Revisiting Q-ball dark matter: closer look at interaction with ordinary matter

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Based on
AK, Takumi Kuwahara and Keiichi Watanabe in progress

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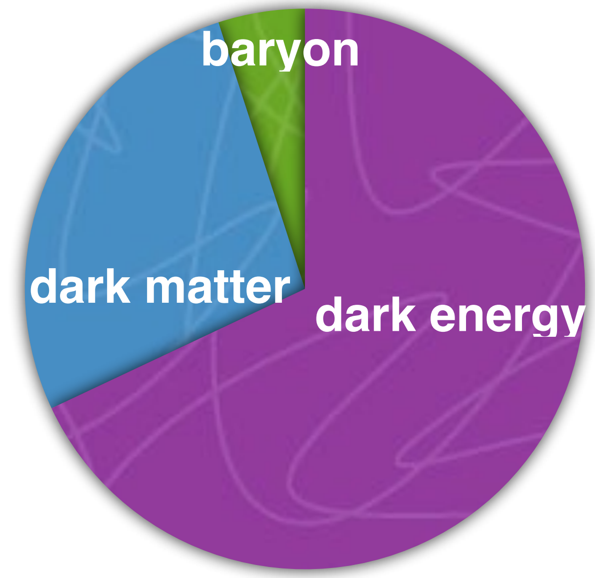
Dark matter

Dark matter

- evident from cosmological observations
  - cosmic microwave background (CMB)…
- one of the biggest mysteries
  - astronomy, cosmology, particle physics…



cosmic energy budget

Heavier than Planck mass $M_{\rm pl} \simeq 2.4 \times 10^{18}\,\mathrm{GeV} \simeq 4.3 \times 10^{-6}\,\mathrm{g}$

- actually we (human beings) are such “dark matter” from the point of view of dark matter
- cannot be point-like particle and thus composite/extended object
- MACHO (MAssive Compact Halo Object)
  - brown dwarfs, floating planets…
  - disfavored by microlensing survey

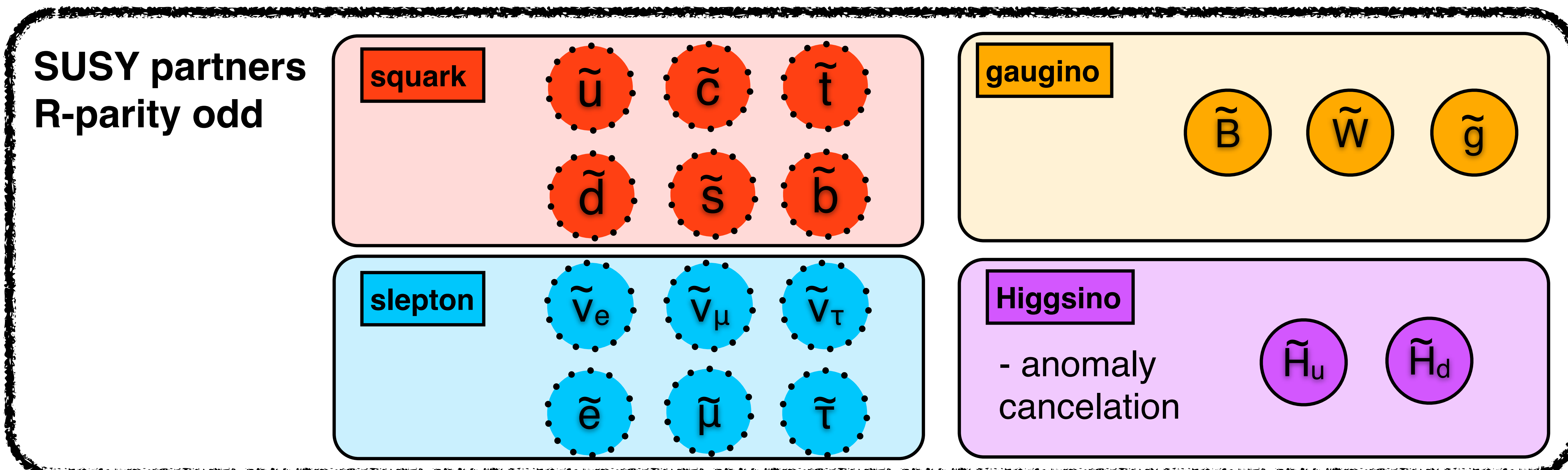
Q-ball dark matter

Extended object carrying large B number

$R > \mathcal{O}(10)\,\mathrm{fm}$

$M > \mathcal{O}(1)\,\mathrm{g}$

- L number and mixture are also possible
- made of scalar particle that carries a B number
- naturally realized in supersymmetric (SUSY) extension of standard model (SM)
  - squarks (scalar) ↔ quark (fermion)



