AG Quantenoptik und Spektroskopie

Quantum computing with trapped ions

Hartmut Häffner

Institute for Quantum Optics and Quantum Information, Innsbruck and *Department of Physics, University of California, Berkeley, USA*

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

€ FWF SFB · SCALA QGATES · Industrie Tirol · IQI GmbH

FWF · bm:bwk · $ IARPA

Innsbruck, May 19th 2009

Physics and information

Information is physical (Rolf Landauer, 1961)

Erasing information generates heat:

0101001101 ➡ 0000000000 + entropy

Physics and information

Physical process

Equivalence ?

Algorithm

Physics and information

Information is physical (Rolf Landauer, 1961)

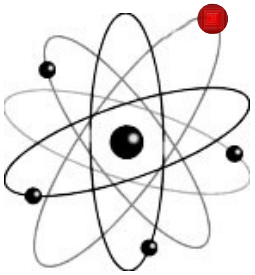
➡ Information is quantum mechanical

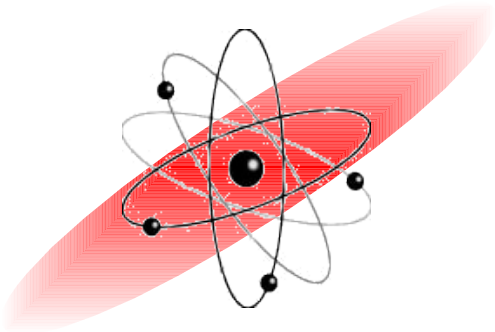
Classical information is a subset in quantum information

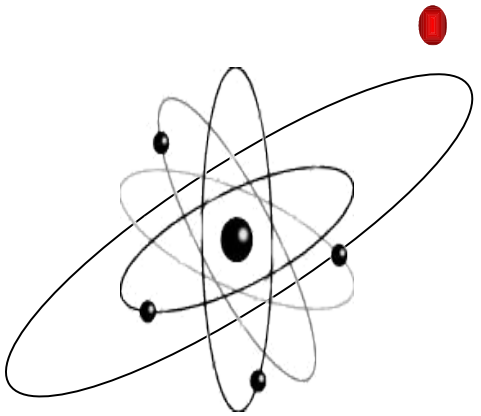
Quantum information: strip down quantum mechanics to bare bones.

- Hilbert space
- unitary operations
- measurement

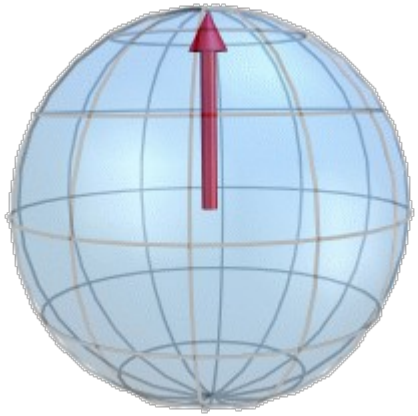
Qubits

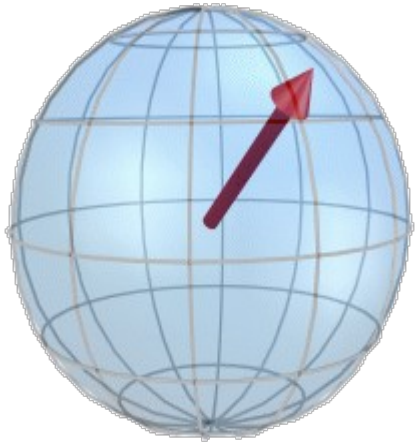


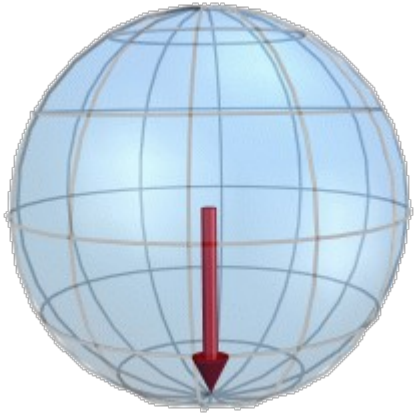




$|0\rangle$ $\alpha|0\rangle + \beta|1\rangle$ $|1\rangle$







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 + 0.0204i 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 0.0309 + 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 + 0.0969i 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 0.0888 + 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 0.1078 + 0.0756i 0.0229 + 0.0099i 0.0537 + 0.0458i 0.0313 + 0.0405i 0.0725 + 0.0179i 0.1033 + 0.0898i 0.0827 + 0.0904i 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 + 0.0330i 0.0013 + 0.0121i 0.0245 + 0.0478i 0.0557 + 0.0503i 0.0494 + 0.0016i 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 + 0.0086i 0.0514 + 0.0436i 0.0240 + 0.0747i 0.0236 + 0.0018i 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 0.0678 + 0.0307i 0.0578 + 0.0276i 0.0293 + 0.0220i 0.0559 + 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 0.0222 + 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 + 0.0566i 0.0166 + 0.0414i 0.0141 + 0.0213i 0.0059 + 0.0284i 0.0006 + 0.0010i 0.0608 + 0.0685i 0.0014 + 0.0667i 0.0677 + 0.0196i 0.0272 + 0.0439i 0.0557 + 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 + 0.0118i 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 0.0715 + 0.0002i 0.0301 + 0.0609i 0.0394 + 0.0396i 0.0072 + 0.0164i 0.0017 + 0.0080i 0.0123 + 0.0121i 0.0651 + 0.0314i 0.0678 + 0.0314i 0.0144 + 0.0041i 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 + 0.0317i 0.0707 + 0.0308i 0.0095 + 0.0390i 0.0010 + 0.0130i 0.0285 + 0.0404i 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 + 0.0064i 0.0306 + 0.0633i 0.0501 + 0.0149i 0.0066 + 0.0343i 0.0593 + 0.0010i 0.0747 + 0.0238i 0.0551 + 0.0675i

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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 0.0309 + 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 + 0.0969i 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 0.0888 + 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 0.1078 + 0.0756i 0.0229 + 0.0099i 0.0537 + 0.0458i 0.0313 + 0.0405i 0.0725 + 0.0179i 0.1033 + 0.0898i 0.0827 + 0.0904i 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 + 0.0330i 0.0013 + 0.0121i 0.0245 + 0.0478i 0.0557 + 0.0503i 0.0494 + 0.0016i 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 + 0.0086i 0.0514 + 0.0436i 0.0240 + 0.0747i 0.0236 + 0.0018i 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 0.0678 + 0.0307i 0.0578 + 0.0276i 0.0293 + 0.0220i 0.0559 + 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 0.0222 + 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 + 0.0566i 0.0166 + 0.0414i 0.0141 + 0.0213i 0.0059 + 0.0284i 0.0006 + 0.0010i 0.0608 + 0.0685i 0.0014 + 0.0667i 0.0677 + 0.0196i 0.0272 + 0.0439i 0.0557 + 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 + 0.0118i 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 0.0715 + 0.0002i 0.0301 + 0.0609i 0.0394 + 0.0396i 0.0072 + 0.0164i 0.0017 + 0.0080i 0.0123 + 0.0121i 0.0651 + 0.0314i 0.0678 + 0.0314i 0.0144 + 0.0041i 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 + 0.0317i 0.0707 + 0.0308i 0.0095 + 0.0390i 0.0010 + 0.0130i 0.0285 + 0.0404i 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 + 0.0064i 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 0.0618 + 0.0393i 0.0515 + 0.0550i 0.0517 + 0.0397i 0.0633 + 0.0467i 0.0748 + 0.0745i 0.0375 + 0.0634i 0.0630 + 0.0245i 0.0494 + 0.0453i 0.0236 + 0.0100i 0.0509 + 0.0196i 0.0276 + 0.0619i 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 0.0124 + 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 + 0.0668i 0.0724 + 0.0764i 0.0642 + 0.0388i 0.0362 + 0.0485i 0.0485 + 0.0611i 0.0045 + 0.0346i 0.0418 + 0.0404i 0.0351 + 0.0132i 0.0665 + 0.0101i 0.0659 + 0.0169i 0.0364 + 0.0081i 0.0607 + 0.0109i 0.0506 + 0.0352i 0.0000 + 0.0607i 0.0101 + 0.0217i 0.0381 + 0.0173i 0.0030 + 0.0701i 0.0175 + 0.0006i 0.0253 + 0.0454i 0.0693 + 0.0418i 0.0242 + 0.0504i 0.0194 + 0.0242i 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 + 0.0711i 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 + 0.0728i 0.0038 + 0.0646i

Information content

40 qubits	10 000 GigaByte
1 additional qubit	Double the memory
300 qubits	Every atom in the Universe would have to hold one classical bit

Why quantum information ?

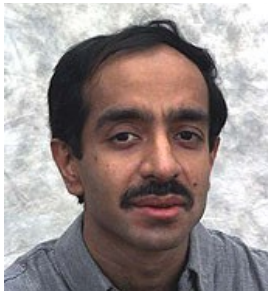
Schrödinger equation for 300 interacting spins.

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

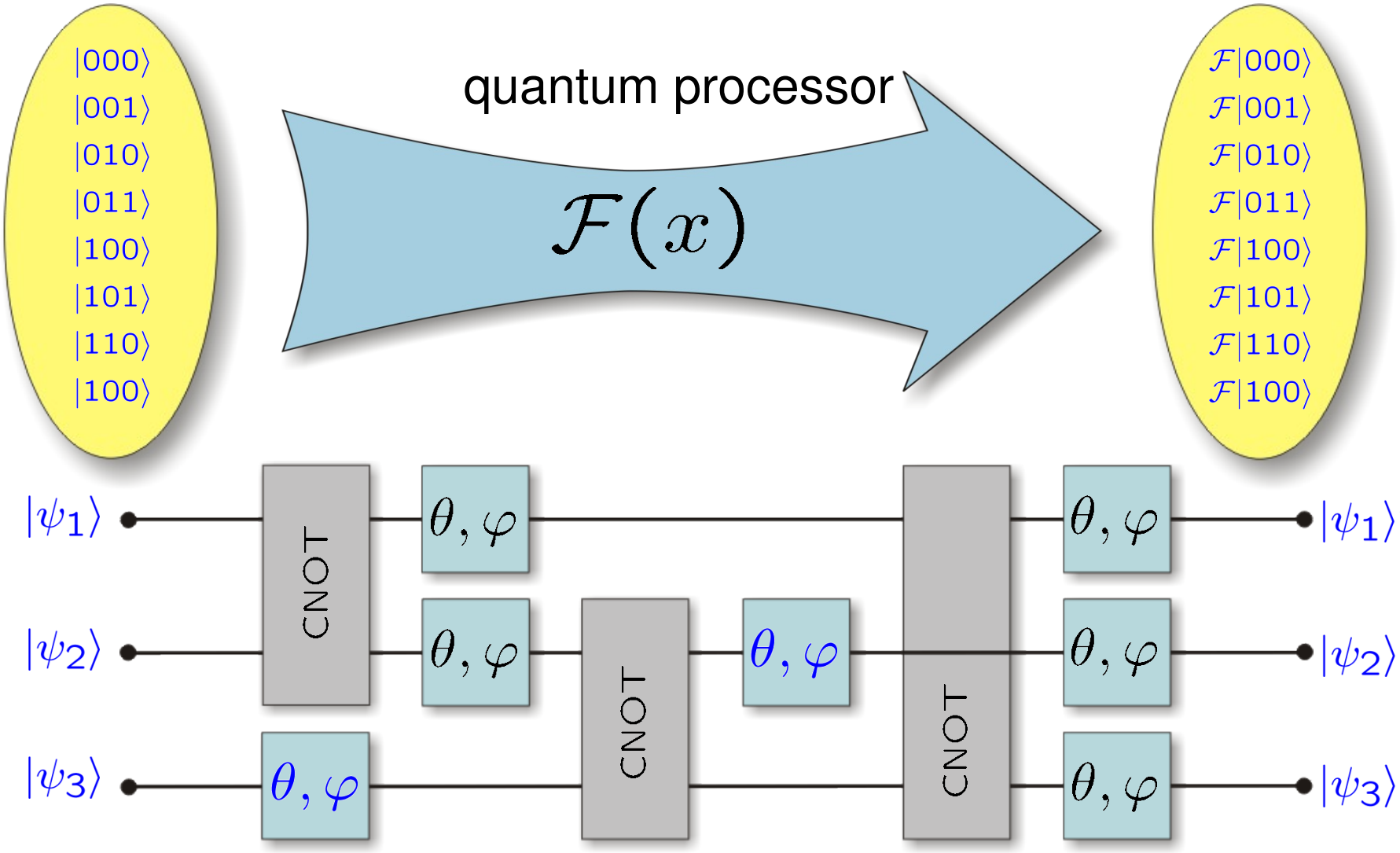
Quantum computer

- 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

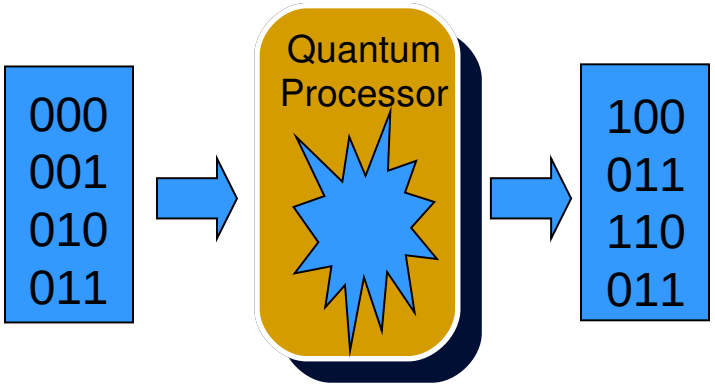
Quantum computing



Input ➡ computation: sequence of quantum gates ➡ output

Quantum computing

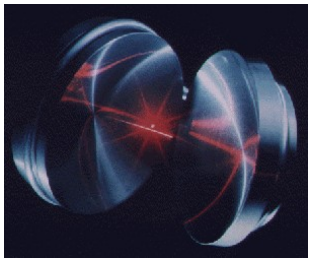
Long term goal: A universal quantum computer



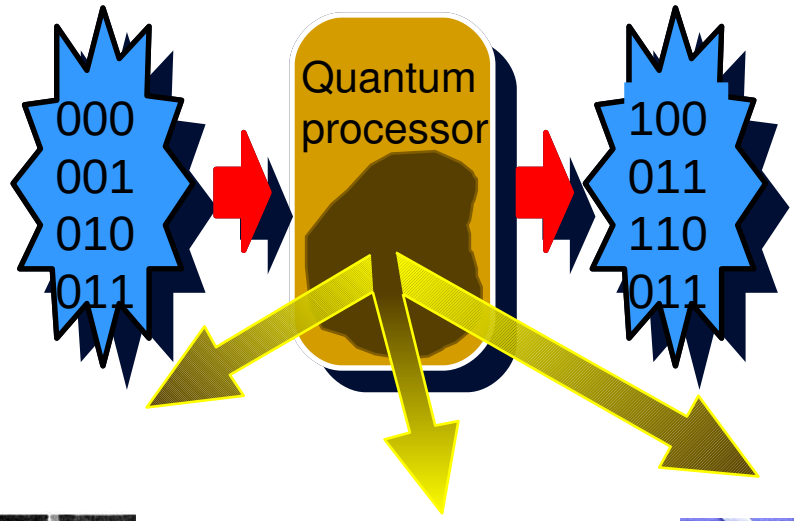
In the mean time:

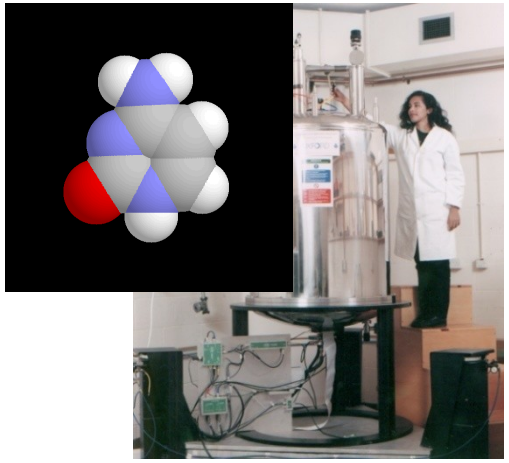
- “understand” quantum mechanics
- apply quantum mechanics
- where does quantum mechanics fail?

Which technology ?

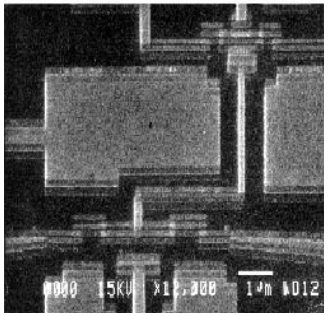


Cavity QED

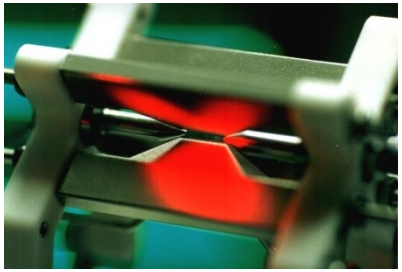


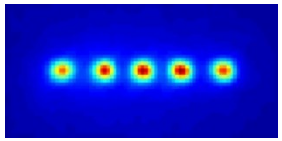


NMR

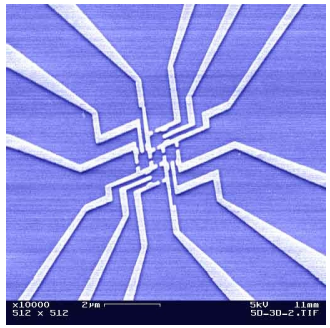


Superconducting qubits





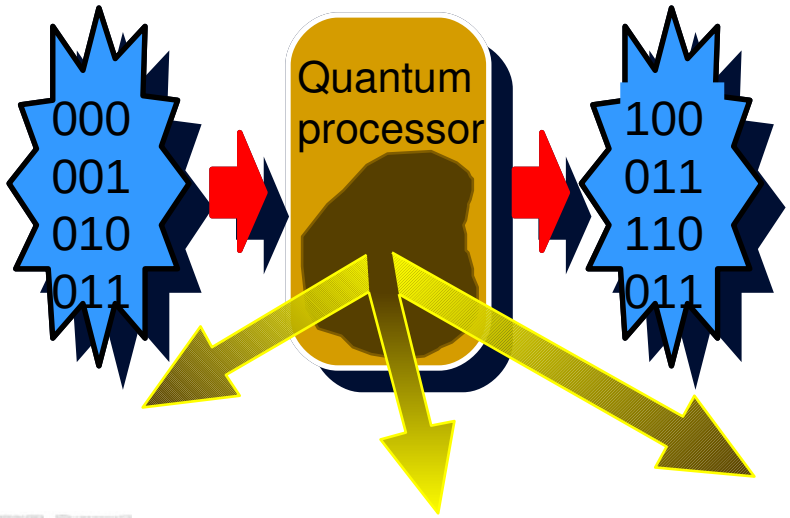
Trapped ions



Quantum dots

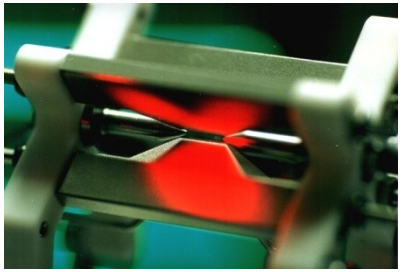
Which technology ?

