Primordial Black Holes from a cosmic phase transition: The collapse of Fermi-balls

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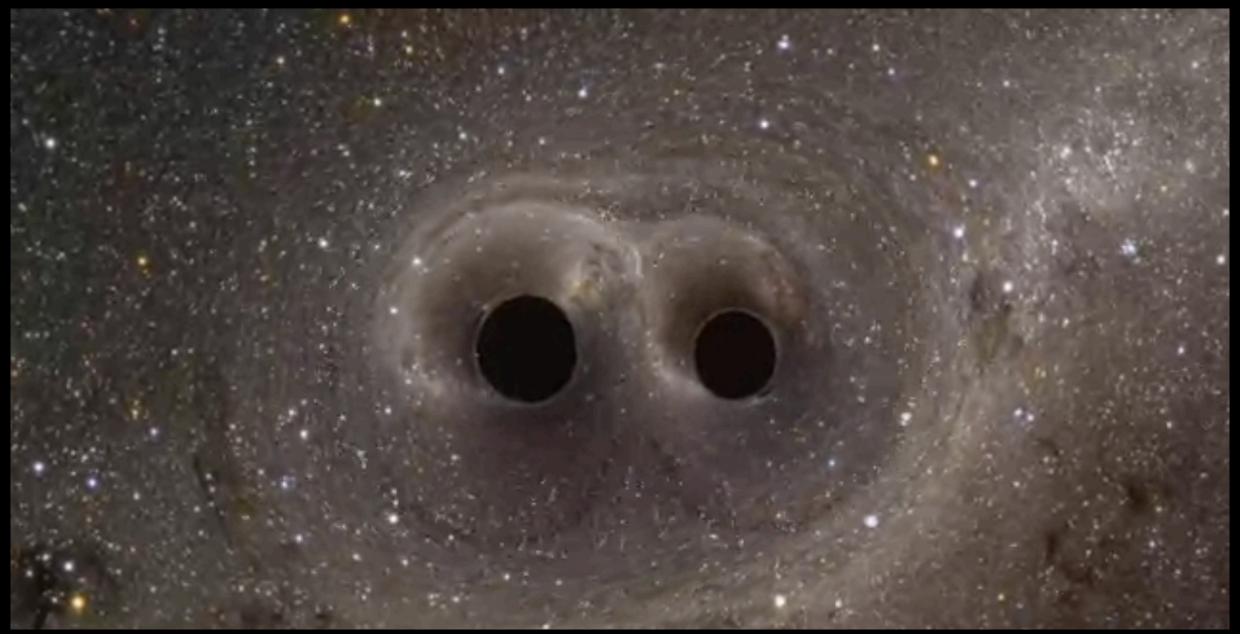
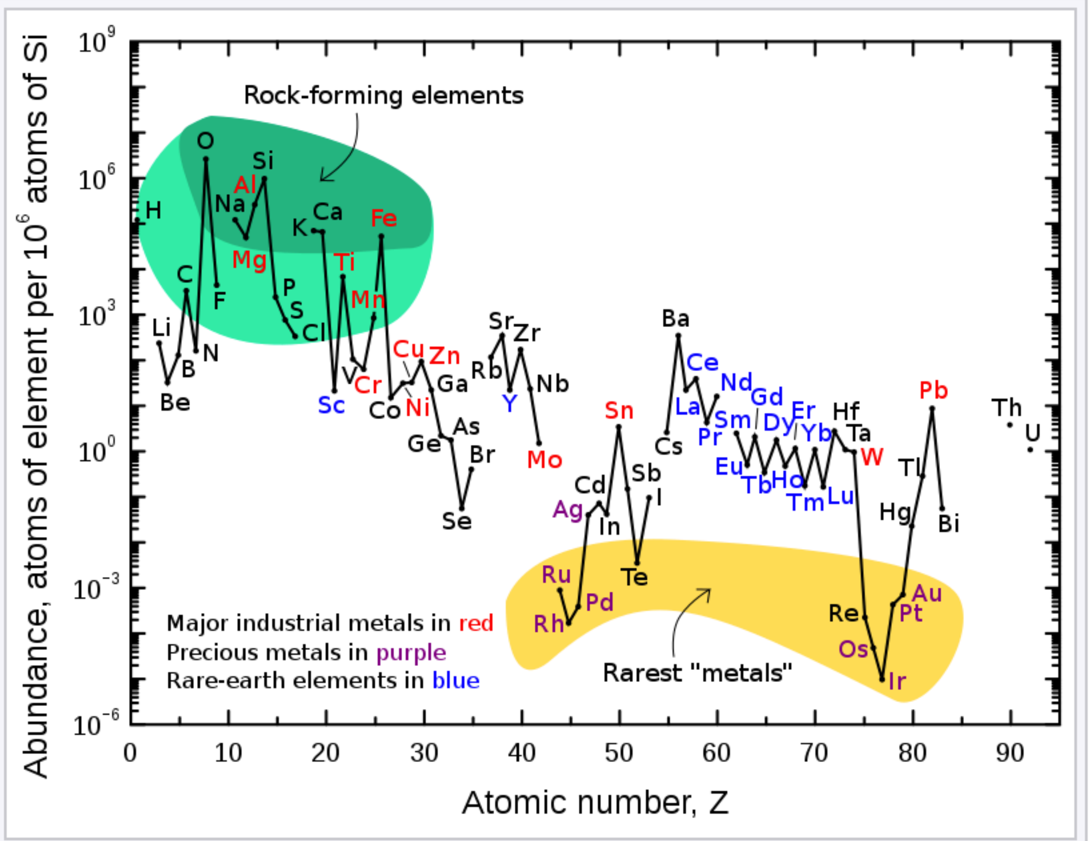
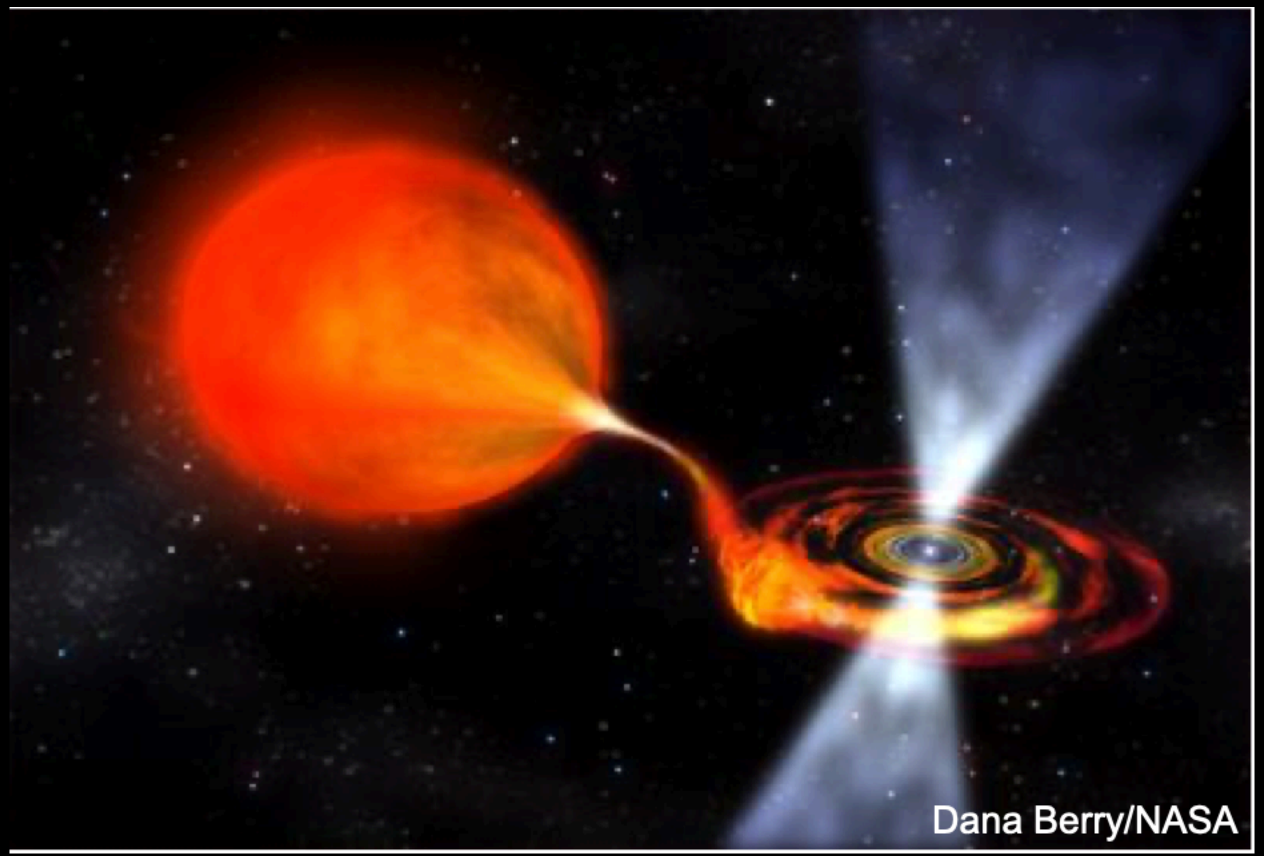
Why Primordial Black Hole is interesting ?

