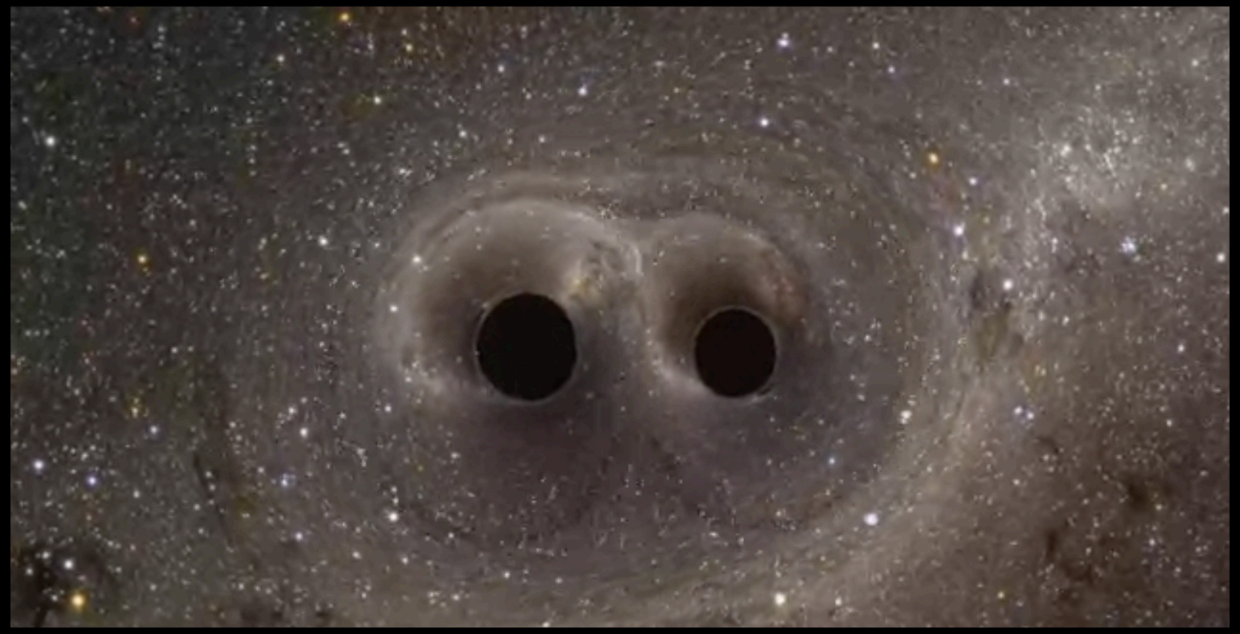
Late-forming PBH: Beyond the CMB era

Kiyoharu Kawana (KIAS)
In collaboration with Philip Lu (SNU) and Alexander Kusenko (UCLA)
arXiv: 2210.16462

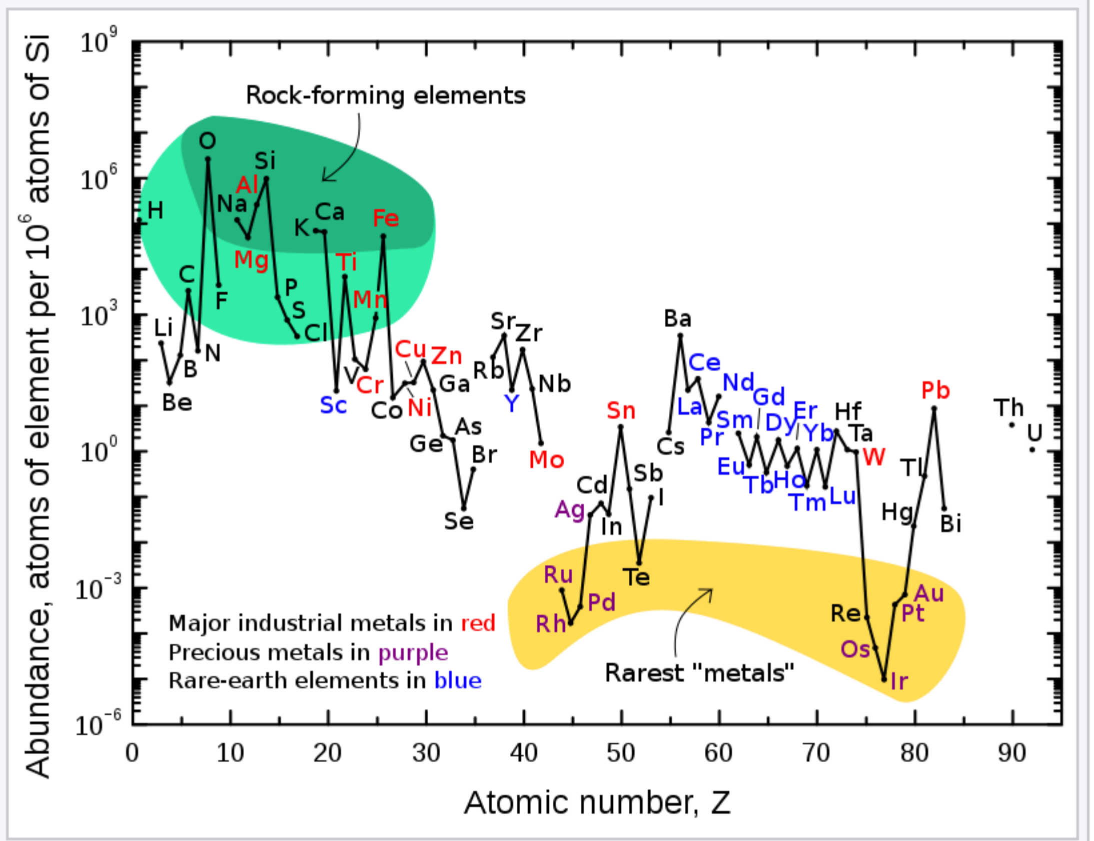
2/20/2023 @ CAU-BSM

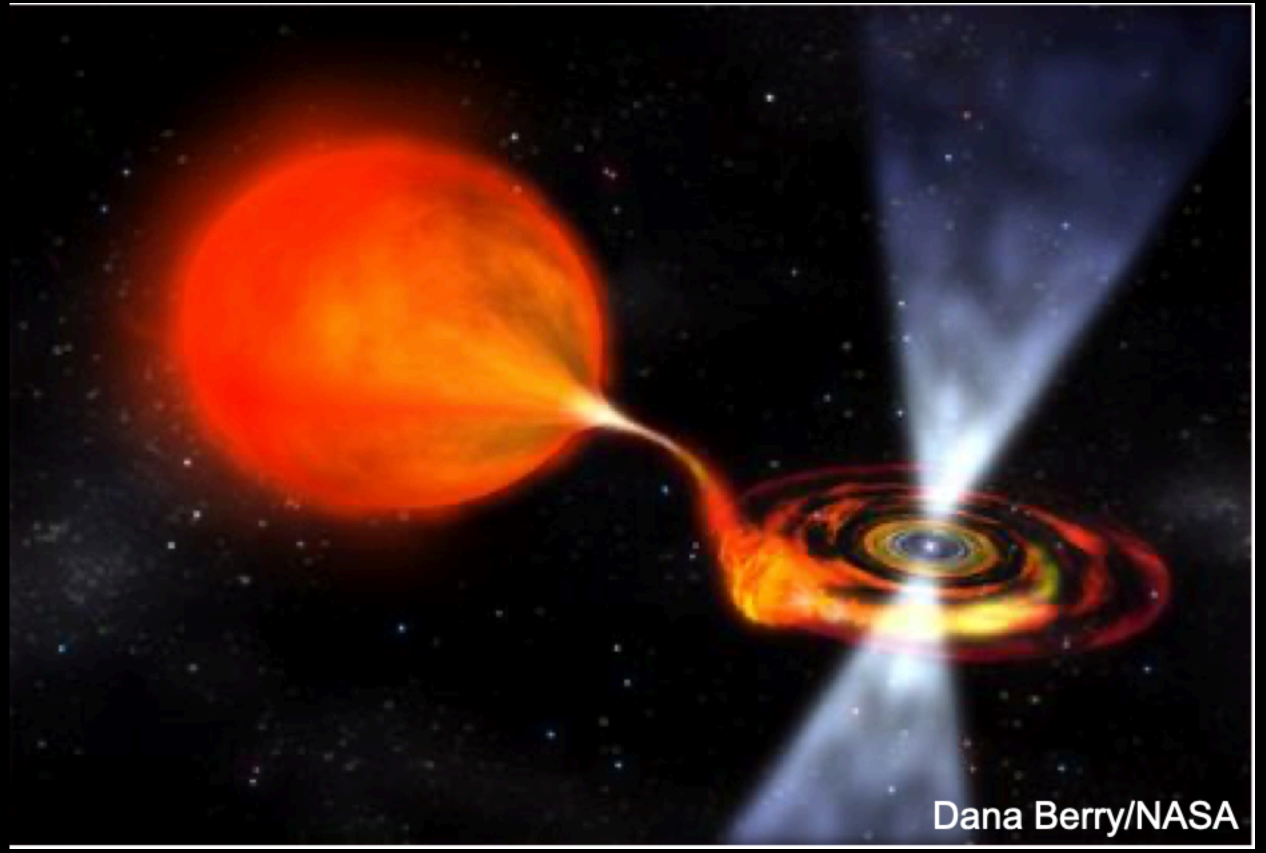
Why Primordial Black Hole (PBH) is interesting ?

