Primordial black holes from a cosmic phase transition

The collapse of Fermi-balls

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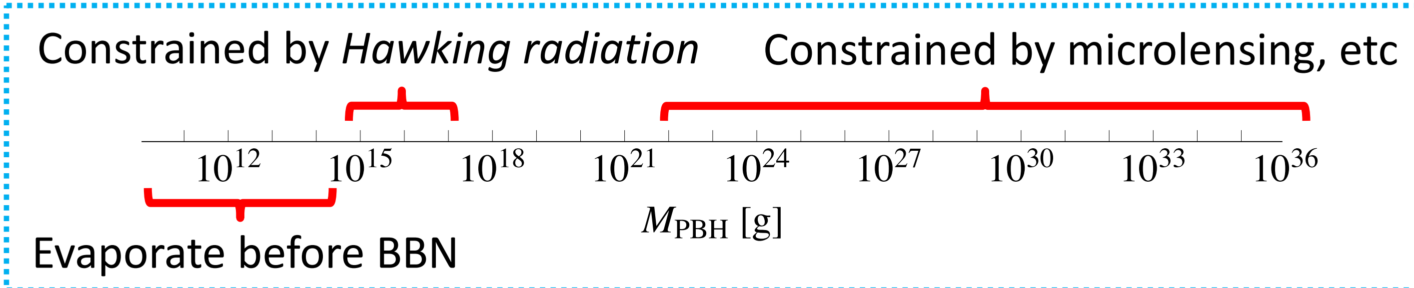
In collaboration with Kiyoharu Kawana [arXiv: 2106.00111]

• Introduction

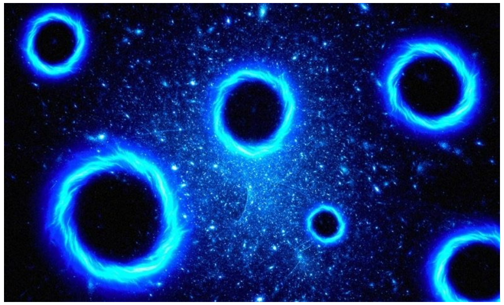
What are primordial black holes?

- They are **Hypothetical** black holes form in the early Universe;[Zel'dovitch *et al*, 1966]
- NOT from the collapse of stars, and hence mass lies in a vast region, not related to the stellar mass.



What can primordial black holes do?

- Naturally be the **dark matter** candidate;
- Seed supermassive black holes;
- Generate the matter-antimatter asymmetry; ...

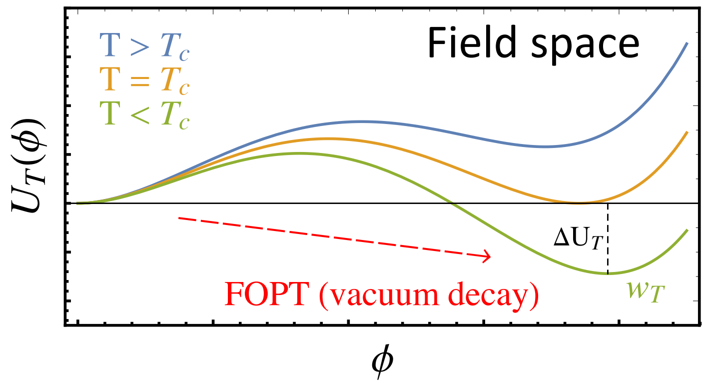


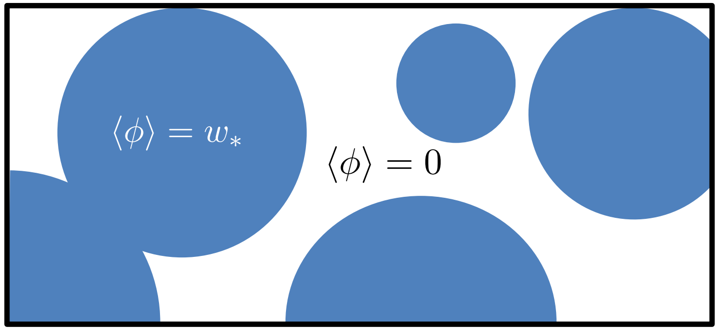
How do primordial black holes form?

- Collapse of the overdense region from primordial perturbations of inflation; [Carr *et al*, MNRAS1974]
- Scalar field fragmentation;[Cotner *et al*, PRL2017]
- First-order cosmic phase transition [this talk]; ...

- # How does the 1st-order PT form PBHs?

What is a 1st-order phase transition?





Spacetime

What is the feature of a 1st-order phase transition?

