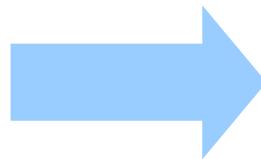


# Quantum Information, Decoherence-free Subspaces and a Michelson-Morley Test with Electrons

*Hartmut Häffner, UC Berkeley*

- Introduction to quantum information
- Improved ion traps for quantum computing
- A Michelson-Morley test with electrons
- Conclusions

# Physics and information



10110010011011
11010101010101
01010101010100

Physical  
process



# Physics and information



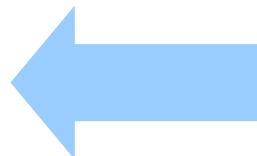
Physical  
process



```
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11010101010101  
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Algorithm

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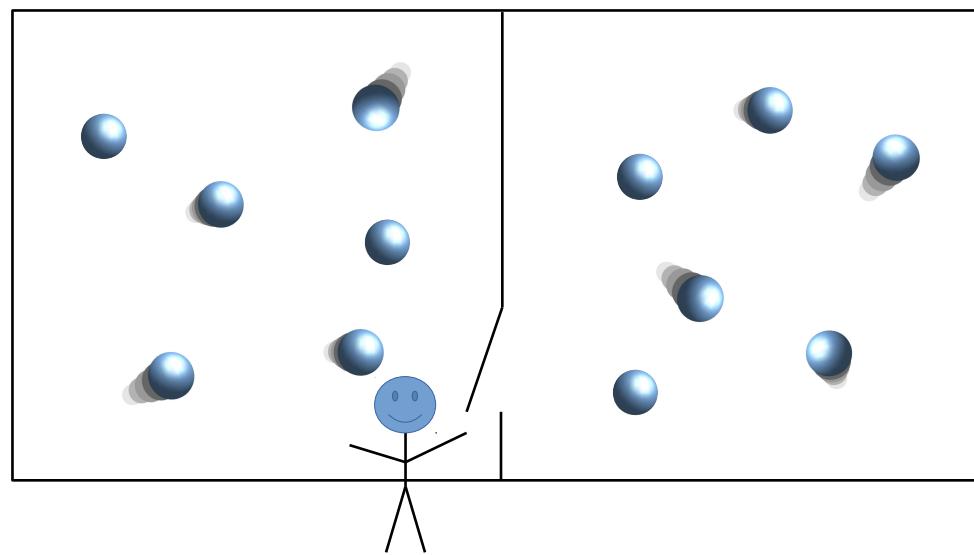


# Physics and information

Information is physical (Rolf Landauer, 1961)



Maxwell's demon



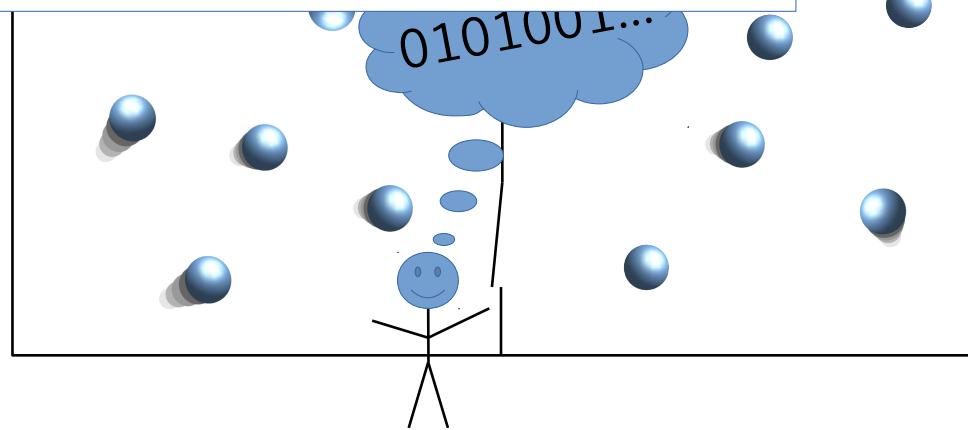
# Physics and information

Information is physical (Rolf Landauer, 1961)



Erasing information generates heat:

0101001101 → 0000000000 + entropy

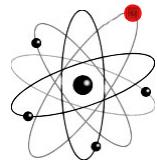


# Physics and quantum information

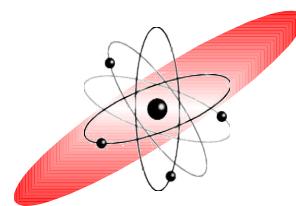
Information is physical (Rolf Landauer, 1961)

→ Information is quantum mechanical ?

