Resonant Leptogenesis

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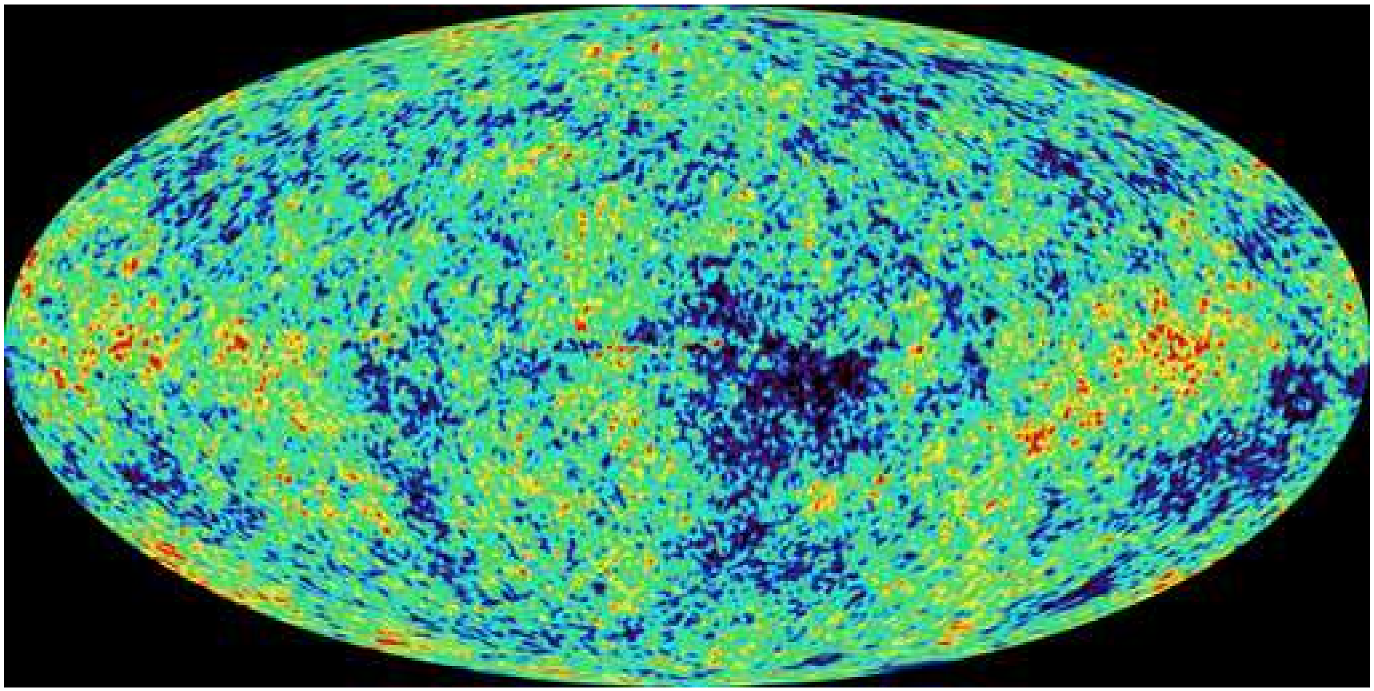
- **WMAP Results and Matter–AntiMatter Asymmetry**
- **Neutrino Masses and Mixings**
- **Resonant Leptogenesis**
- **Phenomenological Implications**
- **Conclusions**

*Talk based on A.P., PR**D56** (1997) 5431; NP**B504** (1997) 61; IJMP**A12** (1999) 1811;
A.P. and T.E.J. Underwood, NP**B692** (2004) 303; hep-ph/0506107;
A.P., hep-ph/0408103.

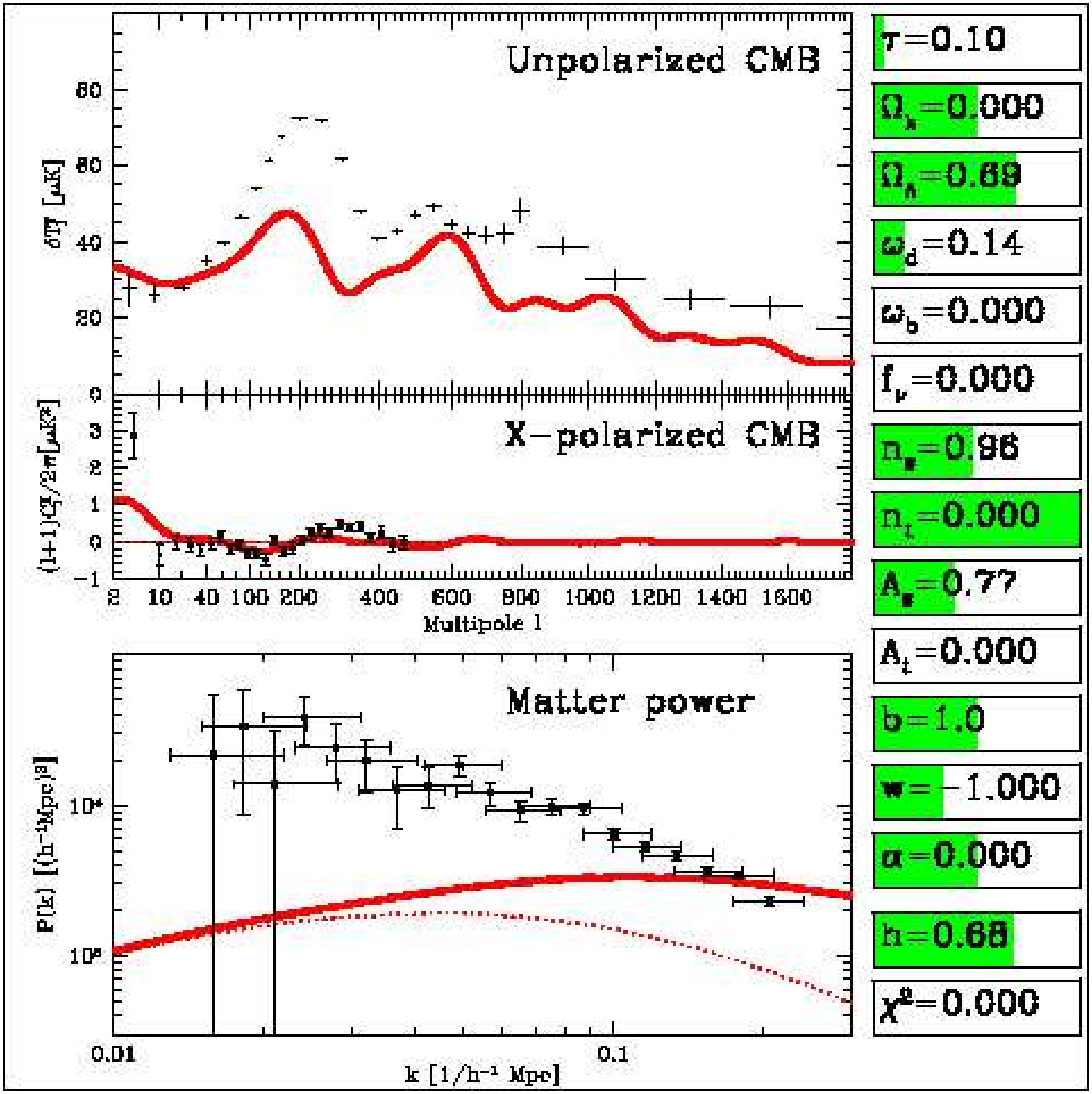
• WMAP Results and Matter–AntiMatter Asymmetry

Density perturbations as observed by WMAP



$$\frac{\delta T}{T} \sim \frac{\delta \rho}{\rho} \sim 10^{-5}$$

[From M. Tegmark's web site]



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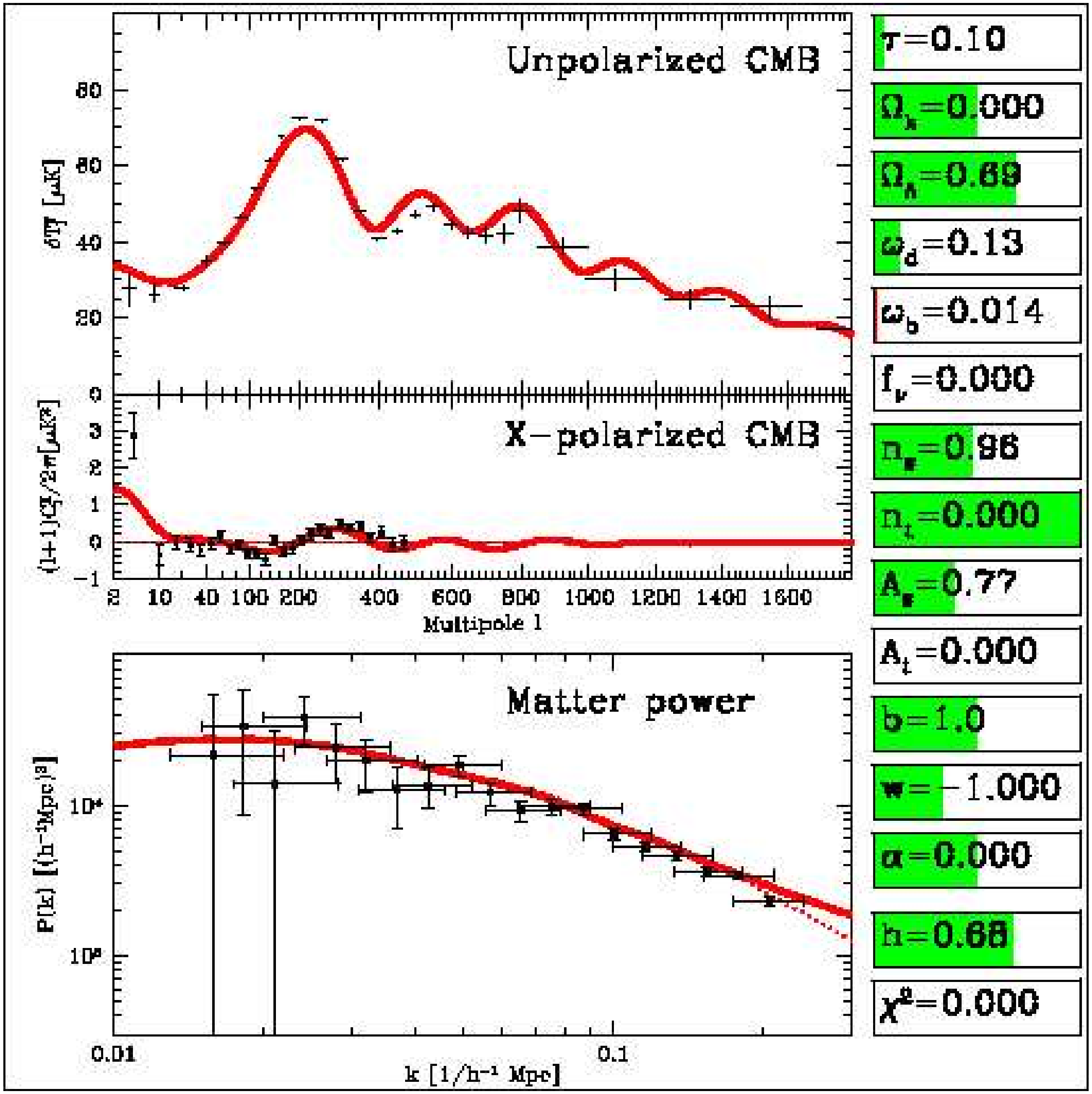

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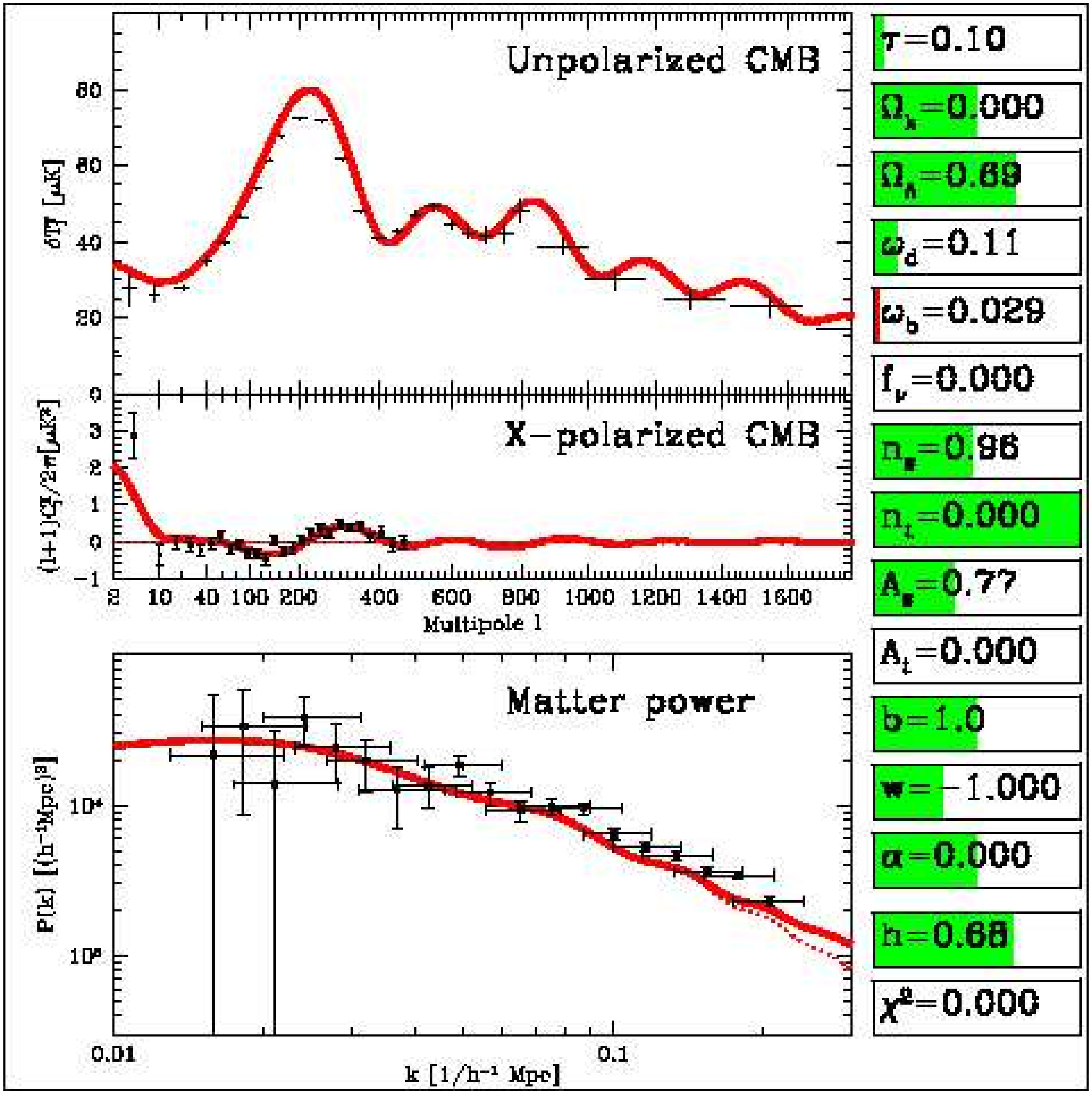