Direct detection experiments

Flux limit

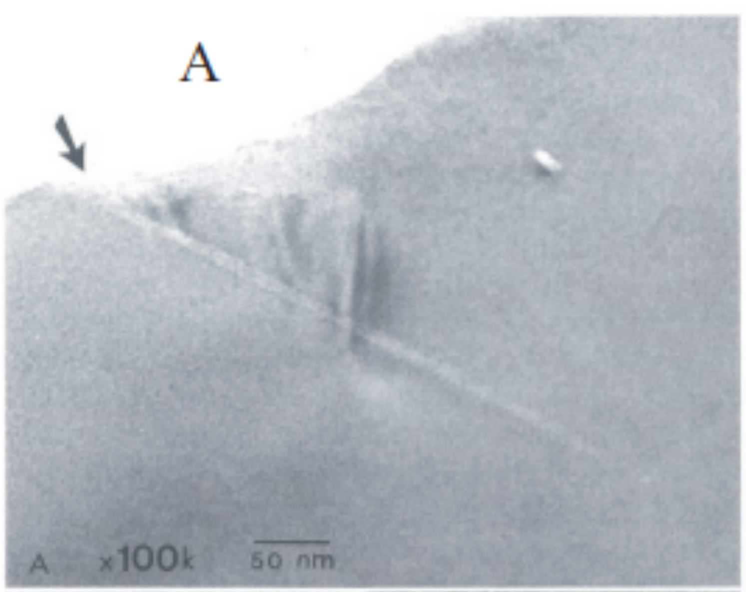
- conventional experiments cannot search for superheavy dark matter because less than one dark matter arrives within a couple of years

$$F_{\rm dm} = 5 \times 10^{-13}/{\rm cm}^2/{\rm s}/{\rm sr} \sim 0.2\,/{\rm m}^2/{\rm yr}/{\rm sr} \times \left(\frac{10^{18}\,{\rm GeV}}{m_{\rm dm}}\right)\left(\frac{v_{\rm dm}}{200\,{\rm km/s}}\right)$$

Paleo detector

Baum, Drukier, Freese, Górski, and Stengel, PLB, 2020

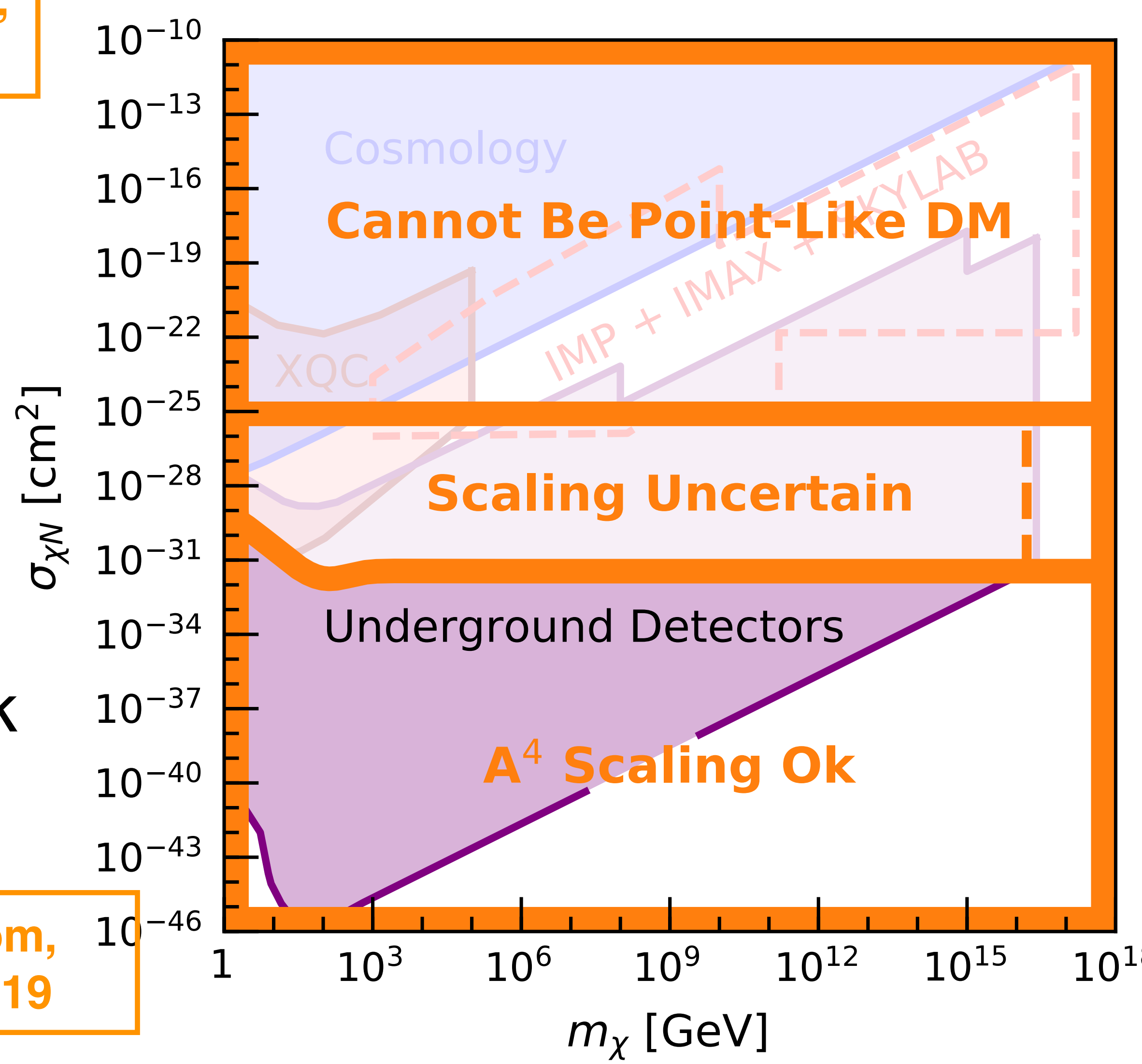
- using ancient mineral as a detector



- exposure

$T_{\rm exp} = \mathcal{O}(10) - \mathcal{O}(10^3)\,{\rm Myr}$

- fission track in apatite



PALEOCCENE collaboration, Phys. Dark Univ., 2023

Digman, Cappiello, Beacom, Hirata, and Peter, PRD, 2019

Direct detection of Q-ball

Paleo detector and Q-ball dark matter

- Q-ball has a large geometrical cross section with nucleon

$$\sigma_Q \gtrsim 10^{-24}\,\mathrm{cm}^2 \simeq 1\,\mathrm{barn}$$

- it has not been well-understood what happens to nucleon
  - elastic
  - inelastic: pion emission; conversion to anti-nucleon
- DM-nucleon elastic scattering is typically assumed in paleo detector
- if inelastic scattering is dominant, analysis should be dedicated to Q-ball dark matter

