Phenomenology of compact objects from a first order phase transition in the dark sector

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[JTA, Po-Yan Tseng (曾柏彥), JHEP 08 (2023) 117
JTA, Danny Marfatia, Po-Yan Tseng, arxiv:24xx.xxxxx]

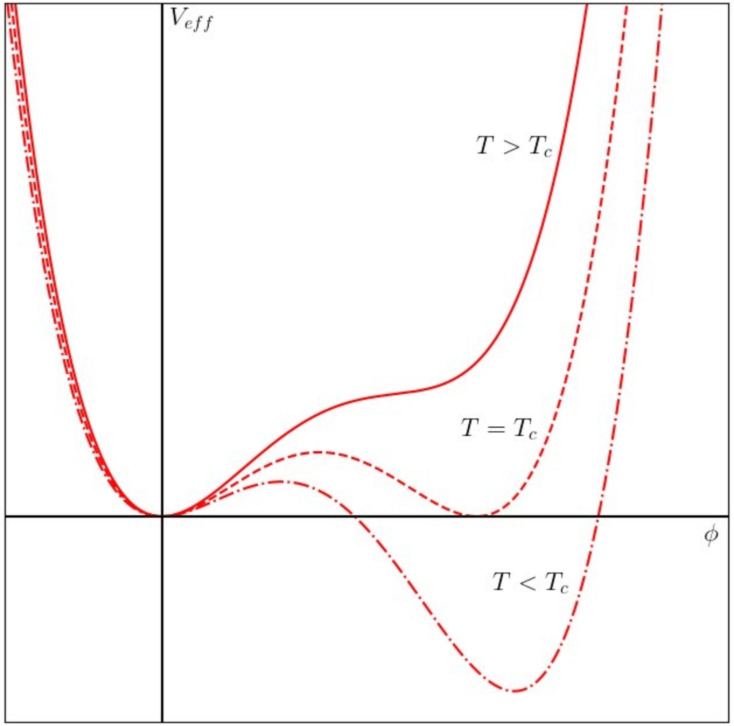
The Future is Flavourful
4th NCTS TG2.1 Future Workshop, NYCU Campus, Hsinchu, Taiwan ROC

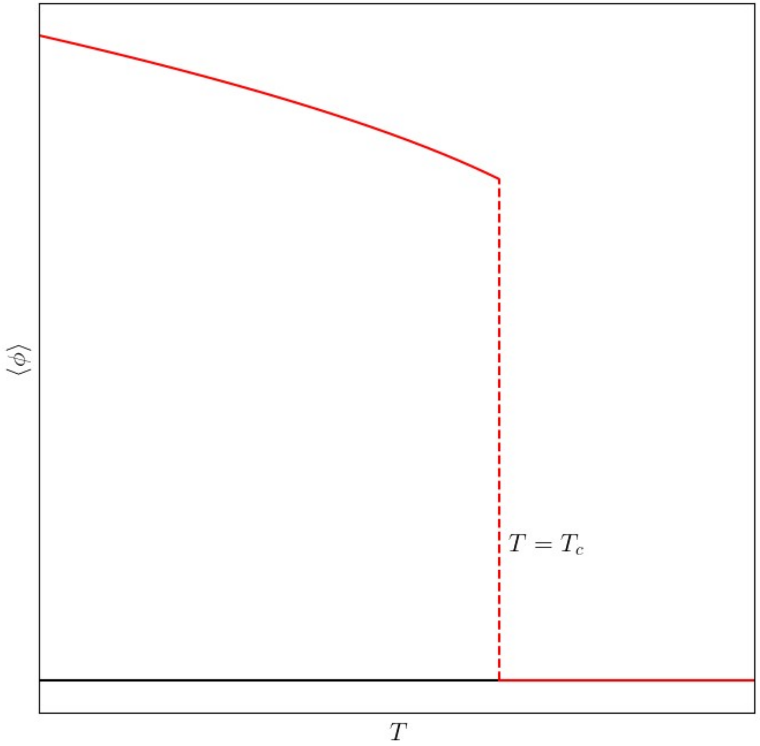
06 June 2024

Outline

- Overview of phase transitions in cosmology
  - sGW production
  - Novel PBH formation mechanism: Fermi ball collapse from dark FOPT
- Pulsar timing
  - Doppler and Shapiro
  - Constraints: sGW and probe of compact objects
- Spin of PBH
- Conclusions

Phase transitions

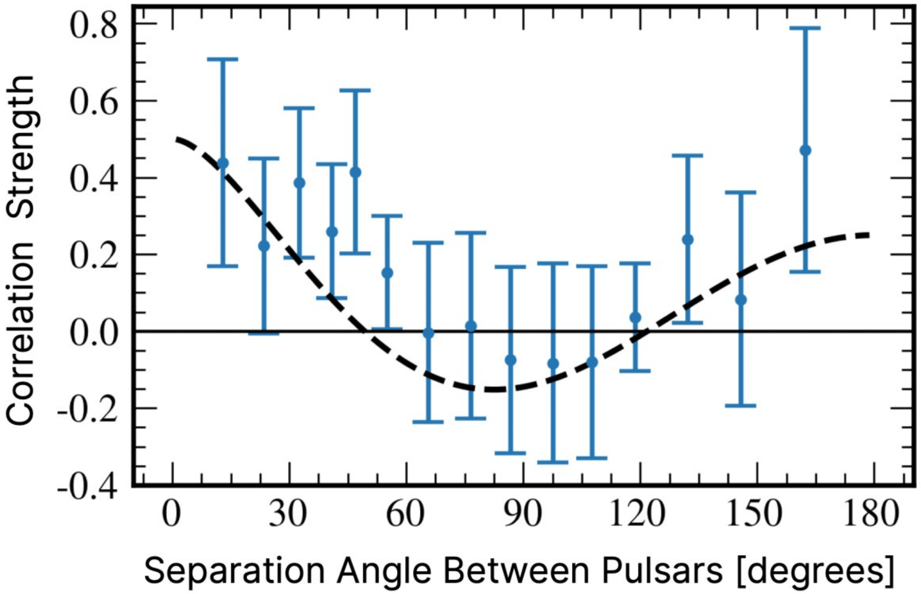




$$V_4(\phi, T) = \frac{\lambda}{4}\phi^4 - (AT + C)\phi^3 + D(T^2 - T_0^2)\phi^2.$$

$$\phi_+(T) = \frac{3(AT + C) + \sqrt{9(AT + C)^2 - 8\lambda D(T^2 - T_0^2)}}{2\lambda}.$$

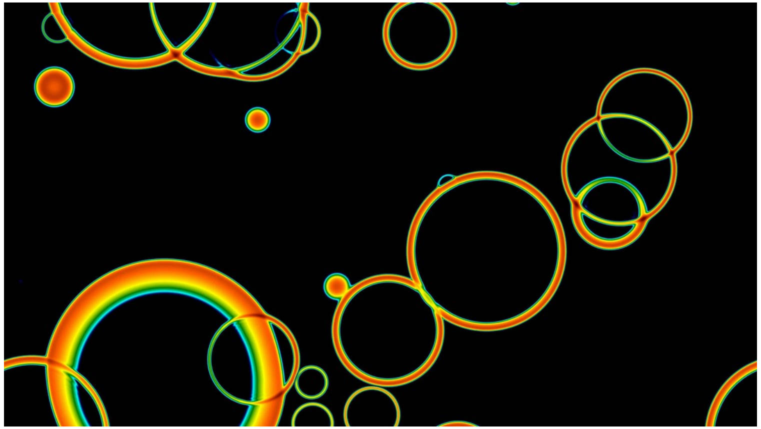
Phase transitions in cosmology



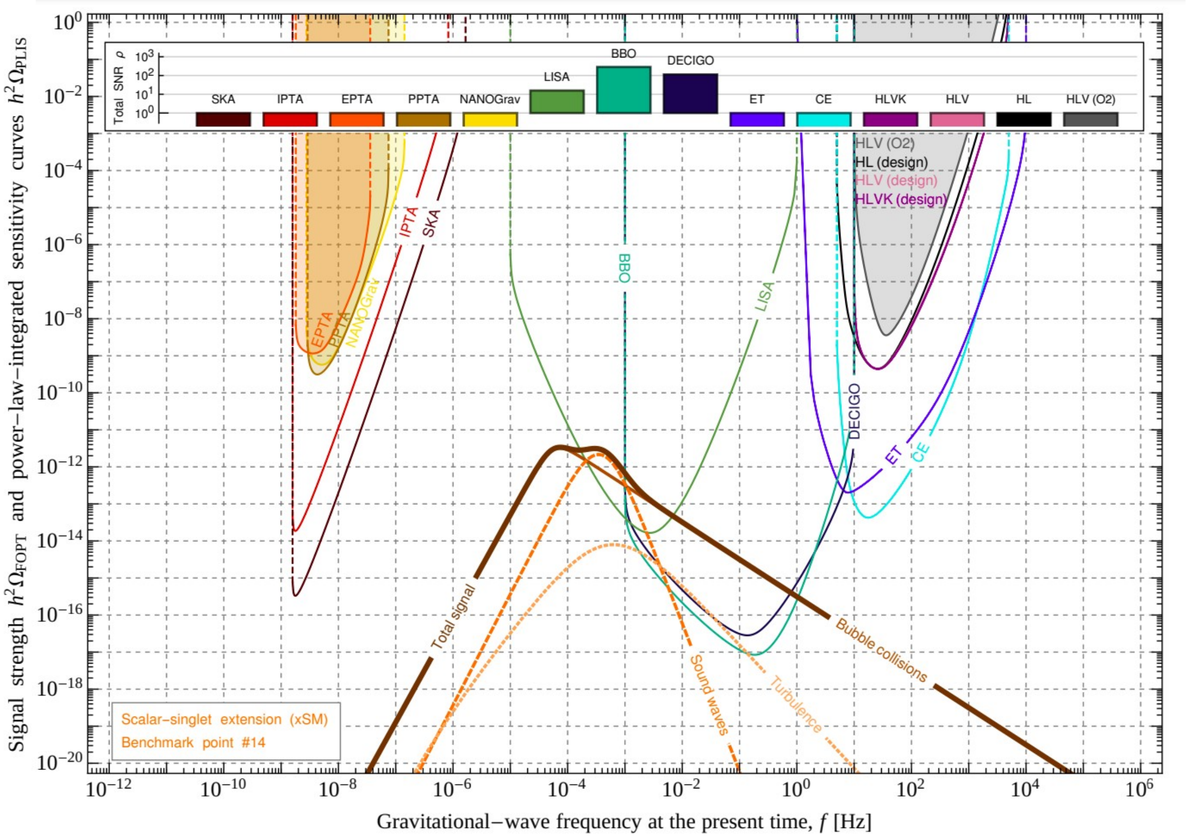
Retrieved from:
https://nanograv.org/15yr/Summary/Background

Retrieved from:
https://nanograv.org/news/nanograv-finds-possible-first-hints-low-frequency-gravitational-wave-background-0

Phase transitions in cosmology

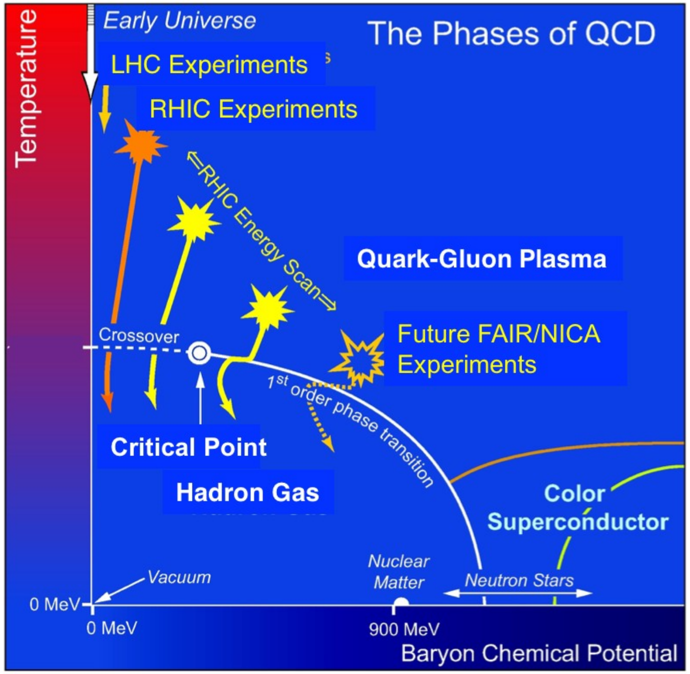


Retrieved from: arXiv:1705.01783



[1]Kai Schmitz (2020)

