Quantum computing with trapped ions - real thought experiments

Hartmut Häffner

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

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

€ FWF SFB
SCALA QGATES
Industrie Tirol
IQI GmbH
FWF Der Wissenschaftsfonds.
bm:bwk
$ IARPA

Toronto, Sep 24th 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)

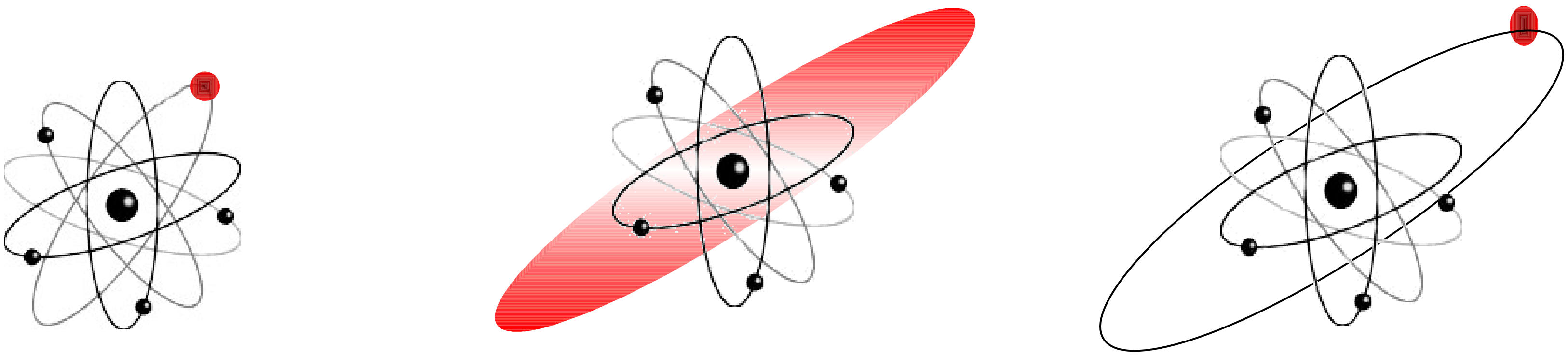
➡ Information is quantum mechanical

Classical information is a subset in quantum information

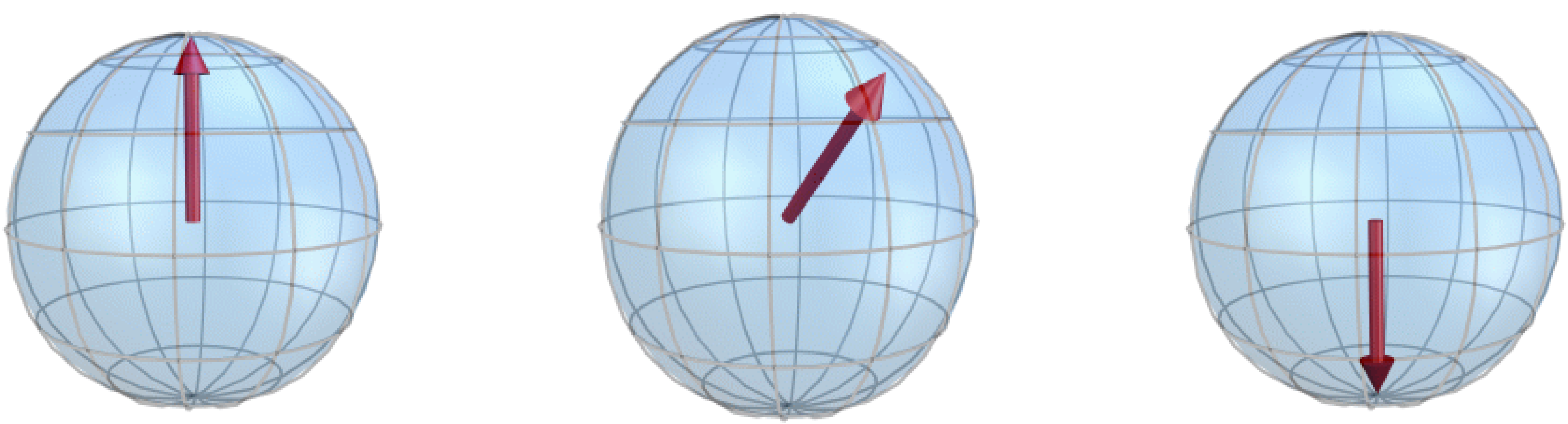
Quantum information: strip down quantum mechanics to bare bones.

- Hilbert space
- unitary operations
- measurement

Qubits



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



Information content

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

# 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

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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	Each atom in the universe holds on bit.

Why quantum information ?

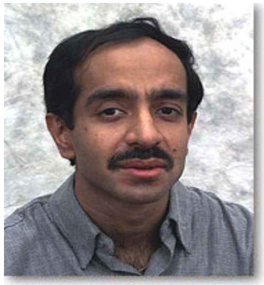
Schrödinger equation for 300 interacting spins.

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

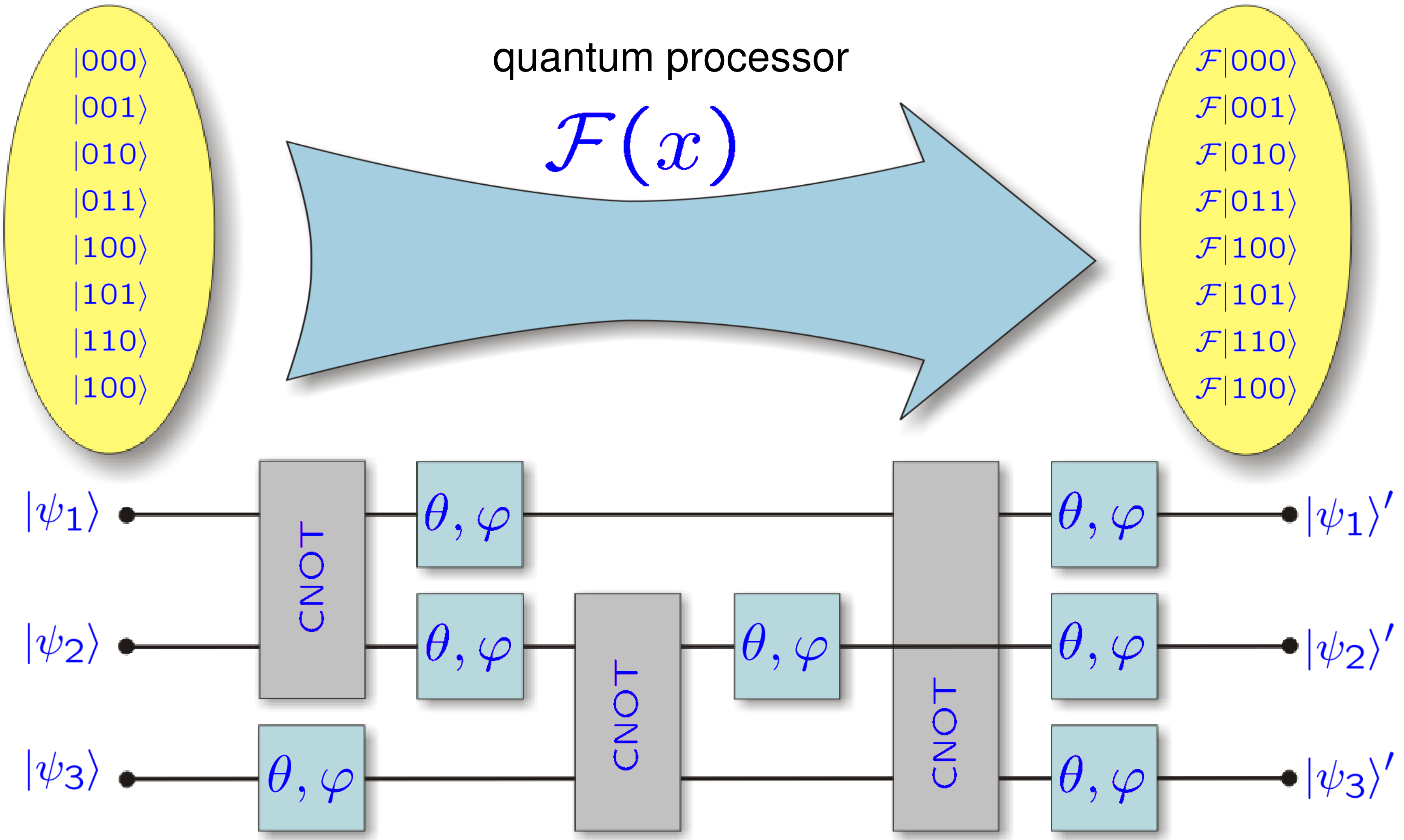
Quantum computer

- 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

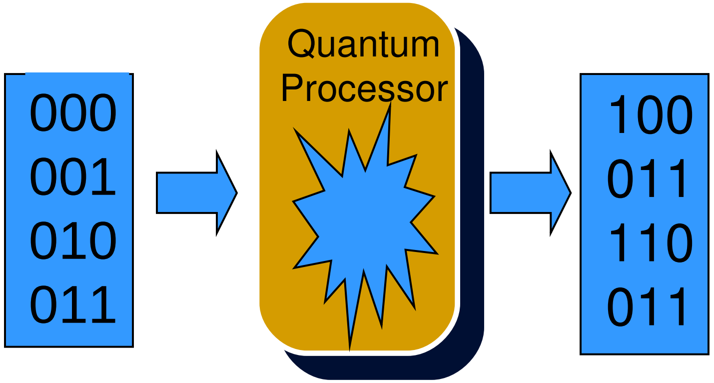
Quantum computing



Input ➡ computation: sequence of quantum gates ➡ output

Quantum computing

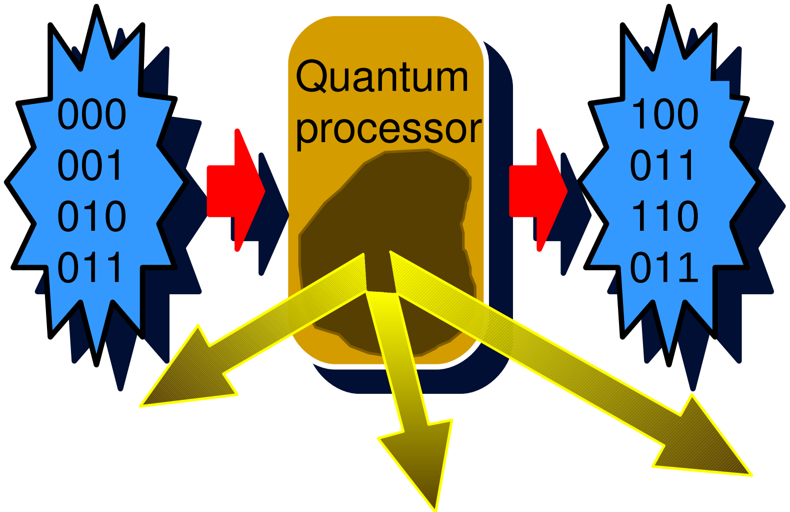
Long term goal: A universal quantum computer

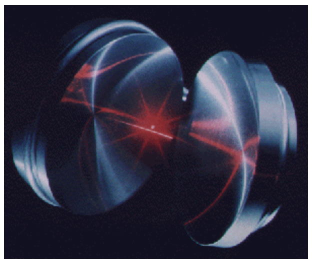


In the mean time:

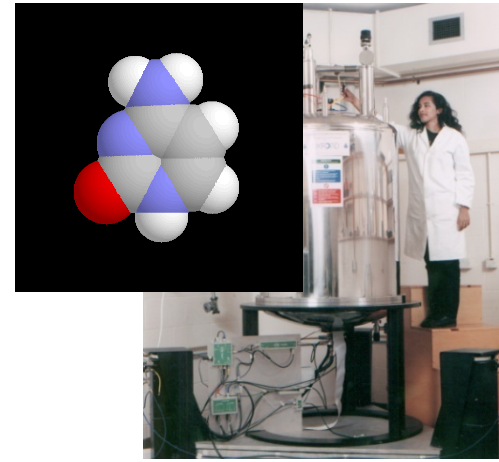
- "understand" quantum mechanics
- apply quantum mechanics
- where does quantum mechanics fail?

Which technology ?

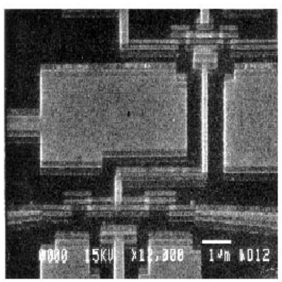




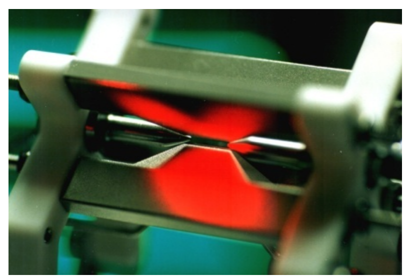
Cavity QED

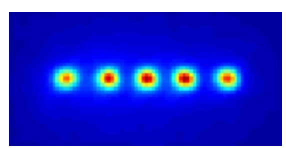


NMR

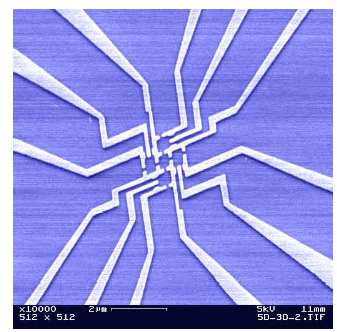


Superconducting qubits



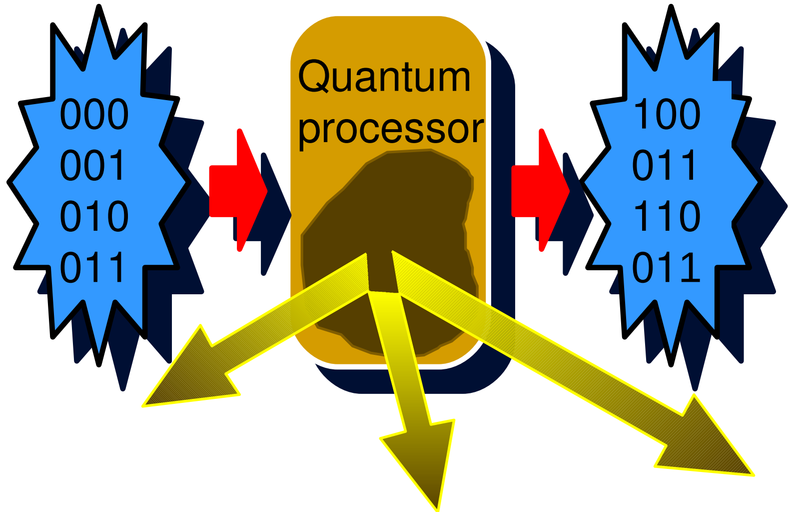


Trapped atoms/ions



Quantum dots

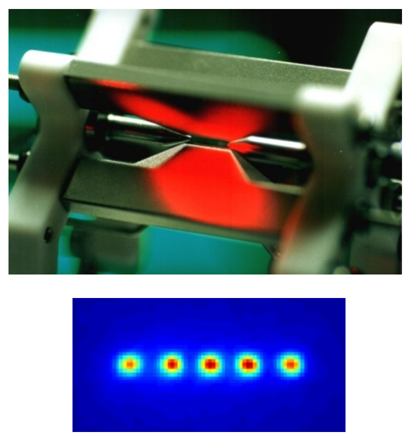
Which technology ?



