Probing primordial black holes from a first order phase transition through pulsar timing and gravitational wave signals

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[JTA, Po-Yan Tseng (曾柏彥), hep-ph/2304.10084 (accepeted for publication in JHEP)]

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2023

Outline

- Novel PBH formation mechanism: Fermi ball collapse from dark FOPT
- Pulsar timing
  - Doppler and Shapiro
  - Constraints
- Complementary probe: stochastic gravitational waves
- Generic quartic potential
- Summary

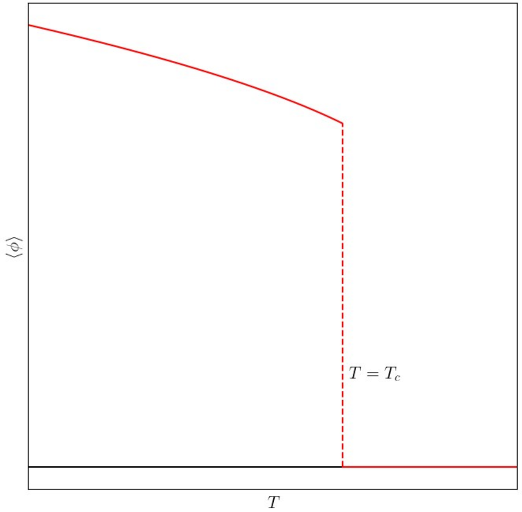
Novel PBH formation mechanism

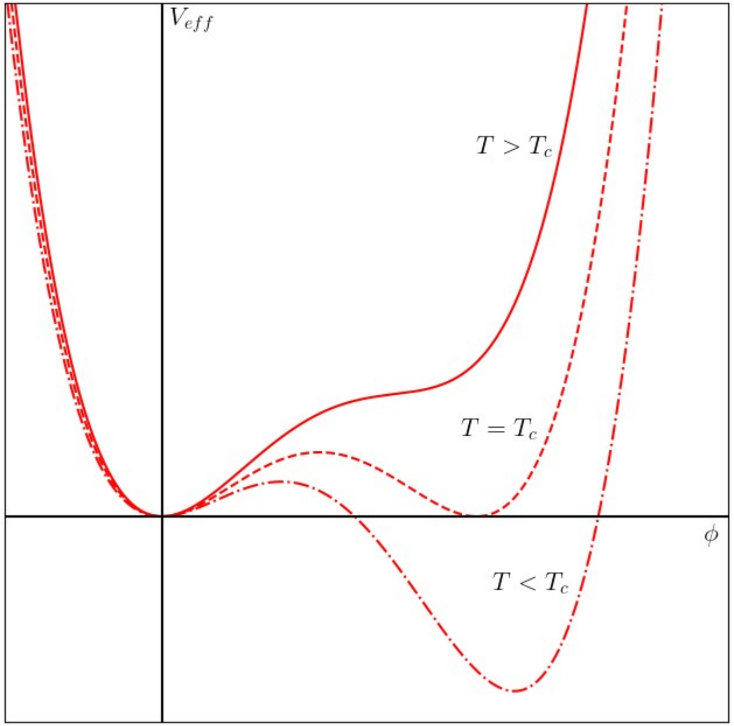
- *Collapse of Fermi balls from filtered out DM during <u>dark</u> FOPT*[1]

$$L=\frac{1}{2}(\partial\phi)^2-V_{eff}(\phi,T)+\overline{\chi}(i\gamma^{\mu}\partial_{\mu}-m_{\chi})\chi-g_{\chi}\phi\overline{\chi}\chi$$

Dark sector
[temp. = T(t)]

