引力波探测器上的暗物质信号
——Composite Dark Matter under siege: from White Dwarf Data to Gravitational Wave Detectors

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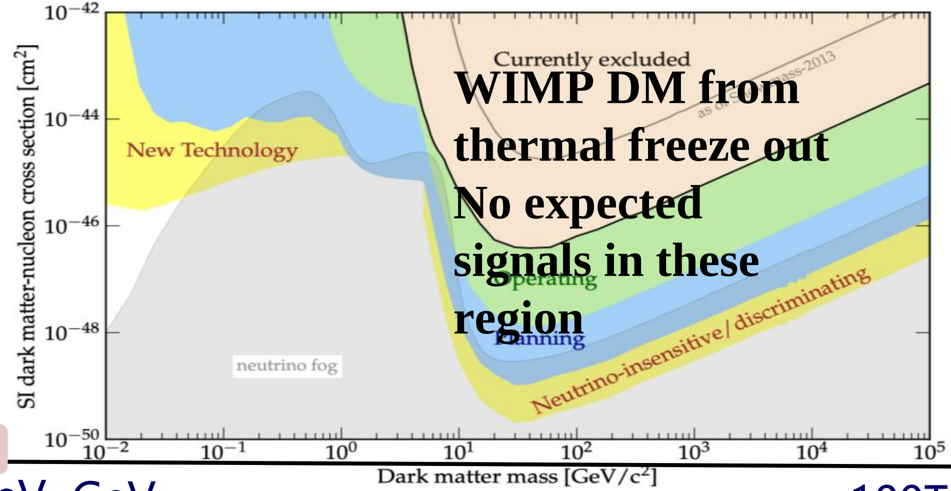
Motivation: DM theory and experiments status

What is the microscopic nature of DM?

How DM relic density is produced?

arXiv: 1904:07915
Snowmass 2021,
arXiv: 2209.07426

Ultralight DM: Axion/ALP



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

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

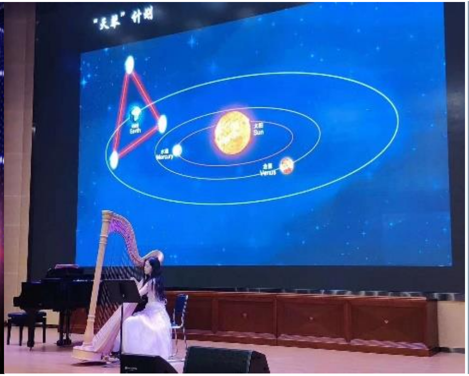
10^{-22}eV   keV   GeV   WIMP   100TeV

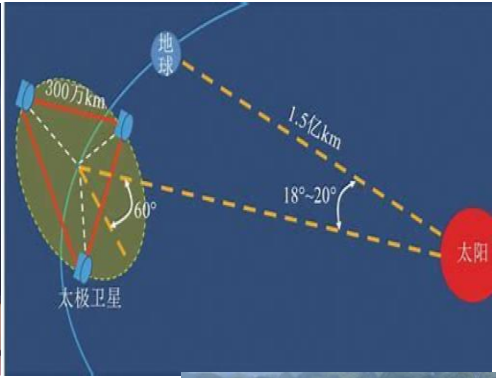
- **new DM production mechanism beyond thermal freeze out: cosmic phase transition, PBH Hawking radiation, superradiance…**
- **new detection method: various GW detector**