Cavity QED

NMR

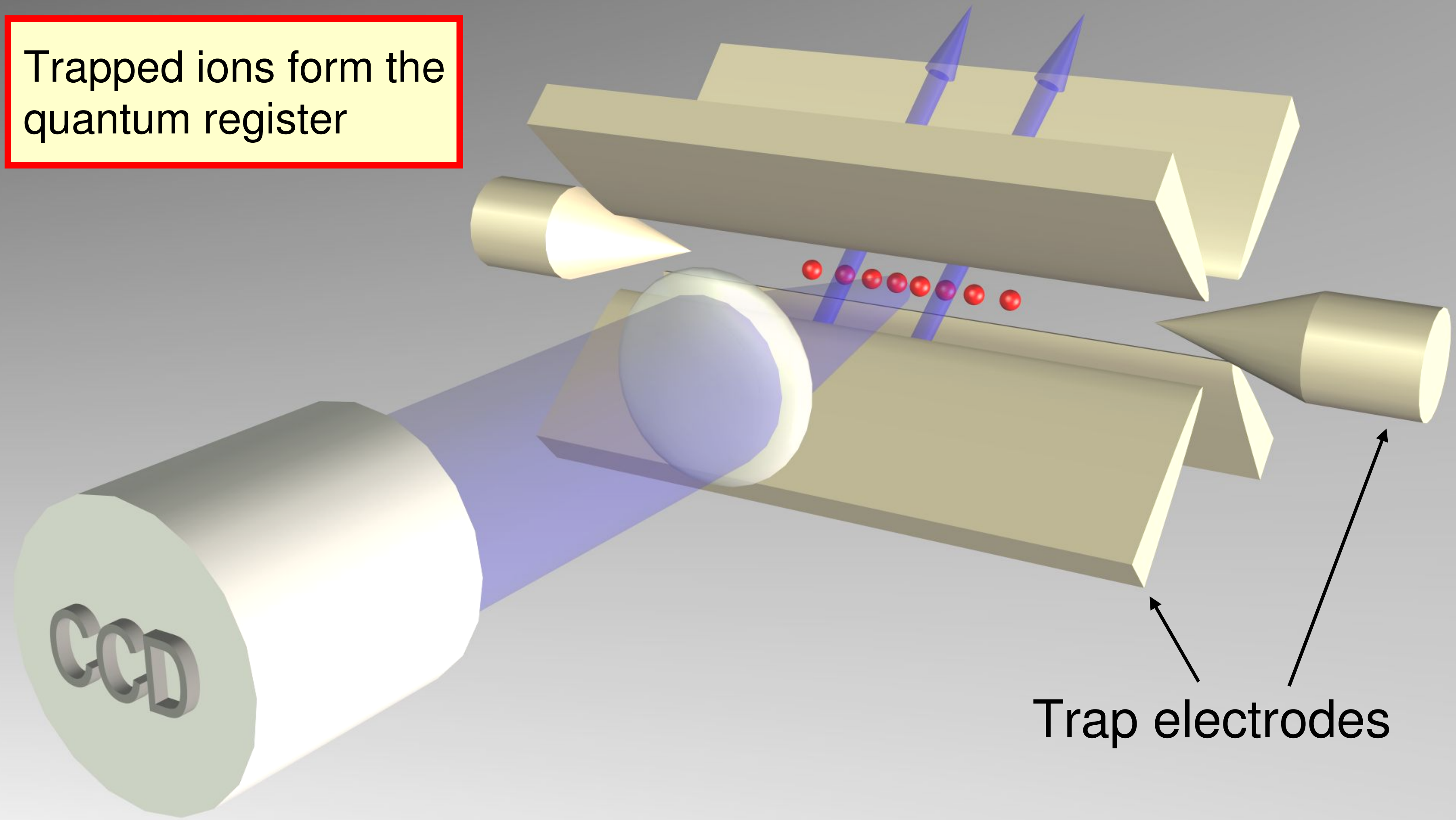
Superconducting qubits



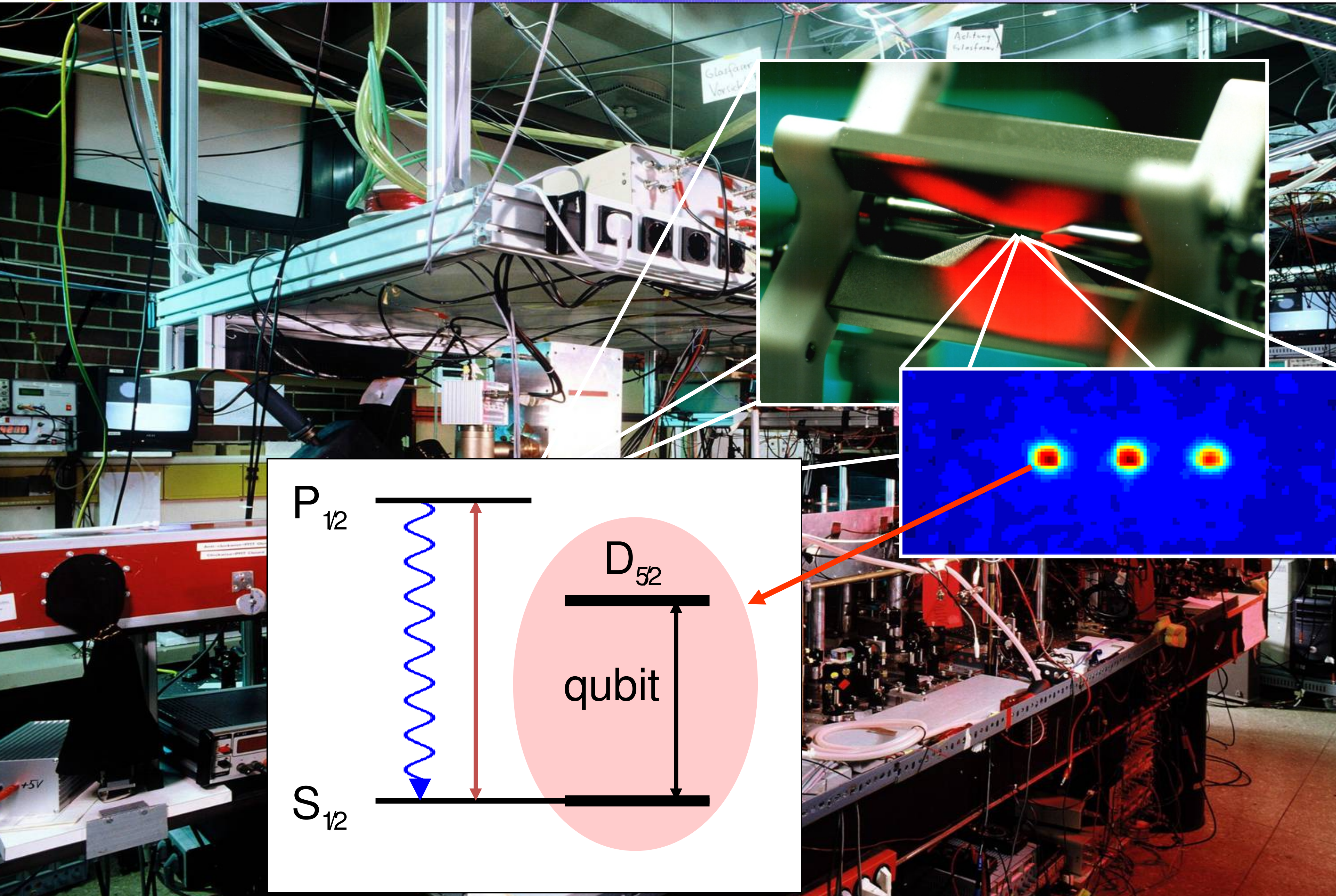
Trapped atoms/ions

Quantum dots

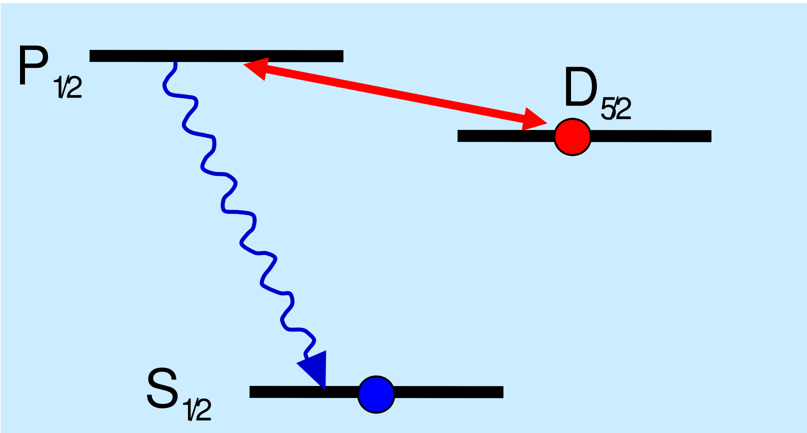
Ion trap quantum computing



The hardware

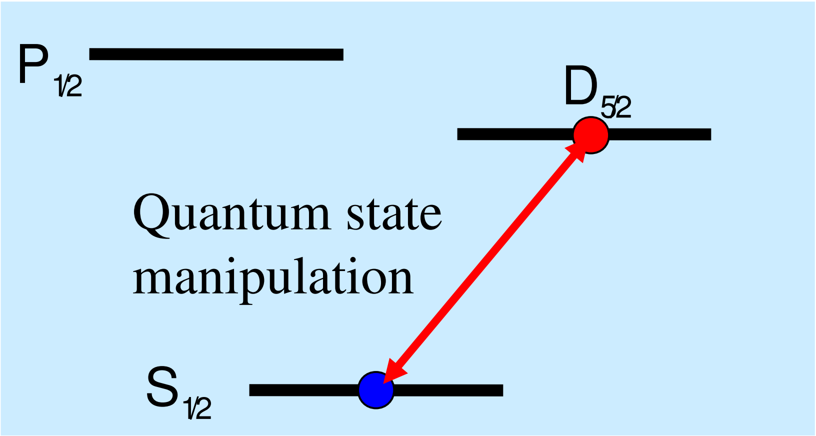


Experimental procedure



1. Initialization in a pure quantum state

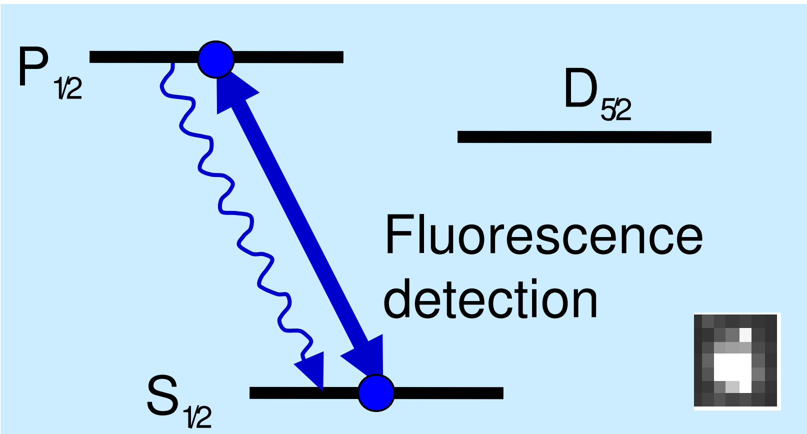
Experimental procedure



1. Initialization in a pure quantum state

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

Experimental procedure

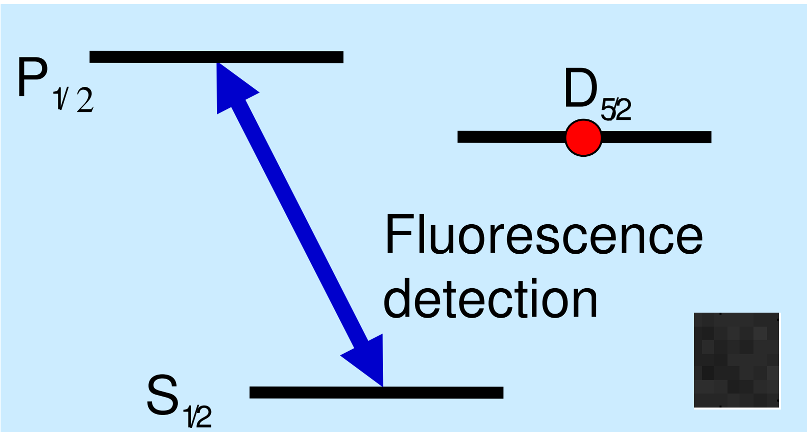


1. Initialization in a pure quantum state

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

3. Quantum state measurement by fluorescence detection

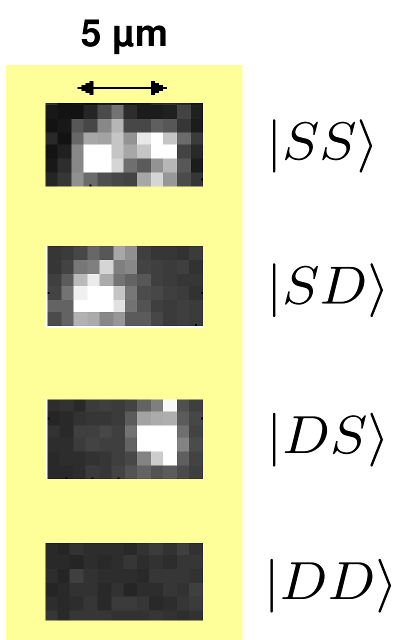
Experimental procedure



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

<u>Two ions:</u>

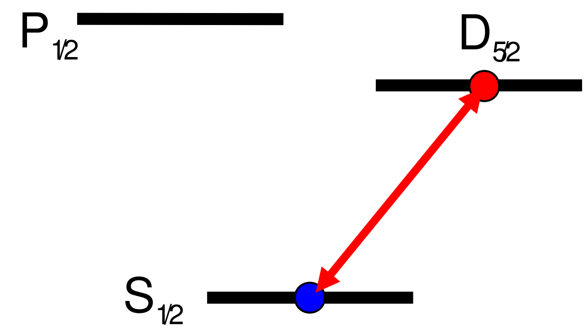
Spatially resolved detection with CCD camera

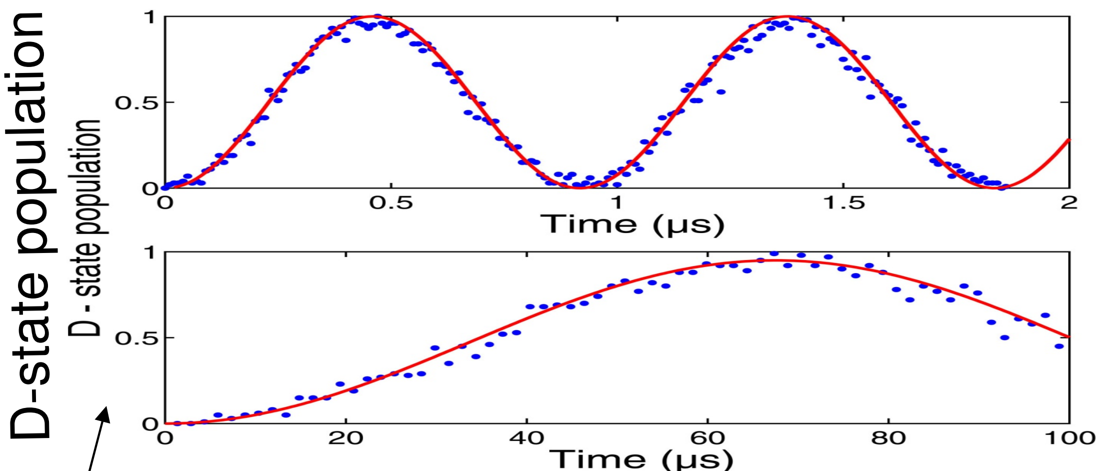


50 experiments / s

Repeat experiments 100-200 times

Rabi oscillations

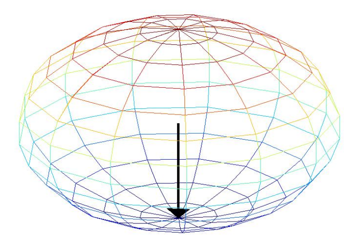




$|S\rangle$

$|D\rangle$

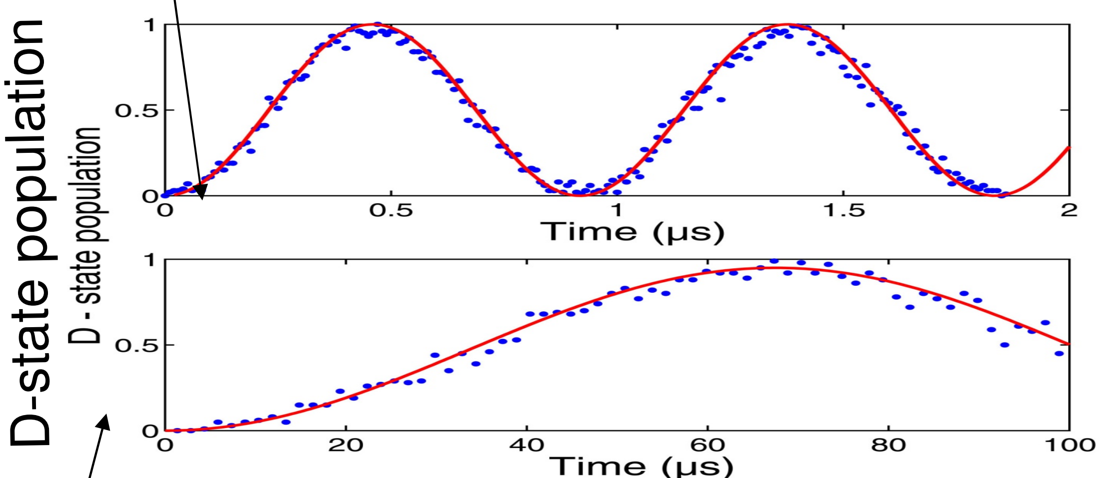
$$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$$



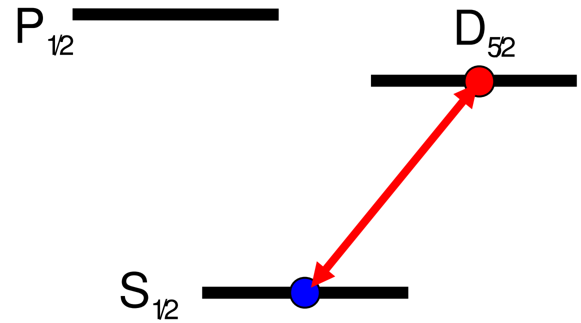
$|S\rangle$

Rabi oscillations

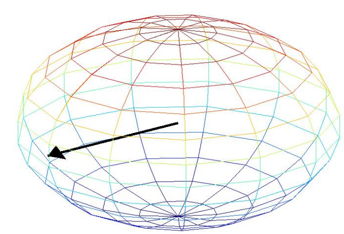
$$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$$



$$|S\rangle$$



$$|D\rangle$$



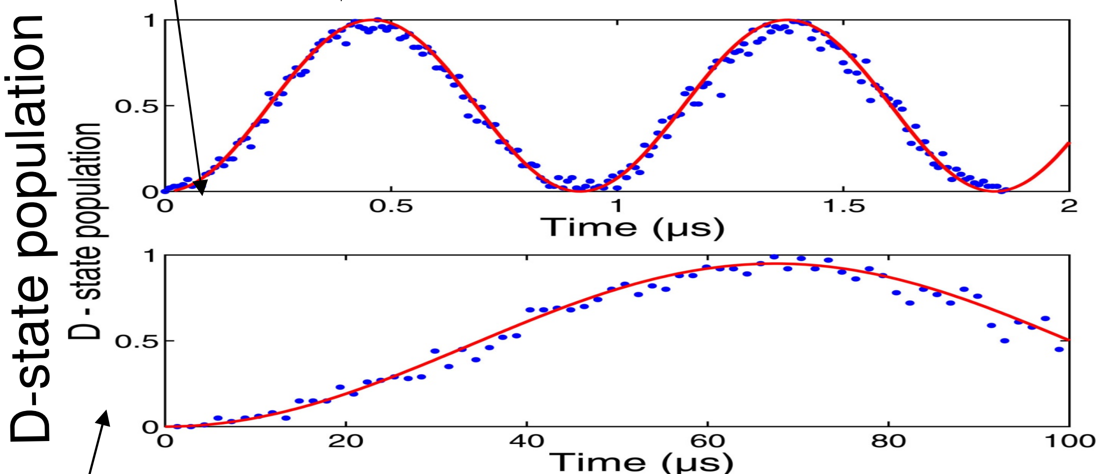
$$\frac{|S\rangle + |D\rangle}{\sqrt{2}}$$

$$|S\rangle$$

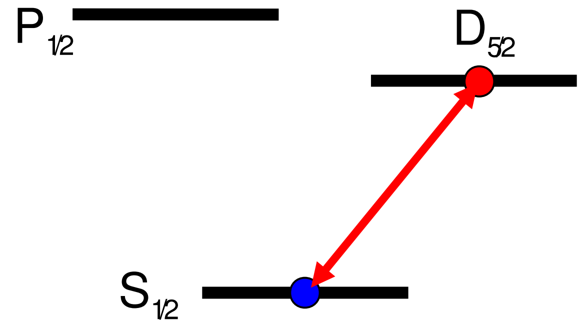
Rabi oscillations

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

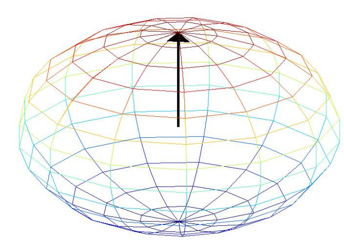
$$|D\rangle$$



$$|S\rangle$$



$$|D\rangle$$



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

$$|S\rangle$$

Requirements for quantum computing

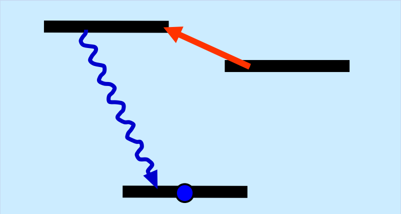
Classical computer

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

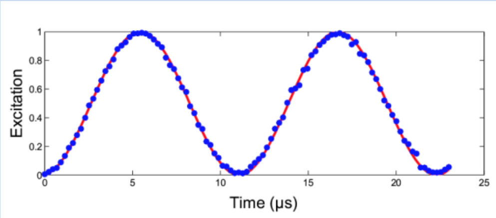
Computational space: 00 01 10 11

- Read out
  ➡ result

Quantum computer

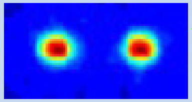


- Initialization ✓



- 1-qubit rotations
  ➡ superpositions ✓
- 2-qubit gates (CNOT gate)
  ➡ entanglement

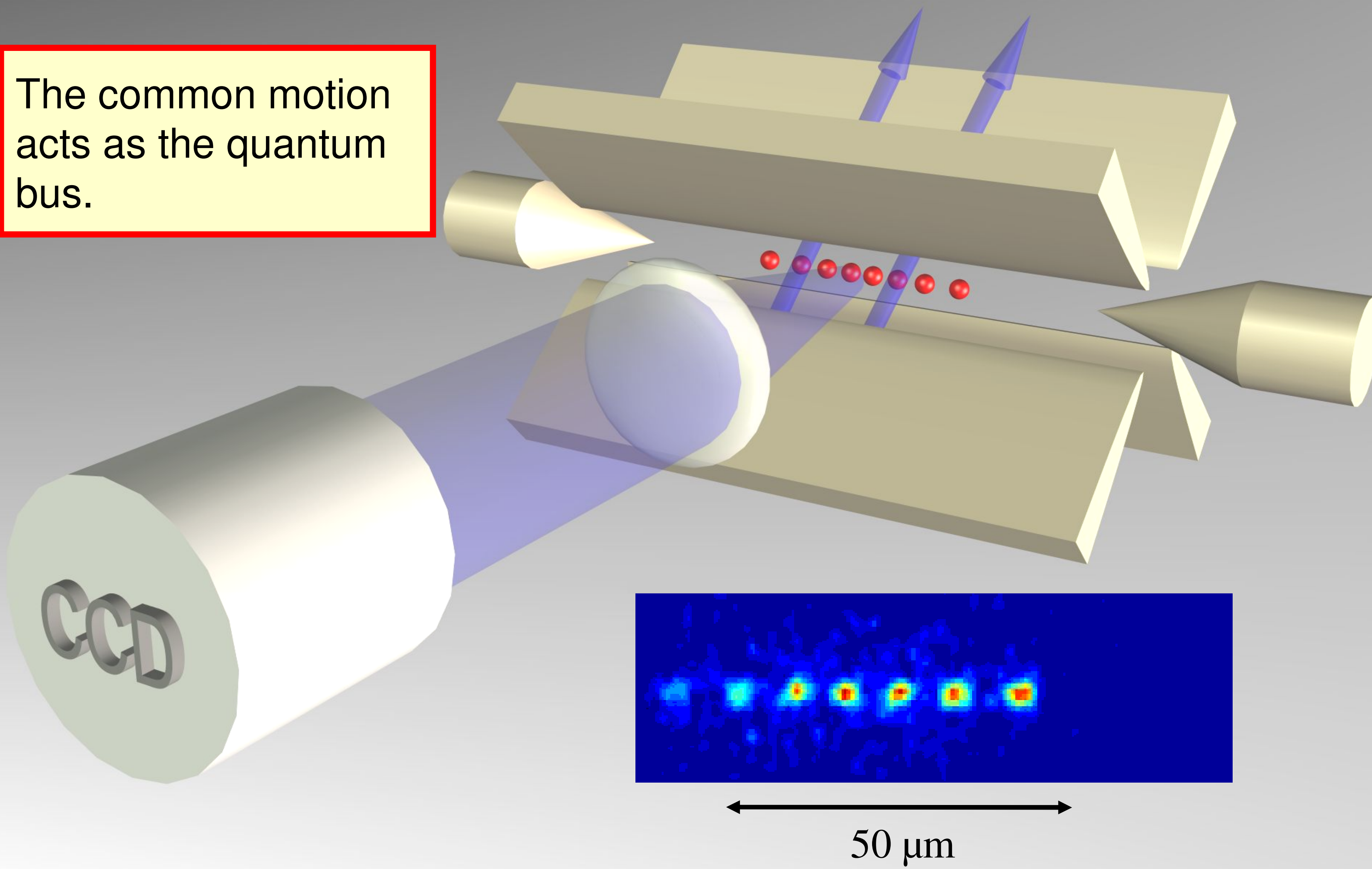
Computational space:



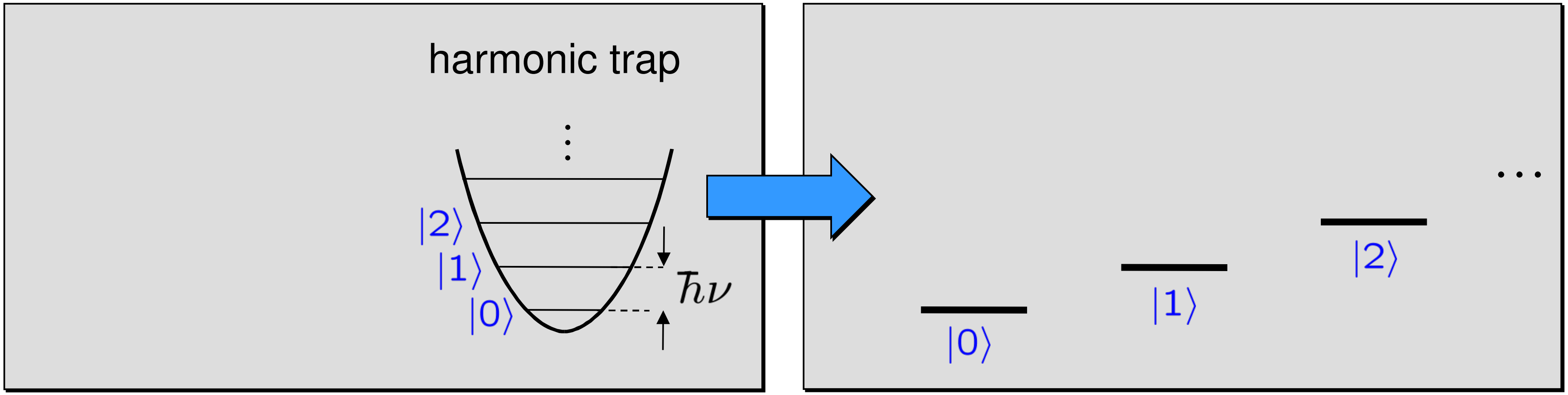
- Read out of qubits ✓
  ➡ gain of classical information

Having the qubits interact

The common motion acts as the quantum bus.

