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Extracting signal from noisy very-long baseline atom interferometers

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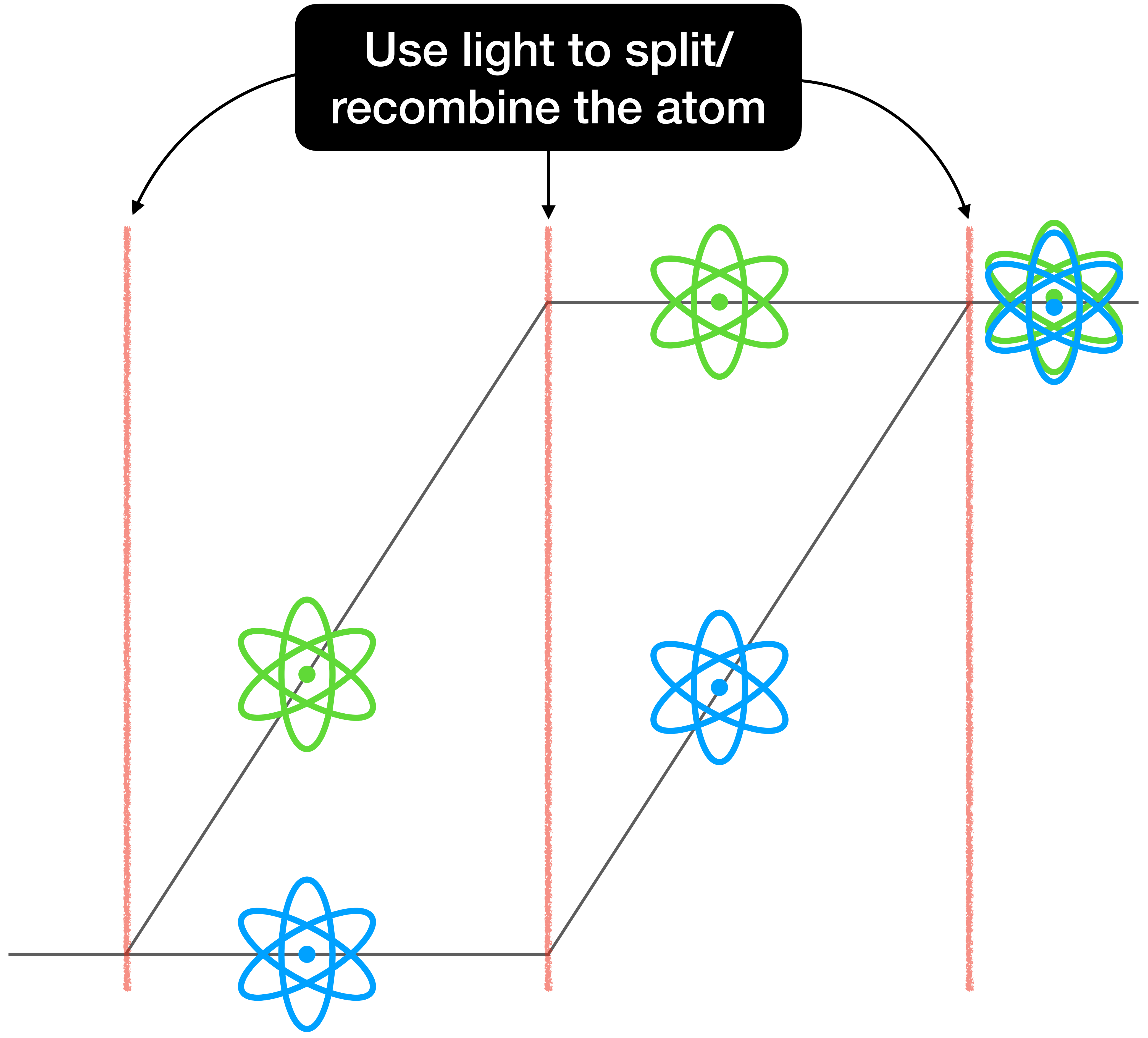
Introduction

Introduction

Atom interferometry in a nutshell

- Use cold atoms (BECs at best).
- Coherently split and recombine them using light fields.
- Atoms can also undergo internal state changes (“Clock Interferometry”).
- Measure the phase difference between two parts of the wave function.

Extremely sensitive to rotations and accelerations!

