# **Solitons** and **Primordial black holes** from a boiling Universe

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Series of work with Jeong-Pyong Hong, Sunghoon Jung, Kiyoharu Kawana, Peisi Huang and Philip Lu

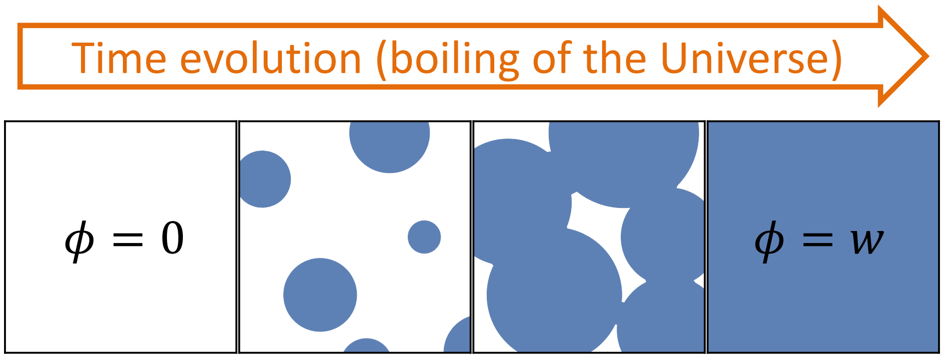
Also at HPNP2023! ↗

# First-order phase transitions

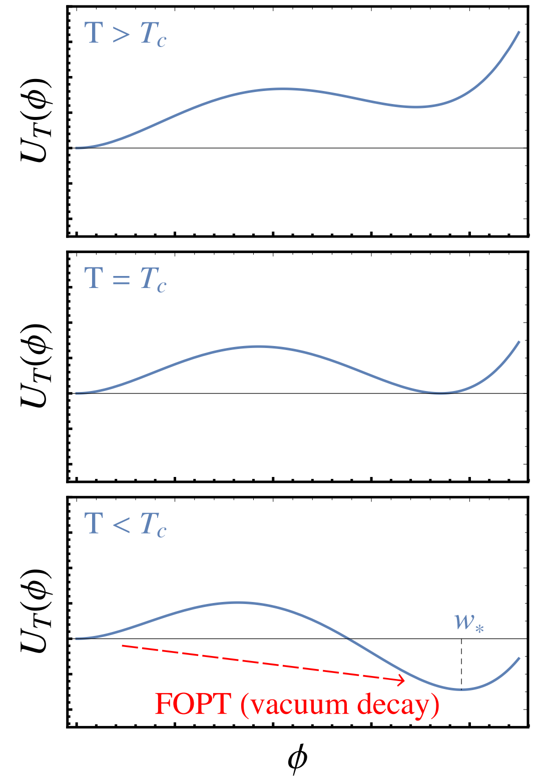
Decay of the vacuum

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - U(\phi)$$

Early Universe $\Rightarrow U_T(\phi, T)$







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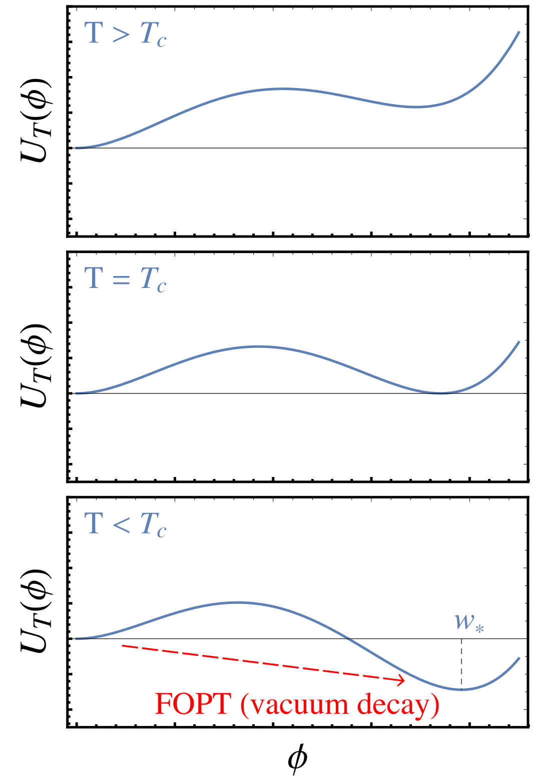
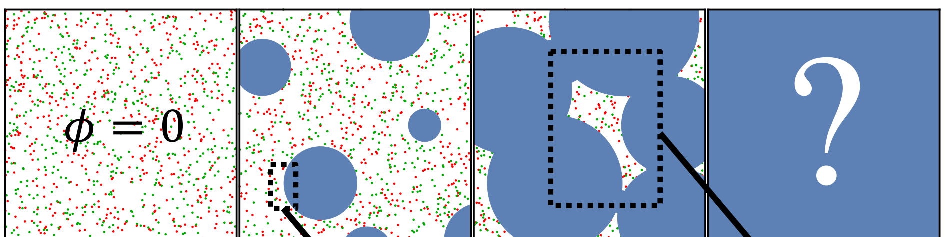
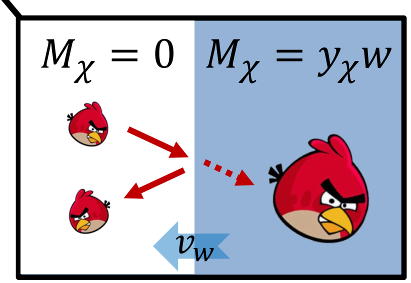