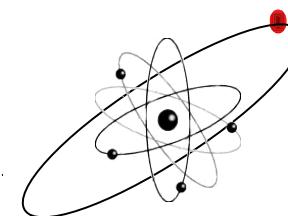
Qubits



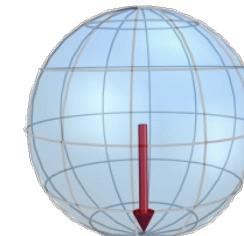
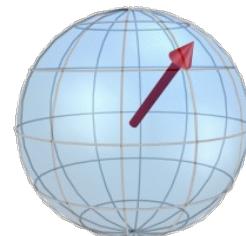
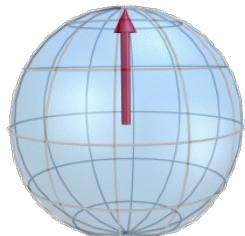
$|0\rangle$



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



$|1\rangle$



# 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	$0.0595 + 0.1064i, 0.0295 + 0.1327i, 0.0929 + 0.0406i, 0.1090 + 0.0379i, 0.0559 + 0.1286i, 0.0015 + 0.0345i, 0.0624 + 0.1196i, 0.1120 + 0.1350i, 0.1180 + 0.0345i, 0.1367 + 0.0356i, 0.1255 + 0.0074i, 0.0547 + 0.0116i, 0.0923 + 0.0952i$ $0.1087 + 0.0284i, 0.0288 + 0.1254i, 0.1345 + 0.0258i, 0.0846 + 0.0254i, 0.0939 + 0.1478i, 0.0348 + 0.0654i, 0.0816 + 0.0505i, 0.1384 + 0.0467i, 0.0498 + 0.0543i, 0.0974 + 0.0584i, 0.0582 + 0.0879i, 0.0932 + 0.0178i, 0.1039 + 0.0057i$ $0.0590 + 0.0682i, 0.0615 + 0.1293i, 0.0974 + 0.1388i, 0.1245 + 0.0933i, 0.0562 + 0.0238i, 0.0632 + 0.1297i, 0.0884 + 0.0354i, 0.0841 + 0.0960i, 0.1065 + 0.1437i, 0.0760 + 0.0988i, 0.1184 + 0.1293i, 0.0727 + 0.0015i, 0.0276 + 0.0204i$ $0.1041 + 0.1217i, 0.1460 + 0.0639i, 0.1199 + 0.1323i, 0.1046 + 0.1092i, 0.0721 + 0.1021i, 0.0170 + 0.0514i, 0.0988 + 0.0247i, 0.0543 + 0.0231i, 0.0208 + 0.0284i, 0.0842 + 0.0628i, 0.1223 + 0.1272i$ $0.1002 + 0.0729i, 0.1485 + 0.1213i, 0.1429 + 0.0685i, 0.0087 + 0.0680i, 0.0535 + 0.0670i, 0.0815 + 0.0613i, 0.0389 + 0.1340i, 0.0888 + 0.0008i, 0.0073 + 0.0442i, 0.0849 + 0.0073i, 0.1042 + 0.1030i, 0.1430 + 0.0966i, 0.1115 + 0.1461i$ $0.1100 + 0.0821i$
7	1001010	$0.0880 + 0.0466i, 0.1054 + 0.0684i, 0.0239 + 0.0866i, 0.0759 + 0.0090i, 0.0563 + 0.1020i, 0.1006 + 0.0988i, 0.0769 + 0.0649i, 0.0246 + 0.0273i, 0.0485 + 0.0942i, 0.0186 + 0.0554i, 0.1045 + 0.0790i, 0.0384 + 0.0455i, 0.0053 + 0.1037i$ $0.0815 + 0.0078i, 0.0965 + 0.0597i, 0.0309 + 0.0315i, 0.0271 + 0.0925i, 0.1006 + 0.0362i, 0.0141 + 0.0734i, 0.1015 + 0.0058i, 0.0757 + 0.0385i, 0.0914 + 0.0537i, 0.0226 + 0.0468i, 0.0491 + 0.0607i, 0.0087 + 0.0665i, 0.0918 + 0.0122i$ $0.0606 + 0.0969i, 0.0344 + 0.0814i, 0.0404 + 0.0853i, 0.0936 + 0.0879i, 0.0401 + 0.0723i, 0.0079 + 0.0217i, 0.0216 + 0.0294i, 0.0053 + 0.0675i, 0.0611 + 0.0579i, 0.0131 + 0.0064i, 0.0563 + 0.0096i, 0.0126 + 0.0293i, 0.0830 + 0.0441i$ $0.0404 + 0.0511i, 0.0888 + 0.0980i, 0.0500 + 0.0643i, 0.0645 + 0.0355i, 0.1024 + 0.0516i, 0.0311 + 