Battling Gravity Gradient Noise in ULDM and GW searches with Vertical Atom Gradiometry

Leonardo Badurina

Based on

PHYSICAL REVIEW D **107,** 055002 (2023)

Ultralight dark matter searches at the sub-Hz frontier with atom multigradiometry

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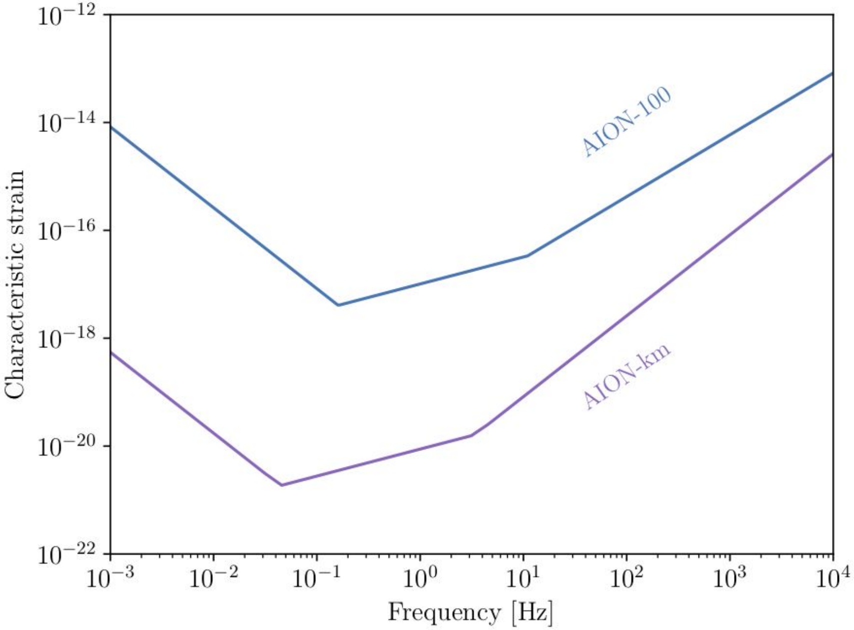
Terrestrial Very Long-Baseline Atom Interferometry Workshop, March 14 2023

Why very long-baseline vertical atom gradiometers?

Very long-baseline atom gradiometers would be excellent accelerometers, mid-frequency GW detectors, ULDM sensors and more!



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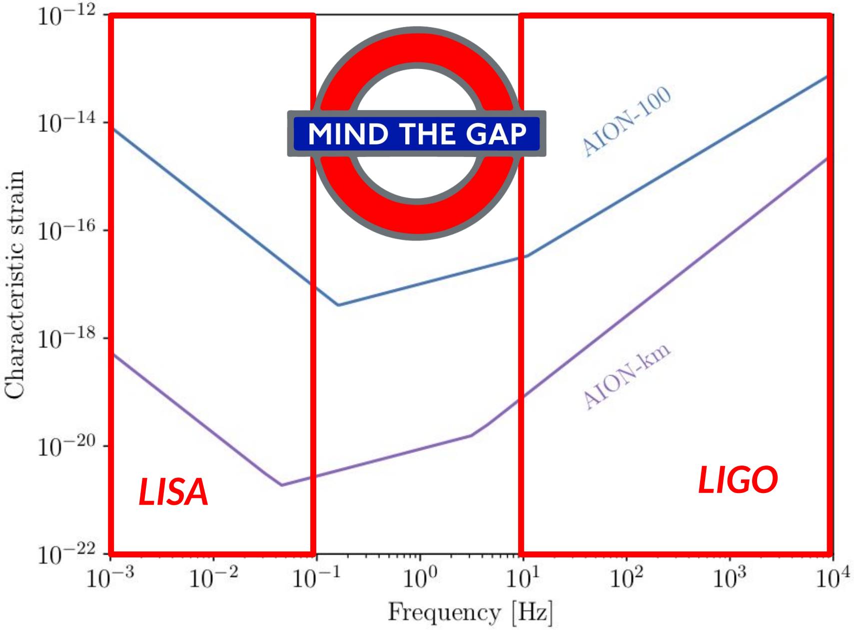

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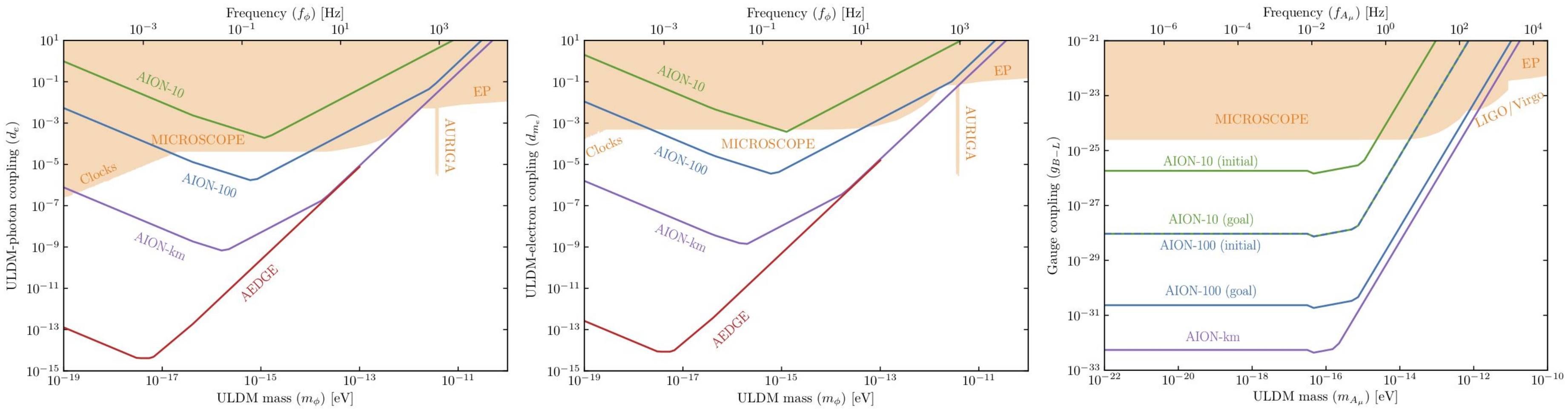

Scalar ULDM

Vector ULDM (coupled to B-L current)

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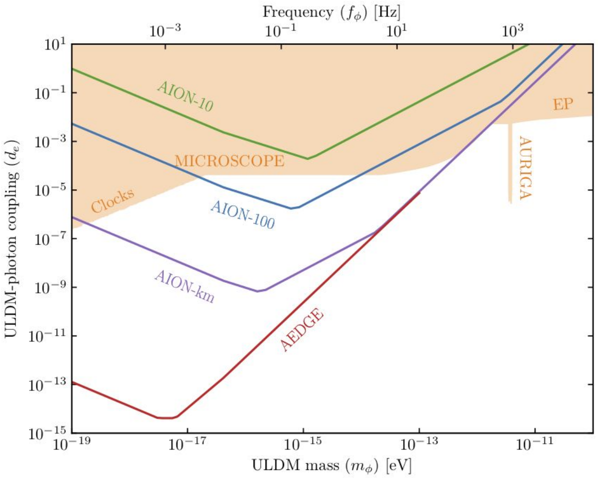

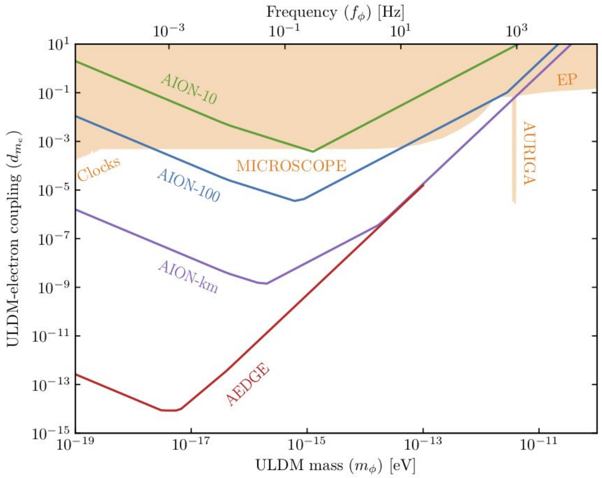

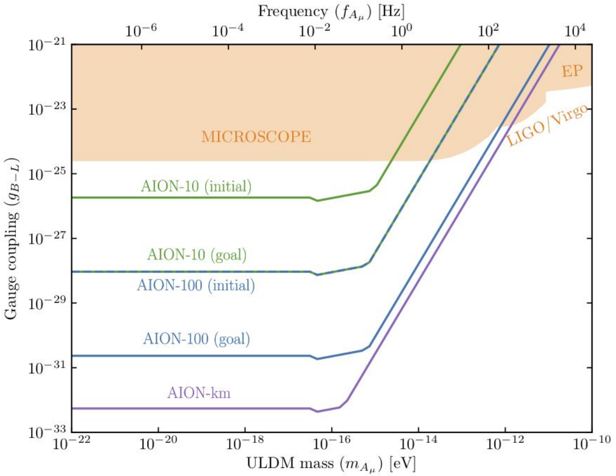

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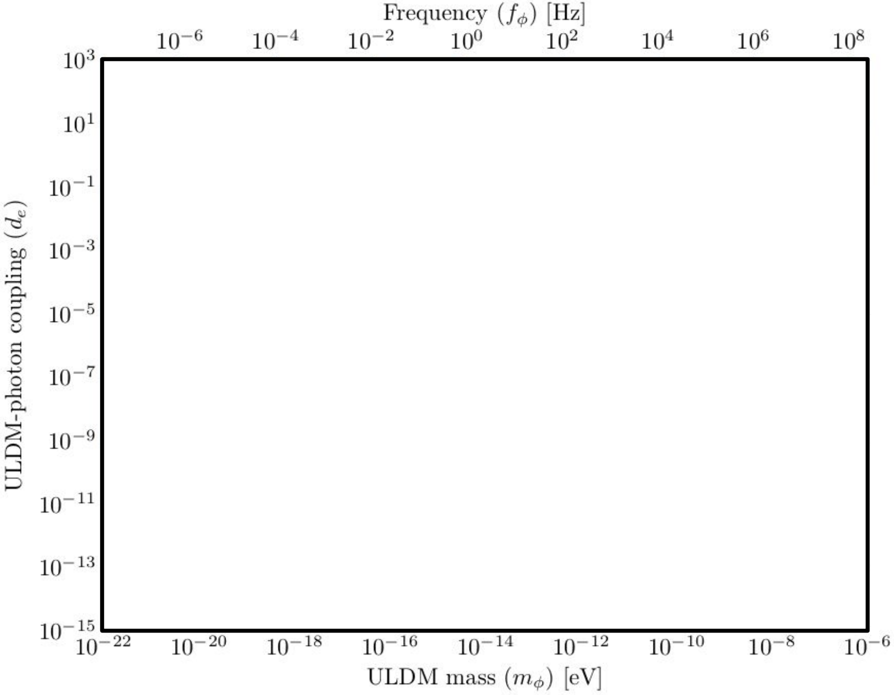
Aside: theory space for linearly-coupled scalar ULDM

$$d_e \frac{\phi}{M_{\rm Pl}} F_{\mu\nu}F^{\mu\nu}$$



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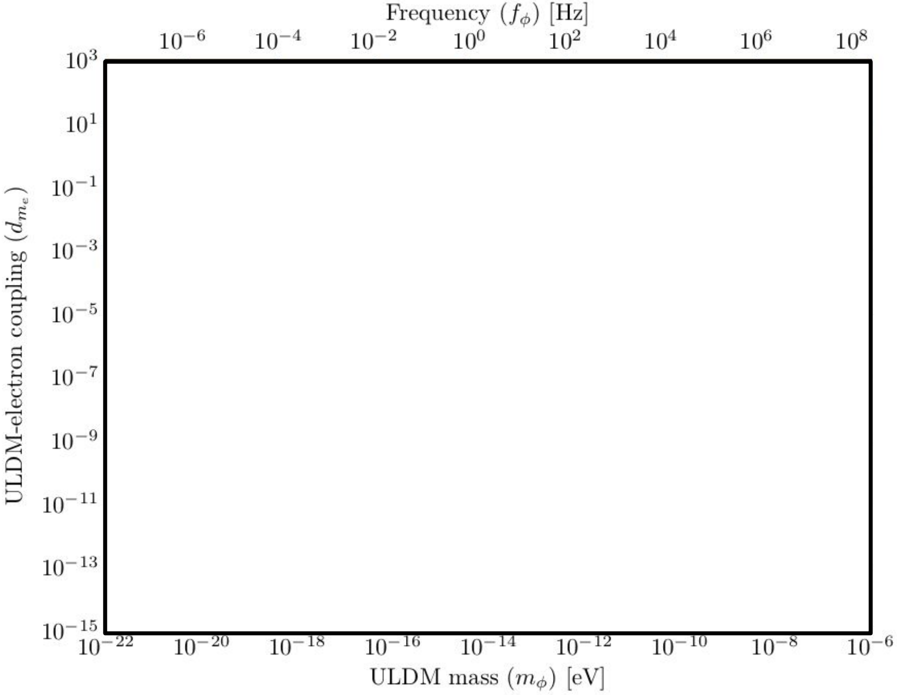

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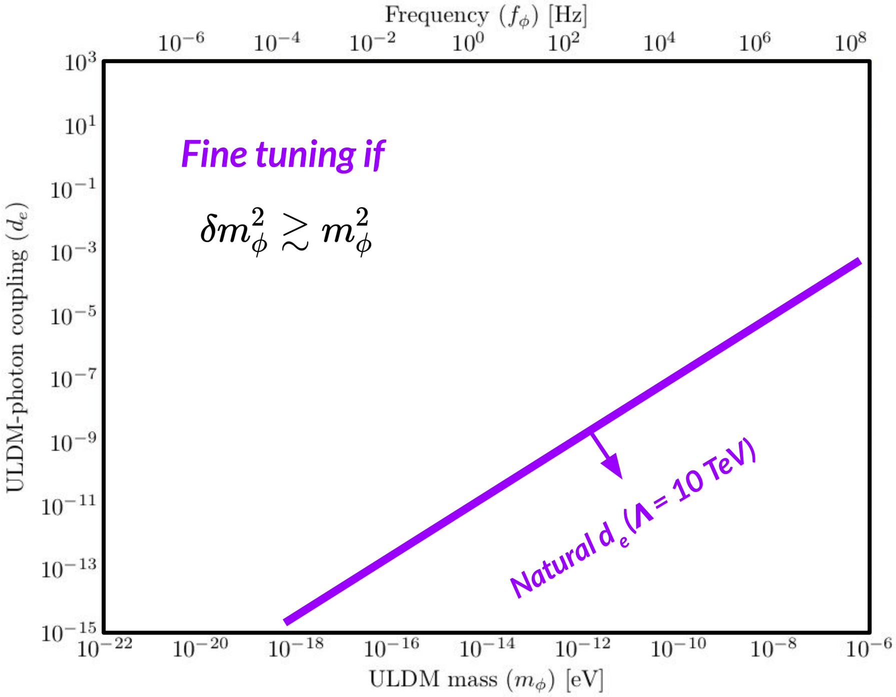

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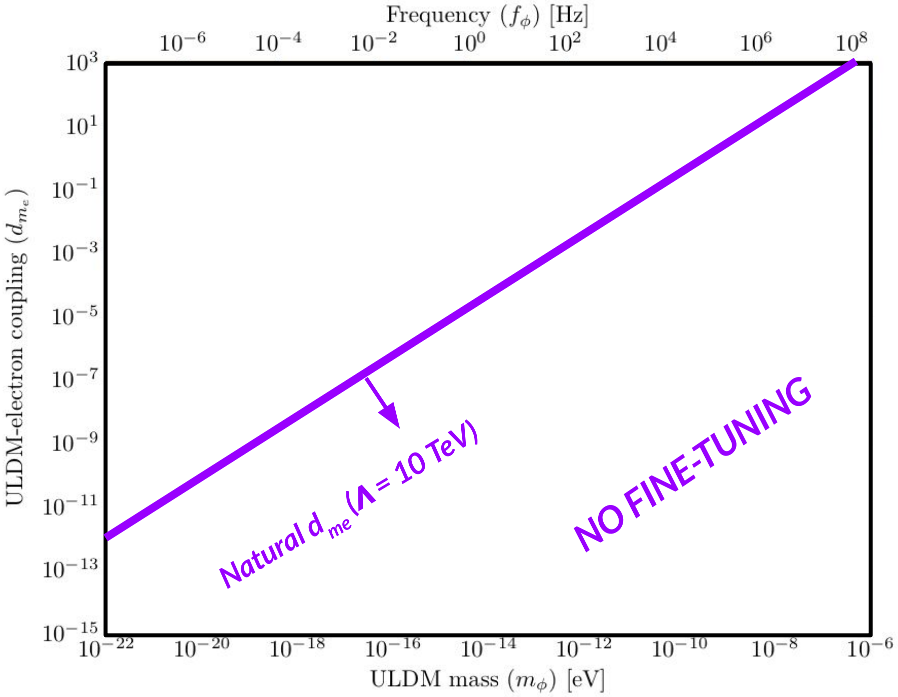

