Macroscopic Dark Matter

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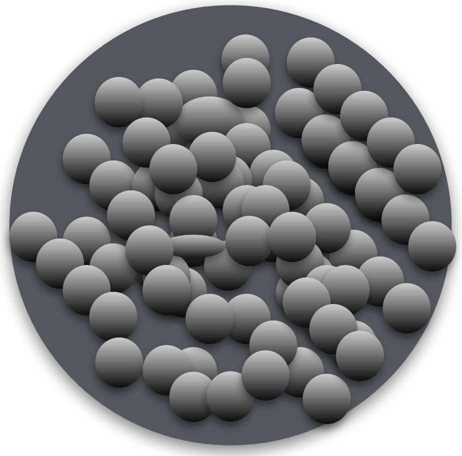
IBS Conference on Dark World, Daejeon, November 6, 2019

Macroscopic Ordinary Matter

- For ordinary matter, there are so many different types

Macroscopic Dark Matter

- Dark matter could be one type of matter made of dark particles



- Macroscopic dark matter is a composite state and may contain many dark matter particles

- Its mass could be much heavier than the Planck mass scale

- Its detections could be dramatically from ordinary WIMP searches

Outline

- **Macroscopic dark matter models**
  - **Quark nuggets with** $\rho^{1/4} \sim \Lambda_{\mathrm{QCD}}$
  - **Dark quark nuggets with** $\rho^{1/4} \sim \Lambda_{\mathrm{dQCD}}$
  - **Electroweak symmetric dark matter ball with** $\rho^{1/4} \sim v_{\mathrm{EW}}$
  - **Others: QCD Axion star, PBH, dark monopole …**
- **Detections**
  - **Lensing**
  - **Direct Detection**
  - **Gravitational waves**
  - **Other methods**

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Quark Nuggets

- **Can we explain dark matter in the SM?**

Cosmic separation of phases

Edward Witten*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 9 April 1984)

A first-order QCD phase transition that occurred reversibly in the early universe would lead to a surprisingly rich cosmological scenario. Although observable consequences would not necessarily survive, it is at least conceivable that the phase transition would concentrate most of the quark excess in dense, invisible quark nuggets, providing an explanation for the dark matter in terms of QCD effects only. This possibility is viable only if quark matter has energy per baryon less than 938 MeV. Two related issues are considered in appendices: the possibility that neutron stars generate a quark-matter component of cosmic rays, and the possibility that the QCD phase transition may have produced a detectable gravitational signal.

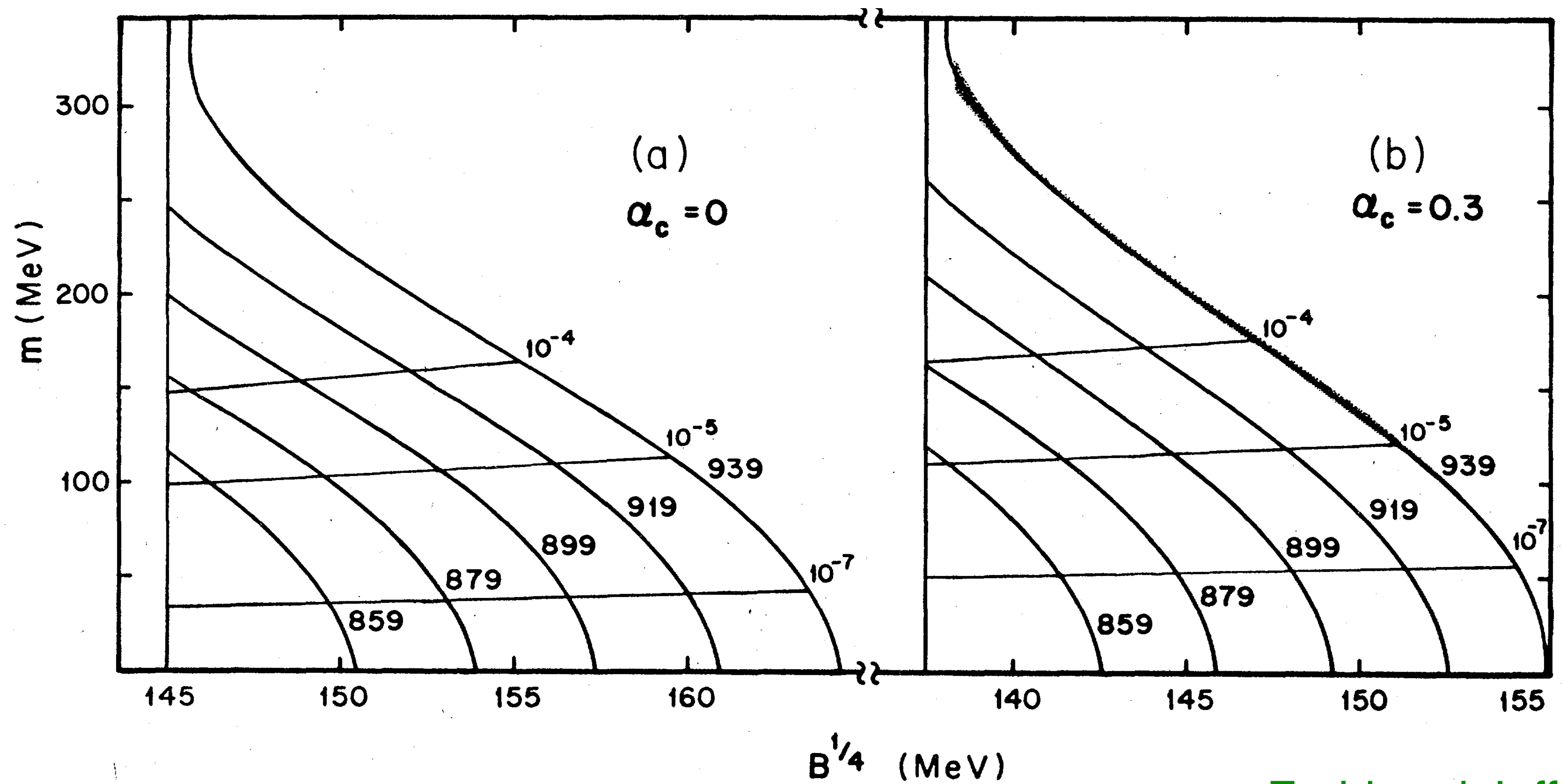
Hogan, '1983; Farhi and Jaffe, '1984; Alcock and Farhi, '1985; Madsen, Heiselberg, Riisager, '1986; Kajantie and Kurki-Suonio, '1986; Olinto, '1987, '1981; Alcock and Olinto, '1989; …….

Quark Matter

- **For Iron, the mass/baryon is** $\frac{M_{F_e}}{A_{F_e}} \approx 930\,\mathrm{MeV}$

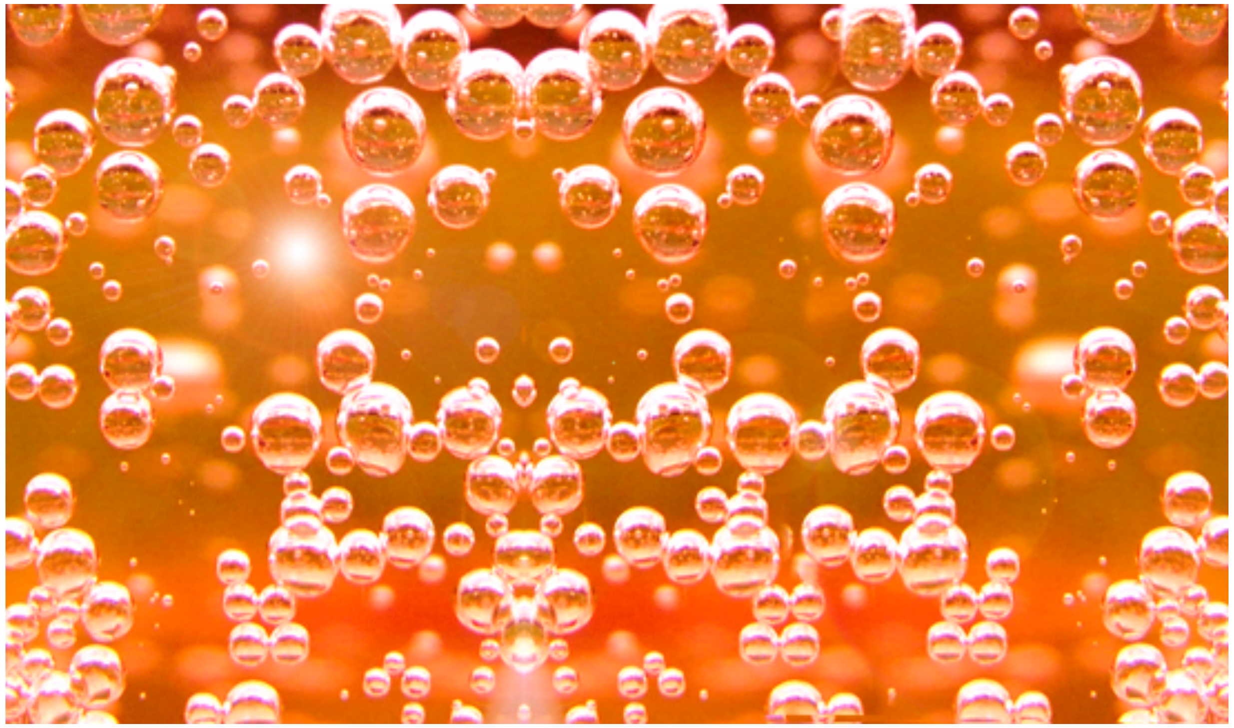
Quark Matter

- **For Iron, the mass/baryon is** $\frac{M_{F_e}}{A_{F_e}} \approx 930\,\mathrm{MeV}$
- **For the quark matter (in QCD deconfined phase), using the degenerate Fermi gas approximation**

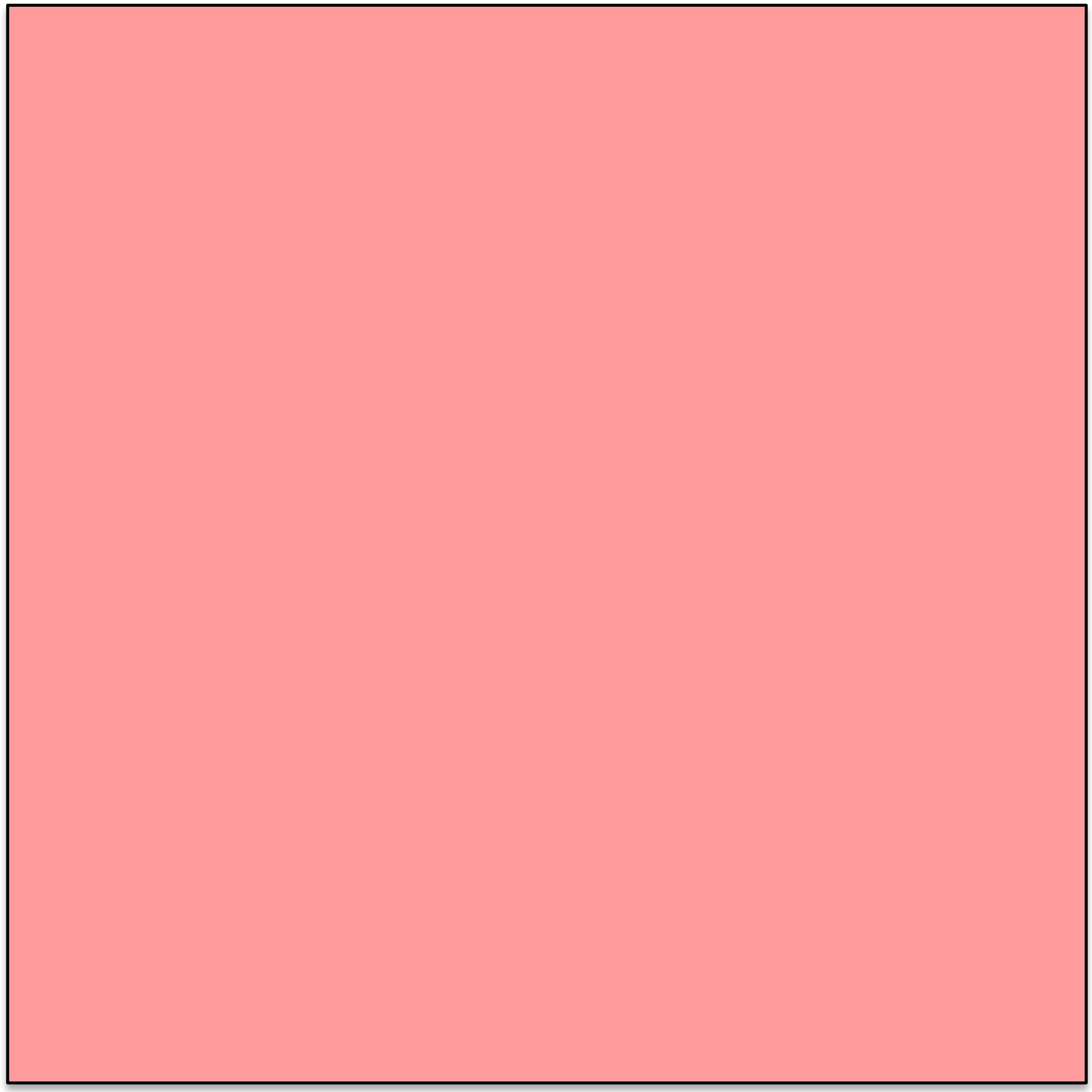


Farhi and Jaffe, '1984

Formation from First-Order Phase Transition



T > Tc



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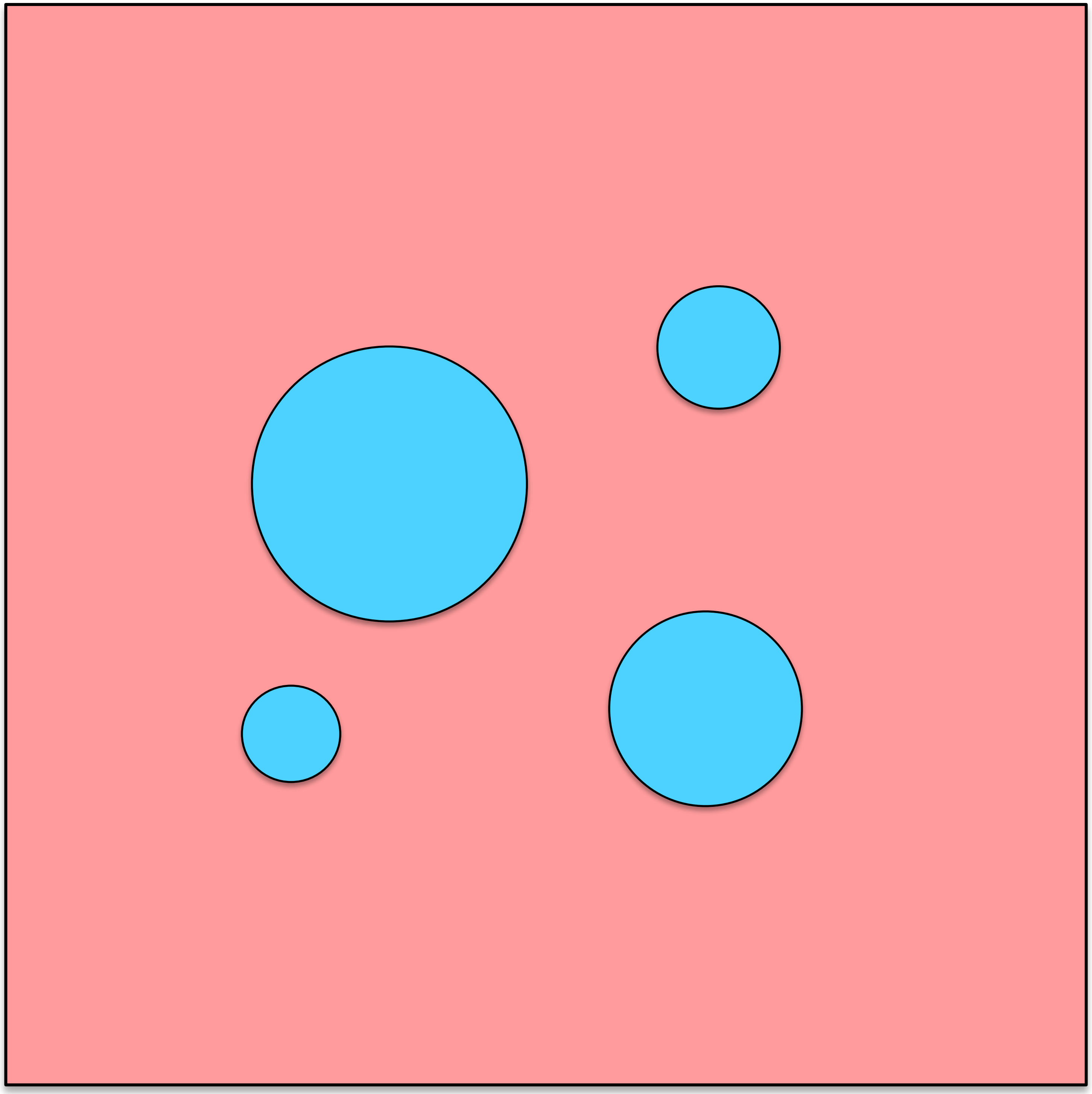