Time evolution (boiling of the Universe)



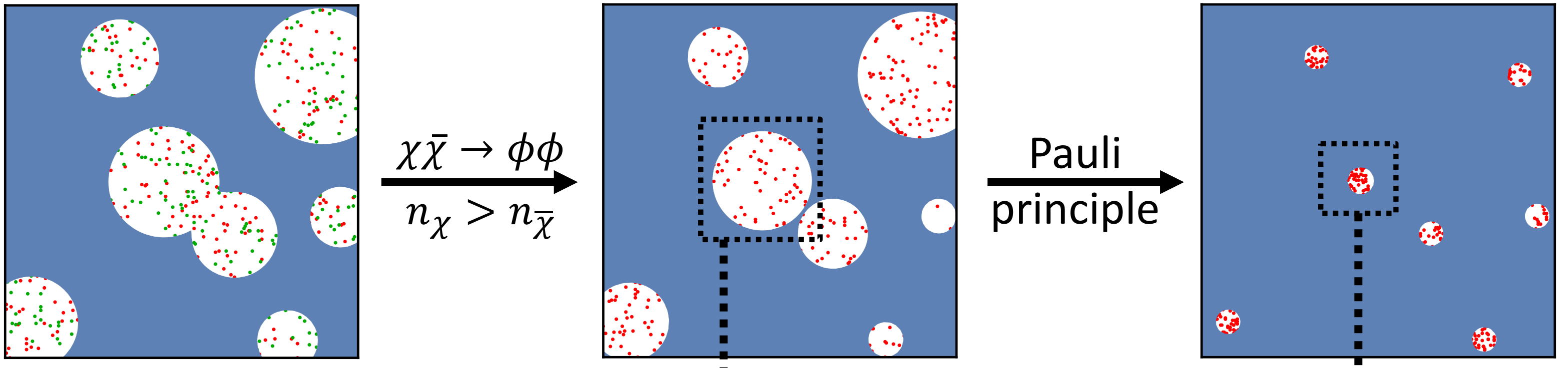

$\mathcal{L} \supset -y_\chi \phi \bar{\chi}\chi$

Cannot penetrate if $M_\chi \gg T_*$

**Fermions get trapped!**

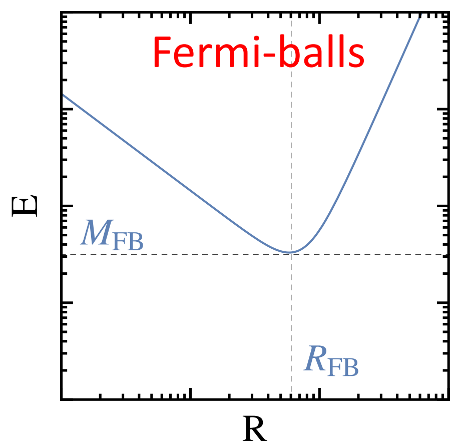
Example: $F_{\text{trap}} = 98\%$ for $M_\chi/T_* = 12$ and $v_w = 0.6$

# Formation of Fermi-ball solitons




Charge trapped: $Q_{\rm FB} \approx \eta_\chi s_* V_*$ ← Remnant volume

Fermion asymmetry $\eta_\chi = \frac{n_\chi - n_{\bar{\chi}}}{s}$




**Could be macroscopic DM**

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

Fermi-gas energy — Volume energy

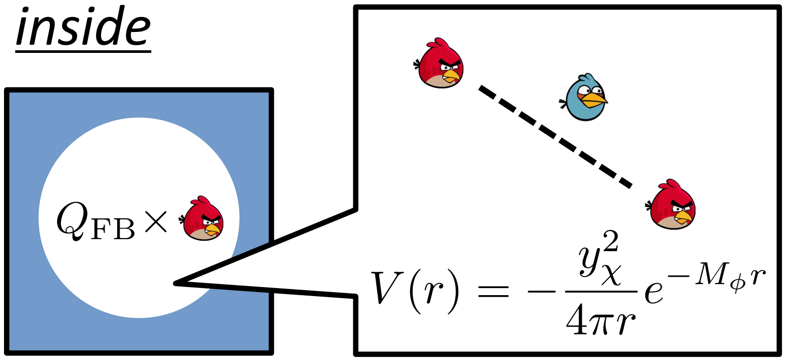
$$M_{\rm FB} = Q_{\rm FB}(12\pi^2 U_0)^{1/4};$$