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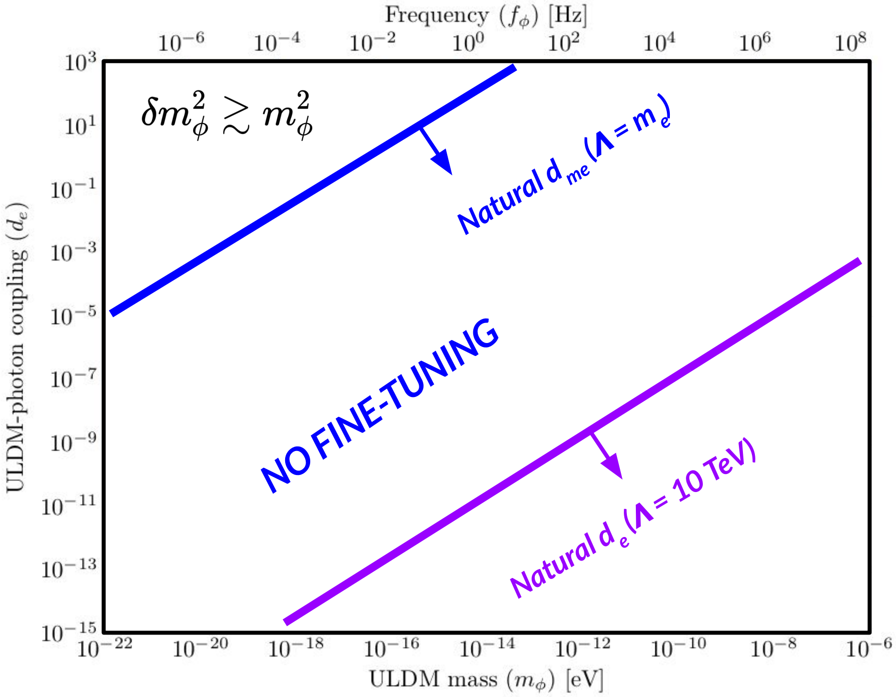

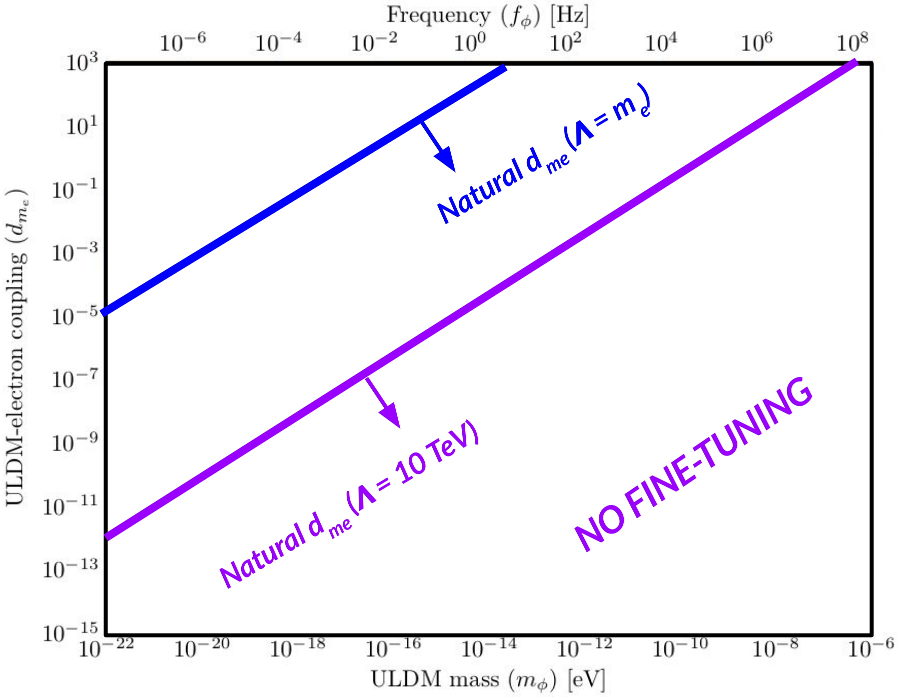

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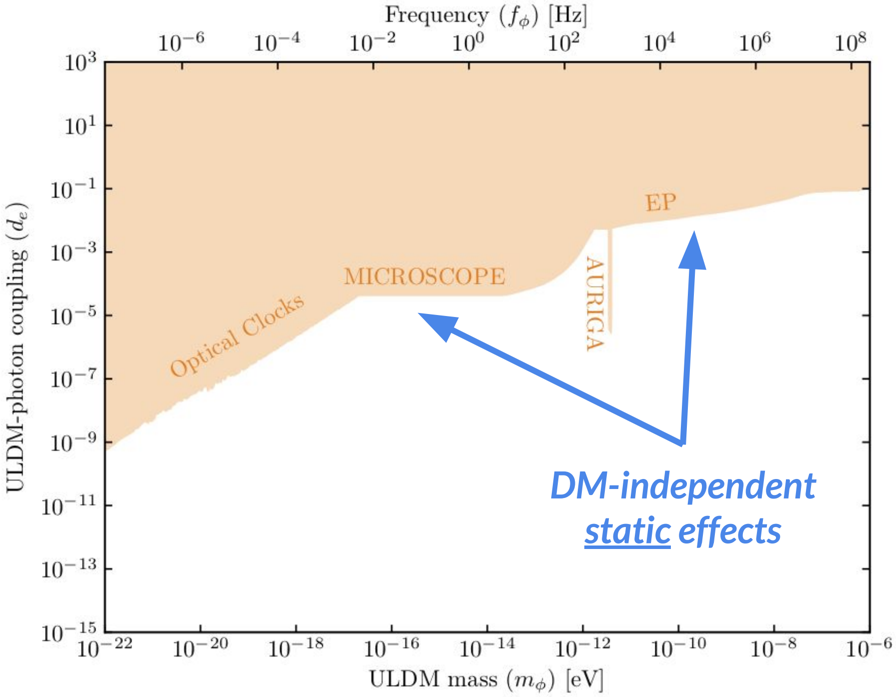

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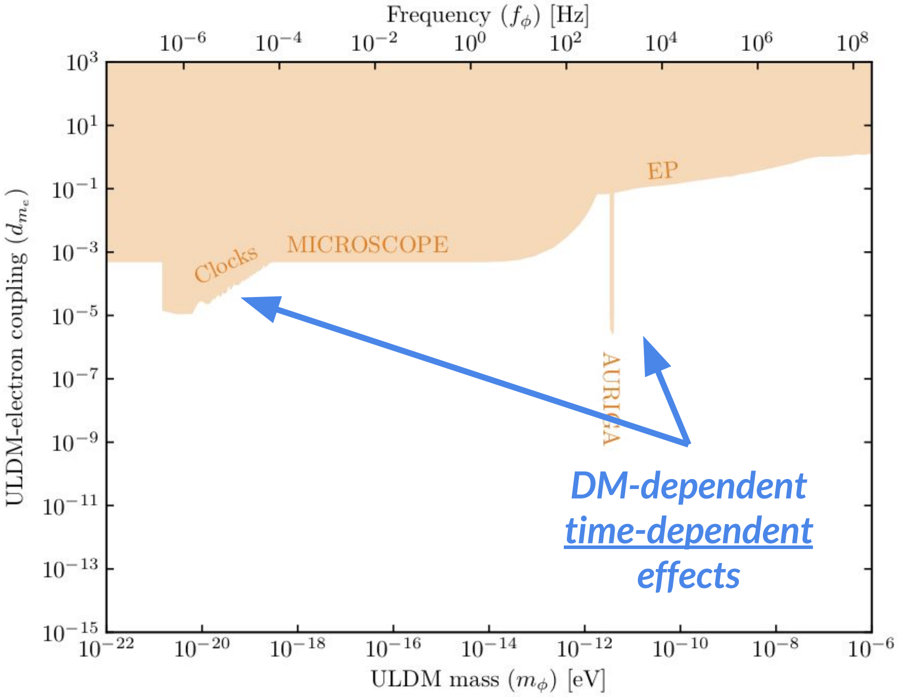

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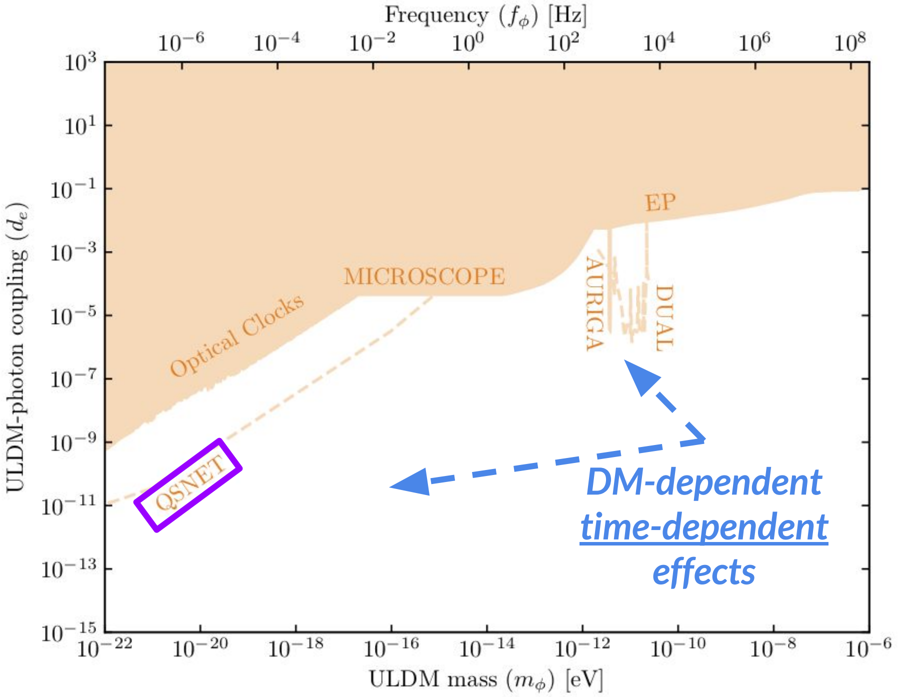

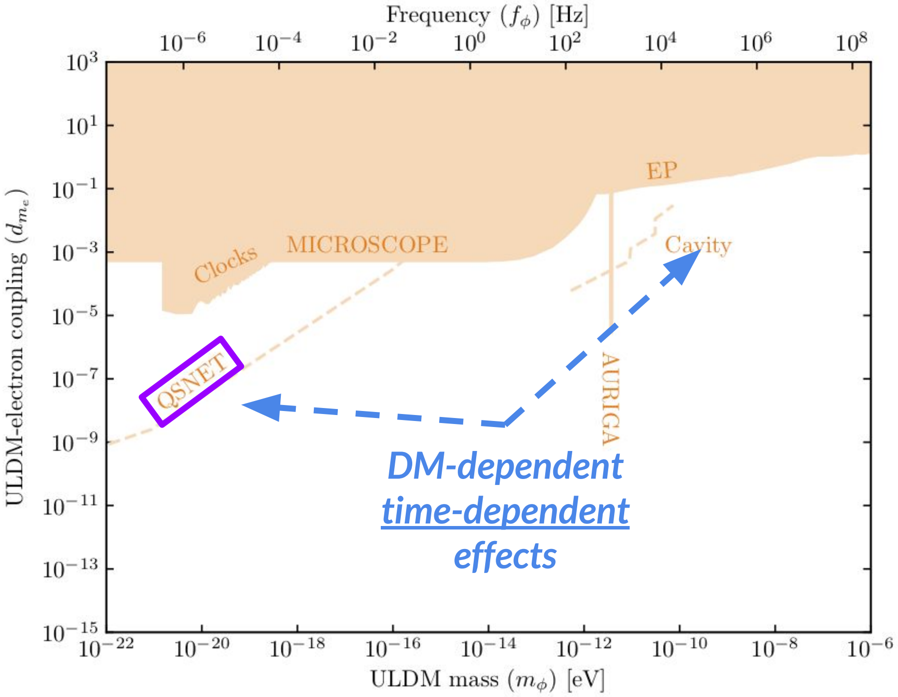

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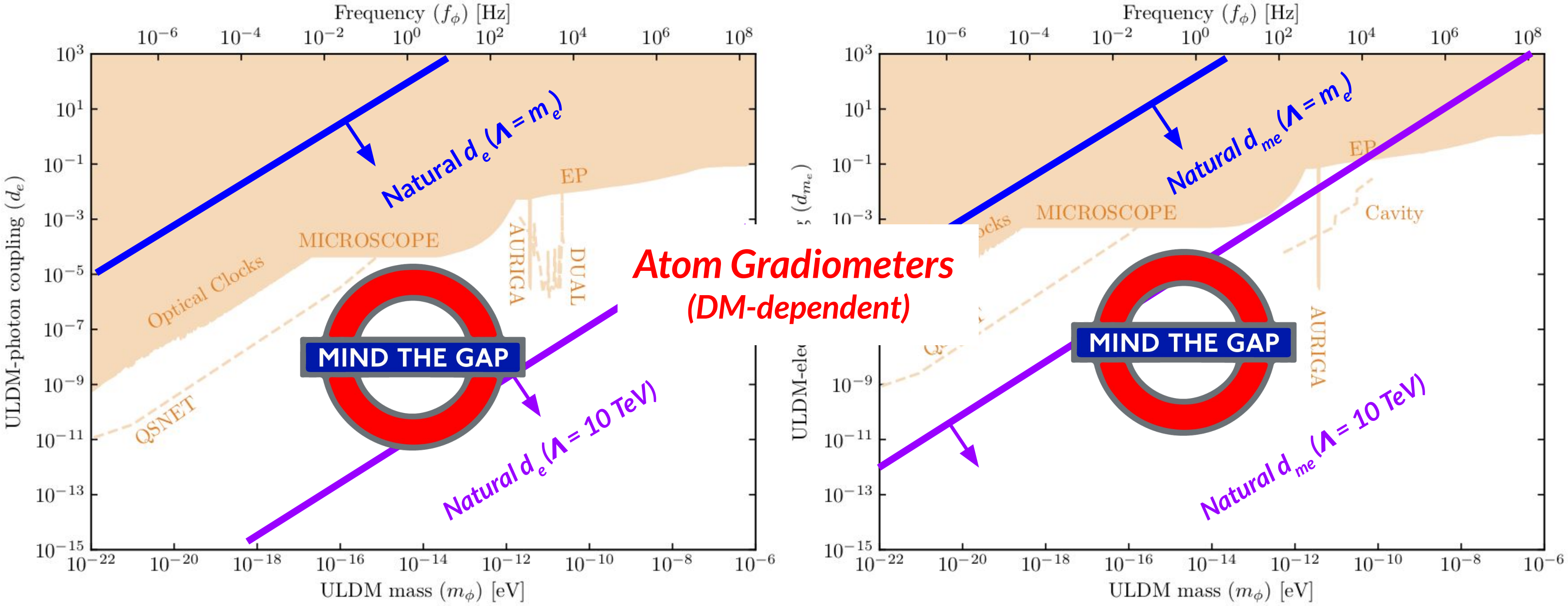
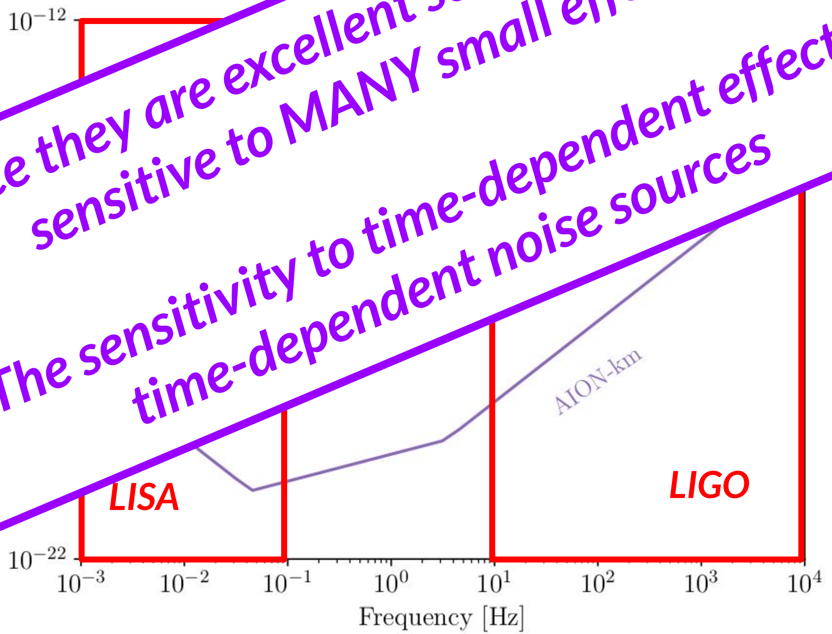


Why very long-baseline vertical atom gradiom

Very long-baseline atom interferometers would
ULDM sensors, mid-frequency

Complication: Since they are excellent sensors, atom gradiometers are sensitive to MANY small effects.

