Kusenko & IS **0905.3929**
IS **0907.0269**

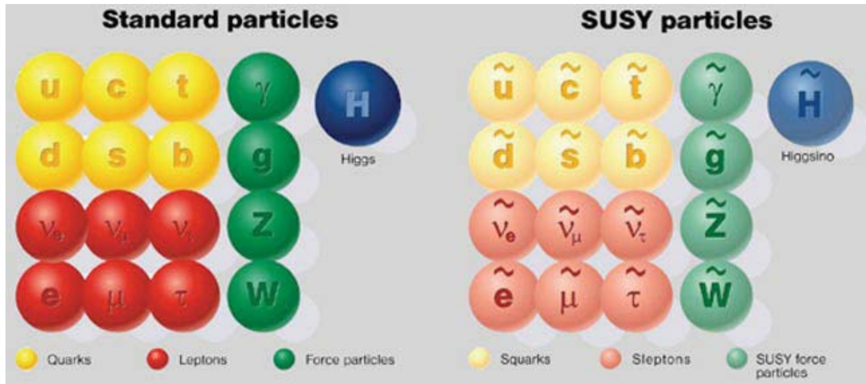
New limits on Q-ball dark matter from neutron stars and neutrinos

Ian Shoemaker
UCLA

OUTLINE

- Dark matter in the MSSM.
- Gauge-mediated SUSY breaking creates stable Q-balls and baryons in the same process (Affleck-Dine).
- Existing limits on Q-ball dark matter.
- New astrophysical limits on Q-balls from neutron star lifetimes.
- New experimental probe of Q-balls from the neutrinos produced in terrestrial passage:
  - Non-trivial zenith angle dependence.
  - Small annual modulation of flux.

Supersymmetry



- Many new fields in the MSSM. The general assumption is that the LSP is the dark matter (neutralino or gravitino).

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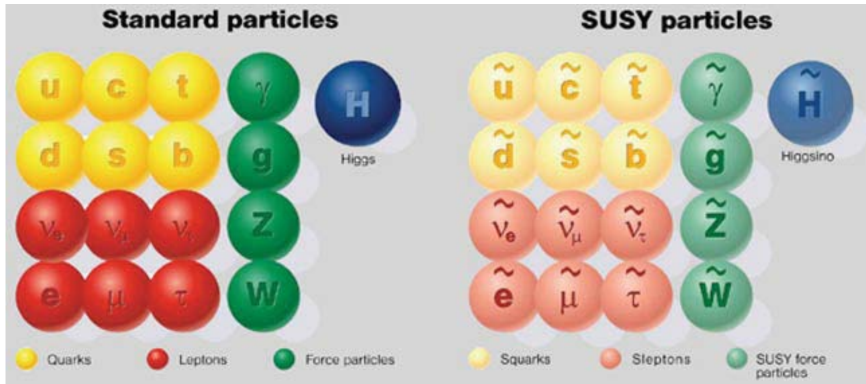

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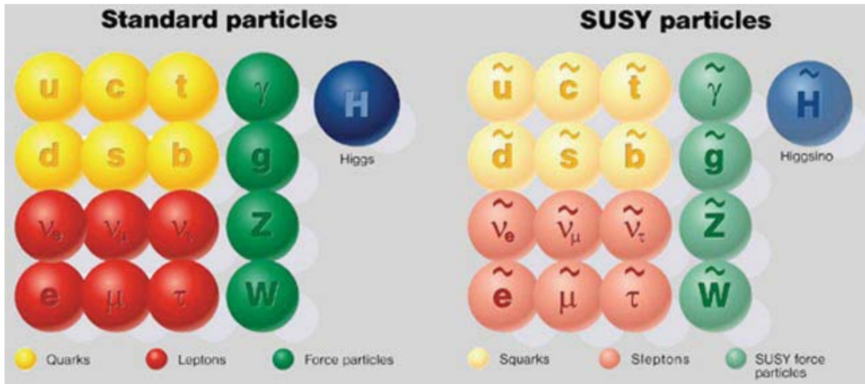

- Many new fields in the MSSM. The general assumption is that the LSP is the dark matter (neutralino or gravitino).
- However, one might wonder whether or not some stable configuration exists of some of the non-LSP fields that could act as dark matter.
- Q-balls are just such an example.

Affleck-Dine Mechanism

[Affleck, Dine (1995)]
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Baryogenesis through a coherent scalar field.

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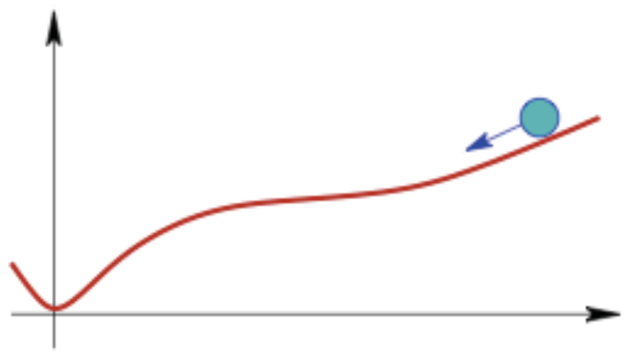
- Phase mismatch between A-terms violates CP.

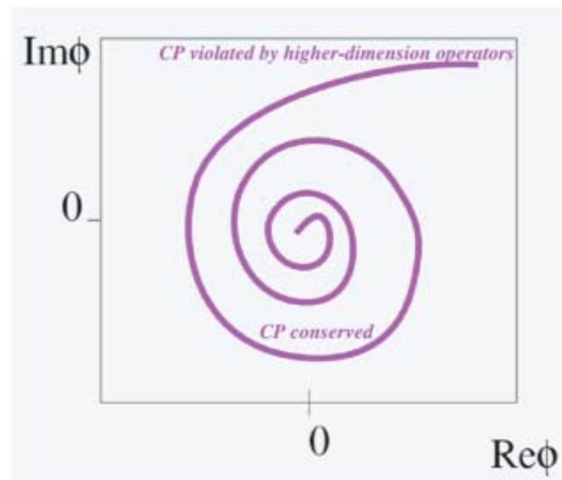
- At the $H \sim m_{3/2}$ epoch, in the radial direction ϕ rolls to the origin.

- At this epoch, the A-terms give a kick to ϕ in the angular direction.



$$\frac{n_B}{s} \sim \frac{n_B}{\rho_I / T_R} \sim \left(\frac{n_B}{n_\phi}\right)\left(\frac{T_R}{m_\phi}\right)\left(\frac{\rho_\phi}{\rho_I}\right)$$

$$\sim 10^{-10}\left(\frac{T_R}{10^9 GeV}\right)\left(\frac{M_p}{m_{3/2}}\right)^{\frac{(n-1)}{(n+1)}}$$



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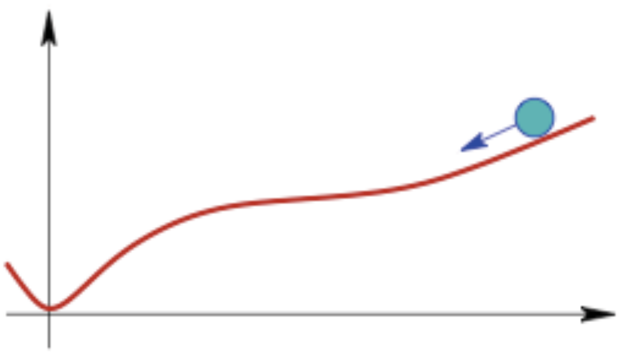

