Electroweak symmetric dark matter balls

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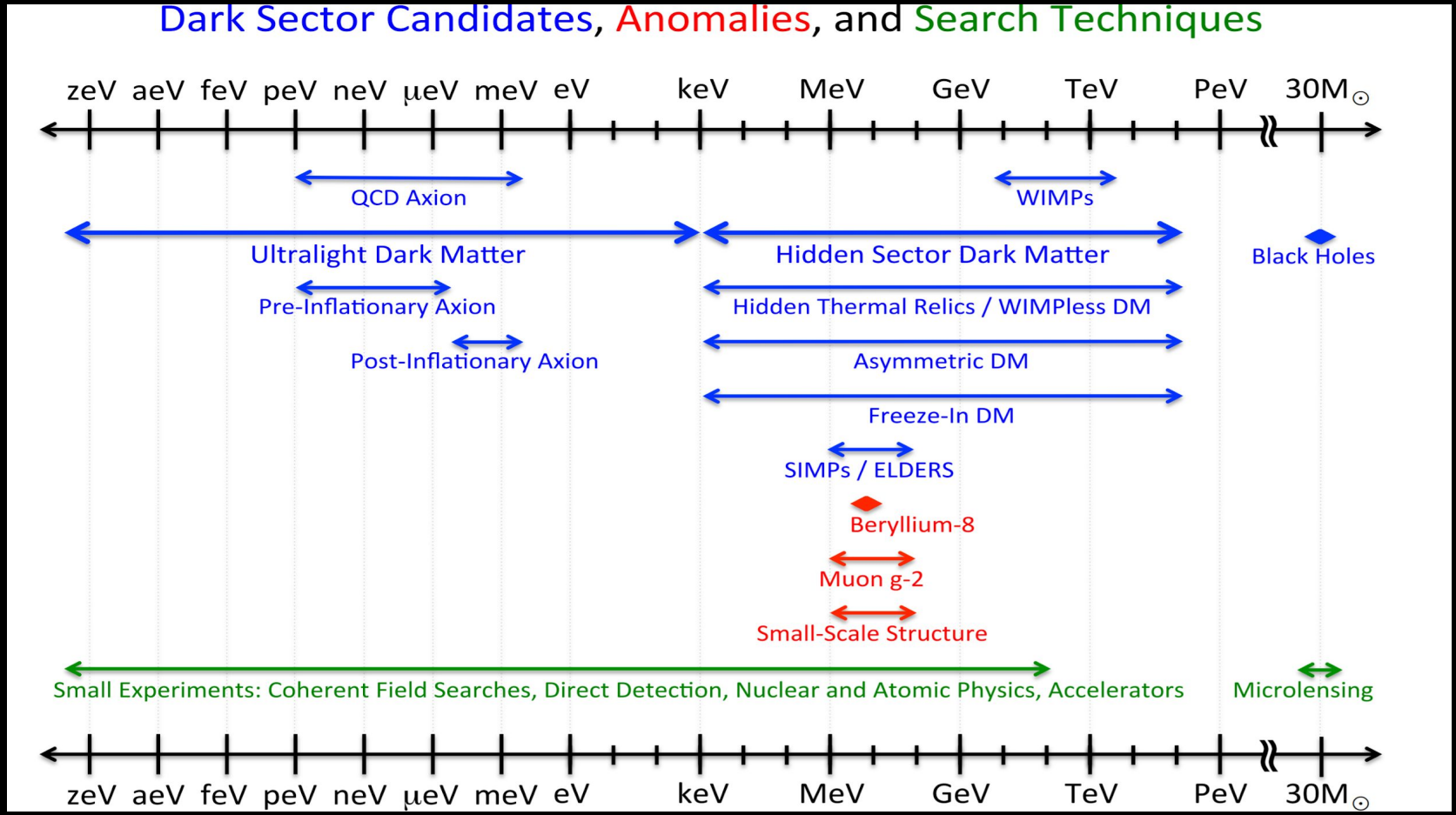
Meeting of the Division of Particles & Fields

