SUSY Q-balls as a dark matter candidate

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Outline

- What are Q-balls?
- Supersymmetric Q-balls
- Baryon number violation and Q-balls
- SUSY Q-balls as dark matter candidates
- Cosmological production
- Matter-antimatter conversion
- Experimental signatures
- Astrophysical constraints
- Conclusions

What are Q-balls?

Simplest example: one scalar field with unbroken U(1) global symmetry:

$$L = \partial_\mu \phi^* \partial^\mu \phi - U(\phi^* \phi)$$

Conserved charge:

$$Q = i \int d^3x \, [\phi^* (\partial_0 \phi) - (\partial_0 \phi^*) \phi]$$

Question:

What is the minimum energy configuration with the charge Q?

What are Q-balls?

Answers:

- Collection of Q well separated scalar particles, $E = mQ$
- If the particles with the same charge are attracted to each other: bound state of Q scalar particles $\equiv$ Q-ball, $E = (m - \Delta m)Q$

Mathematics: find a minimum of energy functional

$$E = \int d^3x \left[|\partial_0 \phi|^2 + |\vec{\nabla} \phi|^2 + U(\phi^* \phi) \right]$$

keeping the charge

$$Q = i \int d^3x \, [\phi^* (\partial_0 \phi) - (\partial_0 \phi^*) \phi]$$

fixed.

What are Q-balls?

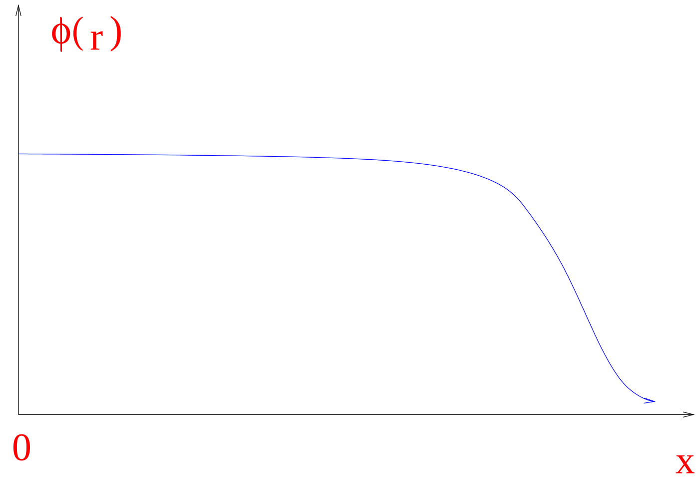
Solution: a spherically symmetric non-topological soliton

$$\phi(r,t) = e^{i\omega t}\phi(r)$$

which exists provided the minimum of

$$\frac{U(\phi^*\phi)}{\phi^*\phi}$$

exists at some $\phi = \phi_0 \neq 0$.



Space profile of the scalar field of a Q-ball

What are Q-balls?

Particle physics models and Q-balls

Renormalizable field theory with one scalar field:

$$U(\phi^*\phi) = m^2\phi^*\phi + \lambda(\phi^*\phi)^2$$

$$\frac{U(\phi^*\phi)}{\phi^*\phi} = m^2 + \lambda\phi^*\phi$$

The only minimum is at $\phi = 0$ → No Q-balls.

Experiment: The only known global symmetries are those associated with baryon number B and lepton number L. But, no scalar fields carrying B or L are known!

SUSY Q-balls

Supersymmetric extention of the standard model: MSSM

SUSY: each particle has a “superpartner"

spin	particle	superpartner	spin
$\frac{1}{2}$	quark	squark	0
$\frac{1}{2}$	lepton	slepton	0
0	higgs	higgsino	$\frac{1}{2}$
0	Z	zino	$\frac{1}{2}$

49 (!) scalar fields carrying baryon and lepton numbers $\longrightarrow$ many types of Q-ball solutions!

Crucial question : Are they stable?

