Quantum optics in new systems: from plasmonics to cold atoms

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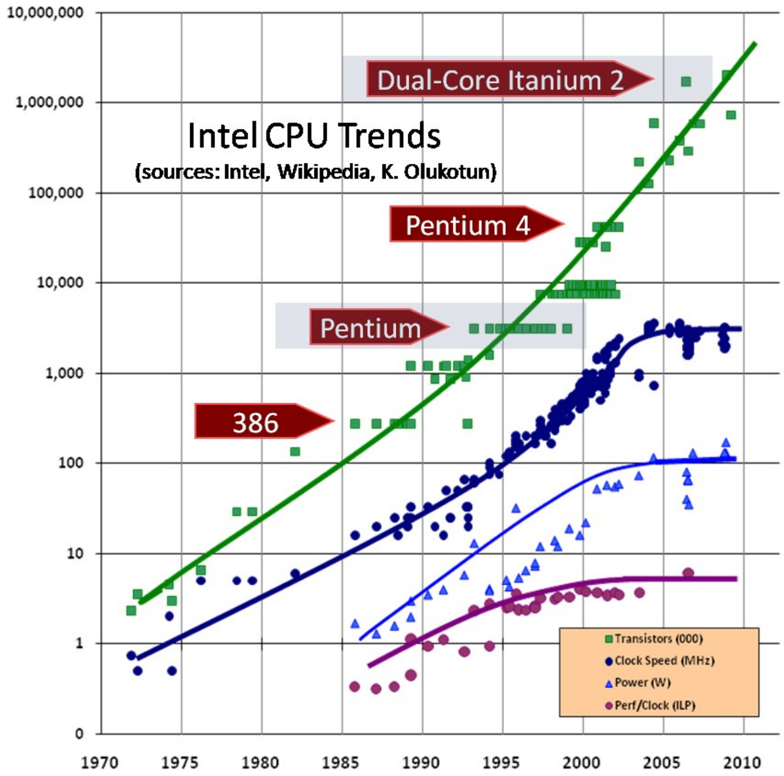
Information Processing

Information technology:

- One of the key technology of modern society
- Mostly built using electrical integrated circuits based on transistors
- Relays on Moor’s law

Communication:

- Integrated in all aspect of our life
- Utilizes light already today
- Suffers from security issues



Intel (Bob Colwell): “Moores Law will be Dead by 2020”

THIS TALK

QUANTUM PLASMONICS AND NANOPHOTONICS

- Efficient quantum interface between light and spin

EXOTIC COLD ATOMS

- Towards “simulating” complex quantum materials

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QUANTUM PLASMONICS AND NANOPHOTONICS

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EXOTIC COLD ATOMS

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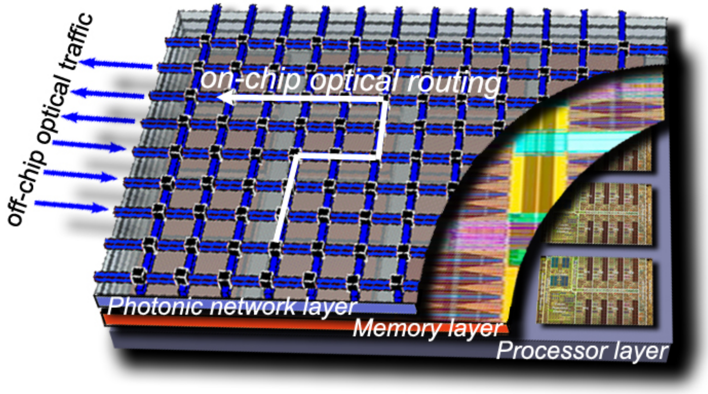
Integrated nanophotonics – next step in Information processing

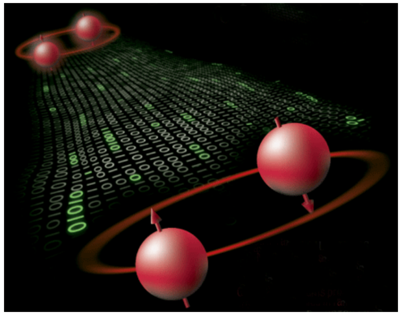


Photons:

- Have no ohmical losses
- Have huge carries frequencies
- IBM already used photonics for processor interconnects

But…

Wide use require **new platforms** for photon switching and processing



Quantum communication:

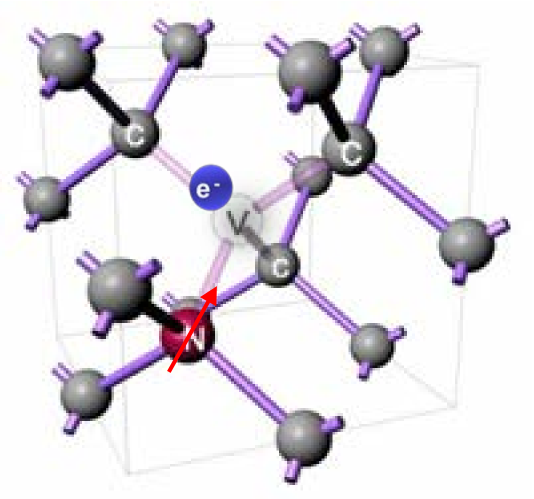
- Offers new security level
- Exits on market as short range solution
- Need quantum repeaters for long distance

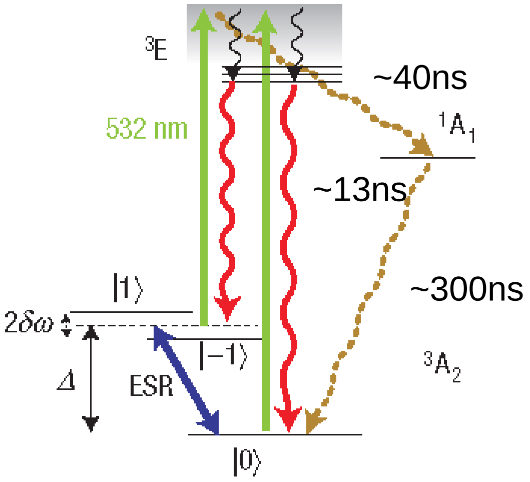
NEED TO INTEGRATE LIGHT AND MATTER ON QUANTUM LEVEL

Key element of active nanphotonics: interface of one atom and one photon

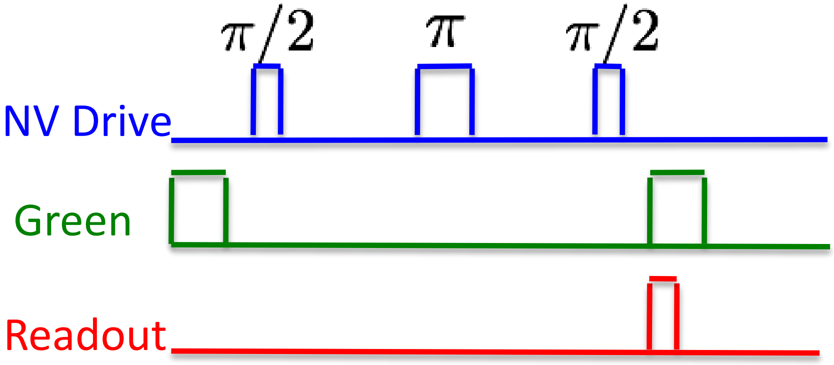
- ✓ Efficient photon reading and writing
- ✓ Single photon sources
- ✓ Sensors and metrology applications
- ✓ Nonlinear optics with single photons
- ✓ Many applications in quantum (and classical) information processing

NV- center in diamond

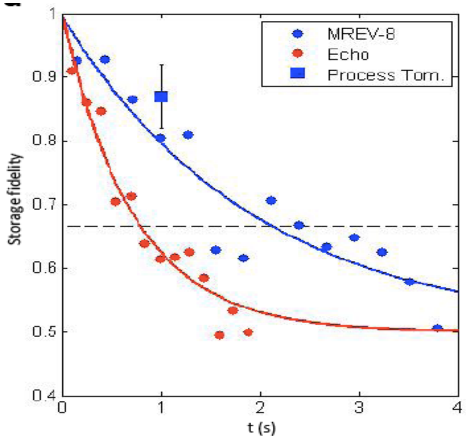




- Non-zero electronic spin (S=1, |ms|=0,1)
- Optical readout of the state
- Optical polarization of the state
- Microwave control over the spin
- Long coherence time up to ms
- Narrow emission line @ 637 nm
- Individual isolation with laser microscopy
- Can be created in nanoscale structures
- Accesses to the nuclear spin



Atom-like systems:current efforts

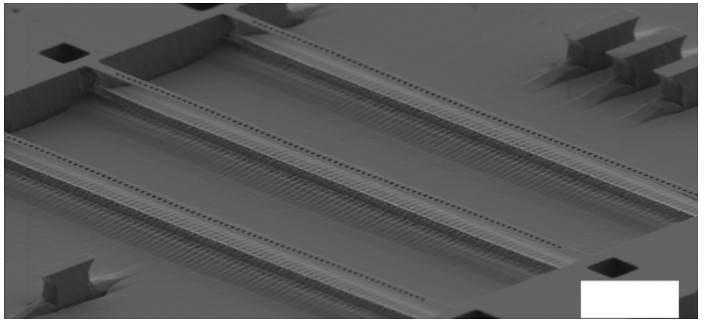


- Coupling to single nuclei: multi-second quantum memory in isotopically pure diamond

  P.Maurer et al (Science, 2012), Lukin group

- Coupling to single photons: diamond nanophotonics for quantum networks

  B. J. M. Hausmann et al (*Nano Lett.*, 2013) Loncar group

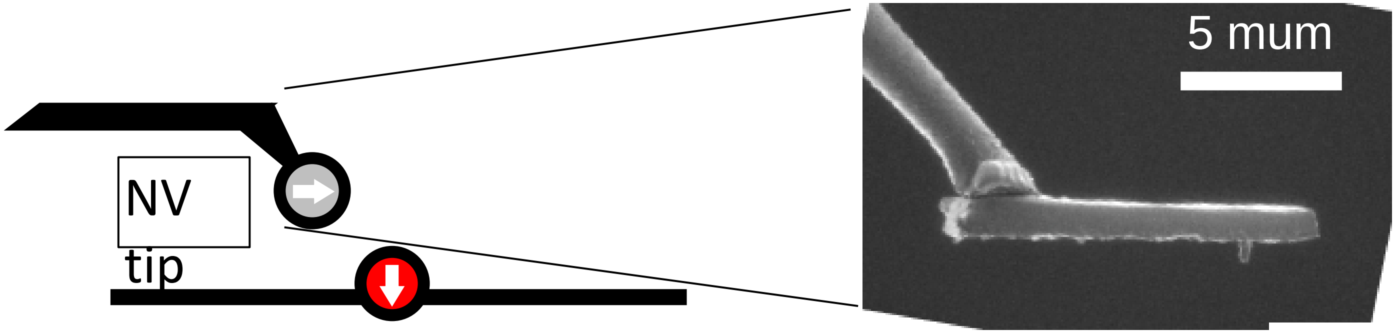


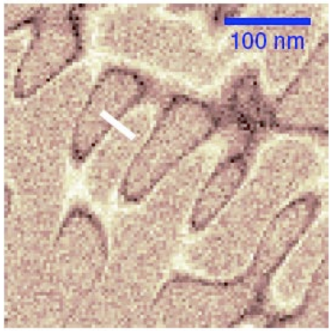
- Sensor and metrology: hig resolution sensing of magnetic field

  P.Malinetsky et al (Nature Nanotechnology , 2012) Yacoby group

- Heralded entanglement between separated NV centers

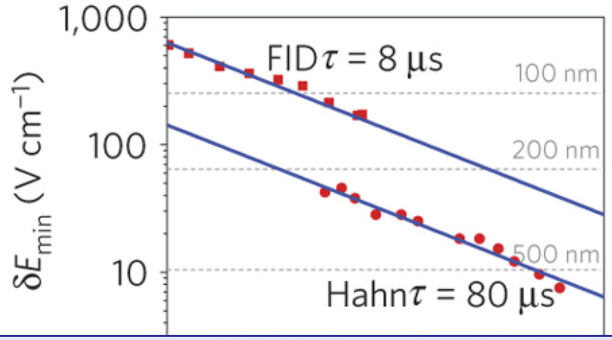
  H. Bernien, et al *Nature*., (Nature , 2013) Hanson group





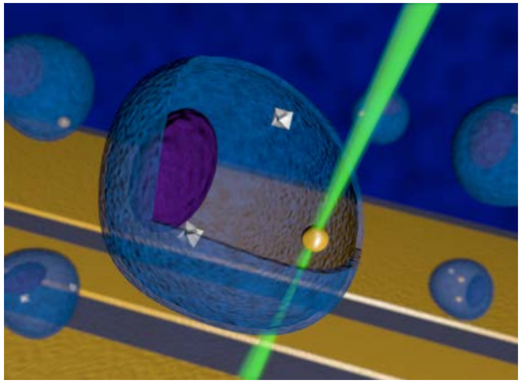
Applications to metrology

- Measurement of electric/magnetic field
- Temperature sensors
- Rotation sensors



Need spin readout with good signal to noise!

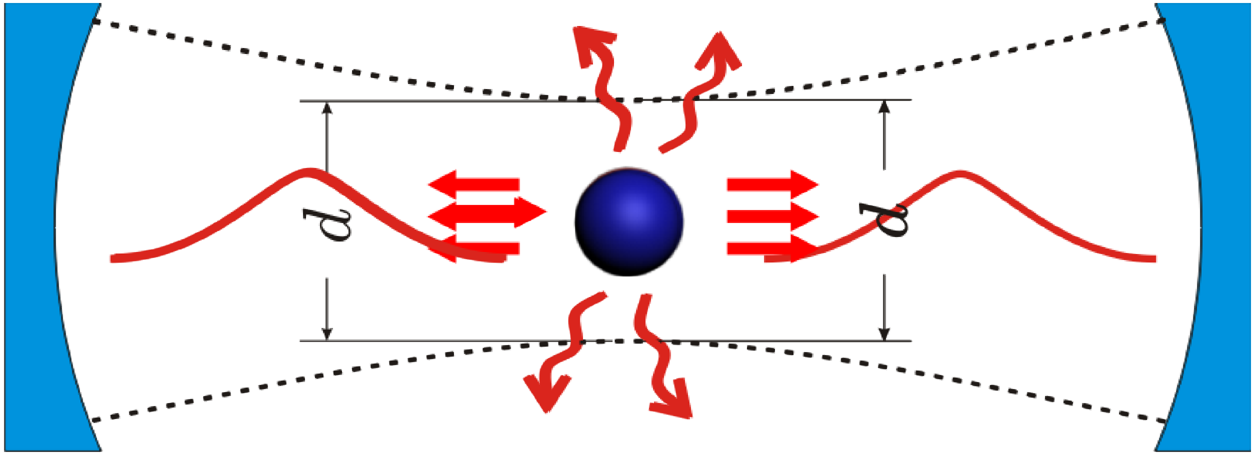
F. Dolde *et al.* Nature Physics **7**, 459–463 (2011)



- In Vivo sensors
- High resolution sensors
- High sensitivity solid state sensors

G Kucsko *et al.* *Nature* **500**, 54-58 (2013)

How to absorb one photon with an atom?



cross-section

✓ Single photon - single atom interaction probability: $\sim \frac{\lambda^2}{d^2} F$

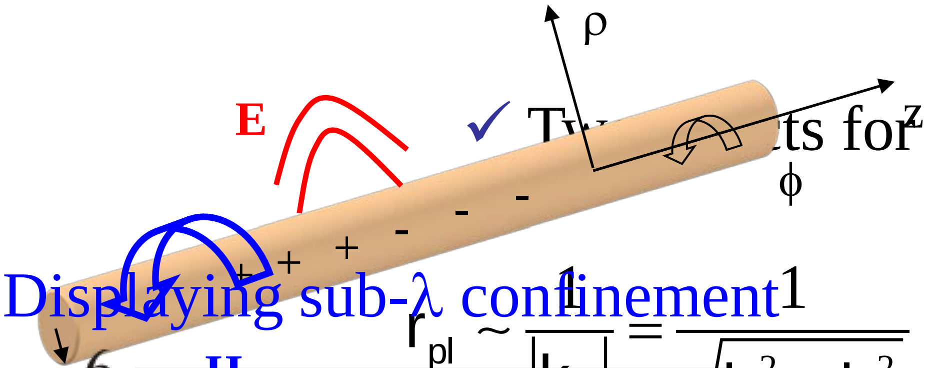
transverse localization

✓ *This talk :*

use unusual materials to improve interaction probability: efficient broadband photon collection using sub wavelength localization

