Intensity Interferometry for Ultralight Bosonic Dark Matter Detection

Grzegorz Łukasiewicz (GNOME Team in Kraków)

15.08.2022

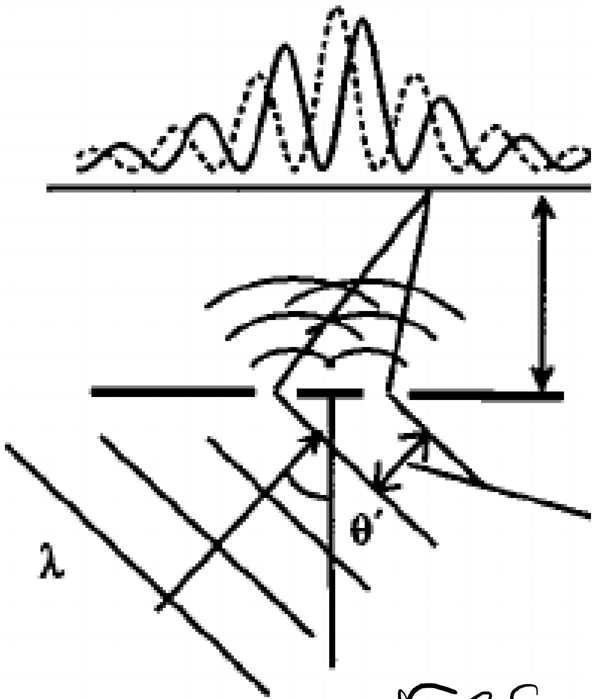
MITP Workshop on Searches for Wave-Like Dark Matter with Quantum Networks

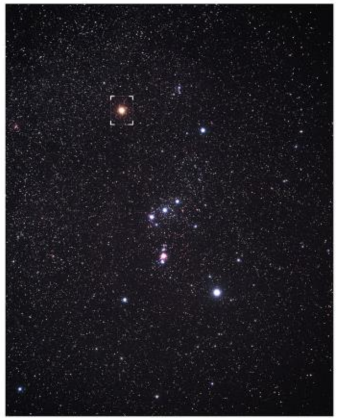
Outline

- A little bit of history
- GNOME as DM intensity interferometer → Expected signals → Sensitivity estimation
- Toy model → Exclusion plot

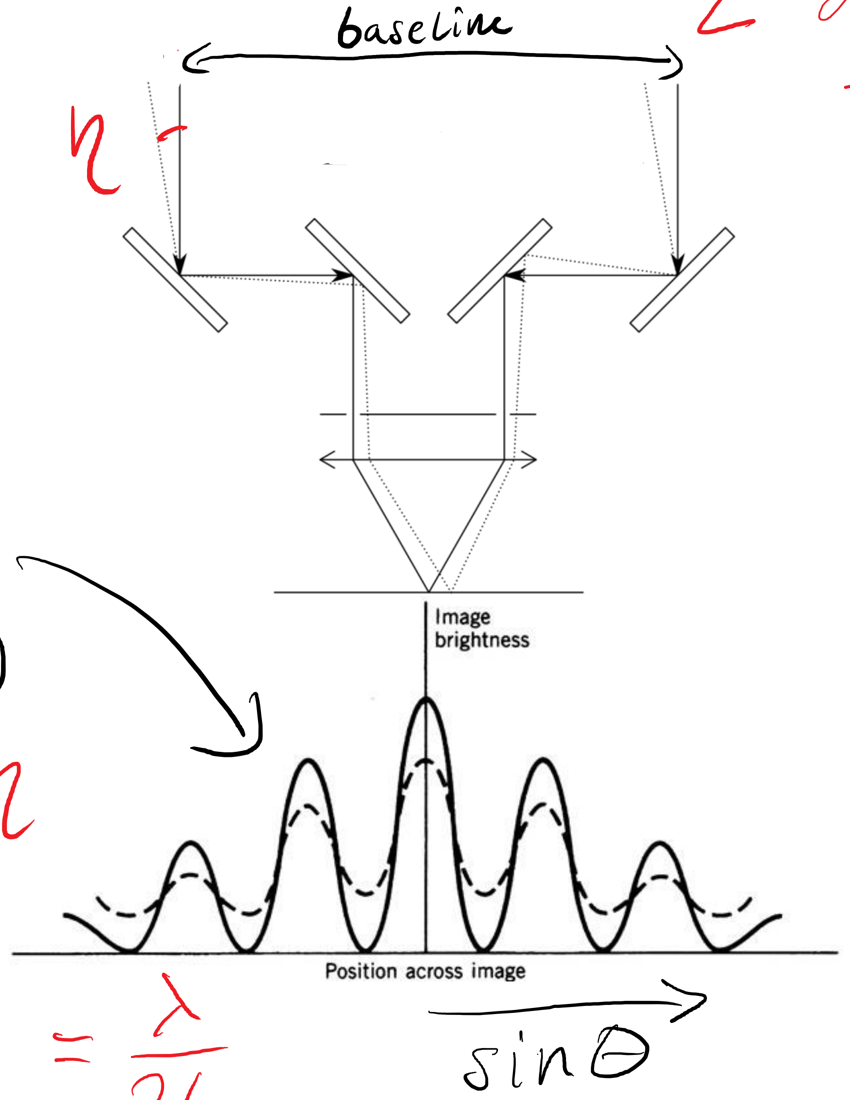
How to Measure Angular Diameter of a Star?

incident wave at an angle





2 distant sources



visibility (contrast)

$\sim \cos \frac{\pi b \eta}{\lambda}$

resolution: $\Delta\eta = \frac{\lambda}{2b}$

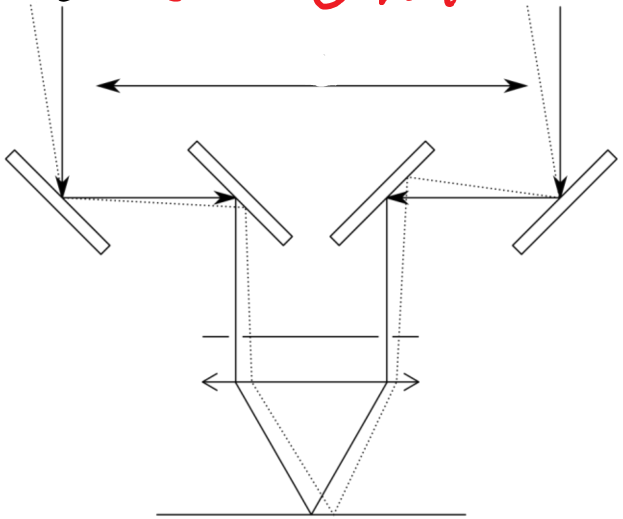
Michelson Stellar Interferometer = Amplitude Interferometer

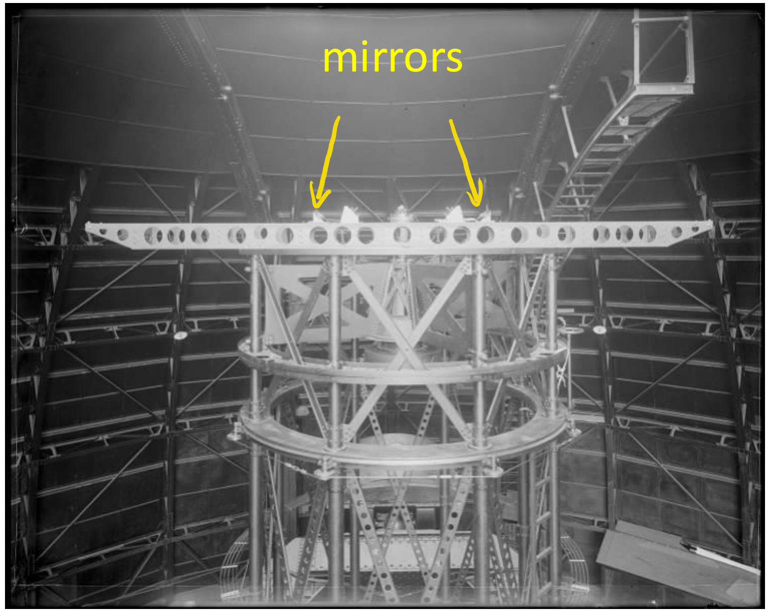
Betelguese angular diameter

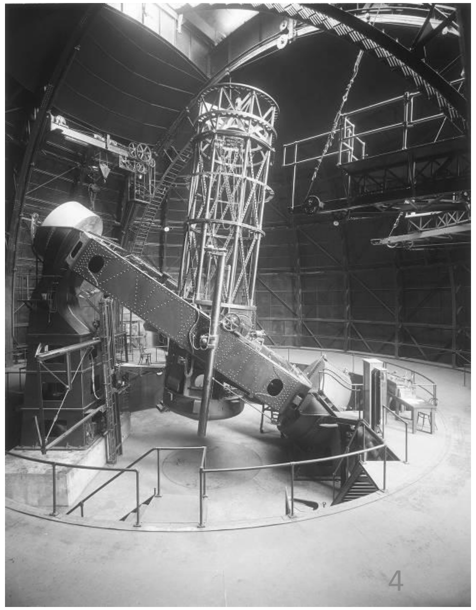
measuremet in 1920 $2{,}3 \cdot 10^{-7}\,\mathrm{rad}$

$\lambda = 575\,\mathrm{nm}$

$b \approx 3\,\mathrm{m}$







Amplitude Interferometer Limitations

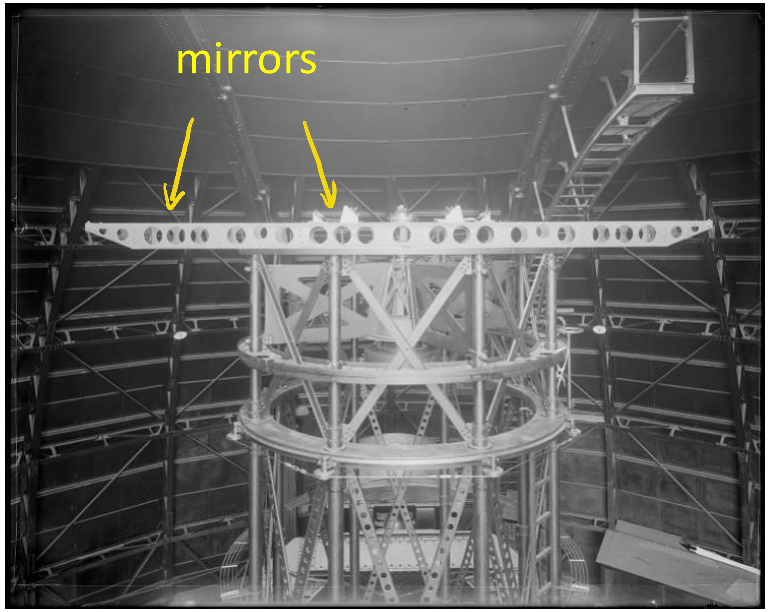
Phase stability in atmosphere and telescope

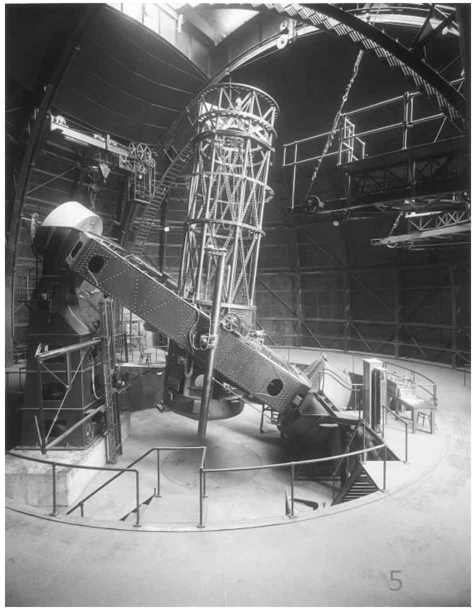
RF astronomy in 1950's

Long baselines needed

RF signals can travel in cables

$\Delta\eta = \frac{\lambda}{2b}$





Intensity (Hanbury-Brown-Twiss) Interferometer

Apparent Angular Sizes of Discrete Radio Sources: Observations at Jodrell Bank, Manchester R. Hanbury Brown, et al, Nature **(1952)**

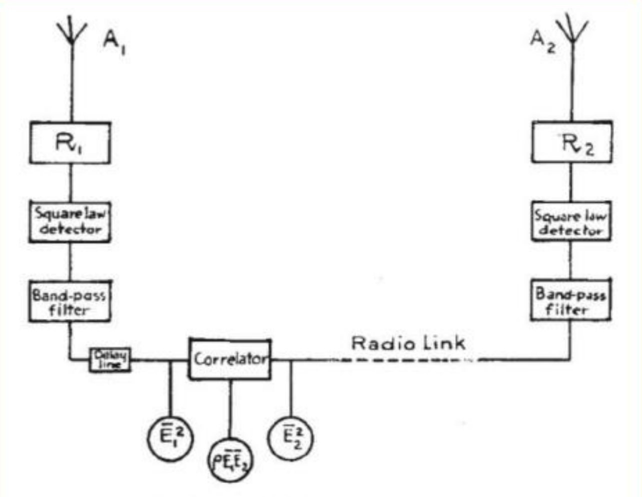


Fig. 1. Schematic diagram of the equipment

The theory of the instrument is involved, and it will be given in detail elsewhere[7]. It can be shown that the value of the cross-correlation coefficient (ρ) is given by an expression similar to that for the visibility of the fringes in a Michelson stellar interferometer :

R. Hanbury Brown & R.Q. Twiss LXXIV. A new type of interferometer for use in radio astronomy, The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science, 45:366, 663-682 **(1954)**

LXXIV. *A New Type of Interferometer for Use in Radio Astronomy*

By R. Hanbury Brown
Jodrell Bank Experimental Station, Cheshire
and
R. Q. Twiss
Services Electronics Research Laboratory, Baldock, Herts.*

[Received March 20, 1954]

Summary

A new type of interferometer for measuring the diameter of discrete radio sources is described and its mathematical theory is given. The principle of the instrument is based upon the correlation between the rectified outputs of two independent receivers at each end of a baseline, and it is shown that the cross-correlation coefficient between these outputs is proportional to the square of the amplitude of the Fourier transform of the intensity distribution across the source. The analysis shows that it should be possible to operate the new instrument with extremely long baselines and that it should be almost unaffected by ionospheric irregularities.

