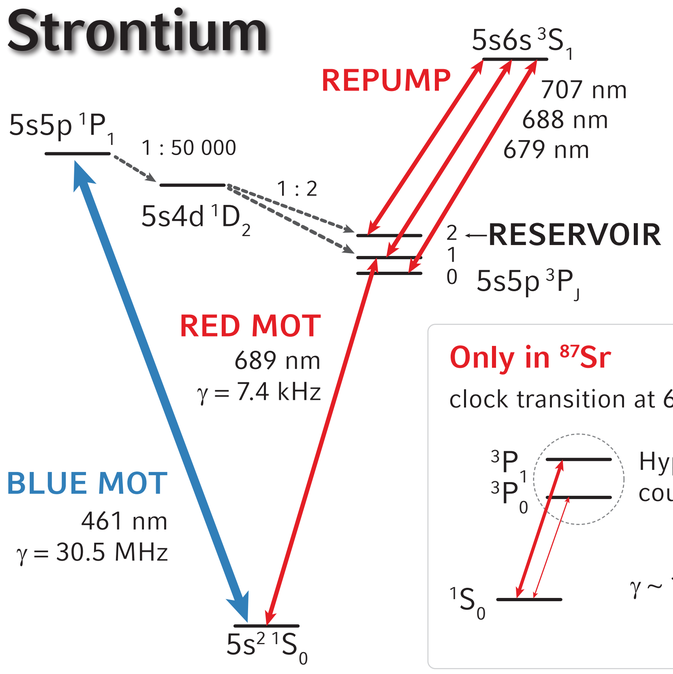
Towards Quantum Simulation of Light-Mattr Interfaces with Strontium in Optical Lattices

Annie Jihyun Park[1], Jan Trautmann[1], Valentin Klüsener[1], Neven Šantić[1], André Heinz[1], Eva Casotti[1], Florian Wallner[1], Yilong Yang[1], Dimitrios Tsevas[1] Immanuel Bloch[1,2] and Sebastian Blatt[1]

[1] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straße 1, 85748 Garching, Germany
[2]LMU, Schellingstraße 4, 80799 München, Germany

ultracold.sr

Strontium

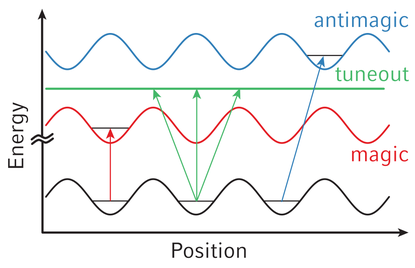


Only in ^{87}Sr

clock transition at 698 nm

$^1S_0$ scattering lengths (a_0)

Isotope	Nuclear spin	^{84}Sr	^{86}Sr	^{88}Sr	^{87}Sr
^{84}Sr (0.56%)	0	123			
^{86}Sr (9.86%)	0	32	800		
^{88}Sr (82.58%)	0	1700	97	-2	
^{87}Sr (7.00%)	9/2	-57	162	55	96



$^1S_0 - {}^3P_0$ interaction parameters

$\|\Psi_{total}\rangle$ =	|elec.⟩ ⊗	|nuclear⟩ ⊗	|motional⟩	parameter (a_0)
s-wave	|gg⟩	$\|m_1m_2\rangle - \|m_2m_1\rangle$	$\|n_1n_2\rangle + \|n_2n_1\rangle$	a_{gg} = 96.2 ± 0.1
	|ee⟩			a_{ee} = 176 ± 11
	|eg⟩ + |ge⟩			a_{eg}^{+} = 160.0 ± 2.8
	|eg⟩ − |ge⟩	$\|m_1m_2\rangle + \|m_2m_1\rangle$		a_{eg}^{-} = 69.1 ± 1.1
p-wave	|gg⟩	$\|m_1m_2\rangle + \|m_2m_1\rangle$	$\|n_1n_2\rangle - \|n_2n_1\rangle$	b_{gg} = 74.6 ± 0.4
	|ee⟩			b_{ee} = −119 ± 18
	|eg⟩ + |ge⟩			b_{eg}^{+} = −169 ± 23
	|eg⟩ − |ge⟩	$\|m_1m_2\rangle - \|m_2m_1\rangle$		b_{eg}^{-} = -42^{+103}_{-22}

