北京航空航天大學
BEIHANG UNIVERSITY

Reviving primordial black hole formation in slow first-order phase transitions

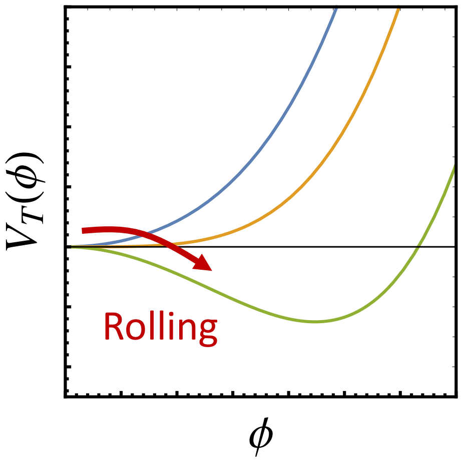
Ke-Pan Xie

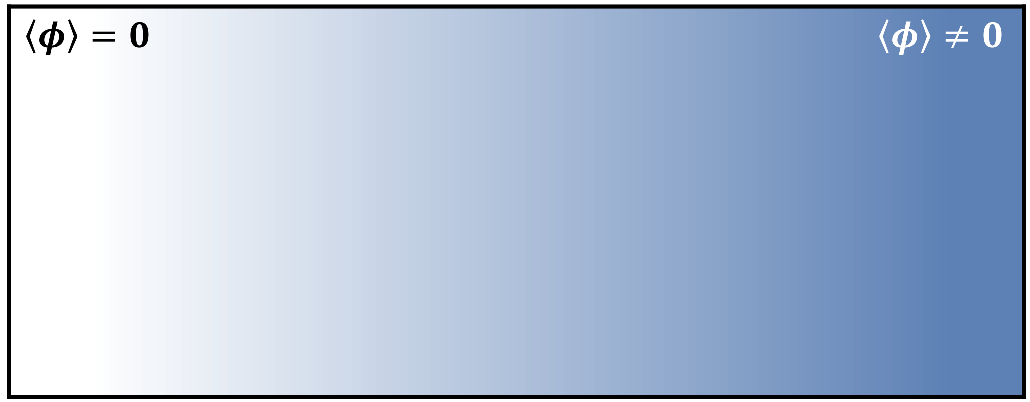
Beihang University

2026.7.20, The Phenomenology of Primordial Black Holes, Mainz, Germany

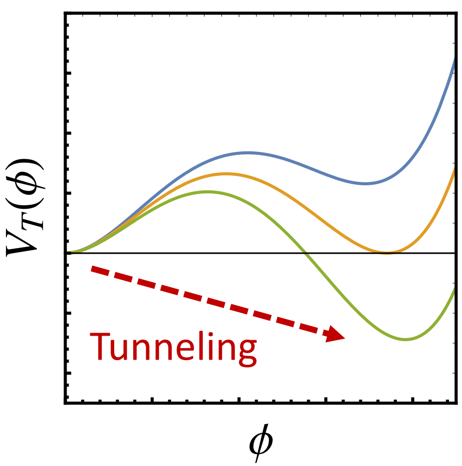
With Wen-Yuan Ai, arXiv: 2605.11332

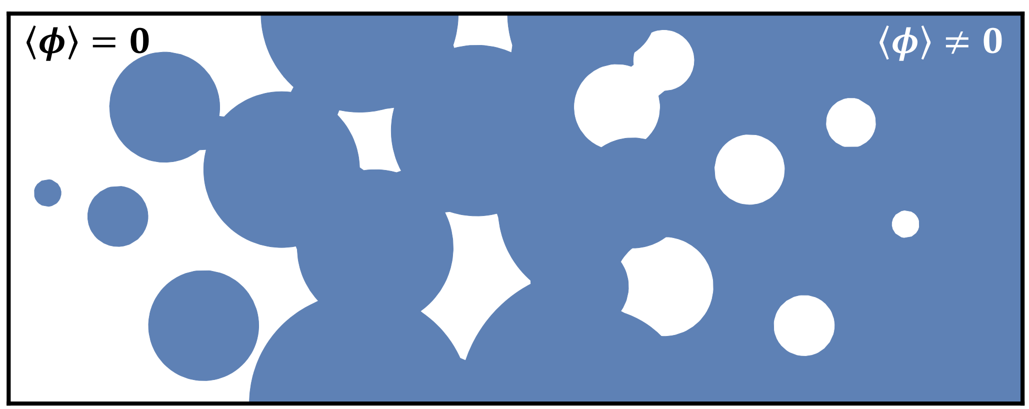
Patterns of symmetry breaking





Second-order phase transition / Crossover

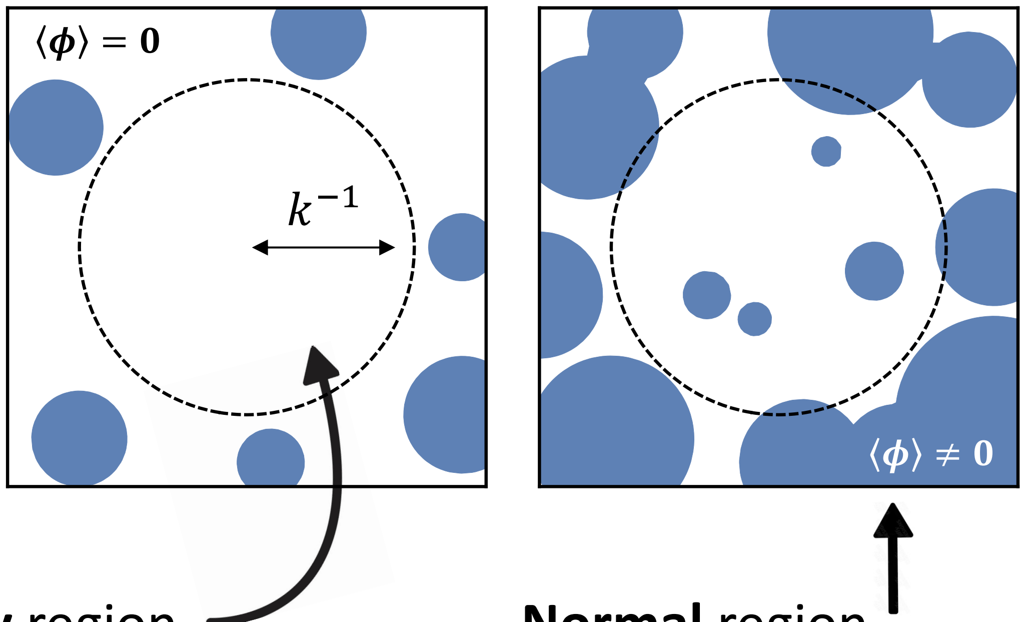




First-order phase transition (FOPT)