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

Hong, Jung and **KPX**, PRD 102 (2020) 7, 075028

# Attractive force inside a soliton

Yukawa force *inside* a Fermi-ball

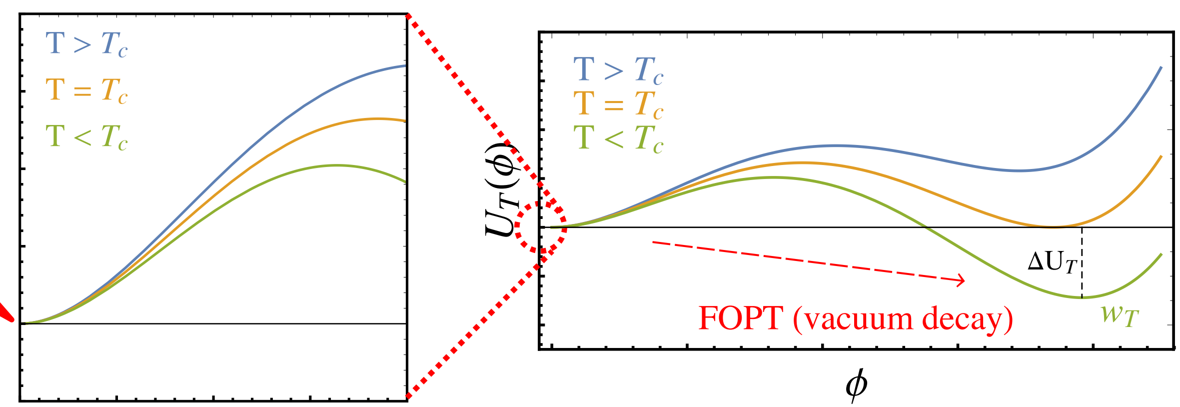



Originates from
$\mathcal{L} \supset -y_\chi \phi \bar{\chi}\chi$
Range of force
$L_\phi = \frac{1}{M_\phi}$

$$E \approx \frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3} \frac{Q_{\rm FB}^{4/3}}{R} + \frac{4\pi}{3} R^3 U_0 - \frac{15 y_\chi^2}{40\pi} \frac{Q_{\rm FB}^2}{R} \left(\frac{1}{R M_\phi}\right)^2$$