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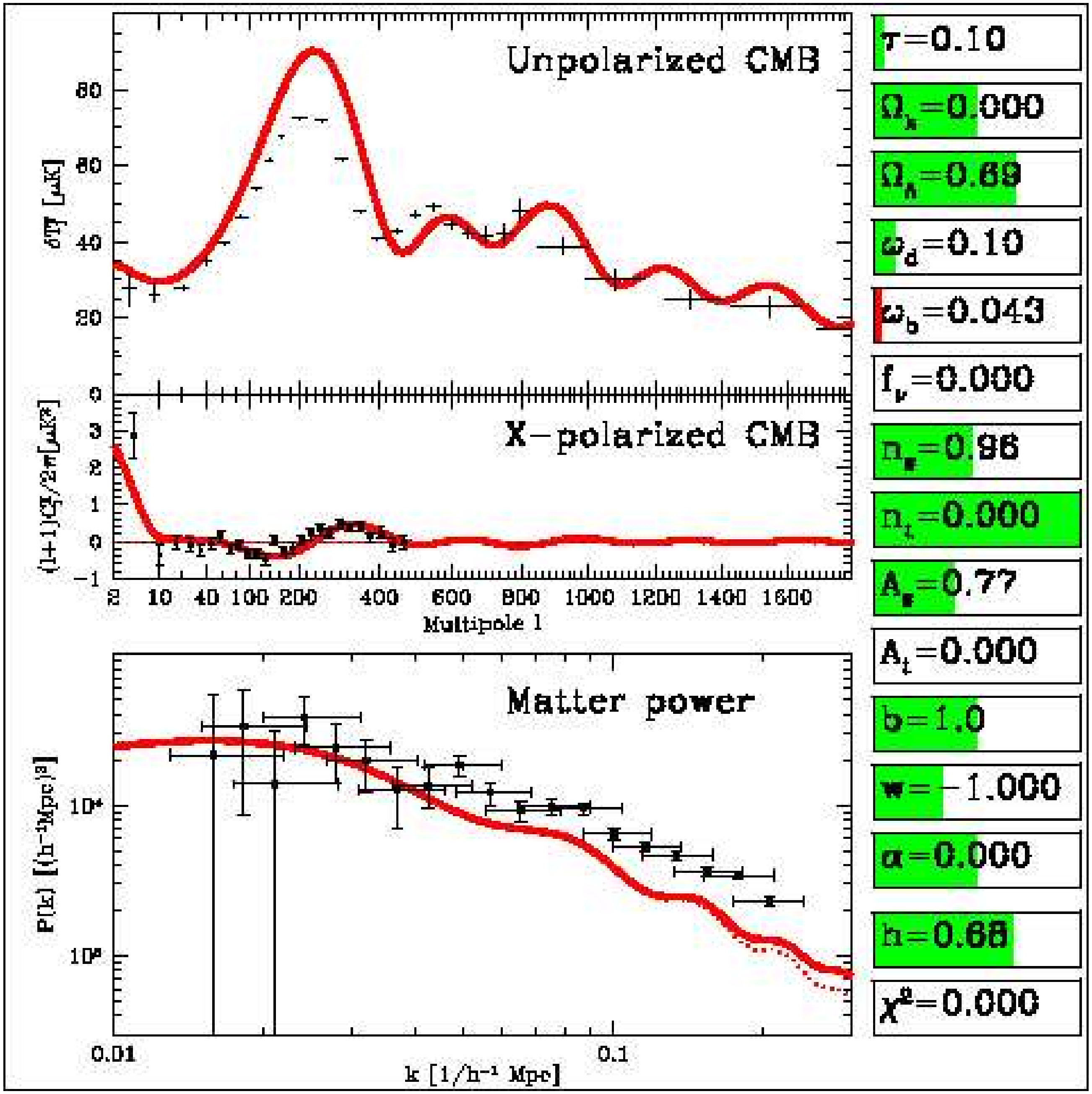
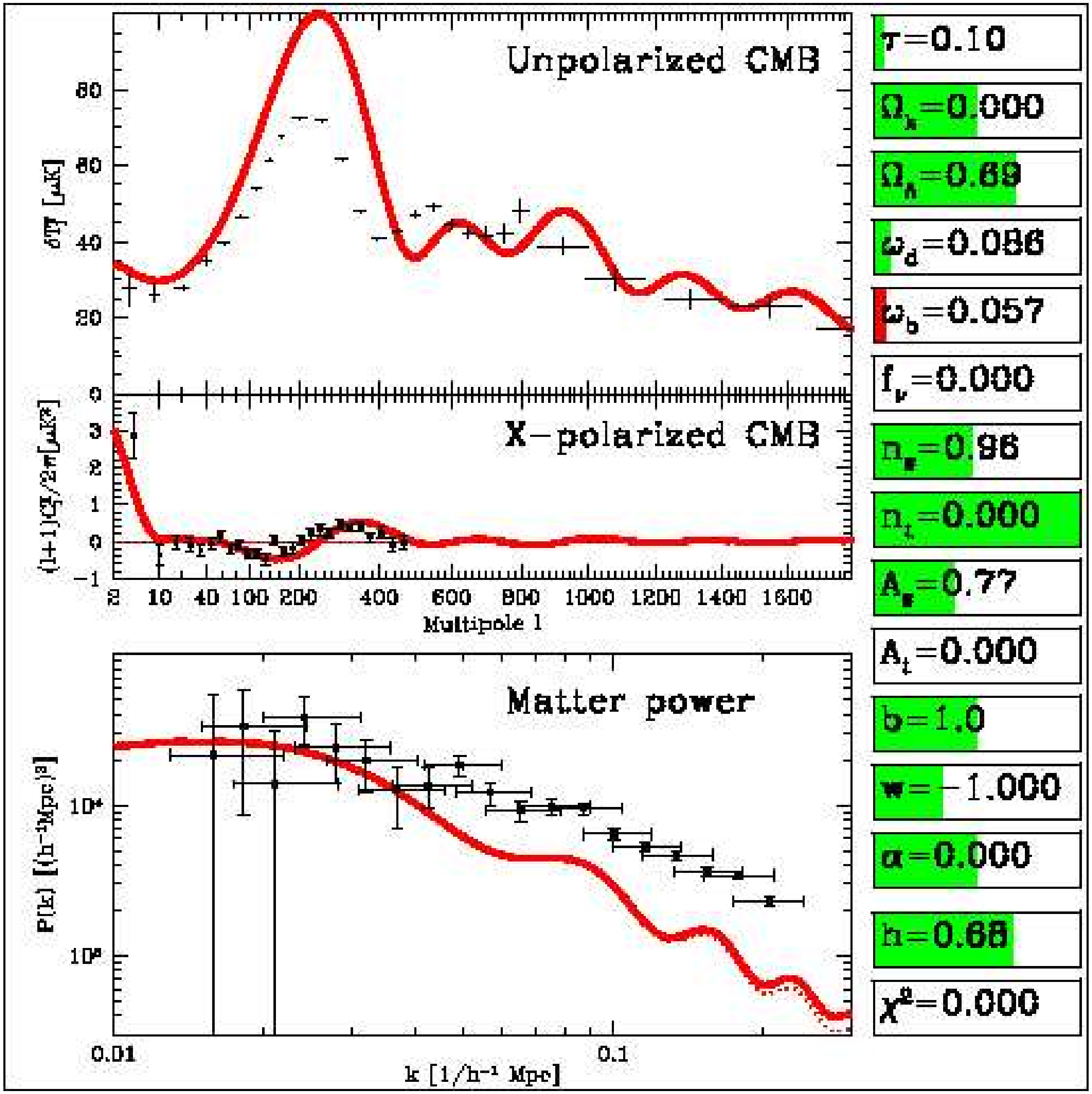


[From M. Tegmark's web site]



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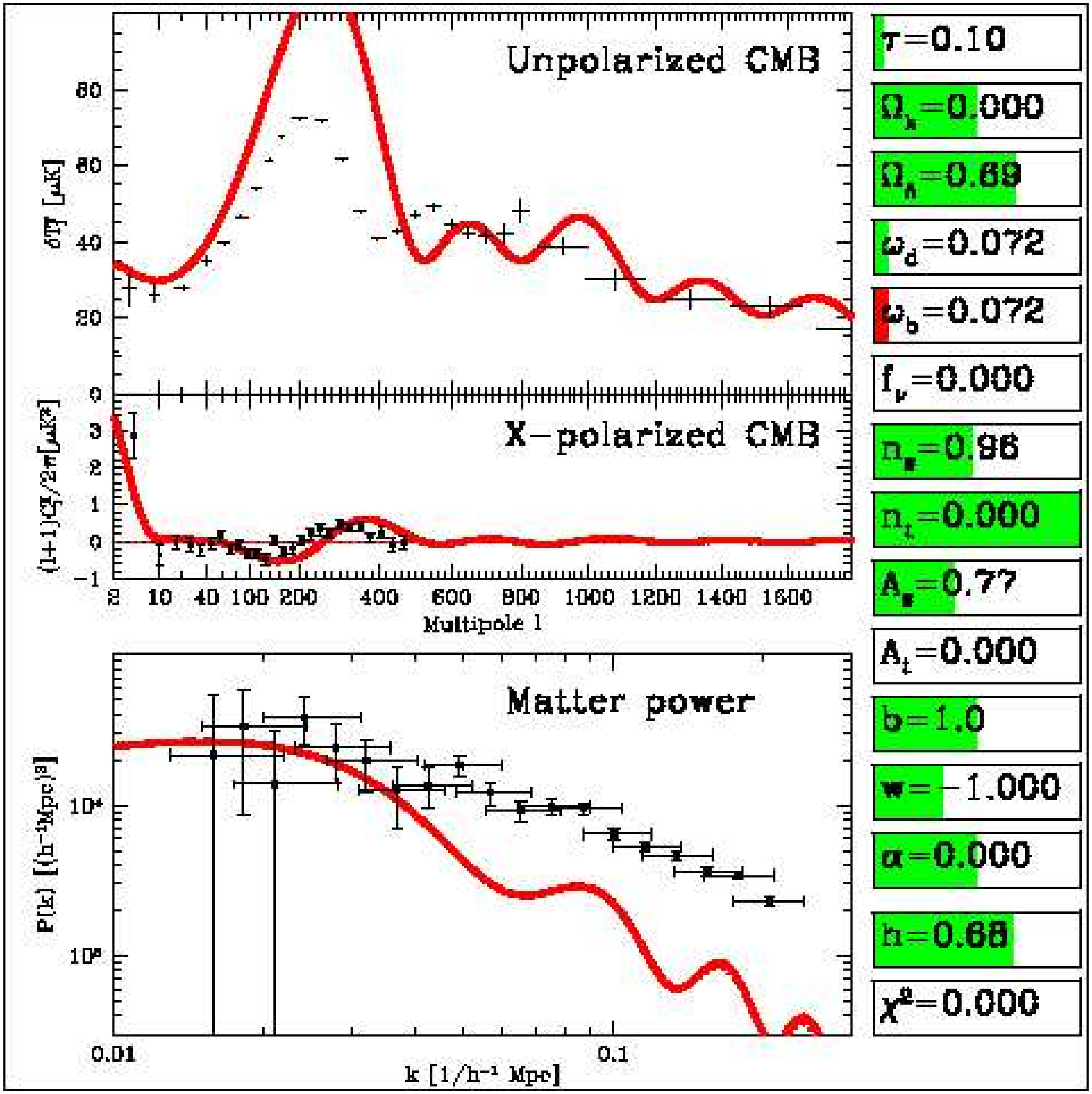

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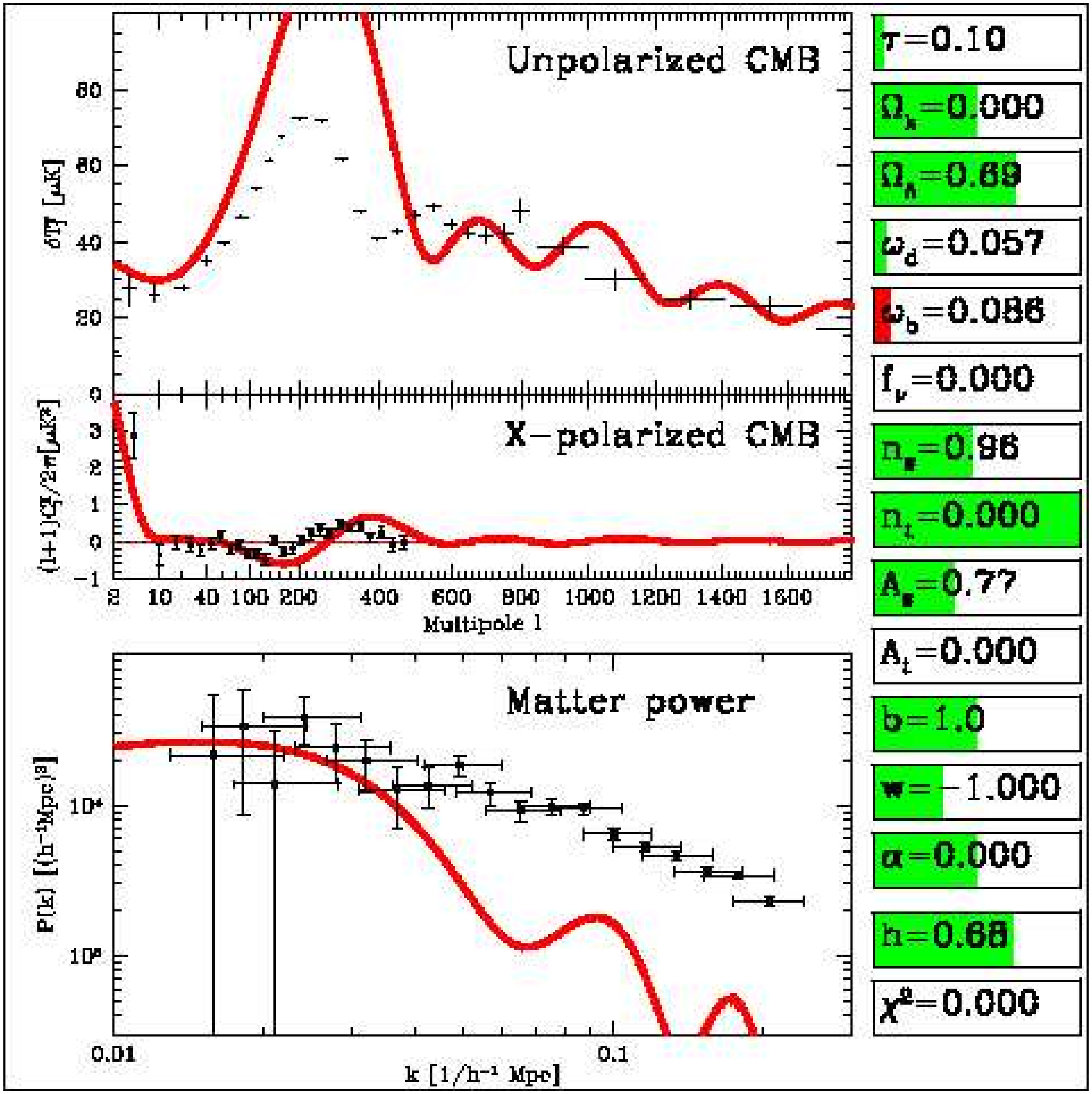

