PBH from EWPT in xSM

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D. Goncalves, A. Kaladharan, **YW; arXiv:** 2406.07622

Introduction

- Electroweak Phase Transition (EWPT)
  - Electroweak symmetry breaking
  - Baryogenesis
  - Dark Matter Production
  - Gravitational Wave Signal

- Primordial Black Hole
  - Test the Evolution in the Early Universe
  - Dark Matter Candidates
  - Microlensing effects

Introduction

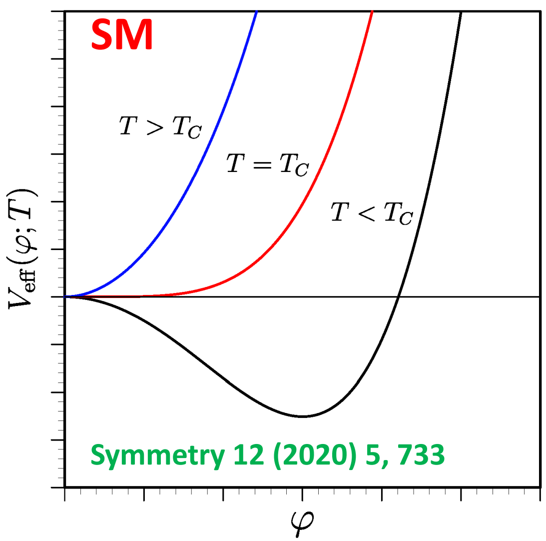
- Formation of PBH during EWPT (1^{st} Order)
  - Bubble Collision
  - Trapped Particles
  - Delayed Vacuum Transition

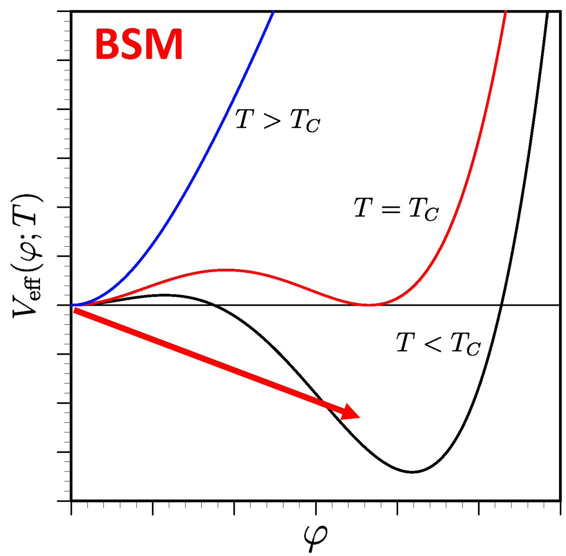
J. Liu, L. Bian, R.-G. Cai, Z.-K. Guo, S.-J. Wang; Phys. Rev. D 105 (2022) L021303

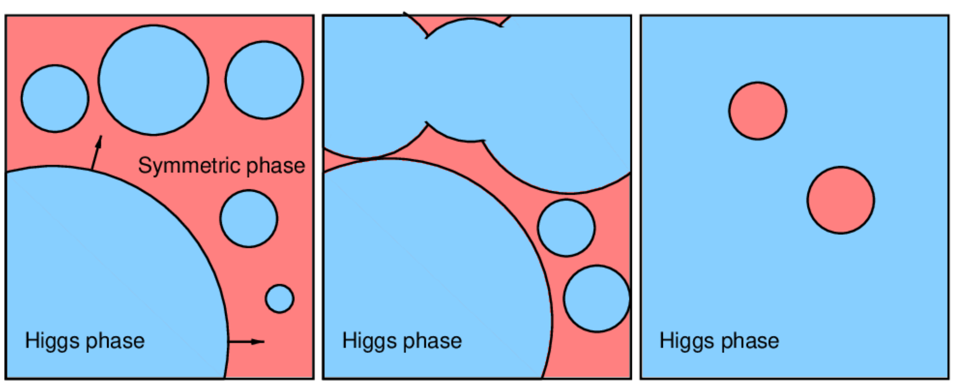
- Implications on BSM
  - Cubic couplings
  - GW vs. Microlensing vs. Collider Searches

EWPT and PBH

- First-order EWPT







Nucleation Rate:

$$\Gamma(T) \approx T^4 \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} e^{-\frac{S_3}{T}}$$

False Vacuum Fraction:

$$F(t) = \begin{cases} 1, & t < t_0 \\ e^{-I(t)}, & t \geq t_0 \end{cases}$$

$$I(t) = \frac{4\pi}{3} \int_{t_0}^{t} dt' \Gamma(t') a^3(t') r^3(t, t')$$

EWPT and PBH

- Randomness – Some patch nucleate late
  - Late Patch
    - Higher False Vacuum Fraction

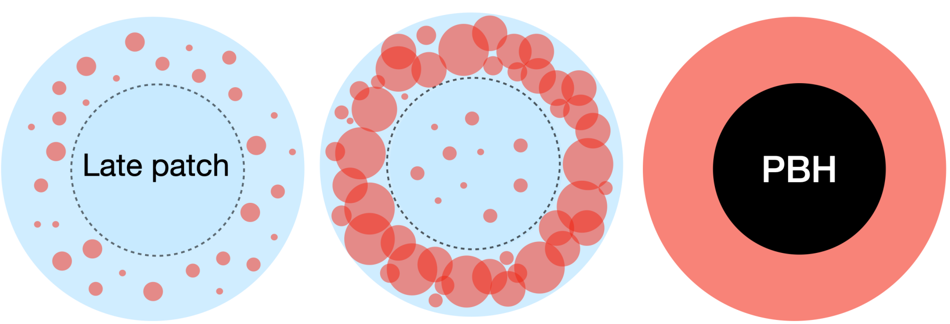
$$\rho_V \sim a^0 \qquad \rho_R \sim a^{-4}$$

