Primordial Black Holes from An Electroweak Phase Transition

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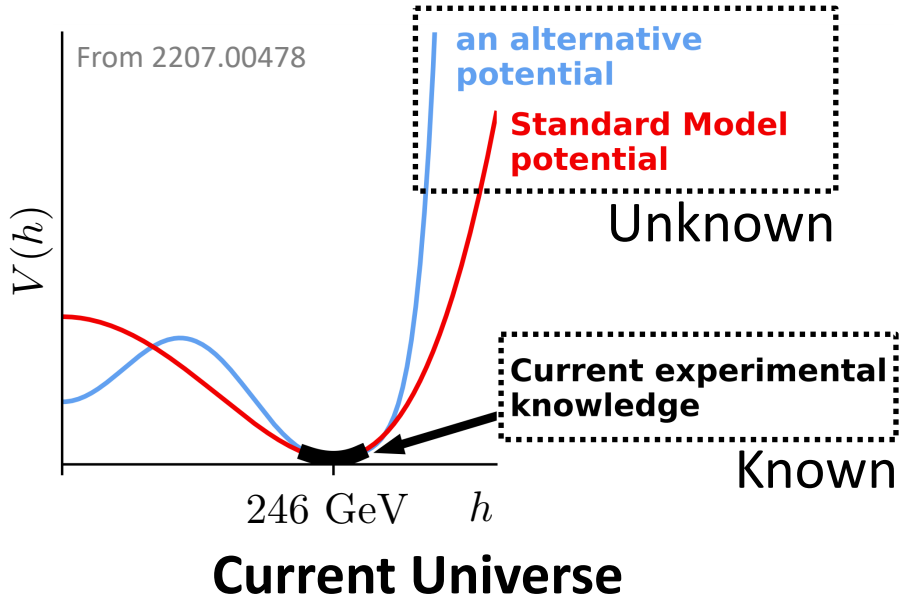
University of Nebraska-Lincoln

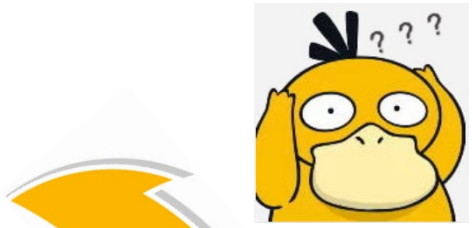
2022.7.27 @Higgs potential 2022 (online)

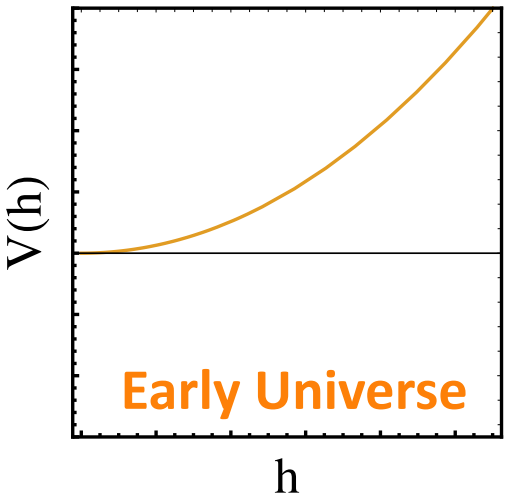
With Peisi Huang, Phys.Rev.D 105 (2022) 11, 115033 [arXiv:2201.07243]

The Higgs potential

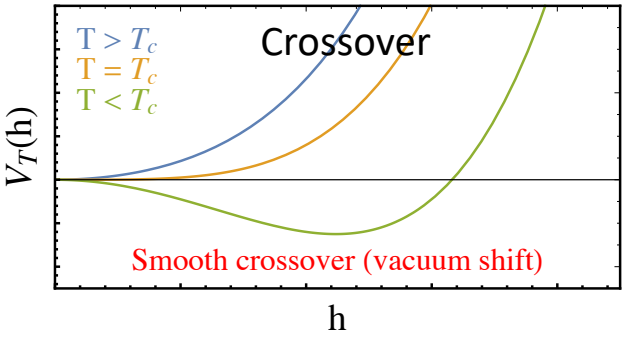


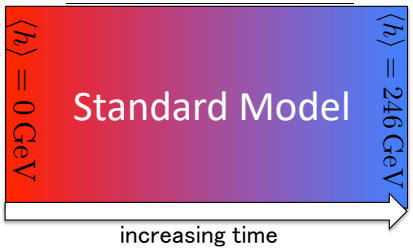
Current Universe

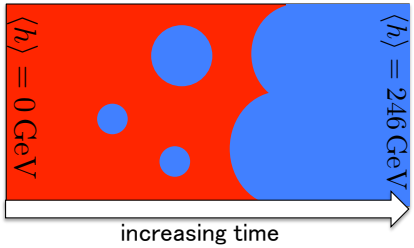


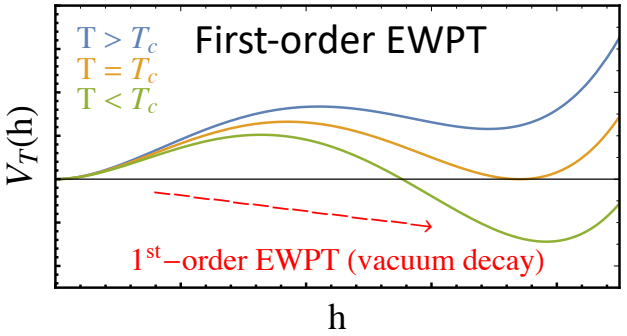


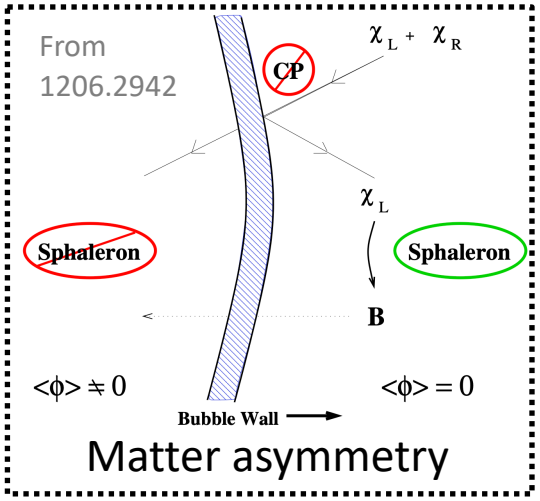
Patterns of the electroweak phase transition

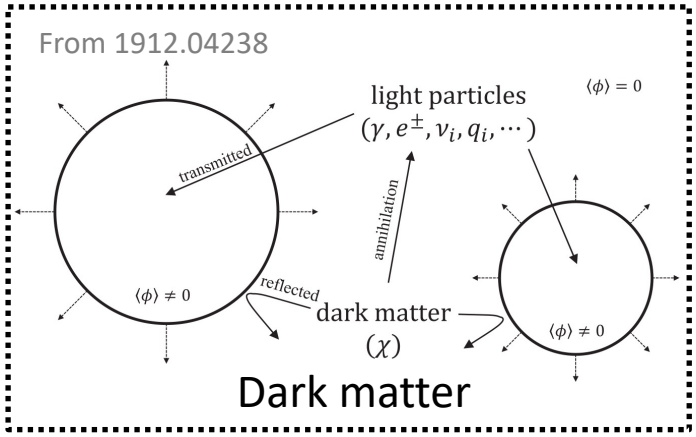


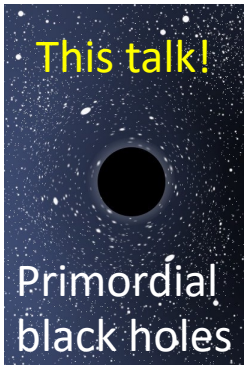




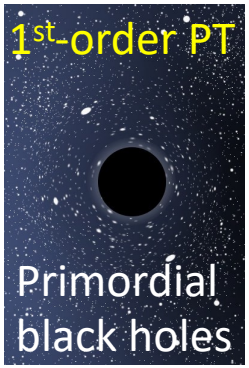








Black holes from 1st-order phase transitions



Bubble collisions

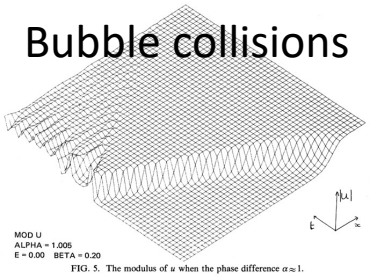
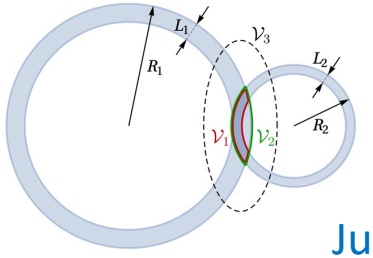


FIG. 5. The modulus of u when the phase difference $\alpha \approx 1$.

