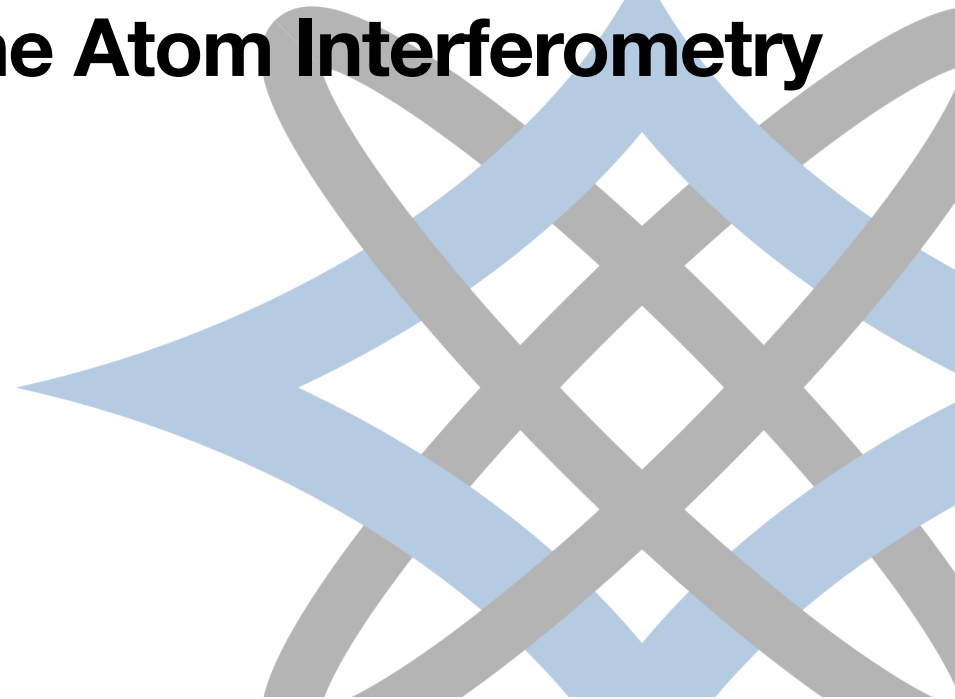


13<sup>th</sup> August 2026 — Gravitational Quantum Physics and Metrology  
(CA23115)

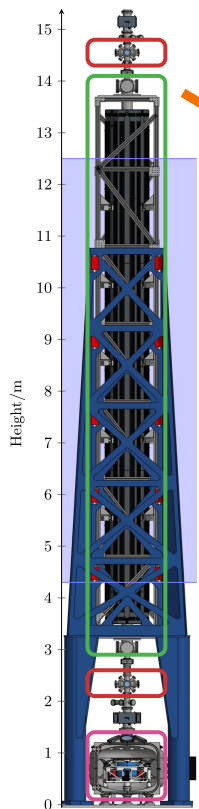
# Realistic Simulator of Gravitational Wave and Dark Matter Detection in long-baseline Atom Interferometry

Michael Werner

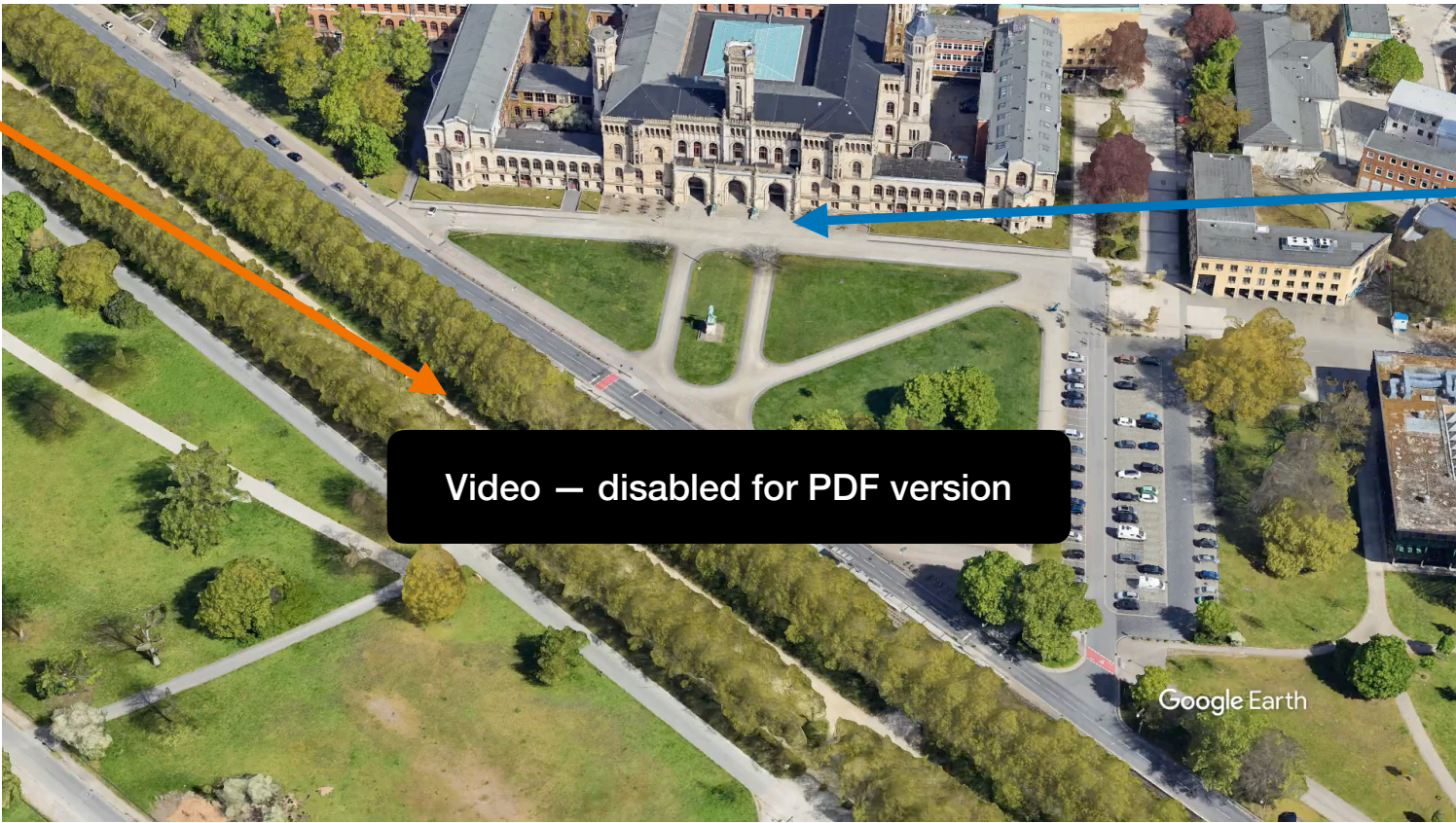
Theory of Quantum Sensing  
(Lead: Dr. Naceur Gaaloul)  
Institute of Quantum Optics  
**Leibniz University Hannover**



# HiTec facility: VLBAI & Einstein Elevator



Schilling et al. "Vertical Gravity Profile in a 10 m Atom Interferometer"



Tahtali et al. "Erforschung kosmischer Kleinkörper am Einstein-Elevator"



# Experiments in $\mu g$ : Einstein Elevator

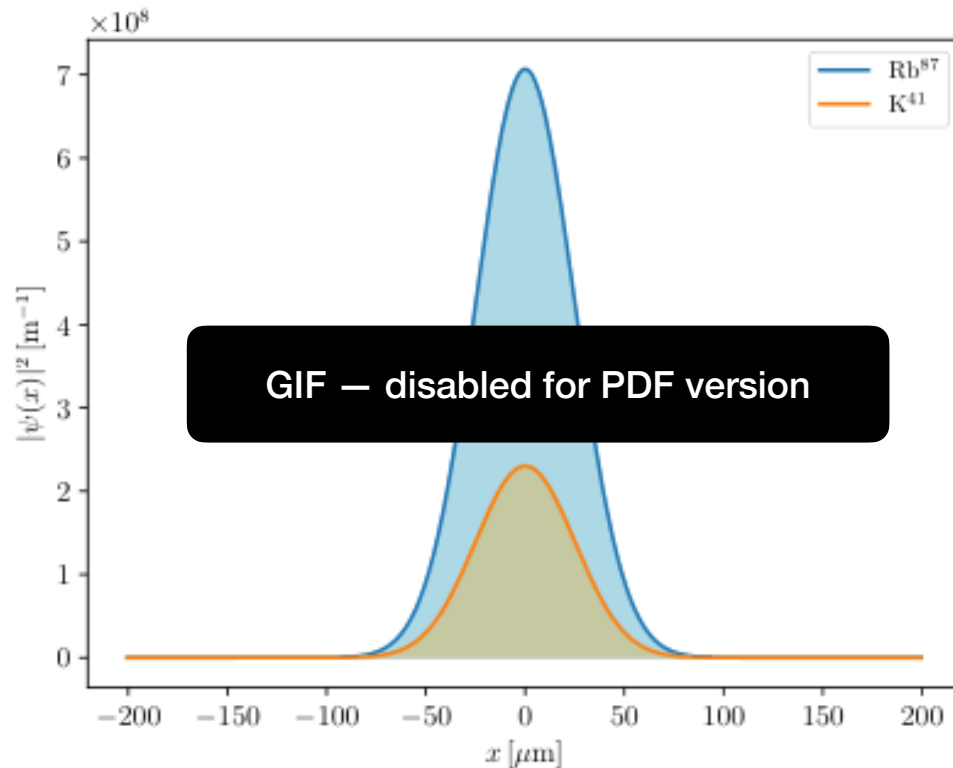
Up to 4 seconds of tunable gravity!



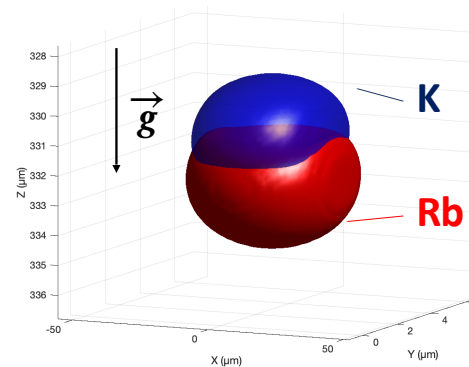
Photos: Leibniz Universität Hannover/Marie-Luise Kolb — Video: Youtube IFES @ LUH

# Bose-Einstein-Condensates (BECs)

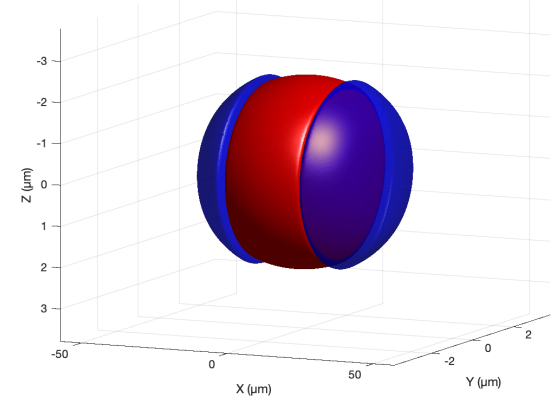
Just bubbles of ultra cold atoms?