Phase transitions in cosmology



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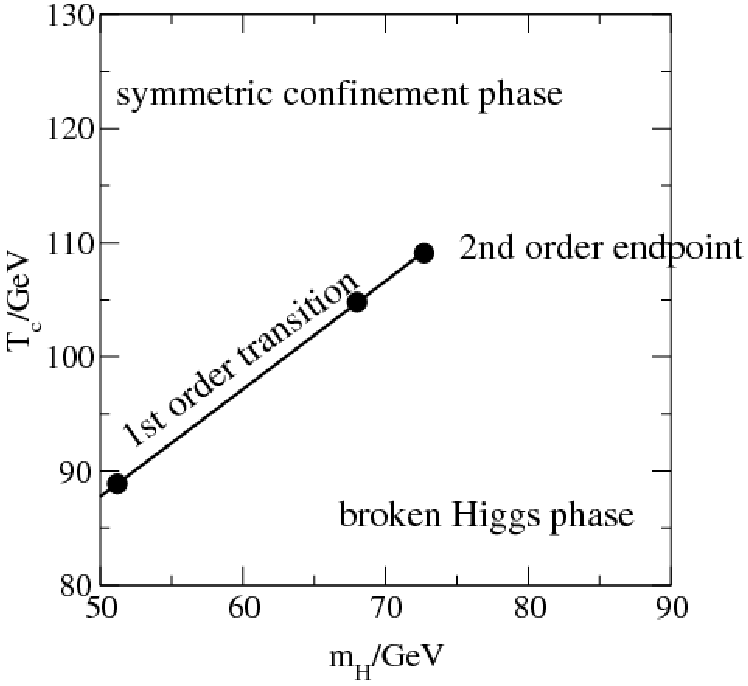
https://cds.cern.ch/record/2729160/files/phases.png



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https://cds.cern.ch/record/471776/files/sm_simple.png

Take-away: all PT in SM are crossovers, strong FOPT may generate huge signal to explain NANOGrav, need physics beyond SM (BSM)

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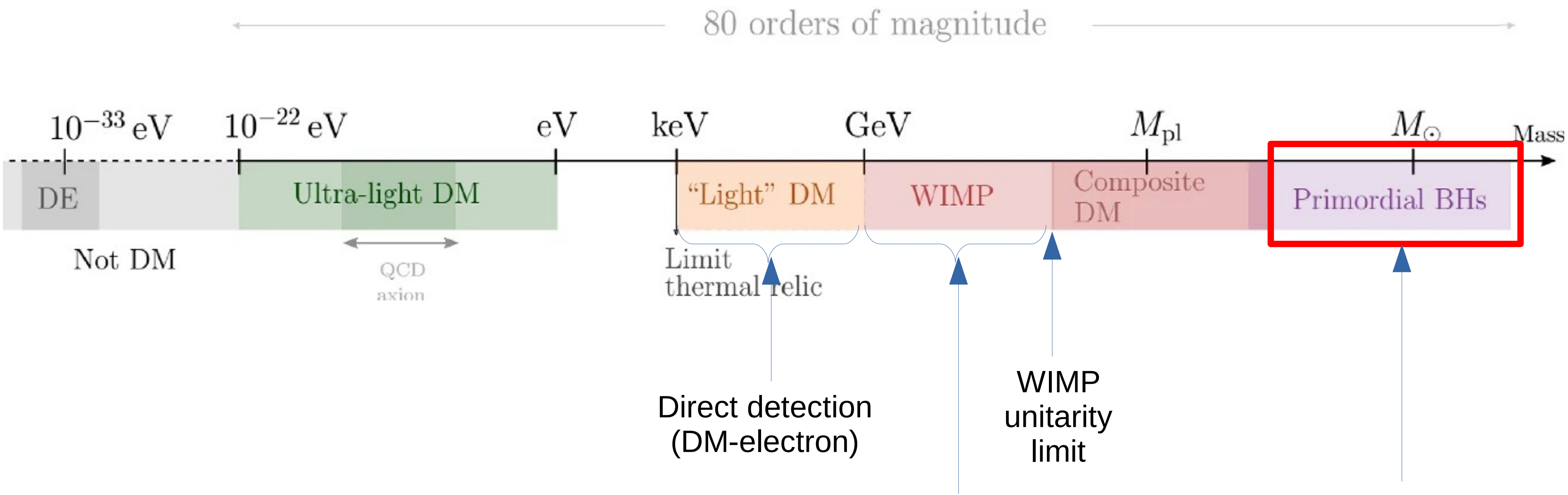
Dark matter



Direct detection (DM-electron)

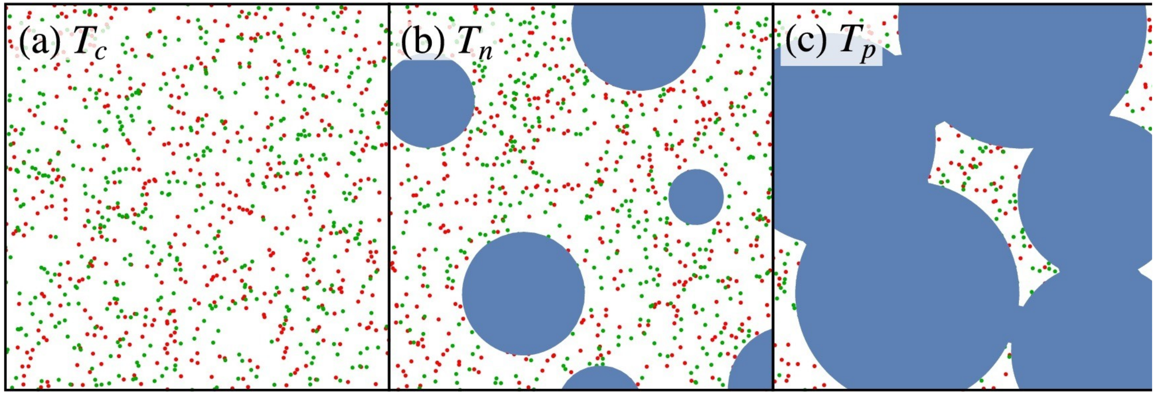
WIMP unitarity limit

Direct detection (DM-nucleon)

Fermi balls, PBH from FOPT

Retrieved from:
https://link.springer.com/article/10.1007/s00159-021-00135-6/figures/1

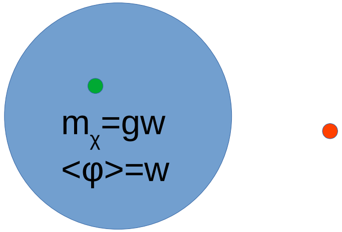
Fermi ball and PBH DM[2]



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

Dark sector
[temp. = T(t)]

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



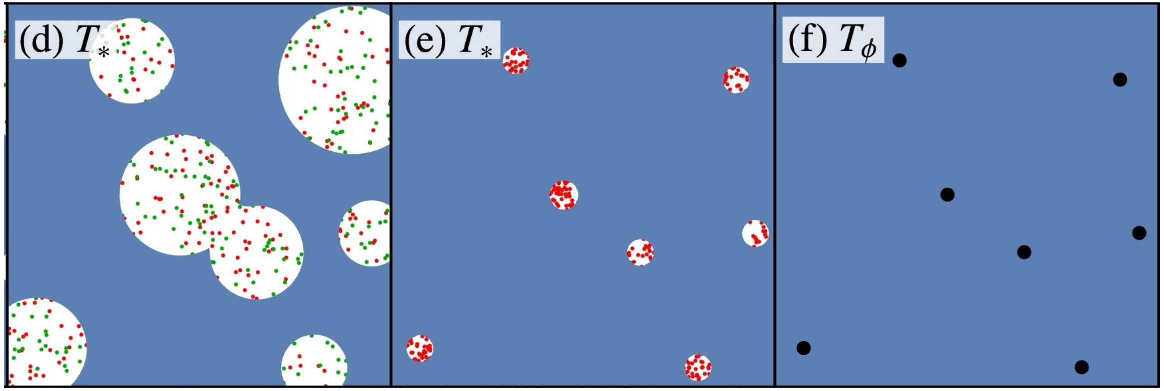
m_χ=gw
<φ>=w

m_χ=0
<φ>=0

gw >> T_*

Panels (a)-(c) taken from:
[2]Kawana, Kiyoharu, and Ke-Pan Xie. (2022)

Fermi ball and PBH DM[2]



FV bubbles split (percolation)

Fermi ball formation

Collapse to PBH

$$U_{tot}=\frac{3\pi}{4}\left(\frac{3}{2\pi}\right)^{2/3}\frac{Q_{FB}^{4/3}}{R}+\frac{4\pi}{3}\Delta V R^3$$

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

U(1) charge in FV bubble

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

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

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

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

Criterion for FB collapse to PBH

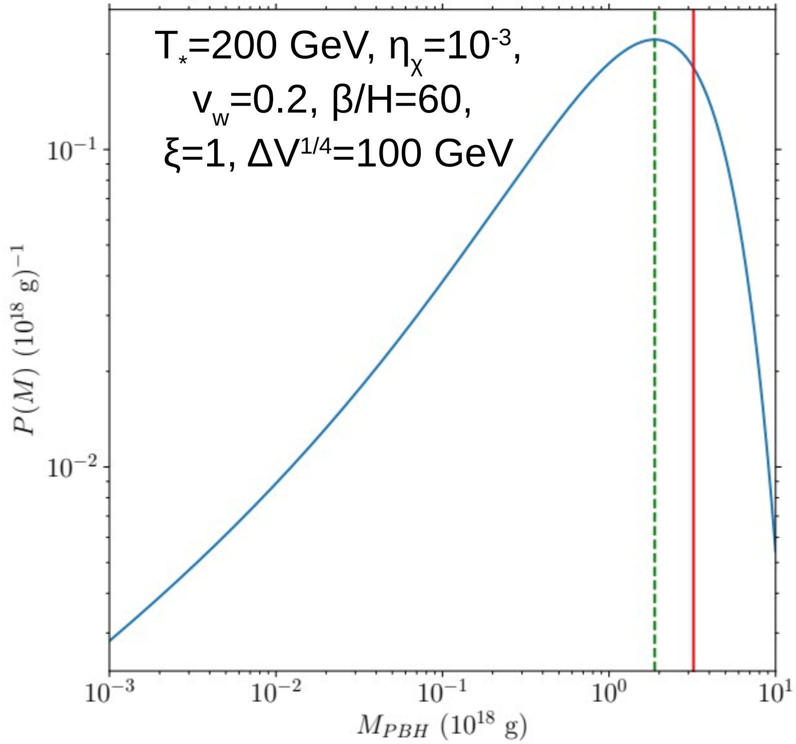
Panels (d)-(f) taken from:
[2] Kawana, Kiyoharu, and Ke-Pan Xie. (2022)

Fermi ball and PBH DM[2]

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

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

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


T_*=200 GeV, η_χ=10^{-3},
v_w=0.2, β/H=60,
ξ=1, $\Delta V^{1/4}$=100 GeV

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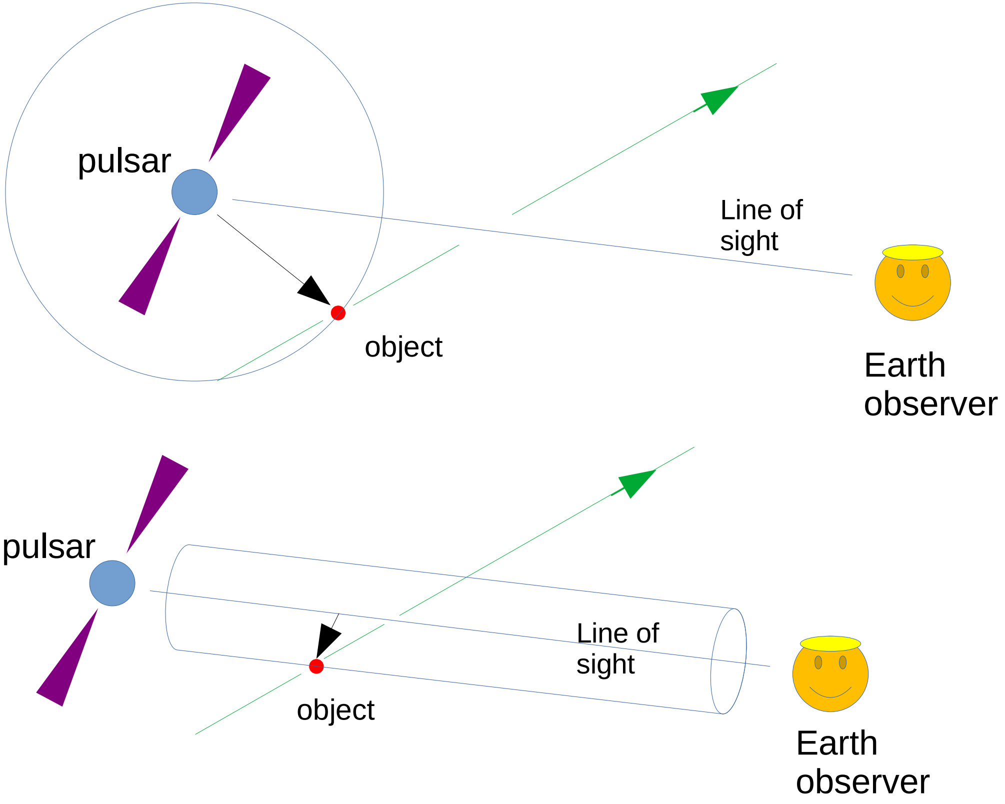
Pulsar timing: Doppler & Shapiro

