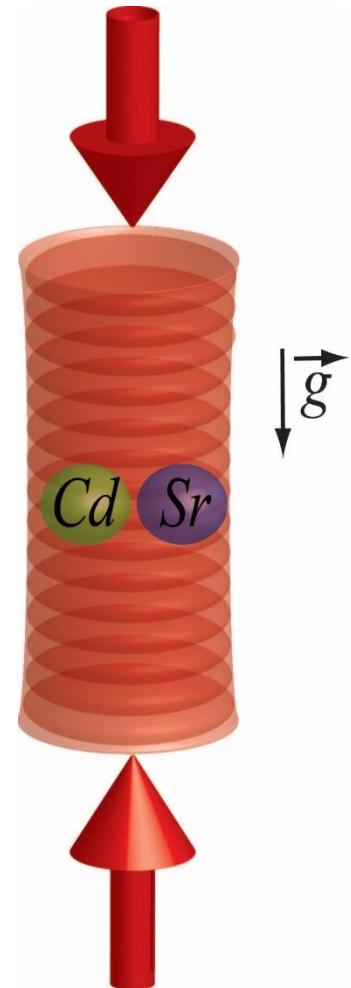


Novel atom interferometers for precision test of fundamental physics

Nicola Poli

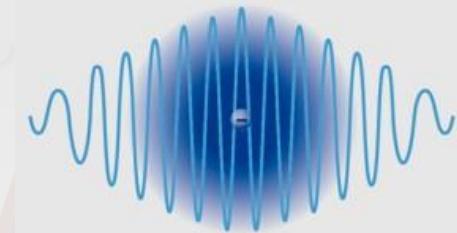
Dipartimento Fisica e Astronomia
Università degli Studi di Firenze

LENS – INFN – CNR/INO



Introduction

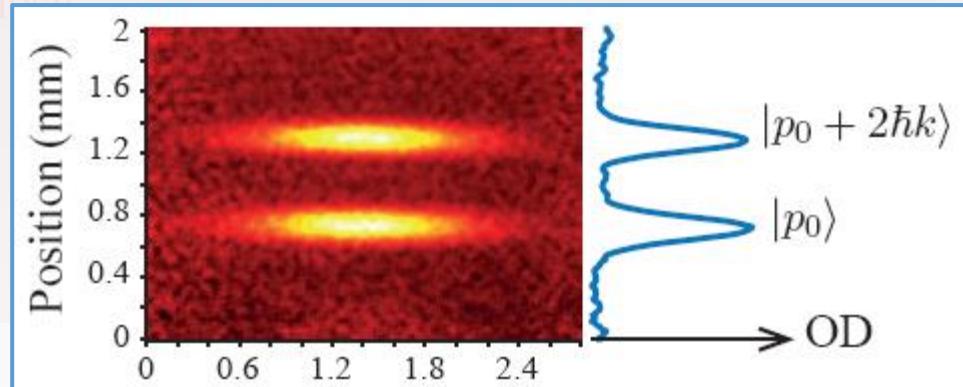
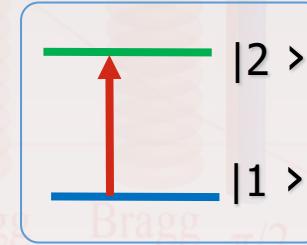
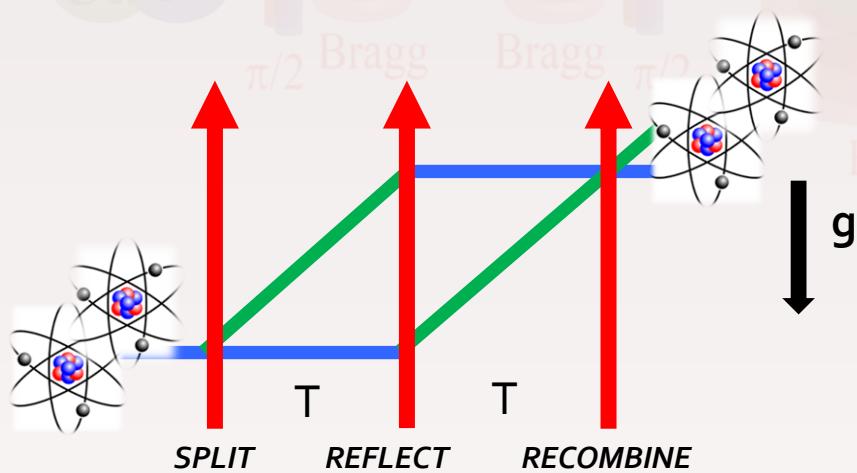
Matter-wave interferometry



$$(\lambda_{dB} = h/p)$$

Atom interferometer:

light -> matter wave



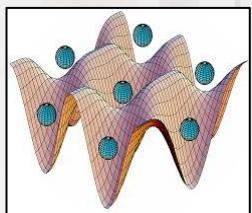
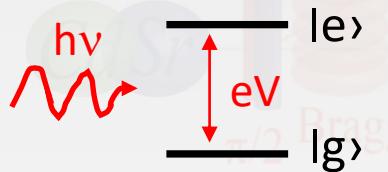
Introduction

Precision measurements with ultra-cold atoms

TIME

Optical atomic clocks

internal d.o.f., electronic states

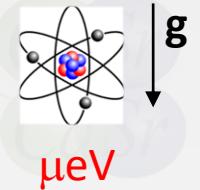
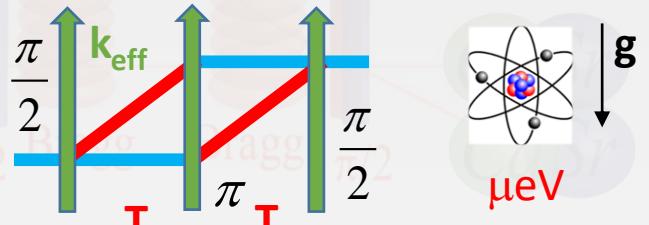


relative precision 10^{-19}

GRAVITY

Atom interferometers (gravimeters/gradiometers)

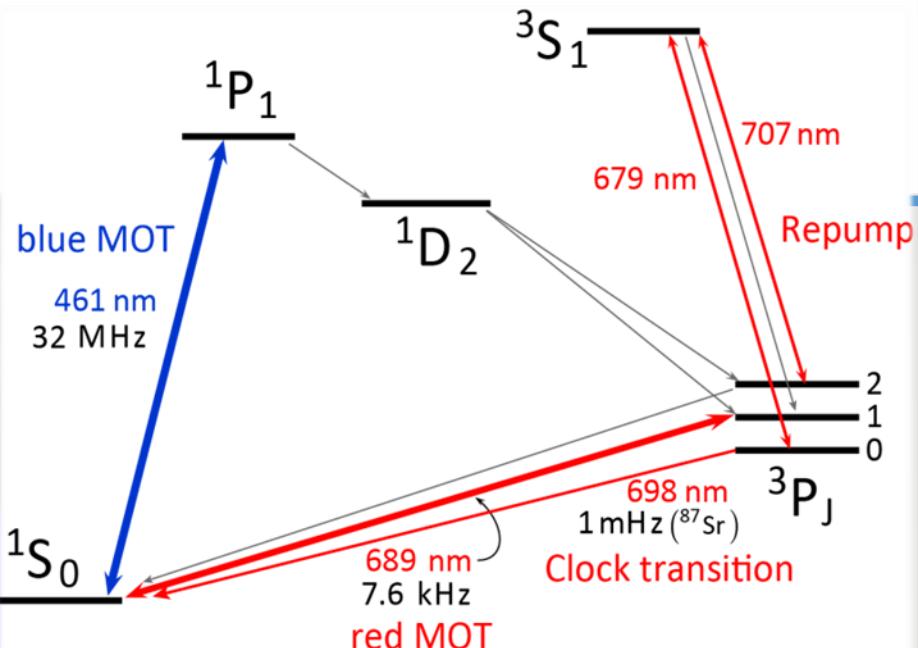
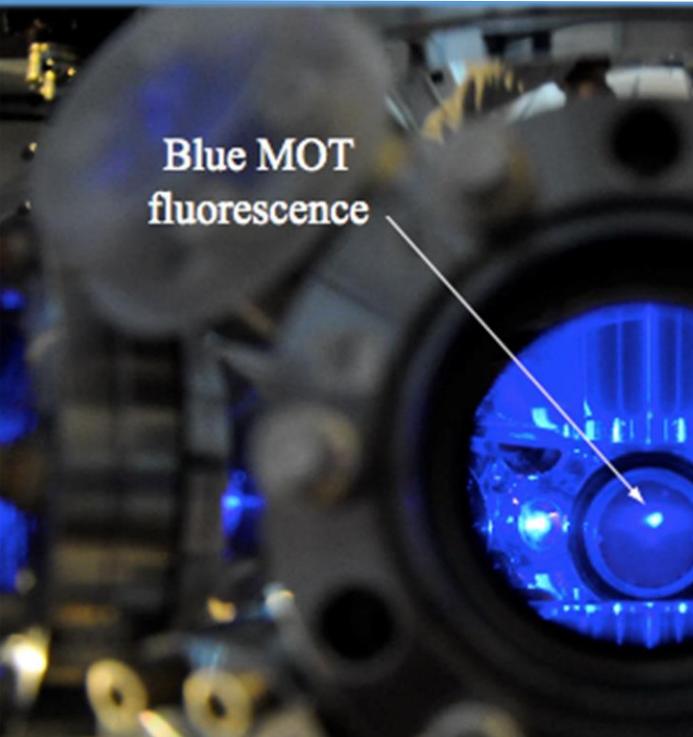
external d.o.f., momentum states



relative precision 10^{-11} g

Alkaline-Earth Atoms

	1	H	Hydrogen	1.008
3	2	Li	Lithium	6.941
11	12	Mg	Magnesium	24.305
19	20	K	Potassium	39.098
37	38	Rb	Rubidium	84.468
55	56	Cs	Ceasium	132.901
87	88	Fr	Francium	223.020
	89-	Ra	Radium	226.025



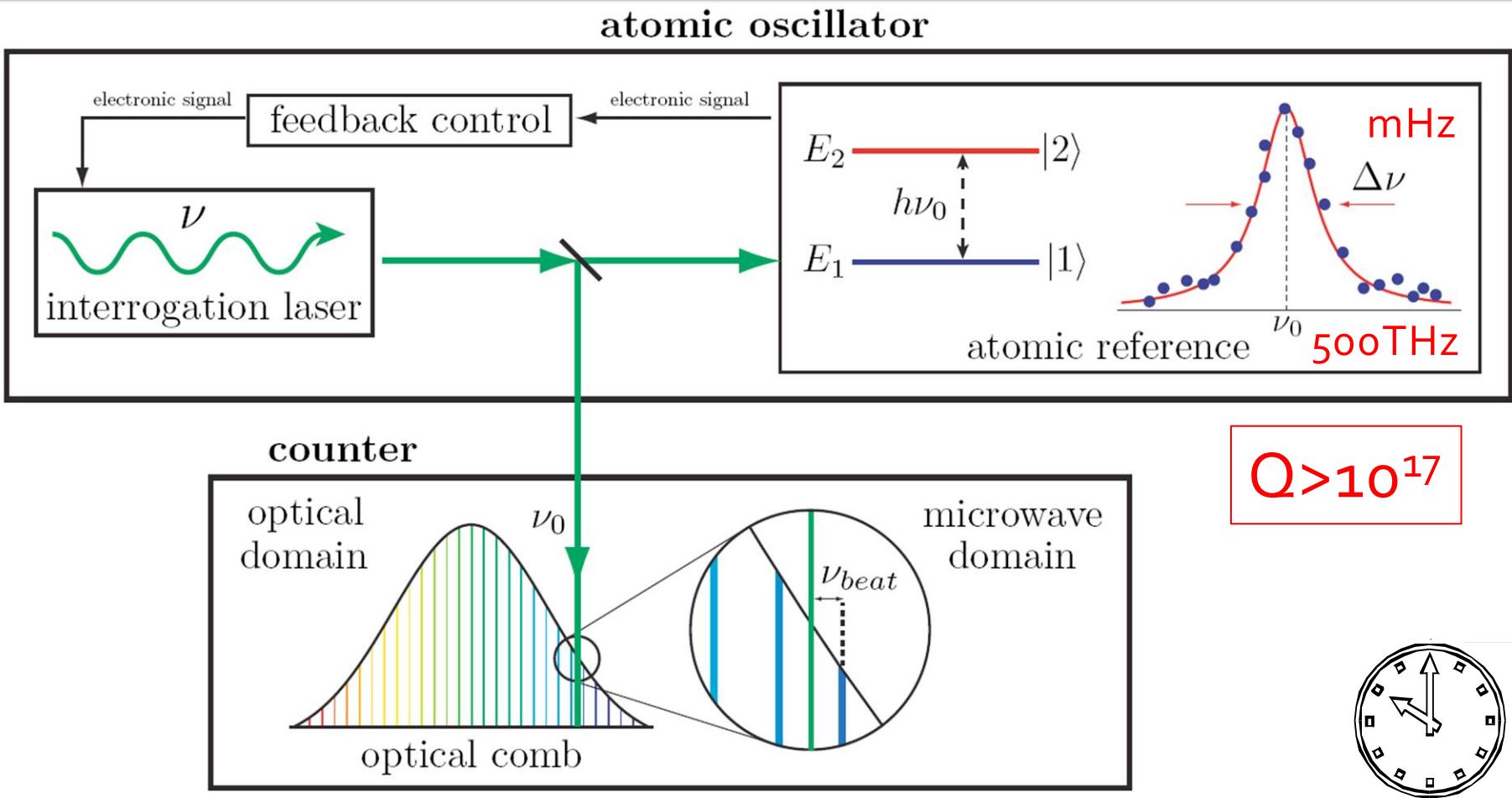
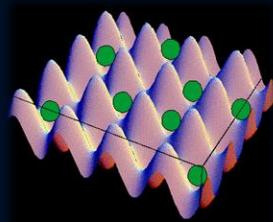
- Dipole allowed transitions (bosons, no hyperfine structure)
-> two-photon interferometers (Bragg diffraction)
- Narrow intercombination transitions to metastable ^3P states
-> single photon interferometers (atomic clocks)

Alkali

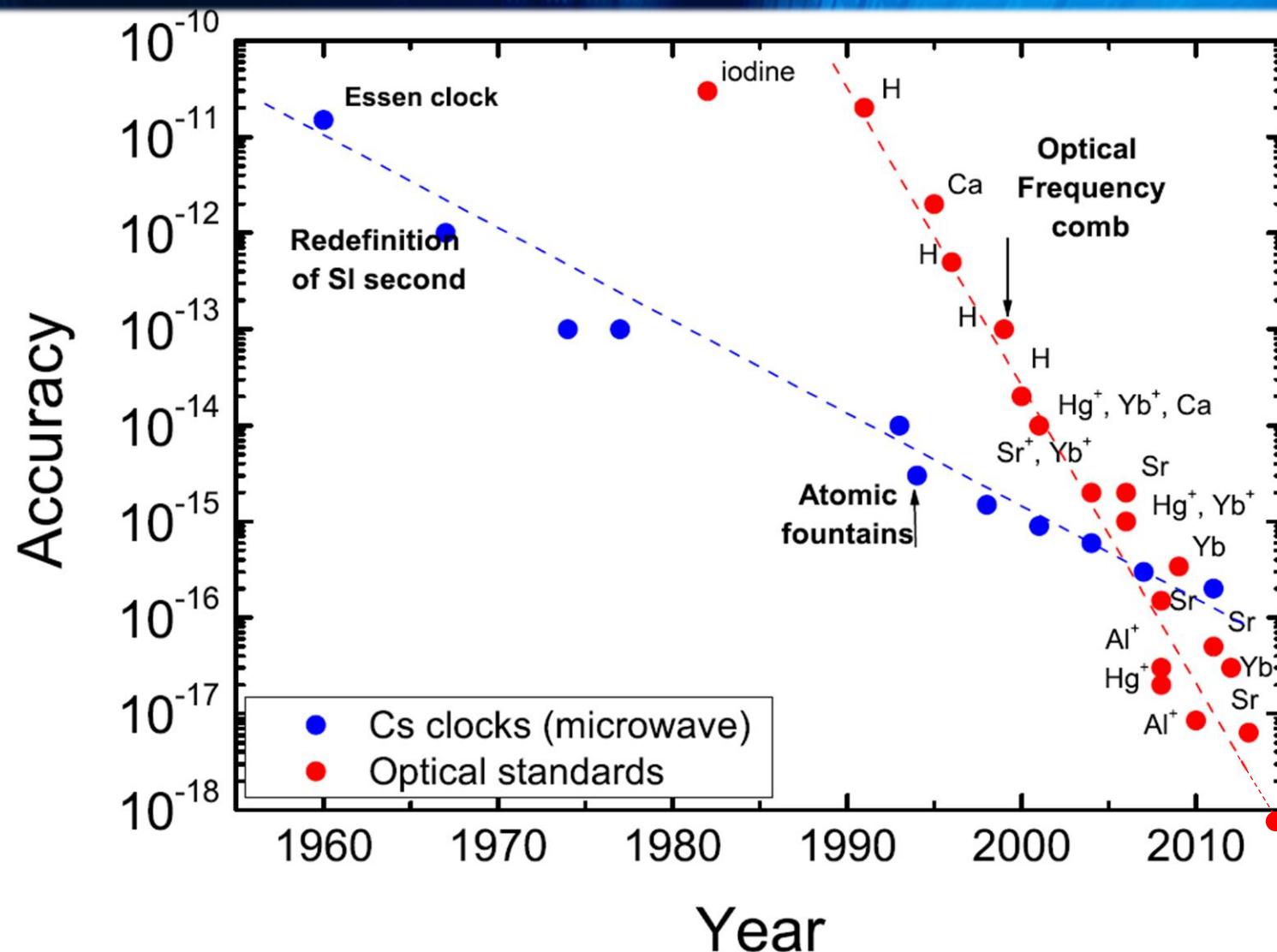
Motivation

- Fundamental physics
 - ✓ Experimental test of Standard Model
 - ✓ Measurements of fundamental constants (G , α)
 - ✓ Definition of SI unit
- Applications
 - ✓ Inertial systems for navigation, geolocalization
 - ✓ Underground prospecting, ...

