Center for Theoretical Physics
SEOUL NATIONAL UNIVERSITY

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

Ke-Pan Xie (谢柯盼)
Seoul National University, Korea

2021.2.3, APCTP dark matter workshop (online)

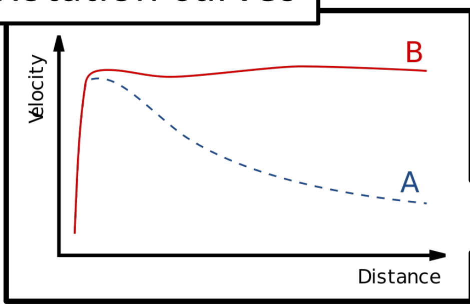
In collaboration with Jeong-Pyong Hong and Sunghoon Jung

Phys.Rev.D 102 (2020) 7, 075028 [arXiv: 2008.04430]

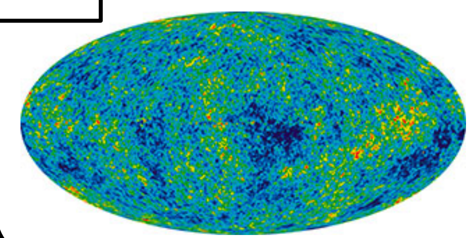
Dark matter as a puzzle in particle physics

- Evidences of dark matter

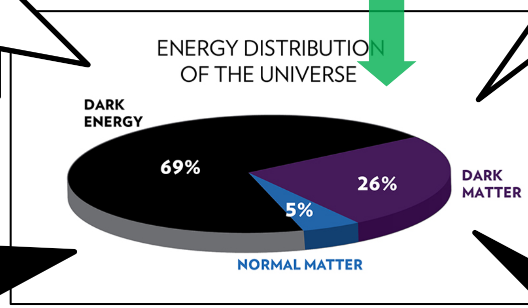
Rotation curves



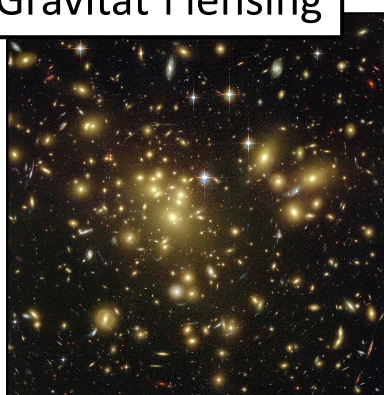
CMB



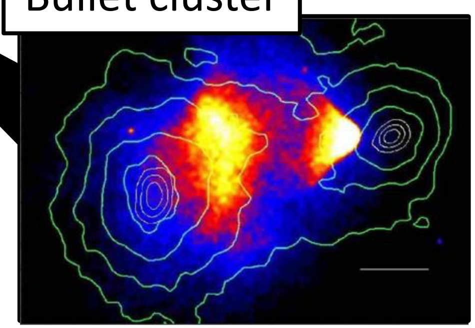
$$\Omega_{\rm DM}h^2 \approx 0.12$$



Gravitat'l lensing



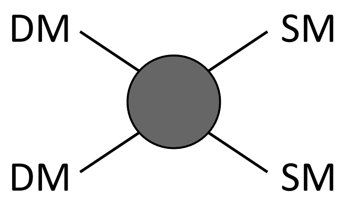
Bullet cluster

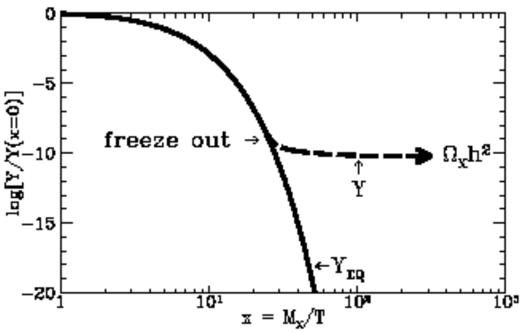


It is there!

- # WIMPs and freeze-out

The "standard explanation" for DM [Lee & Weinberg, PRL1977]





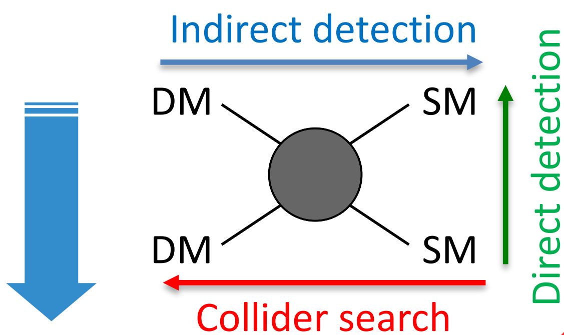
The relic density is estimated as

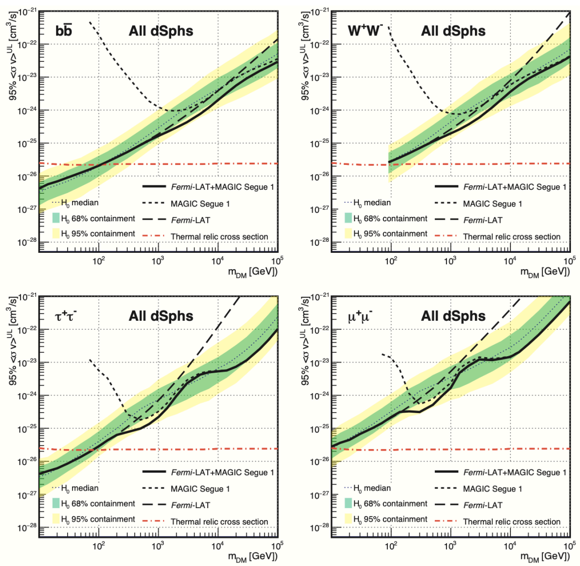
$$\Omega_{\rm DM}h^2 \sim 0.1\left(\frac{0.01}{\alpha_{\rm DM}}\right)^2\left(\frac{M_{\rm DM}}{100\ {\rm GeV}}\right)^2$$

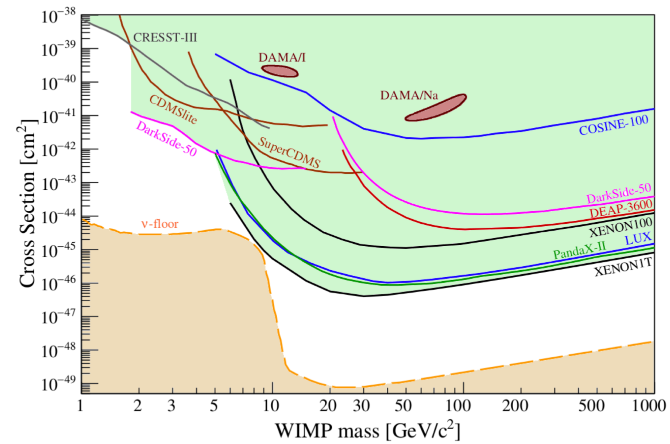
Motivating the <u>weak interacting massive particles</u> (WIMPs)—"WIMP miracle"!

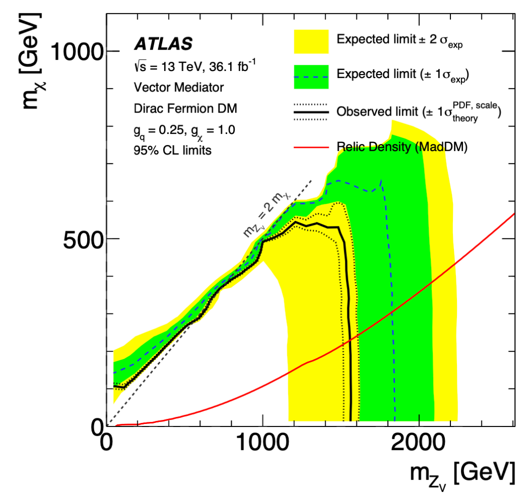
• WIMPs and freeze-out

We have been searching for WIMPs for several decades…



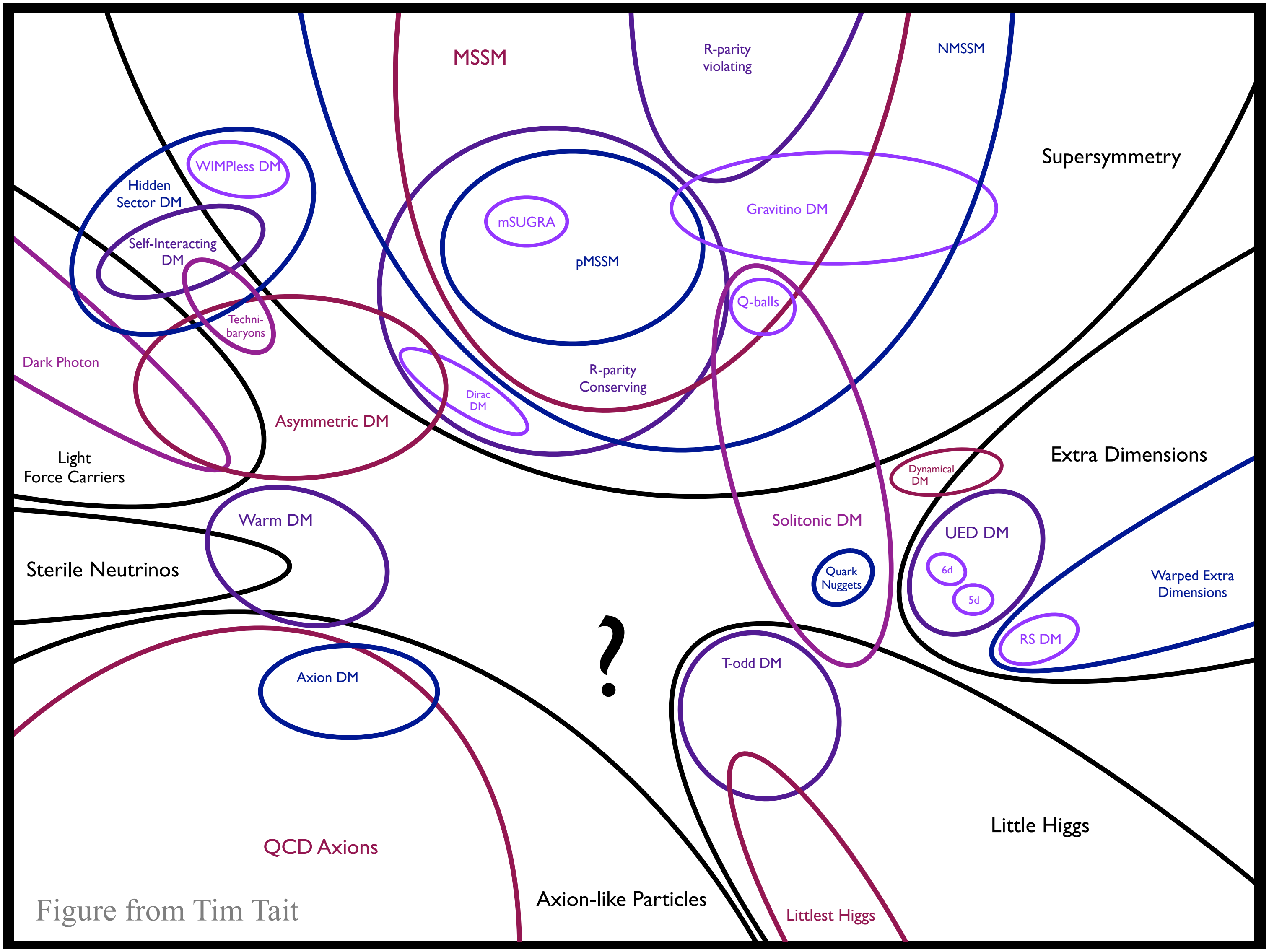






But only obtained null results!! We need ***new mechanisms***?

