Fermi-ball dark matter from a first-order phase transition

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Introduction

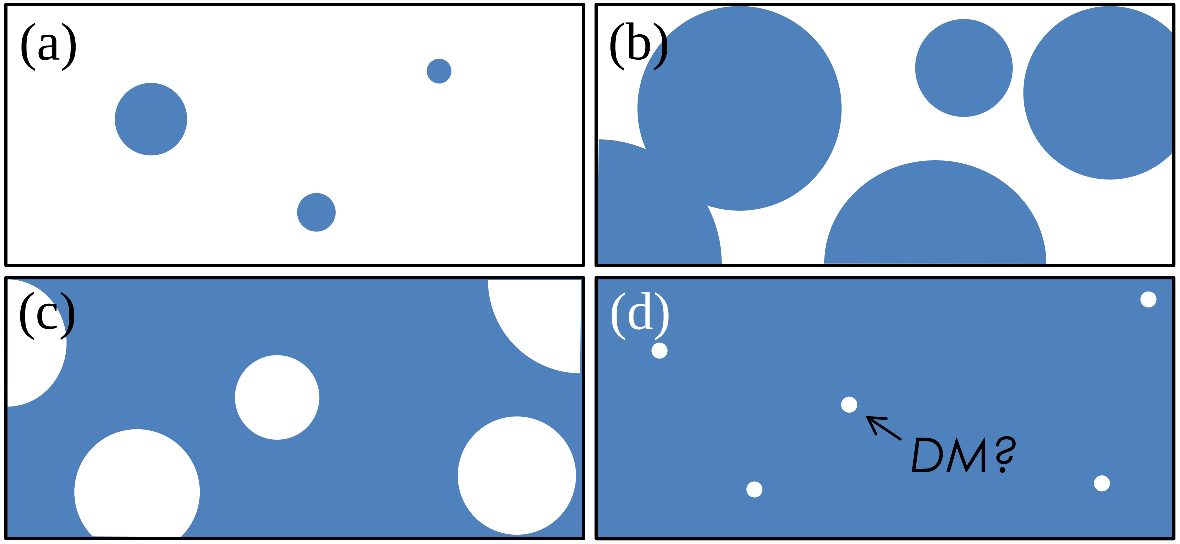
- Cosmological observations show that 27% of the total energy of the present universe consists of non-baryonic DM
- New weakly interacting massive particles (WIMPs) with the freeze-out mechanism has been the most popular explanation for DM for several decades
- However, the continuously reported null results from the direct, indirect and collider searches motivate *new DM paradigms* beyond WIMPs.

Introduction

- Recently, there are a growing number of studies on the DM produced through a first-order phase transition (FOPT), e.g. non-thermal DM, primordial black holes, etc. *Dymnikova et al, Grav. Cosmol.* ***6****, 311 (2000), M. Y. Khlopov, Res. Astron. Astrophys.* ***10****, 495 (2010)* *A. Falkowski et al, JHEP* ***02****, 034 (2013)*
- *False vacua can survive* without completely disappearing, if certain species is *trapped* in them, becoming *compact macroscopic DM* candidates, e.g. Trapping scalar particles into the false vacuum to form Q-ball DM *E. Krylov et al, Phys. Rev. D****87****, 083528 (2013), F. P. Huang et al, Phys. Rev. D****96****, 095028 (2017)*
- We propose a new mechanism where dark fermions are trapped inside the false vacuum and form another type of compact macroscopic DM candidates: *Fermi-balls*
- Fermi-ball is more excited energetically due to the Pauli exclusion principle, since it cannot condense in the ground state like the Q-ball
  - *Fermi-ball mass > Q-ball mass* for a given charge

Introduction

- Compact DM formation after FOPT
  - (a-b) The true vacuum bubbles nucleate and expand
  - (c-d) The true vacuum dominates but the net charge in the false vacuum remnant keeps their finite size by their pressure → <u>*Compact DM?*</u>



