



# Wiring up trapped ions



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- Physics and information
- Ion trap quantum computing
- Scaling up ion trap quantum computers



FWF  
SFB



SCALA  
QGATES



Industrie  
Tirol



IQI  
GmbH



bm:bwk



Information is physical (Rolf Landauer, 1961)



Erasing information generates heat:

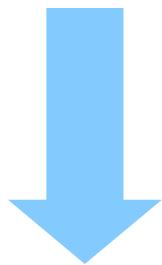
0101001101 → 0000000000 + entropy



## Physics and information



# Physical process



## Algorithm





# Physics and information



Information is physical (Rolf Landauer, 1961)

→ Information is quantum mechanical

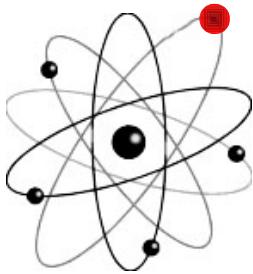
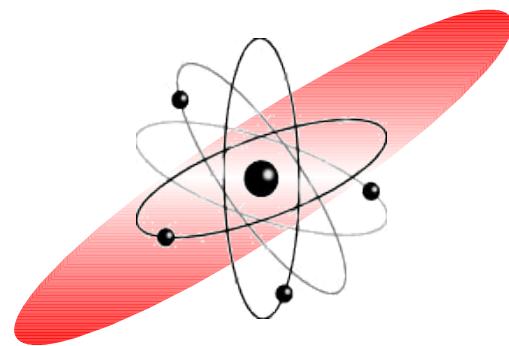
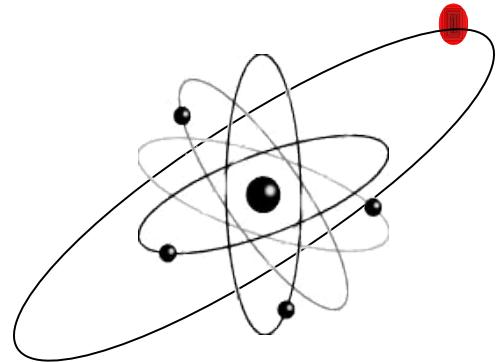
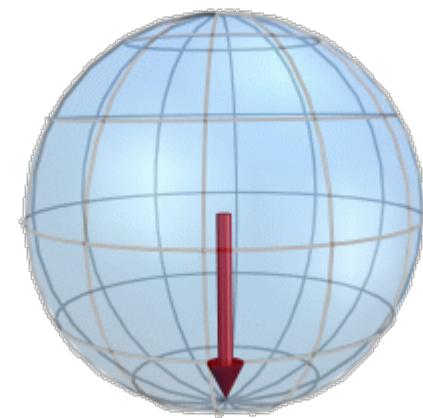
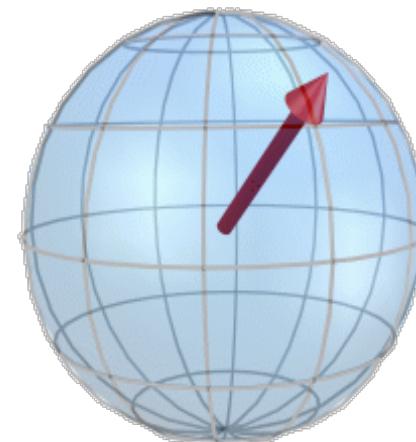
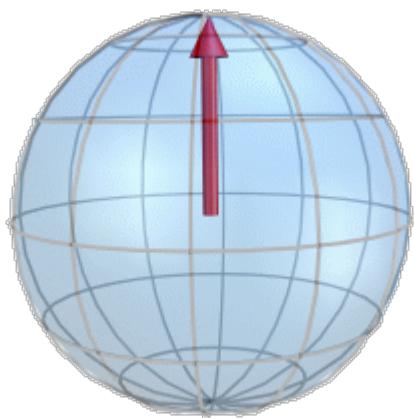
Classical information is a subset in quantum information

Quantum information: strip down quantum mechanics to bare bones.

- Hilbert space
- unitary operations
- measurement



# Qubits

 $|0\rangle$  $\alpha|0\rangle + \beta|1\rangle$  $|1\rangle$ 



# Information content



$$|\Psi\rangle_{\text{reg}} = \alpha_0 |000\rangle + \alpha_1 |001\rangle + \alpha_2 |010\rangle + \alpha_3 |011\rangle + \alpha_4 |100\rangle + \alpha_5 |101\rangle + \alpha_6 |110\rangle + \alpha_7 |111\rangle$$

# bits	classical	quantum mechanical
1	1	$0.5208 + 0.7059i, 0.3014 + 0.3736i$
2	01	$0.2044 + 0.4911i, 0.1732 + 0.3855i, 0.2040 + 0.4890i, 0.3193 + 0.3947i$
3	001	$0.2583 + 0.2704i, 0.2310 + 0.1150i, 0.2956 + 0.3118i, 0.3558 + 0.2113i, 0.1943 + 0.1377i, 0.3273 + 0.2613i, 0.0643 + 0.2033i, 0.3643 + 0.1654i$
4	1010	$0.1691 + 0.0891i, 0.1096 + 0.0828i, 0.1420 + 0.2873i, 0.0741 + 0.2419i, 0.1902 + 0.0448i, 0.2495 + 0.0039i, 0.1738 + 0.2933i, 0.2102 + 0.0653i, 0.0686 + 0.0980i, 0.1246 + 0.2170i, 0.2570 + 0.0933i, 0.2234 + 0.1540i, 0.1513 + 0.0213i, 0.1863 + 0.3243i, 0.2606 + 0.1912i, 0.0194 + 0.1390i$
5	10001	$0.1060 + 0.1416i, 0.0103 + 0.0118i, 0.0064 + 0.0976i, 0.0734 + 0.0716i, 0.0030 + 0.2054i, 0.0902 + 0.0035i, 0.1605 + 0.1804i, 0.0218 + 0.2280i, 0.0083 + 0.2326i, 0.1438 + 0.1853i, 0.1429 + 0.1030i, 0.0037 + 0.1171i, 0.0038 + 0.0503i, 0.0446 + 0.1512i, 0.1379 + 0.0752i, 0.0135 + 0.2255i, 0.0863 + 0.1707i, 0.1483 + 0.0968i, 0.1686 + 0.1749i, 0.1627 + 0.0629i, 0.0197 + 0.1033i, 0.1067 + 0.2192i, 0.1038 + 0.1605i, 0.0830 + 0.0499i, 0.0361 + 0.1971i, 0.1587 + 0.1477i, 0.1642 + 0.0314i, 0.1709 + 0.0487i, 0.1124 + 0.1426i, 0.1303 + 0.1480i, 0.0284 + 0.0870i, 0.1059 + 0.1351i$
6	110101	$0.0595 + 0.1064i, 0.0295 + 0.1327i, 0.0929 + 0.0406i, 0.1090 + 0.0379i, 0.0559 + 0.1286i, 0.0015 + 0.0345i, 0.0624 + 0.1196i, 0.1120 + 0.1350i, 0.1180 + 0.0345i, 0.1367 + 0.0356i, 0.1255 + 0.0074i, 0.0547 + 0.0116i, 0.0923 + 0.0952i, 0.1087 + 0.0284i, 0.0288 + 0.1254i, 0.1345 + 0.0258i, 0.0846 + 0.0254i, 0.0939 + 0.1478i, 0.0348 + 0.0654i, 0.0816 + 0.0505i, 0.1384 + 0.0467i, 0.0498 + 0.0543i, 0.0974 + 0.0584i, 0.0582 + 0.0879i, 0.0932 + 0.0178i, 0.1039 + 0.0057i, 0.0590 + 0.0682i, 0.0615 + 0.1293i, 0.0974 + 0.1388i, 0.1245 + 0.0393i, 0.0552 + 0.0238i, 0.0632 + 0.1297i, 0.0884 + 0.0354i, 0.0841 + 0.0960i, 0.1065 + 0.1437i, 0.0760 + 0.0988i, 0.1154 + 0.1293i, 0.0727 + 0.0015i, 0.0276 + 0.2040i, 0.1041 + 0.1217i, 0.1460 + 0.0639i, 0.1199 + 0.1323i, 0.1046 + 0.1092i, 0.0721 + 0.1021i, 0.0170 + 0.0514i, 0.0988 + 0.0247i, 0.0543 + 0.0231i, 0.0208 + 0.0284i, 0.0842 + 0.0628i, 0.1223 + 0.1272i, 0.1002 + 0.0729i, 0.1485 + 0.1213i, 0.1429 + 0.0685i, 0.0087 + 0.0680i, 0.0535 + 0.0670i, 0.0815 + 0.0613i, 0.0389 + 0.1340i, 0.0888 + 0.0008i, 0.0073 + 0.0442i, 0.0849 + 0.0073i, 0.1042 + 0.1030i, 0.1430 + 0.0966i, 0.1115 + 0.1461i, 0.1100 + 0.0821i$
7	1001010	$0.0880 + 0.0466i, 0.1054 + 0.0684i, 0.0239 + 0.0866i, 0.0759 + 0.0090i, 0.0563 + 0.1020i, 0.1006 + 0.0988i, 0.0769 + 0.0649i, 0.0246 + 0.0273i, 0.0485 + 0.0942i, 0.0186 + 0.0554i, 0.1045 + 0.0790i, 0.0384 + 0.0455i, 0.0053 + 0.1037i, 0.0815 + 0.0078i, 0.0965 + 0.0597i, 0.0309 + 0.0315i, 0.0271 + 0.0925i, 0.1006 + 0.0362i, 0.0141 + 0.0734i, 0.1015 + 0.0058i, 0.0757 + 0.0385i, 0.0914 + 0.0537i, 0.0226 + 0.0468i, 0.0491 + 0.0607i, 0.0087 + 0.0665i, 0.0918 + 0.0122i, 0.0606 + 0.00969i, 0.0344 + 0.0814i, 0.0404 + 0.0853i, 0.0936 + 0.0879i, 0.0401 + 0.0723i, 0.0079 + 0.0217i, 0.0216 + 0.0294i, 0.0053 + 0.0675i, 0.0611 + 0.0579i, 0.0131 + 0.0646i, 0.0563 + 0.0096i, 0.0126 + 0.0293i, 0.0830 + 0.0441i, 0.0404 + 0.0511i, 0.0888 + 0.0980i, 0.0050 + 0.0643i, 0.0645 + 0.0355i, 0.1024 + 0.0516i, 0.0311 + 0.0644i, 0.0959 + 0.0174i, 0.0110 + 0.0894i, 0.0070 + 0.1031i, 0.0253 + 0.0642i, 0.1006 + 0.0031i, 0.0068 + 0.0876i, 0.0285 + 0.0658i, 0.0708 + 0.0756i, 0.0229 + 0.0099i, 0.0537 + 0.0458i, 0.0513 + 0.0405i, 0.0725 + 0.0179i, 0.1033 + 0.0898i, 0.0827 + 0.0094i, 0.0718 + 0.0487i, 0.0141 + 0.1032i, 0.0103 + 0.0159i, 0.0016 + 0.0938i, 0.0311 + 0.0830i, 0.0881 + 0.0479i, 0.1063 + 0.0669i, 0.0019 + 0.1026i, 0.0884 + 0.0690i, 0.0670 + 0.0267i, 0.0604 + 0.0380i, 0.0263 + 0.0203i, 0.0886 + 0.0529i, 0.0284 + 0.0441i, 0.0813 + 0.0500i, 0.0711 + 0.0659i, 0.0231 + 0.0077i, 0.0649 + 0.0339i, 0.0652 + 0.0656i, 0.0711 + 0.0189i, 0.0198 + 0.0670i, 0.0686 + 0.0265i, 0.0184 + 0.0633i, 0.0582 + 0.0546i, 0.0672 + 0.0501i, 0.0740 + 0.0584i, 0.0730 + 0.1016i, 0.0946 + 0.0369i, 0.0014 + 0.0433i, 0.0335 + 0.0332i, 0.0840 + 0.0444i, 0.0331 + 0.0308i, 0.0999 + 0.0425i, 0.0732 + 0.0542i, 0.0080 + 0.0779i, 0.0076 + 0.0303i, 0.0013 + 0.0212i, 0.0245 + 0.0478i, 0.0557 + 0.0503i, 0.0494 + 0.0461i, 0.0758 + 0.0716i, 0.0628 + 0.0781i, 0.0549 + 0.0304i, 0.0080 + 0.0282i, 0.0208 + 0.0764i, 0.0409 + 0.0845i, 0.0893 + 0.0425i, 0.0989 + 0.0562i, 0.0122 + 0.0774i, 0.0876 + 0.0614i, 0.0979 + 0.0497i, 0.0169 + 0.0480i, 0.0132 + 0.0095i, 0.0822 + 0.0478i, 0.0778 + 0.0395i, 0.0703 + 0.0326i, 0.0813 + 0.0919i, 0.0715 + 0.0819i, 0.0953 + 0.1024i, 0.0293 + 0.0602i, 0.0452 + 0.0015i, 0.0230 + 0.0643i$
8	10101011	$0.0199 + 0.0027i, 0.0033 + 0.0063i, 0.0005 + 0.0656i, 0.0443 + 0.0262i, 0.0573 + 0.0359i, 0.0622 + 0.0704i, 0.0491 + 0.0176i, 0.0194 + 0.0664i, 0.0111 + 0.0506i, 0.0502 + 0.0687i, 0.0729 + 0.0376i, 0.0629 + 0.0765i, 0.0717 + 0.0288i, 0.0239 + 0.0410i, 0.0207 + 0.0140i, 0.0413 + 0.0387i, 0.0126 + 0.0325i, 0.0163 + 0.0509i, 0.0167 + 0.0519i, 0.0502 + 0.0738i, 0.0041 + 0.0148i, 0.0177 + 0.0886i, 0.0514 + 0.0436i, 0.0240 + 0.0747i, 0.0239 + 0.0018i, 0.0555 + 0.0671i, 0.0736 + 0.0202i, 0.0101 + 0.0400i, 0.0053 + 0.1348i, 0.0097 + 0.0559i, 0.0228 + 0.0193i, 0.0702 + 0.0720i, 0.0105 + 0.0106i, 0.0476 + 0.0402i, 0.0207 + 0.0690i, 0.0170 + 0.0726i, 0.0549 + 0.0258i, 0.0423 + 0.0337i, 0.0726 + 0.0363i, 0.0254 + 0.0115i, 0.0543 + 0.0105i, 0.0727 + 0.0410i, 0.0448 + 0.0559i, 0.0678 + 0.0307i, 0.0578 + 0.0276i, 0.0293 + 0.0220i, 0.0059 + 0.0670i, 0.0125 + 0.0483i, 0.0737 + 0.0186i, 0.0151 + 0.0754i, 0.0598 + 0.0494i, 0.0473 + 0.0177i$



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6	110101	$0.0595 + 0.1064i, \ 0.0295 + 0.1327i, \ 0.0929 + 0.0406i, \ 0.1090 + 0.0379i, \ 0.0559 + 0.1286i, \ 0.0015 + 0.0345i, \ 0.0624 + 0.1196i, \ 0.1120 + 0.1350i, \ 0.1180 + 0.0345i, \ 0.1367 + 0.0356i, \ 0.1255 + 0.0074i, \ 0.0547 + 0.0116i, \ 0.0923 + 0.0952i, \ 0.1087 + 0.0284i, \ 0.0288 + 0.1254i, \ 0.1345 + 0.0258i, \ 0.0846 + 0.0254i, \ 0.0939 + 0.1478i, \ 0.0348 + 0.0654i, \ 0.0816 + 0.0505i, \ 0.1384 + 0.0467i, \ 0.0498 + 0.0543i, \ 0.0974 + 0.0584i, \ 0.0582 + 0.0879i, \ 0.0932 + 0.0178i, \ 0.1039 + 0.0057i, \ 0.0590 + 0.0682i, \ 0.0615 + 0.1293i, \ 0.0974 + 0.1388i, \ 0.1245 + 0.0393i, \ 0.0552 + 0.0238i, \ 0.0632 + 0.1297i, \ 0.0884 + 0.0354i, \ 0.0841 + 0.0960i, \ 0.1065 + 0.1437i, \ 0.0760 + 0.0988i, \ 0.1154 + 0.1293i, \ 0.0727 + 0.0015i, \ 0.0276 + 0.0204i, \ 0.1041 + 0.1217i, \ 0.1460 + 0.0639i, \ 0.1199 + 0.1323i, \ 0.1046 + 0.1092i, \ 0.0721 + 0.1021i, \ 0.0170 + 0.0514i, \ 0.0988 + 0.0247i, \ 0.0543 + 0.0231i, \ 0.0208 + 0.0284i, \ 0.0842 + 0.0628i, \ 0.1223 + 0.1272i, \\ 0.1002 + 0.0729i, \ 0.1485 + 0.1213i, \ 0.1429 + 0.0685i, \ 0.0087 + 0.0680i, \ 0.0535 + 0.0670i, \ 0.0815 + 0.0613i, \ 0.0389 + 0.1340i, \ 0.0888 + 0.0008i, \ 0.0073 + 0.0442i, \ 0.0849 + 0.0073i, \ 0.1042 + 0.1030i, \ 0.1430 + 0.0966i, \ 0.1115 + 0.1461i, \ 0.1100 + 0.0821i$
7	1001010	$0.0880 + 0.0466i, \ 0.1054 + 0.0684i, \ 0.0239 + 0.0866i, \ 0.0759 + 0.0090i, \ 0.0563 + 0.1020i, \ 0.1006 + 0.0988i, \ 0.0769 + 0.0649i, \ 0.0246 + 0.0273i, \ 0.0485 + 0.0942i, \ 0.0186 + 0.0554i, \ 0.1045 + 0.0790i, \ 0.0384 + 0.0455i, \ 0.0053 + 0.1037i, \ 0.0815 + 0.0078i, \ 0.0965 + 0.0597i, \ 0.0303 + 0.0315i, \ 0.0271 + 0.0925i, \ 0.1006 + 0.0362i, \ 0.0411 + 0.0734i, \ 0.1015 + 0.0058i, \ 0.0757 + 0.0385i, \ 0.0914 + 0.0537i, \ 0.0226 + 0.0468i, \ 0.0491 + 0.0607i, \ 0.0087 + 0.0665i, \ 0.0918 + 0.0122i, \ 0.0606 + 0.0699i, \ 0.0344 + 0.0814i, \ 0.0404 + 0.0853i, \ 0.0936 + 0.0879i, \ 0.0401 + 0.0723i, \ 0.0079 + 0.0217i, \ 0.0216 + 0.0294i, \ 0.0053 + 0.0675i, \ 0.0611 + 0.0579i, \ 0.0131 + 0.0064i, \ 0.0563 + 0.0096i, \ 0.0126 + 0.0293i, \ 0.0830 + 0.0441i, \ 0.0404 + 0.0511i, \ 0.0591 + 0.0675i, \ 0.0126 + 0.0293i, \ 0.0511 + 0.0888i, \ 0.0980 + 0.0590i, \ 0.0229 + 0.0091i, \ 0.0357 + 0.0438i, \ 0.0313 + 0.0405i, \ 0.0725 + 0.0179i, \ 0.1033 + 0.0898i, \ 0.0827 + 0.0904i, \ 0.0718 + 0.0487i, \ 0.0141 + 0.0130i, \ 0.0103 + 0.0159i, \ 0.0016 + 0.0398i, \ 0.0311 + 0.0830i, \ 0.0881 + 0.0479i, \ 0.1063 + 0.0669i, \ 0.0019 + 0.1026i, \ 0.0884 + 0.0690i, \ 0.0670 + 0.0267i, \ 0.0604 + 0.0380i, \ 0.0263 + 0.0203i, \ 0.0886 + 0.0529i, \ 0.0284 + 0.0441i, \ 0.0813 + 0.0500i, \ 0.0711 + 0.0659i, \ 0.0231 + 0.0077i, \ 0.0649 + 0.0339i, \ 0.0652 + 0.0656i, \ 0.0711 + 0.0198i, \ 0.0198 + 0.0670i, \ 0.0680 + 0.0253i, \ 0.0106 + 0.0313i, \ 0.0253 + 0.0644i, \ 0.1026 + 0.0332i, \ 0.0014 + 0.0433i, \ 0.0335 + 0.0332i, \ 0.0840 + 0.0444i, \ 0.0311 + 0.0308i, \ 0.0999 + 0.0425i, \ 0.0732 + 0.0542i, \ 0.0808 + 0.0779i, \ 0.0076 + 0.0300i, \ 0.0013 + 0.0212i, \ 0.0245 + 0.0478i, \ 0.0597 + 0.0503i, \ 0.0494 + 0.0091i, \ 0.0758 + 0.0716i, \ 0.0628 + 0.0781i, \ 0.0549 + 0.0304i, \ 0.0080 + 0.0282i, \ 0.0208 + 0.0764i, \ 0.0409 + 0.0845i, \ 0.0893 + 0.0425i, \ 0.0899 + 0.0562i, \ 0.0122 + 0.0774i, \ 0.0876 + 0.0614i, \ 0.0979 + 0.0497i, \ 0.0169 + 0.0480i, \ 0.0132 + 0.0095i, \ 0.0822 + 0.0478i, \ 0.0778 + 0.0395i, \ 0.0703 + 0.0326i, \ 0.0813 + 0.0919i, \ 0.0715 + 0.0819i, \ 0.0953 + 0.1024i, \ 0.0293 + 0.0602i, \ 0.0452 + 0.0015i, \ 0.0230 + 0.0643i$
8	10101011	$0.0199 + 0.0027i, \ 0.0033 + 0.0063i, \ 0.0005 + 0.0656i, \ 0.0443 + 0.0262i, \ 0.0573 + 0.0359i, \ 0.0622 + 0.0704i, \ 0.0491 + 0.0176i, \ 0.0194 + 0.0664i, \ 0.0111 + 0.0506i, \ 0.0502 + 0.0687i, \ 0.0729 + 0.0376i, \ 0.0629 + 0.0765i, \ 0.0717 + 0.0288i, \\ 0.0239 + 0.0410i, \ 0.0207 + 0.0140i, \ 0.0413 + 0.0387i, \ 0.0126 + 0.0253i, \ 0.0163 + 0.0509i, \ 0.0167 + 0.0519i, \ 0.0502 + 0.0738i, \ 0.0041 + 0.0448i, \ 0.0177 + 0.0886i, \ 0.0571 + 0.0436i, \ 0.0240 + 0.0747i, \ 0.0239 + 0.0108i, \ 0.0555 + 0.0671i, \ 0.0736 + 0.0021i, \ 0.0101 + 0.0400i, \ 0.0053 + 0.0148i, \ 0.0097 + 0.0552i, \ 0.0128 + 0.0193i, \ 0.0702 + 0.0720i, \ 0.0105 + 0.0106i, \ 0.0476 + 0.0402i, \ 0.0207 + 0.0690i, \ 0.0170 + 0.0726i, \ 0.0549 + 0.0258i, \ 0.0423 + 0.0337i, \ 0.0726 + 0.0363i, \ 0.0254 + 0.0115i, \ 0.0543 + 0.0105i, \ 0.0727 + 0.0410i, \ 0.0448 + 0.0559i, \ 0.0657 + 0.0307i, \ 0.0578 + 0.0276i, \ 0.0293 + 0.0220i, \ 0.0059 + 0.0670i, \ 0.0125 + 0.0483i, \ 0.0737 + 0.0186i, \ 0.0151 + 0.0754i, \ 0.0598 + 0.0494i, \ 0.0473 + 0.0177i, \ 0.0125 + 0.0525i, \ 0.0024 + 0.0513i, \ 0.0122 + 0.0104i, \ 0.0748 + 0.0017i, \ 0.0733 + 0.0202i, \ 0.0176 + 0.0090i, \ 0.0739 + 0.0053i, \ 0.0524 + 0.0657i, \ 0.0042 + 0.0139i, \ 0.0462 + 0.0025i, \ 0.0303 + 0.0030i, \ 0.0566 + 0.0168i, \ 0.0141 + 0.0213i, \ 0.0059 + 0.0284i, \ 0.0006 + 0.0101i, \ 0.0608 + 0.0685i, \ 0.0014 + 0.0667i, \ 0.0677 + 0.0196i, \ 0.0272 + 0.0439i, \ 0.0057 + 0.0123i, \ 0.0746 + 0.0458i, \ 0.0120 + 0.0255i, \ 0.0126 + 0.0508i, \ 0.0242 + 0.0666i, \ 0.0023 + 0.0437i, \ 0.0276 + 0.0756i, \ 0.0021 + 0.0610i, \ 0.0612 + 0.0181i, \ 0.0770 + 0.0642i, \ 0.0085 + 0.0148i, \ 0.0480 + 0.0493i, \ 0.0102 + 0.0516i, \ 0.0239 + 0.0595i, \ 0.0104 + 0.0293i, \ 0.0172 + 0.0340i, \ 0.0306 + 0.0372i, \ 0.0104 + 0.0469i, \ 0.0186 + 0.0136i, \ 0.0175 + 0.0020i, \ 0.0301 + 0.0609i, \ 0.0394 + 0.0396i, \ 0.0072 + 0.0164i, \ 0.0017 + 0.0080i, \ 0.0123 + 0.0211i, \ 0.0651 + 0.0314i, \ 0.0678 + 0.0314i, \ 0.0144 + 0.0441i, \ 0.0764 + 0.0726i, \ 0.0549 + 0.0116i, \ 0.0672 + 0.0296i, \ 0.0370 + 0.0240i, \ 0.0382 + 0.0130i, \ 0.0222 + 0.0691i, \ 0.0047 + 0.0249i, \ 0.0202 + 0.0566i, \ 0.0144 + 0.0371i, \ 0.0707 + 0.0308i, \ 0.0095 + 0.0390i, \ 0.0010 + 0.0130i, \ 0.0285 + 0.0044i, \ 0.0538 + 0.0494i, \ 0.0685 + 0.0012i, \ 0.0458 + 0.0645i, \ 0.0121 + 0.0619i, \ 0.0244 + 0.0538i, \ 0.0180 + 0.0356i, \ 0.0006 + 0.0664i, \ 0.0306 + 0.0633i, \ 0.0501 + 0.0149i, \ 0.0066 + 0.0343i, \ 0.0593 + 0.0010i, \ 0.0747 + 0.0238i, \ 0.0551 + 0.0675i, \ 0.0603 + 0.0644i, \ 0.0183 + 0.0257i, \ 0.0151 + 0.0679i, \ 0.0203 + 0.0370i, \ 0.0550 + 0.0432i, \ 0.0753 + 0.0475i, \ 0.0491 + 0.0510i, \ 0.0421 + 0.0475i, \ 0.0654 + 0.0528i, \ 0.0189 + 0.0393i, \ 0.0515 + 0.0550i, \ 0.0517 + 0.0397i, \ 0.0633 + 0.0467i, \ 0.0748 + 0.0745i, \ 0.0376 + 0.0634i, \ 0.0630 + 0.0245i, \ 0.0494 + 0.0453i, \ 0.0236 + 0.0100i, \ 0.0509 + 0.0196i, \ 0.0276 + 0.0169i, \ 0.0723 + 0.0515i, \ 0.0376 + 0.0011i, \ 0.0070 + 0.0433i, \ 0.0519 + 0.0350i, \ 0.0397 + 0.0697i, \ 0.0171 + 0.0217i, \ 0.0559 + 0.0050i, \ 0.0053 + 0.0367i, \ 0.0743 + 0.0758i, \ 0.0160 + 0.0711i, \ 0.0214 + 0.0433i, \ 0.0492 + 0.0503i, \ 0.0000 + 0.0596i, \ 0.0259 + 0.0082i, \ 0.0212 + 0.0001i, \ 0.0034 + 0.0418i, \ 0.0072 + 0.0005i, \ 0.0316 + 0.0348i, \ 0.0630 + 0.0151i, \ 0.0671 + 0.0607i, \ 0.0017 + 0.0477i, \ 0.0560 + 0.0012i, \ 0.0654 + 0.0687i, \ 0.0562 + 0.0587i, \\ 0.0736 + 0.0699i, \ 0.0506 + 0.0585i, \ 0.0572 + 0.0293i, \ 0.0266 + 0.0255i, \ 0.0681 + 0.0389i, \ 0.0268 + 0.0435i, \ 0.0670 + 0.0514i, \ 0.0302 + 0.0522i, \ 0.0195 + 0.0726i, \ 0.0273 + 0.0594i, \ 0.0573 + 0.0568i, \ 0.0502 + 0.0688i, \ 0.0724 + 0.0764i, \ 0.0642 + 0.0388i, \ 0.0362 + 0.0485i, \ 0.0485 + 0.0611i, \ 0.0045 + 0.0404i, \ 0.0351 + 0.0132i, \ 0.0665 + 0.0101i, \ 0.0569 + 0.0169i, \ 0.0364 + 0.0081i, \ 0.0607 + 0.0109i, \ 0.0506 + 0.0217i, \ 0.0381 + 0.0173i, \ 0.0030 + 0.0701i, \ 0.0175 + 0.0065i, \ 0.0253 + 0.0454i, \ 0.0693 + 0.0418i, \ 0.0242 + 0.0504i, \ 0.0334 + 0.0178i, \ 0.0649 + 0.0321i, \ 0.0142 + 0.0230i, \ 0.0392 + 0.0518i, \ 0.0349 + 0.0723i, \ 0.0251 + 0.0264i, \ 0.0293 + 0.0434i, \ 0.0683 + 0.0092i, \ 0.0587 + 0.0130i, \ 0.0681 + 0.0215i, \ 0.0353 + 0.0429i, \ 0.0616 + 0.0374i, \ 0.0103 + 0.0734i, \ 0.0050 + 0.0179i, \ 0.0289 + 0.0369i, \ 0.0288 + 0.0406i, \ 0.0373 + 0.0611i, \ 0.0747 + 0.0149i, \ 0.0264 + 0.0701i, \ 0.0195 + 0.0757i, \ 0.0711i + 0.0451 + 0.0010i, \ 0.0404 + 0.0592i, \ 0.0126 + 0.0730i, \ 0.0375 + 0.0627i, \ 0.0382 + 0.0712i, \ 0.0650 + 0.0153i, \ 0.0621 + 0.0520i, \ 0.0661 + 0.0715i, \ 0.0470 + 0.0265i, \ 0.0436 + 0.0458i, \ 0.0472 + 0.0474i, \ 0.0079 + 0.0003i, \ 0.0122 + 0.0757i, \ 0.0319 + 0.0693i, \ 0.0432 + 0.0534i, \ 0.0207 + 0.0339i, \ 0.0604 + 0.0540i, \ 0.0299 + 0.0470i, \ 0.0024 + 0.0231i, \ 0.0451 + 0.0660i, \ 0.0431 + 0.0086i, \ 0.0155 + 0.0225i, \ 0.0067 + 0.0075i, \ 0.0719 + 0.0306i, \ 0.0200 + 0.0257i, \ 0.0157 + 0.0157i$



