Primordial black holes from slow phase transitions: a model-building perspective

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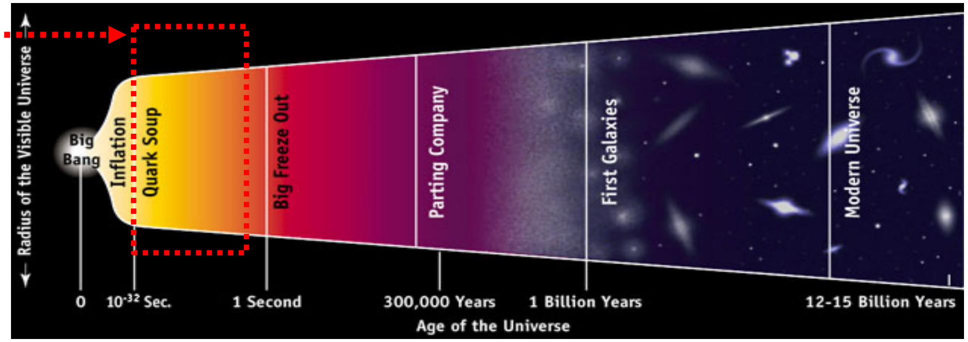
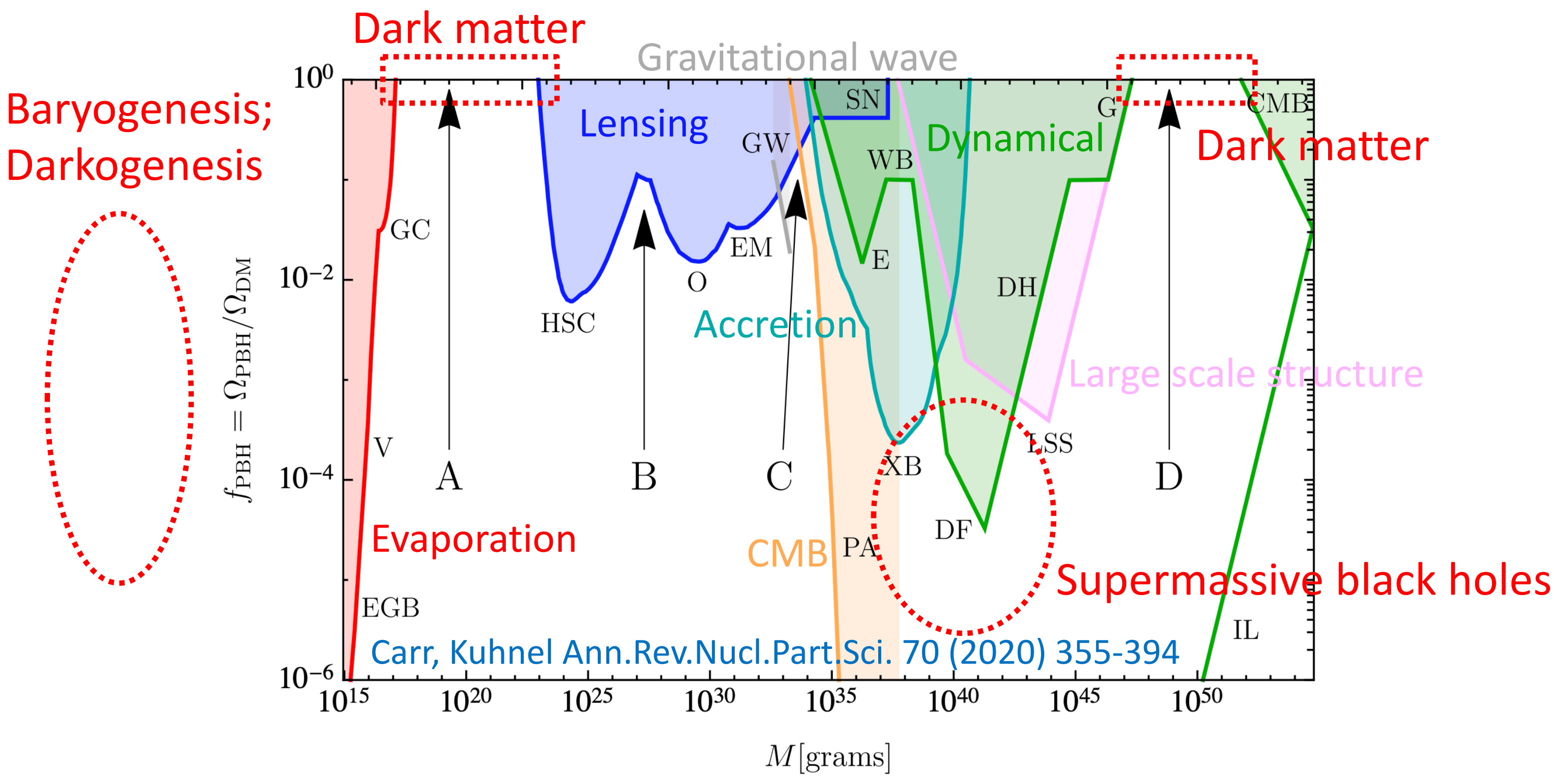
Based on arXiv:2404.00646, with Shinya Kanemura & Masanori Tanaka

Primordial black holes (PBHs)

Formed soon after the Big Bang

With model-dependent mass & densities





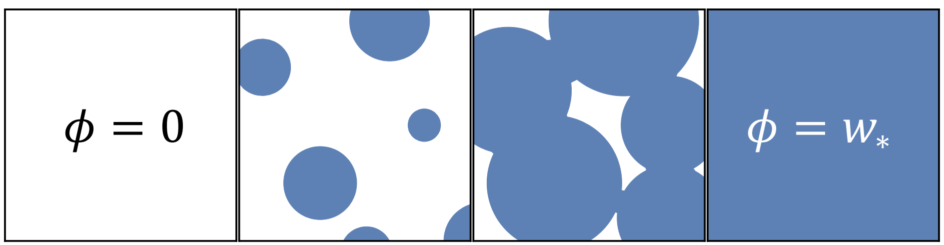
First-order phase transitions

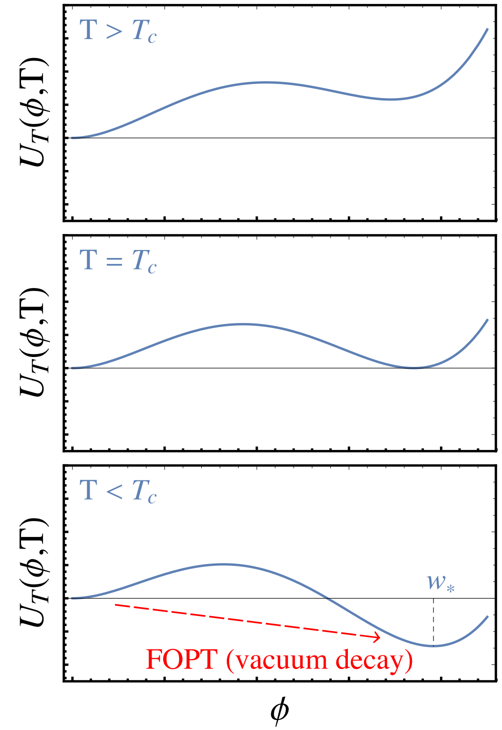
Decay of vacuum

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

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

Time evolution (boiling of the Universe)





Landscape of FOPTs

- GUT -- $T_* \sim 10^{15}$ GeV
- Seesaw & $U(1)_{B-L}$ -- $T_* \sim 10^{12}$ GeV
- EW $SU(2)_L \times U(1)_Y$ -- $T_* \sim 10^2$ GeV [Higgs]
- Dark $U(1)_X$ -- $T_* \sim$ MeV [NANOGrav?]
- …

Phase transitions as source of over-densities

This talk

Bubble collisions

Hawking et al, PRD 26 (1982) 2681

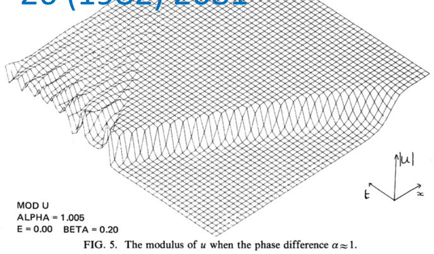
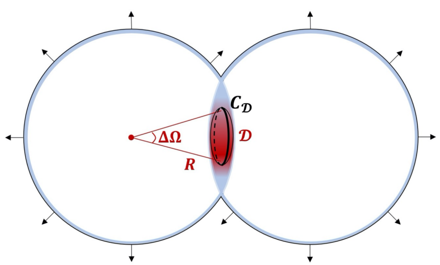


FIG. 5. The modulus of u when the phase difference $\alpha \approx 1$.