Implication: The sensitivity to time-dependent effects is limited by time-dependent noise sources



Gravity gradient noise (GGN)

Mass density fluctuations induce time-dependent accelerations on the <u>atoms</u> $\rightarrow$ time-dependent phase shift $\rightarrow$ time-dependent noise

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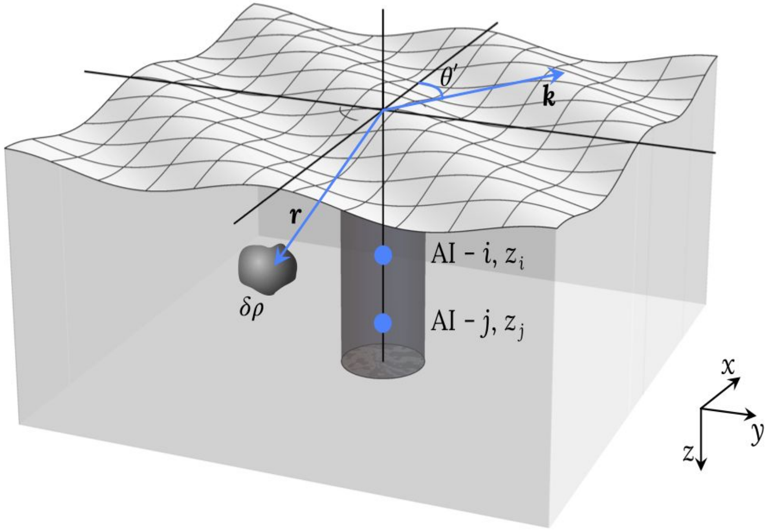
$$\widetilde{A}, -\widetilde{B} \propto \frac{\sin\left(\frac{\omega T}{2}\right)^2}{\omega^2}$$



***Assumptions*: Isotropic sourcing around the shaft, single geological layer (so only fundamental Rayleigh mode)**

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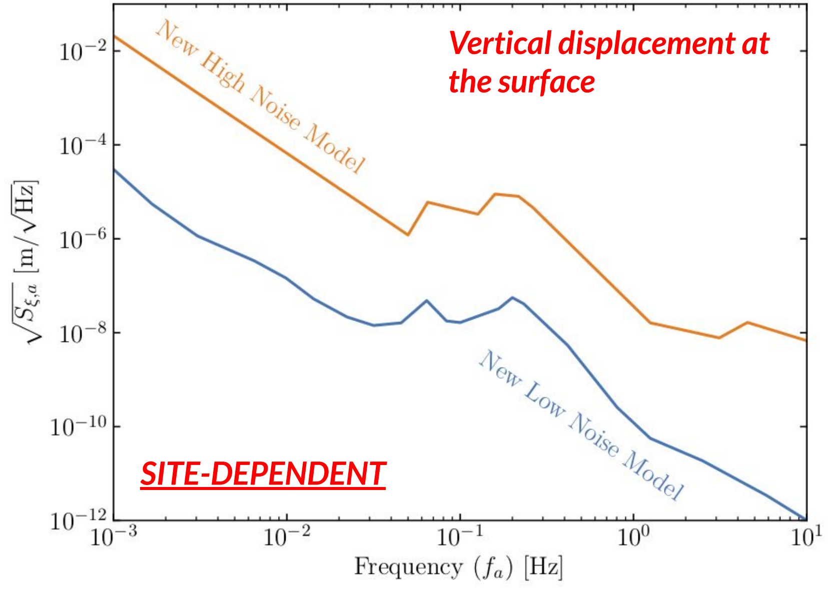
Vertical displacement at the surface



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$$\lambda_{\mathrm{GGN}} = \frac{\boxed{c_H}}{\omega_a} \simeq 100\ \mathrm{m}\left(\frac{250\ \mathrm{m\ s^{-1}}}{c_H}\right)^{-1}\left(\frac{2.5\ \mathrm{Hz}}{\omega}\right)$$

Horizontal speed of propagation
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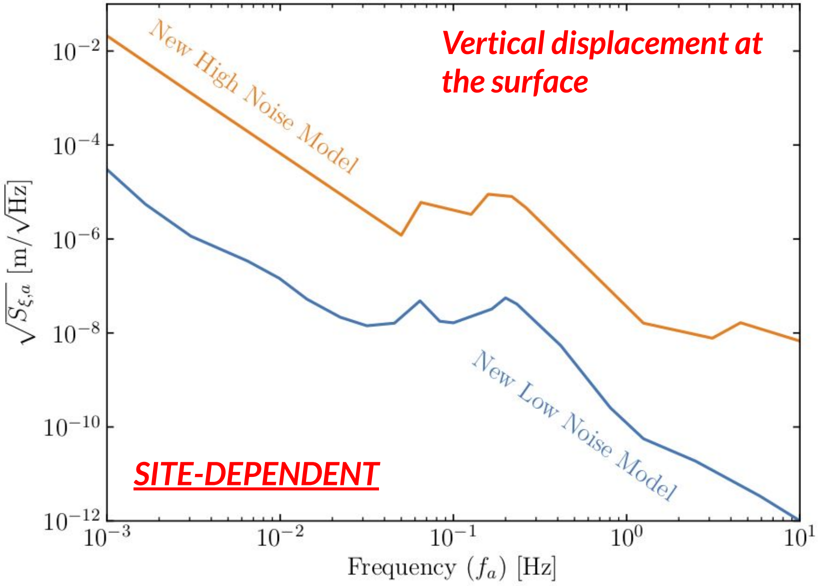

GGN-limited projections (100 m baseline)

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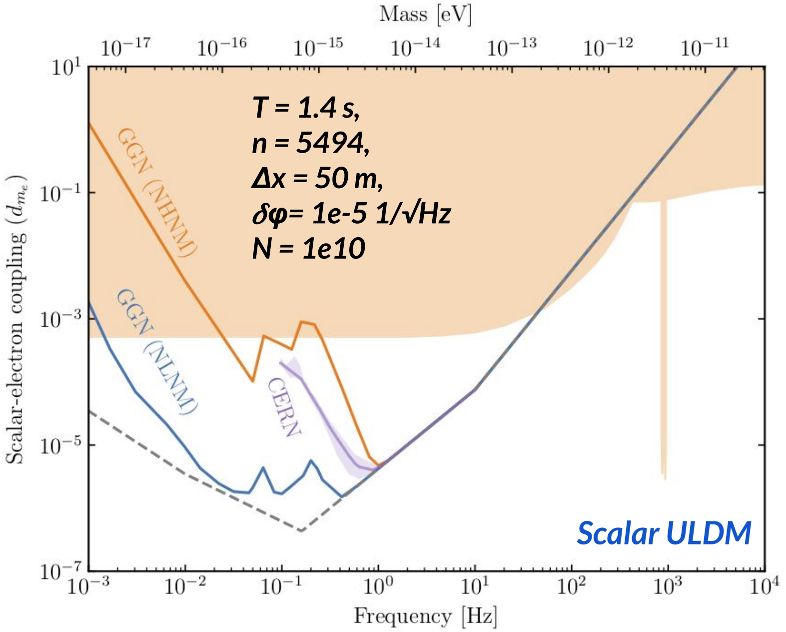

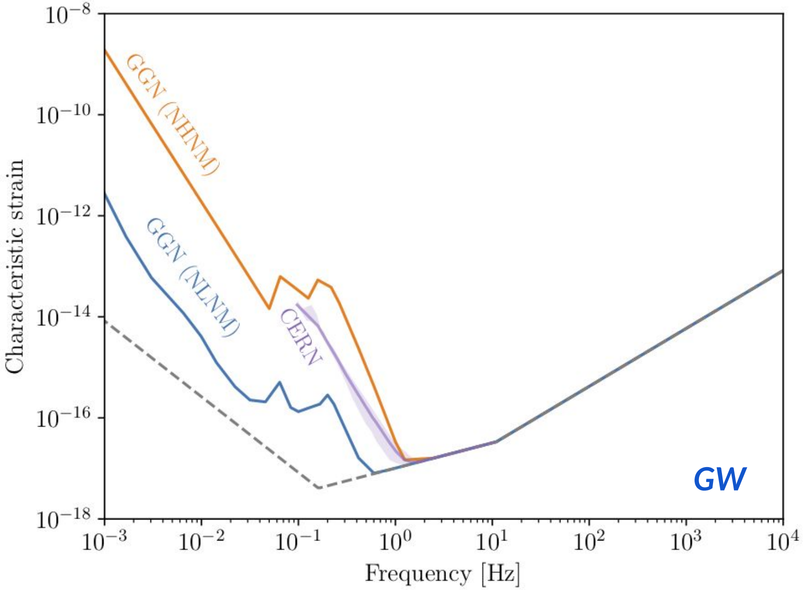

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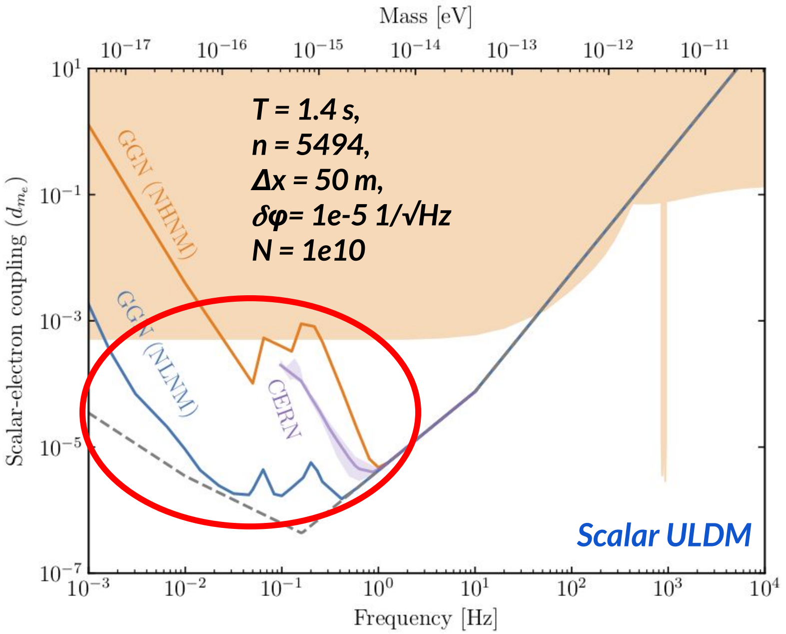

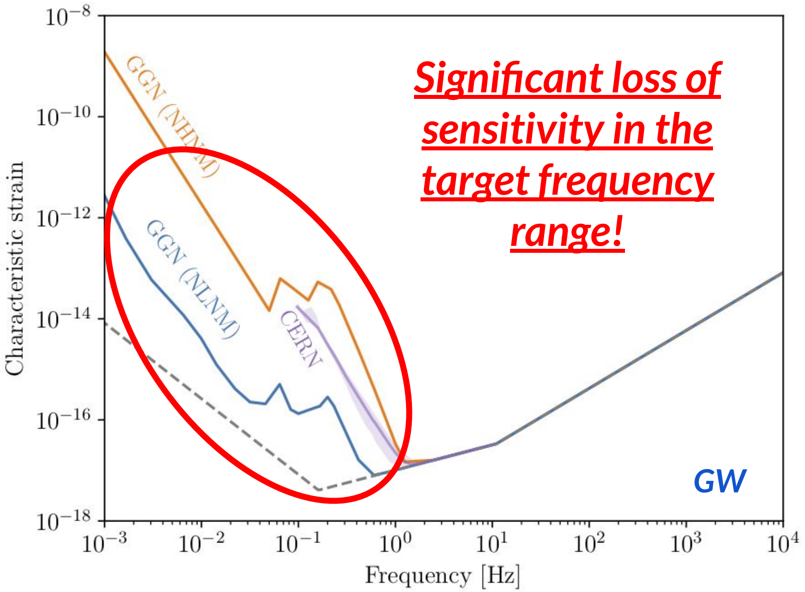

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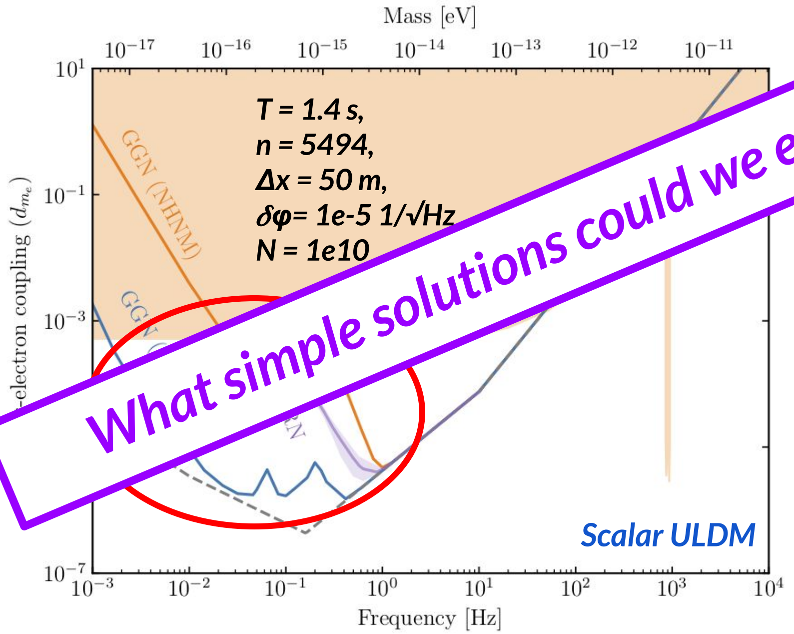
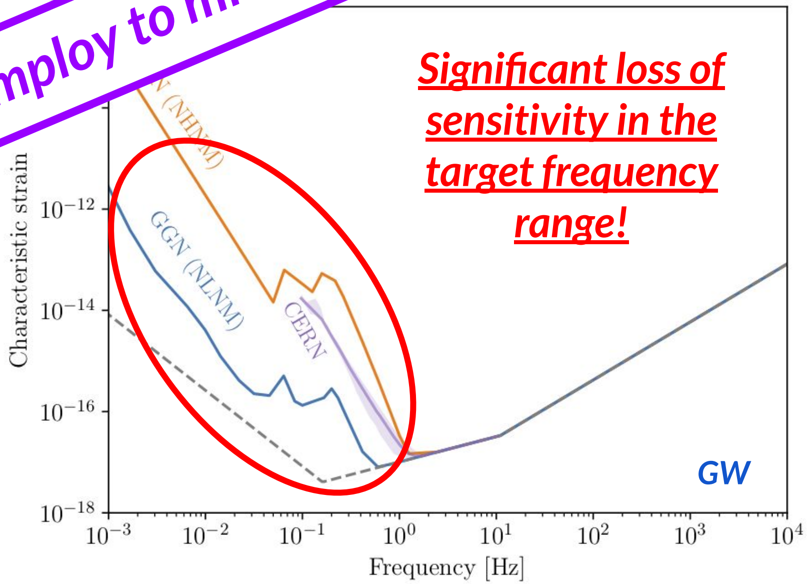
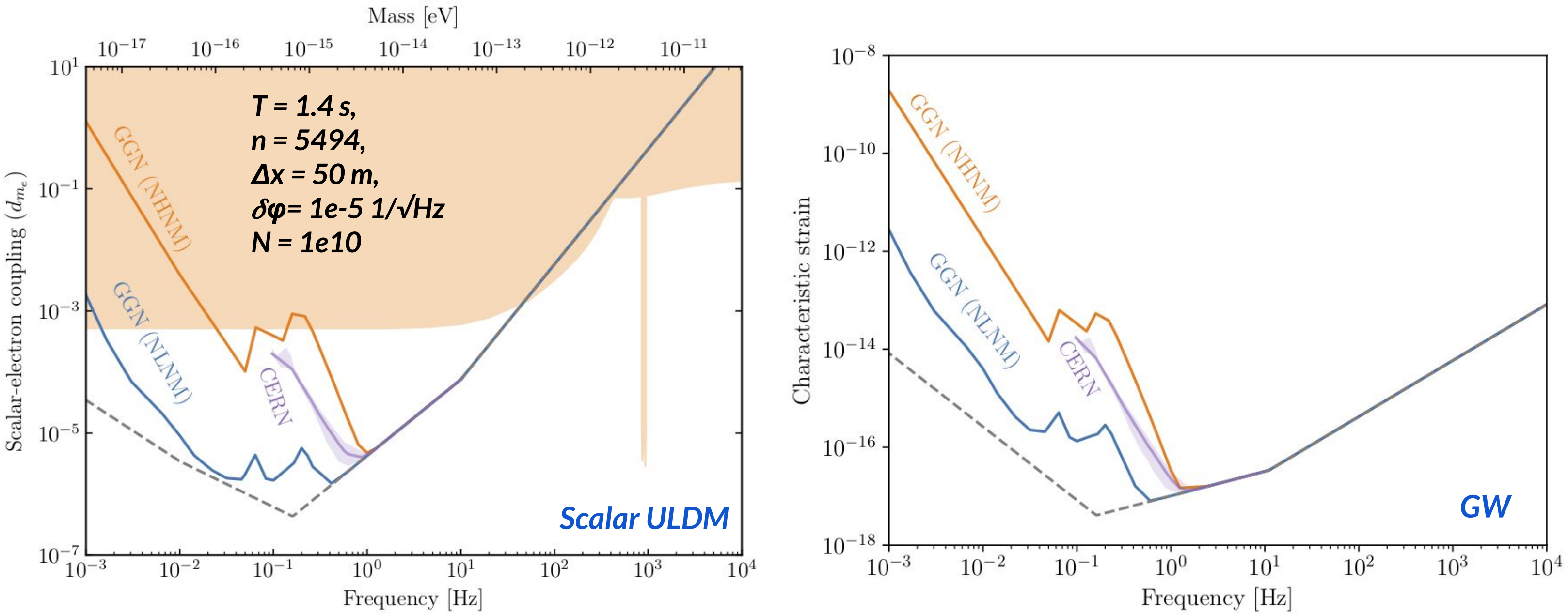
What simple solutions could we employ to mitigate the GGN floor?