- can account for Dark Matter (DM). The DM candidate that is not necessary made of new particles. (Although their productions may need new physics)
- can seed super massive Black Holes, $M \sim 10^9 M_\odot$ (at $z = 6 \sim 7$)
- can contribute Gravitational Wave (GW) signals: Ligo/Virgo/KAGRA, NANOGrav
- is ubiquitous in new physics → Inflation, first-order phase transition, cosmic string (domain wall), scalar condensate, new force, etc
- r-process nucleosynthesis, and more…



From Wikipedia





General Properties of PBHs

- Evaporation

$$\tau \sim \underline{10^{18}\ \mathrm{s}} \left(\frac{M_{\rm PBH}}{10^{15}\ \mathrm{g}}\right)^3$$

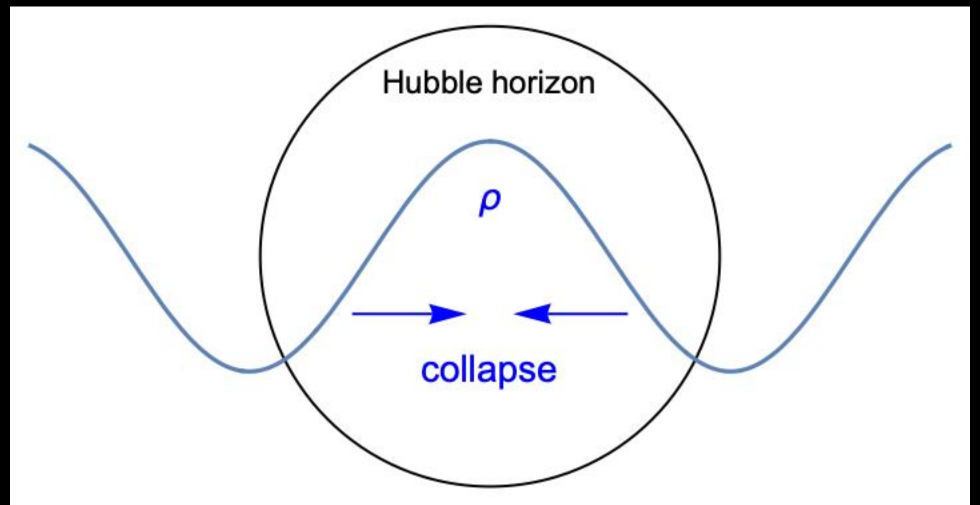
Life time of the Universe

Only PBHs with $M_{\rm PBH} \gtrsim 10^{15}$ g can survive

- In popular formation scenarios, overdense regions collapse when it enters the horizon scale

$$M_{\rm PBH} = \underline{\gamma} \frac{4\pi}{3} \rho H^{-3} = 2 \times 10^5 \gamma \left(\frac{t}{1\ \mathrm{s}}\right) M_\odot$$

Numerical coefficient



∗ Our scenario does not belong to this category. It is similar to gravitational collapse of stars

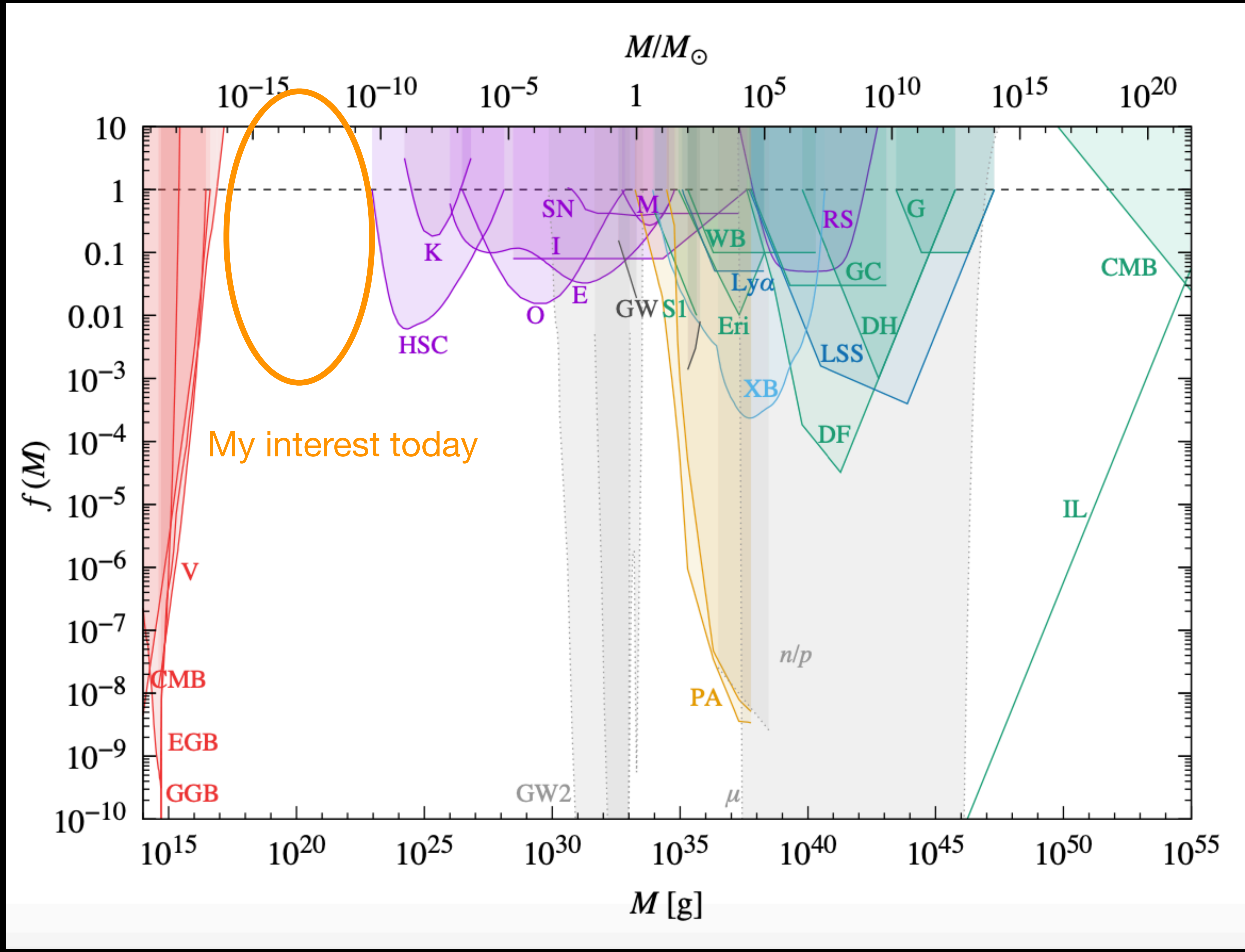
- After the formation, it behaves as matter

$$\rho_{\rm PBH}(t) = \left(\frac{a(t_{\rm form})}{a(t)}\right)^3 \rho_{\rm PBH}(t_{\rm form}) \sim \frac{s(T)}{s(T_{\rm form})} \rho_{\rm PBH}(t_{\rm form}) \ ,$$

Entropy conservation

$$s(T) a(t)^3 = s(T_{\rm form}) a(t_{\rm form})^3$$

Observational Constraints

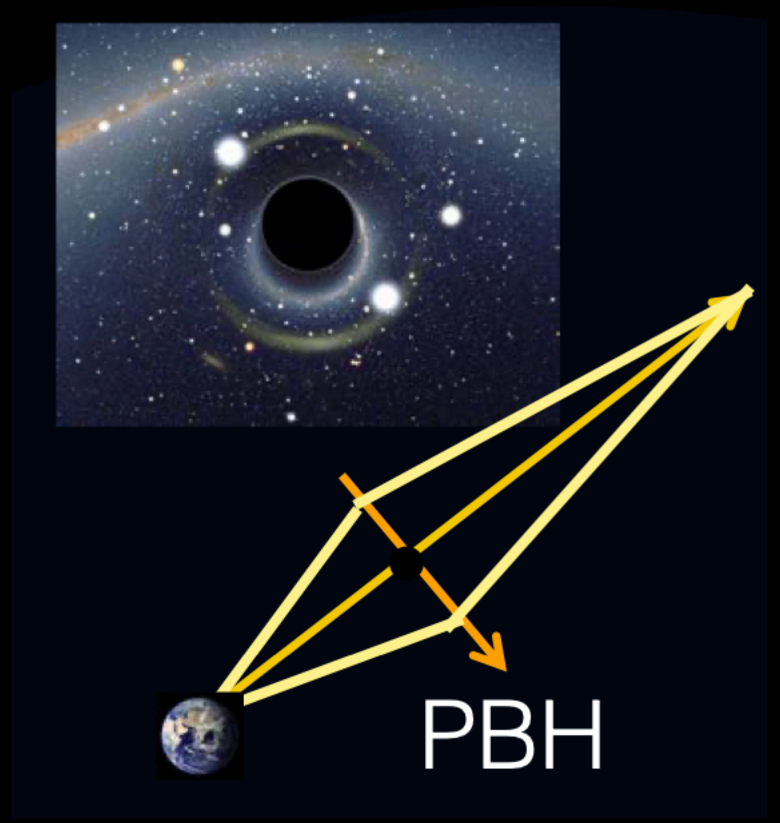


[B. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, (2020), 2002.12778]

Non-evaporating PBHs

$$f(M) = \rho_{\rm PBH}/\rho\,|_{\rm today}$$

- Red: evaporation
- Magenta: Lensing
- Green: dynamical effects
- Yellow: CMB distorsion



Brief Summary

- We propose a new PBH formation mechanism which does not rely on primordial density fluctuations and gravitational force

- Instead, we assume asymmetry of a fermion $\chi : \eta_\chi = (n_\chi - n_{\bar{\chi}})/s \neq 0$

