Macroscopic Dark Matter: models and detections

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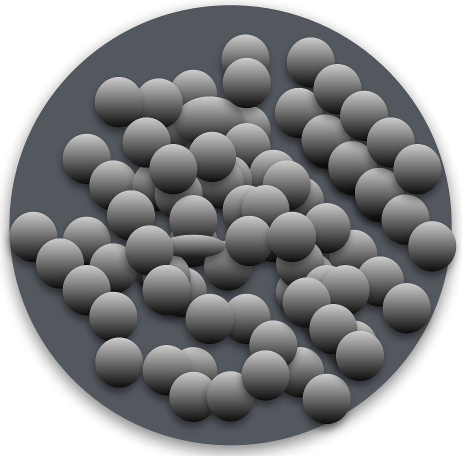
Macroscopic Ordinary Matter

- **For ordinary matter, there are so many different types**

Macroscopic Dark Matter (MDM)

- 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 different from ordinary WIMP searches

Macroscopic Dark Matter

- **Some recent interests (incomplete):**
  - **“Big Bang Darkleosynthesis”, Krnjaic and Sigurdson, 1406.1171**
  - **“Dark Nuclei”, Detmold, McCullough and Pochinsky, 1406.2276**
  - **“Yukawa Bound States of a Large Number of Fermions”, Wise and Zhang, 1407.4121**
  - **“Big Bang Synthesis of Nuclear Dark Matter”, Hardy et. al, 1411.3739**
  - **“Macro Dark Matter”, Jacob, Starkman and Lynn, 1410.2236**
  - **“Early Universe synthesis of asymmetric dark matter nuggets”, Gresham, Lou and Zurek, 1707.02316**
  - **“Detecting Dark Blobs”, Grabowska, Melia and Rajendran, 1807.03788**
  - **“Signatures of Mirror Stars”, Curtin and Setford, 1909.04072**
  - **“N-MACHOs”, Dvali, Koutsangelas and Kuhnel, 1911.13281**
  - **“Gravitational microlensing by dark matter in extended structures”, Croon, McKeen and Raj, 2002.08962**

……

Formations

- **Non-thermal production**
  - **parametric resonance: see Nicholas Orlofsky's talk for dark magnetic monopole, 2005.00503**
  - **misalignment: QCD axion stars**
- **Thermal production: first-order phase transition**
  - **Quark nuggets, Dark quark nuggets (YB, Long, Lu, 1810.04360)**
  - **Non-topological soliton state**

  a later phase transition produces a bigger object
- **Late-time coagulation: grow the size of dark matter states**

Interactions with SM

- **Higgs-portal interaction:** simple and renormalizable
    - interesting interplay with electroweak symmetry breaking
- **Only gravitational interaction**
    - similar to primordial black hole (PBH), but with a larger geometric size
- Constituents of MDM charged under SM gauge groups (not covered in this talk)

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: $M_\Phi = \sqrt{\frac{\lambda_{\phi h}}{2}}\, v$

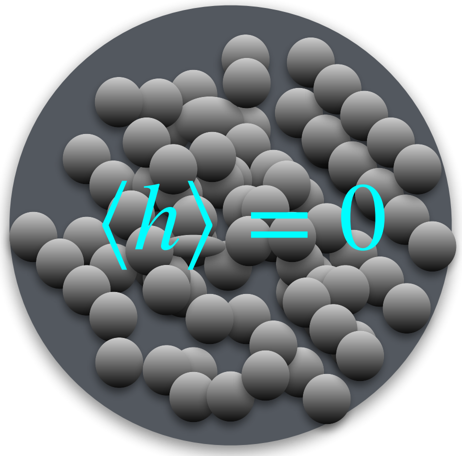
- **For dark matter as a particle state, there are severe experimental bounds from direct detection experiments**

- **There exists a macroscopic dark matter state for this simple model**

Non-topological soliton state or Q-ball

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.



$\langle h \rangle = v$

the vacuum pressure is balanced by the quantum or self-interaction-generated pressure

Equations of Motion

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

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

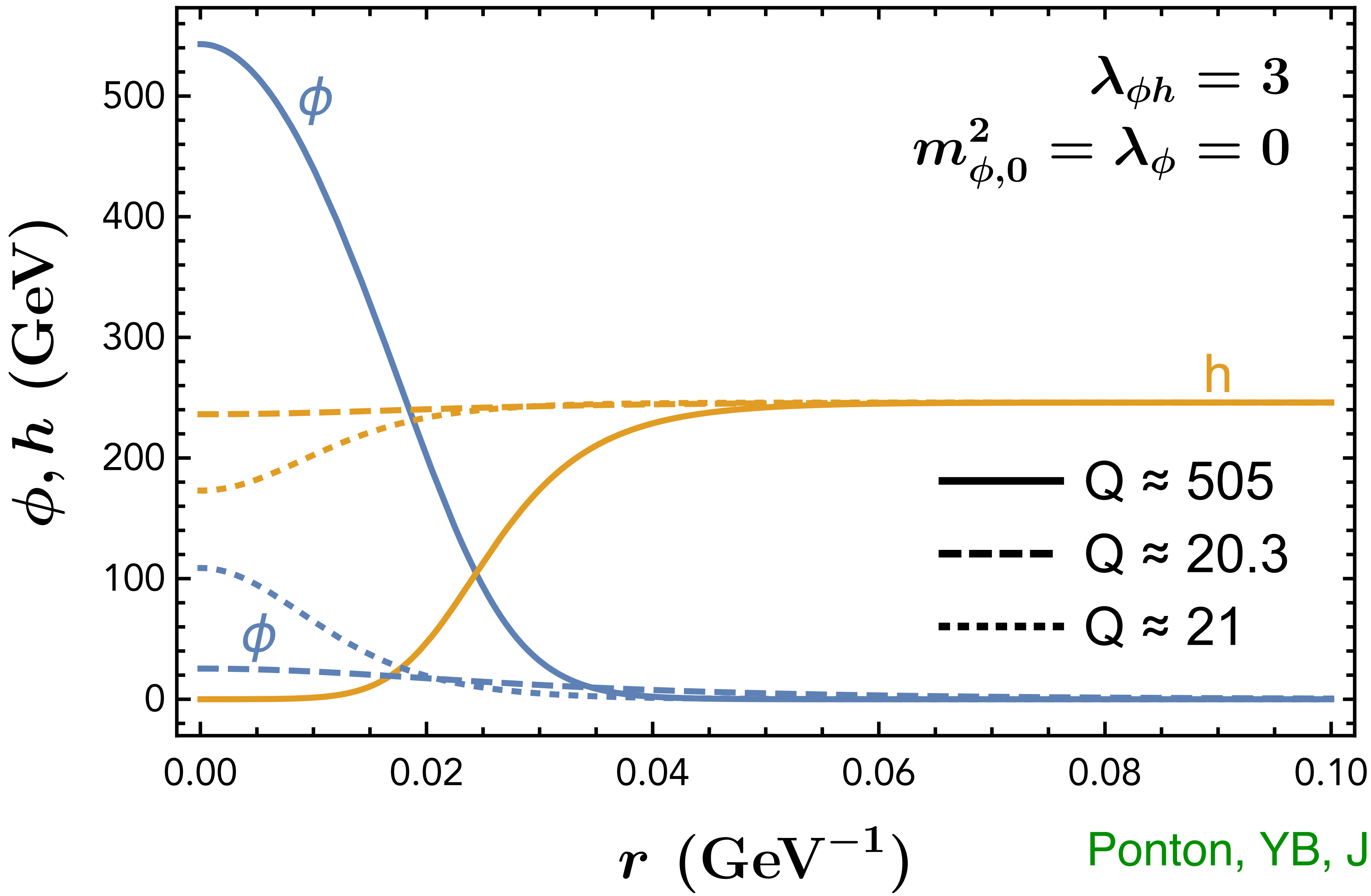
$$\phi''(r) + \frac{2}{r}\phi'(r) + \left[\omega^2 - \frac{1}{2}\lambda_{\phi h} h(r)^2\right] \phi(r) = 0\,,$$

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

- **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

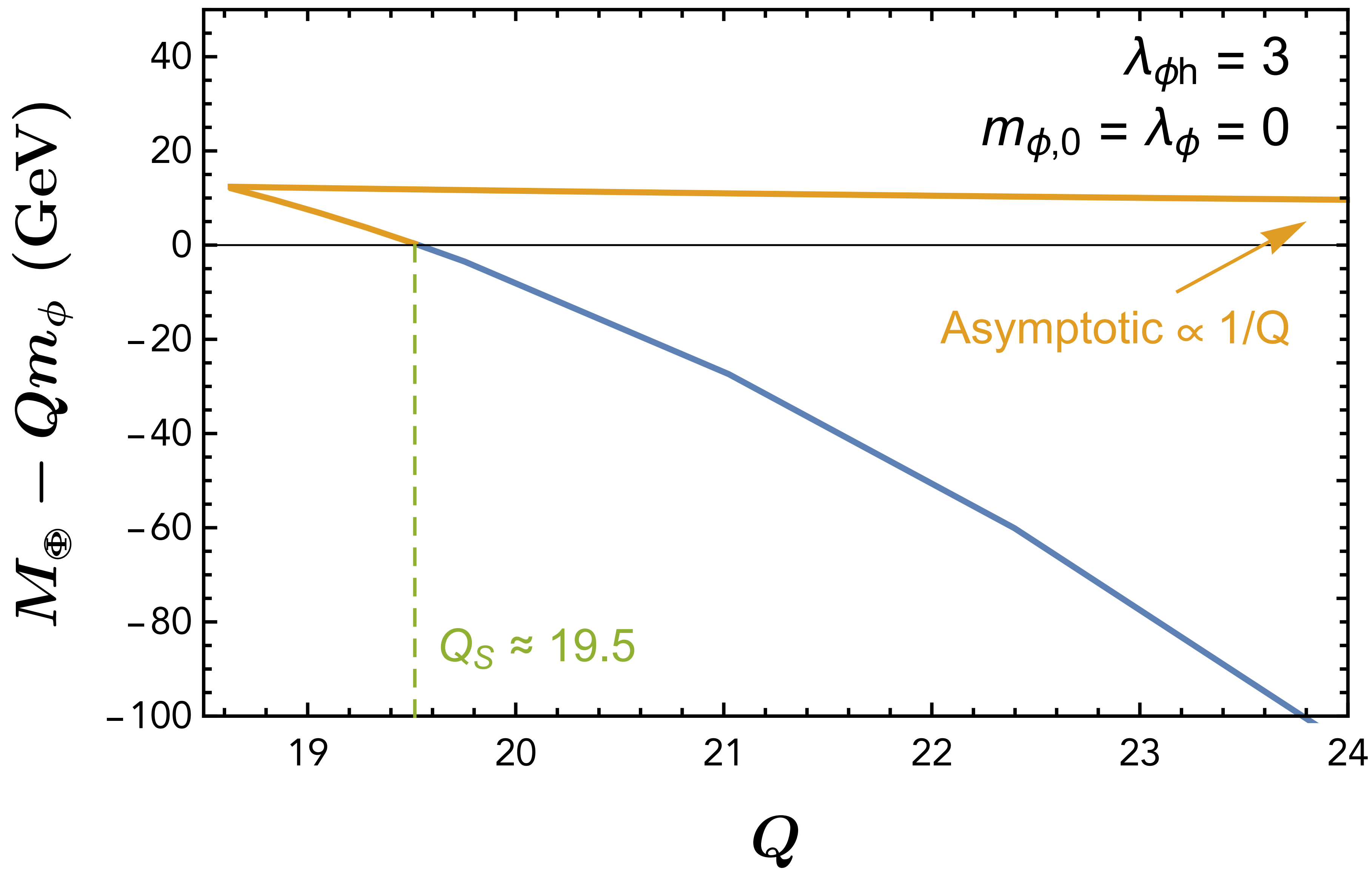
Example Solutions ($\lambda_\phi = 0$)



