PRECISION TEST OF FUNDAMENTAL PHYSICS WITH MATTER-WAVE INTERFEROMETERS

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UNIVERSITÀ DEGLI STUDI FIRENZE

lens European Laboratory for Non-Linear Spectroscopy

erc European Research Council

TICTOC GRAV

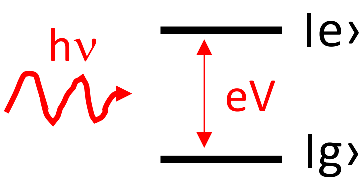
UVQuanT

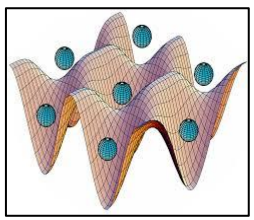
Monday 10th February 2025

TIME

Optical atomic clocks

internal d.o.f., electronic states



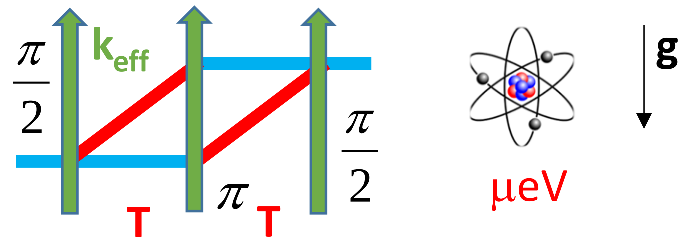


relative precision $<10^{-20}$

GRAVITY

Atom interferometers (gravimeters/gradiometers)

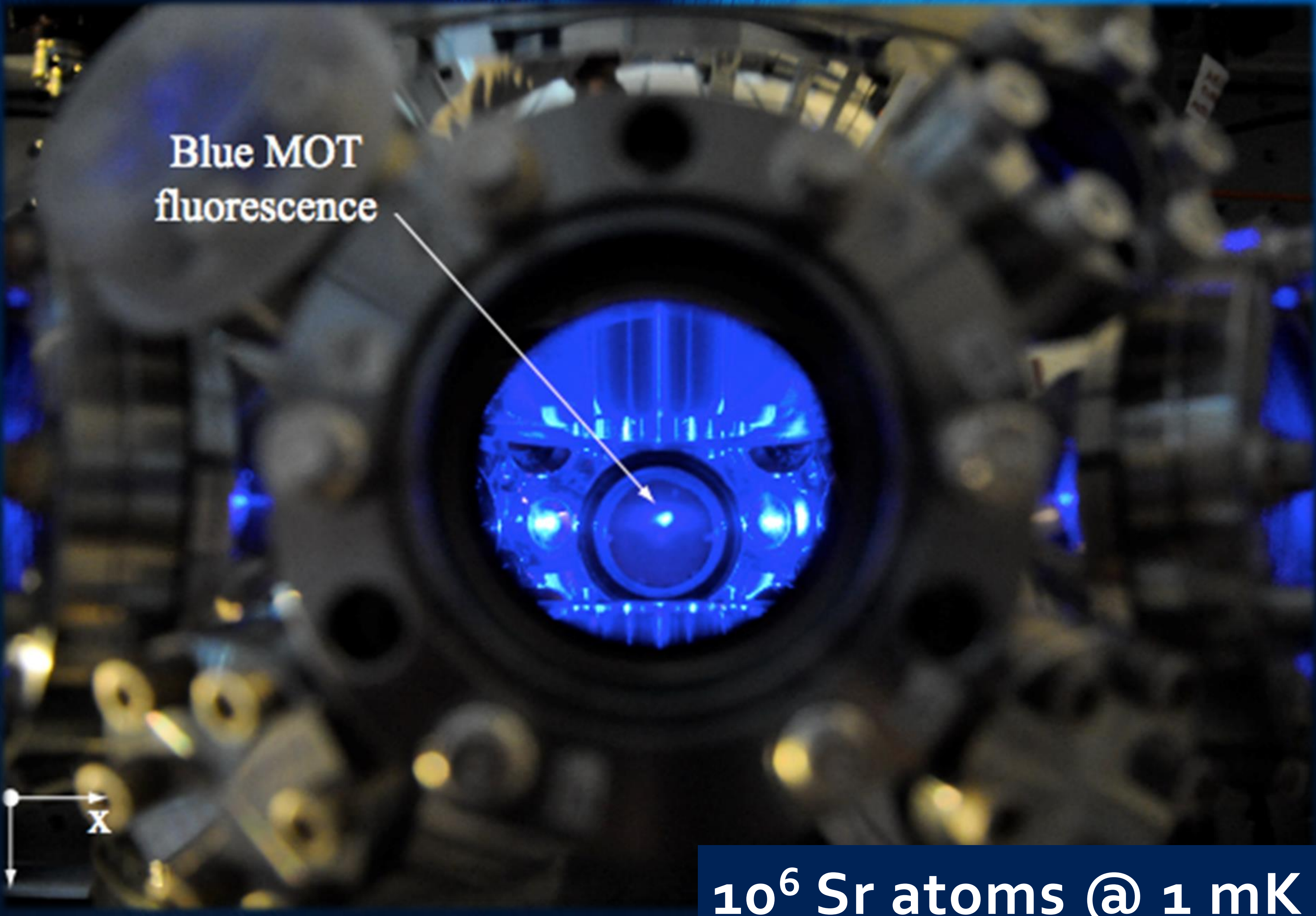
external d.o.f., momentum states



relative precision $< 10^{-11}$ g

Table-top, low-energy experiments, high precision

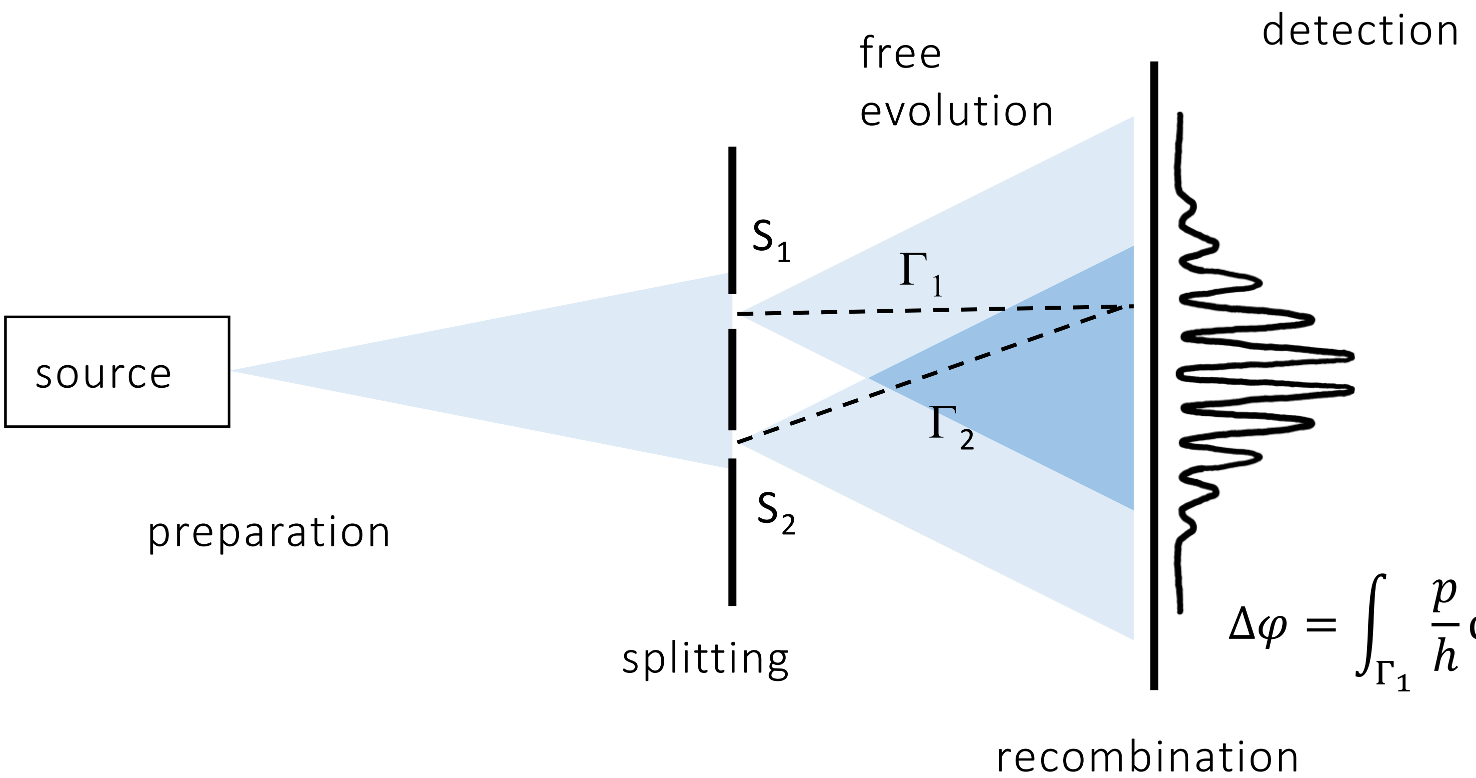
Ultracold Sr atoms



10^6 Sr atoms @ 1 mK

INTERFERENCE OF MATTER WAVES

Young's double-slit experiment



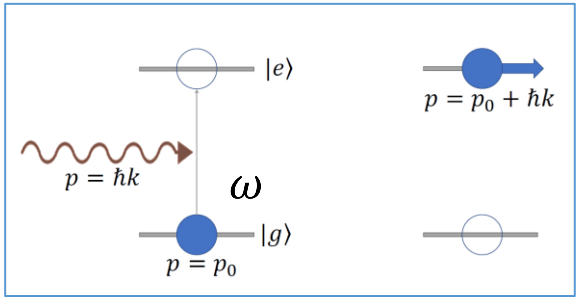
$$\Delta\varphi = \int_{\Gamma_1} \frac{p}{h} \mathrm{d}z - \int_{\Gamma_2} \frac{p}{h} \mathrm{d}z$$

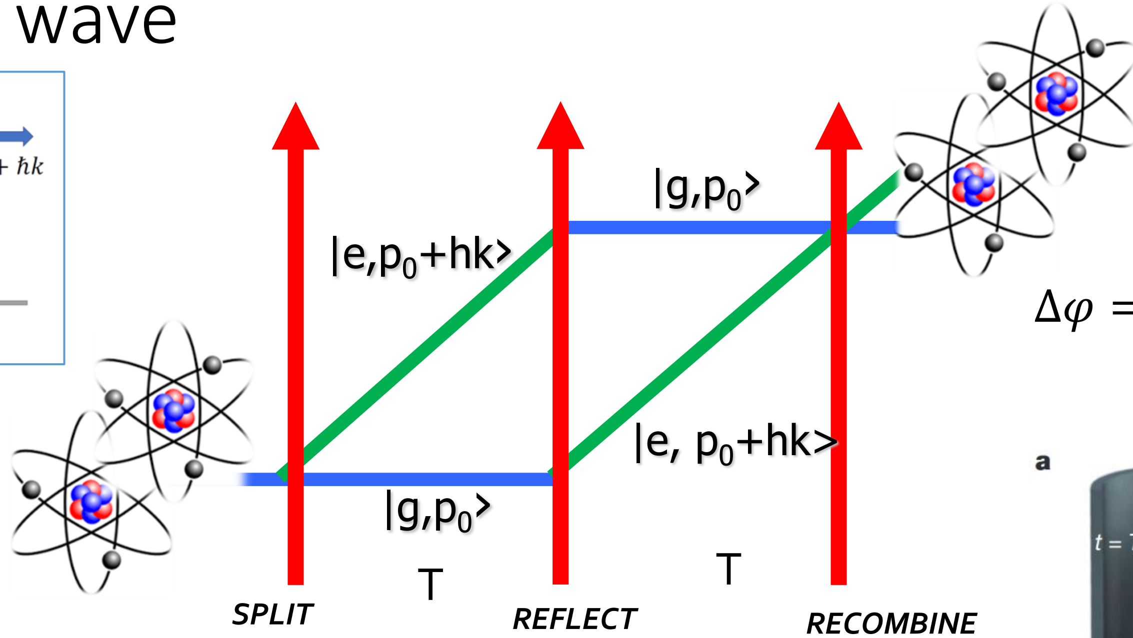
Matter Wave Interferometry = *art* of coherently splitting, reflecting, and recombining *matter waves*

A. D. Cronin, J. Schmiedmayer, D. E. Pritchard, Rev. Mod. Phys. **81**, 1051 (2009)

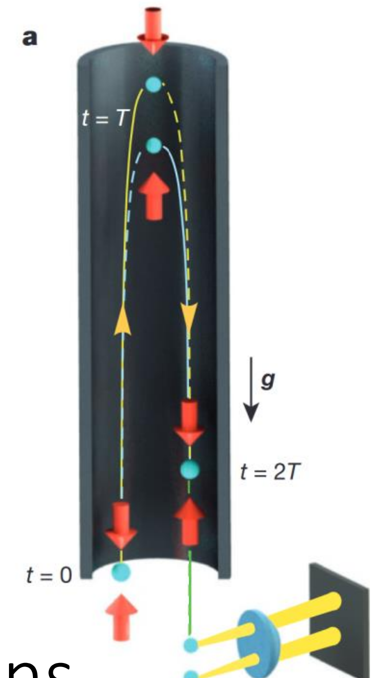
Atom Interferometers

light → matter wave



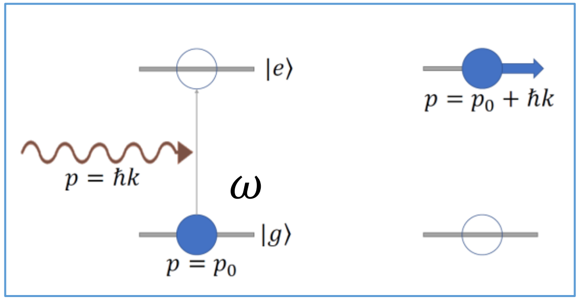


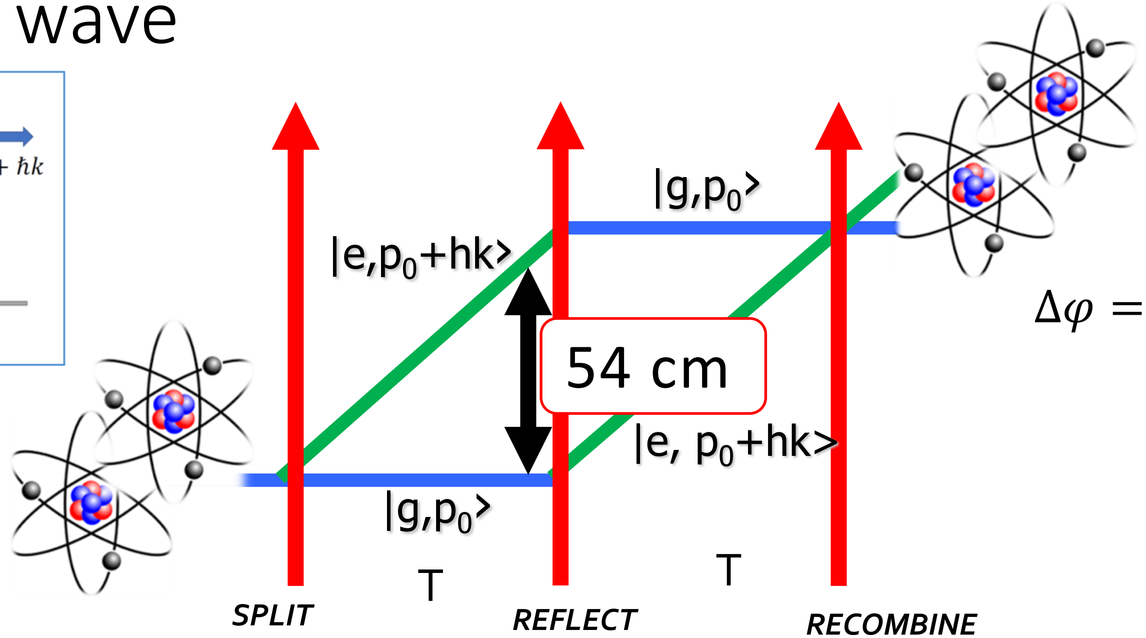
$$\Delta\varphi = \varphi_1 - \varphi_2$$



