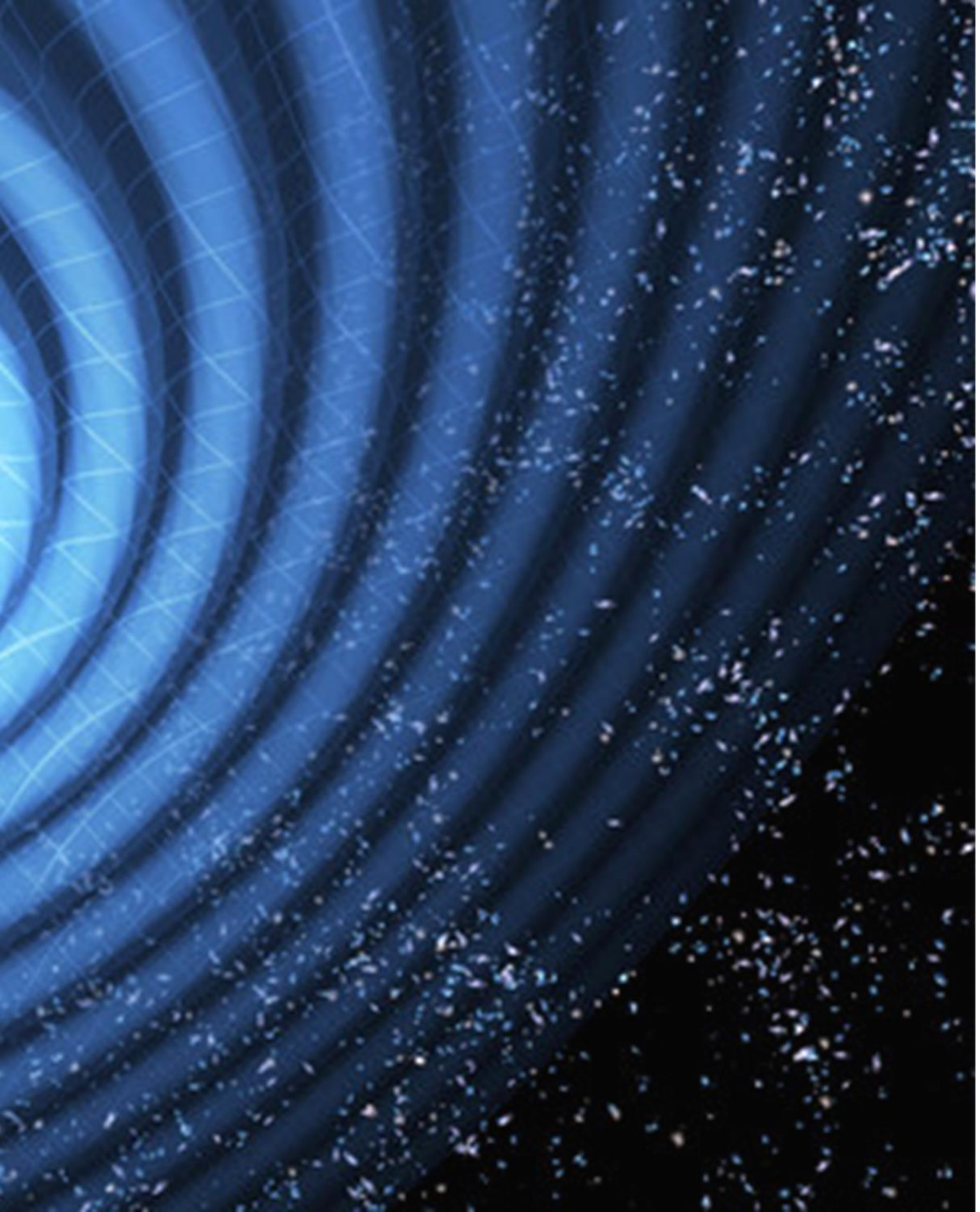

Probing spin-2 ULDM with GW detectors

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In collaboration with

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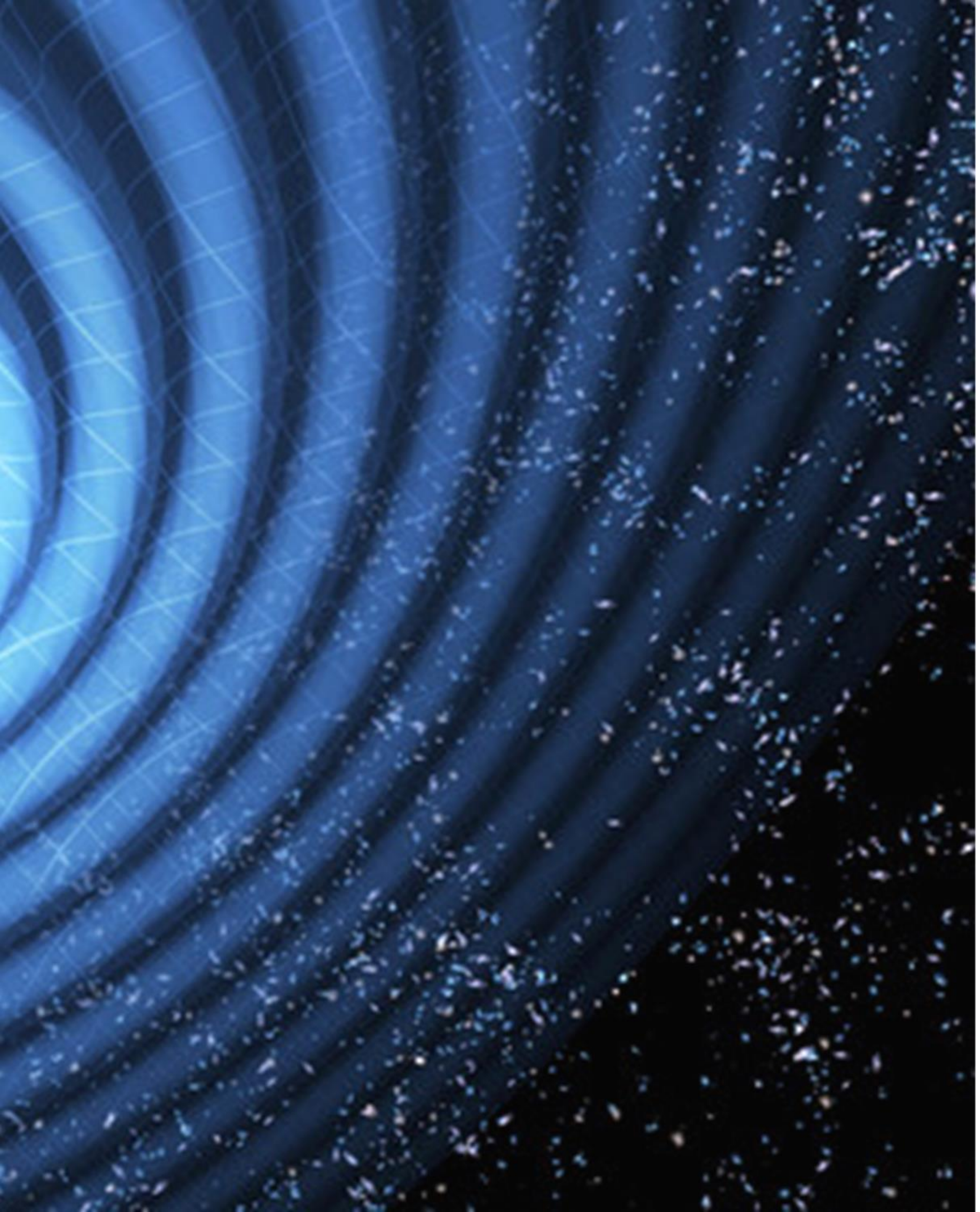
Federico Urban (CEICO – FZU)

Patras Workshop 2025



Overview

- Spin-2 ULDM
- Spin-2 ULDM signals in GW detectors
- Comparison with continuous GWs and spin-1 ULDM signals
- Spin-2 ULDM search in LVK (ongoing)
- Concluding remarks

ULDM

Why ULDM? Let's start from the axion:
- Solution to the strong CP problem;
- Predicted within string theory;
- Suppression of structure formation on small scales.