SUSY Q-balls

$$M_Q = (M_s - \Delta M_s)Q$$

Q-balls are stable in the scalar sector (cannot decay into scalar particles) but may (?) decay quickly when fermions are taken into account:

$$M_Q = (M_s - \Delta M_s)Q \gg m_p Q.$$

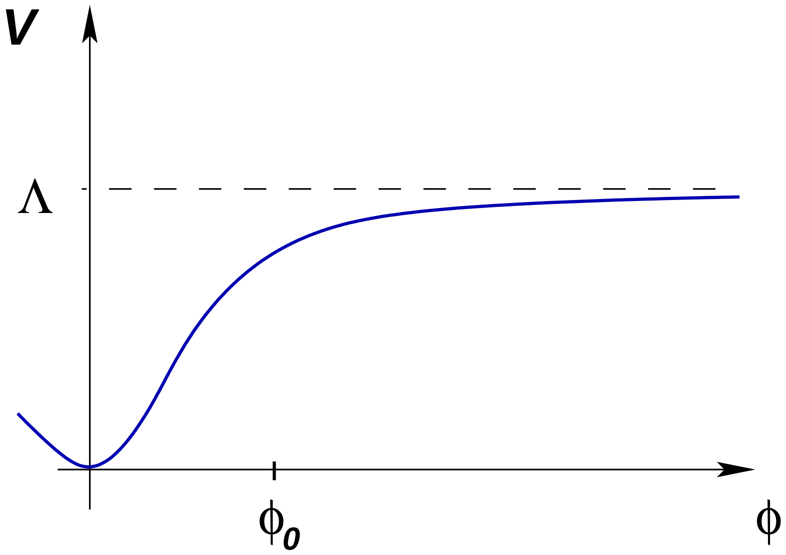
Possible process:

$$\tilde{q} + \tilde{q} \longrightarrow q + q$$

stable SUSY Q-balls

SUSY theories with gauge-mediated supersymmetry breaking:

effective potential is flat along quite a number of directions in the space of scalar fields

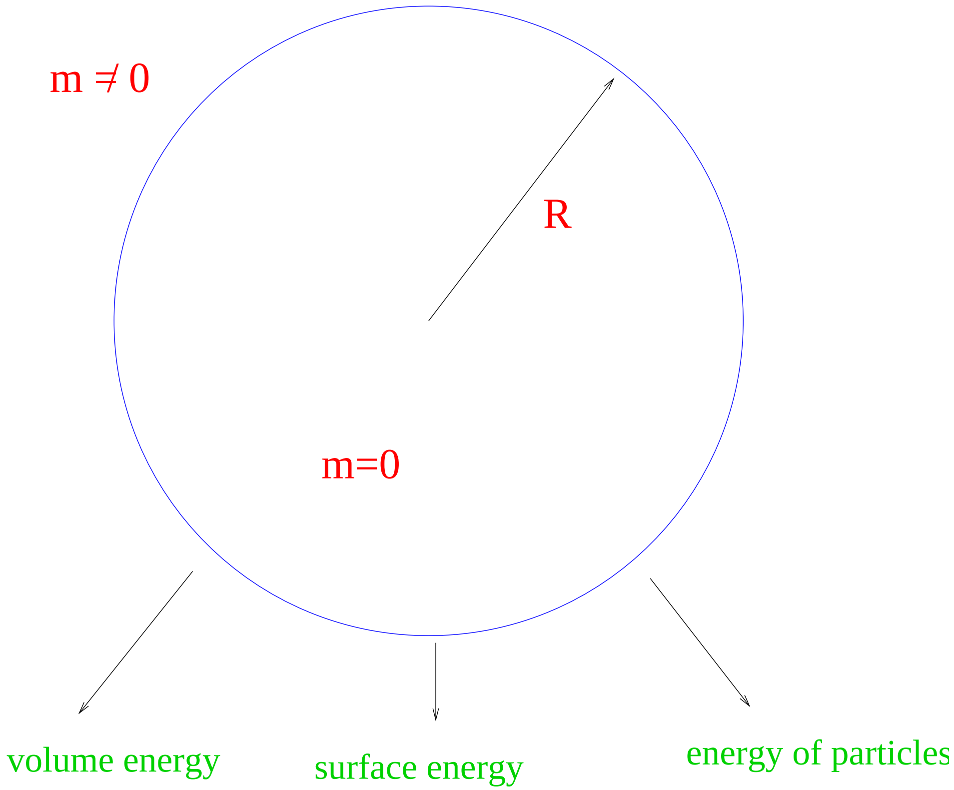


This type of potential leads to existence of stable non-topological solitons, carrying baryon number

Typically, $\Lambda \sim 1 - 10$ TeV, $\phi_0 \sim 1 - 10$ TeV.

stable SUSY Q-balls

Mass of Q-ball:



$m \neq 0$

R

m=0

volume energy

surface energy

energy of particles

$$M(R) = \frac{4}{3}\pi R^3 \Lambda^4 \quad + \quad 4\pi R^2 S \quad + \quad \pi \frac{Q^1}{R}$$

stable SUSY Q-balls

Minimization with respect to R gives:

$$\omega \sim (\pi\sqrt{2})\Lambda Q^{-1/4},$$
$$M_Q \sim (4\pi\sqrt{2}/3)\Lambda\ Q^{3/4}$$
$$R_Q \sim (1/\sqrt{2})\Lambda^{-1}Q^{1/4}$$

If Q is the baryonic charge they are stable for ($\Lambda \sim 1$TeV)

$$Q > (\frac{4\pi\sqrt{2}\Lambda}{3m_p})^4 \sim 10^{15}$$

found from $M_Q < m_p Q$.