Introduction

- Fermi-ball DM scenario requires the following three conditions to be satisfied:
  - 1. Fermions should carry a *conserved charge* ensuring the *stability* of Fermi-ball relics
  - 2. Large *mass gap* of fermions between the false and true vacuum hence can be kinematically *trapped* in the false one
  - 3. *Initial excess* of the charge must be somehow generated in the early universe since the only *net charge* survives from annihilation

Contents

- Fermi-ball formation from first-order phase transition
- Properties
- Fermi-ball dark matter
- Summary

Fermi-ball formation from first-order phase transition

- Consider a global $U(1)$ theory of Dark Dirac fermion χ(charge= +1) coupled to a real scalar φ through the Yukawa: $\mathcal{L} \supset g_\chi \phi \bar{\chi} \chi$
  - The $U(1)$ symmetry will guarantee the stability of the fermi-ball relics
  - If one gauges the symmetry the Fermi-balls become unstable due to the Coulomb repulsion

Fermi-ball formation from first-order phase transition

- Consider a global $U(1)$ theory of Dark Dirac fermion χ(charge= +1) coupled to a real scalar φ through the Yukawa: $\mathcal{L} \supset g_\chi \phi \bar{\chi} \chi$
  - The fermion mass in the true vacuum should be larger than the temperature in order to be trapped in the false vacuum kinematically: $M_\chi \equiv g_\chi w \gg T$
  - Realized by either large w_*/T_* (supercooling) or strong $g_\chi \gg 1$
  - We will see that the *supercooling with $g_\chi \sim O(1)$ is good enough for Fermi- ball DM scenarios*

Fermi-ball formation from first-order phase transition

- Consider a global $U(1)$ theory of Dark Dirac fermion χ(charge= +1) coupled to a real scalar φ through the Yukawa: $\mathcal{L} \supset g_\chi \phi \bar{\chi} \chi$
  - The $U(1)$ symmetry should be broken at some high energy scale in order to generate initial asymmetry, which will give the net charge of the fermi-balls after the annihilation
  - We assume that the initial asymmetry is somehow related to the baryon asymmetry: $\eta_\chi = c_\chi \eta_B$
  - We will find $c_\chi \sim O(10^{-2})$ in our model used in this work

Fermi-ball formation from first-order phase transition

- Critical temperature T_c: where the potential minima becomes degenerate
- Nucleation temperature T_n: where the vacuum decay becomes efficient: $\Gamma(T_n)H^{-4}(T_n) \approx 1$
  - Gamma: decay rate

$$\Gamma(T) \approx T^4 e^{-S_3(T)/T}$$

- Percolation temperature T_p: where true vacuum bubbles become infinitely connected: $p(T_p) \simeq 0.71$

M. D. Rintoul et al, Journal of physics a: mathematical and general ***30****, L585 (1997)*

  - $p(T)$: The fraction of the volume that remains in the old phase
- Fermi-ball formation temperature T_*: where false vacuum bubbles stop being infinitely connected: $p(T_*) \simeq 0.29$
  - Shrinkage of each remnant → *Fermi-ball formation*

