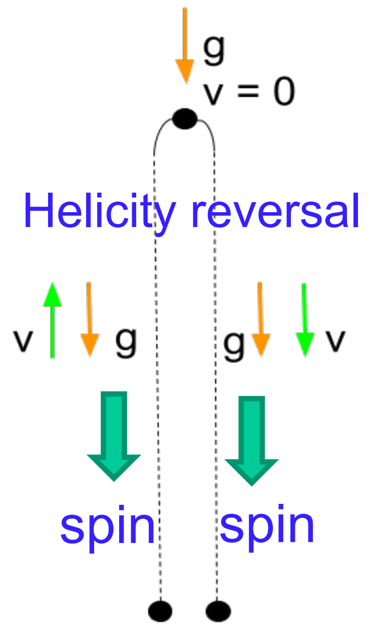
- ITBD rate depends on the helicity, h, of neutrinos

What are the helicities of relic neutrinos?

Evolution of relic neutrino helicity
(from t ~ 1 sec to t ~ 13.8 billion years)

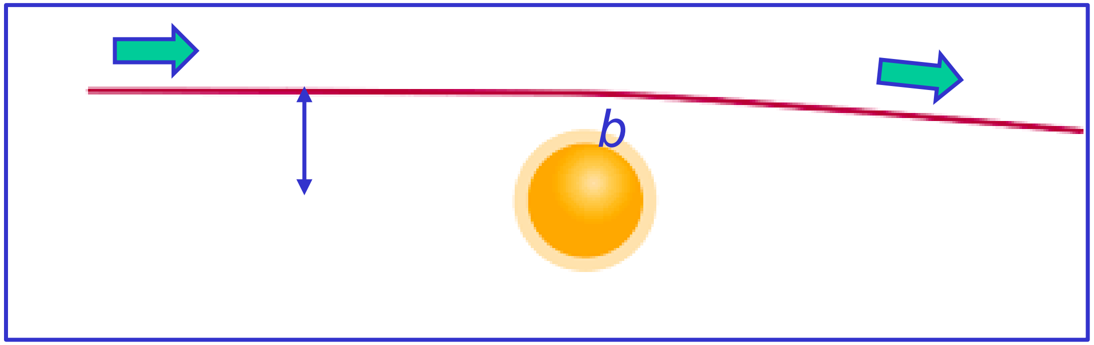
- Relic neutrinos decoupled at a temperature of ~1 MeV, and were highly relativistic. Neutrinos were produced essentially in $h = -1$ state, and antineutrinos in $h = +1$ state.
- Rotation of neutrino spin due to transverse matter source is less than the rotation of neutrino momentum (gravitational lensing of neutrino), changing neutrino helicity.
- Dirac neutrino with non-zero magnetic moment will precess in galactic or cosmic magnetic fields, changing neutrino helicity.

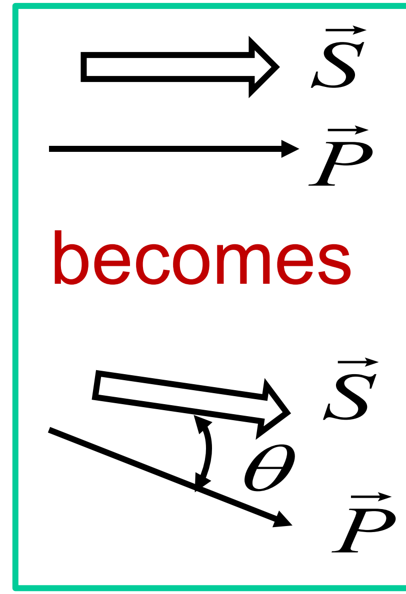
How would gravity modify the neutrino helicity?



If a neutrino with negative helicity is emitted upward from the Earth, it could fall back to the Earth having a positive helicity, affecting its weak interaction rate!

How would gravity modify the neutrino helicity?





Momentum bending: $\Delta\theta_P = \dfrac{2MG}{b\mathrm{v}^2}(1+\mathrm{v}^2)$

Spin bending: $\Delta\theta_S = \dfrac{2MG}{b}\dfrac{2\gamma+1}{\gamma+1}; \quad (\gamma = 1/\sqrt{1-\mathrm{v}^2})$

$$\theta \equiv \Delta\theta_S - \Delta\theta_P = -\frac{2MG}{b\gamma\mathrm{v}^2}$$

(spin bending lags momentum bending)