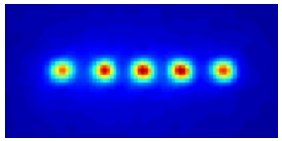
Cavity QED



NMR

Superconducting qubits



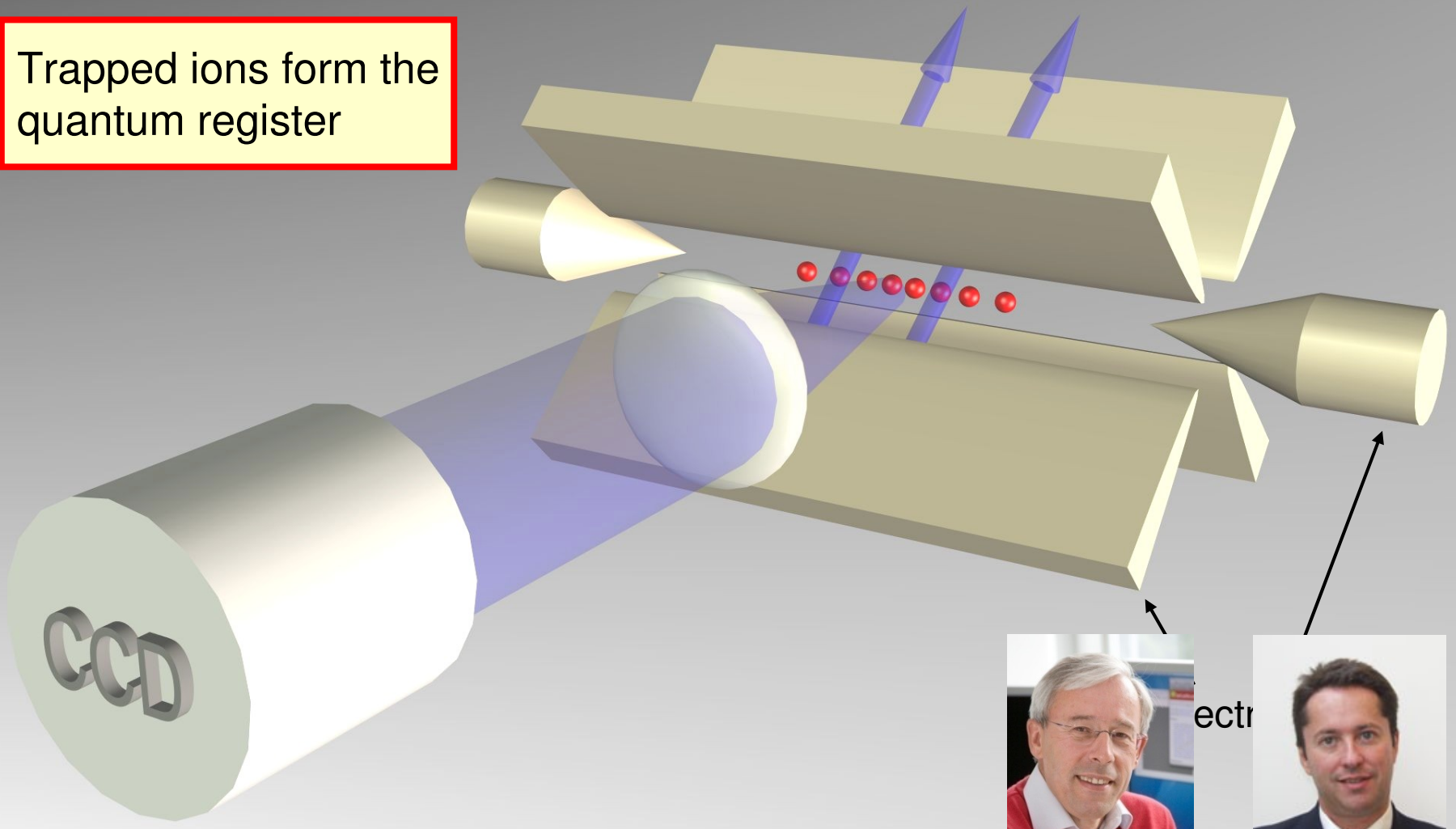


Trapped ions

Quantum dots

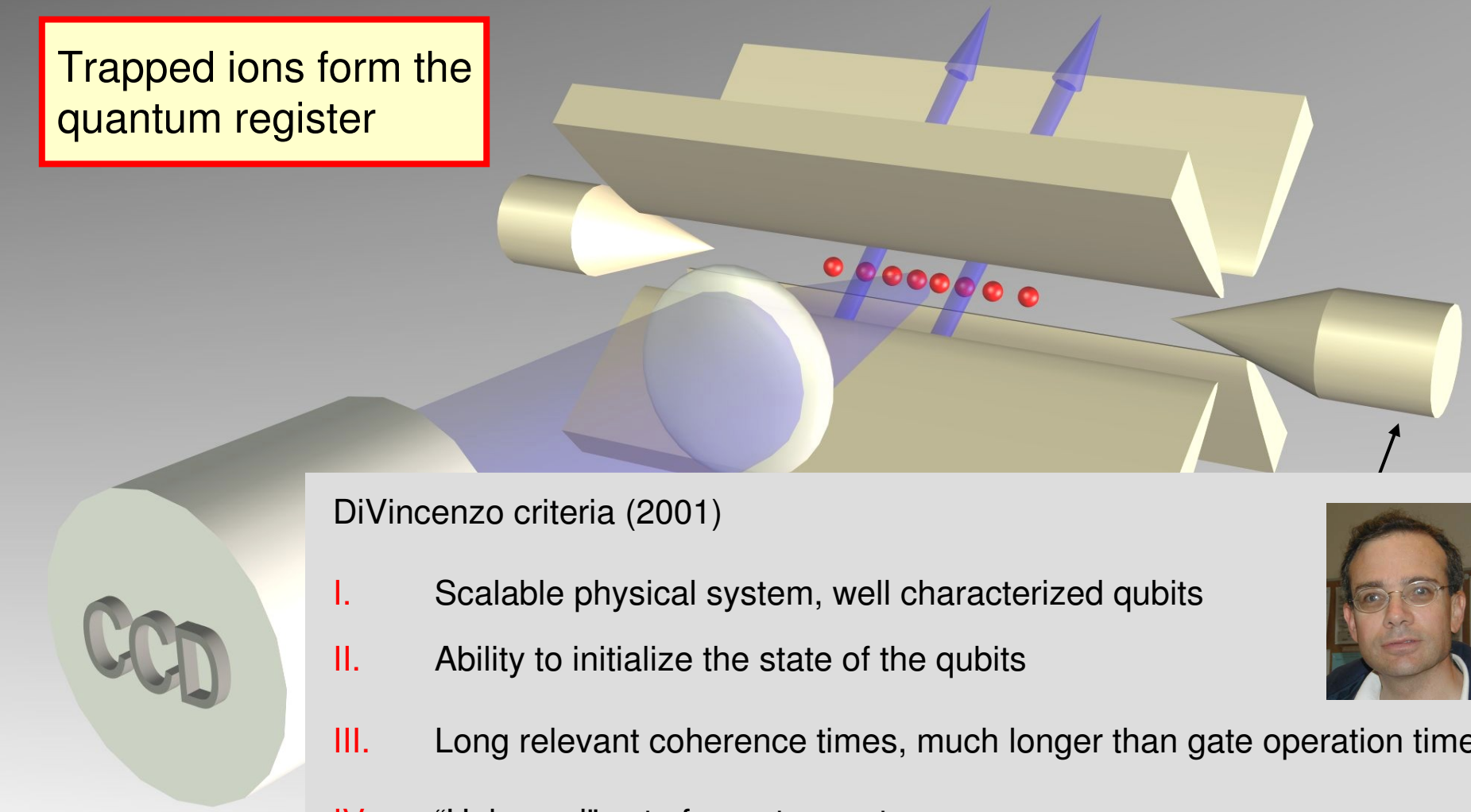
Ion trap quantum computing

Trapped ions form the quantum register



Ion trap quantum computing

Trapped ions form the quantum register



DiVincenzo criteria (2001)

I. Scalable physical system, well characterized qubits

II. Ability to initialize the state of the qubits

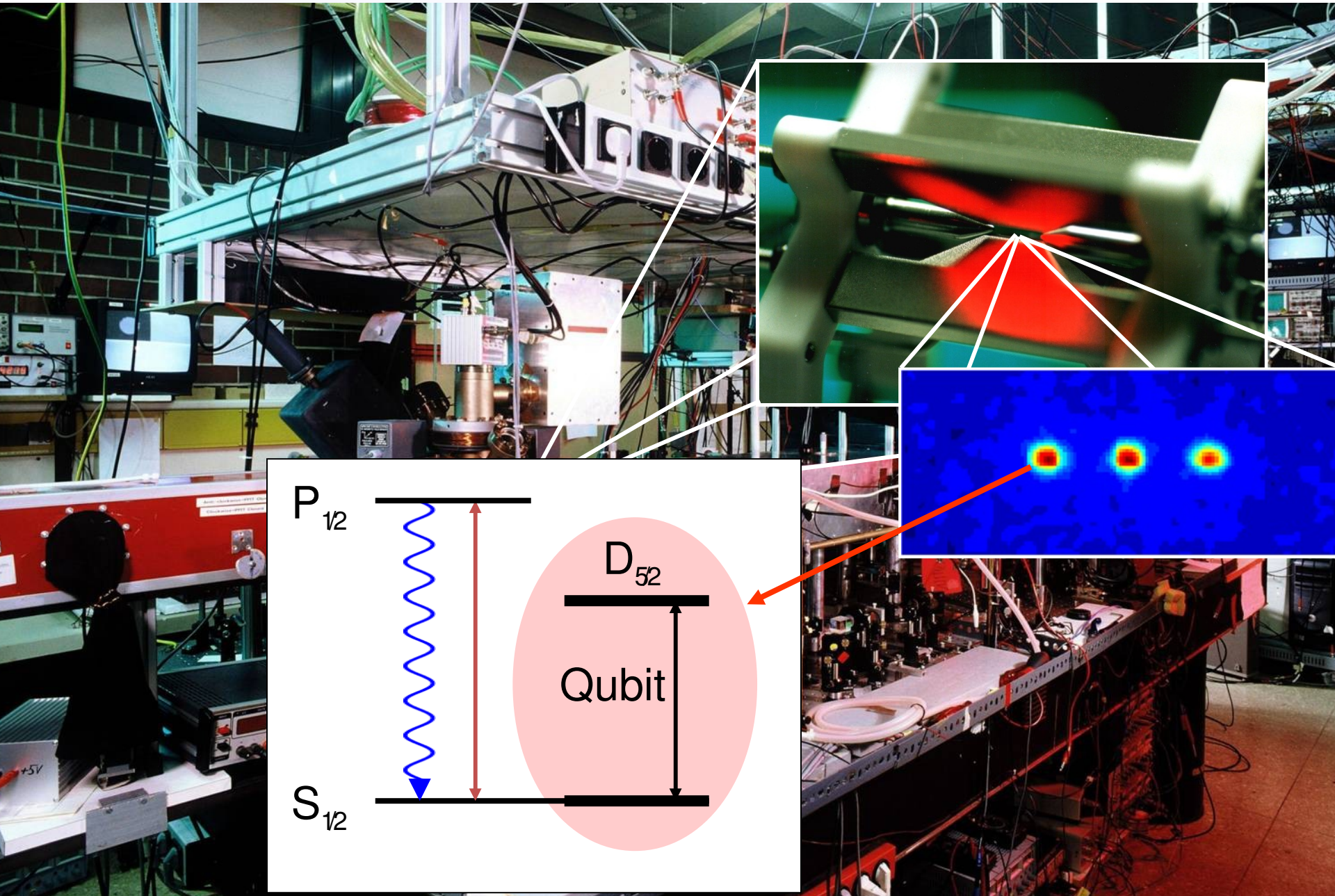
III. Long relevant coherence times, much longer than gate operation time

IV. “Universal” set of quantum gates

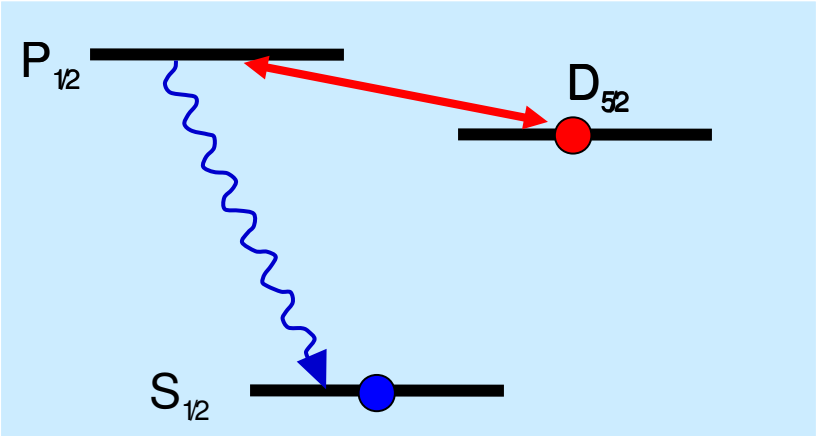
V. Qubit-specific measurement capability

- Introduction to quantum information
- Ion trap quantum computing
- Teleportation and more
- Scaling of ion trap quantum computers

The hardware

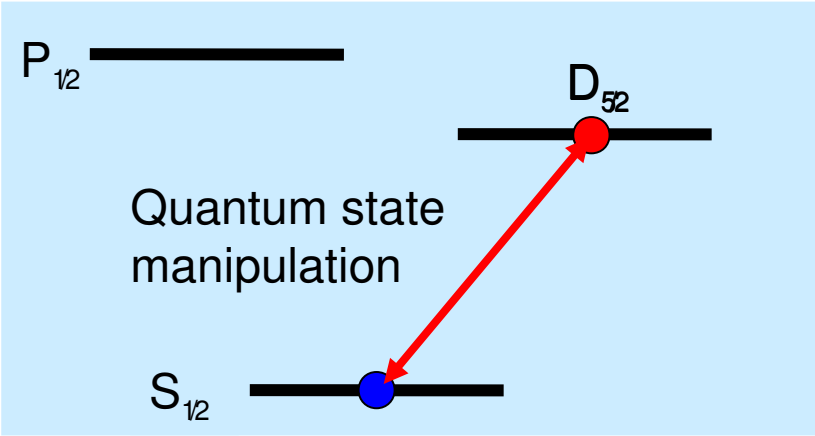


Experimental procedure



1. Initialization in a pure quantum state

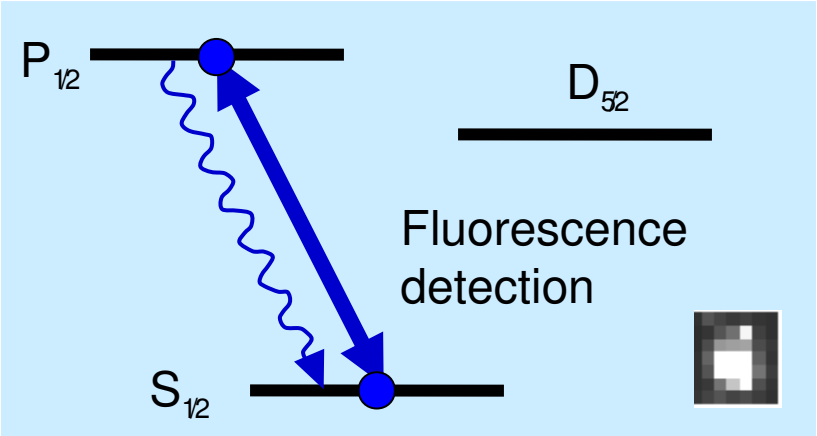
Experimental procedure



1. Initialization in a pure quantum state

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

Experimental procedure

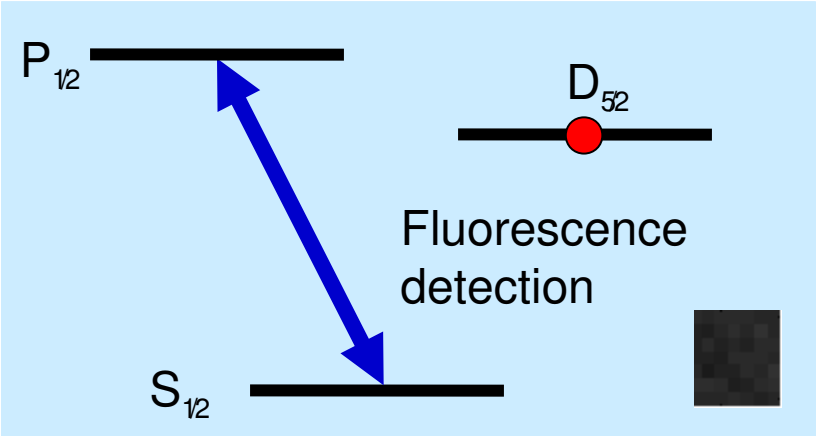


1. Initialization in a pure quantum state:

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

3. Quantum state measurement by fluorescence detection

Experimental procedure



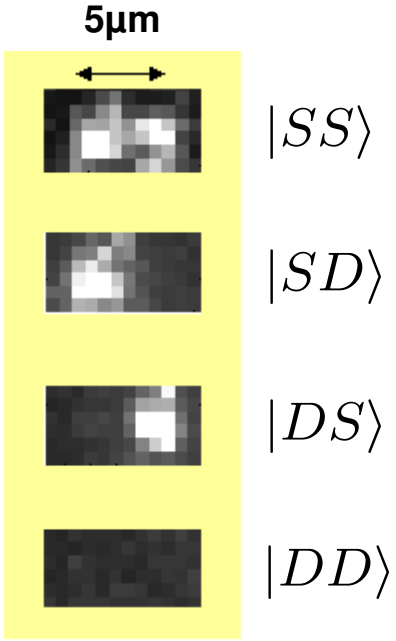
1. Initialization in a pure quantum state:

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

3. Quantum state measurement by fluorescence detection

Two ions:

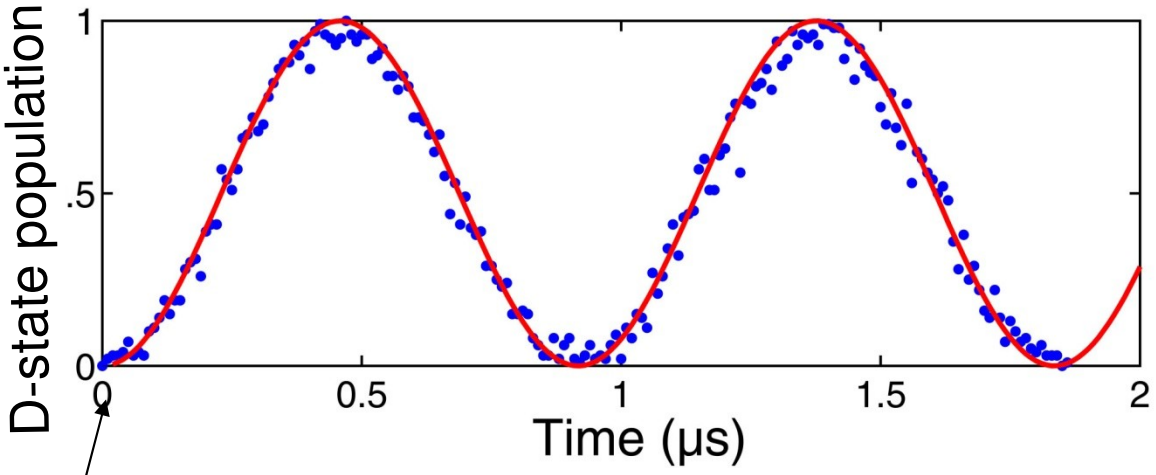
Spatially resolved detection with CCD camera



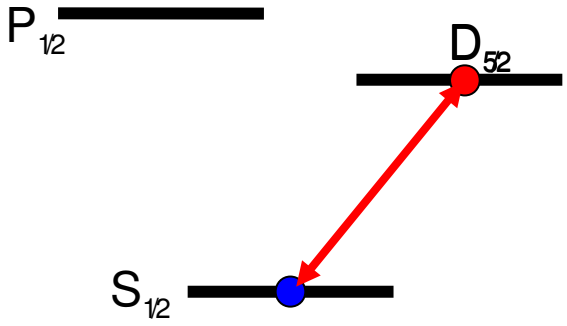
50 experiments / s

Repeat experiments 100-200 times

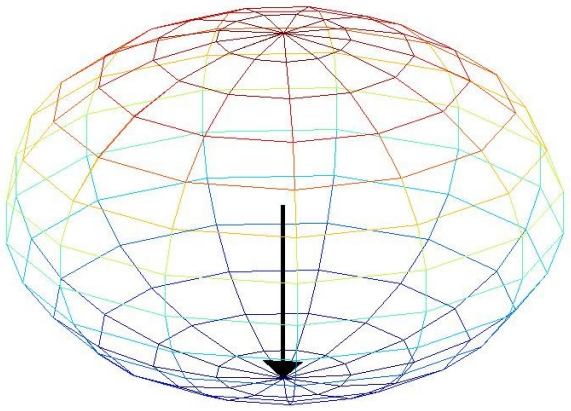
Rabi oscillations



$|S\rangle$



$|D\rangle$

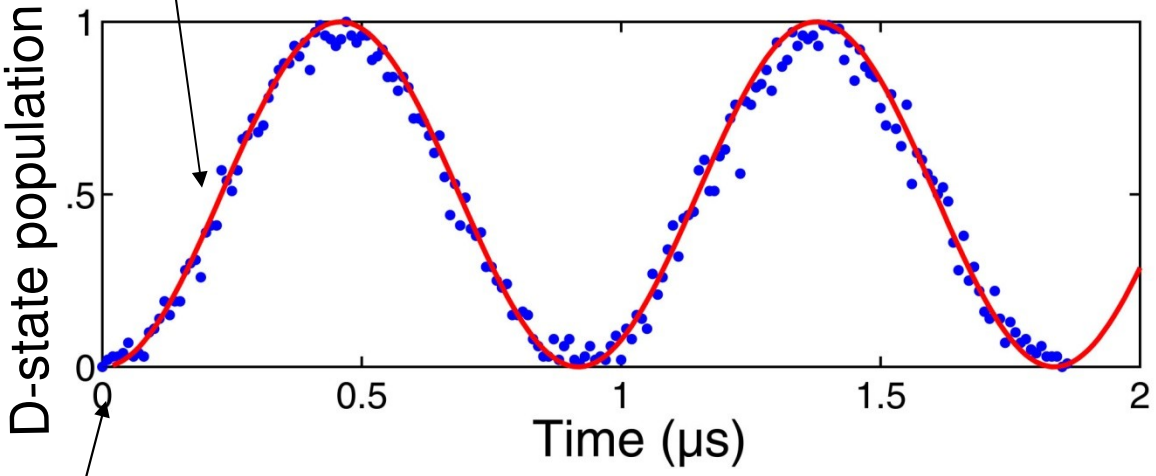


$|S\rangle$

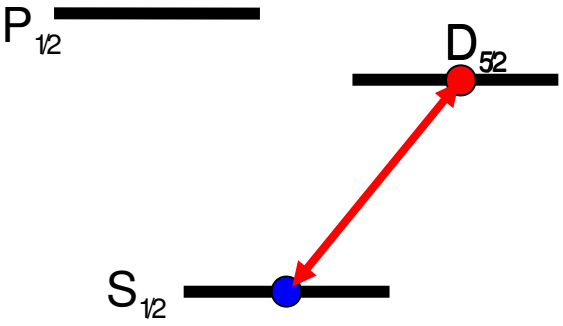
$$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$$

Rabi oscillations

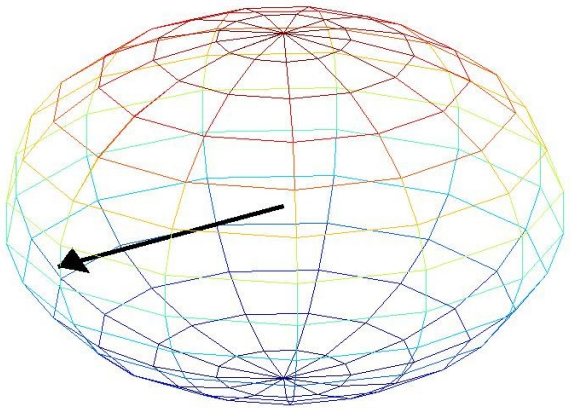
$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$



$|S\rangle$



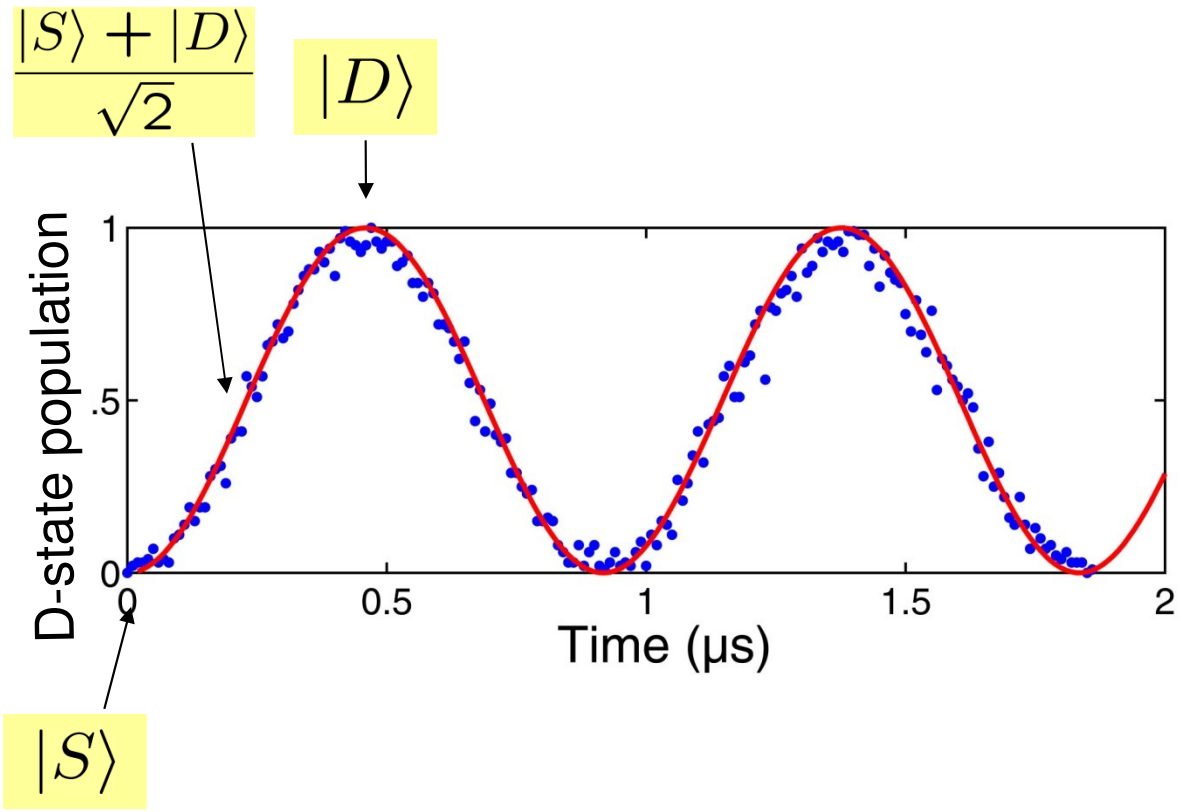
$|D\rangle$

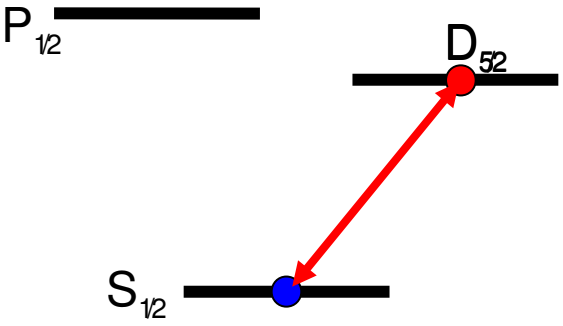


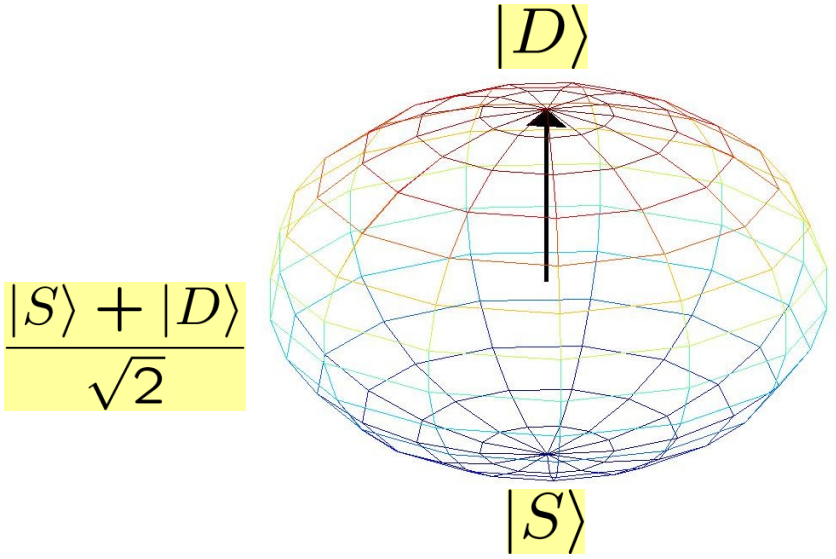
$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$