When a Fermi-ball cools down: $T\downarrow$ and $M_\phi \downarrow$

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

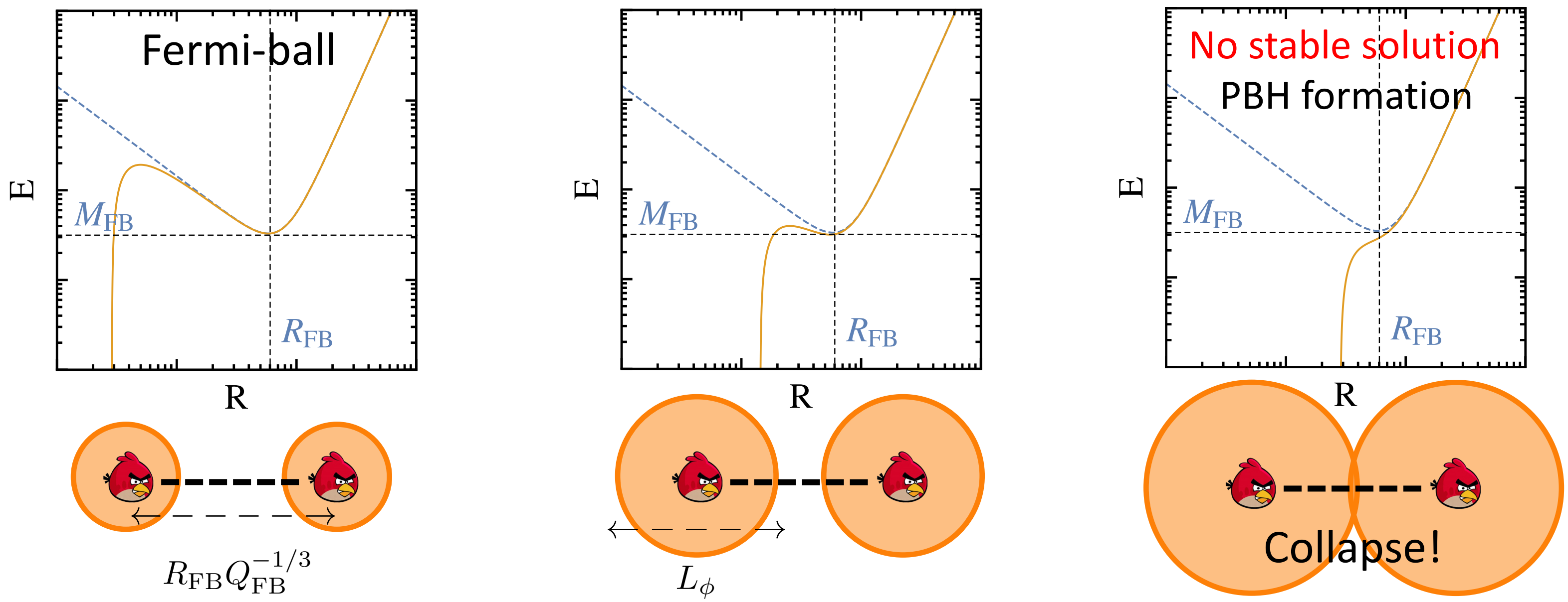


# Fermi-balls may collapse when they cool down

What if the Yukawa energy dominates?

$$E_{\rm Yuk} \approx -\frac{15y_\chi^2}{40\pi}\frac{Q_{\rm FB}^2}{R}\left(\frac{1}{RM_\phi}\right)^2$$

Temperature drops, $T\downarrow$ and $M_\phi\downarrow$




Kawana and **KPX**, PLB 824 (2022) 136791

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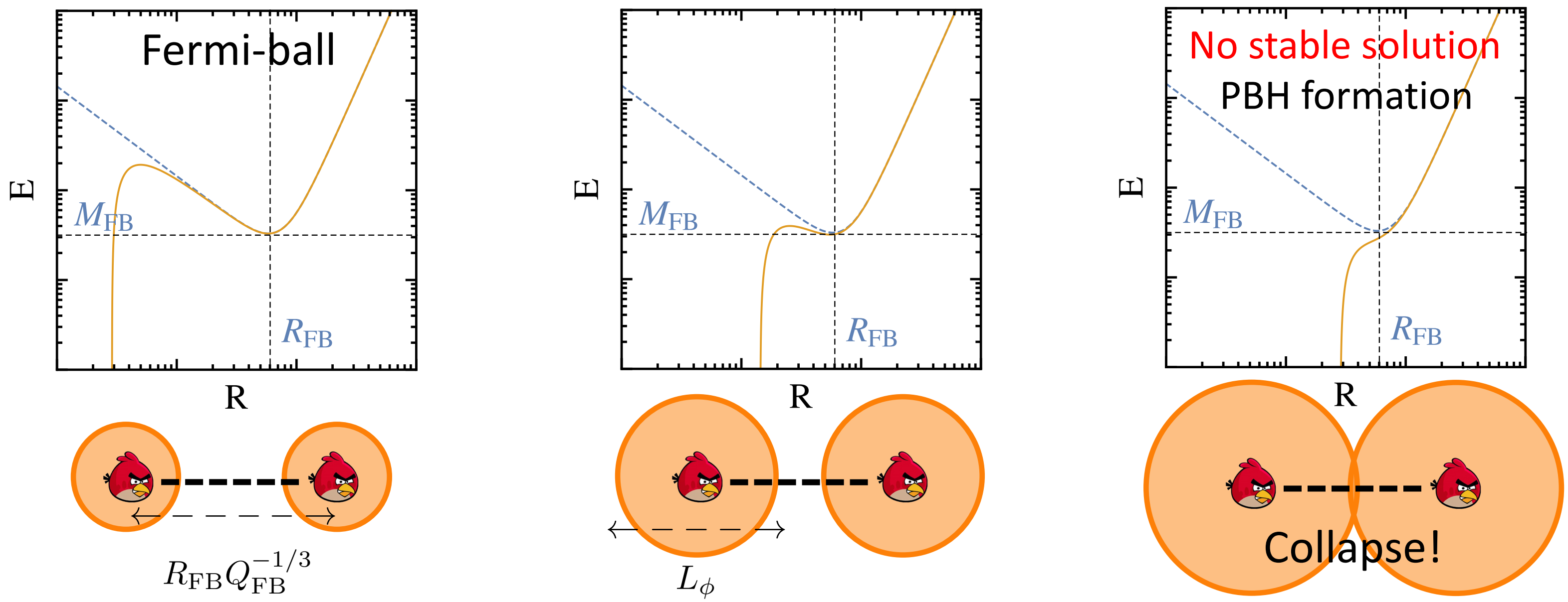


