暗物质研究的新方法

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中山大学物理与天文学院天琴中心

第十八届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会@广西师范大学物理科学与技术学院
2026.04.11

大纲

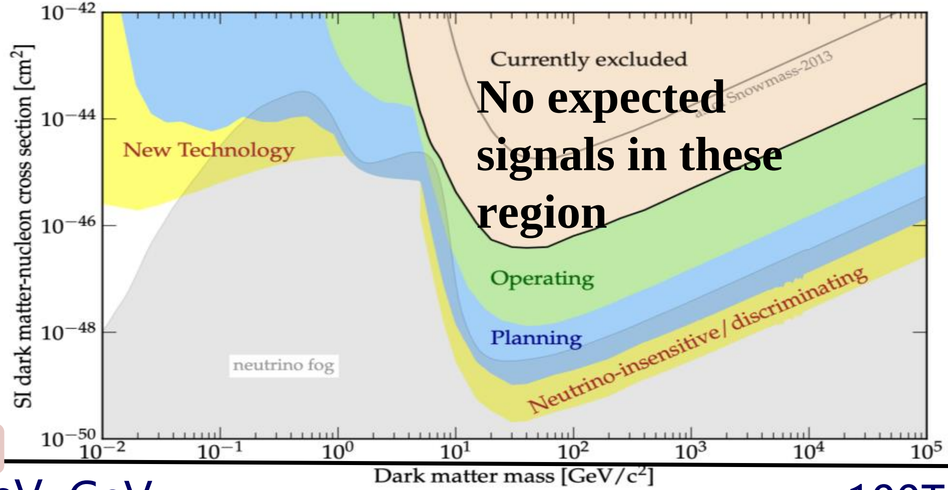
1. 引力波探测暗物质性质的研究背景简介
2. 超轻暗物质的研究新方法
3. 超重暗物质的研究新方法
4. 总结与展望

暗物质的理论和实验研究现状

arXiv: 1904:07915
Snowmass 2021,
arXiv: 2209.07426

What is the microscopic nature of DM?

How DM relic density is produced?



Ultralight DM: Axion/ALP

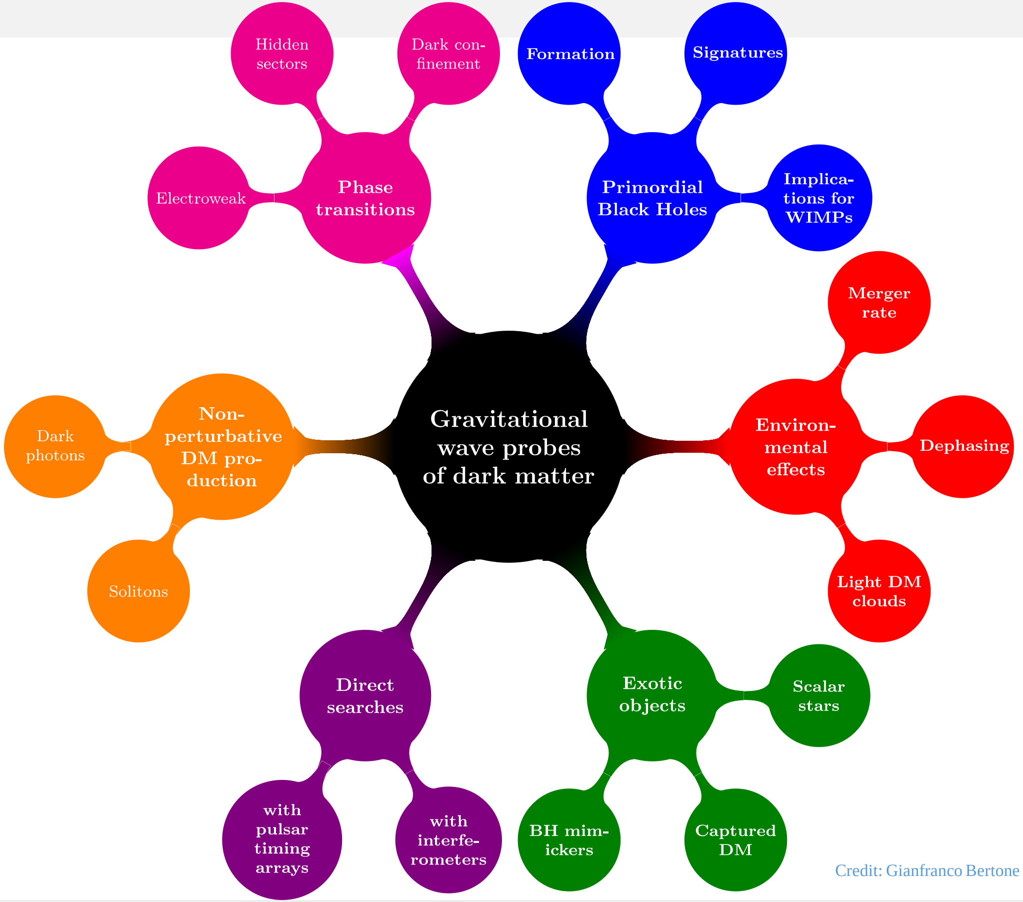
Heavy DM:Q-ball/filtered/ PBH (radiation, superradiance)

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

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

用引力波实验探测暗物质在宇宙早期的产生过程&宇宙晚期在宇宙中的传播

暗物质研究新方法：暗物质的引力波探测



Credit: Gianfranco Bertone et. al.

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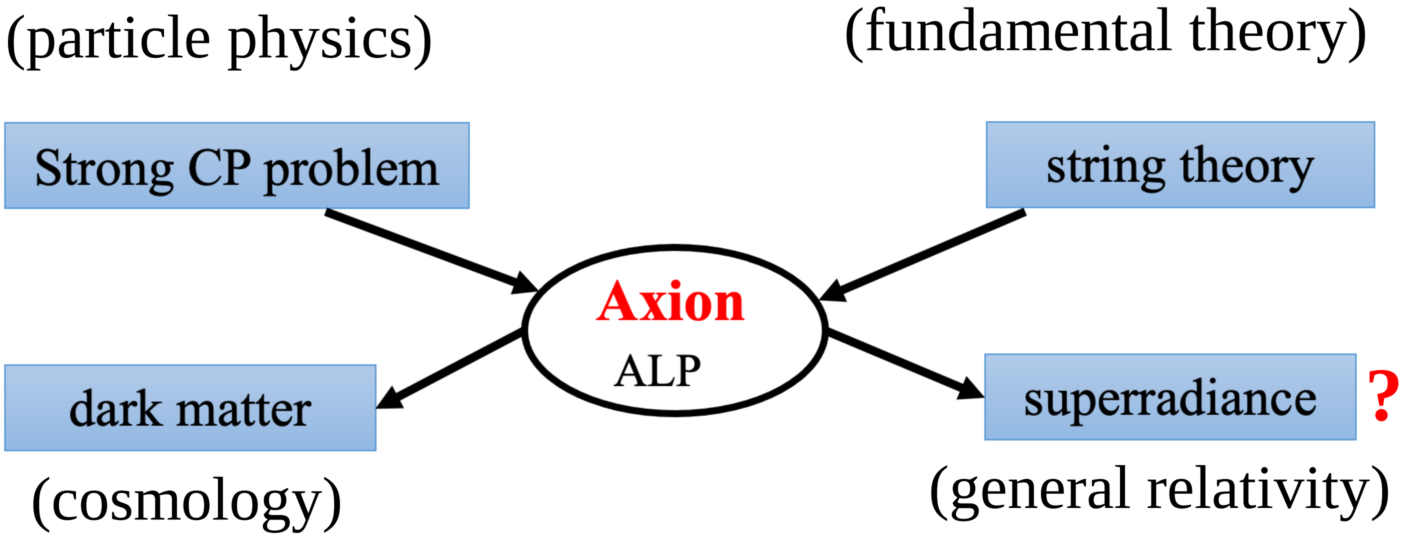
超轻轴子暗物质的引力波探测

Ultralight axion is a promising DM candidate.