Contents

Review of Q-ball dark matter

- stability of Q-ball
- (old) gauge mediation type
- new (gauge mediation) type

Interaction with matter

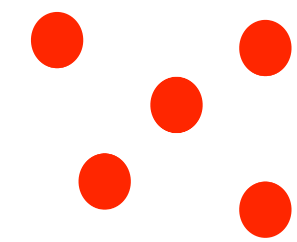
- “colorless” quark in quantum mechanical scattering theory
- Q-ball gets charged via interaction with nucleon
- Q-ball behaves as heavy charged particle

Q-ball

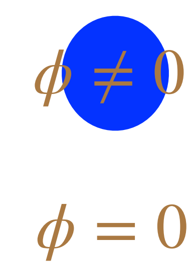
Given N particles with mass m

Coleman, NPB, 1985

- what is most energetically favored configuration?
- configuration 1: free particles
  - energy per particle $\omega_1 = E_1/N = m$



- configuration 2: Q-ball (condensation characterized by a field value ϕ)
  - does not occur in fermion (Pauli-blocking)
  - If $\omega_2 < m$, Q-ball configuration is preferred
  - this is the case, when the scalar potential has some field value satisfying $m_{\rm eff}^2(\phi) = 2V(\phi)/\phi^2 < m^2 = m_{\rm eff}^2(\phi = 0)$



- such a specific scalar potential is naturally realized in SUSY
  - flat direction like udd, which has only SUSY breaking mass and its radiative correction

Supersymmetry

Do you remember?

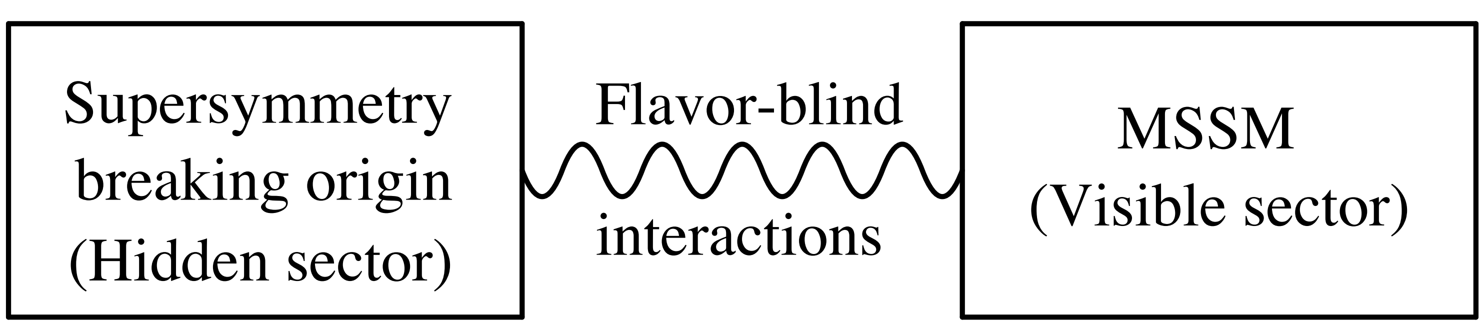
- yes, not as popular as before, but still one of the most compelling candidates of physics beyond SM

- possible explanation why electroweak symmetry breaking $M_{\rm ew} \simeq 246\,{\rm GeV}$ does not occur at Planck scale (hierarchy problem)

- we know all the couplings and thus cannot make an excuse that new particles are feebly interacting with SM particles

- only mass of SUSY partners matter (lower bound around 1 TeV)

- gauge and/or gravity (spacetime gauge) interaction can mediate SUSY breaking to our sector



Martin, Adv. Ser. Direct. High Energy Phys., 2010

Gauge mediation

Q-ball is stable in gauge mediation

Kusenko and Shaposhnikov, PLB, 1998

- in gravity mediation, $\omega_Q < m_{\tilde{q}}$ and thus energetically favored compared to free squarks, but $3\omega_Q > m_N$ and thus decays into nucleons

- in gauge mediation, there are two types of Q-ball depending on which part of the potential is dominant; both can be stable

de Gouvea, Moroi and Murayama, PRD, 1997

$$V = V_{\rm gauge} + V_{\rm grav}$$

$$V_{\rm gauge} = M_F^4 \left[\ln \left(1 + \frac{g|\phi|}{M_{\rm mess}} \right) \right]^2$$

- dominant at $\phi \lesssim \phi_{\rm eq} \simeq \dfrac{M_F^2}{m_{3/2}}$

$$V_{\rm grav} = m_{3/2}^2 |\phi|^2 \left(1 + K \ln \frac{|\phi|^2}{M_*^2} \right)$$