Dark matter ? Various possibilities



Particle state DM

Macroscopic DM

- Visible matter - various states from diluted gas to neutron star
- DM could be macroscopic
- Primordial BH - macroscopic size
- Quark nugget - nuclear energy density, 0.01 -10 cm (size)

Non-topological solitons

Solitons - stable bound states (spatially-localized) at classical/quantum level in nonlinear field theories

Eg: hydrodynamical solitons

Non-topological solitons (some technical points)

- Boundary condition at infinity for soliton state is same as vacuum state
- No degenerate vacuum states needed
- Additional conversation law (condition for existence of non-topological states)

Soliton States in a Higgs-Portal Dark Matter Scenario

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

Post electroweak symmetry breaking

$$m_\phi^2 = \frac{\lambda_{\phi h}}{2} v^2 + m_{\phi,0}^2 \,.$$

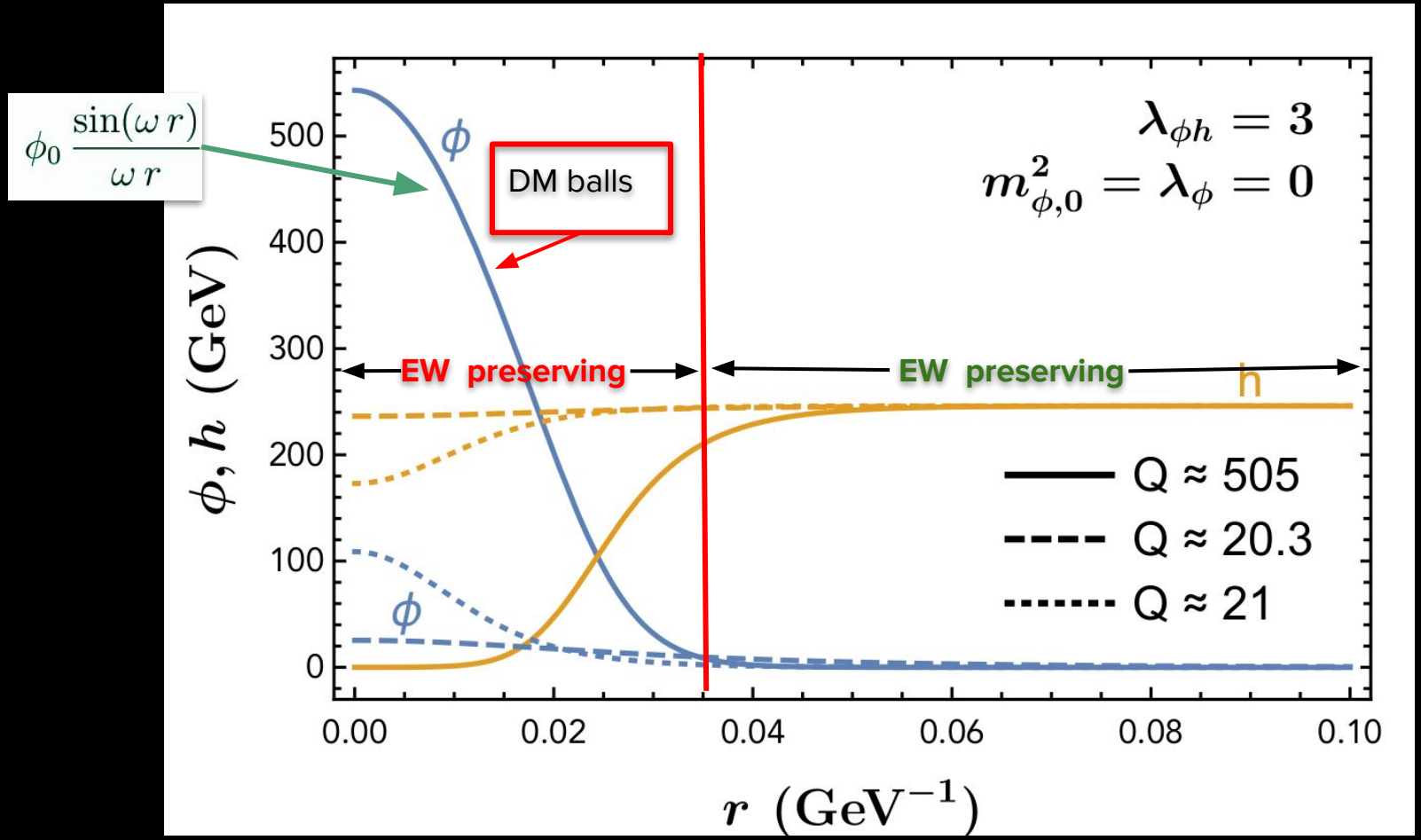
What's relevant? → Non-vacuum field configurations,
Stable (conservation of global U(1) charge, Q)
Spherically symmetric (lowest energy)