- 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 to 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
- and more

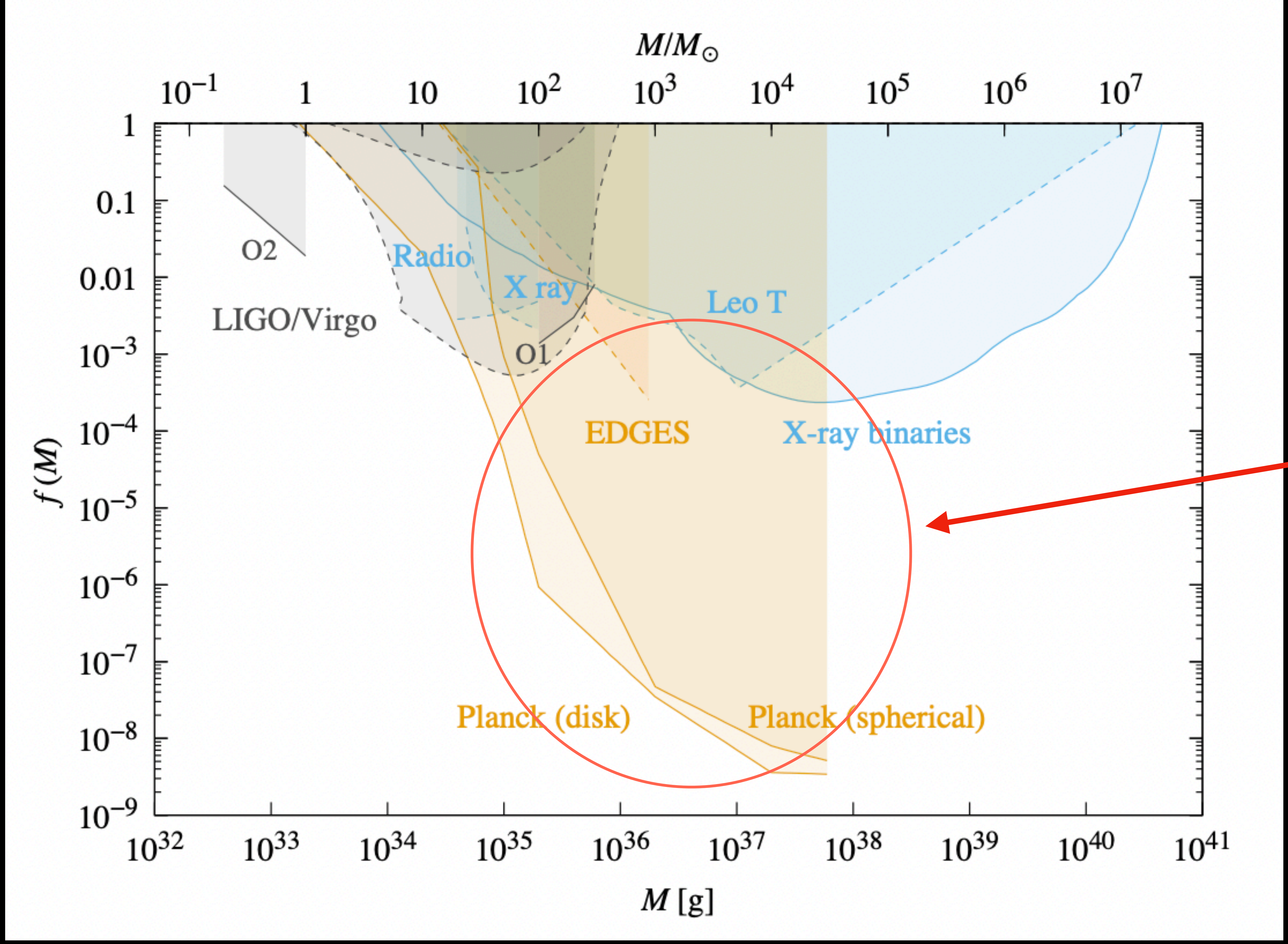


From Wikipedia





Target in this talk



[Carr, Kohri, Sendouda, Yokoyama ('21)]

$$M = \mathcal{O}(100 - 10^5)M_\odot$$

($\leftrightarrow$ produced when $t \lesssim 1s$)

This mass region is interesting because

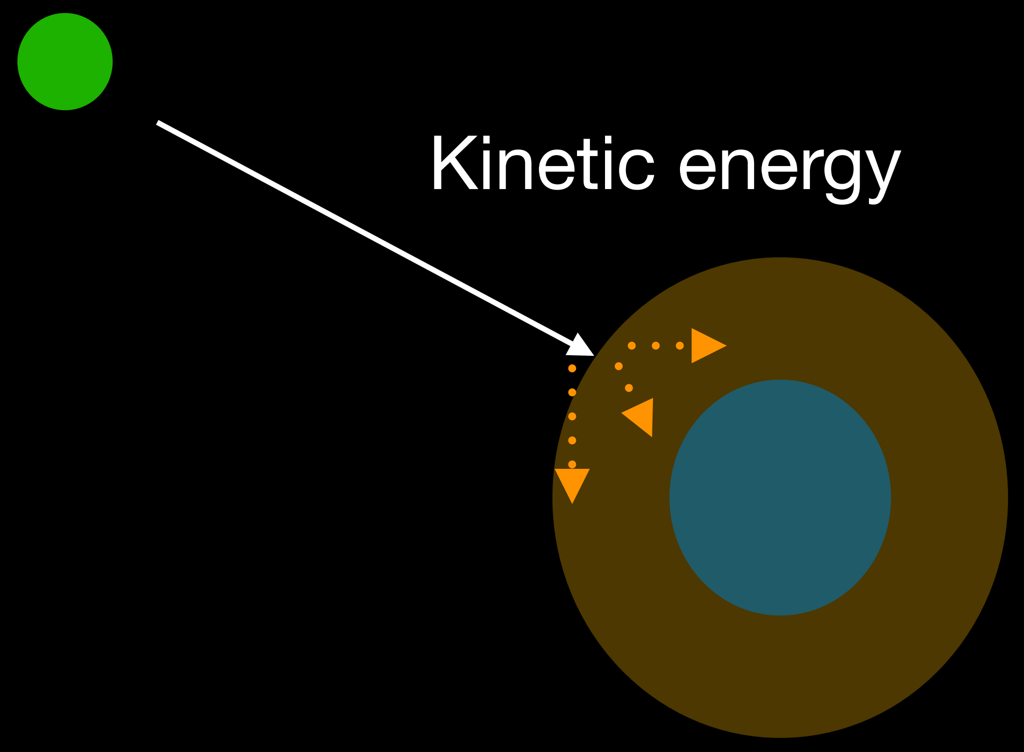
1. can explain binary events (LIGO)
2. can seed supermassive BHs

But, this region is strongly restricted by CMB
→ X-rays emitted by gas accretion onto PBHs affect the CMB spectrum !

Q: Can we evade this bound ?

Accretion rate and luminosity

Ricotti, Ostriker, Mack, ('07)
Ali-Haimoud, Kamionkowski ('17)
Serpico, Pourin, Inman, Kohri ('20)



- Particle with mass m falling from infinity to R has a kinetic energy

$$E = \frac{GMm}{R} = m\epsilon_{\mathrm{max}} \,, \quad \epsilon_{\mathrm{max}} = \frac{R_S}{2R} \,, \quad R_S = 2GM$$

- Luminosity associated with accretion $\dot{M}$ is given by

$$L = \epsilon \dot{M}$$

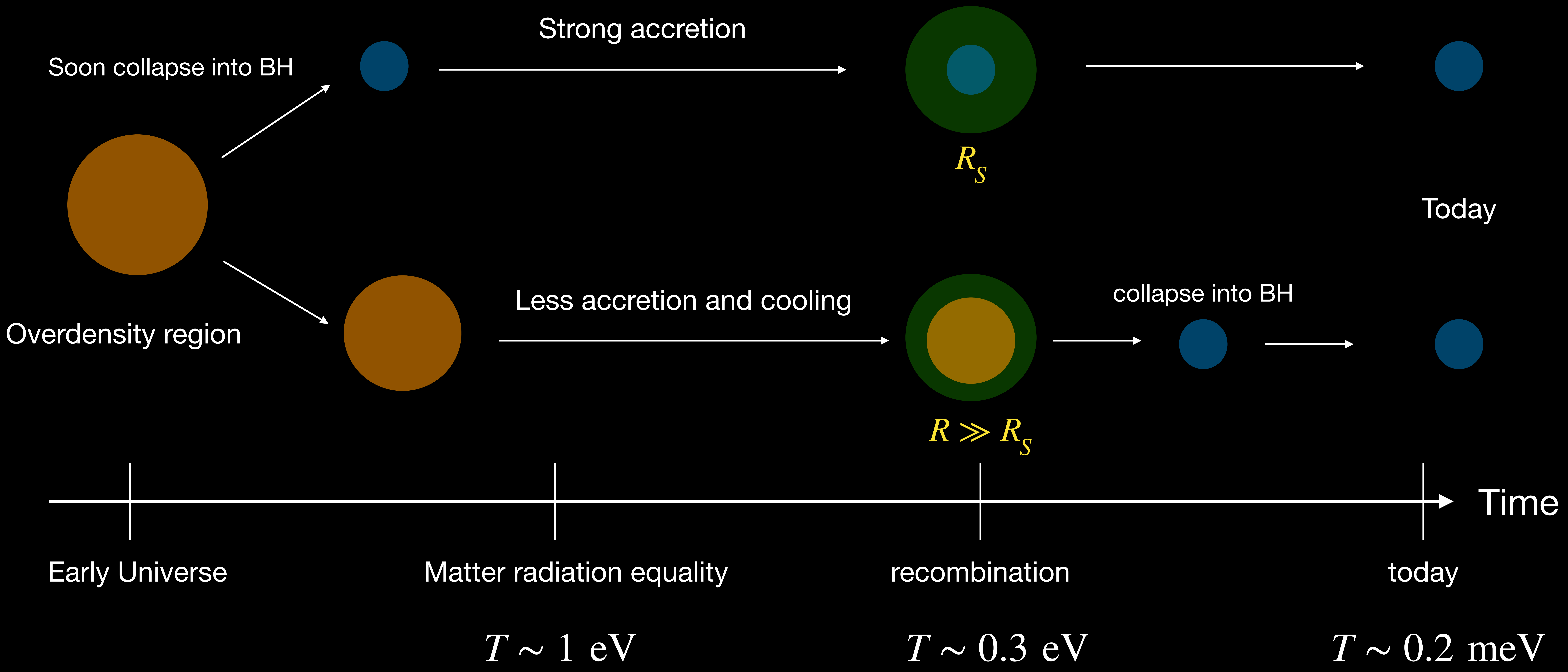
If all the accreted mass contributes to L, we have $\epsilon = \epsilon_{\mathrm{max}}$.
In reality, $\epsilon < \epsilon_{\mathrm{max}}$ because not all the energy is converted to luminosity

Anyway, ϵ_{max} gives the order of magnitude of ϵ

$$\epsilon \sim \epsilon_{\mathrm{max}} = \frac{R_S}{R}$$

The larger R is, the smaller L is !

