Dark matter signals at gravitational wave detectors

Fa Peng Huang (黄发朋)

Sun Yat-sen University, School of Physics and Astronomy, TianQin center
中山大学物理与天文学院天琴中心

mainly based on recent work arXiv:2601.10552; 2511.23263; 2503.14332; 2503.10347 ; 2508.04314

The 4th Topics of Particle, Astro and Cosmo Frontiers (TOPAC 2026)
@University of Electronic Science and Technology of China in Chengdu, 2026.04.19

outline

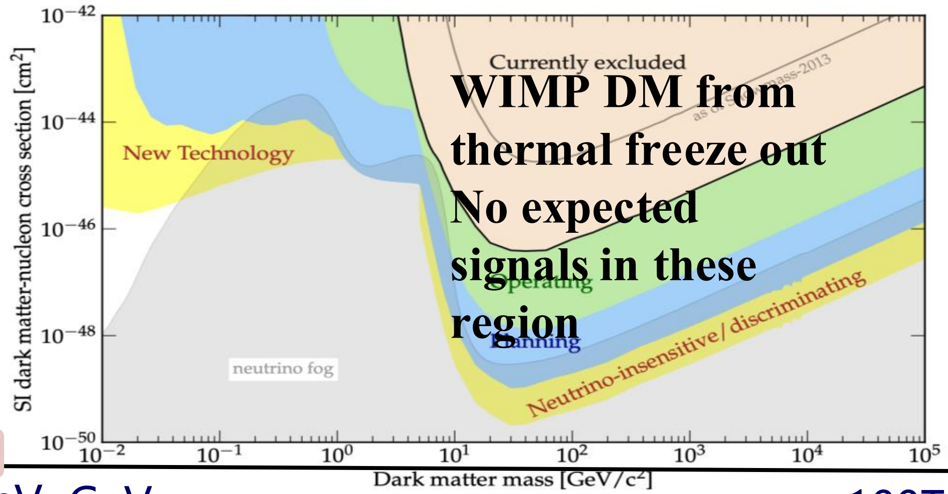
1. Motivation
2. Ultralight DM
3. Ultraheavy DM
4. Summary

Motivation: DM theory and experiments status

What is the microscopic nature of DM?

How DM relic density is produced?

Ultralight DM: Axion/ALP



WIMP DM from thermal freeze out No expected signals in these region

10^{-22}eV keV GeV WIMP 100TeV

arXiv: 1904:07915 Snowmass 2021, arXiv: 2209.07426

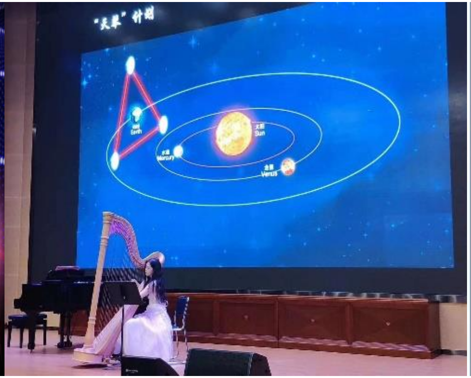
Heavy DM:Q-ball/filtered/ PBH (radiation, superradiance)

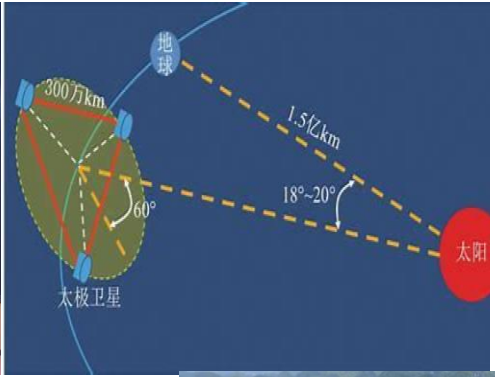
- **new DM production mechanism beyond thermal freeze out: cosmic phase transition, PBH Hawking radiation, superradiance…**
- **new detection method: various GW detector**

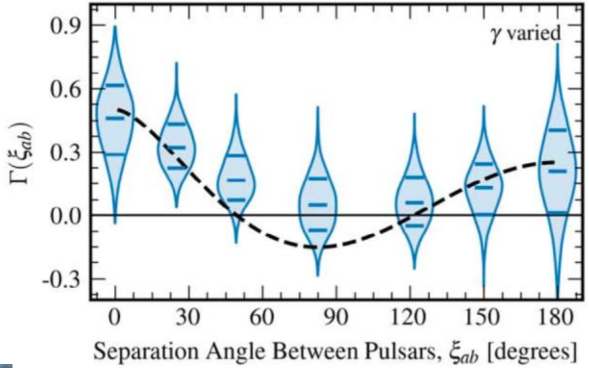
DM Imprints at GW experiments

GW experiments

LISA/TianQin/Taiji ~2034







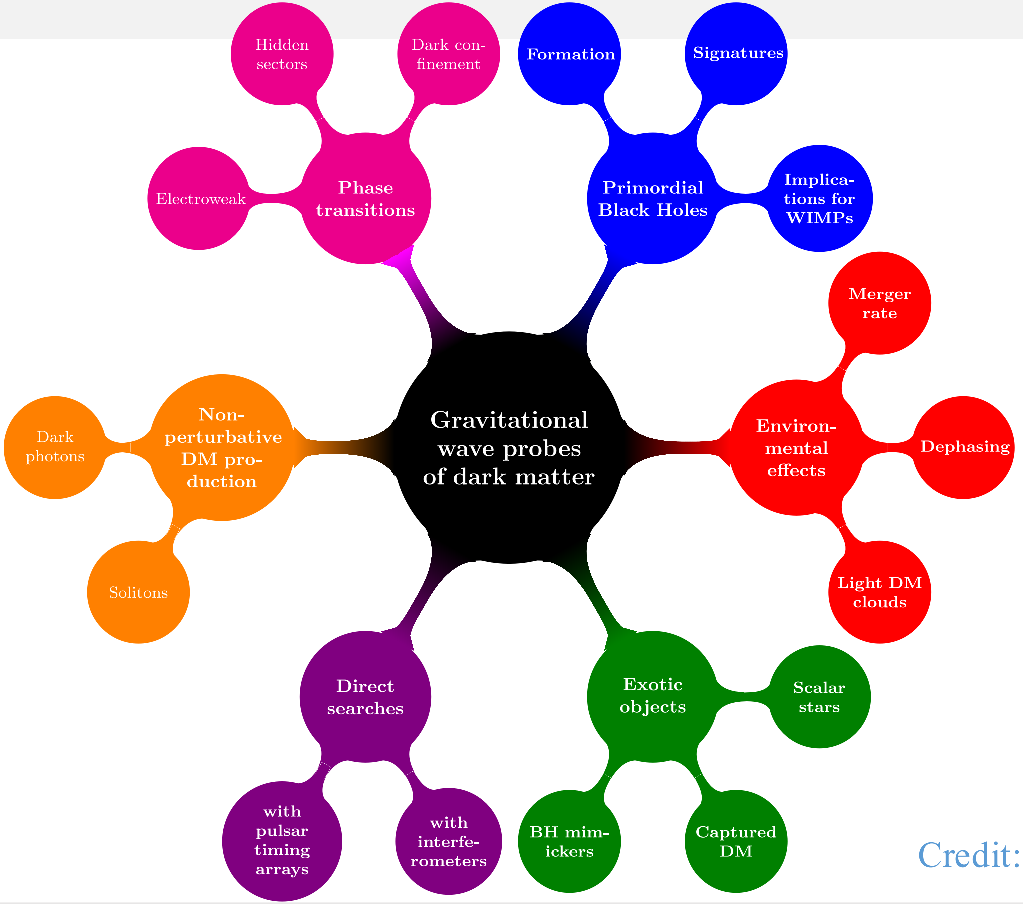
“TianQin”
“Harpe in space”

2023 June 29th： NANOGrav, EPTA, InPTA, Parkes PTA, CPTA

FAST

SKA

Motivation: DM Imprints at GW experiments



Credit: Gianfranco Bertone et. al.

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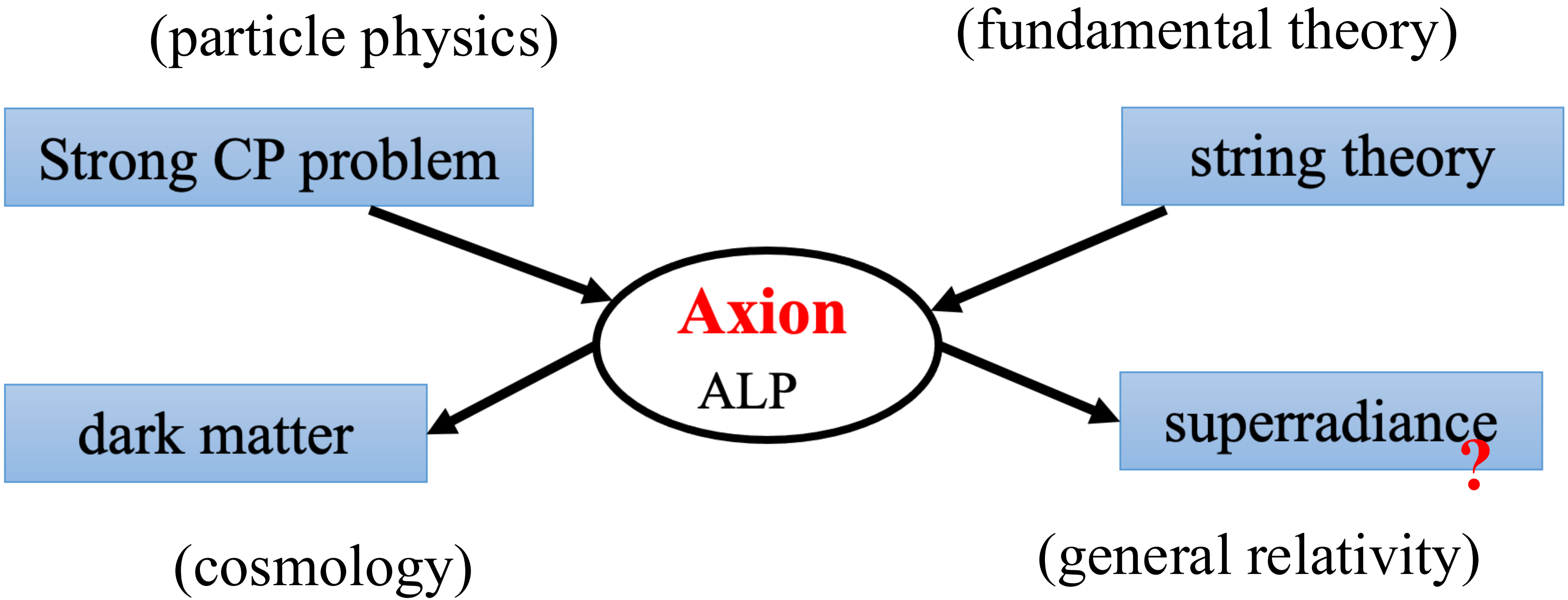
Ultralight DM

Ultralight axion is a promising DM candidate.
See the review talk of Jia Liu



Ultralight DM

When Klein (-Gordon) meets Kerr——superradiance

Penrose process

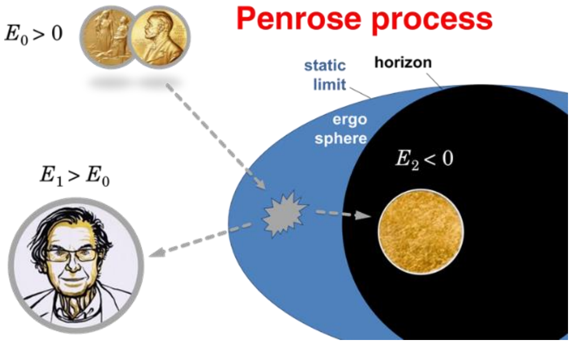
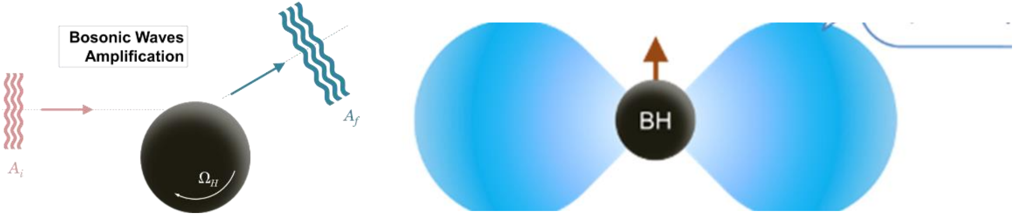


Image Credit: Yi Wang

axion cloud



gravitational atom

Exponential growth solution of Klein-Gordon equation due to the boundary condition at the horizon of Kerr BH.

Ultralight axion can form axion cloud around rotating BH.

Resemble hydrogen atom, gravitational atom

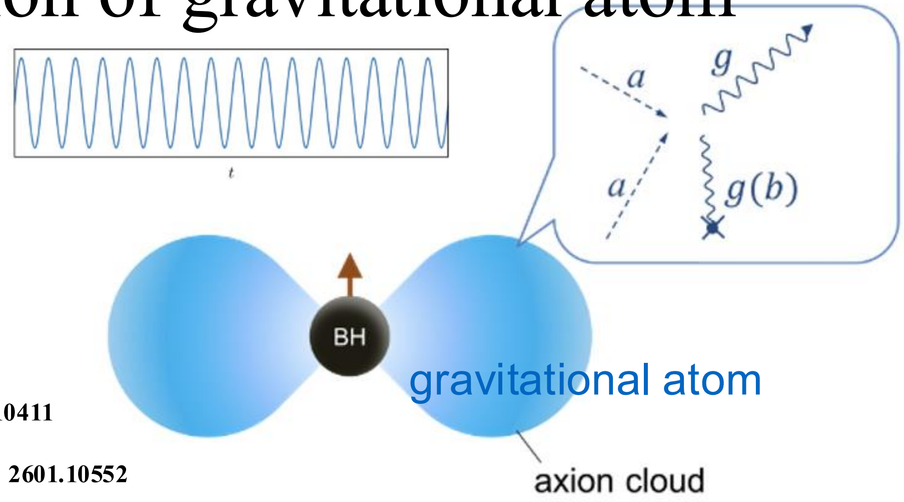
$$\alpha = M_{BH} m_a < 1$$

Penrose '69 '71
Zel'dovich '72
Starobinsky '73

Ultralight DM

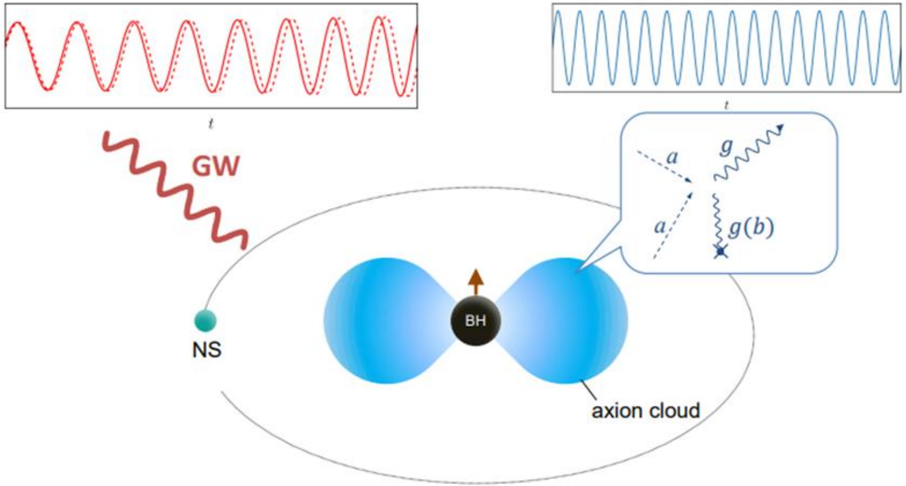
GW of ultralight DM from black hole: gravitational atom from superradiance

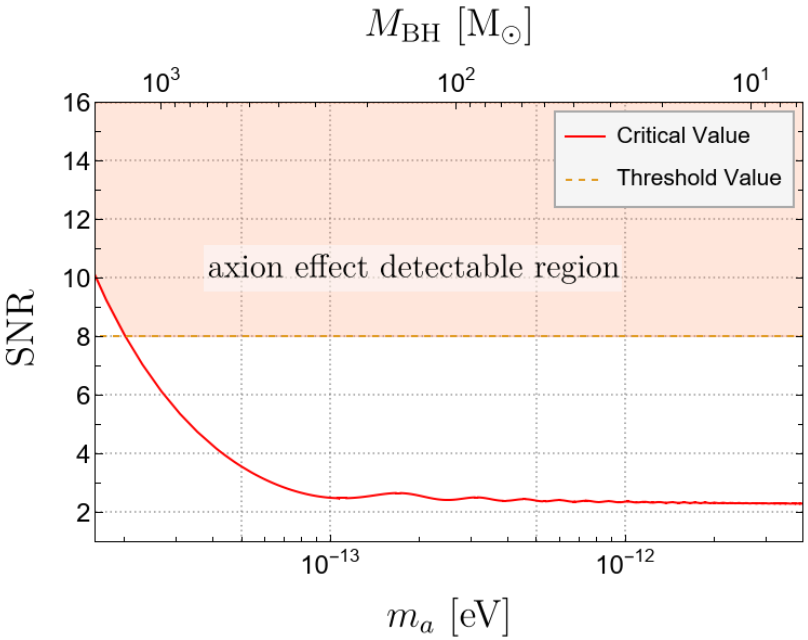
1. Axions can annihilate to GW
2. Energy-level transition of gravitational atom