} DM solitons

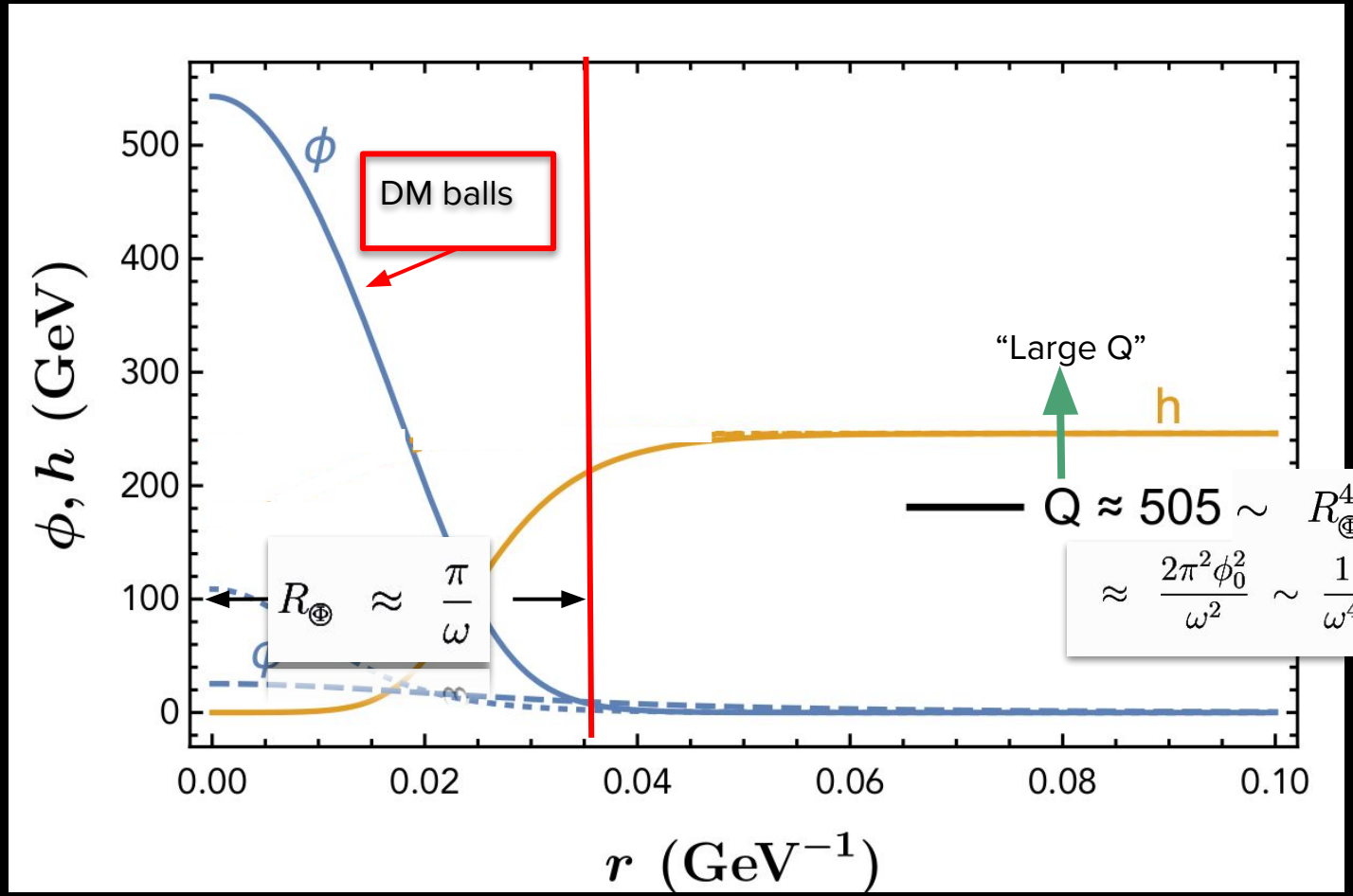
$$\phi''(r) + \frac{2}{r}\,\phi'(r) + \left[\omega^2 - \frac{1}{2}\lambda_{\phi h}\, h(r)^2 \right] \phi(r) = 0 \,,$$