Generation of overdensities

Randomness of bubble nucleation

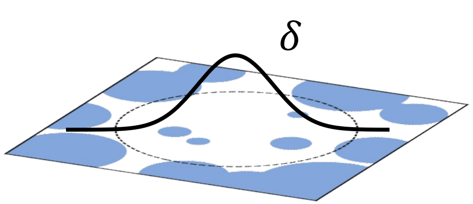


Delayed-decay region
More vacuum energy, $\rho_V \propto a^0$

Normal region
More radiation energy, $\rho_r \propto a^{-4}$

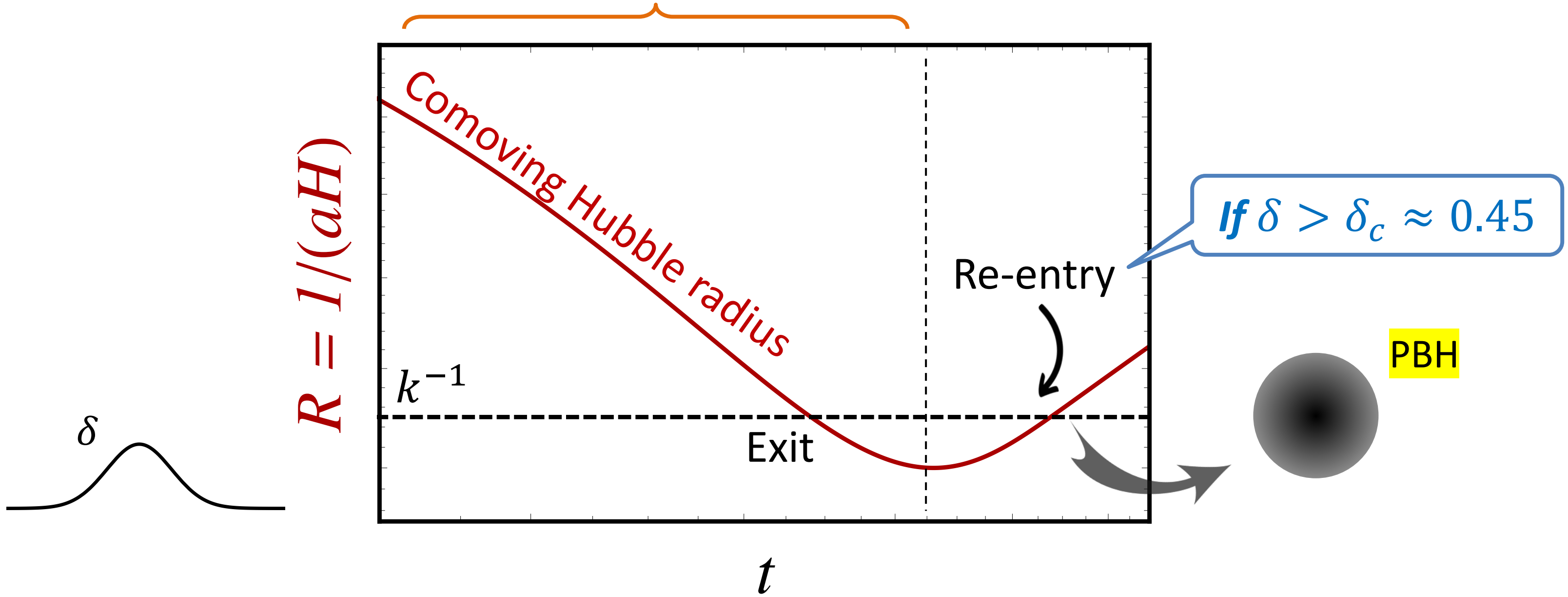
Energy density contrast

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}} > 0$$



Black hole formation

Supercooling: temporary vacuum domination before FOPT



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

Recent **big progress** in Liu *et al*, Phys.Rev.D 105 (2022) 2, L021303

A popular mechanism since 2022

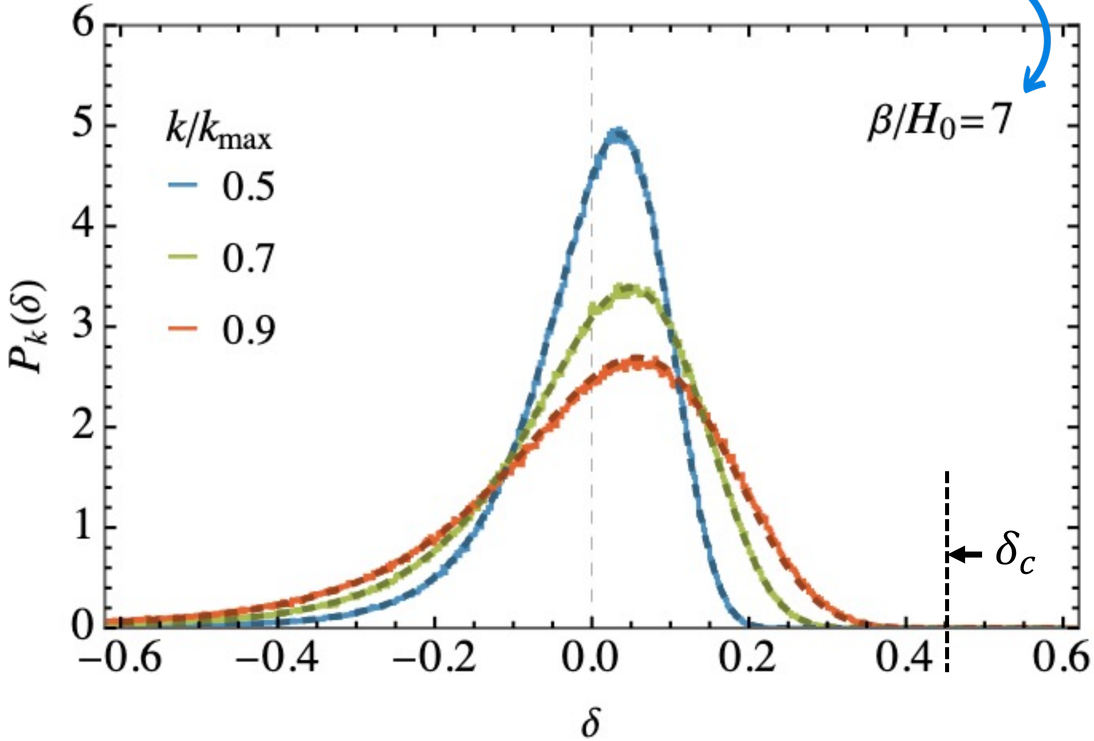
Hashino *et al*, PLB 838 (2023) 137688; Lewicki *et al*, JHEP 09 (2023) 092; He *et al*, SCPMA 67 (2024) 4, 240411; Cai *et al*, SCPMA 67 (2024) 9, 290411; Flores *et al*, PRD 110 (2024) 1, 015005; Kanemura, Tanaka, **KPX**, JHEP 06 (2024) 036; Kawana *et al*, PRD 108 (2023) 103531; Gouttenoire *et al*, PRD 110 (2024) 4, 4; Banerjee *et al*, JCAP 07 (2025) 007; Huang *et al*, PRD 113 (2026) 5, 055013; etc