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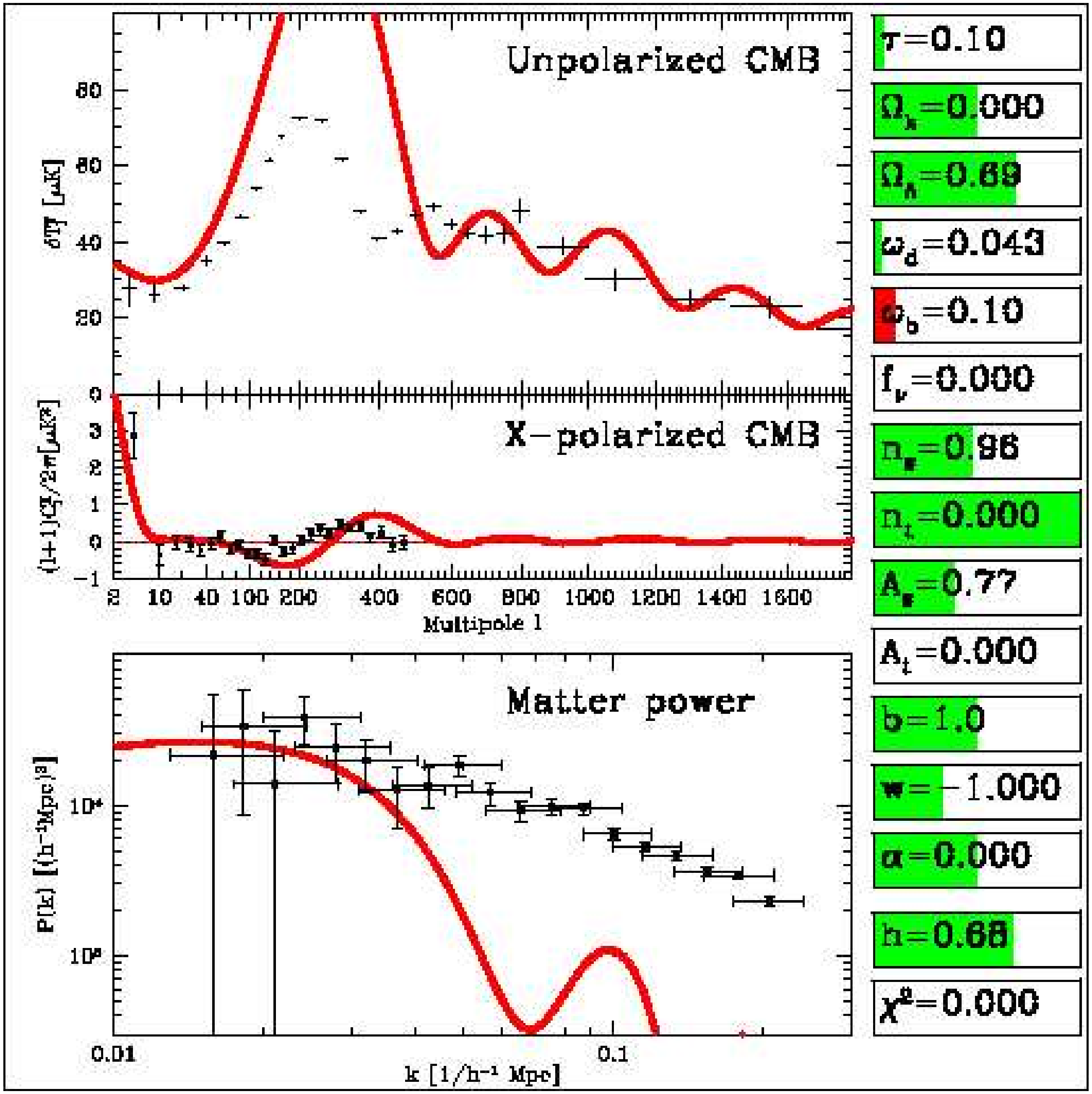

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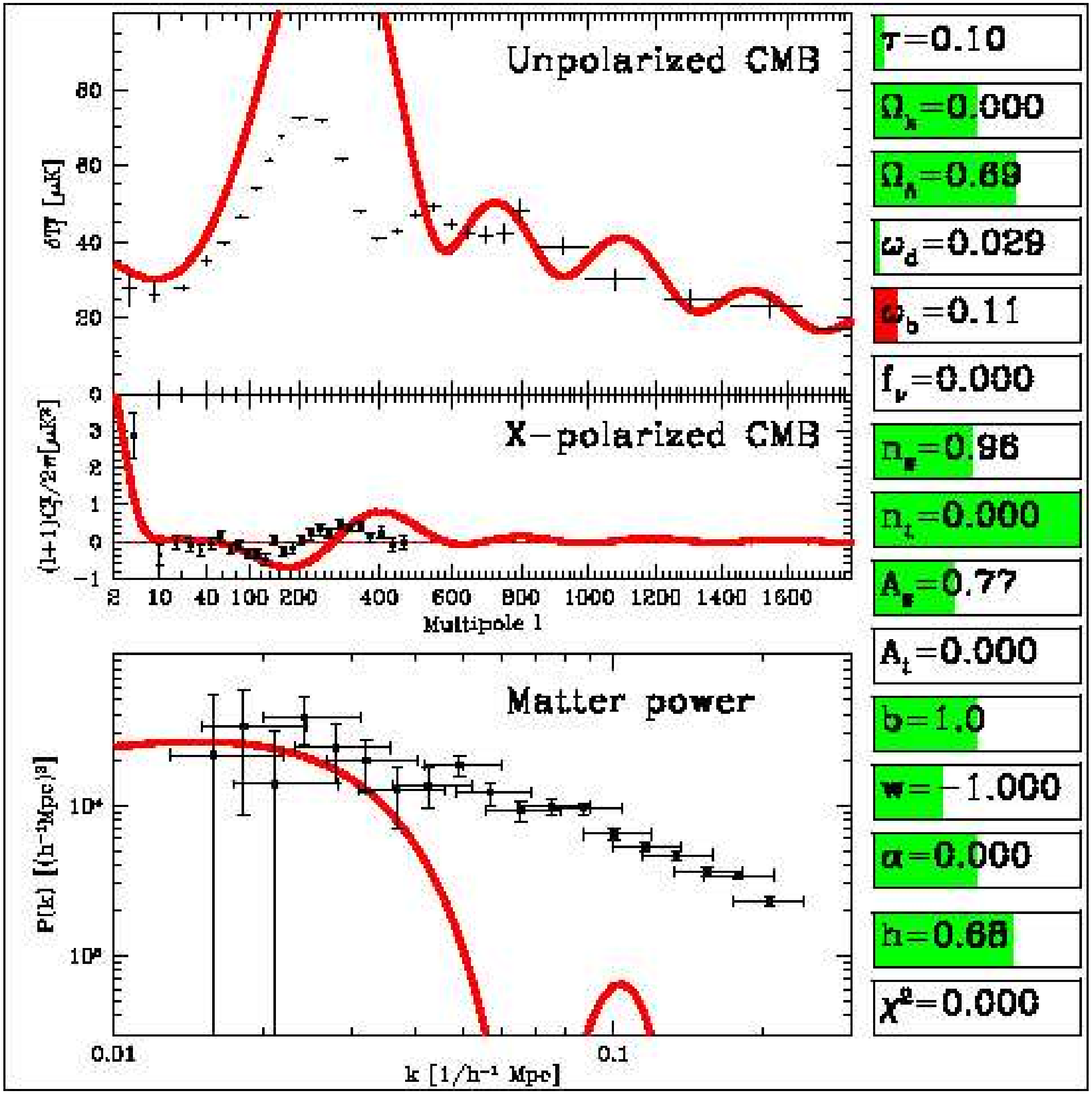

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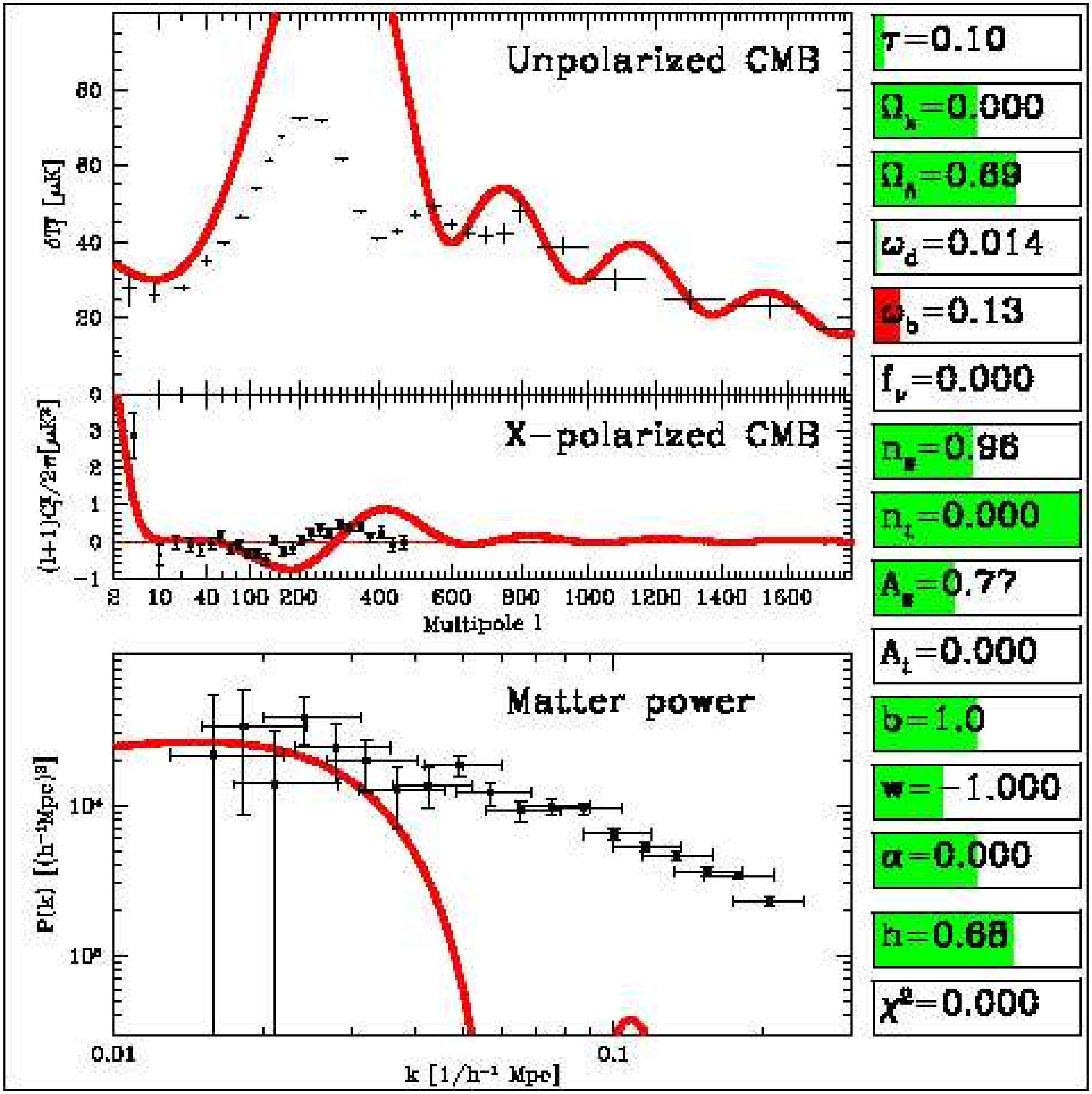