Solutions to classical equations of motion for flat potential:

$$\phi(r,t) \simeq \phi_0 e^{i\omega t}\frac{sin(\omega r)}{\omega r},\ \text{for } r < R_Q,\ \phi(r,t) \simeq 0, \text{for } r > R_Q$$

Baryon number violation

SUSY theory is embedded finally into some GUT ⟶

Baryon number is not conserved ⟶

Q-balls are not stable

Questions:

- Q-ball lifetime
- Modes of decay

Method: add to the action higher-dimensional operators consistent with SUSY and look at the modified Q-ball properties.

The result depends on the structure of flat direction along which Q-ball is constructed

Degeneracy breaking

For large ϕ the degeneracy of potential is broken by higher order operators

$$V^n(\phi)_{\text{lifting}} \approx \lambda_n M^4 \left(\frac{\phi}{M}\right)^{n-1+m} \left(\frac{\phi^*}{M}\right)^{n-1-m}$$

$M \sim 10^{16}$ GeV is the scale of grand unification.

For $Q > Q_c$, (determined from $V^n(\phi)_{\text{lifting}} \sim \Lambda^4$)

$$Q_c \simeq \lambda_n^{-\frac{2}{n-1}} \left(\frac{M}{\Lambda}\right)^{\frac{4n-12}{n-1}}$$

properties of Q-balls change. m and n depend on the structure of flat direction of scalar potential.

Degeneracy breaking

- $m \neq 0$: explicite breaking of the global U(1) symmetry responsible for Q-ball existence → strong baryon number non-conservation → fast Q-ball decay.
- $m = 0$: Q-ball charge can grow beyond Q_c, but the dependence of the parameters of the Q-ball on Q is modified:

$$\phi_0 \sim \varphi_{\rm max}, \quad M \sim \mu Q, \quad \omega \sim \mu, \quad R \sim (\mu Q/\Lambda^4)^{1/3} \ ,$$

where $\mu^2 \sim V(\varphi_{\rm max})/\varphi^2_{\rm max}$

Changing n from $n = 4$ to $n = 7$ the frequency ω ranges from 10 MeV to 10^{-3} MeV and the vev ϕ_0 from 10^7 to 10^{11} GeV.

Baryon number violation - results

- Q-balls formed along $QUDE$, $QLUD$, $QLUDE$ directions cannot have baryon charge greater than $\sim 10^{17}$ and are short lived
- Q-balls formed along directions UE, QL, QU, LUE, UDE, QLE, QLD, QLU, QUD $LUDE$, $QLDE$, $QLUE$, starting from $Q \sim 10^{17}$ have the following mass charge relation:

$$M \sim \omega_0 Q$$

with $\omega_0 \sim 10 MeV$ $(\Lambda \sim 1$ TeV$)$. They decay by emitting neutrinos, antineutrinos and $e^{\pm}$ pairs with typical energies $E \sim \omega_0$. Lifetime in general $\gg$ universe age.

Baryon number violation - results

- other Q-balls (directions $LD,\ LDE$ and some of $UD,\ QUE,\ LUD$) have the similar mass charge relation but with smaller $\omega_0 \sim 10^{-4} - 0.1$ MeV. They decay by emitting neutrinos and antineutrinos and their lifetime is huge compared with the universe age.