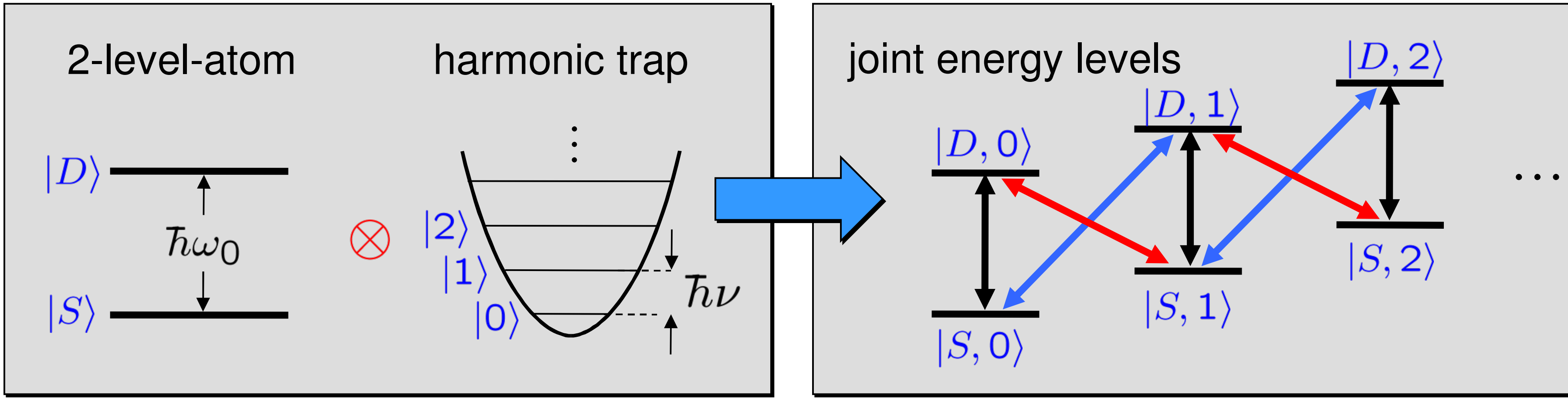


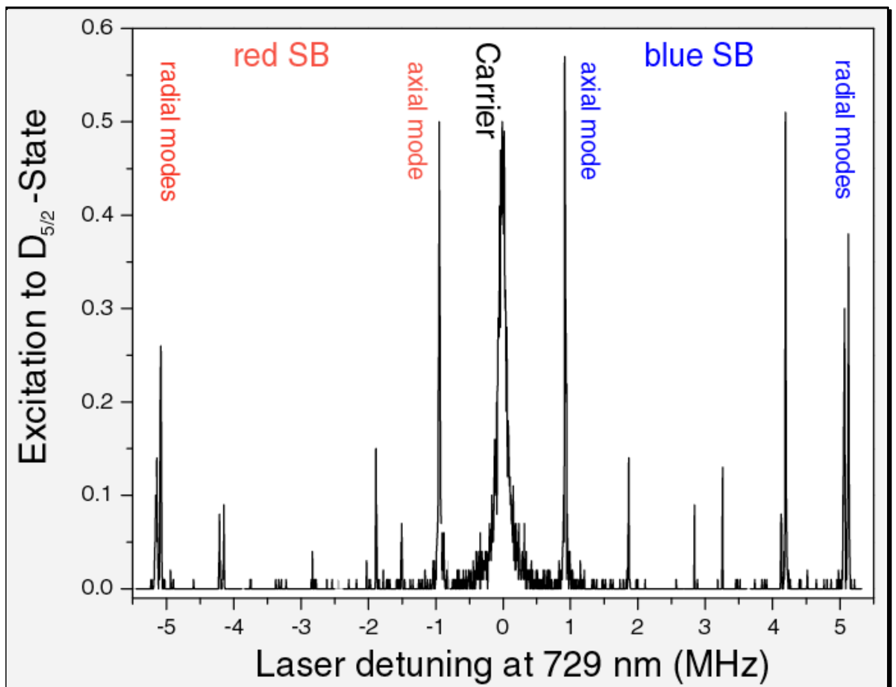
Ion motion



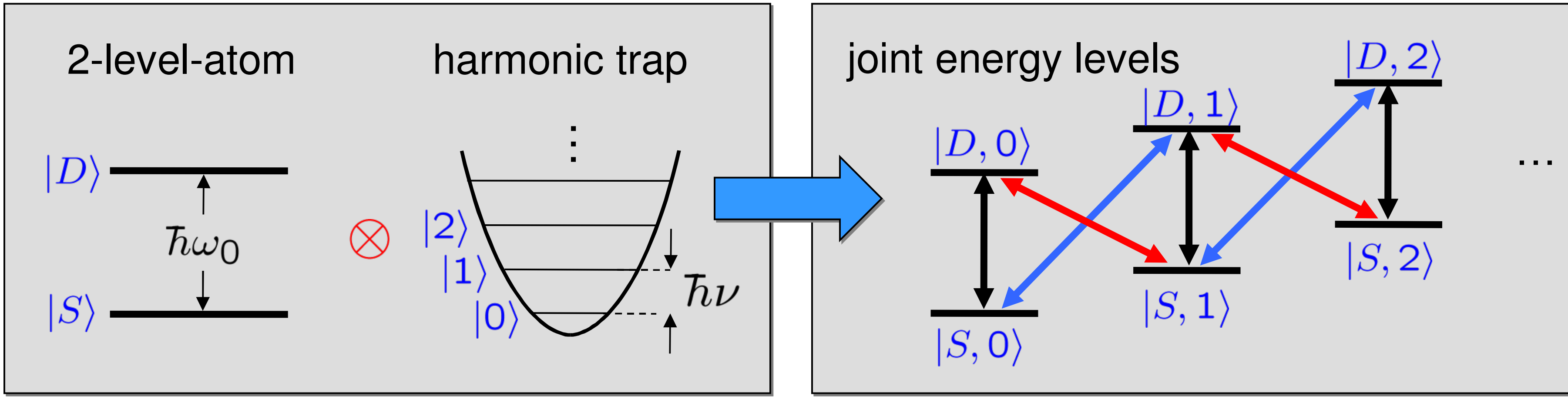
harmonic trap
$|2\rangle$
$|1\rangle$
$|0\rangle$
$\hbar\nu$
$|0\rangle$
$|1\rangle$
$|2\rangle$
$\cdots$

Ion motion


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


red SB
blue SB
radial modes
axial mode
Carrier
axial mode
radial modes
Excitation to $D_{5/2}$-State
Laser detuning at 729 nm (MHz)
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

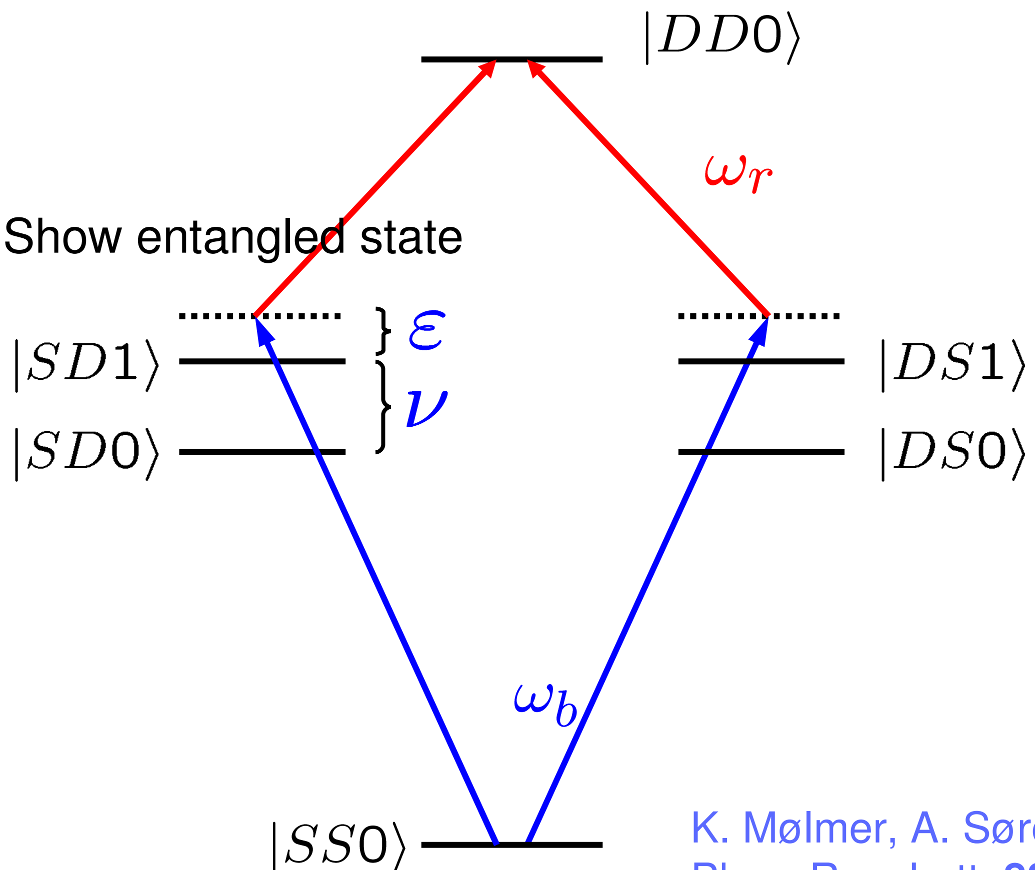
Ion motion



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

Mølmer - Sørensen gate operation

All atoms flip their state together

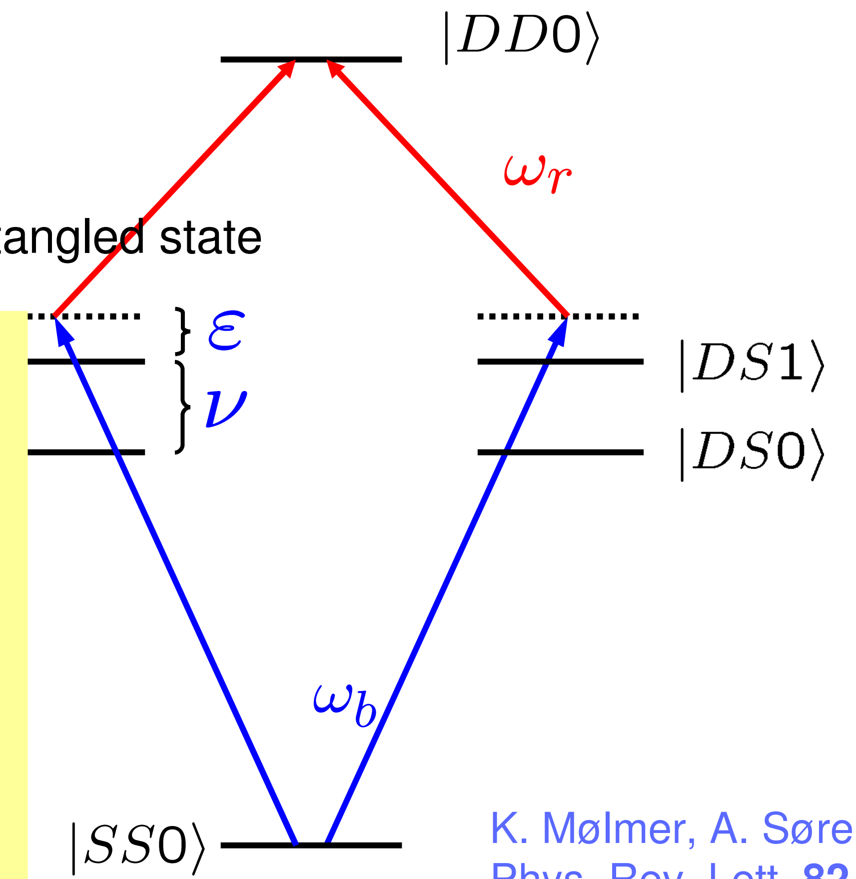


K. Mølmer, A. Sørensen,
Phys. Rev. Lett. **82**, 1971 (1999)
C. A. Sackett et al.,
Nature **404**, 256 (2000)

Mølmer - Sørensen gate operation

All atoms flip their state together

Show entangled state

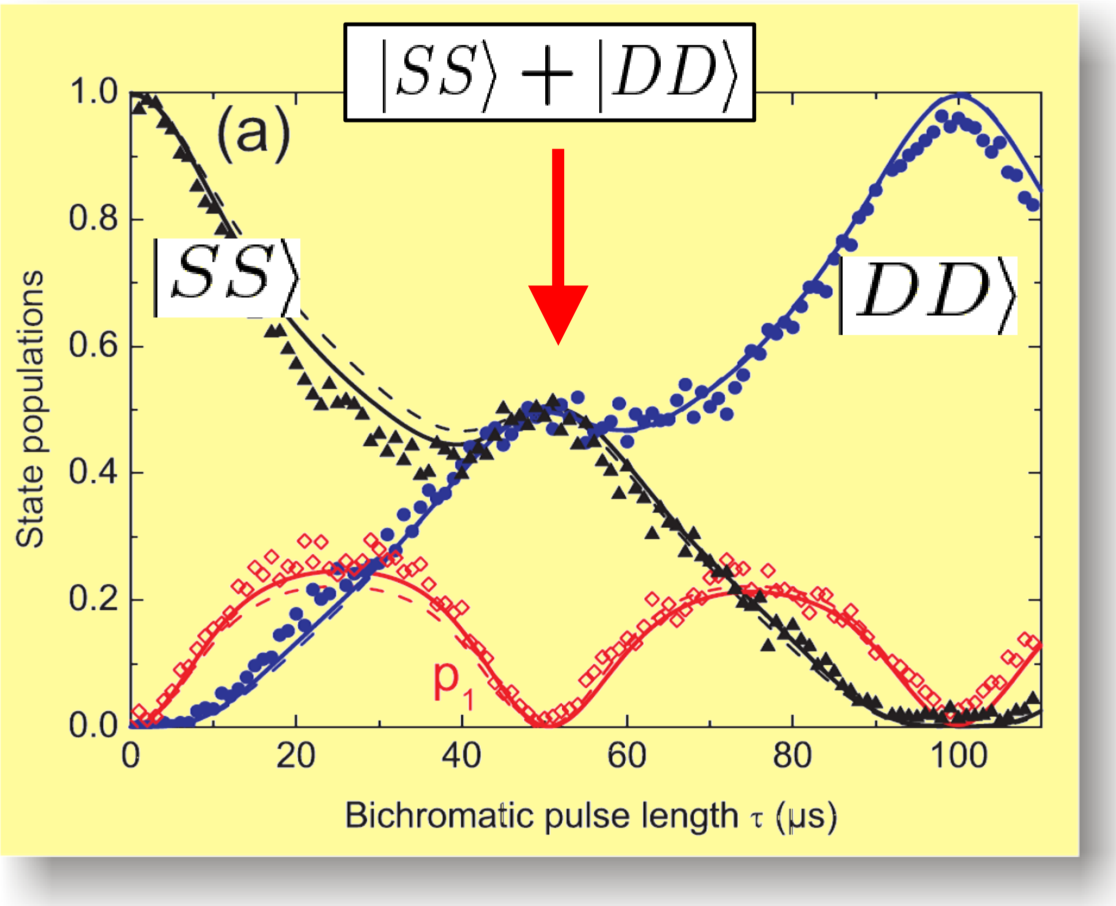


<u>Bell states with atoms</u>

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

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

Bell states using the Mølmer-Sørensen gate



Analysis of Bell states

$$\boxed{|SS\rangle + |DD\rangle}$$

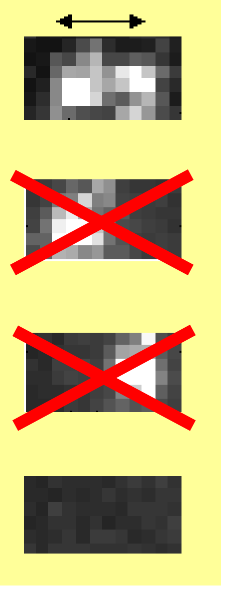
Fluorescence detection with CCD camera:

$|SS\rangle$

$|SD\rangle$

$|DS\rangle$

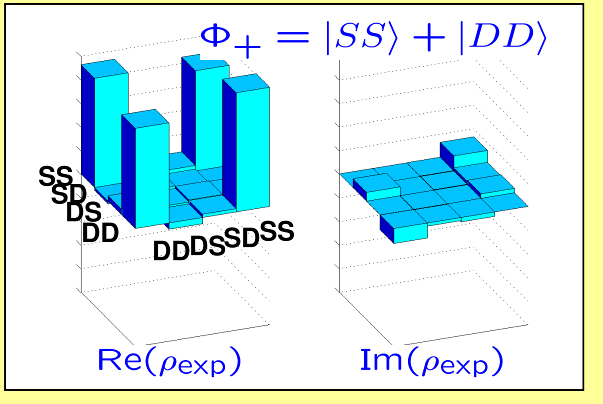
$|DD\rangle$



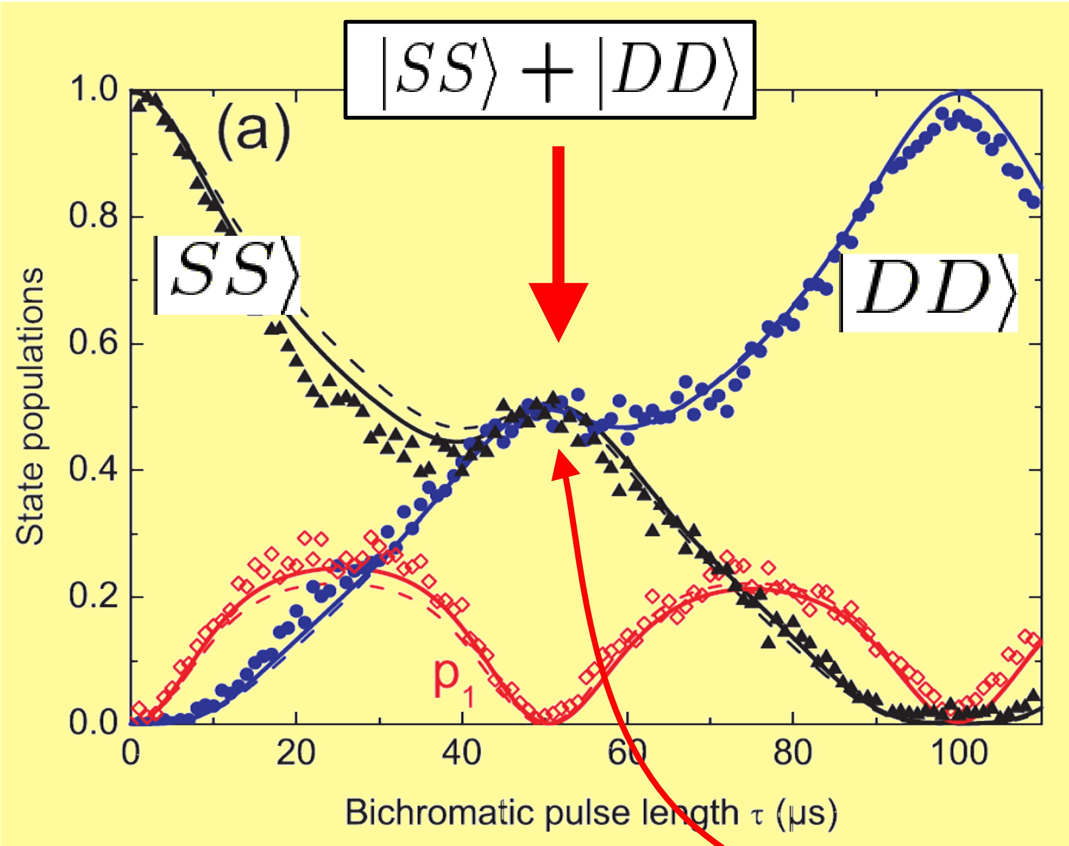
Coherent superposition or incoherent mixture ?

What is the relative phase of the superposition ?

⇨ Measurement of the density matrix:

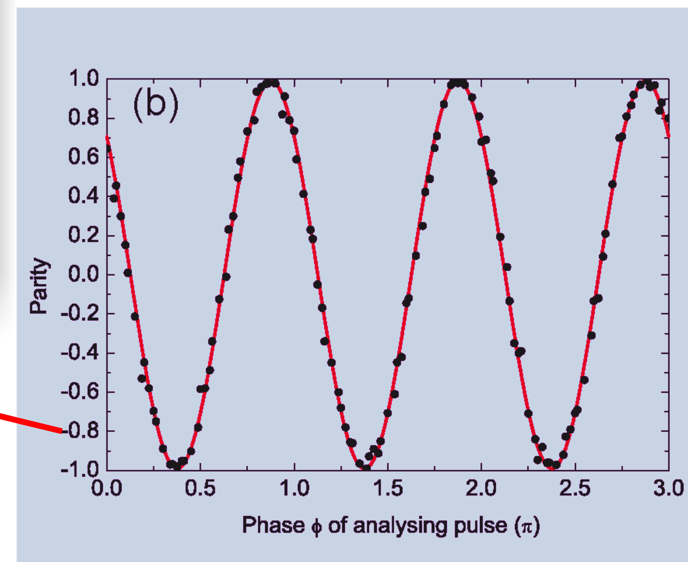


Bell states using the Mølmer-Sørensen gate



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

measure entanglement via parity oscillations

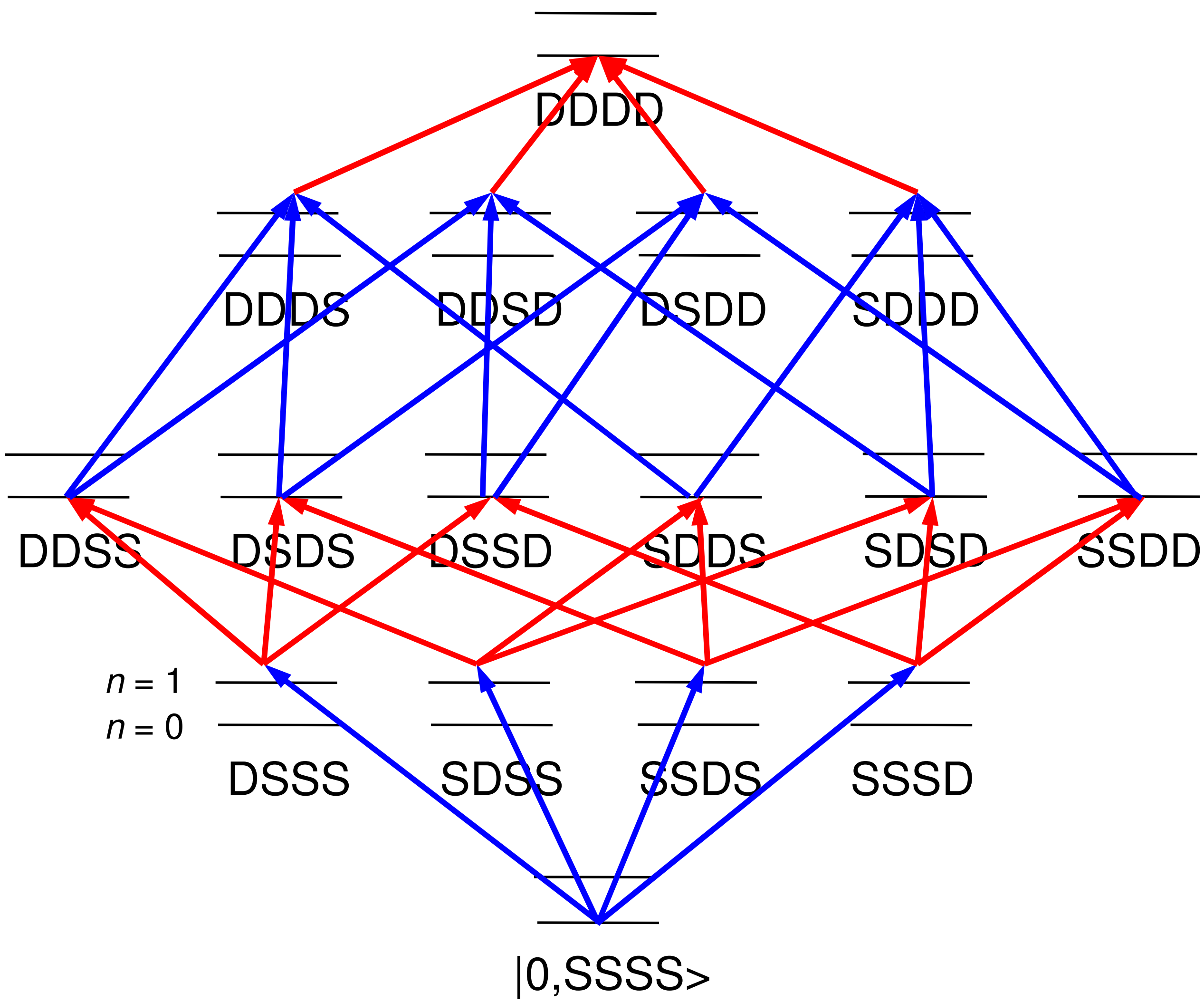


gate duration $51\mu s$

average fidelity

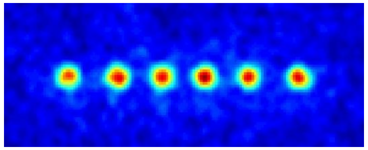
$$F_{\text{MS}} = 99.3(0.2)\%$$

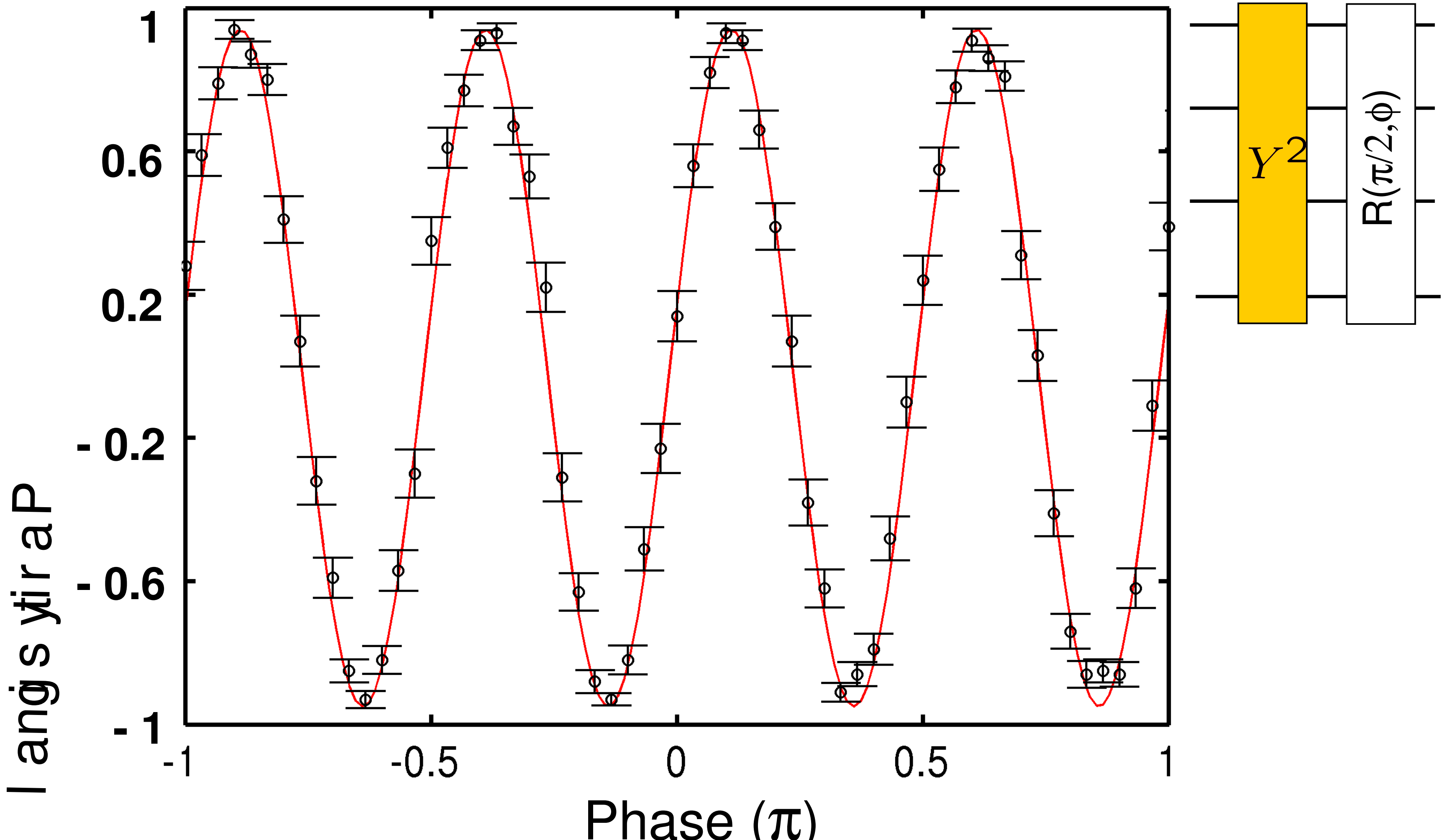
Entangling four ions



$$\Rightarrow (|SSSS\rangle + |DDDD\rangle)/\sqrt{2}$$

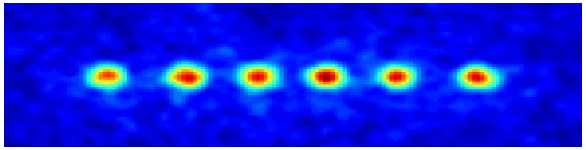
Four-ion GHZ state

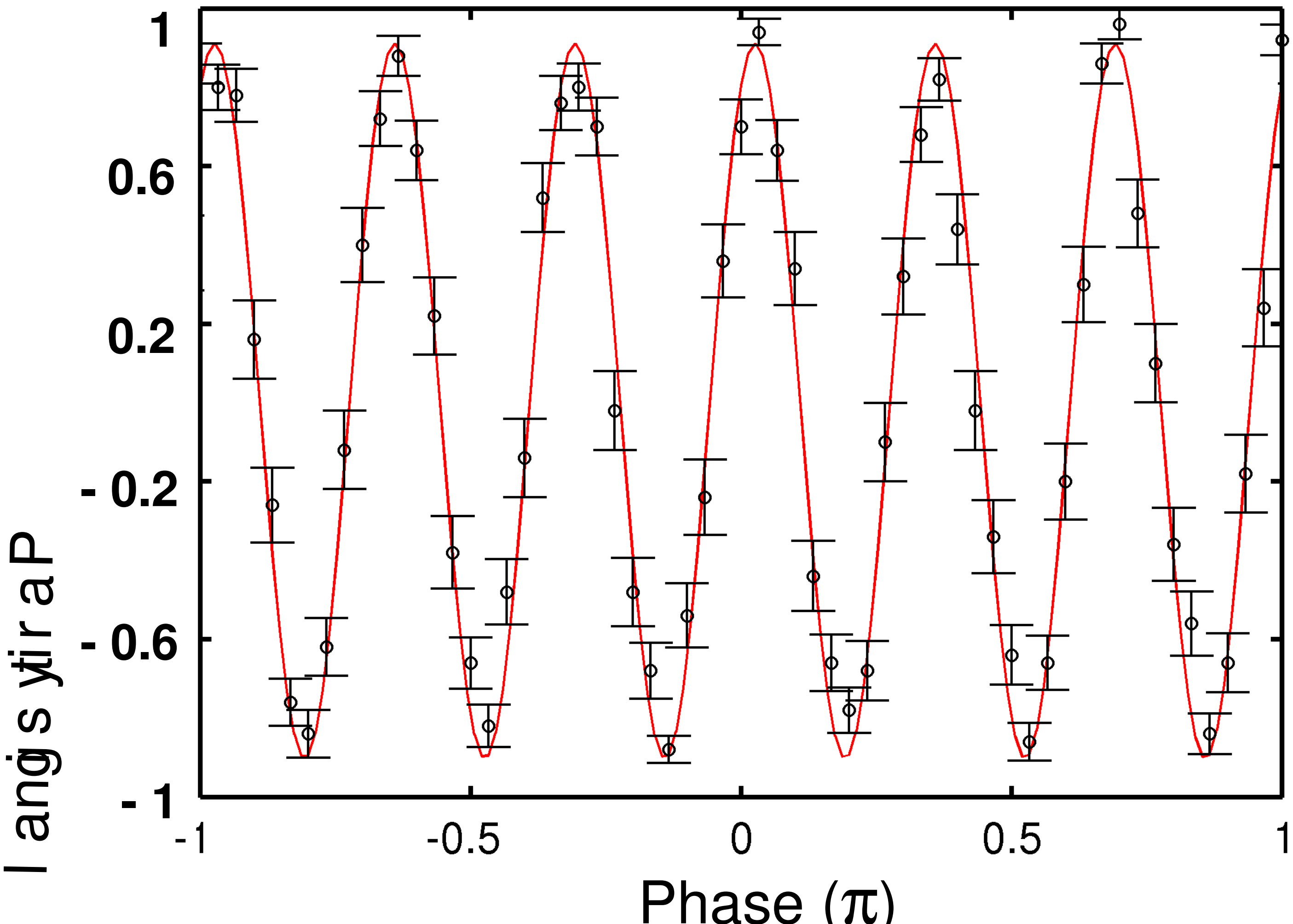




See also: Leibfried *et al.*, Nature **438**, 639 (2005)

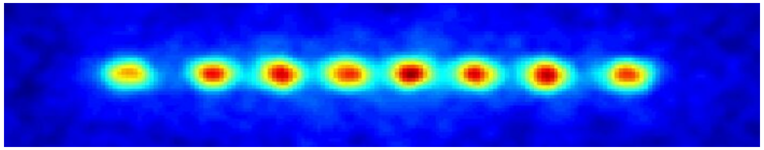
Six-ion GHZ-state



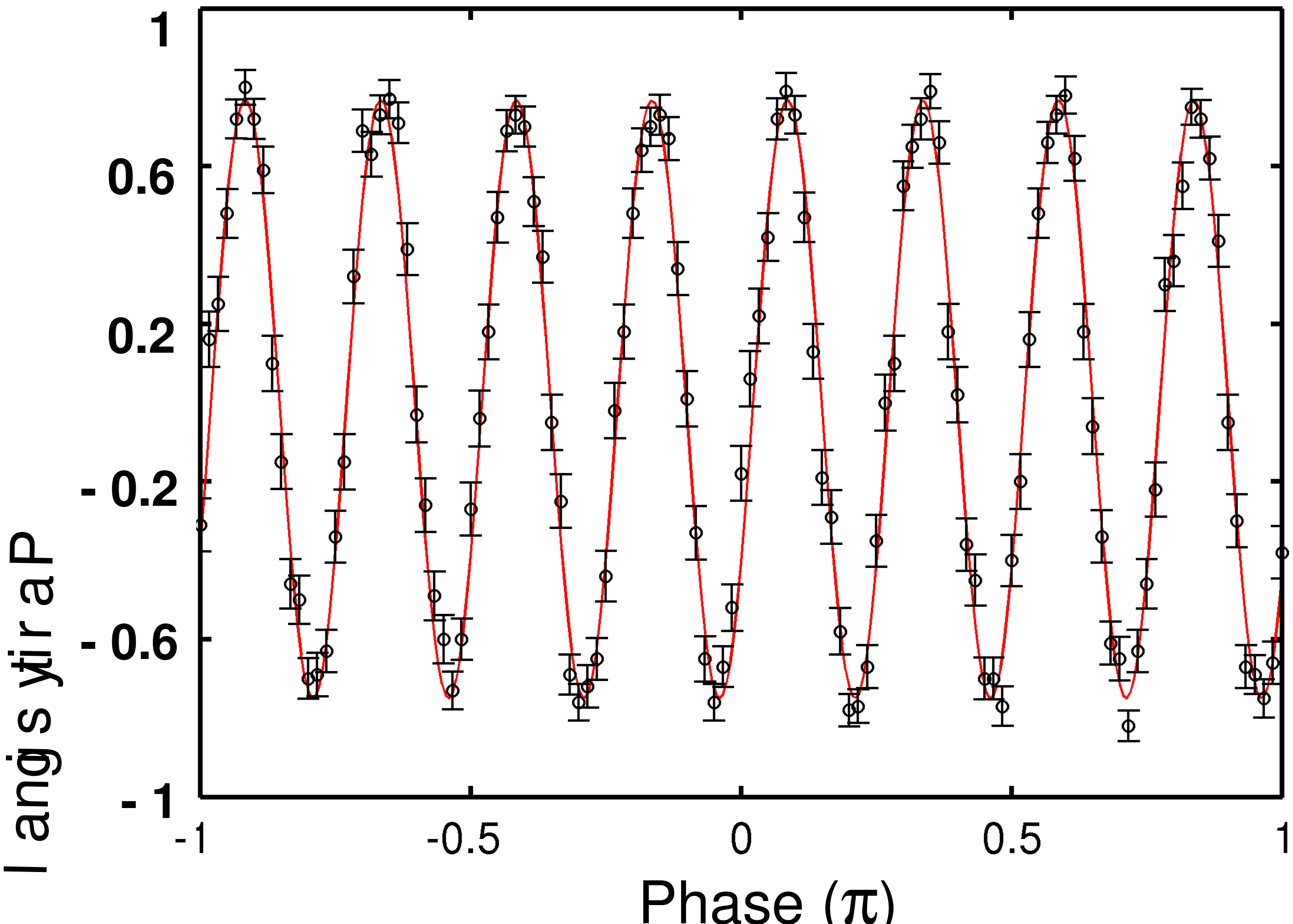


See also: Leibfried *et al.*, Nature **438**, 639 (2005)

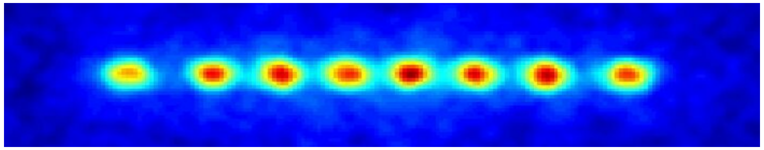
Eight-ion GHZ state



T. Monz, P. Schindler, J. Barreiro,
M. Hennrich, R. Blatt



Eight-ion GHZ state

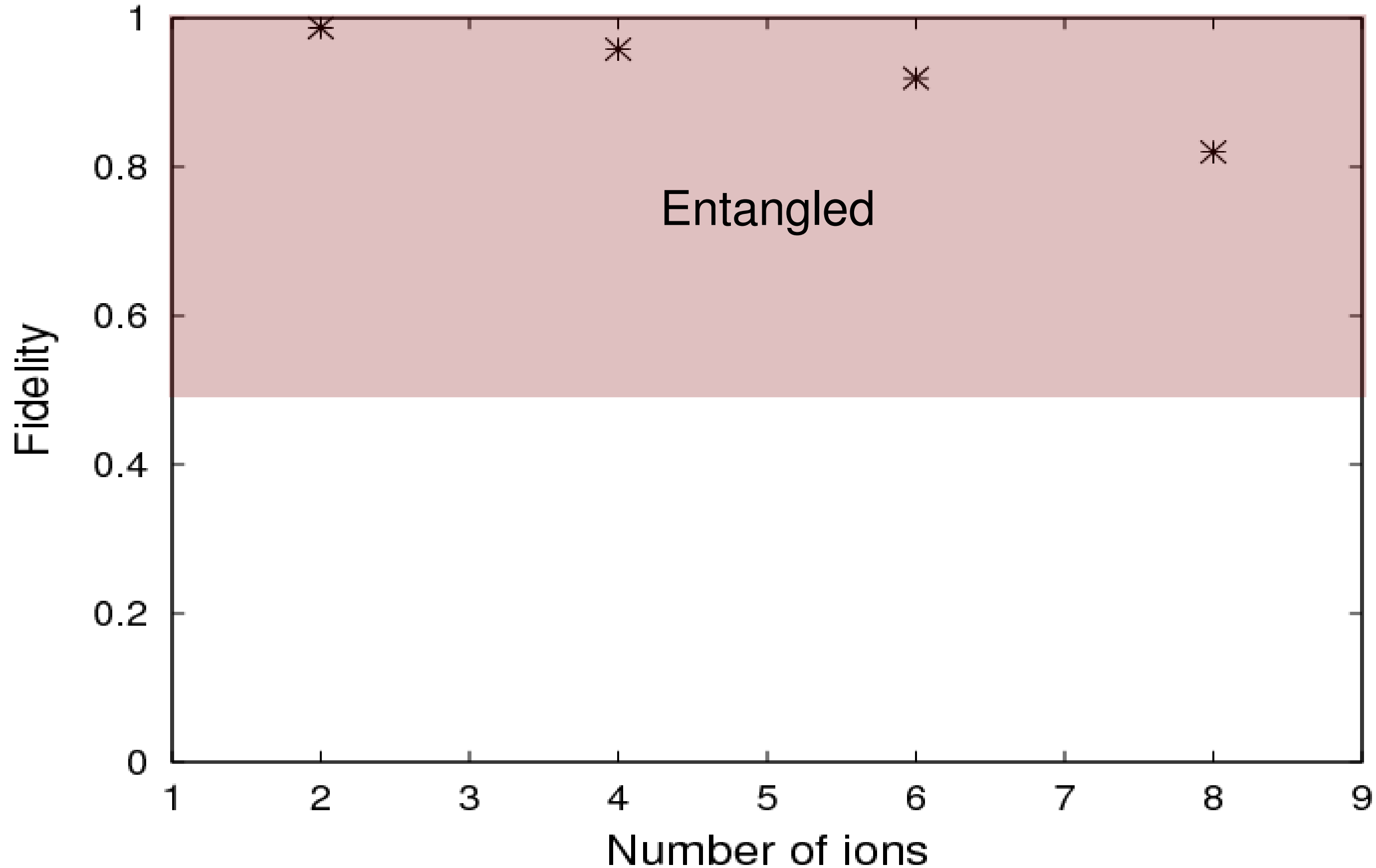


T. Monz, P. Schindler, J. Barreiro,
M. Hennrich, R. Blatt

$$
\begin{aligned}
|\Psi\rangle &= |SSSSSSSS\rangle + |DDDDDDDD\rangle \\
&= |S\rangle\,|\mathrm{alive}\rangle \qquad + |D\rangle\,|\mathrm{dead}\rangle
\end{aligned}
$$

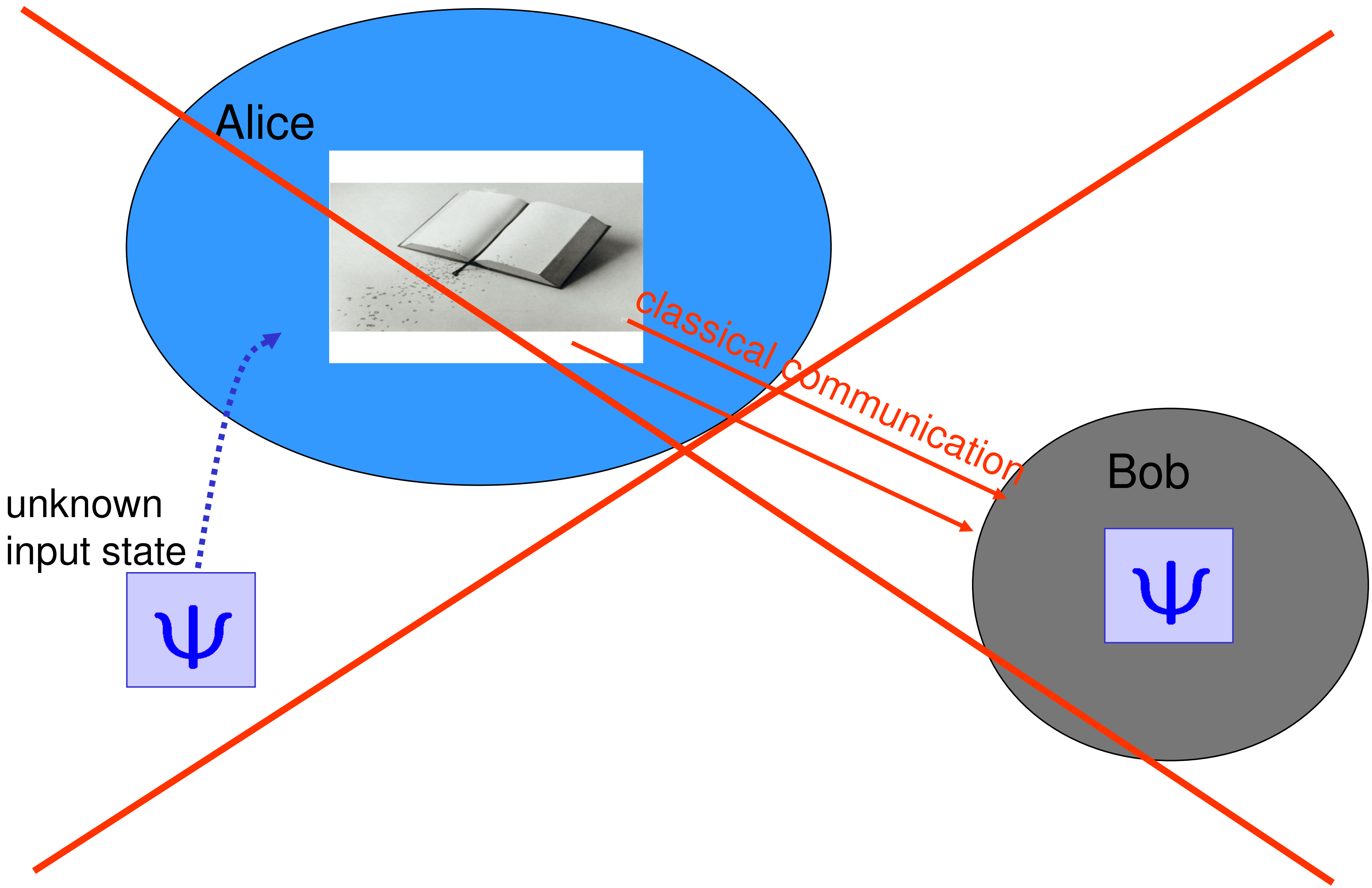
Image-source: wikimedia

GHZ-state fidelities

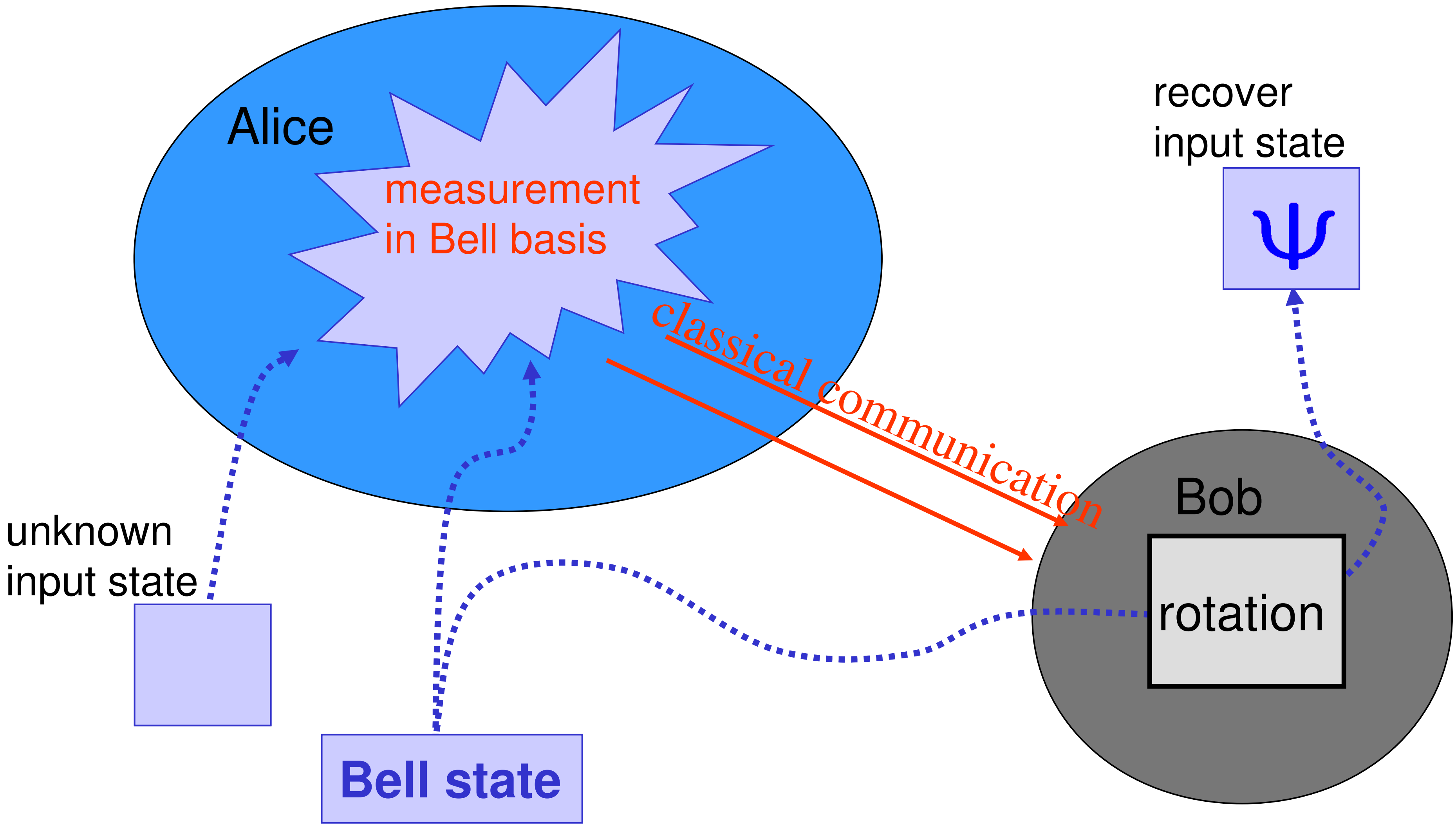


- Physics and information
- Ion trap quantum computing
- Teleportation
- Scaling of ion trap quantum computers

Teleportation

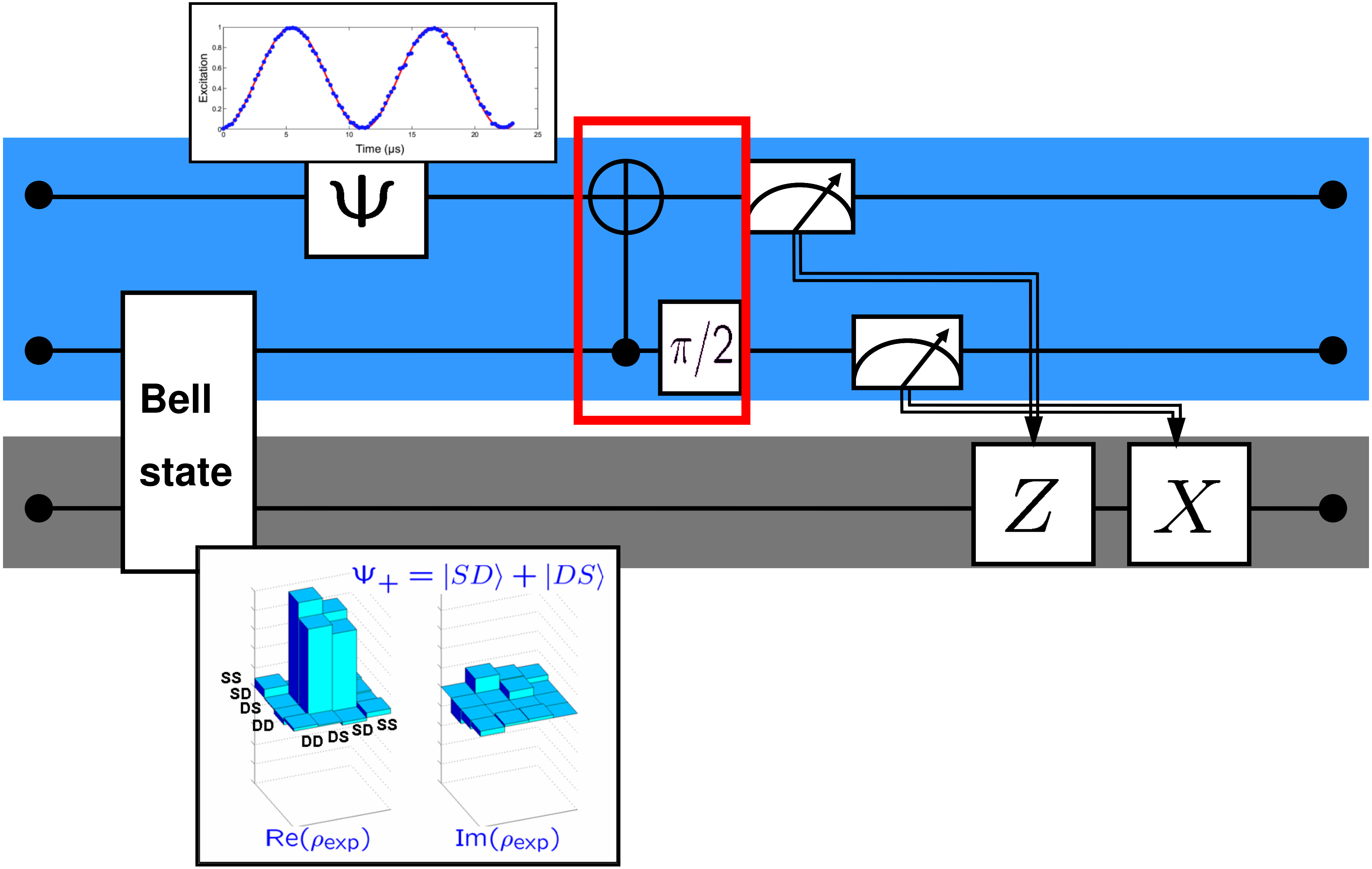


Teleportation



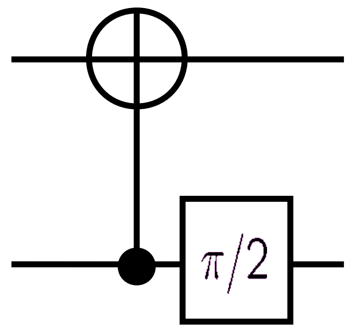
Bennett *et al.*, Phys. Rev. Lett. **70**, 1895 (1993).
Bouwmeester *et al.*, Nature **390**, 575 (1997).