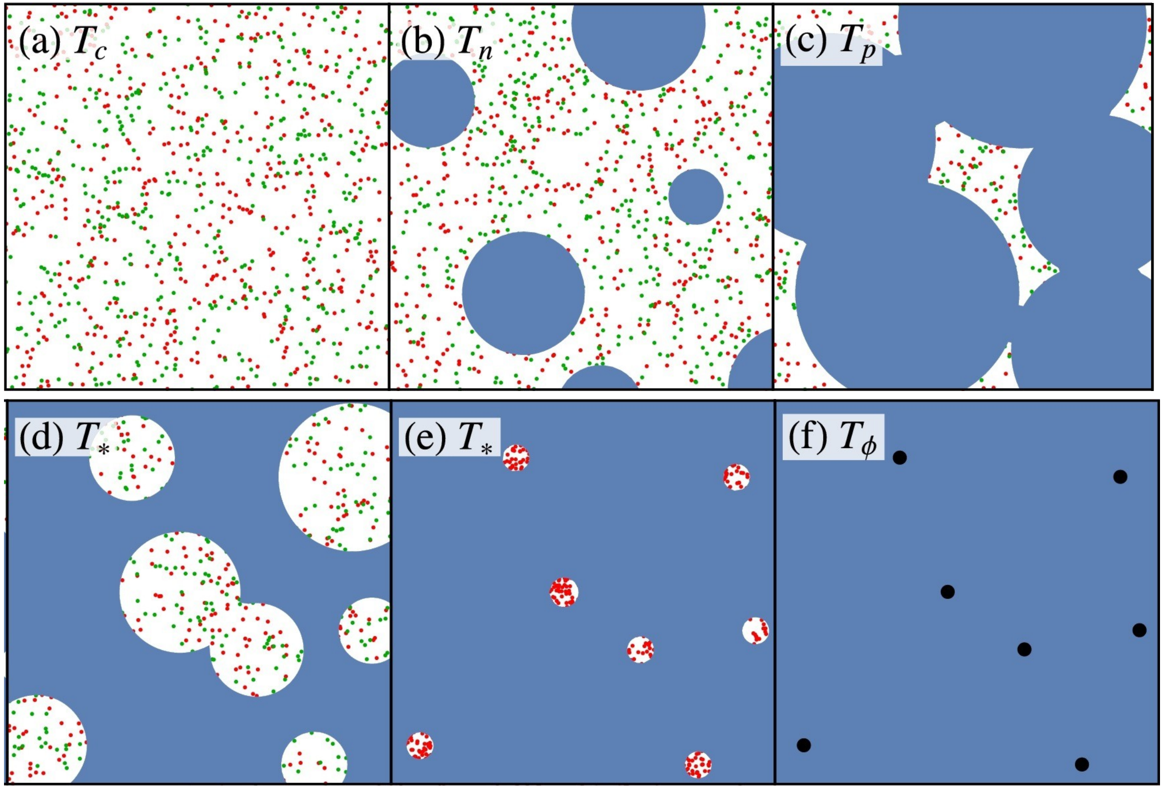
Visible sector
[temp. = T_{SM}(t)]





[1]Kawana, Kiyoharu, and Ke-Pan Xie. "Primordial black holes from a cosmic phase transition: The collapse of Fermi-balls." Physics Letters B 824 (2022): 136791.

Novel PBH formation mechanism



FV bubbles split (f_{FV}=0.29)[2]

Fermi ball formation

Collapse to PBH

$$V = \frac{-g_\chi^2}{4\pi r}\exp(-M_\phi r)$$

$$M_\phi^2 = \frac{d^2 V_{eff}(0,T)}{dT^2} = 2D(T^2 - T_0^2)$$

$$Q_{FB} = \frac{\eta_\chi s_v(t_*)}{f_{FV}(t_*)} A \frac{4\pi R_*^3}{3}$$

U(1) charge in FV bubble

$$M_\phi^{-1} > \frac{R_{FB}}{Q_{FB}^{1/3}}$$

Criterion for FB collapse to PBH

$$M_{FB} = Q_{FB}(12\pi^2 \Delta V_{eff}(T_*))^{1/4}$$

Panels (a)-(f) taken from: Kawana, Kiyoharu, and Ke-Pan Xie. "Primordial black holes from a cosmic phase transition: The collapse of Fermi-balls." Physics Letters B 824 (2022): 136791.

[2]Rintoul, Mark D., and Salvatore Torquato. "Precise determination of the critical threshold and exponents in a three-dimensional continuum percolation model." Journal of physics a: mathematical and general 30.16 (1997): L585.

Novel PBH formation mechanism

- Characterized by a continuous mass distribution
- PBH distribution determined by[3]
  - Generic FOPT parameters: α_{tr}, β/H_*, T_*, T_c
  - Derived FOPT parameters: bubble wall velocity (Chapman-Jouguet; detonations)
  - Other parameters: DM asymmetry parameter (η_χ), $\xi = T/T_{SM}$

$$P(M) = \frac{R_*}{3\left(12\pi^2 \Delta V_{eff}(T_*)\right)^{1/4}} \frac{dn}{dR_r}(t_*) \frac{1}{\eta_\chi s_v(t_*)}$$

$$\alpha_{tr} = \frac{\left(1 - T/4\, d/dT\right)\Delta V_{eff}}{\rho_R}, \alpha_d = \alpha_{tr} \frac{\rho_R}{\rho_d}$$

$$\Delta V_{eff} \approx \epsilon_c \left(1 - \frac{T}{T_c}\right)$$

$$\frac{\beta}{H_*} \simeq T_* \frac{d}{dT}\left[\frac{S_3}{T}\right]_{T=T_*}$$

$$v_w = \frac{1}{\sqrt{3}} \frac{1 + \sqrt{2\alpha_d + 3\alpha_d^2}}{1 + \alpha_d}$$

