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Q-ball DM and its decay through A-term

Based on arXiv:1912.06993

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Outline

Q-ball DM and its decay through A-term

- Non-topological soliton of scalar field
- Q-ball as DM (we focus on MSSM)

- Astronomical constraint on Q-ball DM
- Growth of Q-ball inside the neutron star

- U(1) breaking term in MSSM flat direction
- A-term suppresses the growth of Q-ball

- Numerical simulation of A-term decay

Plan of Talk

- About Q-ball
- Q-ball DM
- Constraint by neutron star
- Numerical calculation
- Conclusion

About Q-ball

- Non-topological soliton of scalar field with U(1) S.R.Coleman1985

  $$\Phi(t,r) = \frac{1}{\sqrt{2}}\phi(r)\exp(i\omega t), \qquad Q = \omega\int dx^3\phi^2(r)$$

  e.g. in Gravity-mediation case in MSSM: $\phi(r) = \phi_0 \exp(-r^2/R_Q^2)$

- U(1) Q-charge stabilizes the non-trivial configuration,

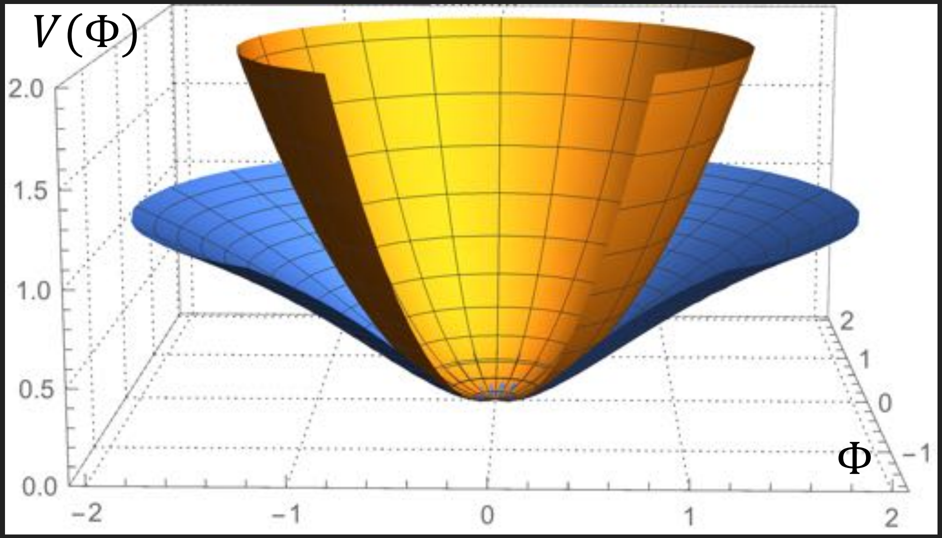
  provided by the condition : $V(|\Phi|)$ is flatter than $\mathrm{m}^2|\Phi|^2$.

Orange:

$\mathrm{V}(\Phi) \propto |\Phi|^2$

Blue:

$\mathrm{V}(\Phi) \propto \mathrm{Log}\left(1 + \frac{|\Phi|^2}{M^2}\right)$



- Q-ball is the lowest energy configuration with conserved charge Q.

About Q-ball in MSSM

- The phenomenology of Q-balls

- Baryogenesis by the flat direction of MSSM

  Affleck-Dine mechanism …I. Affleck, M. Dine1985

- The Q-ball plays important roles in AD mechanism
  - Baryon charge confinement in the Q-ball
  - Its evaporation in thermal plasma
  - The large Q-ball can be a candidate of DM
  - $\text{baryon charge(AD mechanism)} \rightarrow \begin{cases} \text{Small Q} - \text{ball} \rightarrow \text{baryon} \\ \text{Large Q} - \text{ball} \rightarrow \text{Qball as DM} \end{cases}$

Q-ball DM

- The stability of Q-ball as DM
  - ✓ Classical: Flat potential
  - ✓ Quantum: Not decay into light particle (e.g. neutron)

  $\Leftarrow$ small energy per Q-charge: $\frac{\mathrm{E}}{Q} = \omega < \frac{1}{3} m_n$ in $\Phi(t,r) \propto \exp(i\omega t)$