Teleportation



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

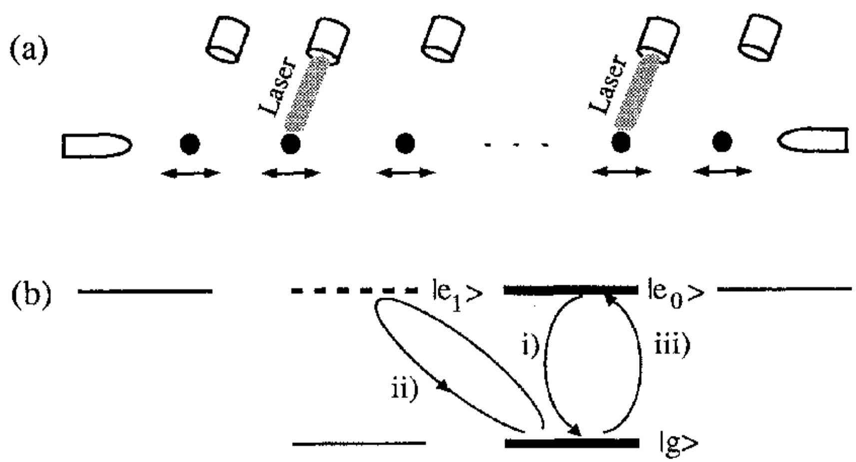


FIG. 1. (a) N ions in a linear trap interacting with N different laser beams; (b) atomic level scheme.

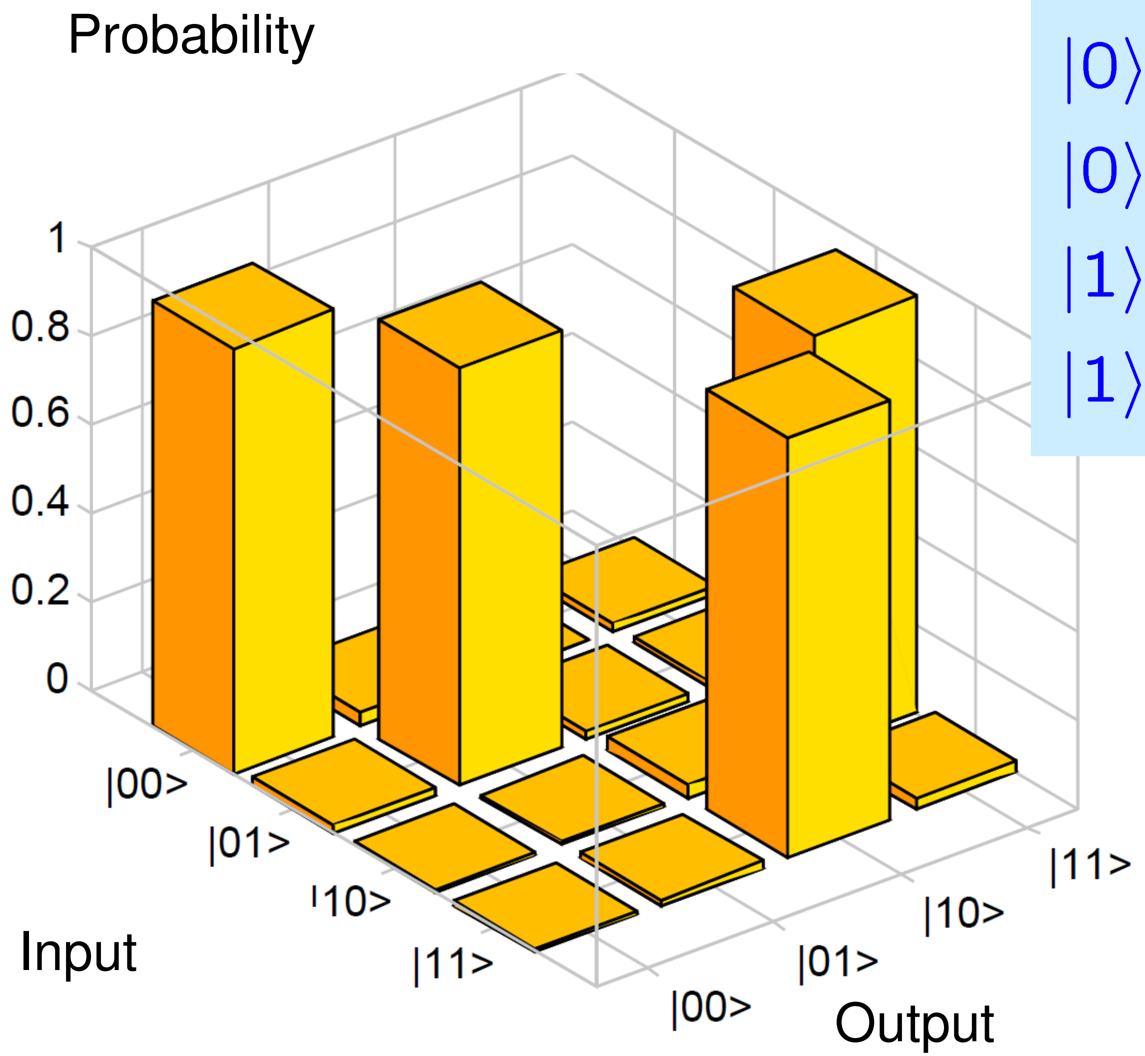
controlled – NOT :

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

$$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$$
$$|0\rangle|1\rangle \rightarrow |0\rangle|1\rangle$$
$$|1\rangle|0\rangle \rightarrow |1\rangle|1\rangle$$
$$|1\rangle|1\rangle \rightarrow |1\rangle|0\rangle$$

control bit target bit

Truth table of a controlled NOT gate



$$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$$
$$|0\rangle|1\rangle \rightarrow |0\rangle|1\rangle$$
$$|1\rangle|0\rangle \rightarrow |1\rangle|1\rangle$$
$$|1\rangle|1\rangle \rightarrow |1\rangle|0\rangle$$

➡ universal set of quantum gates

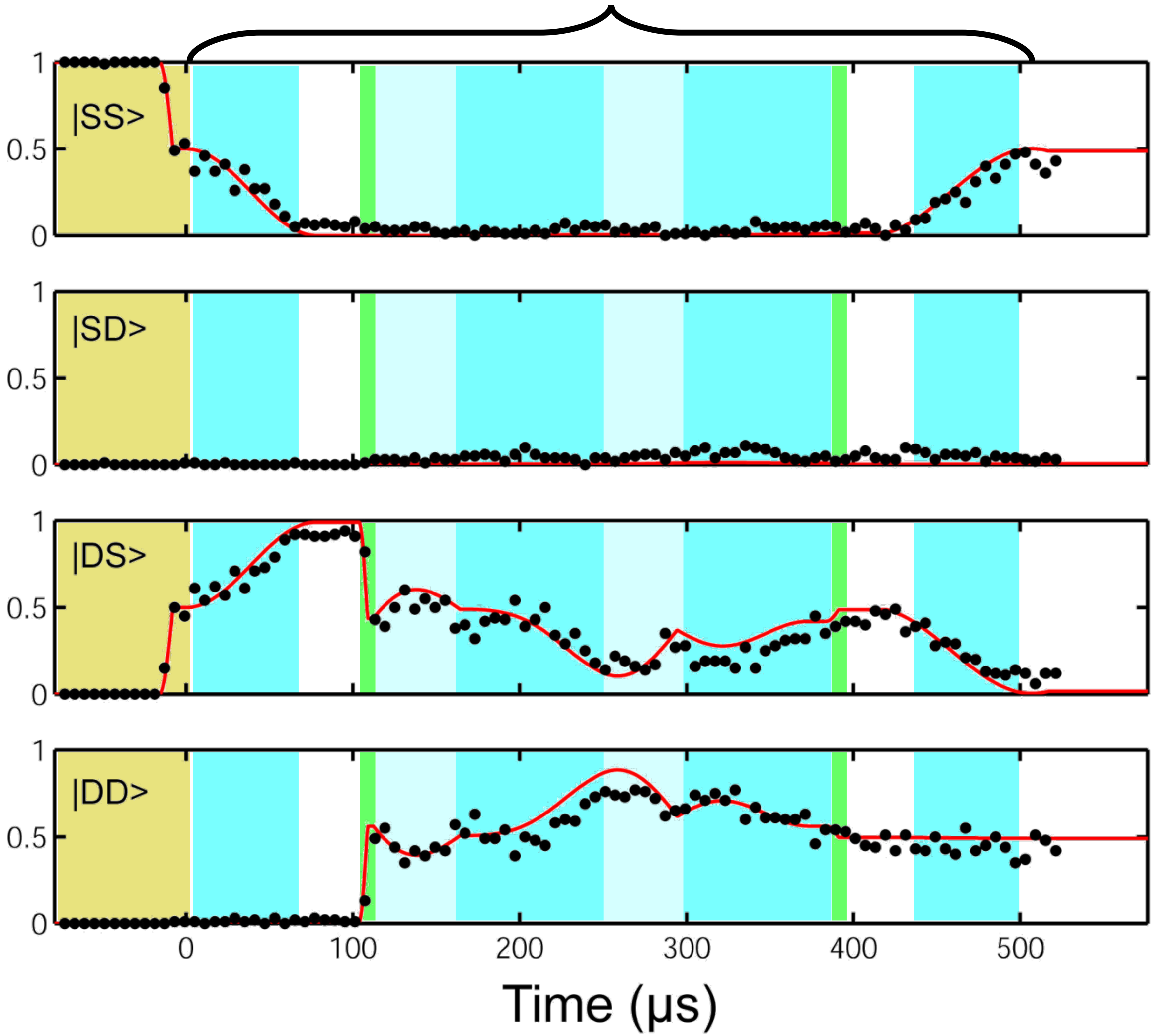
Another way to generate Bell states

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

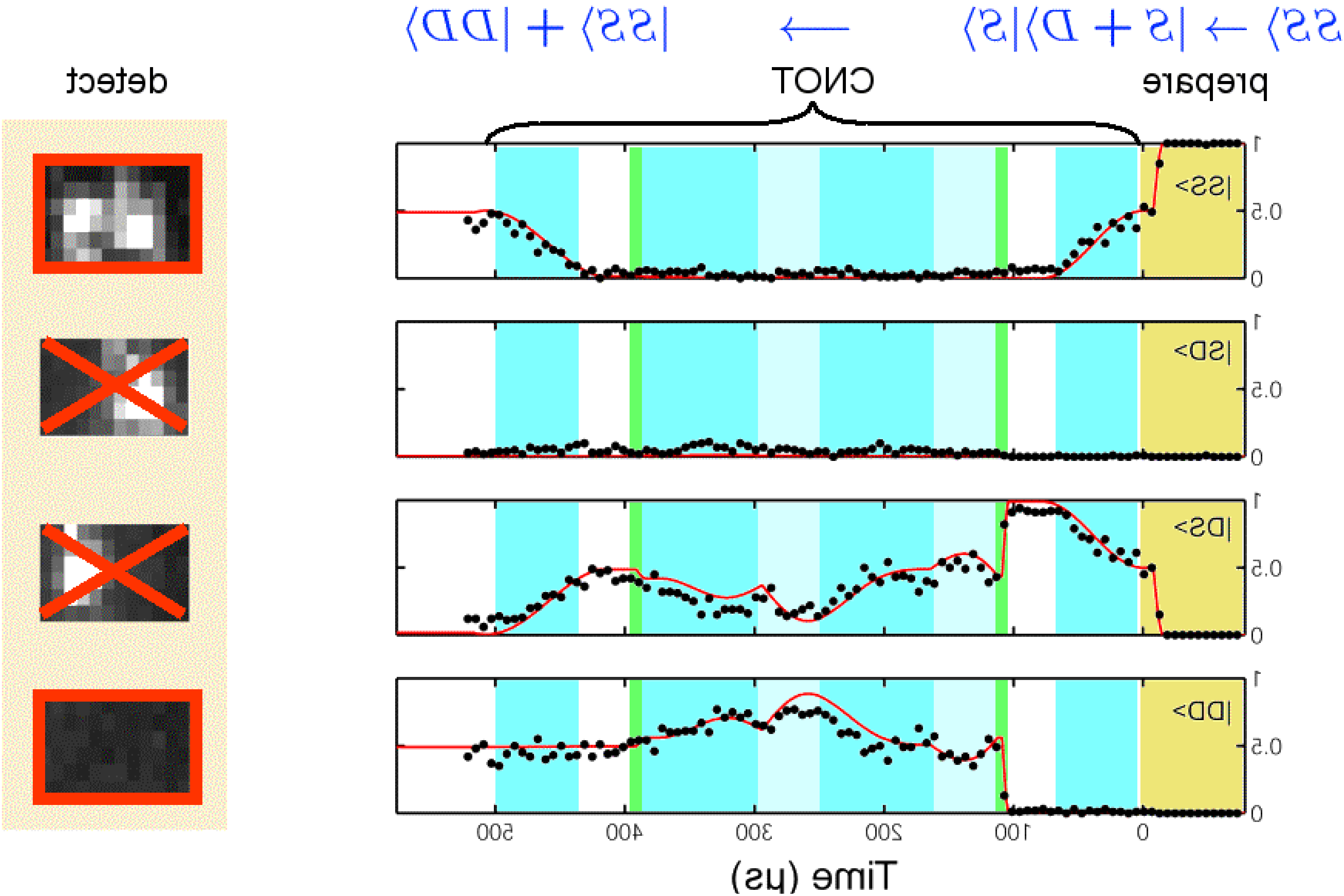
prepare

CNOT

output



And now backwards



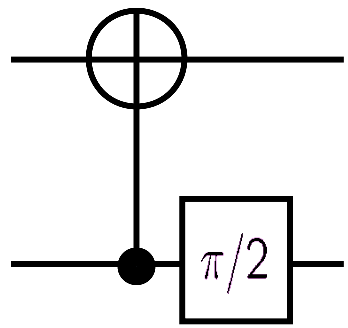
Bell measurement

$$|SS + DD\rangle$$

$$|SD + DS\rangle$$

$$|SS - DD\rangle$$

$$|SD - DS\rangle$$



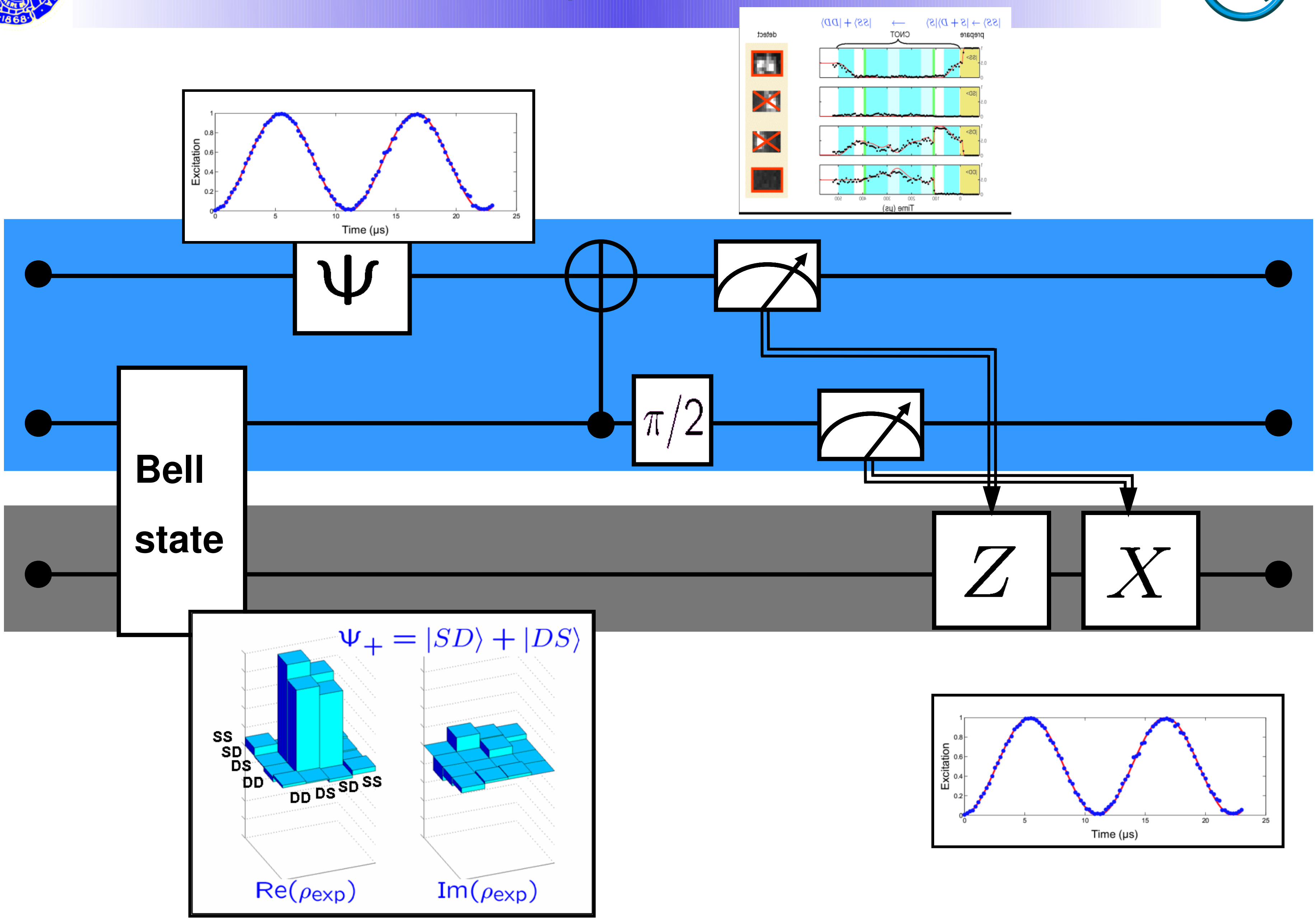
$$|SS\rangle$$

$$|SD\rangle$$

$$|DS\rangle$$

$$|DD\rangle$$

Teleportation



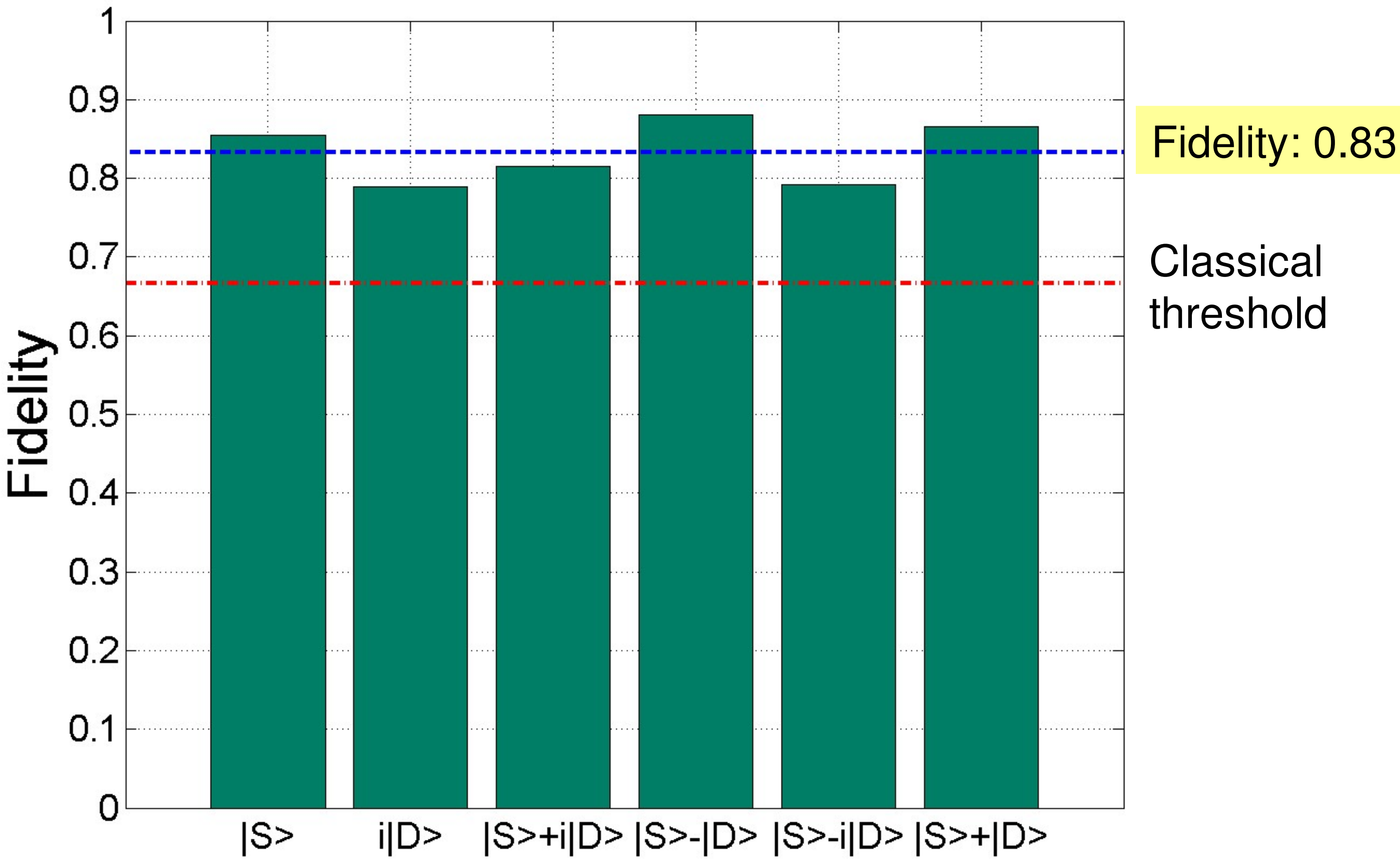
Teleportation analysis

Initial		Input test states $\|\Psi\rangle$		Output states $\|\Psi\rangle$		Final
$\|S\rangle$		$\|S\rangle$		$\|S\rangle$		$\|S\rangle$
$\|S\rangle$		$\|D\rangle$		$\|D\rangle$		$\|S\rangle$
$\|S\rangle$	U	$\|S\rangle + \|D\rangle$	TP	$\|S\rangle + \|D\rangle$	U^{-1}	$\|S\rangle$
$\|S\rangle$		$\|S\rangle + i\|D\rangle$		$\|S\rangle + i\|D\rangle$		$\|S\rangle$
$\|S\rangle$		$\|S\rangle - \|D\rangle$		$\|S\rangle - \|D\rangle$		$\|S\rangle$
$\|S\rangle$		$\|S\rangle - i\|D\rangle$		$\|S\rangle - i\|D\rangle$		$\|S\rangle$