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

DM solitons


$\phi_0 \frac{\sin(\omega r)}{\omega r}$
$\lambda_{\phi h} = 3$
$m^2_{\phi,0} = \lambda_\phi = 0$
DM balls
EW preserving
EW preserving
h
ϕ
ϕ
Q ≈ 505
Q ≈ 20.3
Q ≈ 21
ϕ, h (GeV)
r (GeV^{-1})
0
100
200
300
400
500
0.00
0.02
0.04
0.06
0.08
0.10

DM solitons


ϕ
DM balls
h
“Large Q”
ϕ, h (GeV)
500
400
300
200
100
0
0.00
0.02
0.04
0.06
0.08
0.10
r (GeV^{-1})
$R_\Phi \approx \frac{\pi}{\omega}$
Q ≈ 505 ~ R_Φ^4
$\approx \frac{2\pi^2\phi_0^2}{\omega^2} \sim \frac{1}{\omega^4}$

DM solitons

- For $\lambda_\phi = 0$ & large Q, scaling laws between charge, size and mass of DMBs

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

- Energy density associated with the DM soliton configuration to be of order

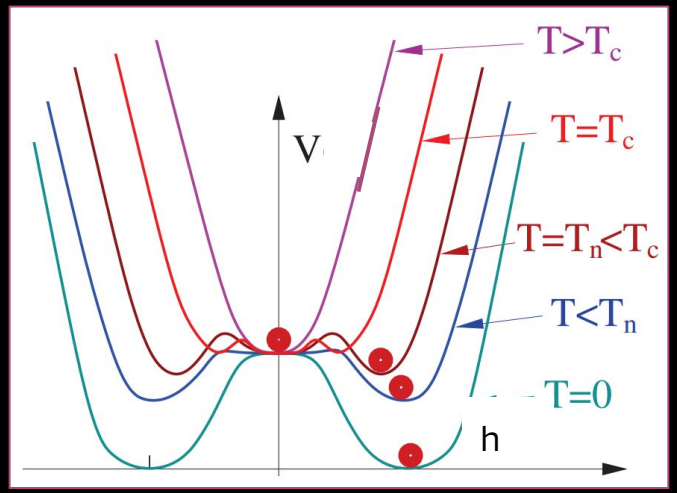
$$\rho = \frac{M_{\Phi}}{(4\pi/3) R_{\Phi}^3} \sim (100 \text{ GeV})^4$$