Jung et al, 2110.04271

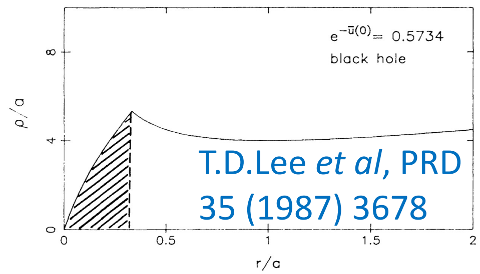
Also see

Moss, PRD 50 (1994) 676-681;

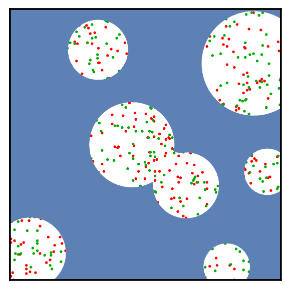
Lewicki *et al*, Phys. Dark Univ. 30, 100672 (2020);

…

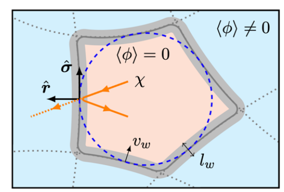
Particle trapping



T.D.Lee *et al*, PRD 35 (1987) 3678



Baker *et al*, 2105.07481



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

Also see

Gross *et al*, JHEP 09 (2021) 033;

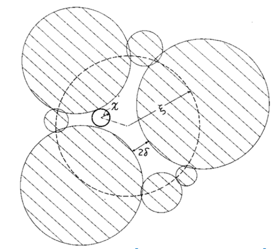
Huang and **KPX**, PRD 105 (2022) 115033;

Marfatia *et al*, JHEP 08 (2022) 001;

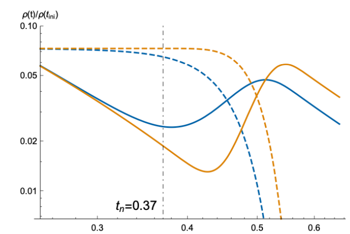
Lewicki *et al*, PRD 108 (2023) 036023;

…

Slow transitions



Kodama *et al*, Prog. Theor. Phys. 68 (1982) 1979



Liu, Bian, Cai, Guo, Wang, PRD 105, L021303

Also see

Kusenko *et al*, PRL 125 (2020) 181304;

Hashino *et al*, PLB 838 (2023) 137688;

He *et al*, SCPMA 67 (2024) 4, 240411;

Cai, Hao, Wang, 2404.06506

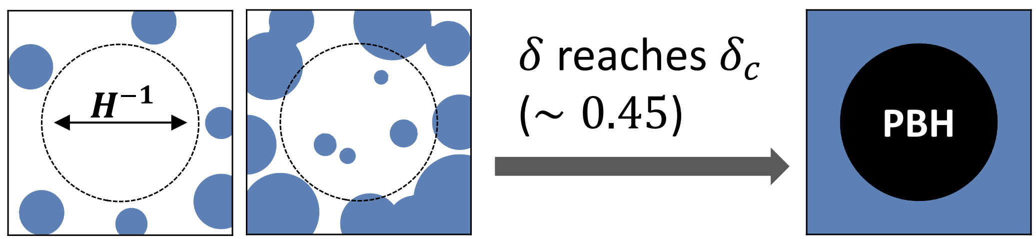
…

PBH formation due to delayed-decay patches

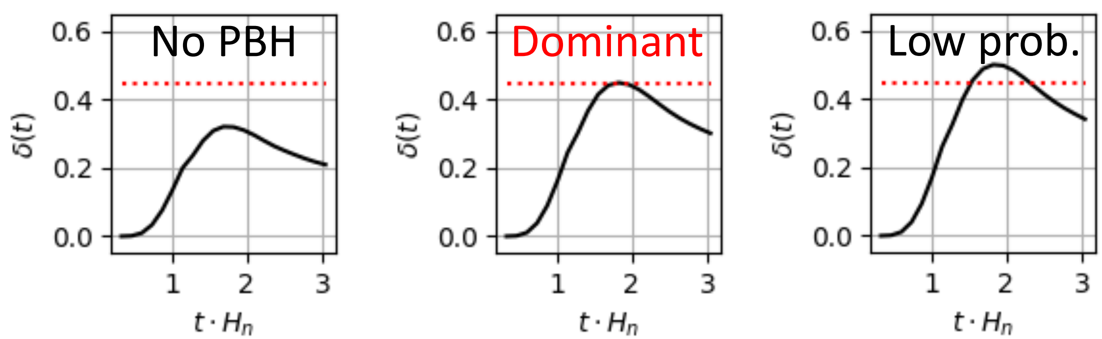
Randomness: some Hubble patches nucleate later than average

- $\rho_r \propto a^{-4}$; $\rho_v \propto a^0$

$\Rightarrow$ Over-density $\delta = \frac{\rho_{\text{delay}}}{\rho_{\text{normal}}} - 1$ forms



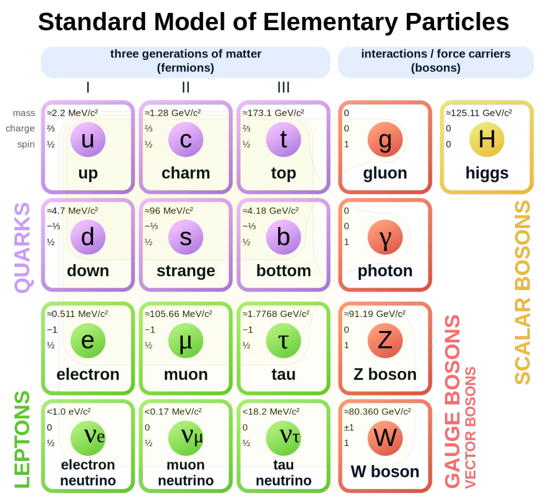
PBH mass $H_*^{-3}\rho_* \sim 10^{31}\ \text{g} \times \left(\frac{\text{GeV}}{T_*}\right)^2$; abundance derived from ↓



Increasing the delayed-decay time

How to realize in a particle model?