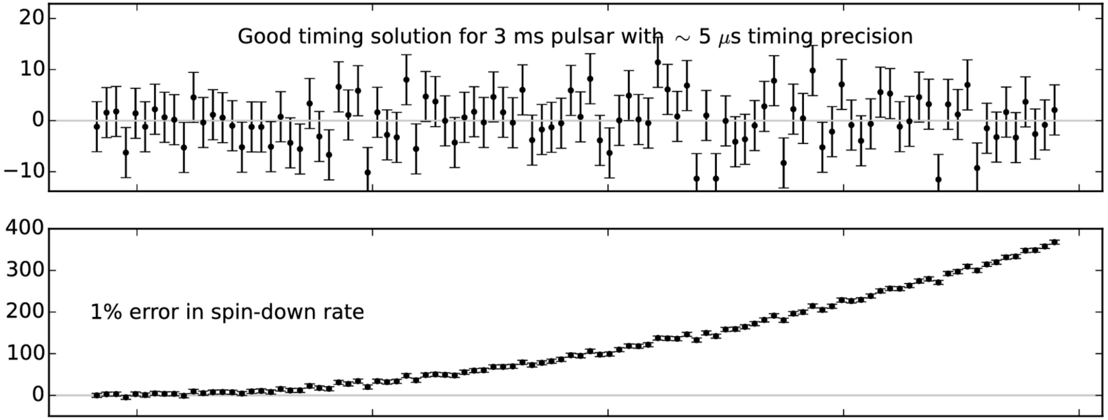


$$\left(\frac{\delta\nu}{\nu}\right)_D = \frac{1}{c}\hat{d}\cdot\int\vec{\nabla}\Phi\ dt$$

$$\left(\frac{\delta\nu}{\nu}\right)_S = -\frac{2}{c^3}\vec{v}\cdot\int\vec{\nabla}\Phi\ dz$$

$$\delta\phi=\int^t dt'\,\delta\nu(t')$$

Pulsar timing: Detector properties



Retrieved from: https://www.cv.nrao.edu/~sransom/web/Ch6.html

PTA property	Value
No. of pulsars	200
RMS timing residual	50 ns
Cadence	2 weeks
Total observation time	20 years

$$\phi(t)=\phi_0+\nu t+\frac{\dot{\nu}}{2}t^2+\frac{\ddot{\nu}}{6}t^3+\dots$$

$$SNR=\frac{|\ddot{\nu}/\nu|}{\sigma_{\ddot{\nu}/\nu}}$$ (?)

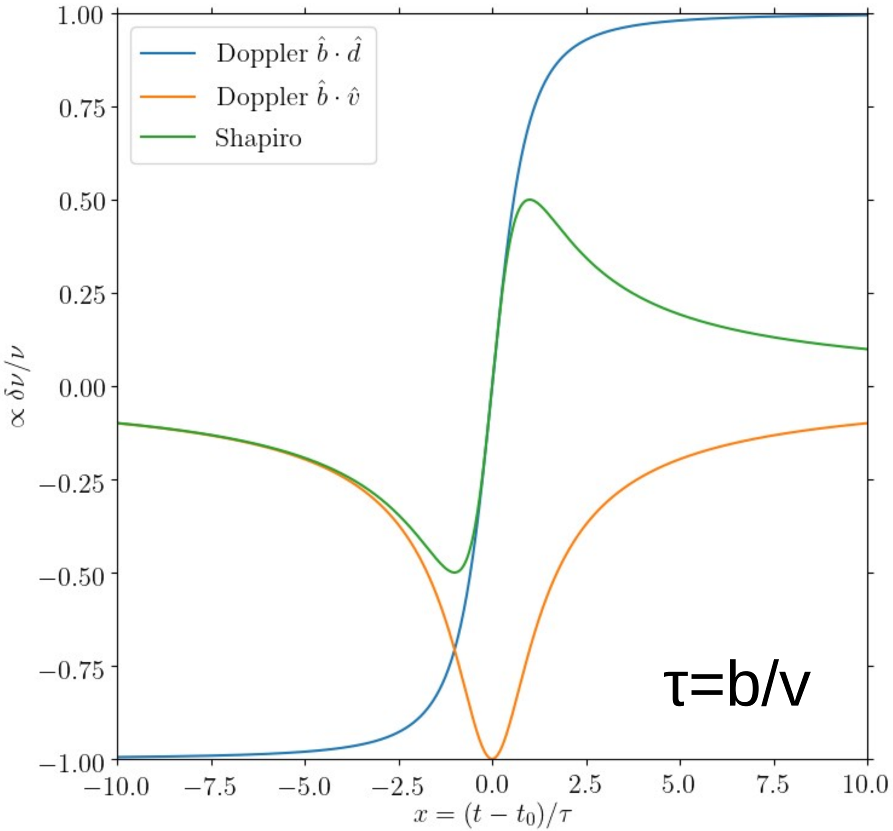
$$\sigma_{\ddot{\nu}/\nu}=6\sqrt{\frac{2800\,\Delta t}{T}}\,\frac{t_{rms}}{T^3}$$

(~2.8 x 10^{-33} Hz^2)

[3]Uncertainty in $\ddot{\nu}/\nu$

[3] Liu, X. J., C. G. Bassa, and B. W. Stappers. (2018)

Pulsar timing: monochromatic, pointlike PBHs



τ=b/v

$$\left(\frac{\delta\nu}{\nu}\right)_D = \frac{G_N M_{PBH}}{v^2 c\tau_D}\frac{1}{\sqrt{1+x_D^2}}(x_D\hat{b}-\hat{v})\cdot\hat{d}$$

$$\left(\frac{\delta\nu}{\nu}\right)_S = \frac{4G_N M_{PBH}}{c^3\tau_S}\frac{x_S}{1+x_S^2}.$$

$$SNR=\frac{|\ddot{\nu}/\nu|}{\sigma_{\ddot{\nu}/\nu}}$$

(~10^{-34} Hz^2)

$$\sigma_{\ddot{\nu}/\nu}=6\sqrt{\frac{2800\,\Delta t}{T}}\frac{t_{rms}}{T^3}$$

(~2.8 x 10^{-33} Hz^2; SNR scales with N_P for Doppler)

Dynamical (τ<<T) vs Static (τ>>T)[4]

[4]Dror, Jeff A., et al. (2019)

Pulsar timing: sensitivity limits[5,6]

$$\delta\phi = \int^{t} dt'\,\delta\nu(t')$$

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

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

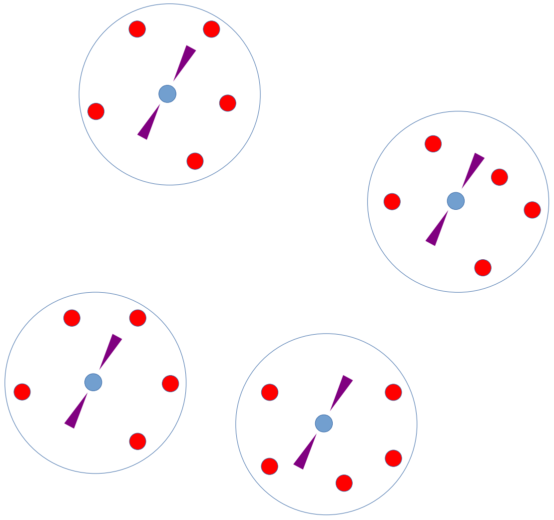
Sensitivity criterion: 90% of mock universes have max SNR > 4

(f,M) -> size of simulation volume

$f\rho_{DM}/M$ -> # density

Maxwell-Boltzmann -> velocity assignment

NB: We developed a parallelizable FORTRAN code to perform the simulation on a 72-core cluster



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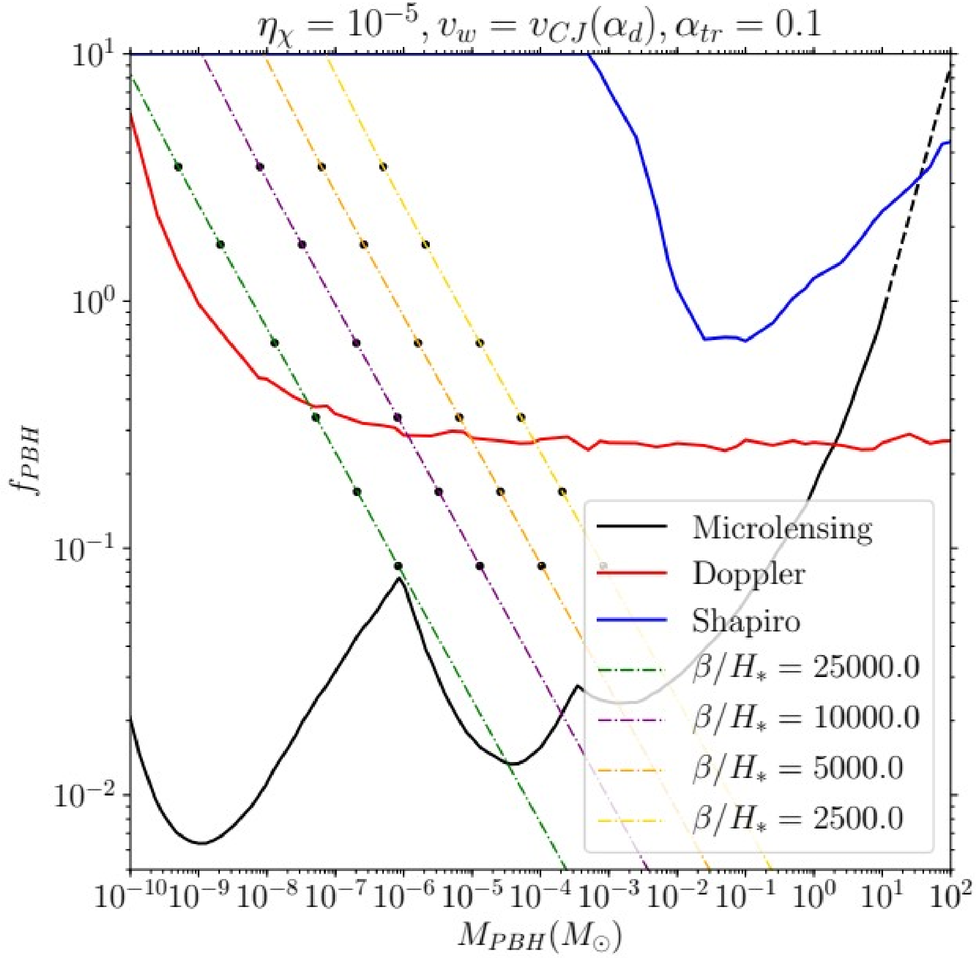
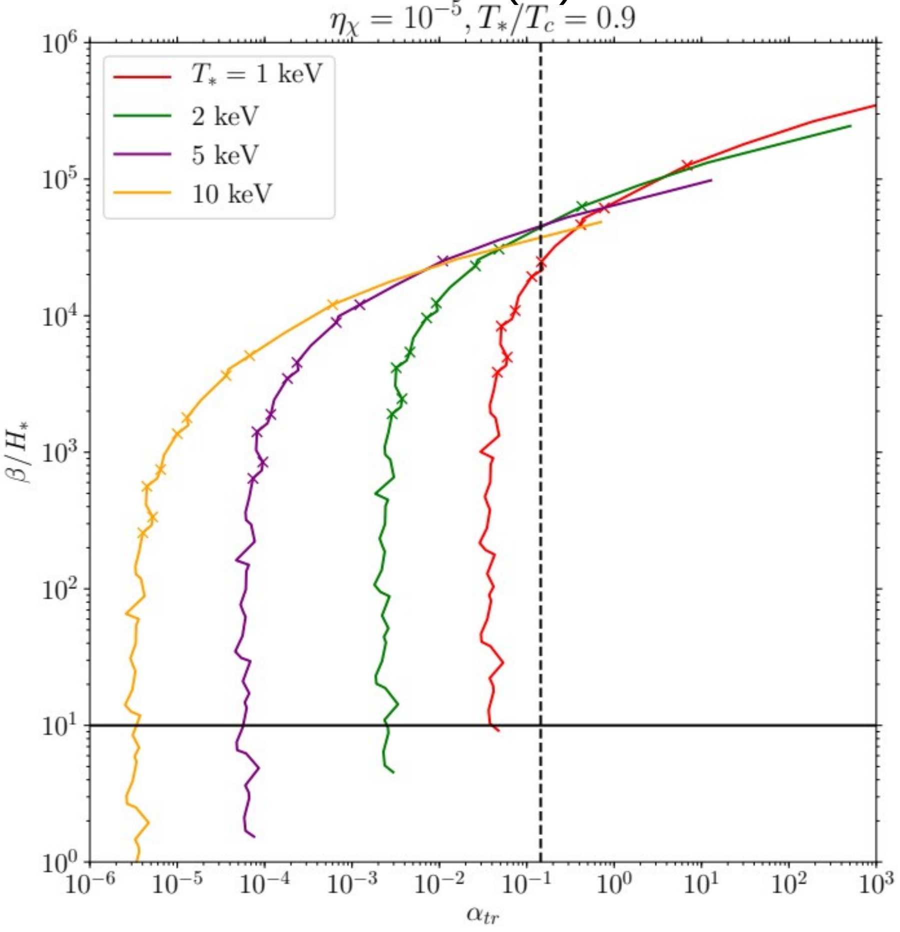
[5] Lee, Vincent SH, et al. (2021)