Calculation framework

Bubble nucleation history simulation Lewicki *et al*, Phys.Rev.Lett. 133 (2024) 22, 221003

- Probability distribution of δ (non-Gaussian)

(Hubble time)/(Transition duration)



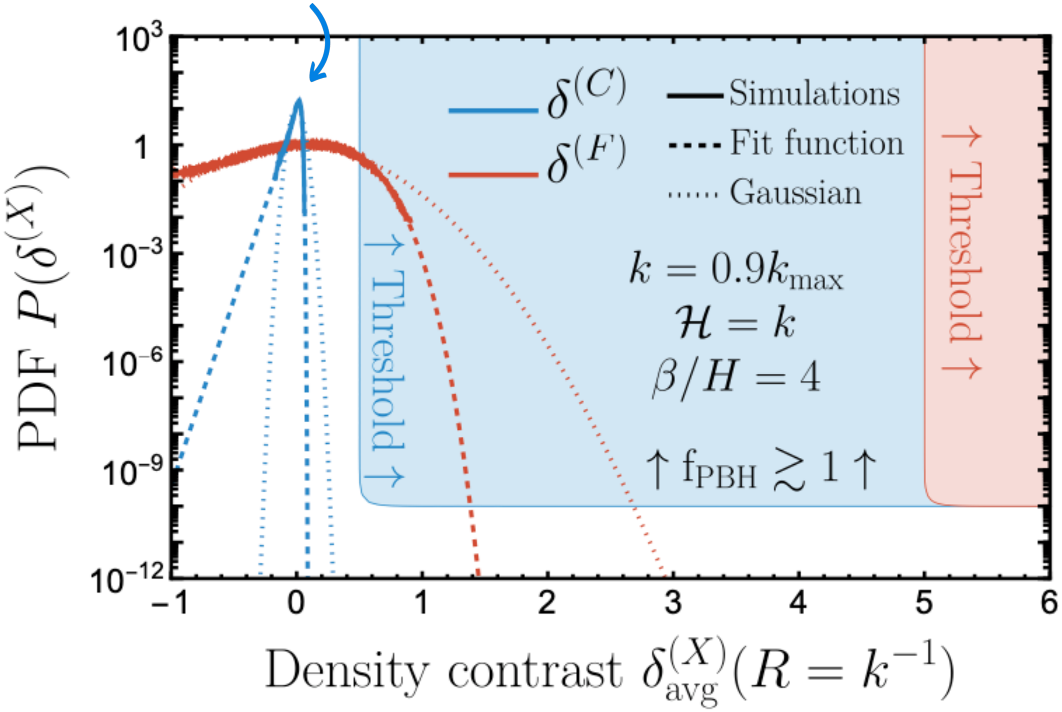
- PBH abundance obtained by integrating $P_k(\delta)$ over $\delta > \delta_c$

Slow transitions with $\beta/H_n \lesssim 10$ lead to abundant PBH formation

Debates

δ depends on coordinate choice Franciolini *et al*, Phys.Rev.Lett. 136 (2026) 17, 171404

- Bubble simulation → *flat-gauge* value $\delta^{(F)}$
- PBH threshold → *comoving-gauge* value $\delta^{(C)} \gtrsim 0.45$
- $\delta^{(C)}$ **too small** to form PBHs!



Similar result obtained independently in Wang *et al*, Phys.Rev.D 113 (2026) 12, 123026

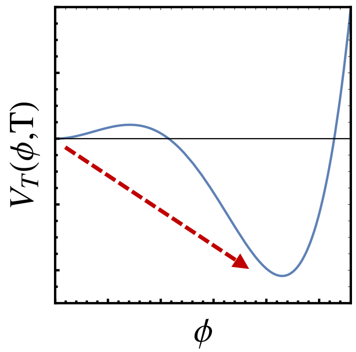
Conclusion: **this mechanism is ruled out** *???*

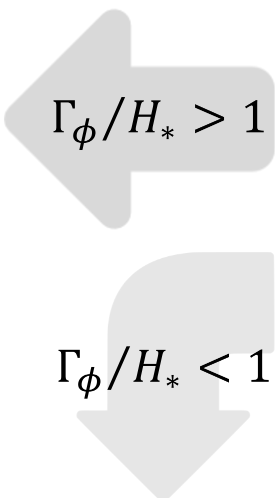
Our insight

A *new* gauge-invariant approach to calculate $\delta^{(C)}$ [this work]

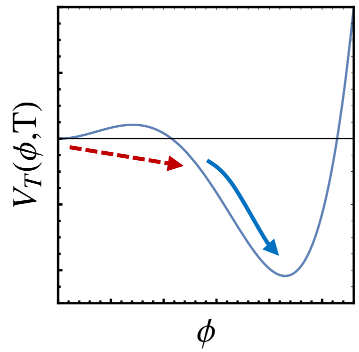
- Confirming $\delta^{(C)} \ll \delta_c \approx 0.45$
- But this does **not** preclude the formation of PBHs

Fast reheating





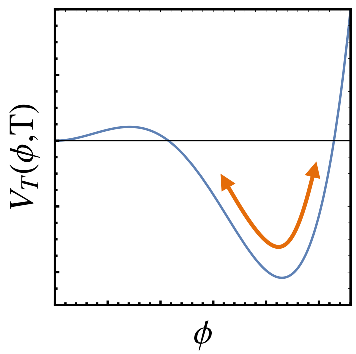
More accurately



Key variable:

$\dfrac{\Gamma_\phi}{H_*}$ — Γ_ϕ Decay width; H_* Hubble at transition

Slow reheating



- ϕ coherently oscillates, decaying to SM particles, reheating the Universe
- **Early matter era** with $\rho_\phi \propto a^{-3}$, pressure ≈ 0
- Small $\delta^{(C)}$ grows and collapses, **forming PBHs** ✓

A unified treatment

	Condition	Energy transfer
Fast reheating	$\Gamma_\phi/H_* > 1$	Vacuum $\rightarrow$ Radiation
Slow reheating	$\Gamma_\phi/H_* < 1$	Vacuum $\rightarrow$ ϕ oscillation $\rightarrow$ Radiation

$\underbrace{\text{Vacuum} \rightarrow \phi \text{ oscillation}}_{\text{Generation of } \delta}$

Two-fluid system

1. Vacuum, $P_V = -\rho_V$
2. Species f with $P_f = w_f \rho_f$

$$\begin{cases} \text{Fast reheating} \rightarrow f = r\ (w_r = 1/3) \\ \text{Slow reheating} \rightarrow f = \phi\ (w_\phi = 0) \end{cases}$$

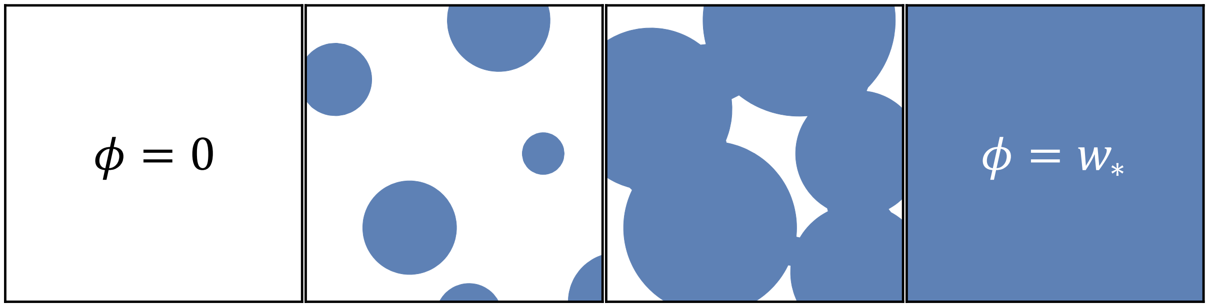
Relativistic perturbation theory

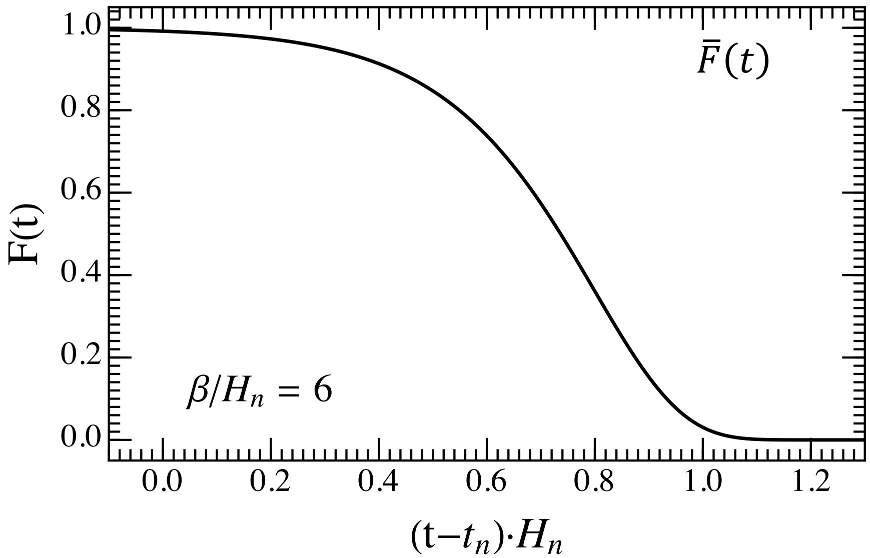
$$\rho(t, \mathbf{k}) = \bar{\rho}(t) + \delta\rho(t, \mathbf{k}); \qquad \delta = \frac{\delta\rho}{\bar{\rho}} = \frac{\delta\rho_V + \delta\rho_f}{\bar{\rho}_V + \bar{\rho}_f}$$

- FOPT yields $\delta\rho_V$ $\rightarrow$ sourcing δ $\rightarrow$ PBH formation

Vacuum energy

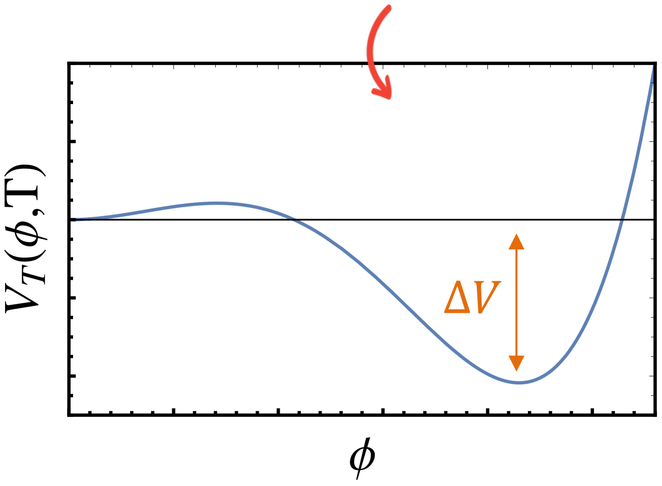
False vacuum volume fraction: the whole Universe





