PBH from EWPT in xSM and its GW signal

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D. Goncalves, A. Kaladharan, **YW; arXiv:** 2406.07622, *Phys.Rev.D* 111 (2025) 035009
D. Goncalves, A. Kaladharan, YW; arXiv: 2510.xxxxx

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
  - Lensing effects
  - GW Signal from Merger/Formation

Introduction

- Formation of PBH during EWPT (1st 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
    - Mass ~ $10^{-6} - 10^{-5} M_{\odot}$

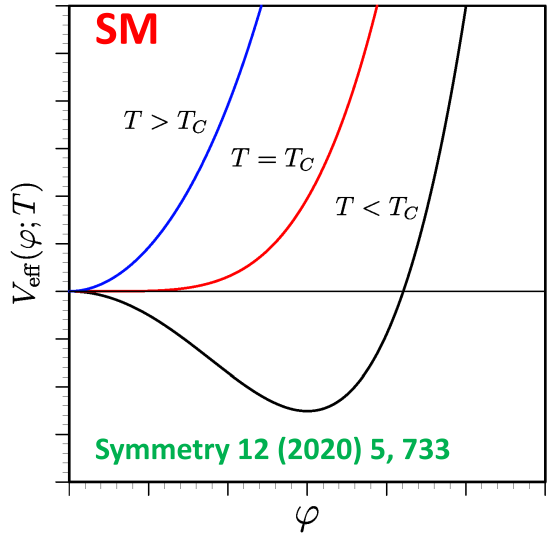
Gauge Issue, see Jinno's Talk

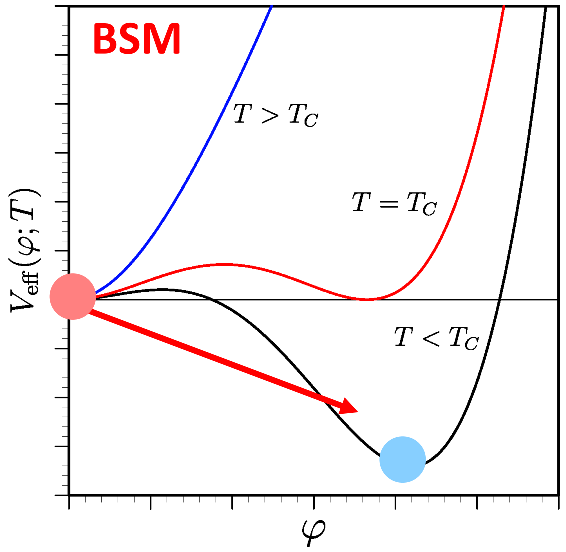
- Implications on BSM
  - Preference on parameter space, i.e., Cubic couplings
  - GW vs. Microlensing vs. Collider Searches

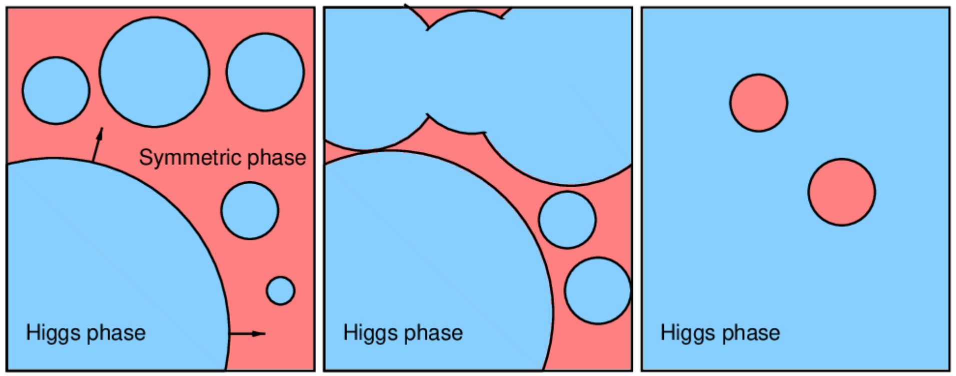
From EWPT vs From BH Binary

EWPT and PBH

- First-order EWPT







Nucleation Rate:

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

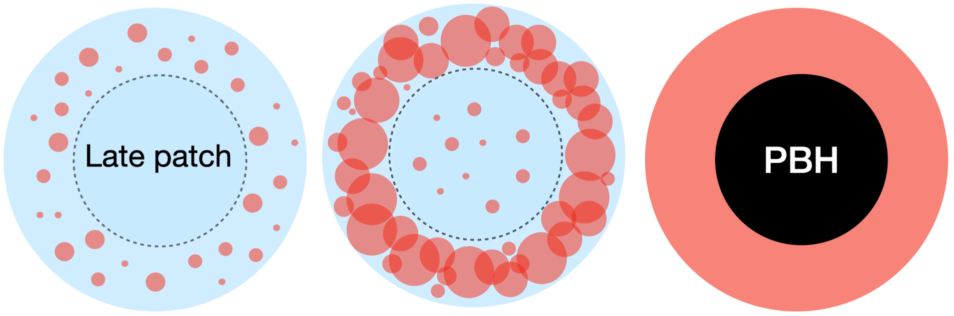
False Vacuum Fraction:

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

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

EWPT and PBH

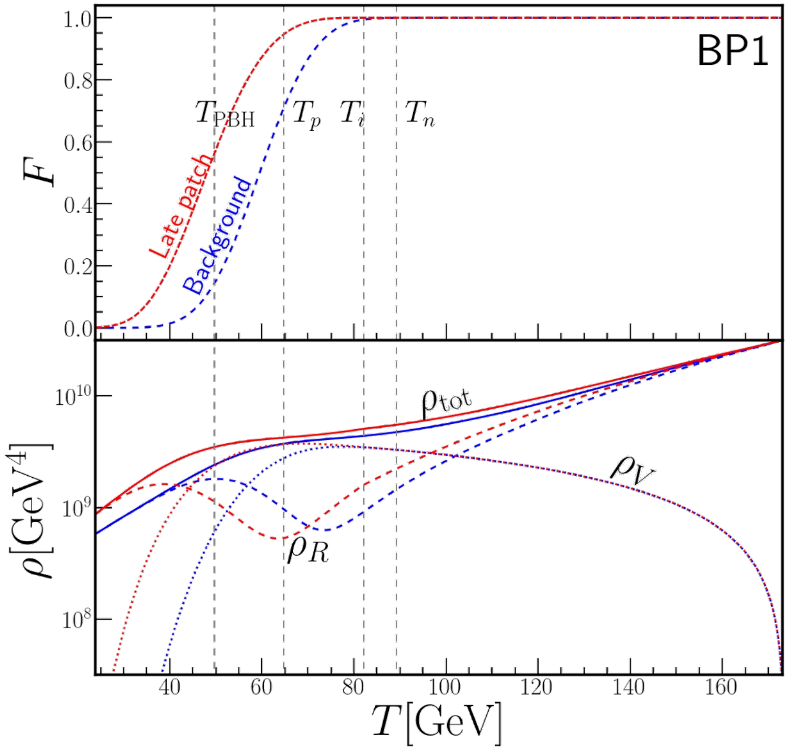
- Randomness – Some patch nucleate late



  - 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

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

$$M_{PBH} \sim 10^{-6}{\sim}10^{-5} M_\odot$$

EWPT and PBH

- The Probability to remain in false vacuum

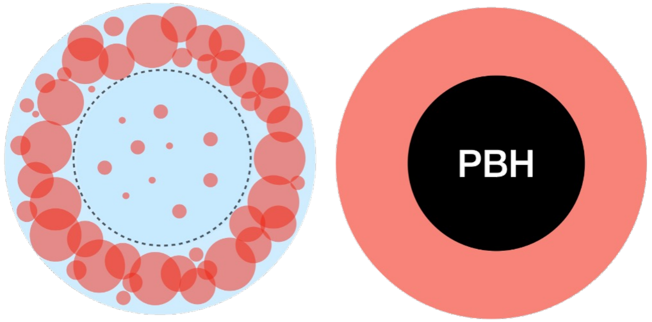
K. Kawana, T. Kim, P. Lu; Phys. Rev. D 108 (2023) 103531

