Relic RH Dirac Neutrinos & Cosmic Neutrino Background

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Progress in Observational Cosmology

1965
Discovery of CMB, Nobel Prize in 1978
Penzias and Wilson

1992
Anisotropy in CMB, Nobel Prize in 2006
COBE

2003
Cosmic Microwave Background (CMB)
WMAP
Progress in Observational Cosmology

The Cosmic Microwave Background as seen by Planck and WMAP

Cosmic Microwave Background (CMB)

Large Scale Structure (LSS) from Sloan Digital Sky Survey (SDSS)
Progress in Observational Cosmology

Big Bang Nucleosynthesis (BBN) and CMB
Standard Model of Cosmology

Cosmic Neutrino Background (CνB)
- Indirect evidence from BBN, CMB and LSS
- How to detect CνB in terrestrial experiments?
Formation of CvB

- ν in thermal equilibrium

@ high temperature

- νανβ ↔ νανβ
- ναν̄νβ ↔ ναν̄νβ
- νανβ ↔ νανβ
- ναν̄να ↔ e+e−
e+e− ↔ γγ

T_v = T_e = T_γ

- neutrino decoupling
  Γ < H @ T ~ 1 MeV
  Weak interactions
  Γ ≈ G_F^2 T^5

- photon reheating
  @ T < m_e
  e^+e^- ↔ γγ

- Basic properties of CvB
  - T_0 = 1.95 K and <p> = 3T_0 = 5 x 10^{-4} eV
  - number density n = 56 cm^{-3} per species

Temperature (MeV)

10^{18} 10^{15} 10^{12} 10^9 10^6 10^3 1 10^{-3} 10^{-6} 10^{-9}

- EW phase transition
- structure formation
- photon decoupling
- Now
- inflation
- neutrino decoupling
- QCD phase transition
- BBN
Neutrino Clustering

Neutrinos in the gravitational potential of CDM halos
- Input CDM halo profiles (Navarro-Frenk-White)
- Neutrinos are treated as perturbations

Singh, Ma, 03; Ringwald, Wong, 04

Clustering in the Milky Way

Distribution function at the Earth

At the Earth, larger by a factor of 1 to 20
Prospects for CvB Detection

- Direct evidence for CvB, trace back to the early Universe at 1s while CMB tells us the story at 380 000 yrs
- Probe intrinsic properties of neutrinos, the only chance to get non-relativistic neutrinos (e.g., Majorana vs. Dirac)

**Temperature today**

\[ T_\nu = \left( \frac{4}{11} \right)^{1/3} \quad T_\gamma \simeq 1.945 \text{ K} \]

**Mean momentum today**

\[ \langle p_\nu \rangle \simeq 3.151 T_\nu \]

\[ \simeq 5.281 \times 10^{-4} \text{ eV} \]

**Relic neutrino capture on \( \beta \)-decaying nuclei**

\[ N \rightarrow N' + e^- + \bar{\nu}_e \]

\[ \nu_e + N \rightarrow N' + e^- \]

At least 2 \( \nu \)'s cold today

NON-relativistic \( \nu \)'s!

(Irvine & Humphreys, 83)

no energy threshold on incident \( \nu \)'s

mono-energetic outgoing electrons

1962

for either active or sterile \( \nu \)'s
Neutrinoless Double Beta Decays

Three possible ways to distinguish between Majorana and Dirac $\nu$'s:
(a) $0\nu\beta\beta$ decays (b) EM dipole moments (c) Nonrelativistic behaviors
Towards a real experiment?

★ first experiment
★ 100 g of tritium
★ graphene target
★ planned energy resolution 0.15 eV

★ CνB capture rate
\[ \Gamma^D_{C\nu B} \sim 4 \text{ yr}^{-1} \]
\[ \Gamma^M_{C\nu B} \sim 8 \text{ yr}^{-1} \]

\[ ^3\text{H} \rightarrow ^3\text{He} + e^- + \bar{\nu}_e \]
\[ \nu_e + ^3\text{H} \rightarrow ^3\text{He} + e^- \]

D = Dirac
M = Majorana

PTOLEMY
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield (Betts et al, arXiv:1307.4738)
Detection of CνB

Capture rate of a polarized neutrino state $\nu_j(s_\nu)$ on a free neutron

$$\sigma_j(s_\nu)\nu_{v_j} = \frac{G_F^2}{2\pi} |V_{ud}|^2 |U_{ej}|^2 F(Z, E_e) \frac{m_p}{m_n} E_e p_e A(s_\nu)(f^2 + 3g^2)$$

Note: Spin-dependent Factor

$$A(s_\nu) \equiv 1 - 2s_\nu \nu_{v_j} = \begin{cases} 1 - \nu_{v_j}, & s_\nu = +1/2 \text{ RH Helicity} \\ 1 + \nu_{v_j}, & s_\nu = -1/2 \text{ LH Helicity} \end{cases}$$

In the limit $\nu_{v_j} \to 1$, the state of $s_\nu = +1/2$ cannot be captured

In the limit $\nu_{v_j} \to 0$, both RH and LH helical states do contribute

Total Rate

Long et al., 14; Lisanti et al., 14

$$\Gamma_{\text{C\nuB}} = \sum_j \left[ \sigma_j \left( +\frac{1}{2} \right) \nu_{v_j} n_j(\nu_{\text{hR}}) + \sigma_j \left( -\frac{1}{2} \right) \nu_{v_j} n_j(\nu_{\text{hL}}) \right] N_T$$
Number Densities of Helical States