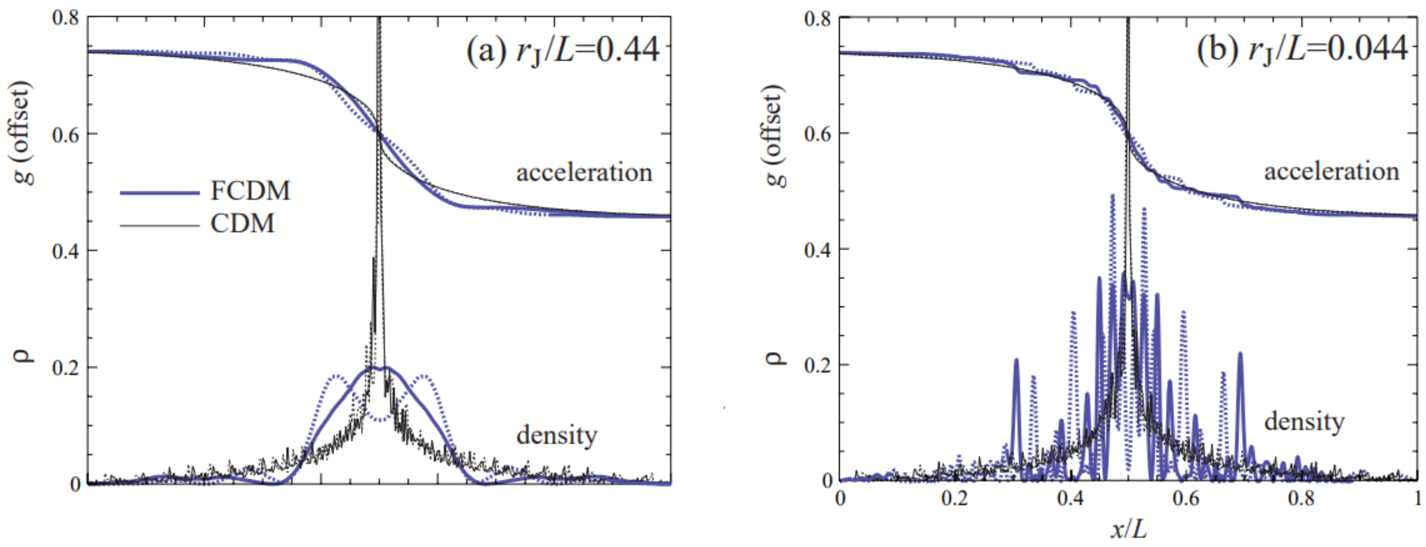


Figure from Phys. Rev. Lett. 85, 1158, Wayne Hu, Rennan Barkana, Andrei Gruzinov.

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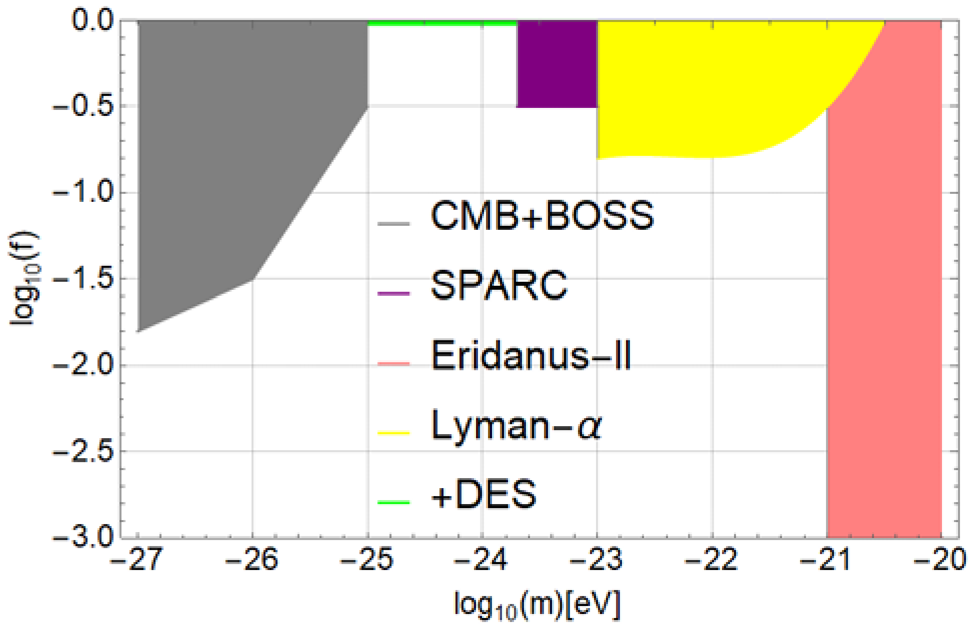
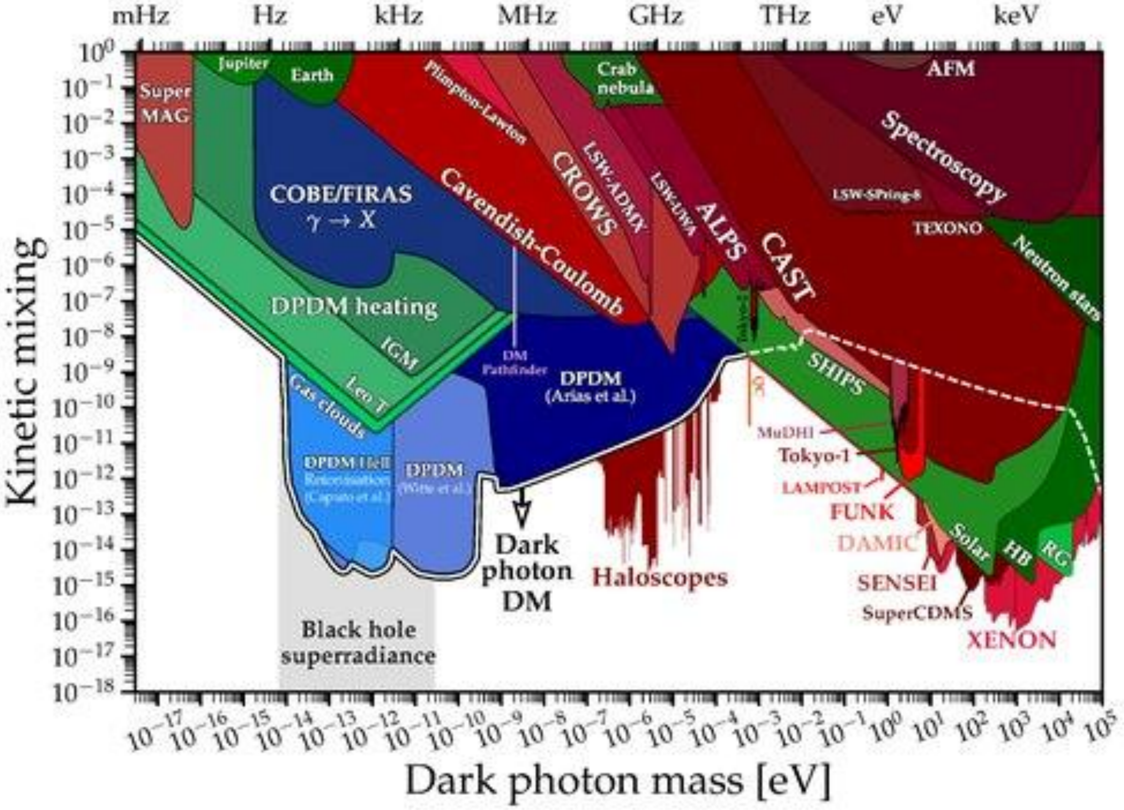


Figure from Phys. Rev. D 108, 123539,
Paola C. M. Delgado.