$\theta \to 0$ as $\mathrm{v} \to 1$

θ is large as $\mathrm{v} \to 0$

An angle θ between the spin and momentum directions means

$$|h=+1\rangle \to \cos(\theta/2)|h=+1\rangle + \sin(\theta/2)|h=-1\rangle$$

Probability for $h=-1$ is $\sin^2(\theta/2)$

Gravitational spin rotation relative to momentum

For massive relic neutrinos, after including matter and dark energy in $\bar{\rho}(a) = \rho_M / a^3 + \rho_V$:

$$\left\langle (\Delta\theta_p)^2 \right\rangle = \frac{9}{8\pi} P H_0^3 \int_0^1 \frac{da}{a^2} \left(\Omega_M a + \Omega_V a^4\right)^{3/2} \mathrm{v} \left(\frac{1}{\mathrm{v}} + \mathrm{v}\right)^2$$

$$\left\langle (\Delta\theta_s)^2 \right\rangle = \frac{9}{8\pi} P H_0^3 \int_0^1 \frac{da}{a^2} \left(\Omega_M a + \Omega_V a^4\right)^{3/2} \mathrm{v}^3 \left(\frac{2\gamma + 1}{\gamma + 1}\right)^2$$

$$\left\langle \theta^2 \right\rangle \equiv \left\langle (\Delta\theta_p)^2 \right\rangle - \left\langle (\Delta\theta_s)^2 \right\rangle = \frac{9}{8\pi} P H_0^3 \int_0^1 \frac{da}{a^2} \left(\Omega_M a + \Omega_V a^4\right)^{3/2} \left(\frac{1}{\mathrm{v}} - \mathrm{v}\right)$$

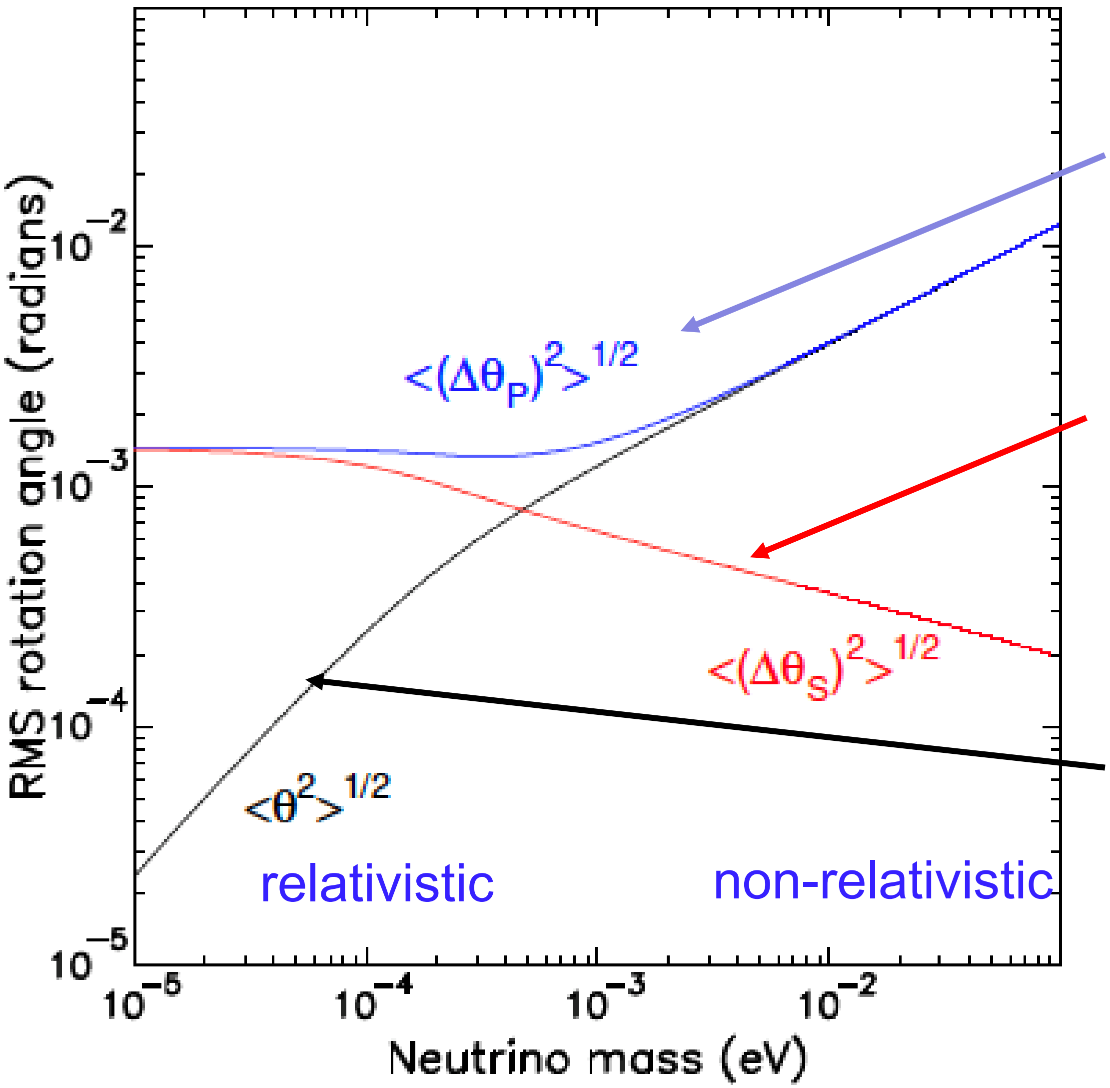
(where Ω_M = matter fraction, Ω_V =dark energy fraction)

Main effect is from matter dominated era (redshift $\sim 10^4$ to now)

(For detailed derivation, see Baym and Peng, PRD 103 (2021))

Spin rotation relative to momentum rotation due to gravity for relic neutrino mass state

