

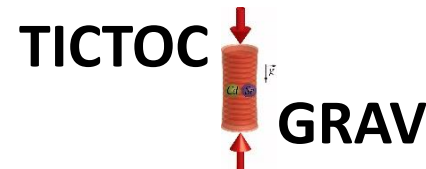
PRECISION TEST OF FUNDAMENTAL PHYSICS WITH MATTER-WAVE INTERFEROMETERS

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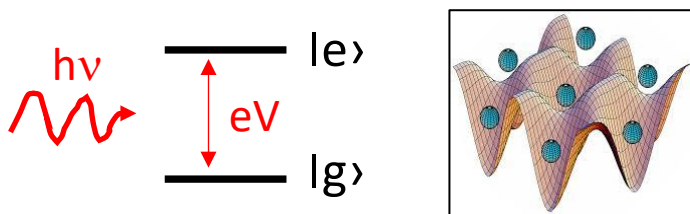
Monday 10th February 2025

ATOMIC CLOCKS & GRAVIMETERS

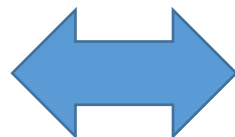
TIME

Optical atomic clocks

internal d.o.f., electronic states



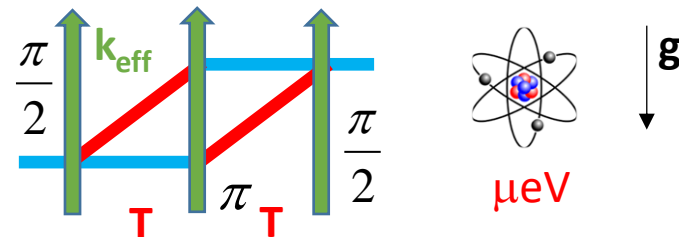
relative precision $< 10^{-20}$



GRAVITY

Atom interferometers (gravimeters/radiometers)

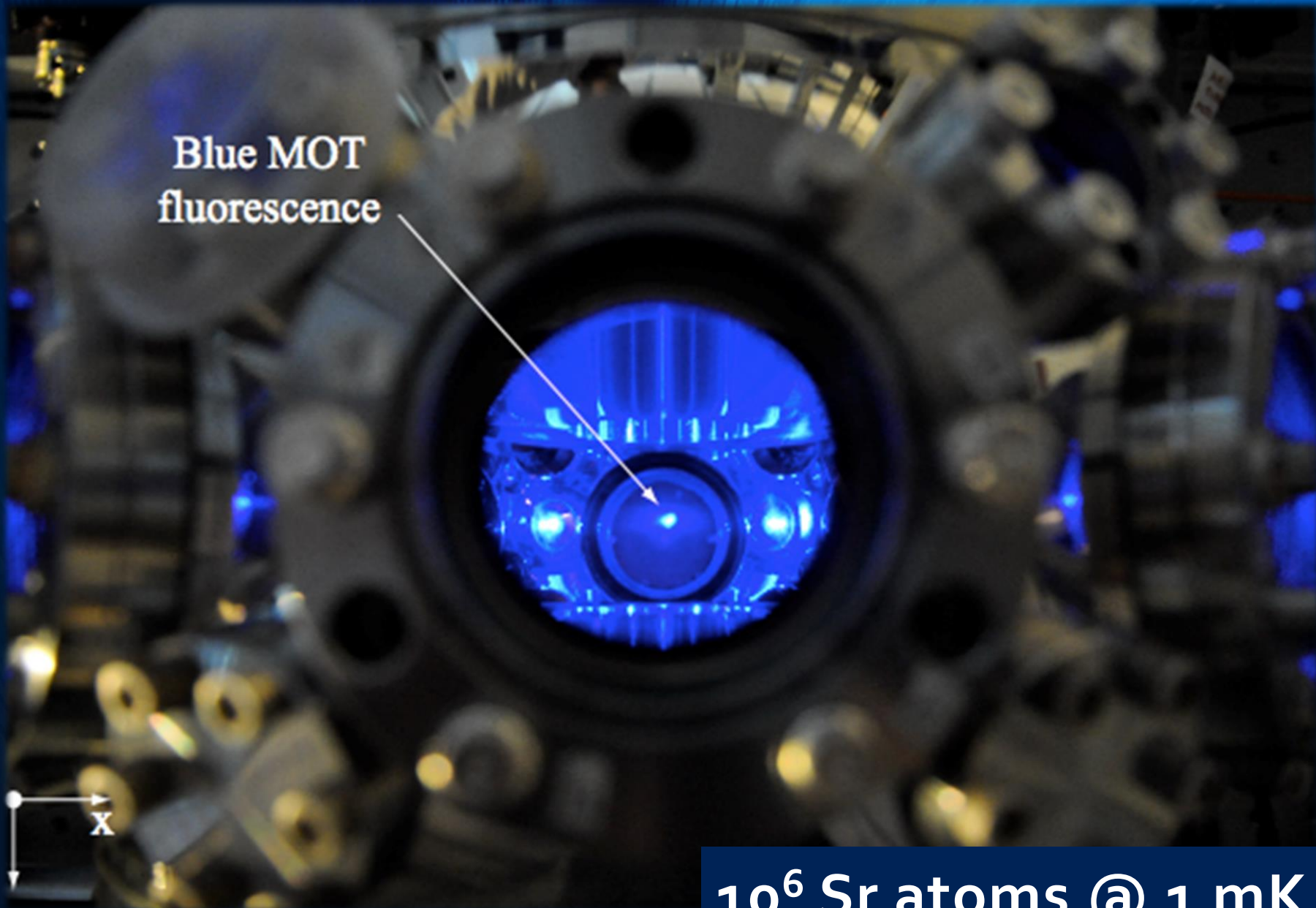
external d.o.f., momentum states



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

Table-top, low-energy experiments, high precision

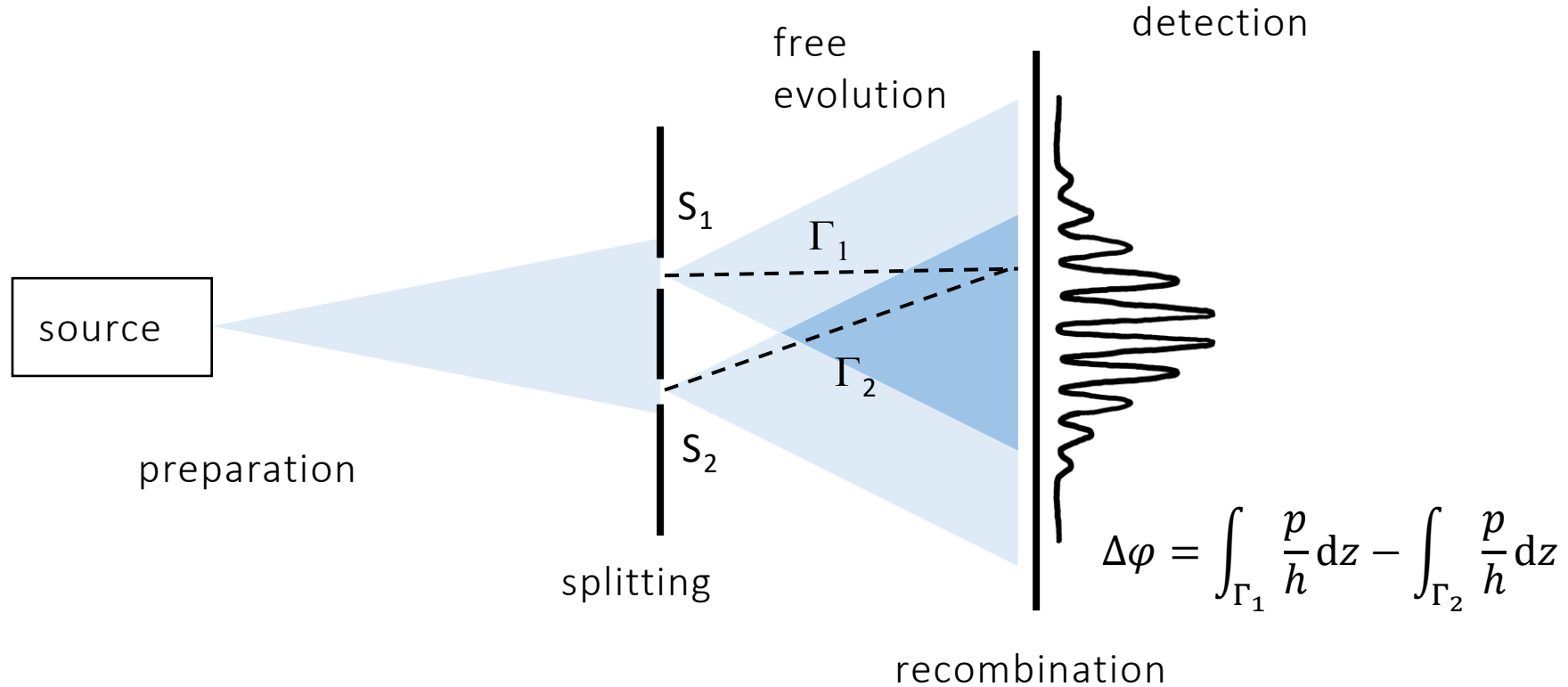
Ultracold Sr atoms



10^6 Sr atoms @ 1 mK

INTERFERENCE OF MATTER WAVES

Young's double-slit experiment

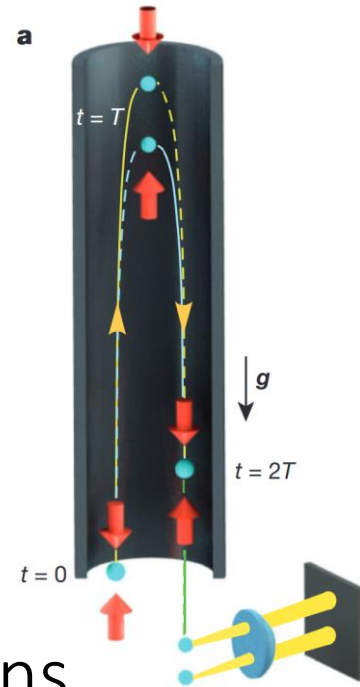
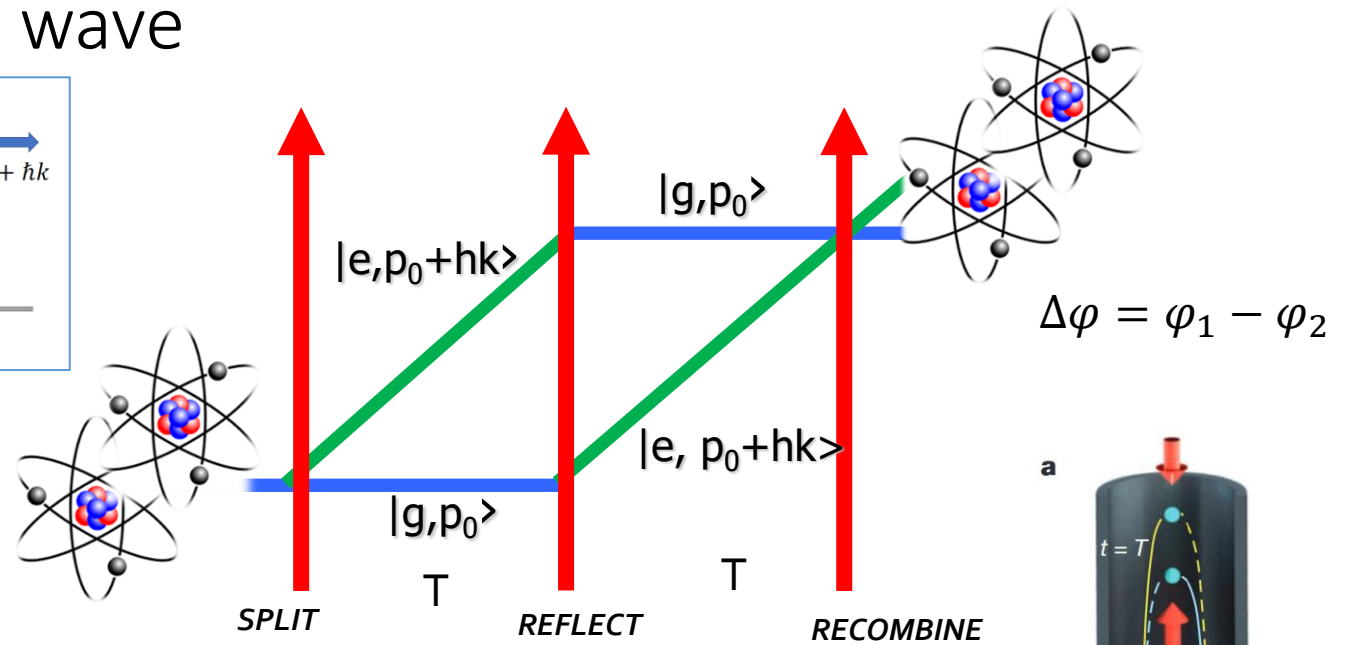
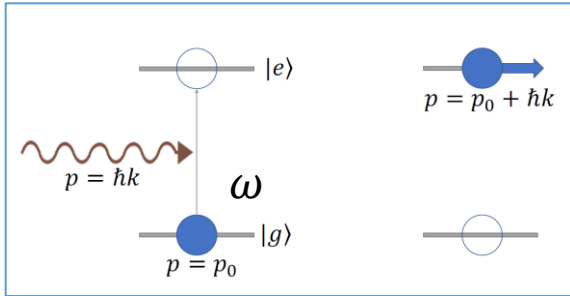


Matter Wave Interferometry = *art* of coherently splitting, reflecting, and recombining *matter waves*

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

ATOM INTERFEROMETERS

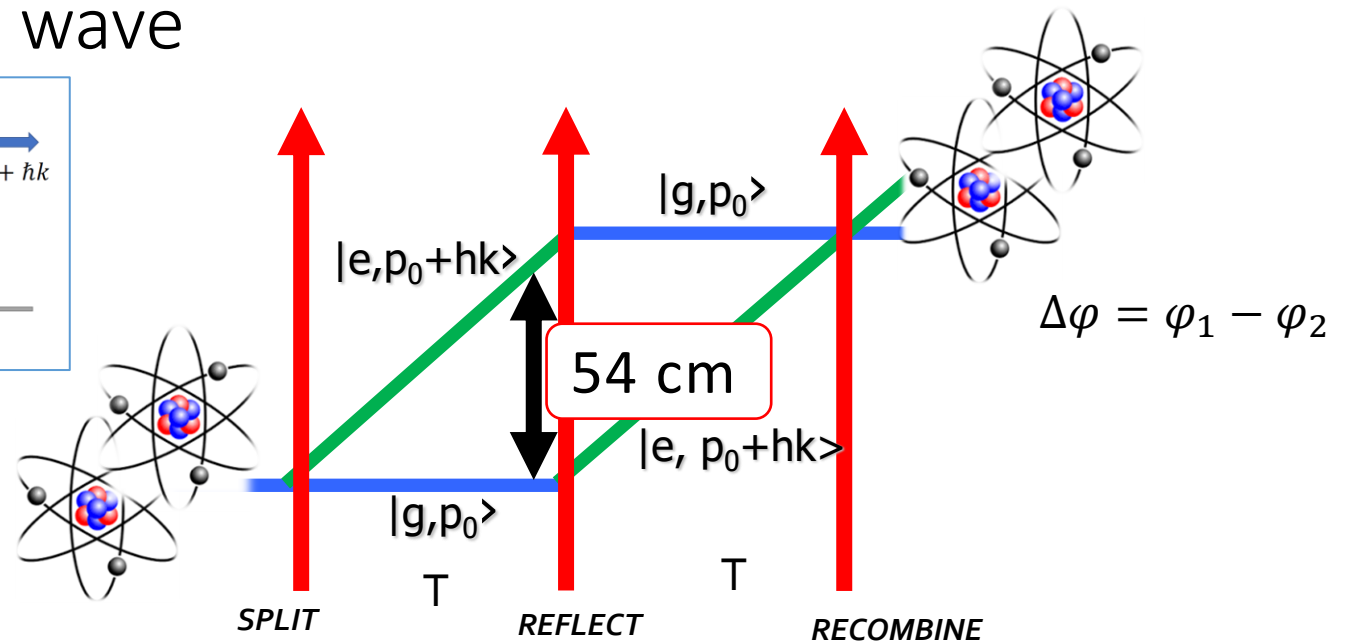
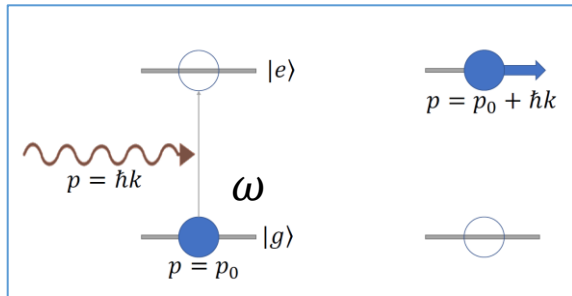
light \rightarrow matter wave