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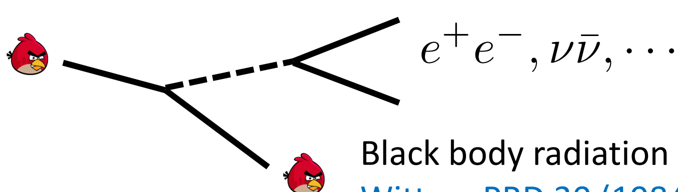
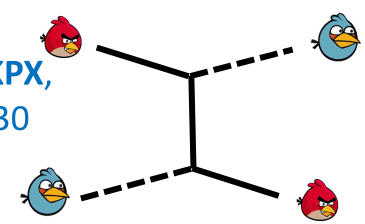
*Cooling of Fermi-balls

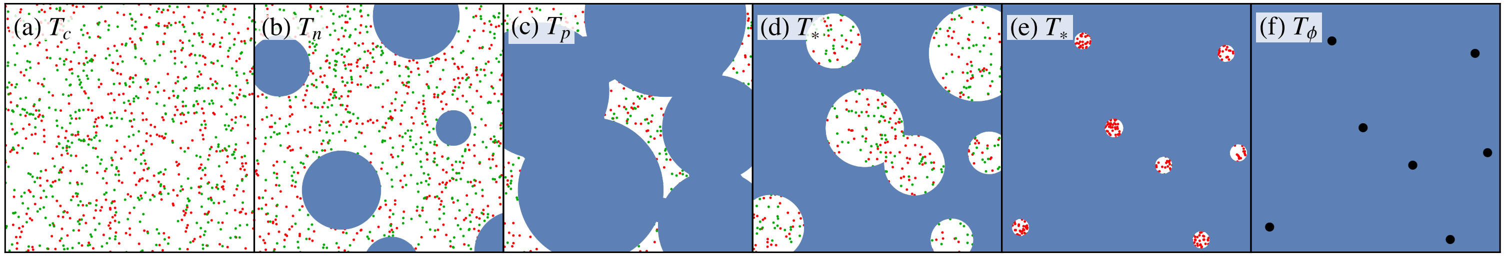



Black body radiation
Witten, PRD 30 (1984) 272-285

Elastic scattering
Kawana, Lu and **KPX**, JCAP 10 (2022) 030

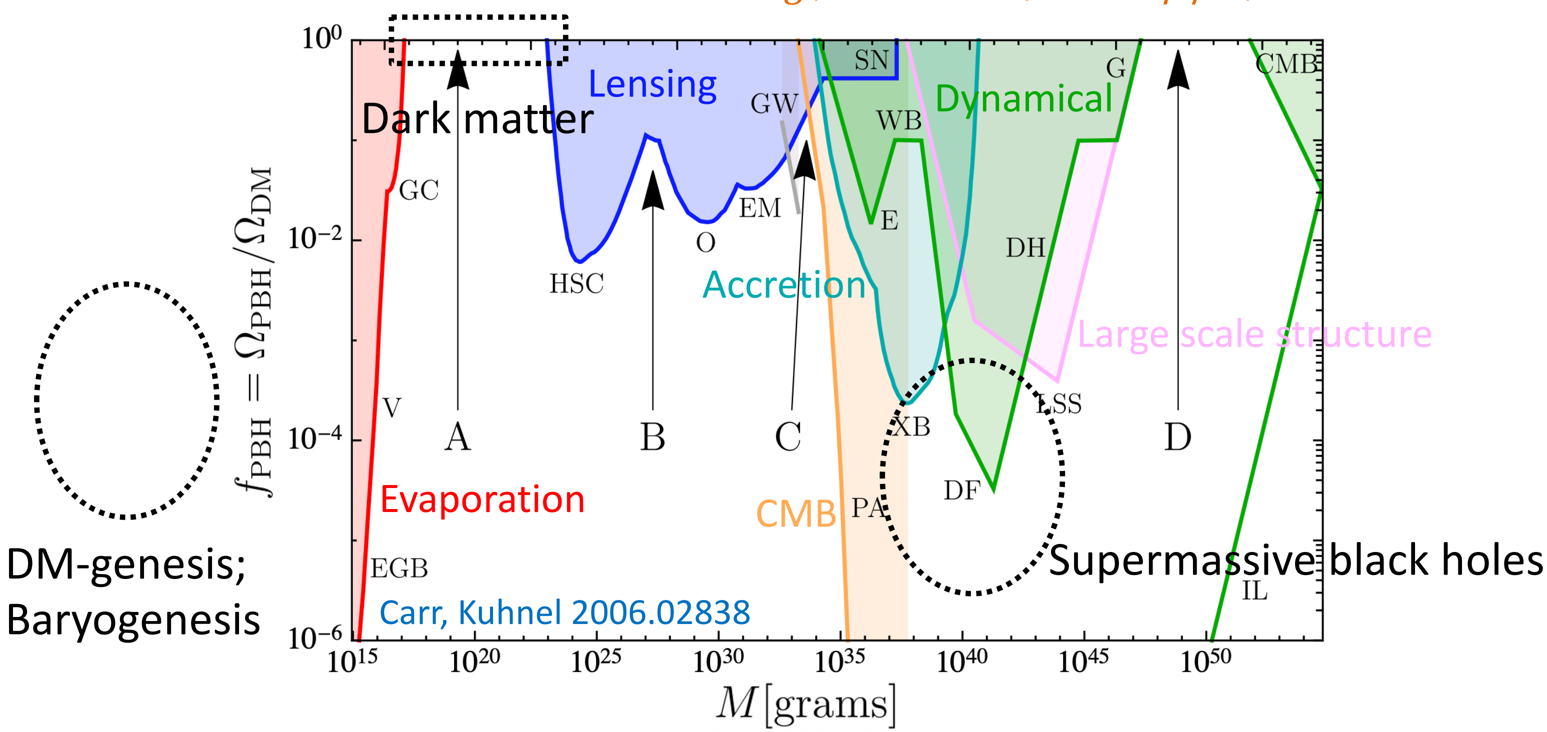


# PBHs from Fermi-ball collapse from a FOPT

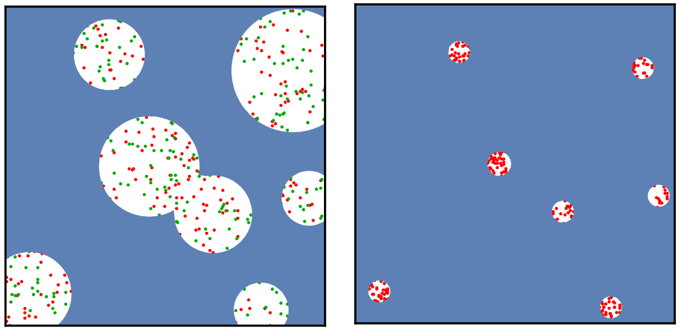



Kawana and **KPX**, PLB 824 (2022) 136791

$$M_{\rm PBH} \approx 1.4\times10^{21}\ {\rm g}\times v_w^3 \left(\frac{\eta_\chi}{10^{-3}}\right)\left(\frac{100}{g_*}\right)^{1/4}\left(\frac{100\ {\rm GeV}}{T_*}\right)^2\left(\frac{100}{\beta/H_*}\right)^3\alpha^{1/4}$$