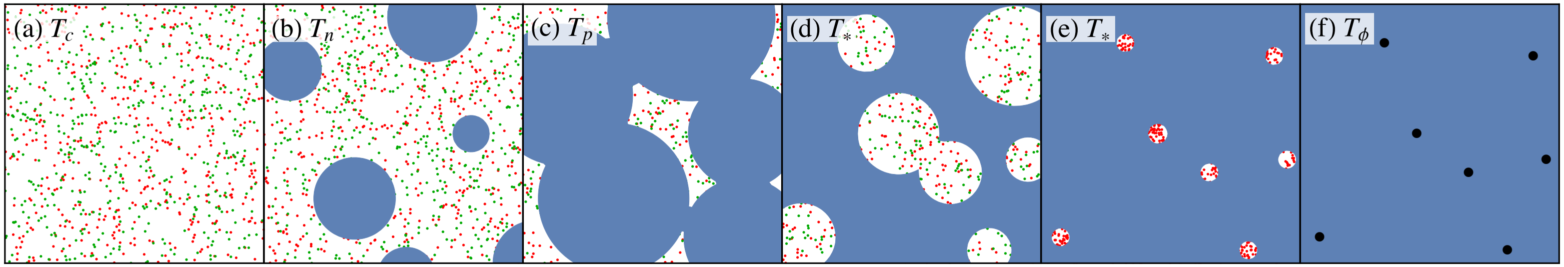
- Vacuum bubble nucleation;
- Particle mass discontinuous when crossing the bubble wall;

How does the 1st-order phase transition form PBHs?

- Compressing the fermions into the critical volume;[Baker *et al*, 2105.07481]
- By the postponed vacuum decay;[Liu, Bian, Cai, Guo and Wang, 2106.05637]
- …
- Forming non-topological solitons which then collapse to primordial black holes [this talk: 2106.00111].

- # Our novel mechanism: collapse of Fermi-balls

The sketch



- Phase transition (a-c) traps fermions (red and green dots) in the old vacuum (d);
- The trapped fermions form *non-topological solitons* called **Fermi-balls** (e);
- **Fermi-balls** collapse to **primordial black holes** (f).

The features

- It is a rather generic mechanism that can apply to a vast number of new physics models;
- Especially it can be linked to the Higgs field on the electroweak phase transition;

Outline of this talk

- I will first introduce the generic feature and then discuss relation with the electroweak phase transition;

What is happening for a fermion during a FOPT?

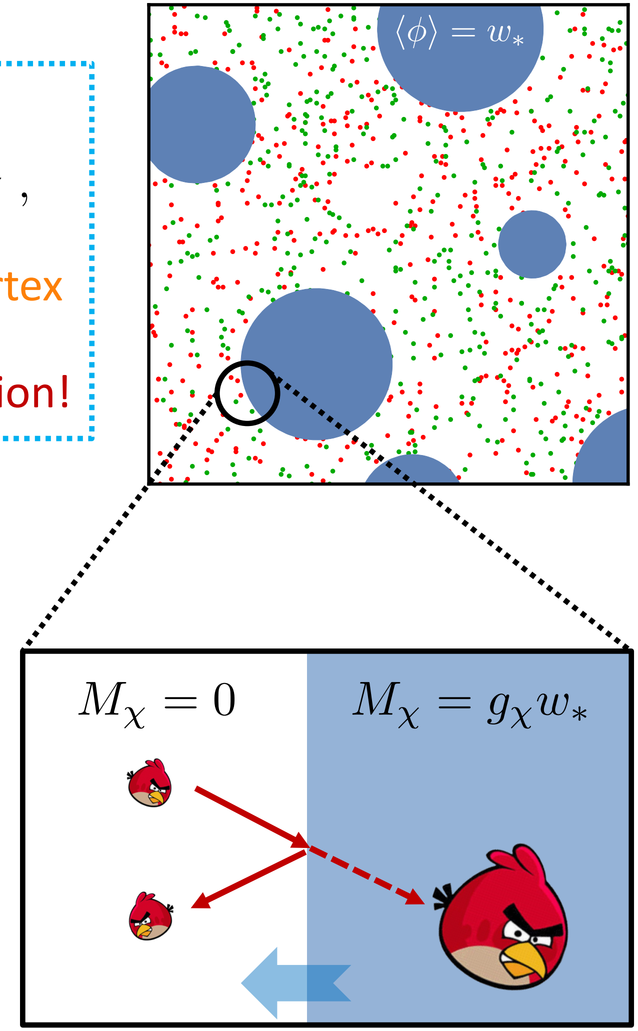
Assume a simple Lagrangian

Scalar — Fermion

$$\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - U(\phi) + \bar{\chi}i\gamma^\mu\partial_\mu\chi - g_\chi\phi\bar{\chi}\chi\ ,$$