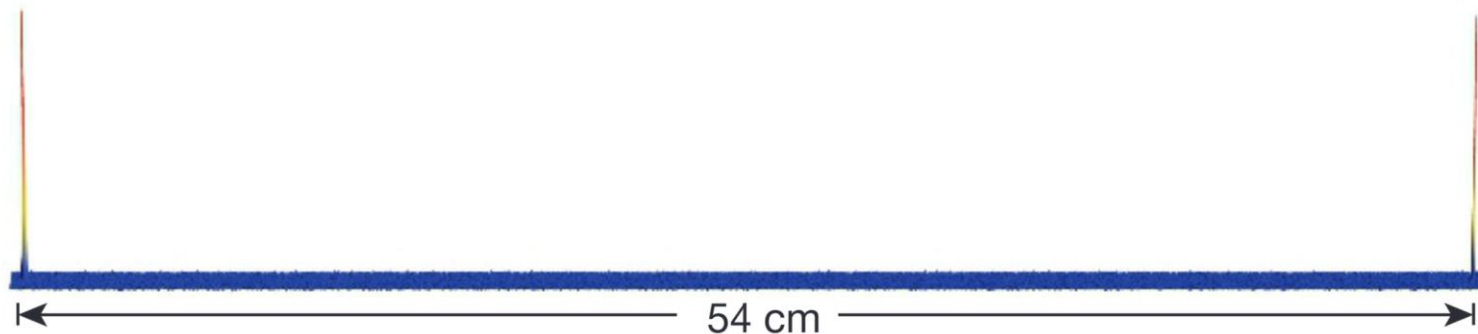
Atomic fountains

ATOM INTERFEROMETERS

light \rightarrow matter wave



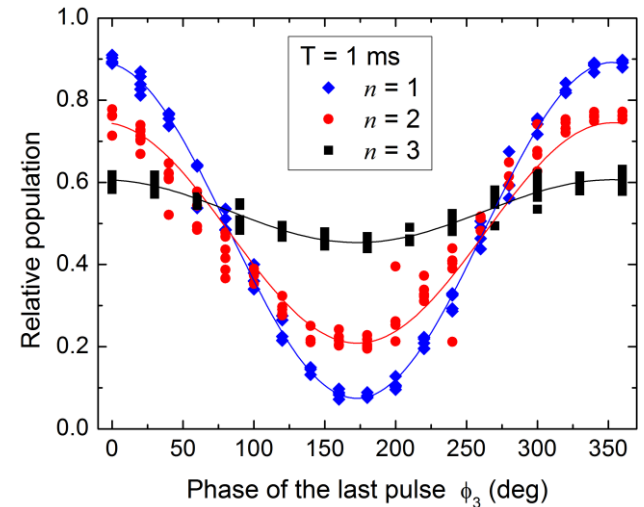
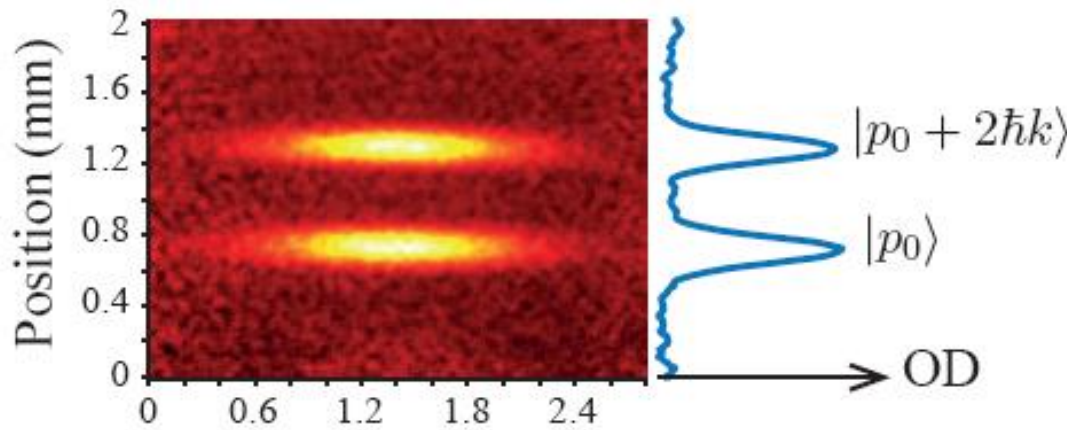
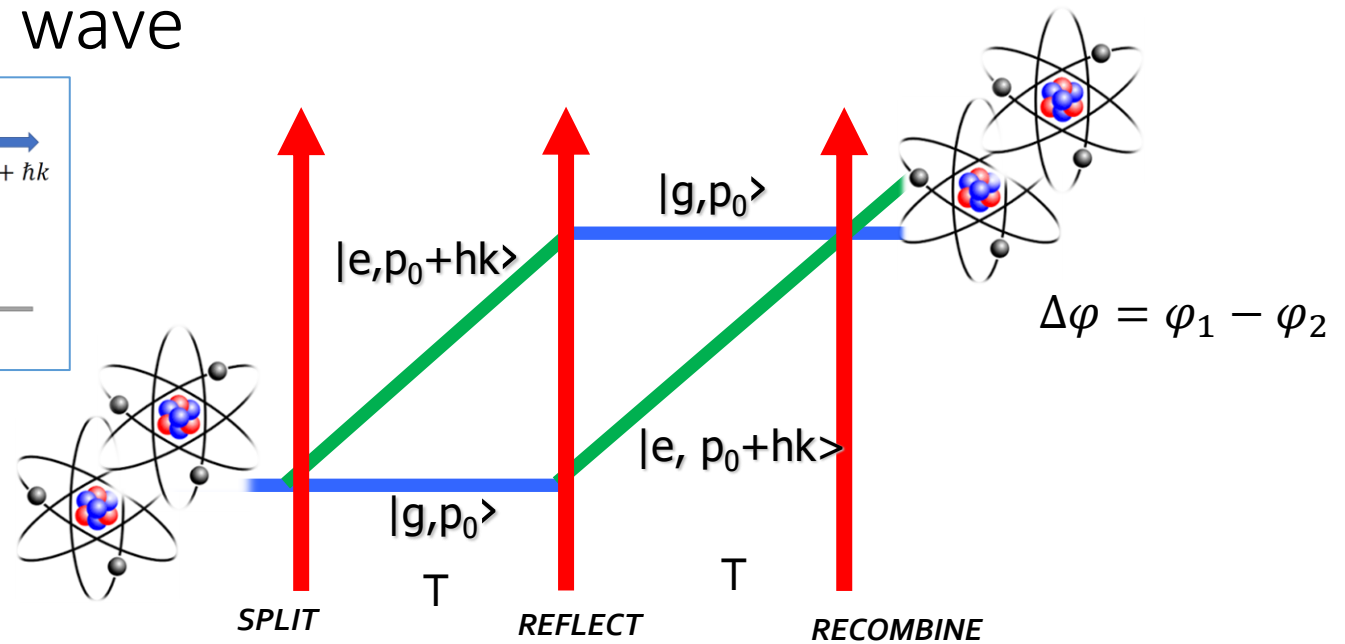
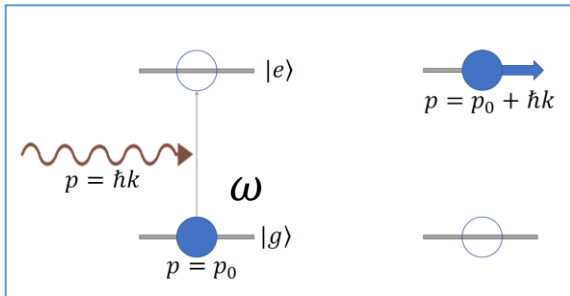
half-meter wave packet separation



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

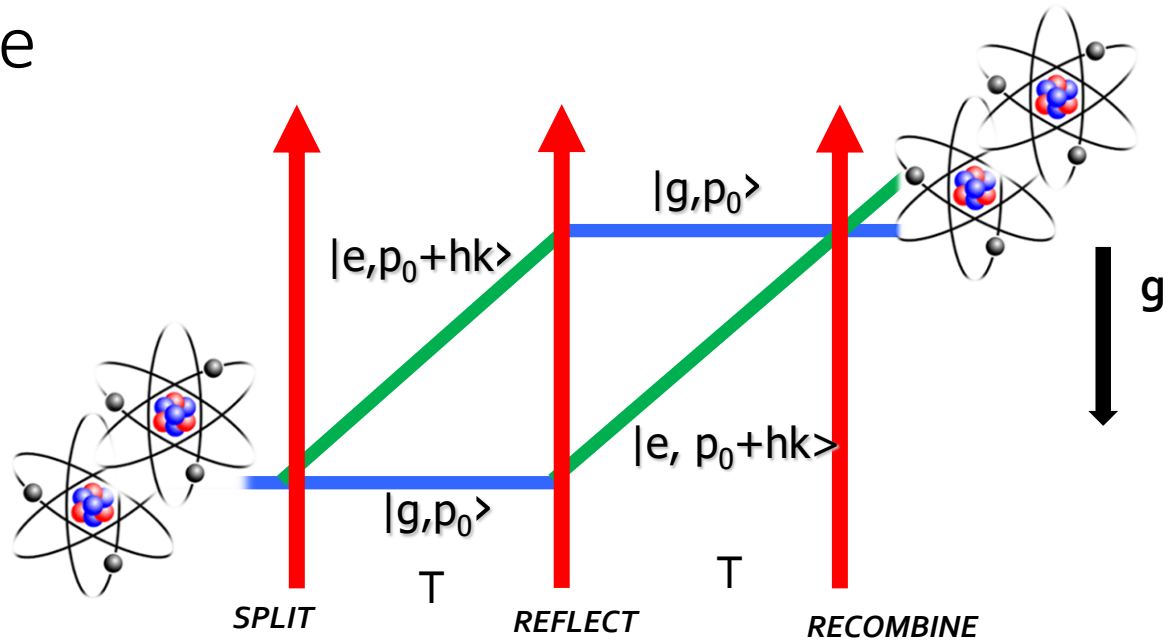
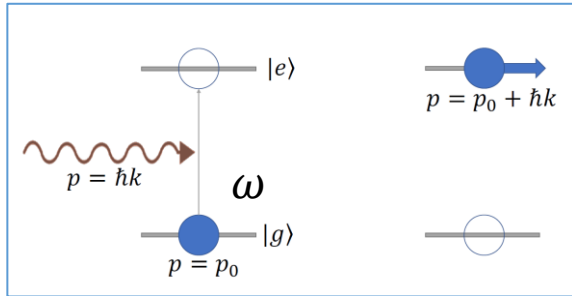
ATOM INTERFEROMETERS

light \rightarrow matter wave



ATOM INTERFEROMETERS - GRAVIMETERS

light \rightarrow matter wave



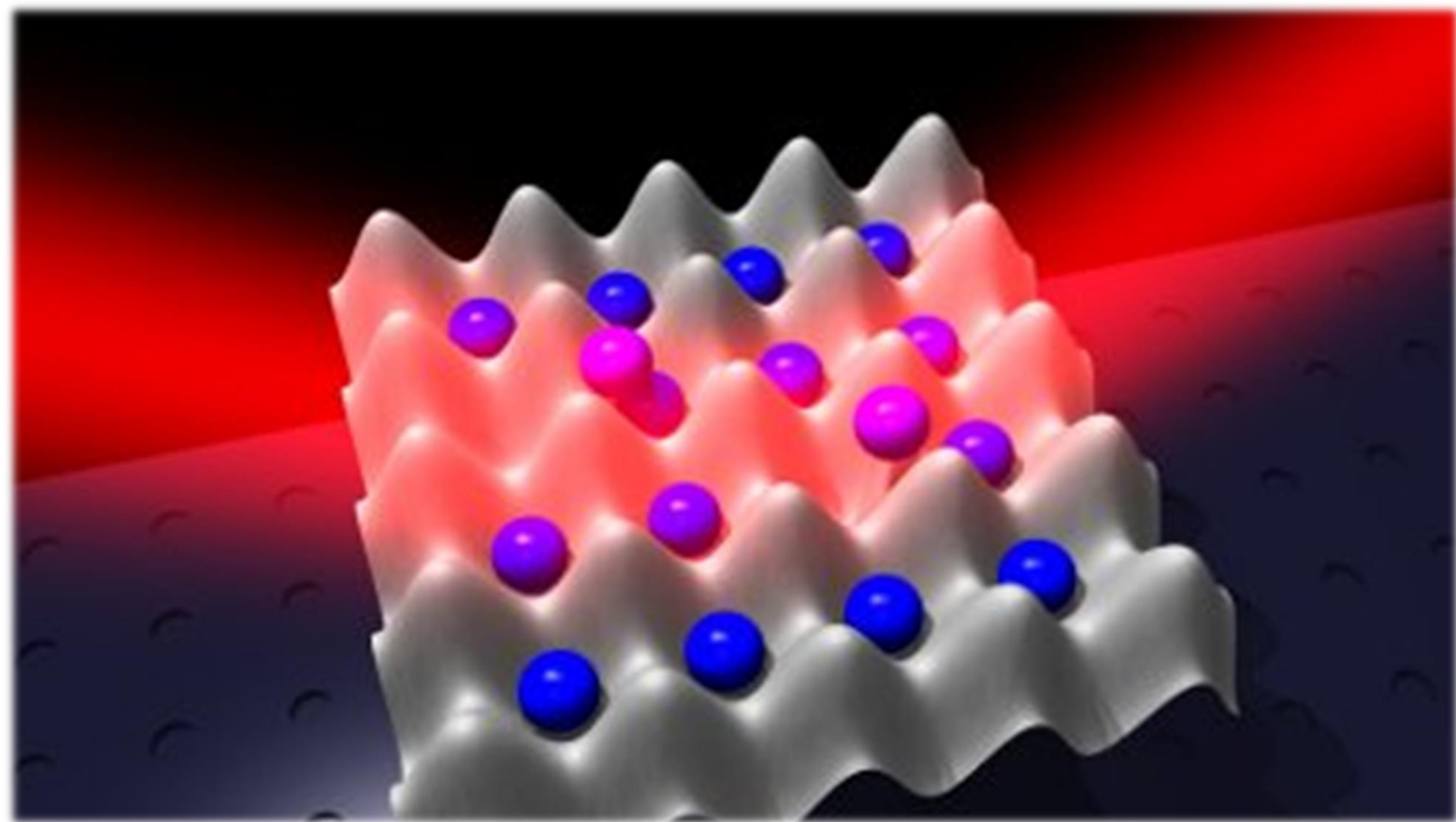
✓ Sensitivity

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

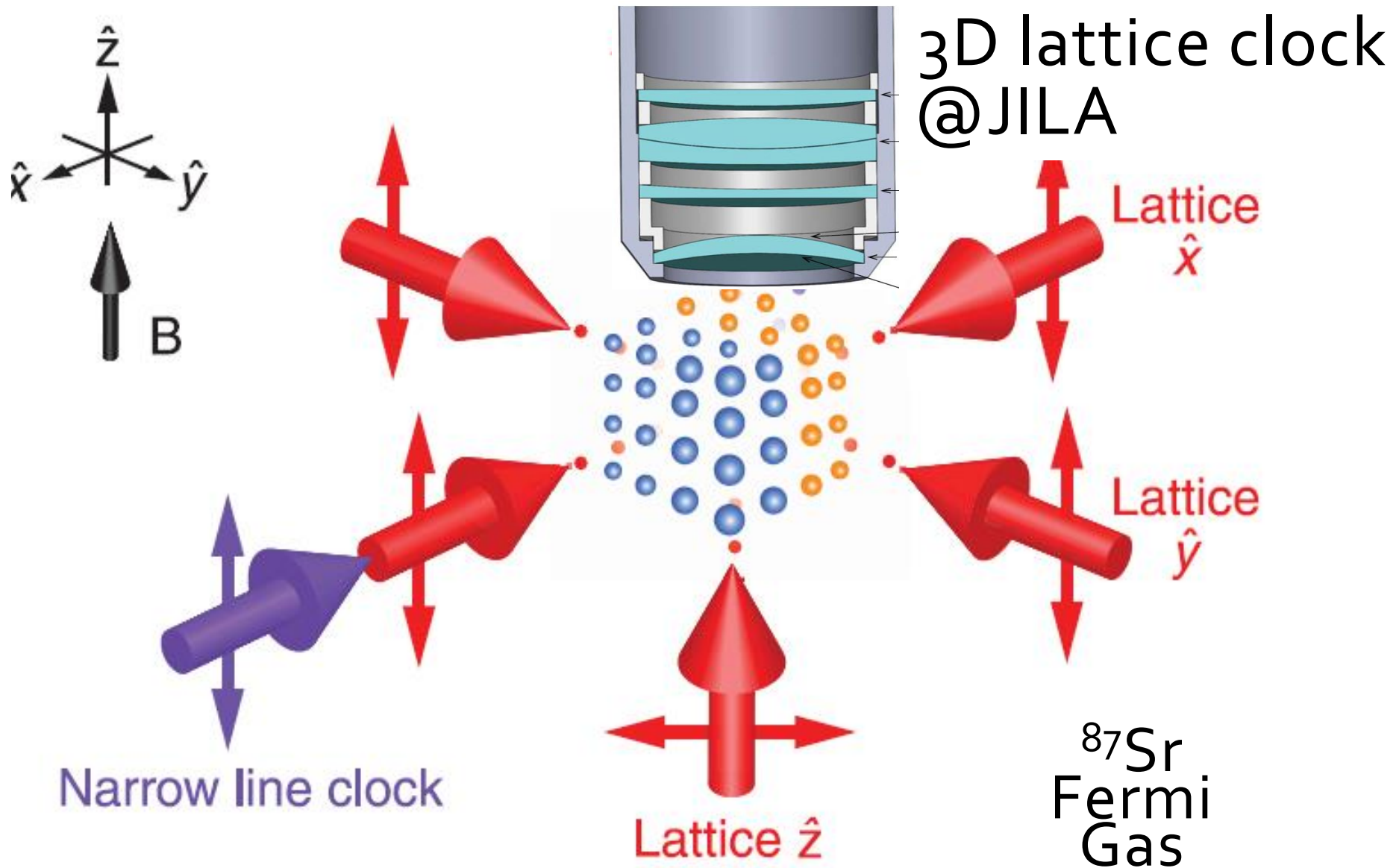
~1 mrad
~107 m⁻¹ ~1 s

Rb, Cs, ...