Fermi-ball formation from first-order phase transition

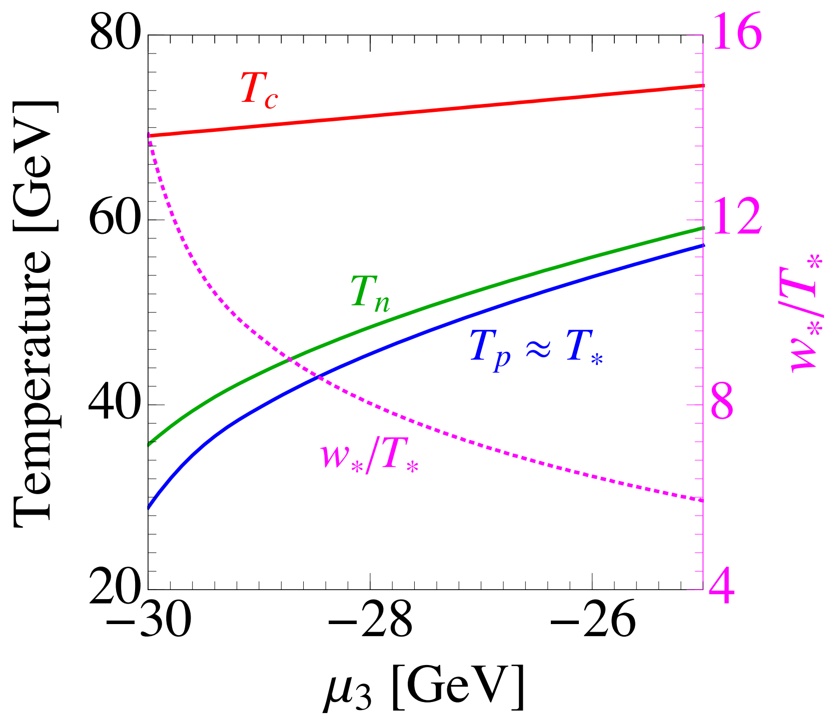
- Consider a toy model $U(\phi,T)=\frac{1}{2}(\mu^2+cT^2)\phi^2+\frac{\mu_3}{3}\phi^3+\frac{\lambda}{4}\phi^4$
  - Critical temperature
    $$T_c=\frac{1}{3\sqrt{2c}}\sqrt{\frac{9M_\phi^4-\mu_3^2w_0^2}{M_\phi^2-\mu_3w_0}}$$
  - Nucleation temperature
    $$\Gamma(T_n)H^{-4}(T_n)\approx 1$$
    $$\frac{S_3(T)}{T}=\frac{123.48(-M_\phi^2/2-\mu_3w_0/2+cT^2)^{3/2}}{2^{3/2}T\mu_3^2}\times f\left(\frac{9(-M_\phi^2/2-\mu_3w_0/2+cT^2)(M_\phi^2/w_0-\mu_3)}{4\mu_3^2w_0}\right)$$
    $$f(u)=1+\frac{u}{4}\left(1+\frac{2.4}{1-u}+\frac{0.26}{(1-u)^2}\right)$$
  - Percolation temperature
    - ($\Gamma(T)$, $v_b\to$) $p(T_p)\simeq 0.71$
  - Formation temperature
    - ($\Gamma(T)$, $v_b\to$) $p(T_*)\simeq 0.29$

Fermi-ball formation from first-order phase transition

- To satisfy DM abundance we set $U_0^{1/4}$=100 GeV, c_χ=O(10^{-2})
  - 100 GeV scale will also yield the GW signals at *mHz*, relevant to the future space-based missions
- Benchmark values for parameters:

$$w_0 = 400\ \text{GeV}, \quad M_\phi = 100\ \text{GeV}, \quad c = 0.4$$

- Supercooling ($w_*/T_* \gg 1$)
  - g_χ ~ O(1) is sufficient for the efficient trapping



Fermi-ball formation from first-order phase transition

- At T_*, false vacuum bubbles start to shrink since the bubbles are not connected anymore
- The maximal size $R(T_*)$ of a remnant that becomes Fermi-ball:
  - The one can shrink to Fermi-ball size before another true vacuum bubble is created inside it *E. Krylov et al, Phys. Rev. D**87**, 083528 (2013)*

$$\Gamma(T_*)V_*\Delta t \sim 1, \quad V_* = \frac{4\pi}{3}R_*^3 \qquad \Delta t = R_*/v_b$$