Very large Q-balls can become black holes,

$$Q_{\rm bh} \simeq 2 \cdot 10^{53} \left(\frac{TeV}{\Lambda}\right)^2 \left(\frac{MeV}{\omega}\right) .$$

SUSY Q-balls as dark matter candidates

A most popular candidate to dark matter particle: neutralino

The logic:

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It is difficult to detect neutralinos as they interact weakly with ordinary matter (WIMP)

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Another candidate to dark matter: superheavy SUSY Q-ball

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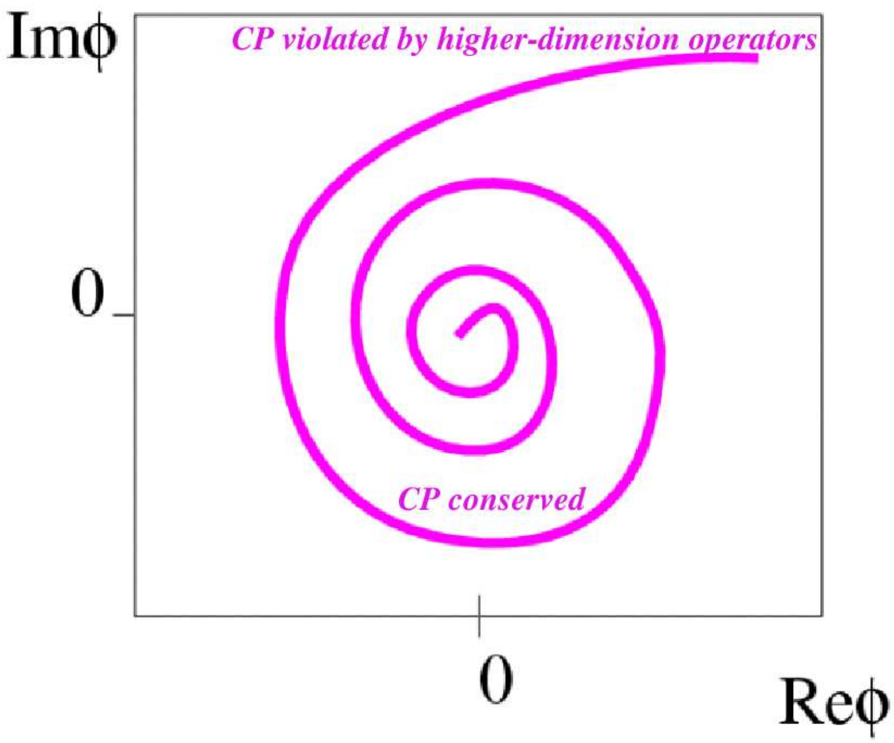
It is difficult to detect Q-balls as their concentration is very small (superheavy dark matter

Cosmological production of Q-balls



Affleck-Dine baryogenesis:

Inflation :Initial energy density $\sim M_{Pl}^4 \gg \Lambda^4 \longrightarrow$ initial value of the scalar field is likely to be large, $\phi \sim M_{Pl} \longrightarrow$ at large ϕ baryon number is not conserved and CP is broken $\longrightarrow$ Due to the classical evolution the universe acquires baryon number in the form of Affleck-Dine-condensate, $\phi \propto e^{i\omega t}\phi_0$

Cosmological production of Q-balls

Uniform configuration with $\phi \propto e^{i\omega t}\phi_0$ – Q-matter.

Observation: Q-balls are better than uniform Q-matter!

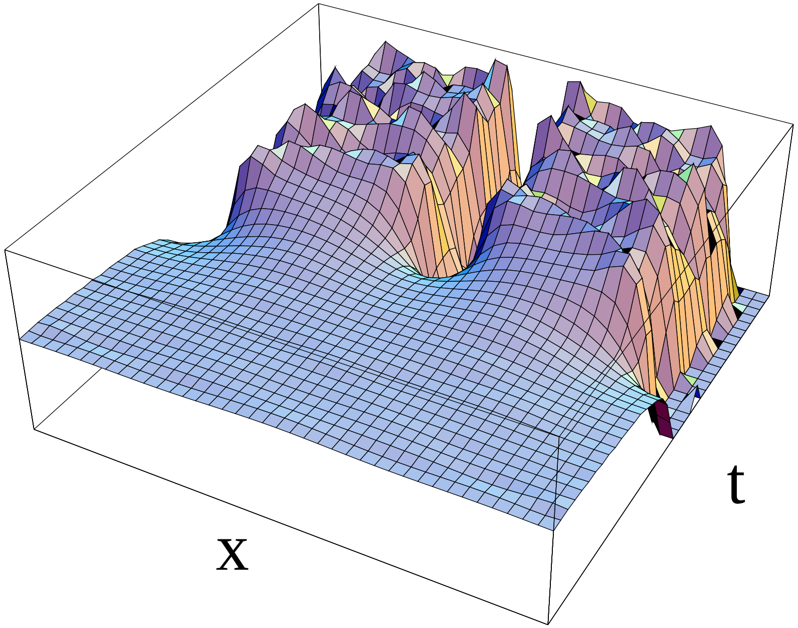
Charge density in Q-matter: n_Q, total charge: $n_Q V$

Mass of Q-matter: $\Lambda^4 V \gg \Lambda (n_Q V)^{3/4}$

$$\Downarrow$$

Q-matter is unstable against Q-ball formation.