# Information content



40 qubits	10 000 GigaByte
1 additional qubit	Double the memory
300 qubits	Each atom in the universe holds one bit.



# Why quantum information ?



Schrödinger equation for 300 interacting spins.

Classical computation needs more bits than there are atoms in the universe.

- Quantum computers can solve certain tasks much more efficiently than classical computers.

Other prominent examples:

- Factoring of large integers (P. Shor 1994)
- Search in an unsorted data base (L. Grover, 1997)
- ...





# Quantum computing



## Classical computer

- Initialization
- 1-bit operations (NOT)
- 2-bit gates (e.g. NAND)

Computational space:

00  
01  
10  
11

- Read out  
→ result

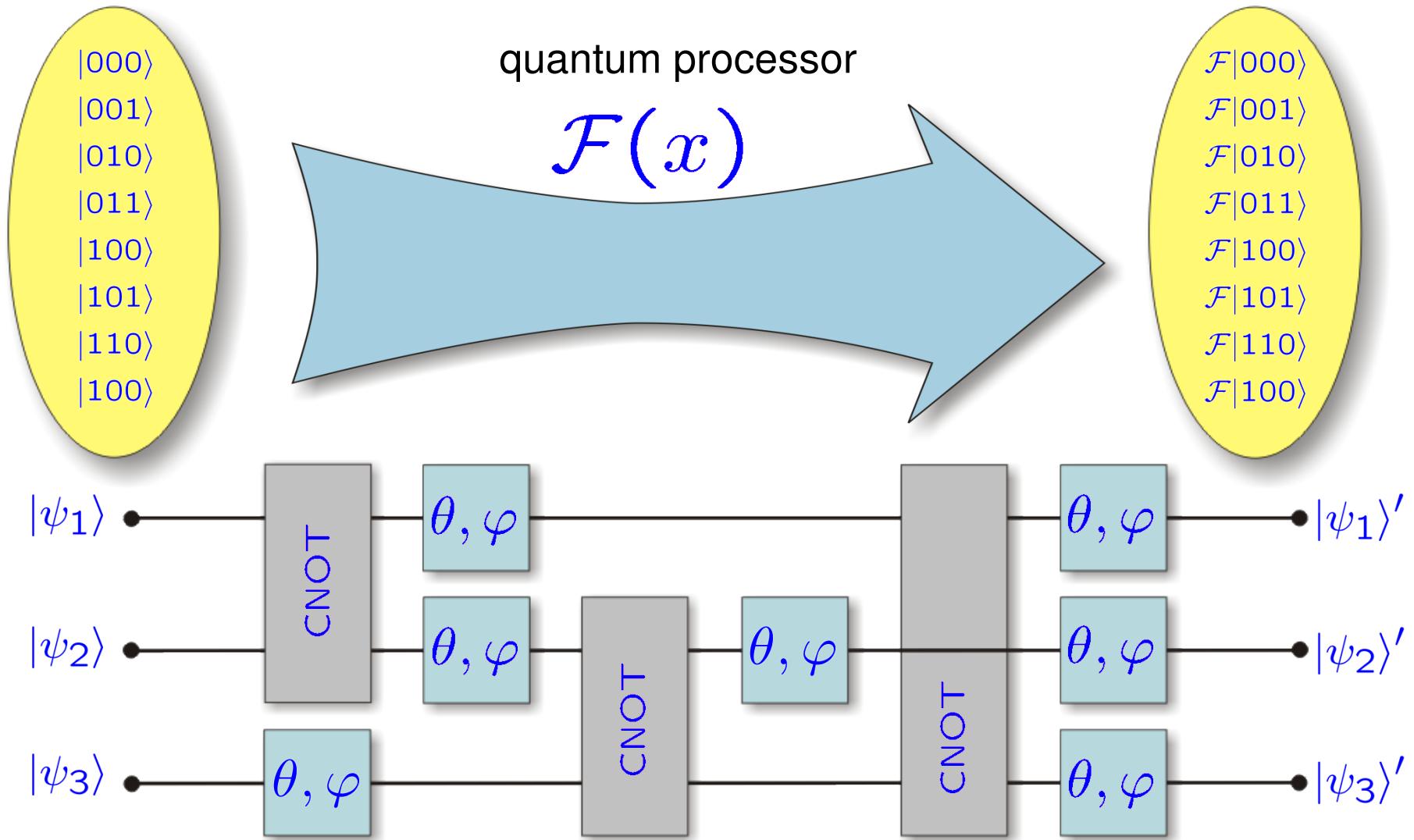
## Quantum computer

- Initialization
- 1-qubit rotations  
→ superpositions
- 2-qubit gates (CNOT gate)  
→ entanglement

Computational space: Hilbert space  
 $2^n$  dimensional

- Read out of qubits  
→ gain of classical information

# Quantum computing



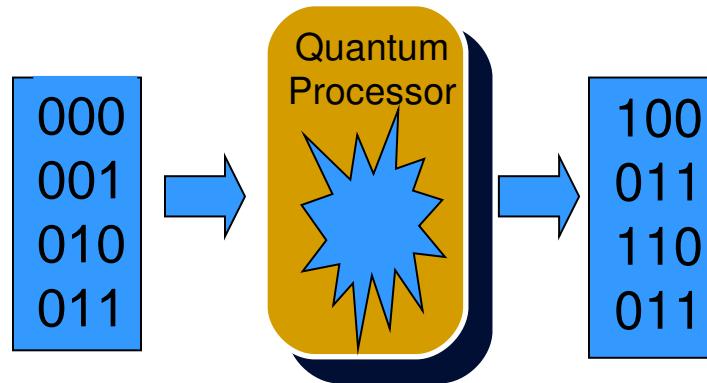
Input →

computation: sequence of quantum gates

→ output

# Quantum computing

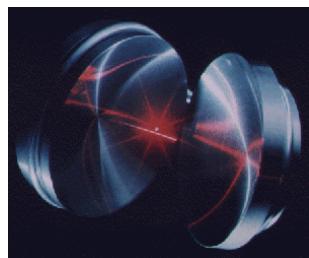
Long term goal: A universal quantum computer



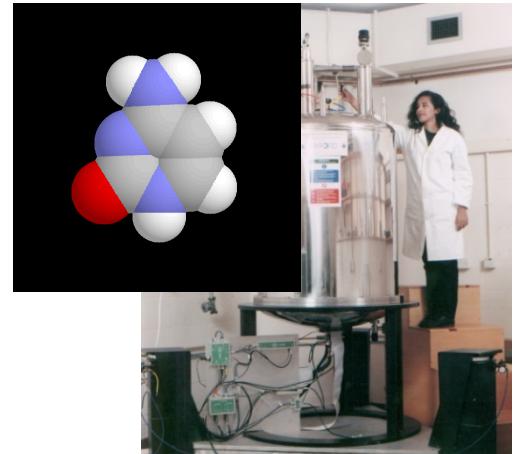
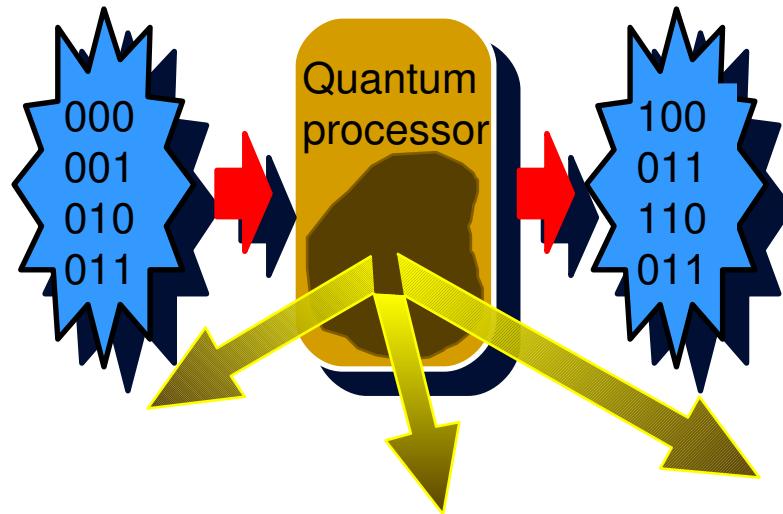
In the mean time:

- “understand” quantum mechanics
- apply quantum mechanics
- where does quantum mechanics fail?

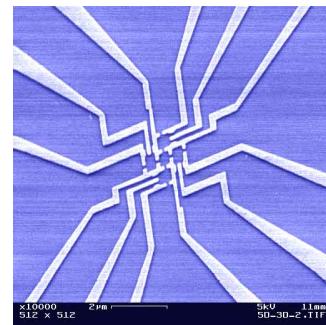
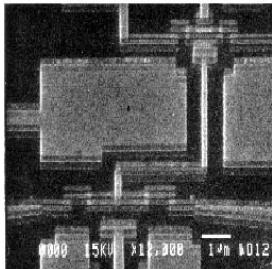
# Which technology ?



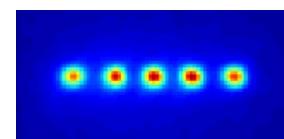
Cavity QED



NMR



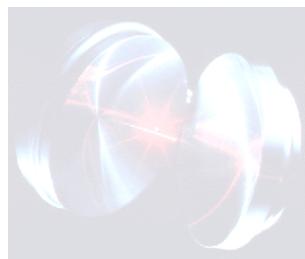
Superconducting qubits



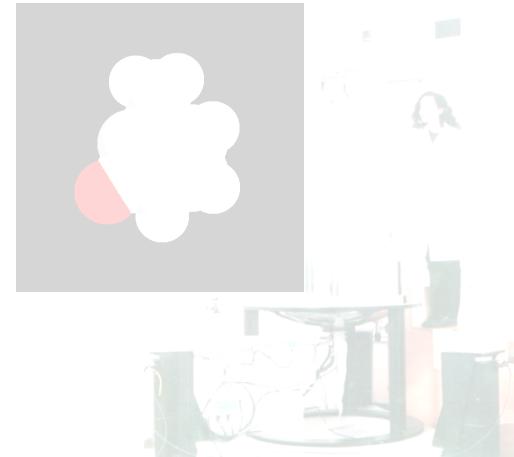
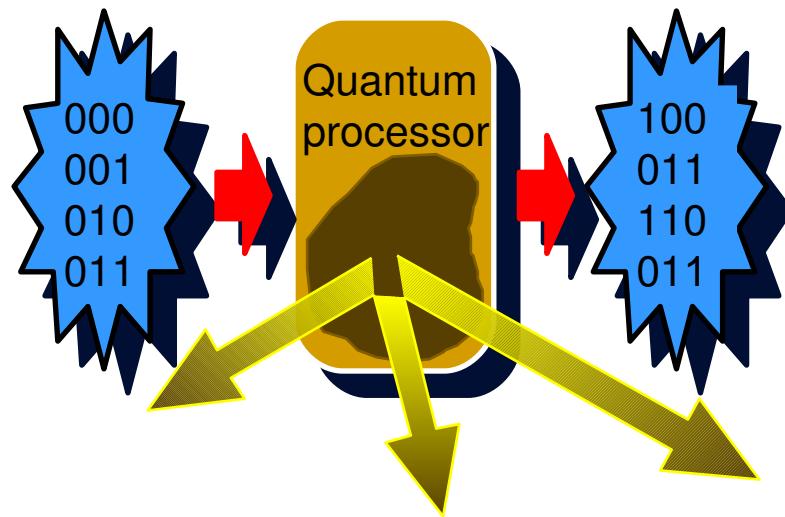
Quantum dots

Trapped atoms/ions

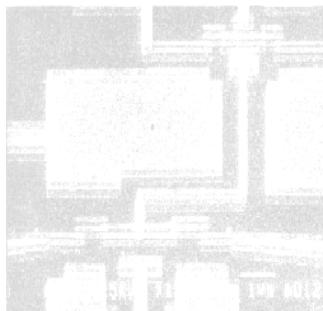
# Which technology ?