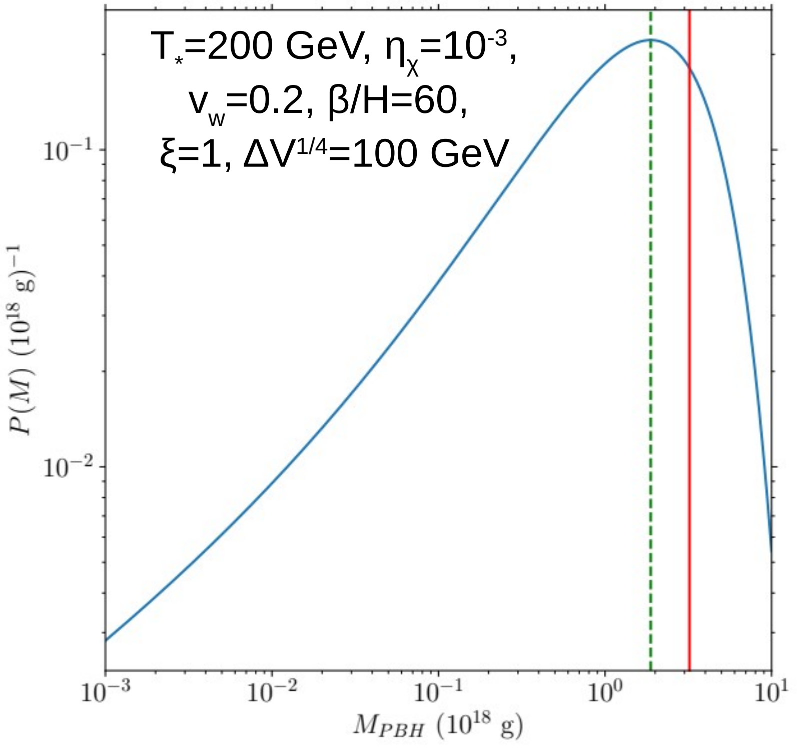
[3]Lu, Philip, Kiyoharu Kawana, and Ke-Pan Xie. "Old phase remnants in first-order phase transitions." Physical Review D 105.12 (2022): 123503.

Novel PBH formation mechanism

$$\langle M \rangle \simeq (4.07 \times 10^{-8} M_{\odot}) \left(\frac{10.63}{g_*}\right)^{1/4} \left(\frac{0.1\,\mathrm{MeV}}{T_*}\right)^2 \left(\frac{\xi}{0.1}\right)^2$$
$$\times \left(\frac{\eta_\chi}{10^{-7}}\right) \left(\frac{v_w}{1}\right)^3 \left(\frac{2.5 \times 10^2}{\beta/H_*}\right)^3 \left(\frac{\alpha_{tr}}{0.1}\right)^{1/4} \left[\frac{\mathcal{F}(T_*/T_c)}{0.308}\right]^{1/4}$$

$$\omega_{PBH,*} \simeq 0.434 \left(\frac{\alpha_{tr}}{0.1}\right)^{1/4} \left(\frac{g_*}{10.63}\right)^{1/4} \left(\frac{T_*}{0.1\,\mathrm{MeV}}\right)$$
$$\left(\frac{0.1}{\xi}\right) \left(\frac{\eta_\chi}{10^{-7}}\right) \left[\frac{\mathcal{F}(T_*/T_c)}{0.308}\right]^{1/4}$$

$$F(x) \equiv \frac{1-x}{1-3x/4}$$



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- Pulsar timing
  - Doppler shift
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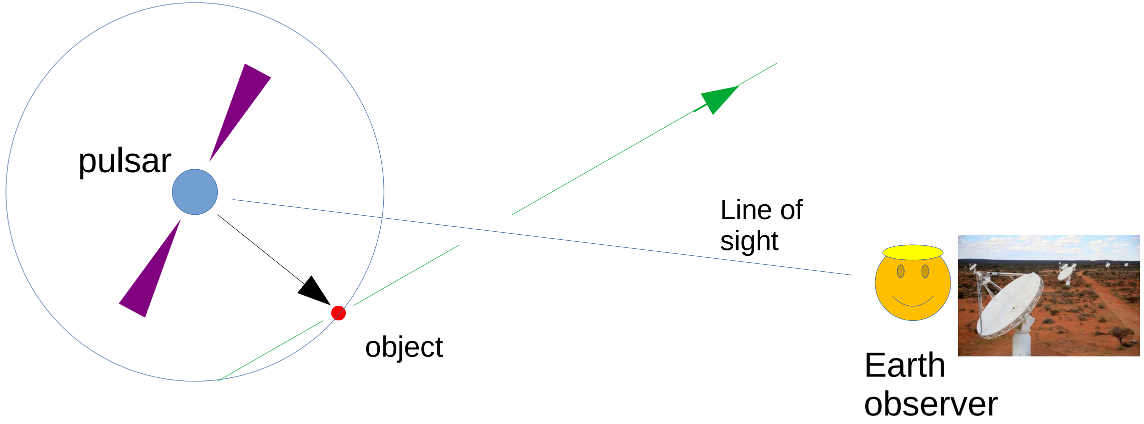
Pulsar timing: Doppler



$$n\pi b^2 vT \sim \pi n^{1/3} vT$$

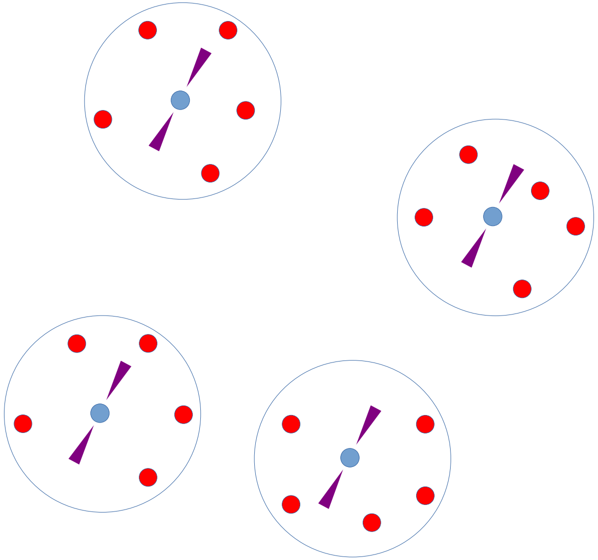
$$\sim f^{1/3}\left(\frac{10^{-8}M_{sun}}{M}\right)^{1/3}\left(\frac{v/c}{10^{-3}}\right)\left(\frac{T}{20\ yrs}\right)$$