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

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

- The fraction of PBH in DM density

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

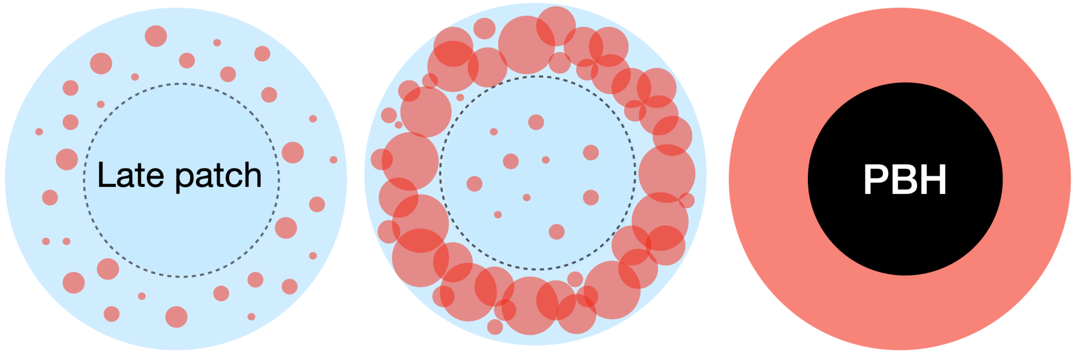


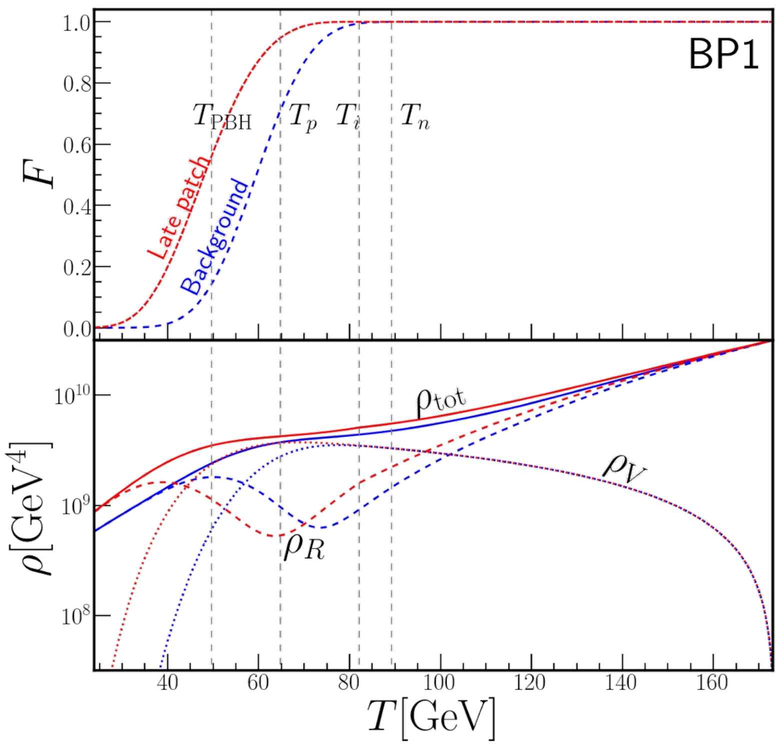
EWPT and PBH

- 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

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

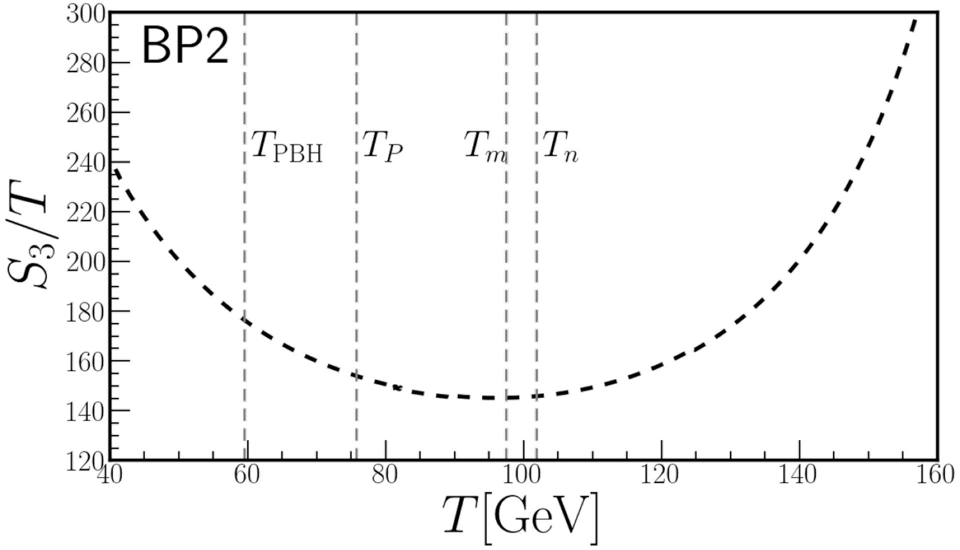
$$\Gamma(T) \approx T^4 \left(\frac{S_3}{2\pi T}\right)^{\frac{3}{2}} e^{-\frac{S_3}{T}}$$