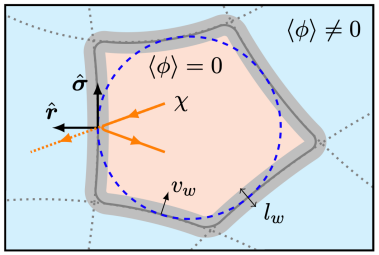


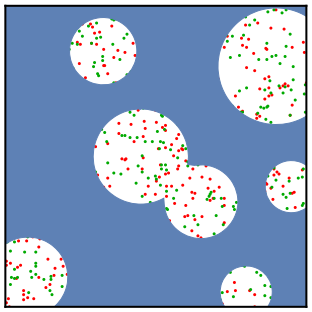
Hawking *et al*, PRD1982;

…

Jung *et al*, 2110.04271; etc

Particle trapping





Baker *et al*, 2105.07481;

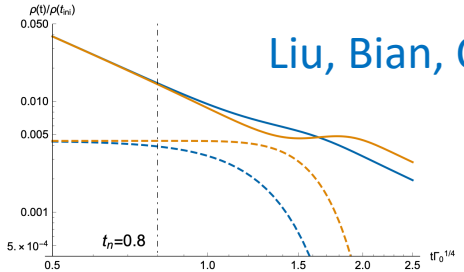
Kawana and **KPX**, 2106.00111;

Baker *et al*, 2110.00005;

Marfatia *et al*, 2112.14588;

Huang and **KPX**, 2201.07243;

Delayed vacuum decay



Liu, Bian, Cai, Guo and Wang, 2106.05637;

Hashino *et al*, 2111.13099;

Extending the scalar sector

Scalar potential (unitary gauge)

Higgs Singlet

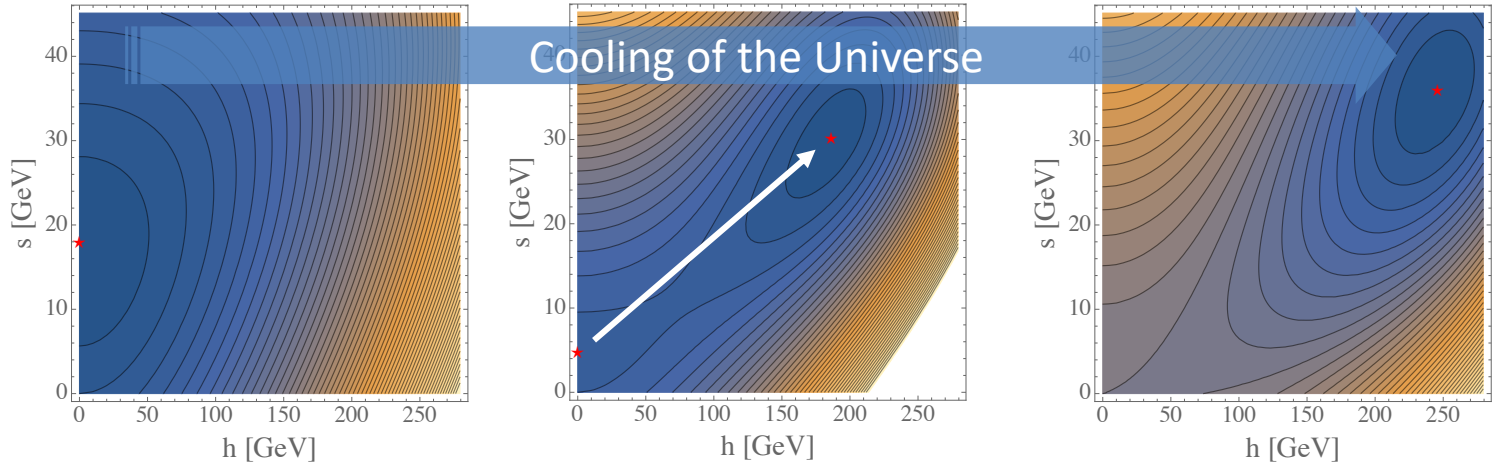
$$V(h,S) = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 + \frac{a_1}{4}h^2 S + \frac{a_2}{4}h^2 S^2 + \frac{b_2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

Thermal correction

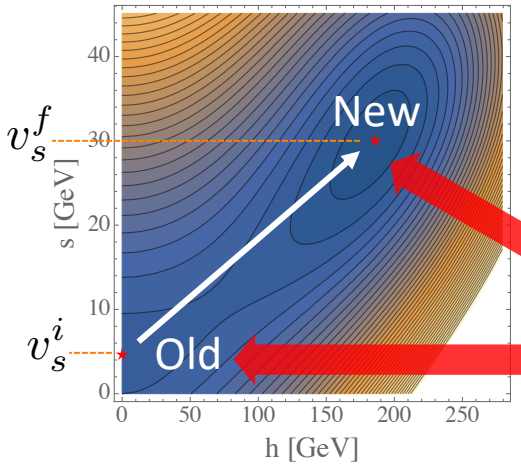
$$\Delta V(h,S,T) = \frac{c_H T^2}{2}h^2 + m_1 T^2 S + \frac{c_S T^2}{2}S^2$$

$$c_H = \frac{3g^2+g'^2}{16} + \frac{y_t^2}{4} + \frac{\lambda}{2} + \frac{a_2}{24},$$
$$c_S = \frac{a_2}{6} + \frac{b_4}{4}, \quad m_1 = \frac{a_1+b_3}{12}.$$

The 1st-order EWPT



Particle trapping in a phase transition



Fermion sector & Yukawa interaction

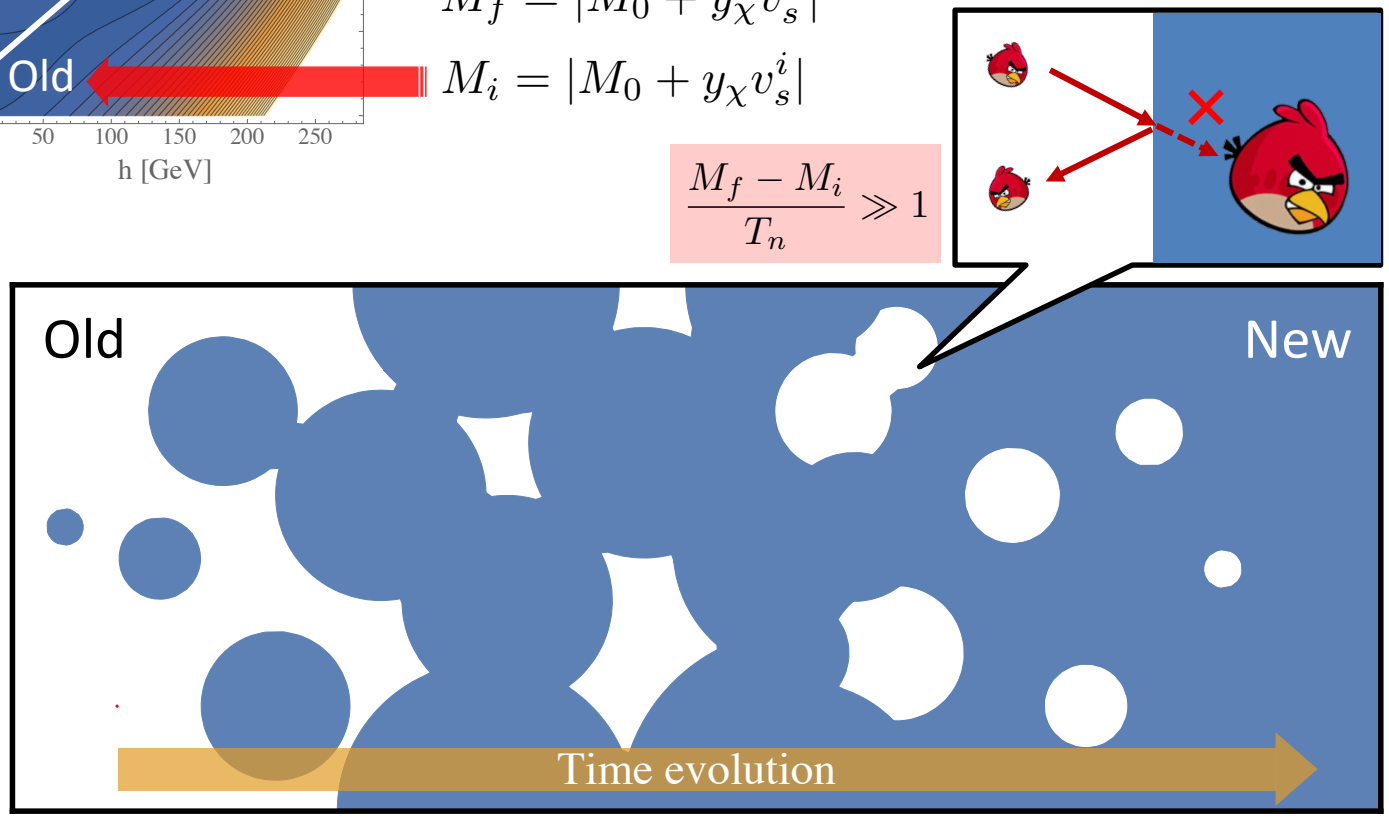
$$\mathcal{L} \supset \bar{\chi}(i\gamma^\mu \partial_\mu - M_0)\chi - y_\chi S \bar{\chi}\chi,$$