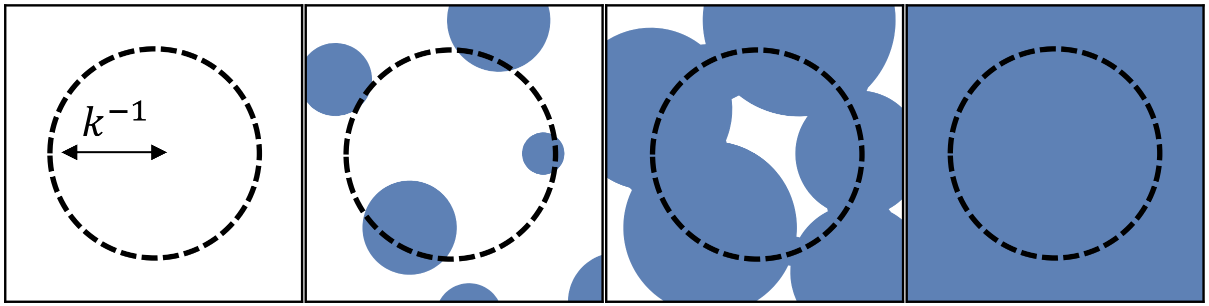
Background vacuum energy

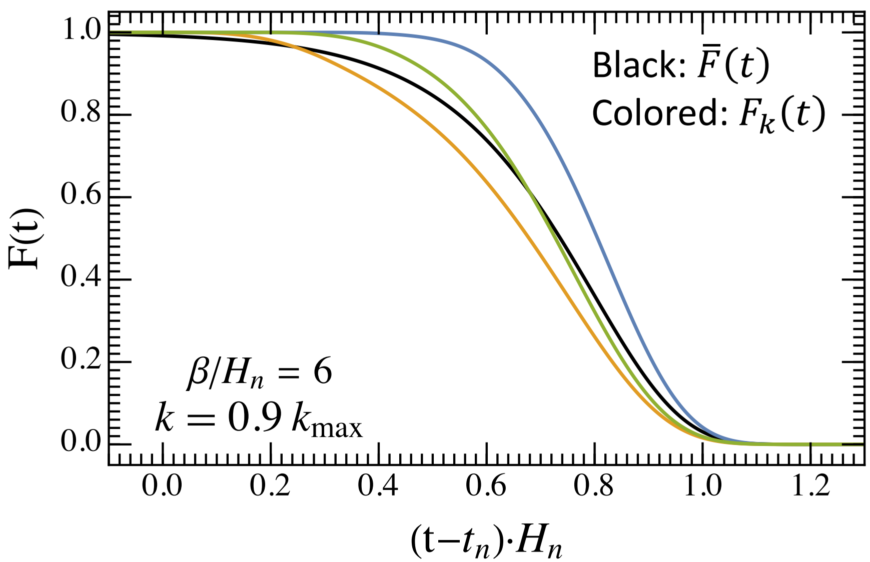
$$\bar{\rho}_V(t) = \Delta V \cdot \bar{F}(t)$$



Vacuum energy perturbation

False vacuum volume fraction: a finite sphere

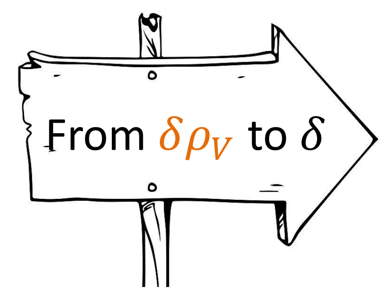




Comoving volume $4\pi k^{-3}/3$

$$\rho_V(t) = \Delta V \cdot F_k(t)$$

Obtained from **bubble nucleation simulation**



Fluctuation $\delta\rho_V = \rho_V - \bar{\rho}_V = \Delta V \cdot \left(F_k(t) - \bar{F}(t)\right)$

Perturbation theory (1)

Textbook: **gauge-invariant** equations

$$\dot{\Delta} - 3H\frac{\bar{P}}{\bar{\rho}}\dot{\Delta} = \left(1 + \frac{\bar{P}}{\bar{\rho}}\right)\frac{k^2\mathcal{V}}{a}; \quad \dot{\mathcal{V}} + H\mathcal{V} = -\frac{1}{a(\bar{\rho} + \bar{P})}\left(\delta P_{\rm nad} + \frac{\dot{\bar{P}}}{\dot{\bar{\rho}}}\bar{\rho}\Delta\right) - \frac{\Phi}{a}$$

Density contrast

$$\Delta = \delta + \frac{a\dot{\bar{\rho}}(v + B)}{\bar{\rho}}$$

Velocity potential

$$\mathcal{V} = v + a\dot{E}$$

with $\mathbf{v} = \nabla v$

Non-adiabatic pressure perturbation

$$\delta P_{\rm nad} = \delta P - \frac{\dot{\bar{P}}}{\dot{\bar{\rho}}}\delta\rho$$

Perturbation theory (2)

Textbook: **gauge-invariant** equations

$$\dot{\Delta} - 3H\frac{\bar{P}}{\bar{\rho}}\dot{\Delta} = \left(1 + \frac{\bar{P}}{\bar{\rho}}\right)\frac{k^2\mathcal{V}}{a}; \quad \dot{\mathcal{V}} + H\mathcal{V} = -\frac{1}{a(\bar{\rho}+\bar{P})}\left(\delta P_{\rm nad} + \frac{\dot{\bar{P}}}{\dot{\bar{\rho}}}\bar{\rho}\Delta\right) - \frac{\Phi}{a}$$

Our work: <u>two-fluid system</u>

- Evaluating $\delta P_{\rm nad}$ in **flat gauge**

$$\dot{Q} + (4+3w_f)HQ = \frac{1+w_f}{a}\delta\rho_V - \left[\frac{w_f}{a}\bar{\rho} + \frac{aH}{2k^2}\left(\dot{\bar{\rho}} - 3(1+w_f)\dot{\bar{\rho}}_V\right)\right]\Delta$$