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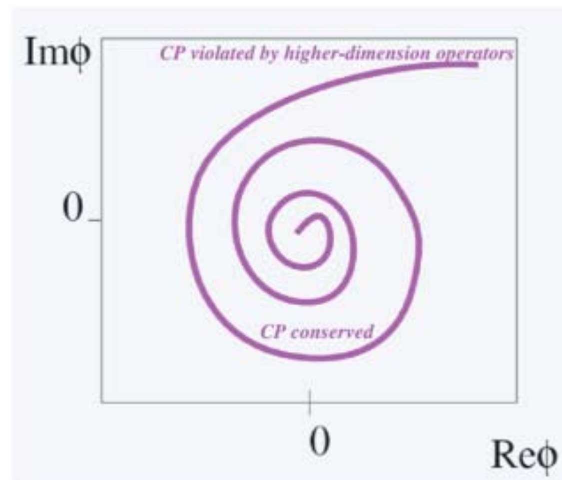
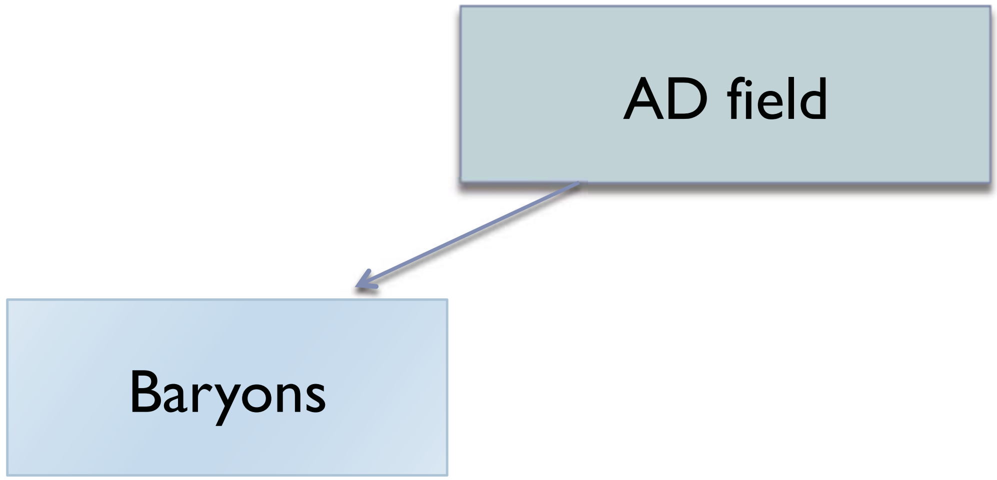


Correct baryon asymmetry for n = 1

Fragmentation of the AD condensate produces Q-balls



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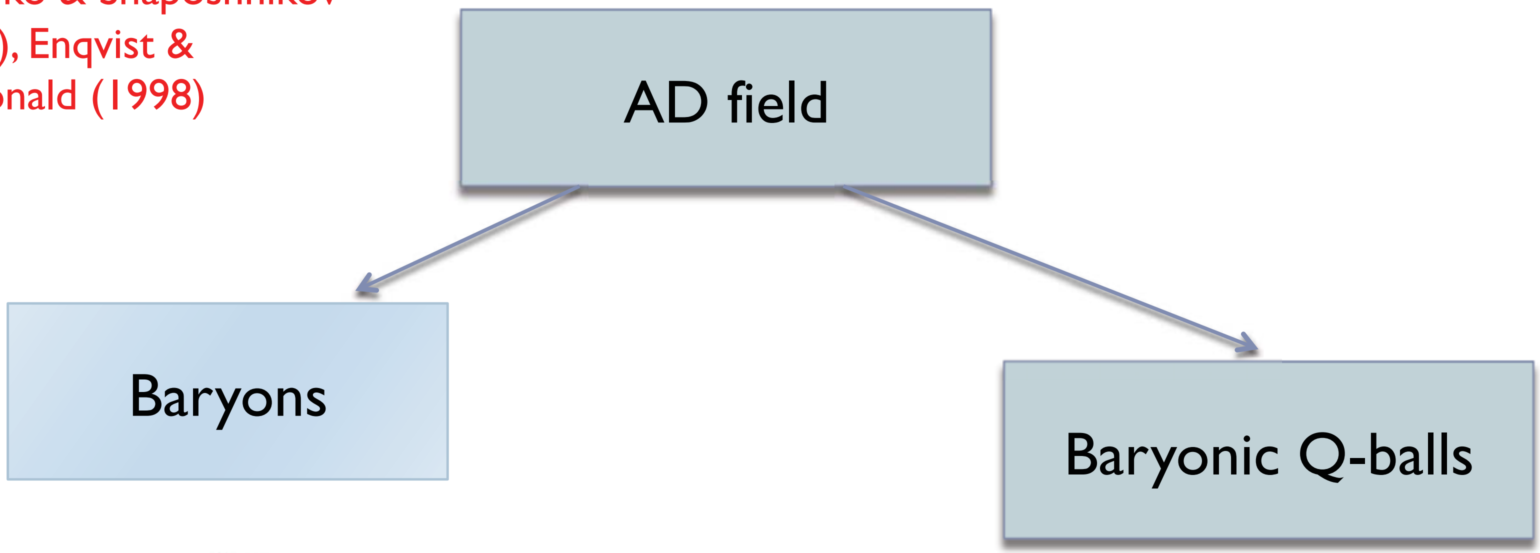
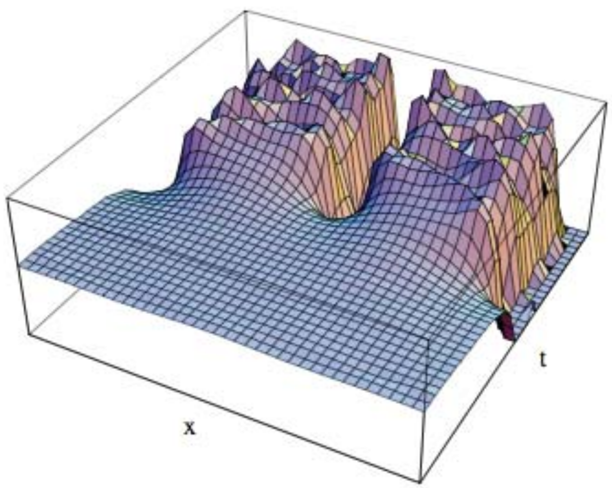
Kusenko & Shaposhnikov (1997), Enqvist & McDonald (1998)