0.0644i, 0.0959 + 0.0174i, 0.0110 + 0.0894i, 0.0070 + 0.1031i, 0.0253 + 0.0642i, 0.1006 + 0.0031i, 0.0068 + 0.0876i, 0.0285 + 0.0658i$ $0.1078 + 0.0756i, 0.0229 + 0.0099i, 0.0537 + 0.0458i, 0.0313 + 0.0405i, 0.0725 + 0.1791i, 0.1033 + 0.0898i, 0.0827 + 0.0090i, 0.0718 + 0.0487i, 0.0141 + 0.1032i, 0.0103 + 0.0159i, 0.0016 + 0.0938i, 0.0311 + 0.0830i, 0.0881 + 0.0479i$ $0.1063 + 0.0689i, 0.0019 + 0.1026i, 0.0884 + 0.0960i, 0.0670 + 0.0267i, 0.0604 + 0.0380i, 0.0263 + 0.0203i, 0.0886 + 0.0529i, 0.0284 + 0.0441i, 0.0813 + 0.0500i, 0.0711 + 0.0659i, 0.0231 + 0.0077i, 0.0649 + 0.0339i, 0.0652 + 0.0656i$ $0.0711 + 0.0189i, 0.0198 + 0.0670i, 0.0686 + 0.0265i, 0.0184 + 0.0633i, 0.0582 + 0.0546i, 0.0672 + 0.0501i, 0.0740 + 0.0584i, 0.0730 + 0.1016i, 0.0946 + 0.0369i, 0.0014 + 0.0433i, 0.0335 + 0.0332i, 0.0840 + 0.0444i, 0.0331 + 0.0308i$ $0.0999 + 0.0425i, 0.0732 + 0.0542i, 0.0800 + 0.0779i, 0.0076 + 0.0330i, 0.0013 + 0.0121i, 0.0245 + 0.0478i, 0.0557 + 0.0503i, 0.0494 + 0.0161i, 0.0758 + 0.0716i, 0.0626 + 0.0781i, 0.0549 + 0.0304i, 0.0080 + 0.0282i, 0.0208 + 0.0764i$ $0.0409 + 0.0845i, 0.0893 + 0.0425i, 0.0989 + 0.0562i, 0.0122 + 0.0774i, 0.0876 + 0.0614i, 0.0979 + 0.0497i, 0.0169 + 0.0480i, 0.0132 + 0.0095i, 0.0822 + 0.0478i, 0.0778 + 0.0395i, 0.0703 + 0.0326i, 0.0813 + 0.0919i, 0.0715 + 0.0819i$ $0.0953 + 0.1024i, 0.0293 + 0.0602i, 0.0452 + 0.0015i, 0.0230 + 0.0643i$
8	10101011	$0.0199 + 0.0027i, 0.0033 + 0.0063i, 0.0005 + 0.0656i, 0.0443 + 0.0262i, 0.0573 + 0.0359i, 0.0622 + 0.0704i, 0.0491 + 0.0176i, 0.0194 + 0.0664i, 0.0111 + 0.0508i, 0.0502 + 0.0687i, 0.0729 + 0.0376i, 0.0629 + 0.0765i, 0.0717 + 0.0288i$ $0.0239 + 0.0410i, 0.0207 + 0.0140i, 0.0413 + 0.0387i, 0.0126 + 0.0325i, 0.0163 + 0.0509i, 0.0167 + 0.0519i, 0.0502 + 0.0738i, 0.0041 + 0.0148i, 0.0177 + 0.0086i, 0.0514 + 0.0436i, 0.0240 + 0.0747i, 0.0236 + 0.0018i, 0.0555 + 0.0671i$ $0.0736 + 0.0021i, 0.0101 + 0.0400i, 0.0053 + 0.0148i, 0.0097 + 0.0052i, 0.0128 + 0.0193i, 0.0702 + 0.0720i, 0.0105 + 0.0106i, 0.0476 + 0.0402i, 0.0207 + 0.0690i, 0.0517 + 0.0726i, 0.0549 + 0.0258i, 0.0423 + 0.0337i, 0.0726 + 0.0363i$ $0.0254 + 0.0115i, 0.0543 + 0.0105i, 0.0727 + 0.0410i, 0.0448 + 0.0559i, 0.0678 + 0.0301i, 0.0578 + 0.0276i, 0.0293 + 0.0220i, 0.0559 + 0.0674i, 0.0125 + 0.0483i, 0.0737 + 0.0186i, 0.0515 + 