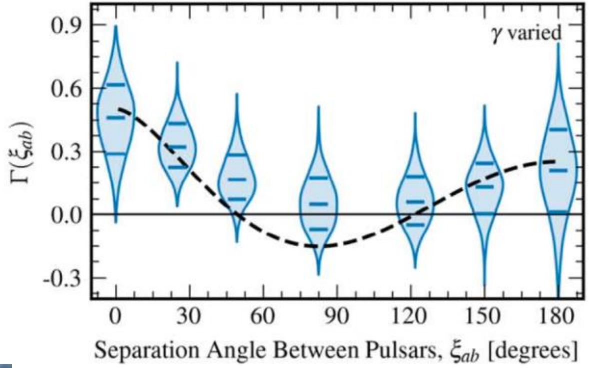
DM Imprints at GW experiments

GW experiments

LISA/TianQin/Taiji ~2034







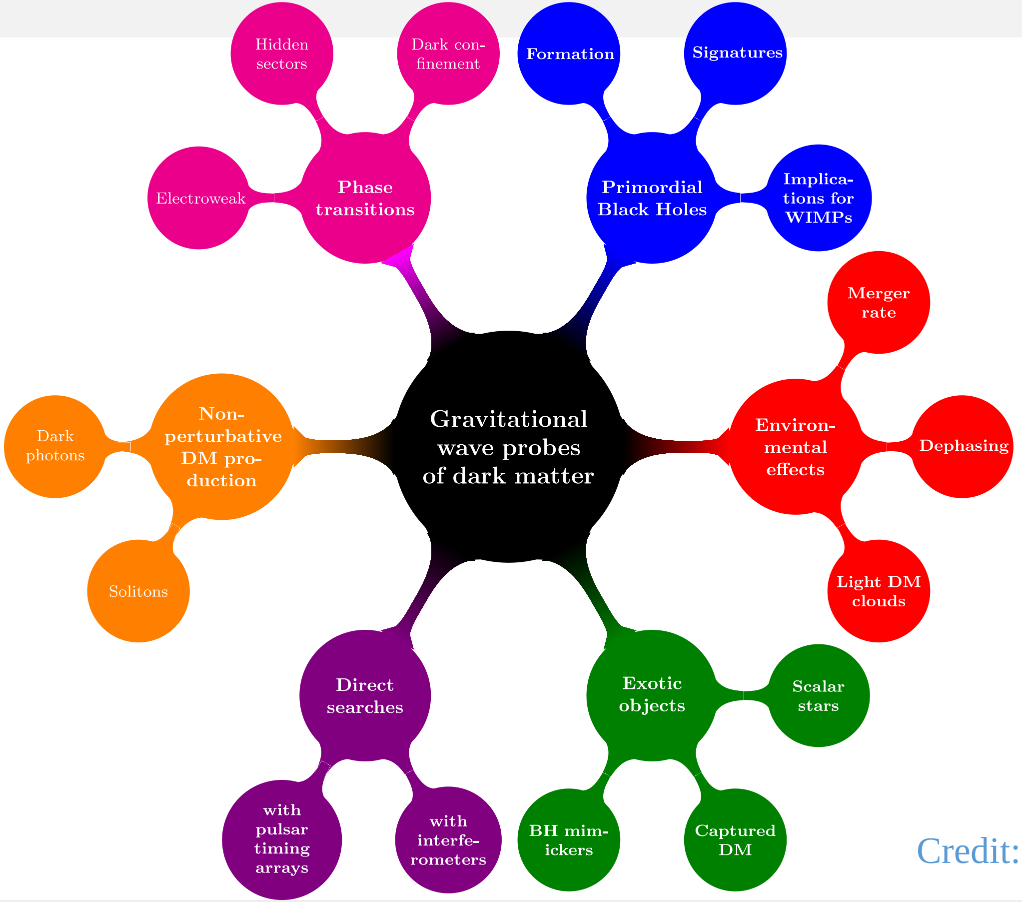
"TianQin"
"Harpe in space"

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

FAST

SKA

Motivation: DM Imprints at GW experiments



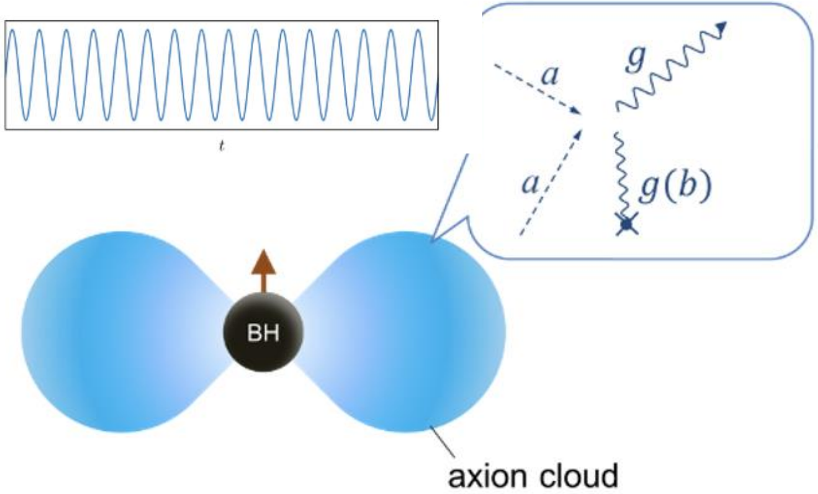
Credit: Gianfranco Bertone et. al.

