Primordial Black Holes from First-Order Phase Transition in the xSM

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1. PBH formation from first-order phase transition
2. XSM model
3. Results
4. Summary

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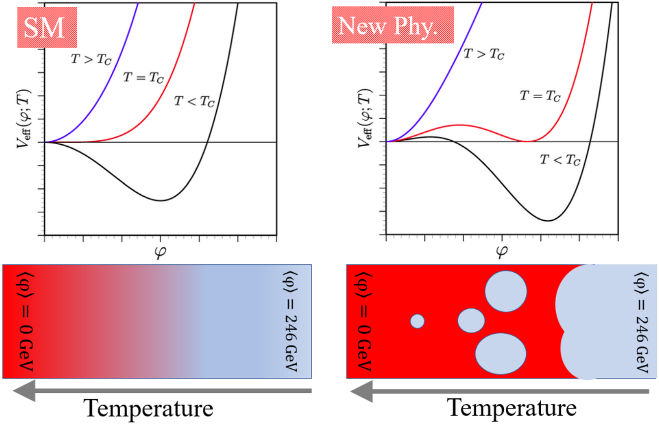
First-order phase transition

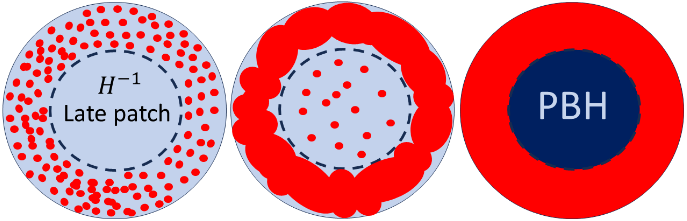


Volume of true vacuum bubble per comoving volume where the first bubble nucleates at t_0.

$$I(t) = \frac{4\pi}{3}\int_{t_0}^{t} dt'\Gamma(t')a^3(t')\left(\int_{t'}^{t}\frac{1}{a(\tilde{t})}d\tilde{t}\right)^3$$

The fraction of false vacuum $F(t) = e^{-I(t)}$

PBH formation



$$\rho = \rho_R + \rho_V$$
$$\rho_R \propto a(t)^{-4}$$
$$\rho_V \text{ nearly constant}$$

- Energy contrast exceeds critical threshold, *late patch* gravitationally collapses into PBH.

$$\delta = \frac{\rho^{\text{in}} - \rho^{\text{out}}}{\rho^{\text{out}}} > 0.45$$

- Probability of no bubble nucleation in the past Hubble volume at $T > T_i$

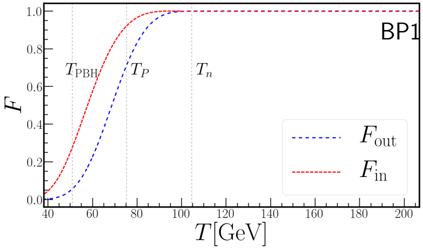
$$P(T_i) = \text{Exp}\left[- \int_{T_i}^{T_c} \frac{dT'\Gamma(T')}{T'H(T')} a_{\text{in}}(T')^3 V_{\text{coll}} \right]$$

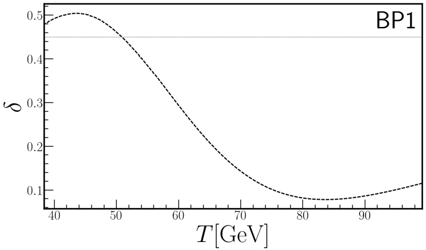
$$V_{\text{coll}} = \frac{4\pi}{3}\left[\frac{1}{a_{\text{in}}(T_{\text{PBH}})H_{\text{in}}(T_{\text{PBH}})} + \int_{T_{\text{PBH}}}^{T'} \frac{d\tilde{T}}{\tilde{T}H(\tilde{T})a_{\text{out}}(\tilde{T})} \right]^3 .$$

PBH formation

- To evaluate δ we evolve energy density using Friedmann equation with $t_0 = t_c$ for background region and $t_0 = t_i$ for late patch,

$$H^2 = \left(\frac{1}{a}\frac{\mathrm{da}}{\mathrm{dt}}\right)^2 = \frac{1}{3M_{\mathrm{pl}}^2}(\rho_V + \rho_R), \quad \frac{d\rho_R}{dt} + 4H\rho_R = -\frac{d\rho_V}{dt}, \quad \rho_V = F(t)\Lambda_{\mathrm{vac}}(t)$$