Optical atomic clocks

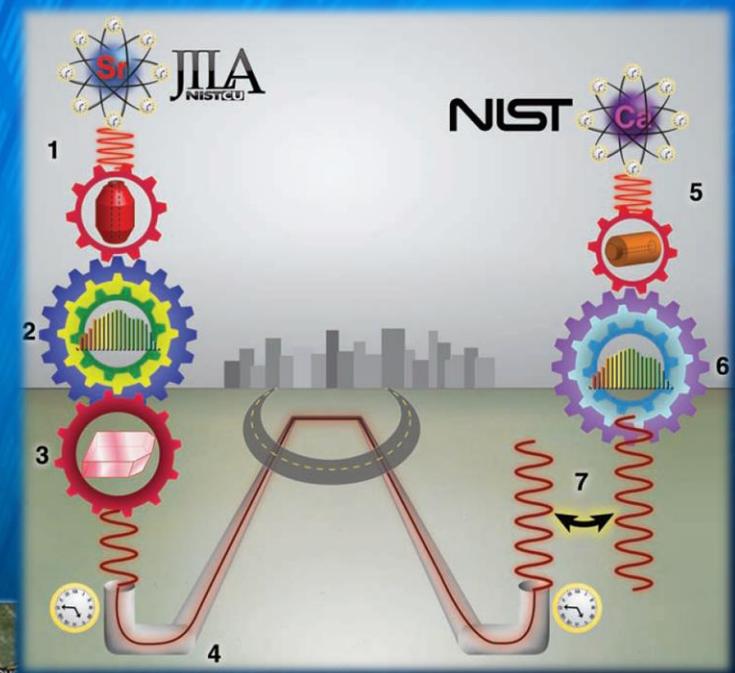


Clock Uncertainty



Optical fiber link

- A. D. Ludlow, et. al. Science **319**, 1805 (2008)
N. Poli, PRIN - MIUR (2009)
D. Calonico et. al. Appl. Phys. B **117**, 979–986 (2014)



Direct fiber link from
UNIFI to INRIM
(Torino) - 642 km

10^{-19} frequency stability



Ministero dell'Istruzione
dell'Università e Ricerca

Imaging optical frequencies

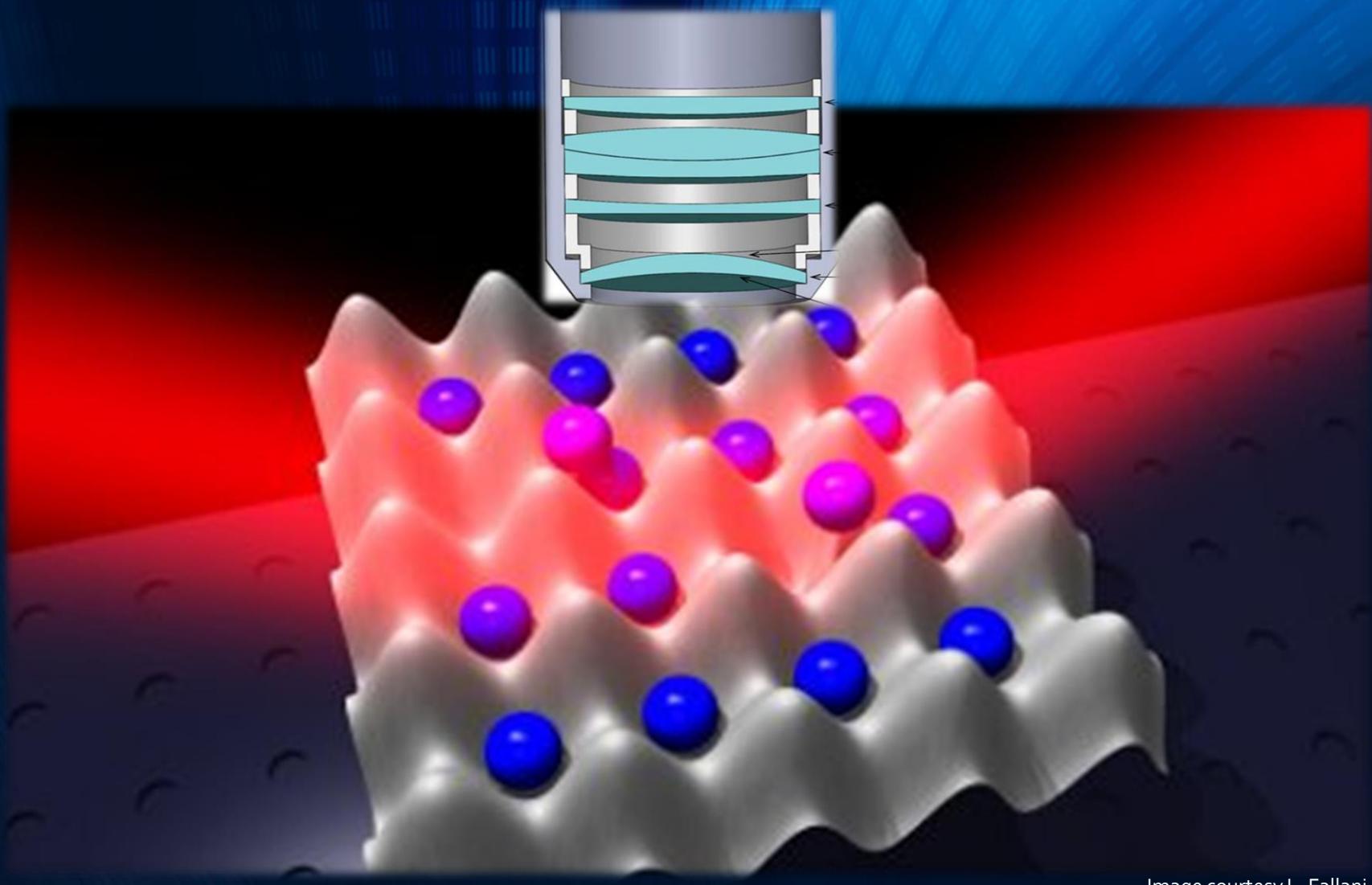
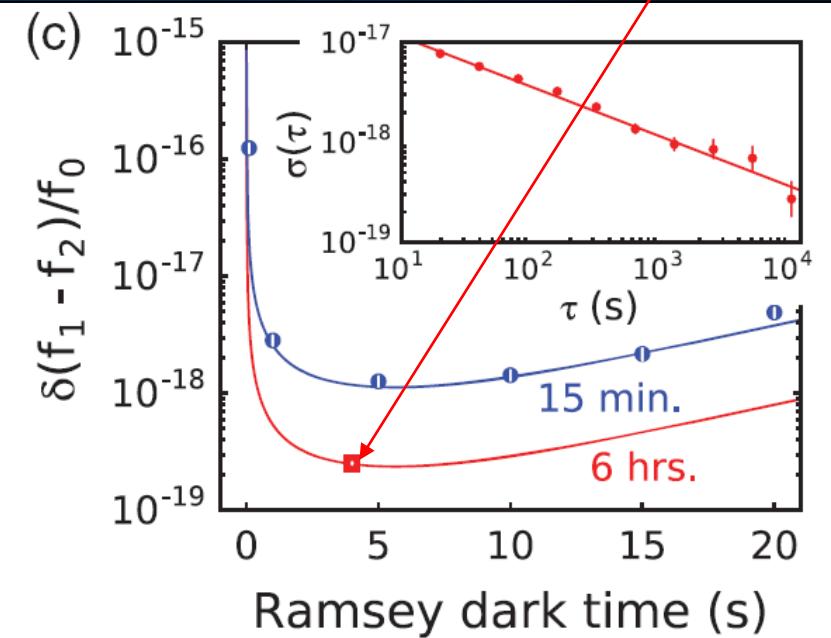
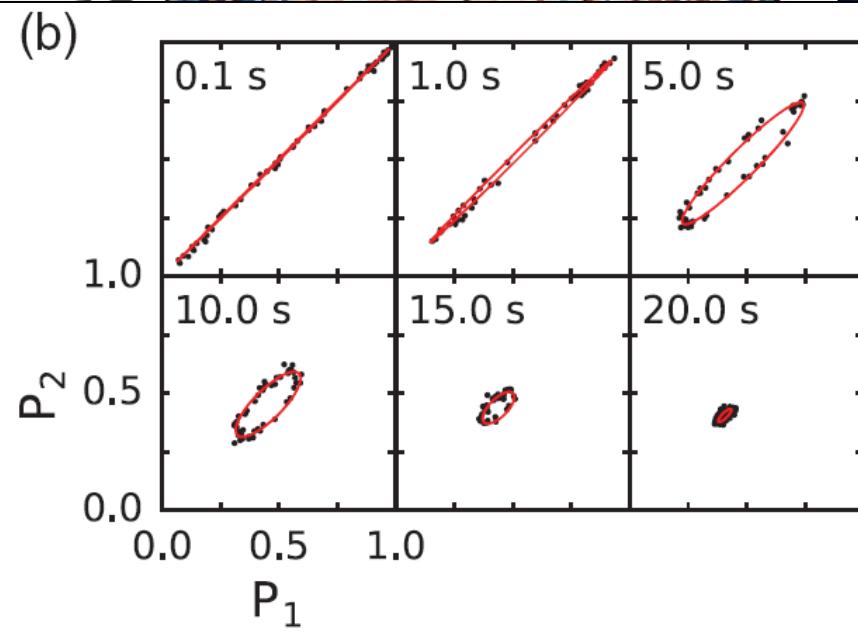
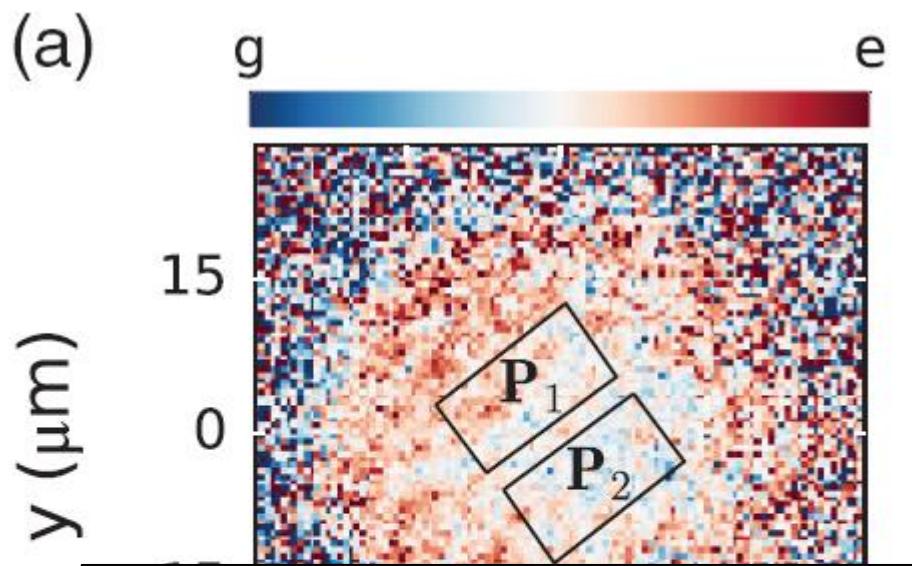


Image courtesy L. Fallani

Imaging optical frequencies

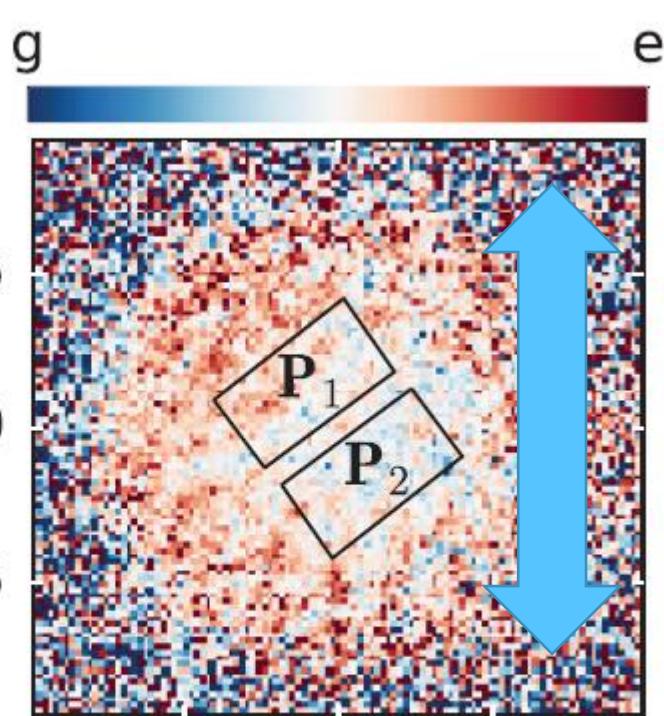


G. E. Marti, R. B. Hutson, A. Goban,
S. L. Campbell, N. Poli, J. Ye,
"Imaging optical frequencies with
100 μHz precision and 1.1 μm
resolution", Phys. Rev. Lett. (2018)

2,5 10⁻¹⁹

Gravitational Red Shift

(a)



$$\frac{\delta f}{f_0} = \frac{g \Delta h}{c^2}$$

10 μm

$$\Delta v/v = 10^{-21}$$

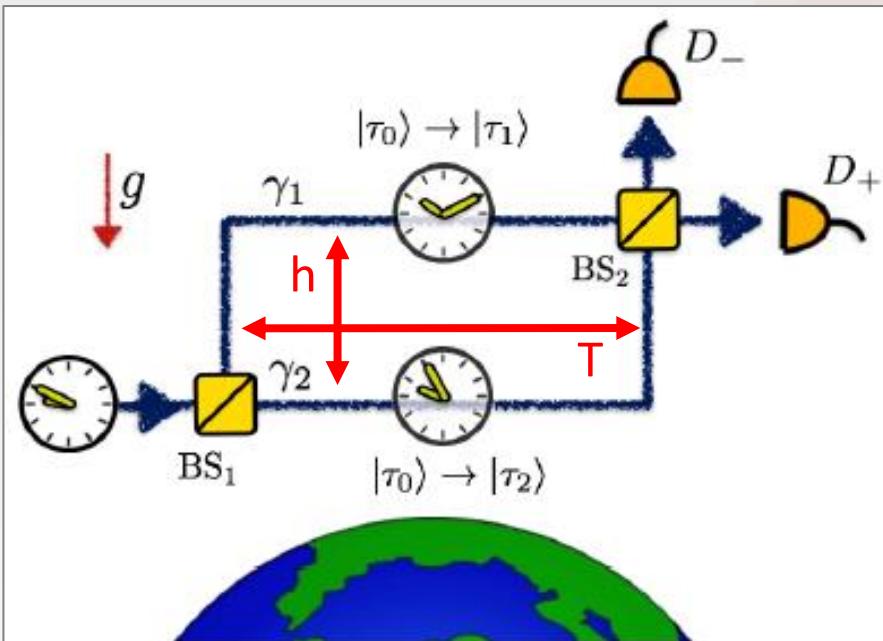
$$\Delta v/v = 10^{-22}$$

$\lambda_{dB} \approx 1 \mu\text{m}$ @ 1nK



Quantum Interference of Clocks

Observe gravity induced “decoherence” in clock interferometers

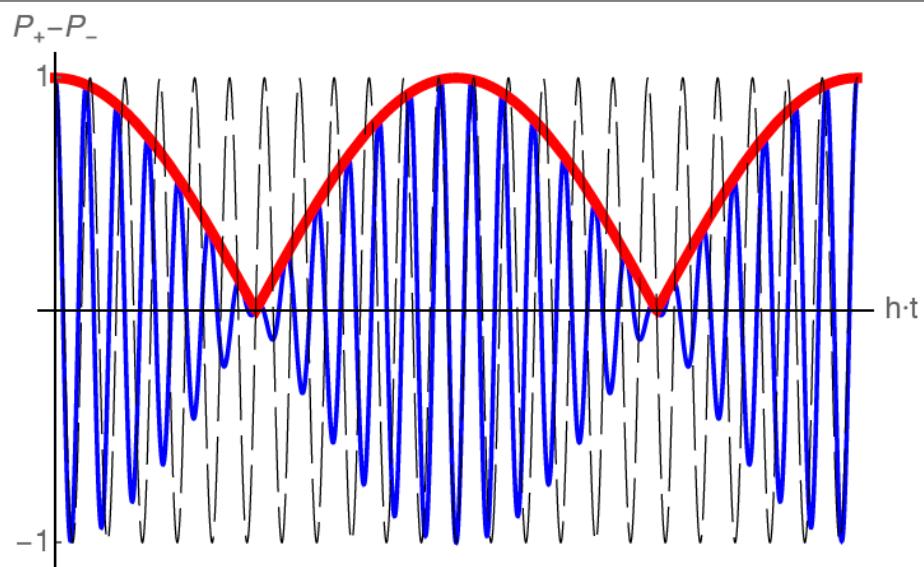


M. Zych et al. Nature Commun. 2(505), 1498 (2011)

- ✓ Quantum superposition of clocks in different locations
(h = height difference)
- ✓ Dephasing introduced by differential time dilation in the two different paths γ_1 and γ_2
(T =time)
- ✓ Interferometer contrast loss
- ✓ Decoherence induced by “which path” information from clock state

