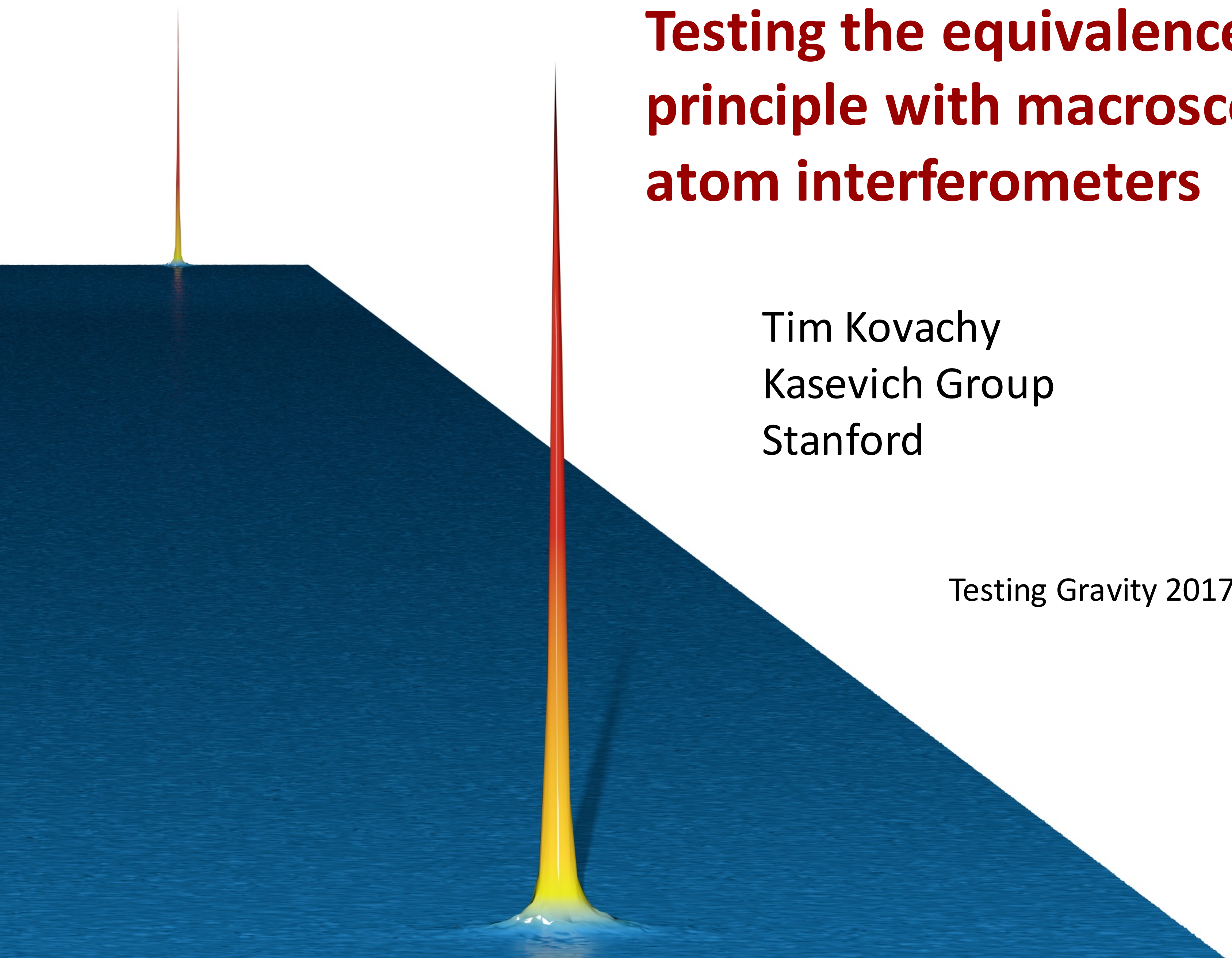
Testing the equivalence principle with macroscopic atom interferometers



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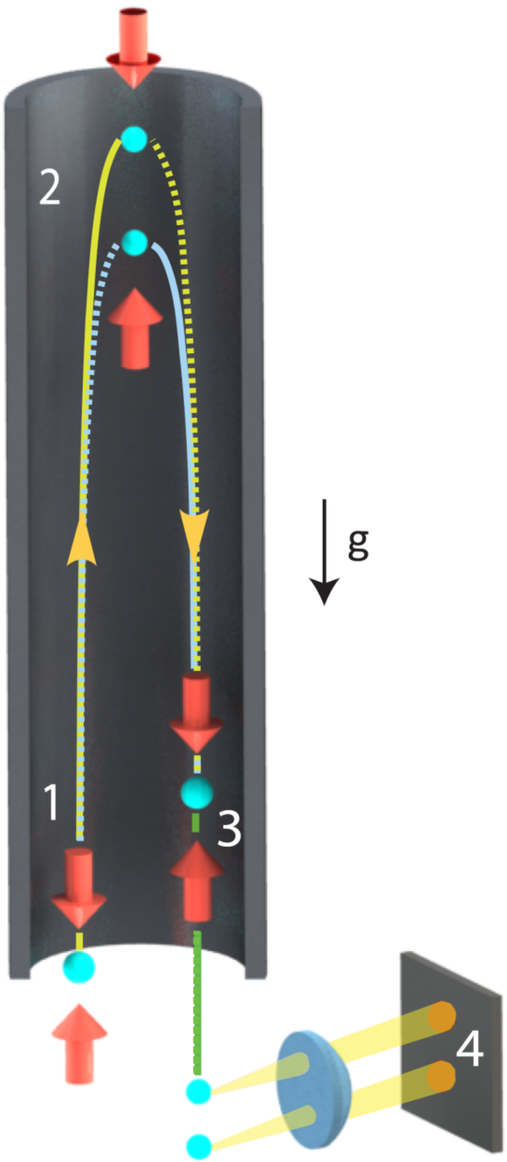
Testing Gravity 2017