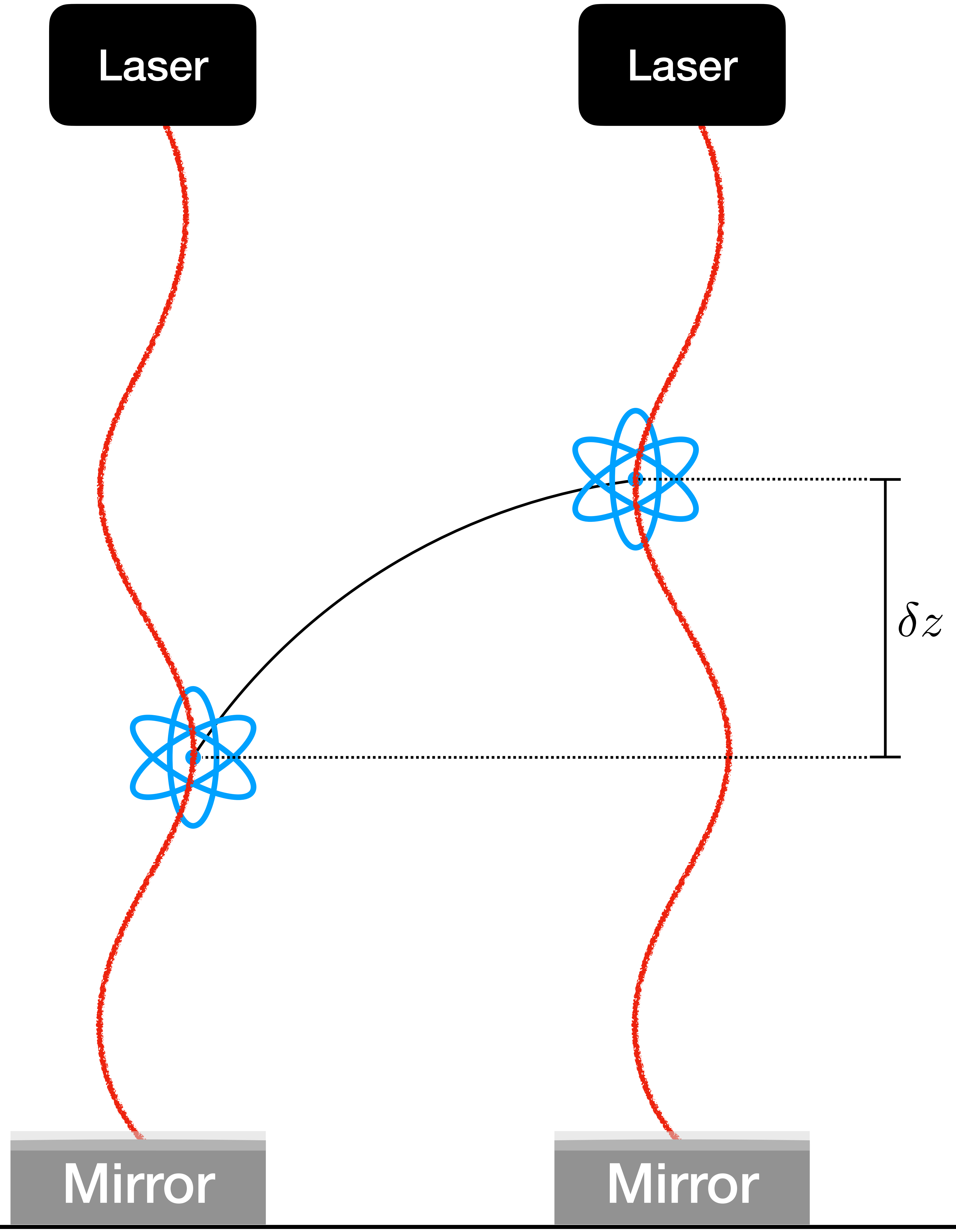


Spatial Superposition $\frac{1}{\sqrt{2}}\left(|\ \rangle+|\ \rangle\right)$

Introduction

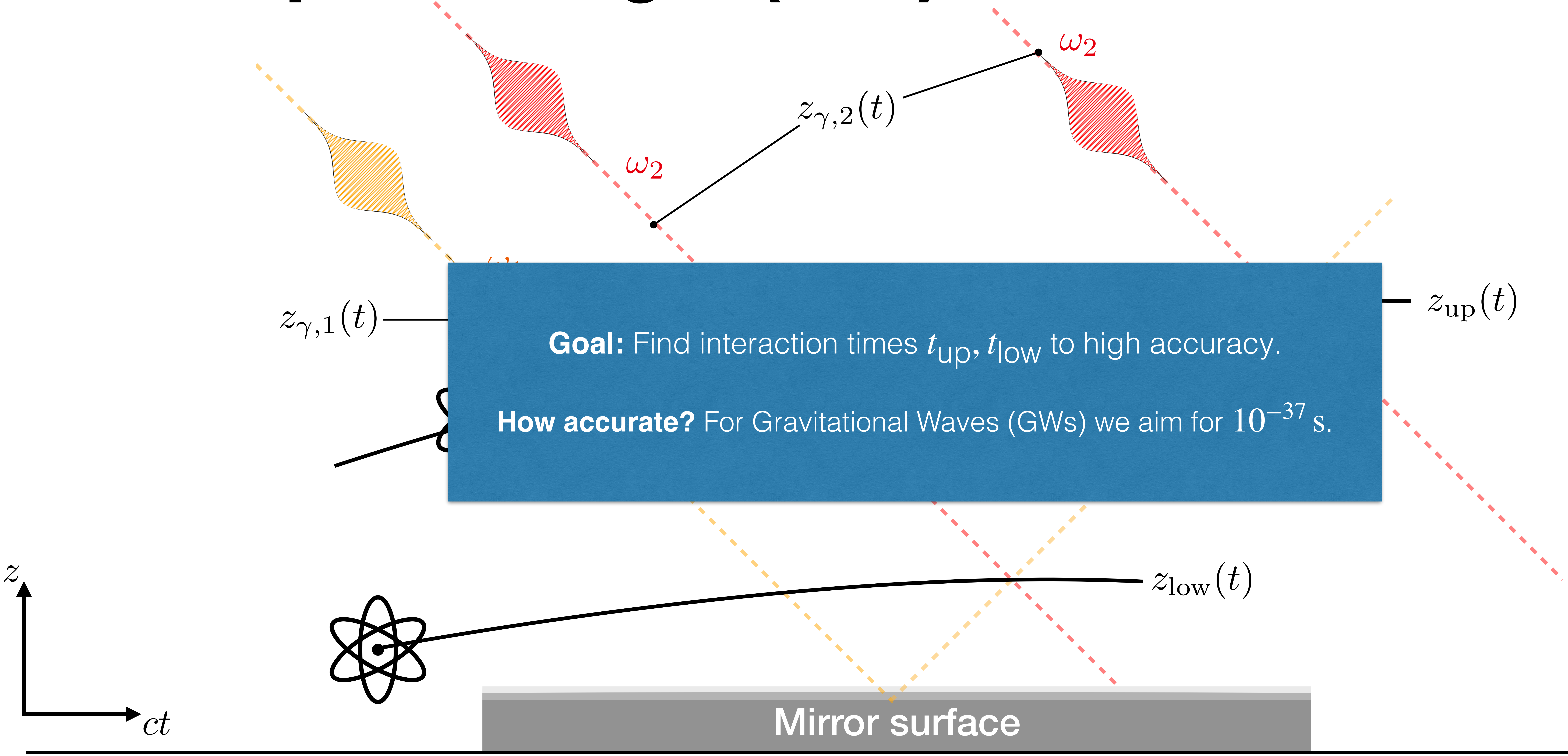
Atom interferometry in a nutshell

- We measure the **atomic position** with respect to the **light field**.
- From atomic position you can get knowledge of **gravitational acceleration** g or the atomic **recoil velocity**.
- For this: **Assume** that the **light field** is **stable**.



Noise Sources

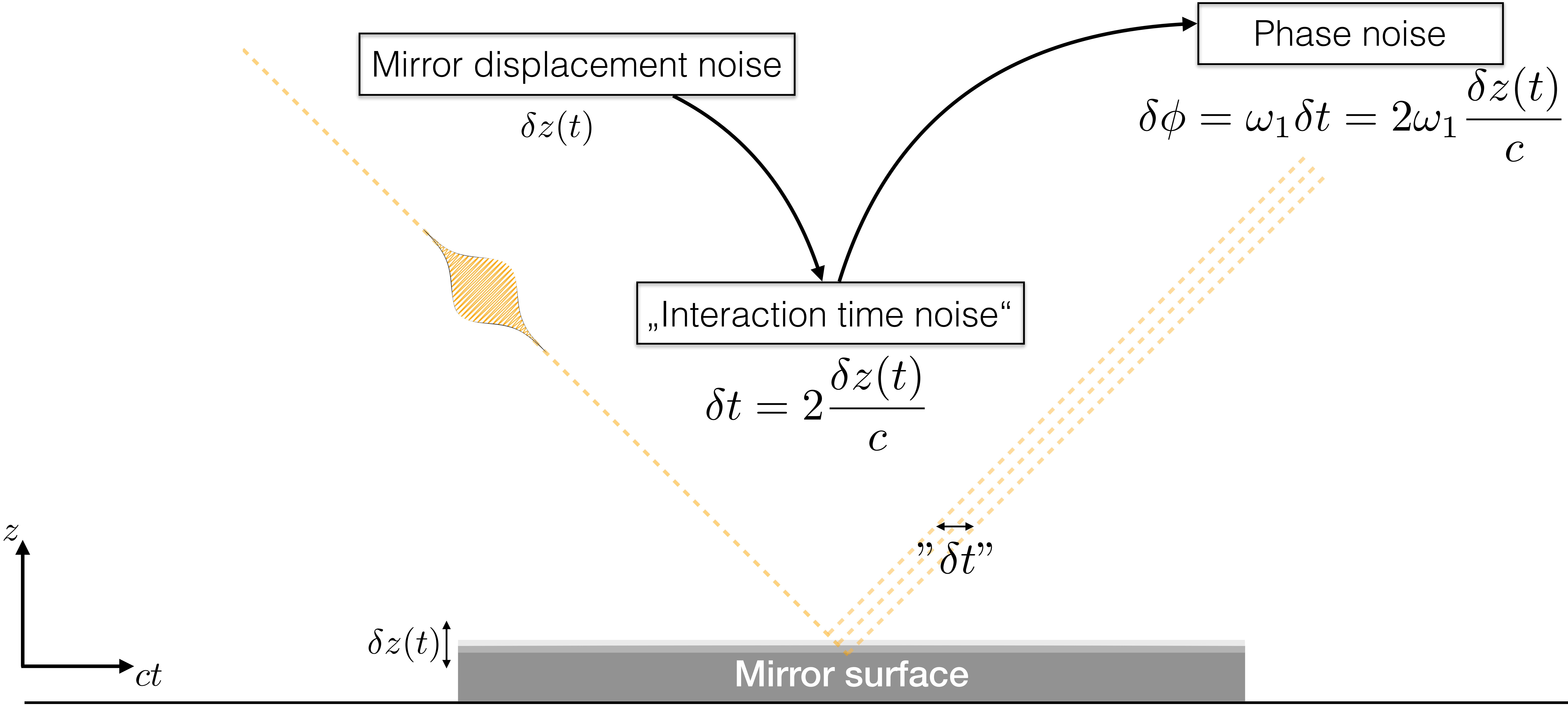
Finite speed of light (FSL)