Atomic fountains

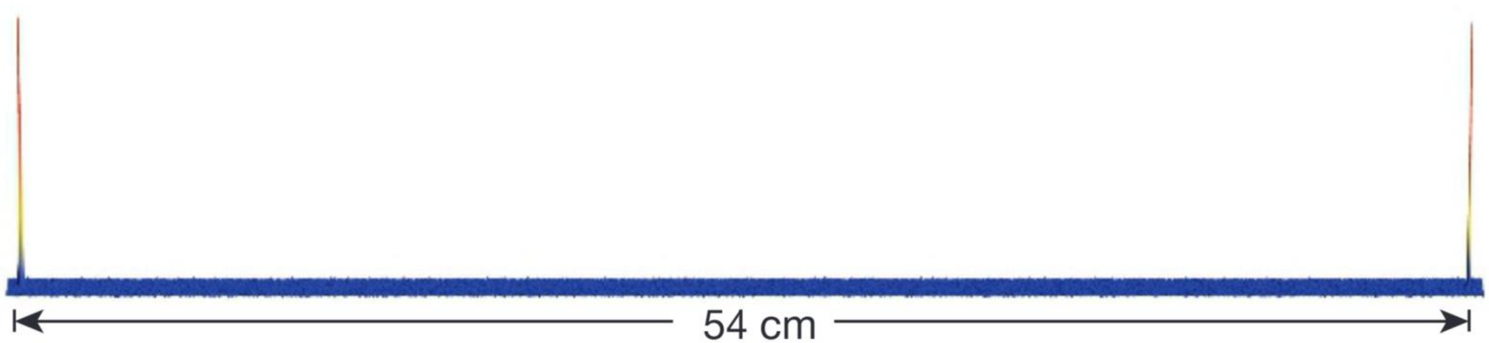
light → matter wave





$$\Delta\varphi = \varphi_1 - \varphi_2$$

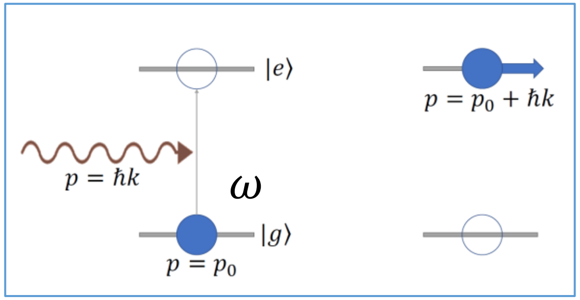
half-meter wave packet separation

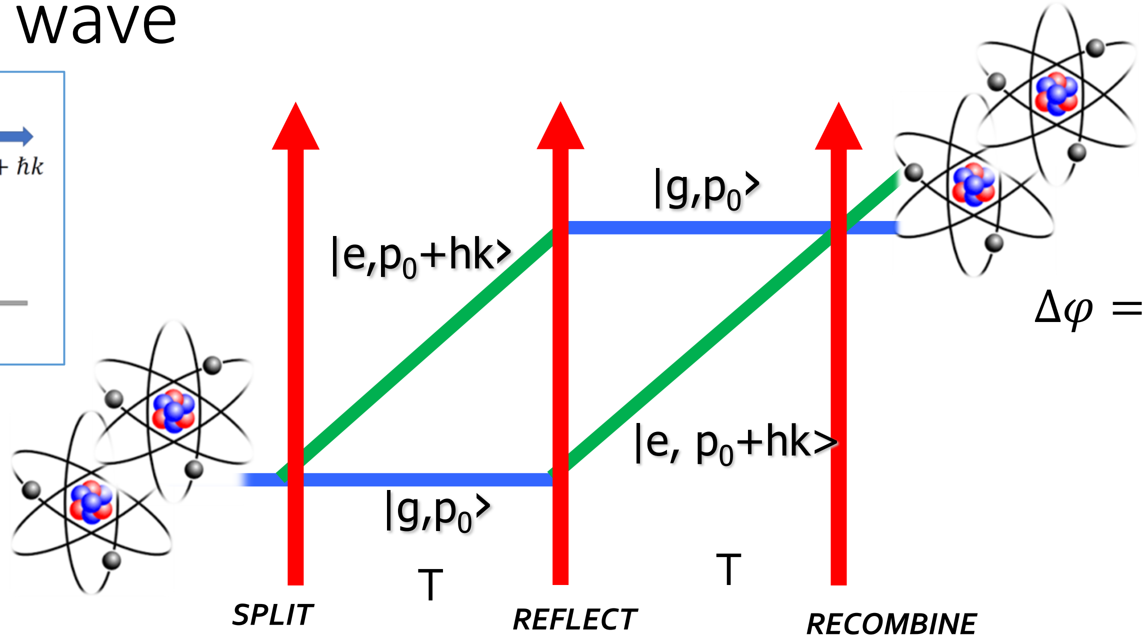


T. Kovachy et al Nature **528**, 530 (2015)

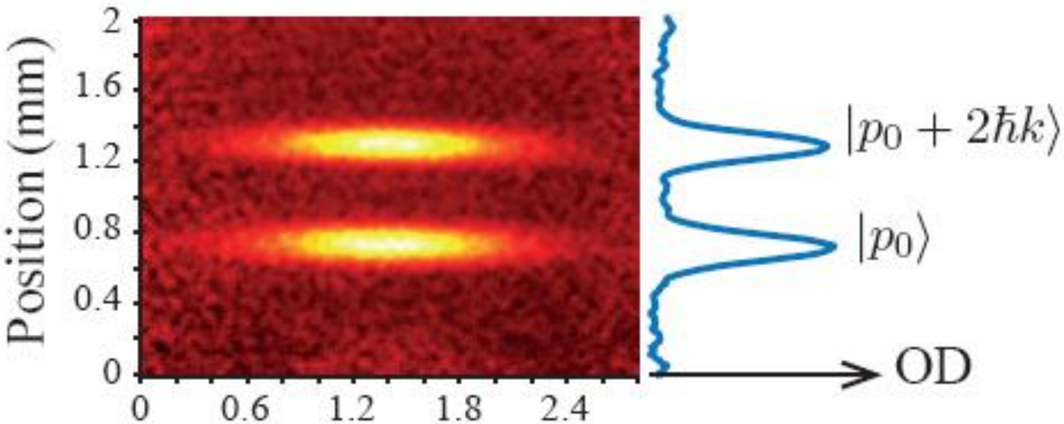
Atom Interferometers

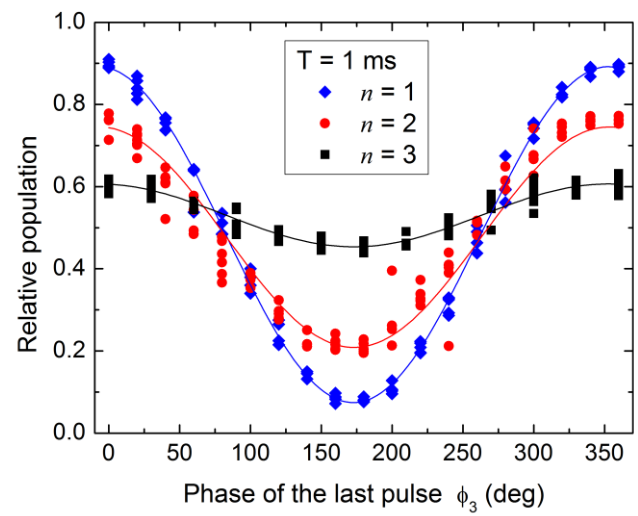
light ➡ matter wave





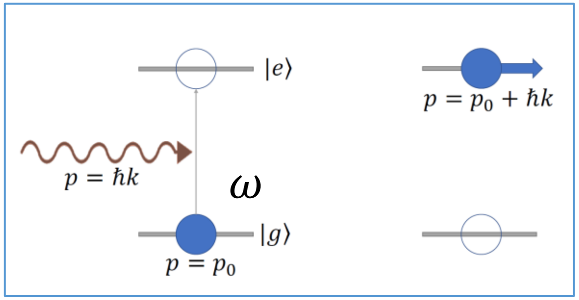
$$\Delta\varphi = \varphi_1 - \varphi_2$$

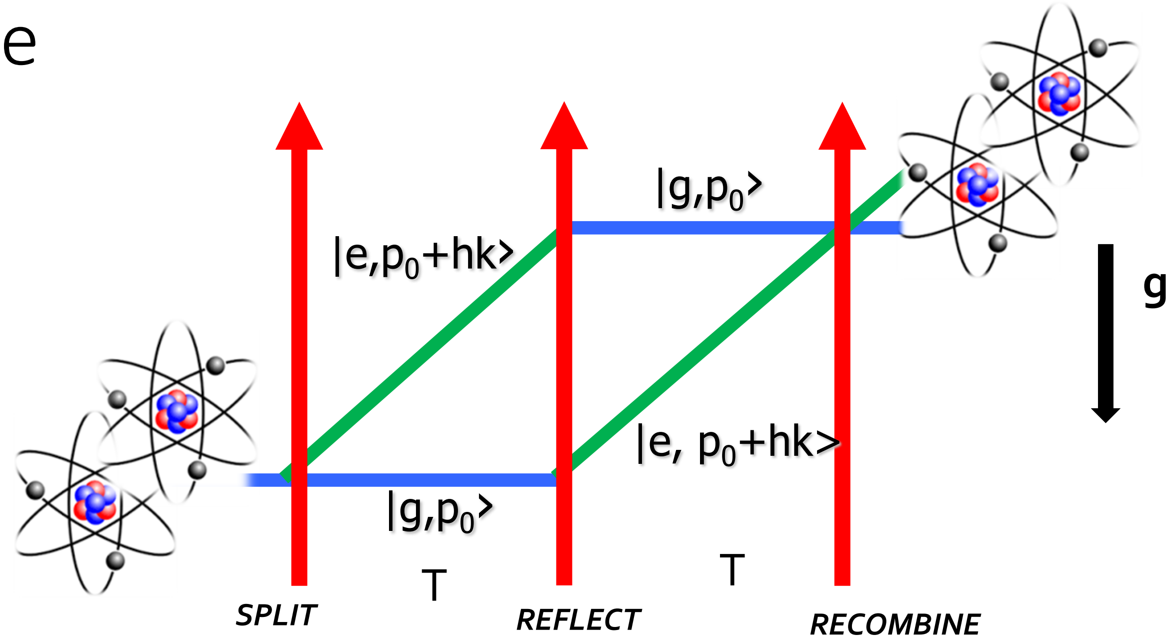




Atom Interferometers - Gravimeters

light → matter wave





- ✓ Sensitivity

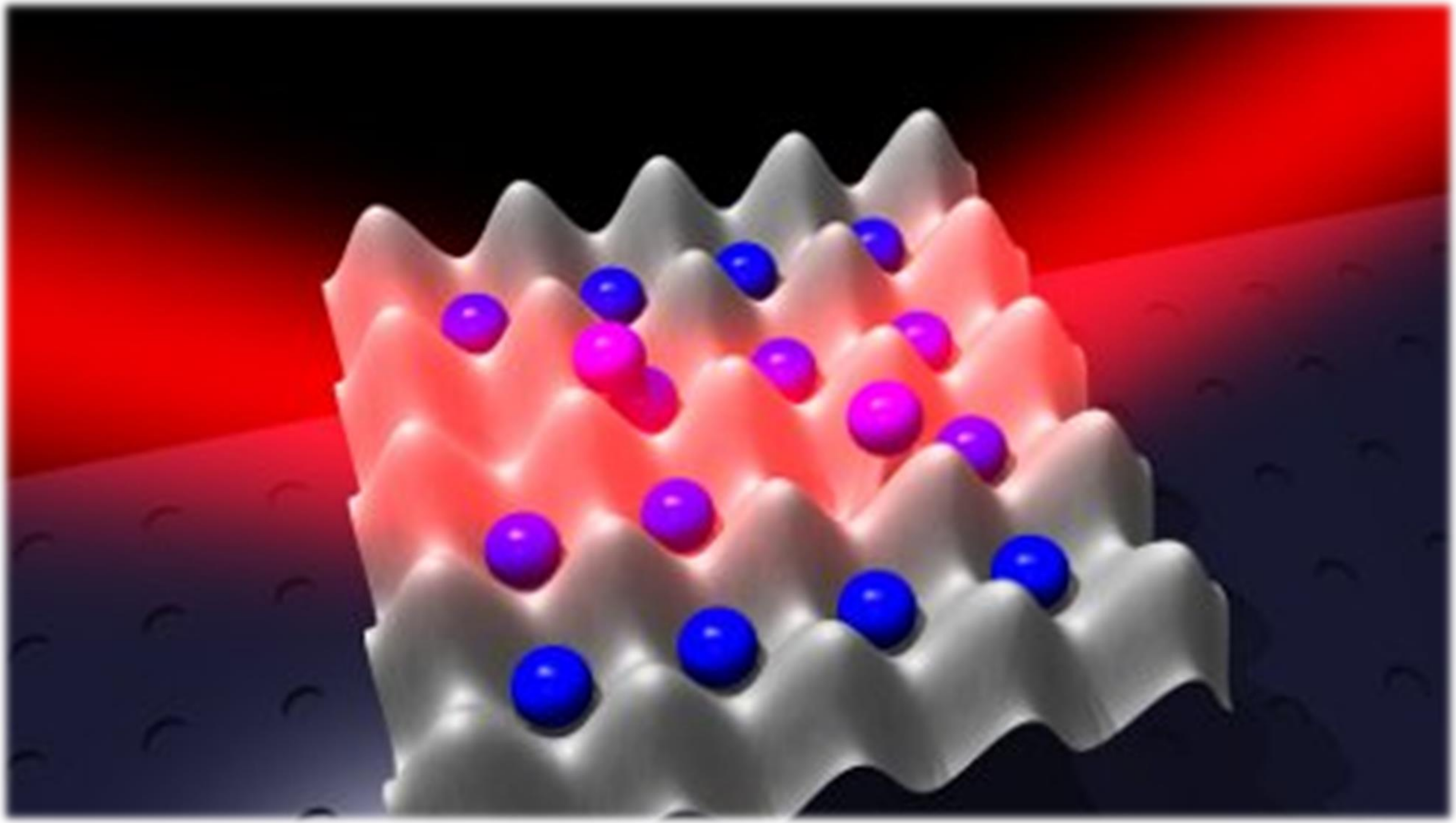
~1 mrad

$$\frac{\Delta g}{g} = \frac{\Delta \Phi}{\Phi} = \frac{\Delta \Phi}{k_{eff}\, g T^2} \quad \sim 10^{-10}/g$$

