ORIGIN OF NONTOPOLOGICAL SOLITON DARK MATTER

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MOTIVATION

Dark matter could be complex, even in simple theories!

With attractive interactions, DM could form <u>large/heavy structures</u>:

- Nontopological solitons (of bosons or fermions) [this talk]

- Dark nuclei [Wise Zhang 1407.4121, 1411.1772; Gresham Lou Zurek 1707.02313, 1707.02316, 1805.04512]

- Dark quark nuggets [Bai Long 1804.10249; Bai Long Lu 1810.04360; Liang Zhitnitsky 1606.00435]

- Dark monopoles [Bai Korwar **NO** 2005.00503]

- Dark/mirror stars [Curtin Setford 1909.04071, 1909.04072; +many follow-ups]

- Boson or axion stars

- Microhalos, dark disks, dissipative DM…

- …many of which could form black holes
  (Even "light" extremal black holes could be stable [Bai **NO** 1906.04858; Bai Berger Korwar **NO** 2007.03703])

MOTIVATION

Nontopological solitons (NTSs):

1. Representative model for several types of dark compact objects.

2. Require minimal new fields.
   Scalar NTSs are generic with *just one* new complex scalar field!

Long history of study:

Early work: [Rosen 1968; Friedberg Lee Sirlin 1976; Coleman 1986].
In SUSY: [Kusenko hep-ph/9704273; Kusenko Shaposhnikov hep-ph/9709492].
With gauge [Lee Stein-Schabes Watkins Widrow 1989; Gulamov Nugaev Panin Smolyakov 1506.05786; Brihaye Cisterna Hartmann Luchini 1511.02757; Heek Rajaraman Riley Verhaaren 2103.06905, 2107.10280]
or topological [Bai Lu **NO** 2111.10360] charge.
Fermion solitons: [Lee Pang 1987; Macpherson Campbell hep-ph/9408387; Hong Jong Xie 2008.04430]
Other works: [Kusenko hep-ph/9704073; Dvali Kusenko Shaposhnikov hep-ph/9707423; Kusenko Shaposhnikov Tinyakov hep-th/9801041; Berkooz Chung Volansky hep-ph/0507218; Bishara Johnson Lennon March-Russell 1708.04620; Heek Rajaraman Riley Verhaaren 2009.08462]
Reviews: [Lee Pang 1992; Nugaev Shkerin 1905.05146]

MOTIVATION & OUTLINE

Questions about NTSs:

☐ How do they form?

☐ How big can they get?

☐ Can they dominate the dark sector?

Outline:

1. Models and properties of scalar NTSs (aka Q-balls)

2. Solitosynthesis

3. Phase transitions

NTS MODELS AND PROPERTIES

Q-BALLS

Two-complex-scalar renormalizable potential:

$$V(S, \phi) = \frac{1}{4}\lambda_\phi(|\phi|^2 - v^2)^2 + \frac{1}{4}\lambda_{\phi S}|S|^2|\phi|^2 + \lambda_S|S|^4 + m_{S,0}^2|S|^2$$

S: $U(1)_S$ global symmetry—Q-ball constituents

ϕ: Any global or gauge symmetry. Here a global $U(1)_\phi$ for simplicity.