[6] Ramani, Harikrishnan, Tanner Trickle, and Kathryn M. Zurek. (2020)

Monochromatic PBH mass (benchmark)



Novel PBH formation scenario w/ P(M)



[4]Dror, Jeff A., et al. (2019)
[7]D. Croon, D. McKeen, N. Raj and Z. Wang, (2020)

Plots from: JTA, Po-yen Tseng
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Complementary signal: Stochastic GWs

- GW through sound waves, nonrunaway regime
- Assess sensitivity reach using some SNR
- Peak-integrated sensitivity curves (PISC)[1] as a means to calculate SNR

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

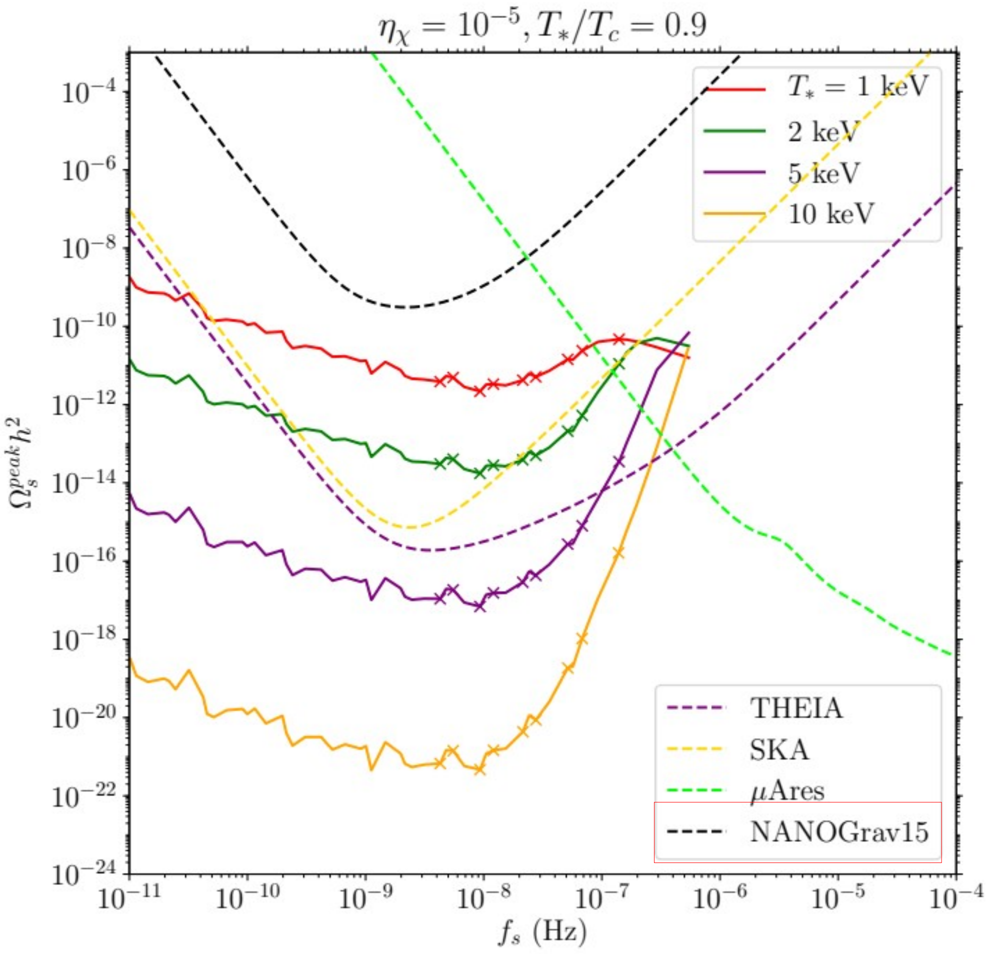
$$\mathcal{S}_s(f, f_s) = \left(\frac{f}{f_s}\right)^3 \left[\frac{7}{4+3(f/f_s)^2}\right]^{7/2}$$

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

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

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

[1] Schmitz, Kai. (2021)



Plot from: JTA, Po-yen Tseng
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<u>Sensitivity criterion</u>: sGW SNR > 1

$$\Omega_s^{peak}h^2 \simeq \boxed{2.65\times10^{-6}}\left(\frac{v_w}{\beta/H_*}\right)\left[\frac{100}{g_{*\rho,v}(T_*)}\right]^{1/3}\left(\frac{\kappa_s\alpha_{tr}}{1+\alpha_{tr}}\right)^2\left(1+\frac{g_{*\rho,d}}{g_{*\rho,v}}\xi^4\right)$$

$$f_s \simeq \boxed{1.9\times10^{-2}\,\mathrm{mHz}}\left[\frac{g_{*v}(T_*/\xi)}{100}\right]^{1/6}\left(\frac{T_*}{100\,\mathrm{GeV}}\right)\left(\frac{\beta/H_*}{v_w}\right)\left(1+\frac{g_{*\rho,d}}{g_{*\rho,v}}\xi^4\right)^{1/2}\frac{1}{\xi}$$

SKA is sensitive to ~1 keV
(~0.1 keV) for $\eta_\chi = 10^{-5}$ (10^{-4})

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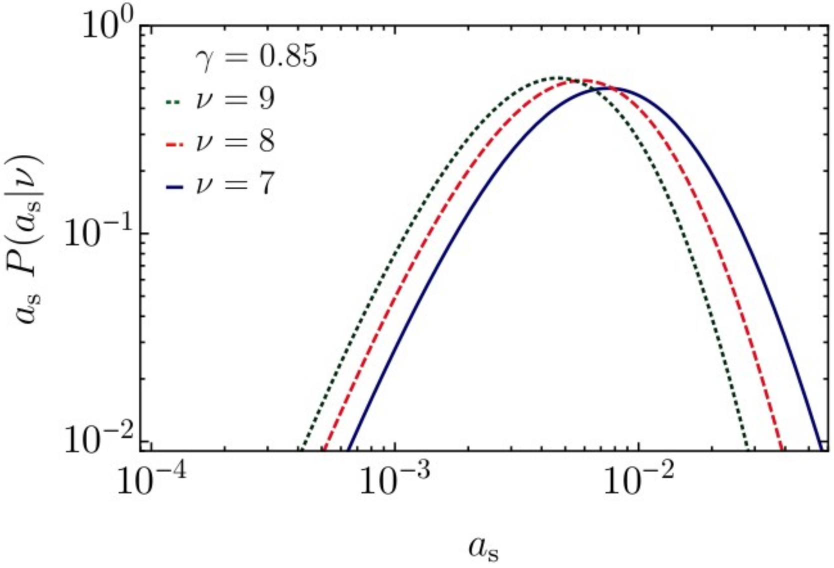
Previous work on PBH spin

- Peebles 1969: galaxy rotation in MD
- Choptuik criticality (Choptuik ‘93; Baumgarte & Gundlach ‘16; Chiba & Yokoyama ‘17)
- 1st vs 2nd order approach (Gruzinov, Mirbabayi, Noreña ‘19; de Luca et al ‘19; Harada et al ‘21)
- *Assume that PBHs are formed from the enhancement of primordial power spectrum*



Taken from: De Luca, Valerio, et al. (2019)

Our approach

- Spin is induced by cosmological perturbations
- Gaussian scale invariant
- Assume spherical proto-object
- Cosmological perturbations could be modified by FOPT[9]

$$\langle \mathcal{R}_k \mathcal{R}_{k'} \rangle = (2\pi)^3 P_{\mathcal{R}}(k)\,\delta^{(3)}(\vec{k}-\vec{k}'),$$

$$P_{\mathcal{R}}(\eta = 0, k) = \frac{2\pi^2}{k^3}\, A_s \left(\frac{k}{k_s}\right)^{n_s-1} .$$

$$A_s = (2.196 \pm 0.060) \times 10^{-9},$$

$$\vec{J}_{F,CM} = \int \rho_F \; a\vec{x} \times \vec{v}\; \sqrt{g_3}\, d^3\vec{x} - \vec{R}_{CM} \times \vec{P}_{CM}$$

$$\vec{J}_{F,CM}(\eta) = 4\pi \bar{\rho}_F R^5 \int d\Pi_k d\Pi_{k'}\; (\vec{k} \times \vec{k}')\, \boxed{\delta_{eff}(\vec{k}, \eta)} \\ \times \left[\boxed{\mathcal{F}(|\vec{k} + \vec{k}'| x_0) - 3\mathcal{F}(k x_0)\mathcal{G}(k' x_0)}\right] \boxed{\hat{\psi}_F(\vec{k}', \eta)}/k' .$$

$$\vec{s} \equiv \frac{\vec{J}}{G_N M^2} .$$

[9] Schmid, Christoph, Dominik J. Schwarz, and Peter Widerin. (1999)

Cosmological evolution

Primordial

$$\mathcal{H} = \frac{1}{\eta}, \quad 0 < \eta < \eta_c$$

Critical point

Supercooling+latent heat release

Percolation

(???)

Fermi ball formation

(???)