Cavity QED



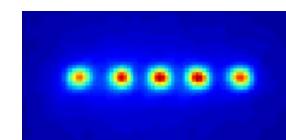
NMR



Superconducting qubits



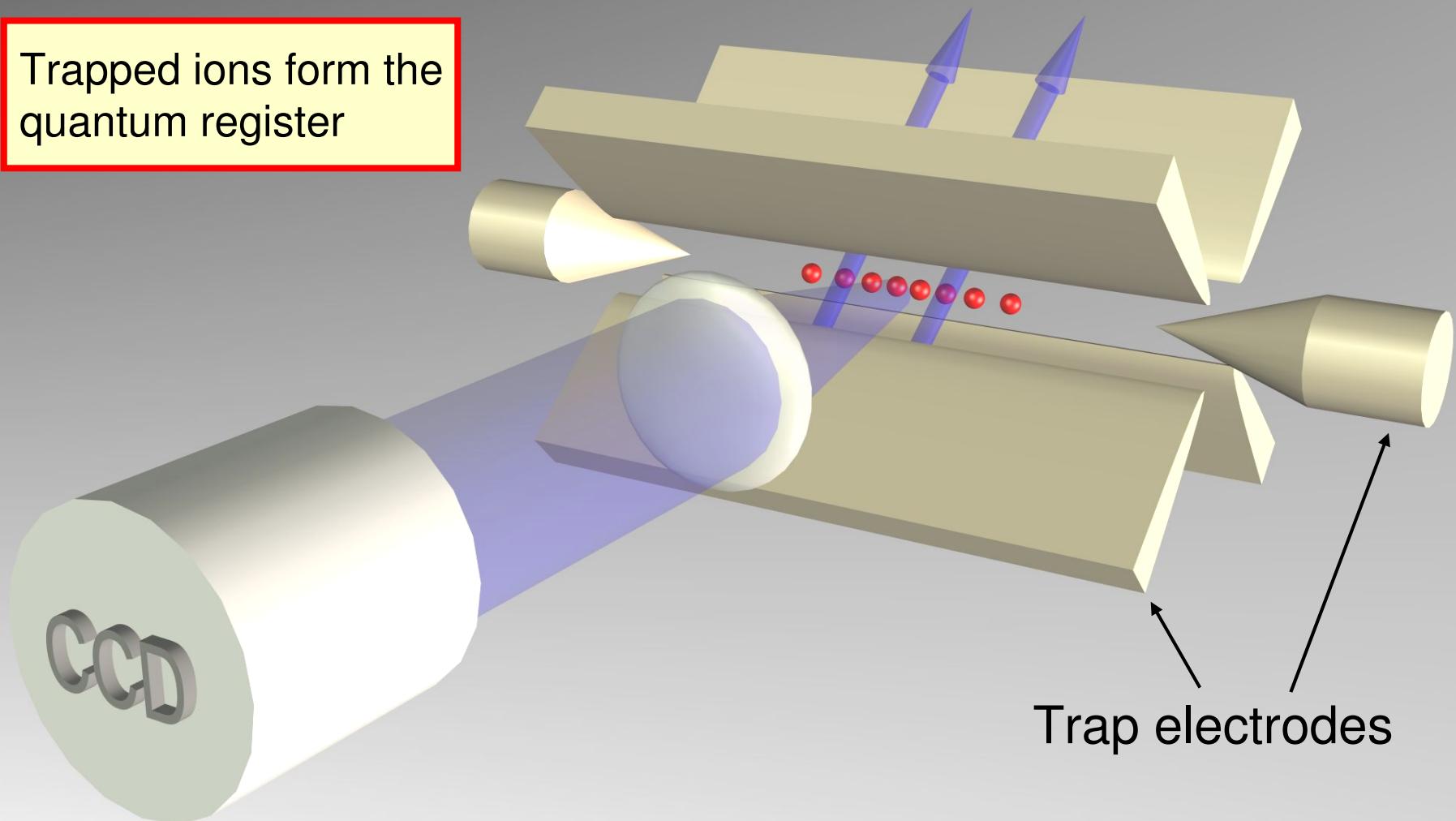
Quantum dots



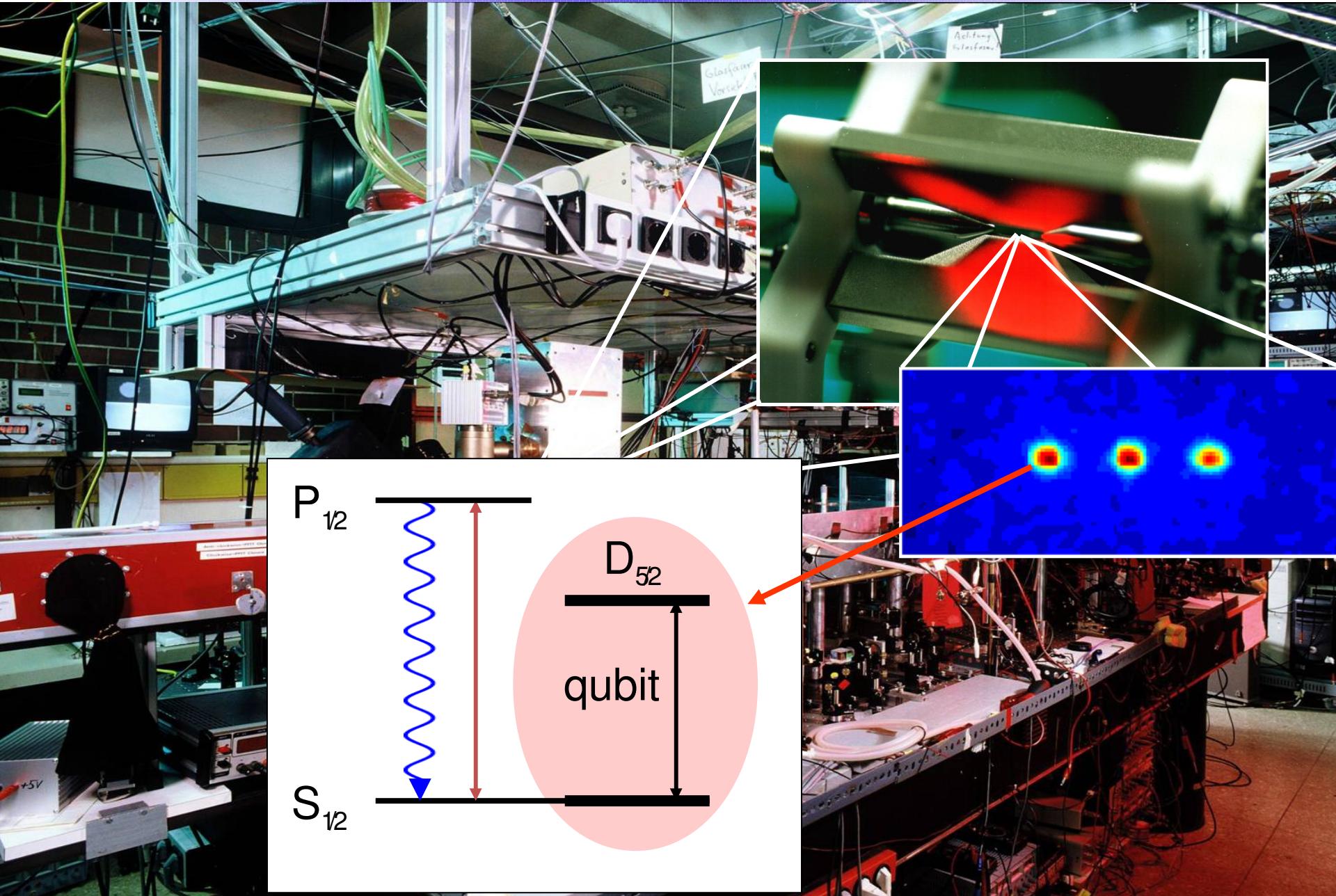
Trapped atoms/ions

# Ion trap quantum computing

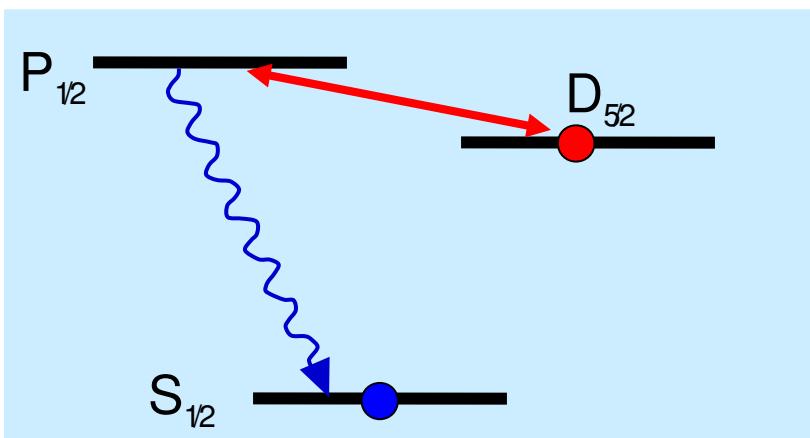
Trapped ions form the quantum register



# The hardware

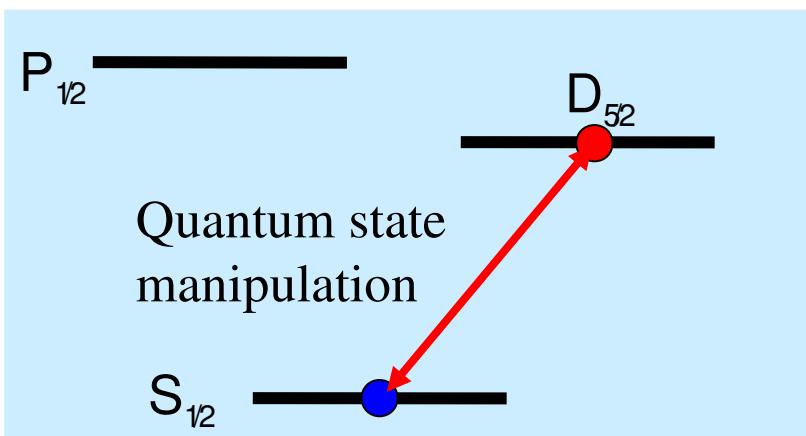


# Experimental procedure



1. Initialization in a pure quantum state

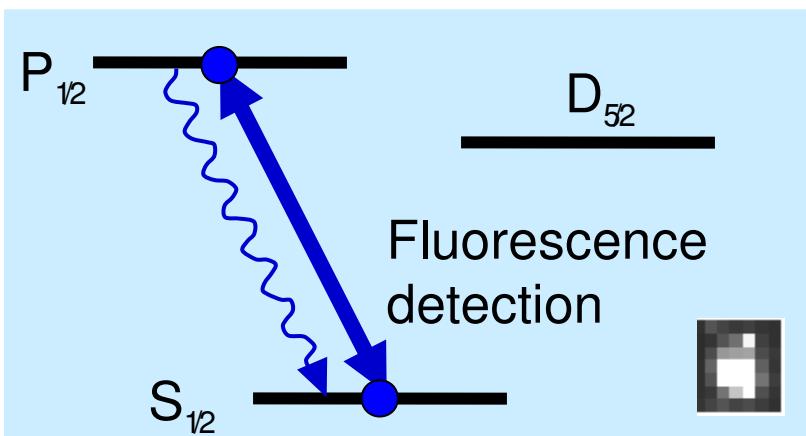
# Experimental procedure



1. Initialization in a pure quantum state

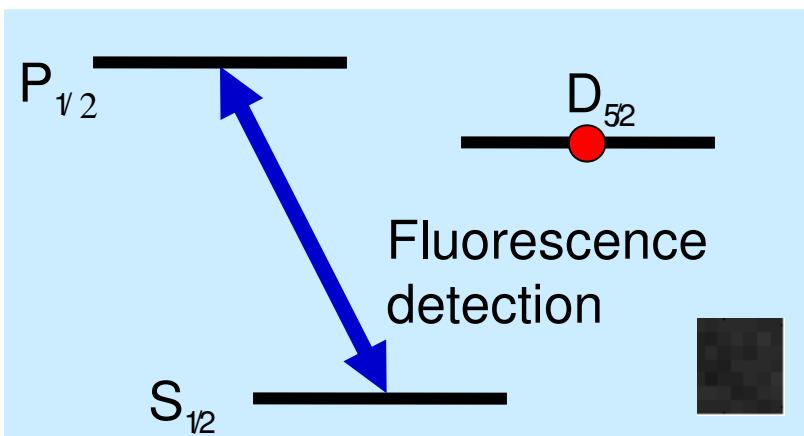
2. Quantum state manipulation on  
 $S_{1/2} - D_{5/2}$  transition

# Experimental procedure



1. Initialization in a pure quantum state
2. Quantum state manipulation on  $S_{1/2} - D_{5/2}$  transition
3. Quantum state measurement by fluorescence detection

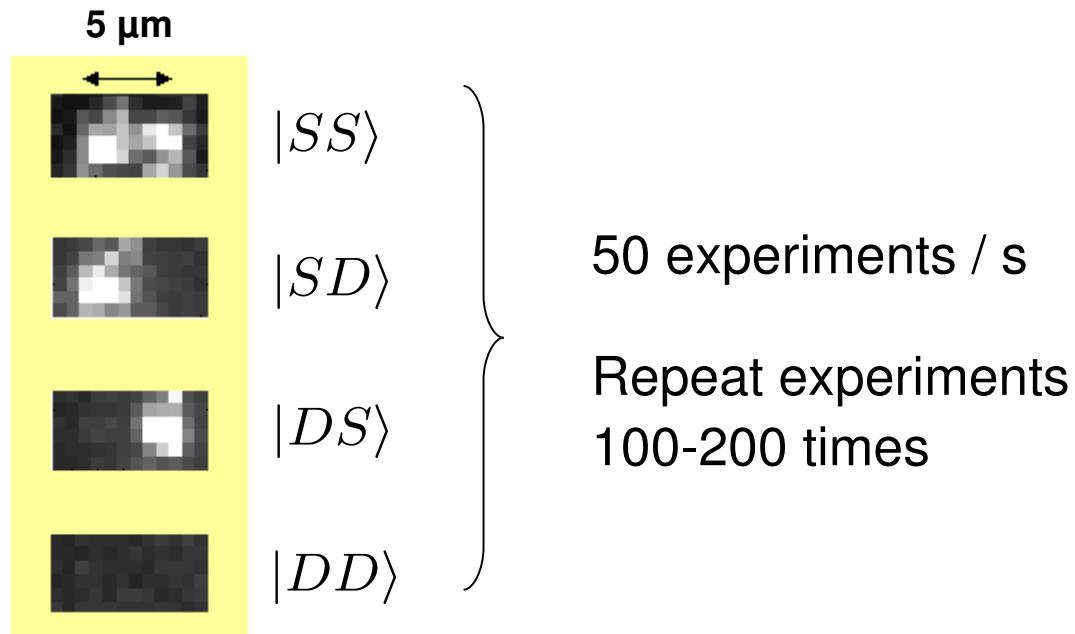
# Experimental procedure



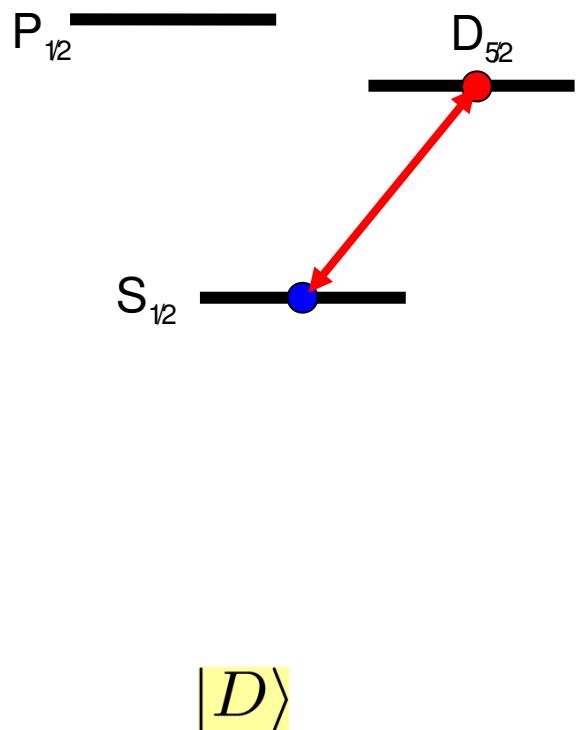
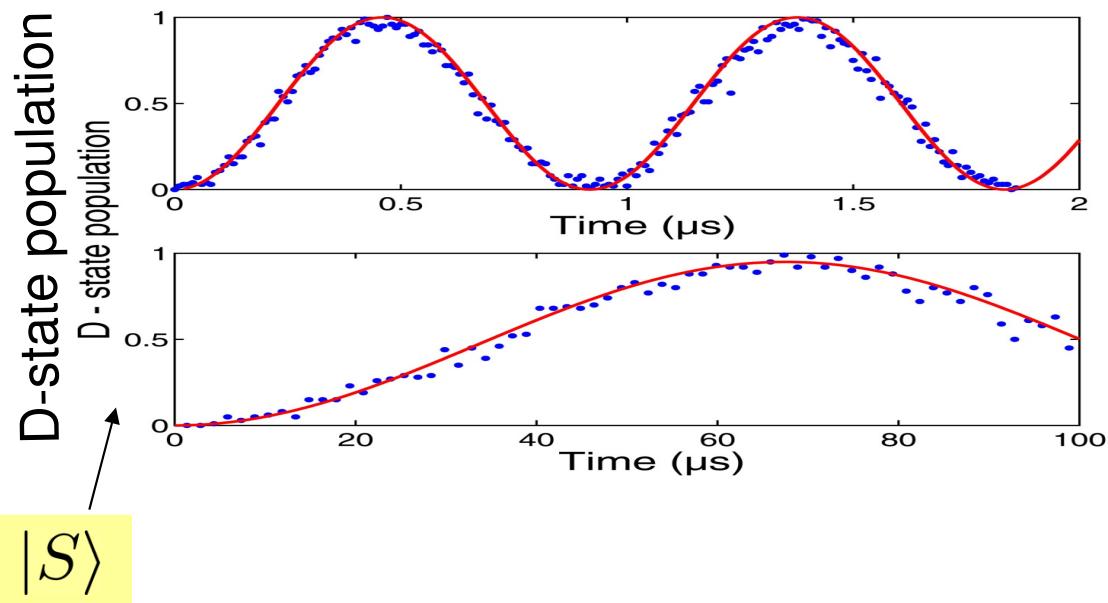
1. Initialization in a pure quantum state
2. Quantum state manipulation on  $S_{1/2} - D_{52}$  transition
3. Quantum state measurement by fluorescence detection

Two ions:

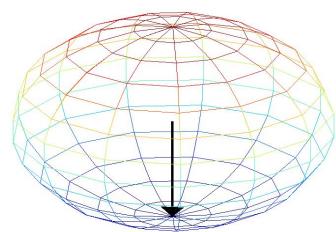
Spatially resolved  
detection with  
CCD camera



# Rabi oscillations



$$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$$



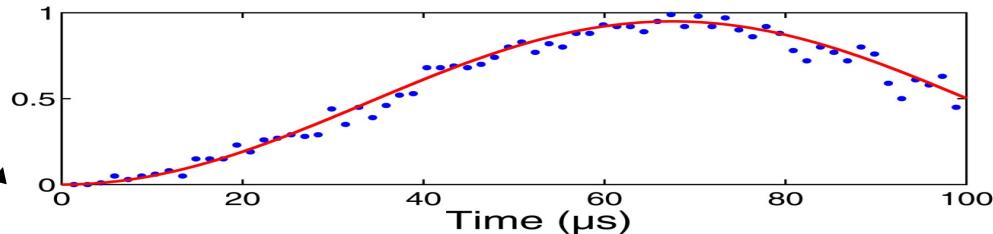
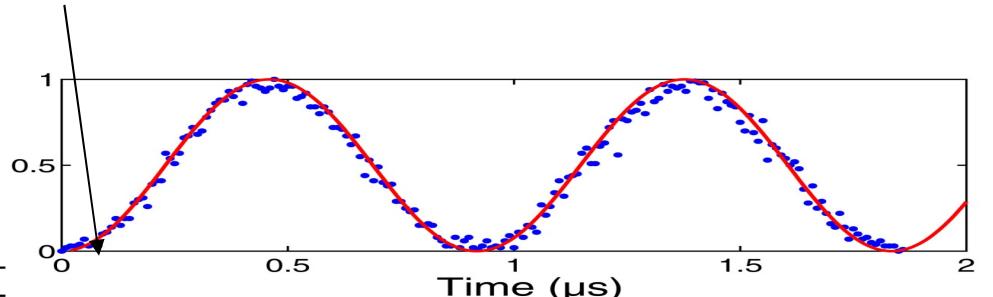
$|S\rangle$

# Rabi oscillations

$$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$$

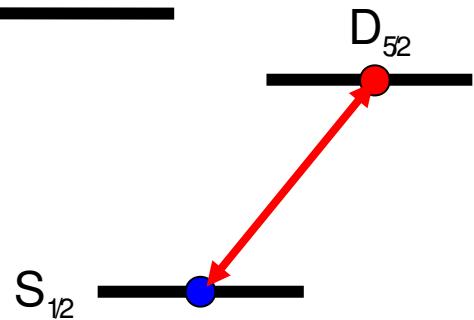
D-state population  
 $|S\rangle$

$$|S\rangle$$

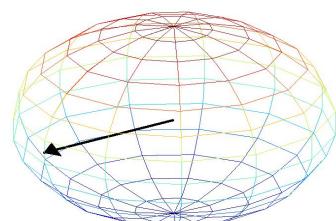


$$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$$

$$P_{1/2}$$

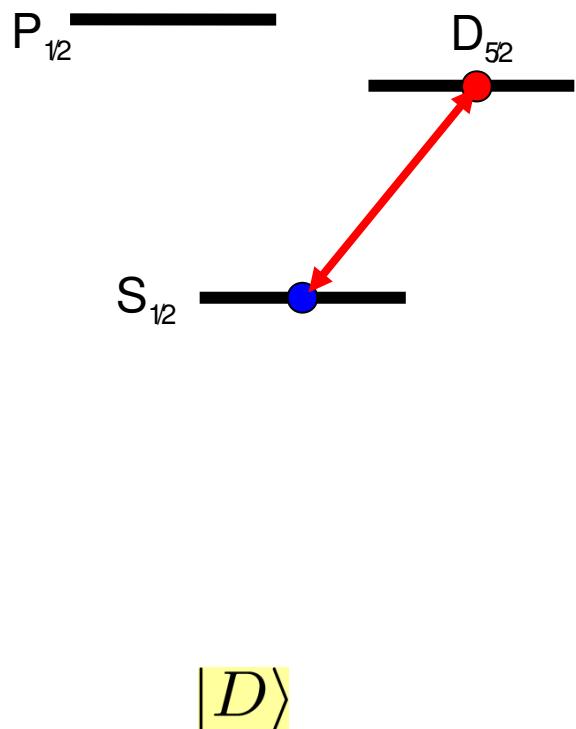
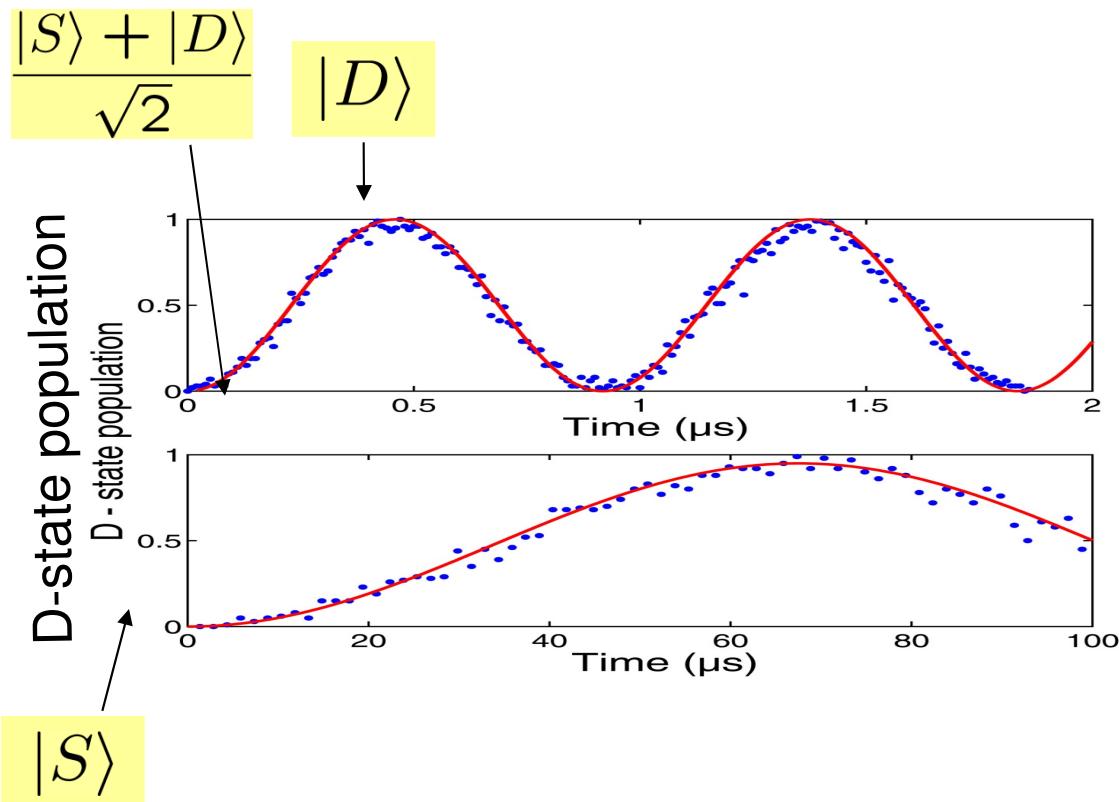


$$|D\rangle$$



$$|S\rangle$$

# Rabi oscillations



$$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$$

$|S\rangle$

## Classical computer

- Initialization
- 1-bit operations (NOT)
- 2-bit gates (e.g. NAND)

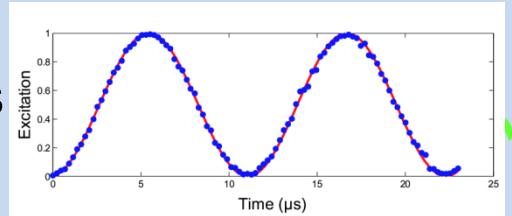
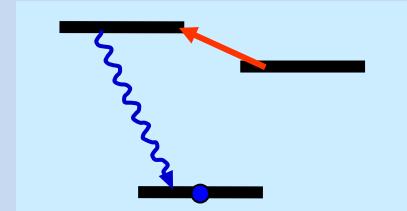
Computational space:

00  
01  
10  
11

- Read out  
→ result

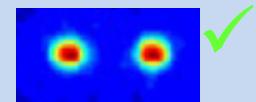
## Quantum computer

- Initialization
- 1-qubit rotations  
→ superpositions
- 2-qubit gates (CNOT gate)  
→ entanglement



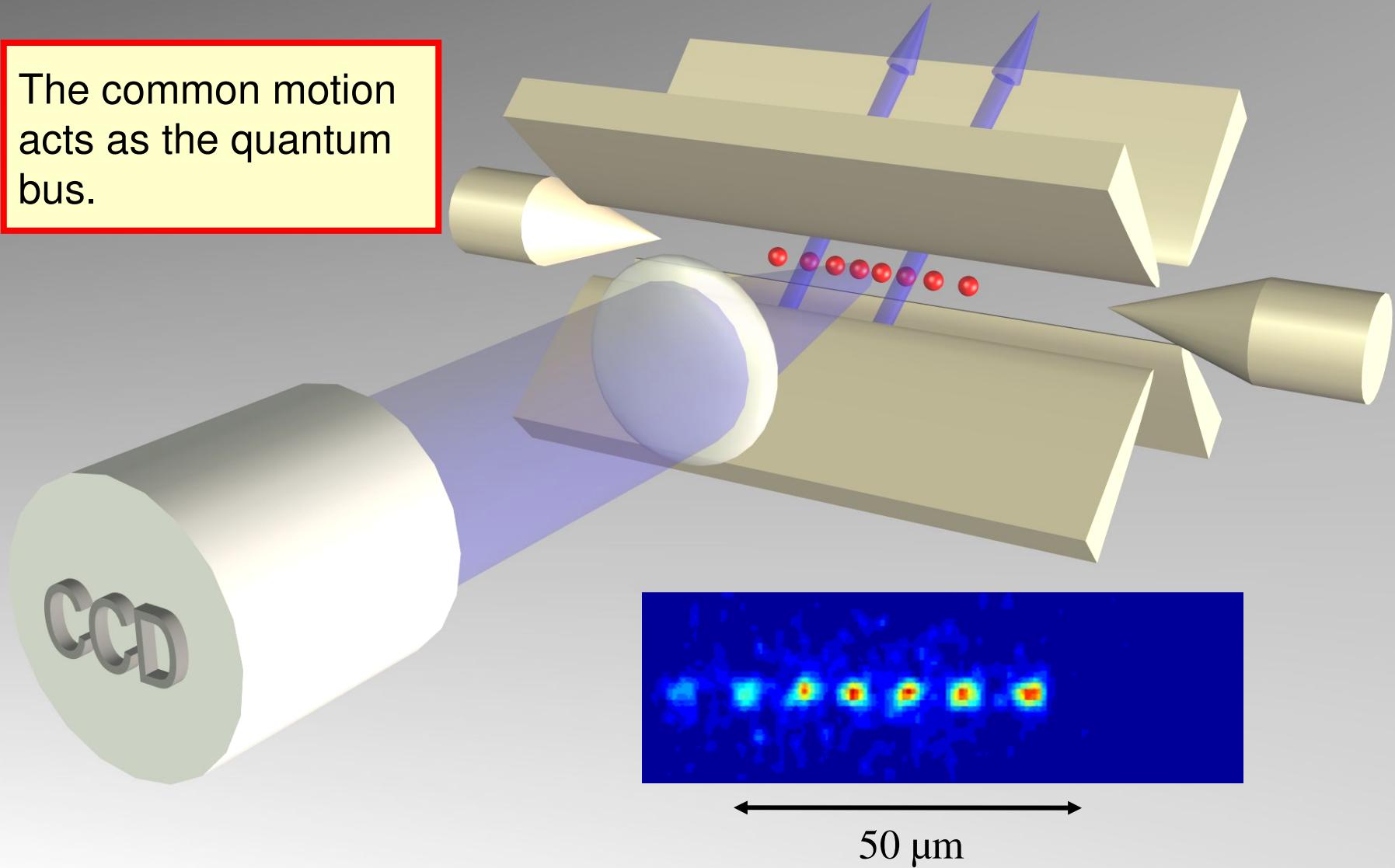
Computational space:

- Read out of qubits  
→ gain of classical information



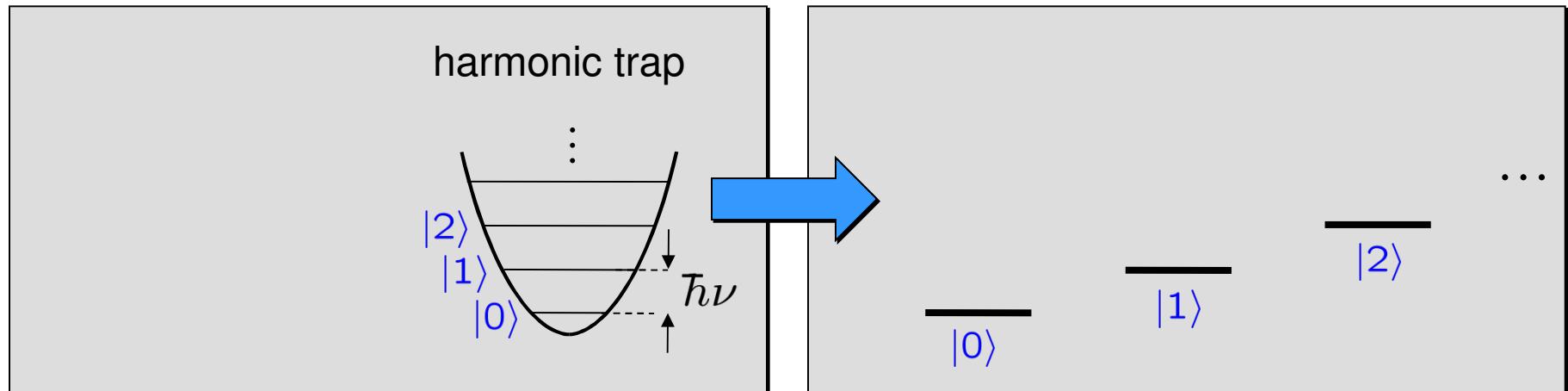
# Having the qubits interact

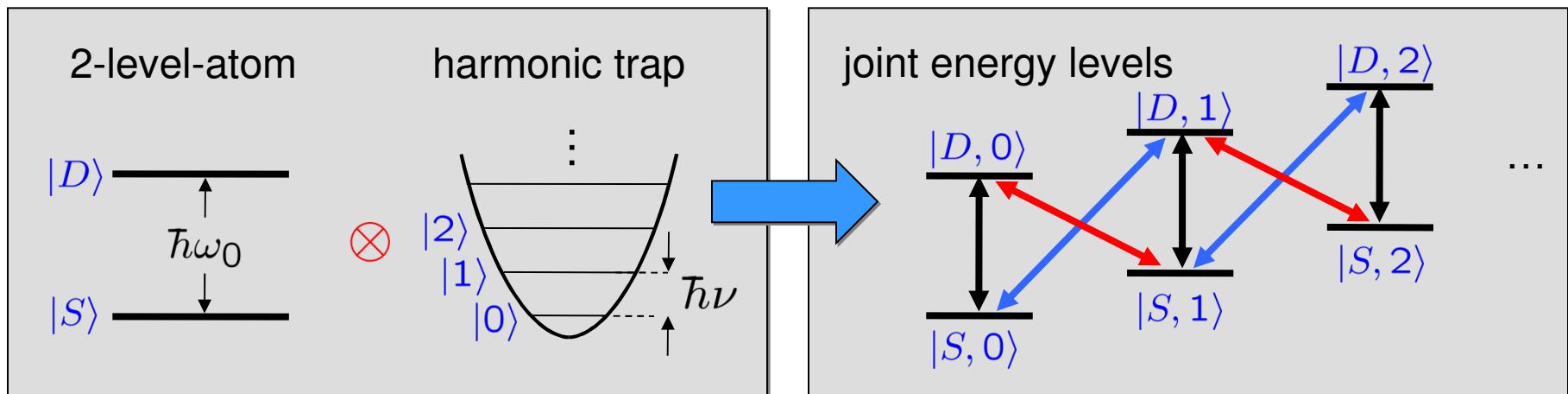
The common motion acts as the quantum bus.



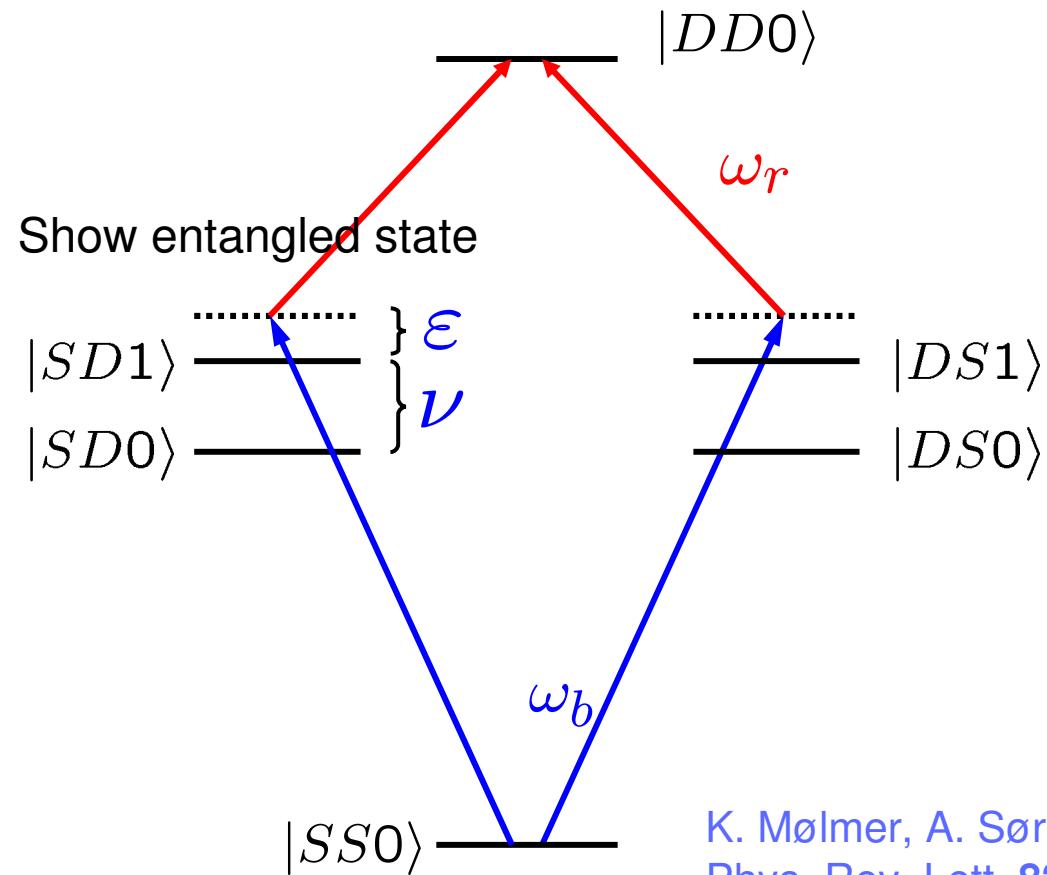


# Ion motion





All atoms flip their state together

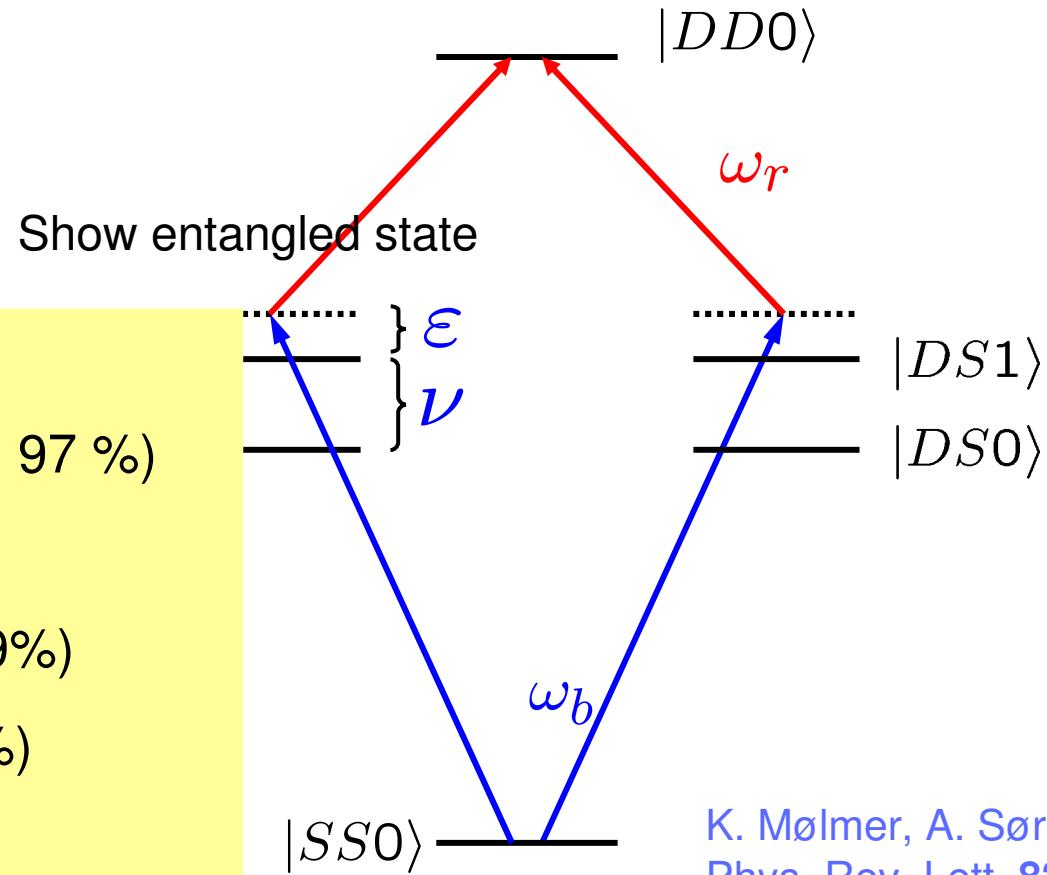


K. Mølmer, A. Sørensen,  
Phys. Rev. Lett. **82**, 1971 (1999)  
C. A. Sackett et al.,  
Nature **404**, 256 (2000)

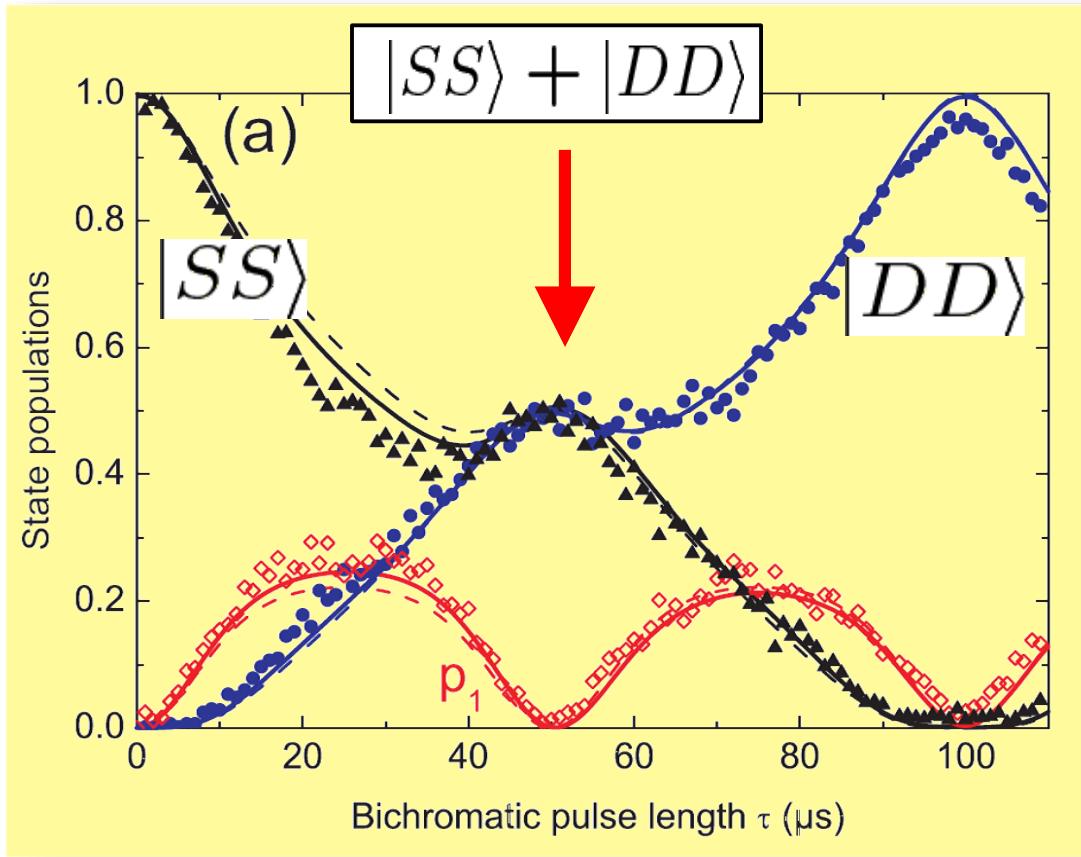
All atoms flip their state together

### Bell states with atoms

- ${}^9\text{Be}^+$ : NIST (fidelity: 97 %)
- ${}^{40}\text{Ca}^+$ : Oxford (83%)
- ${}^{111}\text{Cd}^+$ : Ann Arbor (79%)
- ${}^{171}\text{Yb}$ : Maryland (96%)
- ${}^{25}\text{Mg}^+$ : Munich (97%)
- ${}^{40}\text{Ca}^+$ : Innsbruck (99%)



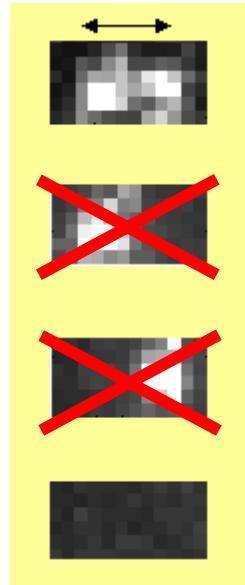
K. Mølmer, A. Sørensen,  
Phys. Rev. Lett. **82**, 1971 (1999)  
C. A. Sackett et al.,  
Nature **404**, 256 (2000)



$$|SS\rangle + |DD\rangle$$

Fluorescence  
detection with  
CCD camera:

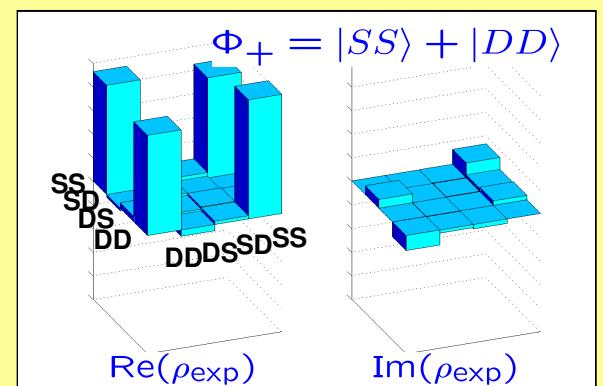
$$\begin{cases} |SS\rangle \\ |SD\rangle \\ |DS\rangle \\ |DD\rangle \end{cases}$$



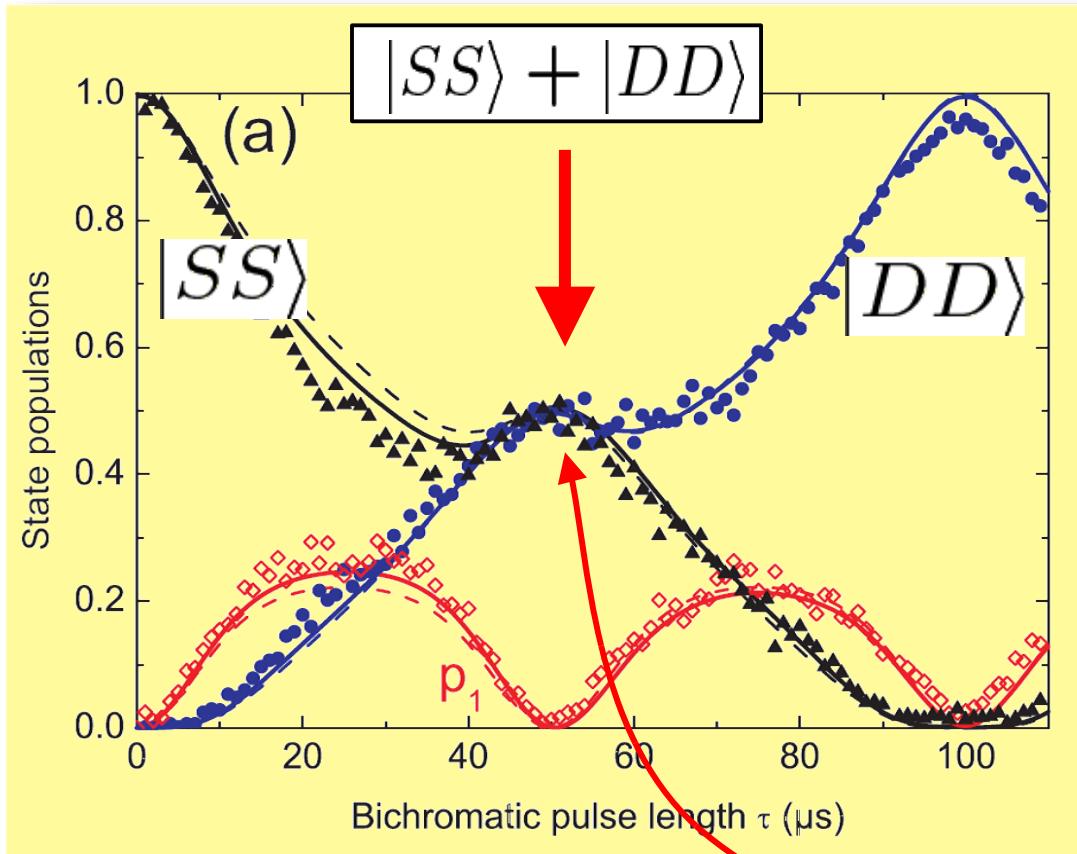
Coherent superposition or incoherent mixture ?

What is the relative phase of the superposition ?

→ Measurement of the density matrix:



## Bell states using the Mølmer-Sørensen gate



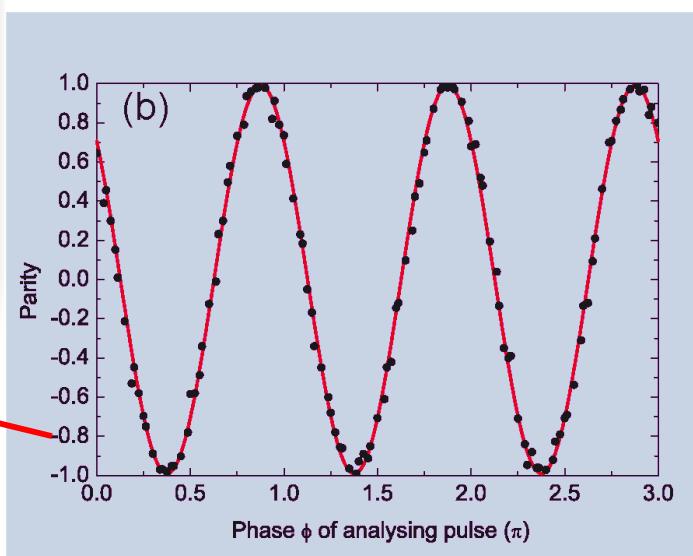
gate duration  $51 \mu\text{s}$

average fidelity

$$F_{\text{MS}} = 99.3(0.2)\%$$

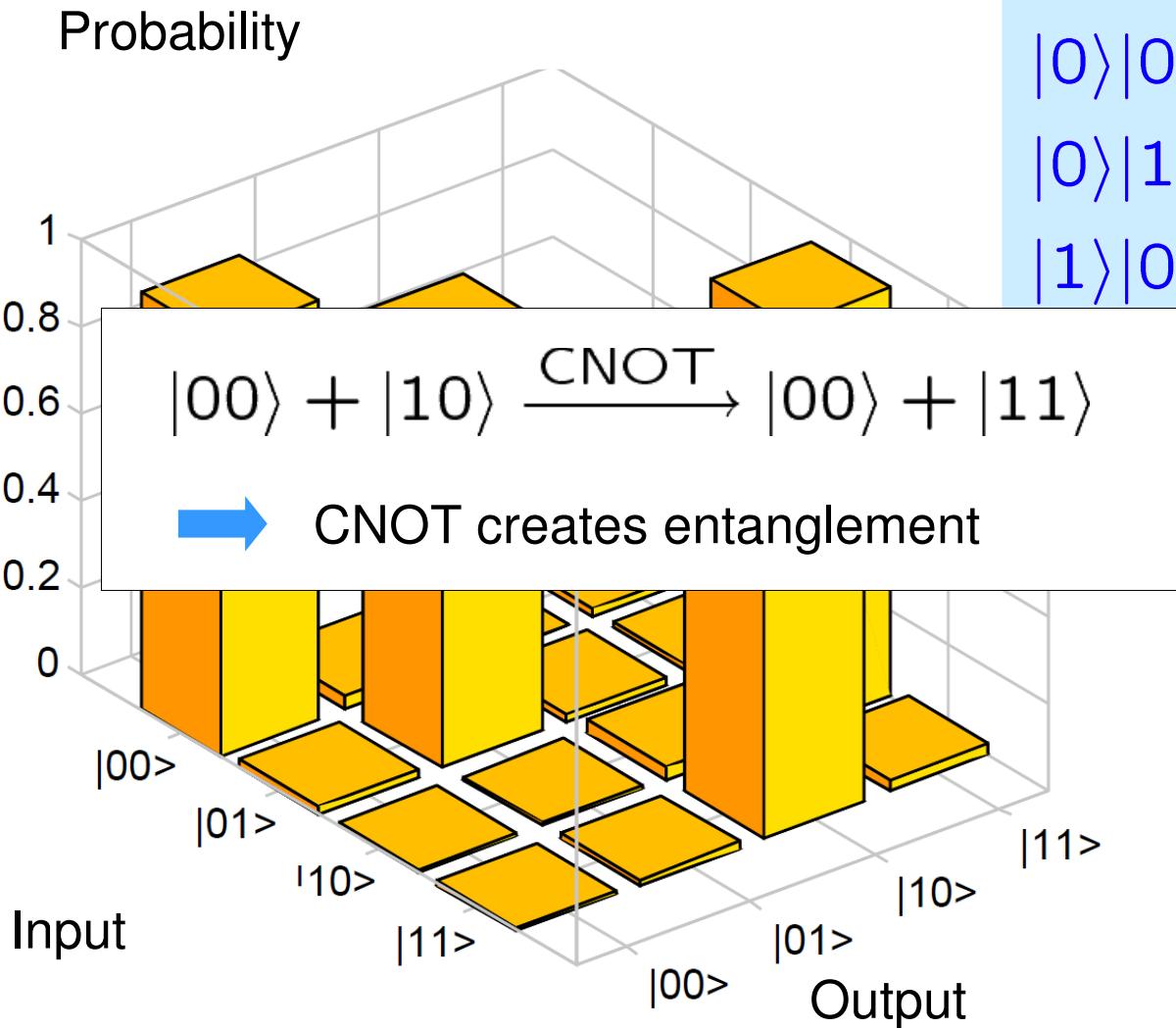
J. Benhelm, G. Kirchmair,  
C. Roos  
Theory: C. Roos,  
New J. Phys. **10**,  
013002 (2008)

measure entanglement  
via parity oscillations





# Truth table of a controlled NOT gate



→ universal set of quantum gates

## Classical computer

- Initialization
- 1-bit operations (NOT)
- 2-bit gates (e.g. NAND)

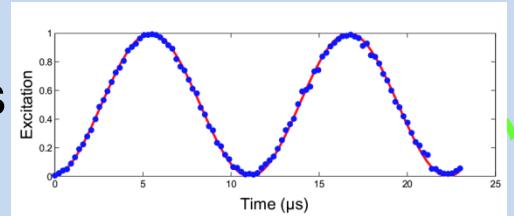
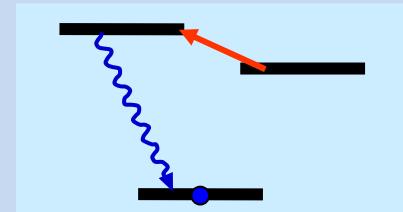
Computational space:

00  
01  
10  
11

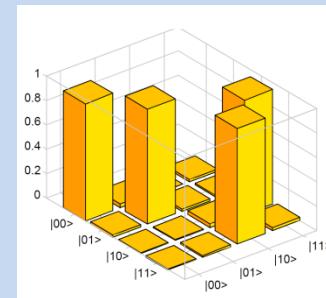
- Read out  
→ result

## Quantum computer

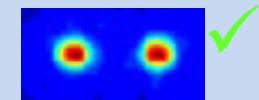
- Initialization
- 1-qubit rotations  
→ superpositions
- 2-qubit gates (CNOT gate)  
→ entanglement



