Search for dark photons with continuous wave methods

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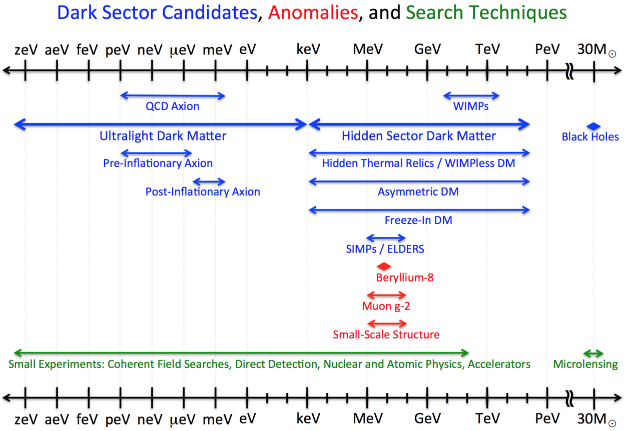
Outline

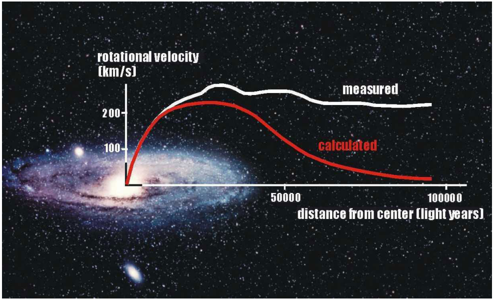
Dark matter



- Any mass is possible, but GW detectors can probe ultra-heavy and ultralight regimes [3]

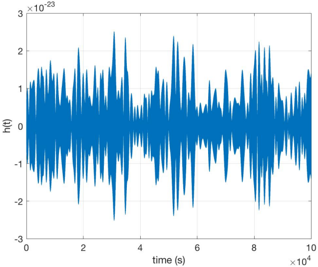
Signatures of ultralight dark matter

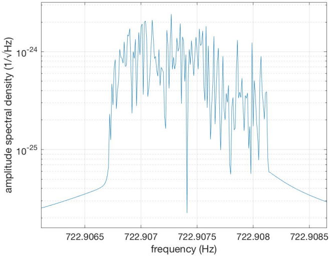
- Superradiantly formed axion clouds around black holes [1]
- Primordial black holes could be linked to dark matter [8, 13]
- Dark photons could couple to baryons in interferometers [11]
- Scalar dark matter could cause time-dependent changes in fundamental constants [6, 14, 2]



Dark photons

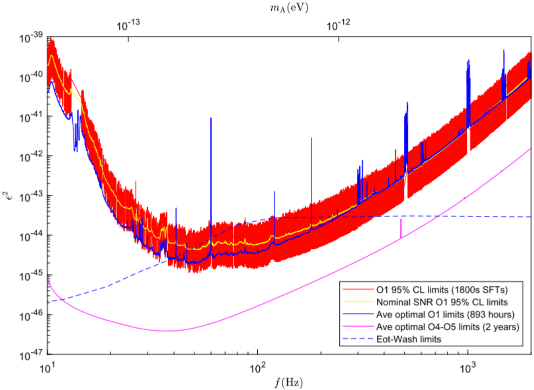
- Narrow-band, stochastic background: a superposition of plane waves with slightly different frequencies [11]
- Velocity of each dark photon follows a Maxwell-Boltzmann distribution $\Delta f \sim \frac{1}{2}\left(\frac{v_0}{c}\right)^2 f_0 \sim O(10^{-6}) f_0$ Hz
    - Continuous wave techniques, originally designed for isolated neutron stars, can be applied
    - Principle of detection: observe for a long time and take long Fast Fourier Transforms (FFTs)