Intensity Interferometry

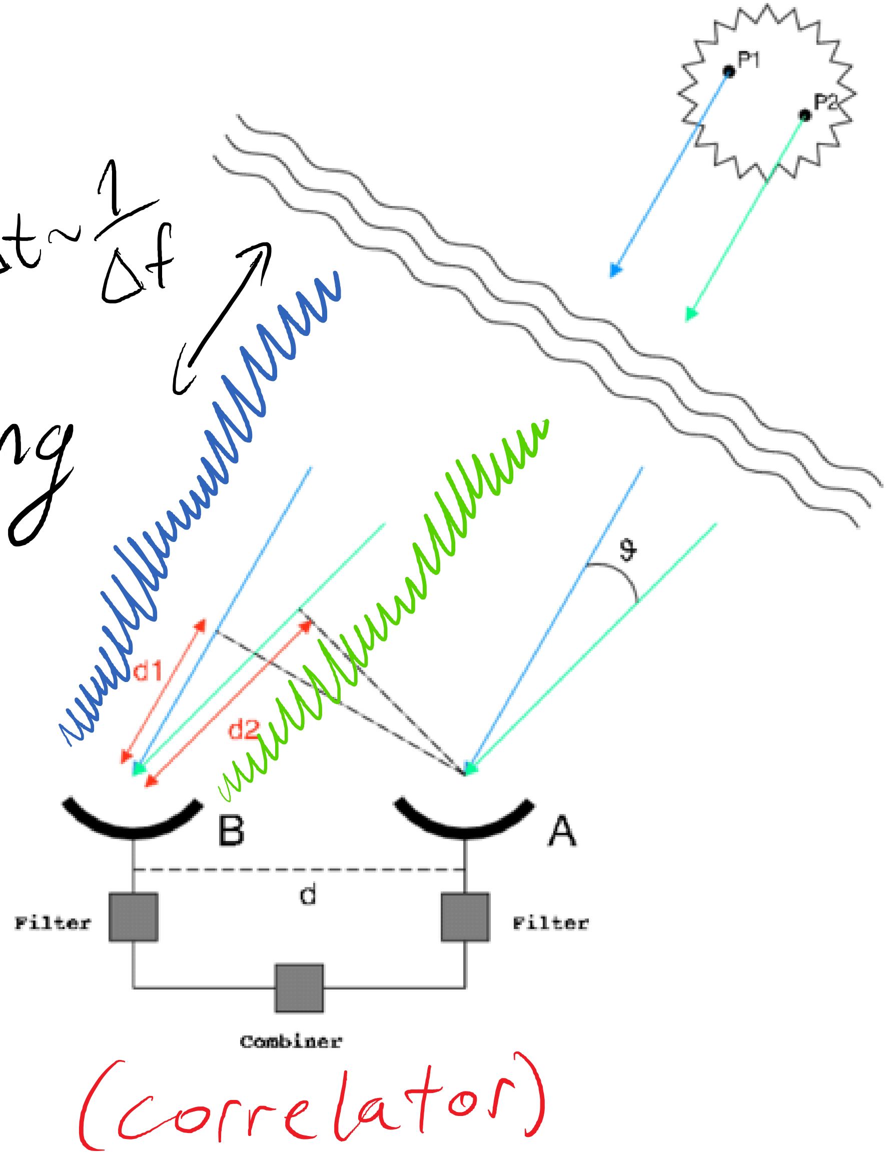
Intensity detectors

Phase is lost

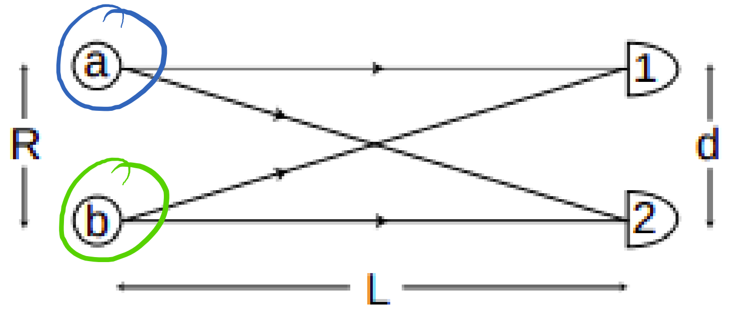
Narrow bandwidth → beating

$$C = \frac{\langle I_A I_B \rangle}{\langle I_A \rangle \langle I_B \rangle}$$

$\Delta t \sim \frac{1}{\Delta f}$



How does it work?



$$A_1 = \frac{1}{L}\left(\alpha e^{ikr_{1a}+i\phi_a} + \beta e^{ikr_{1b}+i\phi_b}\right)$$

$$I_1 = \frac{1}{L^2}\left(|\alpha|^2 + |\beta|^2 + \alpha^*\beta e^{ik(r_{1b}-r_{1a})+i(\phi_b-\phi_a)} + \alpha\beta^* e^{-ik(r_{1b}-r_{1a})+i(\phi_b-\phi_a)}\right)$$

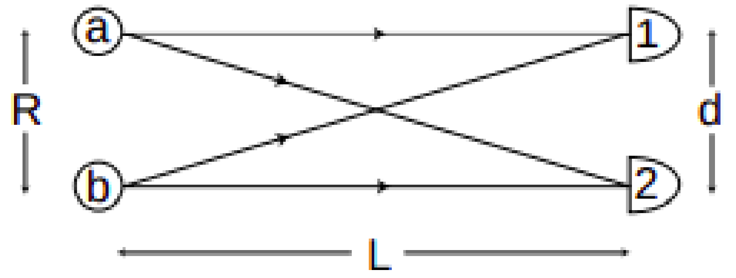
averaged over random phases

$$\langle I_1 \rangle = \langle I_2 \rangle = \frac{1}{L^2}\left(\langle|\alpha|^2\rangle + \langle|\beta|^2\rangle\right)$$

How does it work?

$$I_1 = \frac{1}{L^2}\left(|\alpha|^2 + |\beta|^2 + \alpha^*\beta e^{ik(r_{1b}-r_{1a})+i(\phi_b-\phi_a)} + \alpha\beta^* e^{-ik(r_{1b}-r_{1a})+i(\phi_b-\phi_a)}\right)$$

$$\langle I_1\rangle = \langle I_2\rangle = \frac{1}{L^2}\left(\langle|\alpha|^2\rangle + \langle|\beta|^2\rangle\right)$$

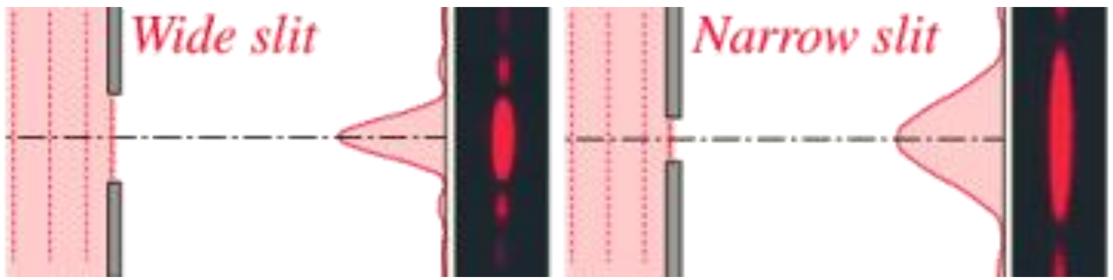


$L \gg R$

Intensity correlation depends on baseline

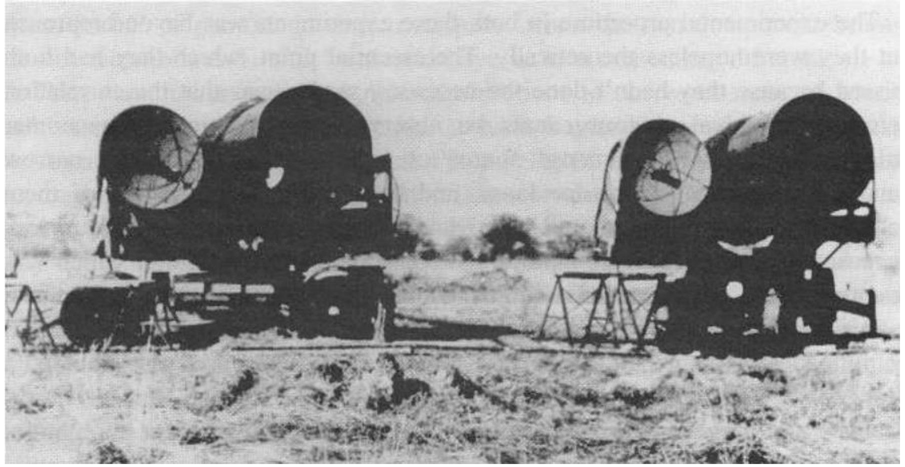
$$\langle I_1 I_2\rangle = \langle I_1\rangle\langle I_2\rangle + \frac{2}{L^4}|\alpha|^2|\beta|^2\cos\left(k\left(r_{1a}-r_{2a}-r_{1b}+r_{2b}\right)\right)$$