Ponton, YB, Jain, 1906.10739

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**

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

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**

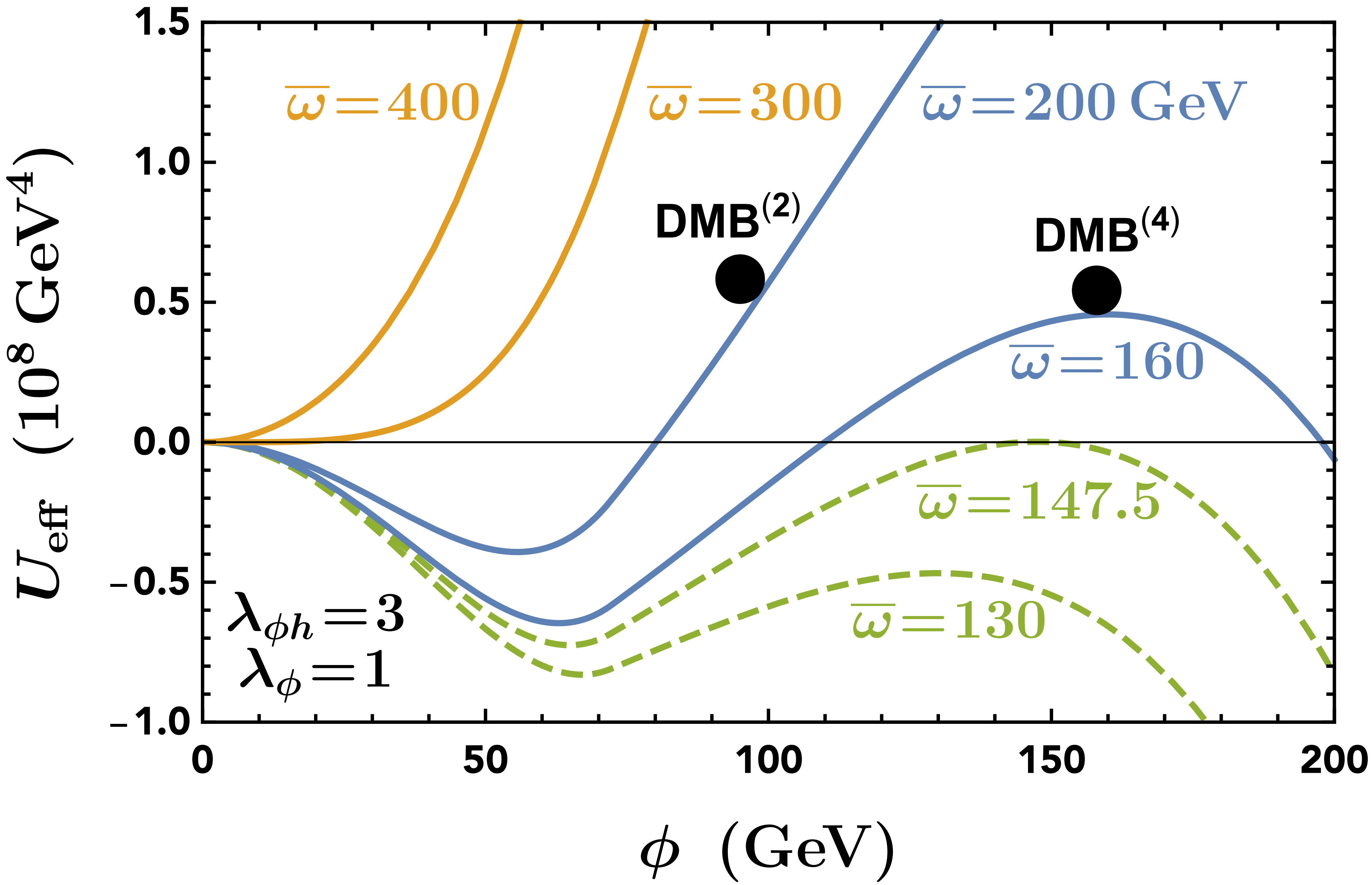
$$h^2 \approx \begin{cases} \frac{m_h^2}{2\lambda_h} - \frac{\lambda_{\phi h}}{2\lambda_h}\,\phi^2 & \text{for} \quad \lambda_{\phi h}\,\phi^2 < m_h^2 \,, \\ 0 & \text{for} \quad \lambda_{\phi h}\,\phi^2 > m_h^2 \,. \end{cases}$$

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

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

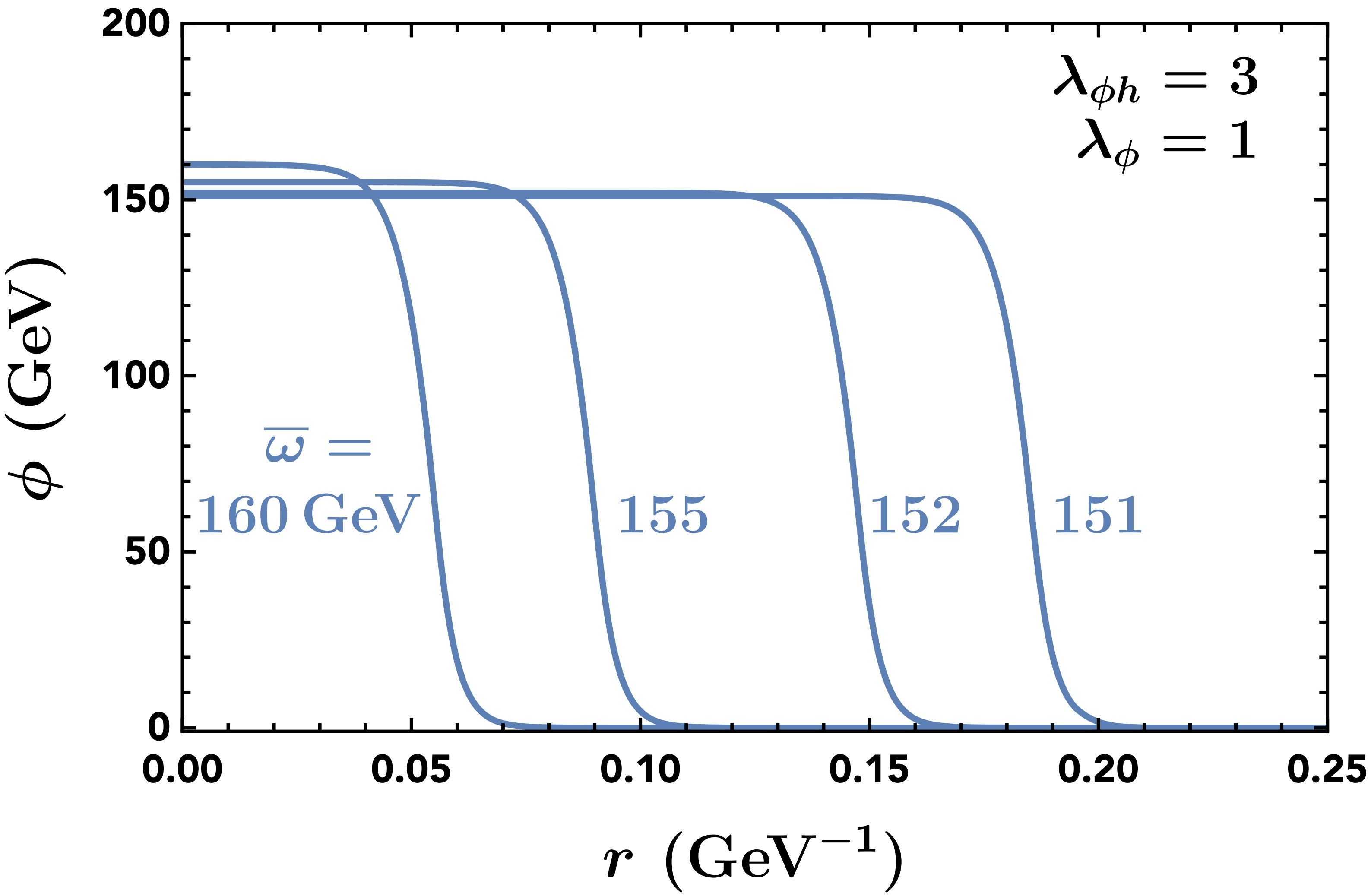
- **Via Coleman, we can use 1D particle description to understand it**

Add Φ Self-Interaction



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

Add Φ Self-Interaction



- **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)**

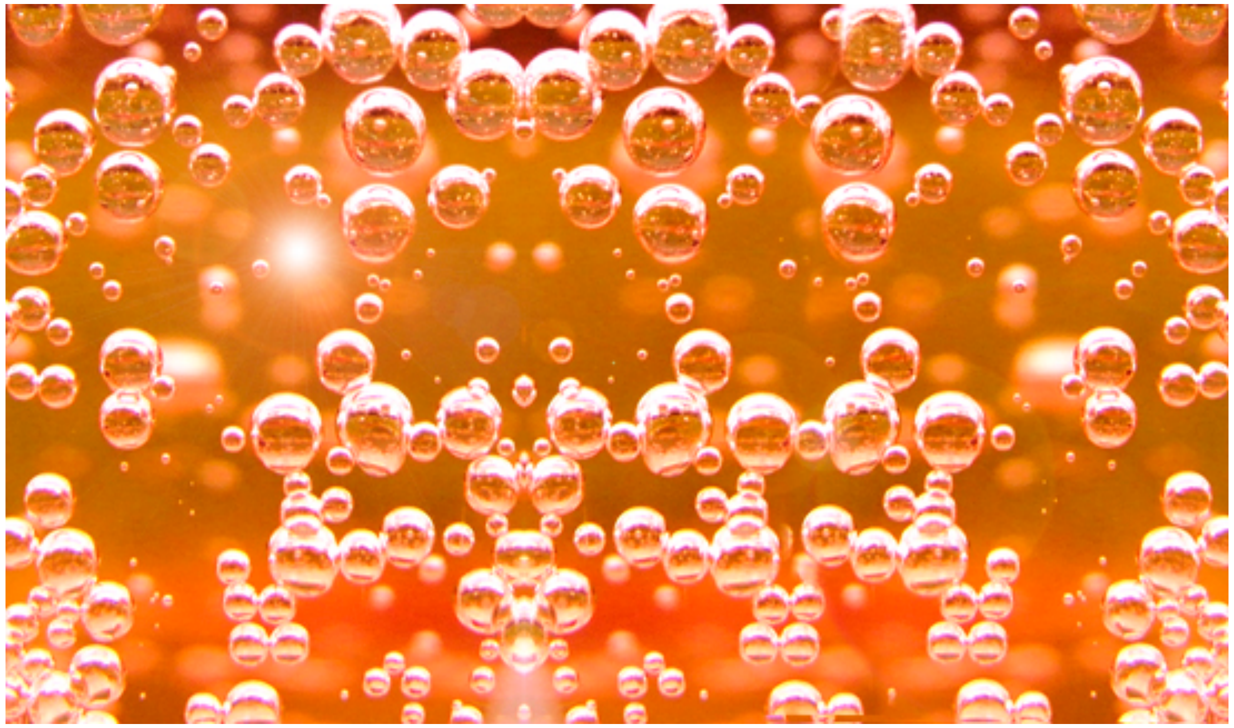
$$Q \sim R_\oplus^4 , \qquad M_\oplus \sim Q^{3/4} \sim R_\oplus^3$$

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

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

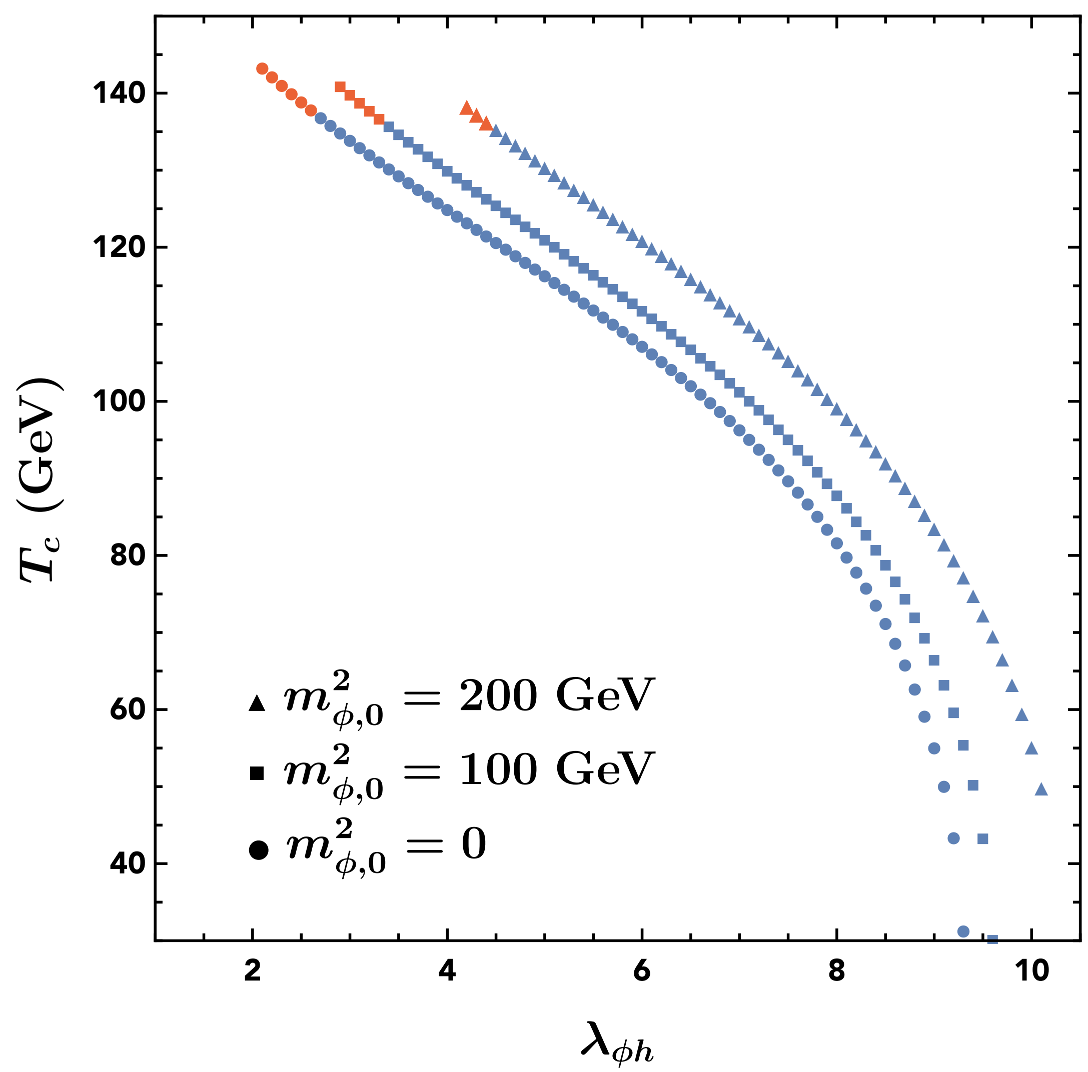
- **Both of them have $\rho^{1/4} \sim v_{\rm EW}$ and unbroken electroweak symmetry in the inner region**

