Probing Dark Matter with Space and Ground-based Gravitational Waves Detectors

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Taiji Program in Space Gravitational wave physics 空间太极计划

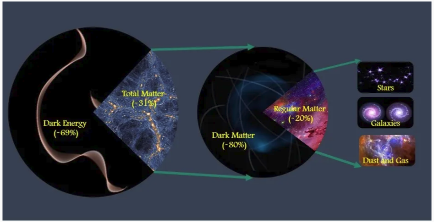
Outline

- Background: Dark Matter and Gravitational Waves
- Probing spin-2 ULDM with space-based GW Detectors
- Search PBHs in binary systems with ground-based GW Detectors

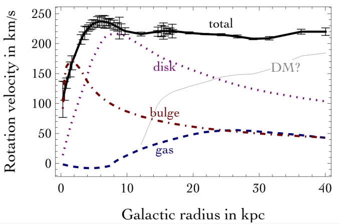
We know dark matter (DM) exists

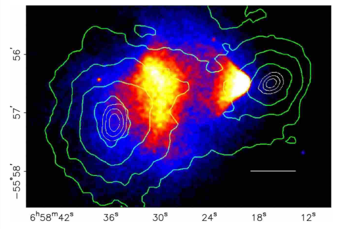
DM constitutes $\sim 85\%$ of matter in the Universe according to standard ΛCDM model.

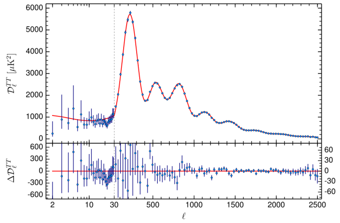
- Galaxy rotation curves
- Gravitational lensing (e.g., Bullet Cluster)
- CMB anisotropies & large-scale structure



(UCR/Mohamed Abdullah)

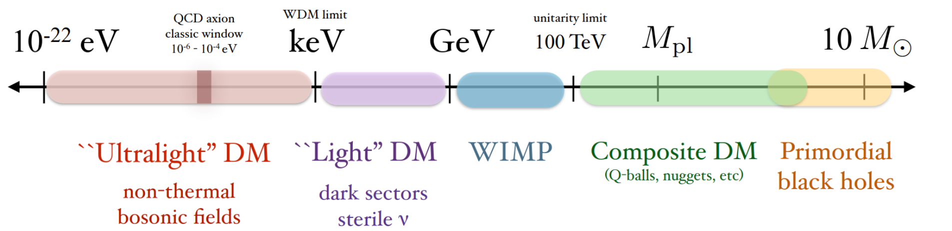






We know little about DM, not even its mass

There are many well-motivated candidates, spanning a vast mass range of about 80 orders of magnitude from $10^{-22}\mathrm{eV}$ to $M_\odot$, such as the QCD axion, WIMPs, PBHs, etc.

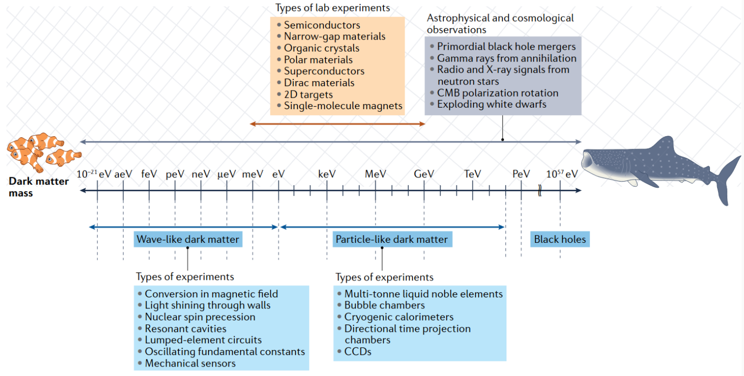


(T. Lin 2019)

Various attempts have been made

Shake it, Break it, Make it

- Direct detection: recoil of nuclei in underground detectors
- Indirect detection: DM annihilation/decay (photons, neutrinos, cosmic rays)
- Collider searches: missing energy/momentum in high-energy collisions



Many more experiments are ongoing or planned. (Hochberg et al. 2023)

Gravitational wave open up a new window

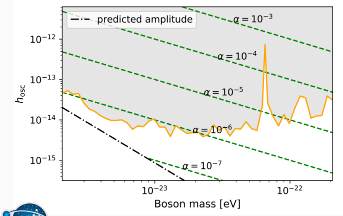
- GW signals (indirect): superradiance, binary dynamics, stochastic background
- Direct interactions: pure gravitational effects, coupling to SM particles

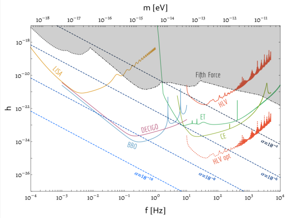
ULDM:

