Gravitational Baryogenesis

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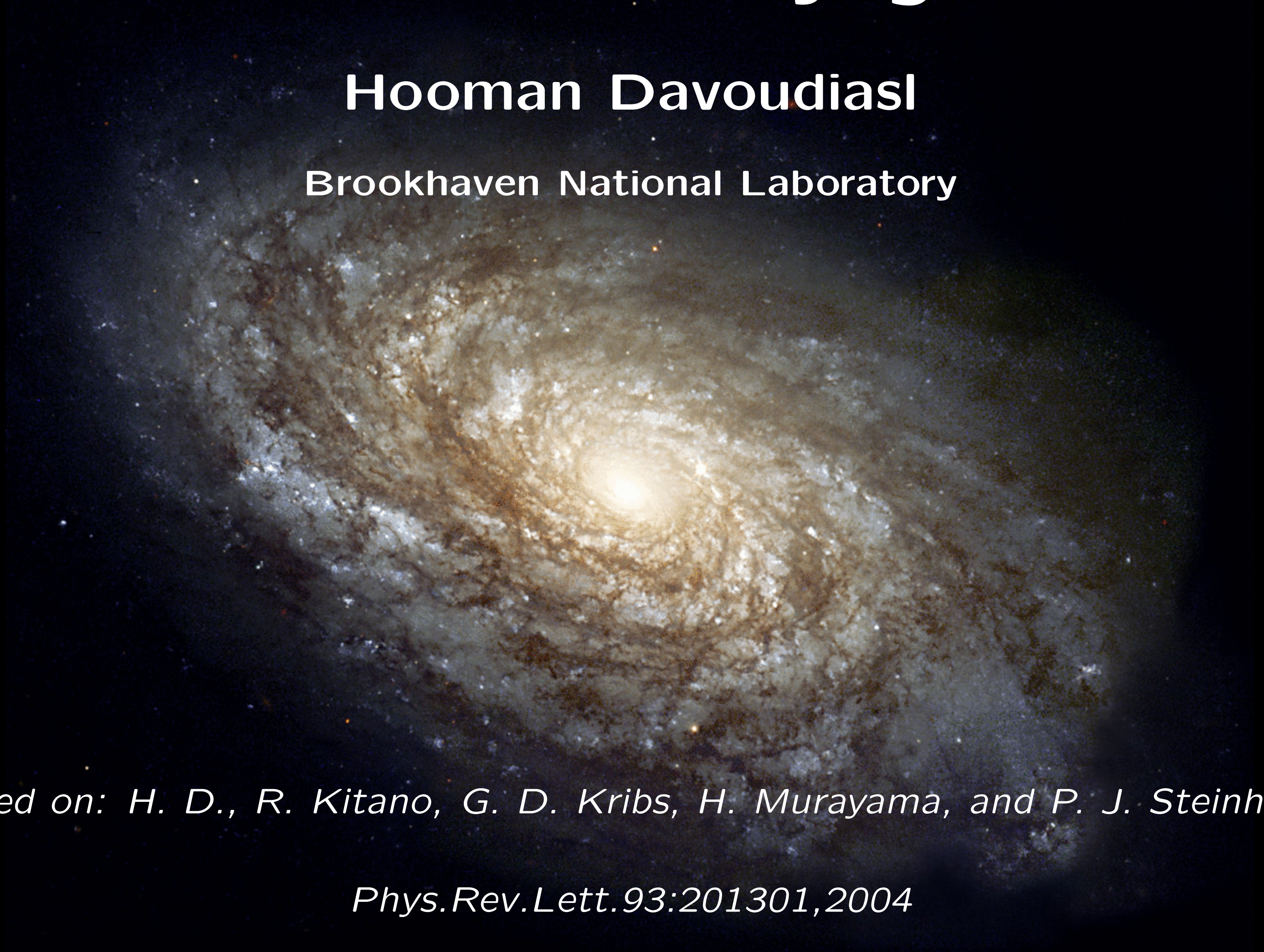

Based on: H. D., R. Kitano, G. D. Kribs, H. Murayama, and P. J. Steinhardt

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Baryogenesis Confronts Experiment

November 7–9, 2007, University of Chicago

Introduction:

- BBN, CMBR, lack of intense γ-rays: $\Delta B > 0$.

$$\boldsymbol{n_B/s = 9.2^{+0.6}_{-0.4} \times 10^{-11}}$$

- Origin of ΔB as yet unknown.

- **Sakharov's conditions:**

(i) $\not{C} \oplus \not{C}\!\not{P}$

(ii) $\not{B}$

(iii) $\neq$

- Not enough in SM: $\not{C}\!\not{P}$ and $\neq$ (EWSB, $m_H \lesssim 45$ GeV)

Strongly points to BSM.