Cosmological production of Q-balls

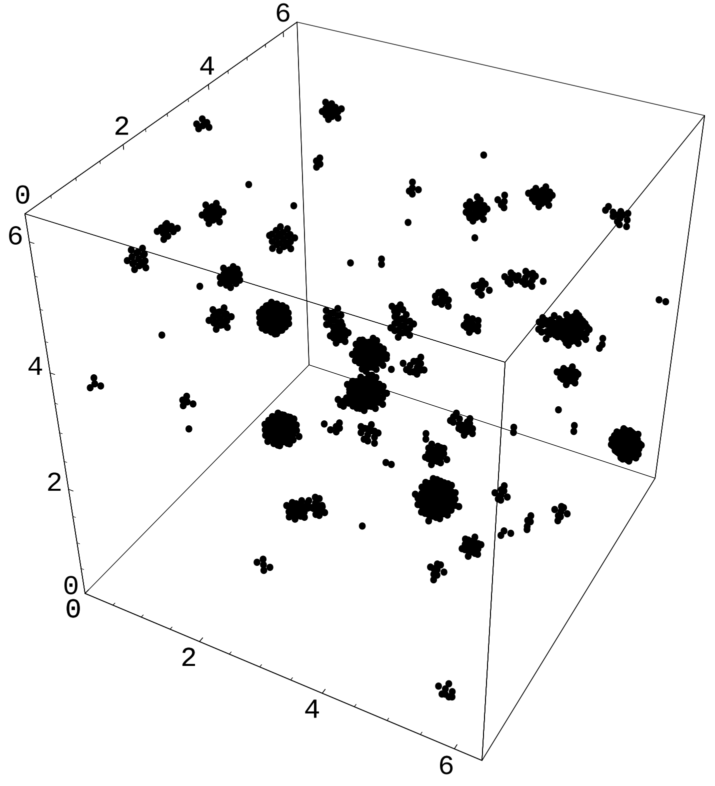


Instabilities in AD condensate

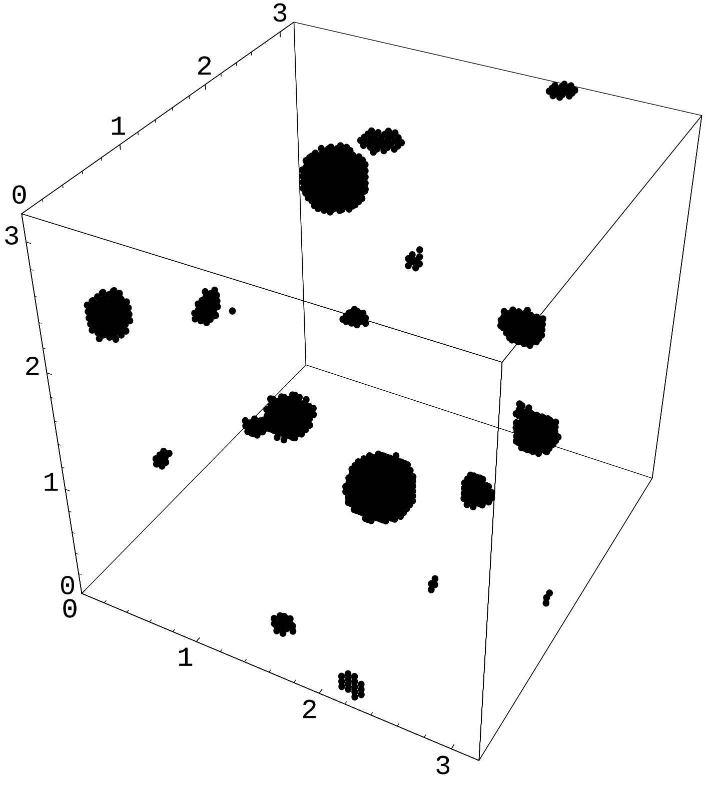
↓

Q-ball formation

Cosmological production of Q-balls



More than 40 Q-balls are formed, and the largest one has the charge with $Q \simeq 5.16 \times 10^{16}$



More than 10 Q-balls are formed, and the largest one has the charge with $Q \simeq 1.74 \times 10^{16}$

Cosmological production of Q-balls

How large a Q-ball could be? Charge density at temperature T:

$n_Q \sim \delta T^3$, $\delta \sim 10^{-10}$ is the baryon asymmetry.

