Baryon Anti-Baryon Segregation in Early Universe due to Spontaneous CP Violating Z(3) Walls

Abhishek Atreya

Institute Of Physics
Bhubaneswar.

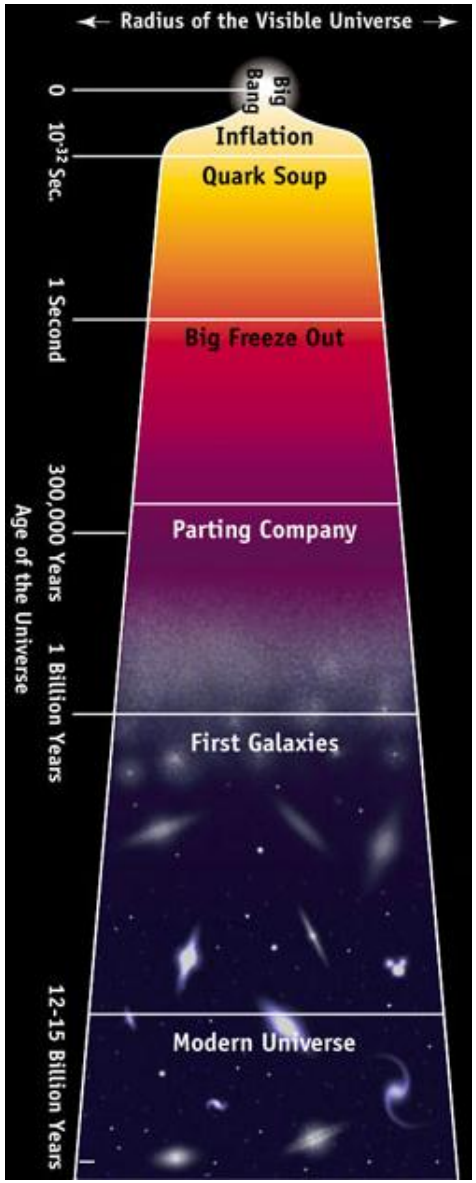
Collaborators:- Anjishnu Sarkar, Ajit M. Srivastava

Matter Under Extreme Conditions, Kolkata

Outline

1. QCD Phase Transition and Early Universe
   - Witten's Scenario
2. $Z(N)$ Domain
   - $Z(N)$ Symmetry
   - CP Violation
3. Nuggets Anti-Nuggets Formation
   - Formation and Evolution
   - Baryon Anti-Baryon Segregation
   - Implications

Evolution of Universe



Quark – Gluon Plasma

- Deconfined Phase; Free quarks and gluons

⟵ Hadronization

- Confined Phase; Hadron formation

⟵ Nucleosynthesis

- Helium Nuclei formed; Decoupling of Photons

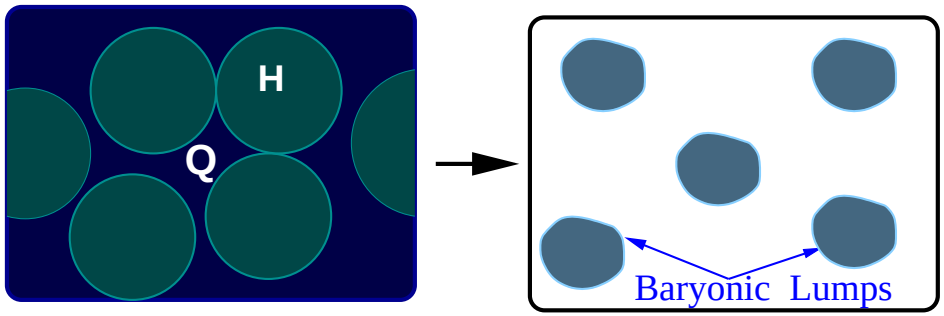
⟵ Star Formation

- Galaxy formation

⟵ Present Universe

Quark Nuggets

- Formation of stable quark nuggets during the phase transition [1].
- If QCD phase transition is first order, then the bubbles of Hadronic phase will form in the QGP Phase.
- As Universe cools, Hadronic bubbles will expand, and coalese.
- The QGP region will shrink, in the process trapping the baryons inside them.