Significant loss of sensitivity in the target frequency range!

Solution 1: Choosing quiet sites (100 m baseline)



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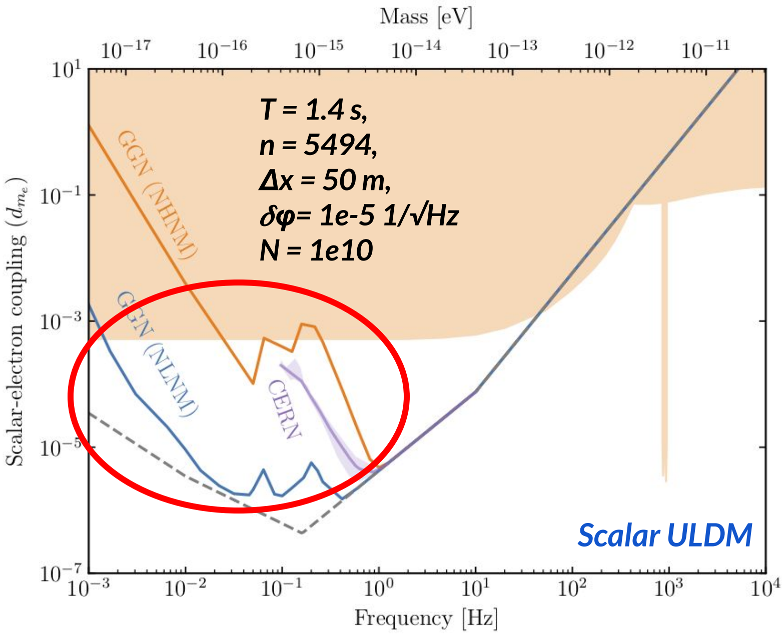
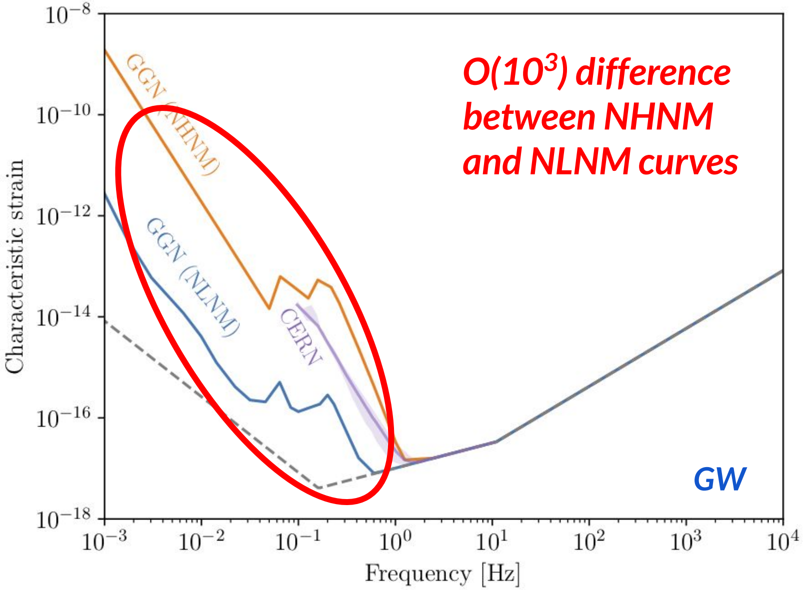
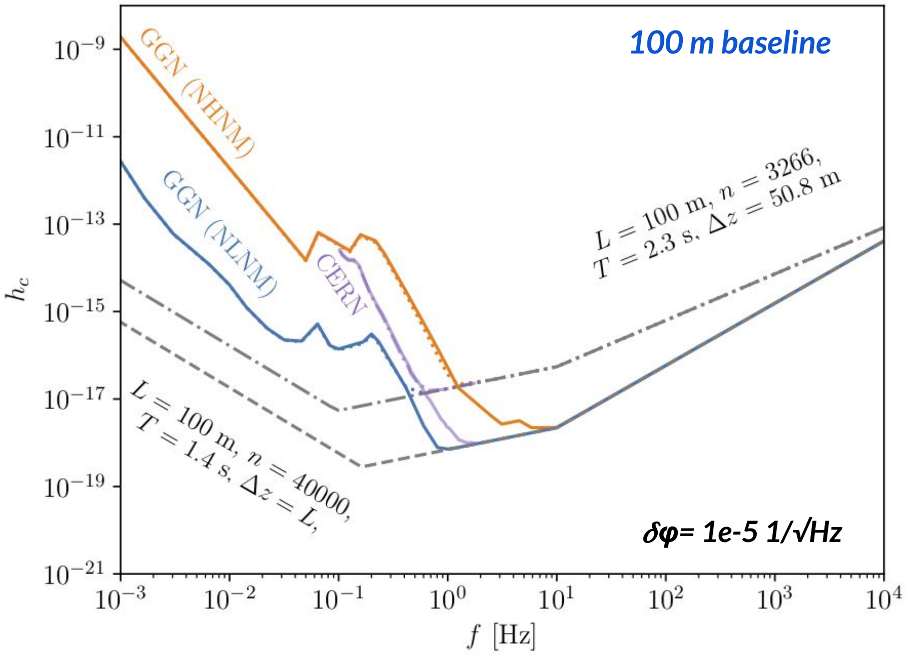
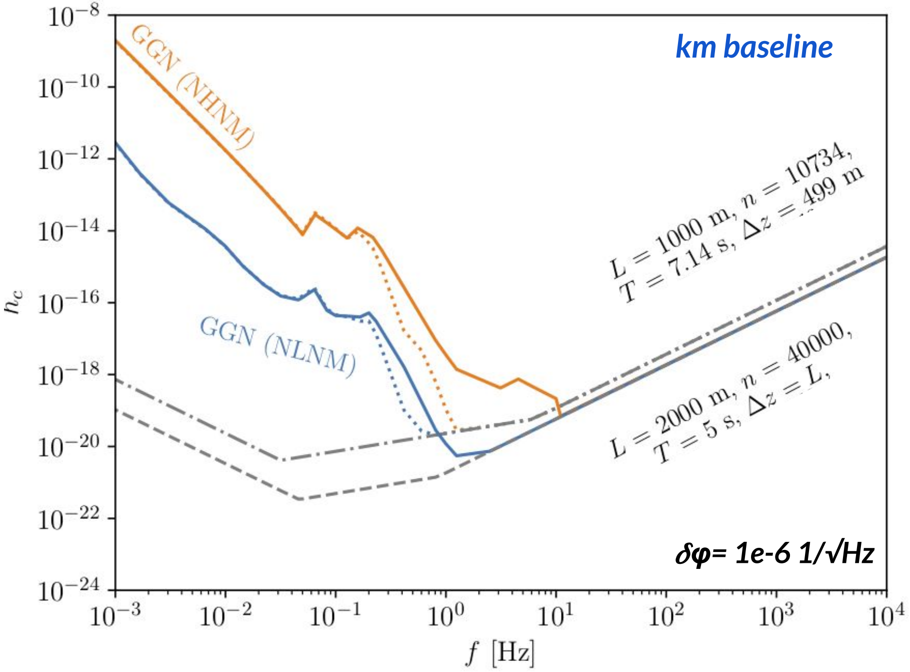




Select sites as close as possible to the NLNM line

Solution 2: Adjusting T and Δz (GW)





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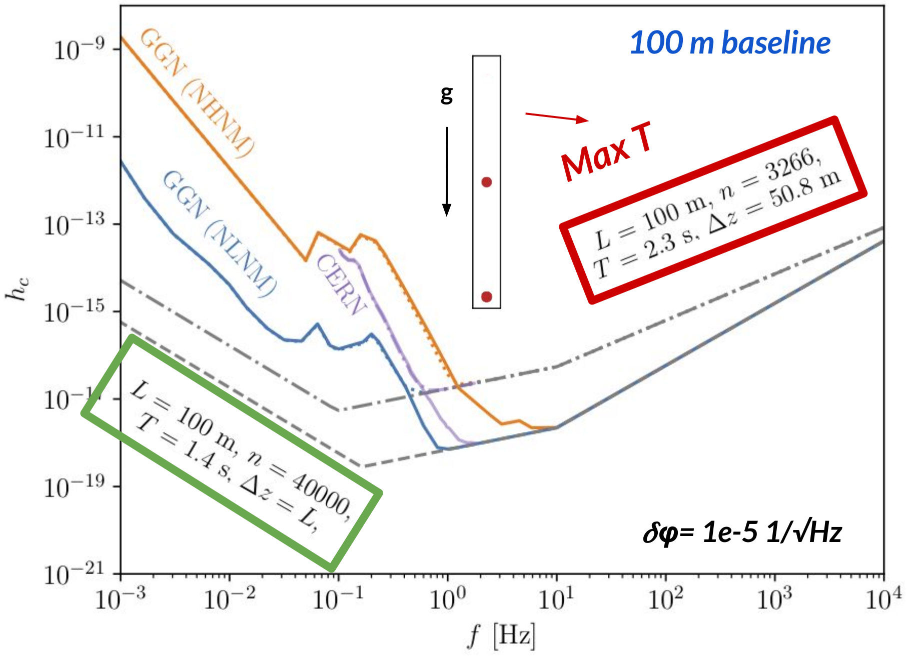

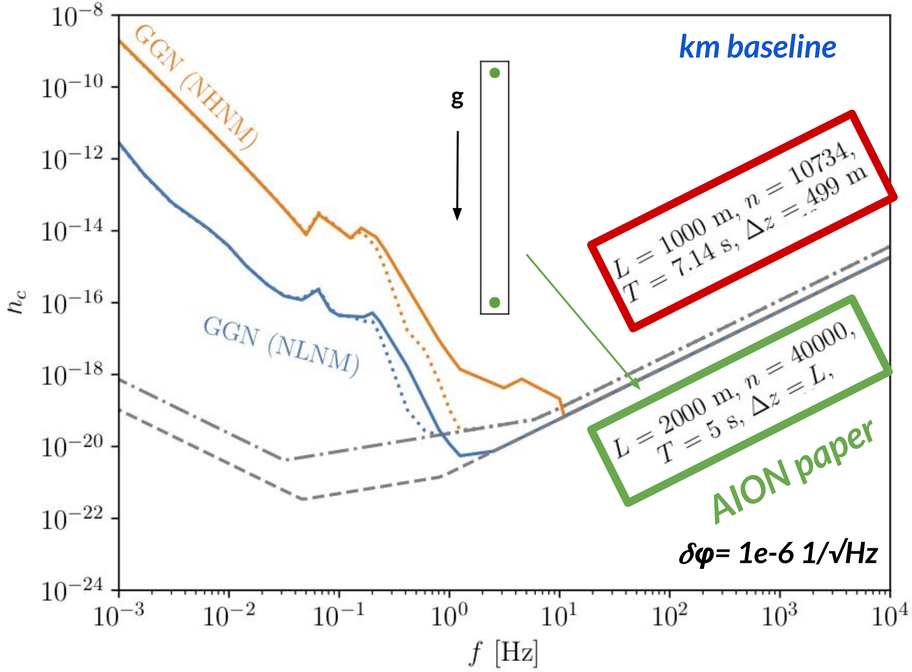

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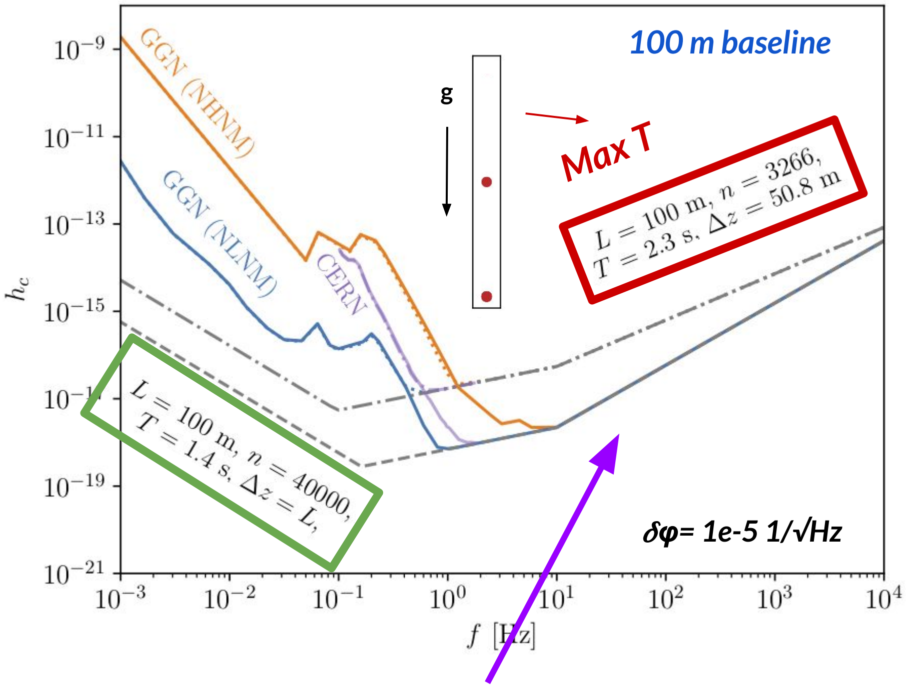

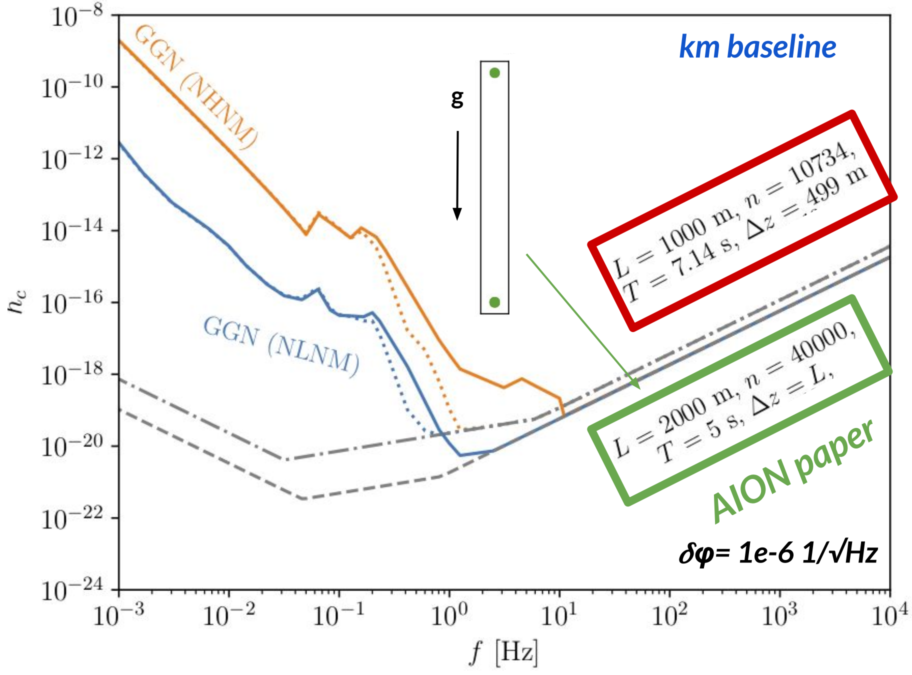

1-2 orders of magnitude loss in sensitivity

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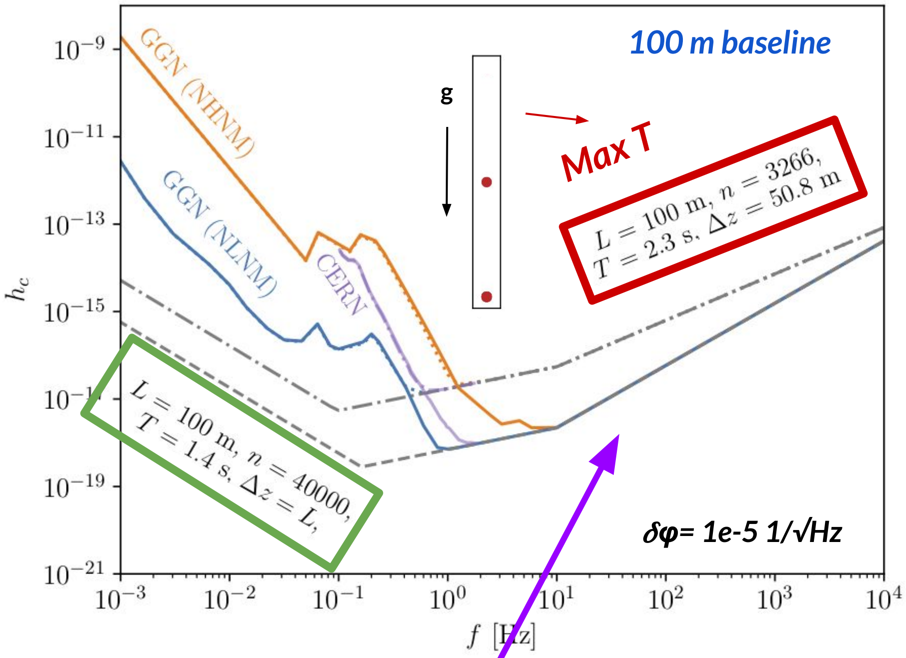