Suppose that instability develops at $T = T_i$. Its size must be smaller than horizon at this time $\Longrightarrow$

$$Q < \delta T^3 \left(\frac{T_i}{T}\right)^3 \left(\frac{M_{Pl}}{T_i^2}\right)^3 \sim \delta \left(\frac{M_{Pl}}{T_i}\right)^3$$

For $T \sim T_{EW} \sim 100$ GeV $Q < 10^{38}$.

Instability analysis: depends on the potential.

Result: Q-balls as large as $Q \sim 10^{26}$ are possible!

Cosmological production of Q-balls

Dark matter and baryon asymmetry - the same source?!

AD condensate $\longrightarrow$ Q-ball formation $\longrightarrow$ Q-ball evaporation $\longrightarrow$ baryon asymmetry $\longrightarrow$ an explanation why $\frac{\Omega_b}{\Omega_{DM}} \sim \frac{1}{7}$?

Computation:

$$\frac{\Omega_b}{\Omega_{DM}} \sim \frac{m_p M_{Pl}}{m_s^2 \sqrt{Q}}$$

Dark matter can be baryonic ?!

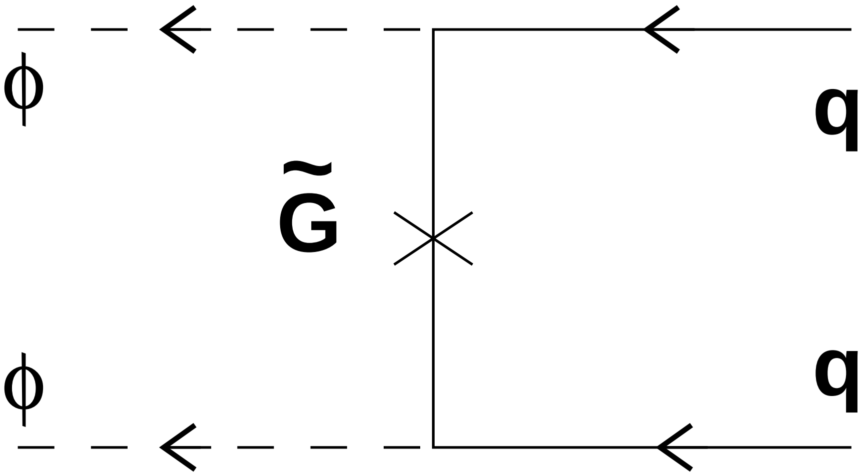
Matter-antimatter conversion

Scalar field inside Q-ball generates Majorana mass for quarks:

$$m_q^M \sim g_s^2 \phi^2 \frac{M_M}{M_G^2}$$

(M_G -gluino mass) coming from

$$L_{eff} = g_s \bar{q} \lambda^a \phi \tilde{G}^a + M_M \tilde{G}^a \tilde{G}^a$$



Matter-antimatter conversion

Majorana mass inside Q-ball $\gg$ 1 GeV $\longrightarrow$ baryons cannot propagate inside and are reflected as antiparticles from the surface of a Q-ball

Q-ball converts matter into antimatter with efficiency $\sim 100\%$:

$$n + Q(B) = \bar{n} + Q(B+2)$$

$$\bar{n} + Q(B) = n + Q(B-2)$$

Analogy - Andreev scattering in superconductors.

Unlimited new source of energy!

In principle, Q-balls can be distinguished from monopoles catalyzing proton decay, strangenets, nuclearites, etc

Experimental signatures

Assume: all DM in Q-balls with baryon number Q

$$n_Q \sim 3 \cdot 10^{-4} Q^{-\frac{3}{4}} \left(\frac{1\,TeV}{\Lambda}\right) cm^{-3}$$

Q-ball flux is

$$F \sim 3 \cdot 10^{11} Q^{-\frac{3}{4}} \left(\frac{1\,TeV}{\Lambda}\right) cm^{-2} yr^{-1}$$