Jing Yang, FPH — Phys.Rev.D 108 (2023) 10, 103002
Jing Yang, Ning Xie, FPH — JCAP 11 (2024) 045
Ning Xie, FPH — Sci. China-Phys. Mech. Astron. 67, 210411
Ning Xie, FPH — Phys.Rev.D 112 (2025) 5, 055028
Zhong-hao Luo, FPH, Pengming Zhang, Chen Zhang, — arXiv: 2601.10552

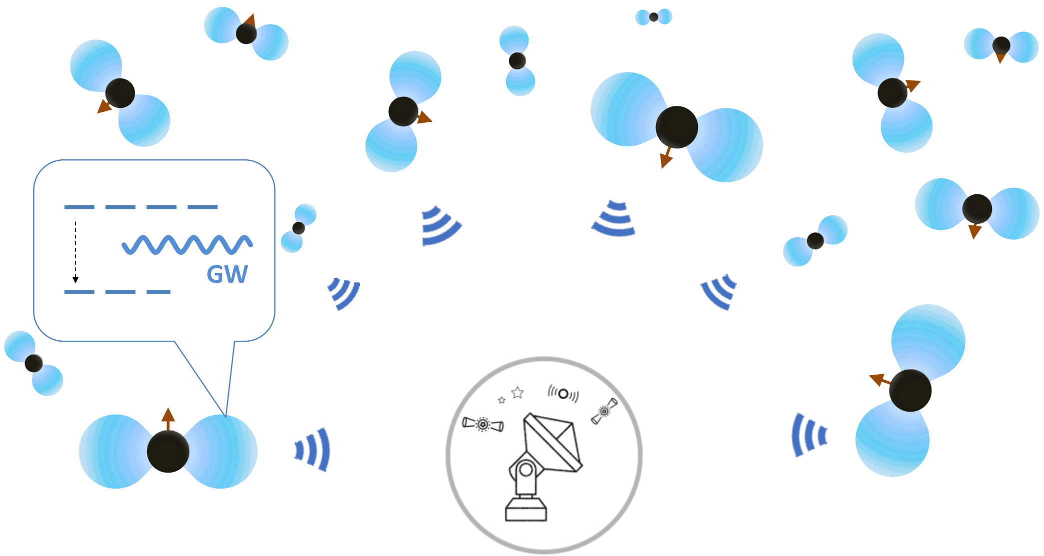
Ultralight DM





Jing Yang, FPH Phys.Rev.D 108 (2023) 10, 103002
Jing Yang, Ning Xie, FPH arXiv:2306.17113
Ning Xie, FPH Sci. China-Phys. Mech. Astron. 67, 210411

Fuzzy axion (DM) particles

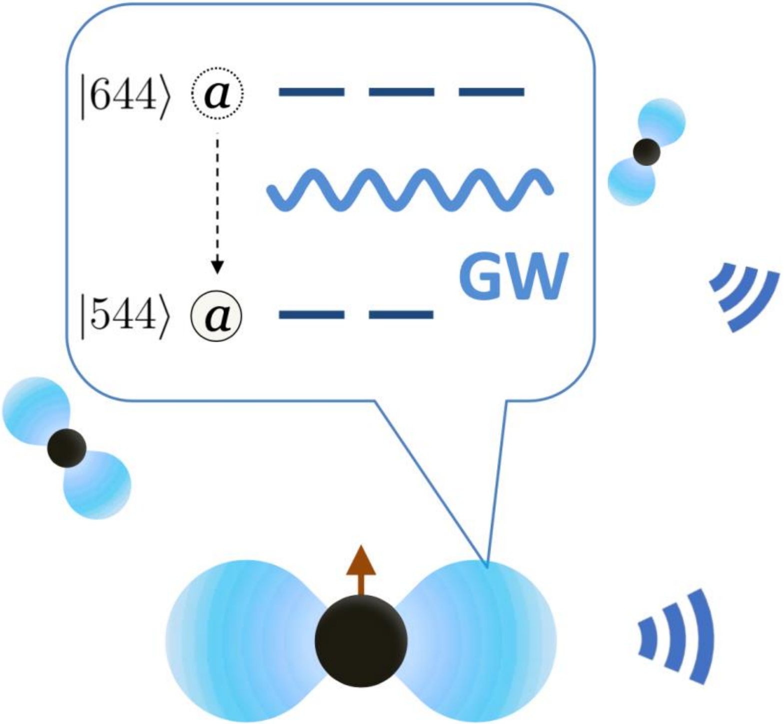


The cosmic populated SMBHs dressed with axion cloud as a natural source of nano-Hertz SGWB. The energy level transition process can radiate GWs continuously, which naturally fall in nano-Hertz frequency band.

Consequently, the PTA could detect this new source which provides a new approach to probe ultralight axion DM and isolated BHs.

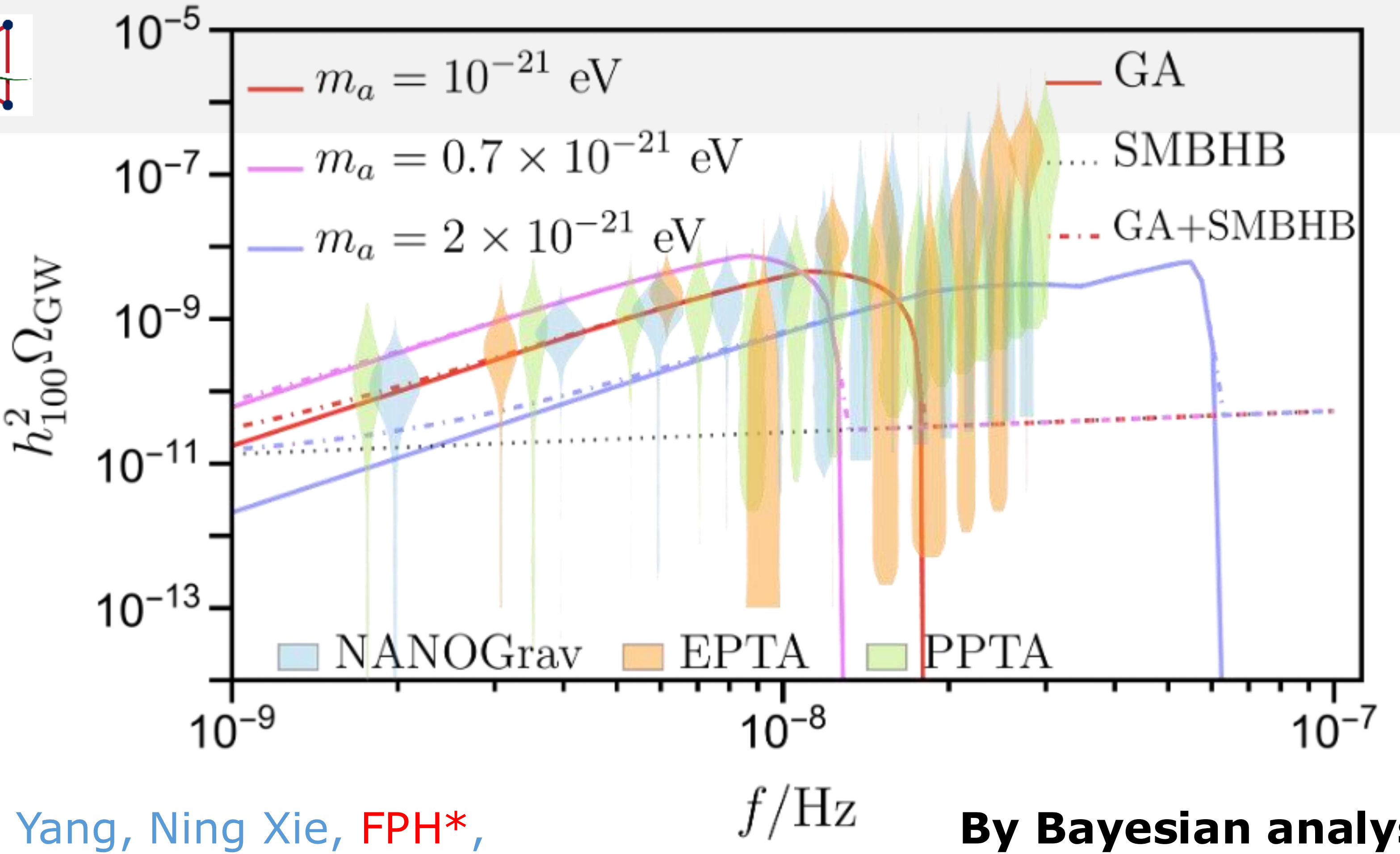
Jing Yang, Ning Xie, FPH*, JCAP 11 (2024) 045

Fuzzy axion (DM) particles



$$\Delta\omega = \frac{11}{1800}\alpha^2 m_a$$

$$P = -\frac{dE}{dt} = \frac{dN_5(t)}{dt}\Delta\omega$$



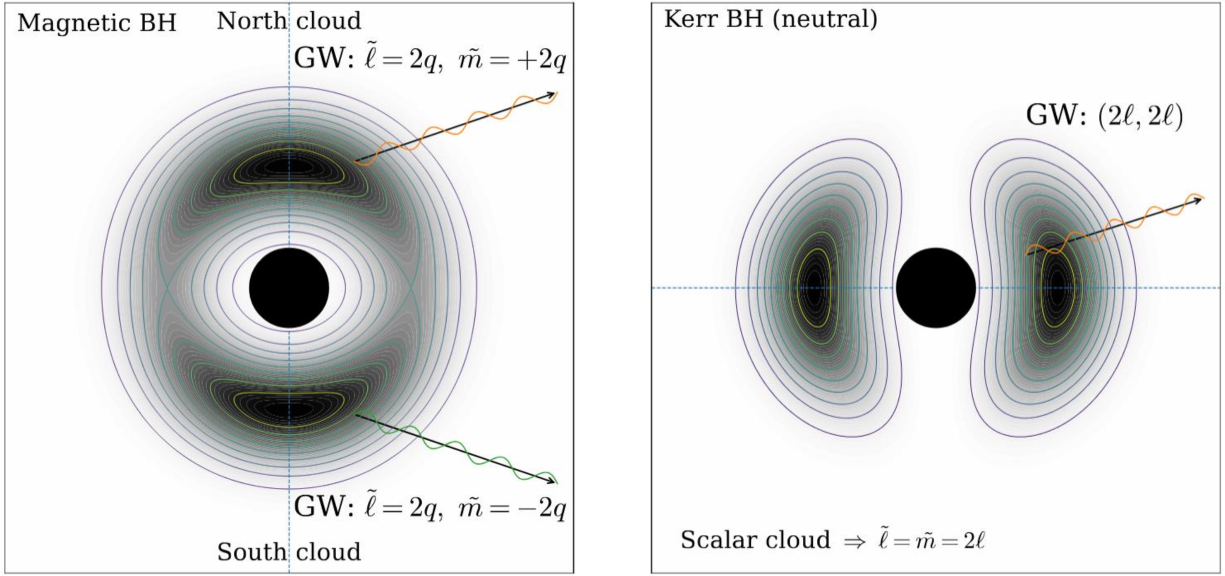
Jing Yang, Ning Xie, FPH*,
JCAP 11 (2024) 045

By Bayesian analysis, we fi
fuzzy DM is favored by the data.

Kerr BH with magnetic monopole

Recently, we propose a potential smoking-gun search strategy for magnetic monopole and ultralight boson: Rapid post-merger signal of circularly polarized gravitational wave from magnetic black hole superradiance

Zhong-hao Luo, FPH, Pengming Zhang, Chen Zhang, arXiv: 2601.10552



Rapid post-merger GW signal

A Deeper Potential Well Induced by a Magnetic Monopole

Two-Order-of-Magnitude Faster Cloud Growth

Zhong-hao Luo, FPH, Pengming Zhang, Chen Zhang, arXiv: 2601.10552

The radial separation equation determines the growth rate of charged scalar clouds

$$\frac{d}{dr}\left(\Delta(r)\frac{d}{dr}R(r)\right)+\left[\frac{\left(\left(r^2+a^2\right)\omega-ma\right)^2}{\Delta(r)}-\mu^2r^2-\Lambda_{q\ell m}+q^2+2am\omega-a^2\omega^2\right]R(r)=0.$$

$\mu M \ll 1$

Far region

$$\frac{d^2(rR)}{dr^2}+\left[\omega^2-\mu^2\left(1-\frac{2M}{r}\right)-\frac{\ell(\ell+1)-q^2}{r^2}\right](rR)=0,$$

Near region

$$z(z+1)\frac{d}{dz}\left[z(z+1)\frac{dR}{dz}\right]+\left[p^2-\left(\ell(\ell+1)-q^2\right)z(z+1)\right]R=0,$$

For the neutral Kerr, $\omega_{I(\mathrm{Kerr})}$ scales as

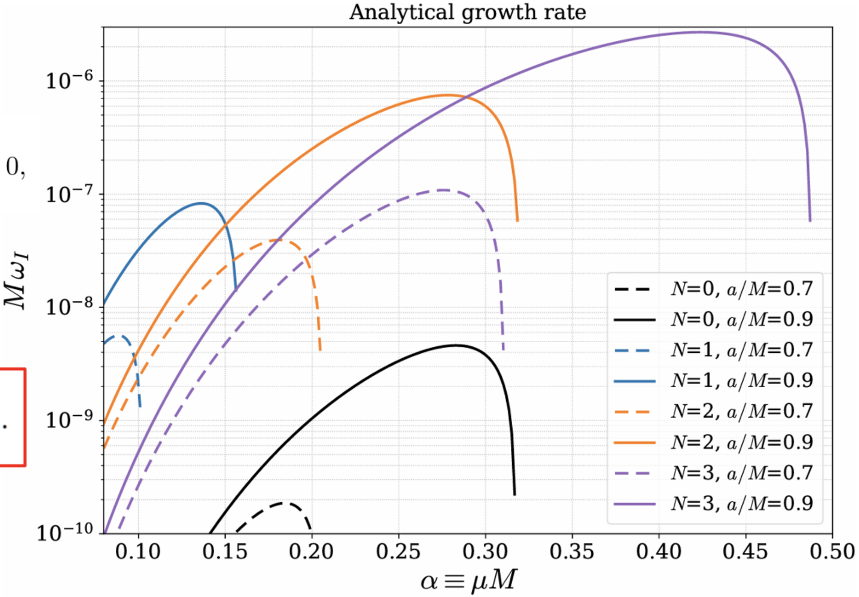
$$\omega_{I(\mathrm{Kerr})}=\frac{\delta\nu_I}{M}\left(\frac{\alpha_{(\mathrm{Kerr})}}{\ell+n_r+1}\right)^3\propto\alpha_{(\mathrm{Kerr})}^{4\ell+5}.$$

For the magnetic case

$$\omega_I=\frac{\delta\nu_I}{M}\left(\frac{\alpha}{\ell_q+n_r+1}\right)^3\propto\alpha^{4\ell_q+5}.$$

$$\omega_I/\omega_{I(\mathrm{Kerr})}\approx 10^2.$$

Here $\ell_q<\ell$.



Rapid post-merger GW signal

Stronger GW Emission

The Kerr result $P_{\rm GW} \propto \alpha^{4\ell+10}$

GW power from thenorth/south clouds

$$P^{\pm}_{\rm GW} = C^{\pm}_{n\ell\ell_q} \left(\frac{E_c}{M}\right)^2 \alpha^{4\ell_q+8}.$$

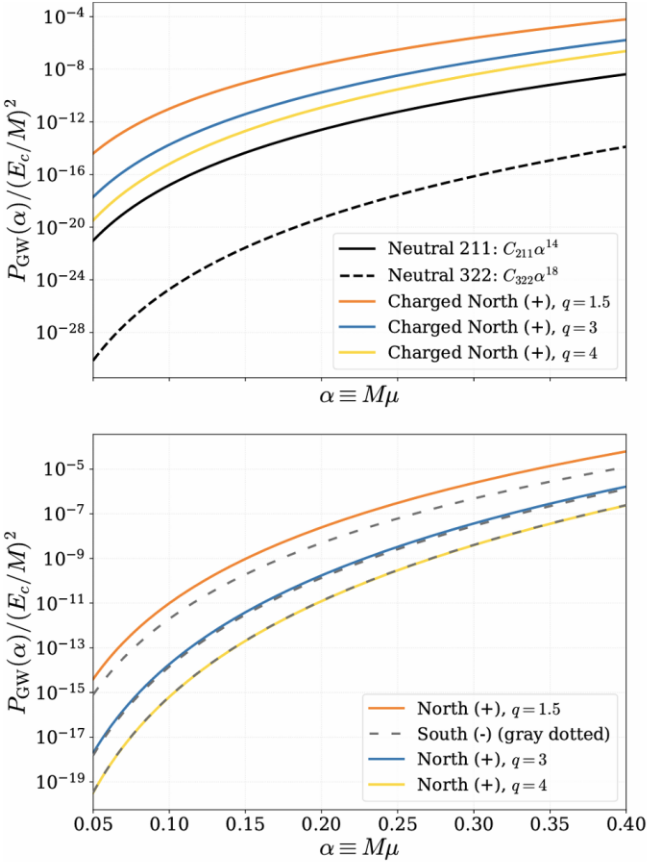
$$\Sigma^{\pm} \equiv I_1^{\pm} C_1 + I_2^{\pm} C_2 + I_3^{\pm} C_3$$

$$C^{\pm}_{n\ell\ell_q} = \frac{2^{2\tilde{\ell}+3}\pi}{n^{4\ell_q+8}} \frac{\Gamma(\tilde{\ell}-1)^2}{\Gamma(2\tilde{\ell}+2)^2} \frac{\Gamma(2\ell_q+\tilde{\ell}+1)^2}{\Gamma(2\ell_q+2)^4} \frac{\Gamma(n+\ell_q+1)^2}{\Gamma(n-\ell_q)^2} |\Sigma^{\pm}|^2.$$

Physically, the enhancement arises from two effects:

(i) Smaller ℓ_q →weaker centrifugal barrier →larger small-r wavefunction →stronger overlap with outgoing GW modes.