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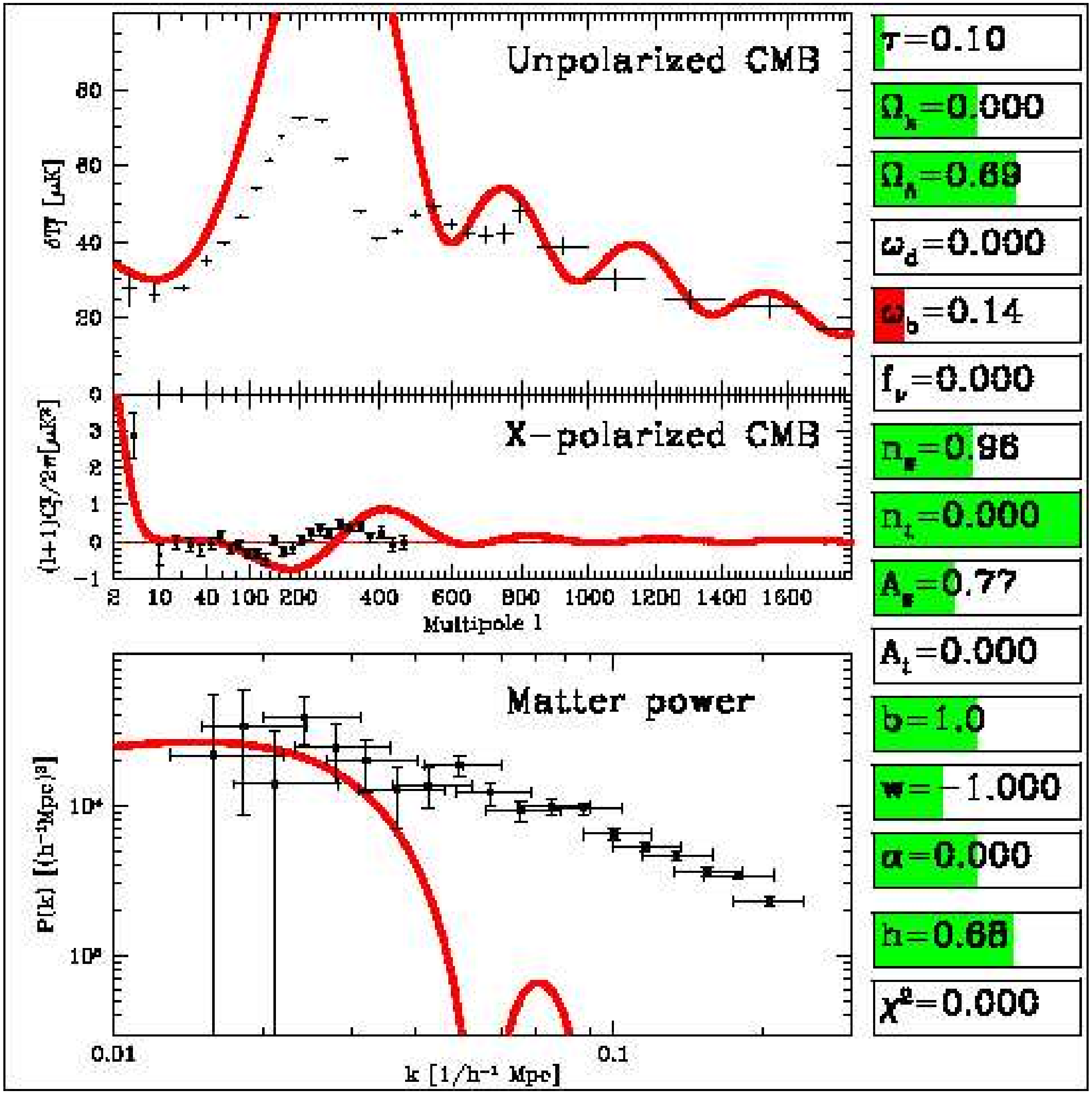


– WMAP Results

"Best" Cosmological Parameters:
Table 3 from ***Wilkinson Microwave Anisotropy Probe (WMAP)* Observations: Preliminary Maps and Basic Results**,
C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*;
available at `http://lambda.gsfc.nasa.gov/`

Description	Symbol	Value	+ uncertainty	− uncertainty
Total density	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_m	0.27	0.04	0.04
Light neutrino density	$\Omega_\nu h^2$	< 0.0076	95% CL	—
CMB temperature (K)[a]	$T_{\rm cmb}$	2.725	0.002	0.002
CMB photon density (cm^{-3})[b]	n_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.5}$	0.44	0.04	0.05
Power spectrum normalization (at $k_0 = 0.05$ Mpc^{-1})[c]	A	0.833	0.086	0.083
Scalar spectral index (at $k_0 = 0.05$ Mpc^{-1})[c]	n_s	0.93	0.03	0.03
Running index slope (at $k_0 = 0.05$ Mpc^{-1})[c]	$dn_s/d\ln k$	−0.031	0.016	0.018
Tensor-to-scalar ratio (at $k_0 = 0.002$ Mpc^{-1})	r	< 0.90	95% CL	—
Redshift of decoupling	z_{dec}	1089	1	1
Thickness of decoupling (FWHM)	Δz_{dec}	195	2	2
Hubble constant	h	0.71	0.04	0.03
Age of universe (Gyr)	t_0	13.7	0.2	0.2
Age at decoupling (kyr)	t_{dec}	379	8	7
Age at reionization (Myr, 95% CL))	t_r	180	220	80
Decoupling time interval (kyr)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular size distance to decoupling (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2

[a] from *COBE* (Mather, J. C. et al., 1999, ApJ, 512, 511)

[b] derived from *COBE* (Mather, J. C. et al., 1999, ApJ, 512, 511)

[c] $l_{\rm eff} \approx 700$

[d] $\ell_A \equiv \pi \theta_A^{-1} \qquad \theta_A \equiv r_s\, d_a^{-1}$

$$\eta_B = \frac{n_B}{n_\gamma} = 6.1^{+0.3}_{-0.2} \times 10^{-10} \qquad (\text{cf.} \quad \eta_B^{\rm SM} \sim 10^{-18})$$

– **Matter–AntiMatter Asymmetry**

Sakharov's conditions for generating the BAU:

- B-violating interactions
- C and CP violation
- Out-of-equilibrium dynamics

3 representative scenarios for Baryogenesis:

- **Baryogenesis through the decay of a heavy particle**
  Out-of-equilibrium, B-violating decay of a heavy GUT particle, e.g. in SO(10).
  [M. Yoshimura, PRL**41** (1978) 281; S. Dimopoulos and L. Susskind, PR**D18** (1978) 4500.]

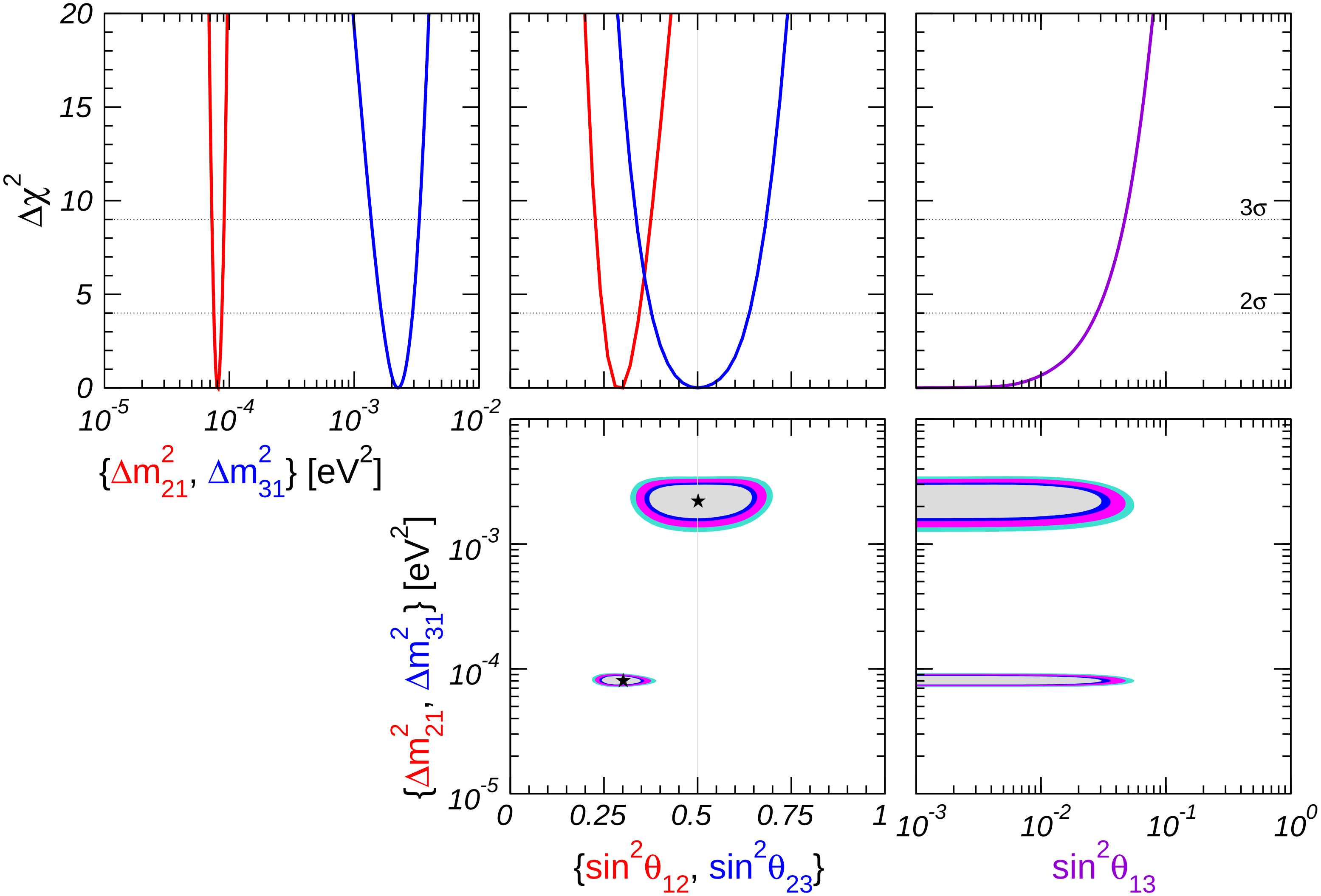
- **Baryogenesis at the electroweak phase transition**
  BAU is generated by means of $(B+L)$-violating sphaleron interactions at $T \sim T_c \approx 200$ GeV, through a 1st order phase transition.
  [V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, PL**B155** (1985) 36;
  MSSM: M. Carena, M. Quirós, C. Wagner, '96 . . .]

- **Baryogenesis through Leptogenesis**
  Out-of-equilibrium L-violating decays of heavy Majorana neutrinos produce a net lepton asymmetry, converted into the BAU through $(B+L)$-violating sphaleron interactions.
  [M. Fukugita and T. Yanagida, PL**B174** (1986) 45.]

• Neutrino Masses and Mixings

Global fit, including SNO-salt, K2K and KamLAND

[M. Maltoni, T. Schwetz, M. A. Tortola and J. W. Valle, hep-ph/0405172]



At the 3σ CL:

$$\begin{aligned}
\Delta m^2_\odot\ [10^{-5}\mathrm{eV}^2] &= 7.1 — 8.9\,,\\
\Delta m^2_{\mathrm{atm}}\ [10^{-3}\mathrm{eV}^2] &= 1.4 — 3.3\,,\\
\sin^2\theta_{12} &= 0.23 — 0.38\,,\\
\sin^2\theta_{23} &= 0.34 — 0.68\,,\\
\sin^2\theta_{13} &\le 0.051\,,
\end{aligned}$$

with $\Delta m^2_\odot = m^2_{\nu_2} - m^2_{\nu_1}$ and $\Delta m^2_{\mathrm{atm}} = m^2_{\nu_3} - m^2_{\nu_1}$.

Cosmological and astronomical limits (WMAP + SDSS) imply

[M. Tegmark et al., PRD**69** (2004) 103501]

$$\sum_{i=1}^{3} m_{\nu_i} \lesssim 1.74\ \mathrm{eV} \quad (95\%\ \mathrm{CL})\,.$$

– The Seesaw Paradigm   [P. Minkowski, PL**B67** (1977) 421 . . .]

$$\begin{aligned}\mathrm{SO(10)} &\to \mathrm{SU(4)_{PS}} \otimes \mathrm{SU(2)}_R \otimes \mathrm{SU(2)}_L \\ &\to \mathrm{SU(3)}_c \otimes \mathrm{SU(2)}_R \otimes \mathrm{SU(2)}_L \otimes \mathrm{U(1)}_{(B-L)} \\ &\to \mathrm{SU(3)}_c \otimes \mathrm{SU(2)}_L \otimes \mathrm{U(1)}_Y \equiv \text{SM} + \nu_R\text{'s}\end{aligned}$$

$$\begin{pmatrix} \nu_L \\ l_L \end{pmatrix}_i , \quad l_{iR}\,, \quad \nu_{iR}\,; \qquad i = 1,2,3 = e,\mu,\tau$$

$$\mathcal{L}_{\rm mass} \;=\; -\frac{1}{2}\,(\bar\nu_L\,,\; \bar\nu_R^C)\,\underbrace{\begin{pmatrix} 0 & m_D \\ m_D^T & m_M \end{pmatrix}}_{:6\times 6\ \text{matrix}}\begin{pmatrix} \nu_L^C \\ \nu_R \end{pmatrix} \;+\; \text{H.c.},$$

with $m_D = \frac{1}{\sqrt{2}}\, h^\nu\, v$.

Seesaw approximation: $(m_M \gg m_D)$

$$m_\nu^{\rm light} \;\approx\; -\,m_D\,\frac{1}{m_M}\,m_D^T \quad\leftarrow\quad 3 \text{ light neutrinos}$$

$$m_N^{\rm heavy} \;\approx\; m_M \quad\leftarrow\quad 3 \text{ heavy neutrinos}$$

– The Non-Seesaw Paradigm   [A.P., T. Underwood, NP**B692** (2004) 303]

Non-trivial structure of m_D and m_M, e.g. by means of the Froggatt–Nielsen mechanism:

$$Q_{\rm FN}: \quad \Sigma(+1)\,;\ \overline{\Sigma}(-1)\,;\ \nu_{1R}(-1)\,;\ \nu_{2R}(+1)\,;\ \nu_{3R}(0)\,.$$

All other fields are taken to be neutral under $\mathrm{U}(1)_{\rm FN}$.

$$m_D \ \sim\ \frac{v}{\sqrt{2}}\begin{pmatrix} \varepsilon & \bar{\varepsilon} & 1 \\ \varepsilon & \bar{\varepsilon} & 1 \\ \varepsilon & \bar{\varepsilon} & 1 \end{pmatrix}\,, \quad m_M \ \sim\ M\begin{pmatrix} \varepsilon^2 & 1 & \varepsilon \\ 1 & \bar{\varepsilon}^2 & \bar{\varepsilon} \\ \varepsilon & \bar{\varepsilon} & \frac{M_X}{M} \end{pmatrix}\,,$$

with $\varepsilon = \frac{\langle\Sigma\rangle}{M_{\rm GUT}}$, $\bar{\varepsilon} = \frac{\langle\overline{\Sigma}\rangle}{M_{\rm GUT}}$ and $M \sim 1$ TeV.