When Klein (-Gordon) meets Kerr——superradiance

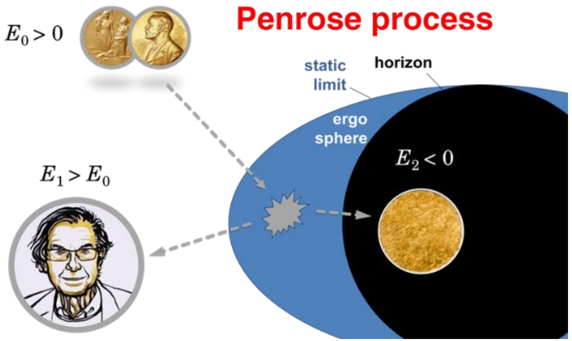
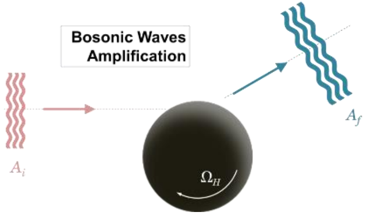
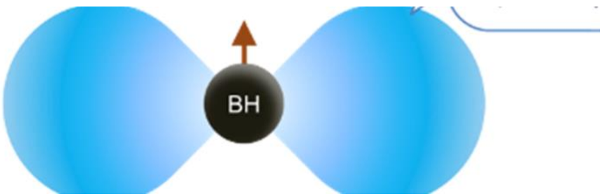


Image Credit: Yi Wang



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

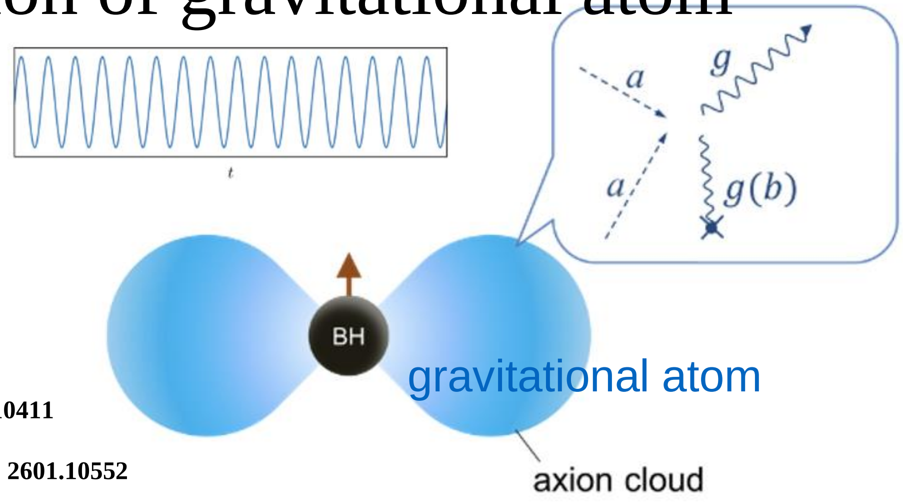
$$\alpha = M_{BH} m_a < 1$$

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

超轻轴子暗物质的引力波探测

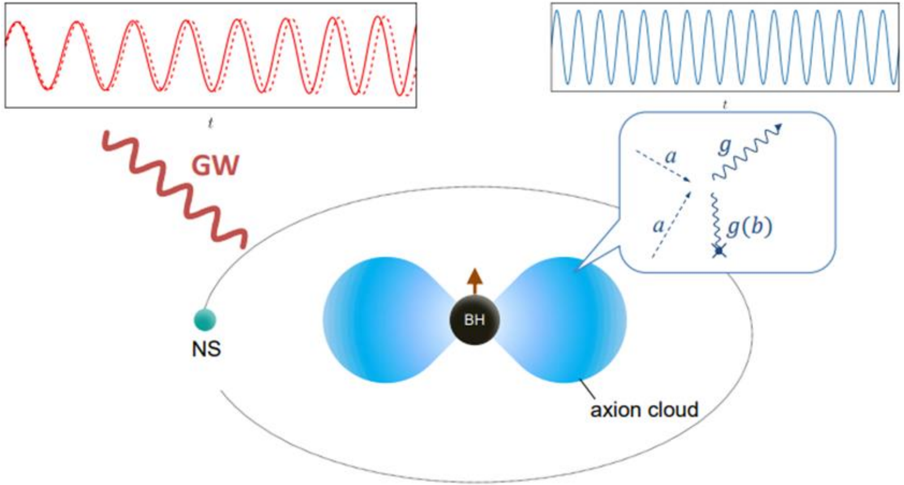
GW of ultralight DM from black hole: gravitational atom from superradiance

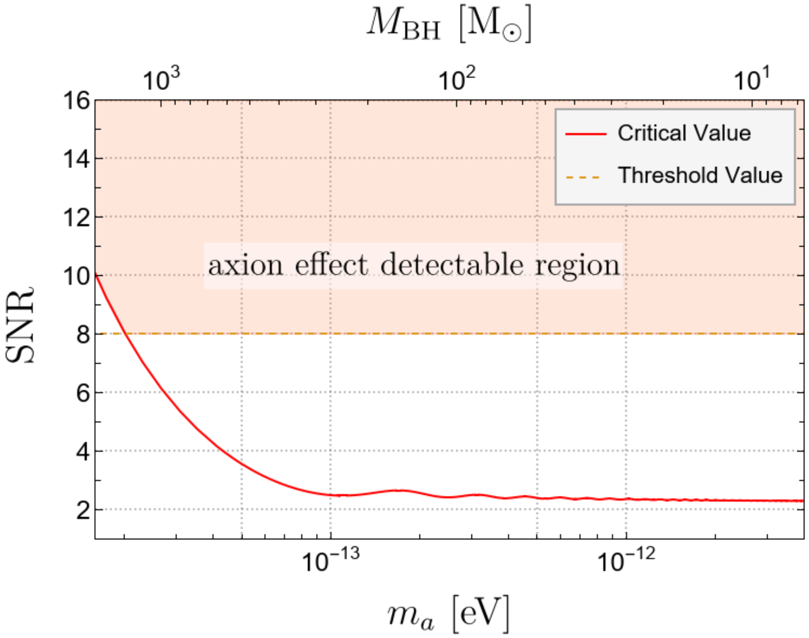
1. Axions can annihilate to GW
2. Energy-level transition of gravitational atom



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

超轻轴子暗物质的引力波探测



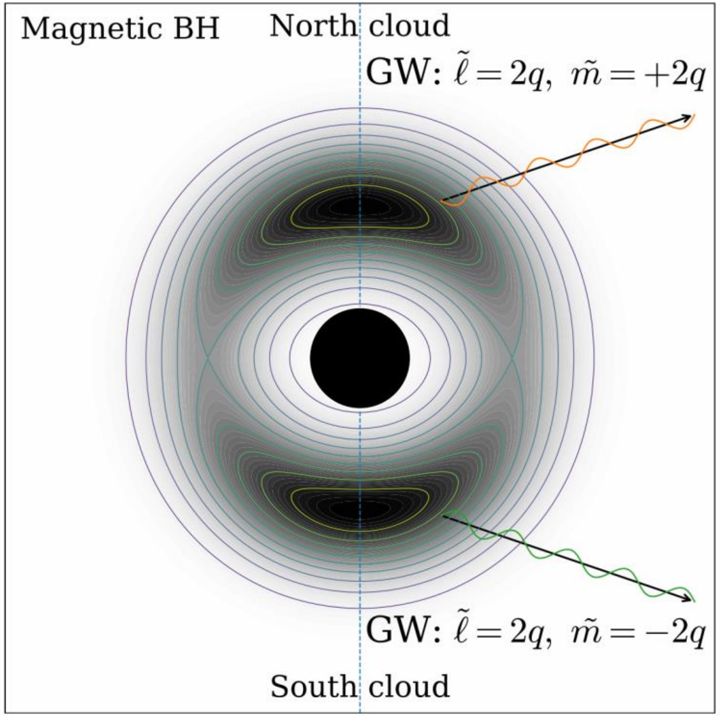


Jing Yang, FPH Phys.Rev.D 108 (2023) 10, 103002
Jing Yang, Ning Xie, FPH arXiv:2306.17113
Ning Xie, FPH Sci. China-Phys. Mech. Astron. 67, 210411

Rapid post-merger GW signal

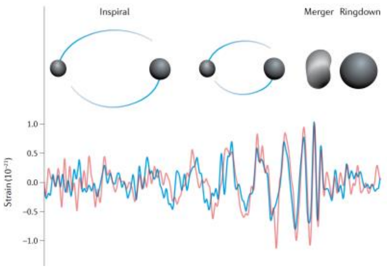
Rapid post-merger signal of circularly polarized gravitational wave from magnetic black hole superradiance: novel approach to detect magnetic monopole and ultralight DM by GW.