How to evade CMB bound

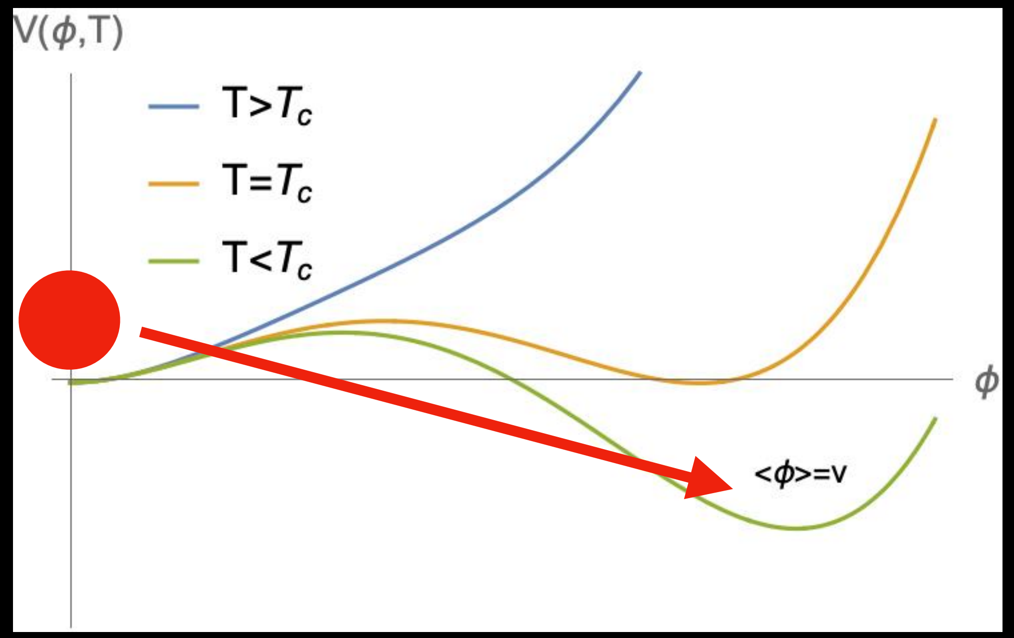


Ok, idea is very simple and easy to understand. But,
How do we realize such a thermal history ?

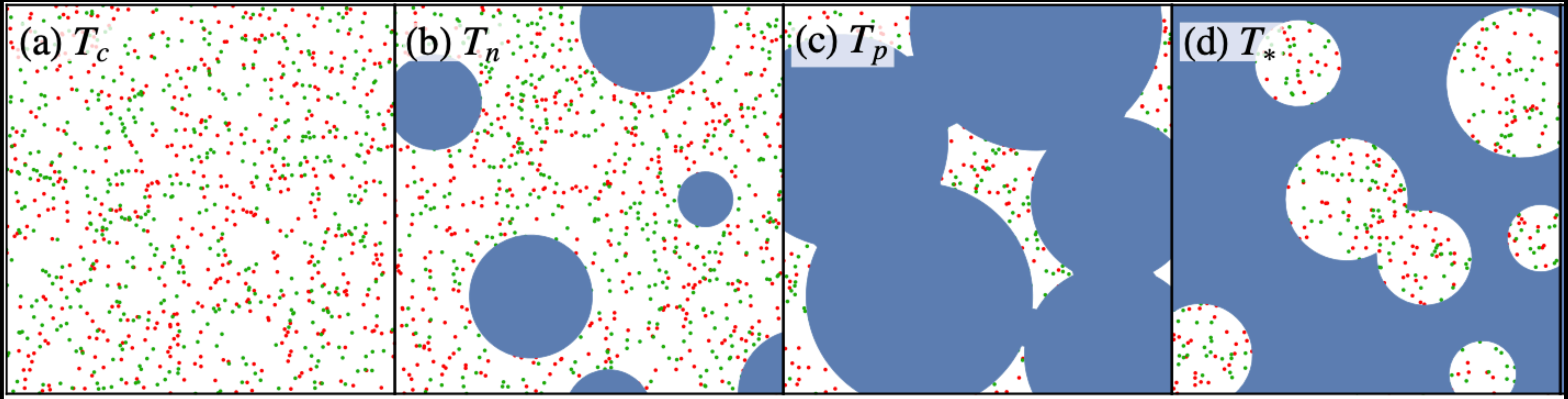
Here I give one possibility which utilizes first-order phase transition
(FOPT)

(I will just talk about model-independent aspects)

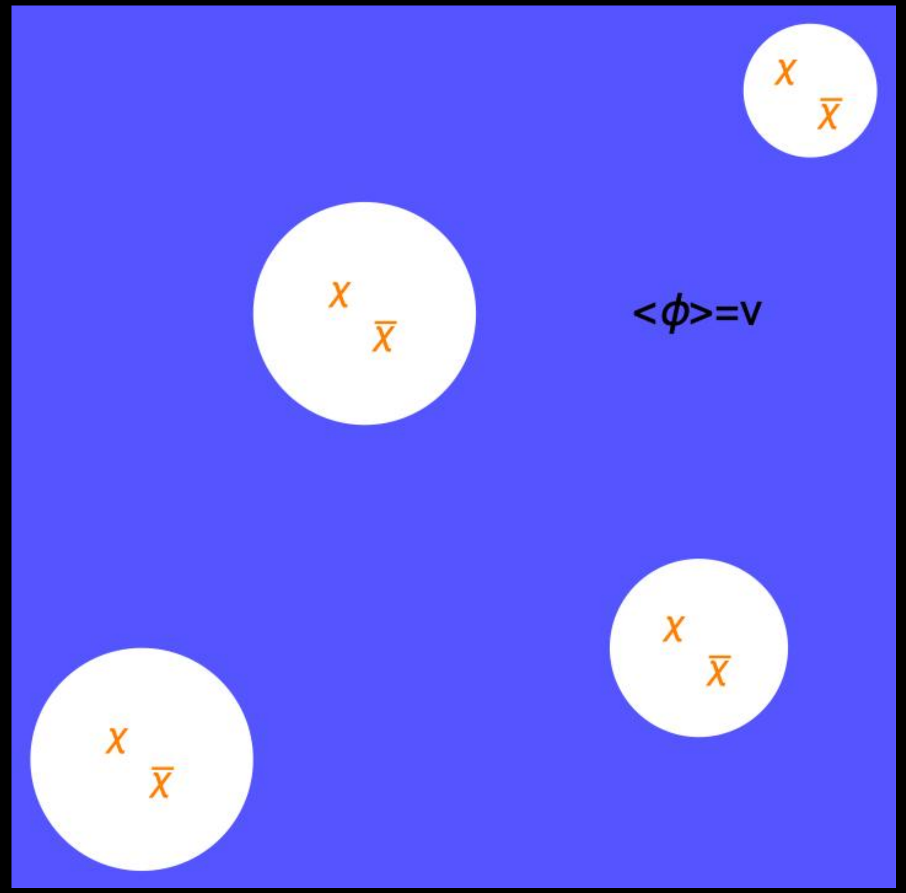
Thermal ball from first-order phase transition



1. Assume first-order phase transition (FOPT) in the early Universe



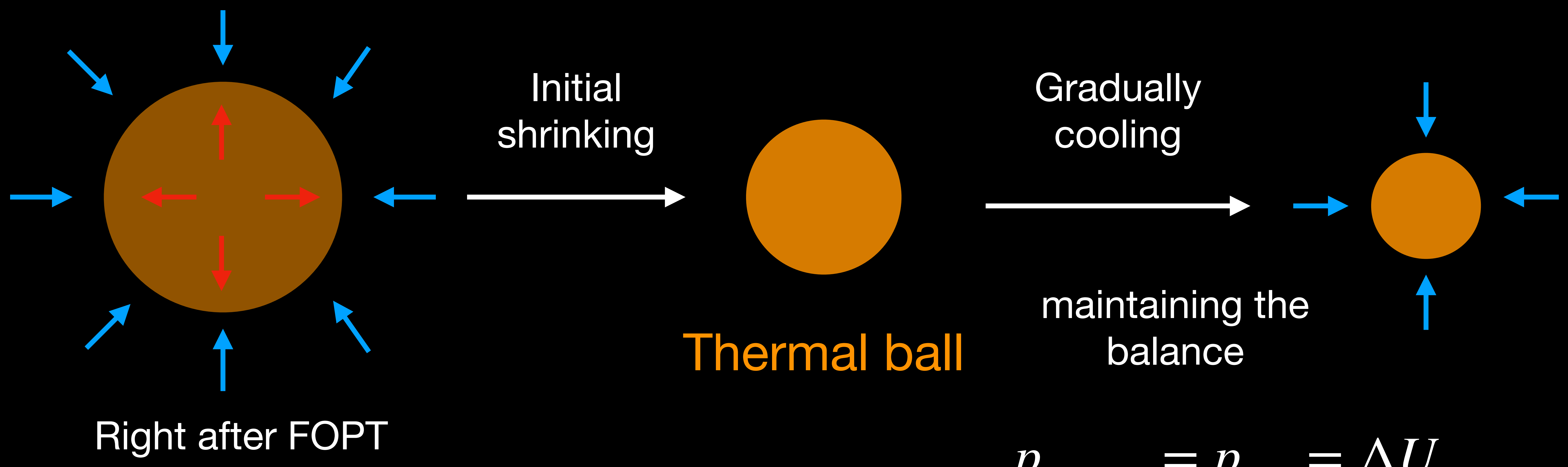
2. If there is a large mass gap between false and true vacua, $\delta m \gg T_*$
   particles are trapped in the false vacuum