(depending on neutrino's mass)

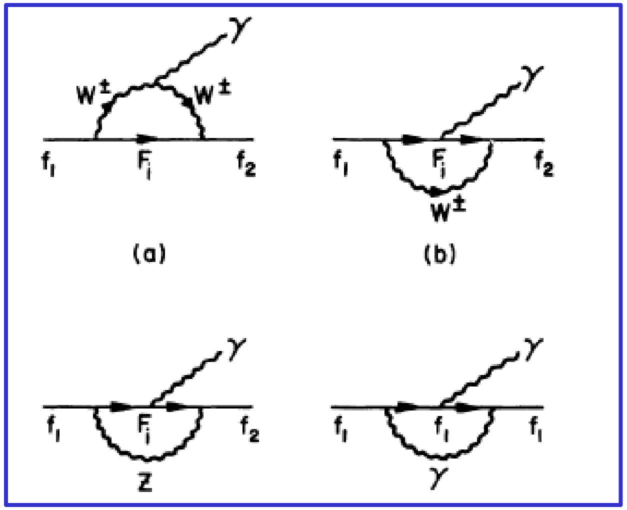


RMS for $\Delta\theta_P$: rotation angle for momentum

RMS for $\Delta\theta_S$: rotation angle for spin

RMS for θ : rotation angle for spin relative to momentum

Rotation of neutrino spins in magnetic fields via neutrino magnetic moment



Standard model processes lead to a non-zero neutrino magnetic moment

$$\mu_\nu^{SM} \simeq \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \simeq 3\times10^{-21} m_{-2}\,\mu_B$$

Fujikawa-Schrock, *PRL* 1980

$$\mu_B = \text{Bohr magneton} = e/2m_e$$

$$m_{-2} = m_\nu / 10^{-2}\,\text{eV}$$

The magnetic moment could be much larger (BSM physics)

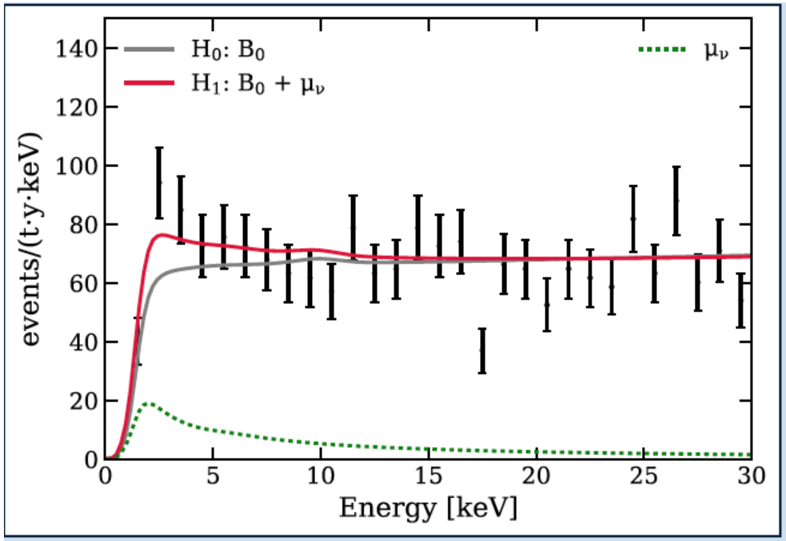
Upper bounds: $\mu_\nu < 2.9\times10^{-11}\mu_B$ GEMMA (2010)

$\mu_\nu < 7.4\times10^{-11}\mu_B$ TEXONO (2007)

$\mu_\nu < 2.8\times10^{-11}\mu_B$ Borexino (2017)

Naturalness upper bound: $\mu_\nu \le 10^{-16} m_{-2}\mu_B$ *Bell et al. PRL* 2005

XENON1T low energy electron event excess



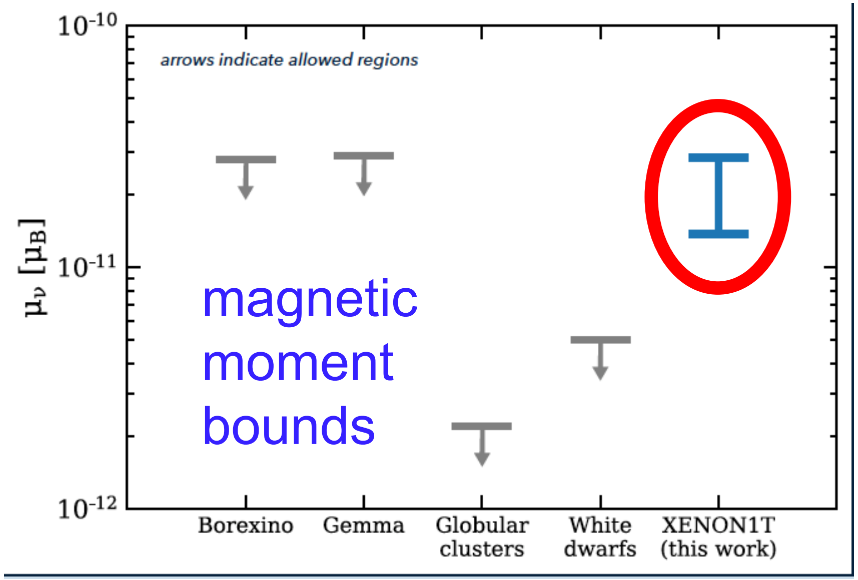
Excess of low energy electron events 1-7 keV over expected background???
Aprile et al. PR D 102, 072004 (2020)