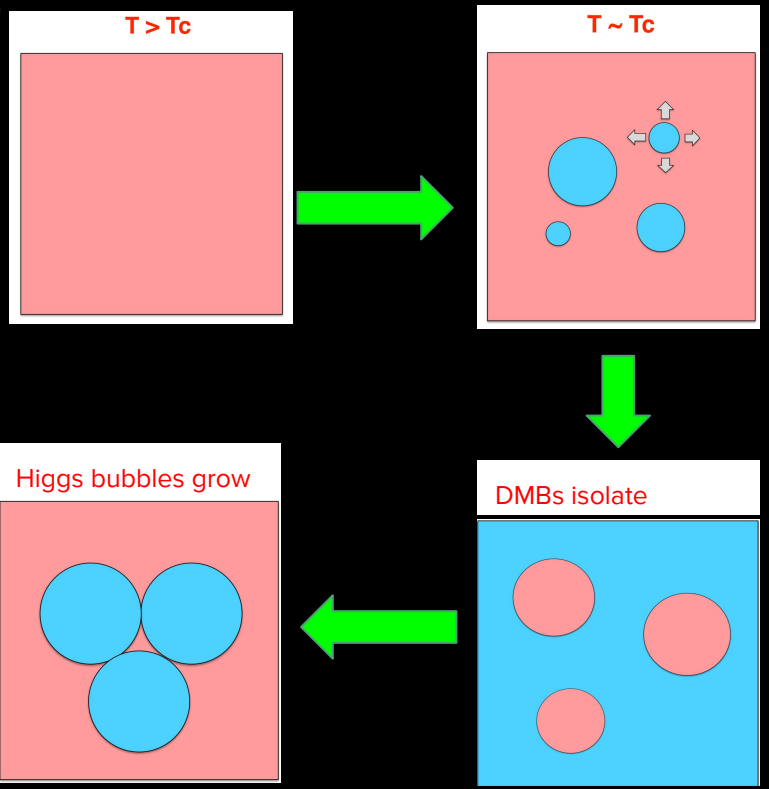
- For large Q, large R DMBs and with $\lambda_\phi \neq 0$

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

Early Universe Production of DMBs

- First order electroweak phase transition (1 step)
- $(\langle h \rangle, \langle \phi \rangle) = (0, 0) \rightarrow (\langle h \rangle, \langle \phi \rangle) = (v, 0)$