$|S\rangle$

Rabi oscillations







Requirements for quantum computing

Classical computer

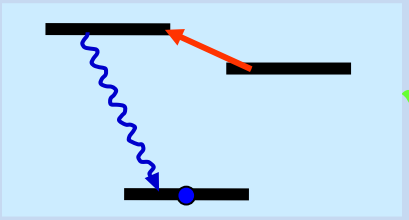
- Initialization
- 1-bit operations (NOT)
- 2-bit gates (e.g. NAND)

Computational space:

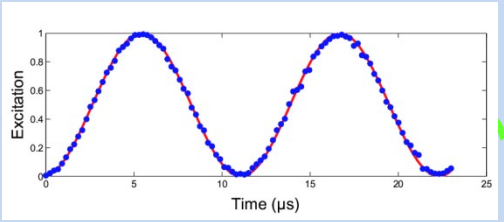
00
01
10
11

- Read out
  ➡ result

Quantum computer



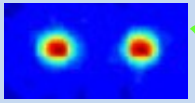
- Initialization
- 1-qubit rotations
  ➡ superpositions



- 2-qubit gates (CNOT gate)
  ➡ entanglement

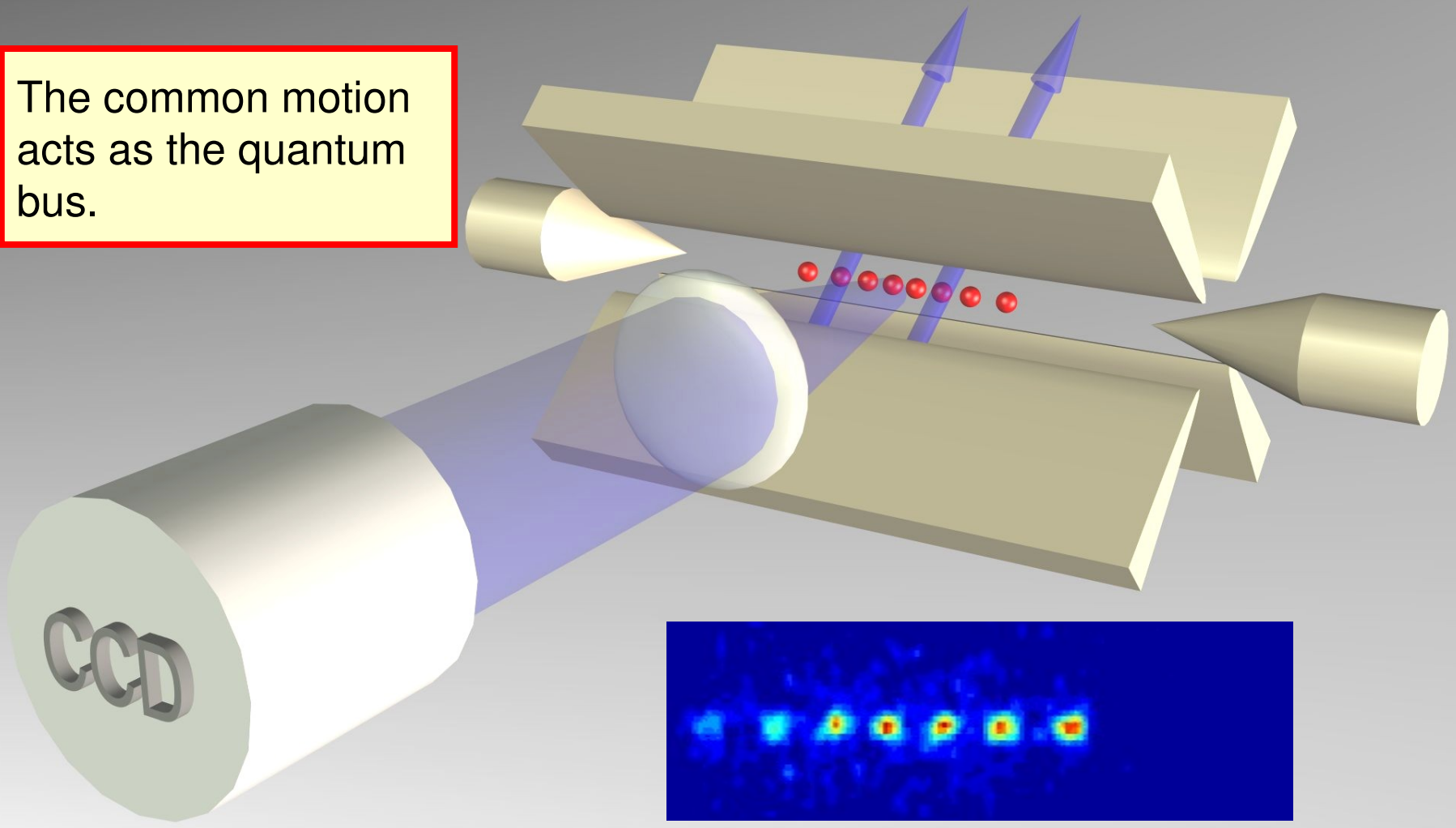
Computational space:

- Read out of qubits
  ➡ gain of classical information

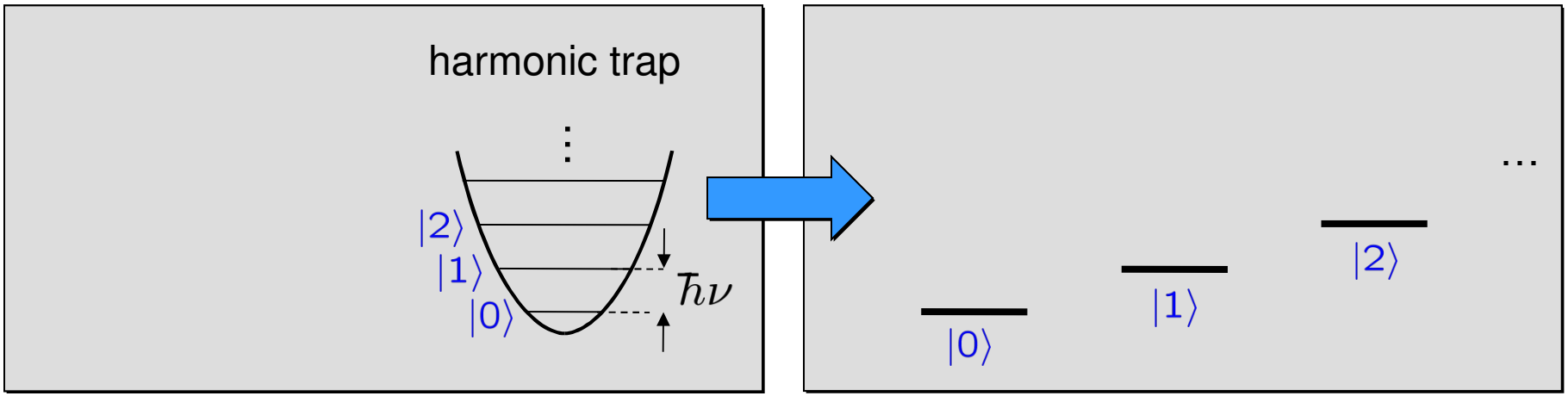


Having the qubits interact

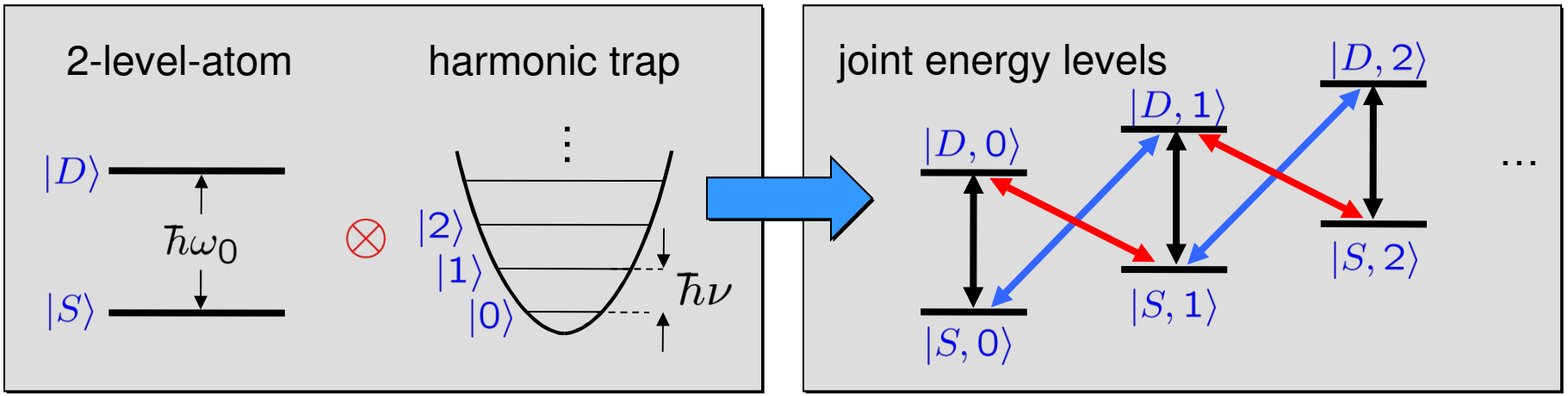
The common motion acts as the quantum bus.

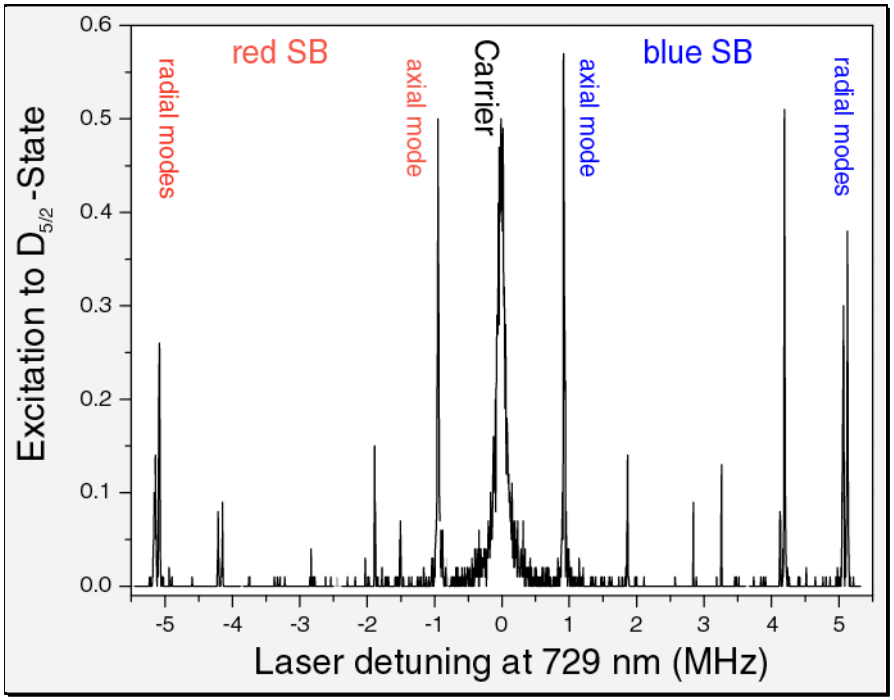


Ion motion

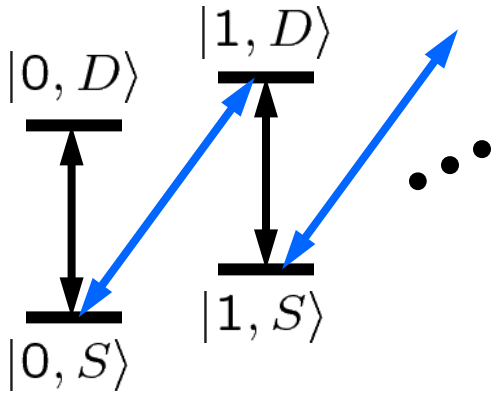


Ion motion

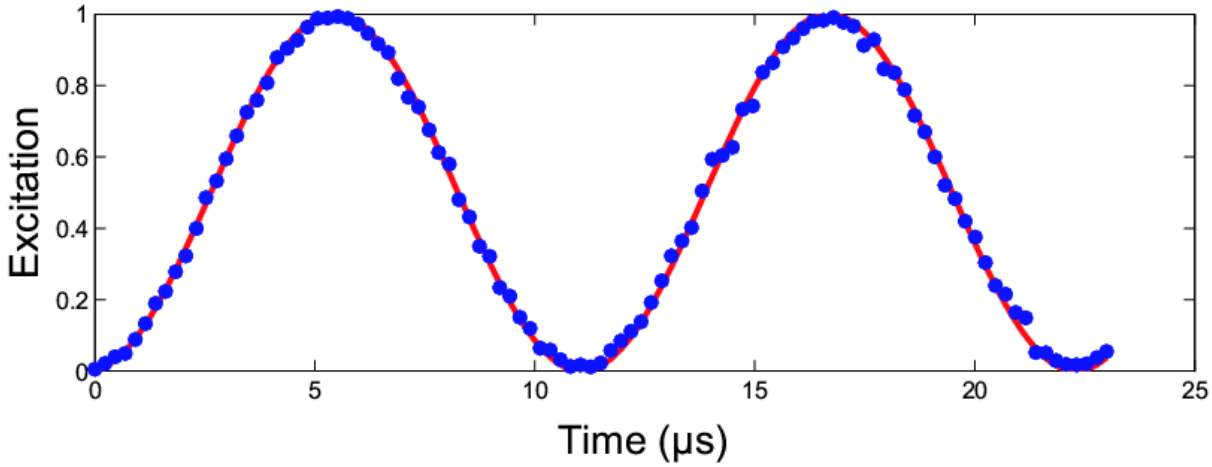

2-level-atom
harmonic trap
joint energy levels
$|D\rangle$
$|S\rangle$
$\hbar\omega_0$
$|2\rangle$
$|1\rangle$
$|0\rangle$
$\hbar\nu$
$|D,0\rangle$
$|D,1\rangle$
$|D,2\rangle$
$|S,0\rangle$
$|S,1\rangle$
$|S,2\rangle$
...


red SB
blue SB
radial modes
axial mode
Carrier
axial mode
radial modes
Excitation to $D_{5/2}$-State
0.0
0.1
0.2
0.3
0.4
0.5
0.6
-5
-4
-3
-2
-1
0
1
2
3
4
5
Laser detuning at 729 nm (MHz)

Coherent manipulation

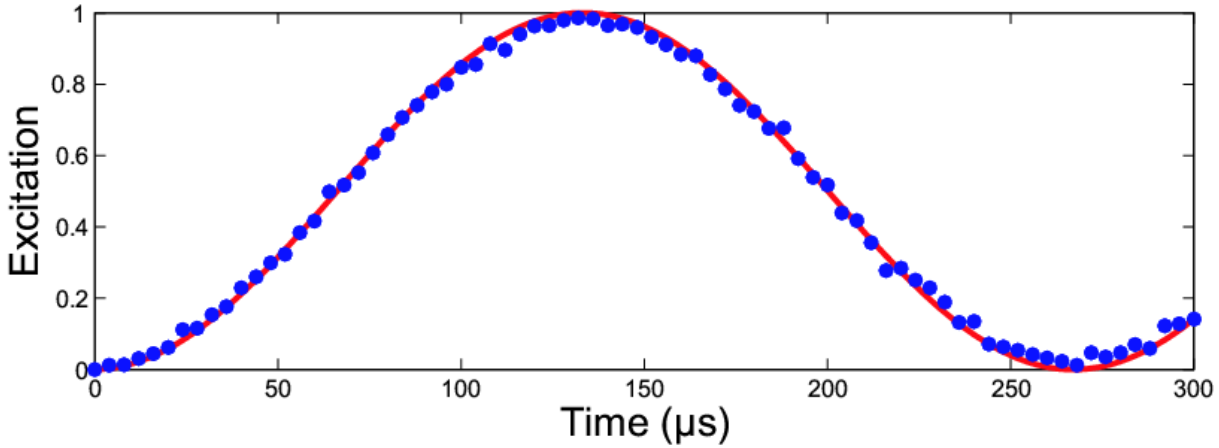


carrier



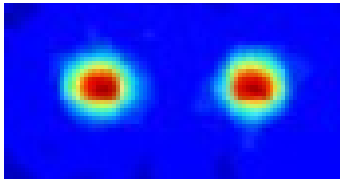
carrier and sideband
Rabi oscillations
with Rabi frequencies