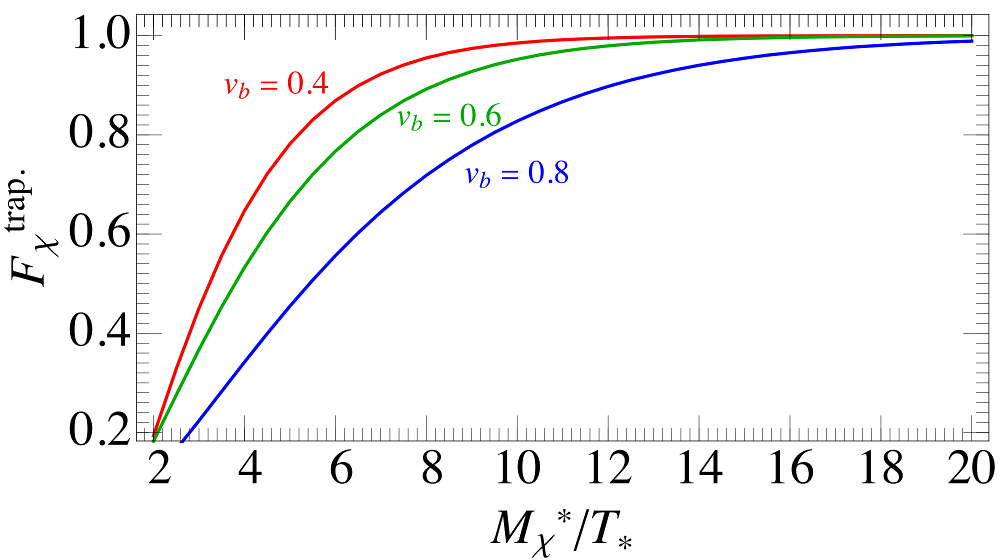
- The charge trapped in a remnant:

$$Q_{\rm FB}^* = F_\chi^{\rm trap.}\frac{c_\chi \eta_B s_*}{n_{\rm FB}^*}$$

  - $n_{\rm FB}$: Number density of the remnants
  - $F_\chi^{\rm trap.}$: Number fraction of χ trapped in the false vacuum

Fermi-ball formation from first-order phase transition

- Trapping fraction $F_{\chi}^{trap.}$ is a function of $M_{\chi}*/T*$ and v_b
  - For a reasonably large $M_{\chi}*/T*$ and relativistic $v_b \sim O(0.1)$, *the trapping is very efficient* with the fraction close to 100%
  - For a given $M_{\chi}*/T*$, the fraction *decreases with v_b* because χ in the wall frame becomes more energetic, having *higher probability to penetrate the barrier*



Properties

- Energy of a Fermi-ball with global charge $Q_{\rm FB}$ and radius *R*

$$E = \frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{\rm FB}^{4/3}}{R} + 4\pi\sigma_0 R^2 + \frac{4\pi}{3}U_0 R^3$$

- Fermi gas pressure + surface effect + volume effect
- Surface term neglected due to large *R*
- Mass and size of a Fermi-ball are determined by energy-minimization as a function of $Q_{\rm FB}$ and U_0:

$$M_{\rm FB} = E\big|_{R=R_{\rm FB}} = Q_{\rm FB}\left(12\pi^2 U_0\right)^{1/4},$$

$$R_{\rm FB} = Q_{\rm FB}^{1/3}\left[\frac{3}{16}\left(\frac{3}{2\pi}\right)^{2/3}\frac{1}{U_0}\right]^{1/4}$$

- Fermi-ball is typically heavier and larger than a Q-ball for a given charge: $M_{\rm QB} \propto Q_{\rm QB}^{3/4}$ $R_{\rm QB} \propto Q_{\rm QB}^{1/4}$

Properties

- Energy of a Fermi-ball with global charge Q_{FB} and radius *R*

$$E = \frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{\rm FB}^{4/3}}{R} + 4\pi\sigma_0 R^2 + \frac{4\pi}{3}U_0 R^3$$

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Pressure term coming from Bose-condensation $\propto Q_{QB}/R$

