Relic RH Dirac Neutrinos
&
Cosmic Neutrino Background

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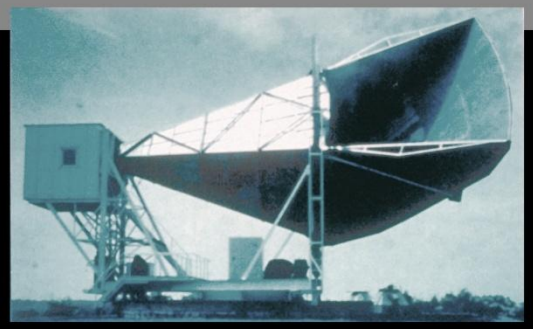
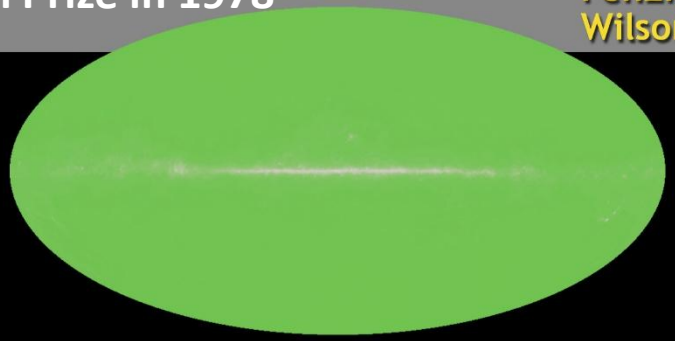
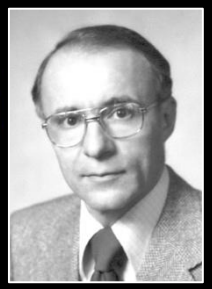
Neutrino Oscillation Wokshop 2016, Otranto, September 5th

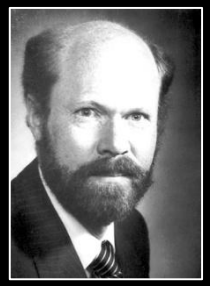
Progress in Observational Cosmology

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

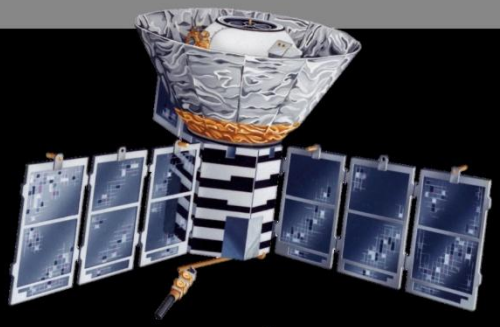


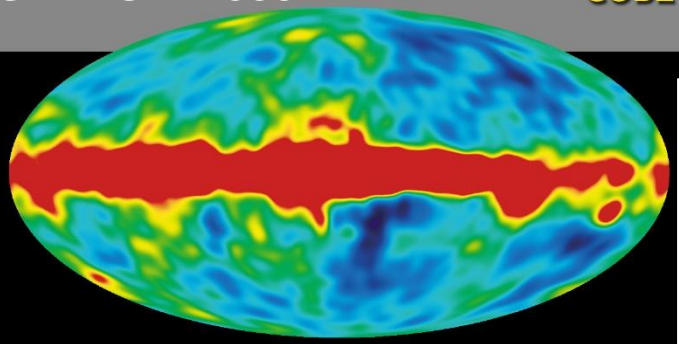


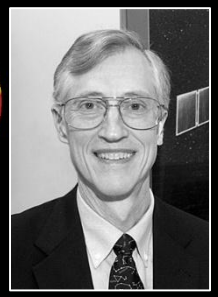




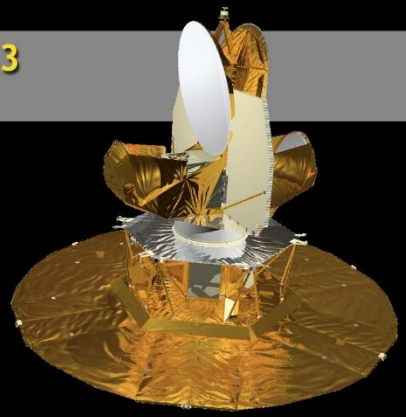
1992 Anisotropy in CMB, Nobel Prize in 2006 COBE

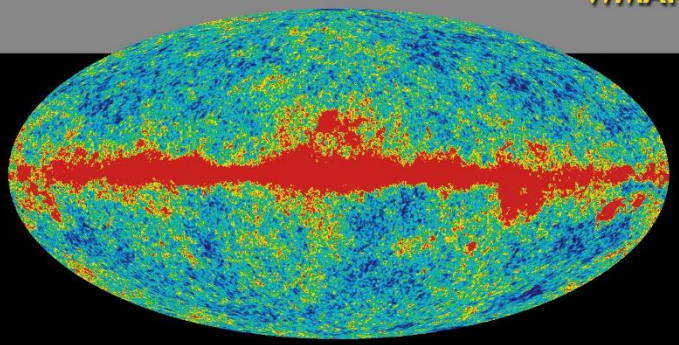






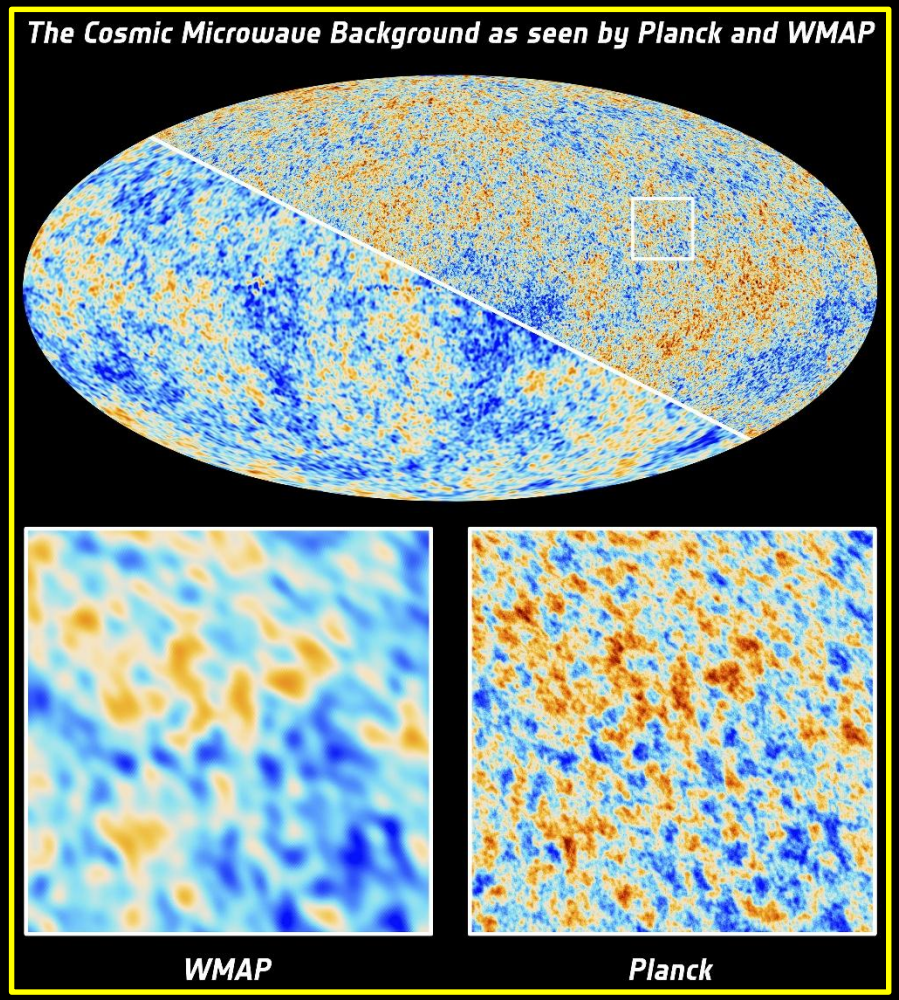
2003 WMAP

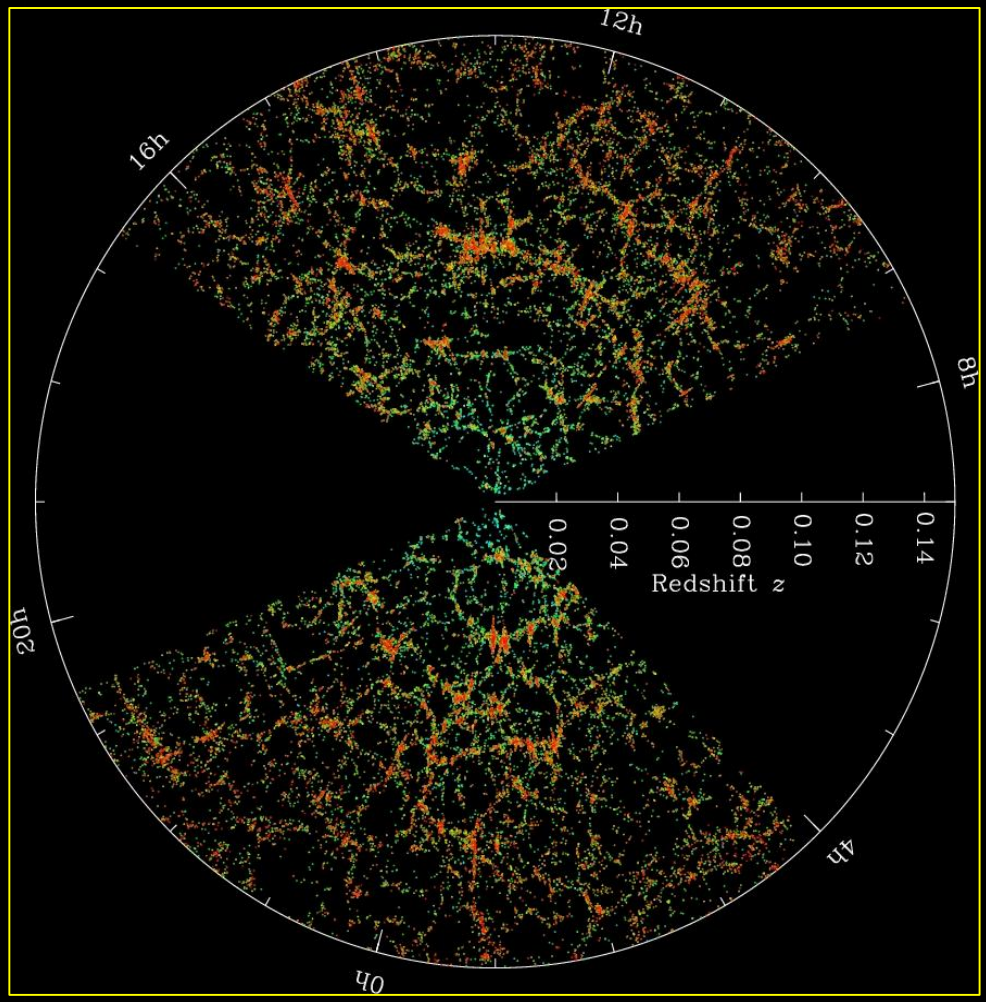




Cosmic Microwave Background (CMB)