→ Formation of remnants

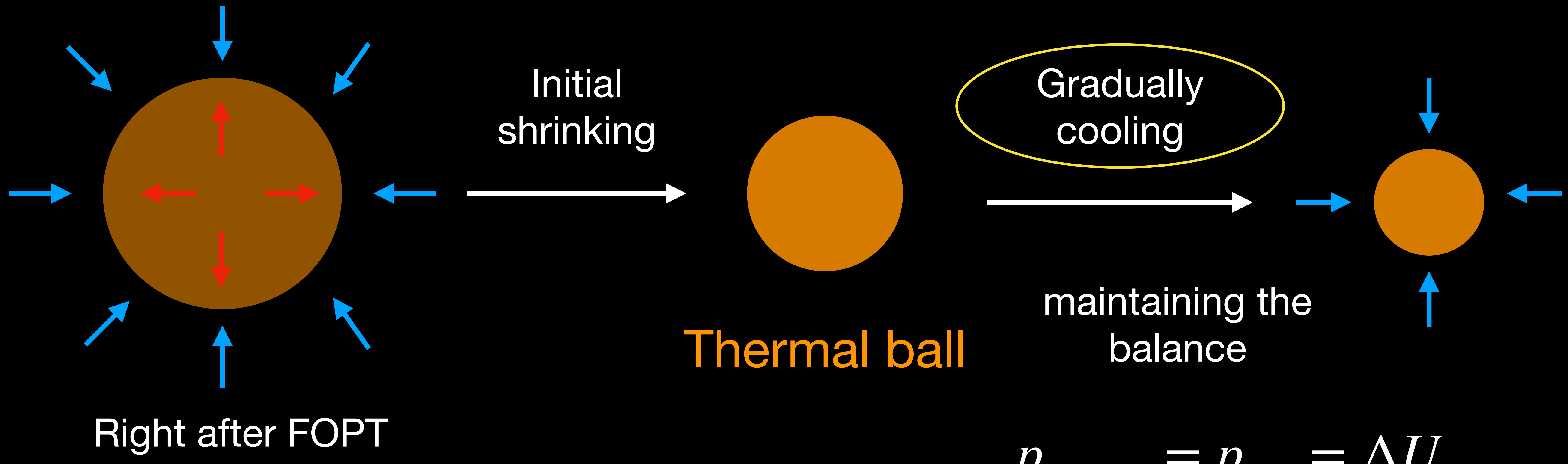
- When energy-loss rate of trapped particles are efficient, i.e. $\Gamma_{\text{loss}} \gtrsim H$, these remnants immediately shrink and disappear

- If not, i.e. $\Gamma_{\text{loss}} \ll H$, the remnants stop initial shrinking when the plasma pressure balances with the vacuum energy pressure



$$p_{\text{plasma}} = p_{\text{vac}} = \Delta U$$

Cont'd



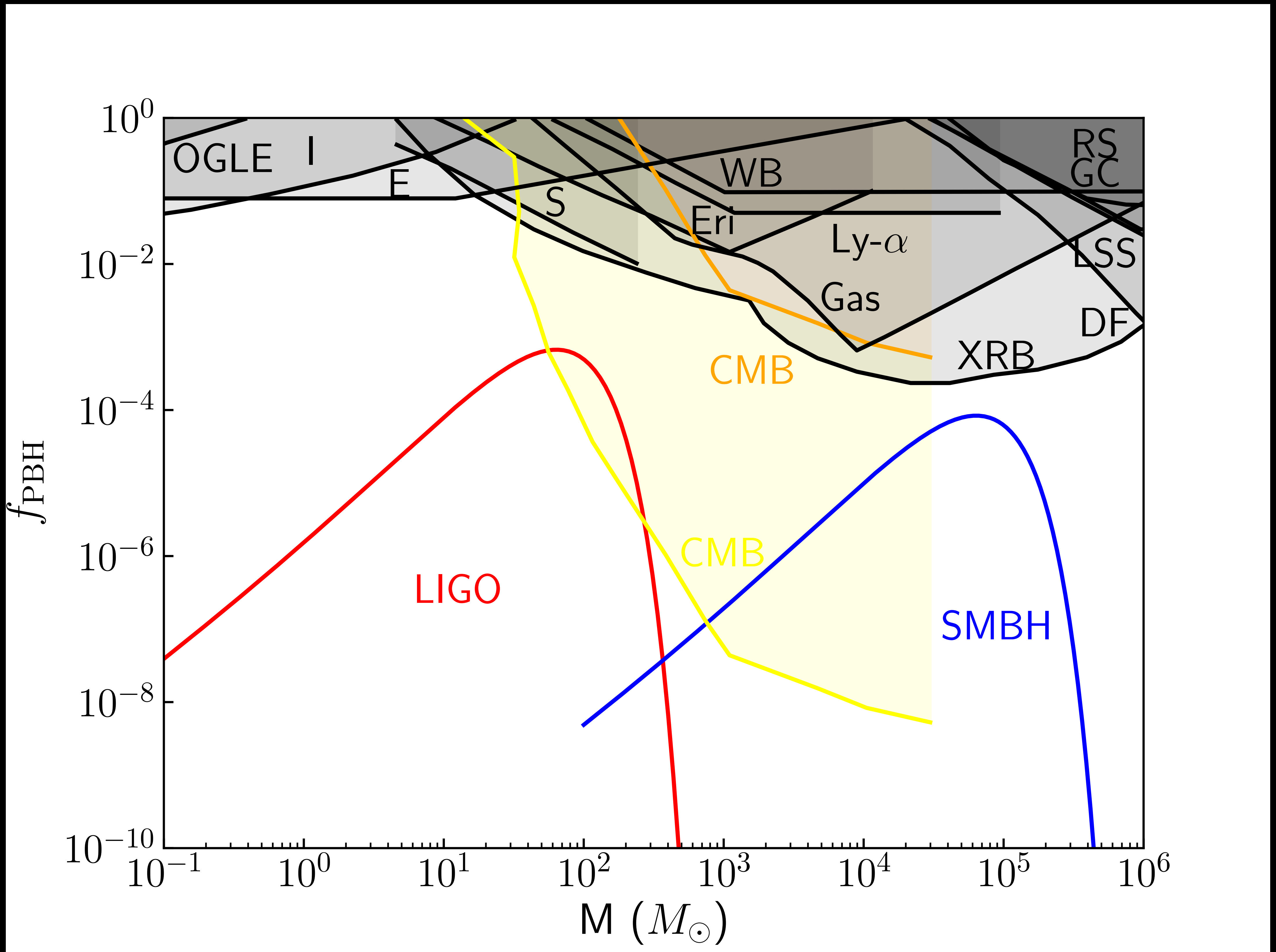
$$p_{\text{plasma}} = p_{\text{vac}} = \Delta U$$

3. If we can make the cooling process long enough, the remnants can exist as thermal balls until the recombination $T \sim 0.3\ eV$

∗ Typical size of thermal ball is $\dfrac{R_{\text{TB}}}{R_S} \sim 10^5 \left(\dfrac{\beta/H_*}{100}\right)^2 \alpha$ Much greater than Schwarzschild radius !

∴ The CMB accretion bound also becomes weaker by the same amount ! $f_{\text{therm}} \sim 10^5 \times f_{\text{PBH}}$

Two benchmark parameters



PBH mass distribution

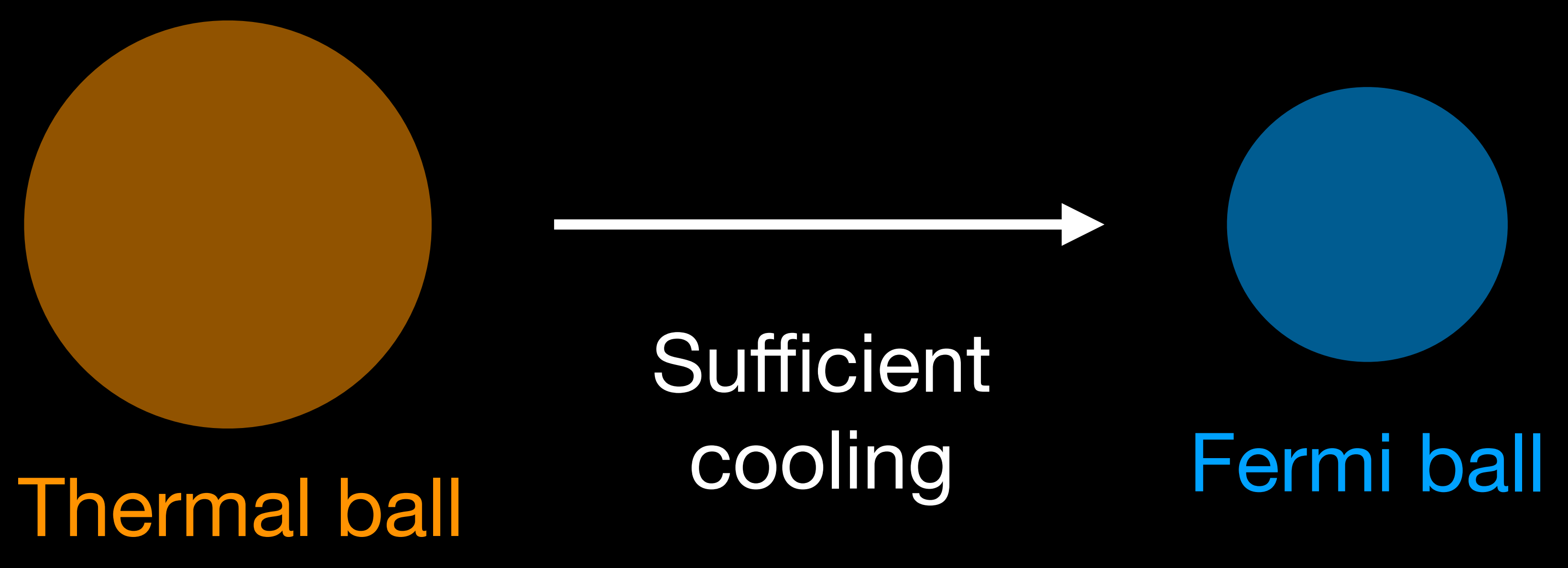
	$\overline{M}_{\rm PBH}$	$T_{\rm SM*}$	η_χ	α	β/H_*	v_w	$f_{\rm PBH}$
LIGO	$30M_\odot$	400 eV	10^{-6}	0.1	300	0.6	10^{-3}
SMBH	$3\times10^4 M_\odot$	40 eV	10^{-6}	0.1	150	0.6	10^{-4}

Yellow = usual CMB accretion bound
Orange = weaker bound

How to realize the collapse into BH ?