Surface plasmons in nanowires

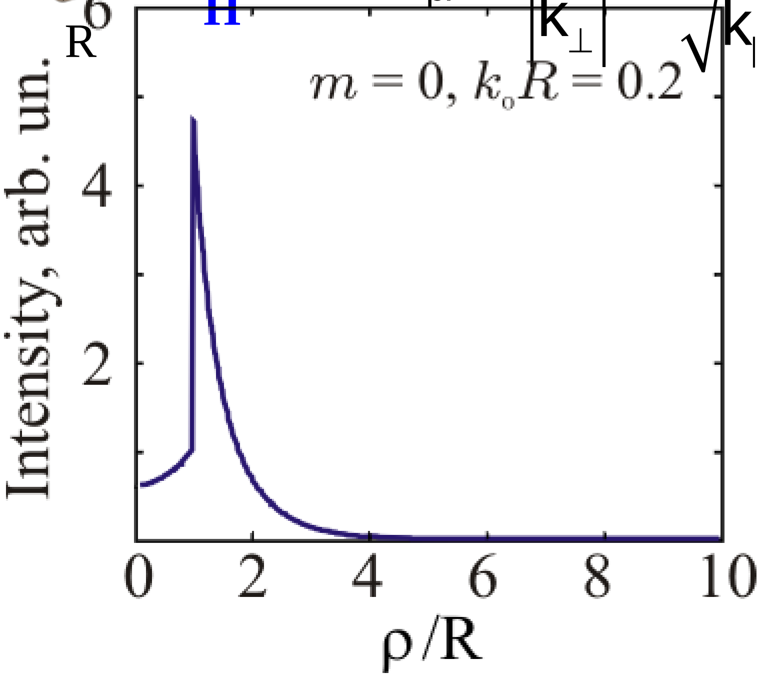
- ✓ Surface plasmons: charge-density waves guided on a conducting cylinder + associated electromagnetic field

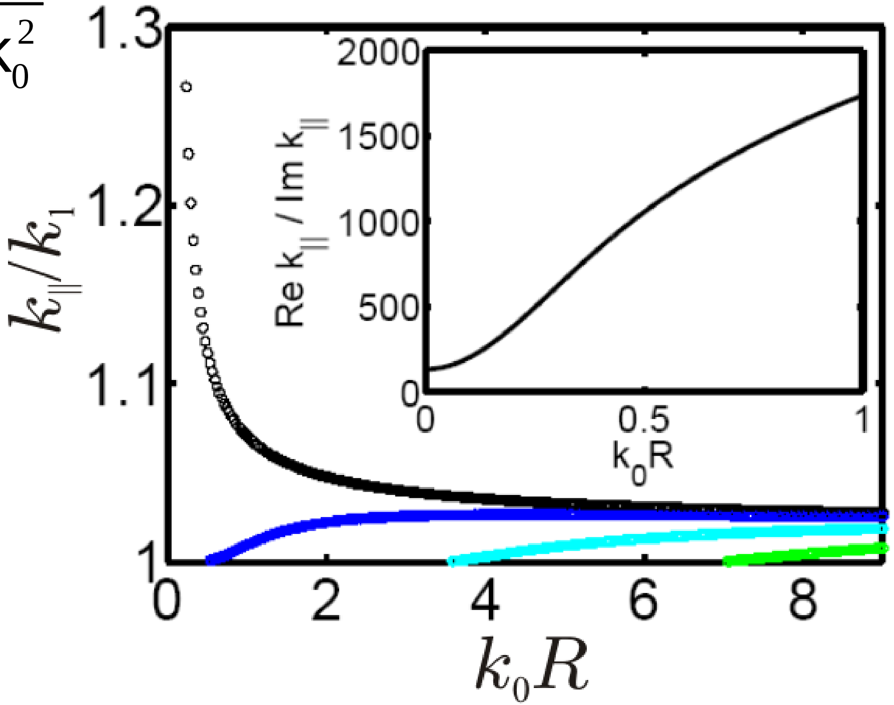


- ✓ Tw ts for thin (sub-wavelength) wires:

Displaying sub-λ confinement for slowly propagating TM mode

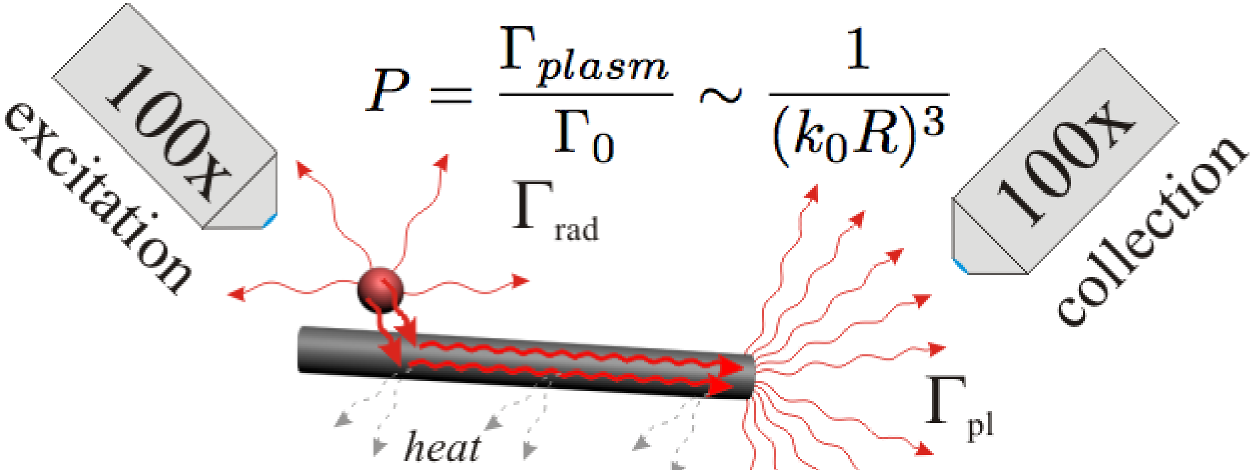
$$r_{pl} \sim \frac{1}{|k_\perp|} = \frac{1}{\sqrt{k_\parallel^2 - k_0^2}}$$





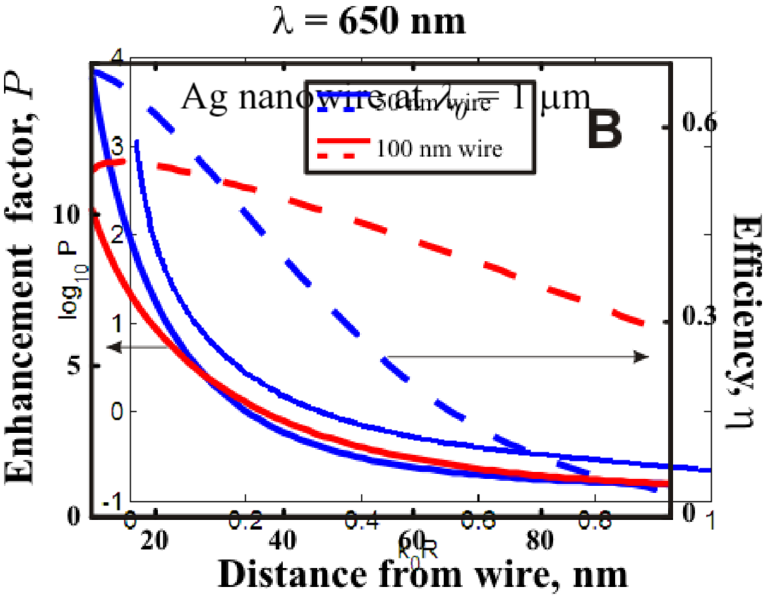
D.E. Chang, A.S. Sorensen, P.R. Hemmer, and M.D. Lukin, *Phys.Rev.Lett*. **97**, 053002 (2006)

Strong coupling with nanowire surface plasmons nanowire as a “super lens”



$$P = \frac{\Gamma_{plasm}}{\Gamma_0} \sim \frac{1}{(k_0 R)^3}$$

- ✓ Atom emission guided almost completely into the wire, this emission should be completely reversible
- ✓ Calculation for realistic system (perturbation theory, includes losses)



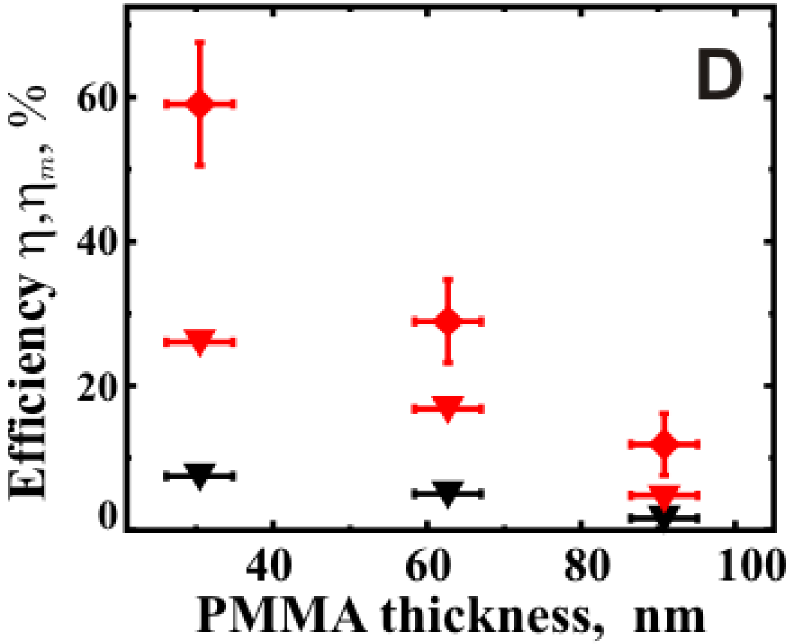
Wire – Qdot distance dependence

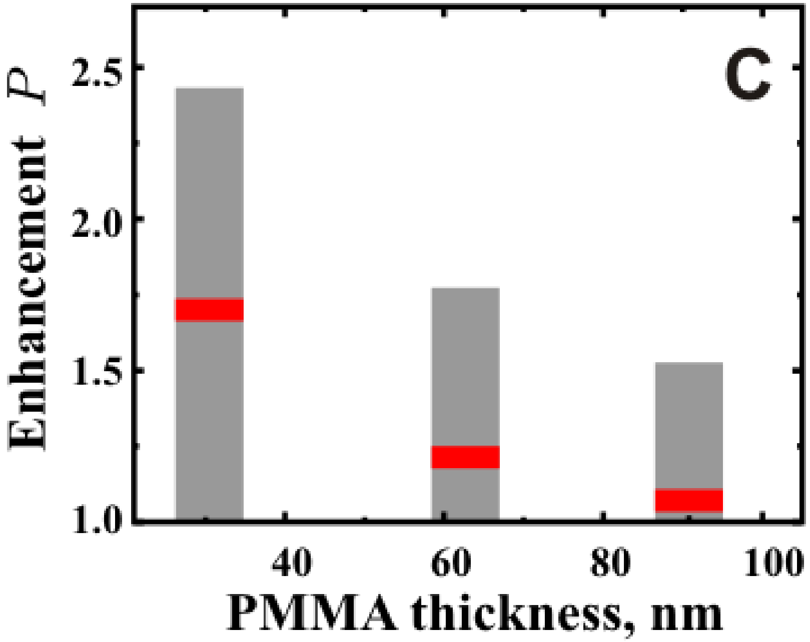
- Efficiency:

$$\eta = \frac{\Gamma_{\mathrm{pl}}}{\Gamma_{\mathrm{tot}}}$$

- Enhancement:

$$P = \frac{\Gamma_{\mathrm{tot}}}{\Gamma^{0}_{\mathrm{rad}}}$$



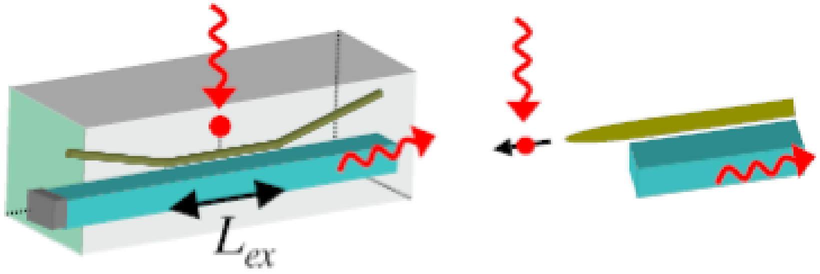


Nature **450**, 402-406

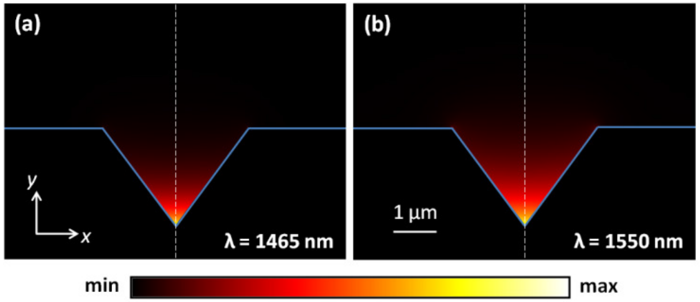
Ways to reduce losses in plasmonic based materials

General idea: to combine properties of metal and dielectric at one:

- Combine plasmon wire with waveguide
- Grow high quality films
- Double wires geometry
- Grooves



Nature Physics 3, 807 - 812 (2007)



OR...

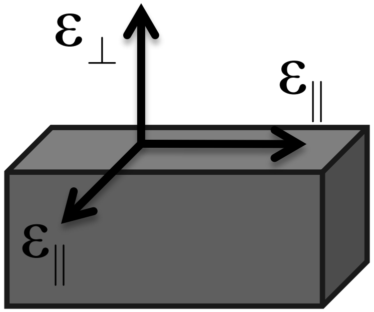
2012 / Vol. 20, No. 5 / OPTICS EXPRESS 57

Hyperbolic Metamaterial: The idea

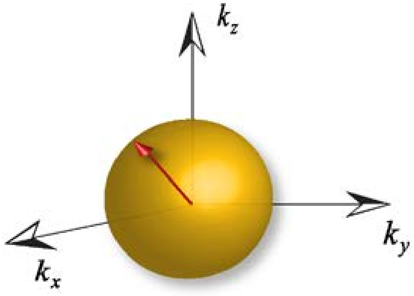
Spontaneous emission:

$$\Gamma_{i\to f} = \frac{2\pi}{\hbar}\left|\left\langle f\left|H'\right|i\right\rangle\right|^2 \times \mathrm{PDOS}$$

Uniaxial anisotropic medium:

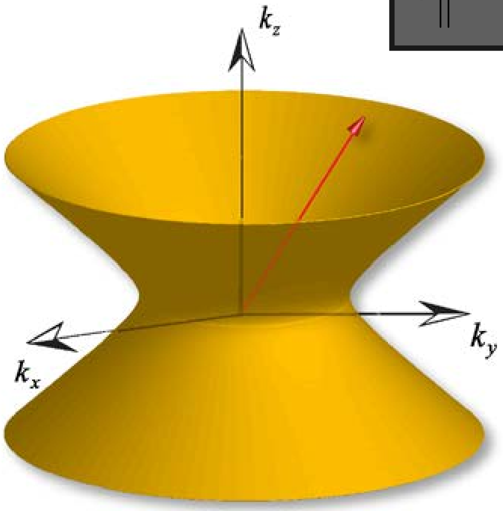


$$\frac{k_\perp^2}{\varepsilon_\parallel} + \frac{k_\parallel^2}{\varepsilon_\perp} = \frac{\omega^2}{c^2}$$



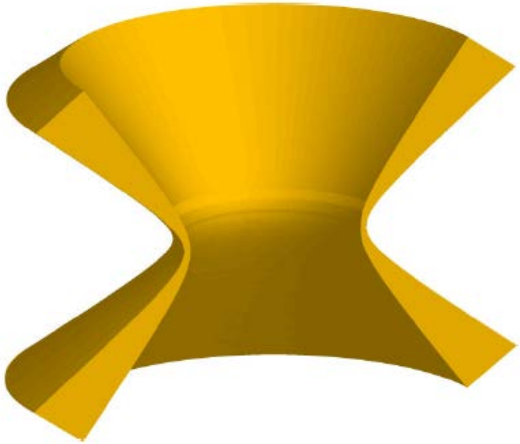
dielectric

$\varepsilon_\parallel, \varepsilon_\perp > 0$



HMM

$\varepsilon_\parallel > 0,\ \varepsilon_\perp < 0$

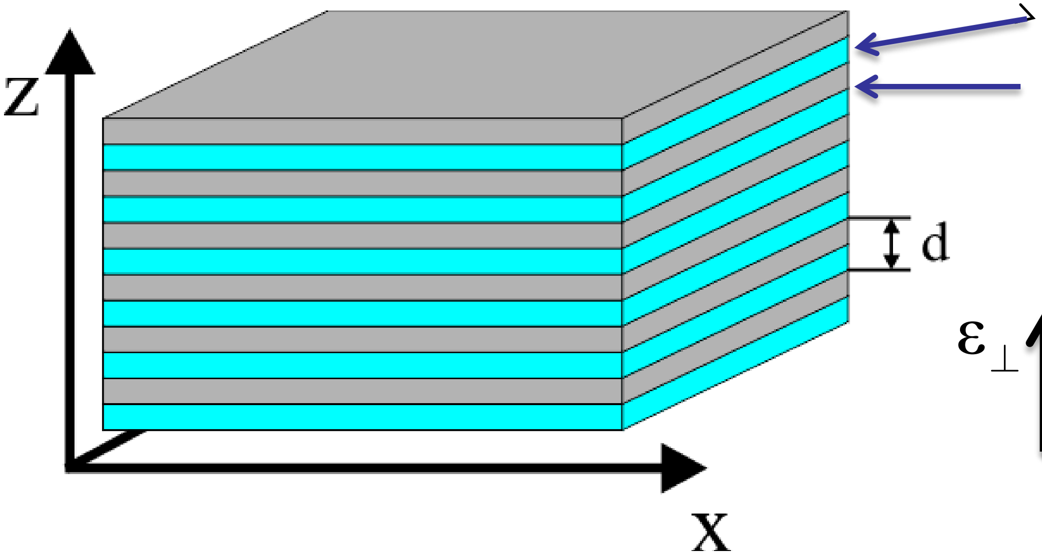


unbounded |k|

singularity in PDOS

Appl. Phys. B, 100(1) 215, 2010

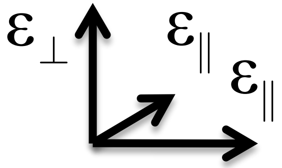
Hyperbolic Material: the structure



Metal $\varepsilon_m < 0$

Dielectric $\varepsilon_d > 0$

$d \ll \lambda$



$$\rho = \frac{d_m}{d}$$

$$D^{\parallel} = D_m^{\parallel}\rho + (1-\rho)D_d^{\parallel}$$

$$E^{\perp} = E_m^{\perp}\rho + (1-\rho)E_d^{\perp}$$

$$\varepsilon_{\parallel} = \rho\varepsilon_m + (1-\rho)\varepsilon_d$$

$$\varepsilon_{\perp} = \frac{\varepsilon_m\varepsilon_d}{\rho\varepsilon_d + (1-\rho)\varepsilon_m}$$