$$\approx \cos\left(\frac{kRd}{L}\right)$$

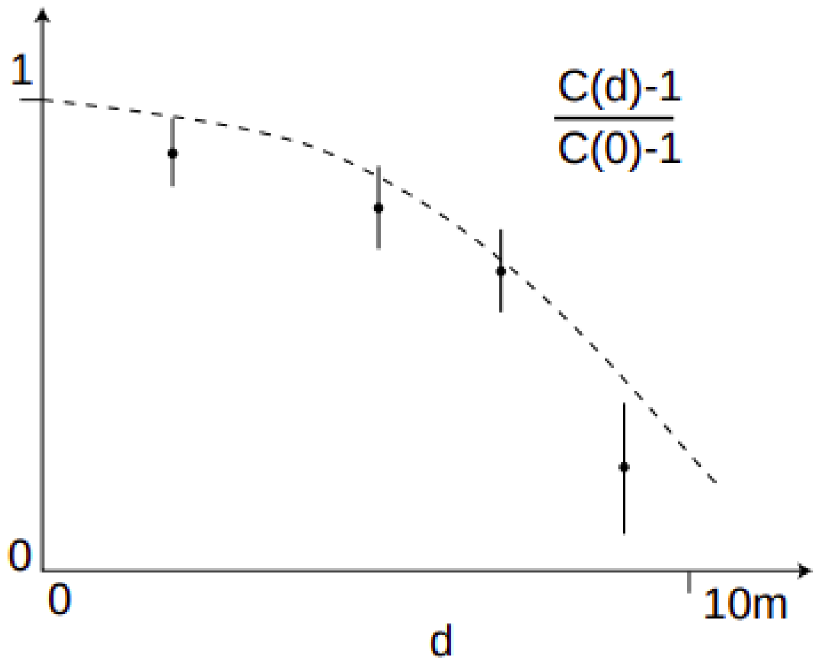


Intensity Interferometry by HBT

1956 measurement of Sirius angular diameter $3{,}1 \times 10^{-8}$ rad



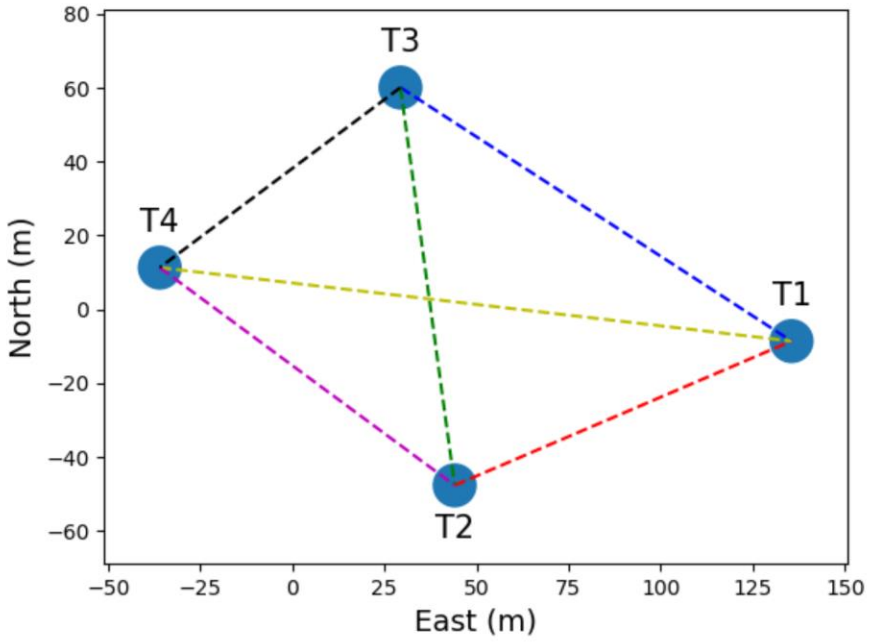
Military searchlights in Jordell Bank



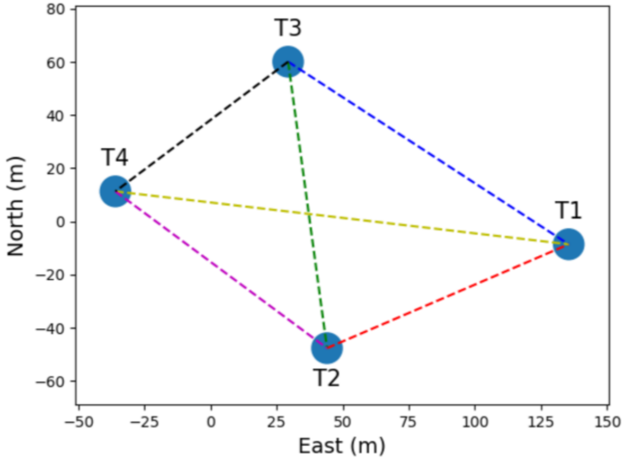
quantum optics?

Back to Present Times

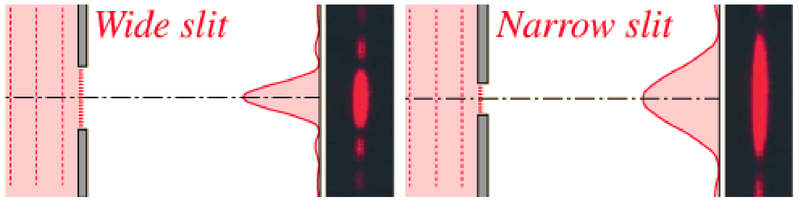
- Very Energetic Radiation Imaging Telescope Array System (VERITAS), Arizona, US



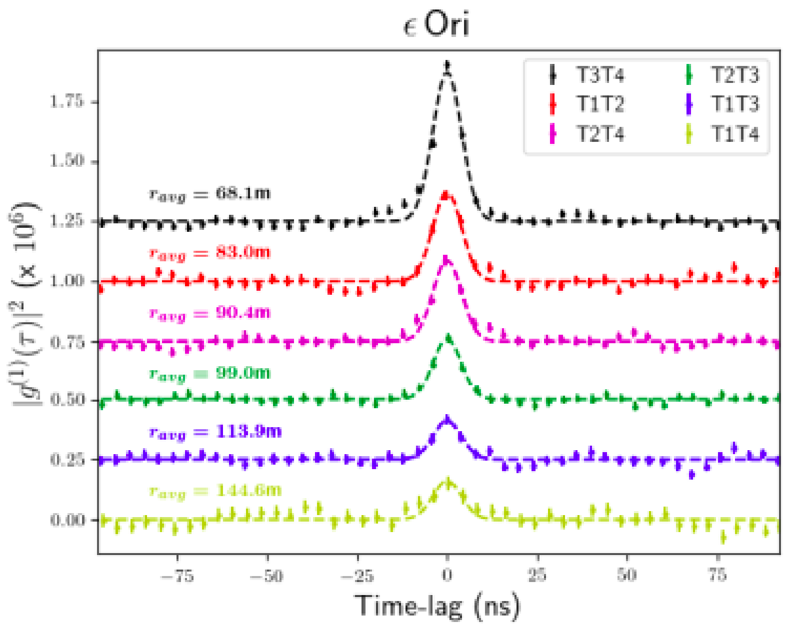
VERITAS



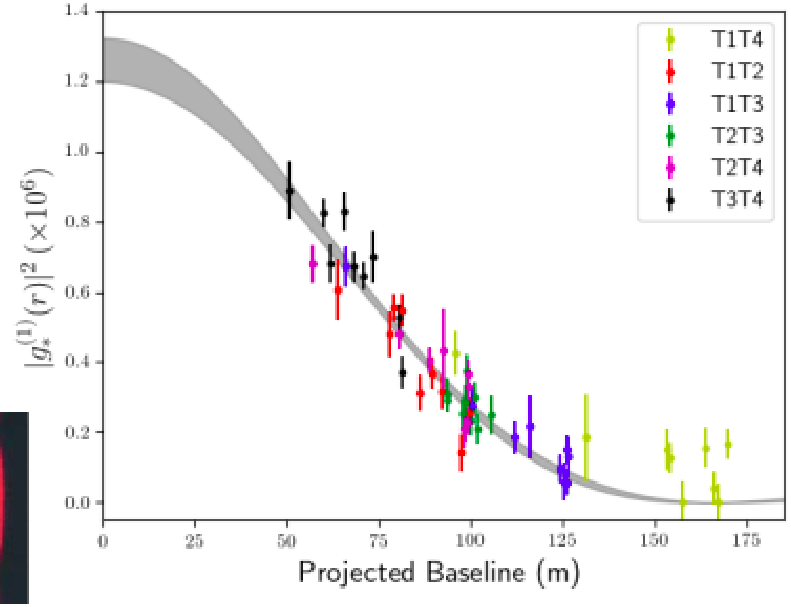
T3
T4
T1
T2
North (m)
East (m)



Wide slit
Narrow slit



ϵ Ori
T3T4
T1T2
T2T4
T2T3
T1T3
T1T4
r_{avg} = 68.1m
r_{avg} = 83.0m
r_{avg} = 90.4m
r_{avg} = 99.0m
r_{avg} = 113.9m
r_{avg} = 144.6m
$|g^{(1)}(\tau)|^2$ (x 10^6)
Time-lag (ns)



T1T4
T1T2
T1T3
T2T3
T2T4
T3T4
$|g_*^{(1)}(\tau)|^2$ ($\times 10^6$)
Projected Baseline (m)

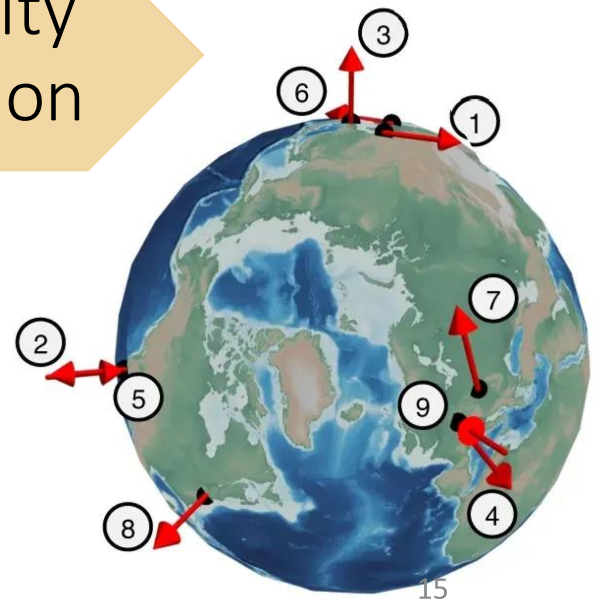
Dark Matter Intensity Interferometer?

A little bit of history

Intensity interferometry for ultralight bosonic dark matter detection, H. Masia-Roig et al., arXiv:2202.02645 (2022)

GNOME as DM intensity interferometer → Expected signals → Sensitivity estimation

Toy model → Exclusion Plot



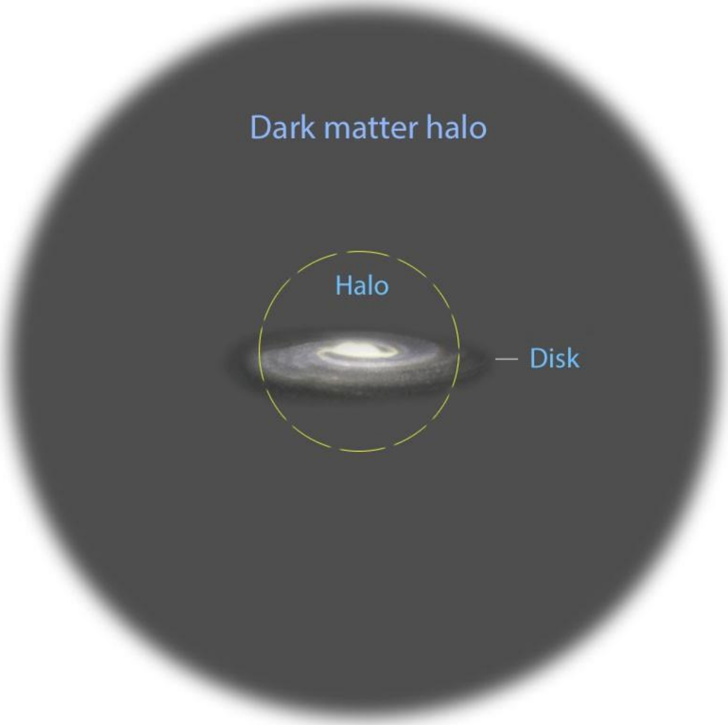
Ultralight DM

- Single particle – plain wave
- Superposition
- Virialization of DM in the galactic halo

$$\omega_n = \omega_c\left(1 + \frac{v_n^2}{2c^2}\right)$$

$$v_0 \simeq 220 \frac{km}{s}$$

Narrow bandwidth



Milky Way model

Stochastic Fluctuations of Dark Matter Field

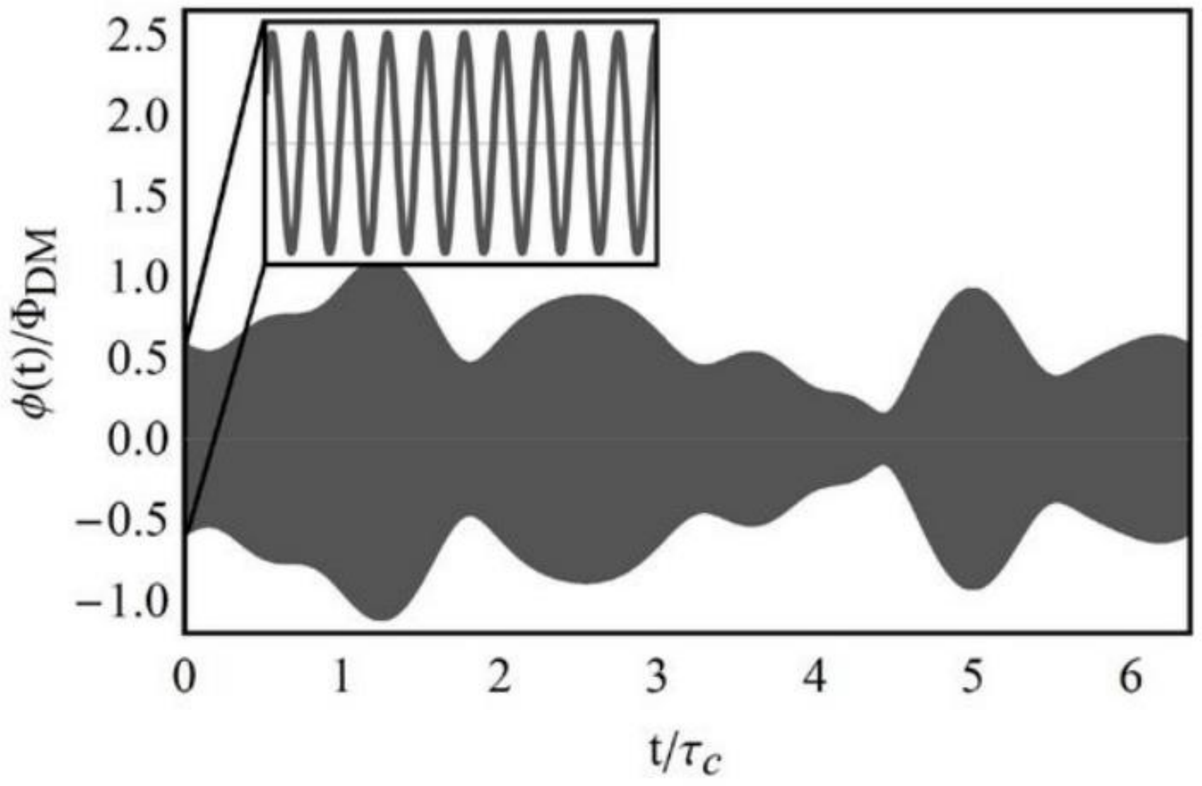
$$\cos(\omega_1 t) + \cos(\omega_2 t) = 2\cos\left(\frac{\omega_1 - \omega_2}{2} t\right)\cos\left(\frac{\omega_1 + \omega_2}{2} t\right)$$

