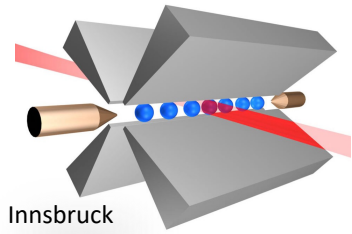


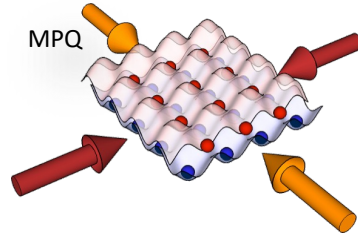
Physics of Quantum Information:

Lecture 2: two-level systems and harmonic oscillators

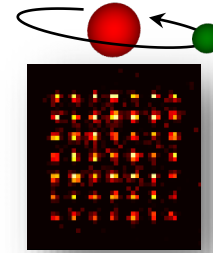
Engineering with individual quantum systems



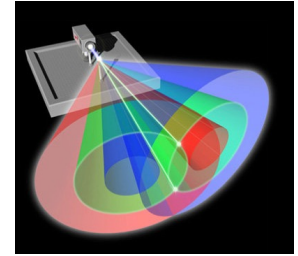
Trapped ions



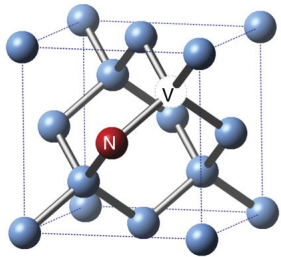
Cold atoms & molecules



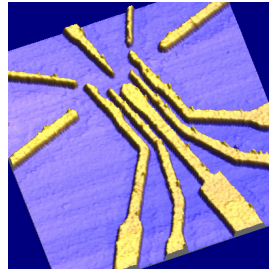
Rydberg atoms



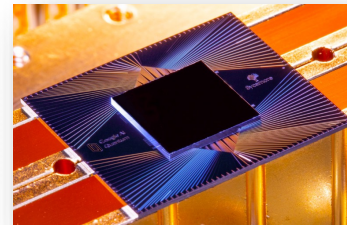
Photons



NV center, SiV

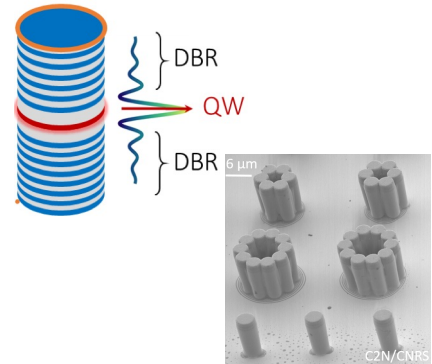


Quantum dots



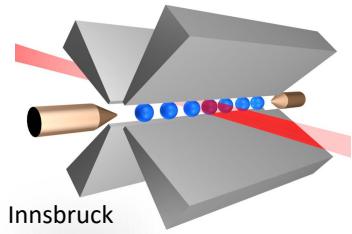
Sycamore processor, Google Inc.

Superconducting circuits

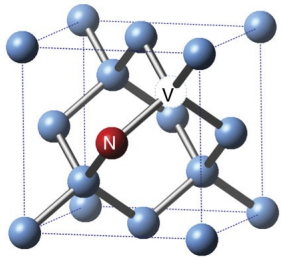


Polaritons in semiconductors

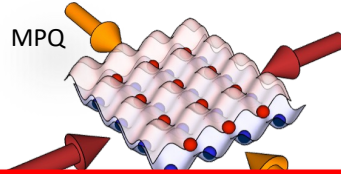
Engineering with individual quantum systems



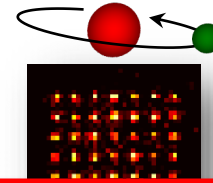
Trapped ions



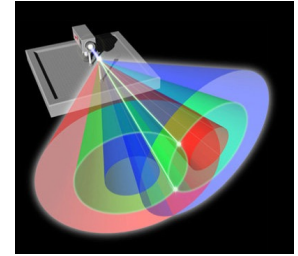
NV center, SiV



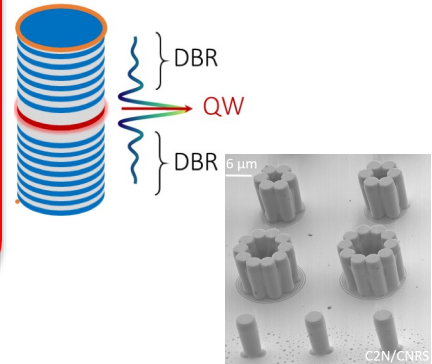
Quantum dots



Superconducting
circuits



Photons

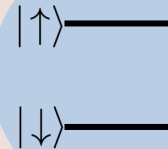


Polaritons in semi-
conductors

Two-level systems to encode a spin:

Cold atoms &
molecules

Rydberg atoms



Addressable + **controlled** interactions

Sycamore processor, Google Inc.

Single atom in tweezer



Alkali atoms = hydrogen-like atoms

Alkali: 1 external electron

$$1s^2 2s^2 \dots (n-1)p^6 ns$$

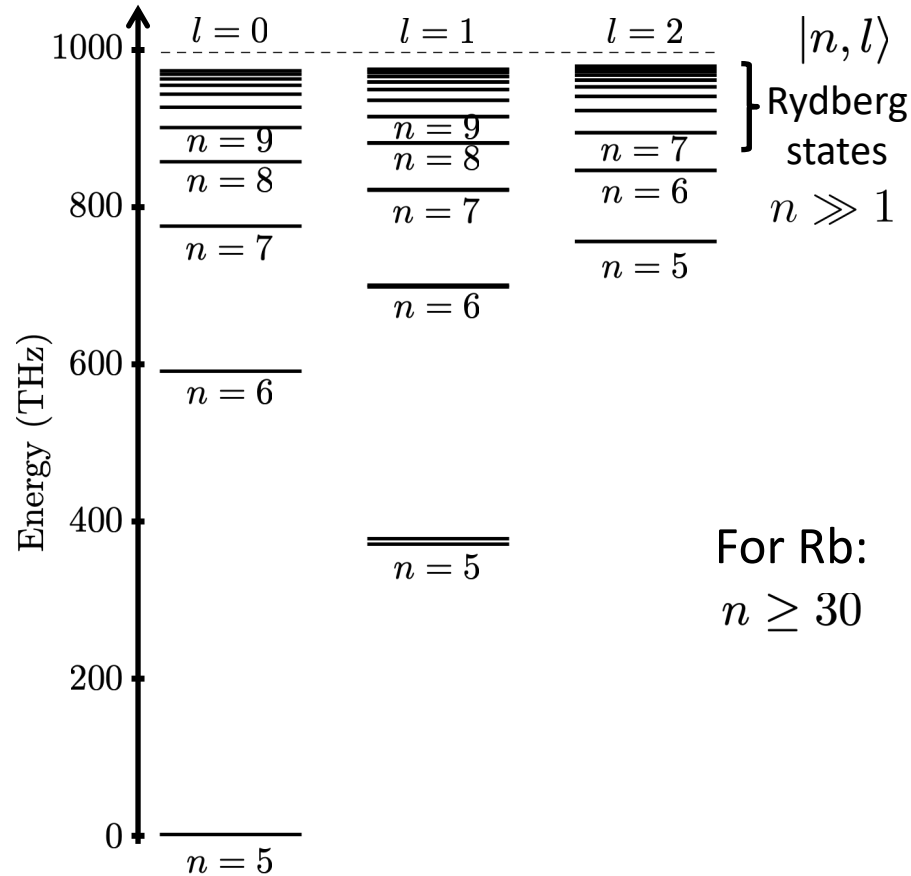
1 IA 1A	1 H Hydrogen 1.008	2 IIA 2A	3 Li Lithium 6.941	4 Be Beryllium 9.012	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S 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 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	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 72.61	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.80	37 Rb Rubidium 84.468	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 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29	55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon 222.018	87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinide Series	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 [278]	114 Fl Flerovium [289]	115 Uup Ununpentium [288]	116 Lv Livermorium [293]	117 Uus Ununseptium [294]	118 Uuo Ununoctium [294]
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Lanthanide Series

Actinide Series

57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
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]

Atomic structure of sodium ($_{37}\text{Rb}$)



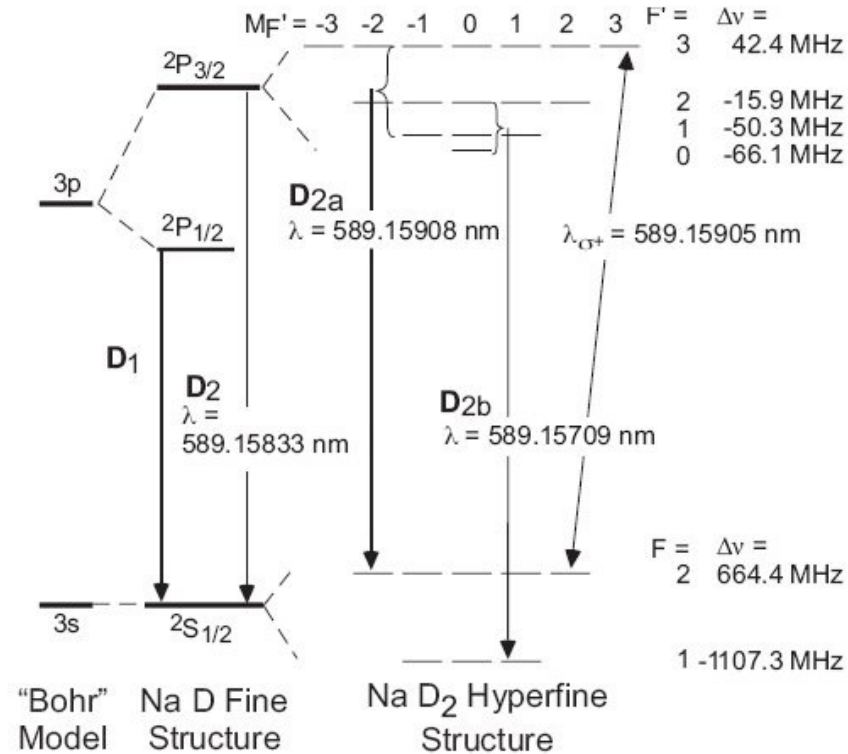
For Rb:
 $n \geq 30$

$$E_n = -\frac{R_y}{(n - \delta_{nlj})^2}$$

Quantum defects
(experimental)

L	J	$\delta_{L,J}$
0	1/2	3.131
1	1/2	2.654
	3/2	2.641
2	3/2	1.348
	5/2	1.346
3	5/2	0.016
	7/2	0.016