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M. Zych et al. Nature Commun. 2(505), 1498 (2011)

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Clock transition in Sr

✓ **^{88}Sr atoms**

- Magnetic field induced transition

$$\Omega_{88} = \alpha_{\text{Sr}} \sqrt{I} B$$

$$\alpha_{88} = 2\pi \ 198 \text{ Hz/T} \sqrt{\text{mWcm}^{-2}}$$

- Typical parameters: $B = 350 \text{ G}$ $I = 25 \text{ W/cm}^2$

$$\Omega_{88} = 2\pi \ 1 \text{ kHz}$$

✓ **^{87}Sr atoms**

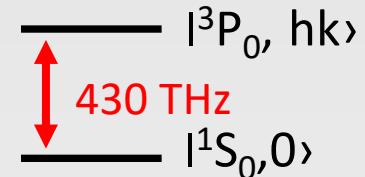
$$\Omega_{87} = \Gamma_{87} \sqrt{I/I_s}$$

$$\Gamma_{87} \approx 2\pi \ 1 \text{ mHz}$$

$$I_s \approx 0.4 \text{ pWcm}^{-2}$$

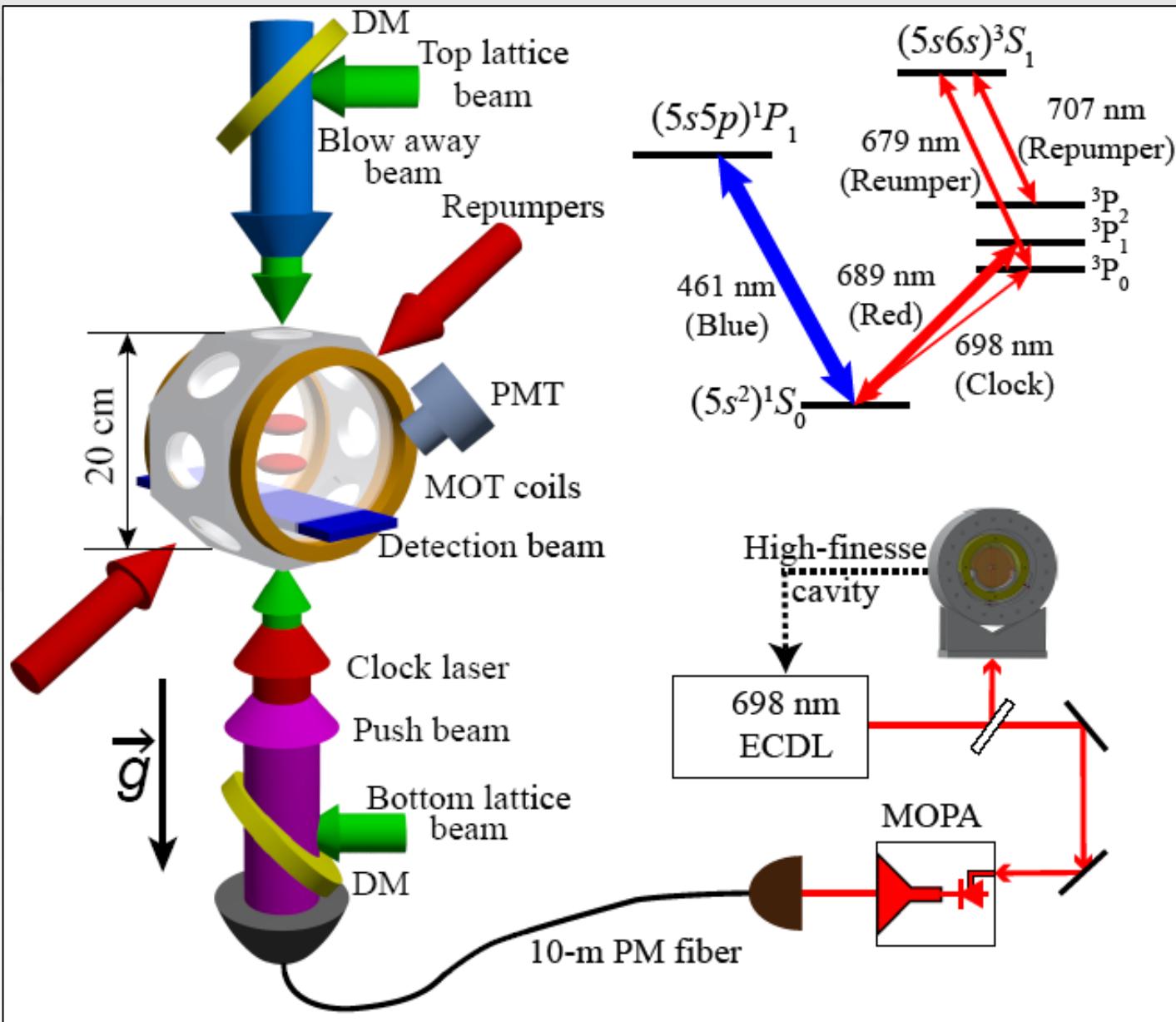
$$I = 41 \text{ W/cm}^2$$

$$\Omega_{87} = 2\pi \ 10 \text{ kHz}$$

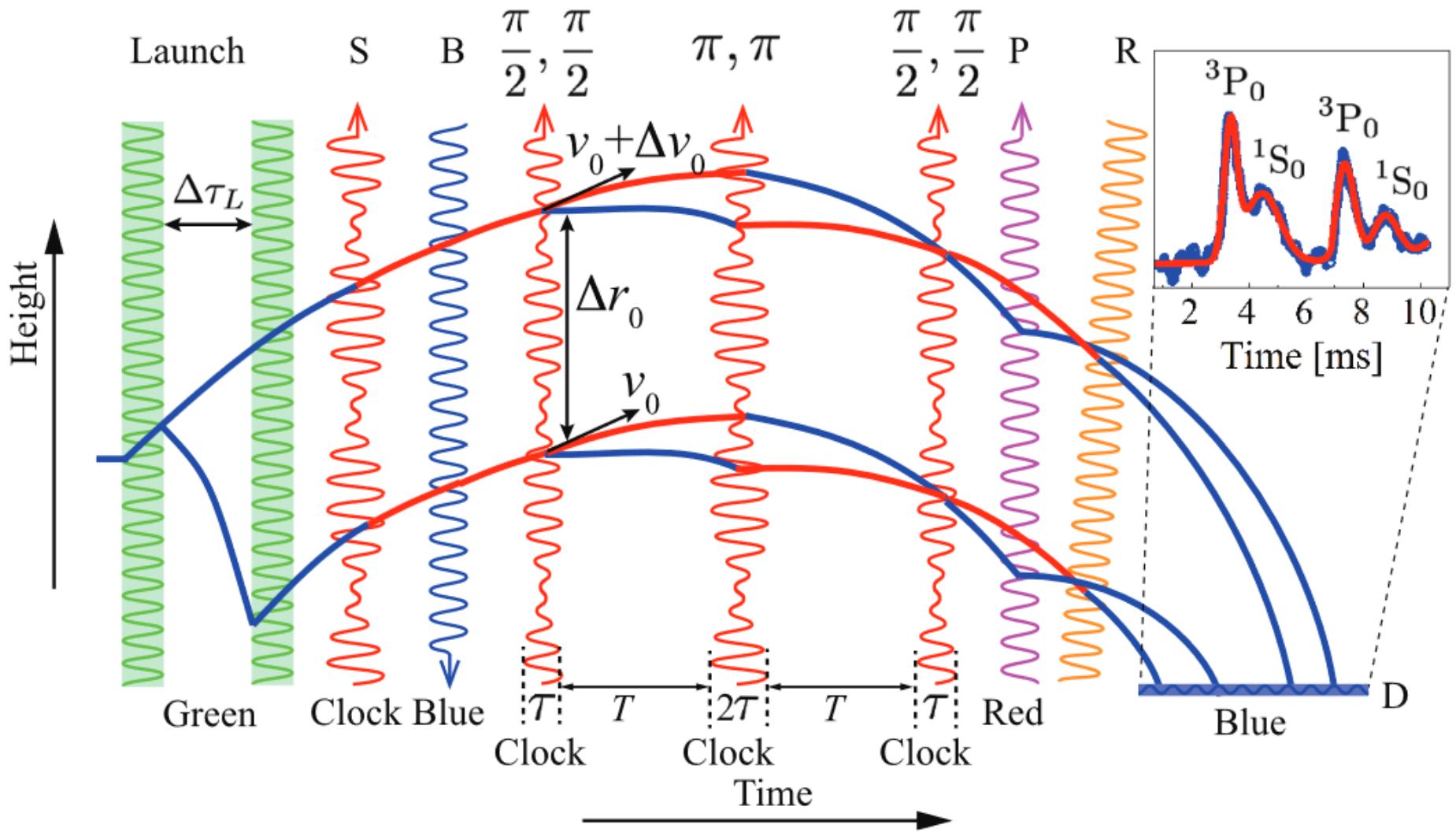


Single photon (momentum states + electronic states)

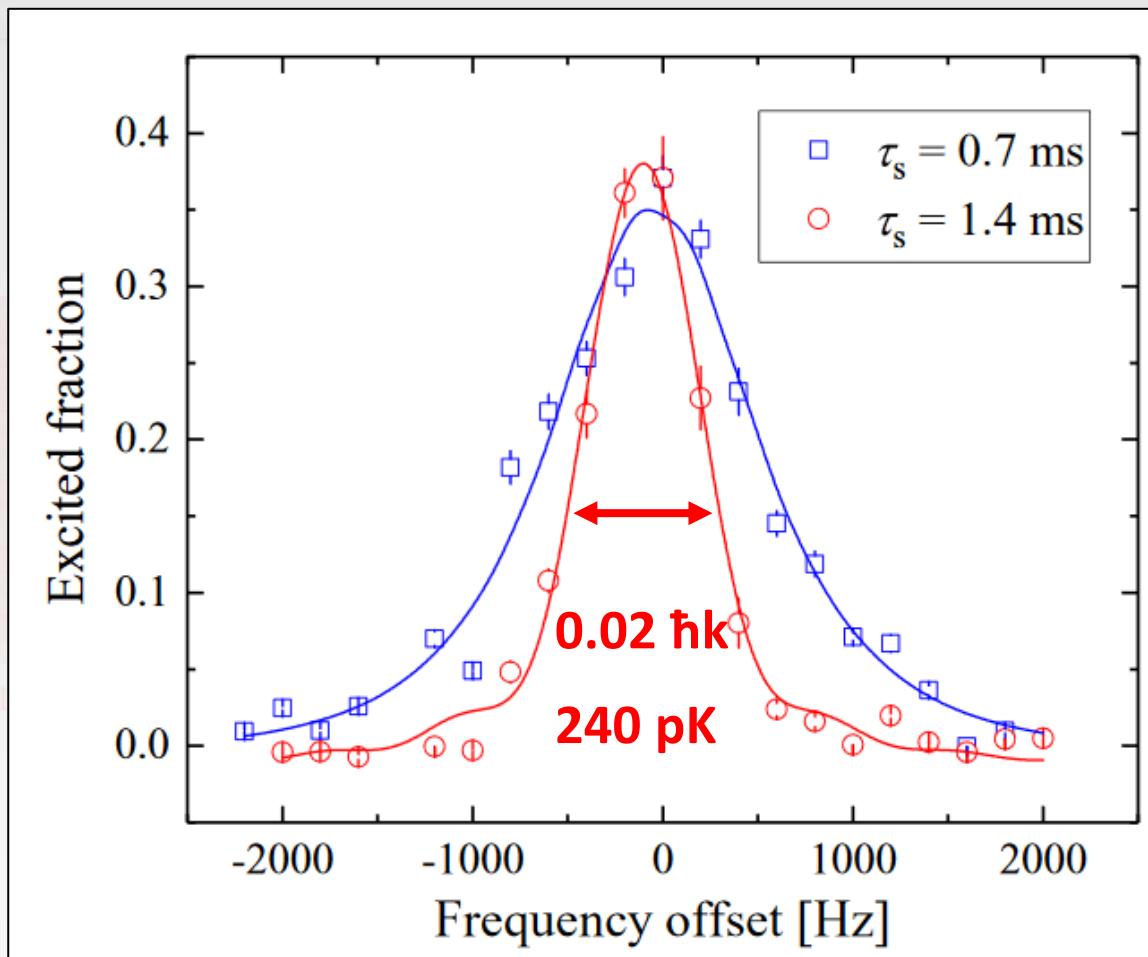
Experimental setup



Experimental sequence (gradiometer)