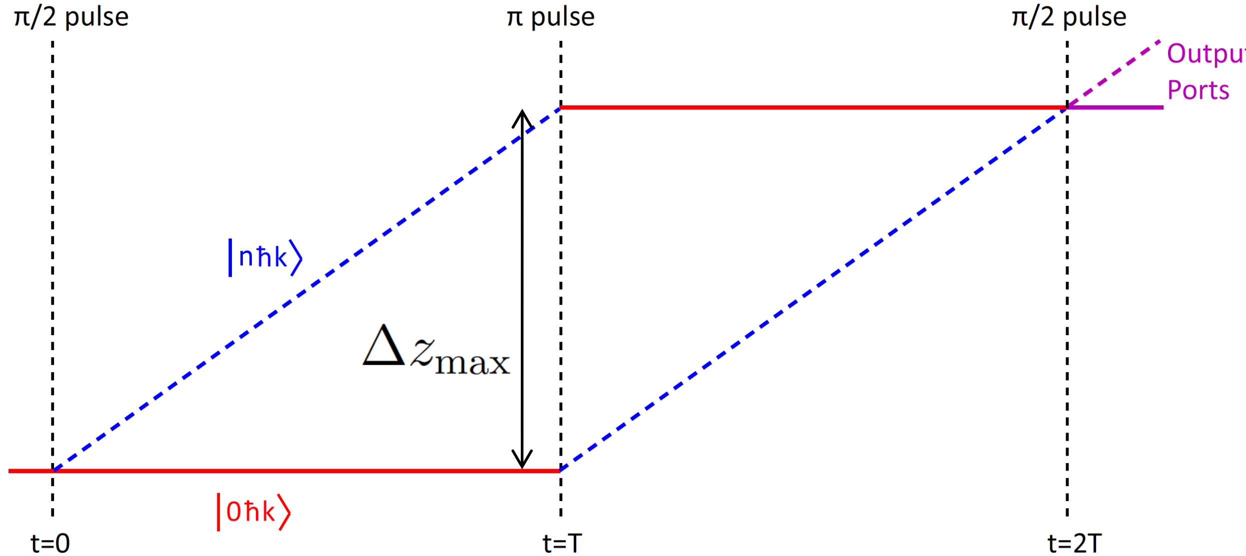
Outline

- Large spacetime area atom interferometry in 10 m atomic fountain

- Differential gravity measurements
  - Precision gravity gradiometry
  - Dual species Rb-85/Rb-87 interferometer for an EP test

Light Pulse Atom Interferometry





Large Spacetime Area Interferometers

- Inertial sensitivity proportional to enclosed spacetime area

$$\Delta\phi = -\frac{m}{\hbar} g \underline{\underline{\Delta z_{\max} T}} \qquad \Delta z_{\max} = \frac{n\hbar k}{m} T \qquad \Delta\phi = -nkgT^2$$

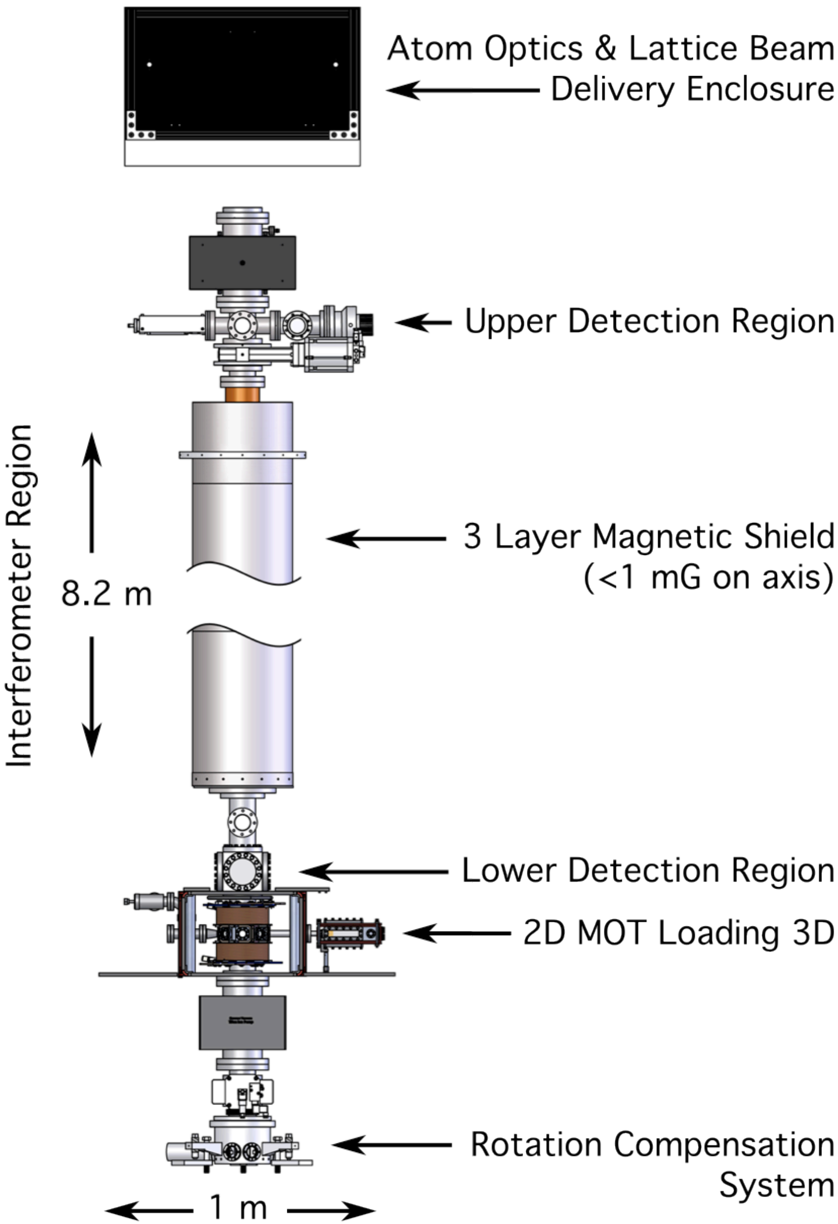
1. Increase momentum splitting $n\hbar k$ between the two interferometer arms.