Properties

- Typical n_{FB}, Q_{FB}, M_{FB}, R_{FB} in toy model

$$w_0 = 400 \text{ GeV}, \quad M_\phi = 100 \text{ GeV}, \quad c = 0.4 \quad \mu_3 = -30 \sim -25 \text{ GeV}$$

$$n_{\mathrm{FB}} = 1.1 \times 10^{-37} \text{ m}^{-3} \sim 9.3 \times 10^{-34} \text{ m}^{-3},$$
$$Q_{\mathrm{FB}} = 3.9 \times 10^{34} \sim 4.0 \times 10^{30},$$
$$M_{\mathrm{FB}} = 2.4 \times 10^{10} \text{ kg} \sim 2.6 \times 10^{6} \text{ kg},$$
$$R_{\mathrm{FB}} = 3.7 \times 10^{-7} \text{ m} \sim 1.8 \times 10^{-8} \text{ m}$$

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: *Very dense and sparsely distributed*

Properties

- Stability against decay or fission

$$\frac{dM_{\rm FB}}{dQ_{\rm FB}} < M_\chi \equiv g_\chi w_0, \qquad \frac{d^2 M_{\rm FB}}{dQ_{\rm FB}^2} \leqslant 0$$

- The first implies that a χ has smaller energy inside the Fermi-ball than outside: $U_0^{1/4} < g_\chi w_0$
- The second implies that the χ's energy inside the ball becomes smaller for a larger total charge, energetically favoring a larger ball for a given total charge or being stable against the fission into smaller balls: automatically satisfied from $M_{FB} \propto Q_{FB}$

Fermi-ball dark matter

- Abundance of the Fermi-ball DM

$$\Omega_{\rm FB}h^2 = \frac{n_{\rm FB}M_{\rm FB}}{\rho_{\rm c}}h^2$$

- Use the formulas for n_{FB} and M_{FB}:

$$\Omega_{\rm FB}h^2 = 0.12 \times F_\chi^{\rm trap.}\left(\frac{c_\chi}{0.0146}\right)\left(\frac{U_0^{1/4}}{100\ {\rm GeV}}\right)$$

- *Fermi-balls can explain the full DM abundance for $c_\chi = O(10^{-2})$ and $U_0^{1/4} = 100$ GeV, if the trapping is efficient*

Fermi-ball dark matter

- Abundance of fermions outside
  - If thermal contribution is dominant: normal freeze-out formula:

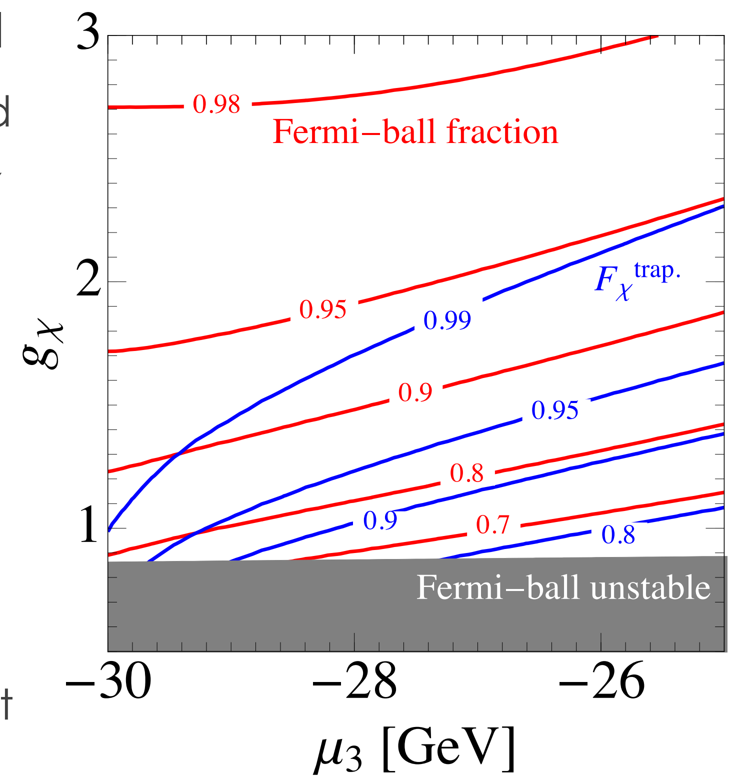
$$(\Omega_\chi^{\rm free} + \Omega_{\bar\chi}^{\rm free})h^2 \approx \frac{2.55 \times 10^{-10}\ {\rm GeV}^{-2}}{\langle \sigma v \rangle}$$
$$\approx 0.11 \times \frac{1}{g_\chi^4}\left(\frac{M_\chi}{1\ {\rm TeV}}\right)^2$$