New Material for Hyperbolic Metamaterial

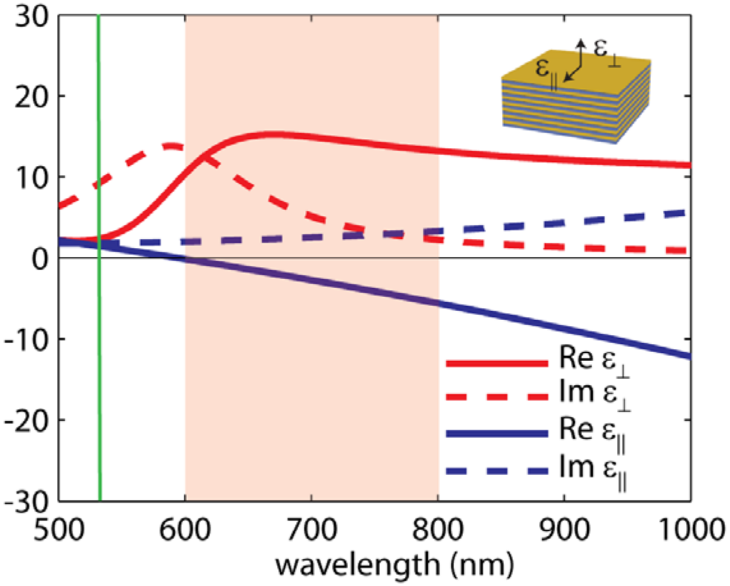
Prof. Alexandra Boltasseva

New Plasmonic Material
titanium nitride (TiN)
CMOS compatible

Prof. Vladimir Shalaev

New MetaMaterial
$TiN/Al_{0.7}Sc_{0.3}N$
CMOS compatible

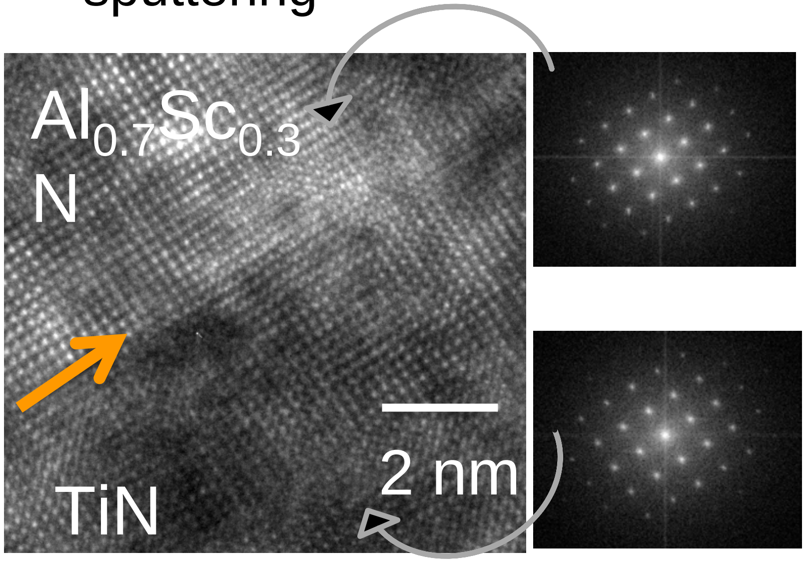
Hyperbolic CMOS-compatible metamaterial



M. Y. Shalaginov, et al CLEO Proceedings (2014)

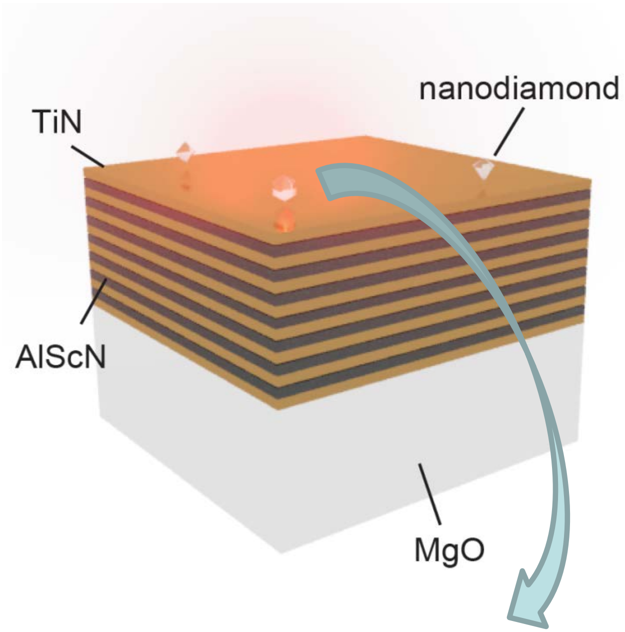
- 1^{st} epitaxial single crystalline metal/semiconductor superlattice
- CMOS-compatible constituent materials

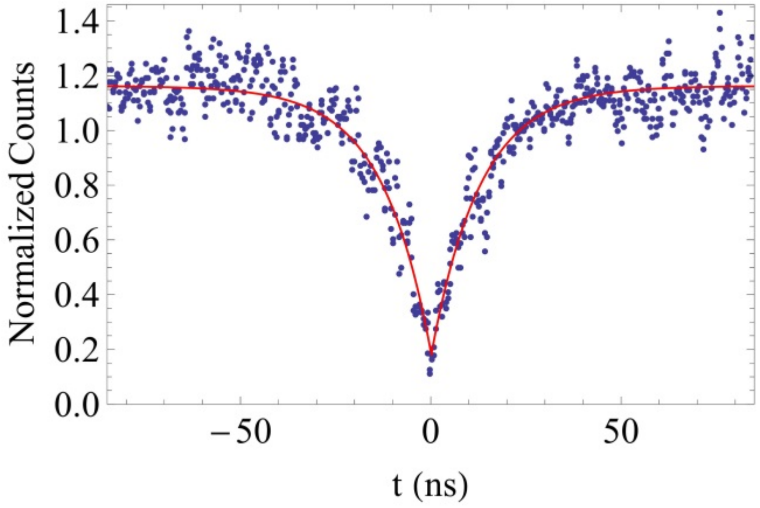
- 10/10 nm, 20 layers,
- [001]-oriented MgO substrate
- epitaxially grown using reactive DC magnetron sputtering

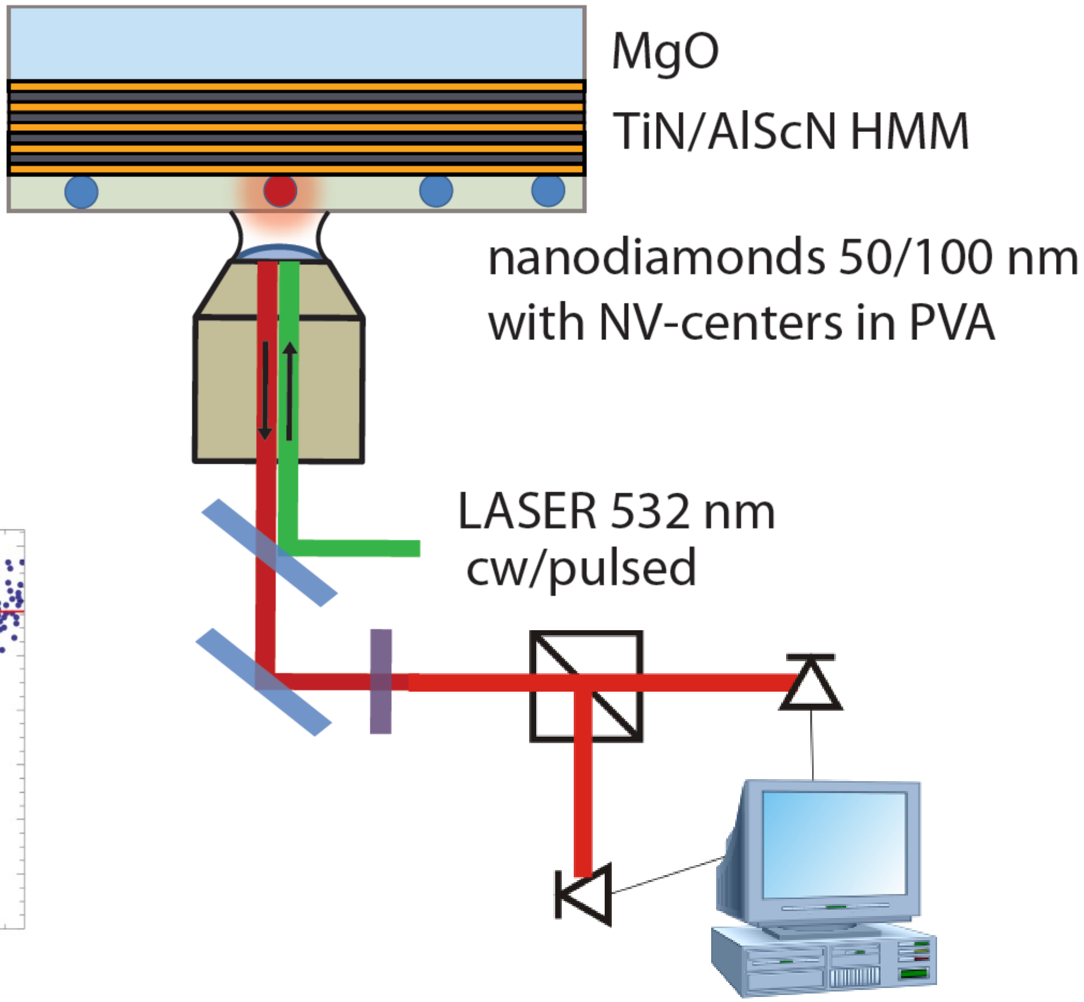


G. Naik, et al PNAS (2014)

Coupling of NV centers to HMM





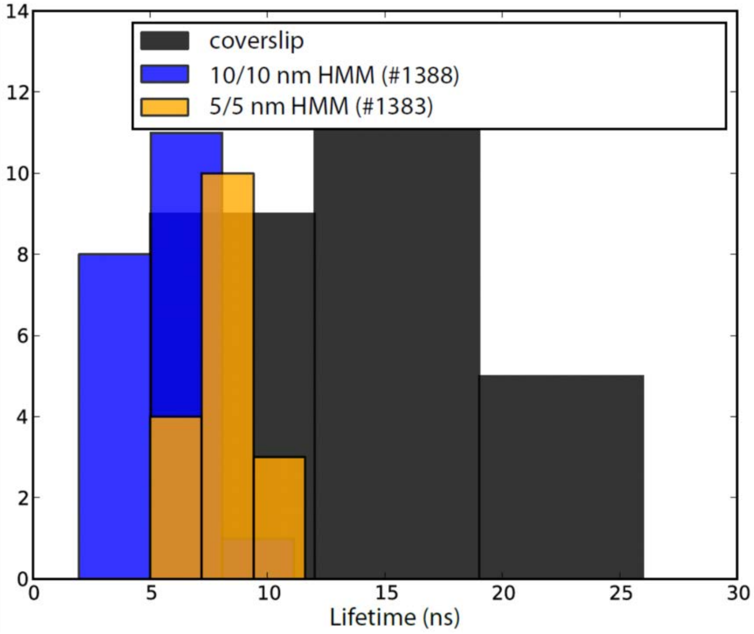

MgO

TiN/AlScN HMM

nanodiamonds 50/100 nm
with NV-centers in PVA

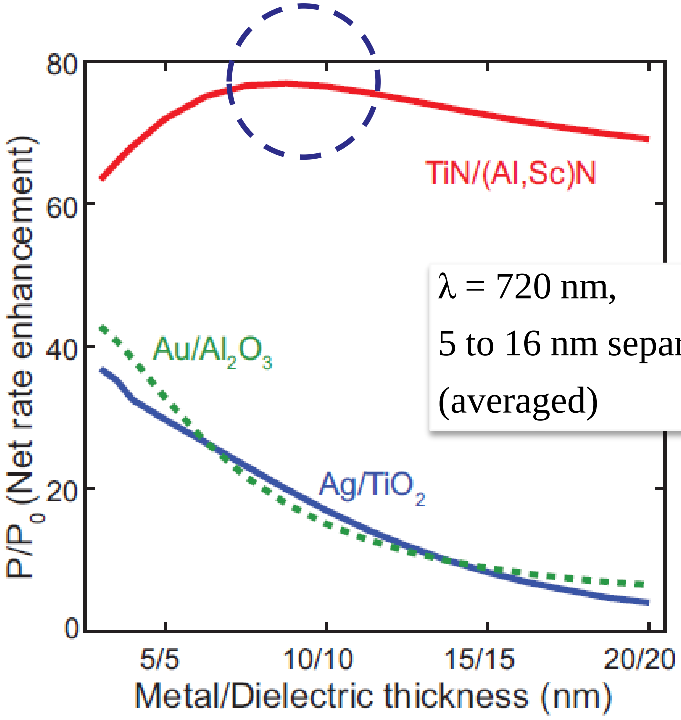
LASER 532 nm
cw/pulsed

Optimization of thickness of layers



- technology allow thickness even below optima

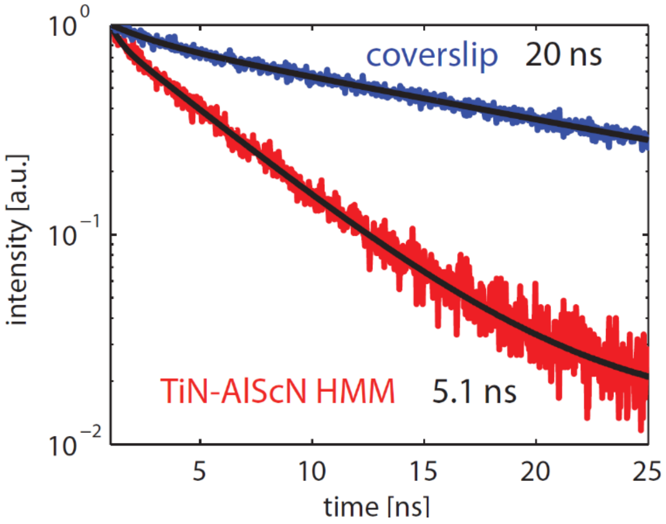
- Thickness of layers has optima
- Density of states is limited

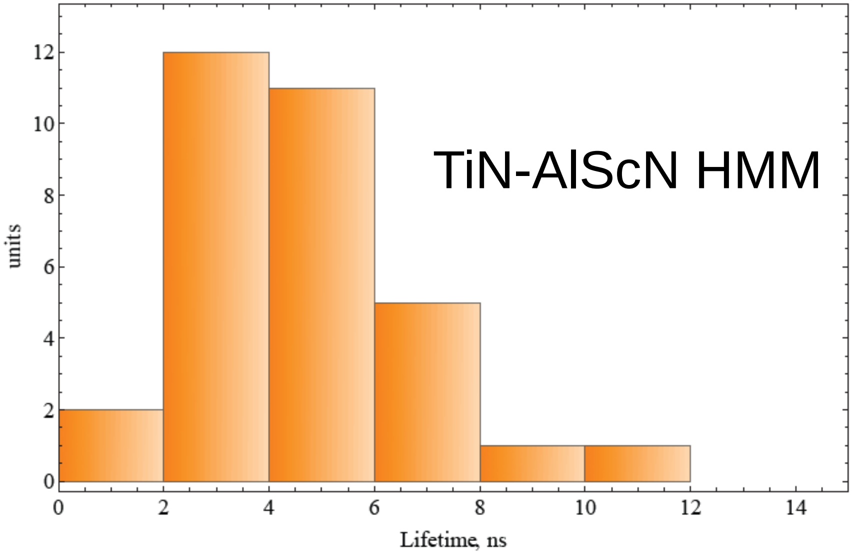


λ = 720 nm,
5 to 16 nm separation
(averaged)