0.0754i, 0.0598 + 0.0494i, 0.0473 + 0.0177i$ $0.0125 + 0.0528i, 0.0024 + 0.0513i, 0.0222 + 0.0104i, 0.0748 + 0.0073i, 0.0733 + 0.0090i, 0.0739 + 0.0053i, 0.0524 + 0.0657i, 0.0042 + 0.0139i, 0.0462 + 0.0259i, 0.0303 + 0.0056i, 0.0166 + 0.0414i, 0.0141 + 0.0213i$ $0.0059 + 0.0284i, 0.0006 + 0.0010i, 0.0608 + 0.0685i, 0.0014 + 0.0667i, 0.0677 + 0.0194i, 0.0272 + 0.0439i, 0.0557 + 0.0123i, 0.0746 + 0.0458i, 0.0240 + 0.0255i, 0.0126 + 0.0508i, 0.0023 + 0.0437i, 0.0276 + 0.0756i$

# Information content

# bits	classical	quantum mechanical
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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	$0.0595 + 0.1064i, \ 0.0295 + 0.1327i, \ 0.0929 + 0.0406i, \ 0.1090 + 0.0379i, \ 0.0559 + 0.1286i, \ 0.0015 + 0.0345i, \ 0.0624 + 0.1196i, \ 0.1120 + 0.1350i, \ 0.1180 + 0.0345i, \ 0.1367 + 0.0356i, \ 0.1255 + 0.0074i, \ 0.0547 + 0.0118i, \ 0.0923 + 0.0952i$ $0.1087 + 0.0284i, \ 0.0288 + 0.1254i, \ 0.1345 + 0.0258i, \ 0.0846 + 0.0254i, \ 0.0939 + 0.1478i, \ 0.0348 + 0.0654i, \ 0.0816 + 0.0505i, \ 0.1384 + 0.0467i, \ 0.0498 + 0.0543i, \ 0.0974 + 0.0584i, \ 0.0582 + 0.0879i, \ 0.0932 + 0.0178i, \ 0.1039 + 0.0057i$ $0.0590 + 0.0682i, \ 0.0615 + 0.1293i, \ 0.0974 + 0.1388i, \ 0.1245 + 0.0393i, \ 0.0552 + 0.0238i, \ 0.0632 + 0.1297i, \ 0.0884 + 0.0354i, \ 0.0841 + 0.0960i, \ 0.1065 + 0.1437i, \ 0.0760 + 0.0988i, \ 0.1154 + 0.1293i, \ 0.0727 + 0.0015i, \ 0.0276 + 0.0204i$ $0.1041 + 0.1217i, \ 0.1460 + 0.0639i, \ 0.1199 + 0.1323i, \ 0.1046 + 0.1092i, \ 0.0721 + 0.1021i, \ 0.0170 + 0.0514i, \ 0.0988 + 0.0247i, \ 0.0543 + 0.0231i, \ 0.0208 + 0.0284i, \ 0.0842 + 0.0628i, \ 0.1233 + 0.1272i$ $0.1002 + 0.0729i, \ 0.1485 + 0.1213i, \ 0.1429 + 0.0685i, \ 0.0087 + 0.0680i, \ 0.0535 + 0.0670i, \ 0.0815 + 0.0613i, \ 0.0389 + 0.1340i, \ 0.0888 + 0.0008i, \ 0.0073 + 0.0442i, \ 0.0849 + 0.0073i, \ 0.1042 + 0.1030i, \ 0.1430 + 0.0966i, \ 0.1115 + 0.1461i$ $0.1100 + 0.0821i$
7	1001010	$0.0880 + 0.0466i, \ 0.1054 + 0.0684i, \ 0.0239 + 0.0866i, \ 0.0759 + 0.0090i, \ 0.0563 + 0.1020i, \ 0.1006 + 0.0988i, \ 0.0769 + 0.0649i, \ 0.0246 + 0.0273i, \ 0.0485 + 0.0942i, \ 0.0186 + 0.0554i, \ 0.1045 + 0.0790i, \ 0.0384 + 0.0455i, \ 0.0053 + 0.1037i$ $0.0815 + 0.0798i, \ 0.0965 + 0.0597i, \ 0.0309 + 0.0315i, \ 0.0271 + 0.0925i, \ 0.0141 + 0.0734i, \ 0.1015 + 0.0558i, \ 0.0757 + 0.0385i, \ 0.0914 + 0.0537i, \ 0.0226 + 0.0468i, \ 0.0491 + 0.0607i, \ 0.0087 + 0.0665i, \ 0.0918 + 0.0122i$ $0.0606 + 0.0968i, \ 0.0344 + 0.0814i, \ 0.0404 + 0.0853i, \ 0.0936 + 0.0879i, \ 0.0401 + 0.0723i, \ 0.0079 + 0.0217i, \ 0.0216 + 0.0294i, \ 0.0053 + 0.0675i, \ 0.0611 + 0.0579i, \ 0.0131 + 0.0064i, \ 0.0563 + 0.0096i, \ 0.0126 + 0.0293i, \ 0.0830 + 0.0441i$ $0.0404 + 0.0511i, \ 0.0888 + 0.0980i, \ 0.0050 + 0.0643i, \ 0.0645 + 0.0355i, \ 0.1024 + 0.0516i, \ 0.0311 + 0.0644i, \ 0.0599 + 0.0174i, \ 0.0110 + 0.0730i, \ 0.0253 + 0.0462i, \ 0.0491 + 0.0607i, \ 0.0088 + 0.0658i, \ 0.0932 + 0.0178i, \ 0.1039 + 0.0057i$ $0.1078 + 0.0756i, \ 0.0229 + 0.0099i, \ 0.0537 + 0.0458i, \ 0.0313 + 0.0405i, \ 0.0725 + 0.0179i, \ 0.1033 + 0.0898i, \ 0.0827 + 0.0904i, \ 0.0141 + 0.1032i, \ 0.0103 + 0.0159i, \ 0.0016 + 0.0938i, \ 0.0311 + 0.0830i, \ 0.0881 + 0.0479i$ $0.1063 + 0.0669i, \ 0.0019 + 0.1026i, \ 0.0884 + 0.0690i, \ 0.0670 + 0.0267i, \ 0.0604 + 0.0389i, \ 0.0263 + 0.0203i, \ 0.0886 + 0.0529i, \ 0.0284 + 0.0441i, \ 0.0813 + 0.0505i, \ 0.0023 + 0.0771i, \ 0.0649 + 0.0339i, \ 0.0652 + 0.0656i$ $0.0711 + 0.0189i, \ 0.0198 + 0.0670i, \ 0.0868 + 0.0265i, \ 0.0184 + 0.0633i, \ 0.0582 + 0.0540i, \ 0.0672 + 0.0501i, \ 0.0740 + 0.0584i, \ 0.0730 + 0.1016i, \ 0.0946 + 0.0369i, \ 0.0014 + 0.0433i, \ 0.0335 + 0.0332i, \ 0.0840 + 0.0444i, \ 0.0331 + 0.0308i$ $0.0999 + 0.0425i, \ 0.0732 + 0.0542i, \ 0.0880 + 0.0779i, \ 0.0076 + 0.0330i, \ 0.0013 + 0.0121i, \ 0.0245 + 0.0478i, \ 0.0557 + 0.0503i, \ 0.0494 + 0.0016i, \ 0.0758 + 0.0716i, \ 0.0628 + 0.0781i, \ 0.0549 + 0.0304i, \ 0.0080 + 0.0282i, \ 0.0208 + 0.0764i$ $0.0409 + 0.0845i, \ 0.0893 + 0.0425i, \ 0.0898 + 0.0562i, \ 0.0122 + 0.0774i, \ 0.0876 + 0.0614i, \ 0.0979 + 0.0497i, \ 0.0169 + 0.0480i, \ 0.0132 + 0.0095i, \ 0.0882 + 0.0478i, \ 0.0778 + 0.0395i, \ 0.0703 + 0.0326i, \ 0.0813 + 0.0191i, \ 0.0715 + 0.0819i$ $0.0953 + 0.1024i, \ 0.0293 + 0.0602i, \ 0.0452 + 0.0015i, \ 0.0230 + 0.0643i$