Extending the Standard Model…



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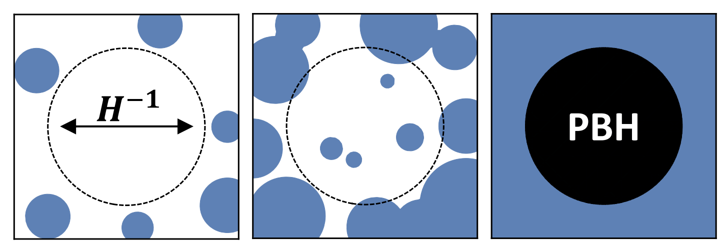


The crucial parameter β

Two important parameters in first-order phase transitions

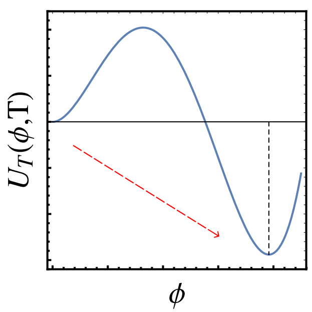
$$\alpha = \frac{\Delta V}{\frac{\pi^2}{30} g_* T_*^4}$$

Strength: vacuum-to-radiation energy ratio

$$\frac{\beta}{H_*} = -\frac{1}{H_*} \frac{\mathrm{d}S}{\mathrm{d}t}\bigg|_*$$

Duration: inverse ratio of FOPT duration to Hubble time

Vacuum decay rate[Linde, NPB 216 (1983) 421]



$$\Gamma \approx T^4 \left(\frac{S}{2\pi}\right)^{3/2} e^{-S}$$

← Euclidean action Evaluated from $U_T(\phi, T)$

$$S(t) \approx S(t_*) - \beta(t - t_*) + \frac{\zeta^2}{2}(t - t_*)^2 + \cdots$$

Exponential approximation $\Gamma \approx \Gamma_* e^{\beta t}$

A small β / H_* means a **slow** transition, which is necessary

Model-building strategies

Classically conformal (scale invariant) potential, e.g.

$$U_T(\phi,T) \approx \frac{3g_{B-L}^4}{2\pi^2}\phi^4\left(\log\frac{\phi}{w}-\frac{1}{4}\right)+\frac{g_{B-L}T^2}{2}\phi^2$$

$S \propto g_{B-L}^{-3}$, small g_{B-L} leads to small $\Gamma \propto e^{-S}$: ultra-supercooling

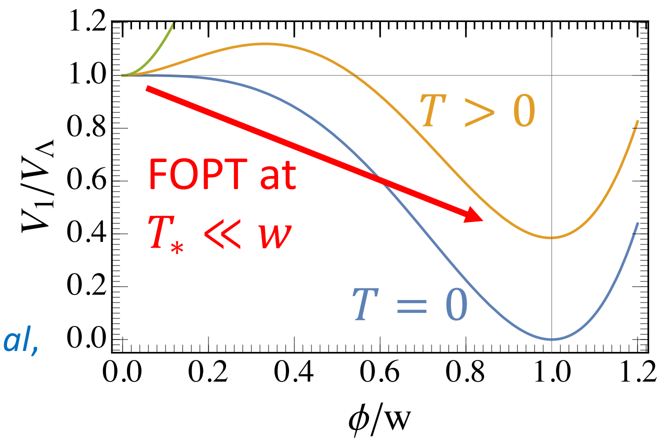
Iso *et al*, PRL 119 (2017) 14, 141301

Transition temperature $T_* \ll w$

- $\alpha \sim w^4/T_*^4 \gg 1$ [super-strong]
- β/H_* small [slow]

A popular choice!

Gouttenoire, 2311.13640; Salvio, 2312.04628; Conaci *et al*, 2401.09411; Baldes *et al*, 2307.11639; etc



This talk: a new type of realization [Kanemura, Tanaka and **KPX**, 2404.00646]

- A purely **slow** transition, not necessary super-strong
- **General relationship** between PBH formation & the particle model structure

A simple example

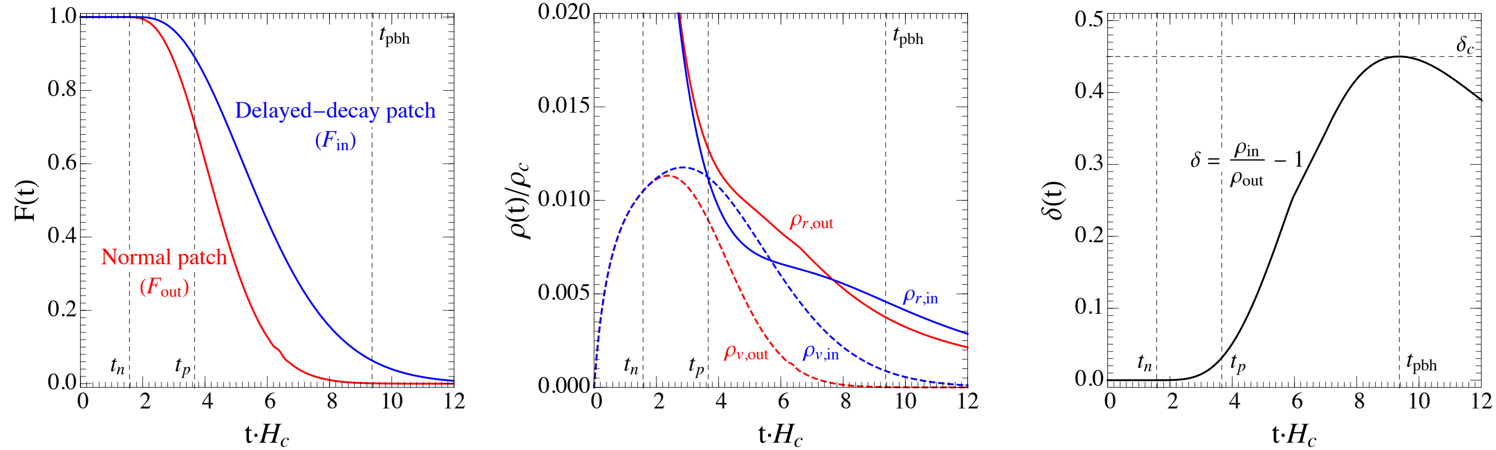
A polynomial potential

$$U_T(\phi,T) \approx \frac{1}{2}(\mu^2 + cT^2)\phi^2 - \frac{\mu_3}{3}\phi^3 + \frac{\lambda}{4}\phi^4$$

$\mu^2 = \frac{\mu_3 w - m_\phi^2}{2}$ and $\lambda = \frac{m_\phi^2}{2w^2}\left(1 + \frac{\mu_3 w}{m_\phi^2}\right)$, vacuum at $\langle\phi\rangle = w$, scalar mass m_ϕ

Realizing the PBH formation --

Benchmark: $m_\phi = 300$ MeV, $w = 900$ MeV, $c = 0.11$, and $\mu_3 = 154.1$ MeV

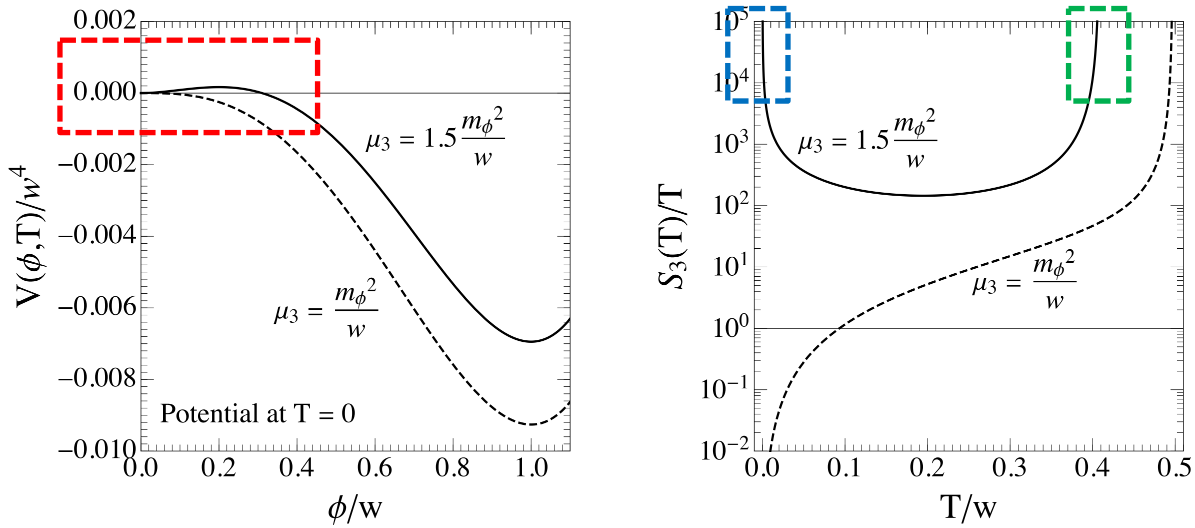


FOPT parameters: $T_n = 168$ MeV, $T_p = 126$ MeV, $\alpha = 2.8$, and $\beta/H_* = 4.7$