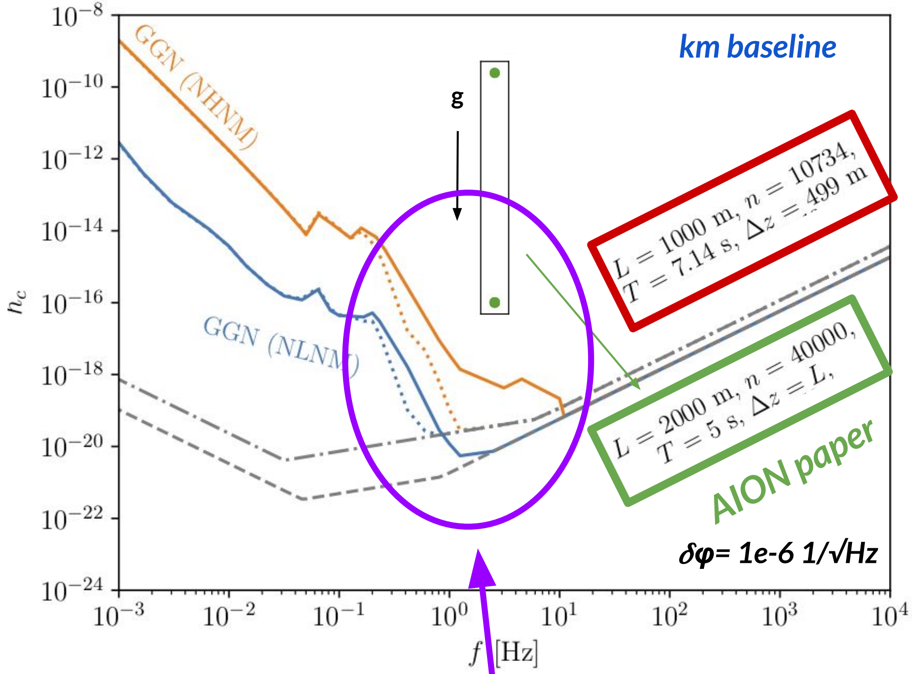

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Better suppression of GGN!

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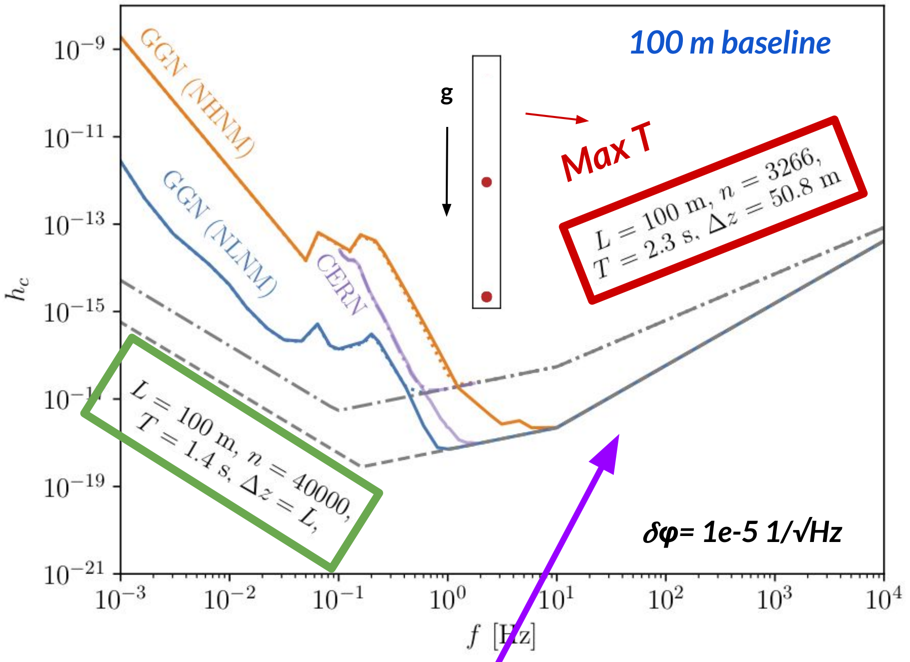
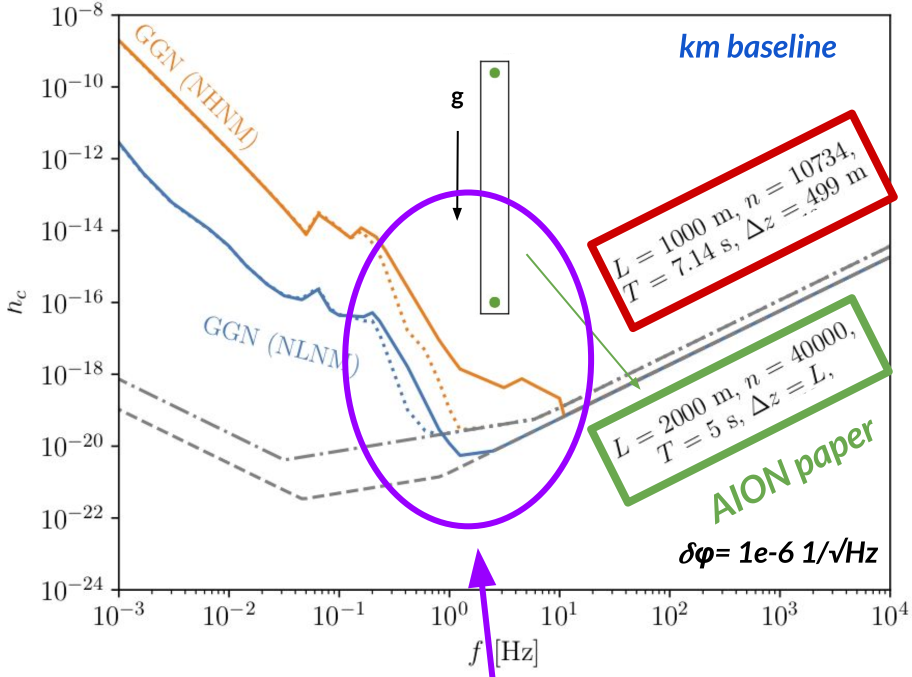
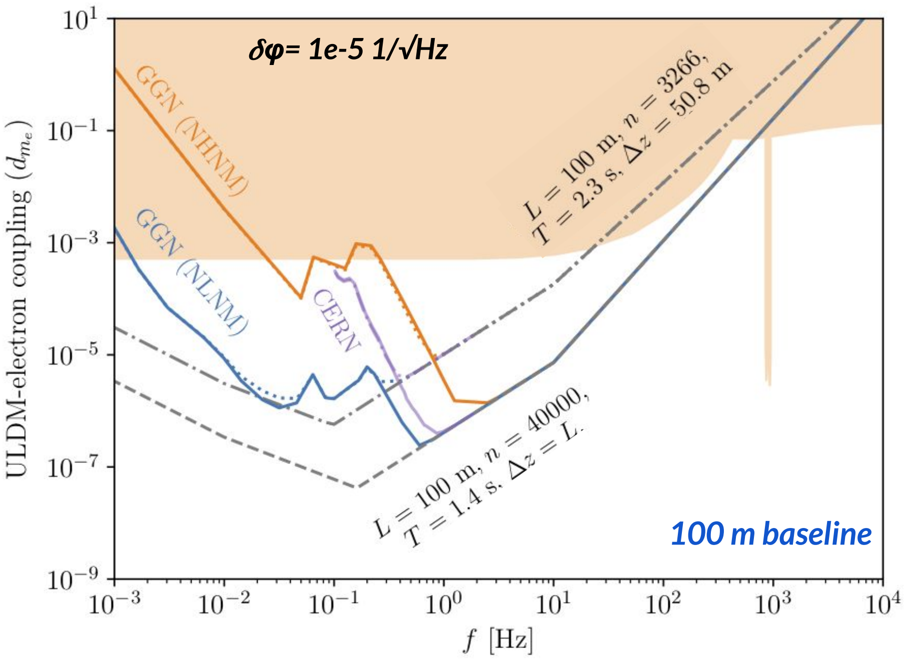
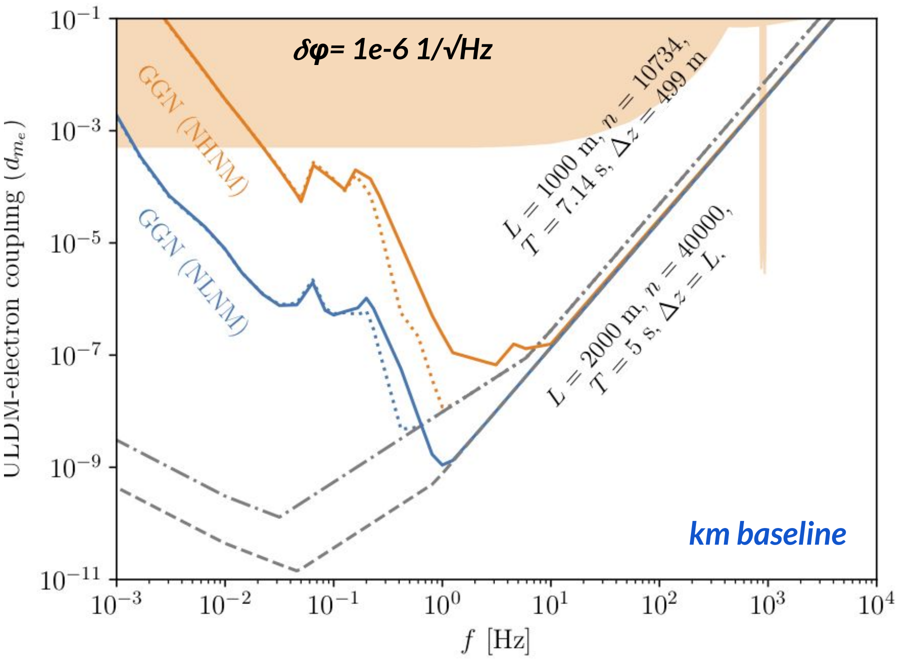




Choose large T and position the experiments away from the surface

Solution 2: Adjusting T and Δz (ULDM)





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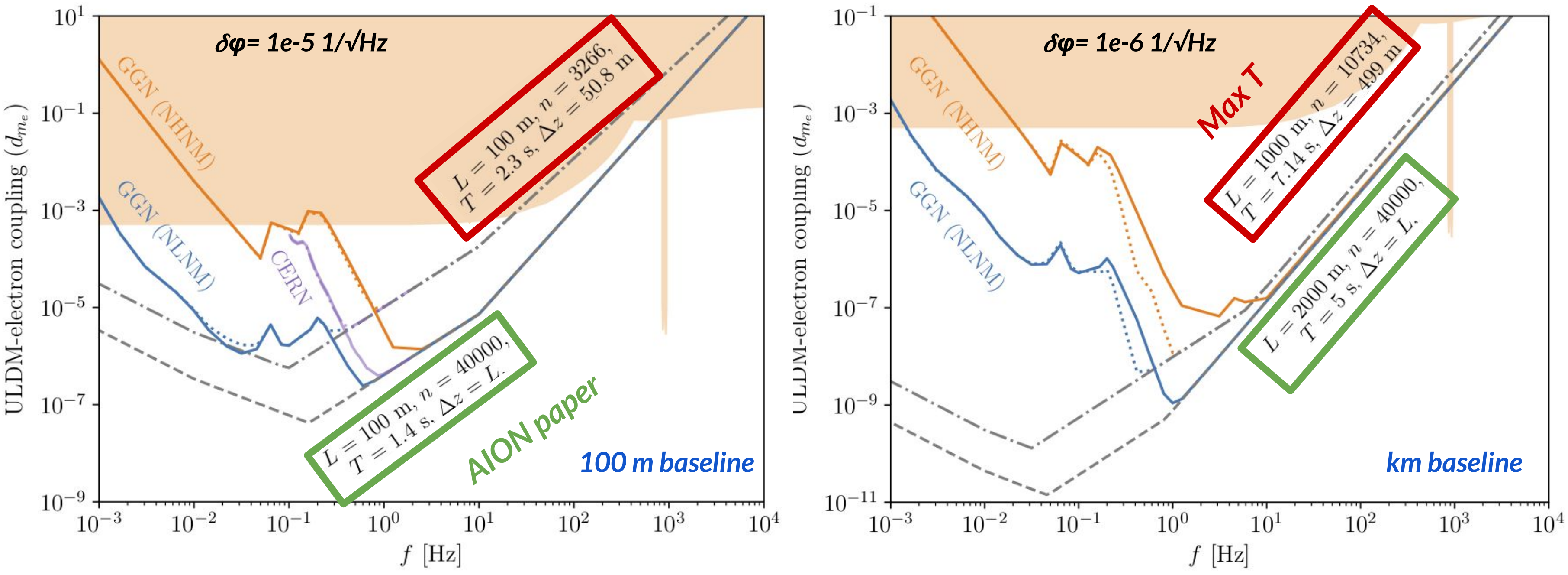

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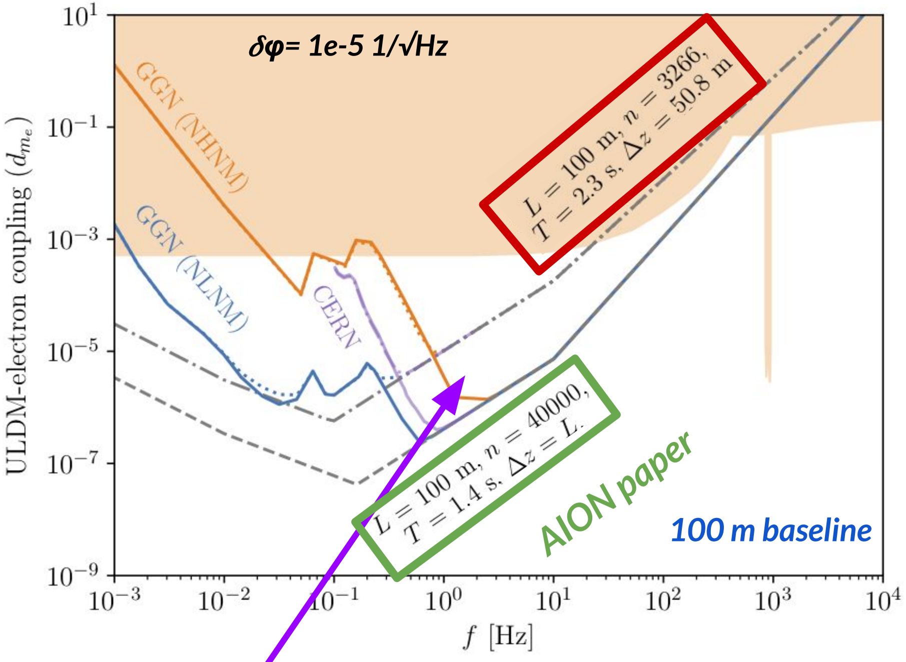