Possible explanations:
Large neutrino magnetic moment (3.2σ)
Solar axions (3.5σ)
Tritium (in Xe) beta decays

Excess consistent with neutrino magnetic moment:

$$\mu_{\nu,1T} \sim 1.4 - 2.9 \times 10^{-11} \mu_B$$

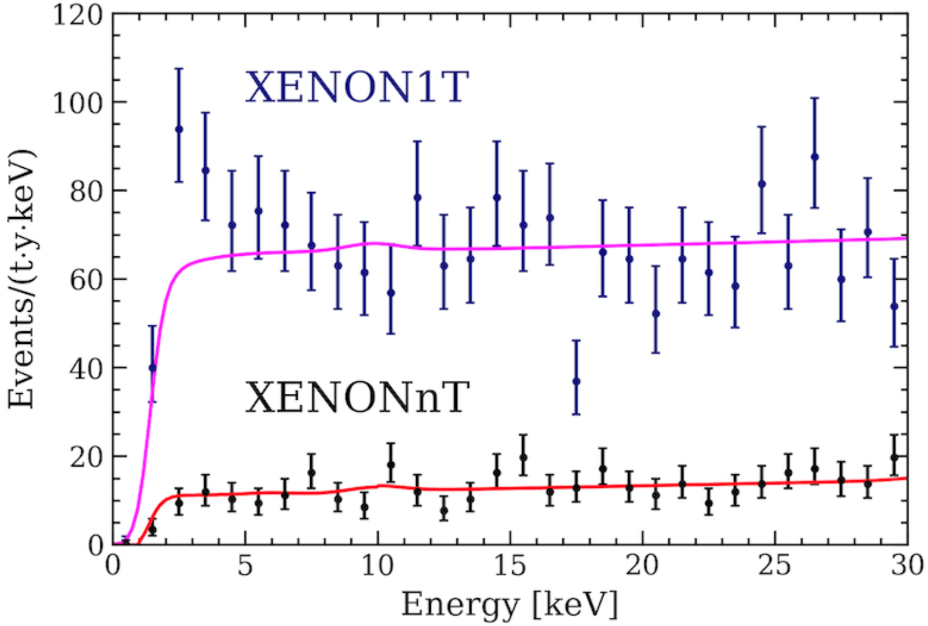
Beyond Standard Model physics??

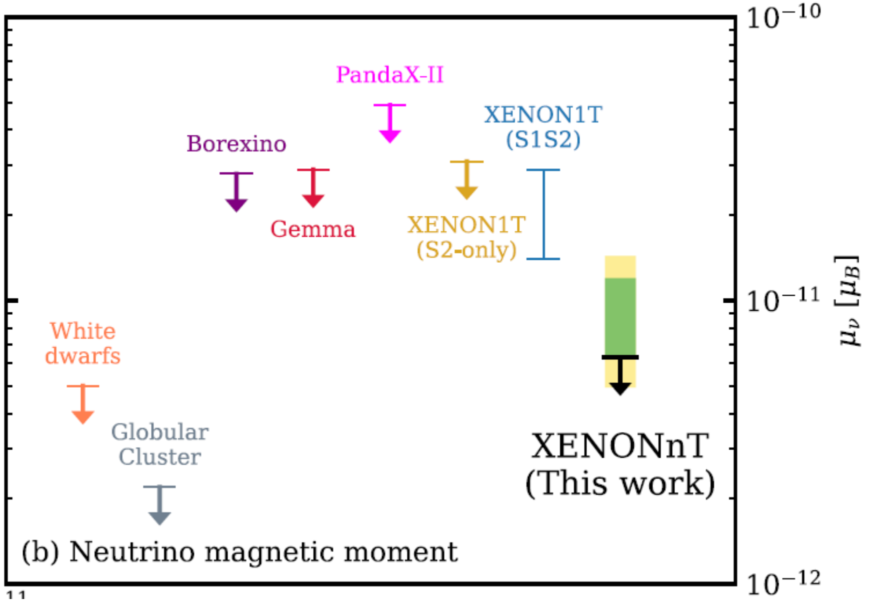


Excess now tracked to tritium contamination

E. Aprile et al, PRL: 129, 161805 (2022)

XENONnT = 6 tons of Xe





No indication of BSM neutrino magnetic moment

Neutrino's spin precesses in B field, but momentum does not

(neutrinos are electrically neutral)

Magnetic fields change neutrino helicity: $h = \hat{S} \cdot \hat{p}$

Define spin in rest frame of neutrino.