Resultant $m_{pbh} = 2.72\times10^{33}$ g $= 1.37 M_\odot$

The underlying reason

A zero-temperature potential barrier exists for $1 < \frac{\mu_3 w}{m_\phi^2} < 3$



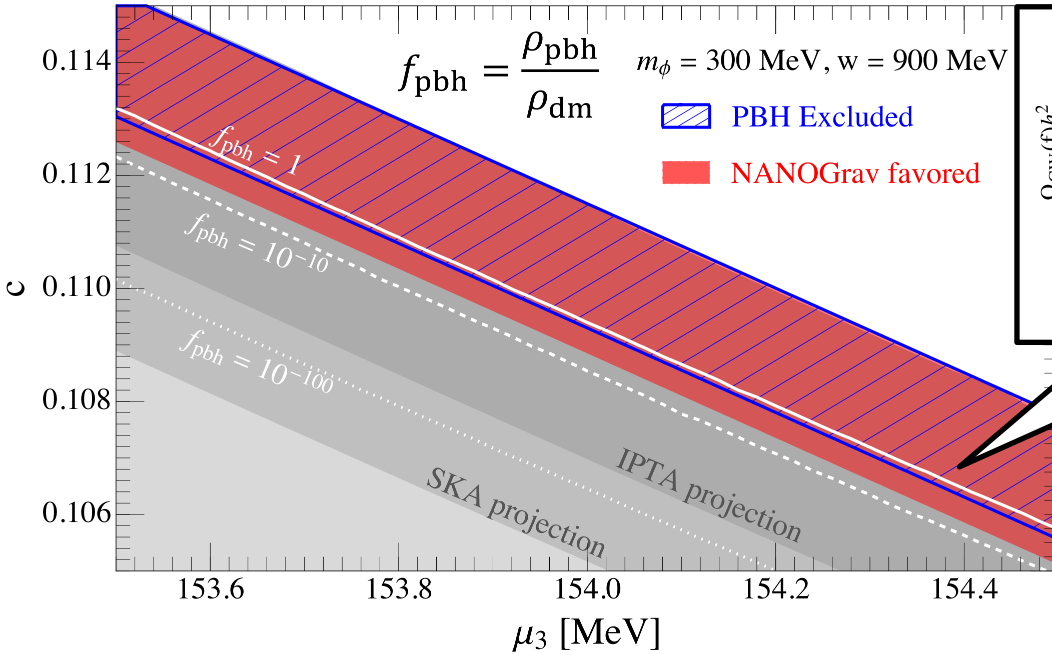
The U-shaped $S(T) = S_3(T)/T$

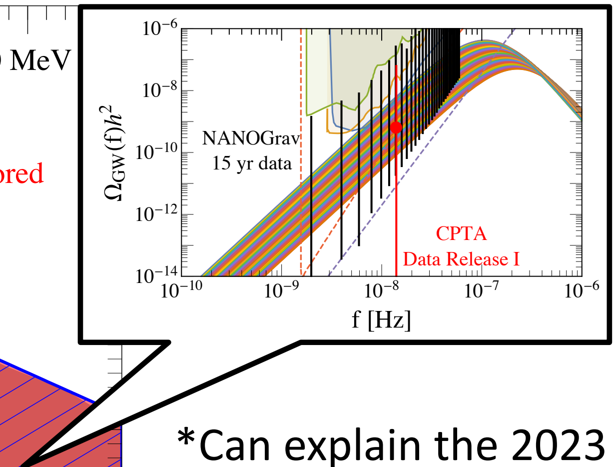
- For $T \to T_c$, two vacua degenerate, $S(T) \to \infty$
- For $T \to 0$, $S_3(T)$ finite, $S(T) \to \infty$

Decay rate $\Gamma \propto e^{-S}$ suppressed ⇒ a **slow** transition!

NOT necessary super-strong: difference between **late** and **slow**

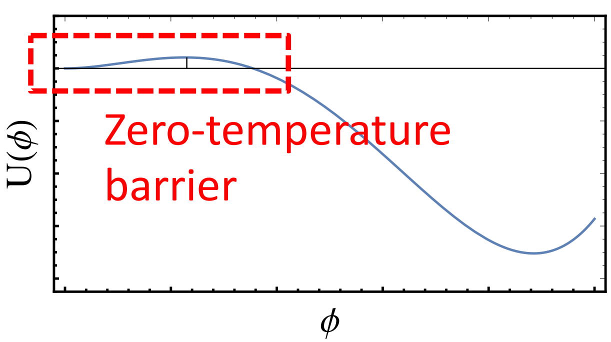
Feature 1: sensitive parameter-dependence

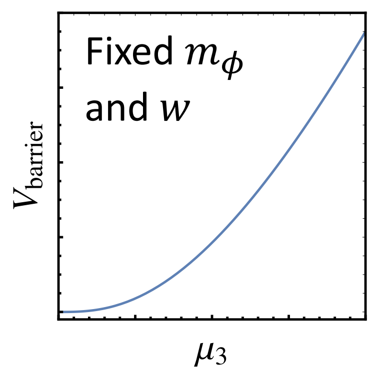




*Can explain the 2023 PTA data excess

$\delta\mu_3/\mu_3 \sim 0.6\%$ and $\delta c/c \sim 9\%$, however $\delta f_{\rm pbh} > 10^{10}$!