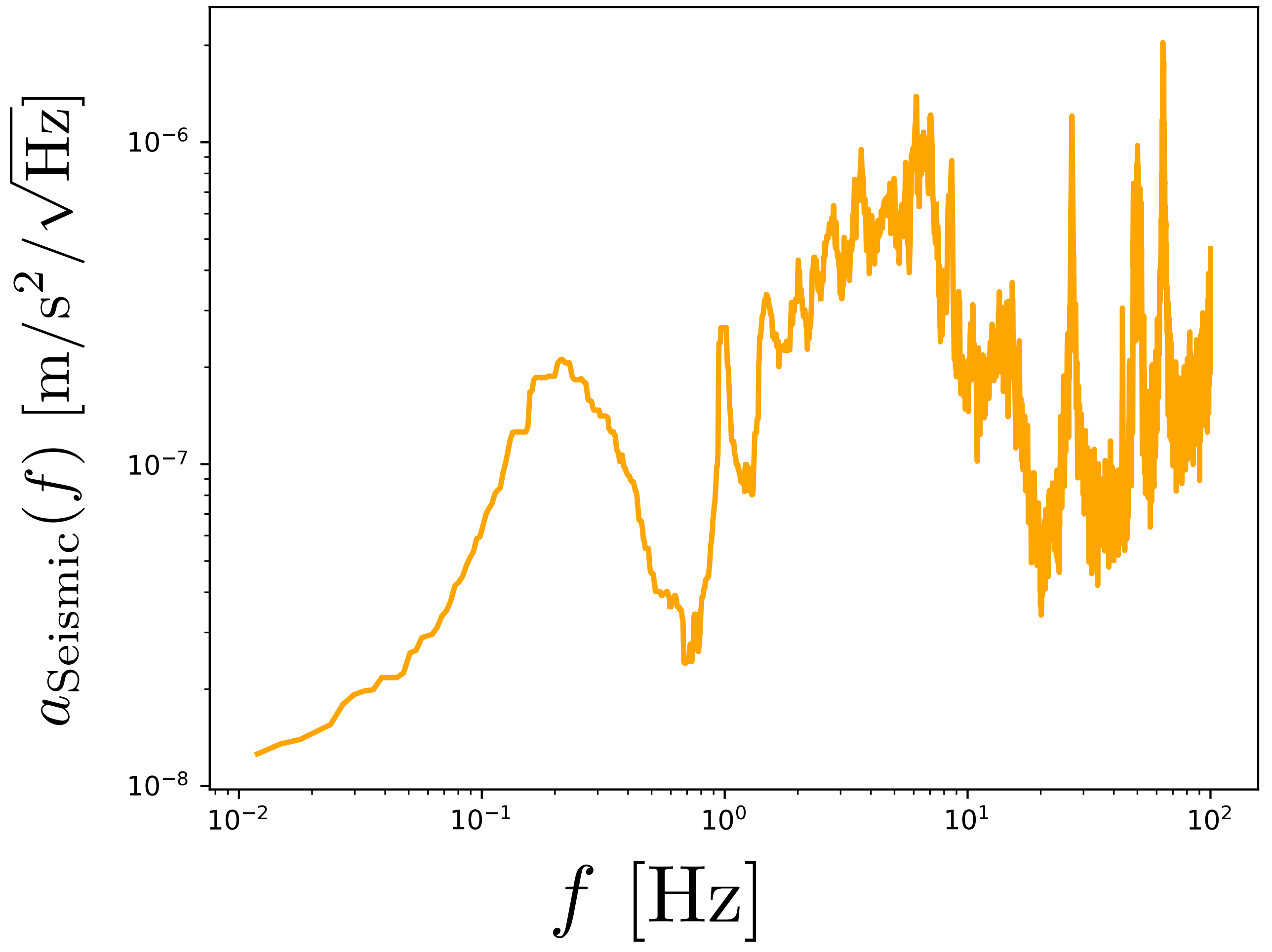
Goal: Find interaction times $t_{\text{up}}, t_{\text{low}}$ to high accuracy.

How accurate? For Gravitational Waves (GWs) we aim for 10^{-37} s.