Potential for phase transition — Yukawa vertex

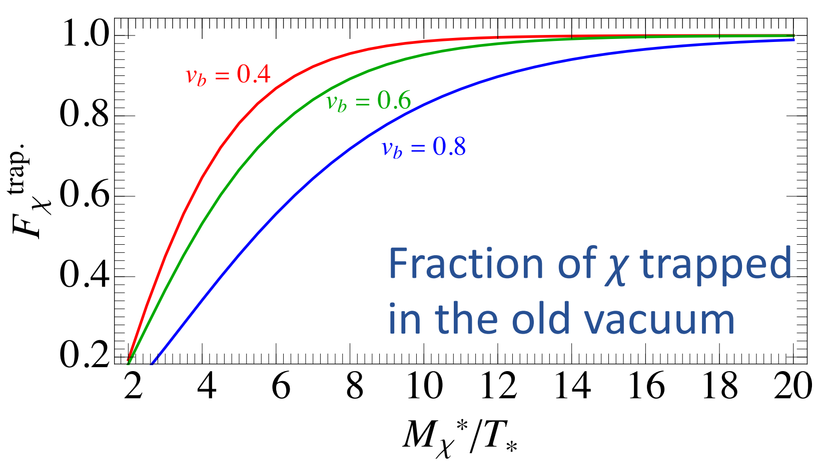
The interaction between bubble and fermion!



Wall velocity v_b

Mass changes across the bubble wall

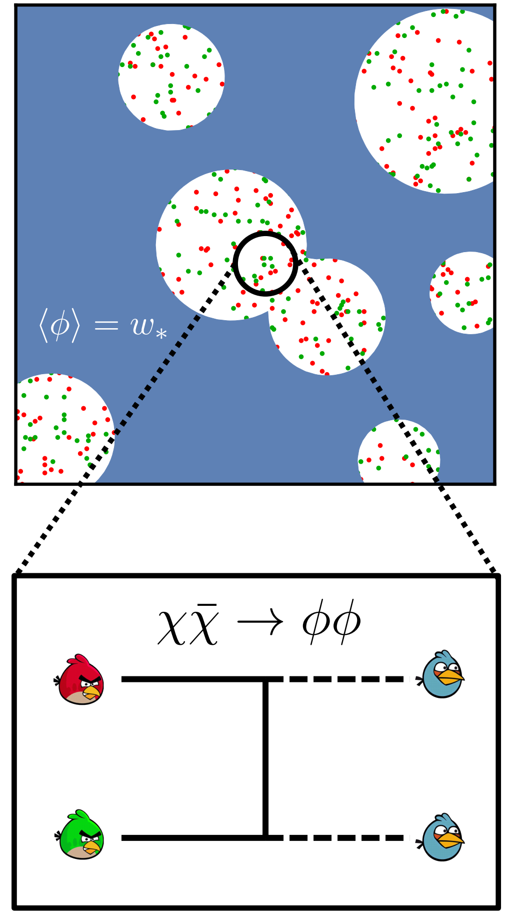
- If mass gap >> temperature T_*, the fermions cannot penetrate the wall!



• What is happening for a fermion during a FOPT?

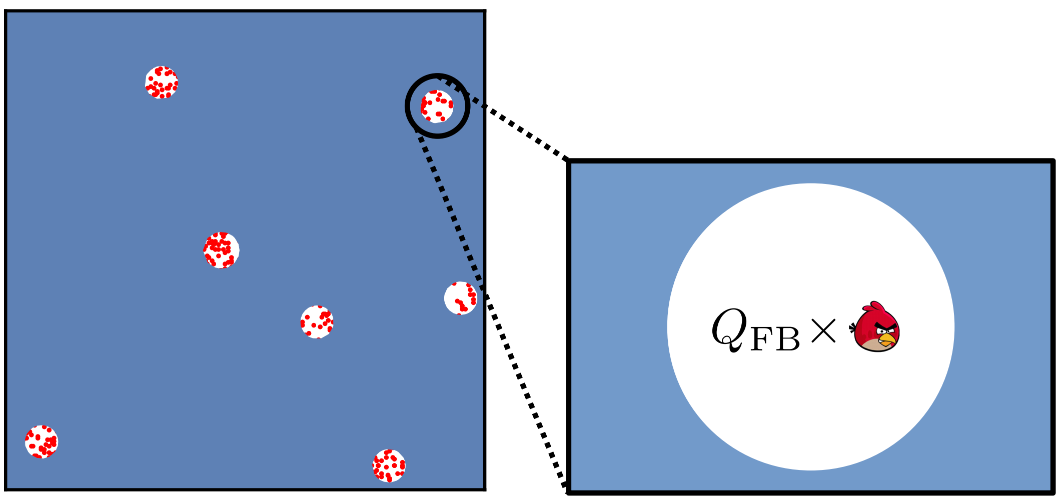
Fermions are trapped in the old vacuum!

- They begin to annihilate with the antiparticles;
- If there is a pre-existing asymmetry between the fermions & antifermions (like *baryon asymmetry*), only fermions survive.



After that, what will happen?

- Residual fermions develop a **degeneracy pressure**;
- Stable **Fermi-balls** form when the pressure is able to balance the vacuum pressure.