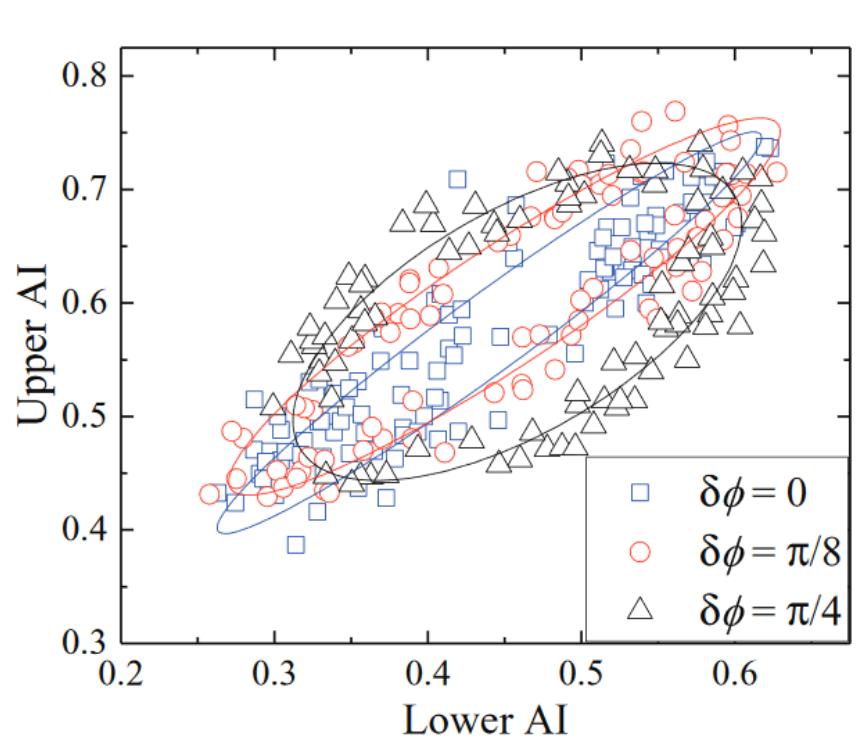


Velocity selection on clock transition

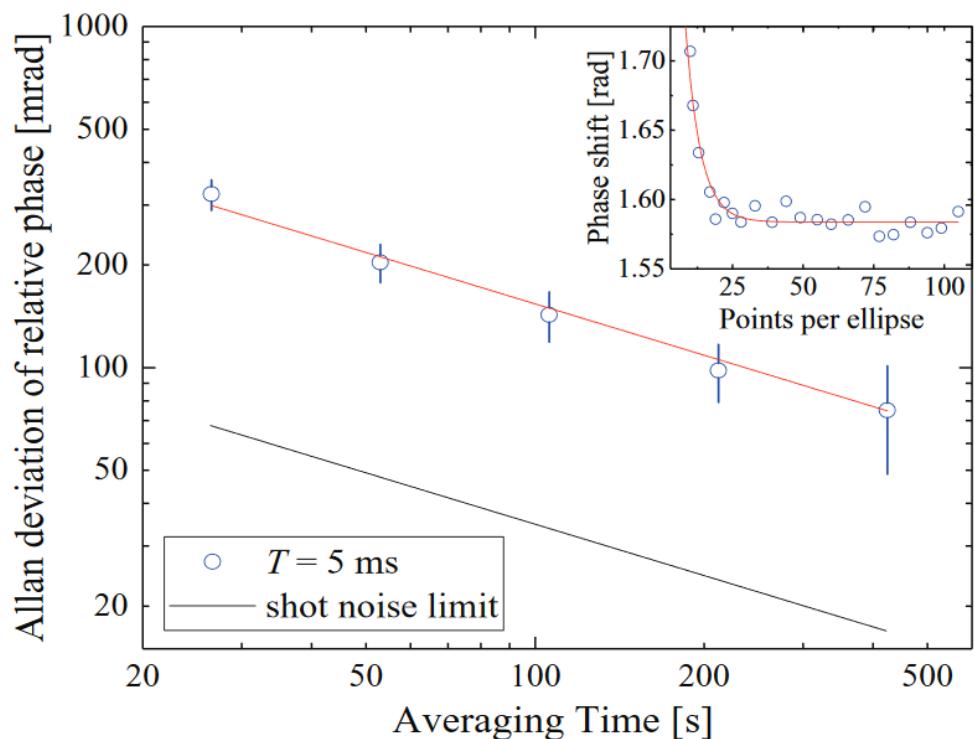


✓ Clock spectroscopy on free-falling atoms

Clock Gradiometer

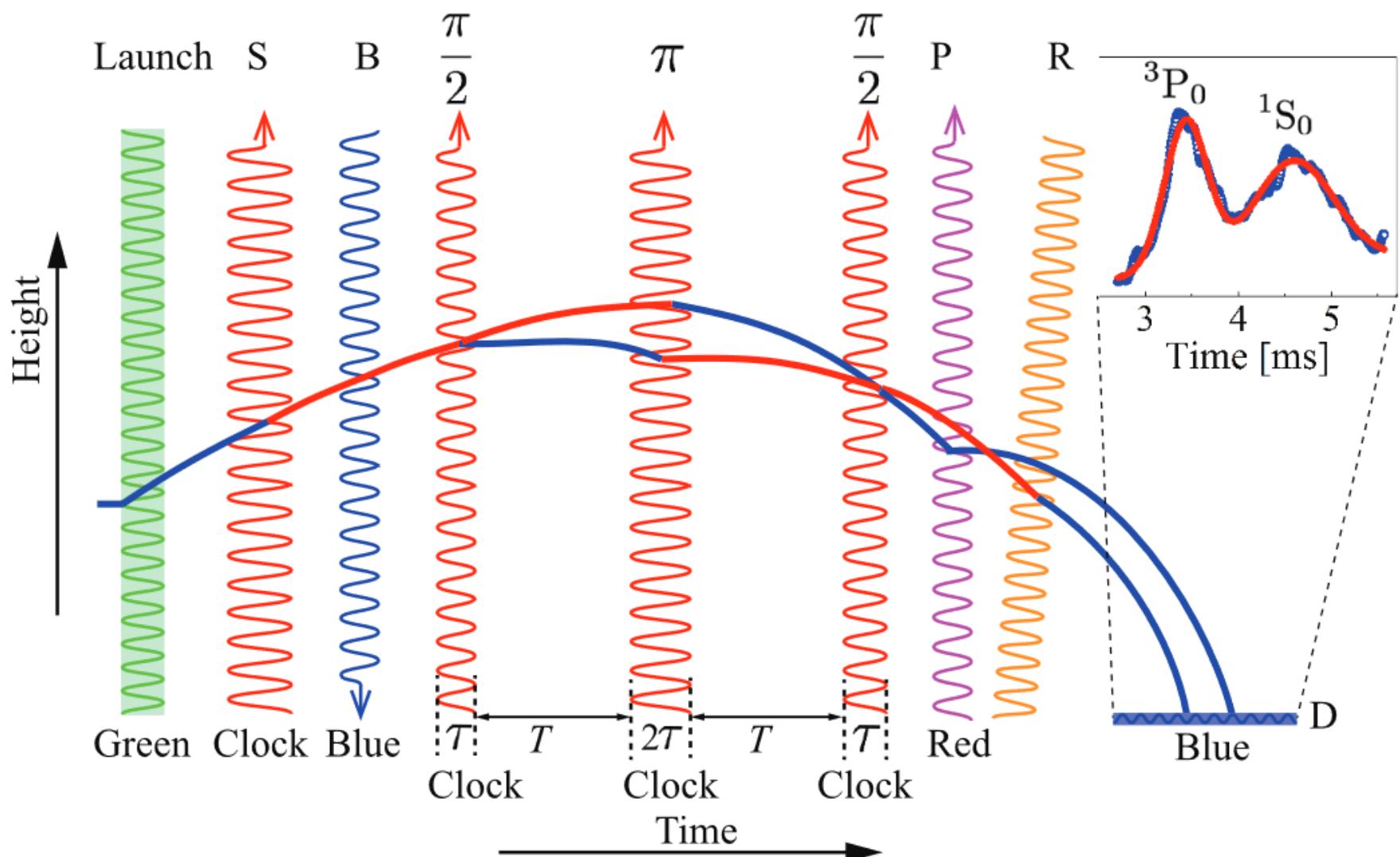


- Up to 30 ms total interferometer time

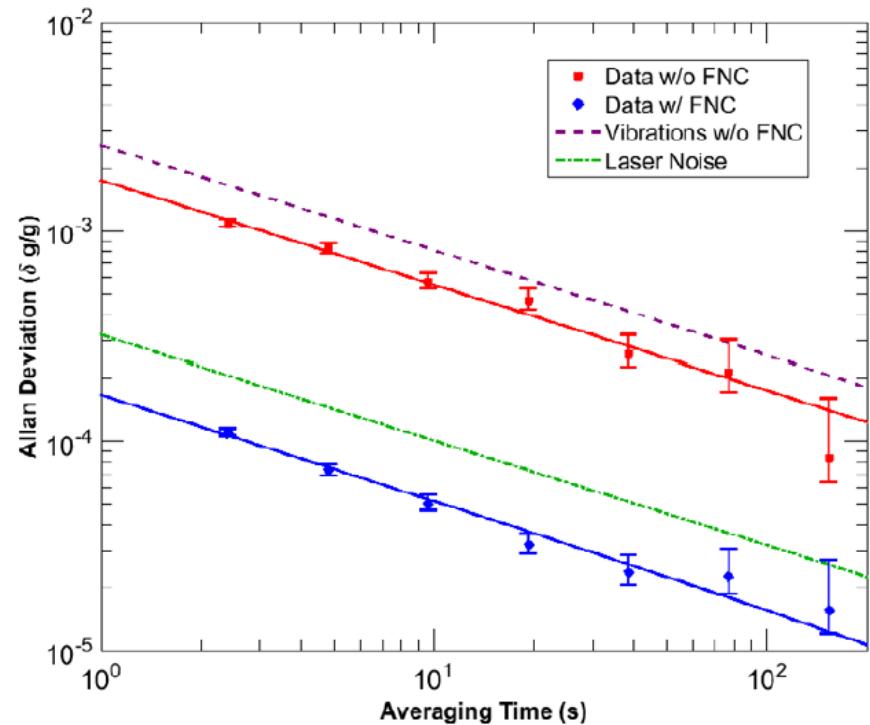
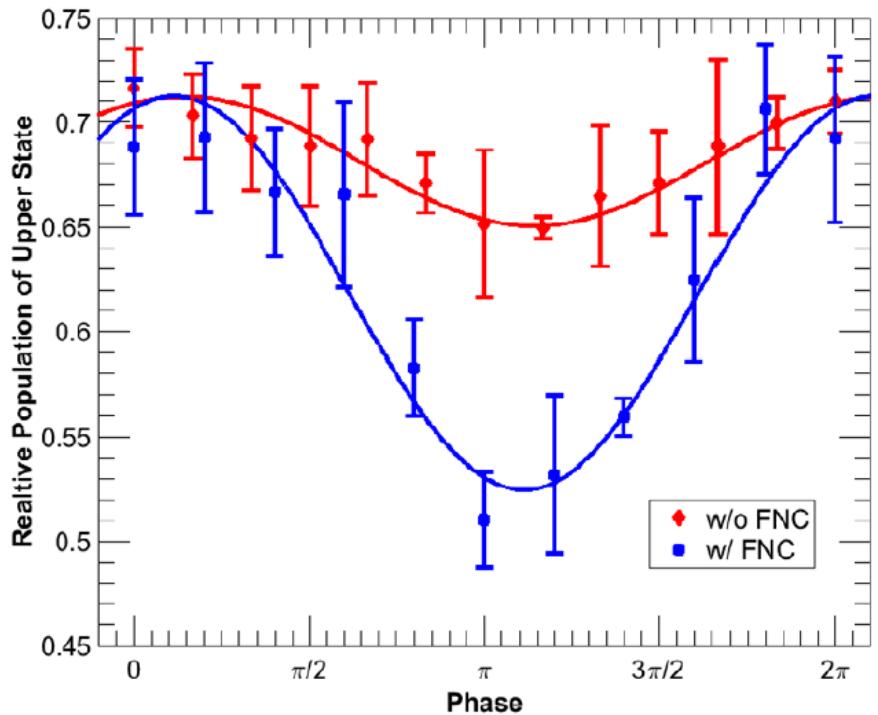


- Factor of 4 from shot noise limit ($N=10^4$, $C=30\%$)

Experimental sequence (gravimeter)

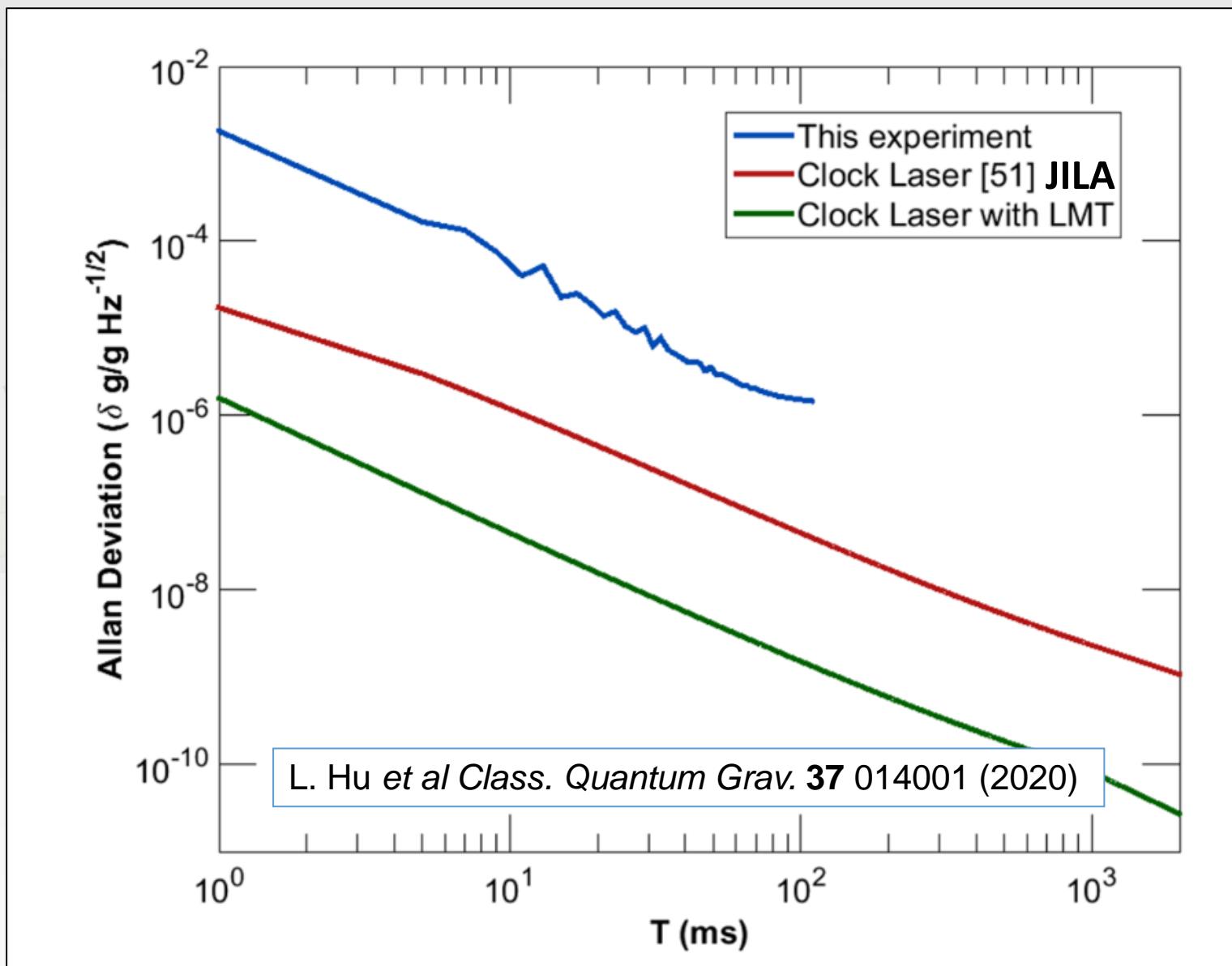


Gravimeter sensitivity



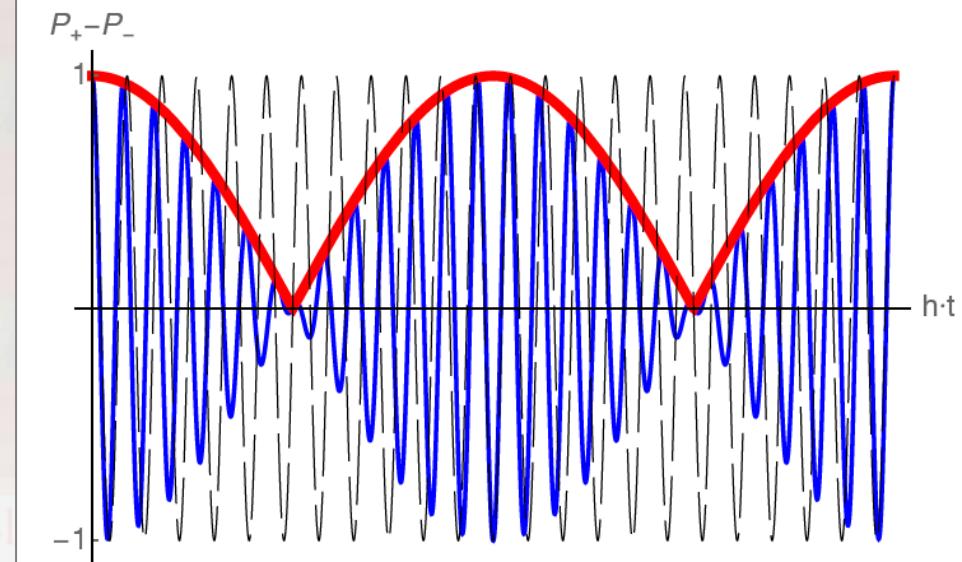
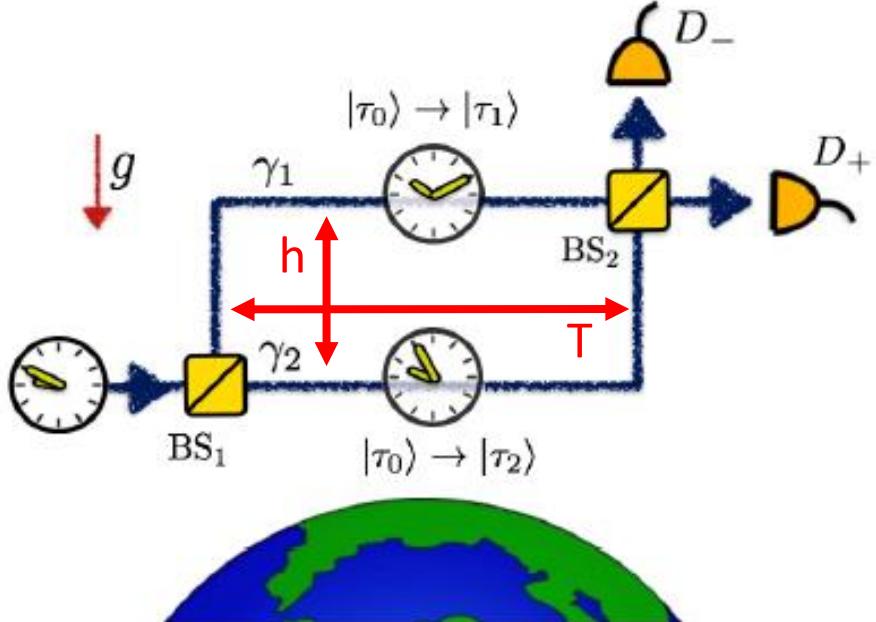
$1.7 \times 10^{-5} @ 150 s$