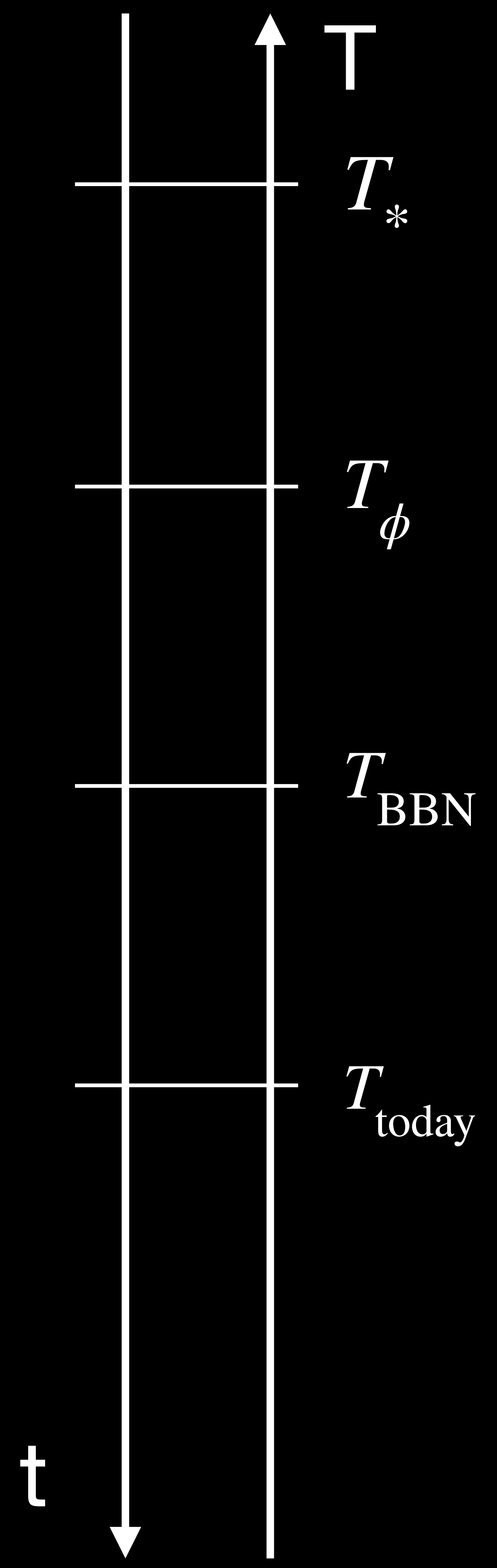
- We first show that compact objects called Fermi-balls are (generally) created during a first-order phase transition (FOPT) [J.-P. Hong, S. Jung, and K.-P. Xie, Phys. Rev. D 102, 075028 (2020)]

- After the FOPT, Fermi-balls collapse into PBHs by Yukawa force $g_\chi \phi \bar{\chi} \chi$

∗ Similar idea was also discussed in [M. Flores, A. Kusenko, Phys. Rev. Lett. 126, 041101 (2021)]

- If there is no dilution epoch after that, the PBHs can account for whole DM when $T_* \sim 10\ \mathrm{GeV}$

Thermal History of Fermi-balls and PBHs

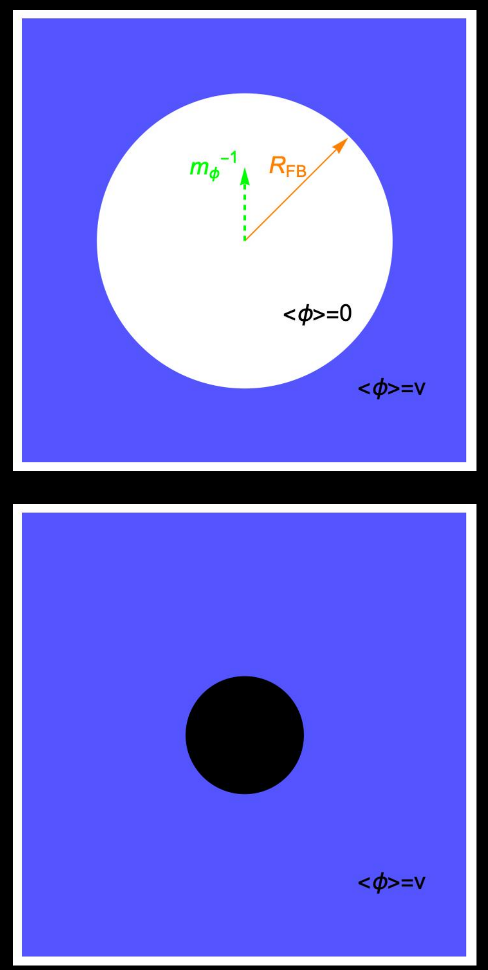


Formation of Fermi-balls by first-order phase transition

Formation of PBHs: Fermi-balls collapse into PBHs.

After that, PBHs dilute as matter

PBHs survive as (cold) Dark Matter !



Need to discuss the stability of Fermi-balls

Plan of Talk

1. Fermi-ball formation by FOPT
2. PBH formation by collapse of Fermi-balls
3. Summary

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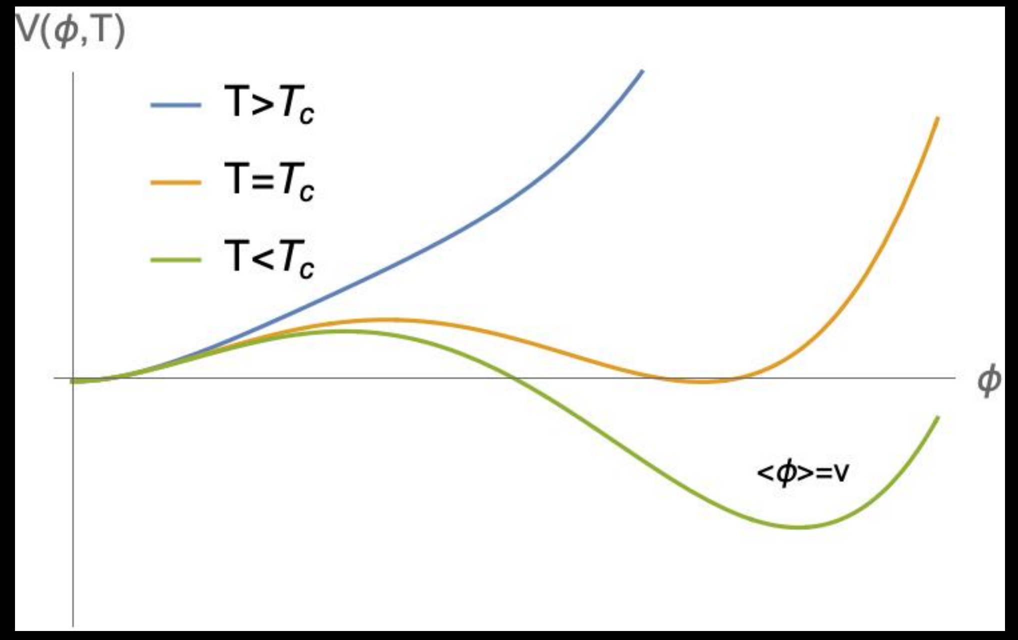
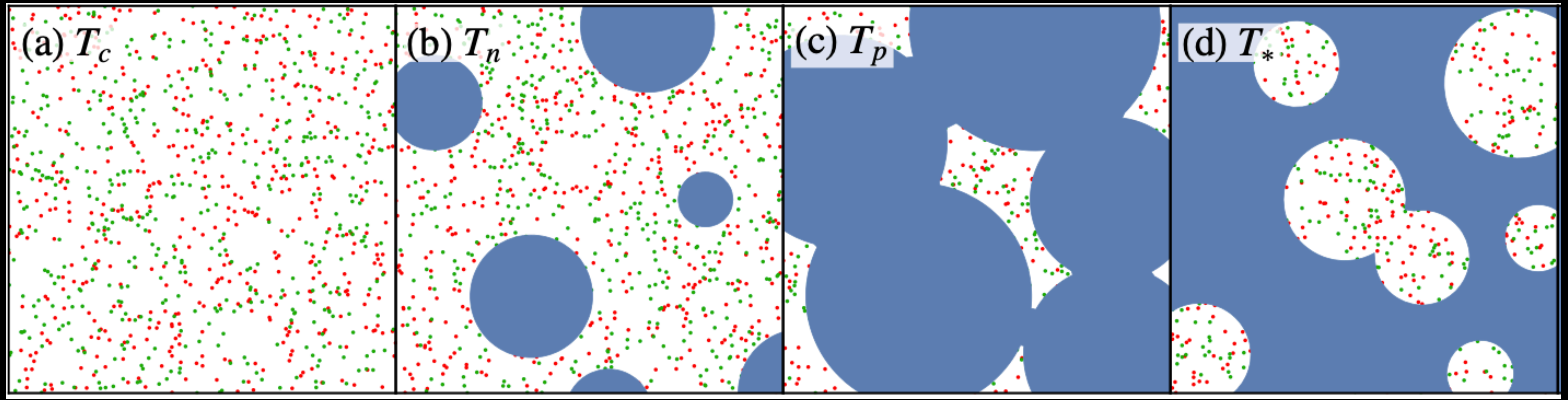
Cosmic first-order phase transition (FOPT)

- The true vacuum of scalar field <φ> changes discontinuously
- After T=T_c i.e. V(φ=0)=V(φ=v), vacuum bubbles starts to nucleate





T=T_c	T=T_n	T=T_p	T=T_*
	$\Gamma \times H^{-4} \sim 1$	$p(T) = 0.71$	$p(T) = 0.29$

← False remnants can not form an infinite connected cluster

∗ p(T)=volume fraction of false vacuum

Γ(T): decay rate per unit volume and unit time

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

$$S_3(T) : \text{bounce action}$$

Cosmic first-order phase transition (FOPT)

Cont'd

- There are two important parameters in FOPT:

$$\alpha = (\rho_{\rm vac}/\rho_{\rm rad})\,|_{T=T_p}\,, \quad \beta = \frac{d\log\Gamma}{dt}\,|_{T=T_p} \qquad \leftrightarrow\ \Gamma \sim \Gamma(T_p)e^{\beta(t-t_p)}$$

Strength of FOPT

Duration of FOPT

- In the radiation dominated epoch, the criteria $p(T_p) = 0.71$ generally reads

$$\left.\frac{S_3}{T}\right|_{T=T_p} \sim 131 - 4\ln\left(\frac{T_p}{100\ {\rm GeV}}\right) - 4\ln\left(\frac{\beta/H}{100}\right) + 3\ln v_b - 2\ln\left(\frac{g}{100}\right)\,,$$

C. Grojean and G. Servant, Phys. Rev. D 75, 043507 (2007),

→ Every (physical) quantities is determined as functions of α, β, T_p, etc.
Gravitational Wave is a good example

