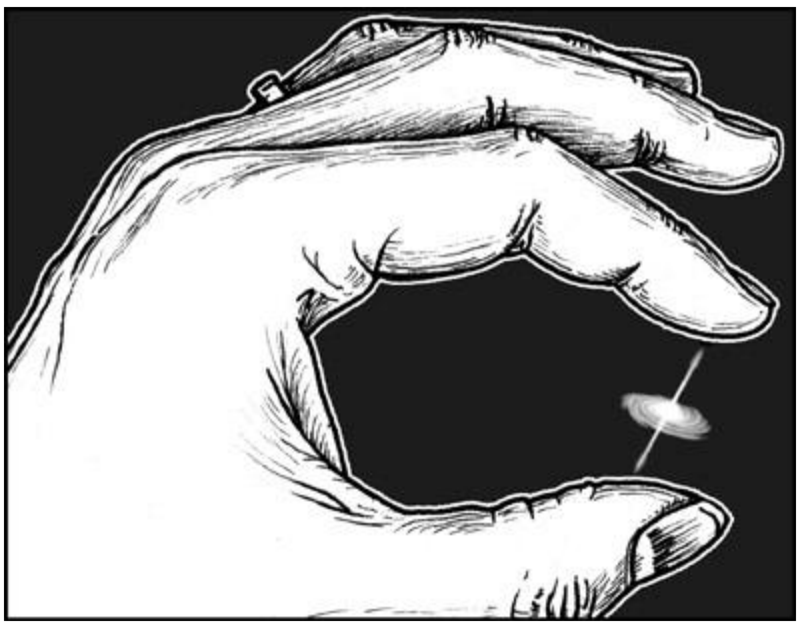
Electroweak baryogenesis with very small CP angle by primordial black holes in braneworld



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Electroweak baryogenesis with very small CP angle by primordial black holes in braneworld

- Baryogenesis is a key issue of cosmology and still open
- Baryogenesis (EW) by primordial black holes in 4d

  - the observed baryon number produced only for large $\Delta\theta_{CP}$

  - Era of black holes domination required
- Brane cosmologies with a high energy regime (RS II): intense <u>accretion</u>

Overview

- The universe is a 4d brane embedded in 5d AdS bulk (RS II)
- Very small PBHs are produced just after the inflation, during the high energy regime of the braneworld.
- During this high energy regime accretion can lead to BH dominated universe.

Overview

- The Hawking radiation thermalizes a spherical region around each PBH to T>100GeV. The symmetry there is restored.
- A domain wall is created, separating the symmetric from the asymmetric region.
- The sphaleron process at the domain wall satisfies the three Sakharov's criteria for baryogenesis:

- it is a baryon violating mechanism
- it is assumed a 2 – Higgs doublet extension ,which provides CP violating phase in the Higgs VEV
- the BH radiation is out of equilibrium

Overview

- The phase transition is of second order
- Accretion plays a dual role supporting baryogenesis:

- It leads to a BH dominated universe
- It prolongs the BH lifetime and so the duration of the baryogenetic mechanism.

Baryogenesis in the standard 4-dim FRW universe

- Y. Nagatani in Phys. Rev. D59: 041301, 1999 showed the possibility of EW baryogenesis by small PBHs in the standard 4-d FRW universe.
- In the present work we improve and extend his idea:

1. We correct a mistake in the 4-d and find new corrected bounds for the masses of the PBHs.
2. We extend his idea to brane cosmology with two successes:

- justification of the BH – dominated era
- efficient baryogenesis for small CP violating angles

Baryogenesis in the braneworld

- Brane Black Holes involved in the proposed mechanism are small enough to ensure that Hawking temperature TBH is much greater than the electroweak critical temperature
- All kinds of SM particles are emitted, on the brane. On the contrary, at bulk only gravitons are emitted.
- The emission on the brane causes the thermalization of a region around the BH.

Baryogenesis in the braneworld

- Local thermalization region around the BH: particles have a mean free path smaller than the size of this region.
- A stationary spherical symmetric solution is

$$T(r) = \left[T_{br}^3 + (T_o^3 - T_{br}^3)\frac{r_o}{r}\right]^{1/3}$$

Baryogenesis in the braneworld

The outgoing diffusion flux must be equal to the Hawking radiation flux and thus we get T_s, the temp of the minimum thermalised sphere. The flux to the bulk can be neglected due to the small value of g_{bulk}.