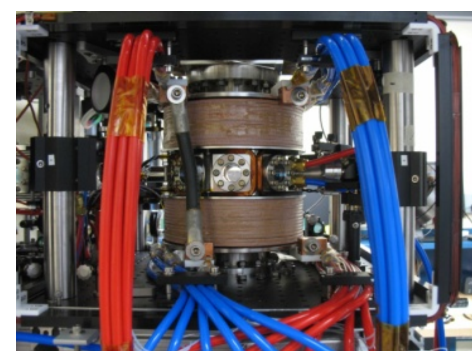
2. Make a tall atomic fountain to increase the free fall distance ~gT^2.

3. Do both at the same time. Typical operating conditions: arm splitting >10 cm, T ~ 1 s

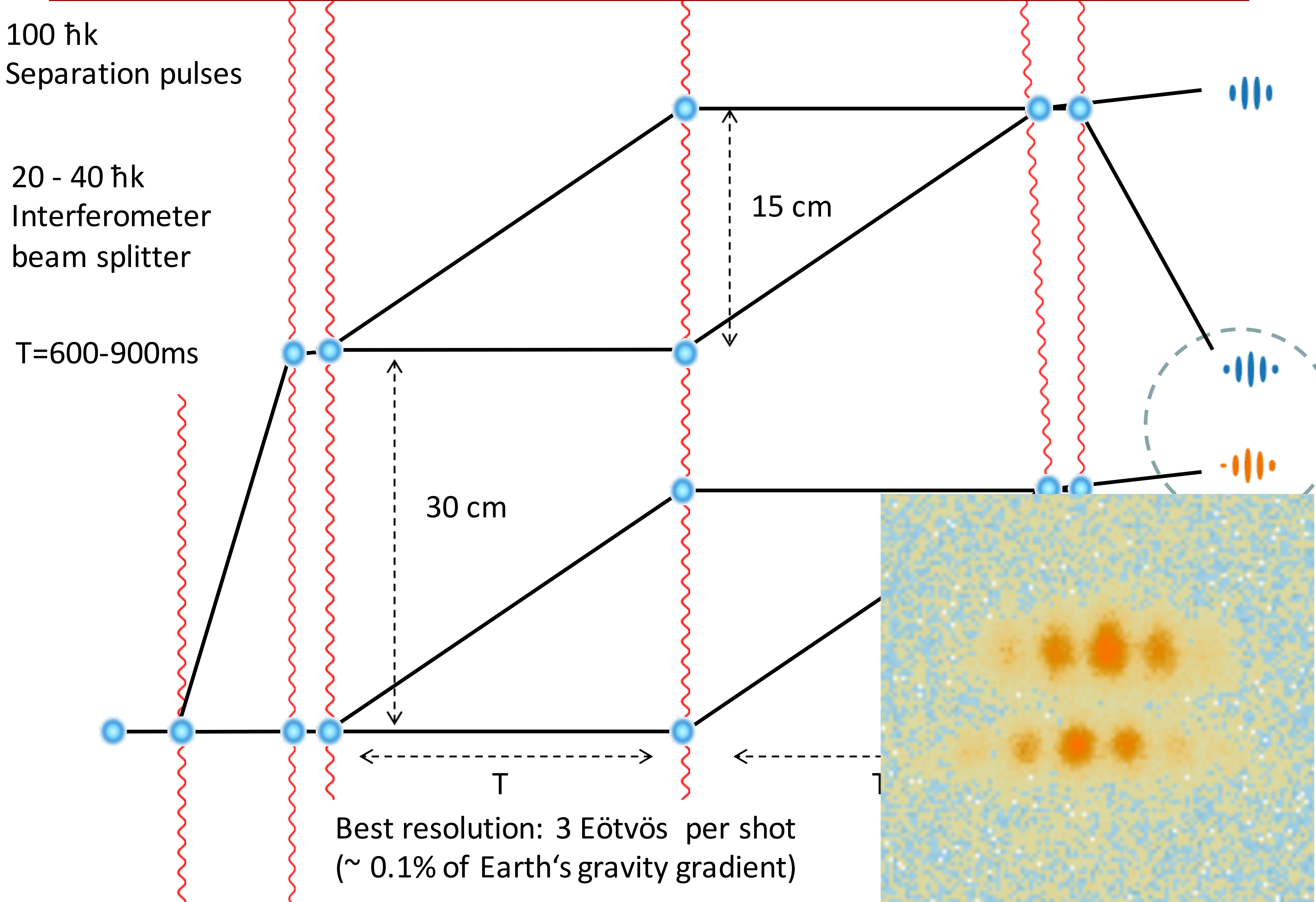
TK, P. Asenbaum, C. Overstreet, C. Donnelly, S. Dickerson, A. Sugarbaker, J. Hogan, and M. Kasevich, Nature 2015
P. Asenbaum, C. Overstreet, TK, D. Brown, J. Hogan, and M. Kasevich, arXiv:1610.03832