PBH collapse

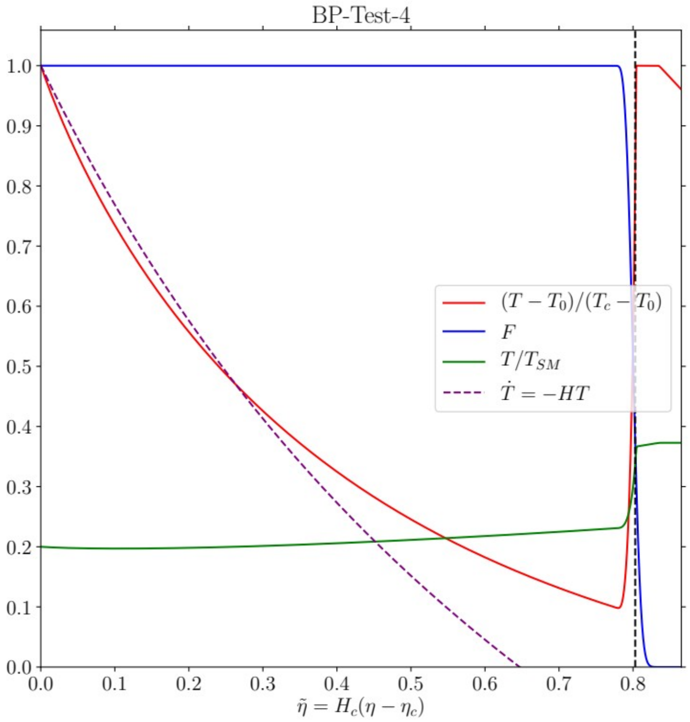
$$\begin{aligned}
\frac{da}{dx} &= ah \\
\frac{dy}{dx} &= -hy\left\{1 - \frac{3FTB'(T)}{4\rho_{\chi+TV}} + \frac{1}{h}\frac{dF}{dx}\left[\frac{B(T) - TB'(T)}{4\rho_{\chi+TV}}\right]\right\}\left[1 - \frac{FT^2B''(T)}{4\rho_{\chi+TV}}\right]^{-1} \\
\frac{dg_1}{dx} &= -8\pi a^3 \frac{\Gamma(T_c y)}{H_c^4} v_w^3 \\
\frac{dg_{i+1}}{dx} &= \frac{g_i}{a}, \quad 1 \le i \le 2 \\
\frac{dF}{dx} &= g_3 \frac{F}{a} \\
\frac{d\tilde{\eta}}{dx} &= \frac{1}{a},
\end{aligned}$$

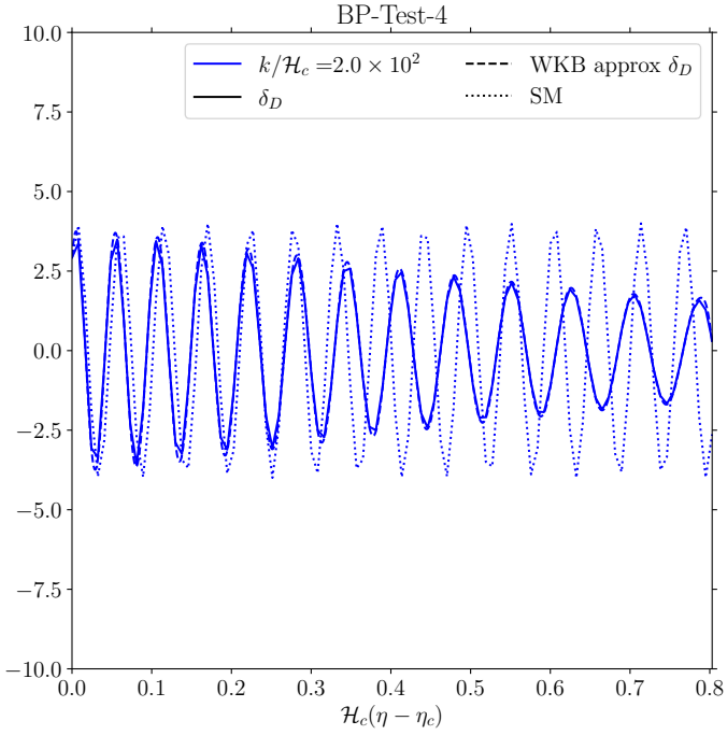
Background evolution

$$\begin{aligned}
\frac{\delta_F'}{\mathcal{H}} - \frac{k}{\mathcal{H}}\hat{\psi}_F + 3(1 + w_F)A_k + 3(c_{s,F}^2 - w_F)\delta_F &= 0, \\
\frac{\hat{\psi}_F'}{\mathcal{H}} + (1 - 3w_F)\hat{\psi}_F + c_{s,F}^2 \frac{k}{\mathcal{H}}\delta_F + (1 + w_F)\frac{k}{\mathcal{H}}A_k &= 0.
\end{aligned}$$

Perturbation evolution

Cosmological evolution



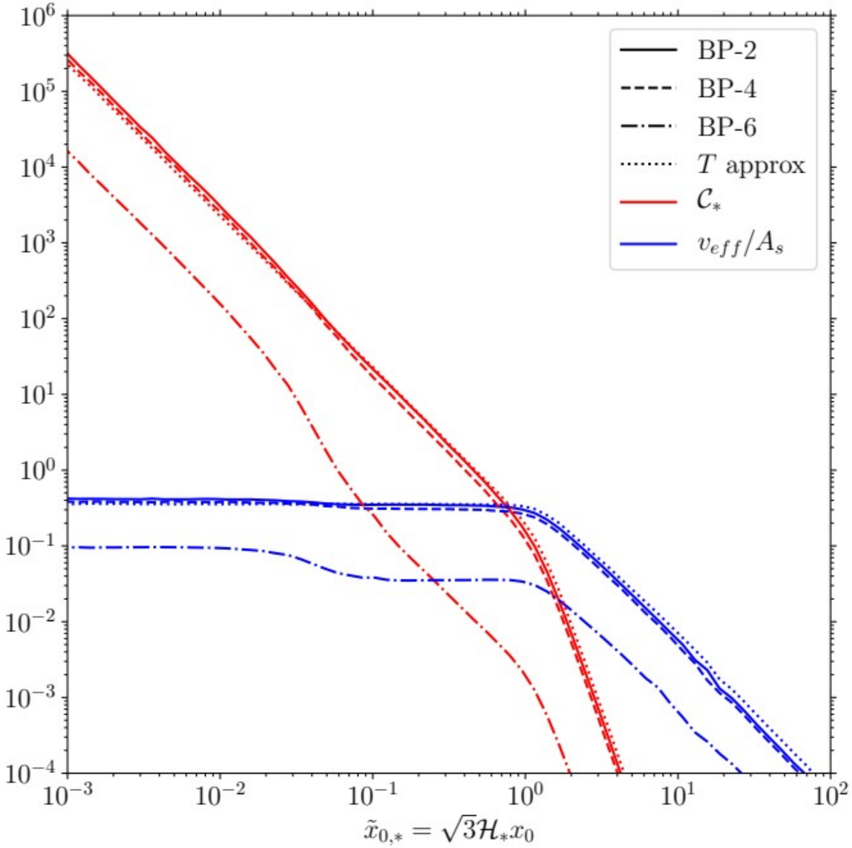


Preliminary results

$$s_{rms,*} = 6\left(1+\frac{\rho_{SM,*}}{\rho_{D,*}}\right)\frac{v_{eff,*}}{\tilde{x}_{0,*}^2},$$

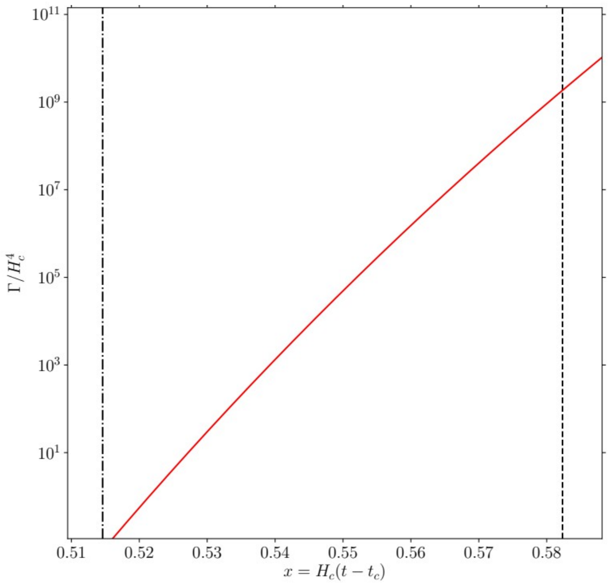
$$v_{eff} = \frac{3}{4}\; A_s \tilde{x}_0(\eta)\mathcal{C}^{1/2}(\tilde{x}_0, x_0),$$

$$\mathcal{C}(\tilde{x}_0, x_0) \equiv A_s^{-2}\int_0^\infty dz\; z\int_0^\infty dz'\; z' \times \int_{-1}^{1} dx\;(1-x^2)\; W^2(z,z';\tilde{x}_0)\Delta^2_{\mathcal{R}}(k)\Delta^2_{\mathcal{R}}(k'),$$



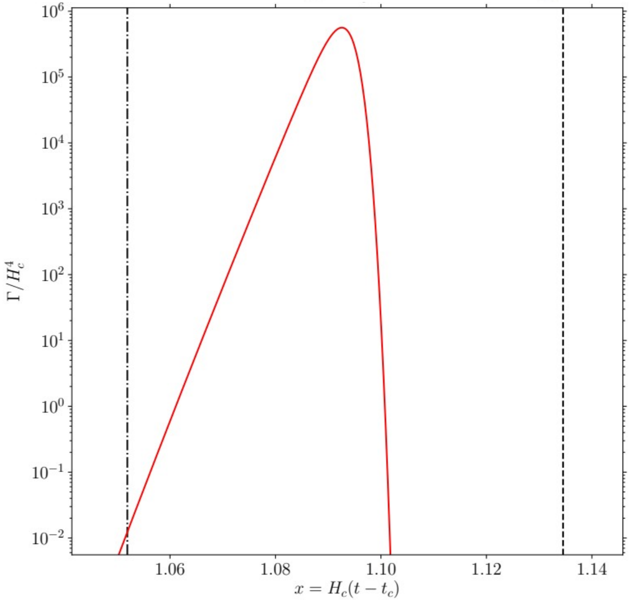
Preliminary results

$$\Gamma(t) \approx \Gamma_0 \exp\left[-\beta_0(t-t_0)\right].$$



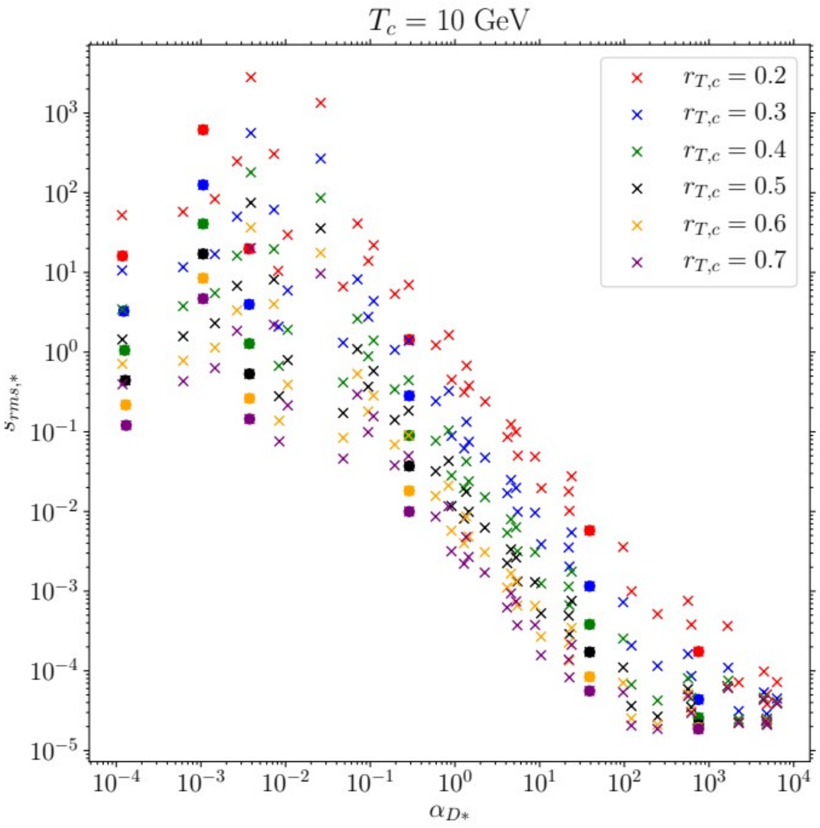
$$\frac{s_{rms,*}}{r^4_{T,c}} \approx \left(\frac{4}{3F_*}\right)^{2/3} v_{eff,*}\left(\frac{\beta_0/H_c}{v_w}\right)^2 \frac{\pi^2}{30}\frac{g_{*SM}}{\frac{3\pi^2}{20}+F_*\frac{L_c}{T_c^4}},$$