Fermion mass

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

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

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

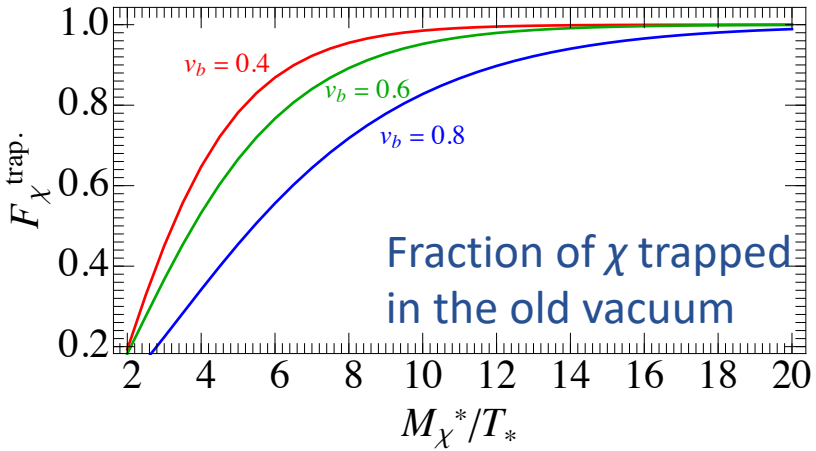


Particle trapping in a phase transition

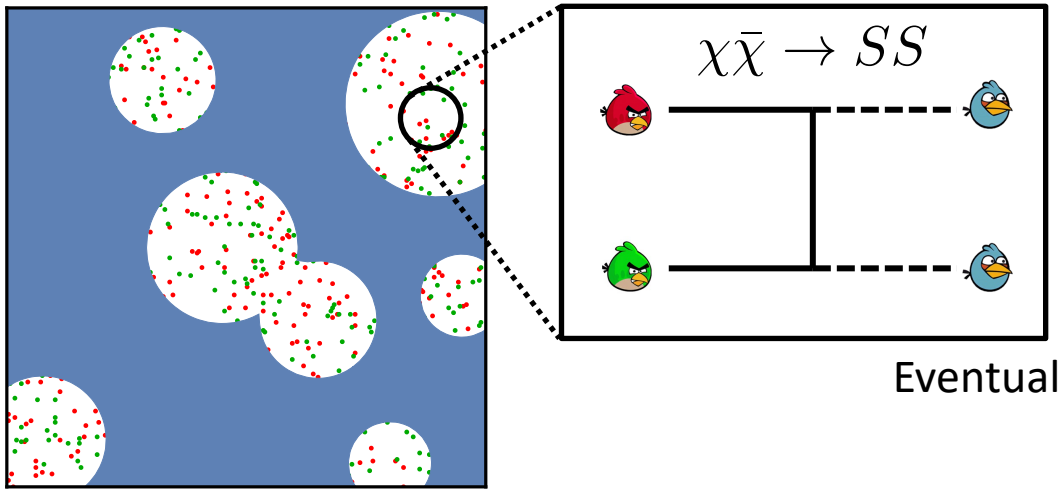
Trapping fraction

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

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



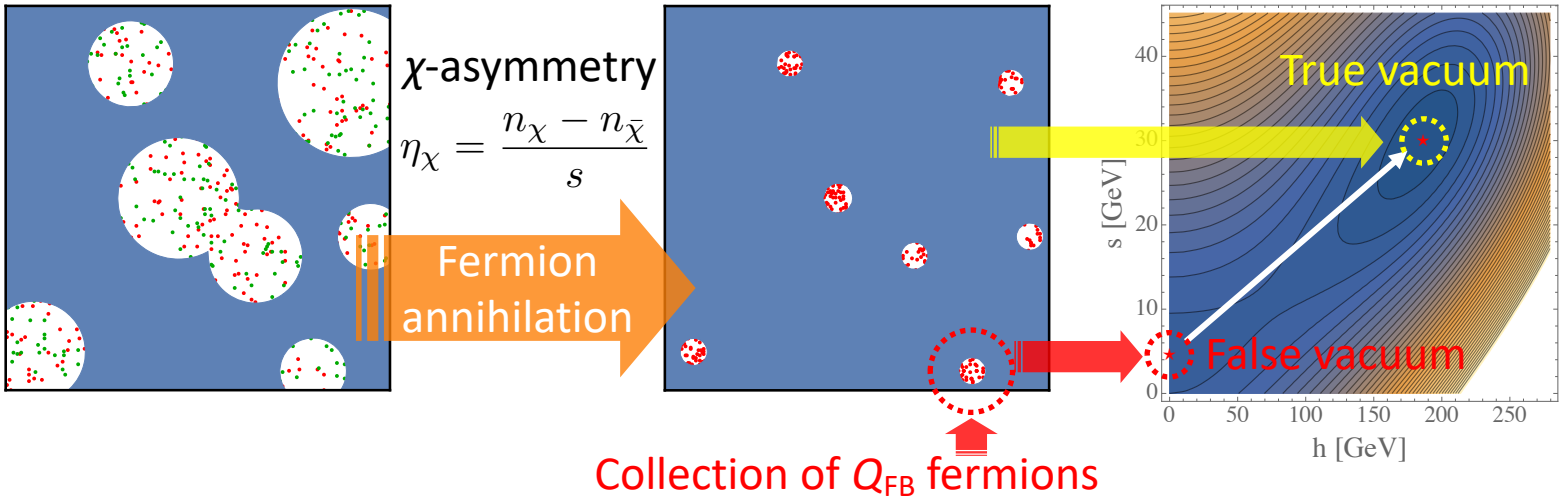
Fermions trapped in old vacuum



Eventually to SM particles

$$\frac{a_1}{4}h^2 S + \frac{a_2}{4}h^2 S^2$$

What happens for the trapped fermions?



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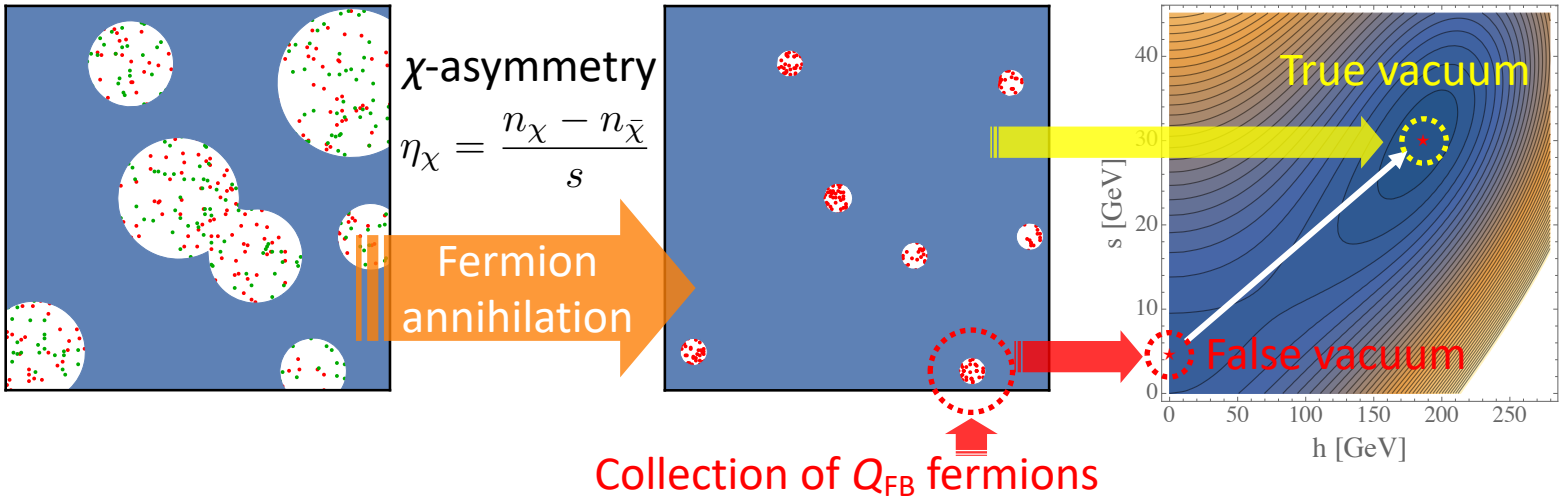
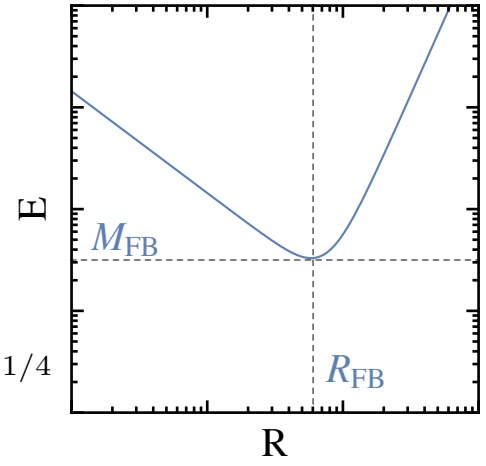


Fermi-gas energy Vacuum energy

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

Degeneracy pressure balances the vacuum pressure → *Fermi-ball* soliton forms!