Strong interaction with matter: geometrical cross-section, $\sigma = \pi R_Q^2$

Signature: energy release ~ 100 Gev/cm

Experimental limits from Baikal, Macro:

$$Q > 10^{23}$$

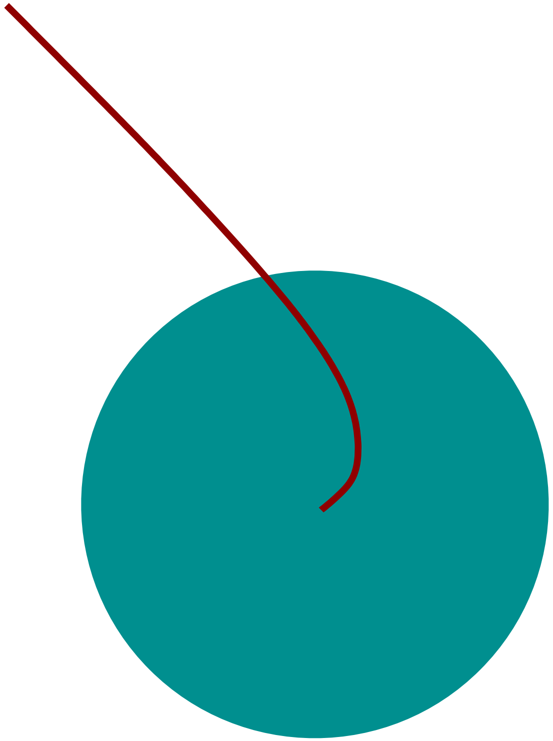
Astrophysical constraints

Q-balls do not accumulate in Earth and Sun: they are too heavy and go through without stopping:

$$\left(\frac{\delta v}{v}\right)_{Earth} \sim 10^{-7}\,, \quad \left(\frac{\delta v}{v}\right)_{Sun} \sim 10^{-5}$$

But neutron stars and white dwarfs stop Q-balls. For 10^8 years typical neutron star accumulates $\sim 10^{12}$ grams of Q-balls ($10^{-20} M_{NS}$).