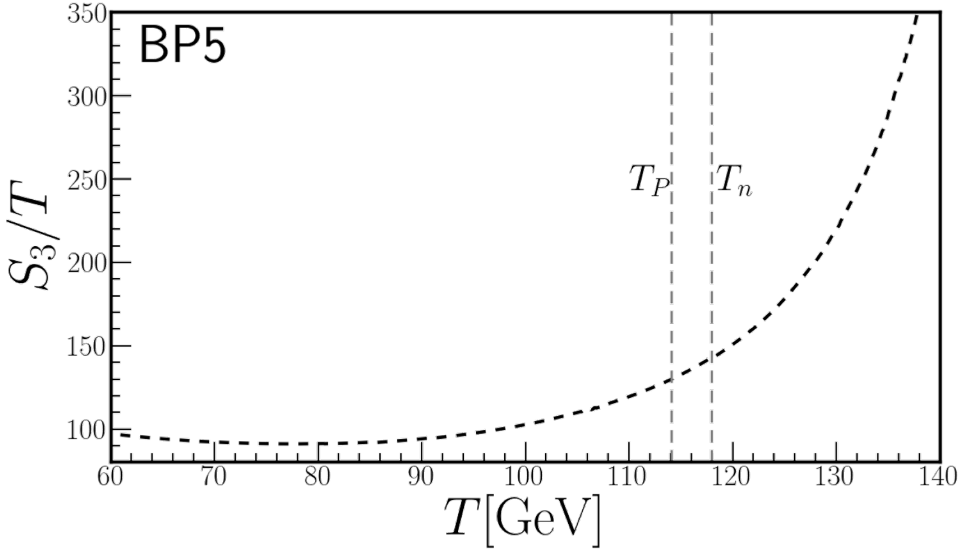
EWPT and PBH

- S_3/T: two cases



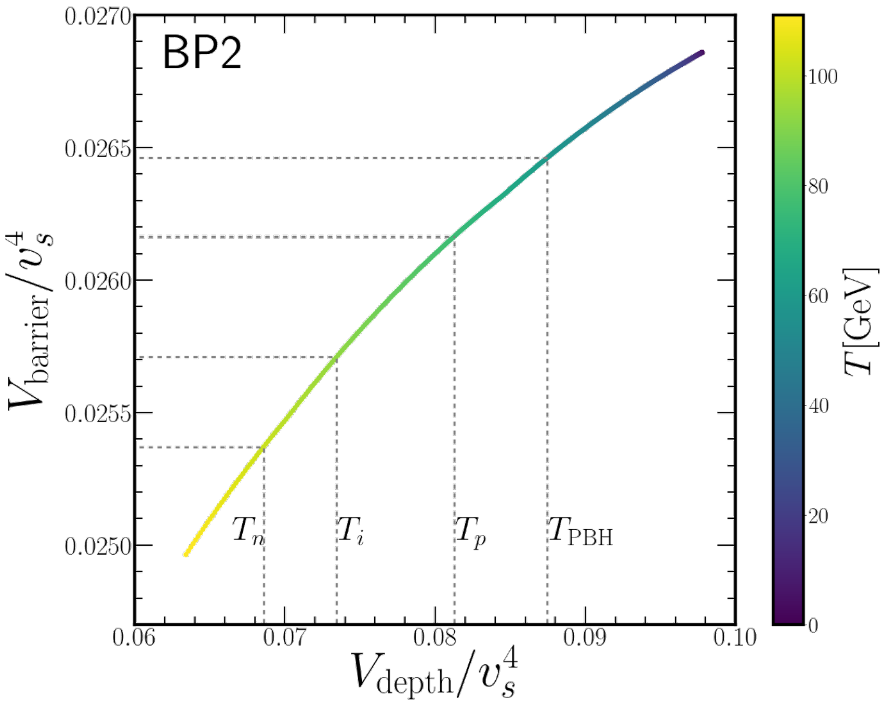
Easier for PBH Formation

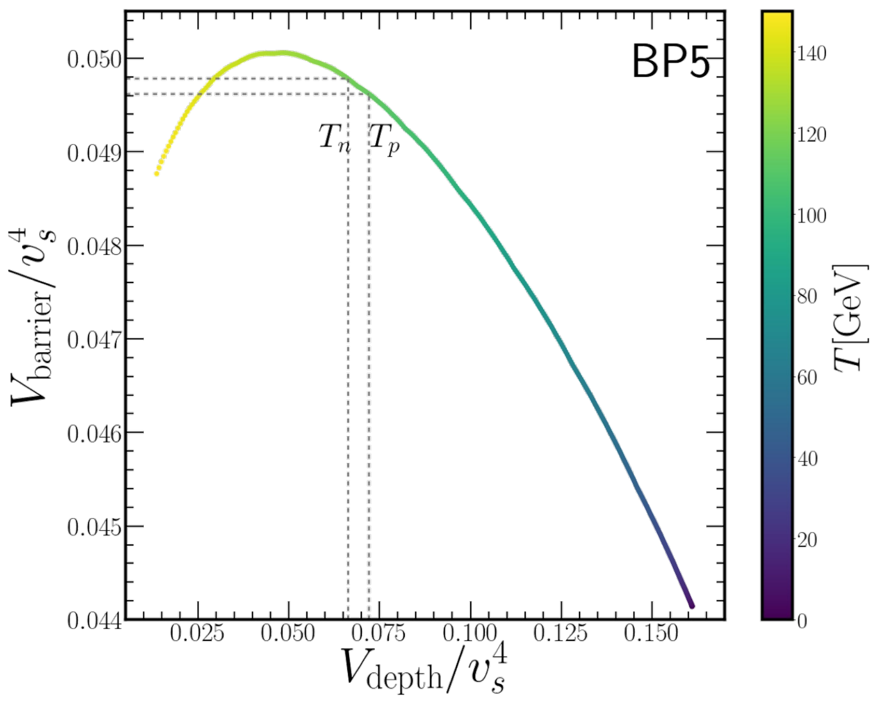
Harder for PBH Formation

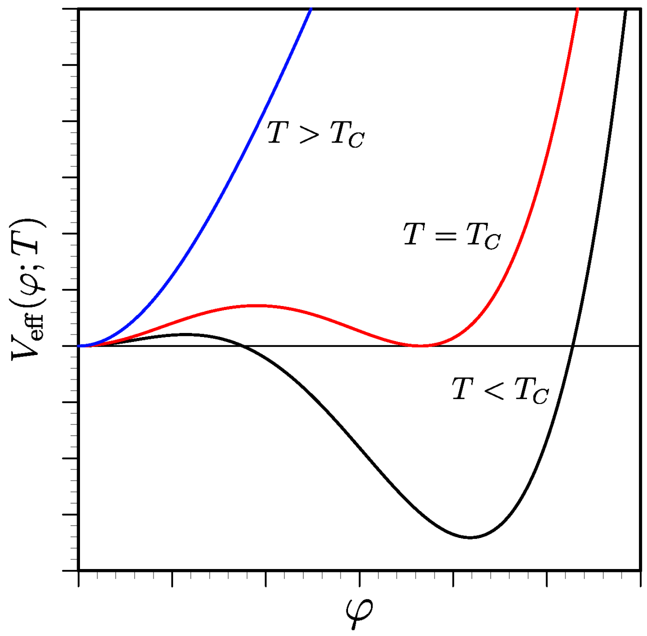


EWPT and PBH

- The potential shape
  - Depth vs Barrier



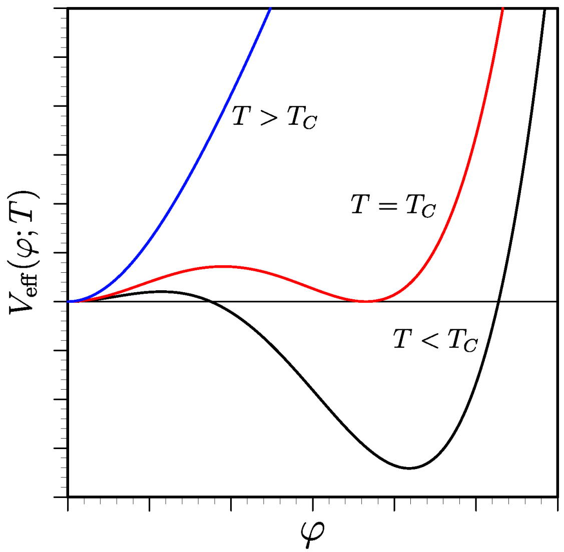




Benchmark Scenario - xSM

- xSM: SM + real scalar 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

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

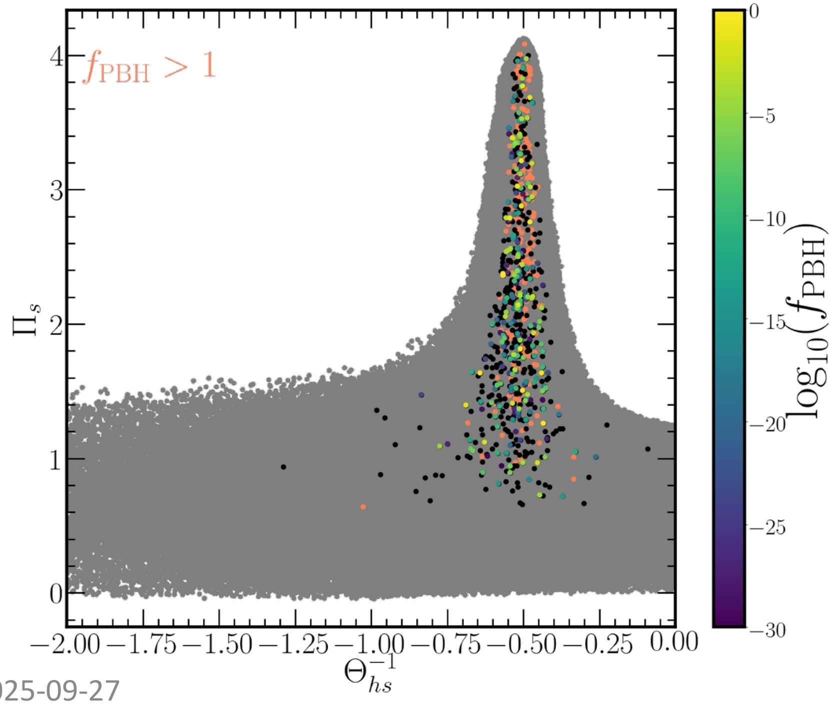


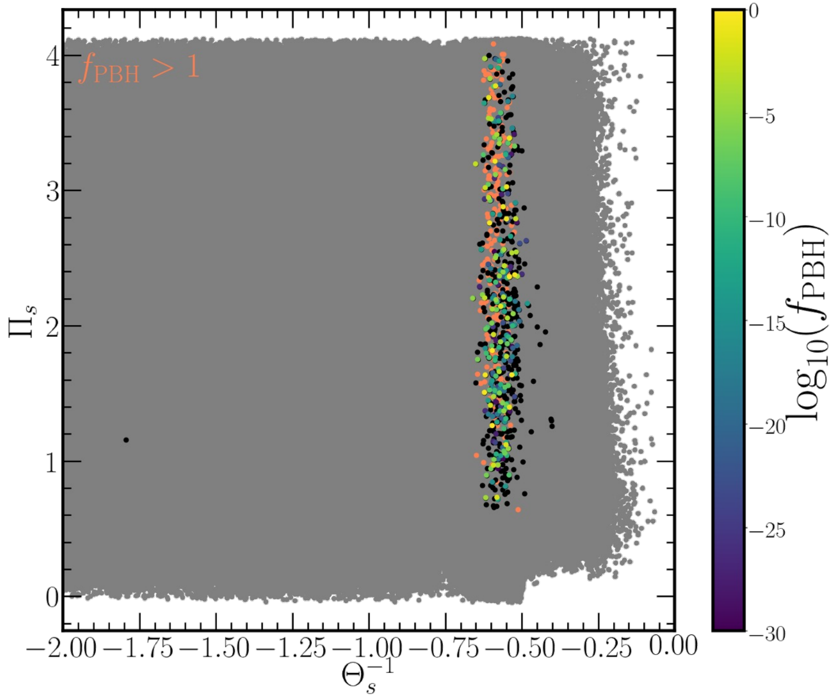
PBH in xSM

- The potential shape
  - Cubic couplings – Normalized by Quartic Couplings

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

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





PBH in xSM

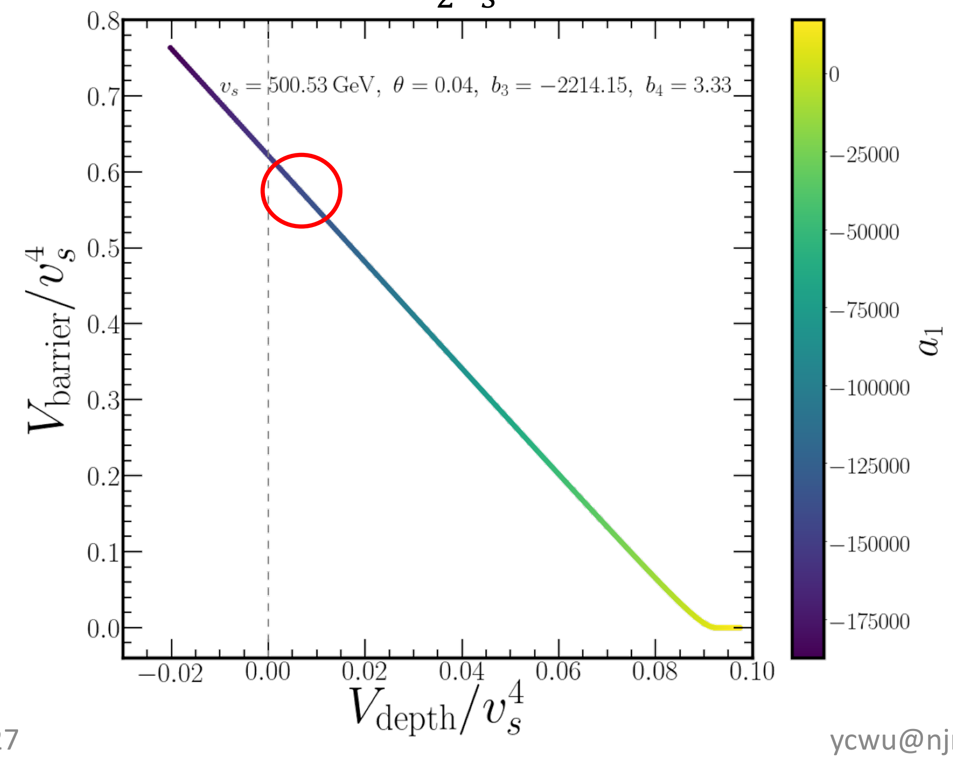
- The potential shape
  - Cubic couplings