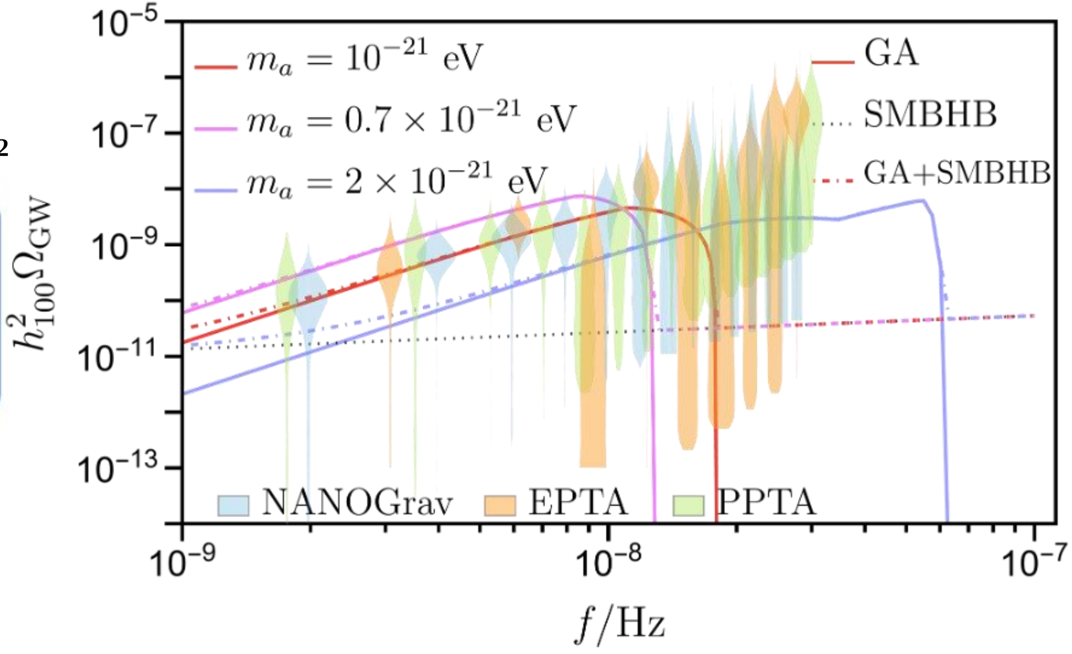
Ultralight DM

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



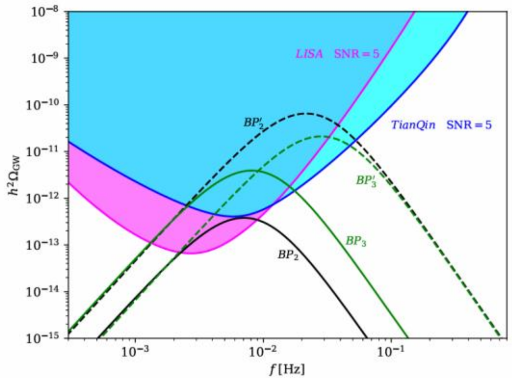


Heavy DM: new production mechanism

1. 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 avoiding the unitarity constraints.

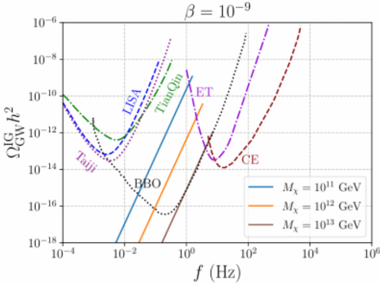
Renaissance of quark nugget DM idea by E. Witten.

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



FPH, Chong Sheng Li, Phys.
Siyu Jiang, FPH, Chong Sheng Li, Phys.Rev.D 108 (2023) 6, 063508
Siyu Jiang, FPH, Pyungwon Ko, JHEP 07 (2024) 053
FPH, Chikako, Aidi, Phys.Rev.D 113 (2026) 5, 055013
Siyu Jiang, FPH, JCAP 06 (2025) 023
Dayun Qiu, Siyu Jiang, FPH, JHEP 02 (2026) 112

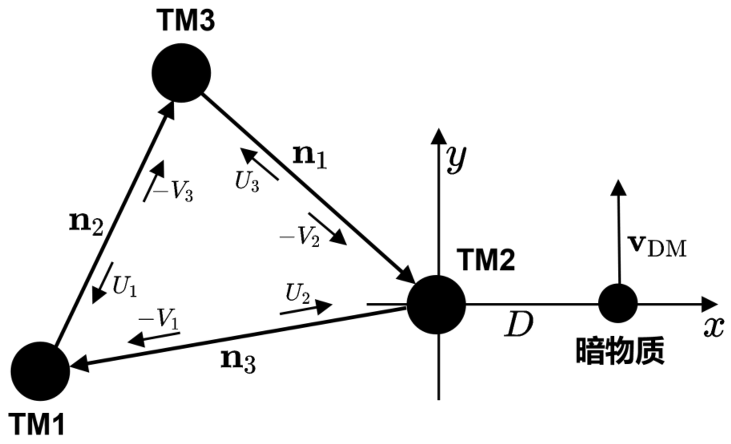
2. Heavy DM from PBH Hawking radiation, superradiance



DM Direct detection on GW experiments

Probing heavy DM frontier presents a distinct experimental challenge: as the constituent mass increases, number density drops precipitously, rendering terrestrial direct detection experiments effectively blind to the resulting low flux.

To overcome this "flux barrier", one can utilize asatrophysical scales. Compact objects like white dwarfs (WDs), acting as vast, long-exposure detectors, offer a powerful alternative.



We apply this detection scheme to macroscopic DM.

GW detector in space is a natural big (astrophysical scale) and precise (high precision laser interferometer) DM detector.

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

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

Composite DM with long-range interaction

For various macroscopic or composite DM models, the DM is composite of dark fermions X.
We show three representative models formed by FOPT below for a broad class of composite DM models, where the DM mass can be parameterized as

$$M_{\rm DM} = \varepsilon \times \frac{4\pi}{3} R_{\rm DM}^3$$

(a) Dark quark nuggets (DQNs): Phys. Rev. D **99**, 055047 (2019)
(b) Axion quark nuggets (AQNs): JCAP **10**, 010 (2003)
(c) Fermi-balls: Phys. Rev. D **102**, 075028 (2020),

$$\mu_{\rm eq} = \left(\frac{6\pi^2\varepsilon}{g_{\rm dof}}\right)^{1/4}, \quad N_{\rm DM} = \frac{2g_{\rm dof}}{9\pi}\mu_{\rm eq}^3 R_{\rm DM}^3$$

We introduce a long-range scalar mediator that couples the DM via $y_{\rm DM}\bar{X}\phi X$ and the nucleons via $y_{\rm SM}\bar{n}\phi n$, such that an additional Yukawa attractive potential arises between two objects $i, j \in \{\rm SM, DM\}$,

$$V_{i-j} = -M_i M_j \frac{G}{r}\left(1 + \delta_i\delta_j e^{-m_{\rm med} r}\right) \qquad \delta_i = \frac{y_i N_i}{\sqrt{4\pi G M_i}}$$

Composite DM with long-range interaction

We will assume the force range λ is larger than the typical lengths in this work, i.e., the radius of white dwarfs (WD) or neutron stars (NS), and the arm length of the GW detector; for instance, we take λ = 0.1 pc.

