Helicity Property of Relic Neutrinos

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Based on three papers in collaboration with Gordon Baym

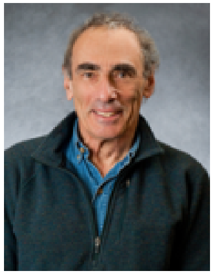
PRL 126, 191803 (2021);
Phys. Rev. D 103, 123019 (2021);
Phys. Rev. D 106, 063018 (2022)

Colloquium

2023/01/04 (10:30-12:00)

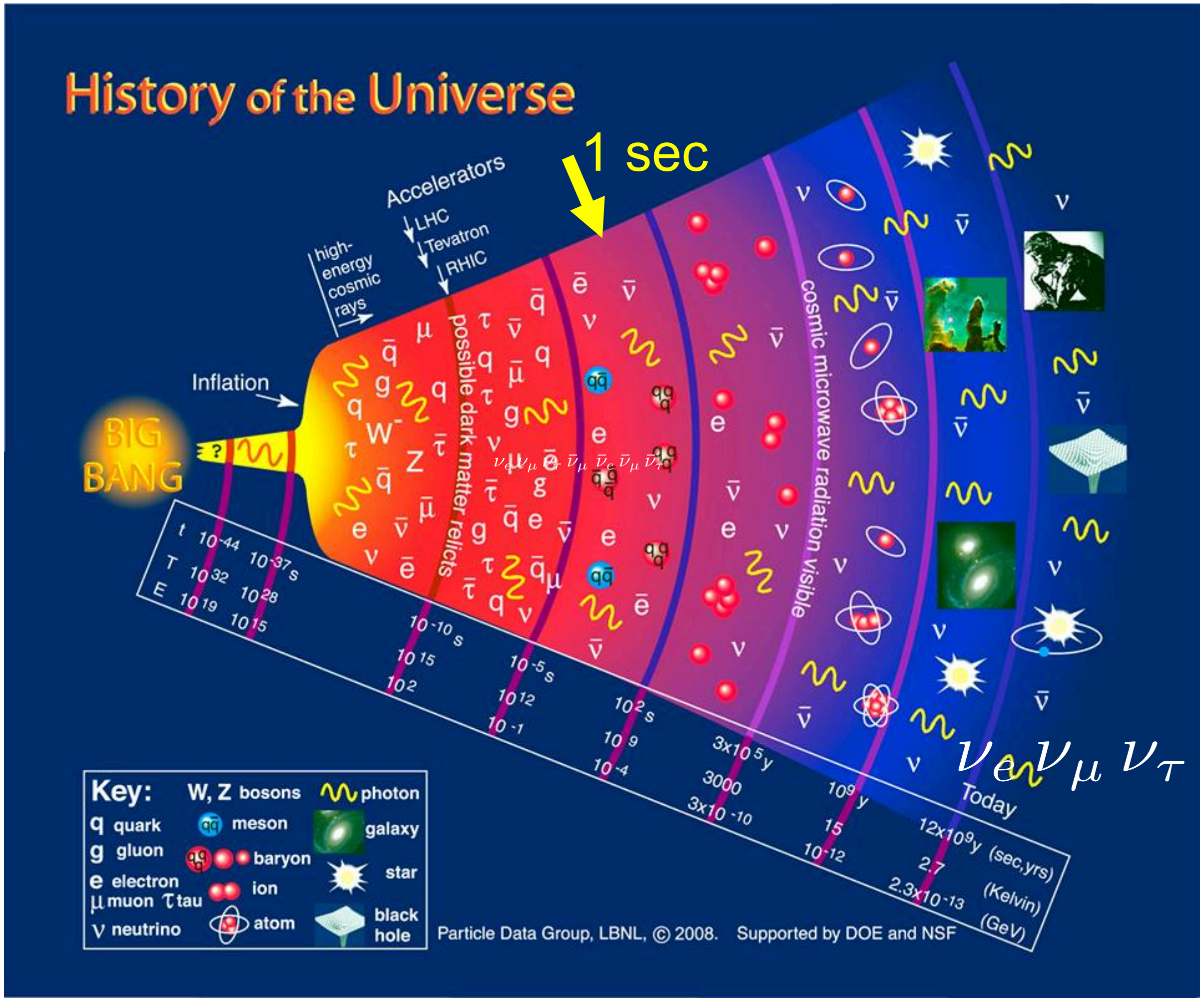
1st Floor(auditorium)

Evolution of primordial neutrino helicities in gravitational inhomogeneities and cosmic and galactic magnetic fields



Prof. Gordon Baym

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



CνB has never been observed !

Various neutrino reactions in thermal equilibrium

Scattering $\quad \nu_x(\bar{\nu}_x) + e^{\pm} \leftrightarrow \nu_x(\bar{\nu}_x) + e^{\pm}$

$x = e, \mu, \tau \quad \nu_x(\bar{\nu}_x) + \nu_{x'}(\bar{\nu}_{x'}) \leftrightarrow \nu_x(\bar{\nu}_x) + \nu_{x'}(\bar{\nu}_{x'})$

Annihilation $\quad \nu_x + \bar{\nu}_{x'} \leftrightarrow e^- + e^+$

$(\nu_x + \bar{\nu}_{x'} \leftrightarrow \mu^- + \mu^+$ occurs for $T > 106$ MeV)

Charge-exchange $\quad \nu_e + e^- \leftrightarrow e^- + \nu_e; \quad \bar{\nu}_e + e^- \leftrightarrow e^- + \bar{\nu}_e$

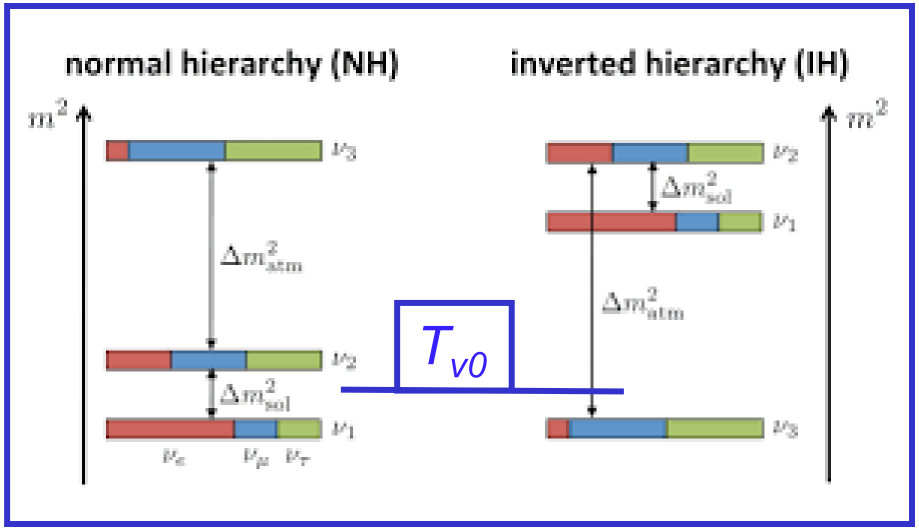
(keep $\nu_e(\bar{\nu}_e)$ in equilibrium longer)

As density decreases in expanding universe, decoupling occurs at

$$T(\nu_\tau) = T(\nu_\mu) \sim 1.5 \text{ MeV}; \qquad T(\nu_e) \sim 1.3 \text{ MeV}$$