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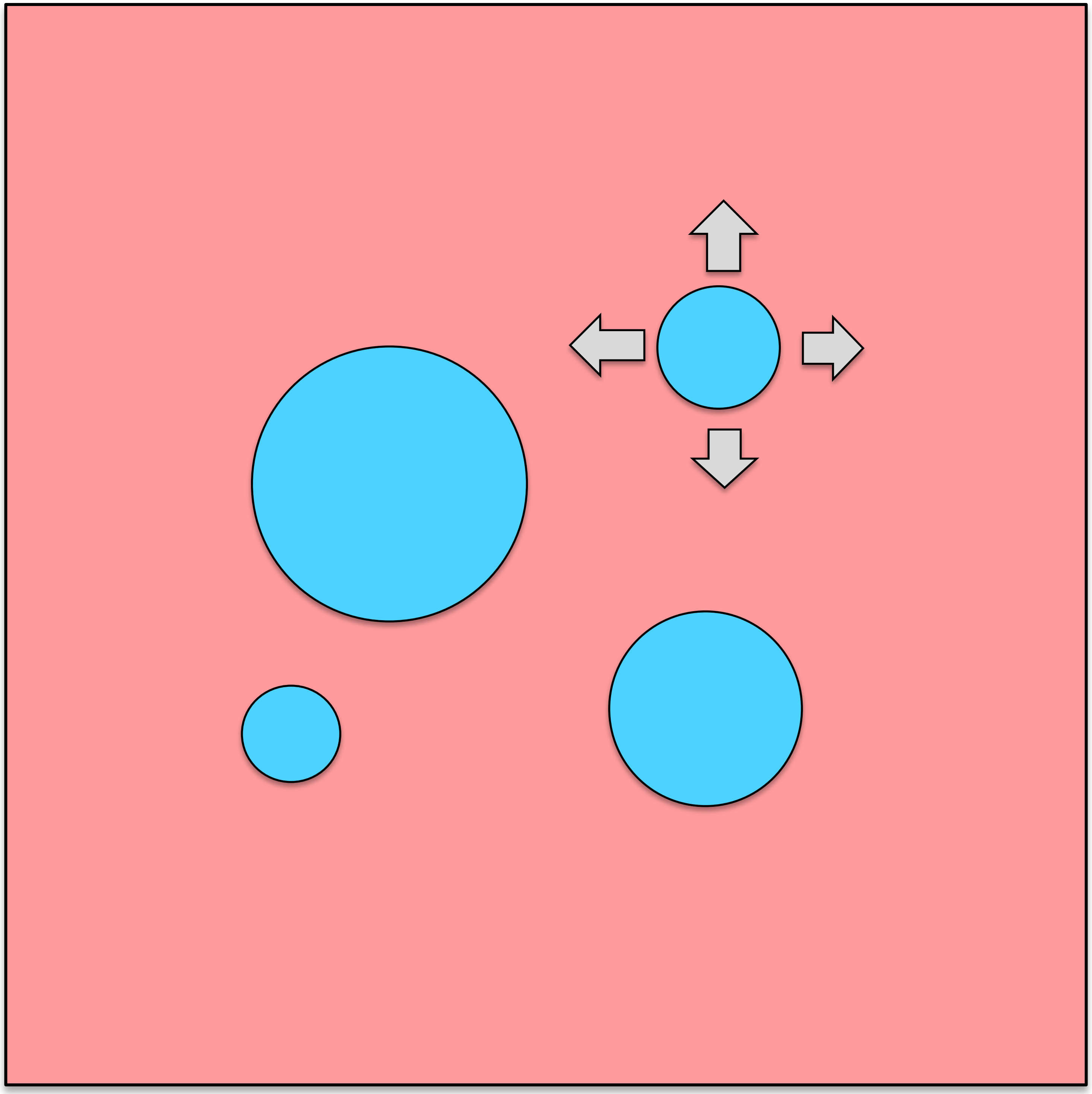
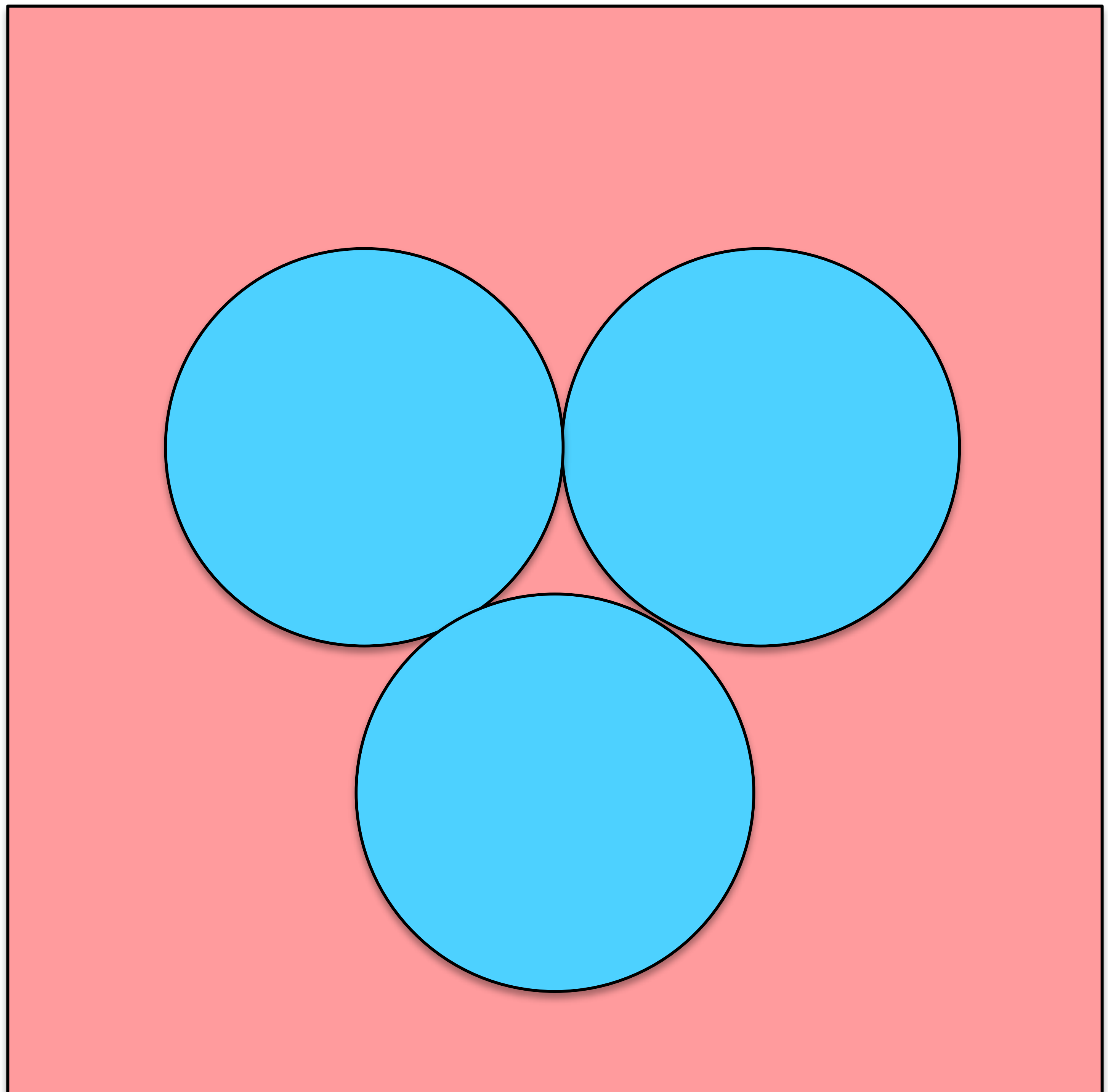
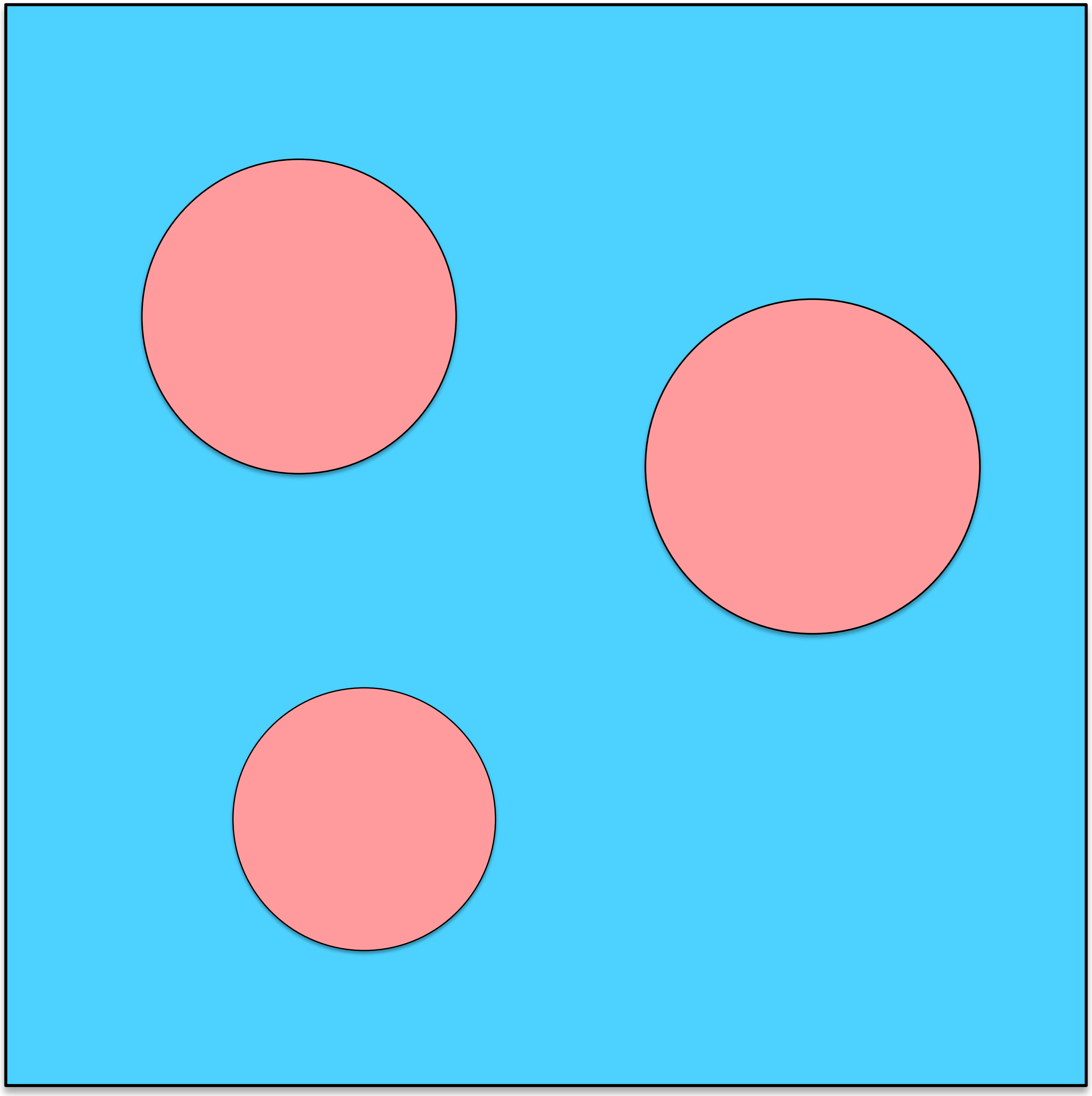


Hadron Bubbles Grow



Quark Nuggets Isolated



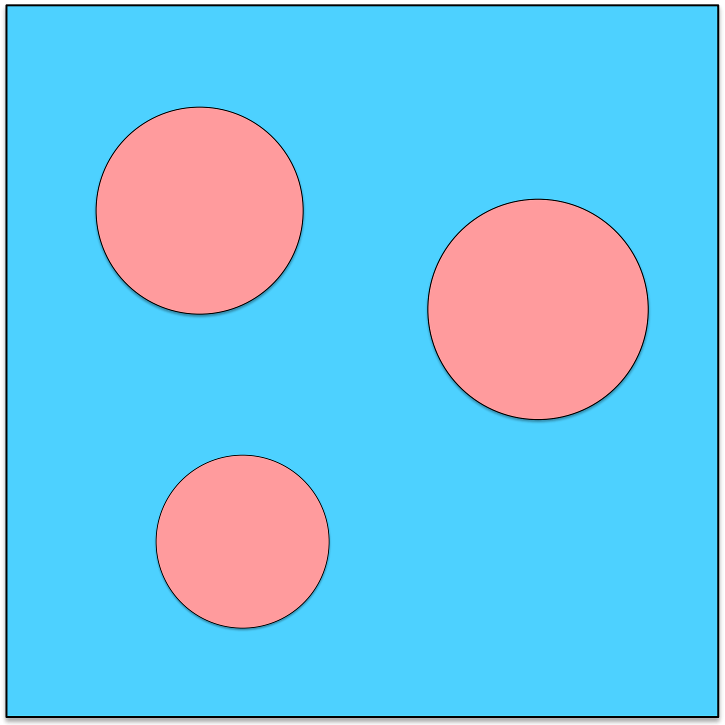
Some Properties

- **Most of baryon numbers are stored in the quark matter**
- **At $\mathrm{T_c}$, the size of quark matter is**

$$\sim d_H/100$$

Hogan, '1983
Kajantie and Kurki-Suonio, '1986

- **The number of baryons inside one quark matter bubble is** $\sim 10^{38}$



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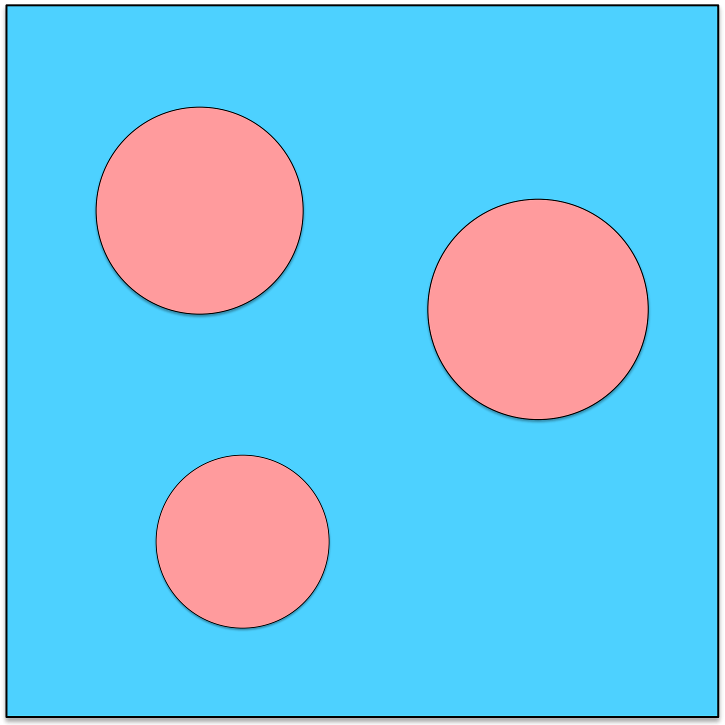
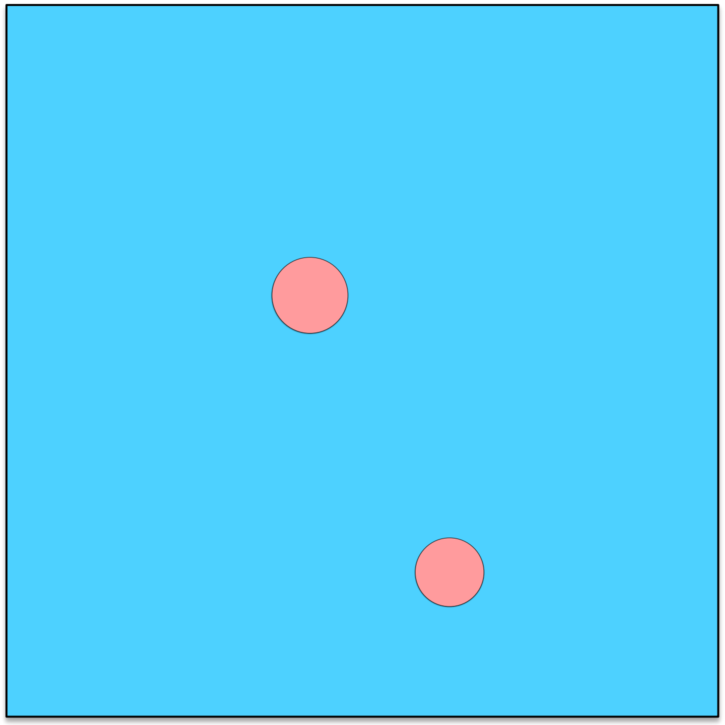


- **The number of baryons inside one quark matter bubble is** $\sim 10^{38}$
- **As T drops, the vacuum pressure shrinks the QM bubble, but the baryon number stays (assuming it does not evaporate)**



- **Eventually, the Fermi pressure balances the vacuum pressure**

3 Flavor Quark Nugget Dark Matter

- **The chemical potential or the number density is related to**

$$n_B \sim B^{3/4} \sim (150\,\mathrm{MeV})^3$$

- **The mass of the 3FQM is**

$$M_{3\mathrm{FQM}} \sim 10^{14}\,\mathrm{g}$$

- **The radius of the 3FQM is**

$$R_{3\mathrm{FQM}} \sim 1\,\mathrm{mm} - \mathrm{cm}$$

- **The density of the QM is similar to a Neutron Star, except with a much smaller radius**

“micro Neutron Star”