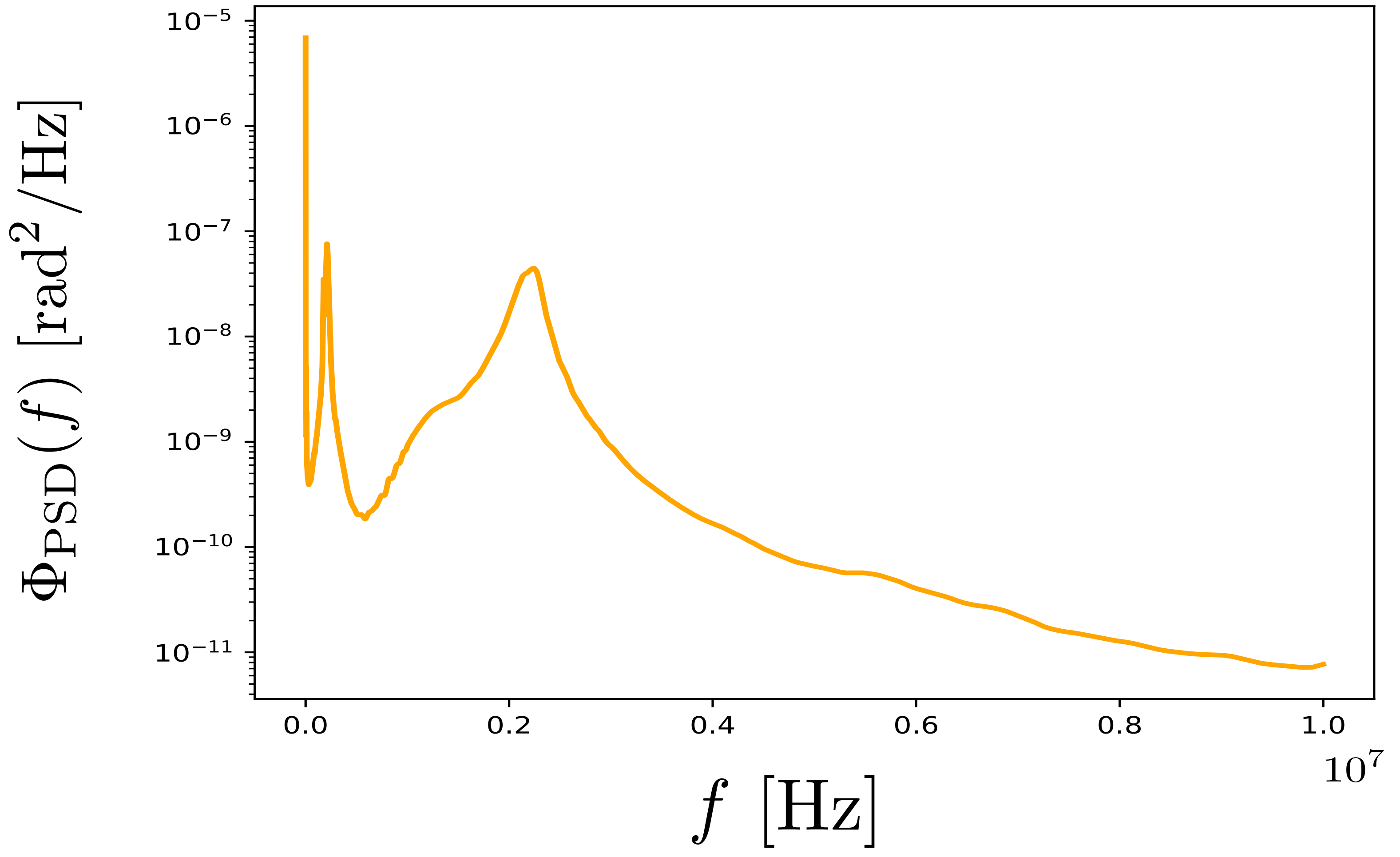
Seismic (Mirror) Noise



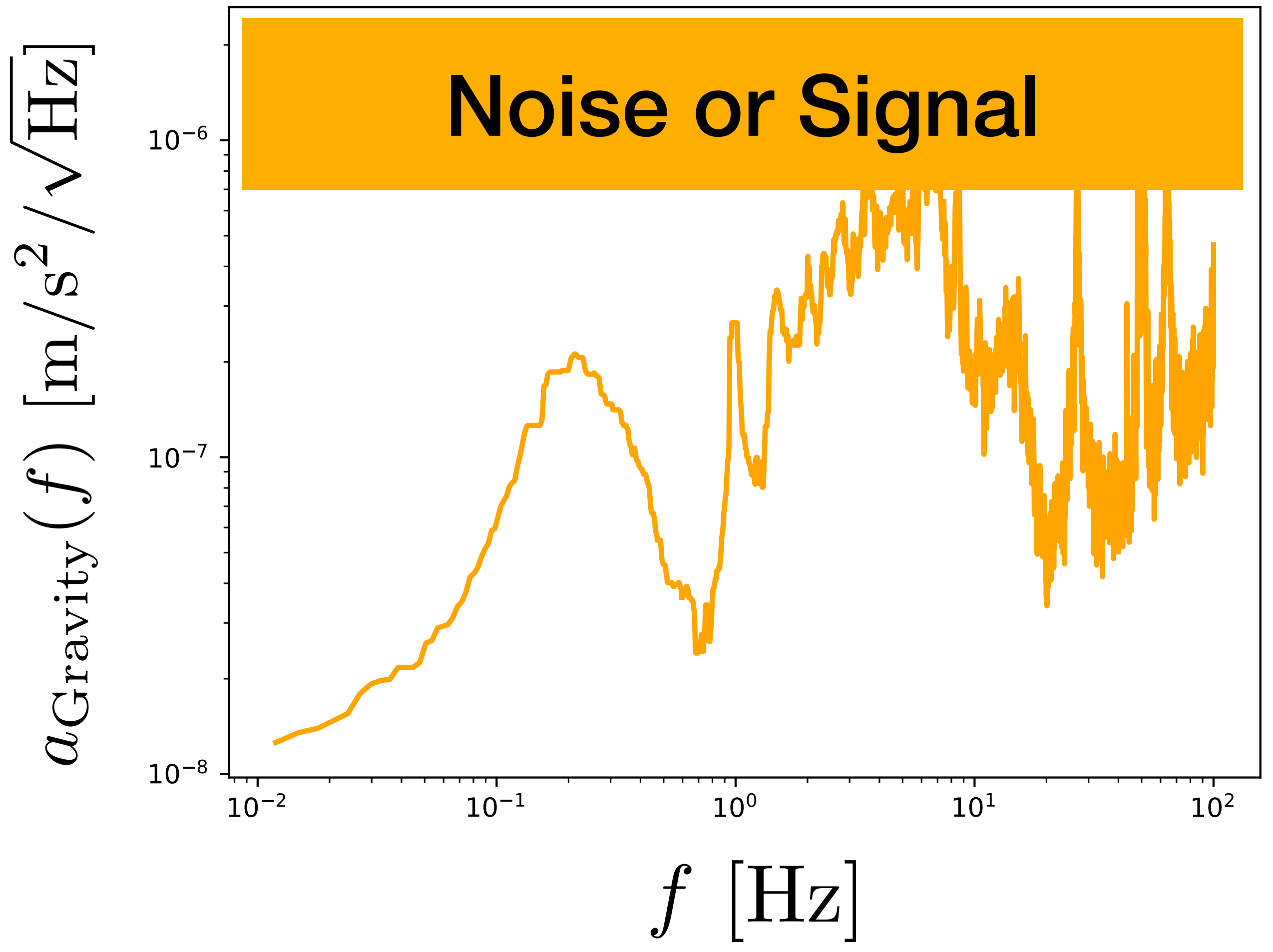
1. Seismic Acceleration ASD



2. Laser Phase Noise PSD



3. Gravity Noise



4. Discretize data

Choose frequencies linearly in the respective intervals

$$f_i \in [10^{-2}\,\mathrm{Hz}, 10^{2}\,\mathrm{Hz}]$$

$$f_j \in [1\,\mathrm{Hz}, 10^{7}\,\mathrm{Hz}]$$

$$f_k \in [10^{-2}\,\mathrm{Hz}, 10^{2}\,\mathrm{Hz}]$$

for indices i, j, k.