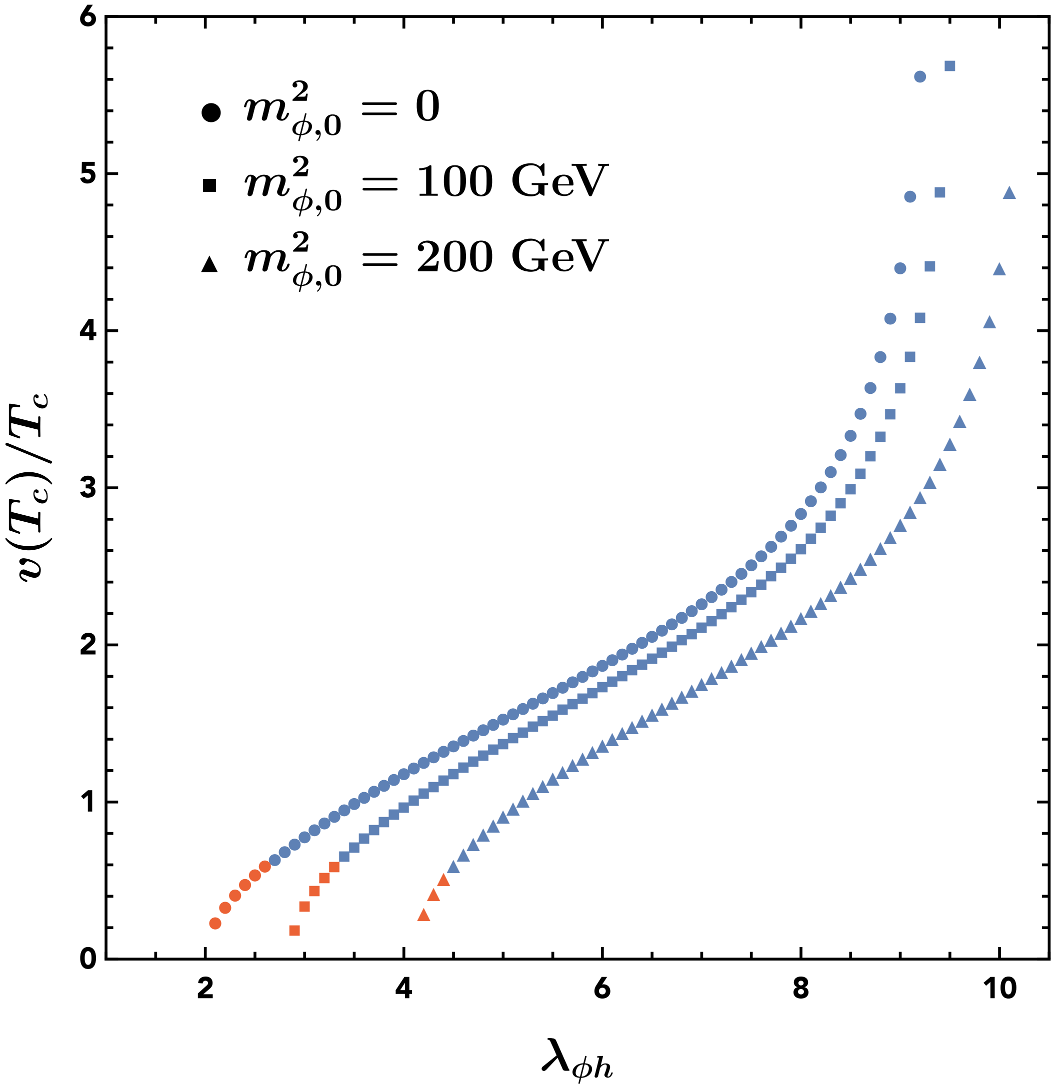
Formation from First-Order Phase Transition



Formation from 1’st Phase Transition

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





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

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

$$Q \sim (7.8\times 10^{24}) \left(\frac{Y_\Phi}{10^{-11}}\right)\left(\frac{134\,{\rm GeV}}{T_c}\right)^3 \left(\frac{\lambda_{\phi h}}{3}\right)^{14}$$

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

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

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

$10^5\,{\rm GeV}^{-1} \sim$ Å

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.**

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

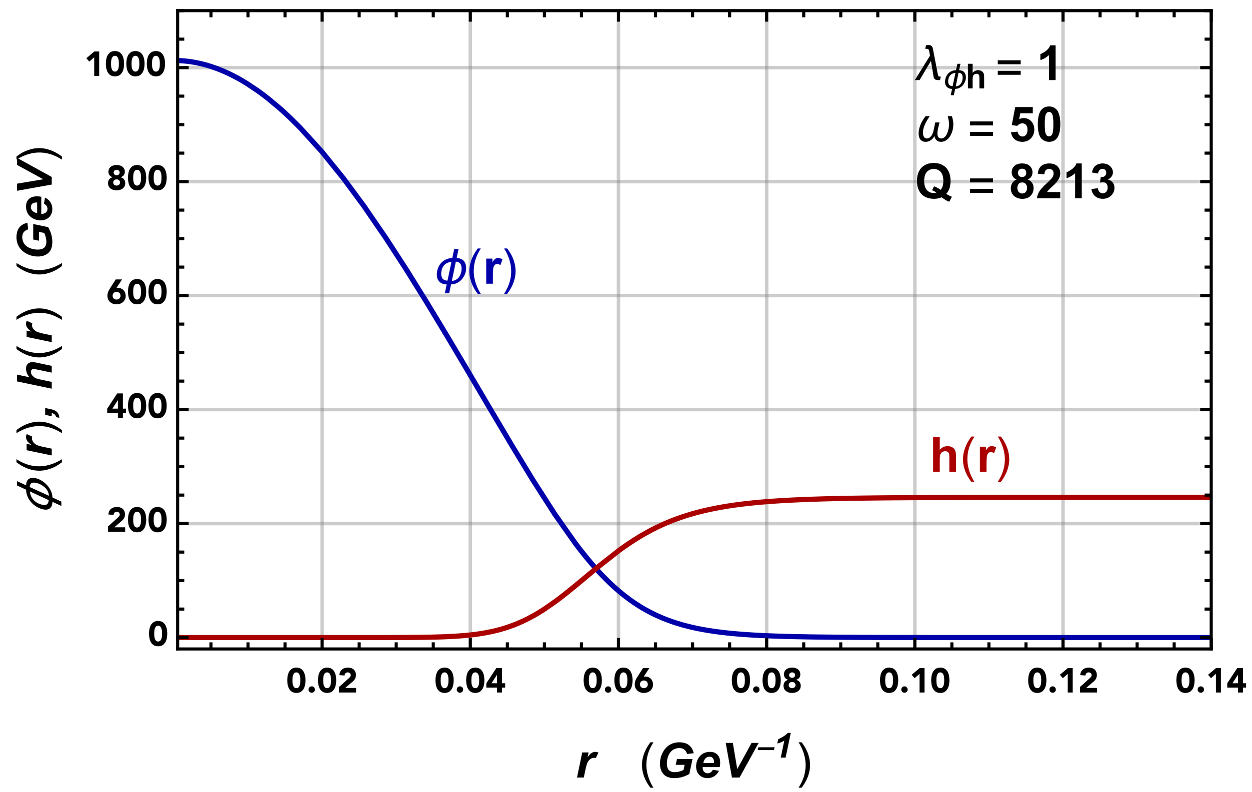
- **Because the cross section is large, it may have multiple scattering with the material in a detector**

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

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

Direct Detection of EWS-DMB

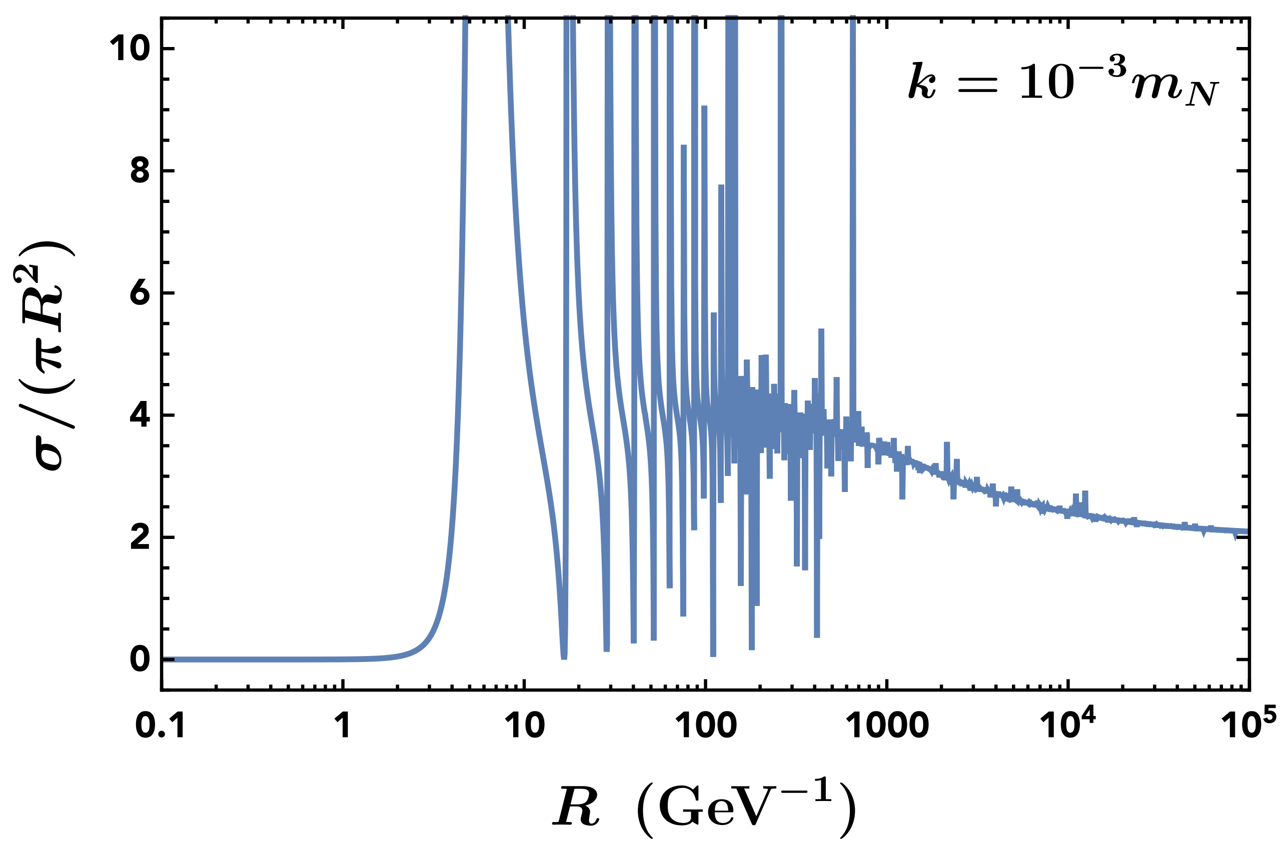
- **The energy density of electroweak symmetric dark matter ball has $\rho \sim (100\,\text{GeV})^4$, and very dense**

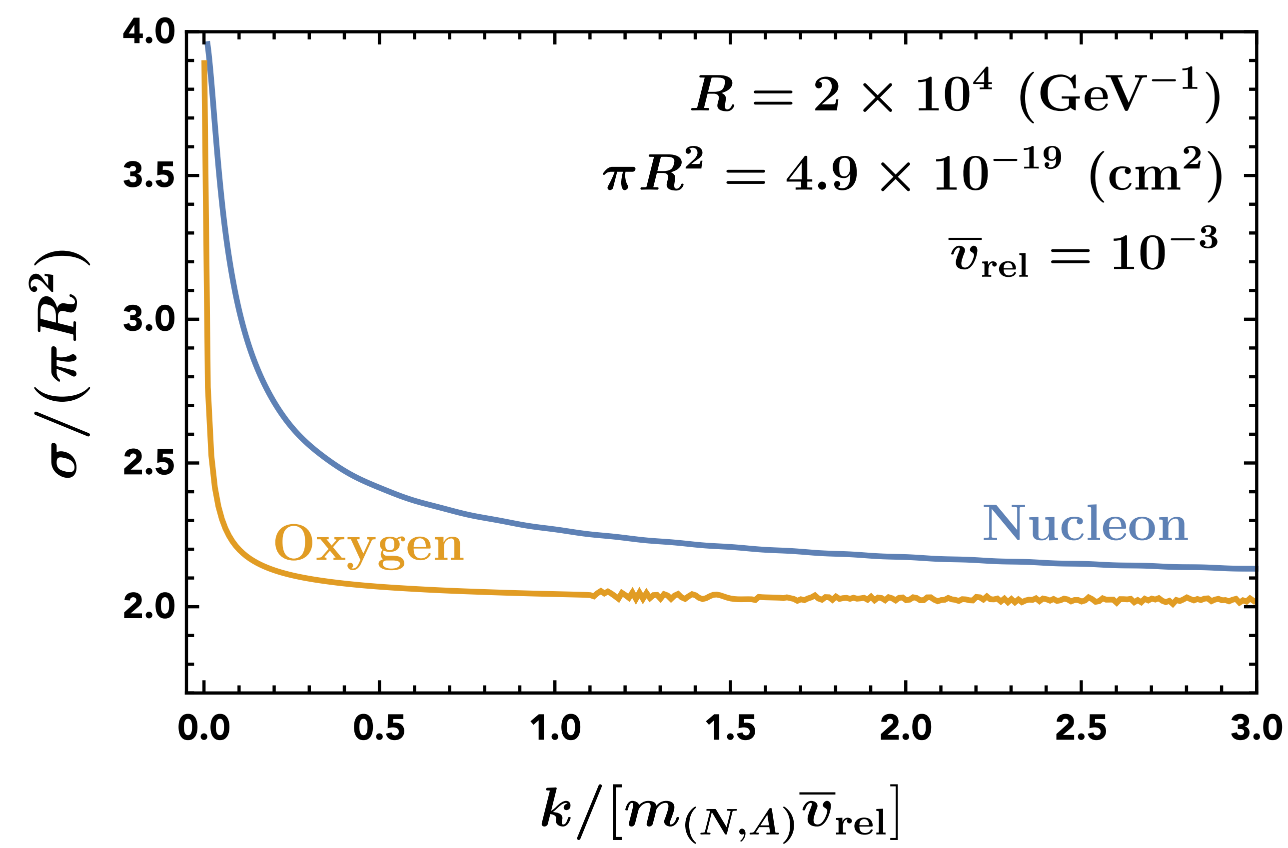


- **When SM particle (nucleon) scattering off the DMB, it will feel a different mass from the zero Higgs VEV inside DMB**