$\sim \Delta\omega$ $\qquad\qquad$ $\sim 2\omega_c$

Stochastic Fluctuations of Dark Matter Field

$$\varphi(\vec{r},t) \sim \sum_n \cos(\omega_n t - \vec{k}_n \vec{r} + \theta_n)$$

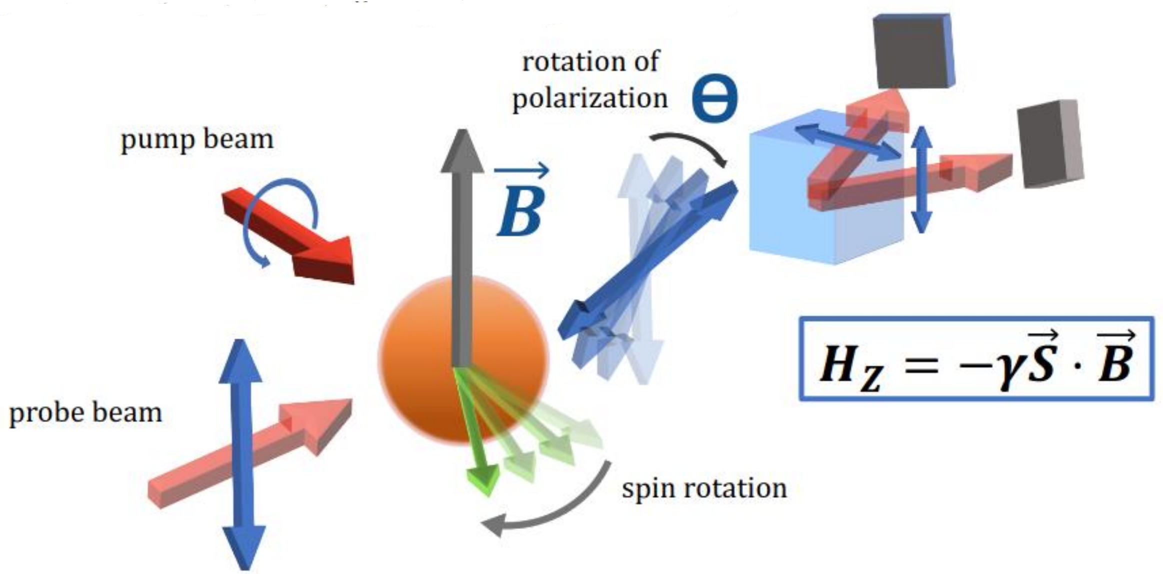
beating $\tau_c \sim \frac{1}{\Delta\omega}$



Intensity Detector - Magnetometer

Quadratic coupling

$$H_\varphi \sim \frac{2\hbar^2 c^2}{f_q^2} \vec{S} \cdot \vec{\nabla} \varphi^2(\vec{r}, t)$$



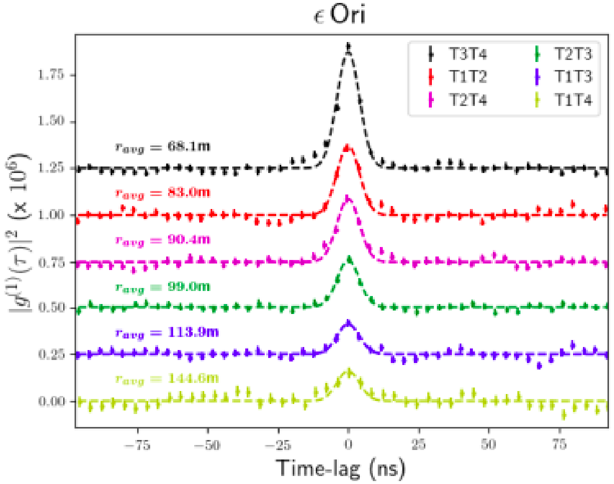
Sensitivity < pT
100 Hz bandwidth

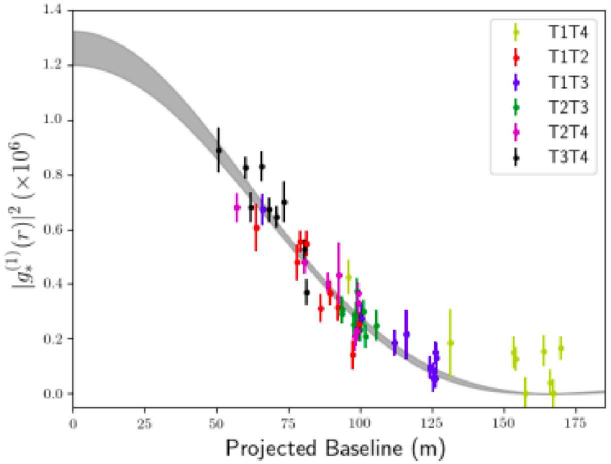
Why quadratic coupling?

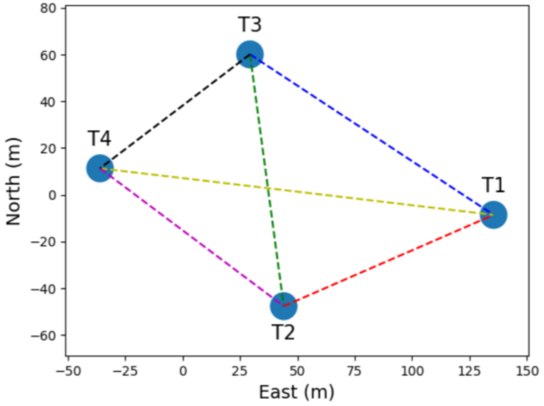
GNOME (simulation)

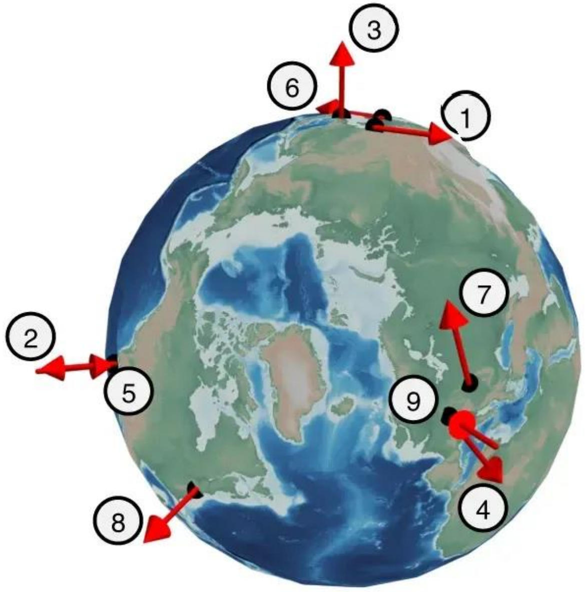
DM Signature = Correlation

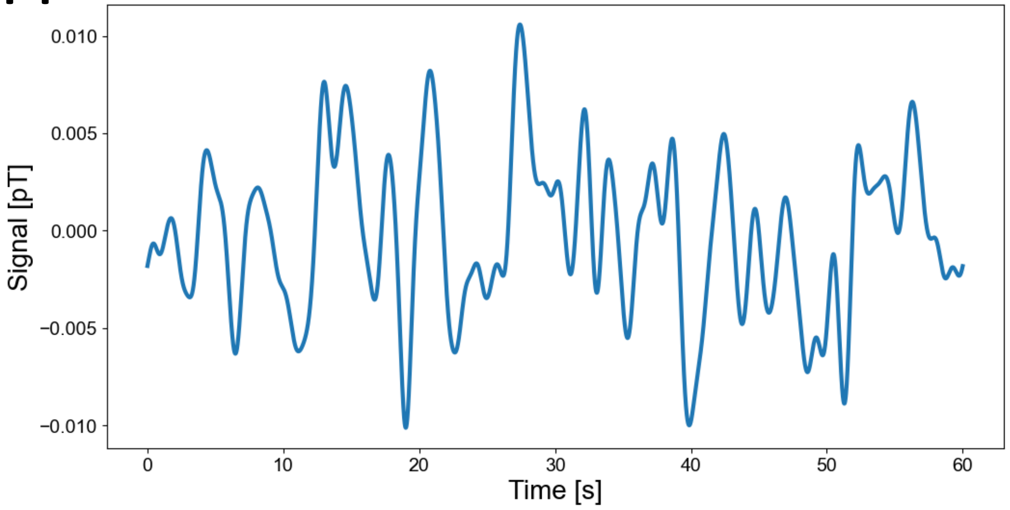
VERITAS

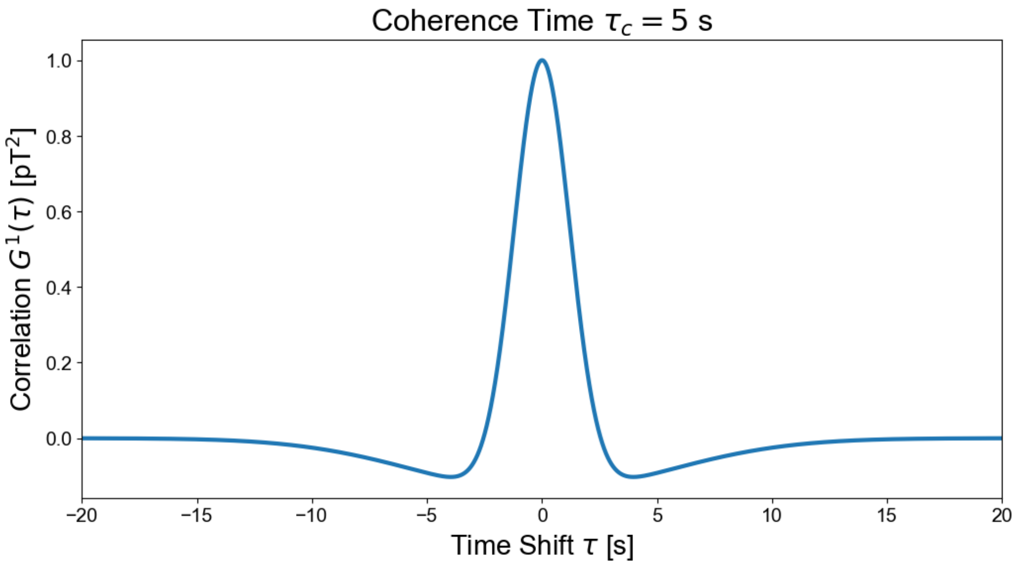








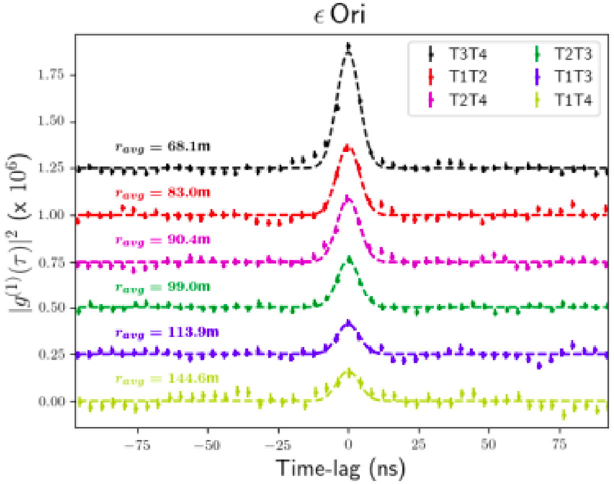


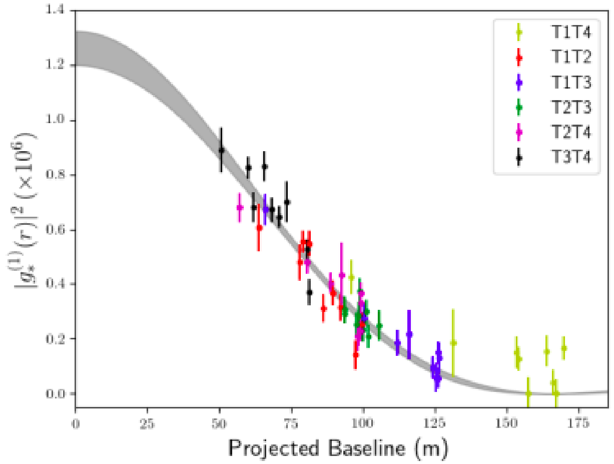


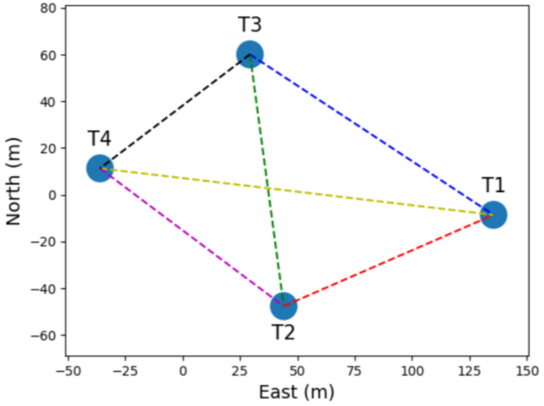
GNOME (simulation)

