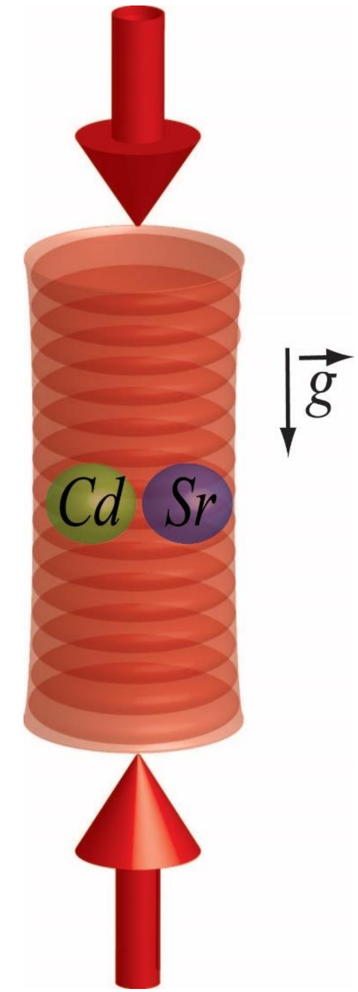
Novel atom interferometers for precision test of fundamental physics



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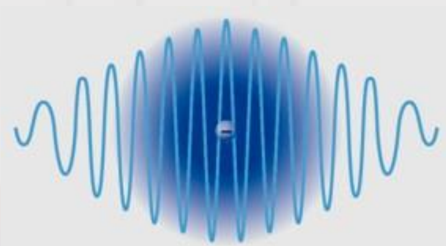
LENS – INFN – CNR/INO

QSS, 01/07/2021

Introduction

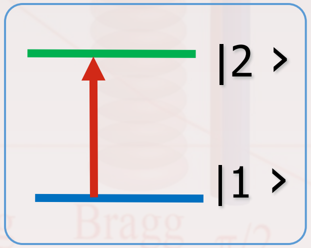
Matter-wave interferometry

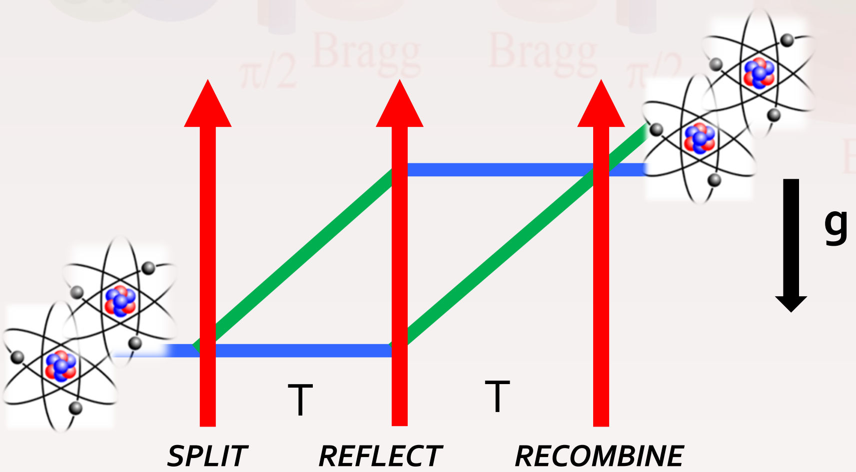


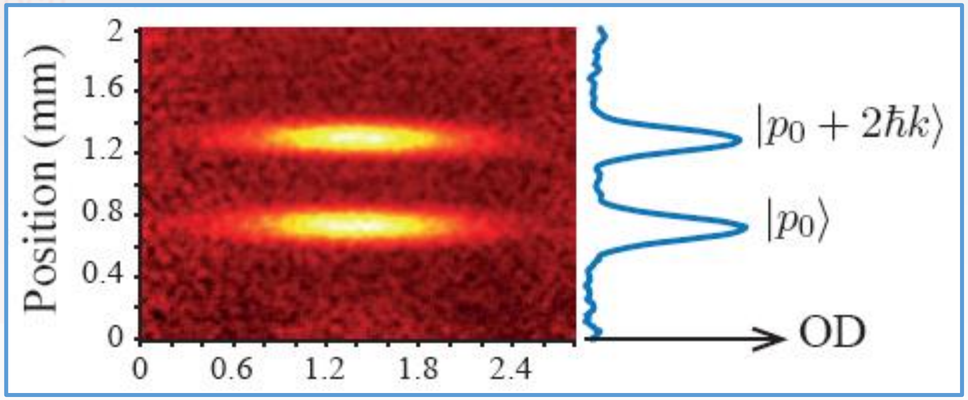
$(\lambda_{dB} = h/p)$

Atom interferometer:

light -> matter wave







Introduction

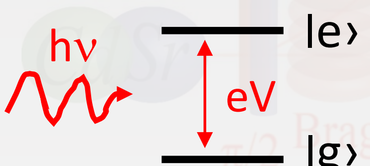
Precision measurements with ultra-cold atoms

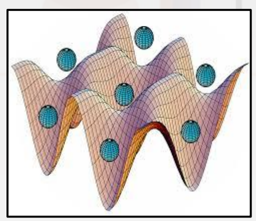
TIME

GRAVITY

Optical atomic clocks

internal d.o.f., electronic states



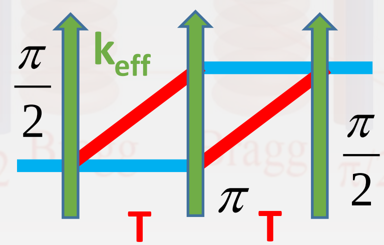


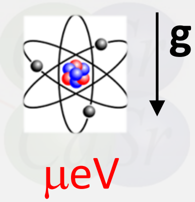
relative precision 10^{-19}

Atom interferometers

(gravimeters/gradiometers)

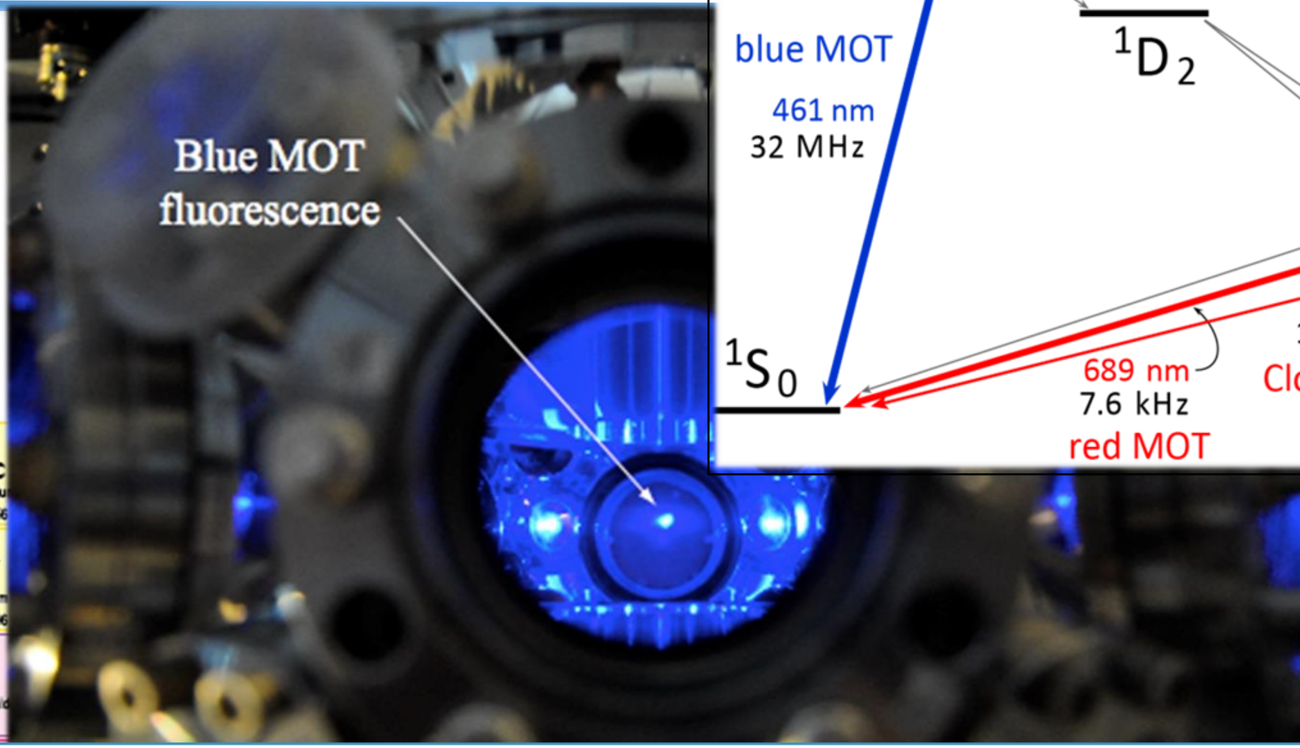
external d.o.f., momentum states

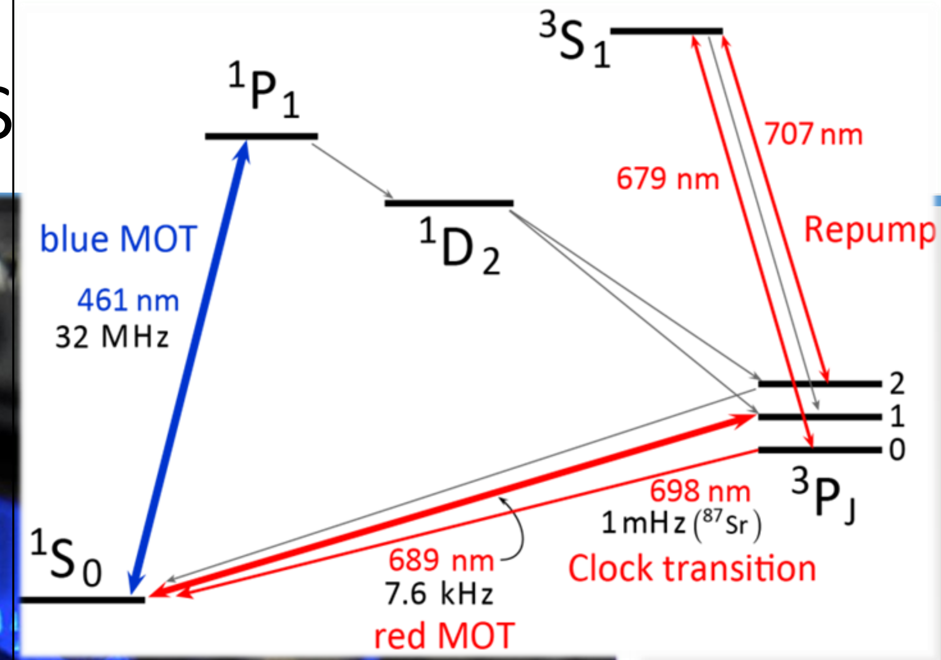




relative precision 10^{-11} g

Alkaline-Earth Atoms





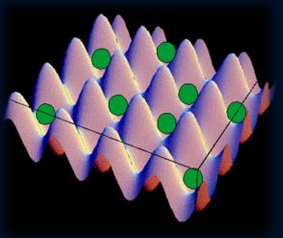
- Dipole allowed transitions bosons, no hyperfine structure)
  -> two-photon interferometers (Bragg diffraction)

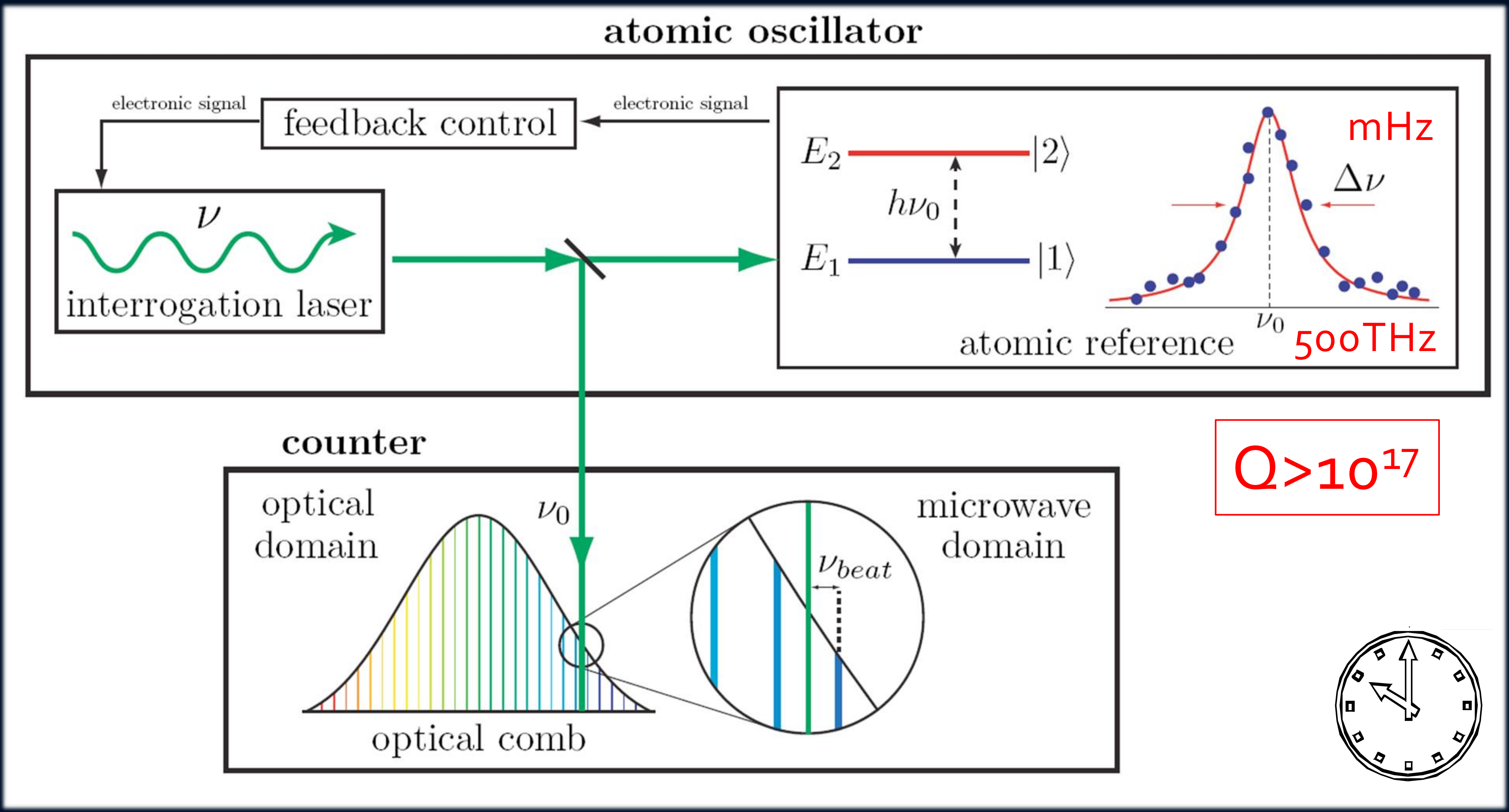
- Narrow intercombination transitions to metastable ^3P states
  -> single photon interferometers (atomic clocks)

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, ...