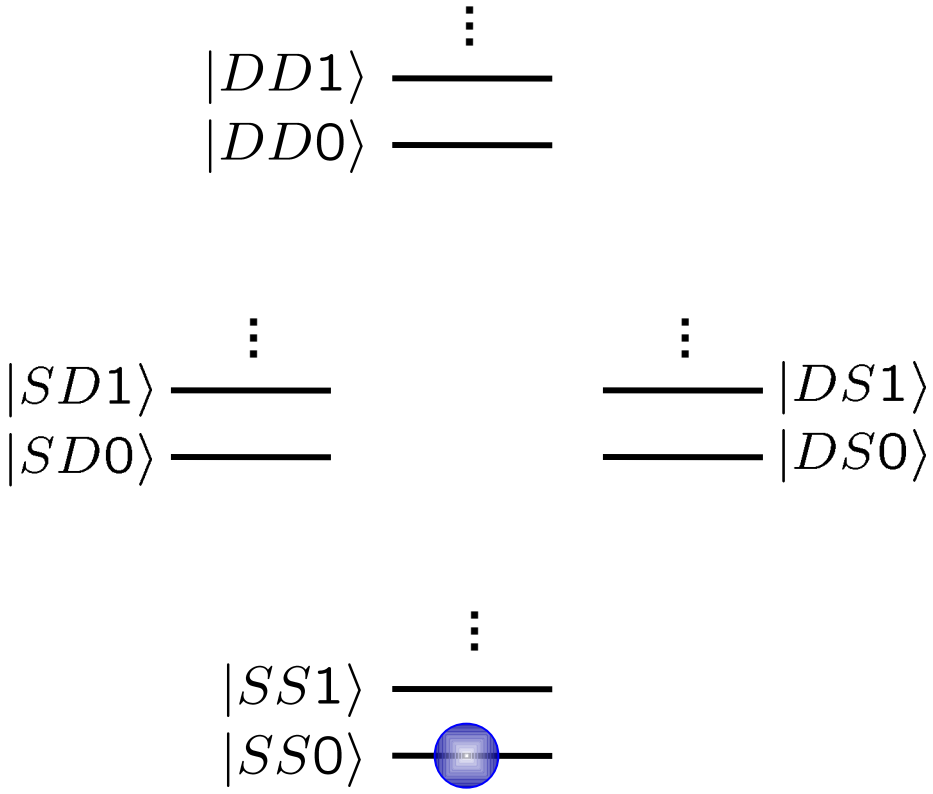
$\Omega, \quad \eta\Omega$



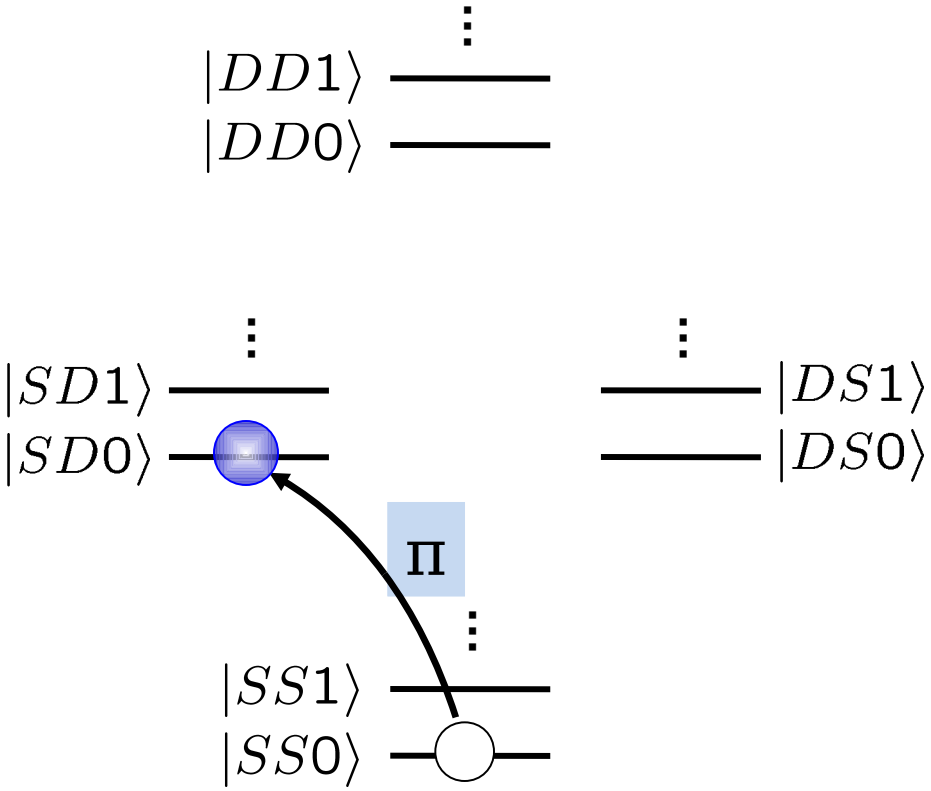
$\eta = kx_0$ Lamb-Dicke parameter

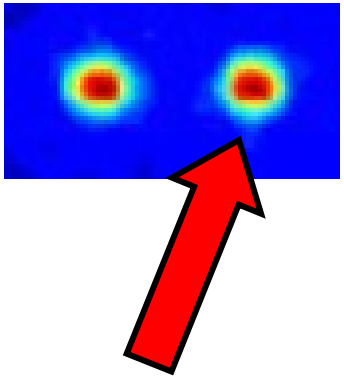
Generation of Bell states



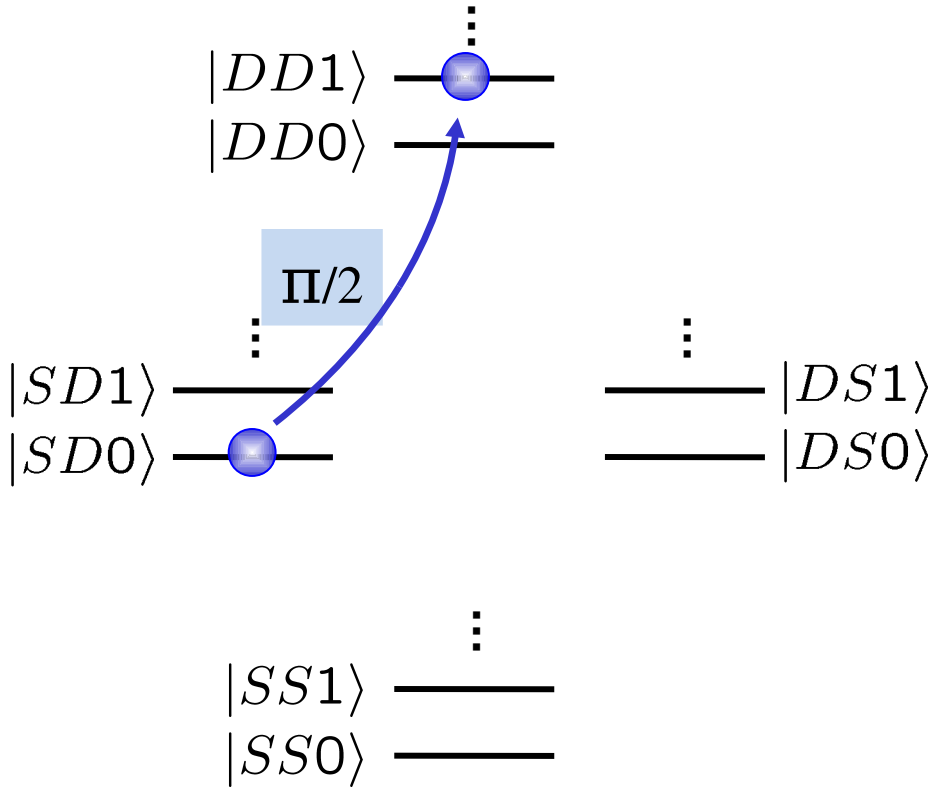


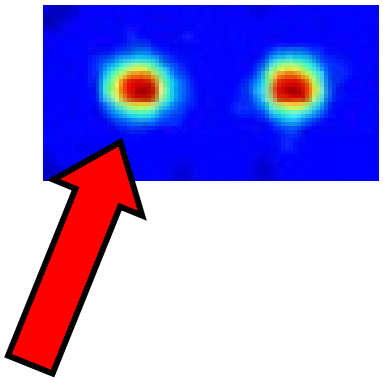
Generation of Bell states



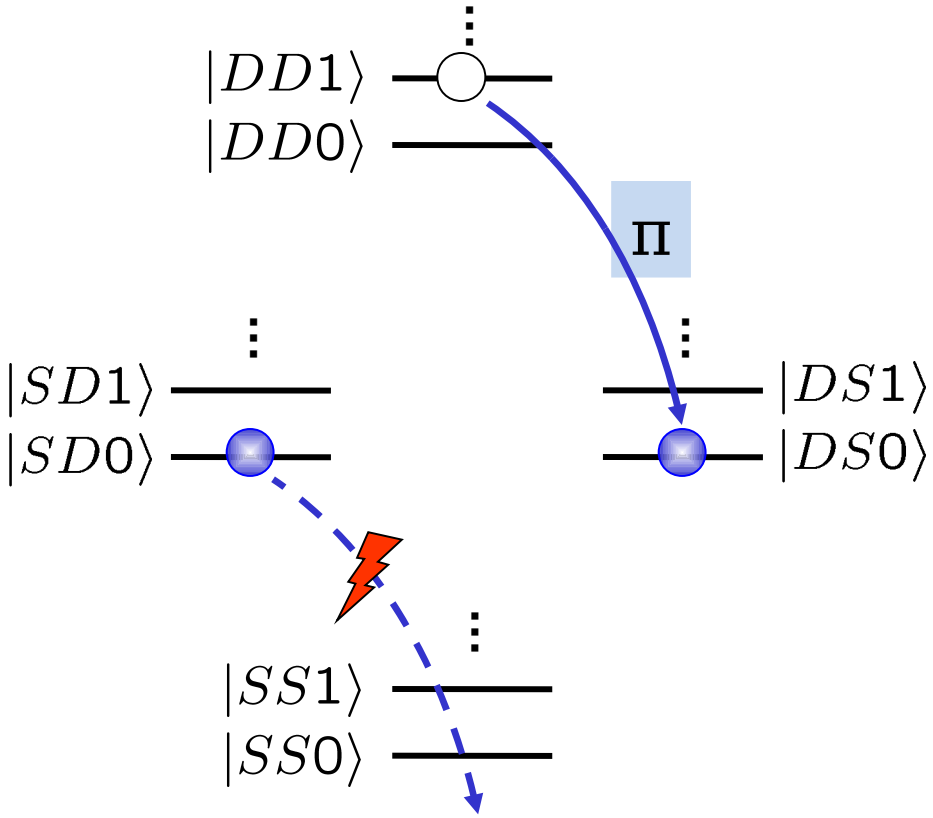


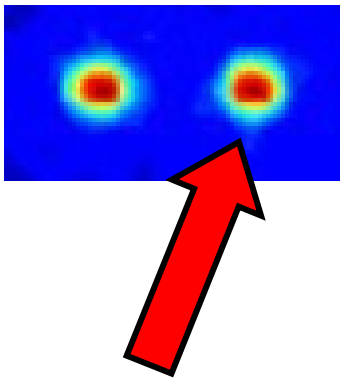
Generation of Bell states



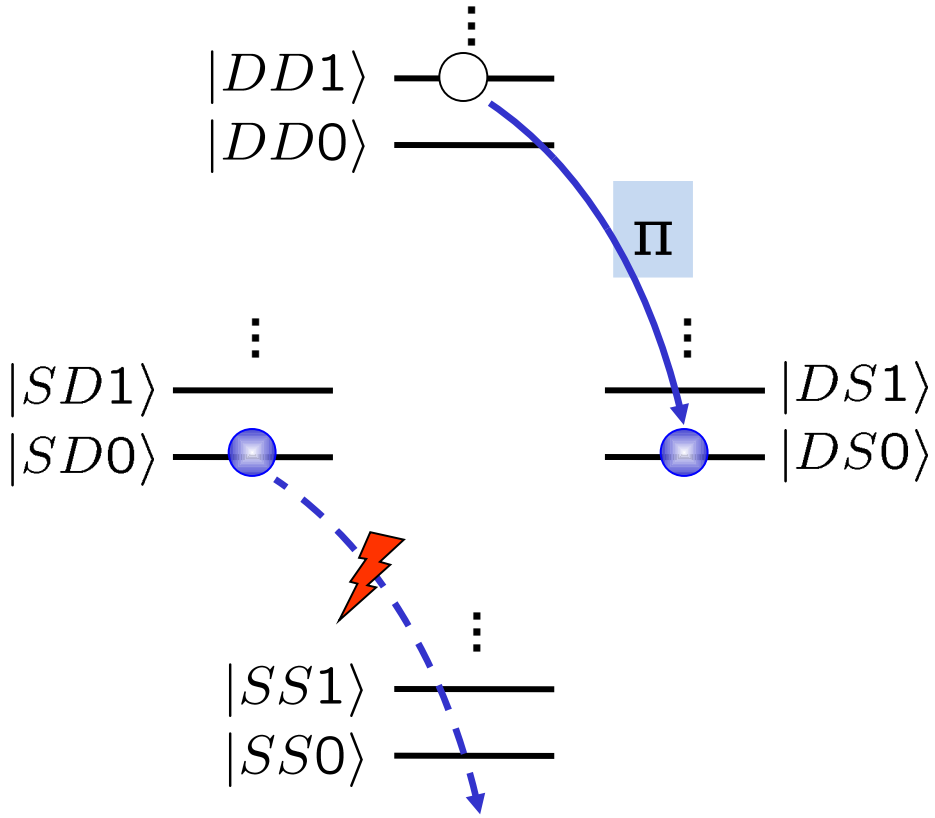


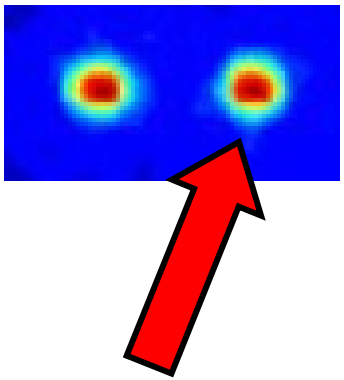
Generation of Bell states





Generation of Bell states





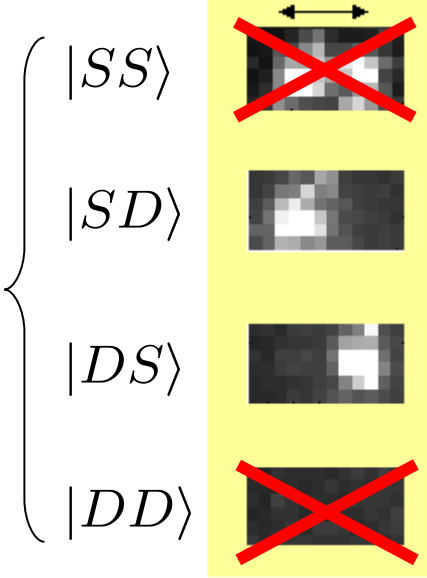
Bell states with atoms

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

Analysis of Bell states

$$|SD\rangle + |DS\rangle$$

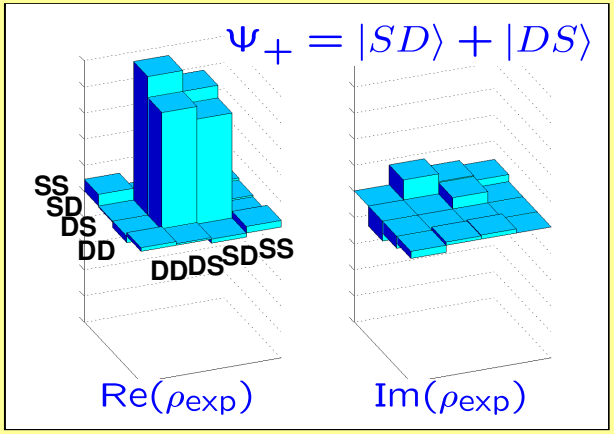
Fluorescence detection with CCD camera:



Coherent superposition or incoherent mixture ?

What is the relative phase of the superposition ?

➡ Measurement of the density matrix:

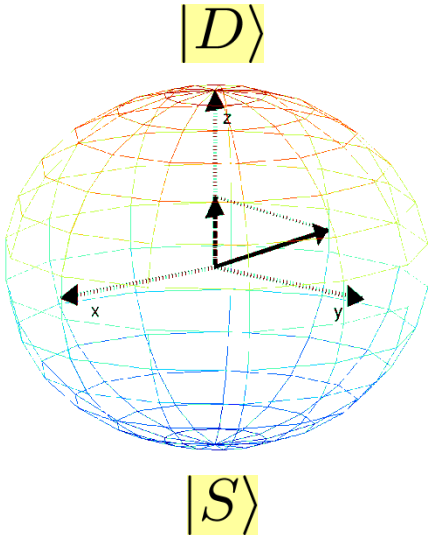


Measuring a density matrix

A measurement yields the *z*-component of the Bloch vector

=> Diagonal of the density matrix

$$\rho = \begin{pmatrix} P_S & C - iD \\ C + iD & P_D \end{pmatrix}$$



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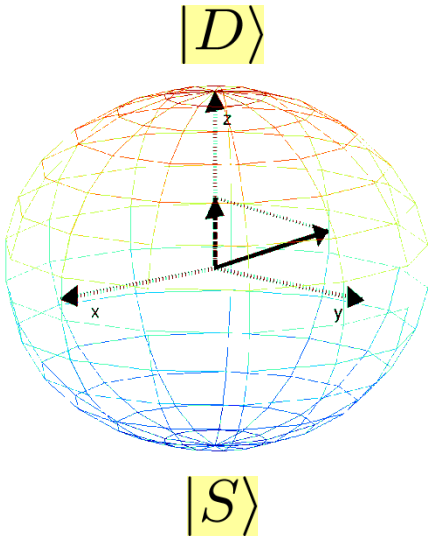
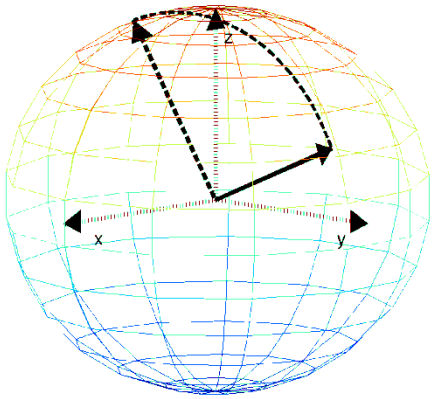


Rotation around the *x*- or the *y*-axis prior to the measurement yields the phase information of the qubit.



Measuring a density matrix

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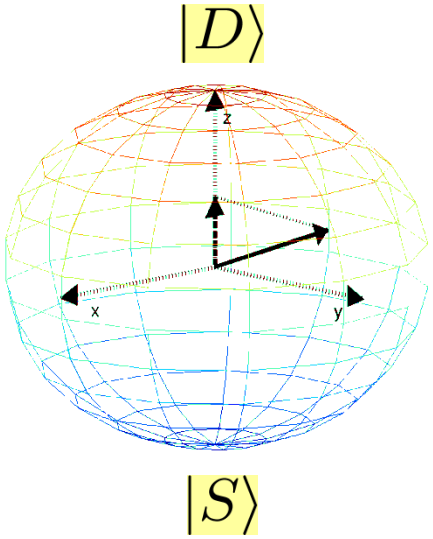
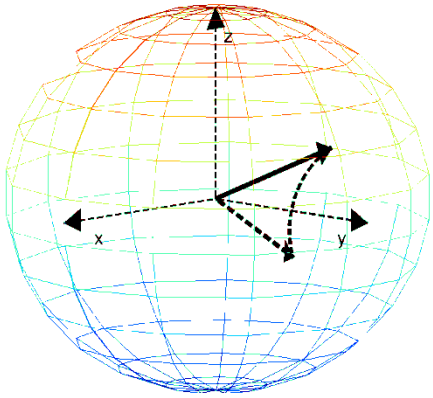
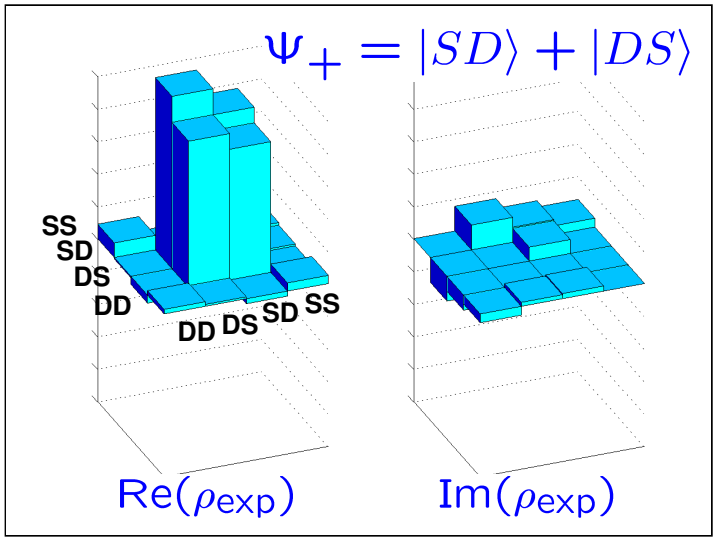


Rotation around the *x*- or the *y*-axis prior to the measurement yields the phase information of the qubit.

=> coherences of the density matrix



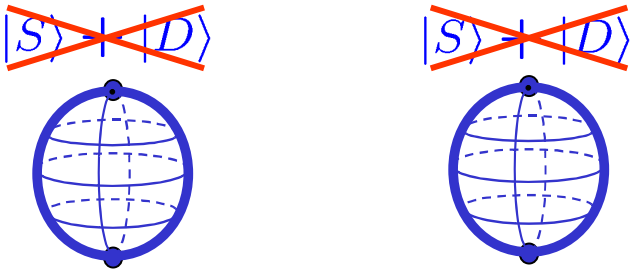
Entanglement



States are fully characterized

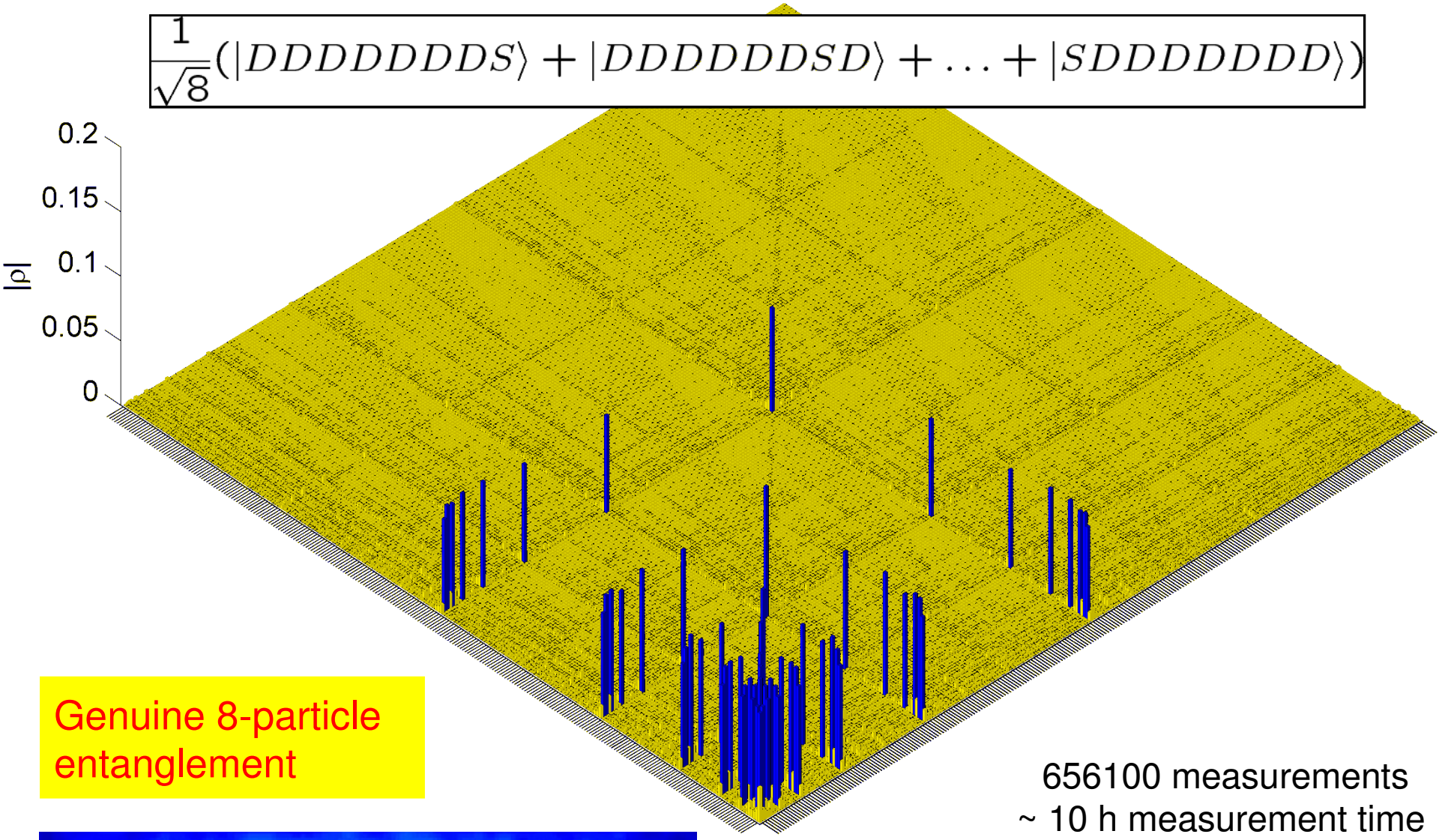
Fidelities: up to 0.99

Entanglement: the state of each qubit is not defined!