[1] E. Witten, Phys.Rev. D32, (1984)

Why First Order?

- Provides with an interface between two region of the universe while being in thermal equillibrium.
- Baryon excess in the collapsing domains is due to the baryon transport across the phase boundary.
- Not Possible in a cross-over or Second order transition.

[2]Gorham PRD 83, 123005; Astone et al arXiv:1306.5164
[3]Berilenkov et al arXiv:1304.7521

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- Even now there are attempts to detect these objects [2].
- They have been proposed as the dark matter and dark energy candidates [3].

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[3] Berilenkov et al arXiv:1304.7521

$Z(N)$ Interfaces

- The interface between two regions of universe need not be from the phase boundary.
- $Z(N)$ interface provide us with an attractive alternative to the phase boundary as proposed by Witten.
- $Z(3)$ domain walls can lead to baryon inhomogeneity generation[5].
- Possibility of quark nuggets formation irrespective of the order of Phase transition.
- In this talk we will discuss a scenario where one can form not only nuggets but also anti nuggets due to the baryon transport across the QCD $Z(3)$ domain walls.

[5] Layek et al PRD 71, 070415 (2005)

Order Parameter

- Polyakov Loop is defined as

$$L(x) = \frac{1}{N} Tr\left[\mathbf{P} exp\left(ig \int_0^\beta A_0(\vec{x}, \tau) d\tau\right)\right]$$

- Related to free energy of a test quark by $\langle L(\vec{x})\rangle = e^{-\beta \Delta F}$.
- Under Z(N), $L(\vec{x}) \longrightarrow z \times L(\vec{x})$.
- $Z(N)$ is the Center of $SU(N)$ with $z = e^{i\phi}\mathbf{1}$.
  $\phi = 2\pi m/N; m = 0, 1 \ldots (N-1)$

Degeneracy and Interfaces

- N -fold degeneracy of ground states.
- Domains with different $L(\vec{x})$ values will be formed.
- Interfaces exist between different domains.

Pisarski Potential[3]

$$V(L) = \left(-\frac{b_2}{2}|L|^2 - \frac{b_3}{6}\left(L^3 + (L^*)^3\right) + \frac{1}{4}(|L|^2)^2\right) b_4 T^4$$