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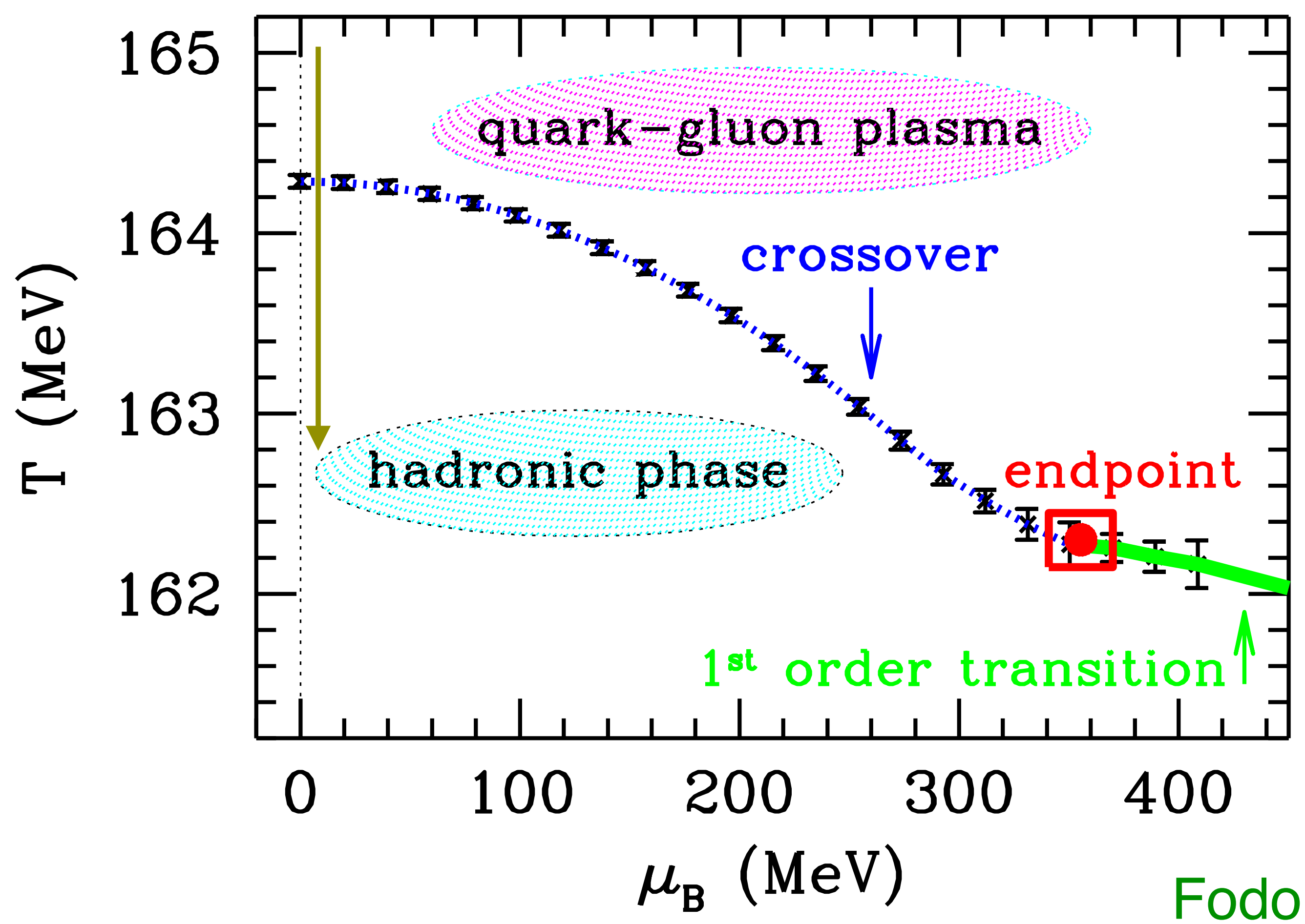
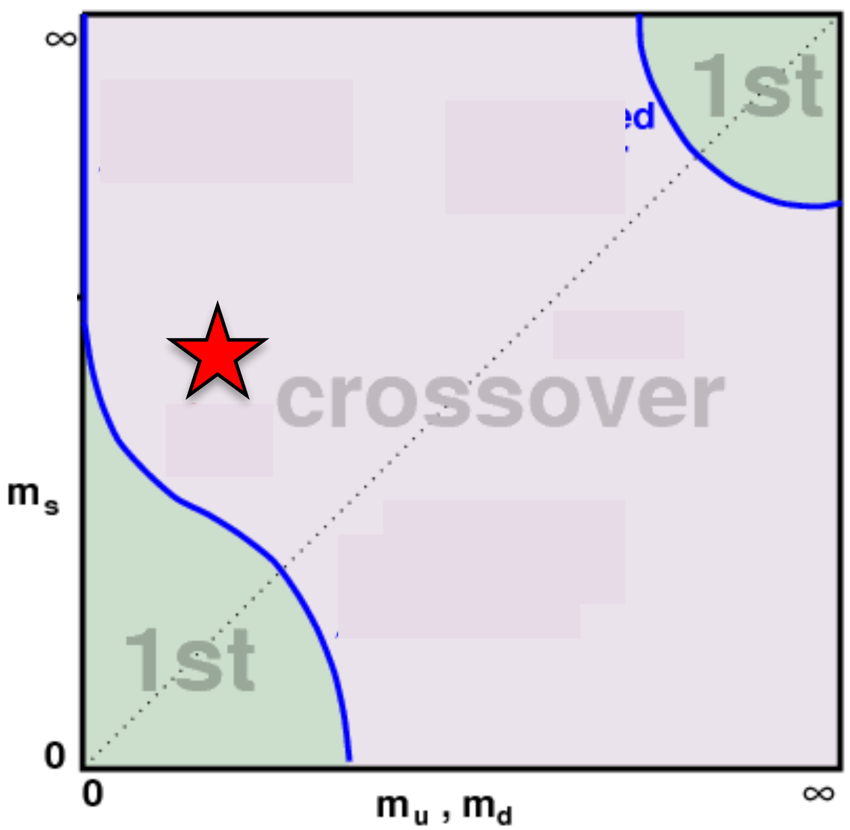


Fodor and Katz, '2004

SM QCD Phase Diagram



- if strange quark is massless, we have 1’st order transition
- More general, once the number of massless quarks is above or equal to 3, the phase transition is first order Pisarski-Wilczek, ’1983

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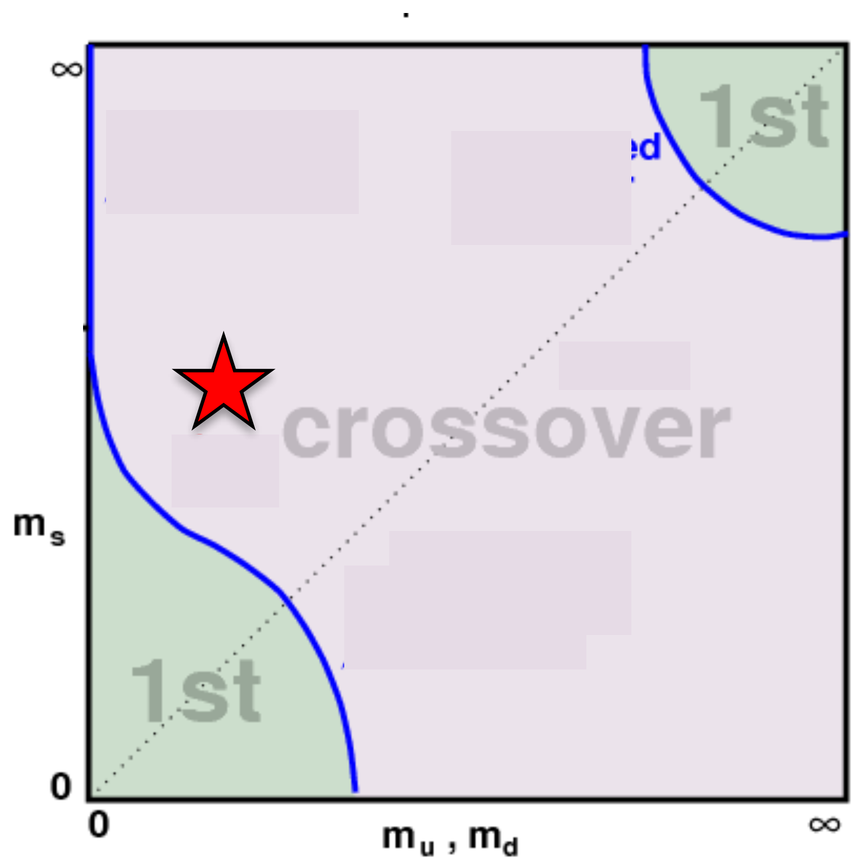

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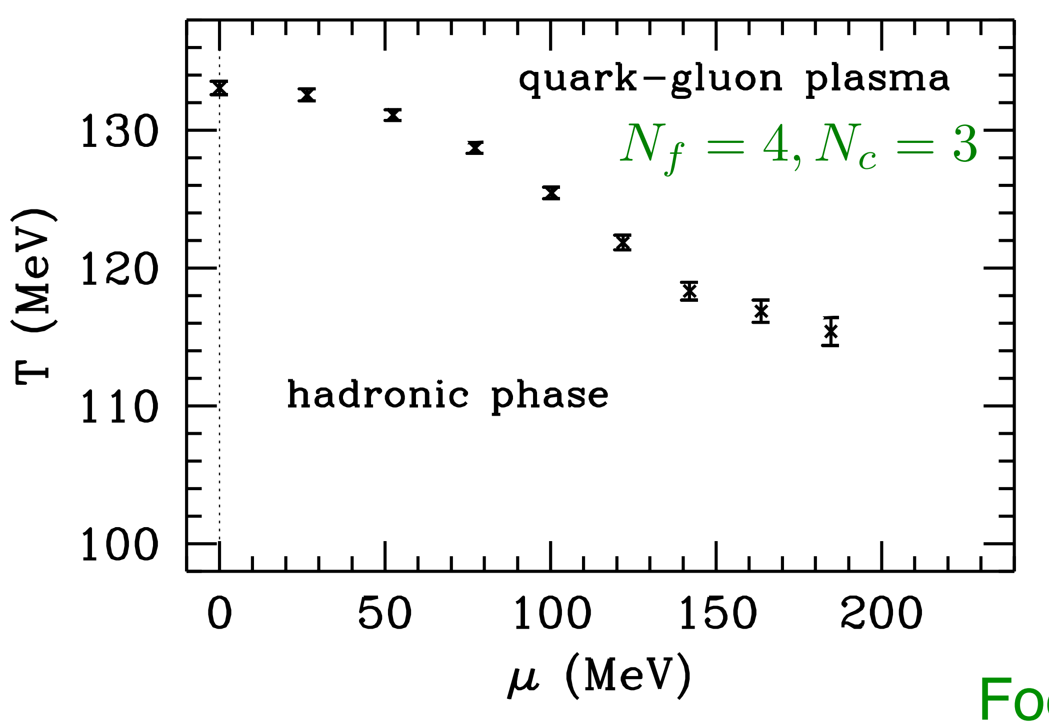
Pisarski-Wilczek, '1983



Fodor and Katz, '2001

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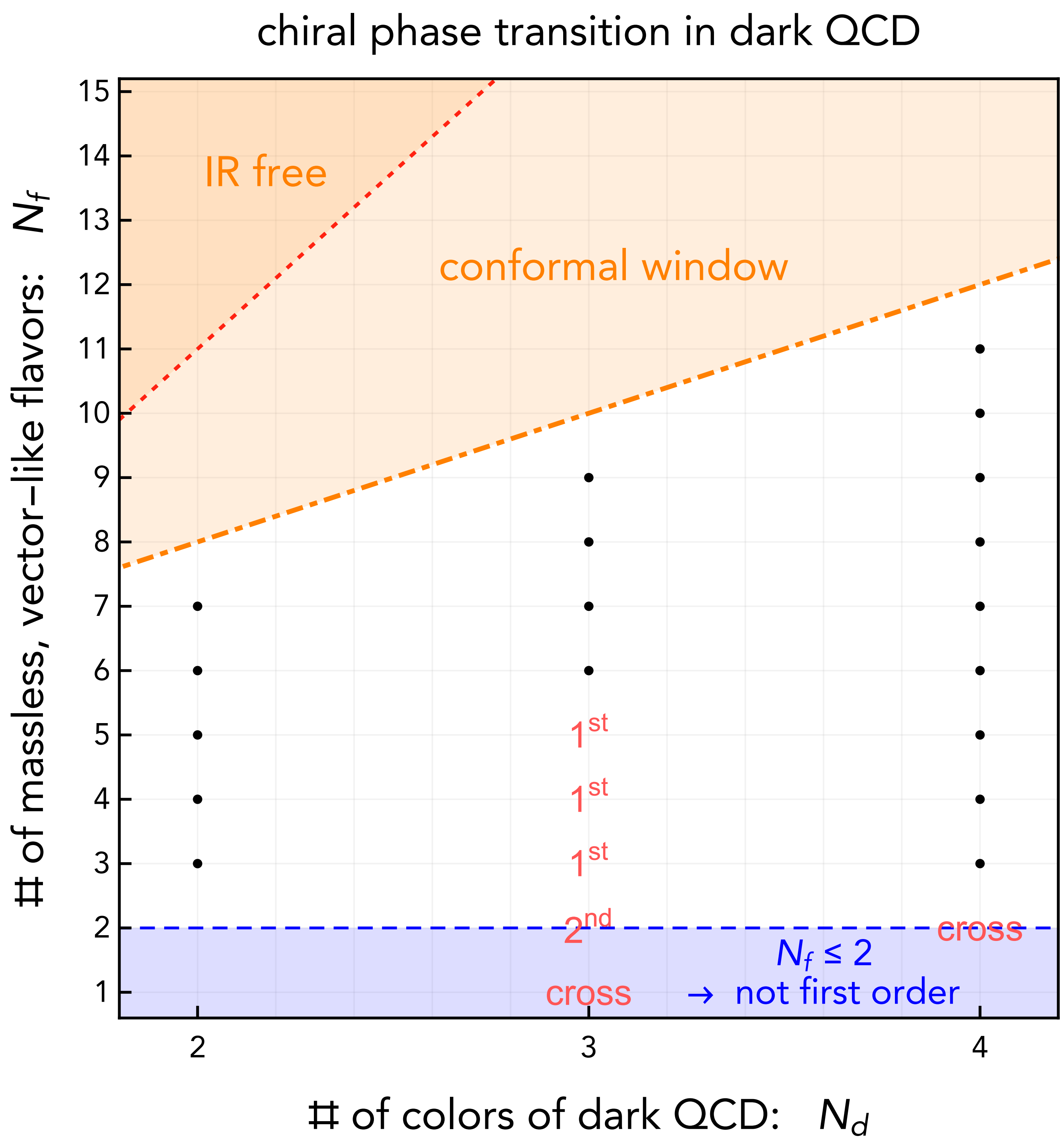
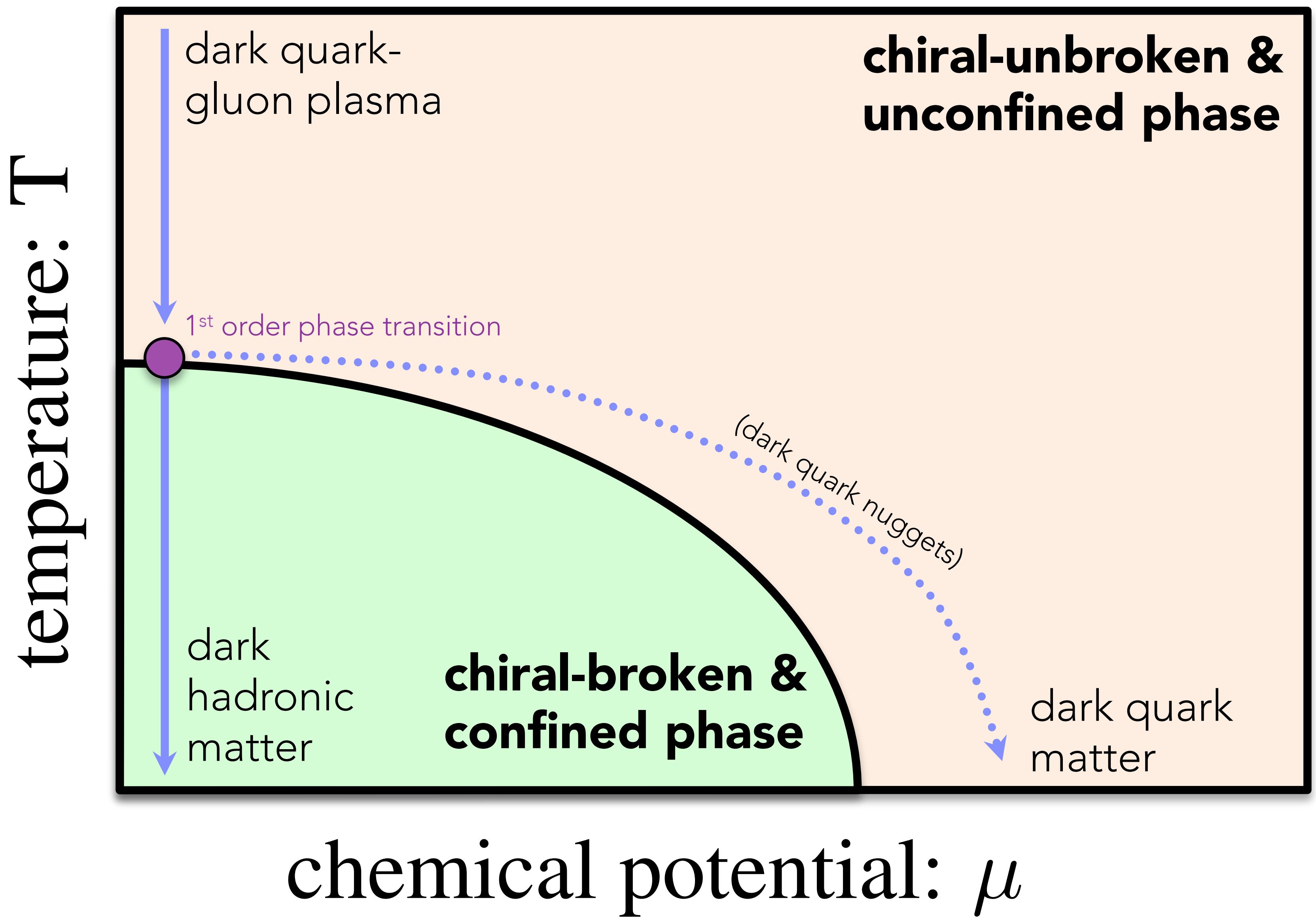
Phase diagram of dark QCD



- **QCD-like gauge theory with massless flavors**
- **Both analytical and the numerical Lattice-QCD methods have been used**
- **For a wide range of models, one has a 1'st order phase transition and potential formation of dark quark nuggets**

YB, Long, Lu, 1810.04360

Phase diagram of dark QCD



- **For dark quark matter to be the lower-energy state:**

$$\frac{B^{1/4}}{m_{B_d}} < 0.175 \left(\frac{N_f/N_d}{1}\right)^{1/4} \left(\frac{N_d}{3}\right)^{-1/2}$$