Rest frame precession :

$$\frac{d\vec{S}}{d\tau} = 2\mu_\nu \vec{S} \times \vec{B}_R \qquad B_R = \text{magnetic field in rest frame}$$

In terms of "lab" frame magnetic field: $B_{\parallel R} = B_\parallel,\ B_{\perp R} = \gamma B_\perp$

Bargmann-Michel-Telegdi (BMT) equation of motion:

$$\frac{d\vec{S}_\perp}{dt} = 2\mu_\nu \left(\vec{S}_\parallel \times \vec{B}_\perp + \frac{1}{\gamma} \vec{S}_\perp \times \vec{B}_\parallel \right)$$

Apply to both galactic and cosmic magnetic fields

Cosmic magnetic field rotation of neutrino spin

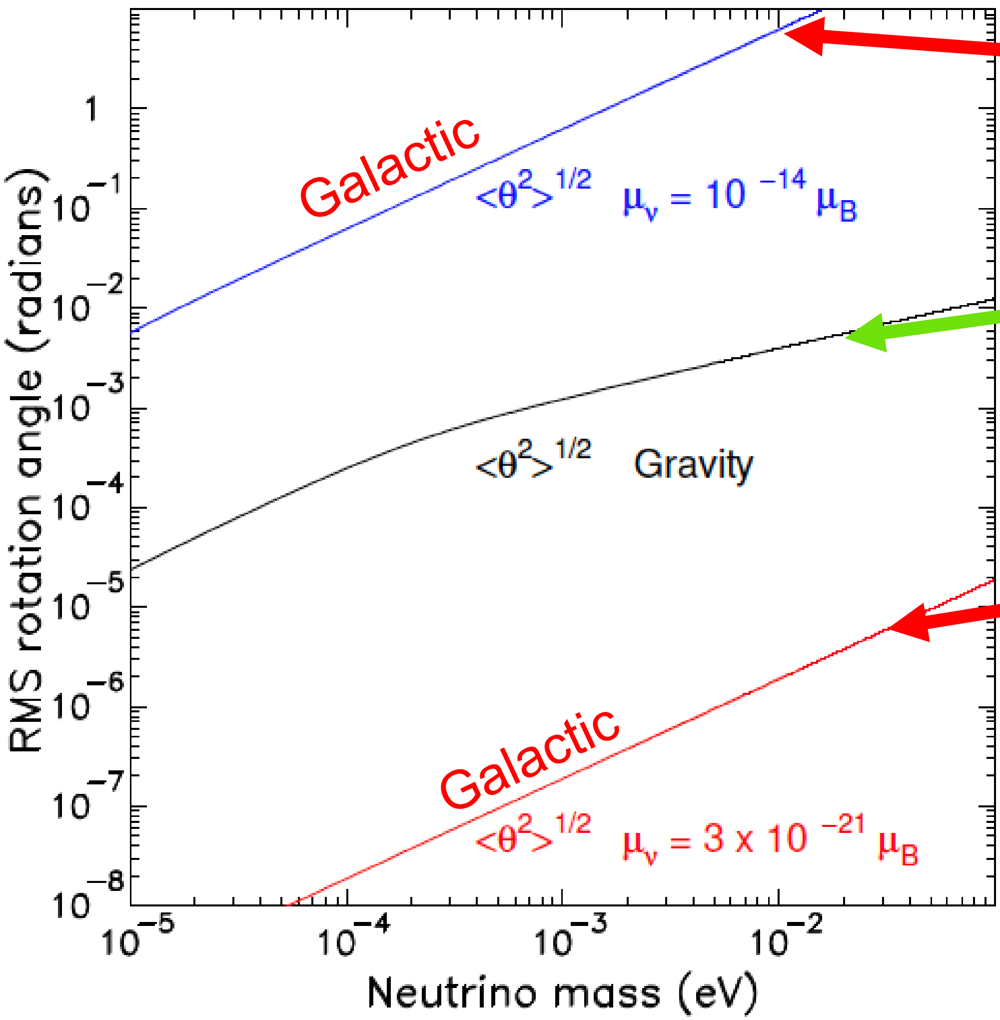
$$\left\langle \theta^2 \right\rangle_{\text{Galaxy}} \sim 4\times10^{29}\, m_{-2}^2 \left(\frac{\Lambda_g}{1kpc}\right)\left(\frac{B_g}{10\mu G}\right)^2 \left(\frac{\mu_\nu}{\mu_B}\right)^2$$

$$\left\langle \theta^2 \right\rangle_{\text{Cosmic}} \sim 2\times10^{27} \left(\frac{\Lambda_0}{1Mpc}\right)\left(\frac{B_0}{10^{-12}G}\right)^2 \left(\frac{\mu_\nu}{\mu_B}\right)^2$$

Λ_0 = coherence length of cosmic magnetic field

To within uncertainties in magnetic fields, coherence lengths, and neutrino masses, spin rotation in cosmic magnetic fields ~ galactic fields

Spin rotation from gravitational vs. magnetic fields



Rotation in Milky Way with magnetic moment ~100 times smaller than current upper limit