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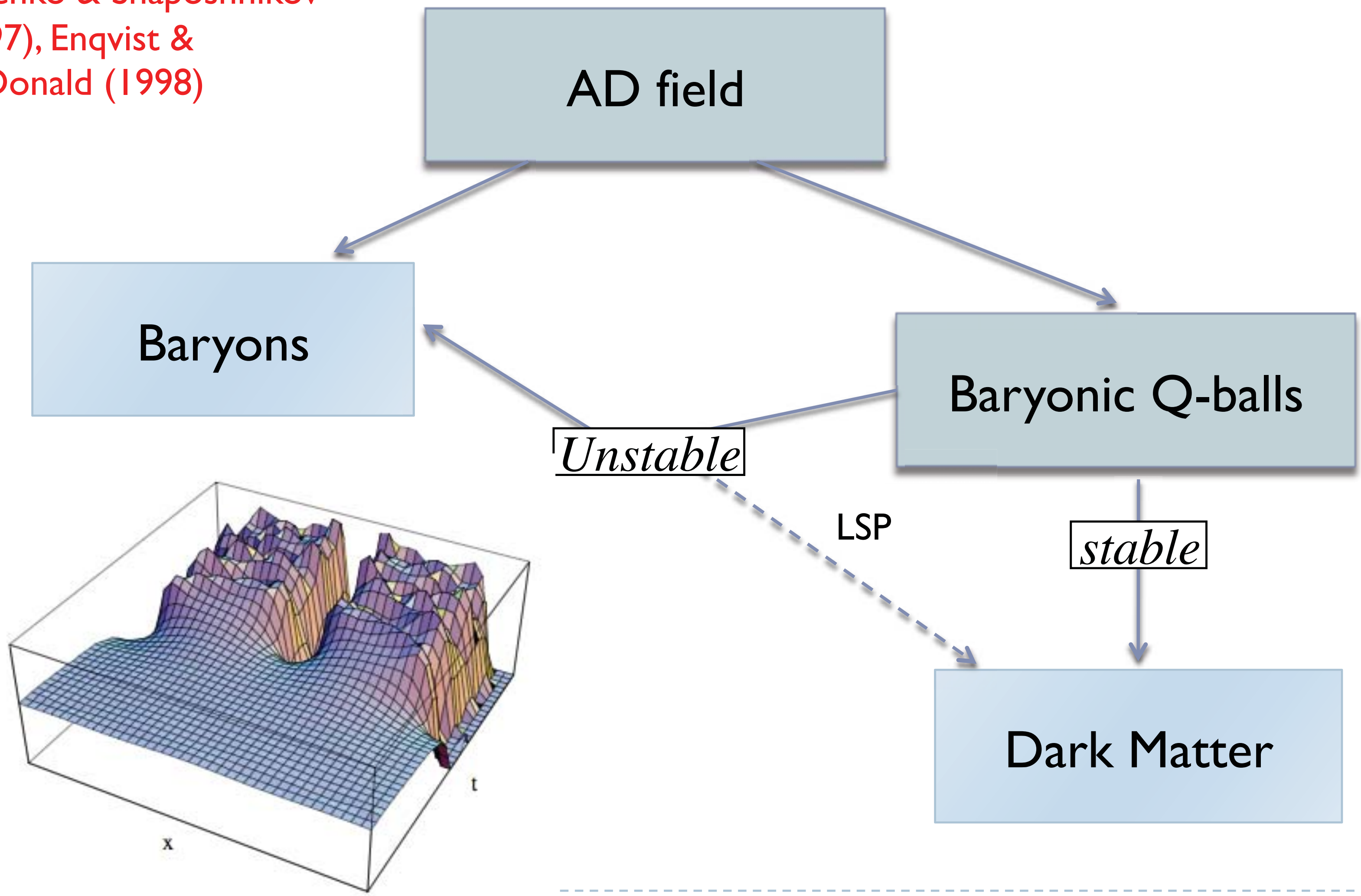

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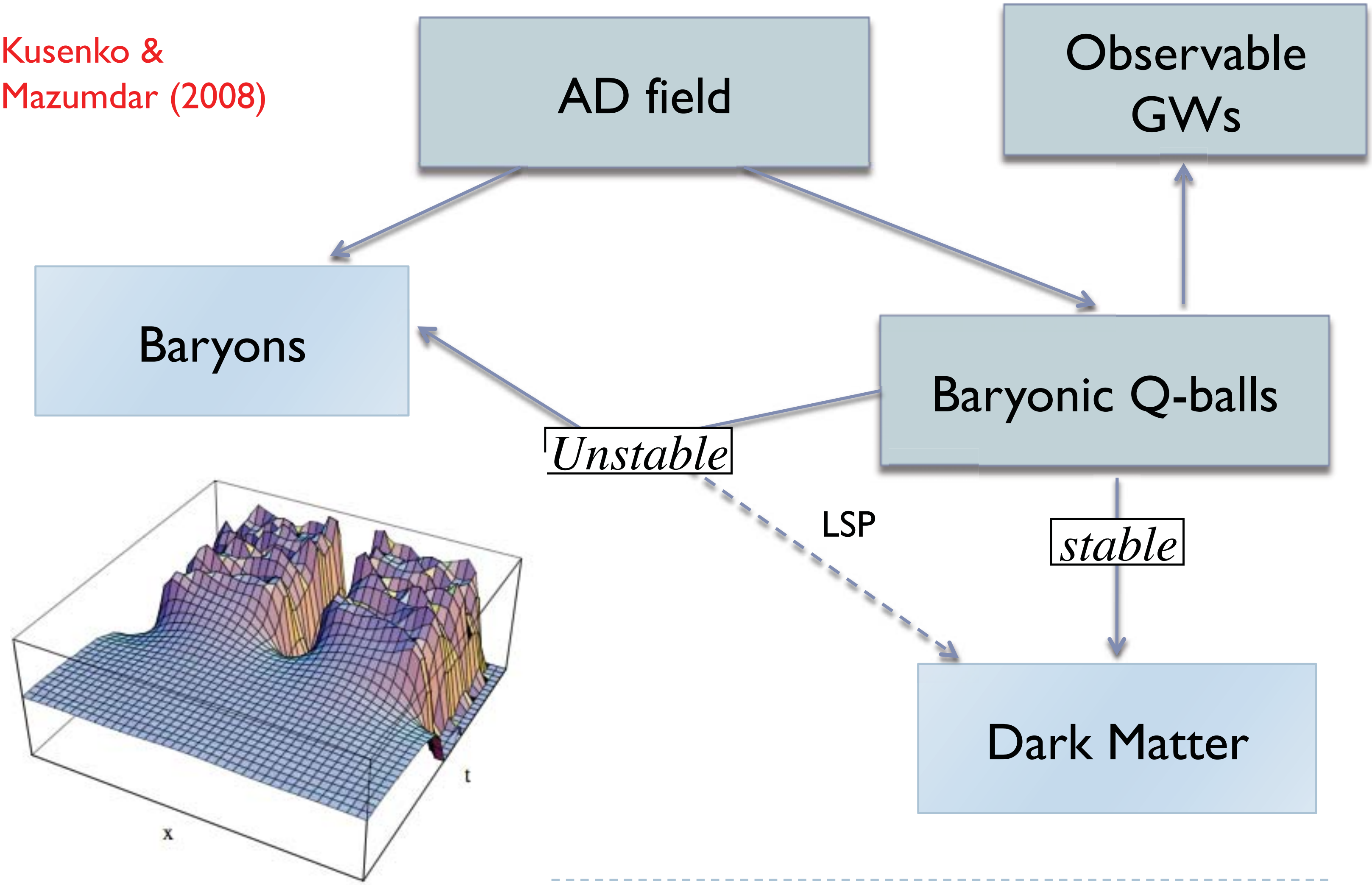

Constructing Q-ball solutions

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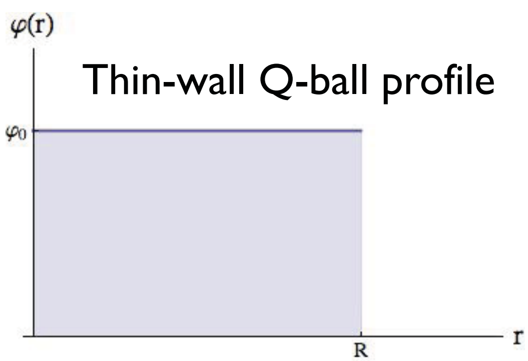
$$E = \int d^3x \left[\frac{1}{2}|\dot{\varphi}|^2 + \frac{1}{2}|\nabla\varphi|^2 + U(\varphi) \right]$$

for a given, constant amount of charge Q.

$$Q = \frac{1}{2i}\int d^3x \left(\varphi^* \partial_0 \varphi - \varphi \partial_0 \varphi^* \right)$$

Solved first by <u>Sidney Coleman</u> (1985).