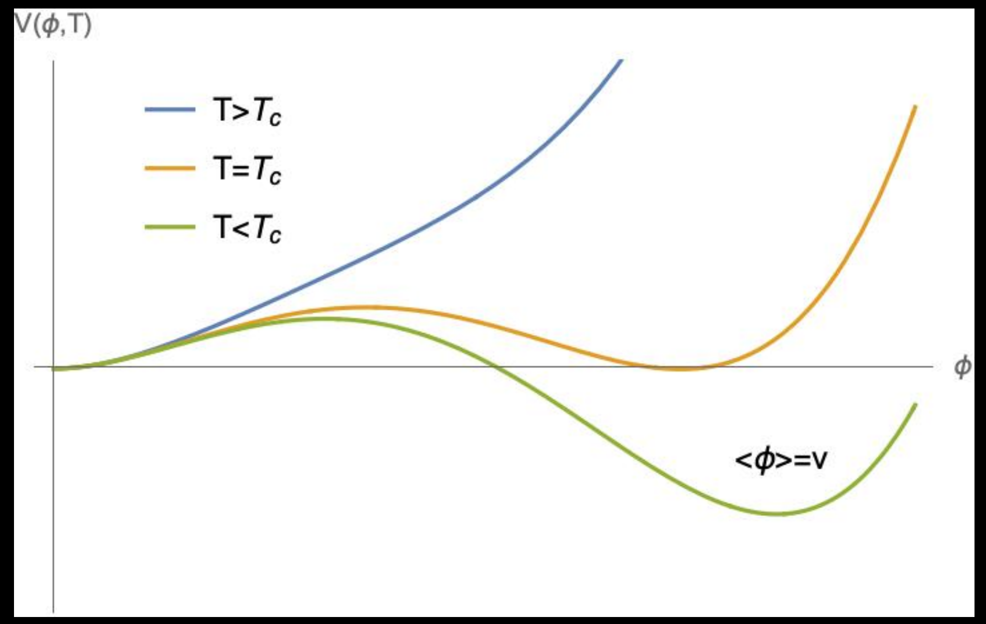
＊ In some FOPTs such as supercooling Universe (α>>1), the above formula does not apply because vacuum energy dominates.

Fermi-ball from first-order phase transition

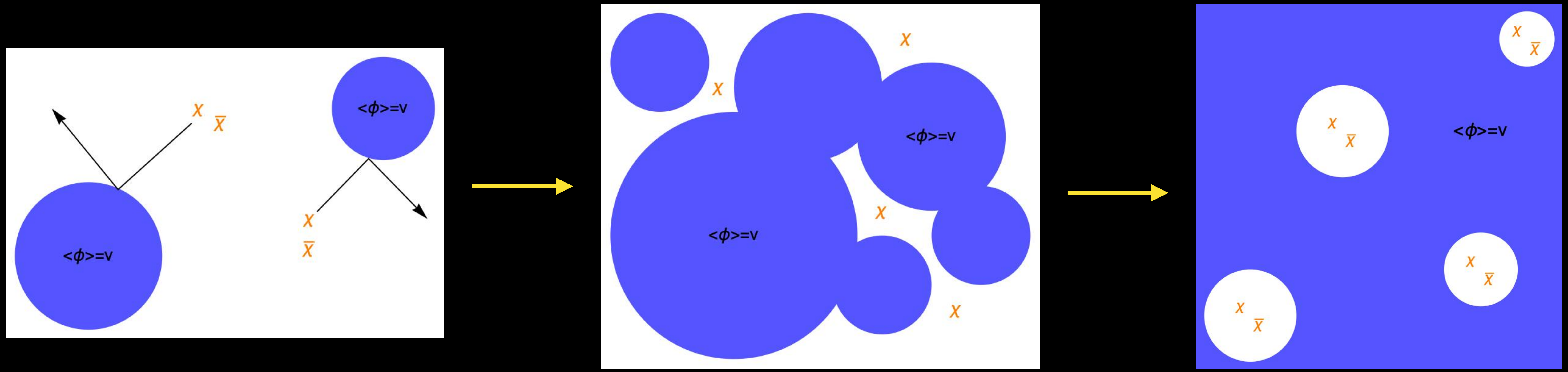
[J.-P. Hong, S. Jung, and K.-P. Xie, Phys. Rev. D 102, 075028 (2020)]

- As a simplest model, let's consider $\mathscr{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \bar{\chi}i\partial\!\!\!/\chi - g_\chi \phi\bar{\chi}\chi$,
- ϕ is a scalar field which causes a FOPT
- When $T < T_c$, χ gets a mass at the true vacuum

$$M_\chi(T) = g_\chi v(T)$$



- If M_χ > (the kinetic energy) ~T, χ $(\bar{\chi})$ can not penetrate into the bubble walls



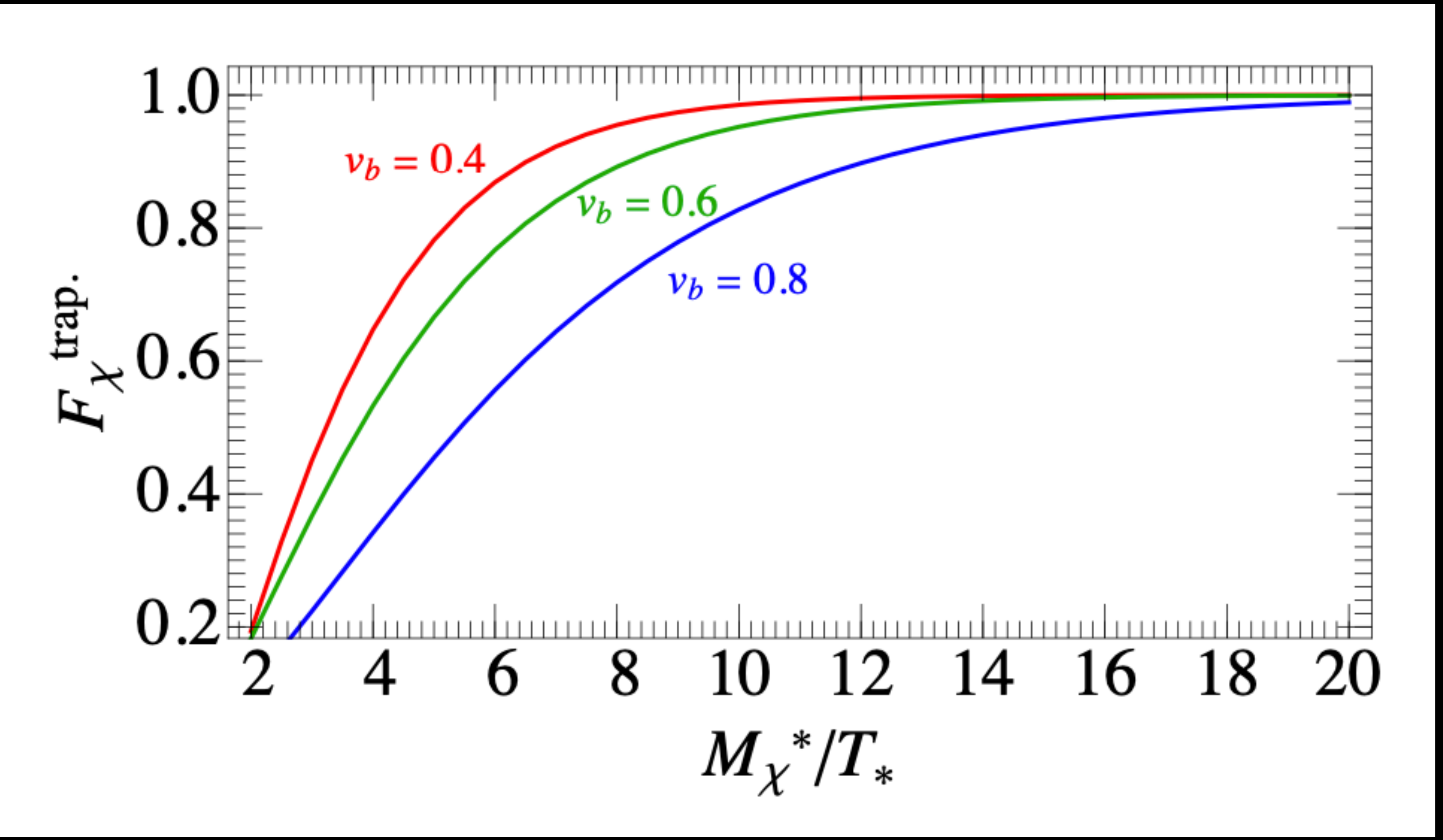
Fermi-ball from first-order phase transition

Cont'd

[J.-P. Hong, S. Jung, and K.-P. Xie, Phys. Rev. D 102, 075028 (2020)]

- It is actually possible to calculate the amount of trapped fermions:

$$F_\chi^{\rm trap} := 1 - \frac{n_\chi^{\rm pene}}{n_\chi^{\rm false}} \to \begin{cases} 1 & \text{all } \chi\text{'s are trapped} \\ 0 & \text{all } \chi\text{'s are penetrating} \end{cases}$$



The larger M_χ is, the larger $F_\chi^{\rm trap}$ is (i.e. more trapped χ's)