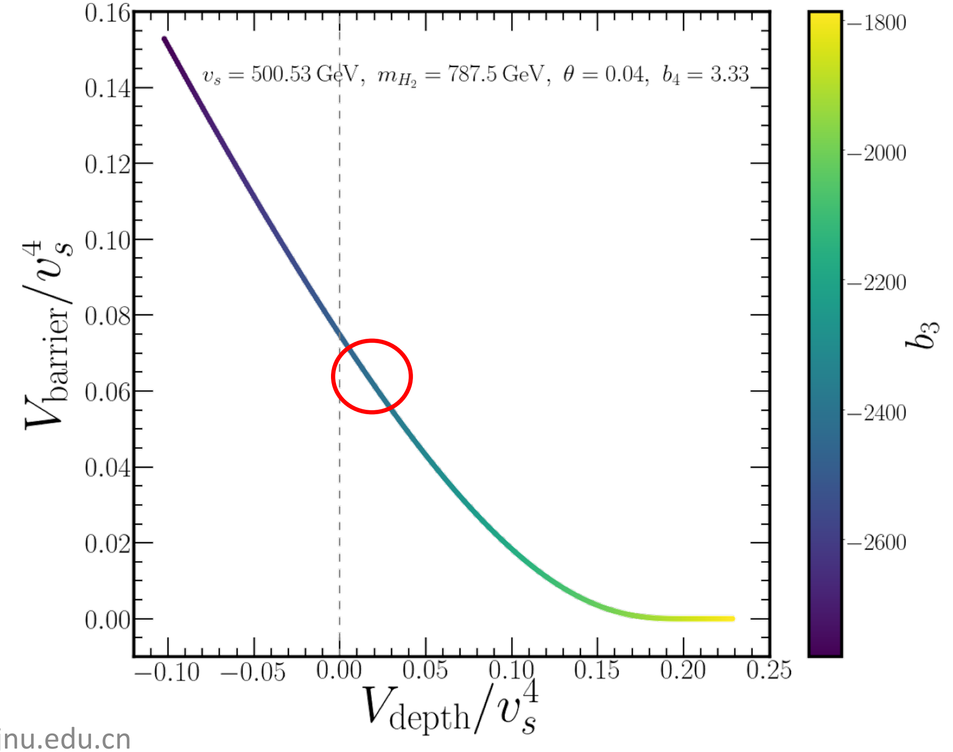
$T = 0$

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

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

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



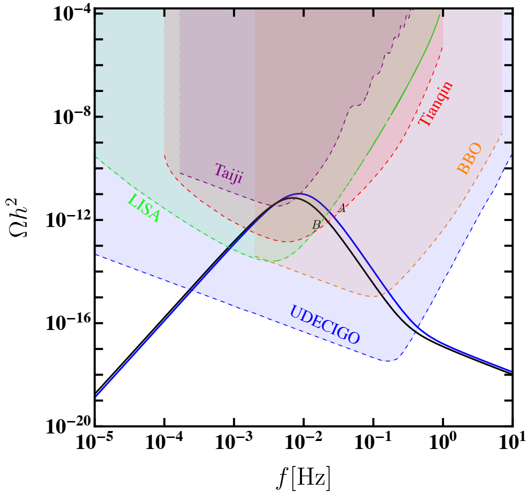


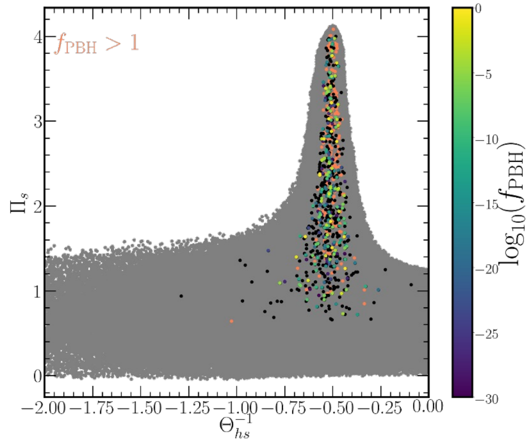
Phenomenology

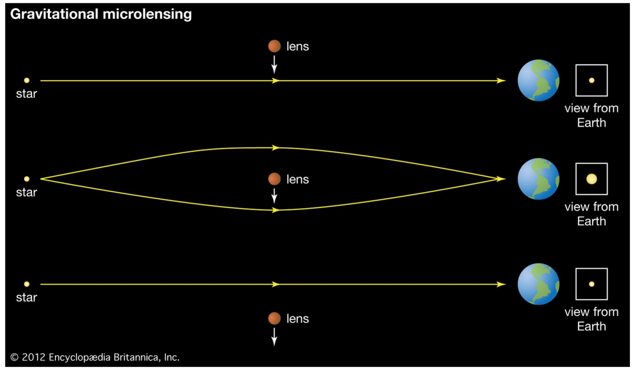
- Signals related to PBH formed from EWPT

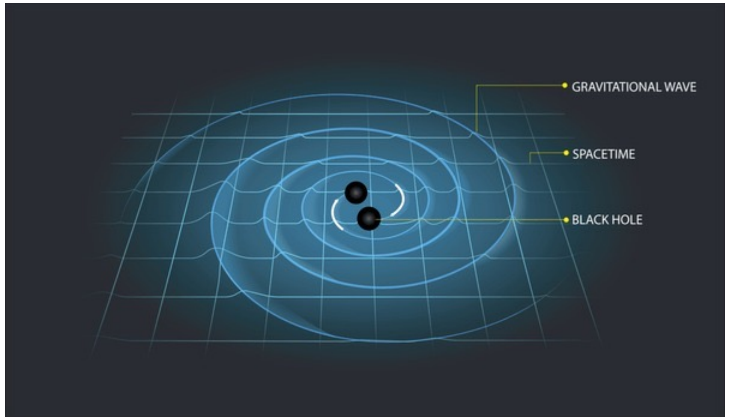
- **Related to EWPT**
  - GW from EWPT
    - Strong 1st order, strong GW signal
  - Cubic couplings etc.
    - Strong preferences

- **Related to PBH**
  - Miscrolensing
  - GW from PBH binaries
    - PBH-PBH
    - ABH-PBH