- # Beyond WIMPs and freeze-out



- Beyond WIMPs and freeze-out

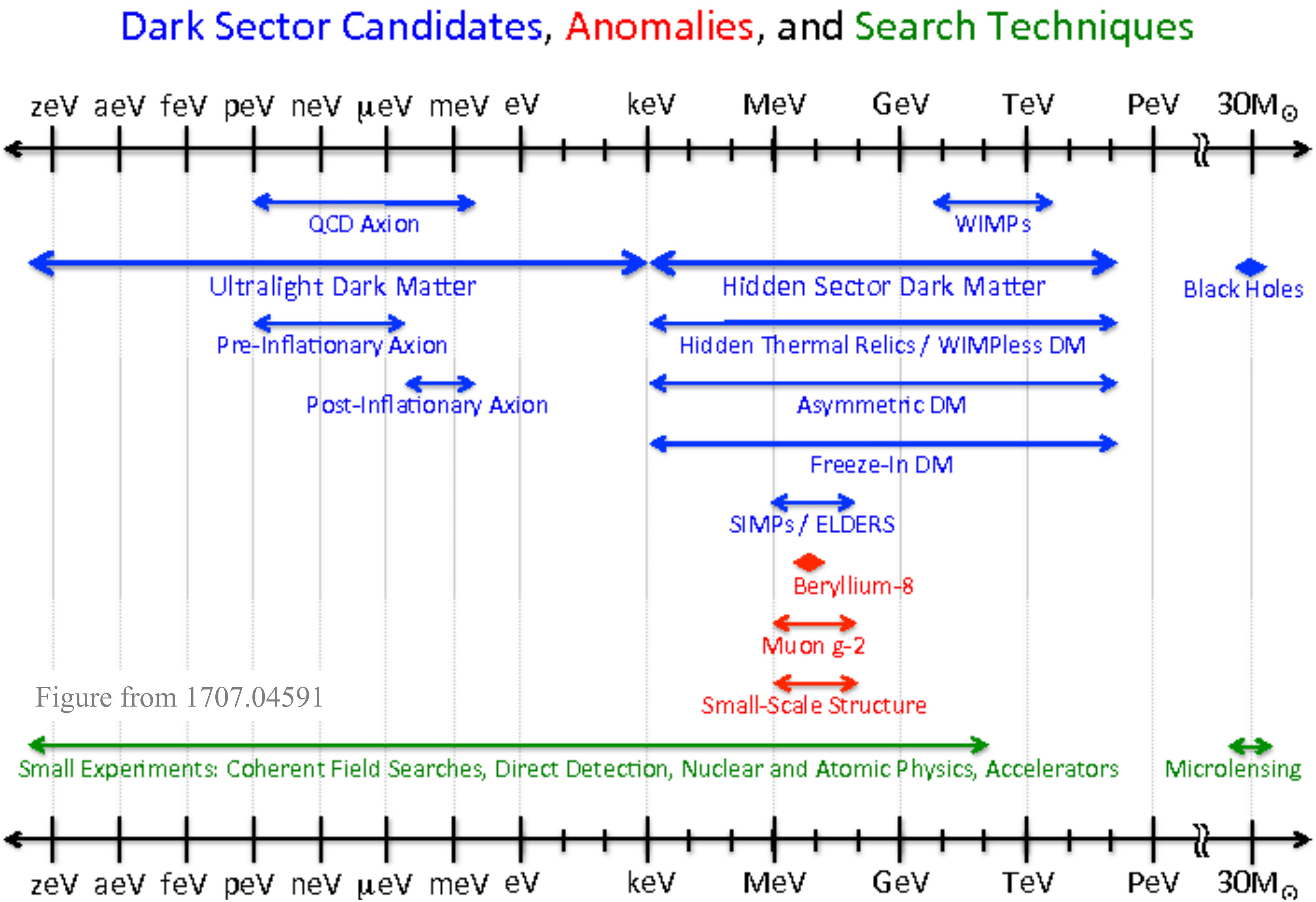
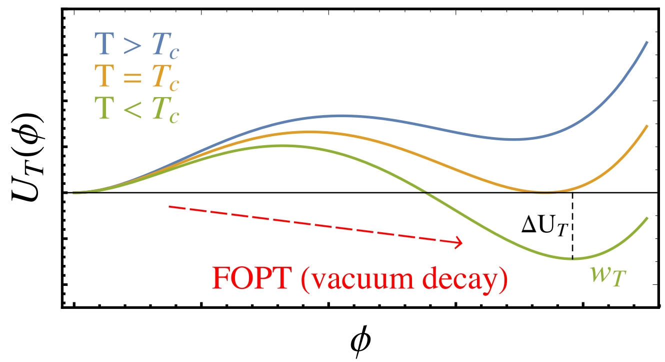


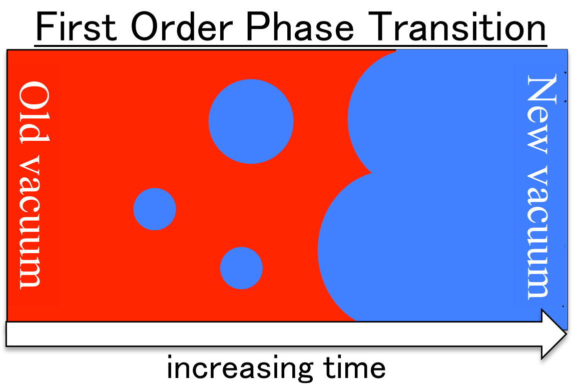
Figure from 1707.04591

Interplay between dark matter and the FOPT

- What is a 1st-order phase transition (FOPT)?

A FOPT is the decay between two vacua separated by a barrier;





Vacuum expectation values of the scalar are different inside and outside the bubbles => Mass of particles are different!

This could provide a background for very rich DM production mechanisms!

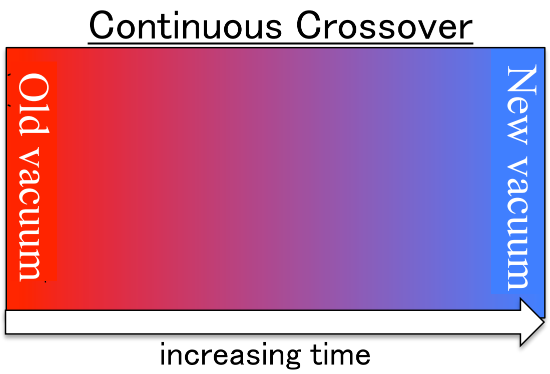
- # How can we achieve a FOPT?

Unfortunately, there is no FOPT in the SM!

Two phase transitions in the SM:

1. Electroweak phase transition;
2. QCD confinement phase transition.

Both are smooth crossover.

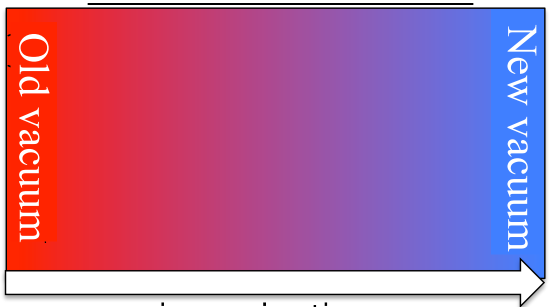


• How can we achieve a FOPT?

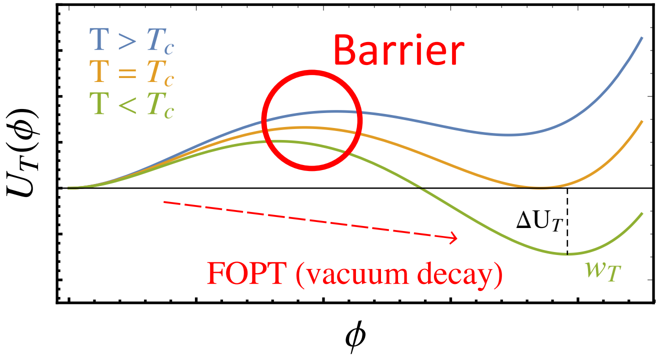
Unfortunately, <u>there is no FOPT in the SM</u>!

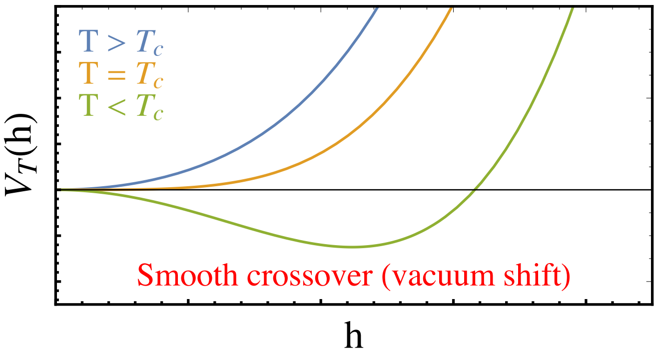
Two phase transitions in the SM:
1. Electroweak phase transition;
2. QCD confinement phase transition.

Both are smooth crossover.



To get a FOPT, we need that a barrier for the (finite temperature) scalar potential.



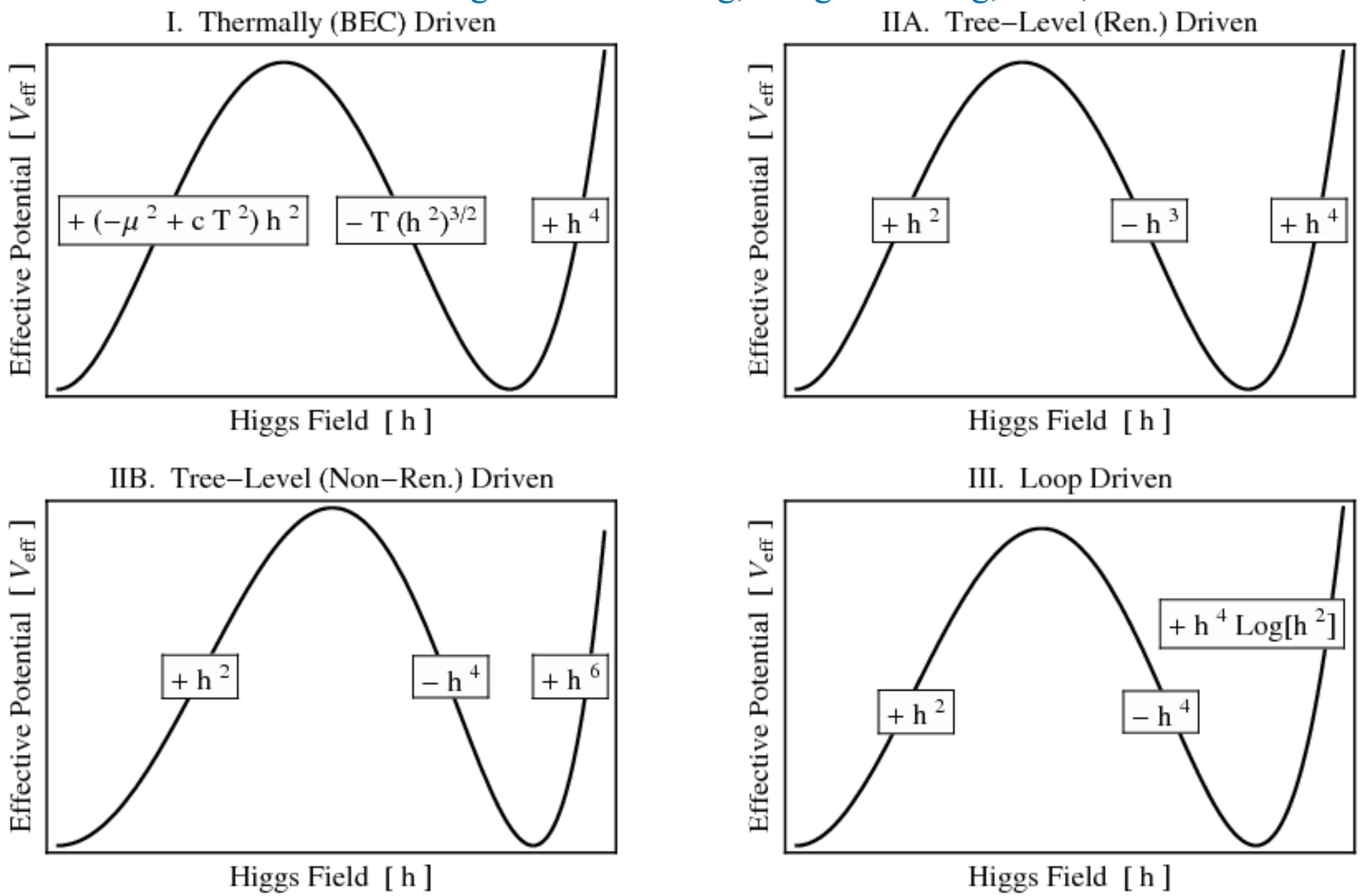


But the SM Higgs potential doesn't have such a barrier!

- # How can we achieve a FOPT?

Adding a barrier (via new physics) to trigger a FOPT!

Figure from: Chung, Long and Wang, PRD, arXiv:1209.1819



(Use Higgs as an illustration but also apply to new physics scalars.)

- # What can a FOPT do for the DM production?

The mass of a particle is discontinuous when crossing the bubble wall. This could –

- ❑ Alter the decay of DM [Baker *et al*, PRL2017]
- ❑ Filter DM to the true vacuum [Baker *et al*, PRL2020; Chway *et al*, PRD2020]
- ❑ Confine quarks into DM nuggets [Witten, PRD1984; Bai *et al*, JHEP2018]
- ❑ ……

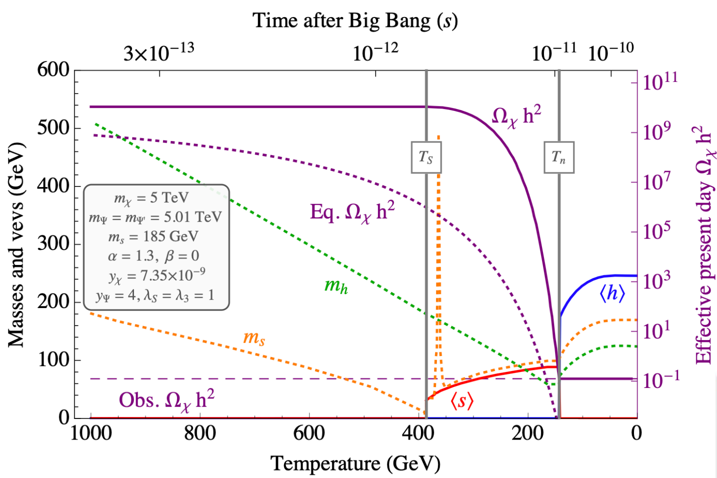


Figure from 1608.07578

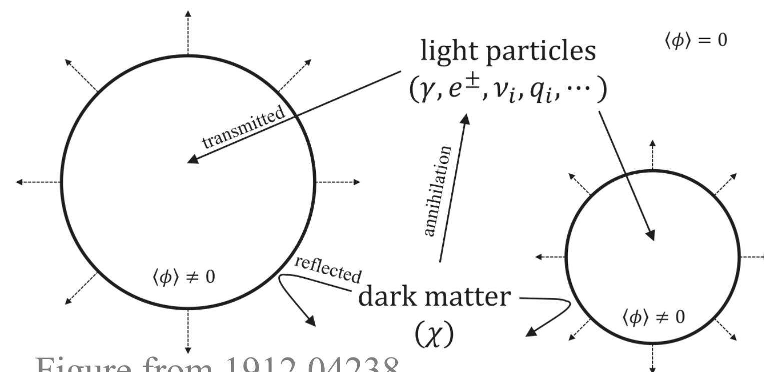
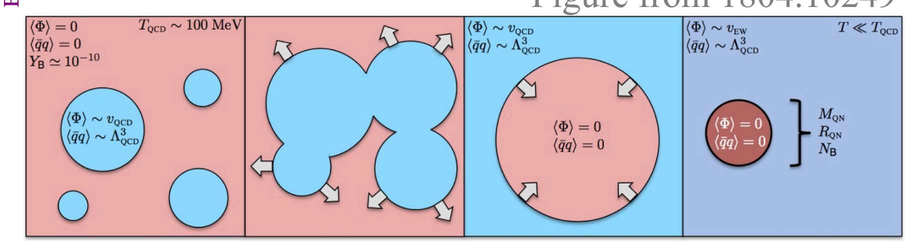


Figure from 1912.04238

Figure from 1804.10249



- # What can a FOPT do for the DM production?