Example compatible with neutrino data
($M_X \gg M = 1$ TeV):

$$\mathbf{m}^\nu \;=\; -\,m_D \frac{1}{m_M} m_D^T \;\approx\; -\frac{v^2 \varepsilon\bar{\varepsilon}}{2M} \begin{pmatrix} -4/9 & 1 & 0 \\ 1 & 4 & 5 \\ 0 & 5 & 4 \end{pmatrix} .$$

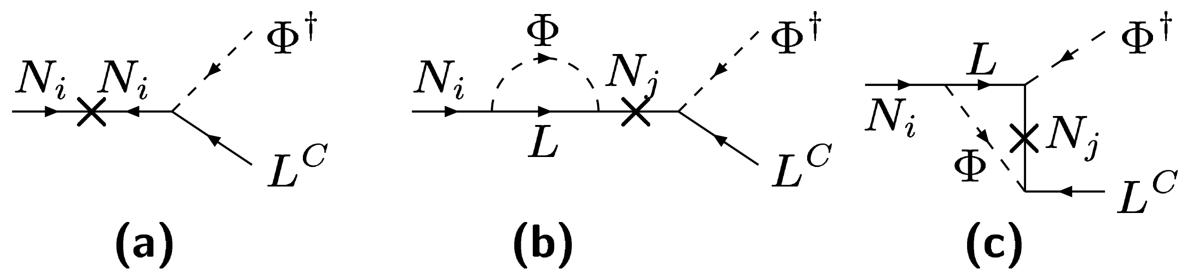
$$\Rightarrow \qquad (\, m_{\nu_1},\; m_{\nu_2},\; m_{\nu_3} \,) \;\approx\; \frac{v^2 \varepsilon\bar{\varepsilon}}{2M}\,(0.04,\; 1.5,\; 9)\,,$$

$$\Rightarrow \qquad |\theta_{\nu_\mu \nu_\tau}| \sim \frac{\pi}{4}\,, \quad |\theta_{\nu_e \nu_\mu}| \sim \frac{\pi}{6}\,, \quad |\theta_{\nu_e \nu_\tau}| \;\lesssim\; 0.1$$

and

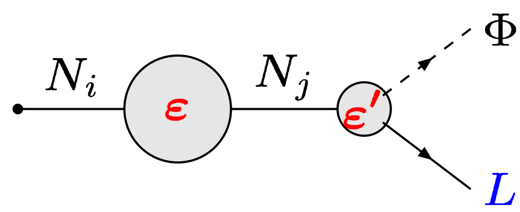
$$|\varepsilon\bar{\varepsilon}| = 1.85 \times 10^{-13}$$

• Resonant Leptogenesis



(a) tree-level graph, and one-loop (b) self-energy and (c) vertex graphs.

– **Field-Theoretic Approach** to incoherent mixing and decay of heavy Majorana neutrinos [A.P., PR**D56** (1997) 5431; NP**B504** (1997) 61]:



$$\times\, [S_{ii}(\not p)]^{-1}\, u_{N_i}(p) \;=\; \mathcal{T}_{N_i}$$

where (2-gens only)

$$S_{ij}(\not p) \;=\; \begin{pmatrix} \not p - m_{N_1} + \Sigma_{11}(\not p) & \Sigma_{12}(\not p) \\ \Sigma_{21}(\not p) & \not p - m_{N_2} + \Sigma_{22}(\not p) \end{pmatrix}^{-1}$$

For 3-gen mixing, see A.P., T. Underwood, NP**B692** (2004) 303.

Resummed Effective Yukawa Couplings and Leptonic Asymmetries

Resummed decay amplitudes:

$$\mathcal{T}_{N_1} \;=\; (\bar{h}^{\nu}_{+})_{l1}\, \bar{u}_l\, P_R u_{N_1}\,, \qquad \mathcal{T}^{\rm CP}_{N_1} \;=\; (\bar{h}^{\nu}_{-})_{l1}\, \bar{u}_l\, P_R u_{N_1}\,,$$

$[(\bar{h}^{\nu}_{+})_{l1} \overset{\rm CP}{\Longleftrightarrow} (\bar{h}^{\nu}_{-})_{l1}]$, where

$$(\bar{h}^{\nu}_{+})_{l1} \;=\; h^{\nu}_{l1} + iB_{l1} - \frac{ih^{\nu}_{l2}\, m_{N_1}\,(m_{N_1} A_{12} + m_{N_2} A^{*}_{12})}{m^2_{N_1} - m^2_{N_2} + 2i\, A_{22}\, m^2_{N_1}}\,,$$

$$(\bar{h}^{\nu}_{-})_{l1} \;=\; h^{\nu\,*}_{l1} + iB^{*}_{l1} - \frac{ih^{\nu\,*}_{l2}\, m_{N_1}\,(m_{N_1} A^{*}_{12} + m_{N_2} A_{12})}{m^2_{N_1} - m^2_{N_2} + 2i\, A_{22}\, m^2_{N_1}}\,,$$

with

$$A_{12} \;=\; \frac{h^{\nu}_{l'i} h^{\nu\,*}_{l'j}}{16\pi}\,, \qquad B_{l1} = \frac{h^{\nu *}_{l'1}\, h^{\nu}_{l'2}\, h^{\nu}_{l2}}{16\pi}\, f\left(\frac{m^2_{N_2}}{m^2_{N_1}}\right)\,,$$

are the resummed effective Yukawa couplings.

Leptonic Asymmetries:

$$\delta_{N_i} = \frac{\Gamma(N_i \to L\Phi) - \Gamma(N_i \to L^C\Phi^\dagger)}{\Gamma(N_i \to L\Phi) + \Gamma(N_i \to L^C\Phi^\dagger)}$$

$$= \frac{(\bar{h}^{\nu\,\dagger}_{+}\bar{h}^{\nu}_{+})_{ii} - (\bar{h}^{\nu\,\dagger}_{-}\bar{h}^{\nu}_{-})_{ii}}{(\bar{h}^{\nu\,\dagger}_{+}\bar{h}^{\nu}_{+})_{ii} + (\bar{h}^{\nu\,\dagger}_{-}\bar{h}^{\nu}_{-})_{ii}}$$

$$\approx \varepsilon'_{N_i} + \varepsilon_{N_i} \,.$$

ε'-type CP violation :

$$\varepsilon'_{N_i} = \frac{\mathrm{Im}\,(h^{\nu\dagger} h^{\nu})^2_{ij}}{(h^{\nu\dagger} h^{\nu})_{ii}\,(h^{\nu\dagger} h^{\nu})_{jj}} \left(\frac{\Gamma^{(0)}_{N_j}}{m_{N_j}}\right) f\left(\frac{m^2_{N_j}}{m^2_{N_i}}\right),$$

where

$$\Gamma^{(0)}_{N_j} = \frac{(h^{\nu\dagger} h^{\nu})_{jj}}{8\pi}\, m_{N_j}$$

is the tree-level decay width of N_j.

ε-type CP violation :

$$\varepsilon_{N_i} = \frac{\mathrm{Im}\,(h^{\nu\dagger} h^{\nu})^2_{ij}}{(h^{\nu\dagger} h^{\nu})_{ii}\,(h^{\nu\dagger} h^{\nu})_{jj}} \frac{(m^2_{N_i} - m^2_{N_j})\, m_{N_i}\, \Gamma^{(0)}_{N_j}}{(m^2_{N_i} - m^2_{N_j})^2 + m^2_{N_i} \Gamma^{(0)\,2}_{N_j}}$$

Note that $\varepsilon_{N_{1,2}}$ are of the same sign!

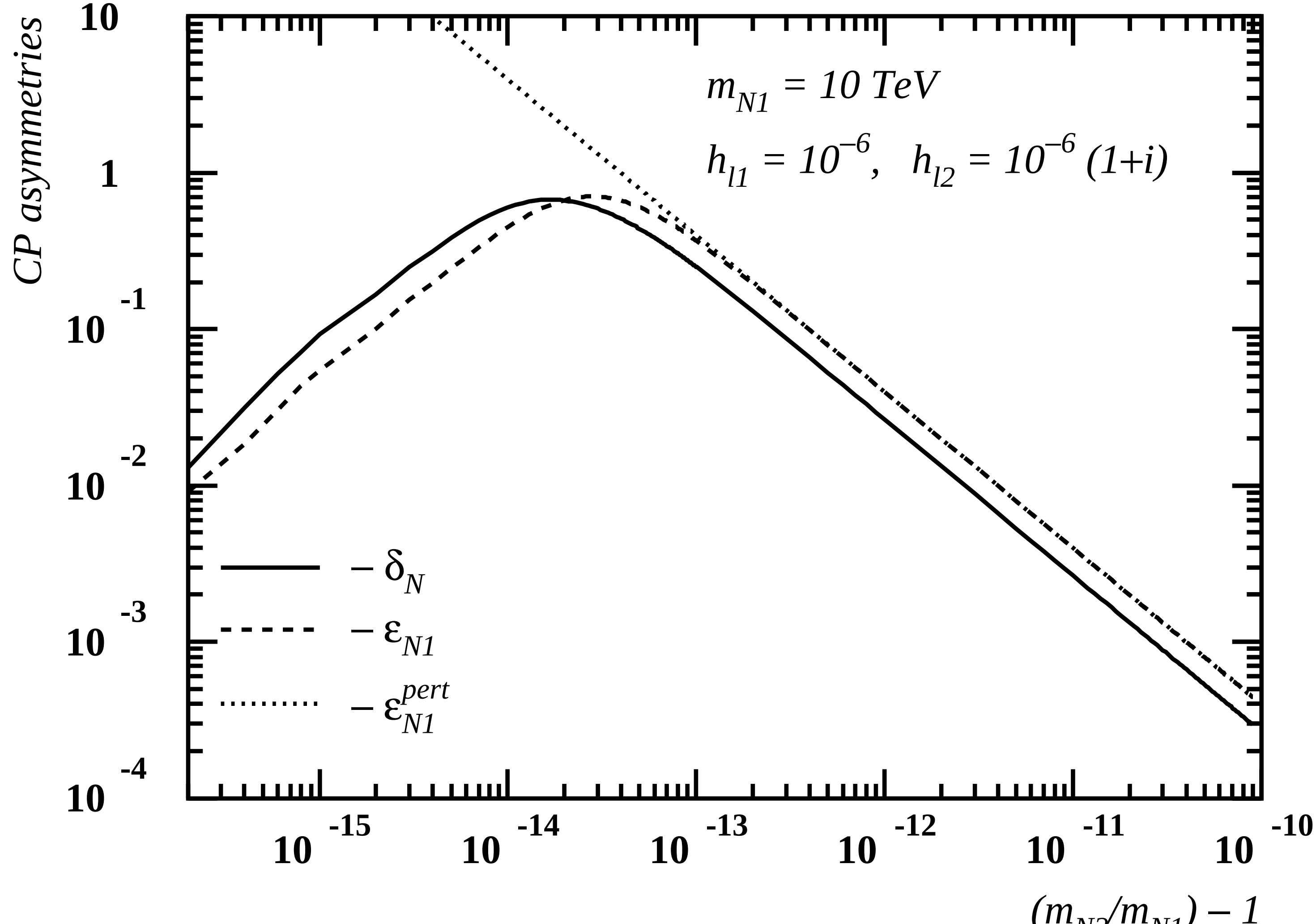
Resonant conditions for $O(1)$ leptonic asymmetries:

$$\Rightarrow \qquad m_{N_2} - m_{N_1} \sim \tfrac{1}{2}\, \Gamma^{(0)}_{N_{1,2}}$$

$$\Rightarrow \qquad \frac{\mathrm{Im}\,(h^{\nu\dagger}\, h^{\nu})^2_{ij}}{(h^{\nu\dagger}\, h^{\nu})_{ii}\,(h^{\nu\dagger}\, h^{\nu})_{jj}} \sim 1$$

[A.P., PR**D56** (1997) 5431.]

[A.P., PR**D56** (1997) 5431.]



(a)

– Boltzmann Equations [A.P., T.E. Underwood, NP**B692** (2004) 303; hep-ph/0506107]

$$\frac{d\eta_{N_\alpha}}{dz} = \frac{z}{H(z=1)} \Big[\Big(1 - \frac{\eta_{N_\alpha}}{\eta^{\rm eq}_{N_\alpha}}\Big) \sum_{k=e,\mu,\tau} \big(\Gamma^{D\,(\alpha k)} + \Gamma^{S\,(\alpha k)}_{\rm Yukawa} + \Gamma^{S\,(\alpha k)}_{\rm Gauge} \big)$$

$$- \frac{2}{3} \sum_{k=e,\mu,\tau} \eta_{\Delta L_k}\, \delta^k_{N_\alpha} \big(\widehat{\Gamma}^{D\,(\alpha k)} + \widehat{\Gamma}^{S\,(\alpha k)}_{\rm Yukawa} + \widehat{\Gamma}^{S\,(\alpha k)}_{\rm Gauge} \big) \Big] ,$$

$$\frac{d\eta_B}{dz} = -\frac{z}{H(z=1)} \Big[\eta_B + \frac{28}{51} \sum_{j=e,\mu,\tau} \eta_{L_j}$$

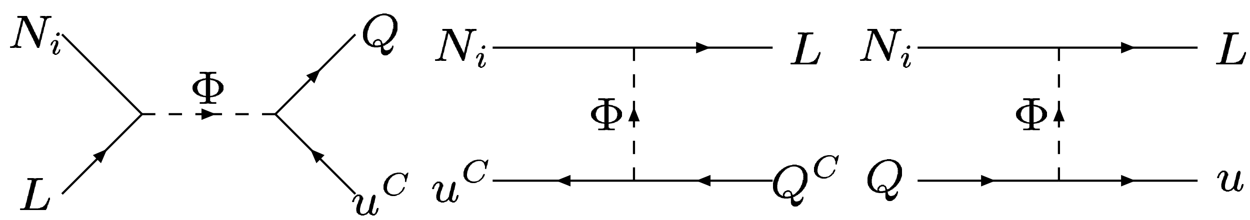
$$+ \frac{225}{561} \frac{v^2(T)}{T^2} \Big(\eta_B + \frac{108}{225} \sum_{j=e,\mu,\tau} \eta_{L_j} \Big) \Big] \Gamma_{\Delta(B+L)} ,$$

$$\frac{d\eta_{L_i}}{dz} = \frac{3}{2} \frac{d\eta_{\Delta L_i}}{dz} - \frac{2}{21} \frac{d\eta_{\Delta L}}{dz} + \frac{1}{3} \frac{d\eta_B}{dz} ,$$

