DIRECT SCALAR FIELD DARK MATTER SEARCH WITH LIGO

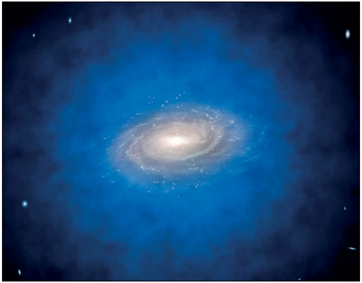
Joint APP, HEPP, and NP conference

10th April 2024 | **Alexandre Göttel** | Gravity exploration Institute — Cardiff University

Scalar field dark matter

Weakly coupled low-mass dark matter could originate in the early universe and manifest as coherently oscillating field:

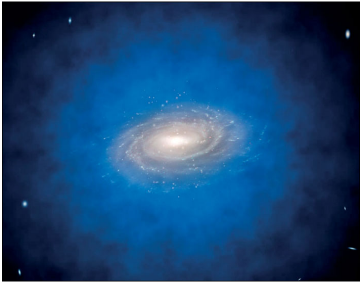
$$\Phi(t, \mathbf{r}) = \Phi_0 \cos(\omega_\Phi t - \mathbf{k} \cdot \mathbf{r})$$



Scalar field dark matter

Weakly coupled low-mass dark matter could originate in the early universe and manifest as coherently oscillating field:

$$\Phi(t, \mathbf{r}) = \Phi_0 \cos(\omega_\Phi t - \mathbf{k} \cdot \mathbf{r})$$



DM virialised in a galactic halo: Dopper broadening → finite coherence time

$$\frac{\delta\omega}{\omega} \approx 10^{-6}$$

Expected signal

Field couples to the electromagnetic field tensor and fermion masses:

$$\mathcal{L} \supseteq \frac{\Phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\Phi}{\Lambda_e} m_e \bar{\Psi}_e \Psi_e$$

$\rightarrow$ DM changes the value of the fine structure constant α and of the electron rest mass m_e

Expected signal

Field couples to the electromagnetic field tensor and fermion masses:

$$\mathcal{L} \supseteq \frac{\Phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\Phi}{\Lambda_e} m_e \bar{\Psi}_e \Psi_e$$

→ **DM changes the value of the fine structure constant α and of the electron rest mass m_e**

→ This effectively changes the sizes and refractive indices of solids

$$a_0 = \frac{1}{m_e \alpha}$$

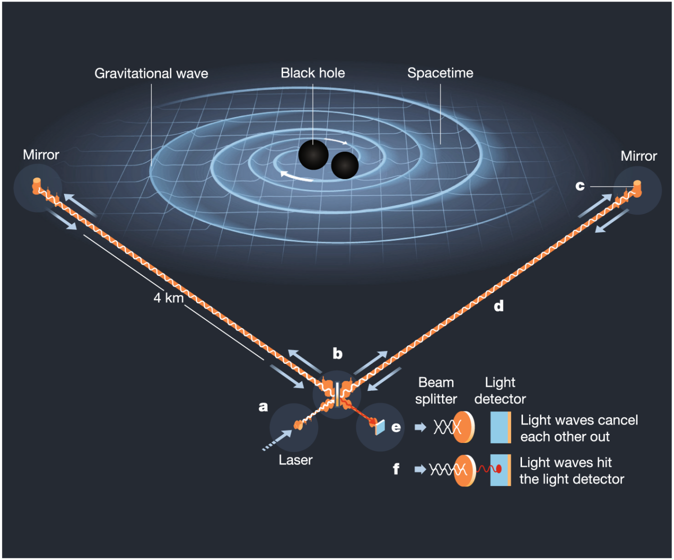
LIGO

Laser Interferometer Gravitational-wave Observatory

- Dual-recycled Fabry-Pérot Michelson Interferometer
- Two detectors, 3000 km apart
- Sensitive to **length differences** of less than a **proton radius**
- For details see G. Hammond's Tuesday talk!

LIGO

Laser Interferometer Gravitational-wave Observatory



DM coupling in LIGO

Why do we see DM?