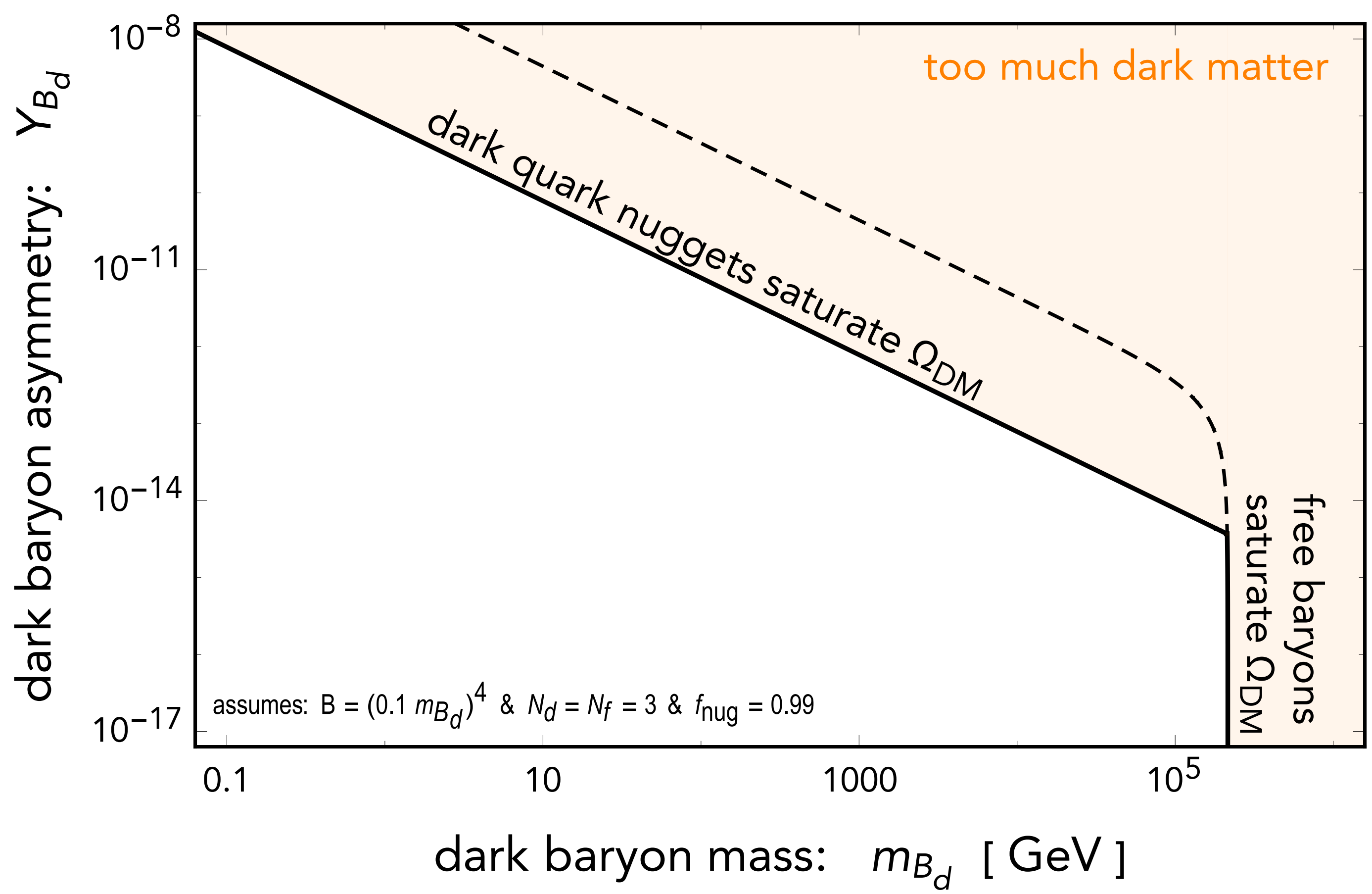
Free Dark Baryons

- **The standard freeze-out story tells us that some fraction of free dark baryon and anti-baryon also exist**

$$\langle \sigma v \rangle \approx (50\,\mathrm{mb}\cdot \mathrm{c}) \left(\frac{1\ \mathrm{GeV}}{m_{B_d}}\right)^2$$

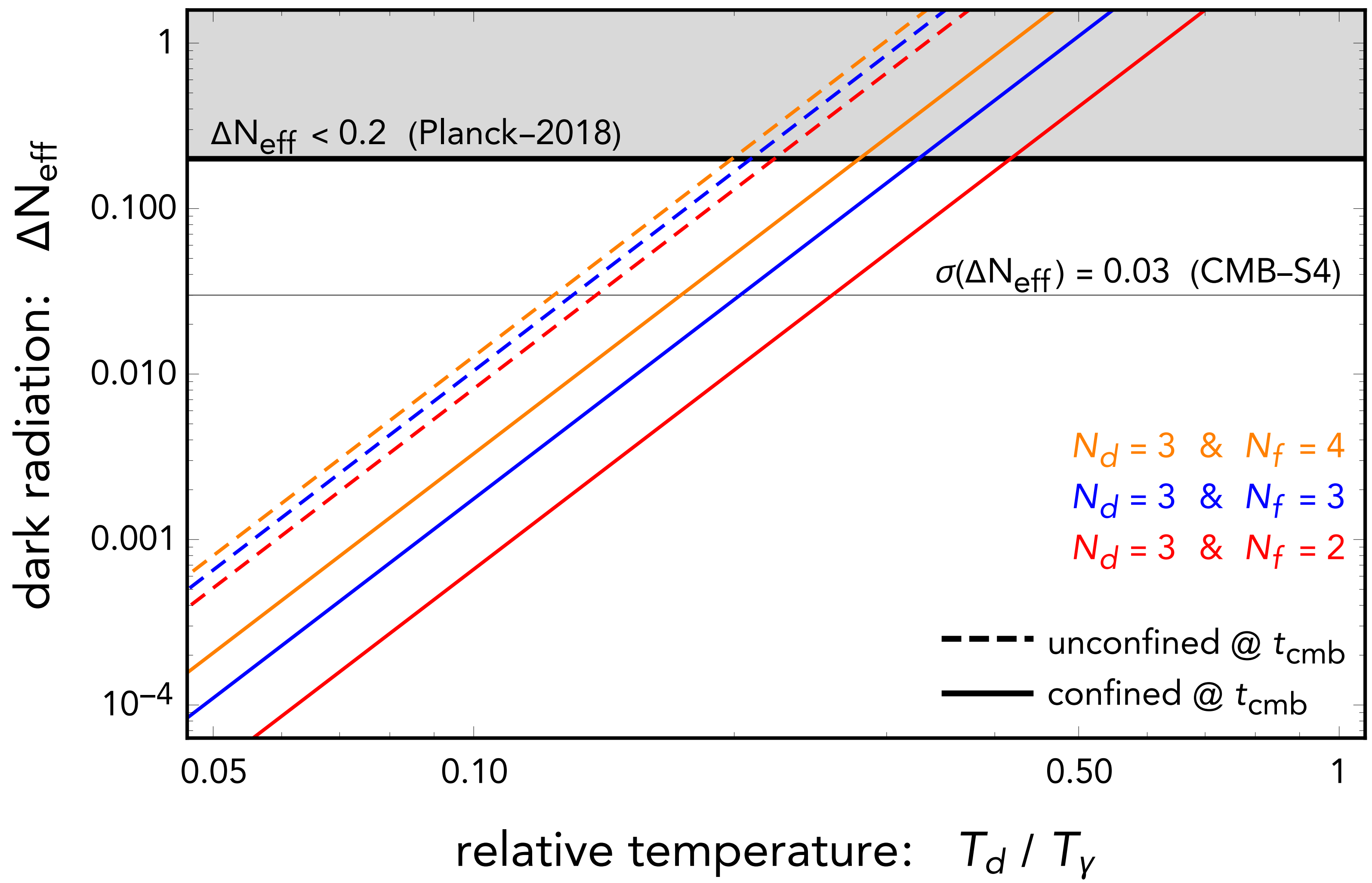
$$\Omega_{B_d} h^2 = \Omega_{\bar{B}_d} h^2 \simeq (0.052) \left(\frac{\langle \sigma v \rangle}{130\, m_{B_d}^{-2}}\right)^{-1} \left(\frac{m_{B_d}}{200\ \mathrm{TeV}}\right)^2 \left(\frac{m_{B_d}/T_d(t_{\mathrm{fo}})}{20}\right) \left(\frac{T_d(t_{\mathrm{fo}})}{T_\gamma(t_{\mathrm{fo}})}\right) \left(\frac{g_*}{100}\right)^{-1/2}$$

relic abundance of free dark baryons & antibaryons



Dark Radiation

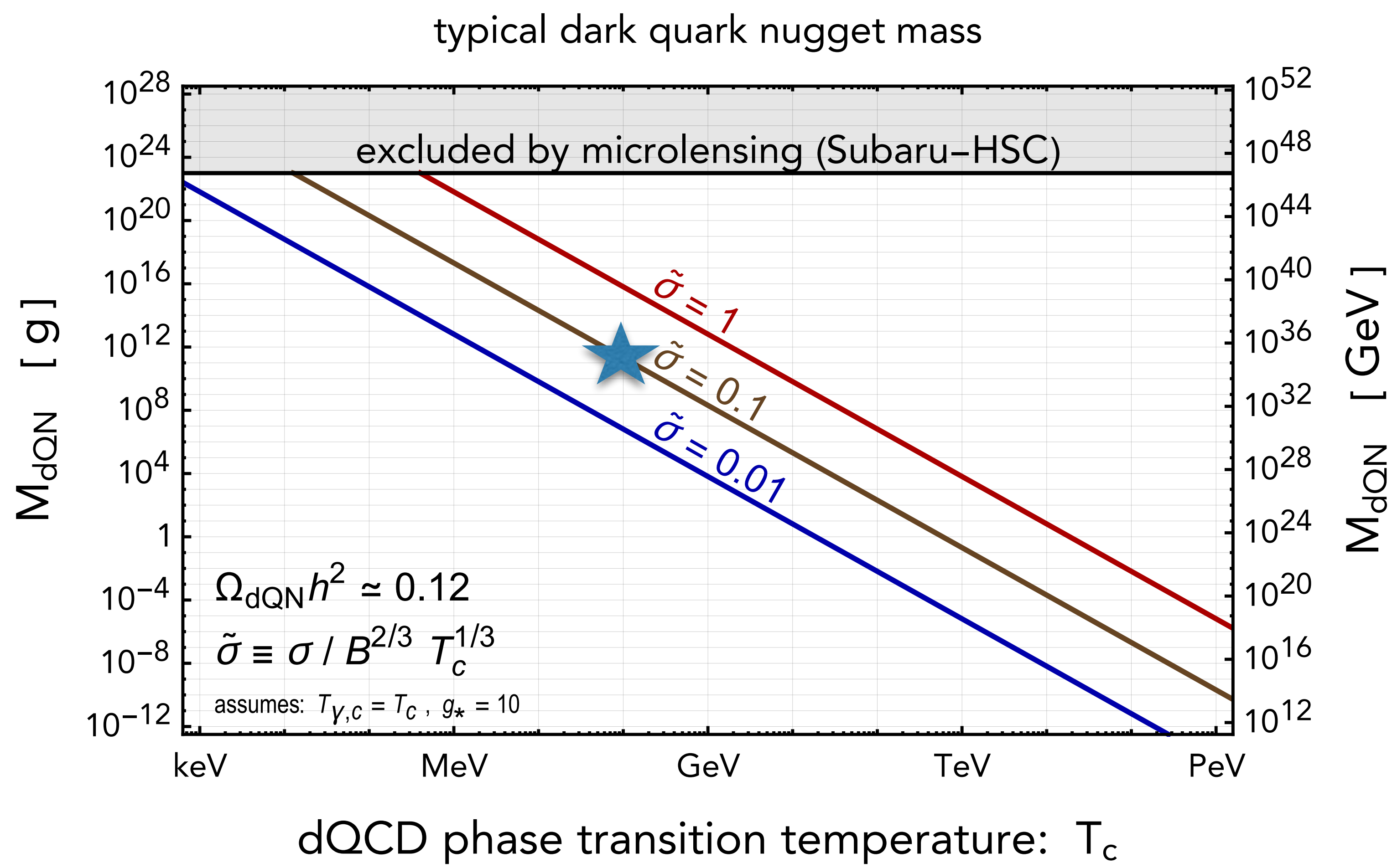
- **If the dark sector is *never* thermalized with us**



- **The dark sector is required to be chilly**

Mass and Size of dQN

- **Dark baryon asymmetry is assumed from early universe**



$$R_{\rm dQN} \simeq (0.081\ {\rm cm}) \left(\frac{\Omega_{\rm dQN} h^2}{0.12}\right)^{1/3} \left[\frac{B}{(0.1\ {\rm GeV})^4}\right]^{-1/3} \left(\frac{T_{\gamma,c}}{0.1\ {\rm GeV}}\right)^{-1} \left(\frac{\tilde{\sigma}}{0.1}\right)^{3/2}$$

$$M_{\rm dQN} \simeq (2.1 \times 10^{11}\ {\rm g}) \left(\frac{\Omega_{\rm dQN} h^2}{0.12}\right) \left(\frac{T_{\gamma,c}}{0.1\ {\rm GeV}}\right)^{-3} \left(\frac{\tilde{\sigma}}{0.1}\right)^{9/2} .$$

- **Lower dark confinement scales have heavier and larger dark quark nuggets**

YB, Long, Lu, 1810.04360

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Non-topological Soliton

- **Was studied extensively by T. D. Lee and collaborators in 70's and Coleman in 80's. Let's use Coleman's paper to set a stage.**

Q-BALLS*

Sidney COLEMAN

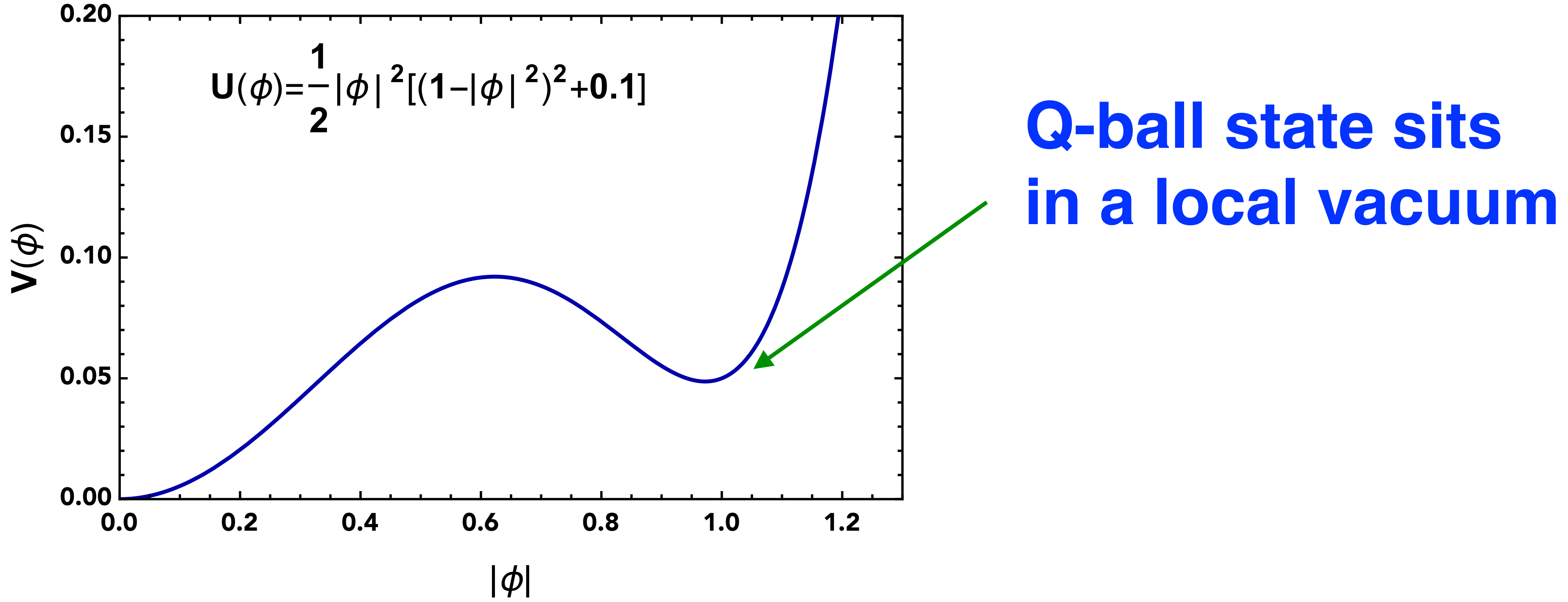
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Received 4 July 1985

A large family of field theories in 3+1 dimensions contains a new class of extended objects. The existence of these objects depends on (among other conditions) the existence of a conserved charge, Q, associated with an ungauged unbroken continuous internal symmetry. These objects are spherically symmetric, and for large Q their energies and volumes grow linearly with Q; thus they act like homogeneous balls of ordinary matter, with Q playing the role of particle number. This paper proves the fundamental existence theorem for these Q-balls, computes their elementary properties, and finds their low-lying excitations.

Non-topological Soliton

- For a complex scalar field with an unbroken global symmetry, there exist nondissipative solutions of the classical field equations that are absolute minima of the energy for a fixed (sufficiently large) Q.