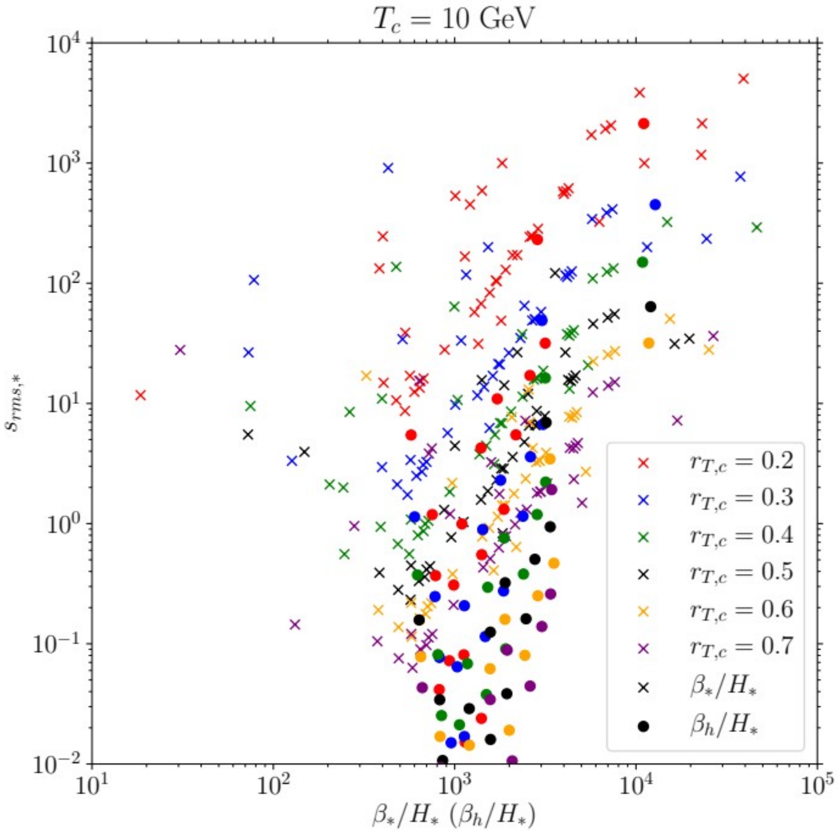
$$\Gamma(t) \approx \Gamma_h \exp\left[-\frac{\beta_h^2}{2}(t-t_h)^2\right].$$



$$\frac{s_{rms,*}}{r^4_{T,c}} \approx \frac{2\pi^3}{15}\, v_{eff,*}\left(\frac{2}{3F_*}\right)^{2/3}\left(\frac{\Gamma_h/H_c^4}{\beta_h/H_c}\right)^{2/3}\frac{g_{*SM}}{\frac{3\pi^2}{20}+F_*\frac{L_c}{T_c^4}},$$

Preliminary results





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Conclusions

- FOPT in early Universe is a subject rich in phenomenology
- Interesting playground to probe fundamental physics and inspiration for exotic physics
- In focus: novel PBH formation mechanism
- Pulsar timing can probe this novel PBH formation scenario
- Sensitivity range: PBH mass of 10^{-8}~10^{-4}, GW frequency of nHz~μHz
- Provided a first step in calculating spin of PBH from this novel formation mechanism

Acknowledgments

- NSTC grant # NSTC 111-2811-M-007-018-MY2
- NTHU IoA CICA cluster

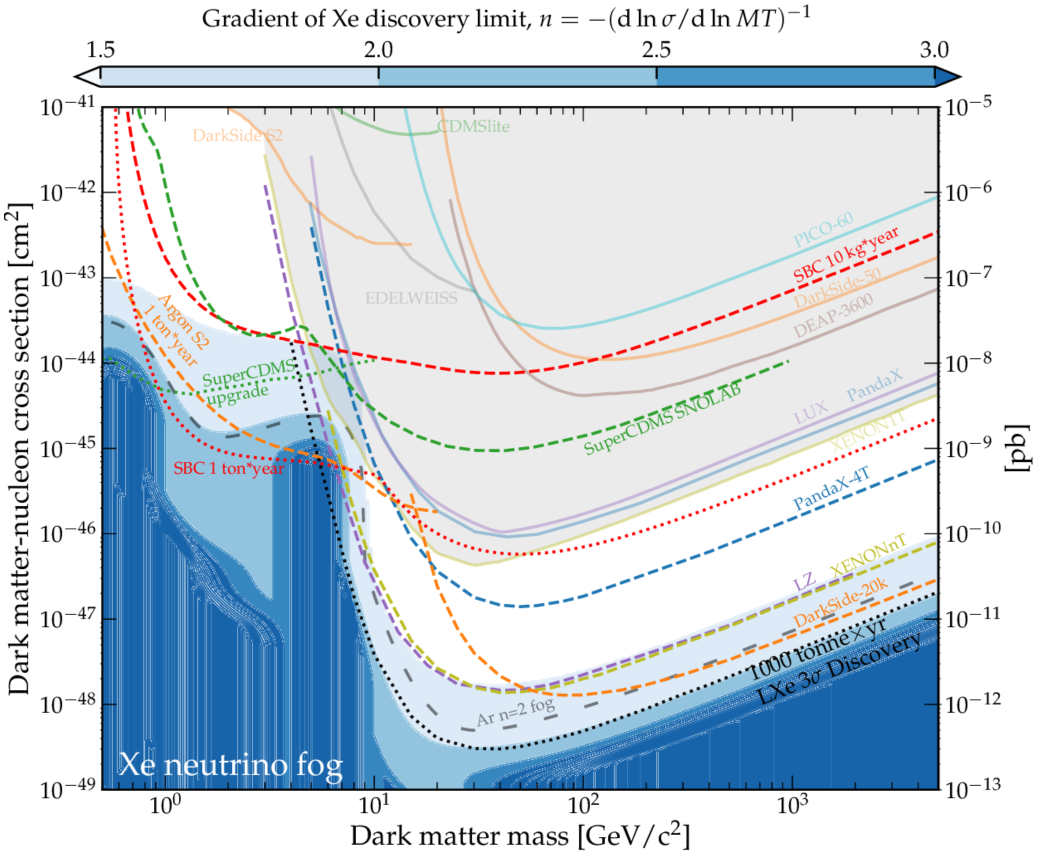
Thank you for your attention!

感謝各位的聆聽！

Tram Acuña
Email: jtacuna@gapp.nthu.edu.tw

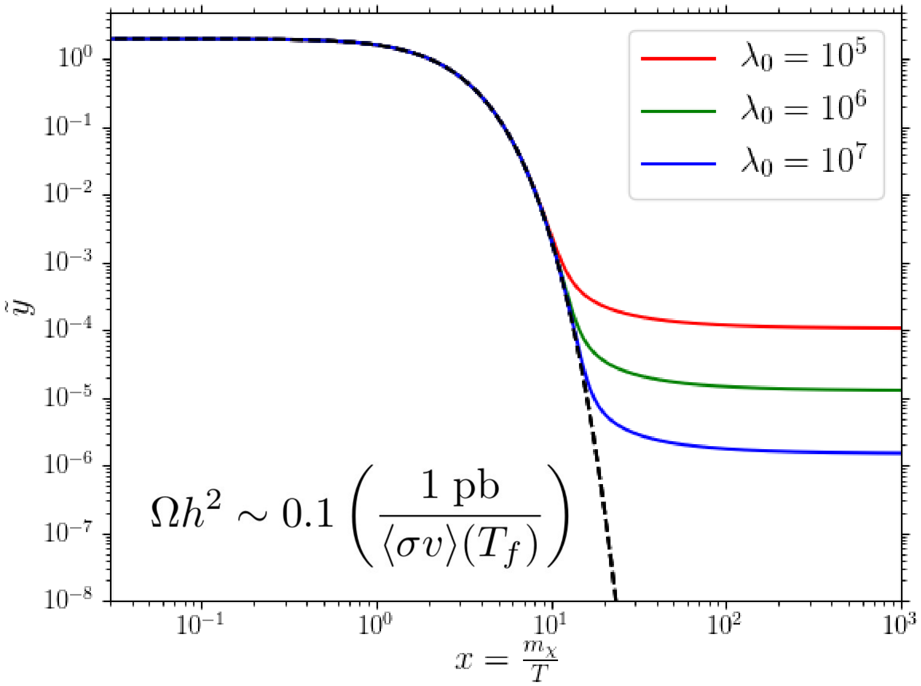
Extra slides

(WIMP) dark matter



Retrieved from: https://lss.fnal.gov/archive/2022/conf/fermilab-conf-22-180-v.pdf

WIMP thermal production



$$\Omega h^2 \sim 0.1 \left(\frac{1\,\mathrm{pb}}{\langle \sigma v \rangle (T_f)} \right)$$

$$\langle \sigma v \rangle \approx (2.5 \times 10^{-9}\,\mathrm{GeV}^{-2}) \left(\frac{\alpha_\chi}{0.5 \times 10^{-2}} \right)^2 \left(\frac{100\,\mathrm{GeV}}{m} \right)^2$$

WIMP unitarity limit: m < 20 TeV

Primordial black holes

- cf. BH from stellar collapse (~1-10 M_{sol})
- Can be formed at any mass[1]
- Potential DM candidate
- Proposed formation mechanisms
  - Collapse of overdense regions from primordial fluctuations
  - Critical collapse and Choptuik scaling
  - PBH from FOPT
    - Softening of fluid EoS (QCD PT)
    - Bubble wall collisions during FOPT[2]
    - ***Collapse of Fermi balls from filtered out DM during <u>dark</u> FOPT***[3]

$$\rho_{BH} = \frac{3}{8\pi G_N}\frac{1}{R_s^2} \qquad \bar{\rho} = \frac{3}{8\pi G_N}\frac{1}{(1/H)^2}$$

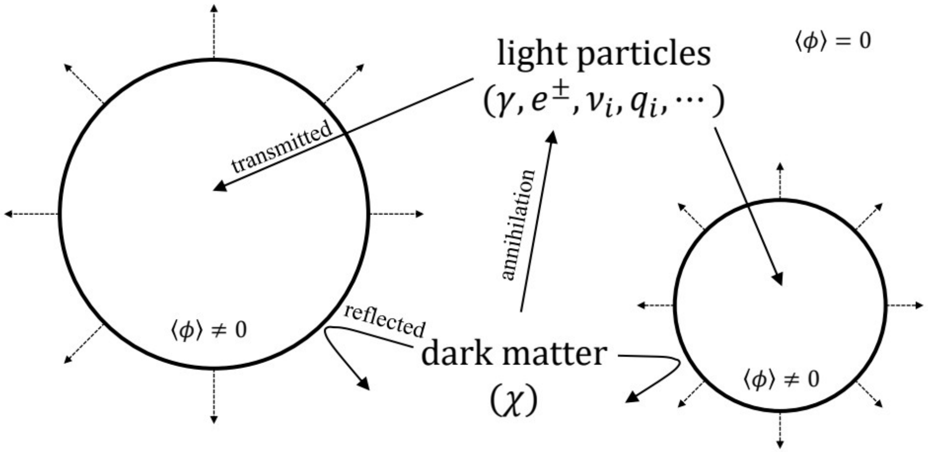
$$M_H = \frac{1}{2 G_N H} = \frac{t}{G_N} \approx 10^{-18} M_{sol}\left(\frac{t}{10^{-23} s}\right)$$

$$T_{Hawking} = 8.62 \times 10^{-12} eV \left(\frac{M_{sol}}{M}\right)$$

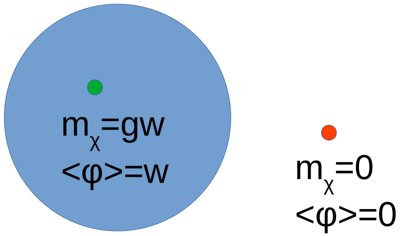
$$\tau = 10^{64} y \left(M / M_{sol}\right)^3$$

[1] Zeldovich Ya., and Novikov I. D. (1974)
[2] Kodama, Hideo, Misao Sasaki, and Katsuhiko Sato. (1982)
[3] Kawana, Kiyoharu, and Ke-Pan Xie. (2022)

Filtered out dark matter



Taken from: Dongjin Chway, Tae Hyun Jung, Chang Sub Shin, Phys. Rev. D 101, 095019 (2020)