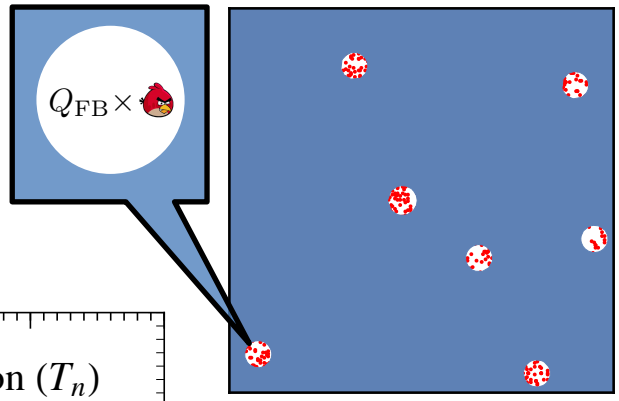
$$M_{\rm FB} = Q_{\rm FB}\left(12\pi^2 U_0\right)^{1/4}, \quad R_{\rm FB} = Q_{\rm FB}^{1/3}\left[\frac{3}{16}\left(\frac{3}{2\pi}\right)^{2/3}\frac{1}{U_0}\right]^{1/4}$$



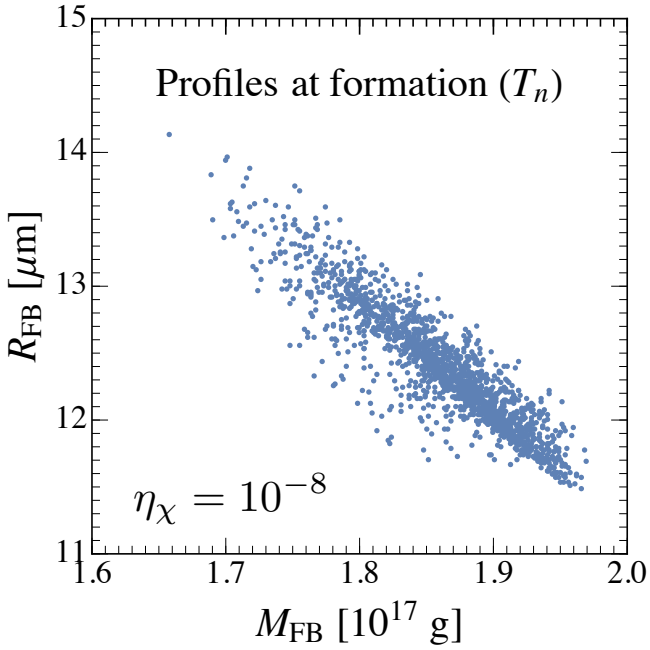
The Fermi-ball profile

At phase transition temperature

$$Q_{\rm FB} \sim 10^{38}, \quad T_n \sim 100\ {\rm GeV}$$



$$R_{\rm FB} \propto \eta_\chi^{1/3}$$

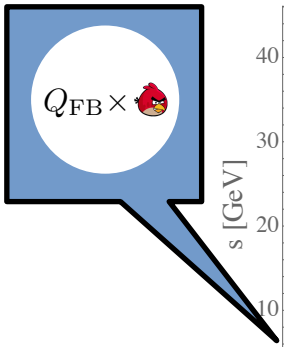


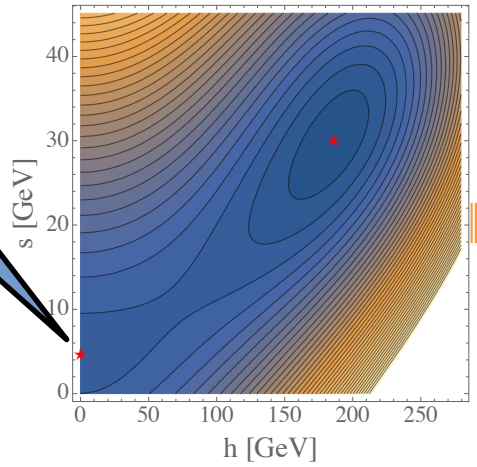
$$\eta_\chi = \frac{n_\chi - n_{\bar\chi}}{s}$$

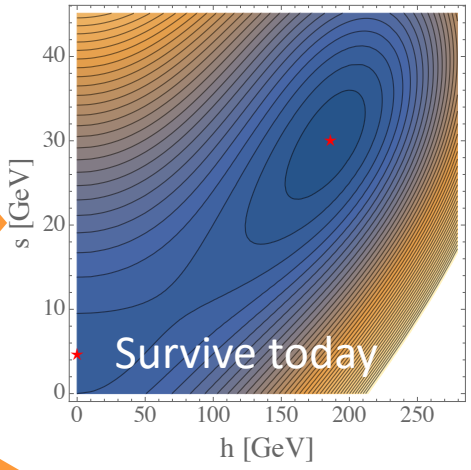
$$M_{\rm FB} \propto Q_{\rm FB} \propto \eta_\chi$$

Evolution of Fermi-balls

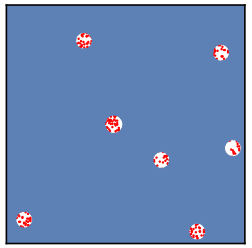
Different fates: [Huang and **KPX**, 2201.07243]



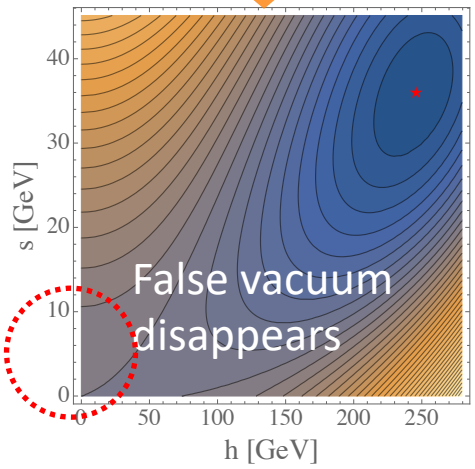




Fate 1:
Soliton DM



2008.04430
Hong, Jung, **KPX**



Fate 2:
Evaporation

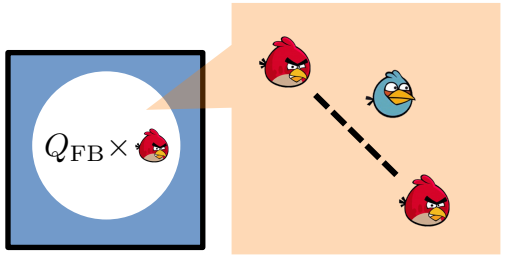
Fate 3:

Black hole formation

2106.00111
Kawana and **KPX**

From Fermi-balls to black holes

Yukawa (attractive) interaction inside a Fermi-ball $\boxed{-y_\chi S\bar{\chi}\chi}$



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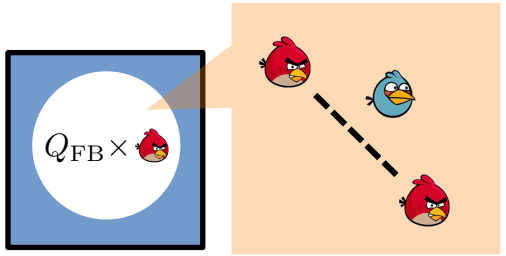