- This will be a non-renormalizable potential for a single field

Non-topological Soliton

- **The charge Q of** $U(1)_\phi$ **, is** $Q = \omega \int d^3x\, |\phi(r)|^2 \approx \omega\, \phi^2\, V$
- **In the large Q limit, the profile is like a step-function.**
- **The energy of state has**

$$E = \frac{1}{2}\frac{Q^2}{\phi^2 V} + U\, V$$

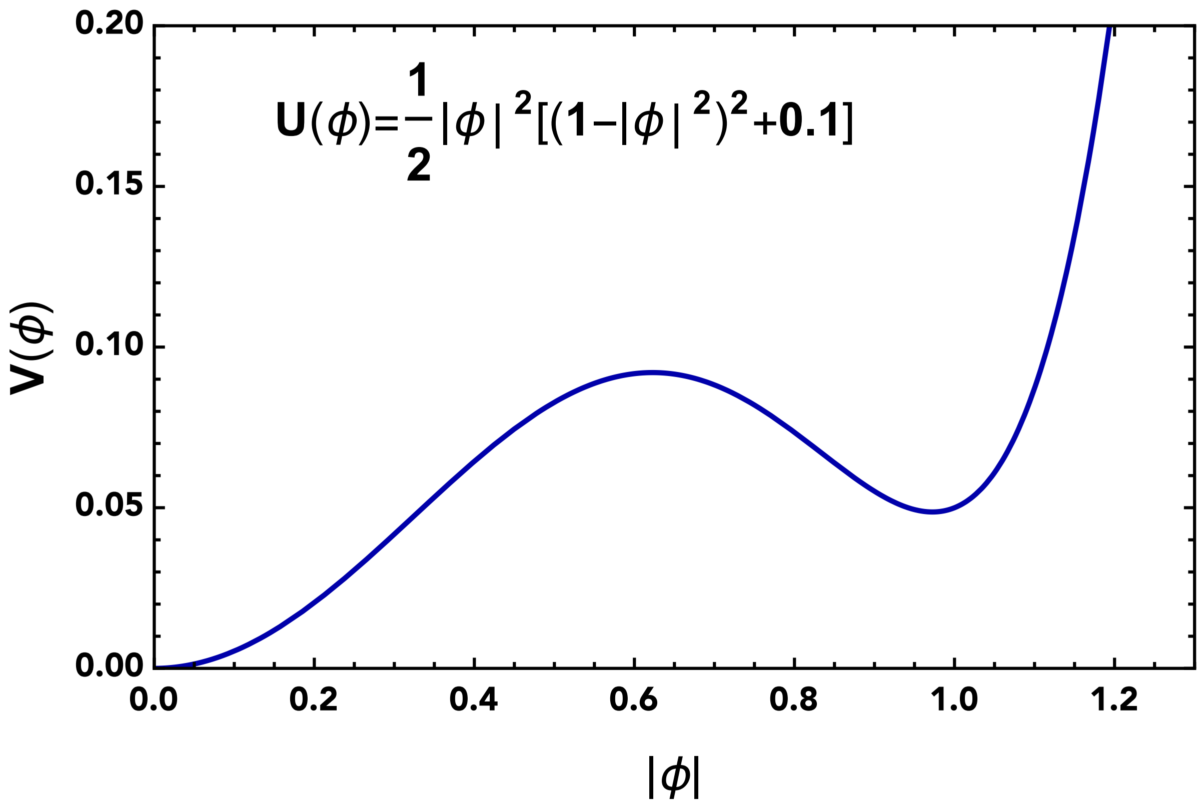
- **Minimizing the energy with respect to the volume**

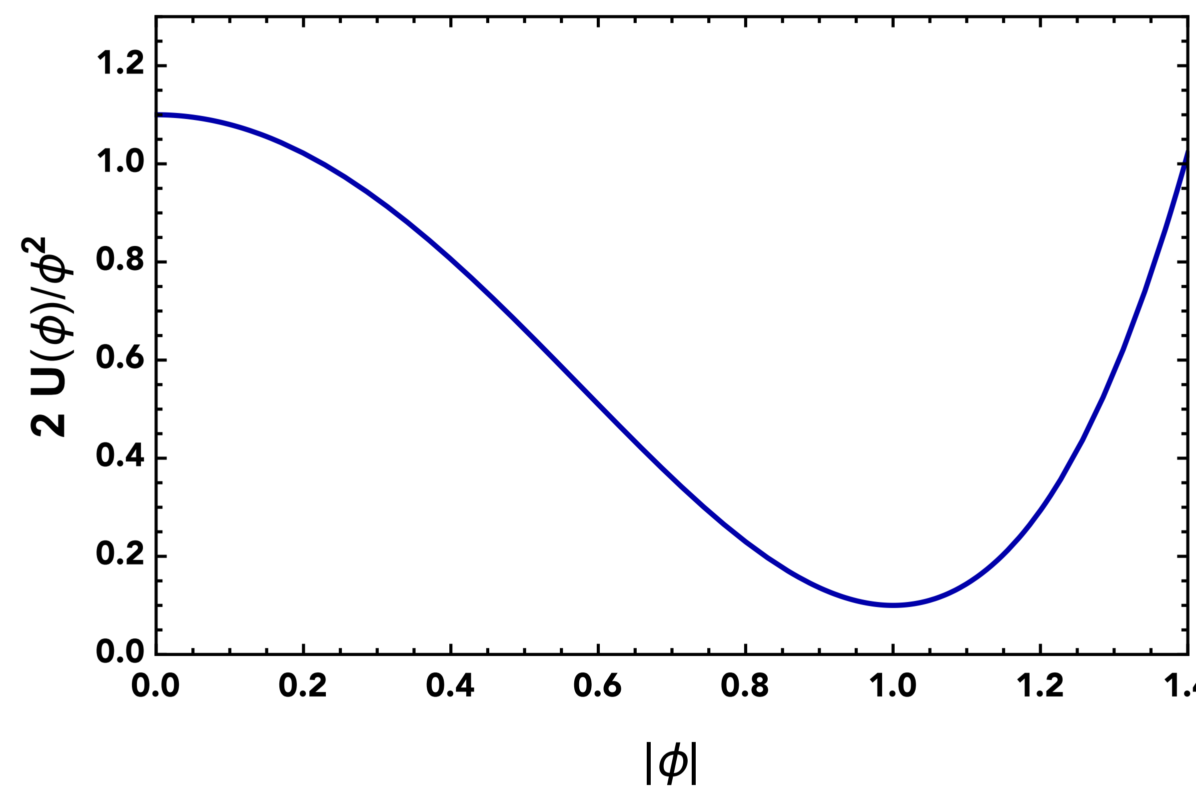
$$V = \frac{Q}{\sqrt{2\phi^2 U}} \qquad\qquad E = Q\sqrt{\frac{2U}{\phi^2}}$$

- **So, for the same Q, the lowest energy state is at some** ϕ_0

$$2U_0/\phi_0^2 = \min[2U/\phi^2]$$

Non-topological Soliton





- The soliton state is also stable at quantum level.
- Its energy is proportional to Q times some intrinsic properties of the potential.
- This is just a feature of a single-field potential. The Q-dependence of energy will be different for two-field cases.

Higgs-portal Dark Matter

- **The simplest extension of the SM is the Higgs-portal dark matter:**

$$\mathscr{L} = \partial_\mu \Phi^\dagger \partial^\mu \Phi + \partial_\mu H^\dagger \partial^\mu H - \lambda_h \left(H^\dagger H - \frac{v^2}{2} \right)^2 - \lambda_{\phi h} \Phi^\dagger \Phi H^\dagger H$$

with all dark matter mass from the Higgs VEV: $M_\Phi = \sqrt{\frac{\lambda_{\phi h}}{2}}\, v$

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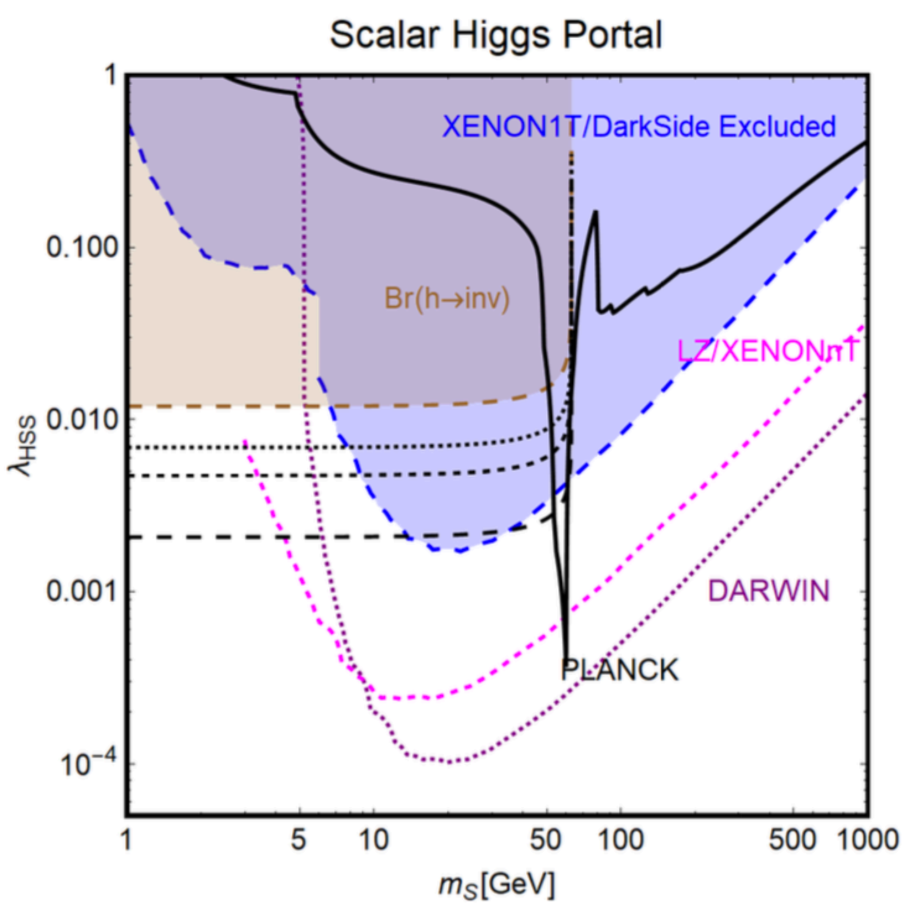
- If one keeps the coupling and mass independent

- Severely constrained by direct detection experiments



Arcadi, Djouadi, Raidal, 1903.03616

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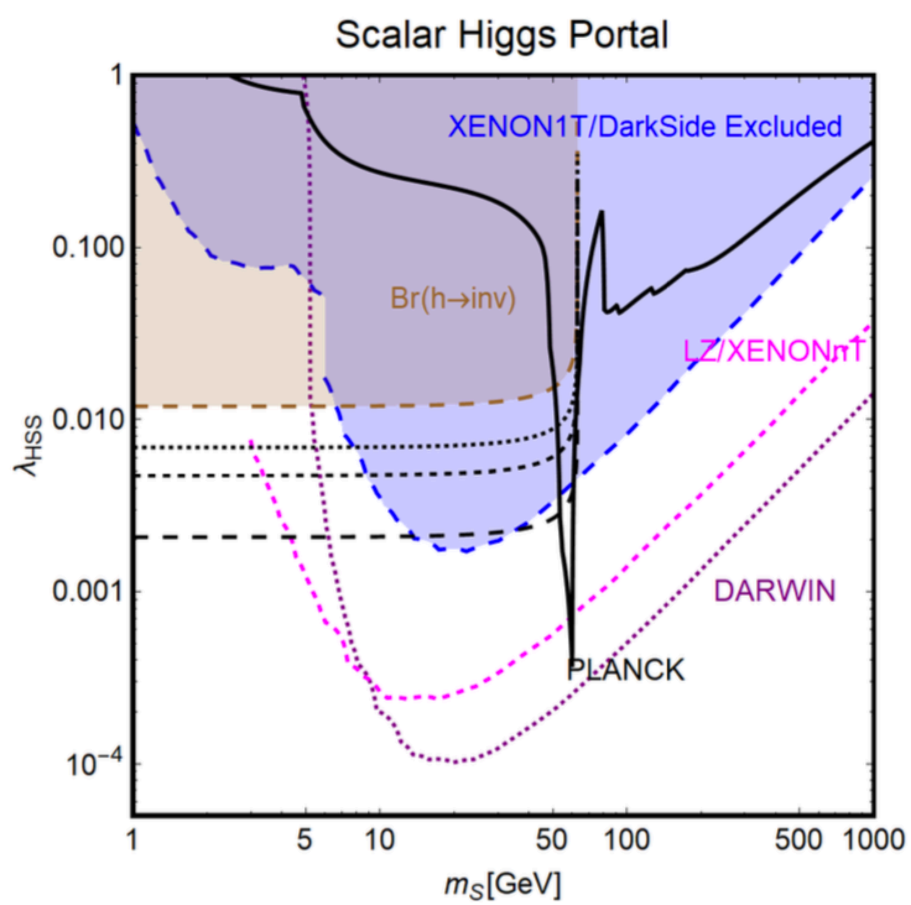

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But, dark matter may not be in the EW-breaking vacuum

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- **The classical equations of motion** $\Phi(x_\mu) = e^{i\omega t}\phi(r)/\sqrt{2} \quad H(x_\mu) = h(r)/\sqrt{2}$

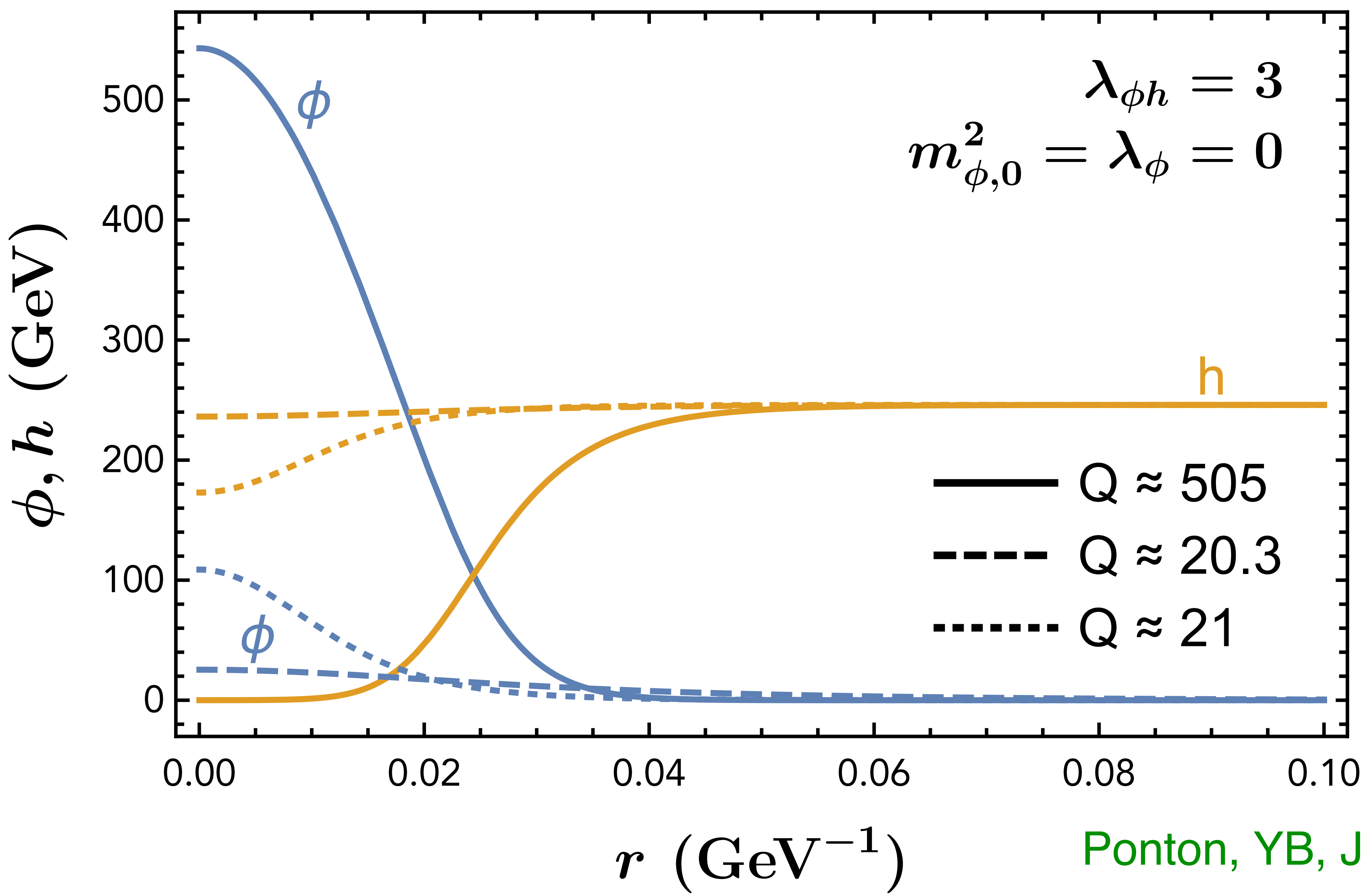
$$\phi''(r) + \frac{2}{r}\phi'(r) + \left[\omega^2 - \frac{1}{2}\lambda_{\phi h} h(r)^2\right] \phi(r) = 0\,,$$

$$h''(r) + \frac{2}{r}h'(r) + \left[\frac{m_h^2}{2} - \lambda_h h(r)^2 - \frac{1}{2}\lambda_{\phi h}\phi(r)^2\right] h(r) = 0\,,$$

- **Four boundary conditions:** $\phi'(0) = h'(0) = 0 \quad \phi(\infty) = 0 \quad h(\infty) = v$

- **Need to double-shooting on $\phi(0)$ and $h(0)$ for a fixed value of ω**

Example Solutions ($\lambda_\phi = 0$)