- The type of Q-balls
  - Gauge-mediation type (2-loop correction related to gauge mediation)

    $$\mathrm{V_{gauge}} = \mathrm{M_F^4} \log\left(\frac{|\Phi|^2}{\mathrm{M_{mess}^2}}\right)^2 \qquad \Rightarrow \omega \sim M_F Q^{-1/4}$$

    Large Q-charge is stable : $\mathrm{Q_{min}} > \left(\frac{M_F}{m_n}\right)^4$

  - Gravity-mediation type (1-loop correction related to gravitino mass)

    $$\mathrm{V_{gravity}} = m_{3/2}^2 \left(1 + \mathrm{K} \log\left(\frac{|\Phi|^2}{M^2}\right)\right) \qquad \Rightarrow \omega \sim m_{3/2}$$

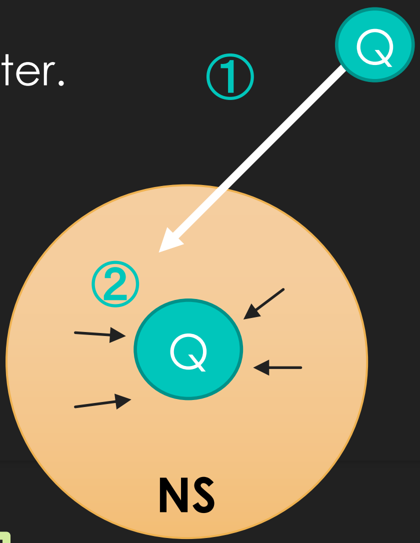
    Small $m_{3/2}$ is stable : $m_{3/2} < \frac{1}{3} m_n$

  - Combination of potential terms (Thin wall type, new type)

Constraint by neutron star

- Current constraints of Q-ball DM
  - Ground-based: Ice cube …S.Kasuya, M.Kawasaki, T.T.Yanagida2015
  - Astronomical: neutron star … A. Kusenko, M. E. Shaposhnikov, P. G. Tinyakov,I. I. Tkachev1998

- The constraints by a neutron star
  1. Q-balls collide, stop and sink inside the neutron star.
  2. The Q-ball absorbs surrounding neutrons.
  3. Its radius becomes larger and absorbs the neutron faster.
  4. The neutron star may be eaten up!



During the growth, the Q-ball change its type

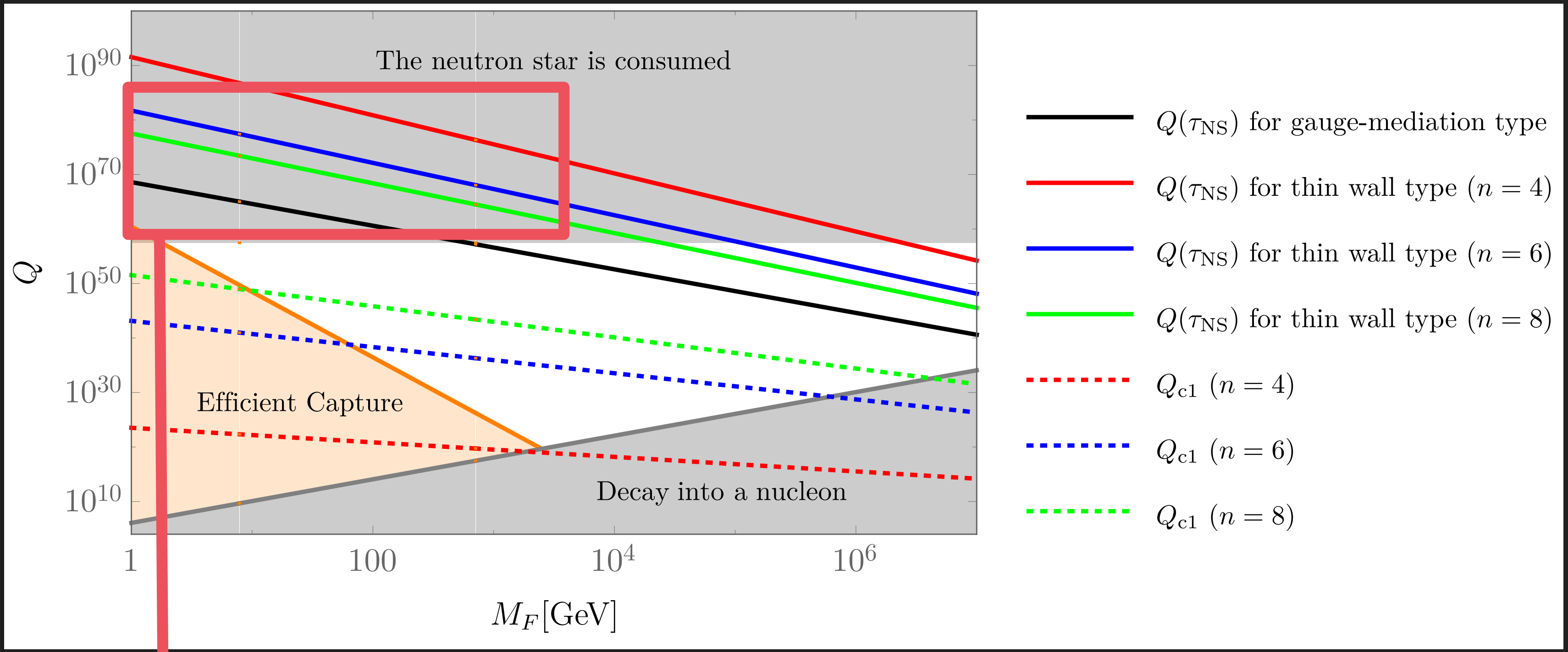
$$V(\Phi) = M_F^4 \log\left(\frac{|\Phi|^2}{M_{mess}^2}\right)^2 + \alpha \frac{|\Phi|^{2n-2}}{M_*^{2n-6}}$$