Progress in Observational Cosmology

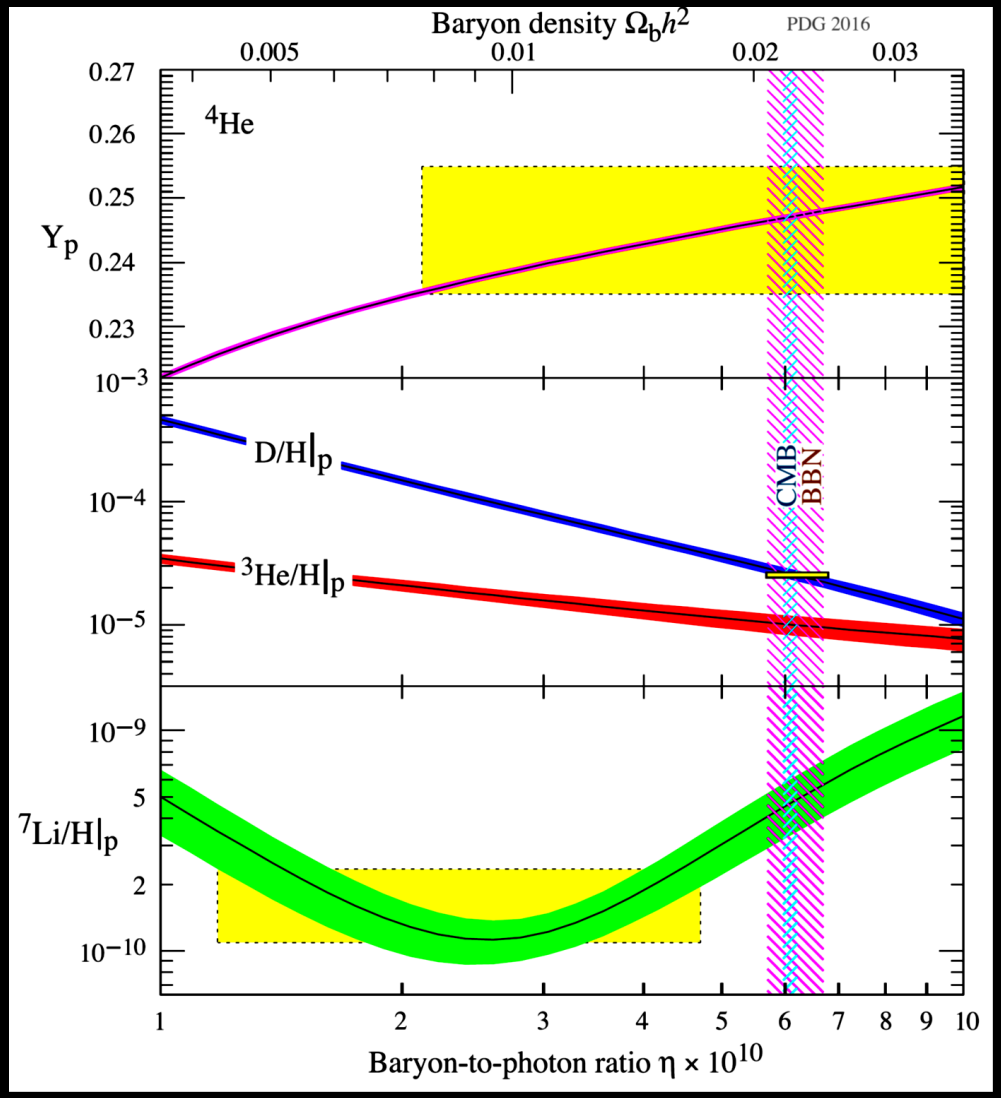


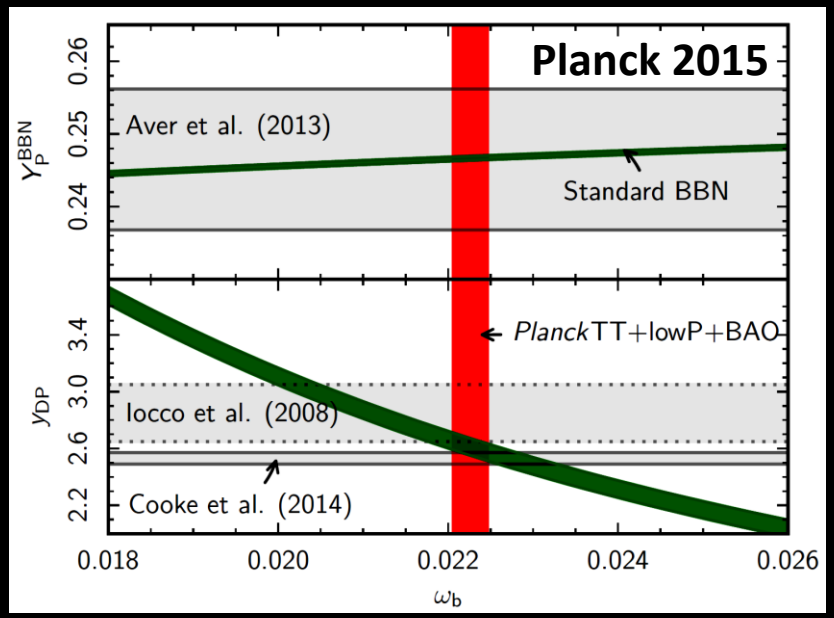


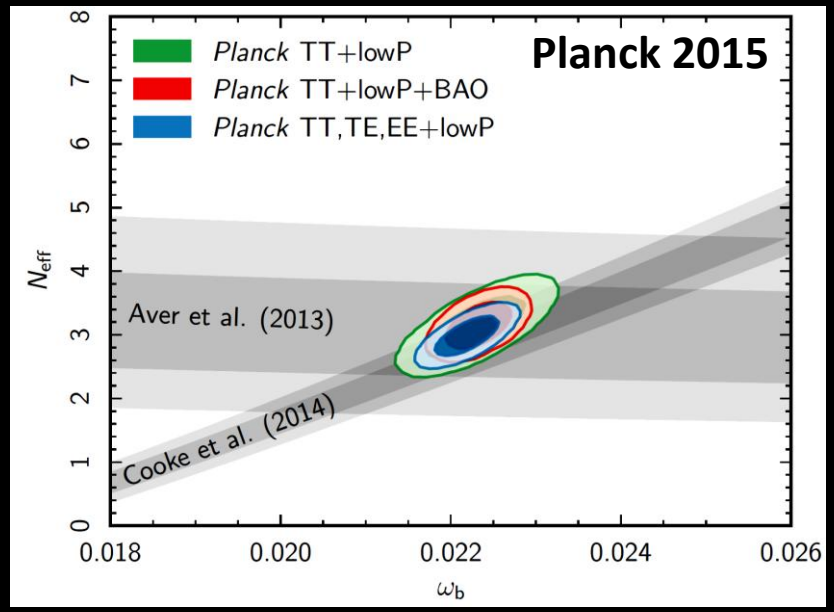
Cosmic Microwave Background (CMB)

Large Scale Structure (LSS) from Sloan Digital Sky Survey (SDSS)