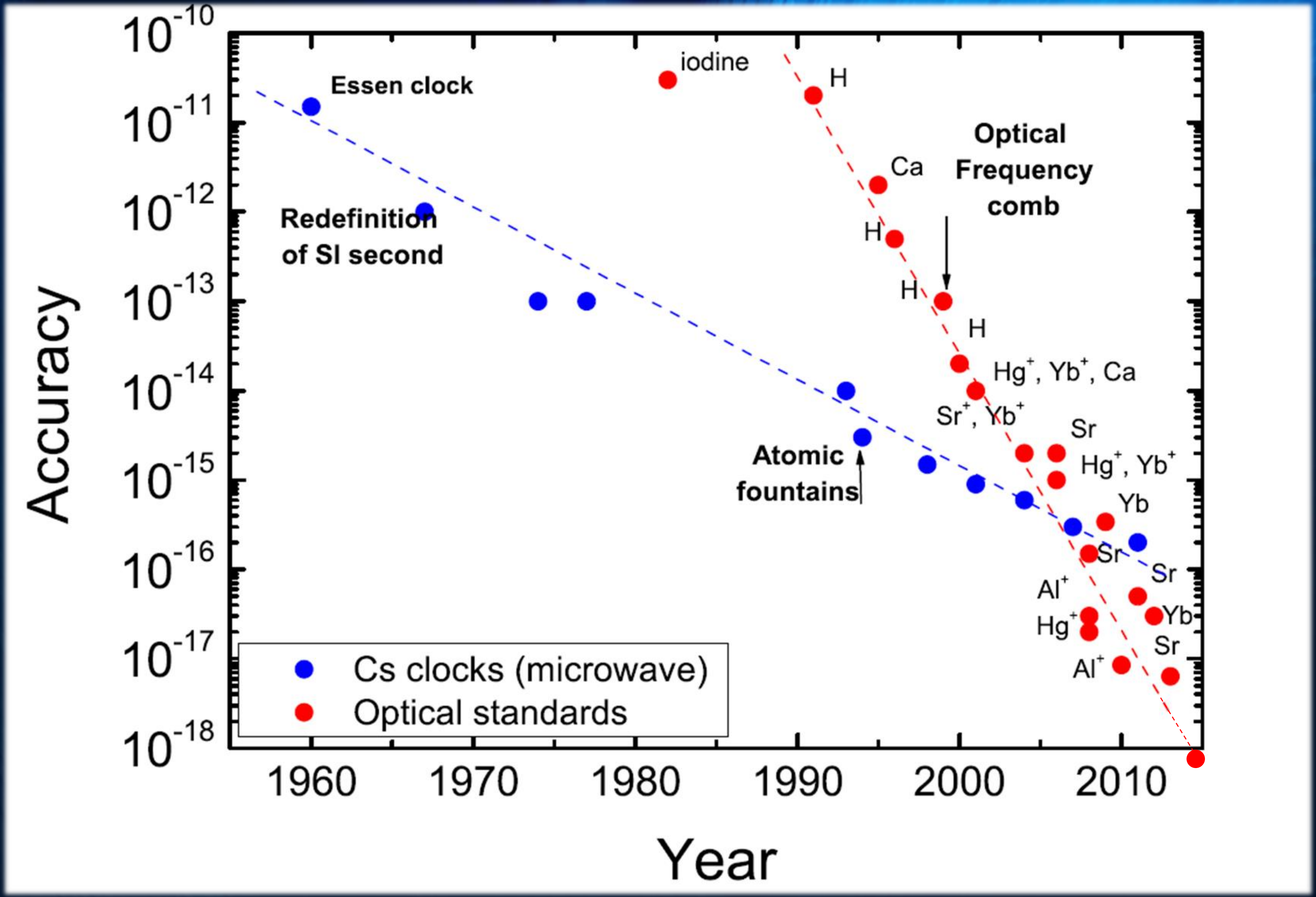
Optical atomic clocks





N. Poli et al. Rivista del Nuovo Cimento 12, 555 (2013)

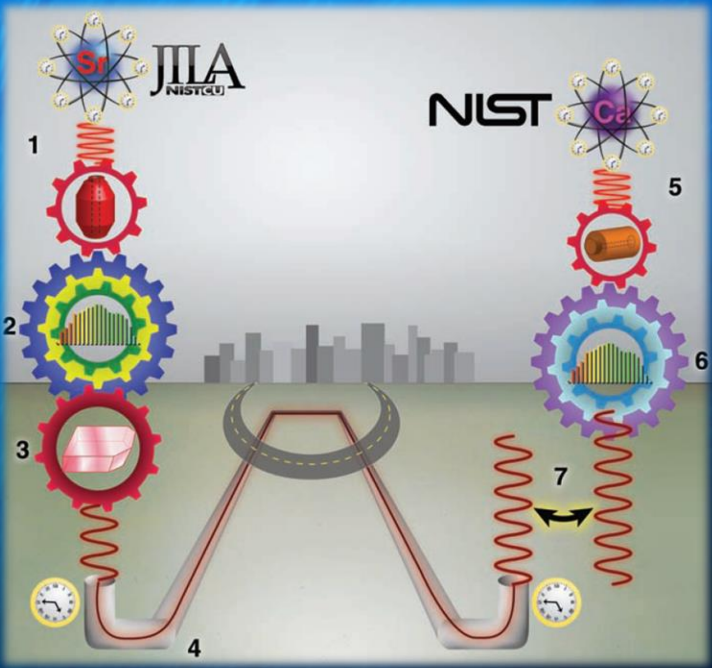
Clock Uncertainty



N. Poli et al. Rivista del Nuovo Cimento 12, 555 (2013)

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 stabillty

Ministero dell'Istruzione dell'Università e Ricerca

Imaging optical frequencies

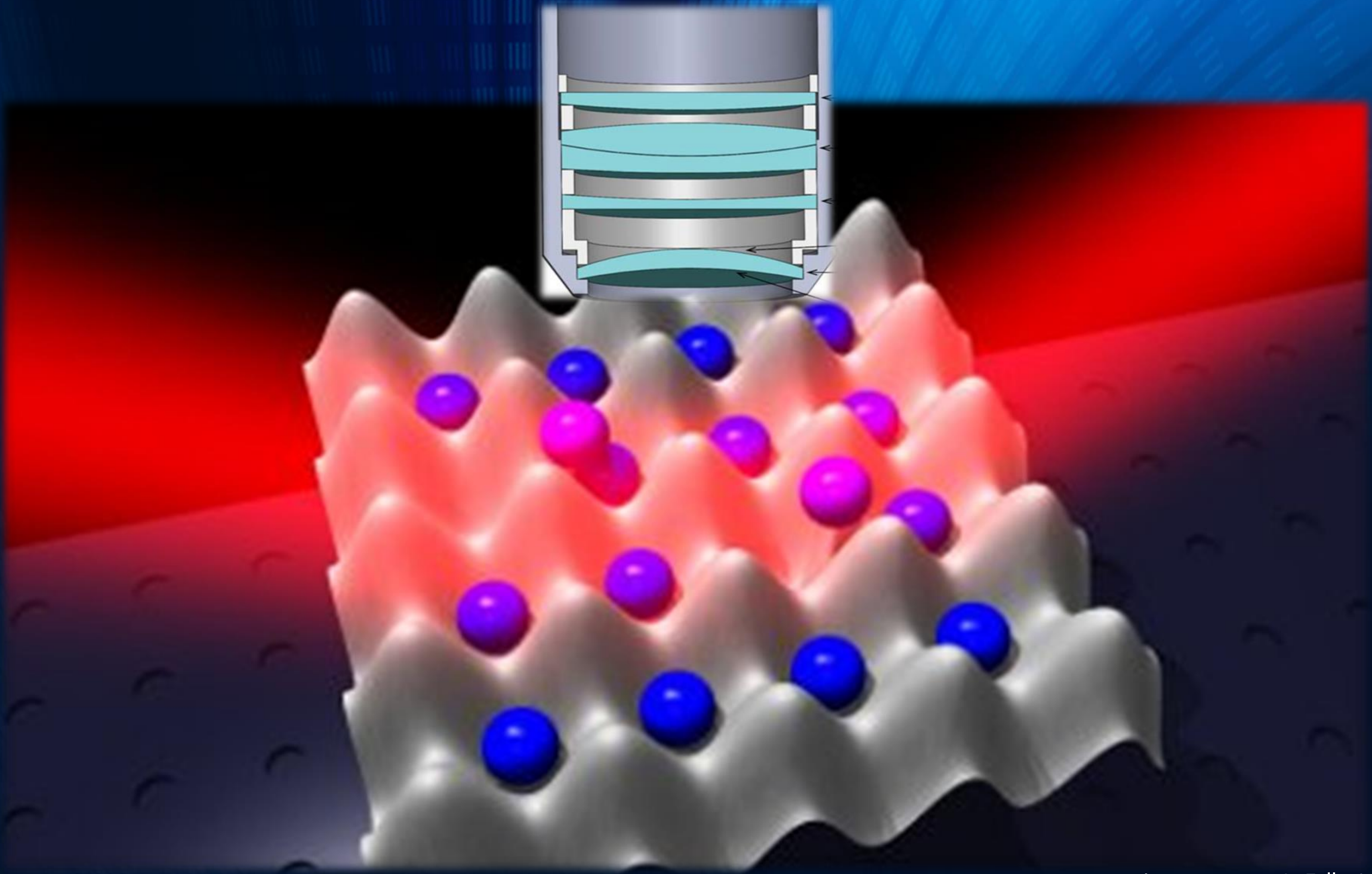
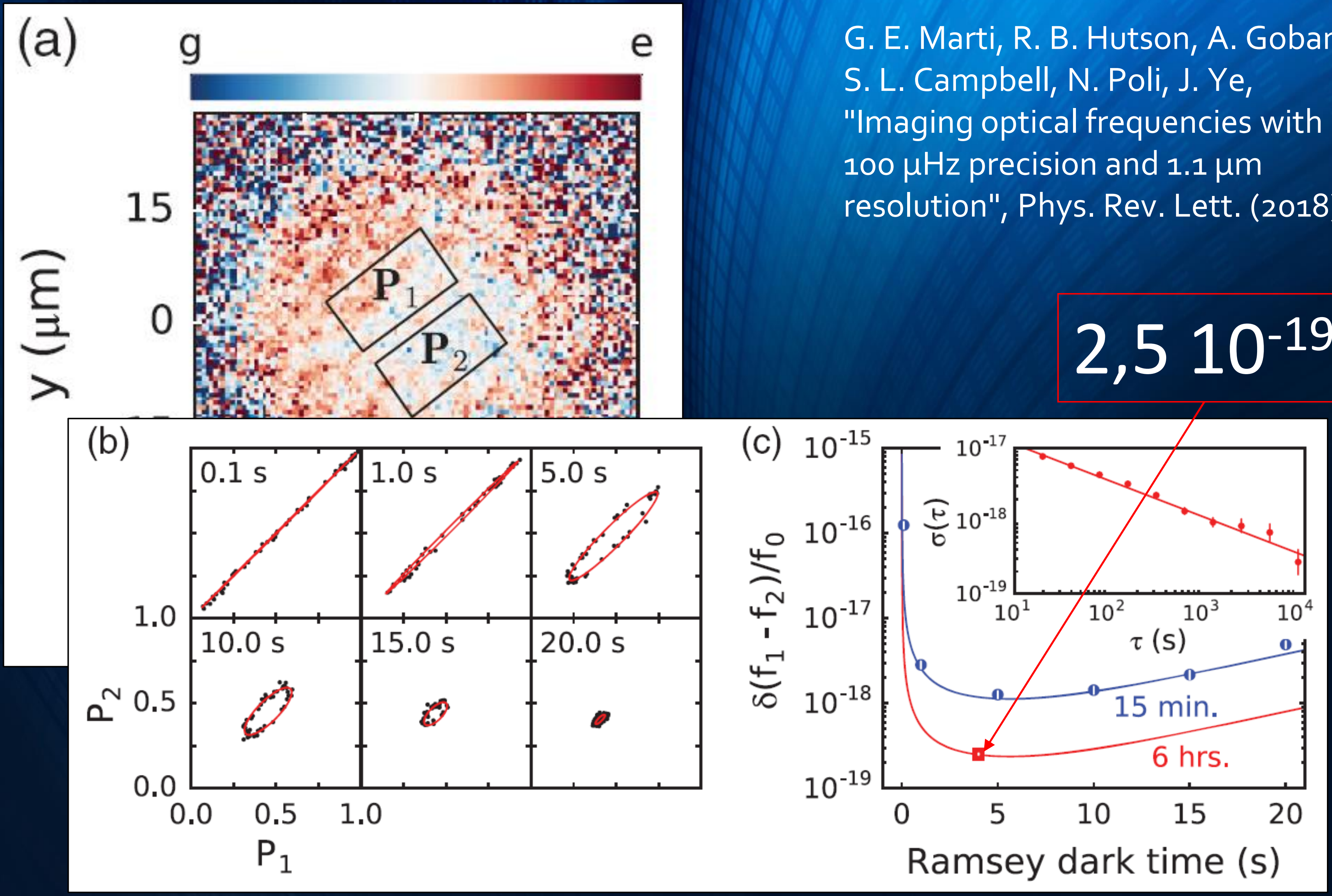


Image courtesy L. Fallani

Imaging optical frequencies

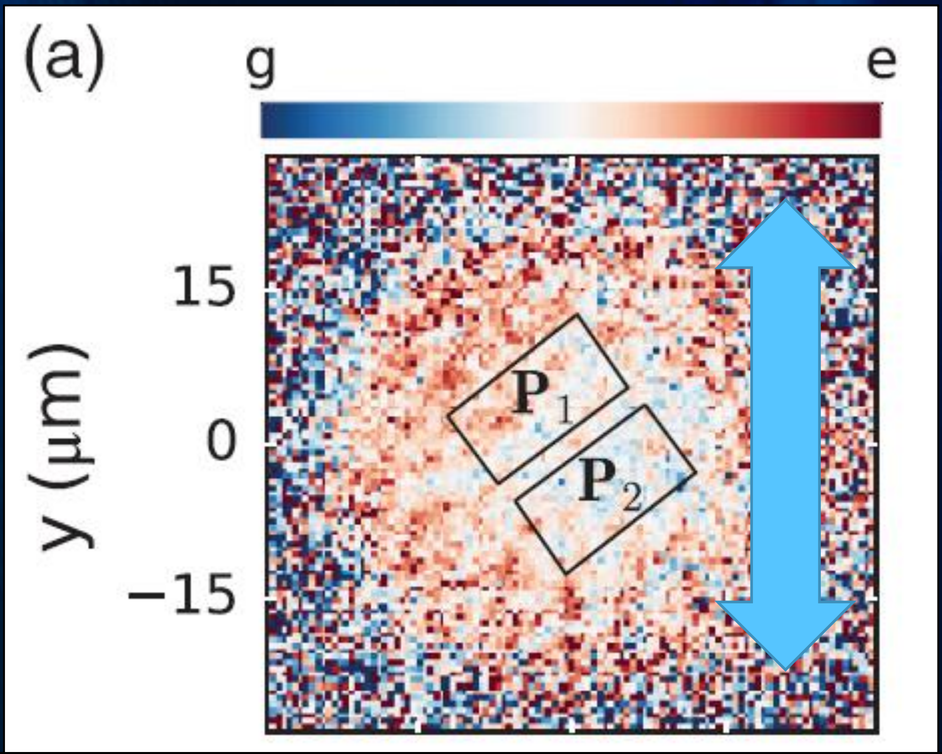
G. E. Marti, R. B. Hutson, A. Goban, S. L. Campbell, N. Poli, J. Ye, "Imaging optical frequencies with 100 μHz precision and 1.1 μm resolution", Phys. Rev. Lett. (2018)

$2{,}5\ 10^{-19}$



Gravitational Red Shift

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



10 μm

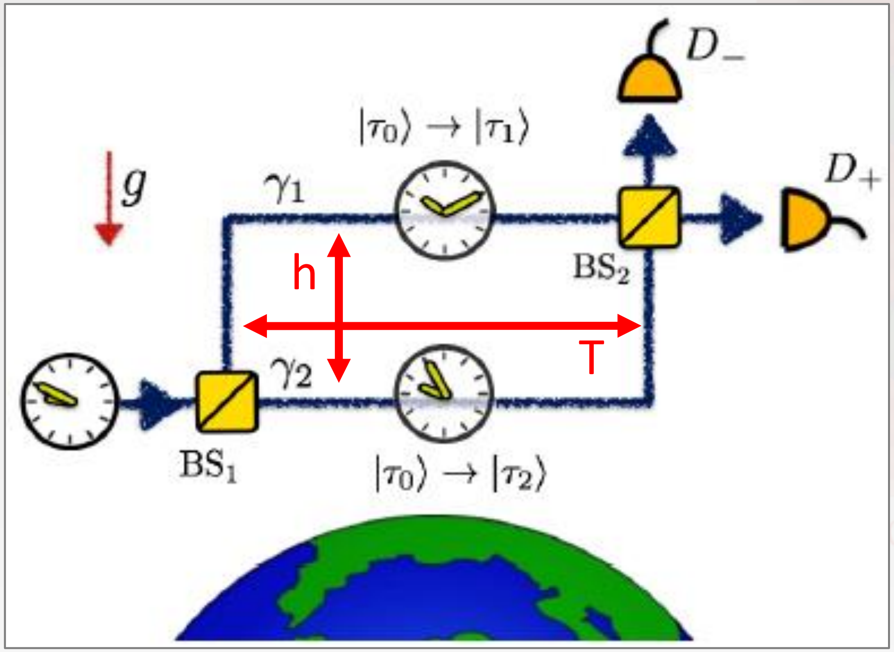
$\Delta\nu/\nu = 10^{-21}$

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

$\lambda_{dB} \approx 1$ μm @ 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