- dominant at $\phi \gtrsim \phi_{\rm eq} \simeq \dfrac{M_F^2}{m_{3/2}}$

- SUSY breaking scale

$$g_s M_F \gtrsim m_{\tilde{q}}/\alpha_s \gtrsim 10\,\mathrm{TeV}$$

- gravitino mass

$$1\,\mathrm{keV} \lesssim m_{3/2}$$

- lower bounds are experimental

- g: gauge coupling

- K: coefficient of running mass

- M_*: running mass

(Old) Gauge-mediation type

Gauge potential is dominant

Kasuya, Kawasaki and Yanagida, PTEP, 2015

- in the following we are crude about O(1) coefficient
- mass and radius are independent parameters

$$10\,\mathrm{fm} = 10^{-12}\,\mathrm{cm}$$

$$1\,\mathrm{g} \simeq 5.6 \times 10^{23}\,\mathrm{GeV}$$

$$M_Q \gtrsim 3 \times 10^{23}\,\mathrm{GeV} \times \left(\frac{R_Q}{10\,\mathrm{fm}}\right)^3$$ - originating from $g_s M_F \gtrsim m_{\tilde{q}}/\alpha_s \gtrsim 10\,\mathrm{TeV}$

$$R_Q \gtrsim 0.5\,\mathrm{fm}$$ - originating from $3\omega_Q < m_N$

- total cross section and energy per baryon are given by radius

$$\sigma_Q \simeq 10^{-24}\,\mathrm{cm}^2 \left(\frac{R_Q}{10\,\mathrm{fm}}\right)^2 \qquad 3\omega_Q \simeq 60\,\mathrm{MeV} \times \left(\frac{10\,\mathrm{fm}}{R_Q}\right)$$

- relic abundance (to dm observed abundance) depends also on reheating temperature $T_{\mathrm{RH}} > 1\,\mathrm{MeV}$

$$\frac{\rho_Q}{\rho_{\mathrm{dm}}} \simeq 200 \times \left(\frac{T_{\mathrm{RH}}}{\mathrm{GeV}}\right)\left(\frac{M_Q}{10^{29}\,\mathrm{GeV}}\right)\left(\frac{10\,\mathrm{fm}}{R_Q}\right) \leq 1$$

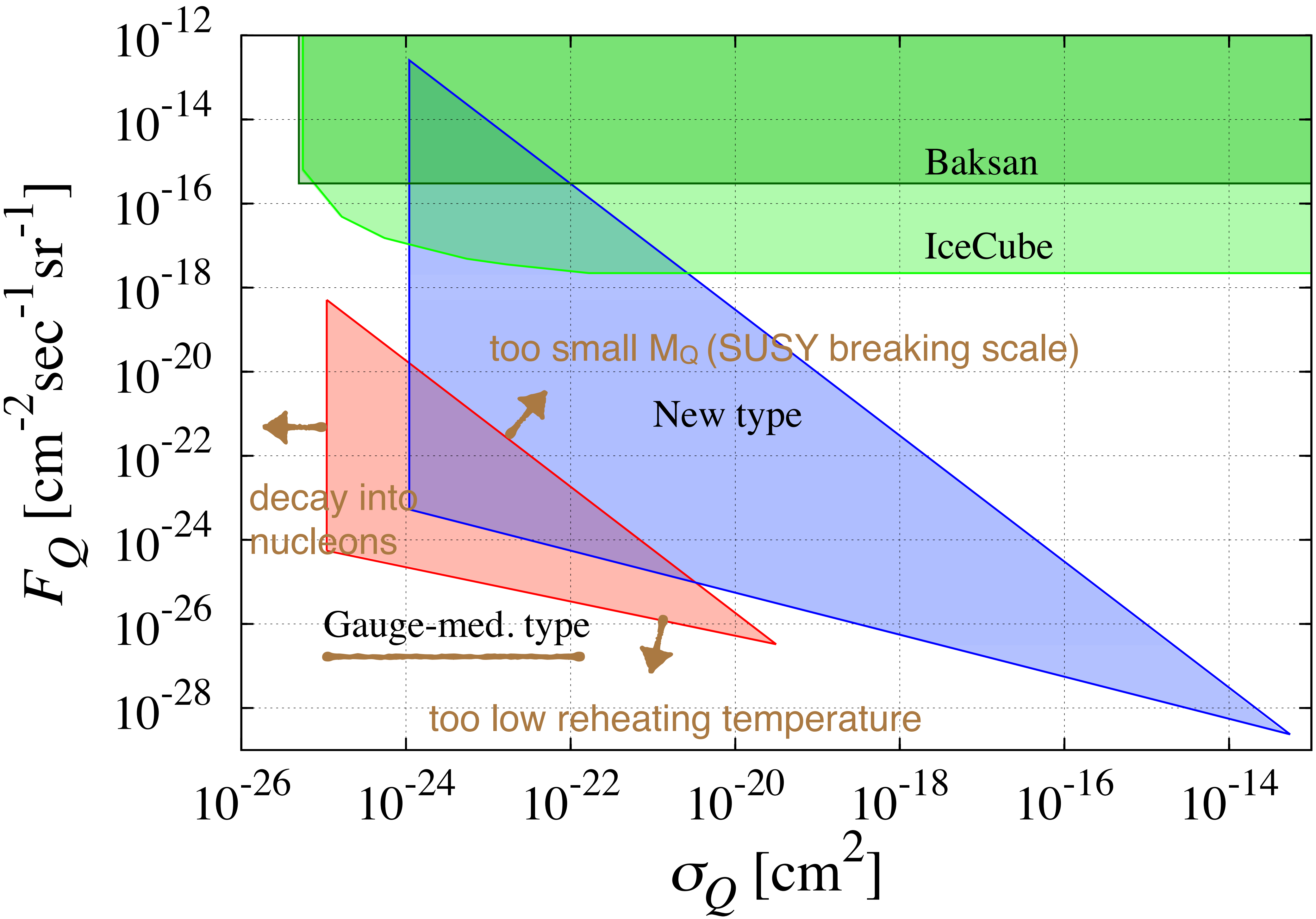
- viable cosmology
- to be a part of dark matter