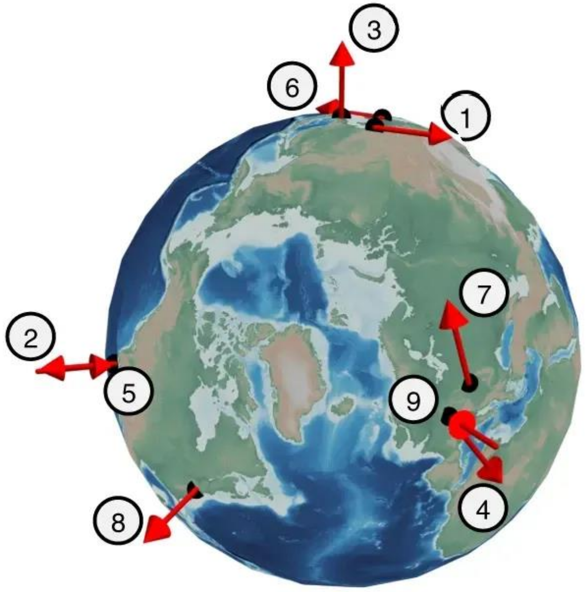
DM Signature = Correlation

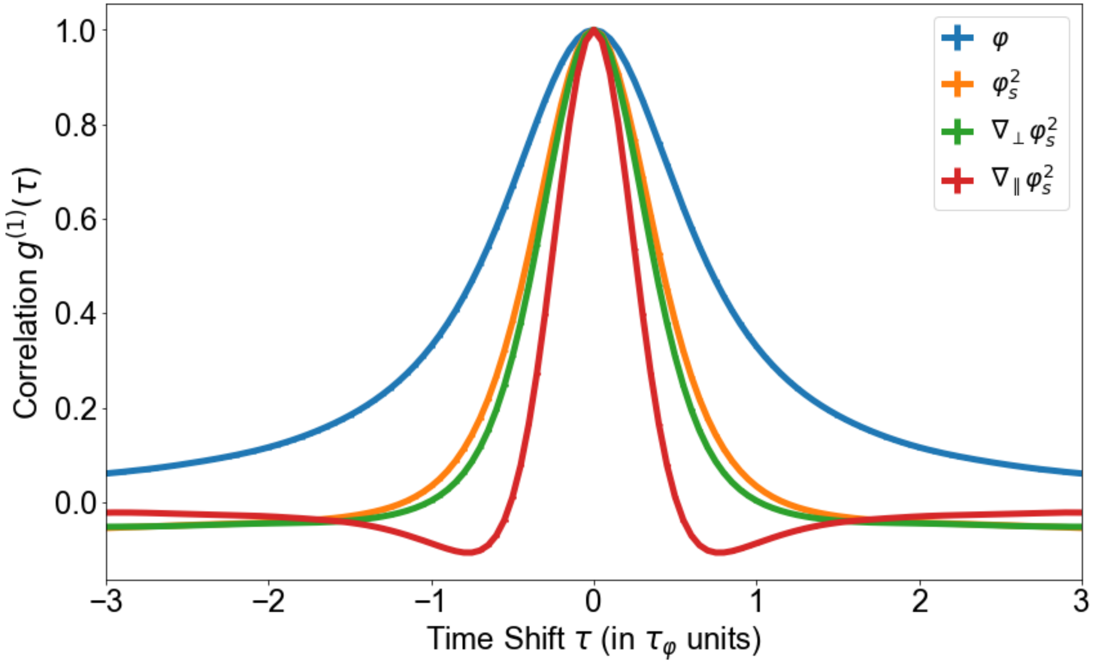
VERITAS









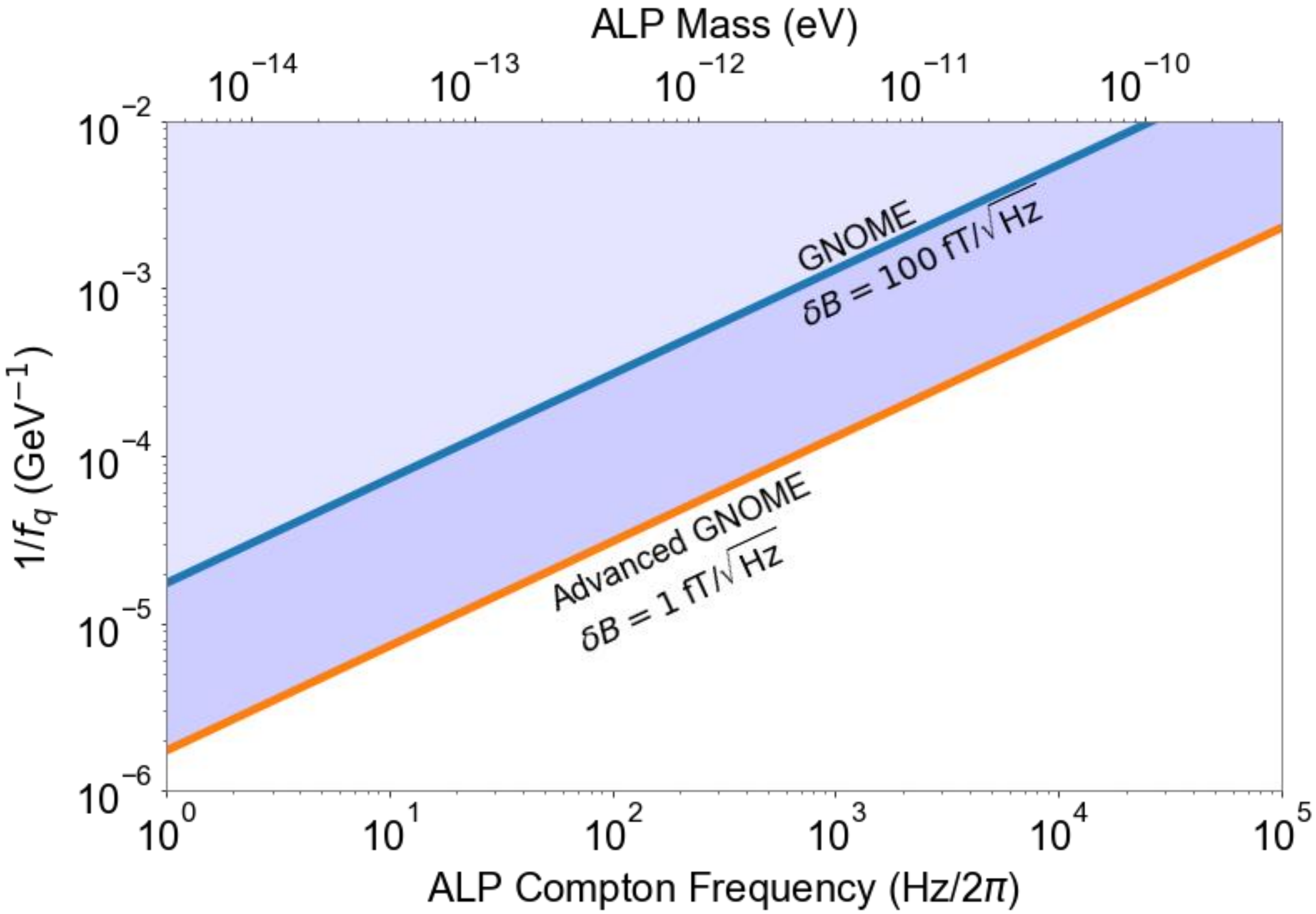


Sensitivity Estimation

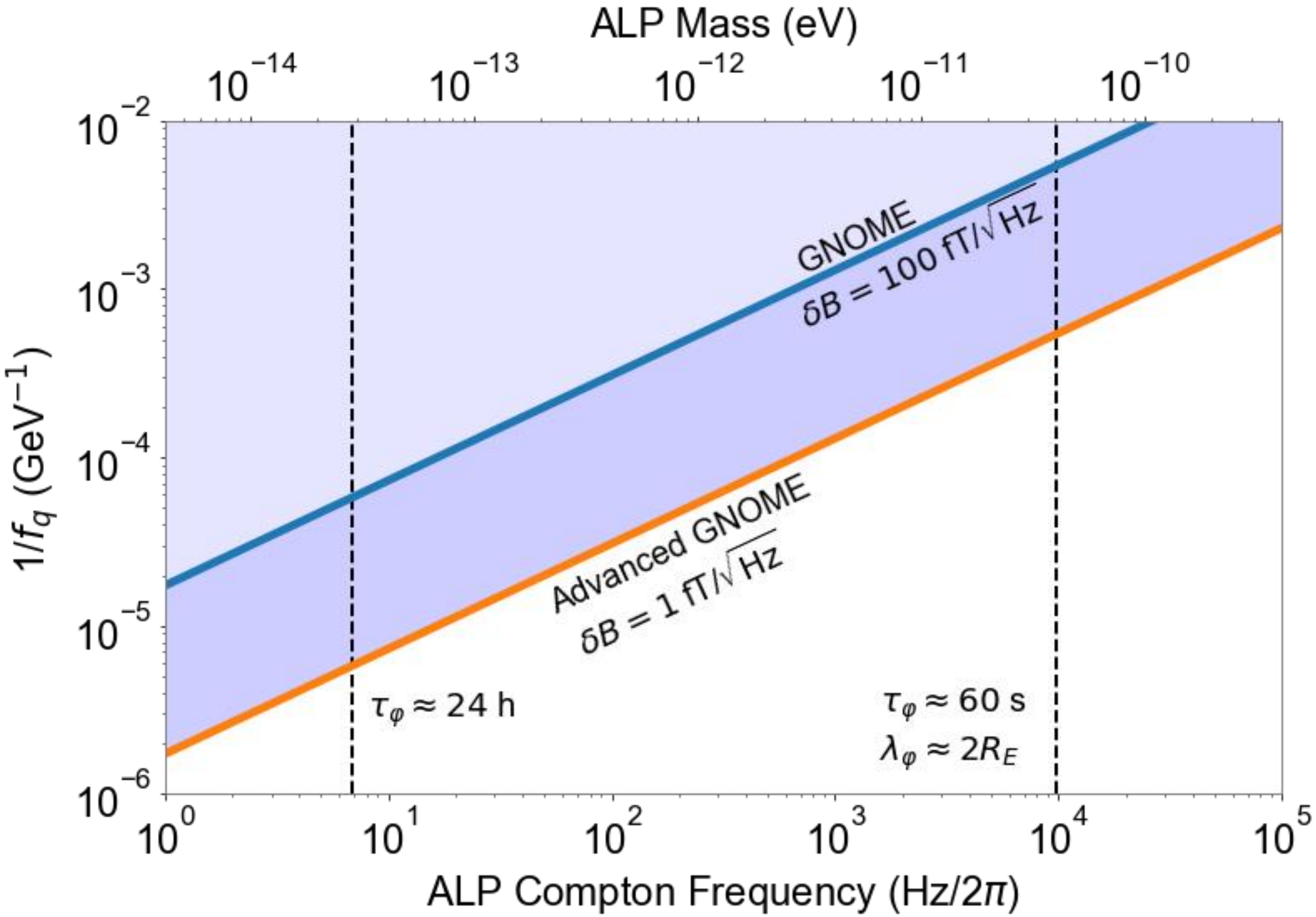
10 sensors

100 days

$\delta B(f) = \text{const.}$

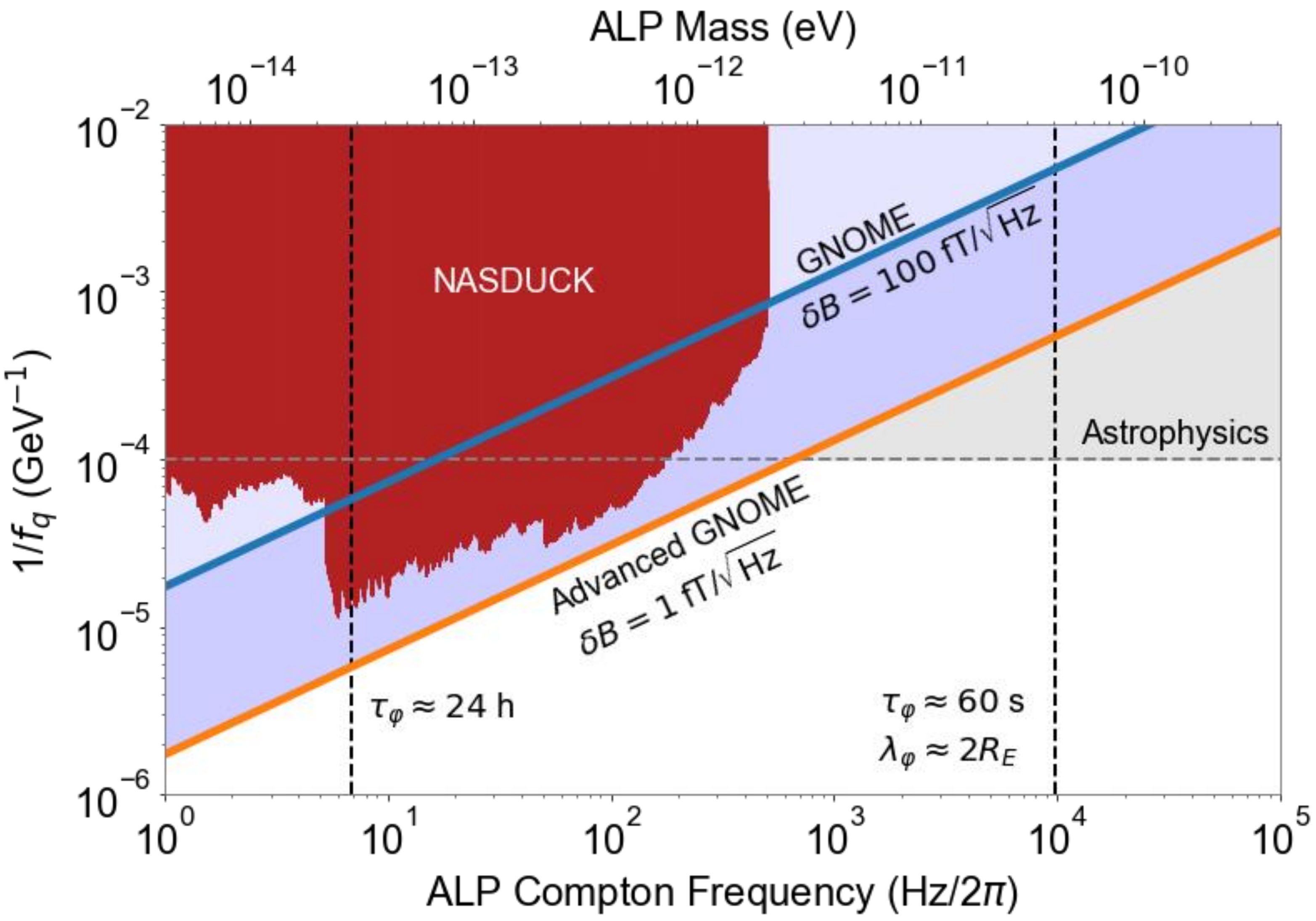


ALP Mass Range Limitations



Current Bounds

Wide frequency bandwidth thanks to intensity interferometry!



Dark Matter Intensity Interferometer?

A little bit of history

Intensity interferometry for ultralight bosonic dark matter detection, H. Masia-Roig et al., arXiv:2202.02645 (2022)

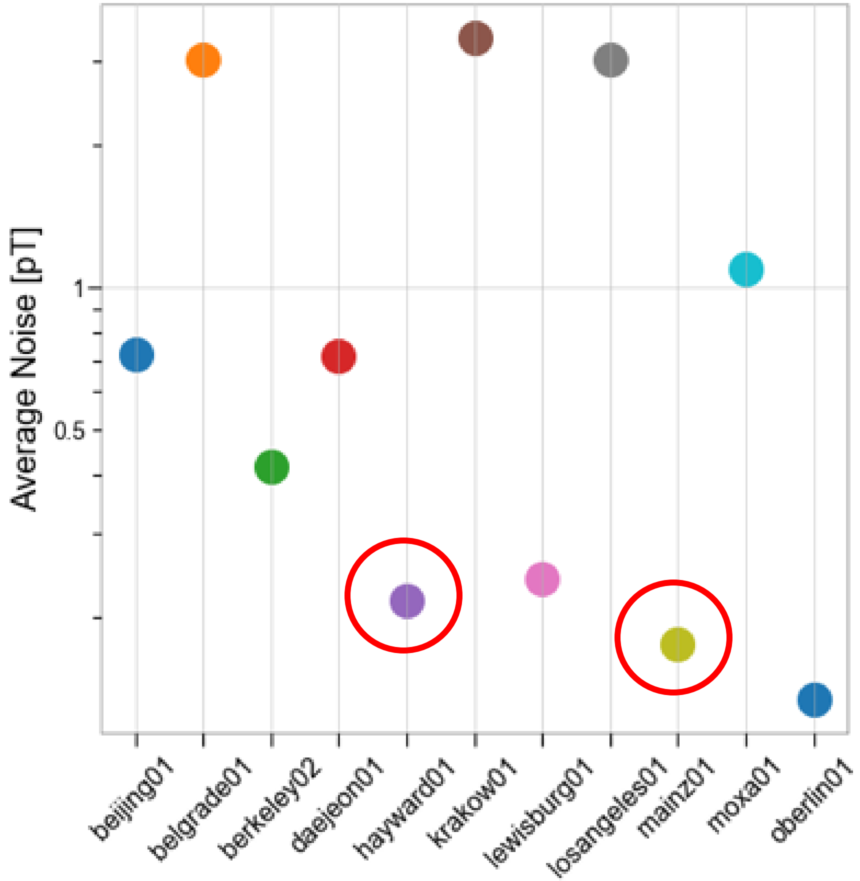
GNOME as DM intensity interferometer → Expected signals → Sensitivity estimation