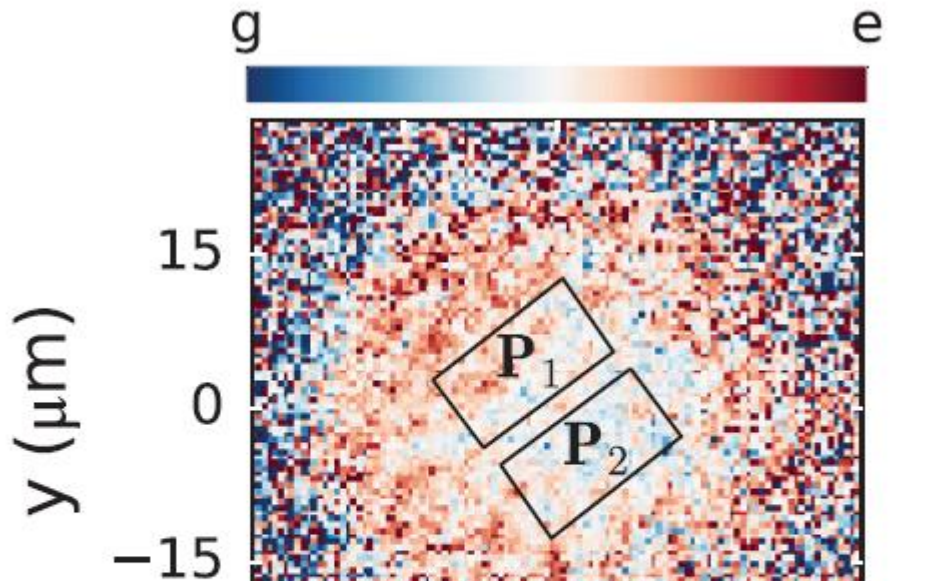
IMAGING OPTICAL FREQUENCIES



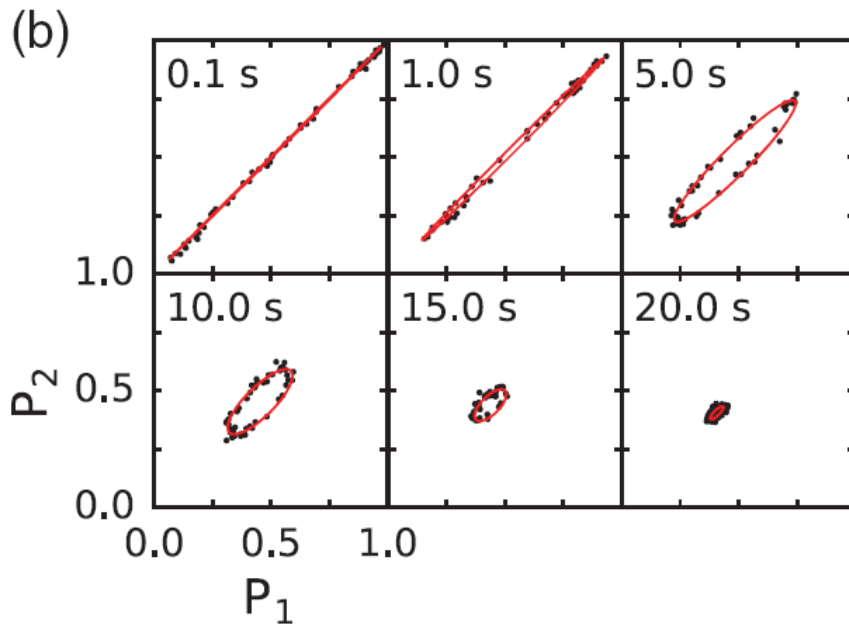
IMAGING OPTICAL FREQUENCIES



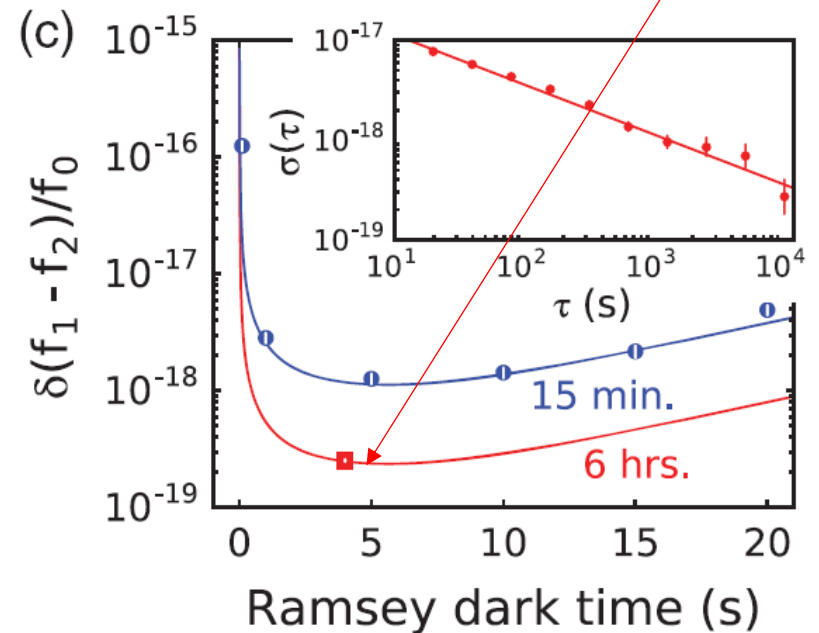
IMAGING OPTICAL FREQUENCIES



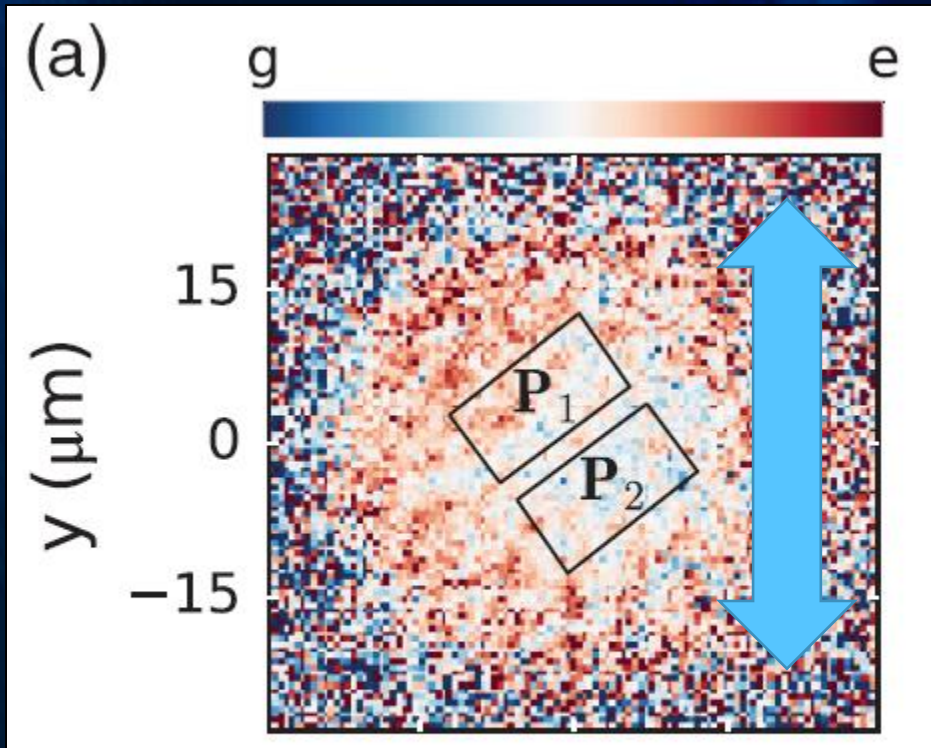
G. E. Marti, R. B. Hutson, A. Goban, S. L. Campbell, N. Poli, J. Ye, "Imaging optical frequencies with 100 μHz precision and 1.1 μm resolution", Phys. Rev. Lett. (2018)



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



Gravitational Red Shift



$10 \mu\text{m}$

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

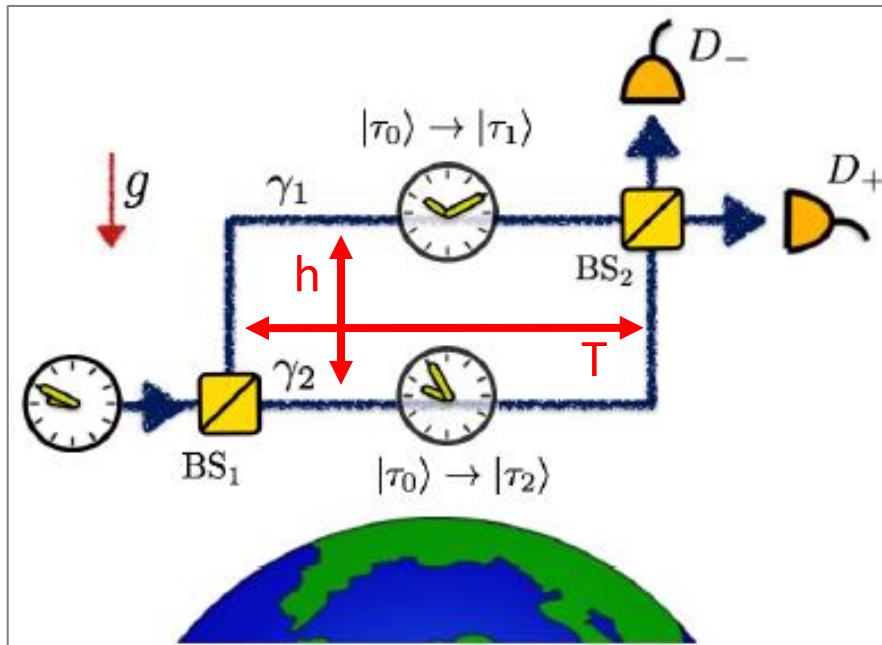
$$\Delta\nu/\nu = 10^{-22}$$

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

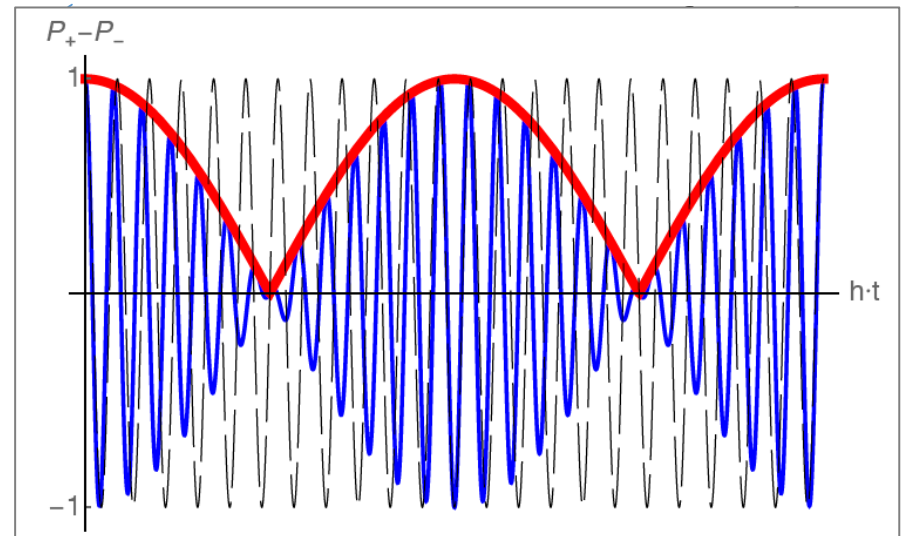


QUANTUM INTERFERENCE OF CLOCKS

Observe gravity induced “decoherence” in clock interferometers

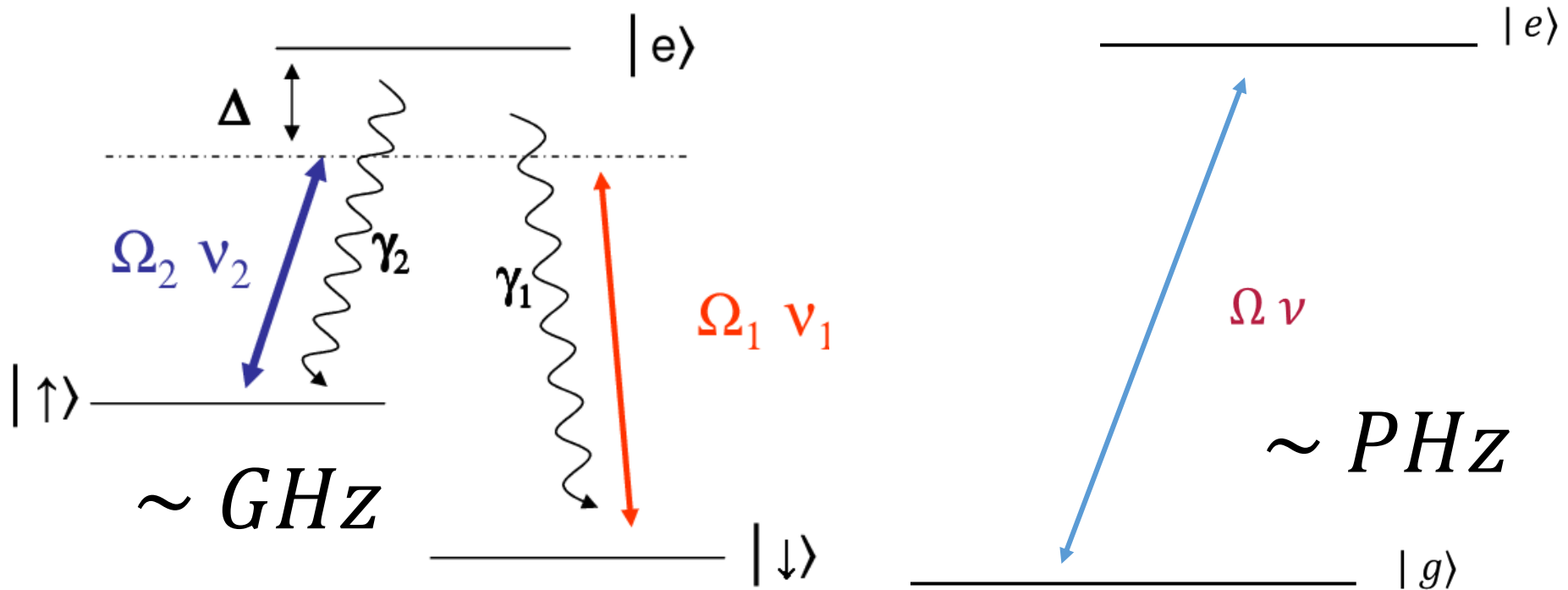


M. Zych et al. Nature Commun. 2(505), 1498 (2011)



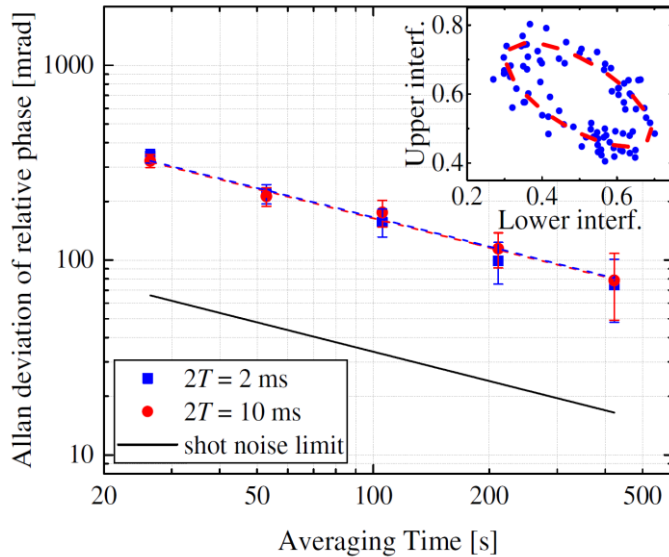
- ✓ Interferometer contrast loss
- ✓ Decoherence induced by “which path” information from clock state

TWO PHOTONS (BRAGG-RAMAN) – SINGLE PHOTON



SINGLE-PHOTON INTERFEROMETRY WITH STRONTIUM ATOMS

Clock Gradiometer Sr – 698 nm

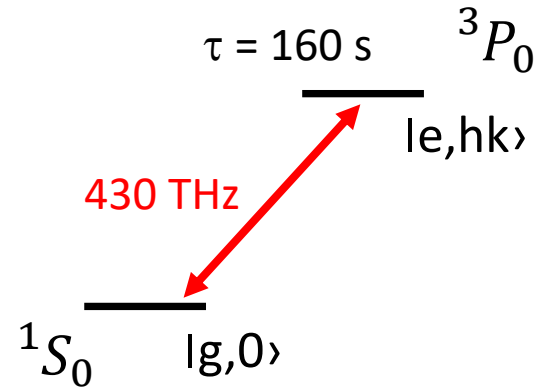


L. Hu *et al.*, *Phys. Rev. Lett.* **119** 263601 (2017)

**100 m tower experiments
on Sr clock interferometry**

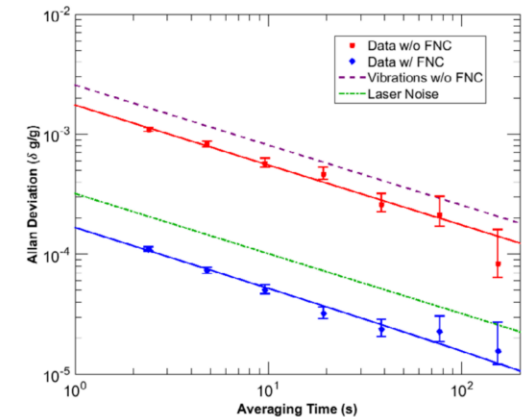
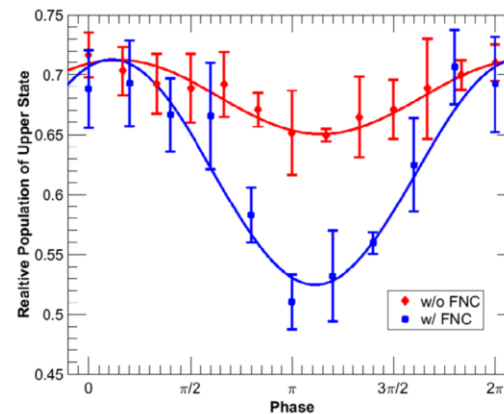
**AION (UK),
MAGIS (USA),**

...