Repeat N_S times

5. Create noise model

Sample uniformly random: $\Phi_i, \Phi_j, \Phi_k \in [0, 2\pi)$

$$\delta z(t) = -\sum_i \frac{a_{\mathrm{Seismic}}(f_i)}{\sqrt{(2\pi f_i)^3}} \cdot \sin(2\pi f_i t + \Phi_i)$$

$$\delta\Phi(t) = \sum_j \sqrt{2\pi f_j \Phi_{\mathrm{PSD}}(f_j)} \cdot \sin(2\pi f_j t + \Phi_j)$$

$$\delta g(t) = \sum_k a_{\mathrm{Gravity}}(f_k) \cdot \sqrt{2\pi f_k} \cdot \sin(2\pi f_k t + \Phi_k)$$

$$\delta\phi(t) = -R_{\oplus}\delta g(t)$$

6. Phase sampling

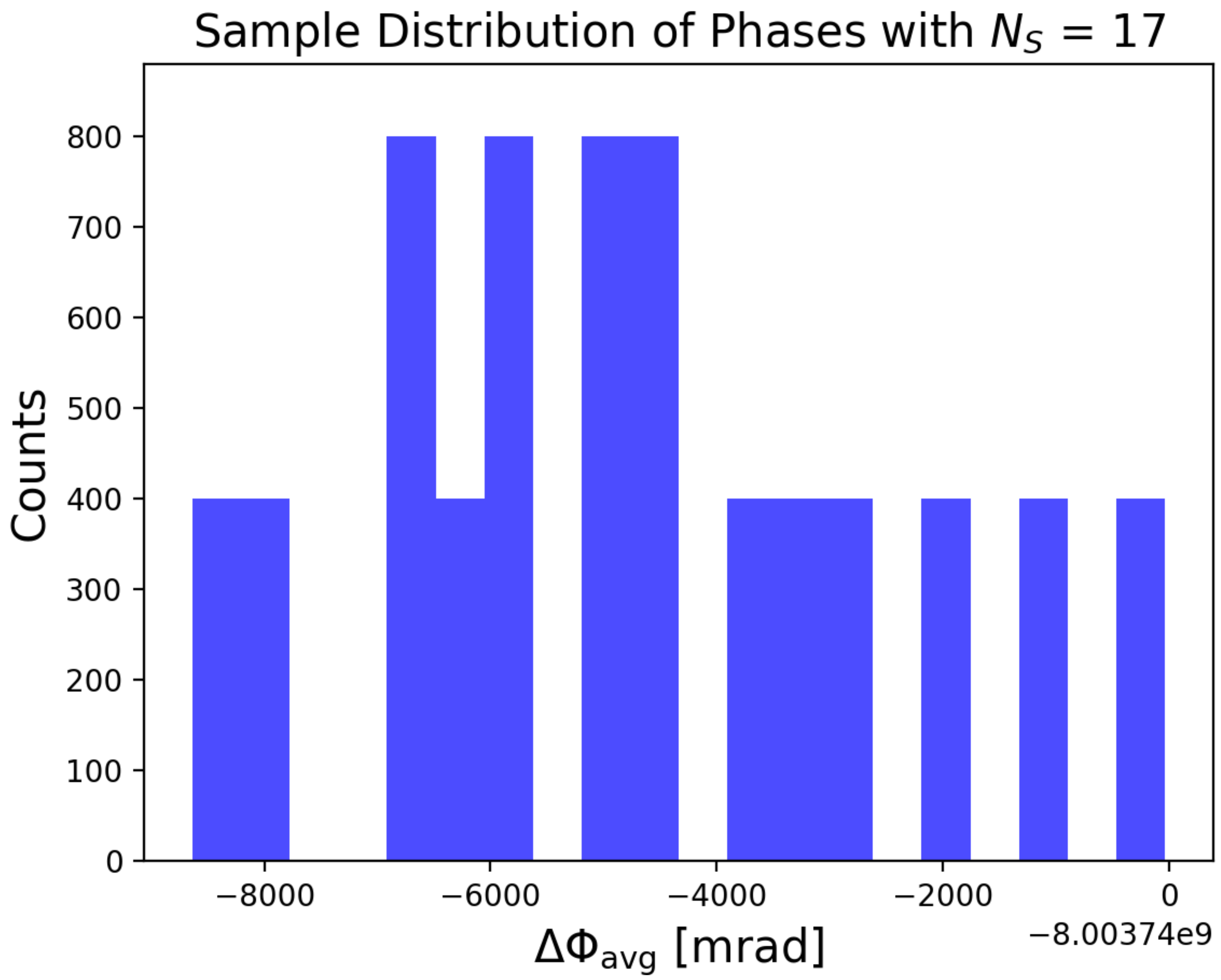
Sample the phase $\Delta\Phi$ of an interferometer with N_I atoms with given spreads in the initial conditions z_0, v_0.

$$\Delta\Phi(\delta z(t), \delta\Phi(t), \delta g(t), \delta\phi(t))$$

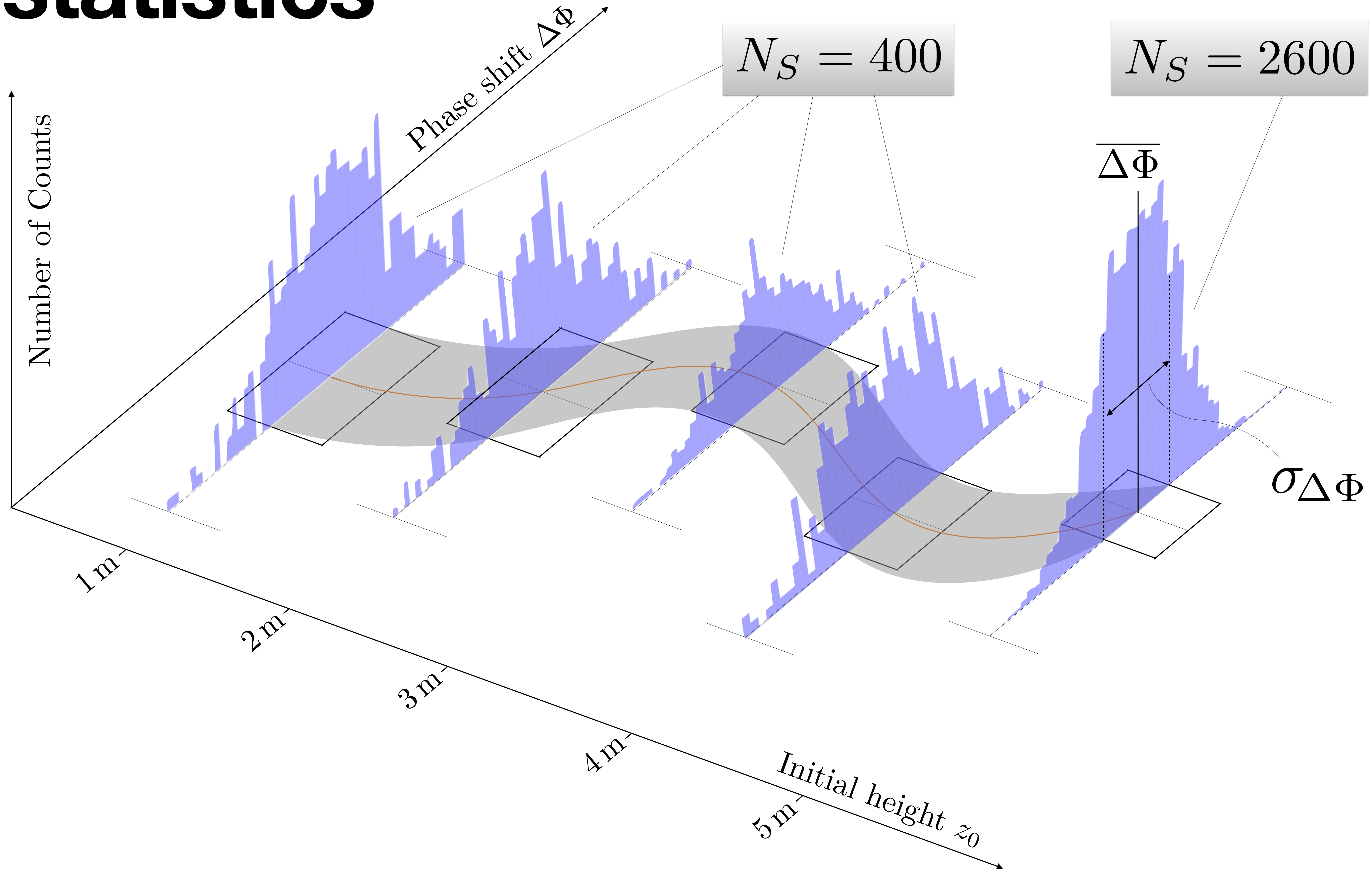
Calculate and save the average phase.