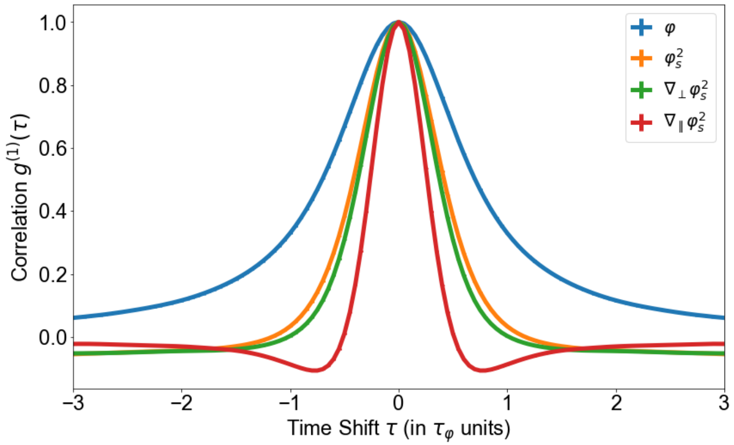
Toy model → Exclusion Plot

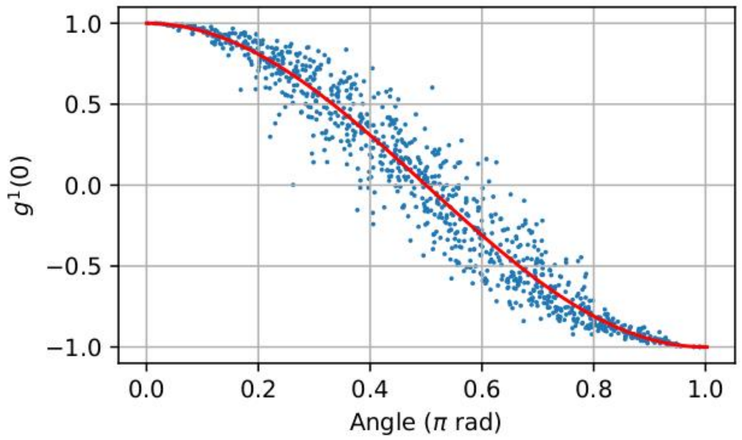
$|G^1(0)| = \max \quad G^1(\tau \gg \tau_c) \approx 0$

Toy Model

$G^1(0)$







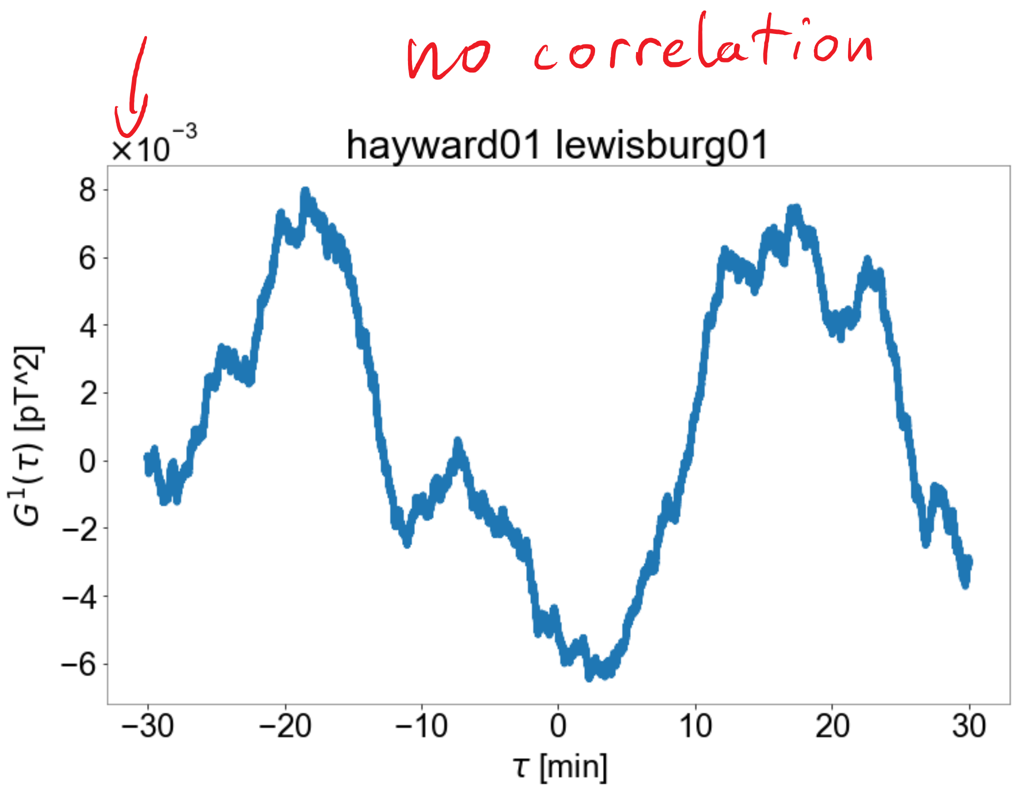
dot products of sensitive axes

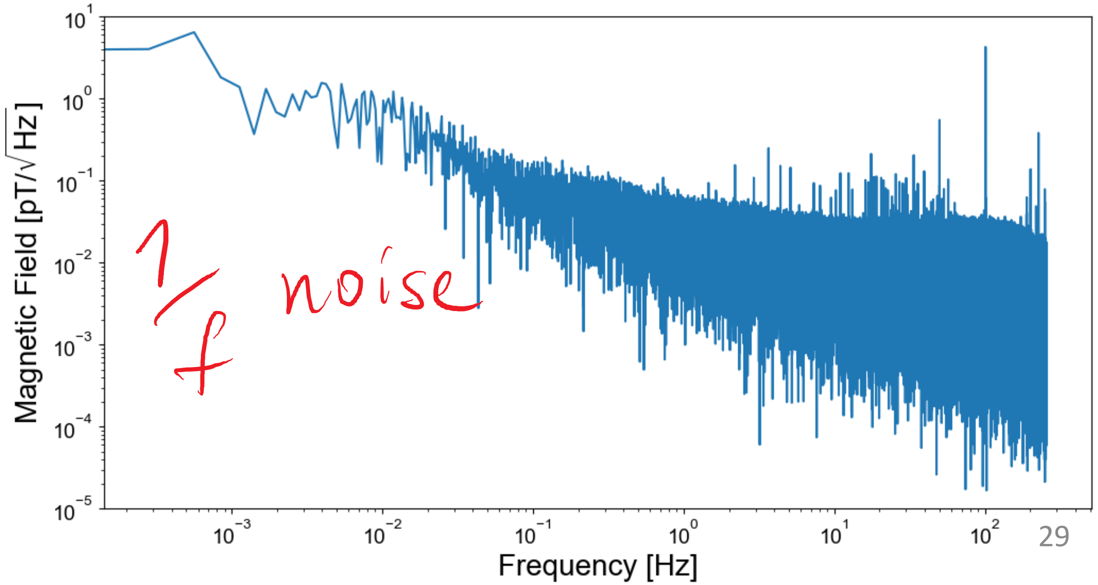
	beijing01	belgrade01	berkeley02	daejeon01	hayward01	krakow01	lewisburg01	losangeles01	mainz01	moxa01	oberlin01
beijing01											
belgrade01											
berkeley02											
daejeon01	0.986011										
hayward01			0.999989								
krakow01		0.950574									
lewisburg01			0.821179		0.821956						
losangeles01											
mainz01		-0.982689				-0.991463					
moxa01							0.754957				
oberlin01				0.798336				0.893642			