G. Naik, et al PNAS (2014)

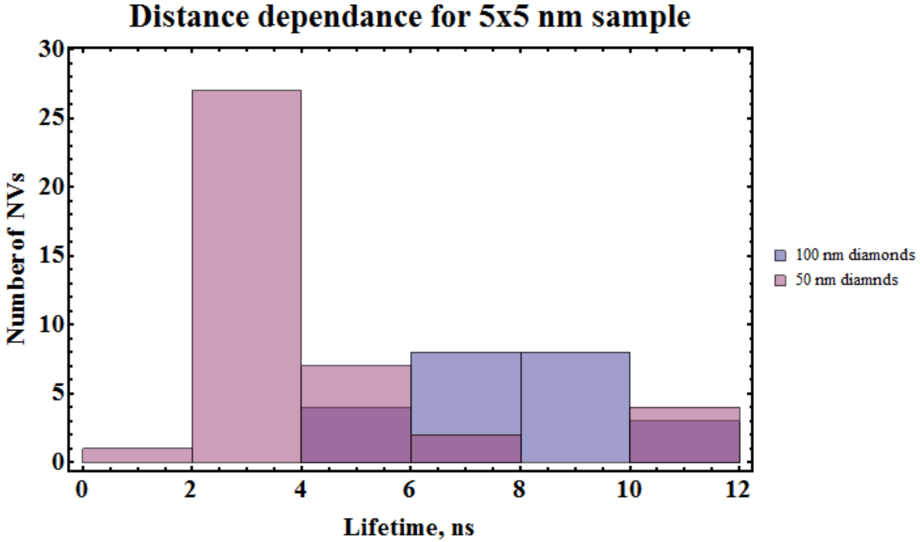
Experiment: modification of the lifetime





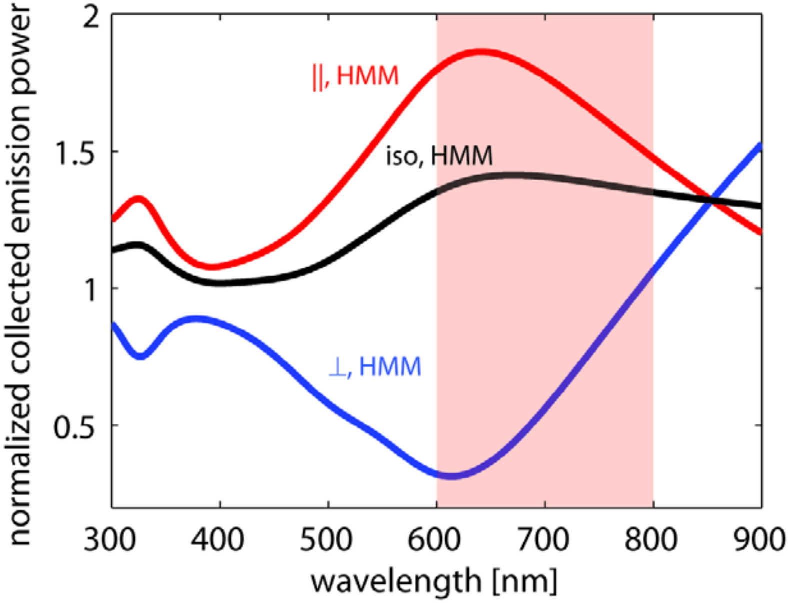
τ_{HMM} = (4.8 ±2) ns

$\tau_{coverslip} \approx$ 20 ns



Measured Purcell factor ≈ 4.2

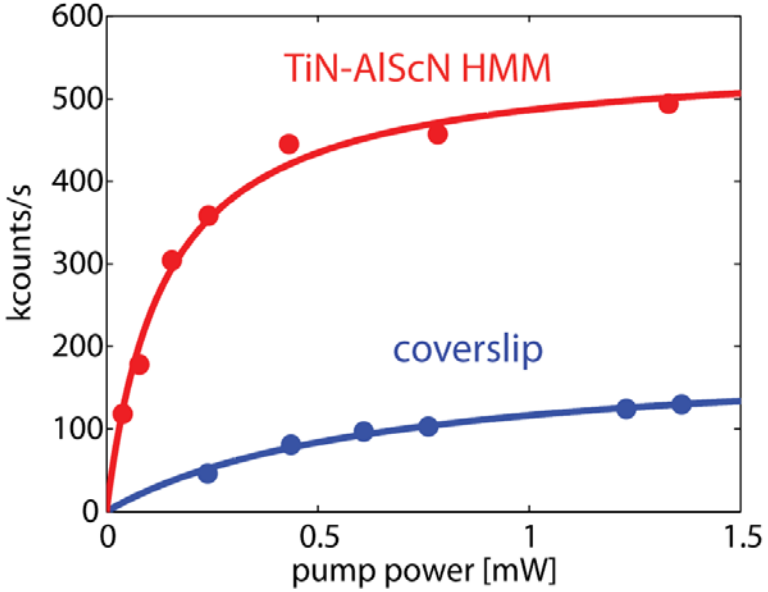
Collected emission enhancement



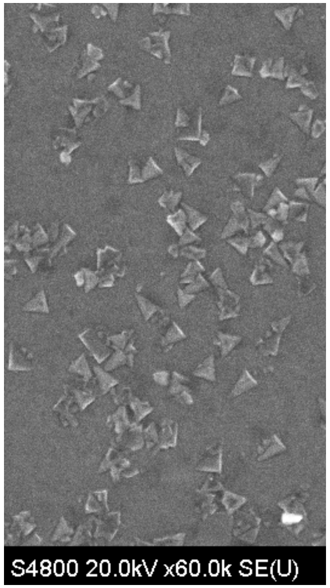
- Emission rate in free space is modified due Fresnel reflection
- Theoretical value of collected counts enhancement is 1.5

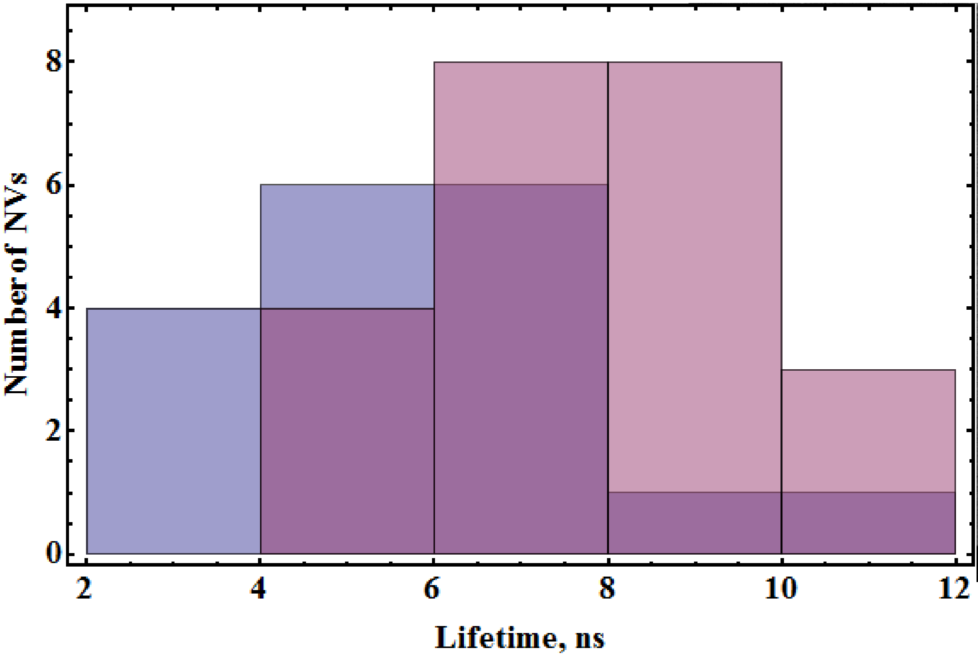
$$I = I_0 \frac{p}{p + p_0}$$

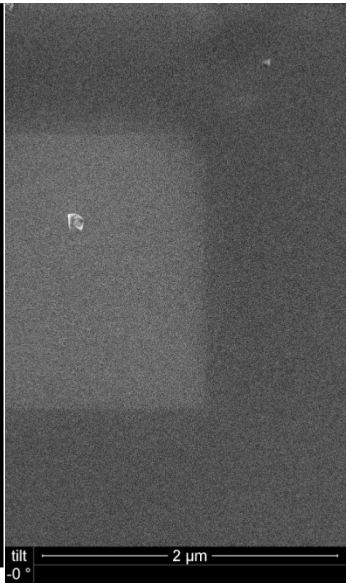
- Some of NV show 4-5 times more emission…



Quality of HMM







Sample with standard procedure

- Measured emission enhancement is around 5

Sample with new procedure:

- Measured emission enhancement is around 2

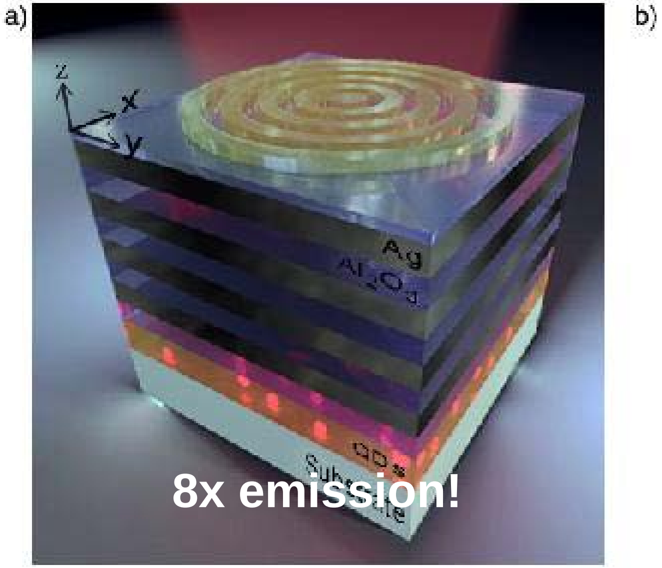
Defects act as a random antenna!

Conclusions

- Demonstrated between nanowires and quantum dots and NV center
- Demonstrated coupling of a single-photon source to hyperbolic metamaterial.
- Paved the way towards CMOS compatible integrated quantum sources.

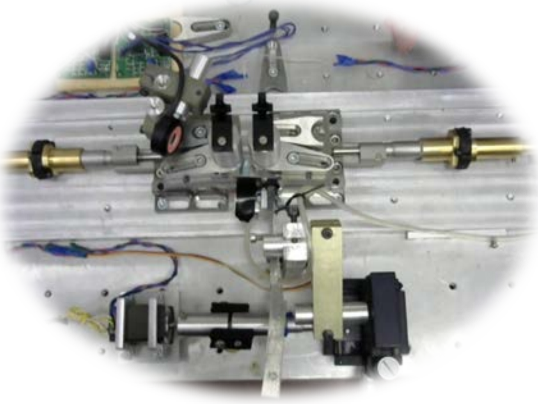
Outlook:
converting high k modes into emission

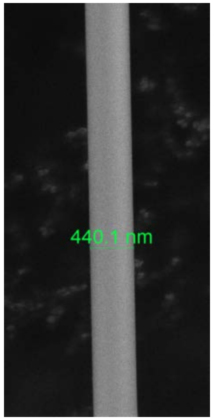
- Antenna can help convert HMM modes into light
- Smaller nano diamonds with optimal NV concentration
- Shallow implanted diamond films
- Integration with the fiber

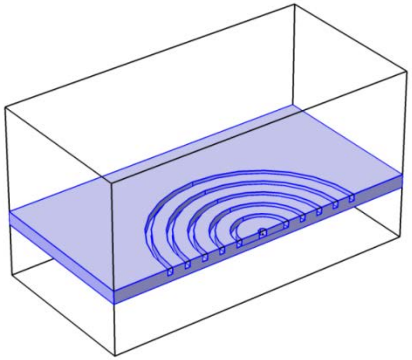


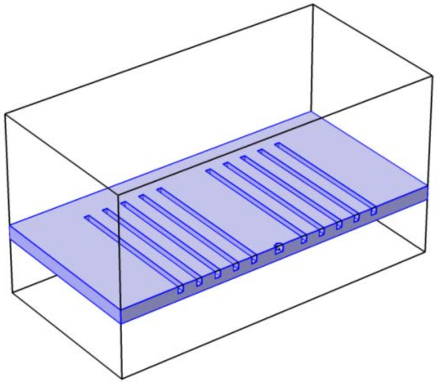
8x emission!

Tal Galfsky, *et al.,* arXiv: 1404.1535









THIS TALK

QUANTUM PLASMONICS AND NANOPHOTONICS

- Efficient quantum interface between light and spin

EXOTIC COLD ATOMS

- **Towards “simulating” complex quantum materials**

Motivation: understanding complicated quantum materials

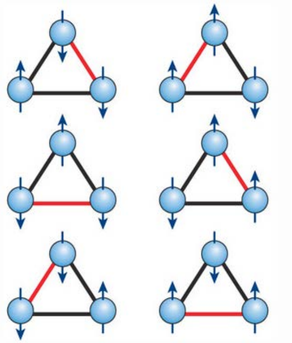
Understanding of complex materials is very challenging:

- High temperature superconductivity
  - Exist at some materials up to 138 K
  - Many potential interesting applications
  - No model with prediction power
- Magnetic materials
  - Frustrated magnets
  - Magnetic phase transitions

Approach: Use controllable quantum system to design material properties

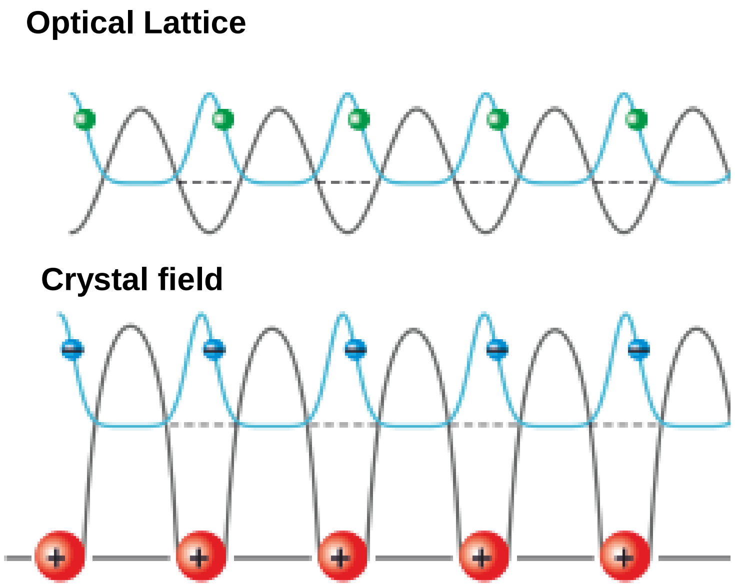
- Other application:
  - Understanding nuclear interactions
  - Modeling phonon interactions