Another DM candidate is the massive spin-1 field, also known as dark photon:

- Dark abelian U(1) gauge symmetry with a massive gauge boson;
- Can kinetically mix with photons.



$$\mathcal{L} \subset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}g_{KM}F_{\mu\nu}F^{D\mu\nu}$$

Figure from Phys. Rev. D 104, 095029, Andrea Caputo, Alexander J. Millar, Ciaran A. J. O'Hare, Edoardo Vitagliano.

Finally, a generalization to spin-2 DM candidates can be motivated e.g. within bigravity theory:

See Phys. Rev. D 97, 024010, Luca Marzola, Martti Raidal, Federico R. Urban.

$$S = \frac{1}{\kappa_g^2}\int d^4x\sqrt{-g}R(g) + \frac{1}{\kappa_f^2}\int d^4x\sqrt{-f}R(f) + $$
$$+ \frac{m^2}{\kappa^2}\int d^4x\sqrt{-g}U(g,f) + S_m[g],$$

$$U(g,f) = \sum_{n=0}^{4} c_n V_n(S^\mu_\nu),\ S^\mu_\nu = \sqrt{g^{\mu\alpha}f_{\alpha\nu}},$$

$$V_0 = 1,$$
$$V_1 = [S],$$
$$V_2 = [S]^2 - [S^2],$$
$$V_3 = [S]^3 - 3[S][S^2] + 2[S^3],$$
$$V_4 = [S]^4 - 6[S]^2[S^2] + 8[S][S^3] + 3[S^2]^2 - 6[S^4].$$

$$h_{\mu\nu} \equiv \frac{\kappa_f}{\kappa_g\kappa}\delta g_{\mu\nu} + \frac{\kappa_g}{\kappa_f\kappa}\delta f_{\mu\nu},$$
$$\varphi_{\mu\nu} \equiv \frac{1}{\kappa}(\delta g_{\mu\nu} - \delta f_{\mu\nu}),$$

Massive spin-2

$$S_2 = \int d^4x\mathcal{L}_{\text{EH}}[h] + \int d^4x\mathcal{L}_{\text{EH}}[\varphi] + $$
$$+ \int d^4x\mathcal{L}_{\text{FP}}[\varphi].$$

Spin-2 ULDM signals in GW detectors

$$M_{ij}(t) = \frac{\sqrt{2\rho_{\rm DM}}}{m}\cos(mt+\Upsilon)\varepsilon_{ij}(\mathbf{r})$$ → Spin-2 dark matter

$$\varepsilon_{ij}(\mathbf{r}) \coloneqq \sum_\kappa \varepsilon_\kappa \mathcal{Y}^\kappa_{ij}(\mathbf{r})$$

$$\mathcal{Y}^\times_{ij} \coloneqq \frac{1}{\sqrt{2}}(p_iq_j + q_ip_j) \qquad \mathcal{Y}^+_{ij} \coloneqq \frac{1}{\sqrt{2}}(p_ip_j - q_iq_j)$$

$$\mathcal{Y}^L_{ij} \coloneqq \frac{1}{\sqrt{2}}(q_ir_j + r_iq_j) \qquad \mathcal{Y}^R_{ij} \coloneqq \frac{1}{\sqrt{2}}(p_ir_j + r_ip_j)$$