On Earth ( $g = 9.81 m \cdot s^{-2}$ )



In microgravity ( $g = 0 m \cdot s^{-2}$ )



Pichery et al. "Efficient numerical description of the dynamics of interacting multispecies quantum gases"

GIF from Joachim Guyomard using FFTArray (Seckmeyer et al. "FFTArray: A Python library for the implementation of discretized multi-dimensional Fourier transforms")



# 10m Atom Interferometer “VLBAI”

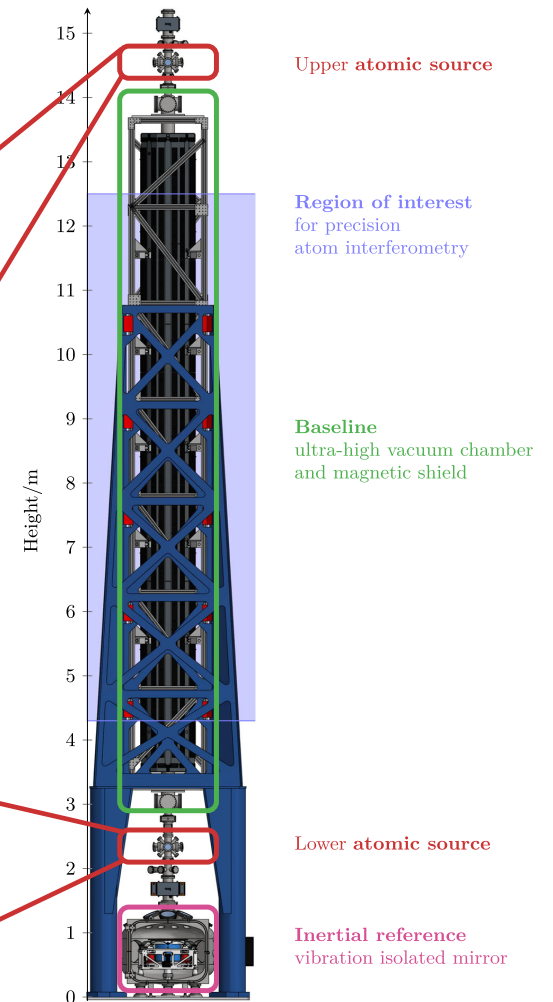
## The Very Long Baseline Atom Interferometer

### Ytterbium source (top) (in progress)

Bosonic:  $^{168}\text{Yb}$   $^{170}\text{Yb}$   $^{174}\text{Yb}$  Fermionic:  $^{171}\text{Yb}$

### Rubidium source (bottom)

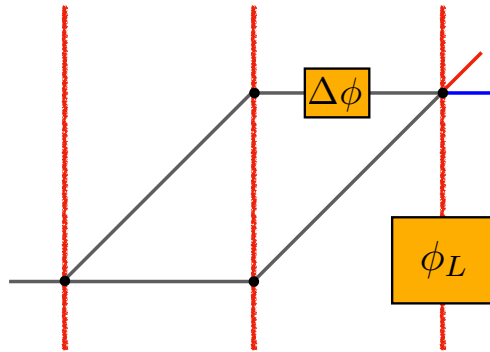
Bosonic:  $^{85}\text{Rb}$   $^{87}\text{Rb}$



Schilling et al. “Vertical Gravity Profile in a 10 m Atom Interferometer”

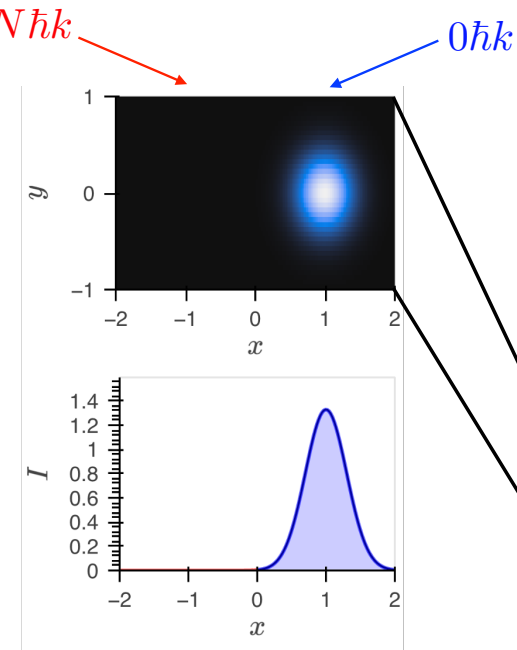
# Phase Readout

## Detecting Temporal Fringes

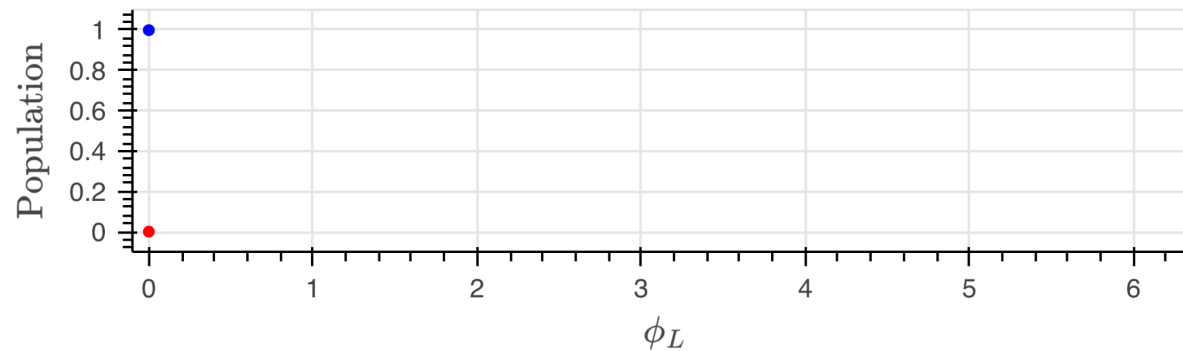


1. CCD Camera Picture

2. Population Estimation



3. Population Scan



CCD renderings and plots by Stefan Seckmeyer

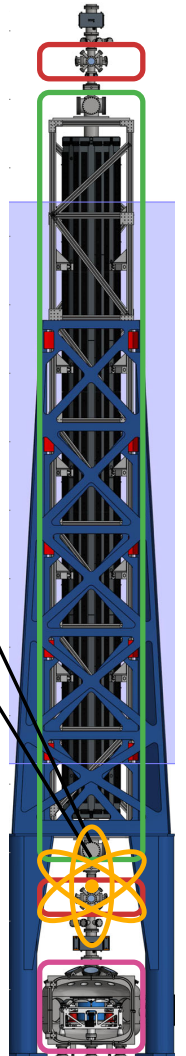


IQ



Michael Werner

Gravitational Quantum Physics and Metrology

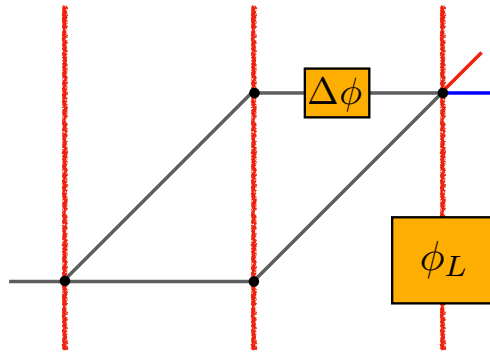


From: Schilling et al. "Vertical Gravity Profile in a 10 m Atom Interferometer"



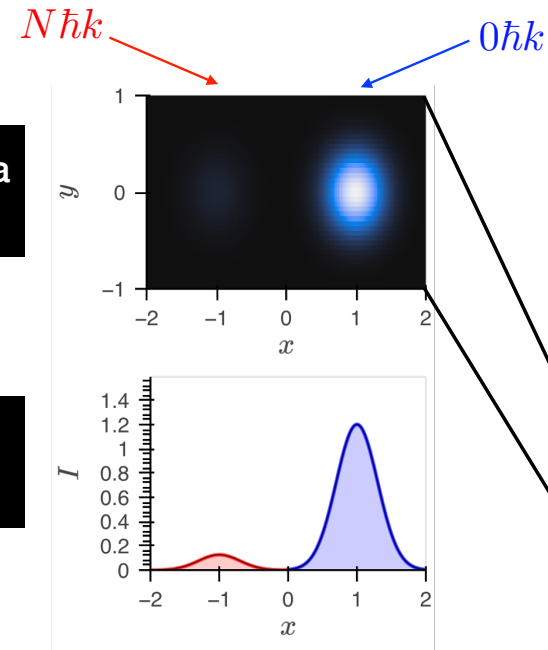
# Phase Readout

## Detecting Temporal Fringes

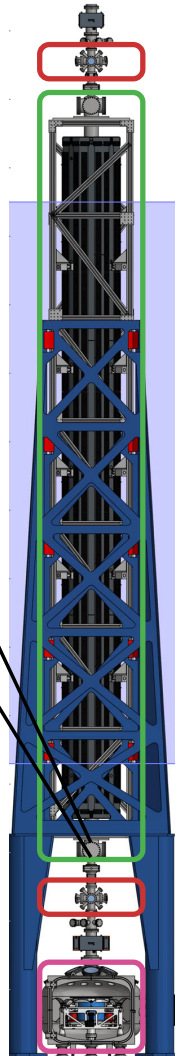
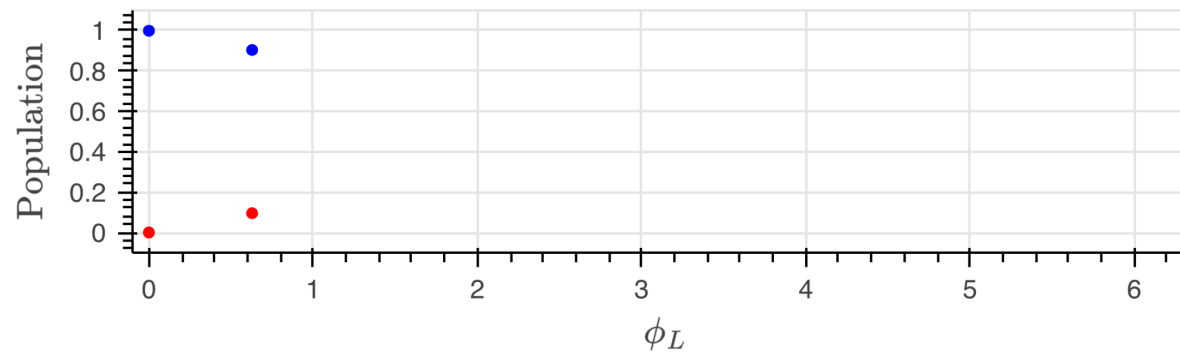


1. CCD Camera Picture

2. Population Estimation



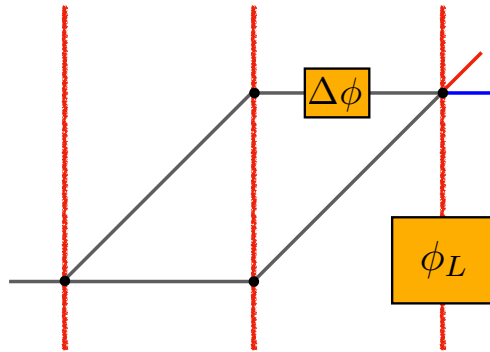
3. Population Scan



CCD renderings and plots by Stefan Seckmeyer

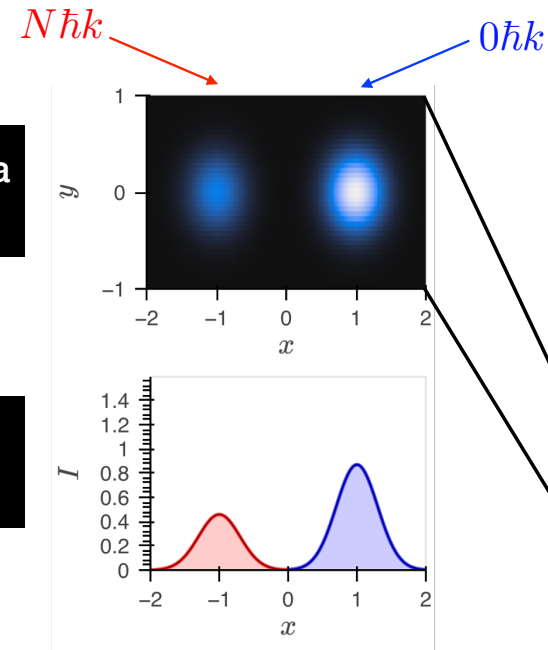
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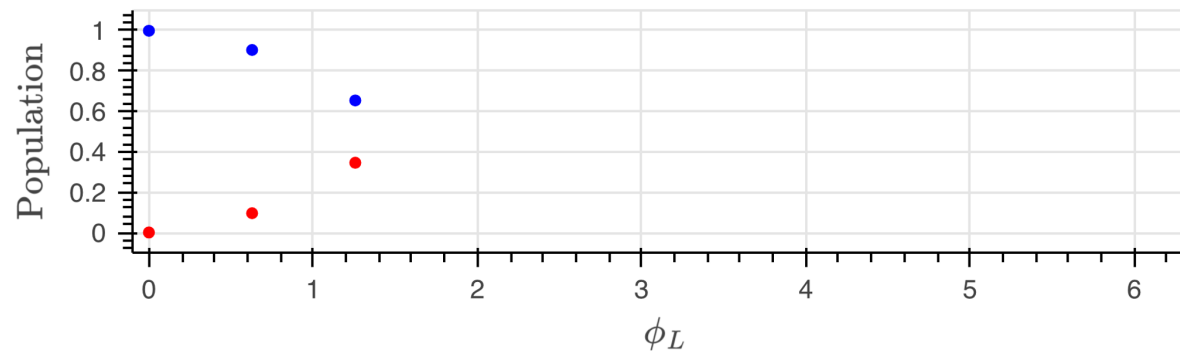


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CCD renderings and plots by Stefan Seckmeyer