(ii) Monopole harmonics remove the Kerr angular cancellation, eliminating the extra α^2suppression.



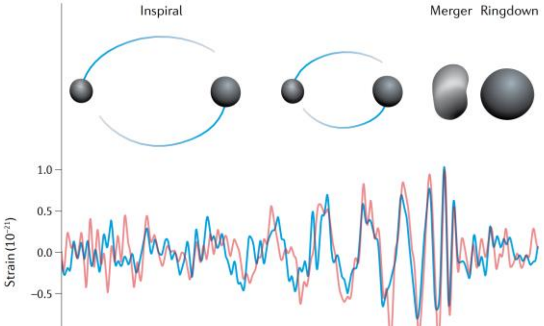
Rapid post-merger GW signal

Rapid post-merger signal of circularly polarized gravitational wave from magnetic black hole superradiance: novel approach to detect magnetic monopole and ultralight DM by GW.

BH mass M	Magnetic $N=3$ $M\omega_I \sim 10^{-6}$	Neutral 211 $M\omega_{I(\mathrm{Kerr})} \sim 2\times 10^{-8}$
$10\,M_\odot$	2.47×10^{1} s (0.41 min)	1.23×10^{3} s (20.5 min)
$10^4\,M_\odot$	2.47×10^{4} s (6.86 hr)	1.23×10^{6} s (14.3 d)
$10^6\,M_\odot$	2.47×10^{6} s (28.6 d)	1.23×10^{8} s (3.9 yr)

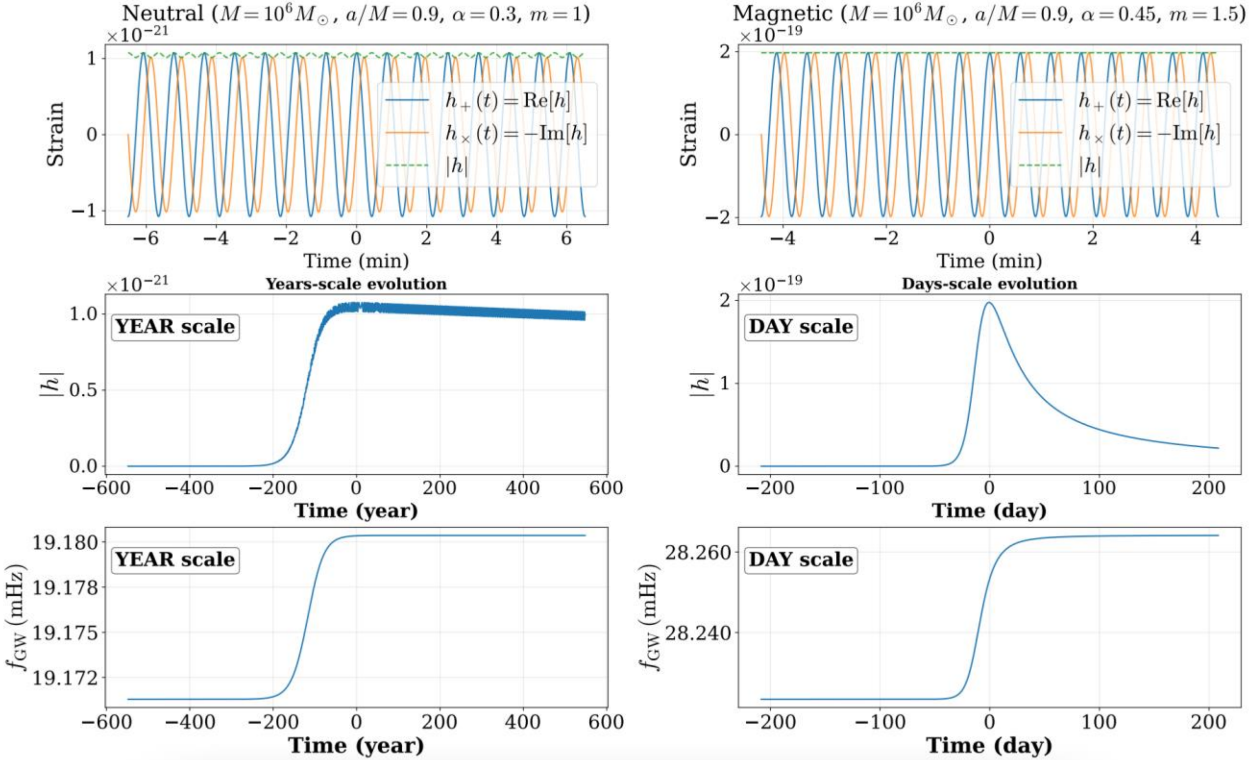
Zhong-hao Luo, FPH, Pengming Zhang, Chen Zhang, arXiv: 2601.10552

Rapid post-merger GW signal



how about the post-merger signal?

Rapid follow-up GW signals from superradiance of black hole merger remnants with monopole.



Zhong-hao Luo, FPH, Pengming Zhang, Chen Zhang, arXiv: 2601.10552

outline

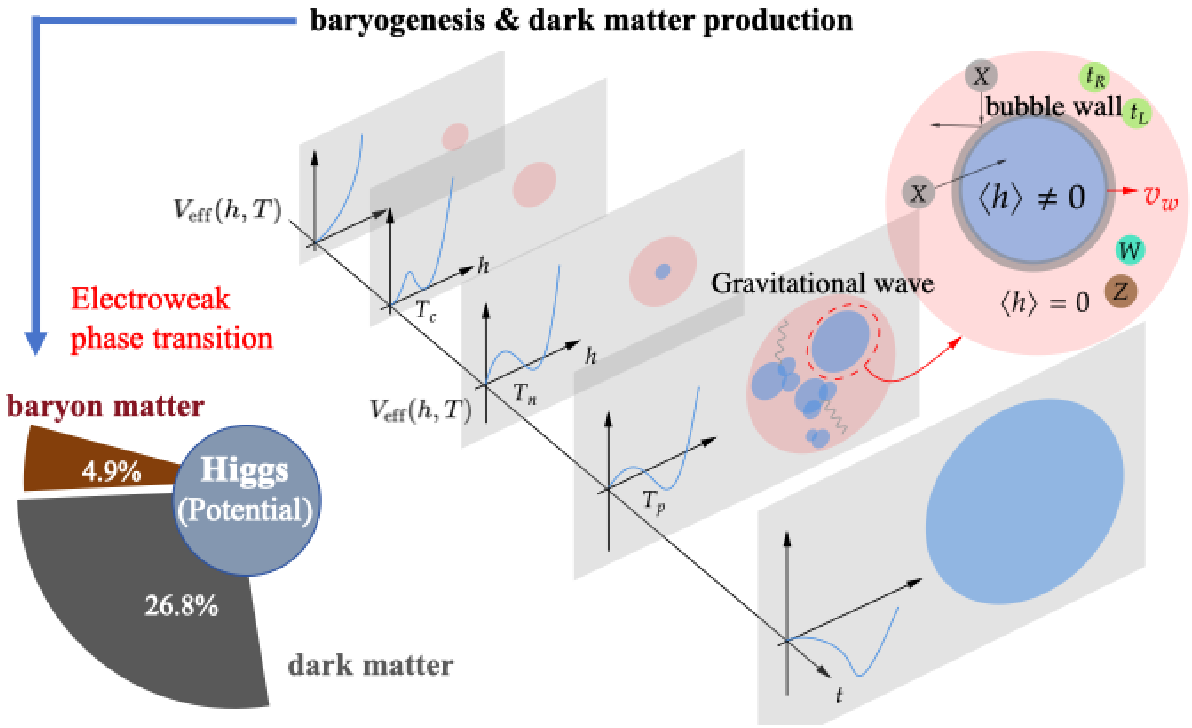
1. Motivation
2. Ultralight DM
3. **Ultraheavy DM**
4. Summary

3.1 Detecting phase transition GW signals from the production of superheavy DM in the early Universe using GW experiments

Heavy DM from cosmic phase transition

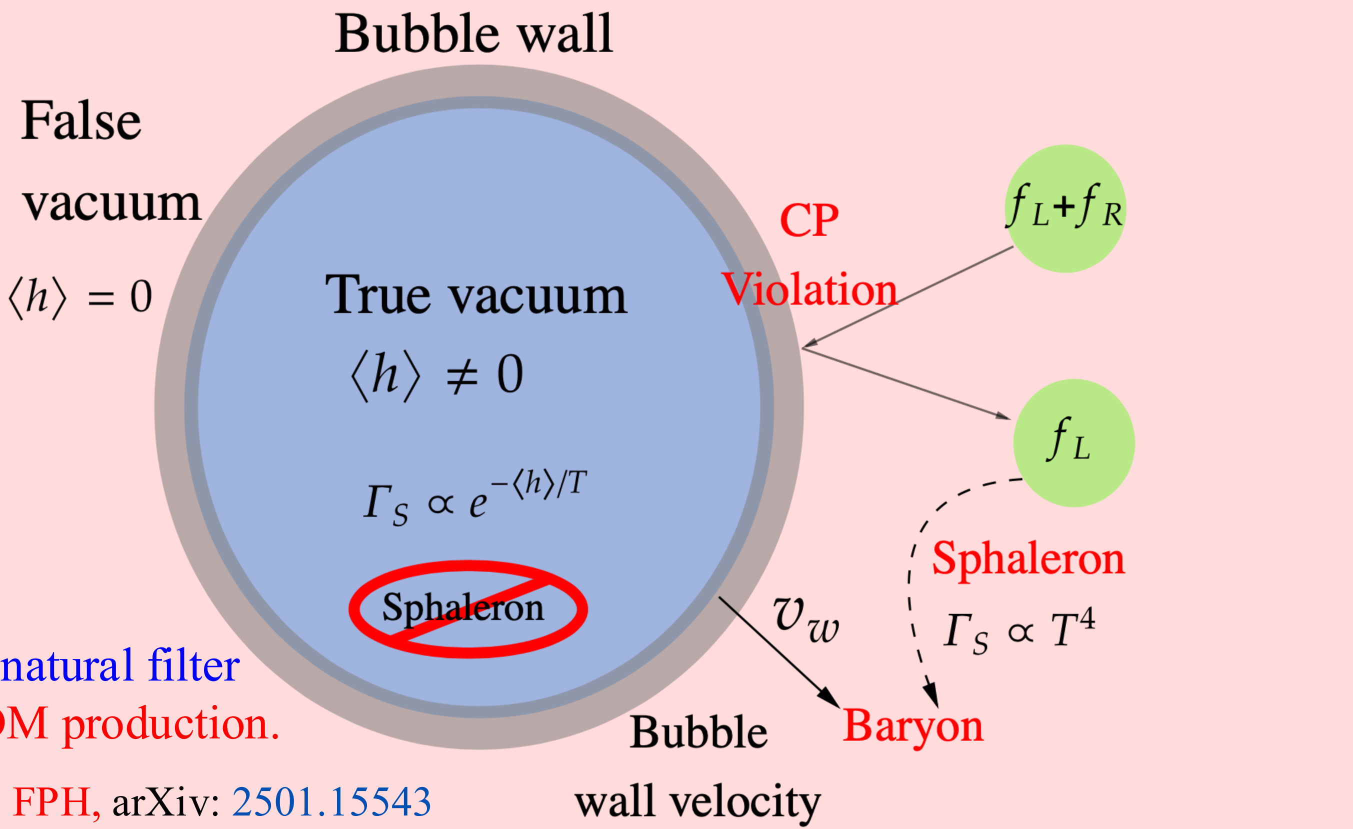
The observation of Higgs@LHC and GW@LIGO initiates new era of exploring DM by GW.

FOPT by Higgs could provide a new approach for DM production.



The First Particles, FPH, arXiv: 2501.15543

DM from cosmic phase transition



Bubble wall is a natural filter
for baryon and DM production.

The First Particles, FPH, arXiv: 2501.15543

Heavy DM from cosmic phase transition

Renaissance of quark nugget DM idea by E. Witten.

Recently, dynamical DM formed by phase transition has became a new idea for heavy. Bubble wall in FOPT can be the "filter" to obtain the needed heavy DM when avoiding the unitarity constraints.

FOPT in the early universe	Coffee making process
Bubble wall	filter
Case I:(gauged) Q-ball DM	Large coffee beans
Case II: filtered DM	Coffee
Case III: PBH	Remants
Phase transition GW	Aroma

E. Krylov, A. Levin, V. Rubakov, Phys.Rev.D 87 (2013) 8, 083528
FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028
arXiv:1912.04238, Dongjin Chway, Tae Hyun Jung, Chang Sub Shin
Phys.Rev.Lett. 125 (2020) 15, 151102 , M. J. Baker, J. Kopp,and A. J. Long
arXiv:2101.05721, Aleksandr Azatov, Miguel Vanvlasselaer, Wen Yin
arXiv:2103.09827, Pouya Asadi , Eric D. Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, J. Smirnov
arXiv:2103.09822, Pouya Asadi , Eric D. Kramer, Eric Kuflik, Gregory W. Ridgway, Tracy R. Slatyer, J. Smirnov
Siyu Jiang, FPH, Chong Sheng Li, arXiv:2305.02218
Siyu Jiang, FPH, Pyungwon Ko, arXiv:2404.16509
more than 100 papers in recent 5 years

Case I: Q-ball DM What is Q-ball?

PHYSICS REPORTS (Review Section of Physics Letters) 221, Nos. 5 & 6 (1992) 251–350. North-Holland PHYSICS REPORTS

Nontopological solitons*

T.D. Lee
Department of Physics, Columbia University, New York, NY 10027, USA

and

Y. Pang
Brookhaven National Laboratory, Upton, NY 11973, USA

Received May 1992; editor: D.N. Schramm

Nuclear Physics B262 (1985) 263–283

Q-BALLS*

Sidney COLEMAN
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Q-ball is the most typical non-topological soliton, initially proposed by Prof. Tsung-Dao Lee and Sidney Coleman. In quantum field theory, a spherically symmetric extended body that forms a non-topological soliton structure with a conserved global quantum number Q is called a Q-ball.

$$\phi = (\phi_R + i\phi_I)/\sqrt{2} \qquad Q = \int j^0 dx = \int \left(\phi_I \dot{\phi}_R - \phi_R \dot{\phi}_I\right) dx.$$

$$\delta(E - \omega Q) = 0$$

↓

$$\phi = f(r) e^{-i\omega t}$$

$$E = \int \left\{ \frac{1}{2}\left[\dot{\phi}_R^2 + \dot{\phi}_I^2 + (\nabla\phi_R)^2 + (\nabla\phi_I)^2\right] + U\left[\frac{1}{2}\left(\phi_R^2 + \phi_I^2\right)\right] \right\} dx$$

Q-ball production mechanism

Q-ball production：

(1) produce the charge asymmetry (i.e. locally produce lots of particles with the same charge to form Q-ball)

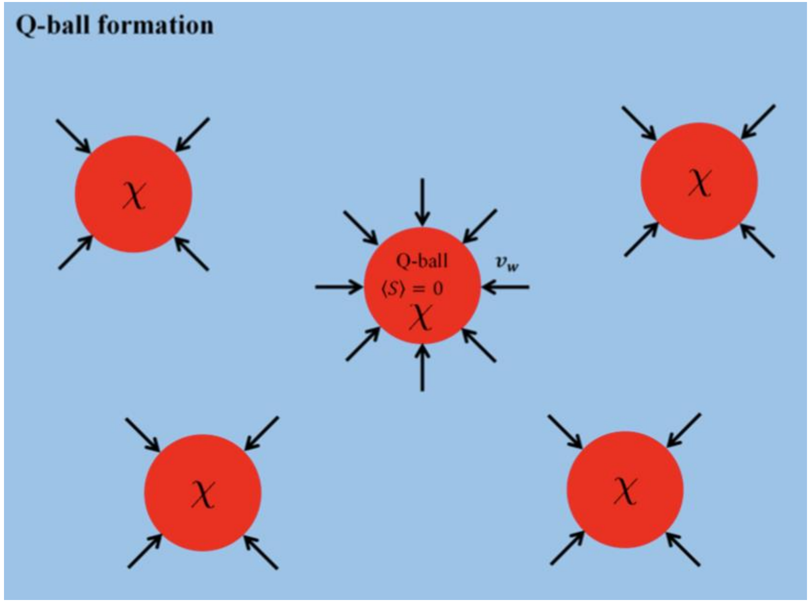
(2) and packet the same sign charge in the small size after overcoming the Coulomb repulsive interaction.

1. Supersymmetry? Affleck-Dine mechanism.

We do not observe the supersymmetry until now!