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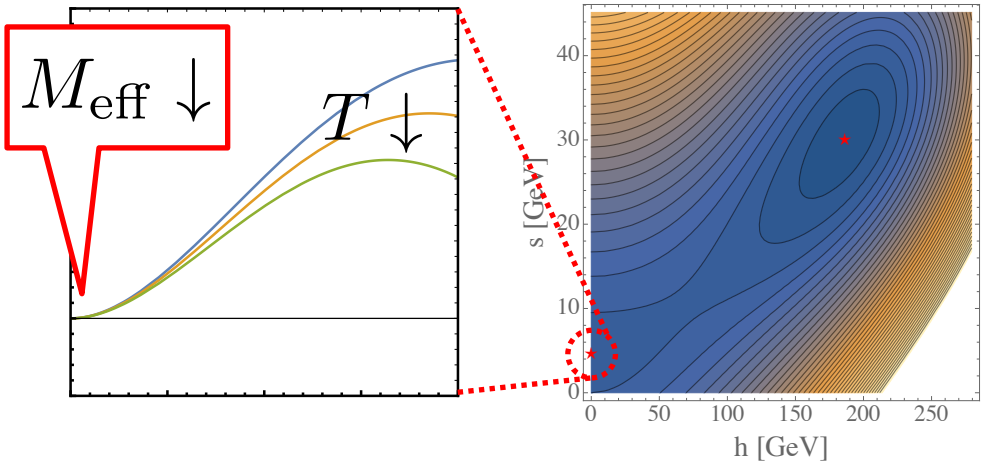
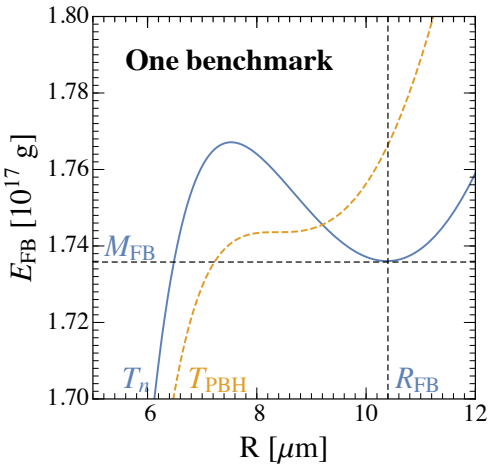
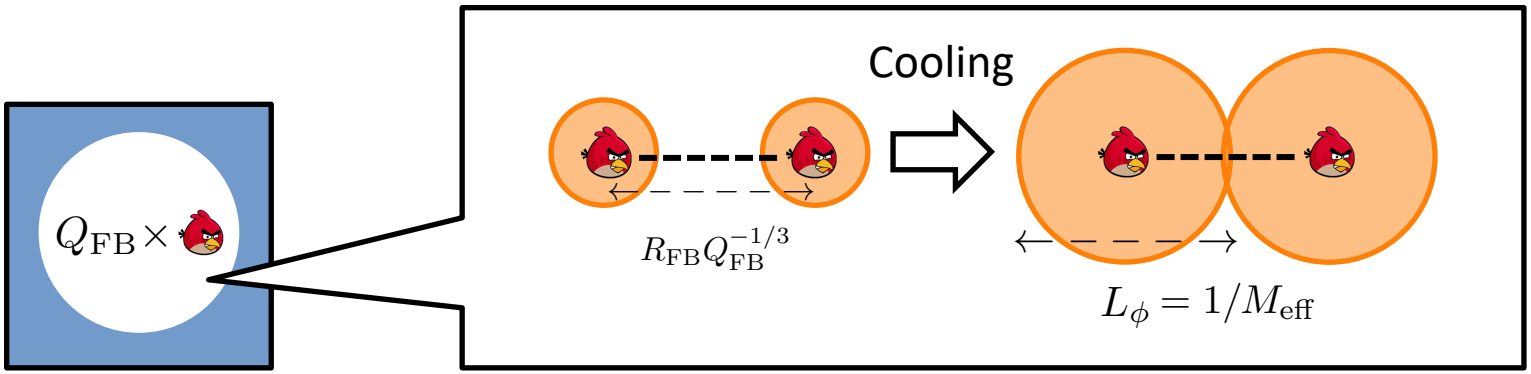
Fermi-balls cool down via black body radiation [Witten, PRD1984]

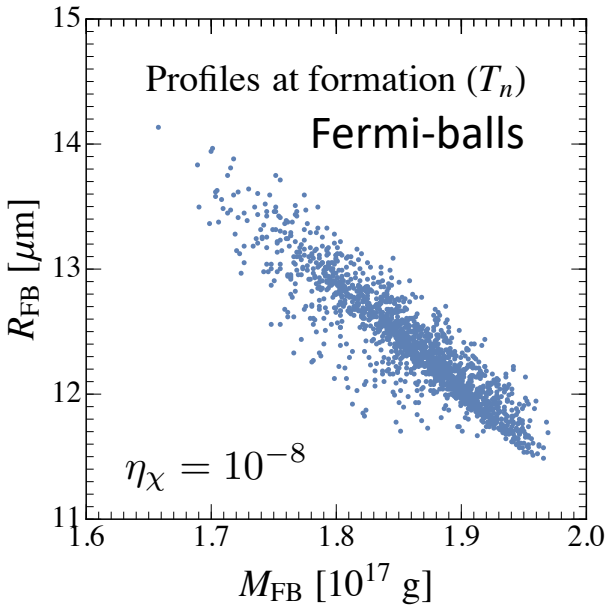




From Fermi-balls to black holes

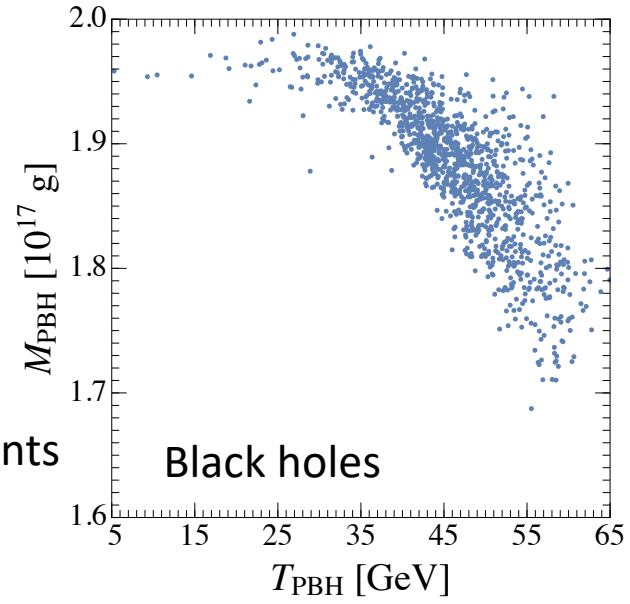
One fermion "sees" another fermion $\frac{1}{M_{\rm eff}} \sim \frac{R_{\rm FB}}{Q_{\rm FB}^{1/3}}$





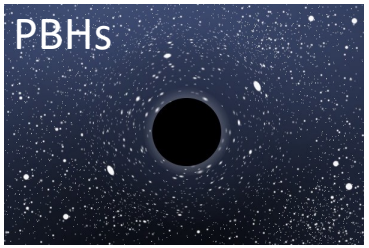
Collapse!

72% of the parameter points



What can primordial black holes do?

Depending on mass:



Dark — A natural **dark matter** candidate;


Seeds of the supermassive black holes;

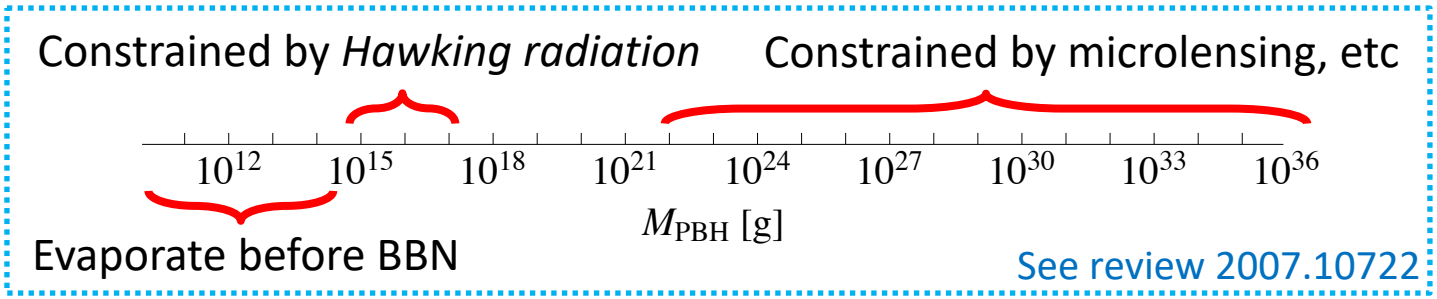

Explaining LIGO/Virgo observations;


Origin of the matter-antimatter asymmetry;

.....

$$M_{\rm PBH} \propto Q_{\rm FB} \propto \eta_\chi$$

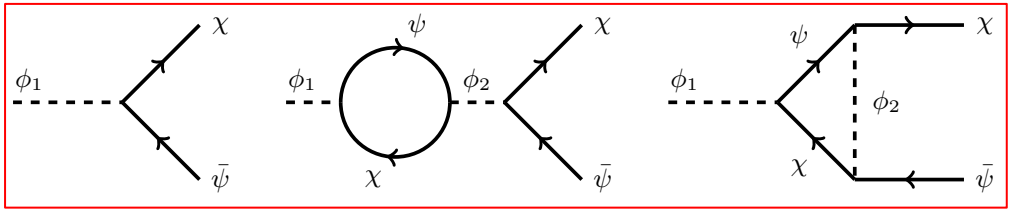
This talk: can be from a 1st-order electroweak phase transition!