Quantum Interference of Clocks

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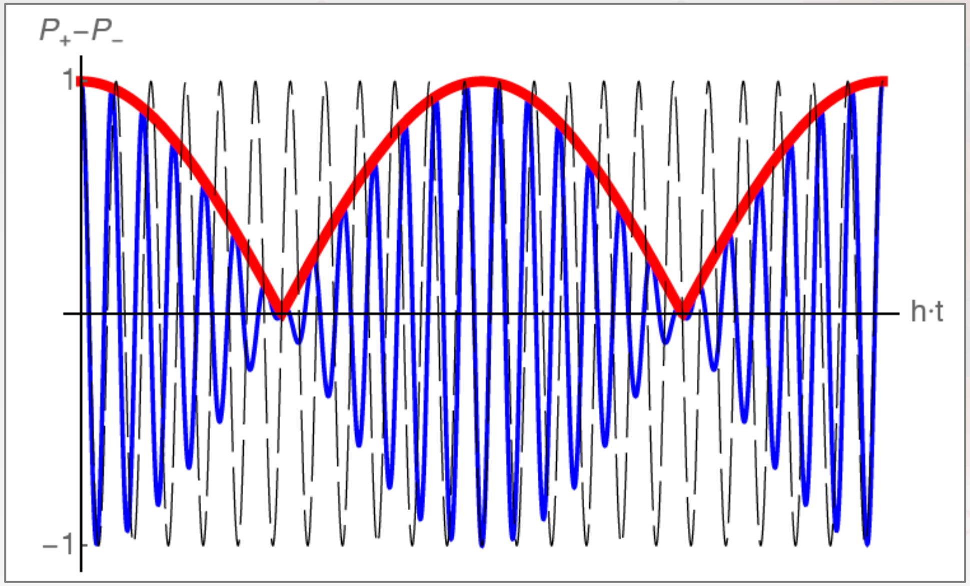

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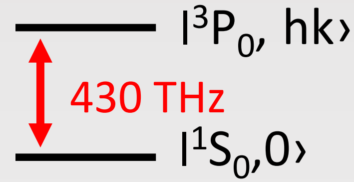
Clock transition in Sr



Single photon (momentum states + electronic states)

✓ **^{88}Sr atoms**

- Magnetic field induced transition

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

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

- Typical parameters: B = 350 G I = 25 W/cm^2

→ $\Omega_{88} = 2\pi\ \ 1\ \mathrm{kHz}$

✓ **^{87}Sr atoms**

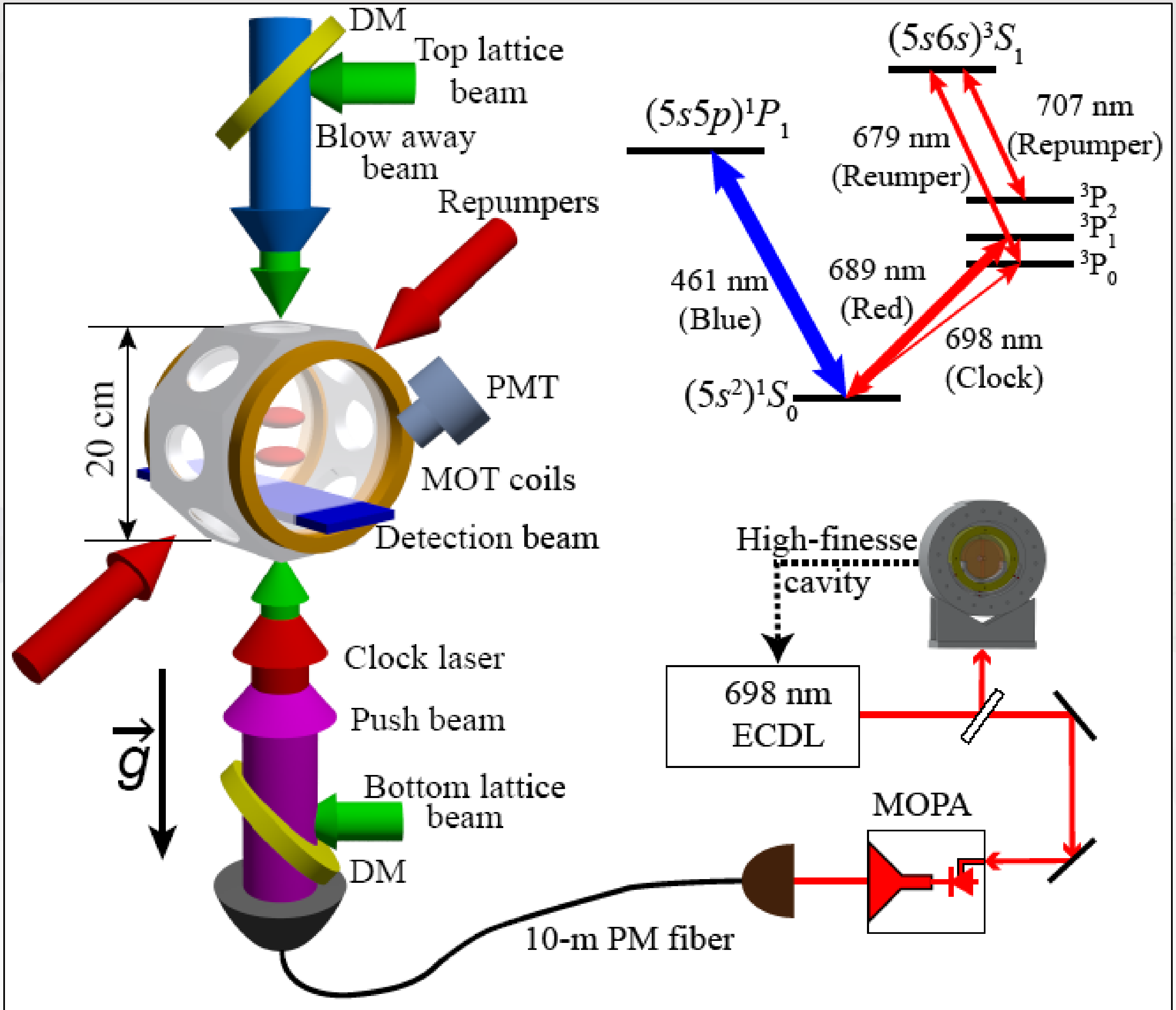
$$\Omega_{87} = \Gamma_{87}\sqrt{I/I_s}$$

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

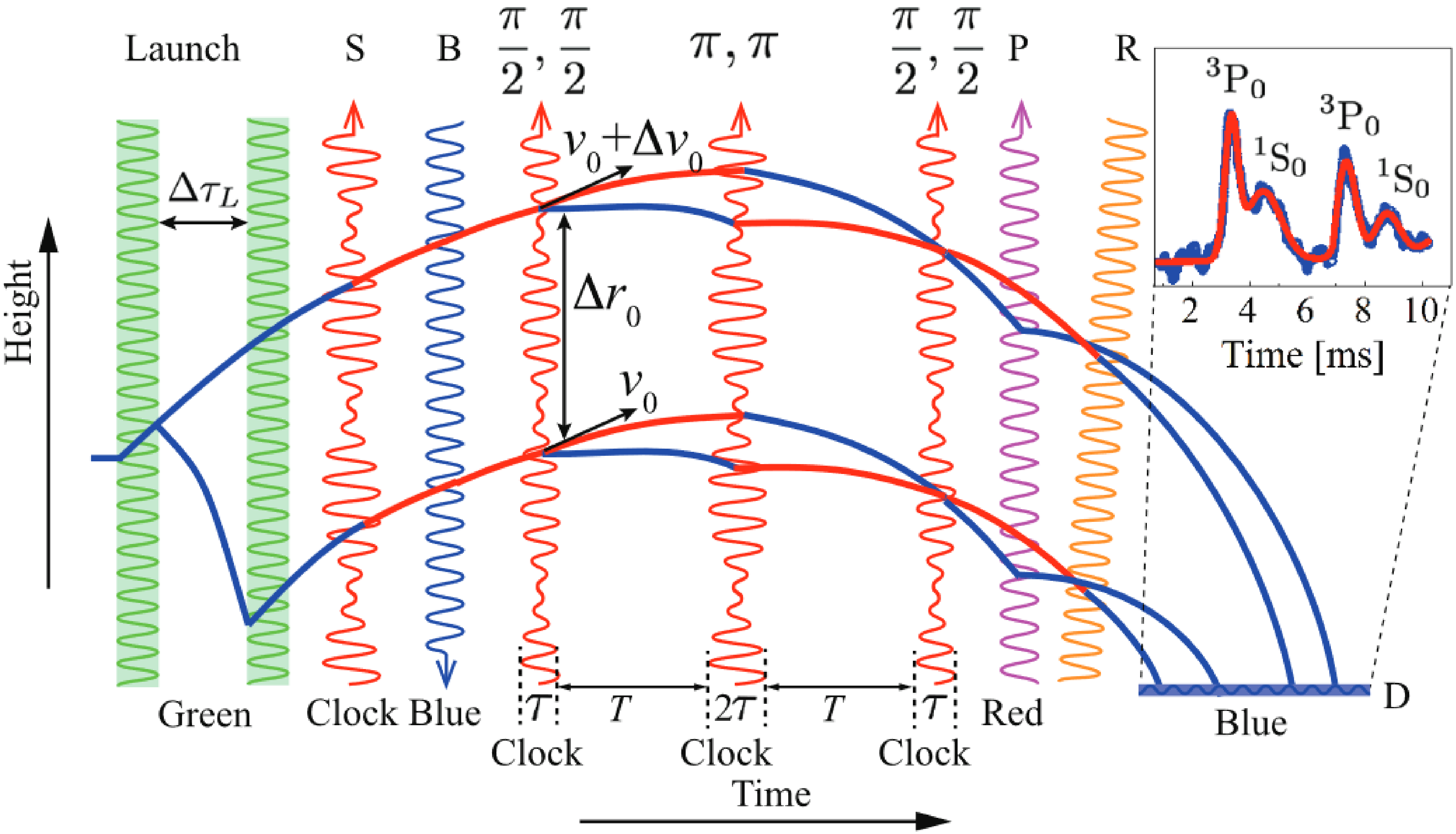
$$I_s \approx 0.4\ \mathrm{pWcm}^{-2}$$

I = 41 W/cm^2 → $\Omega_{87} = 2\pi\ \ 10\ \mathrm{kHz}$

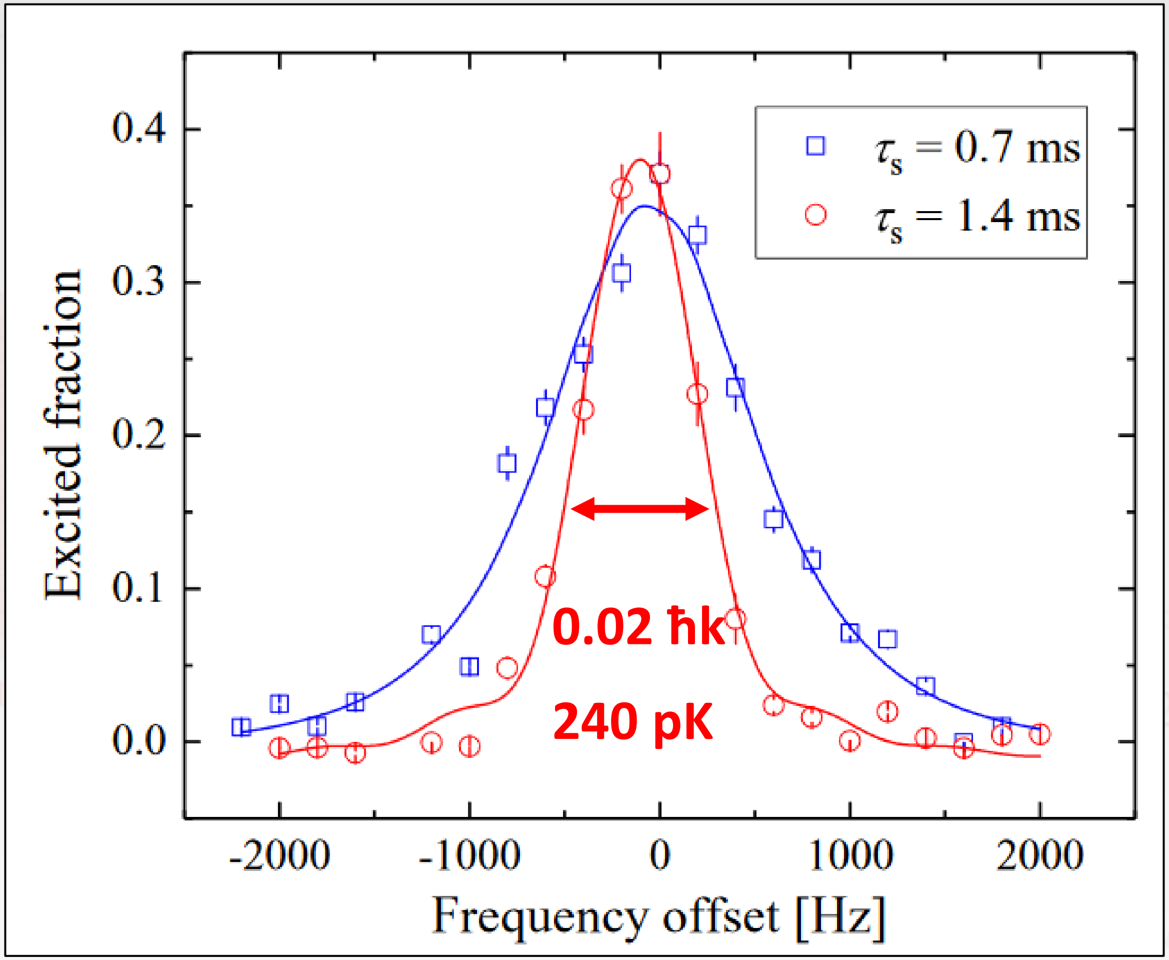
Experimental setup



Experimental sequence (gradiometer)