Ponton, YB, Jain, 1906.10739

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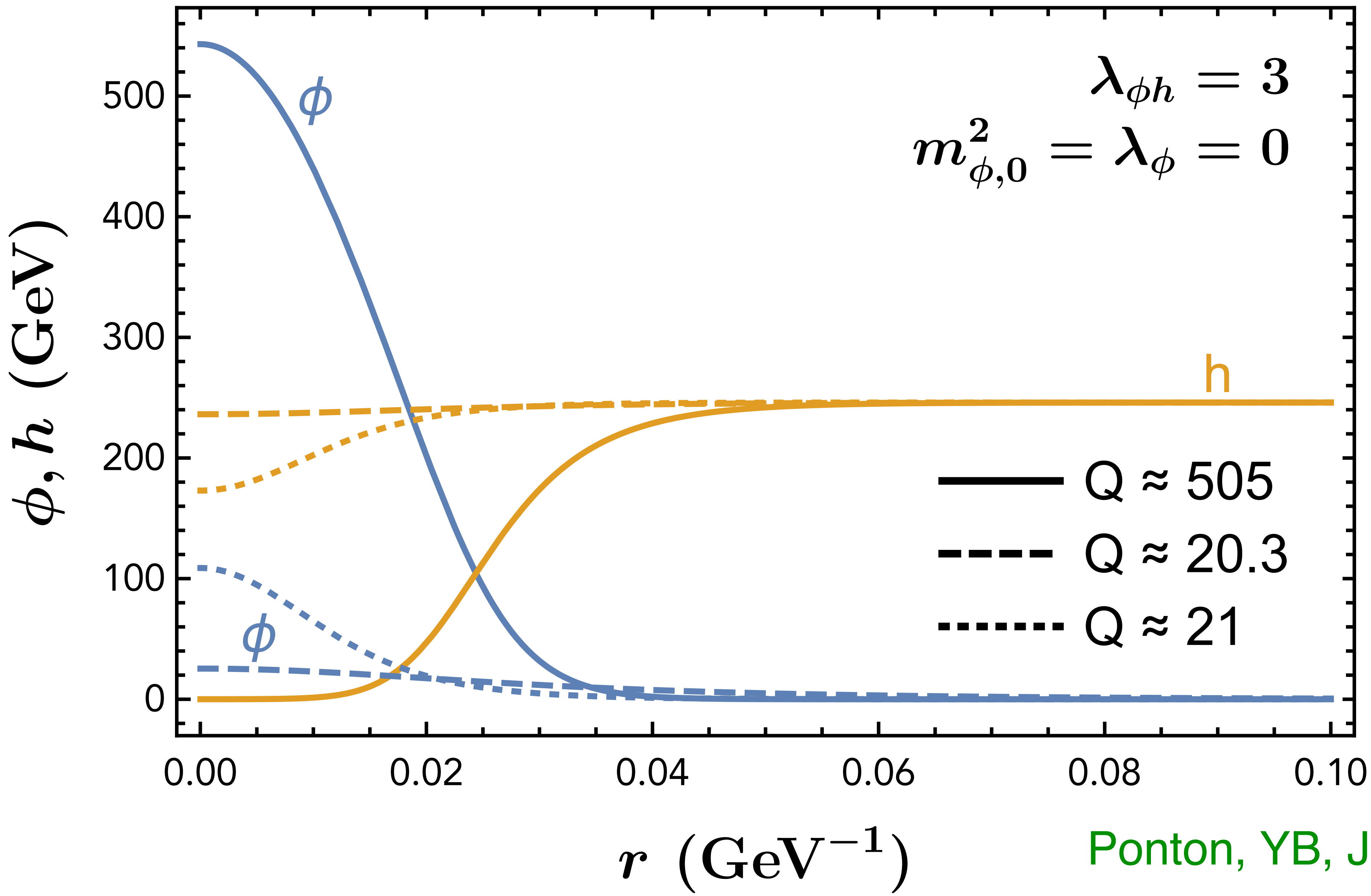
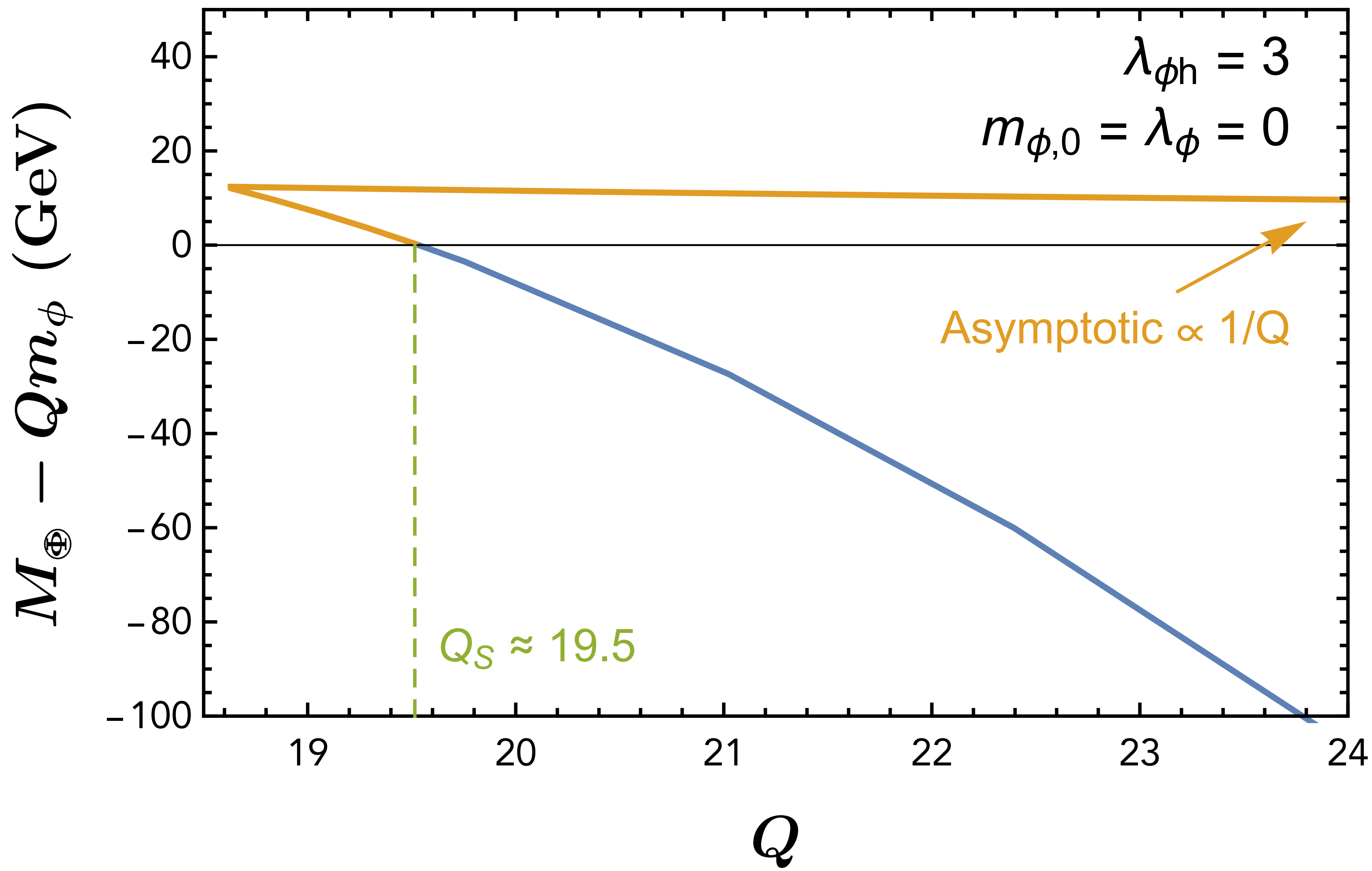


Ponton, YB, Jain, 1906.10739

for a large Q: Electroweak Symmetric Dark Matter Ball

Dark Matter Ball Mass vs. Q



❖ **In the large Q limit, one has a simple relation**

$$Q \sim R_{\oplus}^4 , \qquad M_{\oplus} \sim Q^{3/4} \sim R_{\oplus}^3$$

Add Φ Self-Interaction

$$\mathcal{L} = \partial_\mu \Phi^\dagger \partial^\mu \Phi + \partial_\mu H^\dagger \partial^\mu H - \lambda_h \left(H^\dagger H - \frac{v^2}{2} \right)^2 - \lambda_{\phi h} \Phi^\dagger \Phi H^\dagger H - m_{\phi,0}^2 \Phi^\dagger \Phi - \lambda_\phi (\Phi^\dagger \Phi)^2$$

- **The existence of the self-quartic interaction changes the dark matter ball properties significantly**

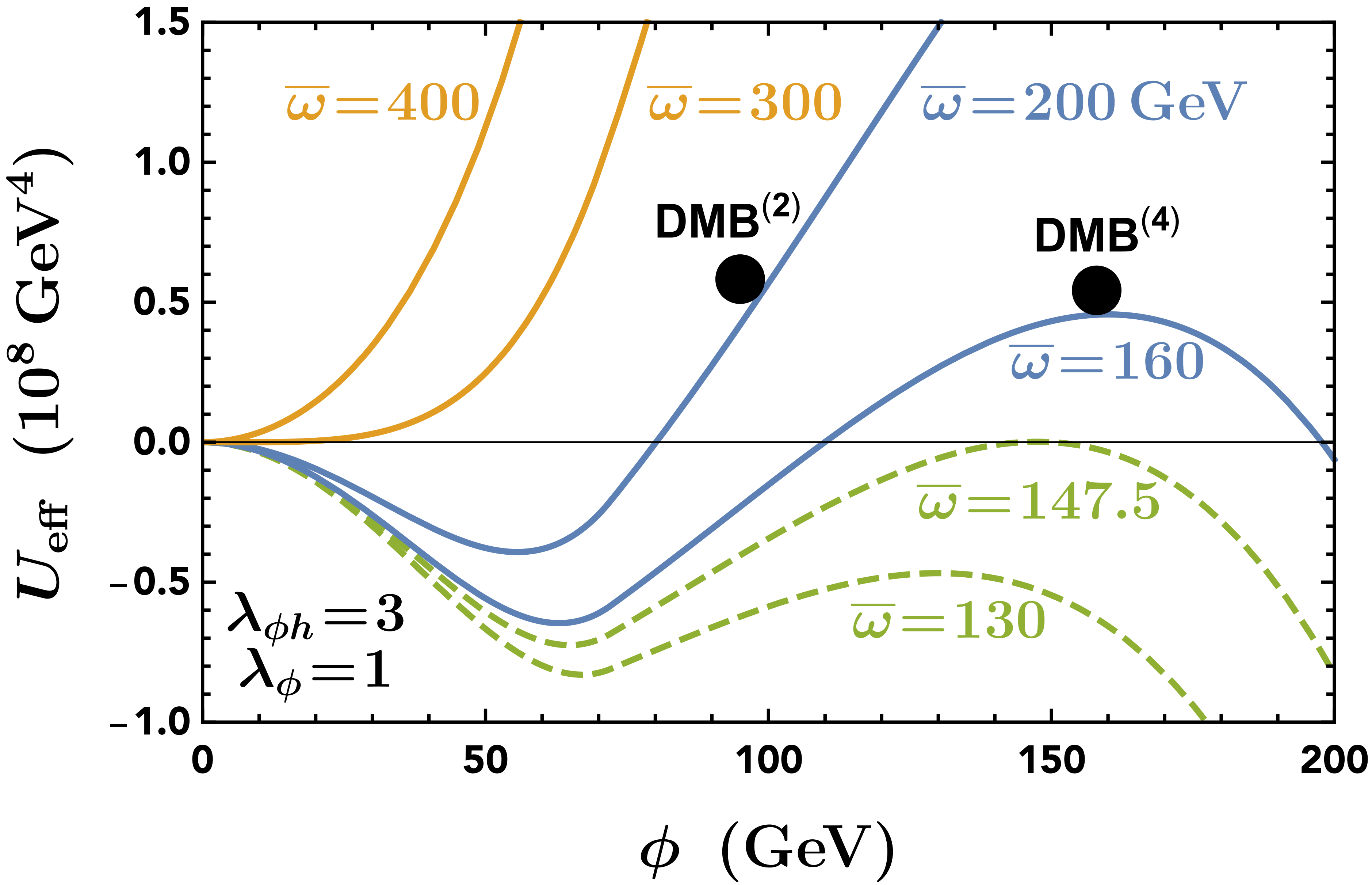
$$h^2 \approx \begin{cases} \dfrac{m_h^2}{2\lambda_h} - \dfrac{\lambda_{\phi h}}{2\lambda_h}\,\phi^2 & \text{for} \quad \lambda_{\phi h}\,\phi^2 < m_h^2 \,, \\ 0 & \text{for} \quad \lambda_{\phi h}\,\phi^2 > m_h^2 \,. \end{cases}$$

$$U_{\rm eff}(\phi) = -V_\Phi(\phi) + \begin{cases} \dfrac{1}{2}\left(\omega^2 - \dfrac{\lambda_{\phi h}\, m_h^2}{4\,\lambda_h}\right)\phi^2 + \dfrac{\lambda_{\phi h}^2}{16\lambda_h}\,\phi^4 & \text{for} \quad \lambda_{\phi h}\,\phi^2 < m_h^2 \,, \\ \dfrac{1}{2}\omega^2\phi^2 - \dfrac{m_h^4}{16\,\lambda_h} & \text{for} \quad \lambda_{\phi h}\,\phi^2 > m_h^2 \,. \end{cases}$$

$$\phi'' + \frac{2}{r}\,\phi' + U'_{\rm eff}(\phi) \approx 0$$

- **Via Coleman, we can use 1D particle description to understand it**

Add Φ Self-Interaction



$$\overline{\omega}^2 = \omega^2 - m_{\phi,0}^2 \qquad\qquad \overline{\omega}_c = \left(\frac{\lambda_\phi}{4\lambda_h}\right)^{1/4} m_h$$

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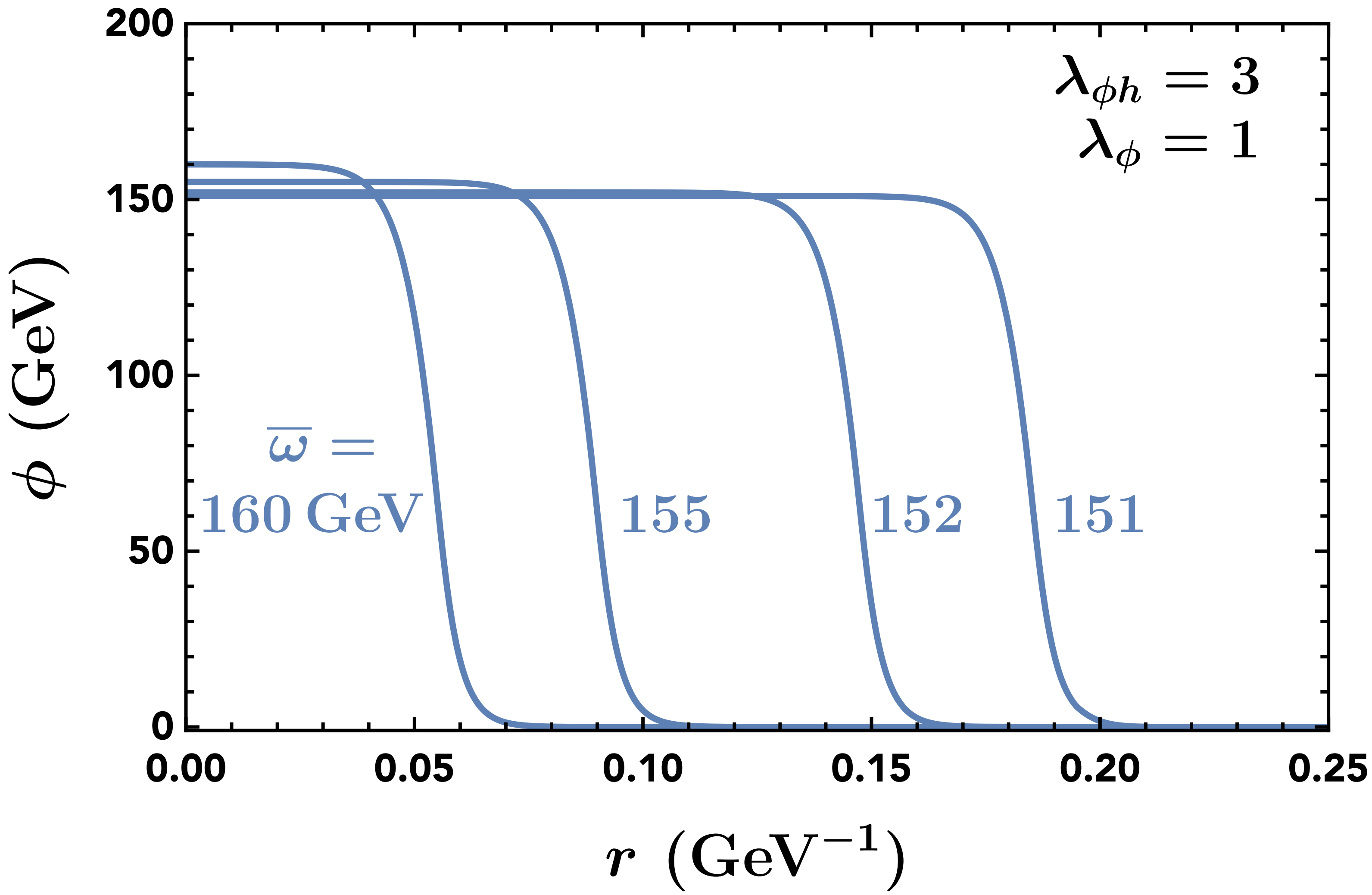


- As a $\overline{\omega} \to \overline{\omega}_c$, the radius increases as $R \approx \dfrac{0.66}{\overline{\omega} - \overline{\omega}_c}$

$$Q \sim R_{\oplus}^3 , \qquad M_{\oplus} \sim Q \sim R_{\oplus}^3 \qquad \rho = \frac{M_{\oplus}}{(4\pi/3)R_{\oplus}^3} \sim (100 \text{ GeV})^4$$