2. Q-ball formation based on FOPT.

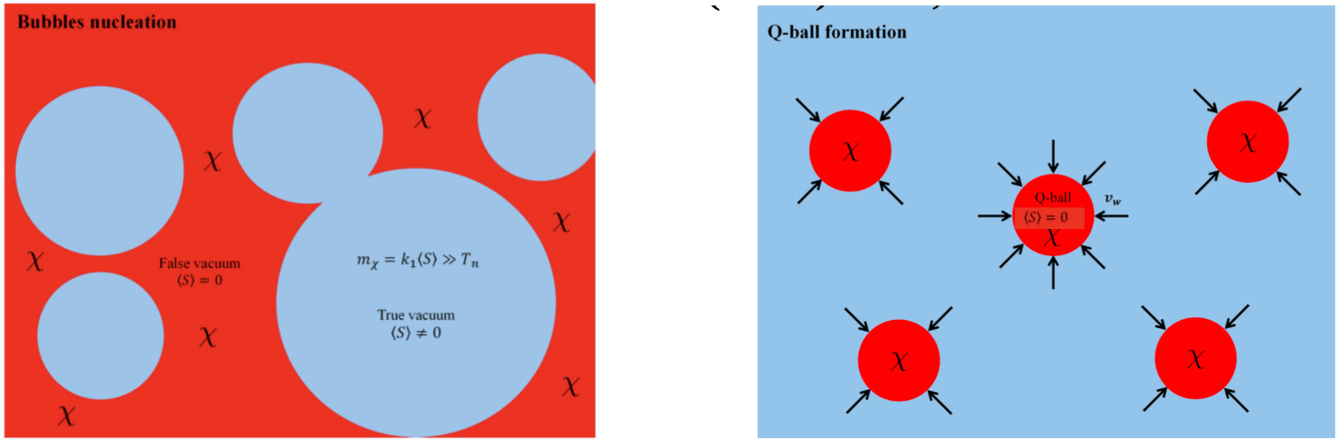
This talk



Case I: Q-ball DM

Global Q-ball DM: The cosmic phase transition with Q-balls production can explain baryogenesis and DM simultaneously.

$$\rho_{DM}^4 v_w^{3/4} = 73.5(2\eta_B s_0)^3 \lambda_S \sigma^4 \Gamma^{3/4}$$



(a) Bubble nucleation: χ particles trapped in the false vacuum due to Boltzmann suppression

(b) Q-ball formation: After the formation of Q-balls, they should be squeezed by the true vacuum

FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028;

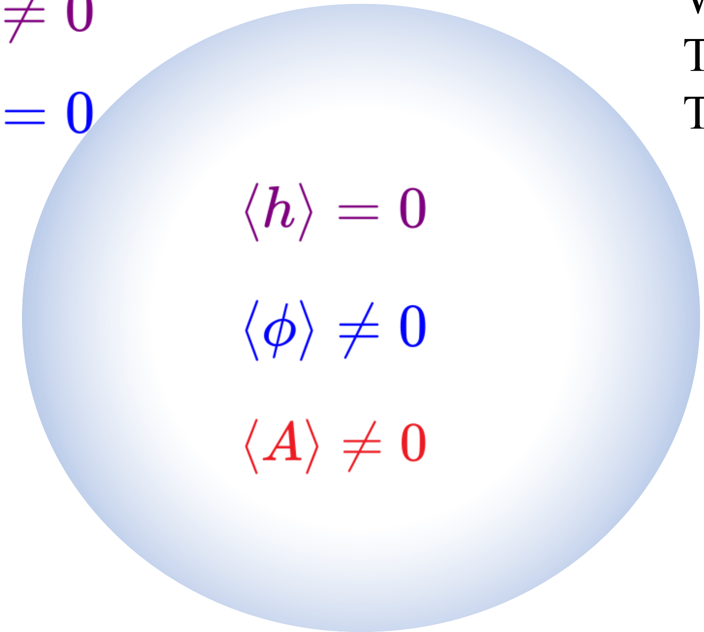
New DM production scenario by the bubbles.
The global Q-ball model proposed by T.D. Lee

Friedberg-Lee-Sirlin model
R. Friedberg, T.D. Lee and A. Sirlin.
Rev. D 13 (1976) 2739

Case I: Gauged Q-ball DM

$\langle h \rangle \neq 0$

$\langle \phi \rangle = 0$



When the conserved U(1) symmetry is local,
This introduces an extra gauge field A.
The minimal model achieving

$$\mathcal{L} = \left(D_\mu \phi\right)^\dagger \left(D^\mu \phi\right) + \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{4}\tilde{A}_{\mu\nu}\tilde{A}^{\mu\nu} - V(\phi, h)$$

$$V(\phi, h) = \frac{\lambda_{\phi h}}{2} h^2 |\phi|^2 + \frac{\lambda_h}{4}\left(h^2 - v_0^2\right)^2$$

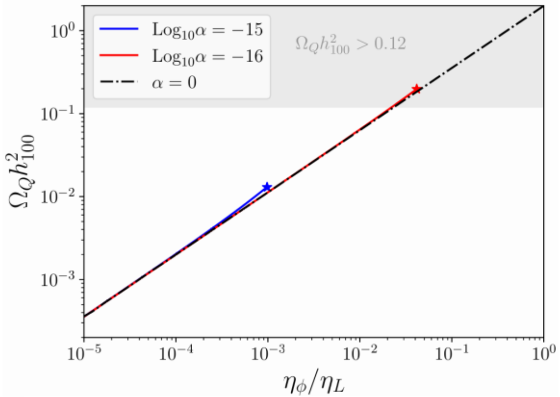
Interestingly, this portal coupling also naturally induces a strong FOPT.

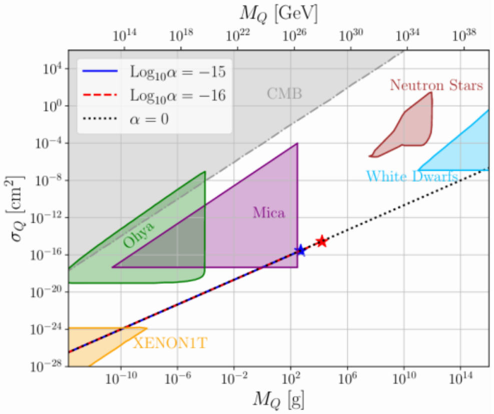
$$J_\mu = i\left(\phi^\dagger \overleftrightarrow{\partial}_\mu \phi + 2i\tilde{g}\tilde{A}_\mu |\phi|^2\right) \qquad Q = \int d^3x J^0$$

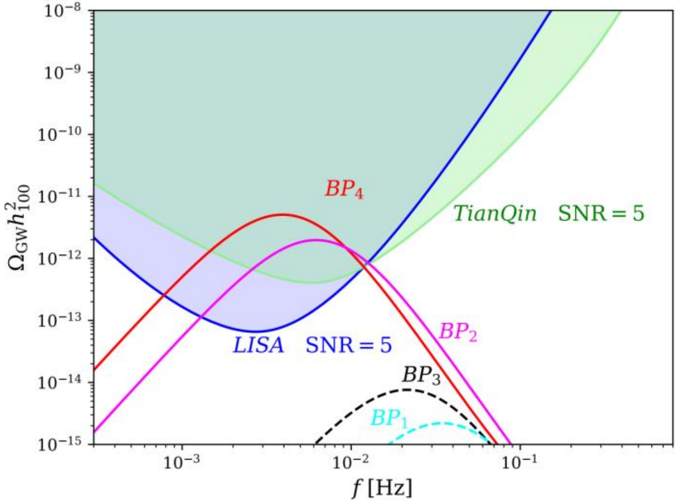
Conserved charge

Siyu Jiang, FPH, Pyungwon Ko, JHEP 07 (2024) 053

Gauged Q-ball DM from a FOPT







$$\Omega_Q h^2_{100}$$

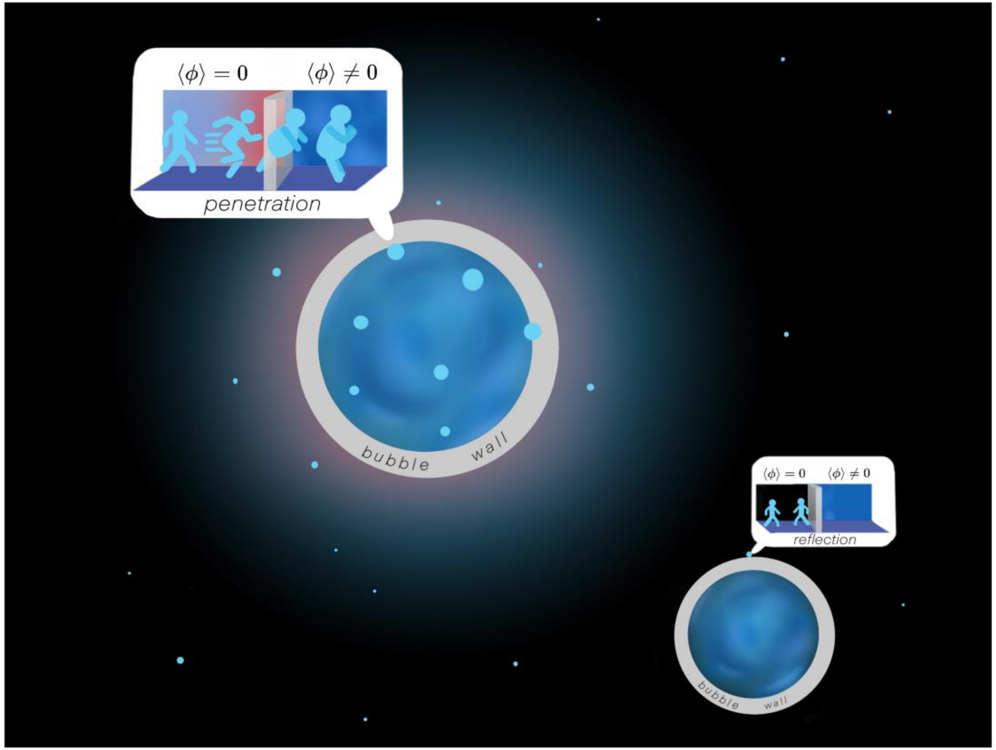
$$\simeq 2.81 \times \left(\frac{s_0 h^2_{100}}{\rho_c}\right)\left(\frac{\Gamma(T_\star)}{v_w}\right)^{3/16} s_\star^{-1/4}(F_\phi^{\rm trap}\eta_\phi)^{3/4}\lambda_h^{1/4} v_0 \left(1 + \frac{108^{1/4}\tilde{g}^2 F_\phi^{\rm trap}\eta_\phi s_\star v_w^{3/4}}{5.4\pi^{7/4}\Gamma(T_\star)^{3/4}}\right)$$

	$\lambda_{\phi h}$	T_p [GeV]	α_p	β/H_p	v_w	$F_\phi^{\rm trap}$	η_ϕ/η_L	$\delta\sigma_{Zh}$	GW
BP_1	6.8	69.8	0.12	540	0.1	0.932	0.48	-0.36%	● (cyan)
BP_2	6.8	70.4	0.12	578	0.6	0.805	3.0	-0.36%	● (magenta)
BP_3	7.0	63.0	0.15	372	0.1	0.965	3.4	-0.37%	● (black)
BP_4	7.0	63.9	0.15	403	0.6	0.858	20.8	-0.37%	● (red)

F_ϕ^{trap}:The fraction of particles trapped into the false vacuum. It is determined by the phase transition dynamics.

Siyu Jiang, FPH,
Pyungwon Ko, JHEP 07 (2024) 053

Case II: filtered DM from a FOPT



Bubble wall plays an essential role in the filtered DM mechanism.

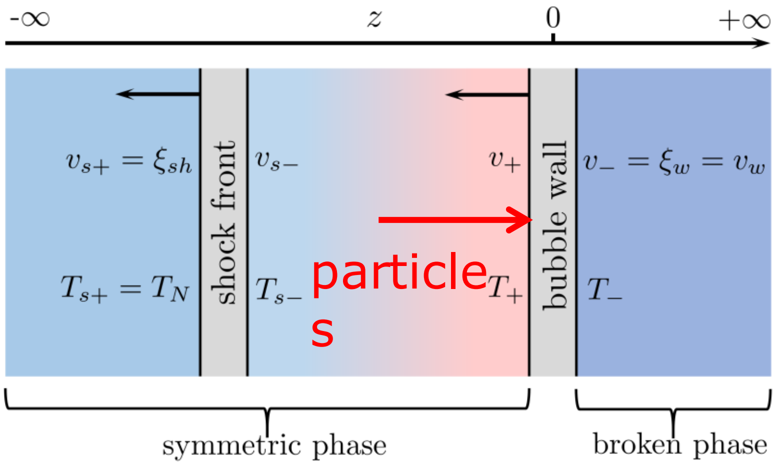
Siyu Jiang, FPH, Chong Sheng Li, Phys.Rev.D 108 (2023) 6, 063508

Case II: filtered DM

Original work:

$$\tilde{v}_{\rm pl} = v_w, \quad T = T' = T_n$$

Phys.Rev.Lett. 125 (2020) 15, 151102 , M. J. Baker, J. Kopp, and A. J. Long



$$\tilde{v}_{\rm pl} = \tilde{v}_+, \quad T = T_+, \quad T' = T_- \qquad \text{(this work with hydrodynamic effects)}\ .$$

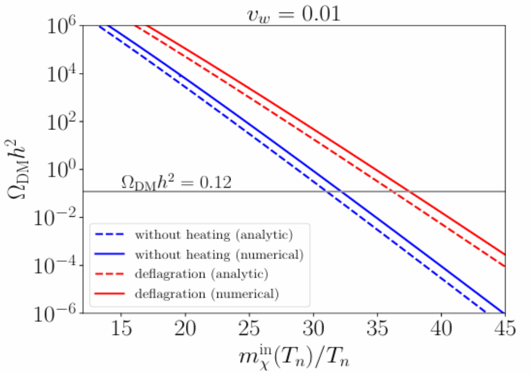
$$J_w^{\rm in} = \frac{g_\chi}{(2\pi)^2}\int_0^{-1} d\cos\theta\cos\theta\int_{-\frac{m_\chi^{\rm in}}{\cos\theta}}^{\infty} dp\frac{p^2}{e^{\tilde{\gamma}_+(1+\tilde{v}_+\cos\theta)p/T_+}} = \frac{g_\chi T_+^3\left(1+\tilde{\gamma}_+ m_\chi^{\rm in}(1-\tilde{v}_+)/T_+\right)}{4\pi^2\tilde{\gamma}_+^3(1-\tilde{v}_+)^2}e^{-\tilde{\gamma}_+ m_\chi^{\rm in}(1-\tilde{v}_+)/T_+}.$$

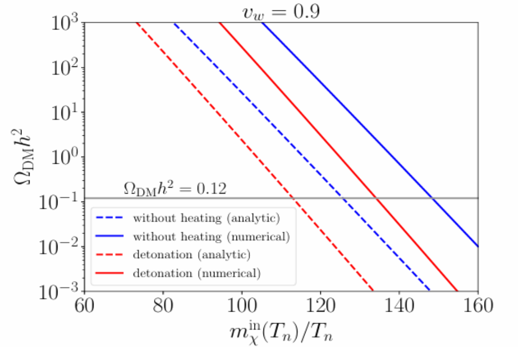
$$n_\chi^{\rm in} = \frac{J_w^{\rm in}}{\gamma_w v_w}$$

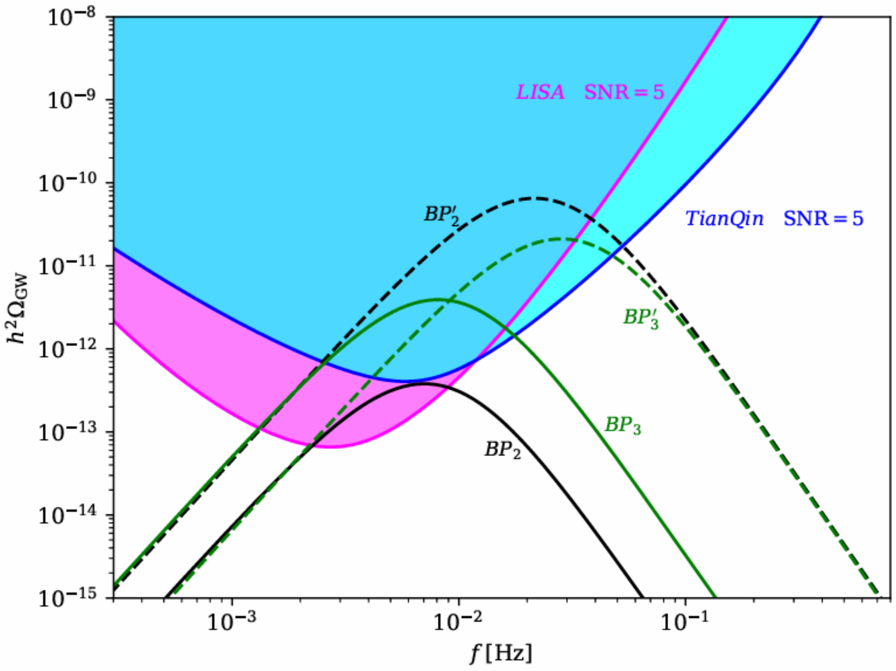
$$\Omega_{\rm DM}^{\rm (hy)}h^2 = \frac{m_\chi^{\rm in}(n_\chi^{\rm in}+n_{\bar\chi}^{\rm in})}{\rho_c/h^2}\frac{g_{\star 0}T_0^3}{g_\star(T_-)T_-^3} \simeq 6.29\times 10^8\frac{m_\chi^{\rm in}}{\rm GeV}\frac{(n_\chi^{\rm in}+n_{\bar\chi}^{\rm in})}{g_\star(T_-)T_-^3}$$

Case II: filtered DM

$$n_\chi^{\rm in} = \frac{T_+}{\gamma_w \tilde{\gamma}_+} \int_0^\infty \frac{dp_z}{(2\pi)^2} \mathcal{A}(z \gg L_w, p_z) \exp\left[\tilde{\gamma}_+ \left(\tilde{v}_+ p_z - \sqrt{p_z^2 + (m_\chi^{\rm in})^2}\right)/T_+\right] \left(\sqrt{p_z^2 + (m_\chi^{\rm in})^2} + \frac{T_+}{\tilde{\gamma}_+}\right)$$