See also Po-Yen’s slides

- Let’s assume that (dark) fermions are trapped in the remnants and have asymmetry η_χ
- After sufficient cooling, Fermi-degeneracy pressure valances with vacuum energy pressure
  → Formation of Fermi-ball



$$p_{\rm deg} = p_{\rm vac} = \Delta U$$

c.f. Chandrasekhar Limit $p_{\rm deg} = p_{\rm grav}$

- But, this is only true when fermions are non-interacting !
  → When there exists (dark) Yukawa force (or other attractive force), it can cause instability

[Ke-Pan Xie and KK, Phys.Lett.B 824 (2022) 136791]

Instability by Yukawa force

Cont'd

- The mass $m_\phi(T_D)$ of mediating (dark) scalar ϕ depends on temperature

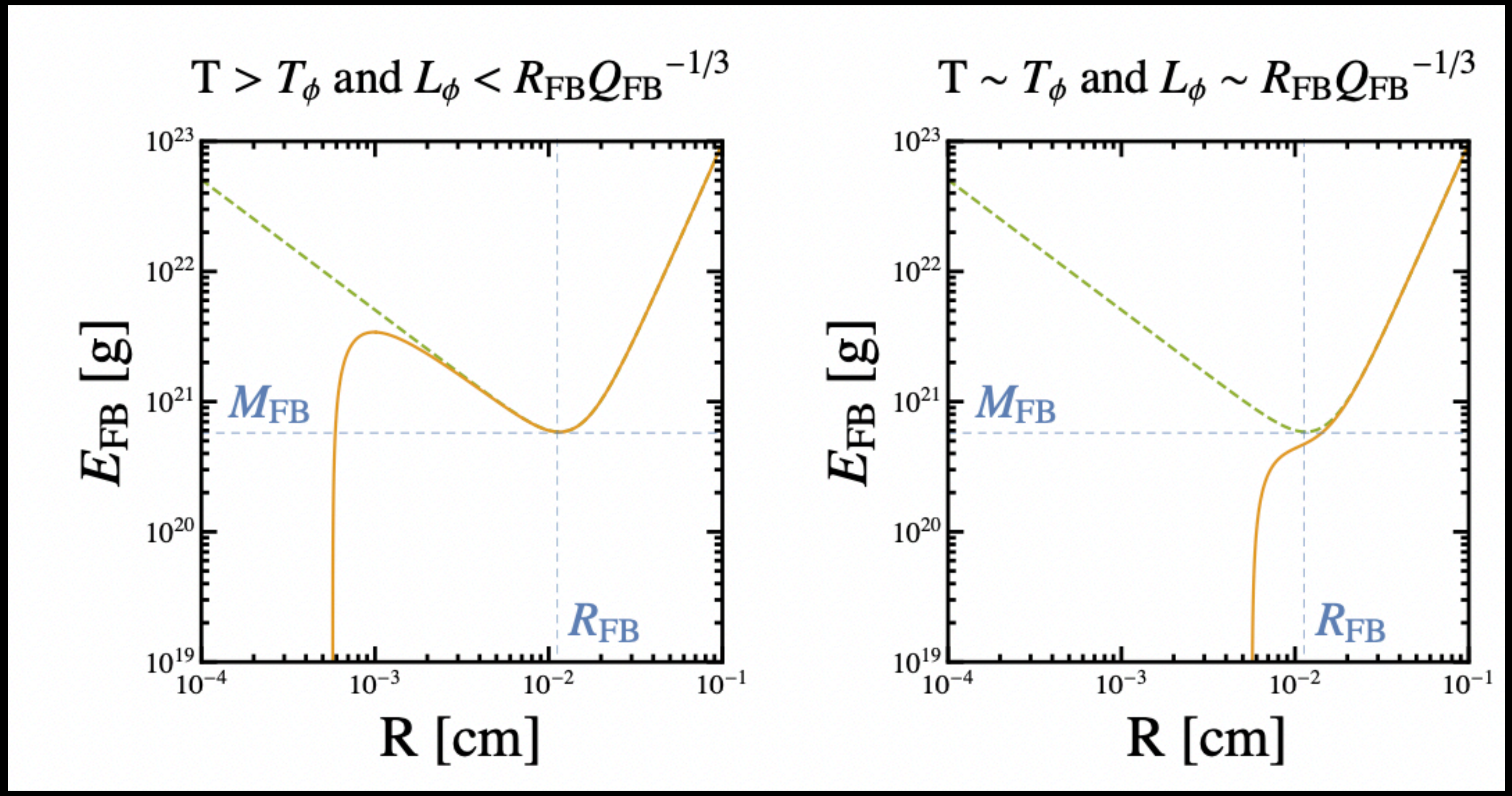
$$m_\phi(T_D)^2 = \mu^2 + cT_D^2$$

which means that Yukawa force rage $L_\phi(T) = m_\phi(T)^{-1}$ increases as T decreases

- The energy of a Fermi-ball:

$$E_{\rm FB}(R) \sim \frac{Q_{\rm FB}^{4/3}}{R} - \frac{Q_{\rm FB}^2}{R}\left(\frac{1}{Rm_\phi(T_D)}\right)^2 + \frac{4\pi}{3}U_0R^3 \ ,$$

degeneracy energy — Yukawa energy — Vacuum energy



Left = high temperature
Right = low temperature

Stable solution (=Fermi ball) disappears at low temperature

When does the collapse happen ?

- Dark real scalar ϕ and dark Dirac fermion χ :

$$\mathscr{L} = -\frac{1}{2}(\partial\phi)^2 - \underline{U(\phi)} - \bar{\chi} i \partial\!\!\!/ \chi - y\phi\bar{\chi}\chi$$

causes FOPT

- No interaction with SM sector
- Trapped particles can only escape by evaporations (high-energy tail of thermal distribution)
- Evaporation rate

$$\frac{dE}{dt} = -\xi \times 4\pi R^2 \times \rho_{\text{dark}}(T_D) \quad \text{with} \quad \xi \sim e^{-m_i/T_D}$$

black body like

m_i = mass in true vacuum

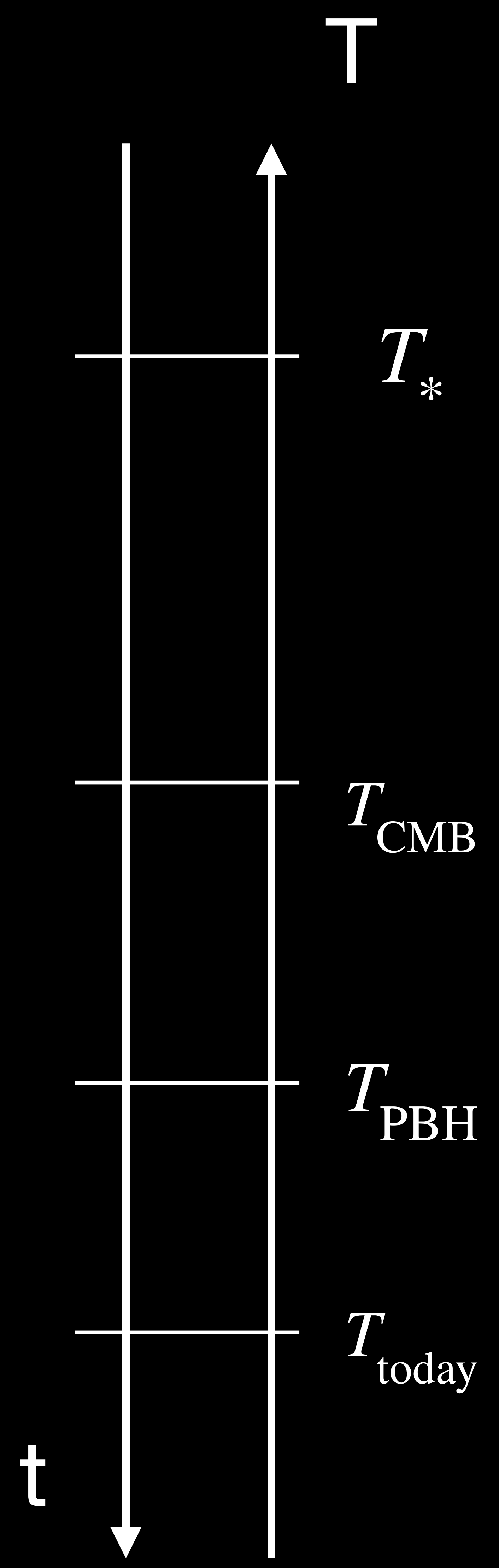
- SM temperature at PBH formation

$$T_{\text{PBH}} \sim T_* \times \xi^{1/2} \sim T_* e^{-m_i/(2T_D)}$$

If $m_i \gg T_D$, we can realize

$$T_{\text{PBH}} \lesssim 1 \text{ eV}$$

Summary of thermal history



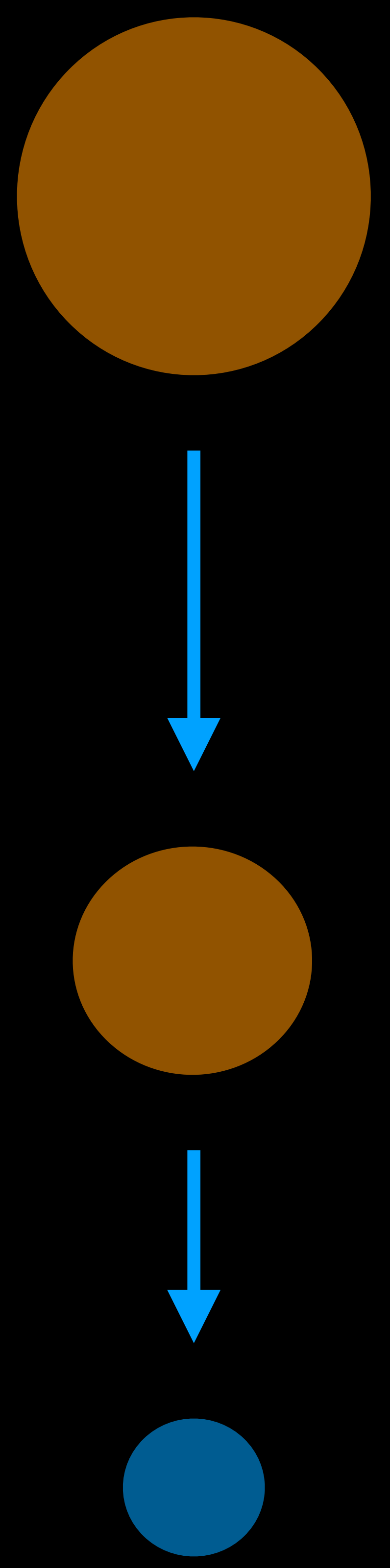
First-order phase transition and formation of Thermal balls

Slow cooling

Thermal balls still survive and we have less accretion

Fermi balls collapse into BHs

Today



Conclusions

- We have considered a possibility to evade the CMB accretion bound in the PBH mass range $10M_\odot \lesssim M_{\rm PBH} \lesssim 10^5 M_\odot$
- In general, we can evade the bound if compact remnants have larger size $R \gg R_{\rm Sch}$ at around the CMB epoch $T_{\rm SM} \lesssim 1\ {\rm eV}$
- Thermal-ball formation in FOPT and its collapse is one possible scenario
- The most difficult point is to realize long cooling until $T_{\rm SM} \lesssim 1\ {\rm eV}$

  → Can we construct a more realistic model with interactions with SM ?
- Other ways/scenarios to evade the bound ?