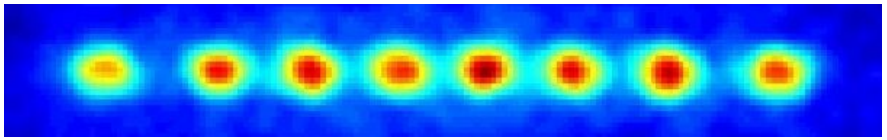


“Large” entangled states

$$\frac{1}{\sqrt{8}}(|DDDDDDDS\rangle + |DDDDDDSD\rangle + \ldots + |SDDDDDDD\rangle)$$



Genuine 8-particle entanglement

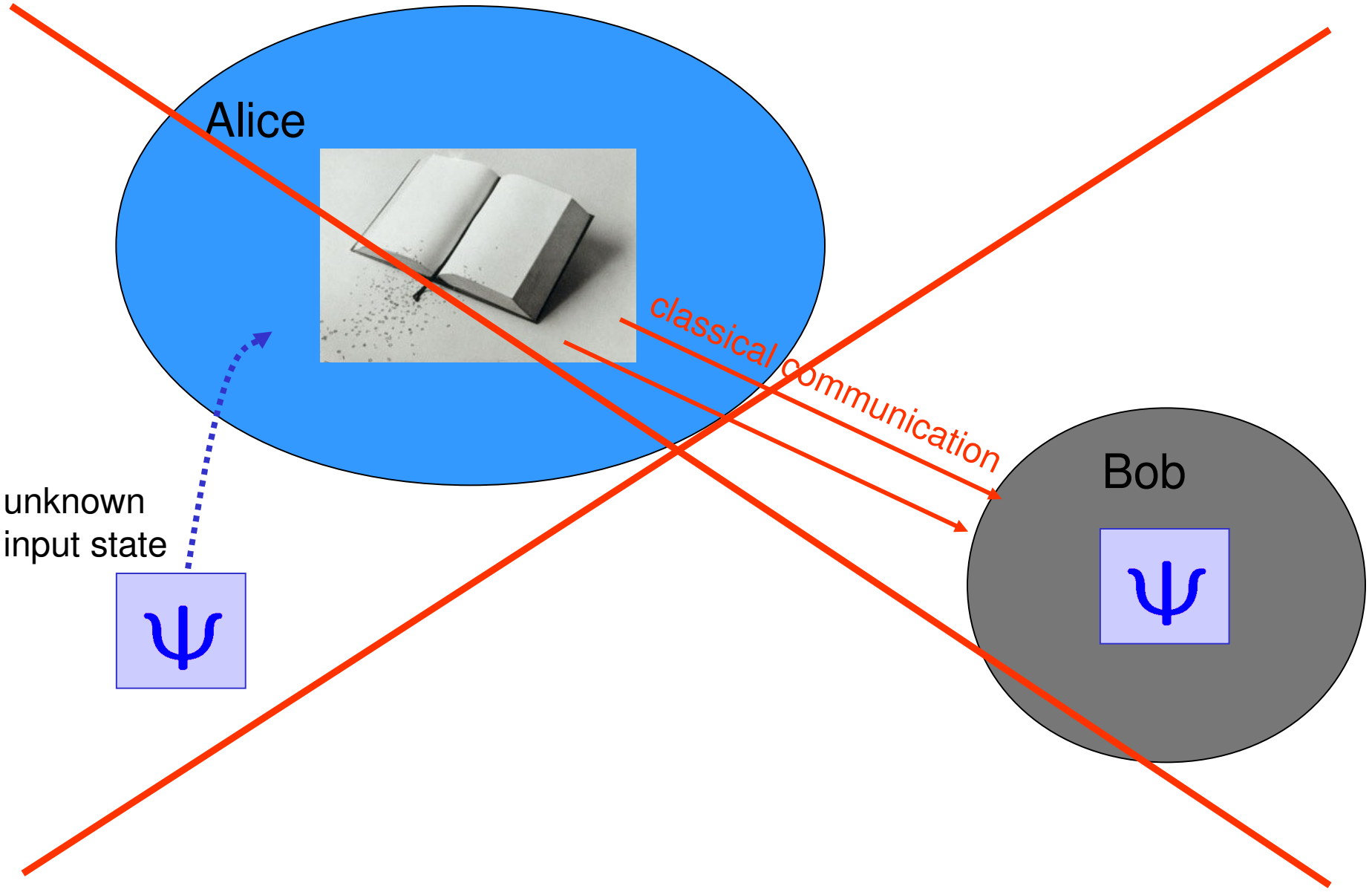


656100 measurements
~ 10 h measurement time

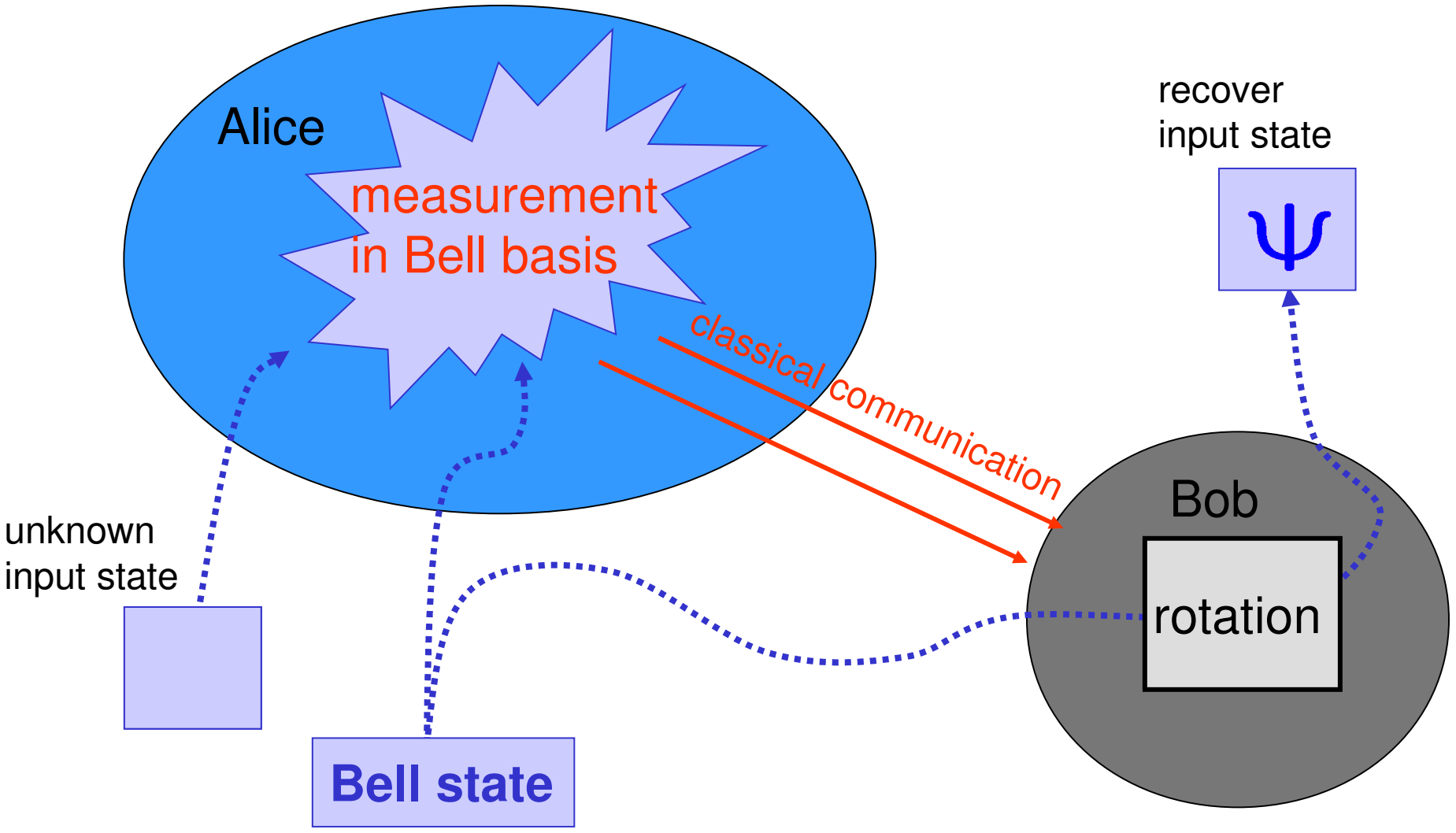
Häffner et al., Nature **438**, 643 (2005)

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

Teleportation

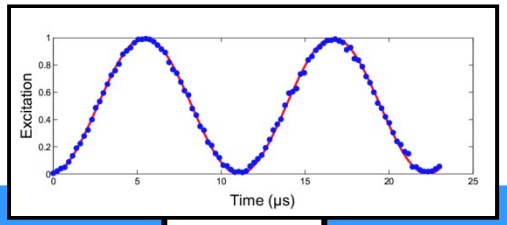


Teleportation



Bennett *et al.*, Phys. Rev. Lett. **70**, 1895 (1993).
Bouwmeester *et al.*, Nature **390**, 575 (1997).

Teleportation



ψ

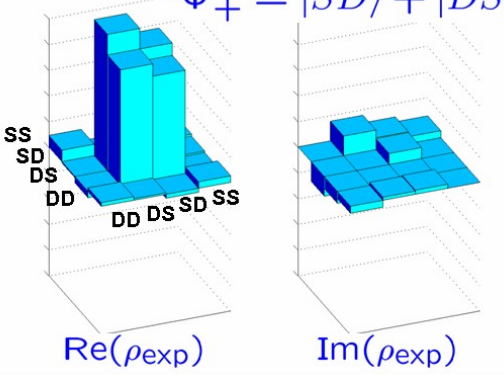
$\pi/2$

Bell state

Z

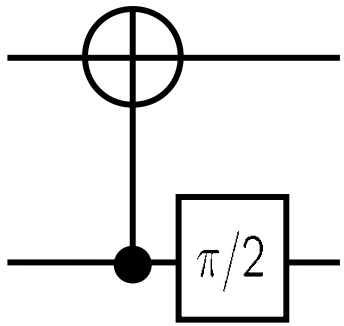
X

$\Psi_+ = |SD\rangle + |DS\rangle$



Bell measurement

$$|SS + DD\rangle$$
$$|SD + DS\rangle$$
$$|SS - DD\rangle$$
$$|SD - DS\rangle$$



$$|SS\rangle$$
$$|SD\rangle$$
$$|DS\rangle$$
$$|DD\rangle$$

Ion trap quantum computing

VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*

Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

PACS numbers: 89.80.+h, 03.65.Bz, 12.20.Fv, 32.80.Pj

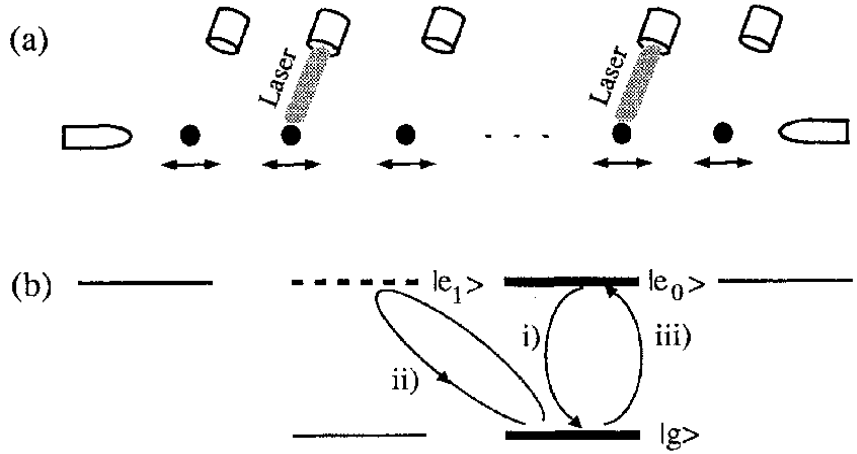


FIG. 1. (a) N ions in a linear trap interacting with N different laser beams; (b) atomic level scheme.

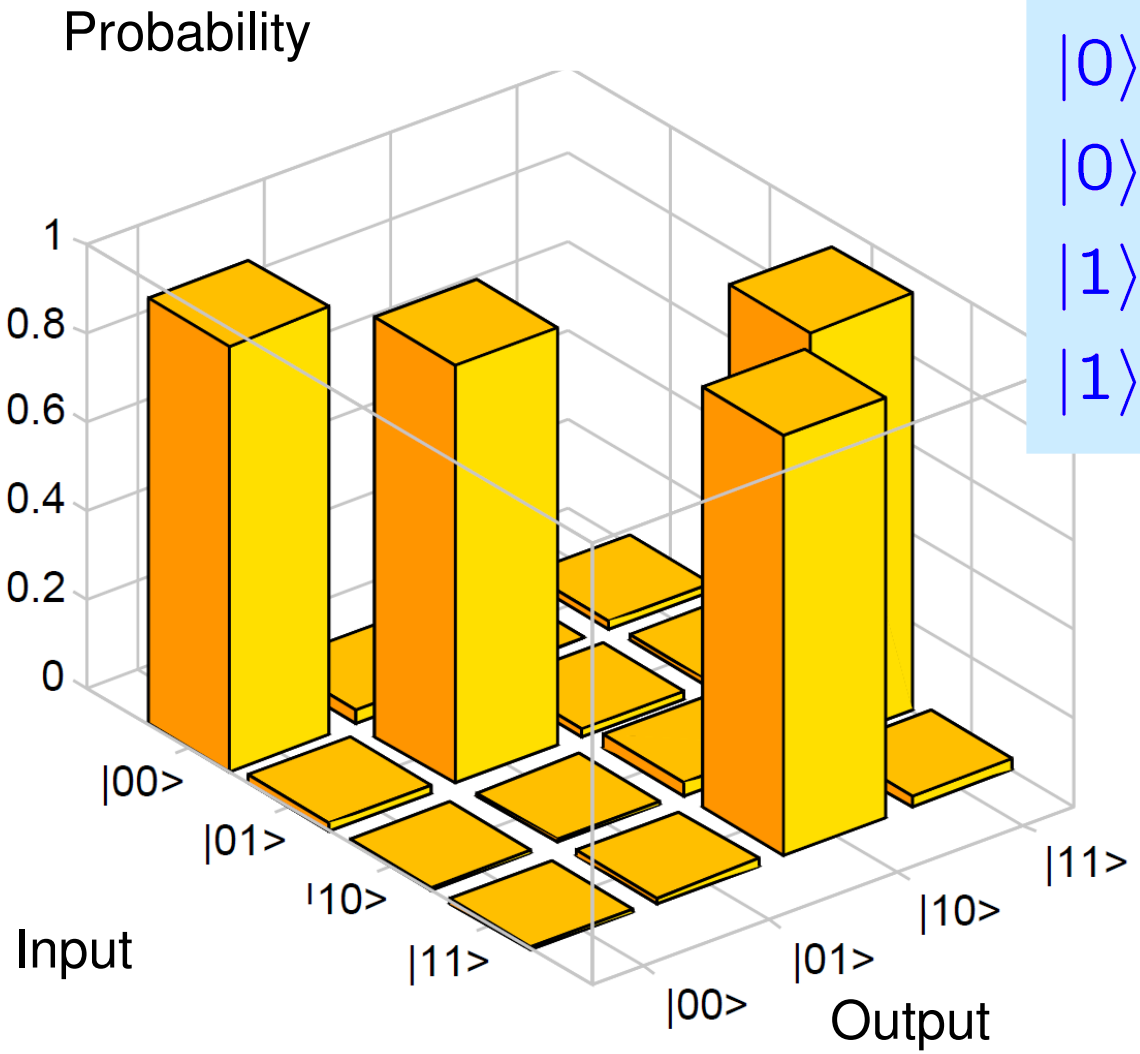
controlled – NOT :

$$|\varepsilon_1\rangle|\varepsilon_2\rangle \rightarrow |\varepsilon_1\rangle|\varepsilon_1 \oplus \varepsilon_2\rangle$$

$$\begin{aligned} |0\rangle|0\rangle &\rightarrow |0\rangle|0\rangle \\ |0\rangle|1\rangle &\rightarrow |0\rangle|1\rangle \\ |1\rangle|0\rangle &\rightarrow |1\rangle|1\rangle \\ |1\rangle|1\rangle &\rightarrow |1\rangle|0\rangle \end{aligned}$$

control bit target bit

Truth table of a controlled NOT gate



$$
\begin{aligned}
|0\rangle|0\rangle &\rightarrow |0\rangle|0\rangle \\
|0\rangle|1\rangle &\rightarrow |0\rangle|1\rangle \\
|1\rangle|0\rangle &\rightarrow |1\rangle|1\rangle \\
|1\rangle|1\rangle &\rightarrow |1\rangle|0\rangle
\end{aligned}
$$

➡ universal set of quantum gates

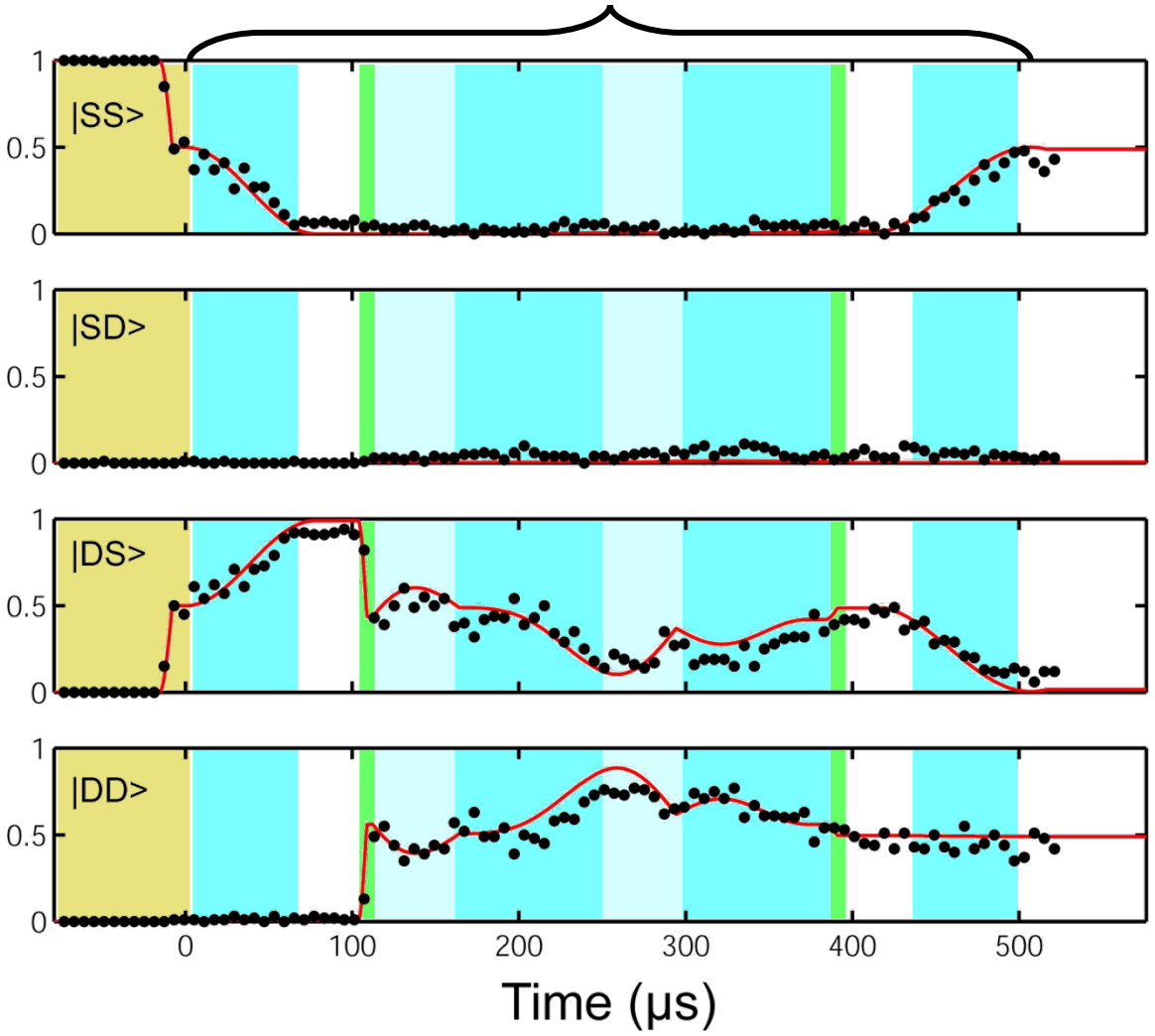
Another way to generate Bell states

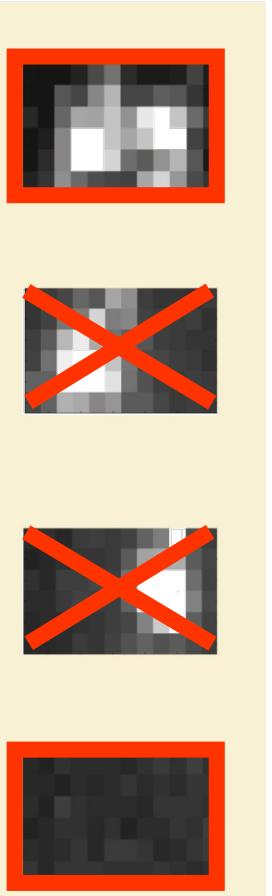
$$|SS\rangle \rightarrow |S+D\rangle|S\rangle \longrightarrow |SS\rangle + |DD\rangle$$

prepare

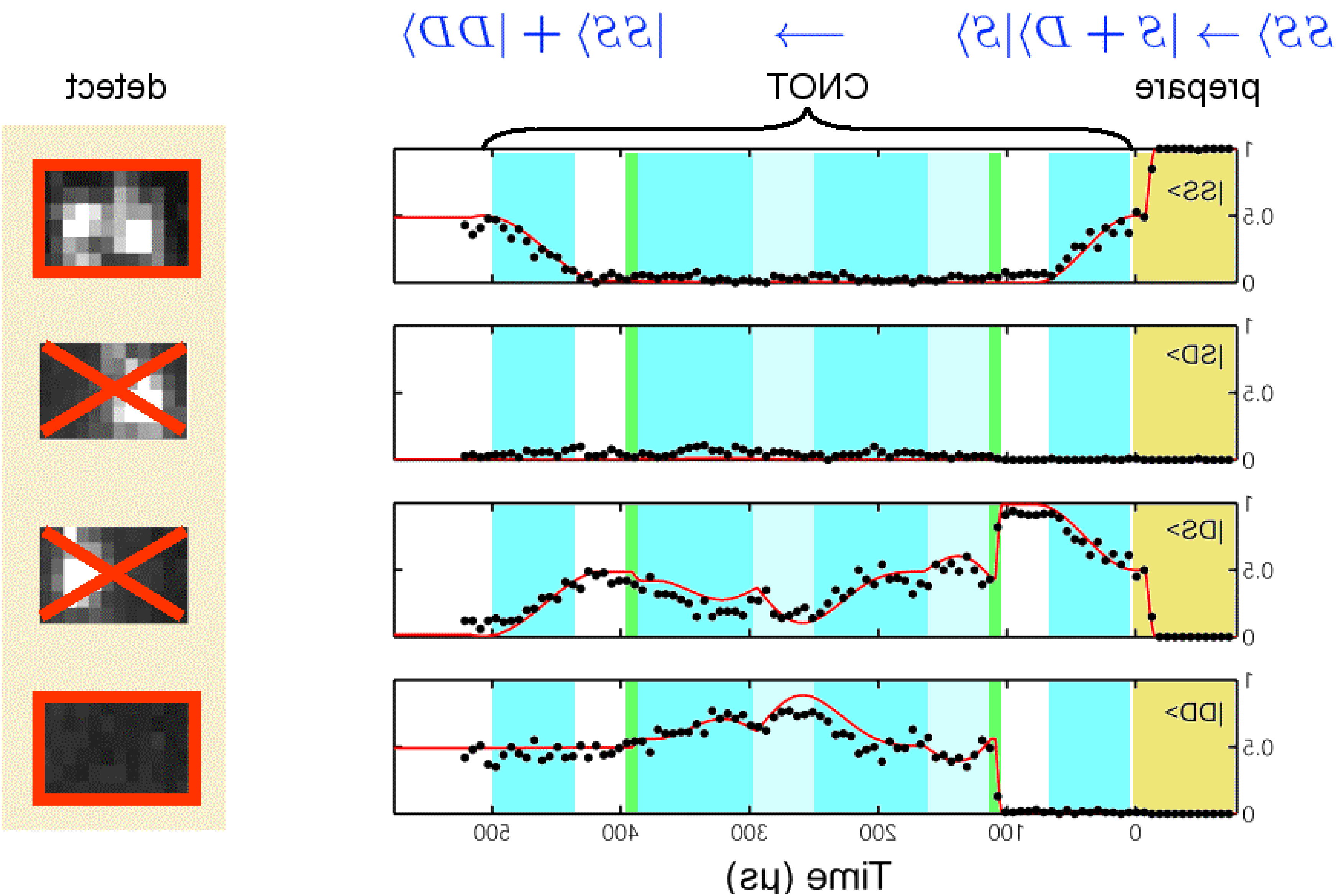
CNOT

output



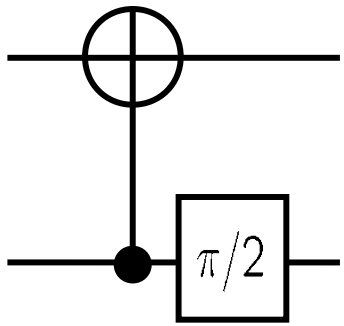


And now backwards



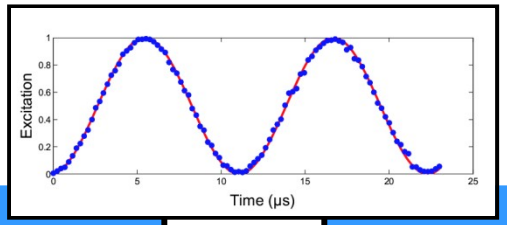
Bell measurement

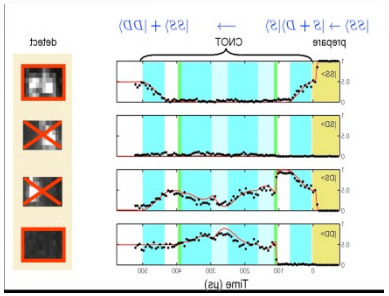
$$|SS + DD\rangle$$
$$|SD + DS\rangle$$
$$|SS - DD\rangle$$
$$|SD - DS\rangle$$