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)



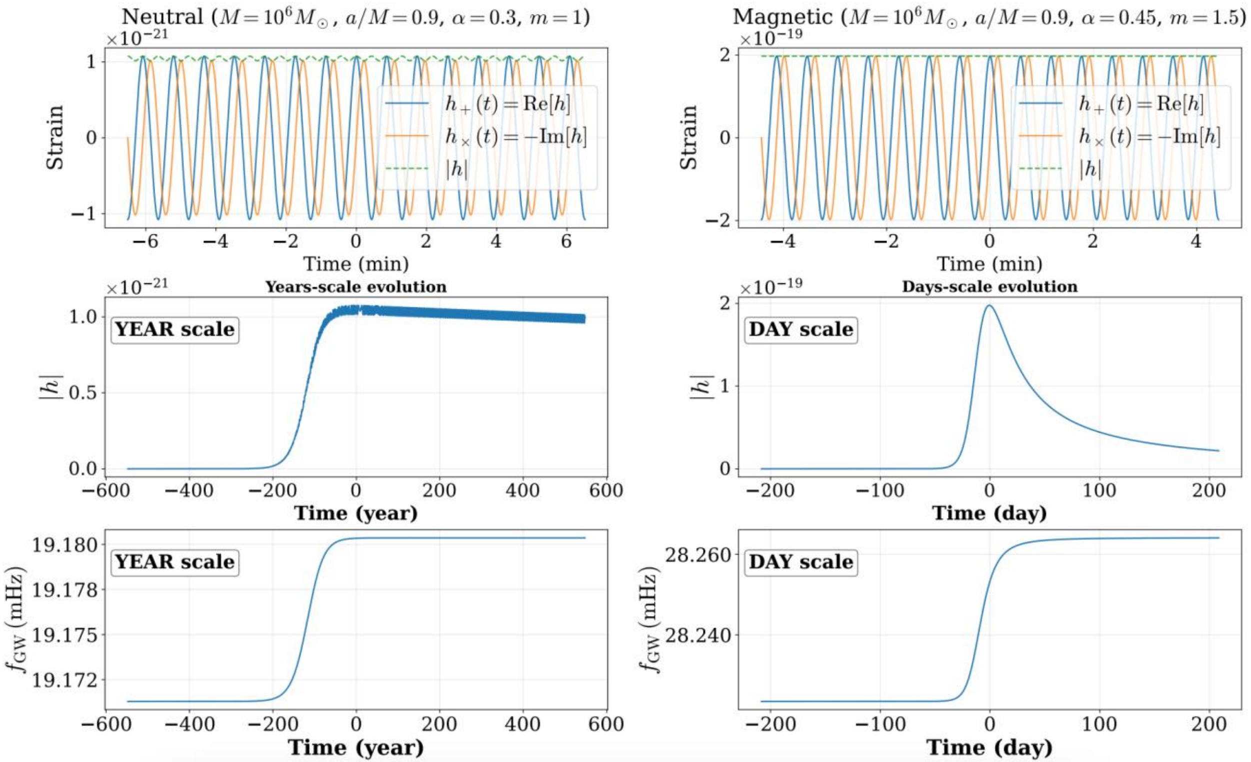
Zhong-hao Luo, FPH, Pengming Zhang, Chen Zhang, arXiv: 2601.10552

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

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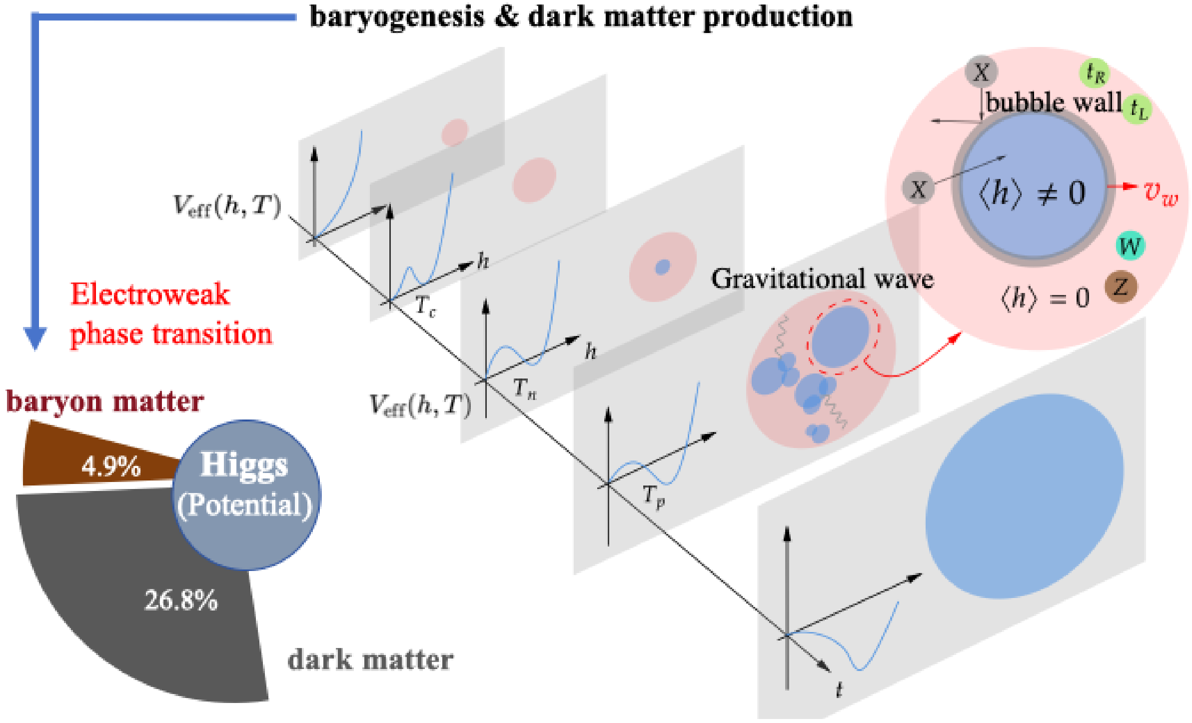
3.1利用引力波实验探测超重暗物质在早期宇宙的产生过程中相变引力波信号