Gravimeter sensitivity



Quantum Interference of Clocks

Observe gravity induced “decoherence” in clock interferometers



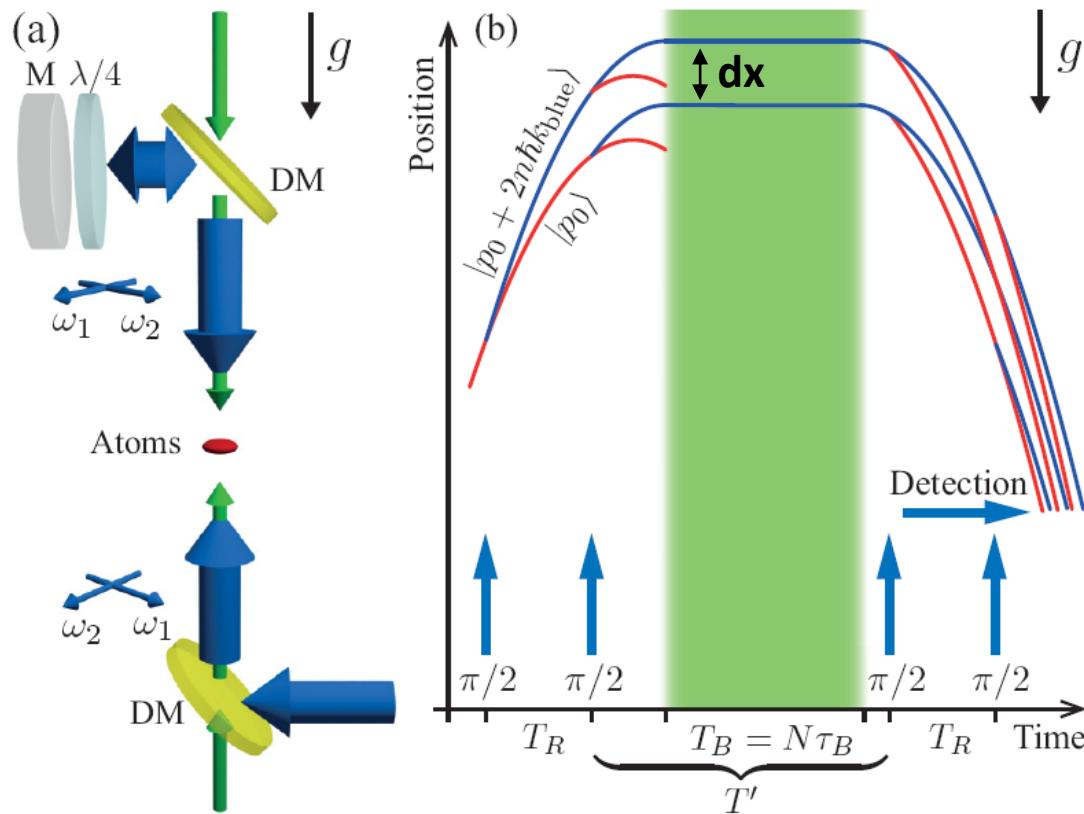
✓ Interferometer contrast **modulation**

$$(h * T)_{Sr} = 21 \text{ m s}$$

Full revival for $h=2 \text{ m}$, time $T = 10 \text{ s}$

M. Zych et al. Nature Commun. 2(505), 1498 (2011)

Ramsey-Bordé + Bloch oscillation



“Trapped” gradiometer
coherent evolution in
vertical lattice ($T_B \sim 1$ s)

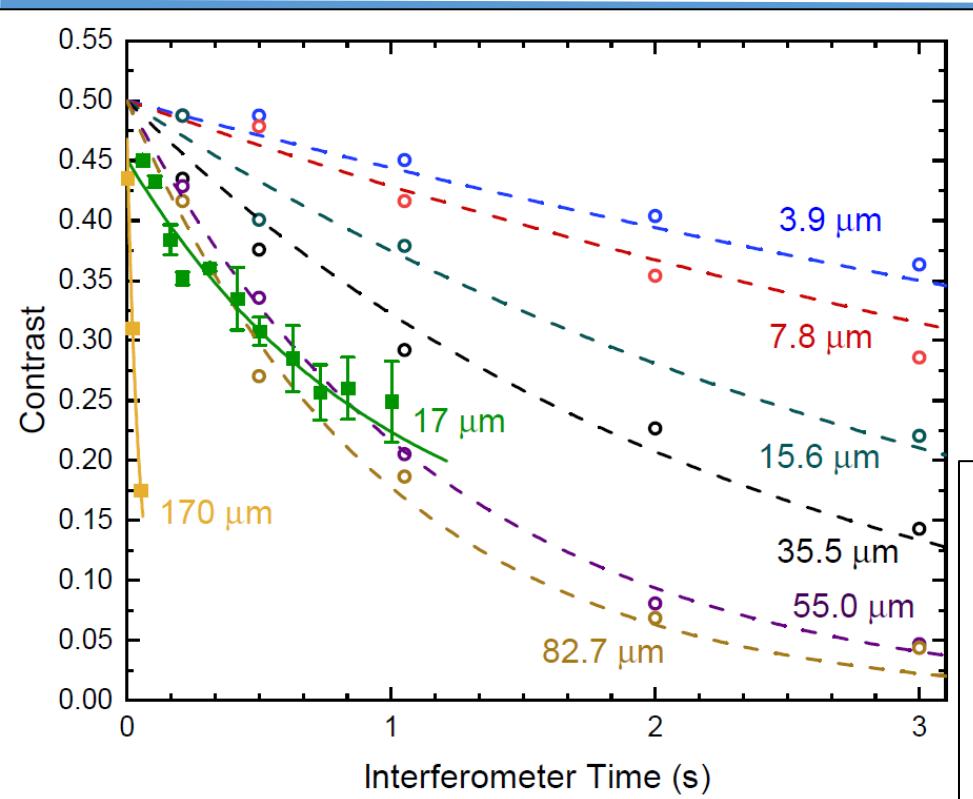
Ramsey time T_R

Bloch oscillations time T_B

Cadoret et al., Phys. Rev. Lett.
101, 230801 (2008)

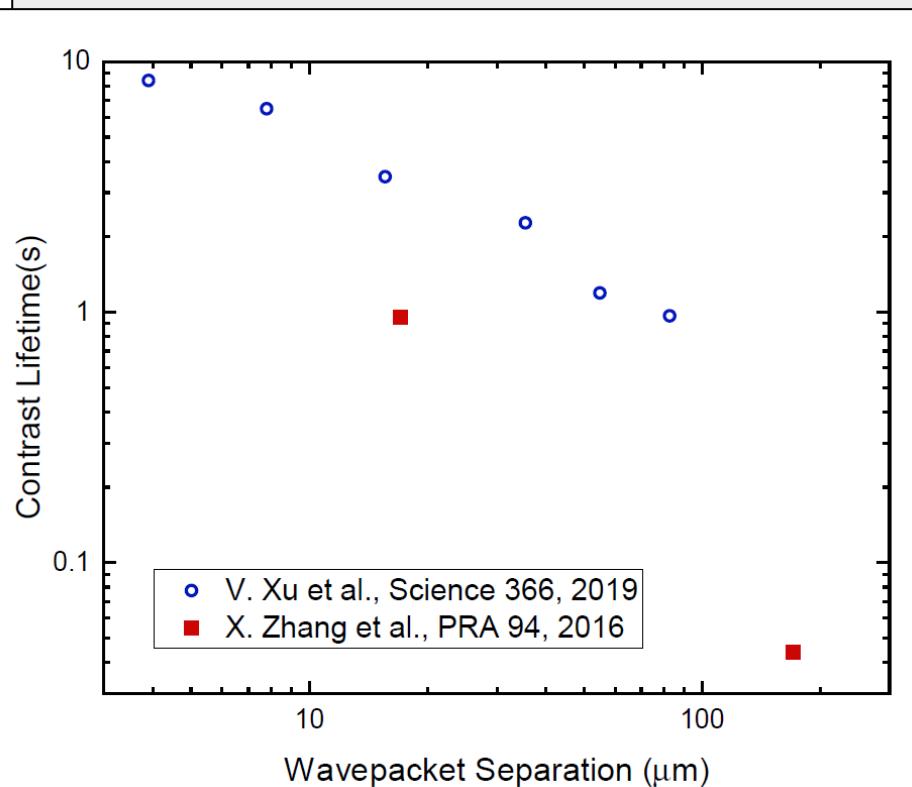
Contrast limited by trapping beam quality
($T_B \sim 1$ s @ $dx = 17\mu\text{m}$)

Contrast comparison



$\lambda_{\text{lat}} = 532 \text{ nm}$
 $w_0 = 800 \mu\text{m}$
 $z_R = 3.0 \text{ m}$

$\lambda_{\text{lat}} = 866 \text{ nm}$
 $z_R = 1.6 \text{ m}$
 $w_0 = 730 \mu\text{m}$



Clock interferometer candidates

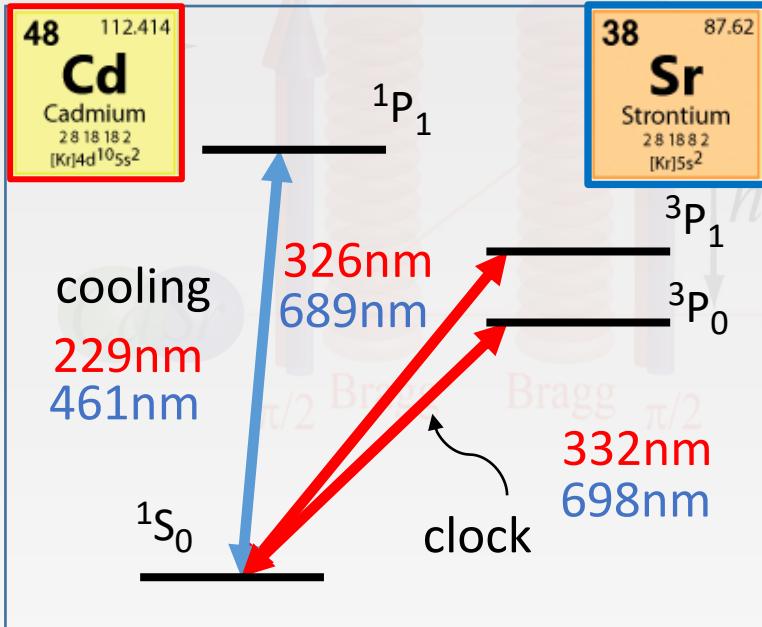
Periodic Table of the Elements

1 H Hydrogen 1.008	2 Be Beryllium 9.012	18 He Helium 4.003
3 Li Lithium 6.941	4 Mg Magnesium 24.305	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 B Boron 10.811
19 K Potassium 39.098	20 Ca Calcium 40.078	14 C Carbon 12.011
37 Rb Rubidium 84.468	21 Sc Scandium 44.956	15 N Nitrogen 14.007
38 Sr Strontium 87.62	22 Ti Titanium 47.867	16 O Oxygen 15.999
39 Y Yttrium 88.906	23 V Vanadium 50.942	17 F Fluorine 18.998
40 Zr Zirconium 91.224	24 Cr Chromium 51.996	18 Ar Argon 39.948
41 Nb Niobium 92.906	25 Mn Manganese 54.938	19 K Potassium 39.098
42 Mo Molybdenum 95.95	26 Fe Iron 55.845	20 Ca Calcium 40.078
43 Tc Technetium 98.907	27 Co Cobalt 58.933	21 Sc Scandium 44.956
44 Ru Ruthenium 101.07	28 Ni Nickel 58.693	22 Ti Titanium 47.867
45 Rh Rhodium 102.905	29 Cu Copper 63.546	23 V Vanadium 50.942
46 Pd Palladium 106.42	30 Zn Zinc 65.40	24 Cr Chromium 51.996
47 Ag Silver 107.865	31 Ga Gallium 69.723	25 Mn Manganese 54.938
48 Cd Cadmium 112.414	32 Ge Germanium 72.631	26 Fe Iron 55.845
49 In Indium 114.818	33 As Arsenic 74.922	27 Co Cobalt 58.933
50 Sn Tin 118.711	34 Se Selenium 78.971	28 Ni Nickel 58.693
51 Sb Antimony 121.760	35 Br Bromine 79.904	29 Cu Copper 63.546
52 Te Tellurium 127.6	36 Kr Krypton 84.798	30 Zn Zinc 65.40
53 I Iodine 126.904	37 Rb Rubidium 84.468	31 Ga Gallium 69.723
54 Xe Xenon 131.294	38 Sr Strontium 87.62	32 Ge Germanium 72.631
55 Cs Cesium 132.905	56 Ba Barium 137.326	33 As Arsenic 74.922
56 Ba Barium 137.326	57-71 Lanthanides	34 Se Selenium 78.971
57 La Lanthanum 138.905	72 Hf Hafnium 178.49	35 Br Bromine 79.904
58 Ce Cerium 140.116	73 Ta Tantalum 180.948	36 Kr Krypton 84.798
59 Pr Praseodymium 140.908	74 W Tungsten 183.84	37 Rb Rubidium 84.468
60 Nd Neodymium 144.243	75 Re Rhenium 186.207	38 Sr Strontium 87.62
61 Pm Promethium 144.913	76 Os Osmium 190.23	39 Y Yttrium 88.906
62 Sm Samarium 150.36	77 Ir Iridium 192.217	40 Zr Zirconium 91.224
63 Eu Europium 151.964	78 Pt Platinum 195.085	41 Nb Niobium 92.906
64 Gd Gadolinium 157.25	79 Au Gold 196.967	42 Mo Molybdenum 95.95
65 Tb Terbium 158.925	80 Hg Mercury 200.592	43 Tc Technetium 98.907
66 Dy Dysprosium 162.500	81 Tl Thallium 204.383	44 Ru Ruthenium 101.07
67 Ho Holmium 164.930	82 Pb Lead 207.2	45 Rh Rhodium 102.905
68 Er Erbium 167.259	83 Bi Bismuth 208.980	46 Pd Palladium 106.42
69 Tm Thulium 168.934	84 Po Polonium [208.982]	47 Ag Silver 107.865
70 Yb Ytterbium 173.055	85 At Astatine 209.987	48 Cd Cadmium 112.414
71 Lu Lutetium 174.967	86 Rn Radon 222.018	49 In Indium 114.818
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908
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60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36
63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925
65 Dy Dysprosium 162.500	66 Ho Holmium 164.930	67 Er Erbium 167.259
67 Ho Holmium 164.930	68 Tm Thulium 168.934	69 Yb Ytterbium 173.055
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A novel atom interferometer

Simultaneous interferometers on optical clock transitions Cadmium & Strontium

Similar atomic level structure:

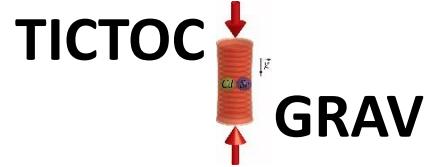


Magic wavelength ratio

→ - Rejection of technical noise

- ✓ Best optical clock
 - Low sensitivity to blackbody shift (Cd!)
 - «Clock interferometry» schemes
- ✓ Higher sensitivity to accelerations than alkalis
- ✓ Lower systematics
 - Very low sensitivity to B & E fields