Computational space:



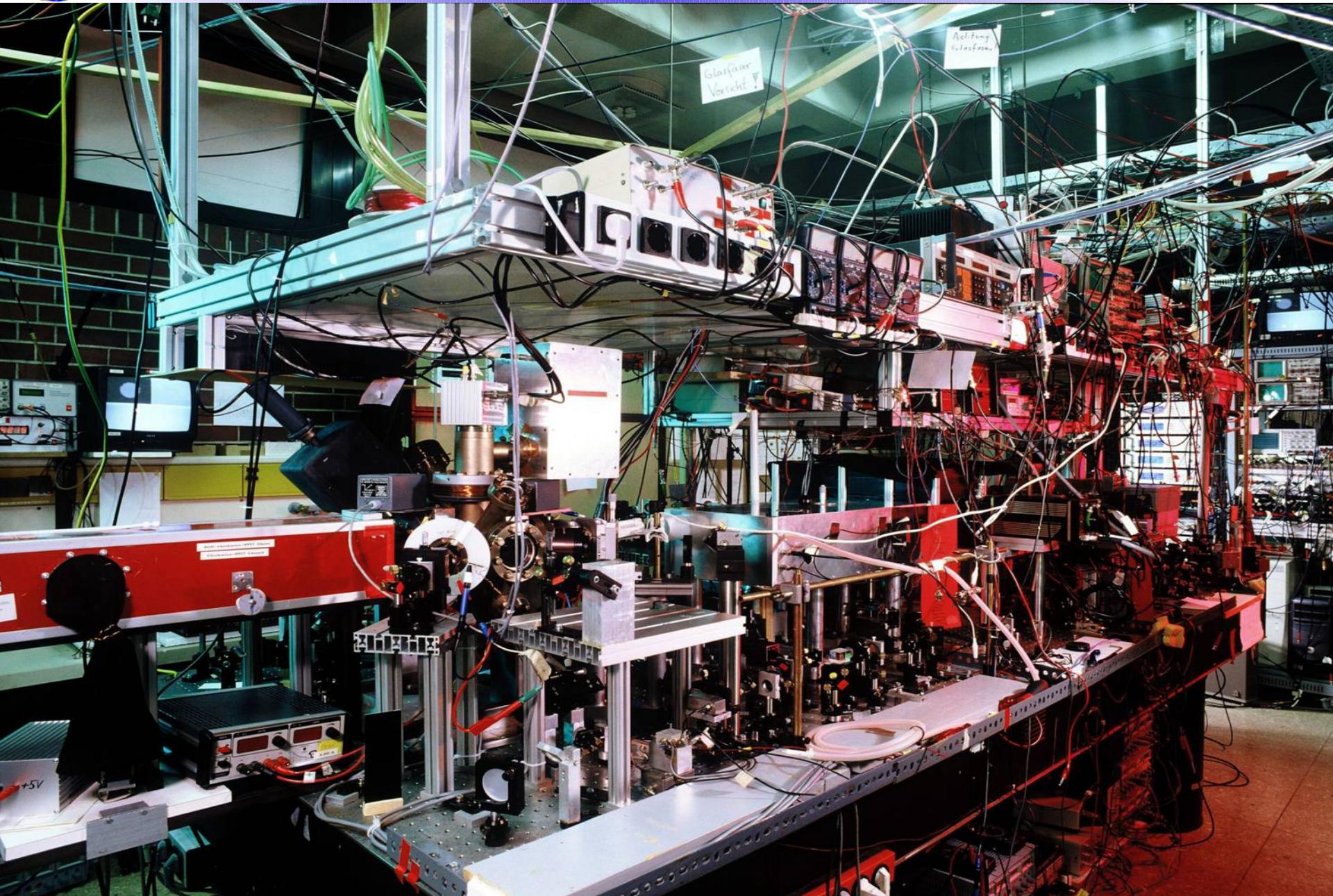
- Read out of qubits  
→ gain of classical information





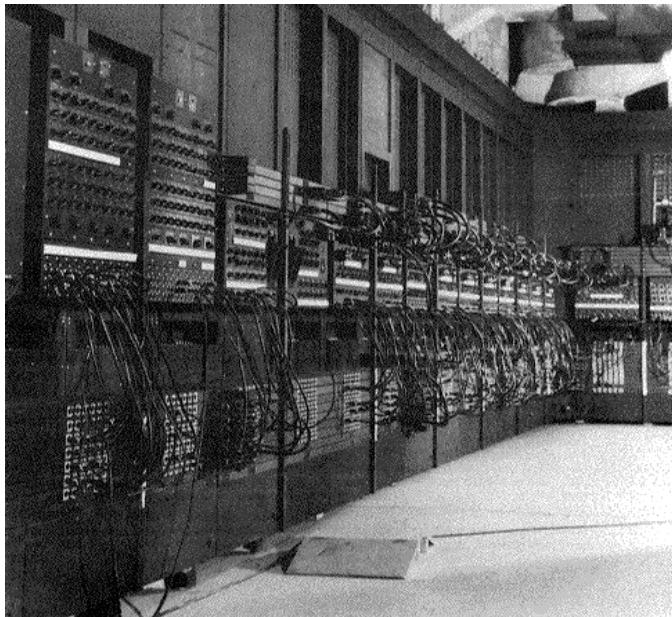
- Physics and information
- Ion trap quantum computing
- Scaling of ion trap quantum computers

# The hardware

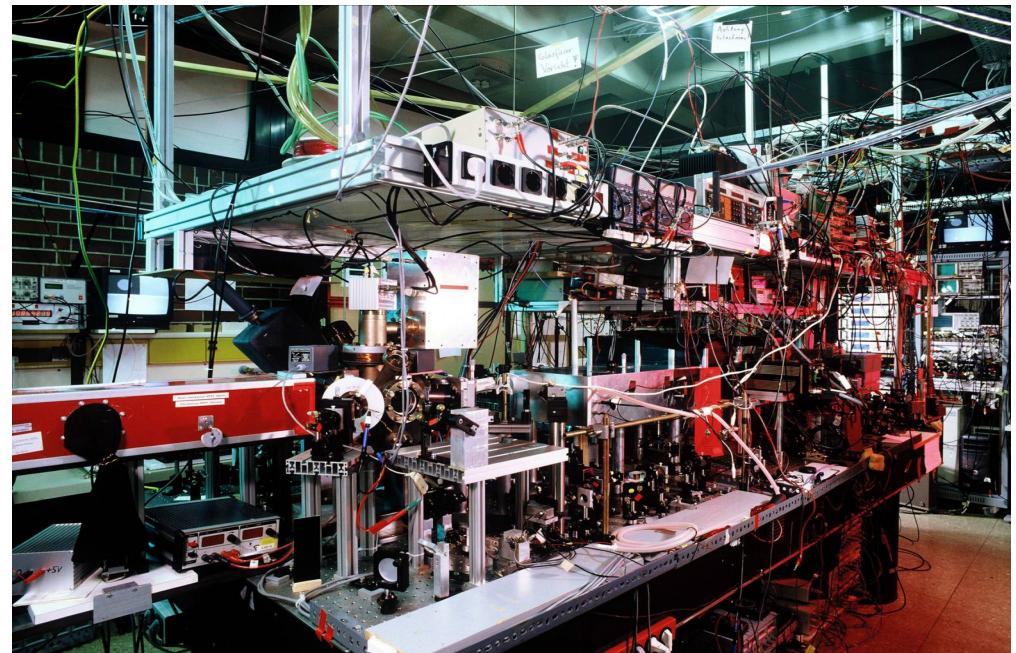




# The hardware



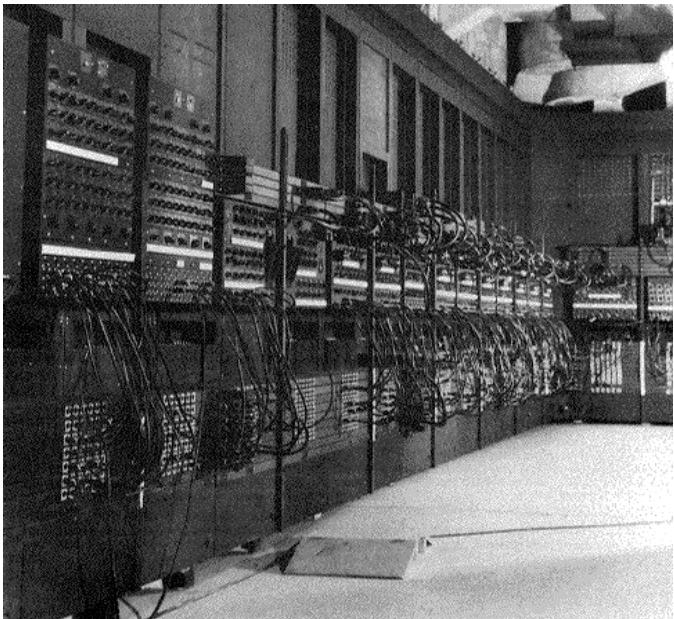
ENIAC, 1950



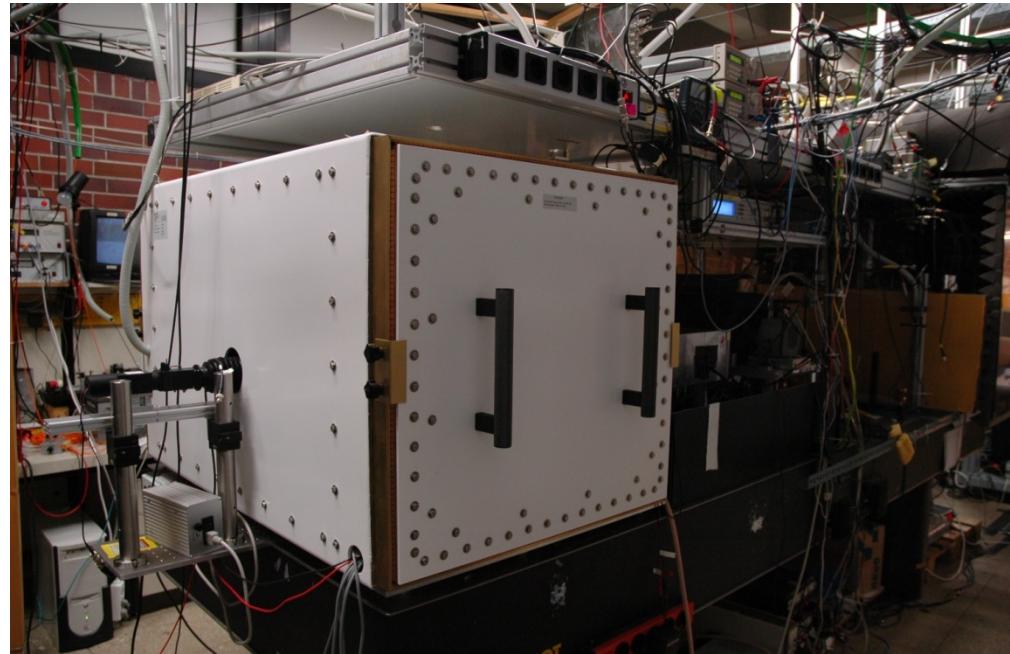
Innsbruck quantum computer, 2005



# The hardware



ENIAC, 1950



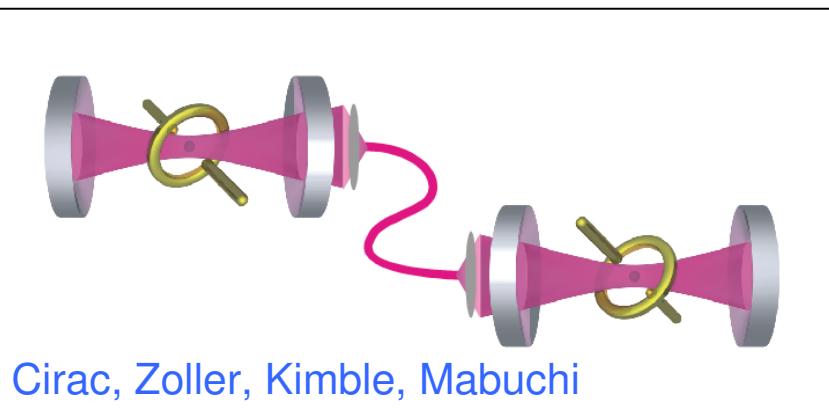
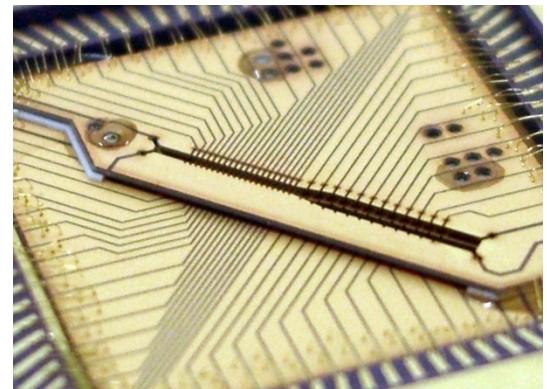
Innsbruck quantum computer, 2009



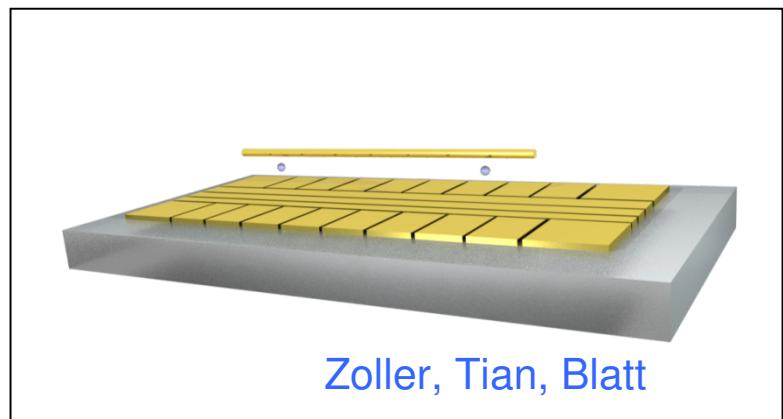
# Scaling of ion trap quantum computers



Kielpinski, Monroe, Wineland



Cirac, Zoller, Kimble, Mabuchi



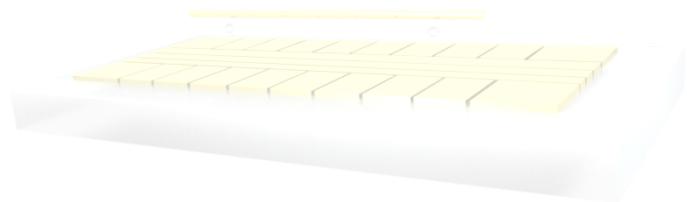
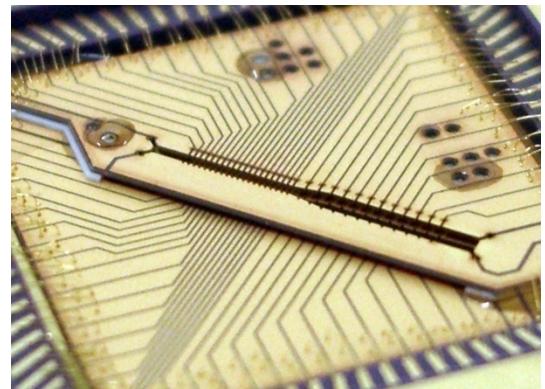
Zoller, Tian, Blatt