Phase statistics

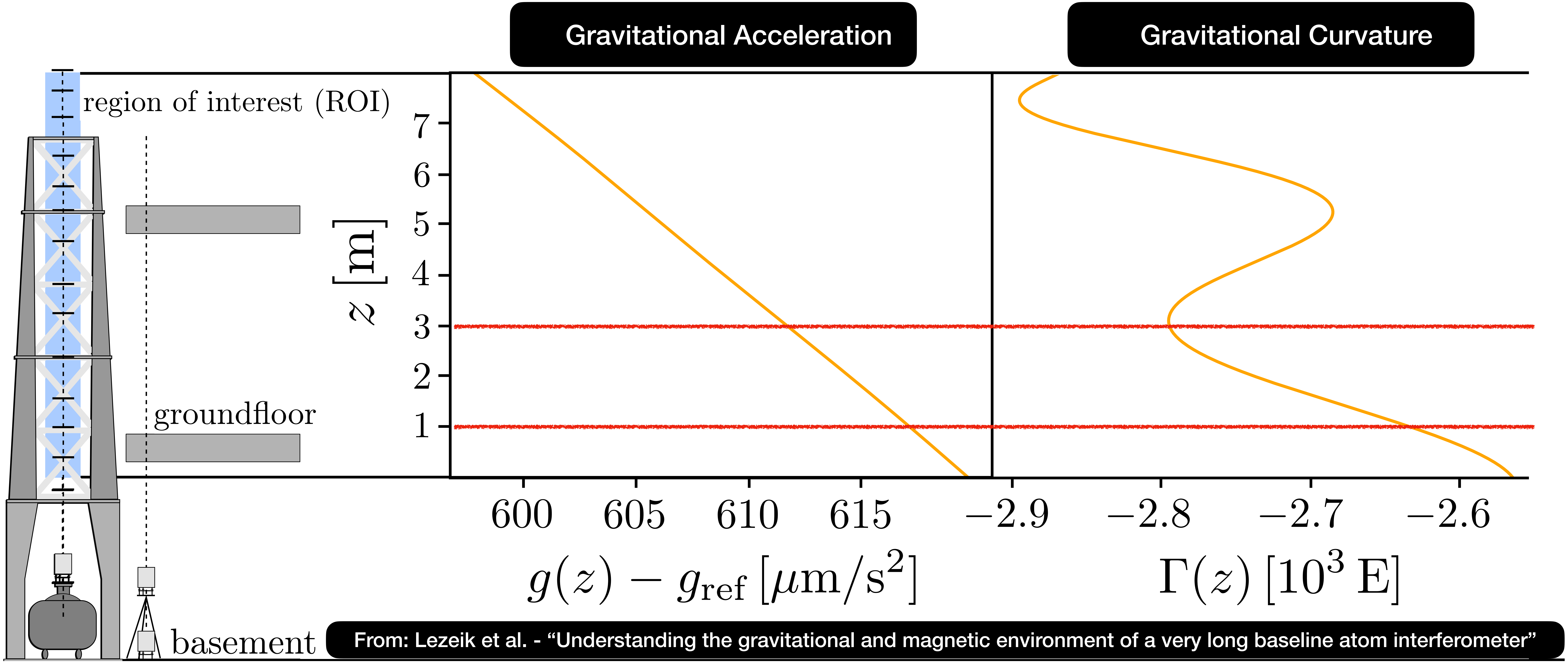
- Get full phase shift statistics for various noise sources.
- Obtain **mean value** and **standard deviation.**
- Use Python "Dask" as a CPU parallelizer and make it **open source.**