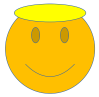
$$\left(\frac{\delta\nu}{\nu}\right)_D = \frac{1}{c}\hat{d}\cdot\int\vec{\nabla}\Phi\ dt$$

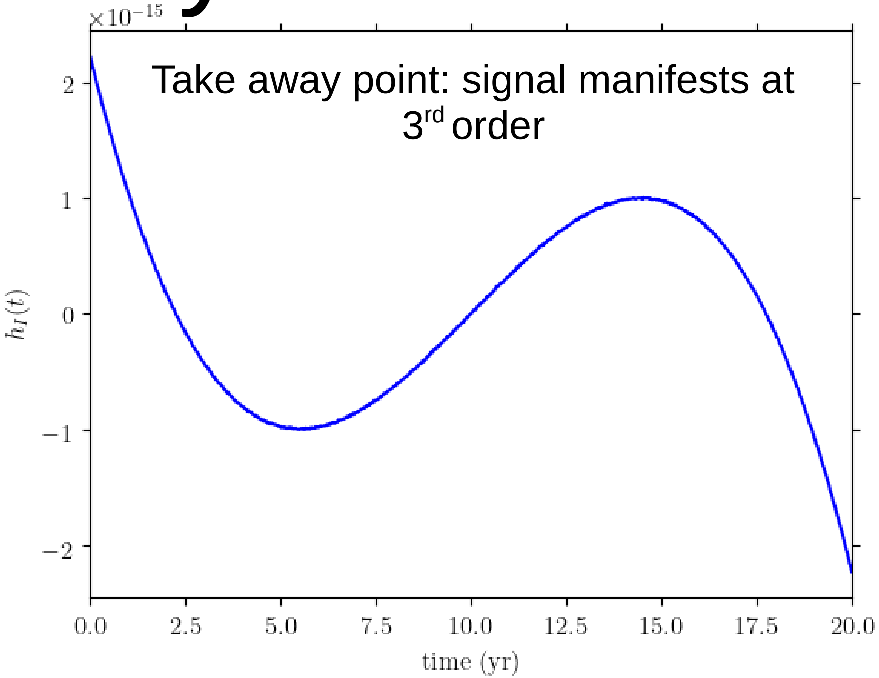
Thumbnail image retrieved from:
https://www.atnf.csiro.au/projects/SKA/index.html

Pulsar timing: sensitivity limits[4,5]