At Small Q-charge
Gauge-mediation type

At Large Q-charge
Thin wall type

Constraint by neutron star

- The fate of the neutron star
  - Baryon number of neutron star : $B_{NS} \sim 10^{57}$
  - Lifetime of neutron star : $\tau_{NS} \gtrsim 0.1\mathrm{Gyr}$
  - For the gauge mediation case



Q-ball DM is constrained

Constraint by neutron star

However....

- Suppression of Q-ball growth ... E. Cotner,A. Kusenko 2016

  U(1) breaking A-term: $\mathrm{V_A} = \mathrm{A\,m_{3/2}}\left(\frac{\Phi^n}{n\,M_*^{n-3}} + h.c.\right)$

  - Inevitable in the AD baryogenesis

  $\Rightarrow$ Q-ball size has an upper bound

  $\Rightarrow$ NS constraints seems ineffective!

- The A-term effect on Q-ball
  - Analytic estimation ...E. Cotner,A. Kusenko 2016

    perturbative calculation, only gauge-mediation potential
  - Numerical estimation ...M. Kawasaki, K. Konya,F. Takahashi, 2015

    only gravity mediation potential

1. Classical lattice simulation provides the concrete results independent of Quantum detail or nonperturbative effects.
2. Our calculation include both types (Gravity-, Gauge-mediation).

Our work

- The comprehensive analysis of Q-ball DM with A-term decay

$$V(\Phi) = V_{\text{gauge}} + V_{\text{gravity}} + Am_{3/2}\left(\frac{\Phi^n}{nM_*^{n-3}} + h.c.\right) + V_{\text{NR}}$$

$$V_{\text{gauge}} = M_F^4 \log\left(\frac{|\Phi|^2}{M_{\text{mess}}^2}\right)^2$$

$$V_{\text{gravity}} = m_{3/2}^2|\Phi|^2\left(1 + K\log\left(\frac{|\Phi|^2}{M^2}\right)\right)$$

$$V_{\text{NR}} = B\frac{|\Phi|^{2n-2}}{M_*^{2n-6}},$$

Depending on the dominant term, Q-ball change its property.

- Three cases of growth depending on the dominant term in $V(\Phi)$

  - Case without V_{gravity} $\quad V_{\text{gauge}} \to V_{\text{NR}},$
  - Case with V_{gravity} $(K<0)$ $\quad V_{\text{gauge}} \to V_{\text{gravity}}(K<0) \to V_{\text{NR}},$
  - Case with V_{gravity} $(K>0)$ $\quad V_{\text{gauge}} \to V_{\text{gravity}}(K>0).$

Our work

- The comprehensive analysis of Q-ball DM with A-term decay

$$V(\Phi) = V_{\rm gauge} + V_{\rm gravity} + \underbrace{A m_{3/2}\left(\frac{\Phi^n}{nM_*^{n-3}} + h.c.\right)}_{\text{A-term suppresses the growth of Q-ball}} + V_{\rm NR}$$