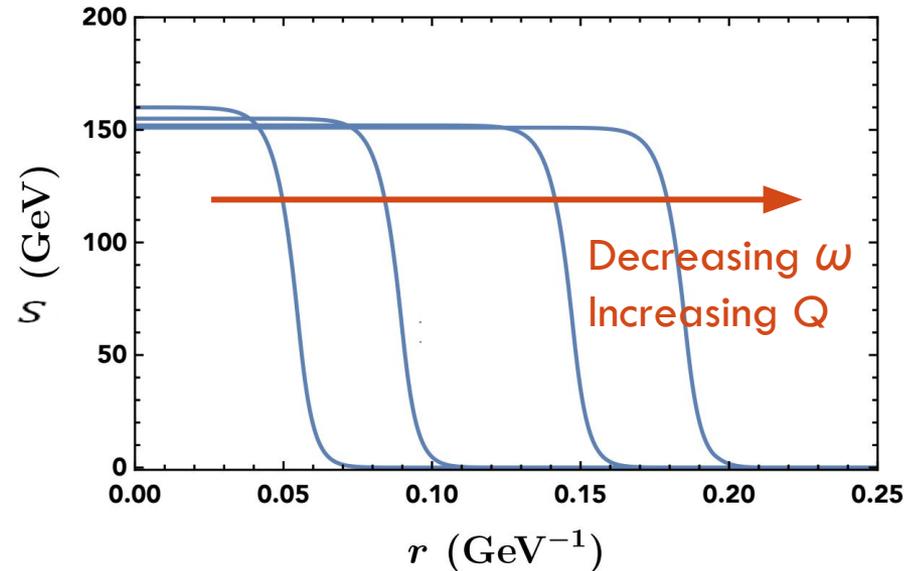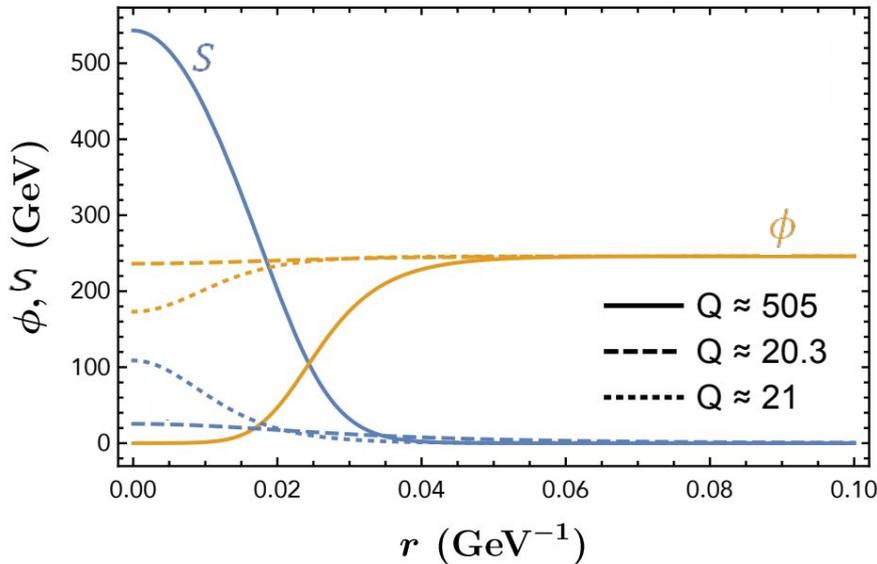🔲 Could even be the Higgs doublet [Pontón Bai Jain 1906.10739]

FIELD PROFILES

$$\phi^- = v\,f(r)\,,\quad S = e^{-i\omega t}\frac{v}{\sqrt{2}}\,s(r)$$

Valid approx at small Q.
Unphysical due to radiative corrections.

$\lambda_S = 0$ $\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $\lambda_S > 0$

