Q-balls and LIGO/VIRGO gravitational wave signals

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Motivation

There are several unusual gravitational wave signals detected by LIGO/VIRGO from stellar-mass mergers:

- GW190814: $20M_\odot$ and $2.5M_\odot$;
- GW200105: $9M_\odot$ and $2M_\odot$;
- GW200115: $6M_\odot$ and $1.5M_\odot$.

One of the objects in such signals lies in the black holes (BH) mass gap and possible explanation is **Q-balls of dark matter**.

R. Abbott et al, AJL (2021)

Model: Lagrangian

Friedberg–Lee–Sirlin Lagrangian:

$$\mathscr{L} = \frac{1}{2}(\partial_\mu \varphi)^2 - U(\varphi) + (\partial_\mu \chi)^* \partial_\mu \chi - h^2 \varphi^2 \chi^* \chi, \tag{1}$$

$$U(\varphi) = \lambda(\varphi^2 - v^2)^2.$$

Q-balls parameters:

$$R_Q = \left(\frac{Q}{4U_0}\right)^{1/4}, \tag{2}$$

$$m_Q = \frac{4\sqrt{2}\pi}{3} U_0^{1/4} Q^{3/4}, \tag{3}$$

$$Q_{min} = \frac{m_Q}{m_\chi} \tag{4}$$

$$U_0 = U(0) - U(v) = \lambda v^4.$$

Friedberg R., Lee T. D., Sirlin A., Phys. Rev. D (1976)

Model: first order phase transition

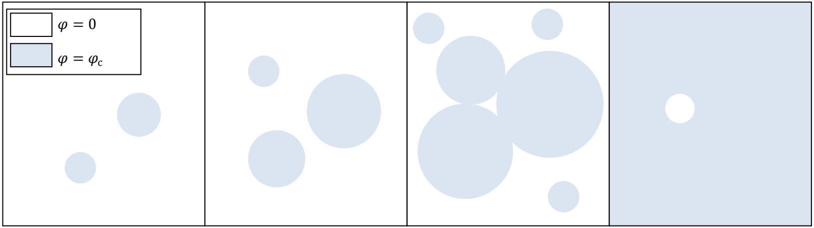

Figure: Schematic representation of a first-order phase transition in the early Universe. The white area is the area of the old phase ($\varphi = 0$), the blue area is the area of the new phase ($\varphi = \varphi_c$). As can be seen from the figure, at some point in time, one region of the old phase will remain in the selected volume, which, for simplicity, in the framework of this work will be considered spherical.

E. Krylov, A. Levin and V. Rubakov, Phys. Rev. D (2013)

Q-balls parameters

Upper charge constraint:

$$\frac{n_\chi - n_{\bar{\chi}}}{s} = \frac{n_Q Q}{s} = \eta_\chi \text{ – asymmetry of } \chi\text{-field}, \tag{5}$$

$$V_\star = \xi \left(\frac{u A^{1/2} M_{pl}^*}{T_c^2 L^{3/2}} \right)^3 \text{ volume of cosmological Q-ball}, \tag{6}$$

$$Q_\star = \eta_\chi \xi \frac{2\pi^2 g_*}{45} \left(\frac{u A^{1/2} M_{pl}^*}{L^{3/2} T_c} \right)^3 \text{ charge of cosmological Q-ball.} \tag{7}$$

So the Q-ball charge lies inside:

$$Q_{min} < Q < Q_\star. \tag{8}$$

E. Krylov, A. Levin and V. Rubakov, Phys. Rev. D (2013)

Q-balls charge distribution

Let us find the probability of the birth of a Q-ball with a charge greater than some $\bar{Q}$.
Probability of a bubble of a new phase appearing in a bubble of an old phase of volume V:

$$F_b = V\Gamma\frac{R}{u}. \qquad (9)$$

The probability of the birth of a Q-ball with a charge greater than $\bar{Q}$:

$$F = 1 - F_b \Rightarrow R_\star^3\Gamma\frac{R_\star}{u} \sim 1 \Rightarrow \qquad (10)$$

$$F = 1 - \frac{V\Gamma R/u}{V_\star\Gamma R_\star/u}. \qquad (11)$$

A. Guth, E. Weindberg, Phys. Rev. D (1981)

Q-balls charge distribution

Let us assume that χ particles are distributed uniformly throughout the Universe, then $Q \sim V$, and, consequently, (11) will take the form:

$$F = 1 - \left(\frac{Q}{Q_\star}\right)^{4/3} = \int \frac{dP}{dQ} dQ, \tag{12}$$

$$\frac{dP}{dQ} = -\frac{F(\bar{Q} + dQ) - F\bar{Q}}{dQ} = -\frac{dF}{dQ}, \tag{13}$$

$$\Rightarrow$$

$$n(Q) \sim A \int_{Q_{min}}^{Q_\star} \frac{dP}{dQ} dQ \sim A \left(\frac{Q}{Q_\star}\right)^{4/3}, \tag{14}$$

$$A = \frac{7}{4}.$$

S. Troitsky, JCAP (2016)

Estimation of the potential parameter

Interaction cross section for dark matter bulk:

$$\langle\bar{\sigma}\rangle_b = \bar{\sigma}_\star \int_0^1 \frac{x^{-1/4}x^{3/4}(1-x)}{x^{3/4}(1-x)}dx \approx 1.3\bar{\sigma}_\star \lesssim 1\ \text{cm}^2/\text{g}, \qquad (15)$$

where $x = Q/Q_\star$, $\bar{\sigma}_\star = \bar{\sigma}(Q_\star)$. Let us find the cross section $\bar{\sigma}(Q)$:

$$\bar{\sigma}(Q) = \frac{\pi R_Q^2}{m_Q} = \frac{3}{8\sqrt{2}} v^{-3} Q^{-1/4}, \qquad (16)$$

$U_0 = v^4,\ m_\chi = kv,\ k = h/\lambda^{1/4}$.
Then from (15) taking into account (16) and (7) we obtain the lower limit for v:

$$v_{min} \gtrsim \frac{1.07\cdot 10^{-7}u^{2/3}}{\eta_\chi^{1/9}}\ \text{GeV}. \qquad (17)$$

T. Multamaki and I. Vilja, Phys. Lett. B (2000)

Estimation of the potential parameter

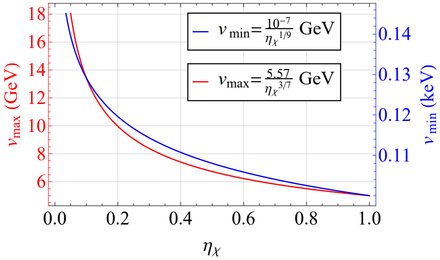

Figure: Cosmological restrictions on v from η_χ in the case of the speed of cosmological Q-balls $u = 0.01$.

$$\rho = \int_0^{Q_\star} m_Q dn(Q) \sim Q^{25/12}, \quad (18)$$

$$\rho_{DM} \gtrsim \frac{4\sqrt{2}\pi}{3} v \cdot Q_\star^{-1/4} \eta_\chi s_0, \quad (19)$$

$$v_{max} \lesssim \frac{5.57 \cdot u^{3/7}}{\eta_\chi^{3/7}} \text{ GeV}. \quad (20)$$

Q-balls merging

Main equation of Q-balls merging in flat expanding Universe:

$$\begin{cases} \dot{Q} = Q_\star \sigma(Q) u \frac{1}{V_\star a^3(t)}, \\ Q(t_c) = Q_\star, \end{cases} \tag{21}$$

where t_c is the epoch of the phase transition and is associated with v. Scale factor is obtained from Friedman equation:

$$a = a_0 \left(\frac{\Omega_M}{\Omega_\Lambda}\right)^{1/3} (\sinh[\frac{3}{2}\sqrt{\Omega_\Lambda} H_0 t])^{2/3}. \tag{22}$$

Unfortunately, for any choice of free parameters, **Q-balls do not interact.** From this we can conclude that it is necessary to create Q-balls with the required masses immediately. For such Q-balls there is a set of parameters (for example, $\eta_\chi = 1$, $u = 1$, $v = 10^{-19}$GeV). In fact, calculations show that the main contribution comes from the v parameter. This parameter v corresponds to the temperature of the Universe 10^{-6}K, which does not correspond to observations.