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

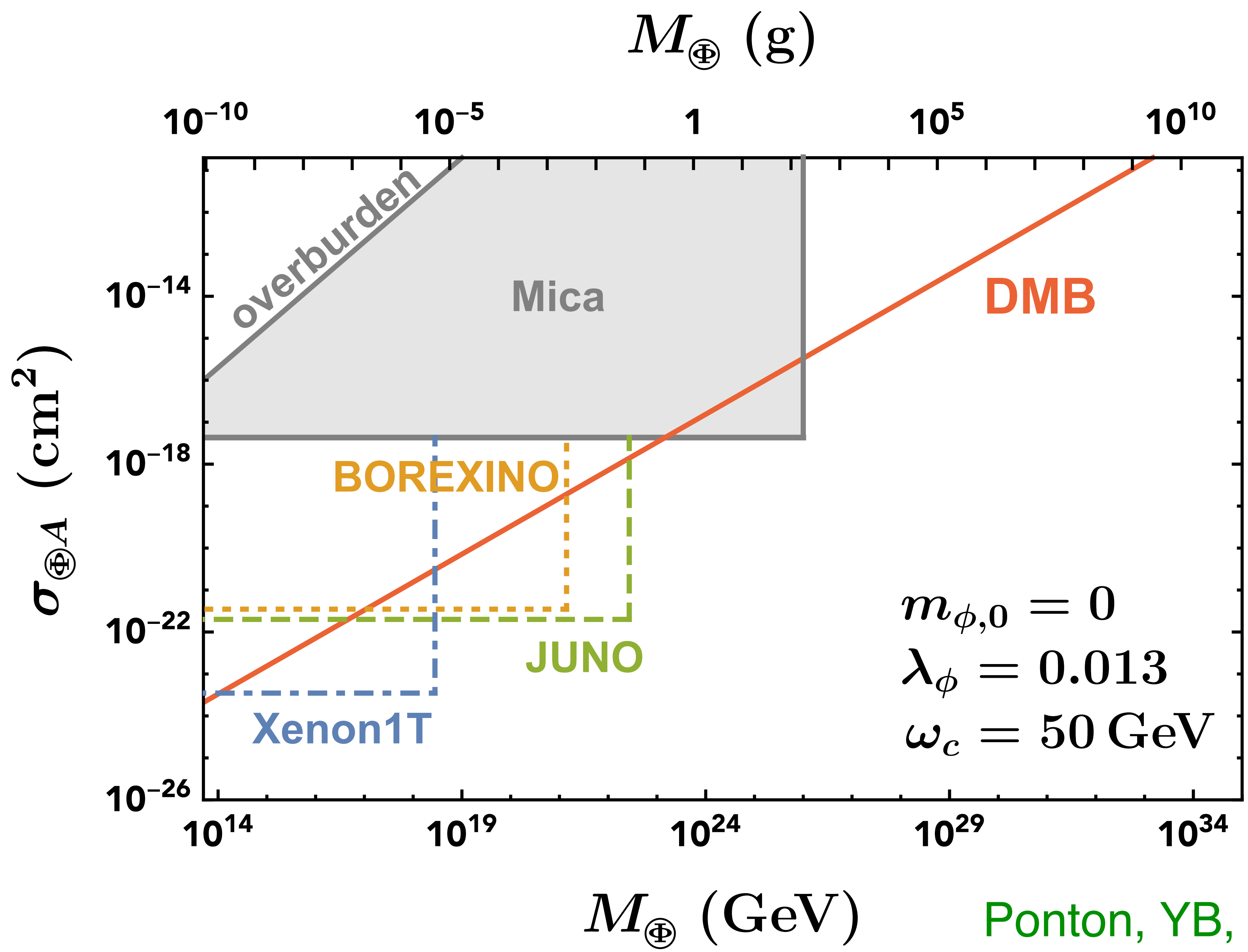
Scattering Cross Sections





- **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



Ponton, YB, Jain, 1906.10739

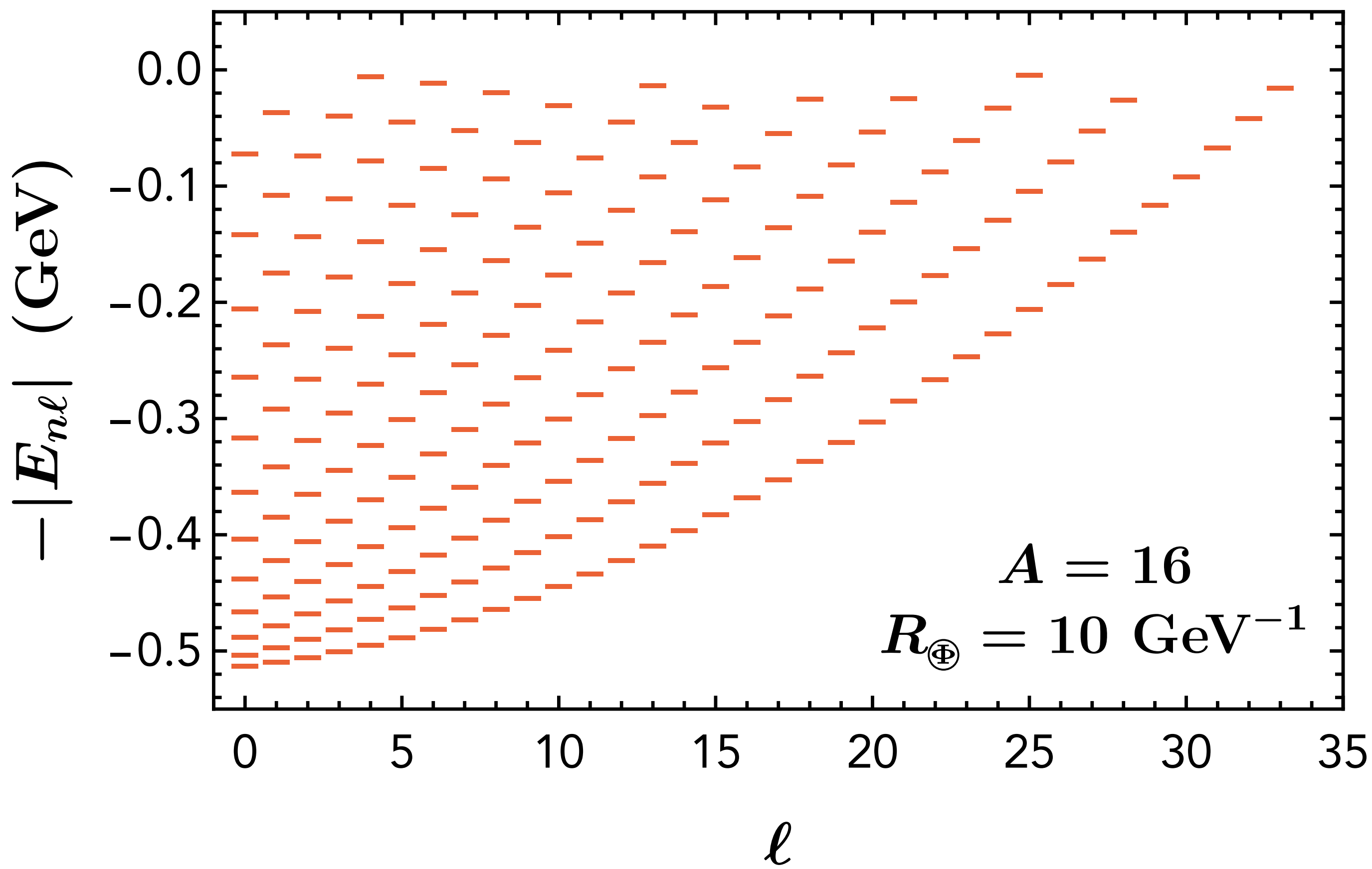
- **Experiments with an energy threshold lower than ~1 MeV have chance to detect elastic scattering of DMB**

see also Bramante, et.al., 1812.09325

Radiative Capture of Nucleus by Dark Matter

- **Just like hydrogen formation from electron and proton**

$$^{A}_{Z}\mathrm{N} + \textcircled{\Phi} \rightarrow \textcircled{\Phi_N} + \gamma$$



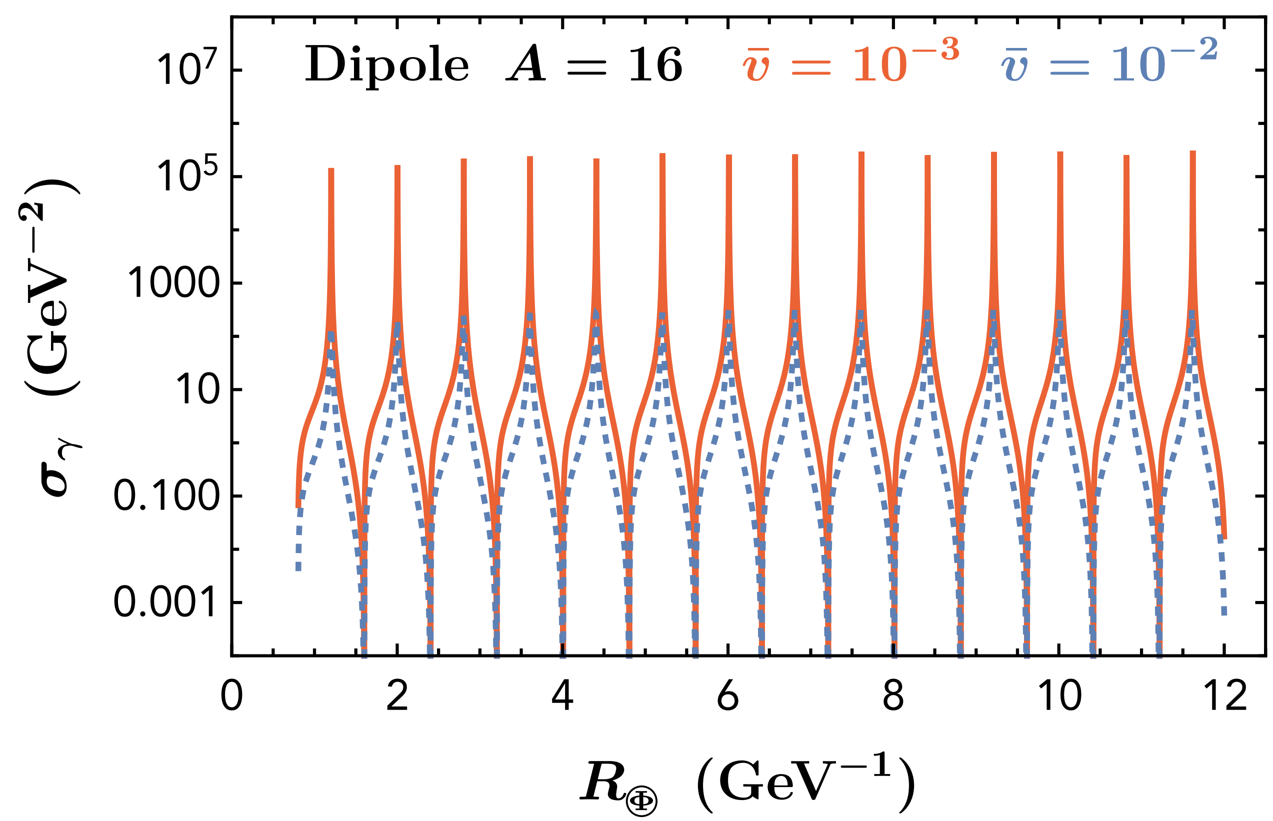
- **Except that one needs to go beyond the dipole approximation**

Radiative Capture Cross Section

$$\mathcal{M}_{n\ell m} = \frac{1}{2\,\mu}\, Z\, e\, \boldsymbol{\epsilon}^* \cdot \int d^3x\, e^{-i\,\mathbf{q}\cdot\mathbf{x}} \left[\nabla\psi^*_{n\ell m}(\mathbf{x})\,\psi_{\mathbf{k}}(\mathbf{x}) - \psi^*_{n\ell m}(\mathbf{x})\,\nabla\psi_{\mathbf{k}}(\mathbf{x})\right]$$

$$\sigma_{\gamma,n\ell} = \frac{1}{v}\int d\Omega\, \frac{|E_{n\ell}|}{8\,\pi^2} \sum_m |\mathcal{M}_{n\ell m}|^2$$