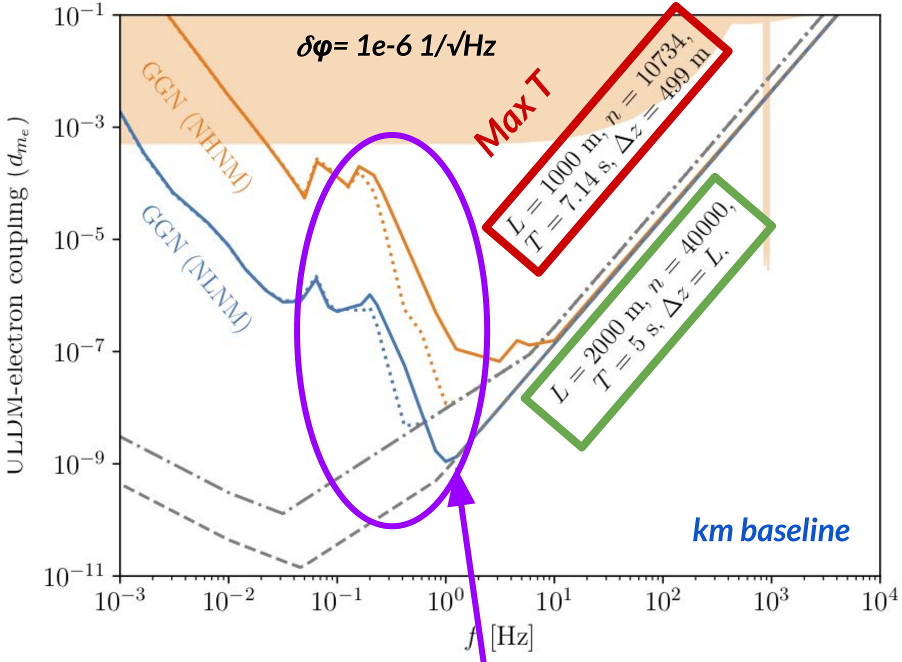

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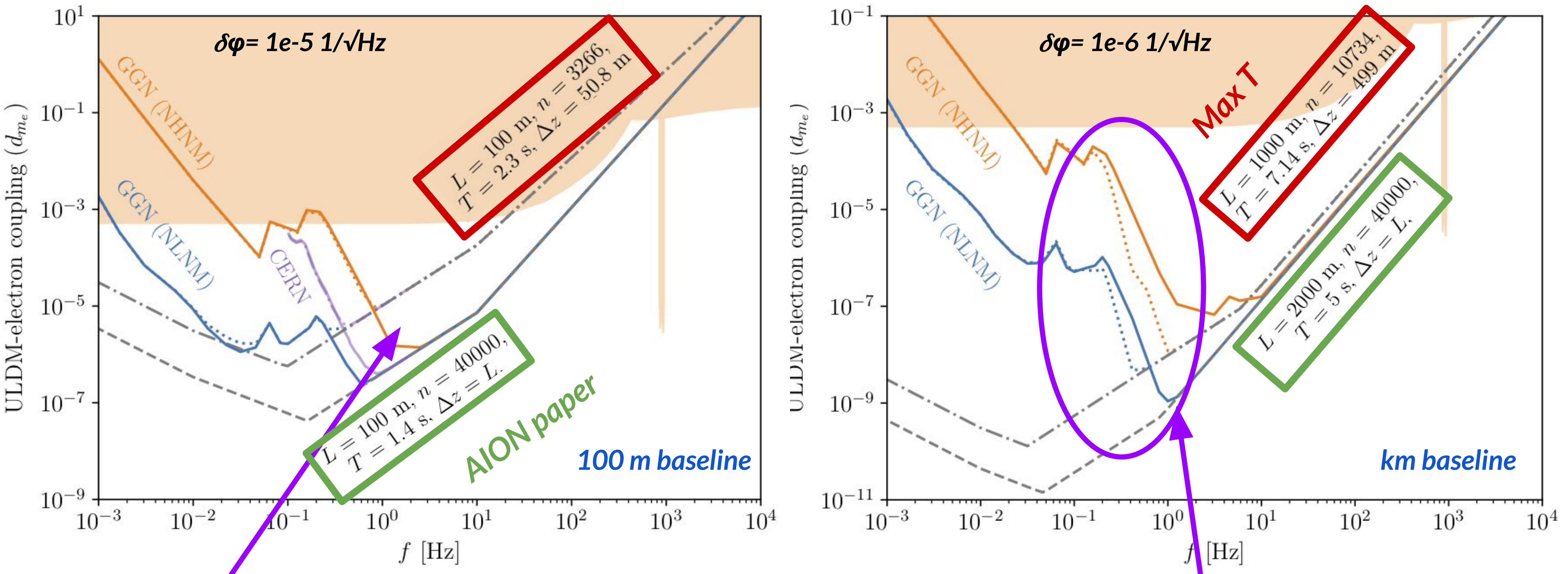

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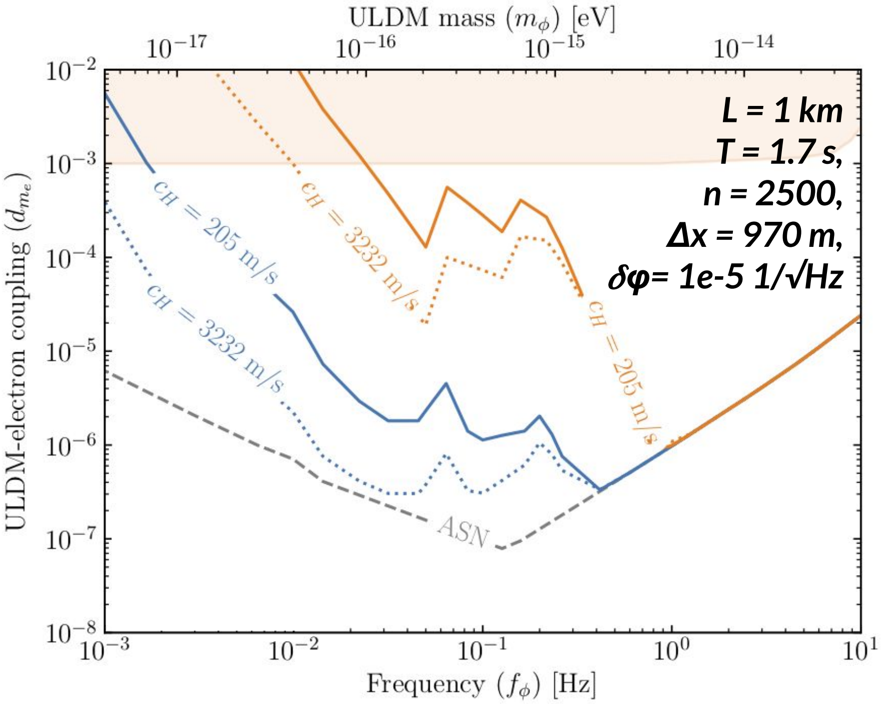

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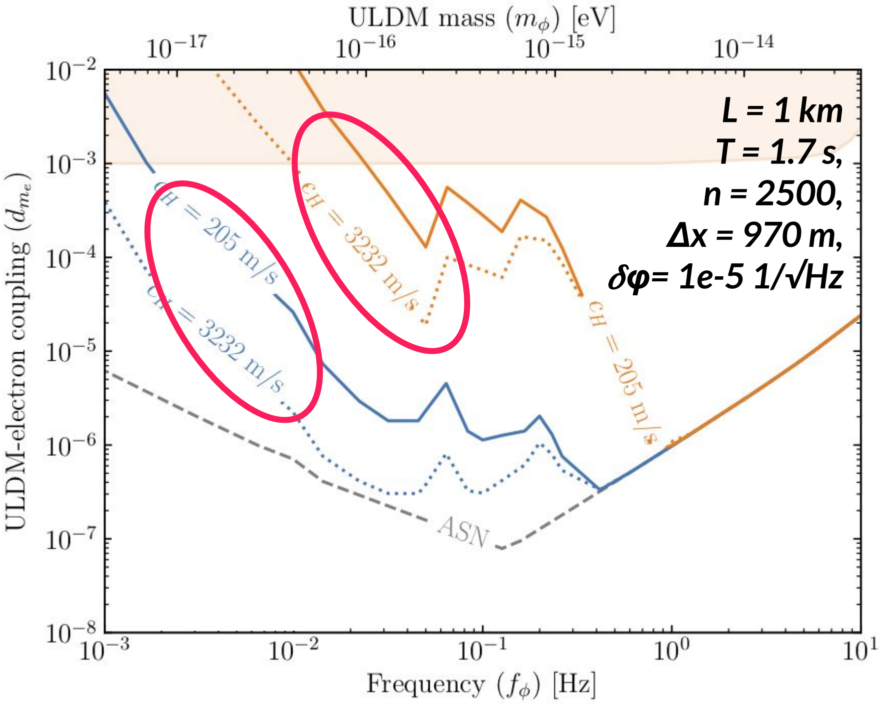

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$$\omega \ll \pi/T$$

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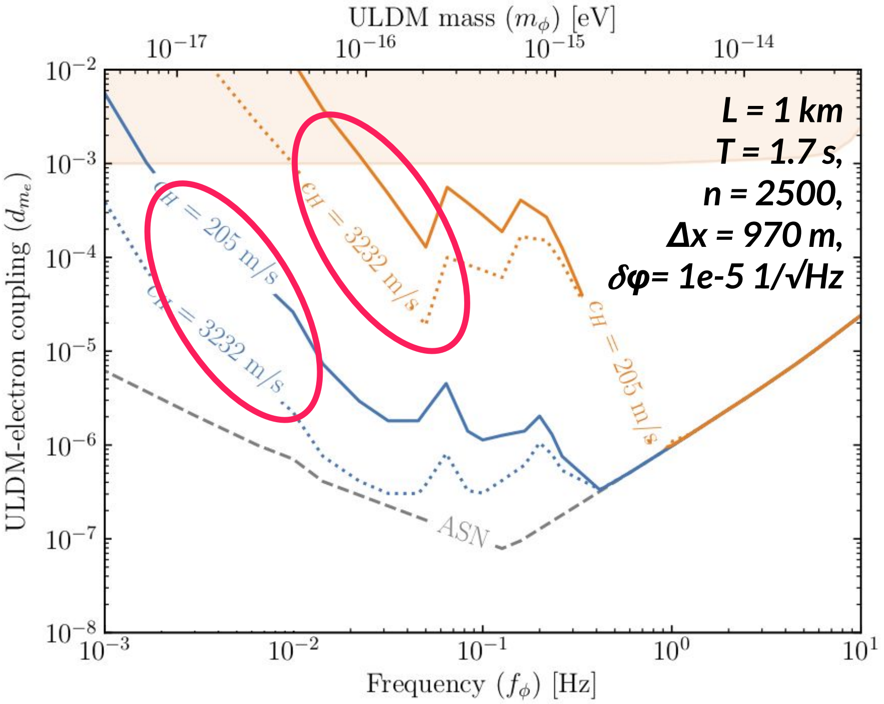

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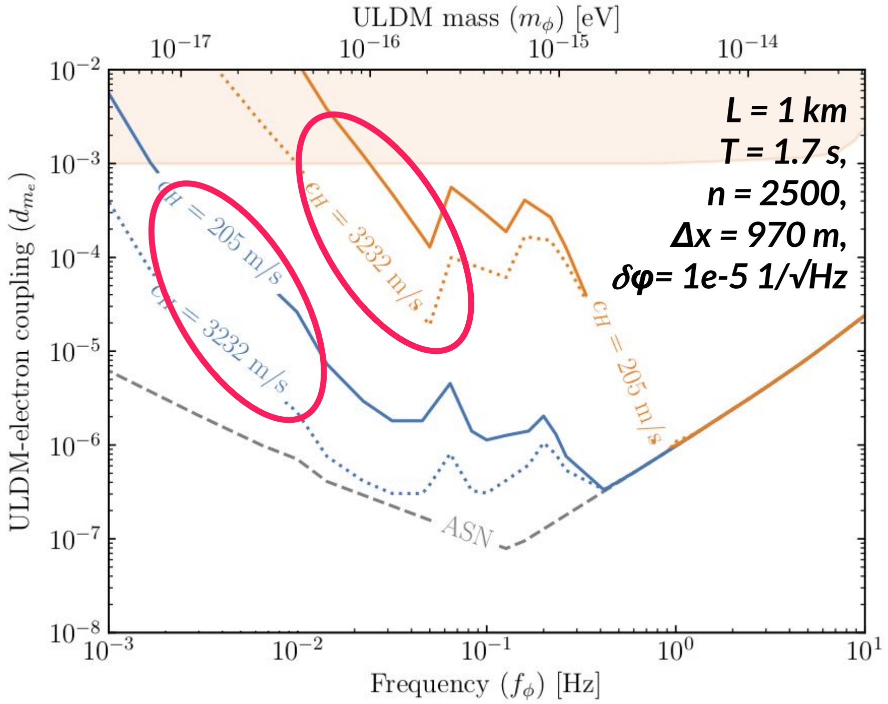

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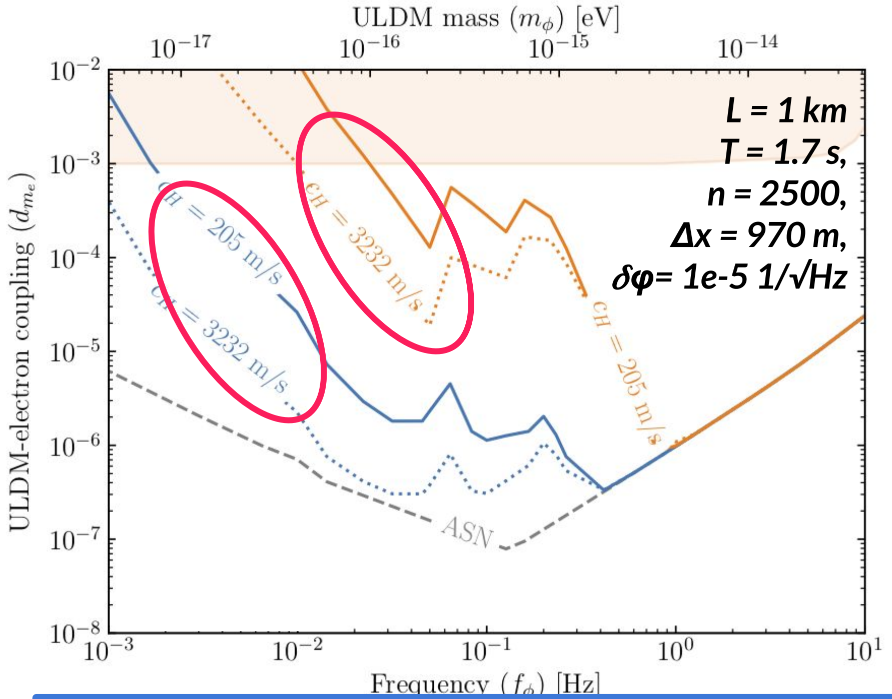

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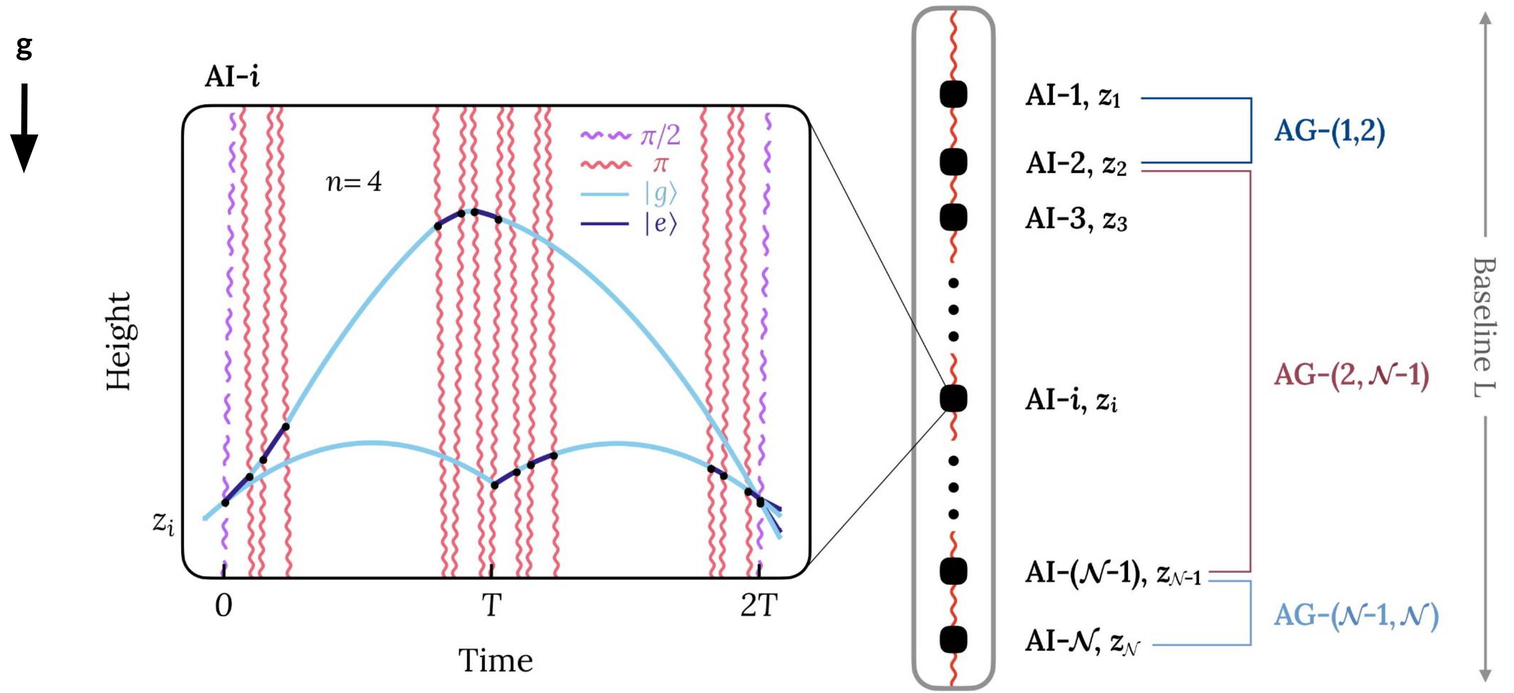
Choose sites with high Rayleigh wave propagation speed