Our work:
evaluate the maximum size of Q-ball suppressed by the A-term

- Three cases of growth depending on the dominant term in $V(\Phi)$

  - Case without $V_{\rm gravity}$ $\quad V_{\rm gauge} \cancel{\to} V_{\rm NR}$,
  - Case with $V_{\rm gravity}$ $(K<0)$ $\quad V_{\rm gauge} \cancel{\to} V_{\rm gravity}(K<0) \cancel{\to} V_{\rm NR}$,
  - Case with $V_{\rm gravity}$ $(K>0)$ $\quad V_{\rm gauge} \cancel{\to} V_{\rm gravity}(K>0)$.

or

Our work

- Classical lattice calculation

▪ dimension = 1 and 2. ▪ Lattice size: $\sim 10^3 m^{-1}$, ▪ Time : $\sim 10^4 m^{-1}$

- Gravity-mediation type ...M. Kawasaki, K. Konya,F. Takahashi, 2015

$$V(\Phi) = m_{3/2}^2 |\Phi|^2 \left(1 + K \log\left(\epsilon + \frac{|\Phi|^2}{M^2}\right)\right) + A m_{3/2} \left(\frac{\Phi^n}{n M_*^{n-3}} + h.c.\right) + \alpha \frac{|\Phi|^{2n-2}}{M_*^{2n-6}}$$

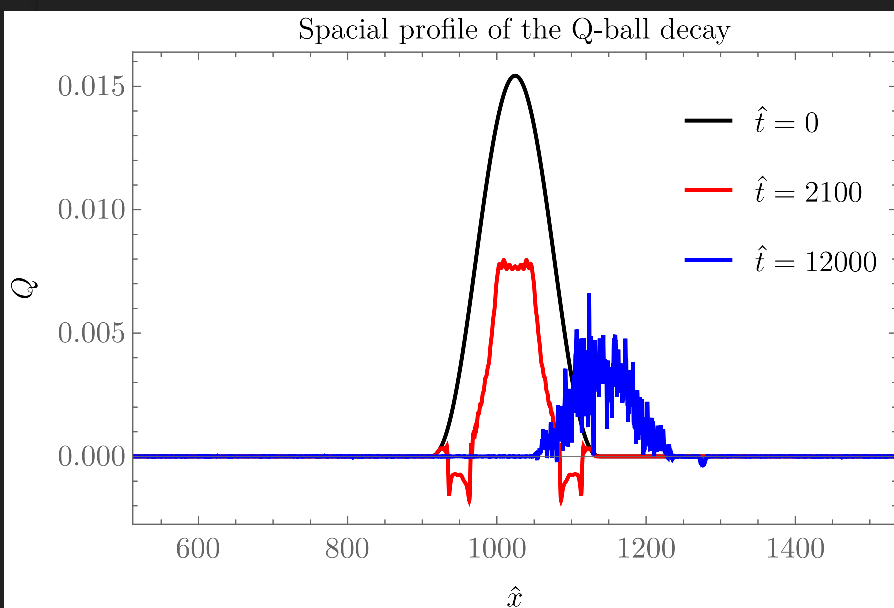
- Gauge-mediation type

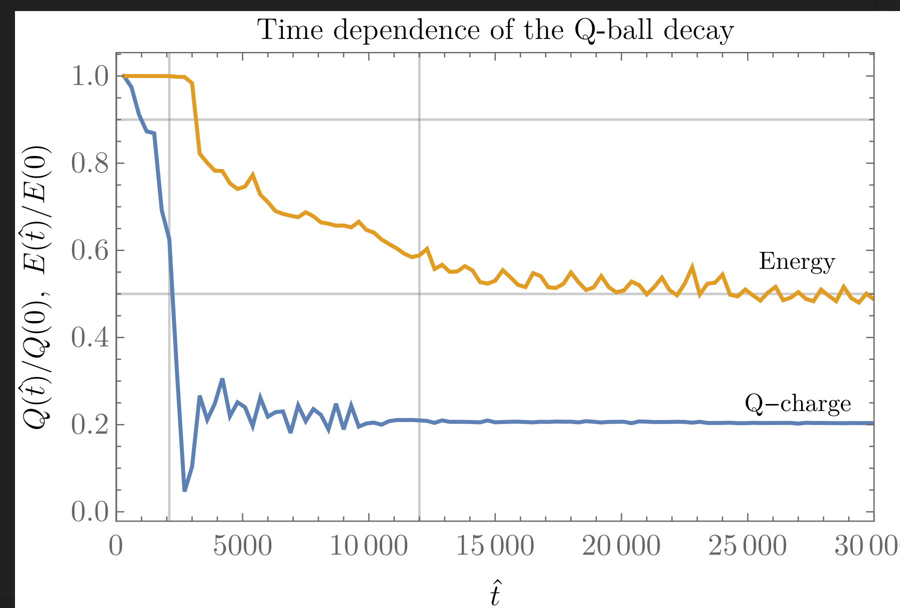
$$V(\Phi) = M_F^4 \log\left(1 + \frac{|\Phi|^2}{M_{\rm mess}^2}\right) + A m_{3/2} \left(\frac{\Phi^n}{n M_*^{n-3}} + h.c.\right) + \alpha \frac{|\Phi|^{2n-2}}{M_*^{2n-6}}$$