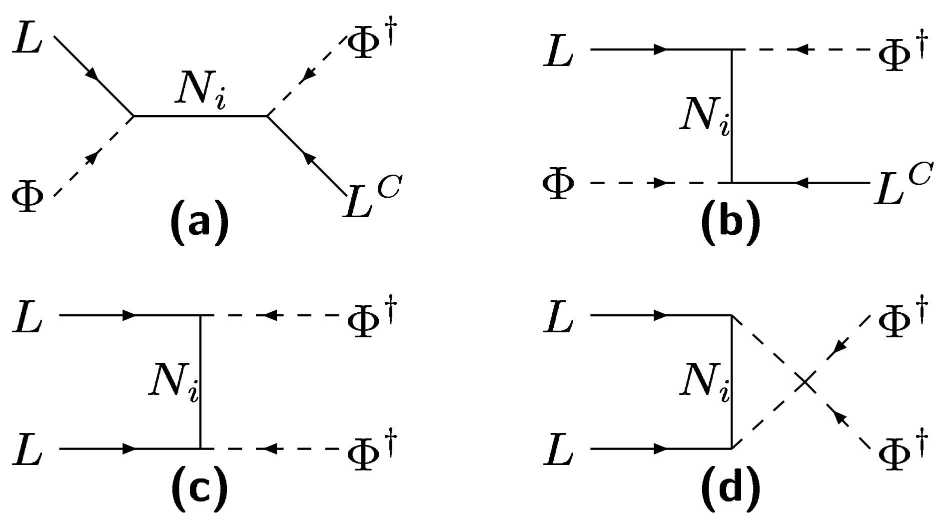
$$
\begin{aligned}
\frac{d\eta_{\Delta L_j}}{dz} &= \frac{z}{H(z=1)} \\
&\times \Big\{ \sum_{\alpha=1}^{3} \delta^{j}_{N_\alpha} \Big(\frac{\eta_{N_\alpha}}{\eta^{\rm eq}_{N_\alpha}} - 1\Big) \sum_{k=e,\mu,\tau} \Big(\Gamma^{D\,(\alpha k)} + \Gamma^{S\,(\alpha k)}_{\rm Yukawa} + \Gamma^{S\,(\alpha k)}_{\rm Gauge} \Big) \\
&- \frac{2}{3}\,\eta_{\Delta L_j} \Big[\sum_{\alpha=1}^{3} B^{j}_{N_\alpha} \Big(\widetilde{\Gamma}^{D\,(\alpha j)} + \widetilde{\Gamma}^{S\,(\alpha j)}_{\rm Yukawa} + \widetilde{\Gamma}^{S\,(\alpha j)}_{\rm Gauge} + \Gamma^{W\,(\alpha j)}_{\rm Yukawa} + \Gamma^{W\,(\alpha j)}_{\rm Gauge} \Big) \\
&\qquad + \sum_{k=e,\mu,\tau} \Big(\Gamma^{\Delta L=2\,(jk)}_{\rm Yukawa} + \Gamma^{\Delta L=0\,(jk)}_{\rm Yukawa} \Big) \Big] \\
&- \frac{2}{3} \sum_{k=e,\mu,\tau} \eta_{\Delta L_k} \Big[\sum_{\alpha=1}^{3} \delta^{j}_{N_\alpha}\, \delta^{k}_{N_\alpha} \Big(\Gamma^{W\,(\alpha k)}_{\rm Yukawa} + \Gamma^{W\,(\alpha k)}_{\rm Gauge} \Big) \\
&\qquad + \Gamma^{\Delta L=2\,(kj)}_{\rm Yukawa} - \Gamma^{\Delta L=0\,(kj)}_{\rm Yukawa} \Big] \Big\}
\end{aligned}
$$

Computational package: LeptoGen

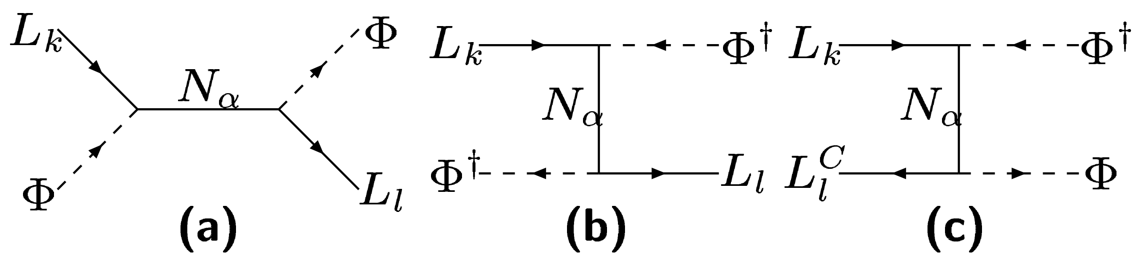
$\Delta L = 1$ scatterings involving L, N_i and quarks



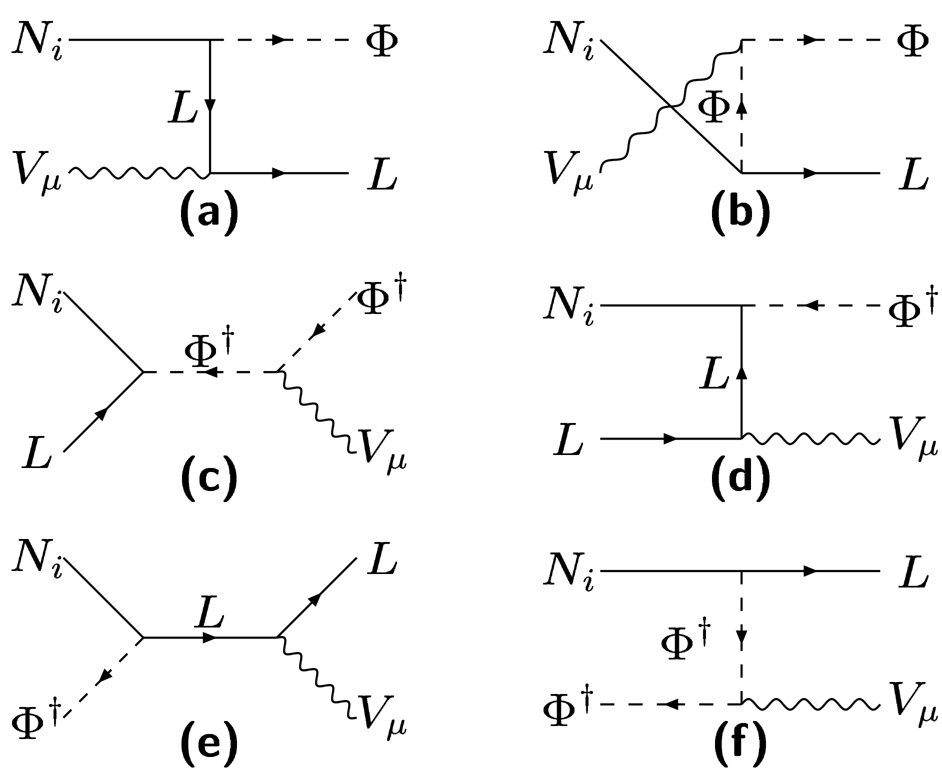
$\Delta L = 2$ scatterings involving L, Φ and N_i



$\Delta L = 0$ scatterings involving L, Φ and N_i



Gauge-mediated $\Delta L = 1$ scatterings



– Order-of-magnitude estimate of the BAU

Total decay width of heavy Majorana neutrino N_i:

$$\Gamma_{N_i} = (h^{\nu\dagger} h^{\nu})_{ii} \frac{m_{N_i}}{8\pi}$$

Define the wash-out K-factors:

$$K_{N_i} \equiv \frac{\Gamma_{N_i}}{H(T = m_{N_1})} ,$$

where

$$H(T) = 1.66\, g_*^{1/2} \frac{T^2}{M_{\rm Planck}}$$

and $g_* \approx 107$ are the relativistic d.o.f. in the SM.

A naive order-of-magnitude estimate of η_B is obtained by (after $(B+L)$ sphaleron conversion)

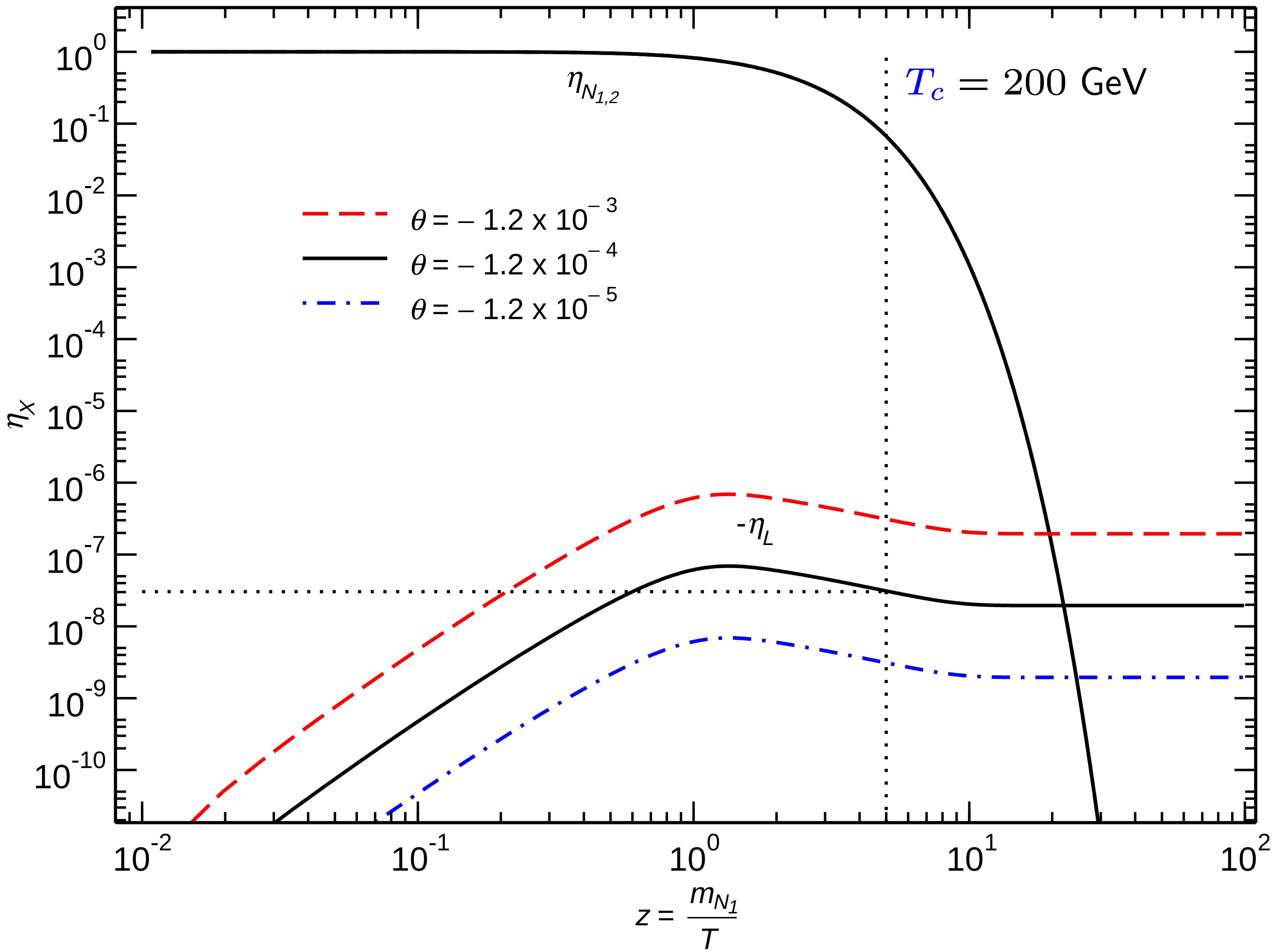
$$\eta_B \sim -\sum_{N_i} e^{-(m_{N_i}-m_{N_1})/m_{N_1}} \frac{\delta_{N_i}}{200\, K_{N_i}} \sim 6 \times 10^{-10}$$

For $K_{N_i} \gtrsim 10$, one needs $\delta_{N_i} \gtrsim 10^{-6}$ $\Rightarrow$ **Resonant Leptogenesis**

LeptoGen

$m_{N_1} = 1$ TeV, $x_N = \frac{m_{N_2}}{m_{N_1}} - 1 = \varepsilon^2$ and $\eta_L^{\rm in} = 0$, $\eta_{N_{1,2}}^{\rm in} = 1$:

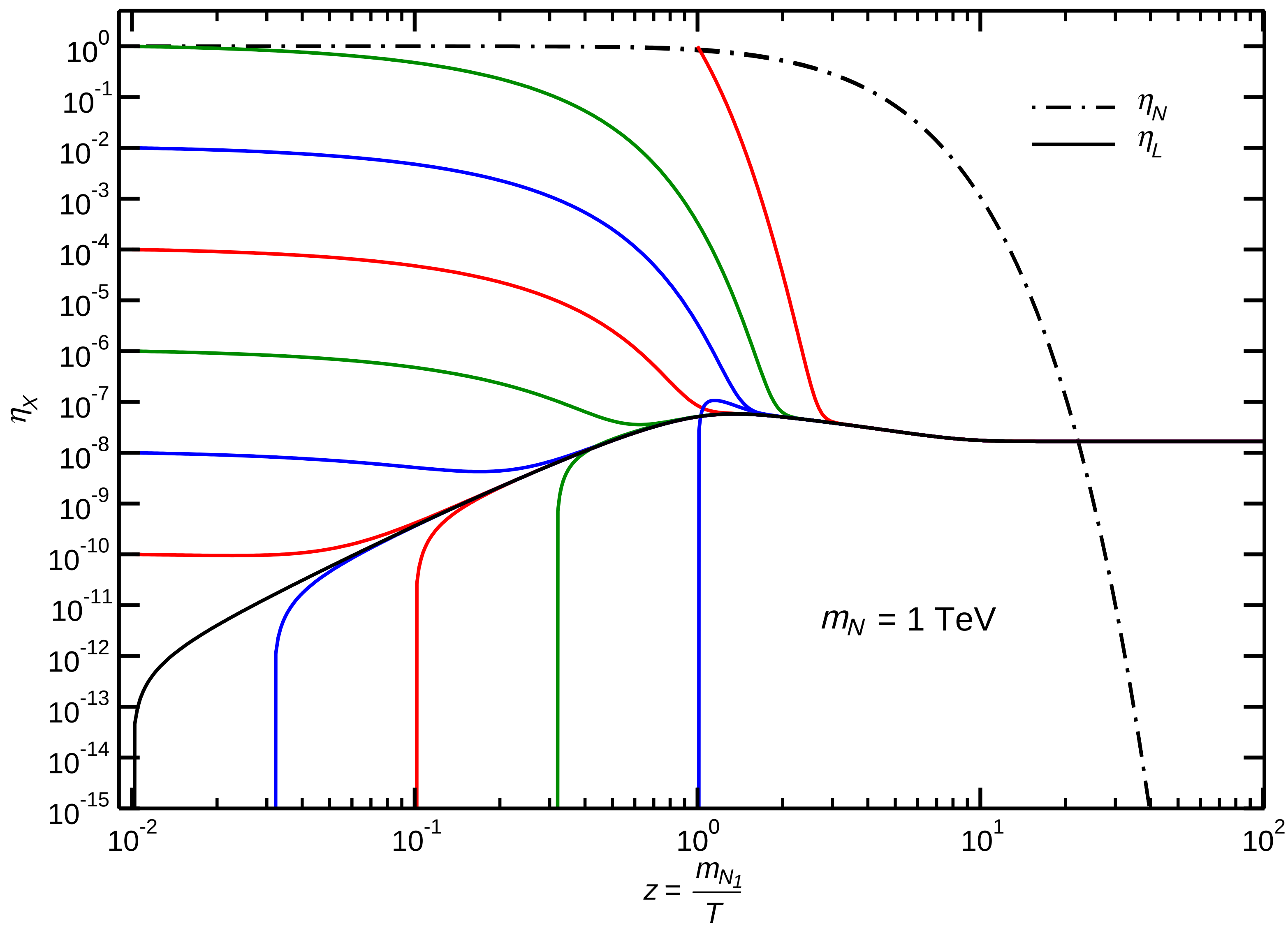
(a) $\bar{\varepsilon} = e^{i\theta}\varepsilon$, $\varepsilon = 4.3 \times 10^{-7}$.



LeptoGen

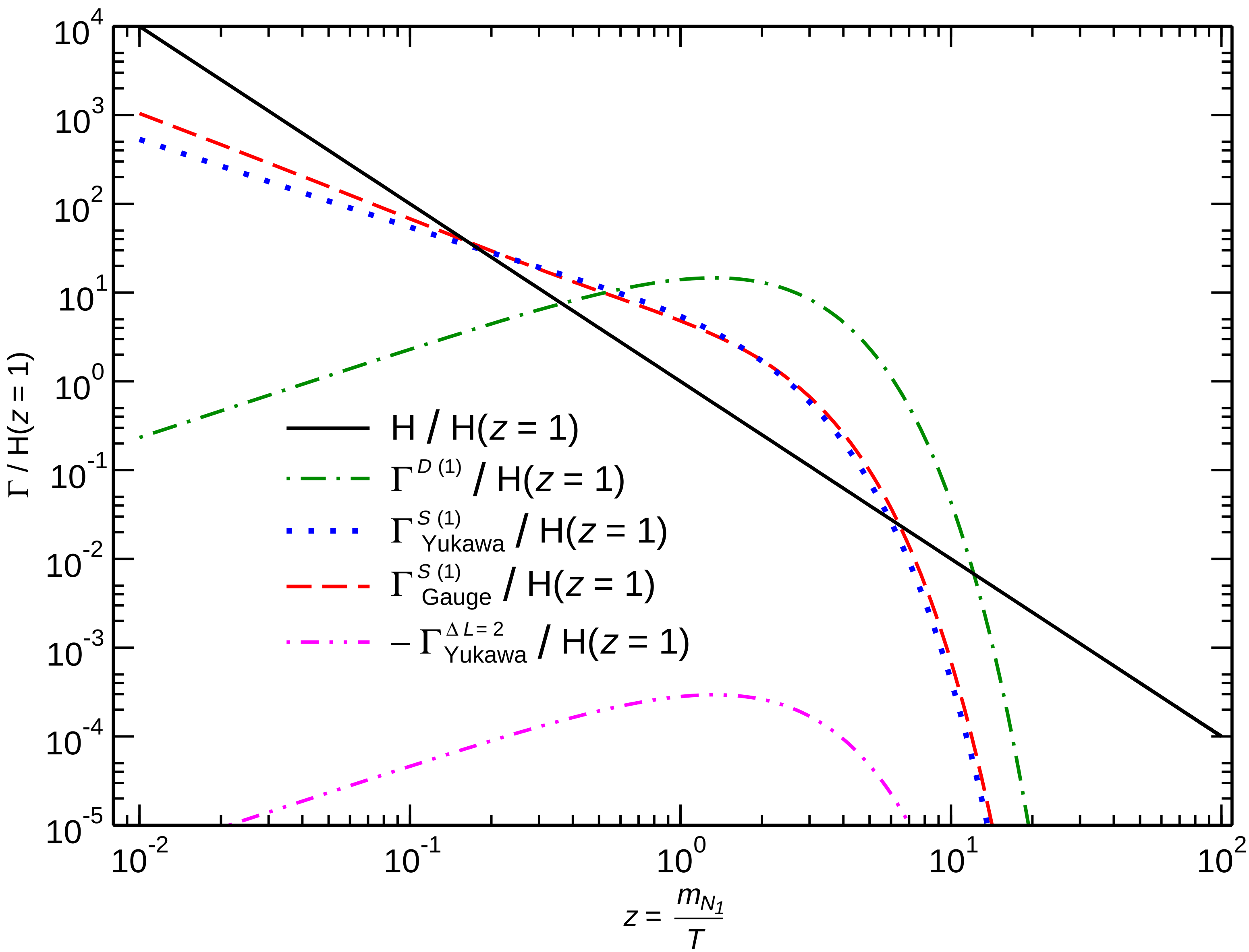
$m_{N_1} = 1$ TeV, $x_N = \frac{m_{N_2}}{m_{N_1}} - 1 = \varepsilon^2$ and $\eta_L^{\rm in} = 0$, $\eta_{N_{1,2}}^{\rm in} = 1$:

(a) $\bar{\varepsilon} = e^{i\theta}\varepsilon$, $\varepsilon = 4.3 \times 10^{-7}$ and $\theta = -1.2 \times 10^{-4}$.



LeptoGen

$\bar{\varepsilon} = e^{i\theta}\varepsilon$, with $\varepsilon = 4.3 \times 10^{-7}$, $\theta = -1.2 \times 10^{-4}$.



– **Resonant τ-Leptogenesis (RτL)** [A.P., hep-ph/0408103]

BAU generated from a single lepton flavour: $\frac{1}{3}B - L_\tau$ asymmetry.
3 gens of heavy Majorana neutrinos needed: $N_{1,2,3}$.

...

3×3 **flavour structure**: SO(3) $\Longrightarrow$ SO(2) $\simeq$ U(1)$_l$.

U(1)$_l$ charges:

$$Q(L_i) \;=\; Q(l_{iR}) = 1\,, \quad Q\Big(\frac{\nu_{2R} + i\nu_{3R}}{\sqrt{2}}\Big) \;=\; -Q\Big(\frac{\nu_{2R} - i\nu_{3R}}{\sqrt{2}}\Big) \;=\; 1\,, \quad Q(\nu_{1R}) = 0$$

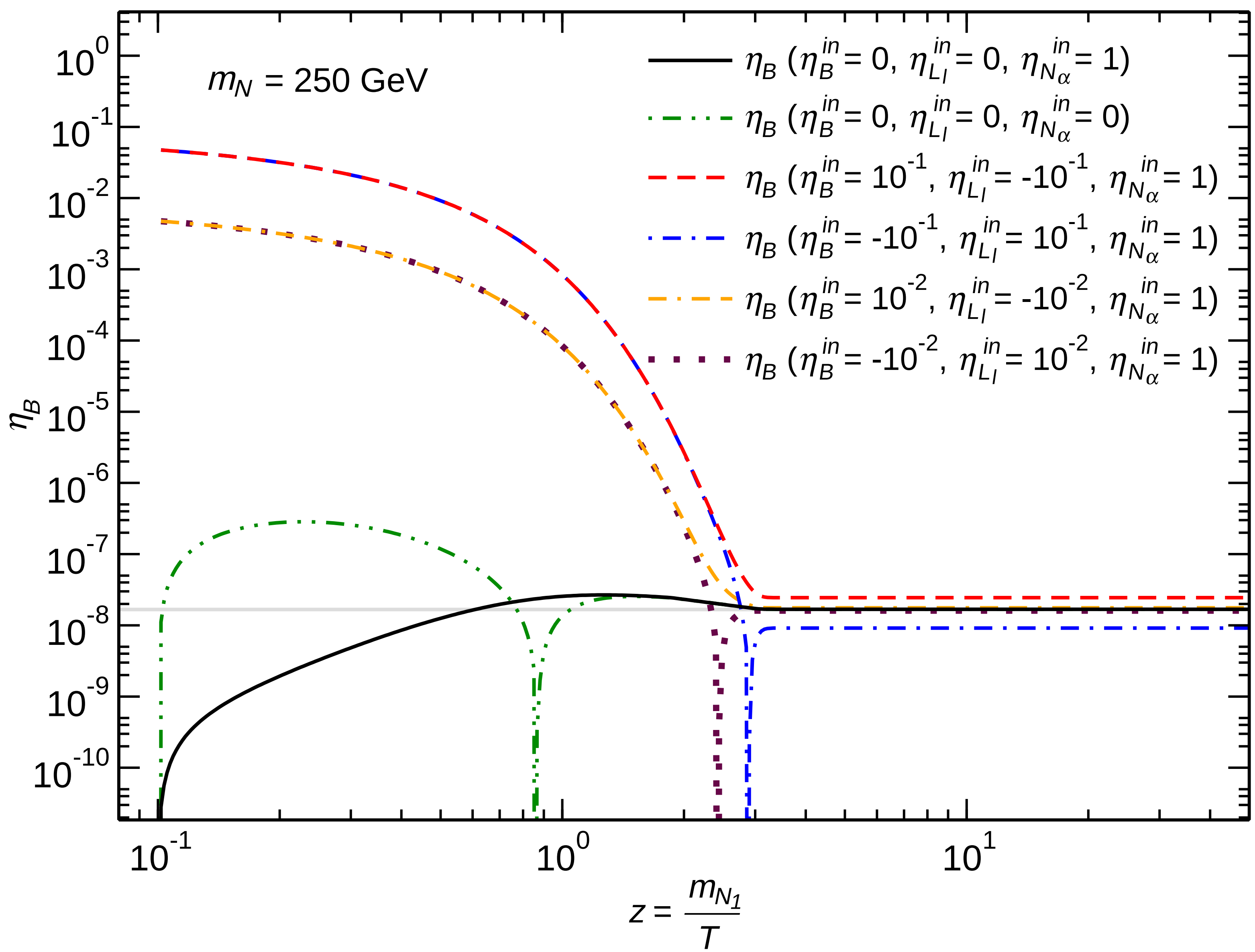
Heavy Majorana neutrino sector: $M_S \;=\; m_N\,\mathbf{1}_3 \;+\; \Delta M_S\,,$
with $|(\Delta M_S)_{ij}| \ll m_N$, e.g. $|(\Delta M_S)_{ij}| \;\lesssim\; 10^{-7} \times m_N$.

Yukawa sector:

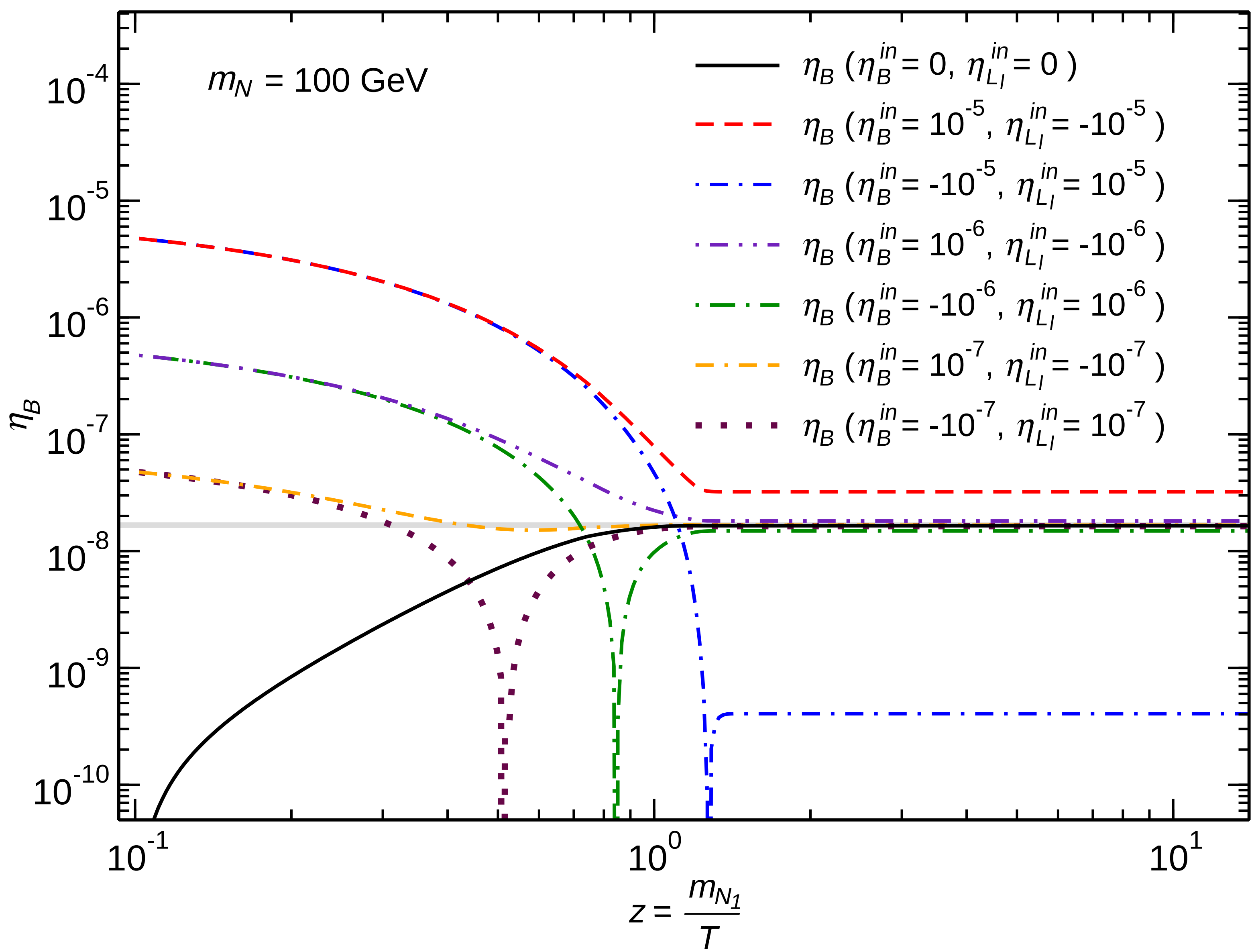
$$h^{\nu_R} \;=\; \begin{pmatrix} \varepsilon_e & a\,e^{-i\pi/4} & a\,e^{i\pi/4} \\ \varepsilon_\mu & b\,e^{-i\pi/4} & b\,e^{i\pi/4} \\ \varepsilon_\tau & c\,e^{-i\pi/4} & c\,e^{i\pi/4} \end{pmatrix},$$

with $|\varepsilon_l| \sim 10^{-7}$, $|c| \sim 10^{-6}$, $|a| \sim |b| \sim 10^{-2}$.