Heavy DM from cosmic phase transition

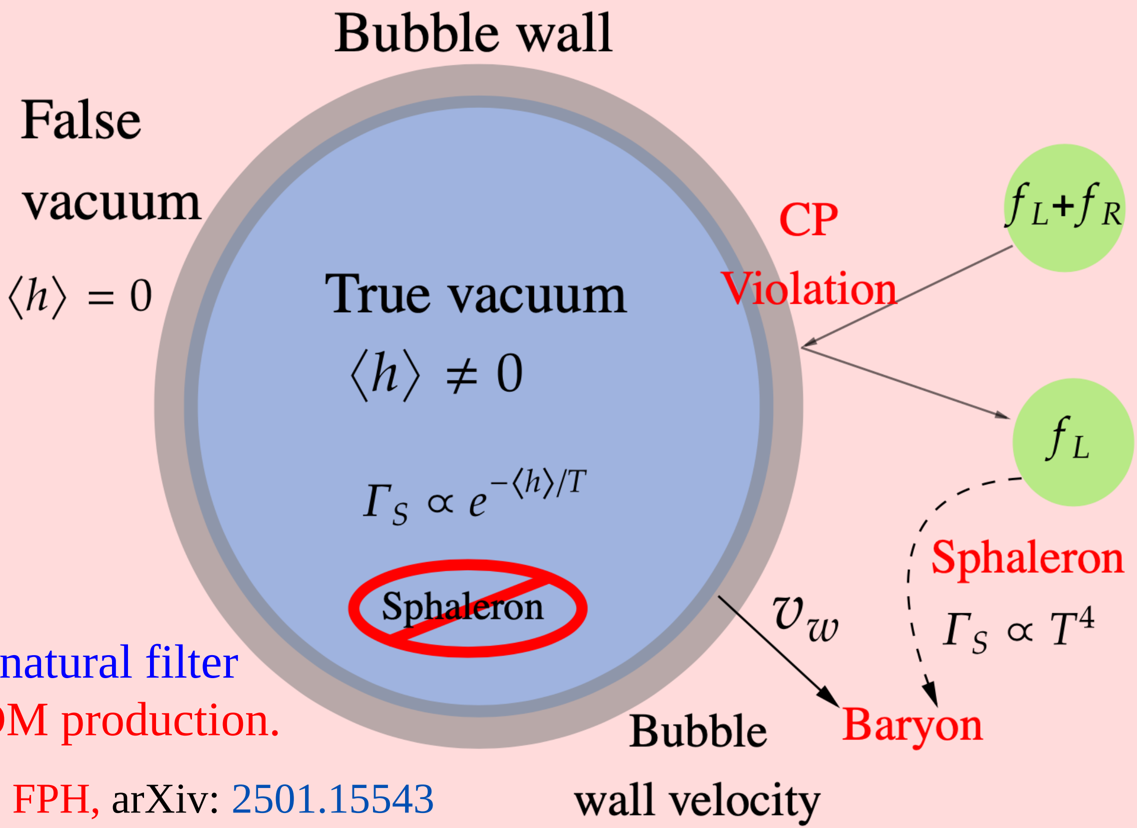
The observation of
Higgs@LHC
and GW@LIGO initiates new era of exploring DM by GW.

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
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Received May 1992; editor: D.N. Schramm

Nuclear Physics B262 (1985) 263–283
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Q-BALLS*

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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.

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

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

$$\downarrow$$

$$E = \int \left\{ \frac{1}{2} \left[\dot{\phi}_R^2 + \dot{\phi}_I^2 + (\nabla \phi_R)^2 + (\nabla \phi_I)^2 \right] + U\left[\frac{1}{2} (\phi_R^2 + \phi_I^2) \right] \right\} dx \qquad \phi = f(r) e^{-i\omega t}$$

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)

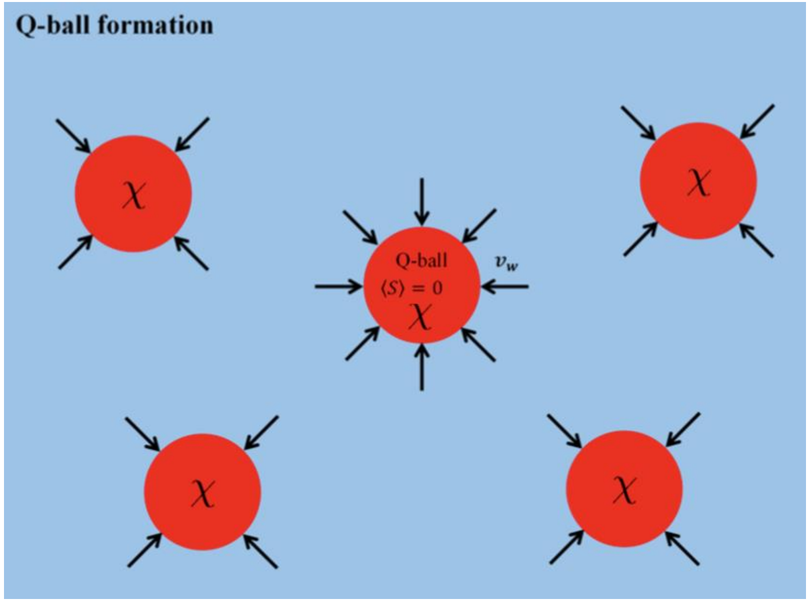
(2) and packet the same sign charge in the small size after overcoming the Coulomb repulsive interaction.

1. Supersymmetry? Affleck-Dine mechanism.

We do not observe the supersymmetry until now!

2. Q-ball formation based on FOPT.

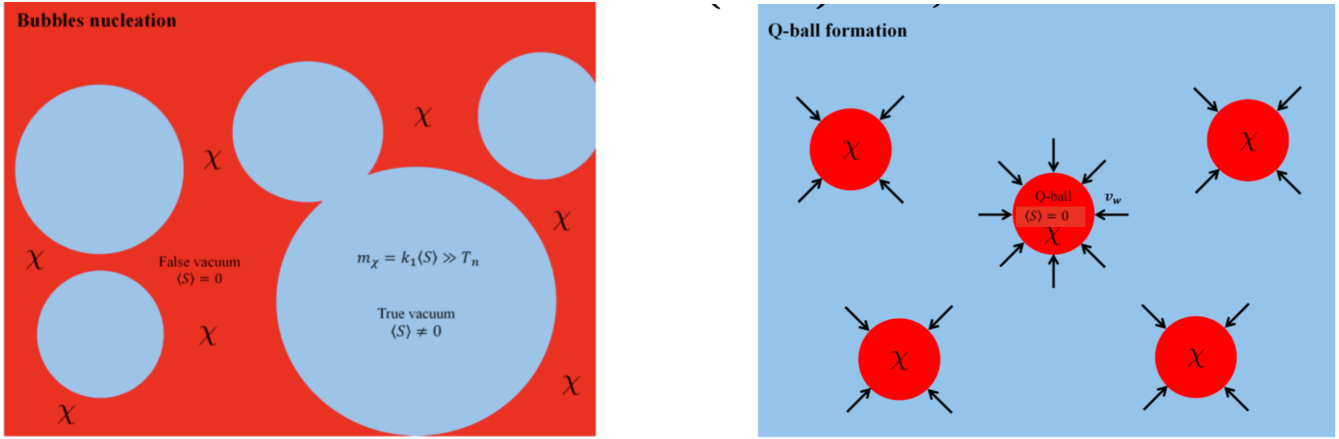
This talk



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

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

Friedberg-Lee-Sirlin model

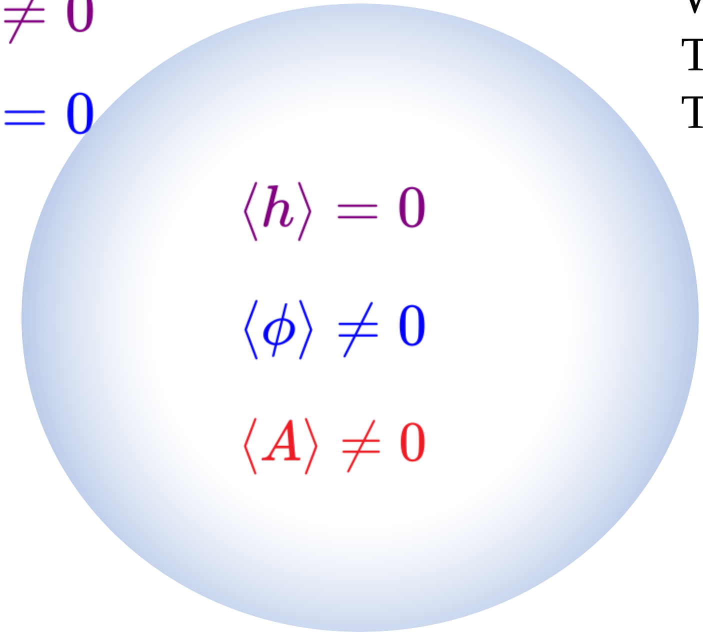
R. Friedberg, T.D. Lee and A. Sirlin.
Rev. D 13 (1976) 2739

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

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

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

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

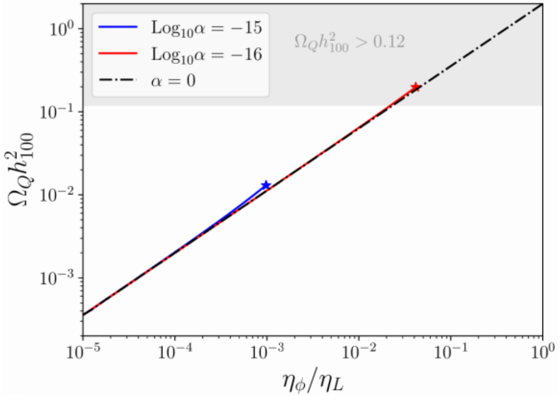
Interestingly, this portal coupling also naturally induces a strong FOPT.