Then the attractive potential between the DM and the nucleons is simply obtained by replacing the Newton constant in the gravitational potential by $G \to G(1+\tilde{\alpha})$ with

$$\tilde{\alpha} = \delta_{\rm SM}\delta_{\rm DM}.$$

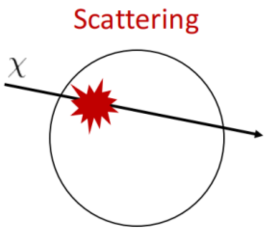
MICROSCOPE experiments: $|\delta_{\rm SM}| < 3 \times 10^{-6}$

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

Runaway fusion of compact objects

Firstly, we briefly discuss the condition of triggering runaway fusion in a WD core and NS ocean. When DM passes a WD or NS, it may deposit energy through scattering with C or O ions. If the energy deposition E_{dep} is enough for the ions to overcome their mutual Coulomb barrier, the runaway fusion occurs.

- ✓ The first condition for fusion is that the energy deposition must raise the temperature of a certain area above some critical value $T_{\mathrm{crit}} \sim$ MeV.
- ✓ The second condition is that the timescale for cooling due to thermal diffusion has to be longer than the timescale corresponding to the heating due to fusion.



The former increases with the size of the heated region but the latter is independent of the size of the region; therefore, there is a critical size λ_T beyond which the heat cannot be efficiently diffused.

The ignition condition reads

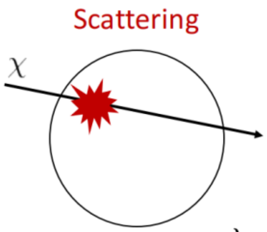
$$E_{\mathrm{dep}} \geq E_{\mathrm{trig}} \equiv \frac{4\pi}{3} \rho \lambda_T^3 \left(\rho, T_{\mathrm{crit}}\right) \bar{c}_p \left(\rho, T_{\mathrm{crit}}\right) T_{\mathrm{crit}}$$

Runaway fusion of compact objects

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

It is often assumed that DM triggers the ignition near the center of a C/O WD. Obtaining the precise density profile of WDs requires solving the Tolman–Oppenheimer–Volkoff (TOV) equation. We use the analytic fit of the WD-mass central density relationship

$$1+\left(\frac{\rho_{\mathrm{WD}}}{1.95\times 10^6\ \mathrm{g/cm^3}}\right)^{\frac{2}{3}} \approx \left[\sum_{i=0}^{6} c_i\left(\frac{M_{\mathrm{WD}}}{M_\odot}\right)^i\right]^{-2}$$



The trigger length λ_T is obtained by comparing the nuclear energy generation rate and the heat diffusion rate. However, the specific nuclear energy generation rates of the WD generally require numerical simulation, and we use an analytical scaling relation

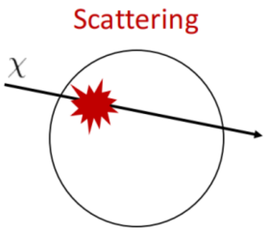
$$\lambda_T = \begin{cases} \lambda_1\left(\frac{\rho}{\rho_1}\right)^{-2}, & \rho \leq \rho_1\,, \\ \lambda_1\left(\frac{\rho}{\rho_1}\right)^{\ln(\lambda_2/\lambda_1)/\ln(\rho_2/\rho_1)}, & \rho_1 < \rho \leq \rho_2 \end{cases}$$

We take 4361 WDs in Montreal White Dwarf Database with known lifetimes and masses spanning $0.8 < M_{\mathrm{WD}}/M_\odot < 1.4$.

Runaway fusion of compact objects

Unlike WD, the thermal nuclear runaway causes the NS to undergo a superburst instead of a supernova. The outer layer of NS consists of an ocean of heavy elements, where the mass fraction of carbon is approximately 10% . For NSs, the precise nature of the initiation of a superburst is still unclear. However, similar to the WDs, the trigger length is also derived by comparing the carbon fusion rate with the heat diffusion rate.

The superbursts source 4U 1820-30 is used to place constraints on the composite DM.

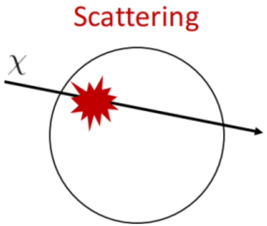


Constraints from supernova and superburst

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.

In addition to the ignition, it is important to investigate the event rate at WDs/NSs. The encounter rate between DM and WD/NS relies on the maximum impact factor $b_{\max}$



$$\Gamma_{\rm enc}^{\rm DM}(r) = f_{\rm DM}\frac{\rho_{\rm DM}(r)}{M_{\rm DM}}v_{\rm DM}(r)\pi b_{\rm max}^2$$

The expected number of DM passing through the WDs is

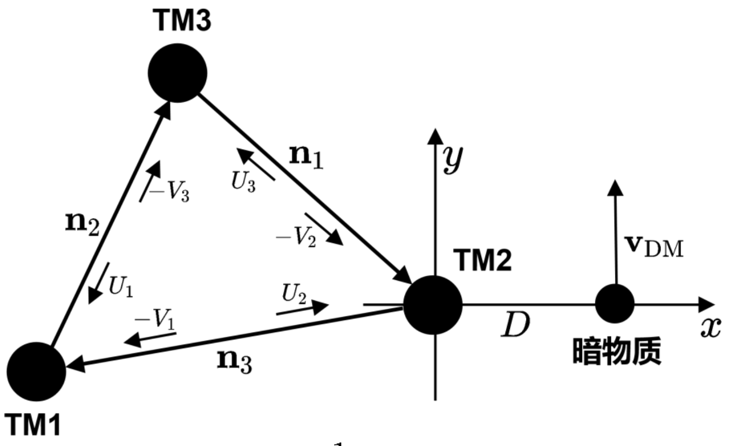
$$N_{\rm enc}^{\rm WD} = \sum_i \Gamma_{\rm enc}^{\rm DM}\tau_{{\rm WD},i}$$

For NSs, the $\tau_{\rm WD}$ has to be replaced by $t_{\rm rec}$.

