Searching for Dark Photon Dark Matter with Gravitational Wave Detectors

Yue Zhao

University of Utah

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Internally reviewed by LIGO.
O1 data analysis is done!
Popular Choices:

- Very light DM particles
  Axion and Dark “Photon”
  $10^{-22} \text{eV} \sim 10^{-2} \text{eV}$

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- WIMPs:
  $100 \text{GeV} \sim \text{TeV}$

Huaike Guo, Keith Riles, Fengwei Yang, Y.Z.

- Primordial Black Holes:
  $10^{-7} \sim 100 \text{ solar mass}$

Huai-Ke Guo, Jing Shu, Yue Zhao

Both ultra-light and ultra-heavy scenarios can be proved by GW detectors!
Popular Choices:

- Very light DM particles
  - Axion and Dark “Photon”
  - $10^{-22}$ eV ~ $10^{-2}$ eV

DM is an oscillating background field.

Dark Photon is dominantly oscillating background dark electric field.

Driving displacements for particles charged under dark gauge group.

- gauge boson of the $U(1)_B$ or $U(1)_{B-L}$
  - $(p+n)$
  - $(n)$
Ultra-light DM – Dark Photon

• Mass

W/Z bosons get masses through the Higgs mechanism.

A dark photon can also get a mass by a dark Higgs, or through the Stueckelberg mechanism.

a special limit of the Higgs mechanism unique for U(1) gauge group

• Relic abundance (non-thermal production)

  Misalignment mechanism
  Light scalar decay
  Production from cosmic string

Ultra-light dark photon can be a good candidate of cold dark matter!
Laser Interferometer Gravitational-Wave Observatory

LIGO (ground-based)

Amazing precision at LIGO: $O(1/1000)$ the radius of a single proton!

Opened a field: Gravitational Wave Astronomy

Enrich our understanding on fundamental physics and early cosmology.
Laser Interferometer Space Antenna

LISA (space-based)

Recently approved by the European Space Agency.

U.S. (NASA) just rejoined the program.

LISA PathFinder is a great success!

(LISA Mission Consortium)
Gravitational wave changes the distance between mirrors.

\[ \rightarrow \text{Gravitational wave} \rightarrow \text{Change photon propagation} \rightarrow \text{interferometer pattern time between mirrors.} \]
Dark photon dark matter moves mirrors. Change photon propagation time between mirrors.
Maximal Displacement:

Local DM energy density:

\[
\frac{1}{2} m_A^2 A_{\mu,0} A_0^\mu \simeq 0.4 \text{ GeV/cm}^3
\]

local field strength of DP

\[
F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu
\]

\[
\partial^\mu A_\mu = 0
\]

\[
E_i \sim m_A A_i \quad \gg \quad B^i \sim m_A v_j A_k \epsilon^{ijk}
\]
Maximal Displacement:

\[ \ddot{a}_i(t) = \frac{\vec{F}_i(t)}{M_i} \approx \epsilon \epsilon \frac{q_{D,i}}{M_i} \partial_t \vec{A}(t, x_i) \]

- dark photon coupling
- dark electric field
- charge mass ratio of the test object

Silicon mirror:

- \( U(1)_B : \frac{1}{\text{GeV}} \)
- \( U(1)_{B-L} : \frac{1}{2\text{GeV}} \)

\[ \Delta s_{\parallel,i} = \int dt \int dt \ a_{\parallel,i}(t) \]
Maximal GW-like Displacement:

\[ \Delta L[t] = (x_1[t] - x_2[t]) - (y_1[t] - y_2[t]) \]

\[
\sqrt{\langle \Delta L^2 \rangle_{LIGO}}_{\text{max}} = \frac{\sqrt{2} |a| |k| L}{3 m_A^2} \\
\sqrt{\langle \Delta L^2 \rangle_{LISA}}_{\text{max}} = \frac{1}{\sqrt{6}} \frac{|a| |k| L}{m_A^2}
\]

Compare this with the sensitivity on strain h.

\( v_{\text{vir}} = 0 \) gives same force to all test objects, not observable. Net effect is proportional to velocity.
Properties of DPDM Signals:

Signal:

- almost monochromatic
  \[ f \simeq \frac{m_A}{2\pi} \]
- very long coherence time
  \[ \frac{\Delta f}{f} = \frac{v_{\text{vir}}^2}{f} \simeq 10^{-6} \]

A bump hunting search in frequency space.