- Explain why this tiny number is so large!

Consider the D=6 interaction:

$$\frac{1}{M_*^2}\int d^4x\sqrt{-g}(\partial_\mu \mathcal{R})J^\mu \qquad (\star)$$

- M_* is cutoff scale; $\mathcal{R}$ is Ricci scalar.

- $(\star)$, *e.g.*, via quantum gravity.

$M_* \sim M_P = (8\pi G_N)^{-1/2} \simeq 2.4 \times 10^{18}$ GeV

- J^μ a B (non-orthogonal to $B-L$) current.

Not erased by EW anomaly.

- $(\star)$, in vacuum, $C\!\!\!/P$, CPT-conserving.

- $(\star)$, *in expanding universe, CPT-violating.*

Dynamical CPT breaking:

$\mathcal{R}, \dot{\mathcal{R}} \neq 0$ bias energetics in favor of $\Delta B \neq 0$.

- Effectively a *chemical potential* for B:

$$\mu \sim \pm \dot{\mathcal{R}}/M_*^2$$

$\not{B} \Rightarrow \Delta B \neq 0$, *in equilibrium*.

$\not{B}$ decoupling at $T = T_D \Rightarrow$ net asymmetry:

$$\frac{n_B}{s} \approx \left. \frac{\dot{\mathcal{R}}}{M_*^2 T} \right|_{T_D} \qquad (\star\star)$$

Close relation to "Spontaneous Brayogenesis": Cohen, Kaplan (1987)

$(\partial_\mu \mathcal{R})J^\mu \to (\partial_\mu \phi)J^\mu$, ϕ a scalar.

- ϕ must be added by hand.

- ϕ must evolve homogeneously in a certain direction.

- ϕ must be spatially flat.

- ϕ oscillation $\to \langle \dot{\phi} \rangle = 0$, tends to cancel n_B.

Advantages of gravitational scenario:

- Time evolution of $\mathcal{R} \propto H^2$ and homogeneity from cosmology.

\- The universe is highly homogeneous.

- $\langle \dot{\mathcal{R}} \rangle \propto H^3 \neq 0$

For equation of state $w \equiv p/\rho$:

$$\dot{\mathcal{R}} = -(1-3w)\frac{\dot{\rho}}{M_P^2} = \sqrt{3}\,(1-3w)(1+w)\frac{\rho^{3/2}}{M_P^3} \qquad (\star\star\star)$$

Radiation Domination:

- For $w = 1/3$, $T^\mu_\mu = 0$ and $(\star\star\star) \rightarrow$ no effect.

$\mathcal{R} \propto T^\mu_\mu$ and $n_B/s \propto \dot{\mathcal{R}}$.

- However, QM $\Rightarrow T^\mu_\mu \propto \beta(g) F^{\mu\nu} F_{\mu\nu} \neq 0$

$1 - 3w = \frac{5}{6\pi^2}\frac{g^4}{(4\pi)^2}\frac{(N_c+\frac{5}{4}N_f)(\frac{11}{3}N_c-\frac{2}{3}N_f)}{2+\frac{7}{2}[N_c N_f/(N_c^2-1)]}$ $\quad$ $SU(N_c)$ plasma, coupling g, N_f flavors.

Kajantie, Laine, Rummukainen, Schroeder (2003)

Generic gauge and matter content $\Rightarrow$ $\mathbf{1 - 3w \sim 10^{-2}\text{–}10^{-1}}$

The asymmetry is given by:

$$\boldsymbol{\frac{n_B}{s} \approx (1 - 3w)\frac{T_D^5}{M_*^2 M_P^3}}$$

- Tensor mode constraints on inflationary scale:

$$M_I \leq 3.3 \times 10^{16}\ \text{GeV}$$

- $T_D < T_{RD} < M_I$ (T_{RD}: Reheat Temperature)

For $M_* \simeq M_P$ we need $T_D \simeq M_I(max)$.

- *Tensor modes nearly observable.*

Matter Domination

- $w = 0$, reheating via oscillating inflaton.

- Decay rate Γ; reheat when $H \simeq \Gamma \simeq T_{RD}^2/M_P$.

$$\rho_{osc} \simeq T_{RD}^4 \left(\frac{a_{RD}}{a}\right)^3 \quad ; \quad \rho_R \simeq T_{RD}^4 \left(\frac{a_{RD}}{a}\right)^{3/2}$$

- $T \simeq T_{RD}(a_{RD}/a)^{3/8}$, $\quad T_D > T_{RD}$, $\quad$ Entropy dilution $(T_{RD}/T_D)^5$

$$\frac{n_B}{s} \simeq \frac{T_D^6}{M_*^2 M_P^3 T_{RD}}$$

- $T_{RD} \gtrsim 10^{-2} T_D$ (linear approximation)

$$\boldsymbol{\frac{n_B}{s} \lesssim 10^2 \frac{T_D^5}{M_*^2 M_P^3}}$$

- 10^{3-4} enhanced relative to $w = 1/3$, allows $T_{RD} \simeq 10^{14}$ GeV.