For details --

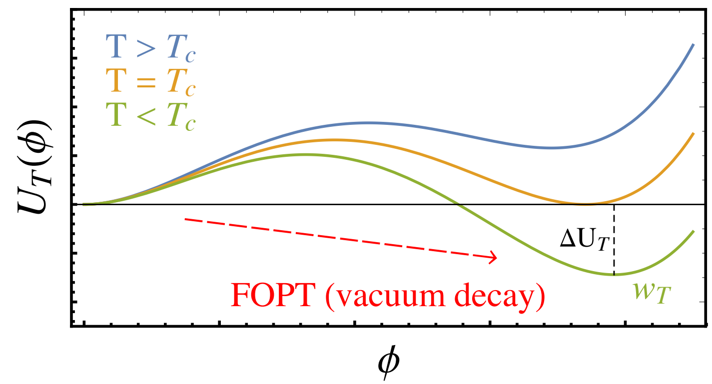
• Formation of Fermi-balls

Phase transition

- The decay rate of vacuum [Linde, NPB1983]

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

Classical action [model-dependent]

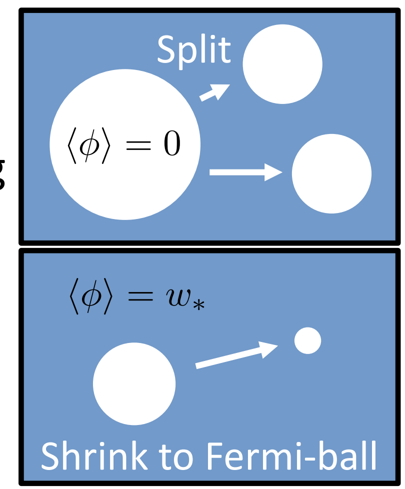


The fate of old vacuum remnants

- Remnants: first split, then shrink to be Fermi-balls
- The critical size of the end of splitting (and the beginning of shrinking):

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

- Such a critical size remnant is **the seed** of a Fermi-ball.



- Number density <u>at formation</u> $n_{\rm FB}^* \approx 0.29 \times V_*^{-1}$

- The number of fermions in a Fermi-ball

$$Q_{\rm FB} = F_\chi^{\rm trap.}\frac{n_\chi - n_{\bar\chi}}{n_{\rm FB}^*} \approx F_\chi^{\rm trap.}\eta_\chi s_* V_*$$

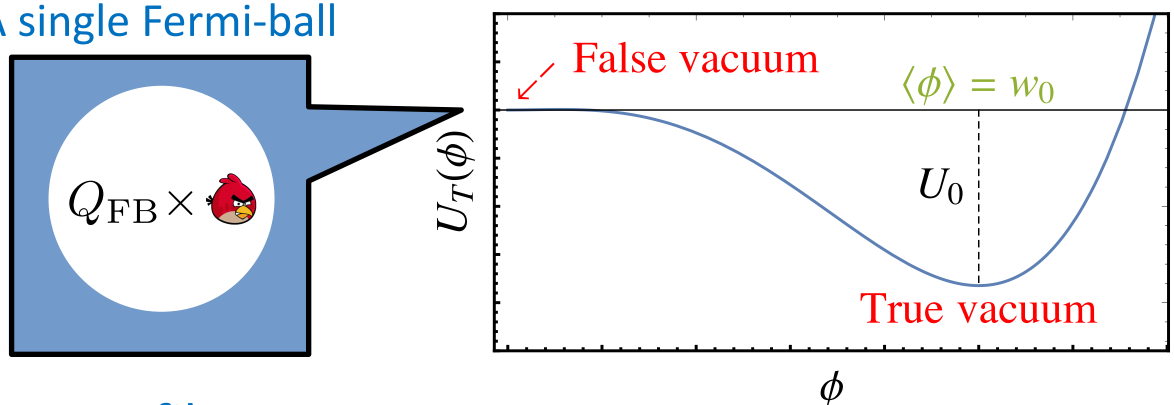
The χ-asymmetry

• The Fermi-ball profile

The physical picture

- A Fermi-ball is a collection of Fermions & false vacuum

A single Fermi-ball

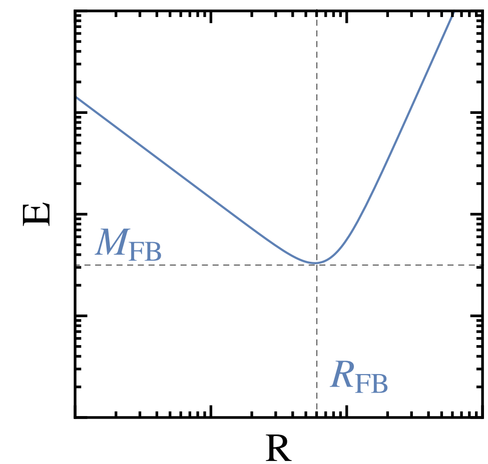


The energy profile

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



- Thermal corrections minorly change the expression;
- The Fermi-ball mass $M_{\rm FB}$ is determined by $dE/dR = 0$.