(Old) Gauge-mediation type

Possible flux vs cross section

$$F_Q = \frac{m_{\rm dm} F_{\rm dm}}{M_Q} \times \frac{\rho_Q}{\rho_{\rm dm}}$$

Kasuya, Kawasaki and Yanagida, PTEP, 2015



New (Gauge-mediation) type

Mass and radius are independent parameters

Kasuya, Kawasaki and Yanagida, PTEP, 2015

- gravity potential is dominant

$$M_Q \gtrsim 6 \times 10^{18}\,\mathrm{GeV} \times \left(\frac{R_Q}{10\,\mathrm{fm}}\right)^3$$

- originating from $\phi \gtrsim \phi_{\mathrm{eq}} \simeq \frac{M_F^2}{m_{3/2}}$

and $g_s M_F \gtrsim m_{\tilde{q}}/\alpha_s \gtrsim 10\,\mathrm{TeV}$

$R_Q \gtrsim 6\,\mathrm{fm}$ - originating from $3\omega_Q < m_N$

- total cross section and energy per baryon are given by radius

$$\sigma_Q \simeq 10^{-24}\,\mathrm{cm}^2 \left(\frac{R_Q}{10\,\mathrm{fm}}\right)^2 \qquad 3\omega_Q \simeq 600\,\mathrm{MeV} \times \left(\frac{10\,\mathrm{fm}}{R_Q}\right)$$

Affleck and Dine, NPB, 1985

Dine, Randall and Thomas, NPB, 1996

- relic abundance (to dm observed abundance) by Affleck-Dine mechanism depends also on reheating temperature $T_{\mathrm{RH}} > 1\,\mathrm{MeV}$

- viable cosmology

$$\frac{\rho_Q}{\rho_{\mathrm{dm}}} \simeq 400 \times \left(\frac{T_{\mathrm{RH}}}{\mathrm{GeV}}\right)\left(\frac{M_Q}{10^{29}\,\mathrm{GeV}}\right)\left(\frac{10\,\mathrm{fm}}{R_Q}\right) \leq 1$$