Solution 4: implementing multigradiometer configurations



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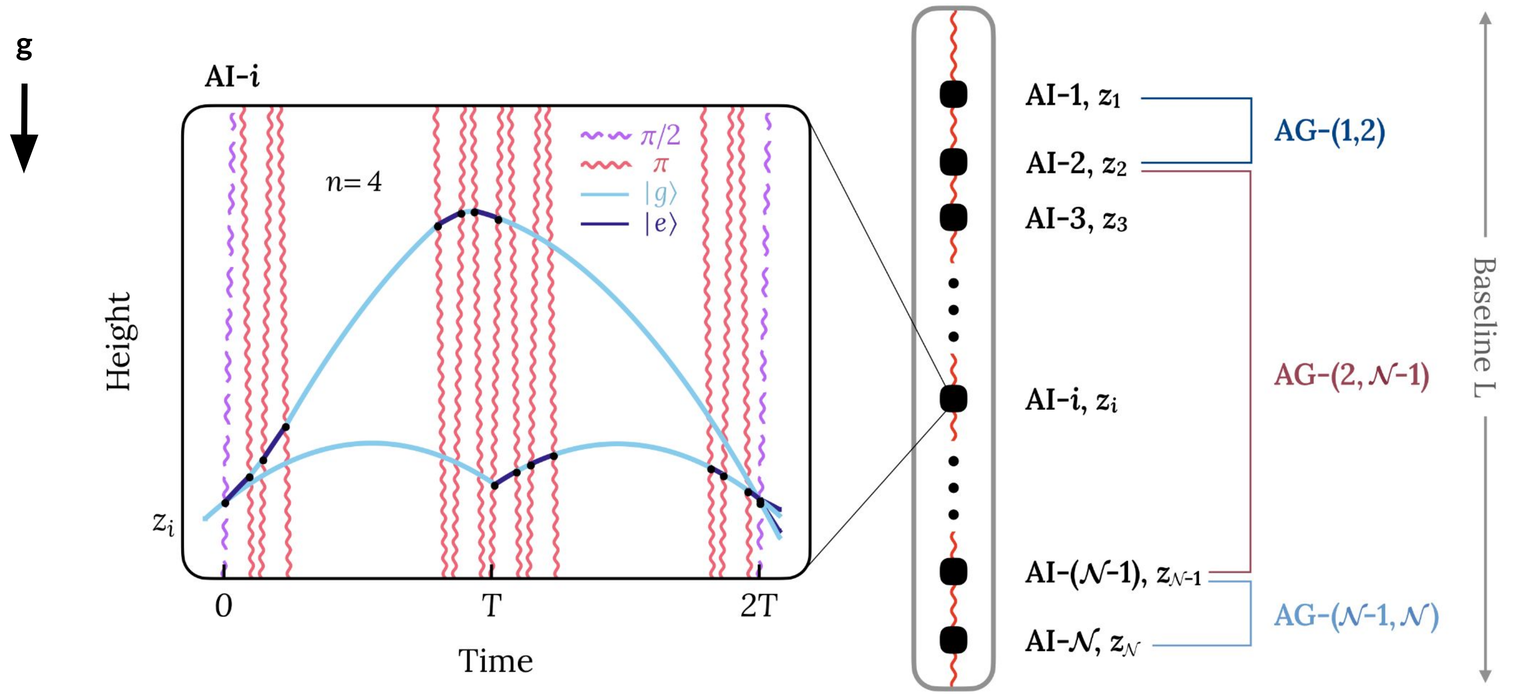
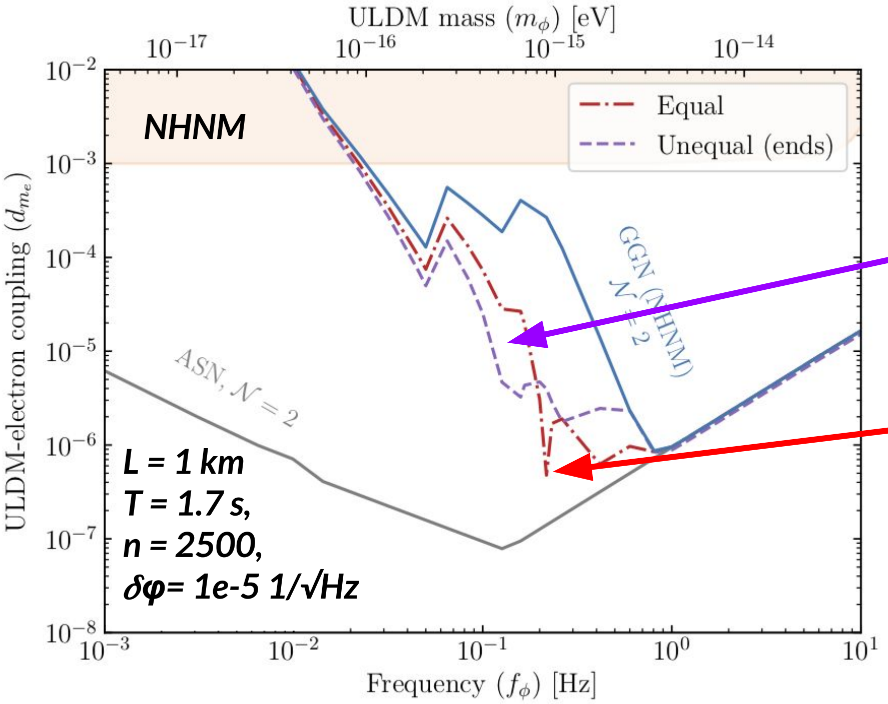
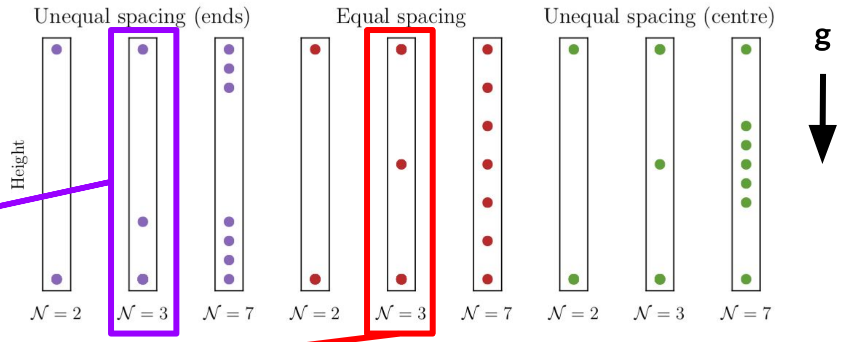


We can benefit from probing different length scales

Solution 4: implementing multigradiometer configurations



Example configurations



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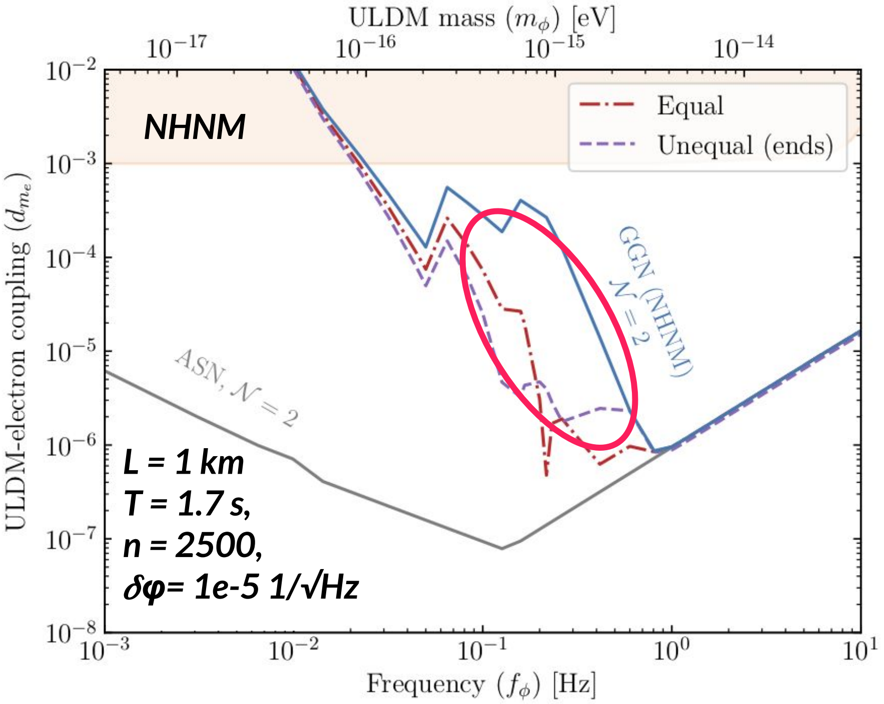

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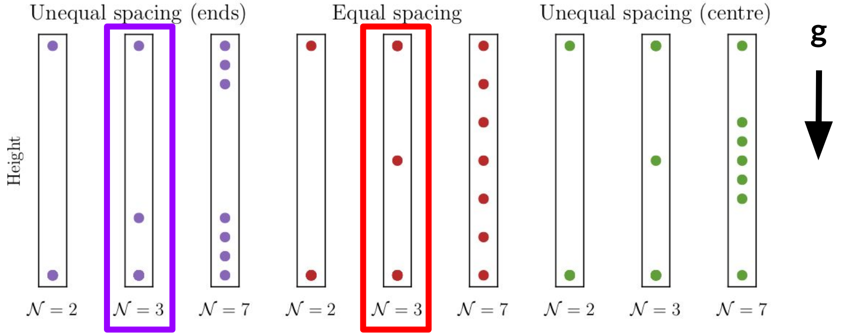
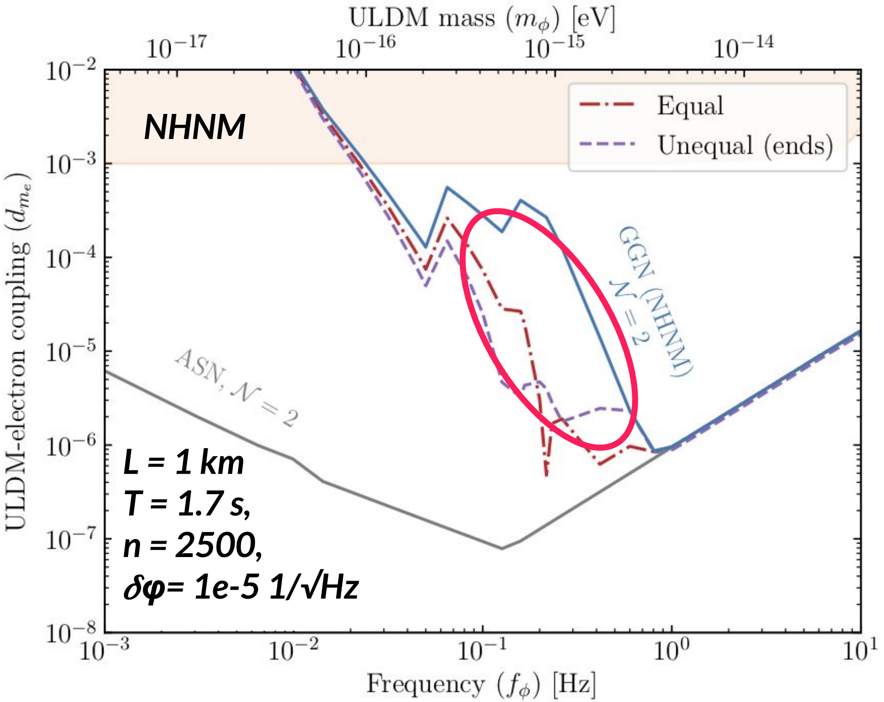


2 to 3 equally-spaced interferometers

Almost an order of magnitude sensitivity improvement between 0.1 Hz and 1 Hz!

Solution 4: implementing multigradiometer configurations



$$\lambda_{\mathrm{GGN}} = \frac{c_H}{\omega_a} \simeq 100\ \mathrm{m}\left(\frac{250\ \mathrm{m\ s^{-1}}}{c_H}\right)^{-1}\left(\frac{2.5\ \mathrm{Hz}}{\omega}\right)$$

$$\lambda_{\mathrm{GGN}} \lesssim \Delta z$$

$$\omega \lesssim \pi/T$$

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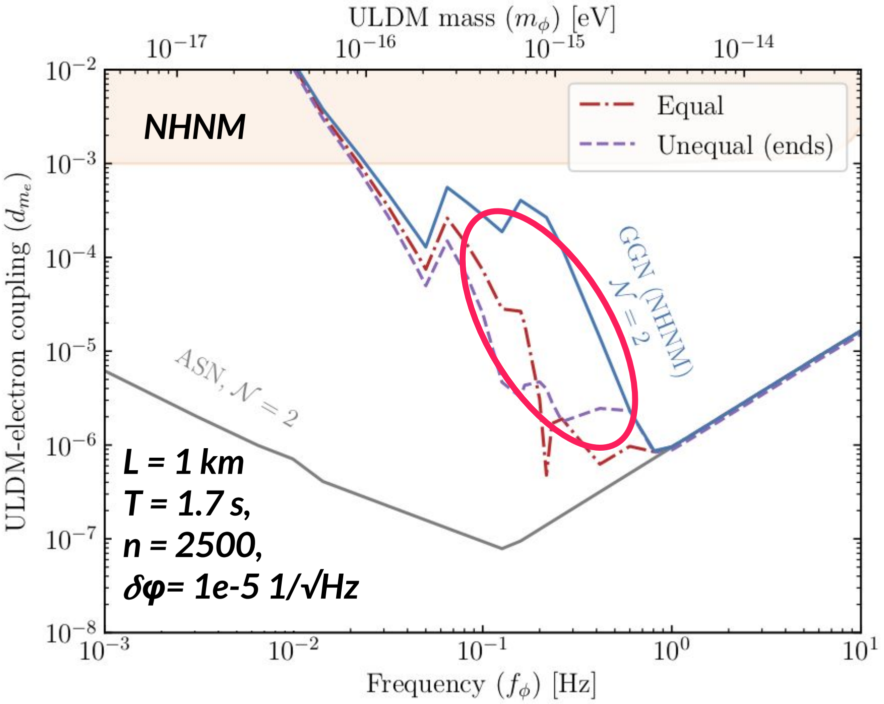

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$$\omega \lesssim \pi/T$$

$$\Phi \propto \Delta z/\omega$$

$$\Phi_{\rm GGN} \propto |\exp(-\omega_a z_i/c_H) - \exp(-\omega_a z_j/c_H)|/\omega_a^2$$

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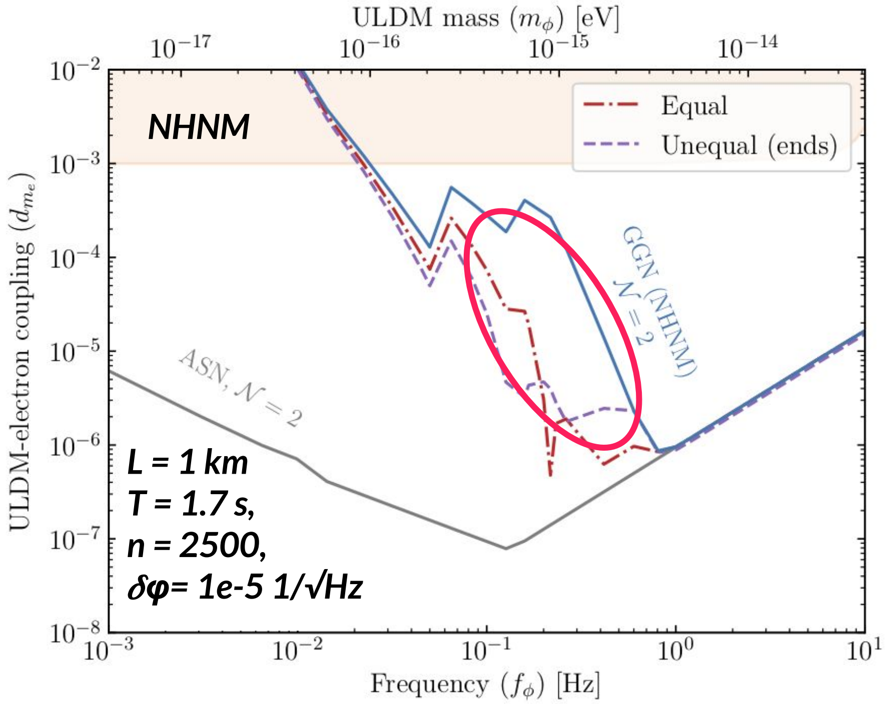