# Scaling of ion trap quantum computers

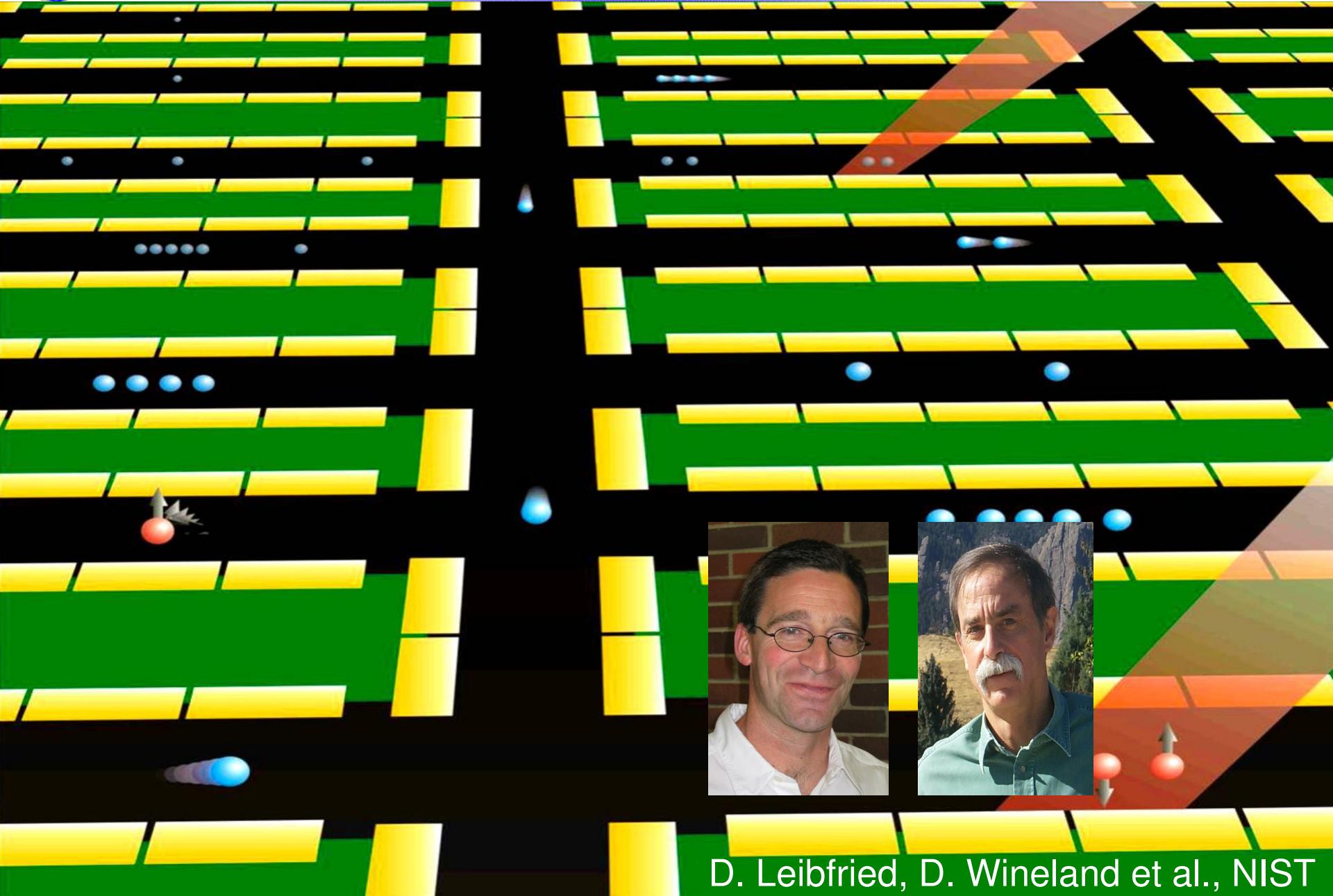


Kielpinski, Monroe, Wineland





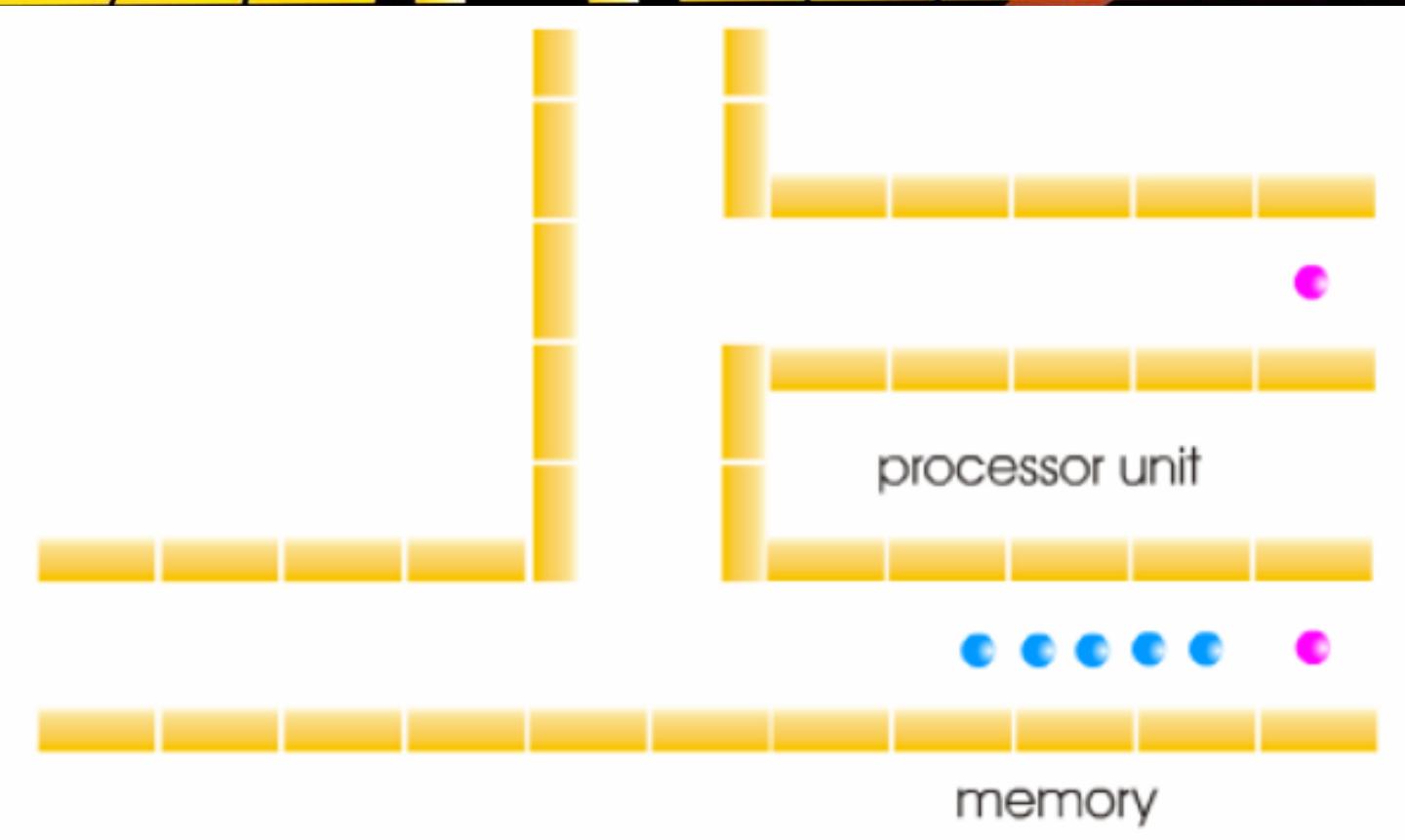
# Scaling of ion trap quantum computers



D. Leibfried, D. Wineland et al., NIST

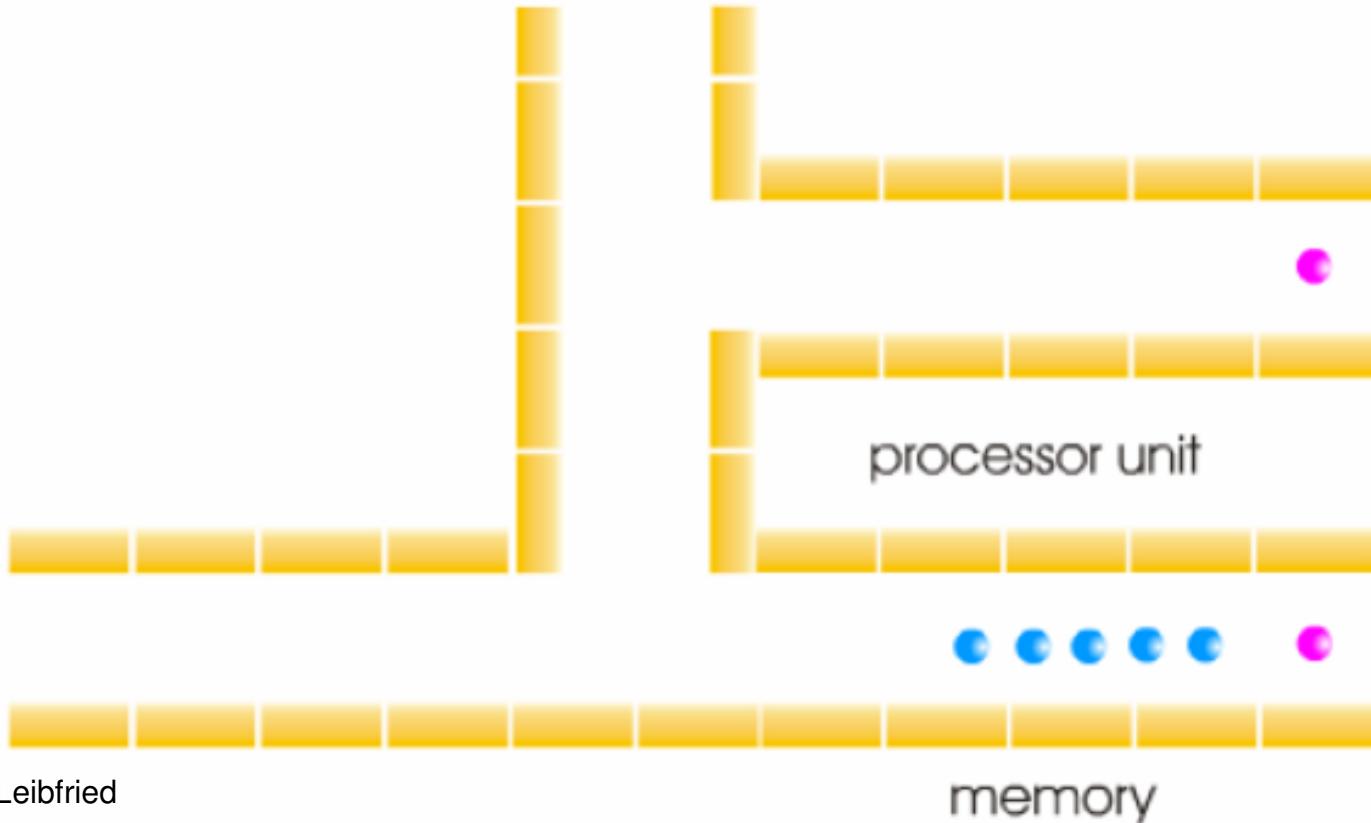


# Scaling of ion trap quantum computers



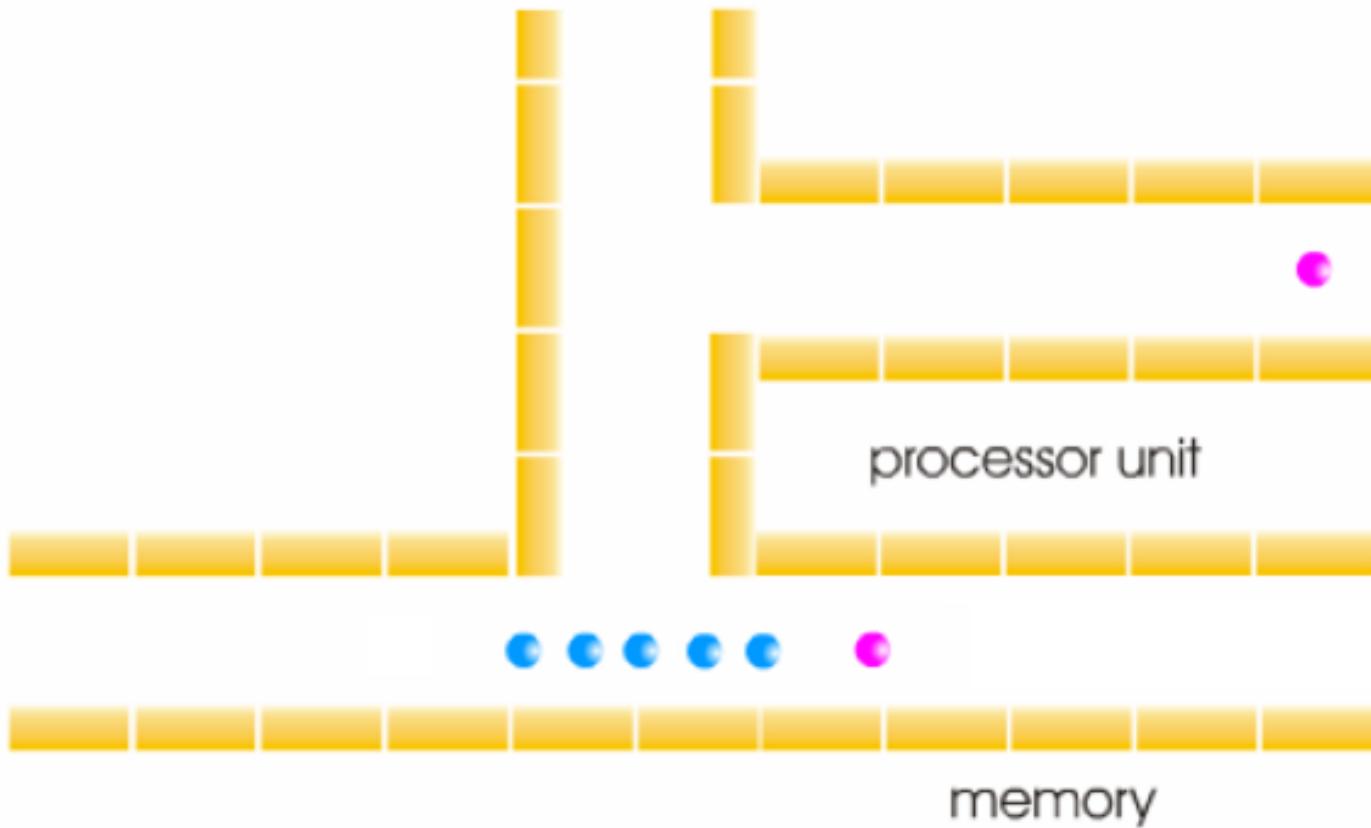


# Scaling of ion trap quantum computers



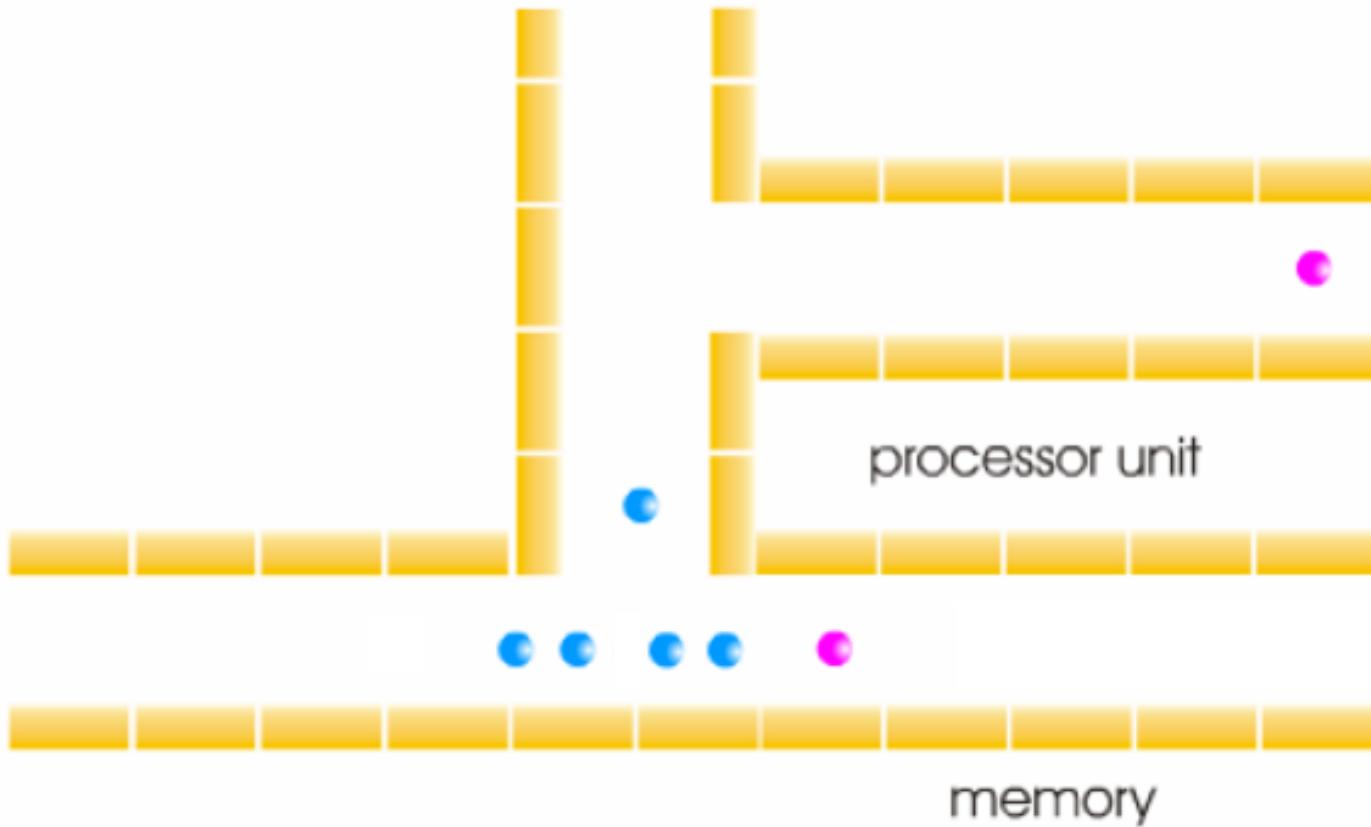


# Scaling of ion trap quantum computers



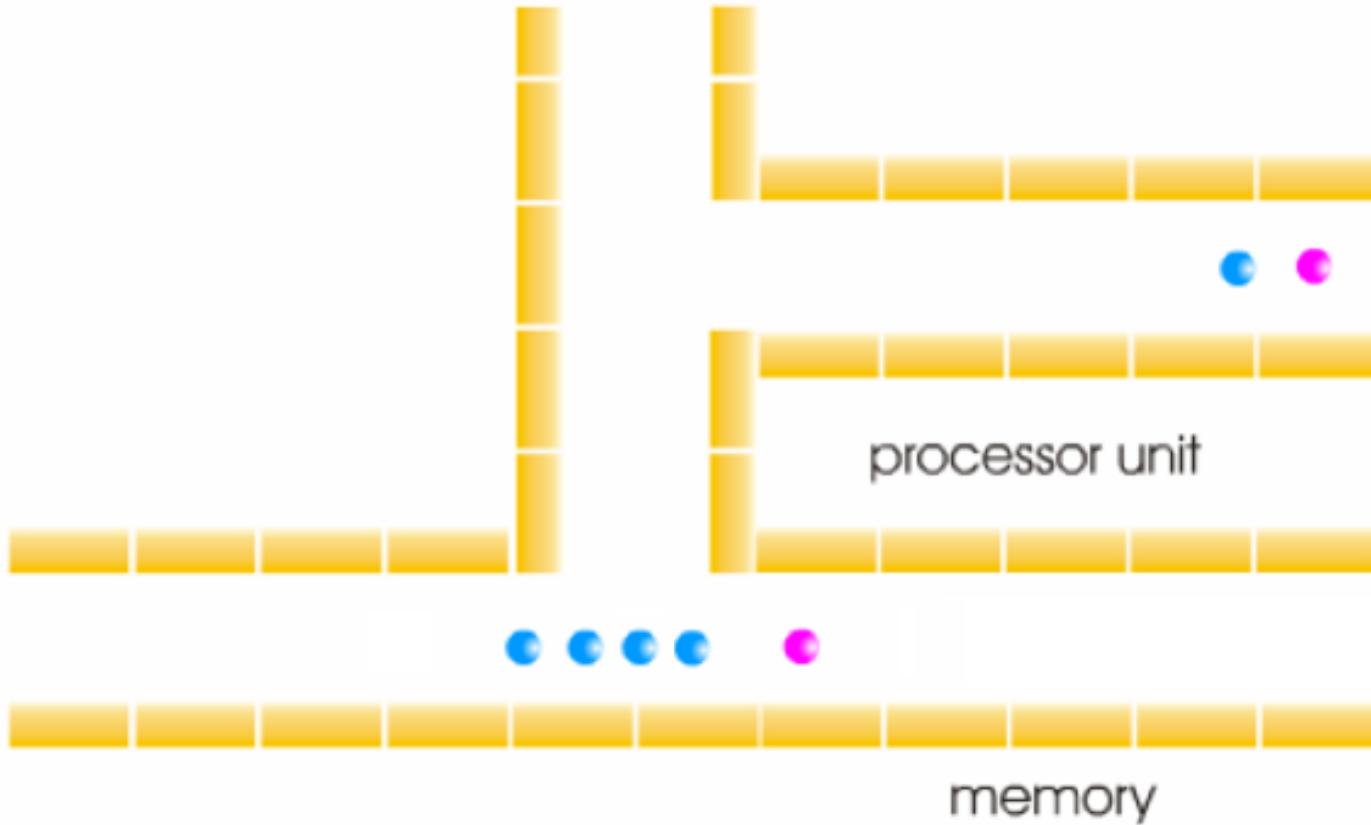


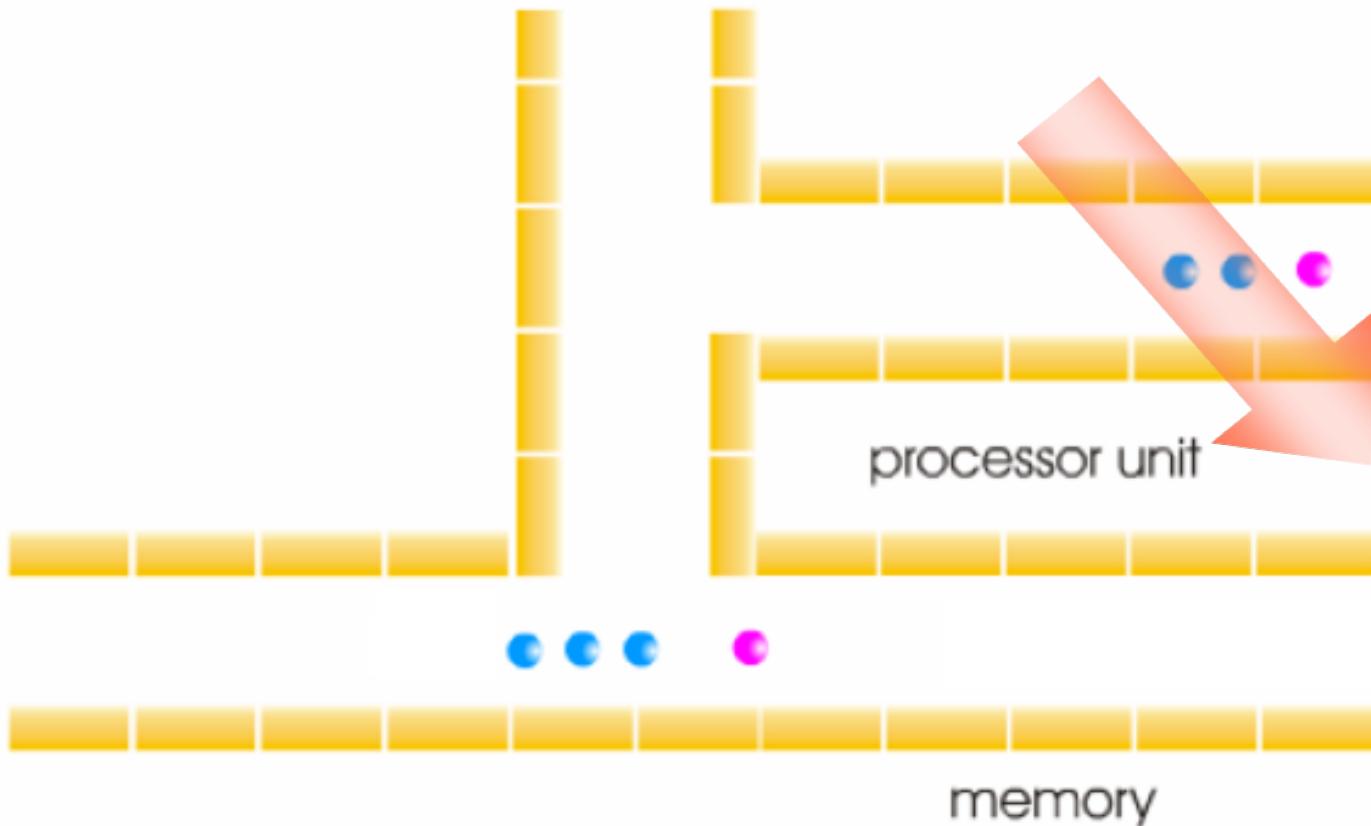
# Scaling of ion trap quantum computers





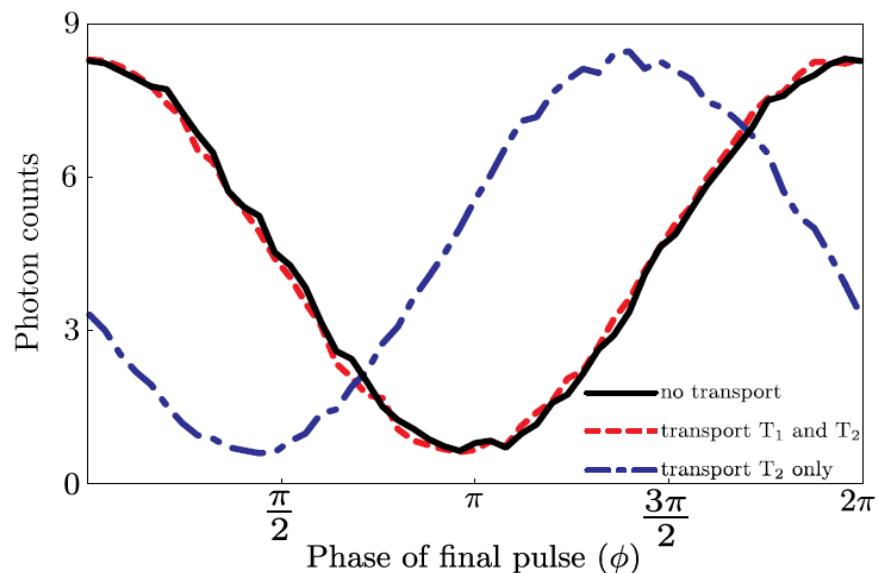
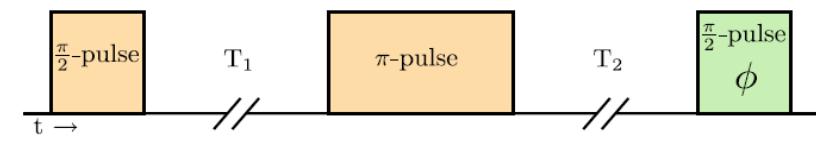
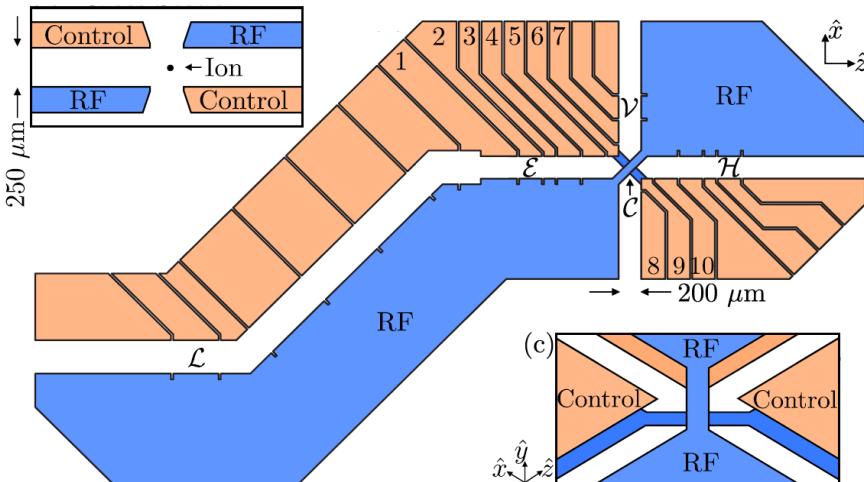
# Scaling of ion trap quantum computers





„Architecture for a large-scale ion-trap quantum computer“,  
D. Kielpinski et al., Nature **417**, 709 (2002).

# Coherent transport through a junction



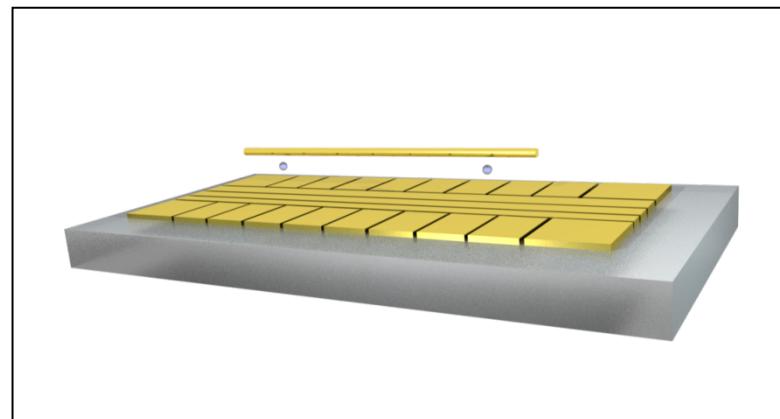
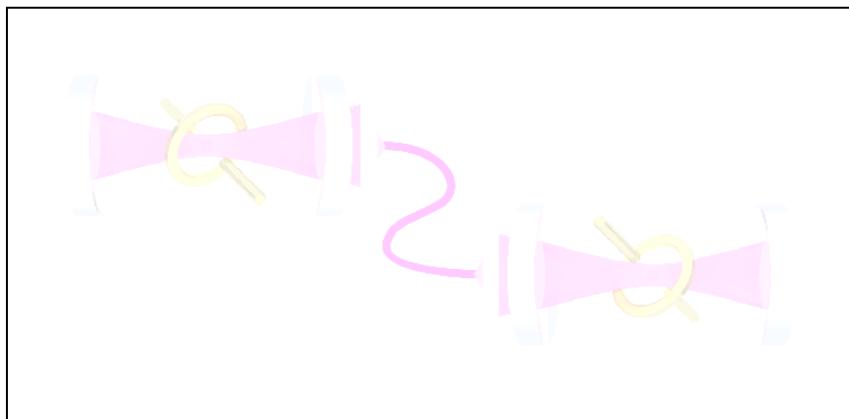
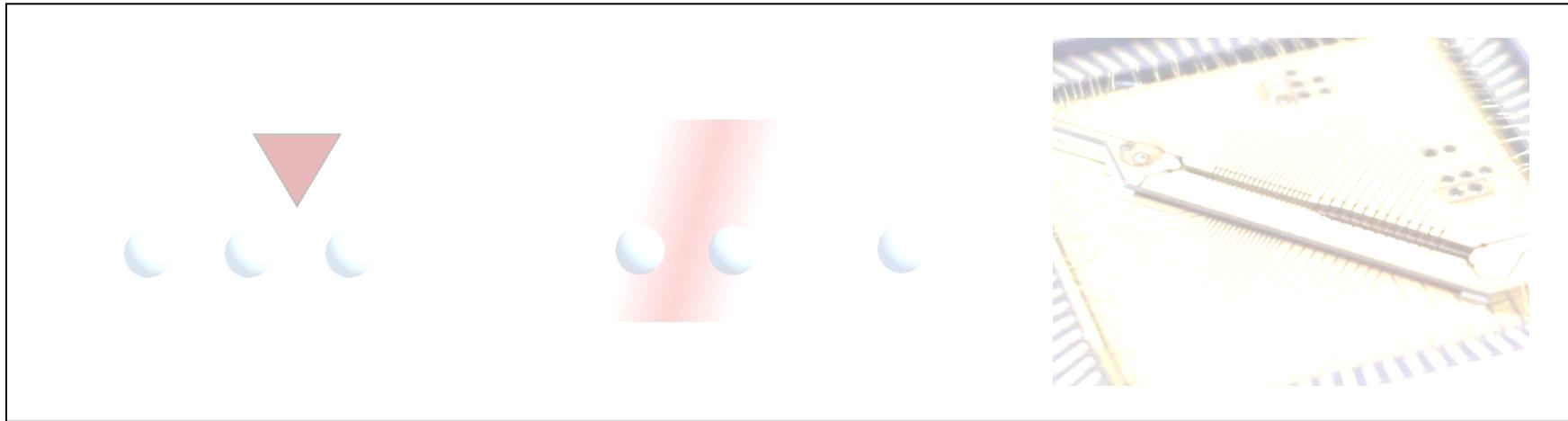
Transport	Energy Gain (recooling method) quanta/trip	
$\mathcal{E}-\mathcal{C}-\mathcal{E}$	1 ion	$3.2 \pm 1.8$
$\mathcal{E}-\mathcal{C}-\mathcal{H}-\mathcal{C}-\mathcal{E}$	1 ion	$7.9 \pm 1.5$
$\mathcal{E}-\mathcal{C}-\mathcal{V}-\mathcal{C}-\mathcal{E}$	1 ion	$14.5 \pm 2.0$
$\mathcal{E}-\mathcal{C}-\mathcal{E}$	2 ions	$5.4 \pm 1.2$
$\mathcal{E}-\mathcal{C}-\mathcal{H}-\mathcal{C}-\mathcal{E}$	2 ions	$16.6 \pm 1.8$
$\mathcal{E}-\mathcal{C}-\mathcal{V}-\mathcal{C}-\mathcal{E}$	2 ions	$53.0 \pm 1.2$

NIST:

Blakestad, et al., "High fidelity transport of trapped-ion qubits through an X-junction trap array", arXiv:0901.0533v1



# Scaling of ion trap quantum computers





# Wiring up trapped ions



Two trapped ions ...