CνB decouples as flavor eigenstate. They are now in mass eigenstates

At least 2 relic neutrino mass states are non-relativistic



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

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

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

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

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 $m_1 = 0$, $\mathrm{v}_1 = 1, \mathrm{v}_2 \sim 1/5, \mathrm{v}_3 \sim 1/20$

Inverted Hierarchy: If $m_3 = 0$, $\mathrm{v}_3 = 1, \mathrm{v}_1 \sim \mathrm{v}_2 \sim 1/20$

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 each of us at this moment
- Density of CνB is ~100 times of solar neutrinos

Incomplete list of proposed searches for CνB

1) Coherent ν-nucleus scattering

(Zeldovich and Khlpov, 1981; Smith and Lewin, 1983; Duda, Gelmini, Nussinov, 2001)

For CνB, $T_\nu \simeq 10^{-4}$ ev, $\lambda_\nu \simeq 2.4$ mm

$$\sigma(\nu\text{-nucleon}) \sim \mathrm{G}_\mathrm{F}^2 E_\nu^2 / \pi \simeq 5\times 10^{-63}\, cm^2 \text{ (Relativistic)}$$

$$\sim \mathrm{G}_\mathrm{F}^2 m_\nu^2 / \pi \simeq 10^{-56} \left(\frac{m_\nu}{ev}\right)^2 cm^2 \text{ (Non} - \text{Relativistic)}$$

- ν – nucleus coherent scattering ⇒ enhancement factor of $\mathrm{A}^2 \approx 10^4$
- coherence over CνB wavelength ⇒ enhancement factor of $\sim 10^{20}$

  (coherence over a volume of $(\lambda_\nu)^3$ containing $\sim 10^{20}$ nuclei)

Isotropic CνB flux ⇒ net force = 0

From COBE dipole anisotropy ⇒ $\mathrm{v}_{sun} = 369 \pm 2.5$ km/s (CνB is non-isotropic, just like the dark matter)

⇒ net acceleration due to "neutrino wind" $\sim 10^{-26}$ cm/s^2 on grain of size λ_ν

2) Astrophysical search with ultra-high energy neutrinos (Z-resonance)

(T. Weiler, 1982, 1999)

$\nu + \overline{\nu} \to Z^0$ resonance formation from interaction of ultra-high energy incident neutrinos with CNB

$$E_\nu^{res} = \frac{m_Z^2}{2m_\nu} = 4.2\times 10^{21}\left(\frac{1\text{ev}}{m_\nu}\right)\text{ev}$$

(Energy depends on the rest masses of neutrinos)

$$\sigma(\nu + \overline{\nu} \to Z^0) \simeq 4\times 10^{-32}\, cm^2$$

Signatures:

a) Dip in the UHE neutrino energy spectrum at energy $E_\nu \geq 10^{22}$ ev (A possible dip in UHE proton could also come from $p + \overline{\nu}_e \to e^+ + n$, see W. Hwang and B.Q. Ma, astro-ph/0502377)

b) "Z-burst"

Observation of UHE p, n, γ, and ν from decay of Z^0

However, sources of UHE neutrinos with $E_\nu \geq 10^{22}$ ev might not exist.

3) 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):

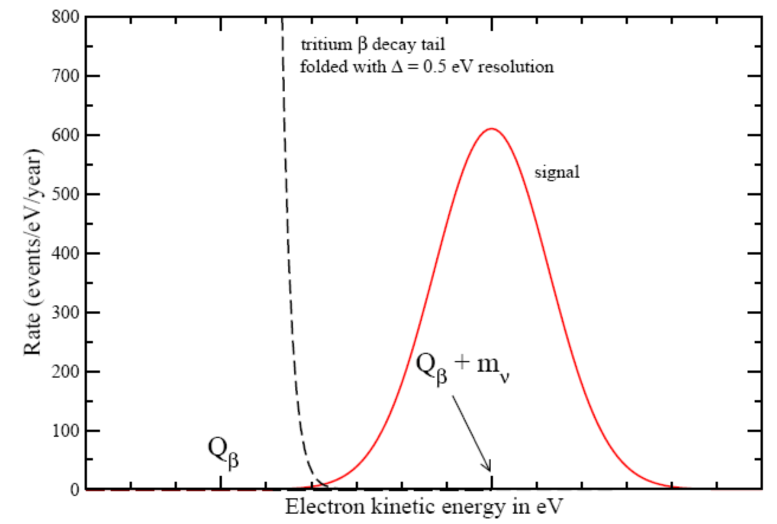
$$b)\ \nu_e + {}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^-$$

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:

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

- 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?

Helicity versus chirality for massive neutrino (where does the 1±β factor come from?)

For a Dirac spinor of momentum p along the z-axis with negative helicity ($h = -1$) we have

$$u^{-}(p) = \begin{pmatrix} 0 \\ \sqrt{E+m} \\ 0 \\ -\sqrt{E-m} \end{pmatrix}; \quad P_R = \frac{1+\gamma^5}{2} = \frac{1}{2}\begin{pmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{pmatrix}; \quad P_L = \frac{1-\gamma^5}{2} = \frac{1}{2}\begin{pmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix}$$

$$u^{-}(p) = u_L^{-}(p) + u_R^{-}(p) = P_L\, u^{-}(p) + P_R\, u^{-}(p)$$

$$u_L^{-}(p) = \frac{1}{2}\begin{pmatrix} 0 \\ \sqrt{E+m} + \sqrt{E-m} \\ 0 \\ -\sqrt{E+m} - \sqrt{E-m} \end{pmatrix}; \quad u_R^{-}(p) = \frac{1}{2}\begin{pmatrix} 0 \\ \sqrt{E+m} - \sqrt{E-m} \\ 0 \\ \sqrt{E+m} - \sqrt{E-m} \end{pmatrix}$$

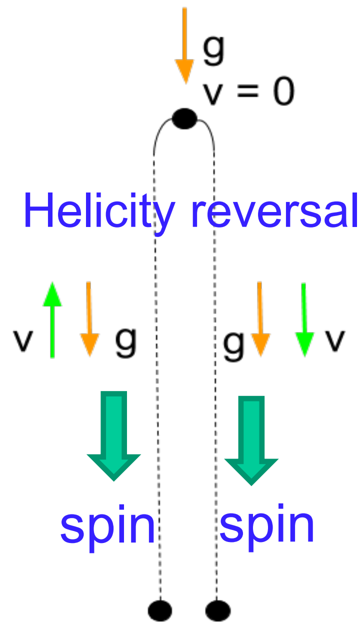
$$R = \frac{\sqrt{E+m} - \sqrt{E-m}}{\sqrt{E+m} + \sqrt{E-m}} = \frac{\sqrt{1-\beta}}{\sqrt{1+\beta}};$$