The mass of a particle is discontinuous when crossing the bubble wall. This could –

- ❑ Alter the decay of DM [Baker *et al*, PRL2017]
- ❑ Filter DM to the true vacuum [Baker *et al*, PRL2020; Chway *et al*, PRD2020]
- ❑ Confine quarks into DM nuggets [Witten, PRD1984; Bai *et al*, JHEP2018]
- ❑ ……

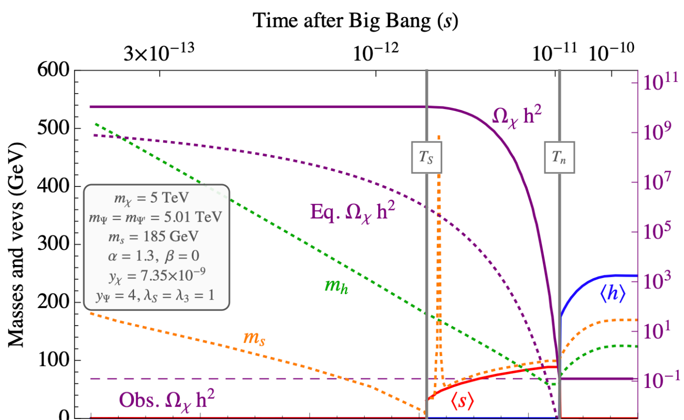


Figure from 1608.07578

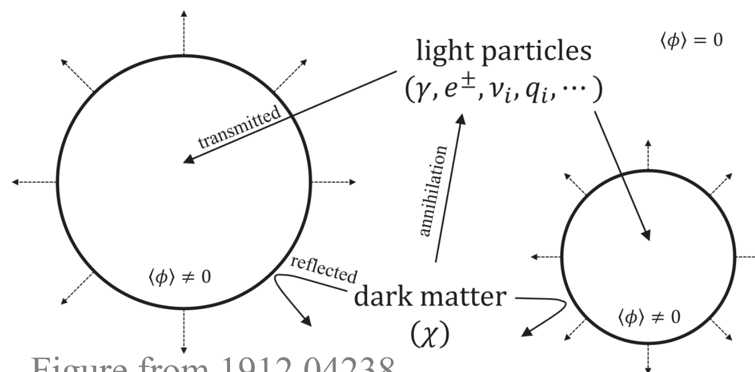
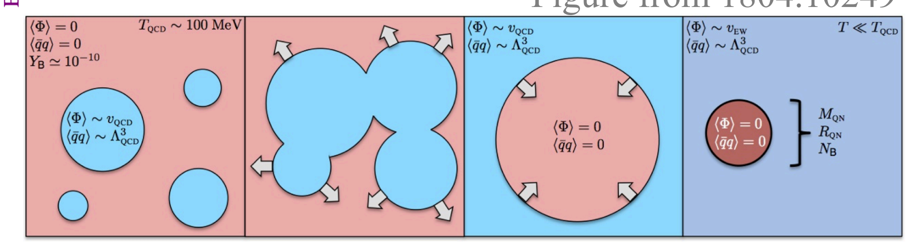


Figure from 1912.04238

Figure from 1804.10249



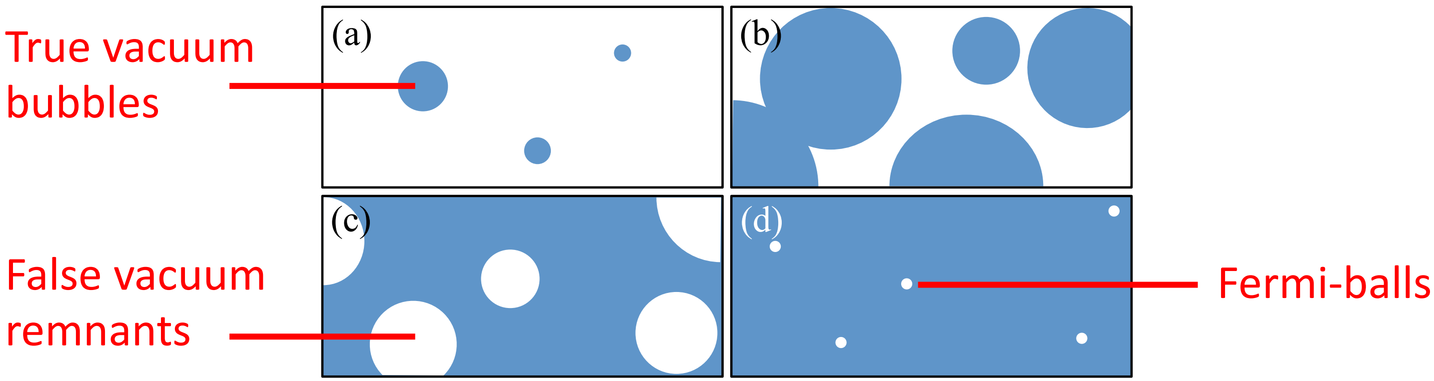
Here we propose a novel mechanism: <u>Fermi-ball</u> from a FOPT.

New!

The Fermi-ball DM from a FOPT

- Summary

During a FOPT, fermions are trapped into the false vacuum to form the non-topological soliton macroscope DM candidate.

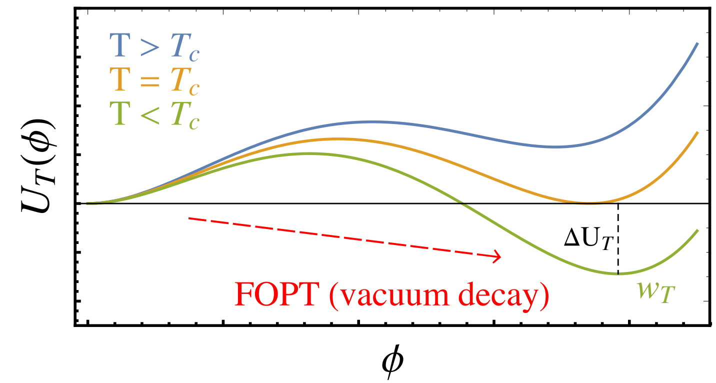


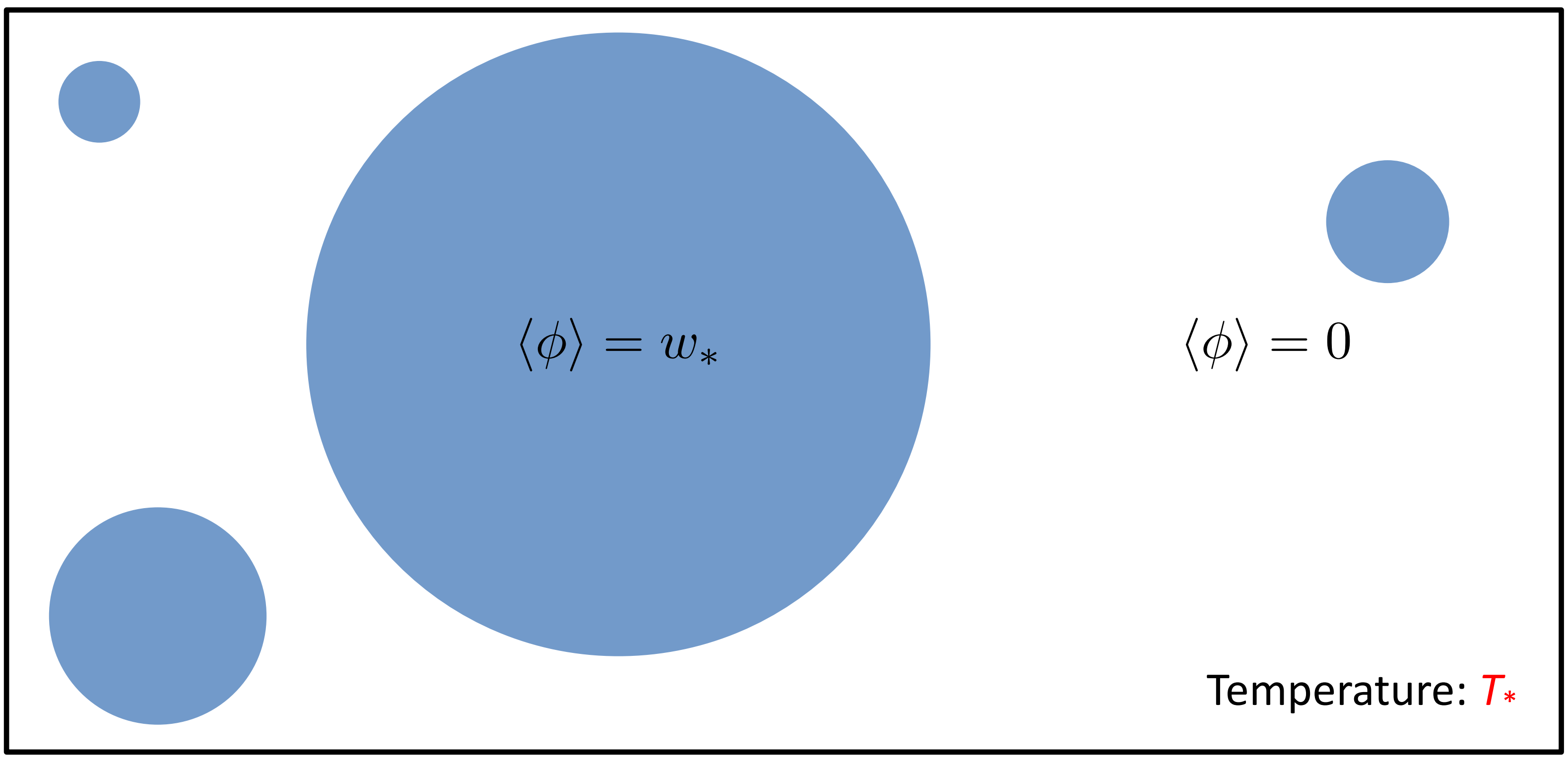
- ✓ We propose a general mechanism which requires three necessary conditions;
- ✓ Our mechanism applies to a wide varieties of new physics models.

- # Sketch of the Fermi-ball DM

Condition 0:
A FOPT triggered by a scalar field ϕ.

The standard FOPT description, satisfied in a lot of models.



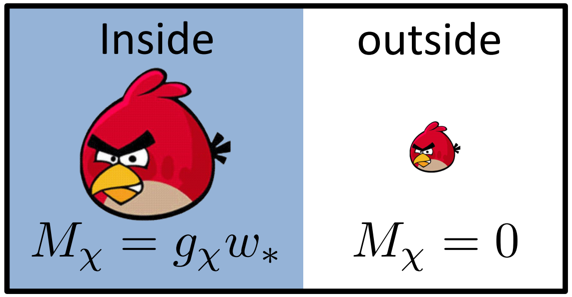


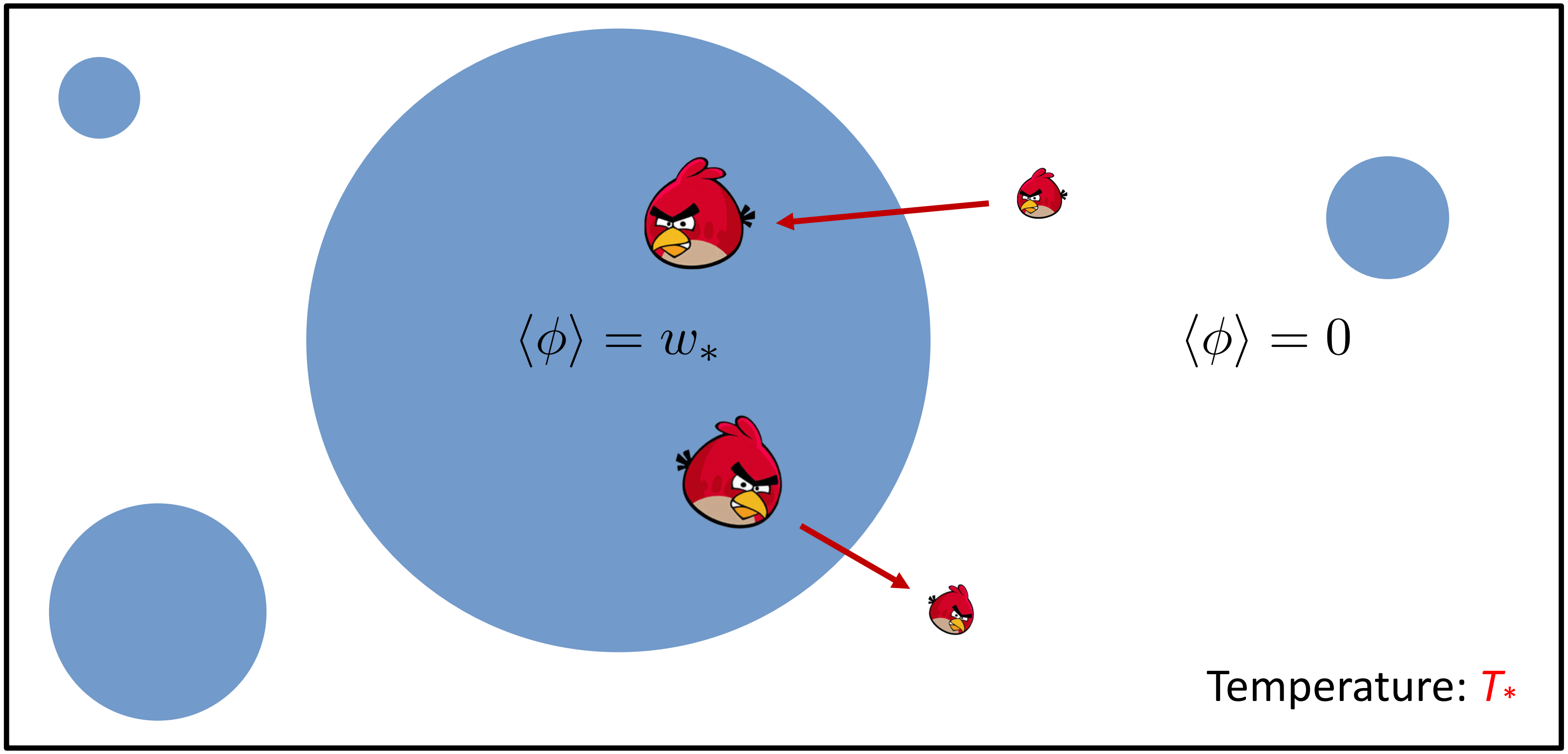
• Sketch of the Fermi-ball DM

$$\mathcal{L} \supset -g_\chi \bar{\chi}\chi\phi$$

<u>Condition 1.1</u>:
A Dirac fermion field χ interacting with ϕ.