8	10101011	$0.0199 + 0.0027i, \ 0.0033 + 0.0063i, \ 0.0005 + 0.0656i, \ 0.0443 + 0.0262i, \ 0.0573 + 0.0359i, \ 0.0622 + 0.0704i, \ 0.0491 + 0.0176i, \ 0.0194 + 0.0664i, \ 0.0111 + 0.0506i, \ 0.0502 + 0.0687i, \ 0.0729 + 0.0376i, \ 0.0629 + 0.0765i, \ 0.0717 + 0.0288i$ $0.0239 + 0.0410i, \ 0.0207 + 0.0140i, \ 0.0413 + 0.0387i, \ 0.0126 + 0.0325i, \ 0.0163 + 0.0509i, \ 0.0167 + 0.0519i, \ 0.0502 + 0.0738i, \ 0.0041 + 0.0148i, \ 0.0177 + 0.0086i, \ 0.0514 + 0.0436i, \ 0.0240 + 0.0747i, \ 0.0236 + 0.0018i, \ 0.0555 + 0.0671i$ $0.0736 + 0.0021i, \ 0.0101 + 0.0400i, \ 0.0553 + 0.0148i, \ 0.0097 + 0.0552i, \ 0.0128 + 0.0193i, \ 0.0702 + 0.0720i, \ 0.0105 + 0.0106i, \ 0.0476 + 0.0402i, \ 0.0207 + 0.0690i, \ 0.0170 + 0.0726i, \ 0.0549 + 0.0258i, \ 0.0423 + 0.0337i, \ 0.0726 + 0.0363i$ $0.0254 + 0.0118i, \ 0.0543 + 0.0105i, \ 0.0727 + 0.0104i, \ 0.0448 + 0.0559i, \ 0.0678 + 0.0307i, \ 0.0578 + 0.0276i, \ 0.0293 + 0.0220i, \ 0.0558 + 0.0670i, \ 0.0125 + 0.0483i, \ 0.0737 + 0.0186i, \ 0.0151 + 0.0754i, \ 0.0598 + 0.0494i, \ 0.0473 + 0.0177i$ $0.0059 + 0.0284i, \ 0.0006 + 0.0010i, \ 0.0608 + 0.0685i, \ 0.0014 + 0.0667i, \ 0.0677 + 0.0196i, \ 0.0272 + 0.0439i, \ 0.0557 + 0.0123i, \ 0.0746 + 0.0458i, \ 0.0120 + 0.0255i, \ 0.0126 + 0.0508i, \ 0.0242 + 0.0666i, \ 0.0023 + 0.0437i, \ 0.0276 + 0.0756i$ $0.0021 + 0.0610i, \ 0.0612 + 0.0118i, \ 0.0770 + 0.0642i, \ 0.0085 + 0.0148i, \ 0.0480 + 0.0493i, \ 0.0102 + 0.0516i, \ 0.0239 + 0.0595i, \ 0.0104 + 0.0293i, \ 0.0172 + 0.0340i, \ 0.0306 + 0.0372i, \ 0.0104 + 0.0466i, \ 0.0186 + 0.0136i, \ 0.0715 + 0.0002i$ $0.0301 + 0.0609i, \ 0.0394 + 0.0396i, \ 0.0072 + 0.0164i, \ 0.0017 + 0.0080i, \ 0.0123 + 0.0164i, \ 0.0851 + 0.0314i, \ 0.0678 + 0.0340i, \ 0.0144 + 0.0041i, \ 0.0764 + 0.0276i, \ 0.0549 + 0.0116i, \ 0.0672 + 0.0296i, \ 0.0370 + 0.0240i, \ 0.0382 + 0.0130i$ $0.0222 + 0.0691i, \ 0.0047 + 0.0249i, \ 0.0202 + 0.0256i, \ 0.0566 + 0.0143i, \ 0.0144 + 0.0317i, \ 0.0707 + 0.0308i, \ 0.0095 + 0.0390i, \ 0.0010 + 0.0130i, \ 0.0285 + 0.0404i, \ 0.0358 + 0.0494i, \ 0.0685 + 0.0012i, \ 0.0458 + 0.0645i, \ 0.0121 + 0.0619i, \ 0.0244 + 0.0538i$ $0.0180 + 0.0356i, \ 0.0006 + 0.0064i, \ 0.0306 + 0.0633i, \ 0.0501 + 0.0149i, \ 0.0666 + 0.0343i, \ 0.0593 + 0.0010i, \ 0.0747 + 0.0238i, \ 0.0551 + 0.0675i, \ 0.0183 + 0.0257i, \ 0.0151 + 0.0679i, \ 0.0203 + 0.0370i, \ 0.0560 + 0.0432i$ $0.0753 + 0.0475i, \ 0.0491 + 0.0510i, \ 0.0421 + 0.0475i, \ 0.0654 + 0.0528i, \ 0.0618 + 0.0393i, \ 0.0515 + 0.0397i, \ 0.0633 + 0.0467i, \ 0.0748 + 0.0745i, \ 0.0375 + 0.0634i, \ 0.0630 + 0.0245i, \ 0.0494 + 0.0453i, \ 0.0236 + 0.0100i$ $0.0509 + 0.0196i, \ 