R is the relative amplitude for a negative helicity neutrino to be right-handed

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

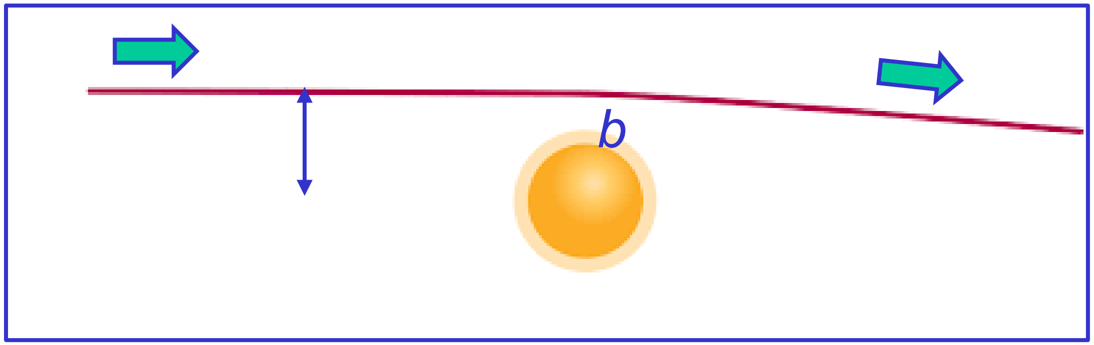
- Relic neutrinos decoupled at a temperature of ~1 MeV, and were highly relativistic. Neutrinos were produced essentially in $h = -1$ state, and antineutrinos in $h = +1$ state.
- Rotation of neutrino spin due to transverse matter source is less than the rotation of neutrino momentum (gravitational lensing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

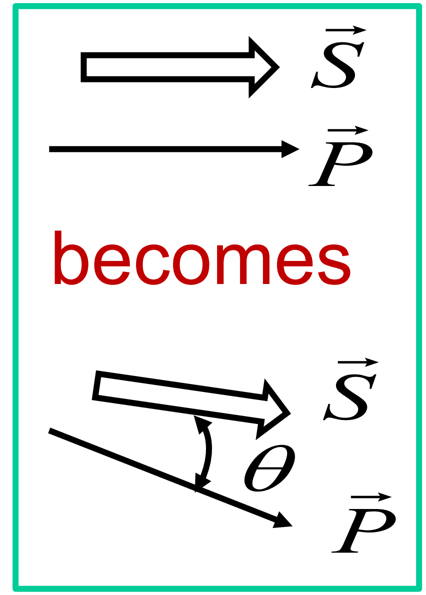
How would gravity modify the neutrino helicity?



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 $\mathrm{v} \to 0$

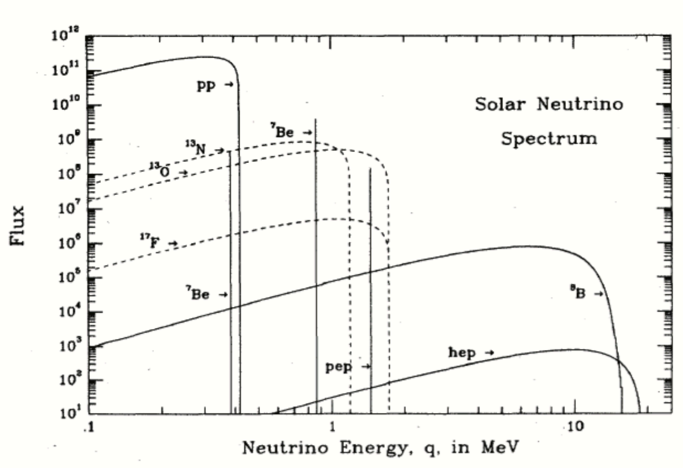
θ is large as $\mathrm{v} \to 1$

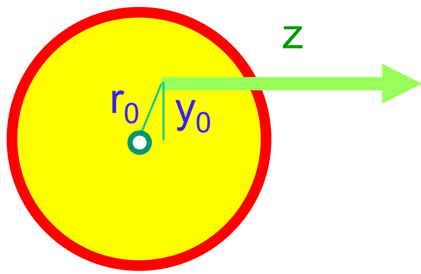
An angle θ between the spin and momentum directions means

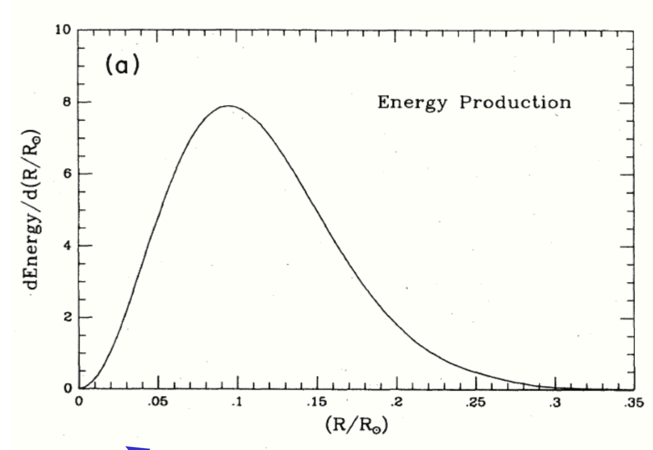
$$|h=+1\rangle \to \cos(\theta/2)|h=+1\rangle + \sin(\theta/2)|h=-1\rangle$$

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

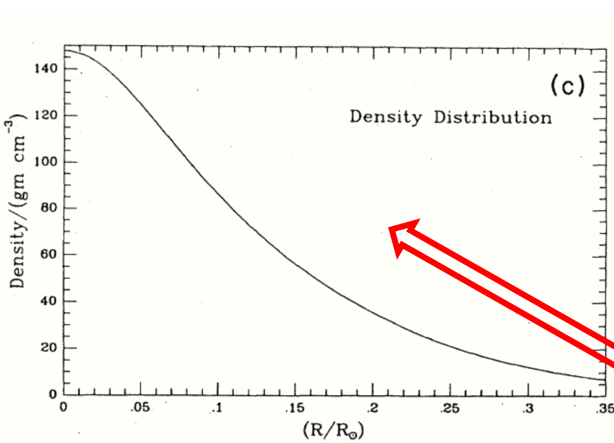
Helicity modification of solar neutrinos by Sun's gravity



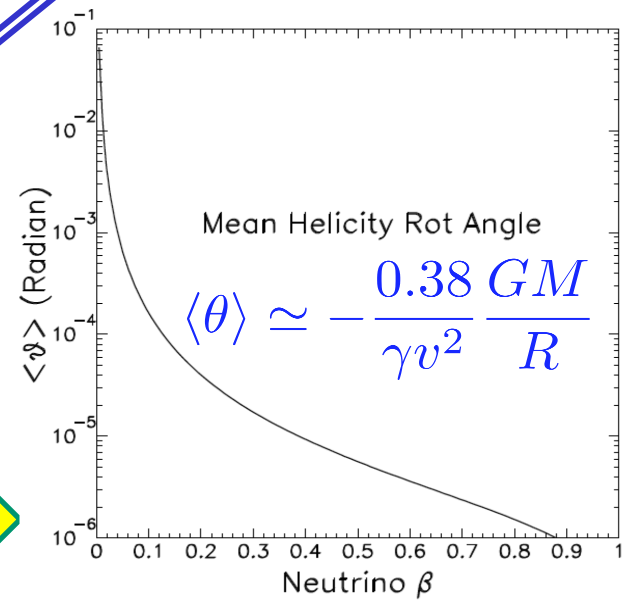




$$\theta(y_0, r_0) = -\frac{1}{\gamma v^2}\int_{z_0}^{\infty} dz \frac{GM(r)y_0}{r^3}$$