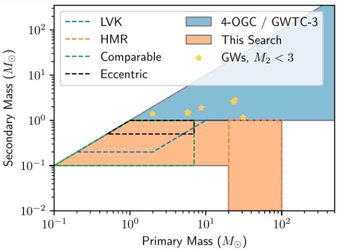
- axion-like(spin-0), dark photon(spin-1), spin-2
- Different GW detectors probe different mass range
  - $10^{-24} \sim 10^{-22}\mathrm{eV}$: PTA
  - $10^{-18} \sim 10^{-15}\mathrm{eV}$: LISA, Taiji, TianQin
  - $10^{-13} \sim 10^{-11}\mathrm{eV}$: LIGO, Virgo, KAGRA

PBHs:

- Sub-solar compact objects in binary systems
- Scalar-induced gravitational waves



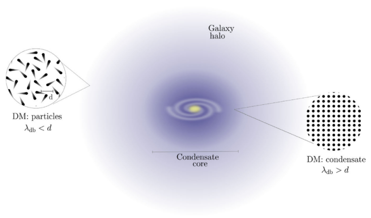




Search for ULDM

$$M_{ij}(t,\vec{x}) = \frac{\sqrt{2\rho_{\rm DM}}}{\sqrt{5}m}\varepsilon_{ij}e^{i(mt-m\vec{v}\cdot\vec{x})}$$

$$h_{ij}(t,\vec{x}) = -\frac{\alpha}{M_{\rm Pl}}M_{ij}$$



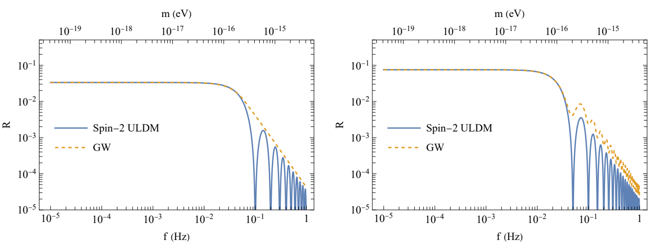
Local DM density: $\rho_{\rm DM} \sim 0.3{\rm GeV/cm^3}$

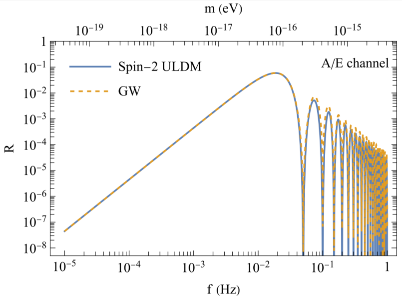
- Frequency: Compton frequency
  $f = \frac{mc^2}{h} \sim 2.4\times 10^{-3}{\rm Hz}\left(\frac{m}{10^{-17}eV}\right)$
- Coherent length scale: de Broglie wavelength
  $\lambda_{dB} \sim \frac{h}{mv} \sim 10^3{\rm AU}\left(\frac{10^{-17}eV}{m}\right)\left(\frac{250{\rm kms^{-1}}}{v}\right)$
- Frequency dispersion: velocity dispersion $v\sim 10^{-3}c \gg$ Earth's orbital velocity
  $\Delta f/f \sim \frac{v^2}{c^2} \sim 10^{-6}$
- Coherent time scale: $T_{\rm coh} \sim \frac{1}{\Delta f} \sim 30{\rm yr}\left(\frac{10^{-3}{\rm Hz}}{f}\right)$

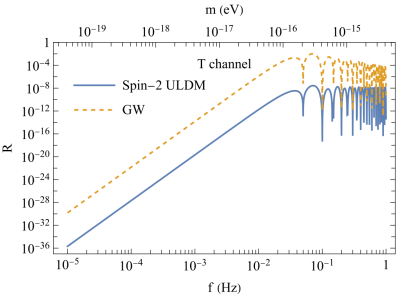
Response of Space-based Detector

Response averaging over the directions of velocity and polarizations over the sky

$$\mathcal{R} = \frac{1}{5}\int \frac{d^2\hat{v}}{4\pi}\int \frac{d^2\hat{r}}{4\pi}\sum_P F^P F^{P*}$$







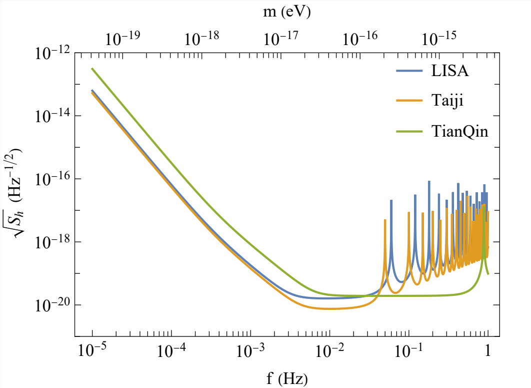
Constraints on Coupling Constant

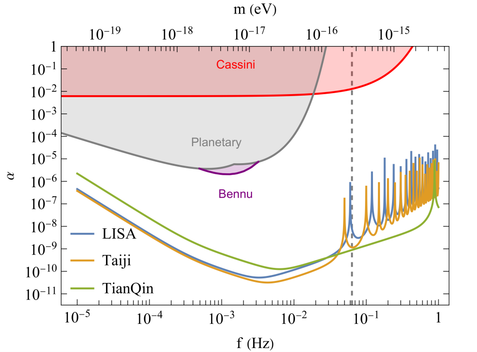
$$S_{A,E,T} = \frac{N_{A,E,T}}{\mathcal{R}_{A,E,T}}$$

$$1/S_{\mathrm{opt}} = 1/S_{\mathrm{A}} + 1/S_{\mathrm{E}} + 1/S_{\mathrm{T}},$$

$$|h|\sqrt{T_{\mathrm{obs}}} = \frac{\alpha\sqrt{2\rho_{\mathrm{DM}}}}{mM_{\mathrm{Pl}}}\sqrt{T_{\mathrm{obs}}} \leftrightarrow \sqrt{S_{\mathrm{opt}}},$$