The spherical thermal distribution surrounding the black hole is

$$T(r) = \left(T_{br}^3 + \frac{9}{256\pi^2} \frac{1}{\beta} \frac{T_{\rm BH}^2}{r} \right)^{1/3}$$

Baryogenesis in the braneworld

The asymmetric minimum for the second doublet is

$$|\langle\phi(r)\rangle| = v f(r),$$

$$f(r) = \begin{cases} 0 & (r \le r_{\rm DW}) \\ \sqrt{1-\left(\frac{T(r)}{T_{\rm W}}\right)^2} & (r > r_{\rm DW}) \end{cases}$$

Baryogenesis in the braneworld

- In this configuration of the Higgs VEV, the width of our domain wall d_{DW} is proportional to the radius of the symmetric region r_{DW}. By $T(r_{DW}) = T_W$ it is

$$d_{\rm DW} = \xi\, r_{\rm DW} = \xi \frac{9}{256\pi^2} \frac{1}{\beta_{br}} [1 - (T_{br}/T_{\rm W})^3]^{-1} \frac{T_{\rm BH}^2}{T_{\rm W}^3}$$

First Constraint from Thermalization Condition without accretion

A first constraint is that domain wall width must be larger than the MFP ($d_{DW} > \lambda_s(T_W)$).

$$\left(\frac{3}{16\pi}\right)^2 \frac{\xi}{\beta_s \beta \gamma} \frac{T_{\mathrm{BH}}^2}{T_{\mathrm{W}}^2} > 1$$

$$m_{BH} = \frac{3}{32\pi} \frac{m_5^3}{T_{BH}^2}$$

$$m_{BH} < \frac{\xi}{2} \left(\frac{3}{16\pi}\right)^3 m_5^3 \, T_W^{-2} \, (\beta_s \beta \gamma)^{-1}$$

First Constraint from Thermalization Condition without accretion

m_5	$\xi = 1$	$\xi = 10$
50 TeV	$m_{BH} < 1.3$ TeV	$m_{BH} < 13$ TeV
100 TeV	$m_{BH} < 10.6$ TeV	$m_{BH} < 106$ TeV
1000 TeV	$m_{BH} < 1.06 \times 10^4$ TeV	$m_{BH} < 1.06 \times 10^5$ TeV
5000 TeV	$m_{BH} < 1.33 \times 10^6$ TeV	$m_{BH} < 1.33 \times 10^7$ TeV
10000 TeV	$m_{BH} < 1.06 \times 10^7$ TeV	$m_{BH} < 1.06 \times 10^8$ TeV

Second Constraint from BH Lifetime without accretion

Black-hole lifetime must be large enough to keep the stationary electroweak domain wall ($t_{evap} > \tau_{DW}$).

The characteristic time scale of the stable electroweak domain wall is:

$$\tau_{\rm DW} \simeq r_{\rm DW}/v_{\rm DW} \quad = \quad \frac{729}{262144\pi^4}\frac{1}{\beta_{br}^3\gamma^3}\frac{T_{\rm BH}^4}{T_{\rm W}^5},$$

Neglecting the evaporation to bulk, the black hole lifetime is

$$t_{evap} \simeq \tilde{g}^{-1}\frac{l}{l_4}\left(\frac{m_{BH}}{m_4}\right)^2 t_4$$

Second Constraint from BH Lifetime without accretion

$$\tilde{g} \simeq \frac{1}{160} g_{brane} + \frac{9\,\zeta(5)}{32\pi^4} g_{bulk}$$

$$m_{BH} > \tilde{g}^{1/4} \frac{6561^{1/4}}{2^7 \pi^{3/2}} \left(\beta\gamma\right)^{-3/4} m_5^{9/4} T_W^{-5/4}$$

The above constraint is the most strict one. It can be naturally relaxed if the black hole is allowed to accrete plasma from its neighbourhood.

