# Can dark-matter Q-balls grow to the mass gap masses?

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# Motivation

There are several unusual gravitational wave events resulting from the merger of stellar mass objects, for example:

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

The mass of one of the objects in such events lies in the mass gap for black holes and neutron stars. Are **dark matter Q-balls** possible explanation?

R. Abbott et al, AJL (2021)

# Model: Lagrangian

Friedberg-Lee-Sirlin Lagrangian is

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

$$U(\varphi) = (\varphi^2 - v^2)^2,$$

Q-balls parameters are

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

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

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

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

# Model: First-order phase transition

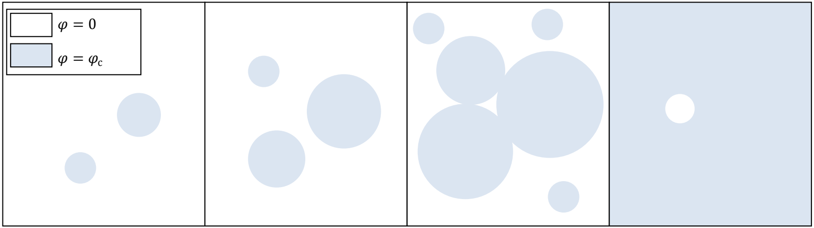


Figure: Schematic representation of the first-order phase transition in the early Universe. The white region is the region of the old phase ($\varphi = 0$), the blue region is the region of the new phase ($\varphi = \varphi_c$). At some point in time, one bubble of the old phase remains in a certain volume, which, for simplicity, we will assume to be spherical. The Q-ball born from this region will be called **cosmological**, and its parameters will be designated by the index "$\star$".

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

# Cosmological Q-balls parameters

$$\frac{n_\chi - n_{\bar{\chi}}}{s} = \frac{n_Q Q}{s} = \eta_\chi \text{ – asymmetry of the particles of } \chi\text{-field,} \qquad (5)$$

$$V_\star = \xi \left( \frac{uA^{1/2} M_{pl}^*}{T_c^2 L^{3/2}} \right)^3 \text{ – the volume from which the cosmological Q-ball is born,} \qquad (6)$$

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

The charge of the cosmological Q-ball lies within this limits:

$$Q_{min} < Q < Q_\star. \qquad (8)$$

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

# Distribution of cosmological Q-balls by charges

Let us find the probability of the birth of a cosmological Q-ball with a charge greater than some $\bar{Q}$.
The probability of the birth of a bubble of a new phase in a bubble of the old $V$ is

$$F_b = V\Gamma \frac{R}{u}. \tag{9}$$

Then, the probability of the birth of a cosmological Q-ball with a charge greater than $\bar{Q}$ is

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

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

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

# Distribution of Q-balls according to their charges

We will assume that $\chi$-particles are uniformly distributed throughout the Universe, then $Q \sim V$, and, accordingly, (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)

# Estimate of the potential parameter

The mean cross section of the interaction of bulk dark matter is

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

where $x = Q/Q_\star$, $\bar{\sigma}_\star = \bar{\sigma}(Q_\star)$. The mean (geometric) cross section of Q-ball $\bar{\sigma}(Q)$ is

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

Then from (15), taking into account (16) and (7), it is possible to derive the lower limit for $v$:

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

M.Rocha et al, MNRAS (2013)

# Estimate of the potential parameter

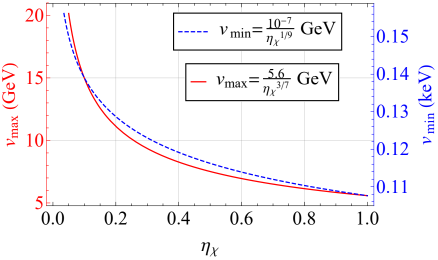


Figure: Cosmological estimates for parameter of Lagrangian $v$ as a function of $\eta_\chi$ in the case $u = 1$.