Progress in Observational Cosmology

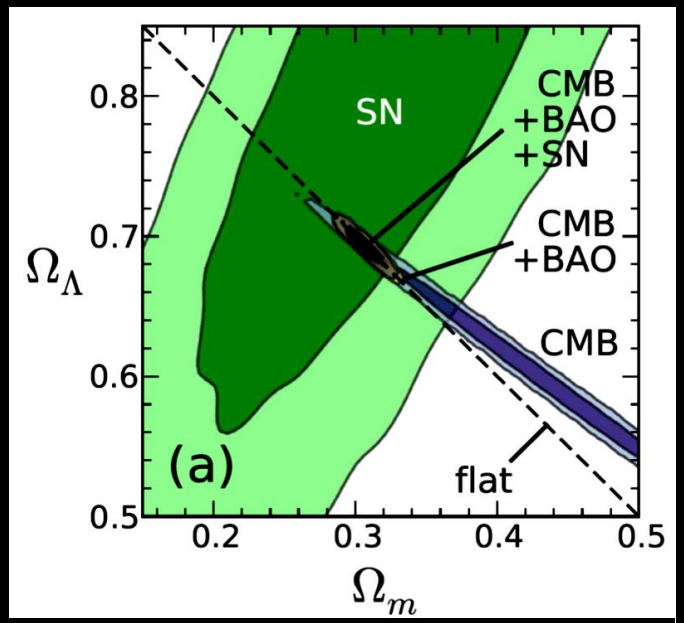


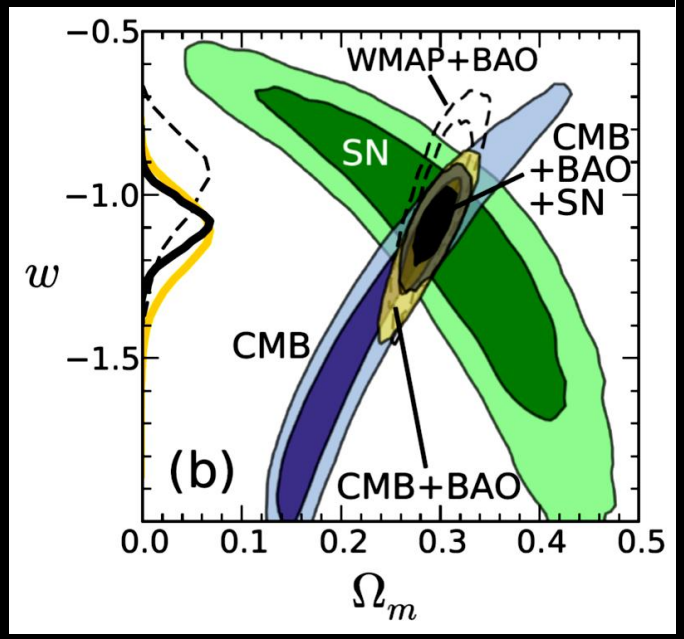




Big Bang Nucleosynthesis (BBN) and CMB

Standard Model of Cosmology



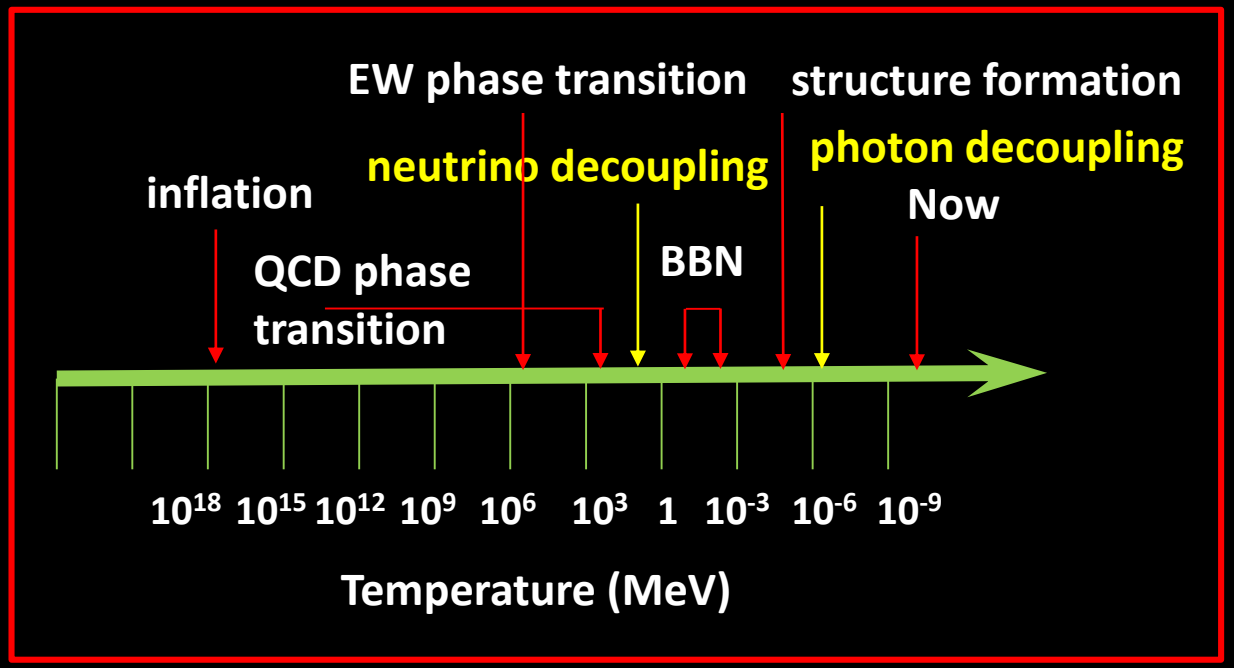


PDG 2016	*Planck*+WP +highL	*Planck*+WP +highL+BAO	*WMAP*9+eCMB +BAO
$\Omega_b h^2$	0.02207 ± 0.00027	0.02214 ± 0.00024	0.02211 ± 0.00034
$\Omega_c h^2$	0.1198 ± 0.0026	0.1187 ± 0.0017	0.1162 ± 0.0020
$100\,\theta_{MC}$	1.0413 ± 0.0006	1.0415 ± 0.0006	–
n_s	0.958 ± 0.007	0.961 ± 0.005	0.958 ± 0.008
τ	$0.091^{+0.013}_{-0.014}$	0.092 ± 0.013	$0.079^{+0.011}_{-0.012}$
$\ln(10^{10}\Delta^2_{\mathcal{R}})$	3.090 ± 0.025	3.091 ± 0.025	3.212 ± 0.029
h	0.673 ± 0.012	0.678 ± 0.008	0.688 ± 0.008
σ_8	0.828 ± 0.012	0.826 ± 0.012	$0.822^{+0.013}_{-0.014}$
Ω_m	$0.315^{+0.016}_{-0.017}$	0.308 ± 0.010	0.293 ± 0.010
Ω_Λ	$0.685^{+0.017}_{-0.016}$	0.692 ± 0.010	0.707 ± 0.010

Cosmic Neutrino Background (CvB)

- **Indirect evidence from BBN, CMB and LSS**
- **How to detect CvB in terrestrial experiments?**

Formation of CνB



- ν in thermal equilibrium

@ high temperature

$$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$$
$$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$$
$$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$$
$$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$$
$$e^+ e^- \leftrightarrow \gamma\gamma$$

$$T_\nu = T_e = T_\gamma$$

- neutrino decoupling

$\Gamma < H$ @ $T \sim 1$ MeV

Weak interactions

$$\Gamma \approx G_F^2 T^5$$

Hubble expansion

$$H = \frac{\sqrt{g_*}\, T^2}{M_{pl}}$$

Fermi-Dirac spectrum

- photon reheating

@ $T < m_e$

$$e^+ e^- \leftrightarrow \gamma\gamma$$

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$$

- Basic properties of **CνB**
  - $T_0 = 1.95$ K and $\langle p \rangle = 3T_0 = 5 \times 10^{-4}$ eV
  - number density $n = 56$ cm^{-3} per species

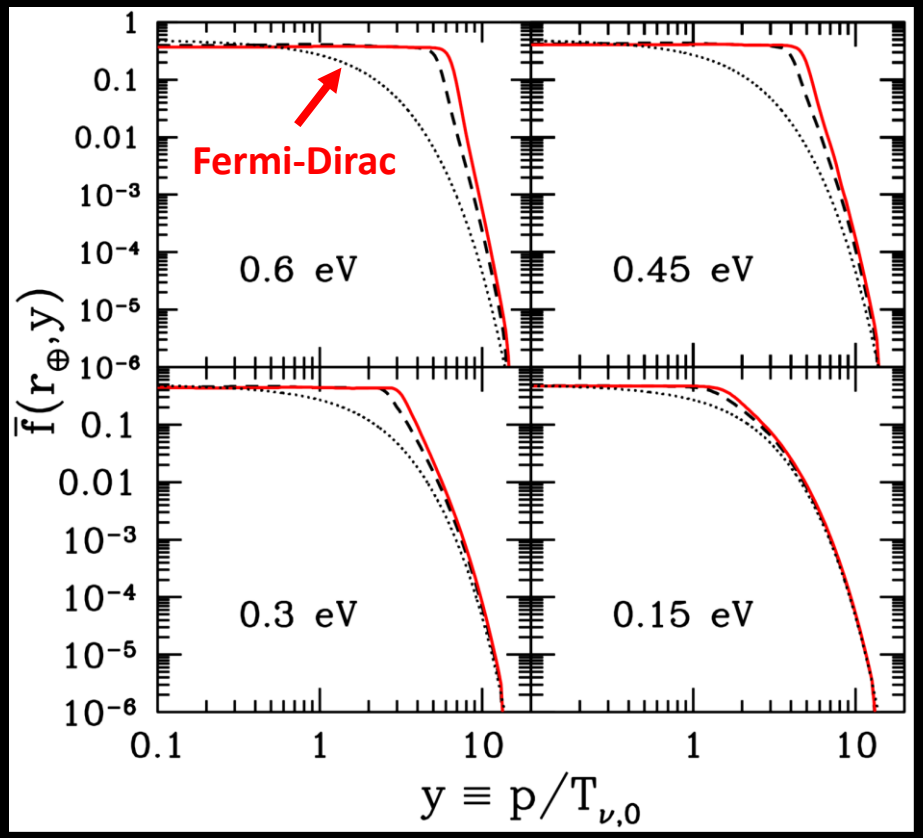
Neutrino Clustering

Neutrinos in the gravitational potential of CDM halos

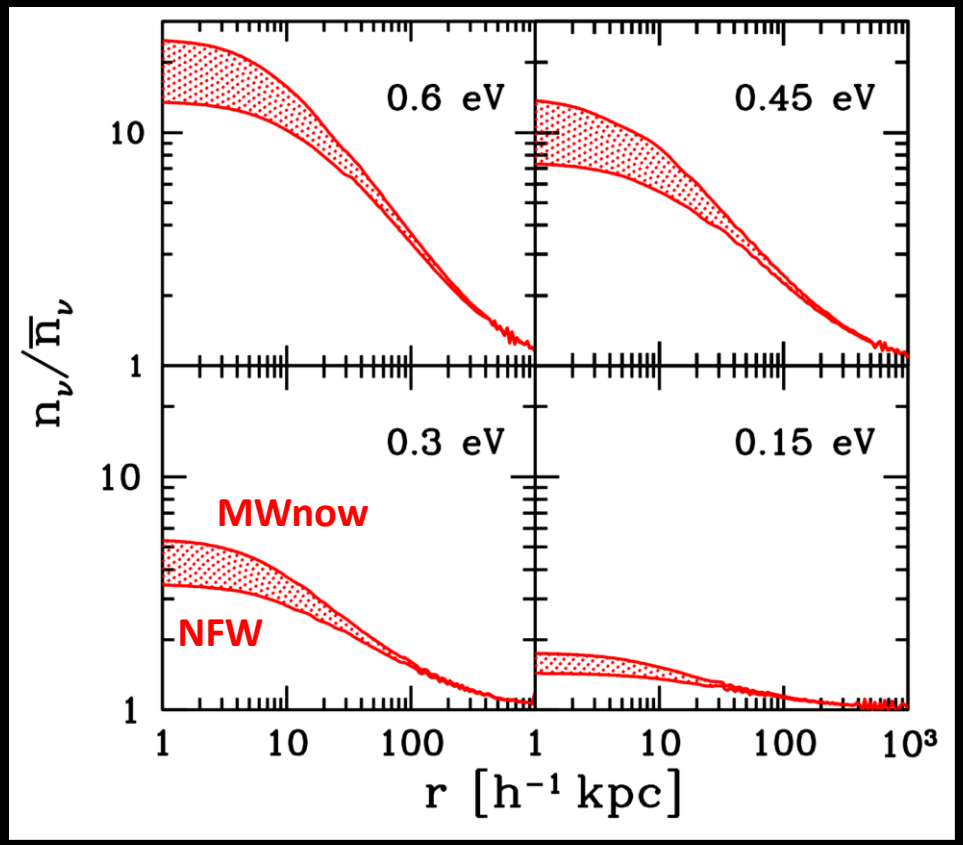
- Input CDM halo profiles (Navarro-Frenk-White)
- Neutrinos are treated as perturbations