Towards a complete model

Origin of the χ-asymmetry

$$\mathcal{L} = \sum_{i=1}^{2}\left(\frac{1}{2}\partial_\mu\phi_i\partial^\mu\phi_i - \frac{1}{2}M_i^2\phi_i^2\right) + \bar{\psi}\left(i\gamma^\mu\partial_\mu - M_\psi\right)\psi - \sum_{i=1}^{2}\left(\lambda_i\phi_i\bar{\chi}\psi + \text{h.c.}\right).$$



$$\epsilon_\chi = \frac{\Gamma(\phi_1 \to \chi\bar{\psi}) - \Gamma(\phi_1 \to \bar{\chi}\psi)}{\Gamma(\phi_1 \to \chi\bar{\psi}) + \Gamma(\phi_1 \to \bar{\chi}\psi)} \approx -\frac{11}{48\pi}\frac{\text{Im}[(\lambda_1^*\lambda_2)^2]}{|\lambda_1|^2}\frac{M_1^2}{M_2^2},$$

$$\eta_\chi = \frac{n_\chi - n_{\bar{\chi}}}{s} \approx \frac{3T_{\text{rh}}}{2M_1}\epsilon_\chi \text{Br}(\phi_1 \to \chi\bar{\psi}/\bar{\chi}\psi)$$

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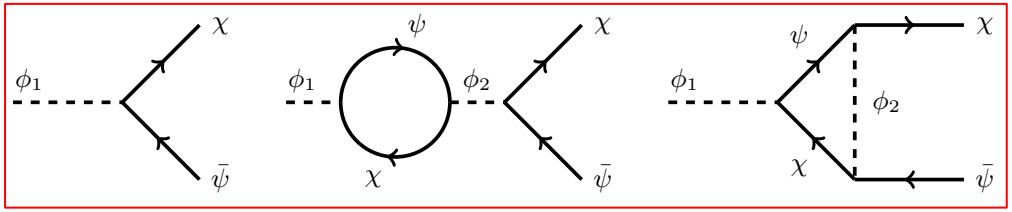

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Primordial black holes density $n_{\text{PBH}} = s \times \frac{n^*_{\text{FB}}}{s_*}$ $\qquad n^*_{\text{FB}} \approx 0.29 \times V_*^{-1}$

Typically over produced: $\Omega_{\text{PBH}} \sim 6000 \times \Omega_{\text{DM}}$

Diluted by $\psi \to \ell H/\bar{\ell}H^*$ (early matter domination era)

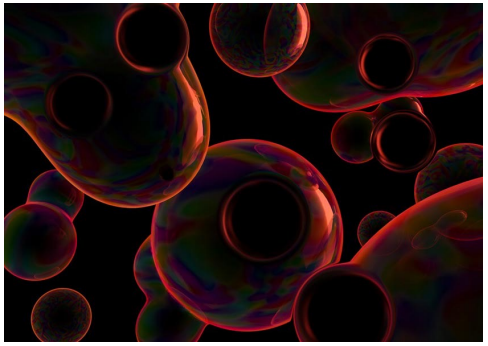
$$\Delta_\psi = 6.24 \times 10^3 \times \left(\frac{1.0}{|\lambda_2|}\right)^2 \left(\frac{g_*}{100}\right)^{1/4} \left(\frac{M_2}{3.5\times 10^{12}\ \text{GeV}}\right)^2 \left(\frac{10^{10}\ \text{GeV}}{M_1}\right)^2 \left(\frac{M_\psi}{10^3\ \text{GeV}}\right)^{1/2} \left(\frac{10^{-12}}{\lambda_\psi}\right)\left(\frac{\eta_\chi}{10^{-8}}\right)$$

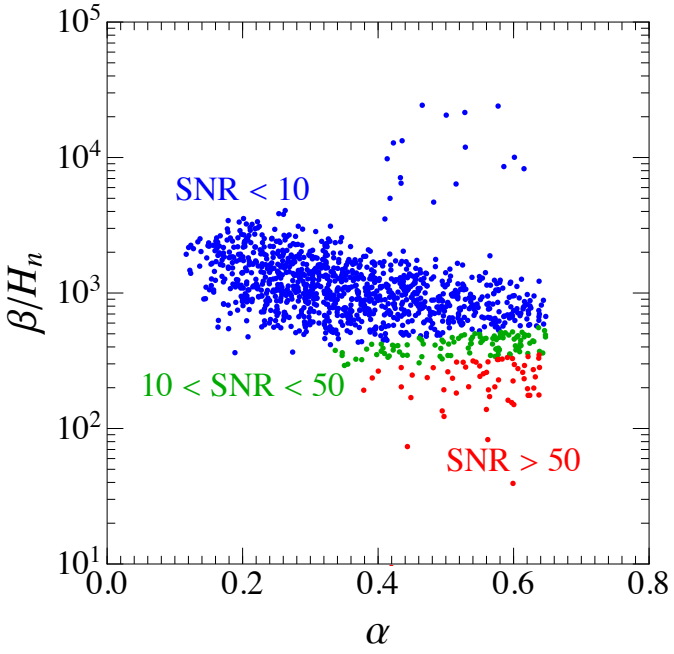
Phenomenology: gravitational waves

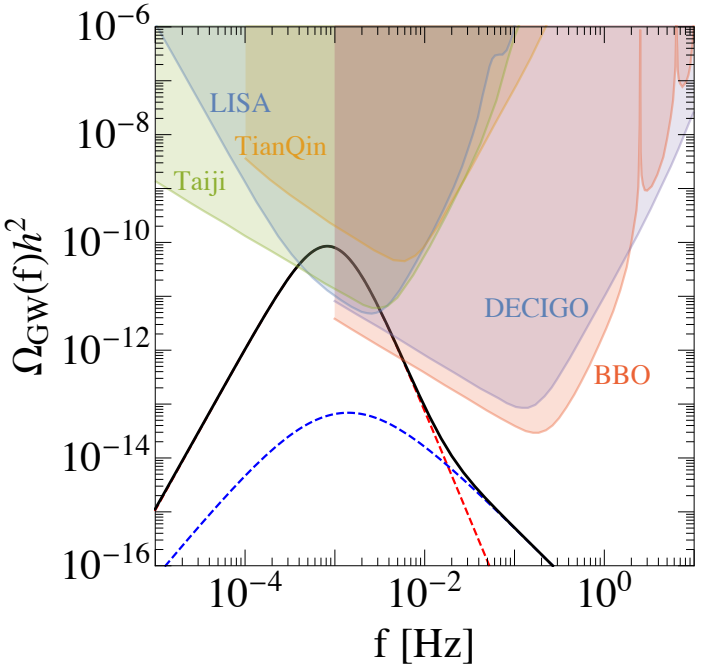
Stochastic GWs:

- ✓ Collision of the bubbles
- ✓ Sound waves in plasma
- ✓ Turbulance in plasma

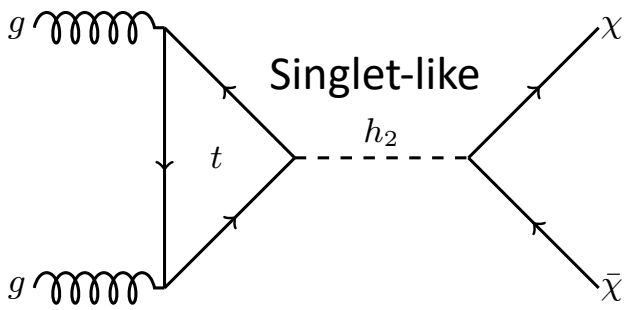
[See Fa Peng's talk for a review]