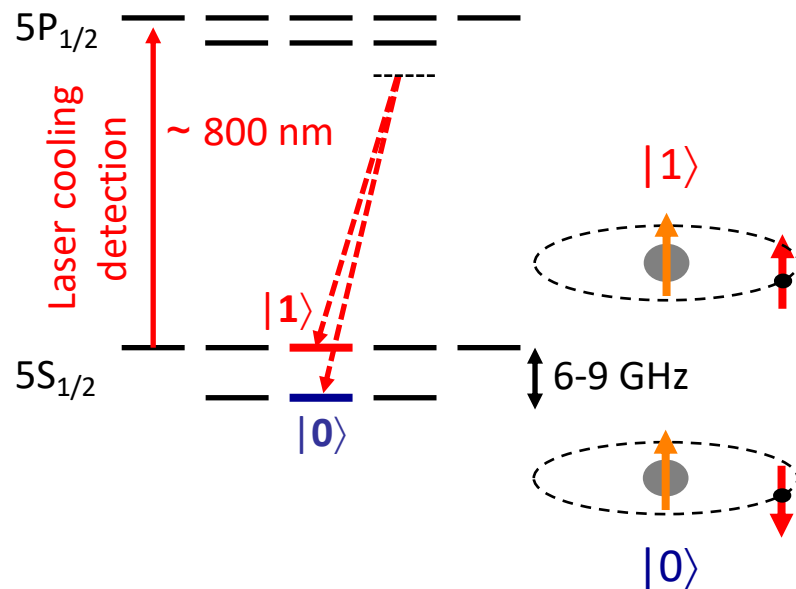
Atomic structure of sodium ($_{11}\text{Na}$)



Different ways to encode the qubit

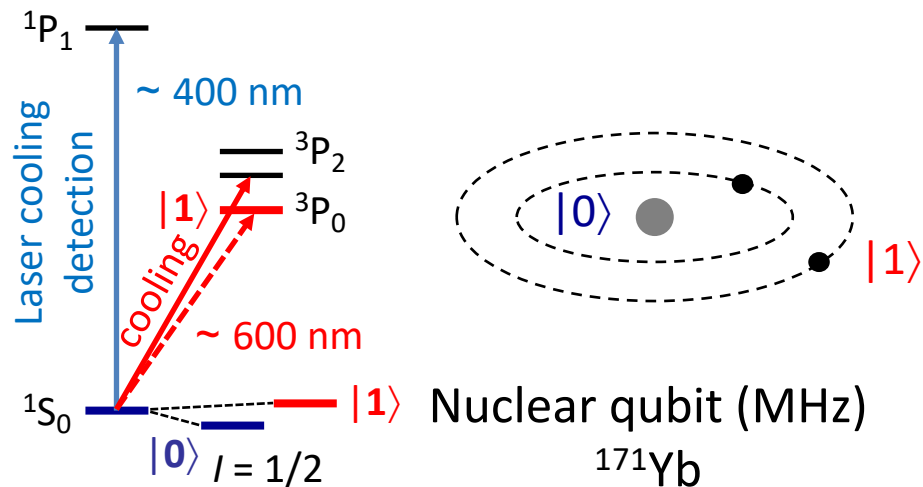
Atomic clocks $\Rightarrow$ **atoms = ideal qubits...**

Hyperfine qubit (Rb, Cs...)



$$T_1 = \infty, T_2 > 1 \text{ s}$$

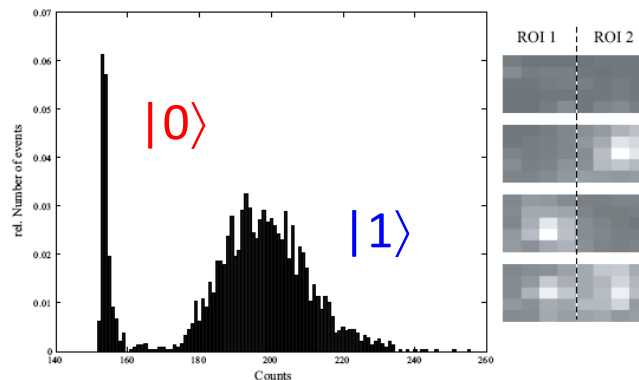
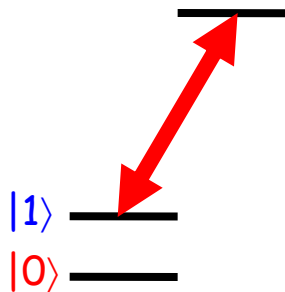
Optical qubit ($2-e^-$: Yb, Sr...)



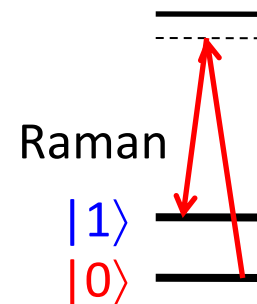
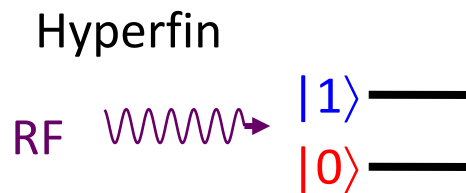
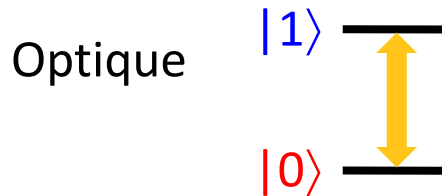
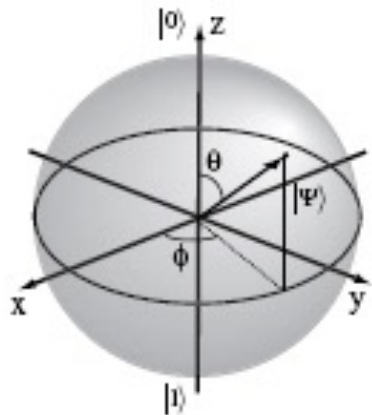
$$T_1, T_2 > 10 \text{ s}$$

Readout and manipulation of atomic qubits

Qubit readout = fluorescence

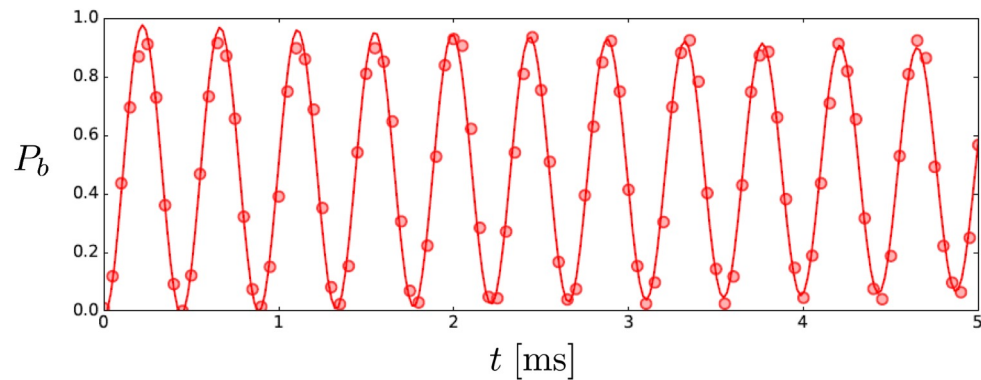
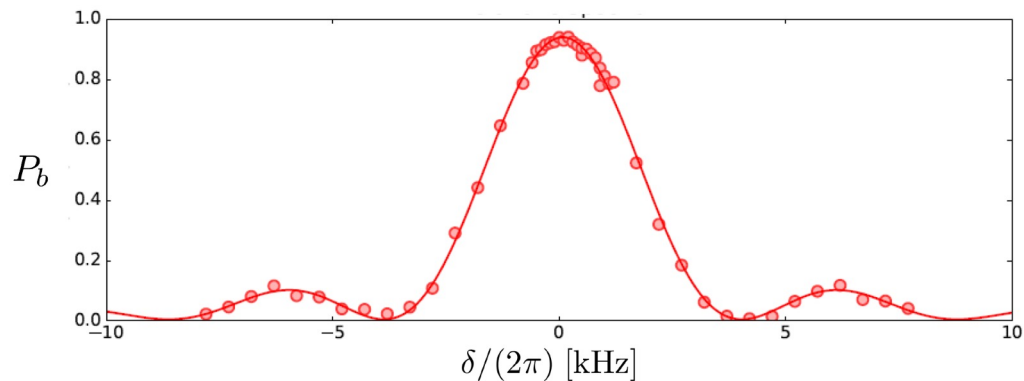
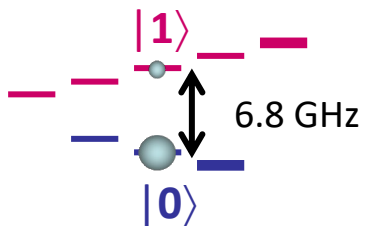


Rotation qubit state $\alpha|0\rangle + \beta|1\rangle$



Exemple d'oscillation de Rabi sur un atome

Chaque point = 200 répétitions

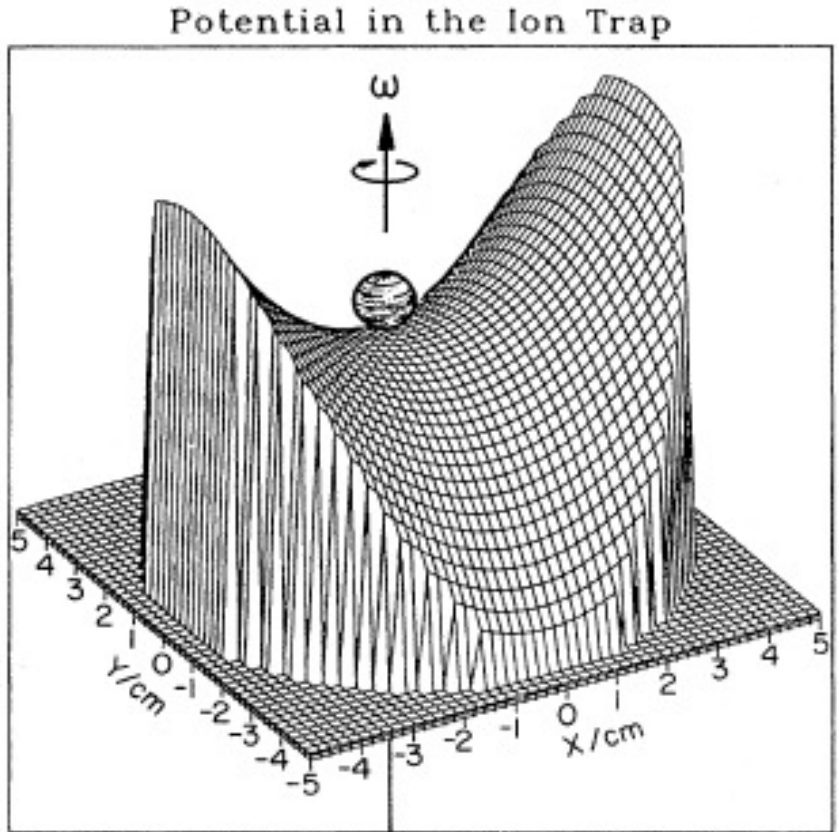


Paul trap for ions

W. Paul

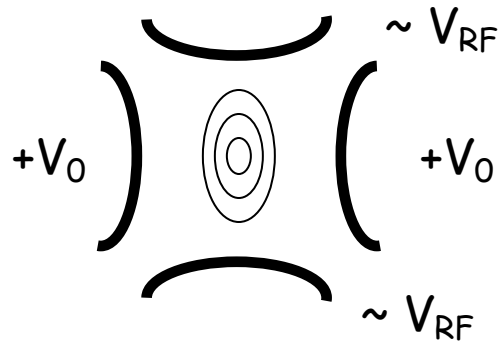


1989 Development of
the ion trap technics

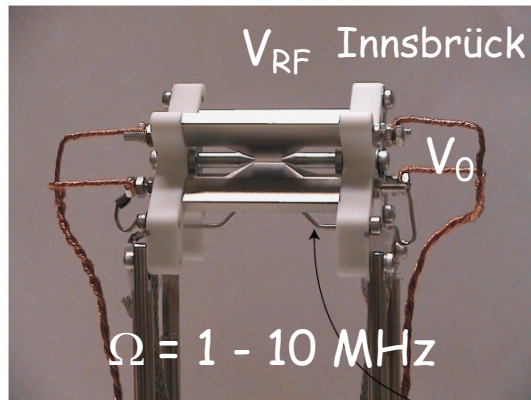


Ion crystals (1990 -)