Singh, Ma, 03;
Ringwald, Wong, 04

Distribution function at the Earth



Clustering in the Milky Way



At the Earth, larger by a factor of 1 to 20

Prospects for CνB Detection

- Direct evidence for CνB, 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

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \simeq 1.945\ \mathrm{K}$$

Mean momentum today

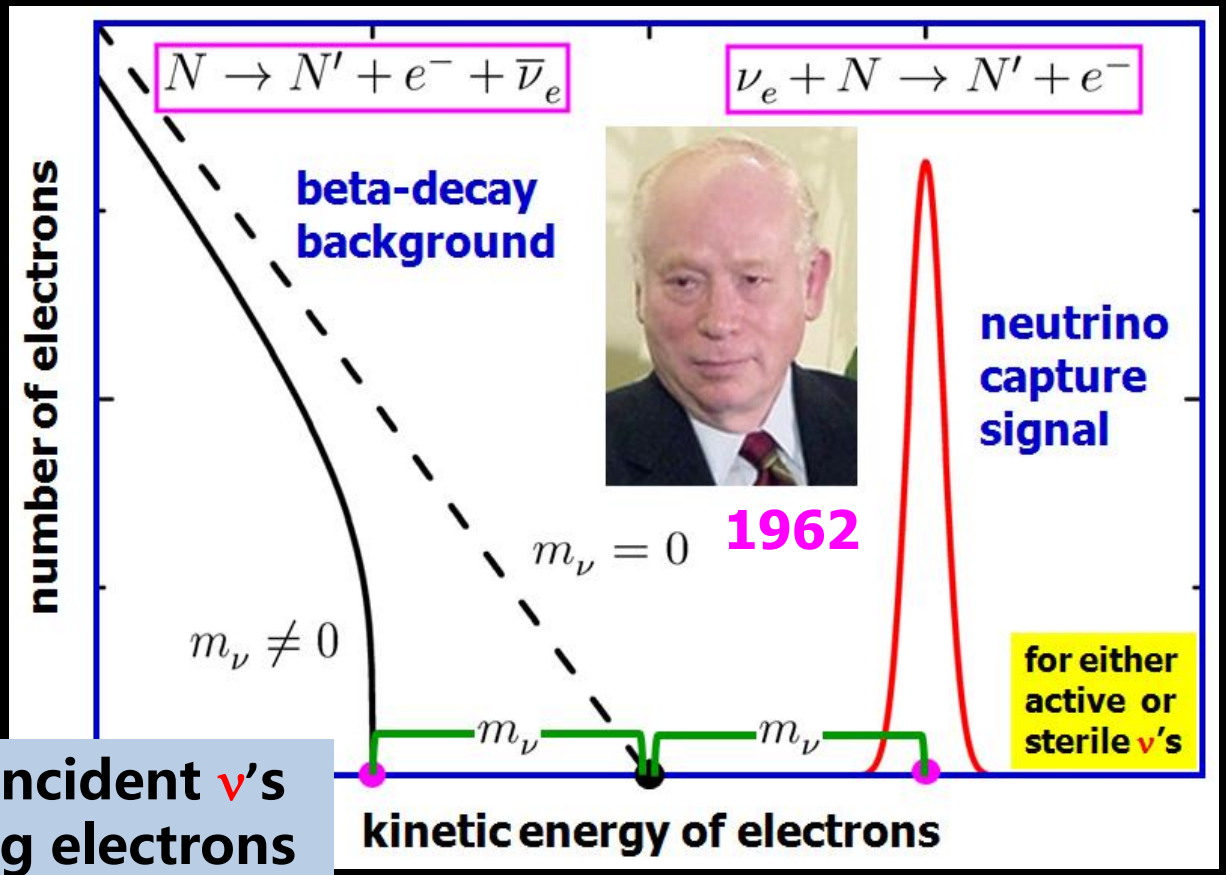
$$\langle p_\nu \rangle \simeq 3.151 T_\nu \simeq 5.281 \times 10^{-4}\ \mathrm{eV}$$

At least 2 ν's cold today

NON-relativistic ν's!

(Irvine & Humphreys, 83)

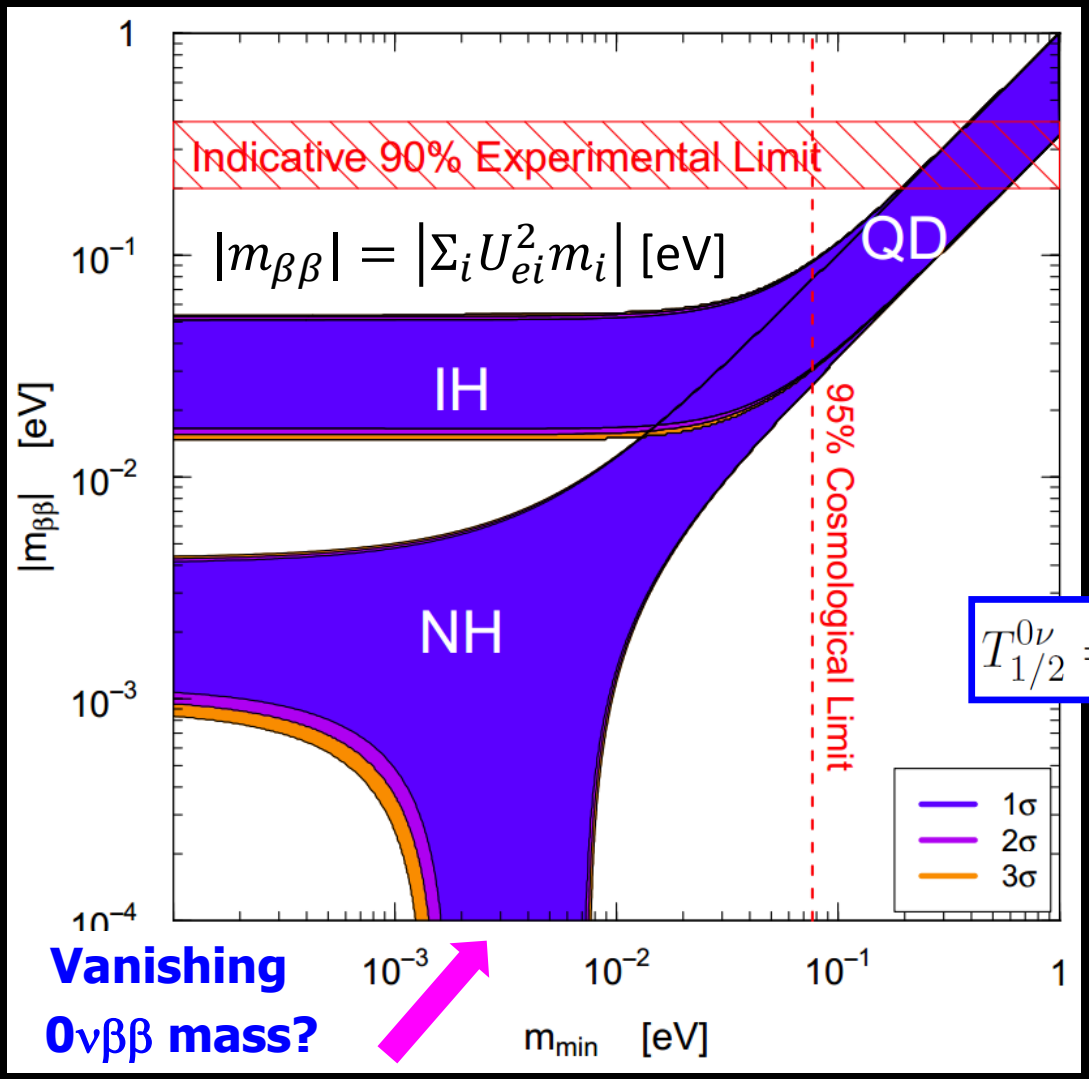
Relic neutrino capture on β-decaying nuclei

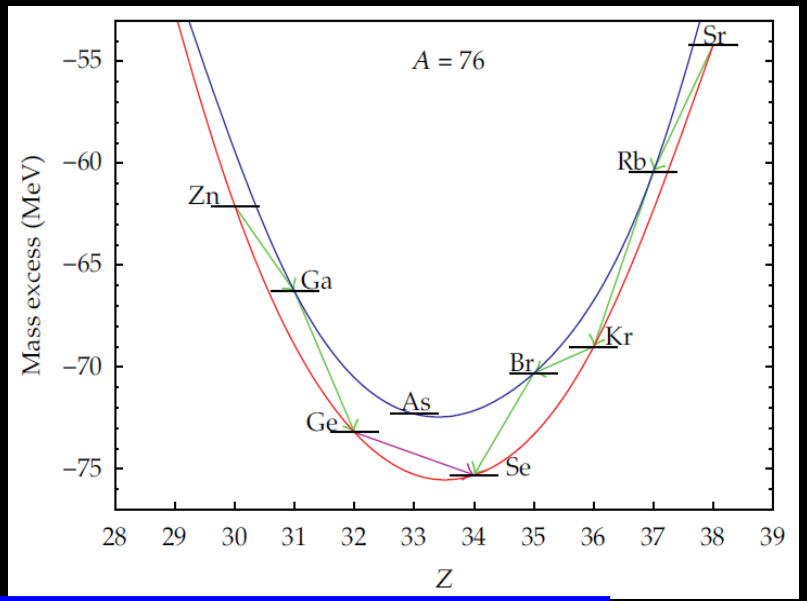


no energy threshold on incident ν's

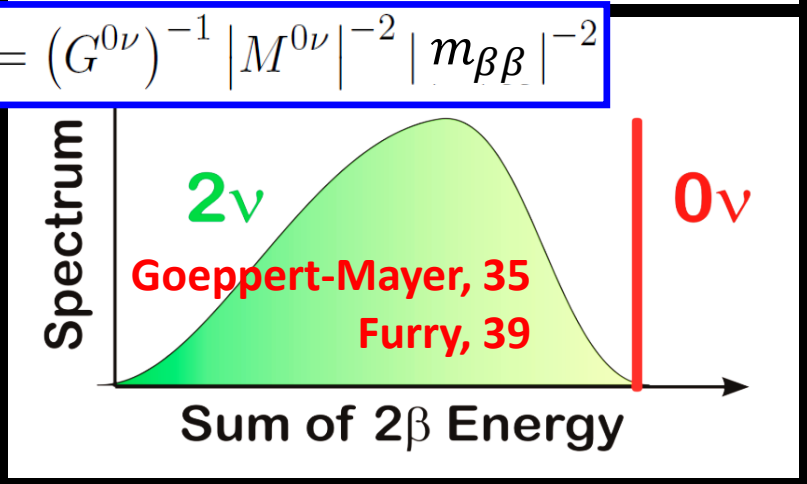
mono-energetic outgoing electrons

Neutrinoless Double Beta Decays



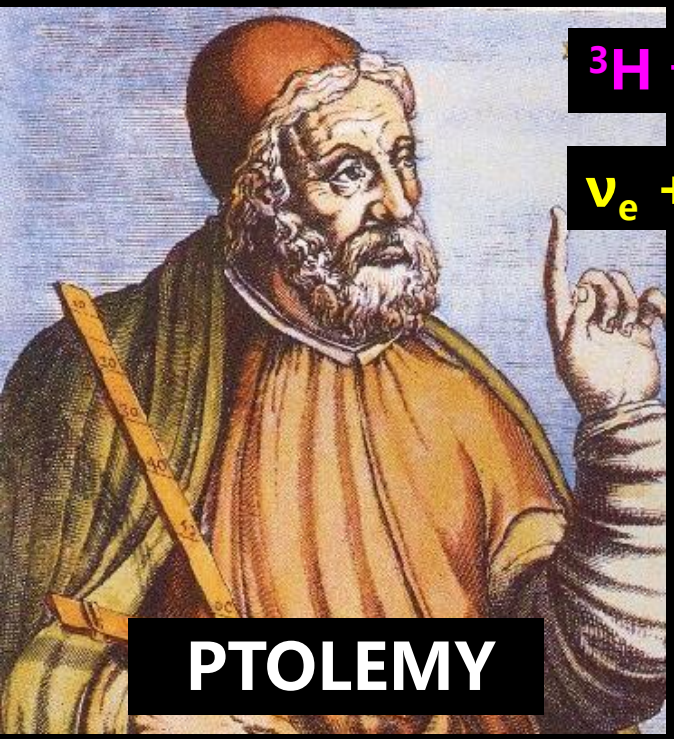


$$T_{1/2}^{0\nu} = \left(G^{0\nu}\right)^{-1} \left|M^{0\nu}\right|^{-2} \left|m_{\beta\beta}\right|^{-2}$$