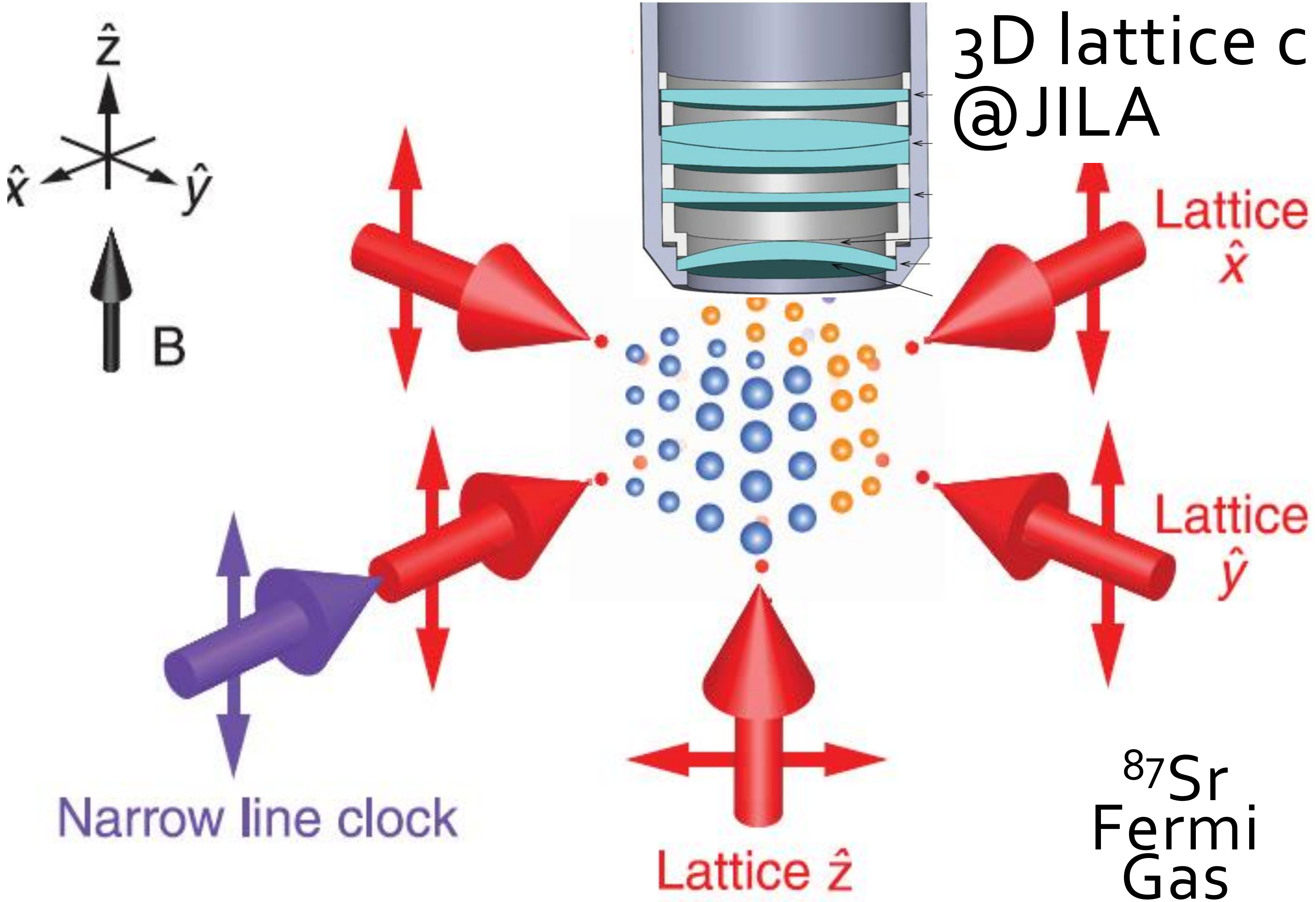
~107 m^{-1} ~1 s

Rb, Cs, …

IMAGING OPTICAL FREQUENCIES



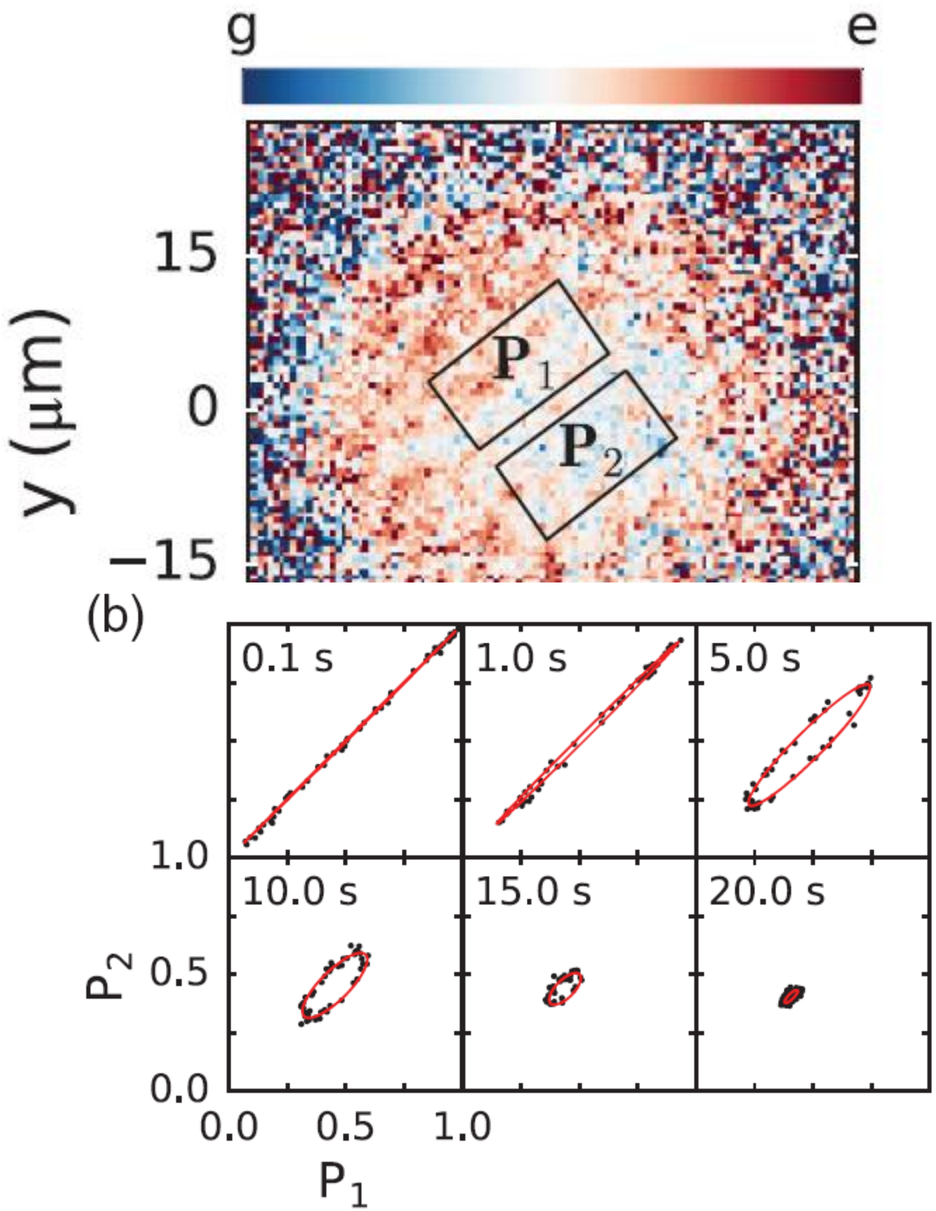
IMAGING OPTICAL FREQUENCIES



3D lattice clock @JILA

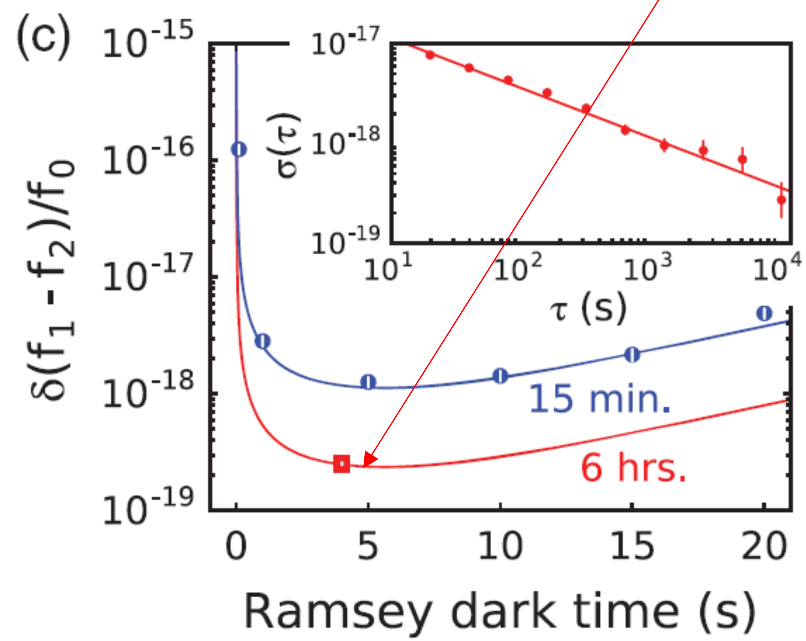
^{87}Sr Fermi Gas

IMAGING OPTICAL FREQUENCIES

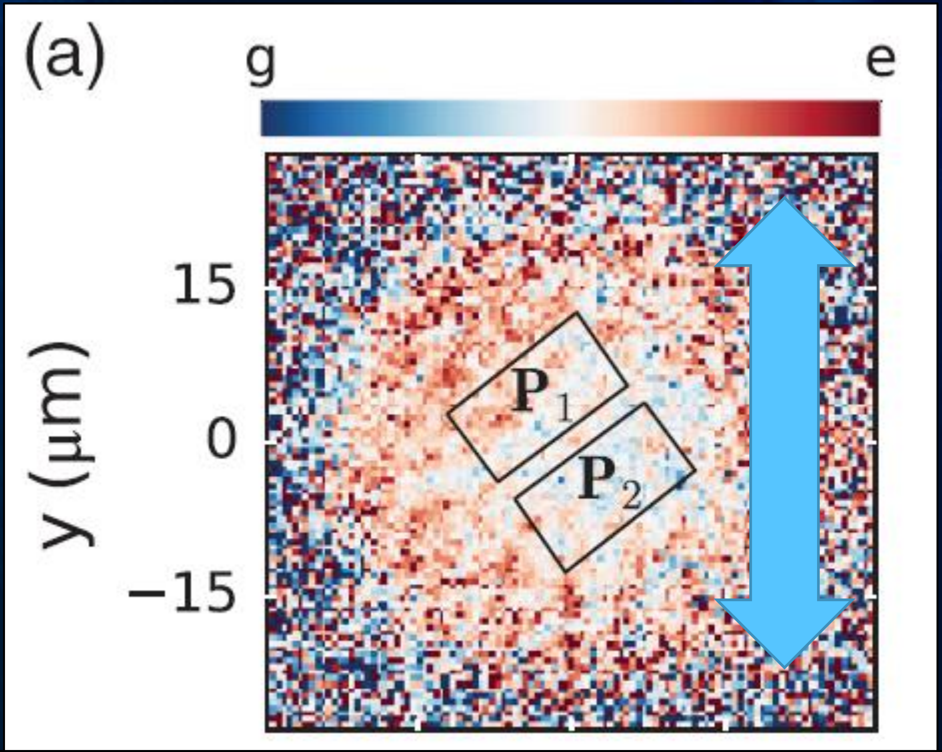


G. E. Marti, R. B. Hutson, A. Goban, S. L. Campbell, N. Poli, J. Ye, "Imaging optical frequencies with 100 μHz precision and 1.1 μm resolution", Phys. Rev. Lett. (2018)

2,5 10^{-19}



Gravitational Red Shift

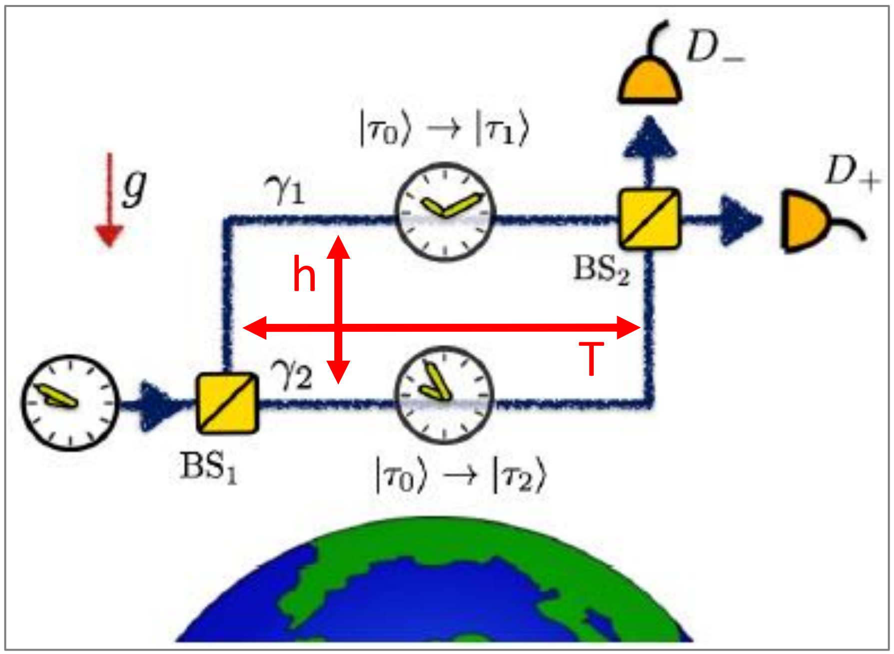


10 μm

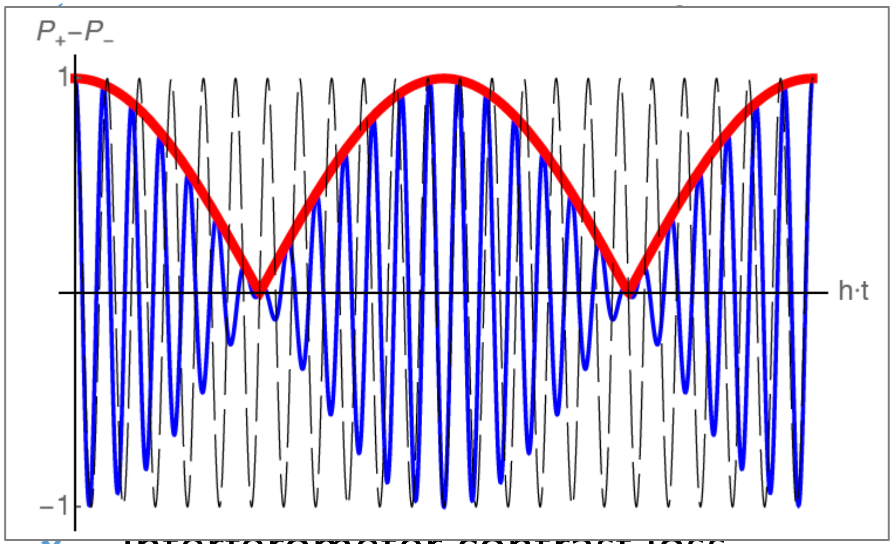
$\Delta\nu/\nu = 10^{-21}$

$\Delta\nu/\nu = 10^{-22}$
$\lambda_{dB} \approx 1$ μm @ 1nK

Observe gravity induced "decoherence" in clock interferometers

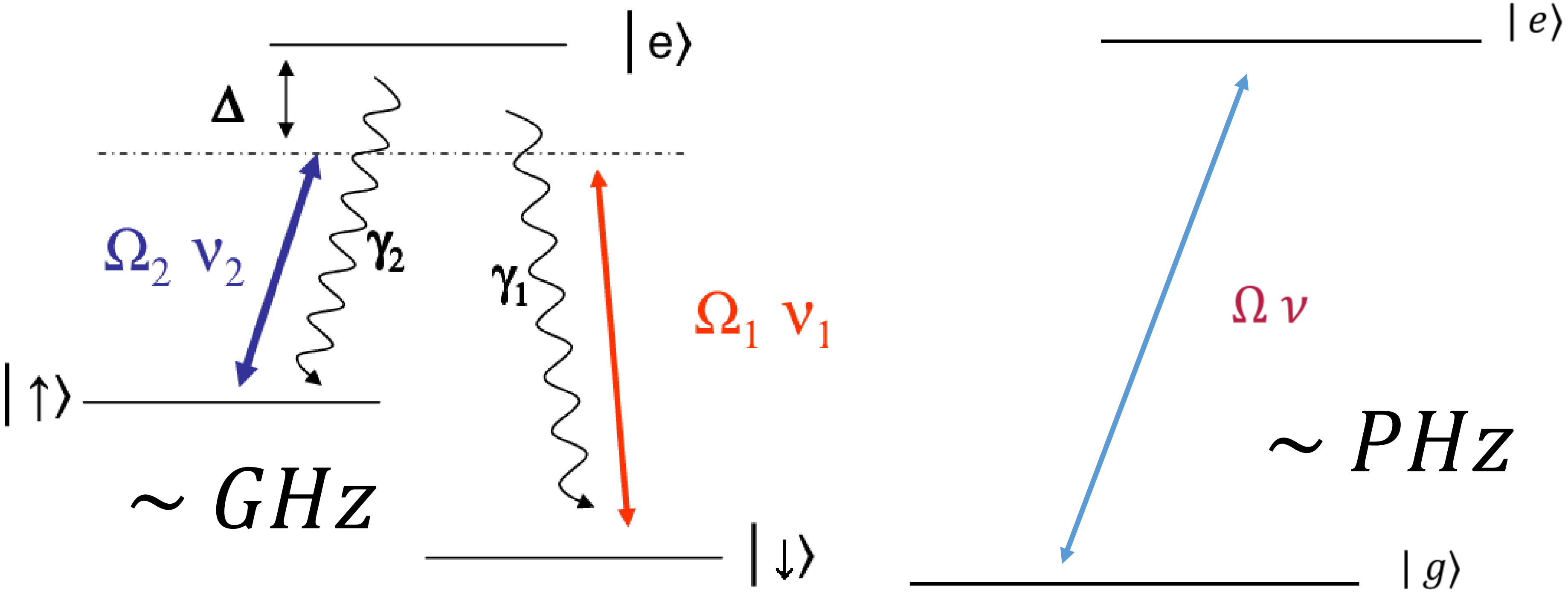


M. Zych et al. Nature Commun. 2(505), 1498 (2011)

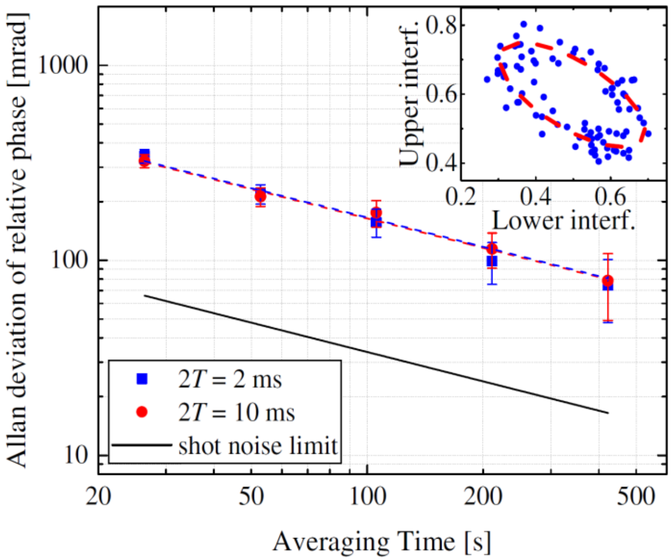


- ✓ interferometer contrast loss
- ✓ Decoherence induced by "which path" information from clock state

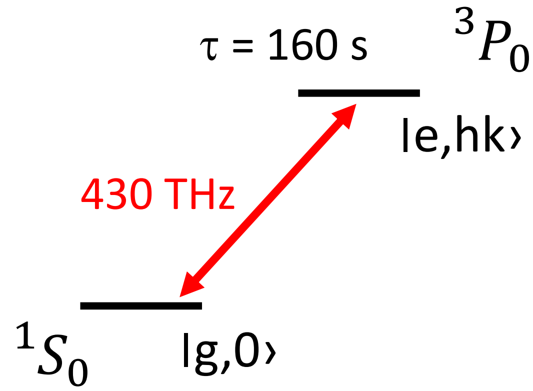
TWO PHOTONS (BRAGG-RAMAN) – SINGLE PHOTON



Clock Gradiometer Sr – 698 nm



L. Hu *et al., Phys. Rev. Lett.* **119** 263601 (2017)

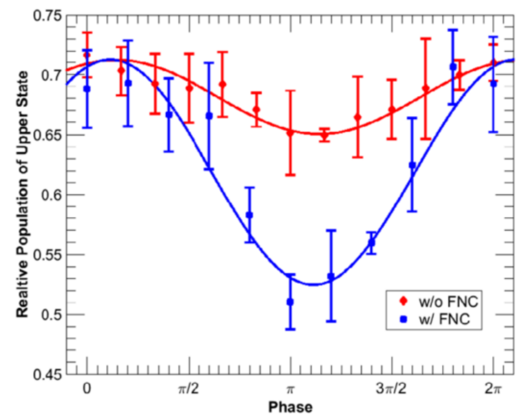


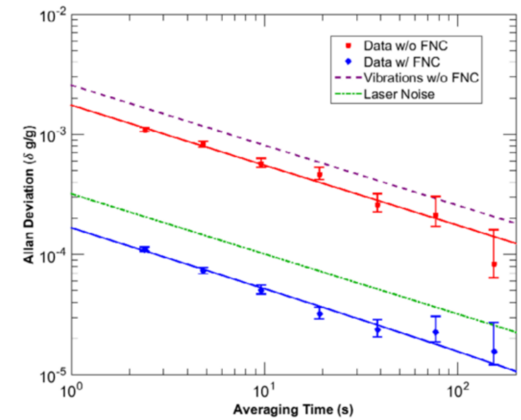
Single photon
(momentum states
+ electronic states)

100 m tower experiments
on Sr clock interferometry

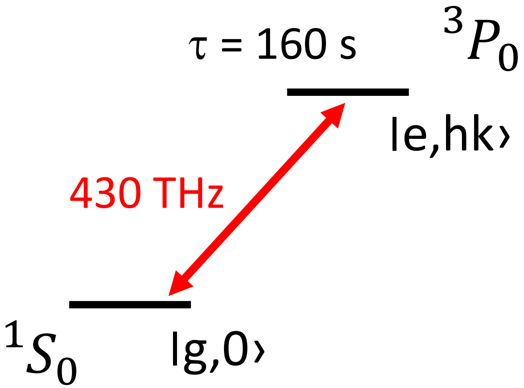
AION (UK),
MAGIS (USA),
…

Clock Gravimeter Sr – 698 nm

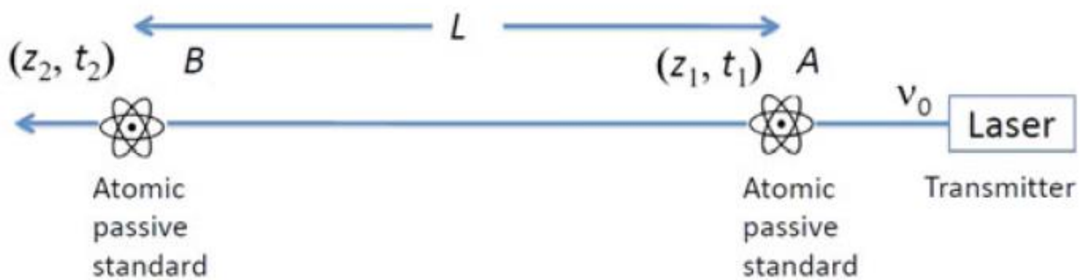




L. Hu *et al., Class. Quantum Grav.* **37** 014001 (2020)

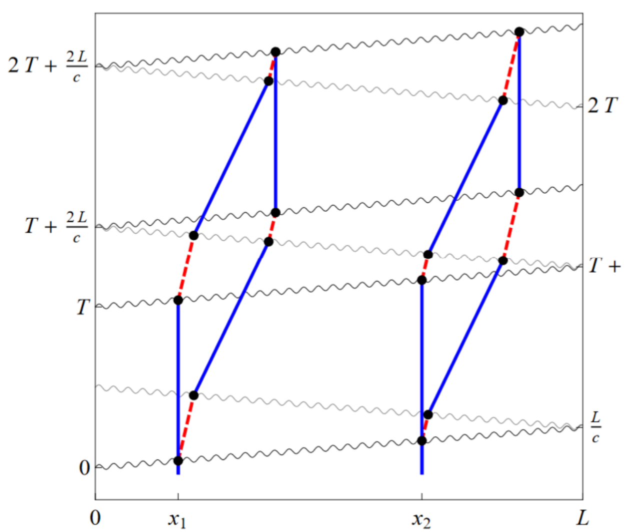


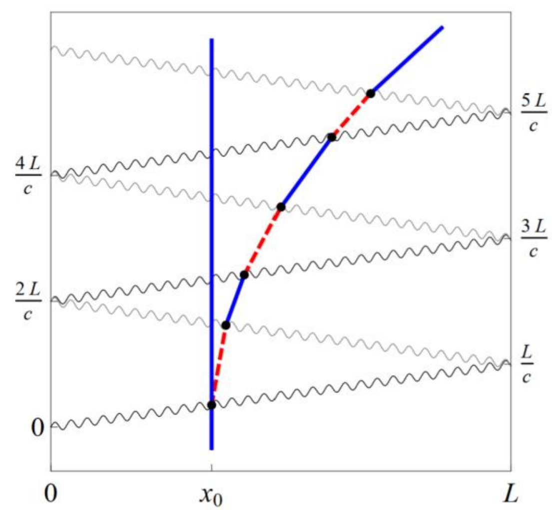
✓ A new GW Detector



N. Yu, M. Tinto, Gen. Relativ. Gravit. **43**, 1943 (2011)

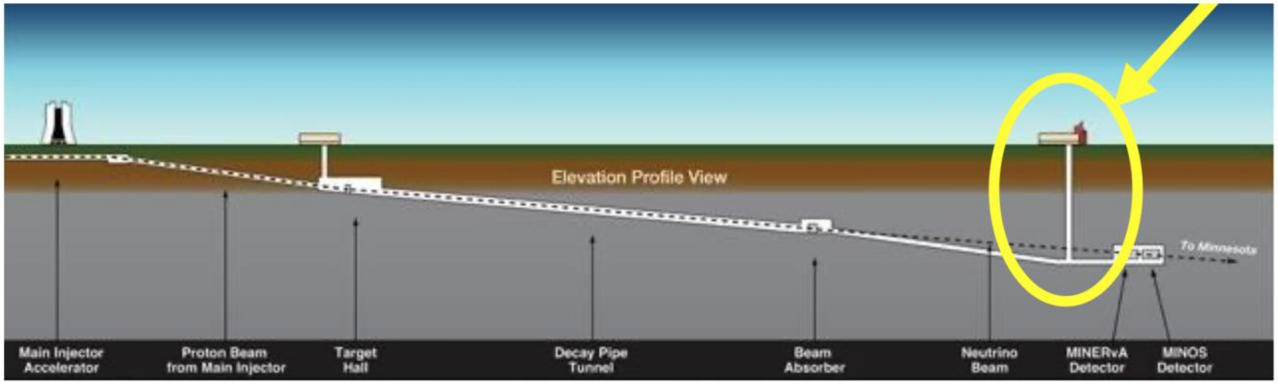
✓ LMT with strontium clock transition



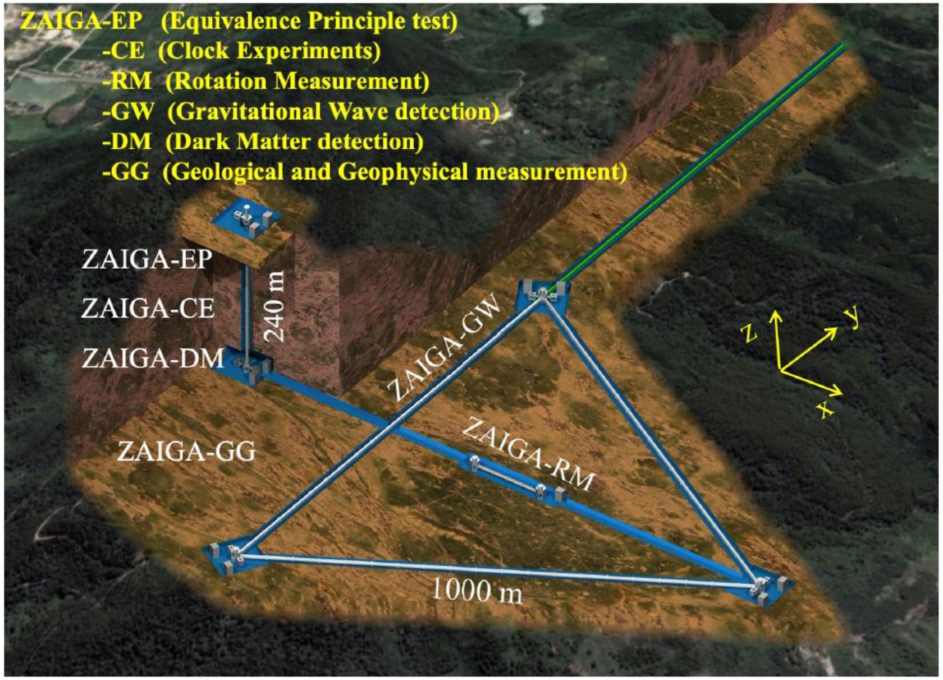


P. W. Graham, et al. Phys. Rev. Lett. **110**, 171102 (2013)

LARGE SCALE ATOM INTERFEROMETERS



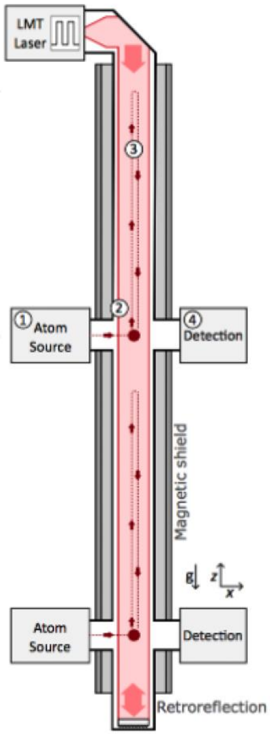
MAGIS 100 (Fermilab - USA)