- PBH mass can be roughly approximated as the Hubble horizon mass at T_{PBH}.

$$M_{\mathrm{PBH}} \approx \frac{4\pi}{3} H_{\mathrm{in}}^{-3}(T_{\mathrm{PBH}})\rho_c = 4\pi M_{\mathrm{pl}}^2 H_{\mathrm{in}}^{-1}(T_{\mathrm{PBH}})$$

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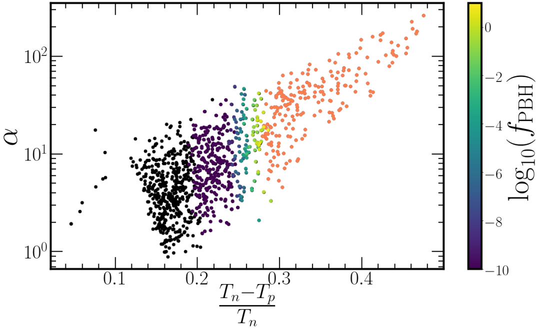
XSM model

SM is extended by one real scalar field S, which is singlet under the SM symmetry. The gauge invariant effective potential is given by

$$V_{\text{eff}}(h,s,T) = \frac{1}{2}[-\mu^2 + \Pi_h T^2]h^2 + \frac{1}{2}[b_2 + \Pi_s T^2]s^2 + \frac{\lambda}{4}h^4 + \frac{a_1}{4}h^2 s + \frac{a_2}{4}h^2 s^2 + \frac{b_3}{3}s^3 + \frac{b_4}{4}s^4$$



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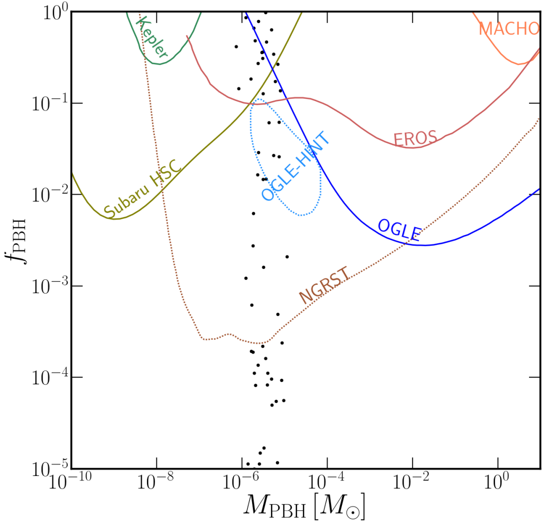
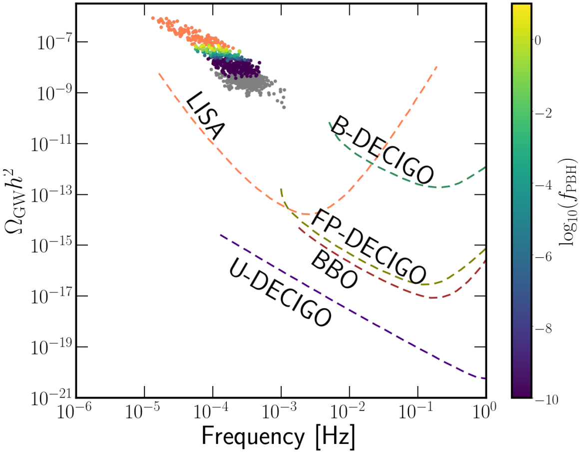
Microlensing experiments