v_b : wall velocity

Intuitively, $F_\chi^{\rm trap} \searrow$ for $v_b \nearrow$

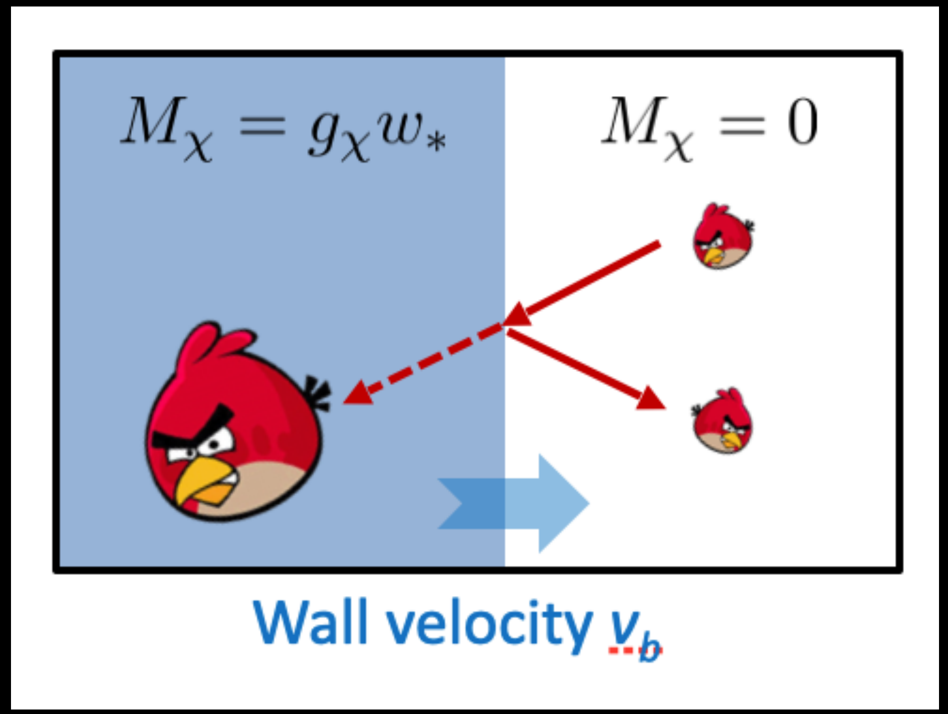


Figure from Ke-Pan's slides

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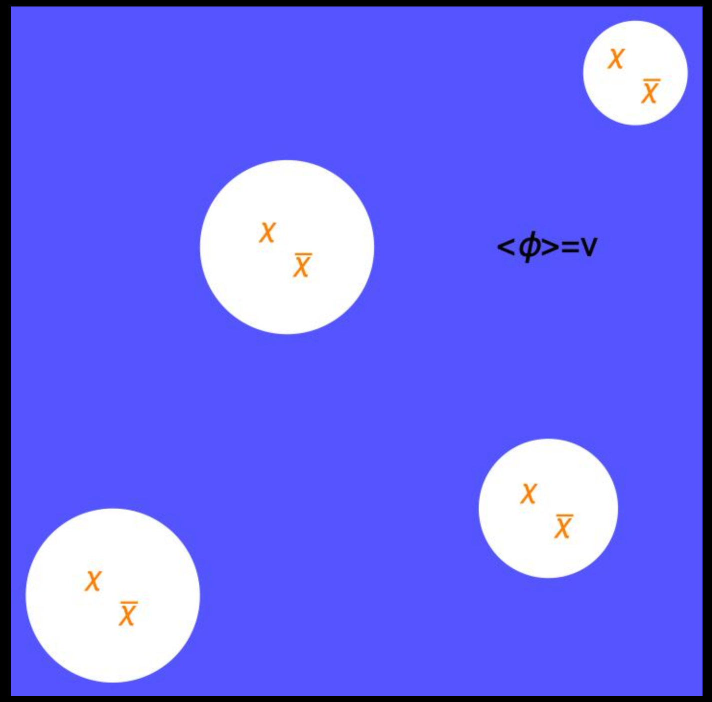
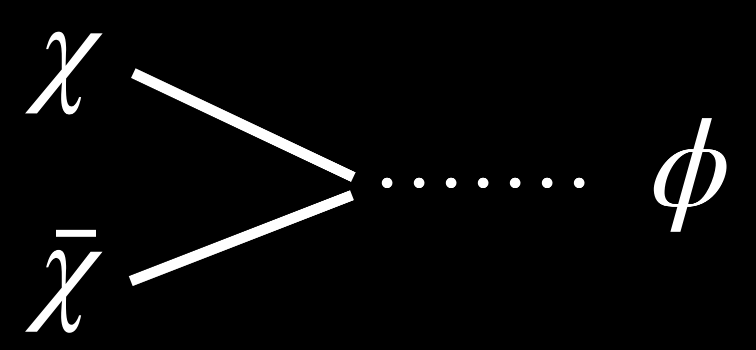
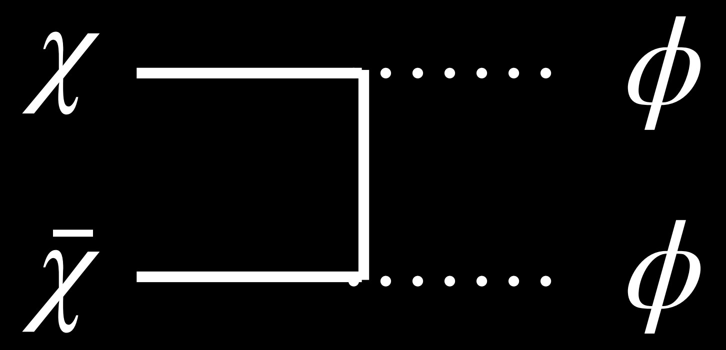


Fermi-ball from first-order phase transition

[J.-P. Hong, S. Jung, and K.-P. Xie, Phys. Rev. D 102, 075028 (2020)]

- In the false vacuum remnants, fermions annihilate via e.g. $\chi\bar{\chi} \to \phi,\ \phi\phi$





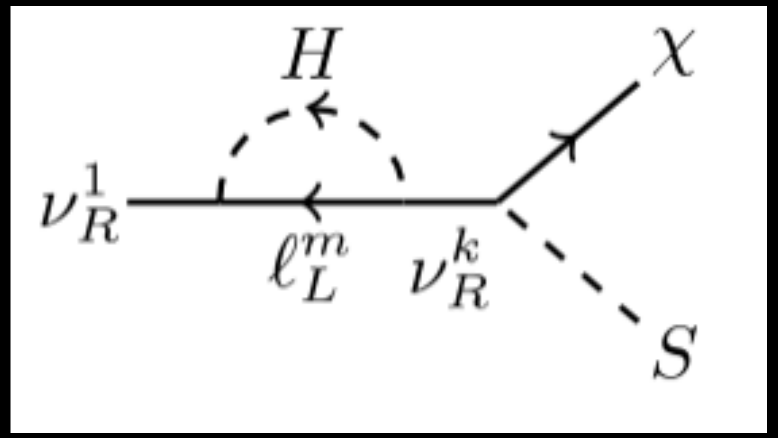
- If there is asymmetry between χ and $\bar{\chi}$, finite number of (anti-)fermions survive, and they form compact objects = Fermi-balls

- χ has a U(1) symmetry $\chi \to e^{i\alpha}\chi$ in the simplest model $\mathscr{L} = -\frac{1}{2}(\partial\phi)^2 - V(\phi) - \bar{\chi} i \partial\!\!\!/ \chi - g\phi\bar{\chi}\chi$,
  → The number of χ $(\bar{\chi})$ of Fermi-balls is conserved

- In the following, we simply assume the asymmetry between χ and $\bar{\chi}$. and will not talk about its origin

∗ It is easy to construct a concrete model for the χ-asymmetry,

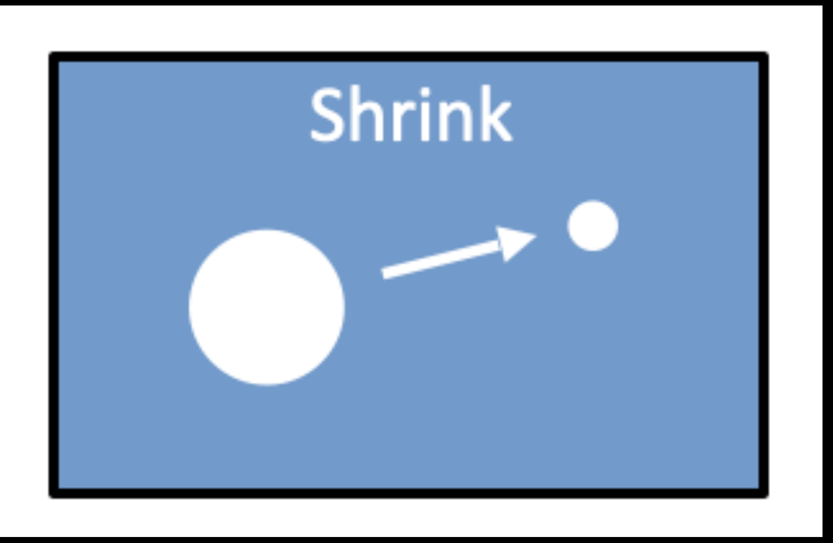
e.g. Thermal χ-genesis.



Fermi-ball profile at the formation time

- Initial radius R_* of a remnant is determined by the condition that another bubble does not appear within a remnant during its shrinking i.e.

$$\Gamma(T_*) \times V_{\rm FB}^* \times \underbrace{\frac{R_*}{v_b}}_{\text{Time-scale of shrinking}} \sim 1, \quad V_{\rm FB}^* = \frac{4\pi}{3} R_*^3$$



$$\Rightarrow \quad n_{\rm FB}(T_*) \times V_{\rm FB}^* = p(T_*) = 0.29 \qquad \therefore n_{\rm FB}(T_*) = 0.29/V_{\rm FB}^* \;,$$

∗ We already know Γ(T). Thus, $n_{\rm FB}(T_*)$ is calculated as a function of parameters of FOPT.