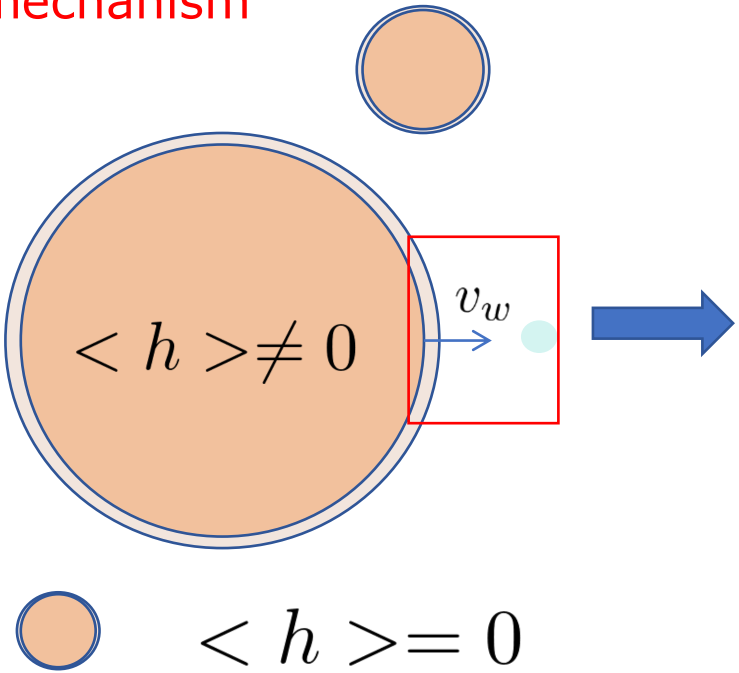


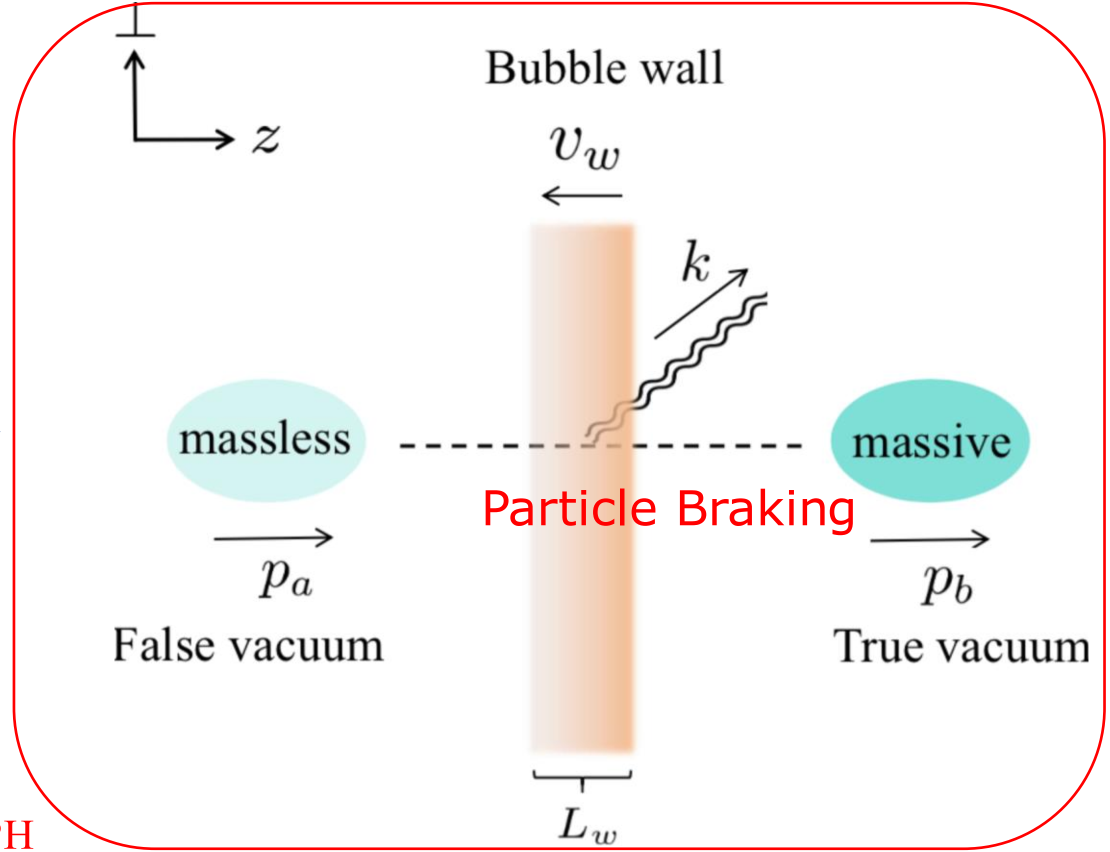


The missing GW source ?

Braking GW from phase transition

New phase transition GW mechanism

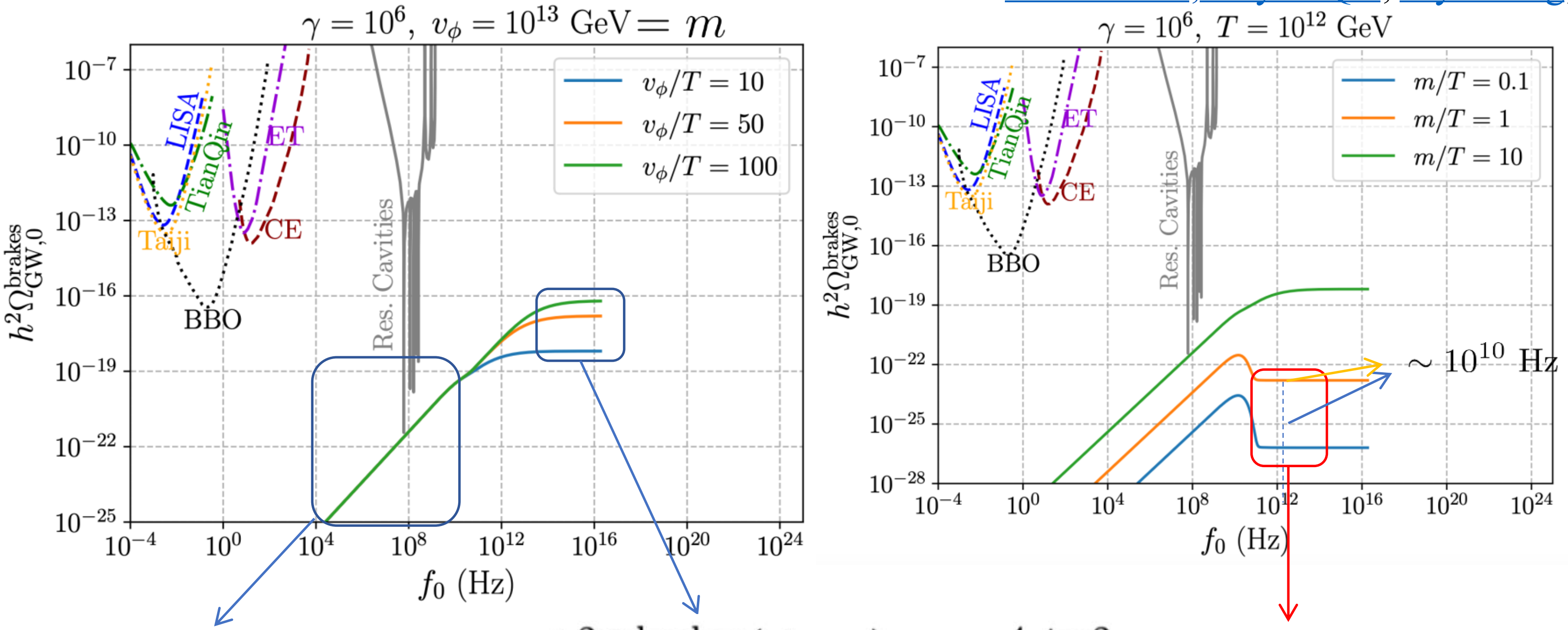




arXiv: 2508.04314, Dayun Qiu, Siyu Jiang, FPH

GW spectrum

arXiv: 2508.04314, Dayun Qiu, Siyu Jiang, FPH



$$h^2\Omega^{\rm brakes}_{\rm GW,0}(f_0) \propto m^2 f_0, \quad h^2\Omega^{\rm brakes}_{\rm GW,0}(f_{\rm peak}) \propto m^4/T^2. \quad \text{when } T \gtrsim m,$$

collinear gravitons non-collinear gravitons double-peaked structure

GW spectrum recap

The GW power spectrum exhibits two distinct behaviors across different frequency regimes.

arXiv: 2508.04314, Dayun Qiu, Siyu Jiang, FPH

- In the low-frequency regime, the spectrum scales linearly with frequency and is proportional to the square of the mass, primarily sourced from ultra-collinear radiation emitted as particles traverse the bubble wall.

- In contrast, the high-frequency regime displays an approximately flat spectrum up to a cutoff frequency and the amplitude scales with the fourth power of the mass, dominated by non-collinear gravitons.

proportional to the Lorentz factor of the bubble wall

These distinct behaviors may help to more directly to extract the new particle information.

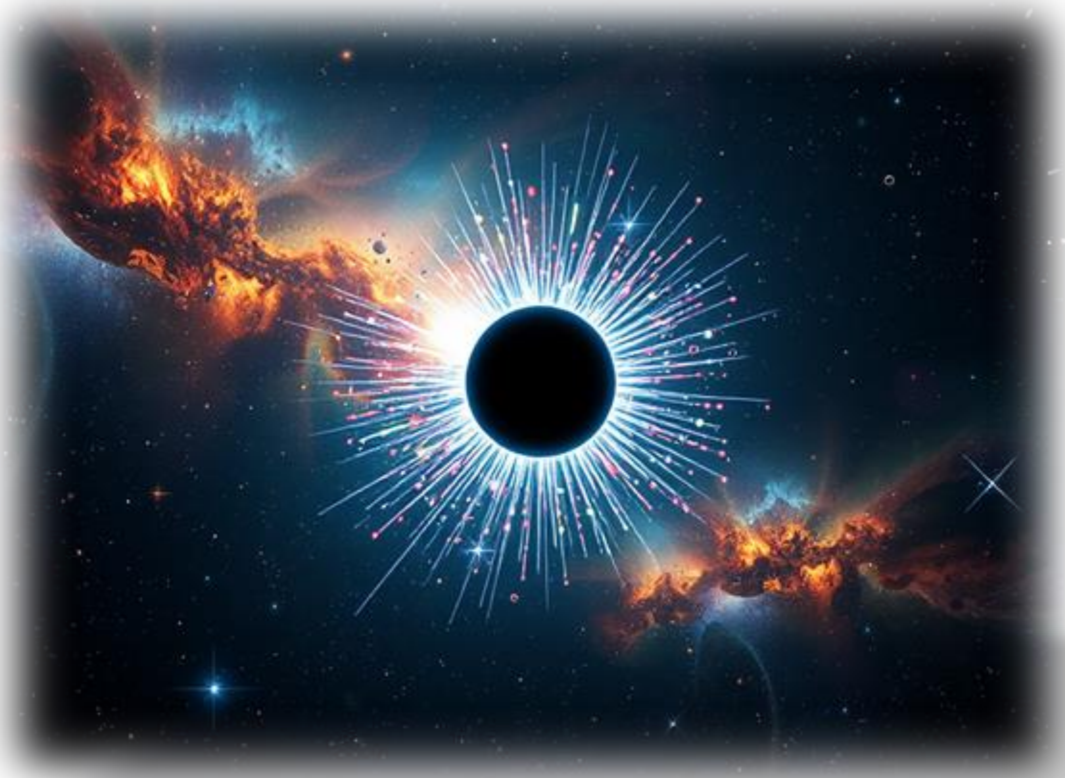
Case III: PBH DM from EWPT

FPH, Chikako, Aidi, Primordial Black Hole Formation and Multimessenger Signals in a Complex Singlet Extension of the Standard Model",arXiv:2510.24007, Phys.Rev.D 113 (2026) 5, 055013, see Chikako's talk this afternoon

Model Parameter Reconstruction of Electroweak Phase Transition with TianQin
arXiv: 2511.02612, Aidi, Chikako, FPH

See Aidi's talk this afternoon

Case IV: Heavy DM from superradiance



PBH can be the particle factory in the early universe.

(Kerr) PHB can produce SM particles and DM through (superradiance) Hawking radiation.

Gravitational interaction is universal.

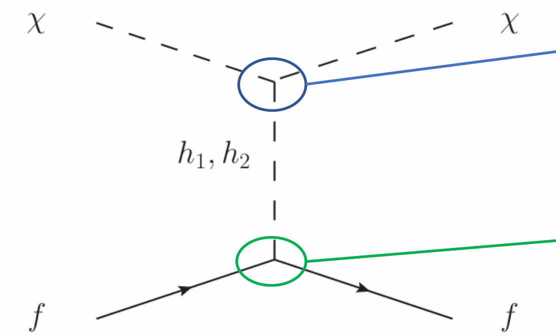
S.W. Hawking, Black hole explosions, Nature 248 (1974) 30

S.W. Hawking, Particle Creation by Black Holes, Commun. Math. Phys. 43 (1975) 199

Pseudo-Goldstone DM

In many well-motivated new physics models, the pseudo-Nambu-Goldstone boson (pNGB) from U(1) symmetry breaking emerges as a promising DM candidate.

Meanwhile, pNGB DM candidate naturally suppress the direct detection signals!



$$\mathcal{L} \supset \frac{v_s}{2}\chi^2\left(\kappa_{\chi\chi h_1}\, h_1 + \kappa_{\chi\chi h_2}\, h_2\right)$$

$$\kappa_{\chi\chi h_1} = +\, m_{h_1}^2/v_s^2\ \sin\theta\,,$$
$$\kappa_{\chi\chi h_2} = -\, m_{h_2}^2/v_s^2\ \cos\theta\,,$$

$$\mathcal{L} \supset -(h_1\cos\theta + h_2\sin\theta)\sum_f \frac{m_f}{v}\bar{f}f\,.$$

$$\mathcal{A}_{dd}(t) \propto \sin\theta\cos\theta\left(\frac{m_{h_2}^2}{t-m_{h_2}^2} - \frac{m_{h_1}^2}{t-m_{h_1}^2}\right) \simeq \sin\theta\cos\theta\,\frac{t\,(m_{h_2}^2 - m_{h_1}^2)}{m_{h_1}^2\, m_{h_2}^2} \simeq 0$$

Phys.Rev.Letts.119.191801

$$t \simeq 0.$$

pNGB DM

Minimal Pseudo-Goldstone DM model

$$V(H,S) = -\frac{\mu_H^2}{2}|H|^2 + \frac{\lambda_H}{2}|H|^4 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_S}{2}|S|^4 + \lambda_{HS}|H|^2|S|^2 - \boxed{\frac{m^2}{4}(S^2 + S^{*2})}$$

Explicit symmetry breaking term to give DM mass

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}, \quad S = \frac{v_s + s}{\sqrt{2}} e^{i\chi/v_s}$$

pNGB coupling is small due to the suppression of high symmetry-breaking scale, then how to produce enough DM relic density?

CP symmetry $S \to S^*$.

$\chi \to -\chi$

DM candidate

$$\begin{pmatrix} h \\ s \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}.$$

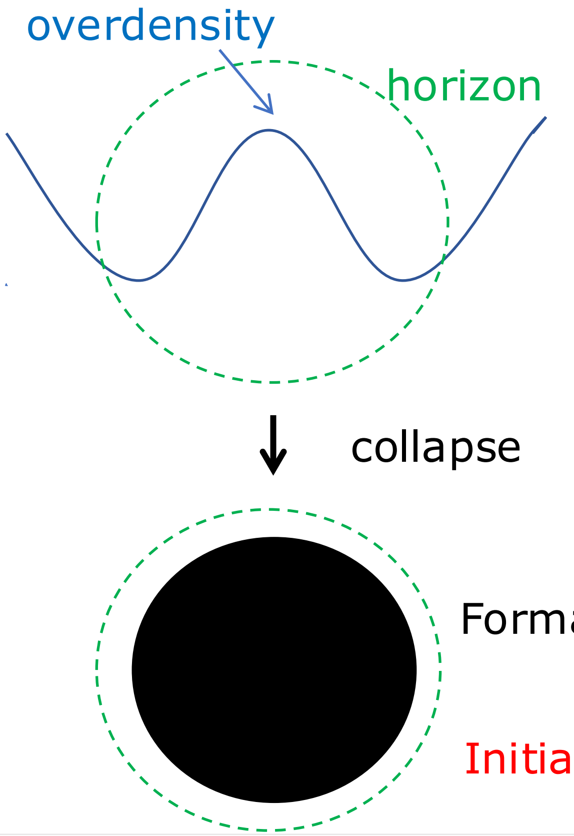
$$m_{h_1}^2 = \frac{1}{2}\left[\lambda_H v^2 + \lambda_S v_s^2 - \sqrt{(\lambda_S v_s^2 - \lambda_H v^2)^2 + 4\lambda_{HS}^2 v^2 v_s^2}\right],$$

$$m_{h_2}^2 = \frac{1}{2}\left[\lambda_H v^2 + \lambda_S v_s^2 + \sqrt{(\lambda_S v_s^2 - \lambda_H v^2)^2 + 4\lambda_{HS}^2 v^2 v_s^2}\right],$$

$$\tan 2\alpha = \frac{2\lambda_{HS} v v_s}{\lambda_S v_s^2 - \lambda_H v^2}$$

$v \ll v_s$ mixing can be ignored

Basic properties of PBH



Initial PHB mass

$$M_{\rm in} \equiv M_{\rm PBH}(T_{\rm in}) = \frac{4\pi}{3}\gamma \frac{\rho_R(T_{\rm in})}{H^3(T_{\rm in})}$$

Plank limit

$$H(T_{\rm in}) \leq 5 \times 10^{13}\ {\rm GeV}$$

$$\longrightarrow \quad M_{\rm in} \geq 0.5\ {\rm g}.$$

Hubble rate

$$H = \sqrt{\frac{8\pi}{3}\frac{\rho_R}{M_{\rm Pl}^2}} = \sqrt{\frac{4\pi^3 g_\star}{45}}\frac{T^2}{M_{\rm Pl}}$$

Formation temperature of PHB

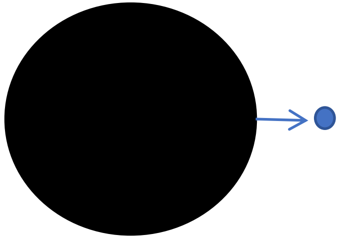
$$T_{\rm in} = \frac{1}{2}\left(\frac{5}{g_* \pi^3}\right)^{1/4}\left(\frac{3\gamma M_{\rm Pl}^3}{M_{\rm in}}\right)^{1/2}$$