Correlation

1 hour long segments
- subtract linear background
- filter 60 Hz

averaged over 1 month





no correlation → how to put constraints?

$$f_q^2 \lesssim \frac{\hbar^3 \rho_{DM} v_0}{g_F \mu_B m_q^2} \frac{1}{\tau_q} \frac{1}{B_q(min)}$$

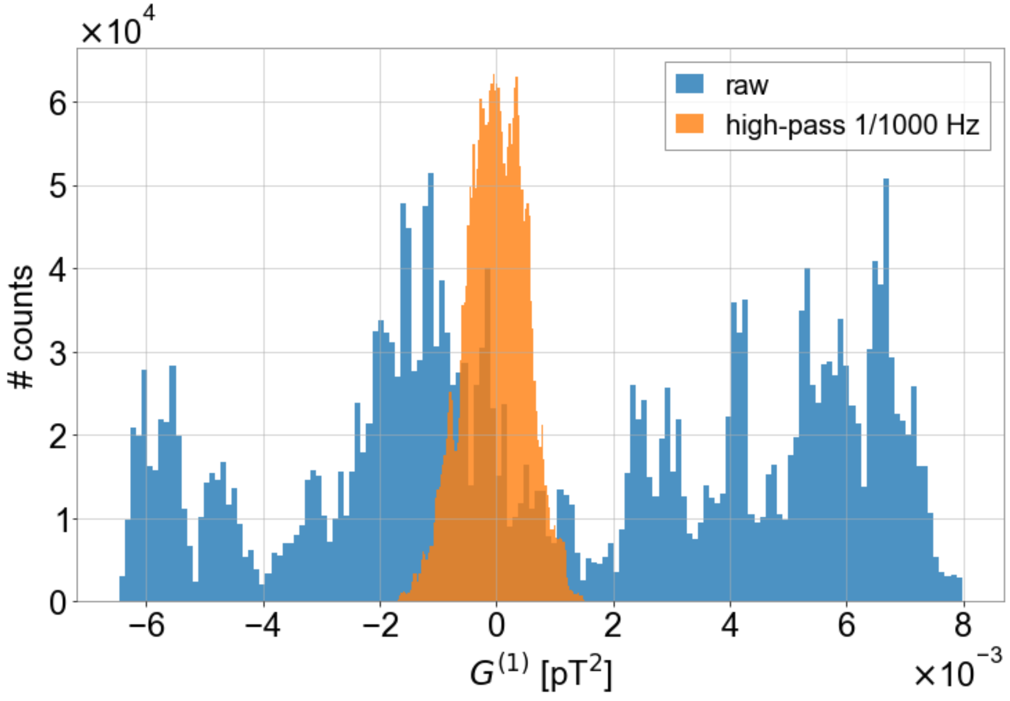
↑ parameters

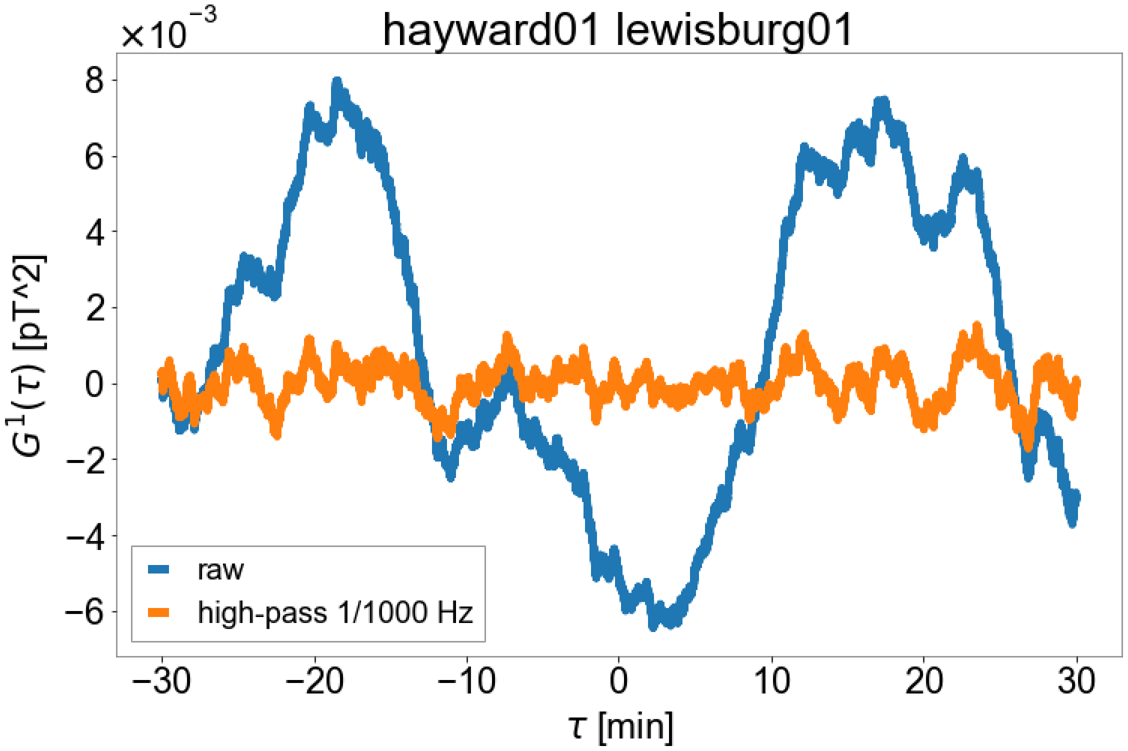
↑ minimum detectable pseudo-magnetic field

(defined by the noise of the correlation)

B_g(min) estimation

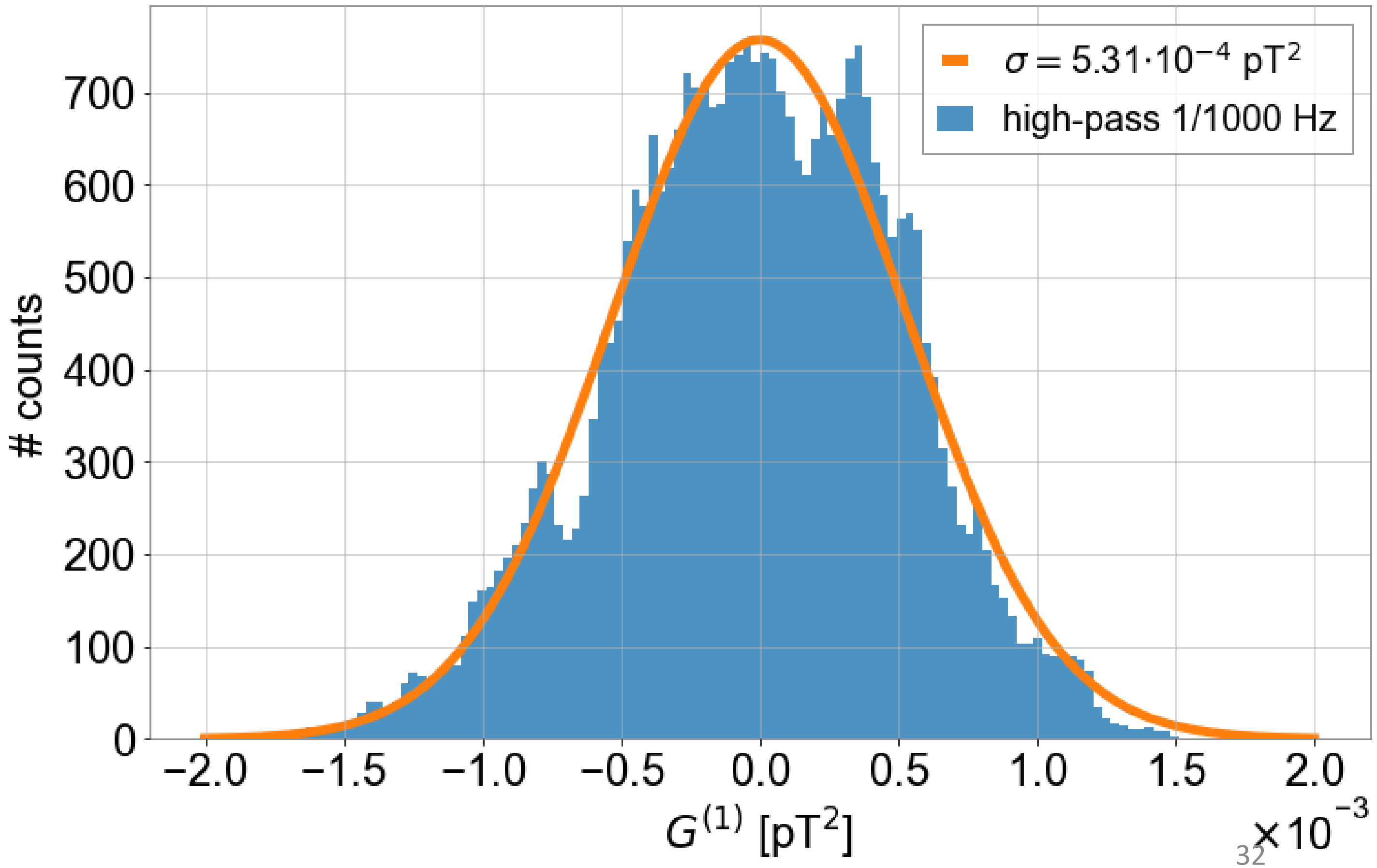
- high-pass filter
- confidence: 3,3355σ ?



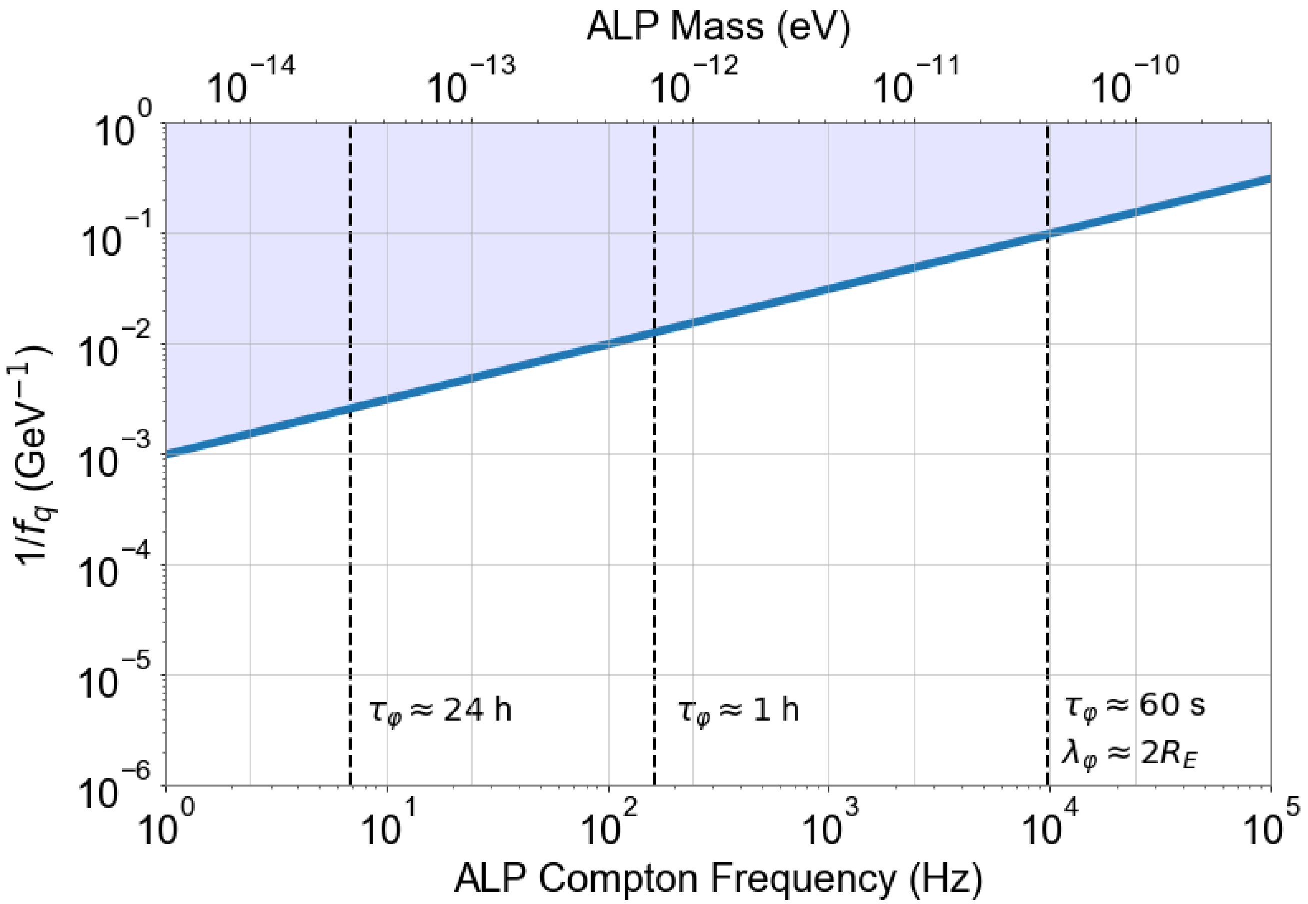


$C = 90\% \; (1{,}5\,\sigma) \longrightarrow B_q(\text{min}) \approx 30 \text{ fT}$