Can be further refined as a detailed template search, assuming Boltzmann distribution for DM velocity.

Once measured, we know great details of the local DM properties!
Properties of DPDM Signals:

Signal:

- very long coherent distance

\[ l_{coh} \approx \frac{1}{m_A v_{vir}} \approx 3 \times 10^9 \text{m} \left( \frac{100 \text{Hz}}{f} \right) \]

Propagation and polarization directions remain constant approximately.
Correlation between two sites is important to reduce background!

Properties of DPDM Signals:

Due to long coherence length, signal is almost the same for both sites.
Sensitivity to DPDM signal of GW detectors:

First we estimate the sensitivity in terms of GW strain.


One-sided power spectrum function:

\[ S_{GW}(f) = \frac{3H_0^2}{2\pi^2} f^{-3} \Omega_{GW}(f) \]

energy density carried by a GW planewave

\[ \rho_{GW}(f) = \frac{\langle h^2 \rangle}{16\pi G} \]

\[ \Omega_{GW}(f) \equiv \frac{f}{\rho_c} \frac{d\rho_{GW}}{df} = \frac{f}{\rho_c} \frac{\rho_{GW}(f)}{\Delta f} \]

\[ \Delta f / f = v_{\text{vir}}^2 \sim 10^{-6} \]

Concretely predicted by Maxwell–Boltzmann distribution!

A template search is possible, and a better reach is expected!

We make simple estimation based on delta function as a guideline.
Sensitivity to DPDM signal of GW detectors:

Signal-to-Noise-Ratio can be calculated as:

\[ S = \langle s_1, s_2 \rangle = \int_{-T/2}^{T/2} s_1(t)s_2(t)dt. \]

observation time of an experiment, O(yr)

\[ S = \frac{T}{2} \int df \gamma(|f|) S_{GW}(|f|) \tilde{Q}(f), \]

overlap function describe the correlation among sites

\[ N^2 = \frac{T}{4} \int df P_1(|f|) |\tilde{Q}(f)|^2 P_2(|f|). \]

optimal filter function maximize SNR

one-sided strain noise power spectra
Sensitivity to DPDM signal of GW detectors:

**DPDM:**

\[ \gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle} \]

**LIGO**: Approximately a constant (-0.9) for all frequencies we are interested.

**Virgo** (-0.25) may be useful for cross checks.

Livingston/Hanford: dark photon field value
Sensitivity to DPDM signal of GW detectors:

DPDM:

LISA

\[ \gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle} \]

\[ A \equiv \frac{1}{3}(2X - Y - Z), \]
\[ E \equiv \frac{1}{\sqrt{3}}(Z - Y), \]
\[ \langle AE \rangle \]

Approximately a constant (-0.3) for all frequencies we are interested.

dark photon field value
Sensitivity to DPDM signal of GW detectors:

Translate strain sensitivity to parameters of DPDM:

\[
SNR = \frac{\gamma(|f|h_0^2)\sqrt{T}}{2\sqrt{P_1(f)P_2(f)\Delta f}}.
\]

effectively the max differential displacement of two arms

a GW with strain h \implies change of relative displacement as h

\[\sqrt{\langle \Delta L^2 \rangle_{LIGO}}|_{max}\]

\[\rightarrow\text{sensitivity of DPDM parameters (mass, coupling)}\]
Sensitivity Plot:

Dark Photon Mass (eV)

Frequency (Hz)

$\mathcal{L}$ [LLR(2$\sigma$), EW(2$\sigma$), $U(1)_B$]

LIGO, LIDMO?

Design sensitivities, 2 yrs
O1 Result:
Modeling DPDM background:

\[ \vec{A}_{total}(t, x) = \sum_{i=1}^{N} \vec{A}_{i,0} \sin(\omega_i t - \vec{k}_i \cdot \vec{x} + \phi_i) \]
LIGO simulation output:

\[ \epsilon^2 = 5 \times 10^{-44}, \quad f = 70.71 \text{ Hz} \quad T_{SFT} = 1800 \text{ s} \quad T_{tot} = 200 \text{ hr} \]

\[ \text{SNR} \approx -8. \]
Earth Rotation Effects:

\[ R_L \approx -\sum_{i=1}^{n} \frac{\cos(\omega_i t + \Phi_i)}{\omega_i^2} \left( C_{2,1}^i \cos(2\omega_E t) + \\
C_{2,2}^i \sin(2\omega_E t) + C_{1,1}^i \cos(\omega_E t) + C_{1,2}^i \sin(\omega_E t) + C_0^i \right) \]

broadening due to finite Tsft
Fine structure of the signal:

Analytic understanding matches very well with numerical result!
Conclusion

The applications of GW experiments can be extended!