Back up

Mass accretion

ρ_∞ = homogeneous mass density

$$\dot{M}_{\rm BHL} = 4\pi\lambda\rho_\infty \frac{(G\,M)^2}{v_{\rm eff}^3}\,,$$

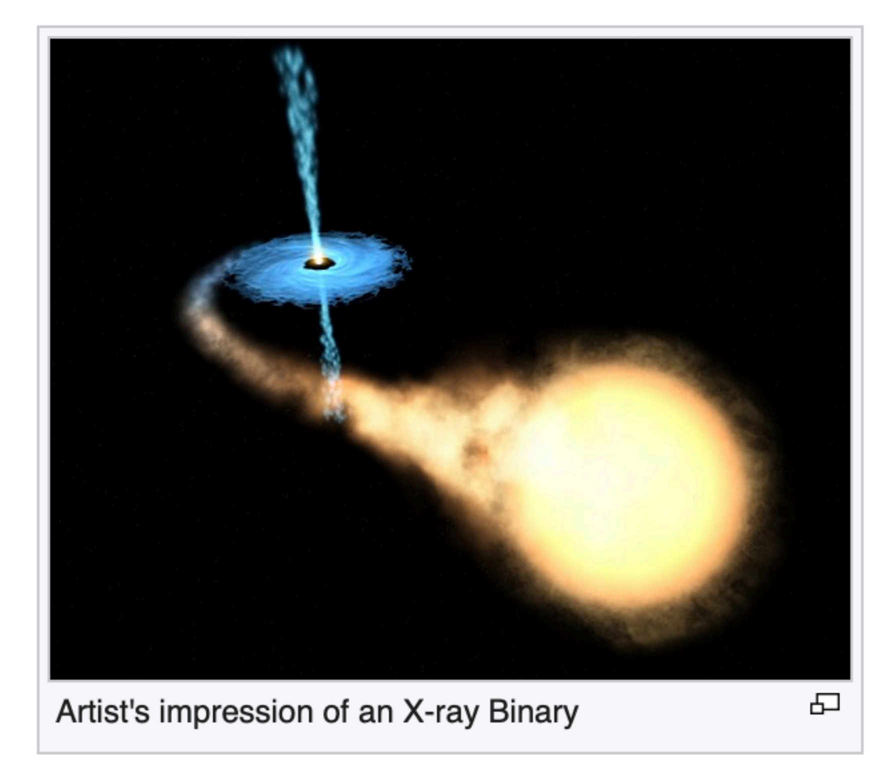
$$v_{\rm eff}^2 \equiv v_{\rm rel}^2 + c_s^2\,,$$

$v_{\rm rel}$ = velocity of BH

- Assume steady energy flow
- When $c_s \gg v_{\rm rel}$ → Spherical symmetric accretion (Bondi accretion)
- When $c_s \ll v_{\rm rel}$ → Ballistic (弾道) limit (Hoyle-Lyttleton)
- λ is a $O(0.1-1)$ coefficient determined by equation of state and cooling/drag details (=adjastable parameter to simulation results)

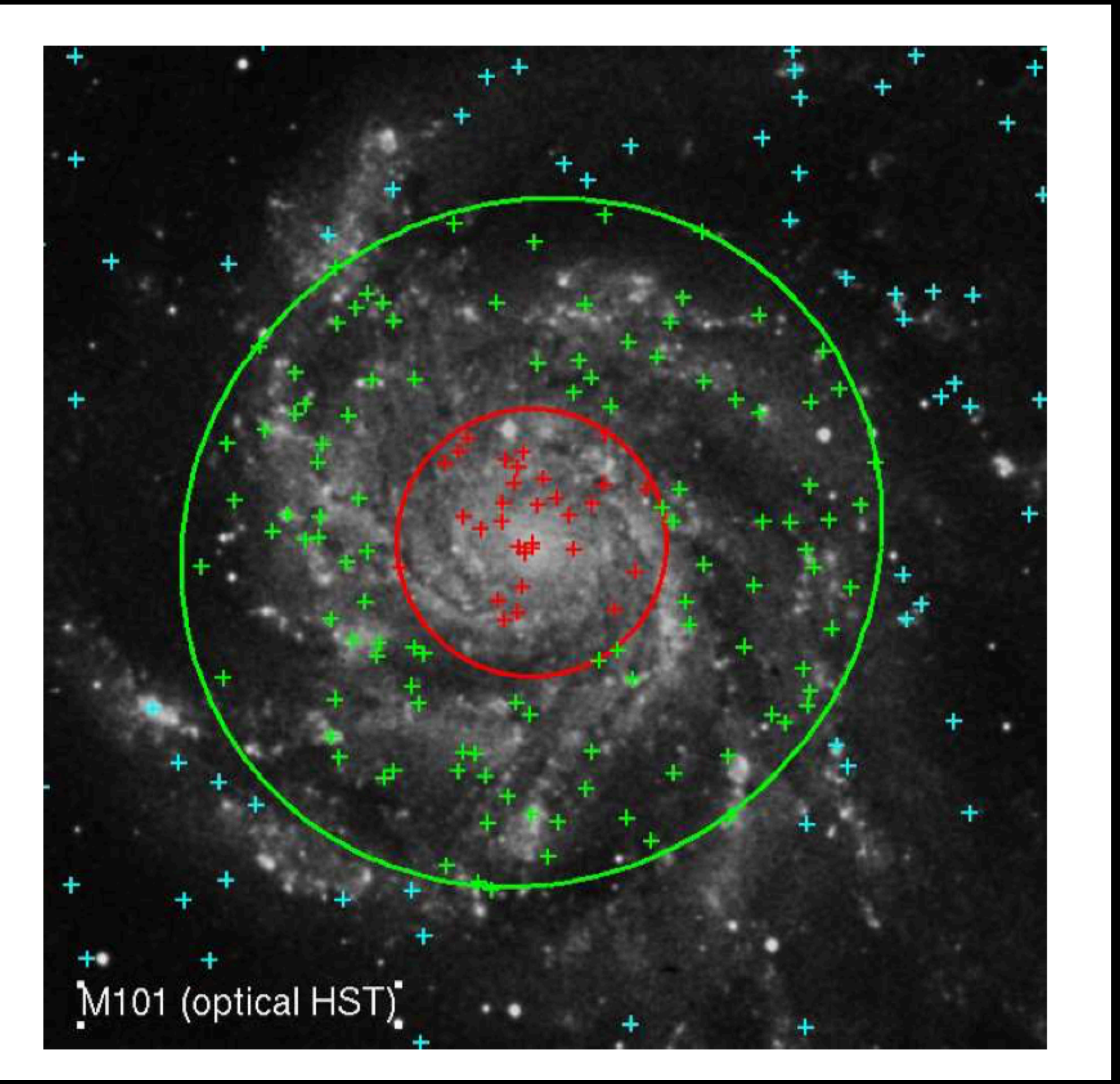
X-ray binary bound

Inoue, Kusenko ('17)

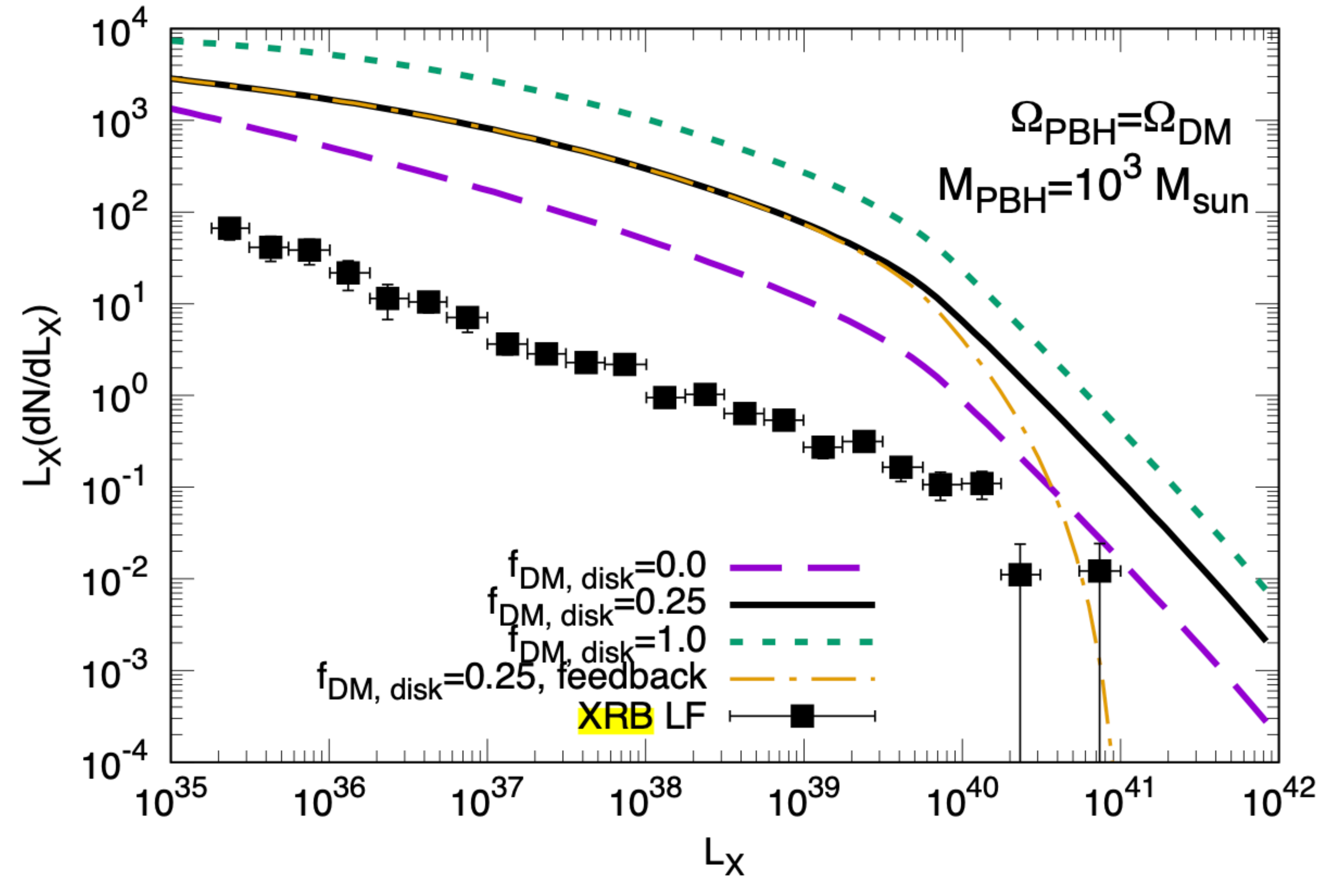


- Apparently PBHs with accretion are another source of X-rays
- Therefore, it is possible to constrain their abundance by counting the number of compact X-ray binary (XRB) in (star-forming) galaxy