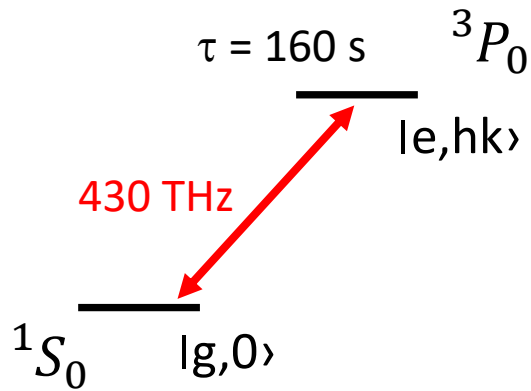
Single photon
(momentum states
+ electronic states)

Clock Gravimeter Sr – 698 nm

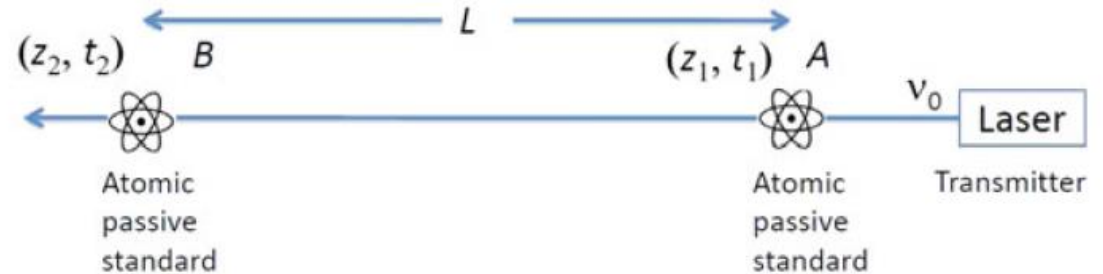


L. Hu *et al.*, *Class. Quantum Grav.* **37** 014001 (2020)

SINGLE-PHOTON INTERFEROMETRY WITH STRONTIUM ATOMS

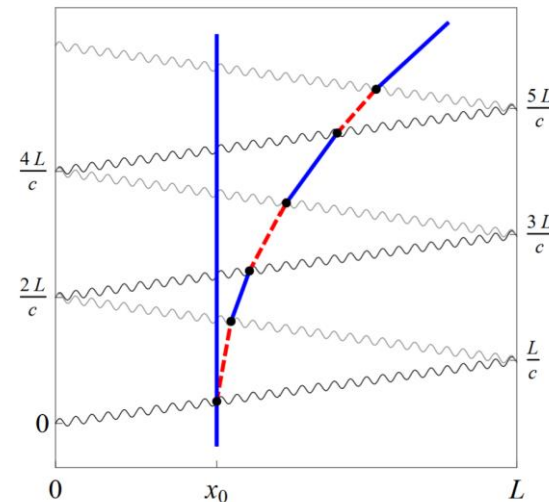
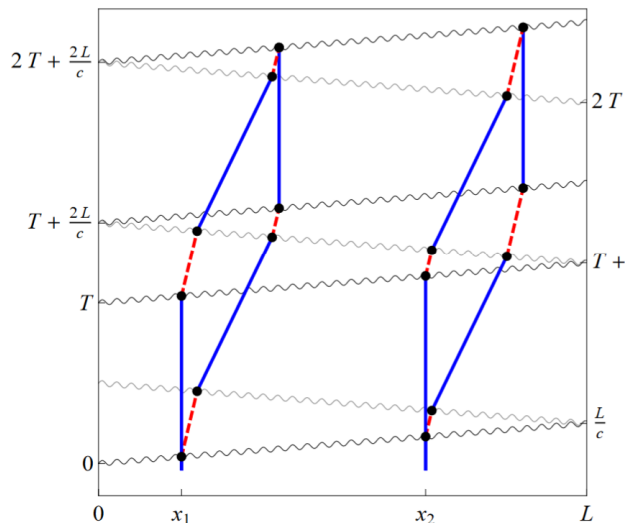


✓ A new GW Detector



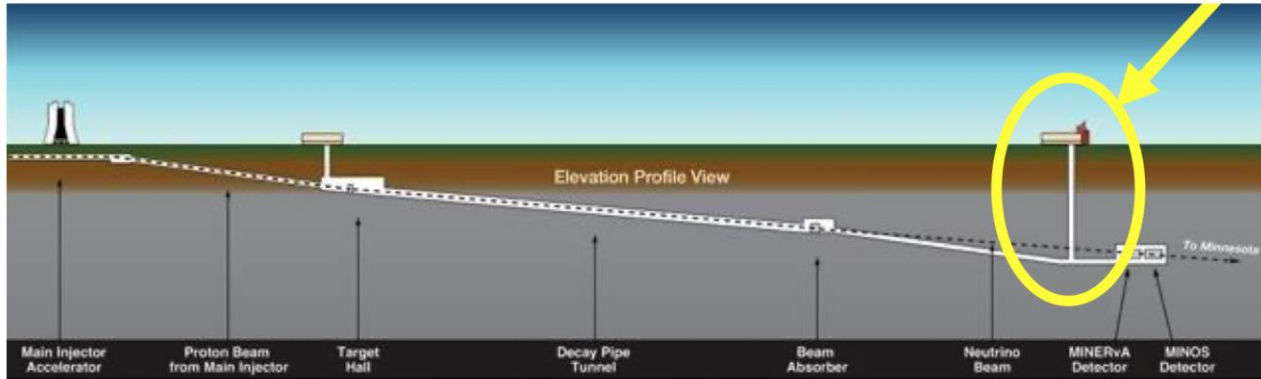
N. Yu, M. Tinto, Gen. Relativ. Gravit. **43**, 1943 (2011)

✓ LMT with strontium clock transition

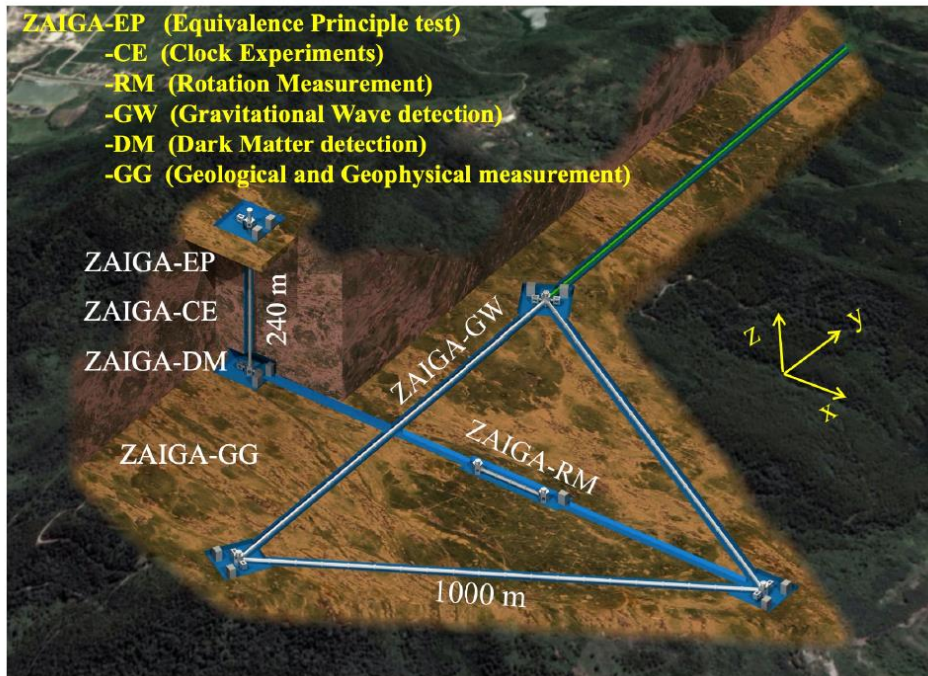


P. W. Graham, et al. Phys. Rev. Lett. **110**, 171102 (2013)

LARGE SCALE ATOM INTERFEROMETERS



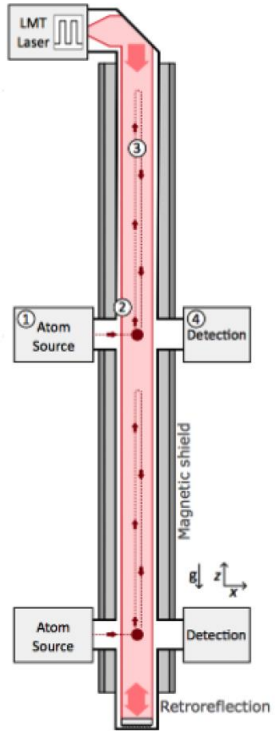
MAGIS 100
(Fermilab - USA)



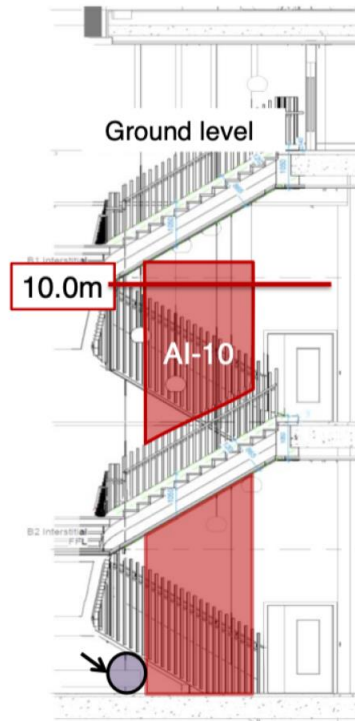
**ZAIGA (Wuhan,
CHN)**

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

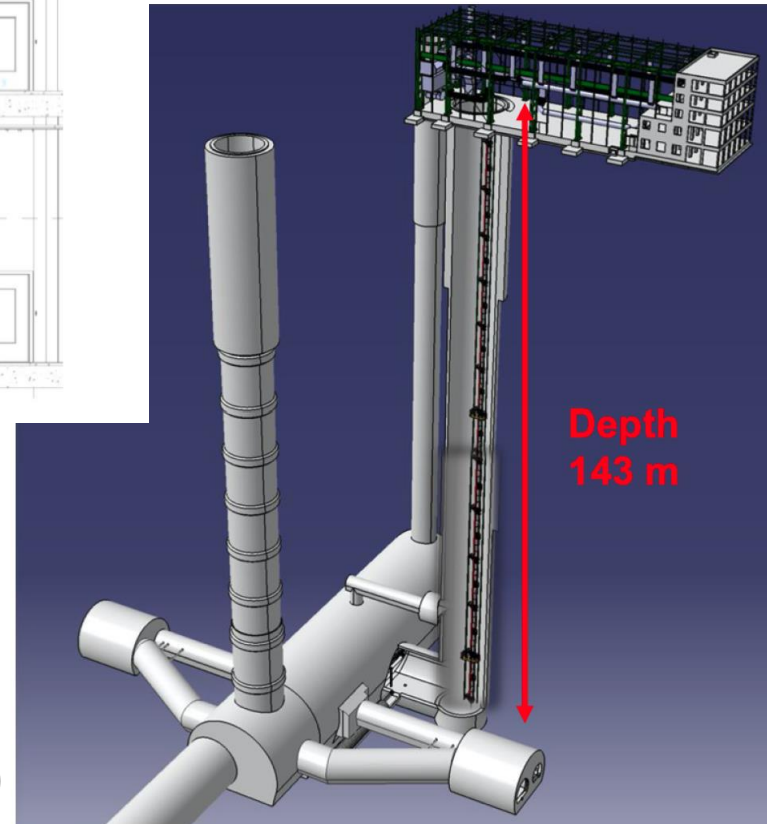
LARGE FOUNTAINS



Laser lab for AION
vibration criterion, VC-G = 10nm@10Hz. Temperature (22±0.1)° C



AION-10 (Oxford, UK)

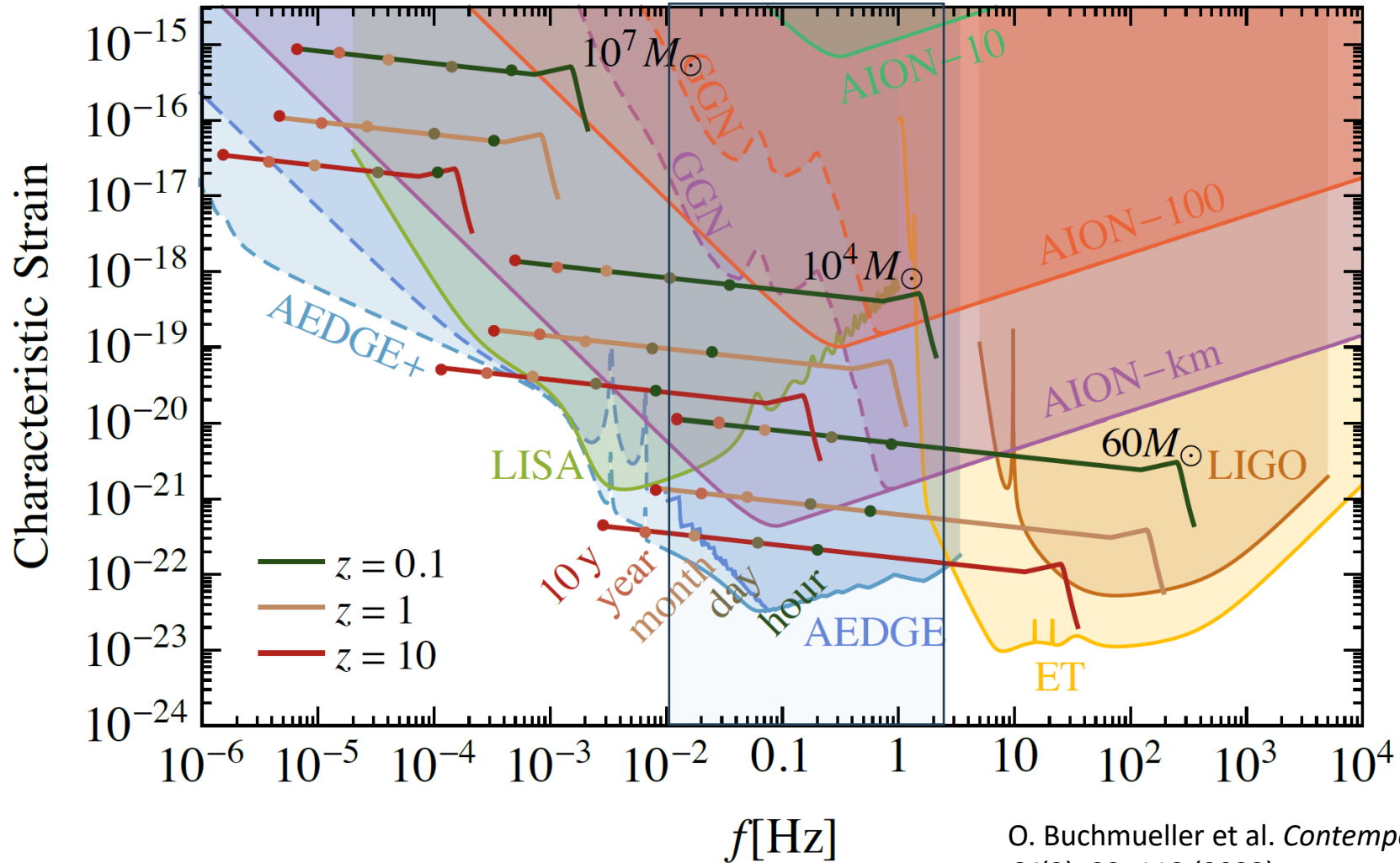


AION 100 (CERN, CH)

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

GRAVITATIONAL WAVES

Mid freq. band (0.01 – 1) Hz

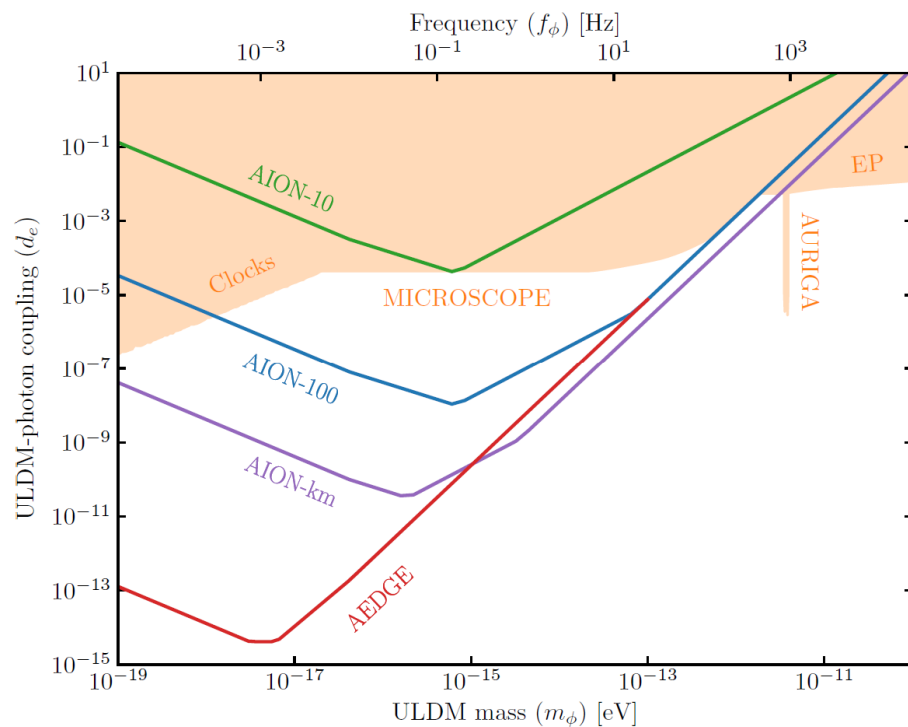
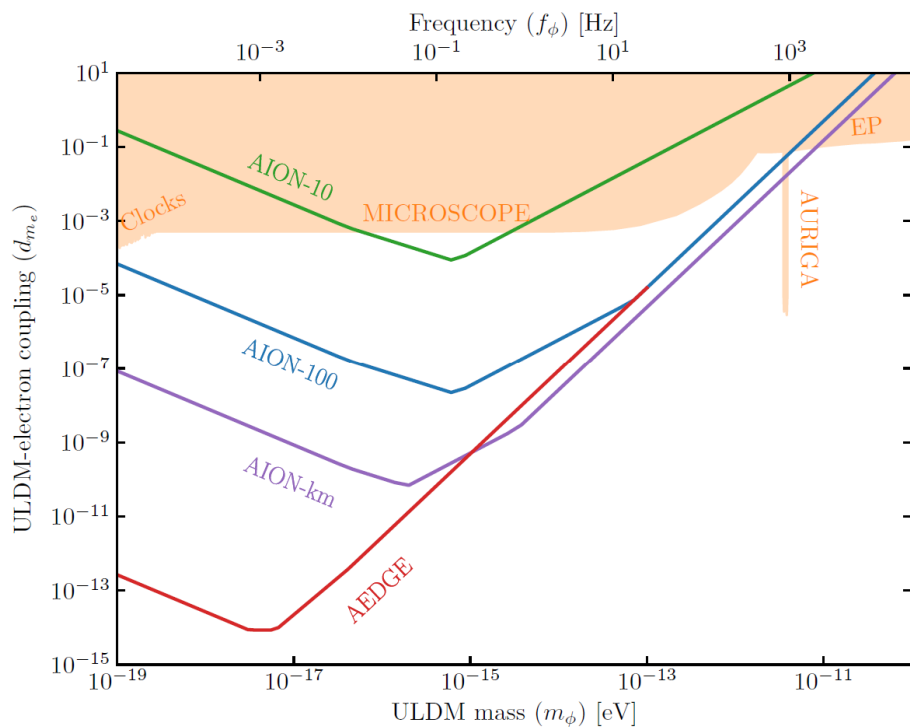


O. Buchmueller et al. *Contemporary Physics*, 64(2), 93–110 (2023)

DARK MATTER SEARCH

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

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



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

CLOCK INTERFEROMETRY CANDIDATES

Periodic Table of the Elements

1 1A H Hydrogen 1.008	2 IIA 2A He Helium 4.003																
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 13 IIIA 3A B Boron 10.811	6 14 IVA 4A C Carbon 12.011	7 15 VA 5A N Nitrogen 14.007	8 16 VIA 6A O Oxygen 15.999	9 17 VIIA 7A F Fluorine 18.998	10 18 VIIIA 8A Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 F1 Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

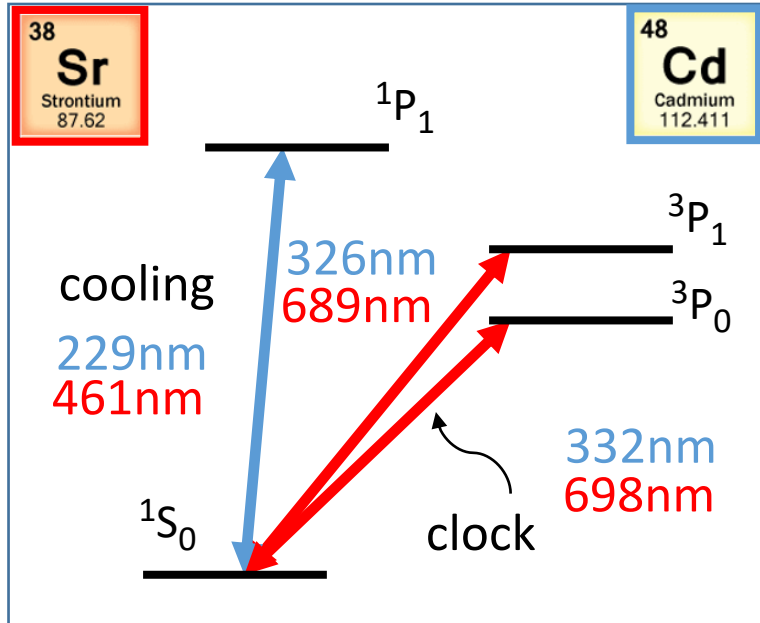
Lanthanide Series	57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide
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sciencenotes.org