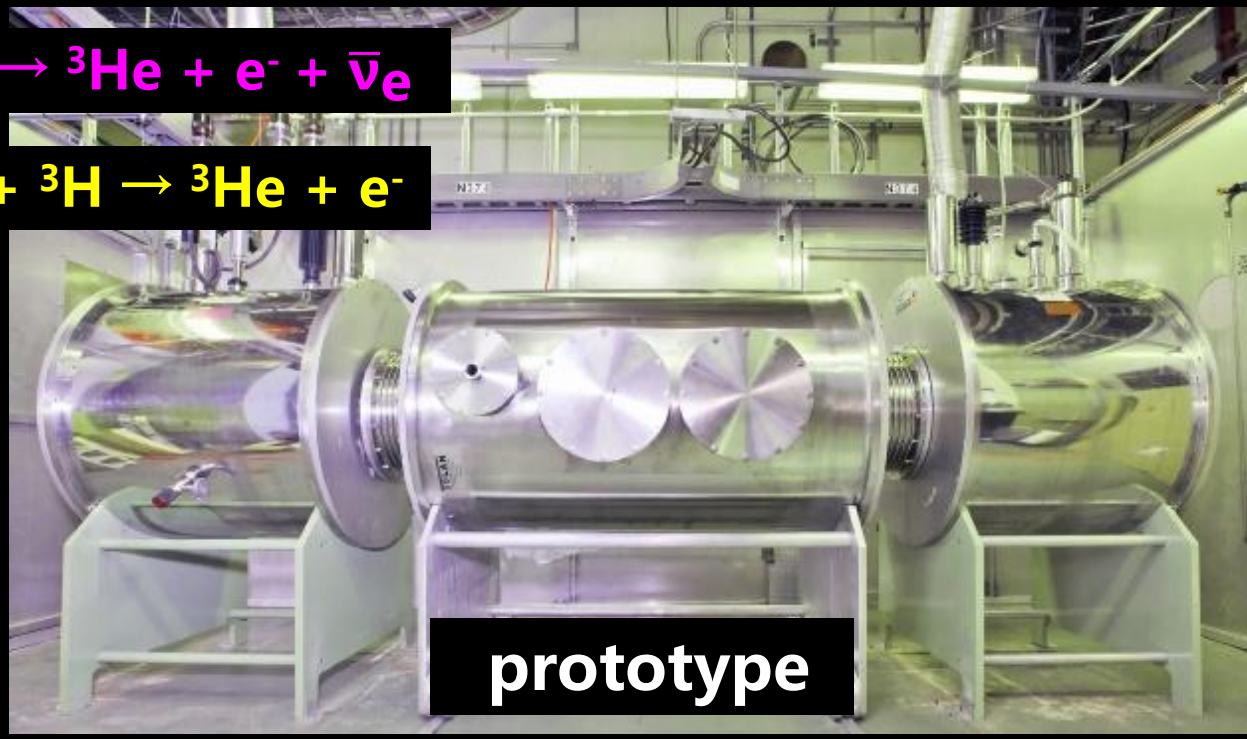
Three possible ways to distinguish between Majorana and Dirac ν's:
(a) 0νββ decays (b) EM dipole moments (c) Nonrelativistic behaviors

Towards a real experiment?



$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

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



★ first experiment

★ 100 g of tritium

★ graphene target

★ planned energy resolution 0.15 eV

★ CνB capture rate

$$\Gamma^{D}_{C\nu B} \sim 4\ \mathrm{yr}^{-1}$$
$$\Gamma^{M}_{C\nu B} \sim 8\ \mathrm{yr}^{-1}$$

D = Dirac

M = Majorana

PTOLEMY
Princeton **T**ritium **O**bservatory for **L**ight, **E**arly-Universe, **M**assive-Neutrino **Y**ield
(Betts et al, arXiv:1307.4738)

Detection of CνB

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

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

Note: Spin-dependent Factor

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

In the limit $v_{\nu_j} \longrightarrow 1$, the state of $s_\nu = +1/2$ cannot be captured

In the limit $v_{\nu_j} \longrightarrow 0$, both RH and LH helical states do contribute

Total Rate

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

$$\Gamma_{C\nu B} = \sum_j \left[\sigma_j\left(+\frac{1}{2}\right)v_{\nu_j}n_j(\nu_{hR}) + \sigma_j\left(-\frac{1}{2}\right)v_{\nu_j}n_j(\nu_{hL})\right]N_T$$

Number Densities of Helical States

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

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

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

Long et al., 14	Dirac Neutrinos		Majorana Neutrinos
Decoupling	$n(\nu_L) = n(z)$, $n(\bar{\nu}_R) = n(z)$,	$n(\nu_R) \approx 0$ $n(\bar{\nu}_L) \approx 0$	$n(\nu_L) = n(z)$ $n(\nu_R) = n(z)$
Nowadays	$n(\nu_{hL}) = n_0$, $n(\bar{\nu}_{hR}) = n_0$,	$n(\nu_{hR}) \approx 0$ $n(\bar{\nu}_{hL}) \approx 0$	$n(\nu_{hL}) = n_0$ $n(\nu_{hR}) = n_0$
Total Rates	$\Gamma^{D}_{C\nu B} = \bar{\sigma} n_0 N_T$	$\bar{\sigma} \approx 3.8 \times 10^{-45}\ \mathrm{cm}^2$	$\Gamma^{M}_{C\nu B} = 2\bar{\sigma} n_0 N_T$

Negligible RH Dirac Neutrinos?

Zhang, S.Z., arXiv:1509.02274

Extension of SM with RH ν's

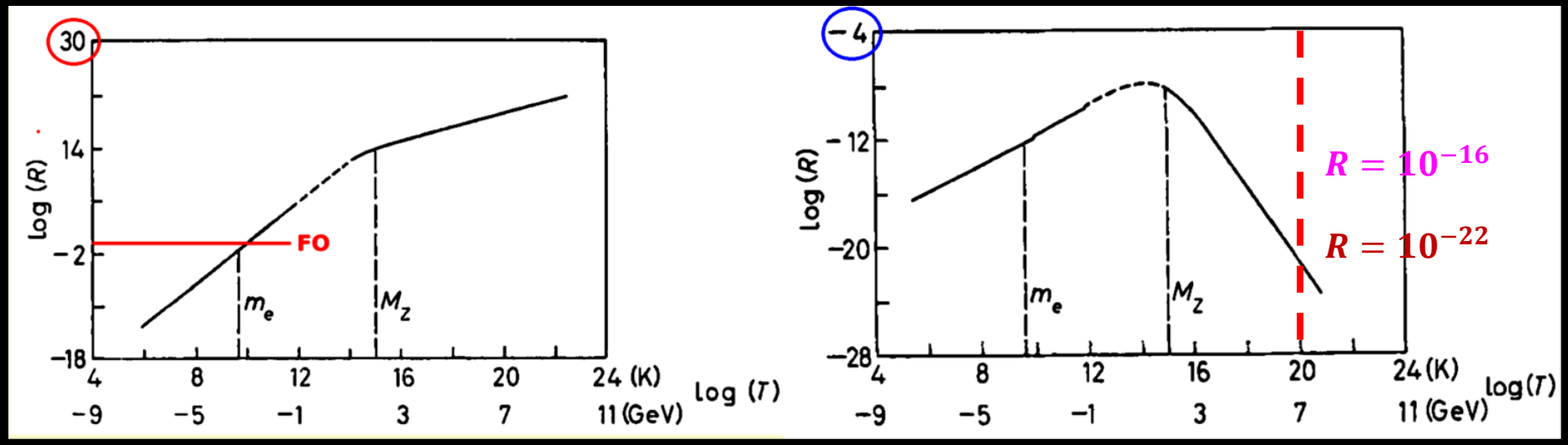
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\nu_{\alpha R}} i\partial\!\!\!/ \nu_{\alpha R} - \left[\overline{\ell_{\alpha L}} (Y_\nu)_{\alpha\beta} \tilde{H} \nu_{\beta R} + {\rm h.c.}\right]$$

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

$$\frac{dn_{\nu_{iR}}}{dt} + 3Hn_{\nu_{iR}} = \left(1 - \frac{n_{\nu_{iR}}}{n^{\rm eq}_{\nu_{iR}}}\right)\gamma_D$$

$$R = \frac{\Gamma_{\nu_R}}{H}$$

$$\gamma(H \to \overline{\nu_{iL}}\nu_{iR}) = \frac{M_H \Gamma_H T^2}{2\pi^2} K_1(M_H/T) \equiv \gamma_D$$