Quantum Interference of Clocks

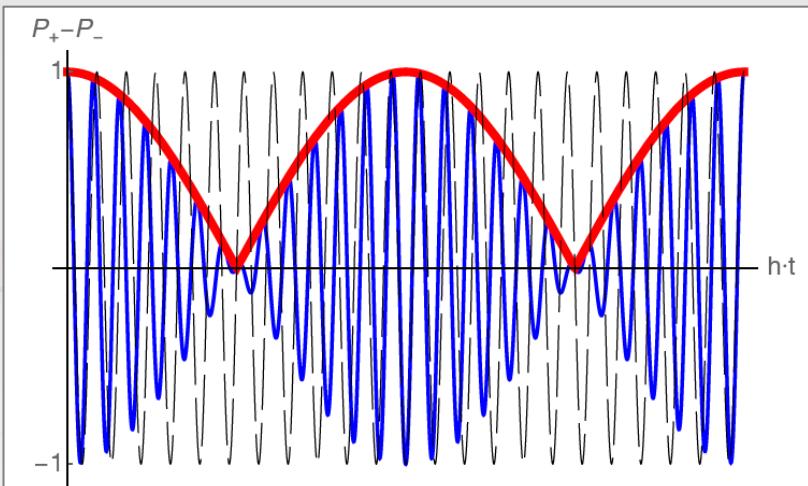


- ✓ Interferometer contrast **modulation**

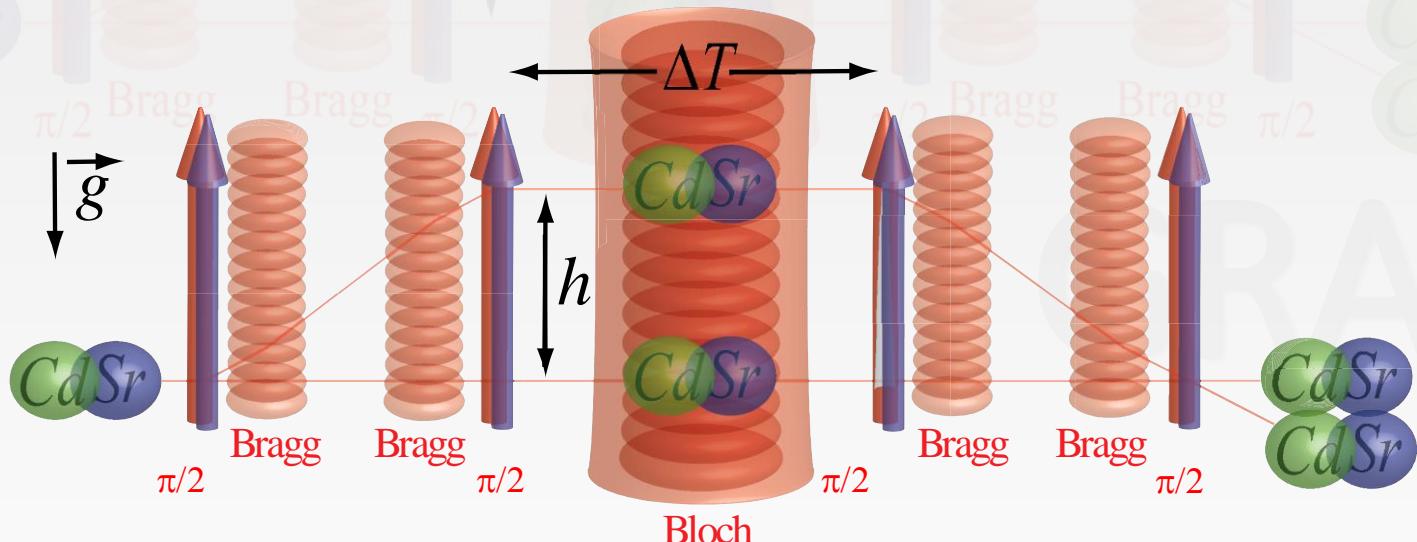
$$(h^*T)_{Sr} = 21 \text{ m s}$$

$$(h^*T)_{Cd} = 10 \text{ m s}$$

Full revival for $h=2 \text{ m}$, time $T = 5 - 10 \text{ s}$



Sr as “contrast reference”, observe on Cd faster contrast decay



Simultaneous Cd – Sr interferometer

✓ A “magic” coincidence for Cd-Sr:

✓ Same interferometer scale
factor $S_j = k_{\text{eff}}^j T^2_j$

		λ_A	λ_B	$r = \sqrt{k_B^{\text{eff}} / k_A^{\text{eff}}}$
A	B	(nm)	(nm)	
Rb	K	780.2	766.7	1.009
Yb	Rb	398.9	780.2	1.011
Sr	Cd	460.9	228.8	1.004
Sr	Cd	689.4	326.1	1.028

Relative phase shift $\delta\phi = (S_1 - S_2) * a$
(a = common acceleration)

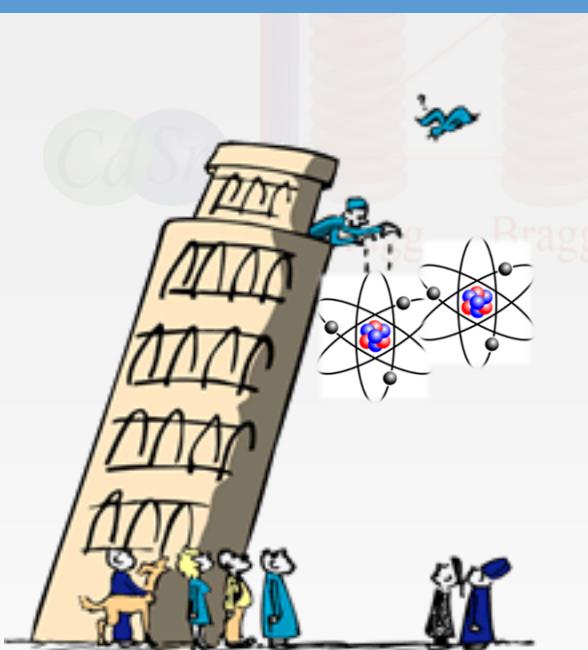
Efficient noise rejection and low systematics : same k_{eff} , Ω_R , τ

Cd –Sr x2 better than Rb-K !

Test WEP

- ✓ Weak form of Einstein Equivalence Principle
Universality of the Free Fall

The trajectory of a freely falling “test” body is independent of its internal structure and composition



- ✓ Test of EEP with not just different masses but also with **different quantum properties.**

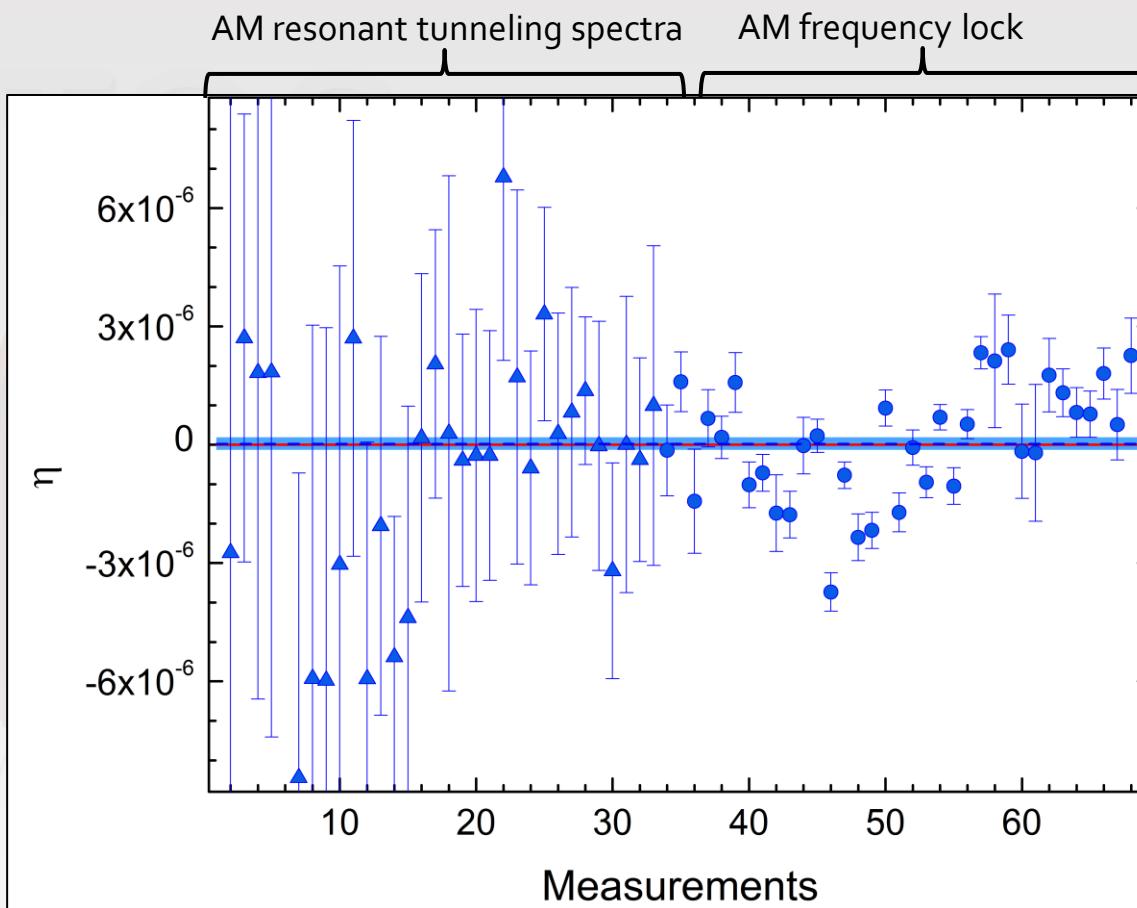
^{88}Sr

- Boson
- Zero total spin

^{87}Sr

- Fermion
- $I=9/2$

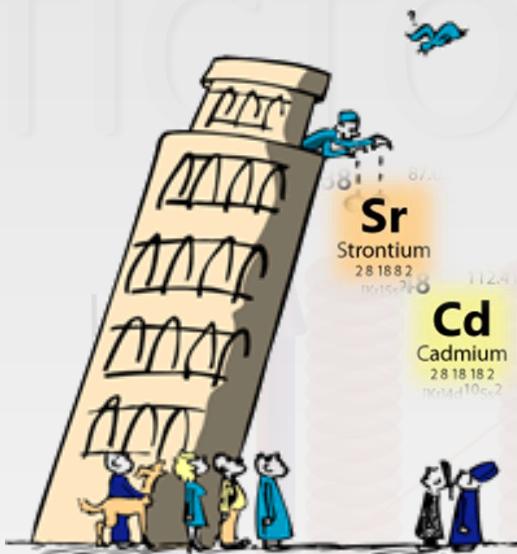
Spin-Gravity test with ^{87}Sr - ^{88}Sr



$$\eta = (0.2 \pm 1.6) 10^{-7}$$

Simultaneous Cd – Sr interferometer

✓ Test WEP Cd - Sr



- Low systematics

- High sensitivity to SME violation parameters

$$\eta_{A,B} \cong D_1(\Delta Q_{A,B}^{(1)}) + D_2(\Delta Q_{A,B}^{(2)})$$

$$\eta_{A,B} \cong \Delta f_{-n} + \Delta f_{+n} + \Delta \bar{f}_{-n} + \Delta \bar{f}_{+n}$$

J. N. Tinsley and N. Poli, ECAMP 13 (2019)

M.A.Hohensee et al., Phys. Rev. Lett. 111, 151102 (2013)

T.Damour *et al.*, Class. Quantum Grav. 29, 184001 (2012)

A	B	$Q_A'^1 - Q_B'^1$ $\times 10^4$	$Q_A'^2 - Q_B'^2$ $\times 10^4$	$f_{\beta_A^{e+p-n}} - f_{\beta_B^{e+p-n}}$ $\times 10^2$	$f_{\beta_A^{e+p+n}} - f_{\beta_B^{e+p+n}}$ $\times 10^4$	$f_{\beta_A^{\bar{e}+p-n}} - f_{\beta_B^{\bar{e}+p-n}}$ $\times 10^5$	$f_{\beta_A^{\bar{e}+p+n}} - f_{\beta_B^{\bar{e}+p+n}}$ $\times 10^4$
⁸⁵ Rb	⁸⁷ Rb	0.84	-0.79	-1.01	1.81	1.04	1.67
³⁹ K	⁸⁷ Rb	-6.69	-23.69	-6.31	1.90	-62.30	0.64
⁸⁴ Sr	⁸⁸ Sr	1.77	-1.59	-2.09	2.71	-11.21	2.27
⁸⁷ Sr	⁸⁸ Sr	0.42	-0.39	-0.49	2.04	10.81	11.85
⁸⁷ Sr	¹⁰⁶ Cd	-6.54	-3.99	1.66	-2.99	42.20	-1.98
⁸⁷ Sr	¹¹⁴ Cd	-2.62	-6.95	-2.30	-2.11	20.71	-1.22
⁸⁸ Sr	¹⁰⁸ Cd	-6.12	-4.23	1.31	-2.95	36.28	-1.87
¹⁰⁶ Cd	¹¹⁶ Cd	3.92	-2.96	-3.96	0.88	-21.49	0.76
¹⁰⁸ Cd	¹¹⁶ Cd	3.07	-2.34	-3.12	-1.19	-26.38	-1.20

Cadmium

✓ Interesting possibility for atomic physics study with Cd atoms

✓ Cold collisional physics

✓ Degenerate gas production

✓ Quantum information

✓ Favorable wavelength ratio of main optical cooling & spectroscopy transitions

^{106}Cd	1.25%	6 bosons ($I=0$)
^{108}Cd	0.89%	2 fermions ($I=1/2$)
^{110}Cd	12.47%	(*) long lifetime
^{111}Cd	12.80%	
^{112}Cd	24.11%	
$^{113}\text{Cd}^{(*)}$	12.23%	
^{114}Cd	28.75%	
$^{116}\text{Cd}^{(*)}$	7.51%	



Sr	transition	λ (nm)	$\Gamma/2\pi$	I_s (mW/cm ²)	T_D
	$^1\text{S}_0 - ^1\text{P}_1$	460.8	32 MHz	42.5	0.7 mK
	$^1\text{S}_0 - ^3\text{P}_1$	689.4	7.5 kHz	3×10^{-3}	200 nK
	$^1\text{S}_0 - ^3\text{P}_0$	698	1 mHz (Sr-87)	$\sim 10^{-9}$	-
Cd	transition	λ (nm)	$\Gamma/2\pi$	I_s (mW/cm ²)	
	$^1\text{S}_0 - ^1\text{P}_1$	229	91 MHz	988	2.2 mK
	$^1\text{S}_0 - ^3\text{P}_1$	325	70 kHz	3×10^{-3}	$1.6 \mu\text{K}$
	$^1\text{S}_0 - ^3\text{P}_0$	335	3 mHz (Cd-113)	3×10^{-3}	-

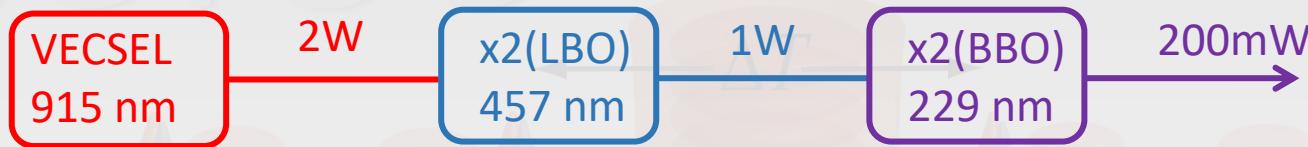
Cd lab !!