χ is massless outside the bubble, while massive inside the bubble.

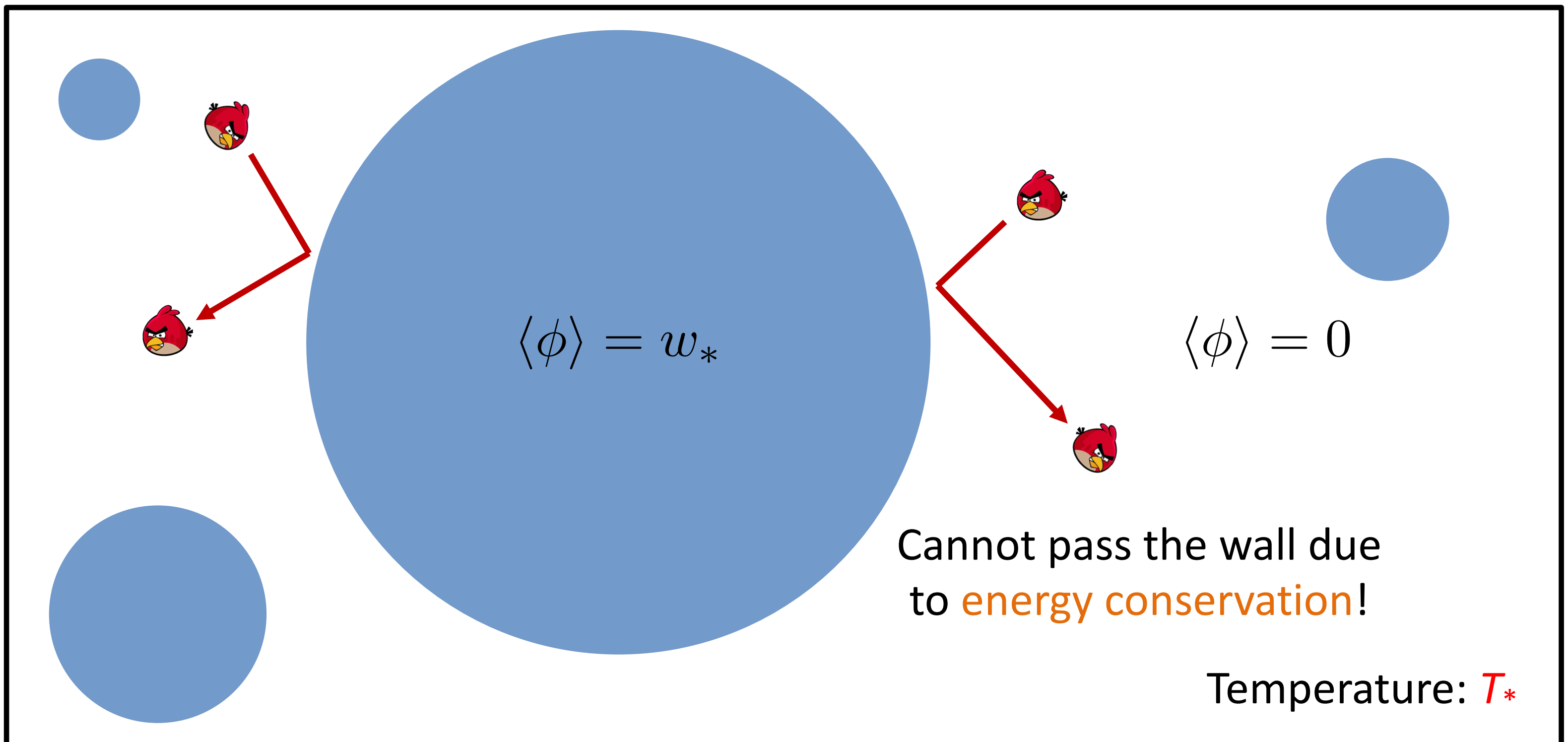




- Sketch of the Fermi-ball DM

Condition 1.2:
Mass gap much larger than kinetic energy: $M_\chi = g_\chi w_* >> T_*$.

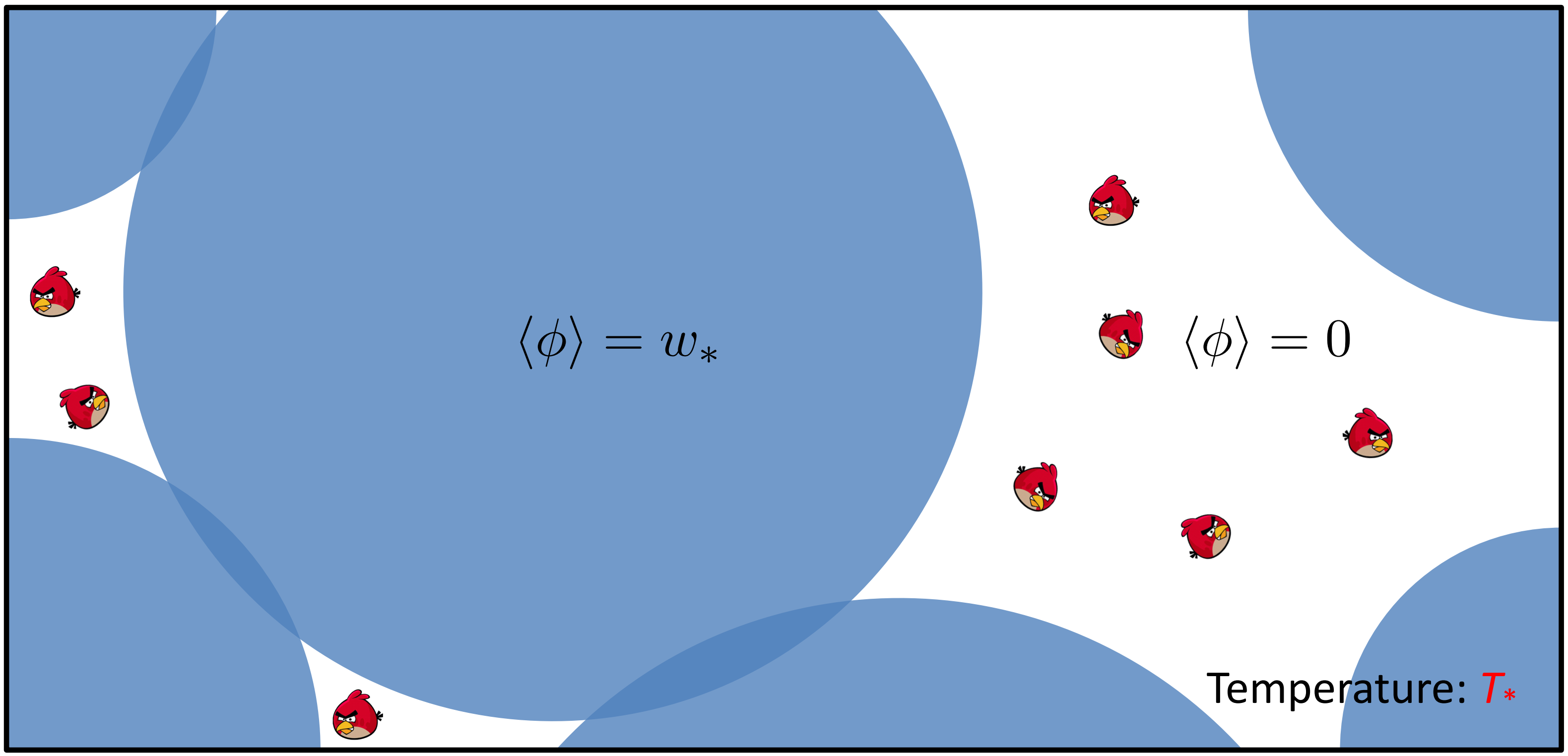
i) Large coupling $g_\chi >> 1$; [Carena *et al*, NPB2005; Angelescu *et al*, PRD2019; …]
ii) Supercooling $w_* >> T_*$. [Creminelli *et al*, JHEP2002; Ellis *et al*, JCAP2019; …]



- # Sketch of the Fermi-ball DM

<u>Condition 1.2</u>:
Mass gap much larger than kinetic energy: $M_\chi = g_\chi w_* >> T_*$.

i) Large coupling $g_\chi >> 1$; [Carena *et al*, NPB2005; Angelescu *et al*, PRD2019; …]
ii) Supercooling $w_* >> T_*$. [Creminelli *et al*, JHEP2002; Ellis *et al*, JCAP2019; …]



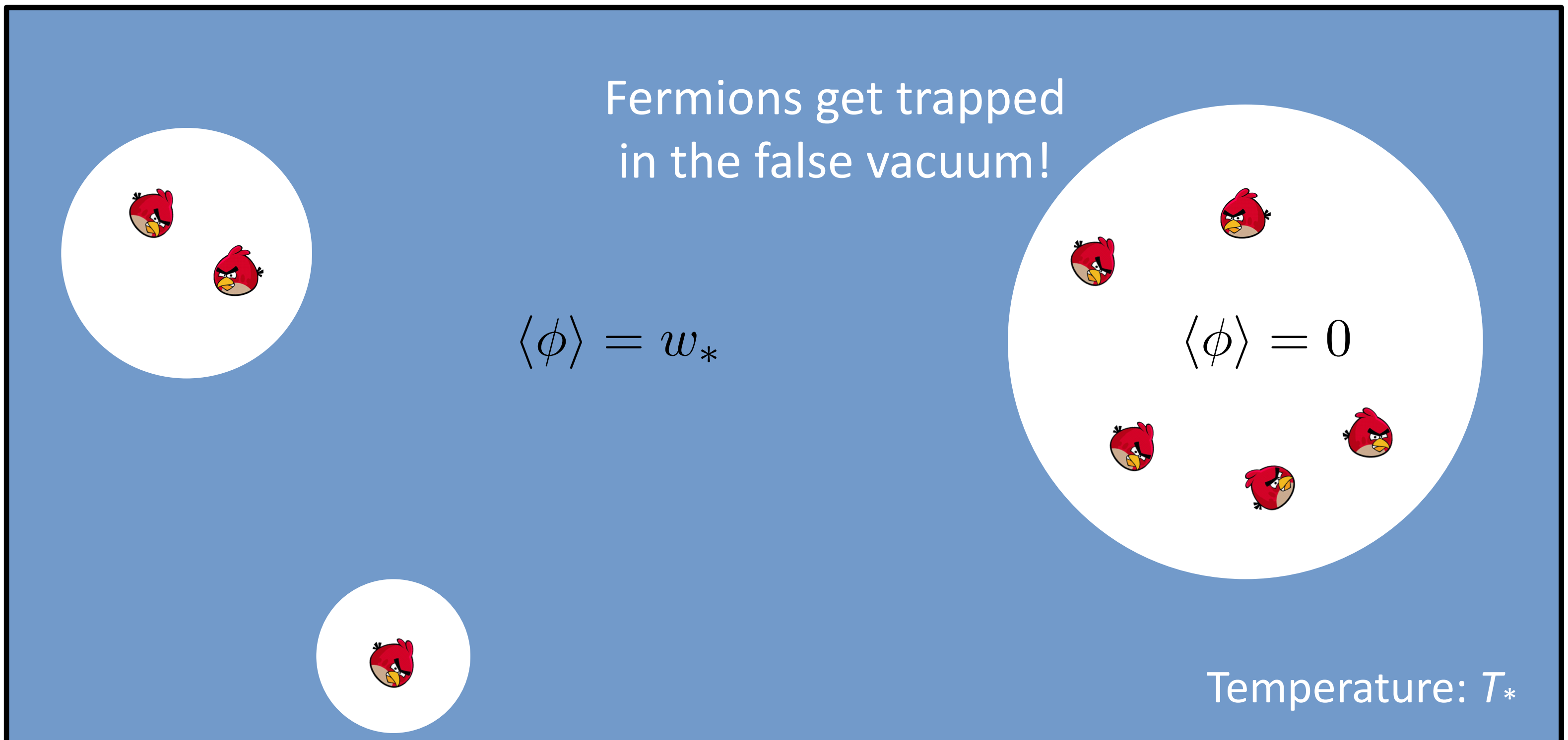
• Sketch of the Fermi-ball DM

<u>Condition 1.2</u>:

Mass gap much larger than kinetic energy: $M_\chi = g_\chi w_* >> T_*$.

i) Large coupling $g_\chi >> 1$; [Carena *et al*, NPB2005; Angelescu *et al*, PRD2019; …]

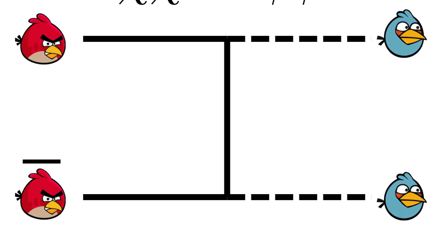
ii) Supercooling $w_* >> T_*$. [Creminelli *et al*, JHEP2002; Ellis *et al*, JCAP2019; …]