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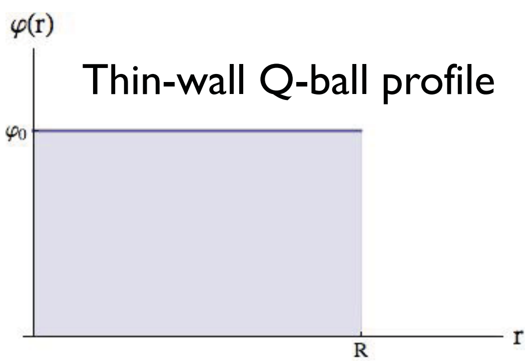

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A Q-ball is an example of a *non-topological* soliton.

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Minimize the energy, $E = \int d^3x \left[\frac{1}{2} |\dot{\varphi}|^2 + \frac{1}{2} |\nabla \varphi|^2 + U(\varphi) \right]$, subject to $Q = const$.

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The final step is to minimize $\mathcal{E}_\omega$ with respect to ω .

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PRL **98,** 265302 (2007) PHYSICAL REVIEW LETTERS week ending 29 JUNE 2007

Magnon Condensation into a *Q* Ball in ^{3}He-*B*

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[1]*Institute Neel, CNRS-UJF, Grenoble, France*

[2]*Low Temperature Laboratory, Helsinki University of Technology, Helsinki, Finland*

[3]*L. D. Landau Institute for Theoretical Physics, Moscow, Russia*

(Received 9 March 2007; published 29 June 2007)

The theoretical prediction of *Q* balls in relativistic quantum fields is realized here experimentally in superfluid ^{3}He-*B*. The condensed-matter analogs of relativistic *Q* balls are responsible for an extremely long-lived signal of magnetic induction observed in NMR at the lowest temperatures. This *Q* ball is another representative of a state with phase coherent precession of nuclear spins in ^{3}He-*B*, similar to the well-known homogeneously precessing domain, which we interpret as Bose-Einstein condensation of spin waves—magnons. At large charge *Q*, the effect of self-localization is observed. In the language of relativistic quantum fields it is caused by interaction between the charged and neutral fields, where the neutral field provides the potential for the charged one. In the process of self-localization the charged field modifies locally the neutral field so that the potential well is formed in which the charge *Q* is condensed.

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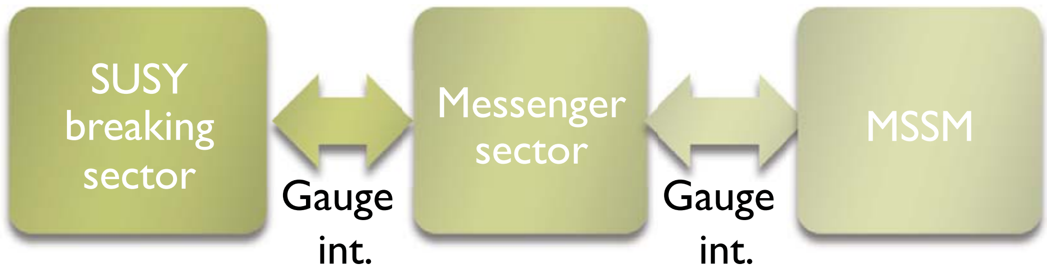
Q-balls have been observed in condensed matter systems. Might they be present elsewhere in nature?

Gauge Mediated Models

Dine et al., 1997

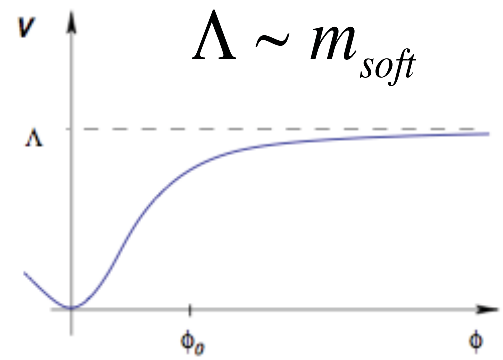


- In gauge mediated models the two-loop effective potential is logarithmic above the messenger scale ➔ Flat direction.

- In these models the SUSY breaking scale is much smaller because of loop factors:

$$m_{soft} \sim \frac{g^2}{16\pi^2} M_{mess} \sim 10^{2-3} GeV$$

$$\Lambda \sim m_{soft}$$



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- Such Q-balls can be stable and exist as a (baryonic) dark matter today.

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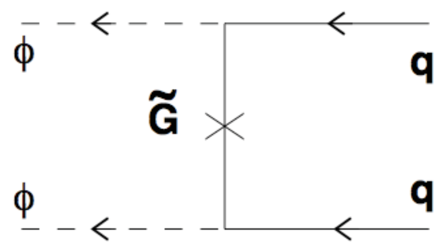
Numerically Kasuya and Kawasaki (2001) have found $Q_{\max} \approx \beta \left(\frac{\phi_0}{M_s}\right)^4$ where $\beta \approx 10^{-3}$, which implies $Q_{\max} \leq 10^{57}$.

“Old” limits on Q-balls

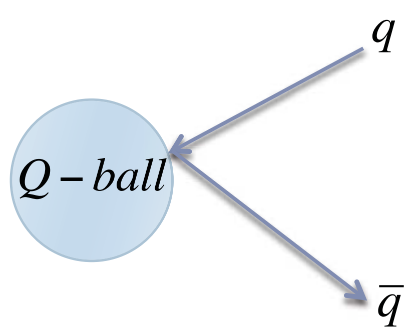
How to detect a Q-ball

Kusenko, Loveridge, Shaposhnikov (2005)

- The non-standard vacuum inside a Q-ball gives a large Majorana mass for the gluino.



- This in turn gives quarks a large Majorana mass, allowing Q-balls to convert baryons to anti-baryons:

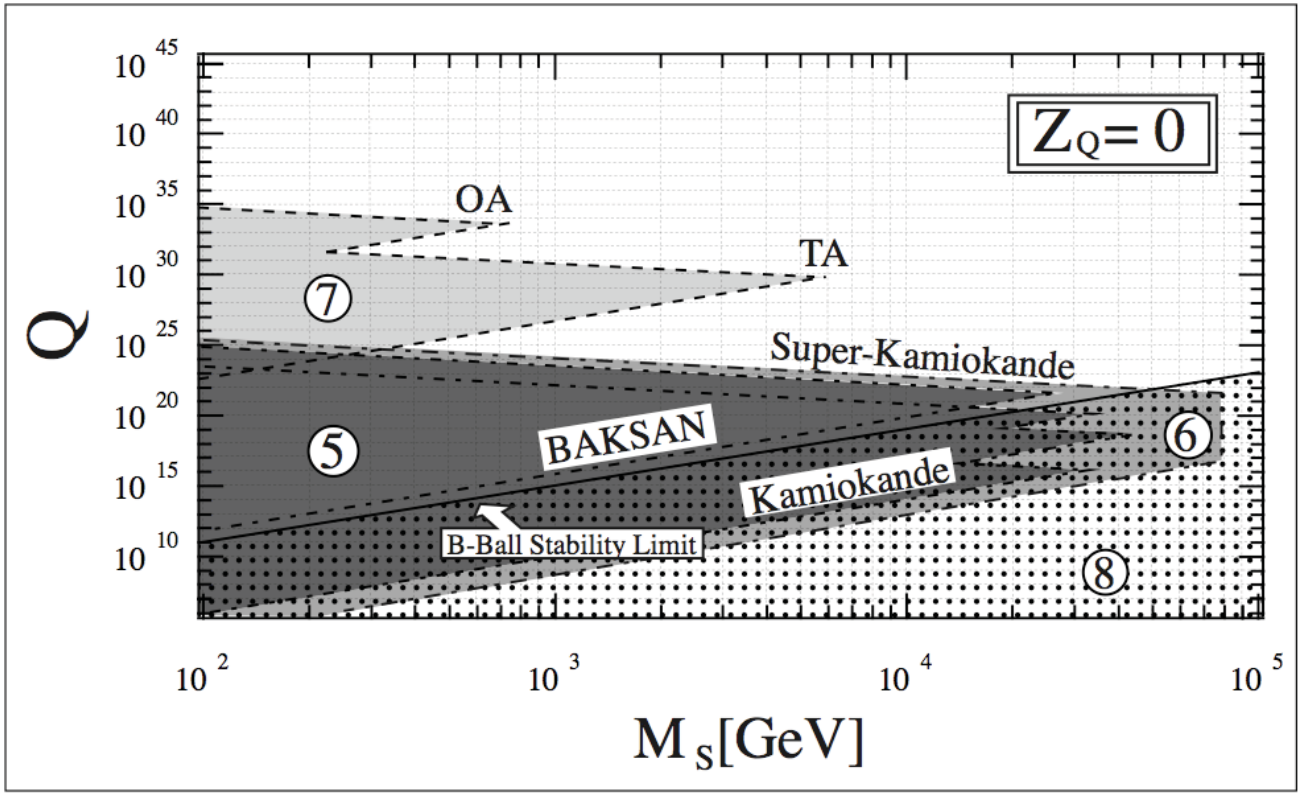


$$n + Q(B) = \overline{n} + Q(B+2)$$

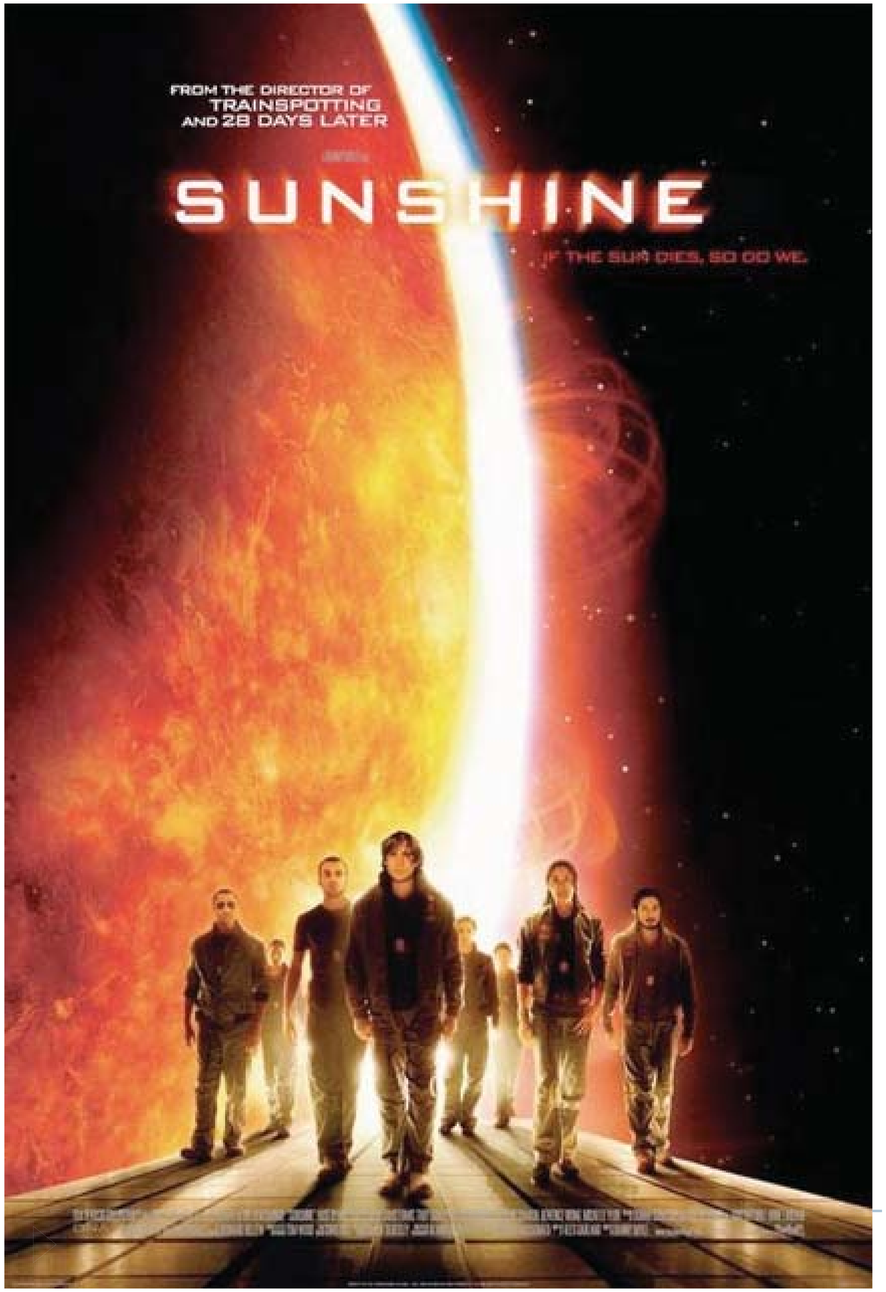
Super-K Limits

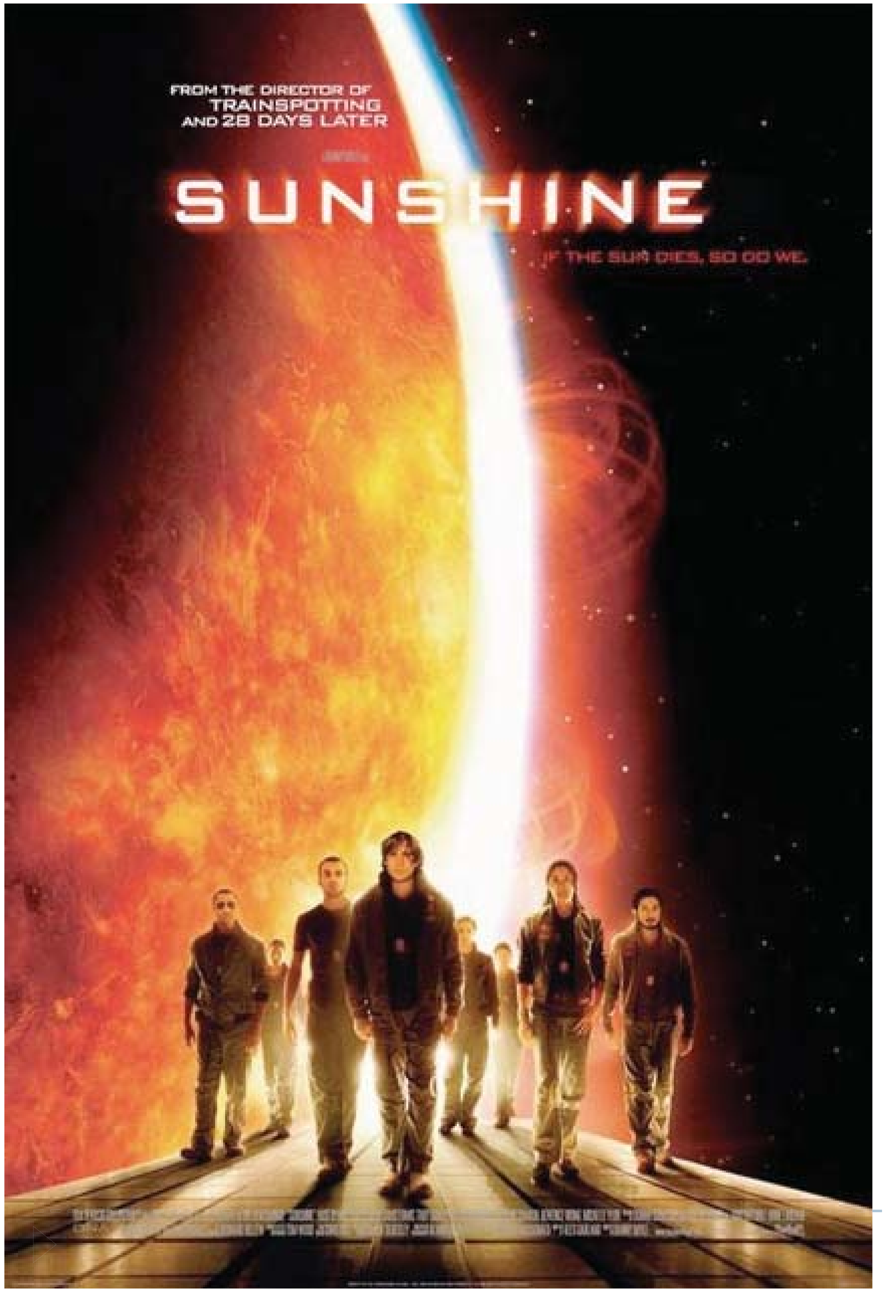
Experimental limit for neutral FD Q-balls: $Q > 10^{22}$