$w > 1/3$ Scenarios (Kinetic-Domination):

- Redshifts *faster* than sub-dominant radiation:

$$\rho_\phi \sim a^{-3(1+w)} \quad ; \quad \rho_R \sim a^{-4}$$

- No need for more entropy to enter radiation-domination.

- n_B/s set at T_D, remains constant.

- Scalar ϕ

E.g., Ekpyrotic, cyclic, inflaton that falls steeply and shoots out.

- $V(\phi) = \lambda\phi^{2N}/M_P^{2N-4} \Rightarrow w = (N-1)/(N+1)$:

$$1/3 < w \leq 1, \text{ for } N > 2 \qquad \text{(Turner, 1983)}$$

The asymmetry

$$\frac{n_B}{s} \sim \frac{T_D^8}{M_*^2 M_P^3 T_{RD}^3} \left(\frac{T_{RD}}{T_D}\right)^{9(1-w)/2} .$$

Significantly enhanced relative to $w = 1/3$: $(T_D/T_{RD})^{3(3w-1)/2}$

- Focus henceforth.

B-violation:

$[\mathcal{O}_{\not B}] = 4 + n \Rightarrow \Gamma_{\not B} = T^{2n+1}/M_B^{2n}$

$\not B$ decoupling: $\Gamma_B < H \sim (T_{RD}^2/M_P)(T/T_{RD})^{3(1+w)/2}$.

$$T_D \sim T_{RD} \left(\frac{M_B^{2n}}{M_P \, T_{RD}^{2n-1}}\right)^{2/(4n-3w-1)}$$

SUGRA: gravitino bound on T_{max} from (I) BBN, (II) Overclosure.

$$Y_{3/2} = \frac{n_{3/2}}{s} \sim 10^{-4} \frac{T_{RD}}{M_P} \left(\frac{T_{max}}{T_{RD}}\right)^{3(1-w)/2}$$

$m_{3/2} \gtrsim 100$ TeV avoids (I).

(II) constrains LSP's from gravitinos:

$Y_{3/2} < 4 \times 10^{-12} (100 \text{ GeV}/m_{LSP})$

$m_{\text{LSP}} = 100$ GeV (dark gray).

$[\mathcal{O}_{\not{B}}] = 5$

Typical $M_B \sim 10^{14}$ GeV.

M_B: Majorana m_ν via seesaw.

Roughly degenerate $m_\nu \gtrsim 0.1$ eV:

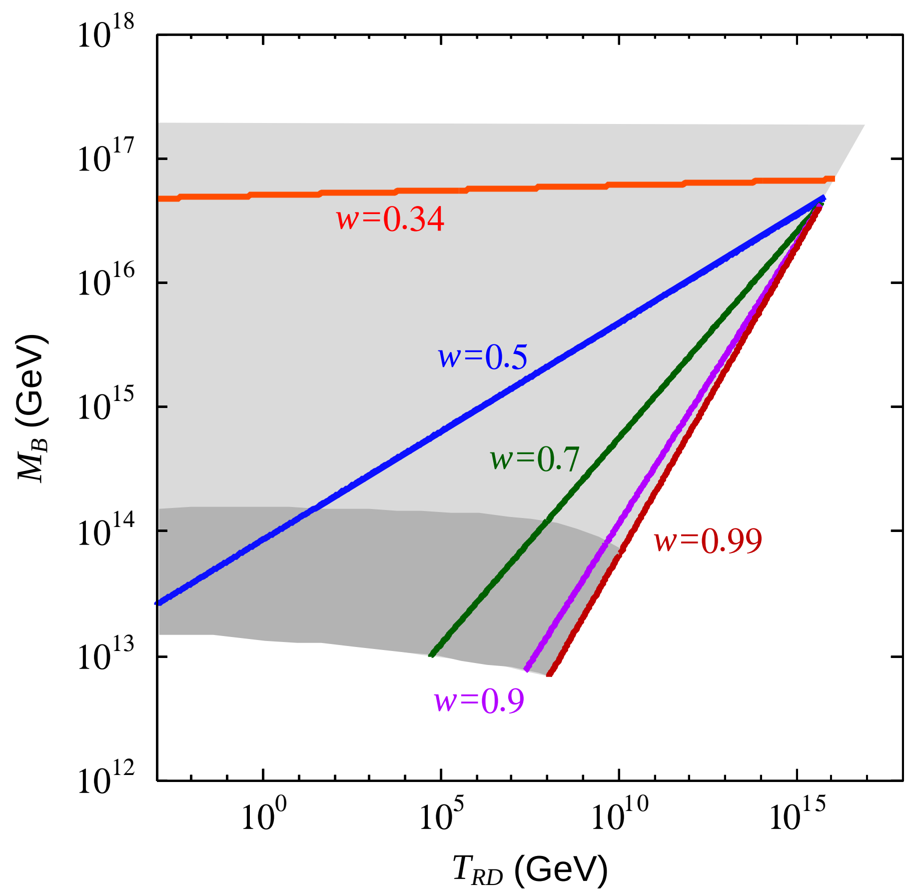
Near future ($0\nu\beta\beta$) experiments.