$$\mathcal{Y}^S_{ij} \coloneqq \frac{1}{\sqrt{6}}(3r_ir_j - \delta_{ij})$$

↓

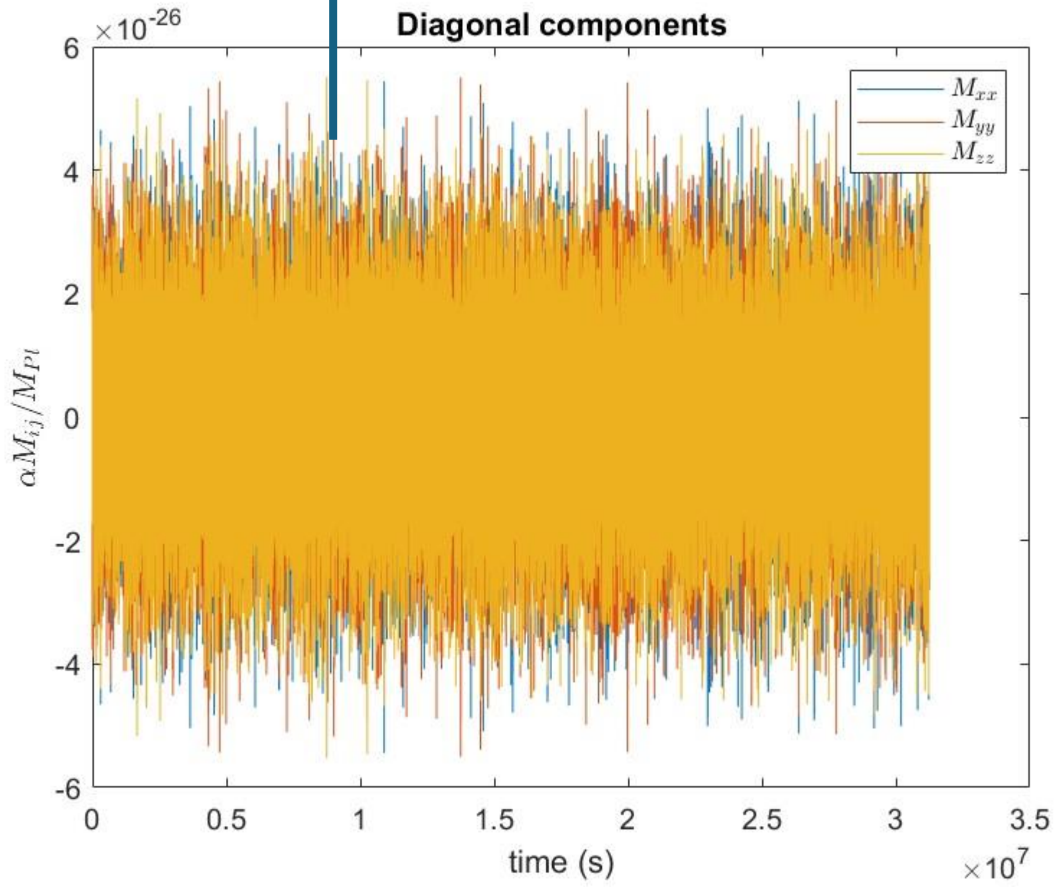
Tensor, vector and scalar polarizations

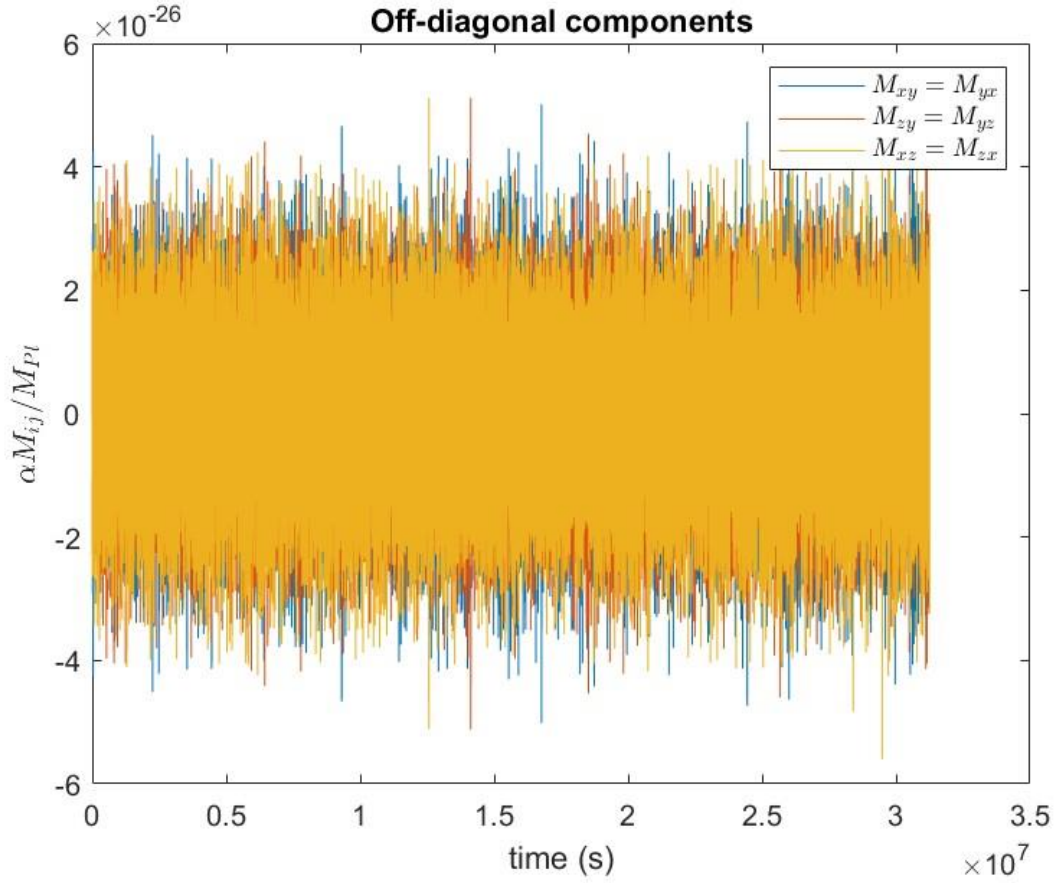
$$S_{\rm int}[g, M_{ij}, \Psi] \coloneqq -\frac{\alpha}{2M_{\rm P}}\int d^4x\,\sqrt{-g}M_{ij}T^{ij}_\Psi$$

$$h_{ij}(t) = \frac{\alpha}{M_{\rm P}}M_{ij}(t) = \frac{\alpha\sqrt{2\rho_{\rm DM}}}{mM_{\rm P}}\cos(mt+\Upsilon)\varepsilon_{ij}(\mathbf{x})$$

The occupation number of ULDM is very high, leading to the superposition of a large number of waves with velocities that follow the Maxwell-Boltzmann distribution:

Noiseless signal





The signal in the GW detector is obtained by contracting the field with the detector response:

$$h(t) = h_0 \cos(mt + \gamma)\Delta\varepsilon$$

$$h_0 \equiv \alpha\sqrt{\rho_{\rm DM}}/(\sqrt{2}mM_{\rm Pl})$$

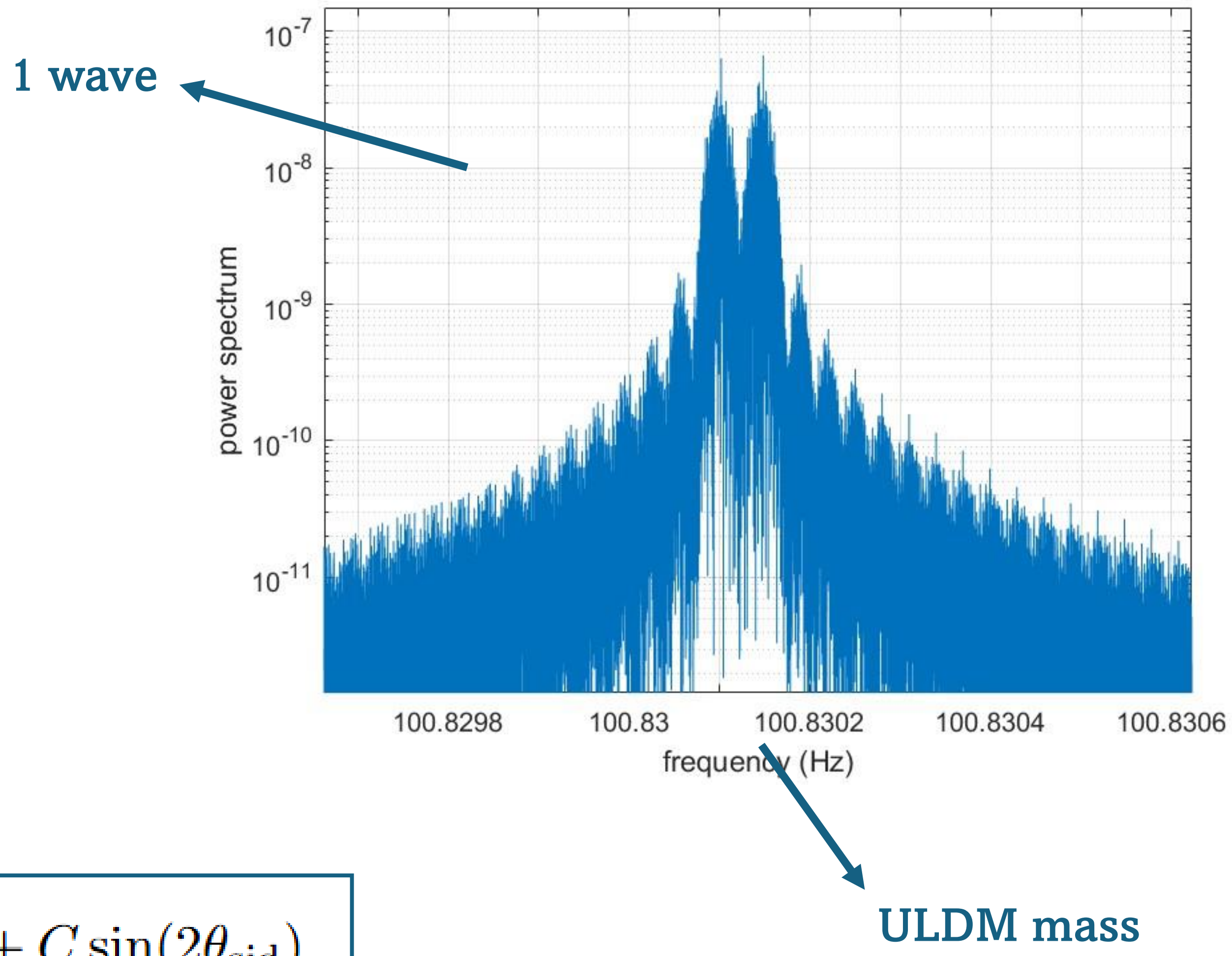
$$\Delta\varepsilon \equiv \varepsilon_{ij}(n^i n^j - m^i m^j)$$