Averaged over spatial distribution of solar neutrino emission and mass distribution in Sun



Significant helicity modification of heavy particles with spin, e.g., dark photons, from Sun

Neutrino propagation in an expanding universe

Metric of expanding universe with weak gravitational inhomogeneities

$$ds^2 = a(u)^2 \left[-(1+2\Phi)du^2 + (\delta_{ij}(1-2\Phi)+h_{ij})dx_i dx_j \right]$$

$a =$ scale factor (a grows from $\sim 10^{-10}$ at $T = 1$ MeV to $a = 1$ now)

$u =$ conformal time; $dt = a\ du$

$x_i =$ comoving spatial coordinates, $h_{ij} =$ gravitational waves

$\Phi =$ weak potential driven by density fluctuations

$$\nabla_x^2 \Phi = 4\pi G\,(\delta\rho(x) + 3\,\delta P(x))\,a(u)^2$$

Radiation dominated era ($P = \rho / 3$), down to redshift $\sim 10^4$

Matter dominated era ($P(x) \to 0$) from redshift $\sim 10^4$ to now

Rotation of neutrino spin and momentum by scalar inhomogeneities

Gravitation potential Φ rotates momentum and spin:

$$\left(\frac{d\hat{p}}{dt}\right)_\perp = -\left(\mathrm{v}+\frac{1}{\mathrm{v}}\right)\vec{\nabla}_\perp\Phi; \qquad \left(\frac{d\vec{S}}{dt}\right)_\perp = -\frac{2\gamma+1}{\gamma+1}\vec{S}\cdot\vec{\mathrm{v}}\;\vec{\nabla}_\perp\Phi$$

Spin bending lags momentum bending: $\left(h\frac{d\hat{S}}{dt}-\frac{d\hat{p}}{dt}\right)_\perp = \frac{m}{p}\vec{\nabla}_\perp\Phi$

Neutrinos undergoes a random walk through the inhomogeneities.

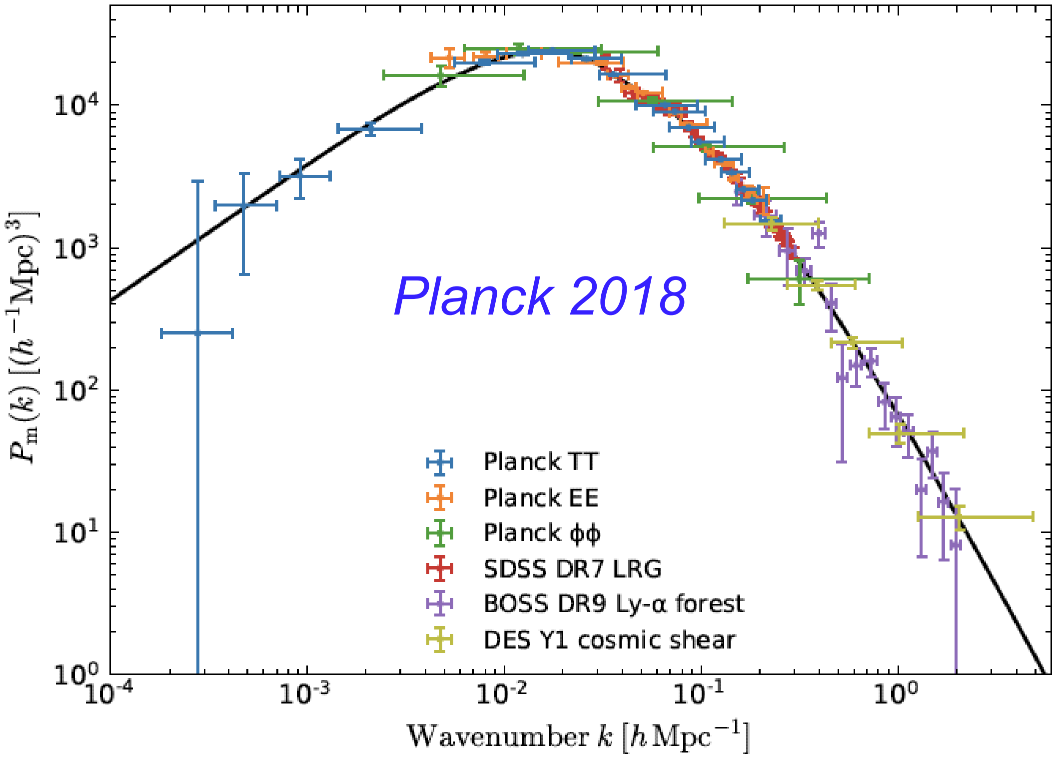
Averaged bending angle is zero, but RMS grows with time

Relate field fluctuations to density fluctuations: $\delta(\vec{x}) \equiv \delta\rho(\vec{x})/\bar{\rho}$

$$\langle\delta(\vec{x})\delta(\vec{x}')\rangle = \int\frac{d^3k}{(2\pi)^3}e^{i\vec{k}\cdot(\vec{x}-\vec{x}')}P(k)$$

$$\langle(\Delta\theta_p)^2\rangle = \frac{2}{\pi}\int du\left(4\pi G\bar{\rho}a^2\right)^2\int dk\,\frac{P(k)}{k}$$

Density fluctuation spectrum $P(k)$



$P(k) \sim k$ for $k < k_{max}$

(Harrison-Zeldovich)

$P(k) \sim k^{-\nu}$ for $k > k_{max}$

$$\left\langle (\Delta\theta_p)^2 \right\rangle = \frac{2}{\pi}\int du \left(4\pi G\bar{\rho}a^2\right)^2 \int dk \frac{P(k)}{k}$$

At present, $\int dk \frac{P(k)}{k} \simeq 7.25\times 10^4 (\mathrm{Mpc/h})^3 \equiv P$

h = Hubble parameter ~ 0.7

Gravitational spin rotation relative to momentum

For massive relic neutrinos, after including matter and dark energy

in $\bar{\rho}(a) = \rho_M / a^3 + \rho_V$:

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

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

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

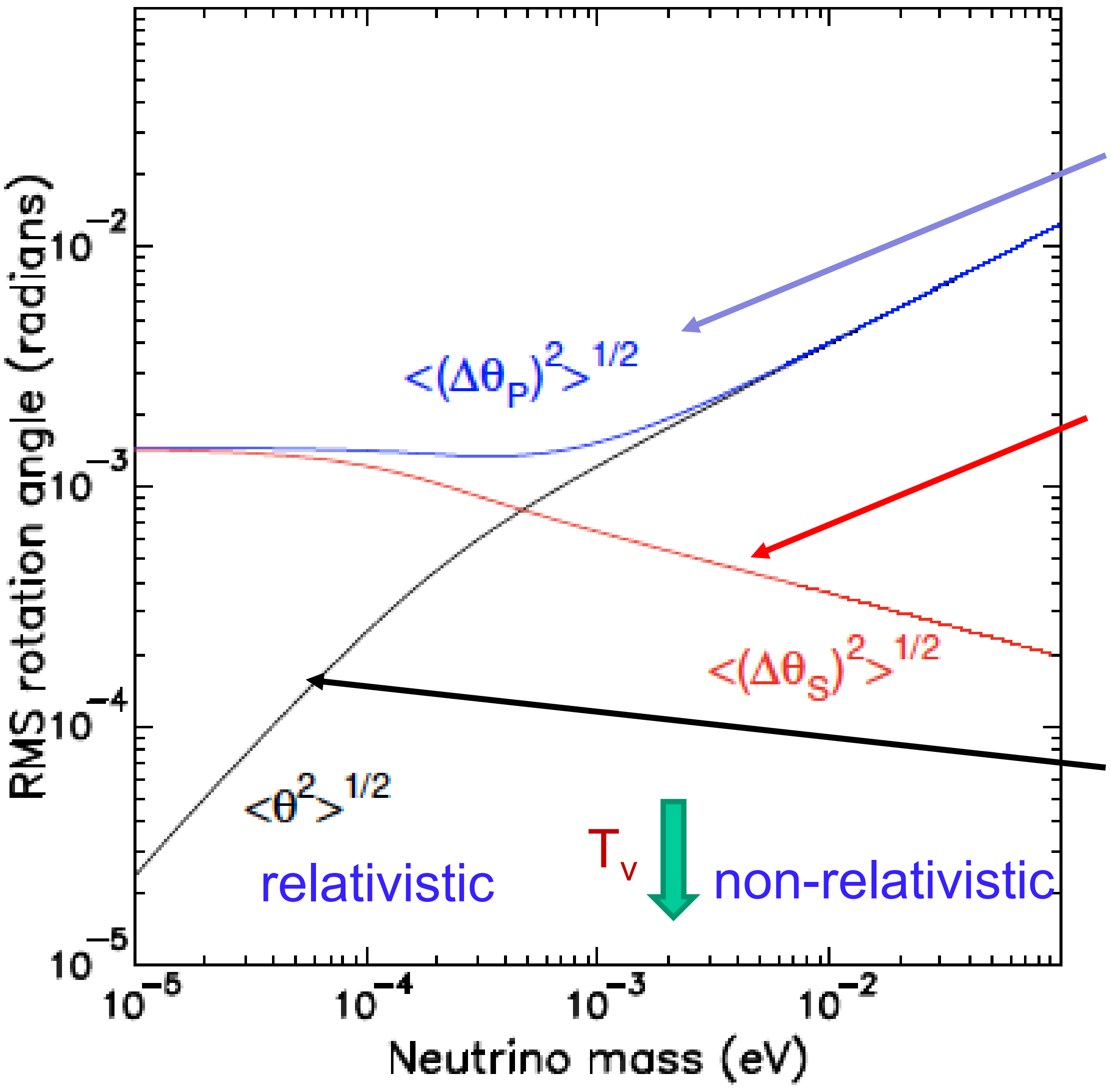
(where Ω_M = matter fraction, Ω_V =dark energy fraction)

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)

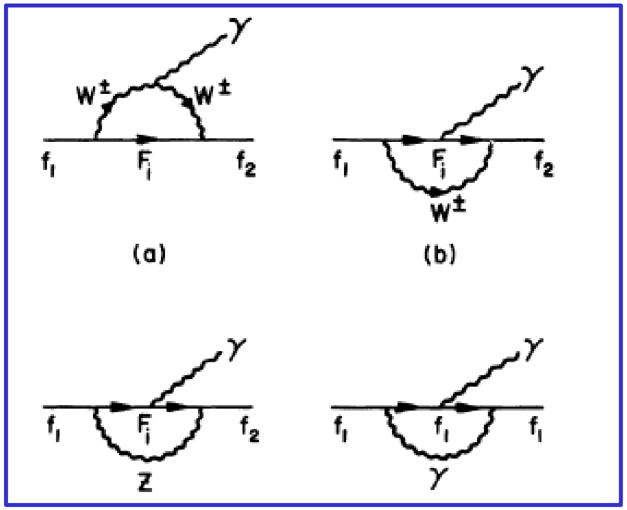


RMS for $\Delta\theta_P$: rotation angle for momentum

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

$$\mu_\nu^{SM} \simeq \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \simeq 3\times 10^{-21} m_{-2}\, \mu_B$$

$$Fujikawa - Schrock\ \ PRL\ 1980$$

$$\mu_B = Bohr\ \ magneton = e/2m_e$$

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

The magnetic moment could be much larger (BSM physics)

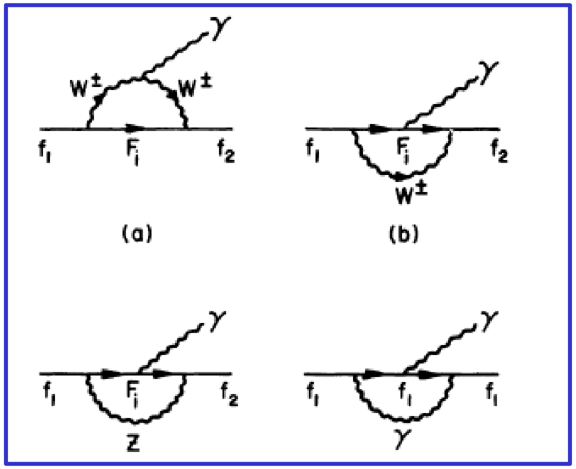
Upper bounds: $\mu_\nu < 2.9\times 10^{-11}\mu_B$ GEMMA (2010)

$\mu_\nu < 7.4\times 10^{-11}\mu_B$ TEXONO (2007)

$\mu_\nu < 2.8\times 10^{-11}\mu_B$ Borexino (2017)

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

Diagonal vs. transition magnetic moments



Diagonal: interaction with magnetic field between equal mass states (neutrino $m_1 = m_2$)

Transition: interaction only between different mass states ($m_1 \neq m_2$)

Are neutrinos Dirac or Majorana fermions?

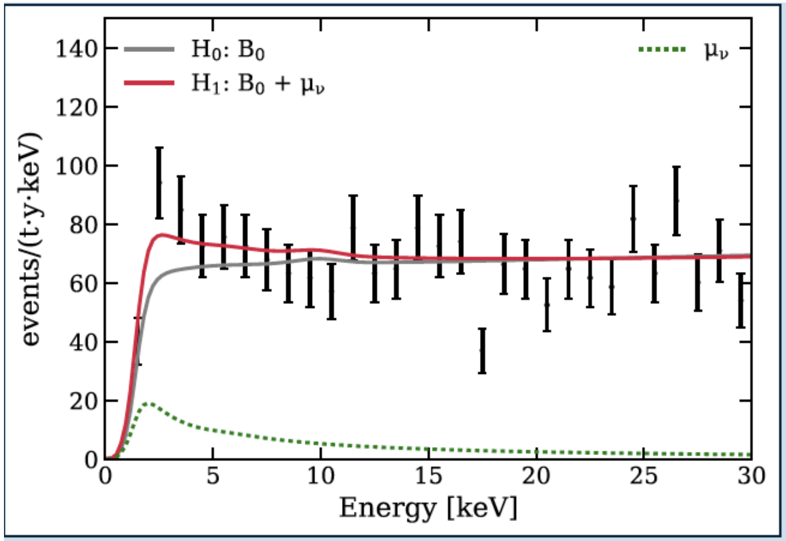
Dirac neutrinos can have both diagonal and transition moments.

Diagonal moments of Majorana neutrinos identically zero; only transition moments.

Propagation through cosmic and galactic magnetic fields cannot change neutrino mass state.

Only Dirac neutrinos can have helicities changed by magnetic fields.