Adapted from [Ponton, Bai, Jain 1906.10739]
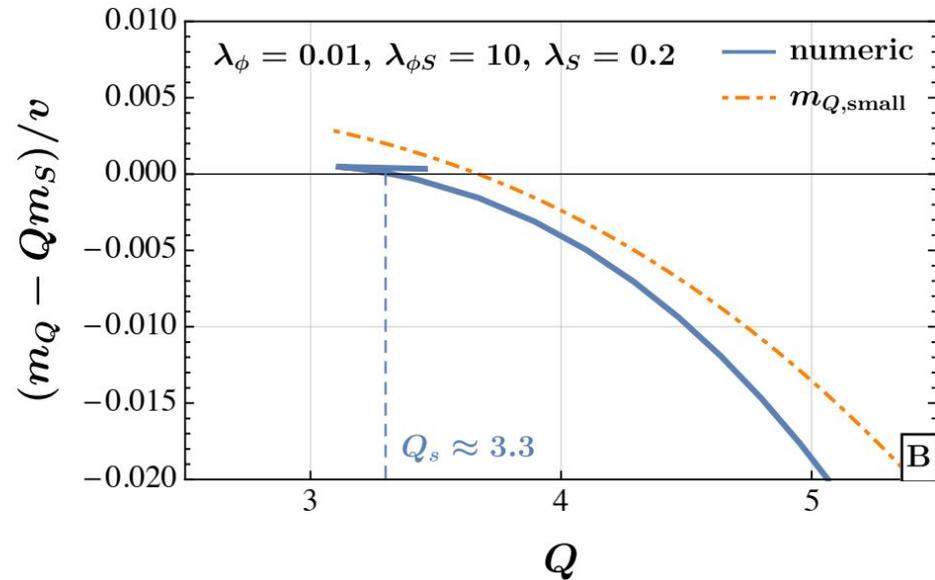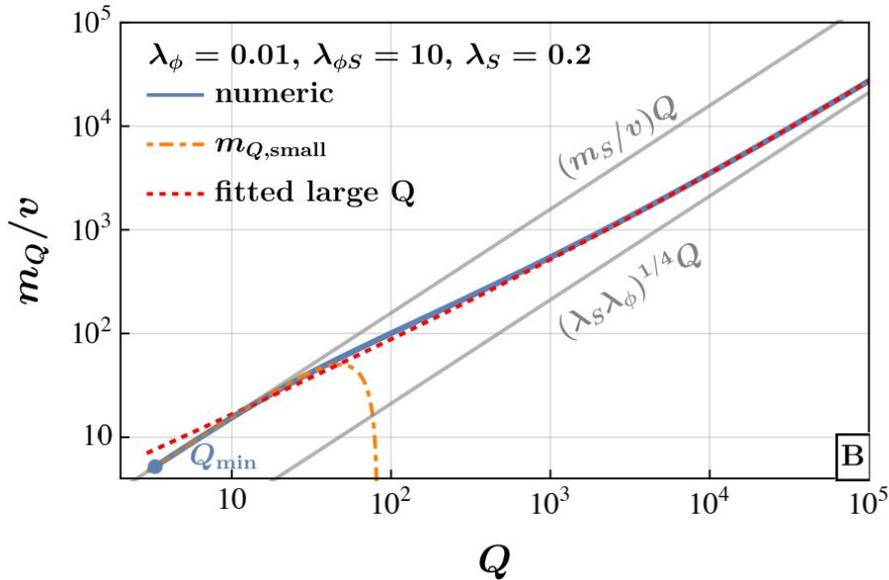
"Building up" $\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ "Building out"

Trade-off of increased vacuum energy for ϕ and decreased mass
for S inside Q-ball.

$$V(S,\phi) = \tfrac{1}{4}\lambda_\phi(|\phi|^2 - v^2)^2 + \tfrac{1}{4}\lambda_{\phi S}|S|^2|\phi|^2 + \lambda_S|S|^4 + m_{S,0}^2|S|^2$$

MASS AND STABILITY

$$m_{Q,\text{large}} \approx v\,Q\left[(\lambda_S \lambda_\phi)^{1/4} + c_2 Q^{-1/3}\right],$$

$$R_{Q,\text{large}} \approx \frac{3^{1/3}\,\lambda_S^{1/12}}{(4\pi)^{1/3}\lambda_\phi^{1/4}\,v}\,Q^{1/3}.$$

SOLITOSYNTHESIS

SOLITOSYNTHESIS

The process of building up NTSs from free particle fusion and accumulation.

Prior work:

[Griest Kolb 1989; Frieman Olinto Gleiser Alcock 1989; Kusenko Shaposhnikov hep-ph/9709492; Postma hep-ph/0110199; Krnjaic Sigurdson 1406.1171; Hardy Lasenby March-Russell West 1411.3739; Gresham Lou Zurek 1707.02316]

Q-BALL INTERACTIONS

$$S + S^\dagger \leftrightarrow \phi + \phi^\dagger \,,$$

S annihilation

$$(Q) + S \leftrightarrow (Q+1) + X \,,$$
$$(Q) + S^\dagger \leftrightarrow (Q-1) + X \,,$$