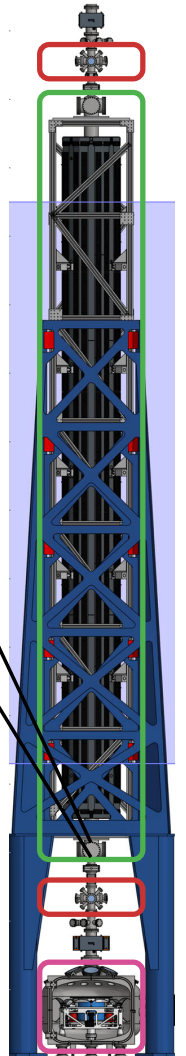


IQ



Michael Werner

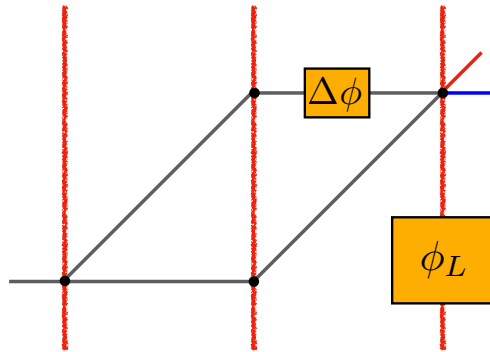
Gravitational Quantum Physics and Metrology



From: Schilling et al. "Vertical Gravity Profile in a 10 m Atom Interferometer"

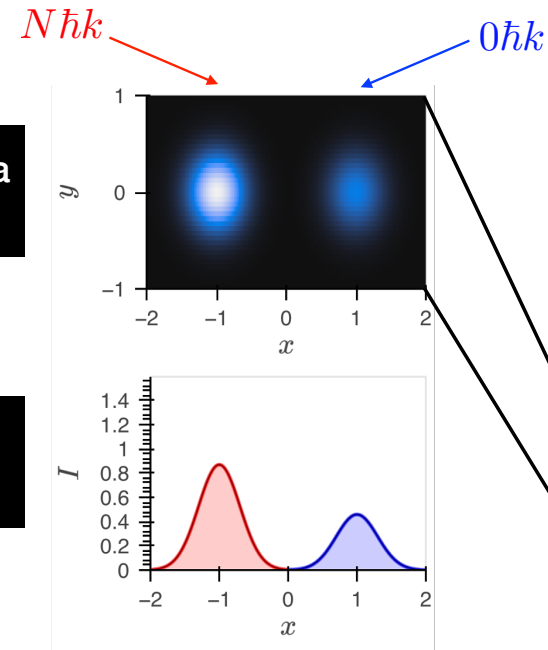
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## Detecting Temporal Fringes

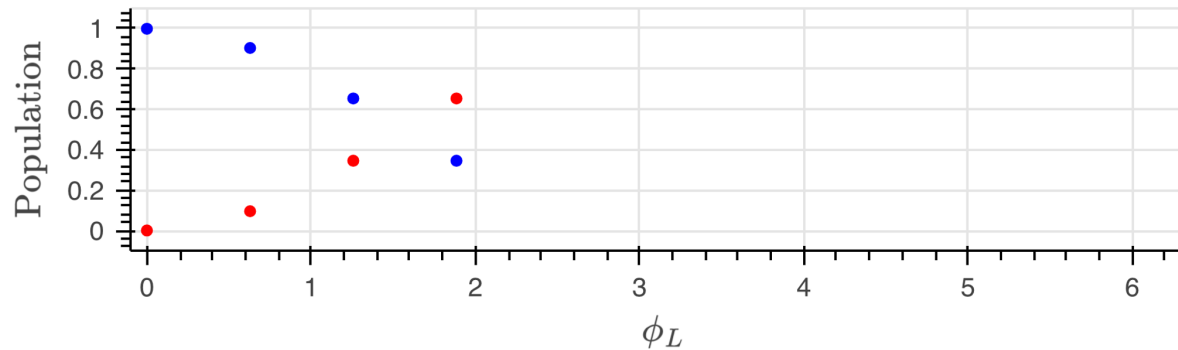


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CCD renderings and plots by Stefan Seckmeyer

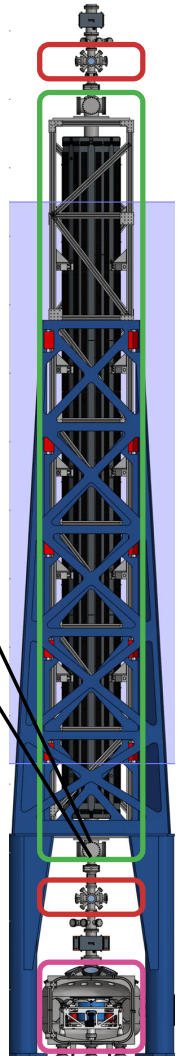


IQ



Michael Werner

Gravitational Quantum Physics and Metrology

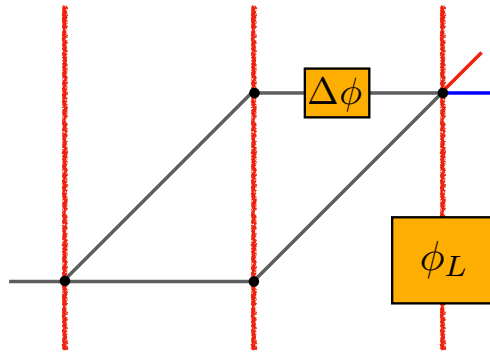


From: Schilling et al. "Vertical Gravity Profile in a 10 m Atom Interferometer"



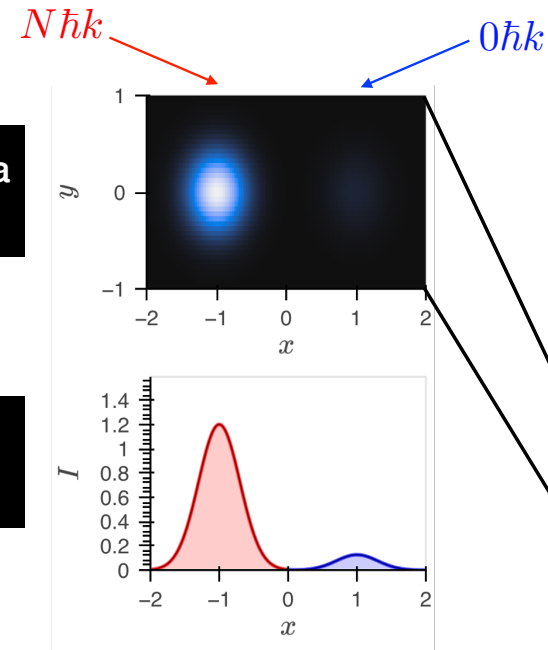
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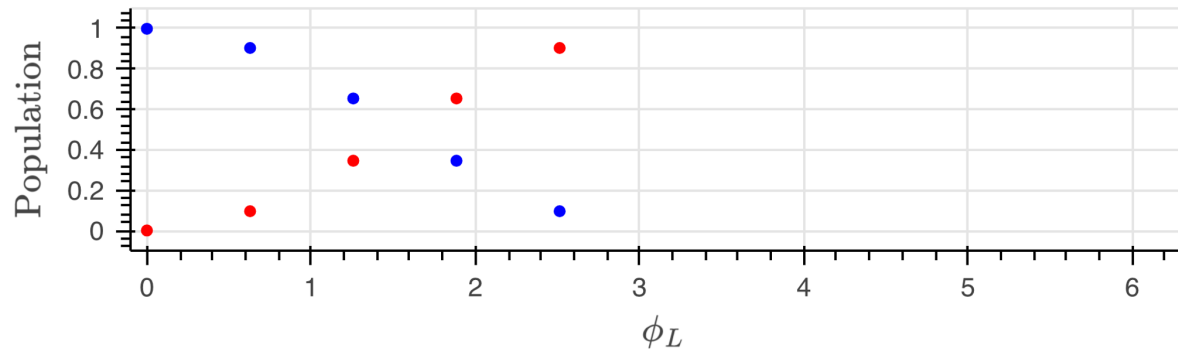


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CCD renderings and plots by Stefan Seckmeyer

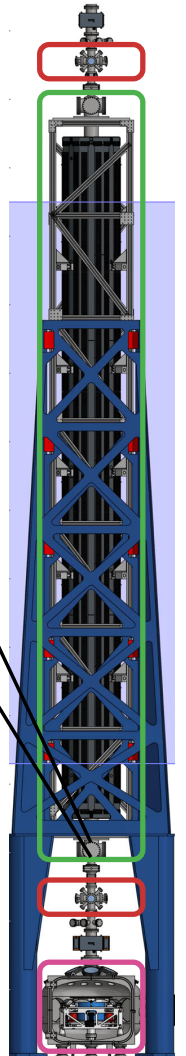


IQ



Michael Werner

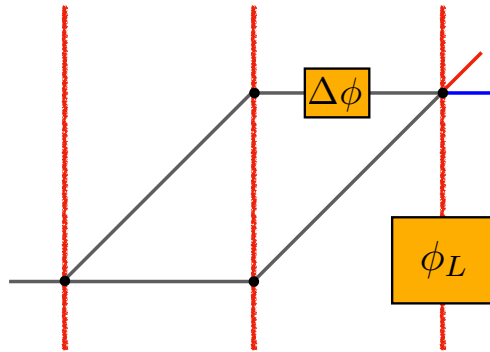
Gravitational Quantum Physics and Metrology



From: Schilling et al. "Vertical Gravity Profile in a 10 m Atom Interferometer"

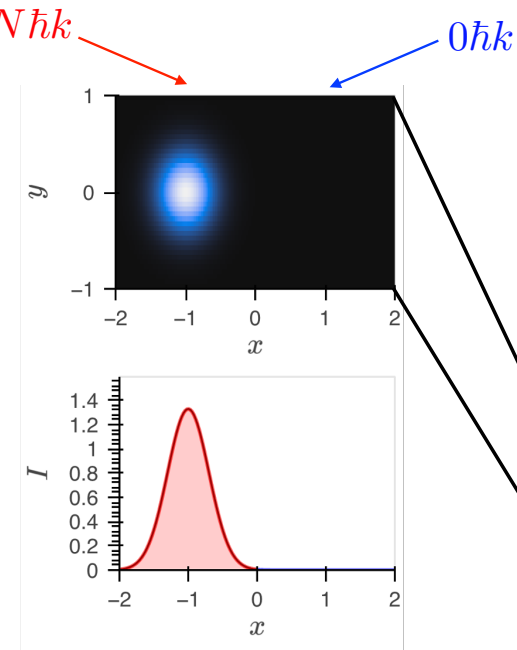
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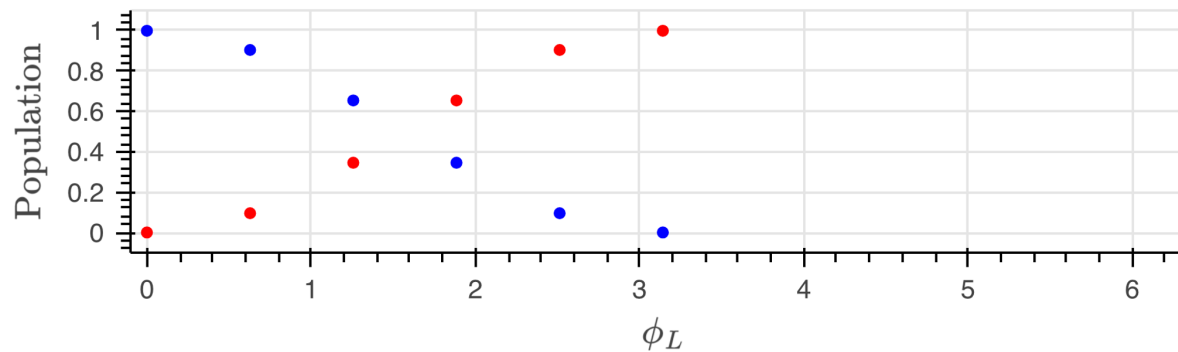


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CCD renderings and plots by Stefan Seckmeyer