Richard Feynman



Leon Balents, Nature 464, 2010

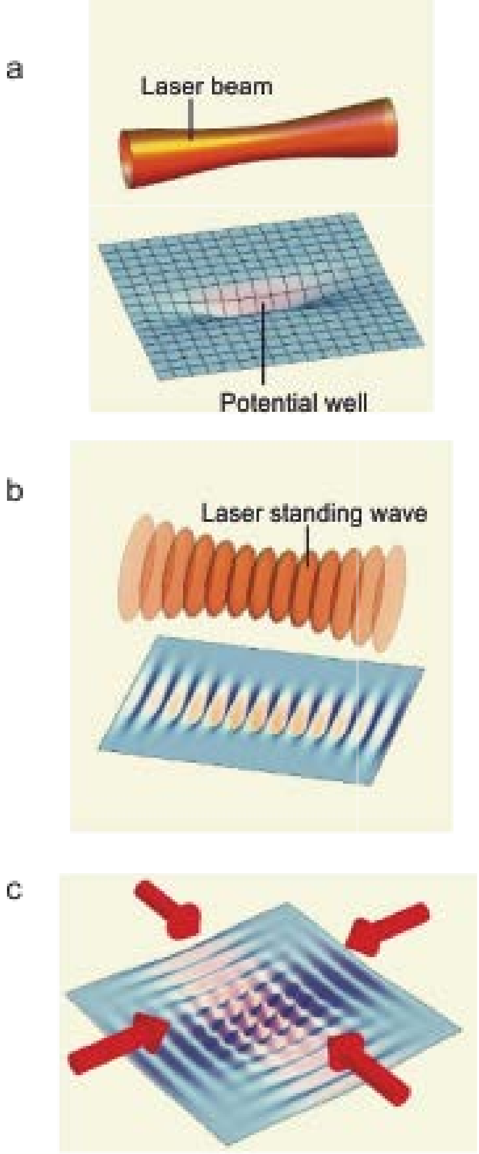
Key idea – use of cold atom ensembles

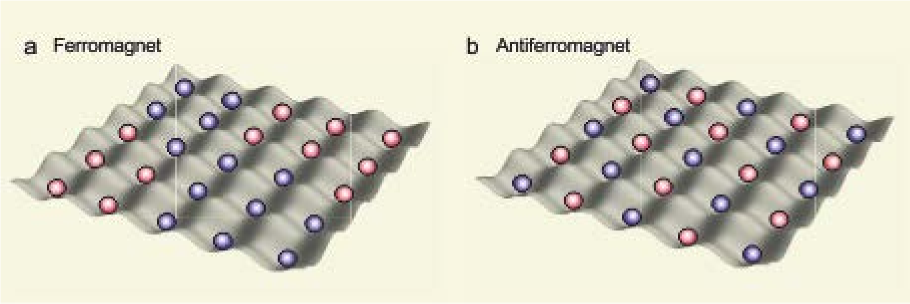


Optical Lattice

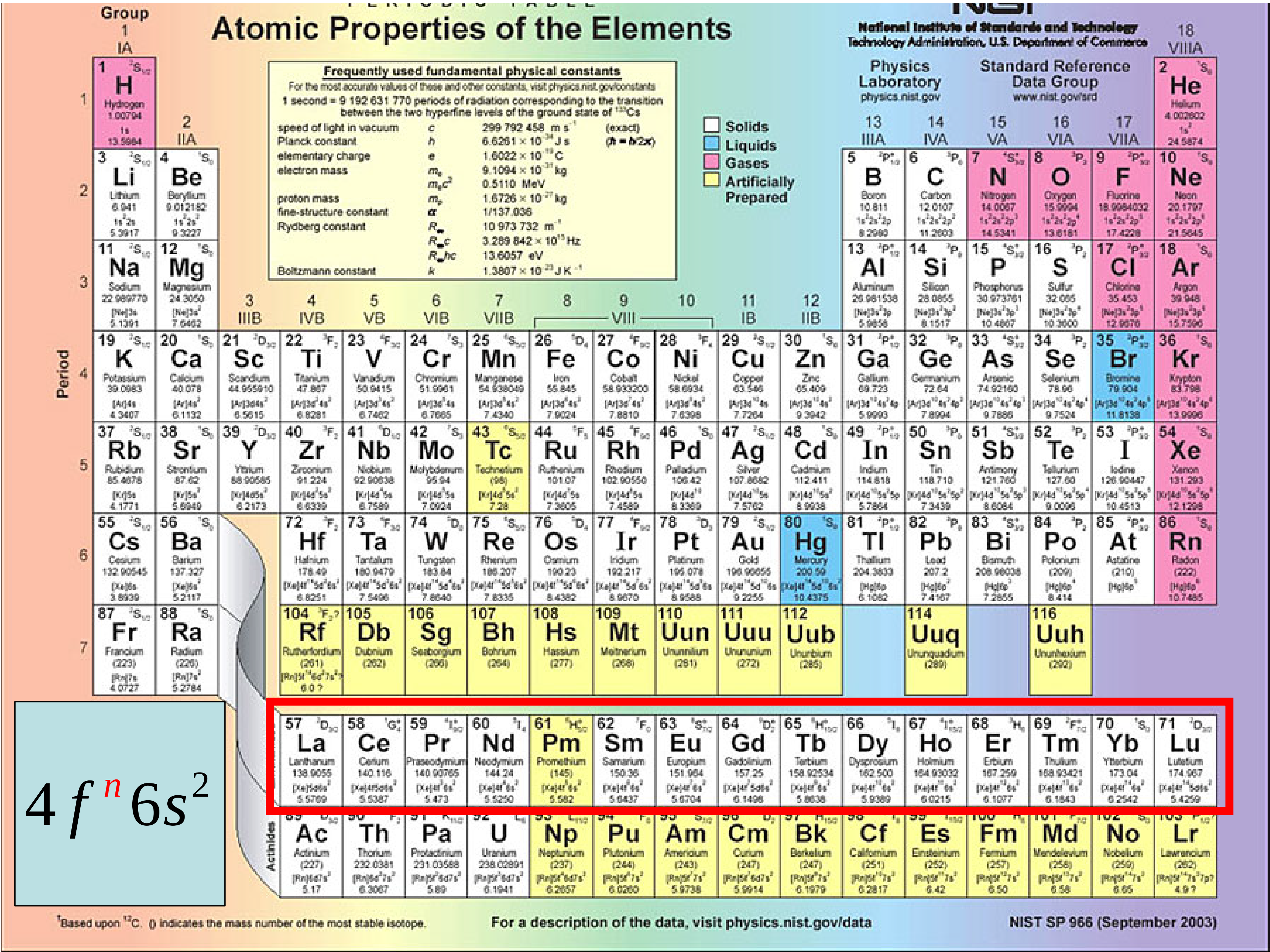
Crystal field

Atoms in optical lattices are similar to electrons in solid state





Markus Greiner and Simon Folling, NATURE, Vol 453



Atomic Properties of the Elements

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

Physics Laboratory
physics.nist.gov

Standard Reference Data Group
www.nist.gov/srd

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	m_ec^2	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,842 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

- ☐ Solids
- 🟦 Liquids
- 🟪 Gases
- 🟨 Artificially Prepared

1	H	Hydrogen	1.00794	13.5984
2	He	Helium	4.002602	24.5874
3	Li	Lithium	6.941	5.3917
4	Be	Beryllium	9.012182	9.3227
5	B	Boron	10.811	8.2980
6	C	Carbon	12.0107	11.2603
7	N	Nitrogen	14.0067	14.5341
8	O	Oxygen	15.9994	13.6181
9	F	Fluorine	18.9984032	17.4228
10	Ne	Neon	20.1797	21.5645
11	Na	Sodium	22.989770	5.1391
12	Mg	Magnesium	24.3050	7.6462
13	Al	Aluminum	26.981538	5.9858
14	Si	Silicon	28.0855	8.1517
15	P	Phosphorus	30.973761	10.4867
16	S	Sulfur	32.065	10.3600
17	Cl	Chlorine	35.453	12.9676
18	Ar	Argon	39.948	15.7596
19	K	Potassium	39.0983	4.3407
20	Ca	Calcium	40.078	6.1132
21	Sc	Scandium	44.955910	6.5615
22	Ti	Titanium	47.867	6.8281
23	V	Vanadium	50.9415	6.7462
24	Cr	Chromium	51.9961	6.7665
25	Mn	Manganese	54.938049	7.4340
26	Fe	Iron	55.845	7.9024
27	Co	Cobalt	58.933200	7.8810
28	Ni	Nickel	58.6934	7.6398
29	Cu	Copper	63.546	7.7264
30	Zn	Zinc	65.409	9.3942
31	Ga	Gallium	69.723	5.9993
32	Ge	Germanium	72.64	7.8994
33	As	Arsenic	74.92160	9.7886
34	Se	Selenium	78.96	9.7524
35	Br	Bromine	79.904	11.8138
36	Kr	Krypton	83.798	13.9996
37	Rb	Rubidium	85.4678	4.1771
38	Sr	Strontium	87.62	5.6949
39	Y	Yttrium	88.90585	6.2173
40	Zr	Zirconium	91.224	6.6339
41	Nb	Niobium	92.90638	6.7589
42	Mo	Molybdenum	95.94	7.0924
43	Tc	Technetium	(98)	7.28
44	Ru	Ruthenium	101.07	7.3605
45	Rh	Rhodium	102.90550	7.4589
46	Pd	Palladium	106.42	8.3369
47	Ag	Silver	107.8682	7.5762
48	Cd	Cadmium	112.411	8.9938
49	In	Indium	114.818	5.7864
50	Sn	Tin	118.710	7.3439
51	Sb	Antimony	121.760	8.6084
52	Te	Tellurium	127.60	9.0096
53	I	Iodine	126.90447	10.4513
54	Xe	Xenon	131.293	12.1298
55	Cs	Cesium	132.90545	3.8939
56	Ba	Barium	137.327	5.2117
72	Hf	Hafnium	178.49	6.8251
73	Ta	Tantalum	180.9479	7.5496
74	W	Tungsten	183.84	7.8640
75	Re	Rhenium	186.207	7.8335
76	Os	Osmium	190.23	8.4382
77	Ir	Iridium	192.217	8.9670
78	Pt	Platinum	195.078	8.9588
79	Au	Gold	196.96655	9.2255
80	Hg	Mercury	200.59	10.4375
81	Tl	Thallium	204.3833	6.1082
82	Pb	Lead	207.2	7.4167
83	Bi	Bismuth	208.98038	7.2855
84	Po	Polonium	(209)	8.414
85	At	Astatine	(210)	
86	Rn	Radon	(222)	10.7485
87	Fr	Francium	(223)	4.0727
88	Ra	Radium	(226)	5.2784
104	Rf	Rutherfordium	(261)	6.0 ?
105	Db	Dubnium	(262)	
106	Sg	Seaborgium	(266)	
107	Bh	Bohrium	(264)	
108	Hs	Hassium	(277)	
109	Mt	Meitnerium	(268)	
110	Uun	Ununnilium	(281)	
111	Uuu	Unununium	(272)	
112	Uub	Ununbium	(285)	
114	Uuq	Ununquadium	(289)	
116	Uuh	Ununhexium	(292)	
57	La	Lanthanum	138.9055	5.5769
58	Ce	Cerium	140.116	5.5387
59	Pr	Praseodymium	140.90765	5.473
60	Nd	Neodymium	144.24	5.5250
61	Pm	Promethium	(145)	5.582
62	Sm	Samarium	150.36	5.6437
63	Eu	Europium	151.964	5.6704
64	Gd	Gadolinium	157.25	6.1498
65	Tb	Terbium	158.92534	5.8638
66	Dy	Dysprosium	162.500	5.9389
67	Ho	Holmium	164.93032	6.0215
68	Er	Erbium	167.259	6.1077
69	Tm	Thulium	168.93421	6.1843
70	Yb	Ytterbium	173.04	6.2542
71	Lu	Lutetium	174.967	5.4259
89	Ac	Actinium	(227)	5.17
90	Th	Thorium	232.0381	6.3067
91	Pa	Protactinium	231.03588	5.89
92	U	Uranium	238.02891	6.1941
93	Np	Neptunium	(237)	6.2657
94	Pu	Plutonium	(244)	6.0260
95	Am	Americium	(243)	5.9738
96	Cm	Curium	(247)	5.9914
97	Bk	Berkelium	(247)	6.1979
98	Cf	Californium	(251)	6.2817
99	Es	Einsteinium	(252)	6.42
100	Fm	Fermium	(257)	6.50
101	Md	Mendelevium	(258)	6.58
102	No	Nobelium	(259)	6.65
103	Lr	Lawrencium	(262)	4.9 ?

[1]Based upon ^{12}C. () indicates the mass number of the most stable isotope.

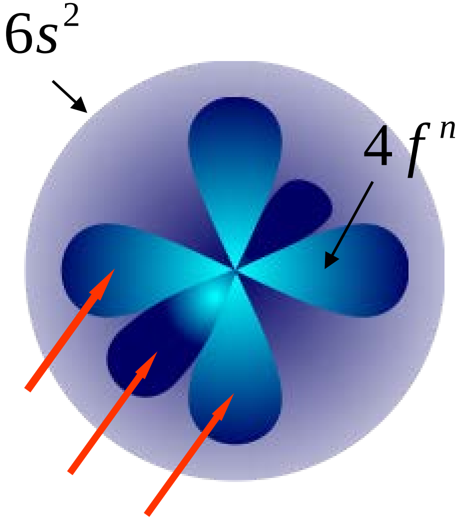
For a description of the data, visit physics.nist.gov/data

NIST SP 966 (September 2003)

$$4f^{n}6s^{2}$$

Why lanthanides?

- Optical electrons are f - shell ones
  - Ground state has orbital momentum
  - Ground state has magnetic momentum
  - Many low-field Feshbach resonances
  - Ground state transitions are somewhat shielded by s-shell
- Strong close to cycling optical transition in visible
- Narrow “clock” transitions

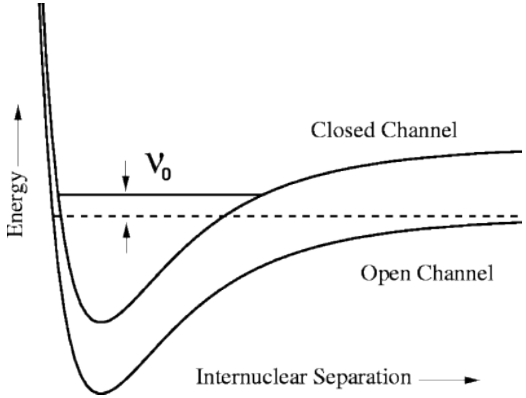


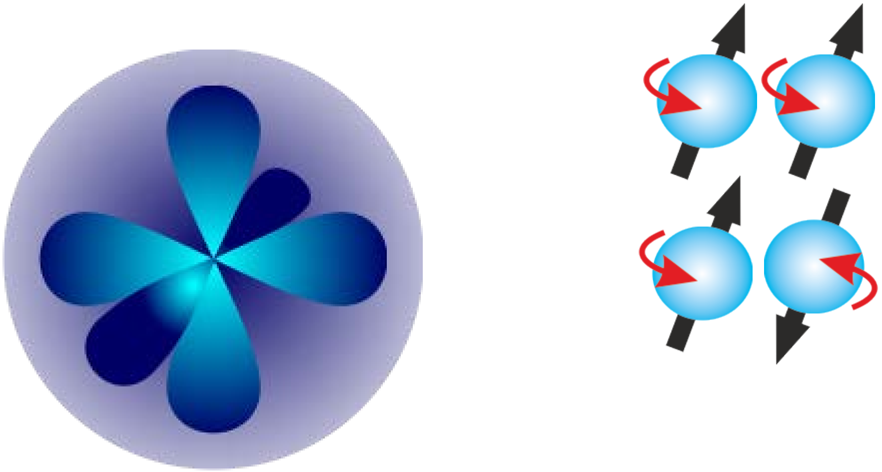
Thulium

✓ Easy to cool
✓ Allow magnetic dipole-dipole interactions
✓ May be suitable for quantum simulations

Tm Vision

- Feshbach resonance in moderate magnetic field are expected
- Suitable for cooling down to BEC via optical dipole trap
- Suitable for magnetic dipole - dipole interactions in green dipole trap (up to 100 times stronger, then with alkali atom)
- Both nuclear spin and electron orbital momentum could be used for spin manipulation
- Single short readout for single side state should be possible for each ground state level.





Cold lanthanides today:

^{66}Dy

$4f^{10}6s^{2}$

- Complicated level structure
- **$10\mu_B$**
- 421 nm 1st stage
- 721nm 2st stage
- 1064 nm dipole trap
- BEC achieved

B.Lev , Stanford University
PRL 107, 190401 (2011)

^{68}Er

$4f^{12}6s^{2}$

- Complicated level structure
- **$7\mu_B$**
- 401 nm 1st stage
- 583nm 2st stage
- 1064/1075 nm dipole trap
- BEC achieved

F. Ferlaino, Innsbruck University
PRL 108, 210401 (2012)

^{69}Tm

$4f^{13}6s^{2}$

- Simple level structure
- **$4\mu_B$**
- 410 nm 1st stage
- 531 nm 2st stage
- 532 nm dipole trap
- ?BEC

A. Akimov, RQC&LPI,
PRA 108, 210401 (2012)

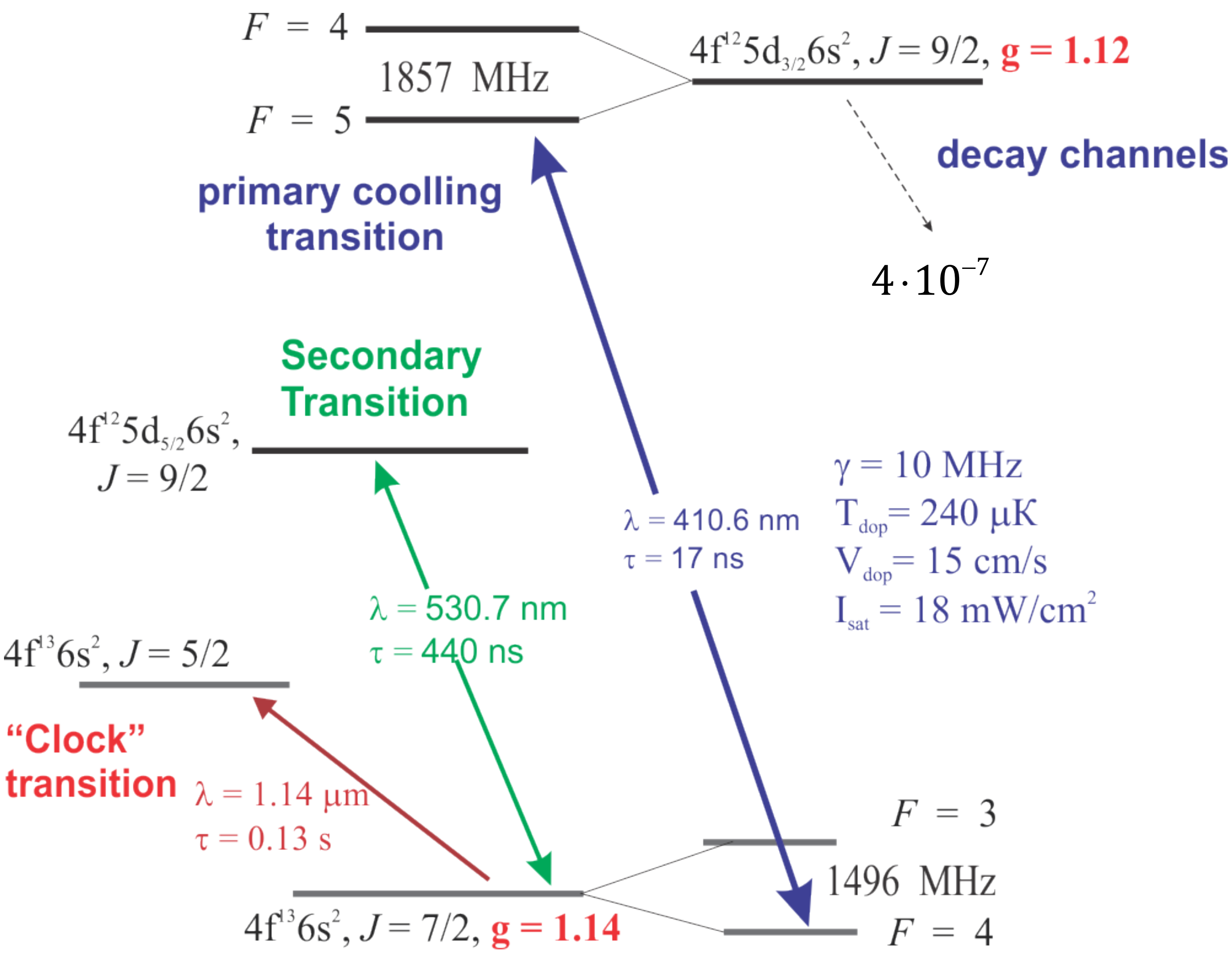
^{70}Yb

$4f^{14}6s^{2}$

- Very simple level structure
- **$0.5\mu_B$**
- 399 nm 1st stage
- 556 nm 2st stage
- 532 nm dipole trap
- BEC achieved