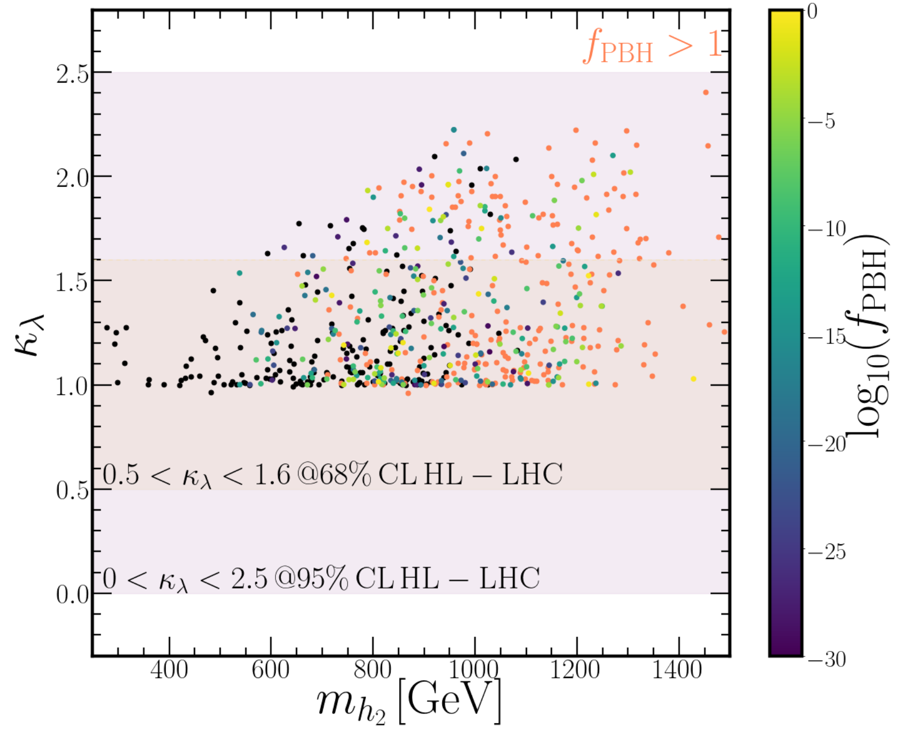


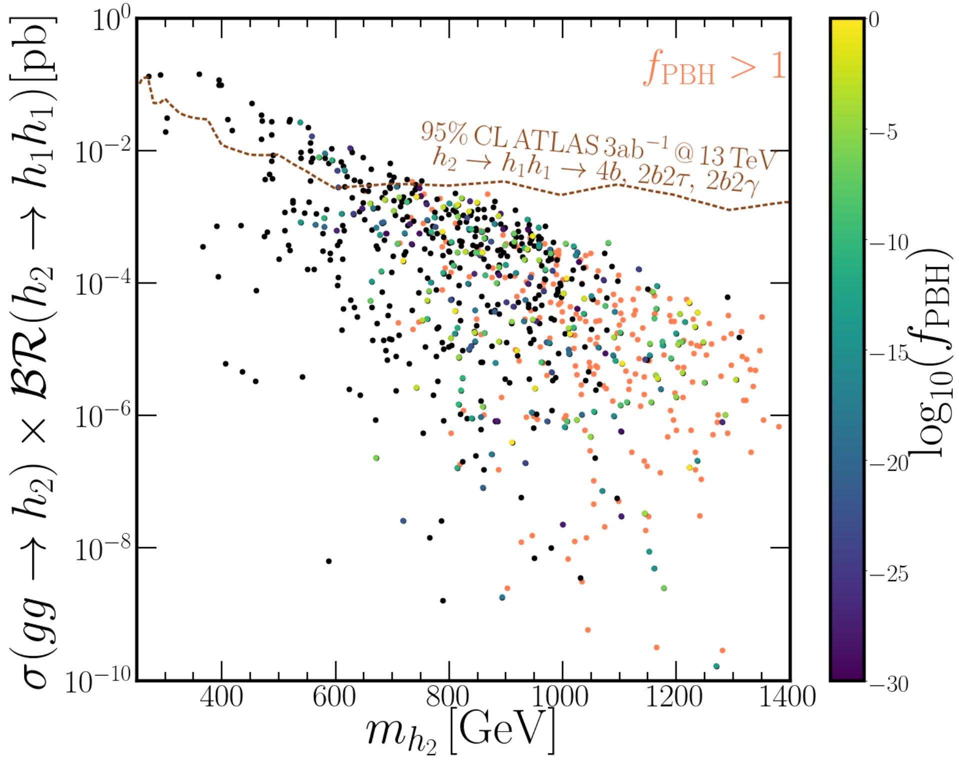




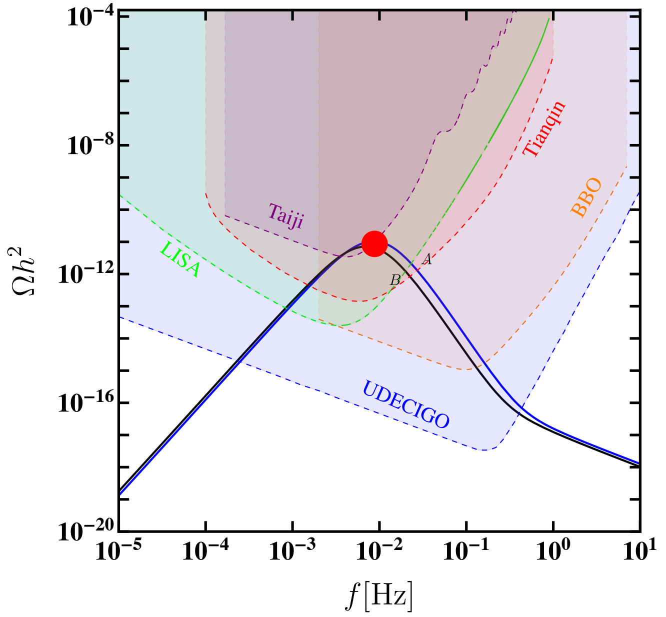
Collider Searches

- Higgs Pair – cubic couplings
  - Non-resonant vs Resonant





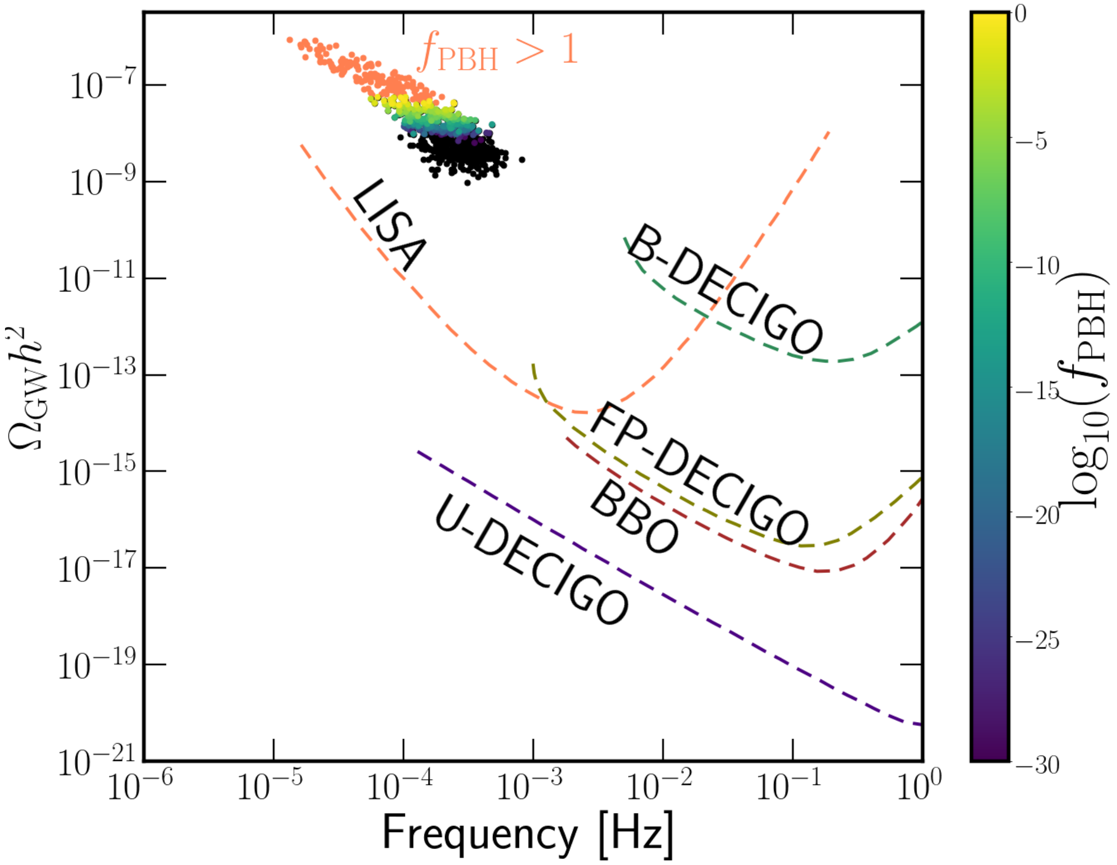
GW from EWPT



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 $M_{PBH} \sim 10^{-5}/10^{-6} M_{\odot}$

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

GW from BH Binary

- Binary with at least one PBH:
  - **PBH-PBH** **M. Raidal, C. Spethmann, V. Vaskonen, H. Veermae; JCAP 02 (2019) 018**
    - Mainly form in the early universe – Poisson Distribution
      - If two PBH are close, torqued by surroundings

$$\frac{d^2R_{PP}(t)}{dm_1 dm_2} \approx \frac{1.6\times10^6}{\mathrm{Gpc^3yr}} f_{\mathrm{PBH}}^{\frac{53}{37}} \left(\frac{t}{t_0}\right)^{-\frac{34}{37}} \left(\frac{M}{M_\odot}\right)^{-\frac{32}{37}} \eta^{-\frac{34}{37}} S[\psi, f_{\mathrm{PBH}}, M] \frac{\psi(m_1)\psi(m_2)}{\langle m\rangle^2}$$

$M = m_1 + m_2, \eta = \frac{m_1 m_2}{M^2}$

    - $\psi(m)$ the PBH mass function
      - Depends on formation mechanism
      - PBH from EWPT, mass is concentrated – EWPT scale
  - **ABH-PBH** **W. Cui, F. Huang, J. Shu, Y. Zhao; Chin. Phys. C 46 (2022) 055103**
    - After the star formation $z \lesssim 5$, close encounter, loss energy due to GW

$$R_{AP} = \int dM_h \frac{dn_h(z, M_h)}{dM_h} R_{AP}^{halo}(z, M_h) \qquad R_{AP}^{halo} = \int dV \int dM_A n_P(M_h, z, \vec{r}) \times \frac{dn_A(M_A, M_h, z, \vec{r})}{dM_A} \times \langle \sigma_{mer} v_{rel} \rangle$$