Q-ball charge/discharge

$$(Q_{\min}) + S^\dagger \leftrightarrow \underbrace{S + S + \cdots + S}_{Q_{\min}-1} + X \,.$$
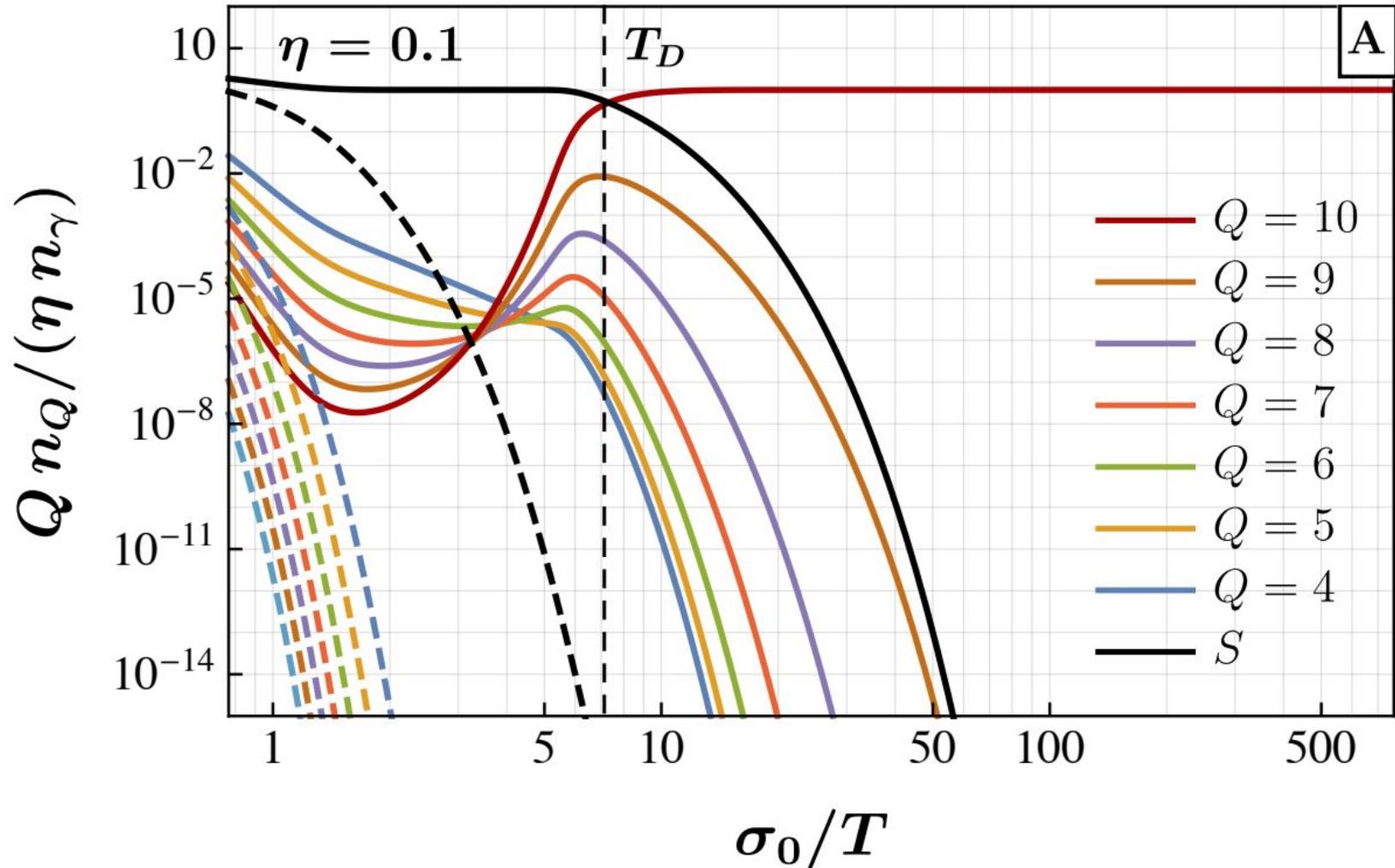
S fusion/Q-ball destruction

$$(Q_1) + (Q_2) \leftrightarrow (Q_1 + Q_2) + X \,,$$

$$(Q_1) + (-Q_2) \leftrightarrow \begin{cases} (Q_1 - Q_2) + X & \text{for } Q_1 - Q_2 \geq Q_{\min} \,, \\ \underbrace{S + S + \cdots + S}_{Q_1 - Q_2} + X & \text{for } Q_{\min} > Q_1 - Q_2 \geq 0 \,. \end{cases}$$