# Note: difference of two scenarios

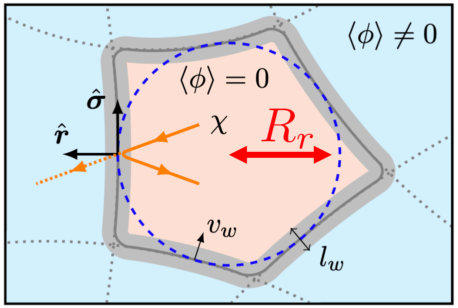


Hong, Jung and **KPX**, PRD 102 (2020) 7, 075028
Kawana and **KPX**, PLB 824 (2022) 136791

Trapping fermions → forming **solitons** → **collapse** to PBHs

$y_\chi \sim \mathcal{O}(1)$, $\chi\bar{\chi} \to \phi\phi$ efficient, $\rho_\chi(t) \sim \rho_\chi^{\rm eq}$ until Fermi-balls form, needs **$\chi$-asymmetry**

Irrelevant to evolution history,
Analytical calculation is sufficient




Baker, Kopp and Mittnacht, 2105.07481; 2110.00005

Trapping fermions → **direct collapse** to PBHs

$y_\chi \ll 1$, $\chi\bar{\chi} \to \phi\phi$ negligible, $\rho_\chi(t) \propto R_r^{-4}(t)$, energy density increase rapidly!