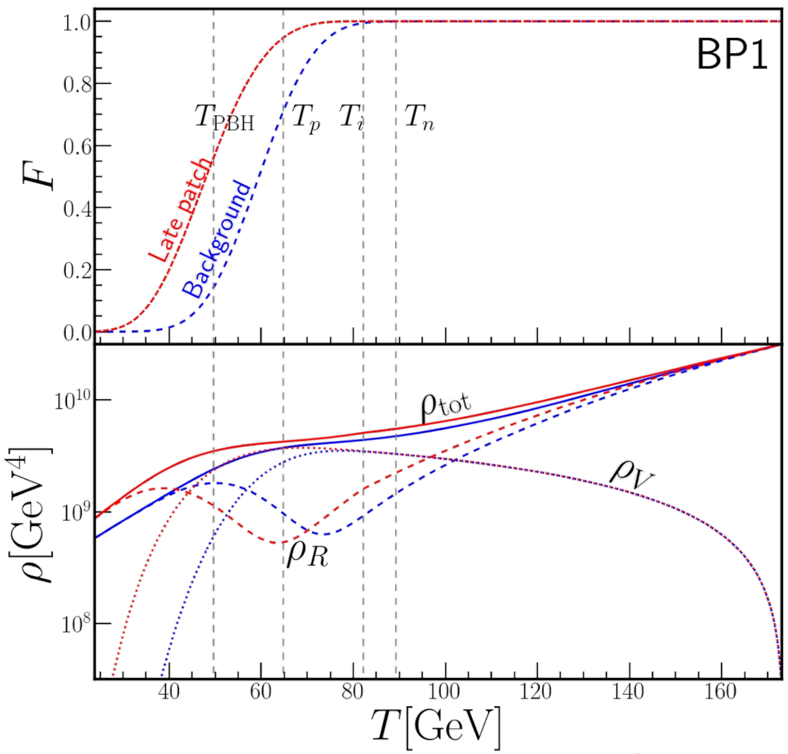
$$\delta = \frac{\rho^{in} - \rho^{out}}{\rho^{out}} \rightarrow \delta_c \approx 0.45$$

- Mass of PBH

$$M_{PBH} \approx \frac{4\pi}{3} H^{-3}(t_{PBH})\rho_c = 4\pi M_P^2 H^{-1}(T_{PBH})$$

$$M_{PBH} \sim 10^{-5} M_\odot$$





EWPT and PBH

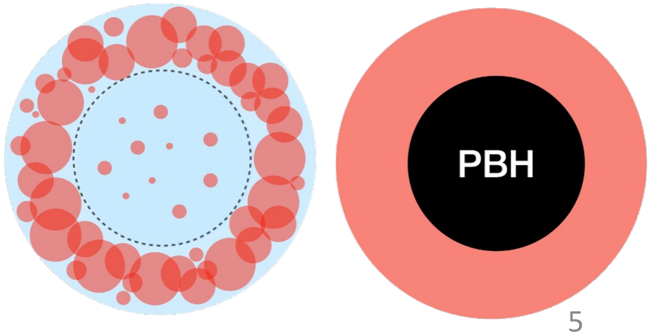
- The Probability to remain in false vacuum

$$P(t_i) = \exp\left[-\int_{t_c}^{t_i} dt'\,\Gamma(t')\,a_{in}^3(t')V_{coll}(t')\right]$$

$$V_{coll}(t') = \frac{4\pi}{3}\left[\frac{1}{a(t_{PBH})H(t_{PBH})} + \int_{t'}^{t_{PBH}} \frac{d\tilde{t}}{a(\tilde{t})}\right]^3$$

- The fraction of PBH in DM density

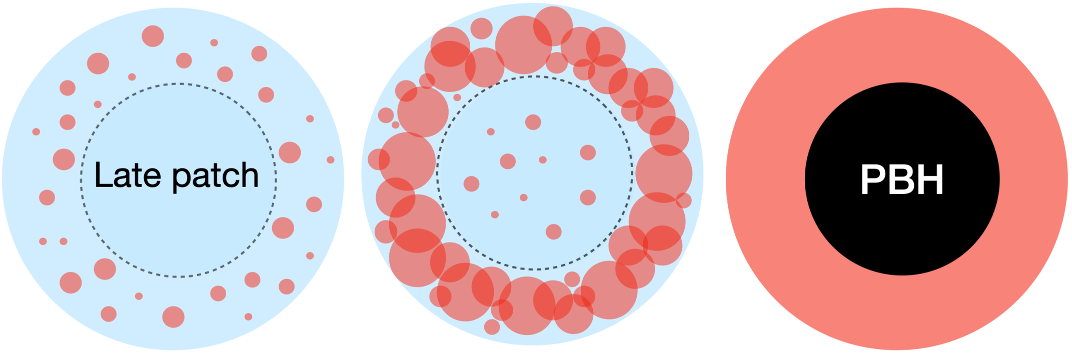
$$f_{PBH} \equiv \frac{\rho_{PBH}}{\rho_{DM}} = \left(\frac{H(t_{PBH})}{H(t_0)}\right)^2 \left(\frac{a(t_{PBH})}{a(t_0)}\right)^3 \frac{P(t_i)}{\Omega_{DM}}$$