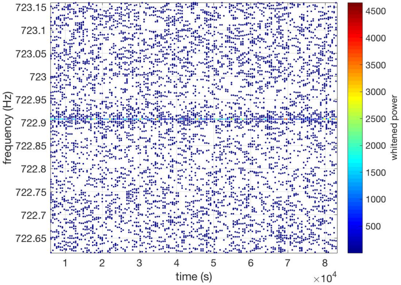
Cross-correlation method

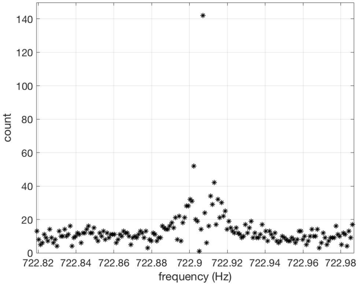
- Separation between detectors << dark photon coherence length → measurements should be almost identical
- Look for excess power above certain threshold, taking into account (1) misalignment and (2) spatial separation of detectors
- Upper limits in LIGO O1 data shown [7]



Continuous wave method to detect dark photons

- Ideally, the FFT length should change based on the frequency/mass we consider
- A semicoherent method exists to search for boson clouds around black holes that varies FFT length [4]
  - The GW signal from a boson cloud was assumed to be monochromatic with a small random walk
- Follow up of dark photon dark matter signals [9]

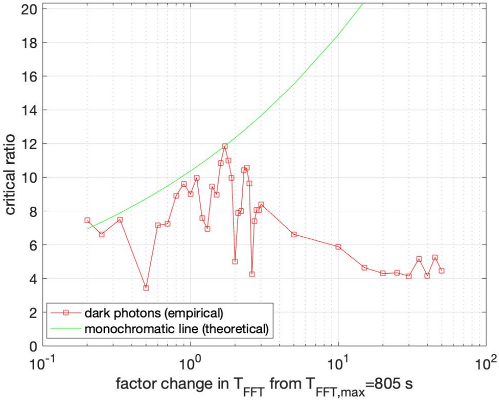




Follow-up techniques

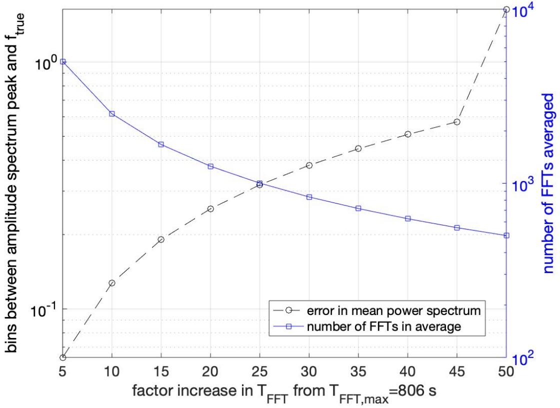
- Increase T_{FFT} and look for a *decrease* in signal-to-noise ratio
- Increase T_{FFT} and average power spectra, looking for a peak at $f_{true} = f_0(1 + \frac{1}{2}v_0^2/c^2)$
- Matched filter (in development)

Follow-up technique 1



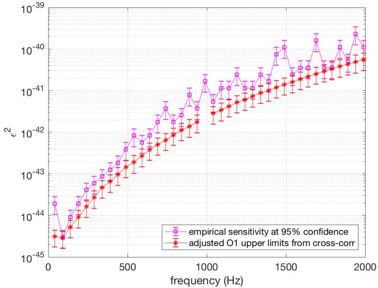
- $f_0 \simeq 744$ Hz; critical ratio falls off as T_{FFT} increases
- Injection done in LIGO O2 Livingston noise for whole O2 run; signal is recovered at 95% confidence

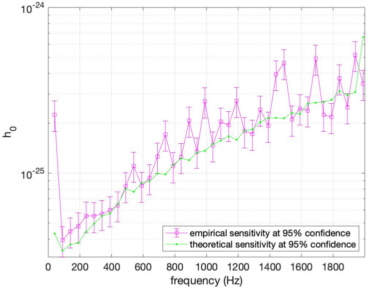
Follow-up technique 2



- Power spectra are averaged for different T_{FFT}. Error in bins from the simulated signal is plotted (no noise)

Sensitivity estimates





- Left: comparison of empirical sensitivity and adjusted upper limits in O1
    - We consider higher maximum v for DPs → lower T_{FFT}
    - Shorter T_{FFT} at higher frequencies
- Right: comparison of empirical and theoretical sensitivities

Conclusions

- Dark photons are a viable candidate of dark matter and can be searched with LIGO/Virgo
- Stochastic and continuous gravitational wave techniques are well-suited to detecting dark photon dark matter
- Combination of particle and gravitational wave physics
- End-to-end analysis scheme to detect dark photons
- Development of matched filter technique for follow-up step in progress
- Method to distinguish dark matter signals detected by interferometers in development

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[3] Marco Battaglieri et al. "US cosmic visions: new ideas in dark matter 2017: community report". In: *arXiv preprint arXiv:1707.04591* (2017).