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)

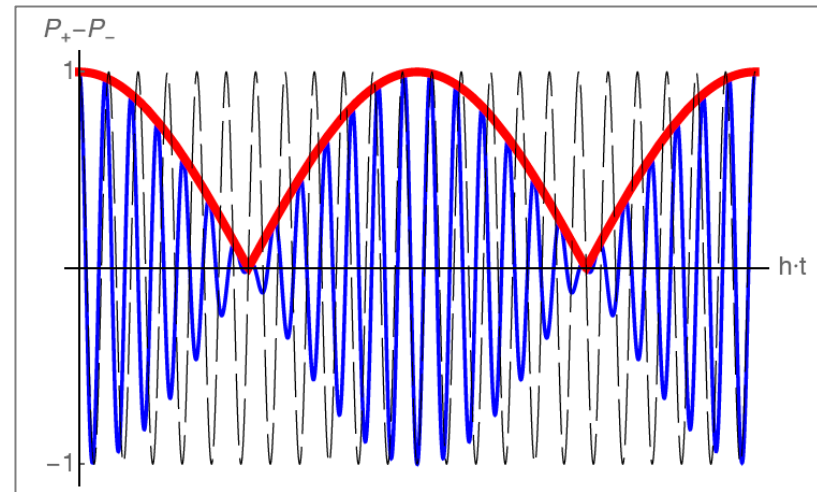
QUANTUM INTERFERENCE OF CLOCKS

- ✓ Interferometer contrast **modulation**

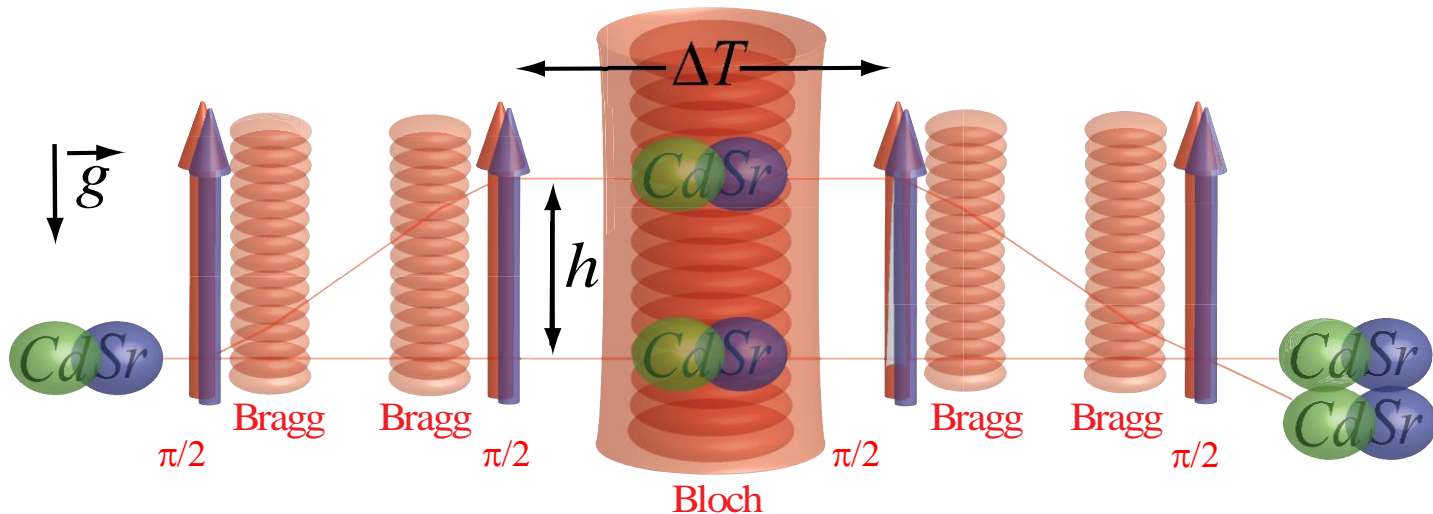
$$(h \cdot T)_{Sr} = 21 \text{ m s}$$

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

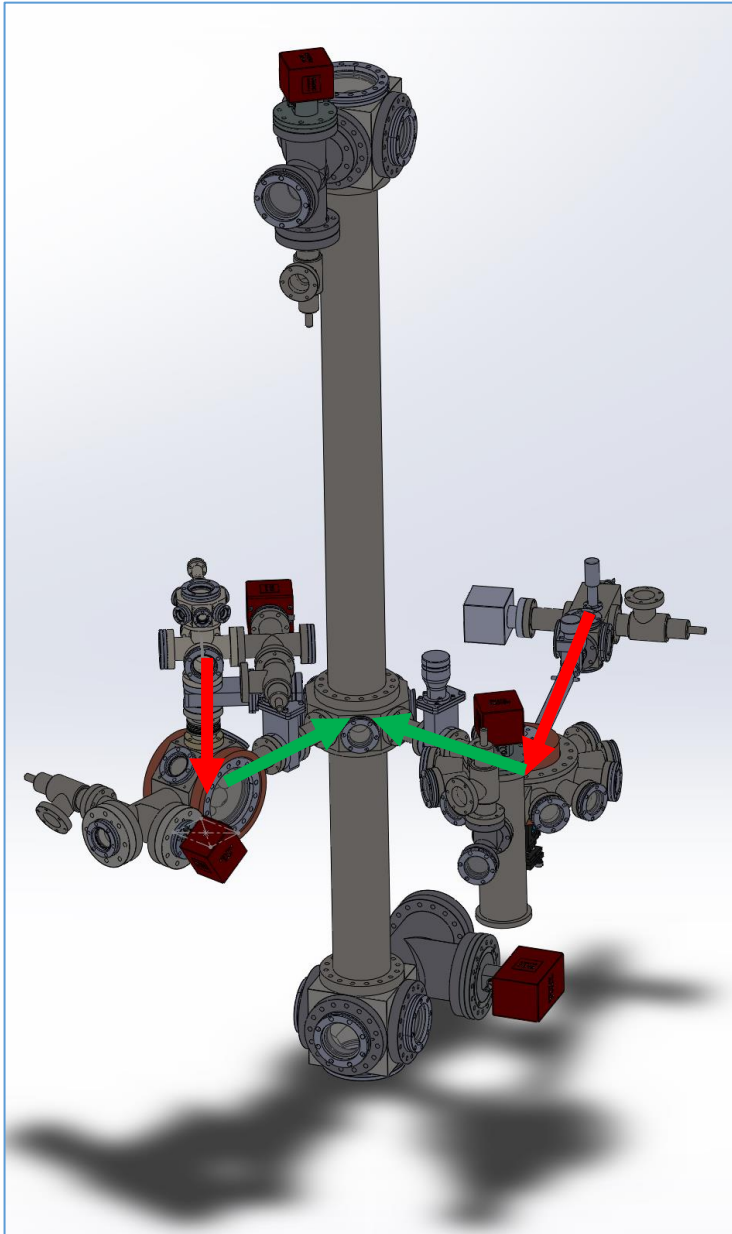
Full revival for $h=2 \text{ m}$, time $T = 5 - 10 \text{ s}$



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



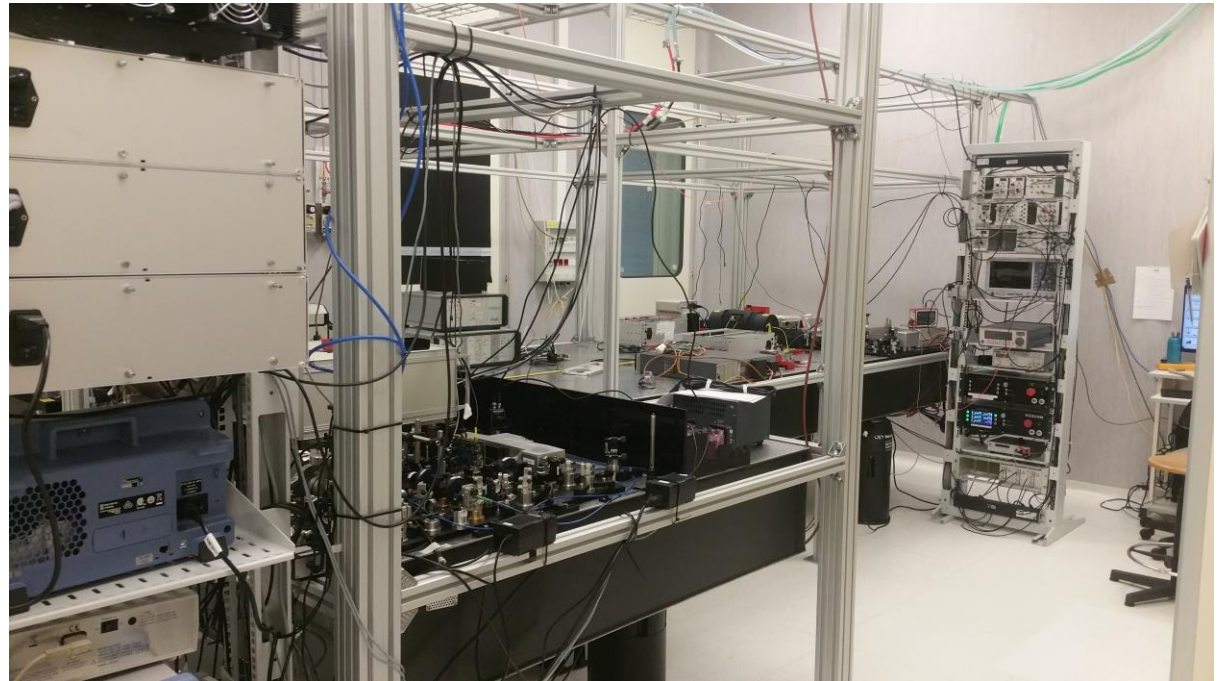
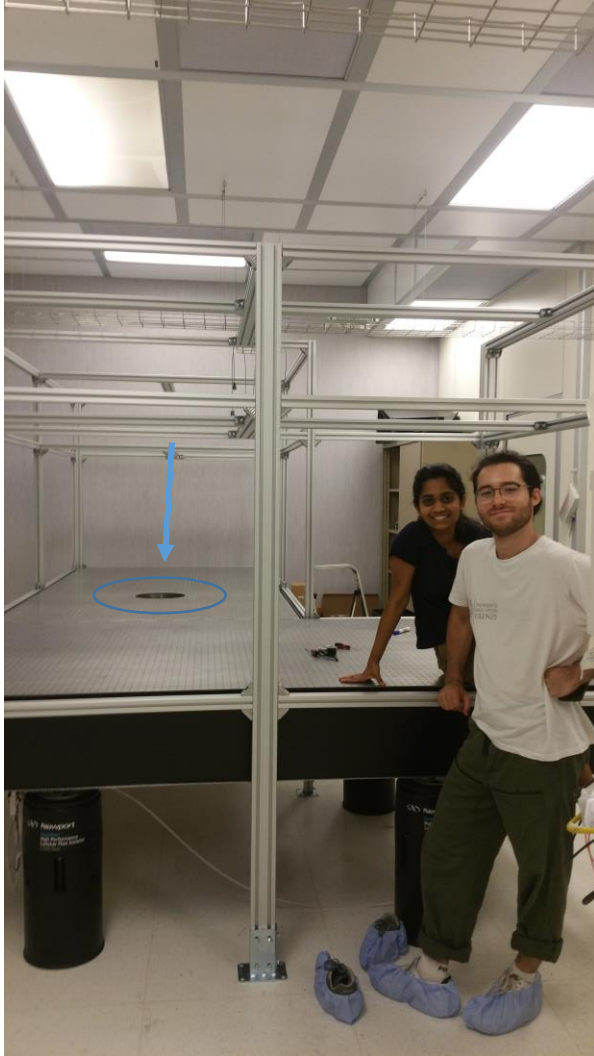
CD-SR INTERFEROMETRY CHAMBER



- 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

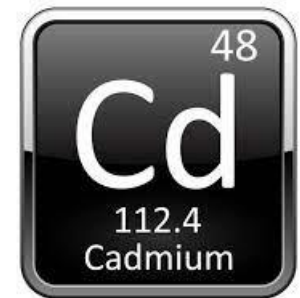


CADMIUM PROPERTIES

- ✓ 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%
$^{113}\text{Cd}^{(*)}$	12.23%
^{114}Cd	28.75%
$^{116}\text{Cd}^{(*)}$	7.51%

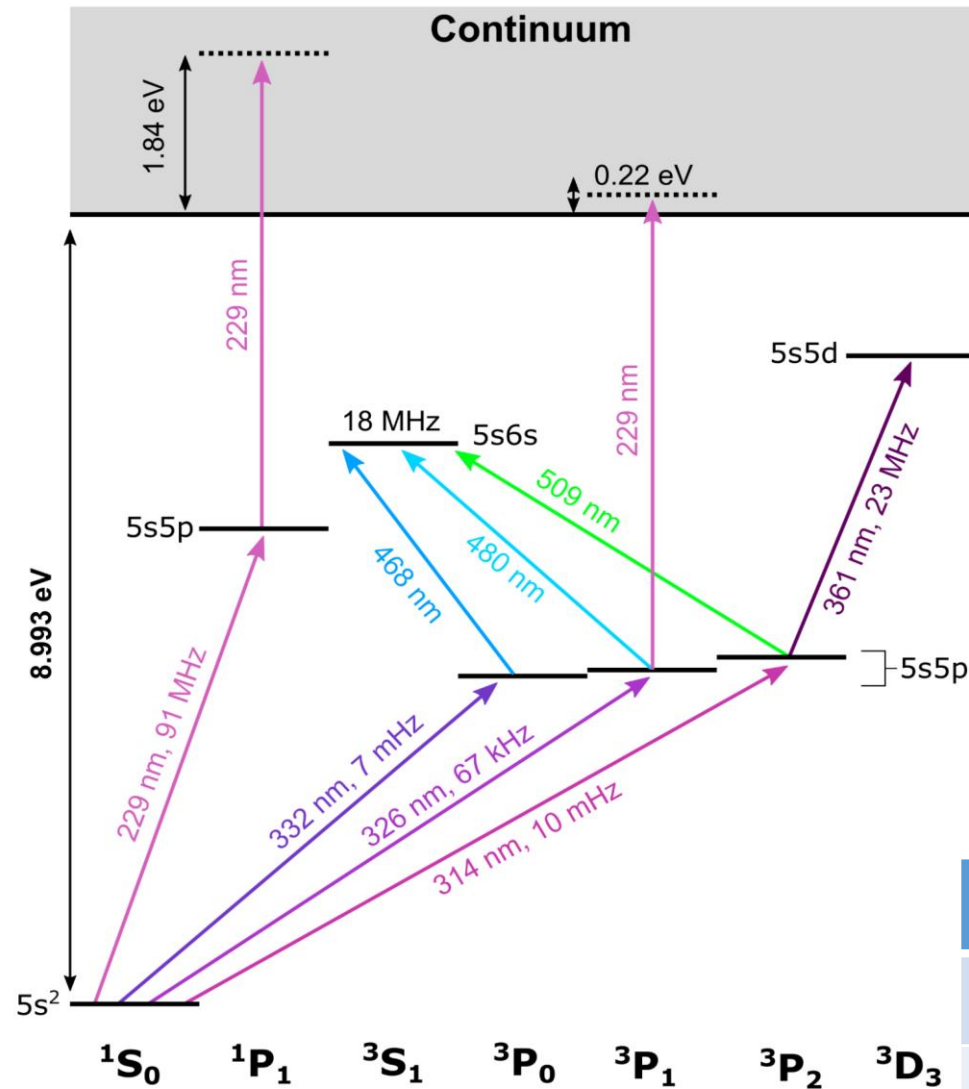
6 bosons ($l=0$)
 2 fermions ($l=1/2$)
 (*) long lifetime



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

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

COOLING AND TRAPPING CADMIUM



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

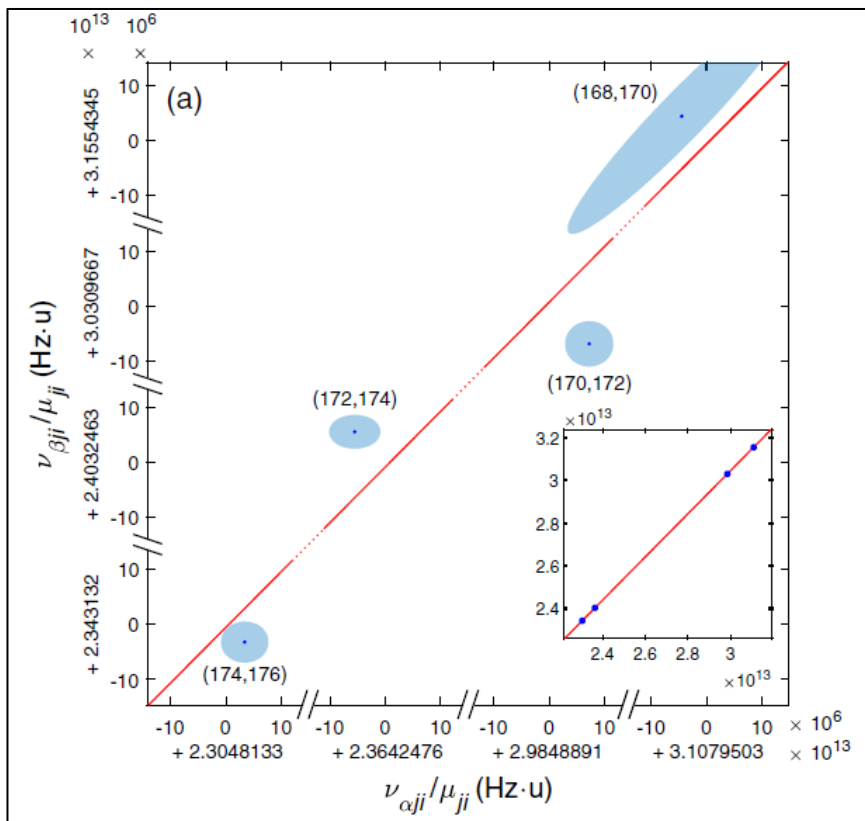
- High power available
- Low Doppler temperature

Transition	λ (nm)	$\Gamma/2\pi$	I_s (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	3×10^{-9}