- Particularly sensitive to relative displacements.
  - Coherently oscillating DPDM generates such displacements.
  - It can be used as a DM direct detection experiment.

The analysis is straightforward!

- Very similar to stochastic GW searches.
  - Better coherence between separated interferometers than Stochastic GW BG.

The sensitivity can be extraordinary!

- O1 data has already beaten existing experimental constraints.
  - Can achieve 5-sigma discovery at unexplored parameter regimes.
  - Once measured, great amount of DM information can be extracted!
Facial mask: prevent the damage to your skin from gravitational wave radiation.
GS-mechanism for massive U(1):

Lagrangian for a massive photon with GS-term:

\[ \mathcal{L}_\alpha = -\frac{1}{4g_A^2} F^A F^A - \frac{1}{4g_a^2} \text{Tr}[G^a G^a] - \frac{1}{2} (\partial^\mu \alpha - M A^\mu)^2 - \frac{1}{2} c_1 \alpha \text{Tr}[G^a \wedge G^a] \]

U(1) gauge transformation:

\[ A^\mu \rightarrow A^\mu + \partial^\mu \epsilon \quad , \quad \alpha \rightarrow \alpha + M \epsilon \]

GS term can be chosen so that the anomaly from fermions are cancelled:

\[ \delta_\epsilon \mathcal{L}_{\text{total}} = -\frac{1}{2} \left( M c_1 - \frac{A}{16\pi^2} \right) \epsilon \text{Tr}[G^a \wedge G^a] \]

\[ A = 16\pi^2 M c_1 \]
Sensitivity Plot:

$U(1)_{B-L}$ charge mass ratio: $1/2 \text{GeV}$

$\ell^2$ vs. $f(\text{Hz})$

$U(1)_{B-L}$

LISA

LLR($2\sigma$)

EW($2\sigma$)

LIGO

$5\sigma, 2\sigma$

design sensitivities operating for 2 years

$m_A(\text{eV})$
Extreme Mass Ratio Inspirals

ABH

SMBH

gravitational wave signal

LISA-like GW exp for PBH
LISA-like GW exp for PBH

Extreme Mass Ratio Inspirals

PBH \rightarrow \text{gravitational wave signal} \rightarrow \text{SMBH}

Same frequency, but smaller amplitude!
Master Formula:

\[ \Gamma = \int R(M, \mu) \left( \frac{dn(M, z)}{dM} dM \right) (p(s, z) ds) \left( \frac{dV_c}{dz} dz \right) \]

- **intrinsic EMRI rate** well studied for SMBH-ABH
- **rescale for PBH mass and density**
- **SMBH mass spectrum** $10^4 - 10^7 M_\odot$
  - provided in astrophysics
- **SMBH spin distribution** likely to be almost extremal
  - little effects to final results
- **volume integral** truncated by SNR
GW Strain:

\[ M = 10^6 \, M_\odot \; ; \; \text{Spin} = 0.999 \; ; \; 1 \, \text{Gpc} \]
Sensitivity:

One observation may be good enough to claim discovery!
Conclusion

LISA-like GW detectors is powerful to search for PBHs!

- Large unexplored parameter space can be probed.
  - PBH mass: $10^{-7} \sim 10\, M_\odot$
  - Fraction can be as small as $10^{-4}$.

- One or few signal events are good enough to declare discovery, if PBH is out of the mass regime of astrophysical COs.
  - Non-COs (planets) are destroyed by tidal force before ISCO.
Conclusion

- Astrophysical uncertainties can be largely reduced by measurements on ABH-SMBH EMRIs.
  - Mass spectrum and spin distribution of SMBHs.
  - Help to remove hard cut-off at $z=1$.

- Lighter SMBH may be more useful to look for smaller PBHs.
  - Larger Frequency Integration Regime (SNR)
  - Guideline in future LISA-like GW experiments

LIGO opens the era of GW astronomy. (Similar to the time when CMB is observed.)
Plenty astrophysics can be studied, as well as non-SM physics.
Dark Matter Overview:

Why do we need DM?

- Galaxy rotation curve (Wikipedia)
- Bullet Cluster (Deep Chandra)

- The CMB Anisotropy Power Spectrum
  (WMAP year 5 data)