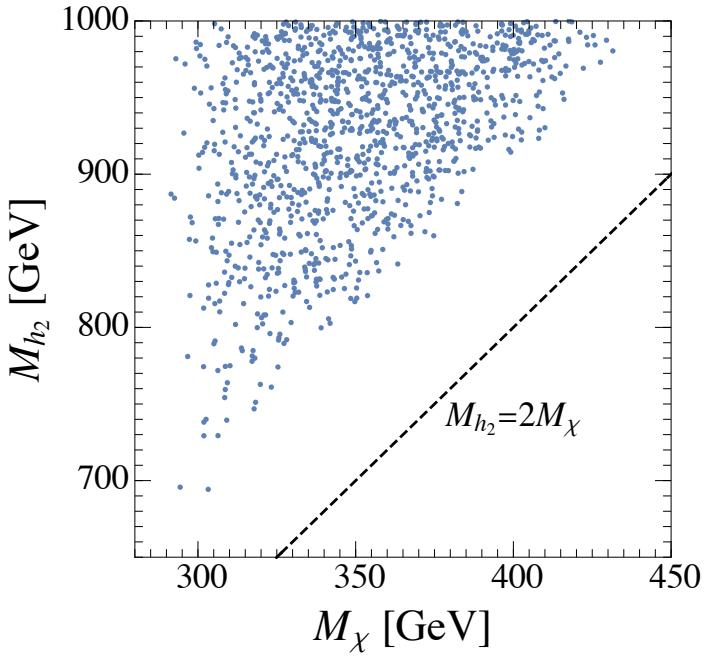


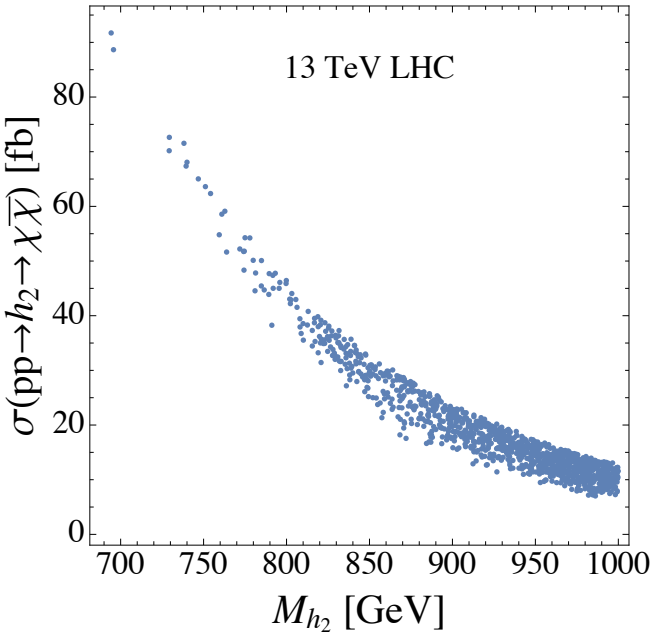
Phenomenology: collider



χ decay: $\lambda_\chi \bar{\ell}_L \tilde{H} \chi$

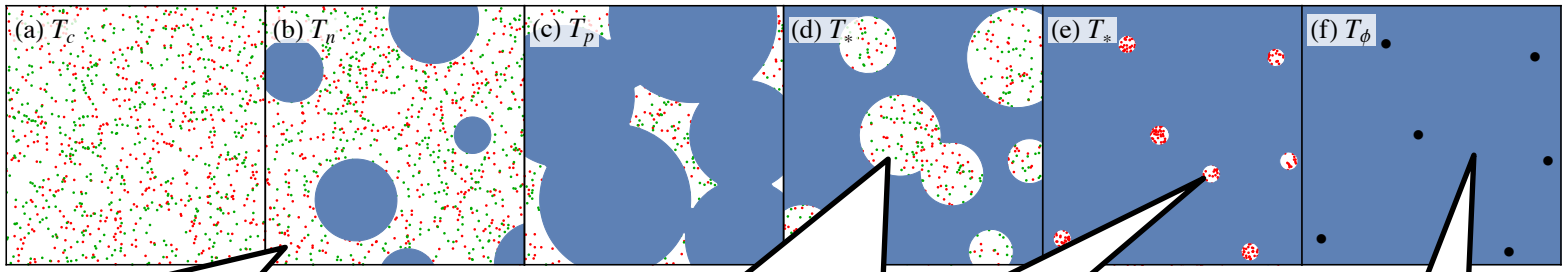
- Multi-lepton & jets;
- Displaced vertex;
- Mono-jet & missing energy.





Conclusion

First-order phase transition (FOPT)



FOPT proceeds: bubble nucleation and expansion

Fermions get trapped in the old vacuum remnants!

Non-topological solitons called Fermi-balls form,

Fermi-balls collapse into PBHs.

Relevant works:

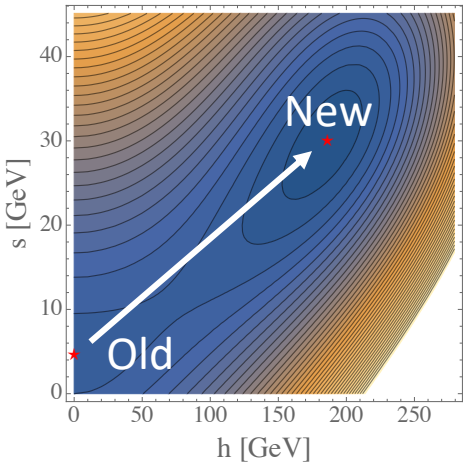
2008.04430, Hong, Jung and **KPX**;

2106.00111, Kawana and **KPX**;

2201.07243, Huang and **KPX**.

Thank you!

Backup: the 1st-order electroweak phase transition



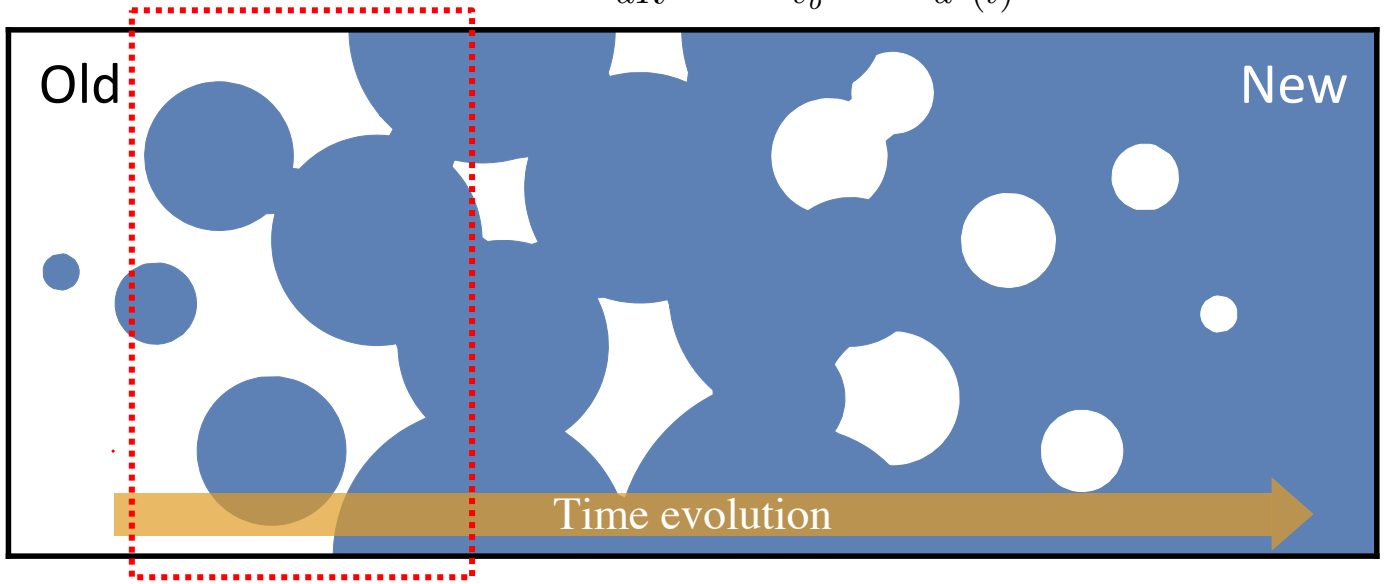
Decay rate per unit volume [Linde, NPB1983]

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

Fraction of old vacuum [Guth *et al*, PRD1981]

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

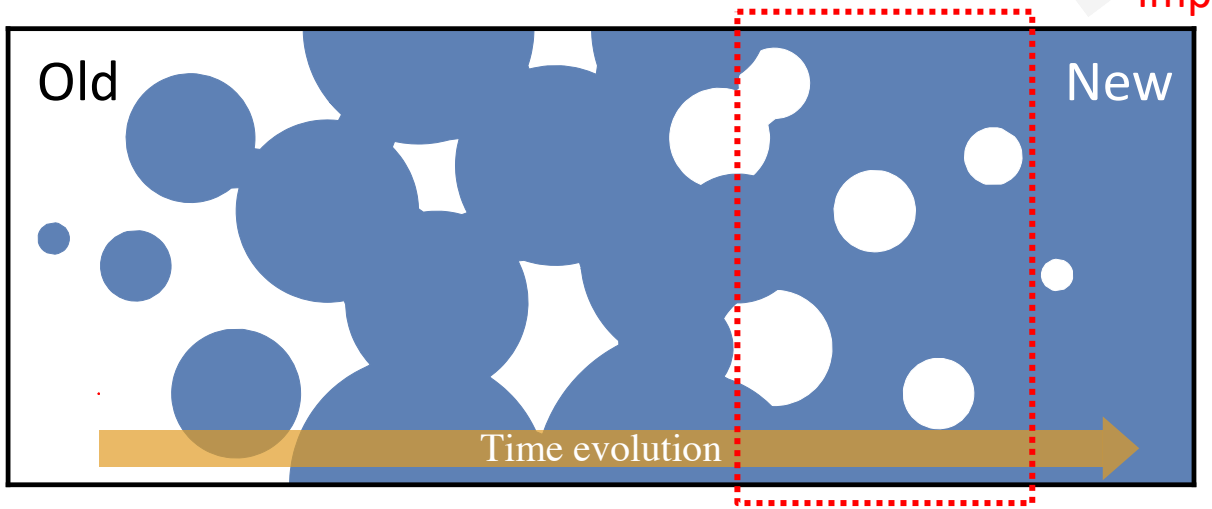
Bubble distribution $\frac{dn}{dR}(t) = \frac{\Gamma(t')}{v_b} p(t') \frac{a^4(t')}{a^4(t)}$