Piège de Paul (RF + statique)

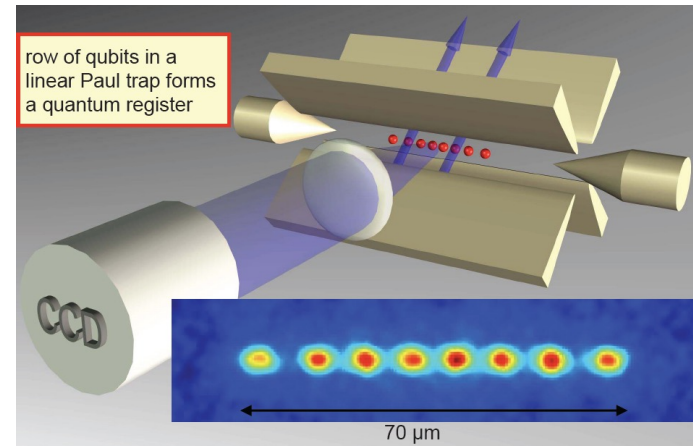
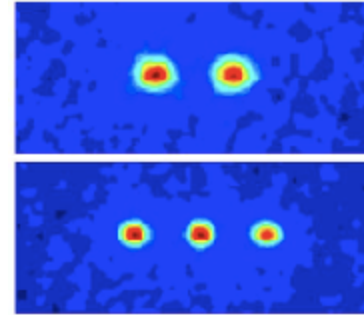


Piège de Paul linéaire



Répulsion de Coulomb

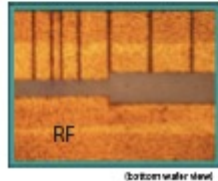
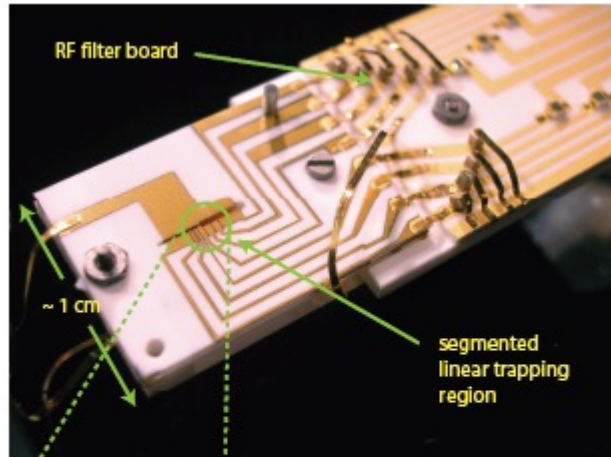
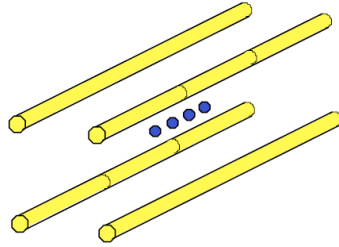
$\Rightarrow$ Cristal ionique



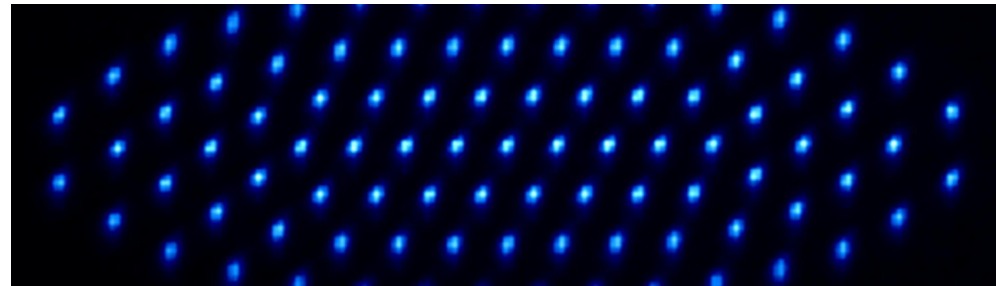
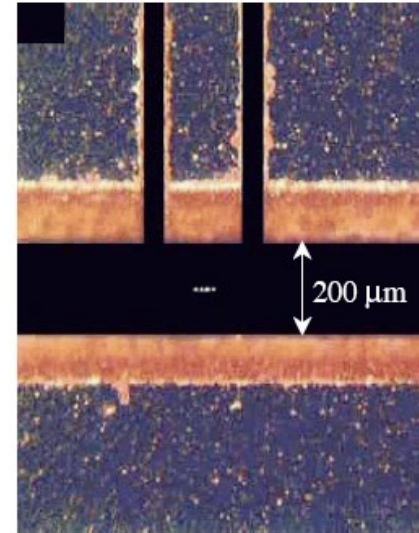
Innsbrück

Ion crystals (1990 -)

Traditional
linear trap:



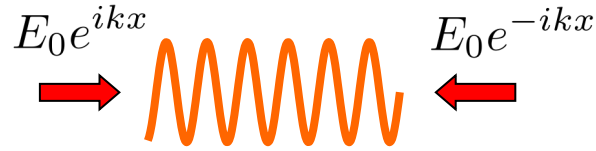
NIST Boulder



Innsbruck, 2020

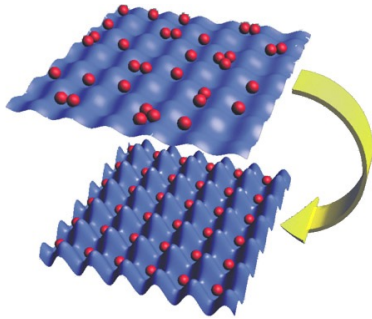
Individual atoms in optical lattices

Dipole force: $\mathbf{F} \propto -\nabla I(\mathbf{r})$

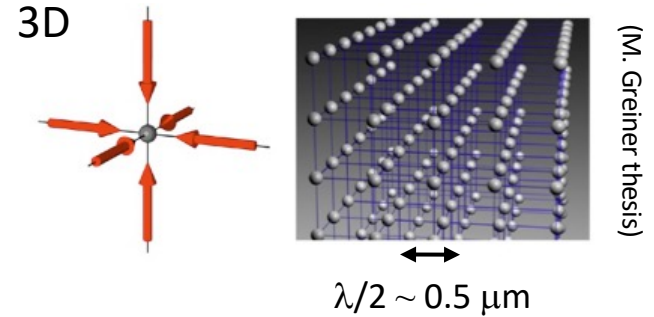


$$I(x) = 2E_0^2(1 + \cos 2kx)$$

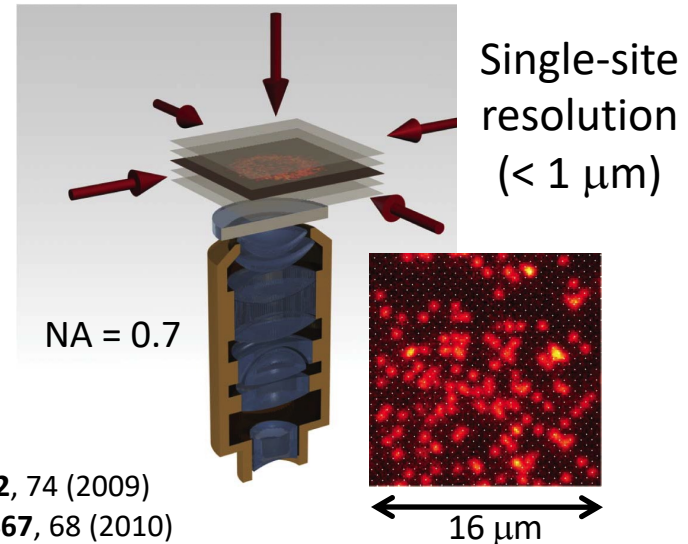
Each site contains 1 atom!



Boson (Rb, Na, ^7Li , ^{39}K , $^4\text{He}^*$),
Fermion (^6Li , ^{40}K),
Magnetic atoms (Cr, Dy...)



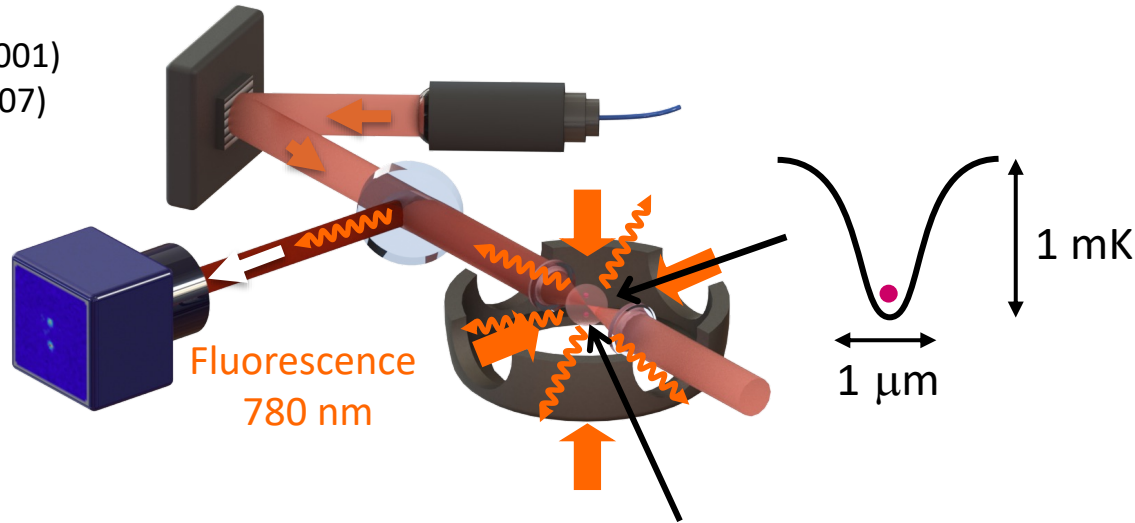
Quantum gas microscope



Bakr *et al.*, Nature **462**, 74 (2009)
Sherson *et al.*, Nature **467**, 68 (2010)

A single Rb atom in an optical tweezer

Grangier (2001)
Sortais (2007)