10 m Atom Fountain



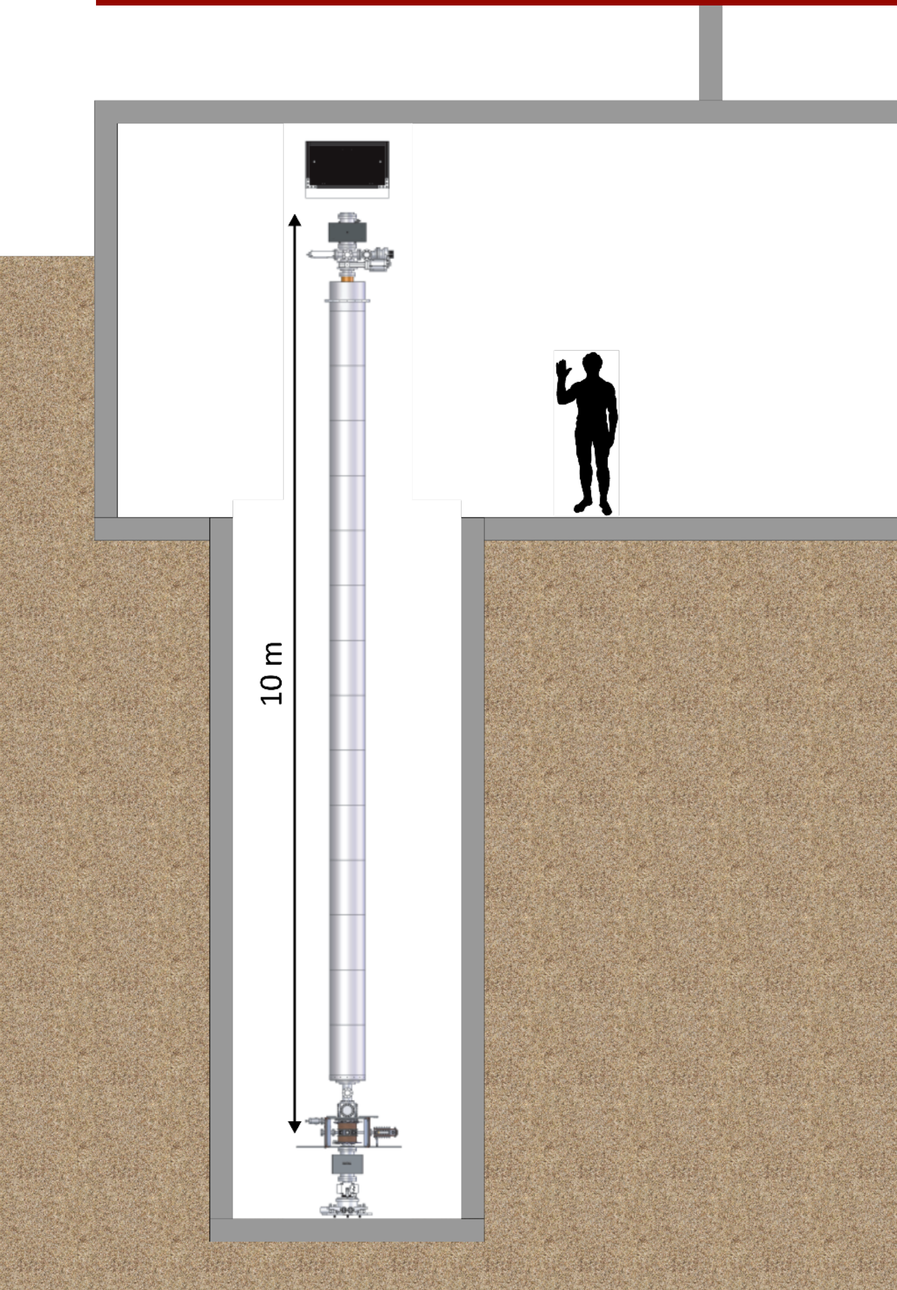


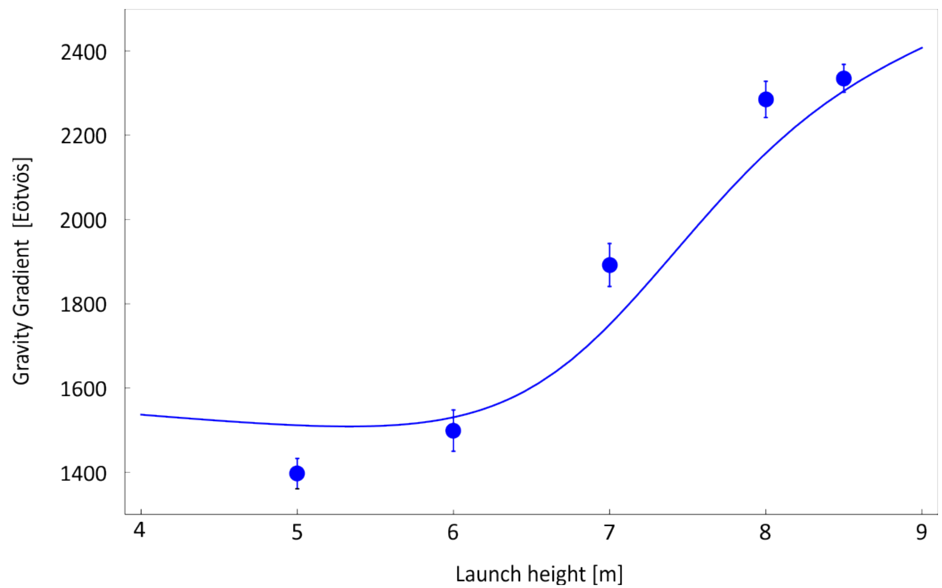
Single Source Gradiometer



Best resolution: 3 Eötvös per shot
(~ 0.1% of Earth's gravity gradient)