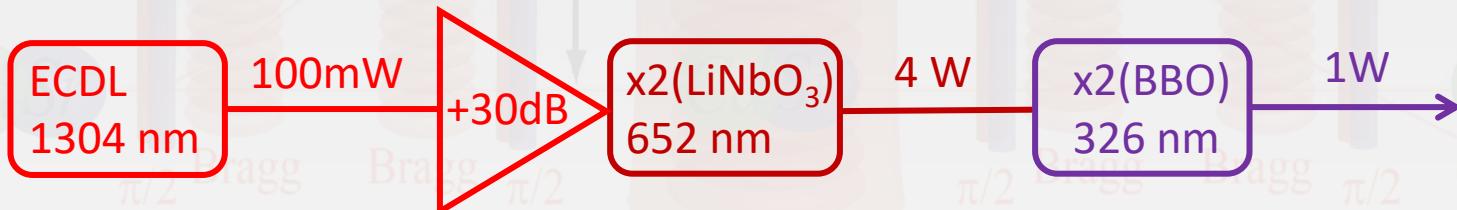
Cd laser sources

- ✓ Frequency quadrupoled laser sources

- main cooling transition:

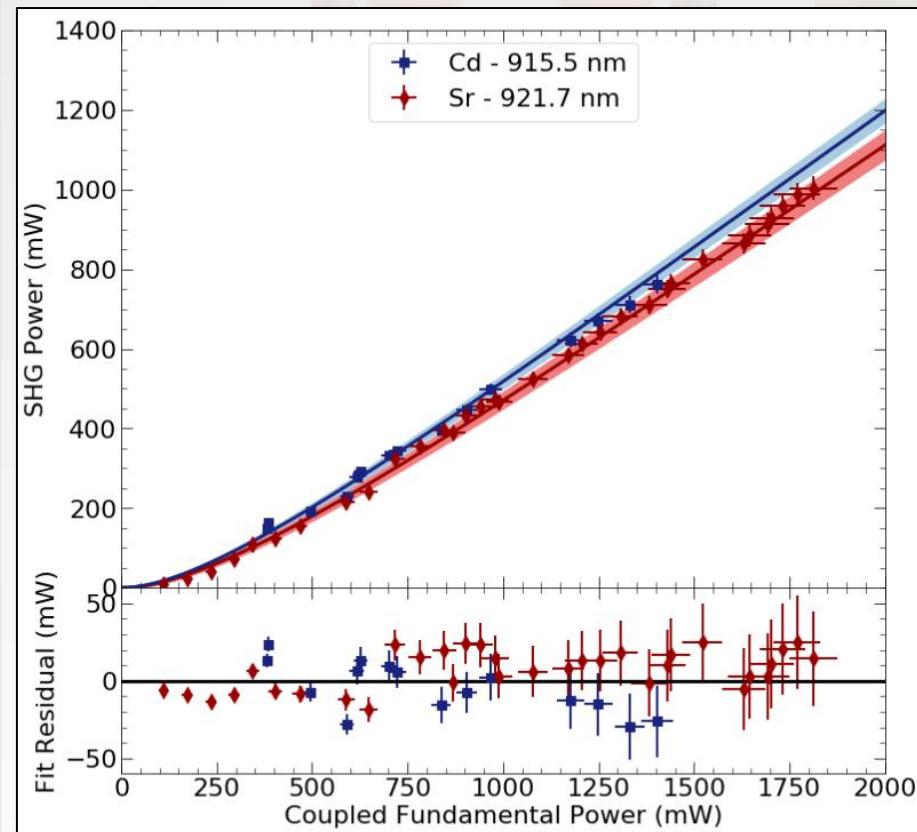


- intercombination transitions:



Cd laser sources

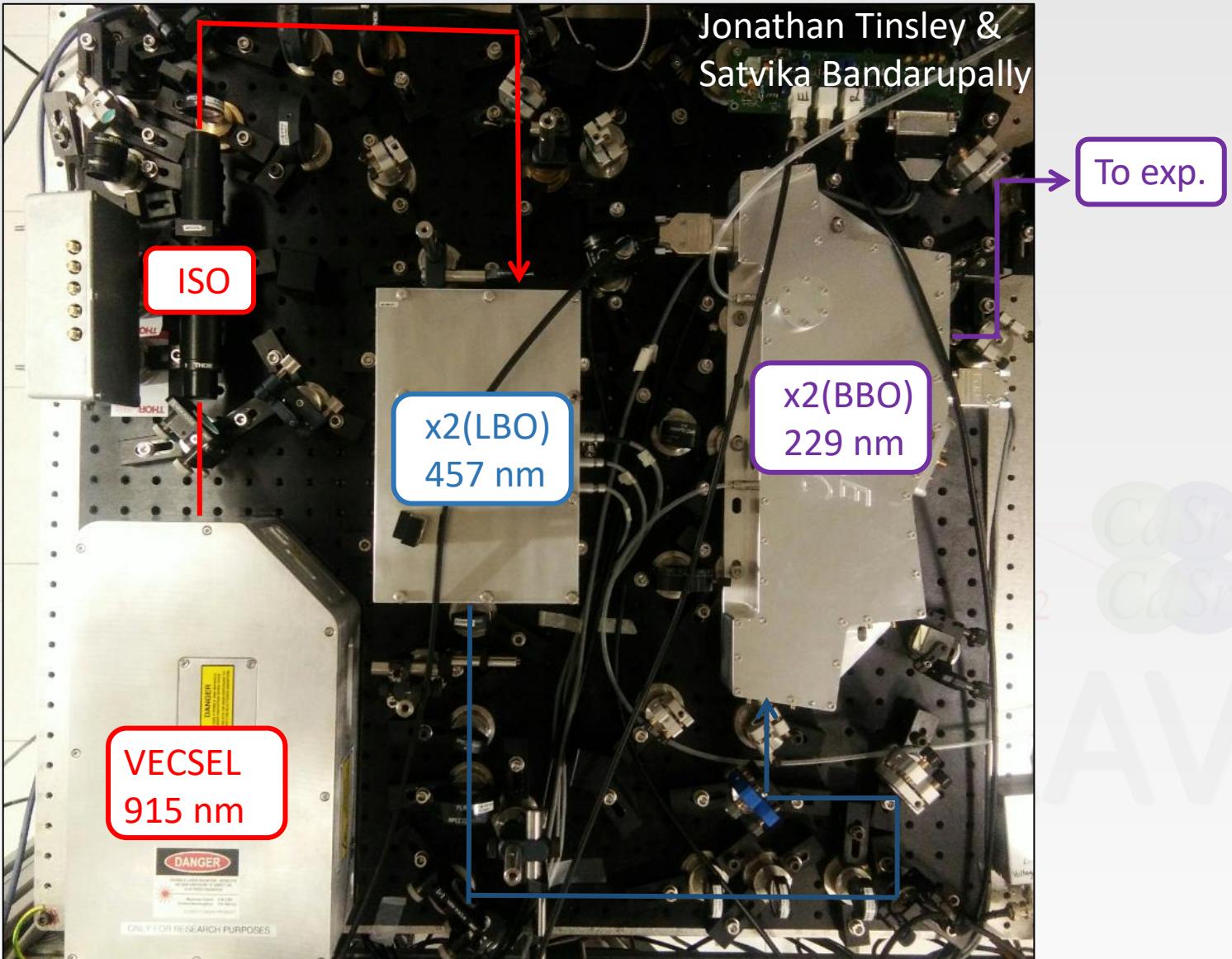
- ✓ Frequency quadrupoled laser sources
 - main cooling transitions:



- Tunable high power VECSEL (915- 928 nm)
 - Sr & Cd cooling transition wavelenghts addressed

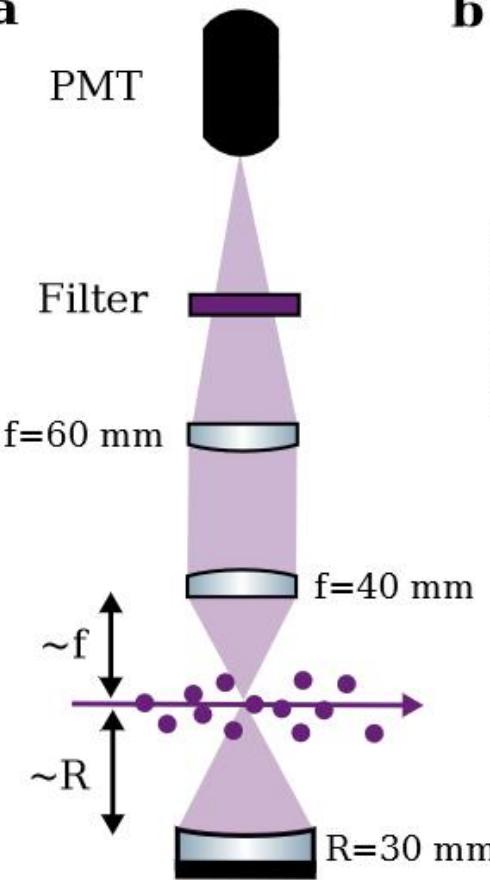
J. N. Tinsley, et al. "Watt-level blue light for precision spectroscopy, laser cooling and trapping of strontium and cadmium atoms", arXiv:2104.11924 (2021)

Cd 229 nm main cooling laser

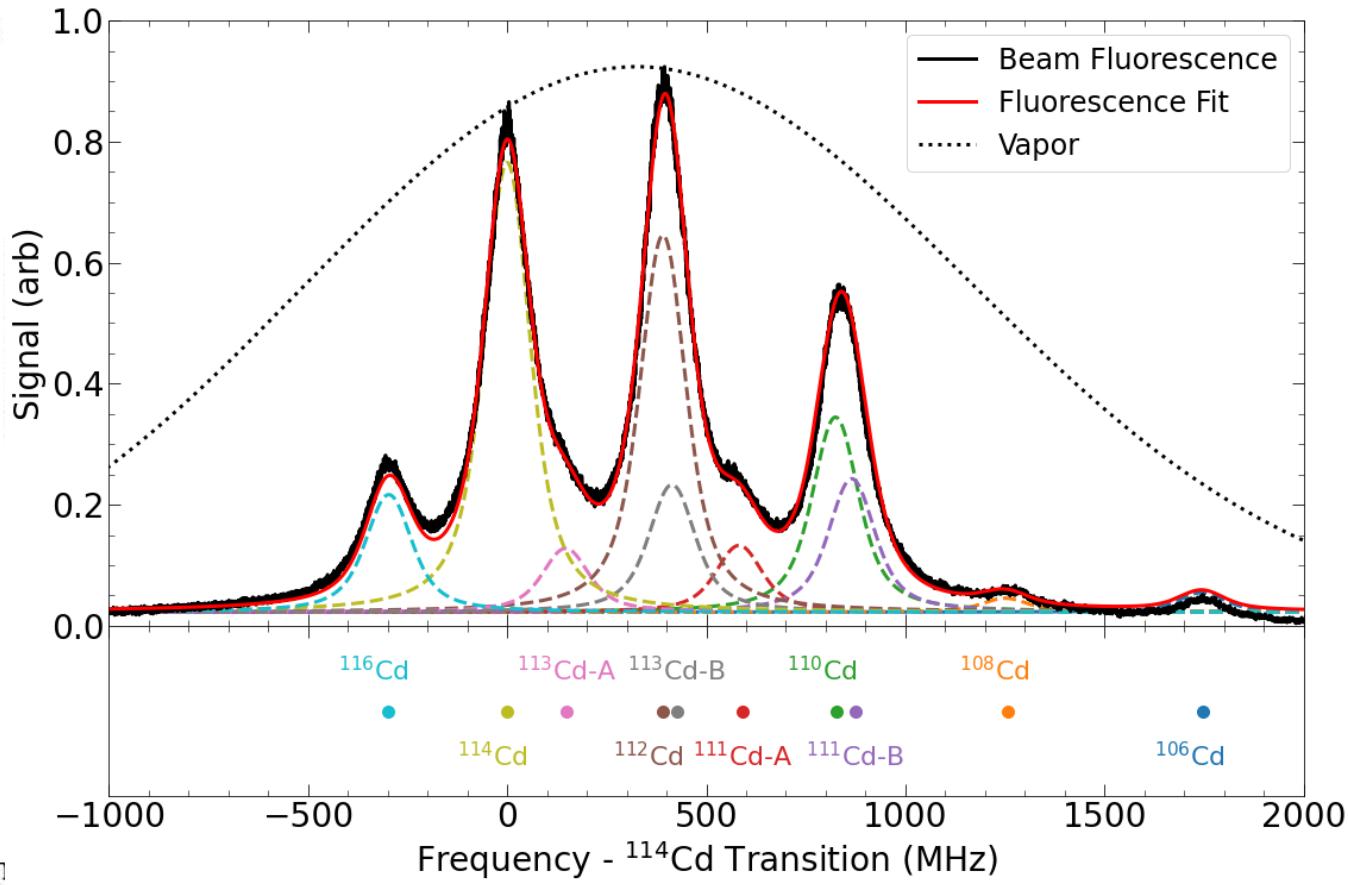


Cd atomic beam spectroscopy

a



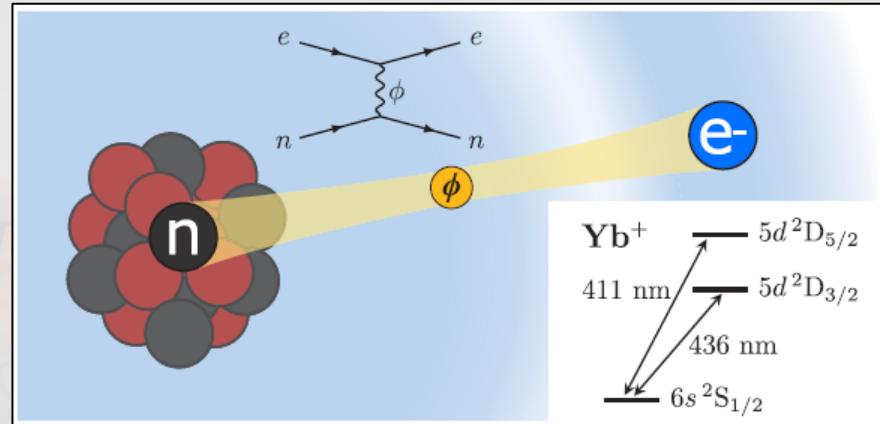
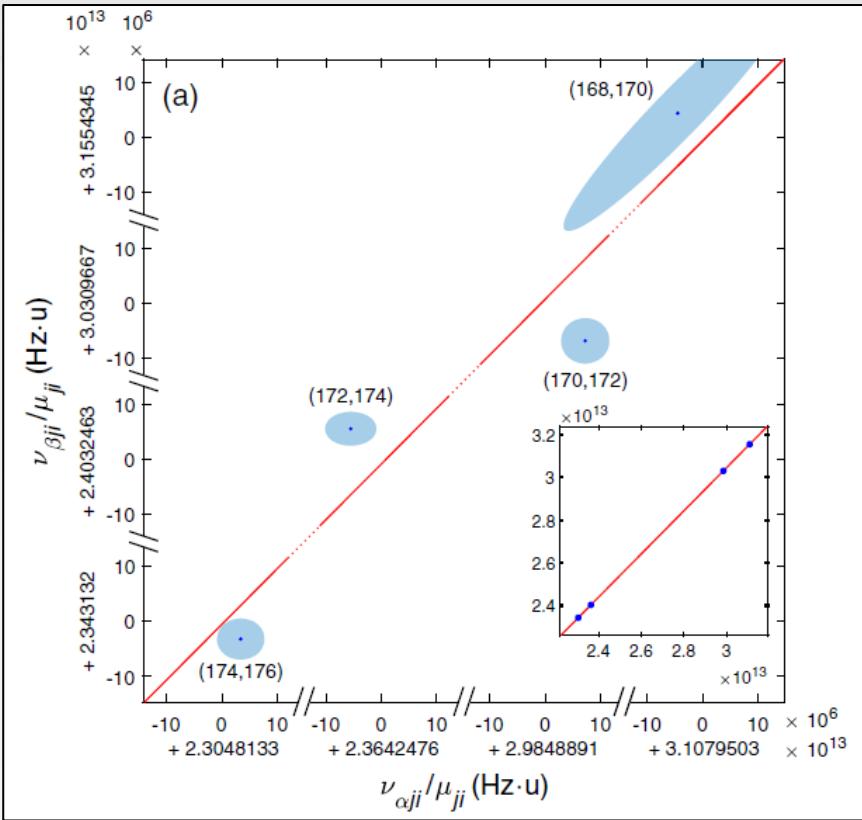
b



Cd atomic beam spectroscopy

Transition	Determination 1 [38]	Determination 2 [38]	This work / MHz
^{106}Cd	-	-	$1748.1 \pm 5.2 \pm 9.7$
^{108}Cd	-	-	$1258.5 \pm 5.3 \pm 7.0$
^{110}Cd	878 ± 17	905 ± 35	$826.2 \pm 4.2 \pm 4.6$
$^{111}\text{Cd} - F'=1/2$	-	-	$591.5 \pm 4.4 \pm 3.3$
$^{111}\text{Cd} - F'=3/2$	878 ± 17	-	$874.7 \pm 4.3 \pm 4.8$
^{112}Cd	375 ± 15	395 ± 30	$391.6 \pm 4.0 \pm 2.2$
$^{113}\text{Cd} - F'=1/2$	-	-	$148.0 \pm 4.2 \pm 0.8$
$^{113}\text{Cd} - F'=3/2$	375 ± 15	-	$426.5 \pm 4.5 \pm 2.4$
^{116}Cd	-	-	$-298.7 \pm 4.0 \pm 1.7$