Physics Lattice Trap Depths for U_{00} = 12 t

	λ (nm)	V_{trap} (E_{rec})	Γ_{sc} (s^{-1})	U_{00} (kHz)	t (Hz)	J_{ex} (Hz)
blue magic $^1S_0 - {}^3P_1$, $^3P_0$	389	7.4	0.27	8.2	680	57
antimagic $^1S_0 - {}^3P_0$	400	7.5	0.30	7.6	630	53
tuneout $^3P_0$	479	-8.0	0.55	4.7	390	32
red magic $^1S_0 - {}^3P_0$	497	-8.1	0.25	4.2	350	29
high power	532	-8.2	0.10	3.5	290	24
tuneout $^3P_0$	633	-8.8	0.023	2.2	180	15
antimagic $^1S_0 - {}^3P_0$	650	-8.9	0.020	2.0	170	14
tuneout $^1S_0$	689.2	-9.0	0.013	1.7	140	12
red magic $^1S_0 - {}^3P_0$	813	-9.5	0.0051	1.1	92	7.7
red magic $^1S_0 - {}^3P_1$	914	-9.9	0.0026	0.80	67	5.6
high power	1064	-10	0.0012	0.53	44	3.7

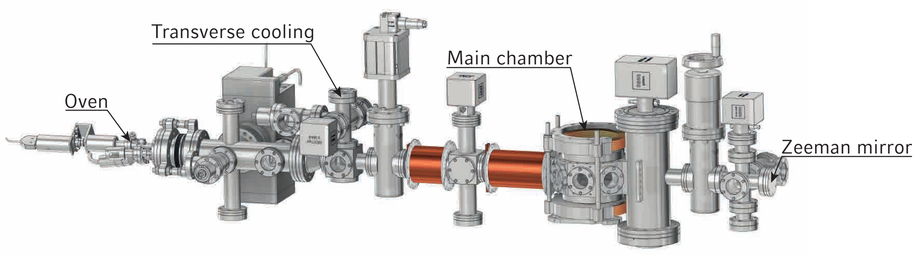
$^1S_0$ scattering lengths:
Stellmer *et al.*, PRA **102**, 013611 (2013)

$^1S_0 - {}^3P_0$ Interaction parameters:
Zhang *et al.*, Science **345**, 1467 (2014)
Goban *et al.*, arXiv:1803.11282 (2018)

Blue magic wavelength:
Takamoto *et al.*, PRL **102**, 063002 (2009)

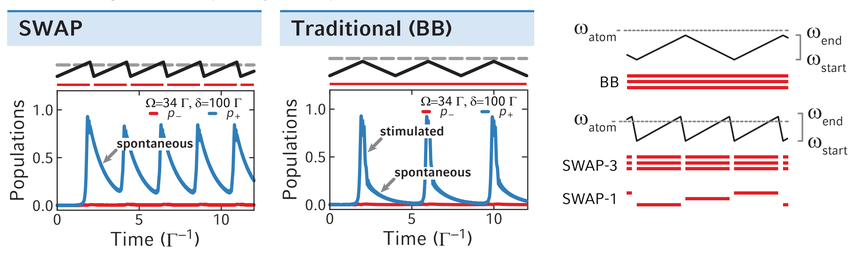
Recent polarizability calculations:
Safronova *et al.*, PRA **92**, 040501(R) (2015)