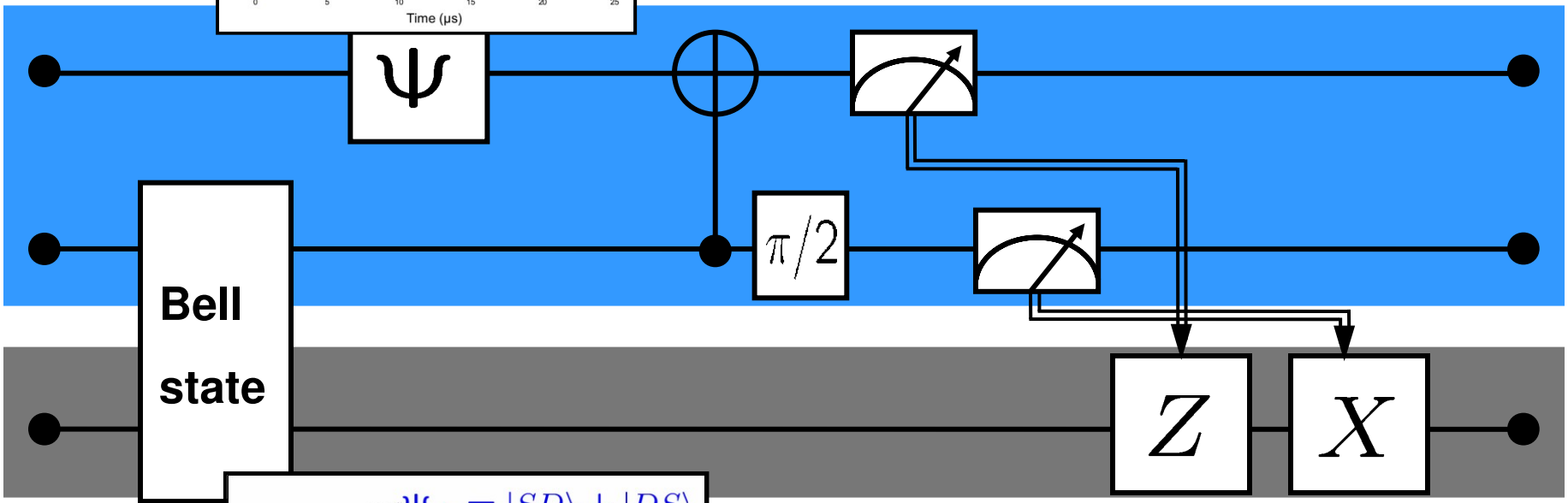


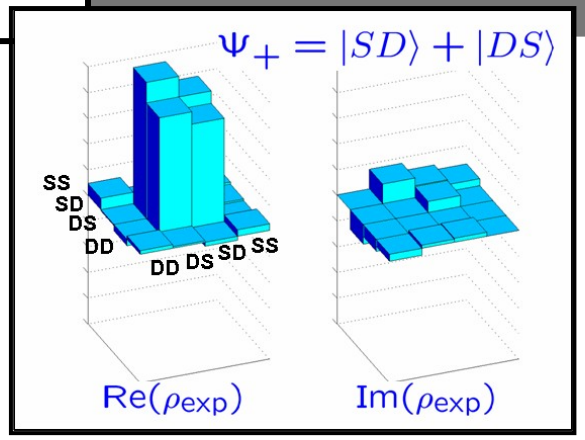
$$|SS\rangle$$
$$|SD\rangle$$
$$|DS\rangle$$
$$|DD\rangle$$

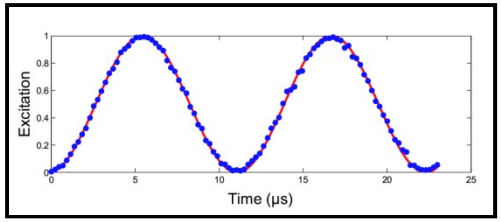
Teleportation



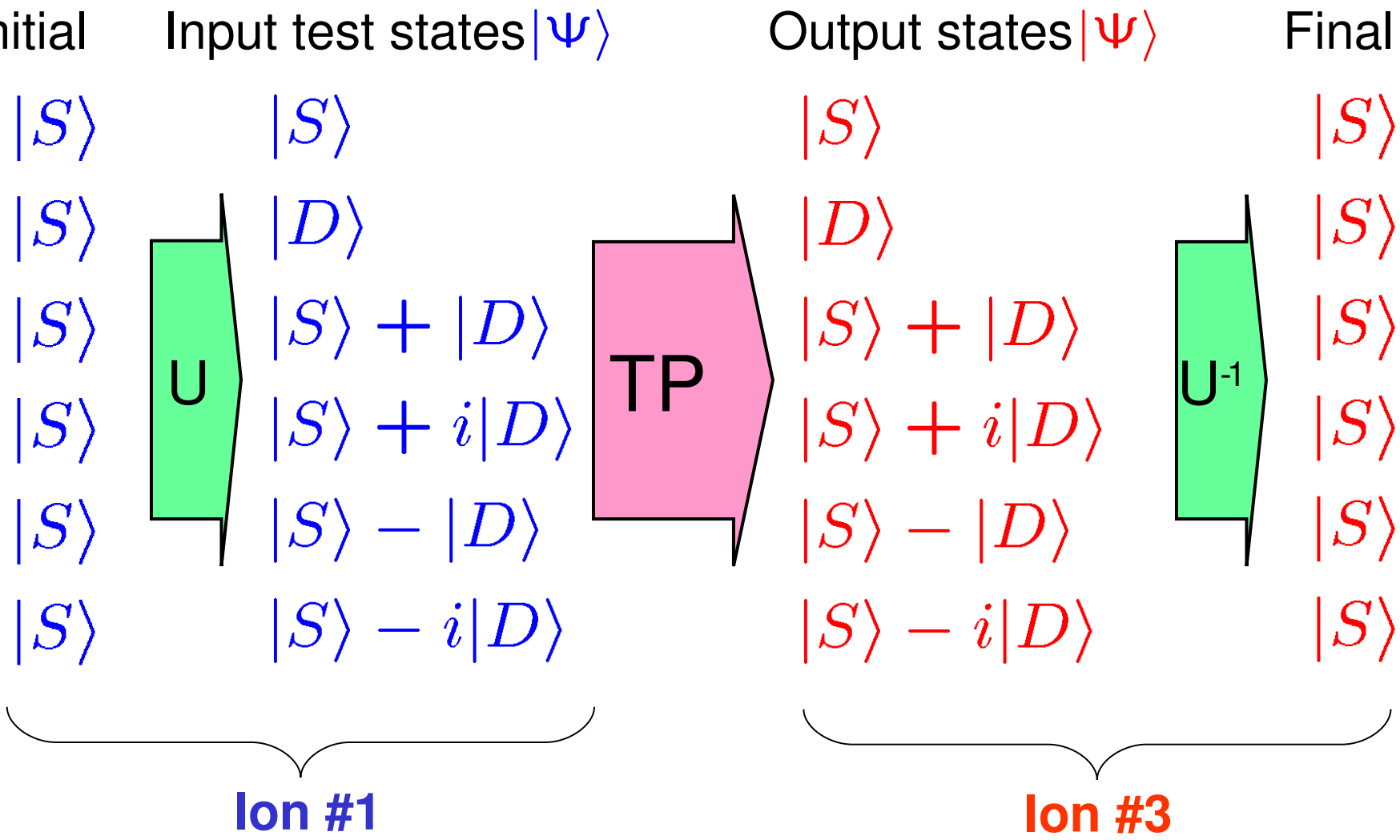




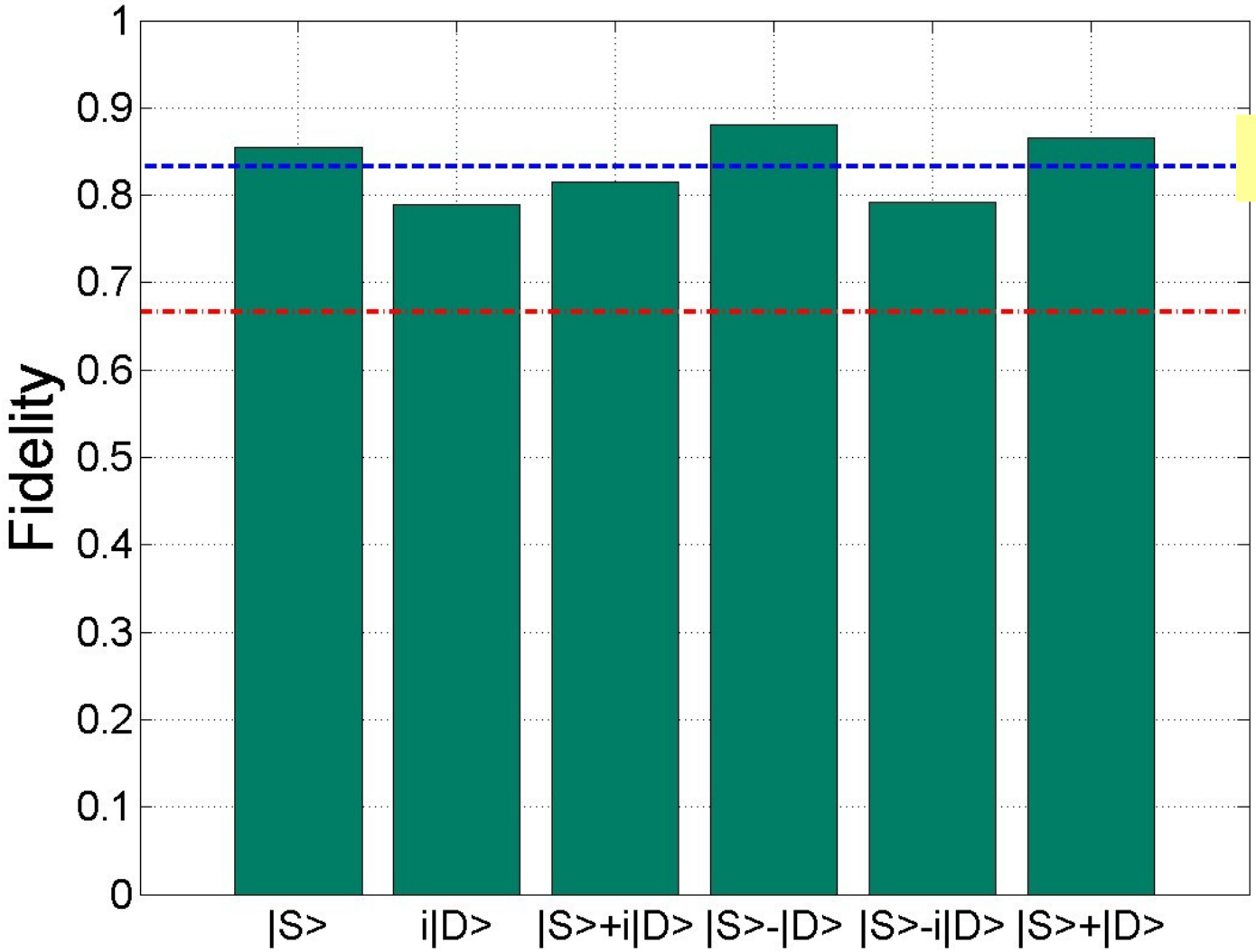




Teleportation analysis



Deterministic teleportation



Fidelity: 0.83

Classical threshold

"Deterministic teleportation with atoms"
Barrett et al., Nature **429**, 737 (2004) and Riebe et al., Nature **429**, 734 (2004)

Requirements for quantum computing

AG Quantenoptik und Spektroskopie

IQI

Classical computer

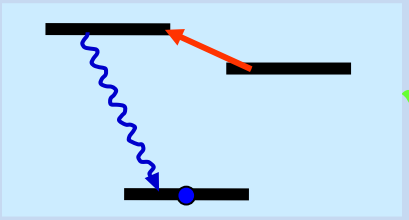
- Initialization
- 1-bit operations (NOT)
- 2-bit gates (e.g. NAND)

Computational space:

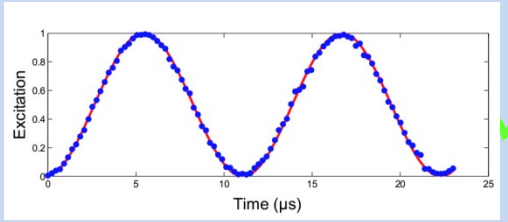
00
01
10
11

- Read out
  ➡ result

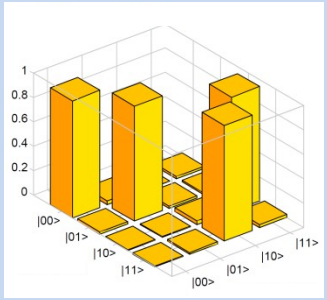
Quantum computer



- Initialization
- 1-qubit rotations
  ➡ superpositions

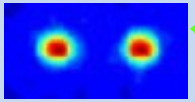


- 2-qubit gates (CNOT gate)
  ➡ entanglement



Computational space:

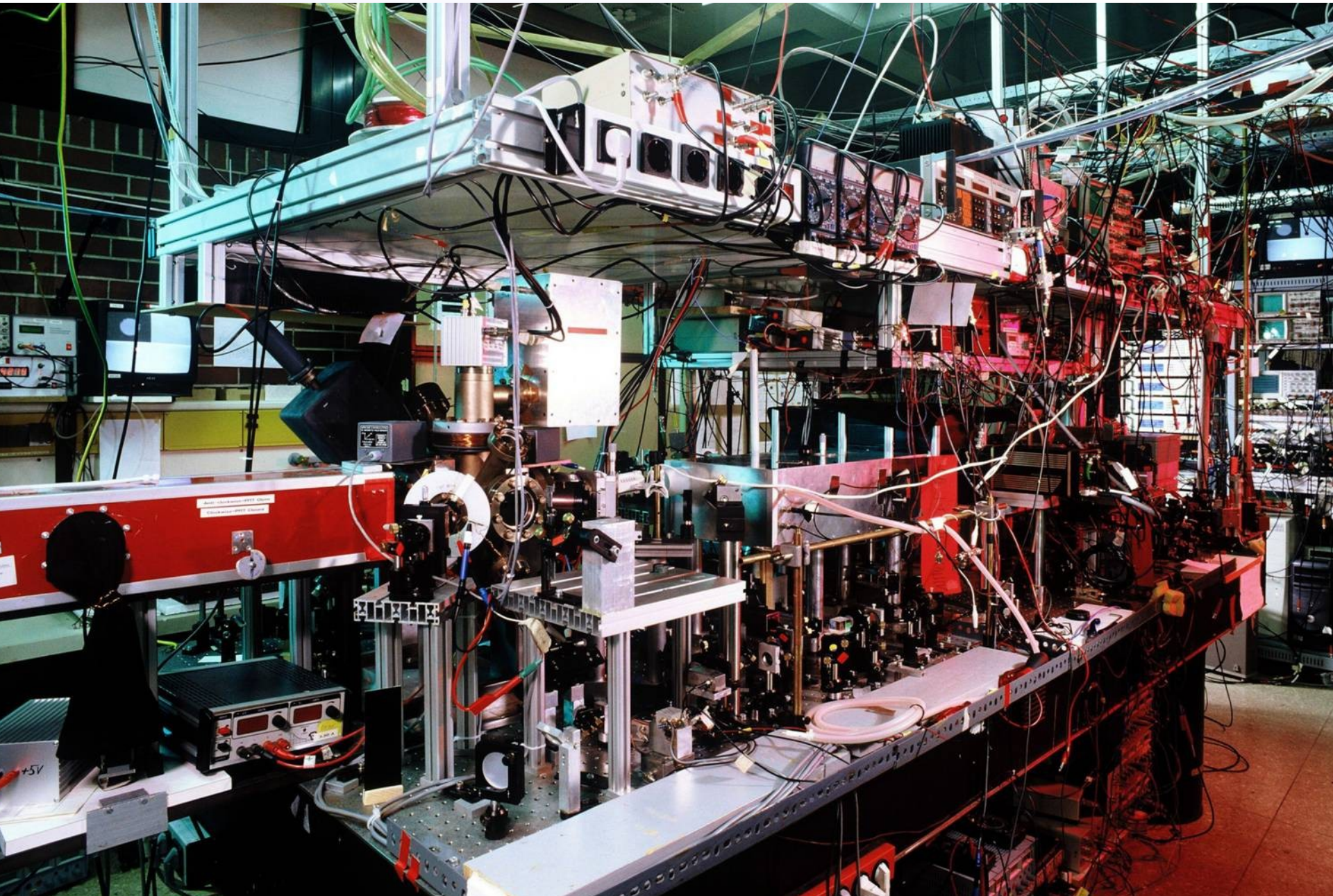
- Read out of qubits
  ➡ gain of classical information



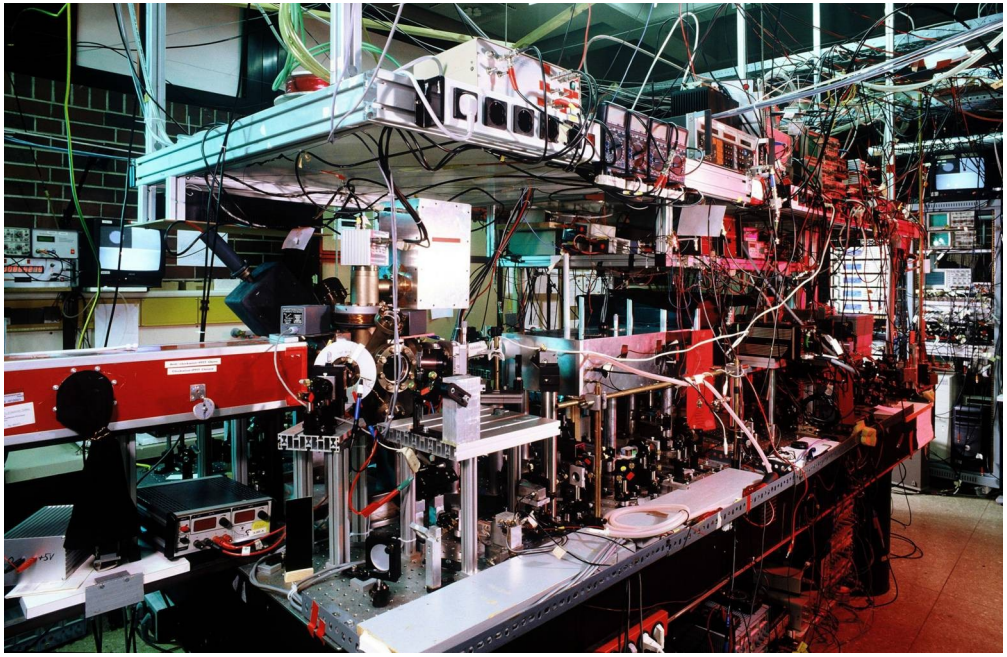
- Physics and information
- Ion trap quantum computing
- Teleportation
- Scaling of ion trap quantum computers