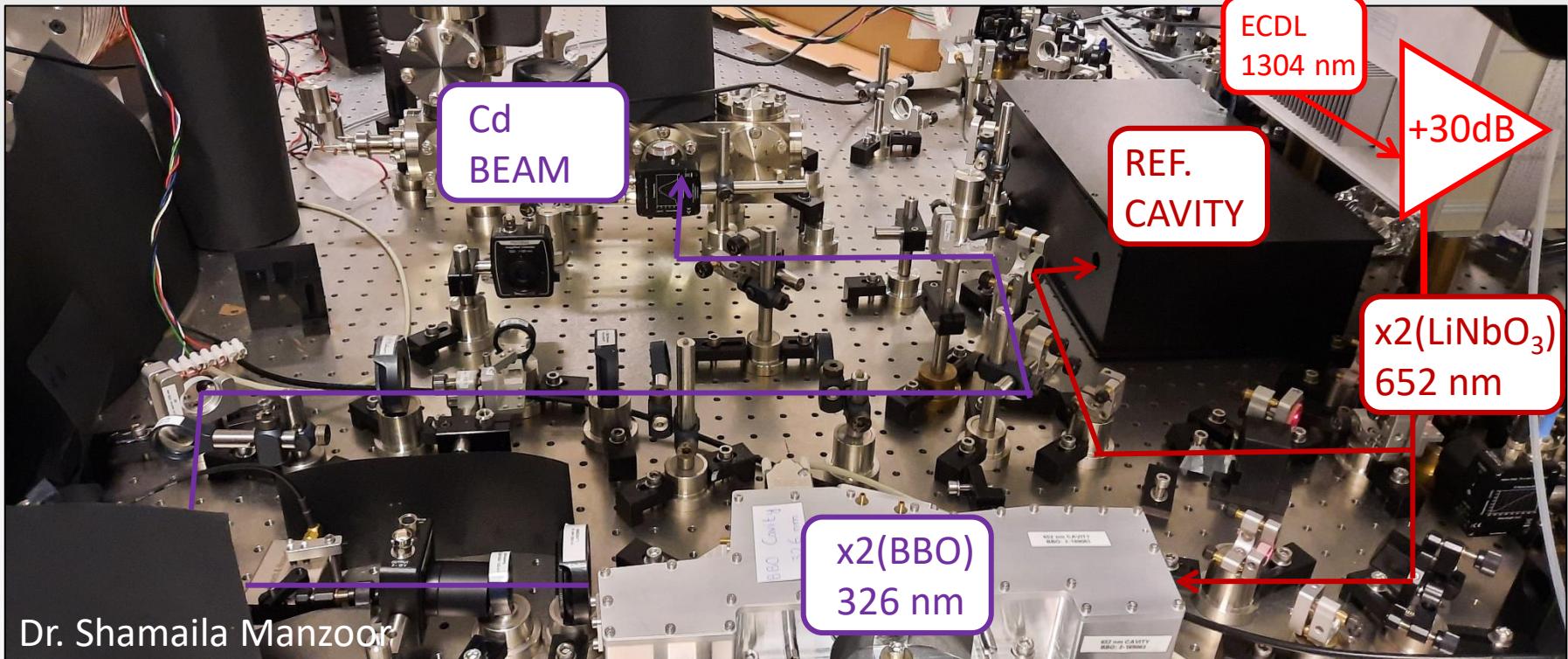
King's Plots



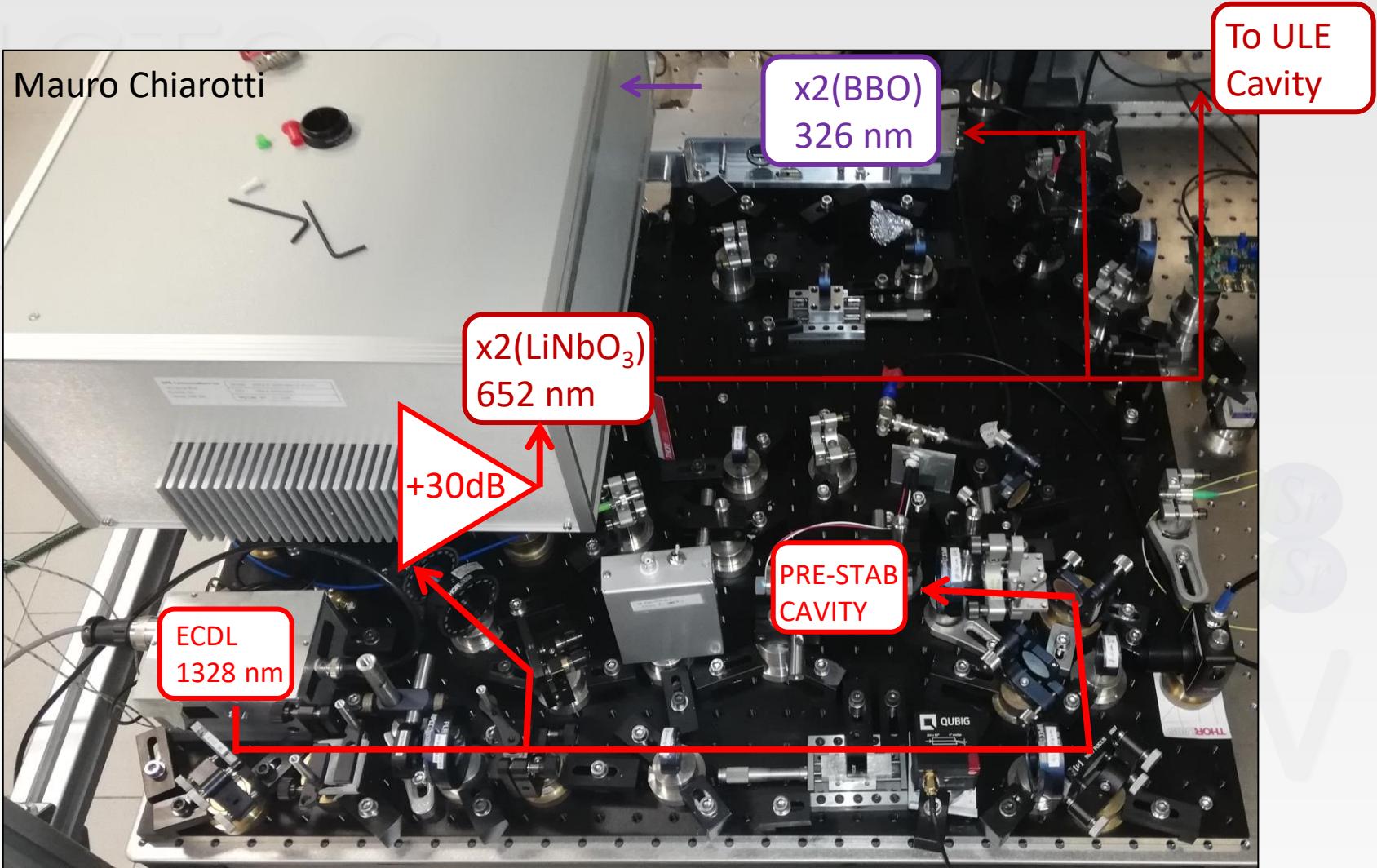
Isotope	Abundance	Nuclear Spin	Mass (u.m.a.)
^{106}Cd	1.25%	0	105.906
^{108}Cd	0.89%	0	107.904
^{110}Cd	12.49%	0	109.903
^{111}Cd	12.80%	1/2	110.904
^{112}Cd	24.13%	0	111.903
^{113}Cd	13.47%	1/2	112.904
^{114}Cd	28.73%	0	113.903
^{116}Cd	7.49%	0	115.905

Cd 326 nm laser source

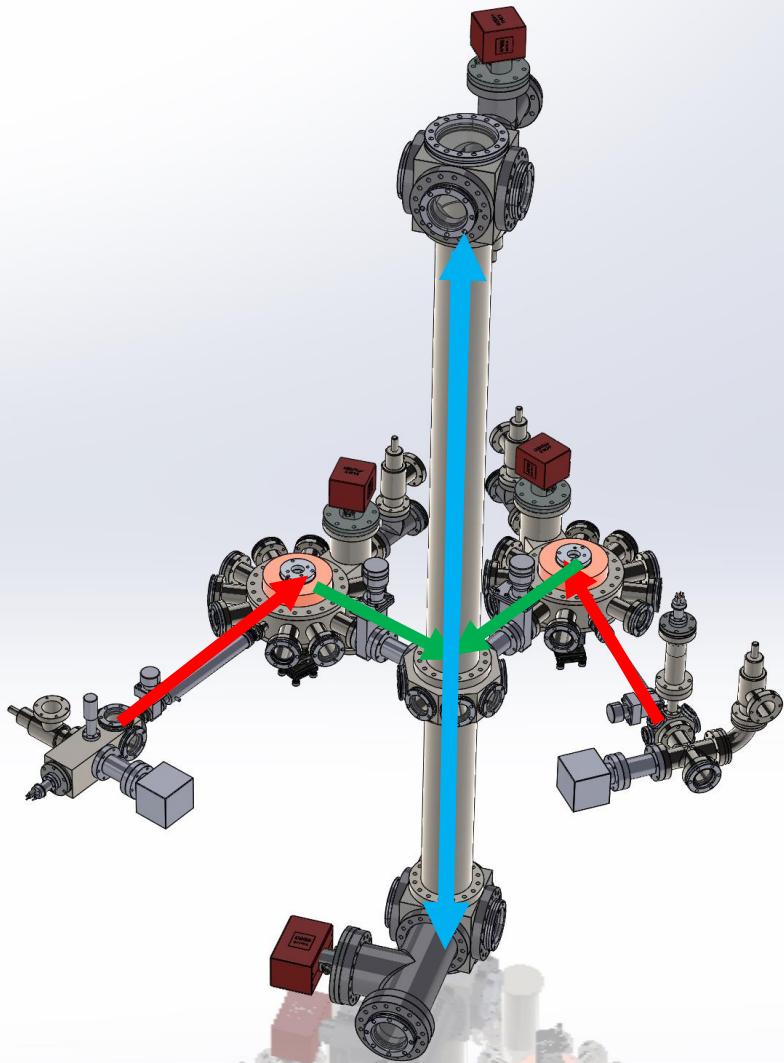
- precision spectroscopy & laser cooling on 3P1 intercombination transition



Cd 332 nm clock source

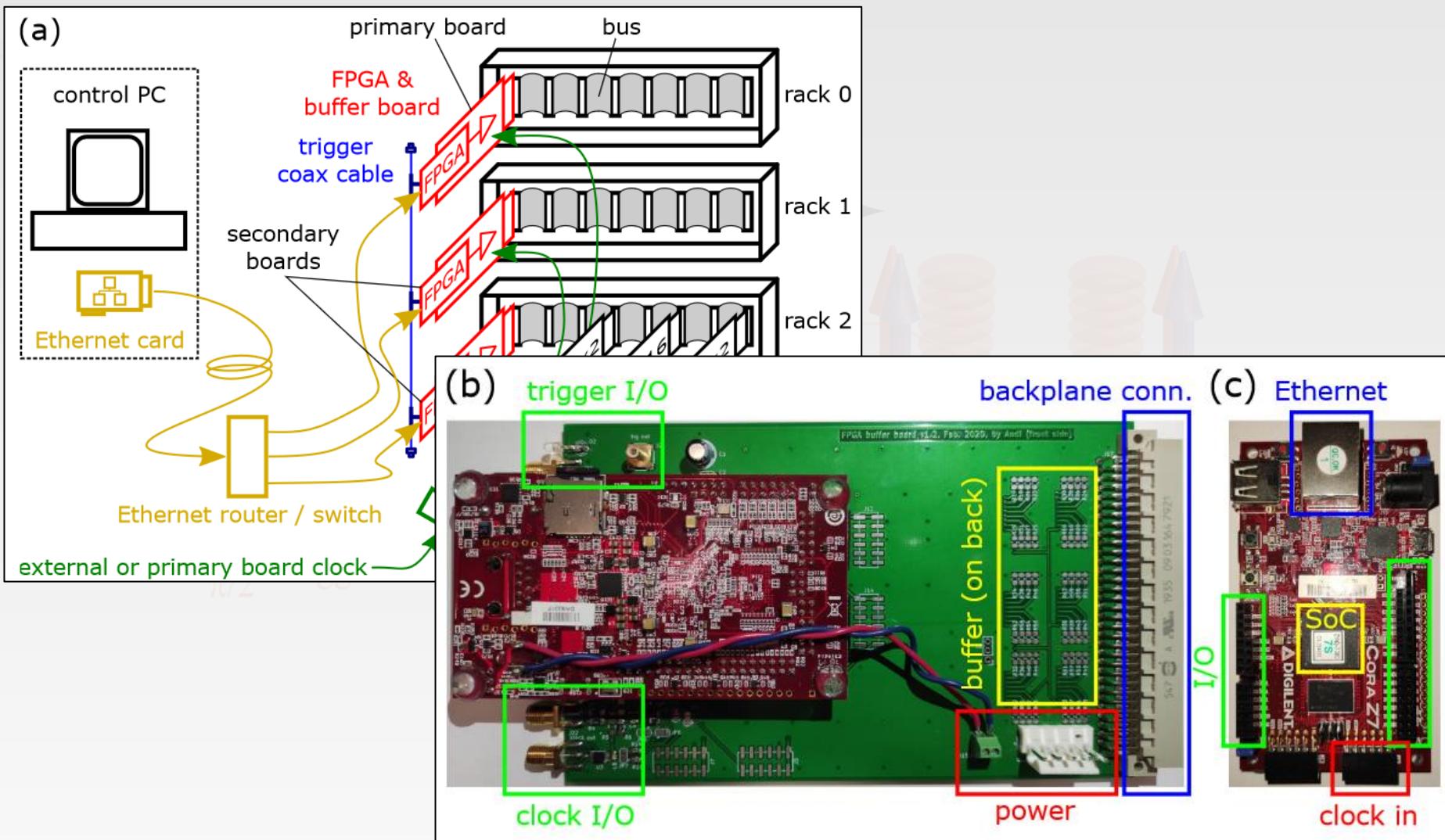


A new Cd-Sr system

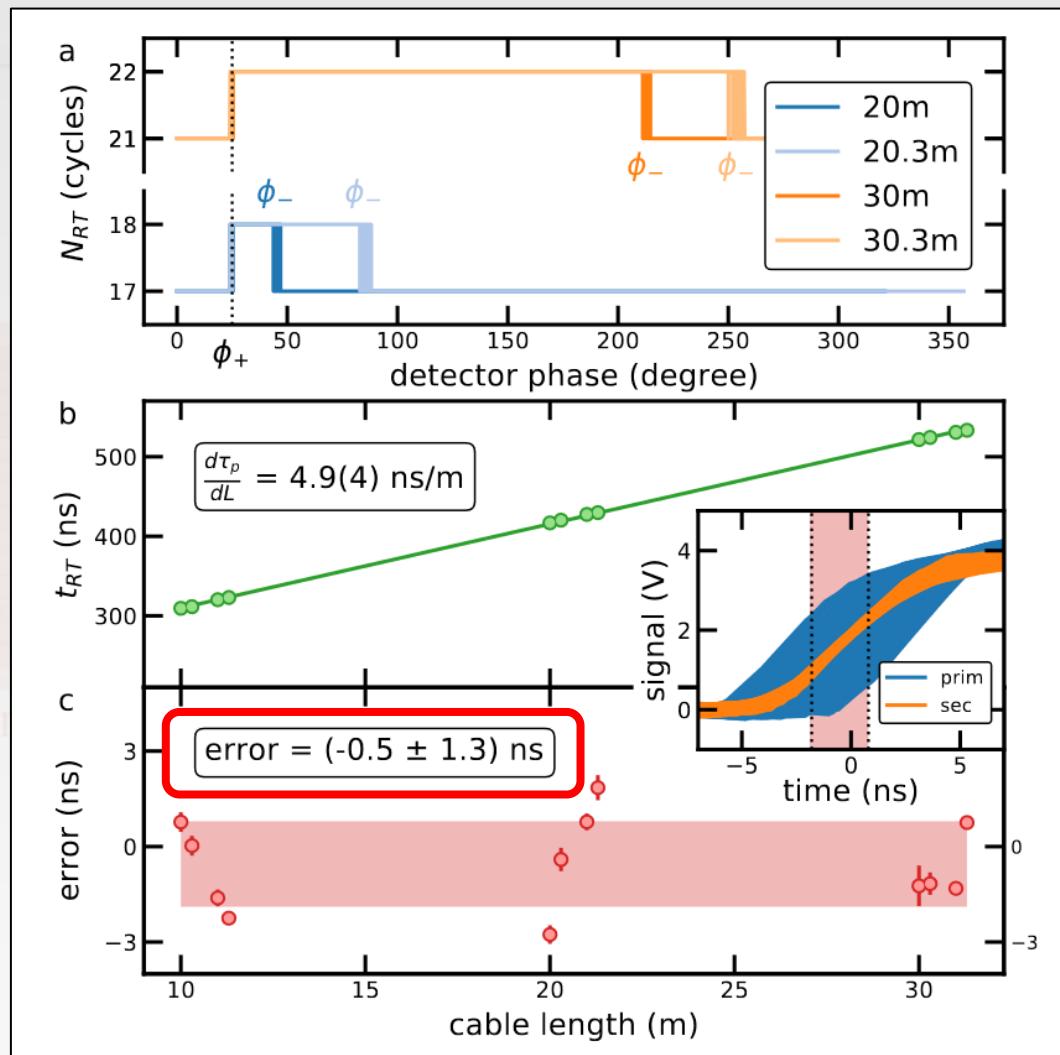


- 2m fountain for Cd & Sr
- Cd & Sr loaded from slowed atomic beams in separated MOT
- optical dipole traps to transfer the atoms at the center of the fountain tube

FPGA-SOC based control system for AMO physics experiments



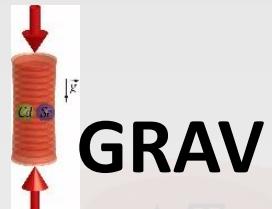
FPGA-SOC based control system for AMO physics experiments



Sr – Cd interferometer



TICTOC



ERC-2017-CoG

Exploring Gravity with Ultra-cold Cadmium and Strontium Optical Clocks and Atom Interferometers

Sr and Cd atom interferometers for fundamental physics test

WEP test/spin gravity test

Quantum interference of “clocks” in different gravitational potential

Thanks!

Thanks for the attention!!!

<http://coldatoms.lens.unifi.it/poli/>