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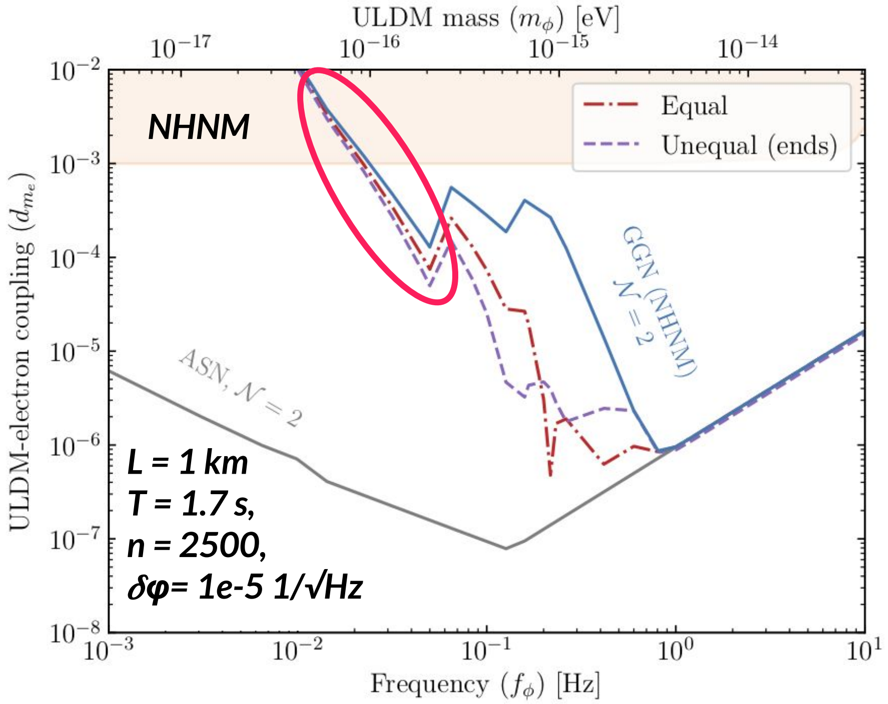
$$d_\phi^{\mathrm{best}} \text{ for } z_1 = L \text{ and } z_1 = \Delta z \text{ small}$$

Solution 4: implementing multigradiometer configurations



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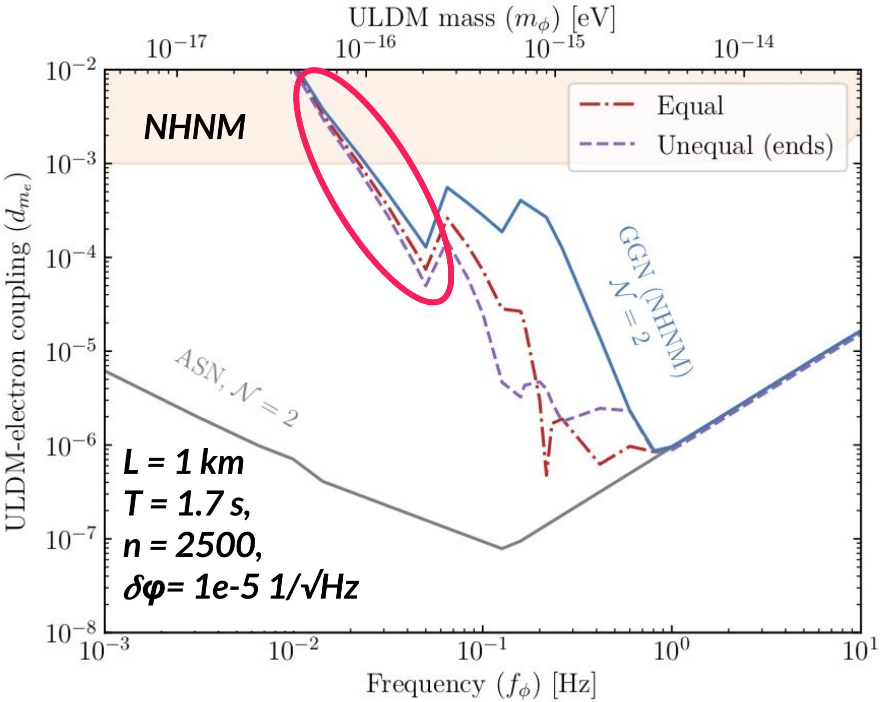

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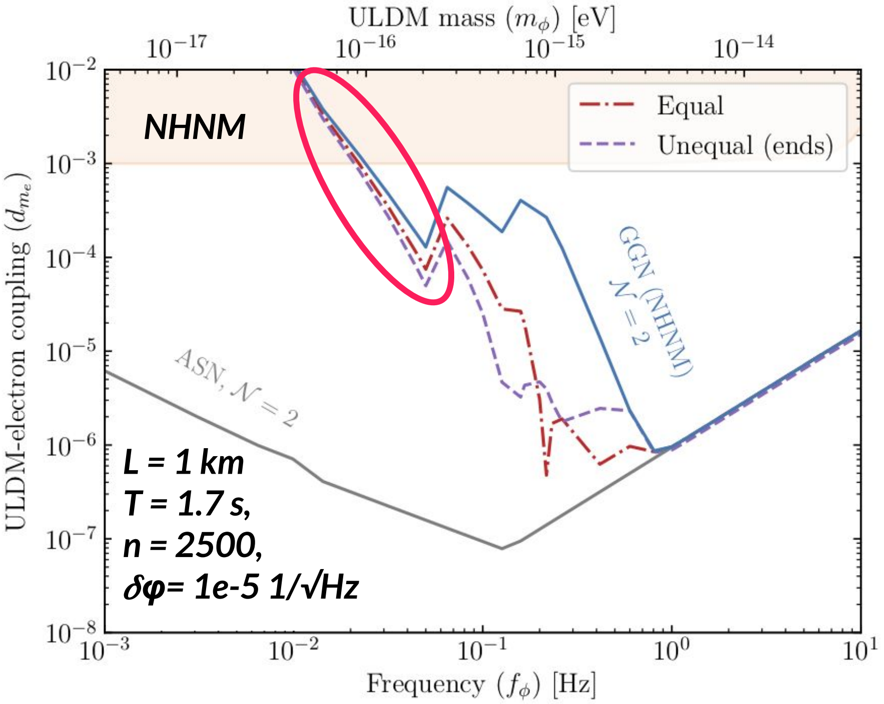

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d_ϕ independent of Δz

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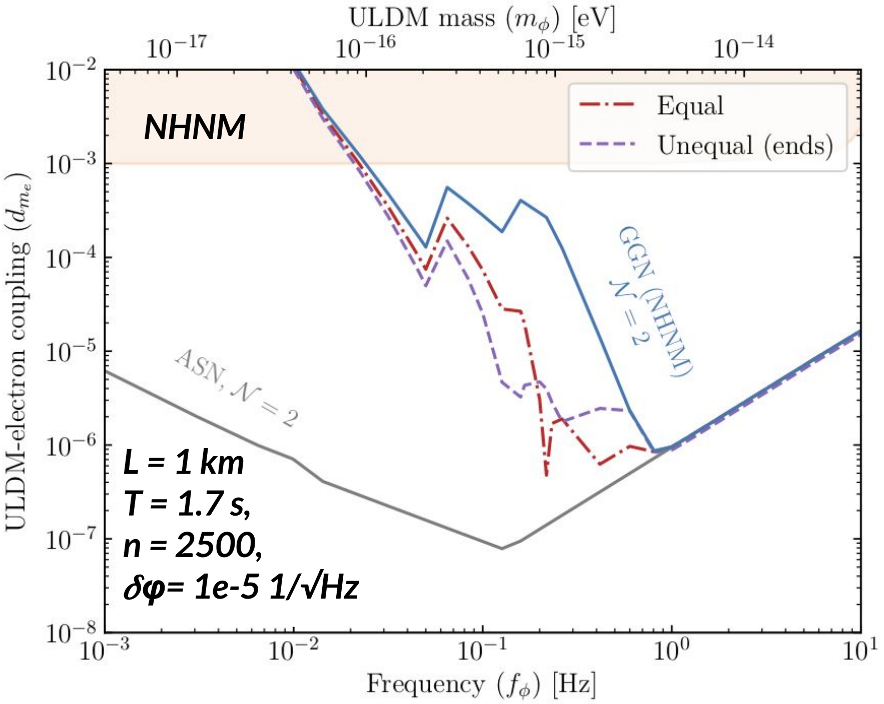

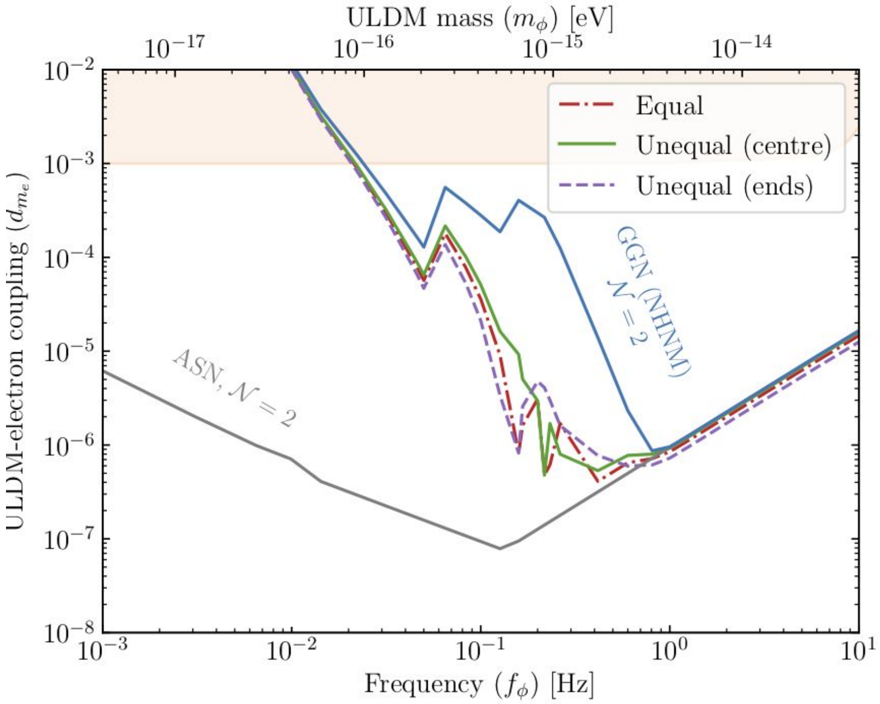

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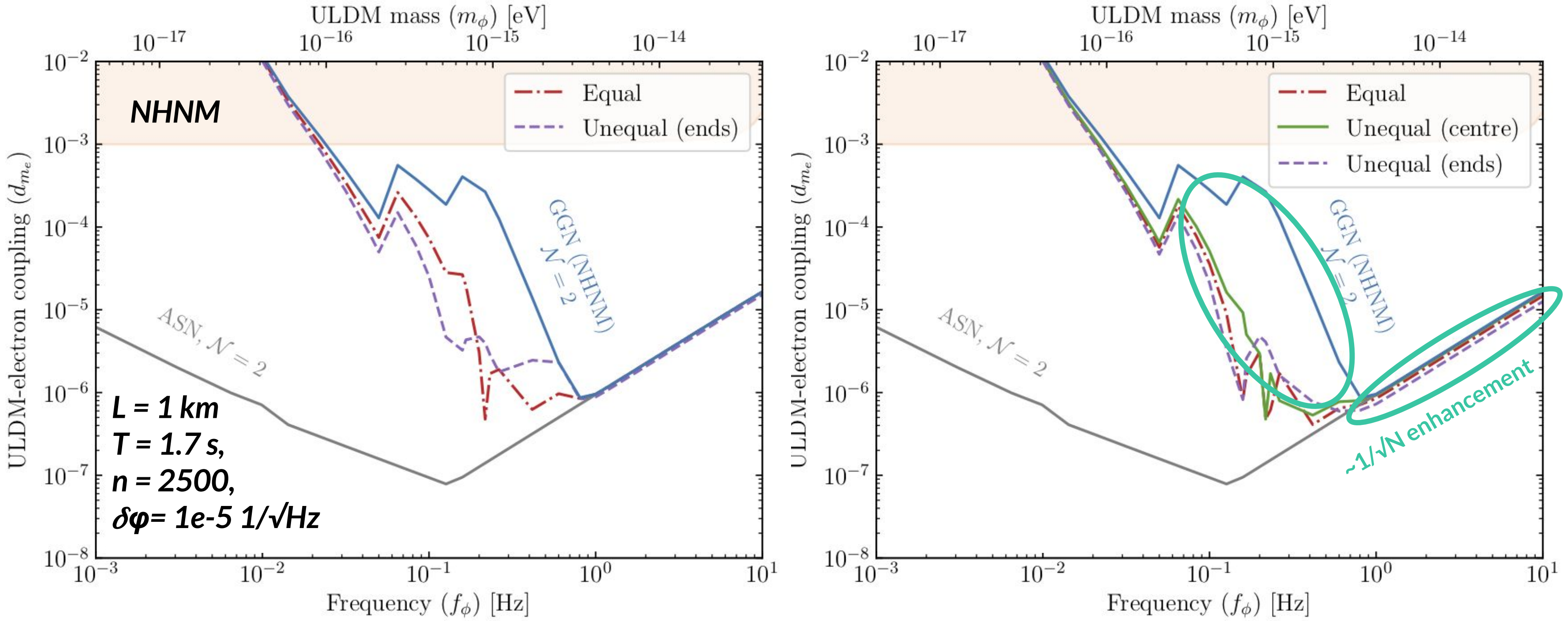
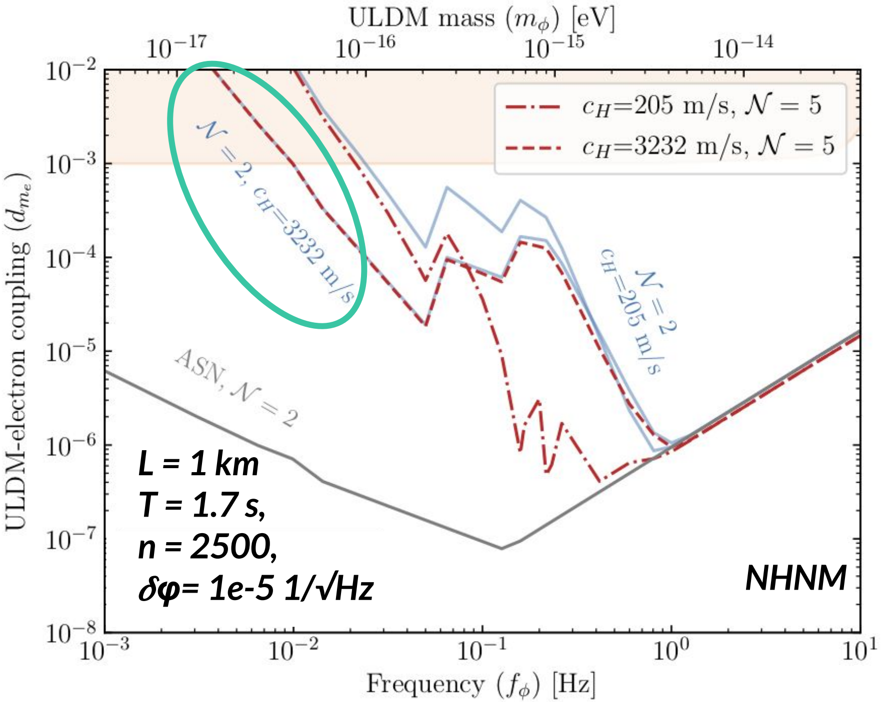


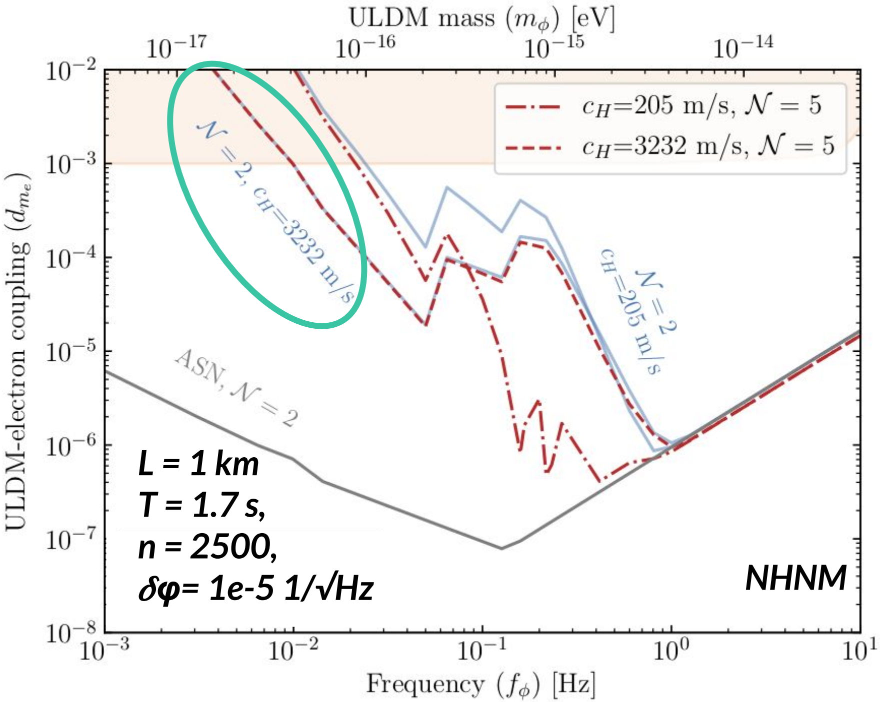
The gain from adding more than 3 interferometers is less dramatic

Solution 4: implementing multigradiometer configurations



A longer decay length renders the multi-gradiometer set-up less useful

Solution 4: implementing multigradiometer configurations



A multigradiometer configuration may be useful in strata with low c_H

Conclusions

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Future work: Mitigation of GGN through active noise-filtering techniques (seismometer array), multi-strata models (Rayleigh overtones).