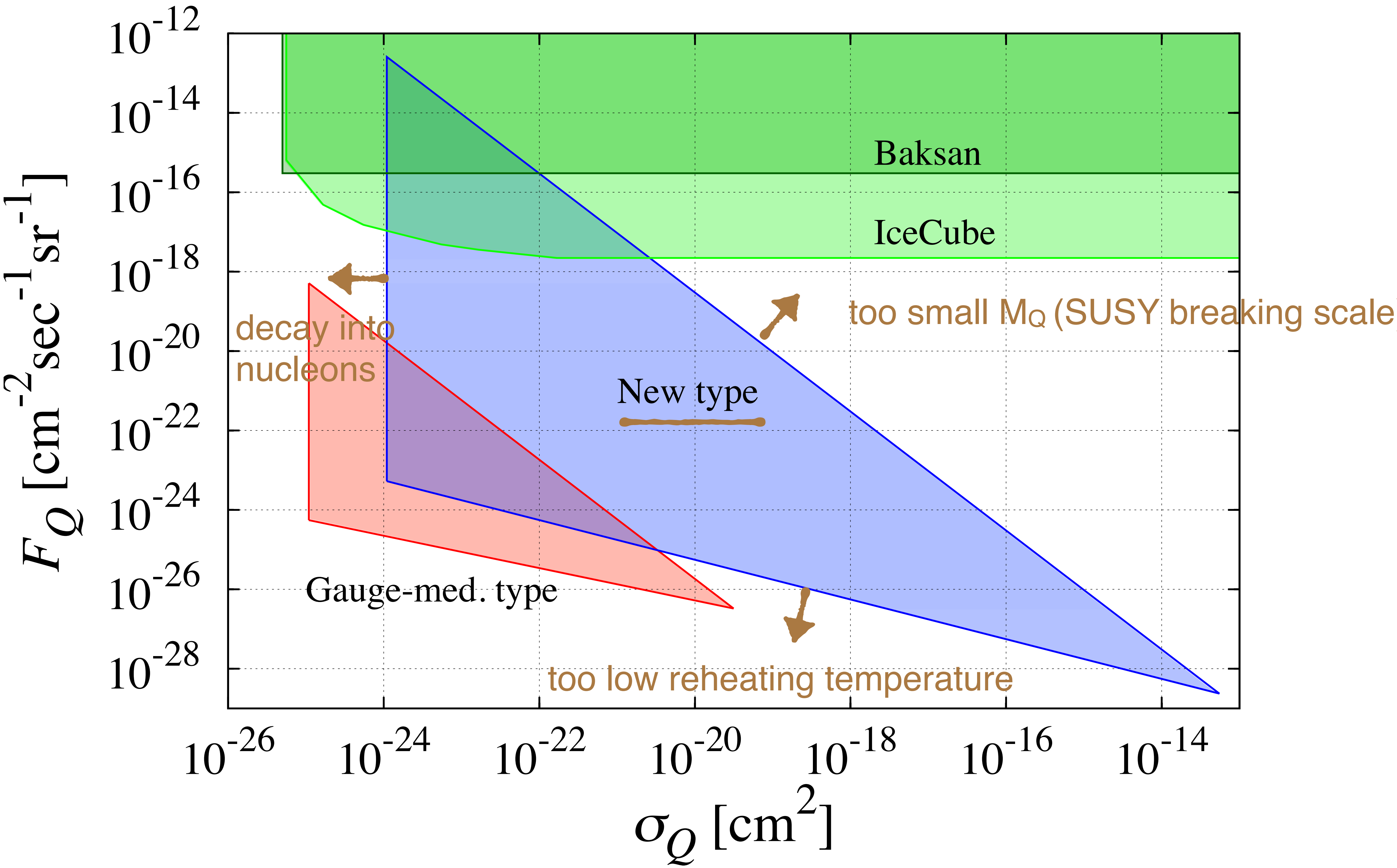
- to be a part of dark matter

New (Gauge-mediation) type

Possible flux vs cross section

$$F_Q = \frac{m_{\rm dm} F_{\rm dm}}{M_Q} \times \frac{\rho_Q}{\rho_{\rm dm}}$$

Kasuya, Kawasaki and Yanagida, PTEP, 2015



- consider that Q-ball is a part (not necessarily all) of dark matter

Contents

Interaction with matter

- "colorless" quark in quantum mechanical scattering theory
- Q-ball gets charged via interaction with nucleon
- Q-ball behaves as heavy charged particle

Inner structure of Q-ball

Large field value of squark

- one linear combination of left-handed and right-handed quark and gluino obtains large mass

    - the other linear combination does not

    - for simplicity let us take right-handed as massive, corresponding to Q-ball made of right-handed squark

- gluon obtains large mass

    - gluon is no more strong but weak like weak gauge boson (Higgsed)

    - hadrons may be dissolved inside Q-ball

Quantum chromodynamics (QCD)

- non-perturbative and difficult to make quantitative prediction even without Q-ball

- let us start with color being turned off (turned on later)

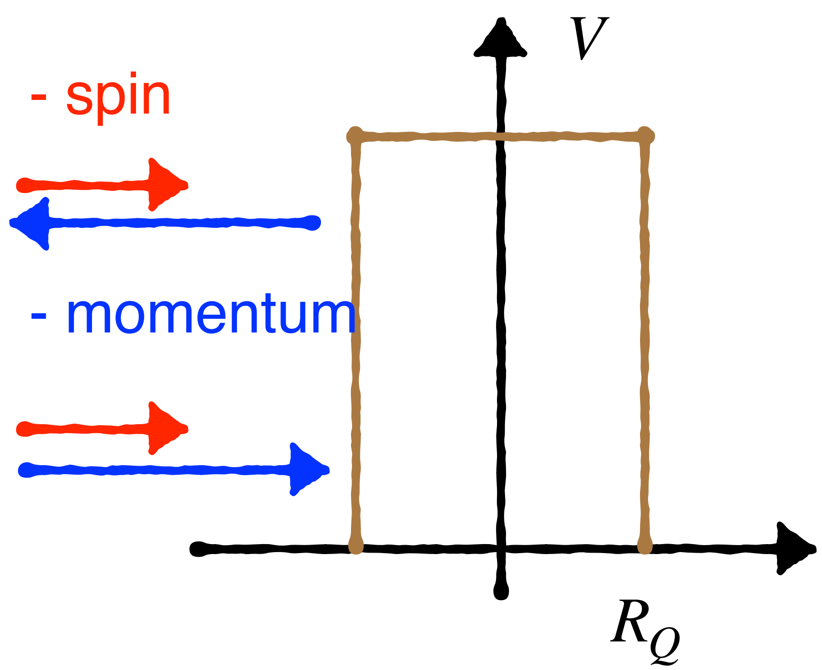
“Colorless” quark

Total reflection/transmission

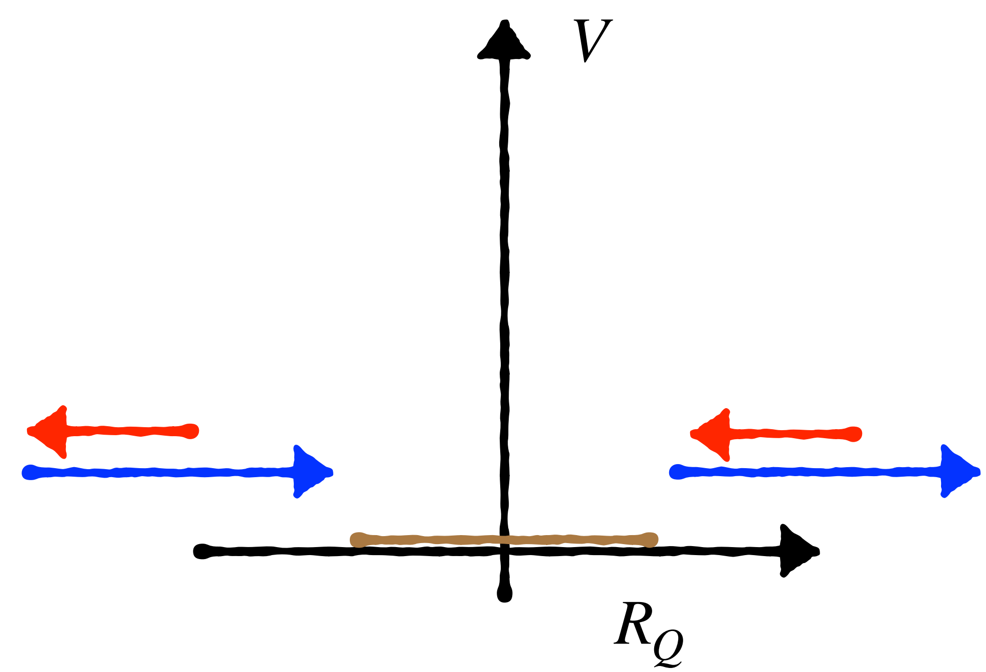
Kusenko, Loveridge and Shaposhnikov, PRD, 2015