- After that, Fermi-balls dilutes as matter

$$n_{\rm FB}(T) = \left(\frac{a(T_*)}{a(T)}\right)^3 n_{\rm FB}(T_*) \sim \frac{s(T)}{s(T_*)} n_{\rm FB}(T_*)$$

On the other hand, the radius keeps shrinking until it reaches the stationary point

Fermi-ball profile at the formation time

Cont'd

- The number of χ fermion inside a Fermi-ball is

$$Q_{\rm FB} = V^*_{\rm FB} \times (n_\chi - n_{\bar\chi})|_{T=T_*} = V^*_{\rm FB} \times \eta_\chi \times \underline{s}|_{T=T_*}\,, \quad \text{where} \quad \eta_\chi = \frac{n_\chi - n_{\bar\chi}}{s}$$

Entropy density

$$\Rightarrow \quad Q_{\rm FB} \sim 10^{42} \times \left(\frac{\eta_\chi}{10^{-3}}\right)\left(\frac{100\ \text{GeV}}{T_*}\right)^3\left(\frac{100}{\beta/H}\right)^3$$

Use $\Gamma(T_*) \times V^*_{\rm FB} \times \frac{R_*}{v_b} \sim 1$

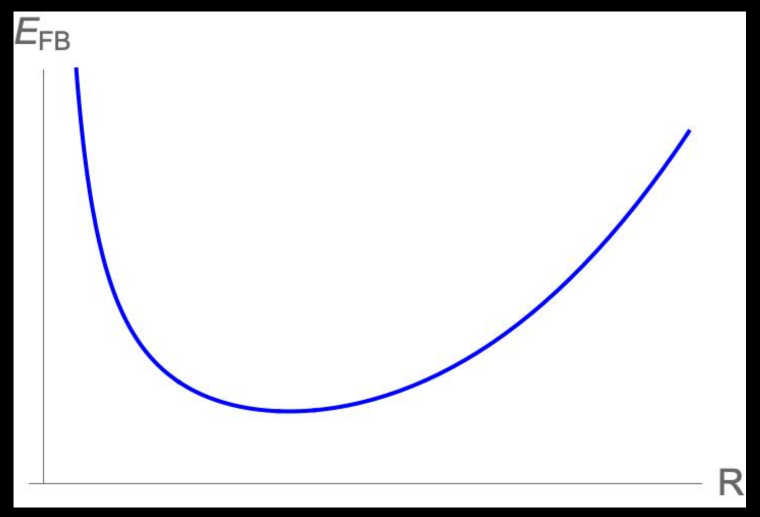
＊ Huge number of fermions exist within a Fermi-ball. Thanks to this, Fermi-balls or resultant PBHs can become heavy ~10^{21} g

Fermi-ball profile (Today)

- The final profile of a Fermi-ball is determined by the minimization of its energy E_{FB}
- There are three contributions to a Fermi-ball energy

E_{FB} = (Fermi-gas energy) + (Vacuum energy) + (surface tension)

- After Fermi-balls well cooled down, Fermi-gas energy is given by the fermi degenerate energy. c.f. white dwarf, neutron star



$$E_{\mathrm{FB}}(R) = \frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{\mathrm{FB}}^{4/3}}{R} + \frac{4\pi}{3}U_0 R^3 + \cancel{4\pi\sigma R^2}\ ,$$

does not change the results much

- The Fermi-ball radius R_{FB} is determined by $\dfrac{dE_{\mathrm{FB}}}{dR} = 0$
- Then, the energy (mass) of a Fermi-ball is given by $M_{\mathrm{FB}} = E_{\mathrm{FB}}(R = R_{\mathrm{FB}})$

Fermi-ball profile (Today)

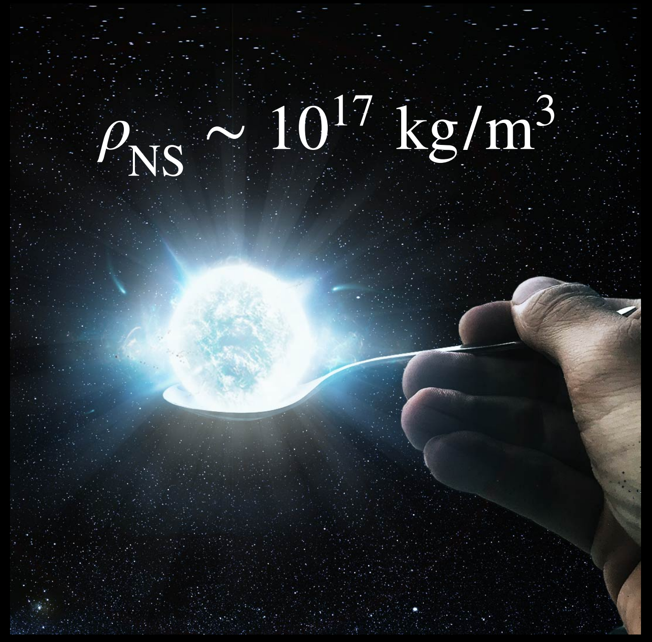
Cont'd

- The results are

$$M_{\rm FB} = Q_{\rm FB}(12\pi^2 U_0)^{1/4} \sim 1.4 \times 10^{14}\ {\rm g} \times \left(\frac{\eta_\chi}{10^{-10}}\right)\left(\frac{100\ {\rm GeV}}{T_*}\right)^2 \left(\frac{100}{\beta/H}\right)^3 \alpha^{1/4}\,,$$

$$R_{\rm FB} = Q_{\rm FB}^{1/3}\left[\frac{3}{16}\left(\frac{3}{2\pi}\right)^{2/3}\frac{1}{U_0}\right]^{1/4} \sim 2.2 \times 10^{-5}\ {\rm cm} \times \left(\frac{\eta_\chi}{10^{-10}}\right)^{1/3}\left(\frac{100\ {\rm GeV}}{T_*}\right)^2 \left(\frac{100}{\beta/H}\right)\alpha^{-1/4}\,,$$

$\Rightarrow$ $\dfrac{M_{\rm FB}}{V_{\rm FB}} \sim 3.0 \times 10^{30}\ {\rm kg/m^3} \times \cdots$ Much denser than a neutron star



- But, not as compact as a similarly produced Q-ball, $\rho_Q \sim 10^{36}\ {\rm kg/m^3}$ due to the Pauli-exclusion principle

[Krylov et al, PRD2013]

∗ Fermi-ball is not a BH $\quad \because R_{\rm Sch} = 2GM_{\rm FB} \sim 10^{-16}\ {\rm cm} \ll R_{\rm FB}$

Fermi-ball profile (Today)

Cont'd

- The present abundance is

$$\rho_{\rm FB}/\rho_{\rm DM} = M_{\rm FB} n_{\rm FB}^{\rm today}/\rho_{\rm DM} \sim 1.3 \times \left(\frac{T_*}{100\ \mathrm{GeV}}\right)^3 \left(\frac{\beta/H}{100}\right)^3 \left(\frac{M_{\rm FB}}{10^{12}\ g}\right),$$

- This result also indicates that Fermi-balls are typically overproduced when $T_* \gtrsim 100\ \mathrm{GeV}$ and $M_{\rm FB} \gtrsim 10^{12}\ \mathrm{g}$.

  ∗Recall $M_{\rm FB} \propto \eta_\chi$. If we allow any small value of η_χ, this is not a problem

- In such a parameter space, we need to dilute Fermi-balls after the formation.

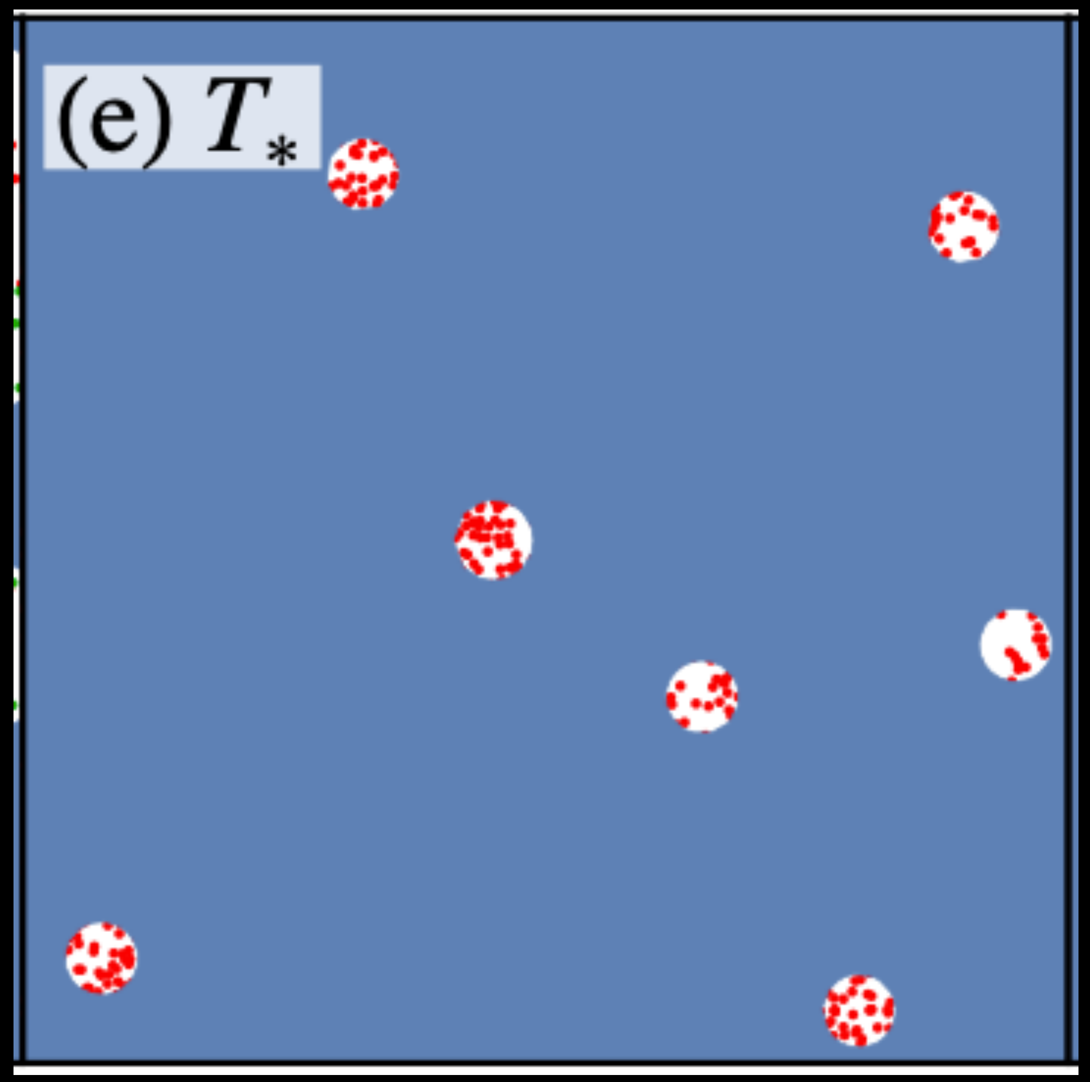
  Actually, it is not so difficult to realize such a dilution

  - Secondary (thermal) inflation [D. H. Lyth and E. D. Stewart, Phys. Rev. Lett. 75, 201 (1995)]
  - domain wall decay [M. Kawasaki and F. Takahashi, Phys. Lett. B 618, 1 (2005)],
  - early matter-dominated era [R. J. Scherrer and M. S. Turner, Phys. Rev. D 31, 681], etc