XENON1T low energy electron event excess

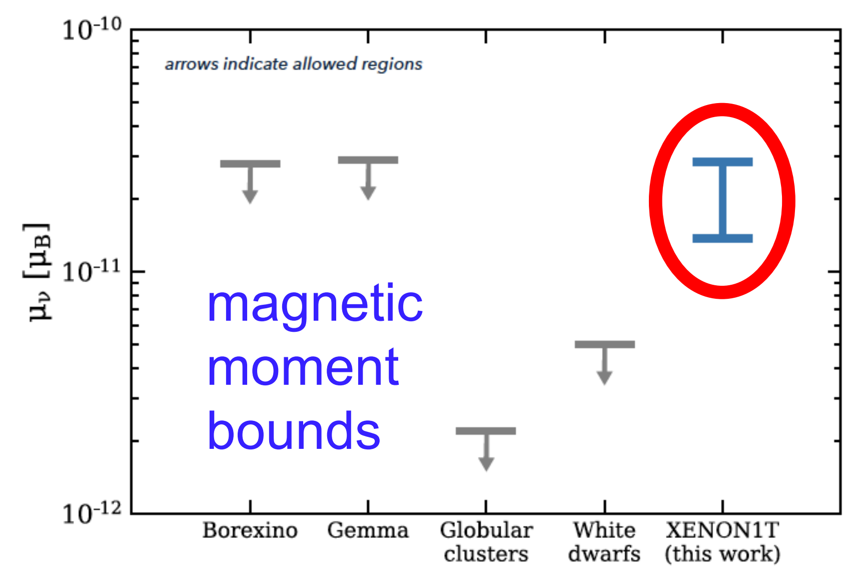


Excess of low energy electron events
1-7 keV over expected background???
Aprile et al. PR D 102, 072004 (2020)

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

Excess consistent with neutrino magnetic moment:

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

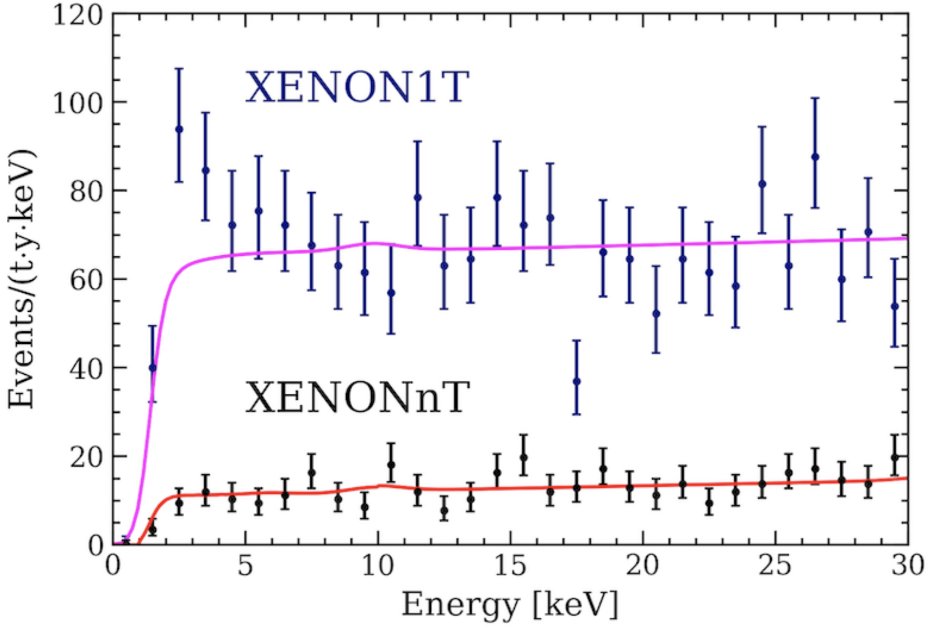


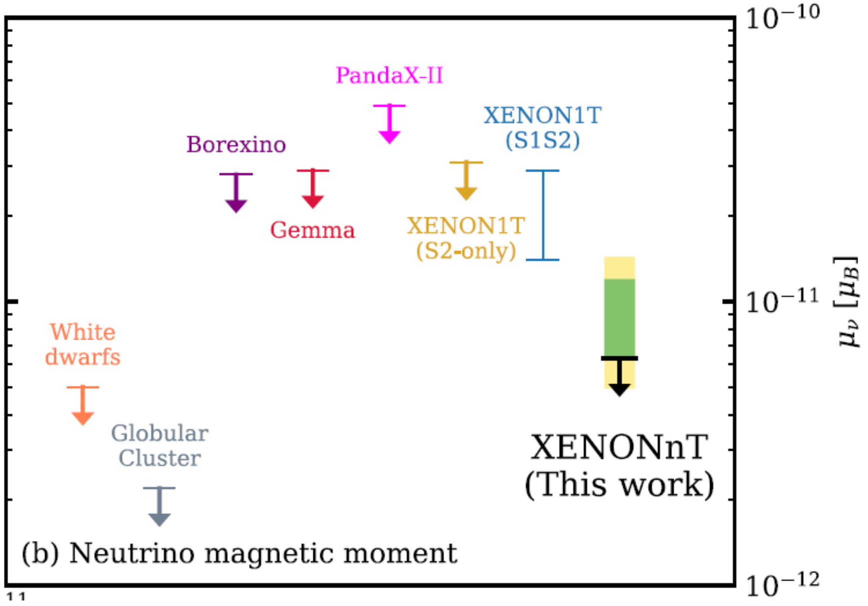
Beyond Standard Model physics??

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

Magnetic field lines in M51-Whirlpool Galaxy

SOFIA (on a 747) IR

Stratospheric Observatory for Infrared Astronomy

Neutrino spin rotation by galactic magnetic field

For uniform galactic magnetic field: $\theta_g \sim 2\mu_\nu B_g \frac{l_g}{\mathrm{v}}$

l_g = mean crossing distance of the galaxy

Since galactic fields are uniform only over coherence length $\Lambda_g \sim kpc$, spin direction undergoes a random walk in magnetic field

$$\left\langle \theta^2 \right\rangle_g \simeq \left(2\mu_\nu B_g \frac{\Lambda_g}{\mathrm{v}} \right)^2 \frac{l_g}{\Lambda_g}$$

Milky Way with characteristic parameters:

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

$\mu_\nu \sim 1.5\times 10^{-15} \mu_B \sim 10^{-4} \mu_{1T} \Rightarrow \sqrt{\left\langle \theta^2 \right\rangle} \sim 1$ helicity randomizes