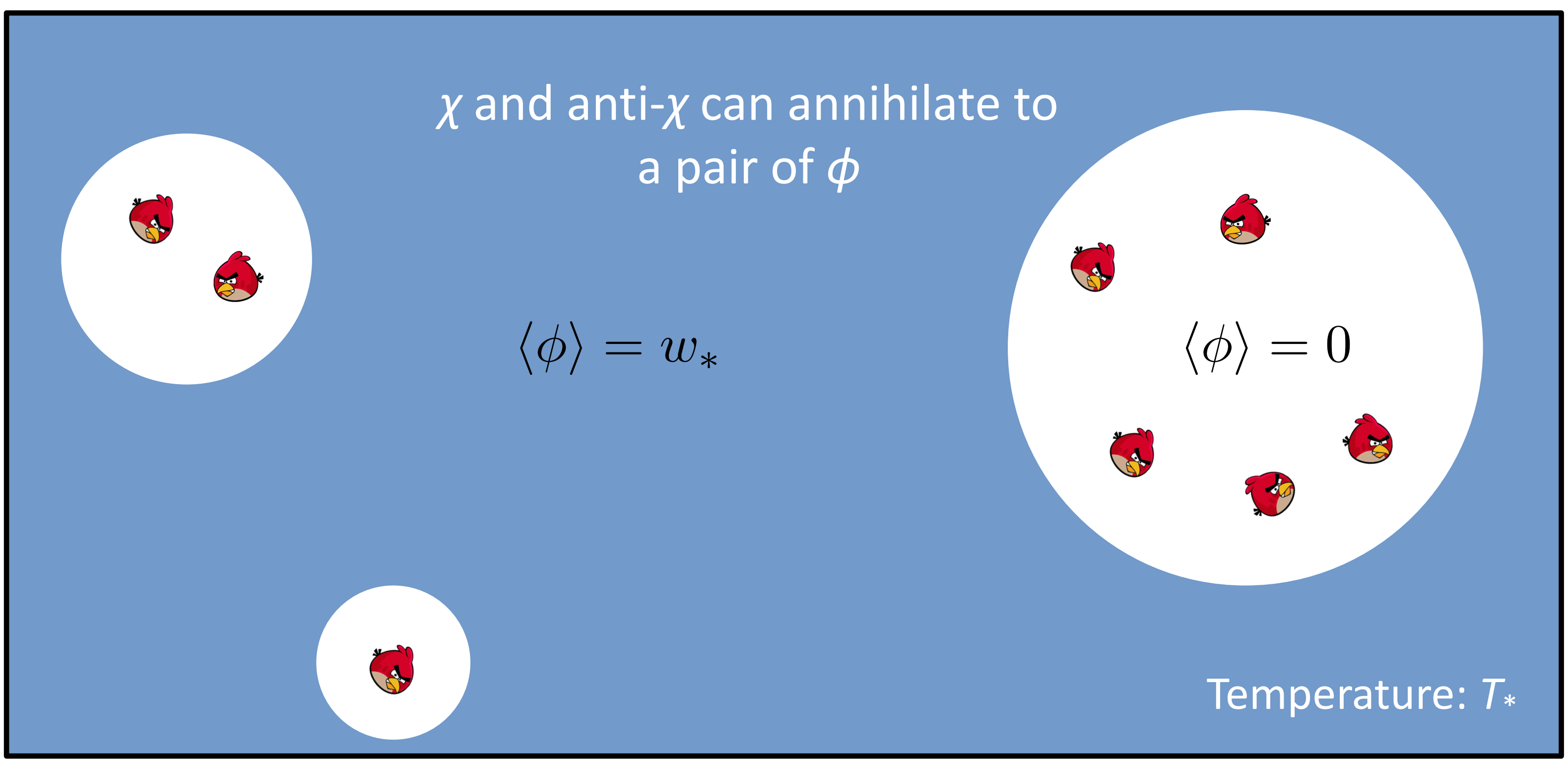


• Sketch of the Fermi-ball DM

$$\mathcal{L} \supset -g_\chi \bar{\chi}\chi\phi$$

$$\chi\bar{\chi} \to \phi\phi$$

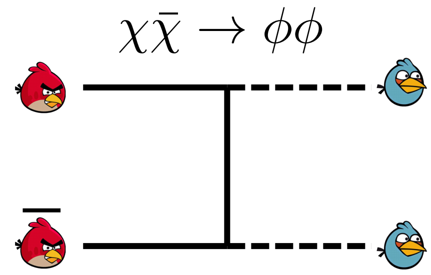


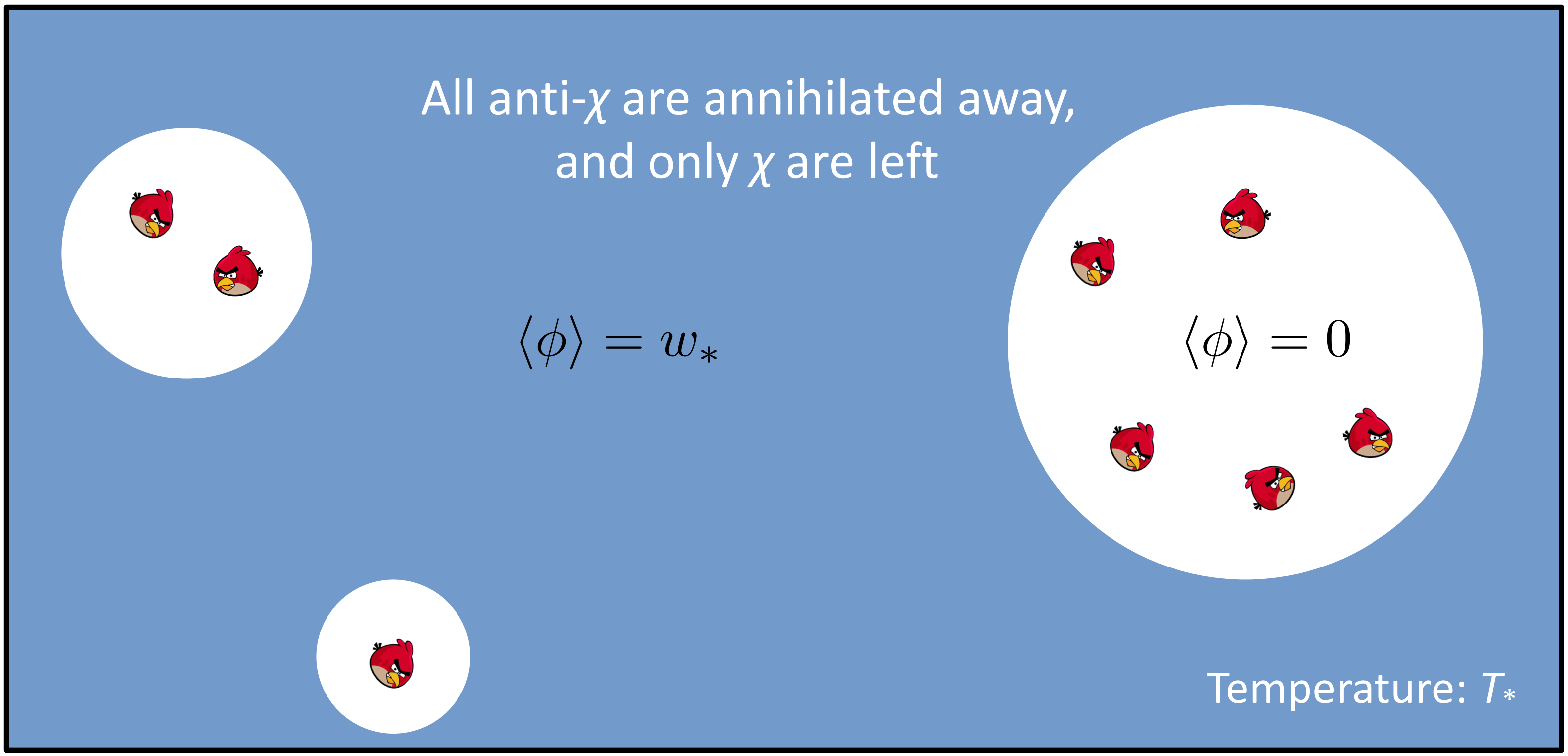


- # Sketch of the Fermi-ball DM

<u>Condition 2</u>:
There is a *χ-asymmetry*: $n(\chi) > n(\bar{\chi})$,

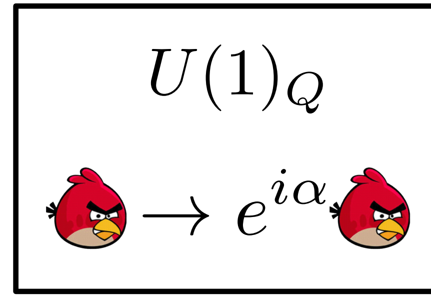
Generally achieved in asymmetric DM models[Kaplan *et al*, PRD2009; Petraki *et al*, IJMPA2013; …]



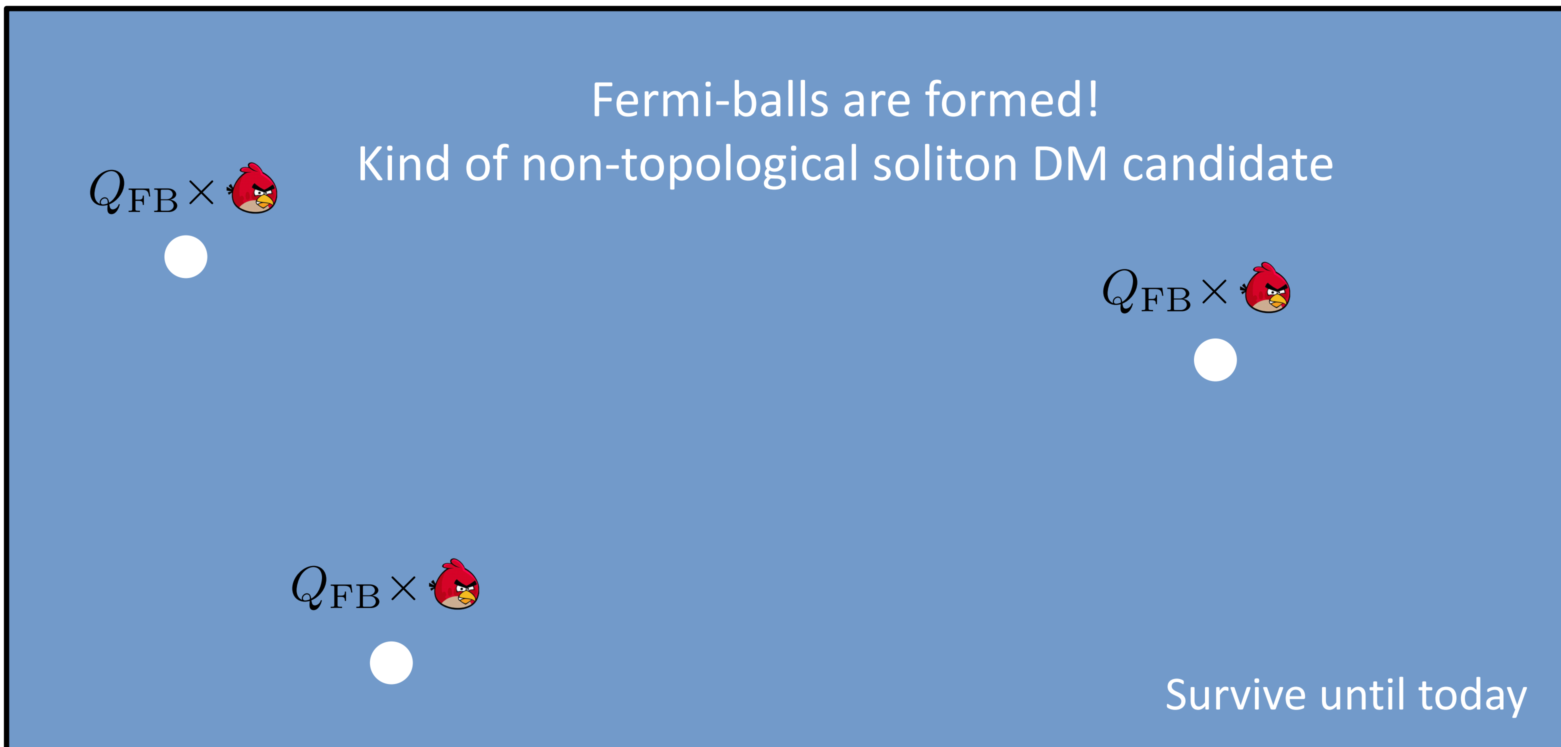


• Sketch of the Fermi-ball DM

Condition 3:
χ carries a conserved U(1) charge Q, so that the Fermi-balls are stable.



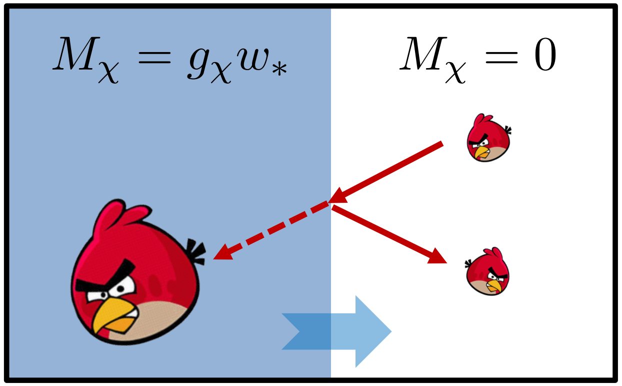
Satisfied in $\mathcal{L} \supset -g_\chi \bar{\chi}\chi\phi$, which is general.