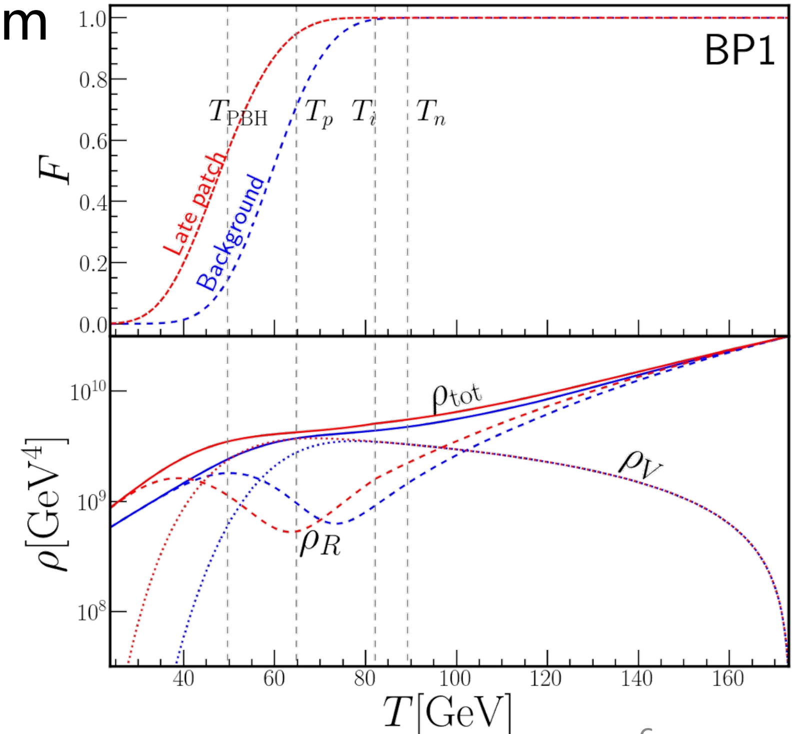


EWPT and PBH

- PBH formation during EWPT
  - Early t_i (Higher T_i),
    - Easier to stay in false vacuum till t_i
    - Harder to reach δ_c
  - Late t_i (Lower T_i)
    - Harder to stay in false vacuum
    - Easier to reach δ_c

$$\Gamma(T) \approx T^4 \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} e^{-\frac{S_3}{T}}$$





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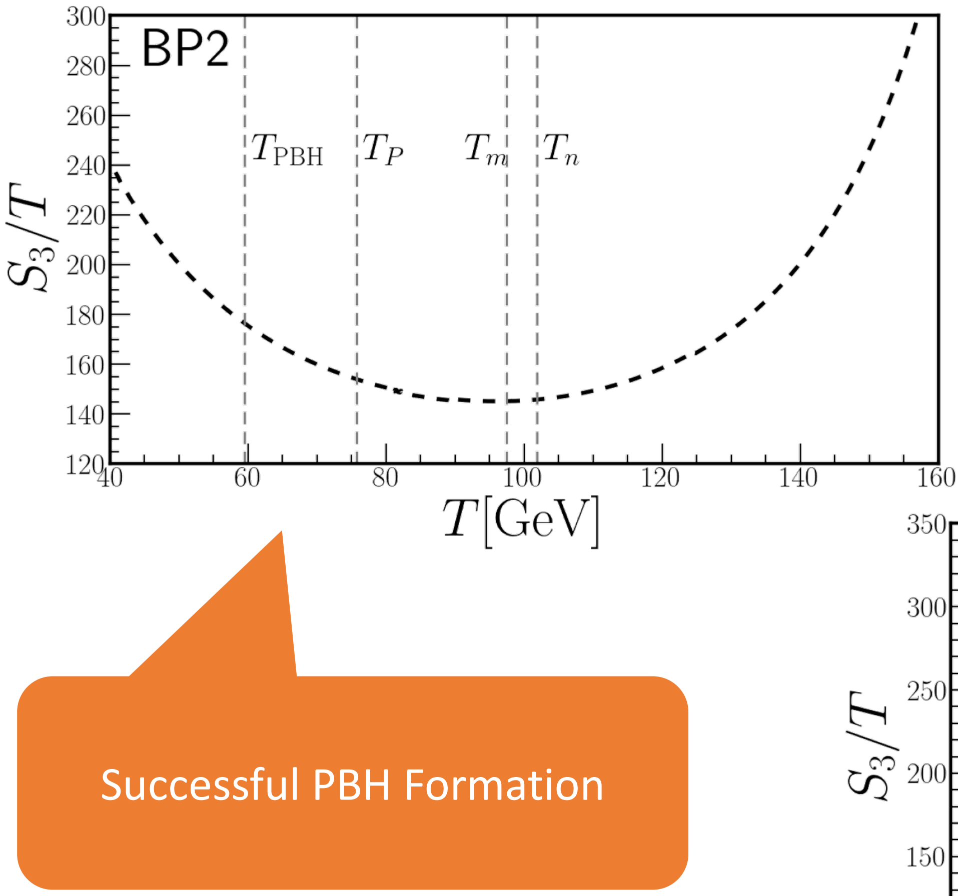
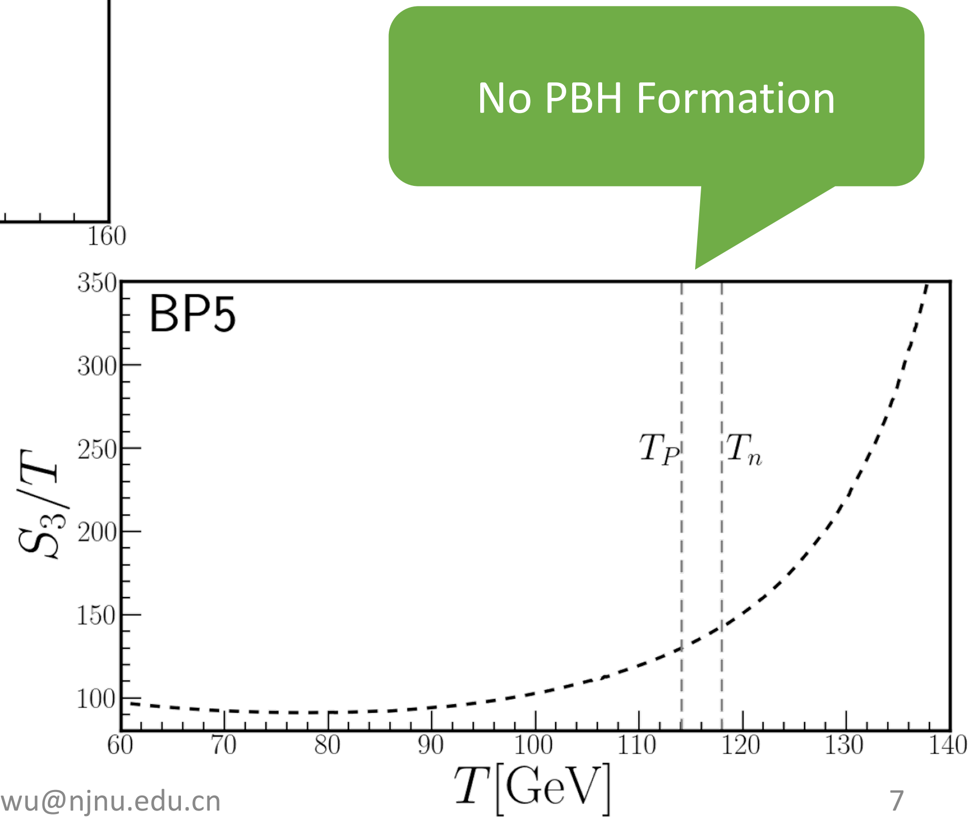
EWPT and PBH