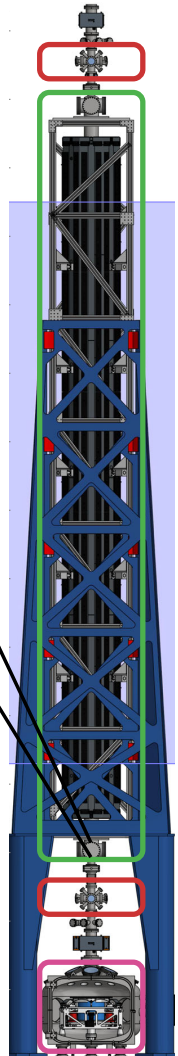


IQ



Michael Werner

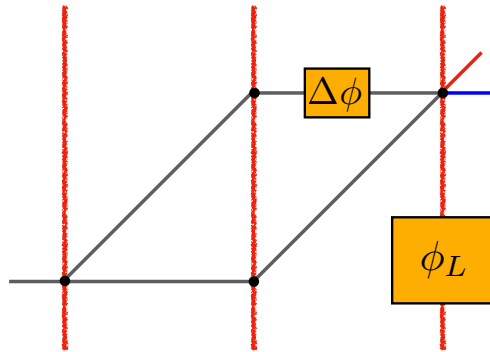
Gravitational Quantum Physics and Metrology



From: Schilling et al. "Vertical Gravity Profile in a 10 m Atom Interferometer"

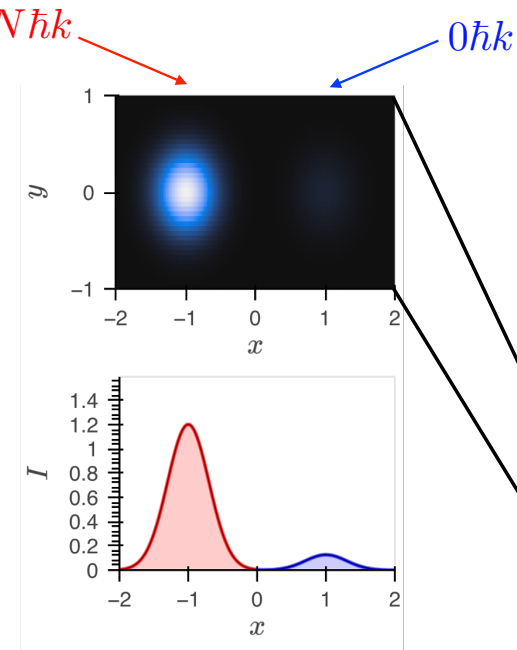
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## Detecting Temporal Fringes

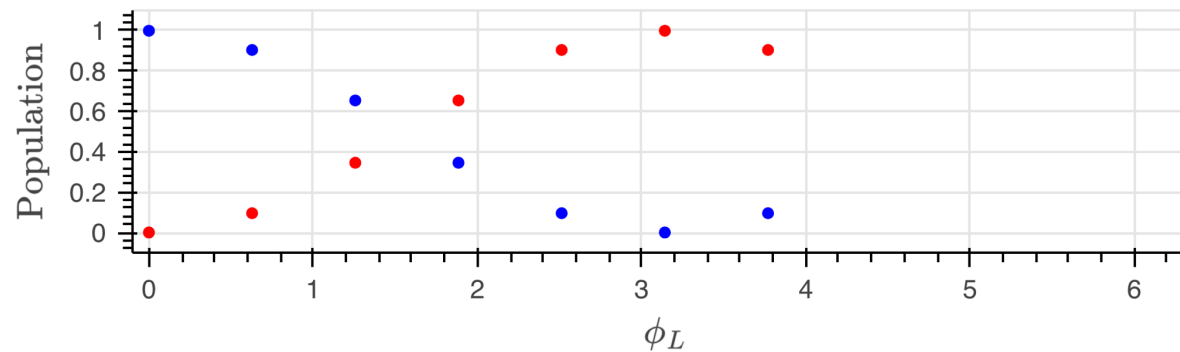


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CCD renderings and plots by Stefan Seckmeyer

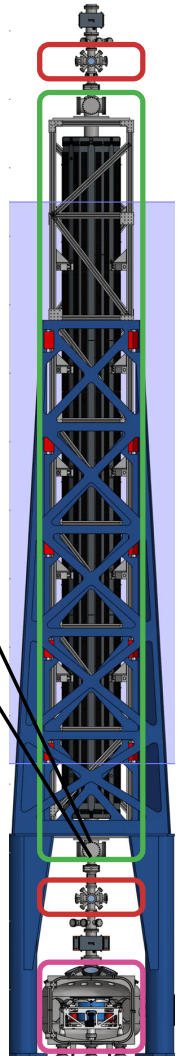


IQ



Michael Werner

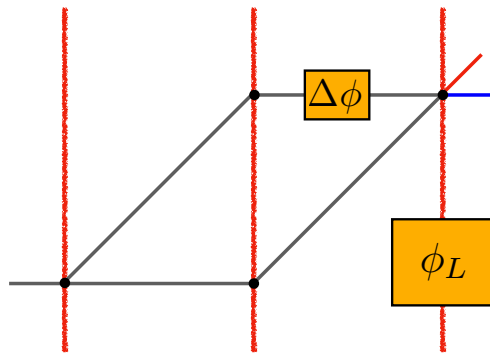
Gravitational Quantum Physics and Metrology



From: Schilling et al. "Vertical Gravity Profile in a 10 m Atom Interferometer"

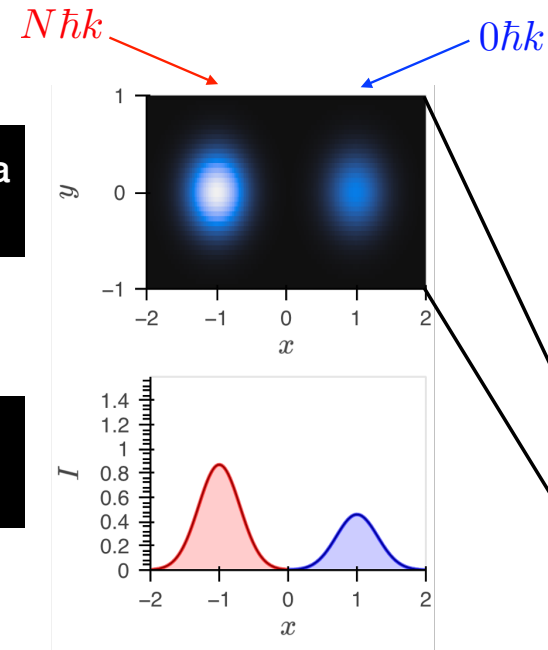
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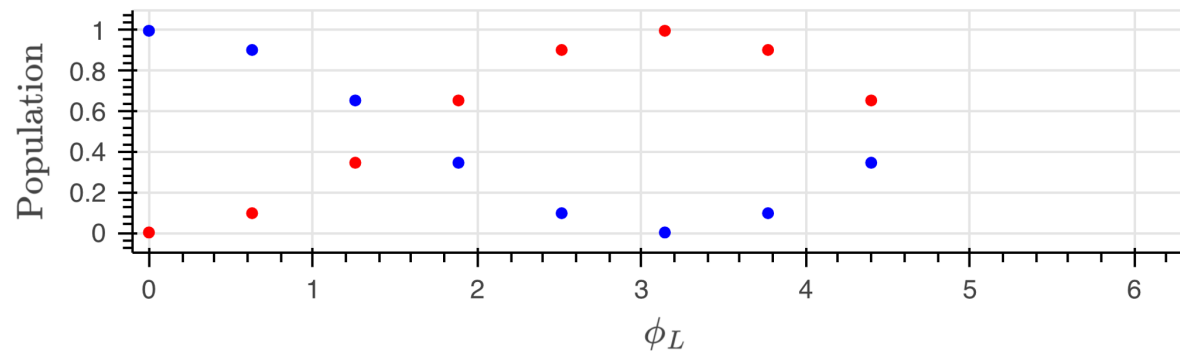


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2. Population Estimation



3. Population Scan

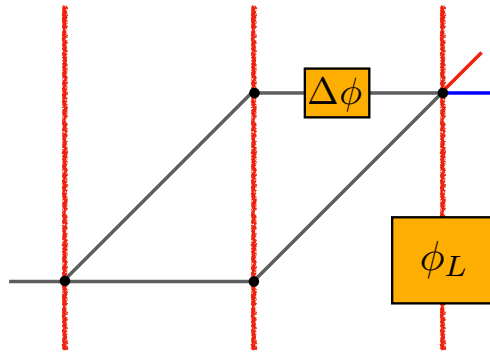


CCD renderings and plots by Stefan Seckmeyer



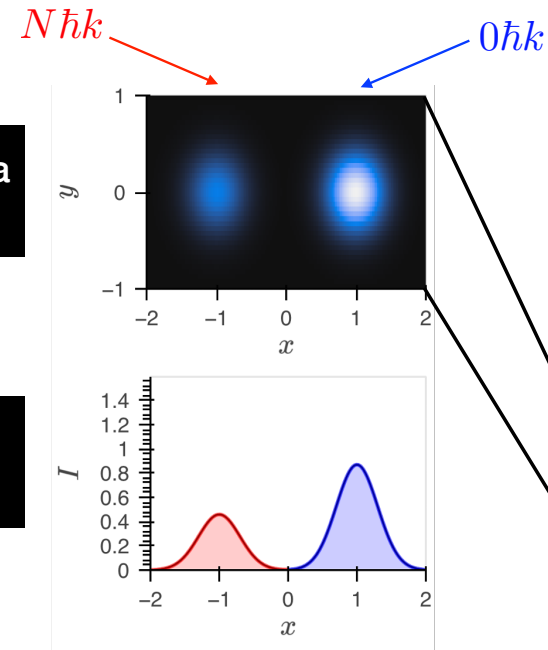
# Phase Readout

## Detecting Temporal Fringes

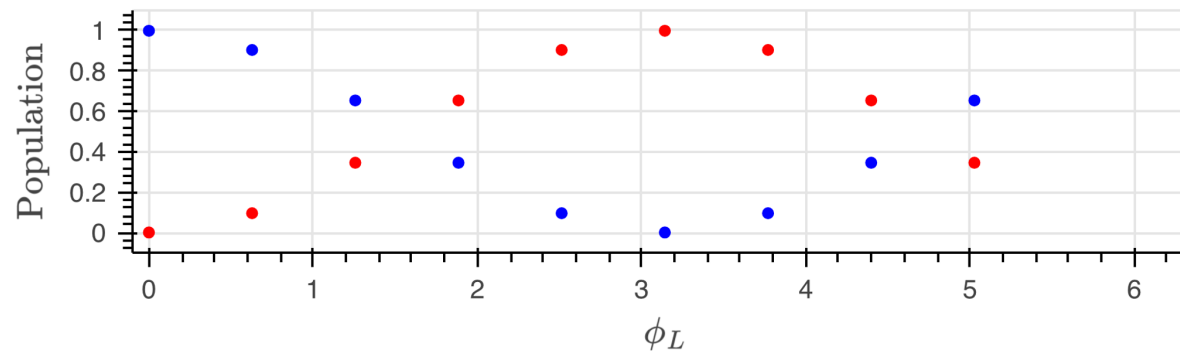


1. CCD Camera Picture

2. Population Estimation



3. Population Scan



CCD renderings and plots by Stefan Seckmeyer

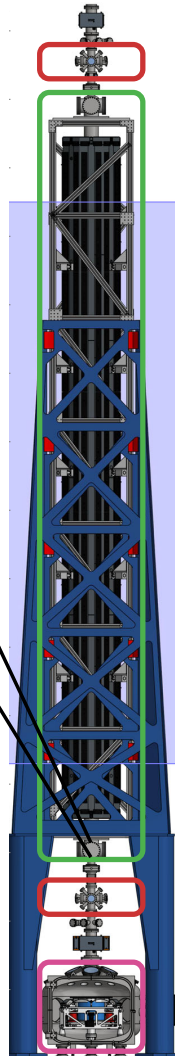


IQ



Michael Werner

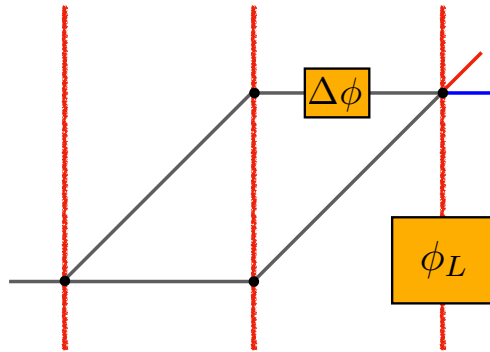
Gravitational Quantum Physics and Metrology



From: Schilling et al. "Vertical Gravity Profile in a 10 m Atom Interferometer"