- **Dipole limit:** $qR_{\oplus} \ll 1$

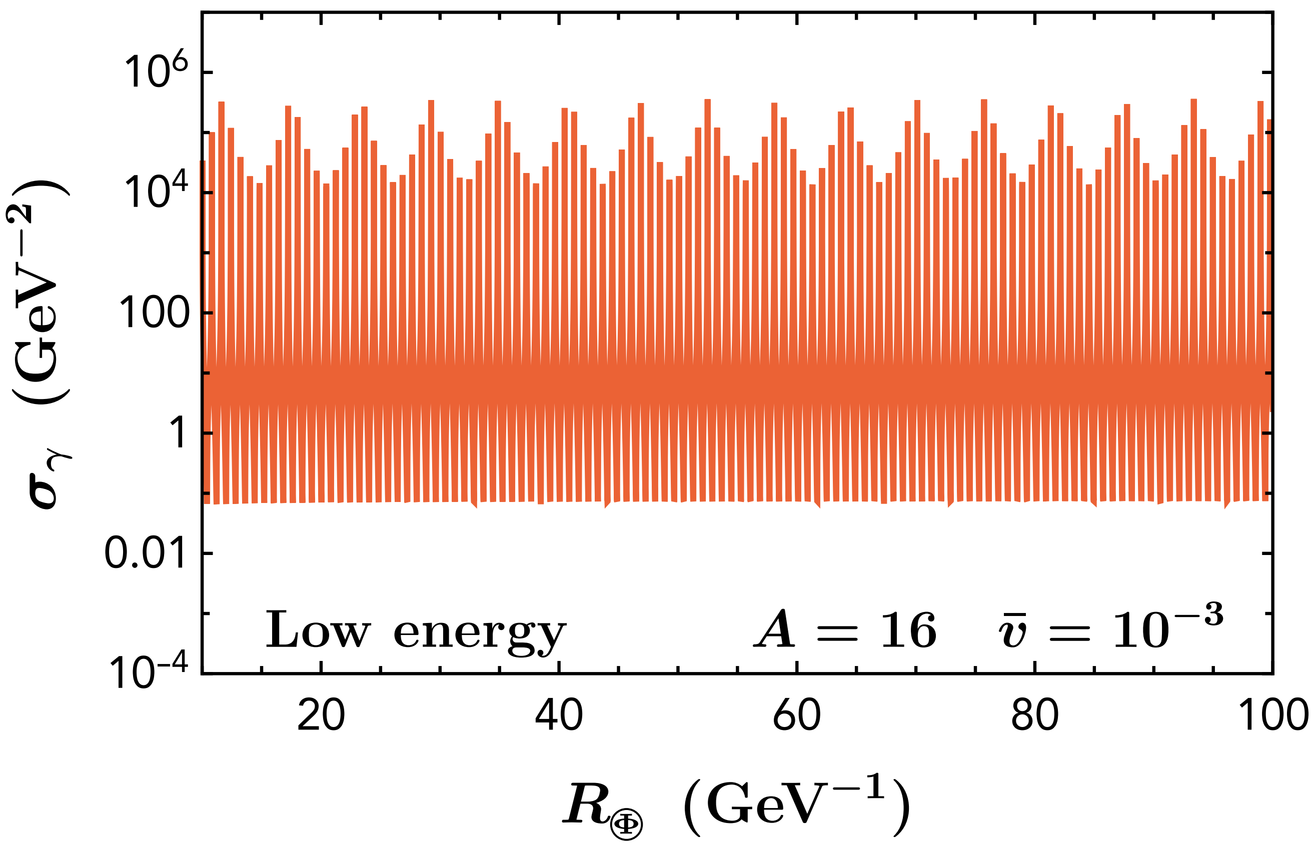


Radiative Capture Cross Section

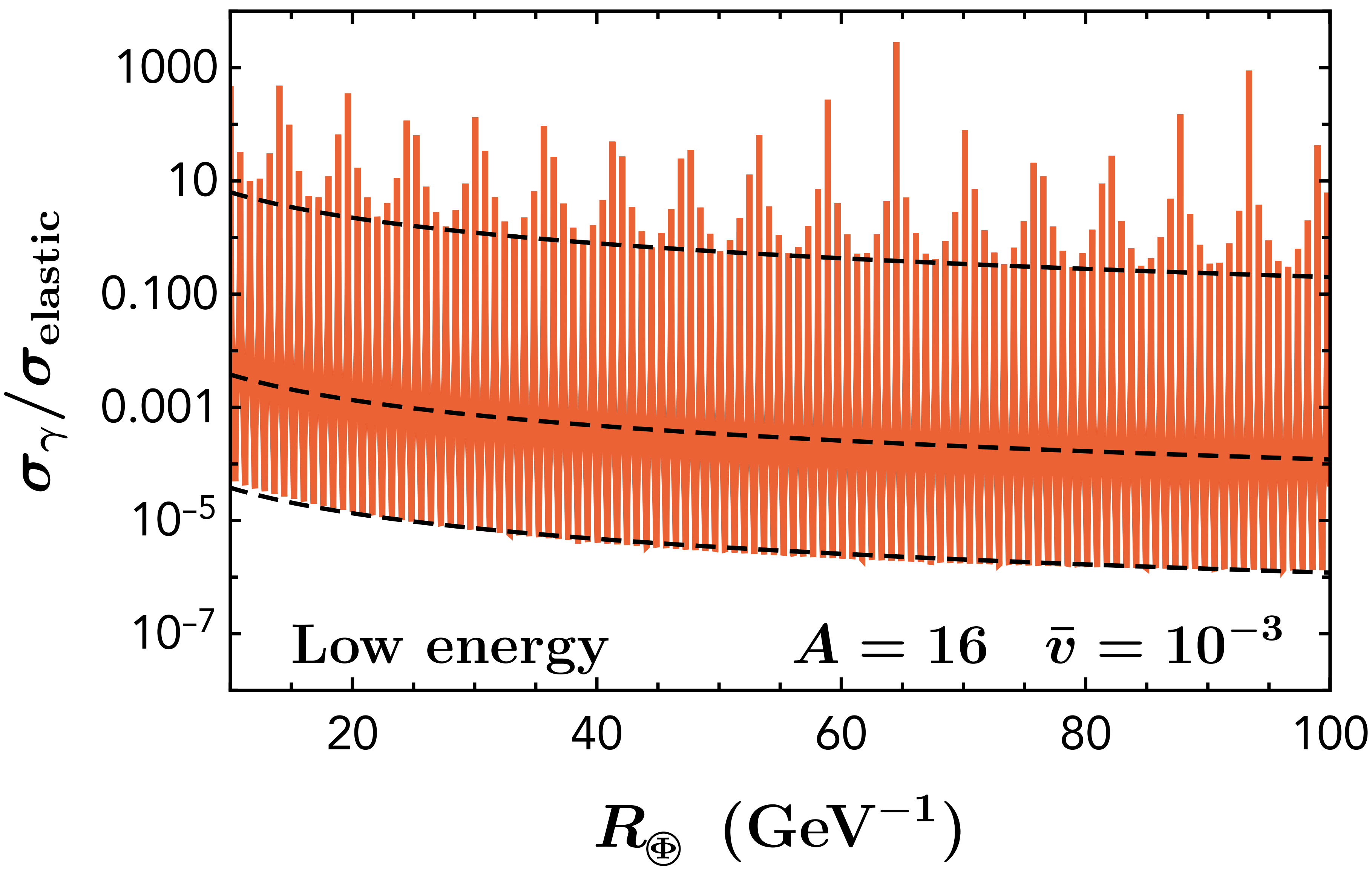
$$\mathcal{M}_{n\ell m} = \frac{1}{2\,\mu}\, Z\, e\, \boldsymbol{\epsilon}^* \cdot \int d^3x\, e^{-i\,\mathbf{q}\cdot\mathbf{x}} \left[\nabla\psi^*_{n\ell m}(\mathbf{x})\,\psi_{\mathbf{k}}(\mathbf{x}) - \psi^*_{n\ell m}(\mathbf{x})\,\nabla\psi_{\mathbf{k}}(\mathbf{x})\right]$$

$$\sigma_{\gamma,n\ell} = \frac{1}{v}\int d\Omega\, \frac{|E_{n\ell}|}{8\,\pi^2} \sum_m |\mathcal{M}_{n\ell m}|^2$$