The detectors' orientation changes with sidereal motion, i.e. we have a sidereal modulation of the signal:

$$R(\theta_{sid}) = \begin{pmatrix} \sin\lambda\cos\theta_{sid} & \sin\lambda\sin\theta_{sid} & -\cos\lambda \\ -\sin\theta_{sid} & \cos\theta_{sid} & 0 \\ \cos\lambda\cos\theta_{sid} & \cos\lambda\sin\theta_{sid} & \sin\lambda \end{pmatrix}$$

$$\theta_{\rm sid} = \phi_r + \Omega_r t$$

$$\Delta\varepsilon = A\cos(2\theta_{\rm sid}) + B\cos\theta_{\rm sid}\sin\theta_{\rm sid} + C\sin(2\theta_{\rm sid})$$



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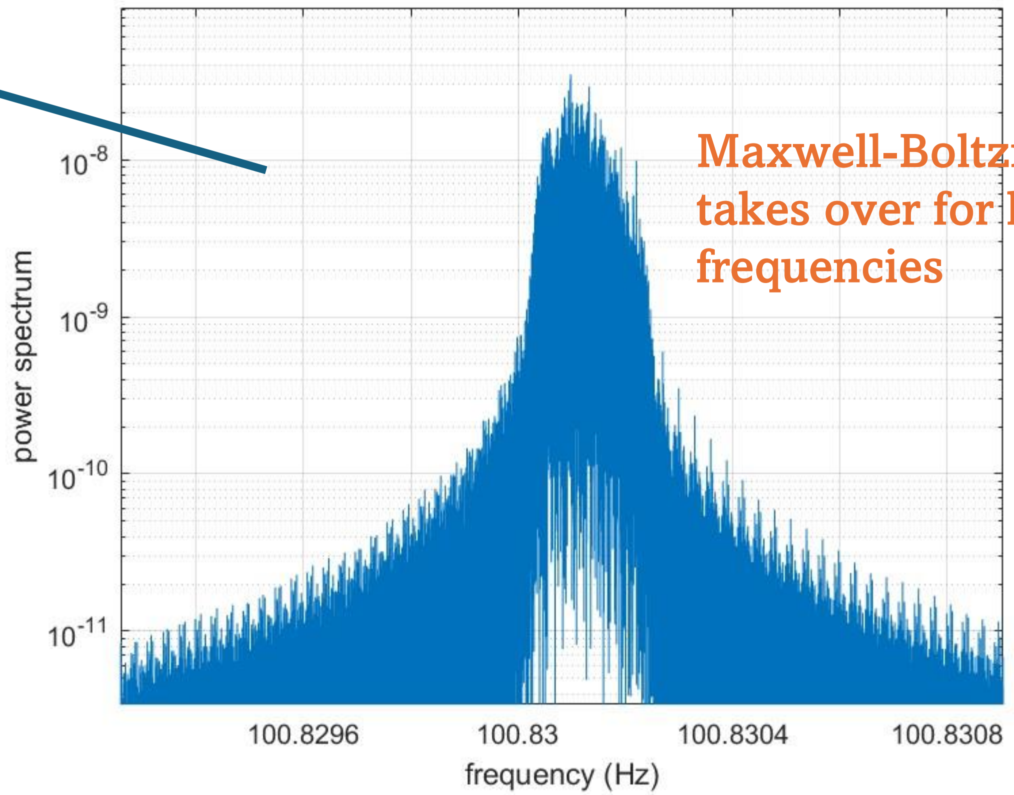
1000 waves



Maxwell-Boltzman takes over for large frequencies

Comparison with continuous GWs and spin-1 ULDM signals

Continuous GWs vs Spin-2 ULDM

# of peaks: 5

See Phys. Rev. D 58, 063001, Piotr Jaranowski, Andrzej Królak, Bernard F. Schutz.

$$\Delta\varepsilon \equiv \varepsilon_{ij}(n^i n^j - m^i m^j)$$

$$\Delta\varepsilon = A\cos(2\theta_{\rm sid}) + B\cos\theta_{\rm sid}\sin\theta_{\rm sid} + C\sin(2\theta_{\rm sid})$$

$$\begin{aligned}\tilde{h}(f) \propto & \delta(-\omega + m + 2\Omega_r),\\ & \delta(-\omega - m + 2\Omega_r),\\ & \delta(-\omega + m - 2\Omega_r),\\ & \delta(-\omega - m - 2\Omega_r).\end{aligned}$$

# of peaks: 1 for large freq, 2 for small freq.

Comparison with continuous GWs and spin-1 ULDM signals

Spin-1 ULDM vs **Spin-2 ULDM**

Spin-1 ULDM

$$\Delta\varepsilon \equiv \varepsilon_i(n^i - m^i)$$

$$\Delta\varepsilon \equiv A\cos\theta_{sid} - B\sin\theta_{sid}$$

Peak separation: $2\Omega_r$

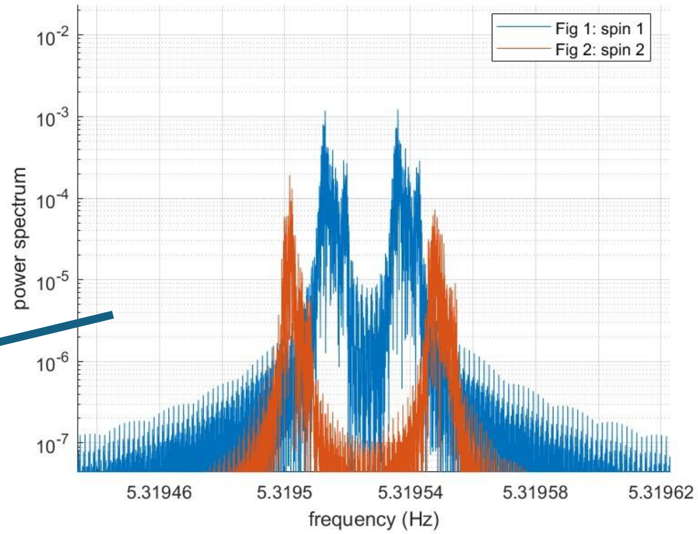
Spin-2 ULDM

$$\Delta\varepsilon \equiv \varepsilon_{ij}(n^i n^j - m^i m^j)$$

$$\Delta\varepsilon = A\cos(2\theta_{\rm sid}) + B\cos\theta_{\rm sid}\sin\theta_{\rm sid} + C\sin(2\theta_{\rm sid})$$

$$\tilde{h}(f) \propto \delta(-\omega + m + 2\Omega_r), \quad \delta(-\omega - m + 2\Omega_r), \quad \delta(-\omega + m - 2\Omega_r), \quad \delta(-\omega - m - 2\Omega_r).$$

Peak separation: $4\Omega_r$



Only for small freq

Spin-2 ULDM search in LVK (ongoing)