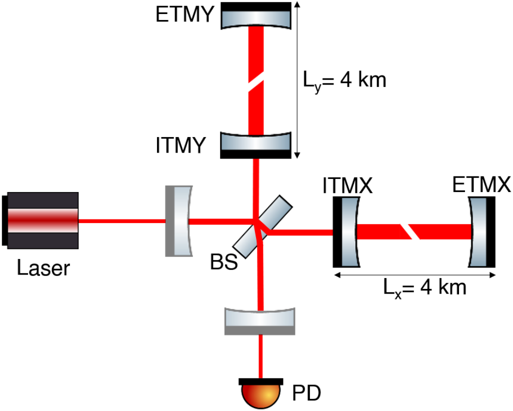
DM “size” effect only:

- **Beamsplitter**

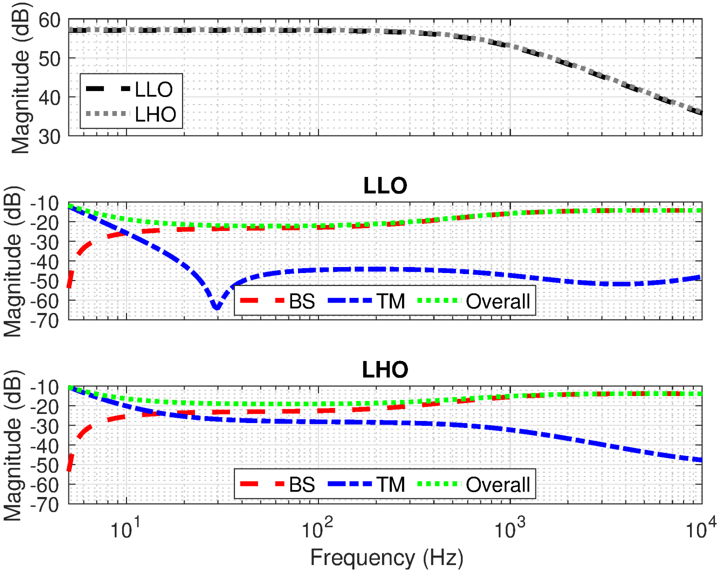
  Splitting occurs far from centre of mass

- **Test masses**

  Asymmetry from thickness differences



GW vs DM transfer functions



Data analysis principle

Data-driven spectral analysis:

- Optimal frequency binning as signal width: $\frac{\delta\omega}{\omega} \approx 10^{-6}$
- Logarithmically spaced frequency bins

- Analysing 400 h of LIGO data would take 2 yr @128 cores (or $\approx$ 100 t of CO_2)
  - → Prohibitive costs

Borrowing from music theory?

LPSD's main calculation:

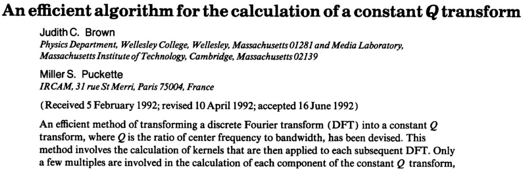
$$\sum_{n=0}^{N_j-1} x_n \cdot w_{n,j} e^{-2\pi i Q/N_j n}$$

Parseval's theorem:

$$\sum_{n=0}^{N-1} x_n y_n^* = \frac{1}{N} \sum_{k=0}^{N-1} X_k Y_k^*$$

Results:

- $\gtrsim 2 \cdot 10^4$ speed-up
- 1500 h of data analysed in hours



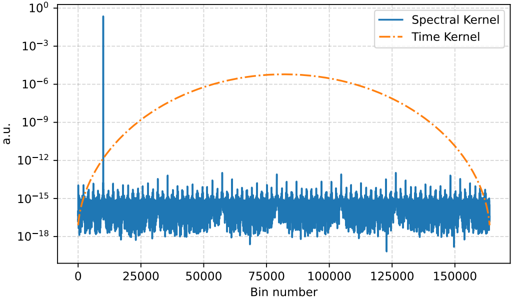
An efficient algorithm for the calculation of a constant Q transform

Judith C. Brown
Physics Department, Wellesley College, Wellesley, Massachusetts 01281 and Media Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

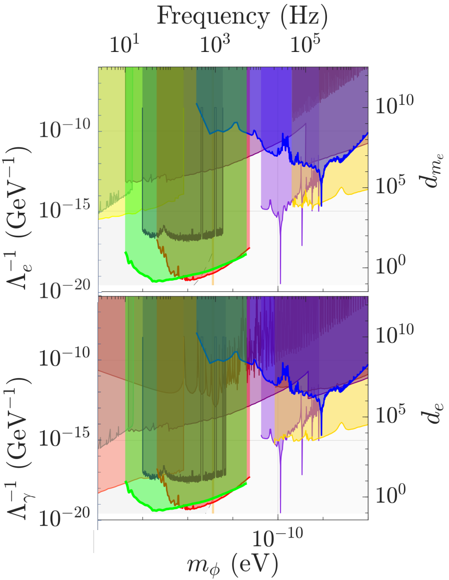
Miller S. Puckette
IRCAM, 31 rue St Merri, Paris 75004, France