Phase statistics



Example: VLBAI Hannover

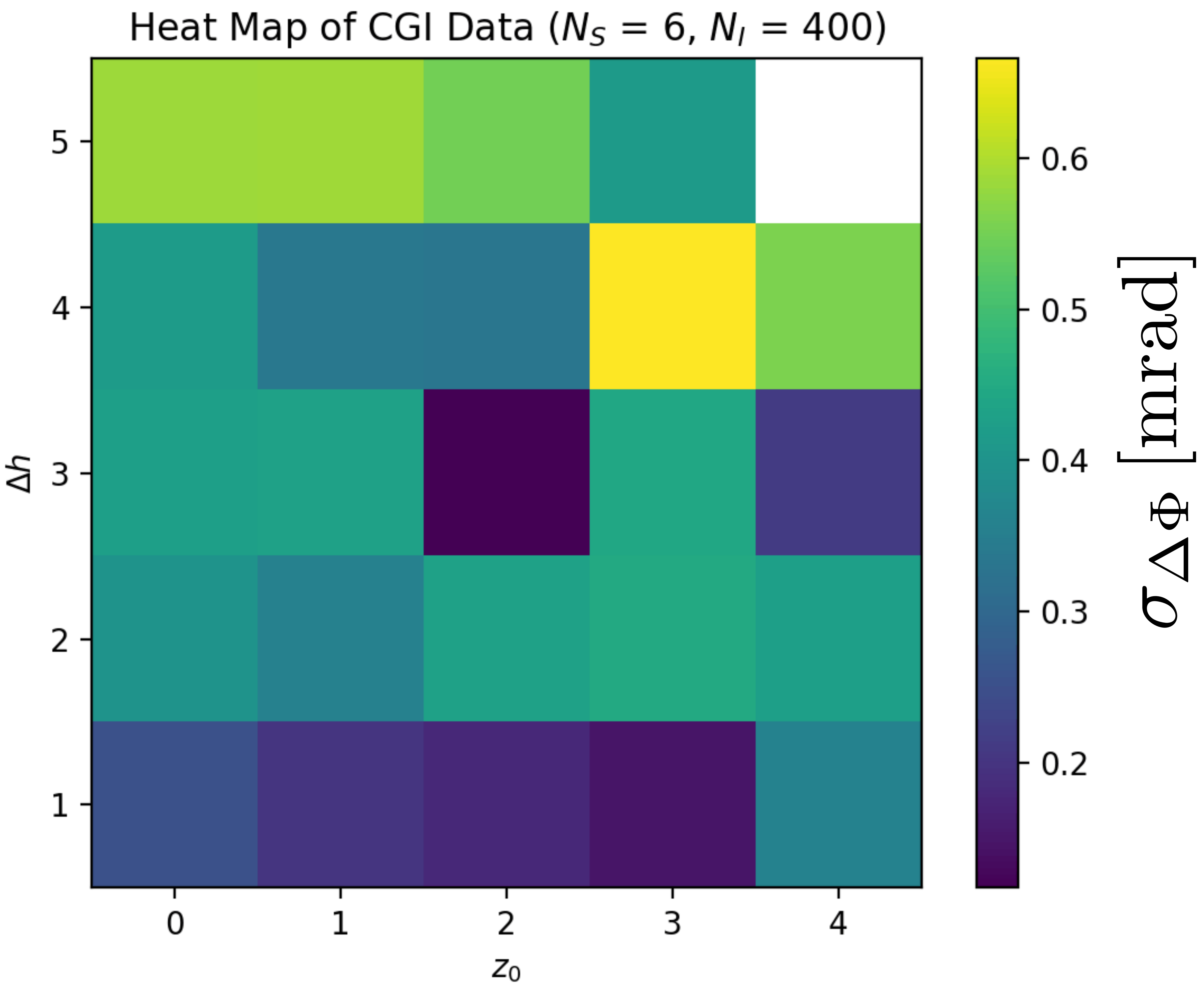


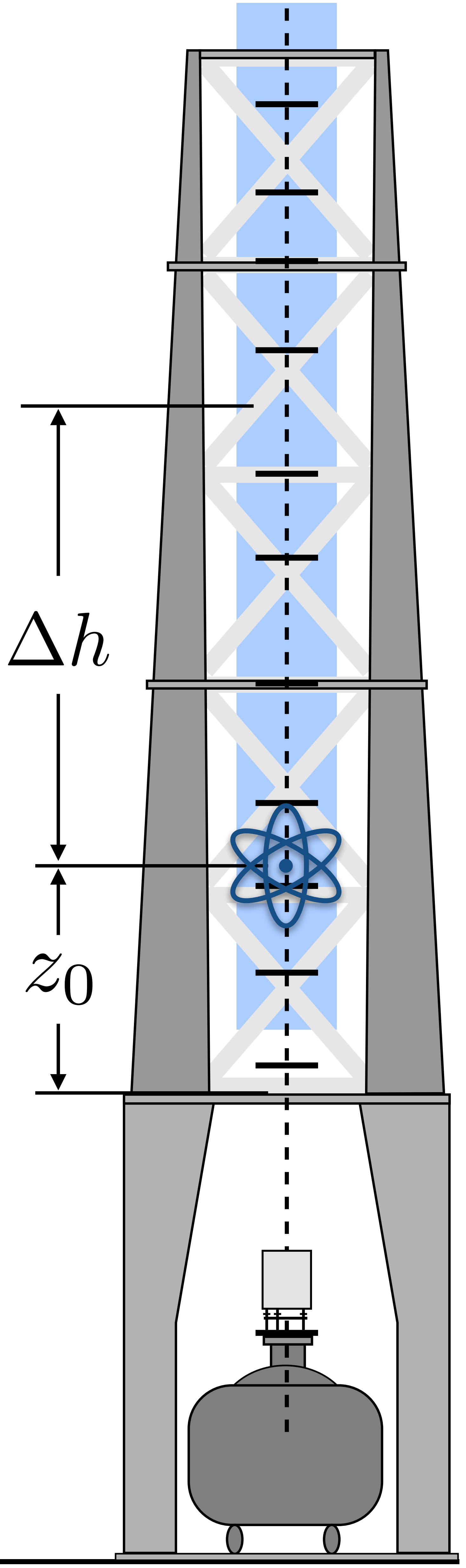
From: Lezeik et al. - “Understanding the gravitational and magnetic environment of a very long baseline atom interferometer”

Where shall I operate an interferometer?