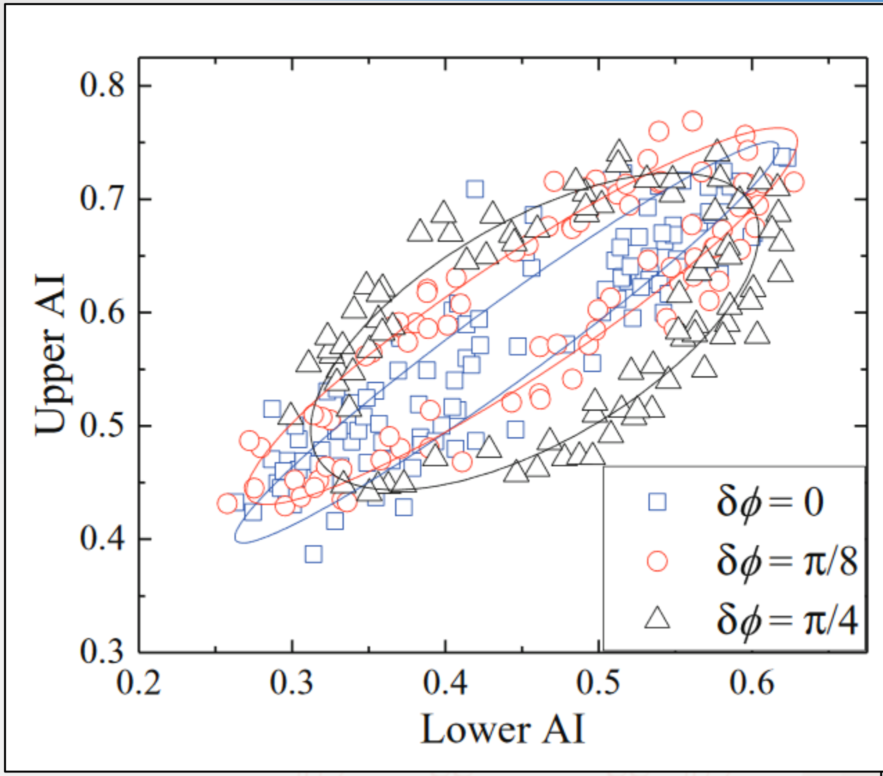


Velocity selection on clock transition



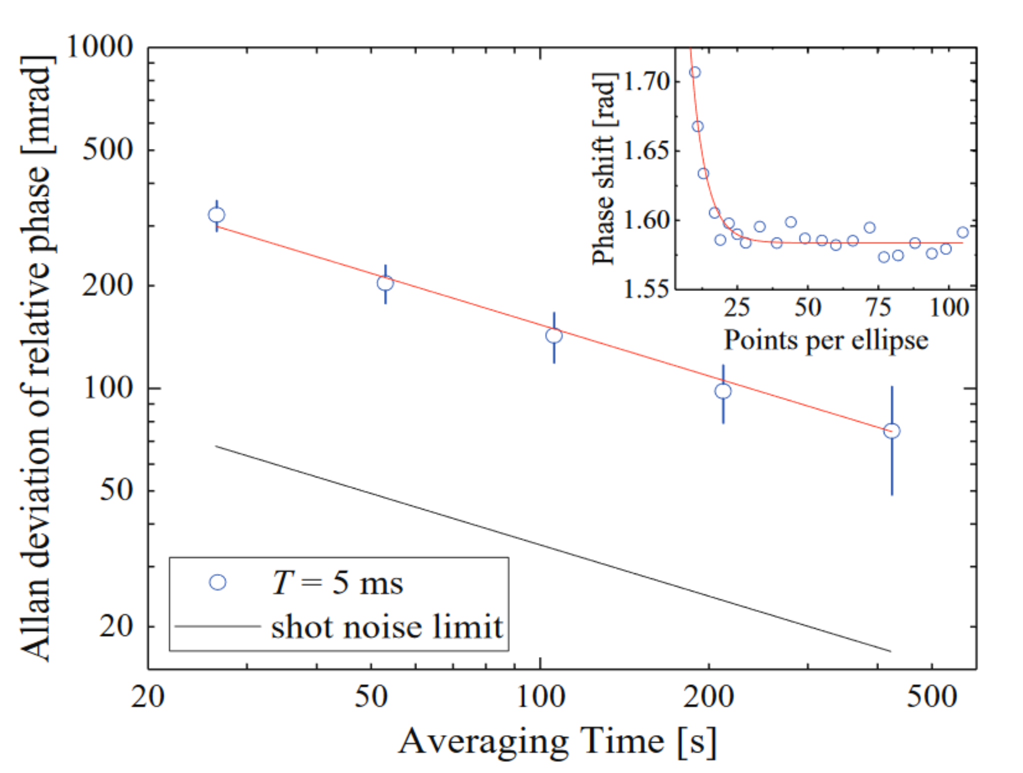
✓ **Clock spectroscopy on free-falling atoms**

Clock Gradiometer



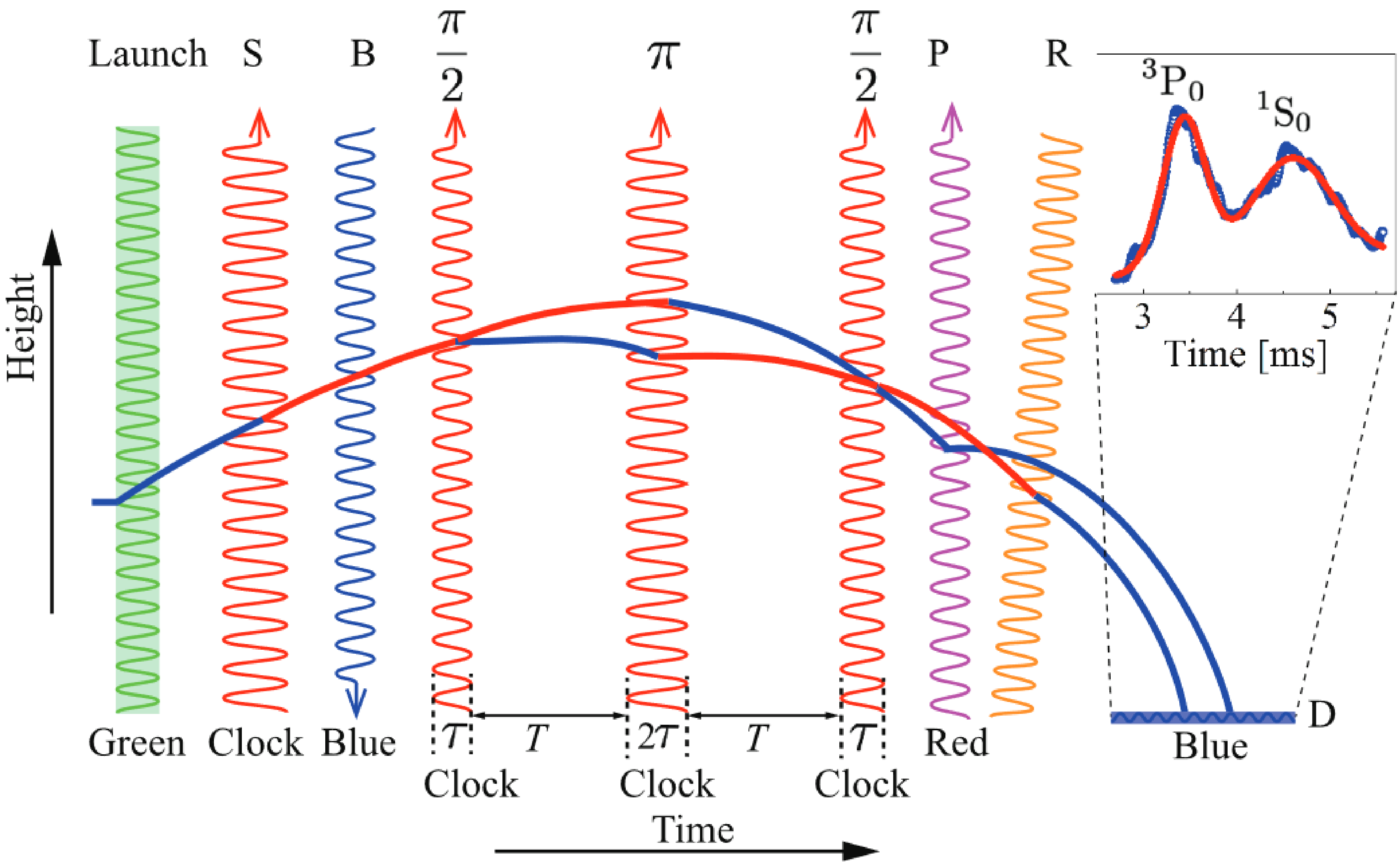
- Up to 30 ms total interferometer time

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

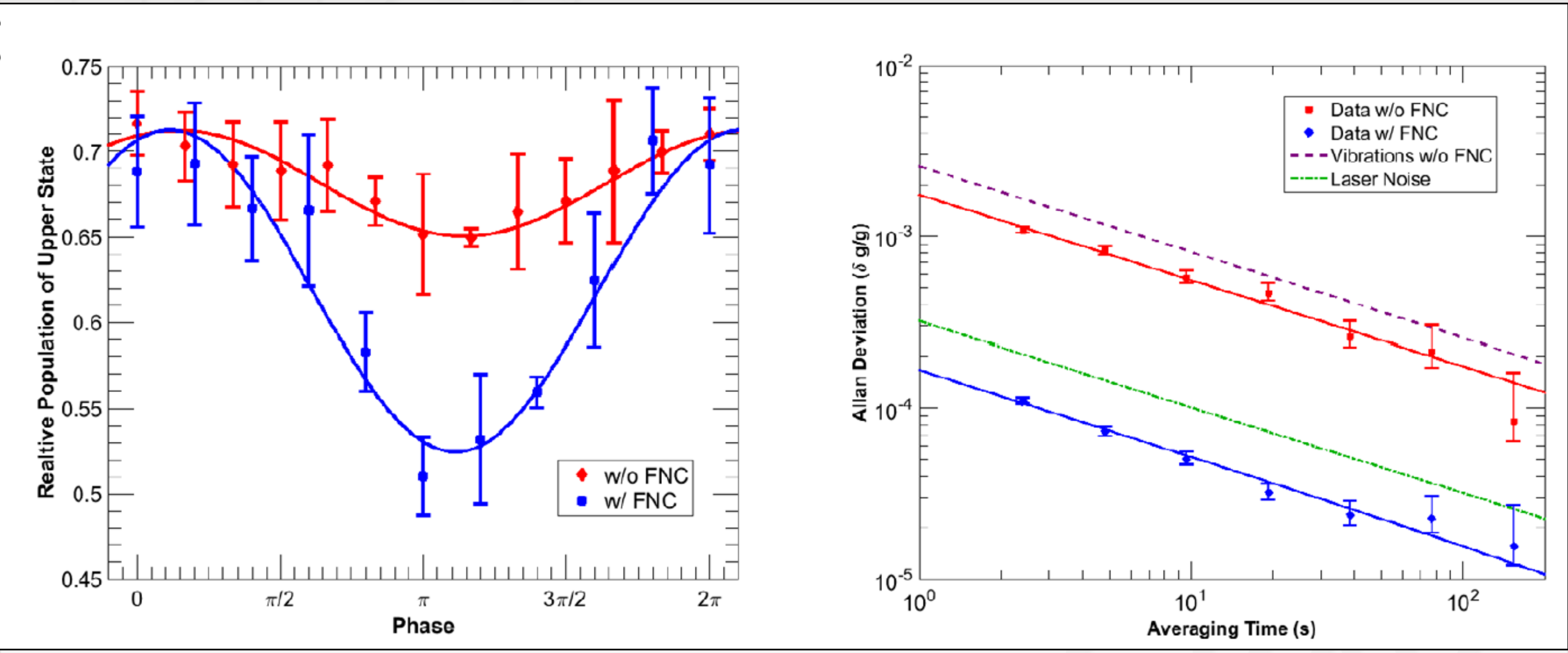


L. Hu *et al Class. Quantum Grav.* **37** 014001 (2020)

Experimental sequence (gravimeter)



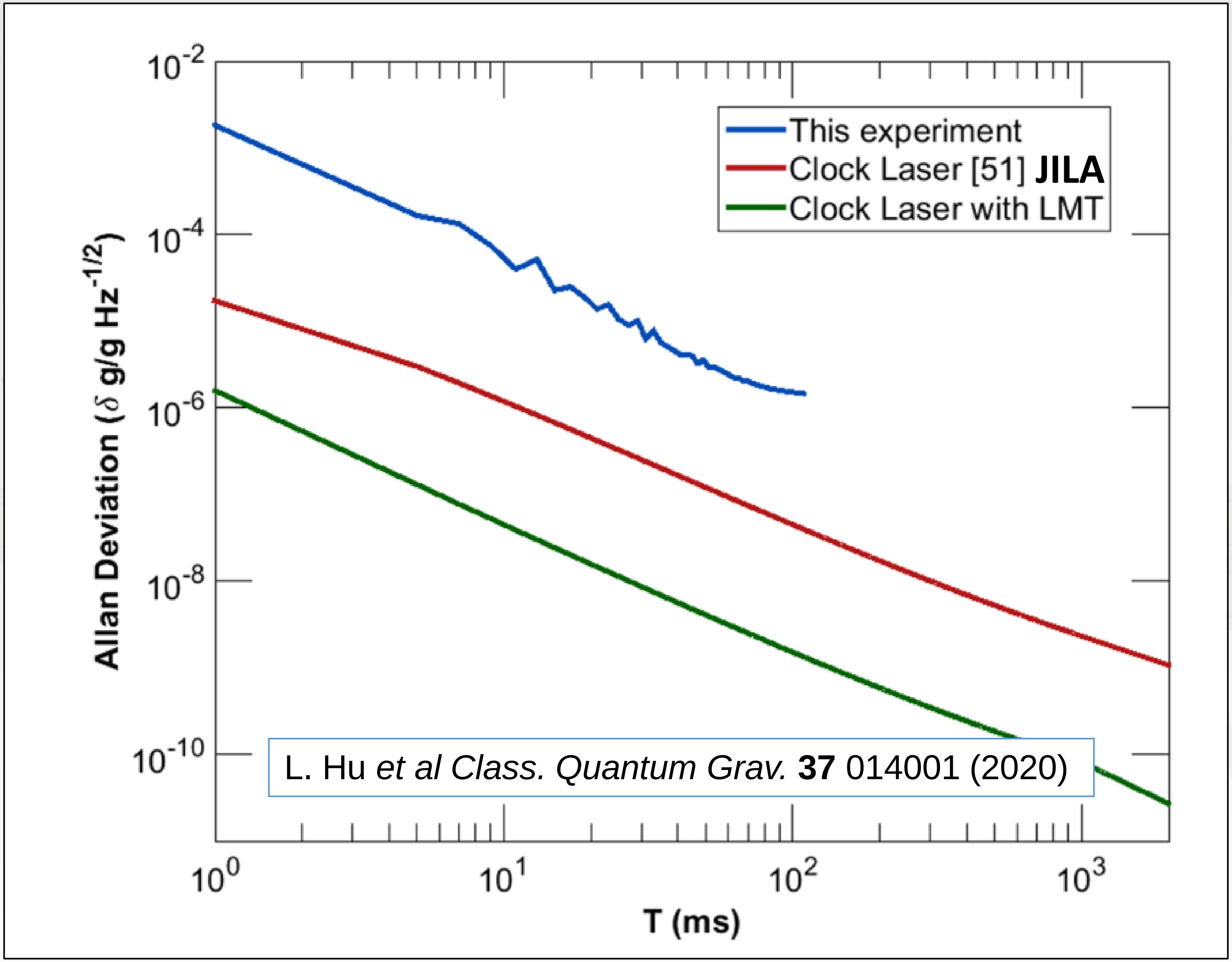
Gravimeter sensitivity



1.7×10^{-5} @ 150 s

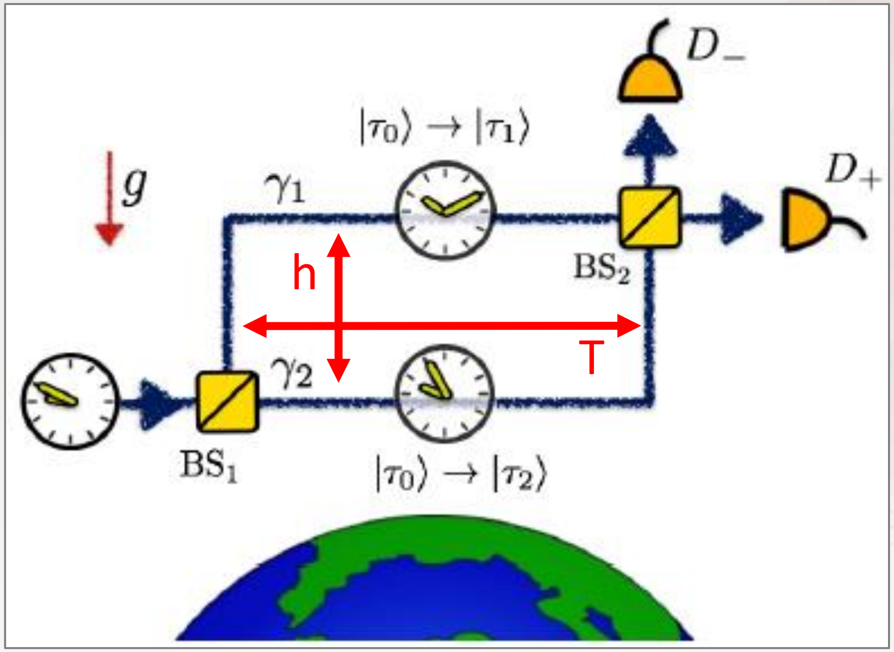
L. Hu *et al Class. Quantum Grav.* **37** 014001 (2020)