Q-balls merging

Since Q-balls do not interact in the case of a flat expanding Universe due to a-term in the main equation of Q-balls merging, it is necessary to "turn off" a-term. One possible way to do this is to "place" Q-balls in galaxies. Let us make some assumptions:

- cosmological Q-balls are distributed evenly throughout the galaxy;
- the Milky Way is taken as a "typical" galaxy;
- galaxies do not evolve
- all dark matter is represented by Q-balls;
- Q-balls do not interact with usual matter.

Gravitational potential of galaxies could "turn off" expansion of Universe and, hence, a-term.

Q-balls merging

Modified main equation of Q-balls merging in the case of galaxies:

$$\begin{cases} \dot{Q} = Q_\star \sigma(Q) u \frac{1}{V_\star}, \\ Q(t_c) = Q_\star, \end{cases} \tag{23}$$

Let us pose the math problem correctly. Firstly, it is necessary to set a lower time limit. The oldest galaxies currently observed are located at a distance of $z \approx 6$, which corresponds to $t_0 \approx 1$ Gyr. The upper limit obviously corresponds to the age of the Universe $t_1 \approx 13.7$ Gyr. Secondly, the mass of the final Q-ball should not exceed the mass of the Milky Way halo $M_{DM} = 1.37^{+0.18}_{-0.17} \times 10^{11} M_\odot$. Finally, it remains to place a constraint on the Lagrangian parameter v:

$$v \geq 1.7 \times 10^{-12} \text{ GeV}.$$

This temperature corresponds to the temperature of the Universe at $z = 6$.

Q-balls merging

Now we can finally pose the mathematical problem:

$$\begin{cases} \dot{Q} = Q_\star \sigma(Q) u \frac{1}{V_\star},\ t_0 \le t \le t_1, \\ Q(t_0) = Q_\star, \\ M_Q(t_1) \le M_{DM}, \\ v \ge 1.7 \times 10^{-12}\ \text{GeV}. \end{cases} \tag{24}$$

This equation has many suitable solutions, for example, with the parameters $\eta_\chi = 10^{-5}$, $v = 1$ GeV, $u = 0.3$. Final mass of the Q-ball:

$$M_Q(t_1) \approx 1 M_\odot,$$

$$R_{Q(t_1)} \approx 1\ \text{km}.$$

It is worth noting that this mass is significantly less than the mass of the dark matter halo in the Milky Way, which makes it possible to obtain many Q-balls of similar masses in one galaxy.

Q-balls merging

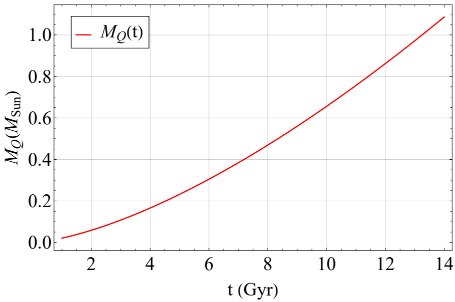

Figure: Mass evolution of cosmological Q-ball.

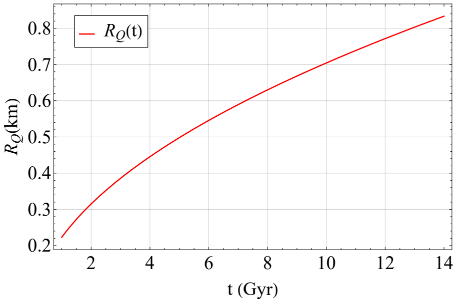

Figure: Radius evolution of cosmological Q-ball.

Results and future work

- ✓ The charge distribution from S. Troitsky, JCAP (2016) has been clarified;
- ✓ Cosmological constraint on the parameter v of the Lagrangian as a function of free parameters of asymmetry and velocity of cosmological Q-balls
- ✓ A naive model of the merger of cosmological Q-balls has been developed;
- ✓ Within the framework of this model, it was found that cosmological Q-balls do not interact in a flat expanding Universe;
- ✓ An alternative mechanism for the interaction of cosmological Q-balls in galaxies has been proposed;
- ? Estimation of the number of Q-balls of stellar mass in galaxies in our epoch;
- ? Clarifying the distribution of dark matter in galaxies;
- ? Checking the conservation of structures in galaxies;
- ? Estimation of the number of gravitational wave signals.

THANK YOU FOR YOUR ATTENTION!

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