As more DM is focused, constraints are amplified when introducing the Yukawa interaction. The maximum value of DM mass to be constrained by WDs is 6.25×10^{18} g and 6.46×10^{20} g for $\tilde{\alpha}=0$ and $\tilde{\alpha}=100$, respectively.

DM Direct detection on GW experiments

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 long-range Yukawa interaction results differential acceleration of TM



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

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

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

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

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

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

permutation symmetry $1\rightarrow 2\rightarrow 3\rightarrow 1$

DM Direct detection on GW experiments

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

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

$$\omega = 2\pi f$$

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

The power spectral density (PSD) of the DM signal

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

Direct detection on GW experiments

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)	$[10^{-4}, 1]$	$[10^{-4}, 1]$	$[10^{-4}, 1]$

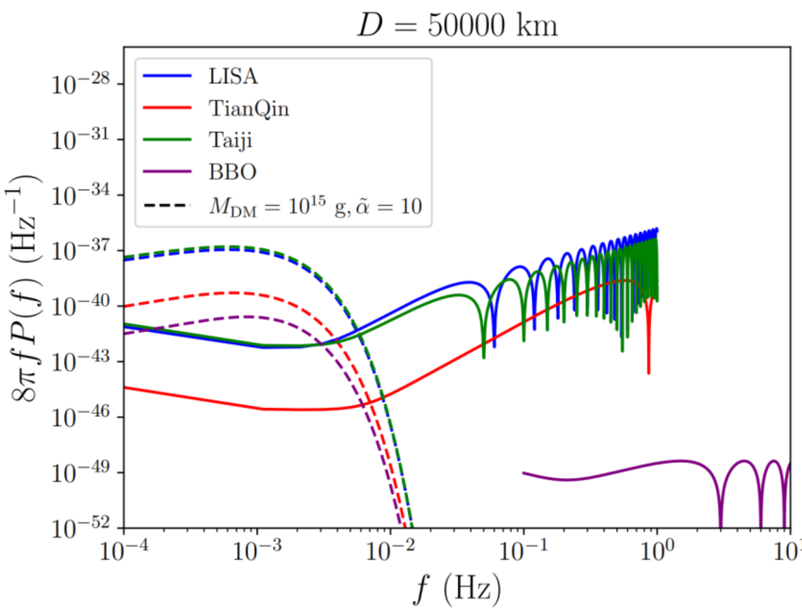
GW detector in space is a natural big (astrophysical scale) and precise (high precision laser interferometer) DM detector.

noise PSD in X channel:

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

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

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



The signal PSD (dashed lines) of composite DM on the GW detectors in the X channel and the corresponding noise PSD (solid lines).

Direct detection on GW experiments

The expected number of DM passing through the detector:

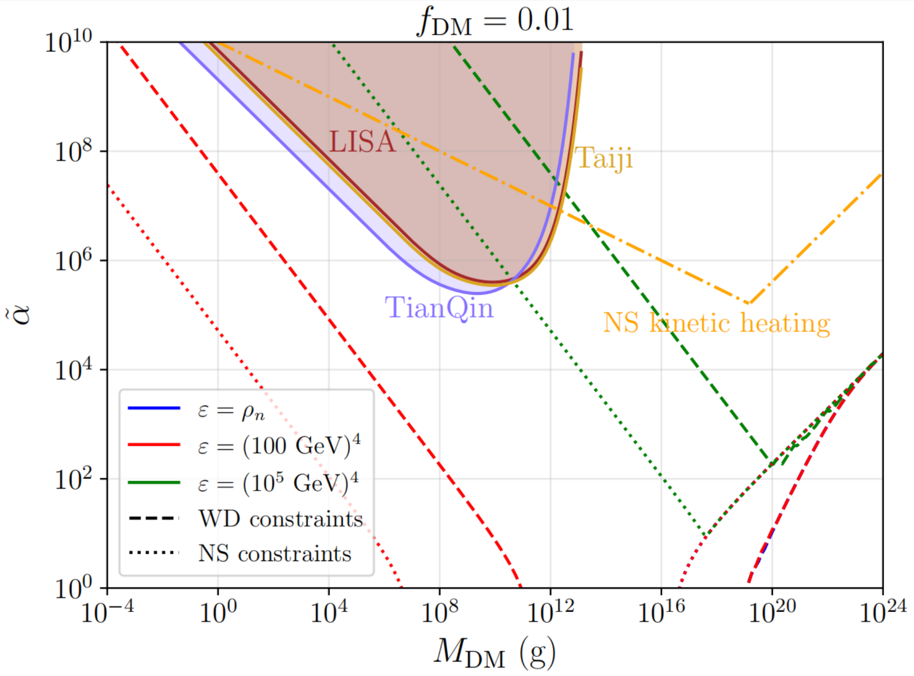
$$N_{\rm enc}^{\rm GW} = \left(f_X \pi D^2 \rho_{\rm DM} v_{\rm DM}/M_X\right) T^i_{\rm obs}$$