(f,M) -> size of simulation volume





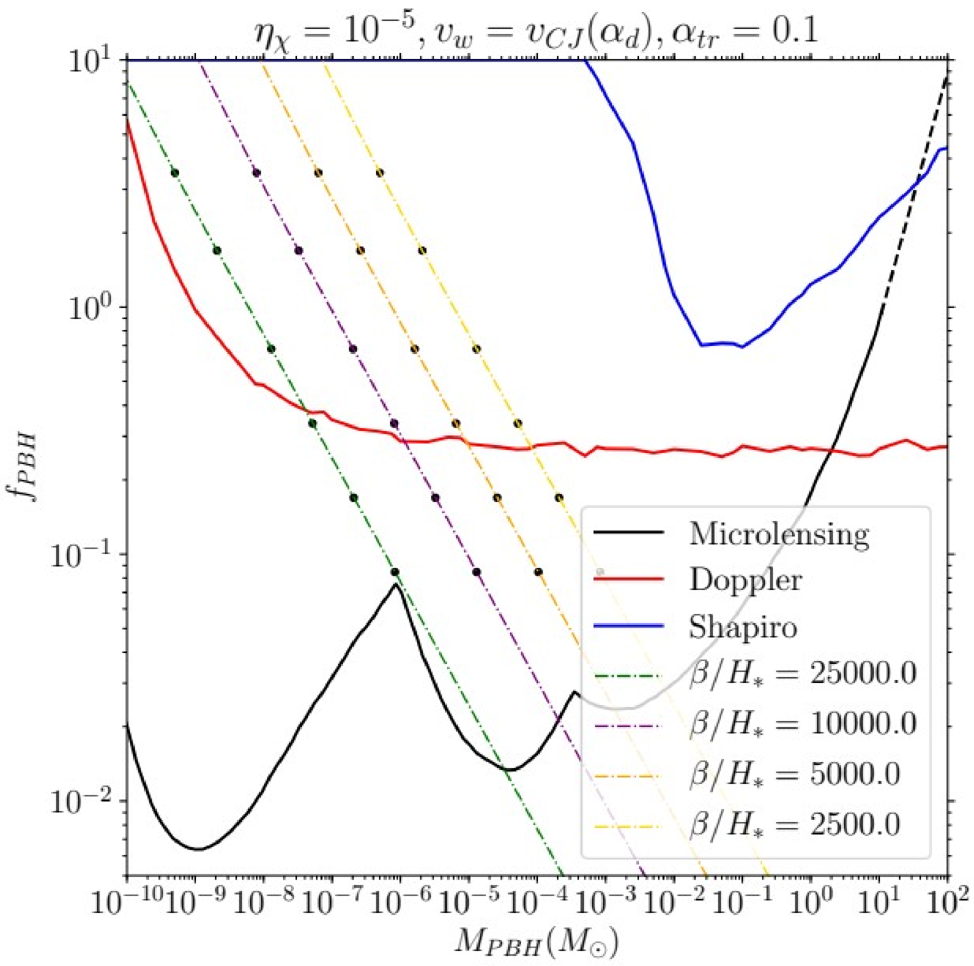


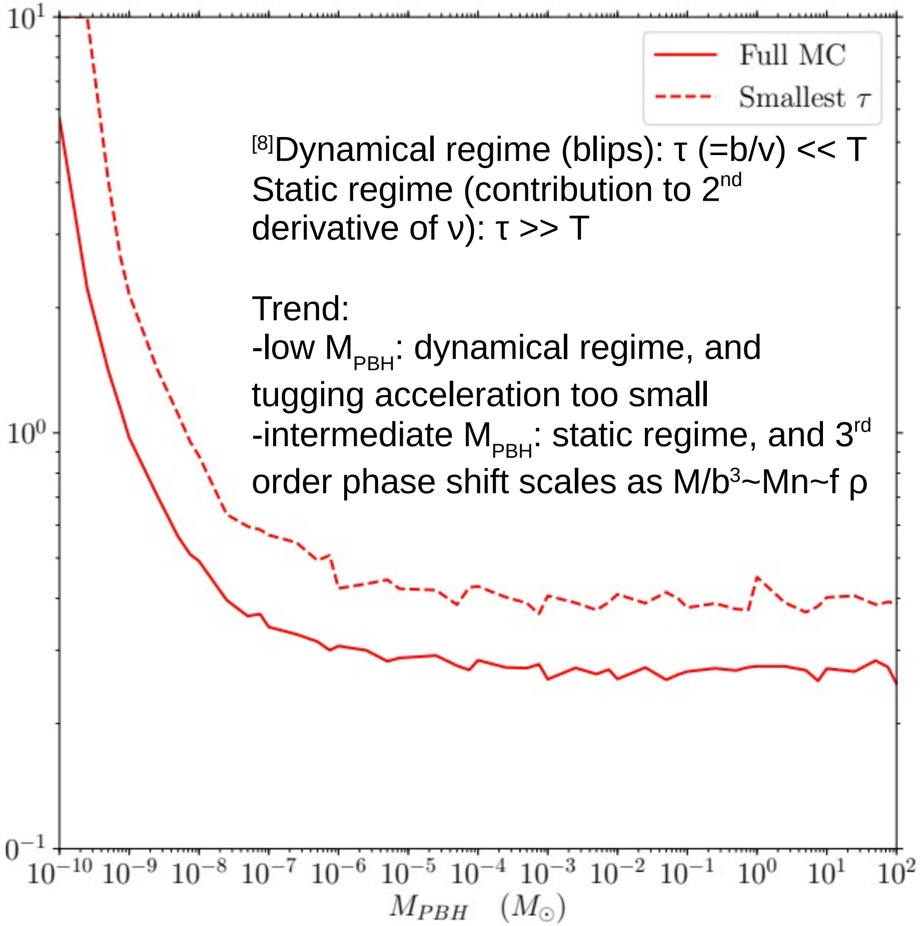
Take away point: signal manifests at 3rd order

$$h_I(t) = \sum_{i=1}^{N} \delta\phi_{I,i}(t) - \delta\phi_{0,I}(t)$$

$$\mathrm{SNR}_I^2 = \frac{1}{\nu_I^2 t_{rms}^2 \Delta t} \int_0^{T_{obs}} dt \; h_I^2(t).$$

[4]Lee, Vincent SH, et al. "Probing small-scale power spectra with pulsar timing arrays." Journal of High Energy Physics 2021.6 (2021): 1-30
[5]Ramani, Harikrishnan, Tanner Trickle, and Kathryn M. Zurek. "Observability of dark matter substructure with pulsar timing correlations." Journal of Cosmology and Astroparticle Physics 2020.12 (2020): 033.