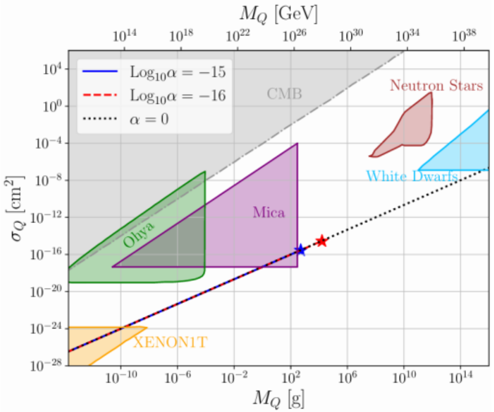
$$J_\mu = i\left(\phi^\dagger \overleftrightarrow{\partial}_\mu \phi + 2i\tilde{g}\tilde{A}_\mu |\phi|^2\right) \qquad Q = \int d^3x J^0$$

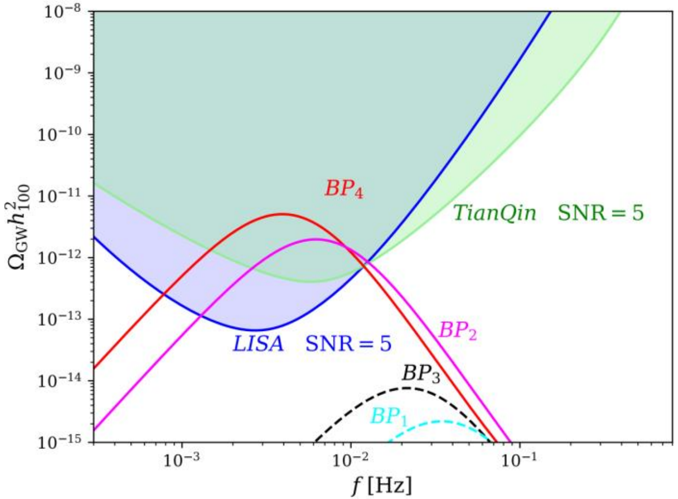
Conserved charge

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.

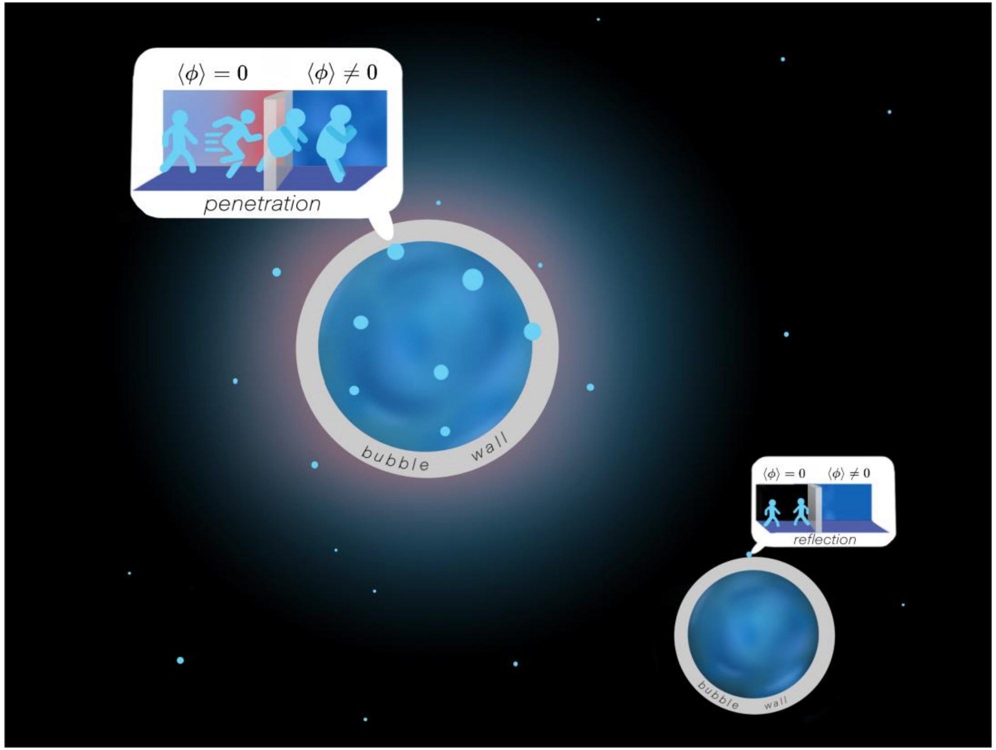
Siyu Jiang, FPH, Pyungwon Ko, JHEP 07 (2024) 053

Case II: filtered DM from a FOPT

DM

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

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

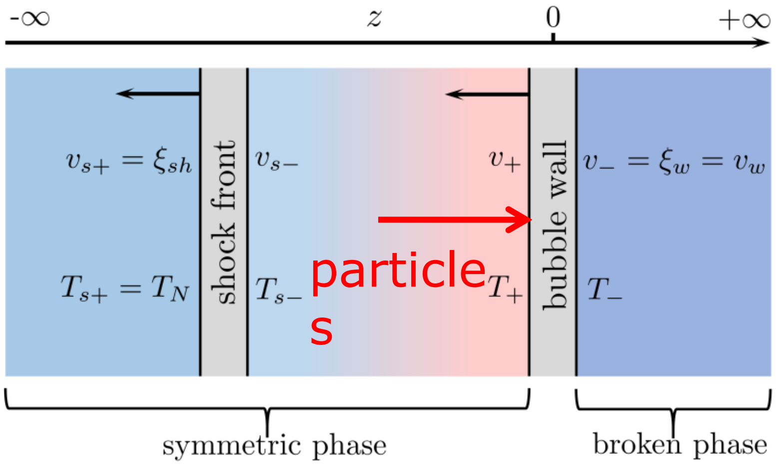


Case II: filtered DM

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



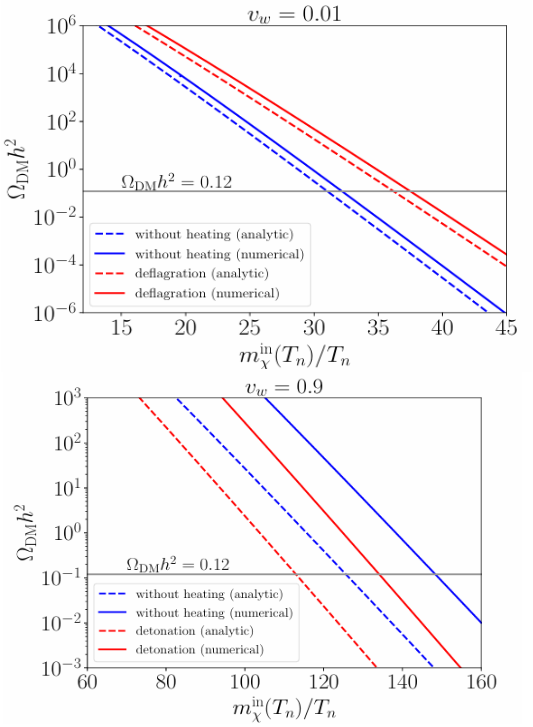
$$\tilde{v}_{\rm pl} = \tilde{v}_+, \quad T = T_+, \quad T' = T_- \qquad \text{(this work with hydrodynamic effects)}\ .$$