Numerical calculation

- Set up:
  1. Set a Q-ball in the large box.
  2. Follow the time evolution with A-term
- Definition of integrated energy and charge

$$E = \int^{|\boldsymbol{x}|<R_*} \mathrm{d}^3\boldsymbol{x} (\partial_\mu \Phi^\dagger \partial^\mu \Phi + V(\Phi)) \ , \quad Q = i \int^{|\boldsymbol{x}|<R_*} \mathrm{d}^3\boldsymbol{x} (\dot{\Phi}^\dagger \Phi - \Phi^\dagger \dot{\Phi}),$$

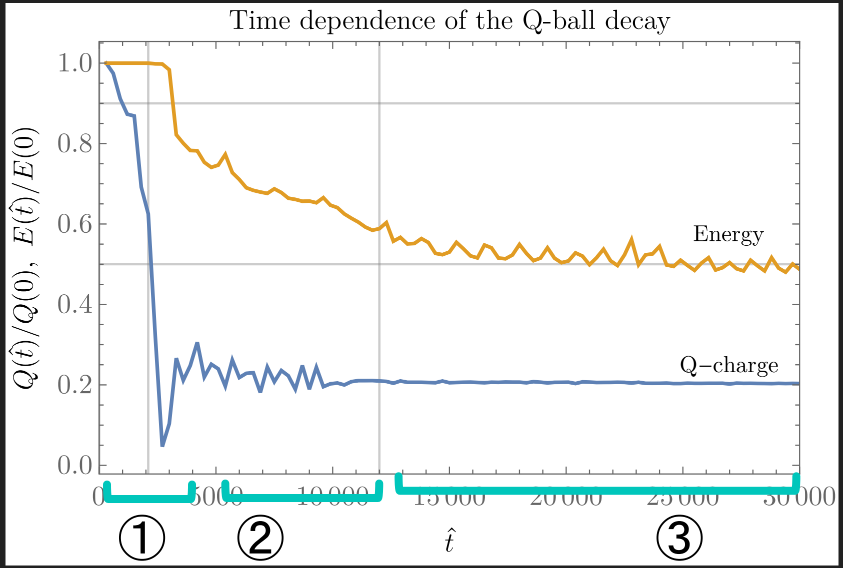




Numerical calculation

- Time evolution of Q-ball
  1. Q-charge is destabilized
  2. Energy gradually decays
  3. A-term becomes ineffective and Q-ball is stabilized
  - Define the decay ratio

$$r_E = \frac{E(t_{stable})}{E(t=0)}, \qquad r_Q = \frac{Q(t_{stable})}{Q(t=0)}$$