Numerical simulation needed

Debates: $\chi$-induced friction stops the wall, not forming PBHs [Lewicki *et al*, 2305.07702]

# Relevant researches


### Original mechanism

Hong, Jung and **KPX**, PRD 102 (2020) 7, 075028
Fermi-ball dark matter

Kawana and **KPX**, PLB 824 (2022) 136791
Fermi-ball collapses to PBH

### Improving the mechanism

Kawana, Lu and **KPX**, JCAP 10 (2022) 030
Analytical estimation of solitons and PBHs

Lu, Kawana and **KPX**, PRD.105.123503
Extended mass function

### Phenomenology

Marfatia *et al*, JHEP 11 (2021) 068
Detecting Fermi-balls with GWs and lensing

Marfatia *et al*, JHEP 08 (2022) 001
Detecting PBHs with $\gamma$-ray and GWs

**KPX**, 2301.02352 (JCAP accepted)
Distinguishing different mechanisms

### Applications

**Higgs!**


Huang and **KPX**, PRD 105 (2022) 11, 115033
Electroweak phase transition to form PBH DM

Tseng *et al*, 2209.01552
Explaining the 511 keV galactic line

Marfatia *et al*, JHEP 04 (2023) 006
Boosted DM from PBH evaporation

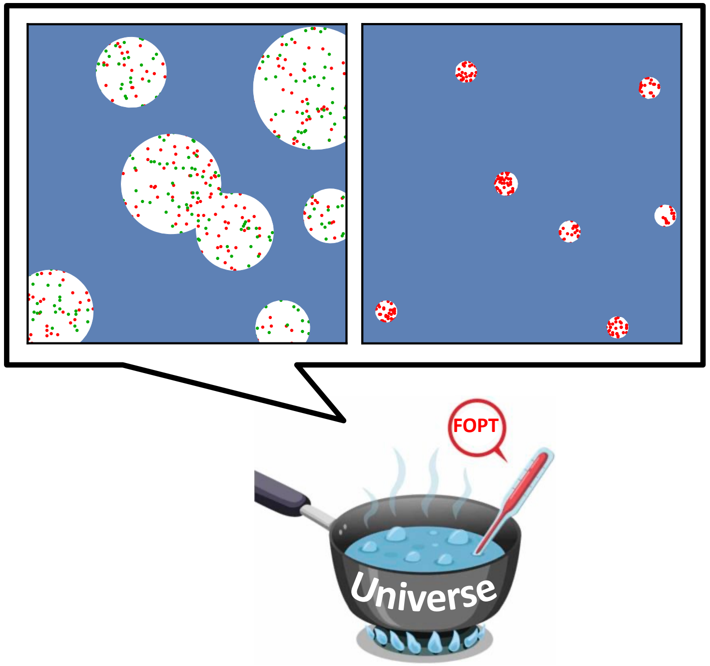
Lu *et al*, 2210.16462
Late forming PBHs beyond CMB era

Chen *et al*, 2305.14399
Type Ia supernovae induced by PBHs

Tseng *et al*, 2304.10084
Interplay with GWs at pulsar timing arrays

# Conclusion

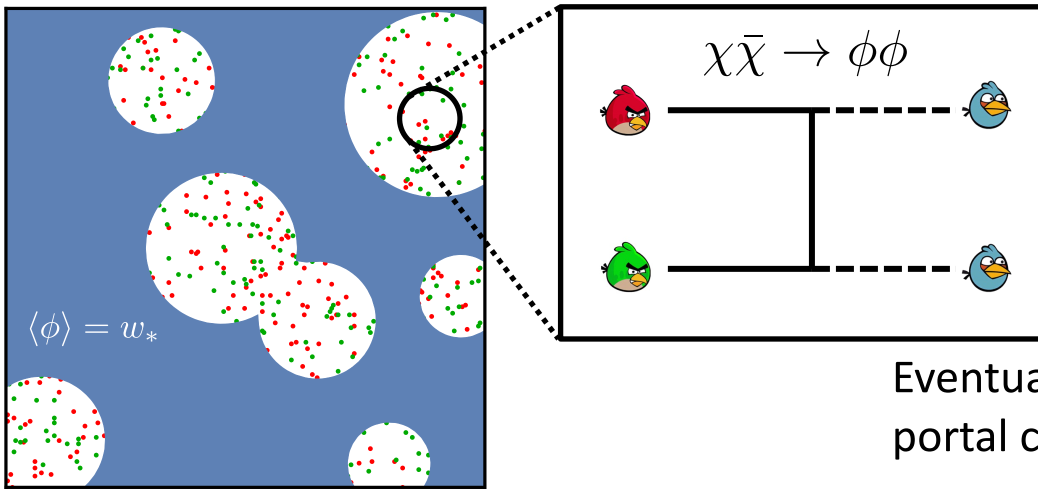
In a boiling Universe, fermions can be trapped and compressed into solitons, which can further collapse to PBHs




Thank you!