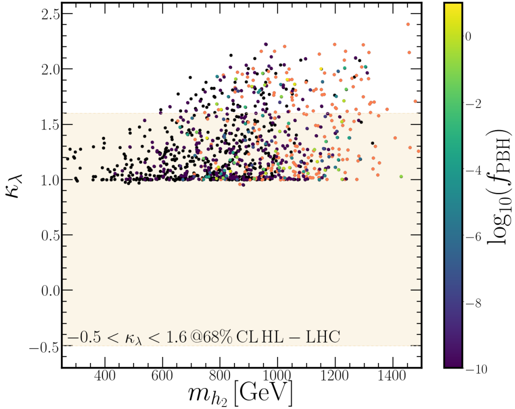
$$f_{\mathrm{PBH}} \equiv \frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{CDM}}} \sim 1.52 \times 10^{11} \left(\frac{0.245}{\Omega_{\mathrm{CDM}}}\right) \left(\frac{T_{\mathrm{PBH}}}{100\ \mathrm{GeV}}\right) P(T_i)$$

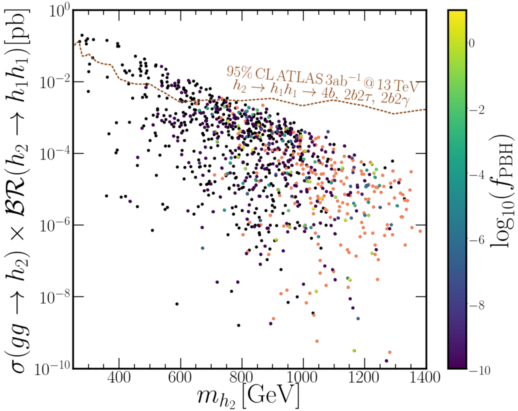
Gravitational wave experiments



- The PBH formation from first-order phase transition requires supercooling and a large value of α, which coincides with promising gravitational wave signatures.
- Given that the phase transition occurs at the electroweak scale, it naturally falls within the frequency range detectable by LISA.

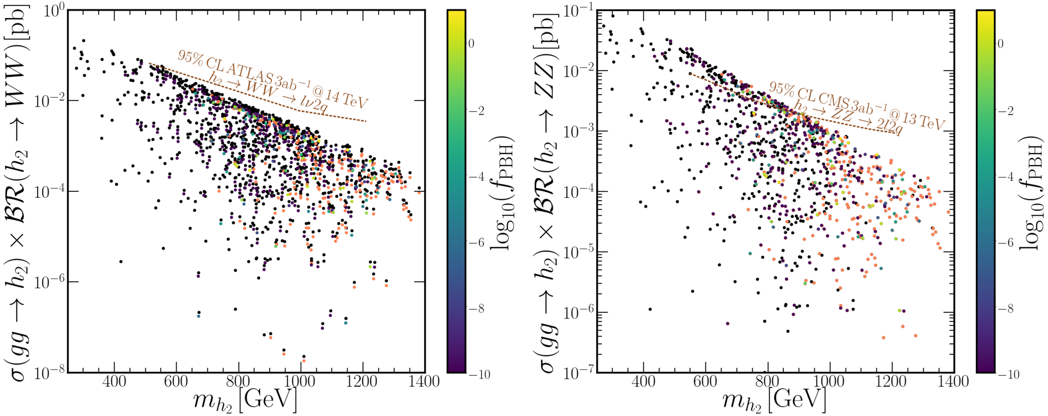
Resonant and Non-Resonant di-Higgs Searches





- HL-LHC will be sensitive to a significant fraction of the parameter points that exhibit PBH formation with the triple Higgs couplings constraints.
- The resonant di-Higgs channel can probe some of the parameter space that displays PBH formation with $m_{h_2} < 800\,\mathrm{GeV}$ with relatively low PBH fraction.

Di-boson Searches



- The $h_2 \to WW$ channel does not offer the sensitivity to probe the PBH formation parameter space.
- The $h_2 \to ZZ$ channel offers sensitivity to PBH formation parameter space at HL-LHC with $m_{h_2} \lesssim 900\,\mathrm{GeV}$ and low $f_{\rm PBH}$.

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- PBH formation during phase transition requires sufficient supercooling such that probability of having a *late patch* where system remains in false vacuum is large.
- The mass of PBH is around $10^{-5} M_{\odot}$, dictated by the scale of phase transition.
- Contribution of PBHs to the dark matter density from xSM can be as high as $f_{PBH} \approx 10^{-1}$, with OGLE, Subaru-HSC, Macho, and Eros experiments placing the most stringent limits.
- GW induced such supercooled EWPT can be naturally covered the future LISA sensitivities with sufficient signal strength due to its supercooled nature.
- The HL-LHC can provide complementarity probe to the PBH parameter space.