GW from BH Binary

- Merger Rate within MW
  - PBH following DM distribution

$$n_P = \frac{\rho_{PBH}}{M_{PBH}} = f_{PBH} \times \frac{\rho_{DM}}{M_{PBH}}$$

    - DM halo – NFW Profile

$$\rho_{DM}(r) = \frac{\rho_0}{r/r_0(1 + r/r_0)^2}$$

  - For PBH-PBH
    - Enhanced within Galaxy

$$\delta = \rho_{DM}(r)/\bar{\rho}_{DM}$$

O. Pujolas, V. Vaskonen, H. Veermae; Phys. Rev. D 104 (2021) 083521

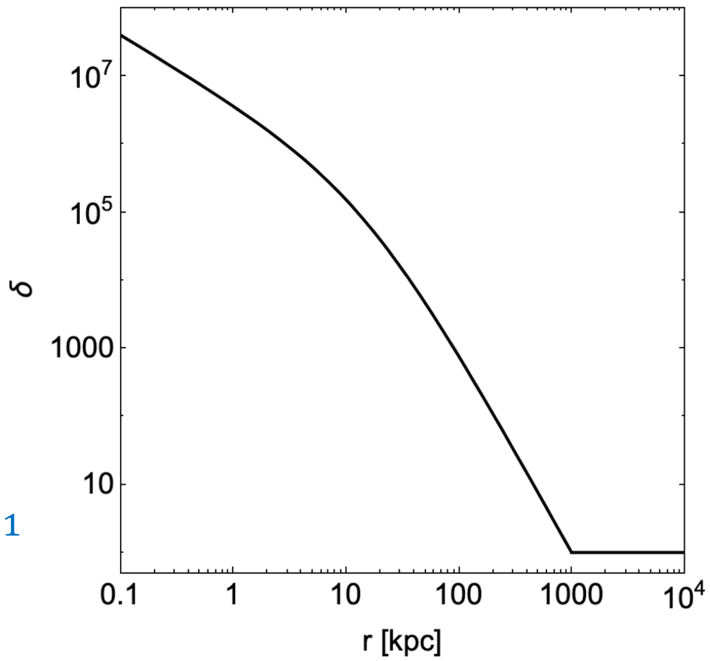
  - For ABH-PBH

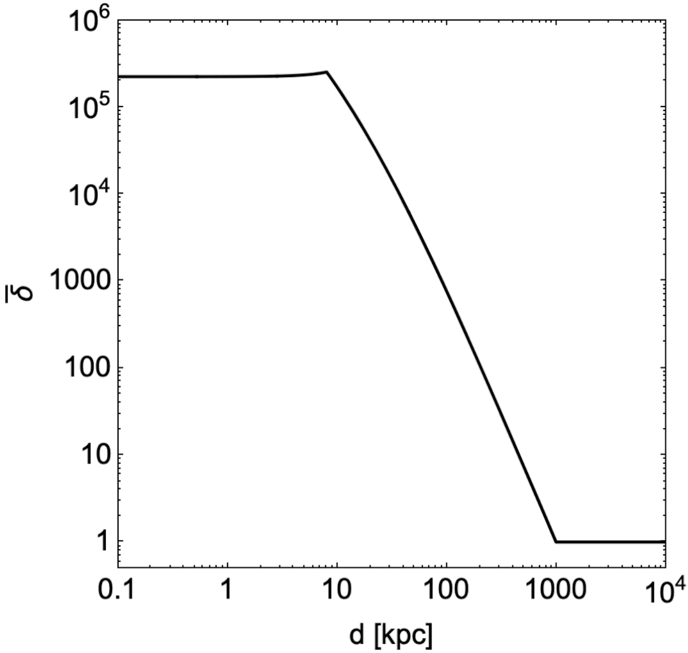
$$M_{PBH} = 10^{-6} M_\odot \quad f_{PBH} = 10^{-3} \qquad R_{AP}^{MW} \approx 7.27\times10^{-11}\text{yr}^{-1}$$

$$R_{PP}(t_0) \approx 8.8\times10^{-12}\text{kpc}^{-3}\text{yr}^{-1} \qquad M_{PBH} = 10^{-6} M_\odot \quad f_{PBH} = 10^{-3}$$

$$r_{\rm vir}^{\rm MW} \sim 200 \text{ kpc}$$

$$R_{PP}^{MW} \approx \int dr\, 4\pi r^2 \delta(r)\, R_{PP}(t_0) \approx 0.2/\text{yr}$$





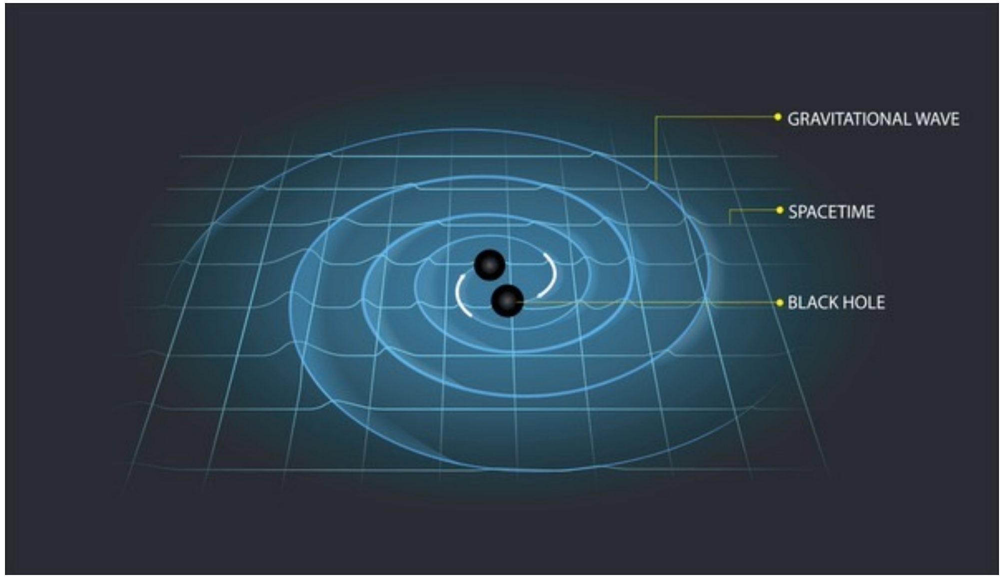
GW from BH Binaries

- GW from individual binary
  - Only consider PBH – PBH Binary
  - ABH – PBH Binary: Rare within MW

$R_{PP}^{MW} \approx 0.2\ \mathrm{yr}^{-1}$

$R_{AP}^{MW} \approx 7.27\times10^{-11}\mathrm{yr}^{-1}$

- Stochastic GW Background
  - PBH – PBH Binary
  - ABH – PBH Binary



GW from BH Binaries

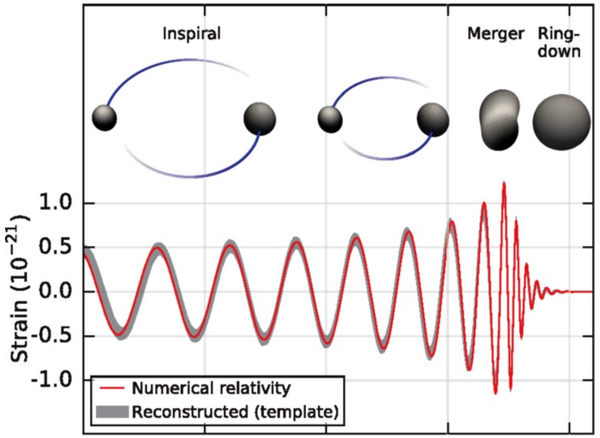
- The Waveform for individual binary – Frequency Domain
  - Inspiral + Merger + Ringdown
    - Numerical Simulation + Matching to PN expansion
  - For non-spinning BH P. Ajith et.al. Phys. Rev. D 77 (2008) 104017

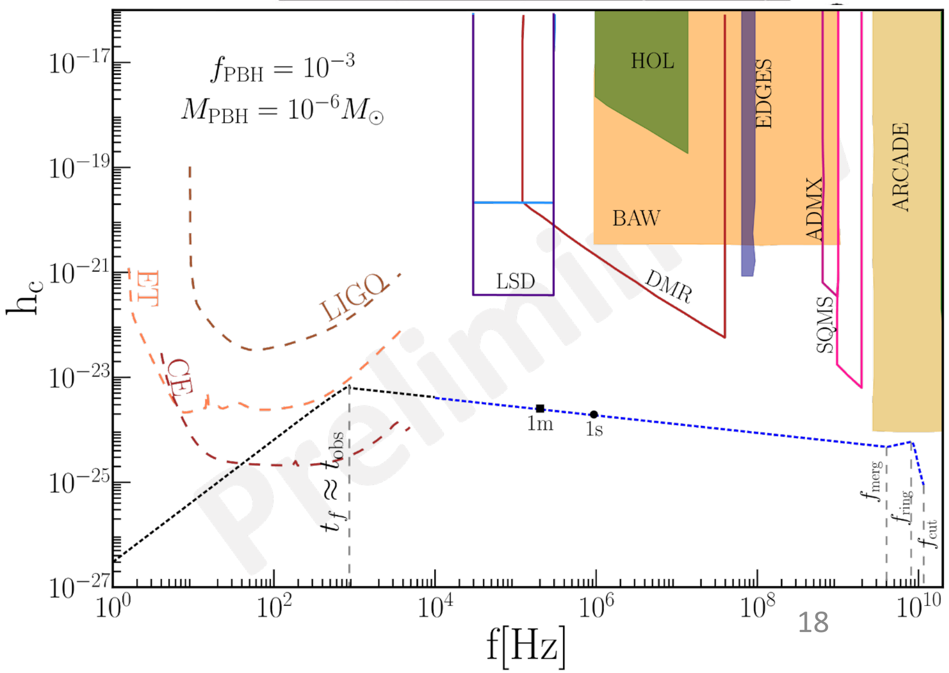
$$\tilde{h}(f) = A(f) e^{i\Psi(f)} \qquad h_c(f) = 2f\tilde{h}(f)$$

$$A(f) = \mathcal{C}\times \begin{cases} \left(\frac{f}{f_{merg}}\right)^{-\frac{7}{6}}, & f < f_{merg} \\ \left(\frac{f}{f_{merg}}\right)^{-\frac{2}{3}}, & f_{merg} \le f < f_{ring} \\ \omega \mathcal{L}(f, f_{ring}, \sigma), & f_{ring} \le f < f_{cut} \end{cases}$$

$$\mathcal{C} = \frac{1}{d_L}\left(\frac{GM}{c^{9/5}\pi^{4/5}}\right)^{5/6}\left(\frac{5\eta}{24}\right)^{1/2} f_{merg}^{-7/6}$$