Green crosses= XRB



# of XRB



Luminosity

Impacts of PBH on CMB

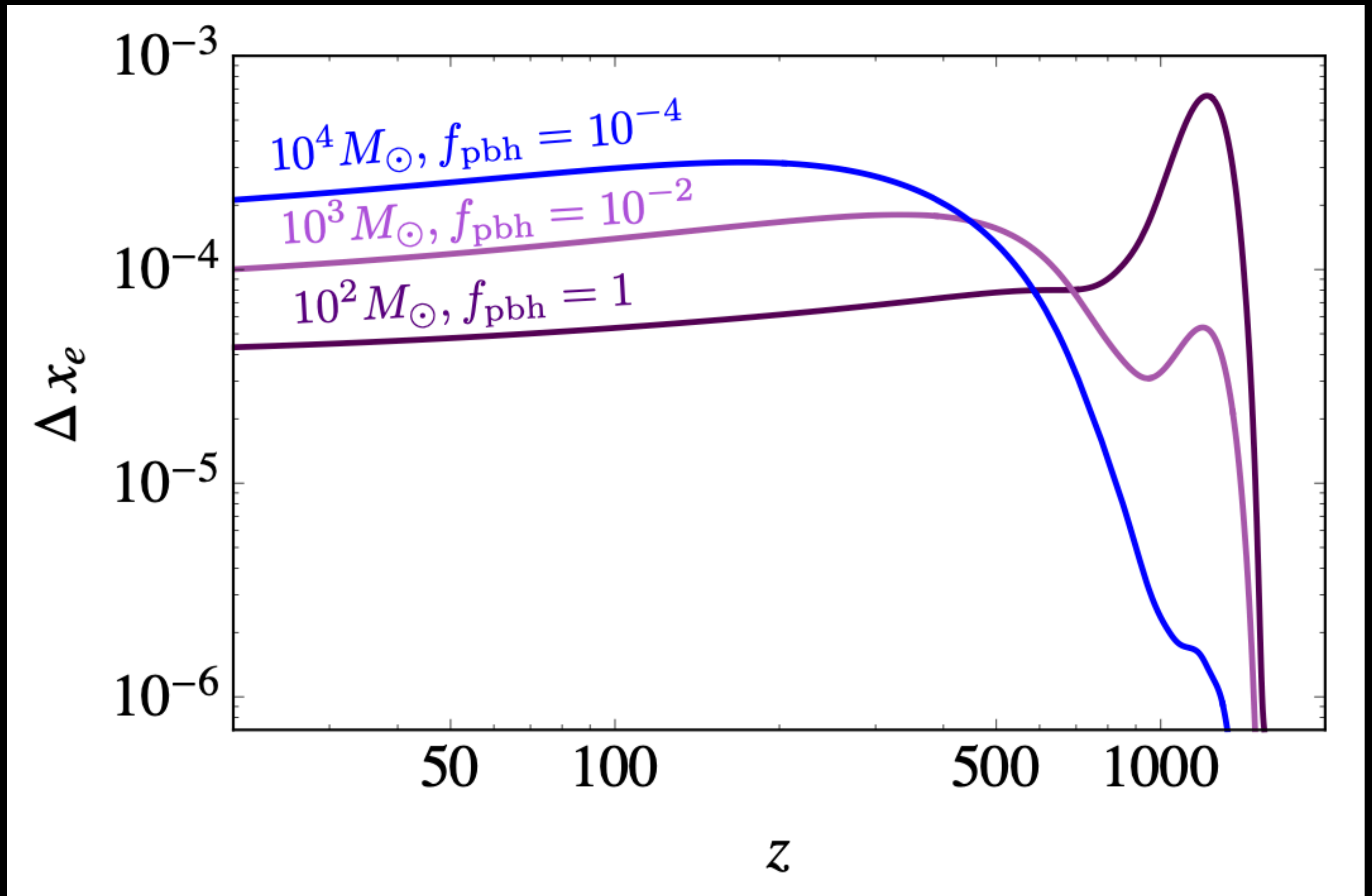
Ricotti, Ostriker, Mack, ('07)
Ali-Haimoud, Kamionkowski ('17)
Serpico, Pourin, Inman, Kohri ('20)

- The key input is energy injection

$$\dot{\rho}_{\rm inj} = f_{\rm pbh} \frac{\rho_{\rm dm}}{M} \langle L \rangle. \quad \propto \epsilon$$

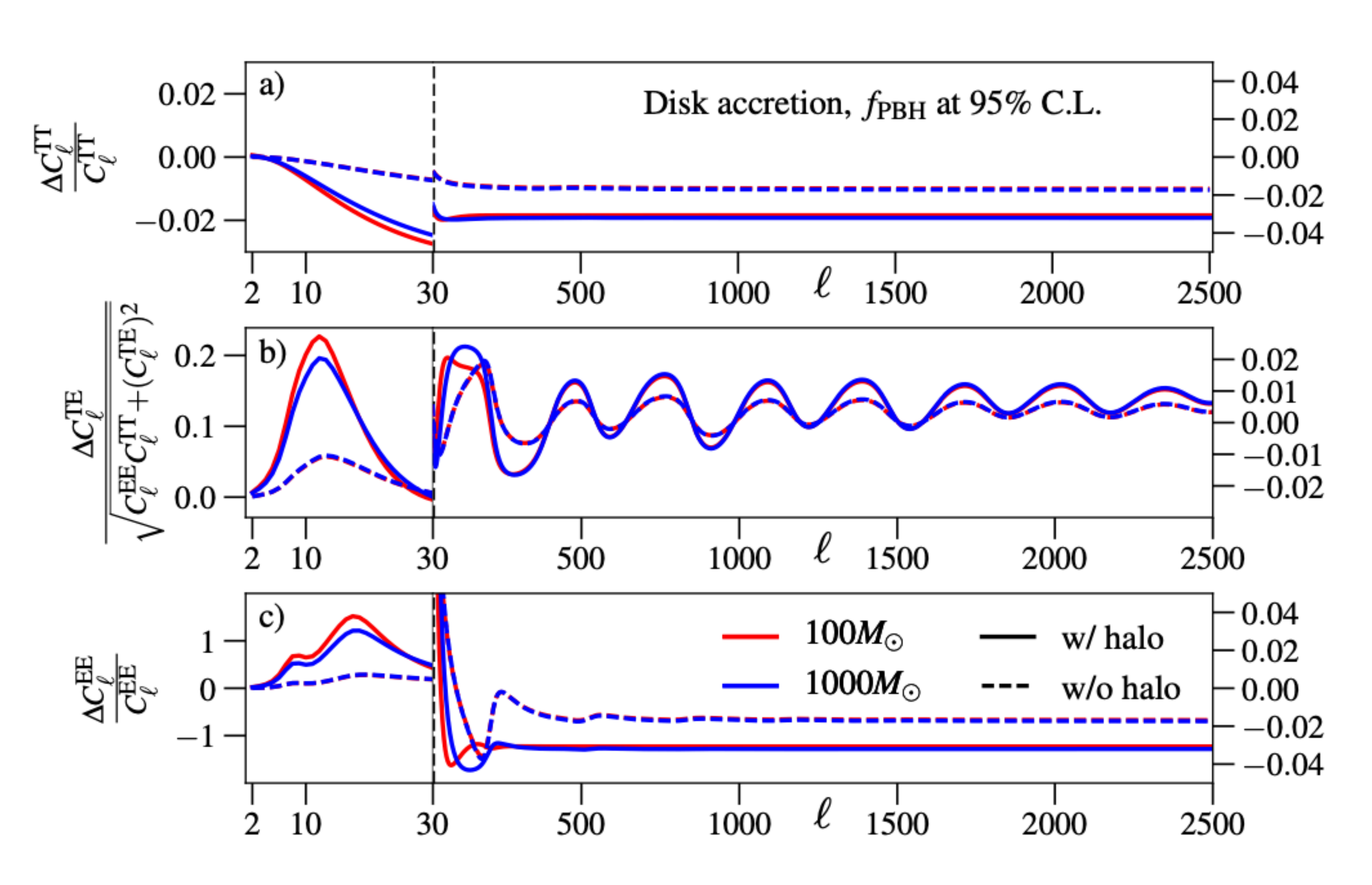
- It affects the ionization history

$$\Delta \dot{x}_e^{\rm direct} = \frac{1 - x_e}{3} \frac{\dot{\rho}_{\rm dep}}{E_{\rm I} n_{\rm H}}, \quad \propto L_{\rm acc} \propto \epsilon$$



Electron fraction (Ionization)

$\Delta C_{ij}(l)$



$f_{\rm PBH}$ = 95% CL
for a given PBH mass
Blue = $10^3 M_\odot$
Red = $10^2 M_\odot$