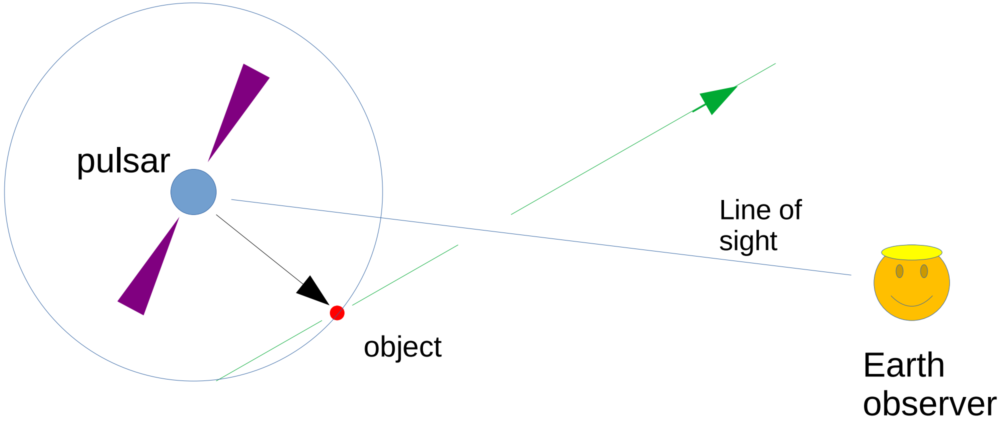
m_χ=gw
<φ>=w

m_χ=0
<φ>=0

gw >> T_*

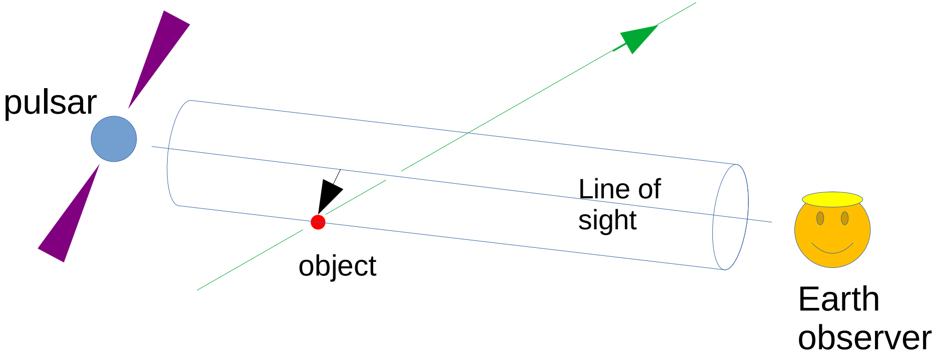
- DM mass is dynamically generated from FOPT
- Key ingredient: mass difference >> T
- DM number density is Boltzmann suppressed like in WIMP freeze out

Pulsar timing: Doppler & Shapiro



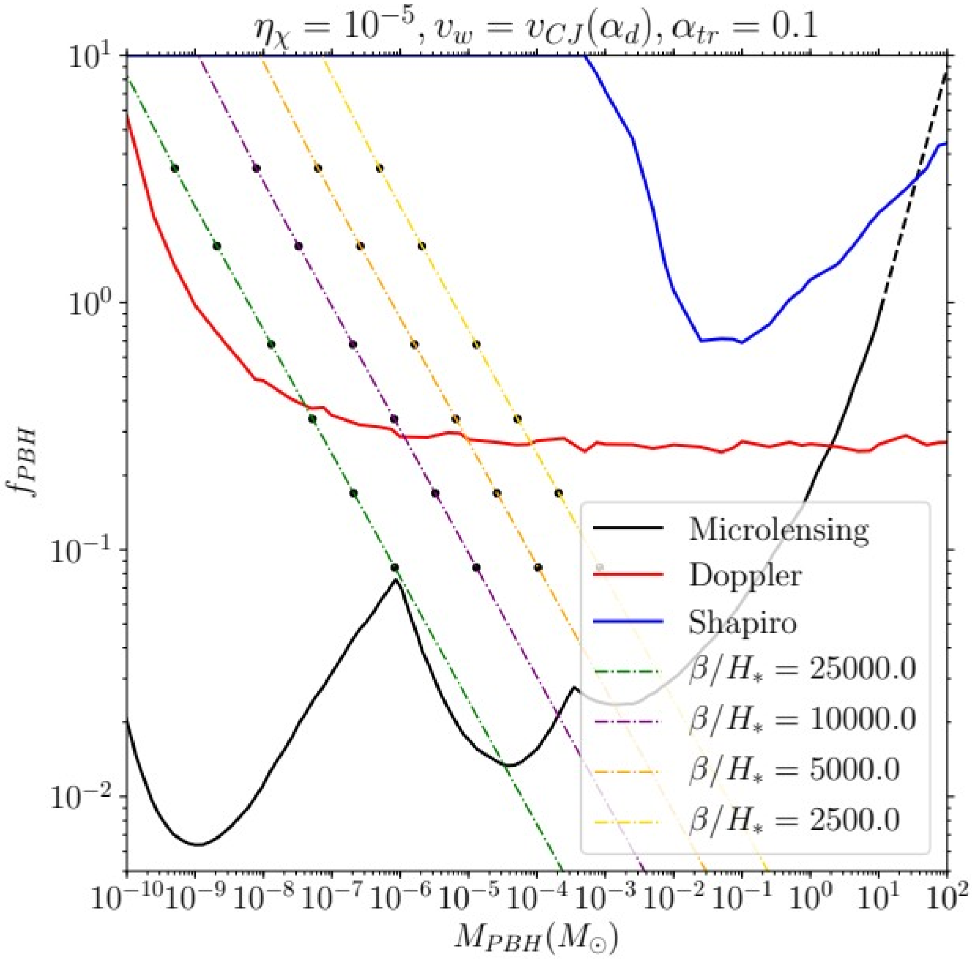
$$\left(\frac{\delta\nu}{\nu}\right)_D = \frac{1}{c}\hat{d}\cdot\int\vec{\nabla}\Phi\; dt$$

$$\Gamma_D \sim \pi v n^{1/3} \sim 0.1 f^{1/3}\left(\frac{M}{10^{-8} M_{sun}}\right)^{-1/3} yr^{-1}$$



$$\left(\frac{\delta\nu}{\nu}\right)_S = -\frac{2}{c^3}\vec{v}\cdot\int\vec{\nabla}\Phi\; dz$$

$$\Gamma_S \sim \pi^{1/2} v (nL)^{1/2} \sim 0.17 f^{1/2}\left(\frac{M}{10^{-4} M_{sun}}\right)^{-1/2}\left(\frac{L}{10\,kpc}\right)^{1/2} yr^{-1}$$



Microlensing

- -multiple images are formed, but not resolved as separate
- -change the magnification
- -microlensing event is registered if magnification is >1.34

Number of expected microlensing events:

- - $N_* T_{obs}$ (rate per source star) (transit time)
- -rate per source star ~ 1/M

Tram Acuña - NTHU

Plots from: JTA, Po-yan Tseng
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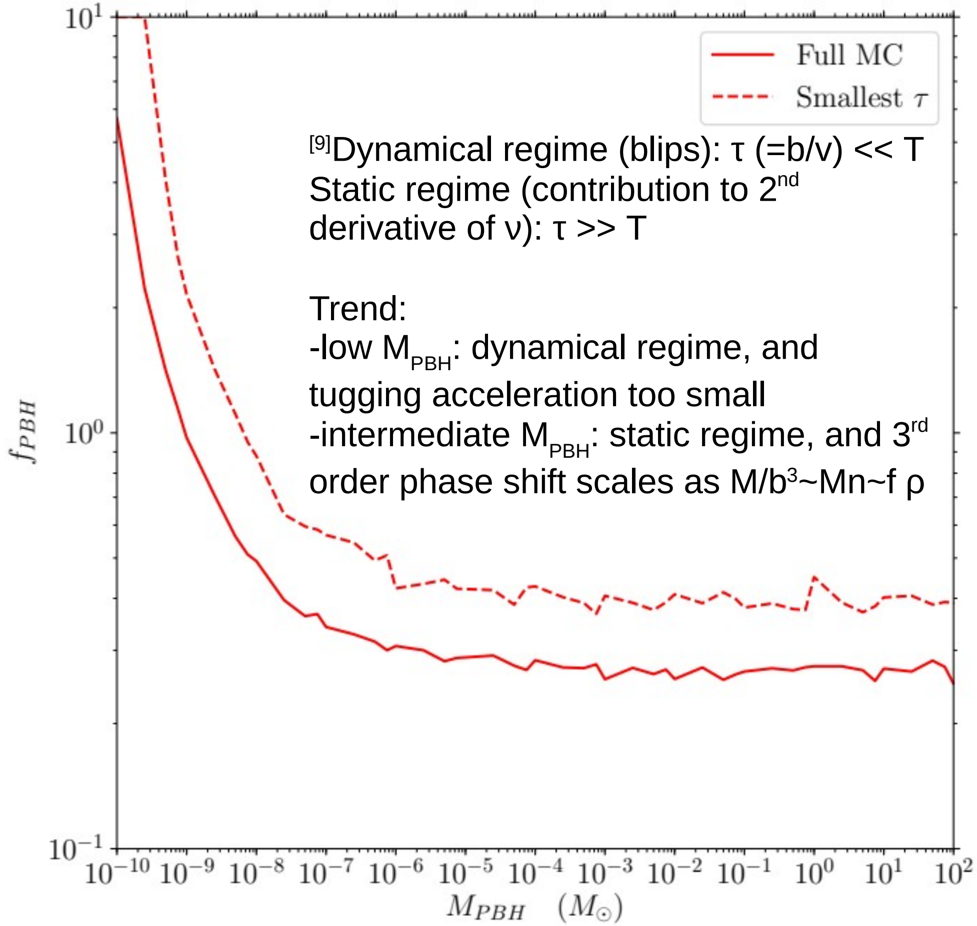
[9] Dror, Jeff A., et al. "Pulsar timing probes of primordial black holes and subhalos." Physical Review D 100.2 (2019): 023003.



[9]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

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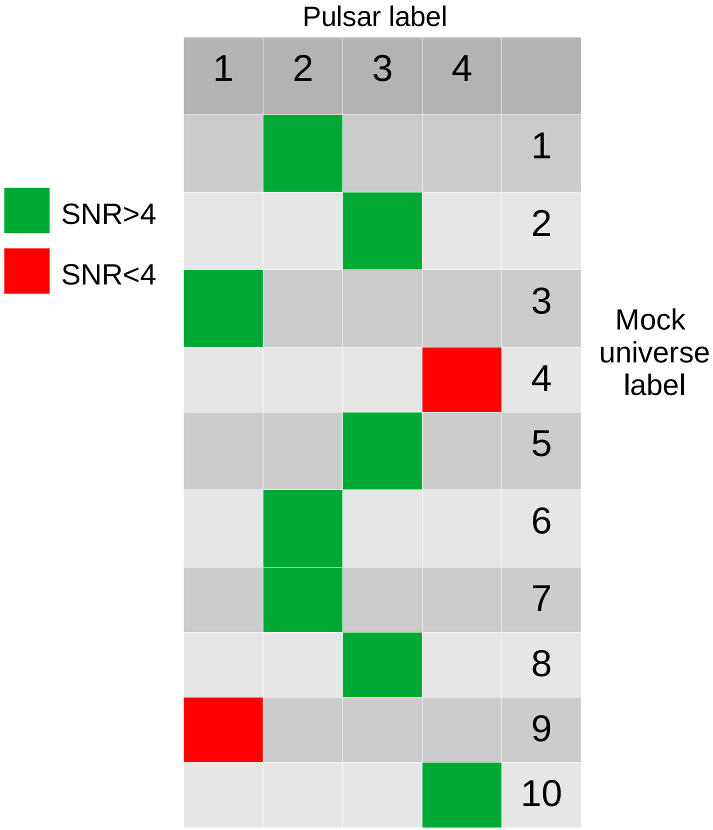
[9] Dror, Jeff A., et al. "Pulsar timing probes of primordial black holes and subhalos." Physical Review D 100.2 (2019): 023003.