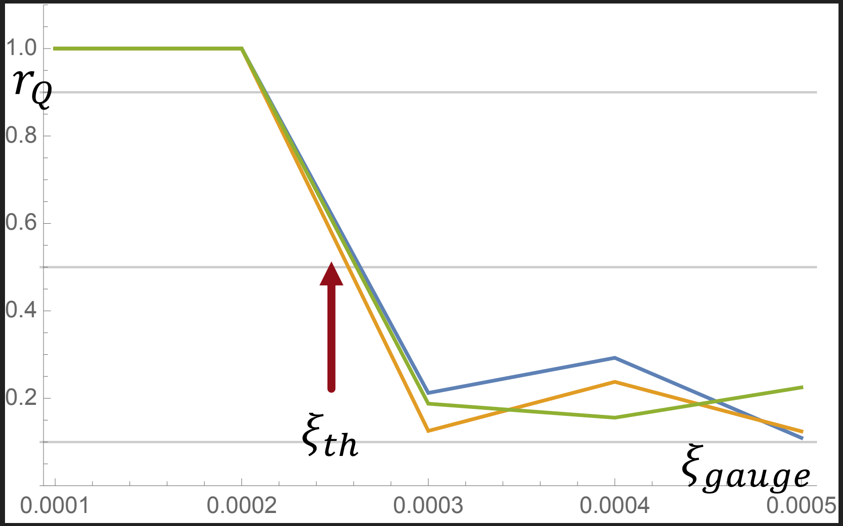


- Strength of A-term and decay ratio
  - Normalize the A-term strength as

$$\xi \sim \frac{V_A}{V_{\text{Grav,Gauge}}}$$

  - For the large A-term, large amount of Q-charge decays.
  - Let us define the threshold value

$$\xi_{th} \quad \text{at} \quad r_Q = 0.5 \ \text{or} \ r_E = 0.9$$



Numerical calculation

- Threshold of A-term decay

$$\xi \sim \frac{V_A}{V_{\text{Grav,Gauge}}}$$

n : $V_A \propto \Phi^n$

- The maximum size of Q-ball

$$\xi_{\text{gauge}} = \frac{2|A|m_{3/2}\Phi_0^n}{nM_F^4 M_*^{n-3}},$$

$$\xi_{\text{gravity}} = \frac{2|A|m_{3/2}\Phi_0^{n-2}}{nm_{3/2}^2 M_*^{n-3}}$$

  - Now we can evaluate the maximum size of Q-ball suppressed by A-term

$$\xi_{\text{th}} \rightarrow \Phi_{max} \rightarrow Q_{max}$$

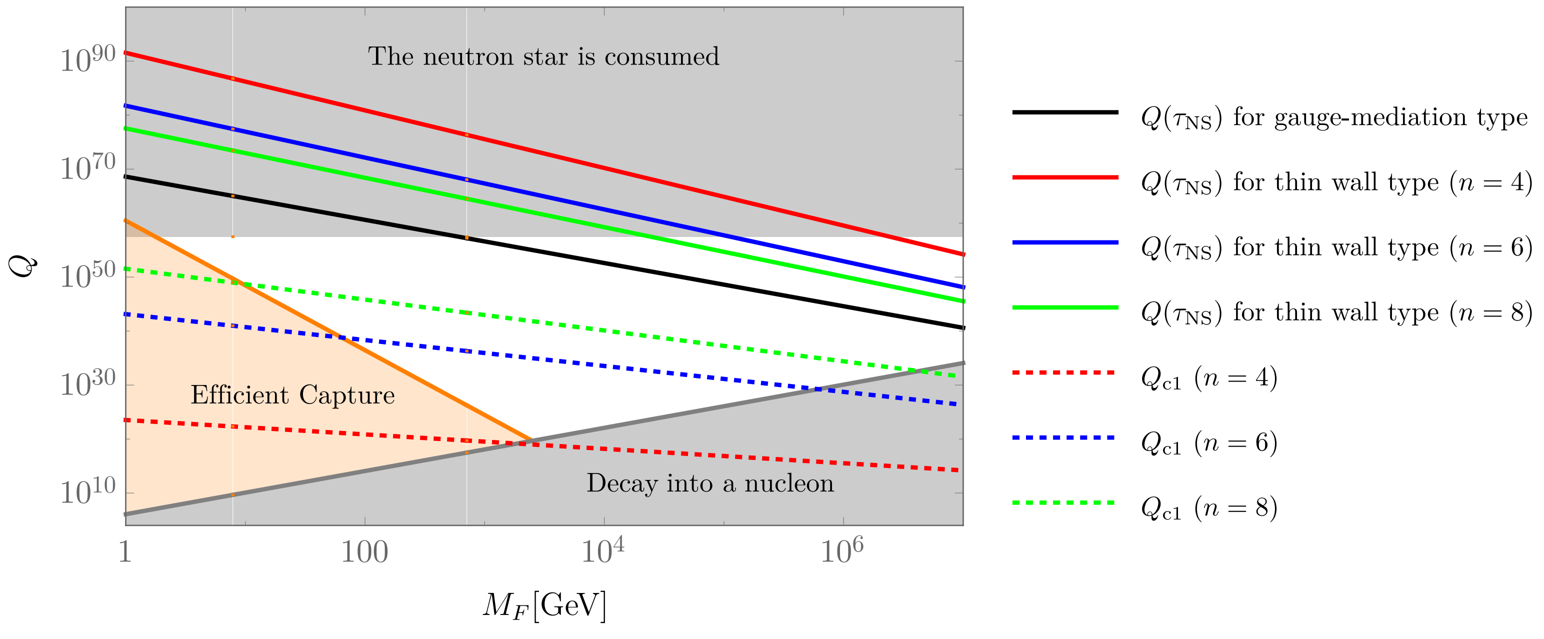
criteria	K = −0.03	K=−0.1	$u = 5 \times 10^3$	$u = 45 \times 10^3$
For n=4				
90% for energy	0.02	0.06	1.0	1.8
50% for charge	0.01	0.03	1.5	1.4
For n=6				
90% for energy	0.05	0.08	1.5	2.25
50% for charge	0.05	0.08	1.5	2.25
For n=8				
90% for energy	0.09	0.17	1.0	1.4
50% for charge	0.16	0.20	1.0	1.4