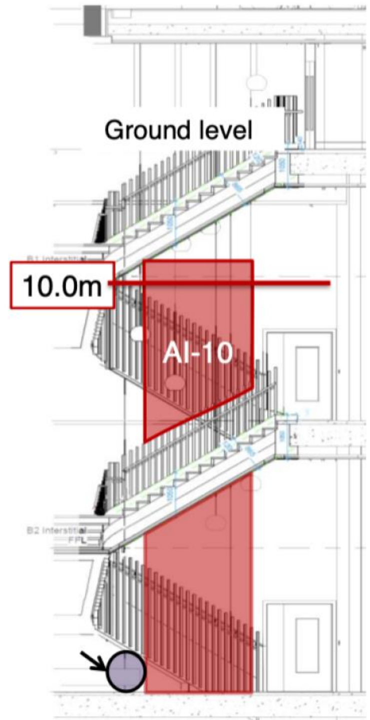


ZAIGA (Wuhan, CHN)

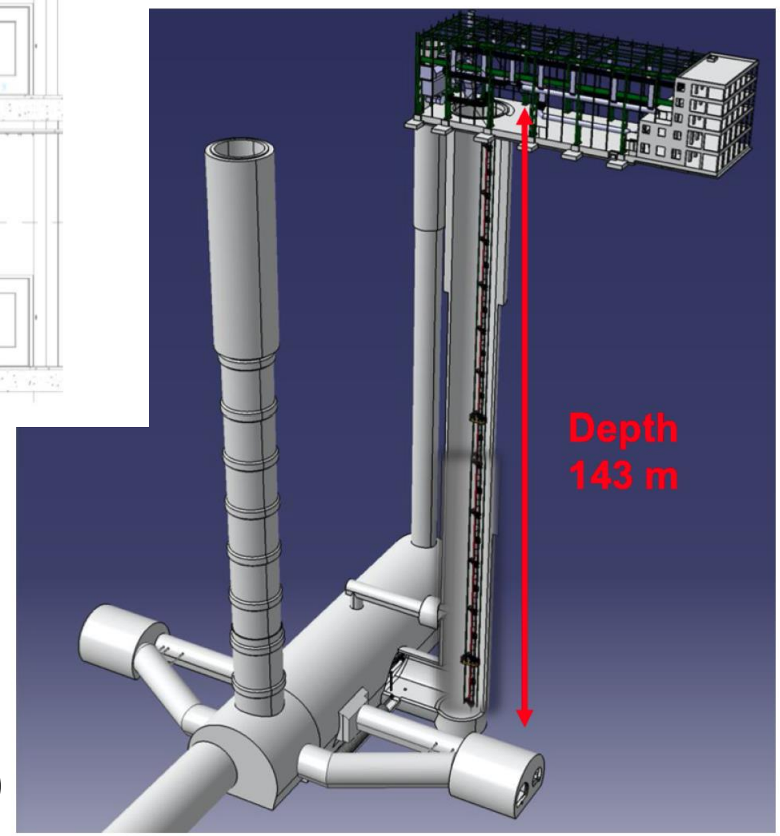
O. Buchmueller et al. *Contemporary Physics*, *64*(2), 93–110 (2023)

Large Fountains





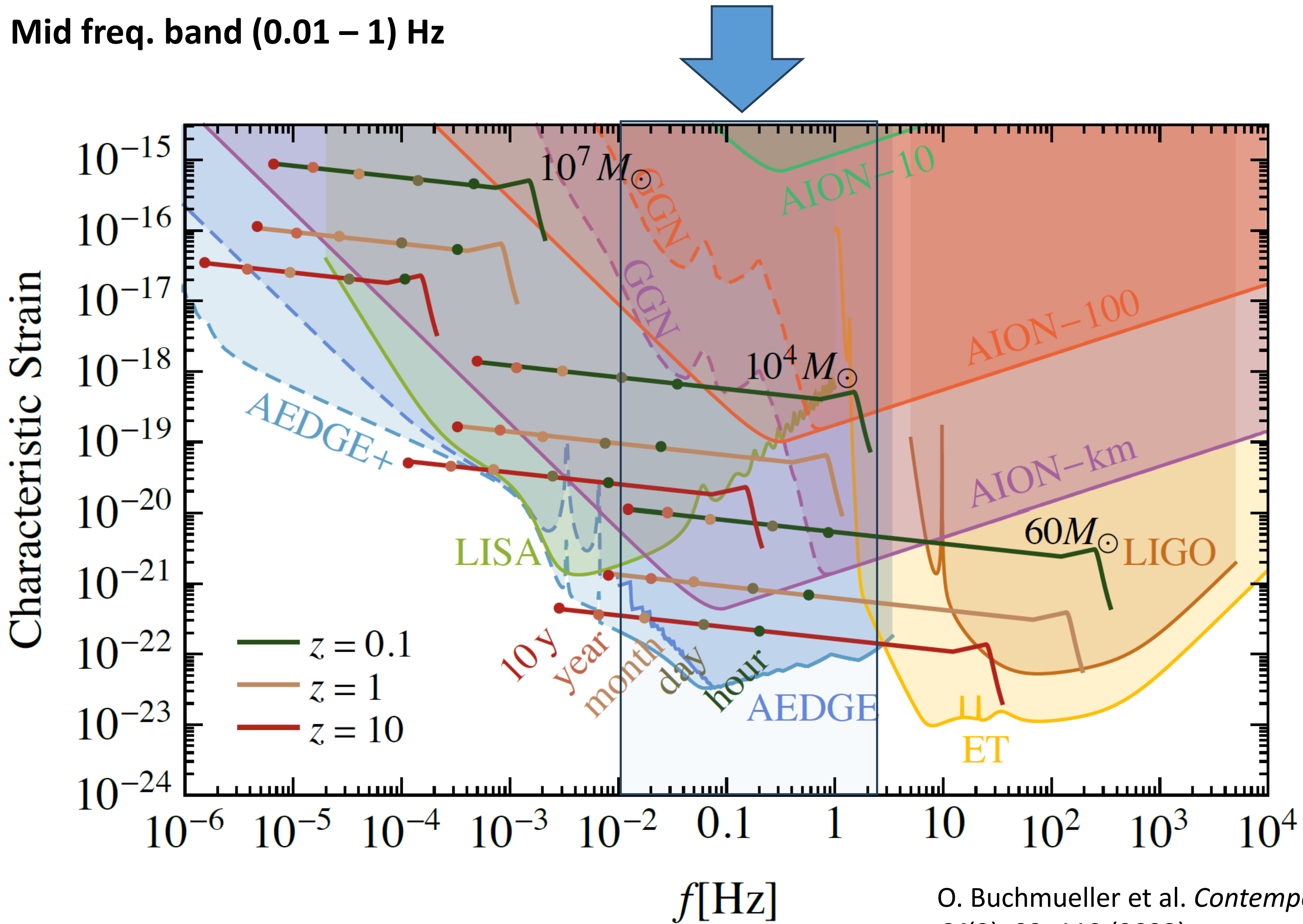
AION-10 (Oxford, UK)



O. Buchmueller et al. *Contemporary Physics*, *64*(2), 93–110 (2023)

AION 100 (CERN, CH)

Mid freq. band (0.01 – 1) Hz

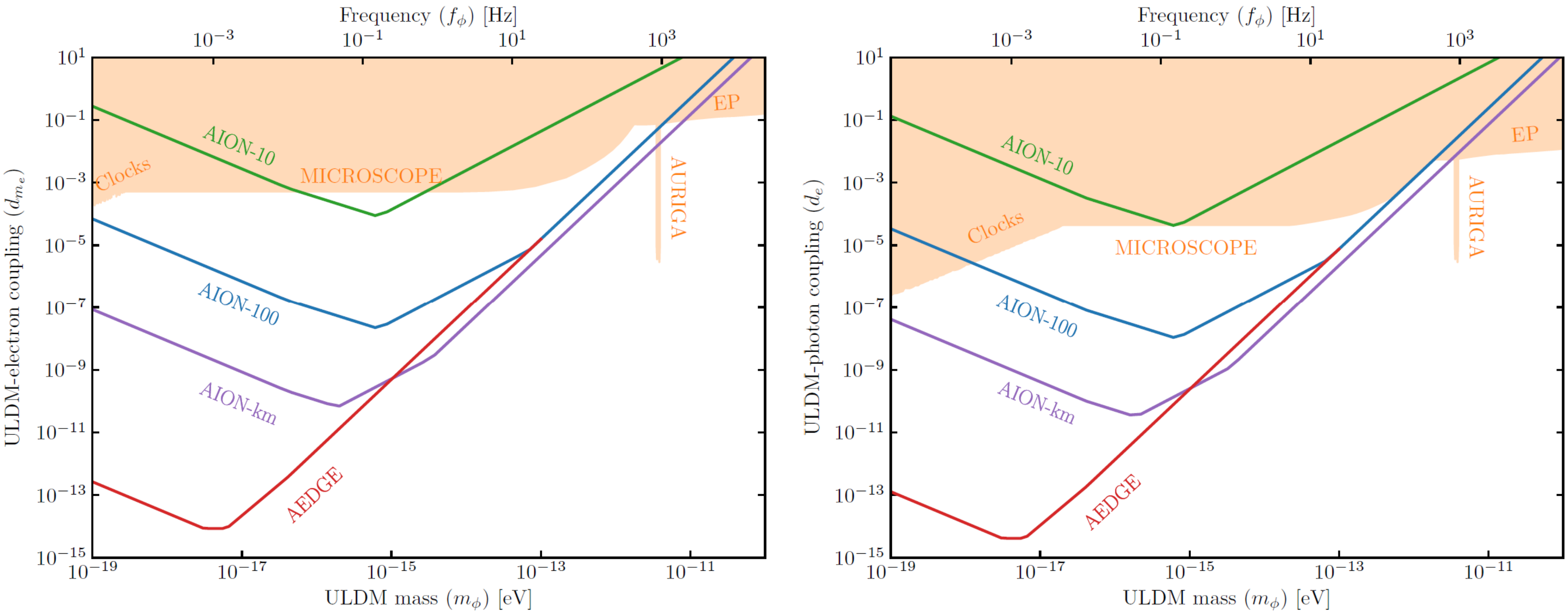


O. Buchmueller et al. *Contemporary Physics*, *64*(2), 93–110 (2023)

DARK MATTER SEARCH

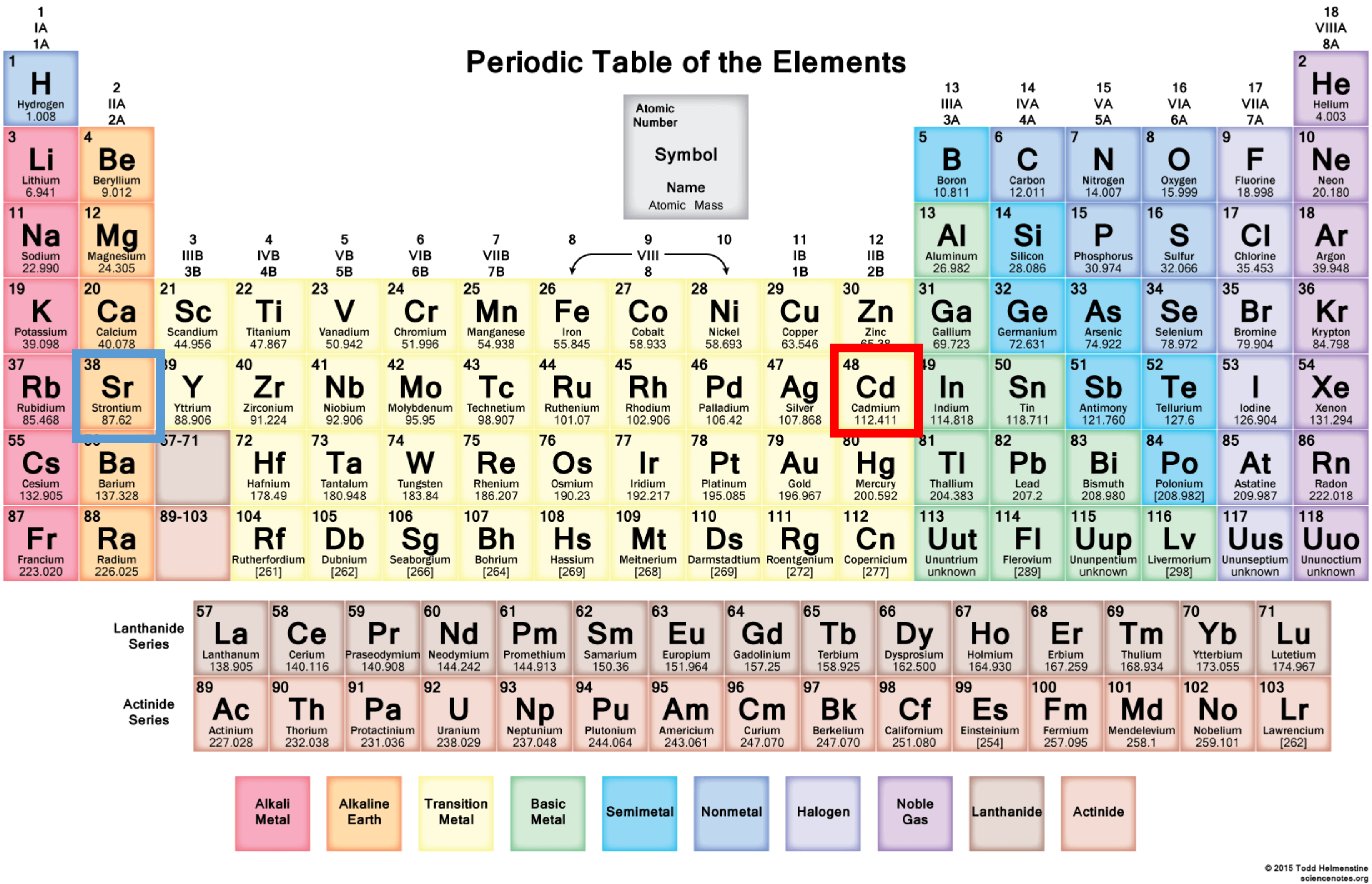
$$\mathcal{L}_{\rm int}^{\rm lin} \supset -\phi(\mathbf{x},t)\cdot\sqrt{4\pi G_{\rm N}}\cdot\left[d_{m_e} m_e \bar{e}e - \frac{1}{4} d_e F_{\mu\nu}F^{\mu\nu} + d_{m_q} m_q \bar{q}q\right] + b\,\phi(\mathbf{x},t)|H|^2$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{-i\omega T} \quad\rightarrow\quad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle e^{-i(\omega+\Delta\omega)T}$$



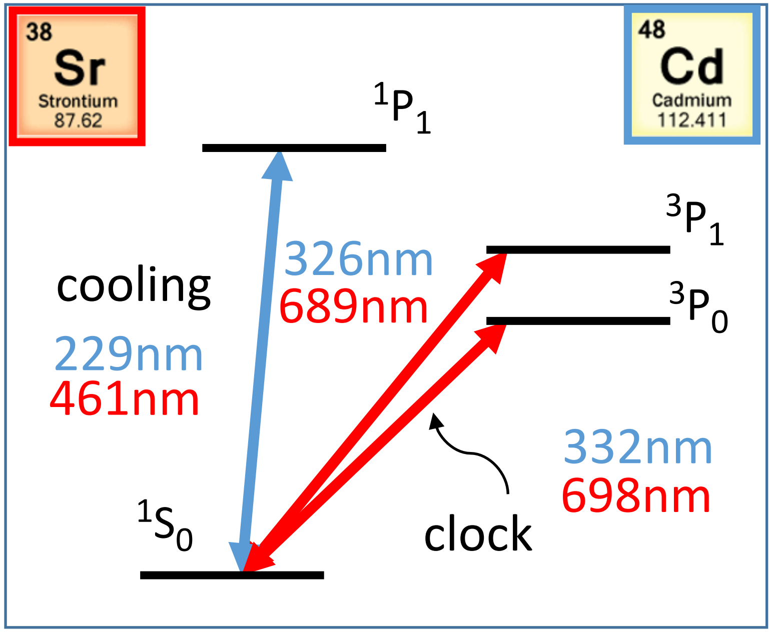
O. Buchmueller et al. *Contemporary Physics*, *64*(2), 93–110 (2023)

Clock Interferometry Candidates



SIMULTANEOUS CD-SR INTERFEROMETER

Similar atomic level structure



- 2:1 transition frequency ratio
- Low sensitivity to blackbody shift (Cd!)
- Very low sensitivity to **B** & **E** fields
- Presence of clock transitions
- Fermions and bosons available

Fundamental Physics Tests

- Weak equivalence principle
- Non-classical time dilation effects
- Spin-Gravity Coupling