Ion #1 (Initial and Input test states)

Ion #3 (Output states and Final)

Deterministic teleportation



“Deterministic teleportation with atoms“

Barrett et al., Nature **429**, 737 (2004) and Riebe et al., Nature **429**, 734 (2004)

Requirements for quantum computing

Classical computer

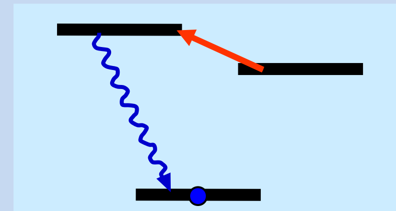
- Initialization
- 1-bit operations (NOT)
- 2-bit gates (e.g. NAND)

Computational space:

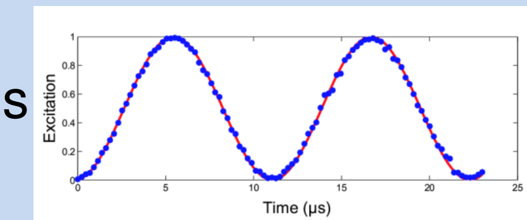
00
01
10
11

- Read out
  ➡ result

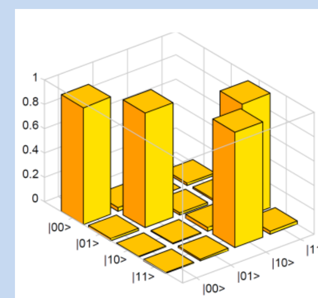
Quantum computer



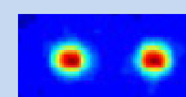
- Initialization
- 1-qubit rotations
  ➡ superpositions



- 2-qubit gates (CNOT gate)
  ➡ entanglement

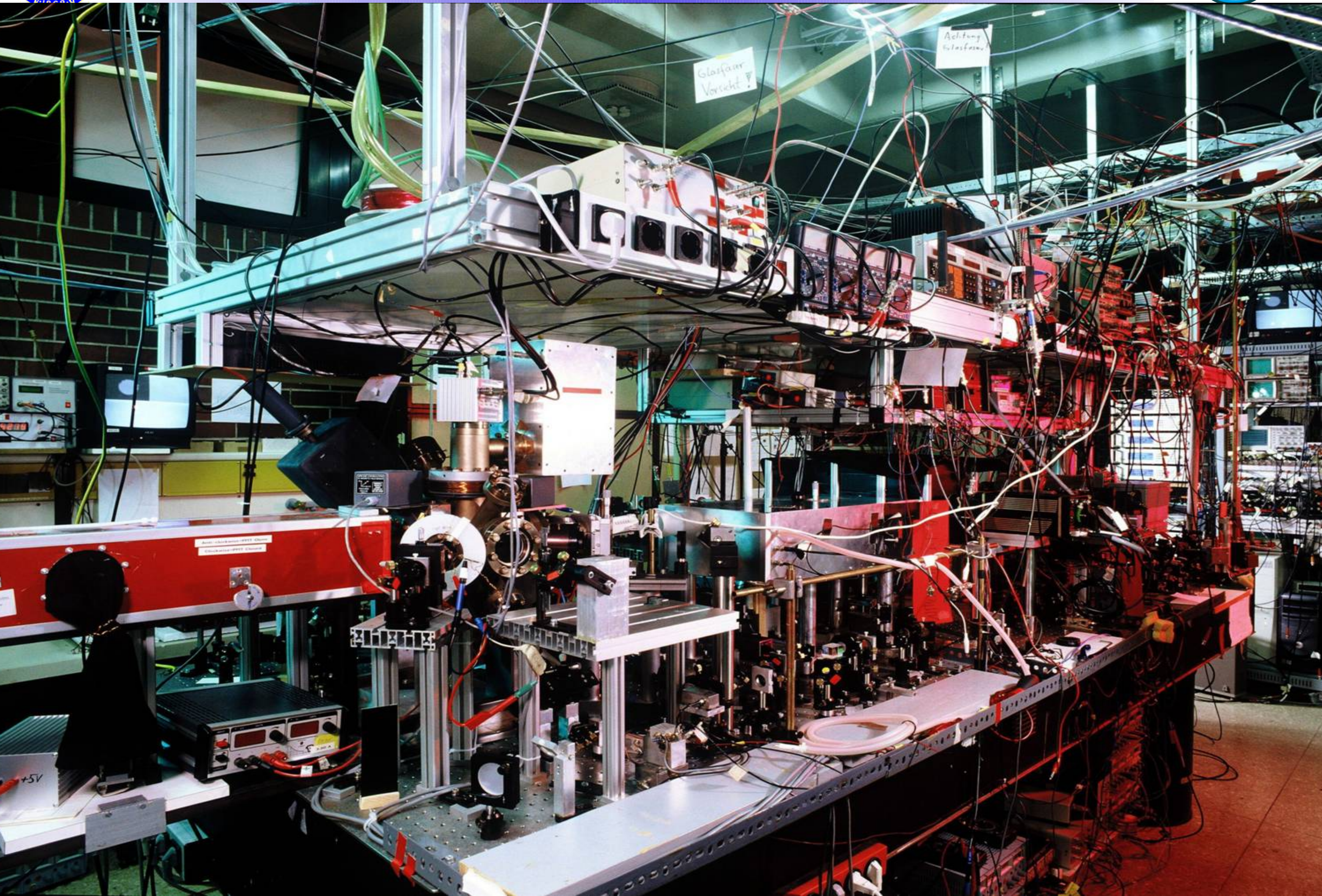


Computational space:



- Read out of qubits
  ➡ gain of classical information

The hardware



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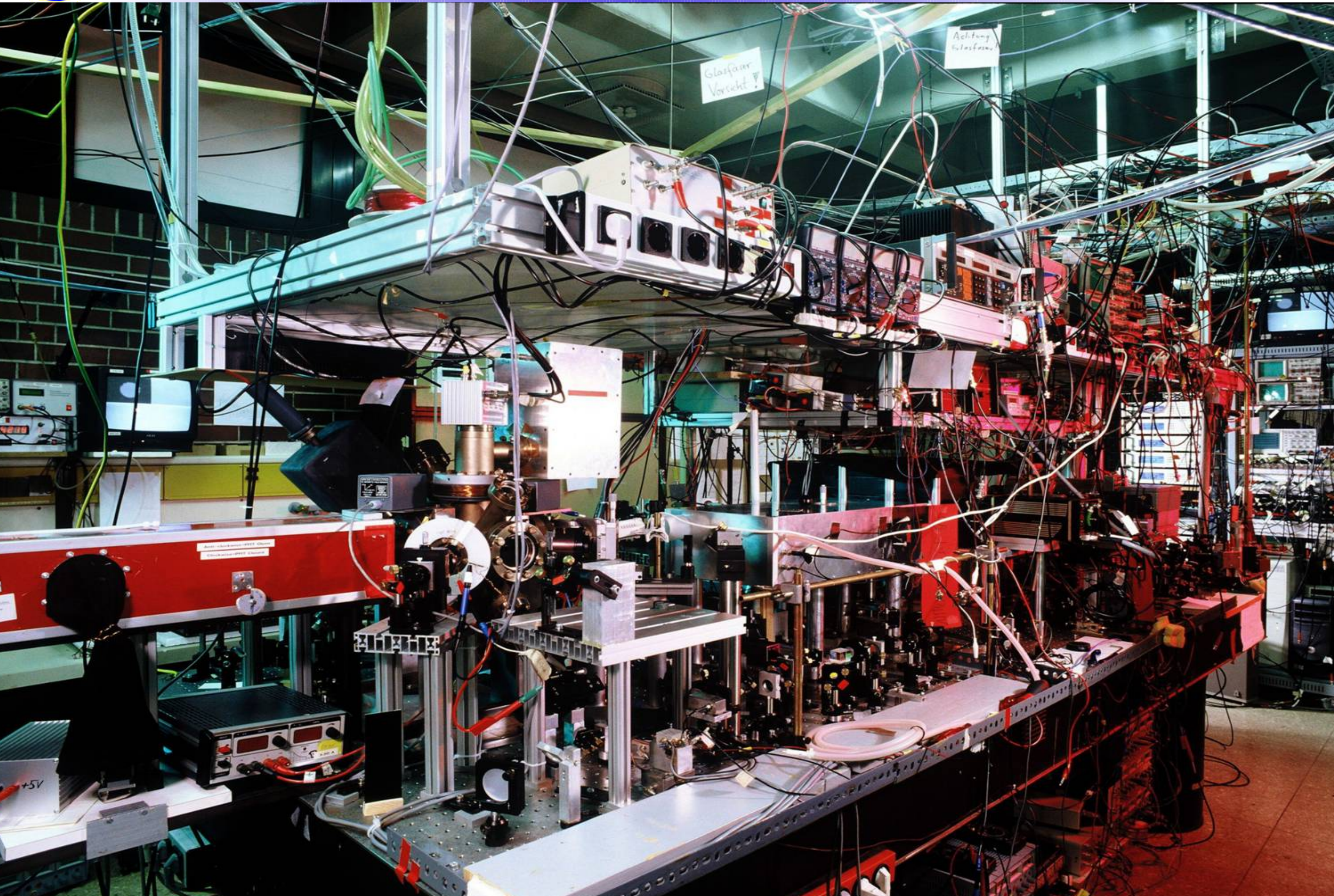
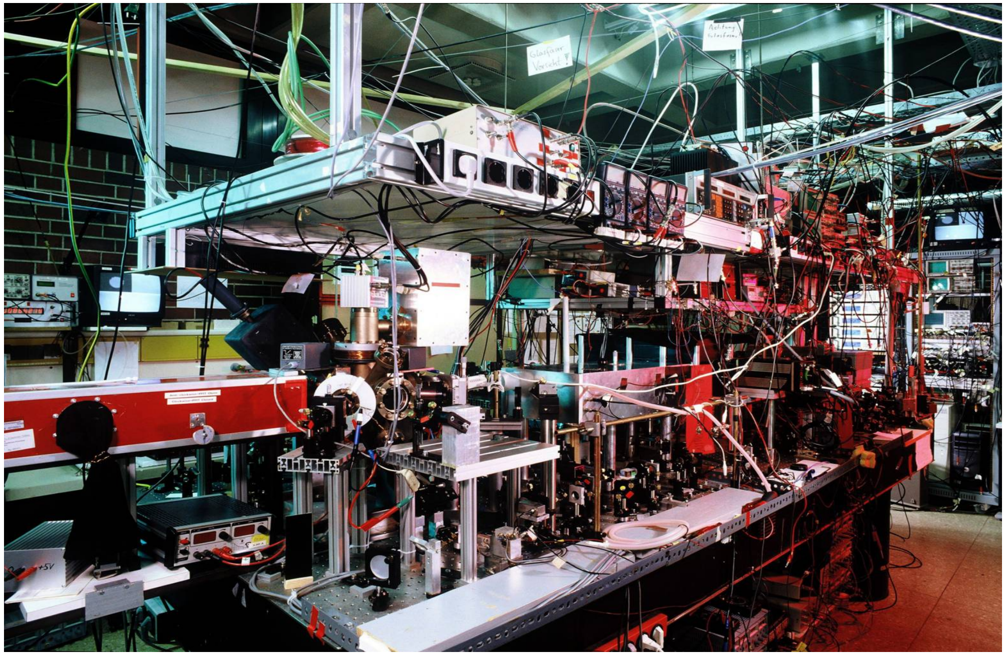
- Scaling of ion trap quantum computers