Momentum perturbation $Q = (\bar{\rho}+\bar{P})\mathcal{V}$

From bubble simulations

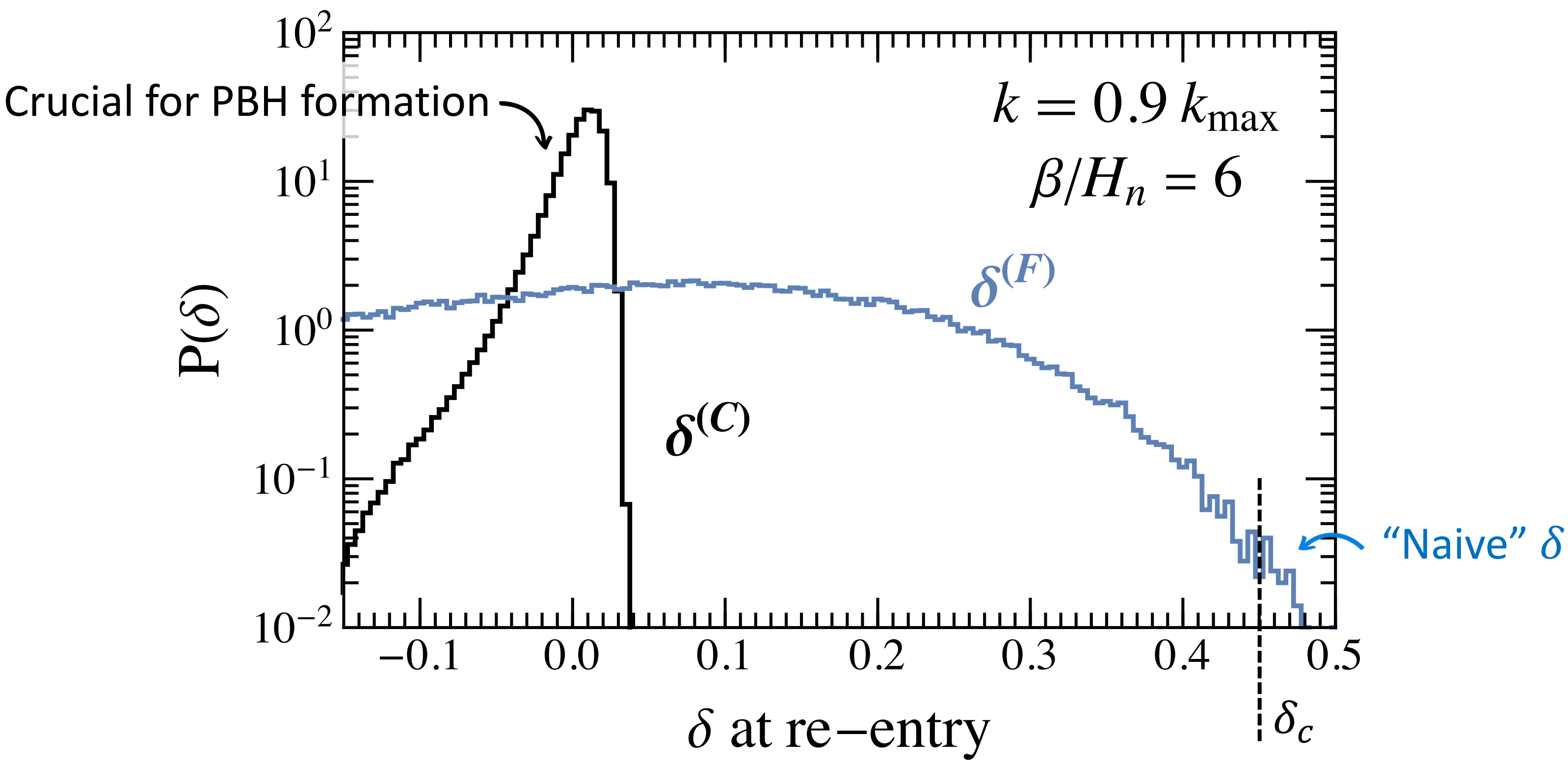
$\Delta \equiv \delta^{(C)}$ [**comoving gauge**] resolved, evolved to horizon re-entry

- Single realization → one $\delta^{(C)}$
- Multiple realizations → probability distribution of $\delta^{(C)}$

Distribution of δ (1)

δ very sensitive to gauge choice

$$\delta^{(C)} \ll \delta^{(F)}$$



Fast reheating:

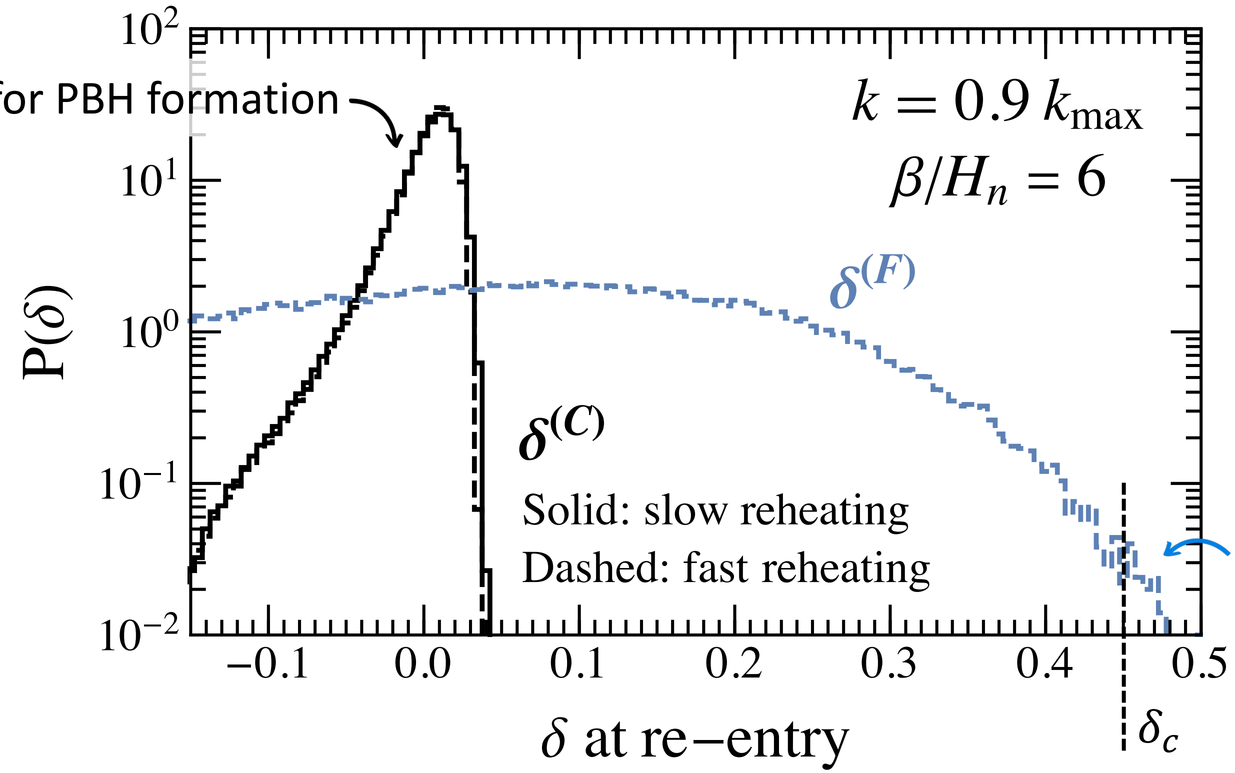
- Consistent with Phys.Rev.Lett. 136 (2026) 17, 171404; Phys.Rev.D 113 (2026) 12, 123026

Distribution of δ (2)