Y. Takahashi, Kyoto University
PRL **98,** 030401 (2007)

Tm working transitions



$F = 4$

1857 MHz

$F = 5$

$4f^{12}5d_{3/2}6s^2$, $J = 9/2$, **g = 1.12**

decay channels

$4 \cdot 10^{-7}$

primary coolling transition

Secondary Transition

$4f^{12}5d_{5/2}6s^2$, $J = 9/2$

$\lambda = 410.6$ nm
$\tau = 17$ ns

$\gamma = 10$ MHz
$T_{dop} = 240$ μK
$V_{dop} = 15$ cm/s
$I_{sat} = 18$ mW/cm^2

$\lambda = 530.7$ nm
$\tau = 440$ ns

$4f^{13}6s^2$, $J = 5/2$

“Clock” transition

$\lambda = 1.14$ μm
$\tau = 0.13$ s

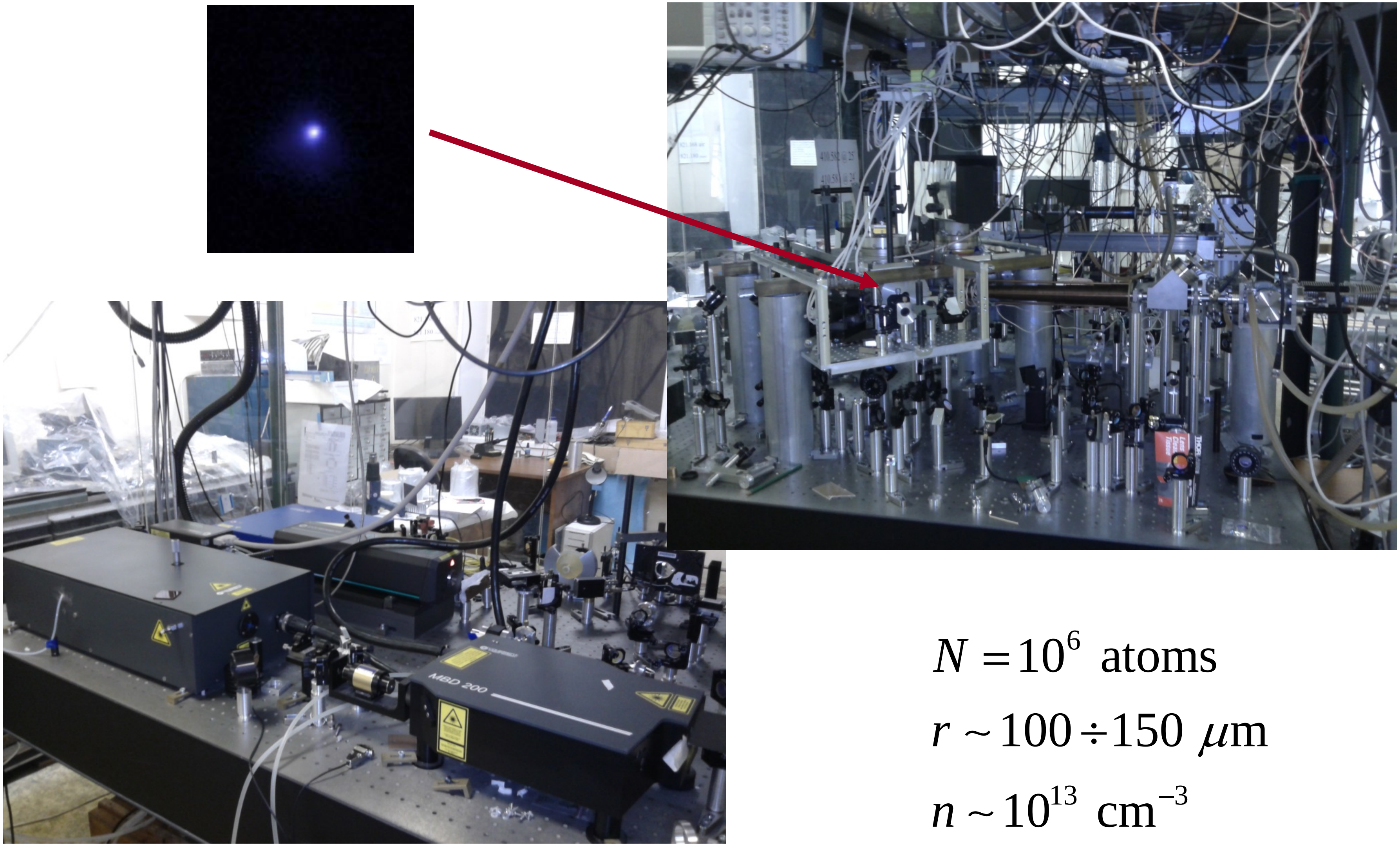
$F = 3$

1496 MHz

$F = 4$

$4f^{13}6s^2$, $J = 7/2$, **g = 1.14**

The setup



$N = 10^6$ atoms

$r \sim 100 \div 150\ \mu\text{m}$

$n \sim 10^{13}\ \text{cm}^{-3}$

Sukachev et al., Phys. Rev. A, **82**, 011405 (2010)

MOT Temperature

Doppler cooling

$$T = \frac{\hbar\Gamma}{4k_B}\frac{1+4((\omega-\omega_0)/\Gamma)^2}{2(\omega-\omega_0)/\Gamma}$$

$$T_D = \frac{\hbar\Gamma}{2k_B}$$

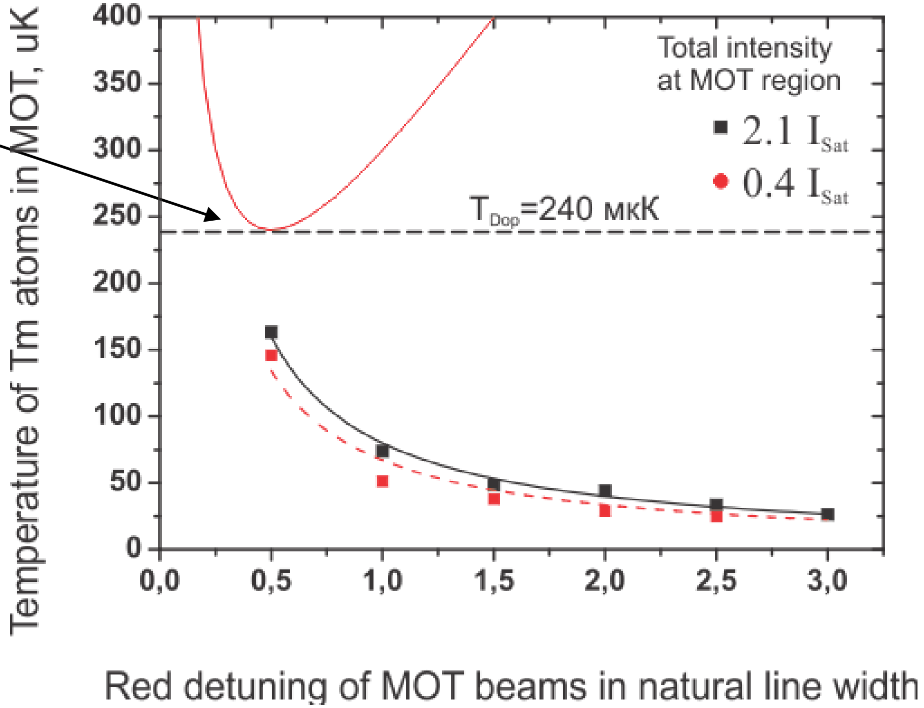
$\sim 240\ \mu K$

Sub Doppler cooling

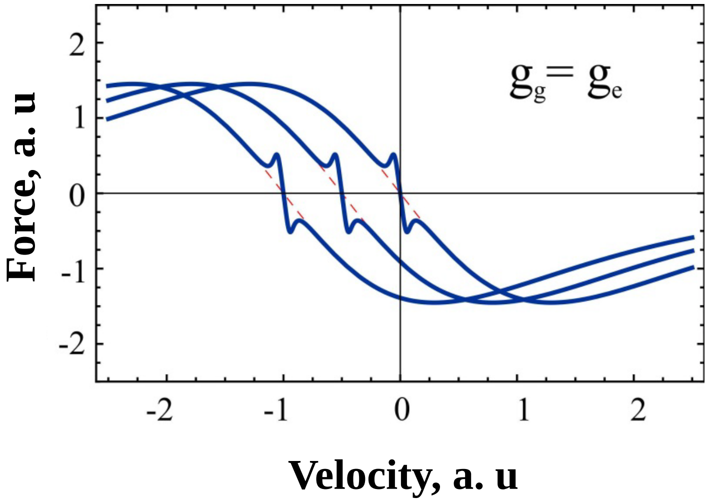
$$T = 0.3\frac{\hbar\Gamma^2 s_0}{2|\delta|k_B}$$

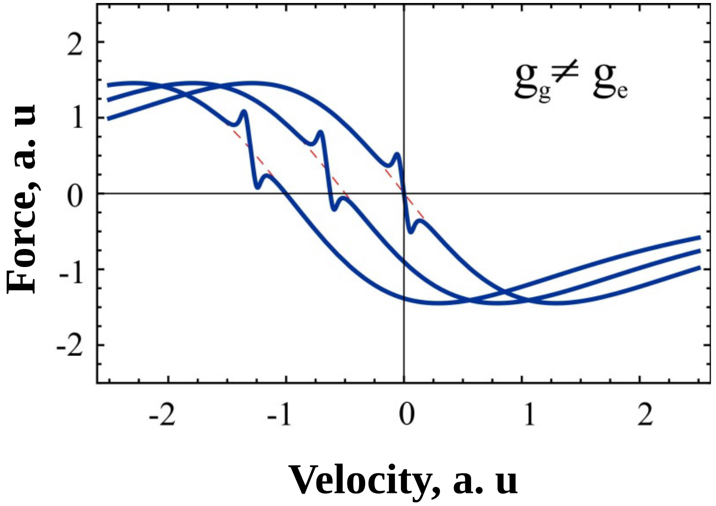
$$T_R = \frac{\hbar^2 k^2}{k_B\, m}$$

$\sim 1\ \mu K$

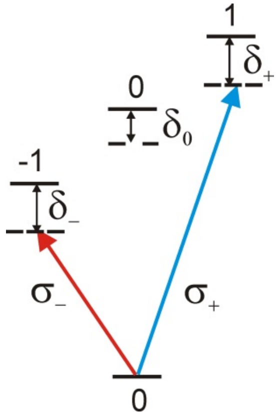


Cooling mechanisms in the magnetic field

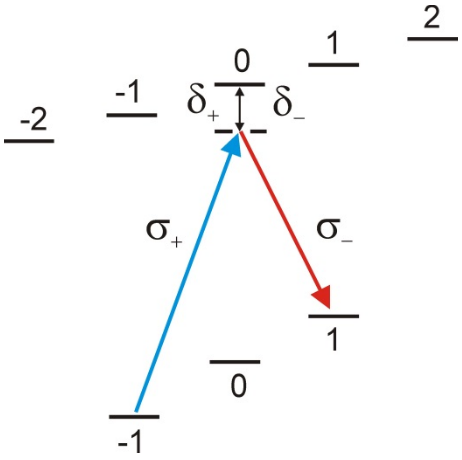




Doppler cooling



Polarization Gradient cooling



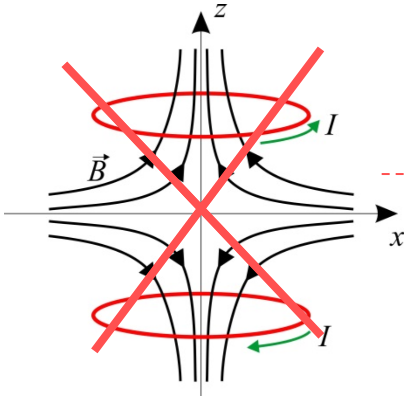
$$v_D = -\boxed{g_e}\frac{\mu_B B}{\hbar k}$$

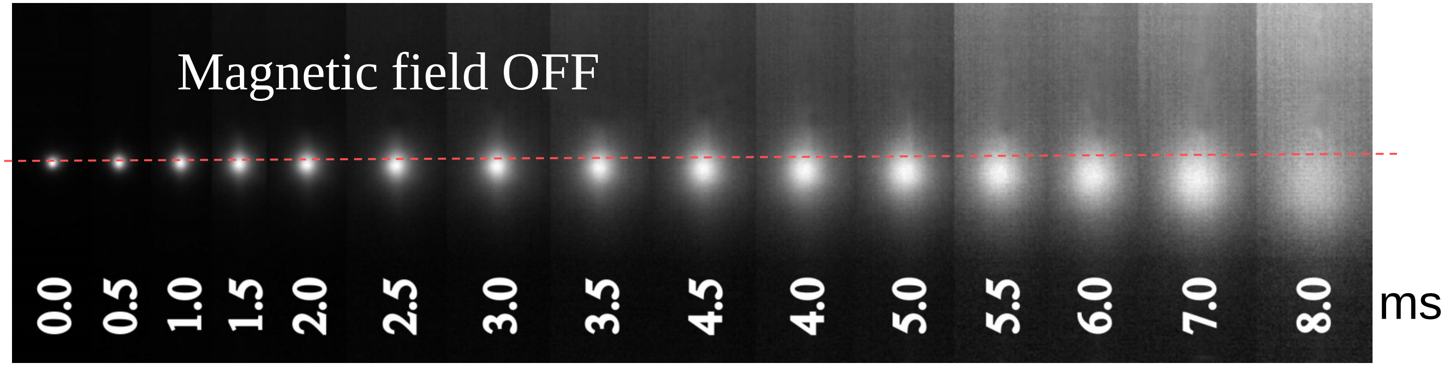
$$v_S = -\boxed{g_g}\frac{\mu_B B}{\hbar k}$$

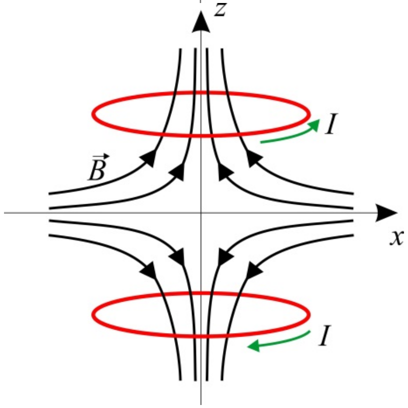
PGC normally is detuned from Doppler cooling

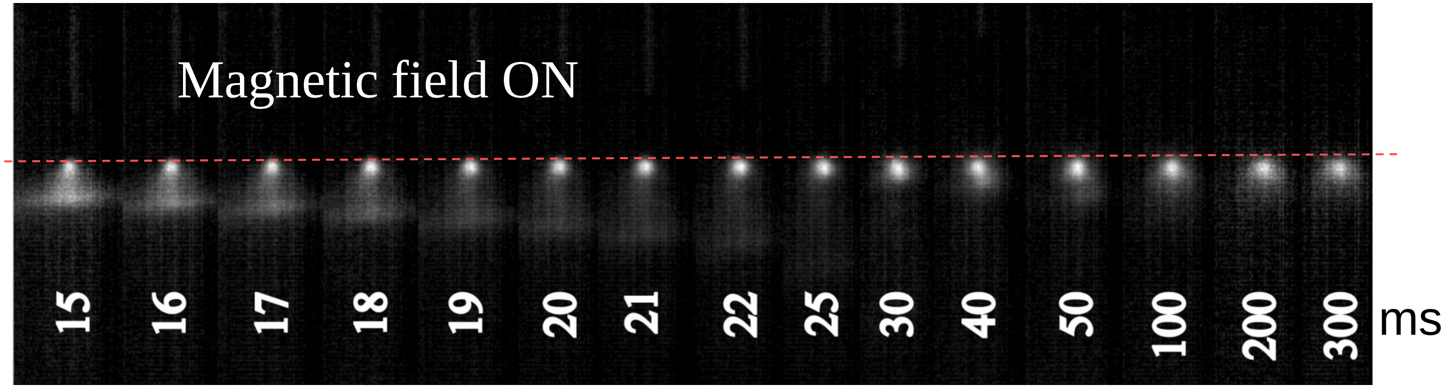
Phillips *et al*, J. Opt. Soc. Am. B, **9**, 1997 (1992);
Valentin, *et al,* EuroPhys. Lett. **17,** 133 (1992)