Arafune et al. (2008)



New limits on Q-balls: neutrinos and neutron stars


FROM THE DIRECTOR OF
TRAINSPOTTING
AND 28 DAYS LATER
SUNSHINE
IF THE SUN DIES, SO DO WE.



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Neutron Star Limits

- Neutron stars are so dense that a collision with a Q-ball is sure to result in capture.
- The time for a neutron star to capture a Q-ball is roughly:

$$\tau_{cap} \sim \frac{1}{4\pi R_{NS}{}^{2} F_{DM}}$$

- All sufficiently light Q-balls are captured inside Neutron stars:

$$Q < 10^{43}\left(\frac{M_s}{TeV}\right)^{4/3}$$

Radiative corrections to the flat direction potential

- Although any given FD has no classical potential, quantum corrections lift this degeneracy:

$$V(\phi) = M_s^4 \log\left(1 + \frac{|\phi|^2}{M_s^2}\right) + m_{3/2}^2 |\phi|^2 \left[1 + K \log\left(\frac{|\phi|^2}{M^2}\right)\right]$$

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- When the first term dominates: $M_{gauge}(Q_B) \sim M_S Q^{3/4}$.
- Gauge-type Q-ball dark matter: Kusenko, Shaposhnikov (1997).

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- When the first term dominates: $M_{gauge}(Q_B) \sim M_S Q^{3/4}$.
- Gauge-type Q-ball dark matter: Kusenko, Shaposhnikov (1997).
- When the second term dominates: $M_{gravity}(Q_B) \sim m_{3/2} Q_B$.
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I.S. arXiv:0907.0269

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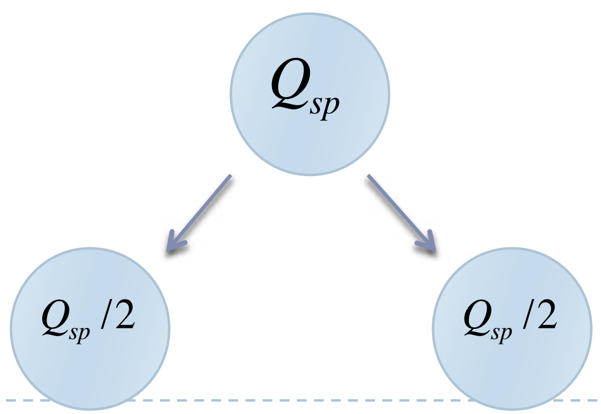

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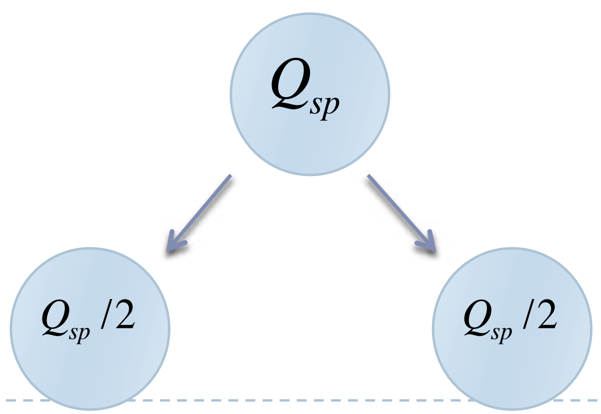

First Q-split occurs after about 1 year inside a neutron star.

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Astrophage of Neutron Stars via Q-splitting

- Q-splitting leads to the exponential growth of Q-balls inside a neutron star:

$$N_Q(t) \approx Q_{sp} 2^{t/t_{sp}}$$

- Typical neutron stars have about $Q_{NS} \sim 10^{57}$, which is consumed by Q-balls in a very short time:

$$t_* < 10^9 \left(\frac{keV}{m_{3/2}} \right)^2 \left(\frac{M_S}{TeV} \right)^4 s$$

- Thus all Q-balls which would be captured by neutron stars are phenomenologically excluded.

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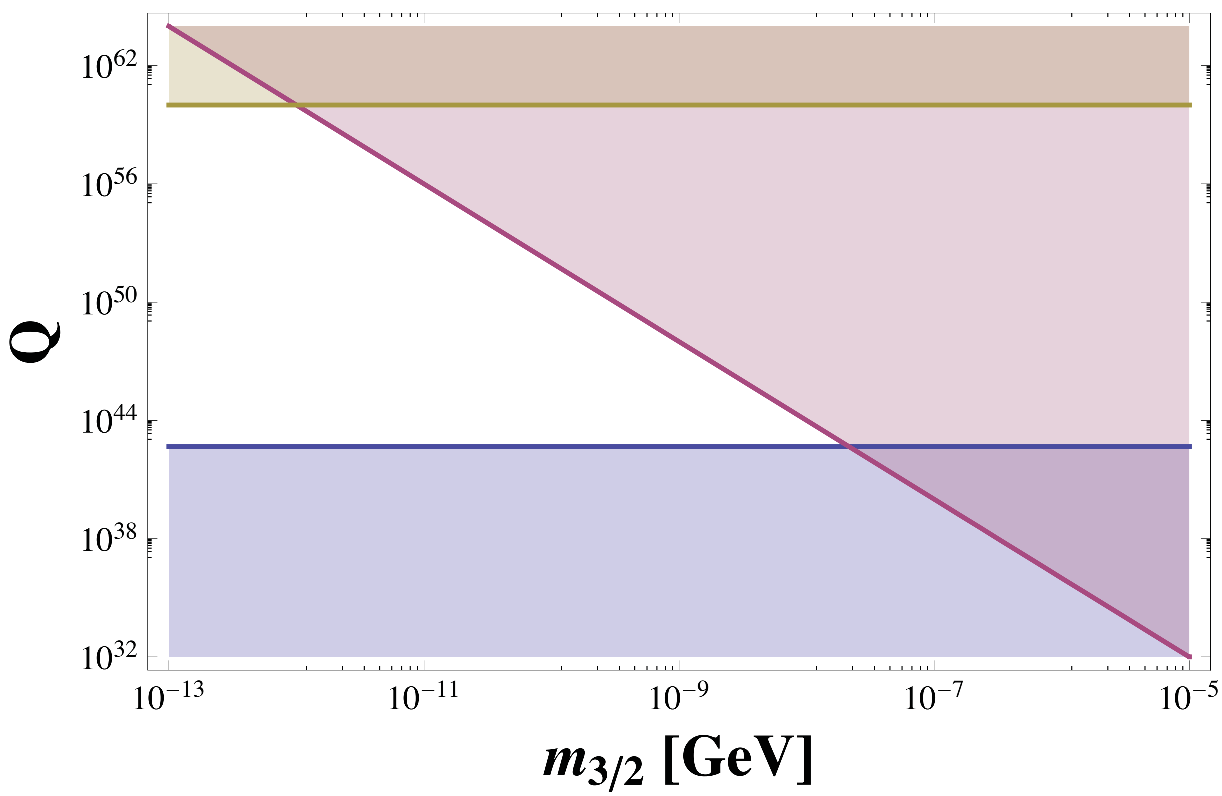
New astrophysical limits on Q-balls