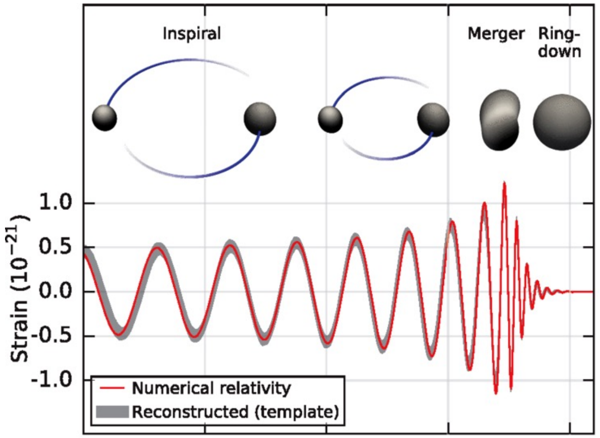
For optimally orientation





Detection of the GW from BH Binary

- Individual Source
  - Inspiral – merger – ringdown
    - Inspiral – can last very long
- Frequency change – Chirp Signal
  - Due to energy loss by GW $m_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$ chirp mass

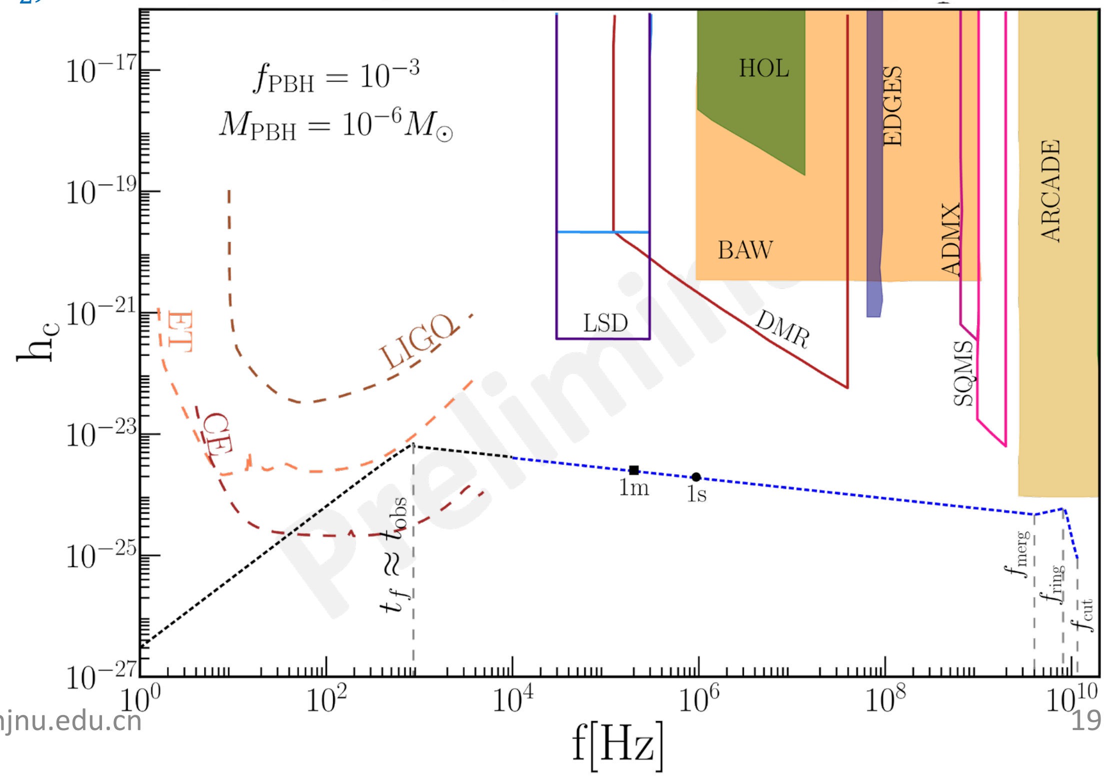


$$\dot{f} = \frac{96}{5}\pi^{\frac{8}{3}}\left(\frac{Gm_c}{c^3}\right)^{\frac{5}{3}} f^{11/3}$$

- Characteristic time
  - Compare with observation time

$$t_f = \frac{f}{\dot{f}} \approx 5.5\times10^8\mathrm{yr}\left(\frac{f}{\mathrm{Hz}}\right)^{-\frac{8}{3}}\left(\frac{m_c}{10^{-6}M_\odot}\right)^{-\frac{5}{3}}$$

- h_c is suppressed



Detection of the GW from BH Binary

- Individual Source
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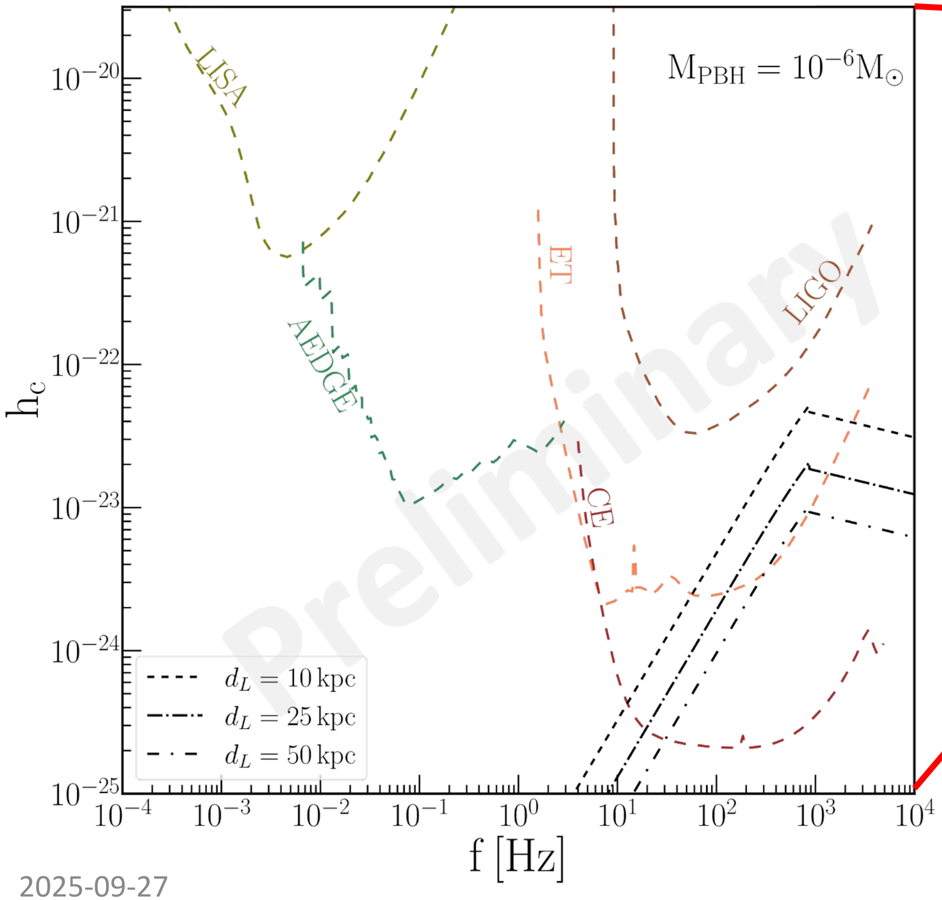
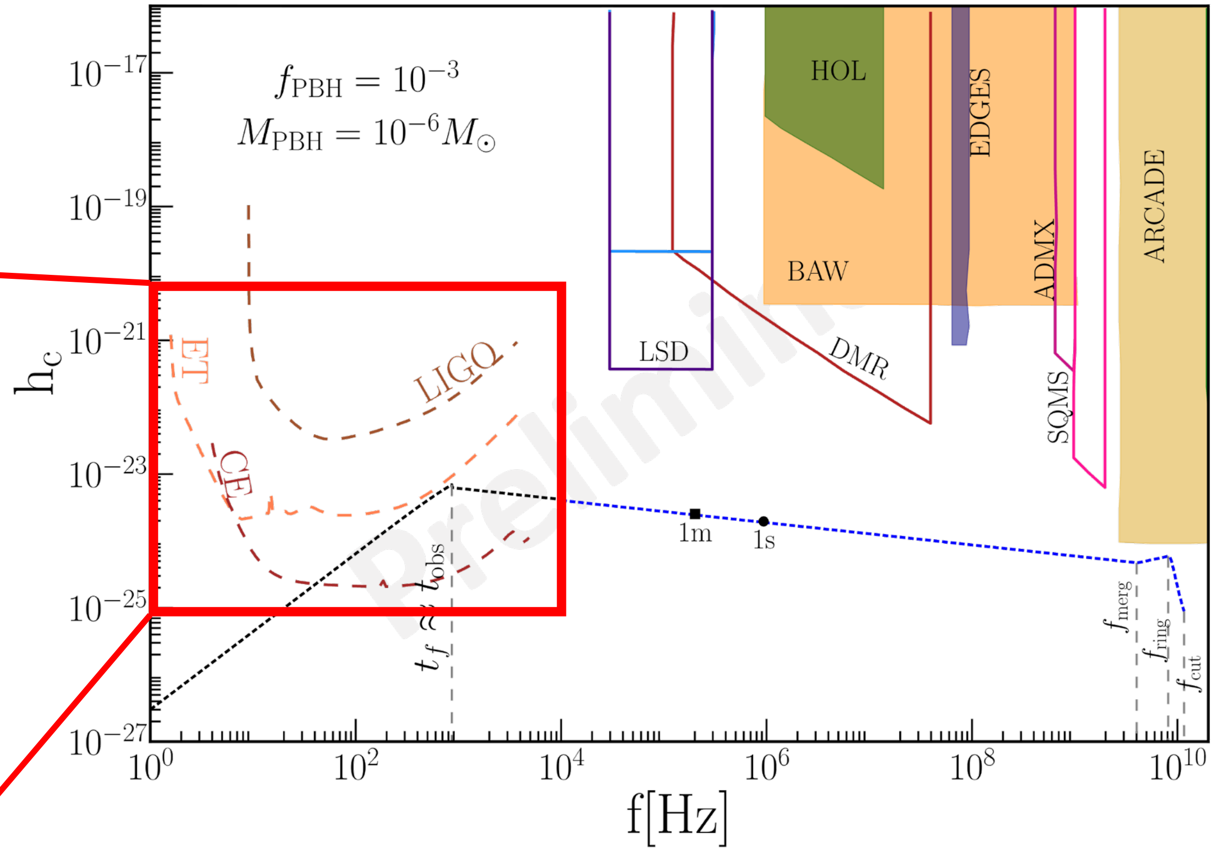