- Quantitative calculation: condition 1 -- trapping

1) In wall frame: χ in equilibrium

$$\tilde{f}_\chi^{\text{f.v.}}(\mathbf{p}) = \frac{1}{e^{(\gamma_b|\mathbf{p}|+\gamma_b v_b p_z-\mu_\chi)/T_*}+1}$$



Wall velocity v_b

2) Particle current

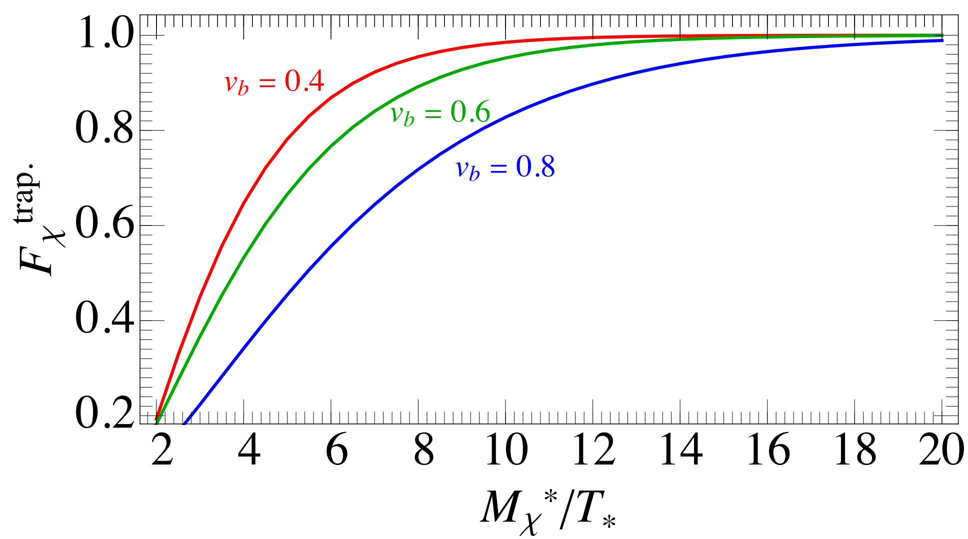
$$\tilde{J}_\chi = 2\int \frac{d^3\mathbf{p}}{(2\pi)^3}\frac{-p_z}{|\mathbf{p}|}\tilde{f}_\chi^{\text{f.v.}}(\mathbf{p})\Theta(-p_z - M_\chi^*)$$

3) Back to plasma frame: trapping fraction [Chway *et al*, PRD2020]

$$J_\chi = \tilde{J}_\chi(1-v_b^2)^{1/2},$$
$$n_\chi^{\text{pene.}} = J_\chi/v_b,$$

$$F_\chi^{\text{trap.}} = 1 - \frac{n_\chi^{\text{pene.}}}{n_\chi^{\text{f.v.}}}$$

Fraction of χ trapped in the false vacuum



• Quantitative calculation: condition 2 -- χ-asymmetry

A leptogenesis[Luty, PRD1992] -like mechanism $n($$) > n(\overline{}$$)$

Right-handed neutrino

$$\mathcal{L} \supset \bar{\nu}_R^i i\gamma^\mu \partial_\mu \nu_R^i - \sum_j \frac{1}{2} M_j \left(\overline{\nu_R^c}^j \nu_R^j + \text{h.c.} \right)$$

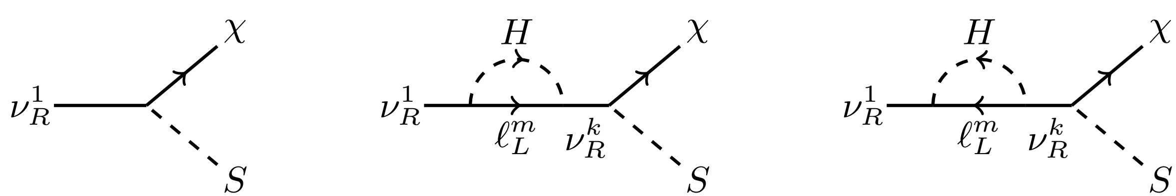
$$- \sum_{i,j} \lambda_\nu^{ij} \bar{\ell}_L^i H \nu_R^j - \sum_j \lambda_\chi^j \bar{\chi}_L S \nu_R^j + \text{h.c.}$$

Seesaw Yukawa (with CPV phase)

Our plugin. S: a singlet scalar

ν_R decay generates the asymmetry

$$\Gamma(\nu_R^1 \to \chi S) > \Gamma(\nu_R^1 \to \bar{\chi} S)$$



Result:

$$\eta_\chi \equiv \frac{n_\chi - n_{\bar{\chi}}}{s} \approx \frac{1}{6} \left(1 - \frac{M_S^2}{M_1^2} \right)^2 \eta_B \equiv c_\chi \eta_B$$

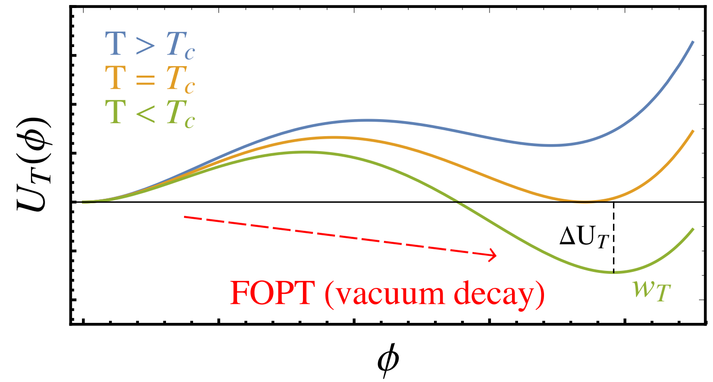
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{s} \approx 10^{-10}$$

- # Quantitative calculation: Fermi-ball formation

Decay of the false vacuum [FOPT]

$$\Gamma(T) \sim T^4 \exp\{-S_3(T)/T\}$$

Classical action [model-dependent]



$p(T)$: the fraction of false vacuum in the Universe [Guth *et al* PRD1981]

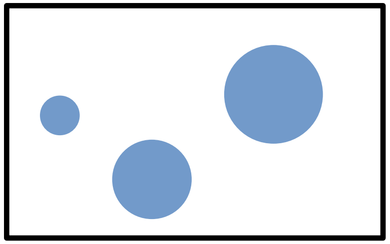
$$p(T) = e^{-I(T)}, \quad I(T) = \frac{4\pi}{3}\int_T^{T_c} dT' \frac{\Gamma(T')}{T'^4 H(T')}\left[\int_T^{T'} d\tilde{T}\frac{v_b}{H(\tilde{T})}\right]^3$$

$p(T)$ decreases monotonically from 1 to 0 as the FOPT proceeds.

There are several important milestones during a FOPT.

• Quantitative calculation: Fermi-ball formation

The processing of a FOPT



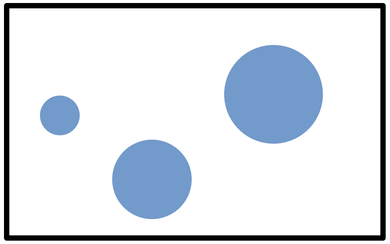
1. Nucleation

$p(T)$: the fraction of false vacuum in the Universe [Guth *et al* PRD1981]

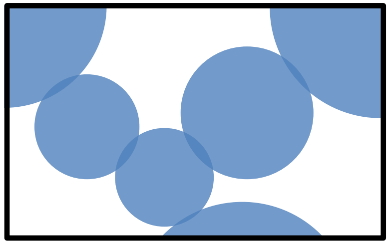
1) True vacuum bubbles start to nucleate: $p(T_n) < 1$;

- # Quantitative calculation: Fermi-ball formation

The processing of a FOPT



1. Nucleation



2. Percolation

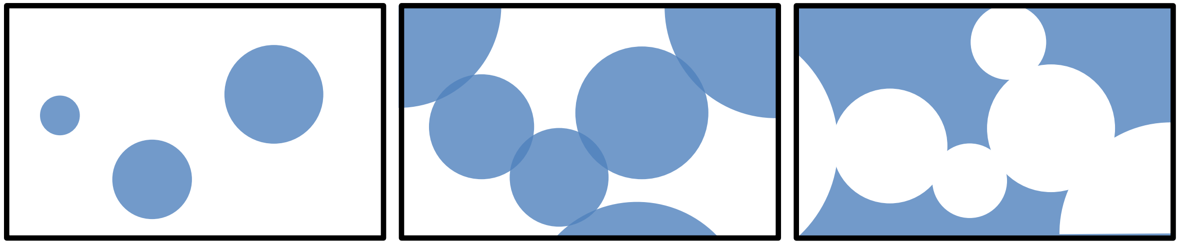
$p(T)$: the fraction of false vacuum in the Universe [Guth *et al* PRD1981]

1) True vacuum bubbles start to nucleate: $p(T_n) < 1$;

2) Bubbles form an infinite connected cluster: $p(T_p) = 0.71$;

- Quantitative calculation: Fermi-ball formation

The processing of a FOPT



1. Nucleation 2. Percolation 3. Fermi-ball formation

$p(T)$: the fraction of false vacuum in the Universe [Guth *et al* PRD1981]

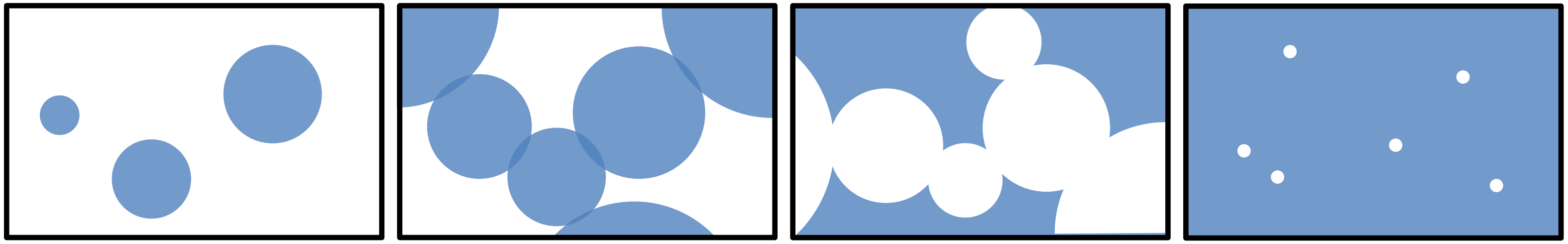
1) True vacuum bubbles start to nucleate: $p(T_n) < 1$;

2) Bubbles form an infinite connected cluster: $p(T_p) = 0.71$;

3) <u>False vacuum remnants are not able to form an infinite connected cluster</u>, and Fermi-balls are formed: $p(T_*) = 0.29$;

- # Quantitative calculation: Fermi-ball formation

The processing of a FOPT



1. Nucleation 2. Percolation 3. Fermi-ball formation 4. Today

$p(T)$: the fraction of false vacuum in the Universe [Guth *et al* PRD1981]

1) True vacuum bubbles start to nucleate: $p(T_n) < 1$;

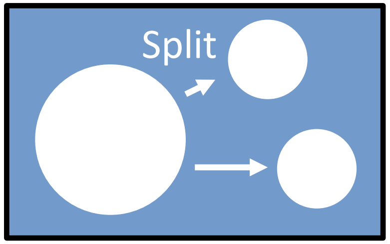
2) Bubbles form an infinite connected cluster: $p(T_p) = 0.71$;

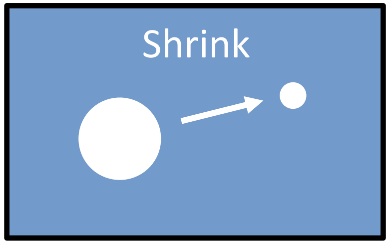
3) False vacuum remnants are not able to form an infinite connected cluster, and Fermi-balls are formed: $p(T_*) = 0.29$;

4) Fermi-balls survive today: $p(T_0) \approx 0$.

- Quantitative calculation: Fermi-ball formation

At the 3) step, the false vacuum remnants first split then shrink:



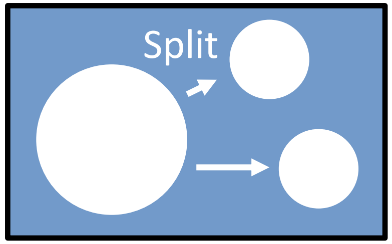


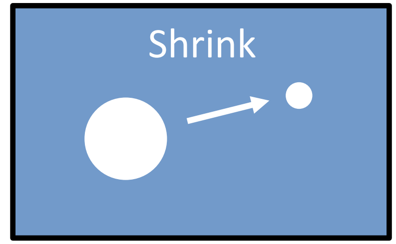
The critical size R_* of a remnant at the end of splitting and the beginning of shrinking:

> It shrinks to negligible size before another bubble containing the true vacuum is created inside it.

• Quantitative calculation: Fermi-ball formation

At the 3) step, the false vacuum remnants first split then shrink:





The critical size R_* of a remnant at the end of splitting and the beginning of shrinking:

> It shrinks to negligible size before another bubble containing the true vacuum is created inside it.