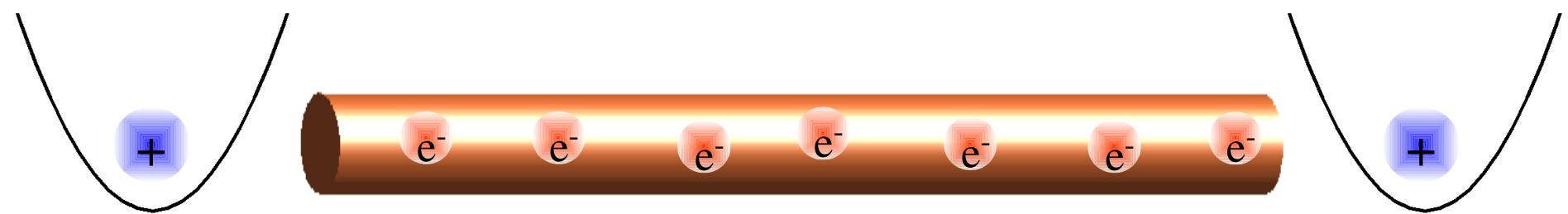




# Wiring up trapped ions

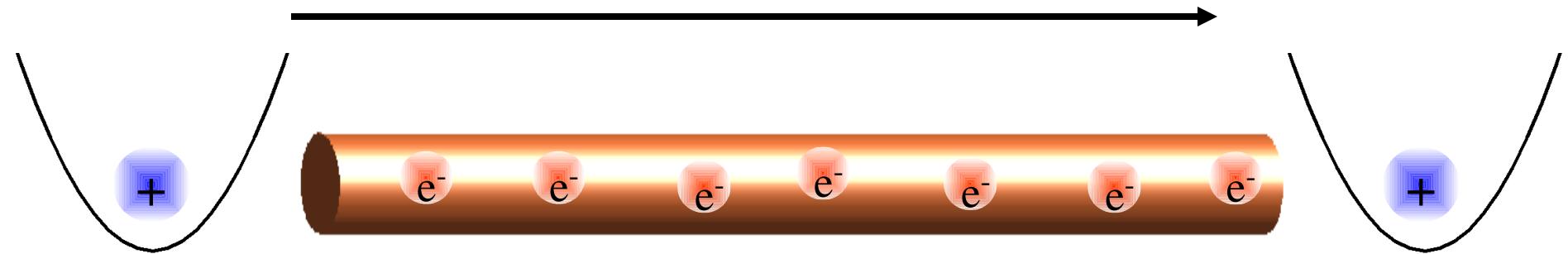


Two trapped ions + a wire

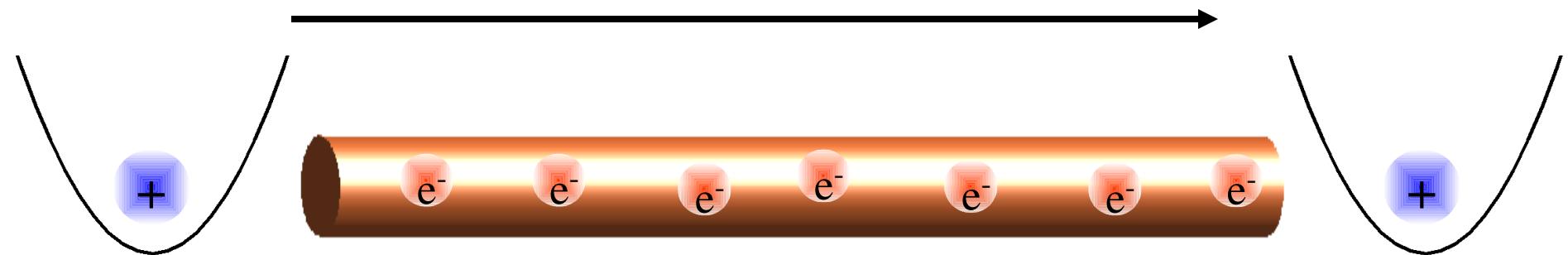


# Wiring up trapped ions

Transport of quantum information



Transport of quantum information

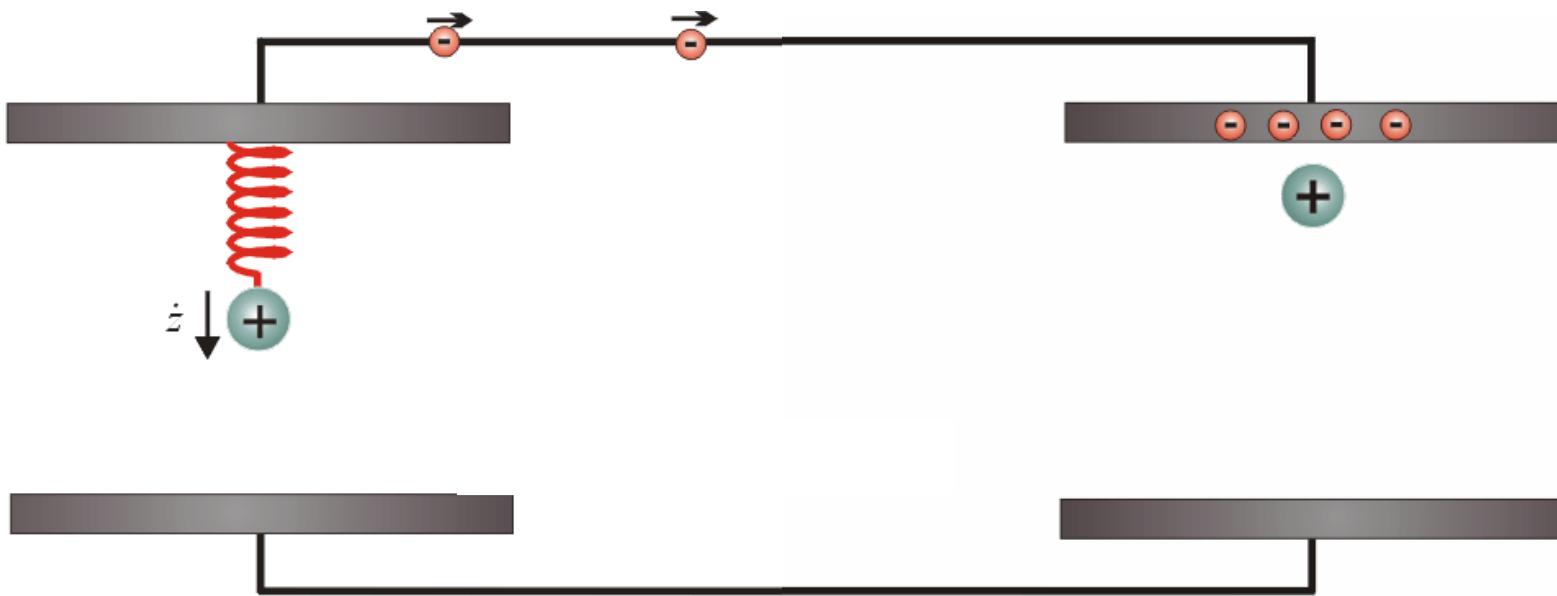


No trace of the quantum information should remain in the wire

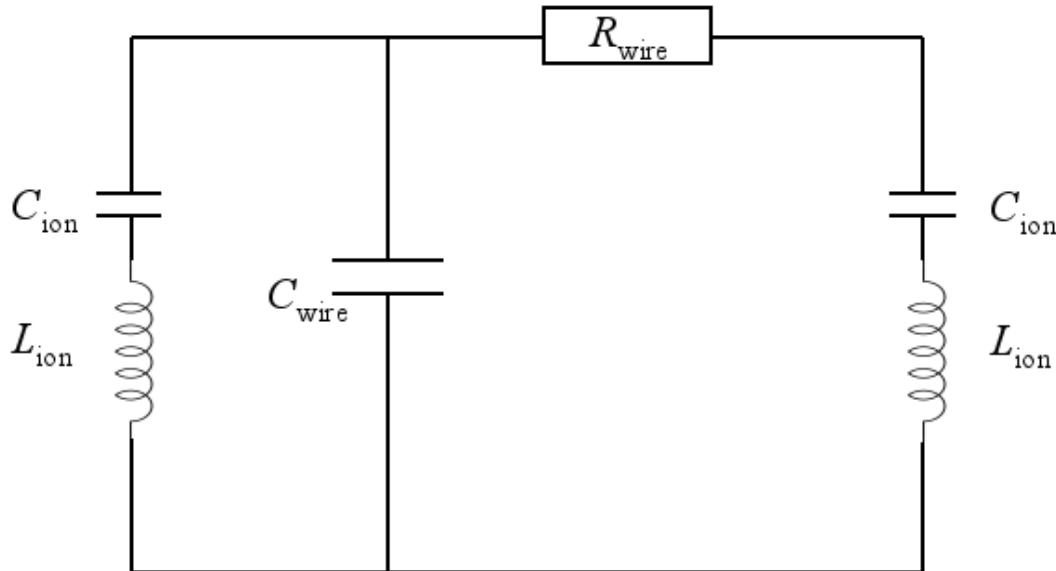
→ ~~super conducting wire~~



# Ion-ion interaction



# Coupling



with  $I = \frac{q}{D} \dot{x}$ ,  $L_{\text{ion}} = \frac{mD^2}{q^2}$ ,  $C_{\text{ion}} = \frac{1}{\omega^2 L_{\text{ion}}}$

Energy exchange rate:  $\frac{1}{T} = \frac{1}{2\pi} \frac{q^2}{mD^2} \frac{1}{\omega} \frac{1}{C_{\text{wire}}}$

D.J. Wineland and H.G. Dehmelt, J. Appl. Phys **46**, 919 (1975).

D.J. Heinzen and D.J. Wineland, PRA **47**, 2977 (1990).

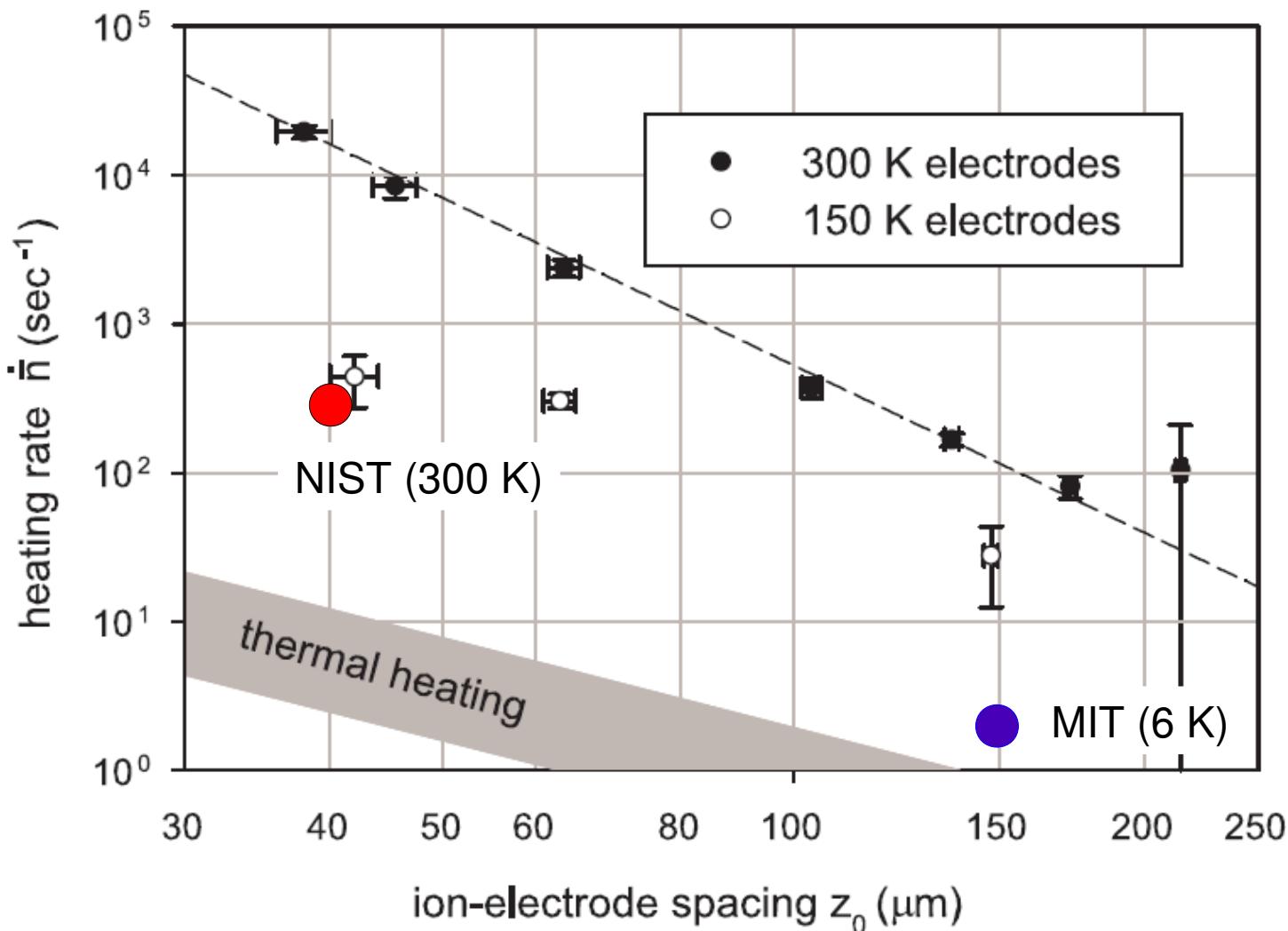
# Projected numbers

- Trap size:  $\sim 50 \mu\text{m}$ , trap distance  $500 \mu\text{m}$
- Induced current:  $\sim 10^{-16} \text{ A}$
- Coupling time:  $\sim 10 \text{ ms}$
- Wire resistivity:  $1 \Omega$

=> Time scales for decoherence:

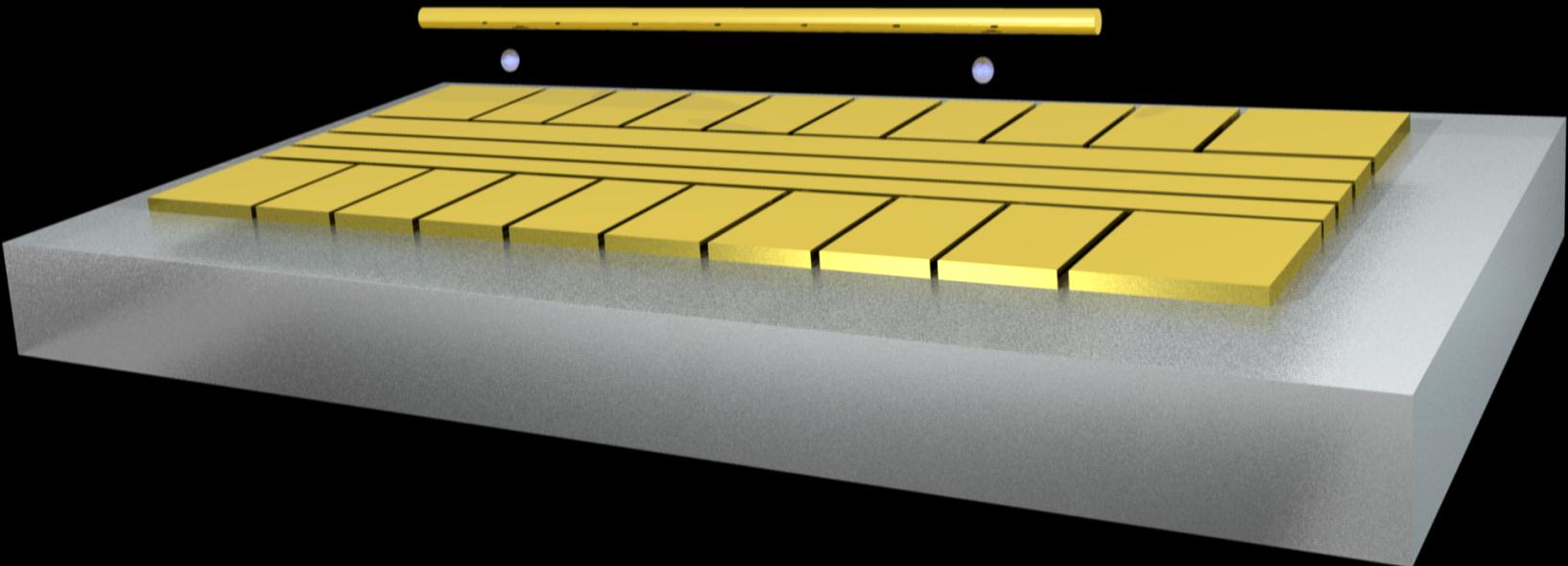
Dissipation of the induced current in the wire	$10^5 \text{ s}$
Johnson noise heating at 300 K	$100 \text{ ms}$
Anomalous heating at 300 K	???

# Anomalous heating



From: L. Deslauriers et al., PRL 97, 103007 (2006).

# Experimental set-up



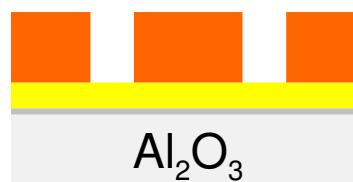
# Trap fabrication

## 1. Evaporation



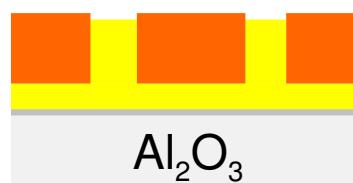
- i. 5 nm Ti adhesion layer
- ii. 100 nm Au seed layer

## 2. Lithography



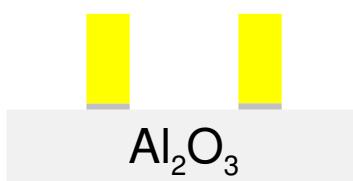
5  $\mu\text{m}$  thick photoresist

## 3. Electroplating



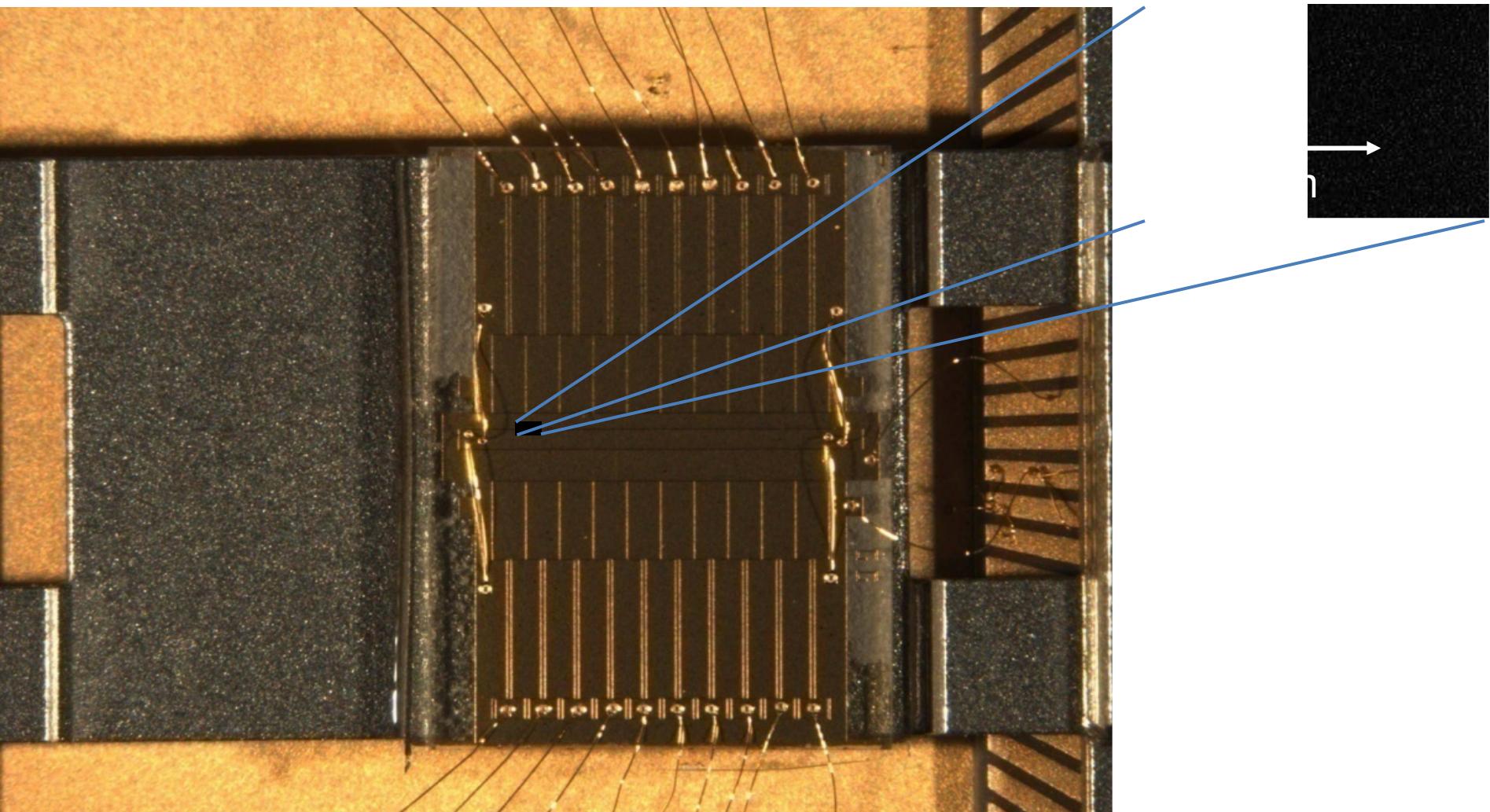
4-5  $\mu\text{m}$  thick Au plated layer