Gravitational rotation *GB+JCP PRD*

Rotation in Milky Way with standard model magnetic moment

ITBD rate depends on the helicity, mass and type of relic neutrinos

- $\sigma_i^h = \frac{G_F^2}{2\pi v_i} |V_{ud}|^2 |U_{ei}|^2 F(Z,E_e) \frac{m(^3He)}{m(^3H)} E_e p_e A_i^h (\bar{f}^2 + 3\bar{g}^2)$
- Define A_{eff} as the sum of $|U_{ei}|^2 A_i^h$ over mass state i and helicity h:

$$A_{eff} = \sum_{i,h=\pm} |U_{ei}|^2 \langle A_i^h \rangle_T$$

- Helicity-dependent factor, A_i^h, is $A_i^{\pm} = 1 \mp \beta_i$; where $\beta_i = v_i / c$
- T denotes the thermal average over the present momentum distribution, $f(p)$, of relic neutrinos: $f(p) = [e^{p/T_0} + 1]^{-1}; T_0 = 0.1676\ m\mathrm{eV}$

- For Dirac type, only neutrinos (not antineutrinos) contribute

$$A_{eff,D} = \sum_{i,h=\pm} |U_{ei}|^2 \langle A_i^h \rangle_T = 1 + \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T$$

- For Majorana type, both neutrinos and antineutrinos contribute

$$A_{eff,M} = (1 + \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T) + (1 - \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T) = 2$$

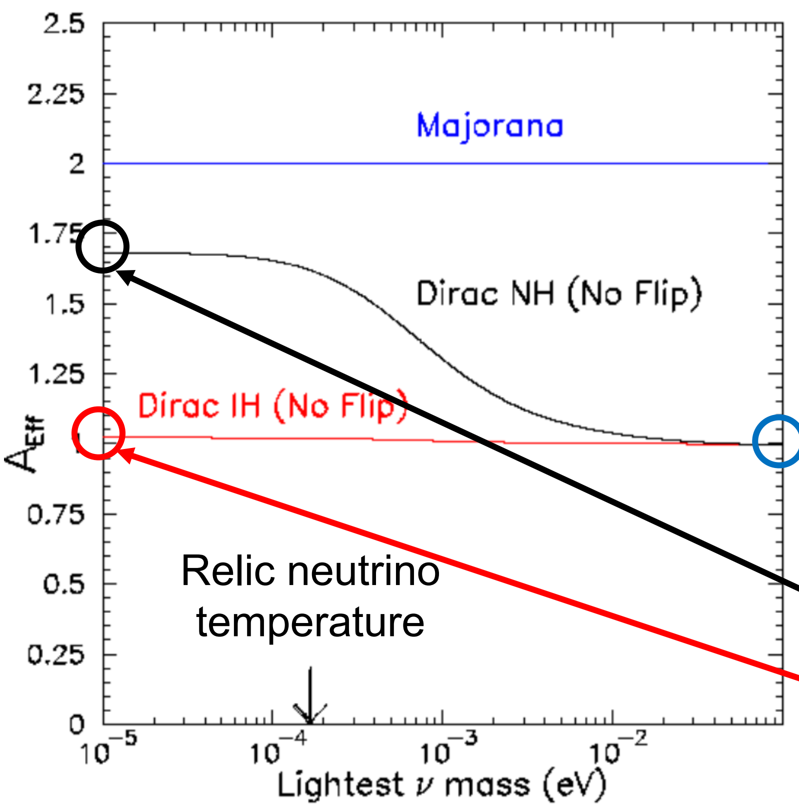
ITBD rate for Dirac neutrinos without helicity flip

- For Majorana type, both neutrinos and antineutrinos contribute

$$A_{eff,M} = (1+\sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T) + (1-\sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T) = 2$$

- For Dirac type, only neutrinos (not antineutrinos) contribute

$$A_{eff,D} = \sum_{i,h=\pm} |U_{ei}|^2 \langle A_i^h \rangle_T = 1+\sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T$$



- For Dirac neutrinos without helicity flip ($\cos\theta_i = 1$)