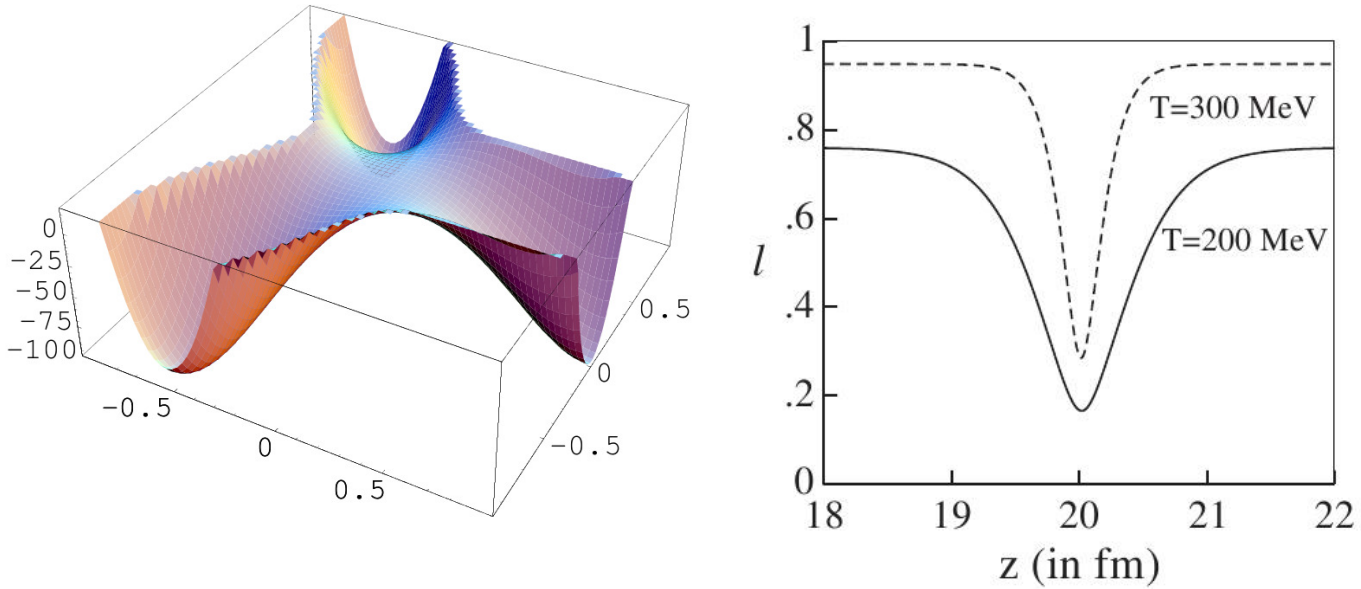

Figure: *Left*:-*Surface plot of the potential.* *Right*:- $L(x)$ *profile.*

[3]PRD 62,111501 (2000), Phys, Lett. B 504, (2001); PRD 66, (2000); Nucl. Phys. A 698 (2002)

CP Violation

- CP Violation in SM due to thermal effects of the phase of Wilson line [6].

$$V_0 \equiv g\mathcal{A}_0 + gA_0 + g'B_0.$$

- Computed the free energy, in perturbation theory.
- There are long lived metastable states.
- Metastable states are *not* CP self-conjugate. CP Violation!
- They then show that non-zero value of the Higgs field forces the phase of the Wilson line either to be zero or in the metastable minimum.

[6] KorthalAltes, Lee, Pisarski, PRL 73, 1754 (1994)

CP Violation

- Dirac eqn in $1+1$ dim Euclidean space is[7]:

$$\left[\gamma_e^0 \partial_0 \delta^{jk} + ig\gamma_e^0 A_0^{jk}(z) + \gamma_e^3 \partial_3\right]\psi_k = 0$$

  where $\gamma_e^0 \equiv \gamma^0$ and $\gamma_e^3 \equiv i\gamma^3$ are Euclidean Dirac matrices.

- $\psi_{1,4}(z) = N \times exp\left[\int_z \left(\pi T - A_0(\zeta)\right) d\zeta\right] exp\left(-\pi i T \tau\right)$

CP Conjugate and Density

- If ψ localizes then its CP conjugate $\gamma^0\gamma^2\psi^*$ does not.
- Density $\left(\psi^\dagger\psi\right)$ is static and localized.

[7] Korthal Altes and Watson, PRL 75, 2799 (1995)

A_0 Profile[8]

$$A_0 = \frac{2\pi T}{g}\left(\frac{a}{3}\lambda_3 + \frac{b}{3}\lambda_8\right)$$

λ_3 and λ_8 are Gell-Mann matrices.