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

J. N. Tinsley *et al.*, "Prospects for a simultaneous atom interferometer with ultracold cadmium and strontium for fundamental physics tests", Proceedings Volume 12016, Optical and Quantum Sensing and Precision Metrology II, 1201602 (2022)

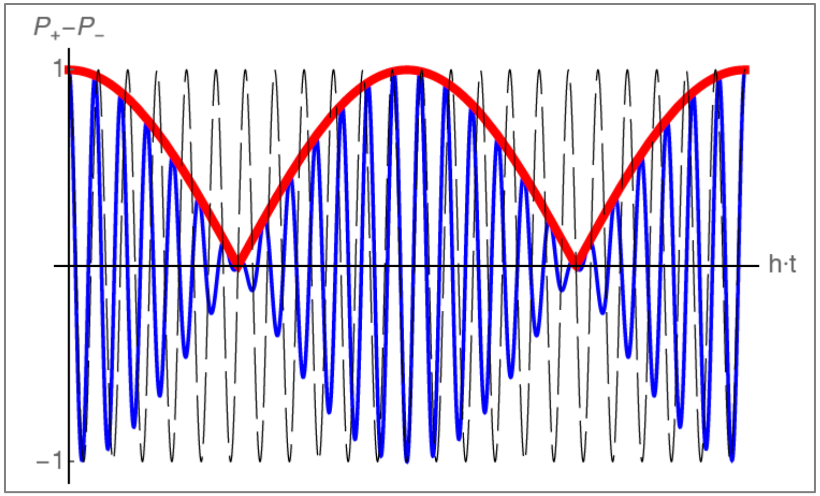
Quantum Interference of Clocks

✓ Interferometer contrast modulation

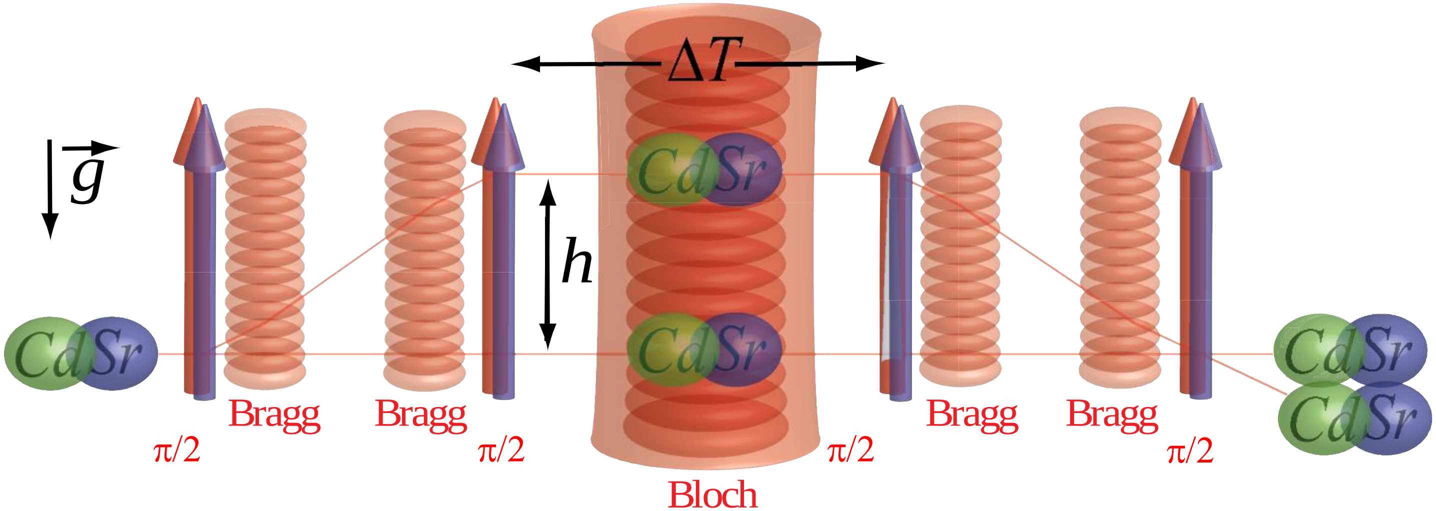
$(h*T)_{Sr}$= 21 m s

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

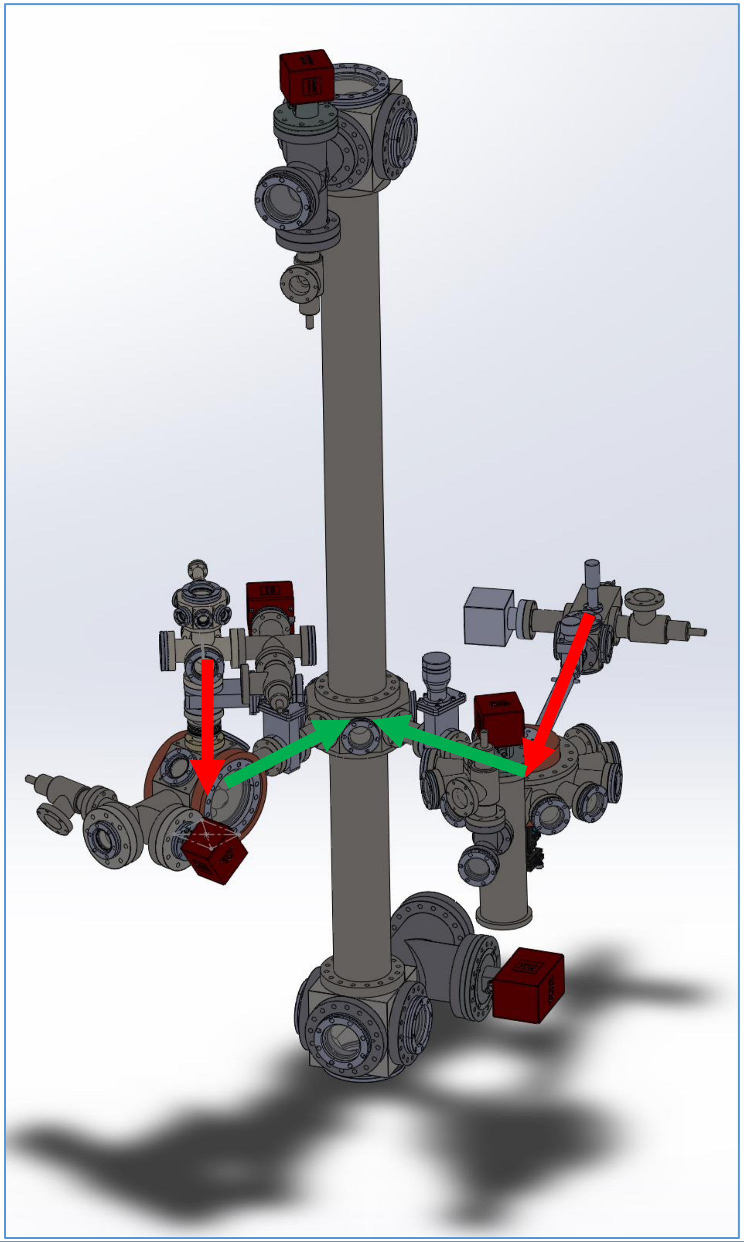
Full revival for h=2 m, time T = 5 - 10 s



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



CD-SR INTERFEROMETRY CHAMBER



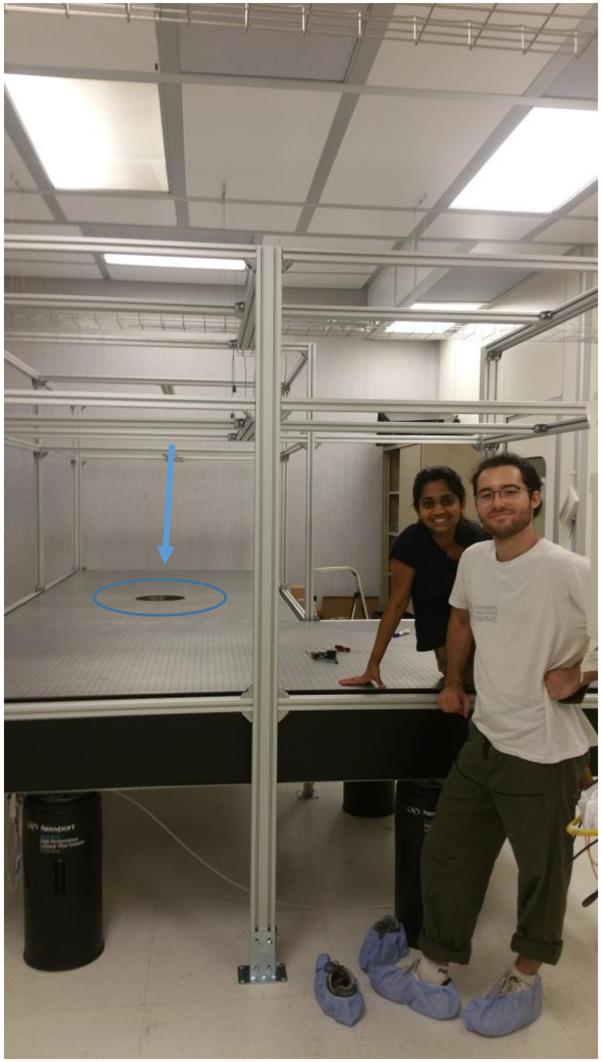
- 2m fountain for Cd & Sr

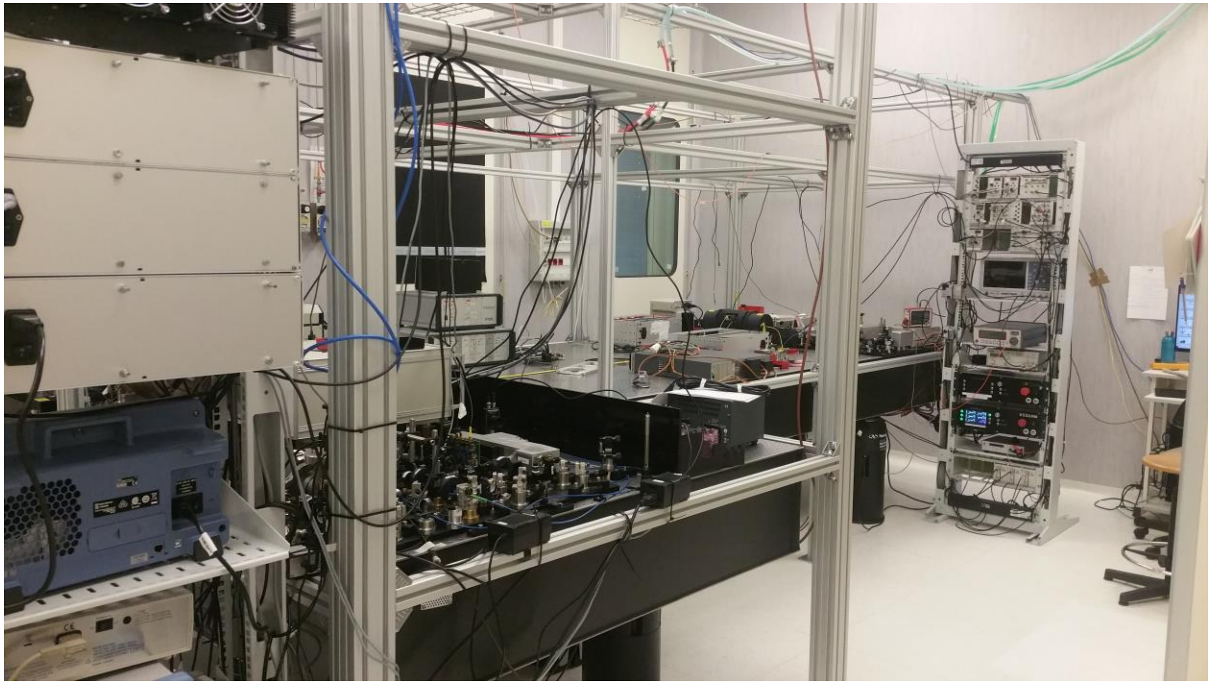
- Cd & Sr loaded from slowed atomic beams in separated MOT

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

S. Bandarupally, PhD thesis

Cd-Sr Lab



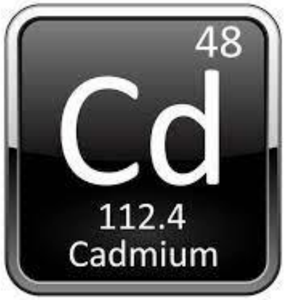


Cadmium Properties

- ✓ Interesting possibilities for atomic physics study
- ✓ Cold collisional physics
- ✓ Degenerate gas production
- ✓ Quantum information

^{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%

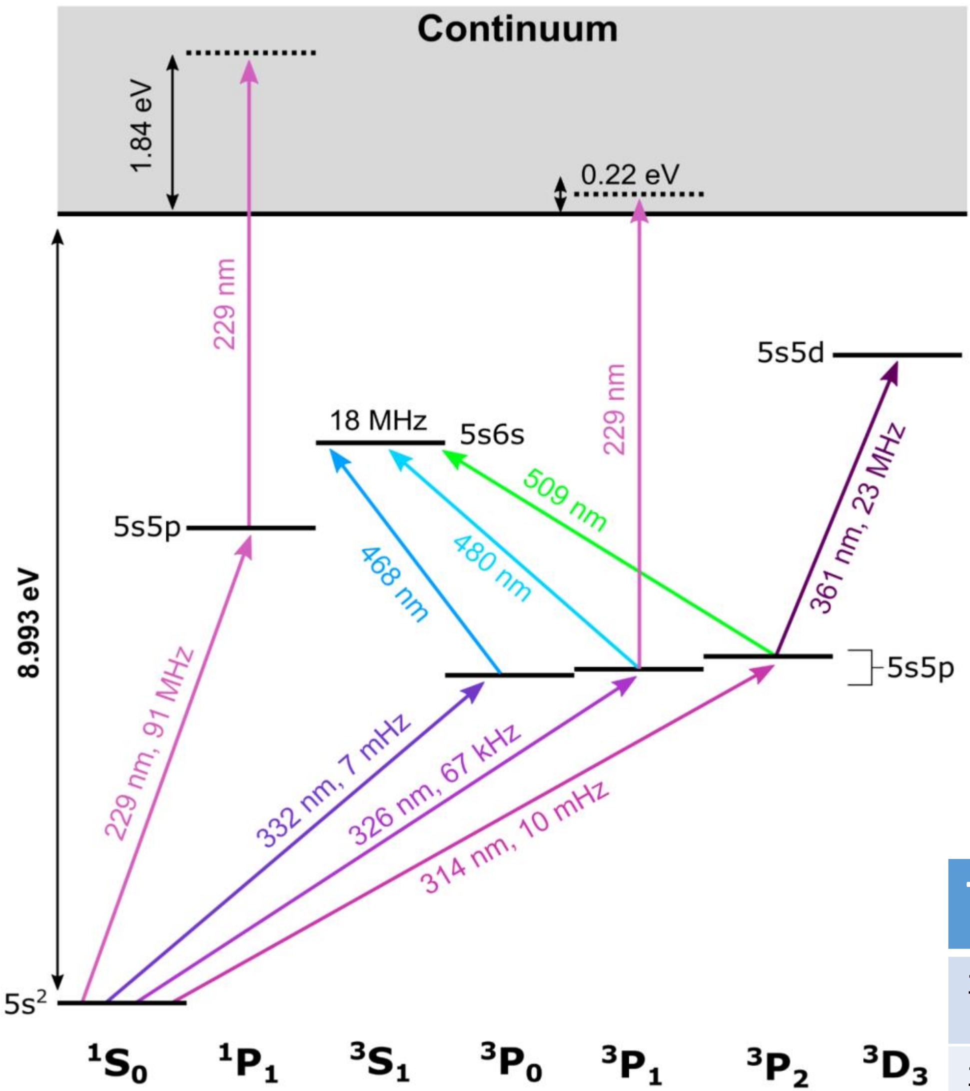
6 bosons (I=0)
2 fermions (I=1/2)
$^{(*)}$ long lifetime



- ✓ Favourable wavelength ratio of main optical cooling & spectroscopy transitions

Cd	Transition	λ (nm)	$\Gamma/2\pi$	I_s (mW/cm^2)	T_D
	^{1}S$_0$-^{1}P$_1$	228.8	91 MHz	992	2.2 mK
	^{1}S$_0$-^{3}P$_1$	326.1	67 kHz	0.252	1.6 μK
	^{1}S$_0$-^{3}P$_0$	332.1	0.8 mHz (^{113}Cd, ^{111}Cd)	3×10^{-9}	–
Sr	**Transition**	**λ (nm)**	**$\Gamma/2\pi$**	**I_s (mW/cm^2)**	**T_D**
	^{1}S$_0$-^{1}P$_1$	460.9	32 MHz	42.5	0.7 mK
	^{1}S$_0$-^{3}P$_1$	689.4	7.4 kHz	3×10^{-3}	180 nK
	^{1}S$_0$-^{3}P$_0$	698.4	1 mHz (^{87}Sr)	$\sim 10^{-9}$	-

Cooling and trapping Cadmium



C. Monroe, H. Katori, K. Gibble, S. Truppe

Challenges

- High magnetic field gradient
- Photoionisation
- Limited power
- Vacuum damage

Advantages

- Huge scattering force
- Small stopping distance

229

Challenges

- Small scattering force
- Low capture velocity

326

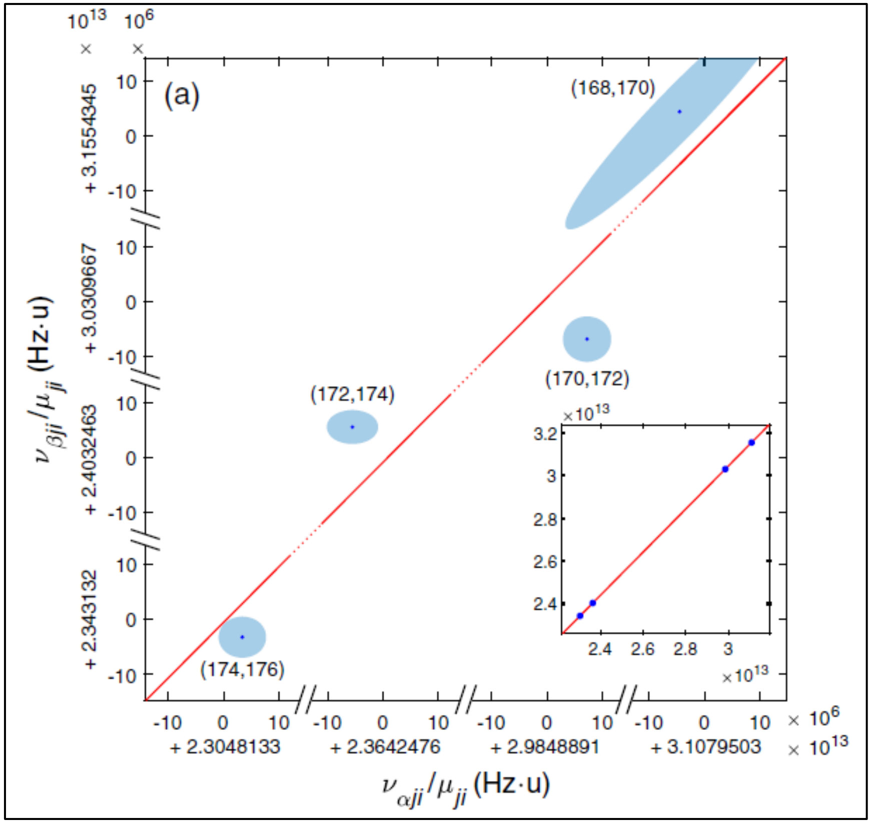
Advantages

- High power available
- Low Doppler temperature

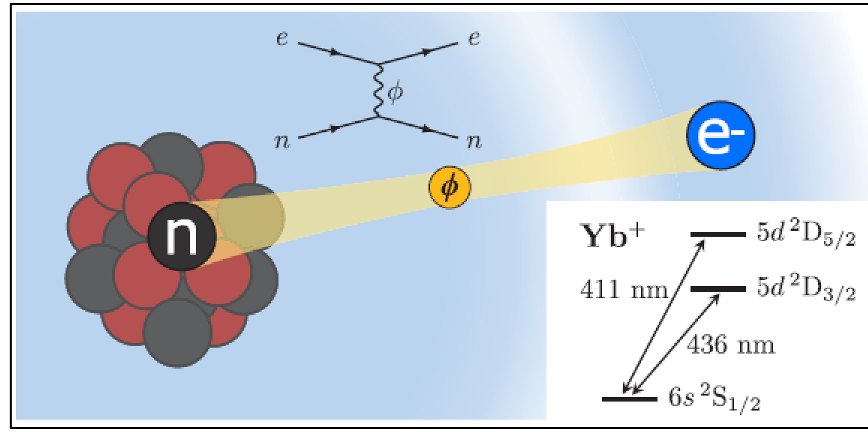
Transition	λ(nm)	$\Gamma/2\pi$	Is (mW/cm^2)
$^1S_0 \rightarrow ^1P_1$	228.8	90 MHz	992
$^1S_0 \rightarrow ^3P_1$	326.1	67 kHz	0.3
$^1S_0 \rightarrow ^3P_0$	332	~mHz	3x10^{-9}