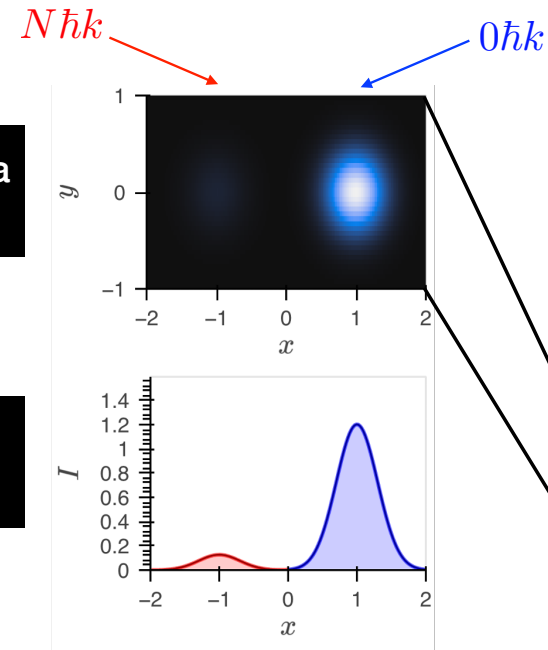
# Phase Readout

## Detecting Temporal Fringes

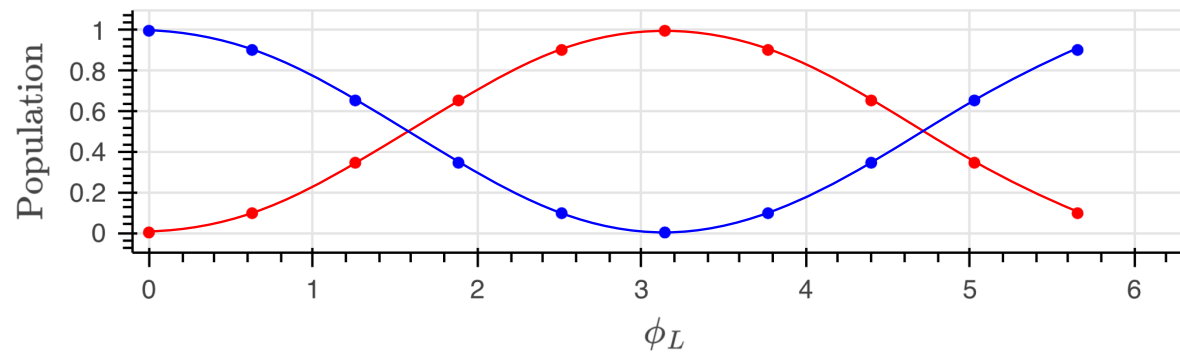


1. CCD Camera Picture

2. Population Estimation



3. Population Scan



CCD renderings and plots by Stefan Seckmeyer

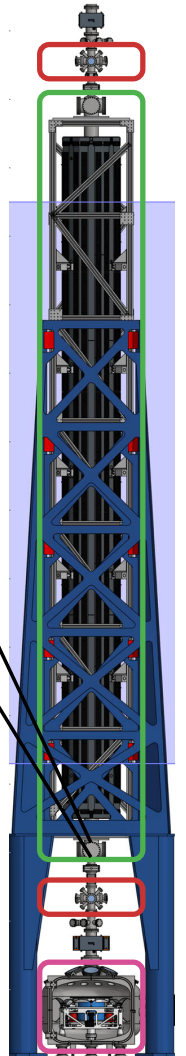


IQ



Michael Werner

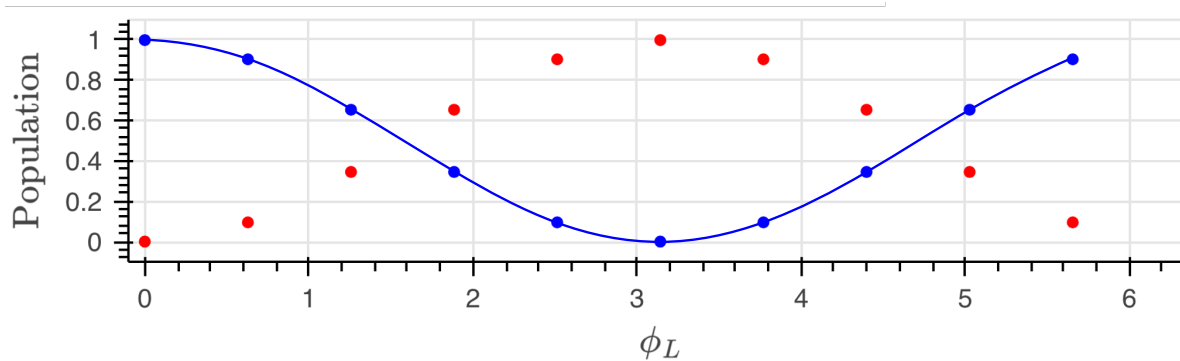
Gravitational Quantum Physics and Metrology



From: Schilling et al. "Vertical Gravity Profile in a 10 m Atom Interferometer"

# Phase Readout

## Detecting Temporal Fringes



$$P(\Delta\Phi) = \frac{1 + C \cos(\Delta\Phi + \Phi_L)}{2}$$

### Experiment

Measure  $P(\Delta\Phi)$   
and get  $\Delta\Phi$

### Theory

Model analytical form of  $\Delta\phi$ :  
Example:  $\Delta\phi = gkT^2$

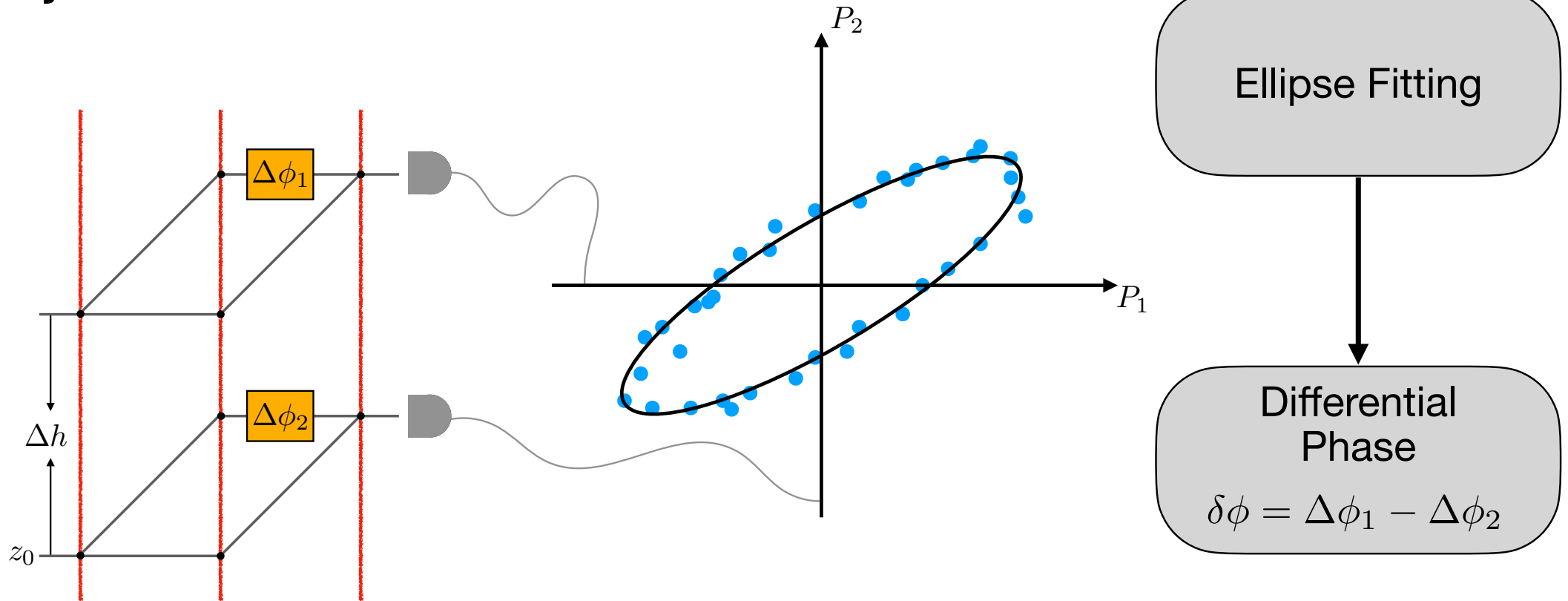
### Get Estimator

Example:  $\hat{g} = \frac{\Delta\phi}{kT^2}$

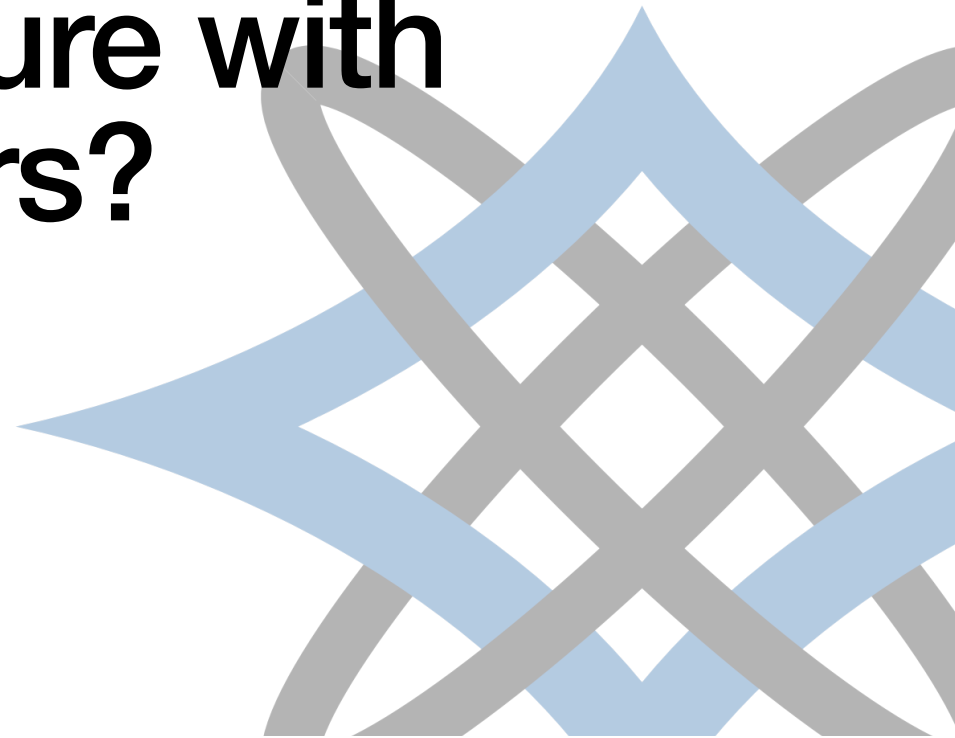


# Differential Phase Readout

## Reject Common Noise



**What can we measure with  
atom interferometers?**





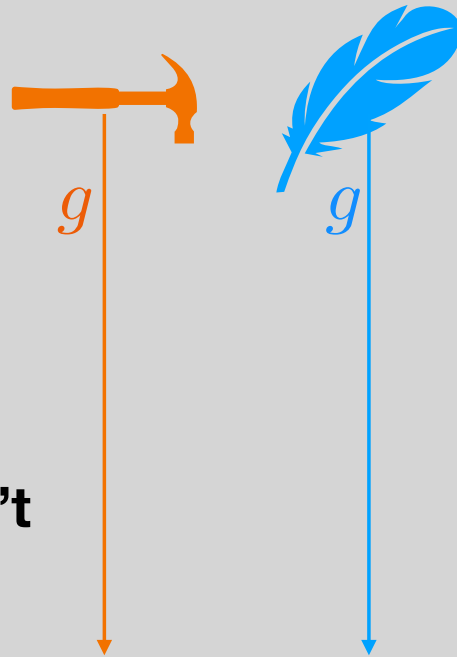
# Weak Equivalence Principle Tests

From **Hammer** & **Feather** to **Atom** & **Atom**

1971

Problem:

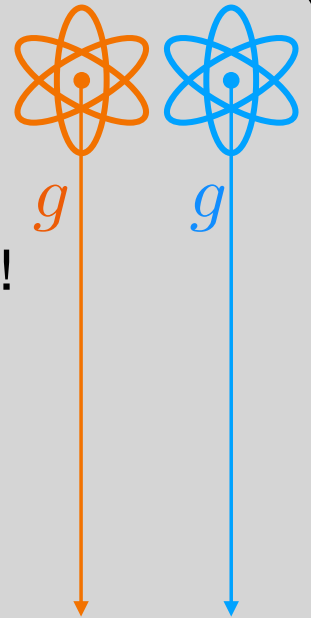
- Higher order mass moments!
- Both objects **don't** accelerate the same way!



Today

Atoms are the **ideal test particles** (in the GR sense)!