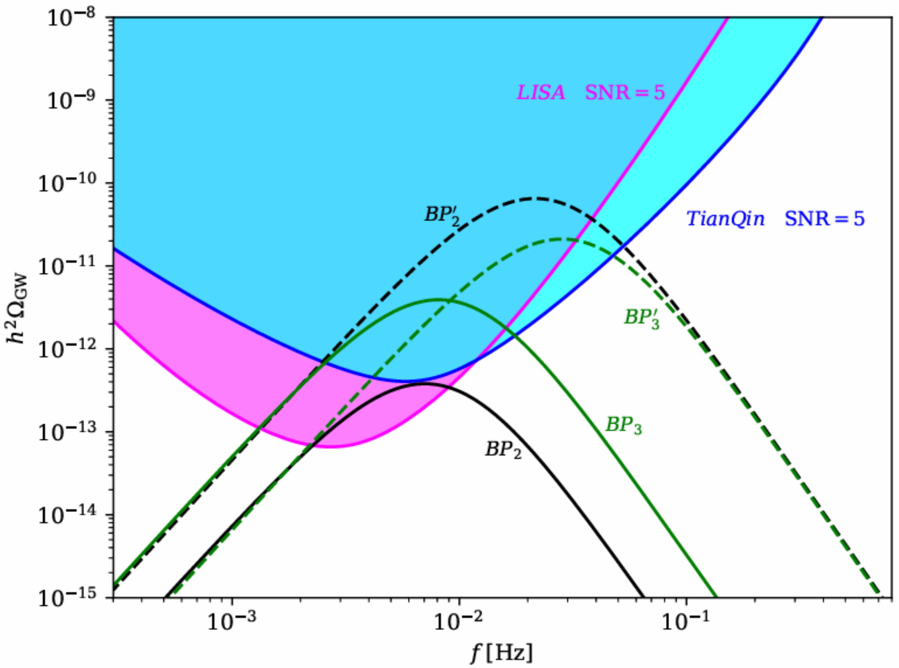
$$J_w^{\rm in} = \frac{g_\chi}{(2\pi)^2}\int_0^{-1} d\cos\theta\cos\theta\int_{-\frac{m_\chi^{\rm in}}{\cos\theta}}^{\infty} dp\frac{p^2}{e^{\tilde{\gamma}_+(1+\tilde{v}_+\cos\theta)p/T_+}} = \frac{g_\chi T_+^3\left(1+\tilde{\gamma}_+ m_\chi^{\rm in}(1-\tilde{v}_+)/T_+\right)}{4\pi^2\tilde{\gamma}_+^3(1-\tilde{v}_+)^2}e^{-\tilde{\gamma}_+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

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

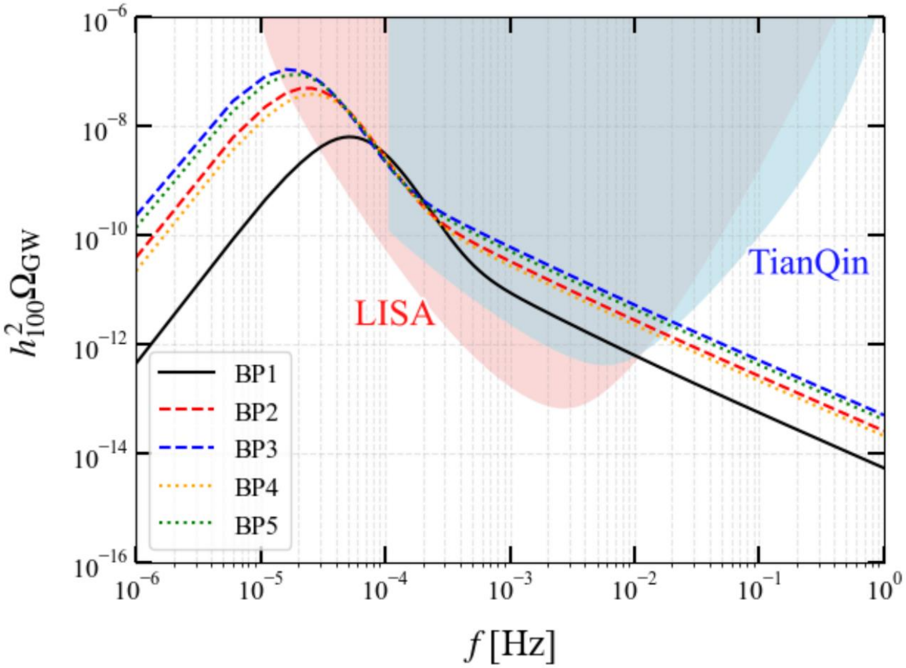
Case II: filtered DM

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





Case III:PBH



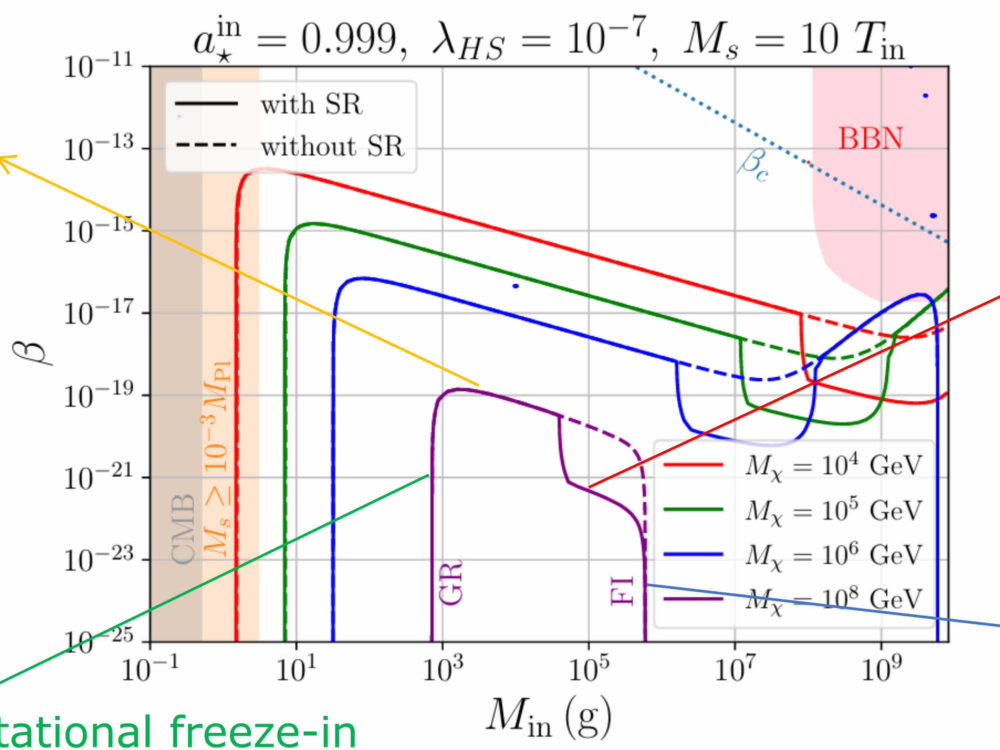
FPH, Chikako, Aidi, Primordial Black Hole Formation and Multimessenger Signals in a Complex Singlet Extension of the Standard Model",arXiv:2510.24007, Phys.Rev.D 113 (2026) 5, 055013

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

这三类超重物质在早期宇宙的产生及其引力波信号敏感的依赖于相变动力学，**从引力波信号中重构出相变参数和模型参数**

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

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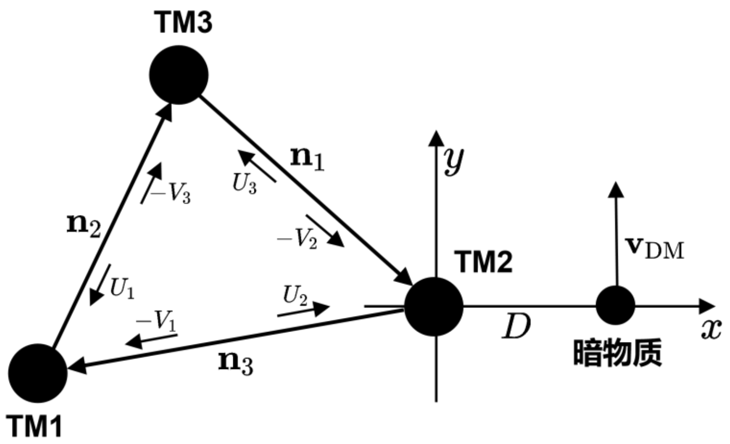
3.2 利用引力波实验探测晚期宇宙暗物质的传播

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.