Magnetic trap



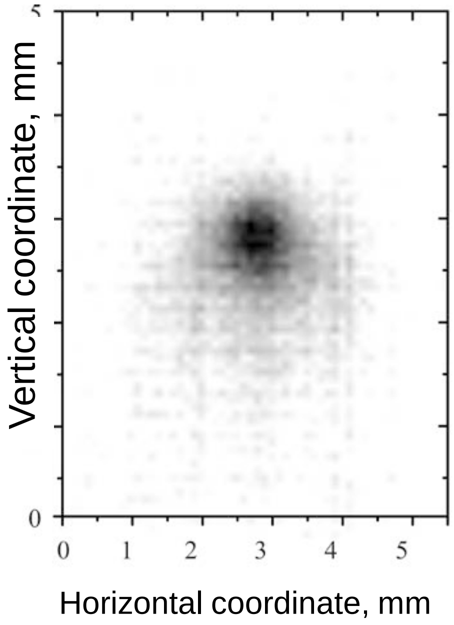


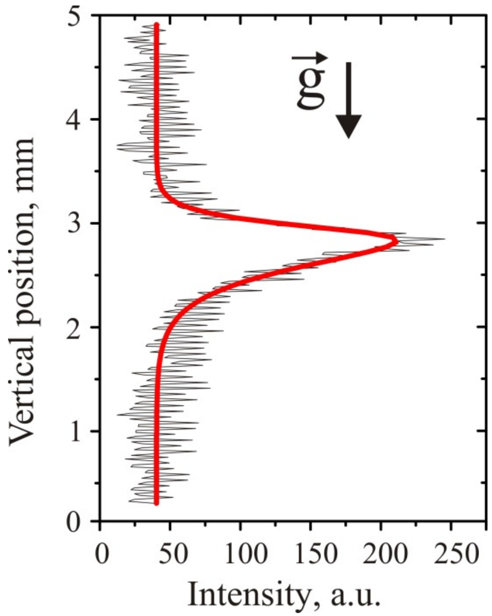


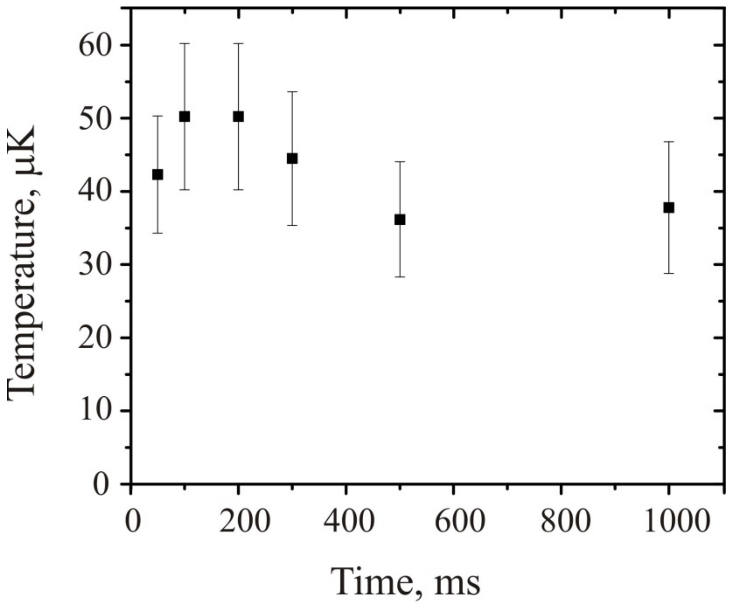


Gradient of magnetic field ~20 G/cm

Magnetic trap Temperature







$$T = \frac{mg}{2k_B}\frac{\widetilde{z}}{\widetilde{g}}\,.$$

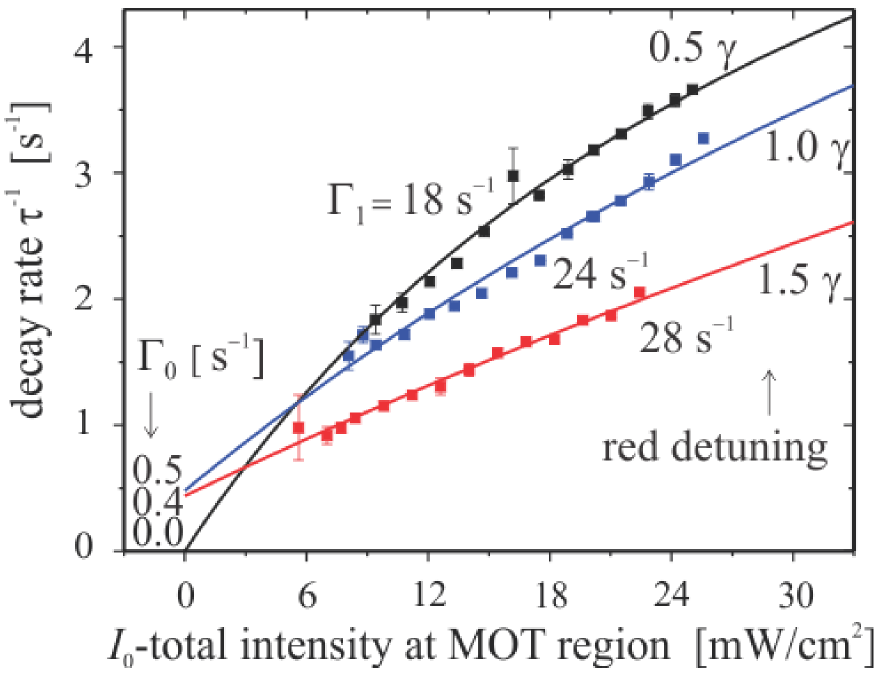
$$N = 40\times10^3 \text{ atoms}$$

$$n_{\max} = 10^9\,\text{cm}^{-3}$$

$T_{MagneticTrap}$ = 40 μK

T_{MOT} = 100 μK

Collisions and cyclicity, first results



- The losses rise with power result from the upper level branching decay.

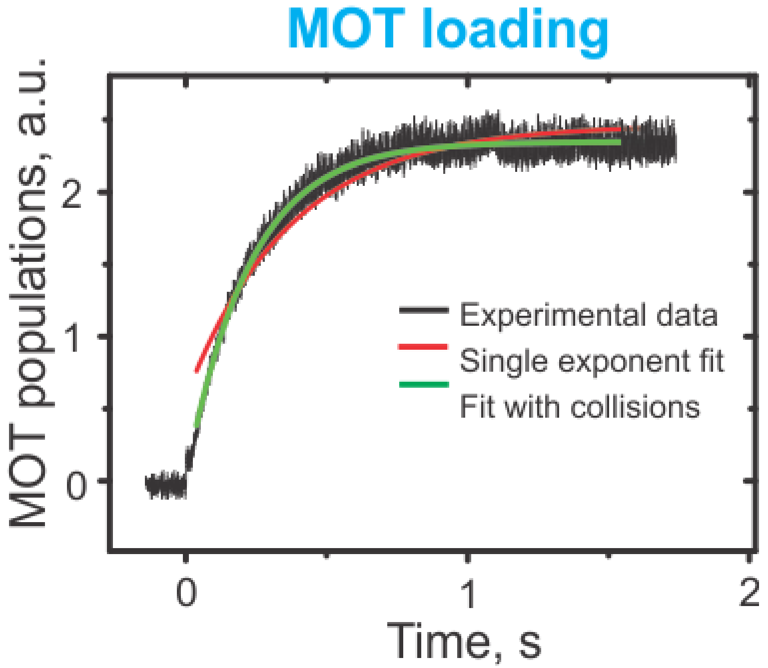
$$\gamma_{loss} \simeq 24\ \mathrm{s}^{-1}, \quad \gamma \simeq 6\cdot 10^{7}\ \mathrm{s}^{-1}$$

- Long Zeeman cooler compatible with Rb is possible .

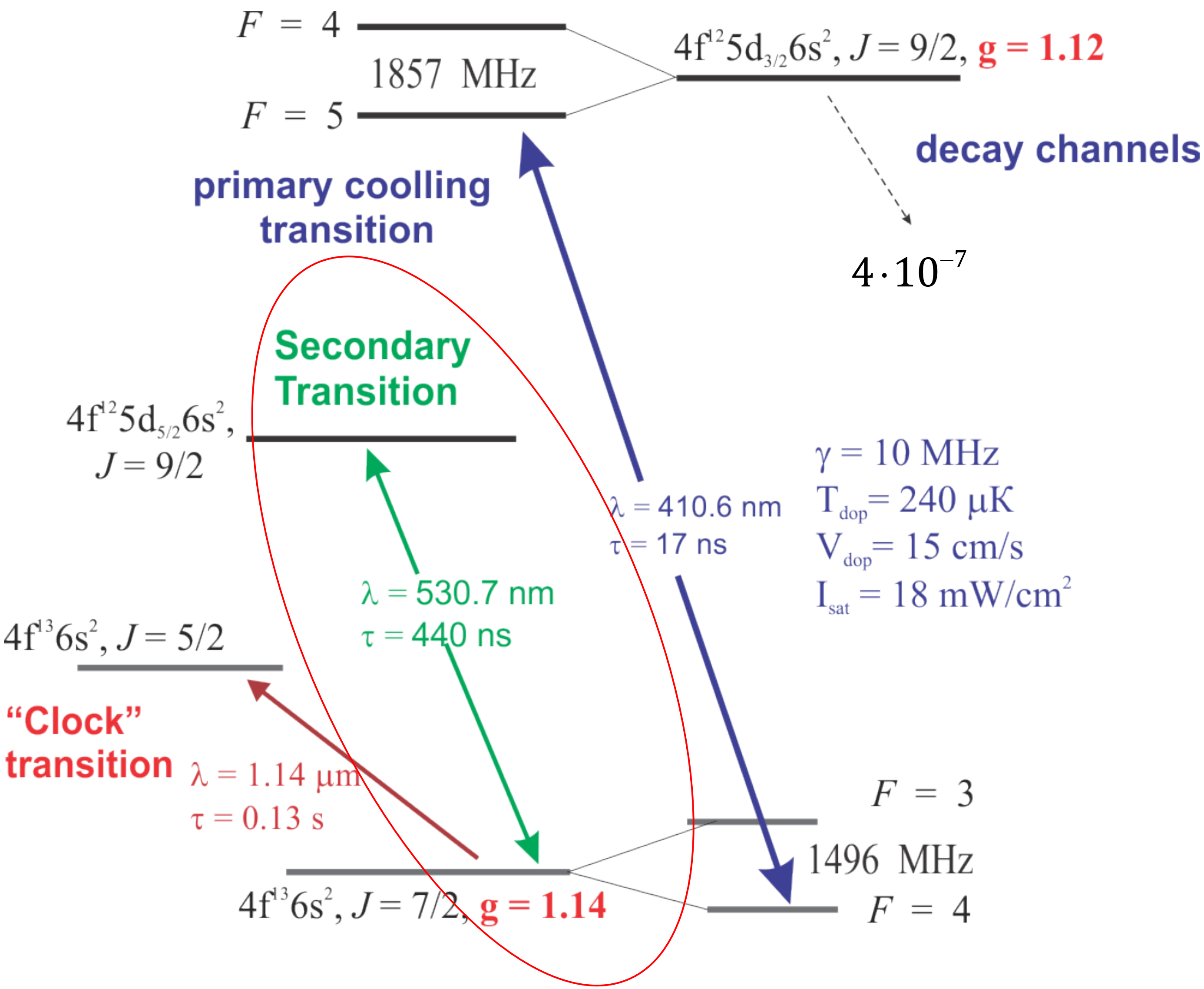
$$\frac{dN}{dt} = R - \gamma N - \beta N^{2}$$

$$\beta = \frac{\sigma}{2\sqrt{2}\pi^{1.5}\omega^{3}}$$

$$\sigma v = 3(2)\cdot 10^{-10}\ \mathrm{cm}^{3}/\mathrm{s}$$



Cycling transition: second stage cooling



$F = 4$

1857 MHz

$F = 5$

$4f^{12}5d_{3/2}6s^2$, $J = 9/2$, **g = 1.12**

decay channels

$4 \cdot 10^{-7}$

primary coolling transition

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$4f^{12}5d_{5/2}6s^2$, $J = 9/2$

$\lambda = 410.6$ nm
$\tau = 17$ ns

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$T_{dop} = 240\ \mu K$
$V_{dop} = 15$ cm/s
$I_{sat} = 18$ mW/cm^2

$\lambda = 530.7$ nm
$\tau = 440$ ns

$4f^{13}6s^2$, $J = 5/2$

"Clock" transition

$\lambda = 1.14\ \mu m$
$\tau = 0.13$ s

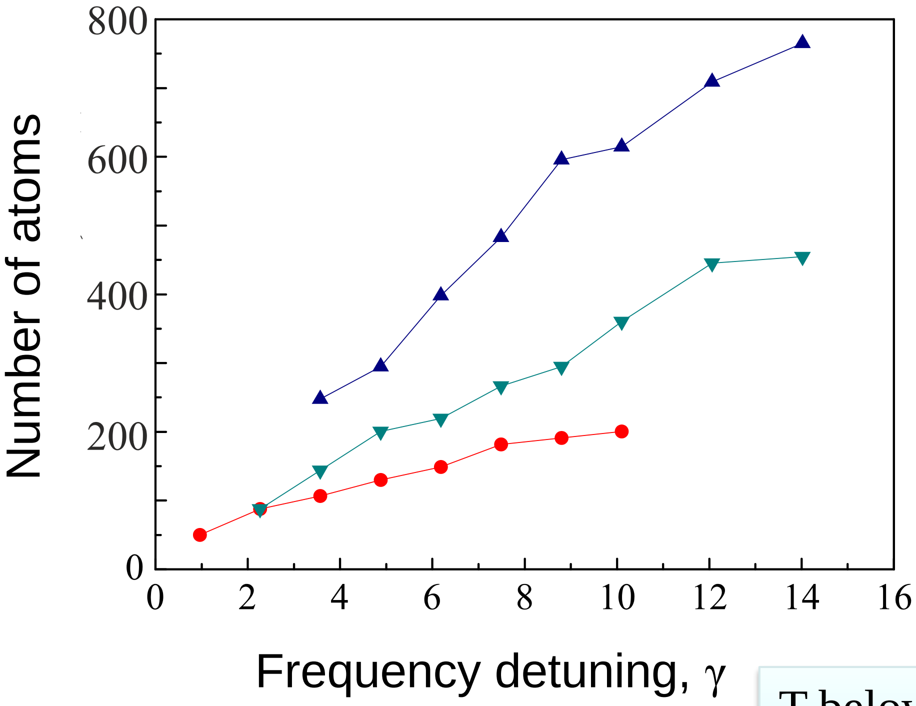
$F = 3$

1496 MHz

$F = 4$

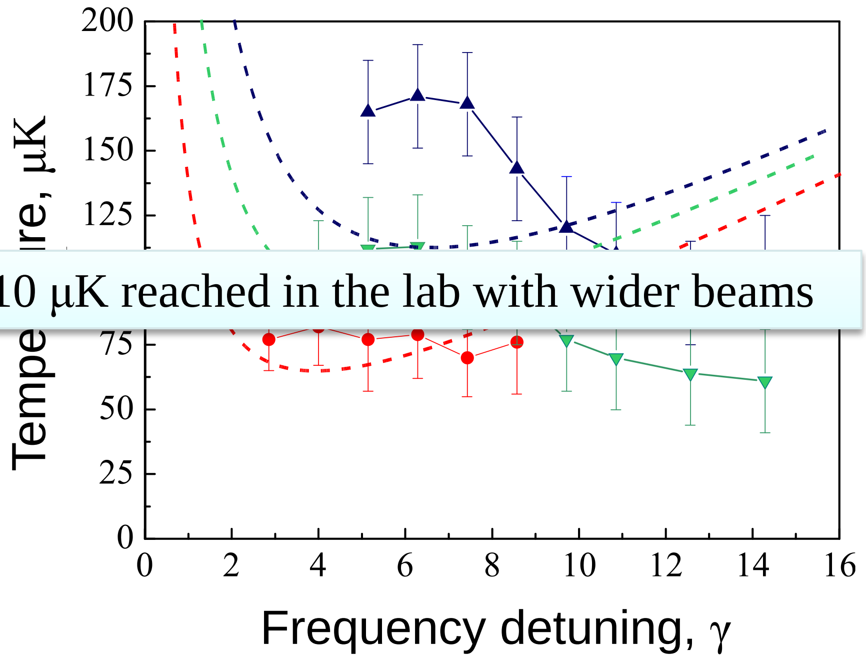
$4f^{13}6s^2$, $J = 7/2$, **g = 1.14**

Atomic Cloud Temperature



▲ $S_0 = 90$
▼ $S_0 = 60$
● $S_0 = 30$

👎■$_{530,7}$ < 20 кГц

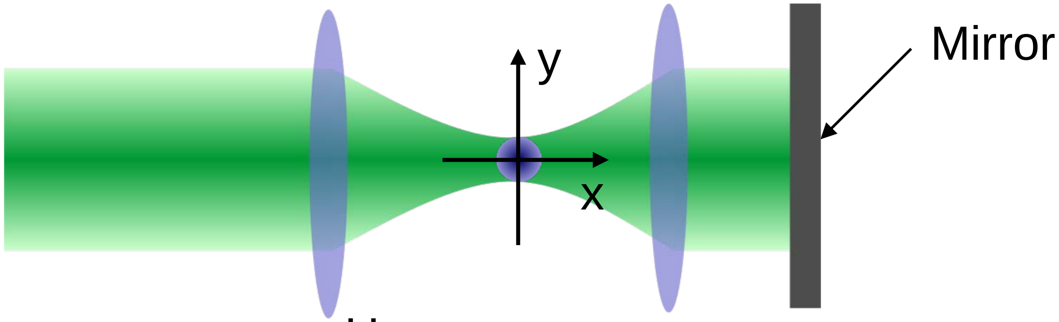


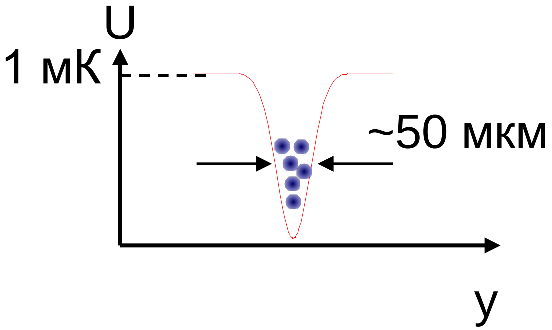
T below 10 μK reached in the lab with wider beams