Second Constraint from BH Lifetime without accretion

m_5	Black hole mass bound
50 TeV	$m_{BH} > 42.9$ TeV
100 TeV	$m_{BH} > 204$ TeV
1000 TeV	$m_{BH} > 3.6 \times 10^4$ TeV
5000 TeV	$m_{BH} > 1.35 \times 10^6$ TeV
10000 TeV	$m_{BH} > 6.45 \times 10^6$ TeV

Baryogenesis without accretion

$$\dot{B} = -V \frac{\Gamma_{\rm sph}}{T_{\rm W}} \mathcal{N} \dot{\varphi}$$

$$= -\frac{1}{16\pi} \mathcal{N} \kappa \, \alpha_{\rm W}^5 \, \epsilon \, \Delta\varphi_{\rm CP} \frac{T_{\rm BH}^2}{T_{\rm W}}$$

- Γ_{sph} is the sphaleron transition rate
- N ≈ O (1) is a model dependent constant
- κ ≈ O (30) is a numerical constant expressing the strength of the sphaleron process
- $\Delta\varphi_{CP}$ is the net CP phase

Baryogenesis without accretion

We use

$$T_{\rm BH} = \sqrt{\frac{3}{32\pi}}\tilde{g}^{-1/4} m_5^{3/4} t_{evap}^{-1/4}$$

and we integrate for the BH lifetime. It becomes

$$B \;=\; \frac{3}{(16\pi)^2} \mathcal{N}\, \kappa\, \alpha_W^5\, \tilde{g}^{-1}\, T_W^{-1} \epsilon\, \Delta\varphi_{CP}\, m_{\rm BH}$$

The total baryon number created from all black holes is
$b = B\, \rho_{BH}/m_{BH}$

Baryogenesis without accretion

The universe is considered BH dominated. At reheating from BHs annihilation it turns to radiation dominated

$$\rho_{BH}\left(t_{reh-}\right) \simeq \rho_{rad}\left(t_{reh+}\right) = \frac{\pi^2}{30} g_{reh} T_{reh}^4$$

$T_{reh} \approx 95GeV < 100GeV$ and $g_{reh} \approx 10$ is the massless degrees of freedom. The entropy is

$$s = \frac{2\pi^2}{45} g_{reh} T_{reh}^3$$

Baryogenesis without accretion

Thus, the baryon to entropy ration is

$$\frac{b}{s} = \frac{9}{(32\pi)^2}\mathcal{N}\kappa\alpha_W^5\tilde{g}^{-1}\frac{T_{reh}}{T_W}\epsilon\Delta\varphi_{CP}$$

Notice that it does not depend neither to m_5 nor to m_{BH}

Baryogenesis without accretion

$$\Delta\varphi_{CP} = \pi \Rightarrow \frac{b}{s} = 1.2 * 10^{-10}$$
$$\Delta\varphi_{CP} = 0.1 \Rightarrow \frac{b}{s} = 4 * 10^{-12}$$

The produced baryon to entropy value gets close to the observed b/s = 6 x 10^{-10}, but only for the maximum and not likely $\Delta\varphi_{CP} = \pi$.

Baryogenesis and constraints ***<u>with accretion</u>***

- At the high energy regime of a brane cosmology accretion is intense. It is expected to lead to

  - BH domination

  - efficient baryogenesis
- A phenomenological way to handle accretion is to introduce an effective factor f > 1 which denotes how much longer becomes the lifetime of the black hole

$$\tau_{BH} = f \tilde{g}^{-1} \, m_5^{-3} \, m_{BH}^2$$

Baryogenesis and constraints with accretion

Now, the produced baryon number is modified to

$$B = \frac{3f^{1/2}}{(16\pi)^2} \mathcal{N} \, \kappa \, \alpha_W^5 \, \tilde{g}^{-1} \, T_W^{-1} \, \epsilon \, \Delta\varphi_{CP} \, m_{\rm BH}$$

In order to have b/s = 6 x 10^{-10}, it must be

$$\begin{aligned}
\Delta\varphi_{CP} &= 1 \Rightarrow f \simeq 2 * 10^2 \\
\Delta\varphi_{CP} &= 0.1 \Rightarrow f \simeq 2 * 10^4 \\
\Delta\varphi_{CP} &= 0.01 \Rightarrow f \simeq 2 * 10^6
\end{aligned}$$

Baryogenesis and constraints with accretion

Such values of f can naturally be realised. It is very easy to produce large values of baryon asymmetry and even larger than the required amount, for very small values of $\Delta\varphi_{CP}$

Baryogenesis and constraints with accretion

The first constraint remains intact. The second bound becomes less strict because the black hole lifetime is lengthened.

$$m_{BH,i} > f^{-1/4}\,\tilde{g}^{1/4}\,\frac{6561^{1/4}}{2^7\pi^{3/2}}\,(\beta\gamma)^{-3/4}\;m_5^{9/4}\,T_W^{-5/4}$$