Pulsar timing: sensitivity limits[6,7]



🟩 SNR>4

🟥 SNR<4

Pulsar label

1	2	3	4	Mock universe label
	🟩			1
		🟩		2
🟩				3
			🟥	4
		🟩		5
	🟩			6
	🟩			7
		🟩		8
🟥				9
			🟩	10

Sensitivity criterion: 90% of mock universes have max SNR > 4

[6] Lee, Vincent SH, et al. (2021)

[7] Ramani, Harikrishnan, Tanner Trickle, and Kathryn M. Zurek. (2020)

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. [10]

$$\begin{aligned} -B &= -DT_0^2\phi_0^2 - C\phi_0^3 + \frac{\lambda}{4}\phi_0^4 \\ 0 &= -2DT_0^2 - 3C\phi_0 + \lambda\phi_0^2, \end{aligned}$$

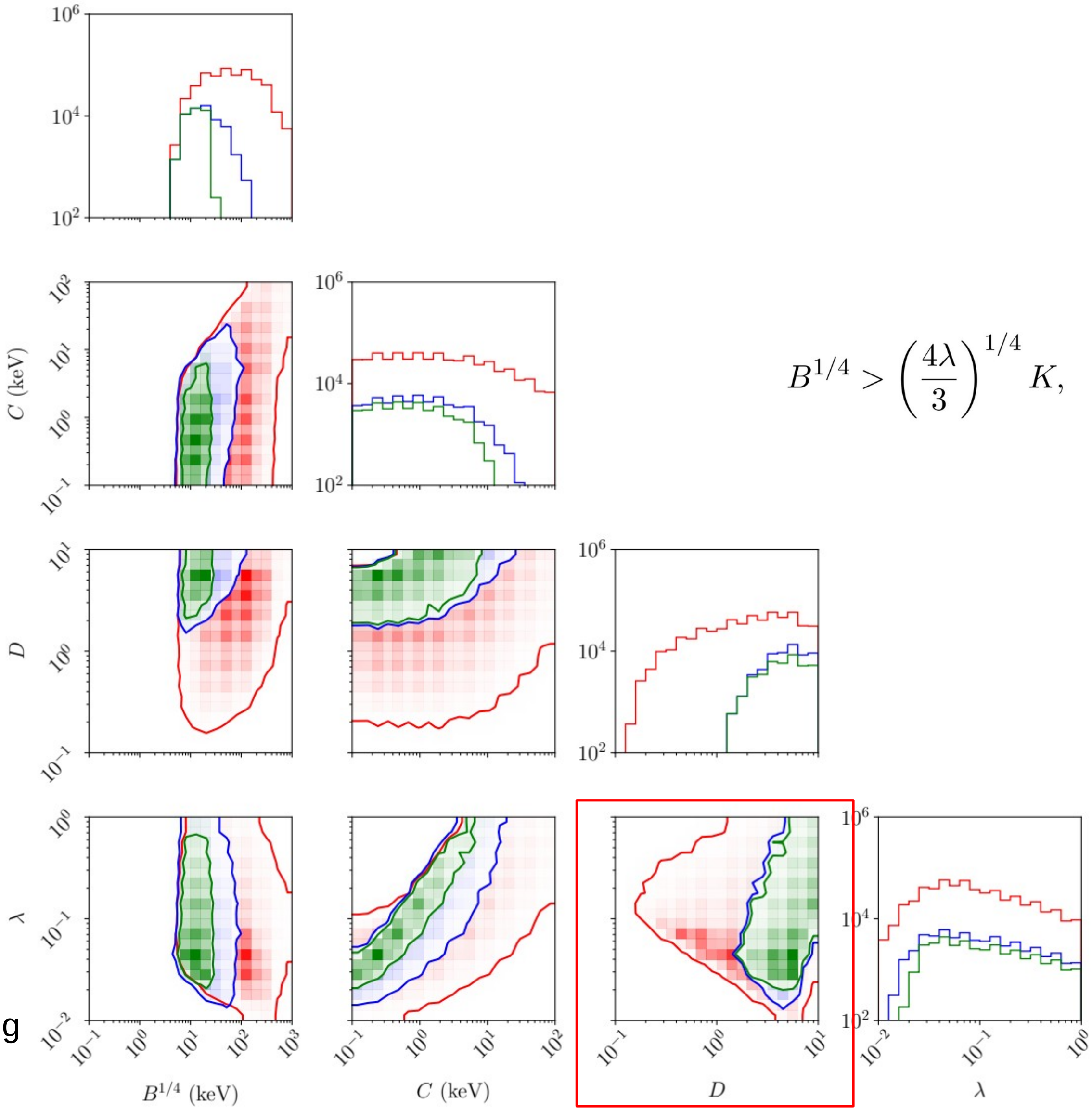
$$\{B^{1/4}, C, D, \lambda\} \longrightarrow \{\eta_\chi, T_*, \alpha_{tr}, T_c, \xi, \beta/H_*, v_w\} \longrightarrow$$

Effective potential parameters

FOPT parameters

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

[12] 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.



$$B^{1/4} > \left(\frac{4\lambda}{3}\right)^{1/4} K, \quad A^2 - \lambda D < \left(\frac{C}{T_0}\right)^2, \quad K \equiv \frac{3C}{2\lambda}$$

- 🟥 PTA only
- 🟦 PTA+GW only
- 🟩 PTA+GW+relic

Plot from: JTA, Po-yan Tseng
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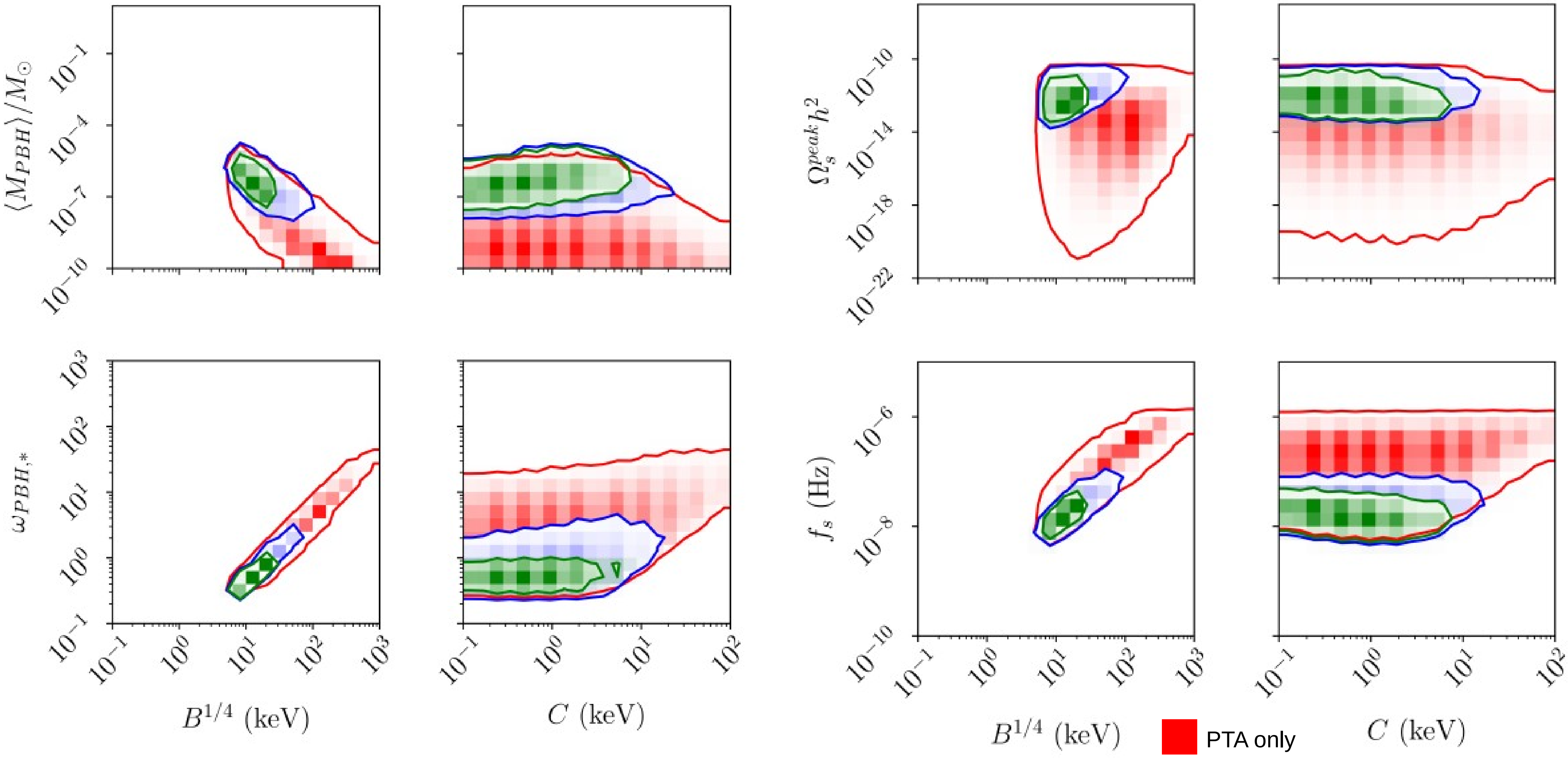

🟥 PTA only

🟦 PTA+GW only

🟩 PTA+GW+relic

Plot from: JTA, Po-yan Tseng
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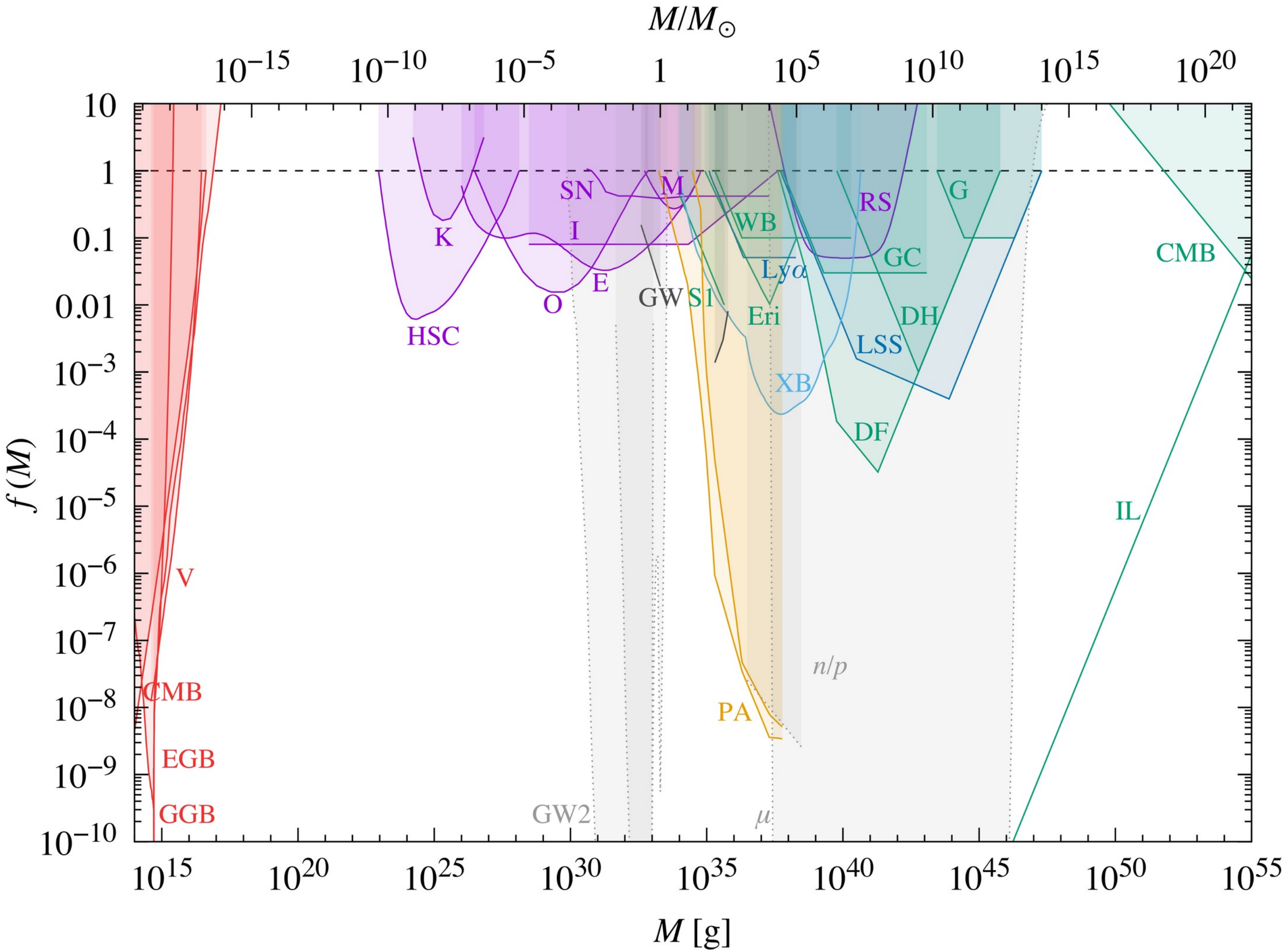

Figure from: B. Carr, K. Kohri, Y. Sendouda and J. Yokoyama, Constraints on primordial black holes, Rept. Prog. Phys. 84(11), 116902 (2021)