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

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

$$v_{max} \lesssim \frac{6 \cdot u^{3/7}}{\eta_\chi^{3/7}} \text{ GeV}. \quad (20)$$

## Q-balls merging: Flat expanding Universe

Let us consider the change in the charge of one **selected** Q-ball per unit of time due to merging with cosmological Q-balls:

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

where $t_c$ is time of the first order phase transition, which is connected with $v$. The solution of (21):

$$Q(t) = \left( -\frac{\pi Q_\star u \sqrt{\Omega_\Lambda}}{12 v^2 V_\star a_0^3 \Omega_M H_0} \coth\left[\frac{3}{2}\sqrt{\Omega_\Lambda} H_0 t\right] + C \right)^2, \tag{22}$$

with scale factor

$$a = a_0 \left(\frac{\Omega_M}{\Omega_\Lambda}\right)^{1/3} (\sinh[\frac{3}{2}\sqrt{\Omega_\Lambda} H_0 t])^{2/3}, \tag{23}$$

and the integration constant is

$$C = \frac{\pi Q_\star u \sqrt{\Omega_\Lambda}}{12 v^2 V_\star a_0^3 \Omega_M H_0} \coth\left[\frac{3}{2}\sqrt{\Omega_\Lambda} H_0 t_c\right] + \sqrt{Q_\star}. \tag{24}$$

# Q-balls merging: Galaxies

Since Q-balls hardly interact due to the scale factor $a$, we can try to "switch it off". This can be done by placing cosmological Q-balls in gravitationally bound structures, such as galaxies. Let us make some assumptions:

- cosmological Q-balls participate in the formation of galaxies and are distributed in them according to known dark matter profiles;
- we will consider the Milky Way as a "typical" galaxy;
- galaxies hardly evolve;
- all dark matter is represented by Q-balls;
- Q-balls do not interact with ordinary matter.

In this case, it is possible to locally "turn off" the expansion of the Universe.

# Q-balls merging: Galaxies

Let us find the concentration of Q-balls. The Burkert profile will be used as the dark matter profile:

$$\rho(r) = \frac{\rho_b}{\left(1+\frac{r}{R_s}\right)\left(1+\frac{r^2}{R_s^2}\right)} \Rightarrow n(r) = \frac{\rho(r)}{m_Q(Q)}. \tag{25}$$

Let us consider the interaction of the selected Q-ball with other Q-balls of different charges:

$$\begin{cases} \dot{Q} = \sum_k kQ_\star u_\star \sigma(kQ_\star) n(kQ_\star), \ t \in [0;13] \text{ Gyr}, \ k \in \mathbb{N}, \\ Q(0) = Q_\star, \end{cases} \tag{26}$$

where $k$-th therm is

$$\dot{Q} \sim (kQ_\star)^{3/4}. \tag{27}$$

A. Burkert, The Astrophysical Journal (1995)

S. Lin et al, A&A (2025)

# Q-balls merging: Galaxies

A simplified equation that follows from the form of the $k$th term in (26) is

$$\begin{cases} \dot{Q} = Qu_\star \sigma(Q) n(Q), \ t \in [0;13] \text{ Gyr}, \\ Q(0) = Q_\star. \end{cases} \tag{28}$$

The solution of (28) is

$$Q(t,r) = \left( \frac{3u_\star \rho(r)}{64\sqrt{2}v^3} t + Q_\star^{1/4} \right)^4 . \tag{29}$$

Q-ball mass taking inro account (29) is

$$m_Q(v,u,\eta_\chi,u_\star,T_c,r,t) = \frac{4\sqrt{2}\pi}{3} v \left( \frac{3u_\star \rho(r)}{64\sqrt{2}v^3} t + Q_\star^{1/4} \right)^3 . \tag{30}$$

Q-ball radius taking into account (29) is

$$R_Q(v,u,\eta_\chi,u_\star,T_c,r,t) = \frac{1}{\sqrt{2}v} \left( \frac{3u_\star \rho(r)}{64\sqrt{2}v^3} t + Q_\star^{1/4} \right) . \tag{31}$$