- **Lower-energy limit:** $kR_{\oplus} \ll 1$

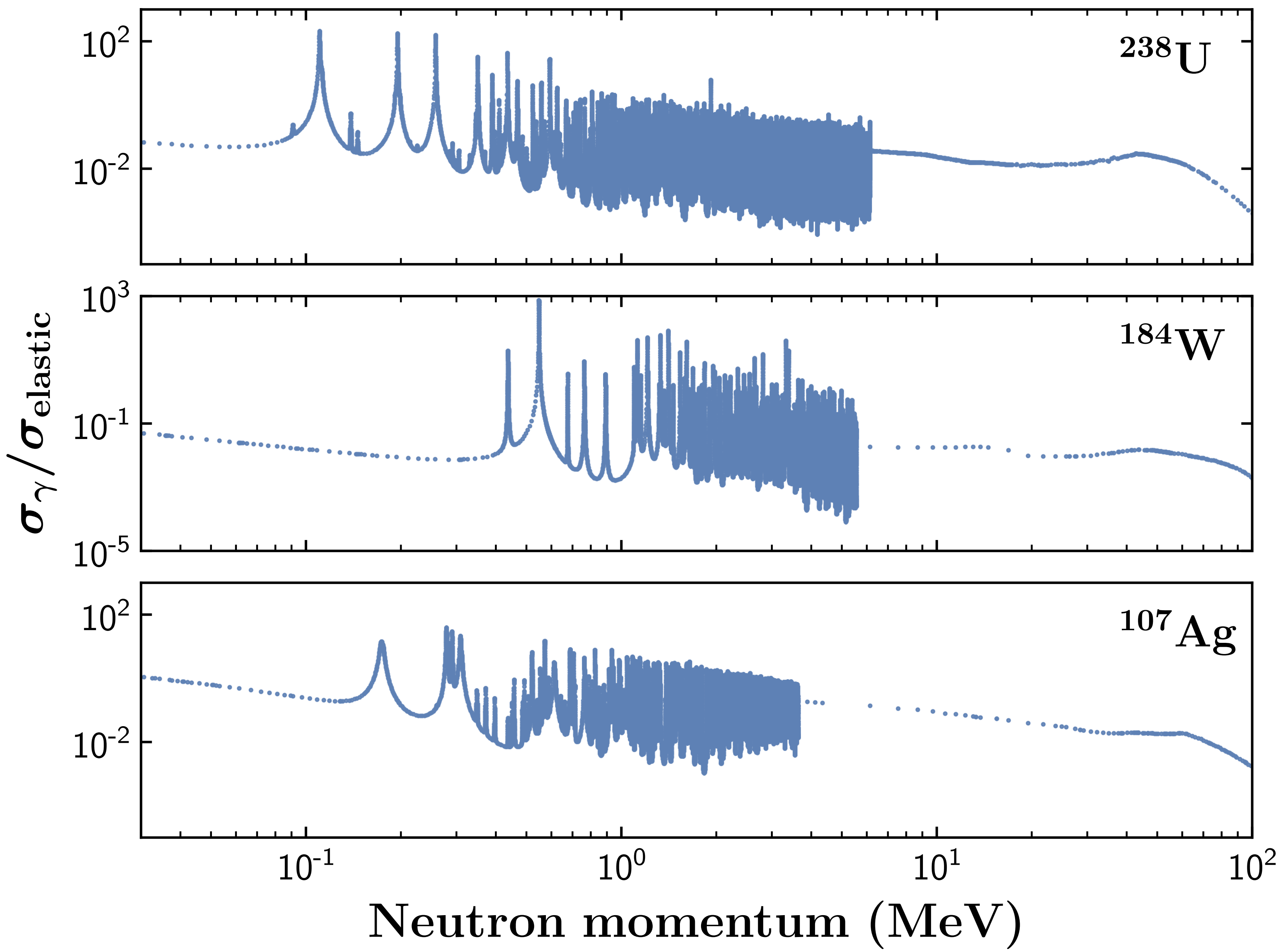


Radiative Capture Cross Section



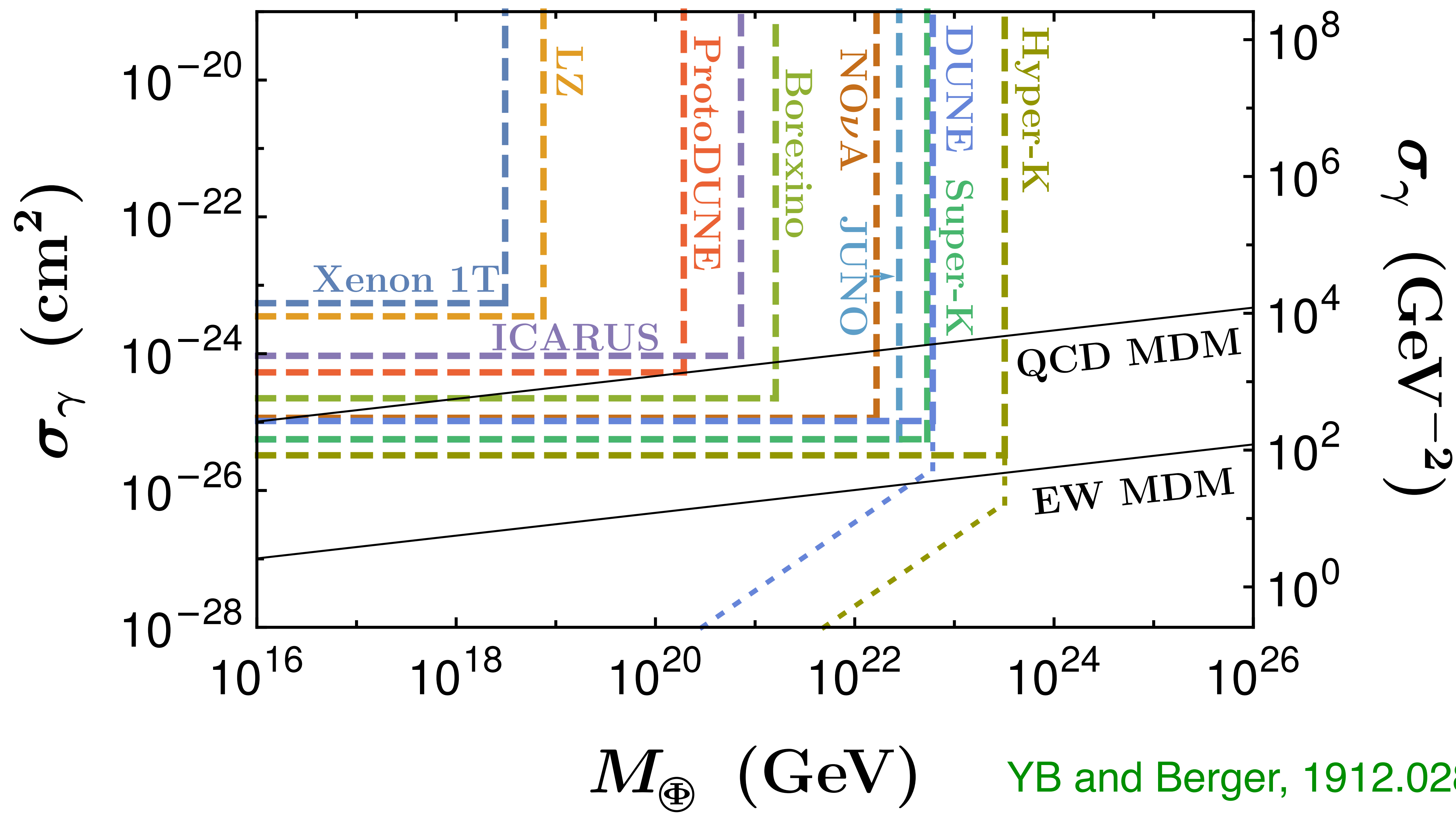
YB and Berger, 1912.02813

Radiative Capture Cross Section



- **Obtain the similar behaviors as neutron capture by a large nucleus**

Detection Sensitivity

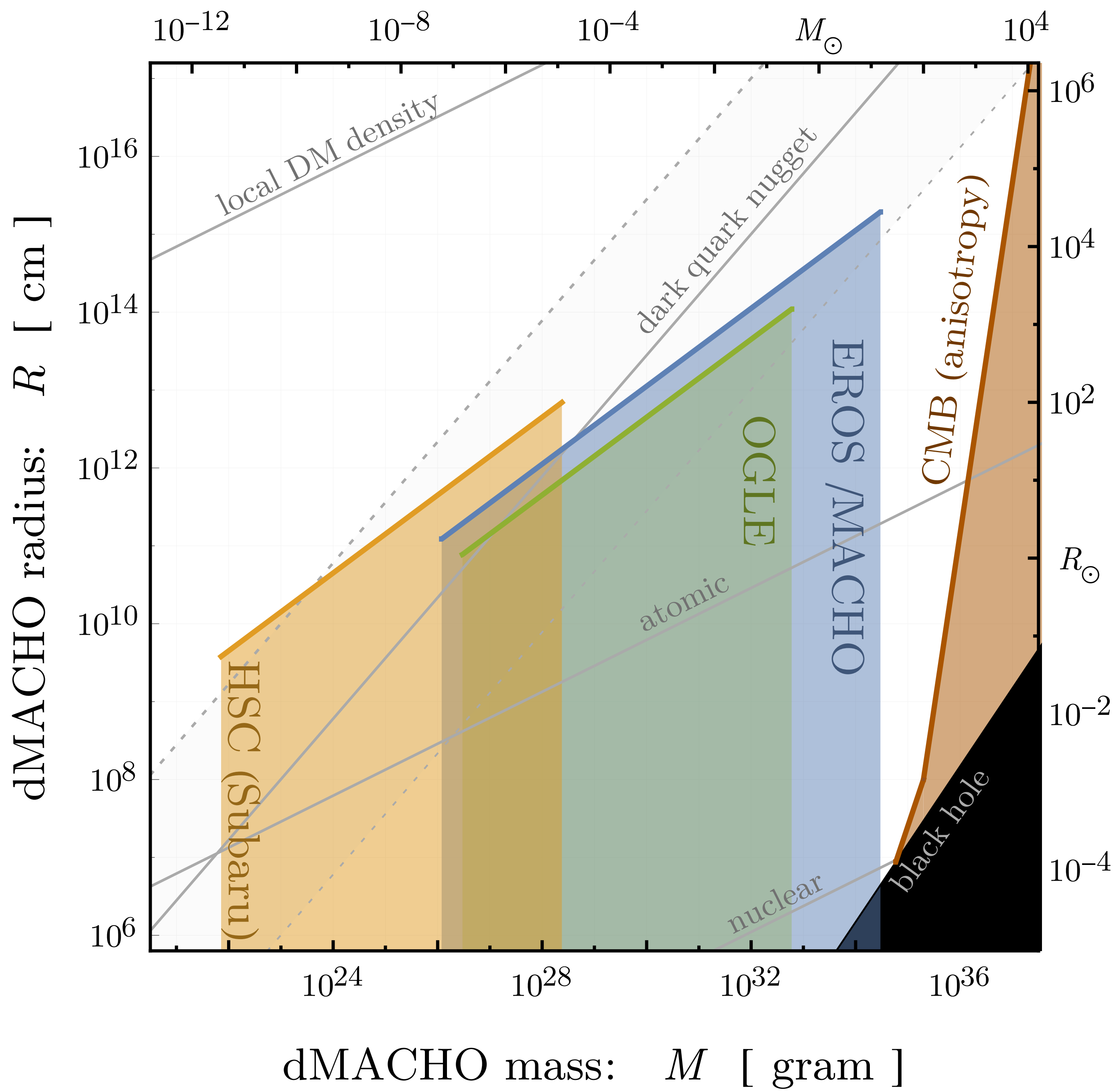


YB and Berger, 1912.02813

- **Working in progress with experimentalists to apply the actual data to search for MDM**

Only Gravitational Interaction

- **Phenomenological model parameter space at a heavy mass**

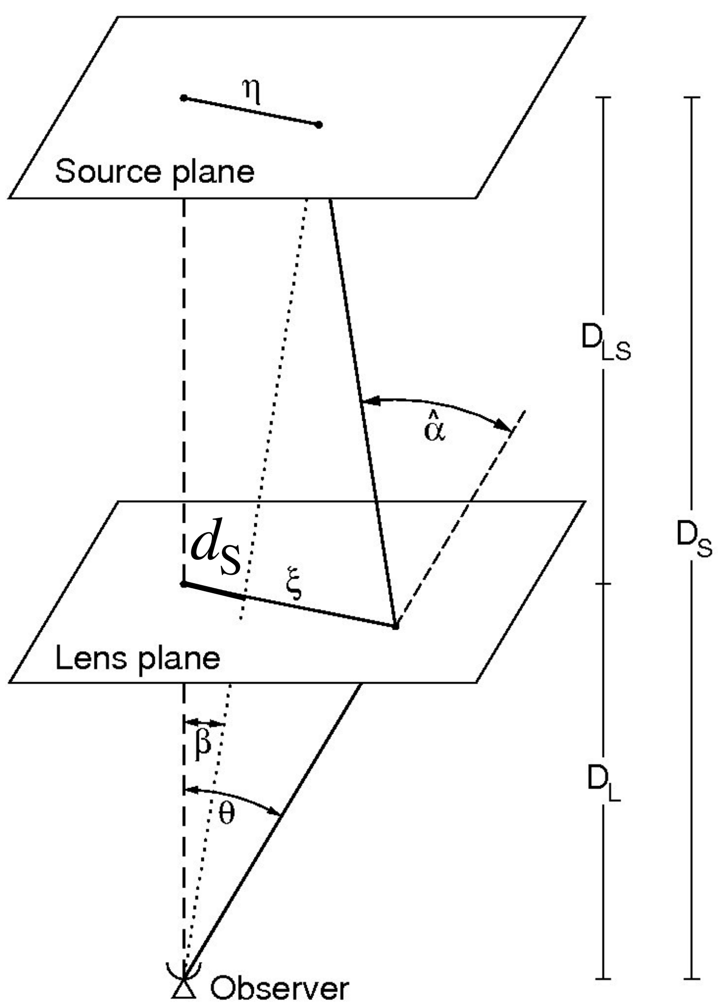


YB, Long and Lu, 2003.13182

Gravitational Lensing

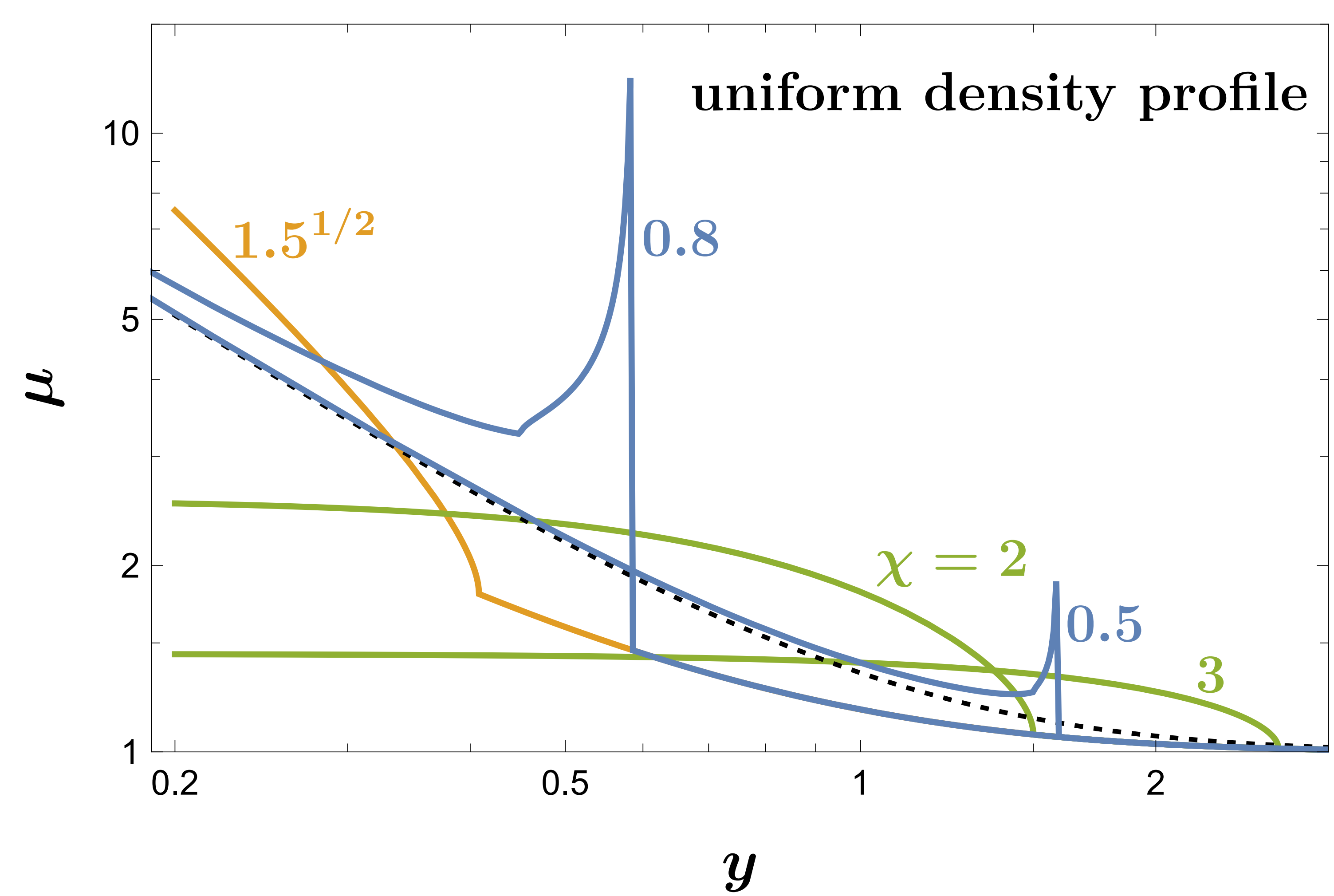
- **Einstein radius:**

$$R_E = \sqrt{4\,G_N\,M\,\kappa(1-\kappa)\,D_S} \approx (1.51\times 10^{14}\ \text{cm}) \times \left(\frac{\sqrt{\kappa(1-\kappa)}}{1/2}\right)\left(\frac{D_S}{50\text{kpc}}\right)^{1/2}\left(\frac{M}{M_\odot}\right)^{1/2}$$