Thermal History

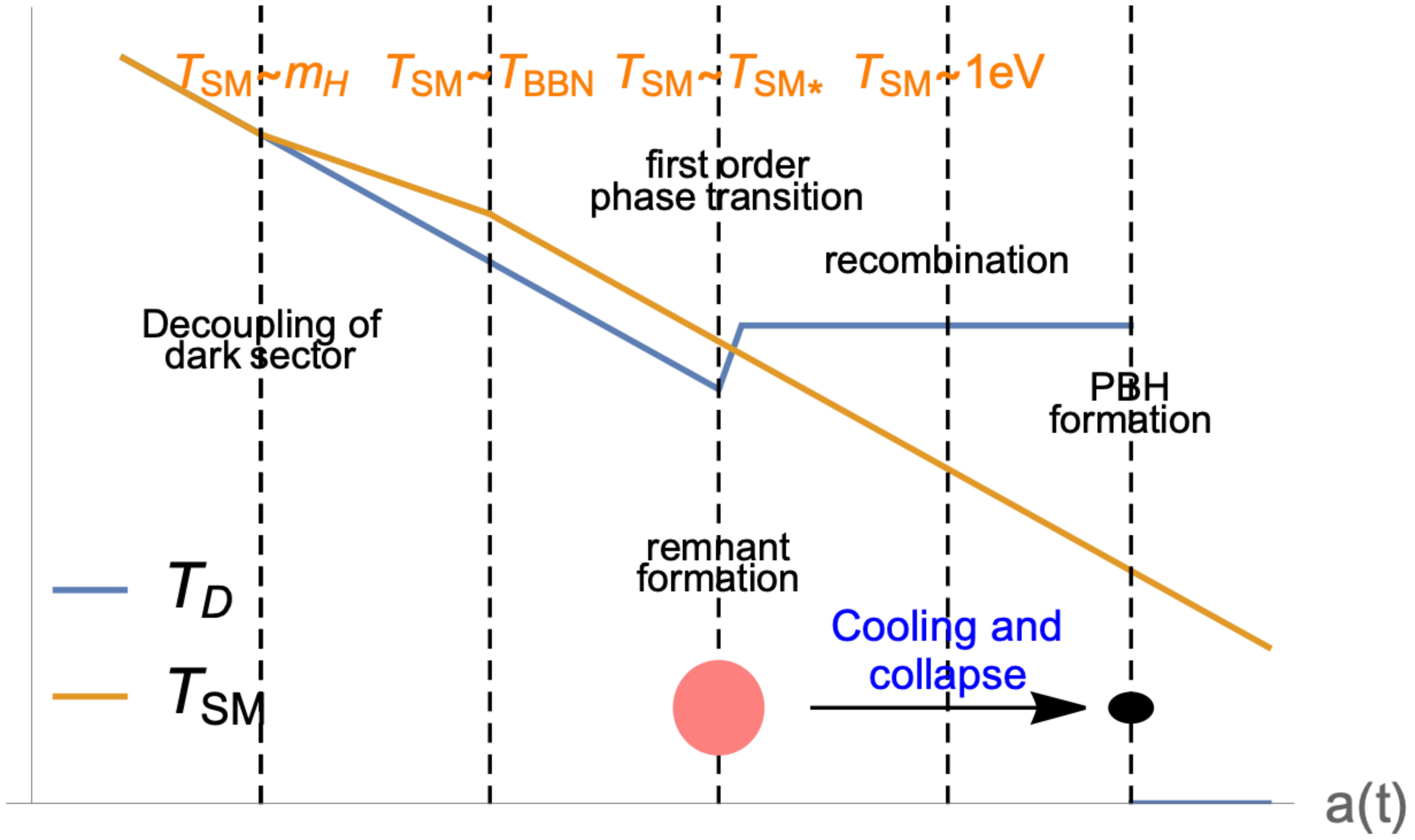


Figure 1. Thermal history of our PBH formation scenario. The orange (blue) line corresponds to the SM (dark-sector) temperature.

2.2 PBH Mass and Abundance

The average mass of the black hole resulting from Fermi ball collapse is [41]

$$\overline{M}_{\rm PBH} \approx 10^2 M_\odot \times \alpha_D^{1/4} v_w^3 F_\chi^{\rm trap} \left(\frac{\eta_\chi}{10^{-5}}\right) \left(\frac{\beta/H_*}{100}\right)^{-3} \left(\frac{g_{D*}}{4}\right)^{-1/4} \left(\frac{g_{{\rm SM}*}}{g_{\rm SM,dec}}\right)^{-2/3} \left(\frac{T_{{\rm SM}*}}{1\ {\rm keV}}\right)^{-2} . \tag{2.10}$$

The present day PBH fraction of DM, $f_{\rm PBH} := \rho_{\rm PBH}/\rho_{\rm DM}$ is [41]

$$f_{\rm PBH} \approx 0.1 \left(\frac{\overline{M}}{10^2 M_\odot}\right) v_w^{-3} \left(\frac{g_{D*}}{4}\right)^{1/2} \left(\frac{g_{{\rm SM}*}}{g_{\rm SM,dec}}\right) \left(\frac{T_{{\rm SM}*}}{1\ {\rm keV}}\right)^3 \left(\frac{\beta/H_*}{100}\right)^3 \left(\frac{\Omega_{\rm DM}}{0.26}\right)^{-1} . \tag{2.11}$$

In this scenario, the PBH mass and abundance is determined by that of Fermi balls

Cooling of thermal balls

- The evolution equation

$$\frac{dR}{dT_{\rm SM}} = \frac{dR}{dE}\frac{dE}{dT_{SM}} = \frac{(45)^{3/2}M_{\rm Pl}}{16\pi^{9/2}g_D g_{\rm SM}^{1/2}R^2T_{D,1}^4T_{\rm SM}^3}\frac{dE}{dt}\,,$$

We can solve this once $\dot{E}$ is given

- Black body case

$$\frac{dE}{dt} = -\xi \times 4\pi R^2 \times \rho_{\rm dark}(T_D)$$

$$\longrightarrow \quad R(T_{\rm SM}) = R_1 - \frac{a_s}{2}\left(\frac{1}{T_{\rm SM}^2} - \frac{1}{T_{\rm SM*}^2}\right)\,, \quad a_s = \frac{(45)^{3/2}\xi_l M_{\rm Pl}}{120\pi^{3/2}g_{\rm SM}^{1/2}}\,,$$

$R_1 \sim v_w/\beta$ = Initial radius of thermal ball

- Since $R_{\rm FB} \ll R_1$, the collapse timing is qualitatively determined by $R(T_{\rm SM}) \sim 0$

$$T_{\rm PBH} \sim T_* \times \xi^{1/2} \sim T_* e^{-m_i/(2T_D)}$$

Other bounds

1. BBN: Extra relativistic species $\Delta N_{\rm eff}$ $(N_{\rm eff} = 3 \text{ in the SM case})$

$$N_{\rm eff} = 2.88 \pm 0.34$$ [Pitrou et al. ('18)]

It seems that dark sector model $(\Delta N_{\rm eff} = 1 + \frac{7}{8} \times 4)$ grossly violates this.

But this is not true because there is entropy production in the SM sector

Assuming dark particles have the same temperature as the SM temperature, we have

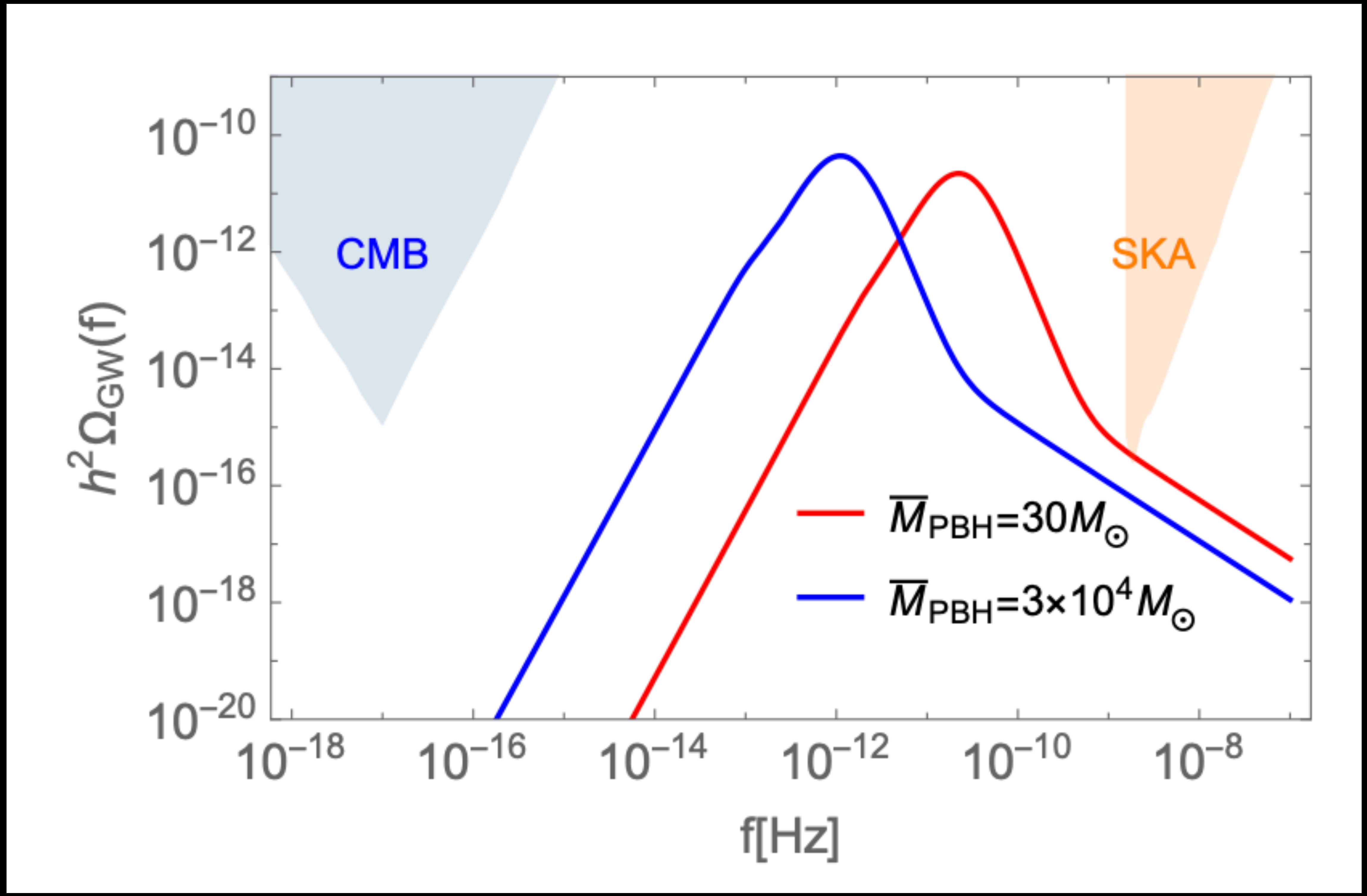
$$T_D/T_{\rm SM}|_{T_{\rm SM}=1\ \rm MeV} \sim 0.5 \quad \rightarrow \quad \Delta N_{\rm eff} \propto (T_D/T_{\rm SM})^4 \ll 1$$

Other bounds

2. Gravitational Waves :

In order to obtain $M_{\rm PBH} \gtrsim 10 M_\odot$, we typically need $T_{\rm SM*} \lesssim 1$ keV

→ The peak frequency of GWs is very small, $f_{\rm peak} \lesssim 10^{-2}$mHz



Well below SKA frequencies