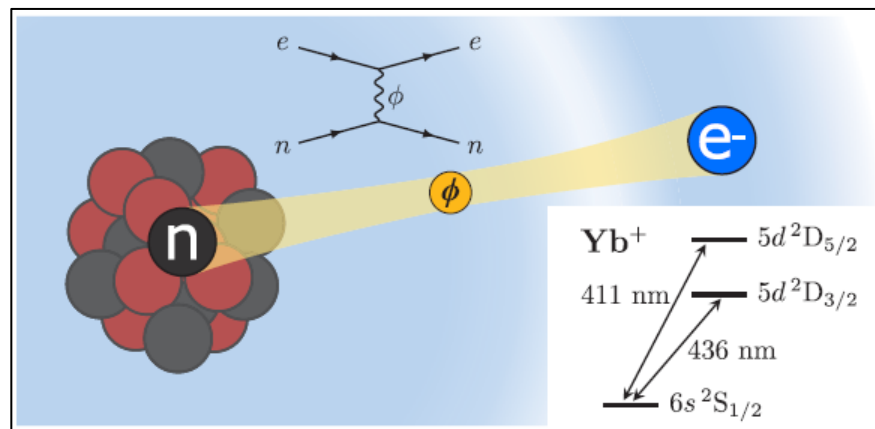
C. Monroe, H. Katori, K. Gibble, S. Truppe

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)

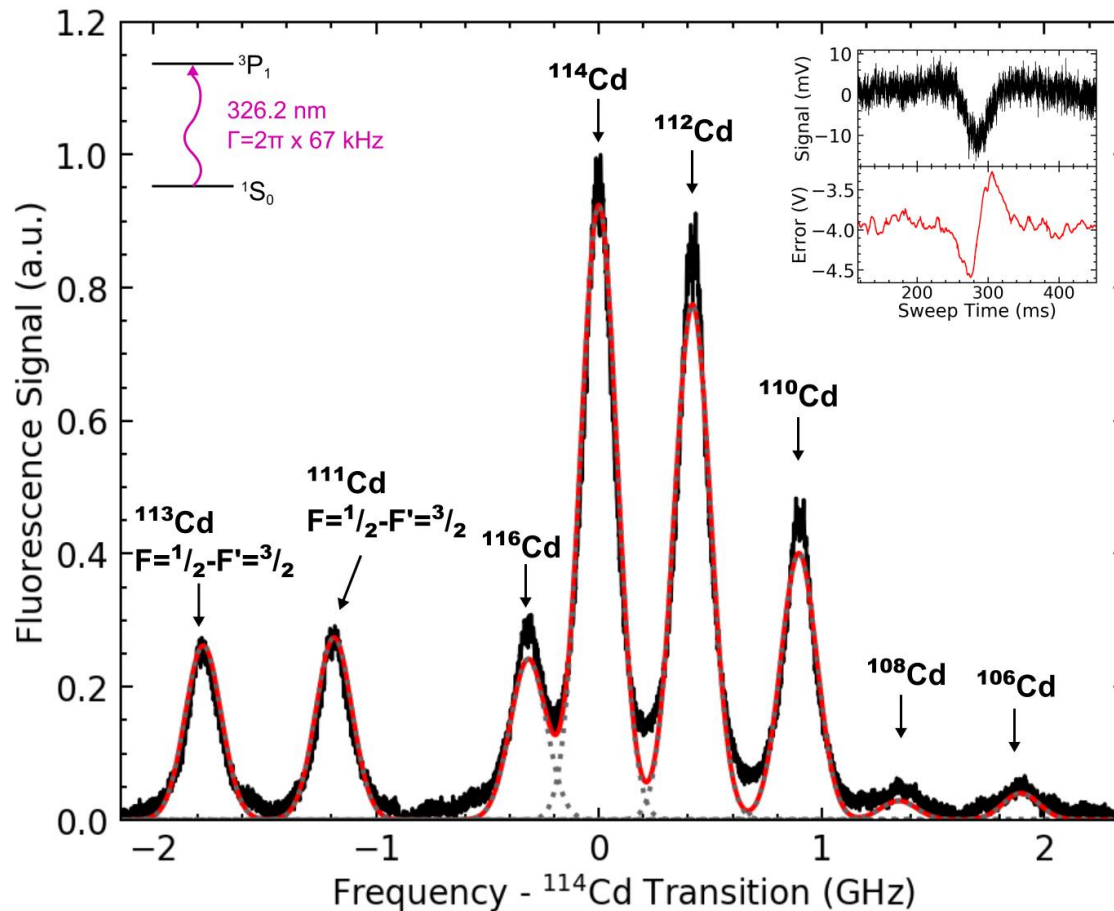


Isotope	Abundance	Nuclear Spin	Mass (u.m.a.)
¹⁰⁶ Cd	1.25%	0	105.906
¹⁰⁸ Cd	0.89%	0	107.904
¹¹⁰ Cd	12.49%	0	109.903
¹¹¹ Cd	12.80%	1/2	110.904
¹¹² Cd	24.13%	0	111.903
¹¹³ Cd	13.47%	1/2	112.904
¹¹⁴ Cd	28.73%	0	113.903
¹¹⁶ Cd	7.49%	0	115.905

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

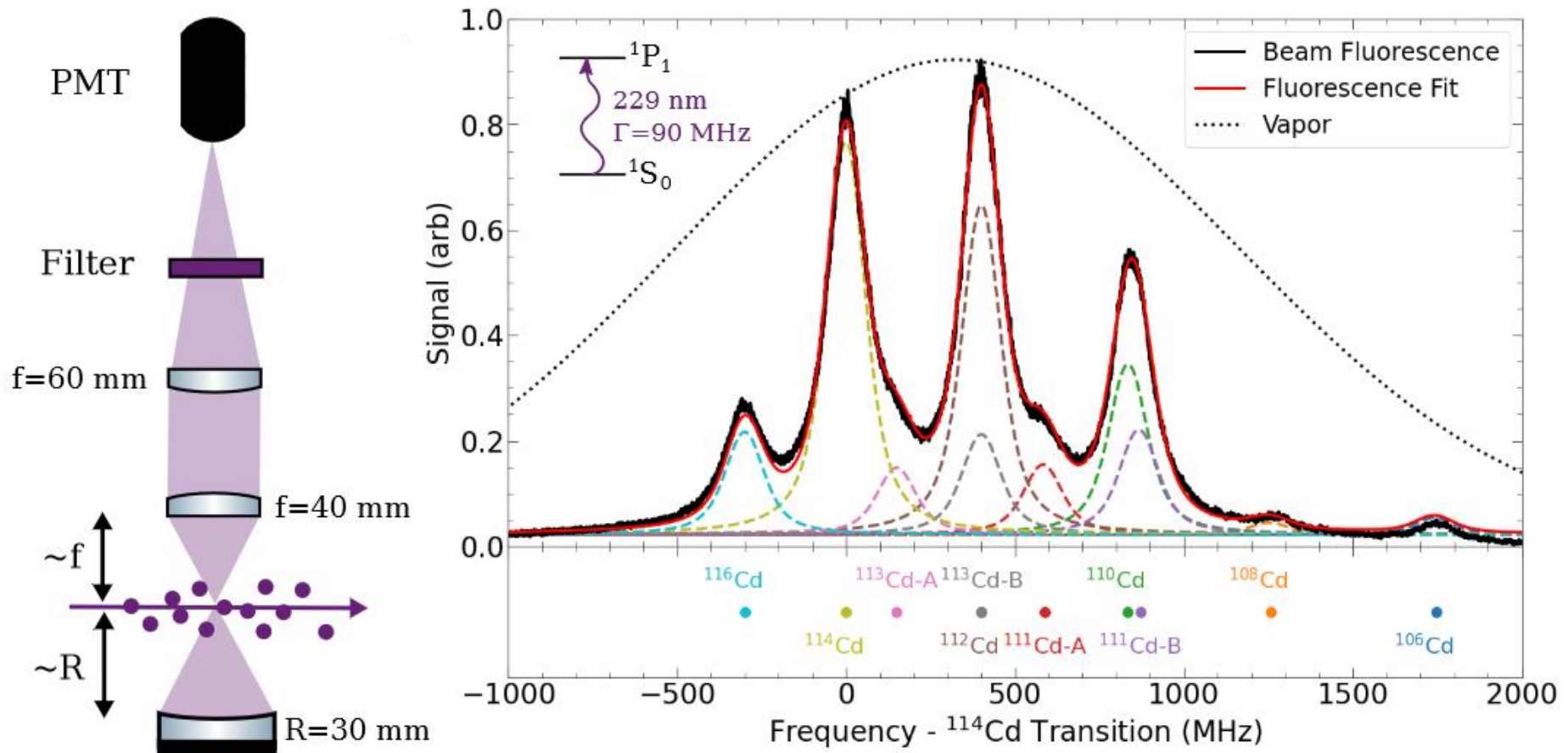
CD BEAM SPECTROSCOPY AT 326 NM

- 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 $^1\text{S}_0$ - $^3\text{P}_1$ 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)

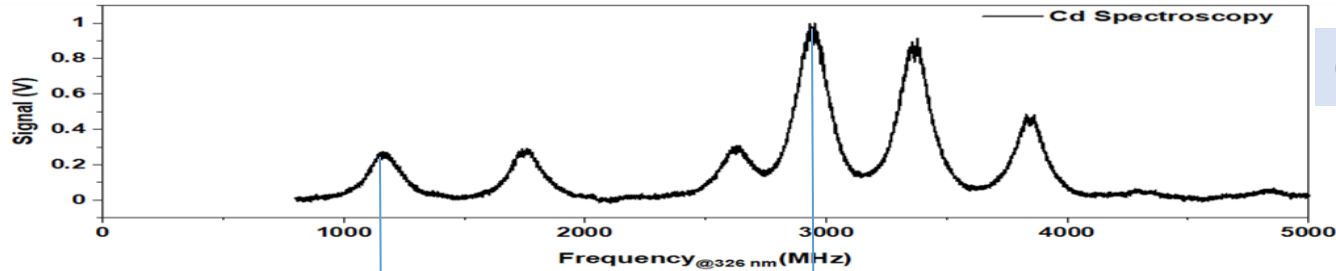
CADMIUM ISOTOPIC SHIFTS

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

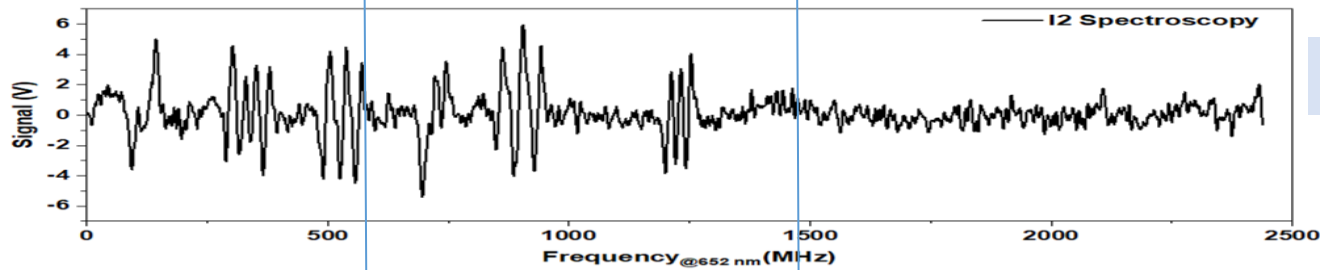
J. N. Tinsley, et al. "Watt-level blue light for precision spectroscopy, laser cooling and trapping of strontium and cadmium atoms", Optics Express 29 (16), 25462 (2021)



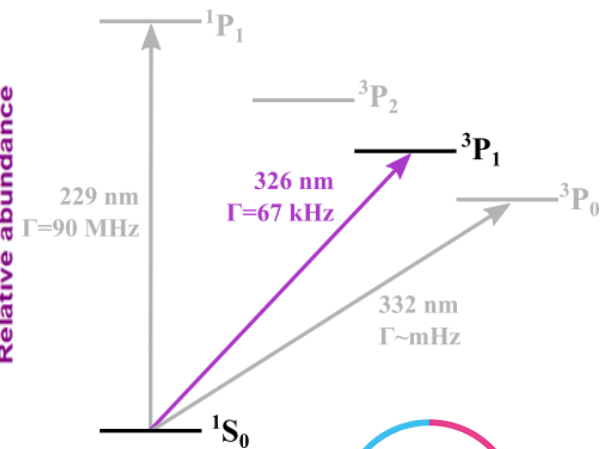
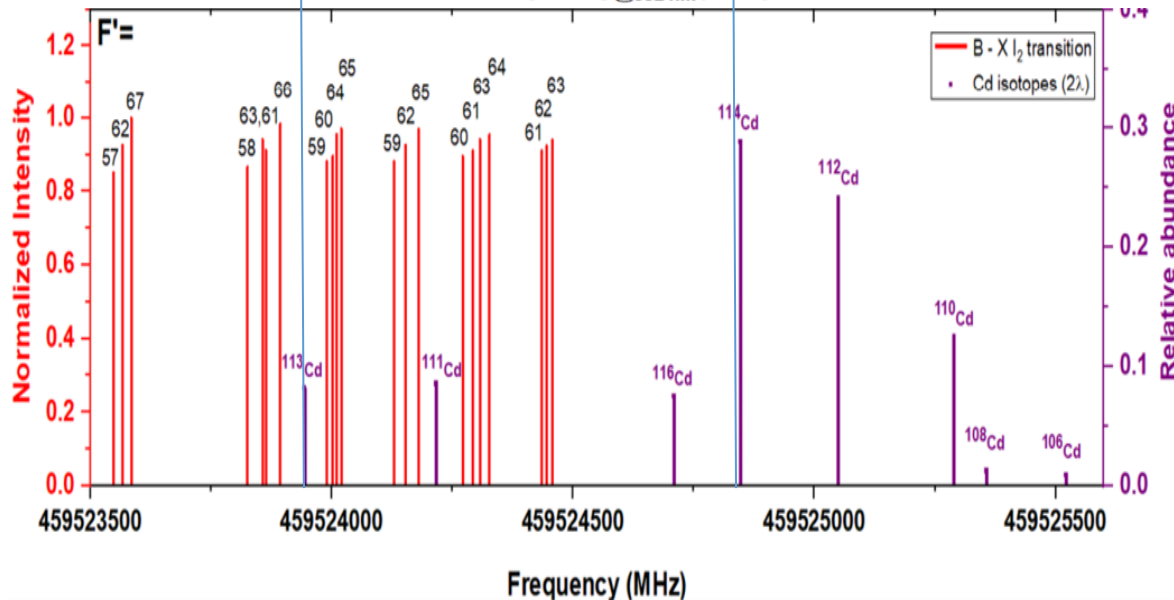
PRECISION SPECTROSCOPY OF IODINE MOLECULE



Cd Spectrum @ 326 nm



I2 spectrum @ 652 nm



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

HYPERFINE PARAMETERS DETERMINATION

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

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

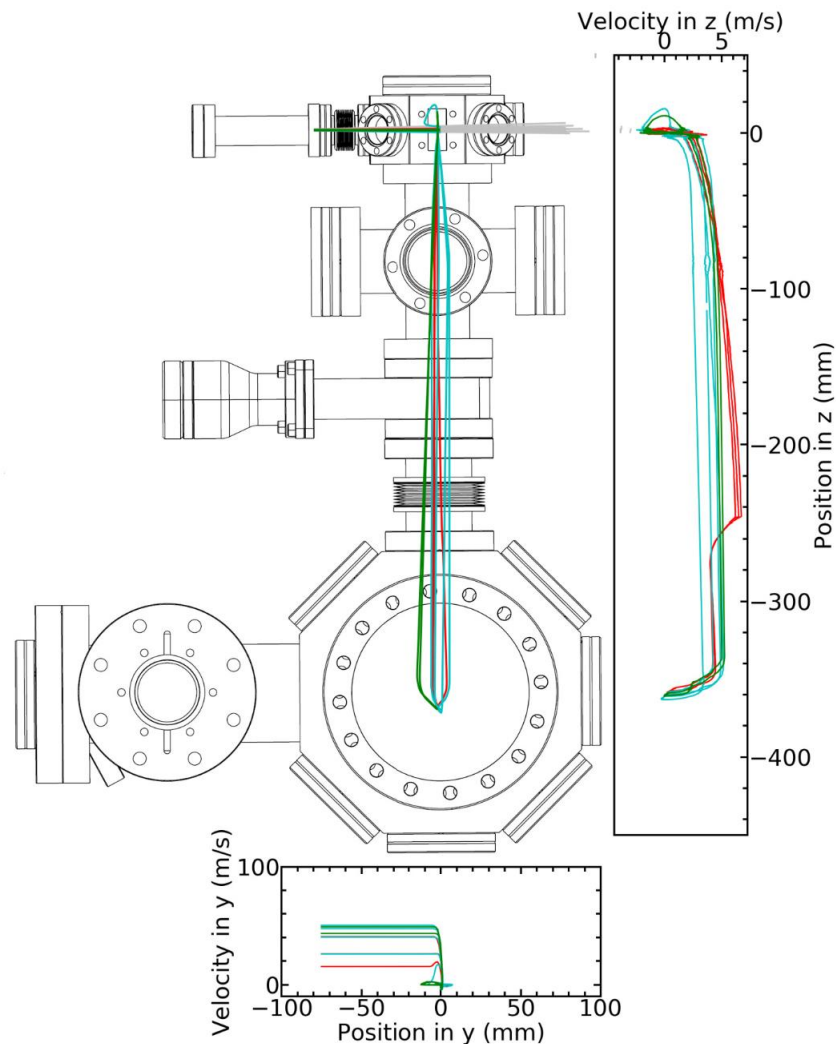
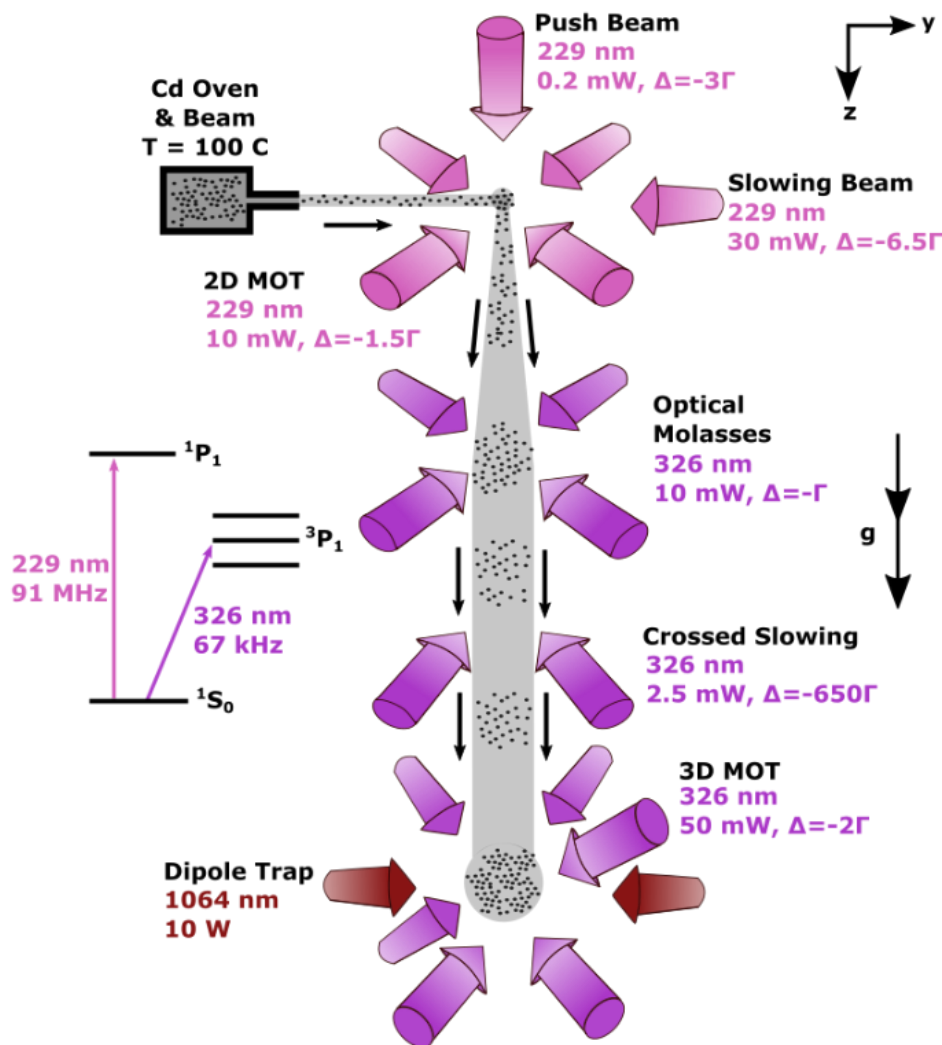
$$\hat{H}_R = T + B\hat{J}^2 - D\hat{J}^4 + H\hat{J}^6 + L\hat{J}^8 + M\hat{J}^{10}$$