A.P. and T. Underwood, hep-ph/0506107.



LeptoGen



m_N = 100 GeV
η_B (η_B^{in} = 0, $\eta_{L_l}^{in}$ = 0)
η_B (η_B^{in} = 10^{-5}, $\eta_{L_l}^{in}$ = -10^{-5})
η_B (η_B^{in} = -10^{-5}, $\eta_{L_l}^{in}$ = 10^{-5})
η_B (η_B^{in} = 10^{-6}, $\eta_{L_l}^{in}$ = -10^{-6})
η_B (η_B^{in} = -10^{-6}, $\eta_{L_l}^{in}$ = 10^{-6})
η_B (η_B^{in} = 10^{-7}, $\eta_{L_l}^{in}$ = -10^{-7})
η_B (η_B^{in} = -10^{-7}, $\eta_{L_l}^{in}$ = 10^{-7})
η_B
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-1}
10^{0}
10^{1}
$z = \frac{m_{N_1}}{T}$

– Order-of-magnitude estimate of the BAU in a RτL model

Define single lepton-flavour wash-out K-factors:

$$K^l_{N_\alpha} \;=\; \frac{\Gamma(N_\alpha \to L_l\Phi) \;+\; \Gamma(N_\alpha \to L^C_l\Phi^\dagger)}{H(T = m_N)}\,.$$

$\boldsymbol{m_N = 250}$ GeV:

$K^l_{N_\alpha}$		α = 1	2	3
	e	1.0×10^{10}	1.0×10^{10}	25
l	μ	1.4×10^{9}	1.4×10^{9}	20
	τ	2.5	2.5	5.0

Naive order-of-magnitude estimate:

$$\eta_B \;\sim\; -\frac{1}{g_*}\sum_{l,\alpha} \delta^l_{N_\alpha}\,\frac{K^l_{N_\alpha}}{K_l\,K_{N_\alpha}} \;\sim\; 6\times 10^{-10}\,,$$

where $\delta^\tau_{N_3} \;\sim\; -10^{-6}$, $K_l = \sum_\alpha K^l_{N_\alpha}$ and $K_{N_\alpha} = \sum_l K^l_{N_\alpha}$.

• Phenomenology of RτL Models

• $0\nu\beta\beta$ Decay

$$ {}^{A}_{Z}X \;\to\; {}^{A}_{Z+2}X \;+\; 2e^- \;. $$

Half-life for $0\nu\beta\beta$ decay:

$$ [T^{0\nu\beta\beta}_{1/2}]^{-1} \;=\; \frac{|\langle m\rangle|^2}{m_e^2}\,|\mathcal{M}_{0\nu\beta\beta}|^2\,G_{01}\;. $$

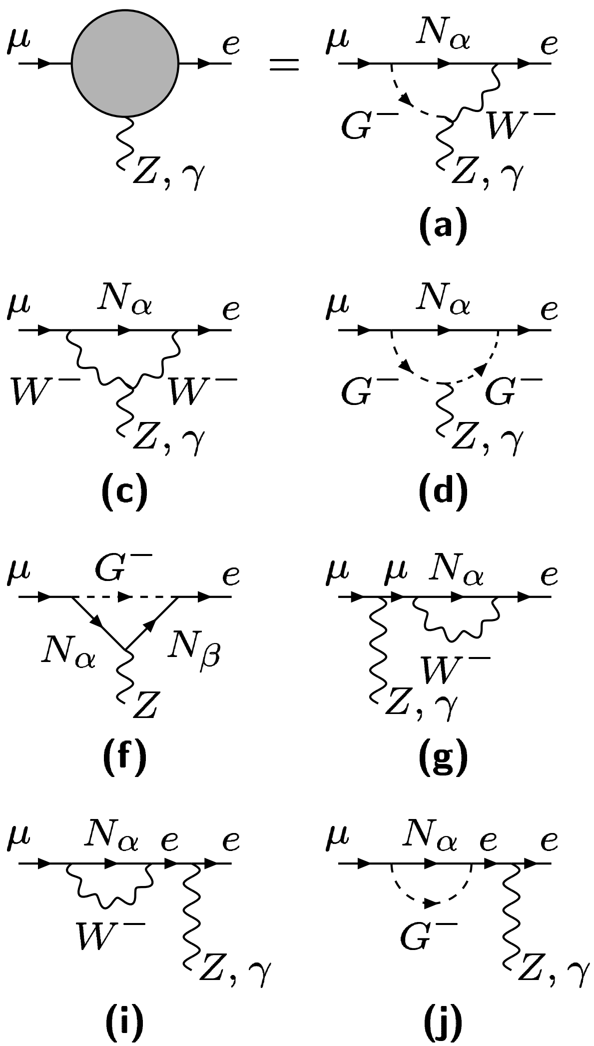
RτL models generically realize an inverted light-neutrino hierarchy, with an effective Majorana mass given by

$$ |\langle m\rangle| \;=\; |(\mathbf{m}^\nu)_{ee}| \;=\; \frac{v^2}{2m_N}\,\Big|\,\frac{\Delta m_N}{m_N}\,a^2 \;-\; \varepsilon_e^2\,\Big| \;\approx\; 0.013\ \mathrm{eV}\;, $$

where $\Delta m_N = 2(\Delta M_S)_{23} + i[(\Delta M_S)_{33} - (\Delta M_S)_{22}]$.

Future proposals for $0\nu\beta\beta$ experiments sensitive to $|\langle m\rangle| \sim 0.01$–$0.05$ eV, such as SuperNEMO . . .

- $\mu \to e\gamma$

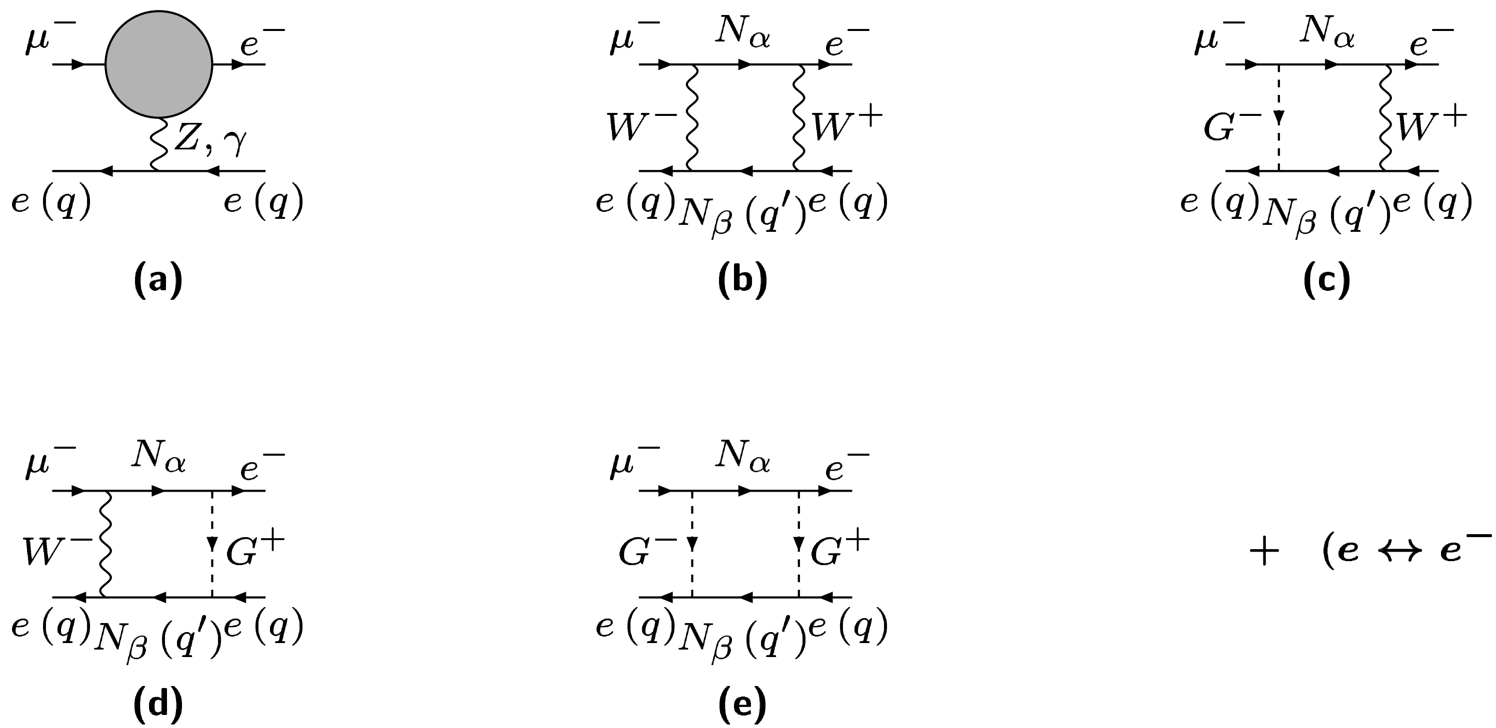


For $h^{\nu}_{eN_{2,3}} = h^{\nu}_{\mu N_{2,3}} = 8 \times 10^{-3}$ and $m_N = 250$ GeV:

$$B(\mu \to e\gamma) \sim 7 \cdot 10^{-4} \times \frac{(h^{\nu}_{eN} h^{\nu}_{\mu N})^2 v^4}{m_N^4} \sim 10^{-12}\,.$$

Proposed experimental sensitivity to $B(\mu \to e\gamma)$ is $\sim 10^{-14}$, according to the MEG collaboration at the PSI.

- **Coherent $\mu \to e$ Conversion in Nuclei ($^{48}_{22}$Ti)**



$+ \quad (e \leftrightarrow e^-)$

$m_N = 250$ GeV:

$$B(\mu \to e) \;\approx\; 0.5 \times B(\mu \to e\gamma) \;\sim\; 5 \times 10^{-13} \,.$$

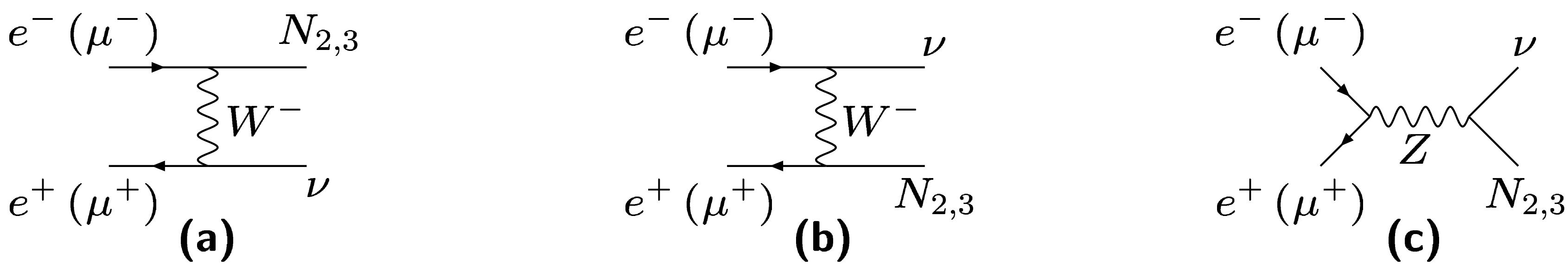
MECO collaboration at BNL will be sensitive to effects at the 10^{-16} level.

- $\mu \to eee$

$$B(\mu \to eee) \;\approx\; 1.4 \cdot 10^{-2} \times B(\mu \to e\gamma) \;\sim\; 1.4 \times 10^{-14} \,.$$

• Collider Heavy Majorana Neutrino Production

[For a recent study, see F. del Aguila and J.A. Aguilar–Saavedra, hep-ph/0503026]



Production cross section for $\sqrt{s} = 1$ TeV ($m_N = 200$–500 GeV):

$$\sigma(e^- e^+ \to N\nu) \;\sim\; 10^5 \times \frac{|h^\nu_{eN}|^2 v^2}{m_N^2} \quad \text{fb}$$

With total integrated luminosity 100 fb^{-1}, we get for $|h^\nu_{eN}| \sim 10^{-2}$ and $m_N \sim v \sim 200$ GeV, about 1000 events!

• Conclusions

- **Resonant Leptogenesis provides an interesting mechanism for generating our observable matter-dominated Universe.**

- **Final Baryon Asymmetry in the Universe is almost independent of the initial conditions.**
  This is due to quasi-in-equilibrium dynamics and the resonant lepton-to-antilepton conversion.

- **Improved Boltzmann equations derived.**
  Scale of leptogenesis can be lowered below the **TeV** energies, even close to $T_c \approx 130$ GeV, in complete agreement with the current neutrino data.

- **Calculable theoretical uncertainties at the $\sim$ 40% level.**
  Not included: thermal effects, Bose–Fermi statistics effects, higher-order corrections, $1 \leftrightarrow 3$ processes, . . .

- **Resonant τ-Leptogenesis could,** *in principle*, **provide a laboratory testable solution to the Baryon Asymmetry in the Universe.**