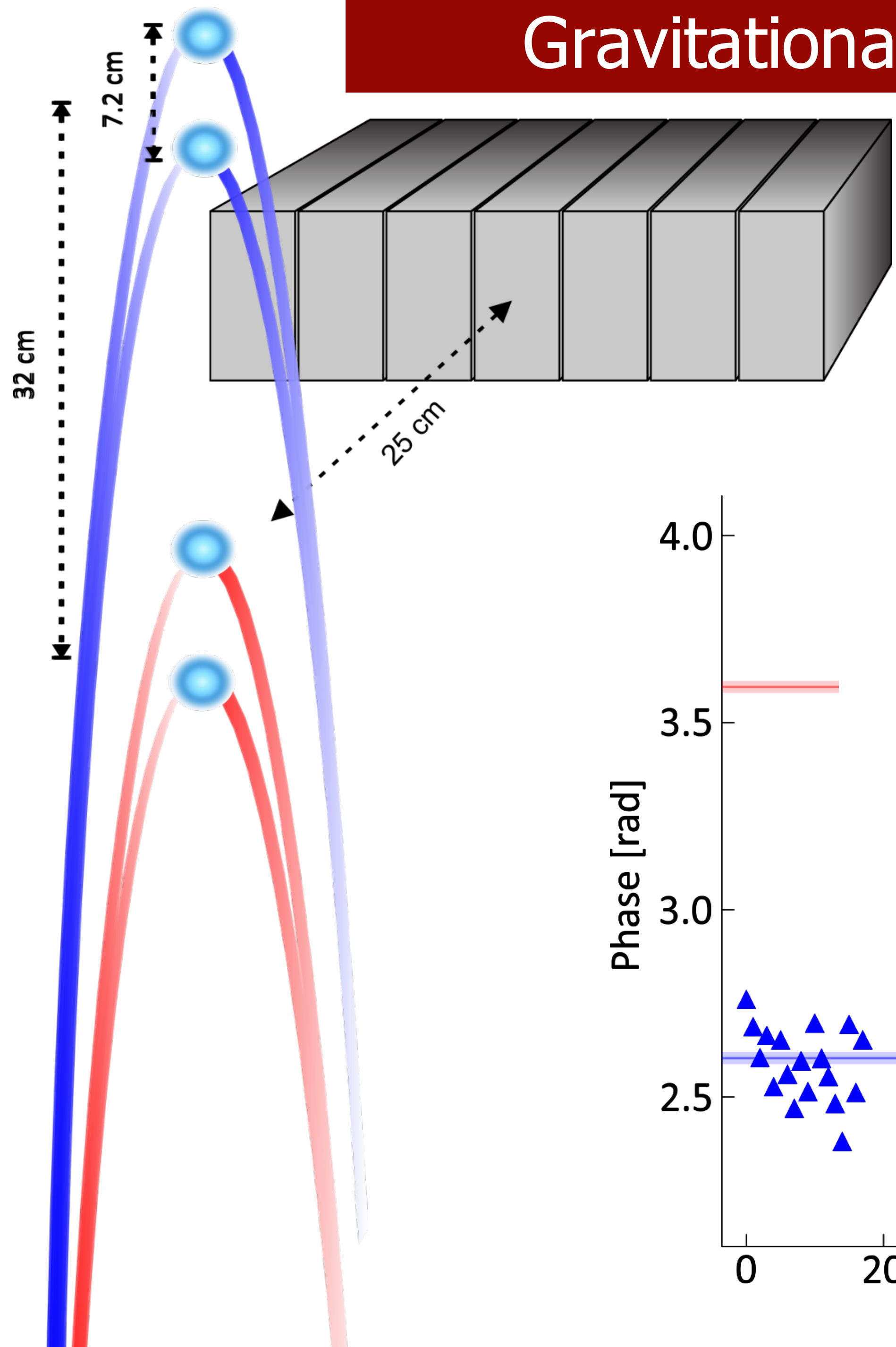
Gravity Gradient vs. Launch Height

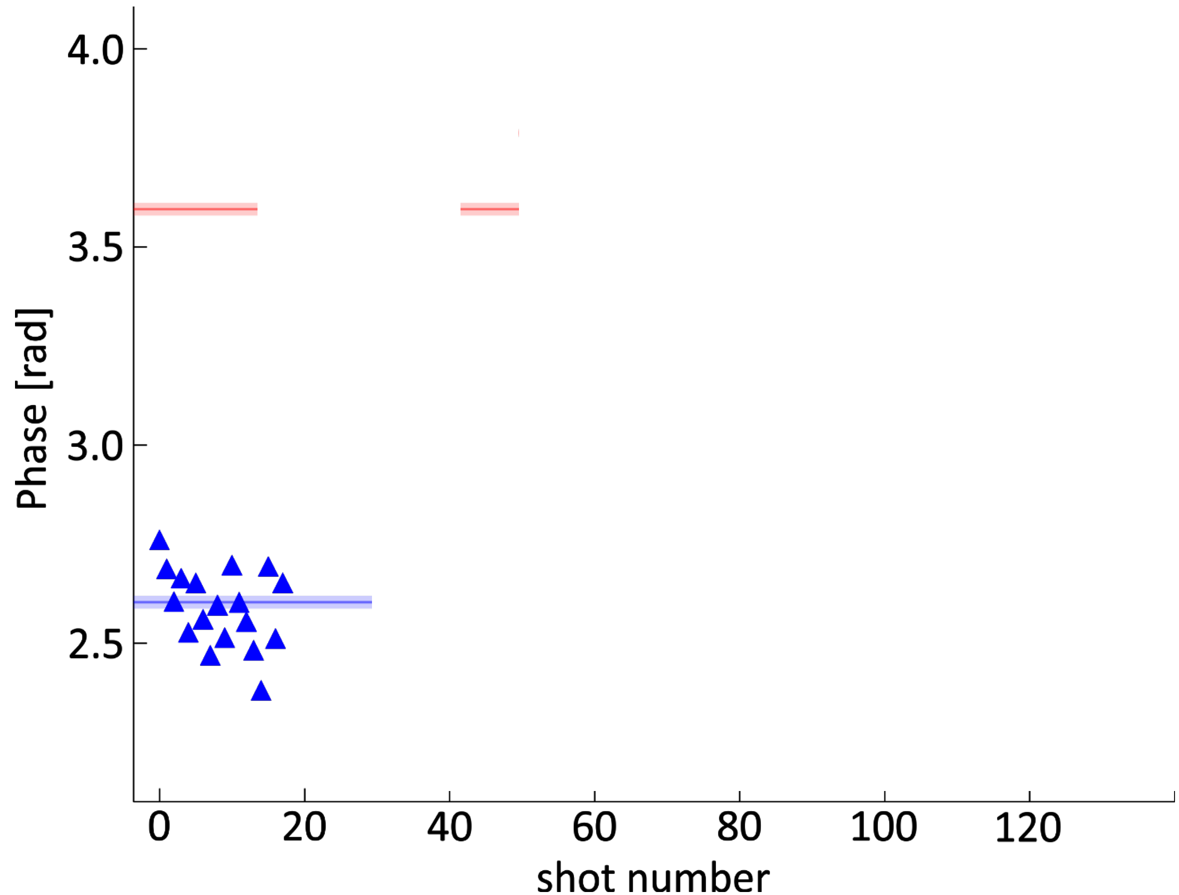




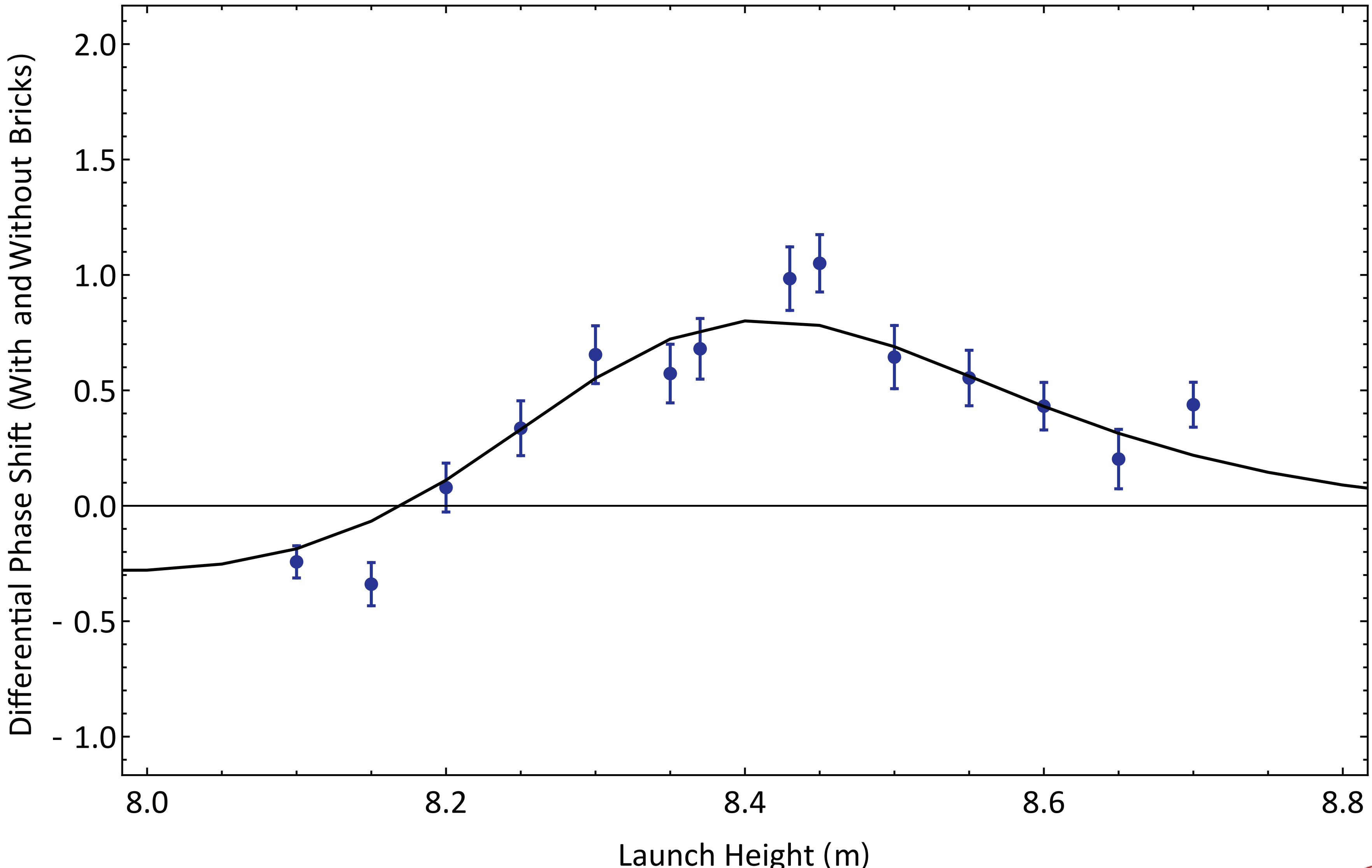
Eötvös = 10^{-9} s^{-2}

Gravitational Force from Test Mass





Phase Shift from Bricks vs. Height



Tidal Phase Shifts

Interferometer paths deflected away from initial trajectory by distances on the spatial scale of the path separation