PROBING NEW LONG-RANGE INTERACTIONS BY SPECTROSCOPY

✓ Non linearity in King's plot



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

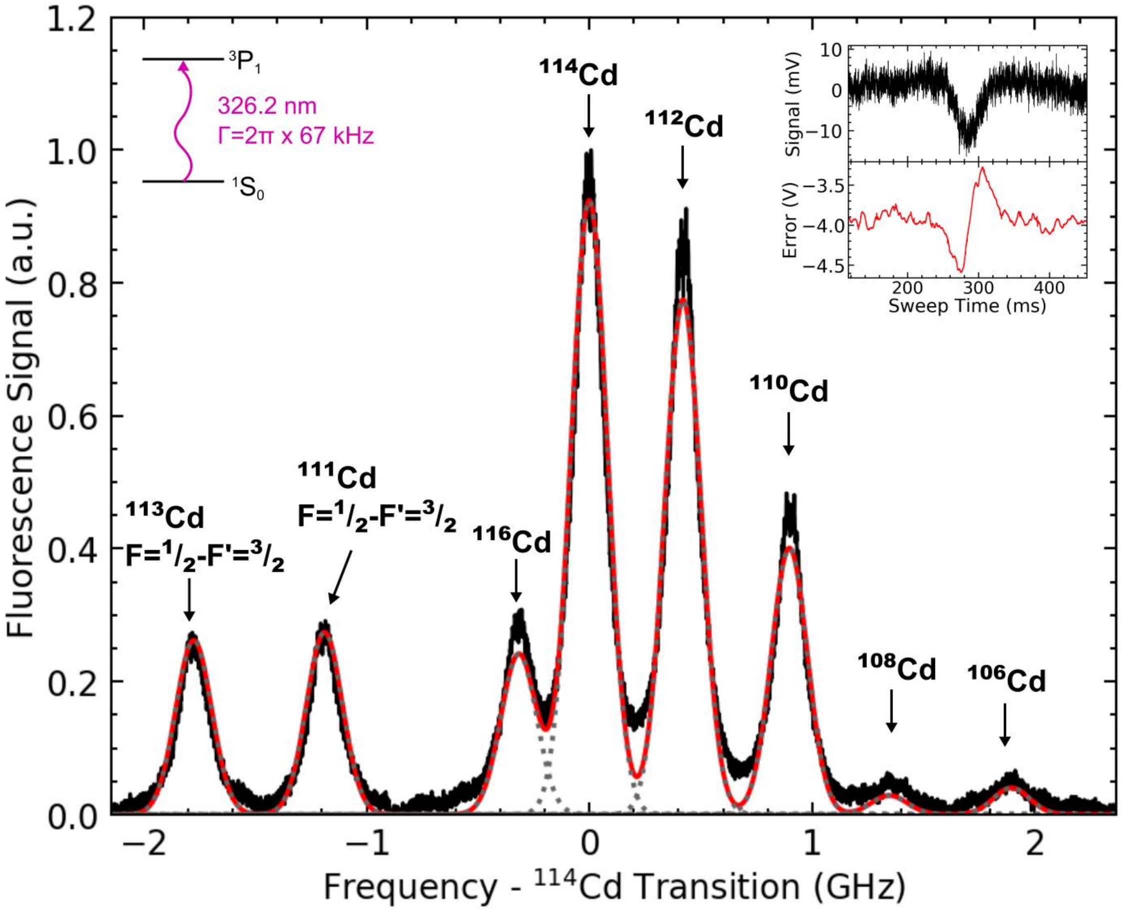


Isotope	Abundancy	Nuclear Spin	Mass (u.m.a.)
^{106}Cd	1.25%	0	105.906
^{108}Cd	0.89%	0	107.904
^{110}Cd	12.49%	0	109.903
^{111}Cd	12.80%	1/2	110.904
^{112}Cd	24.13%	0	111.903
^{113}Cd	13.47%	1/2	112.904
^{114}Cd	28.73%	0	113.903
^{116}Cd	7.49%	0	115.905

C. Delaunay, R. Ozeri, G. Perez, and Y. Soreq, Probing atomic Higgs-like forces at the precision frontier, Phys. Rev. D 96, 093001 (2017).

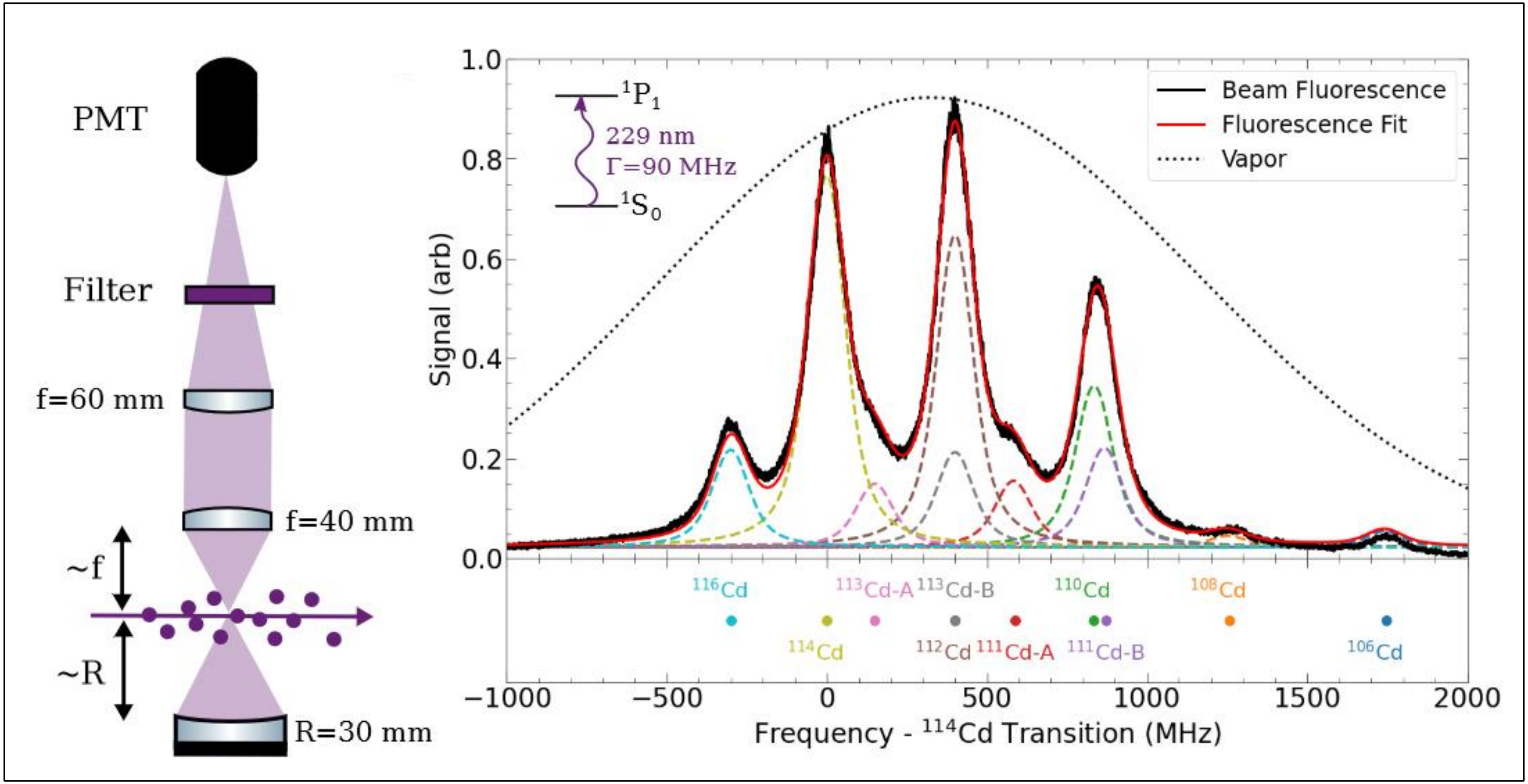
CD BEAM SPECTROSCOPY AT 326 NM

- Spectroscopy and error signal from the atomic beam
- Possibility for high-precision isotope shift measurements ->> King's Plots



S. Manzoor, et al. "High-power, frequency-quadrupled UV laser source resonant with the $^1S_0$-$^3P_1$ narrow intercombination transition of cadmium at 326.2 nm", Optics Letters **47** (10), 2582-2585 (2022)

Cadmium Atomic Beam Spectroscopy



J. N. Tinsley, et al. "Watt-level blue light for precision spectroscopy, laser cooling and trapping of strontium and cadmium atoms", *Optics Express* ***29***, *25462-25476 (2021)*

B. Ohayon New Journal of Physics 24 123040 (2022)

S. Hofsäss Phys. Rev. Research 5, 013043 (2023)

Cadmium Isotopic Shifts

Transition	Determination 1 [38]	Determination 2 [38]	This work / MHz
^{106}Cd	-	-	1747.5 ± 4.3 ± 9.7
^{108}Cd	-	-	1256.0 ± 4.3 ± 7.0
^{110}Cd	878 ± 17	905 ± 35	833.2 ± 2.8 ± 4.6
^{111}Cd - F′=1/2	-	-	587.0 ± 3.1 ± 3.3
^{111}Cd - F′=3/2	878 ± 17	-	871.5 ± 2.9 ± 4.8
^{112}Cd	375 ± 15	395 ± 30	399.2 ± 2.8 ± 2.2
^{113}Cd - F′=1/2	-	-	150.0 ± 2.9 ± 0.8
^{113}Cd - F′=3/2	375 ± 15	-	401.1 ± 4.0 ± 2.2
^{116}Cd	-	-	-299.0 ± 2.6 ± 1.7

J. N. Tinsley, et al. "Watt-level blue light for precision spectroscopy, laser cooling and trapping of strontium and cadmium atoms", Optics Express 29 (16), 25462 (2021)

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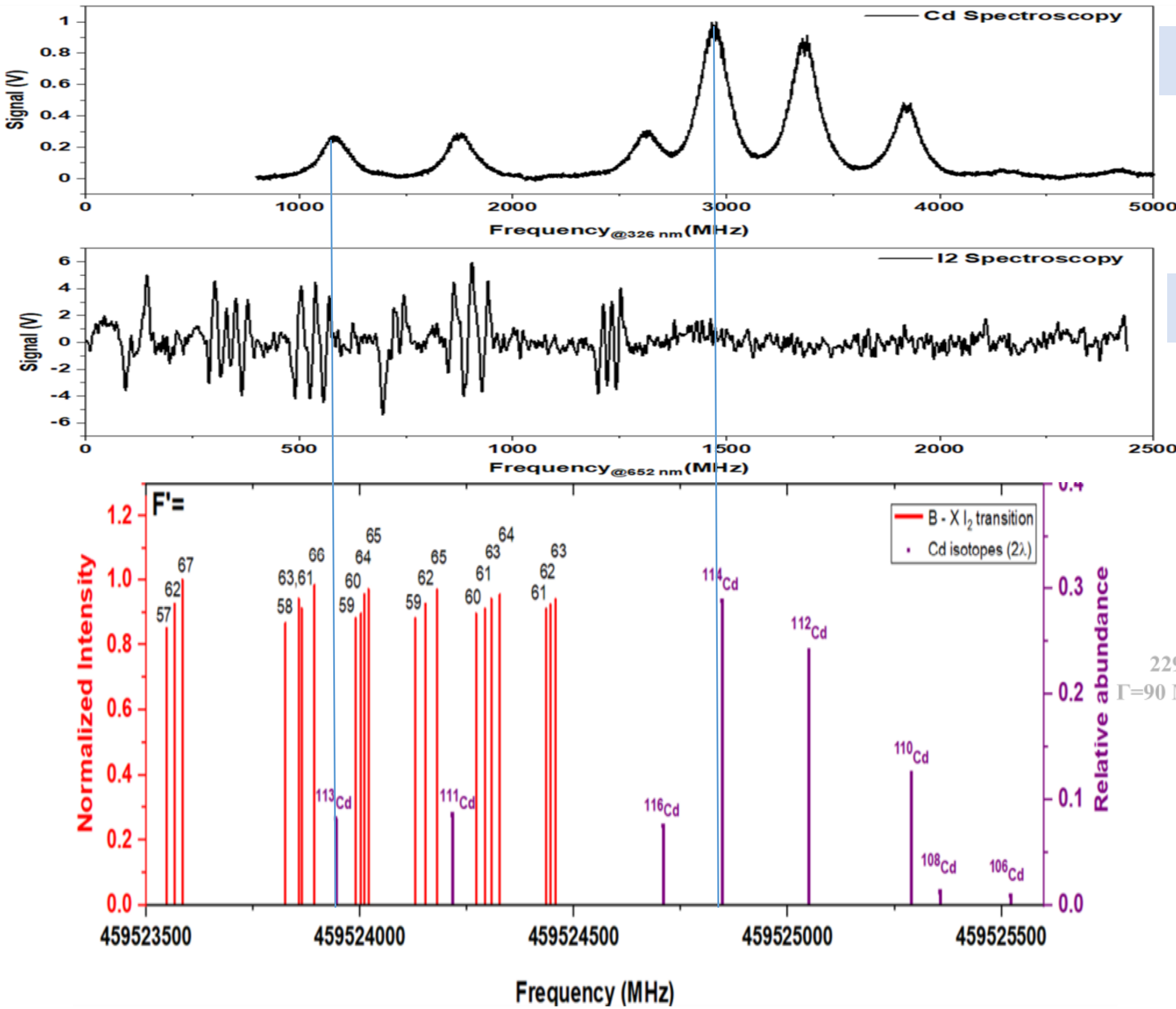
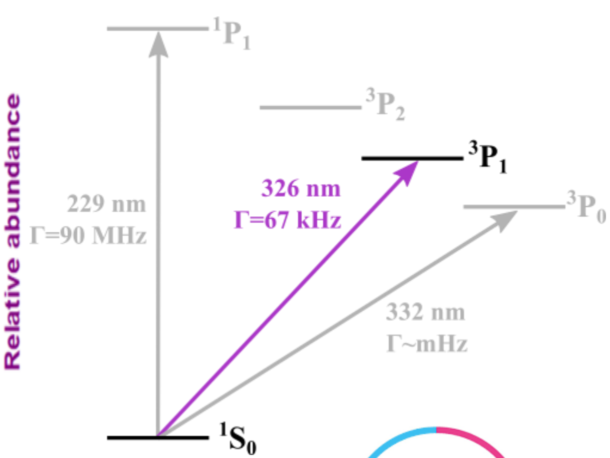
Precision spectroscopy of Iodine Molecule



Cd Spectrum @ 326 nm

I2 spectrum @ 652 nm



S. Manzoor *et al.*, *Opt. Express* ***32****, 44683- 44693 (2024)*

Hyperfine parameters determination

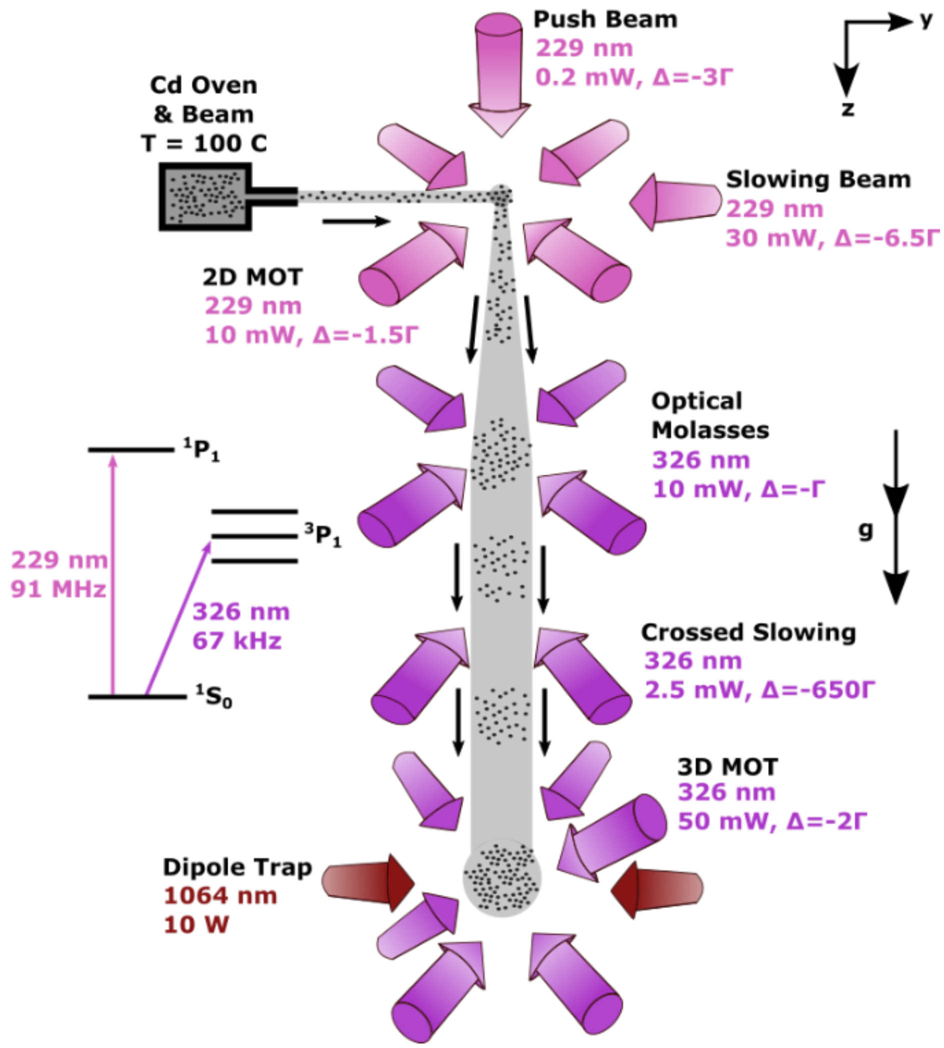
$$\hat{H}_{eff} = \hat{H}_{HFS} + \hat{H}_R$$