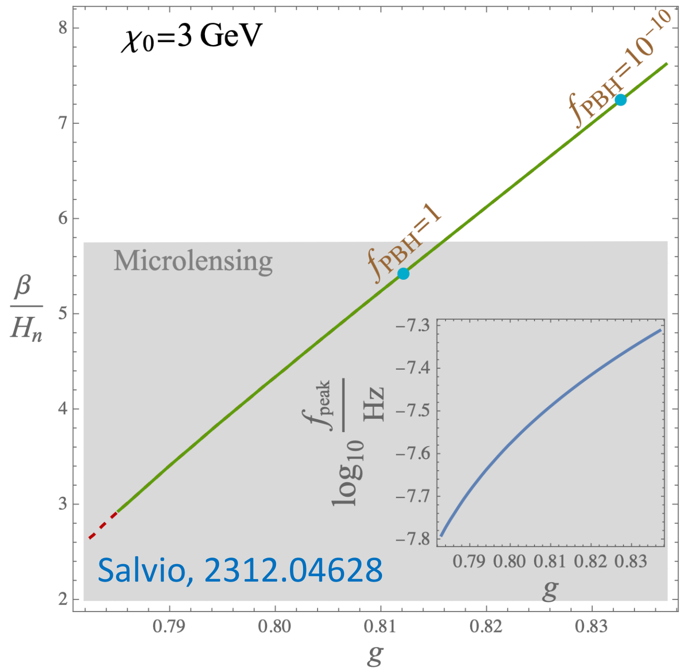


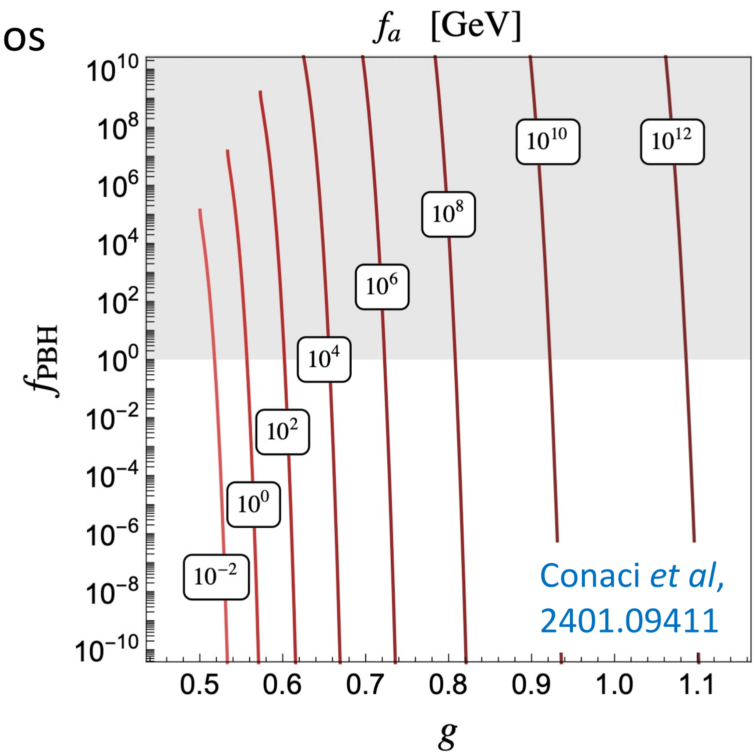
$f_{\rm pbh}$ exponentially sensitive to the barrier height

The sensitive $f_{\rm pbh}$

Similar dependence also obtained in the literature

*For classically conformal scenarios





Reason: $f_{\rm pbh}$ is exponentially sensitive to β/H_*

Fine-tuning is needed for $f_{\rm pbh} \sim 1$

Also the general feature of many conventional PBH mechanisms

Feature 2: the breakdown of exponential nucleation

The vacuum decay rate $\Gamma(t) \sim \Gamma_* e^{-S(t)}$

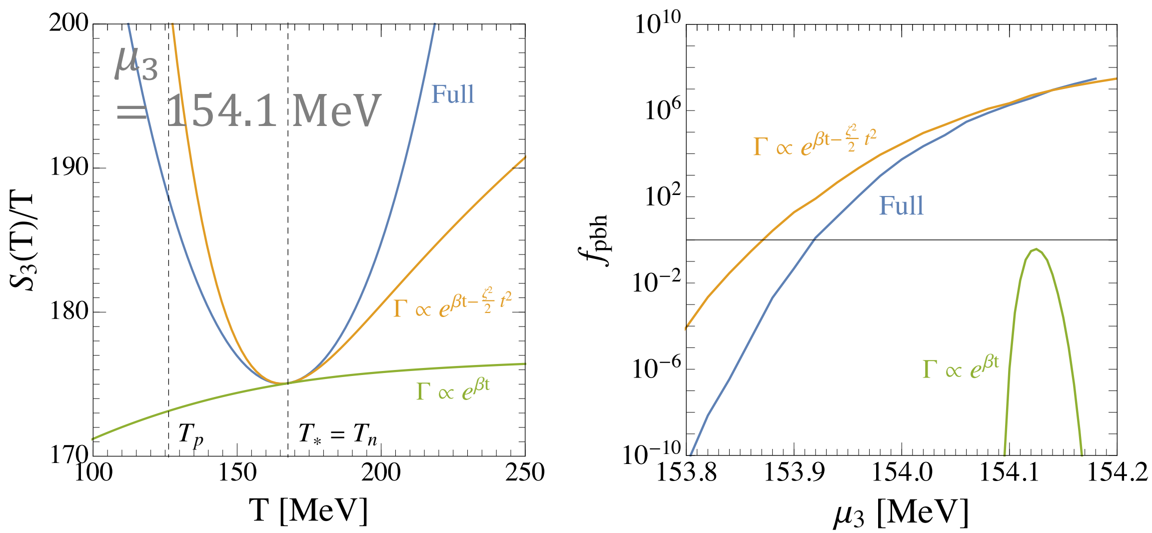
Talyor expansion $S(t) \approx S(t_*) - \beta(t - t_*) + \frac{\zeta^2}{2}(t - t_*)^2 + \cdots$

- $\Gamma(t) \approx \Gamma_* e^{\beta(t-t_*) - \frac{\zeta^2}{2}(t-t_*)^2 + \cdots}$

Linear-order → exponential approximation → parameter β/H_*

"Standard approximation" in FOPT studies

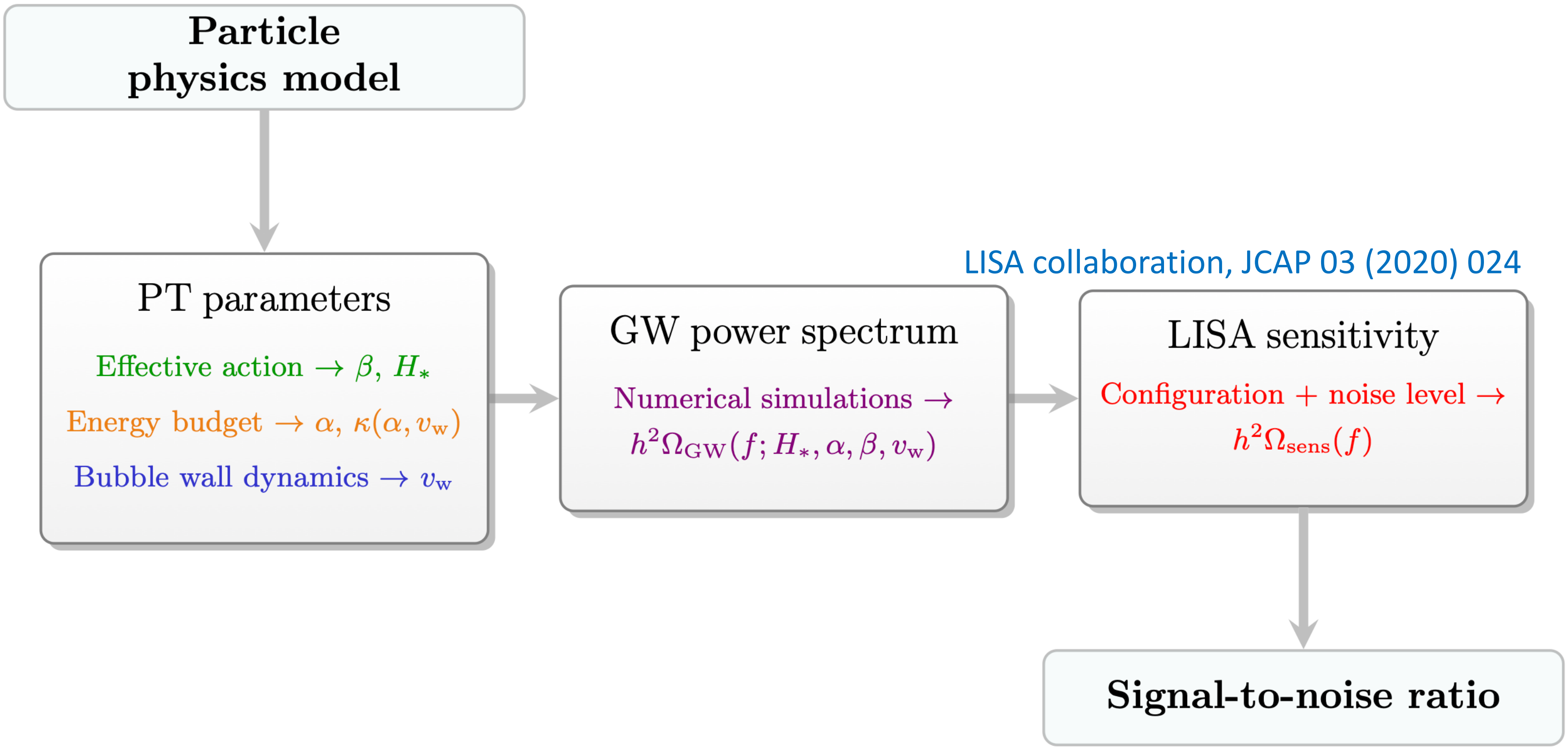
BUT may not apply when β/H_* is small



Benchmark: $m_\phi = 300$ MeV, $w = 900$ MeV, and $c = 0.11$

Importance of including full $S(t)$

The standard "EFT" treatment of FOPTs



In the slow-transition PBH scenario:

- Full description of $S(t)$ is needed
- Replace β/H_* with $(8\pi)^{1/3}v_w/(H_*\bar{R})$ in GW calculation

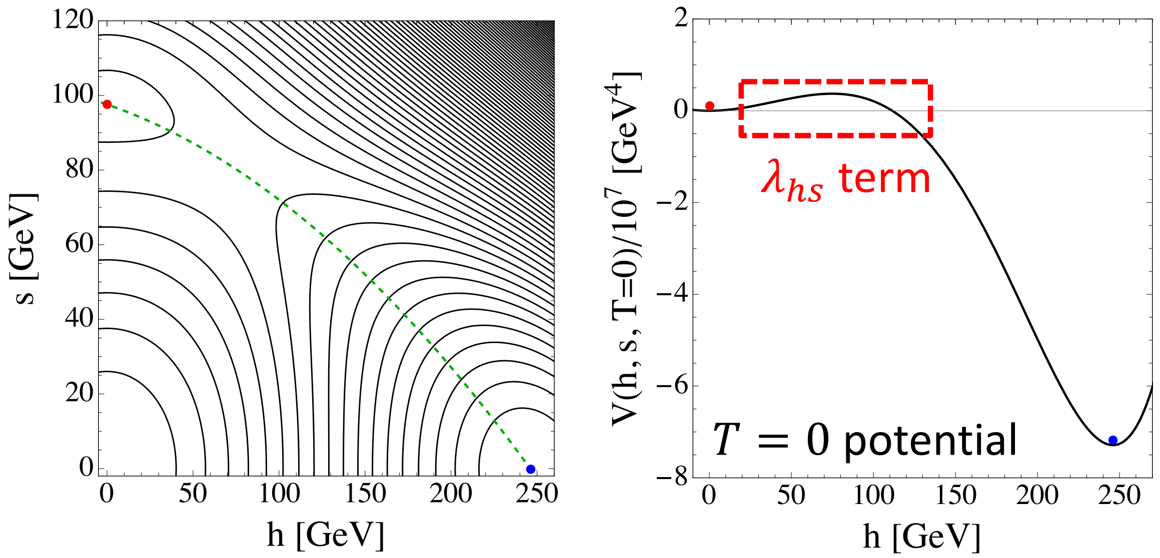
A more realistic model

The $\mathbb{Z}_2$-symmetric singlet extension of the SM ($\mathbb{Z}_2$-xSM)

$$V(h,s) = \frac{\mu_h^2}{2}h^2 + \frac{\mu_s^2}{2}s^2 + \frac{\lambda_h}{4}h^4 + \frac{\lambda_s}{4}s^4 + \frac{\lambda_{hs}}{2}h^2 s^2$$

Given $m_h = 125$ GeV and $\langle h \rangle = v = 246$ GeV,

Only 3 free parameters, chosen as m_s, λ_{hs}, λ_s.



Benchmark: $m_s = 218$ GeV, $\lambda_{hs} = 1.108$, $\lambda_s = 2$

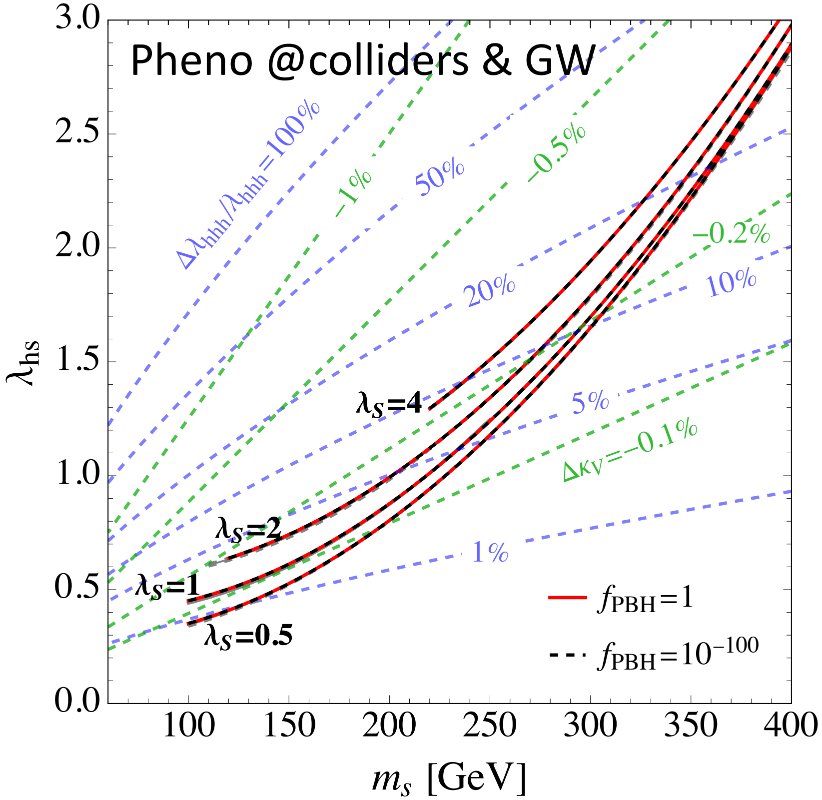
The λ_{hs} term induces the zero-temperature barrier

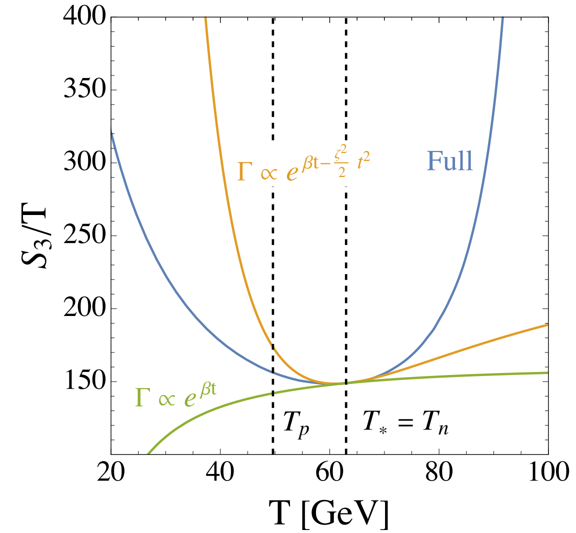
Finite temperature dynamics

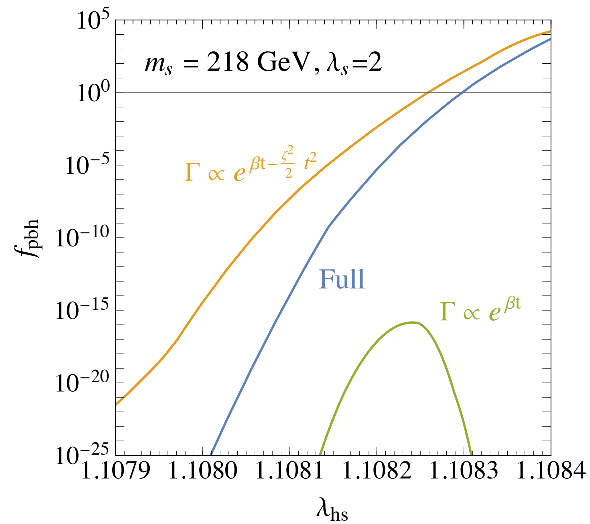
Vacuum decay pattern

$$(h, s) = (0, w_*) \to (v_*, 0)$$

First-order electroweak phase transition (FOEWPT)