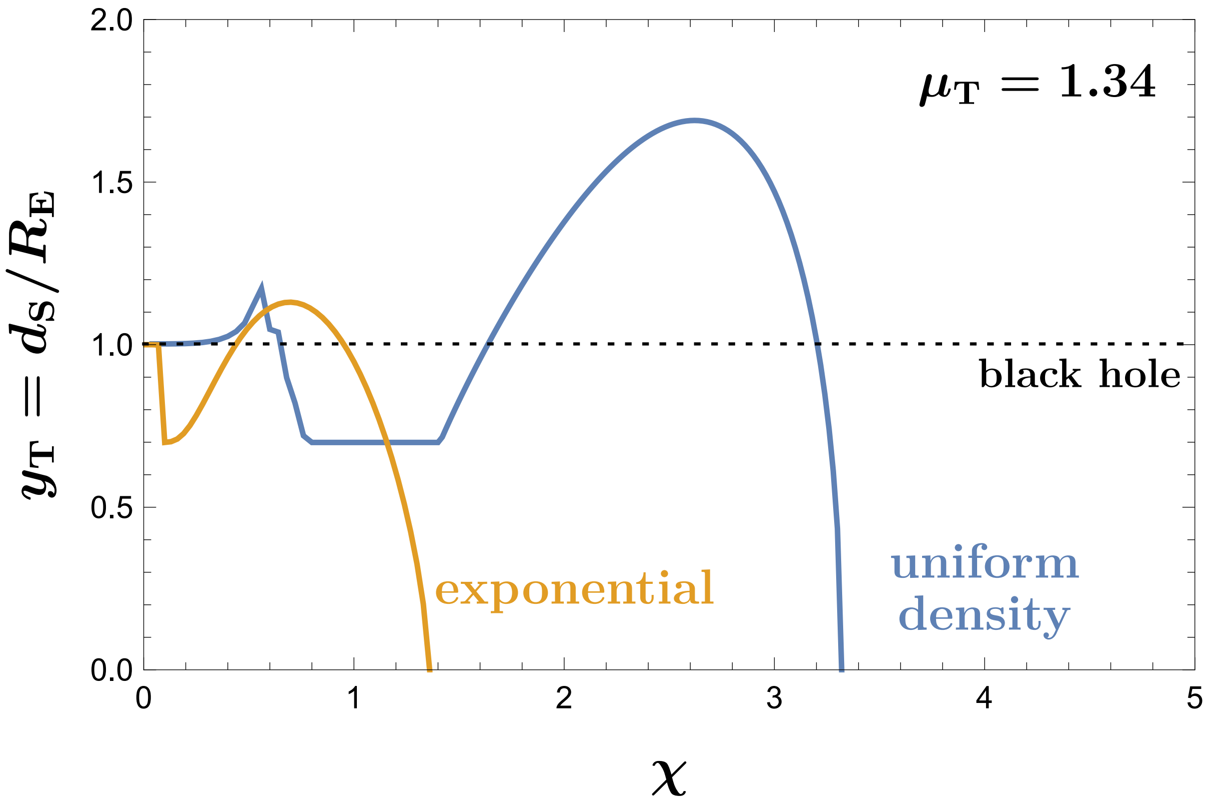
Bartelmann and Schneider, 2001

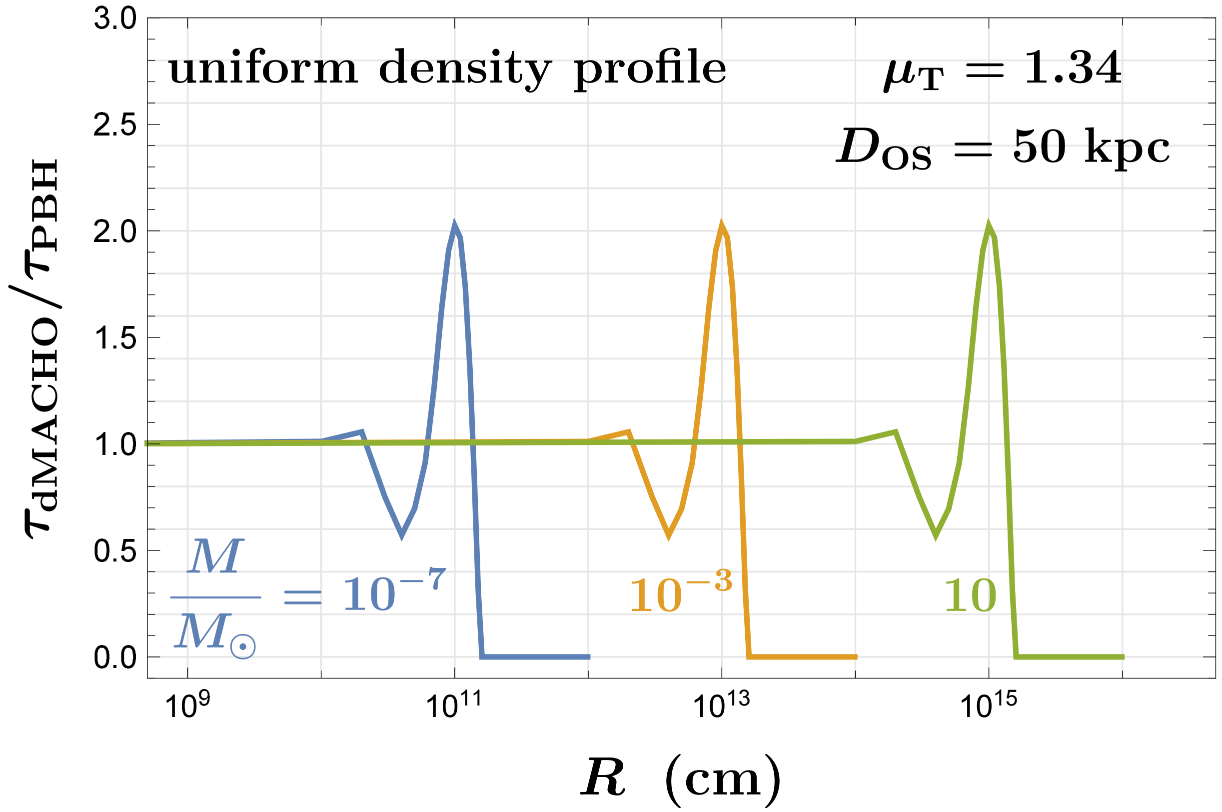
$$y \equiv d_S/R_E \qquad \chi \equiv R/R_E$$



YB, Long and Lu, 2003.13182

Gravitational Lensing

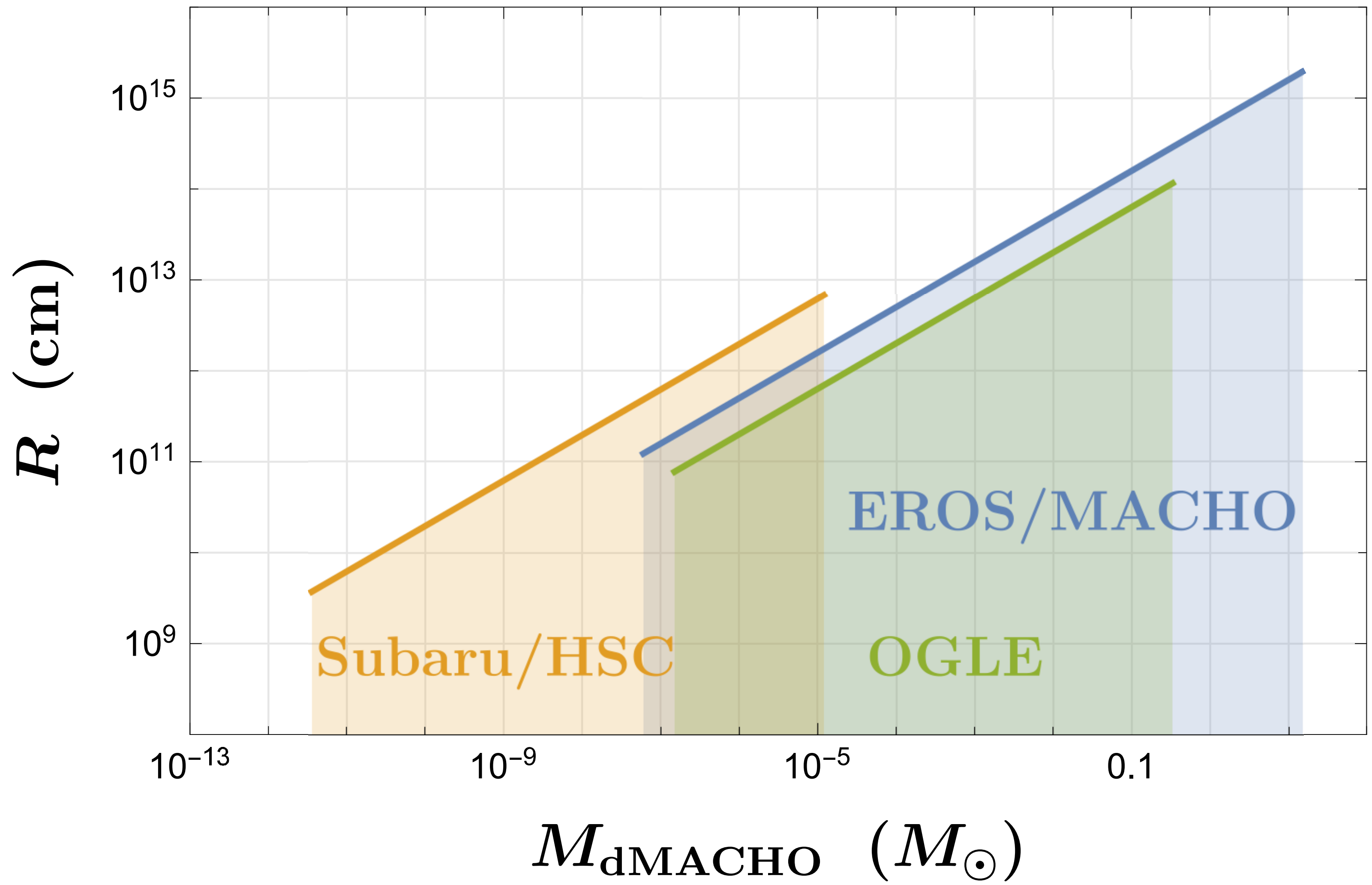




$$\tau = D_{OS} \int_0^1 d\kappa \; n_{lens}(\vec{r}_O + \kappa \, D_{OS} \, \hat{n}_L) \; \pi \, y_T^2\Big(R/R_E(\kappa), \mu_T\Big) \; R_E^2(\kappa)$$

- **Optical depths drop dramatically as** $R \geq \mathcal{O}(R_E)$

Gravitational Lensing



- **Below $\sim 10^{-11}\, M_\odot$, there is no lensing constraint**
- **Other lensing systems to improve the limits in the future**

Dai, Venumadhav, et. al, 1804.03149 Dror, Ramani, et. al, 1901.04490

Accretion of Baryonic Matter

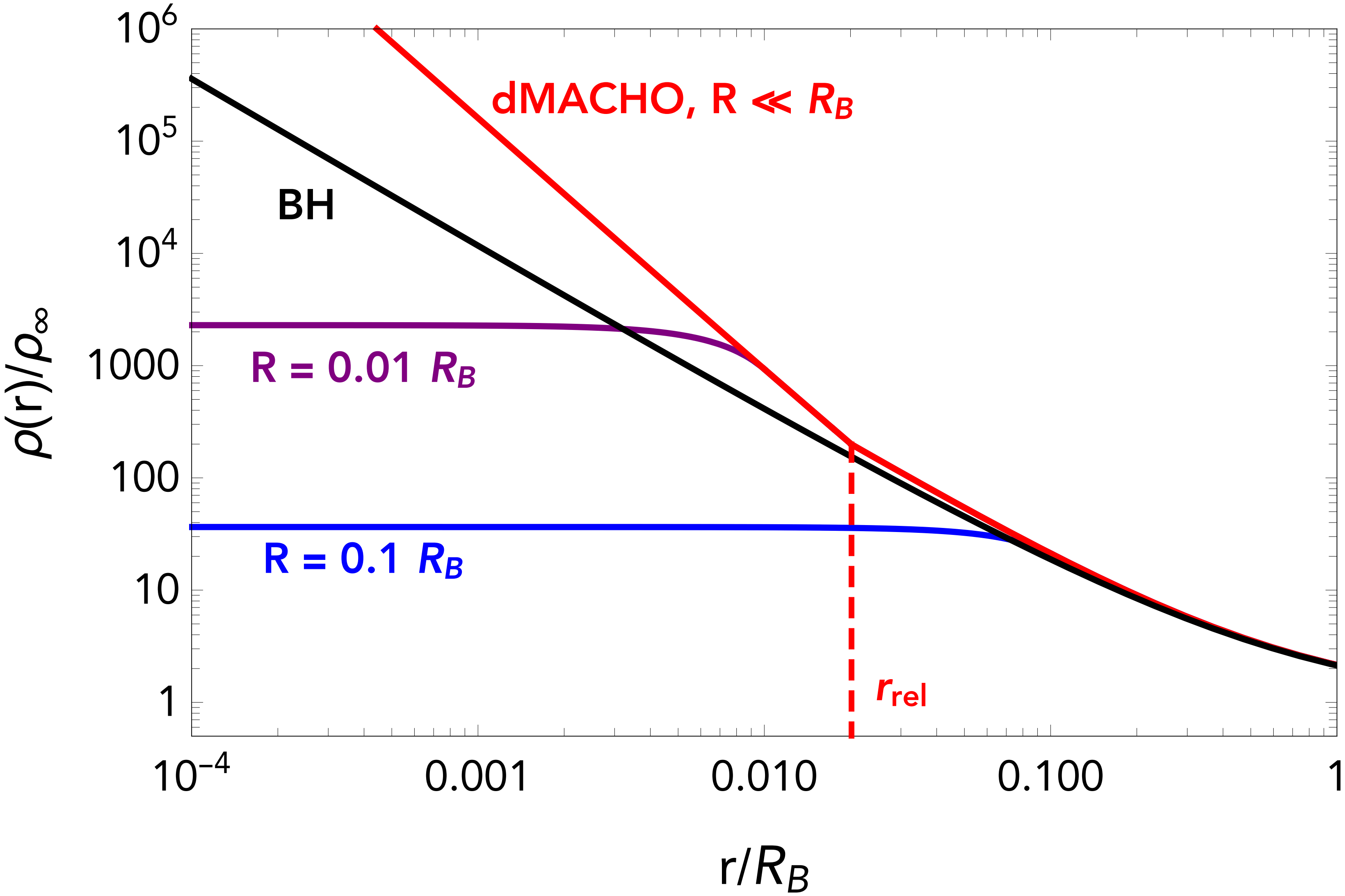
- **Large and localized gravitational potential by MDM can accrete ordinary baryons, which are hot and can radiate photons to change the electron recombination history**
- **For PBH, there are many studies along this direction with either spherical or non-spherical accretion. In our study, we take spherical accretion for simplicity**
- **For PBH, Bondi accretions have been used (see Ali-Haimoud and Kamionkowski, 1612.05644). To obtain stationary solutions, we implement the *hydrostatic approximation***