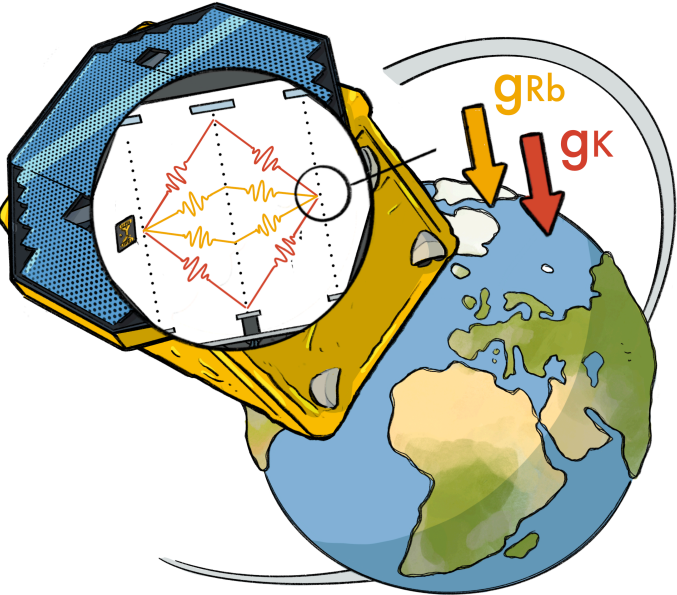
- No charge.
- No mass moments.
- Everywhere identical.



# STE-QUEST: Space Time Explorer and QUantum Equivalence Space Test

M-class mission proposal to the 2025 call in ESA’s science program

Participations of scientists from Germany, France, UK, Italy, Switzerland, Spain, Greece, Sweden and USA



## Mission Goal:

| Class      | Elements                            | $\eta$                | Year [ref] | Comments                         |
|------------|-------------------------------------|-----------------------|------------|----------------------------------|
| Classical  | Be - Ti                             | $2 \times 10^{-13}$   | 2008       | Torsion balance                  |
|            | Pt - Ti                             | $2 \times 10^{-15}$   | 2022       | MICROSCOPE                       |
| Hybrid     | $^{133}\text{Cs}$ - CC              | $7 \times 10^{-9}$    | 2001       | Atom Interferometry              |
|            | $^{87}\text{Rb}$ - CC               | $7 \times 10^{-9}$    | 2010       | and macroscopic corner cube (CC) |
|            | $^{39}\text{K}$ - $^{87}\text{Rb}$  | $3 \times 10^{-7}$    | 2020       | different elements               |
| Quantum    | $^{87}\text{Sr}$ - $^{88}\text{Sr}$ | $2 \times 10^{-7}$    | 2014       | same element, fermion vs. boson  |
|            | $^{85}\text{Rb}$ - $^{87}\text{Rb}$ | $3 \times 10^{-8}$    | 2015       | same element, different isotopes |
|            | $^{85}\text{Rb}$ - $^{87}\text{Rb}$ | $3.8 \times 10^{-12}$ | 2020       | 10 m tower                       |
|            | $^{41}\text{K}$ - $^{87}\text{Rb}$  | $10^{-17}$            | 2041       | STE-QUEST                        |
| Antimatter | $\bar{\text{H}}$ - H                | 0.2                   | 2023       | ALPHA-g at CERN                  |

Gaaloul et al., “STE-QUEST -- Space Time Explorer and QUantum Equivalence principle Space Test: The 2022 medium-class mission concept”  
Struckmann et al., “Platform and environment requirements of a satellite quantum test of the weak equivalence principle at the  $10^{-17}$  level”

# Measure the Fine-Structure Constant $\alpha$

## Essentially: Measure the atomic recoil

The most accurate  $\alpha$  measurements Earth!

Rydberg constant

$$R_\infty = \frac{m_e e^4}{64\pi^3 \varepsilon_0^2 \hbar^3 c}$$

$$\alpha^2 = \frac{e^4}{16\pi^2 \varepsilon_0^2 \hbar^2 c^2} = \frac{4\pi \hbar R_\infty}{m_e c} \frac{m_{\text{At}}}{m_{\text{At}}} = \frac{4\pi}{c} R_\infty \frac{m_{\text{At}}}{m_e} \frac{\hbar}{m_{\text{At}}}$$

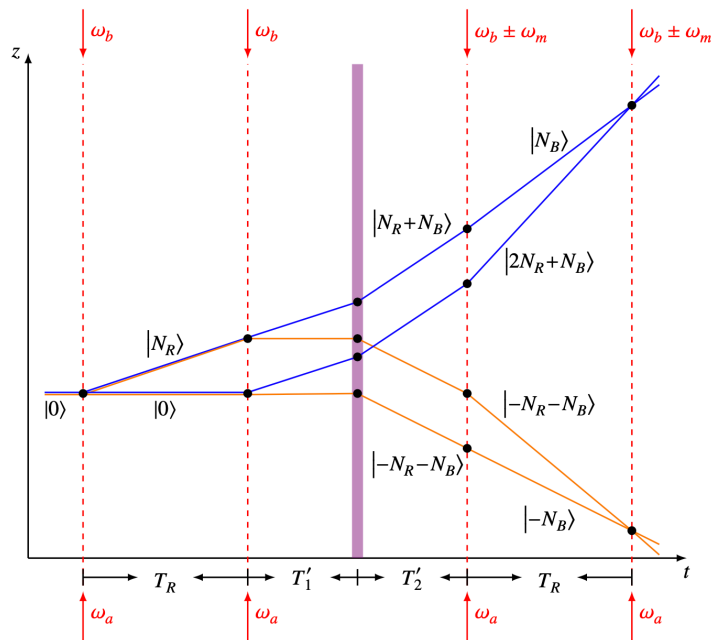
Known to very high precision!

Can be measured with AIFs!

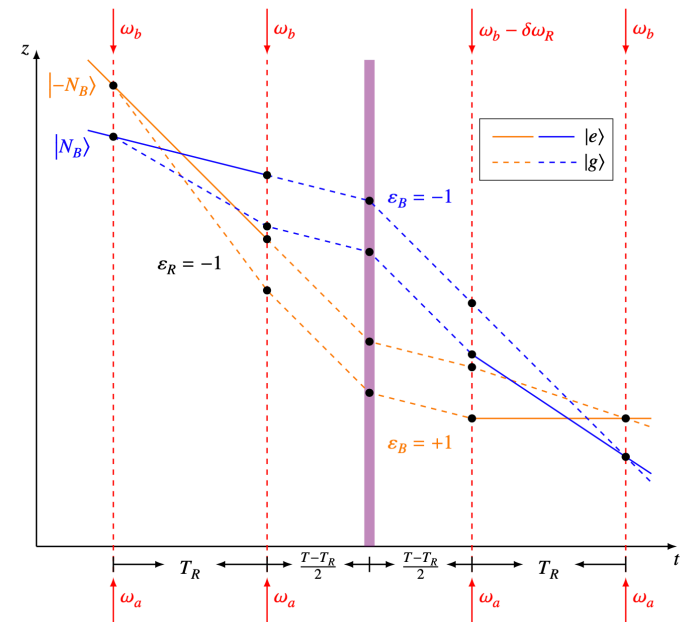
There are interferometer geometries with  $\Delta\phi \sim \frac{\hbar}{m_{\text{At}}}$

# Measure the Fine-Structure Constant $\alpha$

Two main experiments in the world: Berkeley & LKB (Paris)



$$\Delta\phi_{\text{Berkeley}}(\omega_m) = 16N_R(N_R + N_B) \frac{\hbar k_R^2 T_R}{2m_{\text{Cs}}} - 2N_R\omega_m T_R$$



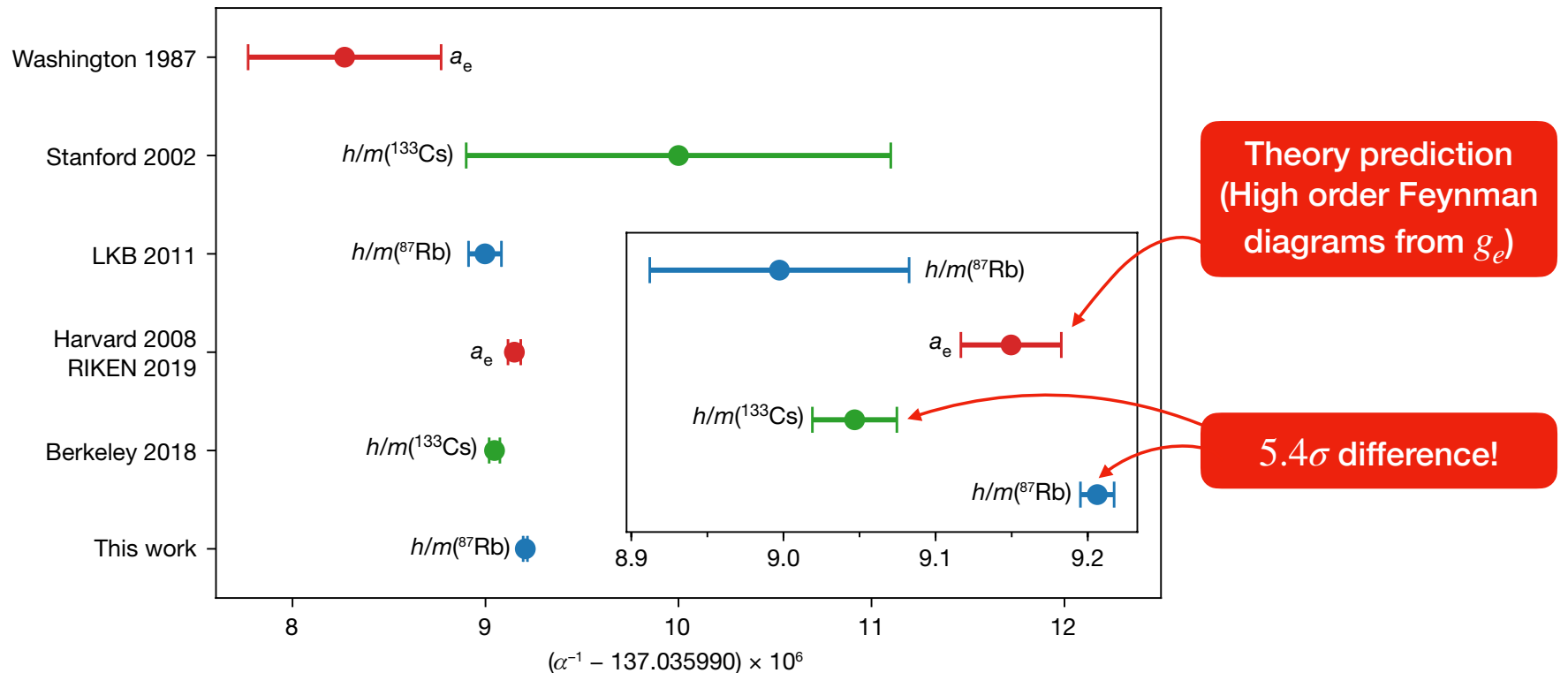
$$\Delta\phi_{\text{LKB}} = T_R \left( 2\varepsilon_R k_R \left( \frac{2\varepsilon_B \hbar k_B}{m_{\text{Rb}}} - g T_R \right) - \delta\omega_R \right)$$

Adapted from R. Parker et al., "Measurement of the fine-structure constant as a test of the Standard Model"

Adapted from L. Morel et al., "Determination of the fine-structure constant with an accuracy of 81 parts per trillion"