Reservoir = laser-cooled Rb atoms
 $T \sim 100 \mu\text{K}$

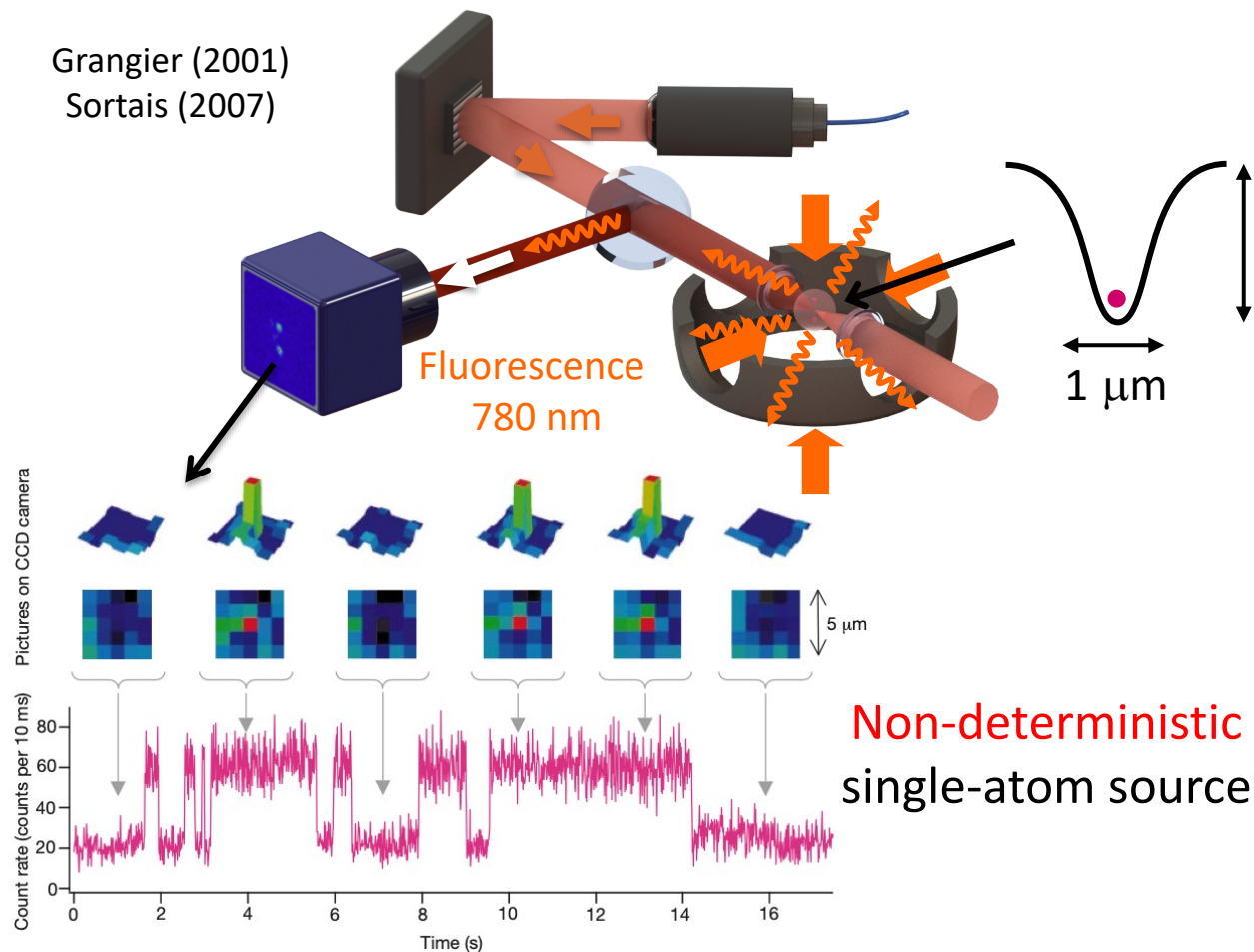


Rubidium

1 1A 1A	2 2A 2A	3 3A 3A	4 4A 4A	5 5A 5A	6 6A 6A	7 7A 7A
1 H Hydrogen 1.008	2 He Helium 4.003					
3 Li Lithium 6.941	4 Be Beryllium 9.012					
5 B Boron 10.81	6 C Carbon 12.011					
7 N Nitrogen 14.007	8 O Oxygen 15.999					
9 F Fluorine 18.998	10 Ne Neon 20.180					
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.45
18 Ar Argon 39.948	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	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 65.38	31 Ga Gallium 69.723
32 Ge Germanium 72.63	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80	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 95.94	43 Tc Technetium 98.906	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91
46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6
53 I Iodine 126.905	54 Xe Xenon 131.29	55 Cs Cesium 132.905	56 Ba Barium 137.327	57 La Lanthanum 138.905	58 Ce Cerium 140.12	59 Pr Praseodymium 140.908
60 Nd Neodymium 144.24	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 162.50
67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.930	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967	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 192.222	78 Pt Platinum 195.084	79 Au Gold 196.967	80 Hg Mercury 200.59
81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222	87 Fr Francium 223
88 Ra Radium 226	89-103 Lanthanide Series	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 266	107 Bh Bohrium 264	108 Hs Hassium 277
109 Mt Meitnerium 268	110 Ds Darmstadtium 271	111 Rg Roentgenium 272	112 Cn Copernicium 285	113 Nh Nihonium 286	114 Fl Flerovium 289	115 Mc Moscovium 288
116 Lv Livermorium 293	117 Ts Tennessine 294	118 Og Oganesson 294	119 Uu Ununennium 295	120 Uub Unbibium 296	121 Uut Untrium 297	122 Uuq Unquadium 298
123 Uub Unbium 299	124 Uut Untrium 301	125 Uuq Unquadium 302	126 Uuh Unhexium 304	127 Uus Unseptium 305	128 Uuo Unoctium 306	129 Uuq Unquadium 307
130 Uuo Unoctium 308	131 Uus Unseptium 309	132 Uuo Unoctium 310	133 Uus Unseptium 311	134 Uuo Unoctium 312	135 Uus Unseptium 313	136 Uuo Unoctium 314
137 Uus Unseptium 315	138 Uuo Unoctium 316	139 Uus Unseptium 317	140 Uuo Unoctium 318	141 Uus Unseptium 319	142 Uuo Unoctium 320	143 Uus Unseptium 321
144 Uuo Unoctium 322	145 Uus Unseptium 323	146 Uuo Unoctium 324	147 Uus Unseptium 325	148 Uuo Unoctium 326	149 Uus Unseptium 327	150 Uuo Unoctium 328
151 Uus Unseptium 329	152 Uuo Unoctium 330	153 Uus Unseptium 331	154 Uuo Unoctium 332	155 Uus Unseptium 333	156 Uuo Unoctium 334	157 Uus Unseptium 335
158 Uuo Unoctium 336	159 Uus Unseptium 337	160 Uuo Unoctium 338	161 Uus Unseptium 339	162 Uuo Unoctium 340	163 Uus Unseptium 341	164 Uuo Unoctium 342
165 Uus Unseptium 343	166 Uuo Unoctium 344	167 Uus Unseptium 345	168 Uuo Unoctium 346	169 Uus Unseptium 347	170 Uuo Unoctium 348	171 Uus Unseptium 349
172 Uuo Unoctium 350	173 Uus Unseptium 351	174 Uuo Unoctium 352	175 Uus Unseptium 353	176 Uuo Unoctium 354	177 Uus Unseptium 355	178 Uuo Unoctium 356
179 Uus Unseptium 357	180 Uuo Unoctium 358	181 Uus Unseptium 359	182 Uuo Unoctium 360	183 Uus Unseptium 361	184 Uuo Unoctium 362	185 Uus Unseptium 363
186 Uuo Unoctium 364	187 Uus Unseptium 365	188 Uuo Unoctium 366	189 Uus Unseptium 367	190 Uuo Unoctium 368	191 Uus Unseptium 369	192 Uuo Unoctium 370
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200 Uuo Unoctium 378	201 Uus Unseptium 379	202 Uuo Unoctium 380	203 Uus Unseptium 381	204 Uuo Unoctium 382	205 Uus Unseptium 383	206 Uuo Unoctium 384
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214 Uuo Unoctium 392	215 Uus Unseptium 393	216 Uuo Unoctium 394	217 Uus Unseptium 395	218 Uuo Unoctium 396	219 Uus Unseptium 397	220 Uuo Unoctium 398
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228 Uuo Unoctium 406	229 Uus Unseptium 407	230 Uuo Unoctium 408	231 Uus Unseptium 409	232 Uuo Unoctium 410	233 Uus Unseptium 411	234 Uuo Unoctium 412
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242 Uuo Unoctium 420	243 Uus Unseptium 421	244 Uuo Unoctium 422	245 Uus Unseptium 423	246 Uuo Unoctium 424	247 Uus Unseptium 425	248 Uuo Unoctium 426
249 Uus Unseptium 427	250 Uuo Unoctium 428	251 Uus Unseptium 429	252 Uuo Unoctium 430	253 Uus Unseptium 431	254 Uuo Unoctium 432	255 Uus Unseptium 433
256 Uuo Unoctium 434	257 Uus Unseptium 435	258 Uuo Unoctium 436	259 Uus Unseptium 437	260 Uuo Unoctium 438	261 Uus Unseptium 439	262 Uuo Unoctium 440
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270 Uuo Unoctium 448	271 Uus Unseptium 449	272 Uuo Unoctium 450	273 Uus Unseptium 451	274 Uuo Unoctium 452	275 Uus Unseptium 453	276 Uuo Unoctium 454
277 Uus Unseptium 455	278 Uuo Unoctium 456	279 Uus Unseptium 457	280 Uuo Unoctium 458	281 Uus Unseptium 459	282 Uuo Unoctium 460	283 Uus Unseptium 461
284 Uuo Unoctium 462	285 Uus Unseptium 463	286 Uuo Unoctium 464	287 Uus Unseptium 465	288 Uuo Unoctium 466	289 Uus Unseptium 467	290 Uuo Unoctium 468
291 Uus Unseptium 469	292 Uuo Unoctium 470	293 Uus Unseptium 471	294 Uuo Unoctium 472	295 Uus Unseptium 473	296 Uuo Unoctium 474	297 Uus Unseptium 475
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319 Uus Unseptium 497	320 Uuo Unoctium 498	321 Uus Unseptium 499	322 Uuo Unoctium 500	323 Uus Unseptium 501	324 Uuo Unoctium 502	325 Uus Unseptium 503
326 Uuo Unoctium 504	327 Uus Unseptium 505	328 Uuo Unoctium 506	329 Uus Unseptium 507	330 Uuo Unoctium 508	331 Uus Unseptium 509	332 Uuo Unoctium 510
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340 Uuo Unoctium 518	341 Uus Unseptium 519	342 Uuo Unoctium 520	343 Uus Unseptium 521	344 Uuo Unoctium 522	345 Uus Unseptium 523	346 Uuo Unoctium 524
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368 Uuo Unoctium 546	369 Uus Unseptium 547	370 Uuo Unoctium 548	371 Uus Unseptium 549	372 Uuo Unoctium 550	373 Uus Unseptium 551	374 Uuo Unoctium 552
375 Uus Unseptium 553	376 Uuo Unoctium 554	377 Uus Unseptium 555	378 Uuo Unoctium 556	379 Uus Unseptium 557	380 Uuo Unoctium 558	381 Uus Unseptium 559
382 Uuo Unoctium 560	383 Uus Unseptium 561	384 Uuo Unoctium 562	385 Uus Unseptium 563	386 Uuo Unoctium 564	387 Uus Unseptium 565	388 Uuo Unoctium 566
389 Uus Unseptium 567	390 Uuo Unoctium 568	391 Uus Unseptium 569	392 Uuo Unoctium 570	393 Uus Unseptium 571	394 Uuo Unoctium 572	395 Uus Unseptium 573
396 Uuo Unoctium 574	397 Uus Unseptium 575	398 Uuo Unoctium 576	399 Uus Unseptium 577	400 Uuo Unoctium 578	401 Uus Unseptium 579	402 Uuo Unoctium 580
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417 Uus Unseptium 595	418 Uuo Unoctium 596	419 Uus Unseptium 597	420 Uuo Unoctium 598	421 Uus Unseptium 599	422 Uuo Unoctium 600	423 Uus Unseptium 601
424 Uuo Unoctium 602	425 Uus Unseptium 603	426 Uuo Unoctium 604	427 Uus Unseptium 605	428 Uuo Unoctium 606	429 Uus Unseptium 607	430 Uuo Unoctium 608
431 Uus Unseptium 609	432 Uuo Unoctium 610	433 Uus Unseptium 611	434 Uuo Unoctium 612	435 Uus Unseptium 613	436 Uuo Unoctium 614	437 Uus Unseptium 615
438 Uuo Unoctium 616	439 Uus Unseptium 617	440 Uuo Unoctium 618	441 Uus Unseptium 619	442 Uuo Unoctium 620	443 Uus Unseptium 621	444 Uuo Unoctium 622
445 Uus Unseptium 623	446 Uuo Unoctium 624	447 Uus Unseptium 625	448 Uuo Unoctium 626	449 Uus Unseptium 627	450 Uuo Unoctium 628	451 Uus Unseptium 629
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466 Uuo Unoctium 644	467 Uus Unseptium 645	468 Uuo Unoctium 646	469 Uus Unseptium 647	470 Uuo Unoctium 648	471 Uus Unseptium 649	472 Uuo Unoctium 650
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487 Uus Unseptium 665	488 Uuo Unoctium 666	489 Uus Unseptium 667	490 Uuo Unoctium 668	491 Uus Unseptium 669	492 Uuo Unoctium 670	493 Uus Unseptium 671
494 Uuo Unoctium 672	495 Uus Unseptium 673	496 Uuo Unoctium 674	497 Uus Unseptium 675	498 Uuo Unoctium 676	499 Uus Unseptium 677	500 Uuo Unoctium 678
501 Uus Unseptium 679	502 Uuo Unoctium 680	503 Uus Unseptium 681	504 Uuo Unoctium 682	505 Uus Unseptium 683	506 Uuo Unoctium 684	507 Uus Unseptium 685
508 Uuo Unoctium 686	509 Uus Unseptium 687	510 Uuo Unoctium 688	511 Uus Unseptium 689	512 Uuo Unoctium 690	513 Uus Unseptium 691	514 Uuo Unoctium 692
515 Uus Unseptium 693	516 Uuo Unoctium 694	517 Uus Unseptium 695	518 Uuo Unoctium 696	519 Uus Unseptium 697	520 Uuo Unoctium 698	521 Uus Unseptium 699
522 Uuo Unoctium 700	523 Uus Unseptium 701	524 Uuo Unoctium 702	525 Uus Unseptium 703	526 Uuo Unoctium 704	527 Uus Unseptium 705	528 Uuo Unoctium 706