# Solution analysis

To explain the events from the mass gap in the first approximation it is necessary:

$$m_Q(v, u, \eta_\chi, u_\star, T_c, r)\Big|_{t=13\text{ Gyr}} \gtrsim 1 M_\odot \Rightarrow \tag{32}$$

There are various suitable solutions, the set of (almost) free parameters presented below will be called **the most successful**, and will be used for further evaluations:

$$\begin{cases} v \approx 10^{-7}\text{ GeV}, \\ u = 1, \\ \eta_\chi = 1, \\ u_\star = 0.0007, \\ T_c \approx 10^{-7}\text{ GeV}. \end{cases} \tag{33}$$

# Solution analysis

The parameters (radius, mass) of Q-balls depend on their location in the galaxy. For example, the mass of Q-balls at a distance of $r = 0.05$ kpc from the center of the galaxy in present epoch is

$$m_Q\Big|_{r=0.05\text{ kpc}} \approx 5\ \mathrm{M}_\odot, \tag{34}$$

and radius is

$$R_Q\Big|_{r=0.05\text{ kpc}} \sim 10^9\ \text{km}. \tag{35}$$

We will name Q-balls with masses greater than or equal to the mass of the Sun as **Q-balls of stellar mass**. It is easy to find in which region of the galaxy such Q-balls are located and their number in present epoch is

$$m_Q(r) = 1\ \mathrm{M}_\odot \Rightarrow r \approx 0.17\ \text{kpc}, \tag{36}$$

$$N_Q^{stellar} = \int_{0\text{ kpc}}^{0.17\text{ kpc}} \frac{4\pi r^2 \rho(r)}{m_Q(r)} dr \approx 4 \times 10^9. \tag{37}$$

## Solution analysis

Similarly, one can find the distance from the center of the galaxy at which the interaction of Q-balls stops in the approximation that the selected Q-ball absorbs all the mass:

$$m_Q(r) = 2m_\star \Rightarrow r \approx 16 \text{ kpc}, \tag{38}$$

Then the current number of Q-balls in the galaxy is

$$N_Q^{total} = \int_{0 \text{ kpc}}^{16 \text{ kpc}} \frac{4\pi r^2 \rho(r)}{m_Q(r)} dr + \int_{16 \text{ kpc}}^{200 \text{ kpc}} \frac{4\pi r^2 \rho(r)}{m_\star} dr \sim 10^{24}. \tag{39}$$

And the modern masses and radius of Q-balls lie within the limits, respectively,

$$\boxed{m_\star \approx 10^{-13} \text{ M}_\odot \leq m_Q(r) \lesssim m_Q(r=0) \approx 10 \text{ M}_\odot,} \tag{40}$$

$$\boxed{R_Q(Q_\star) \approx 9 \times 10^4 \text{ km} \leq R_Q(r) \lesssim R_Q(r=0) \approx 4 \times 10^9 \text{ km}.} \tag{41}$$

# Solution analysis

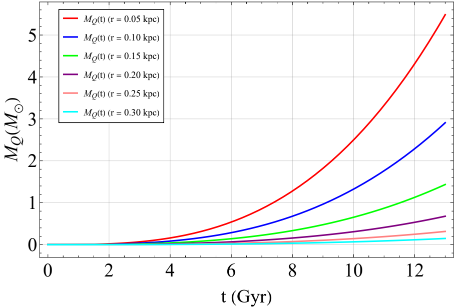


Figure: Evolution of the mass of the selected Q-ball at different distances from the center of the galaxy.

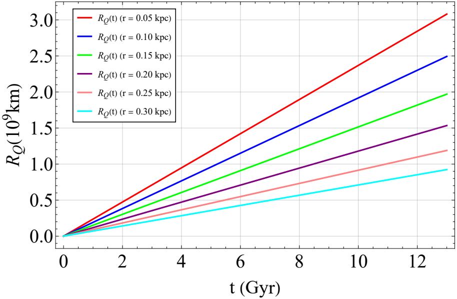


Figure: Evolution of the radius of the selected Q-ball at different distances from the center of the galaxy.