Gravimeter sensitivity

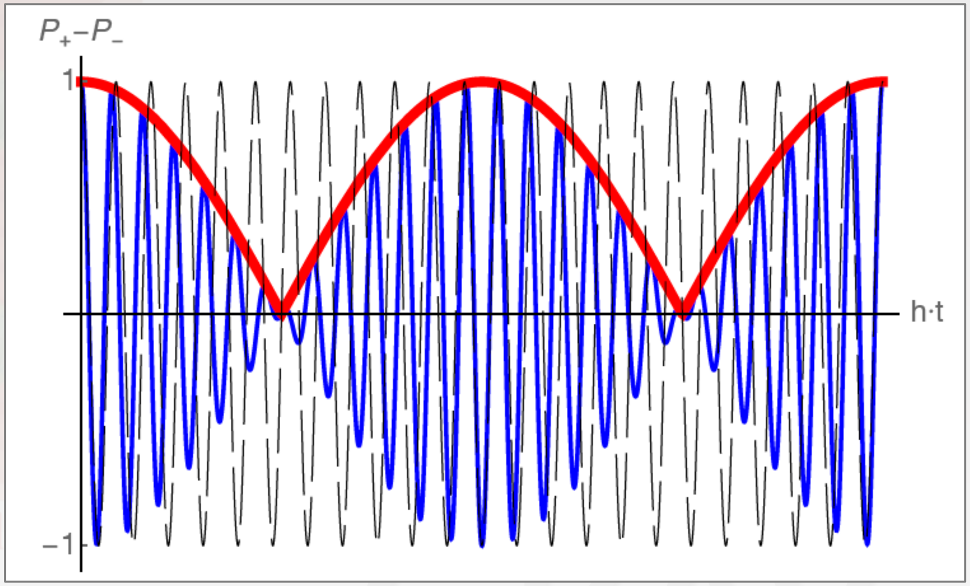


Quantum Interference of Clocks

Observe gravity induced “decoherence” in clock interferometers



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

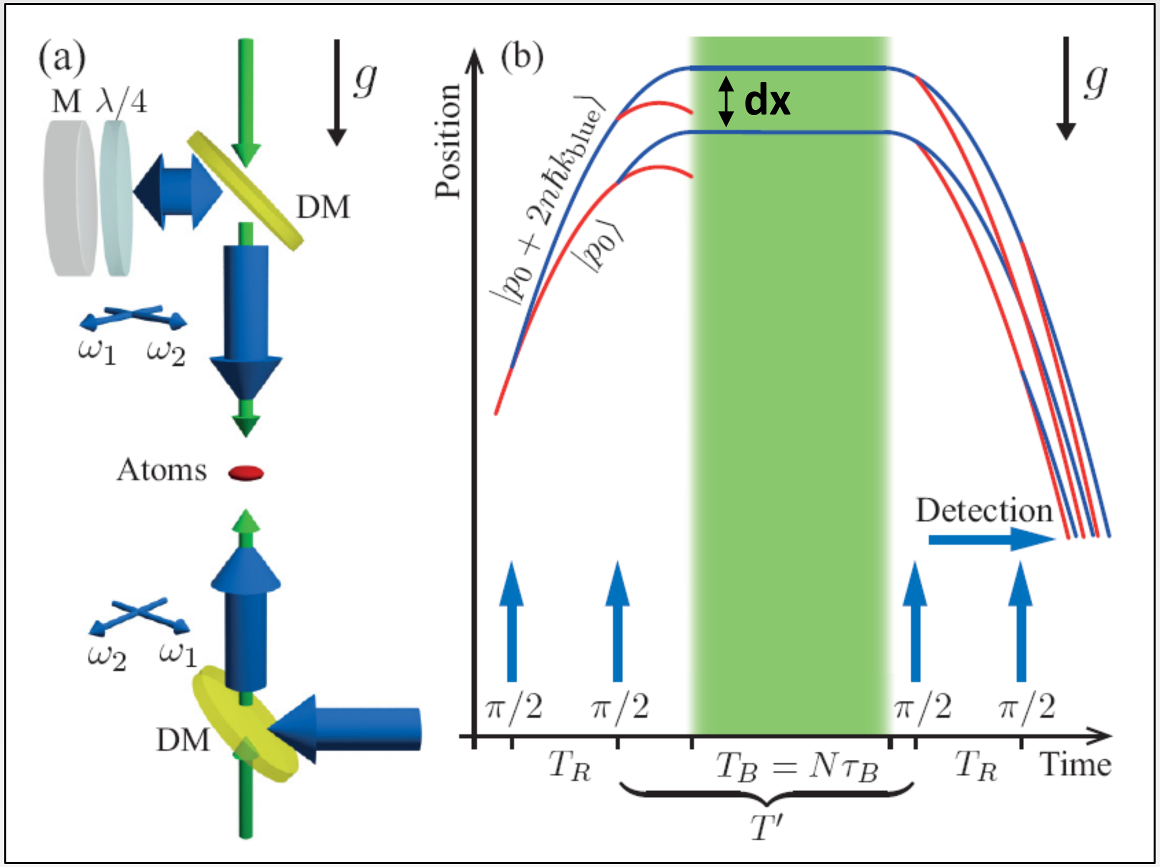


- ✓ Interferometer contrast modulation

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

Full revival for h=2 m, time T = 10 s

Ramsey-Bordé + Bloch oscillation



"Trapped" gradiometer coherent evolution in vertical lattice (T_B ~1 s)

Ramsey time T_R

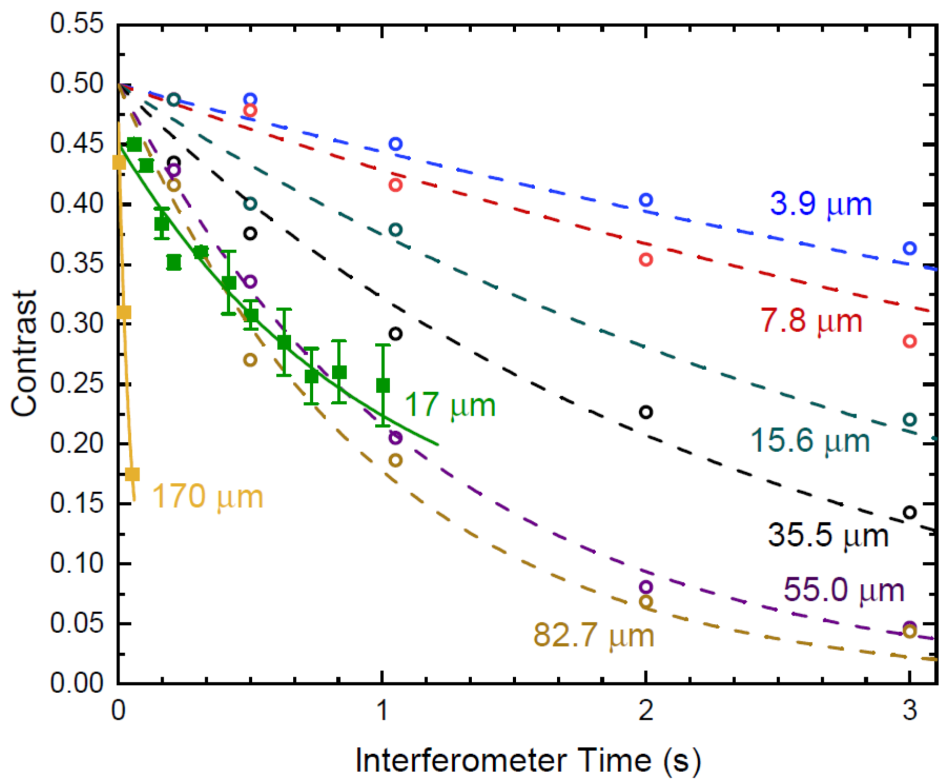
Bloch oscillations time T_B

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

Contrast limited by trapping beam quality (T_B~1s @ dx=17μm)

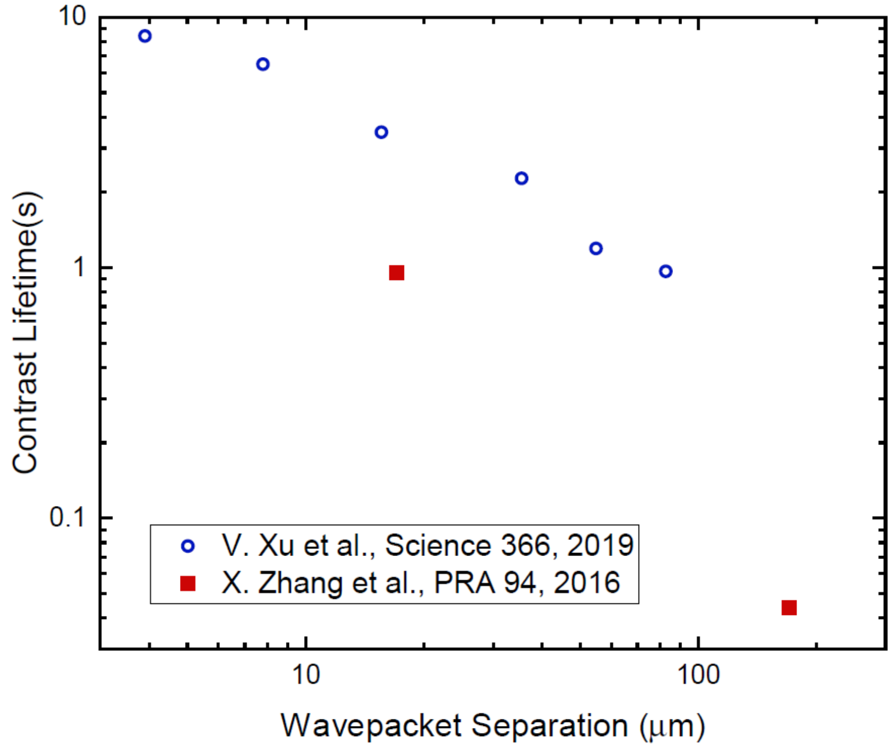
X. Zhang, et al. Phys. Rev. A 94, 043608 (2016)

Contrast comparison

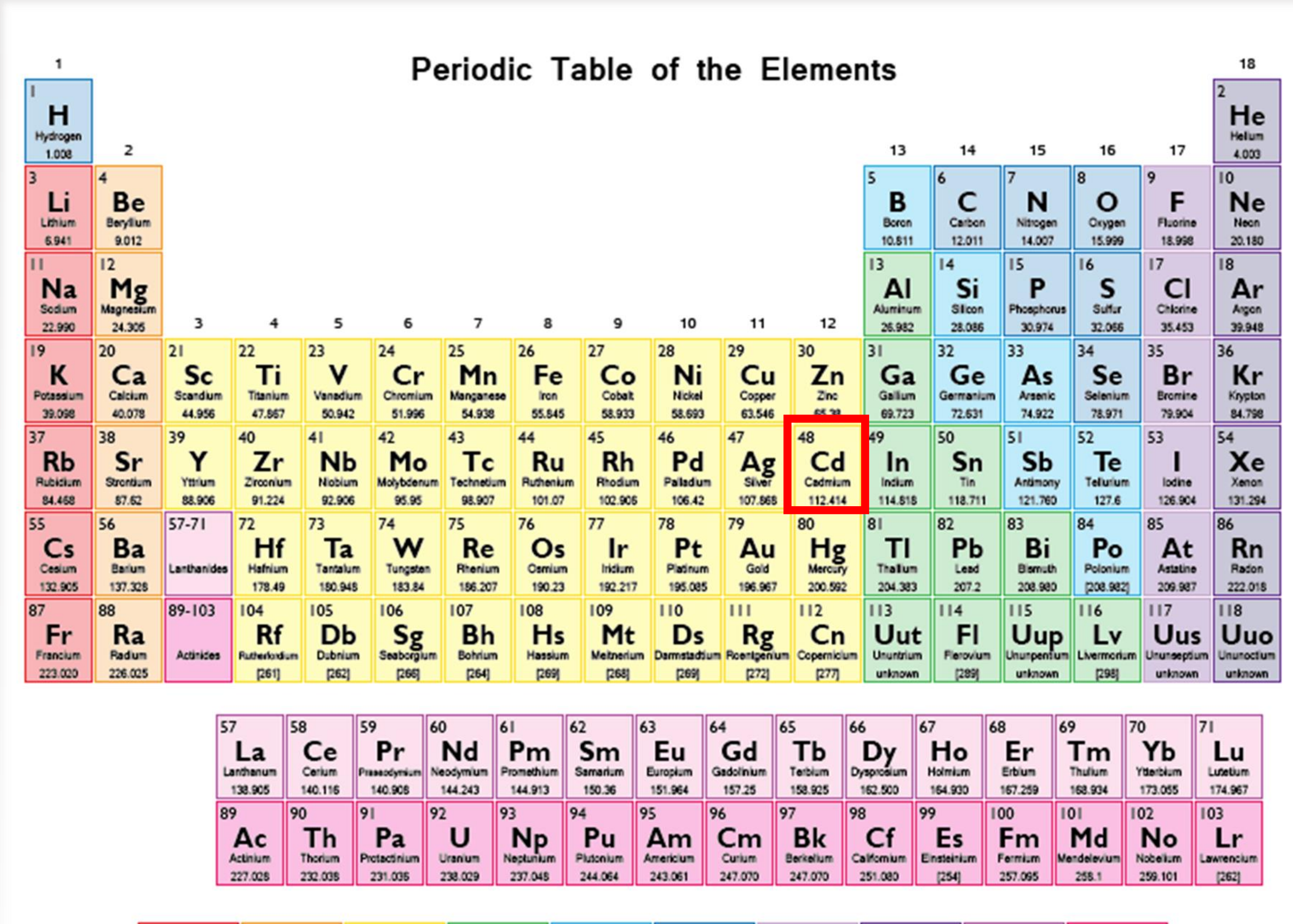


$$\lambda_{lat} = 866\ \text{nm}$$
$$z_R = 1.6\ \text{m}$$
$$w_0 = 730\ \mu\text{m}$$

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



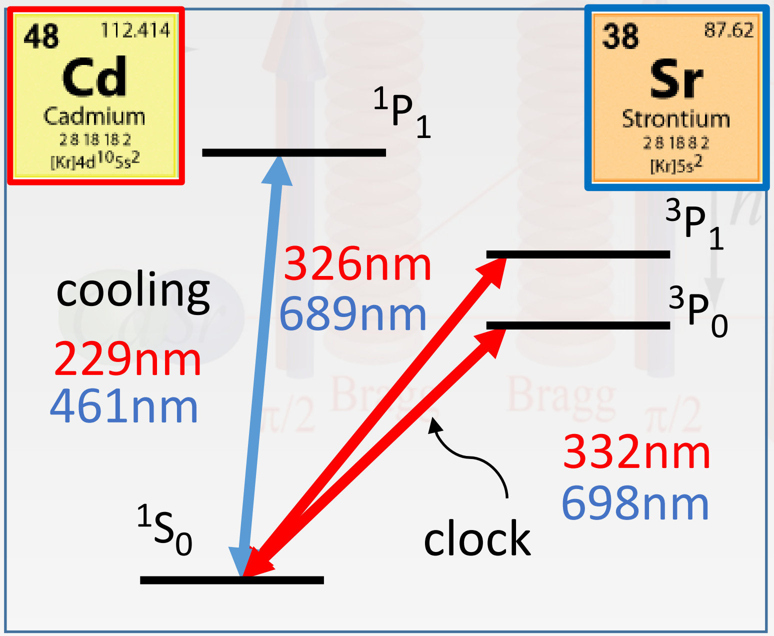
Clock interferometer candidates



A novel atom interferometer

Simultaneous interferometers on optical clock transitions Cadmium & Strontium

Similar atomic level structure:



✓ 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

Magic wavelength ratio → - Rejection of technical noise

J. N. Tinsley and N. Poli, "Exploring Gravity with Ultra-cold Cadmium and Strontium Optical Clocks and Bragg Interferometers," in ECAMP 13,(2019)