A single Rb atom in an optical tweezer

Grangier (2001)
Sortais (2007)



Sub-poissonian loading of single atoms in a microscopic dipole trap

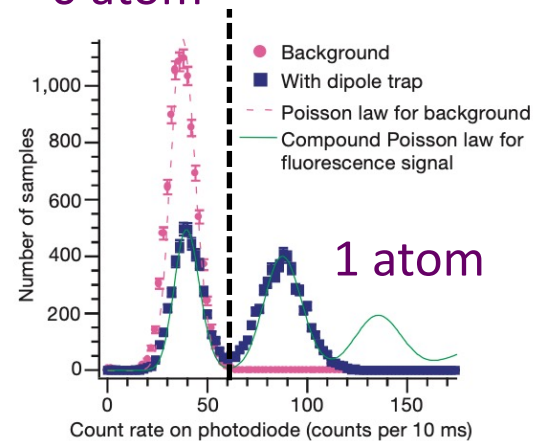
Nicolas Schlosser, Georges Reymond, Igor Protzenko
& Philippe Grangier

Nature 2001

$1\ \text{mK}$

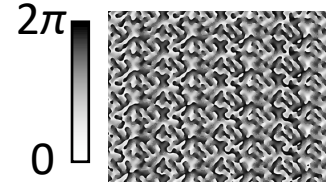
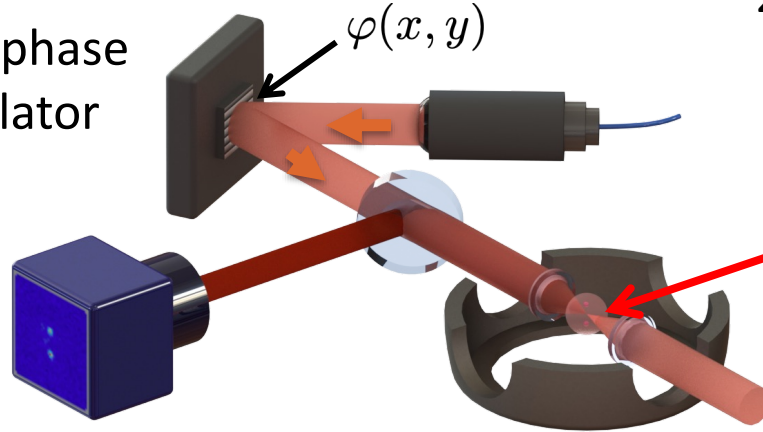
$1\ \mu\text{m}$

0 atom



Atoms in arrays of optical tweezers

Spatial phase
modulator



Phase mask

Nogrette, PRX (2014)

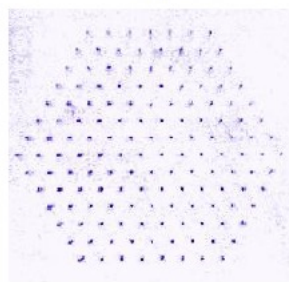
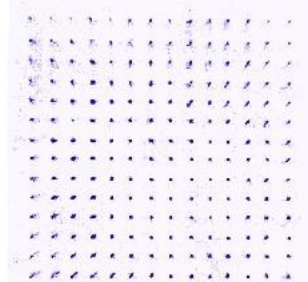
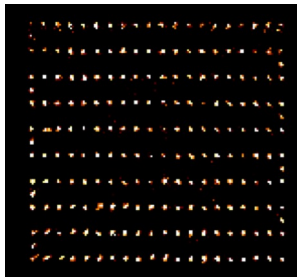
$$\left| \text{FT}[e^{i\varphi(x,y)}] \right|^2$$

Pasqal

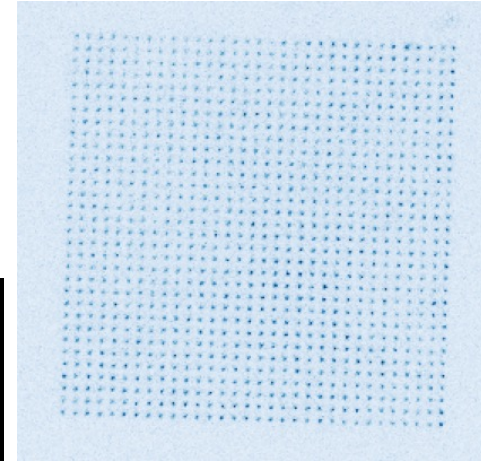
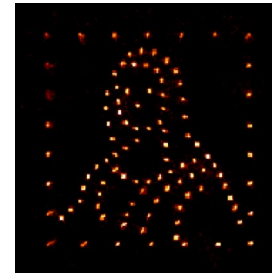
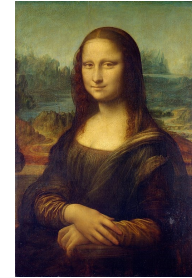
Fluorescence image of atoms ($N \sim 300$)

1D

2D



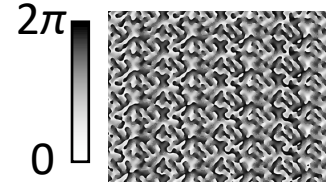
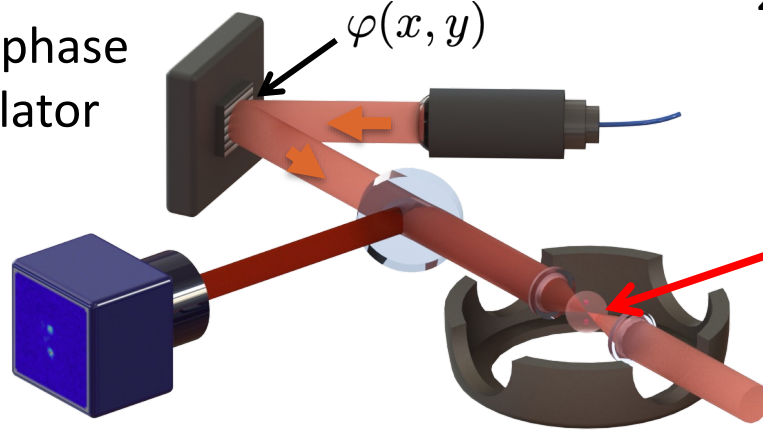
L. da Vinci



~ 1024 atoms

Atoms in arrays of optical tweezers

Spatial phase modulator



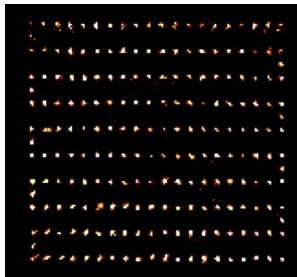
Phase mask

Nogrette, PRX (2014)

$$\left| \text{FT}[e^{i\varphi(x,y)}] \right|^2$$

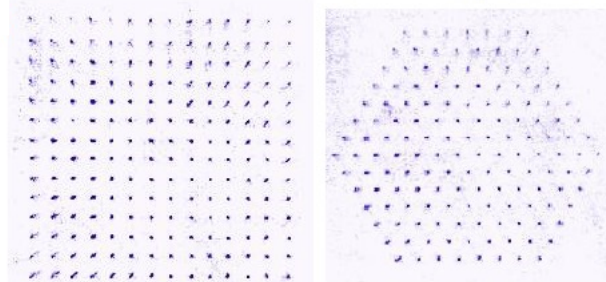
Fluorescence image of atoms ($N \sim 300$)

1D



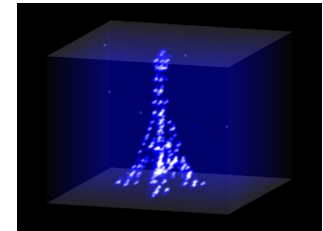
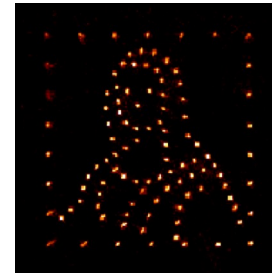
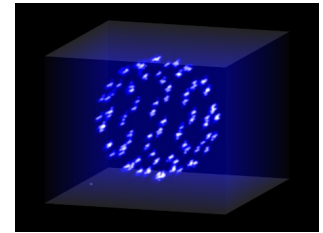
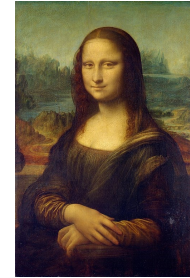
$\sim 100 \mu\text{m}$