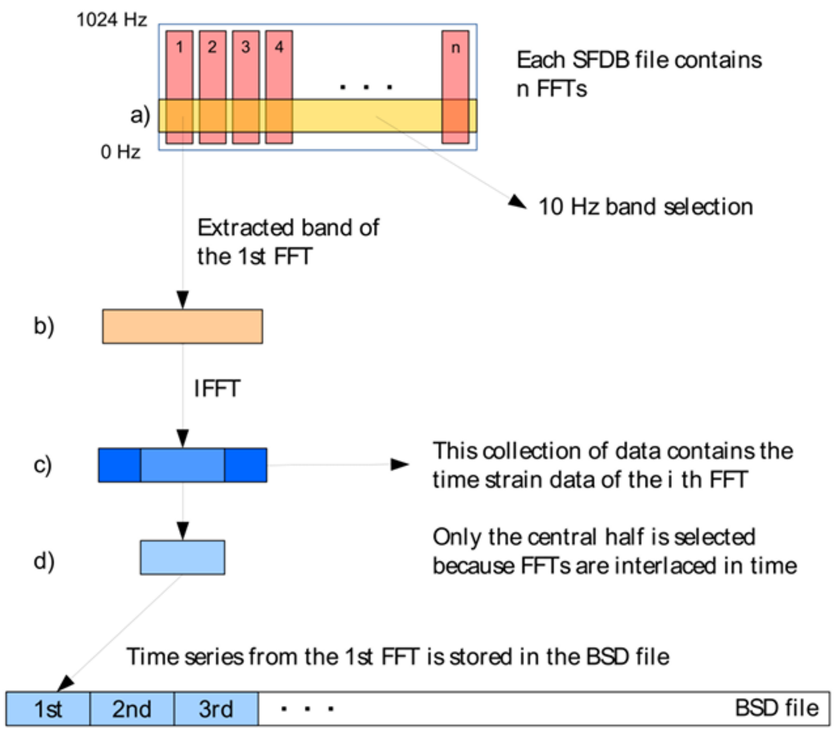


Figure from O J Piccinni et al 2019 Class. Quantum Grav. 36 015008.

Searches developed for continuous GWs are suitable to search for ULDM, given the continuous character of the signal. We are currently developing a spin-2 ULDM search using LIGO-Virgo-KAGRA data and the Band Sampled Data (BSD) analysis framework (O J Piccinni et al 2019 Class. Quantum Grav. 36 015008).

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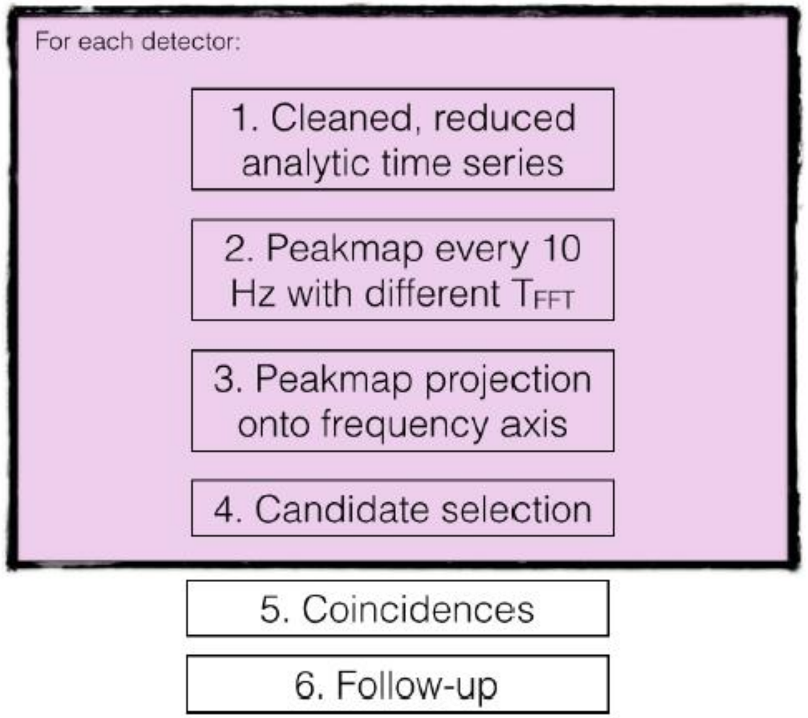

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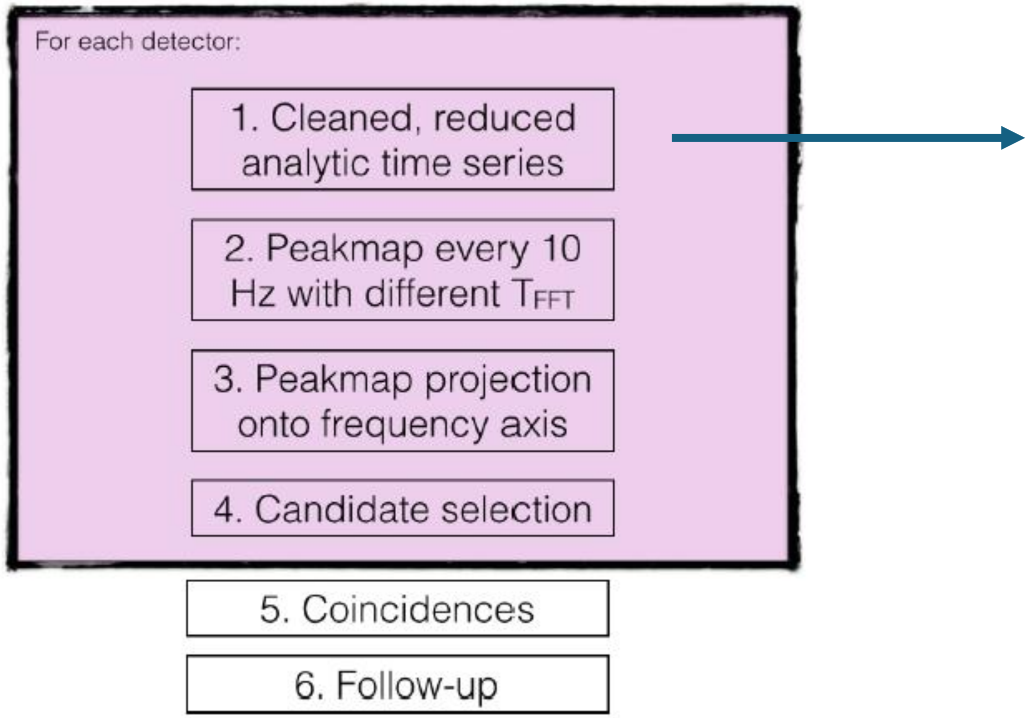
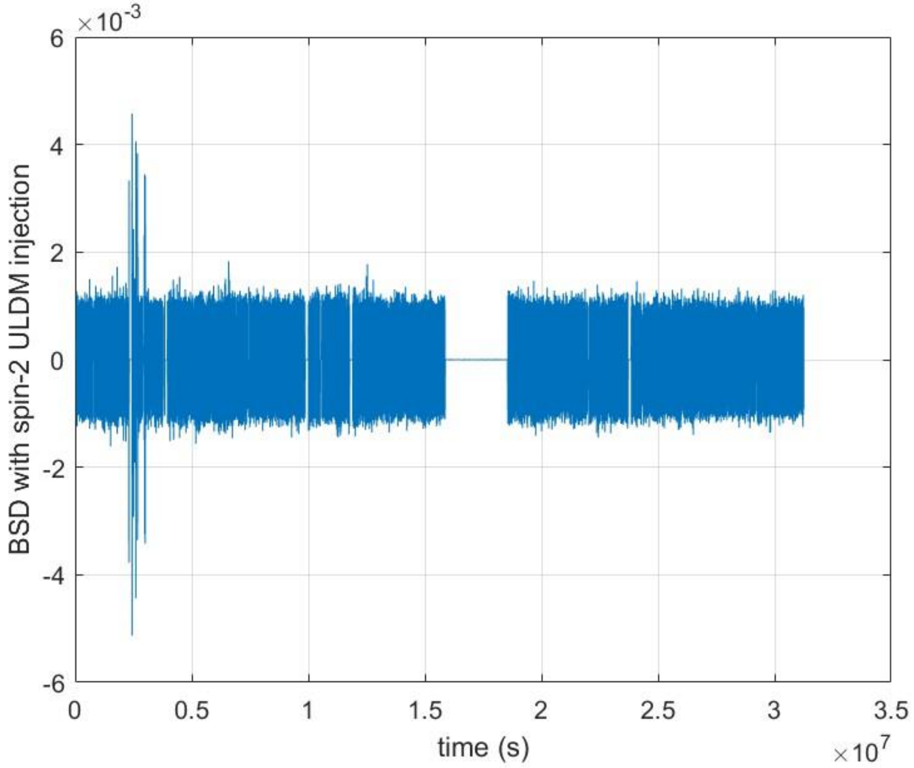
The semi-coherent search developed for continuous GWs has already been successfully adapted to the case of spin-1 ULDM (Phys. Rev. D 103, 103002, Andrew L. Miller et al).