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[5] Mark Goodsell et al. "Naturally light hidden photons in LARGE volume string compactifications". In: *Journal of High Energy Physics* 2009.11 (2009), p. 027.

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[13] Sarah Shandera, Donghui Jeong, and Henry S Grasshorn Gebhardt. "Gravitational waves from binary mergers of subsolar mass dark black holes". In: *Physical review letters* 120.24 (2018), p. 241102.

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Ultralight dark matter

- Axion-like particles
  - Pseudscalar particle that solves the strong CP problem in QCD
    - Problem: no observed CP violations in QCD
  - Couples to gauge bosons (photons)
  - Also arise in compactifications of string theory [5]
- Dark photons: Gauge boson of the $\mathrm{U}(1)_B$ or $\mathrm{U}(1)_{B-L}$ group arising from [11]:
  1. The misalignment mechanism
     - Field starts at nonzero, non-minimal vacuum value during inflation, then dissipates energy over time, eventually oscillating about the (very small) minimum in the potential
  2. Tachyonic instability of a scalar field
     - The potential has a negative mass term, meaning perturbations to the field can cause energy emission in the form of particles
  3. Cosmic string network decays

Strain induced on detector

Start with a superposition of plane waves:

$$\begin{aligned}
\vec{A} &= \sum_{n=1}^{N} \vec{A}_{n,0} \sin\left(m\left(1+\frac{1}{2}\left(\frac{v_n}{c}\right)^2\right)t - \vec{k}\cdot\vec{x} + \phi_n\right) && (1)\\
\vec{E} &= \partial_t \vec{A} \sim m\vec{A} && (2)\\
\vec{B} &= \nabla \times \vec{A} \sim m v_j A_k \epsilon^{ijk} && (3)\\
\vec{a_i} &= \frac{F}{M_i} = \epsilon e \frac{q_{D,i}}{M_i}\vec{A}_0 \cos(mt - \vec{k}\cdot\vec{x_i}) && (4)
\end{aligned}$$

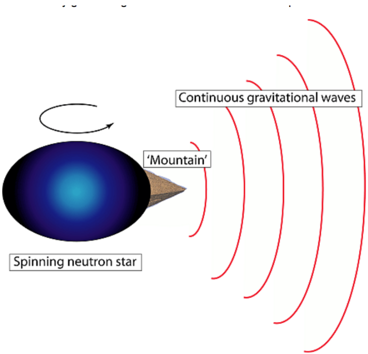
$|\vec{A}_0|$ normalized by current dark matter energy density, integrated over coherent time/space of signal

$$\Delta L(t) = [x_1(t) - x_2(t)] - [y_1(t) - y_2(t)] \quad (5)$$

ΔL contains amplitude and phase evolutions of the signal

Continuous gravitational waves

- Quasi-monochromatic, quasi-infinite signals
- Small frequency variations
- Principle of detection: observe for a long time and take long Fast Fourier Transforms



Stochastic Backgrounds

Normally the power spectrum of a stochastic gravitational wave background is:

$$S_{GW}(f) = \frac{3H_0^2}{2} f^{-3} \Omega_{GW}(f) \tag{6}$$

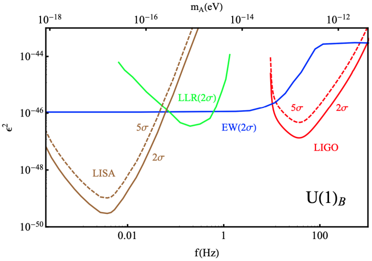
$$\Omega_{GW} = \frac{f}{\rho_c} \frac{d\rho_{GW}}{df} \tag{7}$$