Initial energy fraction of PBH

$$\beta \equiv \frac{\rho_{\rm PBH}(T_{\rm in})}{\rho_R(T_{\rm in})} = \frac{n_{\rm PBH}(T_{\rm in})\, M_{\rm in}}{\rho_R(T_{\rm in})}$$

pNGB from PBH

PBH can radiate particles lighter than the Hawking temperature.



$$T_{\rm PBH} = \frac{M_{\rm Pl}^2}{4\pi M_{\rm PBH}} f(a_\star) = \frac{M_{\rm Pl}^2}{4\pi M_{\rm PBH}} \frac{\sqrt{1-a_\star}}{1+\sqrt{1-a_\star}}$$

$$a_\star \equiv J M_{\rm Pl}^2 / M_{\rm PBH}^2$$

$$\Gamma_{\rm PBH \to i} \equiv \frac{dN_i}{dt} = \frac{27 g_i M_{\rm Pl}^2}{1024\pi^4 M_{\rm PBH}} \begin{cases} 2\zeta(3), & \text{Bosons} \\ \frac{3}{2}\zeta(3), & \text{Fermions} \end{cases}$$

Particle spectrum from Hawking radiation

absorption cross section

$$\frac{{\rm d}^2 N_i}{{\rm d}p{\rm d}t} = \frac{g_i}{2\pi^2} \sum_{l=s_i} \sum_{m=-l}^{l} \frac{\sigma_{s_i}^{lm}\left(M_{\rm PBH}, p, a_\star\right)}{\exp\left[\left(E_i(p) - m\Omega\right)/T_{\rm PBH}\right] - (-1)^{2s_i}} \frac{p^3}{E_i(p)} \qquad E_i(p) = \sqrt{p^2 + m_i^2}$$

horizon angular velocity

$$\Omega = \left(a_\star M_{\rm Pl}^2 / \left(2M_{\rm PBH}\right)\right)\left(1/\left(1+\sqrt{1-a_\star^2}\right)\right)$$

Schwarzschild PBH

geometric limit

$$\frac{dM_{\rm PBH}}{dt} = -\varepsilon\left(M_{\rm PBH}\right)\frac{M_{\rm Pl}^4}{M_{\rm PBH}^2} \approx -\frac{27}{4}\frac{g_{*\rm PBH}}{30720\pi}\frac{M_{\rm Pl}^4}{M_{\rm PBH}^2}$$

$$M_{\rm PBH}(t) = M_{\rm in}\left(1-\frac{t-t_{\rm in}}{\tau}\right)^{1/3}$$

Lifetime of PBH

$$\tau = \frac{40960\pi}{27 g_{*\rm PBH}}\frac{M_{\rm in}^3}{M_{\rm Pl}^4}$$

$\beta < \beta_c$ If the universe were always radiation dominated

$$H(\tau) = 1/(2\tau) \qquad H = \sqrt{\frac{8\pi}{3}\frac{\rho_R}{M_{\rm Pl}^2}} \qquad T_{\rm evap} \simeq \frac{9}{128}\left(\frac{1}{5 g_* \pi^5}\right)^{1/4}\left(\frac{g_{*\rm PBH} M_{\rm Pl}^5}{2 M_{\rm in}^3}\right)^{1/2}$$

$\beta > \beta_c$ Since BHs evolve as matter, if they dominate universe before fully decaying

$$H(\tau) = 2/(3\tau) \qquad H = \sqrt{\frac{8\pi}{3}\frac{M_{\rm in} n_{\rm PBH}(T_{\rm in}) T_{\rm evap}^3/T_{\rm in}^3}{M_{\rm Pl}^2}}$$

$$\beta_c \equiv T_{\rm evap}/T_{\rm in}$$

$$T_{\rm evap}\big|_{\rm PBHdom} \simeq \frac{9}{256}\left(\frac{g_{*\rm PBH}^2}{2\beta}\right)^{1/3}\left(\frac{1}{5^5\pi^{17} g_*^3}\right)^{1/12}\left(\frac{M_{\rm Pl}^{17}}{3\gamma M_{\rm in}^{11}}\right)^{1/6}$$

Schwarzschild PBH

If particle mass is smaller than initial Hawking temperature: $M_i < \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$

$$N_i = \int_0^{M_{\rm in}} \frac{1}{\varepsilon\left(M_{\rm PBH}\right)} \frac{M_{\rm PBH}^2}{M_{\rm Pl}^4} \frac{27 g_i \zeta(3) M_{\rm Pl}^2}{512\pi^4 M_{\rm PBH}} dM_{\rm PBH} = \frac{120\zeta(3)}{\pi^3} \frac{g_i}{g_{*\rm PBH}} \left(\frac{M_{\rm in}}{M_{\rm Pl}}\right)^2$$

If particle mass is heavier than the initial temperature， PBHs firstly radiate other lighter particles and then the temperature increases：

$$N_i = \int_0^{\frac{M_{\rm Pl}^2}{8\pi M_i}} \frac{1}{\varepsilon\left(M_{\rm PBH}\right)} \frac{M_{\rm PBH}^2}{M_{\rm Pl}^4} \frac{27 g_i \zeta(3) M_{\rm Pl}^2}{512\pi^4 M_{\rm PBH}} dM_{\rm PBH} = \frac{15\zeta(3)}{8\pi^5} \frac{g_i}{g_{*\rm PBH}} \left(\frac{M_{\rm Pl}}{M_i}\right)^2$$

If the PBHs dominate the Universe before evaporation, the radiation into SM particles will reheat the Universe and dilute the final DM relic.

$$\frac{\pi^2}{30} g_* T_{\rm evap}^4 + M_{\rm in} \frac{n_{\rm PBH}\left(T_{\rm in}\right)}{s\left(T_{\rm in}\right)} s\left(T_{\rm evap}\right) = \frac{\pi^2}{30} g_* \tilde{T}_{\rm evap}^4 \longrightarrow Y_i \equiv \frac{N_i n_{\rm PBH}\left(T_{\rm evap}\right)}{s\left(T_{\rm evap}\right)} \frac{s\left(T_{\rm evap}\right)}{s(\tilde{T}_{\rm evap})}$$

Schwarzschild PBH

DM relic density

$$\Omega_{\rm DM} = \frac{\rho_{\rm DM}}{\rho_c} = \frac{M_{\rm DM}}{\rho_c}\frac{n_{\rm DM}}{s}(t_0)s_0 = \frac{M_{\rm DM}}{\rho_c}Y_{\rm DM}s_0$$

$\beta < \beta_c$

$$\Omega_{\rm DM} \simeq 1.61\times 10^8 \beta \left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{g_{\rm DM}}{g_{*\rm PBH}}\right)\left(\frac{M_{\rm in}}{M_{\rm Pl}}\right)^{1/2}\left(\frac{M_{\rm DM}}{\rm GeV}\right), \quad M_{\rm DM} < \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$$

$$\simeq 2.55\times 10^5 \beta \left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{g_{\rm DM}}{g_{*\rm PBH}}\right)\left(\frac{M_{\rm Pl}^7}{M_{\rm in}^3 M_{\rm DM}^4}\right)^{1/2}\left(\frac{M_{\rm DM}}{\rm GeV}\right), \quad M_{\rm DM} > \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$$

$\beta > \beta_c$

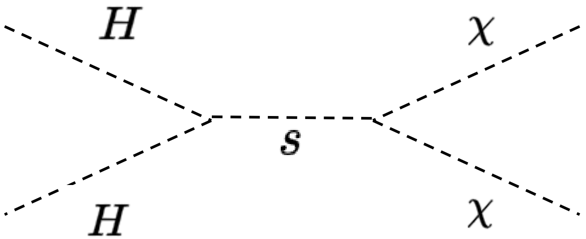
$$\Omega_{\rm DM} \simeq 6.46\times 10^7 \left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{g_{*\rm PBH}}{115}\right)^{1/2}\left(\frac{g_{\rm DM}}{g_{*\rm PBH}}\right)\left(\frac{M_{\rm Pl}}{M_{\rm in}}\right)^{1/2}\left(\frac{M_{\rm DM}}{\rm GeV}\right), \quad M_{\rm DM} < \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$$

$$\simeq 1.02\times 10^5 \left(\frac{g_*}{106.75}\right)^{-1/4}\left(\frac{g_{*\rm PBH}}{115}\right)^{1/2}\left(\frac{g_{\rm DM}}{g_{*\rm PBH}}\right)\left(\frac{M_{\rm Pl}^9}{M_{\rm in}^5 M_{\rm DM}^4}\right)^{1/2}\left(\frac{M_{\rm DM}}{\rm GeV}\right), \quad M_{\rm DM} > \frac{M_{\rm Pl}^2}{8\pi M_{\rm in}}$$

N.B. If PBHs dominate the energy density of the early Universe before they evaporate, the relic density is independent of β.

UV freeze-in

UV freeze-in

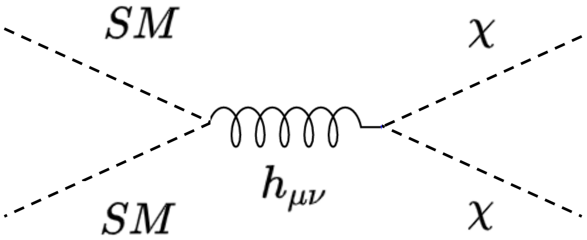


$$\frac{dY_\chi^{\rm FI}(x)}{dz} = \frac{2}{s(z)H(z)z}\gamma_{\chi\chi\to H^\dagger H}$$

$$\gamma_{\chi\chi\to H^\dagger H} \equiv \frac{g_H}{2!2!}\frac{T\lambda_{HS}^2}{2^9\pi^5}\int_{4M_\chi^2}^{\infty} ds\sqrt{s-4M_\chi^2}K_1(\sqrt{s}/T)\frac{s^2}{(s-M_s^2)^2}$$

$$\Omega_\chi^{\rm FI} = 3.34\times 10^{22}\lambda_{HS}^2\left(\frac{100}{g_s}\right)\left(\frac{100}{g_*}\right)^{1/2}\left(\frac{T_{\rm reh}}{M_s}\right)^4\left(\frac{M_\chi}{T_{\rm reh}}\right)$$

Gravitational freeze-in



Phys.Lett.B 774 (2017) 676-681; Phys.Rev.D 97 (2018) 11, 115020; Phys.Rev.D 105 (2022) 7, 075005

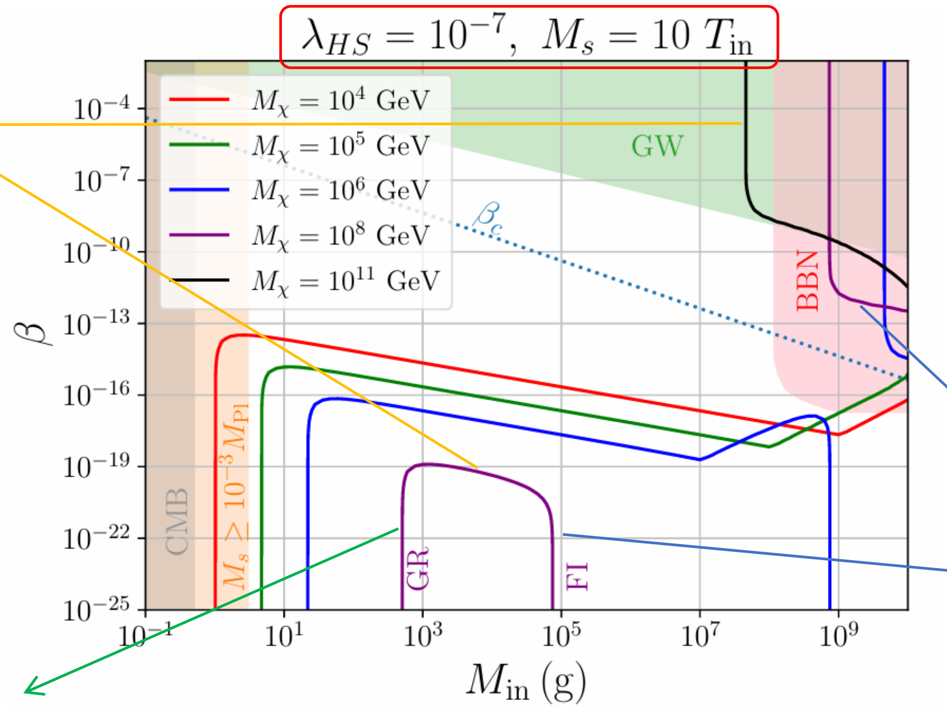
$$\frac{dY_\chi^{\rm GR}(x)}{dz} = \frac{2}{s(z)H(z)z}\gamma_g$$

$$\gamma_g = 64\pi^2\delta\frac{T^8}{M_{\rm Pl}^4} \qquad \delta = \frac{3997\pi^3}{41472000}$$

$$Y_\chi^{\rm GR} = \frac{720\delta}{\pi^2 g_{*s}}\sqrt{\frac{5\pi}{g_*}}\left(\frac{T_{\rm in}}{M_{\rm Pl}}\right)^3\frac{s\,(T_{\rm evap})}{s(\tilde{T}_{\rm evap})}\times\begin{cases}1, & M_\chi \ll T_{\rm in}\\ \left(\frac{T_{\rm in}}{M_\chi}\right)^4, & M_\chi \gg T_{\rm in}\end{cases}$$

Schwarzschild PBH：superheavy DM

DM from PBH evaporation



DM from UV freeze-in

DM from gravitational freeze-in

Siyu Jiang, FPH*, arXiv:2503.14332, JCAP06 (2025) 023

Kerr PBH: superheavy DM

Since the DM is pseudo-Goldstone boson, it can also be produced by superradiance process of Kerr BH.

The superradiance is efficient when the Compton length of the DM particle is comparable with the gravitational radius of Kerr BH.

The superradiant rate can be given approximately and analytically

$$\Gamma_{\rm SR} = \frac{M_\chi}{24}\left(\frac{M_{\rm PBH} M_\chi}{M_{\rm Pl}^2}\right)^8 (a_\star - 2M_\chi r_+)$$

The event horizon

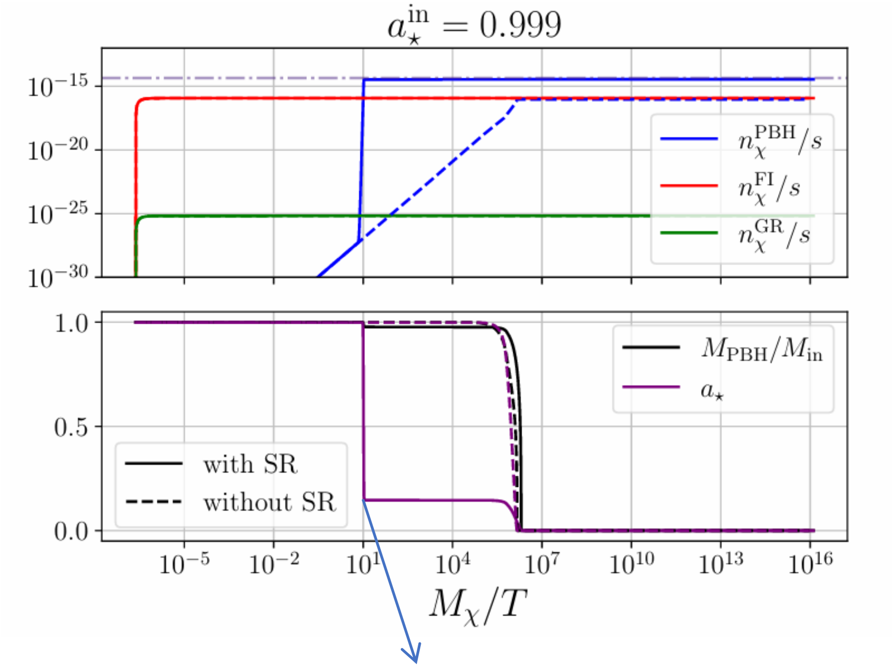
$$r_+ = r_g(1+\sqrt{1-a_\star^2})$$

Or more accurately by solving the Teukolsky equation numerically

$$\frac{1}{\sin\theta}\partial_\theta\left(\sin\theta\,\partial_\theta S\right) + \left[a_\star^2 r_g^2\left(\omega^2-\mu^2\right)\cos^2\theta - \frac{m^2}{\sin^2\theta} + \lambda\right] S = 0\,,$$

$$\Delta\partial_r\left(\partial_r R\right) - \Delta\left[\mu^2 r^2 + a_\star^2 r_g^2 \omega^2 - 2\omega\, m\, a_\star r_g\, r + \left(\omega\left(r^2 + a_\star^2 r_g^2\right) - m\, a_\star r_g\right)^2 + \lambda\right] R = 0$$

Kerr PBH: superheavy DM



Superradiance reduces the BH angular momentum before the Hawking radiation, DM is mainly produced by superradiance.

$$Ha\frac{dN_\chi^{\rm SR}}{da} = \Gamma_{\rm SR} N_\chi^{\rm SR}\,,$$

$$Ha\frac{dM_{\rm PBH}}{da} = -\varepsilon(M_{\rm PBH}, a_\star)\frac{M_{\rm Pl}^4}{M_{\rm PBH}^2} - M_\chi \Gamma_{\rm SR} N_\chi^{\rm SR}\,,$$

$$Ha\frac{da_\star}{da} = -a_\star[\gamma(M_{\rm PBH}, a_\star) - 2\varepsilon(M_{\rm PBH}, a_\star)]\frac{M_{\rm Pl}^4}{M_{\rm PBH}^3} - \left[\sqrt{2} - 2\alpha a_\star\right]\Gamma_{\rm SR} N_\chi^{\rm SR}\frac{M_{\rm Pl}^2}{M_{\rm PBH}^2}\,,$$