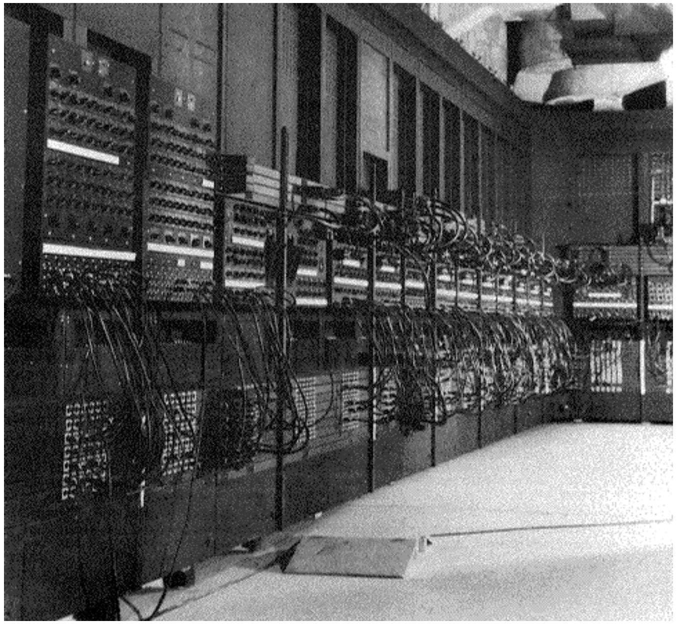
The hardware



The hardware

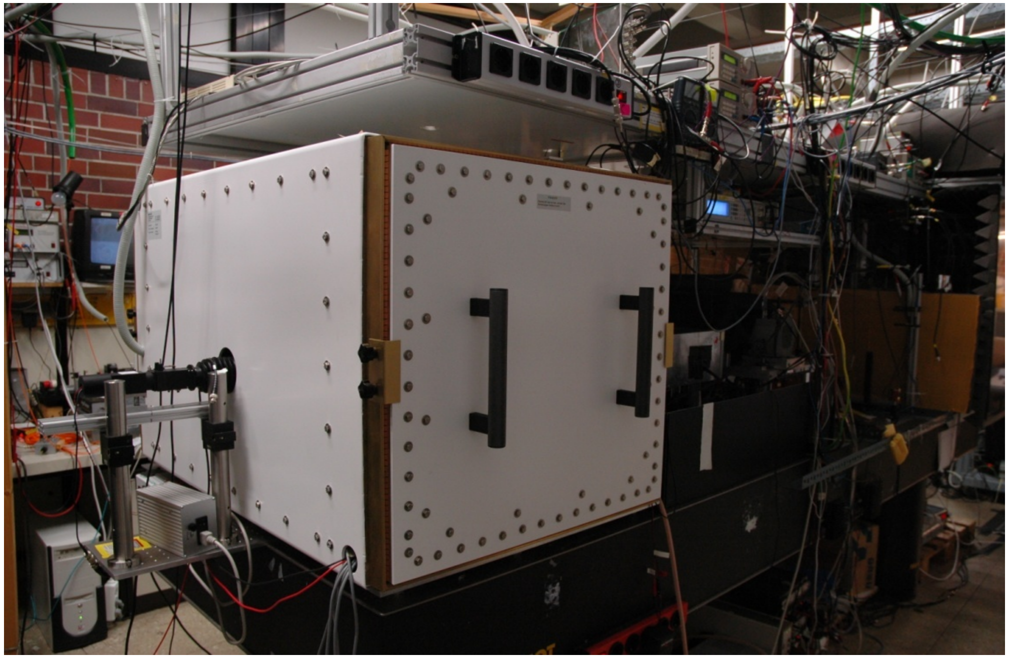


Innsbruck quantum computer, 2005

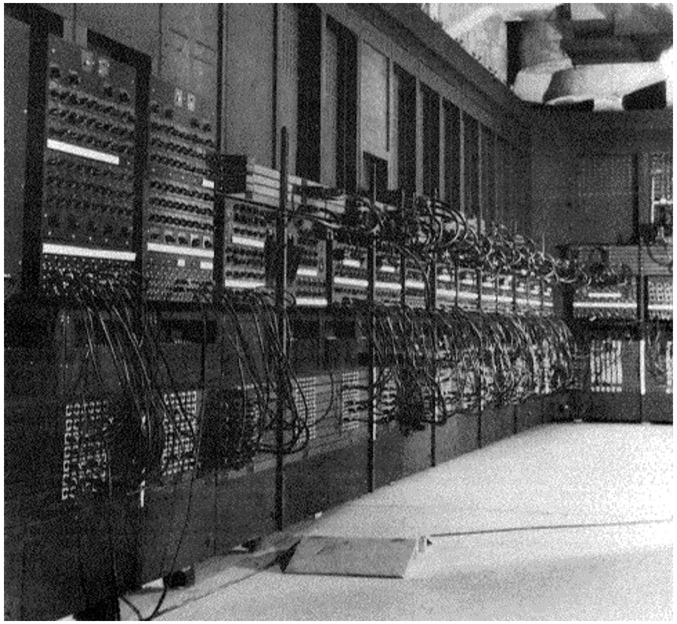


ENIAC, 1950

The hardware



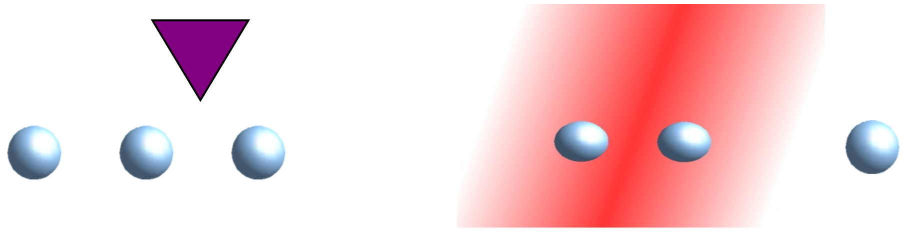
Innsbruck quantum computer, 2009

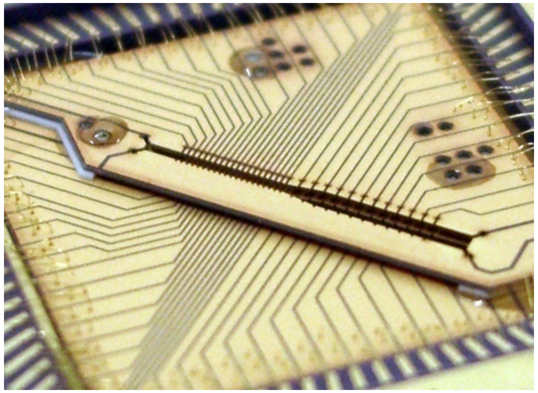


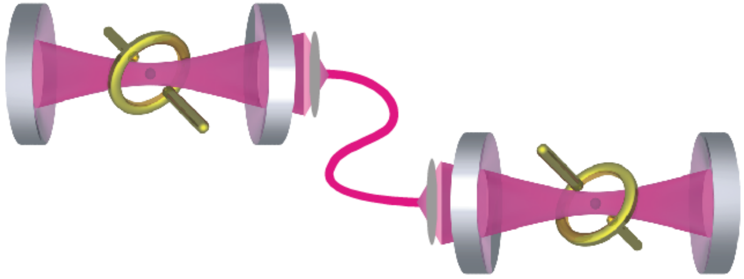
ENIAC, 1950

Scaling of ion trap quantum computers

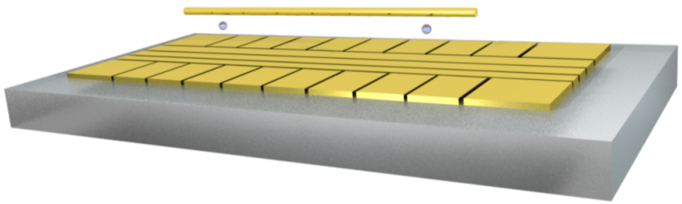
Kielpinski, Monroe, Wineland







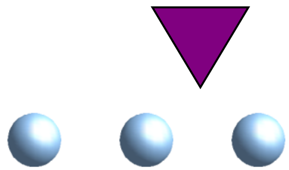
Cirac, Zoller, Kimble, Mabuchi

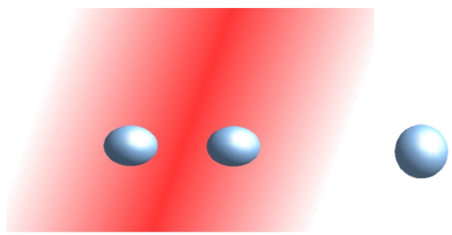


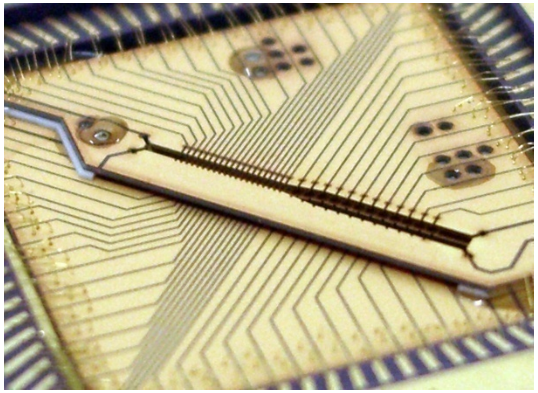
Zoller, Tian, Blatt

Scaling of ion trap quantum computers

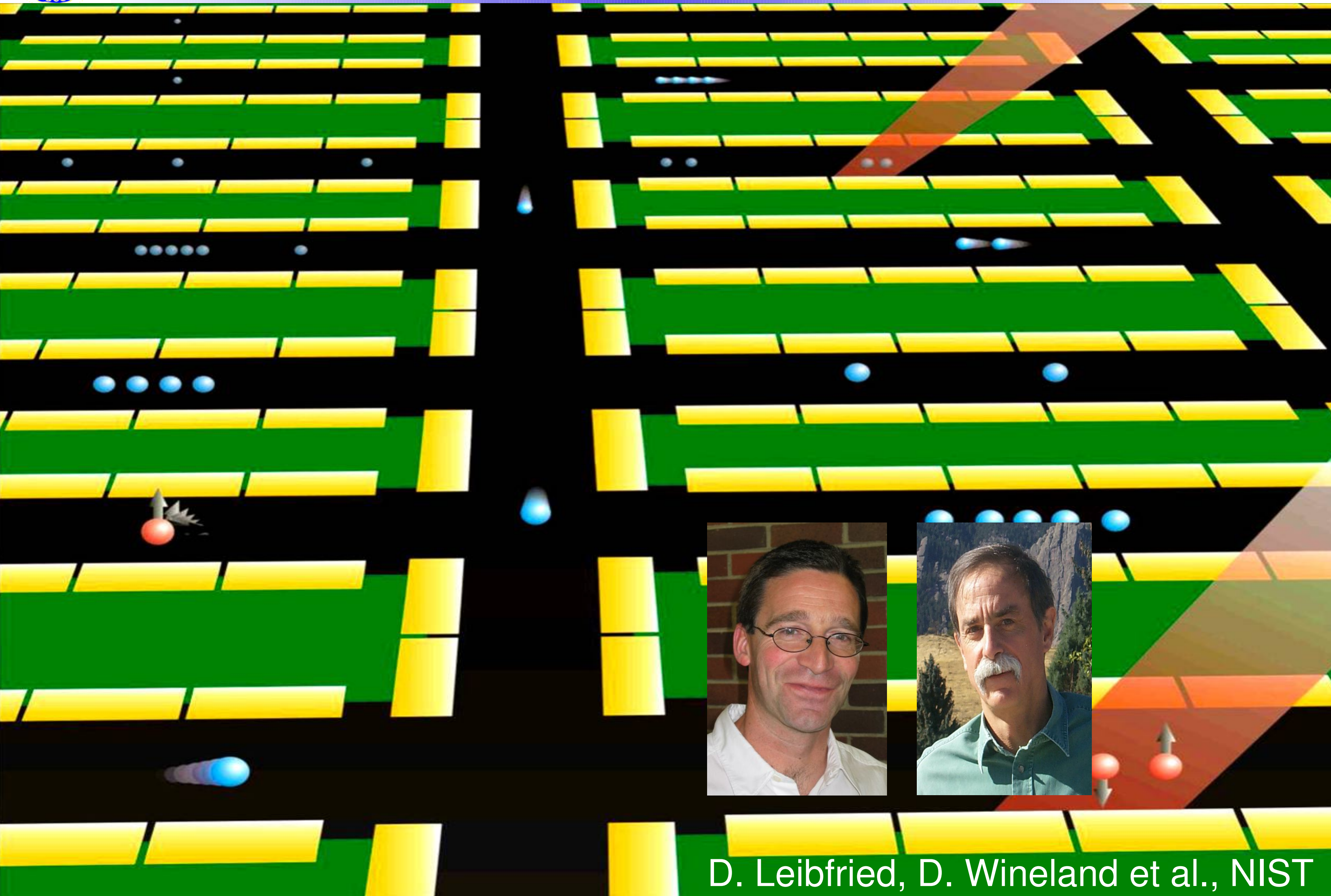
Kielpinski, Monroe, Wineland





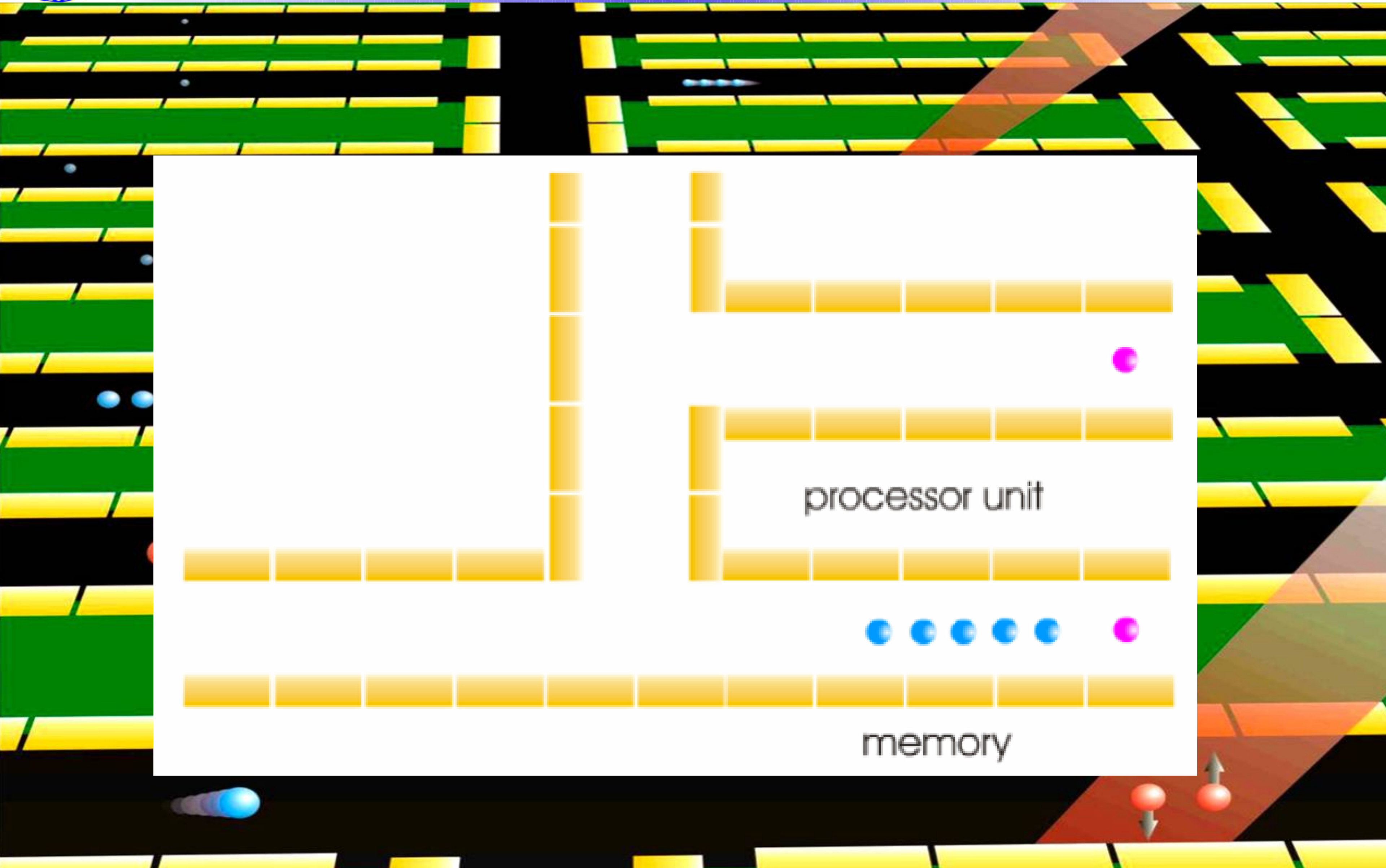


Scaling of ion trap quantum computers



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

Scaling of ion trap quantum computers



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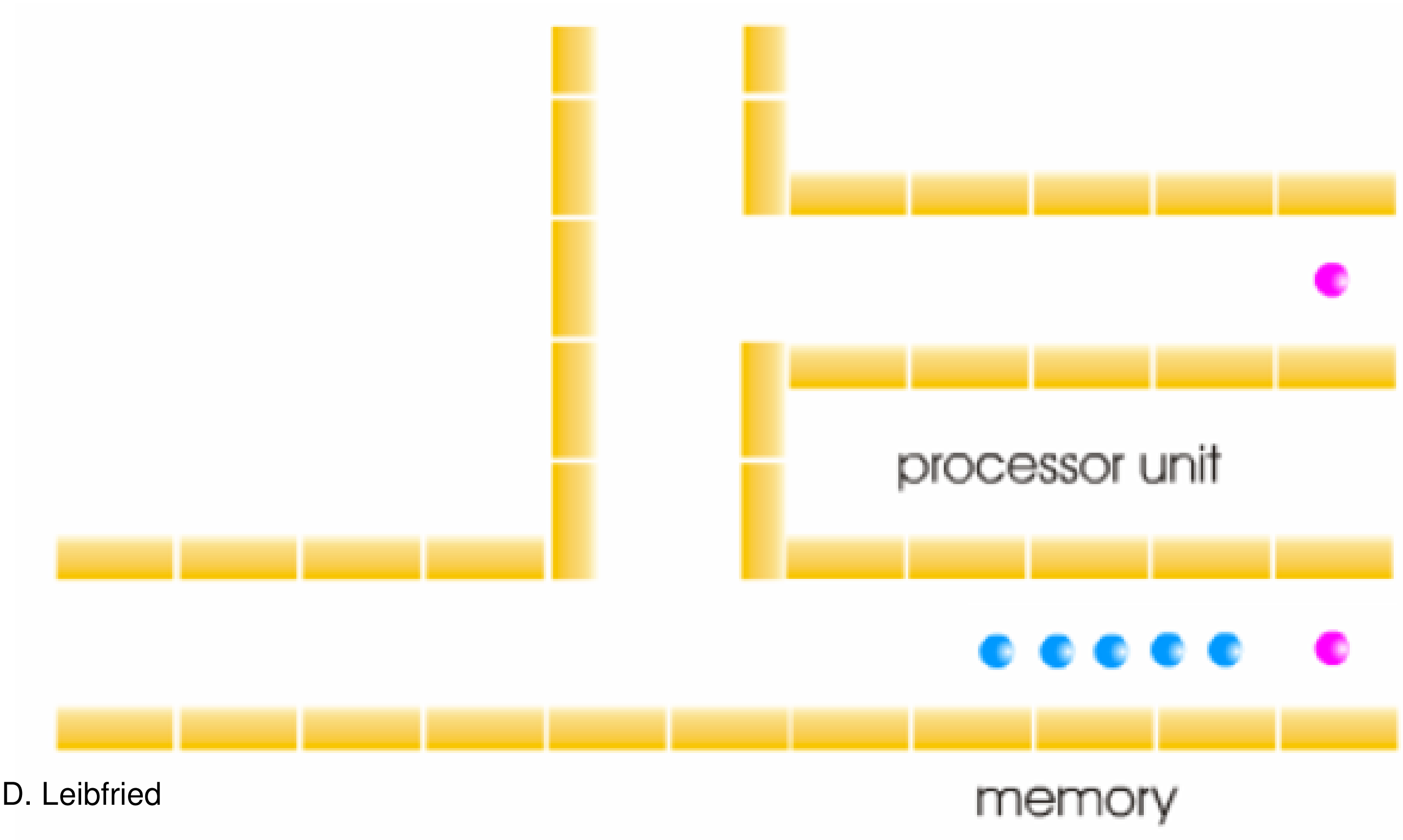

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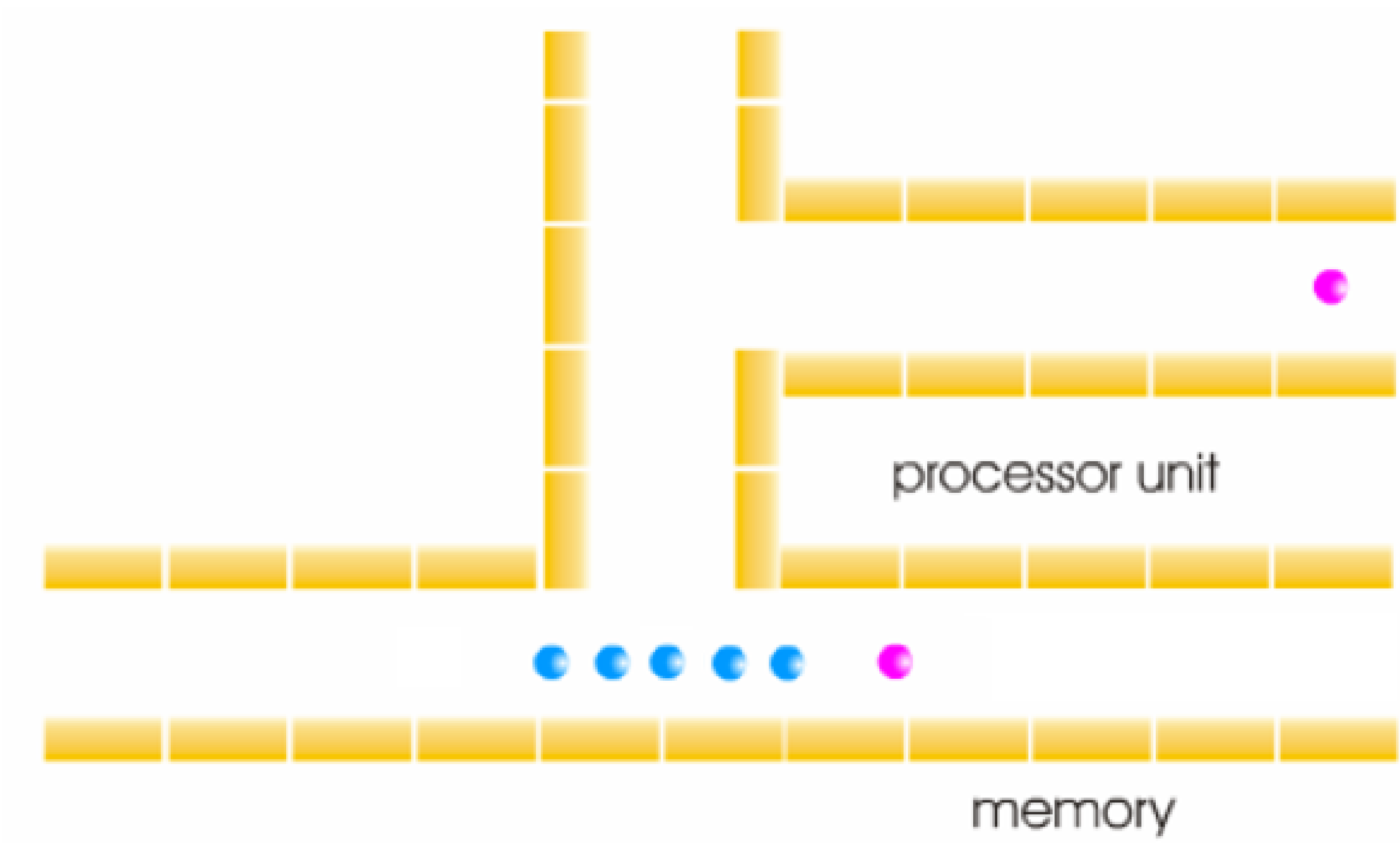
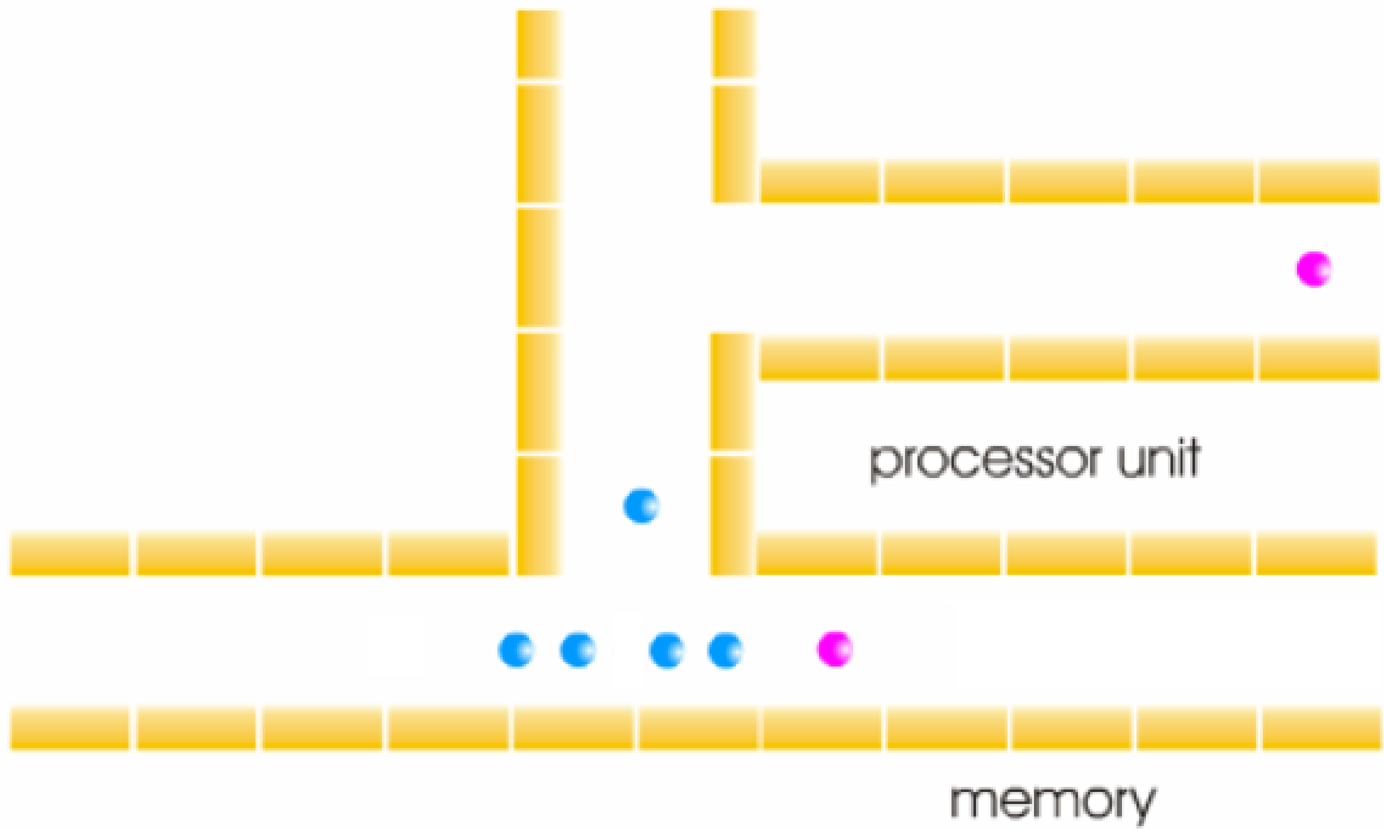
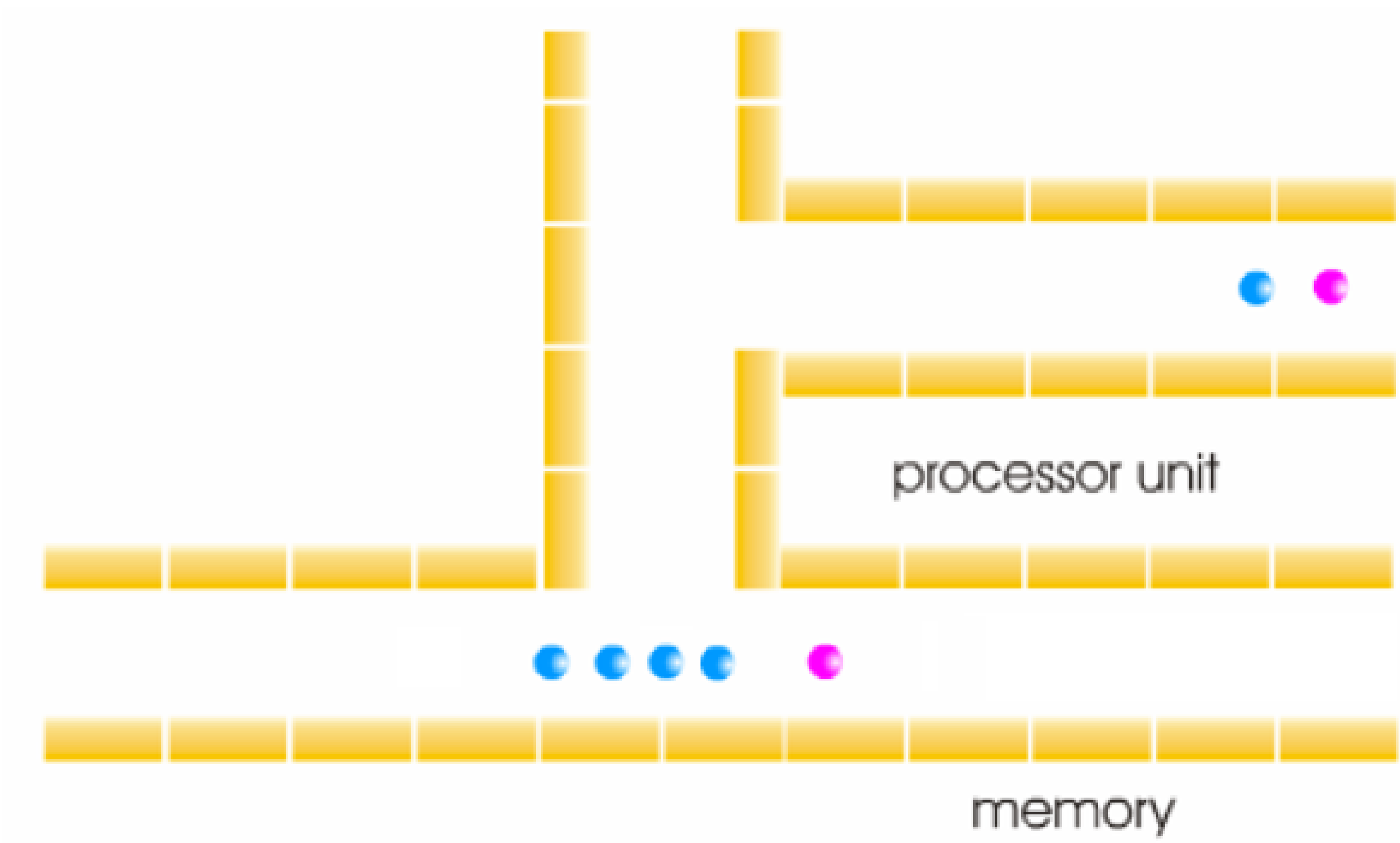
Scaling of ion trap quantum computers