  - If that escaped from false vacuum is dominant: (after annihilation)

$$\Omega_\chi^{\rm free} h^2 = (1 - F_\chi^{\rm trap.}) c_\chi \eta_B s_0 M_\chi$$
$$= 0.036 \times \left(\frac{1 - F_\chi^{\rm trap.}}{0.1}\right)\left(\frac{c_\chi}{0.0146}\right)\left(\frac{M_\chi}{1\ {\rm TeV}}\right)$$

Fermi-ball dark matter

- DM Abundance from our toy model
  - Set the total abundance to observed value of DM by choosing a proper c_χ
- Fermi-balls can explain the full abundance for some c_χ near 10^{-2}
- Fermi-ball fraction is generally high above 80 ~ 90%
  - Increases with $F_\chi^{\text{trap.}}$ as the escaping contribution becomes smaller
  - Increases with g_χ as it suppresses the thermal contribution through efficient annihilation

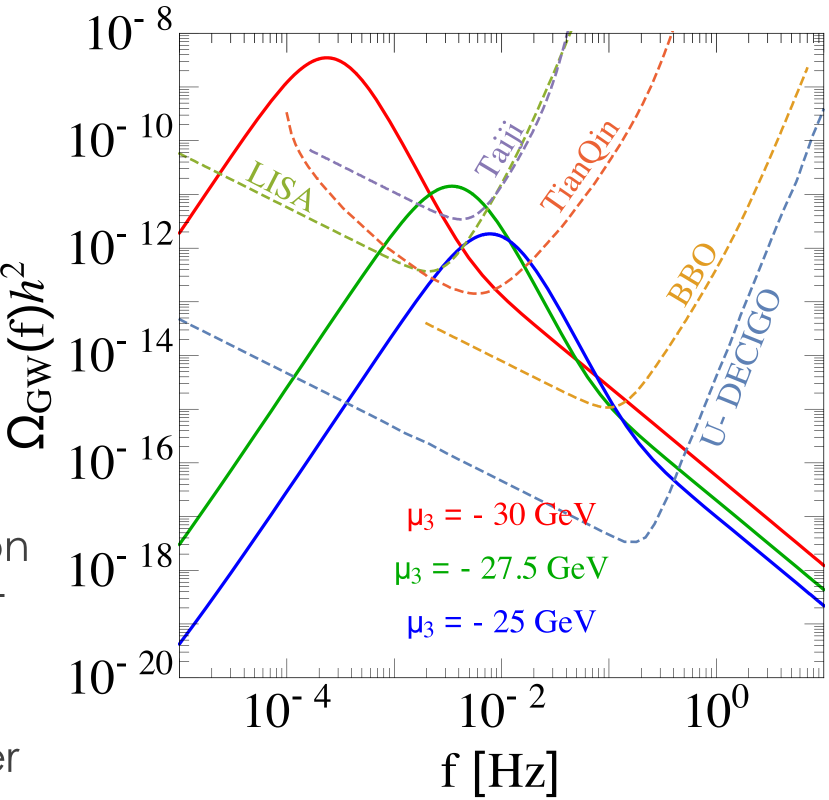


Fermi-ball dark matter

- Direct detection
  - The number density of Fermi-balls is extremely small and it is unlikely to observe Fermi-balls in any direct detection experiments
- Astrophysical signals
  - Although macroscopic in size and mass compared to constituent particles, they are still much small compared to the astrophysical scale
  - They are not that dense, especially of bigger size than Schwarzschild radii, that their gravitational effects are weak
- *It is unlikely that Fermi-ball itself produces detectable signals*