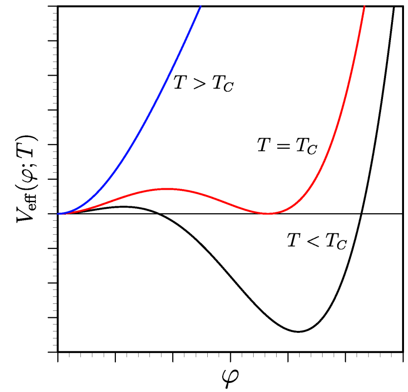
- S_3/T: two cases

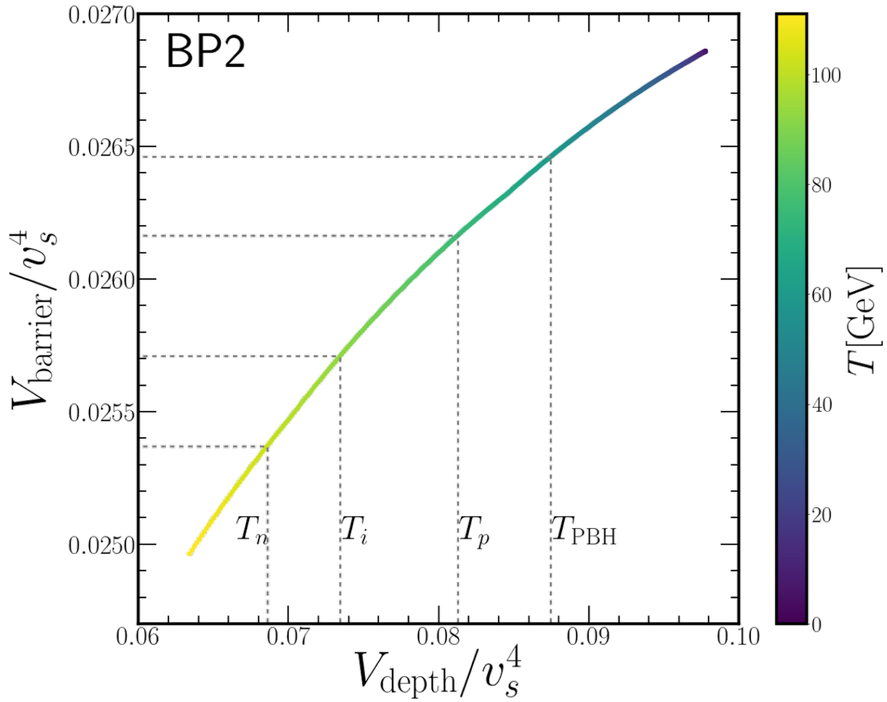


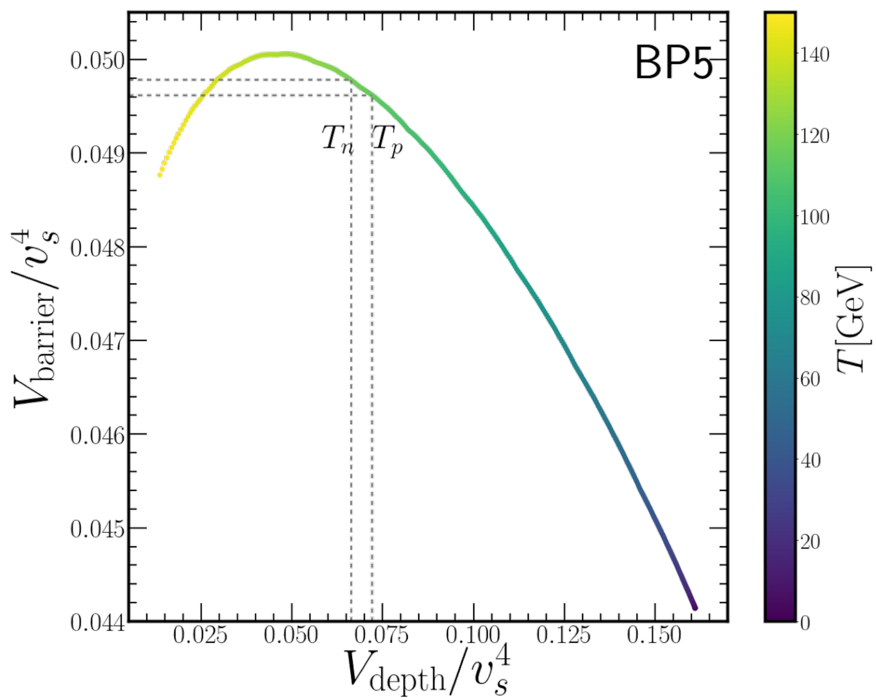


EWPT and PBH

- The potential shape
  - Depth vs Barrier



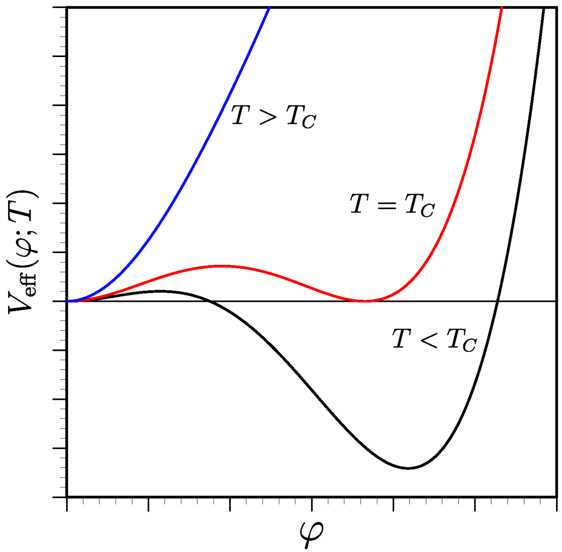




xSM: SM + Singlet

- Simplest SM Extension
  - $H = \begin{pmatrix} G^+ \\ \frac{v_{EW}+h+iG^0}{\sqrt{2}} \end{pmatrix}$ and $S = v_s + s$
- Tree level Potential

$$V = -\mu^2 H^\dagger H + \lambda\left(H^\dagger H\right)^2 + \frac{a_1}{2} H^\dagger H S + \frac{a_2}{2} H^\dagger H S^2 + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$