0.0276 + 0.0619i, \ 0.0723 + 0.0515i, \ 0.0376 + 0.0011i, \ 0.0070 + 0.0433i, \ 0.0519 + 0.0350i, \ 0.0397 + 0.0697i, \ 0.0171 + 0.0217i, \ 0.0559 + 0.0050i, \ 0.0053 + 0.0367i, \ 0.0743 + 0.0758i, \ 0.0160 + 0.0711i, \ 0.0124 + 0.0433i$ $0.0492 + 0.0503i, \ 0.0000 + 0.0596i, \ 0.0259 + 0.0082i, \ 0.0212 + 0.0010i, \ 0.0034 + 0.0418i, \ 0.0072 + 0.0050i, \ 0.0316 + 0.0348i, \ 0.0630 + 0.0151i, \ 0.0671 + 0.0071i, \ 0.0017 + 0.0477i, \ 0.0560 + 0.0012i, \ 0.0654 + 0.0687i, \ 0.0562 + 0.0587i$ $0.0736 + 0.0699i, \ 0.0506 + 0.0585i, \ 0.0572 + 0.0293i, \ 0.0266 + 0.0255i, \ 0.0681 + 0.0389i, \ 0.0268 + 0.0435i, \ 0.0670 + 0.0514i, \ 0.0302 + 0.0522i, \ 0.0195 + 0.0726i, \ 0.0273 + 0.0594i, \ 0.0573 + 0.0568i, \ 0.0502 + 0.0686i, \ 0.0724 + 0.0764i$ $0.0642 + 0.0388i, \ 0.0362 + 0.0485i, \ 0.0485 + 0.0611i, \ 0.0045 + 0.0346i, \ 0.0418 + 0.0404i, \ 0.0351 + 0.0132i, \ 0.0665 + 0.0101i, \ 0.0659 + 0.0169i, \ 0.0364 + 0.0081i, \ 0.0607 + 0.0109i, \ 0.0505 + 0.0352i, \ 0.0000 + 0.0607i, \ 0.0101 + 0.0217i$ $0.0381 + 0.0434i, \ 0.0030 + 0.0701i, 0.0175 + 0.0066i, \ 0.0253 + 0.0454i, \ 0.0693 + 0.0419i, \ 0.0242 + 0.0504i, \ 0.0194 + 0.0242i, \ 0.0334 + 0.0178i, \ 0.0649 + 0.0251i, \ 0.0251 + 0.0323i, \ 0.0349 + 0.0273i, \ 0.0438 + 0.0264i$ $0.0293 + 0.0434i, \ 0.0683 + 0.0092i, \ 0.0587 + 0.0130i, \ 0.0681 + 0.0215i, \ 0.0353 + 0.0429i, \ 0.0616 + 0.0374i, \ 0.0103 + 0.0234i, \ 0.0050 + 0.0179i, \ 0.0289 + 0.0369i, \ 0.0288 + 0.0406i, \ 0.0373 + 0.0611i, \ 0.0747 + 0.0149i, \ 0.0264 + 0.0701i$ $0.0195 + 0.0711i, \ 0.0451 + 0.0010i, \ 0.0404 + 0.0592i, \ 0.0126 + 0.0730i, \ 0.0375 + 0.0621i, \ 0.0382 + 0.0712i, \ 0.0650 + 0.0153i, \ 0.0621 + 0.0715i, \ 0.0261 + 0.0426i, \ 0.0436 + 0.0458i, \ 0.0472 + 0.0474i, \ 0.0079 + 0.0003i$ $0.0122 + 0.0757i, \ 0.0319 + 0.0693i, \ 0.0432 + 0.0534i, \ 0.0207 + 0.0339i, \ 0.0604 + 0.0540i, \ 0.0299 + 0.0470i, \ 0.0244 + 0.0660i, \ 0.0431 + 0.0306i, \ 0.0155 + 0.0225i, \ 0.0067 + 0.0075i, \ 0.0719 + 0.0306i, \ 0.0200 + 0.0257i$ $0.0157 + 0.0728i, \ 0.0038 + 0.0646i$

# Taking advantage of quantum information ?

Schrödinger equation for 300 interacting spins.

Naive 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)
- ...



# Taking advantage of quantum information ?

Schrödinger equation for 300 interacting spins.