$$A_{eff,D} = 1+\sum_i |U_{ei}|^2 \langle \beta_i \rangle_T$$

- If all neutrinos are non-relativistic, $\beta_i \to 0$, then

$$A_{eff,D} = 1$$

- If the lightest neutrino is relativisitic, then

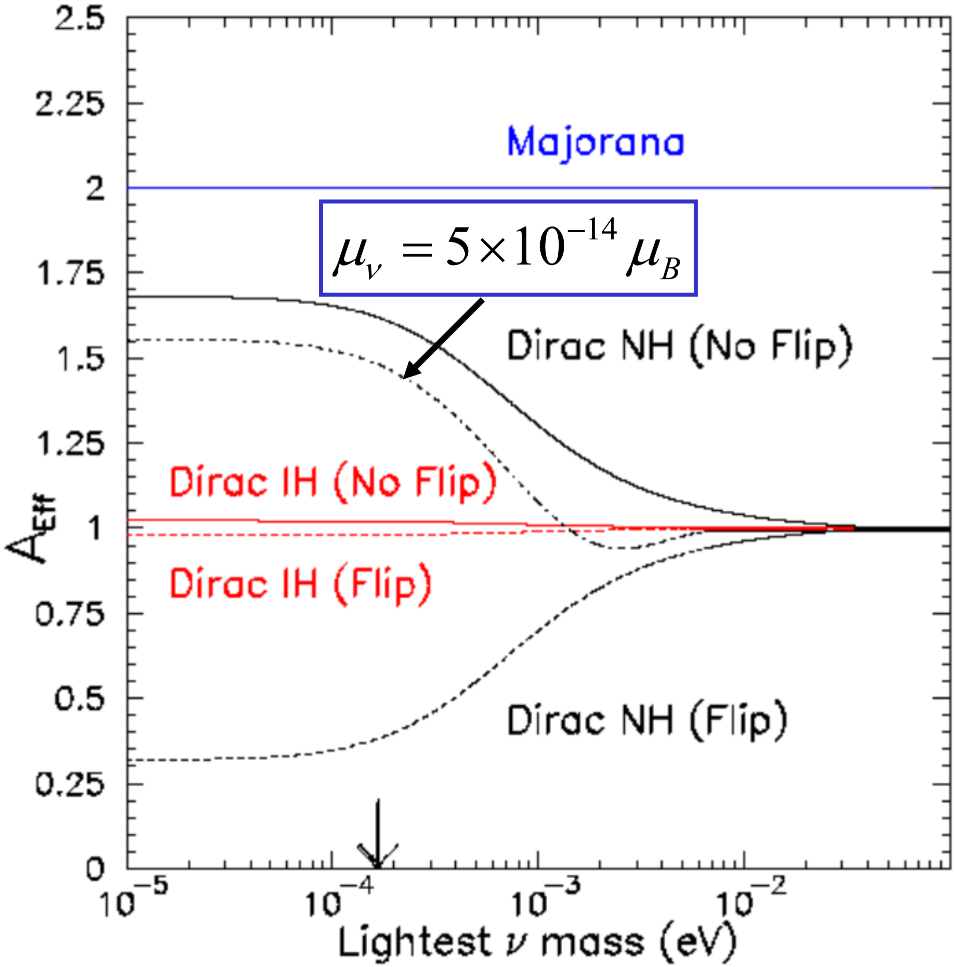
$A_{eff,D} = 1+|U_{e1}|^2 = 1.68$ for normal mass hierarchy

$A_{eff,D} = 1+|U_{e3}|^2 = 1.02$ for inverted mass hierarchy

ITBD rate for Dirac neutrinos with partial helicity flip

- For Dirac type, only neutrinos (not antineutrinos) contribute

$$A_{eff,D} = \sum_{i,h=\pm} |U_{ei}|^2 \langle A_i^h \rangle_T = 1 + \sum_i |U_{ei}|^2 \langle \beta_i \cos\theta_i \rangle_T$$



- For Dirac with NH, ITBD rate is modified even with a modest μ_ν of $5\times10^{-14}\mu_B$
- For Dirac with IH $A_{eff,D} \simeq 1$ insensitive to μ_ν
- For Majorana neutrinos $A_{eff,M} = 2$, independent of μ_ν

Baym and Peng, PRL 126, 191803 (2022)

The ITBD has never been observed yet !

To detect the ITBD, use known sources of electron neutrinos

Peng and Baym, PRD 106, 063018 (2022)

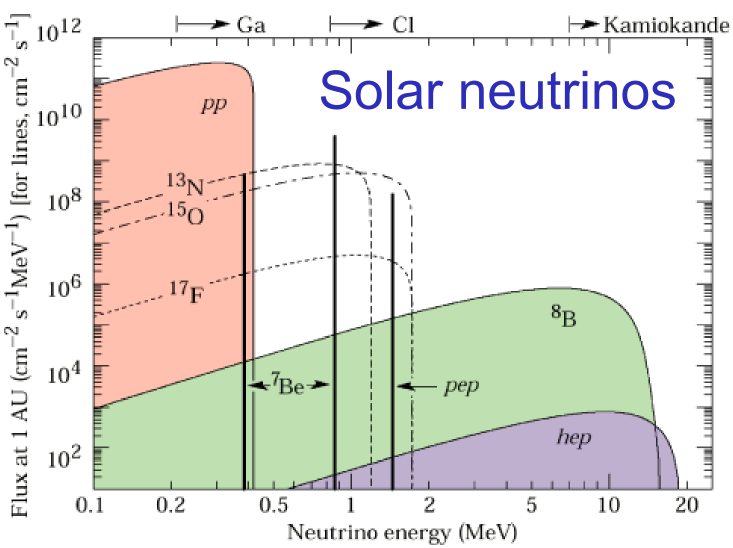
Solar Neutrinos and ^{51}Cr sources

$$^{51}\mathrm{Cr} \rightarrow {}^{51}\mathrm{V} + e^{+} + \nu_e$$

Experiment	Isotope	Strength	Production Process
GALLEX [3]	^{51}Cr	1.69 MCi	Thermal neutron capture on ^{50}Cr
SAGE [2]	^{51}Cr	0.517 MCi	Epithermal neutron capture on ^{50}Cr
GALLEX [1]	^{51}Cr	1.87 MCi	Thermal neutron capture on ^{50}Cr
SAGE [4]	^{37}Ar	0.409 MCi	Fast neutron $^{40}\mathrm{Ca}(n,\alpha)^{37}\mathrm{Ar}$
BEST [5]	^{51}Cr	3.4 MCi	Thermal neutron capture on ^{50}Cr

Table 1: Mega-Curie-scale electron capture neutrino sources that have been produced.