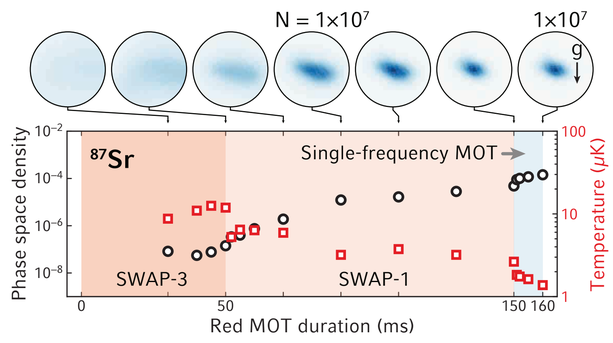
Sample Preparation

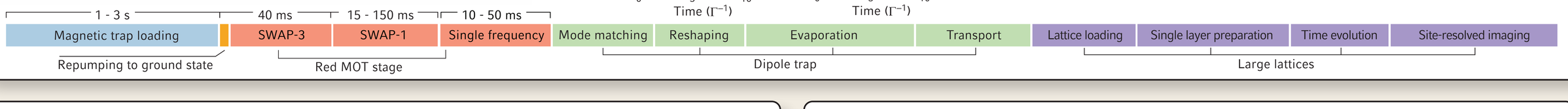


Efficient & fast red MOT loading: Snigirev *et al.*, Phys. Rev. A **99**, 063421 (2019)

Optimized broadband cooling stage based on adiabatic passage (SWAP) combining two cooling strategies: SWAP-3 and SWAP-1, corresponding to the number of bright axes during each frequency sweep.

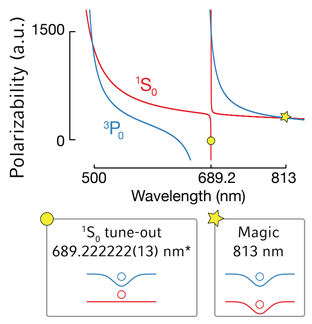




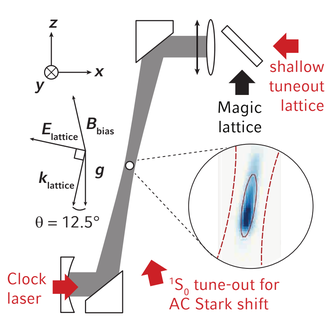


Ground state tune-out

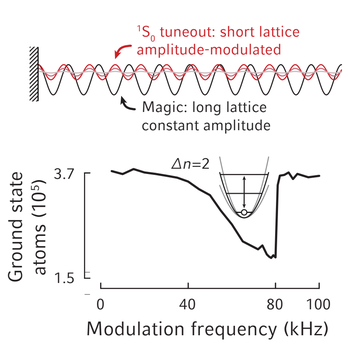
Tuneout & Magic Wavelengths



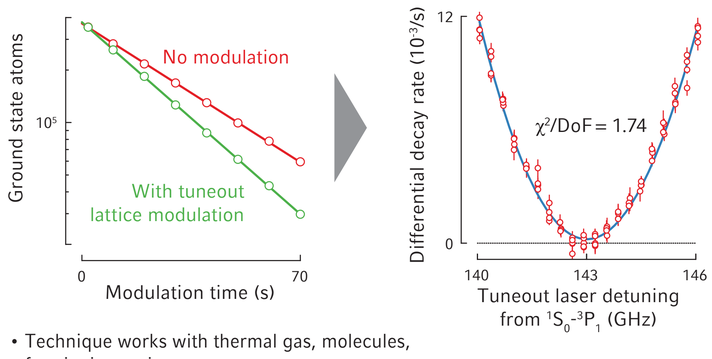
Experimental Setup



Measurement Scheme



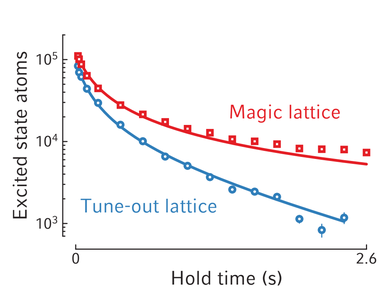
Differential atom loss: enhanced S/N with long exposure