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]
$\nu'=4$ 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)

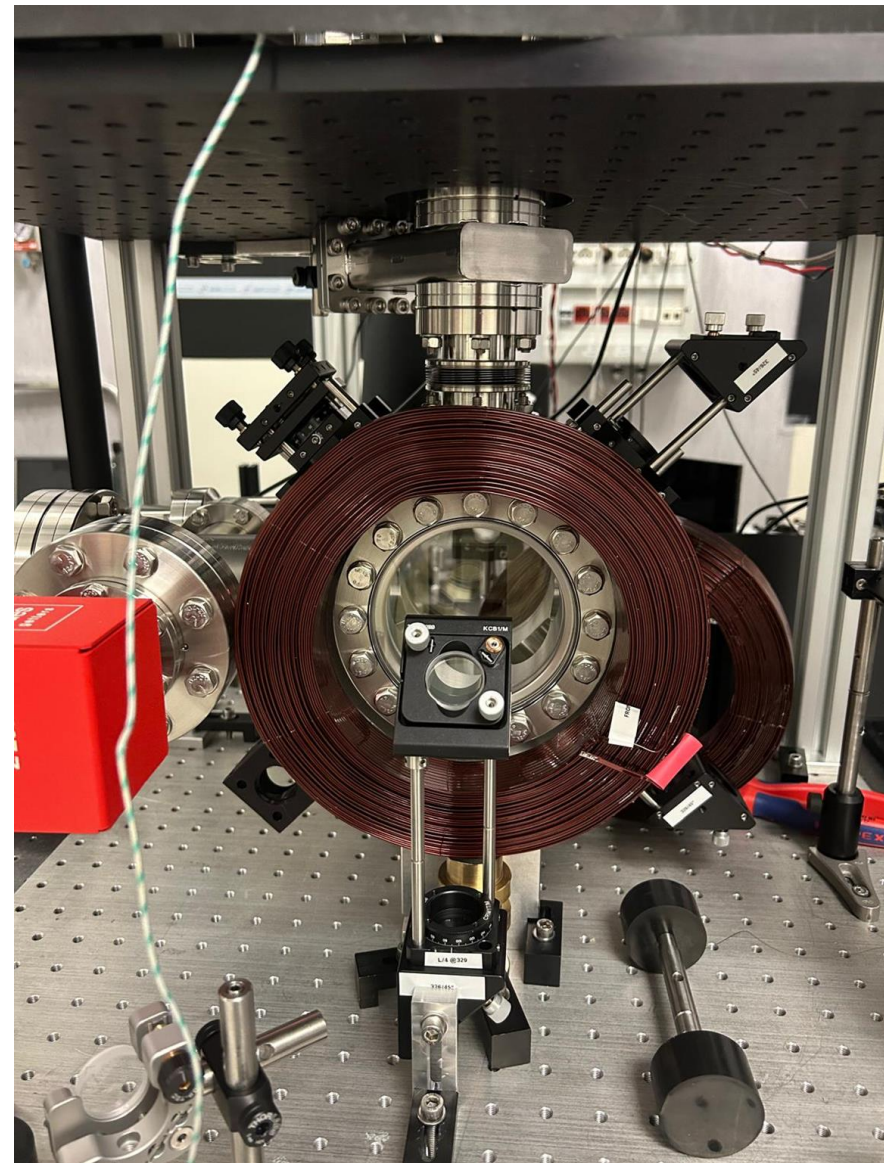
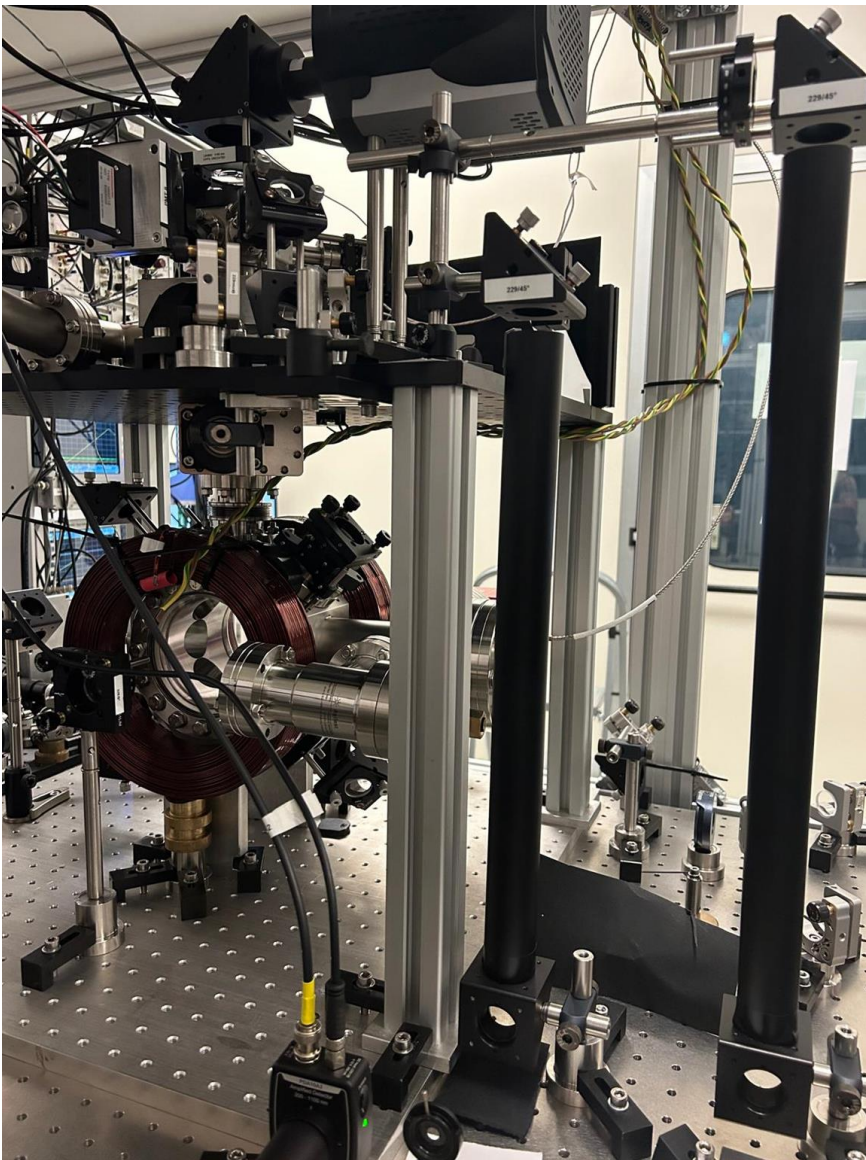


COOLING AND TRAPPING CADMIUM

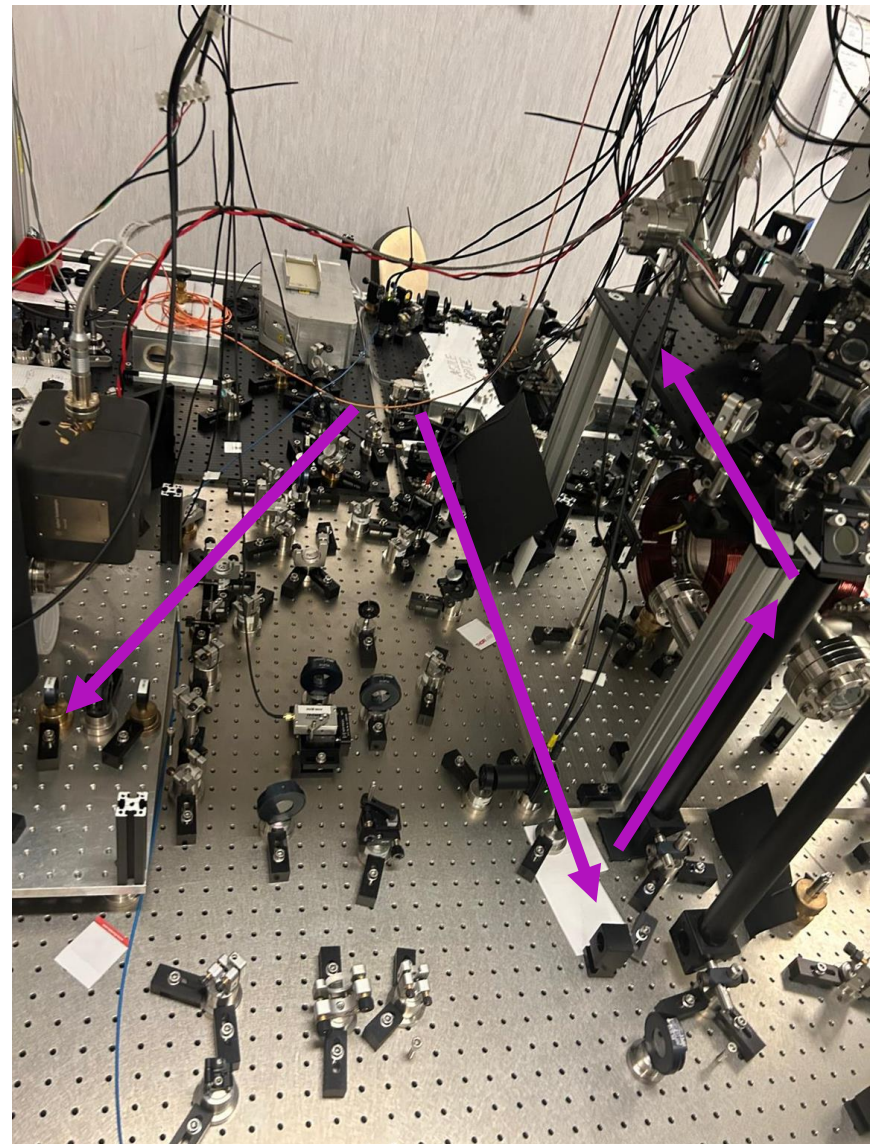
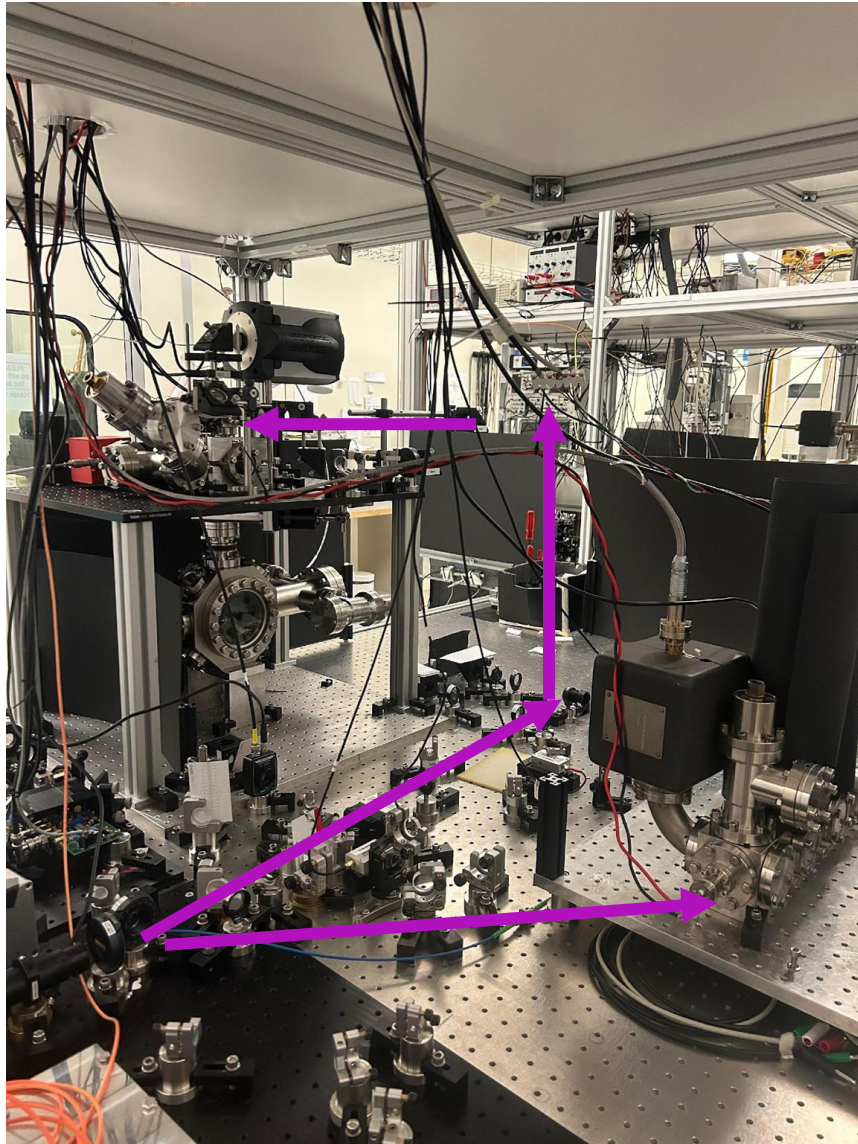


S. Bandarupally *et al.* *J. Phys. B: At. Mol. Opt. Phys.* **56** 185301 (2023)

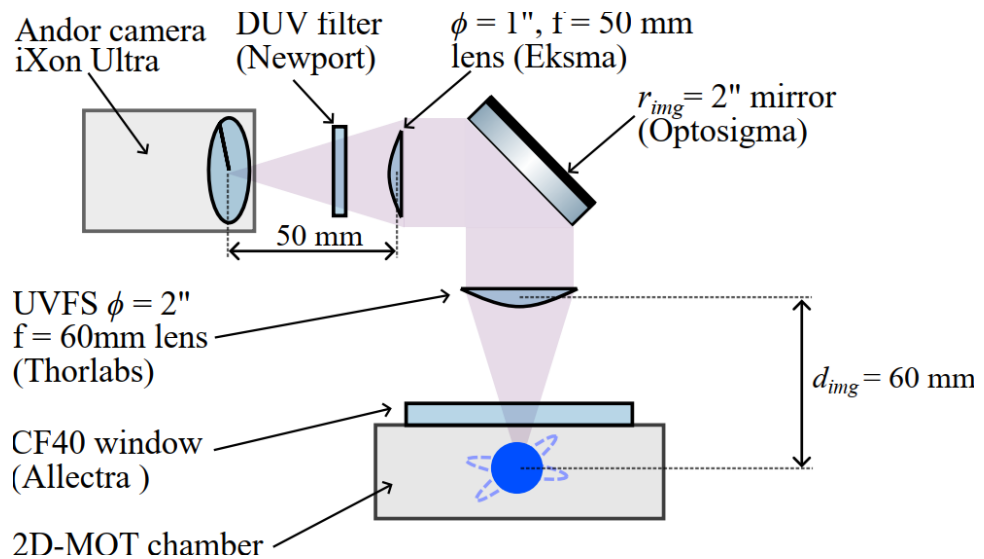
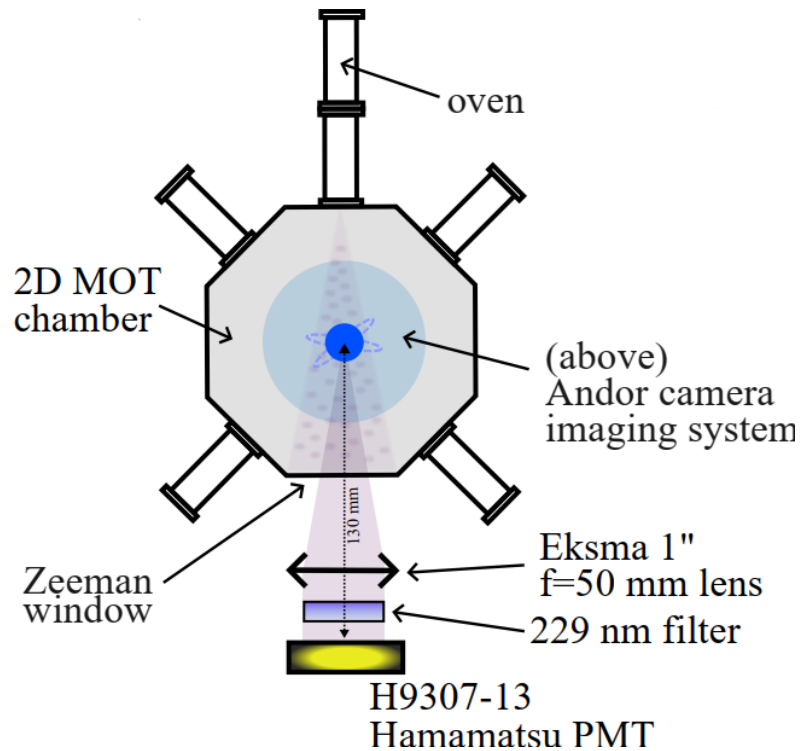
COOLING AND TRAPPING CADMIUM