Contrast: thermal leptogenesis:

$\rightarrow m_\nu \leq 0.11$ eV

Buchmuller, Di Bari, Plumacher, (2003)

$T_{max} = T_D$; $n_B/s \sim 10^{-10}$



Entire shaded region:

$\not{R}$, LSP decay before BBN, or

$m_{\mathrm{LSP}} \ll 100$ GeV, or

$m_{3/2} \ll$ keV, or

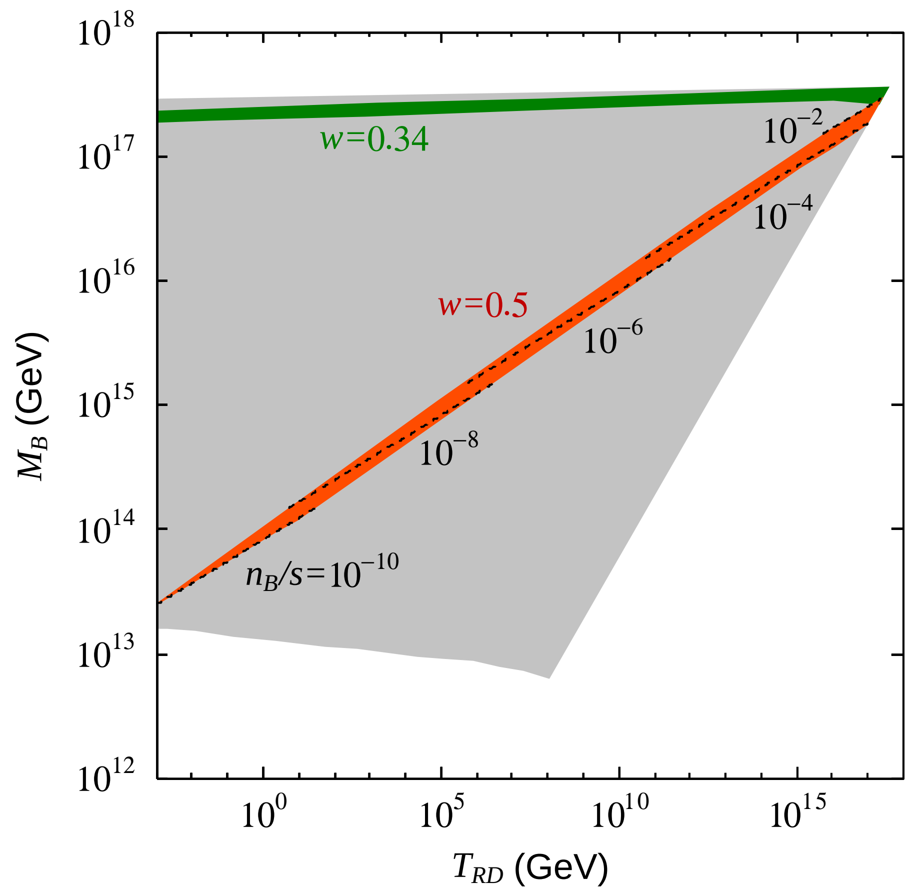
No SUSY.

- Allow entropy production below T_D.

- Dilute gravitinos and n_B/s:

larger viable parameter space.

Other parameters as before.



Conclusions

- **Gravitational Baryogensis:** $\not{C}\not{P}$ from gravity.

- Dynamical CPT violation from $\not{C}\not{P}$ by cosmic expansion.

- Relative energies of particles and antiparticles dynamically shifted.

- CP-conserving $\not{B}$ generates $\Delta B \neq 0$ *in equilibrium*.

- Frozen asymmetry when $\not{B}$ turns off.

- Sufficient n_B/s can be generated for $w = 0, \approx 1/3, \in (1/3, 1]$.

- For $w \in (1/3, 1]$, in particular, gravitino bounds accommodated.