Talk Plan

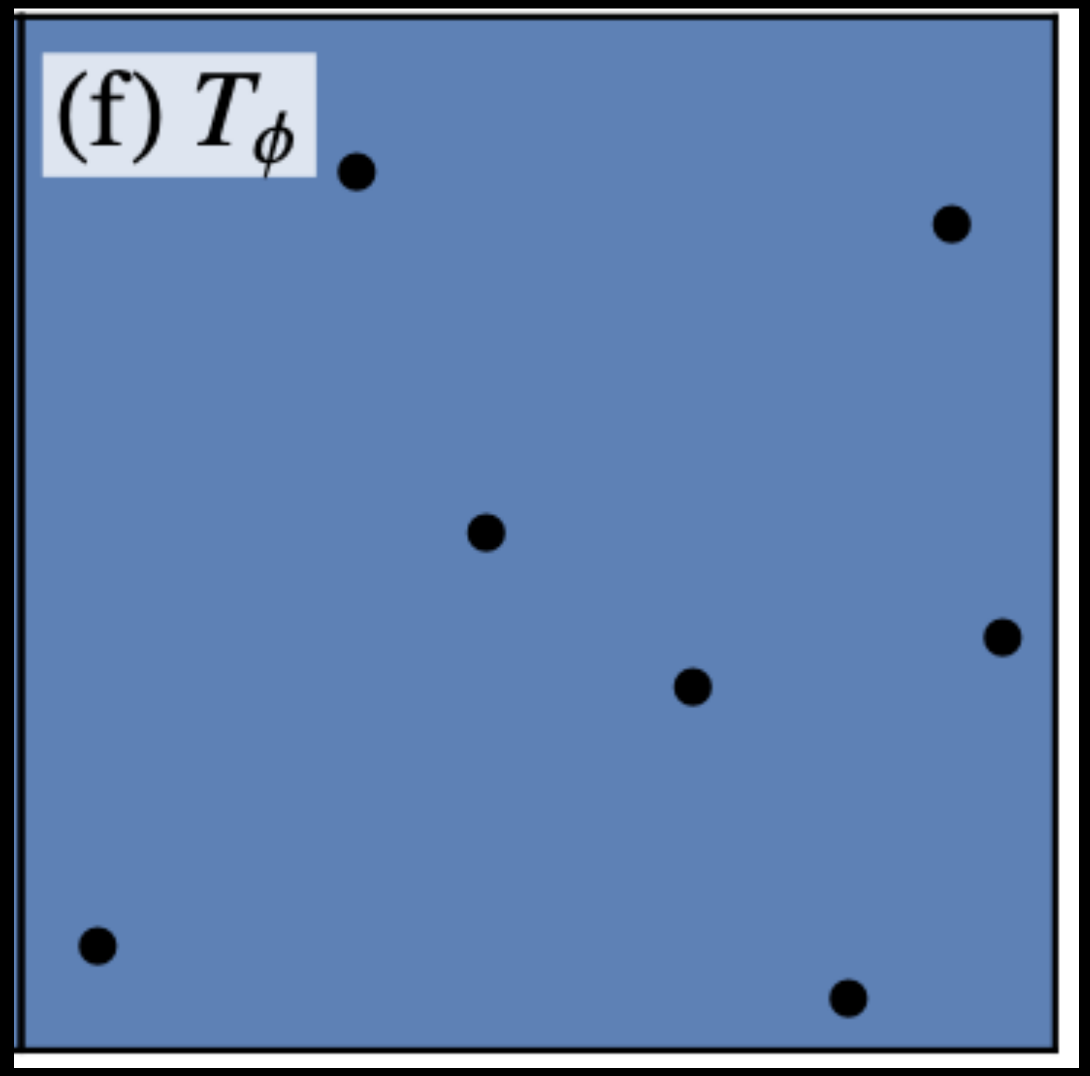
1. Fermi-ball formation by FOPT
2. PBH formation by collapse of Fermi-balls
3. Summary

Collapse of Fermi-balls



Stable Fermi-balls like
stars, white dwarf, neutron stars

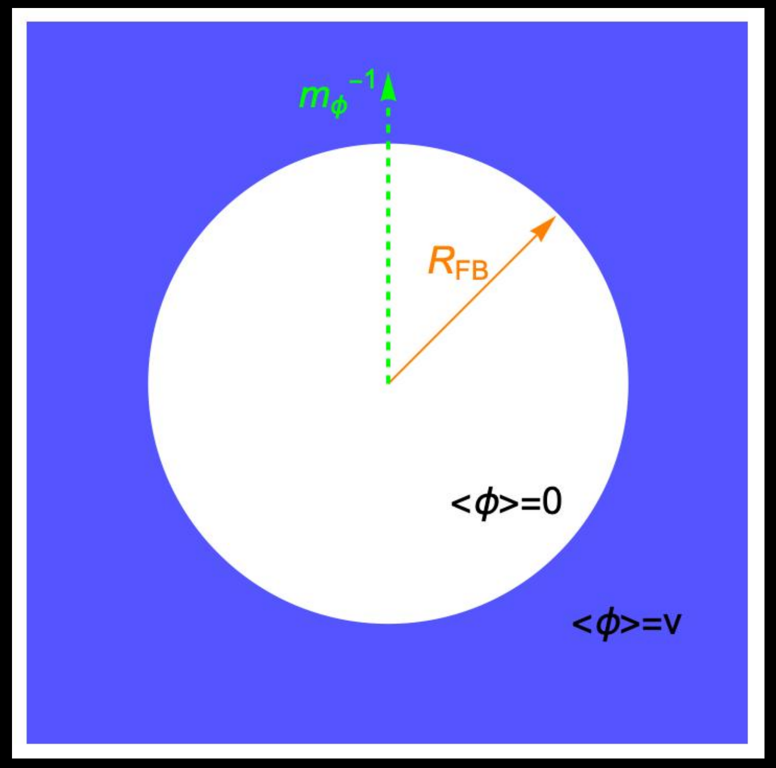
?



PBHs

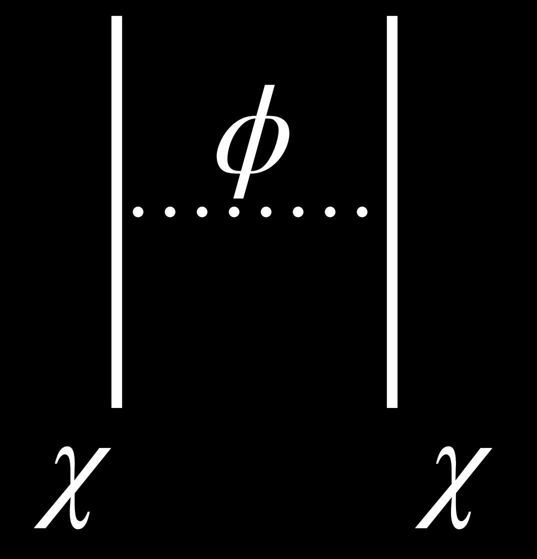
＊ We need to study the stability condition of Fermi-balls. (c.f. Chandrasekhar Limit)
Tolman-Oppenheimer-Volkoff limit

Importance of Yukawa force



- So far, we have neglected the Yukawa potential contribution to the Fermi-ball energy

$$V(r) = -\frac{g_\chi^2}{4\pi}\frac{e^{-m_\phi r}}{r}\,, \quad m_\phi : \text{mass of } \phi \text{ at } \phi = 0$$



- This is ok as long as $m_\phi^{-1} \ll m_{\phi\mathrm{cri}}^{-1}$ (short range).

- On the other hand, when $m_\phi^{-1} \gtrsim m_{\phi\mathrm{cri}}^{-1}$, it actually plays an important role

$$\Delta E_{\mathrm{Yukawa}} \sim -\frac{3\pi Q_{\mathrm{FB}}^2}{20R} \ (\text{for } m_\phi = 0)$$

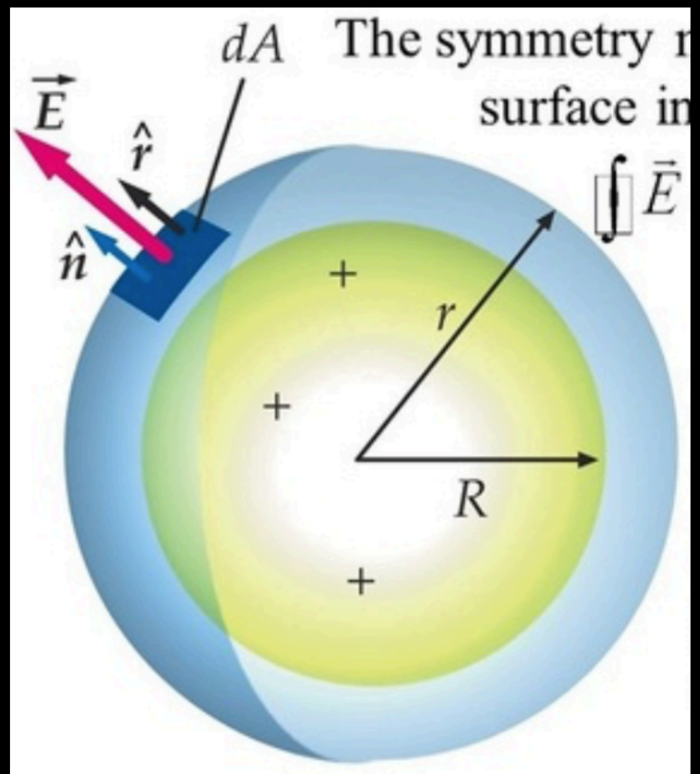
c.f. Chandrasekhar Limit

$$\Rightarrow \quad E_{\mathrm{FB}}(R) = \frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{\mathrm{FB}}^{4/3}}{R} - \frac{3\pi Q_{\mathrm{FB}}^2}{20R} + \frac{4\pi}{3}U_0 R^3\,,$$

$$E(R) \sim \frac{Q^{4/3}}{R} - \frac{GM^2}{R}$$

∴ Yukawa energy is much larger than fermi-gas energy
→ There is no repulsive force and Fermi-balls collapse !