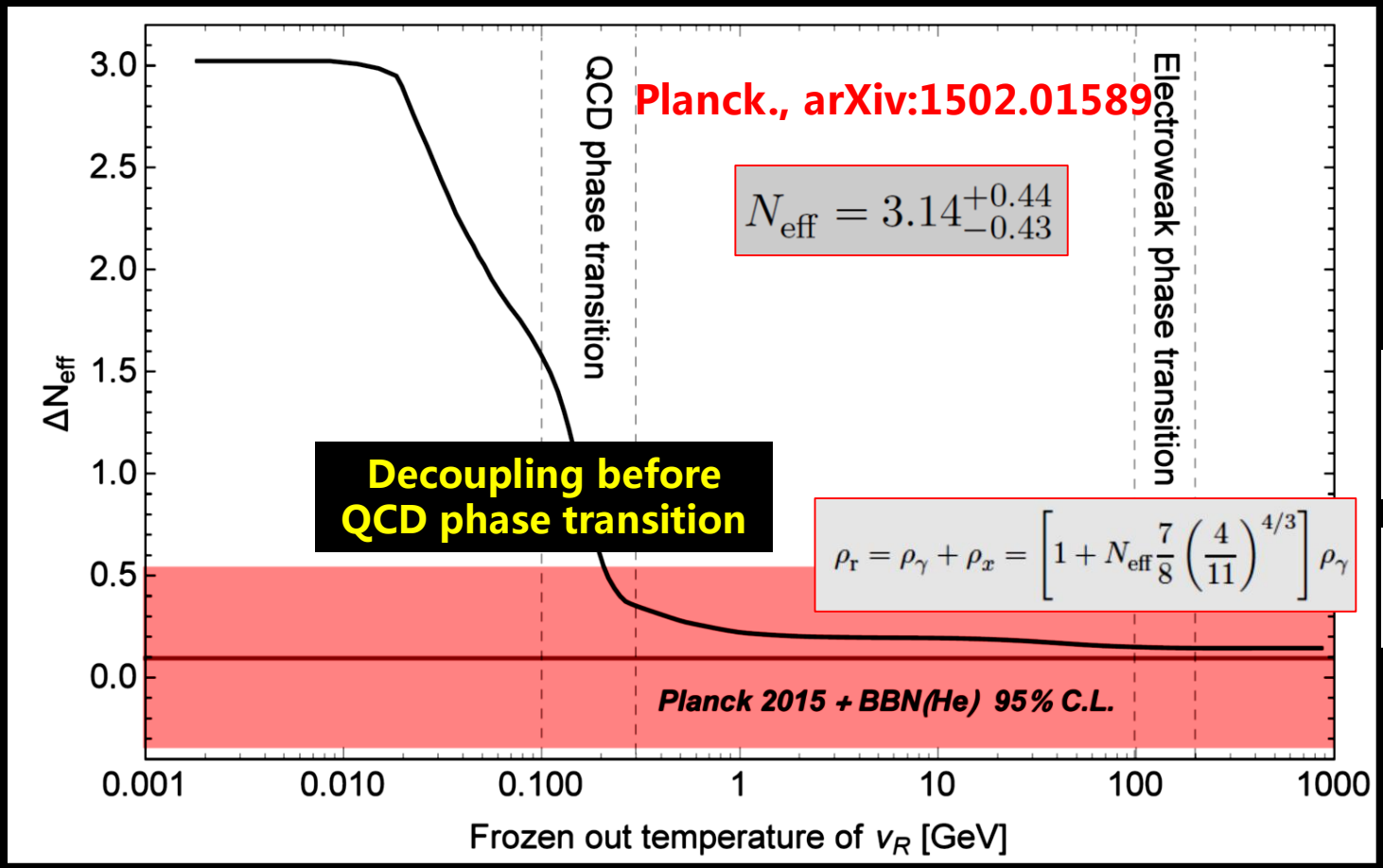


(Antonelli, Fargion & Konoplich, 81)

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

Cosmological Constraints

Zhang, S.Z., arXiv:1509.02274



Anchordoqui, Goldberg, 12;

Anchordoqui, Goldberg, Steigman, 13

$$\frac{n_{\nu_{\rm R}}(T^{\rm L}_{\rm fo})}{n_{\nu_{\rm L}}(T^{\rm L}_{\rm fo})} = \frac{g_{*s}(T^{\rm L}_{\rm fo})}{g_{*s}(T^{\rm R}_{\rm fo})}$$

$$\Delta N_{\rm eff} = \left[\frac{g_{*s}(T^{\rm L}_{\rm fo})}{g_{*s}(T^{R}_{\rm fo})}\right]^{4/3} N^{\nu}$$

$$\Delta N_{\rm eff} = 0.53$$

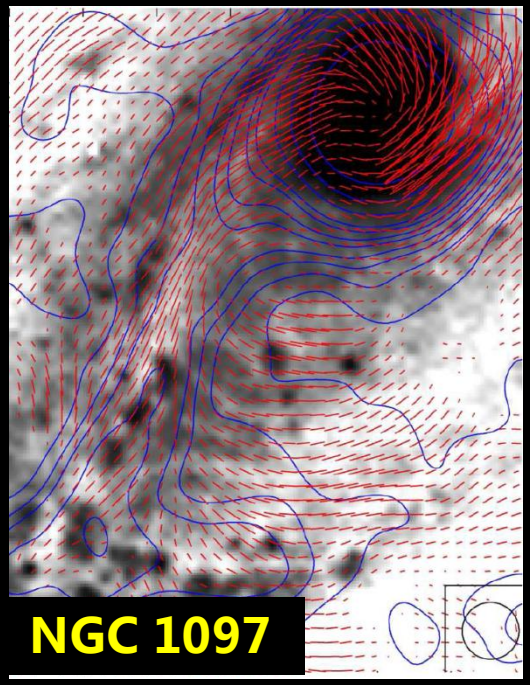
$$\frac{n(\nu_{\rm R})}{n(\nu_{\rm L})} = 0.28$$

★ Assume that RH ν's can be in thermal equilibrium with matter

★ RH ν's will be counted as extra radiation during BBN and CMB

★ QCD phase transition releases a large entropy to dilute RH ν's

Primordial Magnetic Fields



The galactic magnetic fields B ~ O(1) μG are observed

★ seed B fields ~ 10^{-21} G

★ amplified during the galaxy formation

★ phase transitions may generate seed B fields

Enqvist, astro-ph/9803196

Evolution of primordial B fields (a phenomenological model)

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

$$\Gamma_{\mathrm{L}\to\mathrm{R}} = \frac{4}{3}\mu_{\nu_i}^2 B^2 L_0 H^{-1} L_{\mathrm{W}}^{-1}$$

$\mu_{\nu_i} \sim 3\times 10^{-20}\,\mu_{\mathrm{B}}$

Decoupling before QCD phase transition (for p=1/2 and L_0=5x10^{-5}cm)

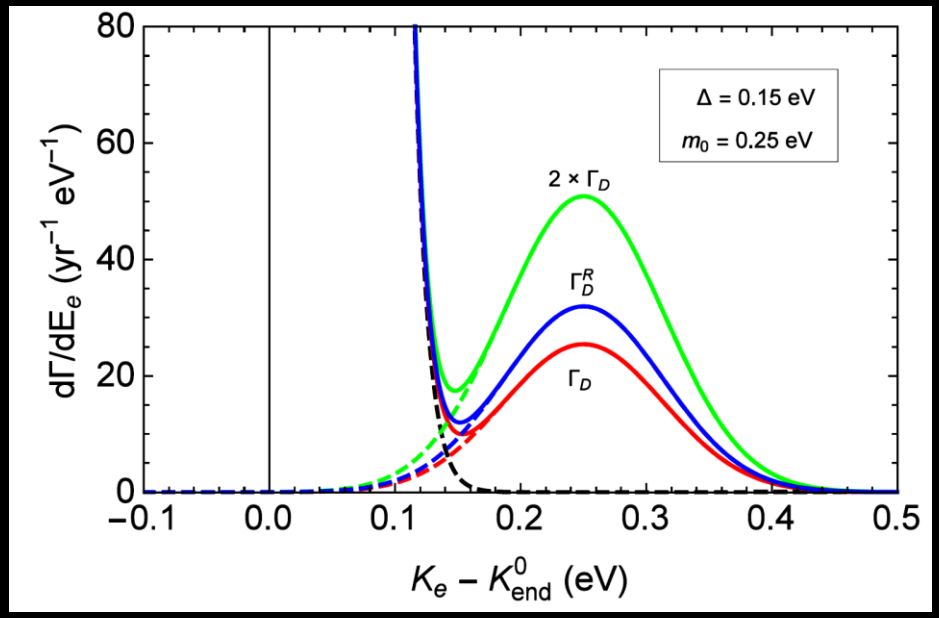
$$B_0 \lesssim 10^{26}\ \mathrm{G}\left(\frac{3\times 10^{-20}\mu_{\mathrm{B}}}{\mu_{\nu_i}}\right)$$

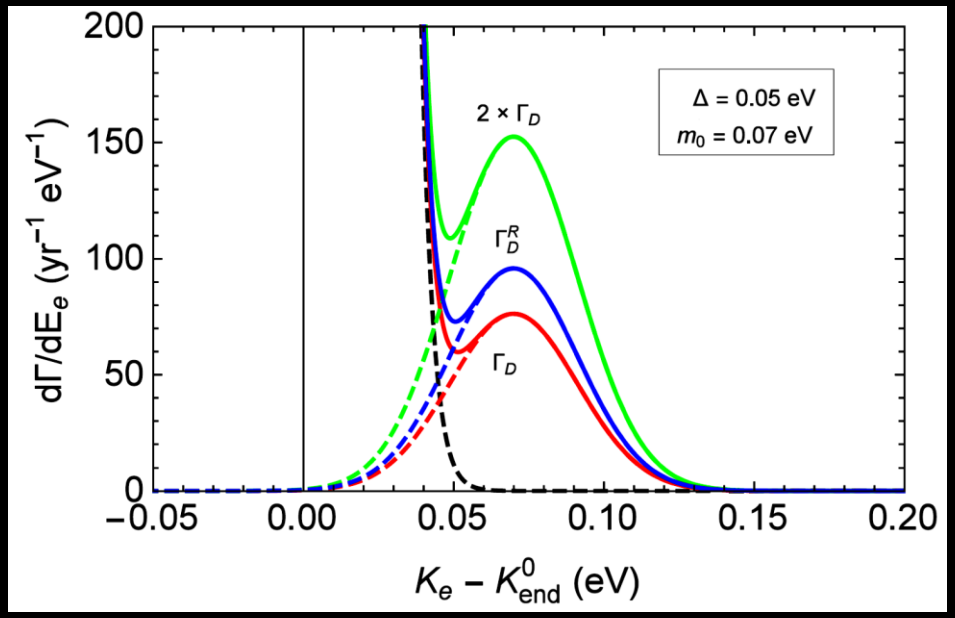
B_0=10^{24} G in EW phase transition

Vachaspati, 91; Enqvist, Rez & Semikoz, 95

Impact on Detection of CνB

J. Zhang, S.Z., arXiv:1509.02274





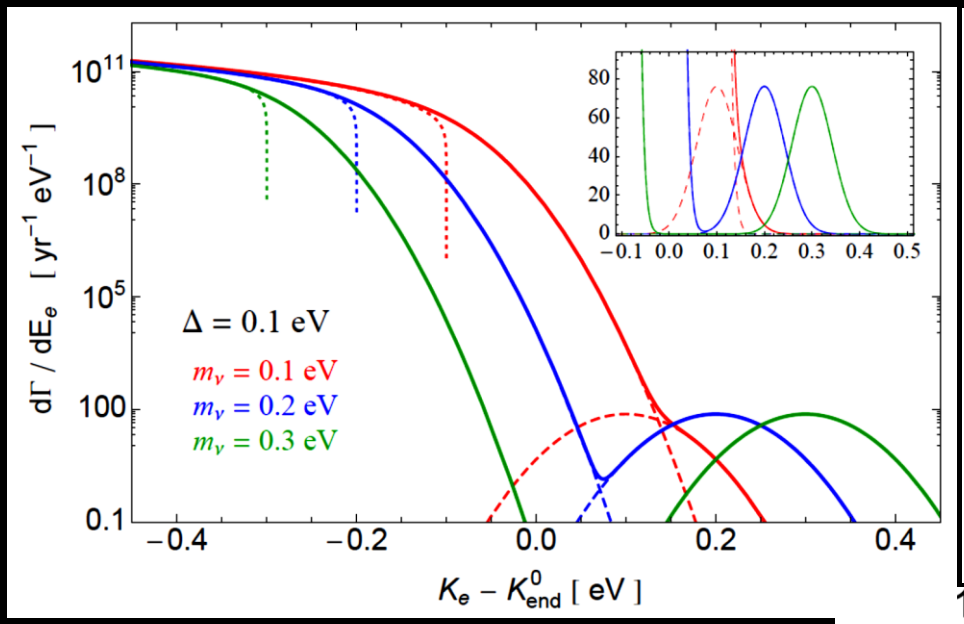
★ Main background comes from the intrinsic β-decay events of ^{3}H