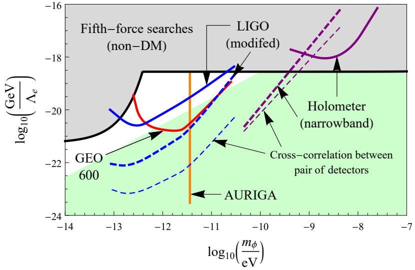
For dark photons, $\rho_{GW} \propto f^2 h_0^2$:

$$S_{GW}(f) = \frac{h_0^2}{2\Delta f} \tag{8}$$

Almost constant background [11]

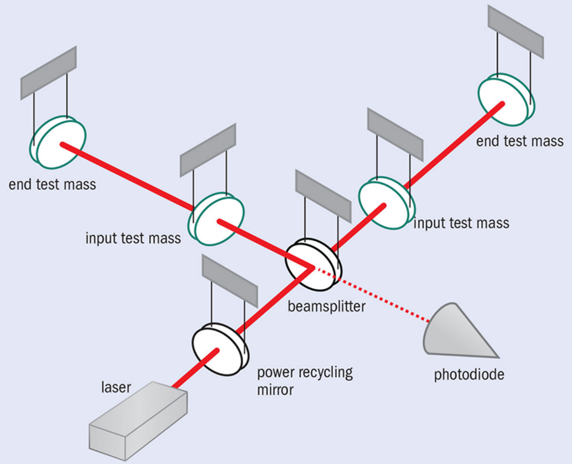
Projected constraints





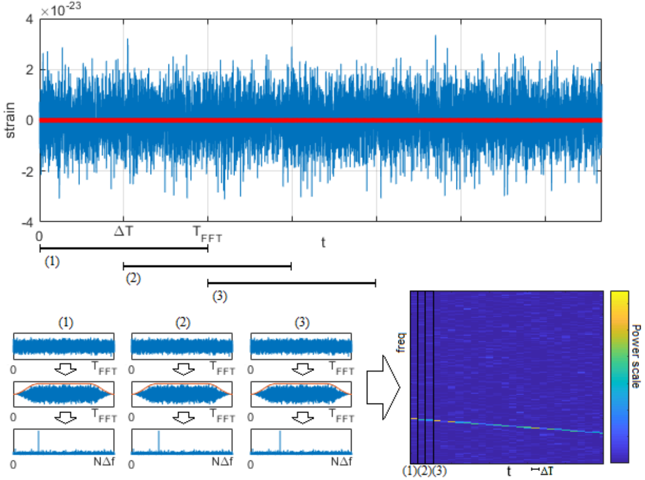
- Projected constraints on dark-photons (left) [12] and scalar dark matter (right) [6]
- Existing detectors can probe interesting portion of parameter space

LIGO/Virgo detectors



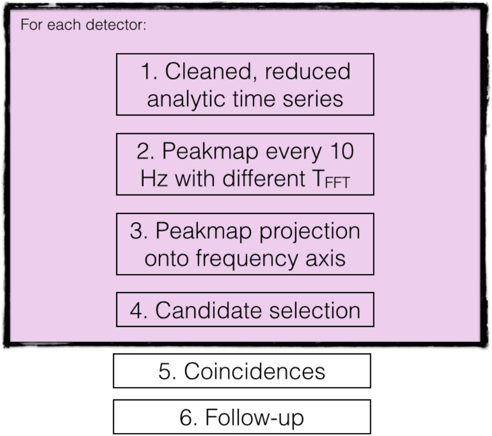
- Each incoming signal moves the mirrors uniquely, creating an interference pattern

Method overview



- Times series → power spectrum, whitening → spectrogram

Continuous wave method to detect dark photons



For each detector:

1. Cleaned, reduced analytic time series
2. Peakmap every 10 Hz with different T_{FFT}
3. Peakmap projection onto frequency axis
4. Candidate selection

5. Coincidences
6. Follow-up

- Ideally, the FFT length should change based on the frequency/mass we consider; based on [4]

Computational cost

- Search begins from 10 Hz BSD files [10]
- T_{FFT} chosen based on maximum frequency in each 10 Hz band
- Sensitivity loss $< 10\%$ compared to using 1 Hz bands
- Using 1 Xeon CPU E5-2695 v2 and analyzing a 1990-2000 Hz band takes ~ 350 s
- Extrapolating to 20-2000 Hz and a one year of observation → 1.6 days
- Dividing the analysis on 2000 cores → search takes $O(mins)$