AK, Kuwahara and Watanabe in progress

- find scattering state in relativistic quantum mechanics (Weyl spinor)
- nearly total reflection/transmission as far as quark energy is much larger than chemical potential



- right-handed quark



- left-handed quark

- because of angular momentum conservation, spin does not flip, meaning that right-handed quark is reflected as left-handed anti-quark

  - remember that opposite helicity particle-anti particle are alway paired up: left-handed neutrino and right-handed anti-neutrino

“Colorless” quark

Conversion: quark → anti-quark

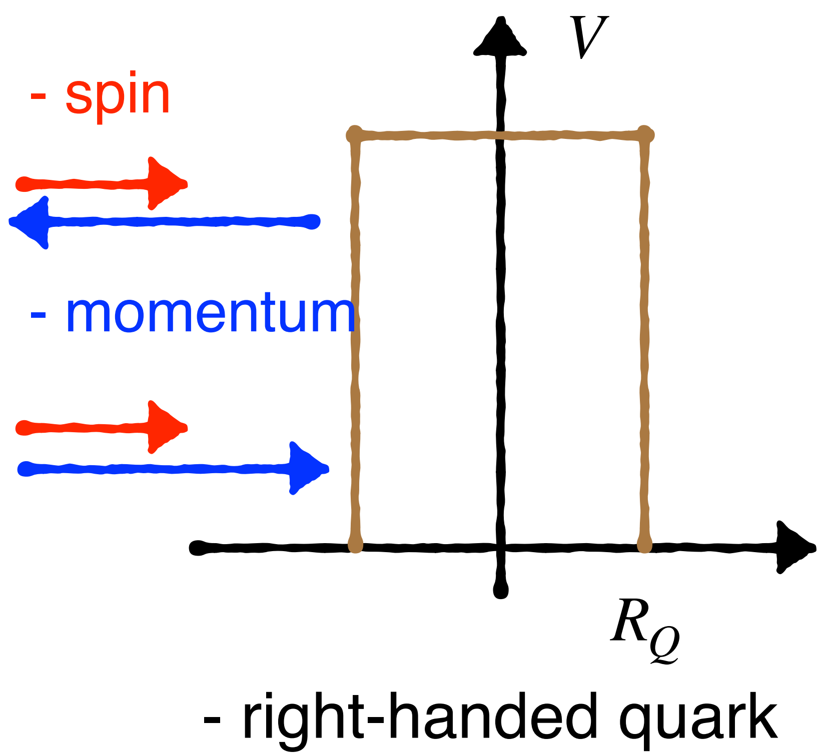
AK, Kuwahara and Watanabe in progress

- conservation of baryon number?
conservation of electromagnetic charge?

- this process should add two right-handed squarks in Q-ball (back-reaction)

- two right-handed squarks cost energy of $2\omega_Q$ and also charge mass of

$$M_{\rm em} \simeq 0.2 Q_{\rm em}^2 \,{\rm MeV} \times \left(\frac{10\,{\rm fm}}{R_Q} \right)$$



- if it cannot pay this energy cost, the scattering solution in relativistic quantum mechanics indicates conversion of annihilation operator to creation operator, which requires quantum field theory

Turning on QCD

Quarks in nucleon

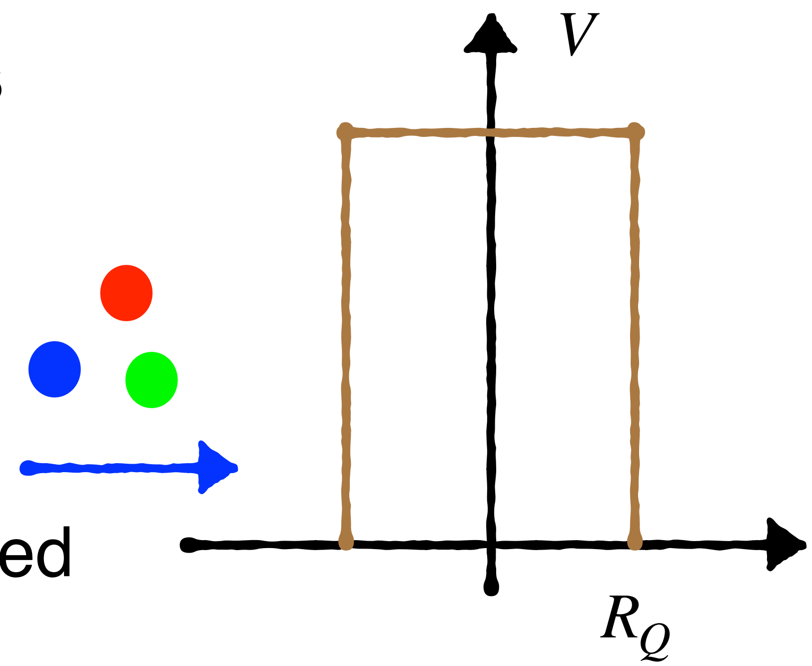
- consider the case where only red quark is reflected as anti-quark