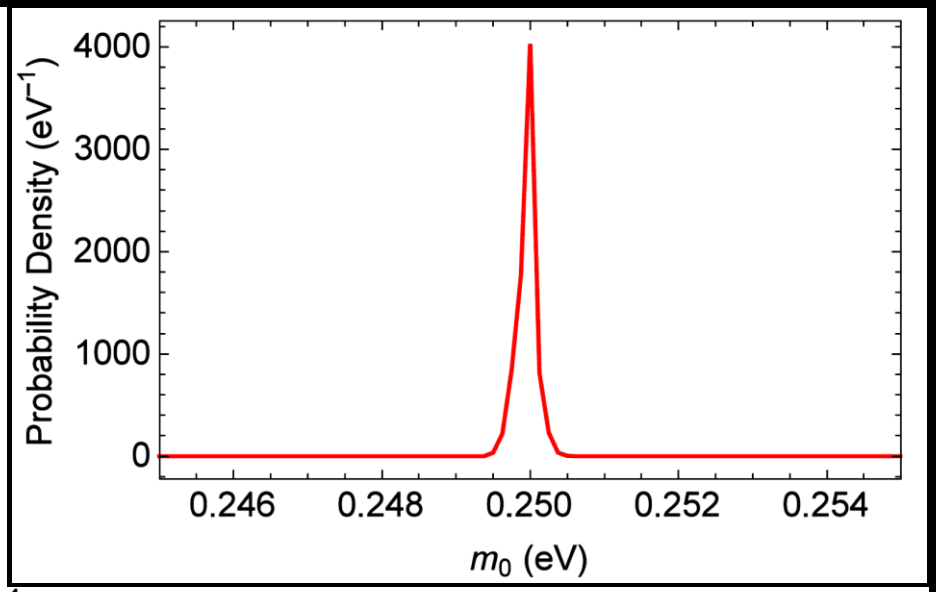
★ Energy resolution **Δ < 0.7 m_i** for signal-to-background ratio > 1

★ For the nominal setup of PTOLEMY **Δ = 0.15 eV**, only sensitive to large ν masses, which are in contradiction with the Planck bound

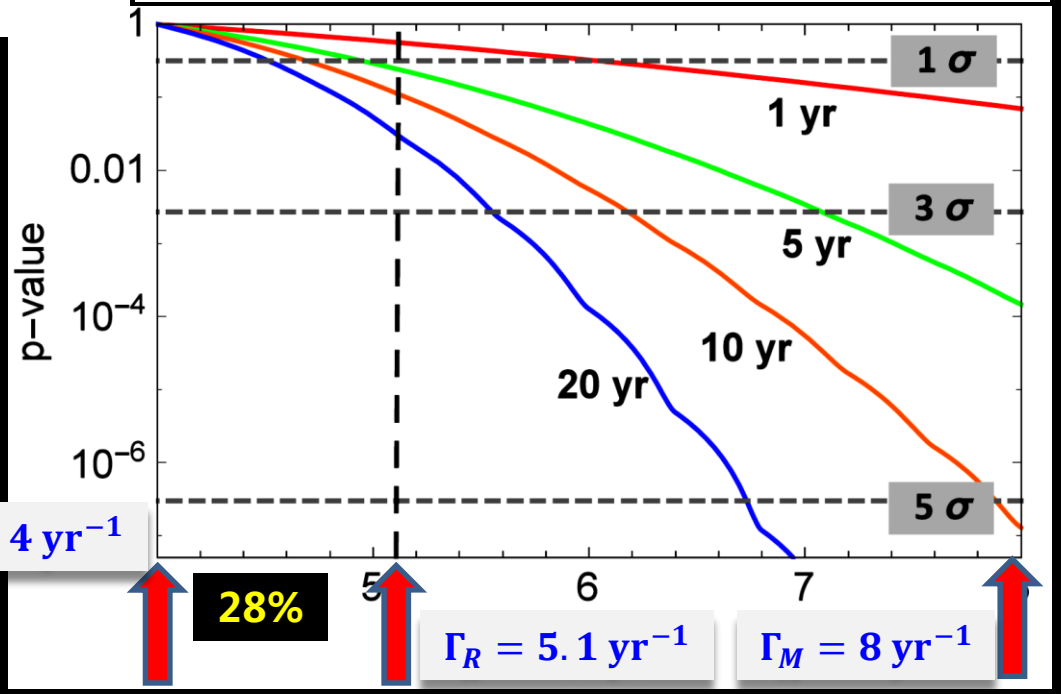
★ The presence of RH ν's changes the capture rate from 4.0 yr^{-1} to 5.1 yr^{-1} in the Dirac case (enhanced by 28%)

Impact on Detection of CνB

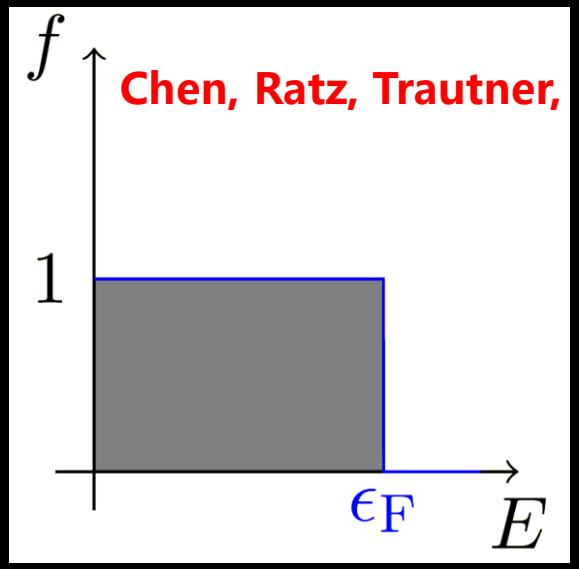




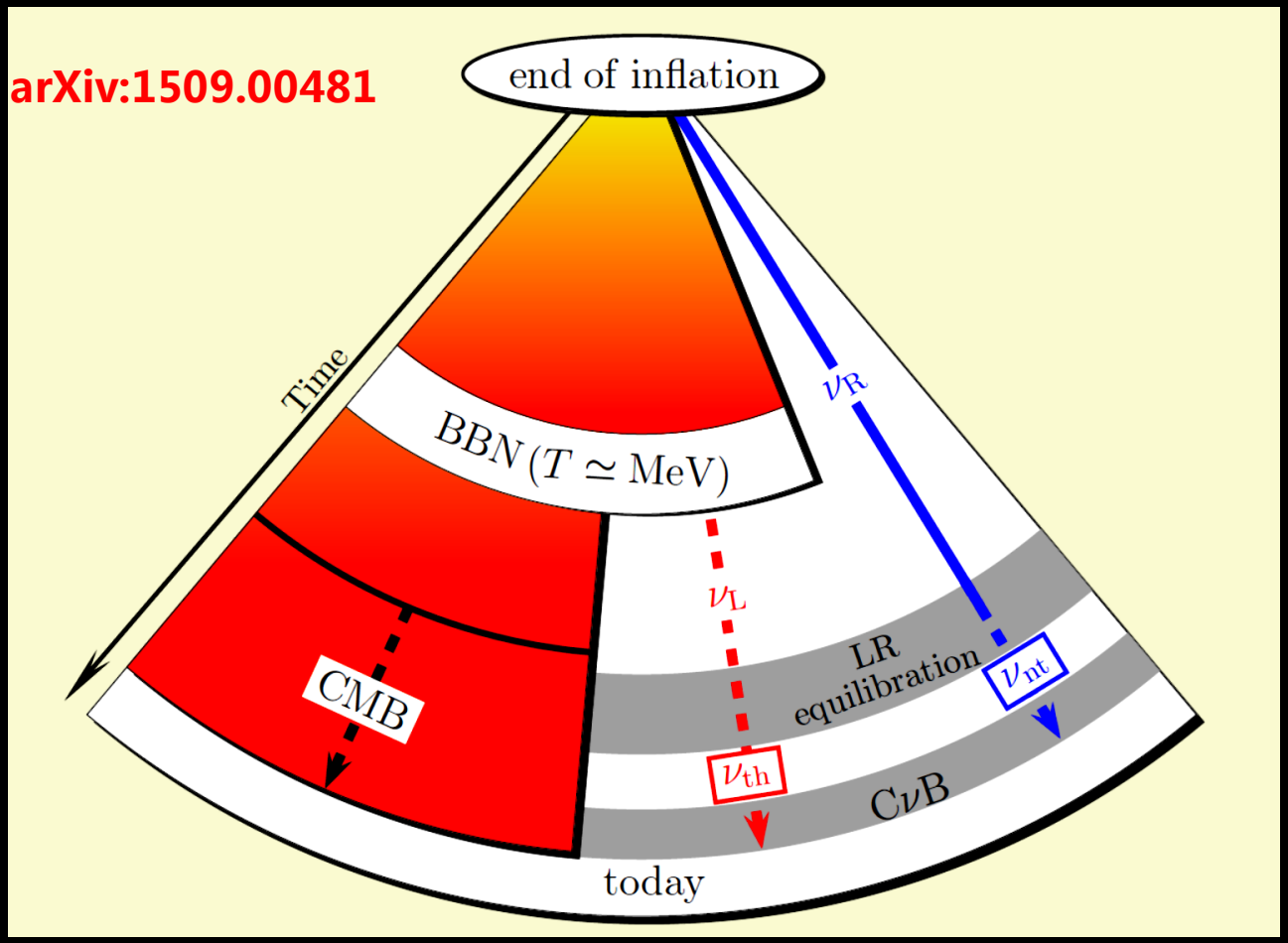
- Capture rate enhanced by 28%
- Probing RH neutrinos at the 3σ needs more than 20 years
- Majorana vs. Dirac, 3-5 years
- Precise measurement of absolute neutrino masses