Two Types of BEC

- When the Φ self-interaction is not important ($\lambda_\phi \ll 1$), the core density could be arbitrarily high (BEC)

$$Q \sim R_{\oplus}^4 , \qquad M_{\oplus} \sim Q^{3/4} \sim R_{\oplus}^3$$

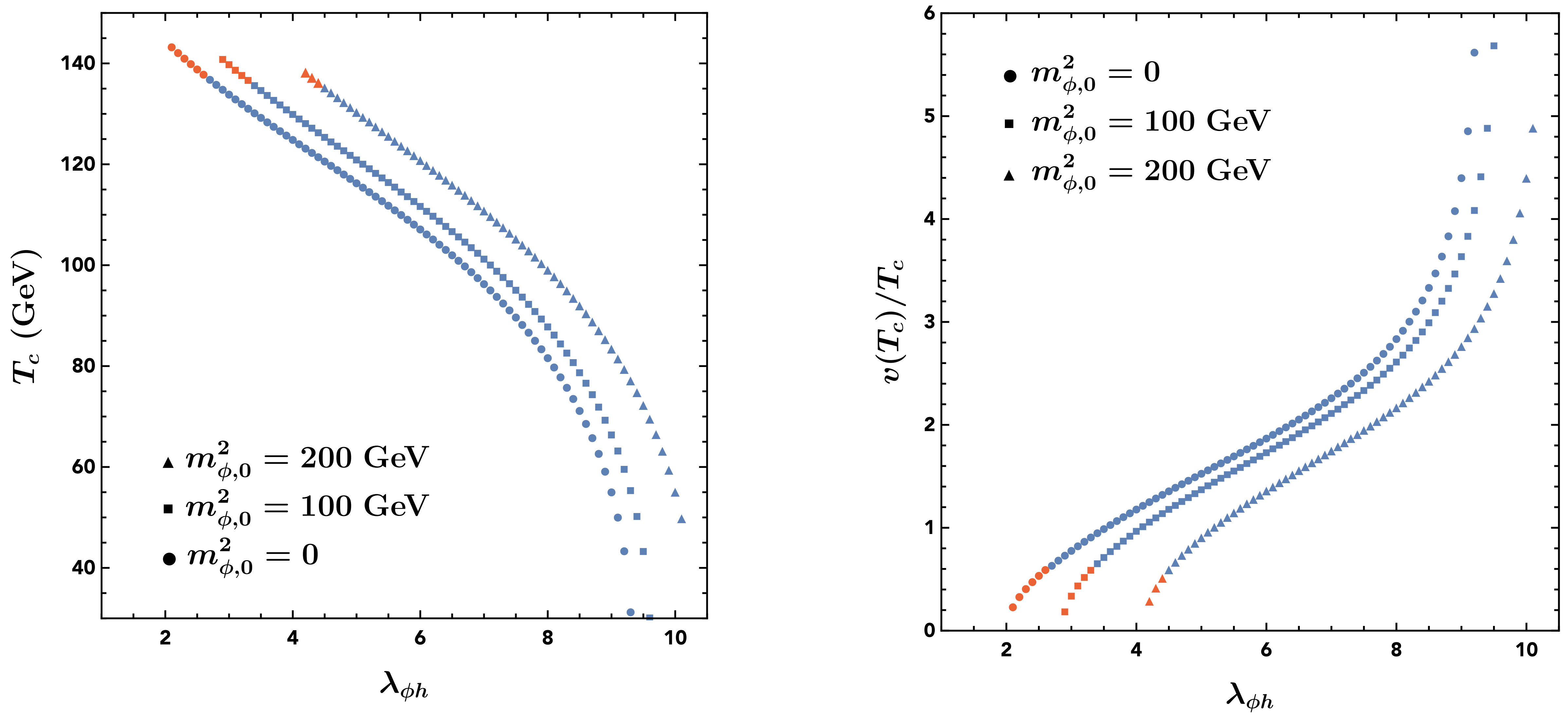
- When the Φ self-interaction is important ($\lambda_\phi \sim 1$), the energy density is flat in the inner region

$$Q \sim R_{\oplus}^3 , \qquad M_{\oplus} \sim Q \sim R_{\oplus}^3$$

- Both of them have $\rho^{1/4} \sim v_{\mathrm{EW}}$ and unbroken electroweak symmetry in the inner region

Formation from 1’st Phase Transition

- **It is known that the Higgs-portal dark matter can also trigger strong first-order phase transition**



- **The formation is similar to the (dark) quark nugget case**

Abundance of Dark Matter Balls

- **Use initial DM number asymmetry Y_Φ to match DM abundance**

- **The total number of dark matter within one Hubble patch is**

$$N_\Phi^{\rm Hubble} \approx Y_\Phi\, s\, d_H^3 \simeq (7.8 \times 10^{37}) \left(\frac{Y_\Phi}{10^{-11}}\right) \left(\frac{134\,{\rm GeV}}{T_c}\right)^3$$

- **The number of nucleation sites within one Hubble volume has**

$$N_{\rm DMB}^{\rm Hubble} \sim 1.0 \times 10^{13} \times \left(\frac{\lambda_{\phi h}}{3}\right)^{-14}$$

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$$M_{\circledPhi} \sim (3.9\times 10^{26}\,{\rm GeV}) \left(\frac{\omega_c\, Y_\Phi}{5\times 10^{-10}\,{\rm GeV}}\right)\left(\frac{134\,{\rm GeV}}{T_c}\right)^3 \left(\frac{\lambda_{\phi h}}{3}\right)^{14}$$

$10^{26}\,\mathrm{GeV} \sim 100\,\mathrm{g}$

$$R_{\circledPhi} \approx (5.8\times 10^5\,{\rm GeV}^{-1}) \left(\frac{\lambda_\phi}{0.013}\right)^{1/12} \left(\frac{Y_\Phi}{10^{-11}}\right)^{1/3} \left(\frac{134\,{\rm GeV}}{T_c}\right) \left(\frac{\lambda_{\phi h}}{3}\right)^{4.7}$$

$10^5\,\mathrm{GeV}^{-1} \sim \mathrm{\AA}$

Abundance of Free Dark Particles

- **During the chemical equilibrium, the ratio of dark matter energy density in the low-temperature phase over the high-temperature phase has**

$$r \equiv \frac{n_\Phi^{(\mathrm{l})}}{n_\Phi^{(\mathrm{h})}} \approx 6 \left(\frac{m_\phi(T)}{2\pi T}\right)^{3/2} e^{-m_\phi(T)/T}$$

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- **The freeze-out temperature is controlled by the process**

$$Ⓕ_Q + \Phi \to Ⓕ_{Q+1} + X$$

$$\Gamma_{Q+\Phi\to Q+1} = \langle \sigma v\rangle\, n_Ⓕ \simeq 4\,\pi\, R_Ⓕ^2(T)\,\frac{Y_\Phi\, s}{Q} = 4\,\pi\, R_Ⓕ^2(T)\,\frac{Y_\Phi}{Q}\,\frac{2\pi^2}{45}\, g_{*s}\, T^3$$

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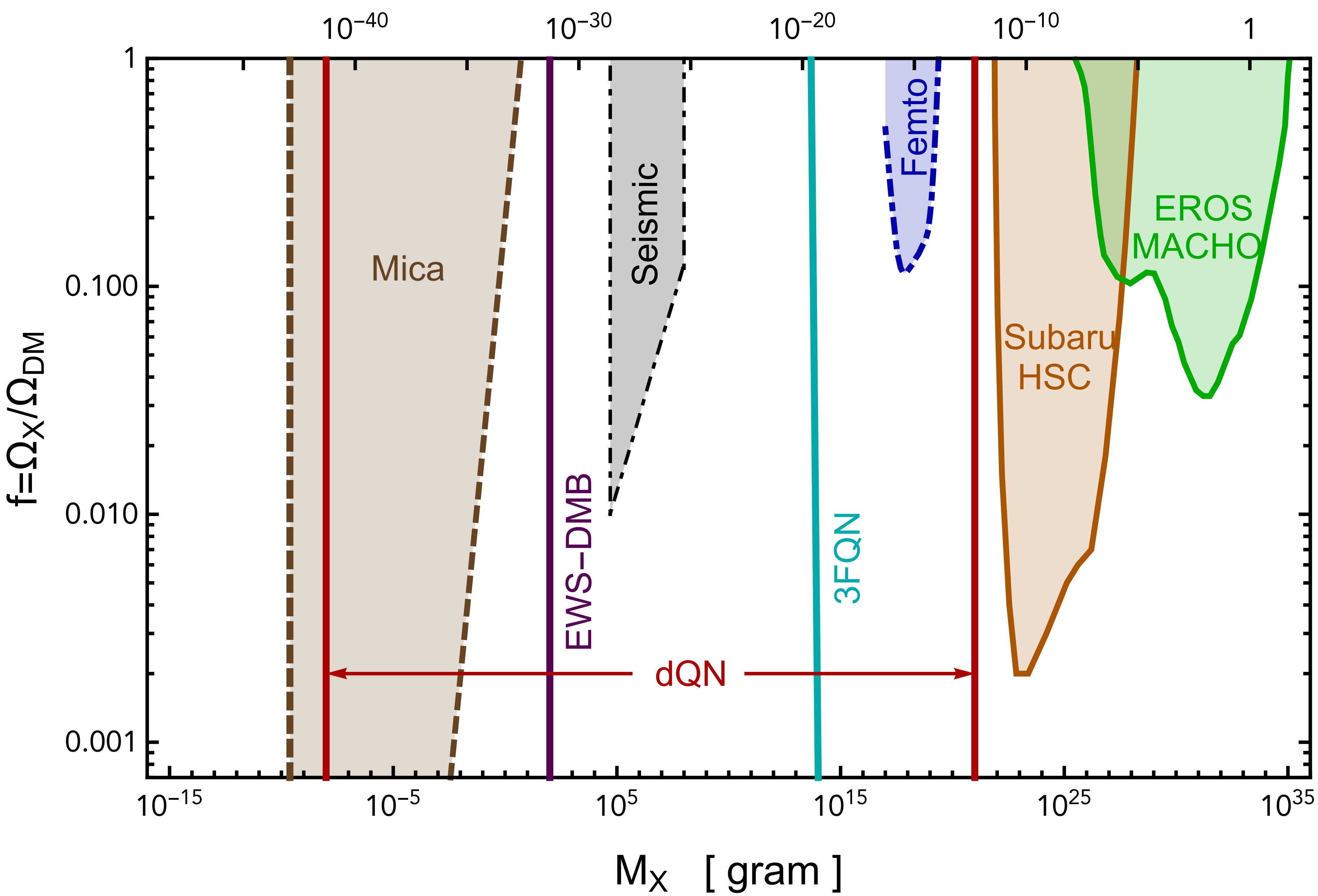
- **The freeze-out temperature is low and below ~ 1 GeV**

- **So, the dark matter fraction in the free particle state is dramatically suppressed and negligible**

Outline

- **Macroscopic dark matter models**
  - **Quark nuggets with** $\rho^{1/4} \sim \Lambda_{\rm QCD}$
  - **Dark quark nuggets with** $\rho^{1/4} \sim \Lambda_{\rm dQCD}$
  - **Electroweak symmetric dark matter ball with** $\rho^{1/4} \sim v_{\rm EW}$
  - **Others: QCD Axion star, PBH, dark monopole …**
- **Detections**
  - **Lensing**
  - **Gravitational waves**
  - **Direct Detection**
  - **Other methods**

Lensing



- **New ideas are needed to probe the gravitational interaction of macroscopic dark matter**

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Stochastic GW

- **A first-order cosmological phase transition can generate a stochastic background of gravitational waves (GW)**

$$\Omega_{\rm gw}h^2 \approx \Omega_\phi h^2 + \Omega_{\rm sw}h^2 + \Omega_{\rm turb}h^2$$

bubble collision sound wave turbulence

Hindmarsh, Huber, et. al., 1504.03291

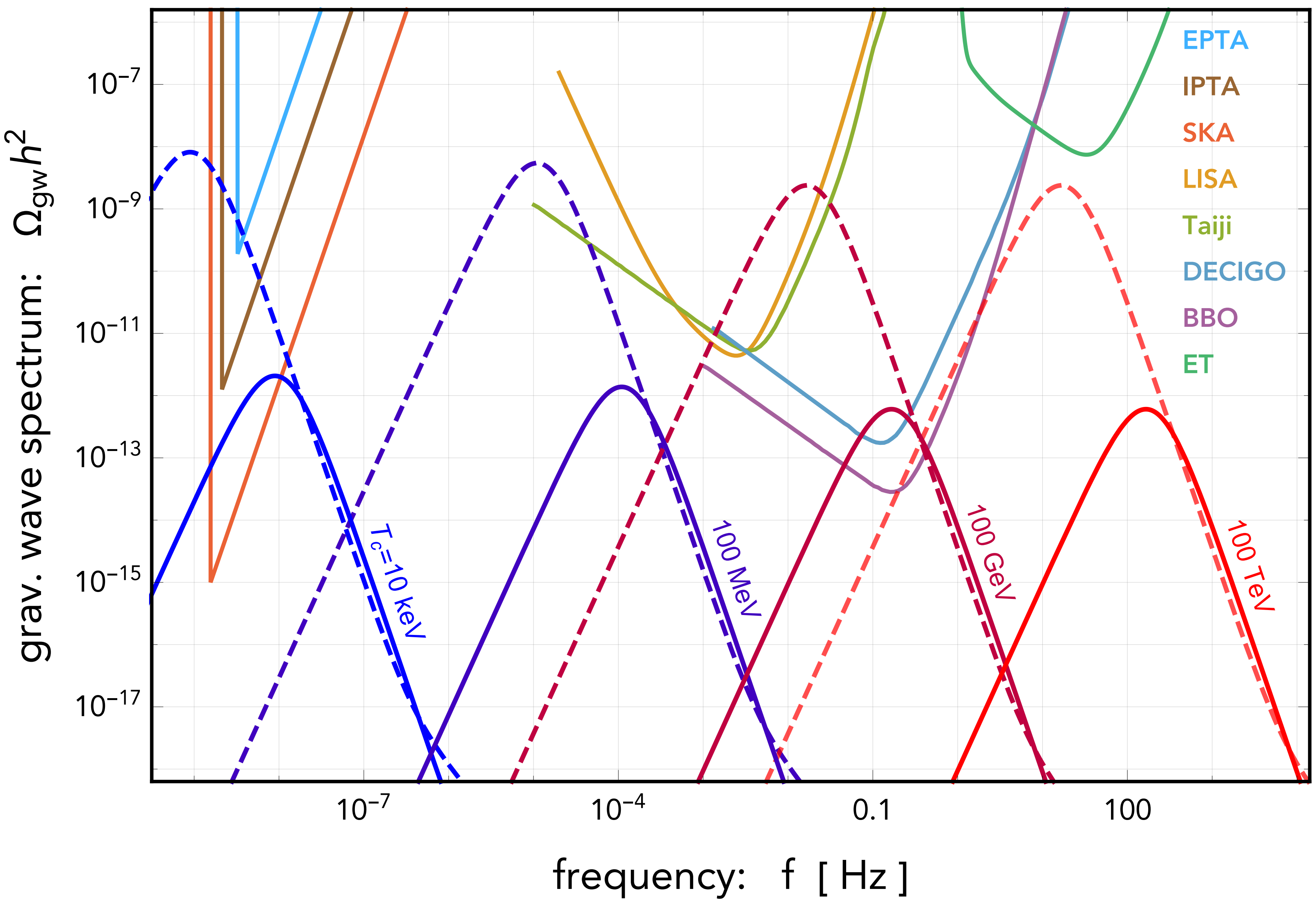
- **For the leading sound-wave contribution**

$$\Omega_{\rm sw}h^2 = (8.5\times 10^{-6})\left(\frac{g_*}{100}\right)^{-1/3}\Gamma^2\,\overline{U}_{\rm f}^4\left(\frac{\beta}{H}\right)^{-1} v_{\rm w}\left(\frac{f}{f_{\rm sw}}\right)^3\left(\frac{7}{4+3(f/f_{\rm sw})^2}\right)^{7/2}$$

$$f_{\rm sw} = (8.9\,\mu{\rm Hz})\,\frac{1}{v_w}\left(\frac{\beta}{H}\right)\left(\frac{z_{\rm p}}{10}\right)\left(\frac{T_{\gamma,c}}{100\ {\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

$$\overline{U}_{\rm f} \approx \sqrt{(3/4)\,\kappa_{\rm f}\,\alpha} \qquad\qquad \kappa_{\rm f} = \frac{\alpha^{2/5}}{0.017+(0.997+\alpha)^{2/5}}$$

Stochastic GW



$$(\alpha,\ \beta/H) = (0.1,\ 10^4)\ \text{(solid) and } (1,\ 10^3)\ \text{(dashed)}$$

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Direct Detection

- **The masses of dark matter balls are heavy, above the Planck mass. So, its flux is small. One needs a large volume detector to search for it.**

$$1 \sim \frac{\rho_{\rm DM}}{m_{\rm DM}}\, v\, A_{\rm det}\, t_{\rm exp} \sim \frac{10^{21}\,\mathrm{GeV}}{m_{\rm DM}}\, \frac{A_{\rm det}}{5\times 10^5\,\mathrm{cm}^2}\, \frac{t_{\rm exp}}{10\,\mathrm{yr}}$$

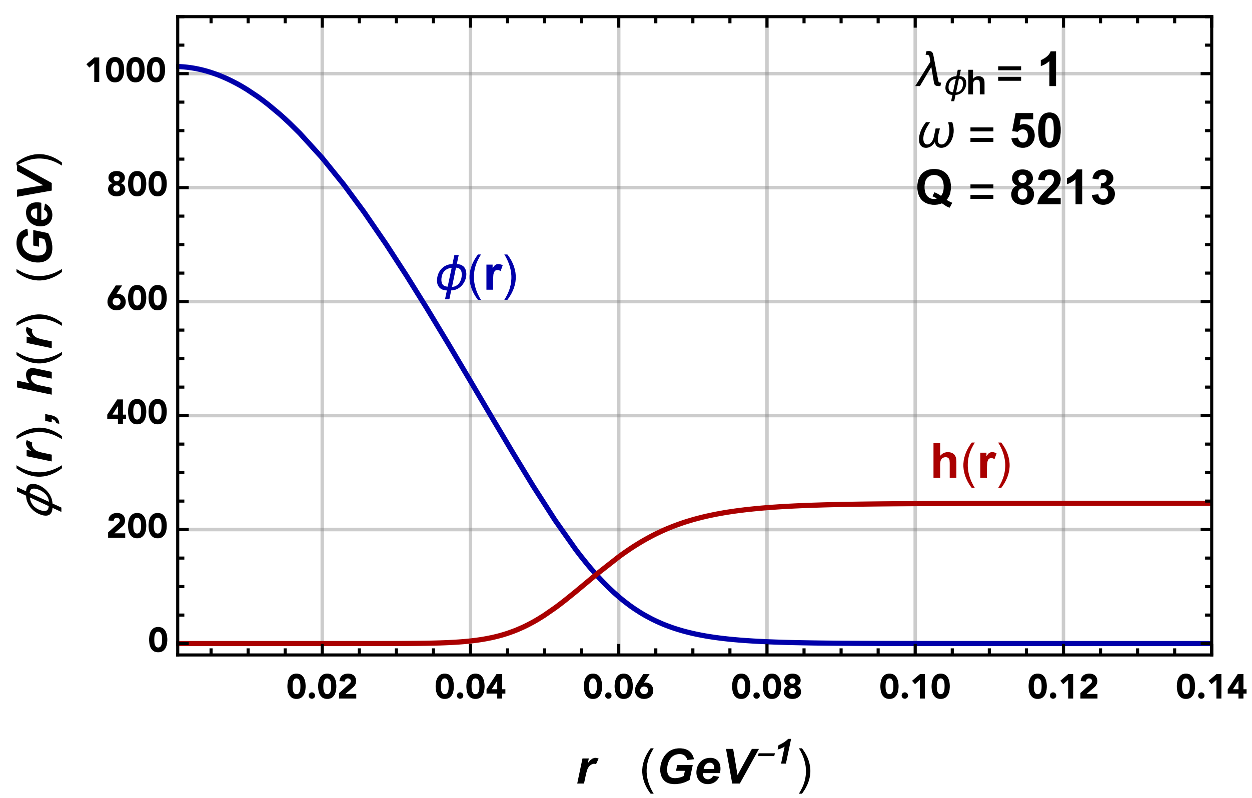
- **Because the cross section is large, it may have multiple scattering with the material in a detector**

$$\Gamma = n_{\rm A}\, \sigma_{\rm DM-ball}\, \bar{v}_{\rm rel}$$

$$E_{\rm sum} \sim \Gamma \times t_{\rm select} \times \langle E_R \rangle \times \kappa \sim N_{\rm scattering} \times 10\,\mathrm{keV} \times \kappa$$