## 4. Cleaning/Etching



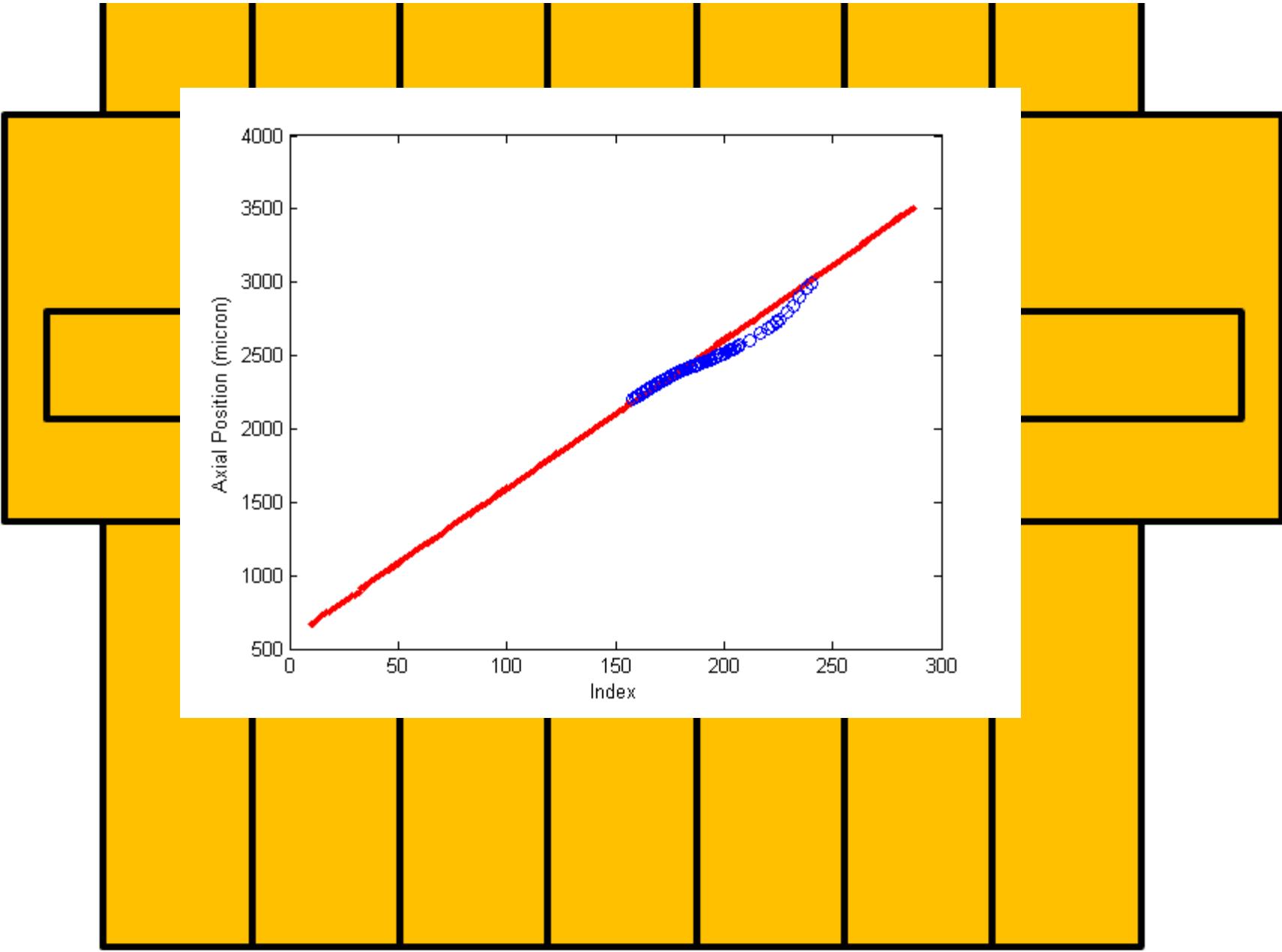
- i. Resist removal
- ii. Au etch
- iii. Ti etch

# Experimental set-up

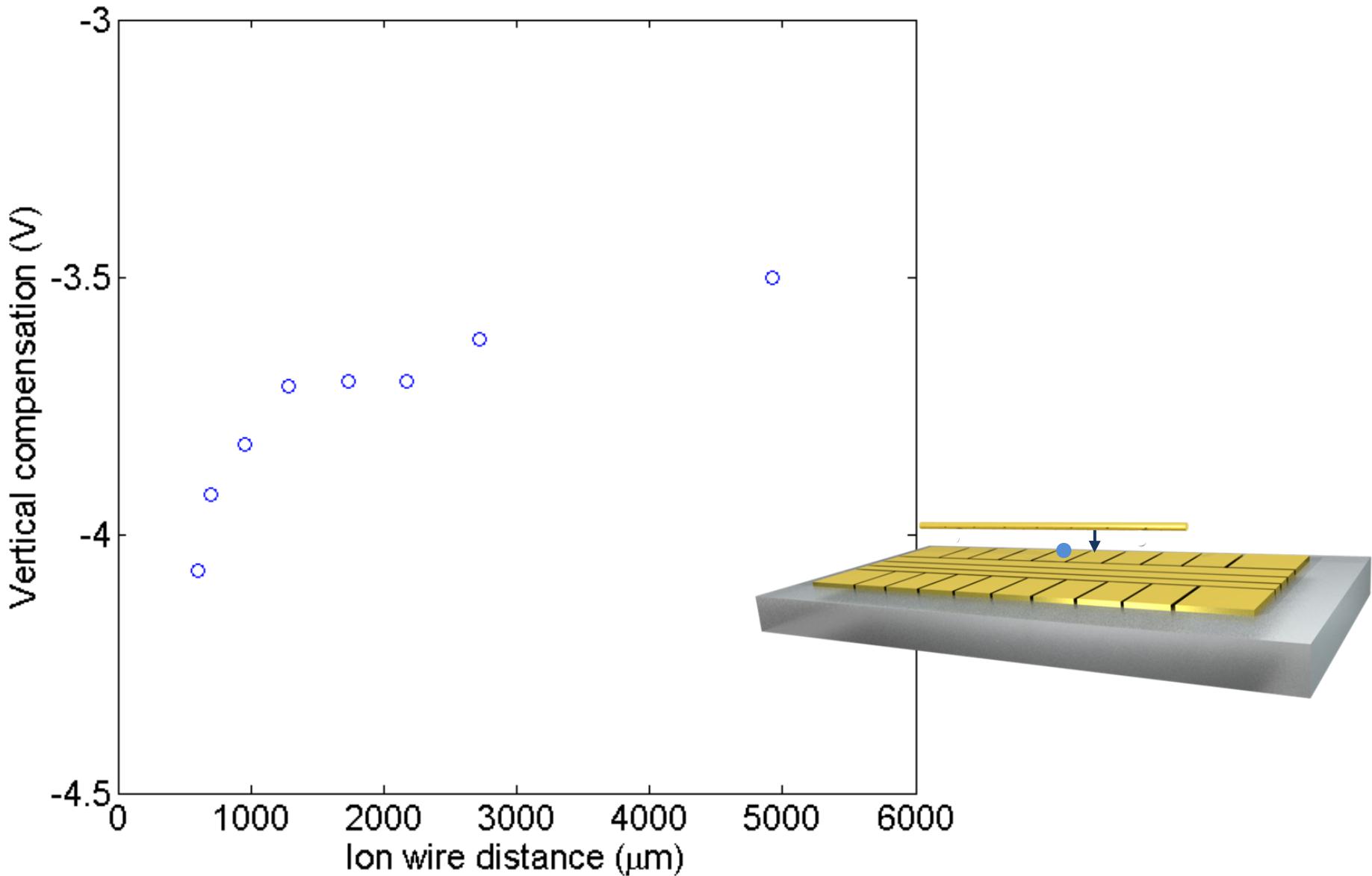




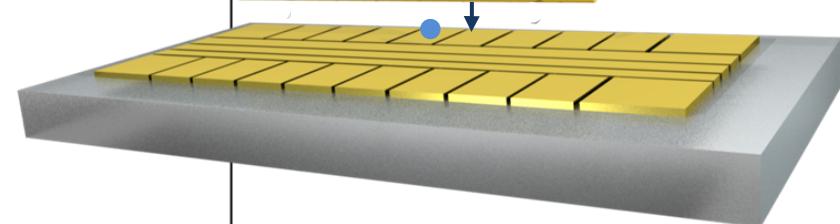
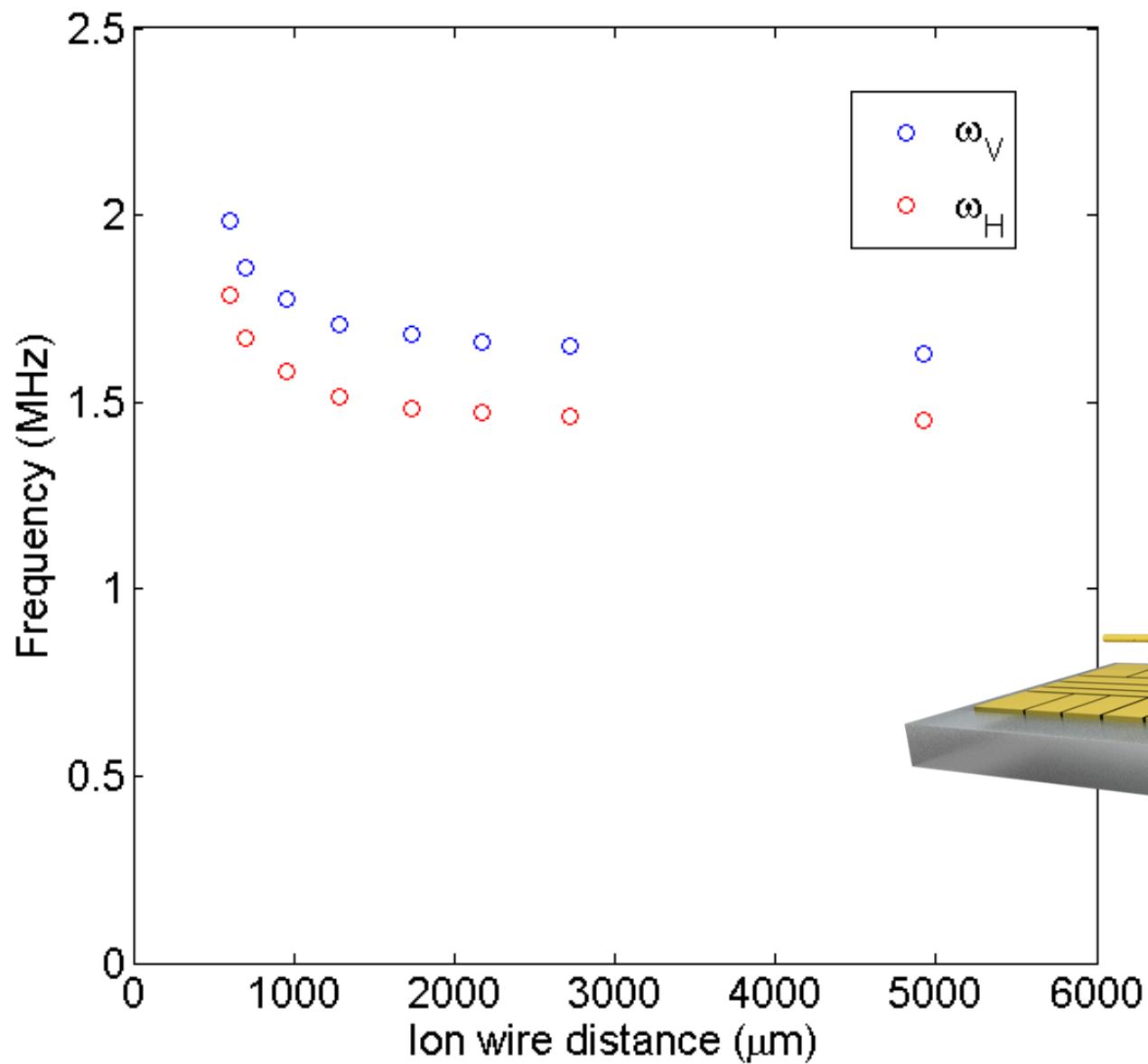
# Ion transport

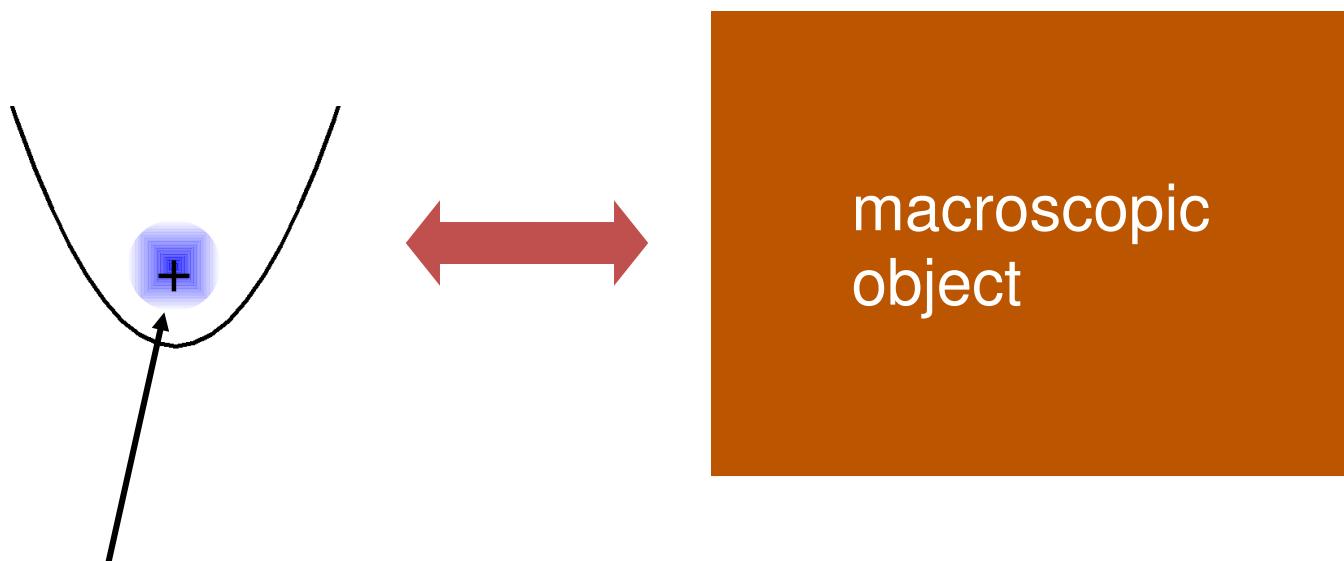


## Moving the wire closer



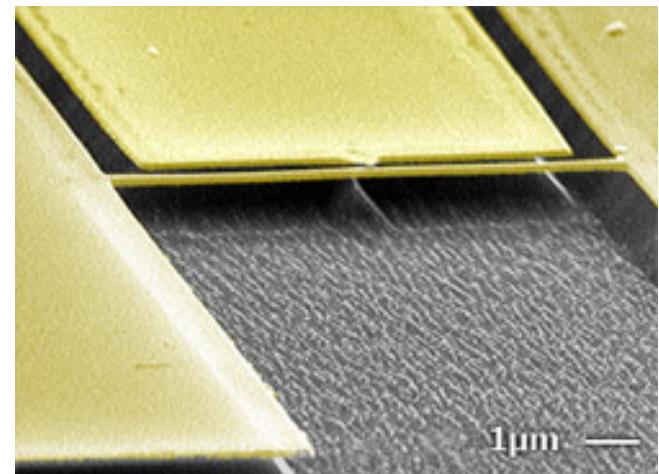
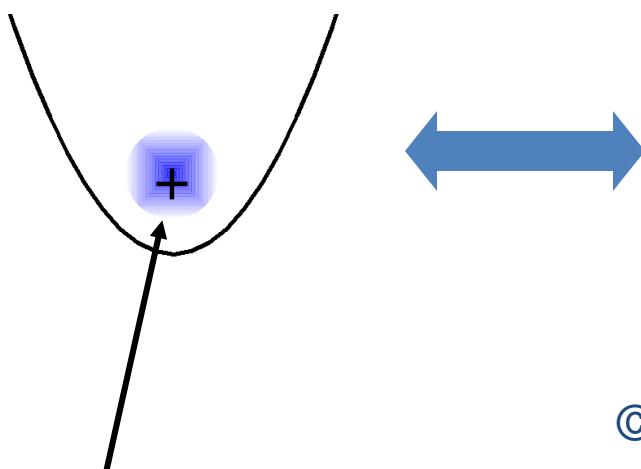
## Moving the wire in





Quantum sensor

Ultimate control and detection



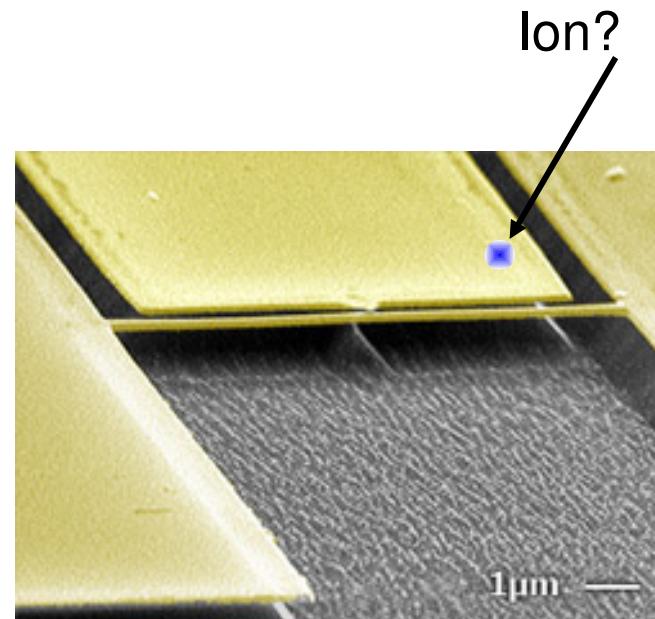
© Nathan Flowers Jacobs, JILA

Quantum sensor

Ultimate control and detection



# Quantum sensors

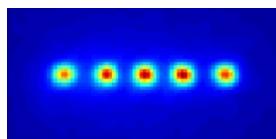


© Nathan Flowers Jacobs, JILA

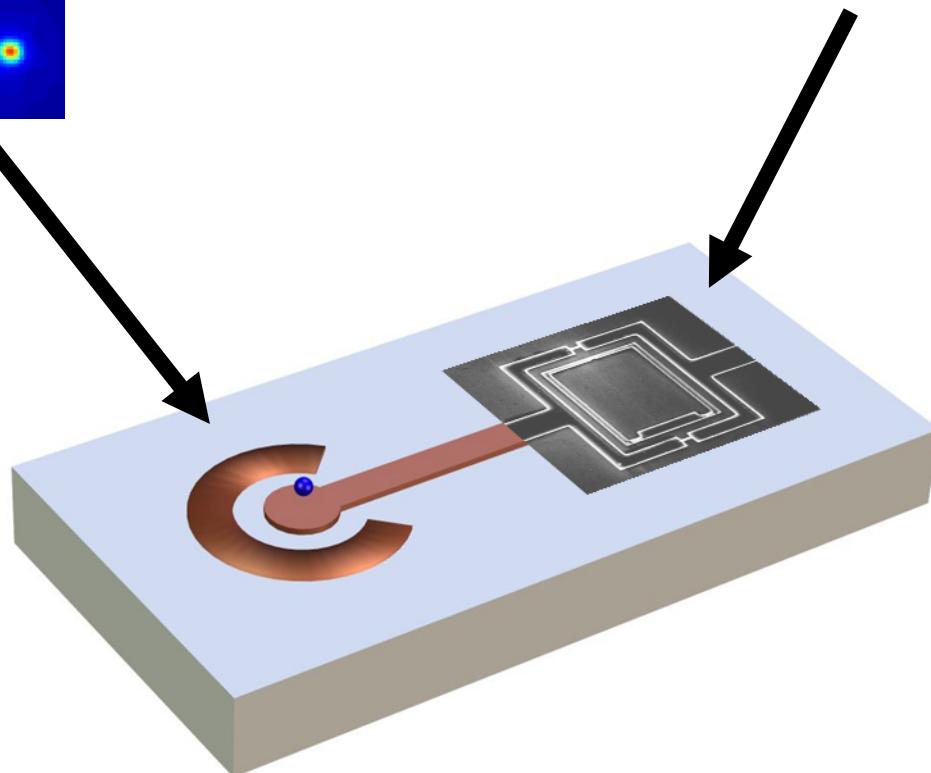
See: L. Tian, P. Zoller, PRL 93, 266403 (2004).  
W. K. Hensinger, PRA 72, 041405R (2005).

# Hybrid devices

Trapped ions

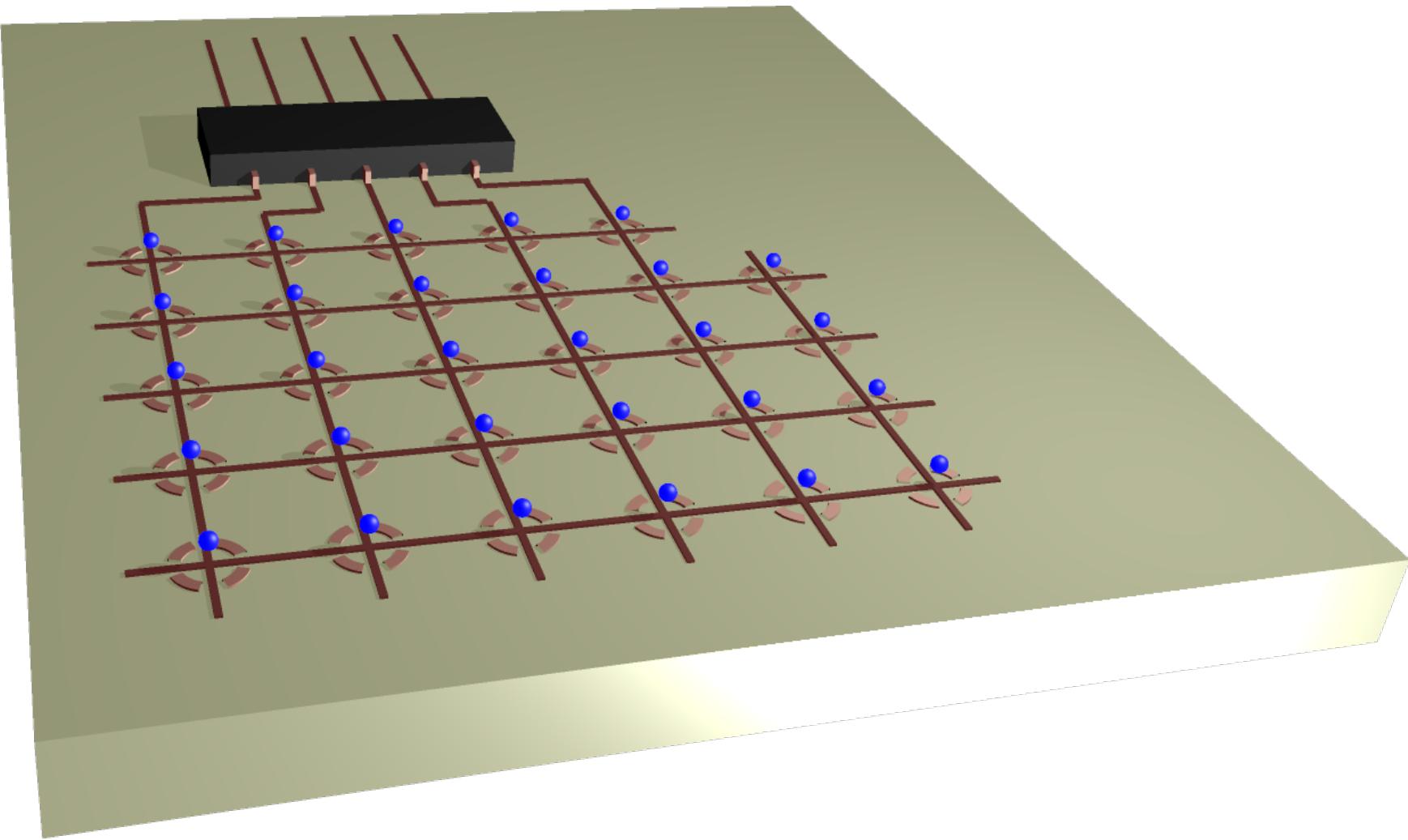


Josephson qubits



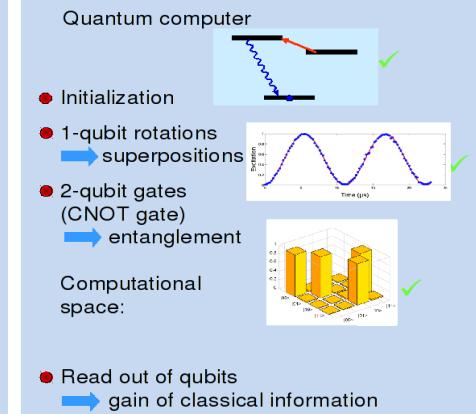
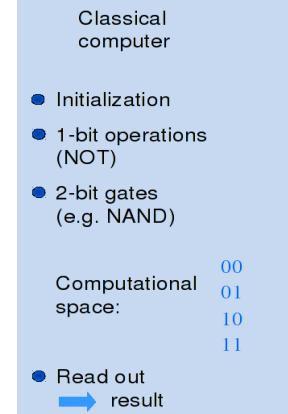
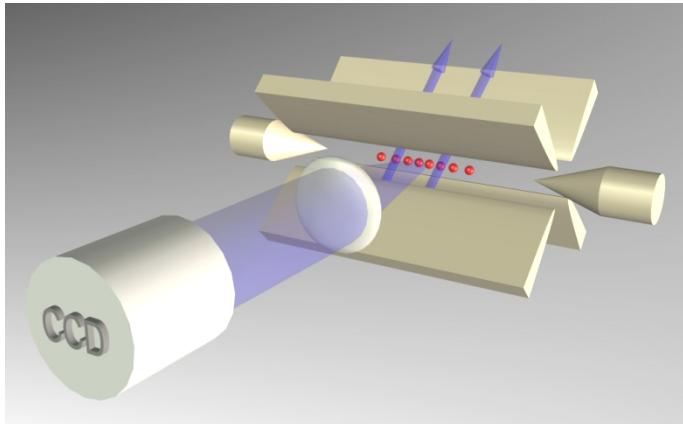


# A vision



# Conclusions

## Ion trap quantum computing



## Scaling of ion traps