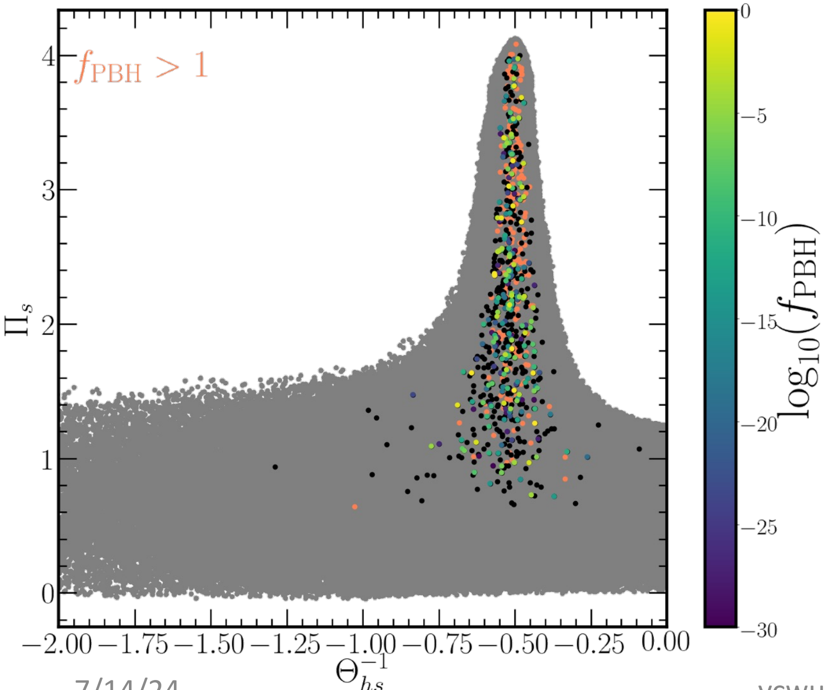
PBH in xSM

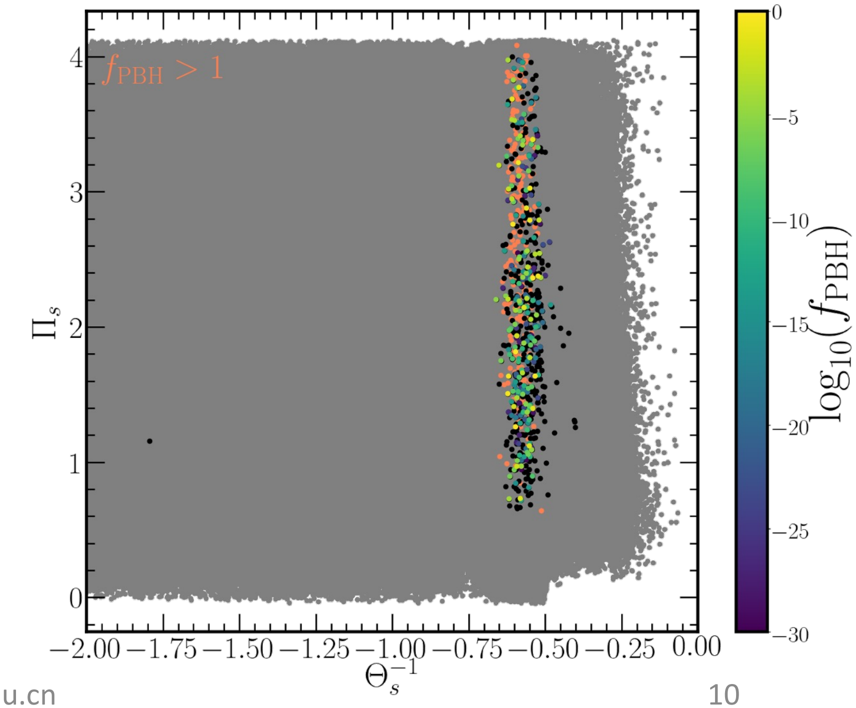
- The potential shape
  - Cubic couplings

$$\frac{a_1}{4} h^2 s + \frac{a_2}{4} h^2 s^2 + \frac{b_3}{3} s^3 + \frac{b_4}{4} s^4$$