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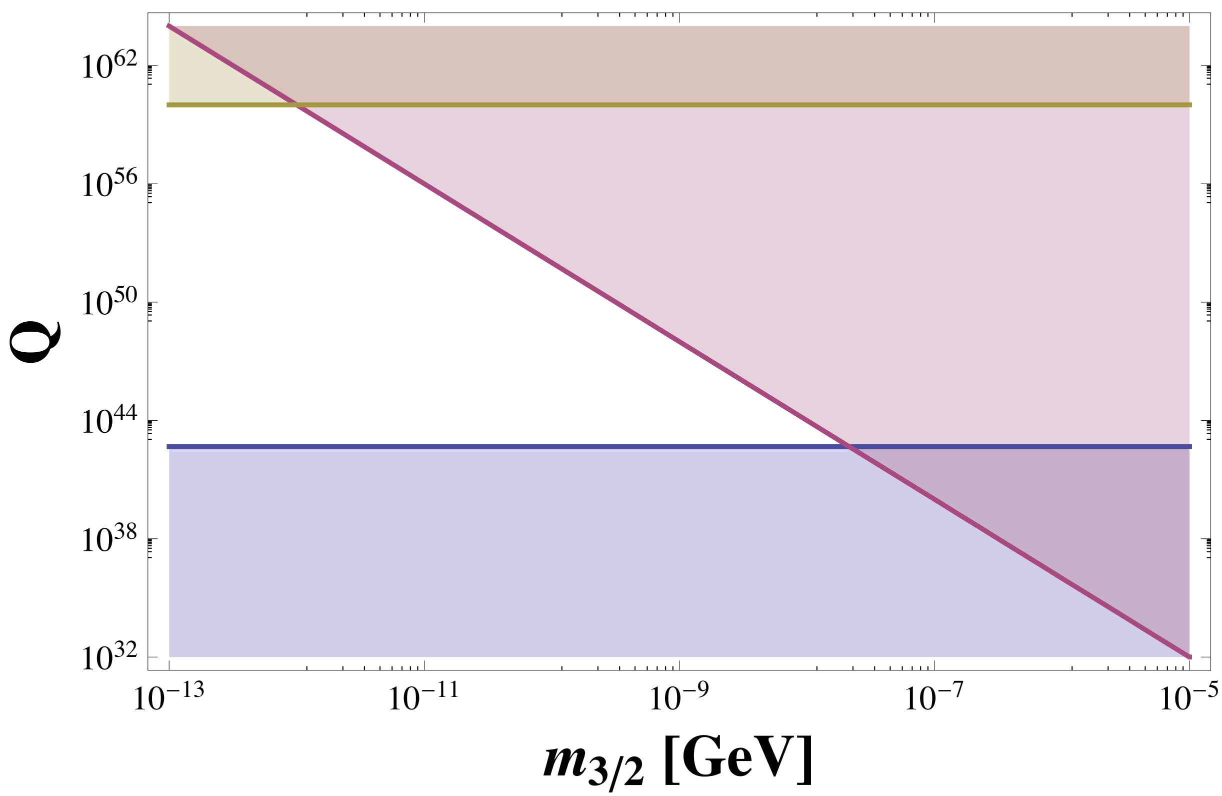


Phenomenological constraints imply:

$$m_{3/2} < keV$$

Which naturally avoids overclosure.

$U(1)_B$ violation can hide the Q-split

- Kusenko, Loveridge, Shaposhnikov (2005) used the higher dimensional operators:

$$V^{(n)}(\phi) = \lambda_n M_G{}^4 \left(\frac{\phi}{M_G}\right)^{n-1+m} \left(\frac{\phi^*}{M_G}\right)^{n-1-m}$$

- To show that a particular flat direction with $m \neq 0$ has a maximum Q-ball size due to U(1) violation:

$$Q_{cr} \sim \left(\frac{M_G}{M_s}\right)^{\frac{4n-12}{n-1}}$$

- Thus FDs for which $Q_{cr} < Q_{sp}$, evade the neutron star limits.

How to constrain Q-balls with $Q_{cr} < Q_{sp}$

Neutrino signal from terrestrial passage of Q-balls

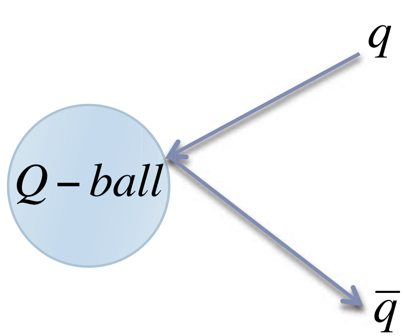
Neutrinos from Q-balls passing through the Earth

- Q-balls convert nucelons into anti-nucleons with high probability. Subsequent annihilations lead to flux of neutrinos:

$$n\bar{n} \to \frac{\langle N_\pi \rangle}{3}\left(\pi^+ + \pi^- + \pi^0\right)$$

$$\pi^\pm \to \mu^\pm + \bar{\nu}_\mu(\nu_\mu)$$

$$\mu^\pm \to e^\pm + \bar{\nu}_e(\nu_e)$$



Neutrino flux

$$N_\oplus \sim \frac{\rho_{DM} V_\oplus}{M(Q_B)} \sim 3\times 10^5 \left(\frac{10^{24}}{Q_B}\right)^{3/4} \left(\frac{TeV}{M_S}\right)$$

$$\frac{dN_\nu}{dt} \sim 10\left(\pi R(Q_B)^2\right) n_n v_0 N_\oplus$$

$$F_{\nu,\oplus} \sim \frac{1}{4\pi R_\oplus{}^2} \frac{dN_\nu}{dt}$$

$$F_{\nu,\oplus} \sim 0.1\left(\frac{10^{24}}{Q_B}\right)^{1/4} \left(\frac{TeV}{M_s}\right)^3 cm^{-2} s^{-1}$$

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This is right around the same energies and total flux as the atmospheric neutrino flux, and may be detectable.