# Measure the Fine-Structure Constant $\alpha$

## Extreme Precision – but an Open Problem?



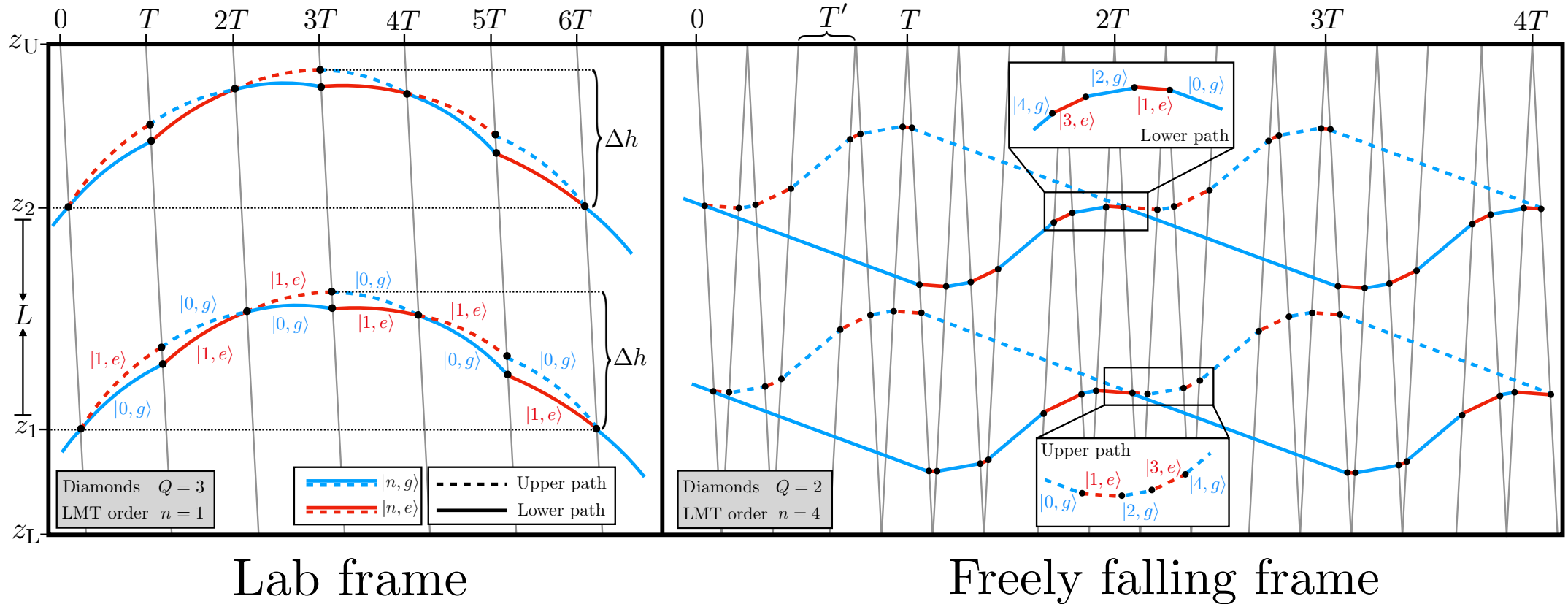
From L. Morel et al., "Determination of the fine-structure constant with an accuracy of 81 parts per trillion"

# **The Dream: Gravitational Wave & Dark Matter Detection**





# Gravitational Wave Detection



Werner et al. - "Terrestrial Gravitational Wave Detection with Atom Interferometers" (in preparation)

Adapted from Graham et al. - "Resonant mode for gravitational wave detectors based on atom interferometry"

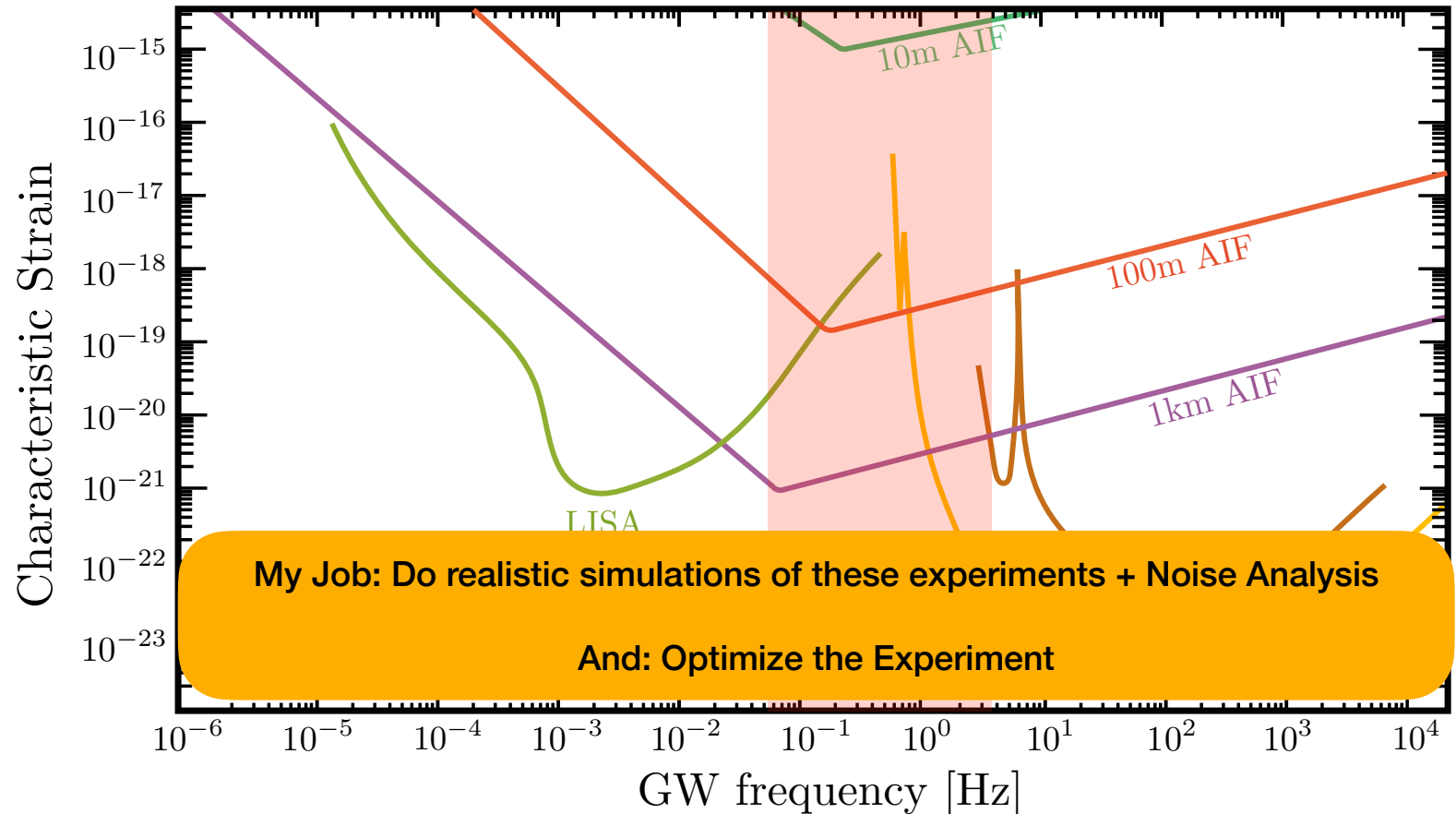
# Gravitational Wave Detection (GWD)

## Mind the gap!

**Proposals:** AIFs can measure GWs in the mid-frequency range!

We need: Baselines of more than 100m.  
First experiments are build as we speak!

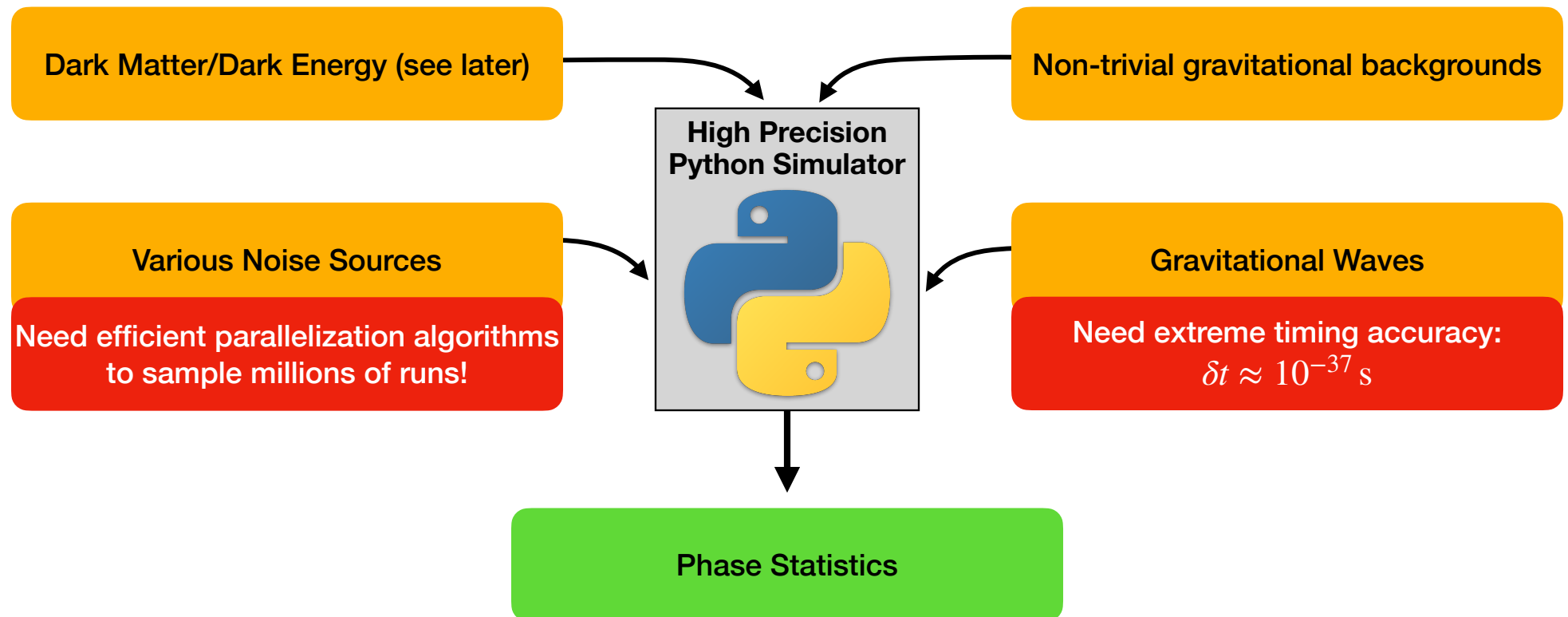
- MIGA
- MAGIS100
- AICE?



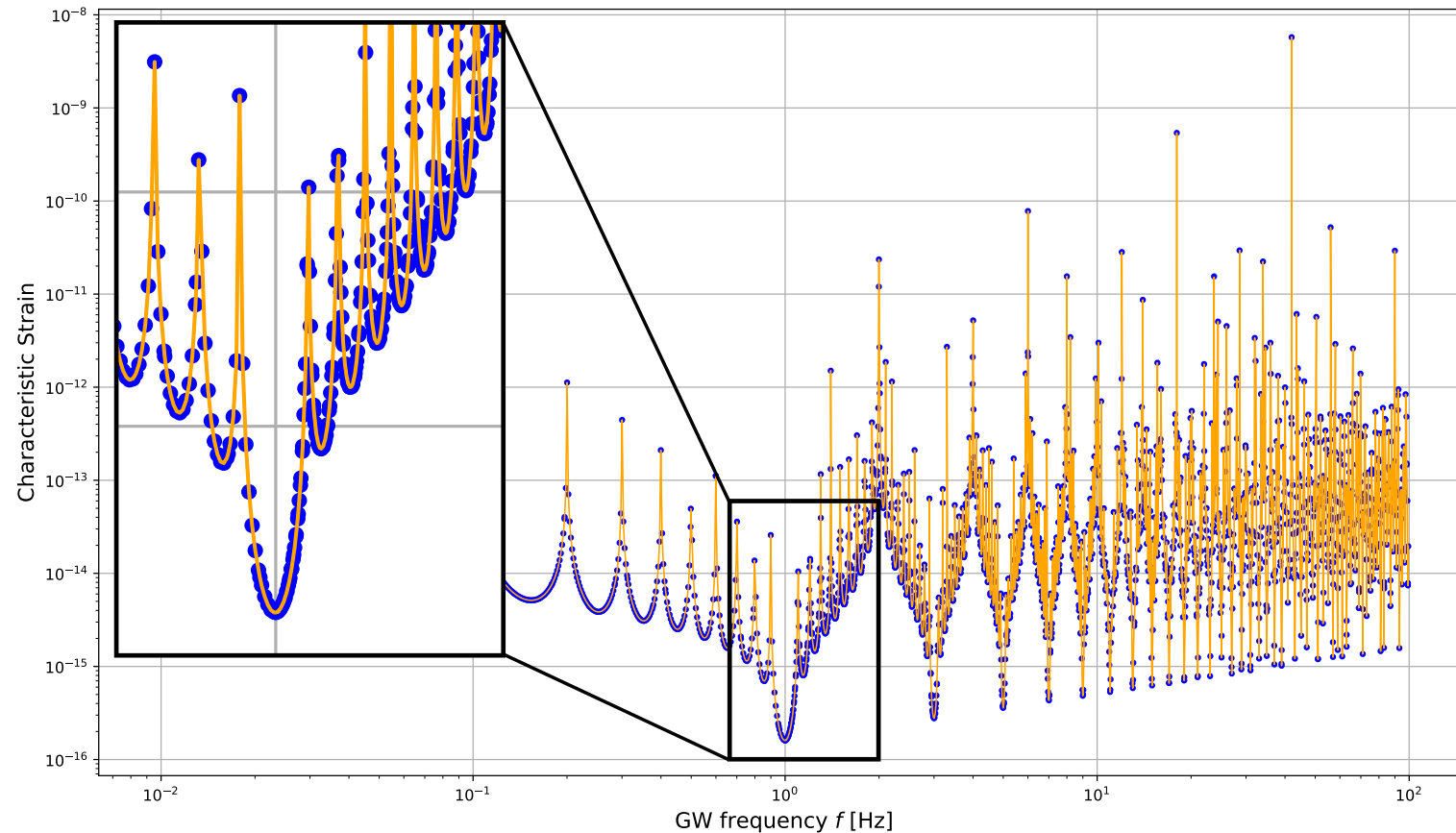
Adapted from Badurina et al. - "Prospective Sensitivities of Atom Interferometers to Gravitational Waves and Ultralight Dark Matter"

# Open Source Python Simulator

Owned — Curated — Developed by the Community



# GWD: Numerics vs. (ideal) Analytics



Werner et al. - "Terrestrial Gravitational Wave Detection with Atom Interferometers" (in preparation)

# Gravity Gradient Noise (GGN)

## Cooperation with Jeremiah Mitchell and the MIGA-Team.

Build on existing GW analysis and include gravity noise.