Baryogenesis and constraints with accretion

m_5	f	Initial black hole mass
50 TeV	$2 \times 10^2 \, (\Delta\varphi_{CP} = 1)$	$m_{BH,i} > 11$ TeV
50 TeV	$2 \times 10^4 \, (\Delta\varphi_{CP} = 0.1)$	$m_{BH,i} > 3.5$ TeV
50 TeV	$2 \times 10^6 \, (\Delta\varphi_{CP} = 0.01)$	$m_{BH,i} > 1.12$ TeV
100 TeV	$2 \times 10^4 \, (\Delta\varphi_{CP} = 0.1)$	$m_{BH,i} > 17$ TeV
100 TeV	$2 \times 10^6 \, (\Delta\varphi_{CP} = 0.01)$	$m_{BH,i} > 5.3$ TeV

Baryogenesis and constraints with accretion

Taking into consideration both first and second constraint

- for m_5 = 50 TeV and $\Delta\varphi_{CP} = 0.01$

$$1.1 \text{ TeV} < m_{BH} < 13 \text{ Tev}$$

- for m_5 = 100 TeV and $\Delta\varphi_{CP} = 0.01$

$$5.3 \text{ TeV} < m_{BH} < 106 \text{ Tev}$$

Increasing f the allowed mass region can be enlarged even for smaller values of CP.

Baryogenesis and constraints with accretion

In the present case, because of the accretion, the range of allowed mass has the following meaning:

- The lower bound is the minimum BH mass, at the beginning of the accretion
- The upper bound is the maximum mass that the black hole may reach due to accretion.

Baryogenesis and constraints with accretion

An extreme case is when accretion is stronger than evaporation and continues till tc, while afterwards evaporation is the dominant term.

$$\tau_{BH} = t_c + \tilde{g}^{-1} m_5^{-3} m_{BH,max}^2 = \frac{1}{2}\frac{m_4^2}{m_5^3} + \tilde{g}^{-1}\frac{m_{BH,max}^2}{m_5^3}$$

where m_{BH} is now the black hole mass at t_c.
For $m_{BH} < m_4$ which is always the case in the present study, it is $\tau_{BH} \approx t_c$

Baryogenesis and constraints with accretion

the baryon number produced by a black hole becomes

$$B = \frac{3/\sqrt{2}}{(16\pi)^2}\tilde{g}^{-1/2}\mathcal{N}\kappa\alpha_w^5\epsilon\Delta\varphi_{CP}T_W^{-1}m_4$$

For b/s ≈ 6 x 10^{-10}

$$\begin{aligned}
m_{BH,max} &= 10^4 TeV \Rightarrow \Delta\varphi_{CP} = 10^{-11} \\
m_{BH,max} &= 10 TeV \Rightarrow \Delta\varphi_{CP} = 10^{-14} \\
m_{BH,max} &= 1 TeV \Rightarrow \Delta\varphi_{CP} = 10^{-15}.
\end{aligned}$$

Baryogenesis and constraints with accretion

The second constraint is always satisfied since now t_c is very large

- i.e. for m_5 = 100TeV , m_{BH} = 10 TeV, $t_c/t_{evap} = 10^{29}$

Successful baryogenesis may be achieved for very small values of CP angles, that may be provided also from other phenomenological models than the Two Higgs model.

- Some of the evaporated radiation that carries baryon asymmetry may be eaten by the BHs during accretion.
- This is not expected to be significant because:

\- the Hawking radiation has the escape velocity from the gravitational field.

\- BHs are assumed widely separated.

Conclusions

- The baryogenesis by very small primordial black holes in braneworld is very efficient even for small CP angles.
- The phase transition needs not to be of first order.
- The allowed by the mechanism BH mass range remarkably coincides with the mass spectrum that is energetically possible to be produced in TeV gravities.
- Baryogenesis is easier than in the standard 4d universe because of the accretion.
- The Higgs sector has not to be necessarily that of the two – Higgs model.

Conclusions

- The universe doesn’t need to be BH dominated at the time of the BHs creation. Because of the accretion it can become later. It is even possible the baryon asymmetry to be produced without BHs domination.
- The key point of producing large baryon number is the accretion because of a high energy regime with an unconventional expansion rate. Any cosmological model with this feature can also give efficient baryogenesis.