Direct Detection of EWS-DMB

- **The energy density of electroweak symmetric dark matter ball has $\rho \sim (100\,\text{GeV})^4$, and very dense**



- **When SM particle (nucleon) scattering off the DMB, it will feel a different mass from the zero Higgs VEV inside DMB**

$$\mathscr{L} \supset -\, m_N\, \bar{N}N - y_{hNN}(h - v)\,\bar{N}N \qquad\qquad y_{hNN} \approx 0.0011$$

Scattering off a Square Well

- **This becomes a QM homework problem.**
- **For a small R, one could just use the Born-approximation**
- **For a large R, bound states exist**

$$-\cot\left(\sqrt{E^2 - m_N^2 + y_{hNN}^2 v^2}\, R\right) = \sqrt{\frac{m_N^2 - E^2}{E^2 - m_N^2 + y_{hNN}^2 v^2}}$$

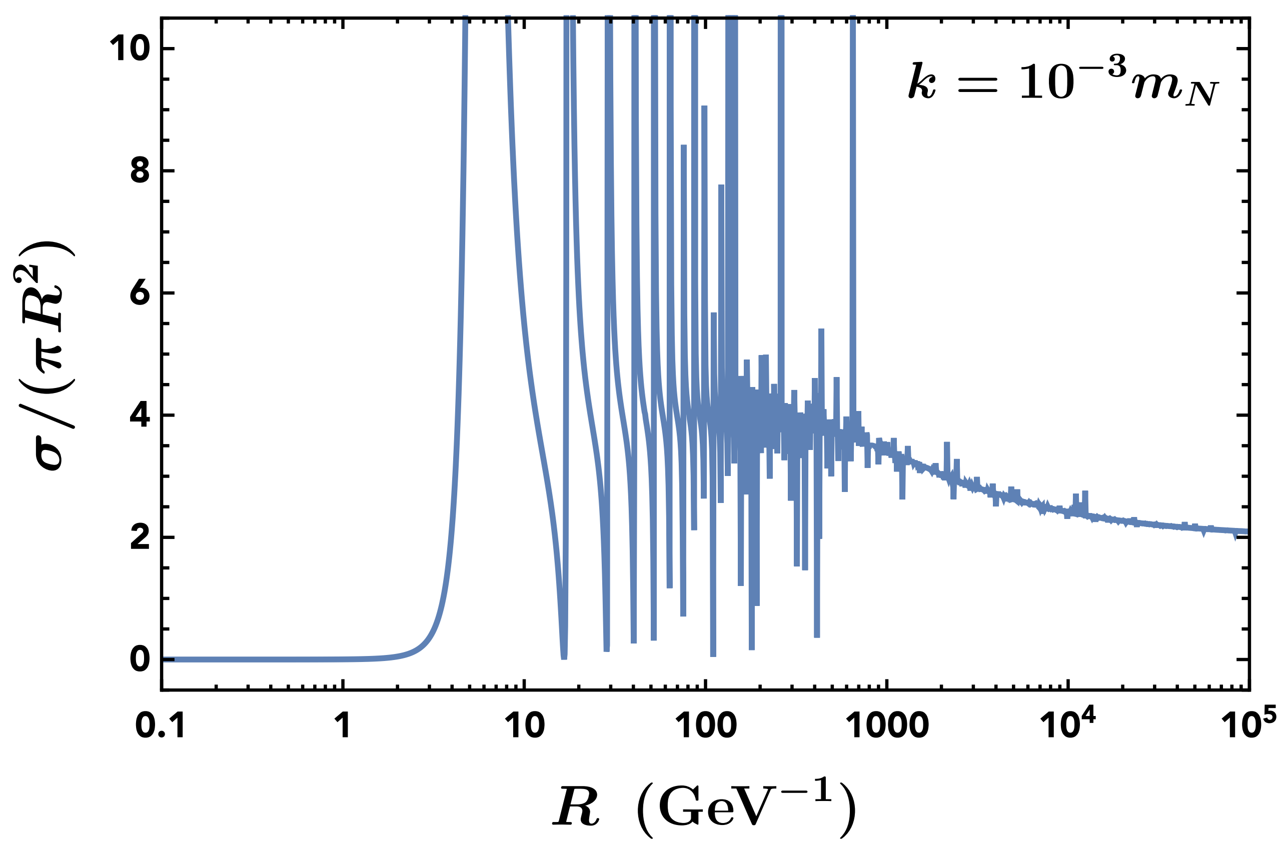
- **The threshold radius for an s-wave bound state is**

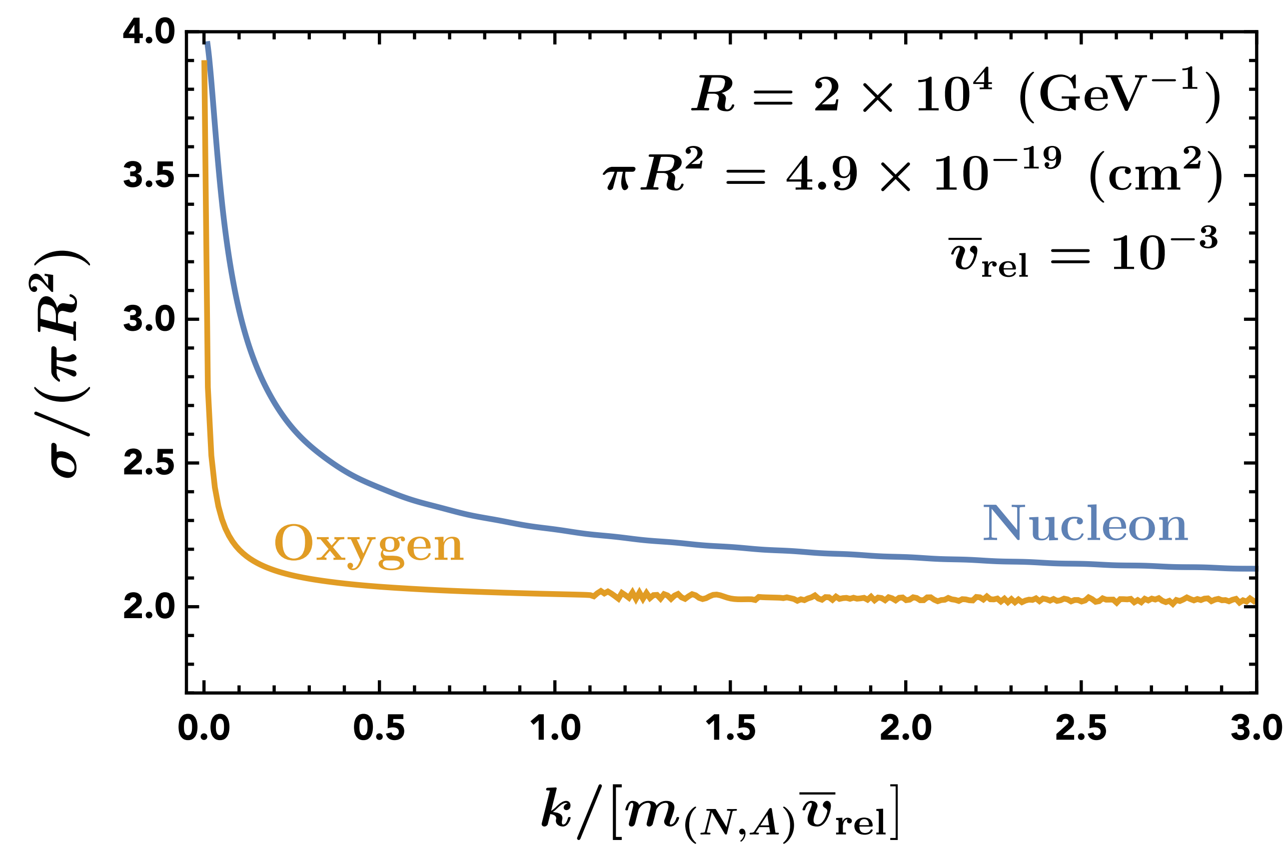
$$R_{\text{th}} = \frac{\pi}{2\, y_{hNN}\, v} = 5.8\,\text{GeV}^{-1}$$

- **One can perform a partial-wave expansion and sum them together to obtain the total scattering cross section**

$$\sigma = \frac{4\pi}{k^2} \sum_l (2l+1)\sin^2\delta_l$$

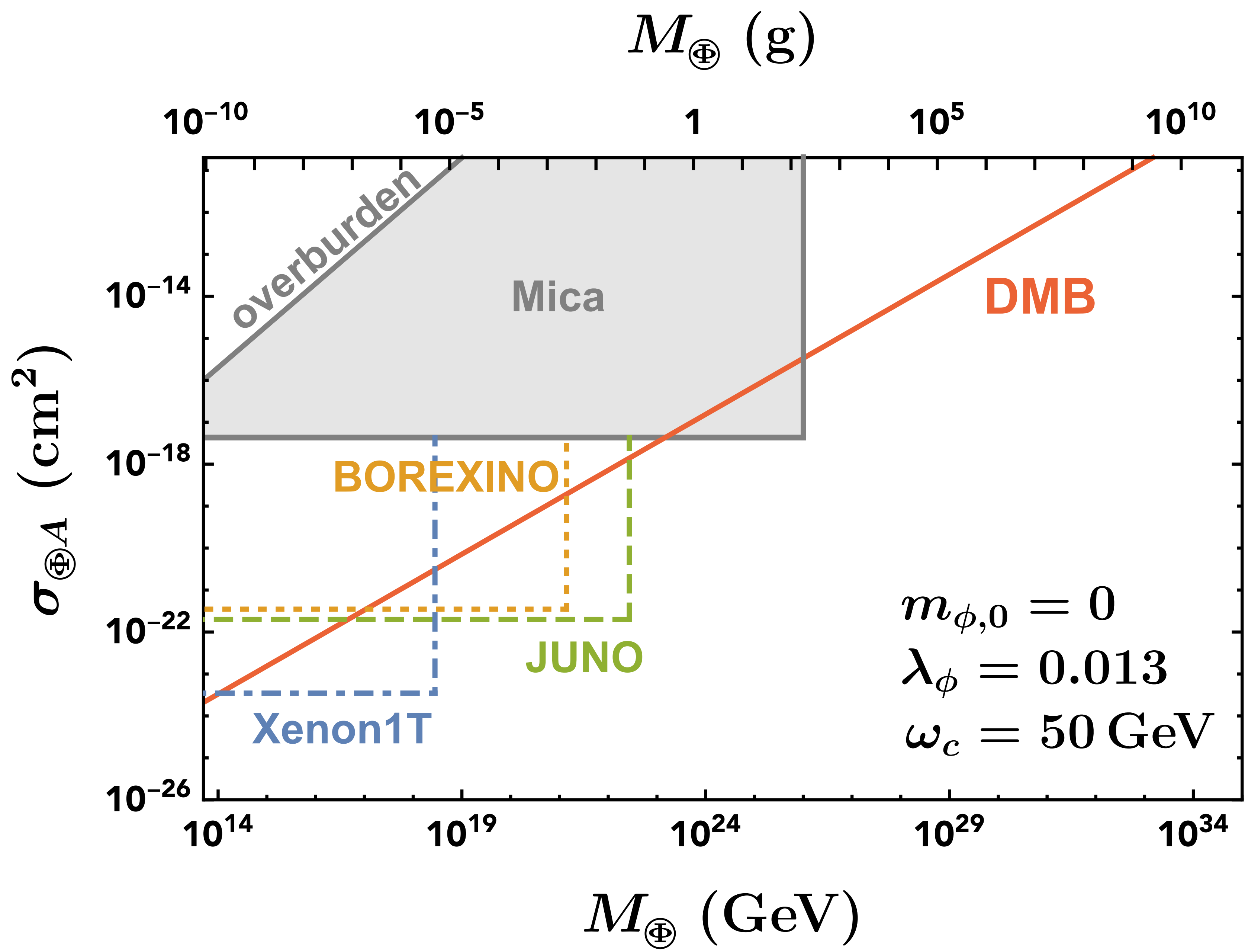
Scattering Cross Sections



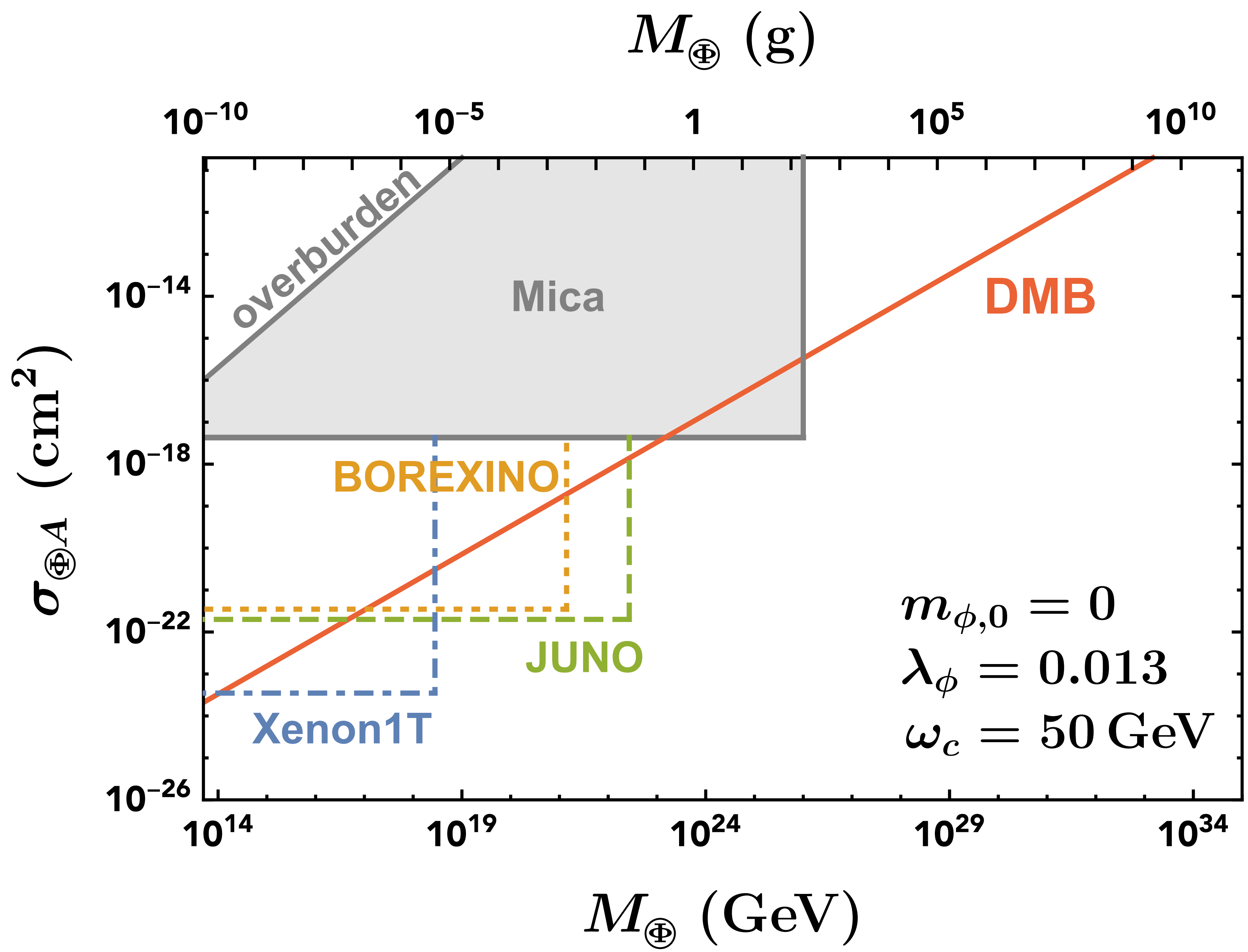


- **The cross sections change from a hard sphere** $4\pi R^2$ **to** $2\pi R^2$
- **They are insensitive to the target nucleon or nucleus masses**

Direct Detection



Direct Detection



- **Existing experiments constrain some parameter space, but leave open space as targeted searches**

Other detection and effects

- With Joshua Berger (Univ. of Pittsburgh), we are working on their potential detections at Super-K and DUNE with radiative capture

$$ {}^{A}_{Z}\mathrm{N} + \Phi \to \mathcal{B} + \gamma $$

- The photon in the final state can have energy above MeV and be detected in a large-size neutrino detector

- Detailed cross section calculations to be done, because the dipole approximation does not apply for this case

Conclusions

- Macroscopic dark matter appears in several simple models
- Non-trivial phase transitions in the early universe generate dark matter in a state different from zero-temperature vacua
- For dark QCD, the dark quark nugget is in the dark QCD unconfining phase and has a wide range of masses
- For Higgs-portal dark matter, the non-topological soliton dark matter is in the electroweak symmetric phase
- An experiment with a large volume and a long-exposure time would be ideal to search for dark matter balls with multi-scattering events

Thanks!