### Gravity noise:

- Gravity Gradient Noise (GGN) = Density fluctuations of surrounding media (air, ground).
- Newtonian noise (NN) = GGN + anthropogenic (and such) noise.

### Example GGN:

$$V_{\text{GGN}}(z, t) = -2\pi G \rho_0 \sum_a \xi_a \frac{c_H}{q\omega_a} \left( \frac{1+s^2}{1-s^2} \right) \left[ (1 + \sqrt{q/s}) \exp(-\omega_a z / c_H) - 2 \exp(-q\omega_a z / c_H) \right] \cos(\omega_a t + \tilde{\theta}_a)$$

with  $\rho_0 = 1800 \text{ kg/m}^3$ ,  $s = 0.36$ ,  $q = 0.88$ ,  $c_H = 205 \text{ m/s}$ .

Jeremiah Mitchell

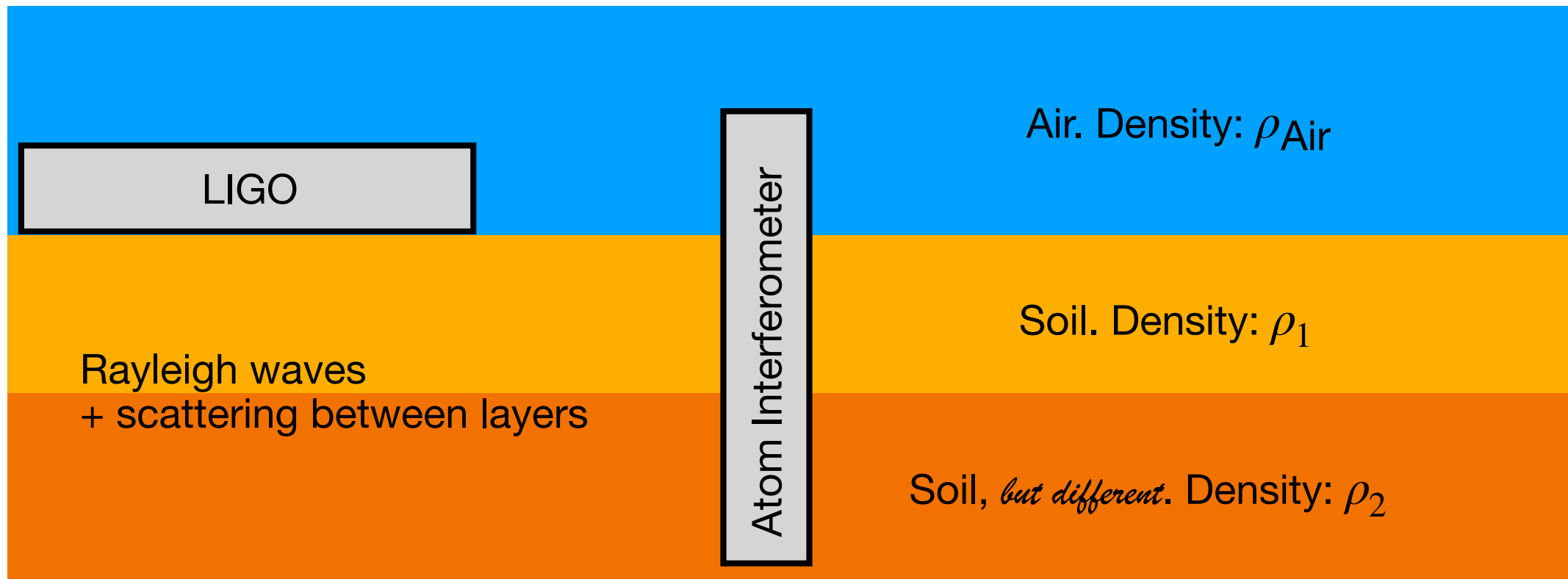


Benjamin Canuel



# Gravity Gradient Noise (GGN)

Goal: Get a more accurate model!



# AIFs in weakly curved spacetimes

Hamiltonian with all  $\mathcal{O}(c^{-2})$  effects:

$$\begin{aligned}
 H_{C,\text{final}} &= \frac{\mathbf{P}^2}{2M} \left[ 1 - \frac{1}{Mc^2} \left( \frac{\mathbf{p}_r^2}{2\mu} + \frac{e_1 e_2}{4\pi\epsilon_0 r} \right) \right] + \left[ M + \frac{1}{c^2} \left( \frac{\mathbf{p}_r^2}{2\mu} + \frac{e_1 e_2}{4\pi\epsilon_0 r} \right) \right] \phi(\mathbf{R}) \\
 &\quad - \frac{\mathbf{P}^4}{8M^3 c^2} + \frac{2\gamma + 1}{2Mc^2} \mathbf{P} \cdot \phi(\mathbf{R}) \mathbf{P} + (2\beta - 1) \frac{M\phi(\mathbf{R})^2}{2c^2}, \\
 H_{A,\text{final}} &= \frac{{}^{(3)}g_{\mathbf{R}}^{-1}(\mathbf{p}_r, \mathbf{p}_r)}{2\mu} + \frac{e_1 e_2}{4\pi\epsilon_0 \sqrt{{}^{(3)}g_{\mathbf{R}}(\mathbf{r}, \mathbf{r})}} \\
 &\quad - \frac{m_1^3 + m_2^3}{M^3} \frac{\mathbf{p}_r^4}{8\mu^3 c^2} + \frac{e_1 e_2}{4\pi\epsilon_0} \frac{1}{2\mu M c^2} \left( \mathbf{p}_r \cdot \frac{1}{r} \mathbf{p}_r + \mathbf{p}_r \cdot \mathbf{r} \frac{1}{r^3} \mathbf{r} \cdot \mathbf{p}_r \right), \\
 H_{AL,\text{final}} &= -\mathbf{d} \cdot \mathbf{E}_{\text{coord.}}(\mathbf{R}) + \frac{1}{2M} \{ \mathbf{P} \cdot [\mathbf{d} \times \mathbf{B}_{\text{coord.}}(\mathbf{R})] + \text{H.c.} \} \\
 &\quad - \frac{m_1 - m_2}{4m_1 m_2} \{ \mathbf{p}_r \cdot [\mathbf{d} \times \mathbf{B}_{\text{coord.}}(\mathbf{R})] + \text{H.c.} \} \\
 &\quad + \frac{1}{8\mu} (\mathbf{d} \times \mathbf{B}_{\text{coord.}}(\mathbf{R}))^2 + \frac{1}{2\epsilon_0} \int d^3\mathbf{x} \left( 1 + (\gamma + 1) \frac{\phi}{c^2} \right) \mathcal{P}_d^{\perp 2}(\mathbf{x}, t), \\
 H_{L,\text{final}} &= \frac{\epsilon_0}{2} \int d^3\mathbf{x} \left( 1 + (1 - 3\gamma) \frac{\phi}{c^2} \right) \left[ \mathbf{E}_{\text{phys.}}^{\perp 2} + c^2 \mathbf{B}_{\text{phys.}}^2 \right] \\
 &= \frac{\epsilon_0}{2} \int d^3\mathbf{x} \sqrt{-g} \left[ \mathbf{E}_{\text{phys.}}^{\perp 2} + c^2 \mathbf{B}_{\text{phys.}}^2 \right]
 \end{aligned}$$

Full Analysis:



Systematically solved the Schrödinger equation and analyzed the effect on AIFs!

With Klemens Hammerer, Domenico Giulini and Philip Schwartz



Photo: Uni Bremen

Photo: Nils Ole Peters

Werner et al. - "Atom interferometers in weakly curved spacetimes using Bragg diffraction and Bloch oscillations" (QR code)



Michael Werner

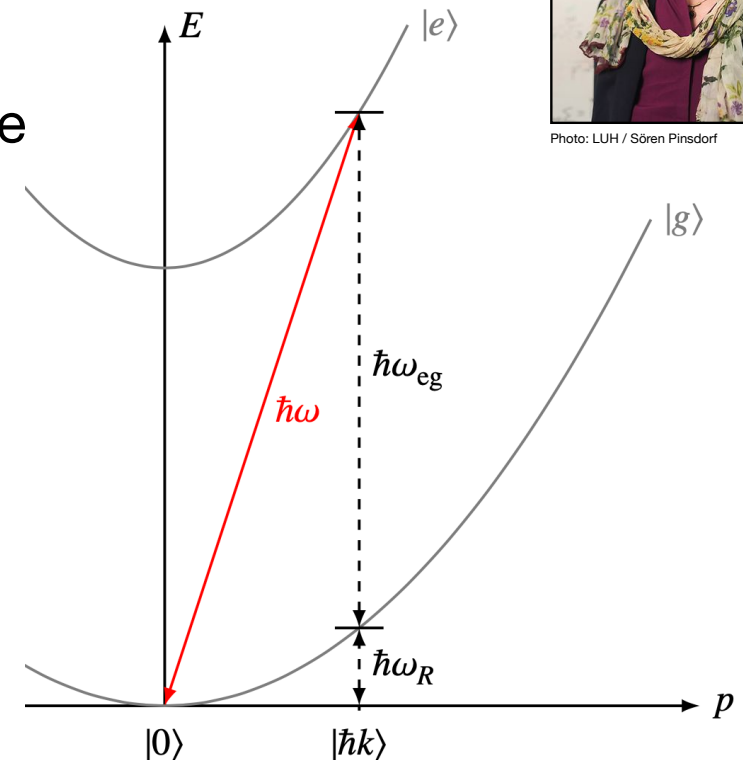
Gravitational Quantum Physics and Metrology



# Dark Matter Detection

## Same Geometry as GWD – Different Physics

- Scalar ULDM acts like a change in  $\alpha$ .
- For a single photon transition this would change the transition frequency  $\omega_{eg}$ .
- Laser frequency  $\omega$  needs to be resonant to varying transition frequency.
- Detect  $\Delta\alpha/\alpha$  variations.
- Scalar DM / Vector DM / Axionic DM / ...



With Elina Fuchs

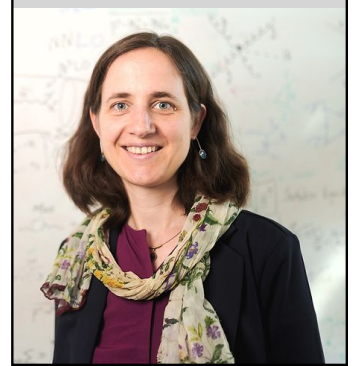


Photo: LUH / Sören Pinsdorf

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# Summary

## AI Fs are Versatile Quantum Sensors!

- Very sensitive devices to measure **inertial forces** (accelerations, rotations).
- Test GR with atoms: **Weak Equivalence Principle**.
- Detect **Gravitational Waves** in the Mid-Frequency range (100+ meters).
- Look for **Dark Matter**: ULDM, Scalar, Axion, Chameleon, ...
- Most accurate measurement of the **fine-structure constant**  $\alpha$ .
- And much more (**Gravitational Aharonov-Bohm** effect, **Gravity Mediated Entanglement**, Seismological Studies, Ground Water Analysis, ...)!

# Thank you for listening!

All of my codes (Python) are open source, since science should be free and accessible to everyone.

Our goal is to create community-driven, free and open software packages for atom interferometry. Interested? Please reach out!

Funding from:



AGAPES Project

Quantum Frontiers



Our team in September 2025

Codes and Contact!