Therefore

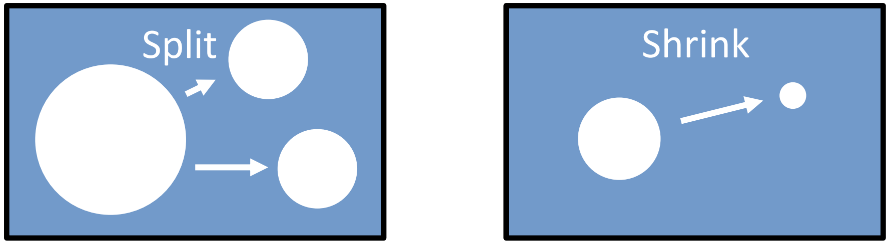
$$\Gamma(T_*)V_*\Delta t \sim 1, \quad V_* = \frac{4\pi}{3}R_*^3, \quad \Delta t = \frac{R_*}{v_b}$$

Hence the critical size

$$R_* = \left(\frac{3v_b}{4\pi\Gamma(T_*)}\right)^{1/4}, \quad V_* = \left(\frac{4\pi}{3}\right)^{1/4}\left(\frac{v_b}{\Gamma(T_*)}\right)^{3/4}$$

- Fermi-ball profiles right after formation

At the 3) step, the false vacuum remnants first split then shrink:



The critical size R_* of a remnant at the end of splitting and the beginning of shrinking

$$R_* = \left(\frac{3v_b}{4\pi\Gamma(T_*)}\right)^{1/4}, \quad V_* = \left(\frac{4\pi}{3}\right)^{1/4}\left(\frac{v_b}{\Gamma(T_*)}\right)^{3/4}$$

And at this point we have

$$n_{\rm FB}^* V_* = p(T_*) = 0.29$$

Therefore

$$n_{\rm FB}^* = \left(\frac{3}{4\pi}\right)^{1/4}\left(\frac{\Gamma(T_*)}{v_b}\right)^{3/4} p(T_*), \quad Q_{\rm FB}^* = F_\chi^{\rm trap.}\frac{c_\chi \eta_B s_*}{n_{\rm FB}^*}$$

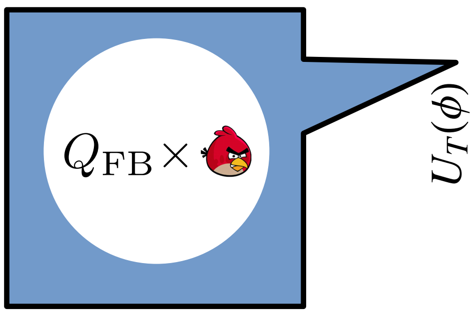
• Fermi-ball profiles today

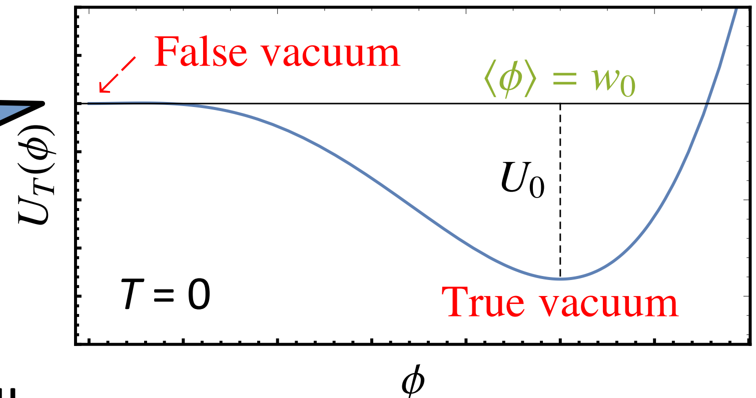
Linking the profiles at T_* to today:

$$n_{\rm FB} = \frac{n_{\rm FB}^*}{s_*} s_0, \quad Q_{\rm FB} = Q_{\rm FB}^*$$

s: entropy density of the universe

A single Fermi-ball





The energy of a Fermi-ball:

Surface tension (negligible)

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

Fermi-gas kinetic energy — Volume energy

The radius is determined by dE/dR = 0.

Fermi-ball profiles today

Minimizing *E* yields the profile

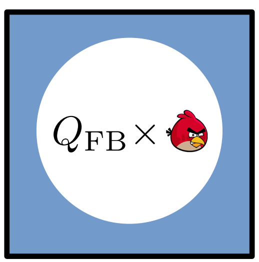
$$M_{\rm FB} = Q_{\rm FB}\left(12\pi^2 U_0\right)^{1/4}, \quad R_{\rm FB} = Q_{\rm FB}^{1/3}\left[\frac{3}{16}\left(\frac{3}{2\pi}\right)^{2/3}\frac{1}{U_0}\right]^{1/4}$$

Density of a single Fermi-ball

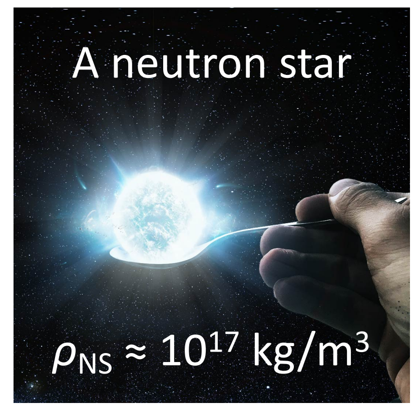
$$M_{\rm FB}/V_{\rm FB} = 9.15\times 10^{28}\ {\rm kg/m^3}\left(\frac{U_0^{1/4}}{100\ {\rm GeV}}\right)^4$$

Very compact!

A single Fermi-ball



is more compact than



But not as compact as a *Q*-ball [Krylov et al, PRD2013]: $\rho_{\rm QB} \approx 10^{36}$ kg/m^3, due to the Pauli exclusion principle.

- # Fermi-ball as DM candidate

Relic density of the Fermi-balls [c_χ is the χ-asymmetry factor]

$$\Omega_{\rm FB} h^2 = \frac{n_{\rm FB} M_{\rm FB}}{\rho_c} h^2 = 0.12 \times \left(\frac{c_\chi U_0^{1/4}}{1.146 \text{ GeV}} \right)$$

To achieve the **DM density**:

- ❑ $c_\chi \approx 1$, $U_0^{1/4} \approx 1$ GeV?
- ❑ $c_\chi \approx 0.01$, $U_0^{1/4} \approx 100$ GeV?

The former case is stringently constrained; we consider the latter.

- # Fermi-ball as DM candidate

Relic density of the Fermi-balls [c_χ is the χ-asymmetry factor]

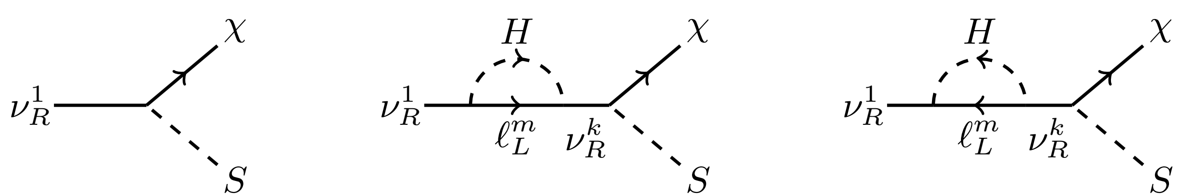
$$\Omega_{\rm FB}h^2=\frac{n_{\rm FB}M_{\rm FB}}{\rho_c}h^2=0.12\times\left(\frac{c_\chi U_0^{1/4}}{1.146~{\rm GeV}}\right)$$

To achieve the **DM density**:

- ❑ $c_\chi \approx 1$, $U_0^{1/4} \approx 1$ GeV?
- ❑ $c_\chi \approx 0.01$, $U_0^{1/4} \approx 100$ GeV?

The former case is stringently constrained; we consider the latter.

Reminder: $\Gamma(\nu_R^1\to\chi S)>\Gamma(\nu_R^1\to\bar\chi S)$



A small c_χ is not that weird!
e.g. $M_S = 4M_1/5$, $c_\chi = 0.02$.

$$\eta_\chi\equiv\frac{n_\chi-n_{\bar\chi}}{s}\approx\frac{1}{6}\left(1-\frac{M_S^2}{M_1^2}\right)^2\eta_B\equiv c_\chi\eta_B$$

- # Fermi-ball as DM candidate

Reminder: vacuum decay rate $T_*^4 e^{-S_3(T_*)/T_*}$
For a EW scale phase transition & a radiation-dominated universe

$$\boxed{\frac{S_3(T_*)}{T_*} \sim 140}$$

Hence we can normalize the profiles to

$$M_{\rm FB} \approx \underline{4.84 \times 10^{11}\ \text{kg}} \times \left(\frac{c_\chi}{0.0146}\right)\left(\frac{U_0^{1/4}}{100\ \text{GeV}}\right)\left(\frac{v_b}{0.6}\right)^{3/4} \exp\left\{\frac{3}{4}\left(\frac{S_3(T_*)}{T_*} - 140\right)\right\},$$

$$R_{\rm FB} \approx \underline{1.08 \times 10^{-6}\ \text{m}} \times \left(\frac{c_\chi}{0.0146}\right)^{1/3}\left(\frac{100\ \text{GeV}}{U_0^{1/4}}\right)\left(\frac{v_b}{0.6}\right)^{1/4} \exp\left\{\frac{1}{4}\left(\frac{S_3(T_*)}{T_*} - 140\right)\right\},$$

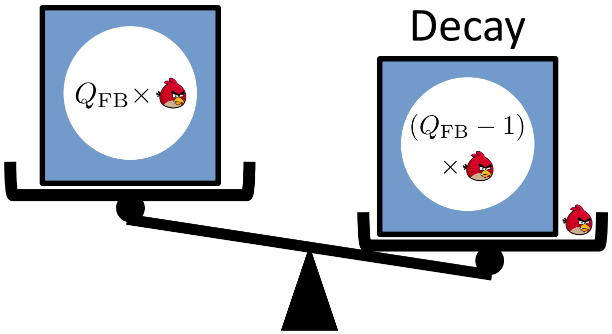
$$Q_{\rm FB} \approx \underline{8.26 \times 10^{35}} \times \left(\frac{c_\chi}{0.0146}\right)\left(\frac{v_b}{0.6}\right)^{3/4} \exp\left\{\frac{3}{4}\left(\frac{S_3(T_*)}{T_*} - 140\right)\right\},$$

$$n_{\rm FB} \approx \underline{4.60 \times 10^{-39}\ \text{m}^{-3}} \times \left(\frac{0.6}{v_b}\right)^{3/4} \exp\left\{-\frac{3}{4}\left(\frac{S_3(T_*)}{T_*} - 140\right)\right\}.$$

But the pre-factors are only very rough estimations, because of the <u>exponents</u> behind them!

- Stability of the Fermi-ball

Decay: a Fermi-ball should not emit a χ fermion



Effective mass per χ

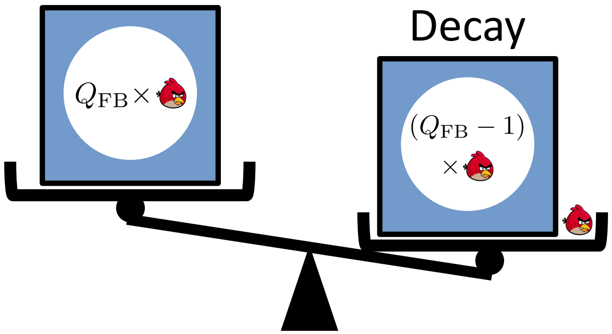
$$M_{\rm FB} = Q_{\rm FB}\left(12\pi^2 U_0\right)^{1/4}$$

$$\frac{dM_{\rm FB}}{dQ_{\rm FB}} < M_\chi \equiv g_\chi w_0$$

Need to be satisfied in a concrete model.

- # Stability of the Fermi-ball

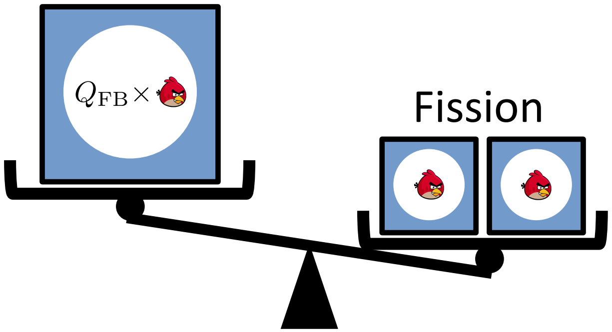
Decay: a Fermi-ball should not emit a χ fermion



$$M_{\rm FB}=Q_{\rm FB}\left(12\pi^2U_0\right)^{1/4}$$
$$\frac{dM_{\rm FB}}{dQ_{\rm FB}}<M_\chi\equiv g_\chi w_0$$

Need to be satisfied in a concrete model.

Fission: a Fermi-ball should not split to two smaller ones



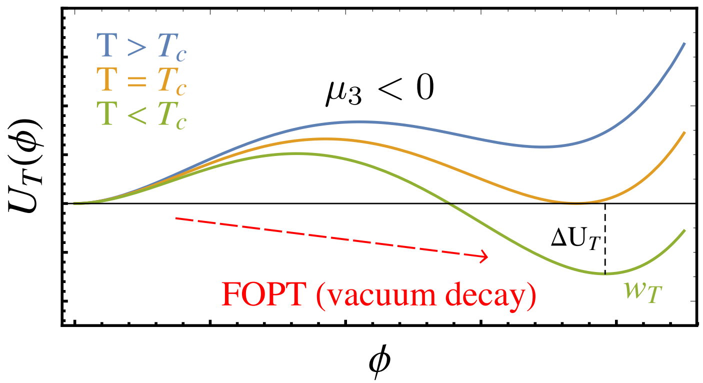
$$\frac{d^2M_{\rm FB}}{dQ_{\rm FB}^2}<0$$

Satisfied when the surface tension ($\propto Q_{\rm FB}^{2/3}$) is included.