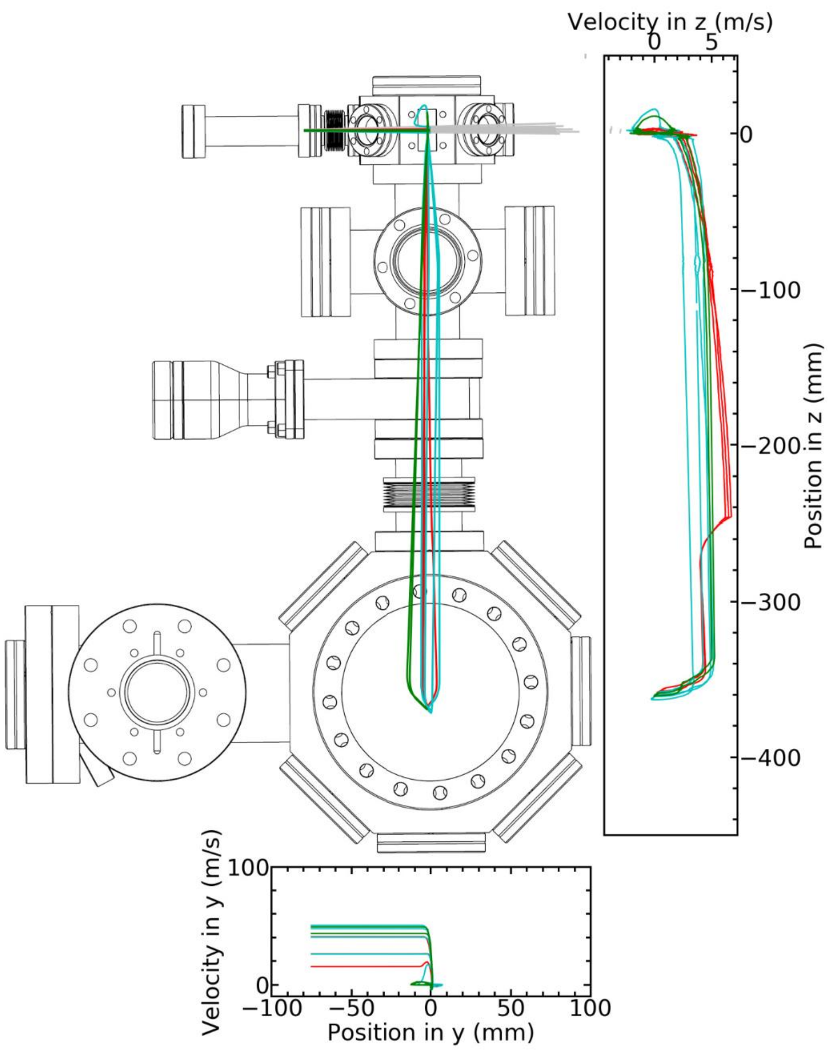
$$\hat{H}_{HFS} = eQq \sum_{\alpha=1}^{2} \frac{\sqrt{6}T^2_{q=0}(\hat{I}_\alpha, \hat{I}_\alpha)}{4I_\alpha(2I_\alpha - 1)} + C\hat{J}\cdot\hat{I} - d\sqrt{6}T^2_{q=0}(\hat{I}_1, \hat{I}_2) + \delta\hat{I}_1\cdot\hat{I}_2$$

$$\hat{H}_R = T + B\hat{J}^2 - D\hat{J}^4 + H\hat{J}^6 + L\hat{J}^8 + M\hat{J}^{10}$$

Parameter	Calculated Values (This Work) / MHz	Literature-derived Values [100, 115]/ MHz
ΔeQq	1 957.67 (71)	1 957.672 (25) [115]
ΔC	20.37(60)	21.4 (10) [115]
ν'=4 Band Origin	486 021 343.15 (12)	486 021 362 (30) [100]
f_g	459 524 036.90 (12)	459 524 056 (30) [100]

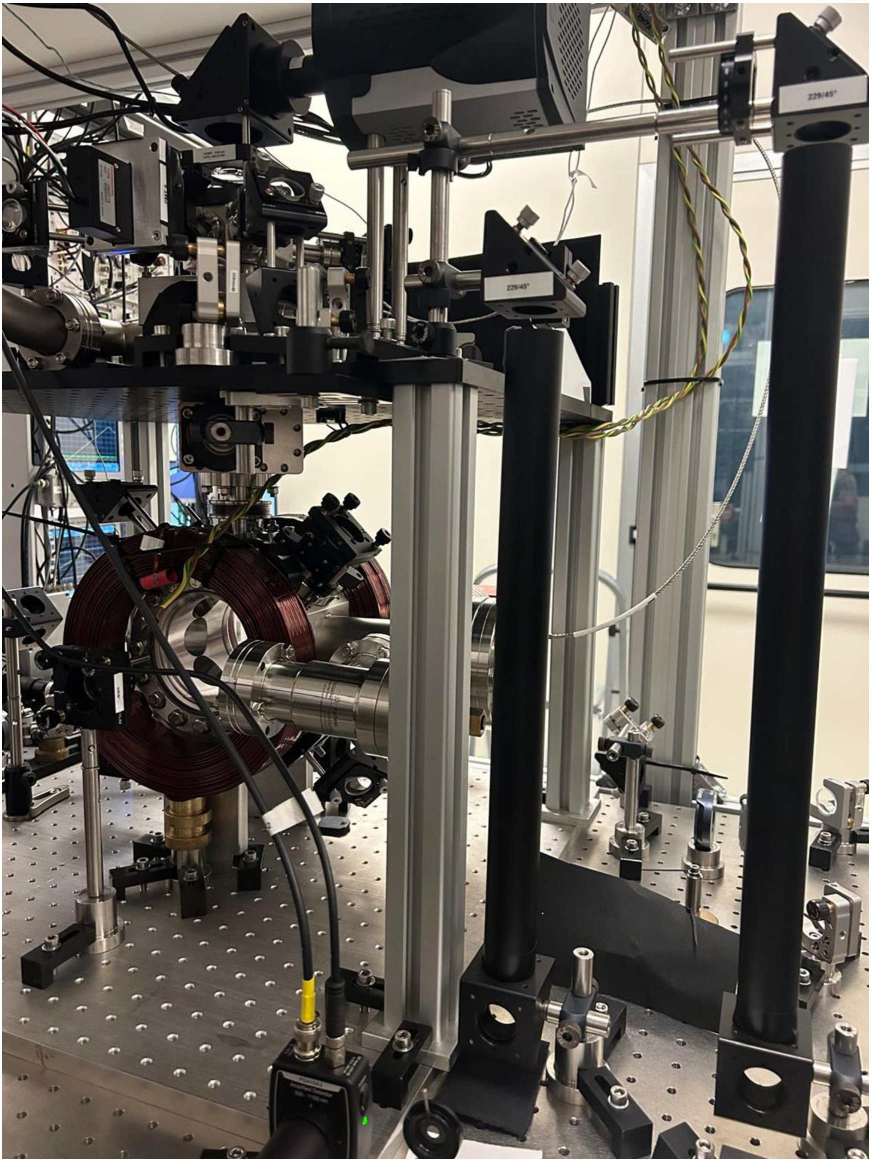
S. Manzoor *et al.*, *Opt. Express* ***32***, *44683- 44693 (2024)*

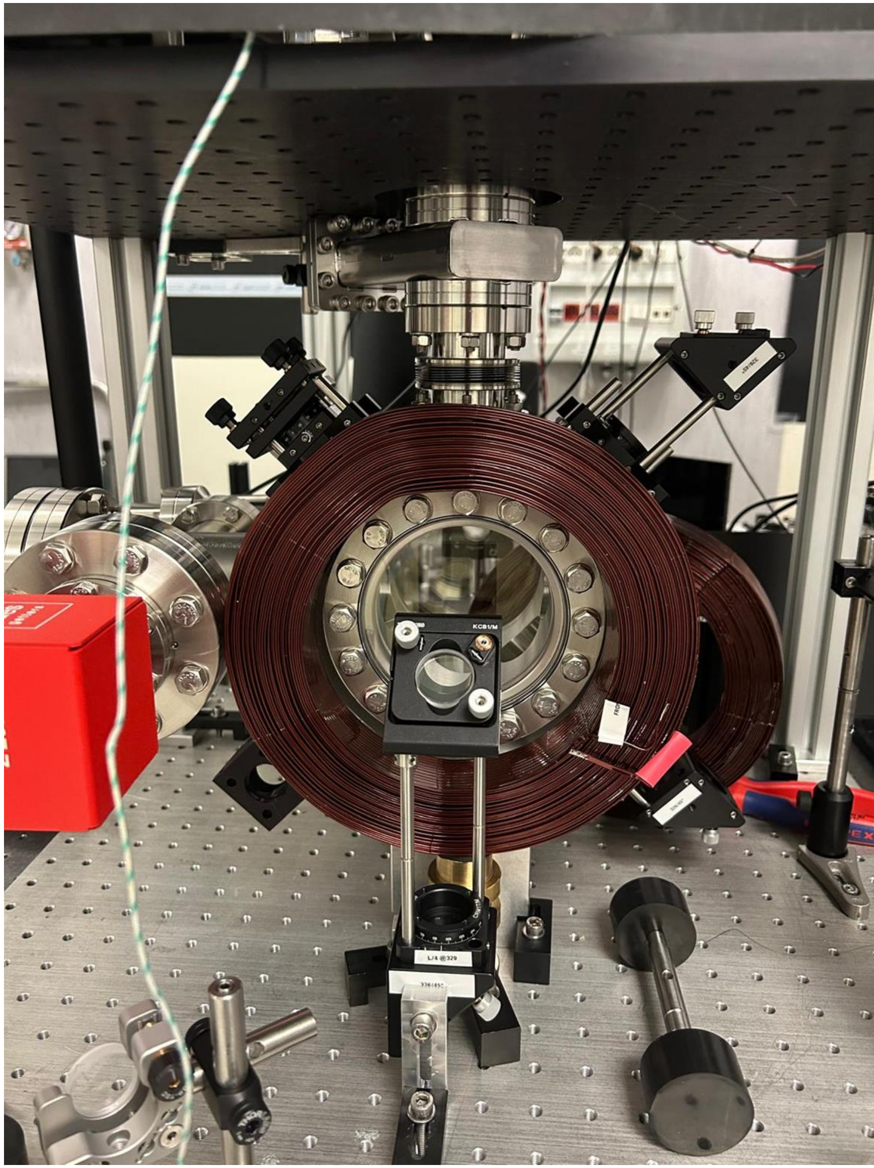




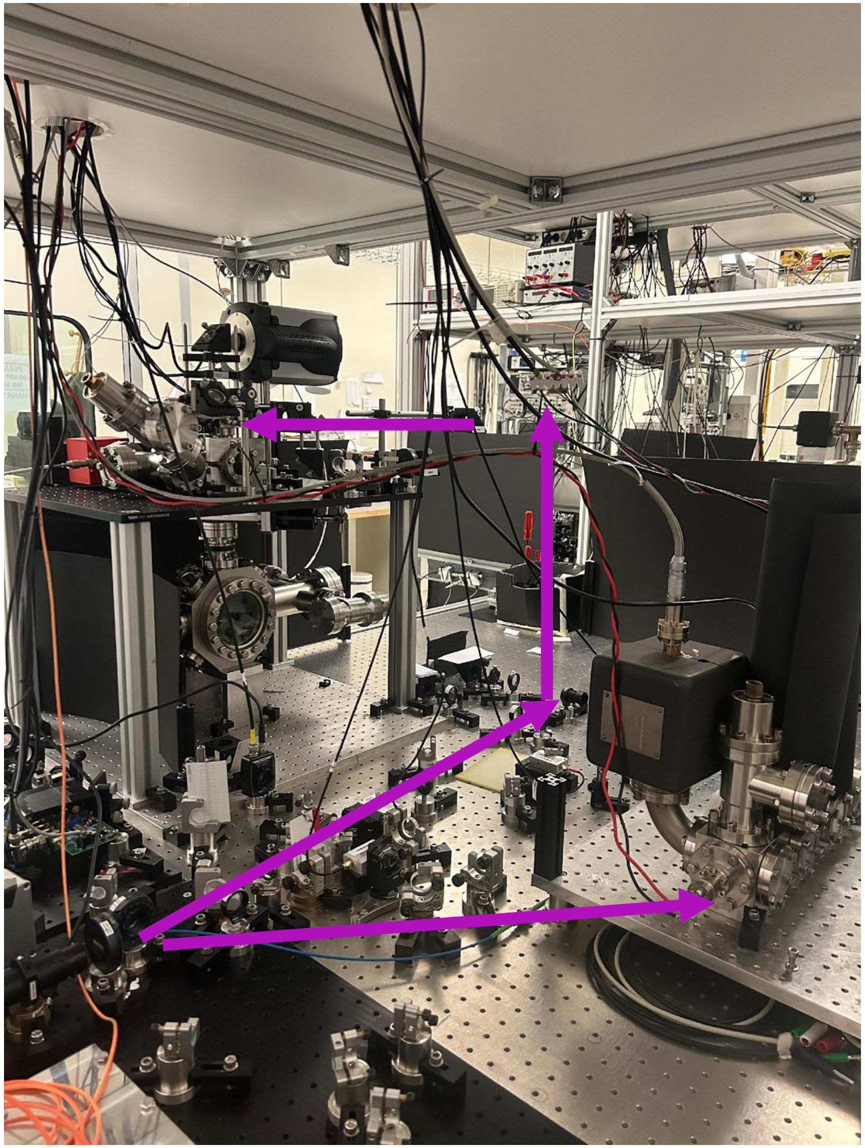
S. Bandarupally *et al*. *J. Phys. B: At. Mol. Opt. Phys.* **56** 185301 (2023)