$$\Theta_{hs} = \frac{a_1}{a_2 v_s}$$

$$\Theta_s = \frac{4 b_3}{3 b_4 v_s}$$





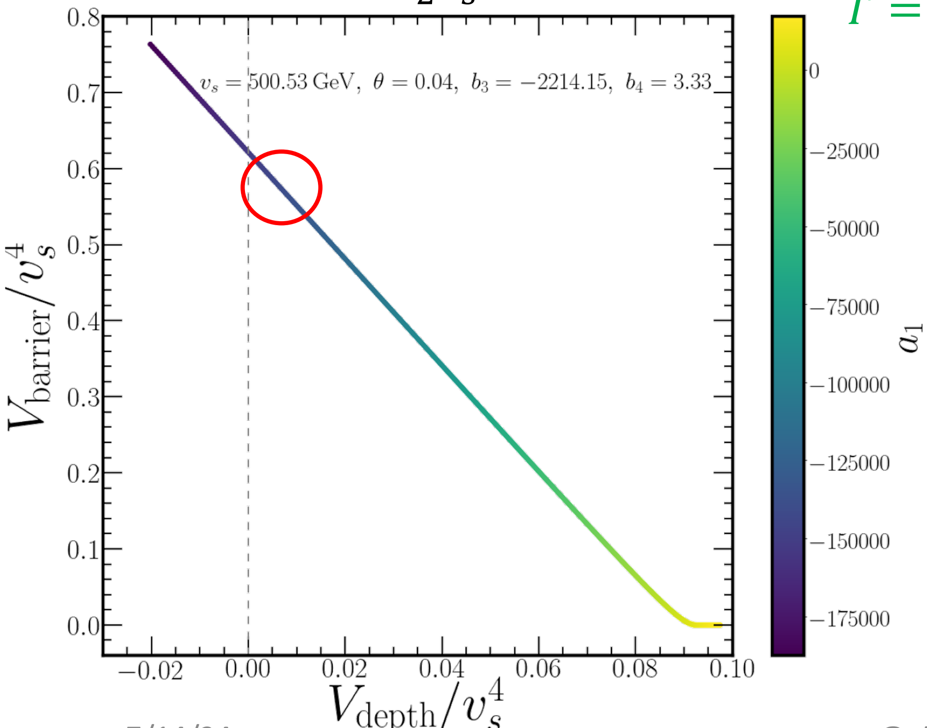
PBH in xSM

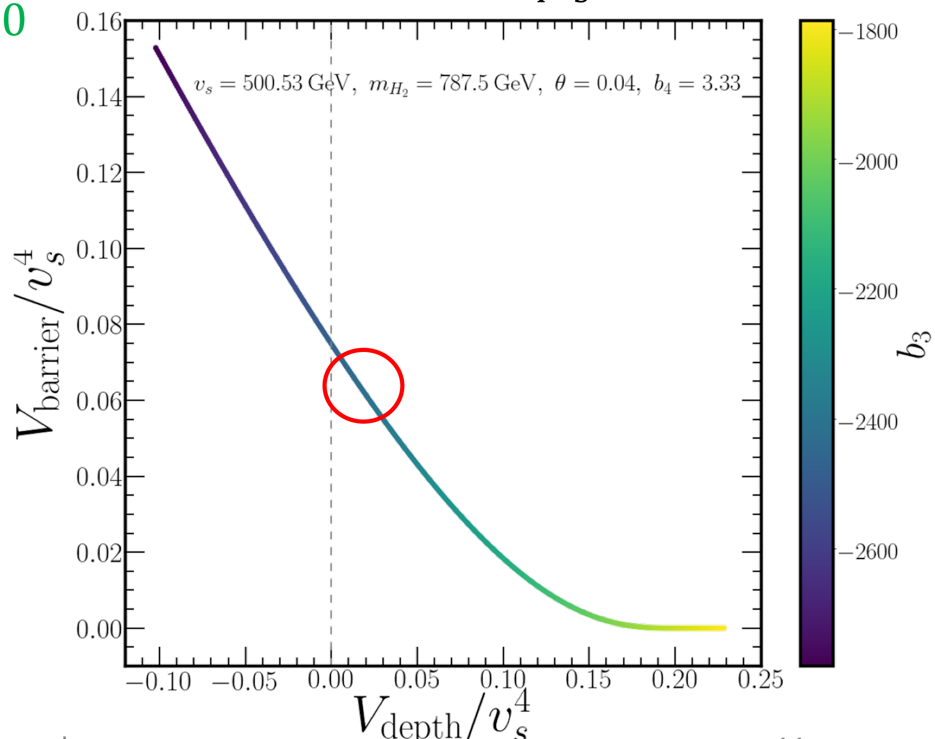
- The potential shape
  - Cubic couplings