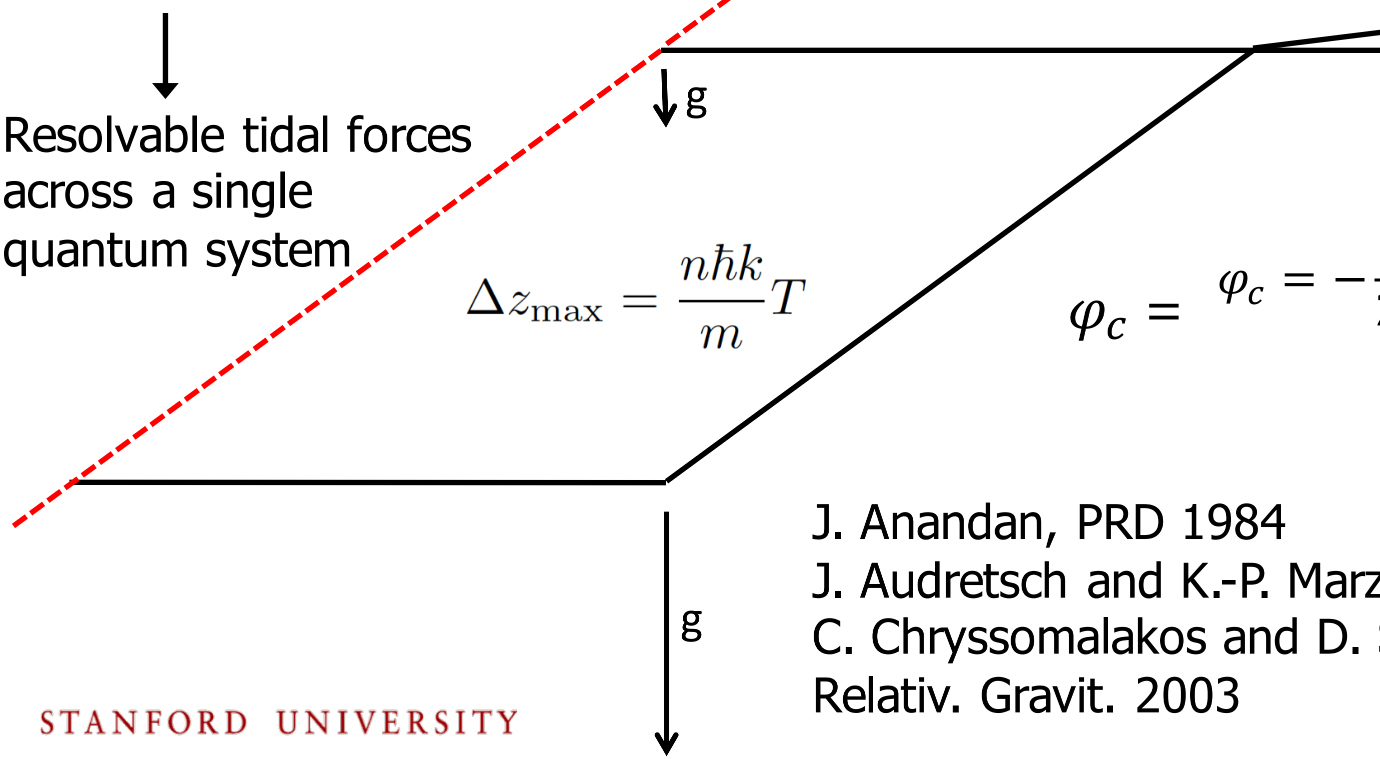
- in presence of gravity gradient, can lead to an additional phase shift

Trajectory ignoring recoil of atoms (limit of very heavy test particle)

This phase shift can be observed when the two interferometer paths experience resolvably different gravitational accelerations

↓

Resolvable tidal forces across a single quantum system



$$\Delta z_{\max} = \frac{n\hbar k}{m} T$$

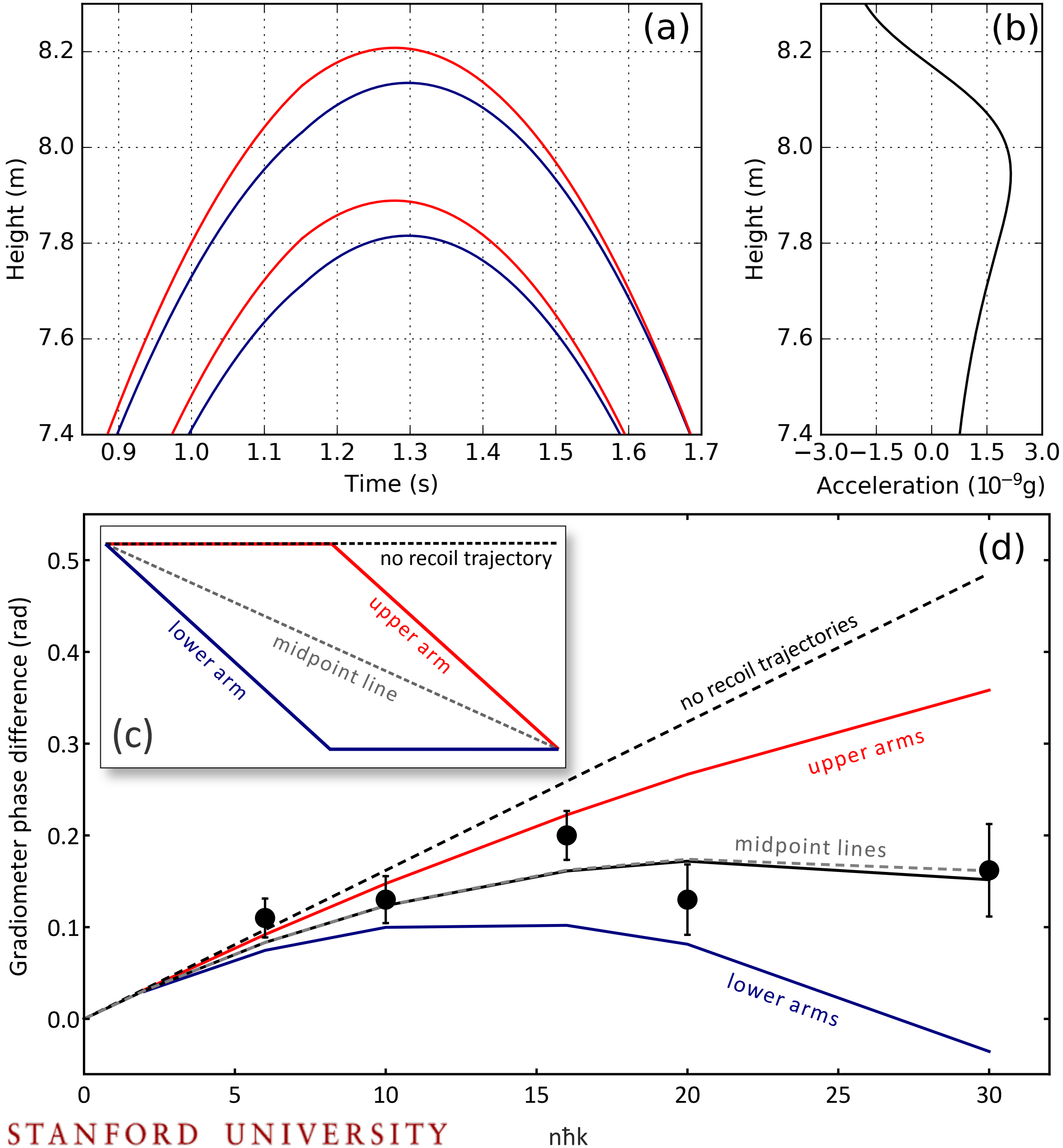
$$\varphi_c = \quad \varphi_c = -\frac{1}{2m}\hbar k_{eff}^2 T_{zz1} T^3 \quad {}_{z2})T^3$$