- For a concrete (toy) model…

The scalar potential

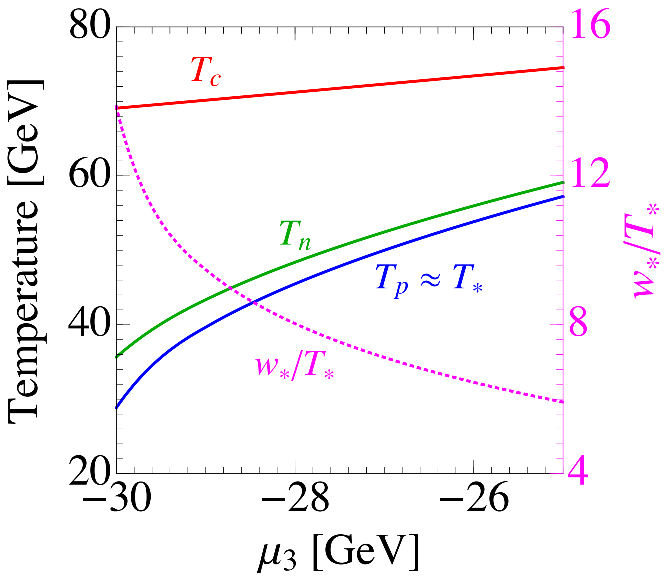
$$U(\phi,T)=\frac{1}{2}(\mu^2+cT^2)\phi^2+\frac{\mu_3}{3}\phi^3+\frac{\lambda}{4}\phi^4$$



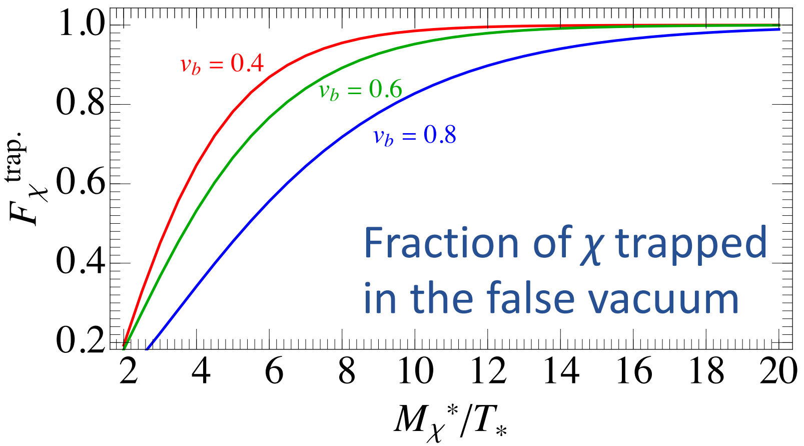
The μ_3 term: tree level barrier.
Benchmark parameters:

$$w_0=\langle\phi\rangle\big|_{T=0}=400\text{ GeV},\quad M_\phi=100\text{ GeV},\quad c=0.4,$$

FOPT profile & Fermi-ball profile



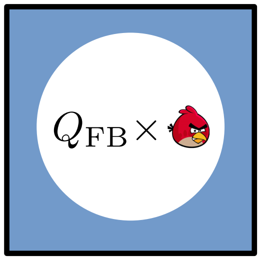
Reminder $M_\chi = g_\chi w_*$



Fraction of χ trapped in the false vacuum

- For a concrete (toy) model…

Fermi-ball (trapped χ in false vacuum)

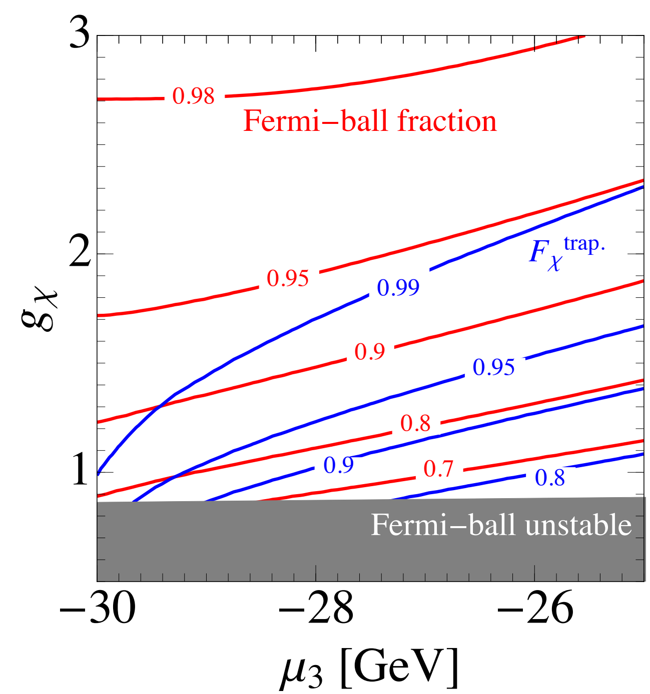


$$n_{\rm FB} = 1.1\times 10^{-37}\ {\rm m}^{-3} \sim 9.3\times 10^{-34}\ {\rm m}^{-3},$$
$$Q_{\rm FB} = 3.9\times 10^{34} \sim 4.0\times 10^{30},$$
$$M_{\rm FB} = 2.4\times 10^{10}\ {\rm kg} \sim 2.6\times 10^{6}\ {\rm kg},$$
$$R_{\rm FB} = 3.7\times 10^{-7}\ {\rm m} \sim 1.8\times 10^{-8}\ {\rm m}$$

$g_\chi w_0$: mass of free χ in the true vacuum; O(TeV).

In the true vacuum, free χ can be produced thermally ($\mathcal{L}\supset -g_\chi\bar{\chi}\chi\phi$) and experiences freeze-out!

It's necessary to check the Fermi-ball fraction of the Universe.

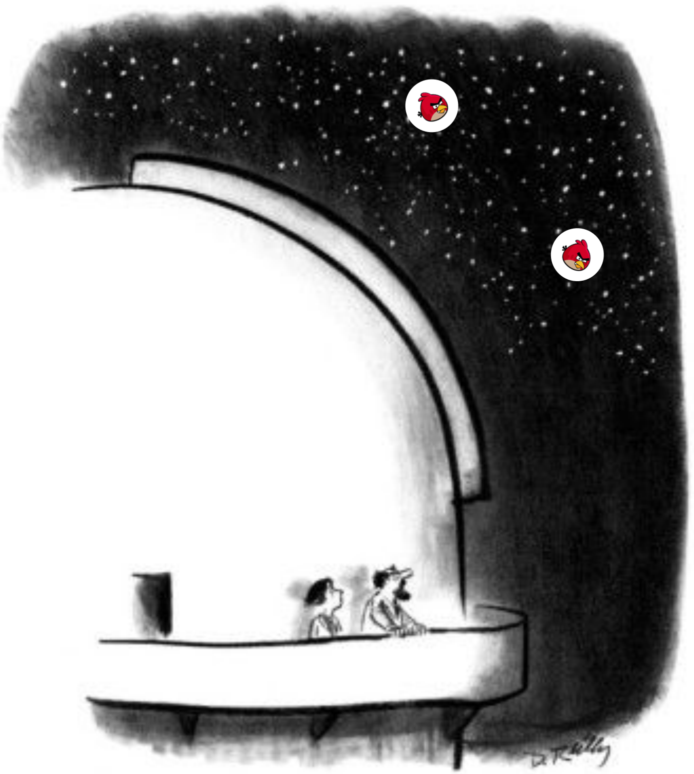


• Experimental detection

Direct detection [$v_{\rm DM} = 10^{-3}$, $L = 10$ m]?

$$n_{\rm FB} \sim 10^{-37}\ {\rm m}^{-3}: \quad n_{\rm FB} v_{\rm DM} L^2 \sim 10^{-22}/{\rm year}$$

Hopeless!!



"Yes, a hole in space three hundred million light-years across does make me pause and feel tiny and insignificant, but a glance around at my peers usually restores my equanimity."

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

• Experimental detection

Direct detection [$v_{\rm DM}$ = 10^{-3}, L = 10 m]?

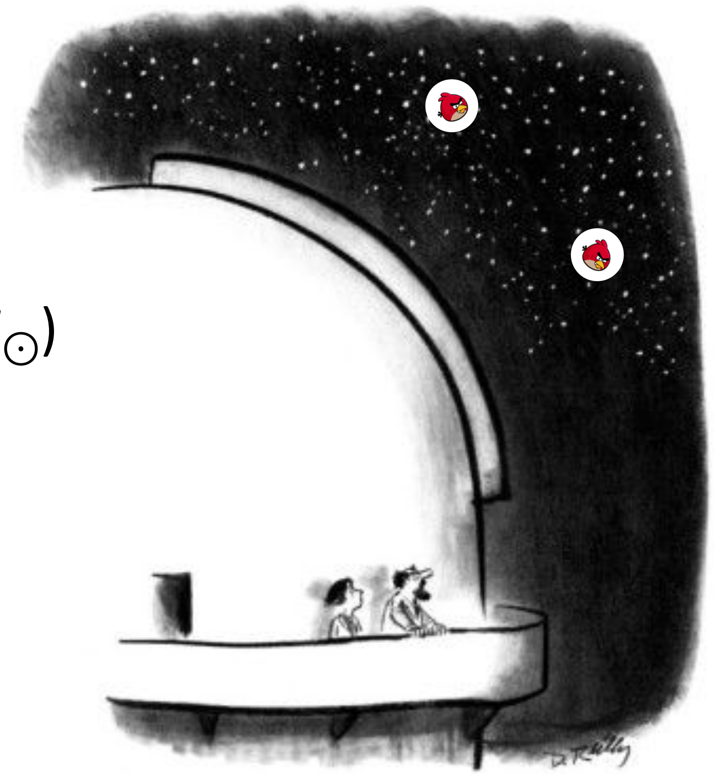
$$n_{\rm FB} \sim 10^{-37}\ {\rm m}^{-3}: \quad n_{\rm FB} v_{\rm DM} L^2 \sim 10^{-22}/{\rm year}$$

Hopeless!!

Gravitational effects?

A single Fermi-ball is too light ($10^{-20}\ M_\odot$) and not compact enough to provide signals such as lensing.

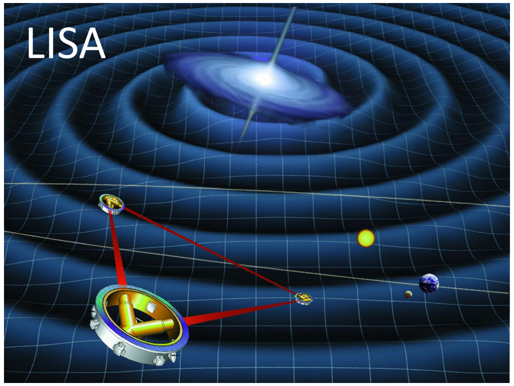
$$n_{\rm FB} = 1.1 \times 10^{-37}\ {\rm m}^{-3} \sim 9.3 \times 10^{-34}\ {\rm m}^{-3},$$
$$Q_{\rm FB} = 3.9 \times 10^{34} \sim 4.0 \times 10^{30},$$
$$M_{\rm FB} = 2.4 \times 10^{10}\ {\rm kg} \sim 2.6 \times 10^{6}\ {\rm kg},$$
$$R_{\rm FB} = 3.7 \times 10^{-7}\ {\rm m} \sim 1.8 \times 10^{-8}\ {\rm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



"Yes, a hole in space three hundred million light-years across does make me pause and feel tiny and insignificant, but a glance around at my peers usually restores my equanimity."

- # Experimental detection

Gravitational waves?

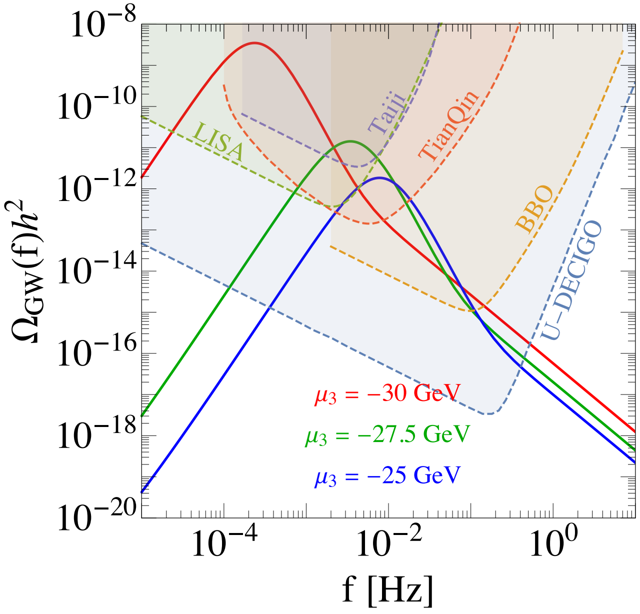


Fermi-balls are produced in association with a FOPT.
Large w_*/T_* implies significant supercooling and hence strong stochastic GW signals.

The FOPT GWs:

1. Collision of the bubbles;
2. Sound waves in plasma;
3. Turbulence in plasma.

Hopefully to be detected in the future space-based detectors.



- # Experimental detection

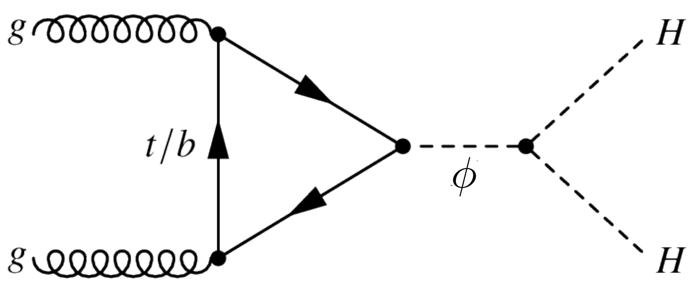
Collider signals?

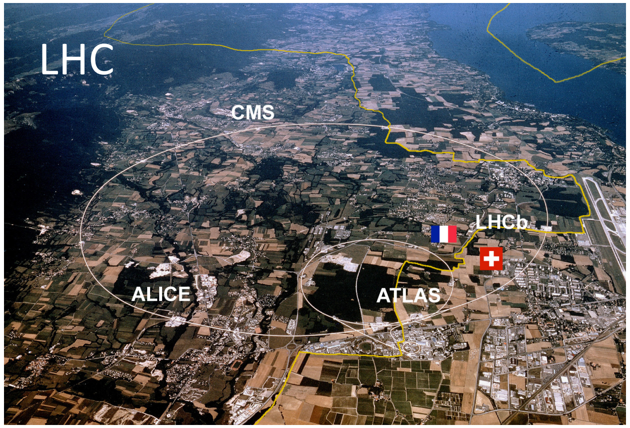
For a concrete model, there might be additional signals, e.g.

1. The <u>portal coupling</u> or even <u>mixing</u> between the Higgs and the ϕ field;
2. The production of χ at the collider;
3. Mono-X signal; displayed vertices; disappearing tracks, etc.

Not so different from the searches for the O(TeV) WIMPs.

Illustrations





Conclusion

We propose a novel DM mechanism:

- ❑ Fermions are trapped into the false vacuum during a FOPT to form non-topological solitons, i.e. the Fermi-ball DM;
- ❑ The formation condition is generally satisfied in many new physics models.

Fermi-ball itself doesn’t yield interesting experimental signals; but the FOPT GWs can be an indirect probe.

For a concrete model we might have collider signals.

$Q_{\text{FB}} \times$ 

Thank you!