$$\frac{a_1}{4}h^2 s + \frac{a_2}{4}h^2 s^2 + \frac{b_3}{3}s^3 + \frac{b_4}{4}s^4$$

$$\Theta_{hs} = \frac{a_1}{a_2 v_s} \qquad \Theta_s = \frac{4b_3}{3b_4 v_s}$$

$T = 0$



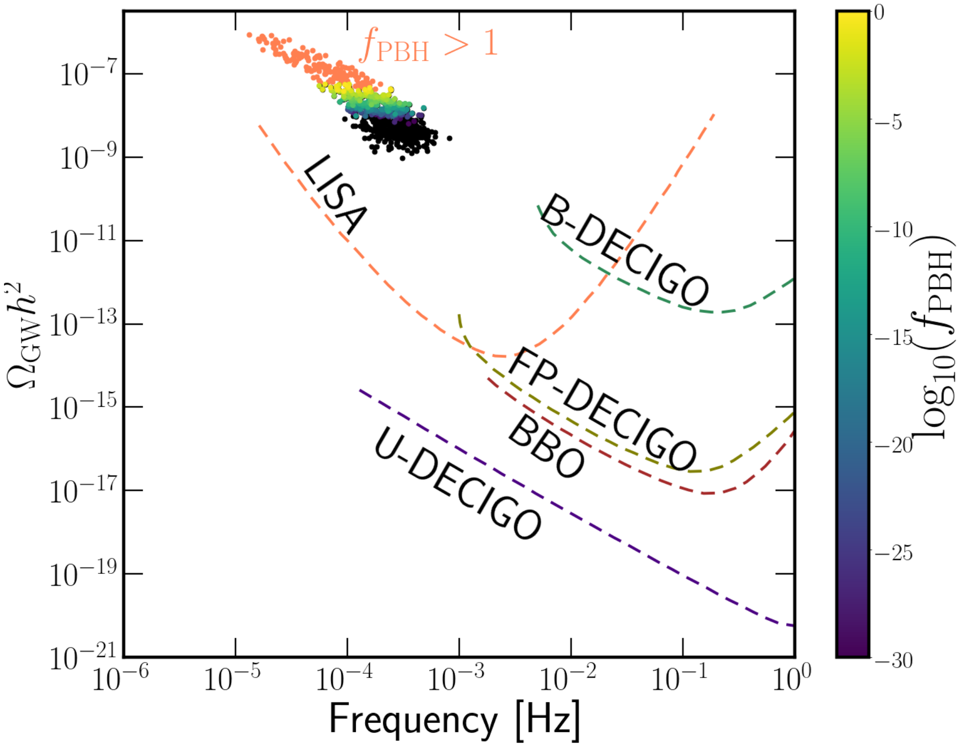


Phenomenology

- Gravitational Waves
- Microlensing for PBH
- Collider search of xSM

Gravitational Waves

- GW from EWPT



PBH formation require supercooling

Larger energy release

Stronger GW signal from EWPT

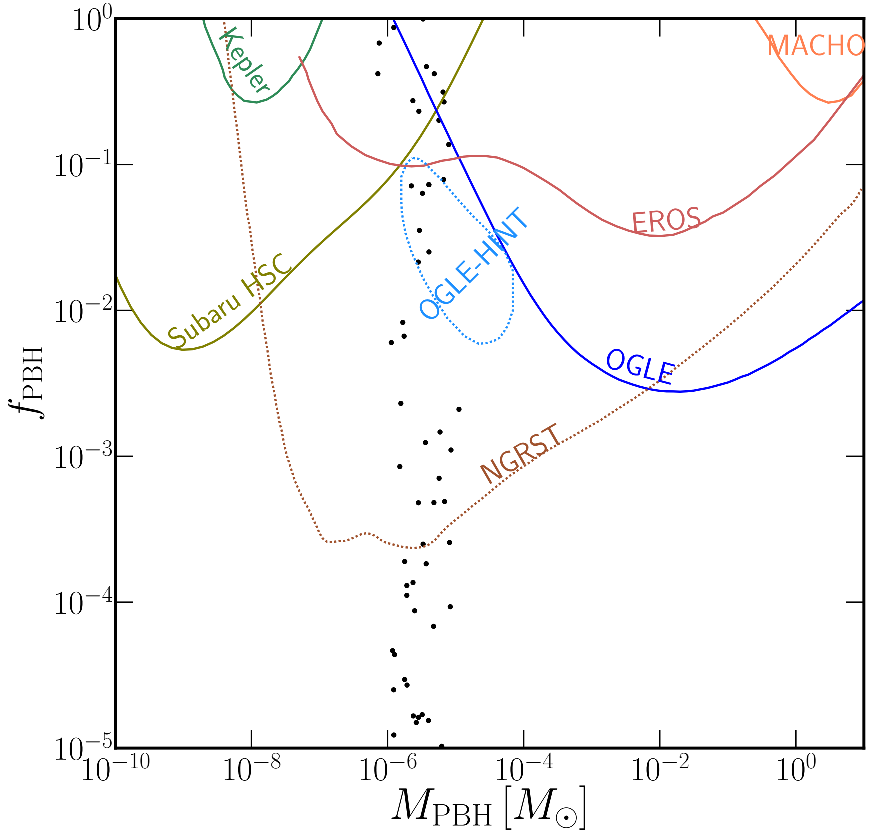
If requiring at least one PBH in the observable Universe