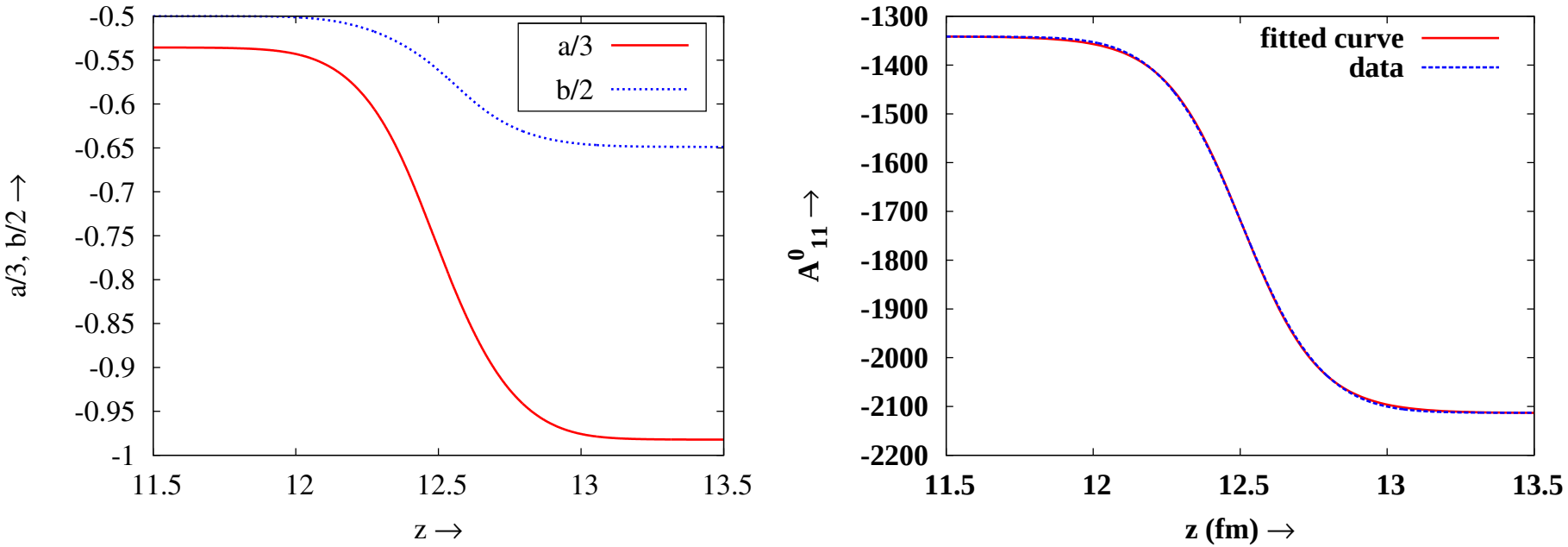

Figure: Left: a and b profile. Right: A_0 Profile

[8] Atreya, Sarkar and Srivastava, PRD 85, 014009 (2012)

Physical Picture

1. Domain Wall Formation

- As inflation ends, universe reheats to a temperature above Quark-Hadron transition.
- A network of $Z(N)$ interfaces is formed.
- Regions enclosed by domain wall start shrinking.

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2. Scattering From Interfaces

- Due to CP violating effects, quarks and anti-quarks scatter differently from interfaces.
- Results in segregation of Baryon number.