Quantum Interference of Clocks

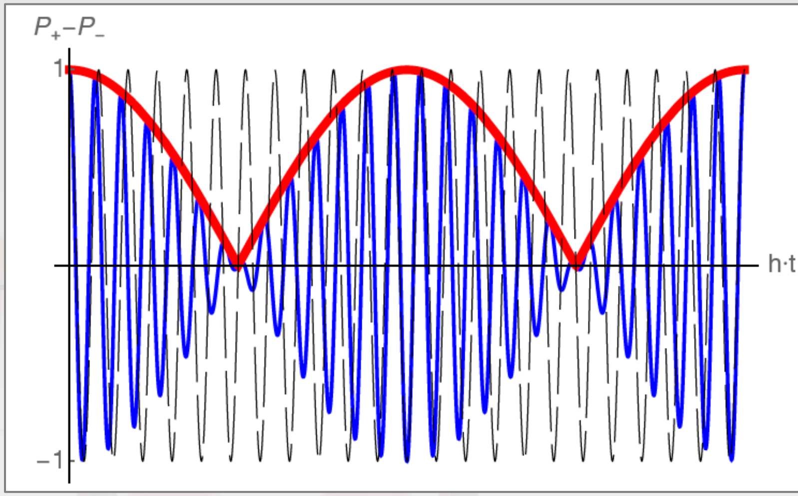
TICTOC GRAV

- ✓ Interferometer contrast modulation

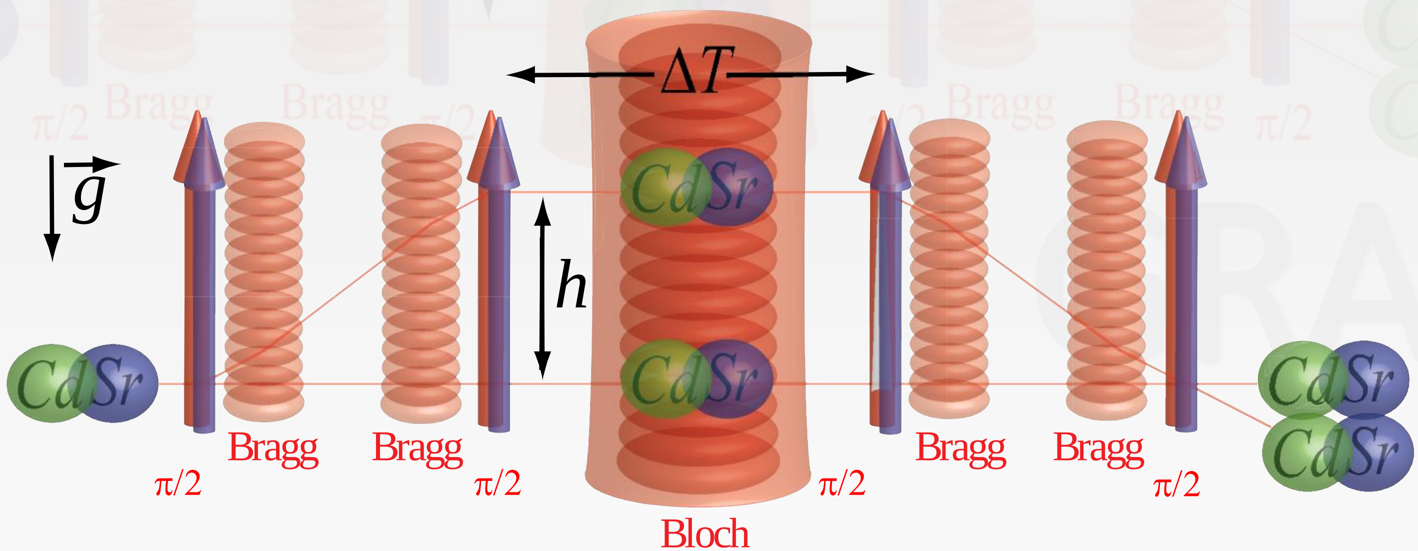
$(h*T)_{Sr}$= 21 m s

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

Full revival for h=2 m, time T = 5 - 10 s



Sr as "contrast reference", observe on Cd faster contrast decay



Simultaneous Cd – Sr interferometer

- ✓ A "magic" coincidence for Cd-Sr:

A	B	λ_A (nm)	λ_B (nm)	$r = \sqrt{k_B^{\rm eff}/k_A^{\rm eff}}$
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

- ✓ Same interferometer scale factor $S_j = k^{eff}_j\, T^2_j$

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

(a = common acceleration)

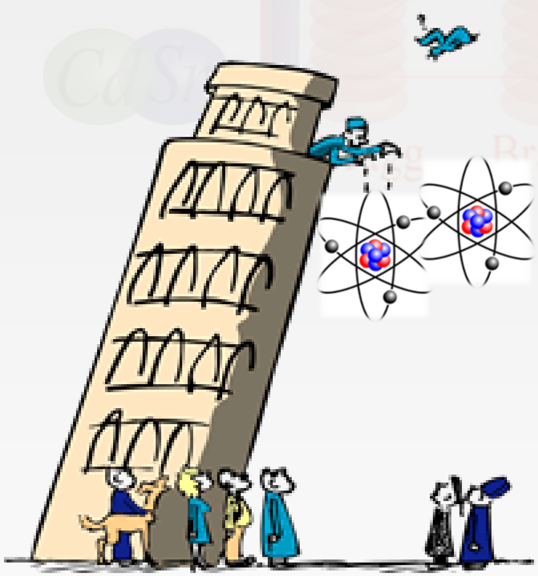
Efficient noise rejection and low systematics : same k_{eff} , Ω_R , τ

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**.

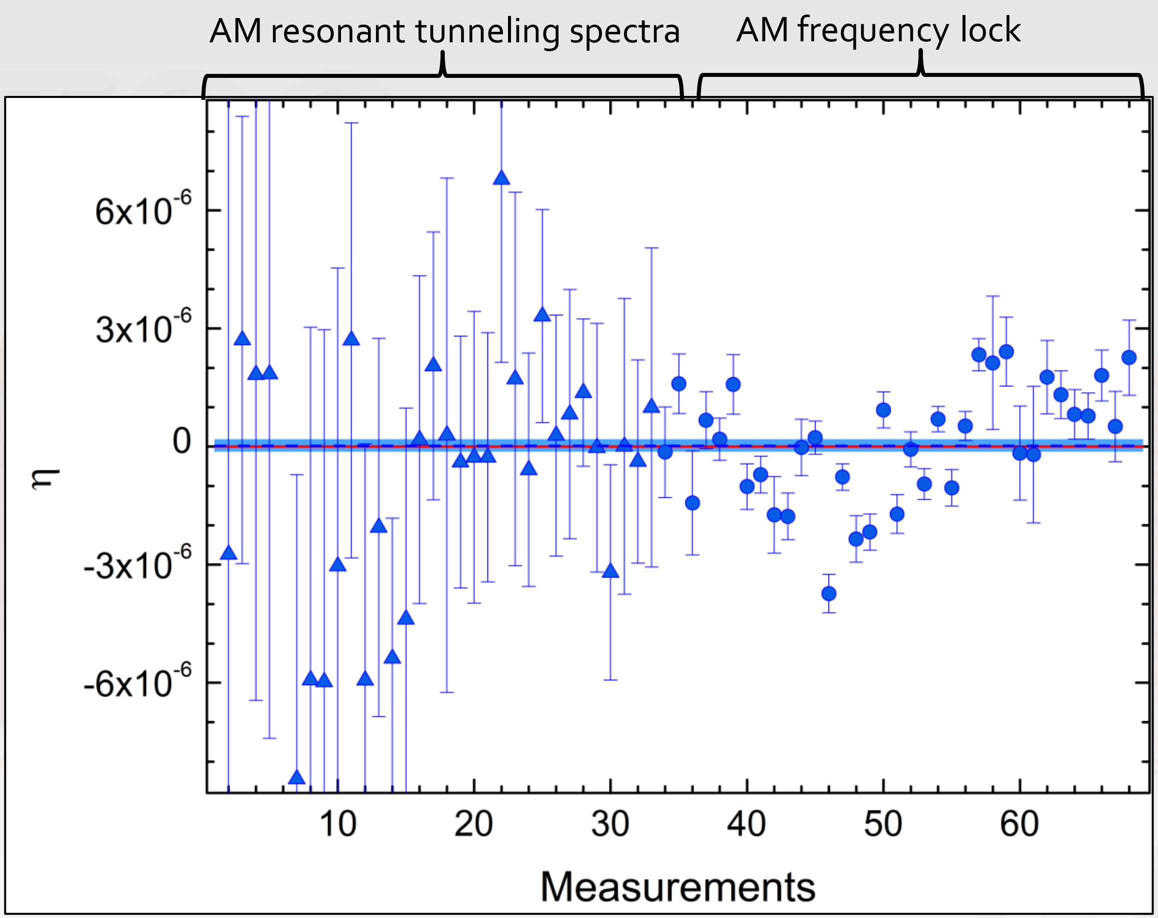
^{88}Sr

- Boson
- Zero total spin

^{87}Sr

- Fermion
- I=9/2

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

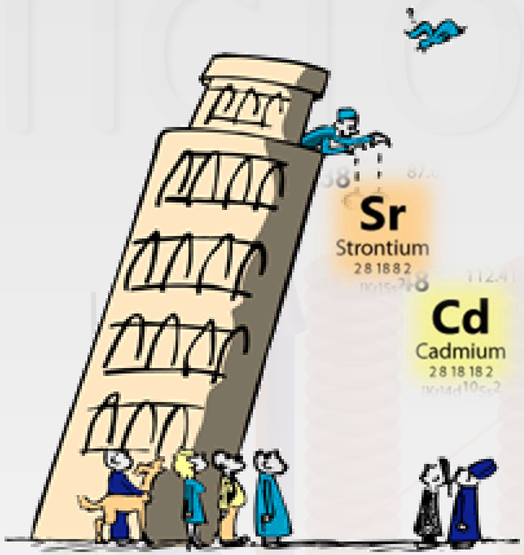


$$\eta = (0.2 \pm 1.6)\ 10^{-7}$$

M. G. Tarallo, et. al., Phys. Rev. Lett. **113**, 023005 (2014)

Simultaneous Cd – Sr interferometer

- ✓ Test WEP Cd - Sr



- Low systematics
- High sensitivity to SME violation parameters

$$\eta_{A,B} \cong D_1\left(\Delta Q'^{1}_{A,B}\right) + D_2\left(\Delta Q'^{2}_{A,B}\right)$$

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

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	$Q'^1_A - Q'^1_B$ $\times 10^4$	$Q'^2_A - Q'^2_B$ $\times 10^4$	$f_{\beta_A^{e+p-n}} - f_{\beta_B^{e+p-n}}$ $\times 10^2$	$f_{\beta_A^{e+p+n}} - f_{\beta_B^{e+p+n}}$ $\times 10^4$	$f_{\beta_A^{\bar{e}+\bar{p}-\bar{n}}} - f_{\beta_B^{\bar{e}+\bar{p}-\bar{n}}}$ $\times 10^5$	$f_{\beta_A^{\bar{e}+\bar{p}+\bar{n}}} - f_{\beta_B^{\bar{e}+\bar{p}+\bar{n}}}$ $\times 10^4$
^{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

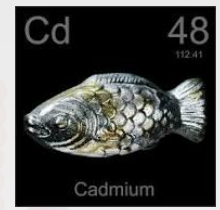
- ✓ Interesting possibility for atomic physics study with Cd atoms
- ✓ Cold collisional physics
- ✓ Degenerate gas production
- ✓ Quantum information
- ✓ Favorable wavelength ratio of main optical cooling & spectroscopy transitions

^{106}Cd	1.25%
^{108}Cd	0.89%
^{110}Cd	12.47%
^{111}Cd	12.80%
^{112}Cd	24.11%
^{113}Cd$^{(*)}$	12.23%
^{114}Cd	28.75%
^{116}Cd$^{(*)}$	7.51%

6 bosons (I=0)

2 fermions (I=1/2)

$^{(*)}$ long lifetime



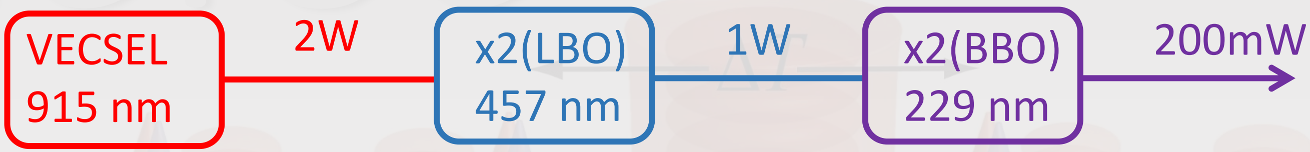
	transition	λ (nm)	$\Gamma/2\pi$	Is (mW/cm^2)	T_D
Sr					
	$^1S_0$-$^1P_1$	460.8	32 MHz	42.5	0.7 mK
	$^1S_0$-$^3P_1$	689.4	7.5 kHz	3×10^{-3}	200 nK
	$^1S_0$-$^3P_0$	698	1 mHz (Sr-87)	$\sim 10^{-9}$	-
Cd	transition	λ (nm)	$\Gamma/2\pi$	Is (mW/cm^2)	
	$^1S_0$-$^1P_1$	229	91 MHz	988	2.2 mK
	$^1S_0$-$^3P_1$	325	70 kHz	3×10^{-3}	1.6 μK
	$^1S_0$-$^3P_0$	335	3 mHz (Cd-113)	3×10^{-3}	–

Cd lab !!

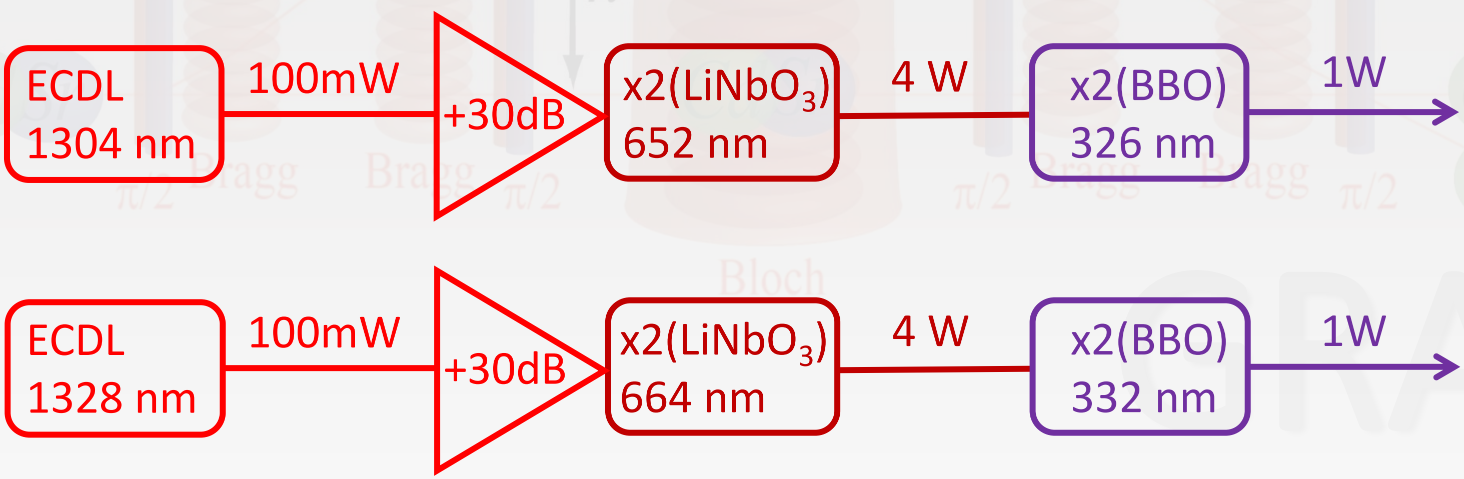
Cd laser sources

✓ Frequency quadrupoled laser sources

- main cooling transition:



- intercombination transitions:



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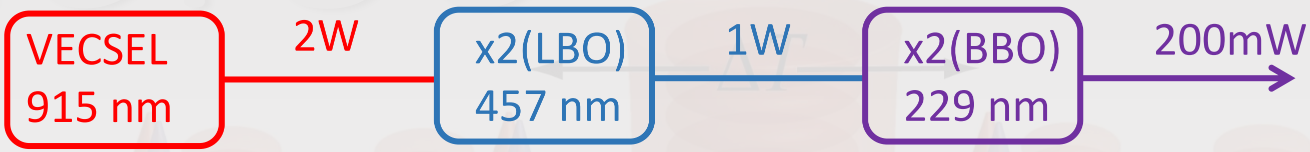
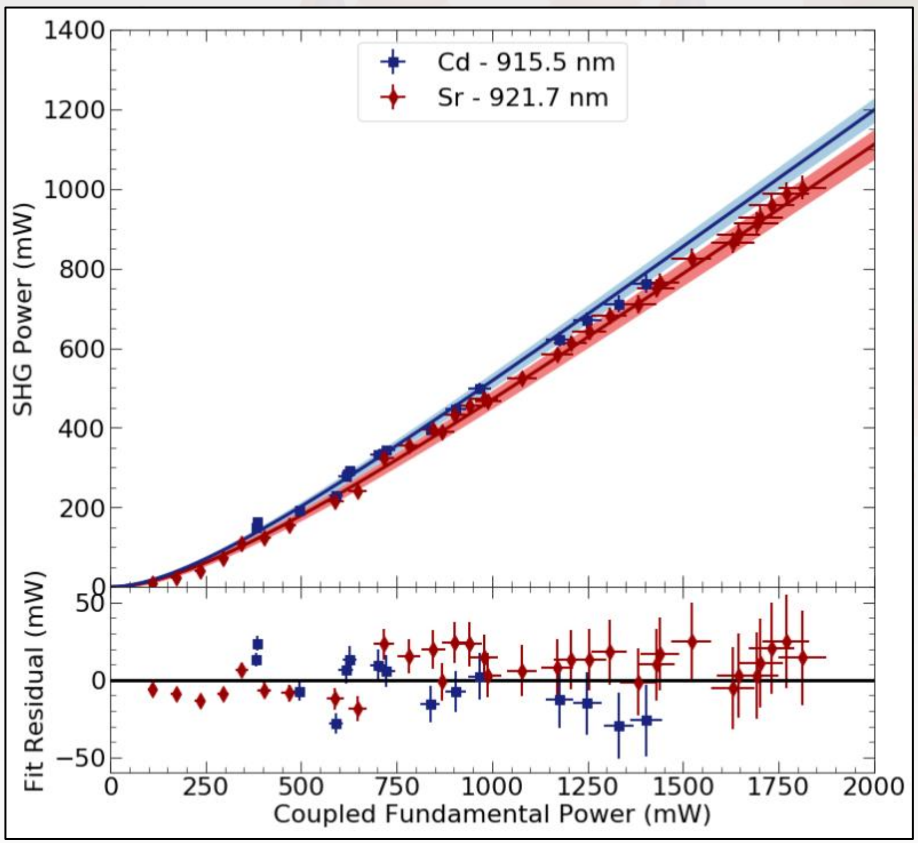
- main cooling transitions:



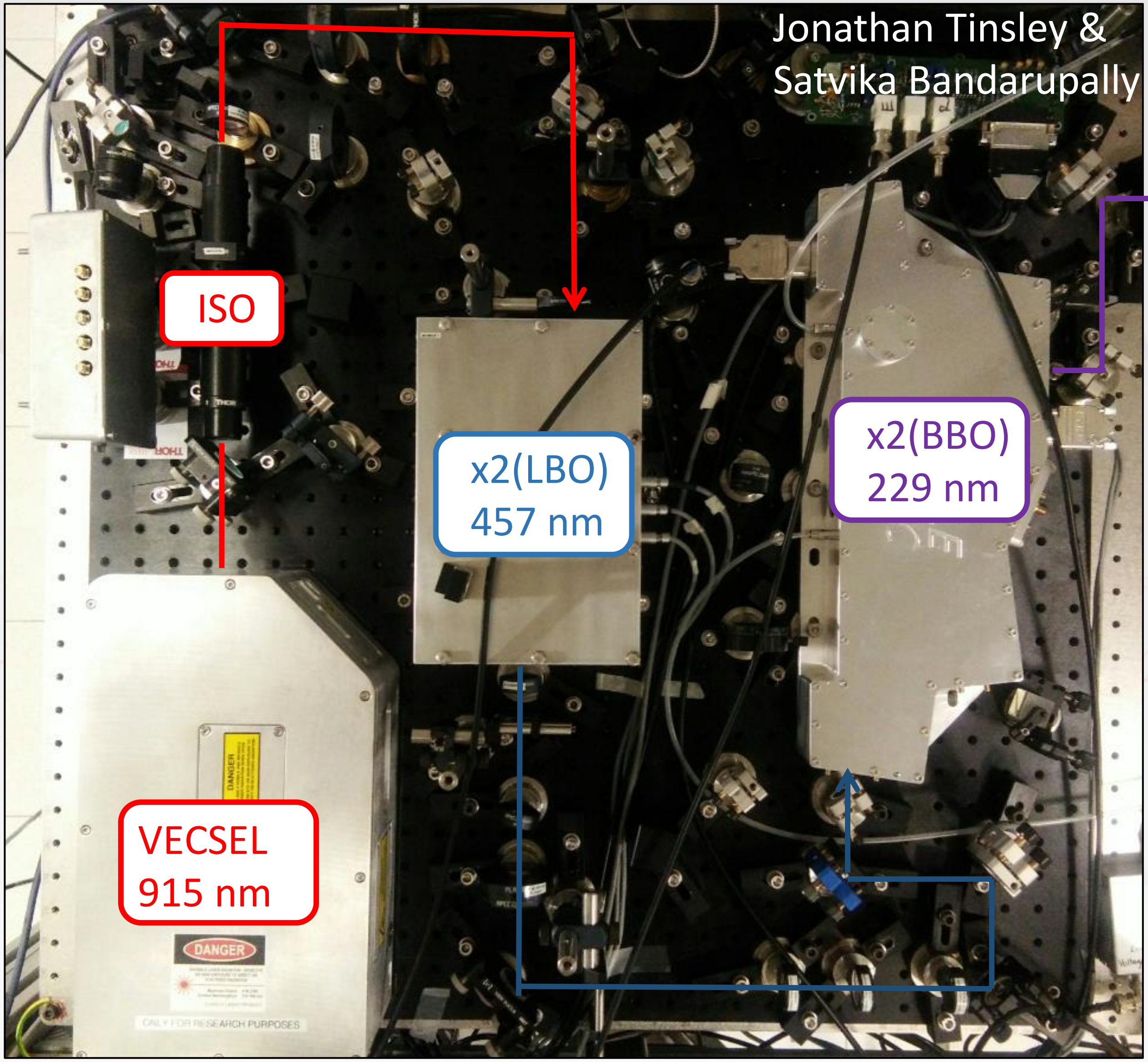


- Tunable high power VECSEL (915- 928 nm)

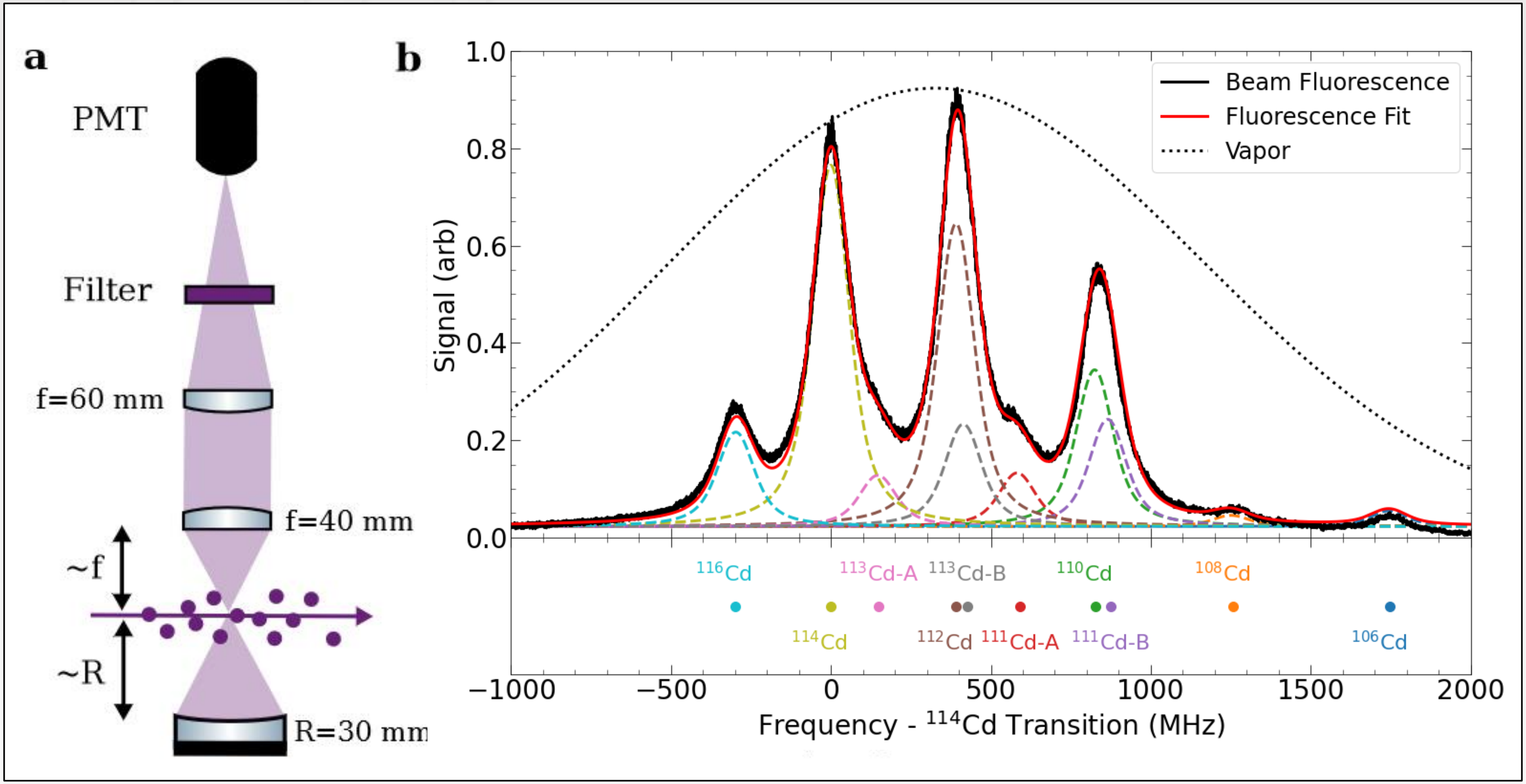
- Sr & Cd cooling transition wavelenghts addressed

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

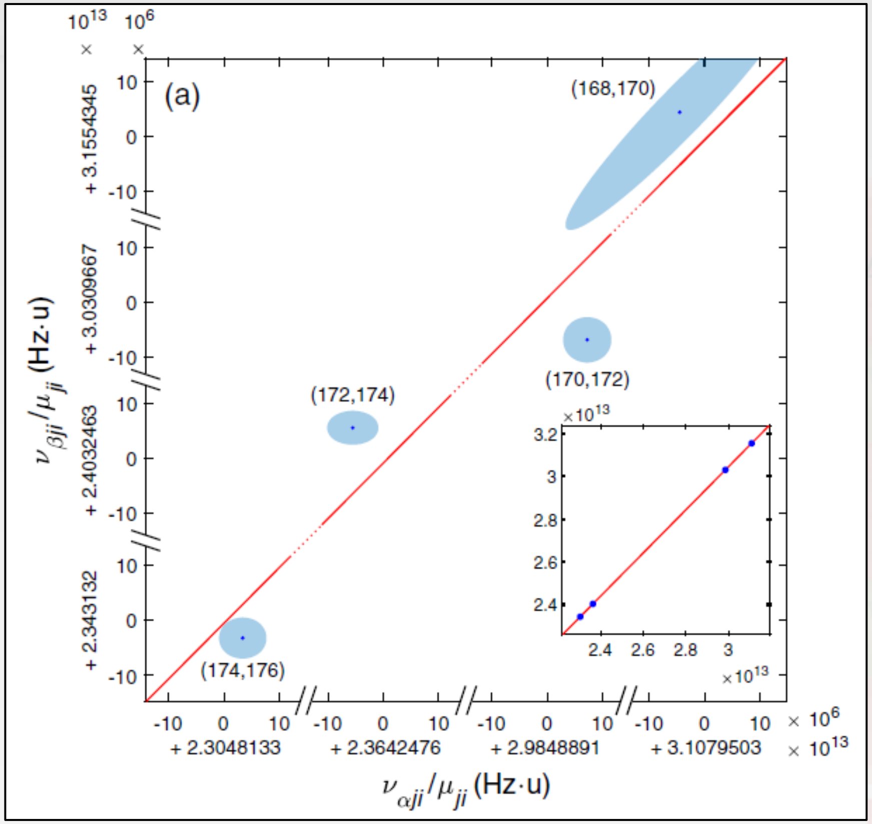


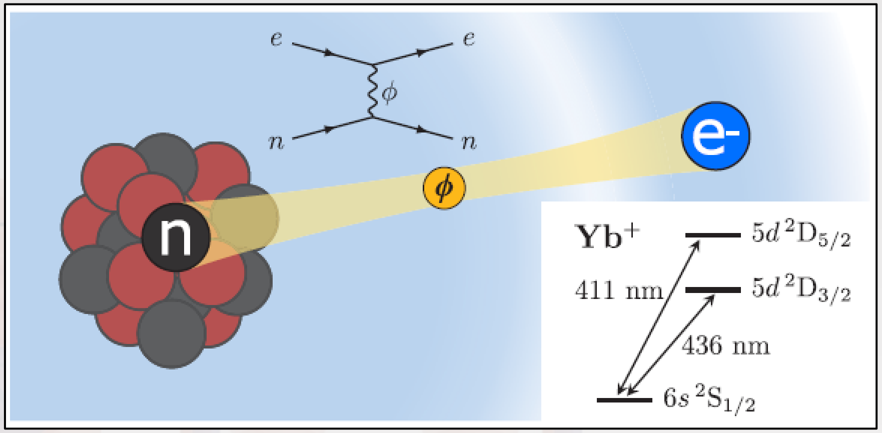
Cd atomic beam spectroscopy

Transition	Determination 1 [38]	Determination 2 [38]	This work / MHz
^{106}Cd	-	-	1748.1 ± 5.2 ± 9.7
^{108}Cd	-	-	1258.5 ± 5.3 ± 7.0
^{110}Cd	878 ± 17	905 ± 35	826.2 ± 4.2 ± 4.6
^{111}Cd - F′=1/2	-	-	591.5 ± 4,4 ± 3.3
^{111}Cd - F′=3/2	878 ± 17	-	874.7 ± 4.3 ± 4.8
^{112}Cd	375 ± 15	395 ± 30	391.6 ± 4.0 ± 2.2
^{113}Cd - F′=1/2	-	-	148.0 ± 4.2 ± 0.8
^{113}Cd - F′=3/2	375 ± 15	-	426.5 ± 4.5 ± 2.4
^{116}Cd	-	-	-298.7 ± 4.0 ± 1.7

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)

King's Plots



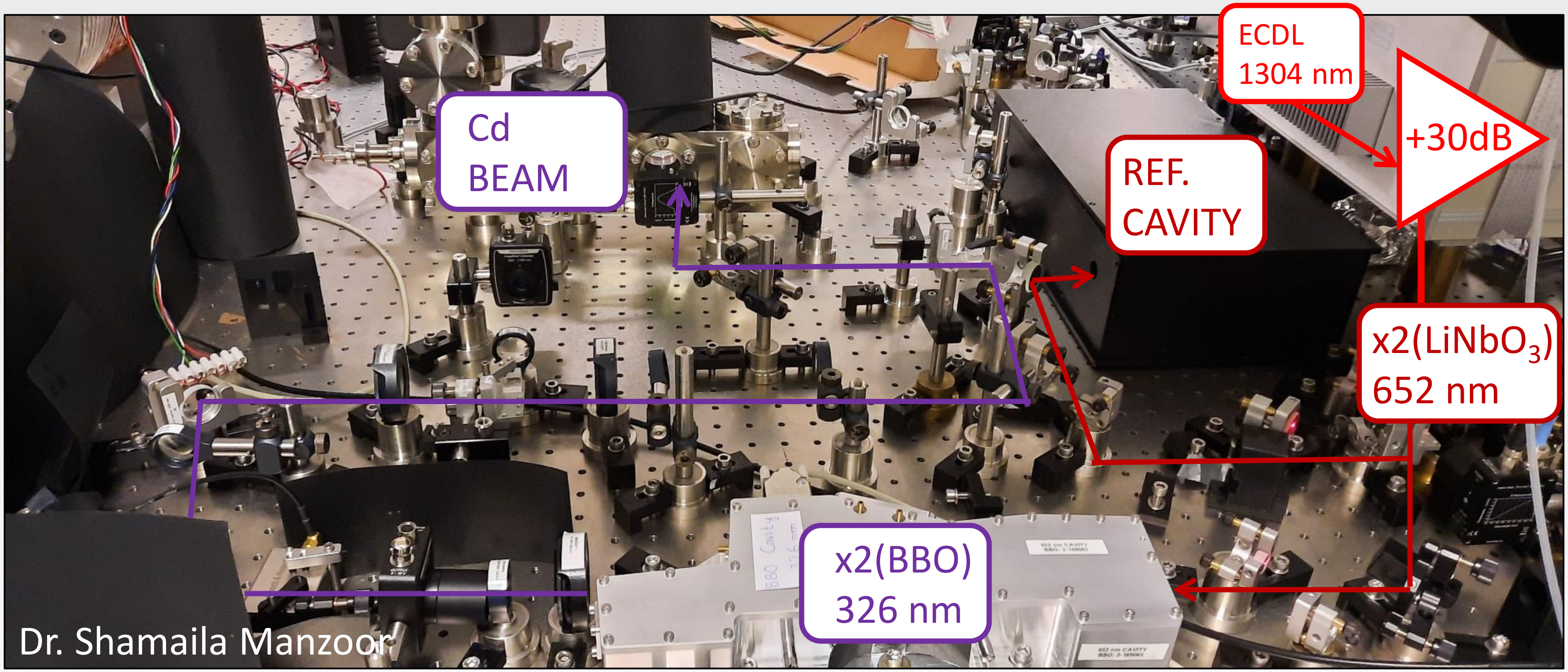


Isotope	Abundancy	Nuclear Spin	Mass (u.m.a.)
^{106}Cd	1.25%	0	105.906
^{108}Cd	0.89%	0	107.904
^{110}Cd	12.49%	0	109.903
^{111}Cd	12.80%	1/2	110.904
^{112}Cd	24.13%	0	111.903
^{113}Cd	13.47%	1/2	112.904
^{114}Cd	28.73%	0	113.903
^{116}Cd	7.49%	0	115.905