Q-ball fusion

Not efficient for sufficiently large Q

Assumption: take Q-ball radiative capture cross sections $\sigma_Q \sim \pi R_Q^2$

IN EQUILIBRIUM

T_D is an analytic estimate

FREEZE OUT

Boltzmann equations:

$$\dot{n}_Q + 3Hn_Q = -\delta_{Q,Q_{\min}}(\sigma v_{\mathrm{rel}})_{Q_{\min}}\left(n_{Q_{\min}}n_{S^\dagger} - n_{Q_{\min}}^{\mathrm{eq}}n_{S^\dagger}^{\mathrm{eq}}\left(\frac{n_S}{n_S^{\mathrm{eq}}}\right)^{Q_{\min}-1}\right)$$

$$-(1-\delta_{Q,Q_{\max}})(\sigma v_{\mathrm{rel}})_Q\left(n_Q n_S - n_Q^{\mathrm{eq}}n_S^{\mathrm{eq}}\left(\frac{n_{Q+1}}{n_{Q+1}^{\mathrm{eq}}}\right)\right)$$

$$+(1-\delta_{Q,Q_{\min}})(\sigma v_{\mathrm{rel}})_{Q-1}\left(n_{Q-1}n_S - n_{Q-1}^{\mathrm{eq}}n_S^{\mathrm{eq}}\left(\frac{n_Q}{n_Q^{\mathrm{eq}}}\right)\right)$$

$$-(1-\delta_{Q,Q_{\min}})(\sigma v_{\mathrm{rel}})_Q\left(n_Q n_{S^\dagger} - n_Q^{\mathrm{eq}}n_{S^\dagger}^{\mathrm{eq}}\left(\frac{n_{Q-1}}{n_{Q-1}^{\mathrm{eq}}}\right)\right)$$

$$+(1-\delta_{Q,Q_{\max}})(\sigma v_{\mathrm{rel}})_{Q+1}\left(n_{Q+1}n_{S^\dagger} - n_{Q+1}^{\mathrm{eq}}n_{S^\dagger}^{\mathrm{eq}}\left(\frac{n_Q}{n_Q^{\mathrm{eq}}}\right)\right)$$

FREEZE OUT

Summed Boltzmann equations:

$$\dot{n}_{\mathrm{NTS}} + 3\,H\,n_{\mathrm{NTS}} = -(\sigma v_{\mathrm{rel}})_{Q_{\min}} \left(n_{Q_{\min}} n_{S^\dagger} - n_{Q_{\min}}^{\mathrm{eq}} n_{S^\dagger}^{\mathrm{eq}} \left(\frac{n_S}{n_S^{\mathrm{eq}}} \right)^{Q_{\min}-1} \right)$$
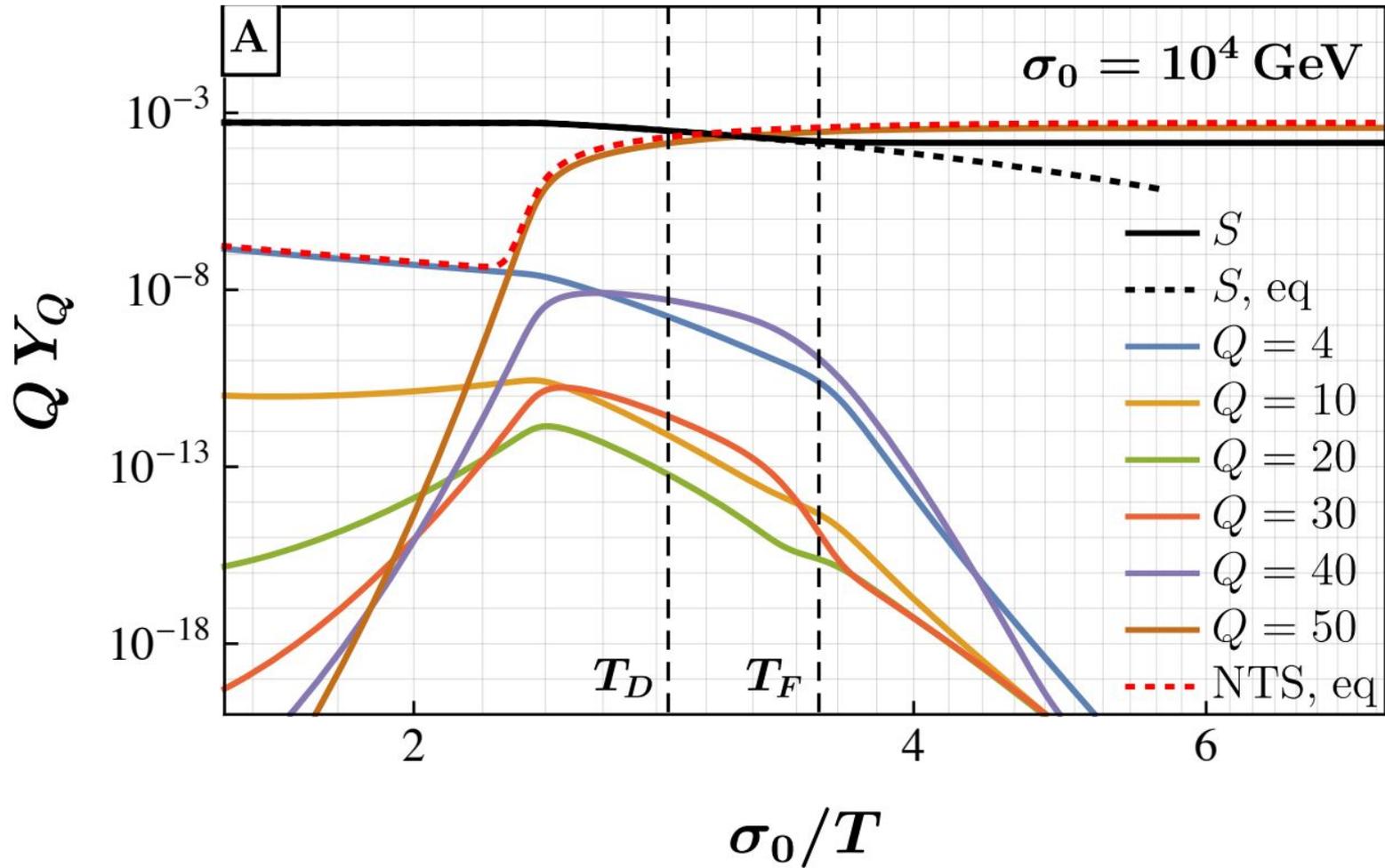
$$n_{\mathrm{NTS}} \equiv \sum_{Q=Q_{\min}}^{Q_{\max}} n_Q$$

Freeze-out temperature:

$$H\, n_{\mathrm{NTS}}^{\mathrm{eq}} \sim (\sigma v_{\mathrm{rel}})_{Q_{\min}}\, n_{Q_{\min}}^{\mathrm{eq}}\, n_{S^\dagger}^{\mathrm{eq}} \,\big|_{T=T_F}$$
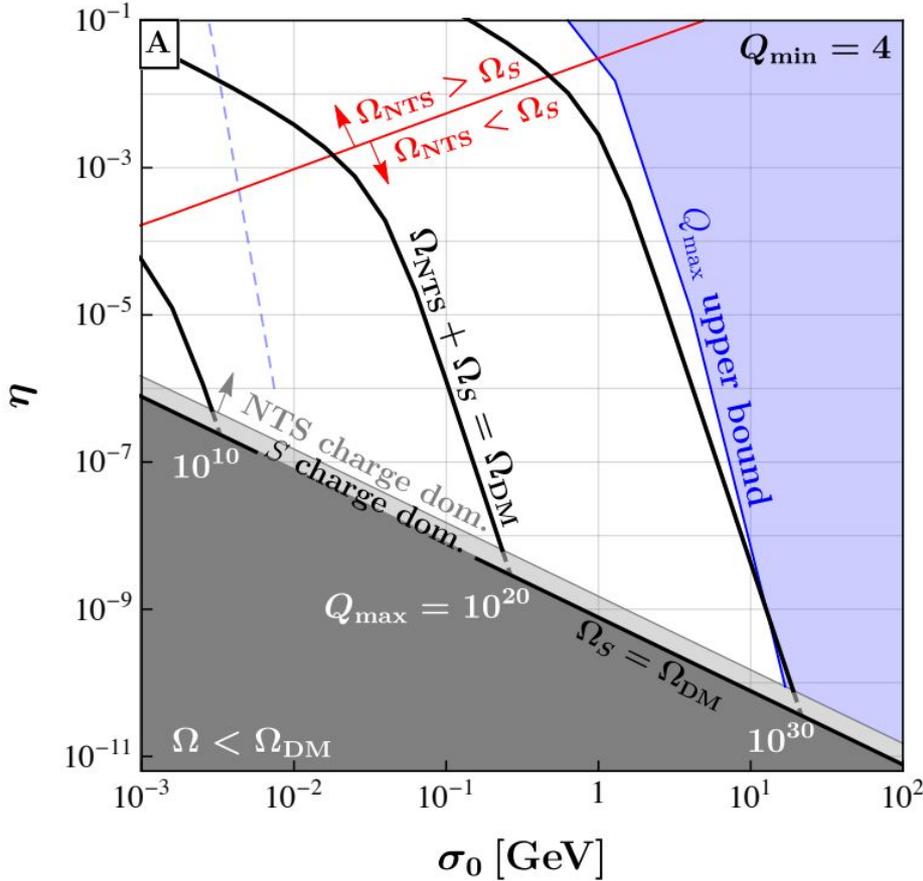
Get an analytic estimate for $T < T_D$ using $n_{\mathrm{NTS}}^{\mathrm{eq}} \approx n_{Q_{\max}}^{\mathrm{eq}}$.
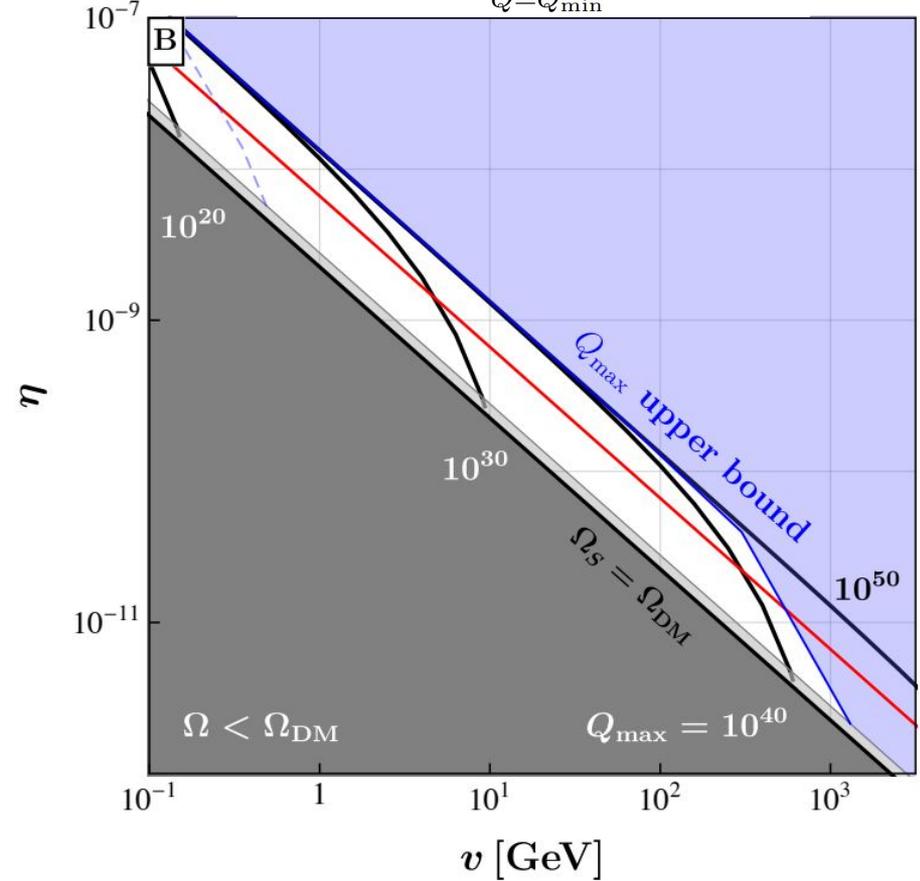
FREEZE OUT