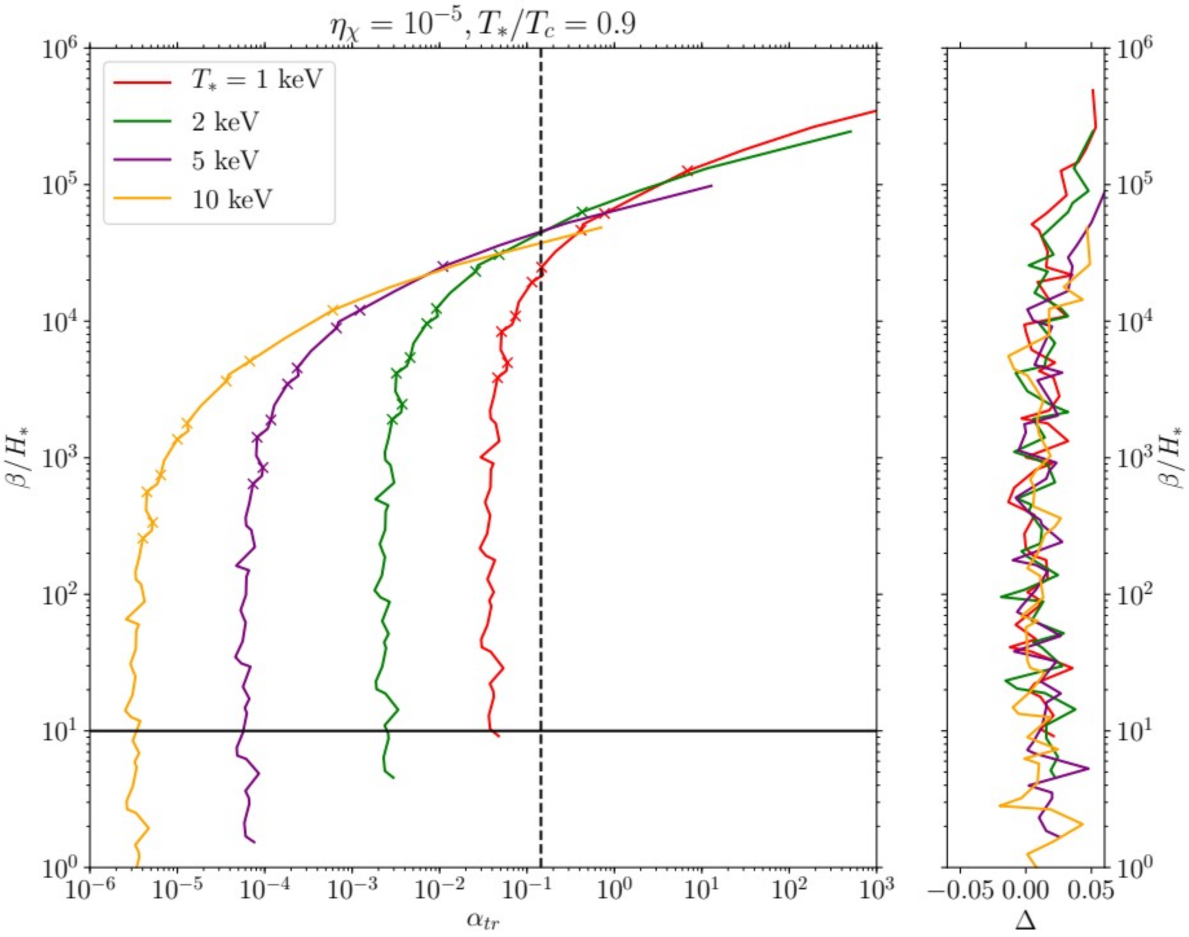


[8]Dynamical regime (blips): τ (=b/v) << T
Static regime (contribution to 2nd derivative of ν): τ >> T

Trend:
-low M_{PBH}: dynamical regime, and tugging acceleration too small
-intermediate M_{PBH}: static regime, and 3rd order phase shift scales as M/b^3~Mn~f ρ

Plots from: JTA, Po-yan Tseng hep-ph/2304.10084

[6]Dror, Jeff A., et al. "Pulsar timing probes of primordial black holes and subhalos." Physical Review D 100.2 (2019): 023003.



Pulsar timing limits:
Novel PBH scenario

Recall:
-f depends on: $\alpha^{1/4}$ T_*
-<M> depends on $\alpha^{1/4}$, s/β^3

Plot from: JTA, Po-yan Tseng
hep-ph/2304.10084

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Complementary signal: Stochastic GWs

- GW through sound waves, nonrunaway bubbles
- Assess sensitivity reach using some SNR
- Peak-integrated sensitivity curves (PISC)[7] as a means to calculate SNR