Neutron stars



Q-balls are trapped by

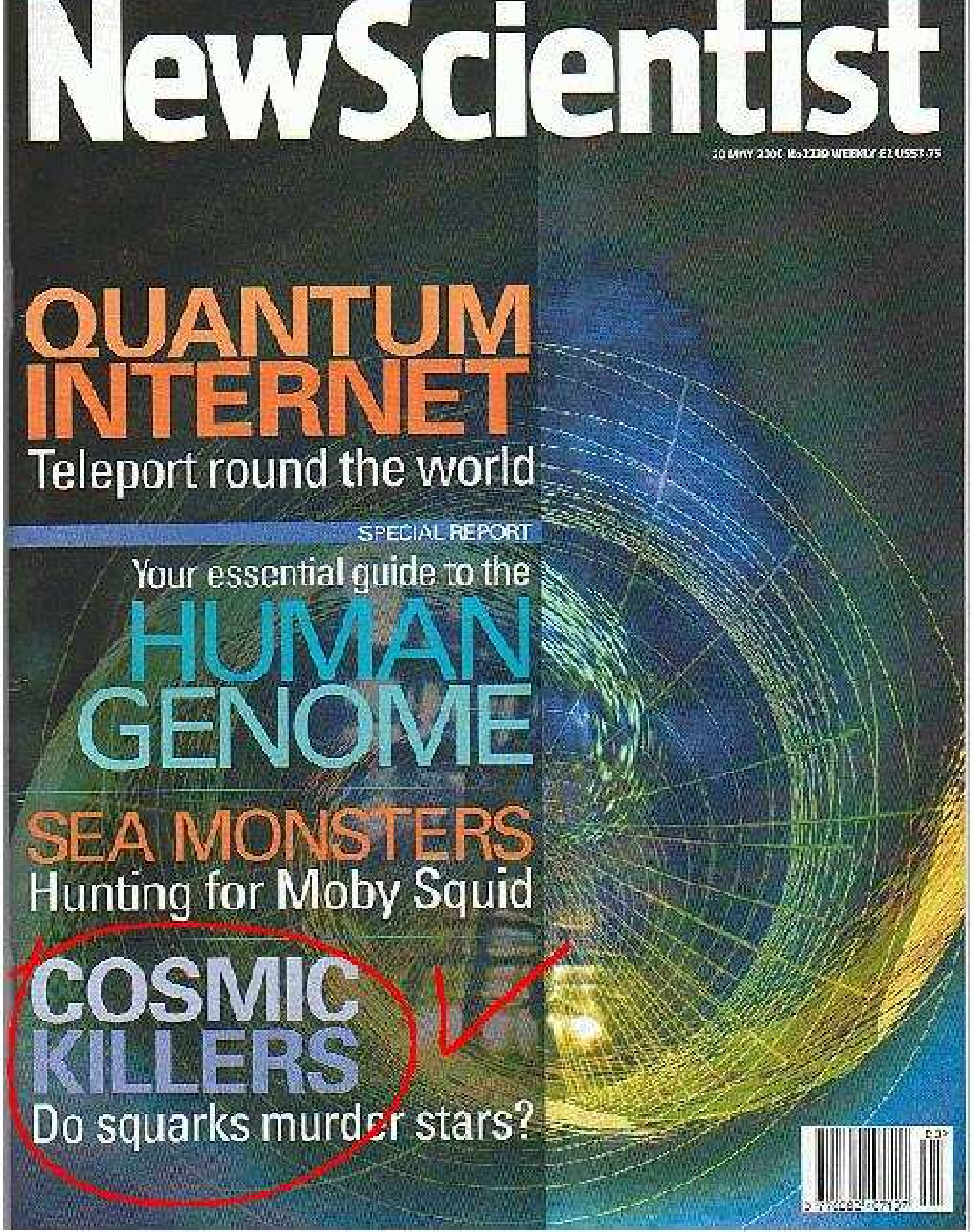
the neutron stars

Naive estimate of the neutron star conversion rate to Q-ball:

$$\frac{dQ}{dt} \sim 4\pi R_Q^2 n_n$$

$$t \sim \frac{(\omega_c \phi_{max}^2)^{2/3}}{n_0} (Q_{bh})^{1/3} \sim 1\text{day??!}$$

Q-balls are excluded? (Neutron stars are known to live at least 1 Gyr)



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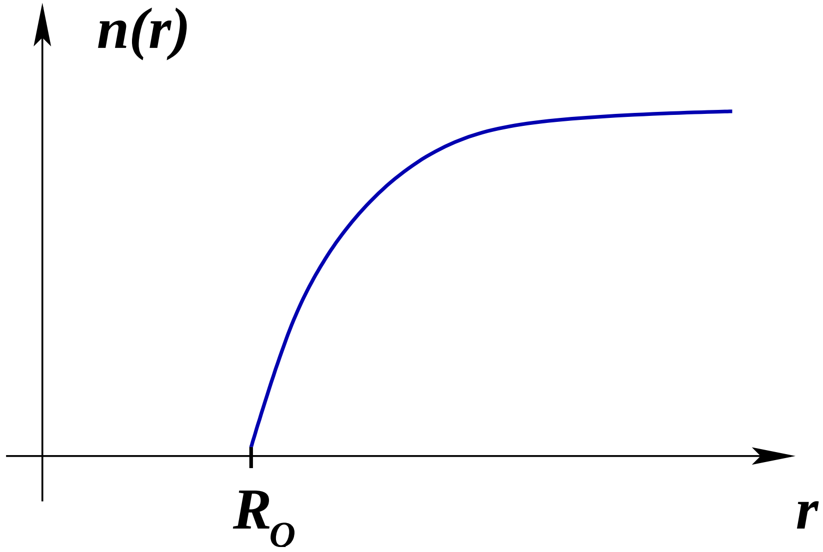
Neutron stars

Diffusion and radiation pressure effects change the estimate completely

Diffusion:



$$\frac{dQ}{dt} \sim 4\pi R_Q D_n n_n$$

D_n - neutron diffusion length

$$t \sim \frac{\Lambda}{n_n D_n} (N_n)^{\frac{1}{4}} \sim 10^{13} \text{ years}$$

Neutron stars

Eddington Accretion Limit: Radiation pressure force per nucleon:

$$F_{Edd} = \frac{\dot{M}\sigma}{4\pi r^2}.$$

is compensated by the gravity force $F_{Grav} = \frac{GM_Q m_p}{r^2}$.

Equilibrium at:

$$t = \frac{\sigma}{4\pi G\omega} \ln \frac{Q_{bh}}{Q_i} \approx 4 \times 10^{12} \text{years.}$$

Too long to be observed...

Conclusions

- Superheavy SUSY Q-balls, associated with most of flat directions are practically stable
- They can be used to convert easily matter into antimatter
- They can be copiously produced in the early universe
- Baryon asymmetry and dark matter can be related
- Q-balls can play a role of superheavy dark matter
- They have a very specific experimental signature