DARK MATTER ABUNDANCE

$$\tau_{Q_{\min} \to Q_{\max}} = \sum_{Q=Q_{\min}}^{Q_{\max}} \frac{1}{n_S \, (\sigma v_{\rm rel})_Q} \lesssim H^{-1}$$

$$m_Q = 5.15 \sigma_0 \lambda^{1/4} Q^{3/4} \,,$$
$$R_Q = 0.8 \lambda^{-1/4} \sigma_0^{-1} Q^{1/4} \,.$$

$$m_{Q,\rm large} \approx v \, Q \left[(\lambda_S \lambda_\phi)^{1/4} + c_2 Q^{-1/3} \right] \,,$$
$$R_{Q,\rm large} \approx \frac{3^{1/3} \lambda_S^{1/12}}{(4\pi)^{1/3} \lambda_\phi^{1/4} \, v} \, Q^{1/3} \,.$$

ϕ PHASE TRANSITION

1ˢᵗ ORDER PHASE TRANSITION FORMATION

Adapted from [Asadi, *et. al.* 2103.09827]

See [Frieman Gelmini Gleiser Kolb 1988; Griest Kolb Massarotti 1989; Frieman Olinto Gleiser Alcock 1989; Macpherson Campbell hep-ph/9408387; Bai Long Lu 1810.04360; Pónton Bai Jain 1906.10739; Hong Jung Xie 2008.04430; Bai Lu **NO** 2111.10360;…]

PHASE TRANSITION FORMATION

Q-ball properties determined by number of S particles in each false vacuum region:

$$N_S^{\text{Q-ball}} \sim p_{\text{in}}\, n_S / n_{\text{Q-ball}}$$

$$\langle Q \rangle \ \sim \ \max \left[\underbrace{\eta N_S^{\text{Q-ball}}}_{}, \ \underbrace{(N_S^{\text{Q-ball}})^{1/2}}_{} \right]$$

Asymmetric component

Symmetric component

BENCHMARKS

Points where free particles + Q-balls make up all of dark matter:

Mechanism	Model	η	m_Q (g)	R_Q (m)	$\langle Q \rangle$	σ_0 or v (GeV)
Solitosynthesis	A	10^{-10}	3	3×10^{-10}	6×10^{29}	10
	B	10^{-10}	5×10^{22}	2×10^{-3}	1×10^{45}	1×10^2
	B	10^{-6}	6×10^{30}	3×10^5	1×10^{57}	1×10^{-2}
FOPT	A	0	9×10^{-6}	5×10^{-23}	3×10^{11}	2×10^9
	B	0	2×10^{-3}	4×10^{-19}	1×10^{14}	4×10^7
	B	10^{-4}	8×10^{26}	1×10^5	7×10^{53}	3×10^{-3}
SOPT	A	0	2×10^{-20}	3×10^{-15}	5×10^4	7×10^{-1}
	B	0	1×10^{-20}	5×10^{-13}	5×10^4	2×10^{-2}

Q-balls dominate the $U(1)_S$ global charge density in all cases.

Q-balls dominate the energy density in all cases except first row.

SUMMARY

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- Q-balls are generic in theories with multiple scalar fields.

- Both solitosynthesis and phase transitions can make macroscopically large Q-balls.

  - For solitosynthesis, particle-antiparticle asymmetry could match SM.
    For phase transitions, no particle-antiparticle asymmetry required.

- These Q-balls can explain dark matter.