- We investigate a detectable *GW signal from a FOPT*, indirectly related to the Fermi-ball DM

Fermi-ball dark matter

- Observable GW signals are possible at <u>*mHz frequencies*</u> for the weak-scale phase transition, which are relevant to the next-generation space-based GW detectors
- The detection of GWs however <u>*does not necessarily imply a Fermi-ball DM scenario*</u>
  - The GW properties depend only on scalar field dynamics, while Fermi-ball DM depends on the coupling to the fermions
  - Fermi-ball DM is possible in a larger parameter space that may not produce detectable GWs



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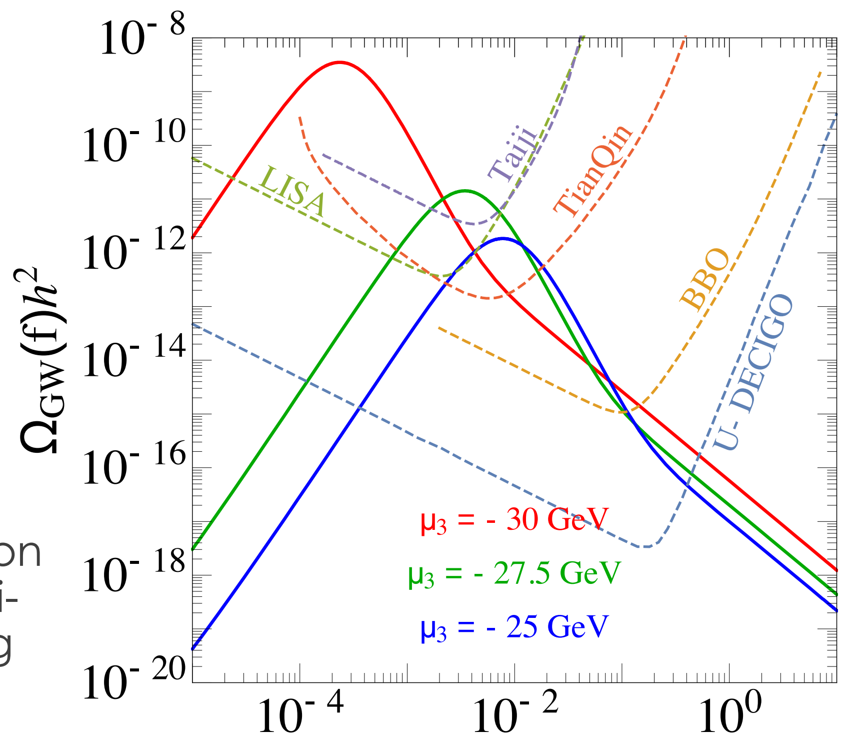

<u>*GW detection and the Fermi-ball DM do not have strong causal connection*</u>

Summary

- We have developed a new DM scenario, where Fermi-balls formed during a strong FOPT can be the DM candidate
- The necessary conditions and ingredients for Fermi-ball DM are discussed and studied in a toy model
- The DM abundance can be explained in a large range of parameter space, determined most crucially by the initial asymmetry and the FOPT scale
- The Fermi-ball DM scenario generally produces no detectable signals
- GWs from FOPT is detectable at the next-generation space-based missions
- GW detection probing FOPT does not necessarily imply a Fermi-ball DM, but would make such a DM scenario more worth considering