$$\underbrace{\text{K columns}}_{\xi_{\text{Grav,th}} \sim O(0.1)} \qquad \underbrace{u \text{ columns}}_{\xi_{\text{Gauge,th}} \sim O(1)}$$

Conclusion

- Without A-term

Case without V_{gravity} $\quad V_{\text{gauge}} \to V_{\text{NR}}$

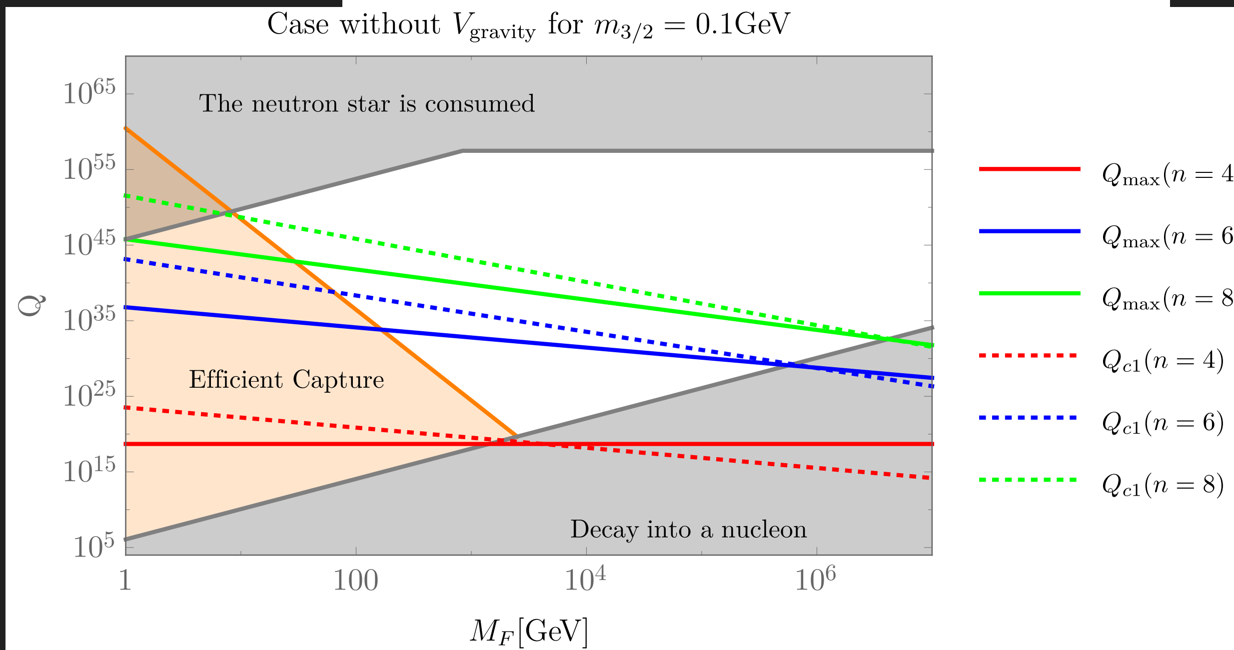


- Without A-term, the Q-ball become thin wall type and consume the neutron star

Conclusion

- With A-term

Case without V_{gravity} $V_{\text{gauge}} \cancel{\to} V_{\text{NR}}$

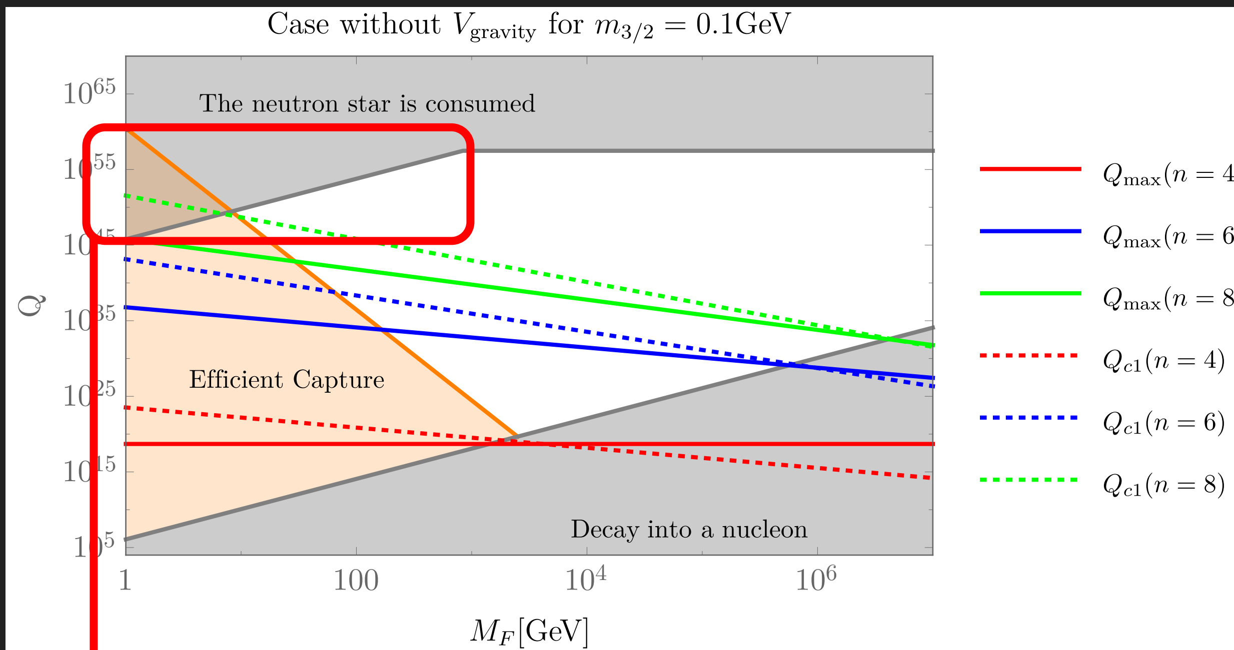


- With A-term, the Q-ball growth is suppressed.

Q-ball DM avoids the constraint by s neutron star

Conclusion

- Case without V_{gravity} $\qquad V_{\mathrm{gauge}} \to V_{\mathrm{NR}}$



- With A-term, the Q-ball growth is suppressed and avoids the constraints.
- The additional region is where the Q-ball with Q_{max} constantly absorbs the surrounding neutrons and consumes the neutron star.

Q-ball DM avoids the constraint by s neutron star

Conclusion

- About Q-ball
  - Q-ball plays key role in the Affleck-Dine baryogenesis
  - The possibility of Q-ball DM is also interesting!
- A-term decay weakens the constraint on Q-ball DM
  - Astronomical constraints by a neutron star
  - A-term decay suppresses the growth of Q-ball
- Numerical lattice simulation of A-term decay
  - Two different potential (Gravity-,Gauge-mediation type)
  - The threshold value of A-term decay
- Comprehensive analysis of Q-ball growth inside the neutron star

- Case without $V_{\rm gravity}$ $\quad V_{\rm gauge} \to V_{\rm NR}$,
- Case with $V_{\rm gravity}$ $(K<0)$ $\quad V_{\rm gauge} \to V_{\rm gravity}(K<0) \to V_{\rm NR}$,
- Case with $V_{\rm gravity}$ $(K>0)$ $\quad V_{\rm gauge} \to V_{\rm gravity}(K>0)$.

Avoid constraints!
In this talk

In our paper
arXiv:1912.06993

Thank you for listening