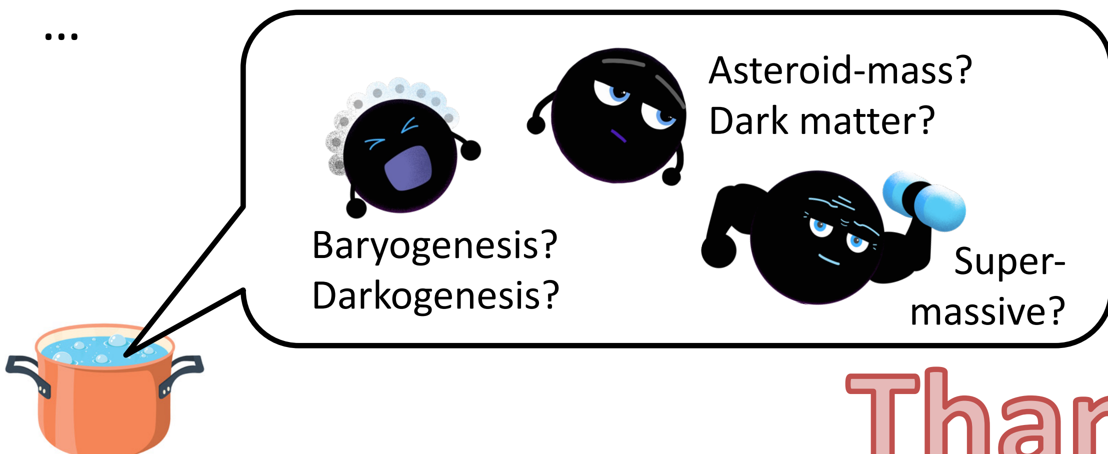
Closing remarks

Slow FOPTs favor potentials with zero-temperature barriers

1. PBH abundance depends sensitively on barrier height
2. The breakdown of $\Gamma \propto e^{\beta t}$ approximation

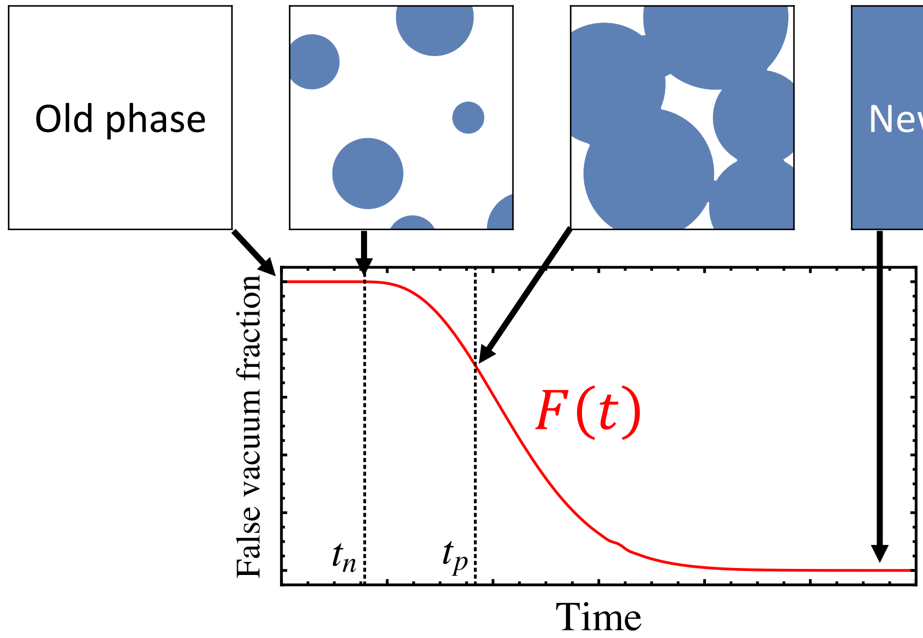
$m_{\rm pbh} \propto T_*^{-2}$: Landscape of FOPTs ⇒ **Landscape of PBHs**

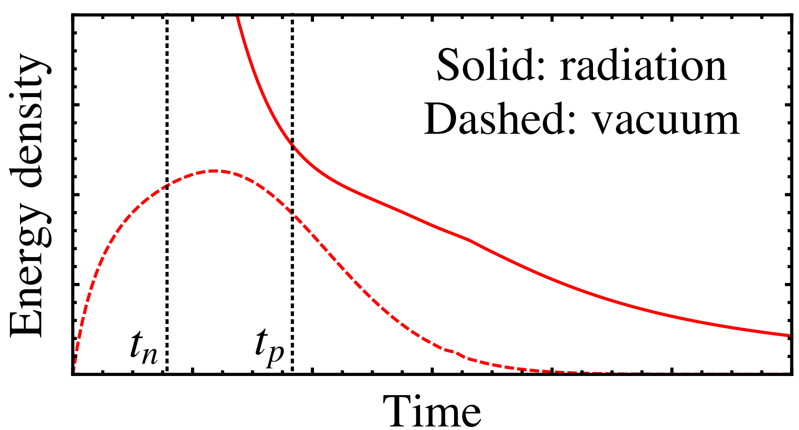
- GUT -- $T_* \sim 10^{15}$ GeV ⇒ $m_{\rm pbh} \sim 10$ g
- Seesaw & $U(1)_{B-L}$ -- $T_* \sim 10^{12}$ GeV ⇒ $m_{\rm pbh} \sim 10^7$ g
- EW $SU(2)_L \times U(1)_Y$ -- $T_* \sim 10^2$ GeV [Higgs] ⇒ $m_{\rm pbh} \sim 10^{27}$ g
- Dark $U(1)_X$ -- $T_* \sim$ MeV [NANOGrav?] ⇒ $m_{\rm pbh} \sim 10^{37}$ g
- …



Thank you!