2D



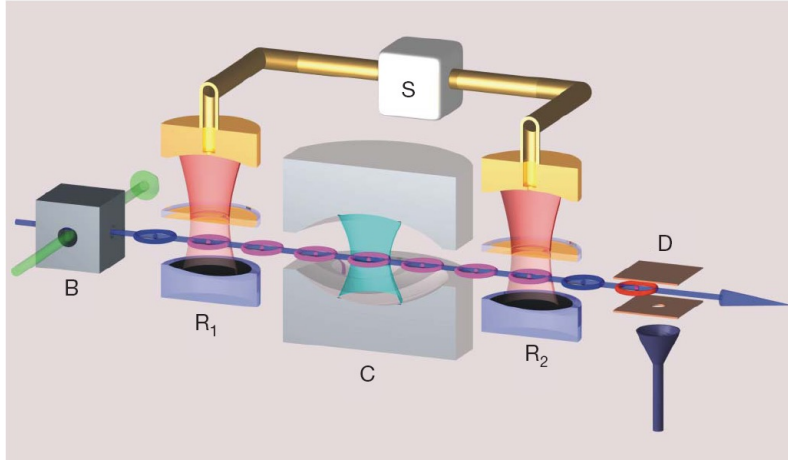
Barredo, Science 2016 ; Schymik, PRA 2020, 2022; PRAppl. 2021

L. da Vinci



Barredo, Nature (2018)

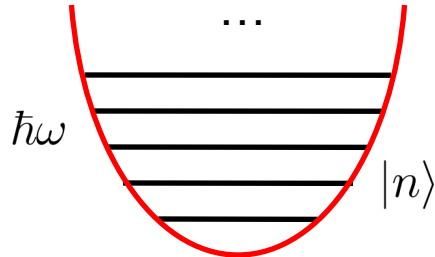
Single photons in a cavity



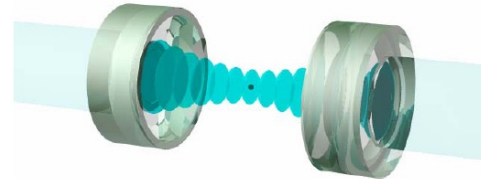
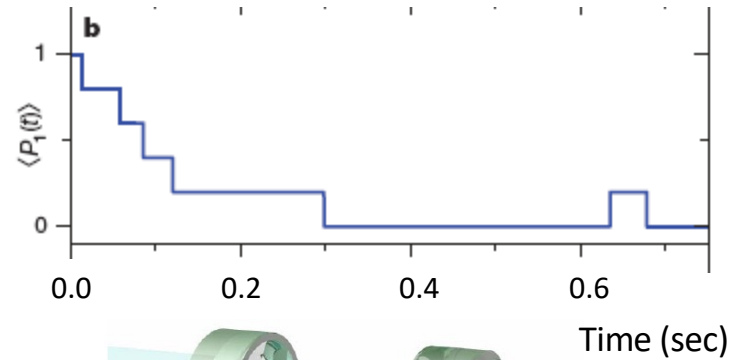
S. Haroche
2012



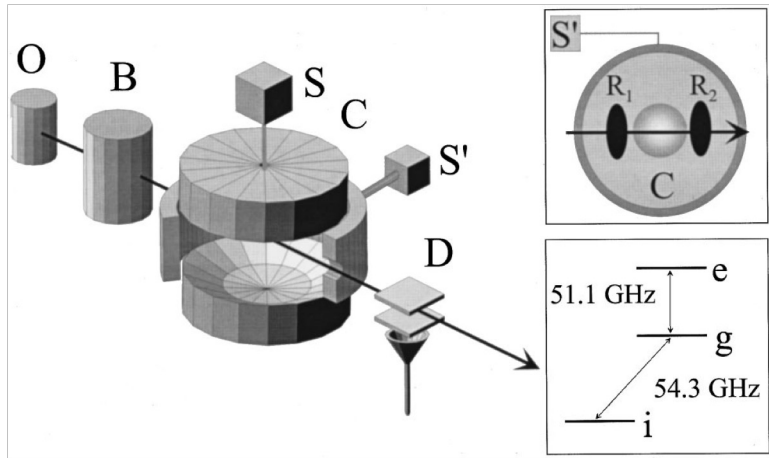
$$\hat{E} = \sqrt{\frac{\hbar\omega}{2\epsilon_0 V}} (\hat{a} + a^+)$$



Cavity field, ω



“Single photon” Rabi oscillations

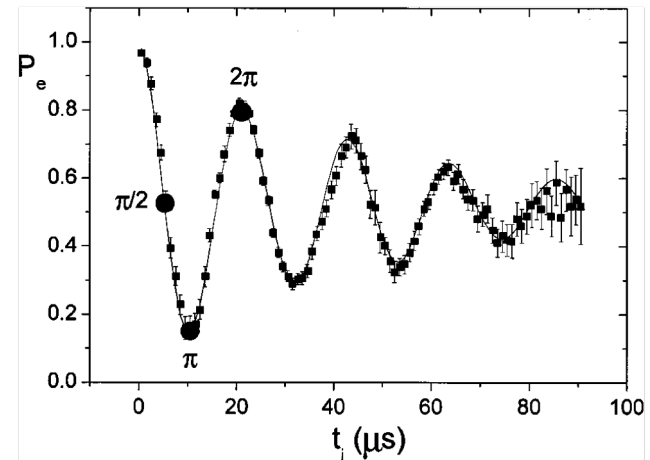


M. Brune, PRL **76**, 1800 (1996)

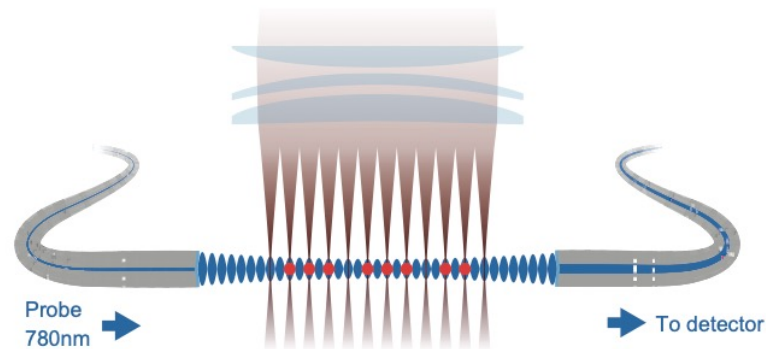
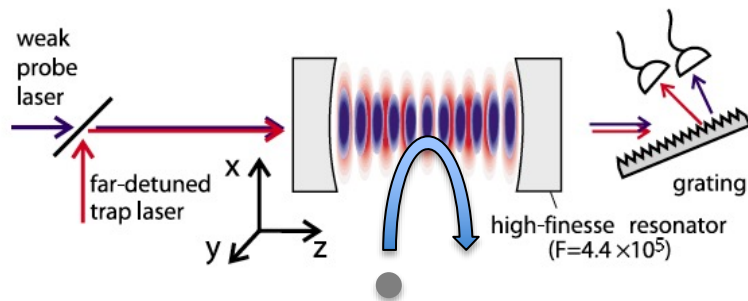


Nobel Prize 2012

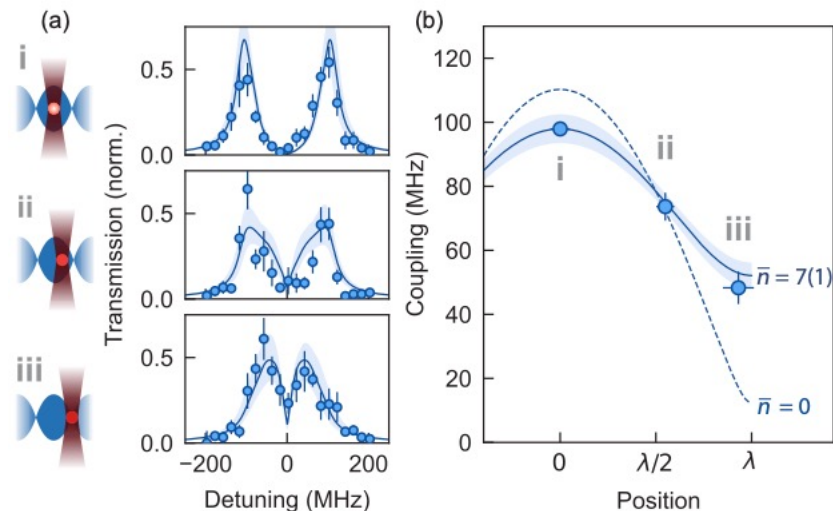
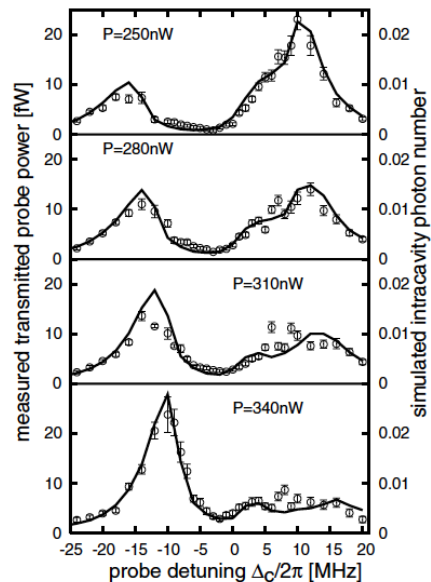
S. Haroche, D.J. Wineland



Normal mode splitting in a cavity

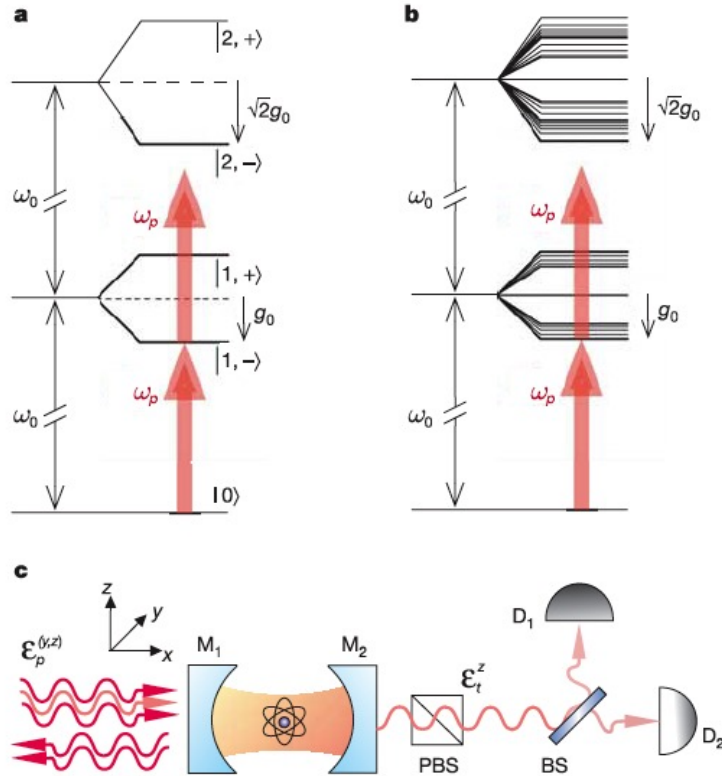


Maunz,
PRL **94**, 033002 (2005)