Cosmic magnetic field rotation of neutrino spin

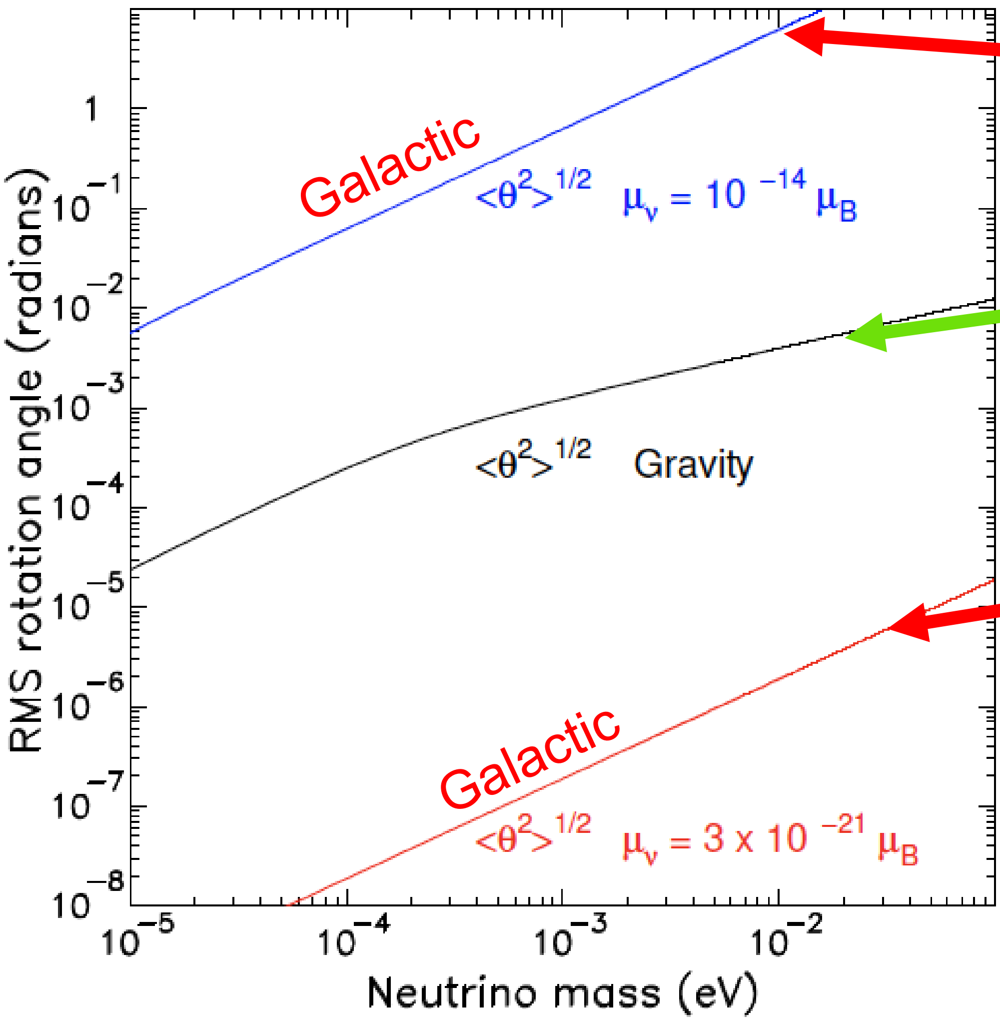
$$\left\langle \theta^2 \right\rangle_{\text{Galaxy}} \sim 4\times10^{29} m_{-2}^2 \left(\frac{\Lambda_g}{1kpc}\right)\left(\frac{B_g}{10\mu G}\right)^2 \left(\frac{\mu_\nu}{\mu_B}\right)^2$$

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

$\Lambda_0 = \text{coherence length of cosmic magnetic field}$

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 of the relic neutrinos

- Helicity-dependent factor, A_i^h , is $A_i^{\pm} = 1 \mp \beta_i$; where $\beta_i = v_i / c$
- A_{eff} is the sum of A_i^h over mass state i and helicity state h, weighted by $|U_{ei}|^2$:

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

- T denotes the thermal average over the present momentum distribution, $f(p)$, of relic neutrinos:

$$f(p) = \frac{1}{e^{p/T_0} + 1} \quad \text{and} \quad T_0 = 0.1676\ meV$$

- 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

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

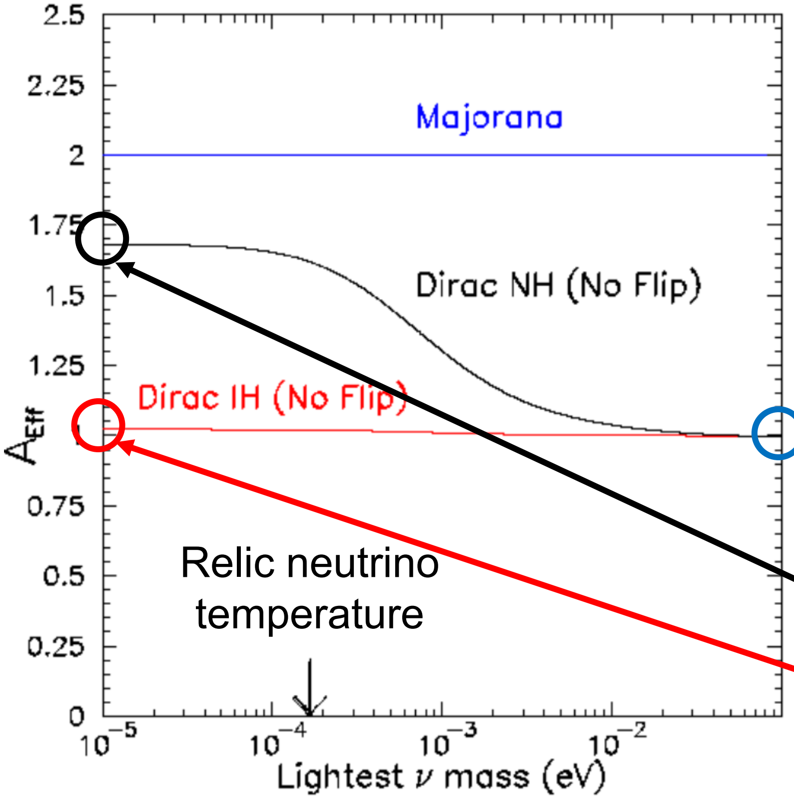
ITBD rate for Dirac neutrinos without helicity flip

- 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

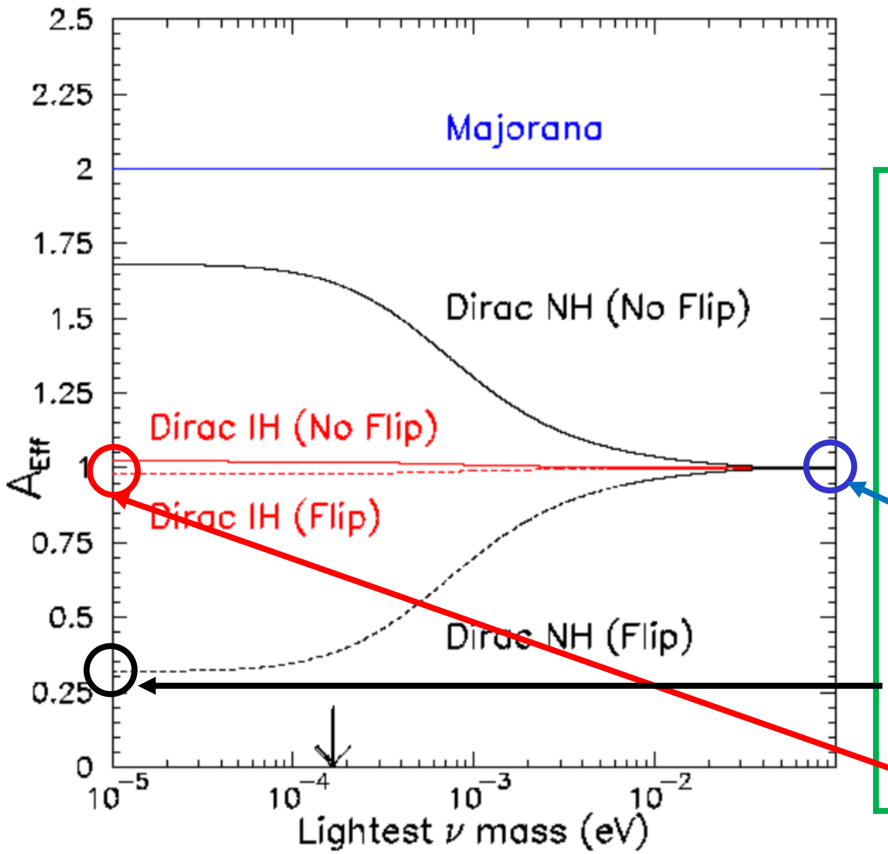
$A_{eff,D} = 1+|U_{e1}|^2 = 1.68$ for normal mass hierarchy