Some properties

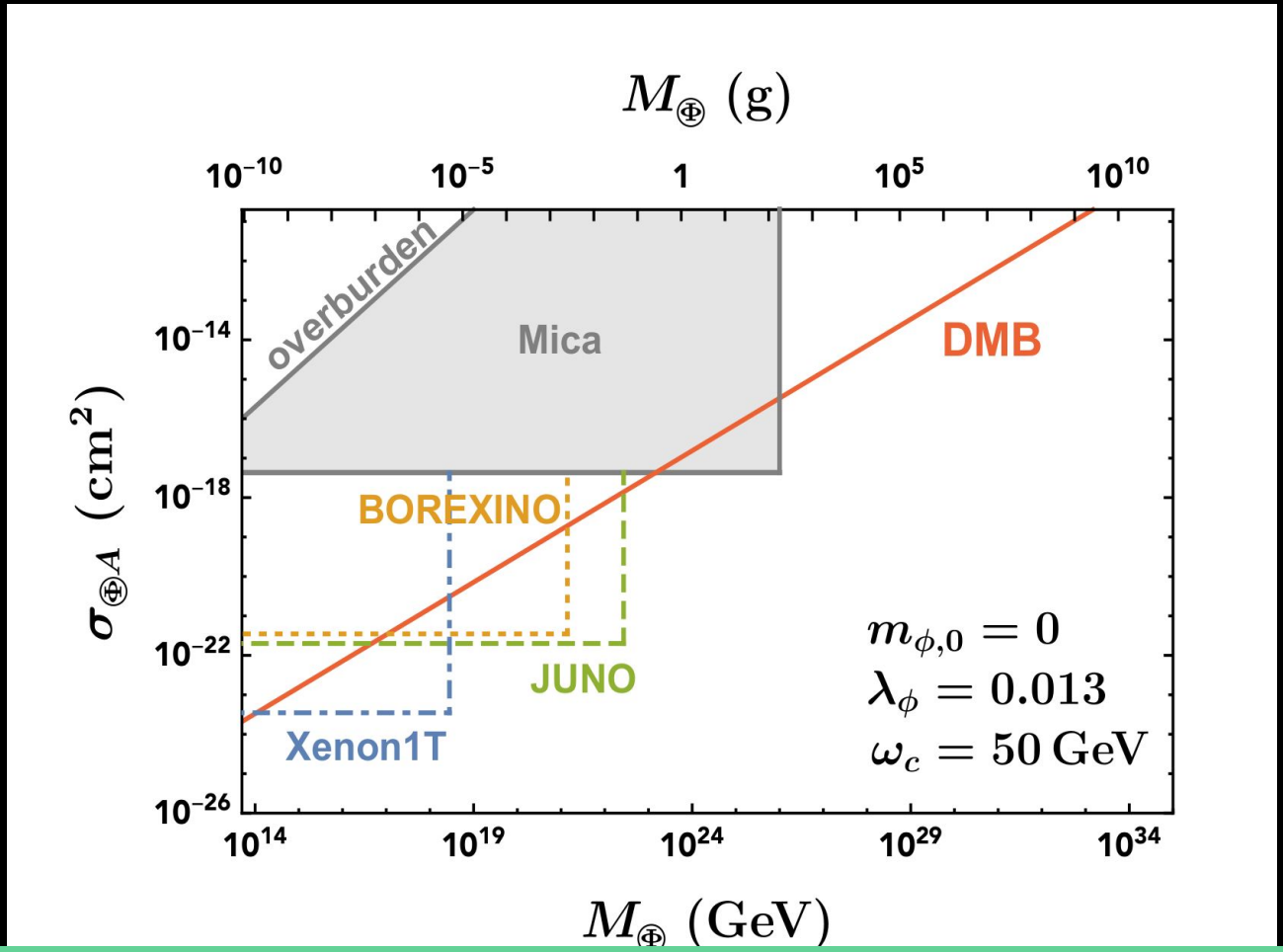
- Large DM fraction in unbroken phase $r \approx 4.3 \times 10^{-265}$ for $\lambda_{\phi h} = 3.$
- After DMB formation, free DM number gets rid of symmetric component - Asymmetric DM
- $T_c \sim 130$ GeV
- Freeze out occurs at $T_f \sim 0.49$ GeV
- Average DMB number

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

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

- For $2 < \lambda_{\phi h} < 9$, DMB radius is 10^{-9} cm (10^5 GeV^{-1}) to 10^{-6} cm (10^8 GeV^{-1})

DMB detection



Summary

- Non-topological soliton state could be the main appearance of dark matter (shown using Higgs portal DM model)
- Electroweak symmetric dark matter ball is a type of macroscopical dark matter with mass 1 - 10^{10} g
- These dark matter balls can be formed from first order electroweak phase transition
- Radius of spherically-symmetric dark matter ball varies from 10^{-9} - 10^{-6} cm
- Energy density of DMB is at electroweak scale and it can penetrate the earth without stopping
- Experiments with large detector size or a long exposure time are ideal to search for DMBs.
- The existing Xenon 1T and BOREXINO or the future JUNO experiments may discover a DMB with mass from 10^{-14} - 0.1 g based on multi-hit events.

We are deeply saddened by the passing away of Eduardo Pontón (4 April 1971 – 13 June 2019). Eduardo has been an excellent mentor and collaborator. He has provided invaluable guidance for us from his passion and rigorous scientific attitude.