Figure from Phys. Rev. D 103, 103002, Andrew L. Miller et al.

Spin-2 ULDM search in LVK (ongoing)





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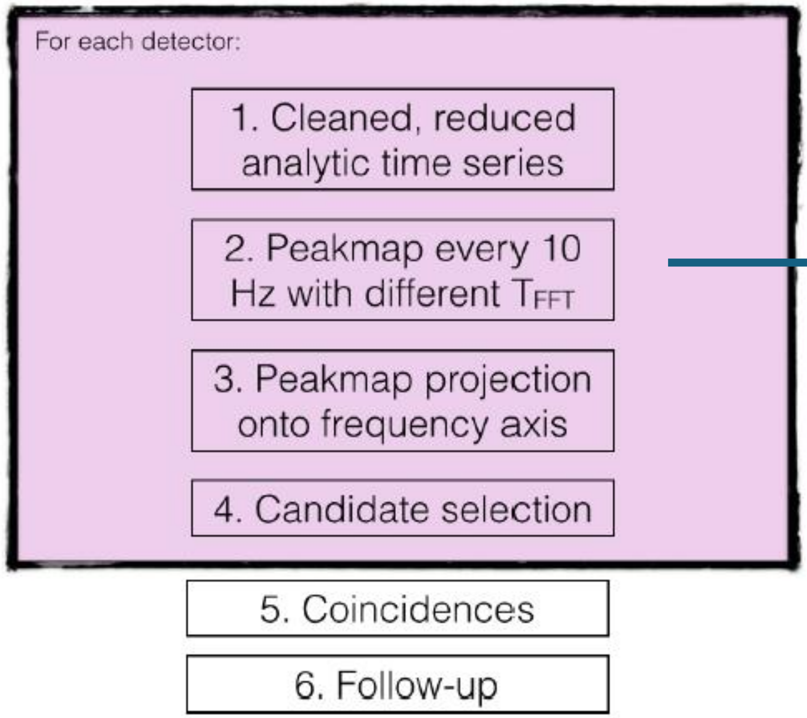


$$\delta f = 1/T_{\mathrm{FFT}}$$

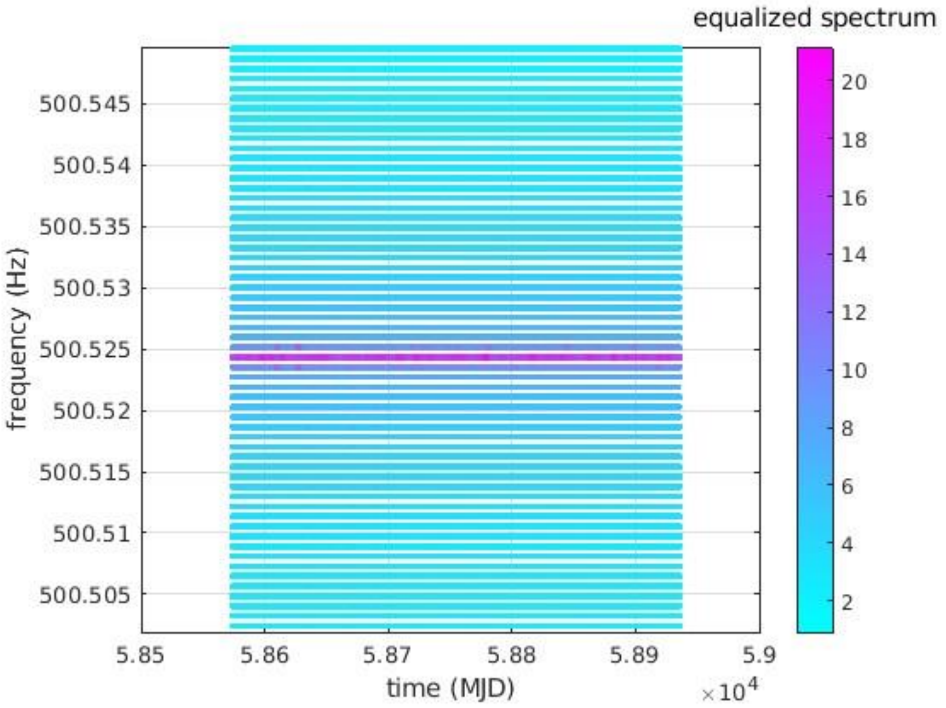


Figure from Phys. Rev. D 103, 103002, Andrew L. Miller et al.

1 at frequencies where the power in the equalized spectrum exceeds a threshold at a specific time; 0 otherwise.

Spin-2 ULDM search in LVK (ongoing)