δ not sensitive to the efficiency of post-FOPT reheating

$$\delta^{(C)}(f=r) \approx \delta^{(C)}(f=\phi)$$

Crucial for PBH formation



"Naive" δ

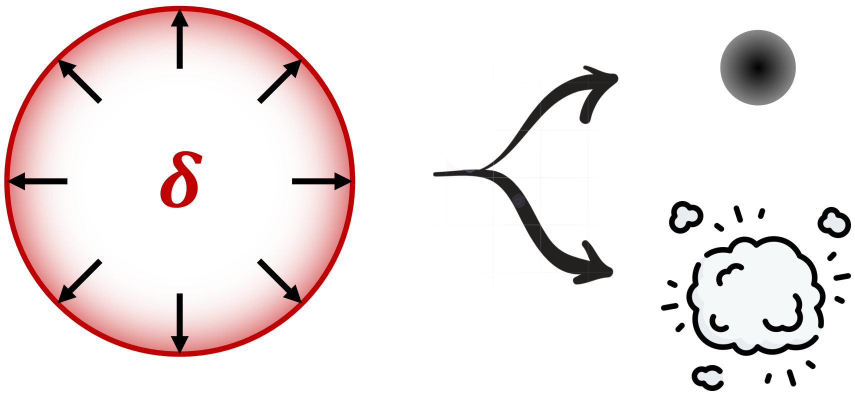
Hereafter, δ solely denotes $\delta^{(C)}$

Slow reheating:

- New in our paper, crucial for PBH formation

Fate of the density contrast

Fast reheating: pressure $P_r = \rho_r/3$ resists collapse



$\delta > \delta_c$: instantaneous collapse

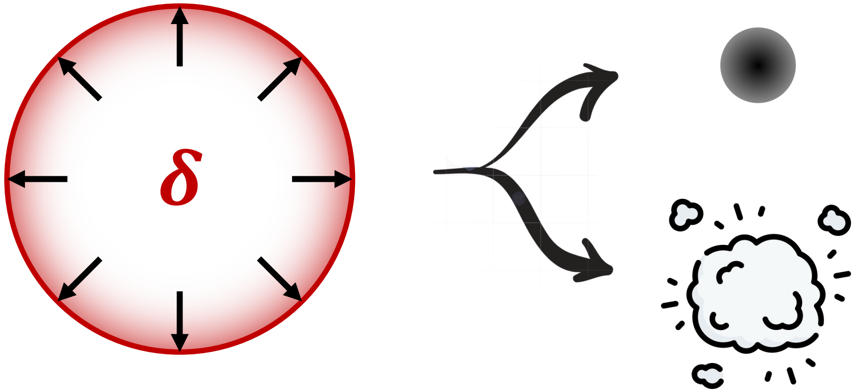
Black hole formation

$\delta < \delta_c$: no collapse

Overdensity dissipates

Fate of the density contrast

Fast reheating: pressure $P_r = \rho_r/3$ resists collapse



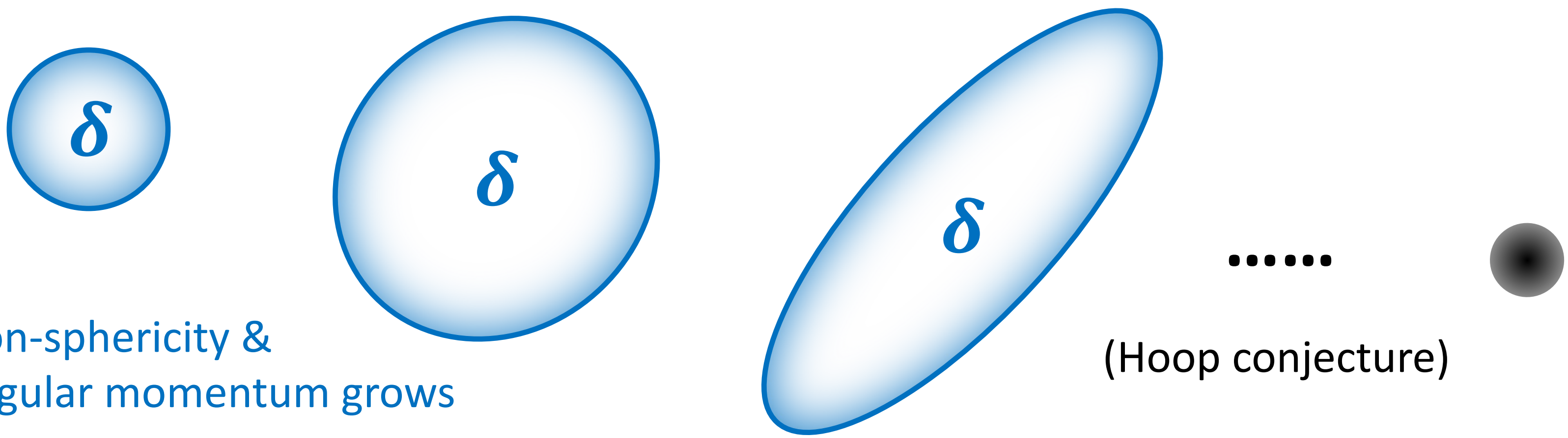
$\delta > \delta_c$: instantaneous collapse

Black hole formation

$\delta < \delta_c$: no collapse

Overdensity dissipates

Slow reheating: $P_\phi \approx 0$, perturbation δ increases with time



"Pancake collapse" at late time, **black hole** formation

PBH formation in the matter era

Perturbation shape describe by the **deformation tensor** $\boldsymbol{\mathcal{D}_{3\times 3}}$

Our crucial assumption

$$P(\mathcal{D}) = P(\delta) \times P_{\widetilde{\mathcal{D}}}\left(\widetilde{\mathcal{D}}_{ij}\right)$$

From our simulation (Non-Gaussian) ⟵ $\delta = -\operatorname{tr}\mathcal{D}$ Trace part

$\widetilde{\mathcal{D}}_{ij} = \mathcal{D}_{ij} + \frac{\delta_{ij}}{3}\delta$ ⟶ Assumed to be Gaussian

Traceless part

(Calling for future detailed simulations!)