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

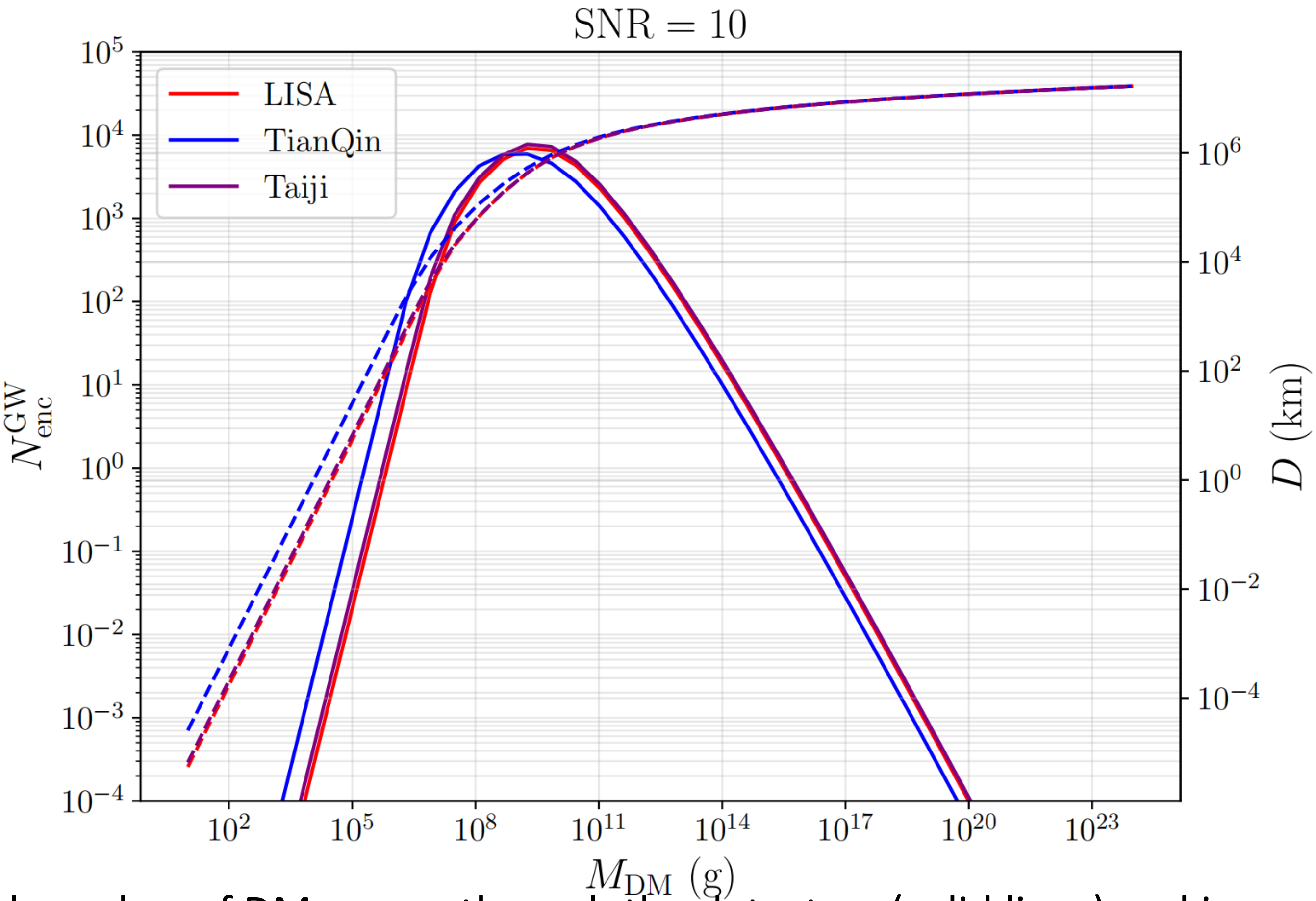
Signal-to-noise ratio

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

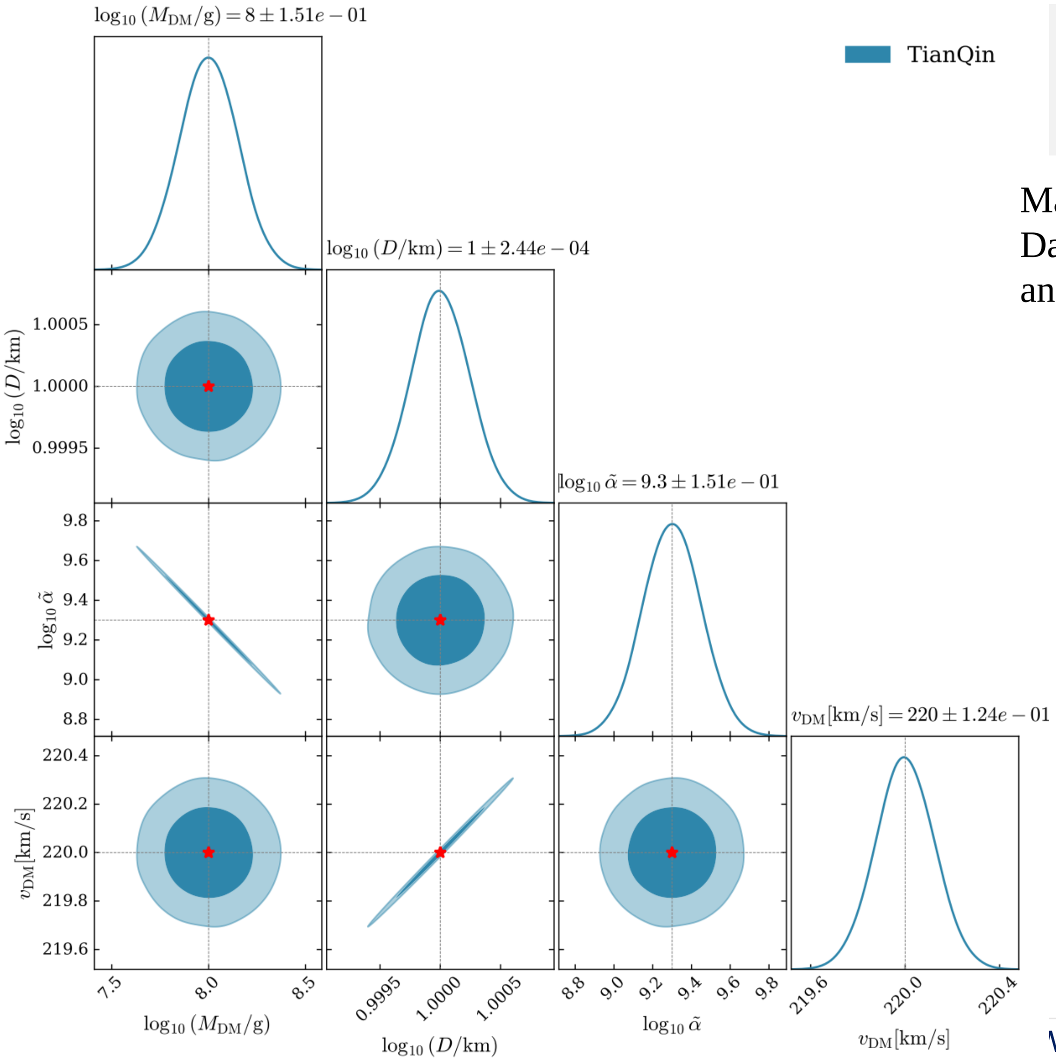
We find that space-based GW experiments can cover most of the parameter ranges beyond these astrophysical limits. And its results depend only on