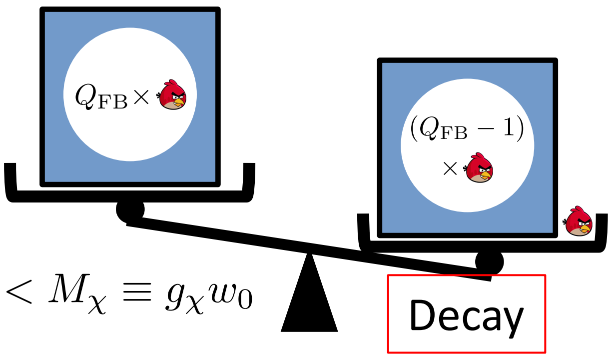
- # The Fermi-ball profile

The mass and radius

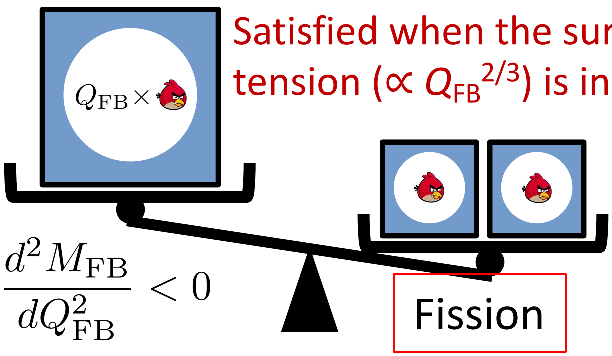
$$M_{\rm FB} = Q_{\rm FB}\left(12\pi^2 U_0\right)^{1/4}, \quad R_{\rm FB} = Q_{\rm FB}^{1/3}\left[\frac{3}{16}\left(\frac{3}{2\pi}\right)^{2/3}\frac{1}{U_0}\right]^{1/4}$$

The stability conditions

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



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



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

Then we have the stable Fermi-balls! [J.P.Hong, S.Jung and **K.P.Xie**, PRD2020]

- Non-topological solitons
- Dark matter candidate

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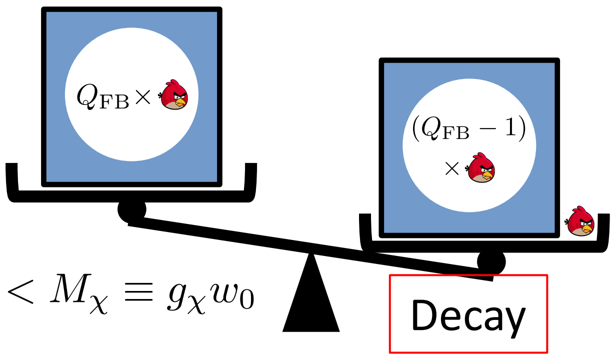

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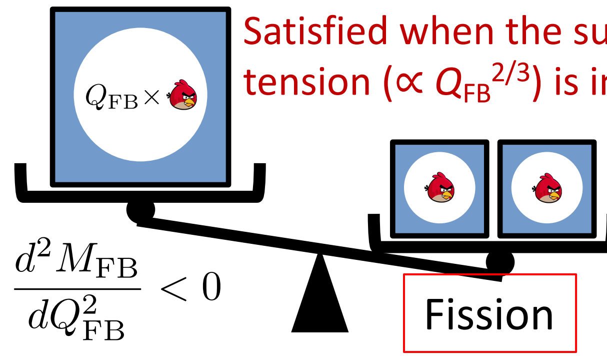

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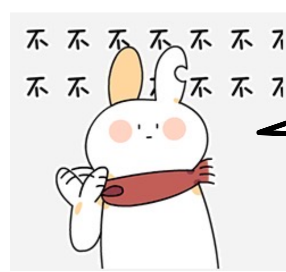
- Non-topological solitons
- Dark matter candidate



Something is missed!

... Is that the whole story?

• Recall the Fermi-ball profile

The improved energy profile

- We missed the Yukawa energy caused by $\mathcal{L} \supset -g_\chi \bar{\chi}\chi\phi$ of the fermions!

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

$$-\frac{15 g_\chi^2}{40\pi}\frac{Q_{\rm FB}^2}{R}\left(\frac{L_\phi}{R}\right)^2$$

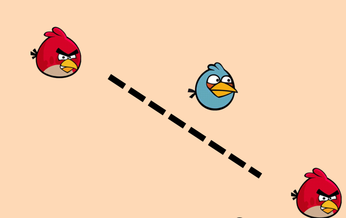
- **Negative** contribution due to the attractive feature of Yukawa;
- Range of force $L_\phi = 1/M_\phi$, where M_ϕ is the ϕ mass inside the Fermi-ball;

The features of the Yukawa interaction:

- Enhanced by $Q_{\rm FB}^2$, but suppressed by L_ϕ^2;
- It dominates the energy when

$$L_\phi \sim R_{\rm FB} Q_{\rm FB}^{-1/3}$$

- Which means the range of force reaches the <u>mean separation</u> of fermions in the Fermi-ball!