2023.6.4 @Osaka

# Backup: how to generate the $\chi$-asymmetry

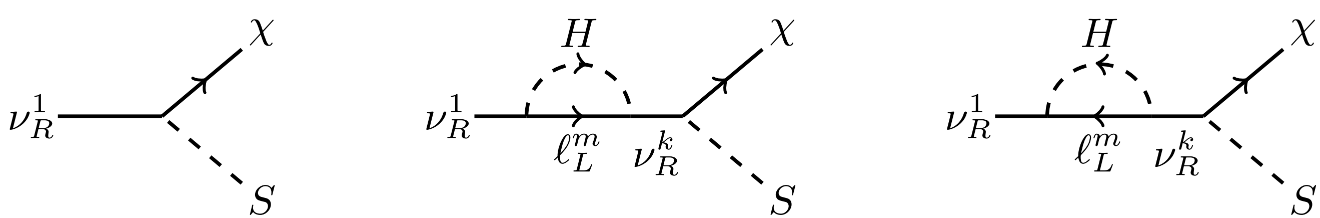



$-y_\chi \phi \bar{\chi} \chi$

Eventually to SM particles via portal coupling $\lambda_{H\phi}|H|^2\phi^2$

To have a nontrivial result, there should be $N(\chi) \neq N(\bar{\chi})$

1. Thermal fluctuation;[Asadi *et al*, PRL 127 (2021) 21, 211101]
2. "Asymmetric dark matter" scenario;[Shelton *et al*, PRD 82 (2010) 123512]



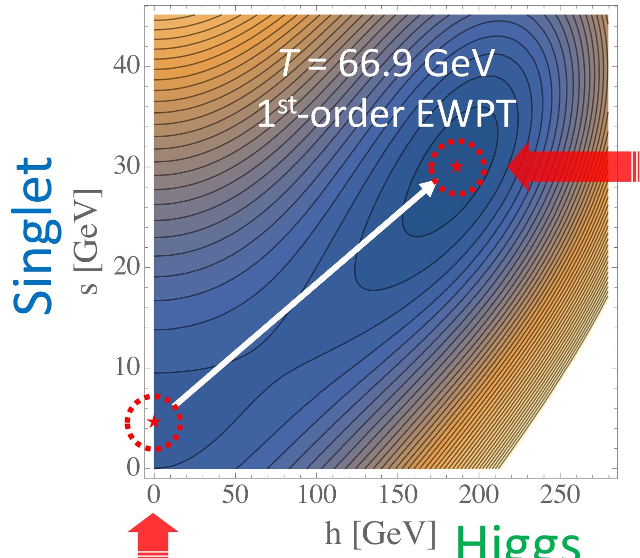

$\Gamma(\nu_R^1 \to \chi S) > \Gamma(\nu_R^1 \to \bar{\chi} S)$

$\eta_\chi \equiv \frac{n_\chi - n_{\bar{\chi}}}{s}$

*Similar to baryon asymmetry of the Universe

# Backup: application to a first-order EW phase transition

Extending the SM: $\mathcal{L} \subset -V(H,S) - \bar{\chi}(i\gamma^\mu \partial_\mu - M_0)\chi - y_\chi S \bar{\chi}\chi$

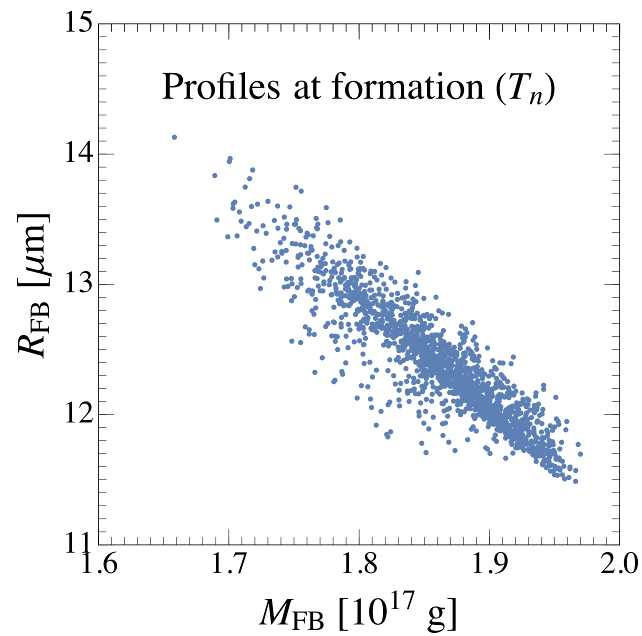



$$M_f = |M_0 + y_\chi v_s^f|$$

Trapping: $\frac{M_f - M_i}{T_n} \gg 1$

$$M_i = |M_0 + y_\chi v_s^i|$$

Huang and **KPX**, PRD 105 (2022) 11, 115033




Three fates of a Fermi-ball (fraction of parameter space):

1. Collapses into a PBH (72%);
2. Survives today as soliton DM (1%);
3. Evaporates (27%).