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

ITBD rate for Dirac neutrinos with helicity flip

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

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



- Dirac neutrinos with 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, $\beta_i \to 0$,

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

- If the lightest neutrino is relativisitic,

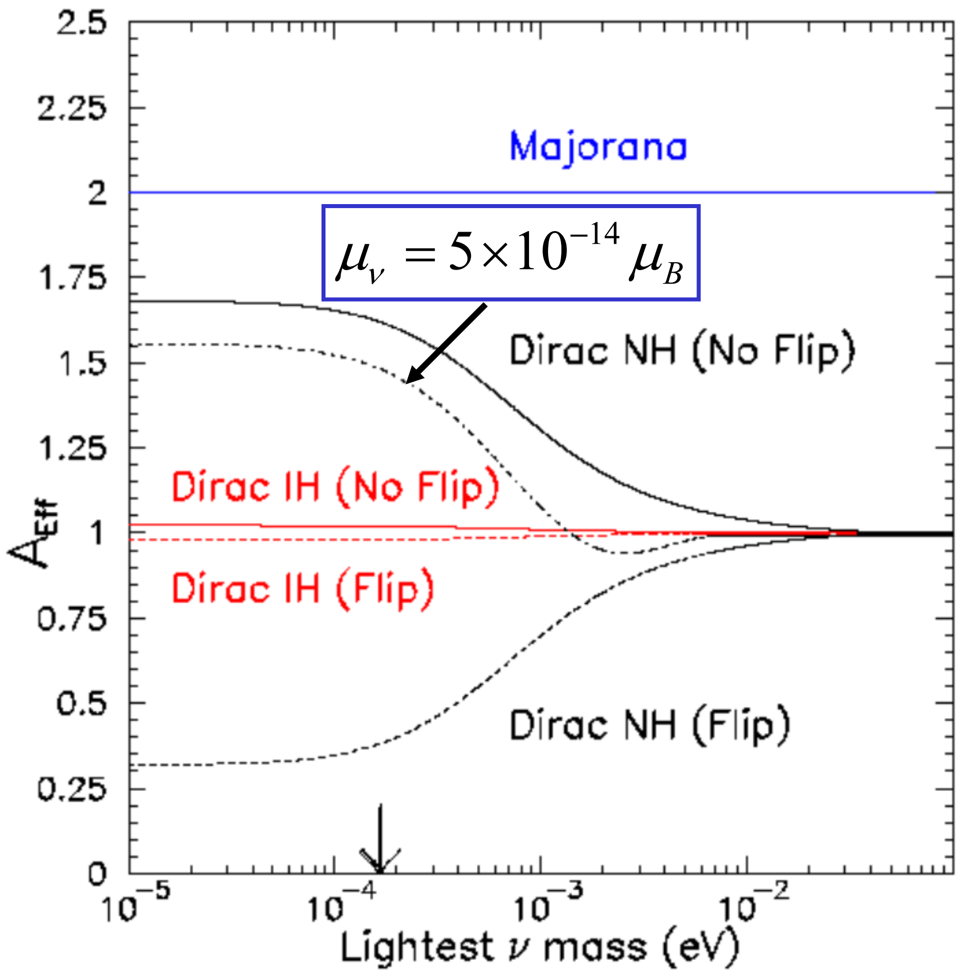
$$A_{eff,D} = 1 - |U_{e1}|^2 = 0.32 \quad \text{normal hierarchy}$$

$$A_{eff,D} = 1 - |U_{e3}|^2 = 0.98 \quad \text{inverted hierarchy}$$

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 $5\times10^{-14}\mu_B$ (~200 times smaller than the current upper limit)
- 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)

But not only have relic neutrinos never been observed, neither has the ITBD!

To detect the ITBD for the first time, one could use known sources of electron neutrinos

Solar neutrinos and ^{51}Cr source:

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

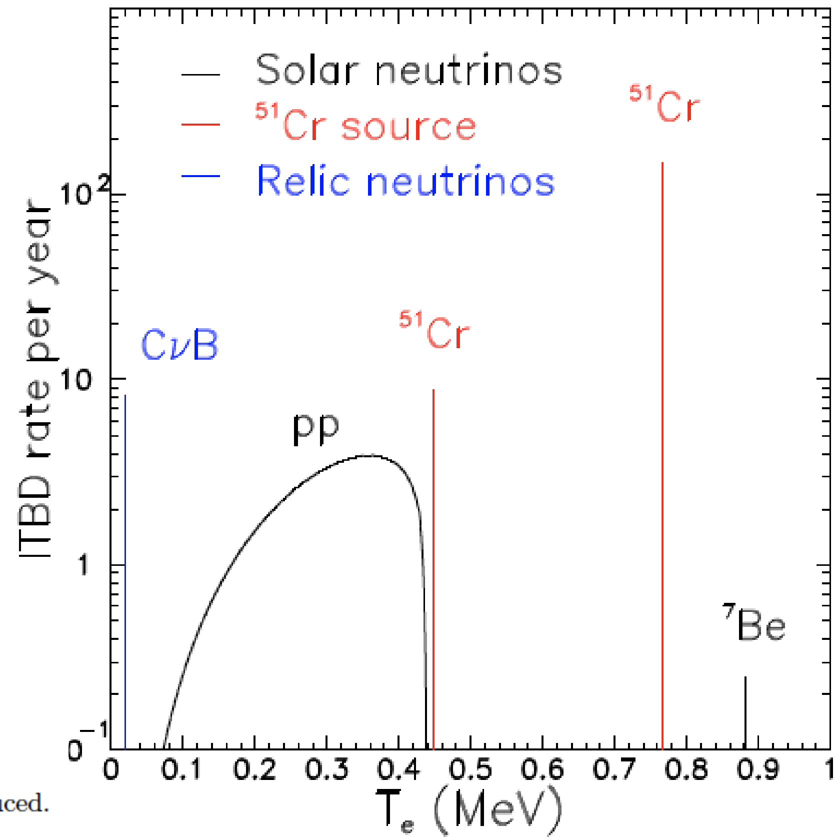
3.0-MCi ^{51}Cr at 50 cm

(double GALLEX)

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}Ca$(n,\alpha)^{37}$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)



Peng and Baym, PRD 106, 063018 (2022)

Conclusion

- Relic neutrino helicities could be modified by gravitational 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!