$$V(r) = -\frac{g_\chi^2}{4\pi r}e^{-M_\phi r}$$

- After including the (negative) Yukawa energy…

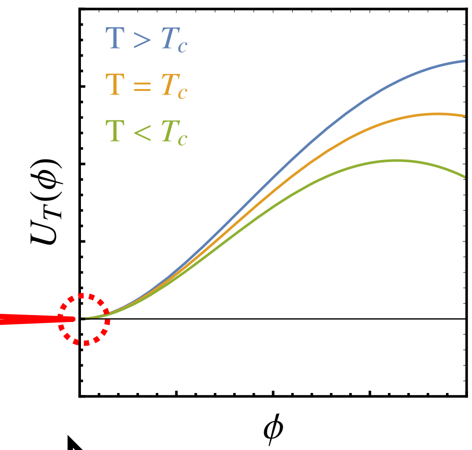
Two important facts

1. A Fermi-ball is a very dense object

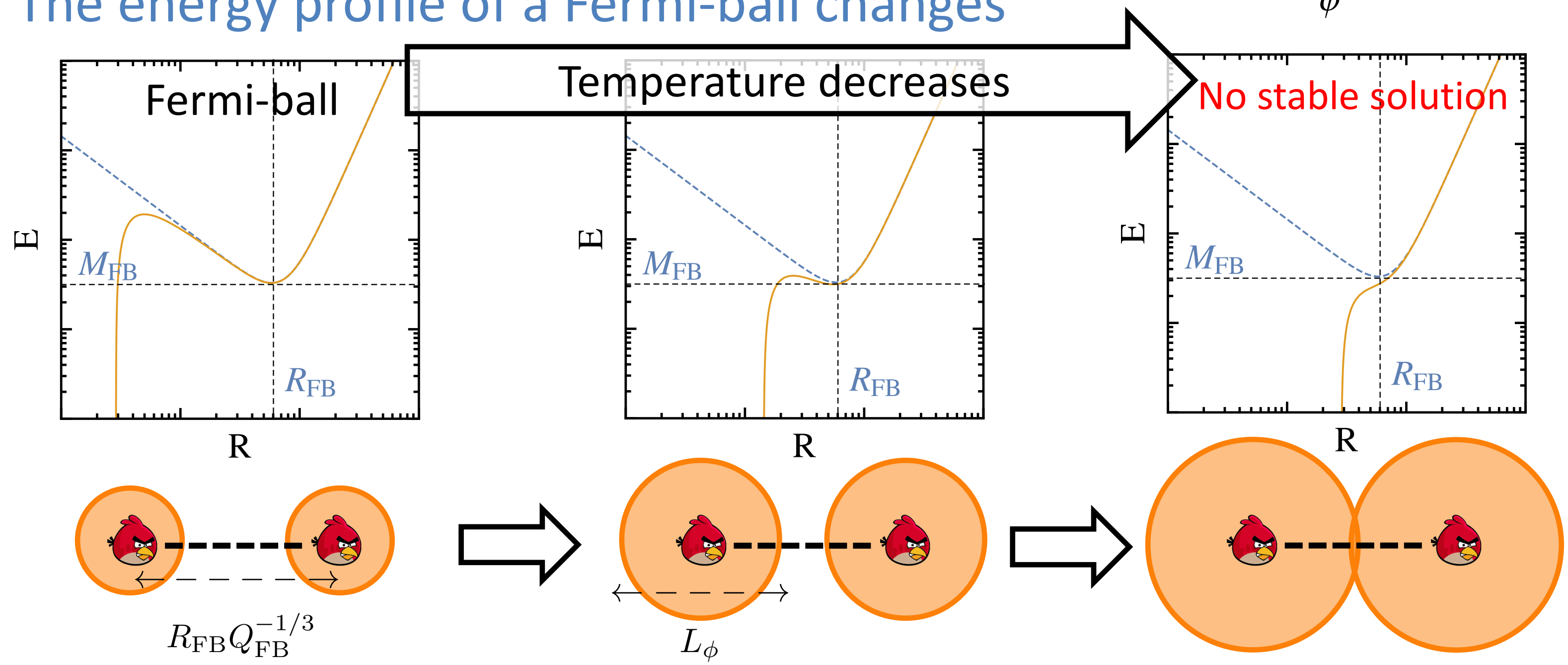
$$M_{\rm FB}/V_{\rm FB} = 9.15\times 10^{28}\ {\rm kg/m^3}\left(\frac{U_0^{1/4}}{100\ {\rm GeV}}\right)^4$$