Conservation of Helicity: $[\hat{H}, \hat{h}] = 0$ for free particles after decoupling

\[
\hat{H} \equiv \gamma^0 m + \gamma^0 \vec{\gamma} \cdot \vec{p} = \begin{pmatrix} m & \vec{\sigma} \cdot \vec{p} \\ \vec{\sigma} \cdot \vec{p} & -m \end{pmatrix} \quad \hat{h} \equiv \frac{\vec{\Sigma} \cdot \vec{p}}{|\vec{p}|} = \frac{1}{|\vec{p}|} \begin{pmatrix} \vec{\sigma} \cdot \vec{p} & 0 \\ 0 & \vec{\sigma} \cdot \vec{p} \end{pmatrix}
\]

In the rest frame of CvB, the background neutrinos are isotropic

Long et al., 14

**Dirac Neutrinos**

- Decoupling
  - $n(\nu_L) = n(z)$,
  - $n(\bar{\nu}_R) = n(z)$,

- Nowadays
  - $n(\nu_{hL}) = n_0$,
  - $n(\bar{\nu}_{hR}) = n_0$,

- Total Rates
  - $\Gamma_{CvB}^{D} = \bar{\sigma} n_0 N_T$
  - $\bar{\sigma} \approx 3.8 \times 10^{-45} \text{ cm}^2$

**Majorana Neutrinos**

- Decoupling
  - $n(\nu_R) \approx 0$

- Nowadays
  - $n(\nu_{hR}) \approx 0$

- Total Rates
  - $\Gamma_{CvB}^{M} = 2\bar{\sigma} n_0 N_T$
Negligible RH Dirac Neutrinos?

Extension of SM with RH $\nu$'s

$$m_i = O(0.1 \text{ eV}) \quad \Rightarrow \quad y_i = O(10^{-12}) \ll 1$$

The production rate found to be much larger, but not large enough.

(Zhang, S.Z., arXiv:1509.02274)

(Antonelli, Fargion & Konoplich, 81)
Cosmological Constraints

Assume that RH $\nu$'s can be in thermal equilibrium with matter
RH $\nu$'s will be counted as extra radiation during BBN and CMB
QCD phase transition releases a large entropy to dilute RH $\nu$'s
Primordial Magnetic Fields

The galactic magnetic fields $B \sim O(1) \, \mu G$ are observed
★ seed B fields $\sim 10^{-21} \, G$
★ amplified during the
galaxy formation
★ phase transitions may
generate seed B fields

Evolution of primordial B fields (a phenomenological model)

$$B(t, L) = B_0 \left( \frac{a_0}{a(t)} \right)^2 \left( \frac{L_0}{L} \right)^p$$

$$\Gamma_{L \rightarrow R} = \frac{4}{3} \mu_{\nu_i}^2 B^2 L_0 H^{-1} L_W^{-1}$$

Decoupling before QCD phase transition (for $p=1/2$ and $L_0=5 \times 10^{-5} \, \text{cm}$)

$$B_0 \lesssim 10^{26} \, \text{G} \left( \frac{3 \times 10^{-20} \mu_B}{\mu_{\nu_i}} \right)$$

$$B_0 = 10^{24} \, \text{G} \text{ in EW phase transition}$$

Vachaspati, 91; Enqvist, Rez & Semikoz, 95
Main background comes from the intrinsic $\beta$-decay events of $^3$H.

Energy resolution $\Delta < 0.7 \ m_i$ for signal-to-background ratio $> 1$.

For the nominal setup of PTOLEMY $\Delta = 0.15 \ eV$, only sensitive to large $\nu$ masses, which are in contradiction with the Planck bound.

The presence of RH $\nu$'s changes the capture rate from $4.0 \ yr^{-1}$ to $5.1 \ yr^{-1}$ in the Dirac case (enhanced by 28%).
Capture rate enhanced by 28%

Probing RH neutrinos at the 3σ needs more than 20 years

Majorana vs. Dirac, 3-5 years

Precise measurement of absolute neutrino masses

$\Delta = 0.1 \text{ eV}$
$m_\nu = 0.1 \text{ eV}$
$m_\nu = 0.2 \text{ eV}$
$m_\nu = 0.3 \text{ eV}$

$\Gamma_D = 4 \text{ yr}^{-1}$
$\Gamma_R = 5.1 \text{ yr}^{-1}$
$\Gamma_M = 8 \text{ yr}^{-1}$
Nonthermal Background of RH \( \nu \)'s

- Degenerate RH \( \nu \)'s from inflaton decays
- Concentrated on low energies, so high number density (64%)
- Further reduce the difference between Dirac and Majorana cases
- Gravitational clustering of massive neutrinos increases the rate & the uncertainties of CDM profiles are large, worsening the situation
Nonthermal or Thermal RH ν’s: Annual Modulation

- Gravity focus by the Sun
- Assume neutrinos unbound to the Milky Way
- Large modulations for slow neutrino velocities
- Visible difference between TH and NT RH neutrinos