Detection of the GW from BH Binary

- Observed Number of PBH-PBH Merger

$$N_{\text{events}} = t_{\text{obs}} R(t_0) \int dS dr\, \bar{\delta}(r) p_{\text{det}} \left(\frac{\text{SNR}_{\text{thr}}}{\text{SNR}} \right)$$

Enhancement due to local DM density

Accounting different orientations

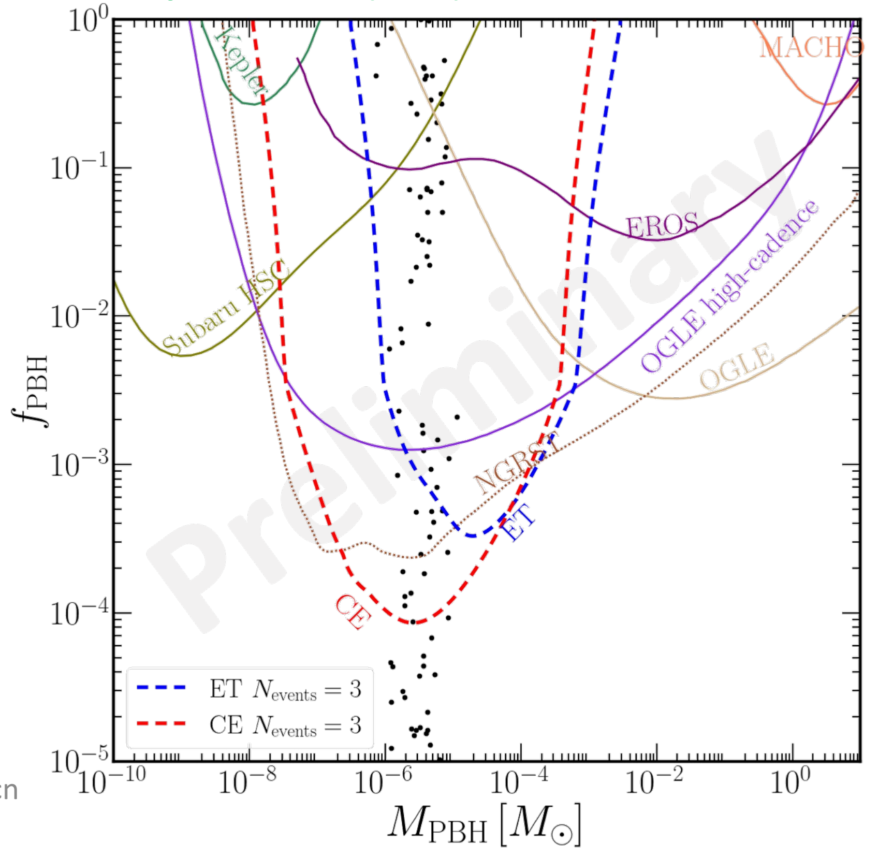
L.S. Finn, D. F. Chernoff; Phys. Rev. D 47 (1993) 2198

$$\text{SNR} = \sqrt{\int d(\ln f) \frac{|h_c(f)|^2}{|h_n(f)|^2}}$$

$$\text{SNR}_{\text{thr}} = 8$$

For $M_{PBH} = 10^{-6} M_{\odot}$, at 10 kpc

$$\text{SNR}_{\text{ET}} \sim 7.8$$
$$\text{SNR}_{\text{ARCADE}} \sim 1.5$$



Detection of the GW from BH Binary

- Stochastic GW Background – from unresolvable binaries
  - Incoherent superposition

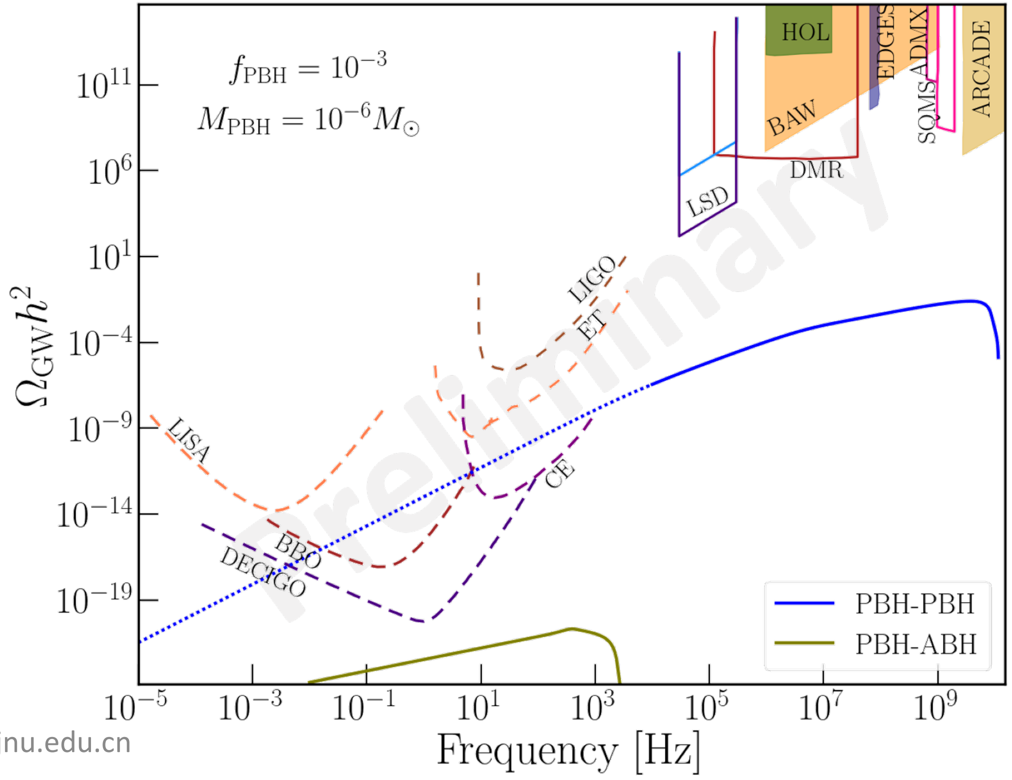
$$\Omega_{GW}(f) = \frac{f}{\rho_c c^2}\int_0^{z_{max}} \frac{dz}{(1+z)H(z)} R(z) \frac{dE_{GW}(f_s)}{df_s}\Big|_{f_s=(1+z)f}$$

$$\frac{dE_{GW}}{df} = \frac{8c^3\pi^2 r^2}{5G} f^2 |\tilde{h}(f)|^2$$

Averaged over orientations

$z_{max} = \min\left\{\frac{f_{cut}}{f} - 1, z_{EWPT}\right\}$ for PBH-PBH

$z_{max} \approx 5$ for ABH-PBH



- Low frequency regime
  - PBH initial distributions

Summary

- Electroweak Phase Transition
  - Interesting Scenario for many important Phenomena
- PBH from EWPT
  - Mass around $10^{-5} \sim 10^{-6} M_{\odot}$
- Microlensing constraint
  - $f_{PBH} \sim 10^{-3}$
- GW from EWPT can cover the parameter space
  - Require at least one PBH in observable Universe
- GW from PBH binary merger – complementary information
  - $f_{PBH} \sim 10^{-4}$
- Collider targets – cubic vs quartic couplings

Backups

The Suppression factor

- S_1: Excluding initial configurations with the interruption from 3rd PBH and other surroundings

$$S_1 \approx 0.24 \left(1 + 2.3 \frac{\sigma_M^2}{f_{PBH}^2}\right)^{-21/74} \qquad \sigma_M \approx 0.005$$

- S_2: Excluding binaries that become part of DM halo, where close encounters with other PBH are very likely

$$S_2(t) \approx \min\left[1, 9.6\times10^{-3} f_{PBH}^{-0.65} \left(\frac{t}{t_0}\right)^{-0.286} e^{0.03 \ln^2 f_{PBH}}\right]$$

The Waveform parameters

$$\alpha_i = \frac{a_i\eta^2 + b_i\eta + c_i}{\pi} \times \frac{c^3}{GM}$$

Parameter	a_i	b_i	c_i
$f_{\rm merg}$	2.9740×10^{-1}	4.4810×10^{-2}	9.5560×10^{-2}
$f_{\rm ring}$	5.9411×10^{-1}	8.9794×10^{-2}	1.9111×10^{-1}
σ	5.0801×10^{-1}	7.7515×10^{-2}	2.2369×10^{-2}
$f_{\rm cut}$	8.4845×10^{-1}	1.2848×10^{-1}	2.7299×10^{-1}