2. The range of force increases as T drops!

$$M_\phi = \sqrt{\mu^2 + cT^2}$$



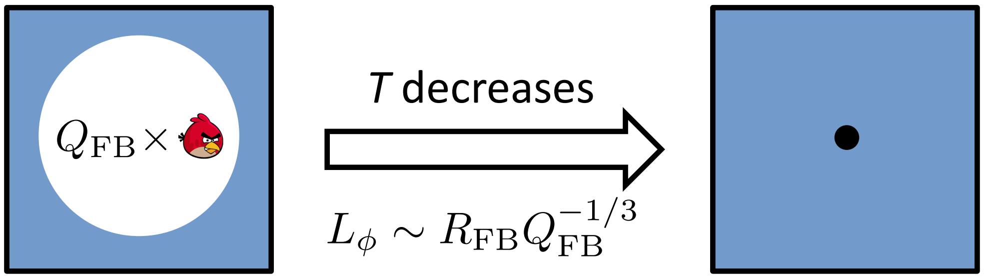
The energy profile of a Fermi-ball changes



From Fermi-balls to primordial black holes

The meaning of "no stable solution"

- The Fermi-ball collapses to a **primordial black hole** because of the Yukawa interaction!



- Collapse temperature defined as T_ϕ .

The resultant primordial black hole

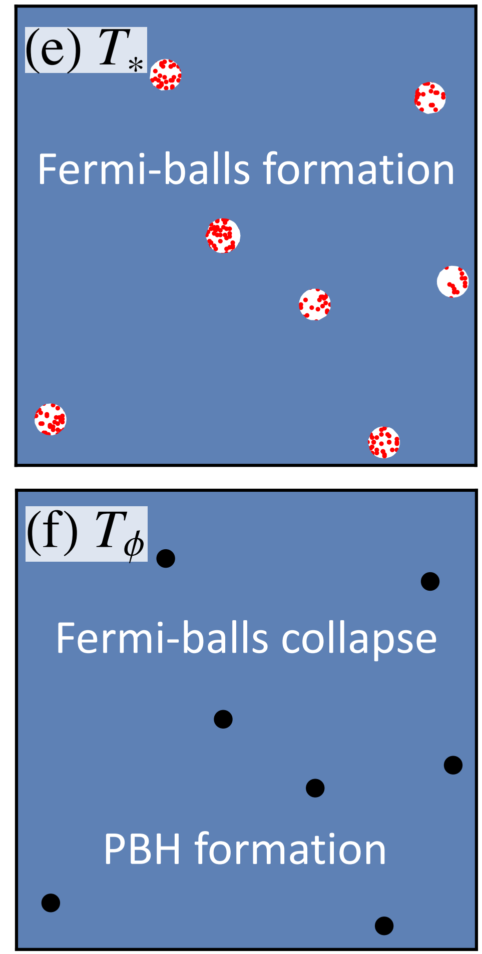
- Inherits the mass from the mother Fermi-ball

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

- The number density scales as

$$n_{\rm PBH} = s \times \frac{n_{\rm FB}^*}{s_*}$$

- That is our PBH formation mechanism!



- # Fermi-ball/Primordial black hole profile

The rigorous calculation

- Calculate the vacuum decay rate (by action S_3), the critical size of the old vacuum remnant, the mass & number density of the Fermi-balls, etc

A quick estimate

- The action is approximately[Huber *et al* JCAP2008]

The ratio of Hubble time to phase transition duration

$$\frac{S_3(T_*)}{T_*} \approx 131 - 4\ln\left(\frac{T_*}{100\ \text{GeV}}\right) - 4\ln\left(\frac{\beta/H}{100}\right) + 3\ln v_b - 2\ln\left(\frac{g_*}{100}\right) ,$$

- And assume the energy difference between new & old vacuums $U_0(T_*) \approx \alpha \times \frac{\pi^2}{30} g_* T_*^4$
- Now we are able to drive

$$Q_{\text{FB}} \approx 1.0 \times 10^{42} \times v_b^3 \left(\frac{\eta_\chi}{10^{-3}}\right) \times \left(\frac{100}{g_*}\right)^{1/2} \left(\frac{100\ \text{GeV}}{T_*}\right)^3 \left(\frac{100}{\beta/H}\right)^3 ,$$

$$R_{\text{FB}} \approx 4.8 \times 10^{-3}\ \text{cm} \times v_b \left(\frac{\eta_\chi}{10^{-3}}\right)^{1/3} \times \left(\frac{100}{g_*}\right)^{5/12} \left(\frac{100\ \text{GeV}}{T_*}\right)^2 \left(\frac{100}{\beta/H}\right) \alpha^{-1/4},$$

$$M_{\text{FB}} \approx M_{\text{PBH}} \approx 1.4 \times 10^{21}\ \text{g} \times v_b^3 \left(\frac{\eta_\chi}{10^{-3}}\right) \times \left(\frac{100}{g_*}\right)^{1/4} \left(\frac{100\ \text{GeV}}{T_*}\right)^2 \left(\frac{100}{\beta/H}\right)^3 \alpha^{1/4},$$

$$f_{\text{PBH}} \approx 1.3 \times 10^3 \times v_b^{-3} \left(\frac{g_*}{100}\right)^{1/2} \left(\frac{T_*}{100\ \text{GeV}}\right)^3 \times \left(\frac{\beta/H}{100}\right)^3 \left(\frac{M_{\text{PBH}}}{10^{15}\ \text{g}}\right)$$; DM fraction