(Received 5 February 1992; revised 10 April 1992; accepted 16 June 1992)

An efficient method of transforming a discrete Fourier transform (DFT) into a constant Q transform, where Q is the ratio of center frequency to bandwidth, has been devised. This method involves the calculation of kernels that are then applied to each subsequent DFT. Only a few multiples are involved in the calculation of each component of the constant Q transform,



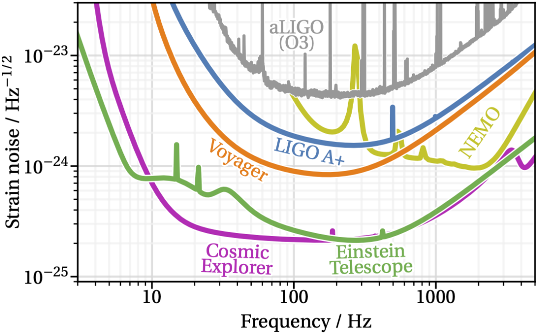
Results



- Our results in green
- Up to x1000 improvement below 180 Hz
- Competitive up to 5 kHz

Outlook

- Already world-leading in mass range
- Directed mirror thickness change studies?
- Directly applicable to next-gen detectors



Questions?

Thank you for your attention!

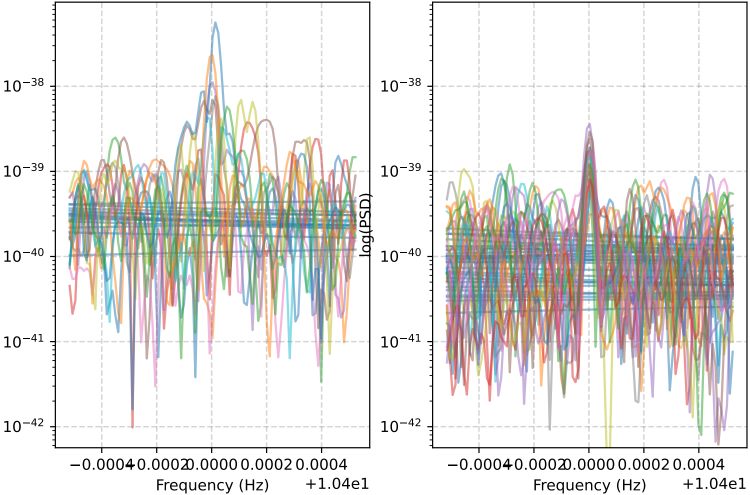
Alexandre S. Göttel

gottela@cardiff.ac.uk

- Aldo Ejlli
- Kanioar Karan
- Sander M. Vermeulen
- Lorenzo Aiello
- Vivien Raymond
- Hartmut Grote

$10.4\,\mathrm{Hz}$: our best candidate

LHO vs LLO data



Calibrated strain

Available strain data is calibrated to **gravitational waves**:

$$h(\omega) = \frac{I_{\mathsf{PD}}(\omega)}{L\, \mathrm{T}_{\mathrm{GW}}(\omega)\, e^{i\phi_{\mathrm{GW}}}}$$

We are instead interested in **DM-induced strain**:

$$s_{\mathrm{DM}}(\omega) = \frac{I_{\mathsf{PD}}(\omega)}{\left|n\, t_{\mathsf{B}} \mathrm{T}_{\mathrm{B}} e^{i\phi_{\mathrm{B}}} + t_{\mathsf{M}} \mathrm{T}_{\mathrm{M}} e^{i\phi_{\mathrm{M}}}\right|}$$

Profile likelihood ratio search

q_0: Look for positive signals

$$q_0 = \begin{cases} -2\ln \frac{\mathcal{L}(0,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})} & \text{if } \hat{\mu} \geq \mu \\ 0 & \text{if } \hat{\mu} < \mu \end{cases}$$

q_μ: Determine upper limits

$$q_\mu = \begin{cases} -2\ln \frac{\mathcal{L}(\mu,\hat{\hat{\theta}})}{\mathcal{L}(\hat{\mu},\hat{\theta})} & \text{if } \hat{\mu} \leq \mu \\ 0 & \text{if } \hat{\mu} > \mu \end{cases},$$