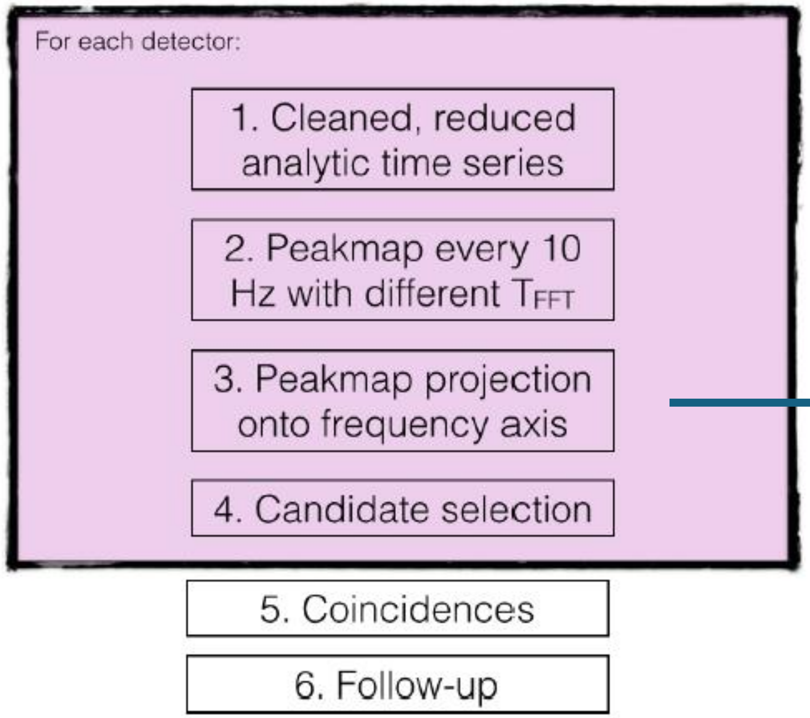


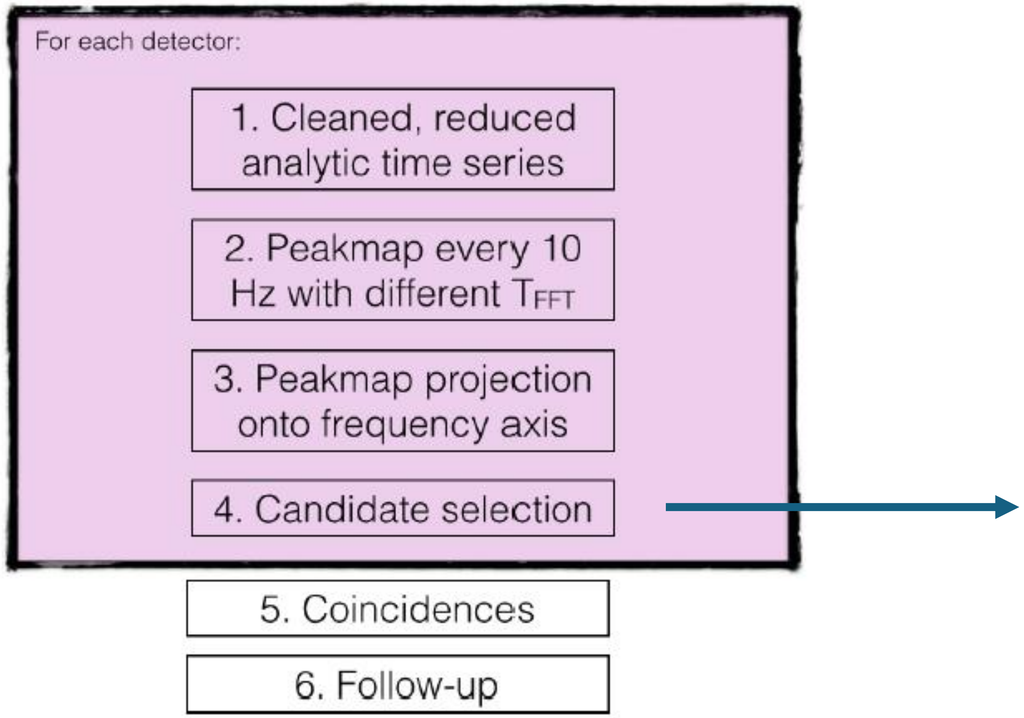
Figure from Phys. Rev. D 103, 103002, Andrew L. Miller et al.

Project the peakmap onto frequency and compute the critical ratio (significance of each candidate):

$$CR = \frac{y - \mu}{\sigma}$$

- y: # peaks in bin
- μ: median of peaks across band
- σ: std of peaks across band

Spin-2 ULDM search in LVK (ongoing)



FAP shows how compatible the candidate is with noise:

$$FAP = \frac{1}{2}\, erfc(CR/\sqrt{2})$$

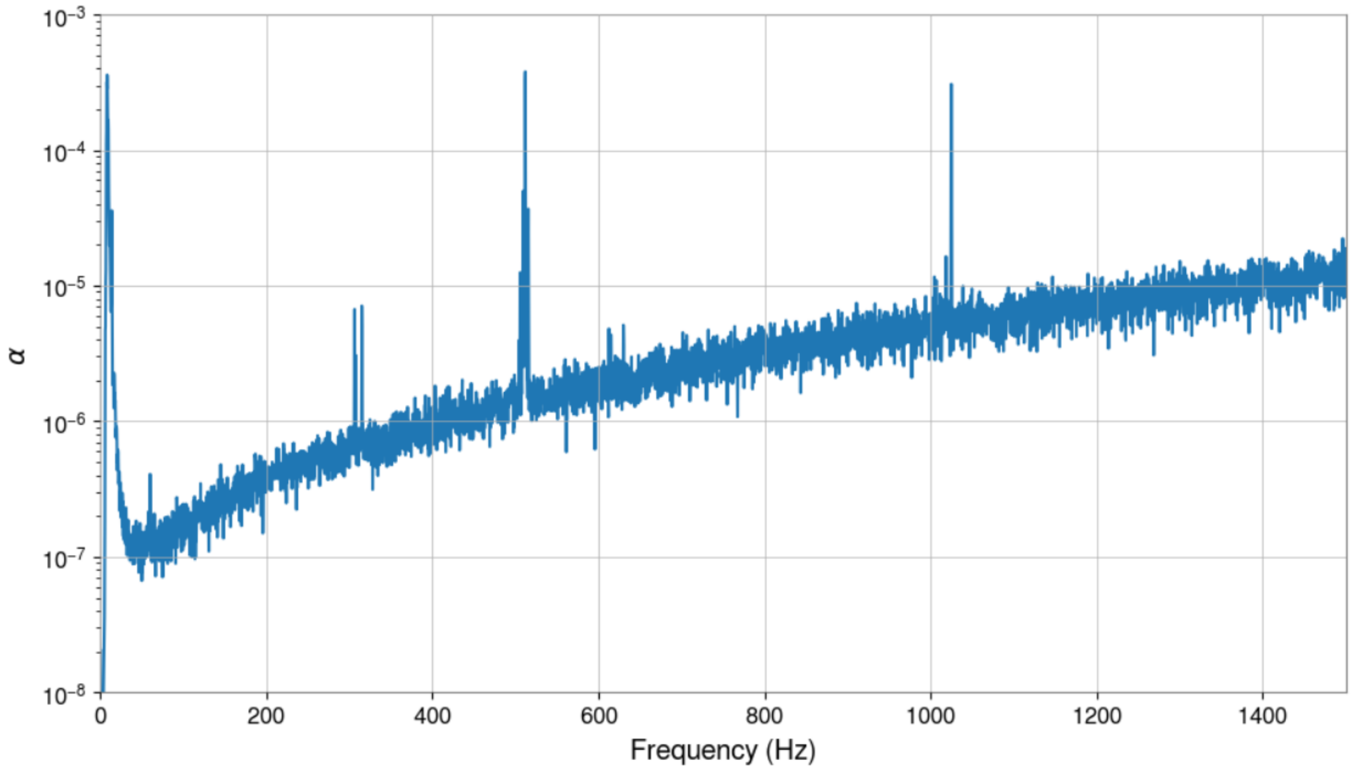
Figure from Phys. Rev. D 103, 103002, Andrew L. Miller et al.

Theoretical sensitivity: $$h_{0,\mathrm{opt}} \propto \sqrt{\frac{S_n(f)}{T_{\mathrm{FFT,max}}}}\sqrt{CR_{\mathrm{thr}} - \sqrt{2}\mathrm{erfc}^{-1}(2\Gamma)}$$

See JCAP04(2021)053, Juan Manuel Armaleo, Diana López Nacir, Federico R. Urban.

Detector PSD

C.L.



For LIGO O3 Livingston, 95% confidence level

Concluding remarks

- Spin-2 ULDM interacts with GW detectors and can be probed by LVK;
- The signal is continuous, with 1 or 2 peaks in frequency domain. This might allow us to distinguish between ULDM and continuous GWs;
- Spin-1 and spin-2 signals have different peak separations in frequency domain, which is only visible for low frequencies.
- LIGO's sensitivity allows us to constrain the coupling of spin-2 DM to the standard model up to ~1e-5 – 1e-7;
- Spin-2 search ongoing ☺

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Thank you!