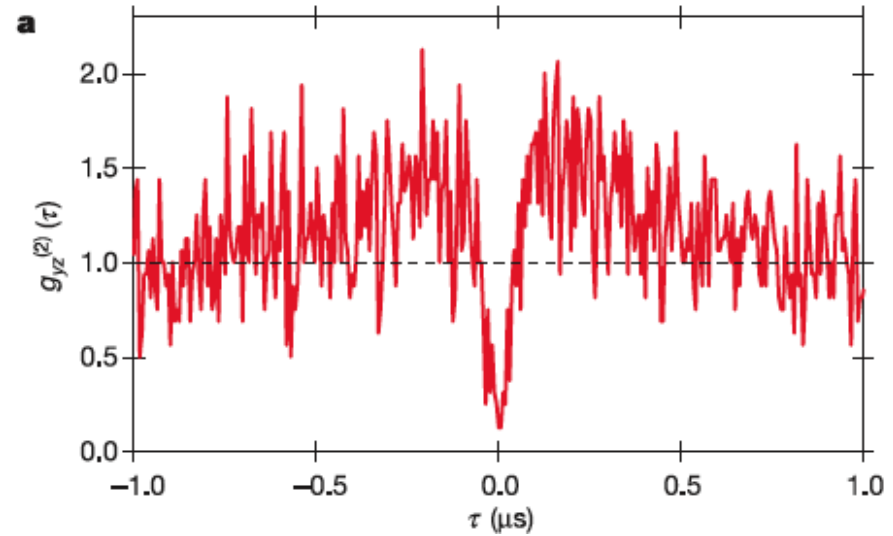


arXiv:2608.20291

Photon blockade

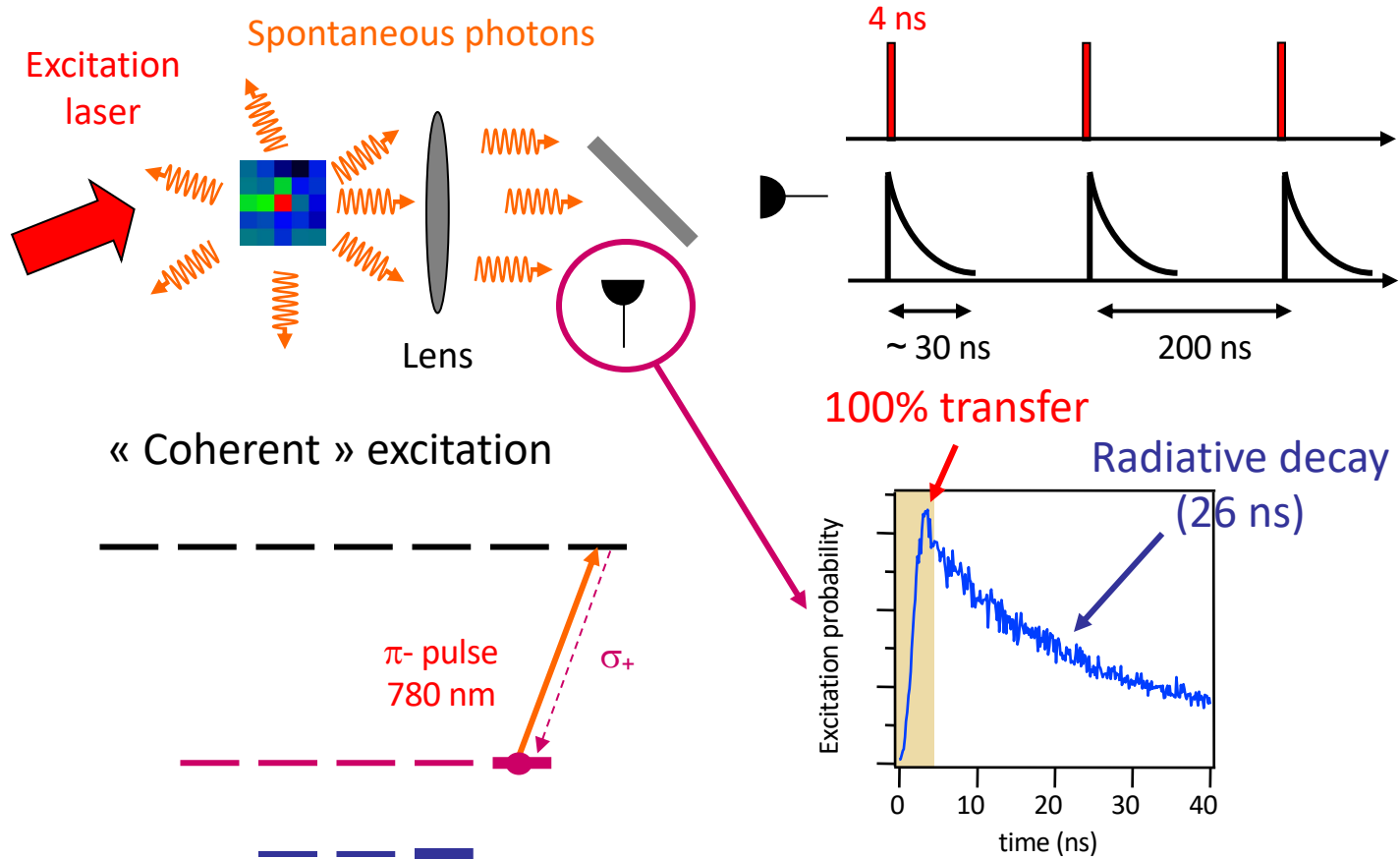


Probability to get 2 photons
at the output

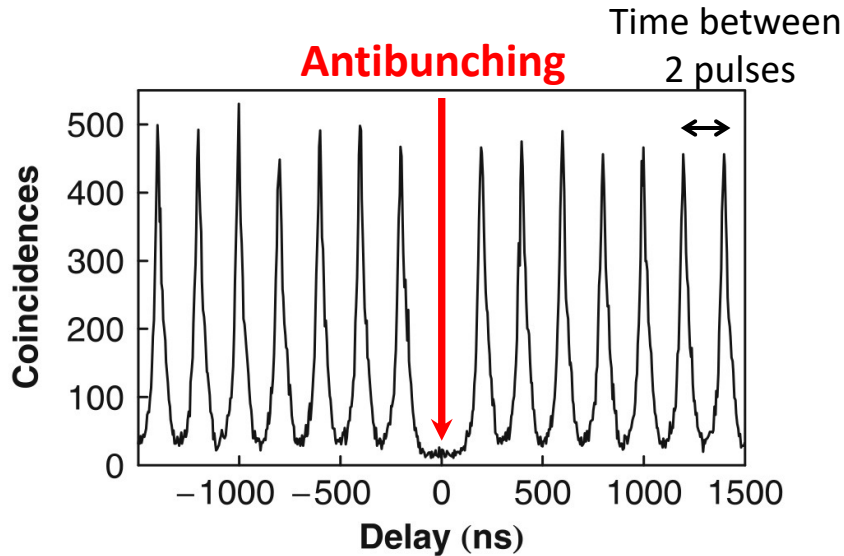
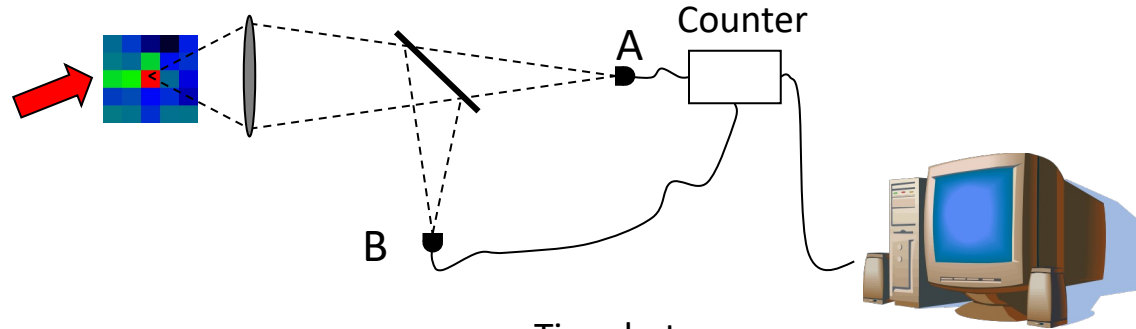


Birnbaum, Nature **436** 87 (2005)

Triggered emission of single photons by an atom

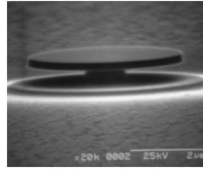
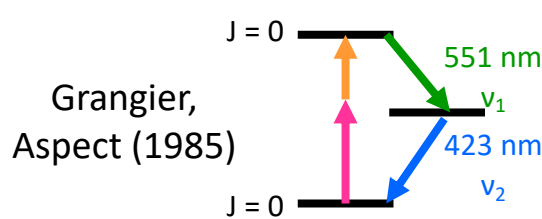


Is it really a single-photon source?

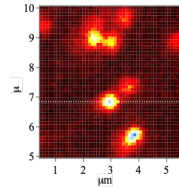
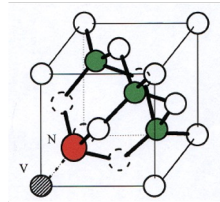


« Microscopic » single photon sources

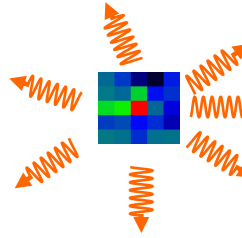
Based on photon emission by a **single** microscopic dipole



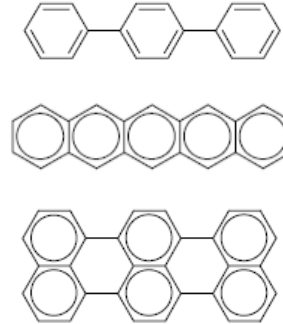
Quantum dots
(+ cavity)(2001)



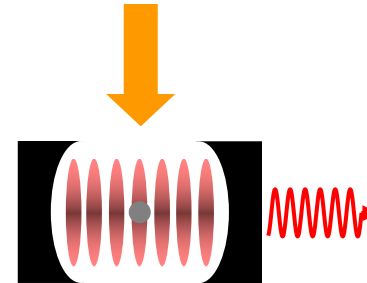
NV center
(2000)



Single trapped atom (2005)