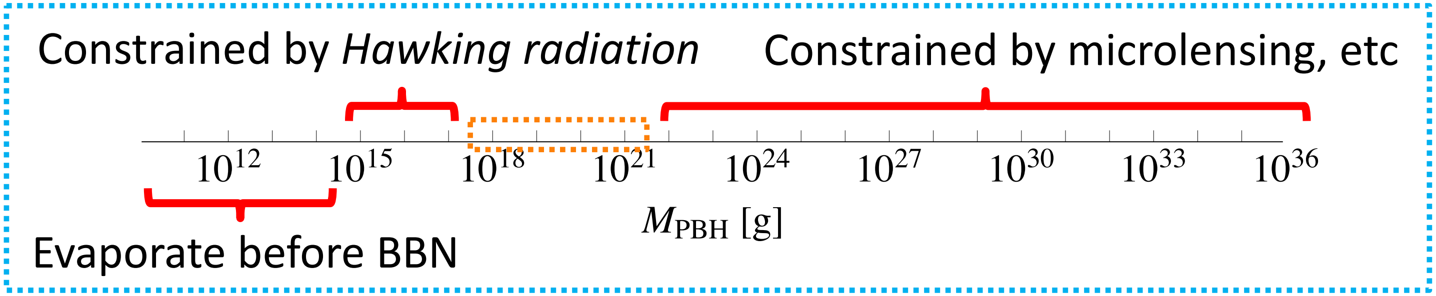
Can the electroweak phase transition form PBHs?

Extending the SM with a singlet scalar and fermion

- The scalar potential is able to trigger a 1st-order EW phase transition

$$V = -\mu^2|H|^2 + \lambda|H|^4 + \frac{a_1}{2}|H|^2\phi + \frac{a_2}{2}|H|^2\phi^2 + b_1\phi + \frac{b_2}{2}\phi^2 + \frac{b_3}{3}\phi^3 + \frac{b_4}{4}\phi^4,$$

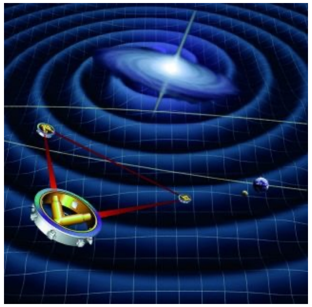
- The resultant PBH mass around 10^{21} g, which can explain all dark matter;



- But $f_{\rm PBH} \approx 10^3$, implying that an appropriate entropy production mechanism is necessary to dilute the PBH density (entire DM means $f_{\rm DM} = 1$);

Rich phenomenology

- The phase transition gravitational waves at future interferometers, e.g. LISA, TianQin or Taiji;
- Phenomenology at colliders, i.g. di-Higgs production.
- Work in progress!



- # Conclusion

We propose a novel mechanism for **primordial black holes** formation

❑ Phase transition first forms a kind of no—topological solitons called **Fermi-balls**;

❑ **Fermi-balls** then collapse into **black holes**, due to the Yukawa attractive force;

❑ Such collapse could happen, because the range of Yukawa force increases as the Fermi-balls cool down;

❑ This mechanism can be applied to the electroweak phase transition (in progress).

Thank you!

• Backup

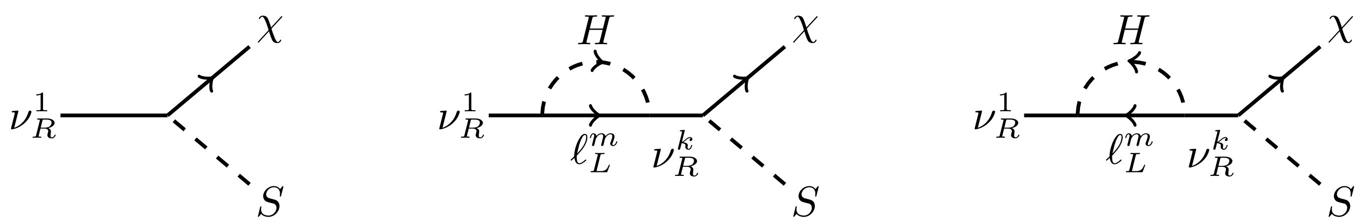
The rigorous expression for the Yukawa energy

$$E_{\rm Yuk.}=-\frac{3g_\chi^2}{20\pi}\frac{Q_{\rm FB}^2}{R}f\left(\frac{L_\phi}{R}\right);\quad f(\xi)=\frac{5}{2}\xi^2\left[1+\frac{3}{2}\xi\left(\xi^2-1\right)-\frac{3}{2}\xi(\xi+1)^2e^{-2/\xi}\right]$$

- $f(0)=0$ and $f(\infty)=1$.

Generating the fermion asymmetry

- A leptogenesis-like mechanism



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

$$\eta_B\equiv\frac{n_B-n_{\bar B}}{s}\approx10^{-10}$$