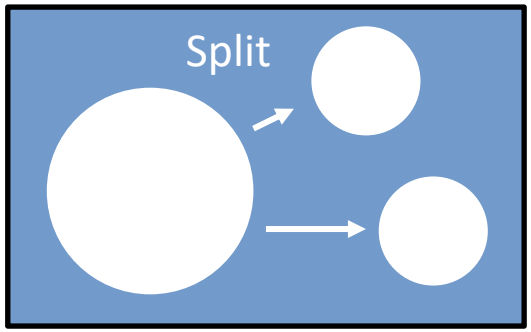
Backup: volume of old vacuum remnants

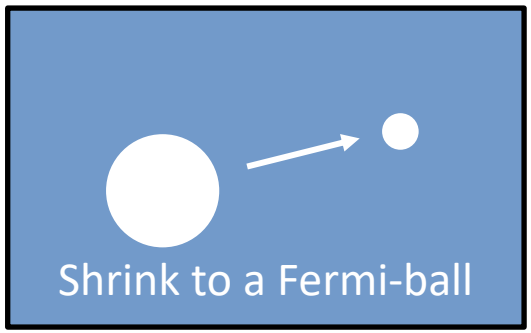
Charge collected in a Fermi-ball $Q_{\rm FB} = F_\chi^{\rm trap} \eta_\chi s V$

Remnant volume Important!



A detailed study see [Lu, Kawana and **KPX**, 2202.03439]; a simple model here



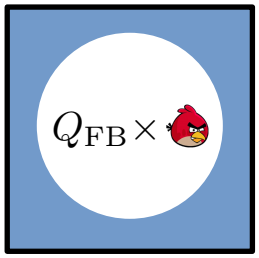


Average volume $\Gamma(T_*) V_* \Delta t \sim 1, \quad V_* = \frac{4\pi}{3} R_*^3, \quad \Delta t = \frac{R_*}{v_b}$

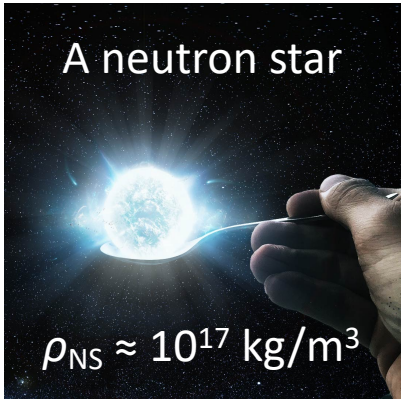
Backup: stability condition

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

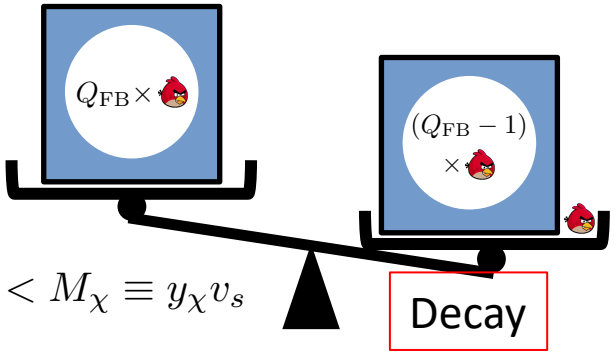
Mass density of a single Fermi-ball



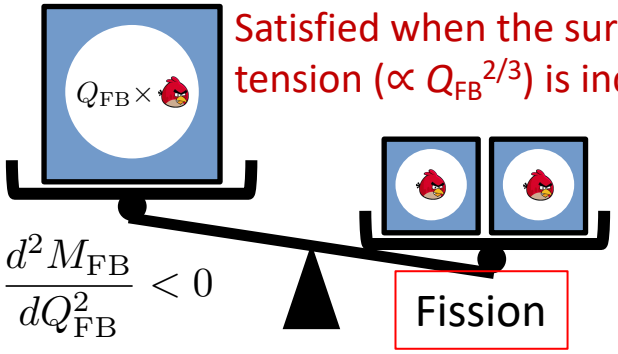
$$: 9.15\times 10^{28}\ {\rm kg/m^3}\left(\frac{U_0^{1/4}}{100\ {\rm GeV}}\right)^4 >$$



The stability conditions



$$\frac{dM_{\rm FB}}{dQ_{\rm FB}} < M_\chi \equiv y_\chi v_s$$



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

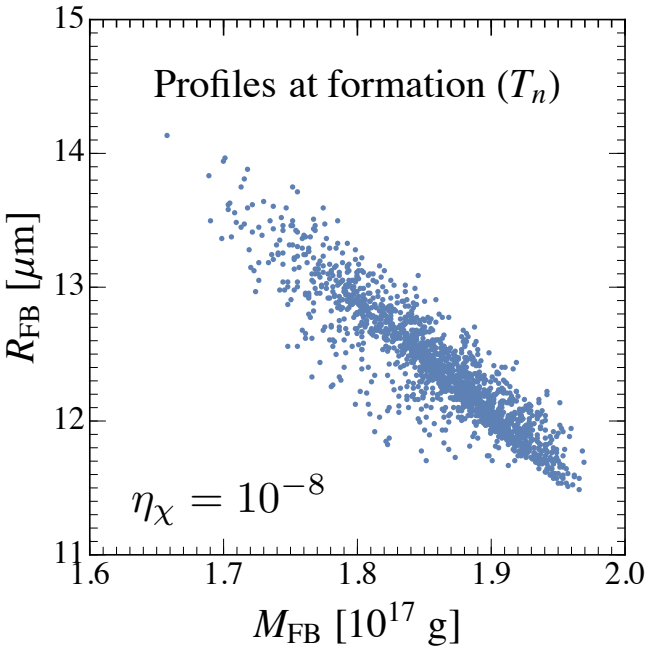
Satisfied when the surface tension ($\propto Q_{\rm FB}^{2/3}$) is included.

Backup: the Fermi-ball profile

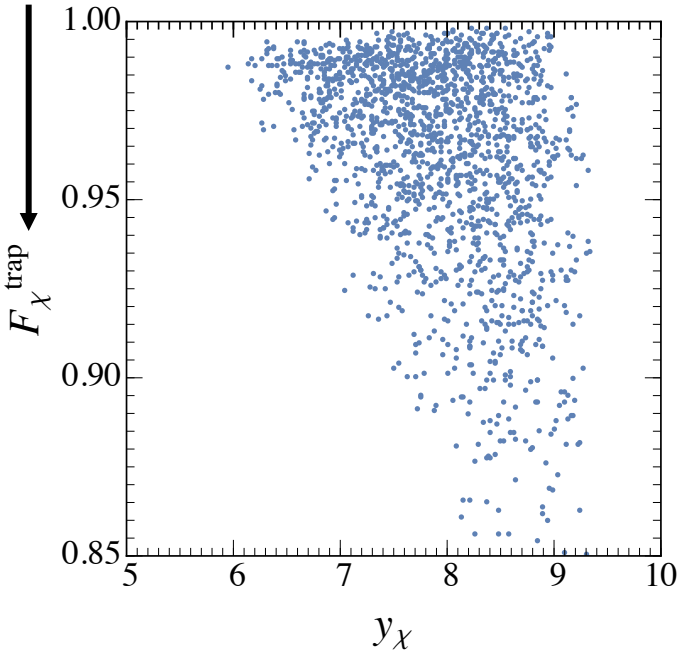
At phase transition temperature

$$Q_{\rm FB} \sim 10^{38}, \quad T_n \sim 100\ {\rm GeV}$$

$$M_{\rm FB} \propto Q_{\rm FB} \propto \eta_\chi, \quad R_{\rm FB} \propto \eta_\chi^{1/3}$$



Trapping fraction



Large Yukawa required by trapping.

Composite Higgs model?