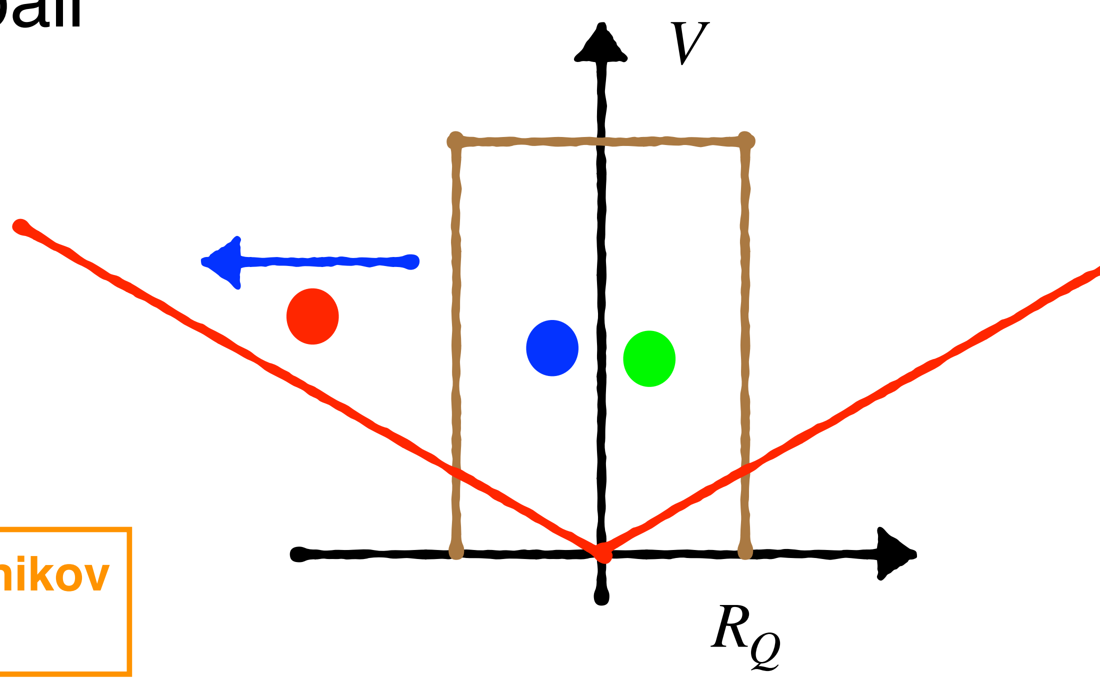
- red quark feels a color potential, which is linear to distance

    - this is why no free quark has been observed

- bosonic Q-ball becomes fermionic Q-ball* (intermediate state)

$$\sigma_Q \simeq 10^{-24}\,\mathrm{cm}^2 \left(\frac{R_Q}{10\,\mathrm{fm}}\right)^2$$





Decay of Q-ball*

- emitting pion(s) **Kusenko, Kuzmin, Shaposhnikov and Tinyakov, PRL, 1998**

- emitting (anti-)nucleon **Kusenko, Loveridge and Shaposhnikov, PRD, 2015**

Interaction with nucleon

Emitting pion(s)

- leaving fermionic Q-ball' with increased baryon number by one
- maximal energy of pions $m_N - 3\omega_Q$
  - likely up to two multiplicity Wise, Blankenbecler and Abbott, PRD, 1981
- in the subsequent absorption of nucleon, it becomes bosonic Q-ball

Emitting nucleon

- elastic scattering

Emitting anti-nucleon

- inelastic scattering: it needs to pay an energy cost $6\omega_Q$
  - impossible for interaction between Q-ball dark matter and nucleon at rest

AK, Kuwahara and Watanabe in progress

$$T_{Q-N} = \frac{1}{2} m_N v_{\rm dm}^2 \simeq 0.2\,\mathrm{keV} \left(\frac{v_{\rm dm}}{200\,\mathrm{km/s}} \right)^2$$

Charging up Q-ball

Ends up with positive charge

<u>AK</u>, Kuwahara and Watanabe in progress

- frequent interaction with nucleons
    - $L_{\rm mfp} = \mathcal{O}(1)\,{\rm Mpc}$ for 1 barn cross section in MW environment
- both obtaining positive/negative charges per interaction are possible
    - absorbing proton and emitting neutral pion
    - absorbing neutron and emitting proton
- all nuclei are positively charged
- further interaction of positively charged Q-ball with nucleus is prohibited by Coulomb barrier

Behave as heavy charged particle

- ionization track in detectors

Summary

Q-ball dark matter

- extended object made of bosonic quark (squark)
  - naturally realized in gauge-mediation scenario of supersymmetric extension of the standard model
- good target of paleo-detector experiments
  - macroscopic mass like gram or heavier
  - geometrical cross section like barn or larger

Interaction with matter

- absorbing nucleon and emitting pion(s)/nucleon
  - not emitting anti-nucleon
- obtaining charge through interaction and ending up with positive charge

Thank you