- Technique works with thermal gas, molecules, fermionic species
- **46 dB suppresion** of effect on ground state *c.f.* Leonard *et al.*, PRA **92**, 052501 (2015)

Δ_t = 143.009(10) GHz
= 1.92287(15) × 10^7 $\Gamma(^3P_1)$
λ_t = 689.222222(16) nm

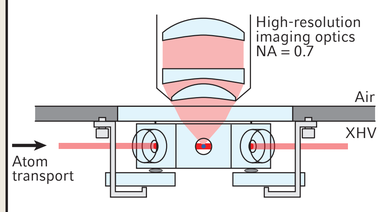
Trapped $^3P_0$ atoms in tune-out lattice

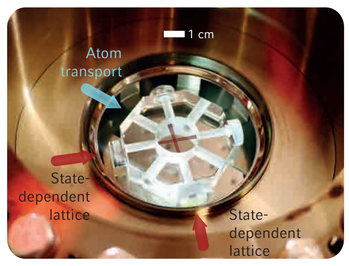


- Proof-of-principle trapping of $^3P_0$ atoms in $^1S_0$ tune-out lattice vs. $^1S_0$-$^3P_0$ magic lattice
- Lifetime of $^3P_0$ atoms in tune-out lattice in a Mott insulator state ~ 1 s

➡ A. Heinz, A. J. Park, N.Santic, J. Trautmann, S. G. Porsev, M. S. Safronova, I. Bloch, and S. Blatt, PRL **124**, 203201 (2020)

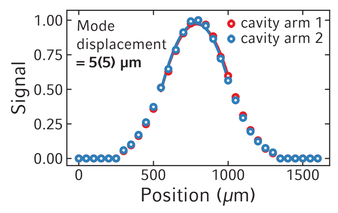
Large-volume lattices





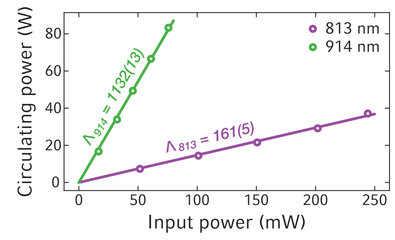
- In-vacuum buildup cavity features very large **mode-diameter of 0.9 mm**
- Estimated Mott insulator size **200 x 200, order of magnitude more than state-of-the-art**

Small mode displacement



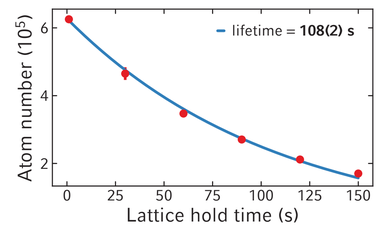
- Power enhancement factor of 110 enabled by finesse of 475 at $^1S_0$ tune-out wavelength
- Multiband coating allows using other interesting wavelengths (633, 1064 nm)

Multiband cavity mirrors



Coated for several wavelengths from VIS - NIR with buildup factors 100-1000

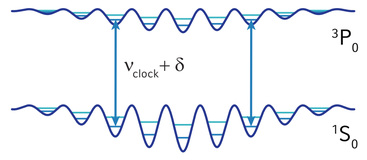
Atomic lifetime in the cavity

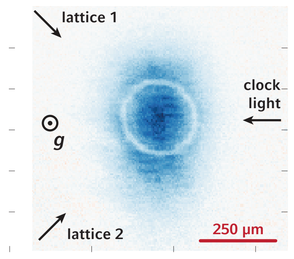


- Measured for 1D lattice at 813 nm
- Atomic lifetime in 1D or 2D lattice not limited by phase noise at 813 nm and 914 nm

Lattice homogeneity

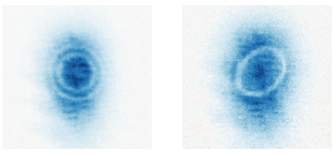
- Ground state atoms trapped in two-dimensional 914 nm lattice
- 813 nm light sheet supports against gravity
- Excitation to clock state shows ring-shaped depletion in atomic population