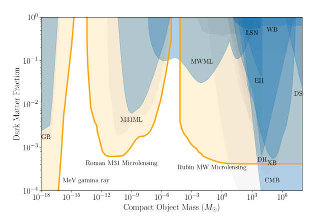
$$\alpha = mM_{\mathrm{Pl}}\sqrt{\frac{5S_{\mathrm{opt}}}{2T_{\mathrm{obs}}\rho_{\mathrm{DM}}}}.$$



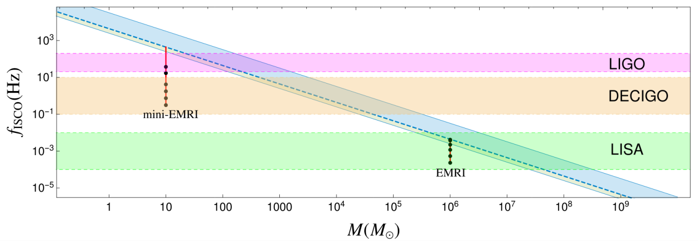


mini-EMRI System

- Open windows of fPBHs: planetary masses ($10^{-7} \sim 10^{-2} M_{\odot}$), asteroid masses ($10^{-15} \sim 10^{-10} M_{\odot}$)
- Paired with stellar-mass BHs or neutron stars, forming extreme-mass-ratio inspiral (EMRI) system, here we call them mini-EMRIs



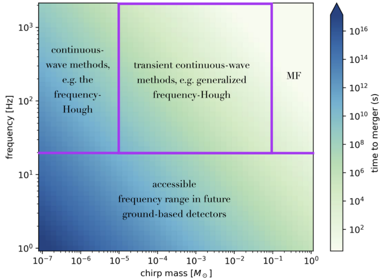
(Bird et al. 2023)

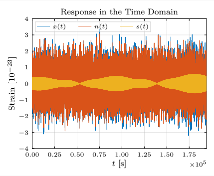


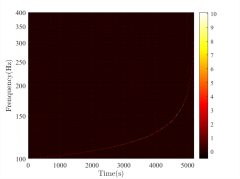
(Guo & Miller 2022)

Searching Methods

- Signal characteristics
  - Slow frequency evolution: quasi-monochromatic or continuous waves(CWs)
  - Long-duration: days to years before merger
- Search strategies
  - target search
  - directed search
  - all-sky search
- Analysis methods
  - Fully Coherent
  - Semi-coherent
  - Cross-correlation





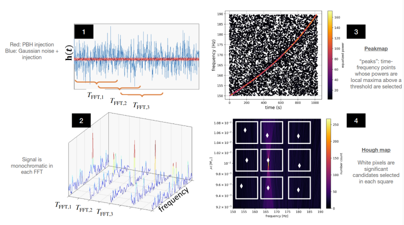


Searching for mini-EMRI System

The search for PBHs in binary systems is commonly based on CW methods.
Under the Newtonian approximation:

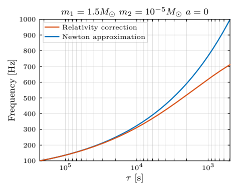
$$\dot{f}_{\rm N} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}_c}{c^3}\right)^{5/3} f^{11/3} \equiv k f^{11/3}$$

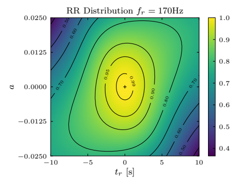
$$f(t) = f_0\left[1 - \frac{8}{3}k f_0^{8/3}(t-t_0)\right]^{-3/8}$$



Adapting to mini-EMRI systems:

- Faster frequency evolution
- General relativistic corrections
- Window functions and spectral leakage





Update detection limit, parameter space grid, improve the search sensitivity.

Summary

- Dark matter remains a mystery. Gravitational waves open a new window to probe dark matter candidates at both the low-mass and high-mass ends.
- At the low-mass end, we analyze the response of spin-2 ULDM for space-borne detectors. With 1-year of observation, the constraints on the coupling constant can reach down to $\alpha \sim 10^{-10}$ ($m \sim 10^{-17}\mathrm{eV}$), providing significant improvement over current limits.
- At the high-mass end, PBHs in binary systems are ideal targets for ground-based detectors. New search pipelines are under development based on continuous-wave search methods. These searches will help constrain the remaining window for PBHs in the planetary- and asteroid-mass ranges.

Thanks!