Physical Picture

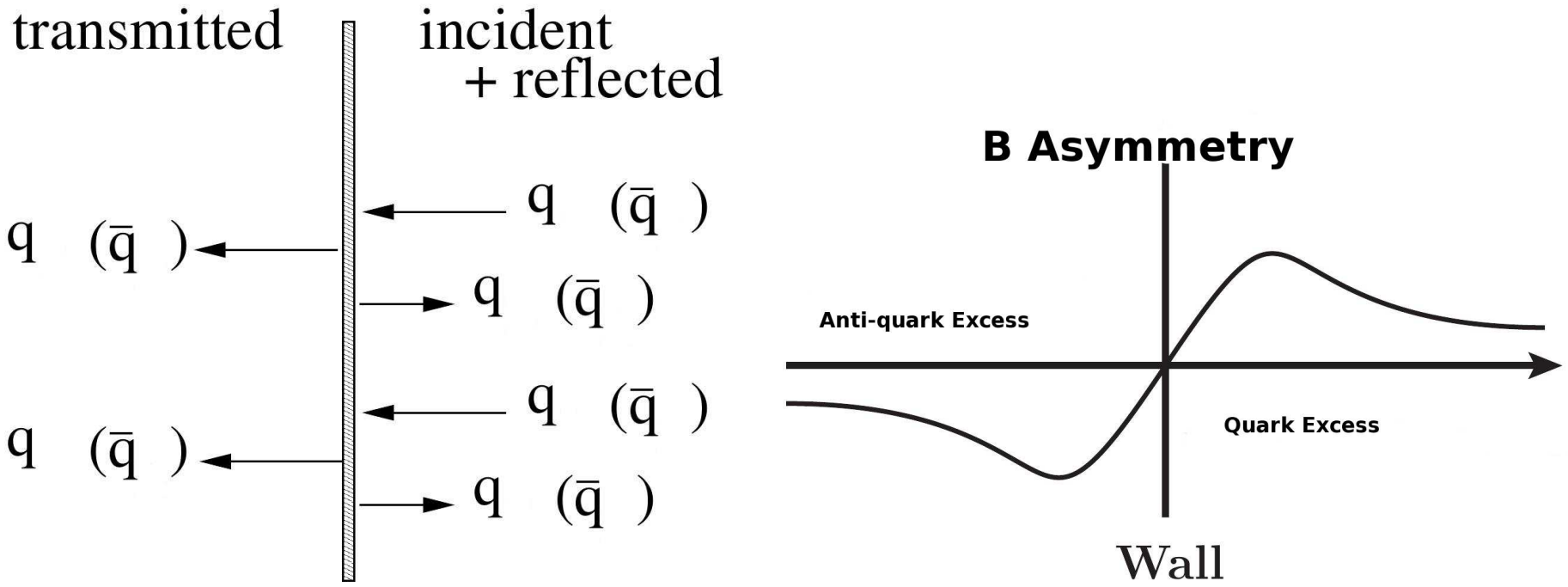

Figure: Left: CP violating scattering of quarks (anti-quarks) from domain wall. Right: Resulting B asymmetry.

Number Density Evolution

Total number of particle inside the wall

$$N_i = n_i V_i$$

$$\Rightarrow \dot{N}_i = \dot{n}_i V_i + n_i \dot{V}_i$$

$$\dot{N}_i = \left(\underbrace{-\frac{2}{3} v_w T_w n_i}_{\Downarrow} + \frac{v^o_{rel} n_o T_{(-)}}{6} - \frac{v^i_{rel} n_i T_{(+)}}{6} \right) S$$

$$\underbrace{\qquad\qquad\qquad\qquad}_{\textit{Inside quarks moving parallel to wall}}$$

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$$\dot{n}_o = \left(\frac{2}{3} v_w T_w n_i - \frac{v^o_{rel} n_o T_{(-)} - v^i_{rel} n_i T_{(+)}}{6}\right)\frac{S}{V_o} + n_o \frac{\dot{V}_i}{V_o}$$