Nonthermal Background of RH ν's



Chen, Ratz, Trautner, arXiv:1509.00481



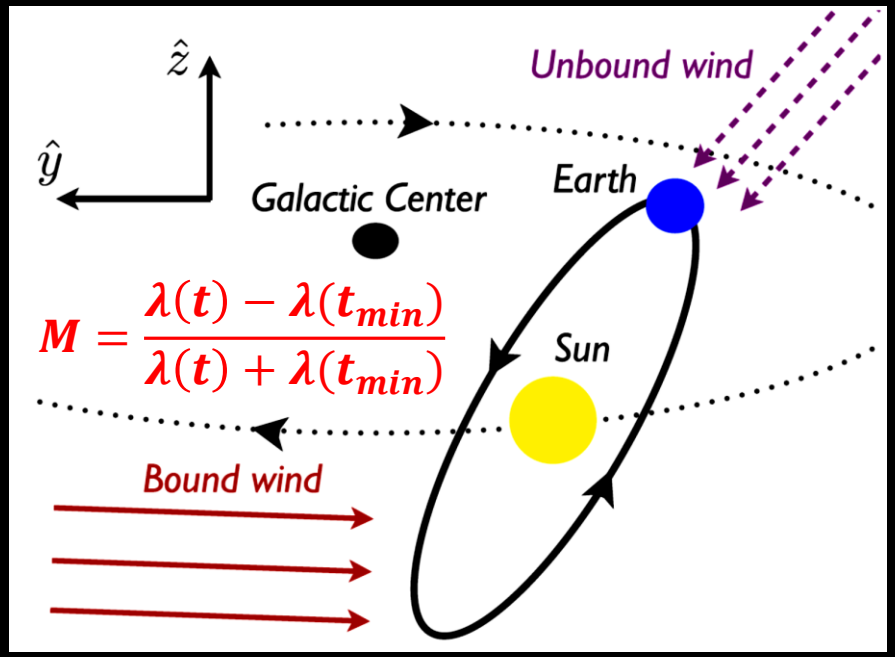
★ Degenerate RH ν's from inflaton decays

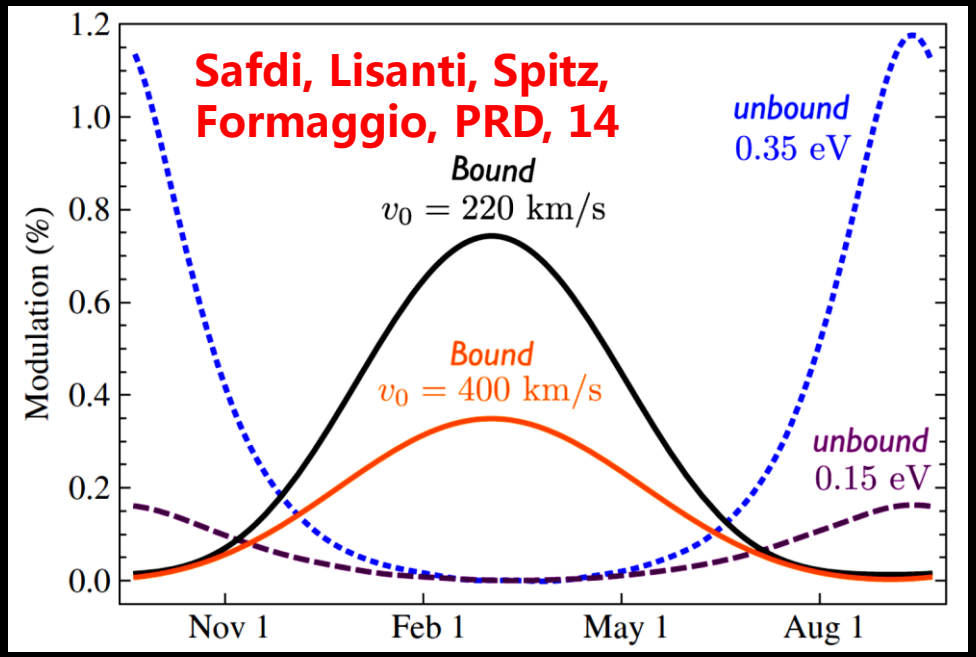
★ Concentrated on low energies, so high number density (64%)

★ Further reduce the difference between Dirac and Majorana cases

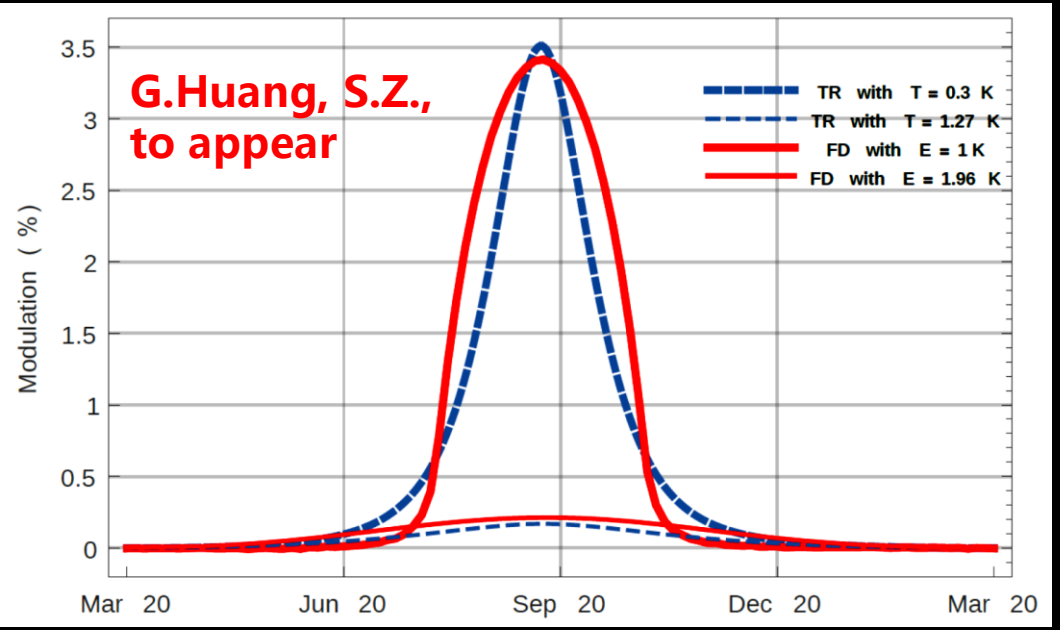
★ Gravitational clustering of massive neutrinos increases the rate & the uncertainties of CDM profiles are large, worsening the situation

Nonthermal or Thermal RH ν's: Annual Modulation



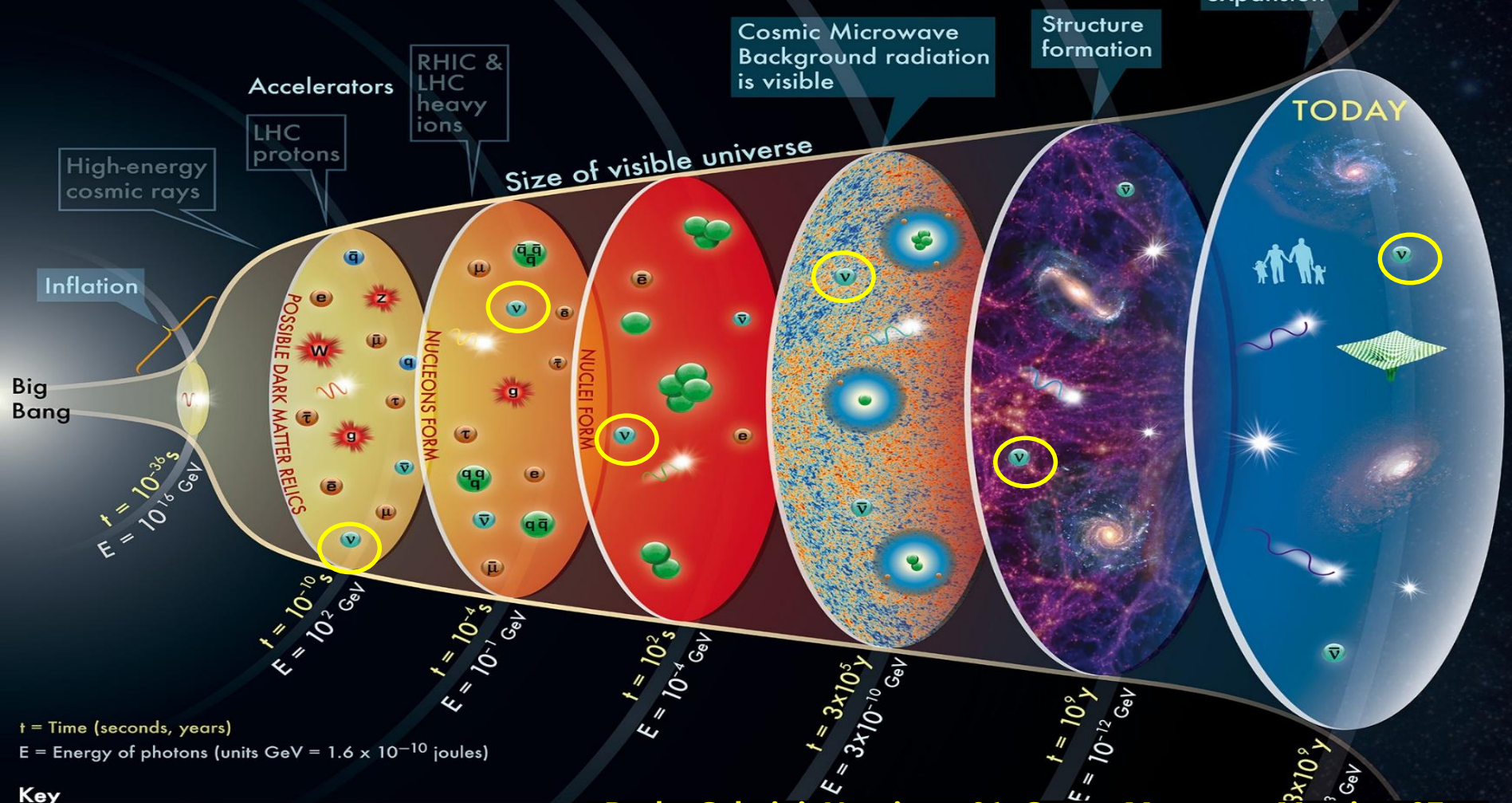


- Gravity focus by the Sun
- Assume neutrinos unbound to the Milky Way
- Large modulations for slow neutrino velocities
- Visible difference between TH and NT RH neutrinos



HISTORY OF THE UNIVERSE

Weinberg, 62; Stodolsky, 75; Lewis, 80; Irvine,Humphreys, 83; Smith, Lewis, 83



t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

Key

quark	neutrino	ion	star
gluon	bosons	atom	galaxy
electron	meson	photon	black hole
muon	baryon		
tau			

The concept for the above figure originated in a 1986 paper by Michael Turner.

Duda, Gelmini, Nussinov, 01; Cucco, Mangano, Messina, 07; Blennow, 08; Li, Luo, Xing, 11; Li, Xing, 11; Long, Lunardini, Sabancilar, 15; Lisanti, Safdi, Tully, 15; Zhang, Zhou,15; Chen, Ratz, Trautner, 15;Dias, Klinkhamer, 16; Faessler et al, 16;……

Supported by DOE