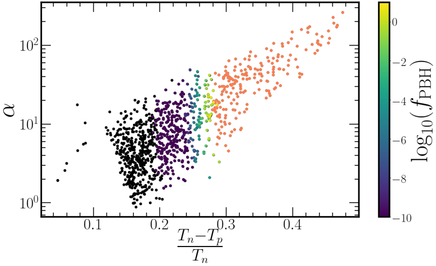
Thank You

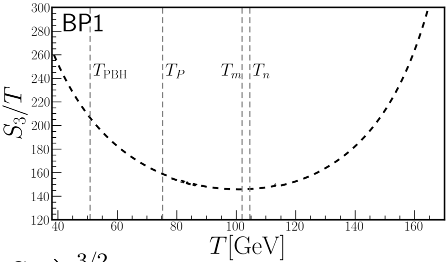
Backup slides

XSM model

SM is extended by one real scalar field S, which is singlet under the SM symmetry. The gauge invariant effective potential is given by

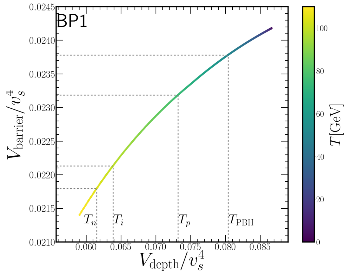
$$V_{\text{eff}}(h,s,T) = \frac{1}{2}[-\mu^2 + \Pi_h T^2]h^2 + \frac{1}{2}[b_2 + \Pi_s T^2]s^2 + \frac{\lambda}{4}h^4 + \frac{a_1}{4}h^2 s + \frac{a_2}{4}h^2 s^2 + \frac{b_3}{3}s^3 + \frac{b_4}{4}s^4$$

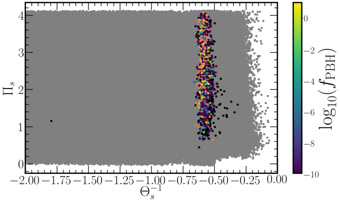


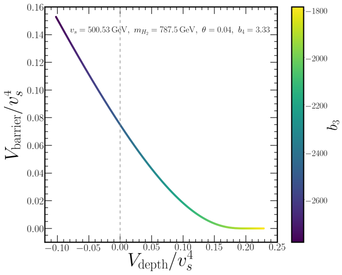


$$\Gamma(T) \approx T^4 \left(\frac{S_3}{2\pi T}\right)^{3/2} e^{-\frac{S_3}{T}}$$

PBH formation in XSM



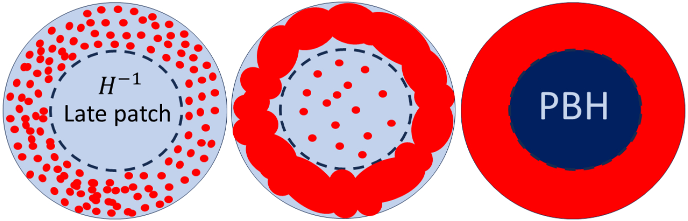




- Cubic terms dominate the barrier at zero temperature. $\Theta_s \equiv \frac{4b_3}{3b_4 v_s}$
- As b_3 becomes increasingly negative, cubic term dominates over quartic term, uplifting the EW broken vacuum compared to EW symmetric vacuum
- Domination of the cubic term leads to the increase in the barrier height.
- PBH formation prefers parameter space where the potential has a shallow EW vacuum and sufficient high barrier.

PBH formation

- Due to probabilistic bubble nucleation, large regions may be filled with the false vacuum where nucleation is delayed and surrounded by true vacuum bubbles.



- Radiation energy density decreases with $\rho_R \propto a(t)^{-4}$, while the vacuum ρ_{vac} energy remains nearly constant. This causes the total energy density to increase in regions where false vacuum decay is delayed compared to regions where it is not.
- Energy contrast exceeds critical threshold, *late patch* gravitationally collapses into PBH.

$$\delta = \frac{\rho^{\text{in}} - \rho^{\text{out}}}{\rho^{\text{out}}} > 0.45$$

(I. Musco, V. D. Luca, G. Franciolini, and A. Riotto 2021)