$$R(t) = \frac{t}{N_d^{1/3}} - v_w (t - t_0)$$

Baryon Anti-Baryon Segregation

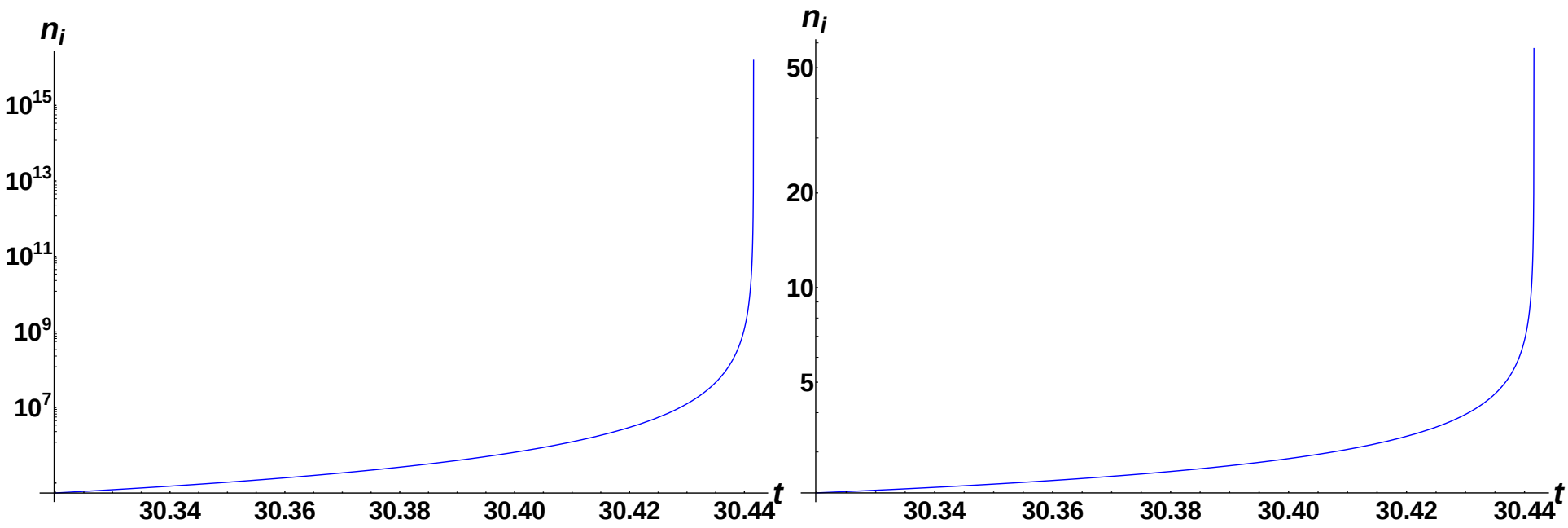

Figure: Evolution of number densities inside the domain wall. Left: For charm-quark. Right: For anti-charm.

Baryon Density Profile

$$\rho(R) = \frac{\dot{N}_i}{4\pi v_w R^2}$$

- $n_b \sim 10^{52} - 10^{53}$ for $R < 1\ m$.

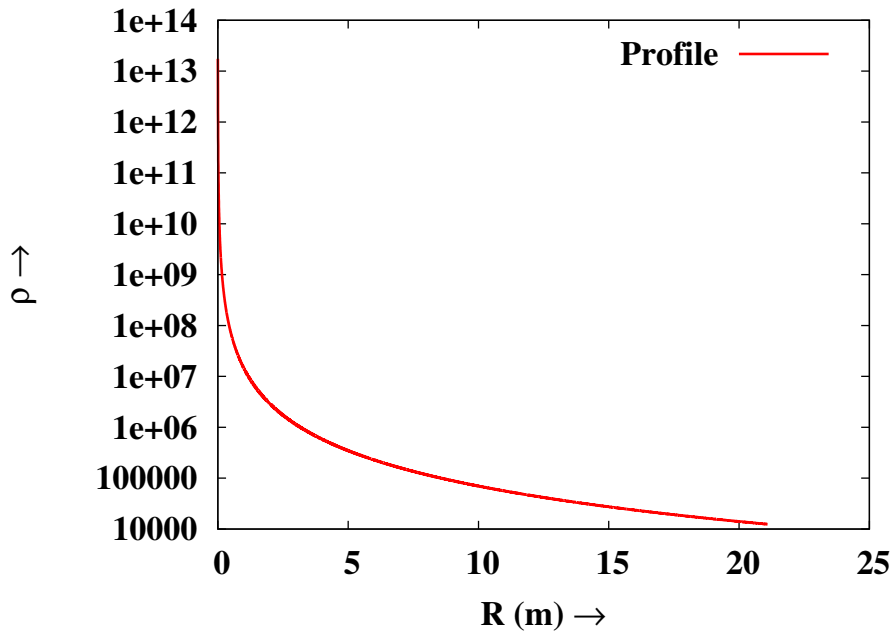

Figure: Baryon density left behind by collapsing wall.

Implications

- Dark Matter candidates within the standard model of particle physics.
- Quark nuggets may act as the seed for Black hole formation[10].
- Important role in the structure formation.
- Inhomogeneties produced near QCD Phase transition can modify the dynamics of QCD phase transition[11].
- The over-densities which are produced near the electro-weak transition can alter the baryogenesis scenario.
- ...

[10] Lai and Xu, arXiv:0911.4777
[11] S. Sanyal PRD 67, 074009 (2003)

Thank You !