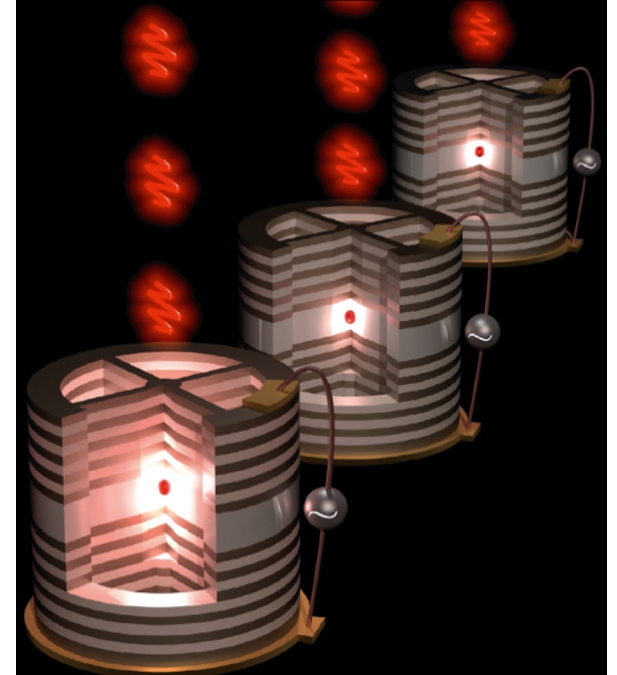
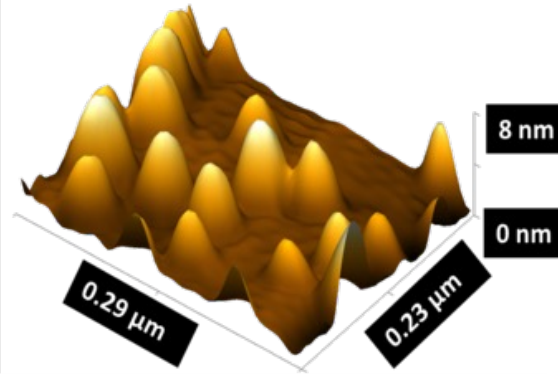
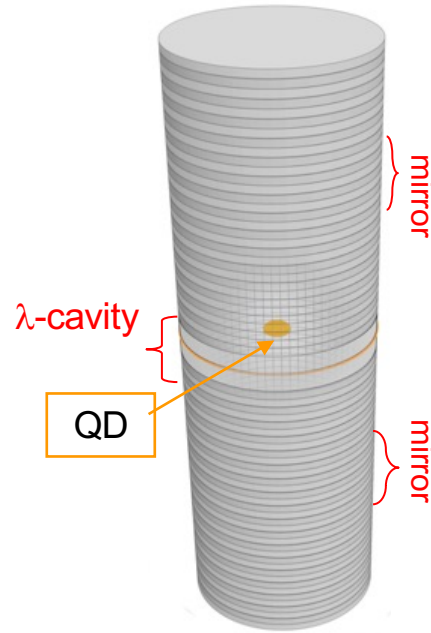
Molecules in solid
(1999-2000)



CQED with ions,
Atoms (2002-2004)

Sources **triggered** by the excitation = « deterministic »

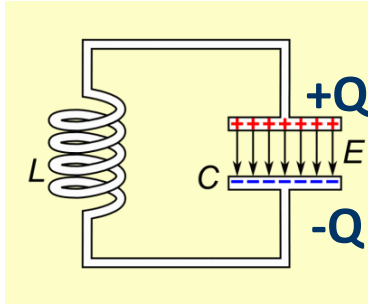
Commercial single-photon sources



Flux: $80 \times 10^6 \text{ s}^{-1}$

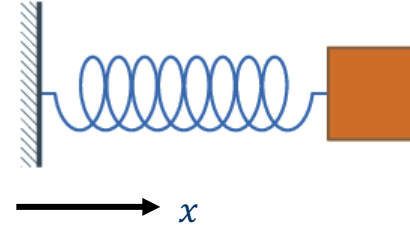
Quantum circuit and harmonic oscillator

LC circuit



$$E = \frac{L\dot{Q}^2}{2} + \frac{Q^2}{2C}$$

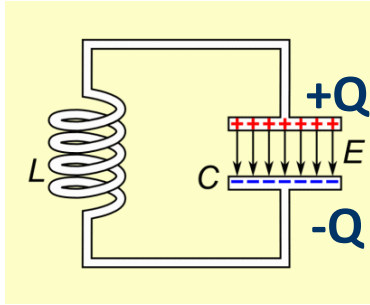
Mass with a spring



$$E = \frac{m\dot{x}^2}{2} + \frac{kx^2}{2}$$

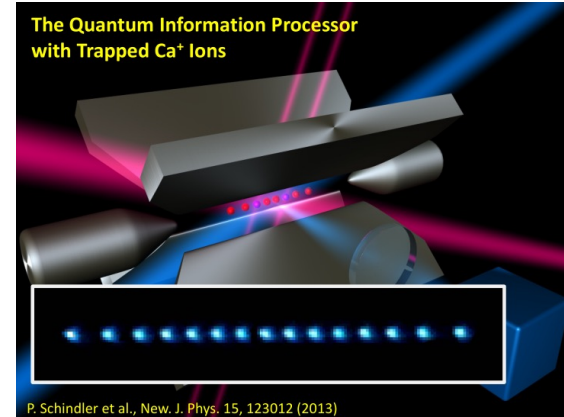
Quantum circuit and harmonic oscillator

LC circuit



$$E = \frac{L\dot{Q}^2}{2} + \frac{Q^2}{2C}$$

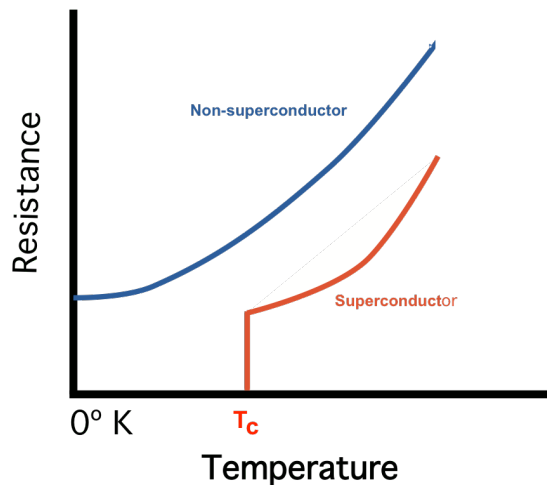
Mass with a spring



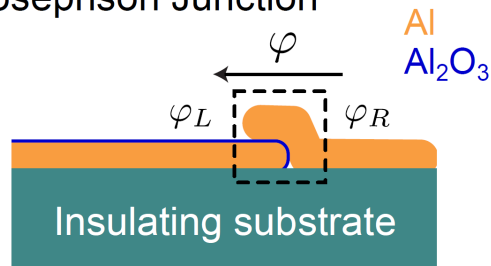
$$E = \frac{m\dot{x}^2}{2} + \frac{kx^2}{2}$$

Superconducting circuit and qubits

Superconductivity



Josephson Junction

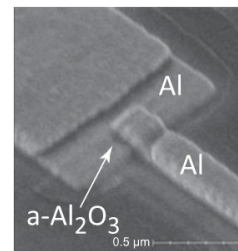
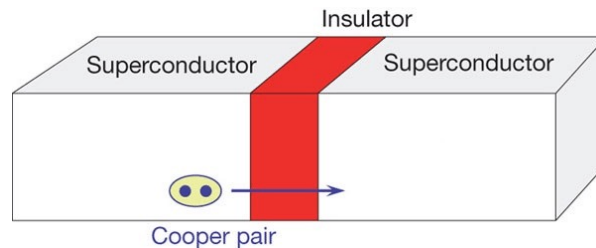
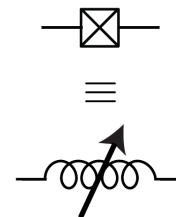


$$I = I_c \sin \varphi$$

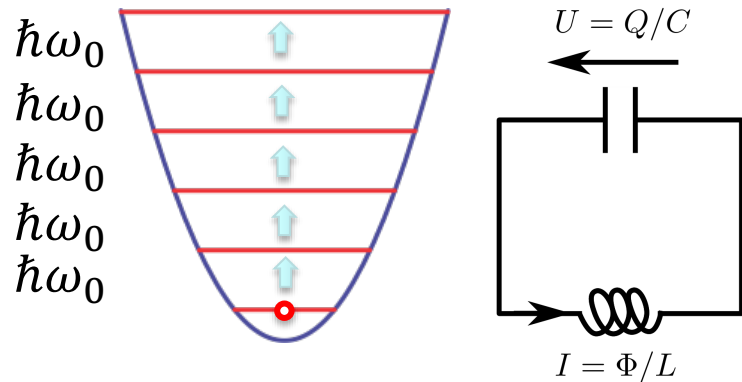
$$V = \varphi_0 \times \dot{\varphi}$$



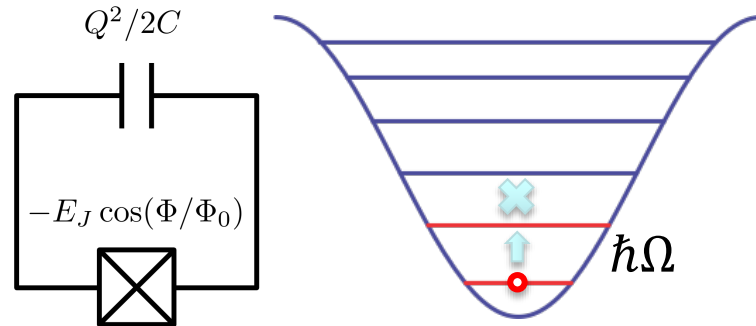
$$I = L_J(\varphi)\dot{\varphi}$$



Superconducting circuit and qubits

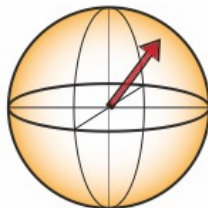


Oscillateur harmonique



Oscillateur anharmonique

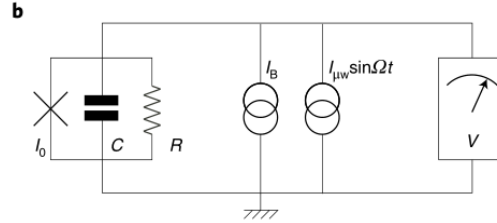
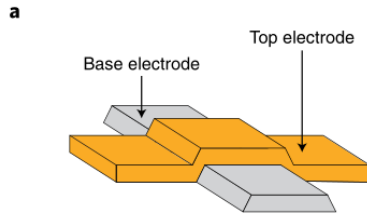
Système à 2 niveaux
(spin)



$$\hat{H} = \frac{\hbar\Omega}{2} (|1\rangle\langle 1| - |0\rangle\langle 0|) = -\frac{\hbar\Omega}{2} \hat{\sigma}_z$$

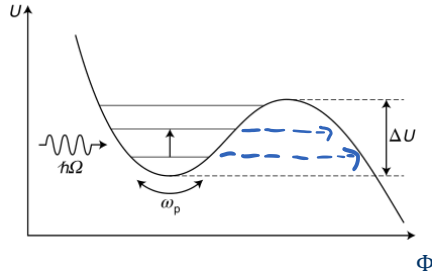
$$\hat{\sigma}_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Demonstration of the quantum nature of circuits

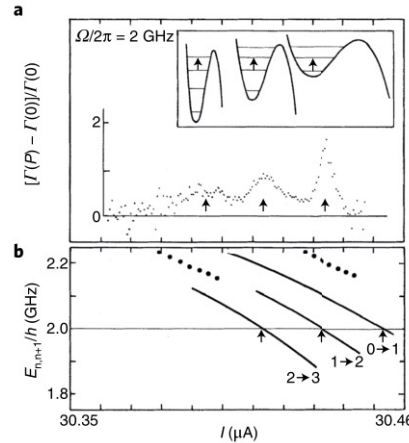


John Martinis

Potentiel incliné avec un courant DC



Détection des niveaux par effet tunnel le long de l'axe Φ



Michel Devoret



John Clarke

Superconducting circuit and qubits

IBM



Google