$$\dot{\rho} + \frac{1}{r^2}\left(r^2 \rho v\right)' = 0$$

$$\rho\, \dot{v} + \rho\, v\, v' + P' = \rho g \quad \xrightarrow{v \to 0} \quad \frac{G_N \widetilde{M}(r)}{r^2} + \gamma\, K\, \rho(r)^{\gamma - 2} \frac{d\rho}{dr} = 0$$

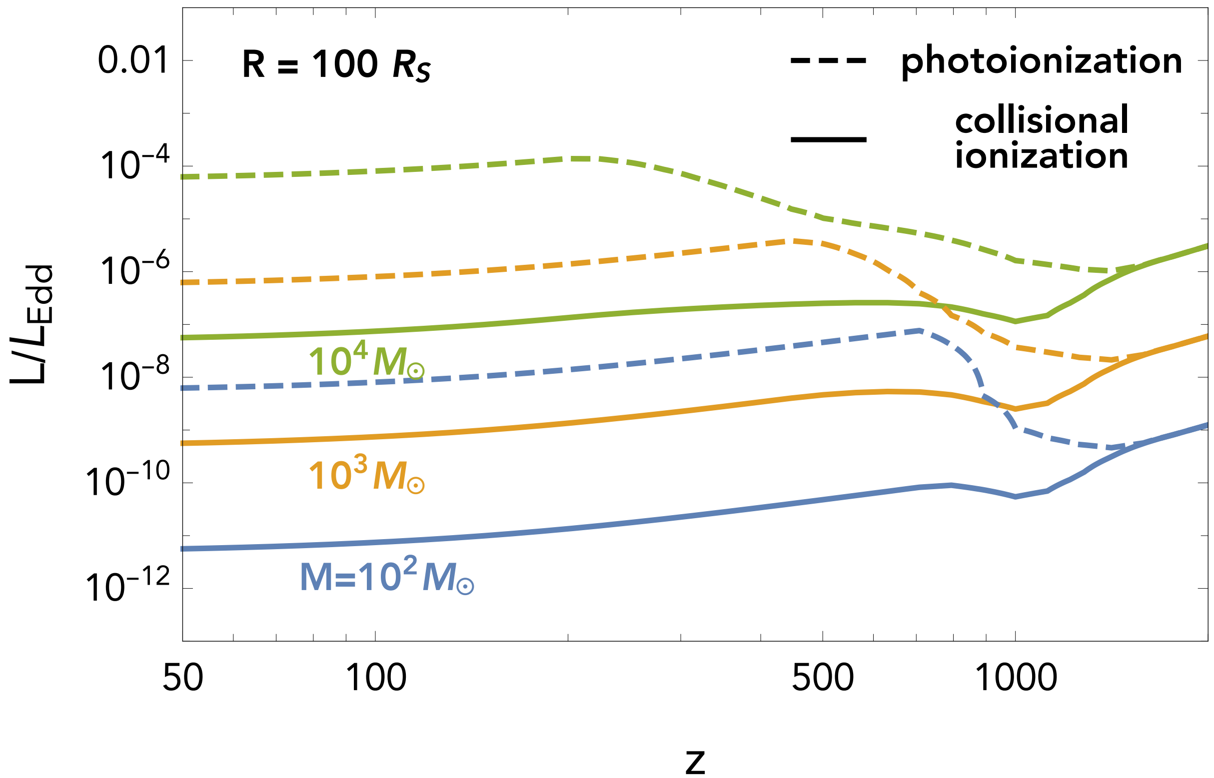
$$\rho\left(\epsilon/\rho\right)^{\bullet} + \rho\, v\, \left(\epsilon/\rho\right)' + P \frac{1}{r^2}\left(r^2 v\right)' = \dot{q}$$

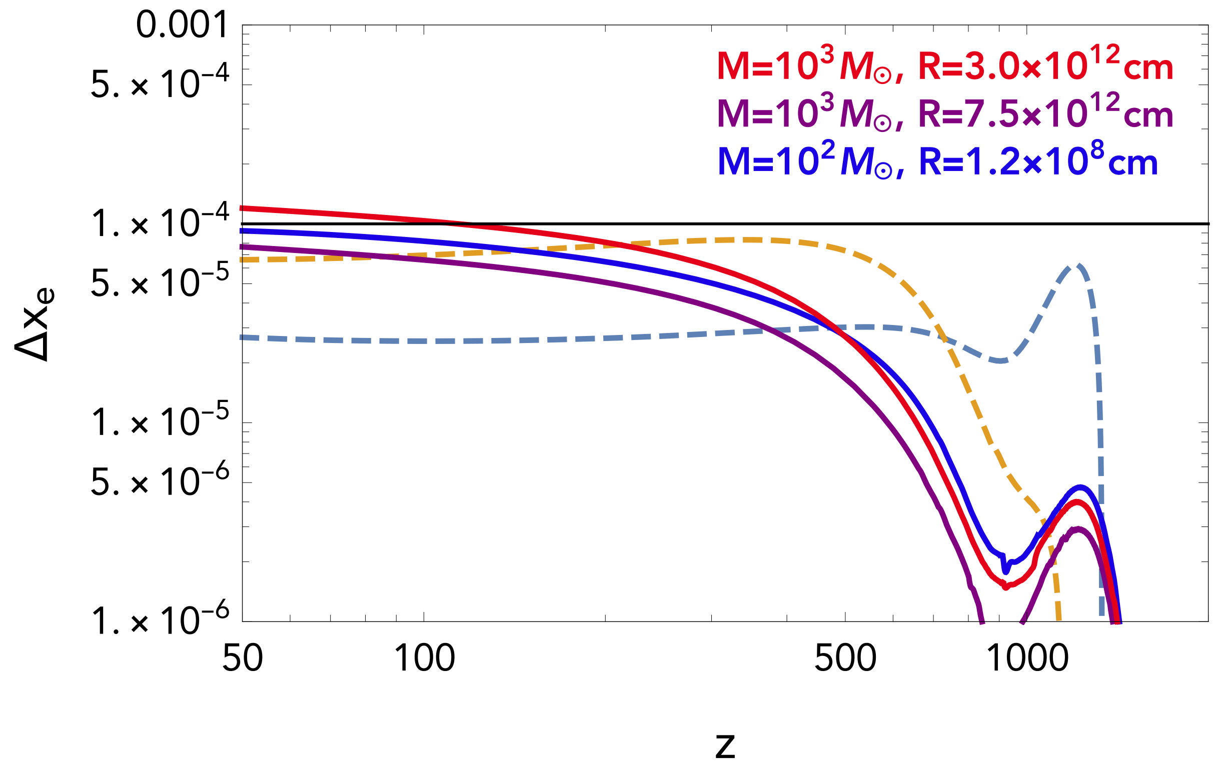
Bondi vs. Hydrostatic



- **Bondi radius:** $R_B = G_N M / c_\infty^2$ **with the sound speed** $c_\infty = \sqrt{5P_\infty / 3\rho_\infty}$

Luminosity and Ionization





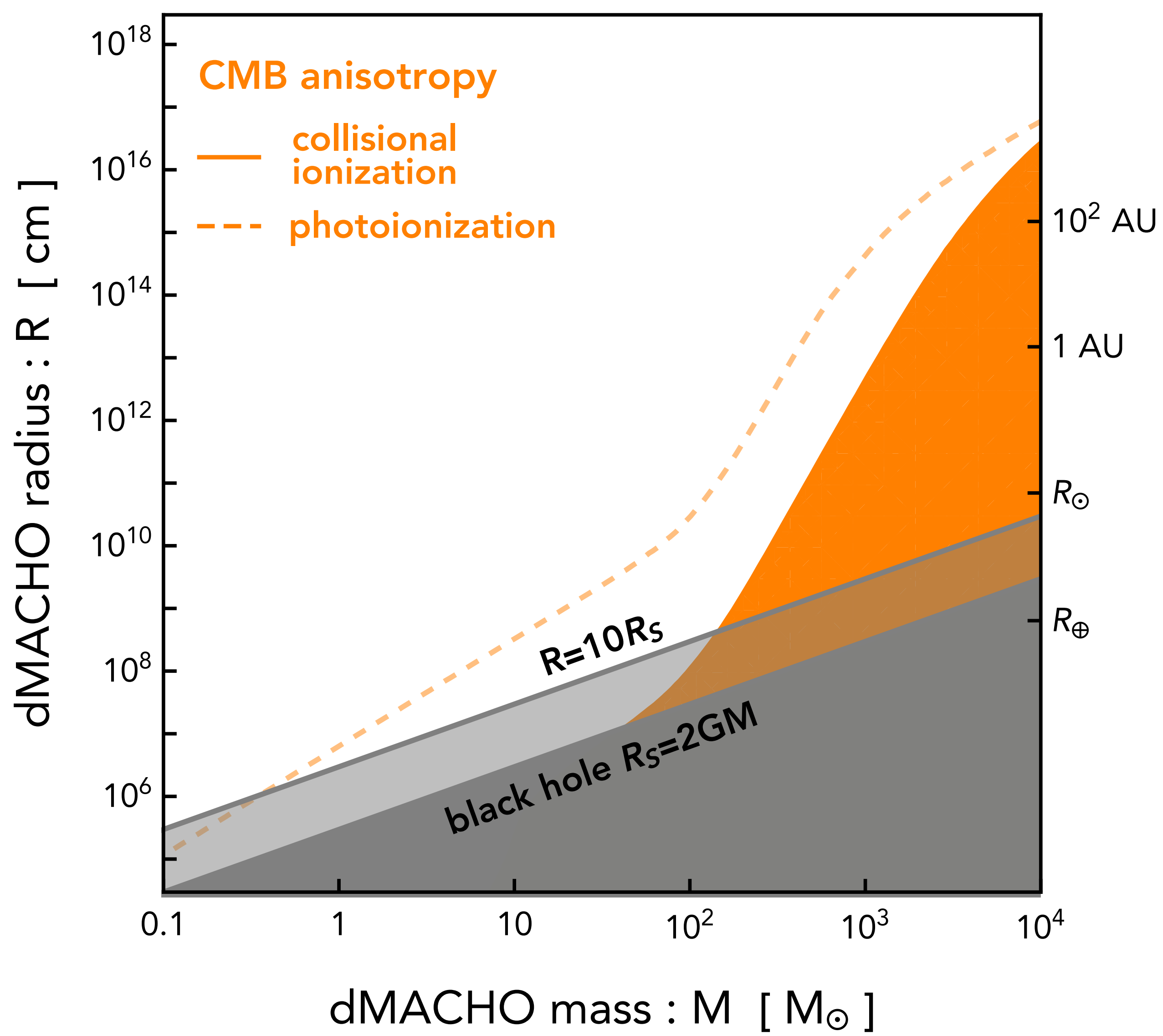
$$L_{\rm Edd} = 4\pi G_N M m_p/\sigma_{\rm T}$$

$$L \approx 4.1\times10^{-6} \times \frac{\rho_\infty^2\, m_p^{3/2}\,(G_N M)^{7/2}}{T_\infty^3\, m_e^{3/2}\, R^{1/2}}$$

dashed blue: $M = 10^2\, M_\odot, f_{\rm PBH} = 1$

dashed yellow: $M = 10^3\, M_\odot, f_{\rm PBH} = 0.01$

Constraints from CMB anisotropy



- **Assume dMACHO account for 100% dark matter**
- **We require** $\Delta x_e(z = 50) < 10^{-4}$

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 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 up to mass of one gram
- Gravitational lensing and CMB experiments probe the parameter space from the heavy side till 10^{22} grams

Thanks!

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**

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

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

$$\textcircled{\Phi}_Q + \Phi \to \textcircled{\Phi}_{Q+1} + X$$

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

- **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**