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

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

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

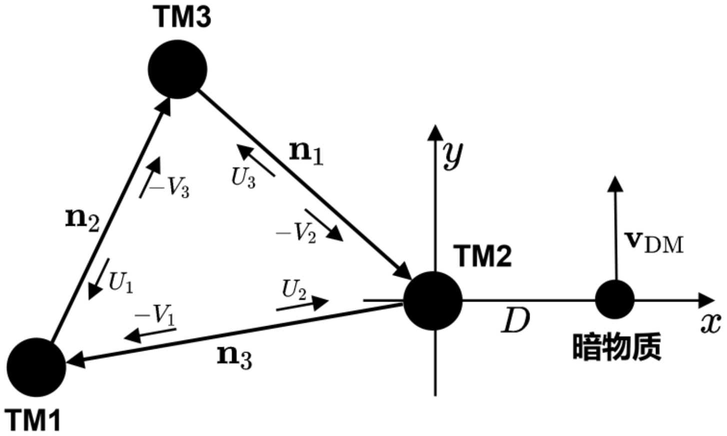
$$\alpha_X = y_X^2/4\pi \quad \alpha_{\mathrm{SM}} = y_n^2/4\pi$$

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

MICROSCOPE experiments: $|\delta_{\mathrm{SM}}| < 3\times10^{-6}$

Bullet cluster constraints: $\delta_X^2 < 2\times10^6\left(\frac{M_X}{M_\odot}\right)^{-1/2}\left(\frac{v_{\mathrm{DM}}}{10^{-2}}\right)^2 e^{4\times10^{-3}\sqrt{\frac{M_X}{M_\odot}\frac{\mathrm{pc}}{\lambda}}}$

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 $1 \to 2 \to 3 \to 1$

DM Direct detection on GW experiments

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

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

$\omega = 2\pi f$

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

signal power spectral density (PSD)

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

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

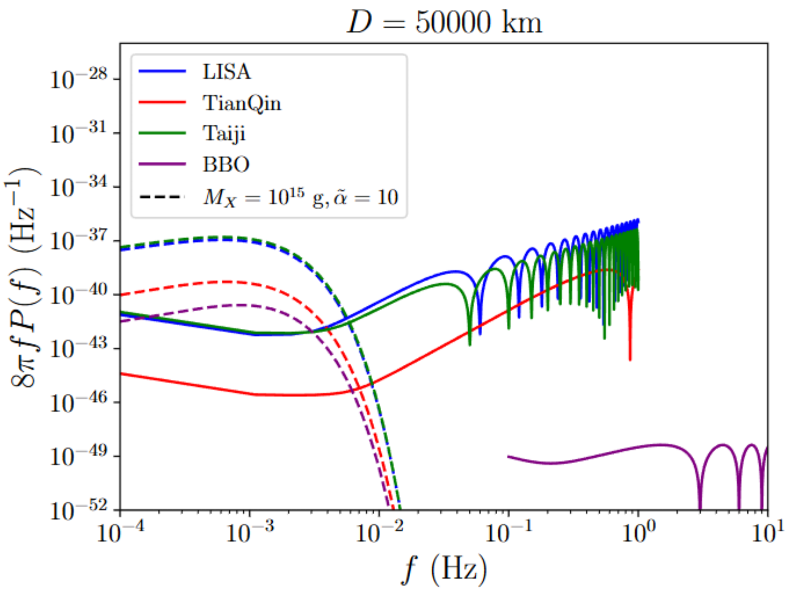
Parameter	LISA	TianQin	Taiji
Arm length L (10^9 m)	2.5	0.17	3
$P_{\rm oms}$ (10^{-12} m)	15	1	8
$P_{\rm acc}$ (10^{-15} m $\cdot$ s^{-2})	3	1	3
$T_{\rm obs}$ (yr)	4.5	2.5	5
Frequency range (Hz)	$[10^{-4}, 1]$	$[10^{-4}, 1]$	$[10^{-4}, 1]$

noise PSD in X channel:

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

$$S_{\rm oms}(f) = \left(\frac{2\pi f P_{\rm oms}}{c}\right)^2\left[1+\left(\frac{2\times10^{-3}\ \mathrm{Hz}}{f}\right)^4\right]\mathrm{Hz}^{-1}$$

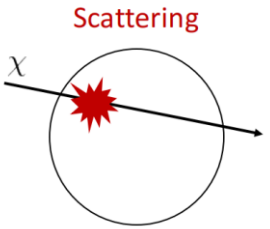
$$S_{\rm acc}(f) = \left(\frac{P_{\rm acc}}{2\pi f c}\right)^2\left[1+\left(\frac{0.4\times10^{-3}\ \mathrm{Hz}}{f}\right)^2\right]\times\left[1+\left(\frac{f}{8\times10^{-3}\ \mathrm{Hz}}\right)^4\right]\mathrm{Hz}^{-1}$$



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

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

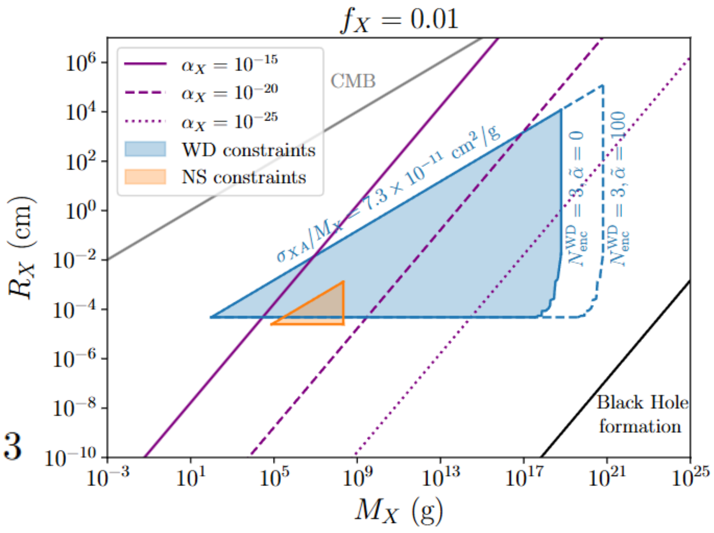
Encounter rate

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

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

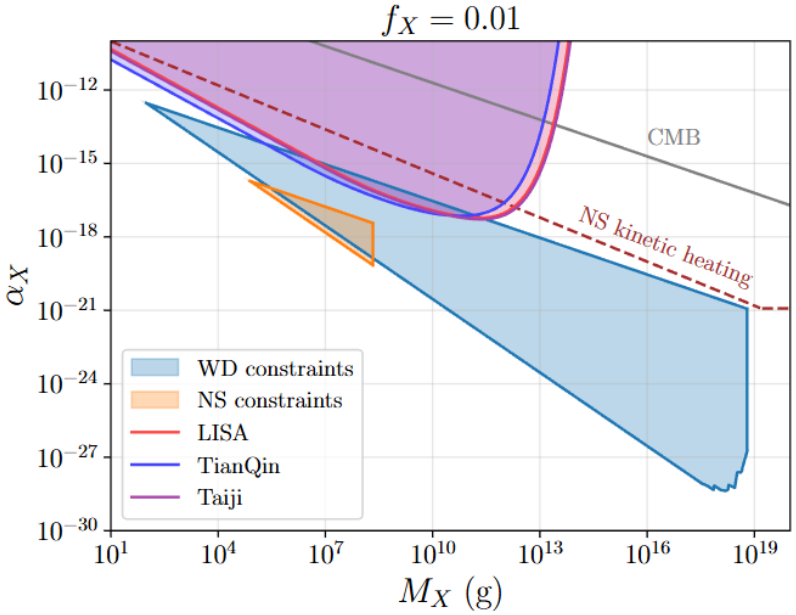
The expected number of DM passing through the detector:

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

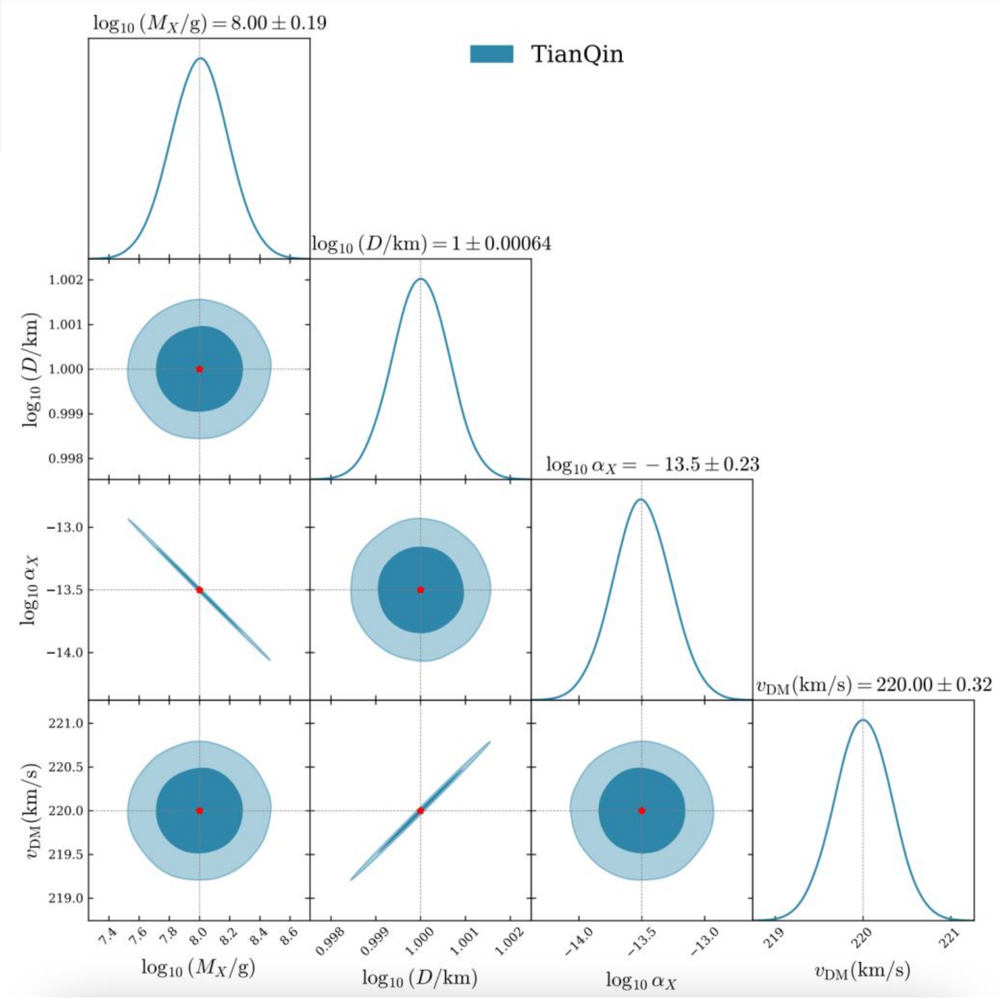
We restrict at least one DM induced event will be expected during the lifetime of the experiments.

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. 总结与展望

引力波实验将有助于探索：

1. **暗物质在早期宇宙的产生机制；**
2. **暗物质在晚期宇宙中的分布和传播；**
3. **质量、相互作用等微观性质**

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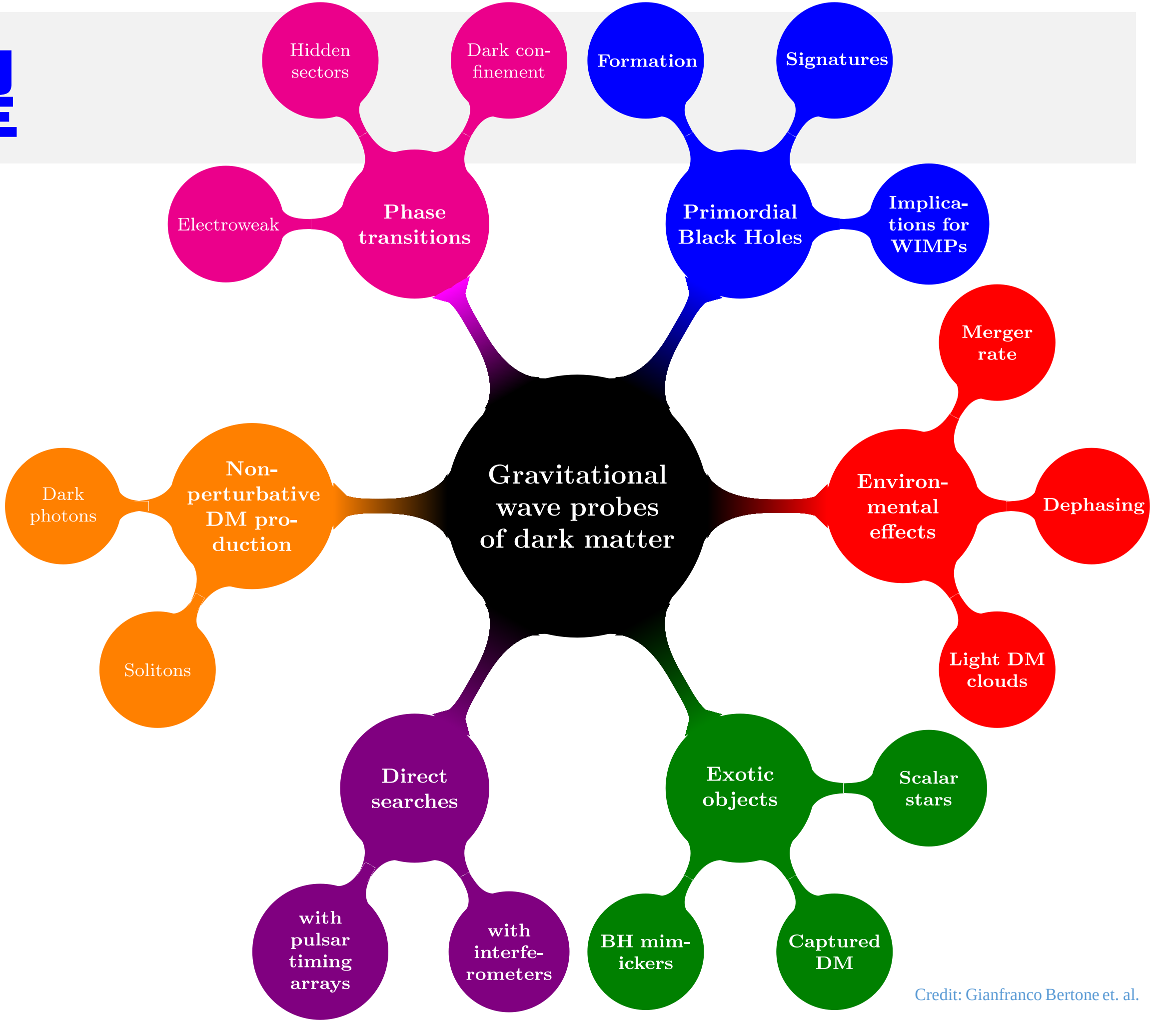

Credit: Gianfranco Bertone et. al.

谢谢