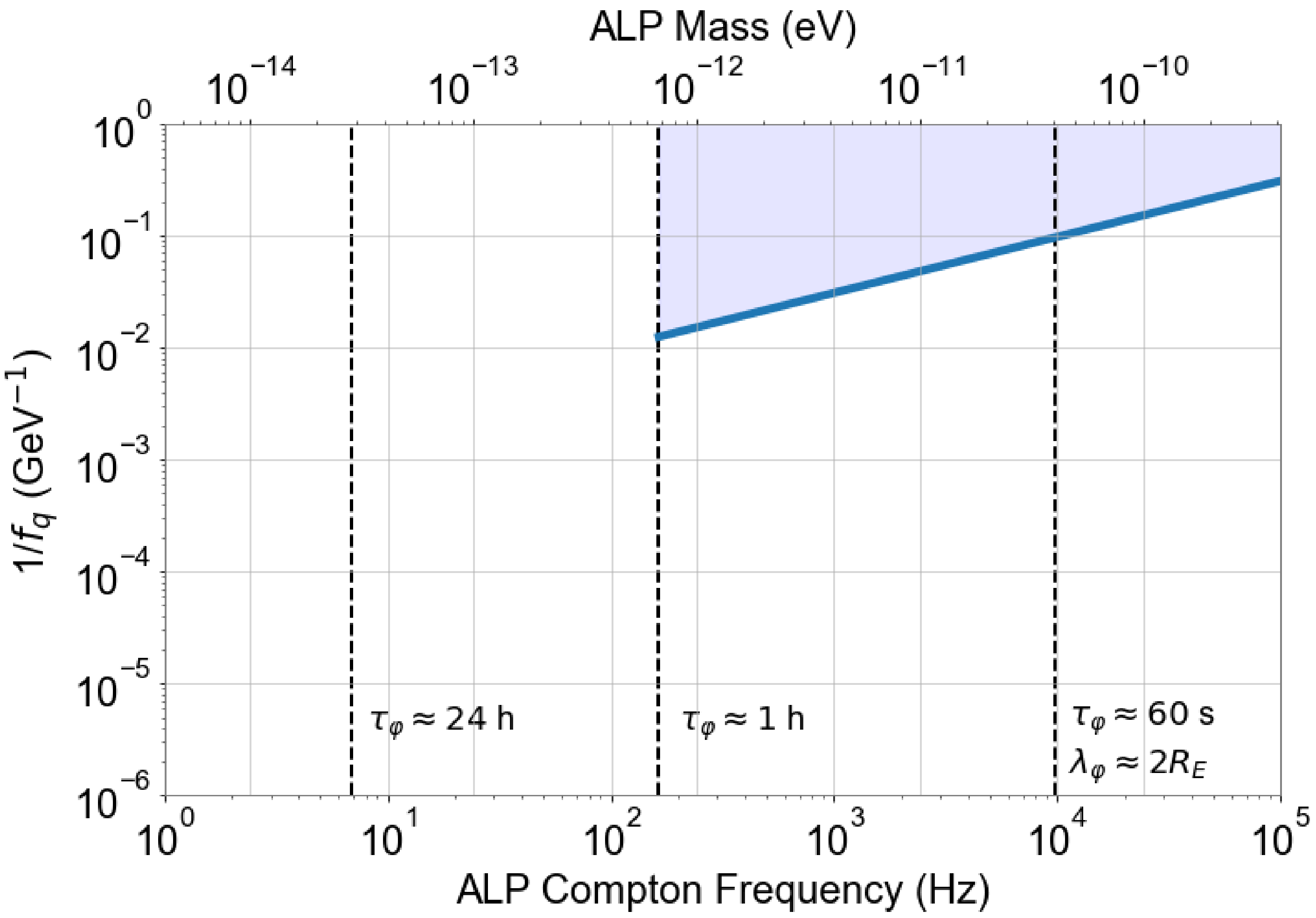
$C = 99{,}9\% \; (3{,}3355\,\sigma) \longrightarrow B_q(\text{min}) \approx 42 \text{ fT}$



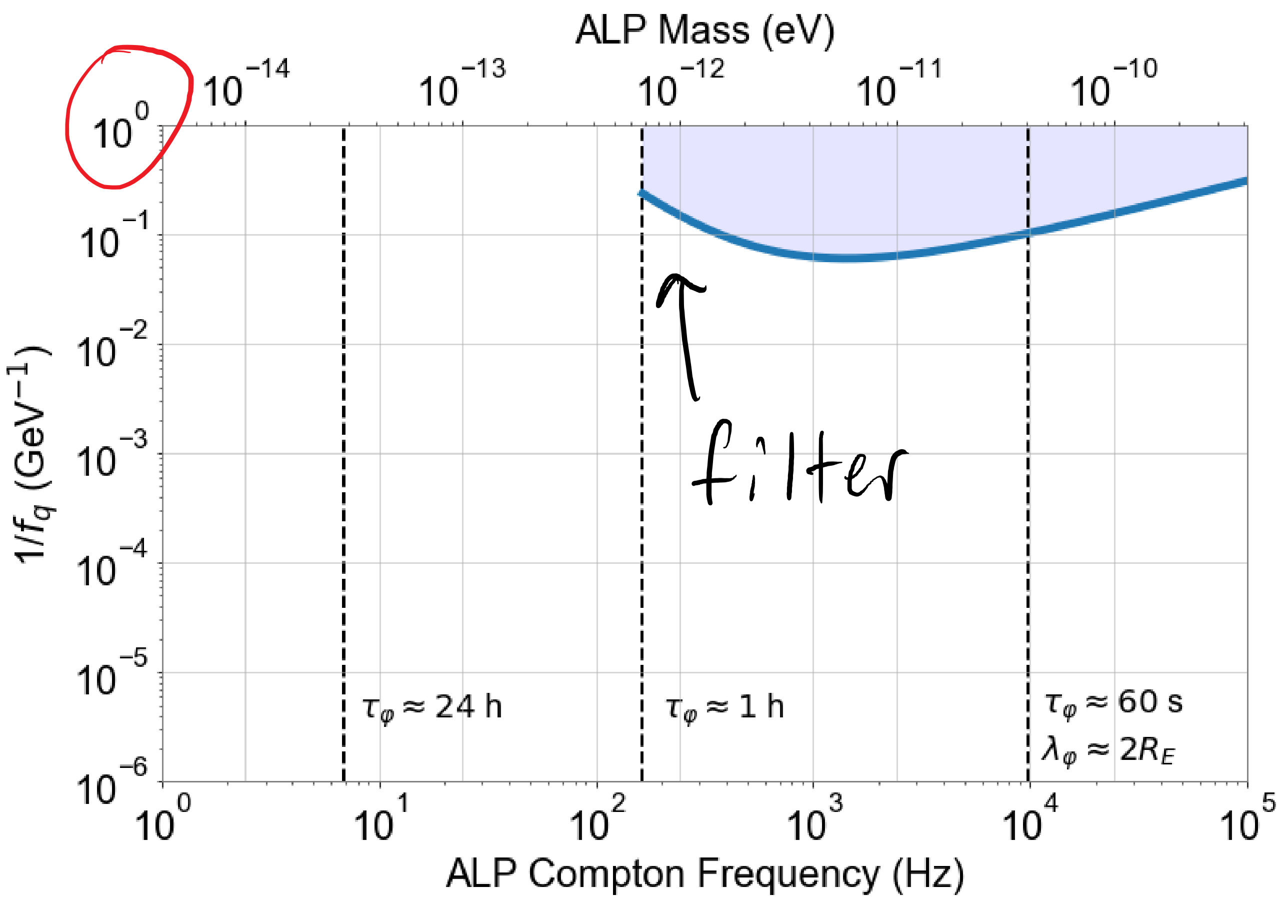
Toy Model Exclusion Plot

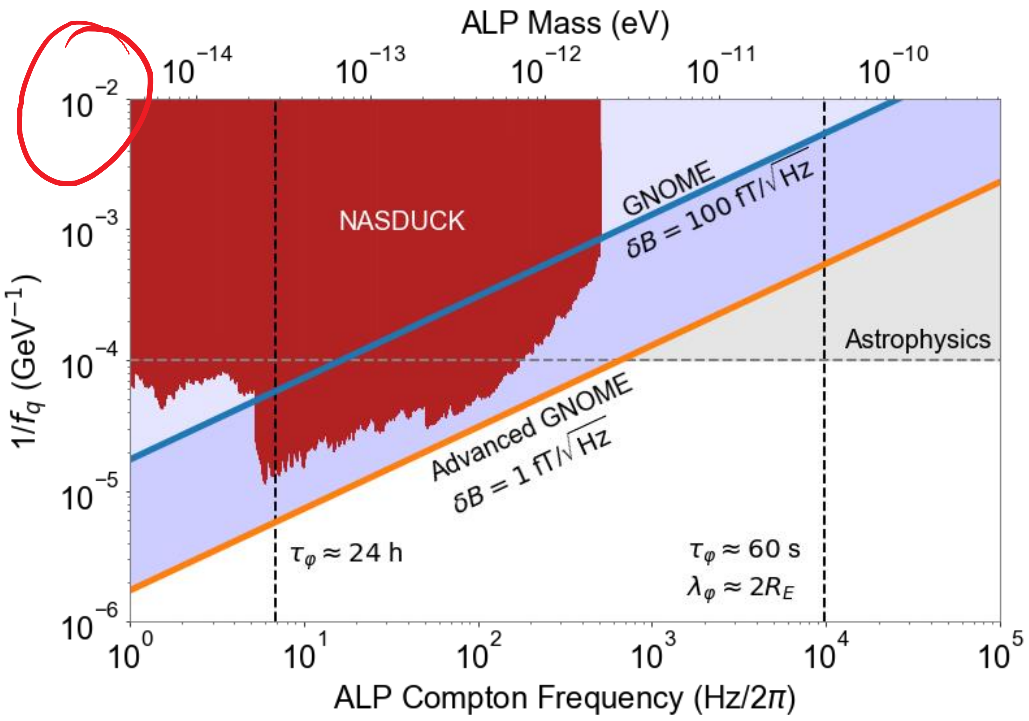


Toy Model Exclusion Plot



Toy Model Exclusion Plot





Outlook

- DM intensity interferometry is possible!
- Fitting lineshape instead of looking at G1(0) alone
- Need for longer coherence times correlation (Hayward team)
- Low frequency magnetic noise can be suppressed in co-magnetometers (Advanced GNOME)

Bibliography and Sources

- *p. 1: CfA/Rick Peterson /* https://www.cfa.harvard.edu/facilities-technology/telescopes-instruments/very-energetic-radiation-imaging-telescope
- p. 3 top-right, p. 4 bottom-center: https://en.wikipedia.org/wiki/Michelson_stellar_interferometer
- p. 4 top-right: https://pl.wikipedia.org/wiki/Betelgeza
- p. 4 bottom-right: https://hdl.huntington.org/digital/collection/p15150coll2/id/899
- p. 3 bottom-right: https://www.researchgate.net/figure/a-Schematic-diagram-of-the-Michelson-Pease-stellar-interferometer-The-incoming-rays_fig3_314247837
- p.3 left: https://www.researchgate.net/figure/Effect-of-the-incident-angle-to-the-slit_fig2_234961268
- p. 7 left: https://www.aanda.org/articles/aa/pdf/2009/45/aa11739-09.pdf
- p. 9, p. 12 center: https://www.actaphys.uj.edu.pl/fulltext?series=Reg&vol=29&page=1839
- p.12 right: https://en.wikipedia.org/wiki/Sirius
- p. 13: https://veritas.sao.arizona.edu/the-science-of-veritas/veritas-results/516-stellarinterferometry
- p. 14: https://arxiv.org/pdf/2007.10295.pdf
- p. 17: https://medium.com/roaming-physicist/have-we-really-found-dark-matter-46601f62671f
- p. 21 center: Afach, S., Buchler, B.C., Budker, D. *et al.* Search for topological defect dark matter with a global network of optical magnetometers. *Nat. Phys.* **17**, 1396–1401 (2021). https://doi.org/10.1038/s41567-021-01393-y
- History of HBT interferometry and picture p. 12 left based on lecture by https://www.ictp-saifr.org/wp-content/uploads/2022/06/SaoPauloJune2022_compressed.pdf
- Nasduck exclusion Itay M. Bloch et. al. *New constraints on axion-like dark matter using a Floquet quantum detector,* Science Advances Vol. 8**,** Issue 5**,** (2022) https://doi.org/10.1126/sciadv.abl8919