$$\Omega_s(f)h^2 = \Omega_s^{peak}h^2 \; \mathcal{S}_s(f, f_s)$$

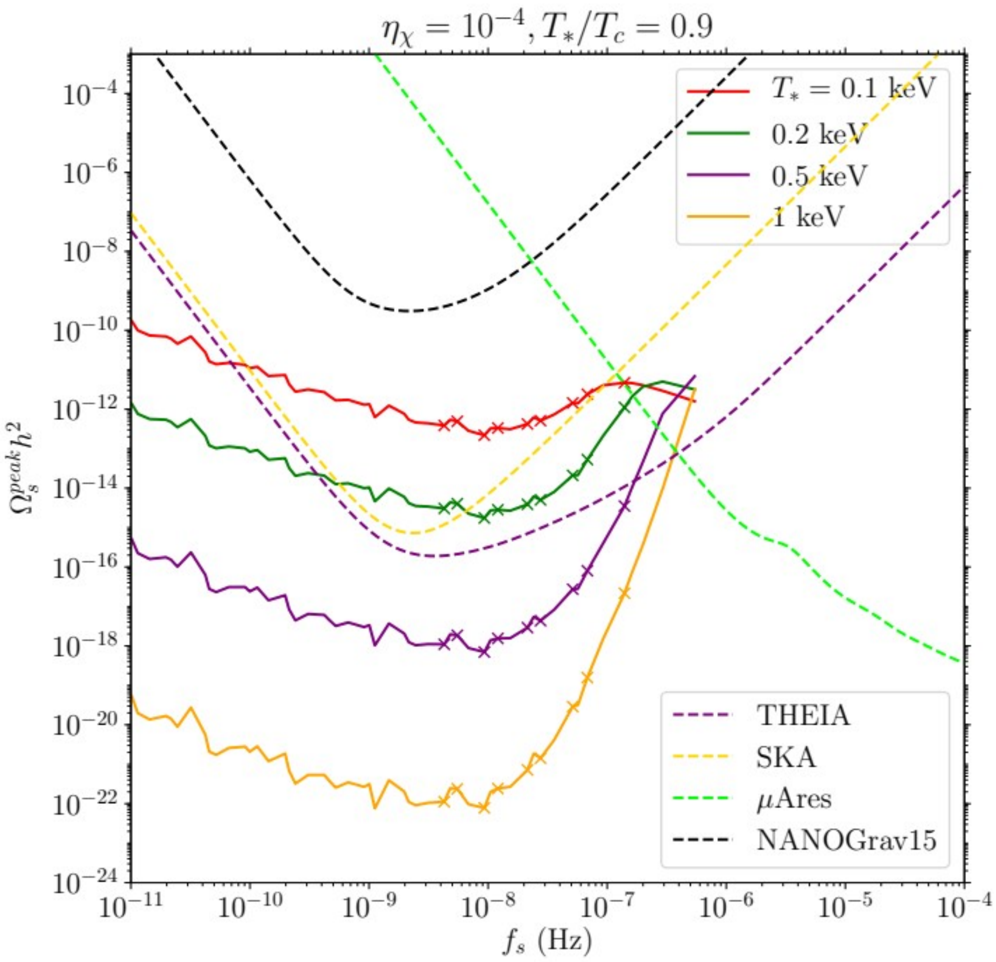
$$\mathcal{S}_s(f, f_s) = \left(\frac{f}{f_s}\right)^3 \left[\frac{7}{4 + 3(f/f_s)^2}\right]^{7/2}$$

$$\rho^2 \equiv n_{det}\tau_{obs,GW} \int_{f_{min}}^{f_{max}} df \; \left[\frac{\Omega_{sig}(f)h^2}{\Omega_{noise}(f)h^2}\right]^2$$

$$\rho(f_s) = \frac{\Omega_{peak}h^2}{\Omega_{PIS}(f_s)h^2}$$

$$\left(\Omega_{PIS}h^2\right)^{-2}(f_s) \equiv n_{det}\tau_{obs,GW} \int_{f_{min}}^{f_{max}} df \; \left[\frac{\mathcal{S}(f, f_s)}{\Omega_{noise}(f)h^2}\right]^2$$

[7] Schmitz, Kai. "New sensitivity curves for gravitational-wave signals from cosmological phase transitions." Journal of High Energy Physics 2021.1 (2021): 1-62.



$$\Omega_s^{peak} h^2 \simeq 2.65 \times 10^{-6} \left(\frac{v_w}{\beta/H_*}\right) \left[\frac{100}{g_{*\rho,v}(T_*)}\right]^{1/3} \left(\frac{\kappa_s \alpha_{tr}}{1+\alpha_{tr}}\right)^2 \left(1 + \frac{g_{*\rho,d}}{g_{*\rho,v}}\xi^4\right)$$

$$f_s \simeq 1.9 \times 10^{-2}\,\text{mHz} \left[\frac{g_{*v}(T_*/\xi)}{100}\right]^{1/6} \left(\frac{T_*}{100\,\text{GeV}}\right) \left(\frac{\beta/H_*}{v_w}\right) \left(1 + \frac{g_{*\rho,d}}{g_{*\rho,v}}\xi^4\right)^{1/2} \frac{1}{\xi}$$

SKA is sensitive to ~0.1 keV (~1 keV) for η = 10^{-4} (10^{-5})