the mass of dark matter and its interaction strength with ordinary matter.



Sensitivity of GW detectors to composite DM with updated astrophysical constraints.

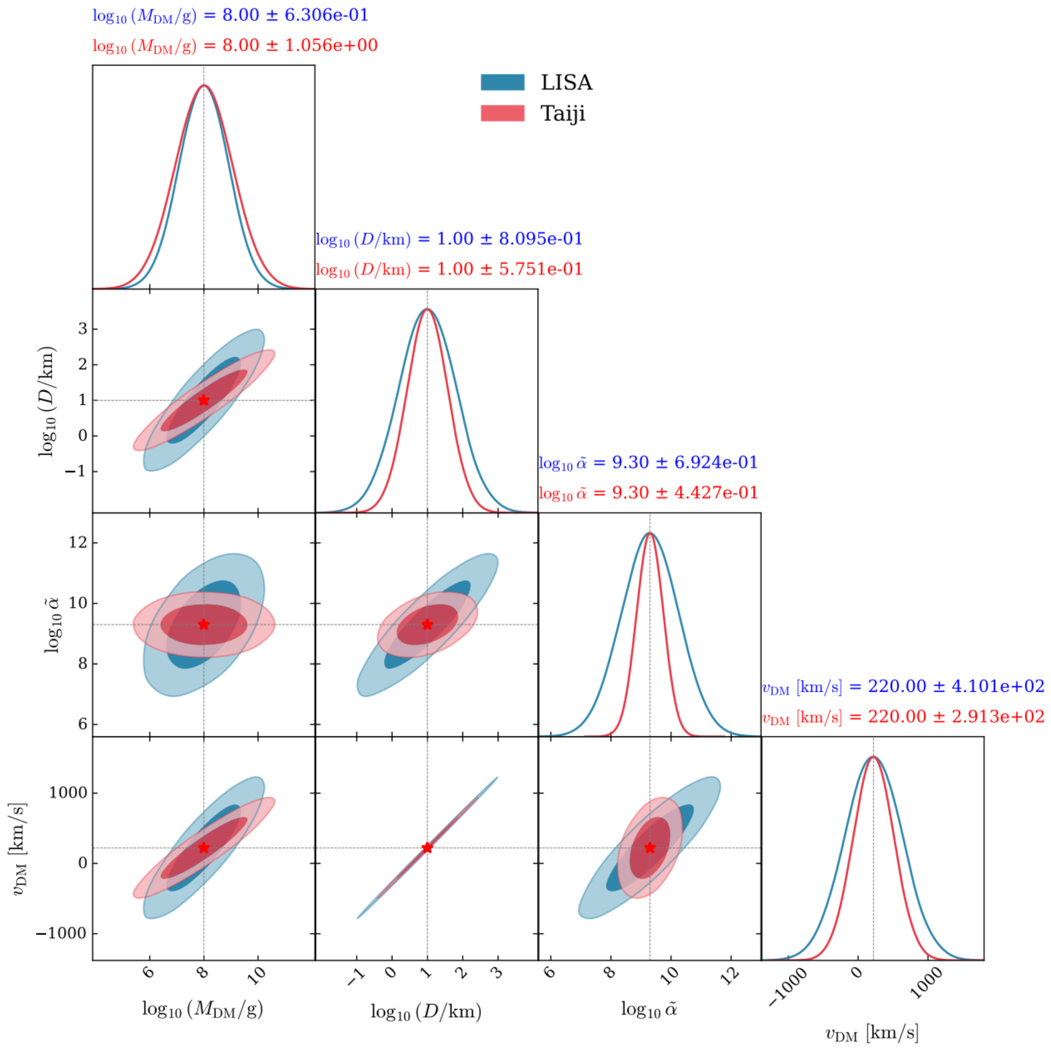


Expected number of DM passes through the detectors (solid lines) and impact factor (dashed lines) of composite DM as functions of DM mass in the X channel.