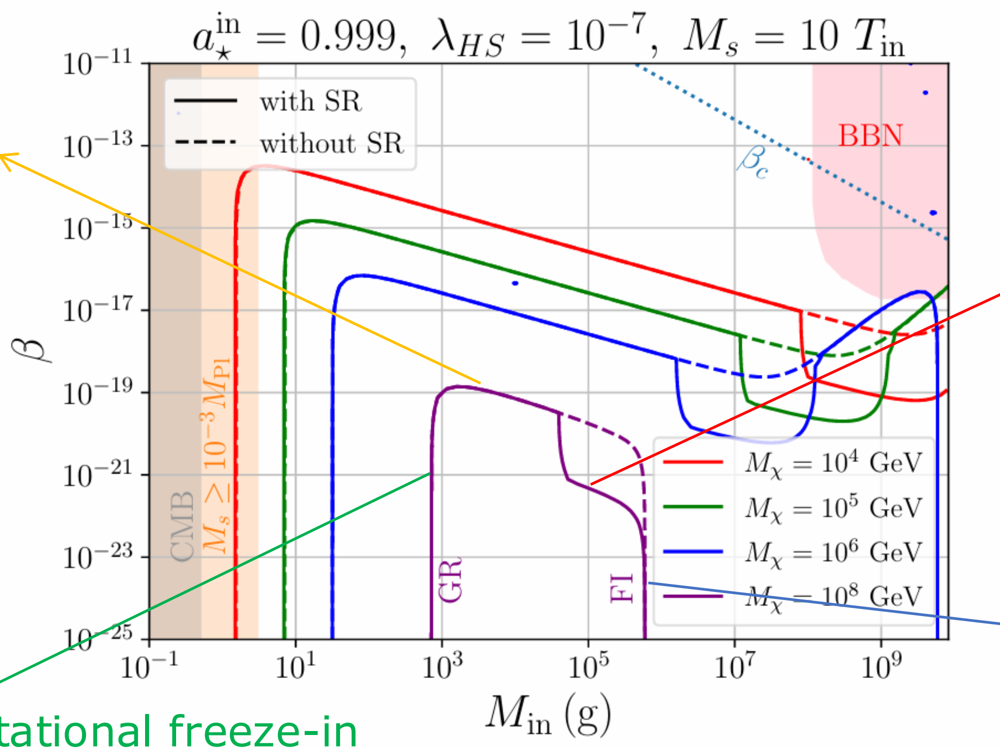
$$Ha\frac{dN_\chi^{\rm PBH}}{da} = \frac{\varrho_{\rm PBH}}{M_{\rm PBH}}\left[\Gamma_{\rm PBH\to\chi} + \Gamma_{\rm SR} N_\chi^{\rm SR}\right]\,,$$

$$Ha\frac{dN_\chi^{\rm FI}}{da} = 2a^3\gamma_{\chi\chi\to H^\dagger H}\,, \qquad Ha\frac{dN_\chi^{\rm GR}}{da} = 2a^3\gamma_g$$

Solve by using ULYSSES (2301.05722)

Case IV: Heavy DM from superradiance

DM from PBH evaporation



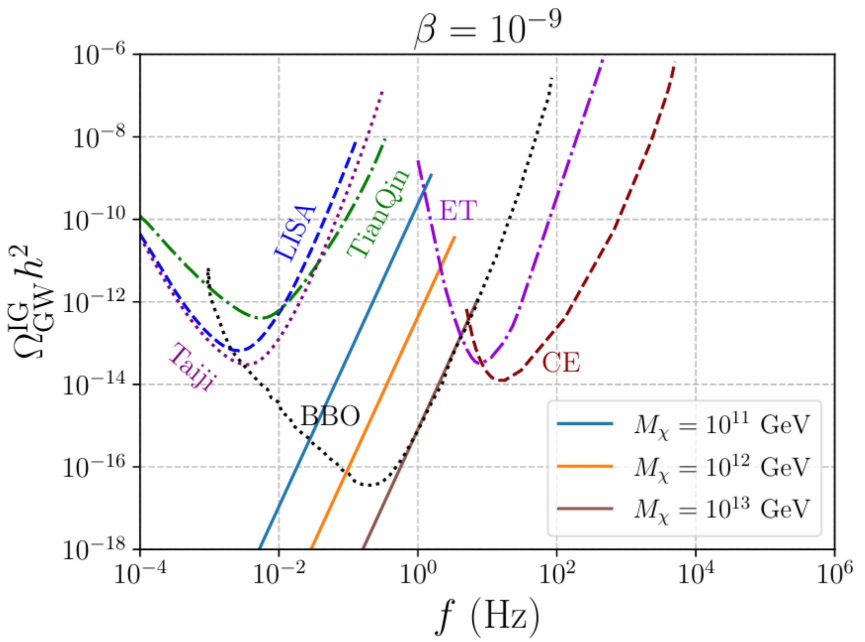
DM from superradiance

DM from UV freeze-in

DM from gravitational freeze-in

Siyu Jiang, FPH*, arXiv:2503.14332, JCAP06 (2025) 023

Induced GW from superheavy DM



When the PBHs begin to dominate the energy density of the Universe, the inhomogeneous distribution of PBHs leads to curvature perturbations. Subsequently, at second order, these perturbations can generate GWs.

$$f_p^{\rm IG} \simeq 1.7 \times 10^3 \ {\rm Hz} \left(\frac{M_{\rm in}}{10^4 \ {\rm g}}\right)^{-5/6}$$

$$\simeq 0.33 \ {\rm Hz} \left(\frac{M_\chi}{10^9 \ {\rm GeV}}\right)^{1/3}$$

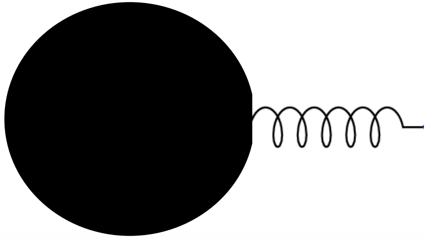
$$\Omega_p^{\rm IG} h^2 \simeq 9 \times 10^{-7} \left(\frac{\beta}{10^{-8}}\right)^{16/3} \left(\frac{M_{\rm in}}{10^7 \ {\rm g}}\right)^{34/9}$$

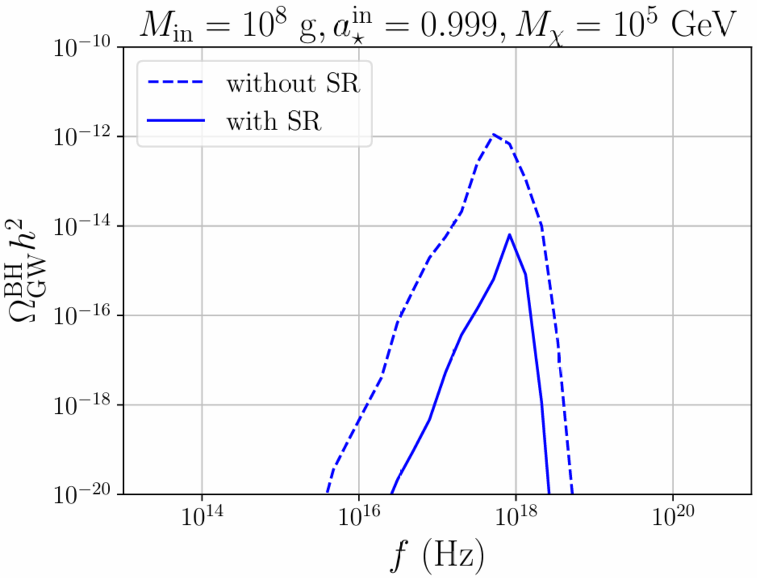
$$\Omega_{\rm GW}^{\rm IG} h^2 \simeq \Omega_p^{\rm IG} h^2 \left(\frac{f}{f_p^{\rm IG}}\right)^{11/3} \Theta\left(f_p^{\rm IG} - f\right)$$

Siyu Jiang, FPH*, arXiv:2503.14332, JCAP06 (2025) 023

JCAP 04 (2021) 062; JCAP 03 (2021) 053; JHEP 03 (2023) 127

GW from Hawking radiation





$$\frac{d\rho_{\rm GW}}{dt\,dp} = n_{\rm PBH}(t)\,p\,\frac{dN_{\rm grav}}{dt\,dp}$$

↓

public code BlackHawk

$$\frac{d\rho_{\rm GW,0}}{d\ln p_0} = 2\times 10^{32}\beta M_{\rm in}^{-3/2} p_0^4 \int_{\frac{a_0}{a_{\rm evap}}}^{\frac{a_0}{a_{\rm in}}} dx \frac{\sigma_{s_i}^{lm}}{\exp\left[\left(x p_0 - m\Omega\right)/T_{\rm PBH}\right] - 1}$$

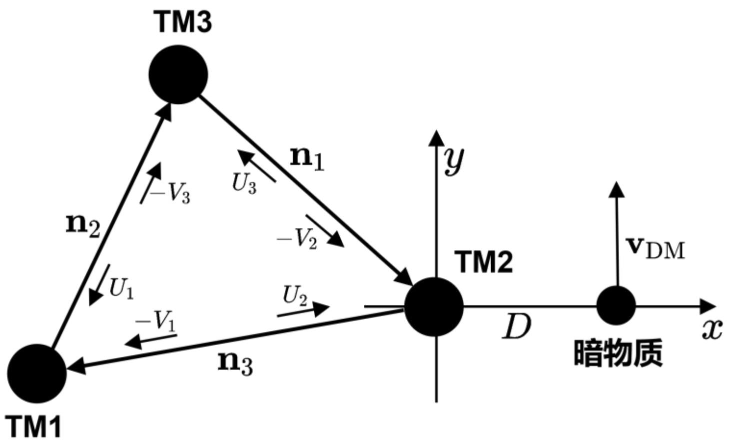
$$\Omega_{\rm GW}^{\rm BH} h^2 = \frac{h^2}{\rho_c}\frac{d\rho_{\rm GW,0}}{d\ln p_0}$$

outline

1. Motivation
2. Ultralight DM
3. **Ultraheavy DM**
4. Summary

3.2 Detecting the Propagation of DM in the Late Universe Using Gravitational Wave Experiments

DM Direct detection on GW experiments



As a macroscopic DM object passes near the detector, its interaction with TM causes differential acceleration among the test masses of GW detectors, producing a detectable Doppler signal.

We apply this detection scheme to macroscopic DM.

Macroscopic Dark Matter under siege: from White Dwarf Data to Gravitational Wave Detection Siyu Jiang,Aidi Yang, and FPH, arXiv:2511.23263

DM Direct detection on GW experiments

We apply this into the minimal Fermi-ball model

$$\mathcal{L} = \frac{(\partial\phi)^2}{2} - \frac{1}{2}m_\phi^2\phi^2 + \bar{X}i\partial\!\!\!/ X - m_X\bar{X}X + y_X\bar{X}\phi X$$

Fermi balls naturally induce a Yukawa interaction between DM and ordinary matter by treating scalar particles as mediator particles.

$$i, j \in \{\mathrm{SM}, X\},$$

$$V_{i-j} = -M_i M_j \frac{G}{r}\left(1 + \delta_i\delta_j e^{-m_\phi r}\right)$$

$$\delta_i = \frac{\sqrt{\alpha_i}}{\sqrt{G\bar{m}_i}}. \quad \bar{m}_i = M_i/N_i$$

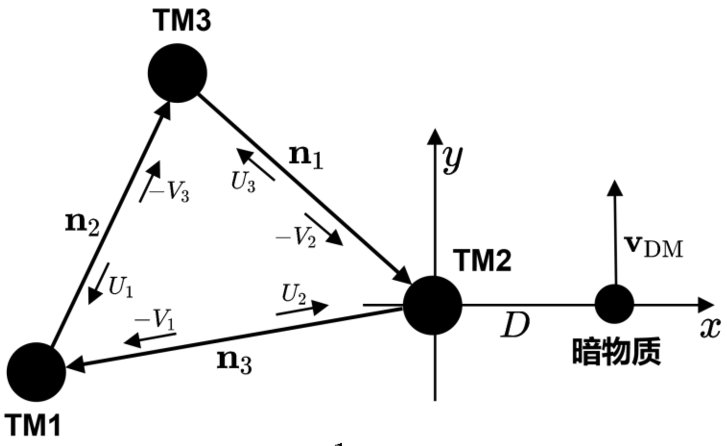
$$\alpha_X = y_X^2/4\pi \quad \alpha_{\mathrm{SM}} = y_n^2/4\pi$$

$$\delta_X = \left(\frac{g_X\alpha_X^5 M_X^2}{4\pi G^2 m_X^6}\right)^{1/4} = \frac{2}{3}\left(\frac{m_X^4 R_X^5}{3\pi G^2 M_X^3}\right)^{1/4}$$

MICROSCOPE experiments: $|\delta_{\mathrm{SM}}| < 3 \times 10^{-6}$

Bullet cluster constraints: $\delta_X^2 < 2\times 10^6 \left(\frac{M_X}{M_\odot}\right)^{-1/2}\left(\frac{v_{\mathrm{DM}}}{10^{-2}}\right)^2 e^{4\times 10^{-3}\sqrt{\frac{M_X}{M_\odot}\frac{\mathrm{pc}}{\lambda}}}$

DM Direct detection on GW experiments



$$r >> m_\phi^{-1}:$$

$$\tilde{G} = G(1+\tilde{\alpha}), \quad \tilde{\alpha} = \delta_{\rm SM}\delta_X$$

In the scenario where DM transits near a GW detection satellite, we assume the process occurs within the x − y plane, with the DM moving along the y-direction. The resulting differential acceleration

$$\mathbf{g}(t) = \frac{\tilde{G}M_X}{D^2}\frac{1}{\left(1+\left(\frac{v_{\rm DM}t}{D}\right)^2\right)^{3/2}}\begin{pmatrix}1\\ \frac{v_{\rm DM}t}{D}\\ 0\end{pmatrix}$$

→

$$\mathbf{v}(t,D) = \frac{\tilde{G}M_X}{Dv_{\rm DM}}\begin{bmatrix}1+\frac{v_{\rm DM}t/D}{\sqrt{1+v_{\rm DM}^2t^2/D^2}}\\ -\frac{1}{\sqrt{1+v_{\rm DM}^2t^2/D^2}}\\ 0\end{bmatrix}$$

→

$$U_1(t) = \mathbf{n}_2\cdot\frac{\mathbf{v}_1(t)-\mathbf{v}_3(t-L/c)}{c}$$

$$V_1(t) = \mathbf{n}_3\cdot\frac{\mathbf{v}_1(t)-\mathbf{v}_2(t-L/c)}{c}$$

permutation symmetry $1\to2\to3\to1$

DM Direct detection on GW experiments

In order to effectively cancel the laser noise, we employ the time-delay interferometry:

$$X(t) = U_1(t) + V_1(t) - U_1\left(t - \frac{2L}{c}\right) - V_1\left(t - \frac{2L}{c}\right) + U_2\left(t - \frac{3L}{c}\right) + V_3\left(t - \frac{3L}{c}\right) - U_2\left(t - \frac{L}{c}\right) - V_3\left(t - \frac{L}{c}\right)$$

$$\omega = 2\pi f$$

$$\tilde{X}(\omega) = \sqrt{\frac{2}{\pi}}\left(1 - e^{4i\omega L/c}\right)\frac{\tilde{G}M_X}{cv_{\rm DM}^2}\sin\vartheta \times \left[K_0\left(\frac{D\omega}{v_{\rm DM}}\right)\sin\varphi - iK_1\left(\frac{D\omega}{v_{\rm DM}}\right)\cos\varphi\right] + \sqrt{\frac{8}{\pi}}\left(e^{3i\omega L/c} - e^{i\omega L/c}\right)\frac{\tilde{G}M_X}{cv_{\rm DM}^2}\sin\vartheta \times \left[K_0\left(\frac{D'\omega}{v_{\rm DM}}\right)\sin\varphi - iK_1\left(\frac{D'\omega}{v_{\rm DM}}\right)\cos\varphi\right].$$

The power spectral density (PSD) of the DM signal

$$P(\omega) = \left\langle\left|\tilde{X}(\omega)\right|^2\right\rangle = \frac{1}{4\pi}\int d\vartheta\sin\vartheta\int d\varphi|\tilde{X}(\omega)|^2 = \frac{32}{3\pi}\left(\frac{\tilde{G}M_X}{cv_{\rm DM}^2}\right)^2\sin^2(\omega L/c) \times \left\{\left[K_0\left(\frac{D\omega}{v_{\rm DM}}\right)\cos(\omega L/c) - K_0\left(\frac{D'\omega}{v_{\rm DM}}\right)\right]^2 + \left[K_1\left(\frac{D\omega}{v_{\rm DM}}\right)\cos(\omega L/c) - K_1\left(\frac{D'\omega}{v_{\rm DM}}\right)\right]^2\right\}.$$