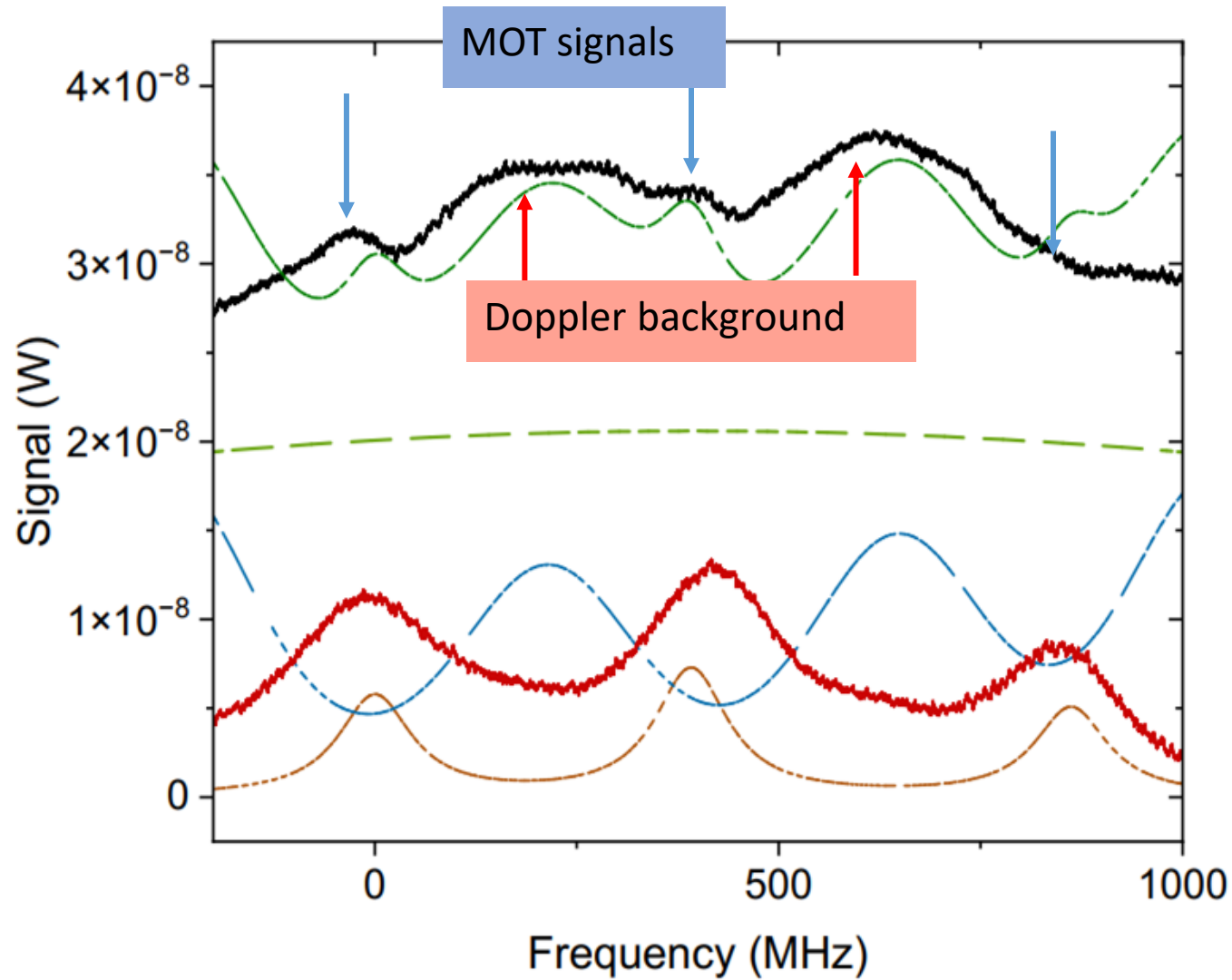
COOLING AND TRAPPING CADMIUM



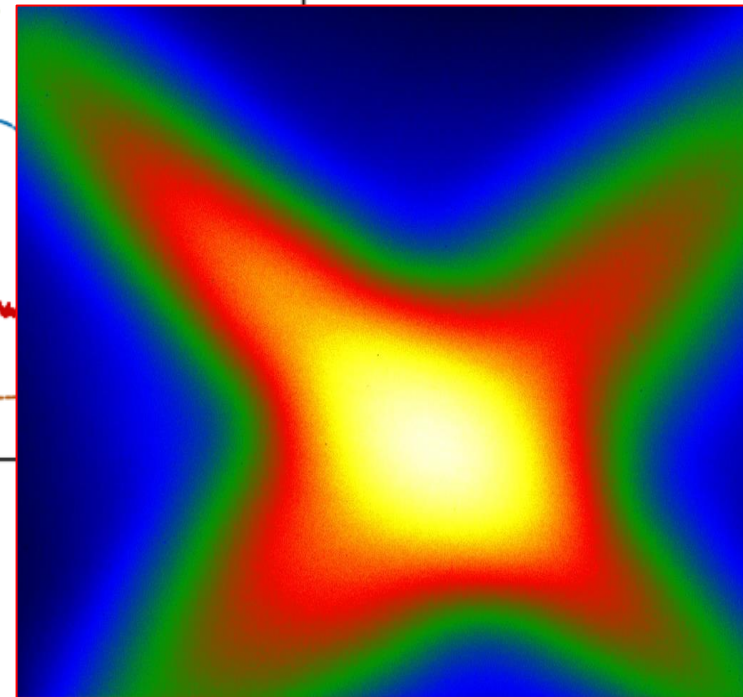
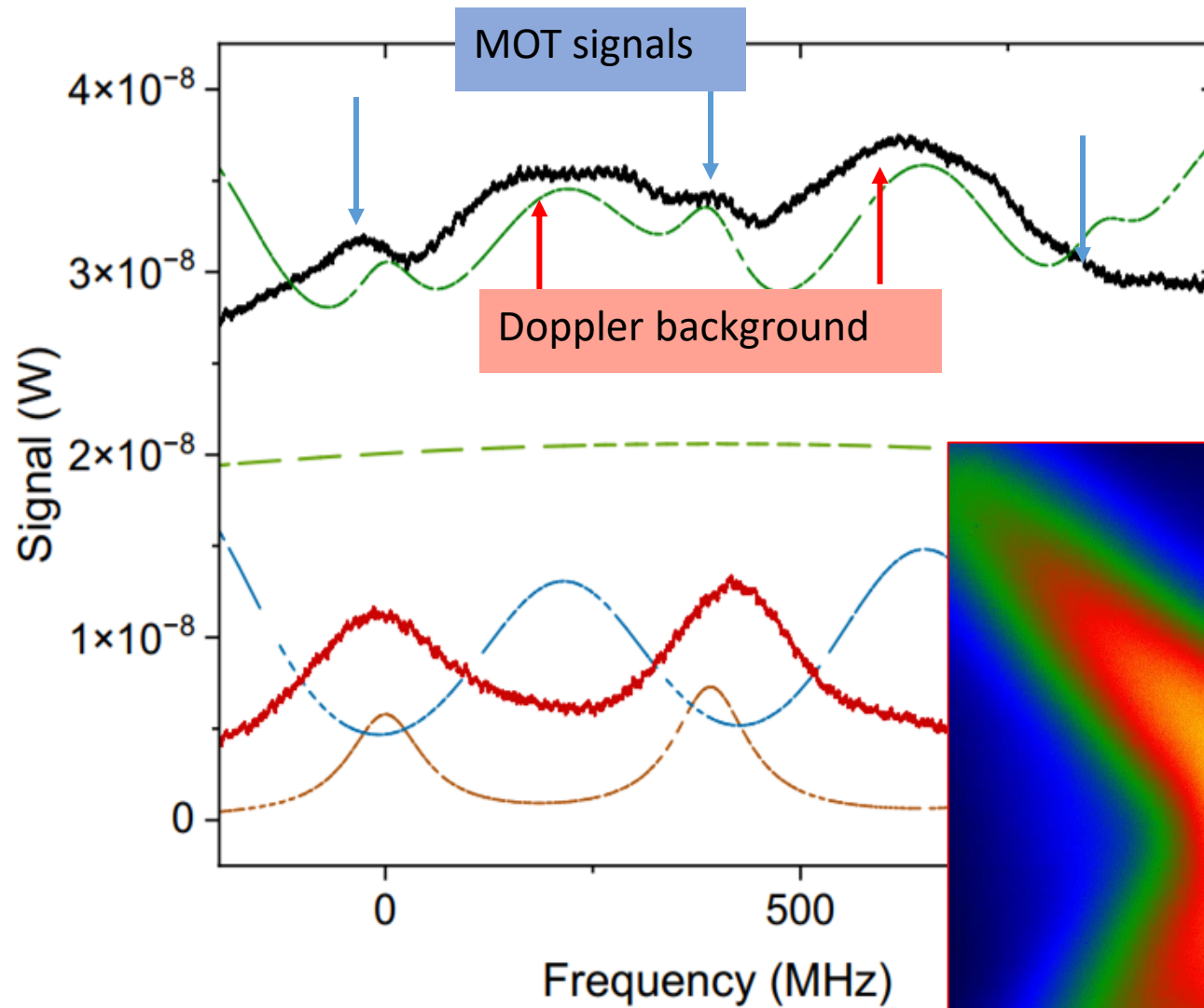
IMAGING DUV - 2D MOT



DUV 2D MOT - CADMIUM

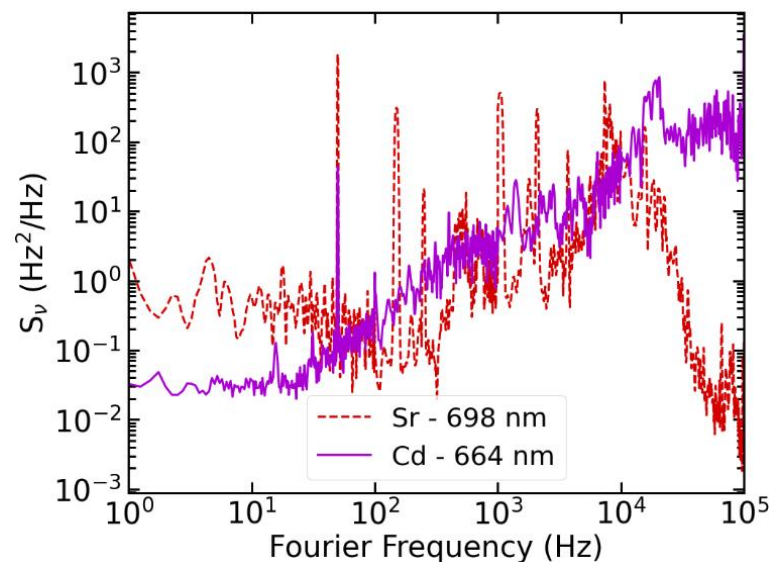
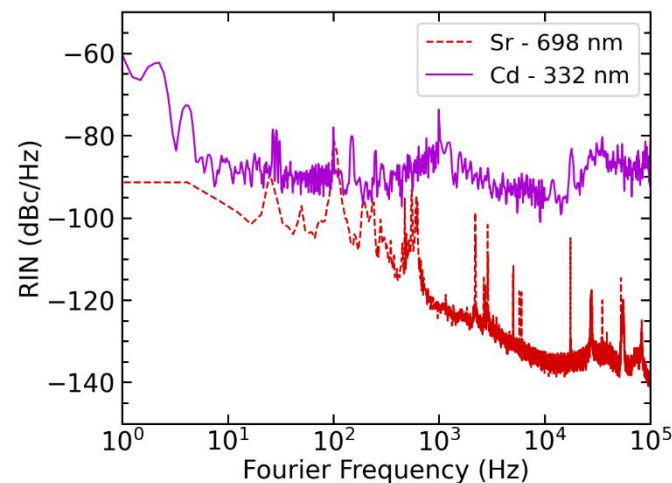
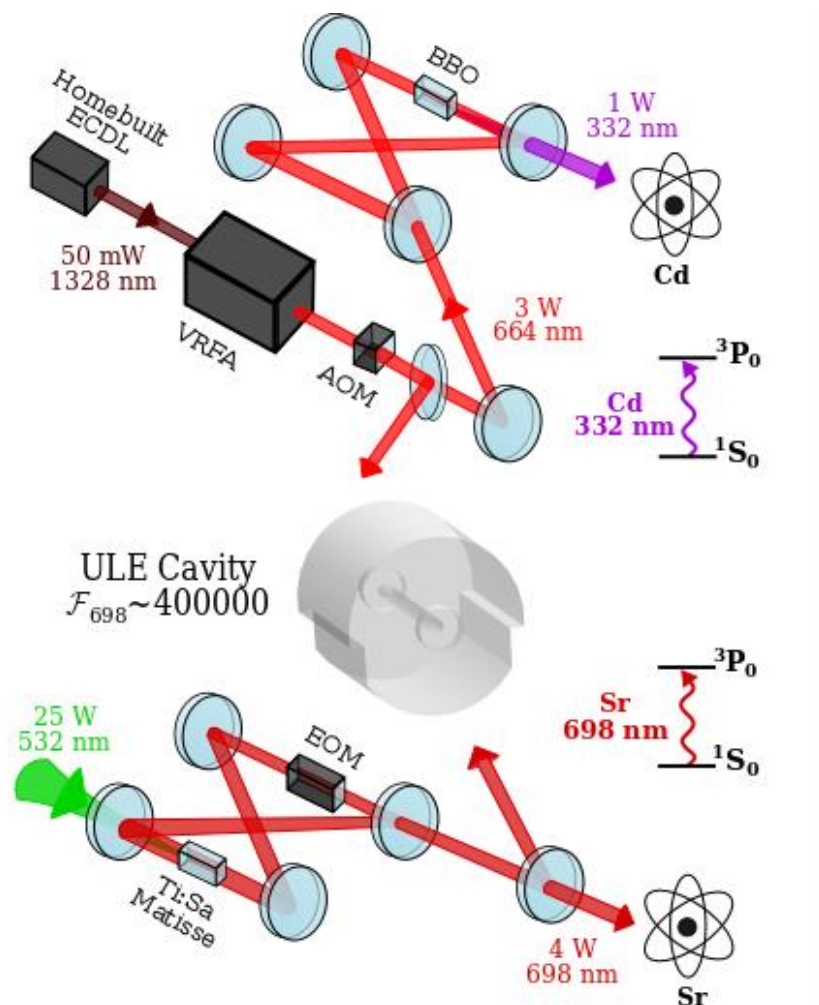


DUV 2D MOT - CADMIUM



CD 332 NM & SR 698 NM CLOCK ATOM INTERFEROMETRY LASERS

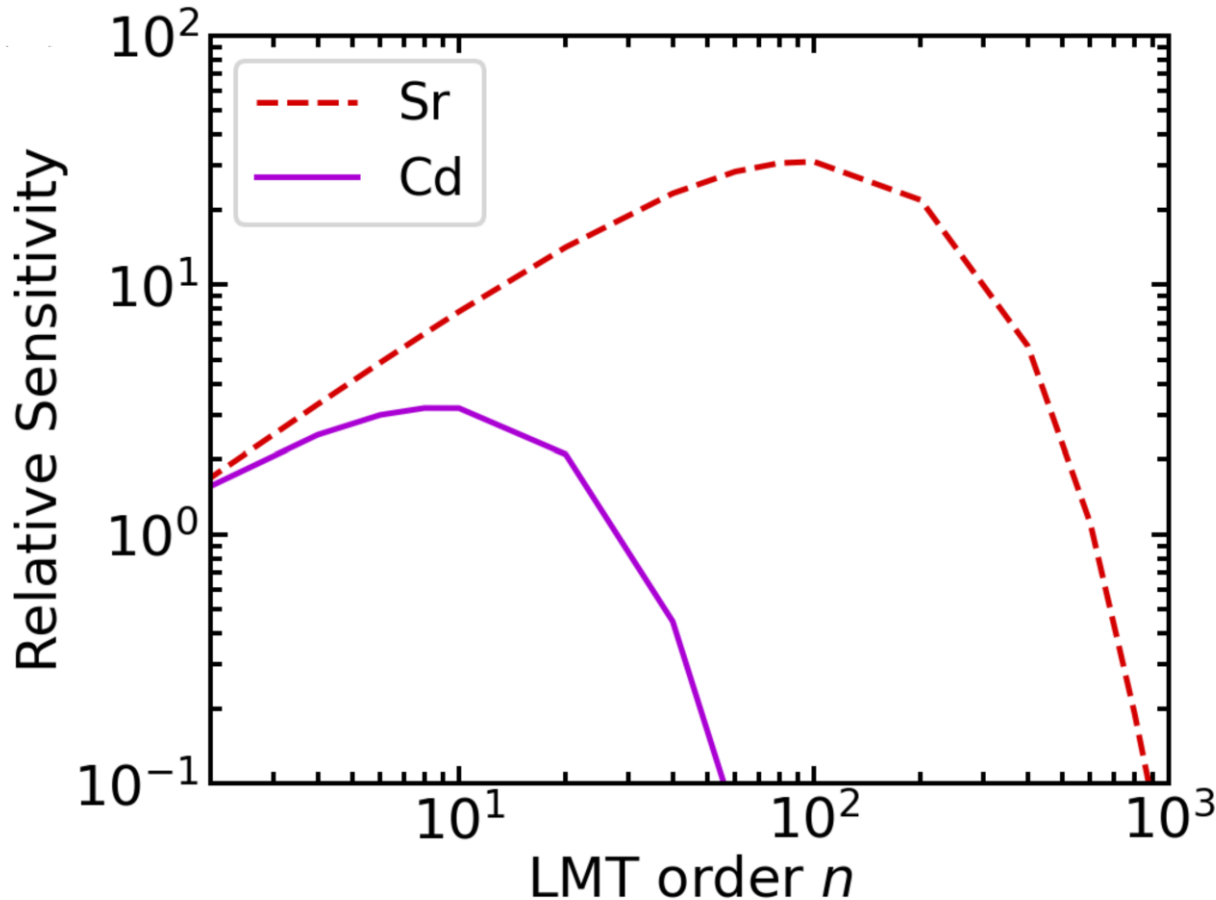
- Requirement of high power (> 1 W) and narrow linewidth (Hz level)



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 ($w = 5 \text{ mm}$)



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

UVQuant



Nicola Poli

Michele Sacco

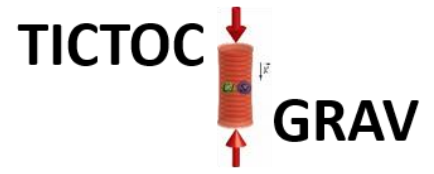
Satvika Bandrupally

Mauro Chiarotti

Jonathan Tinsley

Shamaila Manzoor

Paul Robert



POST-DOC & STUDENT POSITIONS AVAILABLE!
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