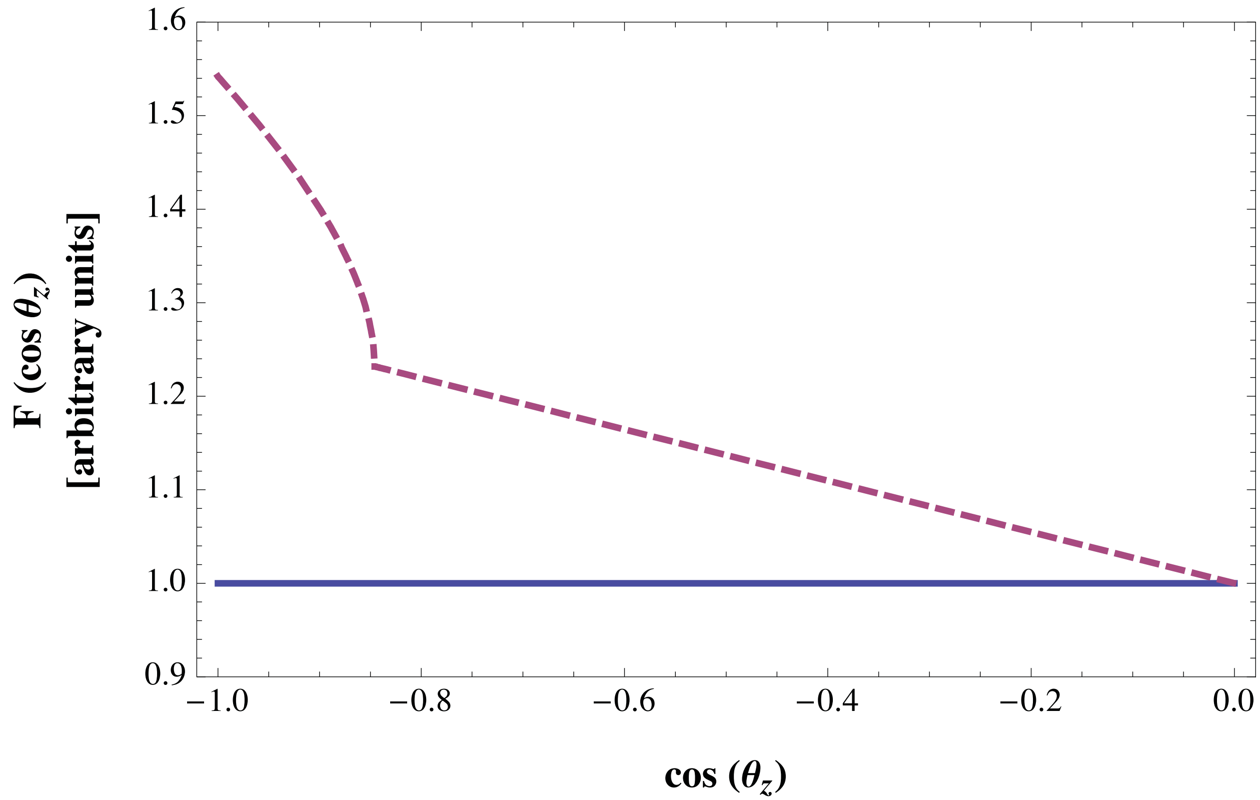
Zenith Angle Dependence

- The isotropy of the Q-ball flux on the Earth implies a zenith angle dependence determined by the Earth geometry:

$$F_\nu(\theta_z) \propto \begin{cases} 0, & \theta_z < \pi/2 \\ \rho_{\rm m} \cos\theta_z, & \pi/2 \le \theta_z \le \theta_{\rm c} \\ \rho_{\rm m} \cos\theta_z + (\rho_{\rm c} - \rho_{\rm m}) f_c(\theta_z), & \theta_{\rm c} \le \theta_z \le \pi \end{cases}$$

where $f_c(\theta_z) = \sqrt{(R_{\rm c}/R_\oplus)^2 - \sin^2\theta_z}$, and $\rho_{\rm m}$ and $\rho_{\rm c}$ are the mantle and core densities respectively.

Zenith Angle dependence



Q-ball induced neutrino spectrum

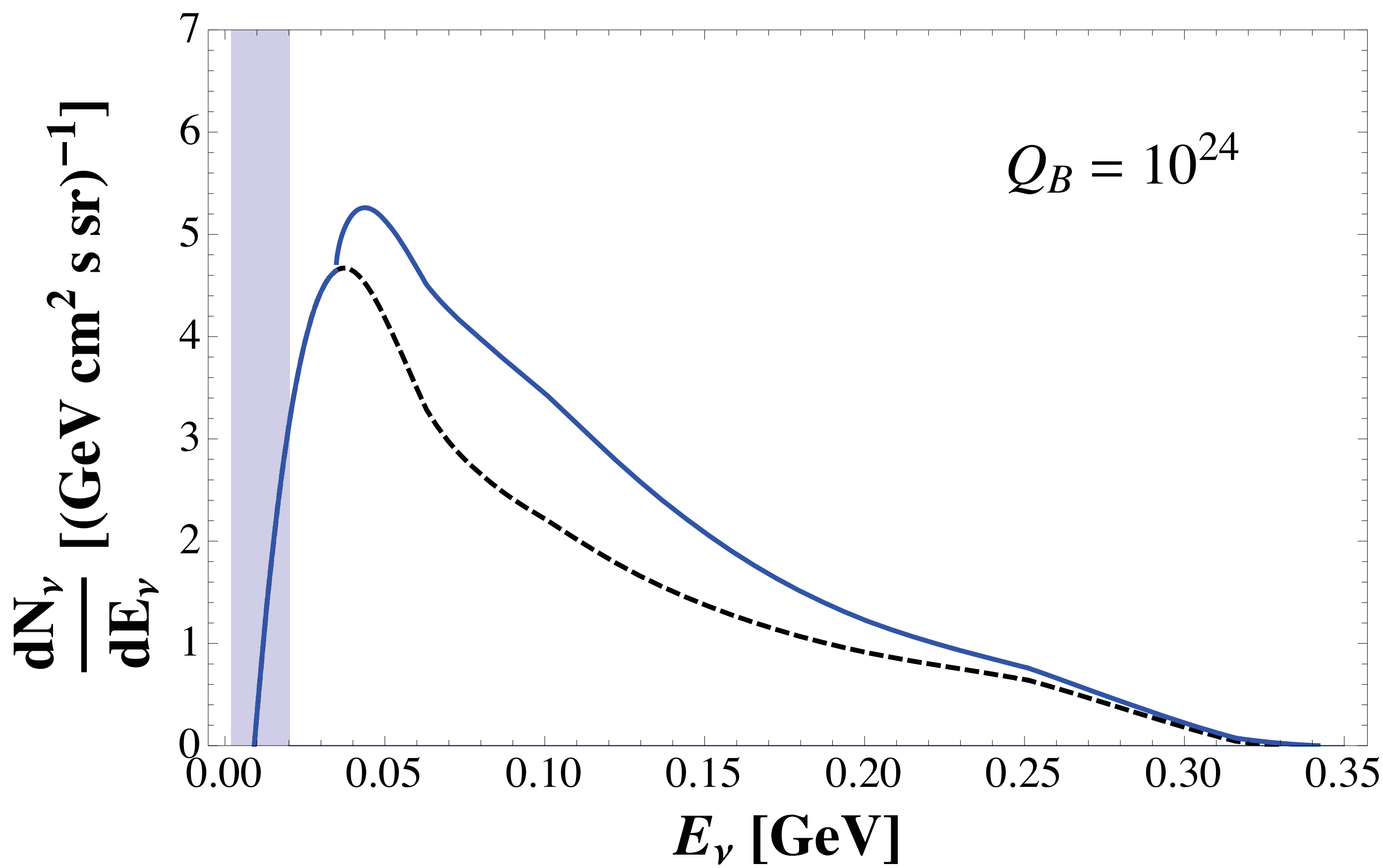
- The neutrino spectrum can be found from the experimentally known pion spectrum from at rest $p\bar{p}$ annhiilations

$$\frac{dN_\nu}{dE_\nu} = \frac{\partial N_\nu}{\partial N_\pi}\frac{\partial k_\pi}{\partial E_\nu}\left(\frac{dN_\pi}{dE_\pi}\right)$$

- And normalizing to the overall flux found earlier:

$$F_Q = \int \frac{dN_\nu}{dE_\nu} dE_\nu$$

Neutrino Spectrum



Spectrum of Q-ball produced neutrinos

- Important note: this spectrum ignores possibly important matter effects.
- Pion and muon interactions in matter may cause their decay at rest, induces a monochromatic line in the neutrino spectrum.
- If confirmed, this will aid in the prospects for detection.

Conclusions

- We have presented stringent new limits on Q-balls for which $Q_{cr} > Q_{sp}$.

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- Q-balls in the opposite limit are much less constrained, but their transitory passage through the Earth may produce a detectable level of neutrinos.
  - Such a signal has a peculiar zenith angle dependence and a small annual modulation.