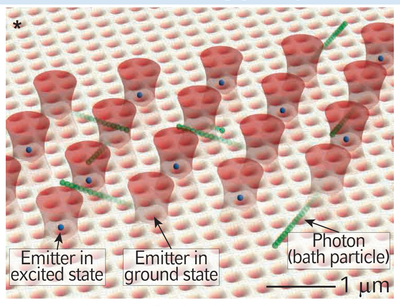
different motional states

different trap frequencies along lattices



Strongly coupled light-matter interfaces

Quantum emitters strongly coupled to baths



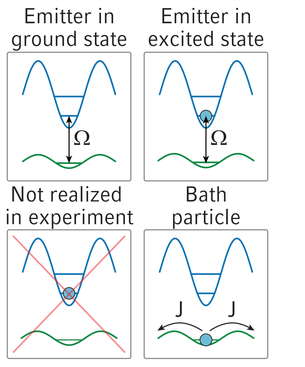
Described by the Dicke Hamiltonian:

$$H = \Delta \sum_{j=1}^{N} \sigma_{ee}^{j} + \sum_{k} \varepsilon_k a_k^{\dagger} a_k + g \sum_{j=1}^{N} \sum_{k} (\sigma_{eg}^{j} a_k + \text{h.c.})$$

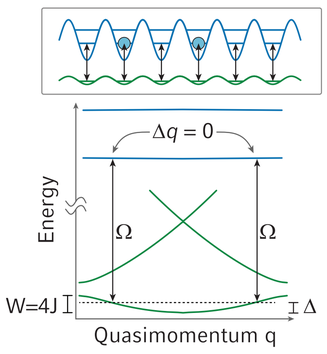
Also see Krinner *et al.*, Nature **559**, 589–592 (2018)

Mapping

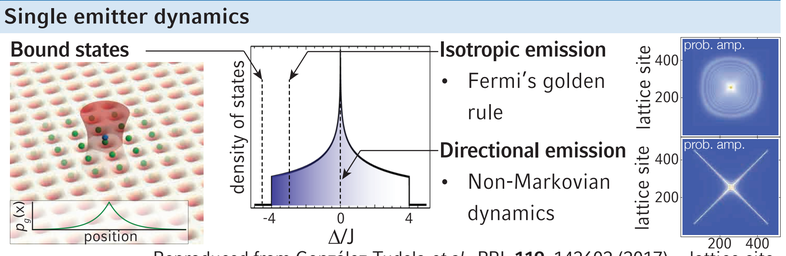
quantum emitters ↔ atoms in state-dependent lattice



Coupling using clock transition → tunable Δ and Ω



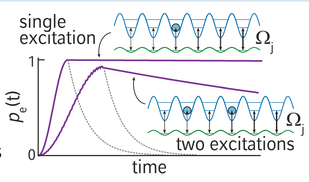
Single emitter dynamics

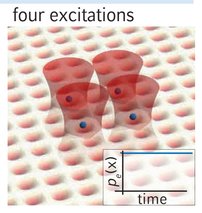


Reproduced from González-Tudela *et al.*, PRL **119**, 143602 (2017)

Strong coupling between multiple emitters

- **Subradiant states** with multiple excitations easily achievable in 1D
- ***Perfect* subradiant states** in 2D by arranging emitters





Reproduced from D. Plankensteiner *et al.*, Sci. Rep. 5, 16231 (2015).

We acknowledge technical contributions by

M. Kruljac
S. Snigirev
F. Finger
I. Kokhanovskyi
L. Eck
L. Kimmig
E. Davletov
S. Wissenberg
L. Homeier
R. González Escudero
E. Staub
R. Haindl
N. Janša
L. Tepliakov
P. Paranjape
Y. Ji
Z. Guo
Q. Fang
K. Förster