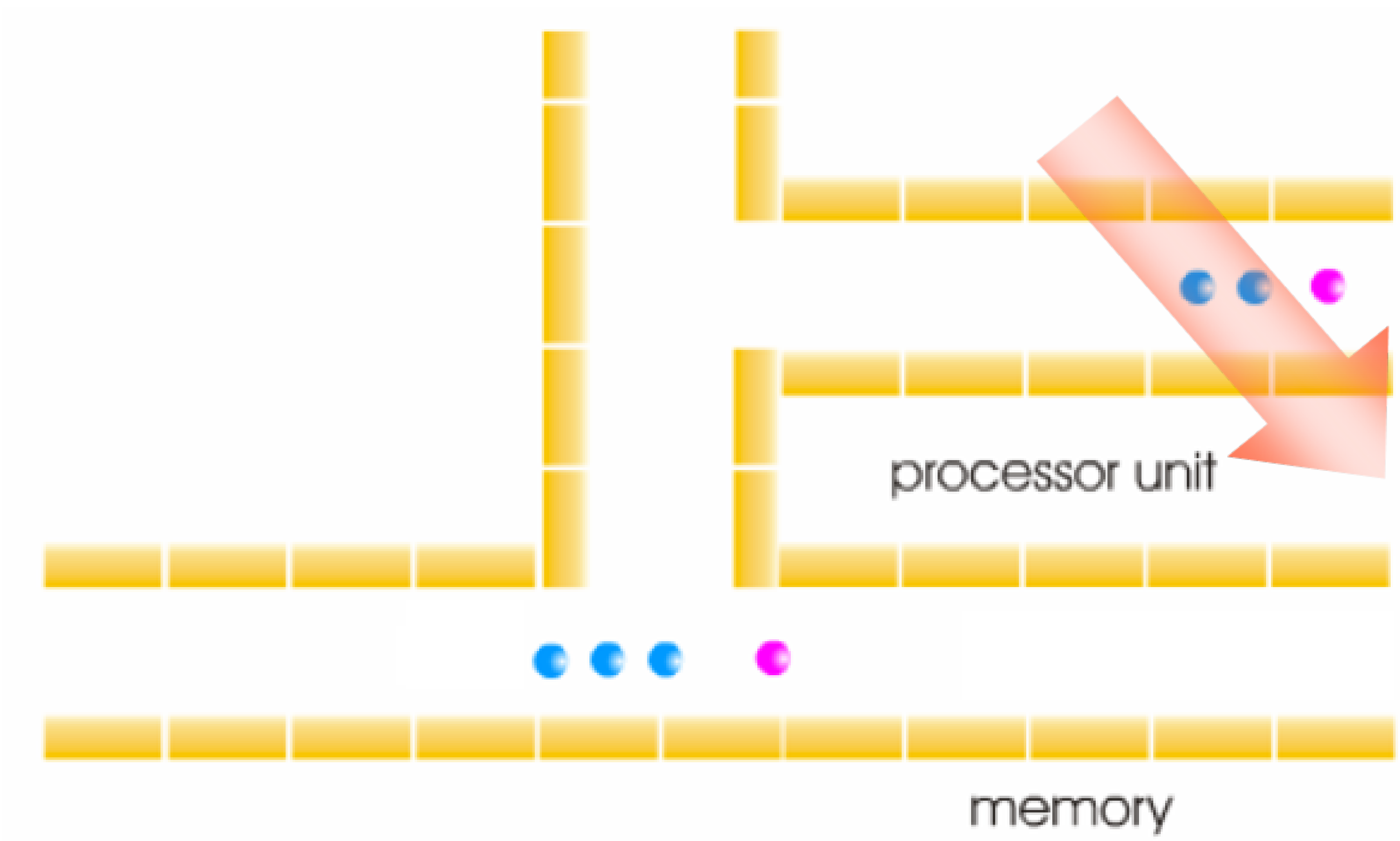
Scaling of ion trap quantum computers



Scaling of ion trap quantum computers

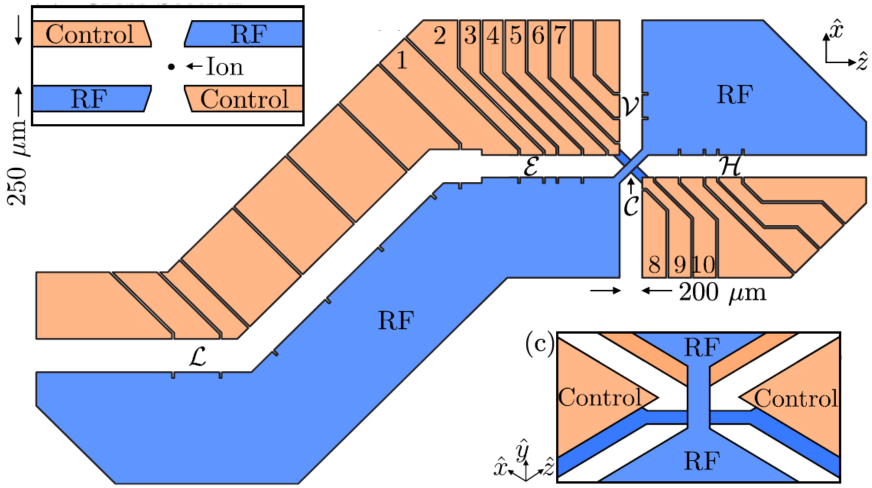


Scaling of ion trap quantum computers

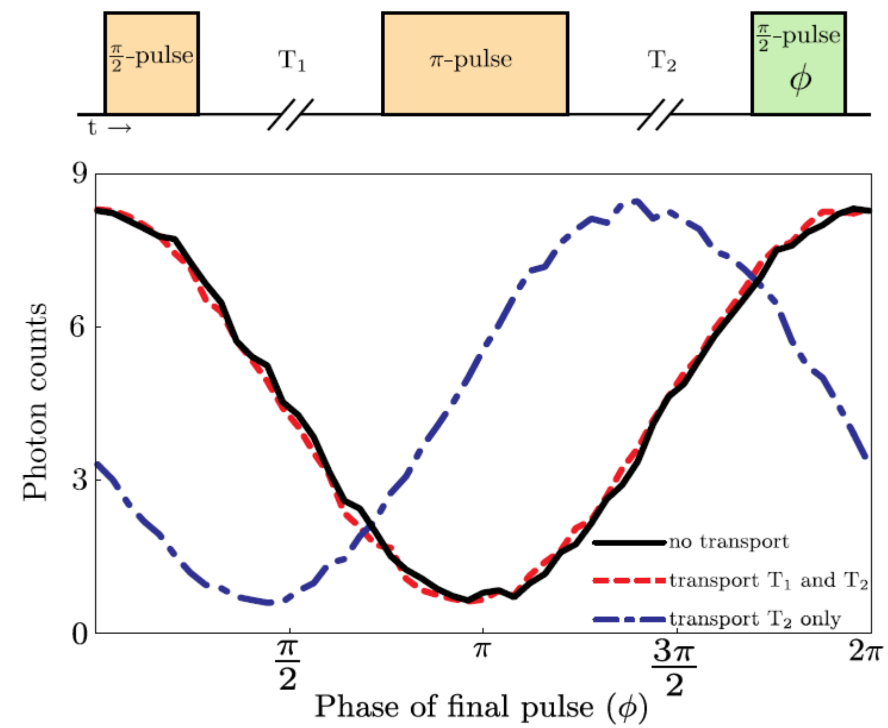


„Architecture for a large-scale ion-trap quantum computer“,
D. Kielpinski et al., Nature **417**, 709 (2002).

Coherent transport through a junction

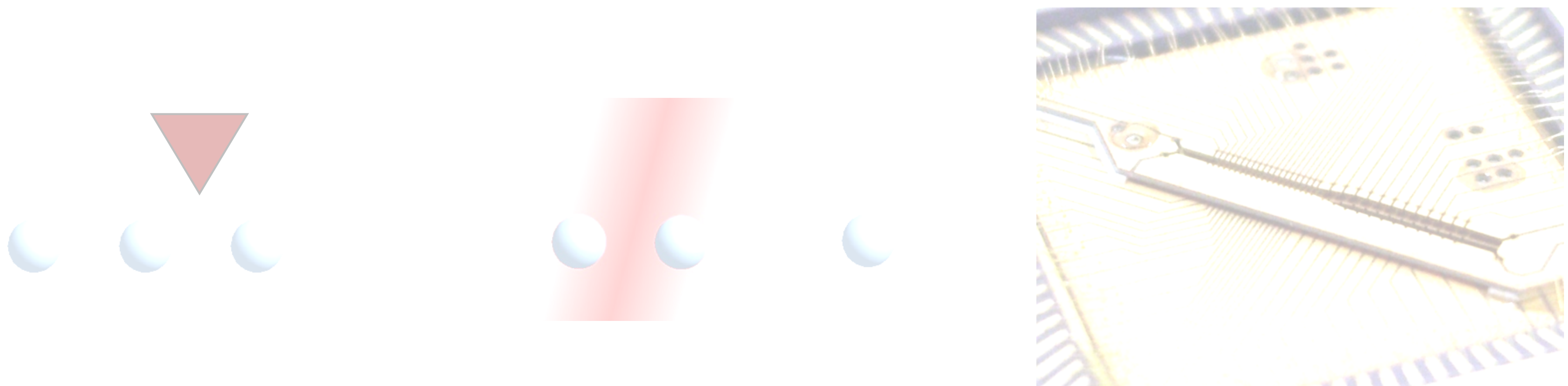


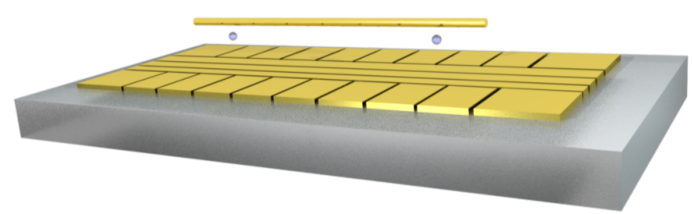
Transport		Energy Gain (recooling method) quanta/trip
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{E}$	1 ion	3.2 ± 1.8
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{H}$-$\mathcal{C}$-$\mathcal{E}$	1 ion	7.9 ± 1.5
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{V}$-$\mathcal{C}$-$\mathcal{E}$	1 ion	14.5 ± 2.0
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{E}$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

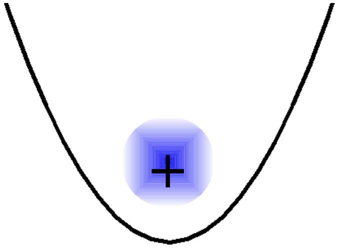
Scaling of ion trap quantum computers

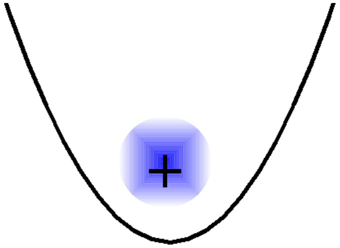




Wiring up trapped ions

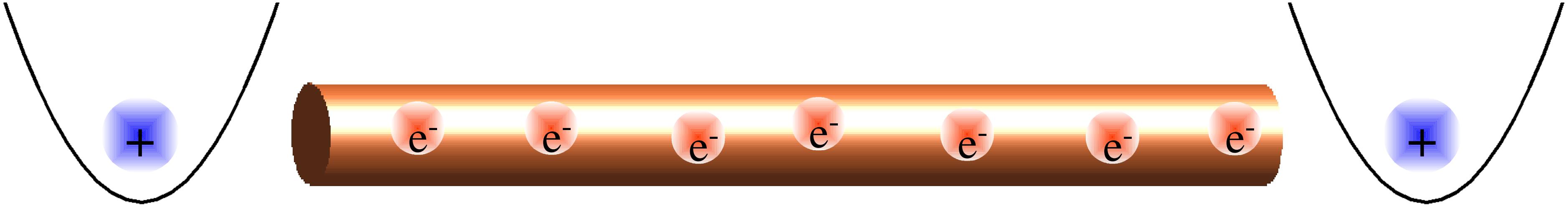
Two trapped ions …





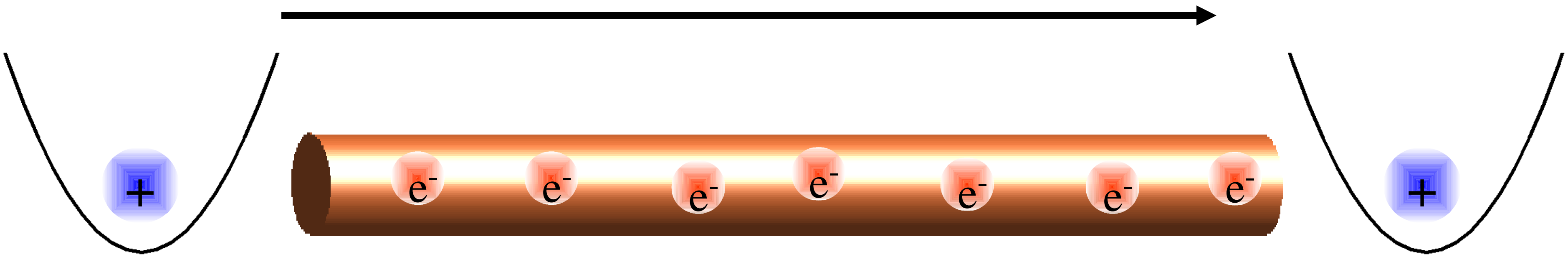
Wiring up trapped ions

Two trapped ions + a wire



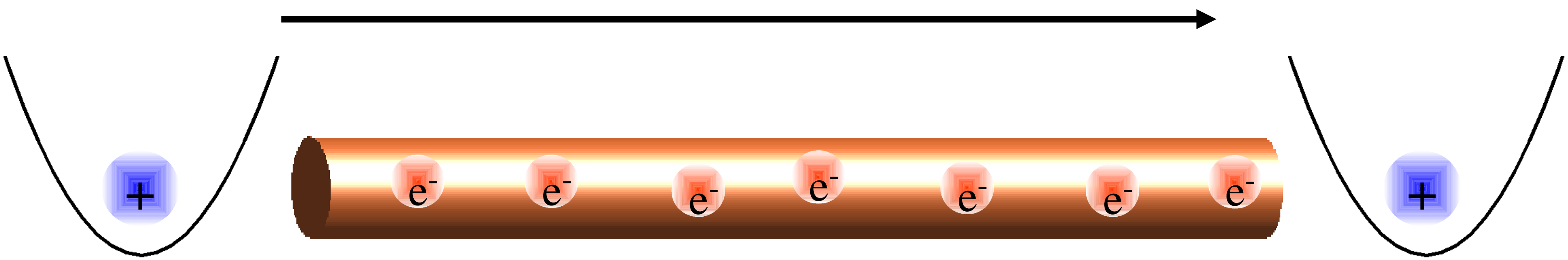
Wiring up trapped ions

Transport of quantum information



Wiring up trapped ions

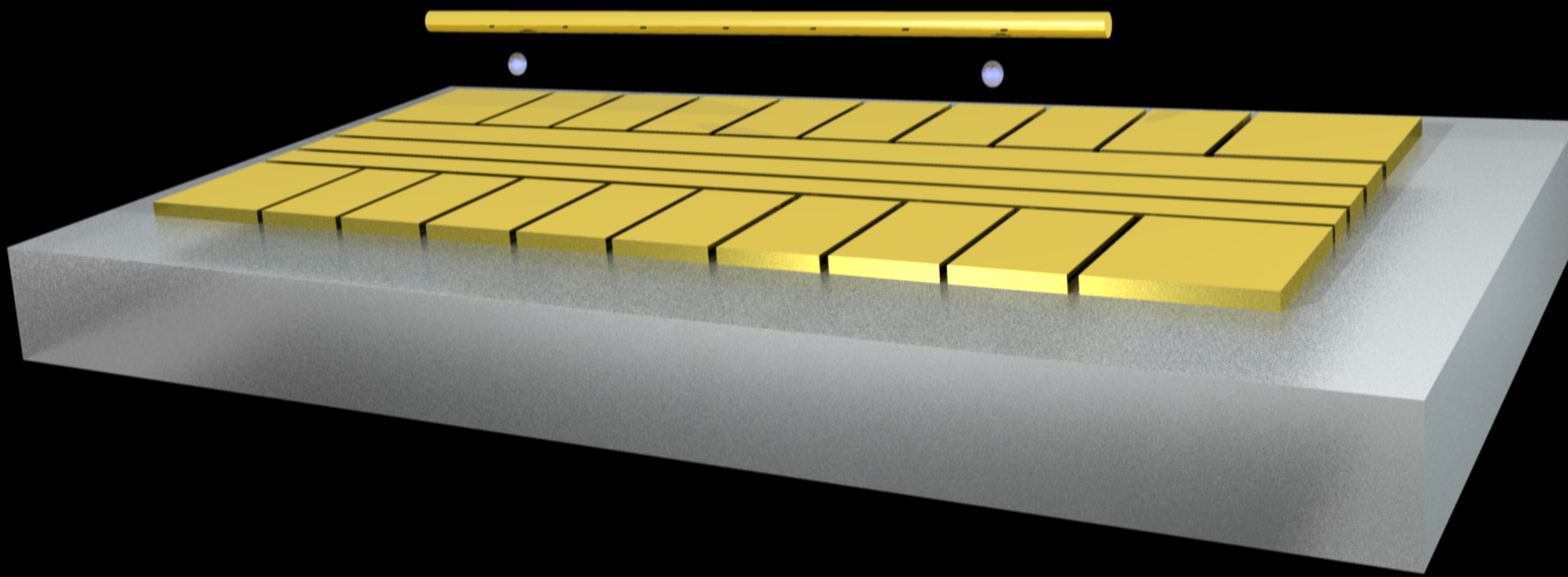
Transport of quantum information



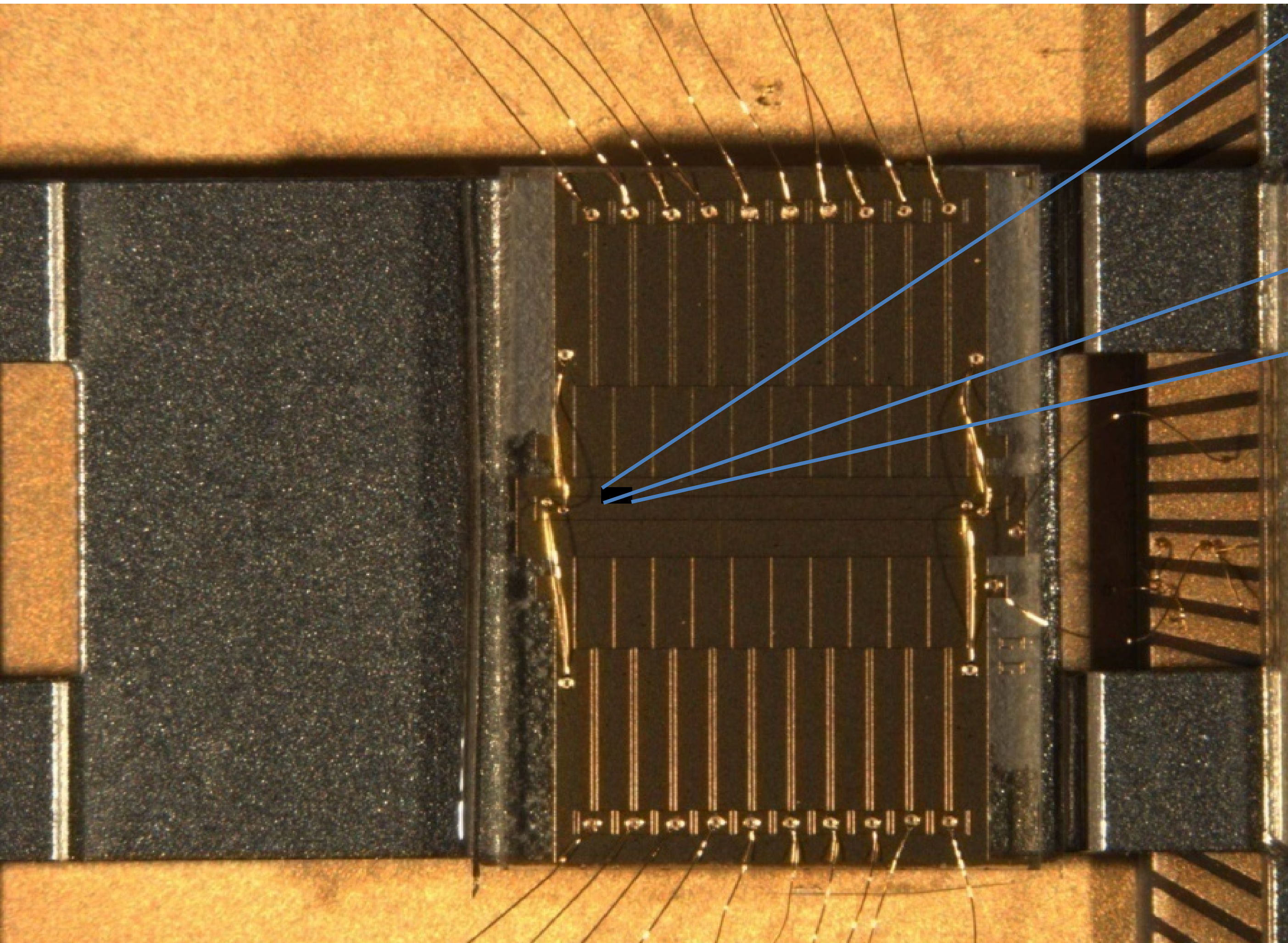
No trace of the quantum information should remain in the wire

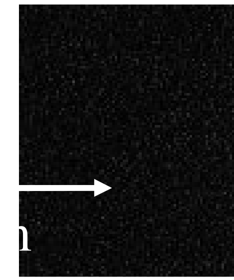
- ~~super conducting~~ wire

Experimental set-up



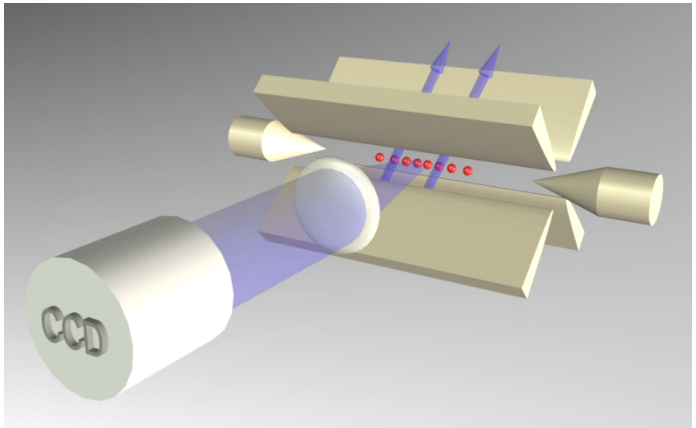
Experimental set-up



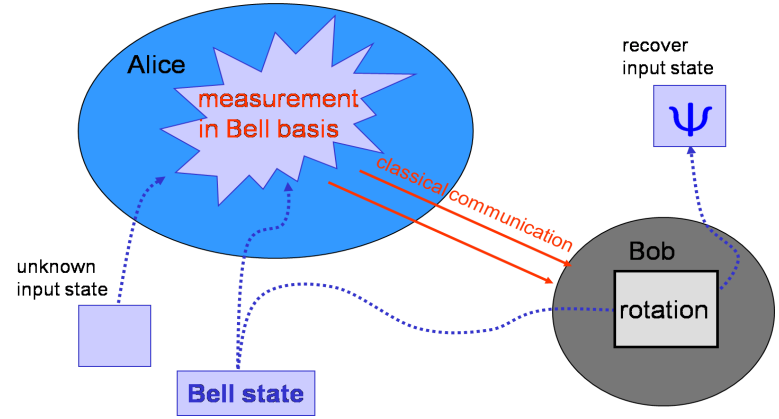


Conclusions

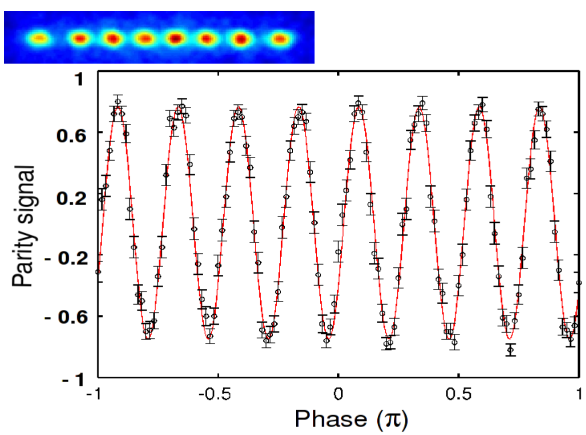
Ion trap quantum computing



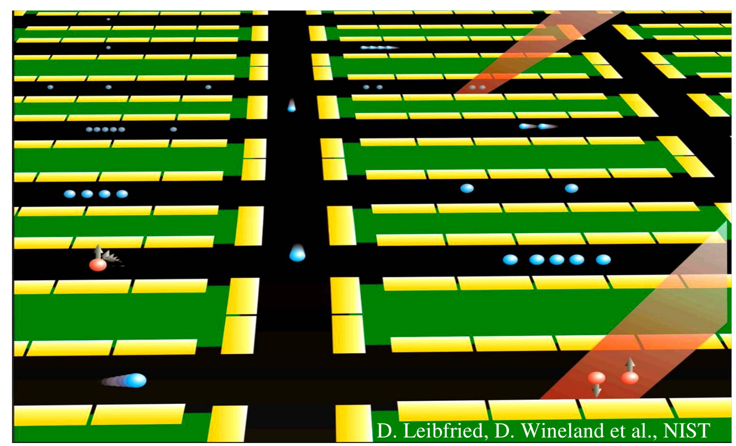
Teleportation



Schrödinger kitten



Scaling of ion traps



AG Quantenoptik und Spektroskopie

The Innsbruck ion trap group

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