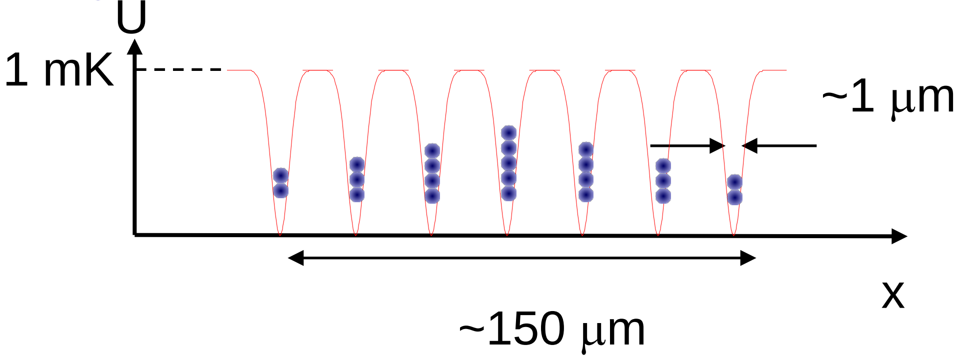
$$kT_{\min} = \frac{\hbar\Gamma}{4}\frac{1+2s_0+4\left(\frac{\delta}{\gamma}\right)^2}{\left(\frac{2\delta}{\gamma}\right)^2}$$

But… Lifetime of atoms in green trap is 2 seconds, residual gas collisions limited

Optical lattice

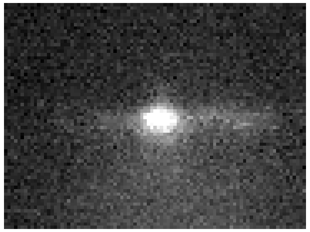


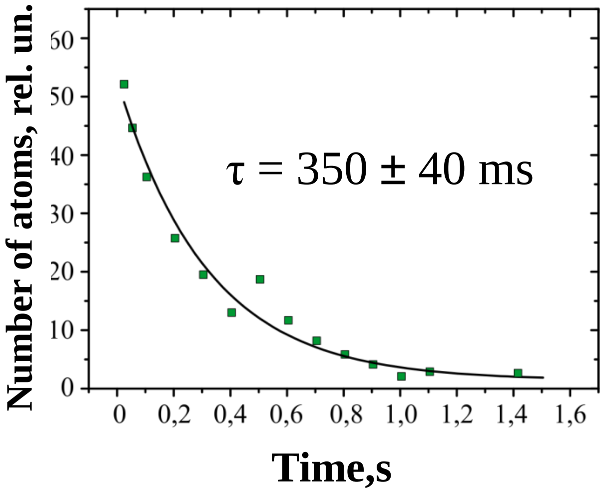




Single dimension

Double dimensions

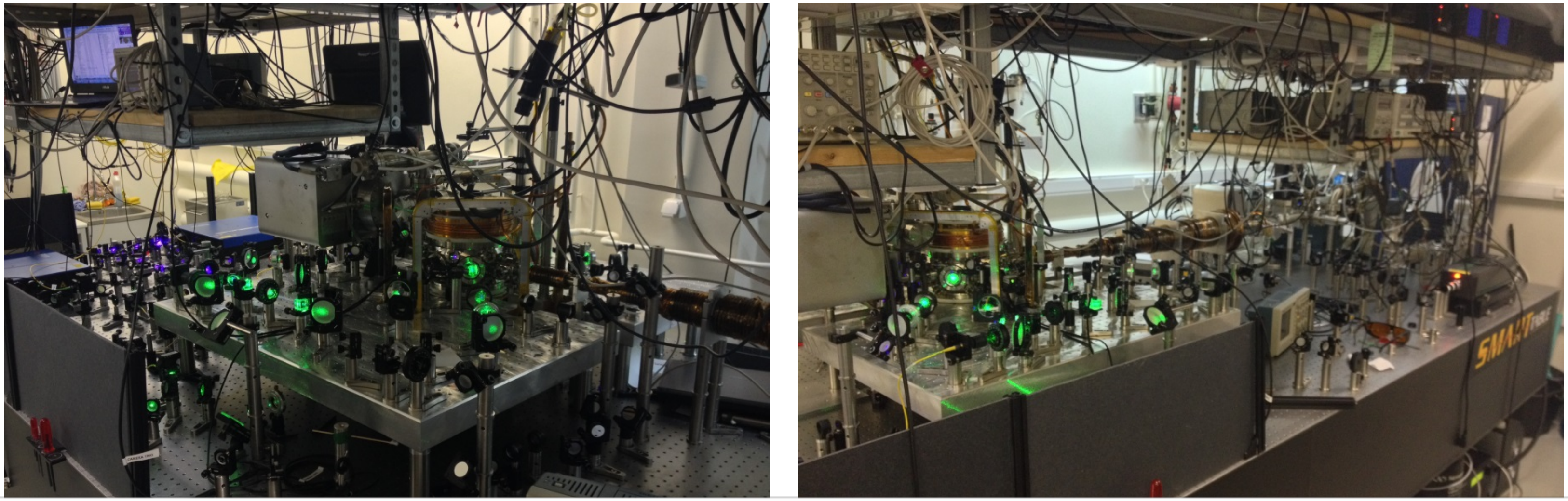




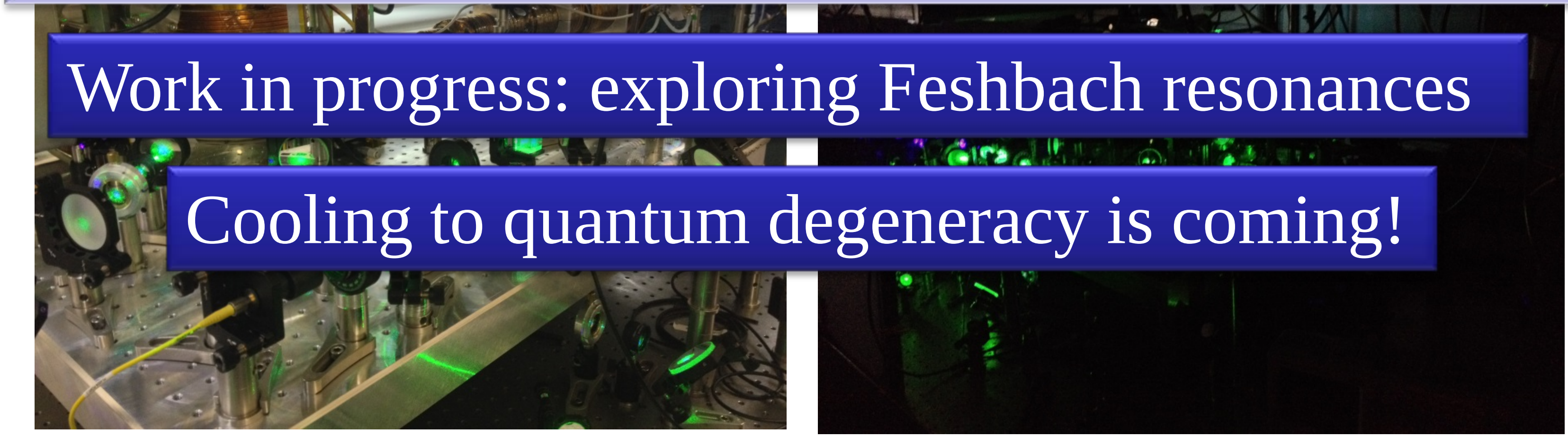
Where we are:

- Laser cooling and trapping of Thulium at 410 nm was demonstrated.
- “Free” subDoppler cooling down to 25 μK (0.1 Doppler limit), was demonstrated
- Magnetic trap was demonstrated
- Second stage cooling at 530.7nm is realized down to 10 μK
- Deep dipole trap/lattice at 532 nm was demonstrated

Getting more atoms: new setup



Current status: 5 10^6 atoms in blue MOT at 60 μK, γ/2 detuning,
Strong magnetic trap
Green MOT is under optimization

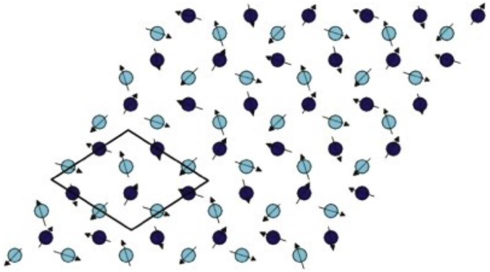


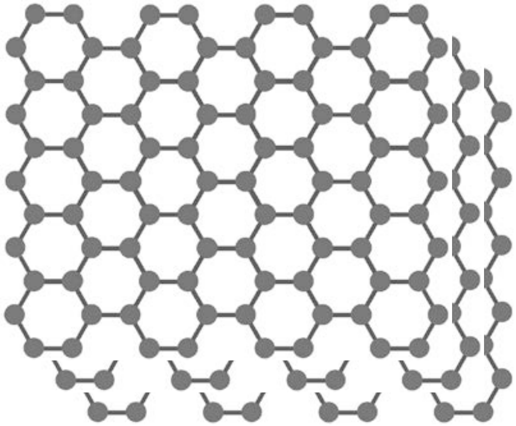
Work in progress: exploring Feshbach resonances

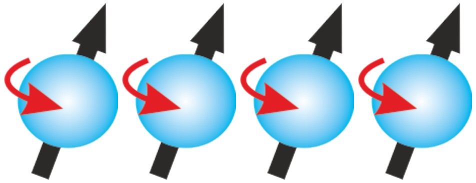
Cooling to quantum degeneracy is coming!

Outlook

- Simulation of exotic magnetic phases due to high orbital/magnetic moment
- Novel optical clock
- Simulation of complex dipolar systems

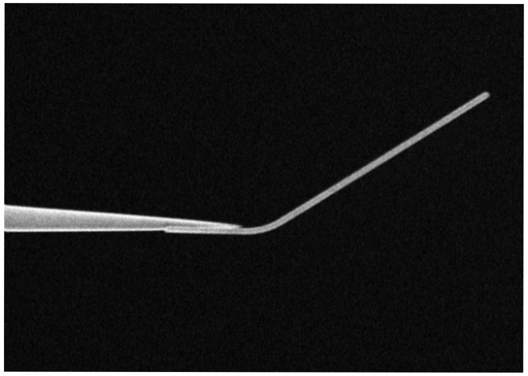




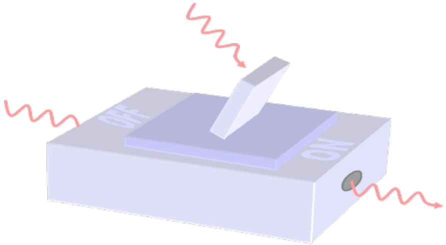


Outlook: integration with photonics

- Combining photonic cavities or plasmonic structures with ultaracold atoms
    - Recent progress: *Tobias G. Tiecke, Jeff D. Thompson, Nature 508, 241-244*

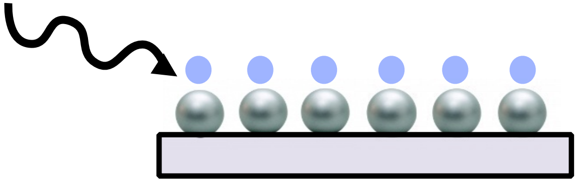


- Single photon nonlinear optics, switches, transistors



- Sub-wavelength optical lattices for cold atoms
    - using plasmonic nano-particle array

      M. Gullans et al Phys. Rev. Lett. 109, 235309 (2012)



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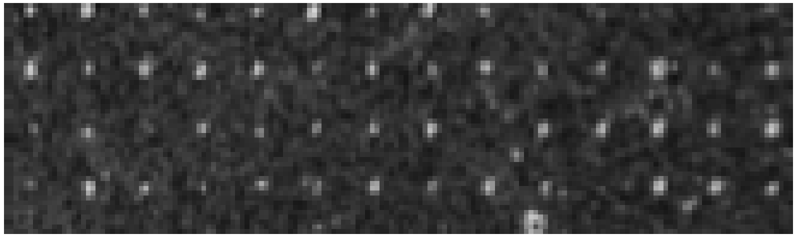
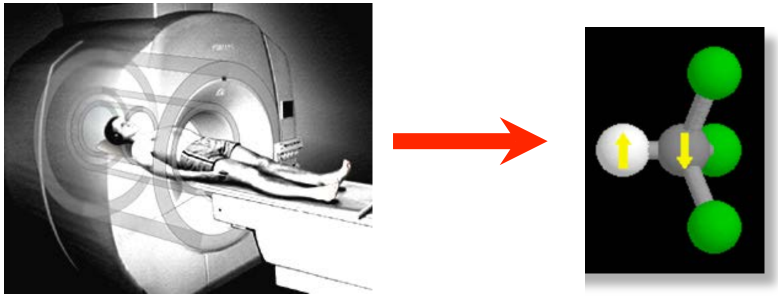
Integrated Quantum Nanophotonics: research plans

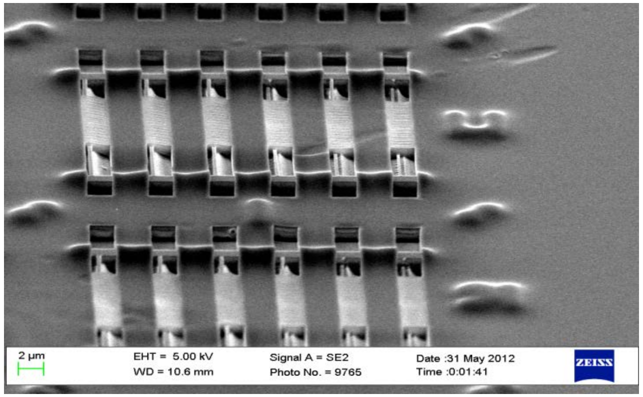
- Goal: development of integrated quantum nanophotonics using NV centers in diamond.
  - Light spin interfaces at room temperature
    - Metamaterial based
    - Metasurfaces based
  - Sensors of magnetic and electric fields, rotation or temperature
    - High sensitivity sensors using bulk diamond
    - High resolution sensors based on interfaces



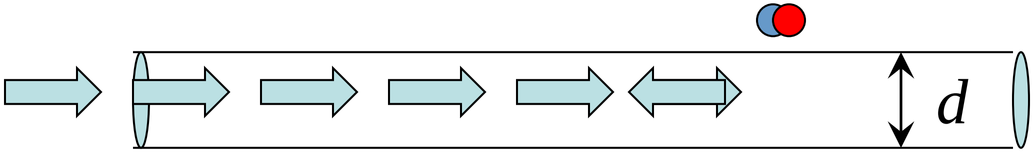


Integrated Quantum Nanophotonics: research plans

- Goal: development of integrated quantum nanophotonics using color centers
  - Cavity QED approach
    - Diamond fabrication
    - Plasmonic cavities
    - Exploring novel emitters such as SiV centers

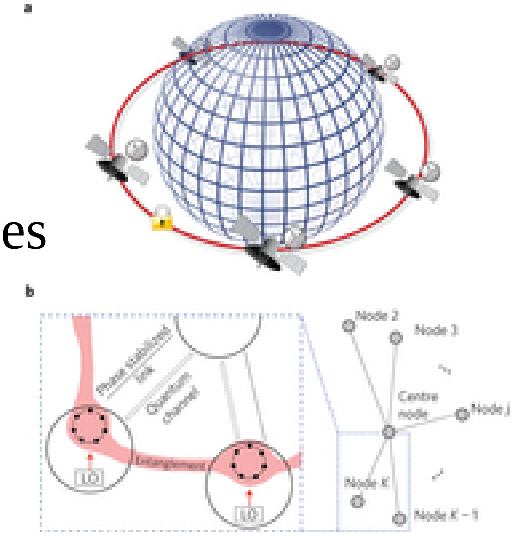


  - Fully integrated circuit, including diamond nanophotonics, fast detectors, fiber couplers and electrical interfaces.
    - Quantum photonics based on NV centers
    - Single photon transistors



Exotic cold atoms – research plans

- **Goal: Quantum simulations**
  - Exploring Feshbach resonances & collisional properties in Tm
    - Search for strong isolated low field resonances
  - Cooling of atomic thulium down to BEC temperatures
  - Simulation of complicated dipolar systems
    - Studying magnetic phases in an optical dipole trap
    - Exploring transport in complex lattices
  - Cold atom based nanophotonics/plasmonics
    - Photonics cavities including “self assembled” cavities
    - Plasmonic structures for cold atoms
  - New applications: compact optical clocks



Thank you for your attention!