AG Quantenoptik
und Spektroskopie

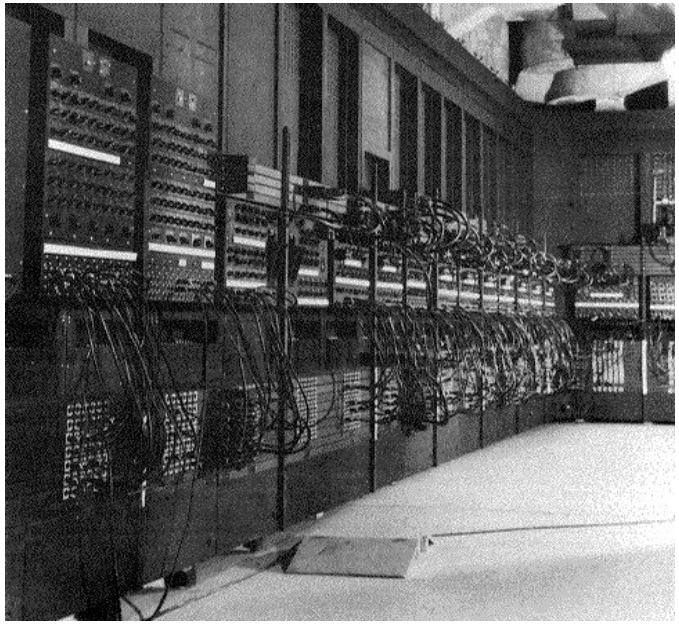
The hardware



The hardware

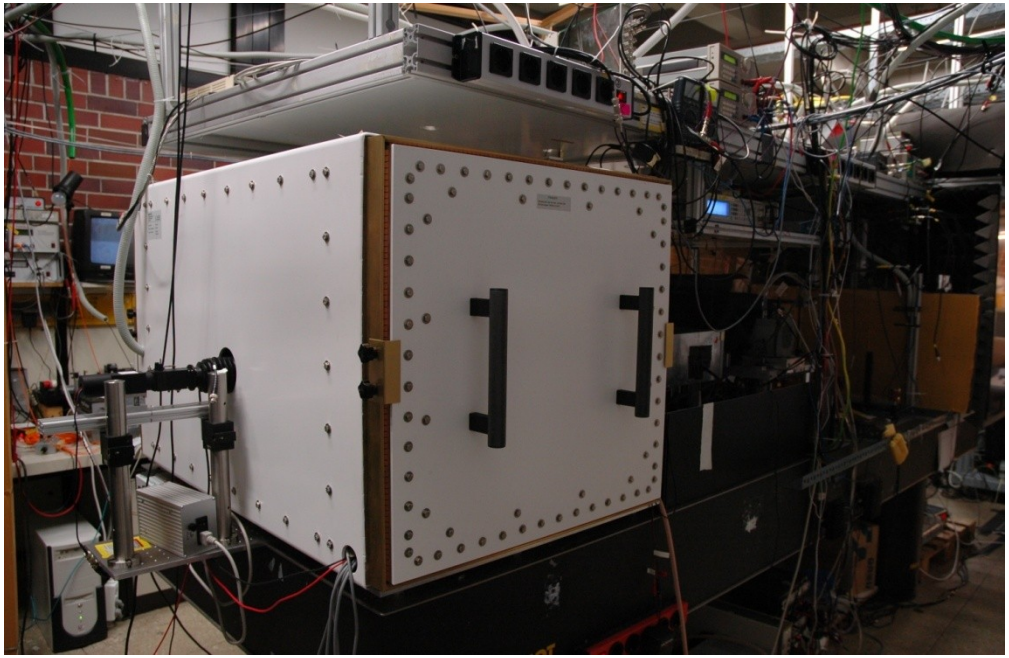


Innsbruck quantum computer, 2005

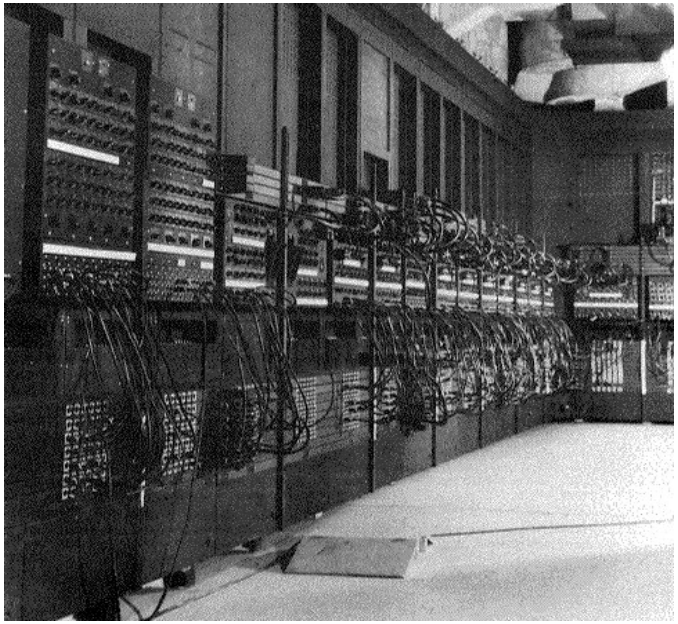


ENIAC, 1950

The hardware



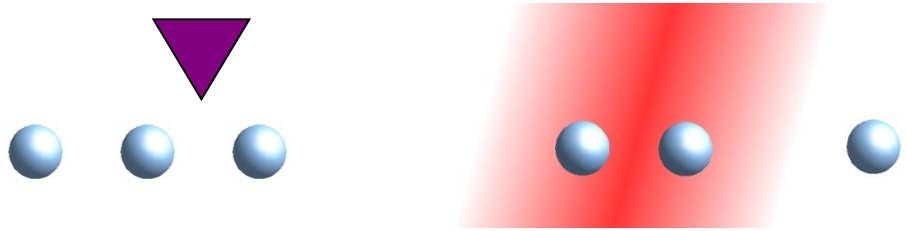
Innsbruck quantum computer, 2009

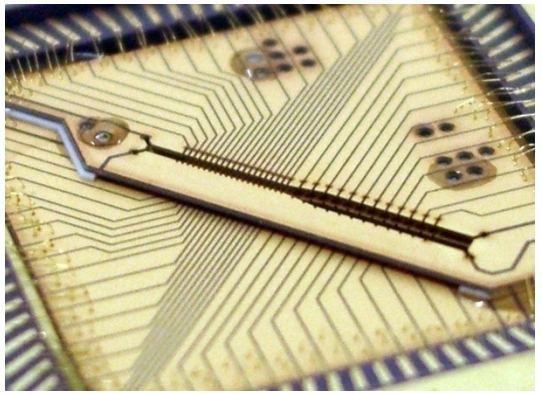


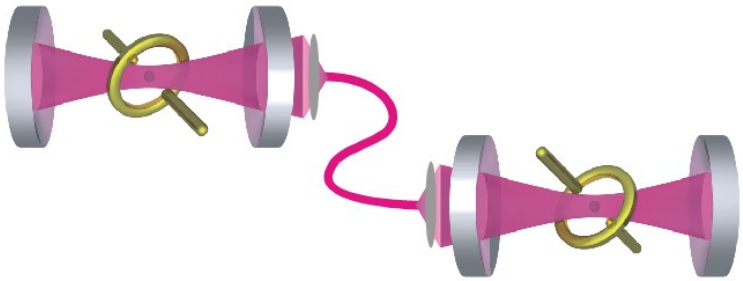
ENIAC, 1950

Scaling of ion trap quantum computers

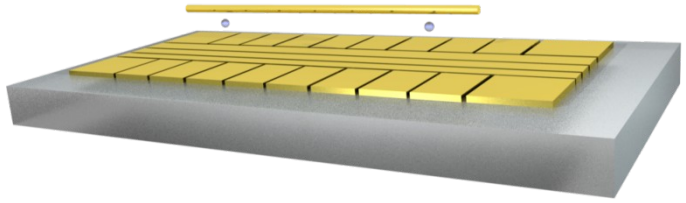
Kielpinski, Monroe, Wineland







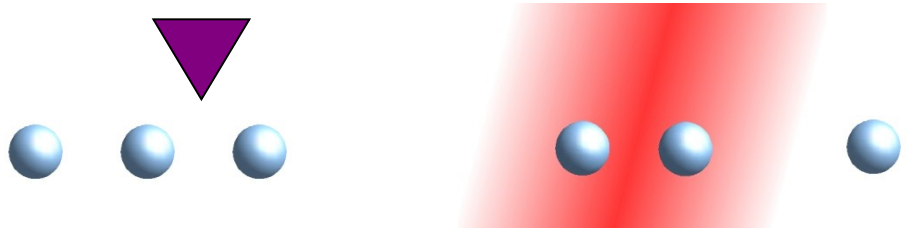
Cirac, Zoller, Kimble, Mabuchi

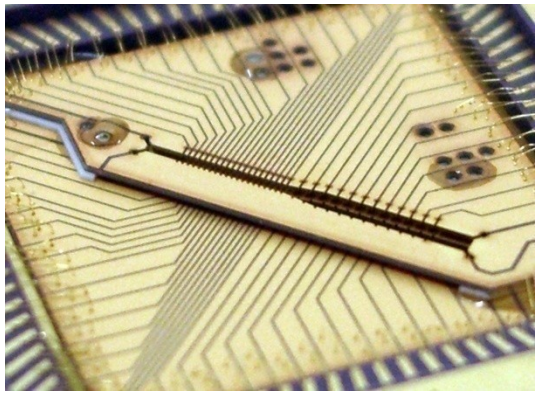


Zoller, Tian, Blatt

Scaling of ion trap quantum computers

Kielpinski, Monroe, Wineland





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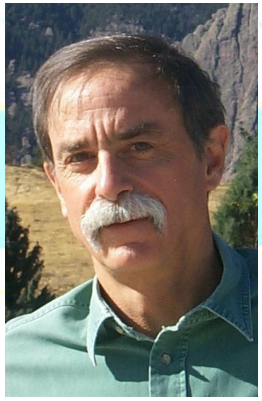
Scaling ion trap quantum computing

IQI



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

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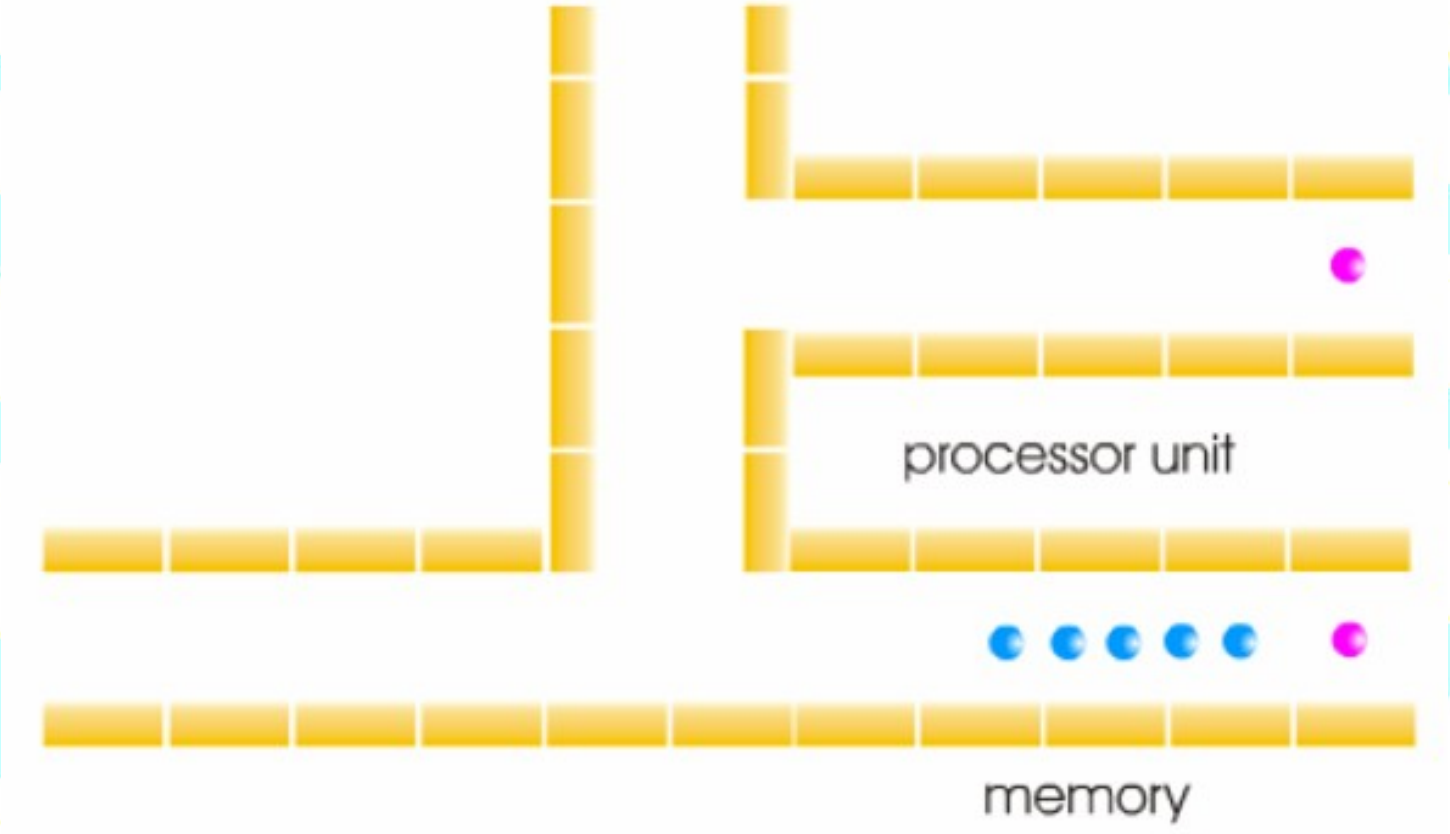
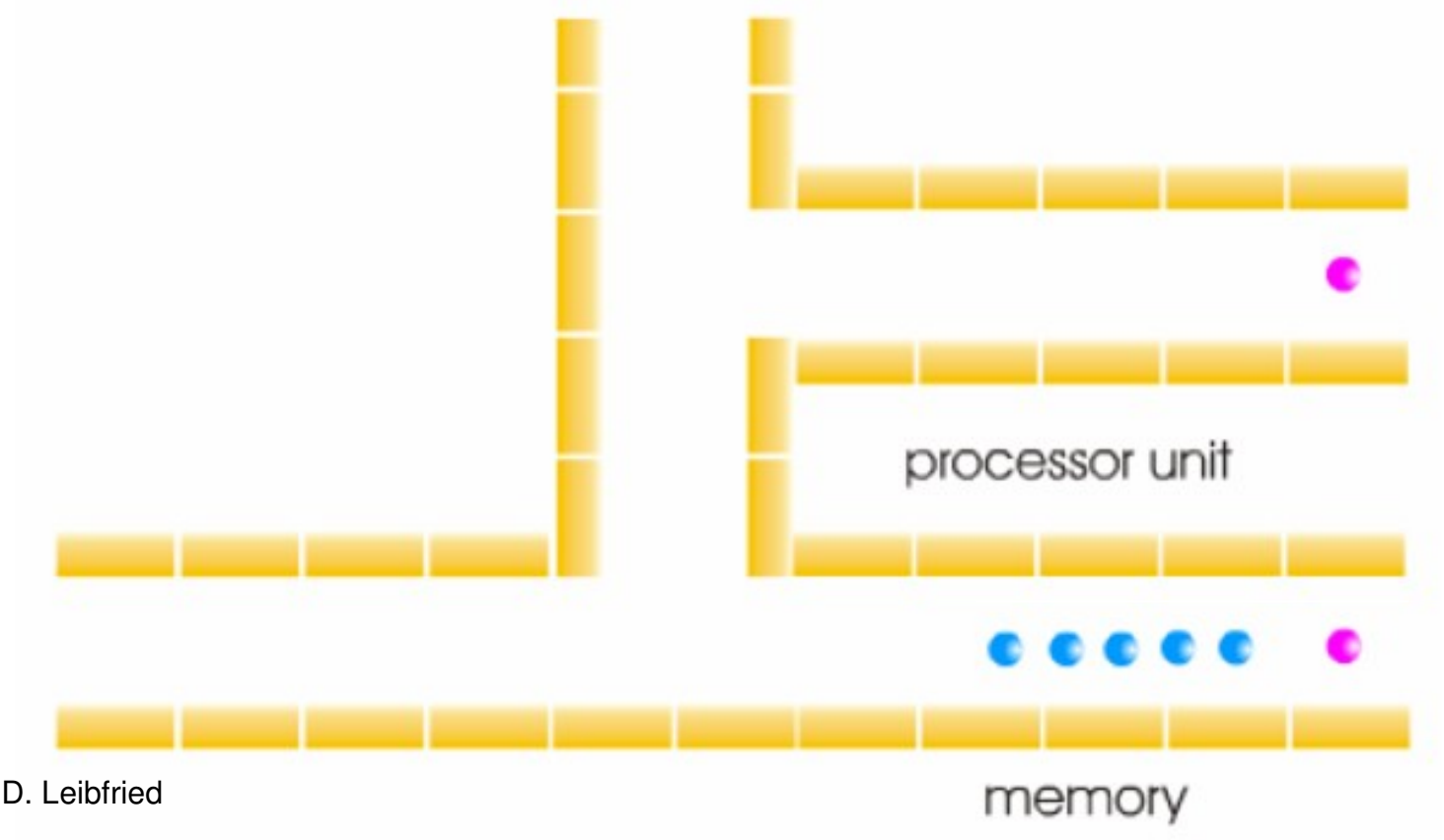
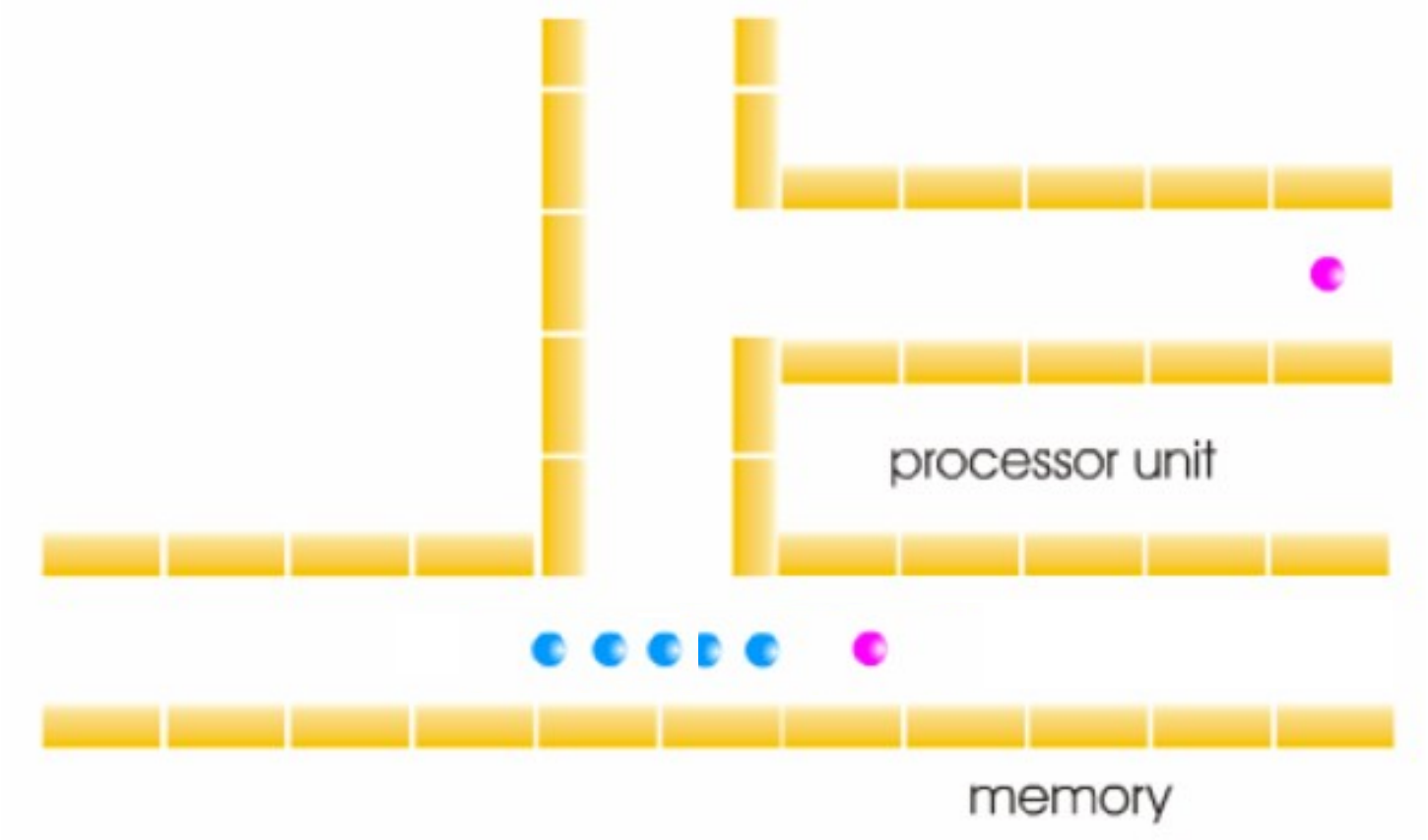
Scaling ion trap quantum computing



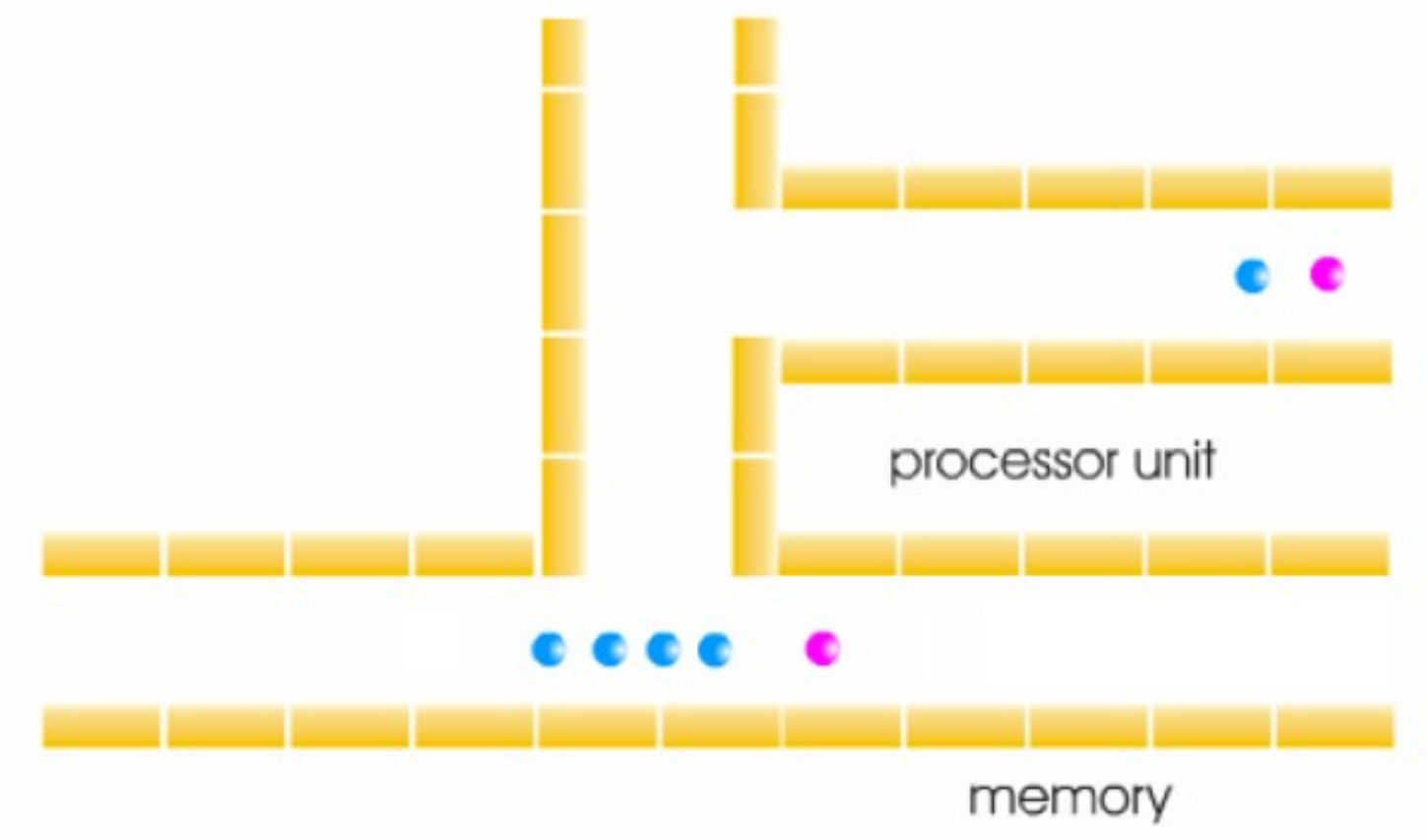
Scaling ion trap quantum computing



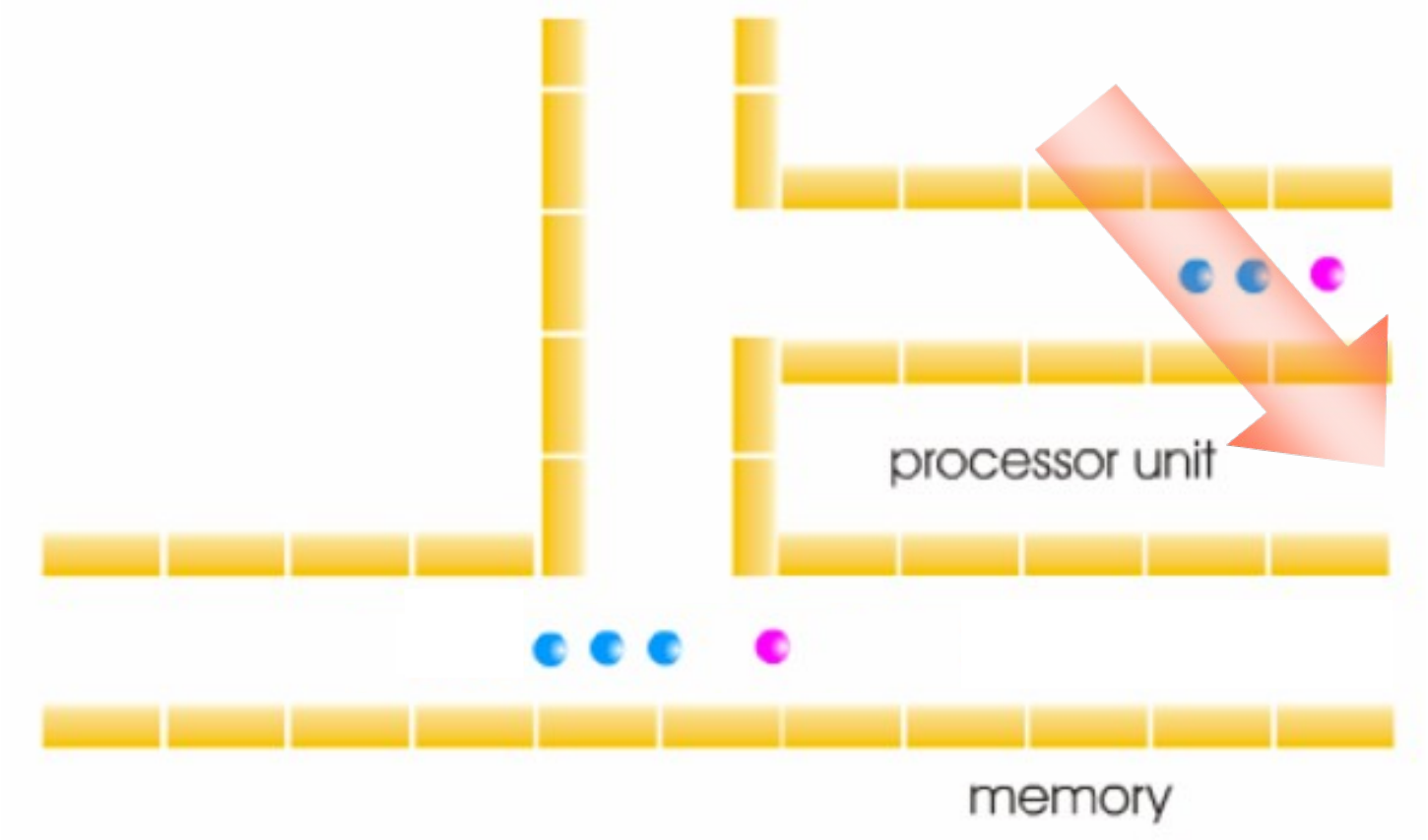
Scaling ion trap quantum computing



Scaling ion trap quantum computing

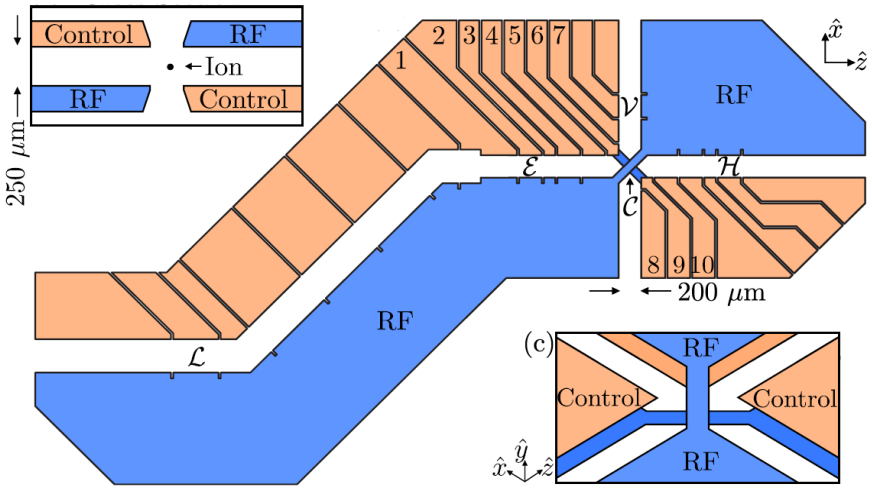


Scaling ion trap quantum computing

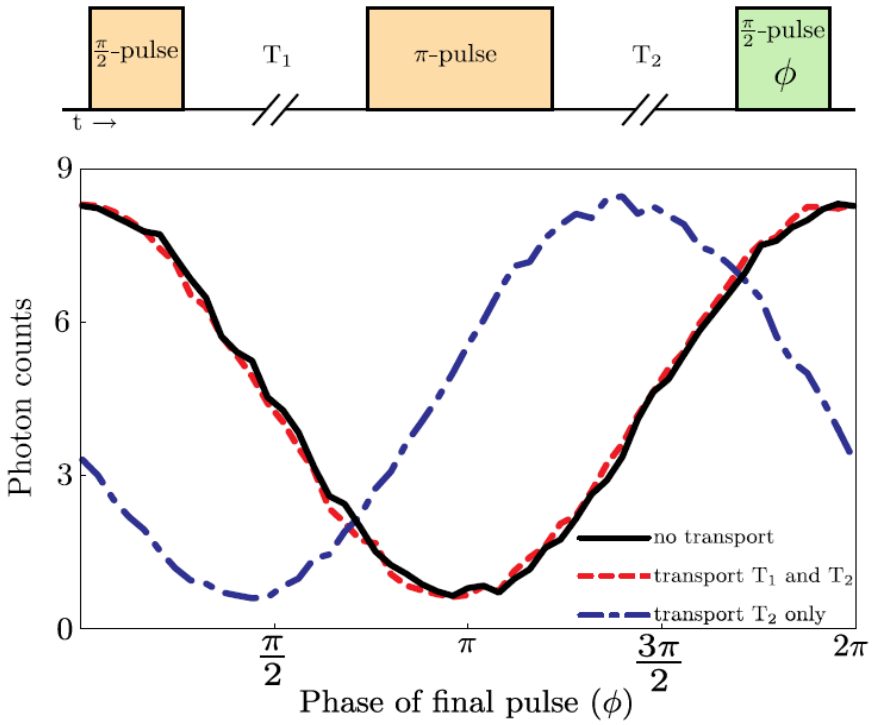


„Architecture for a large-scale ion-trap quantum computer“,
D. Kielpinski et al., Nature **417**, 709 (2002).