Plot from: JTA, Po-yan Tseng
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Generic quartic potential

$$V_{eff}(\phi, T) = D\left(T^2 - T_0^2\right)\phi^2 - (AT + C)\phi^3 + \frac{\lambda}{4}\phi^4$$

cf. Ref. [8]

$$-B = -DT_0^2\phi_0^2 - C\phi_0^3 + \frac{\lambda}{4}\phi_0^4$$

$$0 = -2DT_0^2 - 3C\phi_0 + \lambda\phi_0^2,$$

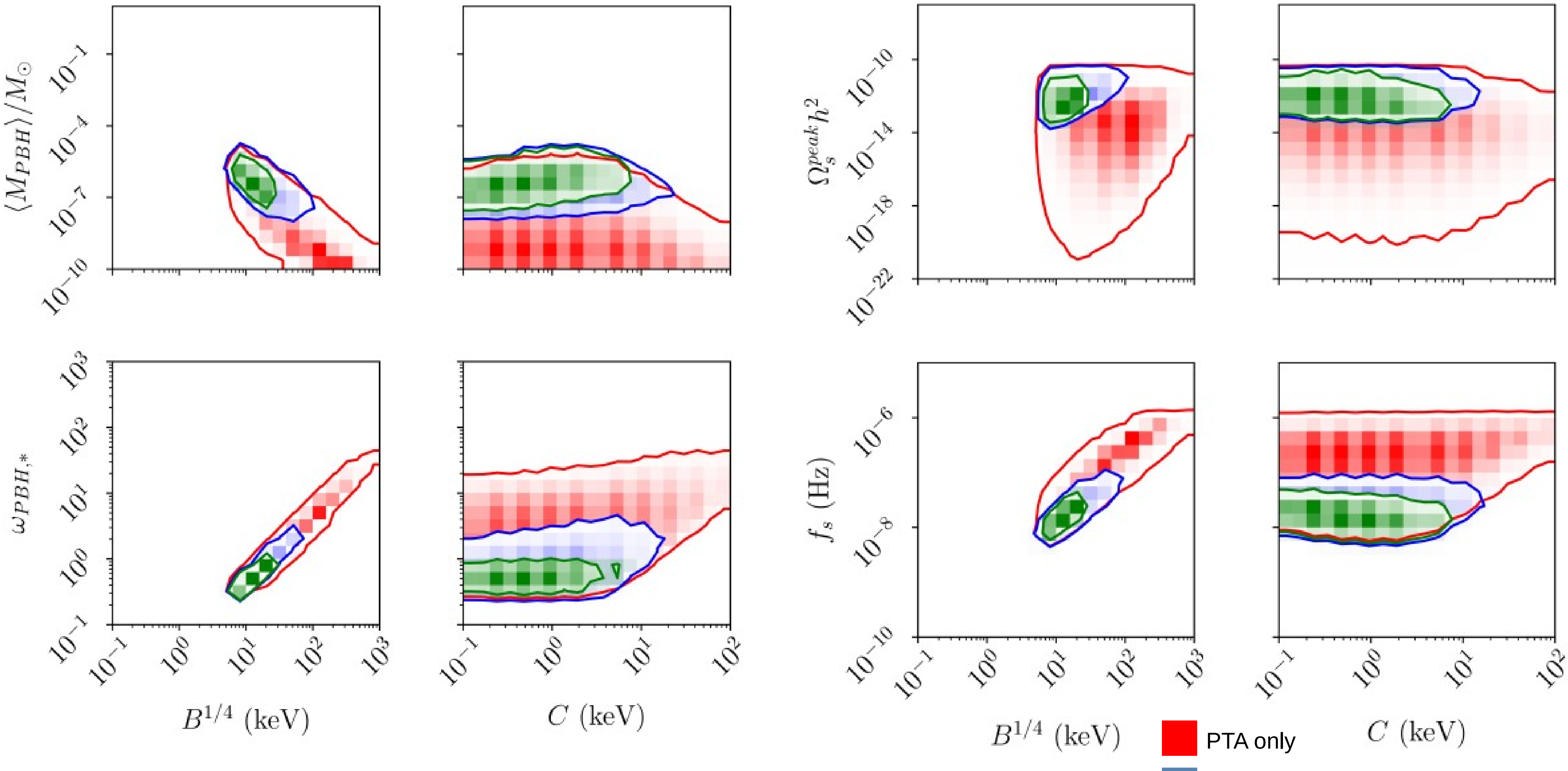
$\{B^{1/4}, C, D, \lambda\}$ → $\{\eta_\chi, T_*, \alpha_{tr}, T_c, \xi, \beta/H_*, v_w\}$ → Observables:

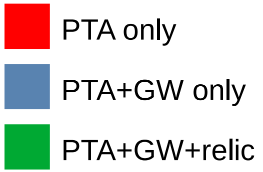
Effective potential parameters

FOPT parameters

Observables:
- -Ave. PBH mass
- -PBH fraction
- -Peak GW abundance
- -Peak GW frequency

[8]Marfatia, Danny, and Po-Yan Tseng. "Correlated signals of first-order phase transitions and primordial black hole evaporation." Journal of High Energy Physics 2022.8 (2022): 1-14.





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Summary

- Presented dark FOPT scenario to produce PBHs and sGWs
- PTA facility can be used to also search for PBHs
- Parameter region: PBH mass of 10^{-8}~10^{-4}, GW frequency of nHz~μHz
- Parameter region: keV-scale FOPT, FOPT rate of 10^{3}~10^{4}, FOPT strength from 10^{-6}~0.1
- Obtained a viable class of generic quartic potentials

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Thank you for your attention!
Cảm ơn đã lắng nghe!
感謝各位的聆聽！

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