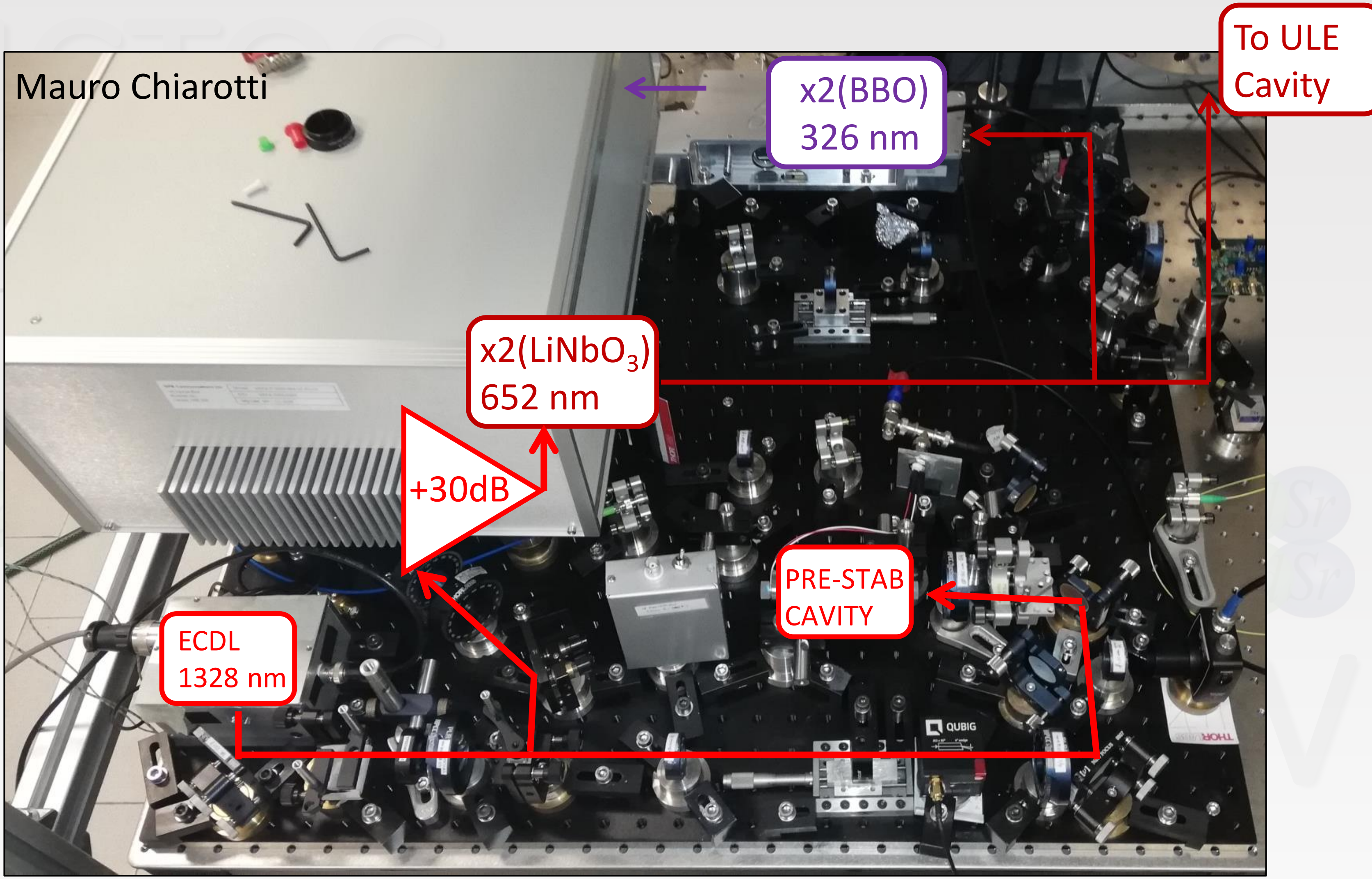
I.Counts "Evidence for Nonlinear Isotope Shift in Yb+ Search for New Boson", Phys Rev Lett 125, 123002 (2020)

Cd 326 nm laser source

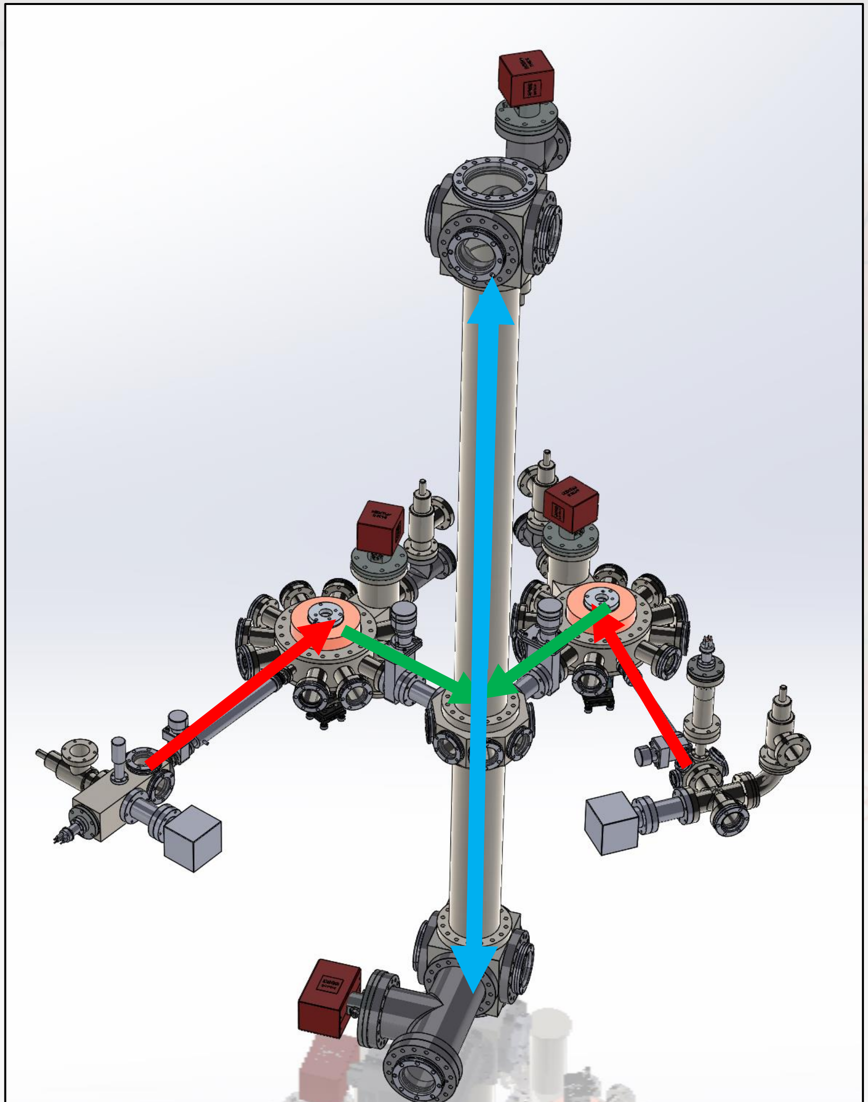
- precision spectroscopy & laser cooling on 3P1 intercombination transition



Cd 332 nm clock source



A new Cd-Sr system

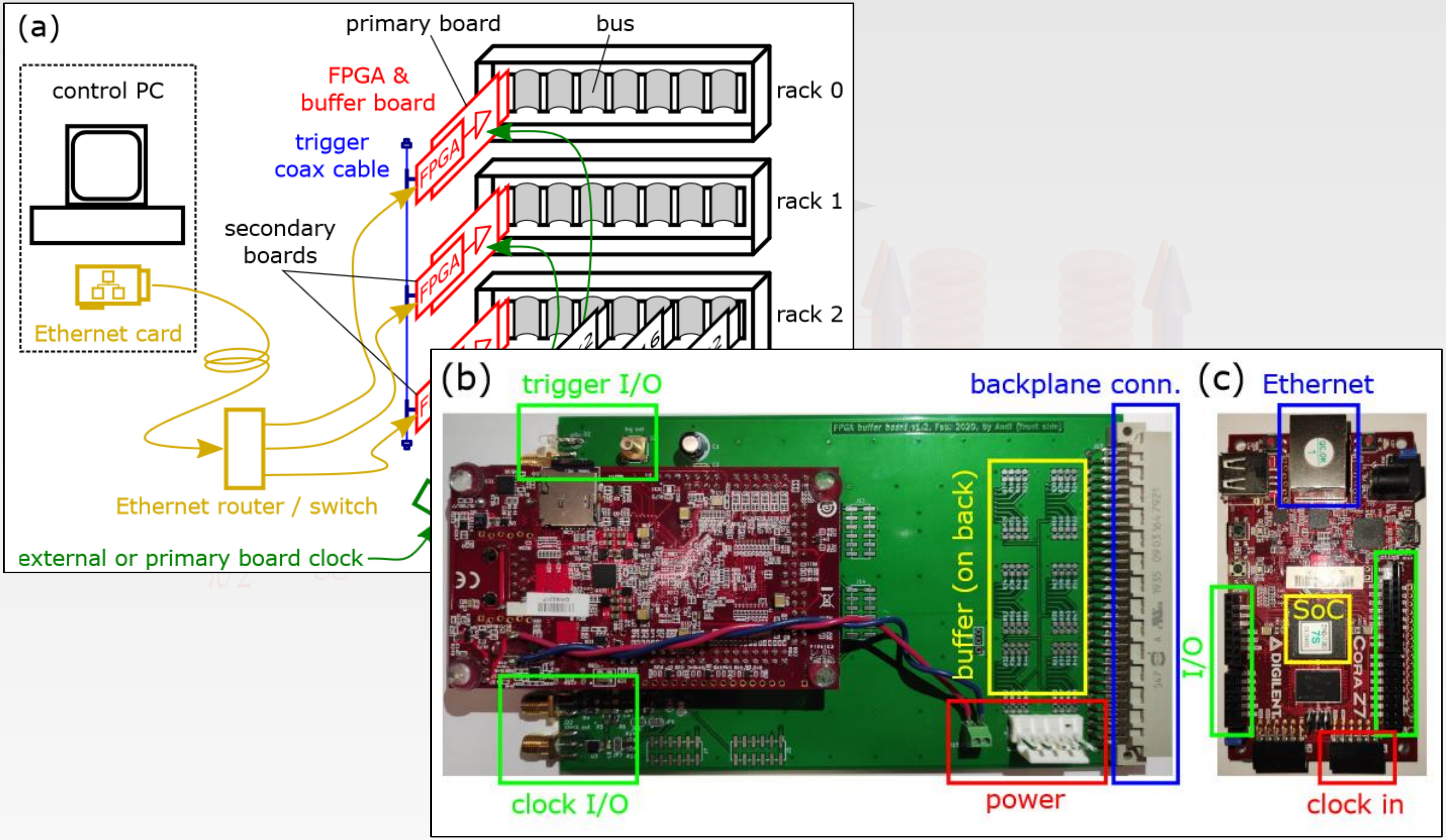


- 2m fountain for Cd & Sr

- Cd & Sr loaded from slowed atomic beams in separated MOT

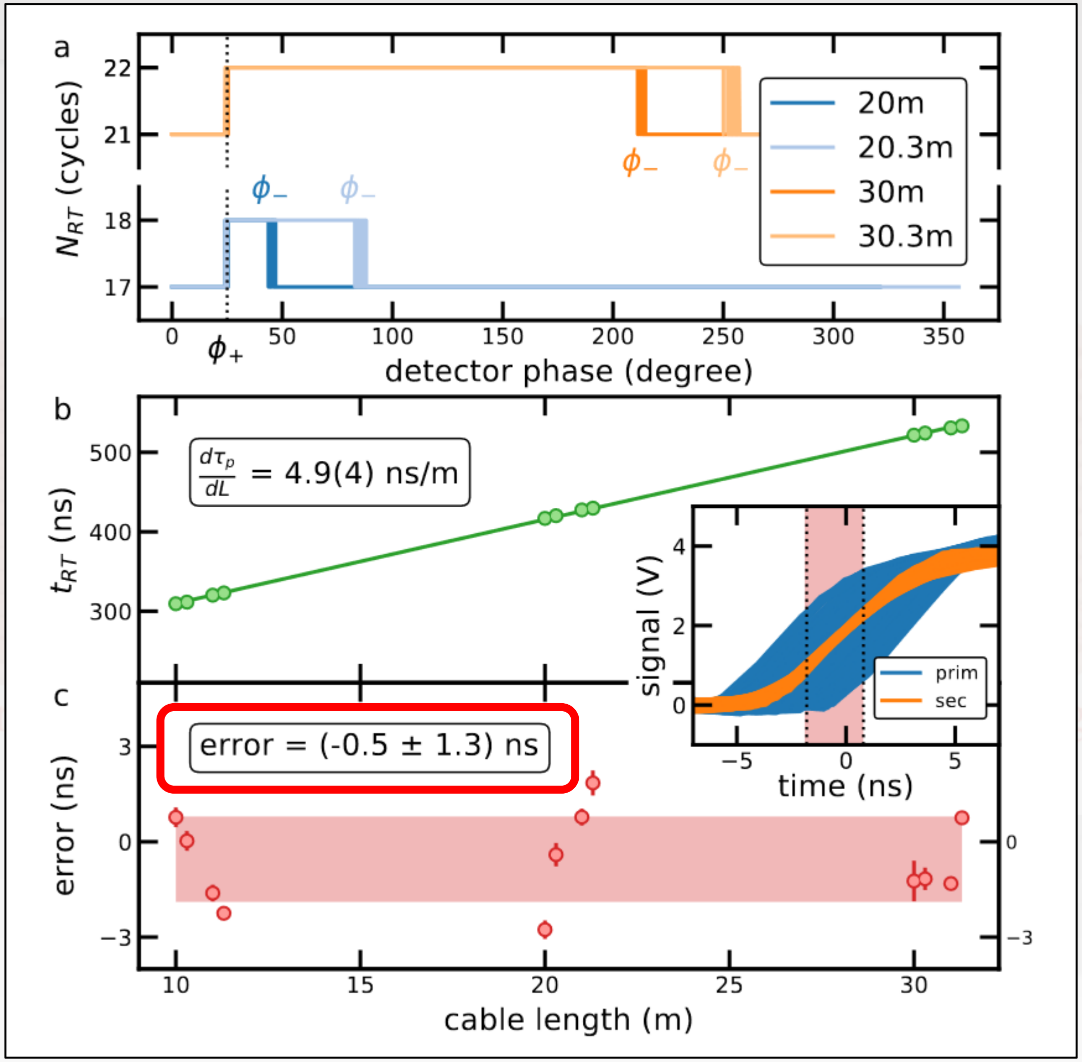
- optical dipole traps to transfer the atoms at the center of the fountain tube

FPGA-SOC based control system for AMO physics experiments



A. Trenkwalder, M. Zaccanti, N. Poli, "A flexible control system for atomic, molecular and optical physics experiments", arXiv:2106.02889 (2021)

FPGA-SOC based control system for AMO physics experiments



A. Trenkwalder, M. Zaccanti, N. Poli, "A flexible control system for atomic, molecular and optical physics experiments", arXiv:2106.02889 (2021)

Sr – Cd interferometer

European Research Council
Established by the European Commission

TICTOC GRAV

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/