Coherent transport through a junction



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

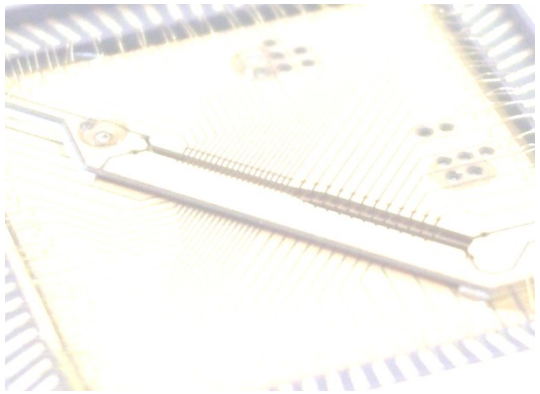


NIST:

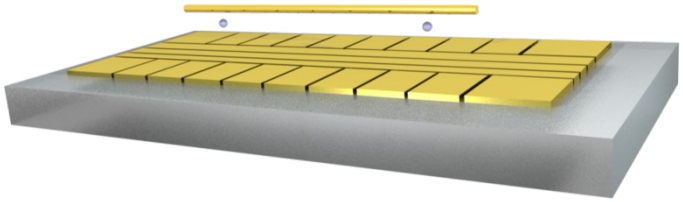
Blakestad, *et al.,"High fidelity transport of trapped-ion qubits through an X-junction trap array"*, arXiv:0901.0533v1

Scaling of ion trap quantum computers

Kielpinski, Monroe, Wineland



Cirac, Zoller, Kimble, Mabuchi



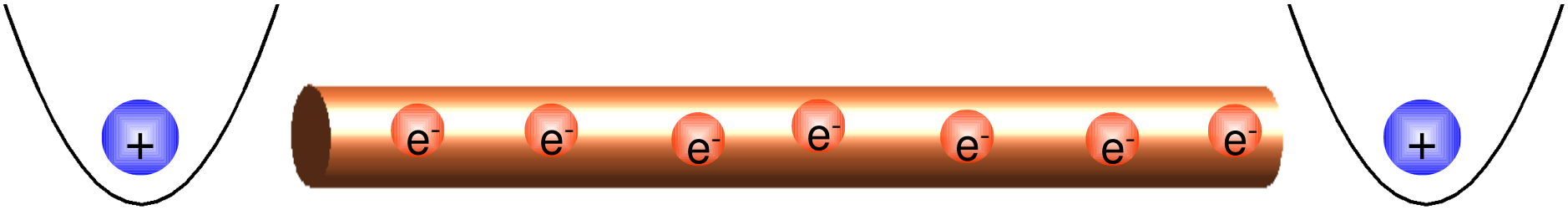
Zoller, Tian, Blatt

Wiring up trapped ions

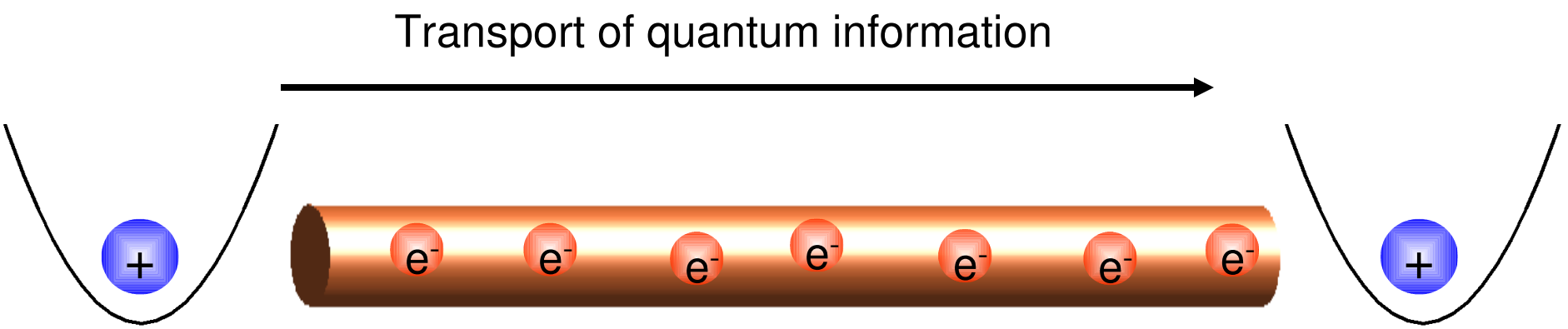
Two trapped ions …

Wiring up trapped ions

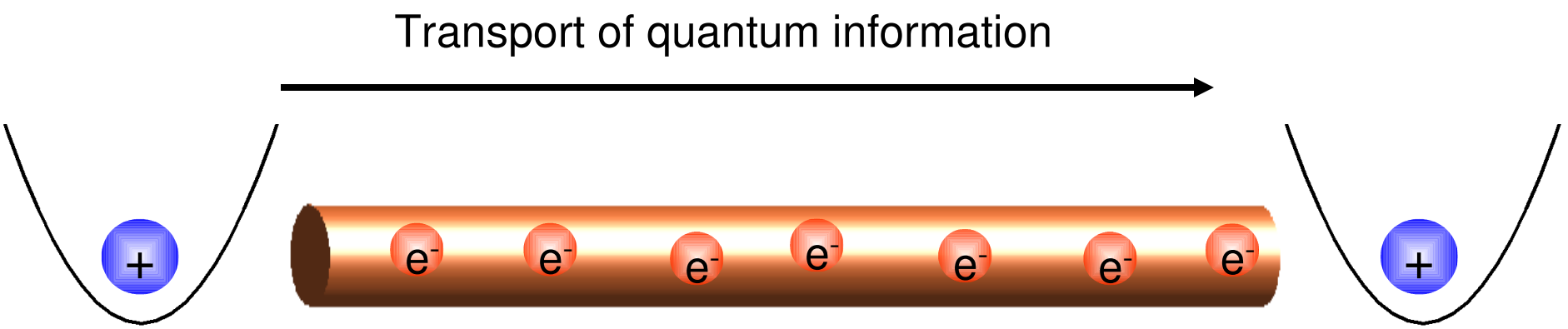
Two trapped ions + a wire



Wiring up trapped ions



Wiring up trapped ions



No trace of the quantum information should remain in the wire

➡ ~~super conducting~~ wire

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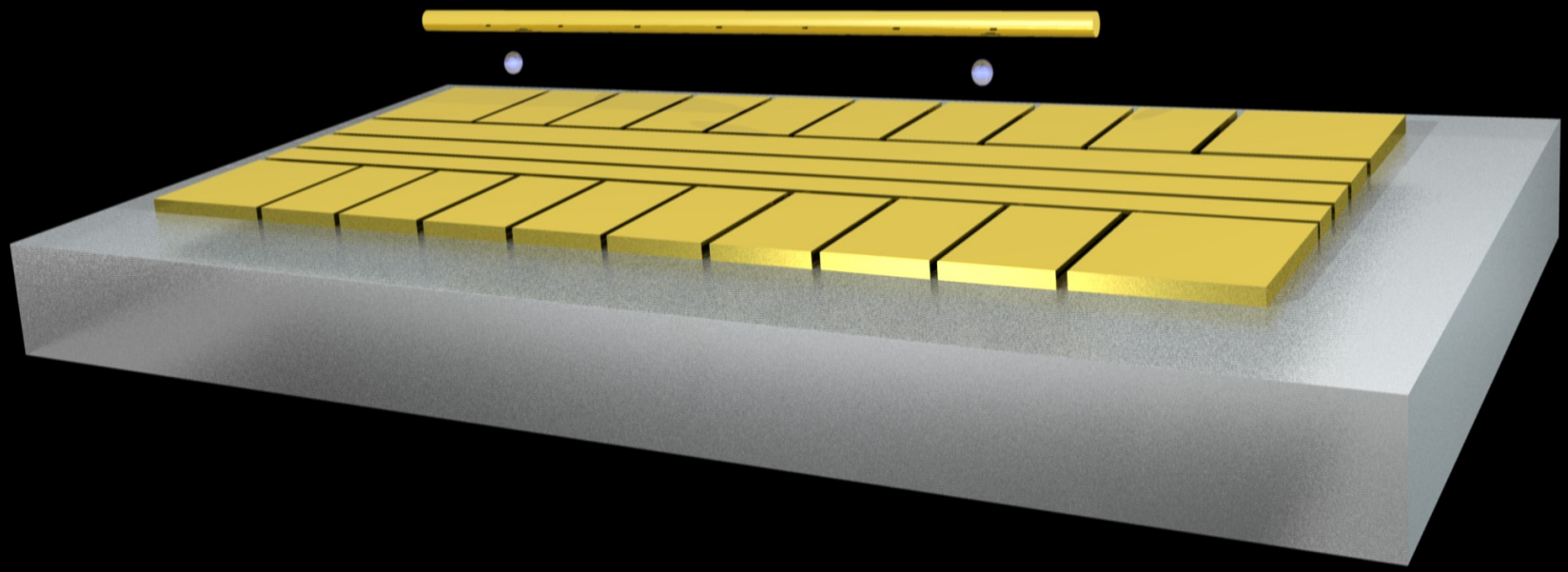
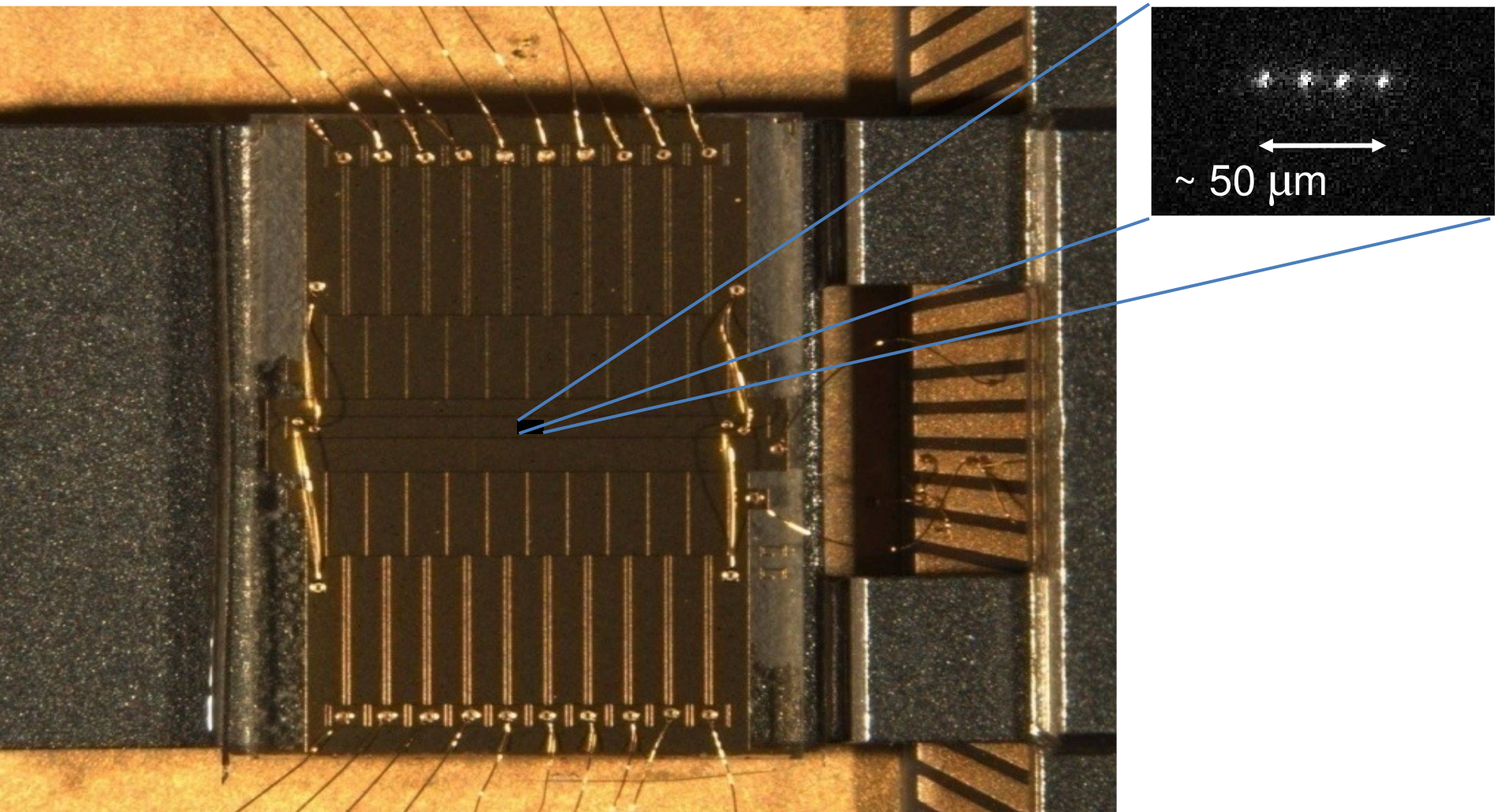
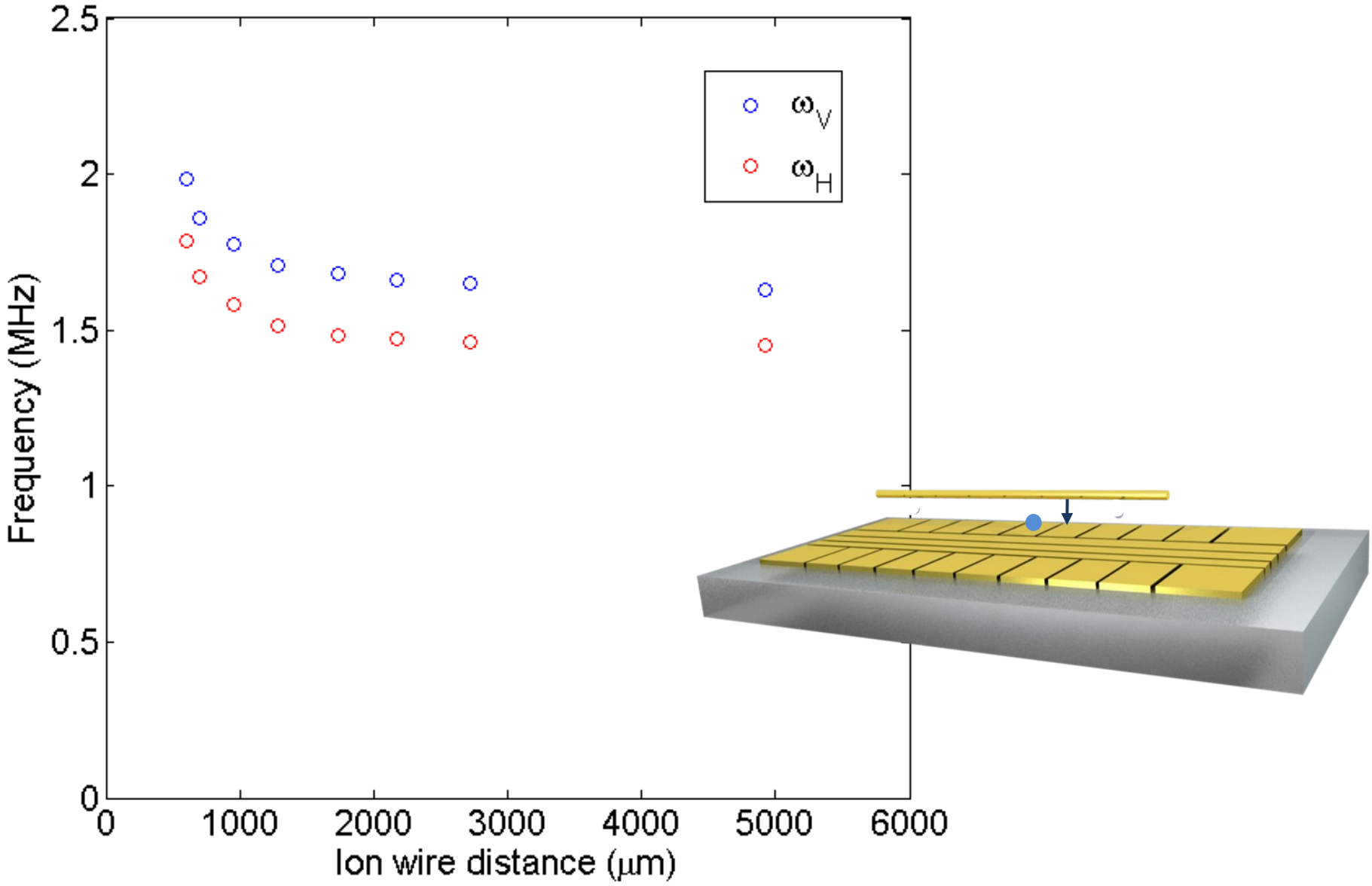
Experimental set-up



Experimental set-up



Moving the wire in



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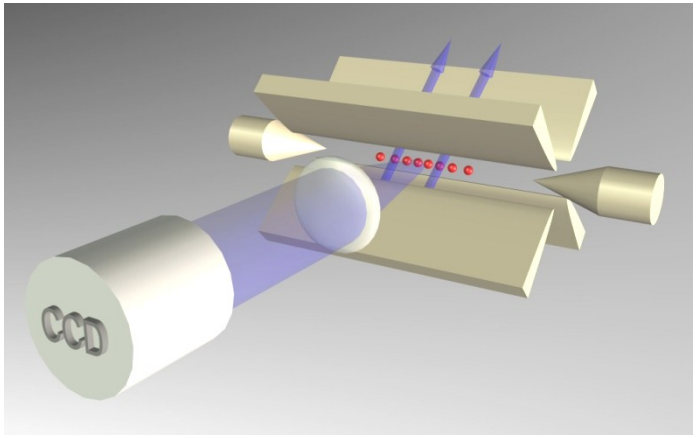
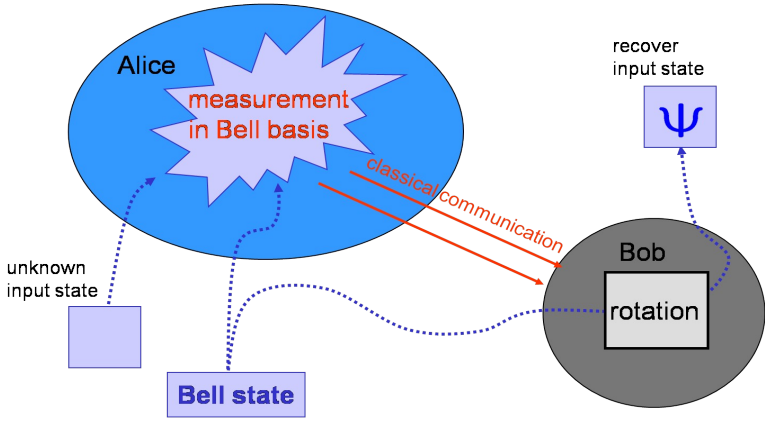
Conclusions

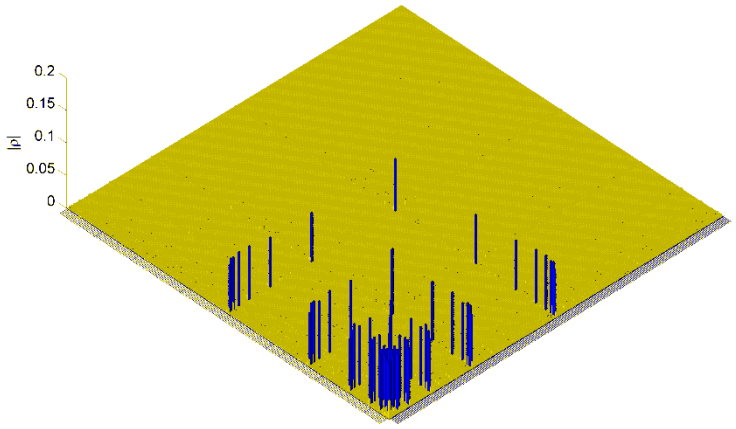
Ion trap quantum computing



Teleportation



Entanglement



Scaling of ion traps

AG Quantenoptik
und Spektroskopie

The Innsbruck ion trap group

universität
innsbruck

€

FWF
SFB

CONQUEST
SCALA

Industrie
Tirol

IQI
GmbH

FWF bm:bwk

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DTO