Stability Analysis: CGI

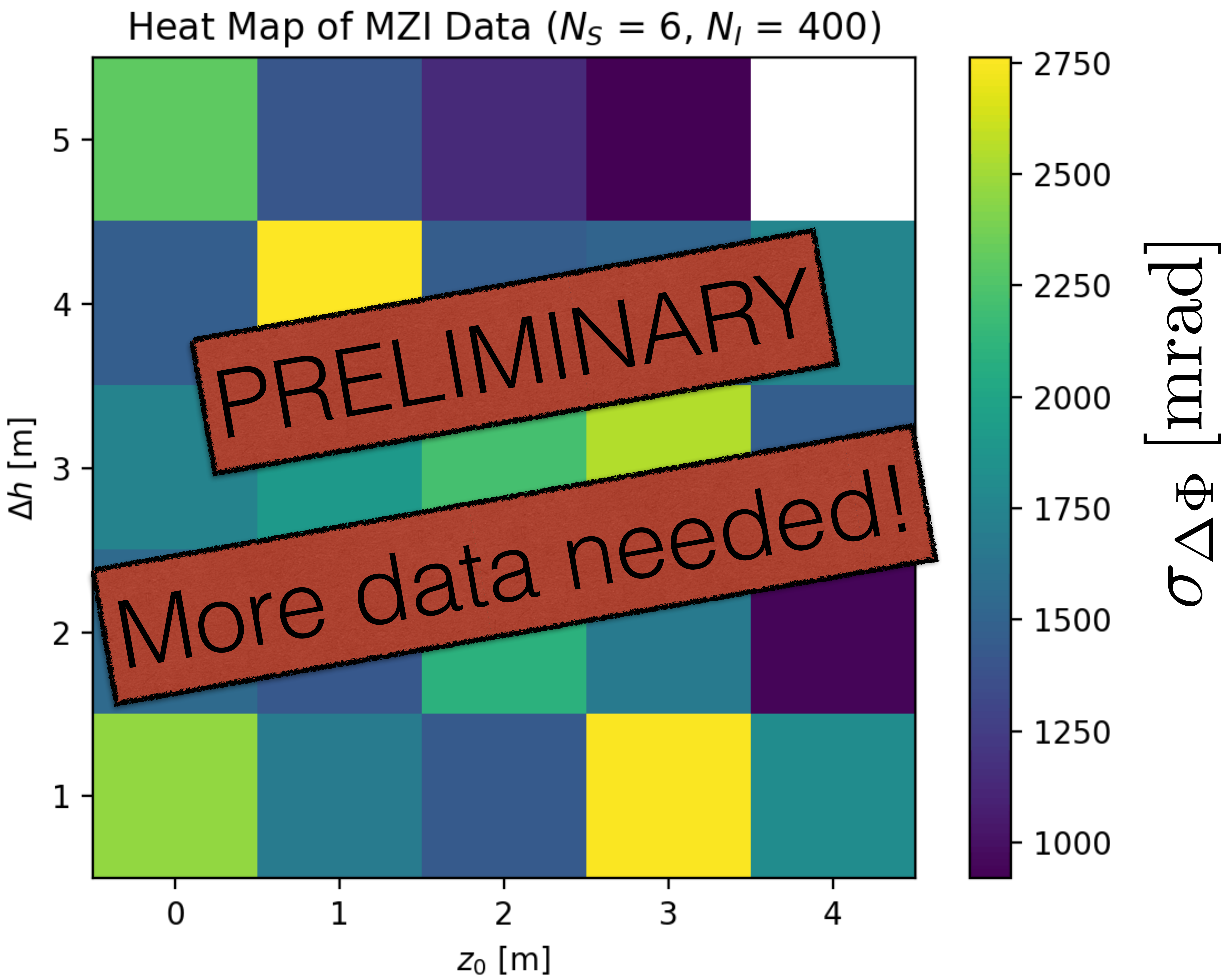
CGI = Measure $\Gamma(z)$

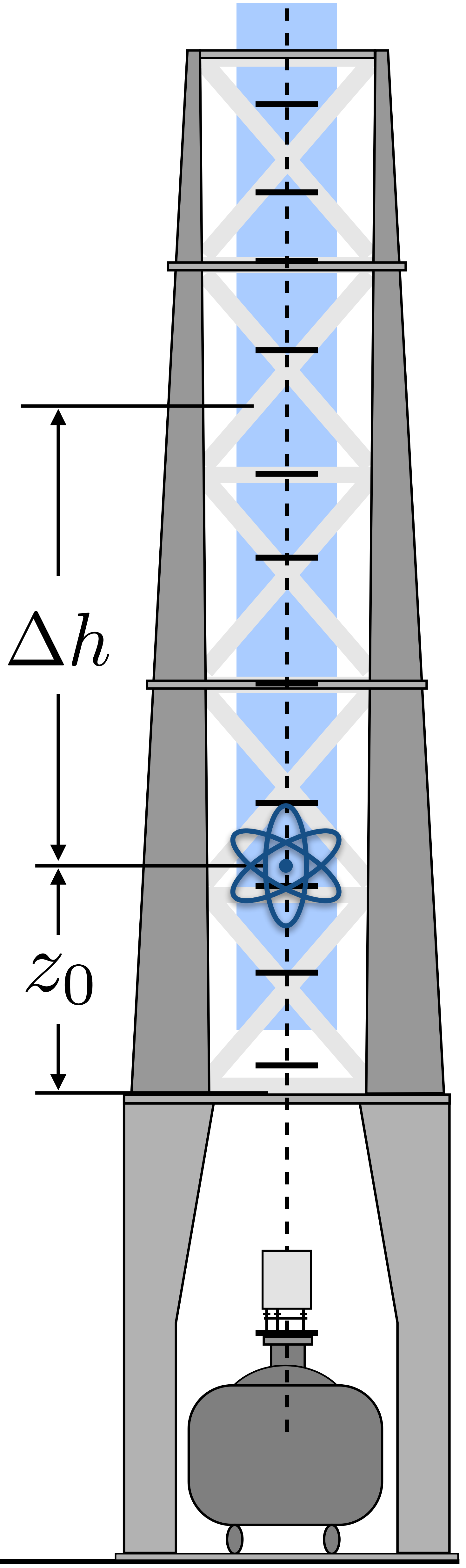




Stability Analysis: MZI

MZI = Measure $g(z)$





Outlook & Next steps

- Include **Gravitational Wave** (GW) and **Dark Matter** (DM) simulations.
- **Optimize** experiments for GW/DM searches **including noise**.
- Model **Gravity Gradient Noise** (GGN) numerically.
- Go from 1D to 3D (+ Coriolis effect, + Eötvös effect, + Wave front aberrations, …).
- Include **imperfect** Atom-Light **interactions**.

Any questions?

And a big thanks to these people!
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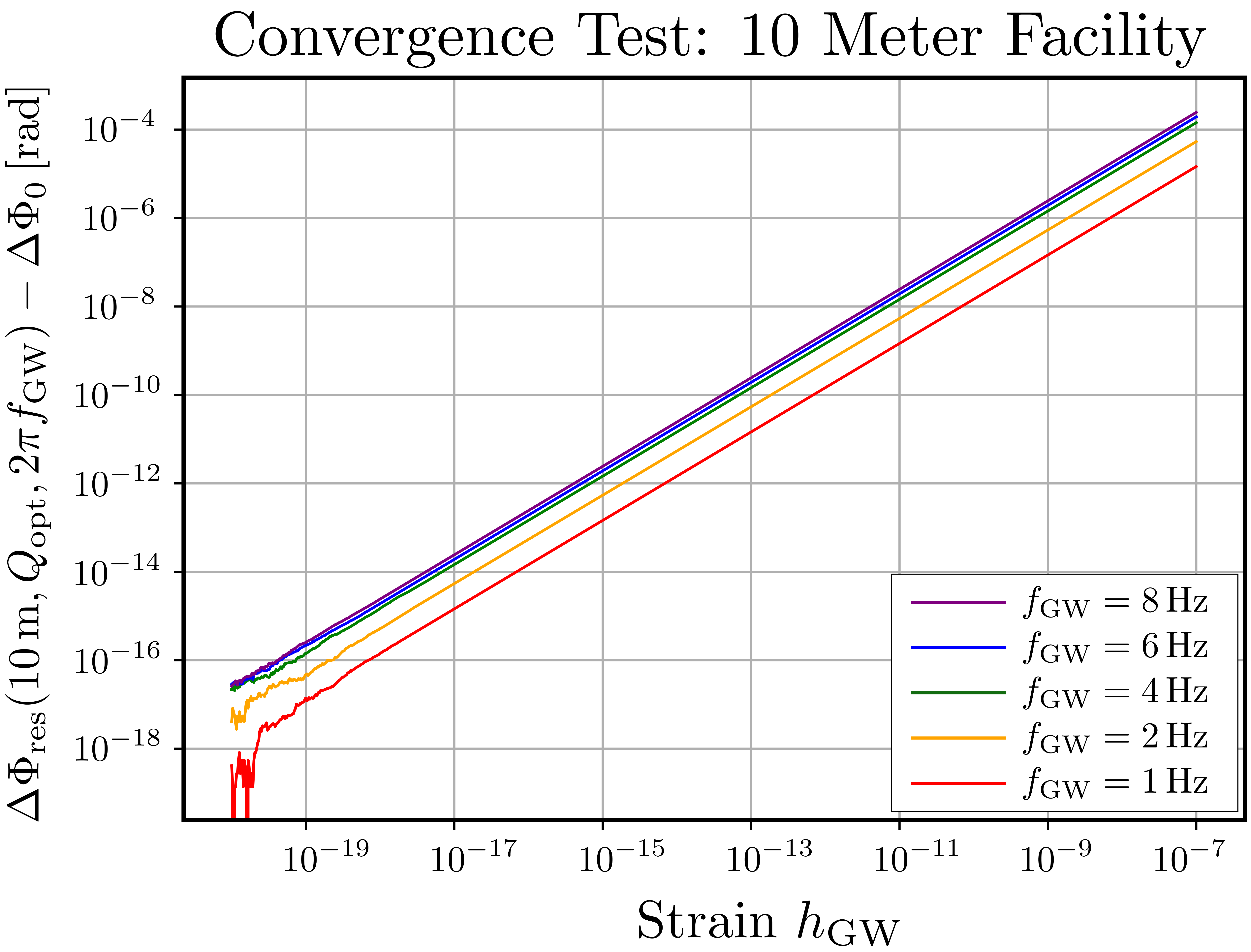
Gaaloul group (T-SQUAD), Sep. 2025


Convergence Test: 10 Meter Facility
$\Delta\Phi_{\mathrm{res}}(10\,\mathrm{m}, Q_{\mathrm{opt}}, 2\pi f_{\mathrm{GW}}) - \Delta\Phi_0$ [rad]
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-19}
10^{-17}
10^{-15}
10^{-13}
10^{-11}
10^{-9}
10^{-7}
Strain h_{GW}
$f_{\mathrm{GW}} = 8\,\mathrm{Hz}$
$f_{\mathrm{GW}} = 6\,\mathrm{Hz}$
$f_{\mathrm{GW}} = 4\,\mathrm{Hz}$
$f_{\mathrm{GW}} = 2\,\mathrm{Hz}$
$f_{\mathrm{GW}} = 1\,\mathrm{Hz}$