We improve Refs. Harada *et al*, Astrophys. J. 833 (2016) no. 1, 61, PRD 96 (2017) no. 8, 083517

PBH formation criterion: $\Gamma_\phi / H_* \lesssim 10^{-3}$ (long matter era)

Probability

$$\beta_k \approx \int_{\delta_{\rm th}}^{\infty} \mathrm{d}\delta \int_{-\infty}^{\infty} \mathrm{d}y \int_{2|y|}^{\infty} \mathrm{d}z \left[P(\delta) \frac{9\sqrt{2}}{\sqrt{\pi}\sigma_3^5} (z^3 - 4zy^2) e^{-(2y^2+3z^2/2)/\sigma_3^2} \right]$$

From hoop conjecture, typically $\delta_{\rm th} \ll 0.45$

PBH profile

Key variables
$$
\begin{cases}
\text{New physics scale } \Lambda_{\rm NP} \approx \Delta V^{1/4} \\
\boldsymbol{\beta/H_n} = (\text{Hubble time})/(\text{Transition duration}) \\
\boldsymbol{\Gamma_\phi/H_*} = (\text{Hubble time})/(\text{Early matter era duration})
\end{cases}
$$

PBH mass & dark matter fraction

No accretion Ballesteros *et al*, JCAP 06 (2020) 014

$$M_{\rm min} \sim 10^{20}\,{\rm g} \times \left(\frac{10^6\,{\rm GeV}}{\Lambda_{\rm NP}}\right)^2$$

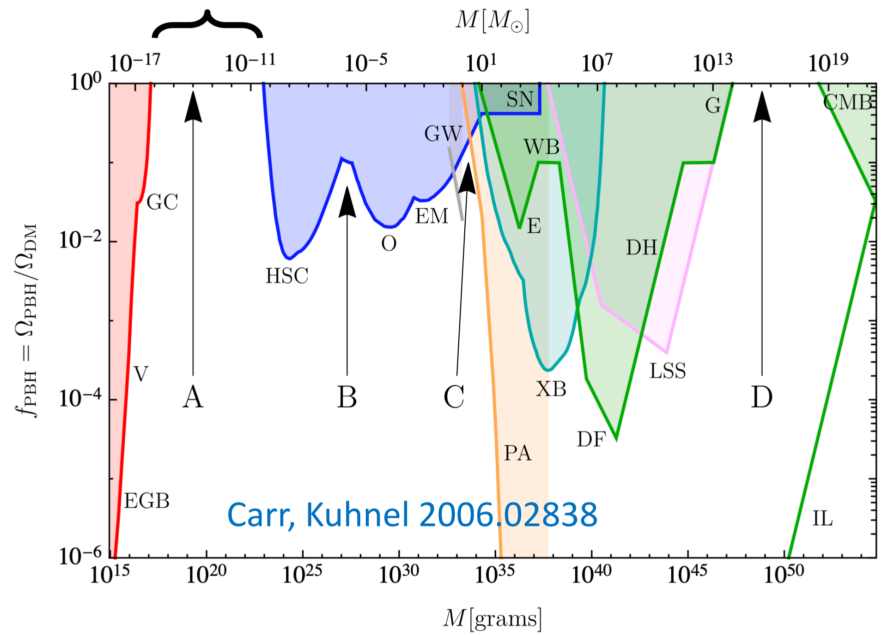
$$f_{\rm min} \sim 10^{0.4\cdot(12-\beta/H_n)} \left(\frac{\Lambda_{\rm NP}}{10^6\,{\rm GeV}}\right) \left(\frac{\Gamma_\phi}{H_*}\right)^{1/2}$$

Maximal accretion de Jong *et al*, JCAP 03 (2022) 03, 029

$$M_{\rm max} \sim 10^{20}\,{\rm g} \times \left(\frac{10^6\,{\rm GeV}}{\Lambda_{\rm NP}}\right)^2 \left(\frac{H_*}{\Gamma_\phi}\right)$$

$$f_{\rm max} \sim 10^{0.4\cdot(12-\beta/H_n)} \left(\frac{\Lambda_{\rm NP}}{10^6\,{\rm GeV}}\right) \left(\frac{H_*}{\Gamma_\phi}\right)^{1/2}$$

Asteroid-mass (10^{20} g $-$ 10^{22} g), allowing for 100% **dark matter**



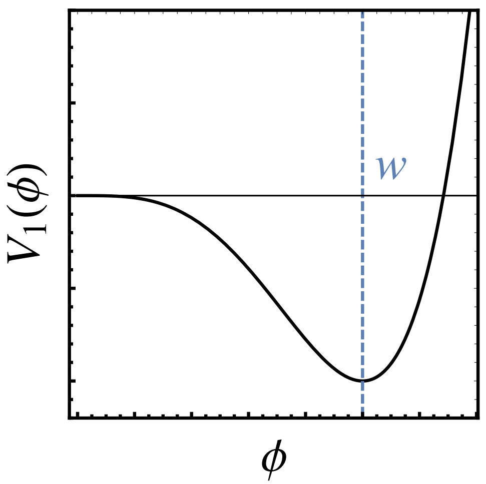
Model-building guide

Supercooled and slow FOPT

- Classically conformal principle

$$V_1(\phi) = \frac{B}{4}\phi^4\left(\log\frac{\phi}{w} - \frac{1}{4}\right)$$

- Motivated by hierarchy problem Bardeen, FERMILAB-CONF-95-391-T; Meissner *et al*, PLB 660 (2008) 260-266
- Leads to supercooling Iso *et al*, PRL 119, 141301 (2017)



Slow (post-FOPT) reheating

- Suppressed $\phi \to$ SM SM decay

Dark $U(1)_X$ model

Babu *et al*, Phys. Rev. D 57 (1998) 6788–6792

- Scalar Φ, boson X
- Kinetic mixing

$$\mathcal{L} \sim -\frac{\epsilon}{2}X_{\mu\nu}B^{\mu\nu}$$

- $\phi \to X^*X^* \to f\bar{f}f'\bar{f}'$, $\Gamma_\phi \propto g_X^{10}\epsilon^4$

Minimal $U(1)_{B-L}$ model

Iso *et al*, Phys.Lett.B 676 (2009) 81-87

- Scalar Φ, gauge boson Z'
- Higgs mixing

$$\theta \approx \frac{v_{\rm ew}}{w}\frac{m_h^2}{m_h^2 - m_\phi^2} \sim g_{B-L}^2\left(\frac{v_{\rm ew}}{m_\phi}\right)^3$$

- $\Gamma_\phi \propto \theta^2$

Conclusion

This work Ai and **KPX**, arXiv: 2605.11332

- Gauge-invariant derivation of $\delta^{(C)}$ from FOPT without super-horizon approximations
- **PBH formation revived** via slow reheating

Outlook

- Full simulations of $\mathcal{D}_{3\times3}$ & PBH spin distribution
- Gravitational waves from FOPT (with matter-domination imprint) & non-spherical collapse
- Particle phenomenology, e.g., collider, neutrino oscillation, etc

"Problems worthy of attack
prove their worth by fighting back."
— Piet Hein

Thank you!