Backup: energy transition during FOPTs





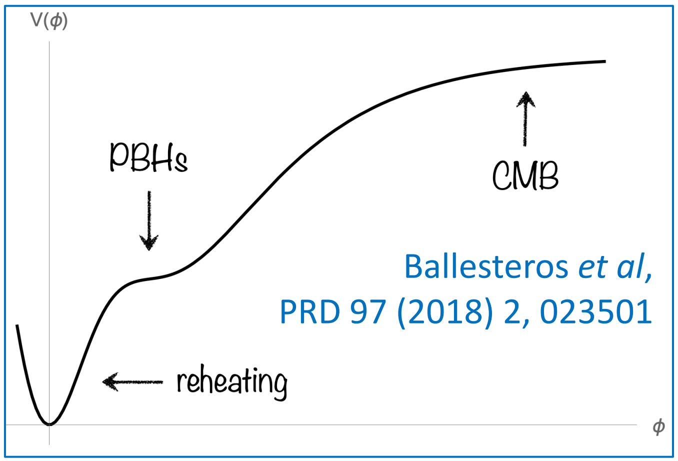
Radiation energy $\rho_r = \frac{\pi^2}{30} g_* T^4$

Vacuum energy $\rho_v = \Delta V \cdot F$

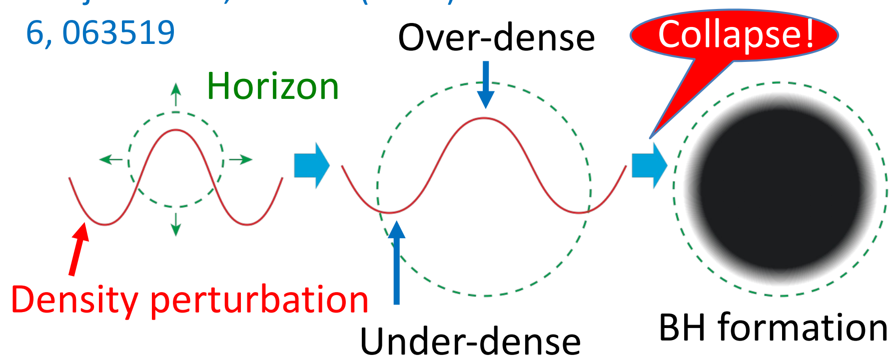
$$\frac{\mathrm{d}\rho_r}{\mathrm{d}t} + 4H\rho_r = -\frac{\mathrm{d}\rho_v}{\mathrm{d}t}$$

Backup: other PBH scenarios

The "conventional" scenario:
Inflationary fluctuation [Carr & Hawking, MNRAS 168 (1974) 399–415]



Kitajima *et al*, PRD 87 (2013) 6, 063519



Other scenarios:

1. Collapse from inhomogeneities during radiation-dominated era
2. Critical collapse
3. Collapse from single-field inflation
4. Collapse from multi-field inflation
5. Collapse from inhomogeneities during matter-dominated era
6. Collapse of cosmic string loops
7. Collapse from bubble collisions
8. Collapse of scalar field
9. Collapse of domain walls

Carr *et al*, Rept.Prog.Phys. 84 (2021) 11, 116902

Backup: PBHs from density perturbation

Carr *et al*, Mon. Not. Roy. Astron. Soc. 168, 399 (1974)

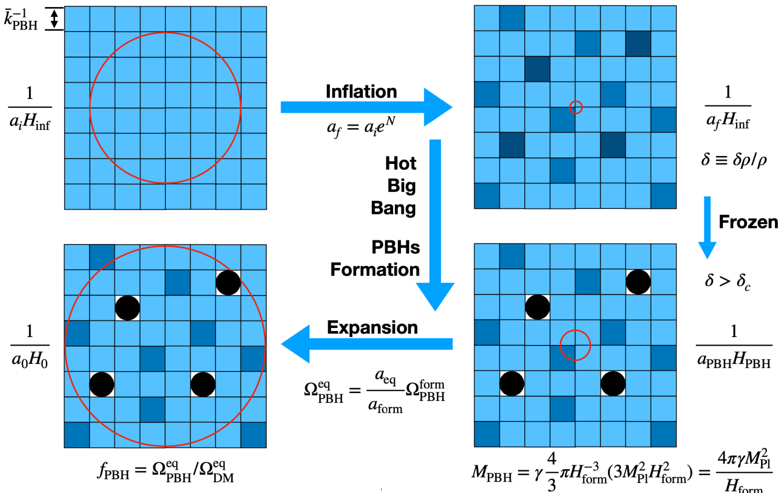


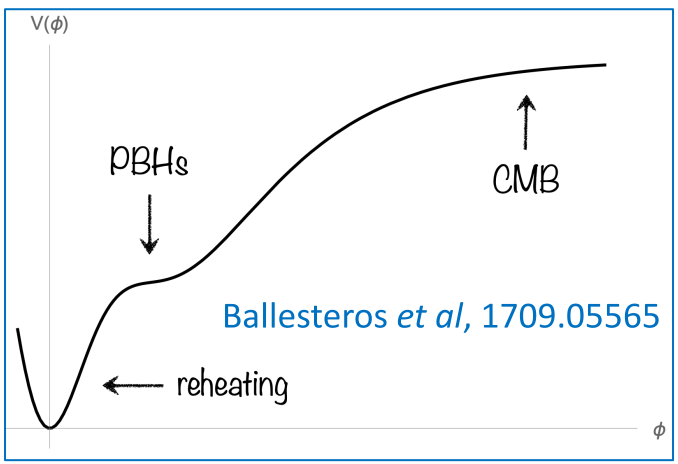
Figure from talk of Shao-Jiang Wang

The curvature perturbation power spectrum

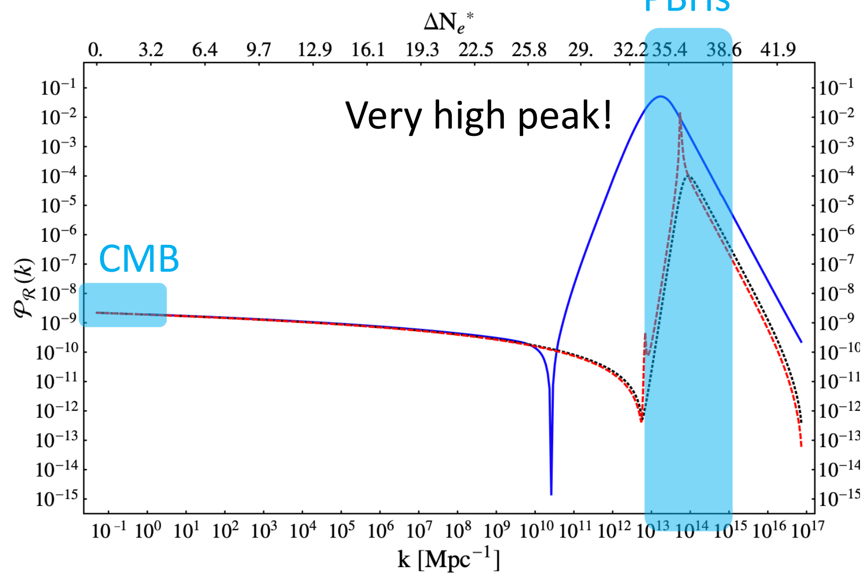
$$P_\zeta(k) \approx \frac{A}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{\log^2(k/k_p)}{2\sigma^2}\right)$$

PBH mass peak

$$M_{\rm PBH}^{\rm peak} \sim 10^{15}\ {\rm g} \times \left(\frac{k_p}{10^{15}\ {\rm Mpc}^{-1}}\right)^{-2}$$



Ballesteros *et al*, 1709.05565

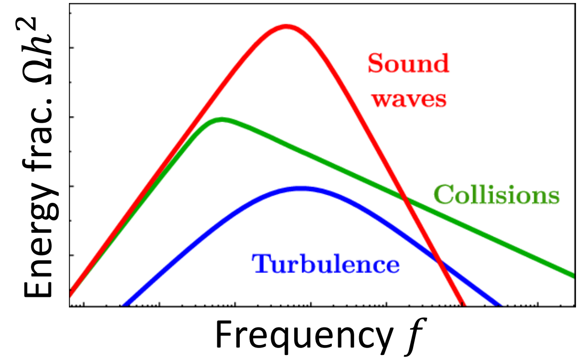


Backup: FOPT GWs

Stochastic gravitational wave signals [Caprini *et al*, JCAP 1604 (2016) 001]

1. Bubble collision;
2. Sound waves in plasma;
3. Turbulence in plasma.

- $f_{\rm peak} \sim 10^{-9}\,{\rm Hz} \times \left(\frac{1}{v_w}\right)\left(\frac{\beta/H_*}{10}\right)\left(\frac{T_*}{\rm MeV}\right)$



Landscape of GWs from FOPTs