Critical range of Yukawa force



- When m_ϕ is finite, the Yukawa energy is calculated as
  (Recall the calculation of static energy of uniformly charged sphere)

$$\Delta E_{\text{Yukawa}} = -\frac{3\pi Q_{\text{FB}}^2}{20R_{\text{FB}}} f\left(\frac{1}{R_{\text{FB}} m_\phi}\right) \;,\quad f(\xi) = \frac{5}{2}\xi^2 \left[\underbrace{1 + \frac{3}{2}\xi(\xi^2-1) - \frac{3}{2}e^{-2/\xi}\xi(1+\xi)^2}_{\mathcal{O}(1)\ \text{function}}\right] \;,\quad f(\infty) = 1$$

Roughly

$$\Rightarrow \quad \Delta E_{\text{Yukawa}} \sim -\frac{Q_{\text{FB}}^2}{R_{\text{FB}}}\left(\frac{1}{R_{\text{FB}} m_\phi}\right)^2$$

- The critical range (mass) $m_{\phi\,\text{cri}}^{-1}$ of the Yukawa force is determined by

$$|\Delta E_{\text{Yukawa}}| \sim \frac{Q_{\text{FB}}^2}{R_{\text{FB}}}\left(\frac{1}{R_{\text{FB}} m_{\phi\text{cri}}}\right)^2 \sim \Delta E_{gas} \sim \frac{Q_{\text{FB}}^{4/3}}{R_{\text{FB}}} \qquad \therefore\; m_{\phi\text{cri}}^{-1} \sim Q_{\text{FB}}^{-1/3} R_{\text{FB}} \sim \underbrace{n_\chi^{-1/3}}_{\text{Mean separation of }\chi} \sim g_\chi^{-1} T_*^{-1} \alpha^{-1/4} \,,$$

∴ Collapse can happen even the force range is much shorter than R_{FB} thanks to the huge number of fermions

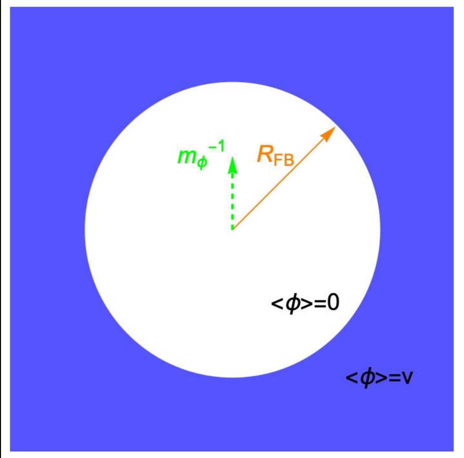
Thermal History of Fermi-balls and PBHs

Mass parameter in the Lagrangian

T

T_* Formation of Fermi-balls: They are still hot, and m_ϕ has thermal contribution $m_\phi^2(T) = \mu^2 + cT^2$

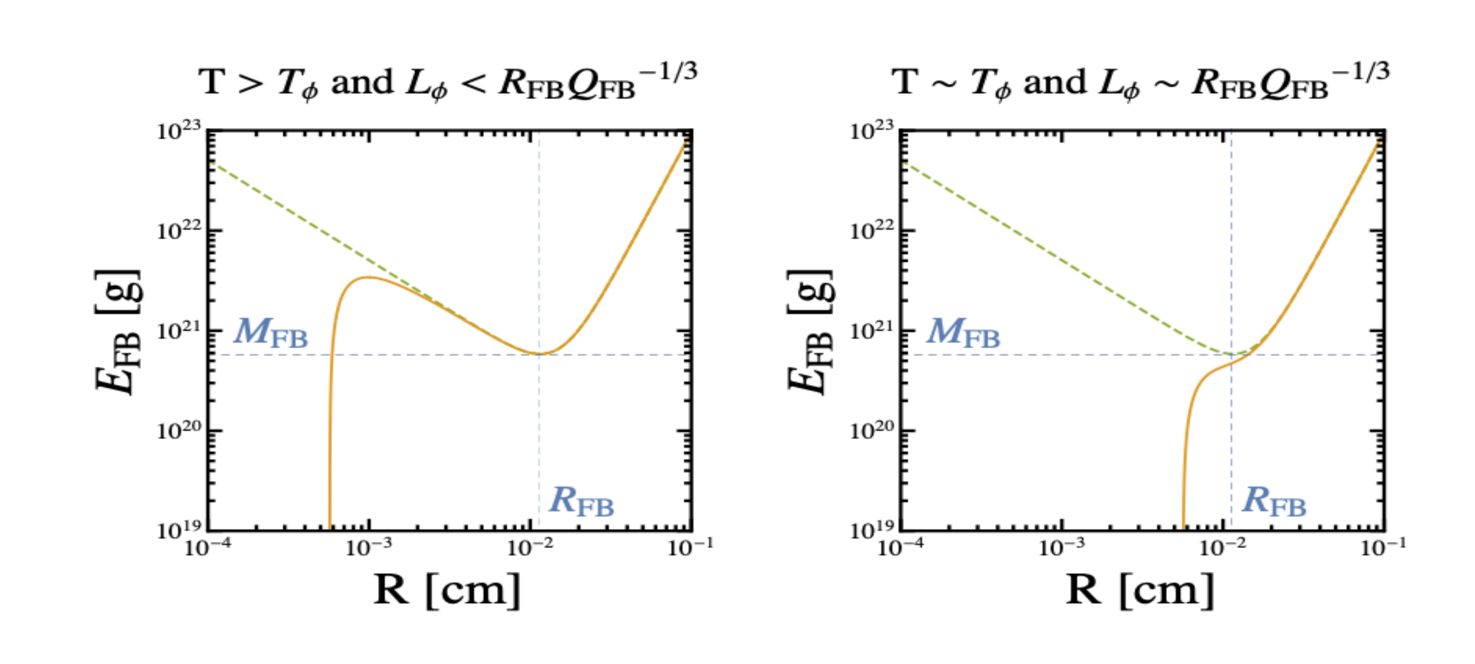
As long as $|\mu^2| \lesssim T_*^2$, $g_\chi \sim 0.1$, we typically have $m_\phi(T_*) > m_{\phi\mathrm{cri}} \sim g_\chi T_* \alpha^{1/4}$

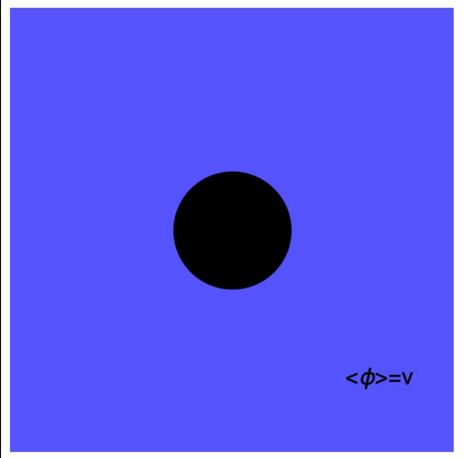


T_ϕ Formation of PBHs: As Fermi-balls cool down, $m_\phi^{-1}(T)$ also increases and finally reaches $m_{\phi\mathrm{cri}}^{-1}$.

Then, Fermi-ball collapse into PBHs.

T_{BBN}





After that, PBHs dilute as matter

T_{today}

PBHs survive as (cold) Dark Matter !

t

PBH profiles

- In this scenario, the PBH profile is the same as that of Fermi-balls as long as we neglect the energy loss during the collapse

$$M_{\rm PBH} \sim M_{\rm FB} = Q_{\rm FB}(12\pi^2 U_0)^{1/4} \sim 1.4 \times 10^{15}\ {\rm g} \times \left(\frac{\eta_\chi}{10^{-9}}\right)\left(\frac{100\ {\rm GeV}}{T_*}\right)^2 \left(\frac{100}{\beta/H}\right)^3 \alpha^{1/4}\,,$$

$$\rho_{\rm PBH}/\rho_{\rm DM} = \rho_{\rm FB}/\rho_{\rm DM} = M_{\rm FB} n_{\rm FB}^{\rm today}/\rho_{\rm DM} \sim 1.3 \times \left(\frac{T_*}{10\ {\rm GeV}}\right)^3 \left(\frac{\beta/H}{100}\right)^3 \left(\frac{M_{\rm FB}}{10^{15}\ g}\right)\,,$$

Overproduced when $T_* \gtrsim 10\ \mathrm{GeV}$

$\therefore$ It is possible to obtain massive PBHs for reasonable parameter regions !

Good points of this scenario

- We don't need primordial density fluctuations, but asymmetry of fermions
- We don't need any fine-tunings of parameters $(\mu^2, g_\chi, \alpha, \beta, \cdots)$
- If there is no dilution of PBHs, our scenario is very predictable

$$\rho_{\rm PBH}/\rho_{\rm DM} = \rho_{\rm FB}/\rho_{\rm DM} = M_{\rm FB} n_{\rm FB}^{\rm today}/\rho_{\rm DM} \sim 1.3 \times 10^3 \times \left(\frac{T_*}{100\ {\rm GeV}}\right)^3 \left(\frac{\beta/H}{100}\right)^3 \left(\frac{M_{\rm FB}}{10^{15}\ g}\right),$$

c.f. $$\beta = \int_{\delta_c}^{\infty} P(\delta) \sim \frac{1}{2}{\rm Erfc}\left(\delta_c \Big/ \sqrt{2\sigma_2^2}\right), \quad \sigma_2 : \text{variance of density perturbations}$$

- If there is a dilution, any T_* and $M_{\rm PBH}$ are allowed. In this sense, our scenario can be widely applicable in many new physics models.

Conclusion

- We proposed a new formation mechanism of PBHs from FOPT based on the formation of Fermi-balls and their collapse
- In this scenario, we do not need primordial density fluctuations but asymmetry of fermions
- Our scenario is applicable to many new physics models if we can realize a dilution of PBHs
- There are still many interesting questions (possibilities) that should be addressed
    - Constructing a concrete model of particle physics
    - Is it possible that PBHs are directly produced by FOPT ?
    - Supercooling case ? etc
    - More generally, physics of strong force in early universe is interesting !

Thank you for your attention !