Direct detection on GW experiments

$$\alpha(t) = U_1(t) + V_1(t) + U_3(t-\frac{L}{c}) + V_2(t-\frac{L}{c}) + U_2(t-\frac{2L}{c}) + V_3(t-\frac{L}{c})$$
$$= -\mathbf{n}_1 \cdot \frac{\mathbf{v}(t,D) - \mathbf{v}(t-3L/c,D)}{c} - 3\mathbf{n}_1 \cdot \frac{\mathbf{v}(t-2L/c,D') - \mathbf{v}(t-L/c,D')}{c}$$

$$P_\alpha(\omega) = \left\langle |\tilde{\alpha}(\omega)|^2 \right\rangle = \frac{8}{3\pi}\left(\frac{\tilde{G}M_X}{cv_{\rm DM}^2}\right)^2 \sin^2\left(\frac{\omega L}{2c}\right) \times \left\{\left[K_0\left(\frac{D\omega}{v_{\rm DM}}\right)\left(1+2\cos\left(\frac{\omega L}{c}\right)\right) - 3K_0\left(\frac{D'\omega}{v_{\rm DM}}\right)\right]^2 + \left[K_1\left(\frac{D\omega}{v_{\rm DM}}\right)\left(1+2\cos\left(\frac{\omega L}{c}\right)\right) - 3K_1\left(\frac{D'\omega}{v_{\rm DM}}\right)\right]^2\right\},$$

$$\zeta(t) = U_1(t-\frac{L}{c}) + V_1(t-\frac{L}{c}) + U_2(t-\frac{L}{c}) + V_2(t-\frac{L}{c}) + U_3(t-\frac{L}{c}) + V_3(t-\frac{L}{c})$$
$$= -\mathbf{n}_1 \cdot \left[\frac{\mathbf{v}(t-L/c,D) - \mathbf{v}(t-2L/c,D)}{c} + \frac{\mathbf{v}(t-2L/c,D') - \mathbf{v}(t-L/c,D')}{c}\right]$$

$$P_\zeta(\omega) = \left\langle \left|\tilde{\zeta}(\omega)\right|^2 \right\rangle = \frac{8}{3\pi}\left(\frac{\tilde{G}M_X}{cv_{\rm DM}^2}\right)^2 \sin^2\left(\frac{\omega L}{2c}\right) \times \left\{\left[K_0\left(\frac{D\omega}{v_{\rm DM}}\right) - K_0\left(\frac{D'\omega}{v_{\rm DM}}\right)\right]^2 + \left[K_1\left(\frac{D\omega}{v_{\rm DM}}\right) - K_1\left(\frac{D'\omega}{v_{\rm DM}}\right)\right]^2\right\}.$$

Direct detection on GW experiments

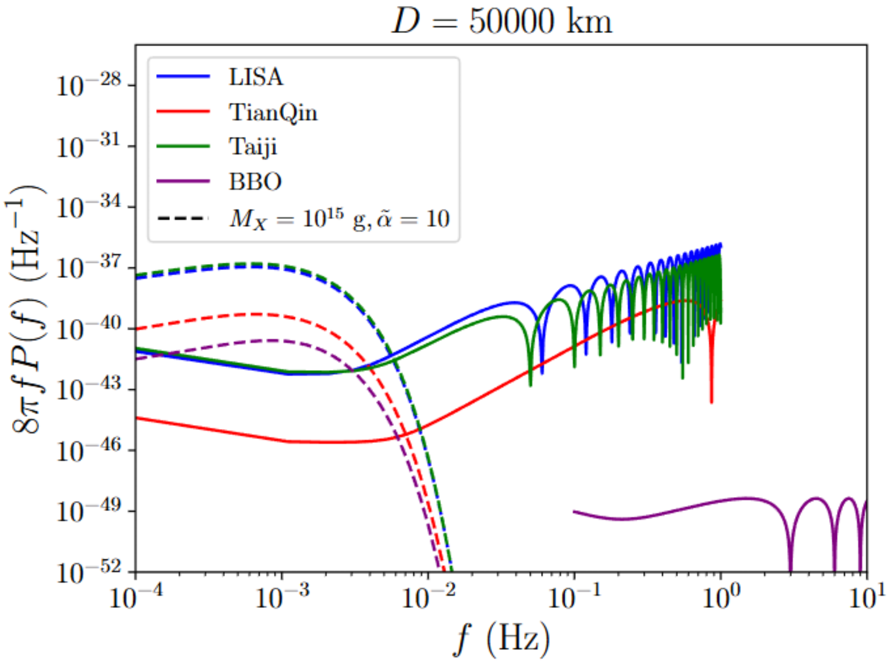
Parameter	LISA	TianQin	Taiji
Arm length L (10^9 m)	2.5	0.17	3
$P_{\rm oms}$ (10^{-12} m)	15	1	8
$P_{\rm acc}$ (10^{-15} m $\cdot$ s^{-2})	3	1	3
$T_{\rm obs}$ (yr)	4.5	2.5	5
Frequency range (Hz)	$[10^{-4}, 1]$	$[10^{-4}, 1]$	$[10^{-4}, 1]$

noise PSD in X channel:

$$S_X(f) = 16\sin^2\left(\frac{2\pi f L}{c}\right)\left\{\left[3+\cos\left(\frac{4\pi f L}{c}\right)\right]S_{\rm acc}(f)+S_{\rm oms}(f)\right\}$$

$$S_{\rm oms}(f) = \left(\frac{2\pi f P_{\rm oms}}{c}\right)^2\left[1+\left(\frac{2\times 10^{-3}\ {\rm Hz}}{f}\right)^4\right]{\rm Hz}^{-1}$$

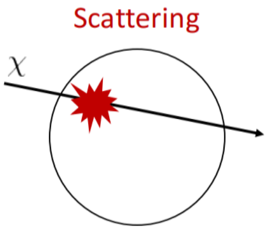
$$S_{\rm acc}(f) = \left(\frac{P_{\rm acc}}{2\pi f c}\right)^2\left[1+\left(\frac{0.4\times 10^{-3}\ {\rm Hz}}{f}\right)^2\right]\times\left[1+\left(\frac{f}{8\times 10^{-3}\ {\rm Hz}}\right)^4\right]{\rm Hz}^{-1}$$



Direct detection on GW experiments

We also included the constraints from astrophysical detections:

DM may interact with nucleons on the surface of white dwarfs or neutron stars, thereby triggering supernovae or superbursts.



Energy deposition

$$E_{\rm dep} \geq \frac{4\pi}{3}\rho\lambda_T^3\left(\rho, T_{\rm crit}\right)\bar{c}_p\left(\rho, T_{\rm crit}\right)T_{\rm crit}$$

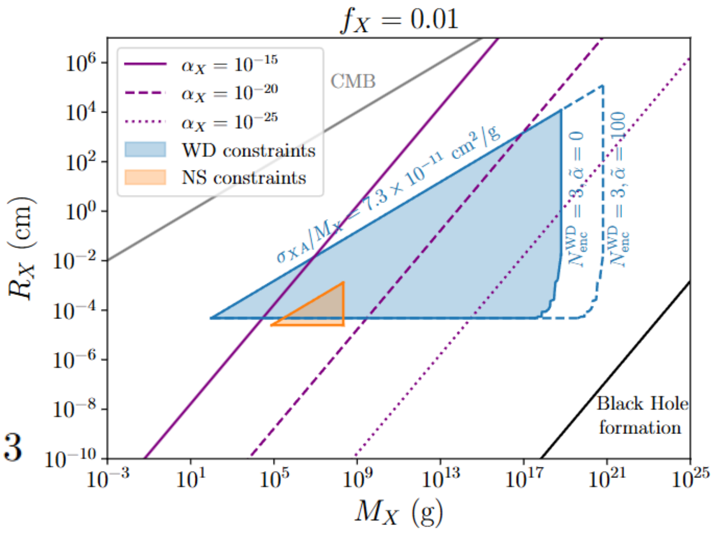
Encounter rate

$$\Gamma^X_{\rm enc}(r) = f_X\frac{\rho_{\rm DM}(r)}{M_X}v_{\rm DM}(r)\pi b^2_{\rm max} \qquad N^{\rm WD}_{\rm enc} = \sum_i \Gamma^X_{\rm enc}\tau_{{\rm WD},i} = 3$$

Penetration condition:

$$\frac{dE_{\rm dep}}{dx} \approx \rho_{\rm env}\sigma_{XA}v^2_{\rm esc}(1+\tilde{\alpha}) < \frac{M_X v^2_{\rm esc}(1+\tilde{\alpha})}{R_{\rm env}}$$

4361 white dwarfs



Constraints from white dwarfs and neutron stars

Direct detection on GW experiments

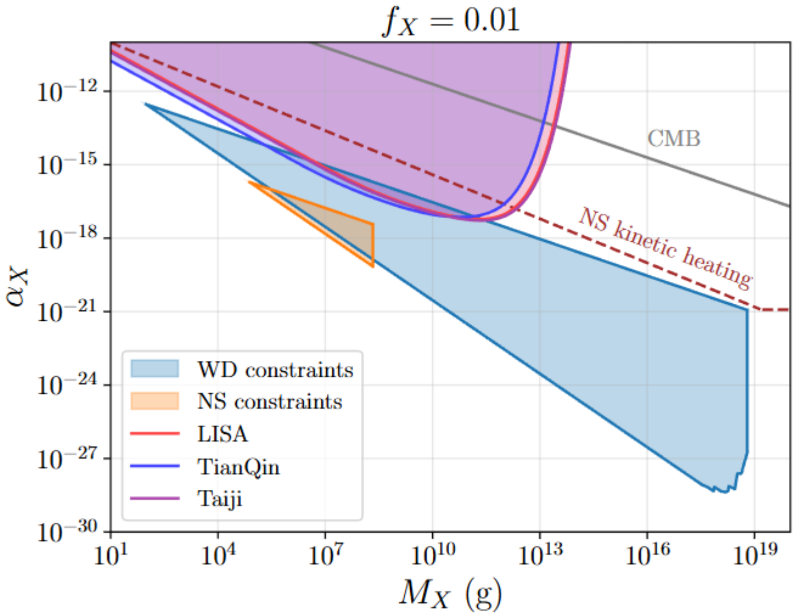
The expected number of DM passing through the detector:

$$N_{\rm enc}^{\rm GW} = \left(f_X \pi D^2 \rho_{\rm DM} v_{\rm DM} / M_X\right) T_{\rm obs}^i$$

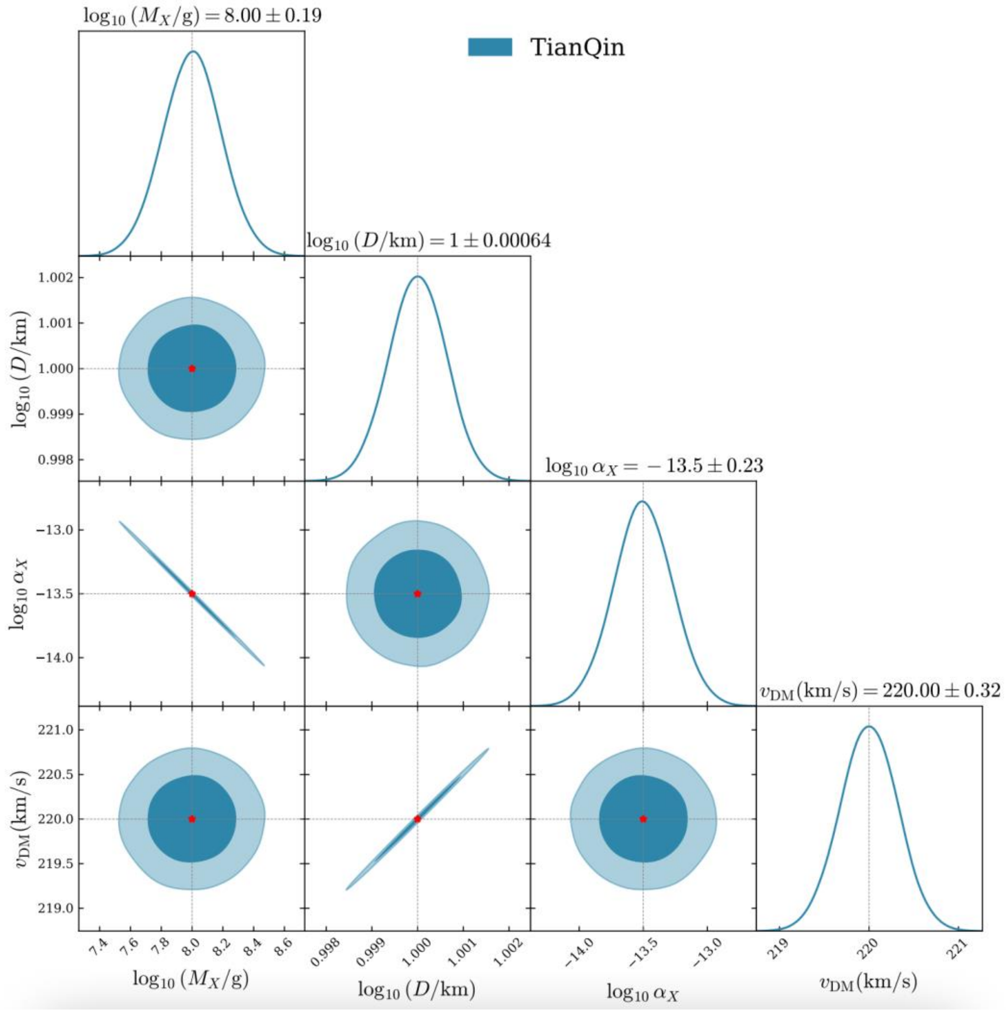
We restrict at least one DM induced event will be expected during the lifetime of the experiments.

Signal-to-noise ratio

$$\mathrm{SNR} = \left(4 \int_0^\infty \mathrm{d}\omega \frac{P(\omega)}{S_n(\omega)}\right)^{\frac{1}{2}} \geq 10$$



We find that space-based GW experiments can cover most of the parameter ranges beyond these astrophysical limits. And its results depend only on the mass of dark matter and its interaction strength with ordinary matter.



Macroscopic Dark Matter under siege: from White Dwarf Data to Gravitational Wave Detection, Siyu Jiang, Aidi Yang, and FPH, arXiv:2511.23263

Triangle plot of the Fisher analysis for a signal at TianQin induced by DM.

For example, our results indicate that for $M_X = 10^8$ g, $\alpha_X = 10^{-13.5}$ and $D = 10$ km, the uncertainties are $\log_{10}(M_X/\mathrm{g}) = 8.0 \pm 0.19$ and $\log_{10}\alpha_X = -13.5 \pm 0.23$ at TianQin, showing the superiority of GW detectors for DM detections.

4. Summary

GW detectors will help to explore:

1. **the DM production mechanism in the early universe**
2. **the distribution and propagation of DM in the late universe**
3. **the microscopic nature of DM, such as its mass and interaction**

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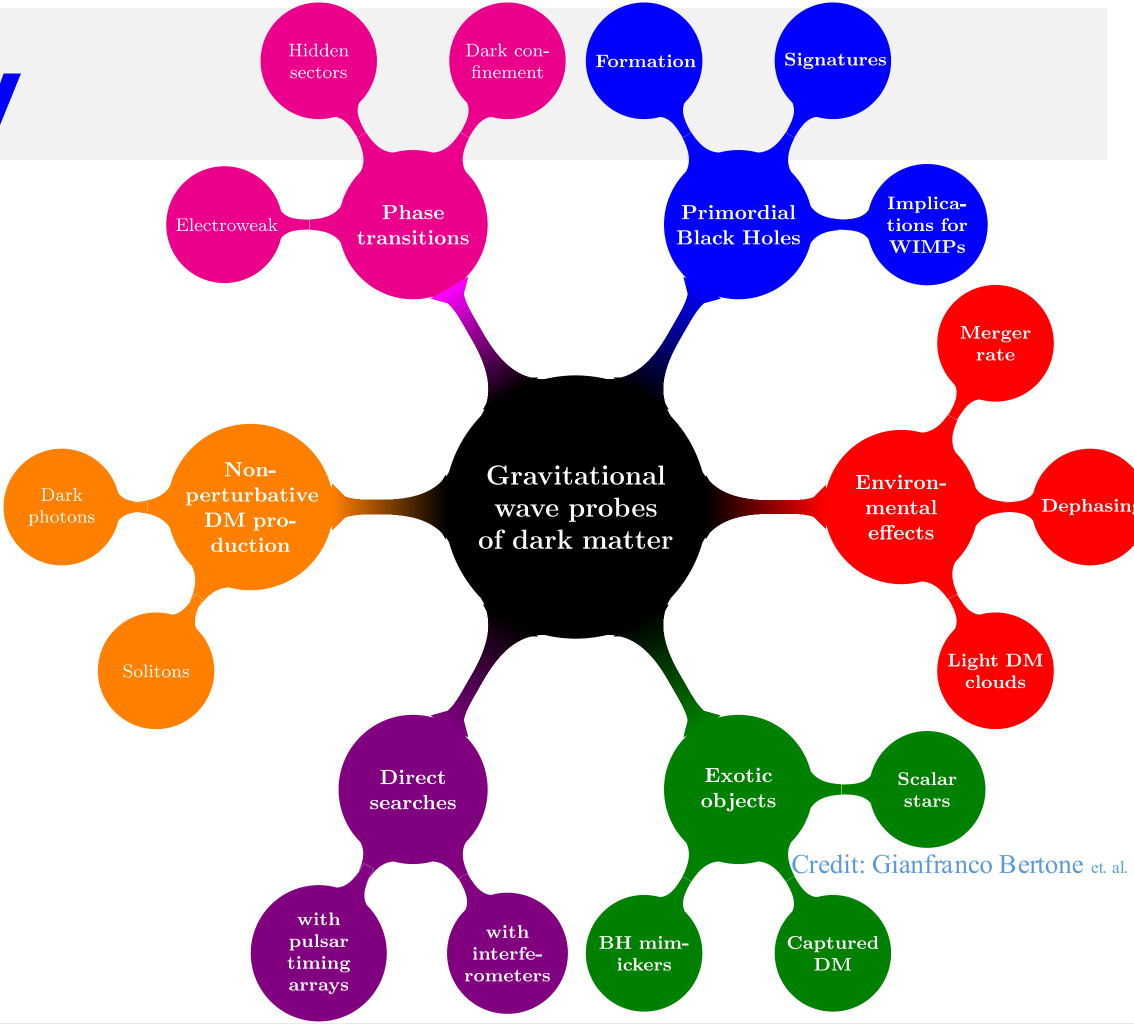

Credit: Gianfranco Bertone et. al.

Thanks!