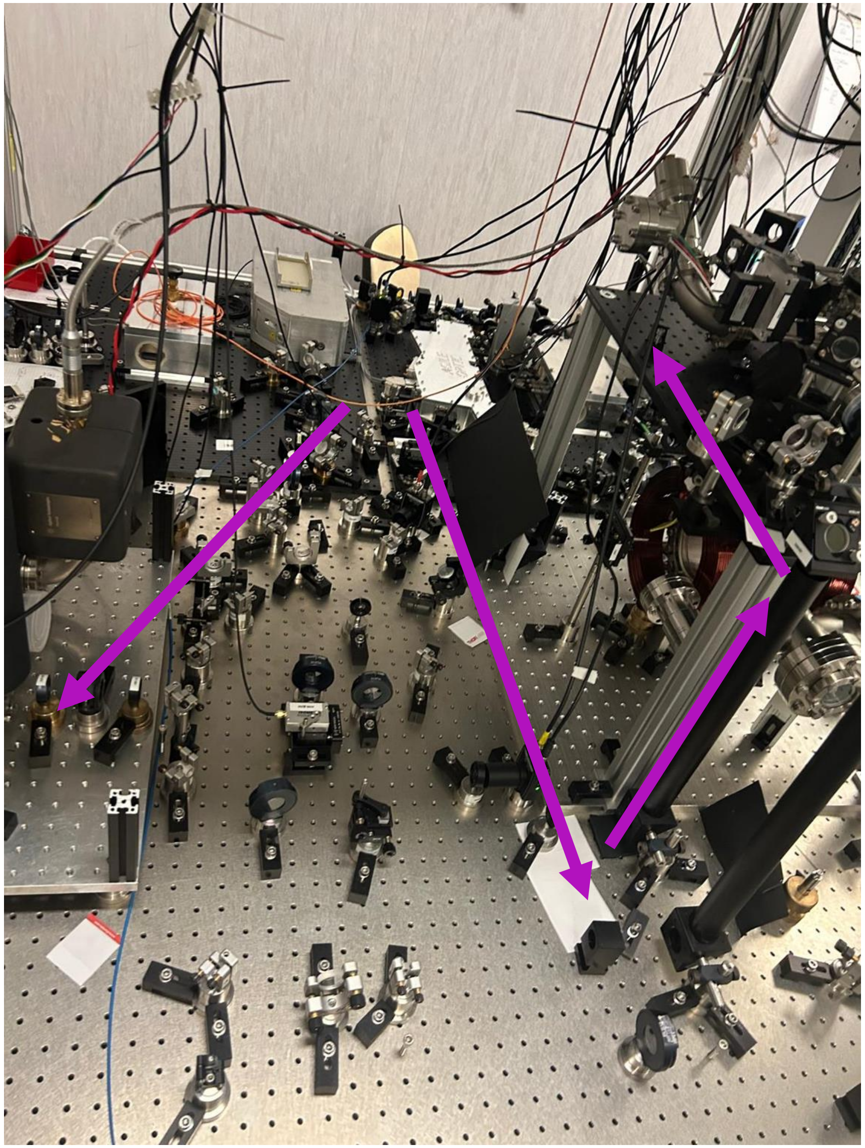
Cooling and trapping Cadmium



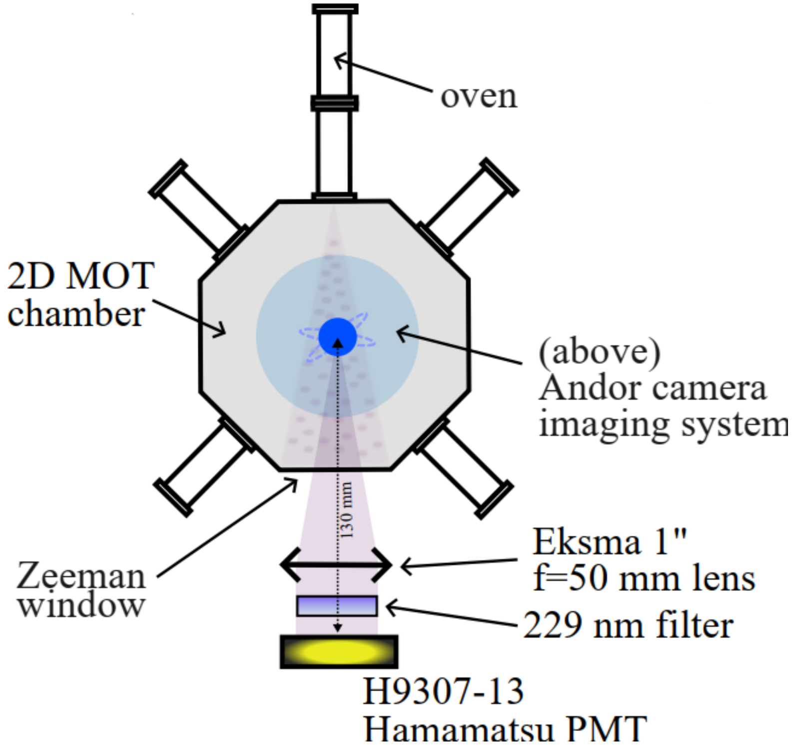


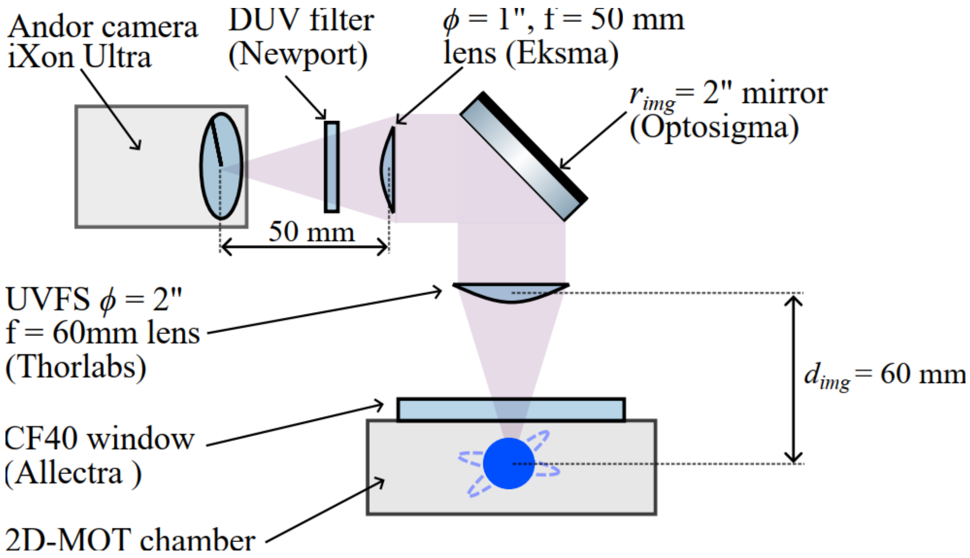
COOLING AND TRAPPING CADMIUM



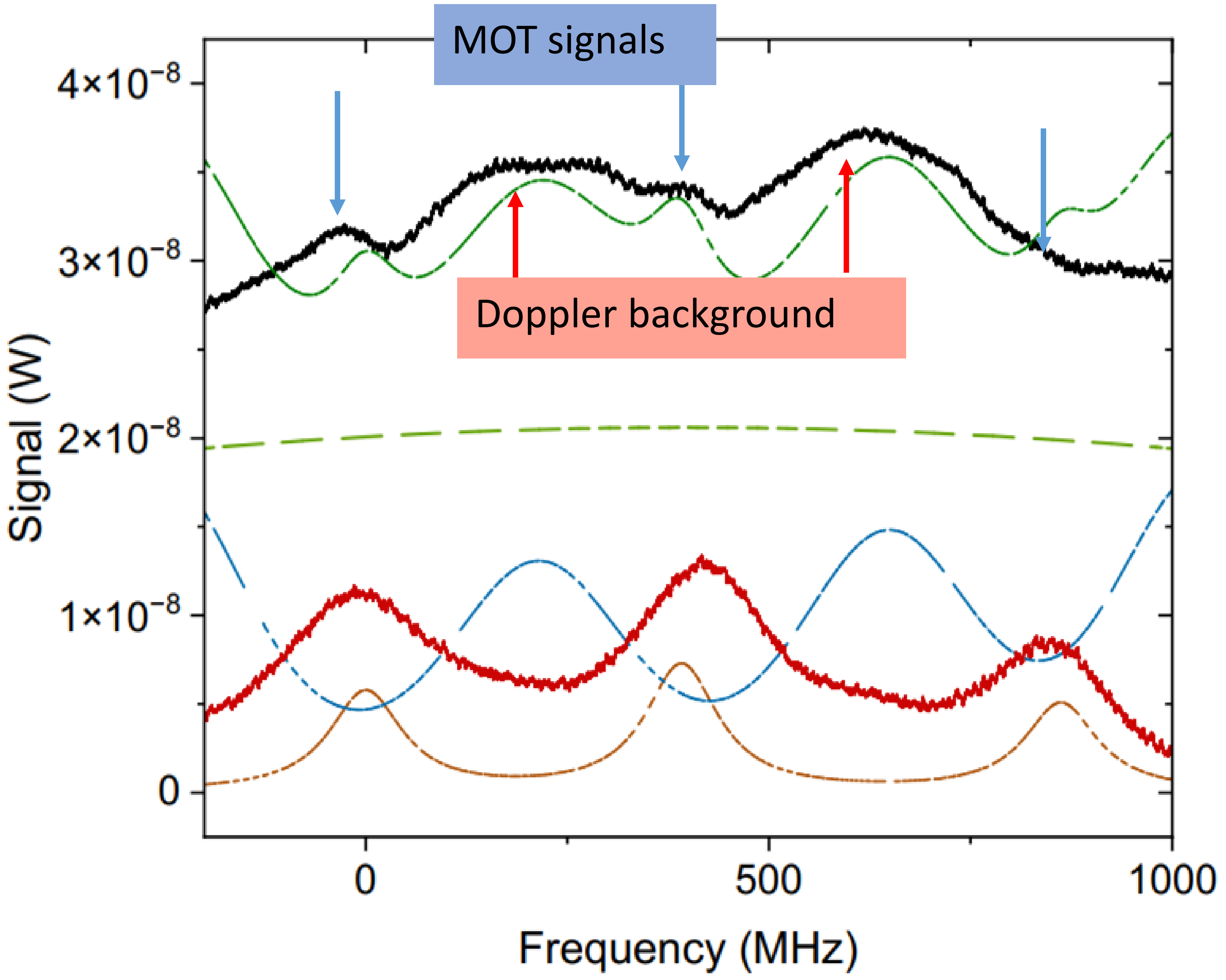


IMAGING DUV - 2D MOT

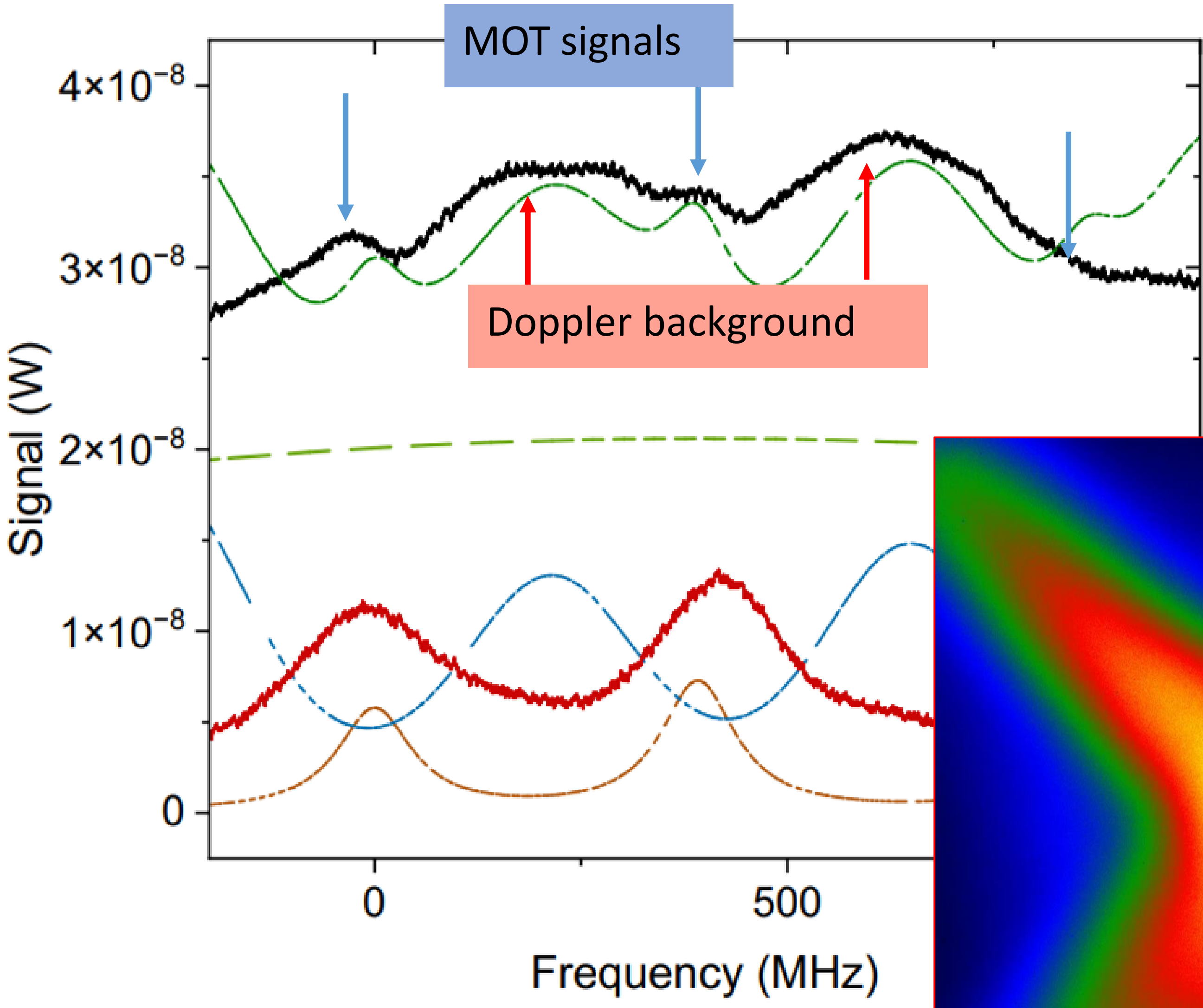


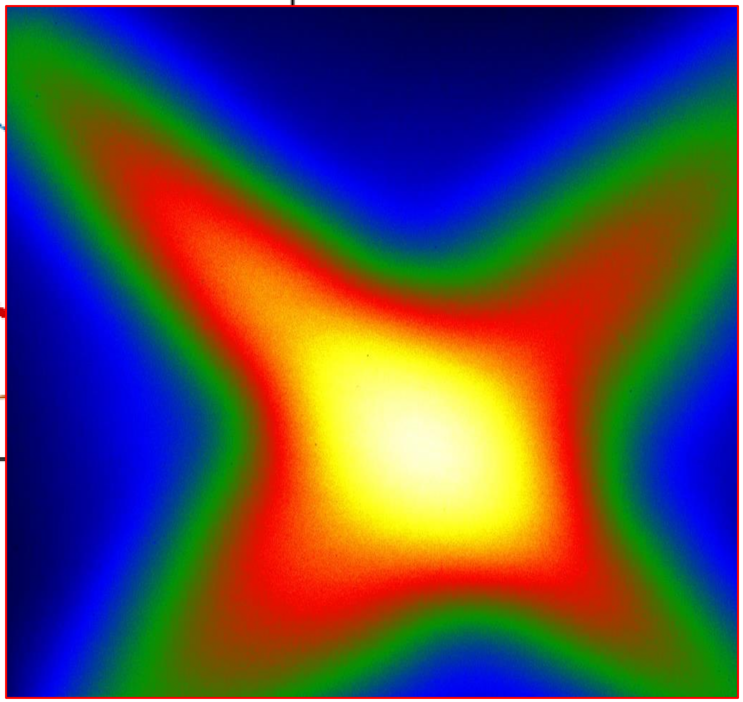


DUV 2D MOT - CADMIUM



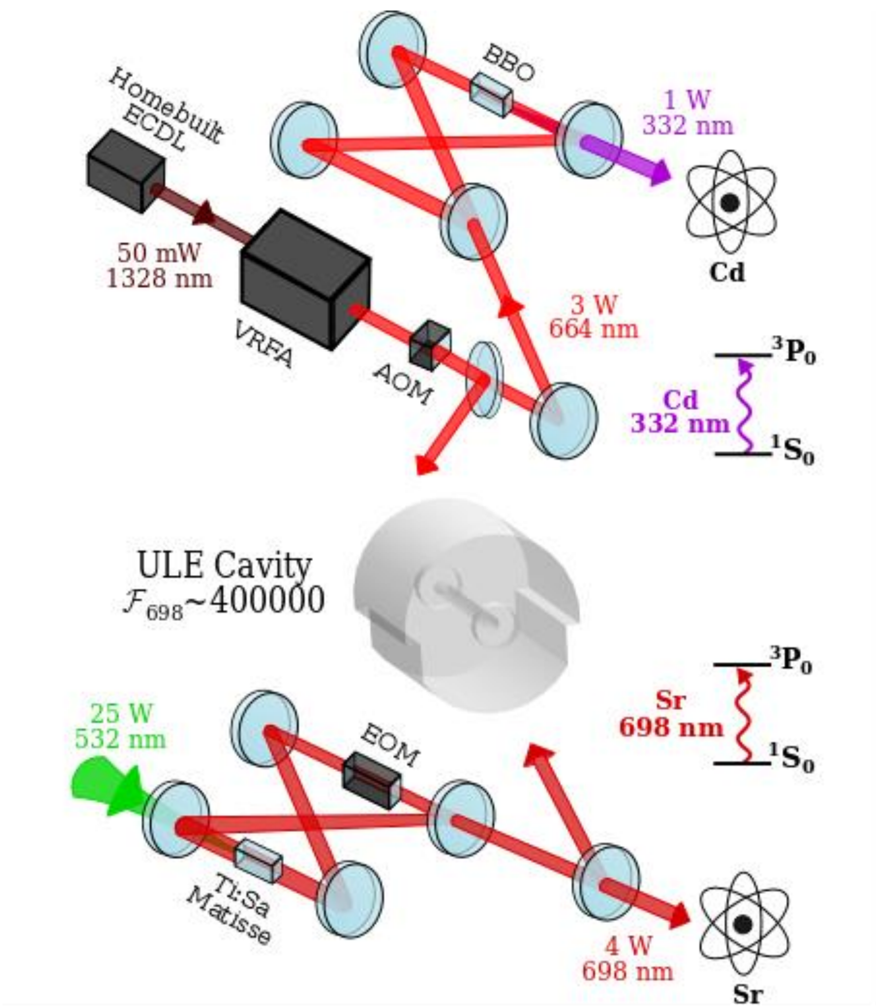
DUV 2D MOT - CADMIUM

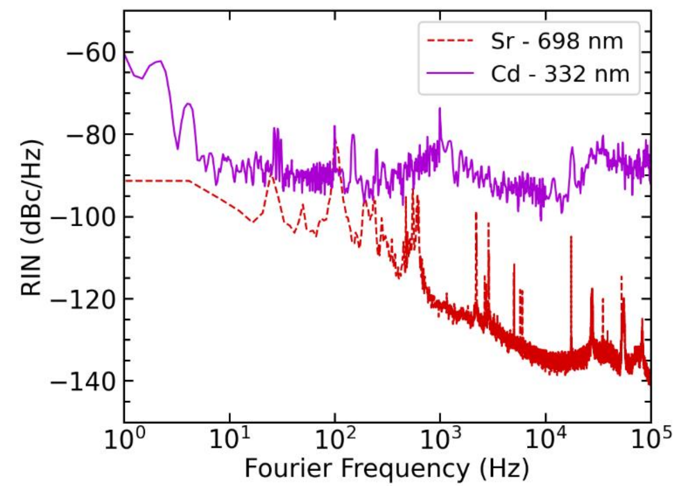


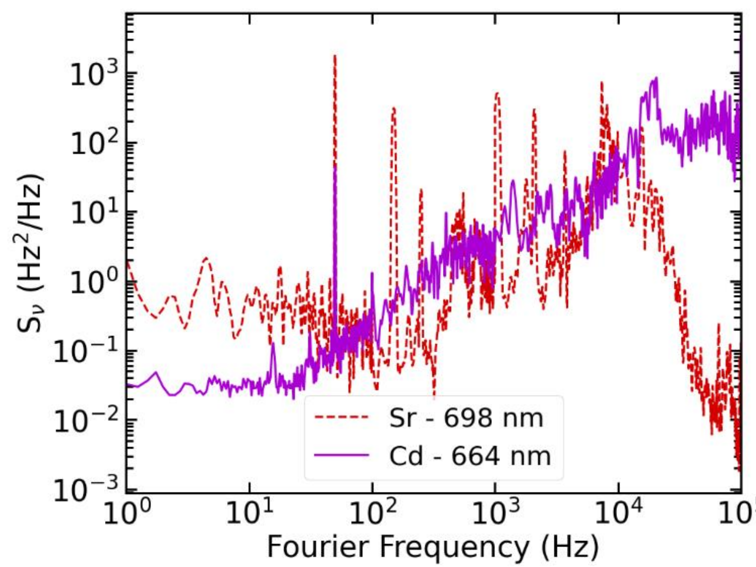


Cd 332 nm & Sr 698 nm Clock Atom Interferometry Lasers

- Requirement of high power (> 1 W) and narrow linewidth (Hz level)



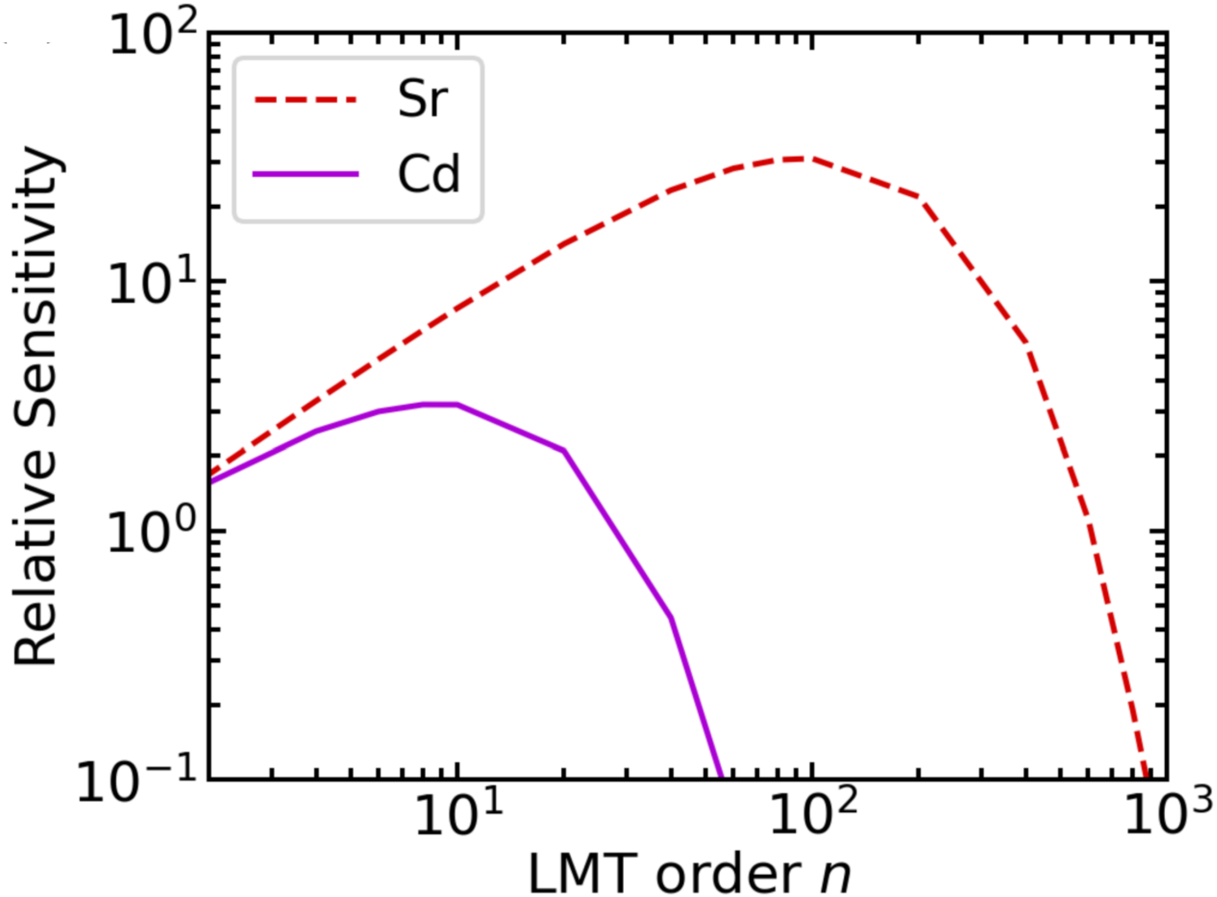




M. Chiarotti et al. Phys. Rev. X Quantum **3**, 030348 (2022)

LMT Fidelity – Developed Laser

- Can apply this to the measured laser noise
- Using the Rabi frequency expected from the measured power (w = 5 mm)



High finesse cavity @ 332 nm for UV-DUV lasers frequency stabilization

UVQuanT

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