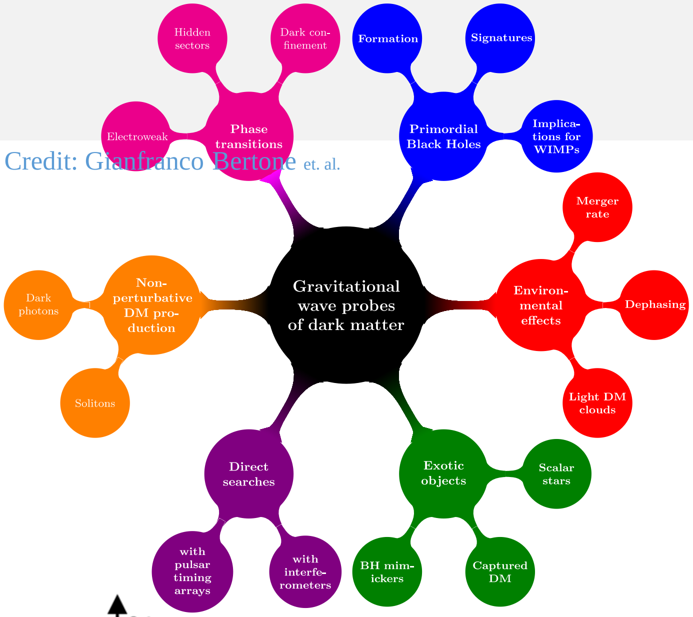


Macroscopic Dark Matter under siege: from White Dwarf Data to Gravitational Wave Detection Siyu Jiang,Aidi Yang and FPH, arXiv:2511.23263, and work in progress

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


$\log_{10}(M_{\rm DM}/{\rm g})$ = 8.00 ± 6.306e-01
$\log_{10}(M_{\rm DM}/{\rm g})$ = 8.00 ± 1.056e+00
LISA
Taiji
$\log_{10}(D/{\rm km})$ = 1.00 ± 8.095e-01
$\log_{10}(D/{\rm km})$ = 1.00 ± 5.751e-01
$\log_{10}\tilde{\alpha}$ = 9.30 ± 6.924e-01
$\log_{10}\tilde{\alpha}$ = 9.30 ± 4.427e-01
$v_{\rm DM}$ [km/s] = 220.00 ± 4.101e+02
$v_{\rm DM}$ [km/s] = 220.00 ± 2.913e+02
$\log_{10}(D/{\rm km})$
$\log_{10}\tilde{\alpha}$
$v_{\rm DM}$ [km/s]
$\log_{10}(M_{\rm DM}/{\rm g})$
$\log_{10}(D/{\rm km})$
$\log_{10}\tilde{\alpha}$
$v_{\rm DM}$ [km/s]

4. Summary

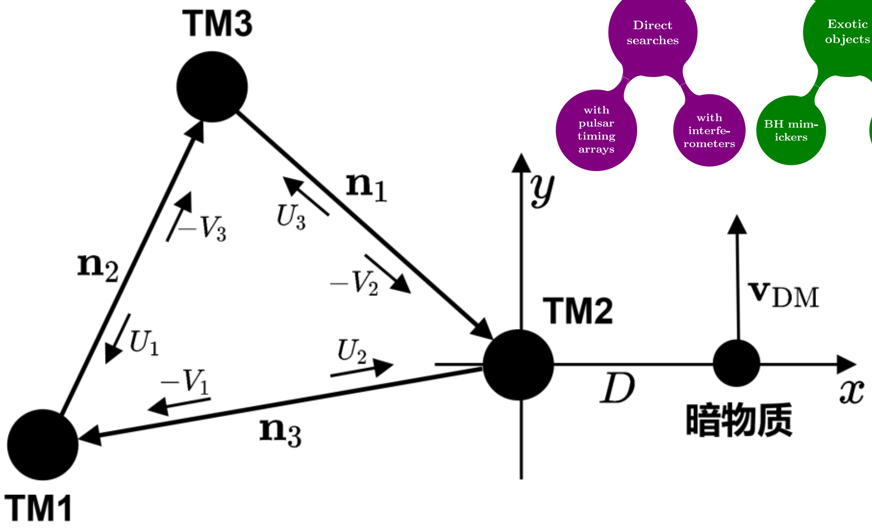


Credit: Gianfranco Bertone et. al.

GW detectors will help to explore the DM production mechanism in the early universe, the distribution and propagation of DM in the late universe, and the microscopic nature of DM, such as its mass and interaction

GW detector in space is a natural big (astrophysical scale) and precise (high precision laser interferometer) DM detector.

……



Thanks!

Direct detection on GW experiments

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

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

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

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