Minimum Value of f_{PBH} with $M_{PBH} \sim 10^{-5} M_{\odot}$

$f_{PBH} \gtrsim 10^{-30}$

Microlensing

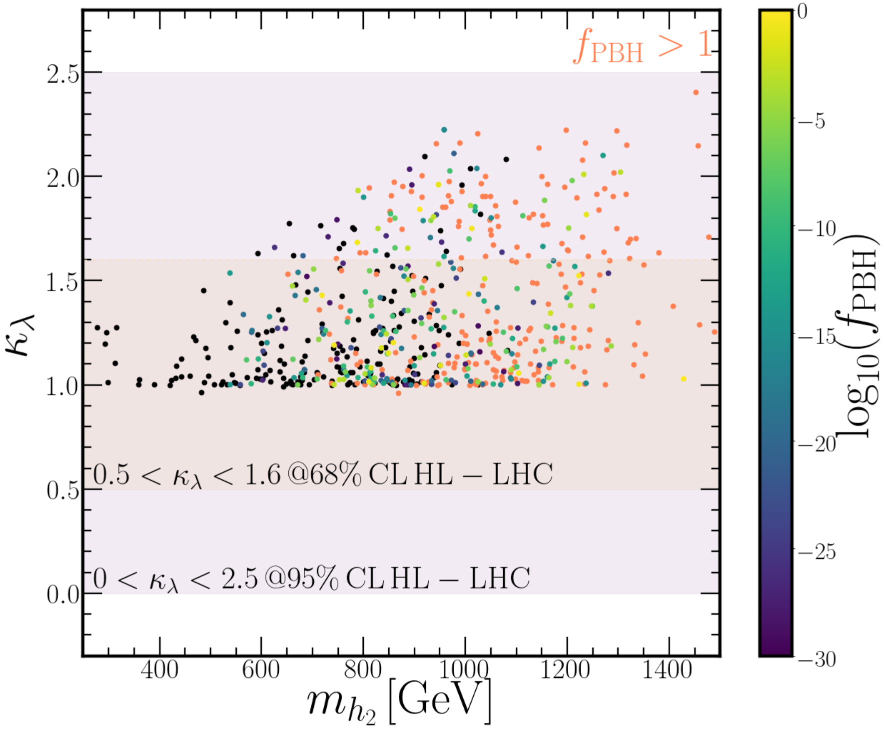
- Gravitational Effect

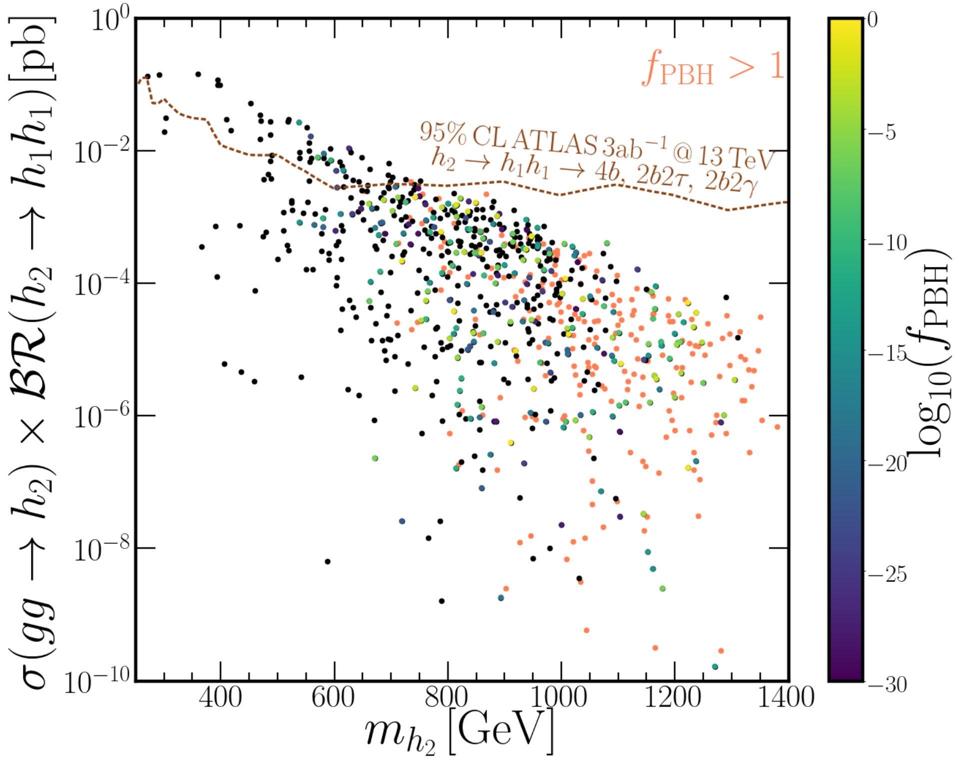


Mass of PBH $\Longleftarrow$ Scale of EWPT

Collider Searches

- Higgs Pair
  - Non-resonant vs Resonant





Summary

- EWPT
  - Interesting Scenario for many important Phenomena
- PBH from EWPT in xSM
  - Mass around $10^{-5} M_{\odot}$
- Microlensing constraint
  - $f_{PBH} \lesssim 10^{-2}$
- GW probes can cover the parameter space
  - Require at least one PBH in observable Universe
- Collider searches provide complementarity probes