Coloma et al. (Snowmass 2020)



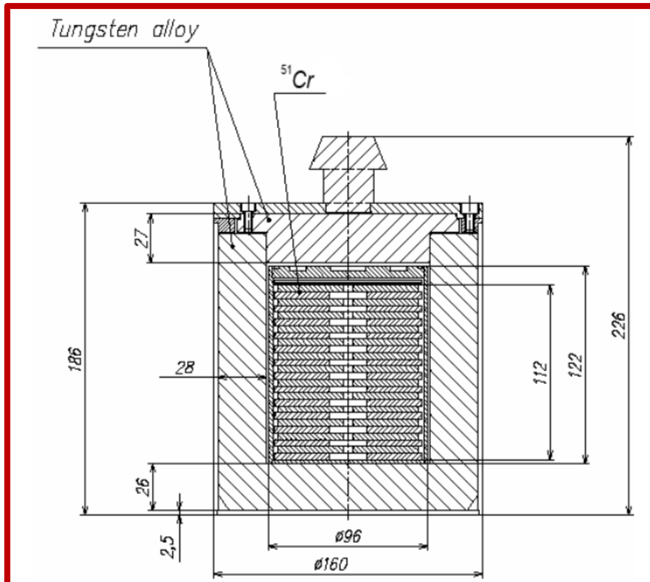


Figure 2. Neutrino source based on ^{51}Cr, all dimensions are in mm.

3.4 MCi ^{51}Cr source for the experiment BEST

Expected ITBD rates from various sources

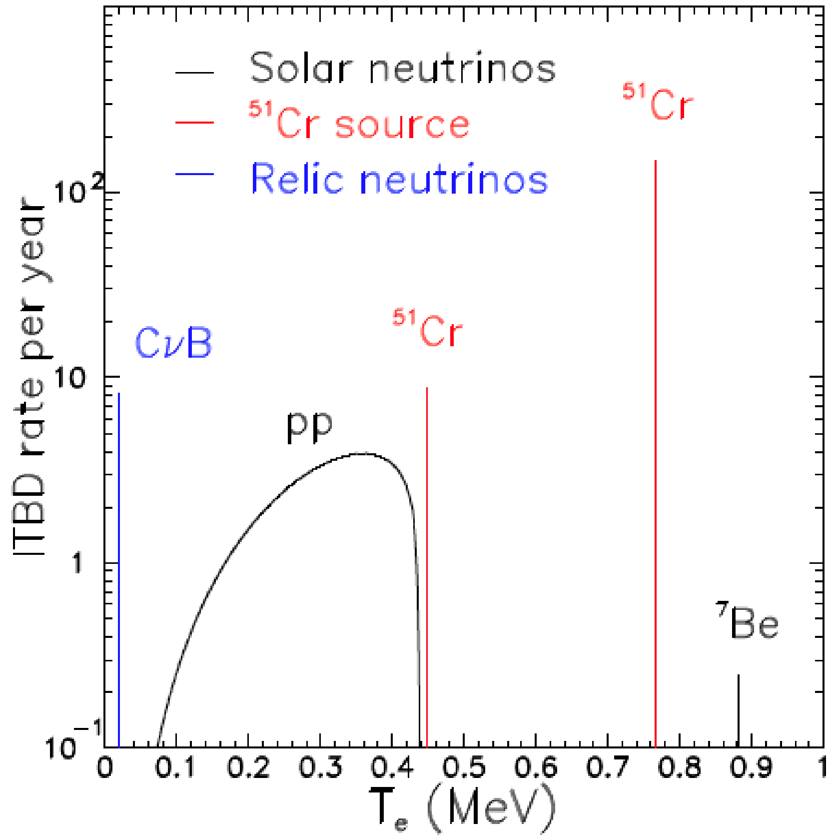
Assuming a 100 g tritium target

Peng and Baym, PRD 106, 063018 (2022)

3.0-MCi ^{51}Cr at 50 cm away from 100 g tritium target

TABLE I. ITBD rate for various sources of electron neutrinos, together with the electron kinetic energies, T_e. The relic neutrinos are assumed to be Majorana in the rate calculation.

Source	T_e (MeV)	Rate (1/year)
^{51}Cr 0.427 + 0.432 MeV ν_e	0.447	8.8
^{51}Cr 0.747 + 0.752 MeV ν_e	0.767	147.0
Solar pp ν_e	0.0186 to 0.44	0.8
Solar ^{7}Be ν_e	0.881	0.23
Relic $\nu_e/\bar{\nu}_e$	0.018	8.2



Conclusion

- Relic neutrino helicities could be modified by gravity and magnetic fields
- Detection rate of relic neutrinos via the ITBD reaction is sensitive to the Dirac/Majorana nature of neutrino, and to the masses of neutrinos
- For Dirac neutrino with normal hierarchy, the ITBD rate also depends on neutrino helicity, which is sensitive to neutrino magnetic moment
- Detection of relic neutrinos can reveal fundamental properties of neutrinos and the Early Universe


Thank you!