J. Anandan, PRD 1984

J. Audretsch and K.-P. Marzlan, PRA 1994

C. Chryssomalakos and D. Sudarsky, Gen. Relativ. Gravit. 2003

Tidal Phase Shifts



Acceleration due to bricks as a function of height

Equivalence Principle

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$$\eta_{A,B} = 2\frac{g_A - g_B}{g_A + g_B}$$

Current Bounds on WEP

©news.cnrs.fr

$$\eta(M,E) = (-1.0 \pm 1.4)\times 10^{-13}$$

Williams et al, PRL 2004

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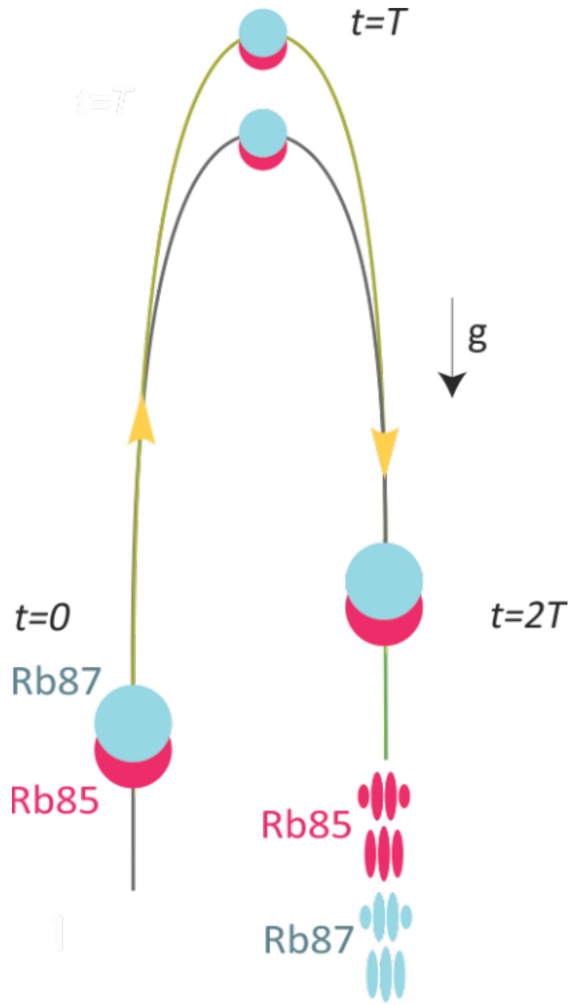
$$\eta(Be,Ti) = (0.3 \pm 1.8)\times 10^{-13}$$

Schlamminger et al, PRL 2008

Simultaneous dual species interferometers



Suppresses time varying effects

- Mirror motion
- …

Bragg Interferometer

- Common Bragg laser beams

Common velocity selection

AC stark shift compensation

Phase shear readout

- Contrast & amplitude noise

Sugarbaker et al, PRL 2013

$2\hbar k$ Dual Species Run

Rb-87

Rb-85

Rb-87 and Rb-85 are in phase

2T = 2.08 s

10$\hbar k$ Dual Species Run

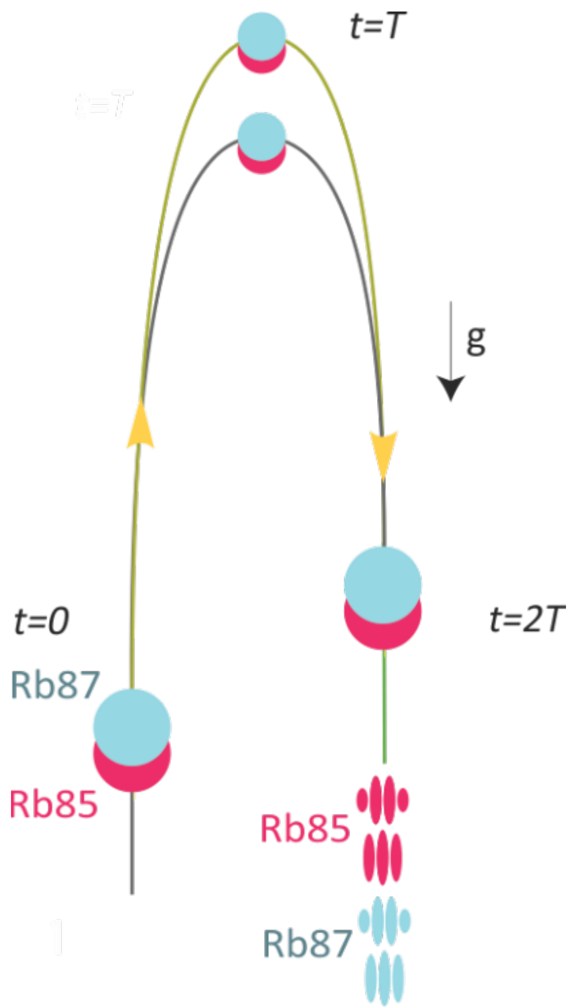
Rb-87

Rb-85

Rb-87 and Rb-85 are in phase

2T = 2.08 s

Statistical Sensitivity Goal



$$\phi_0 = k_{eff} g T^2$$

phase shift $\phi_0 = 2\times10^9$ rad per g at 20 ħk

Shot noise on phase read out:

N= 10^5 atoms per shot

$$\Delta\varphi = \frac{\sqrt{N}}{N} \sim 3\times10^{-3} \text{ per shot}$$

$$\Delta\varphi/\varphi \sim 1.5\times10^{-12} \text{ per shot}$$

➡ 1.5×10^{-14} with 10^4 shots ~ 1 week

Outlook

- Gravity gradient compensation (Albert Roura)
- Lots of EP data runs, study systematics
- Big G?

Acknowledgements

Peter Asenbaum
Chris Overstreet
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