# Solution analysis

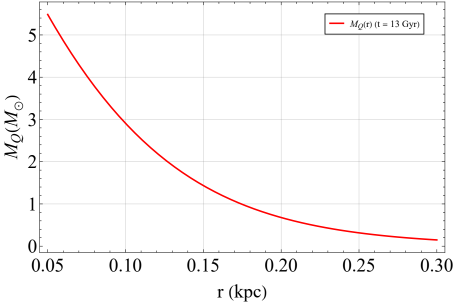


Figure: Mass profile of a selected Q-ball in present epoch.

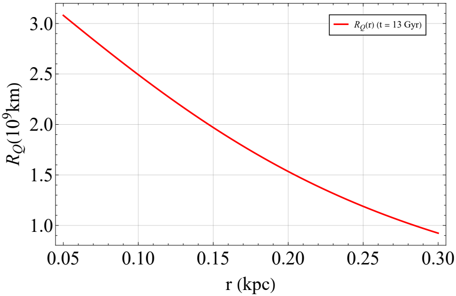


Figure: Radius profile of a selected Q-ball in present epoch.

# Solution analysis

| $v \sim 10^{-7}$ GeV, $T_c \sim 10^{-7}$ GeV, $\eta_\chi = 1$, $u = 1$, $u_\star = 0.0007$ | | | | | | |
|---|---|---|---|---|---|---|
| $r$ (kpc) | 0.05 | $0.17^{(1)}$ | $0.30^{(2)}$ | $8^{(3)}$ | $16^{(4)}$ | $200^{(5)}$ |
| $M_Q$ ($M_\odot$) | 5 | 1 | 0.15 | $10^{-12\,(6)}$ | $10^{-13}$ | $10^{-13}$ |
| $R_Q$ (km) | $10^{9\,(7)}$ | $10^9$ | $10^9$ | $10^5$ | $10^5$ | $10^{5\,(8)}$ |

Table: The main parameters of Q-balls in the modern epoch.

1. The region where stellar mass Q-balls are located;
2. Radius of the central region of the galaxy;
3. Distance from the center of the galaxy to the Earth;
4. The distance from the center of the galaxy at which Q-balls stop interacting;
5. Dark matter halo radius;
6. Mass of the order of Juno;
7. The radius is of the order of the distance from the Sun to Neptune;
8. The radius is about two times the radius of Jupiter.

# Solution analysis

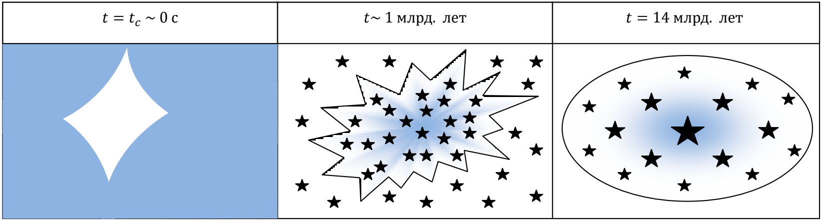


Figure: Schematic representation of the model of Q-ball merging in galaxies. First stage: first-order phase transition in the early Universe, birth of cosmological Q-balls. Second stage: cosmological Q-balls participate in the formation of galaxies. Third stage: in the modern galaxy there are different populations of Q-balls – the further from the center of the galaxy, the lighter the Q-balls.

# Results

- ✓ The charge distribution of cosmological Q-balls from S. Troitsky, JCAP (2016) has been refined;
- ✓ Cosmological constraints on the Lagrangian parameter $v$ are obtained;
- ✓ Two models of Q-ball merging were created: free cosmological Q-balls in a flat expanding Universe and Q-ball merging in galaxies;
- ✓ It has been shown that Q-balls in galaxies are capable of gaining significant mass, however, their configuration is more similar to "clouds" of dark matter;
- ✓ Modern Q-balls can have different populations: the further the selected Q-ball is located from the center of the galaxy, the lighter it is;
- ✓ In the proposed models, Q-balls cannot close the mass gap, since they are very "loose", however, they may be of interest in other areas of astrophysics and cosmology.

# THANK YOU FOR YOUR ATTENTION!

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