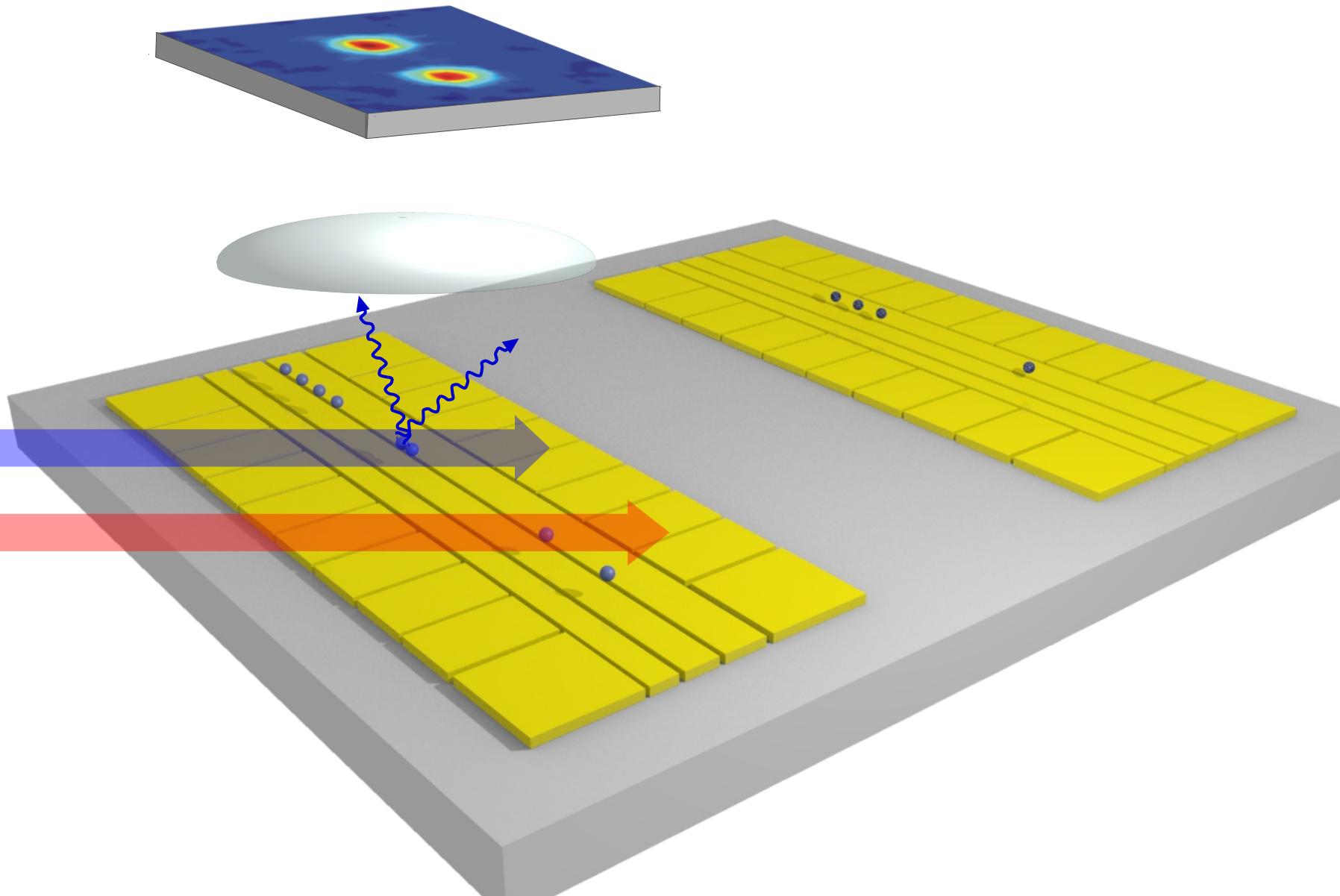
Naive classical computation needs more bits than there are atoms in the universe.

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

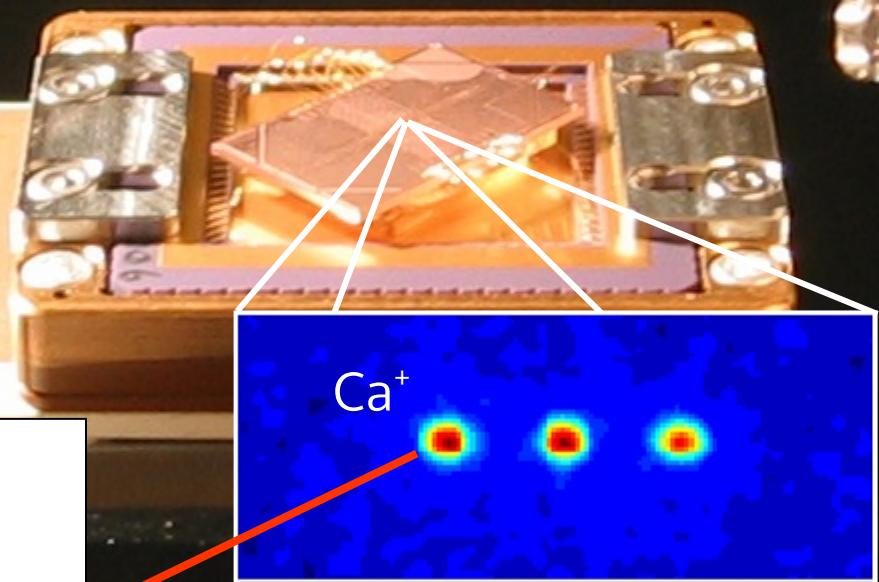
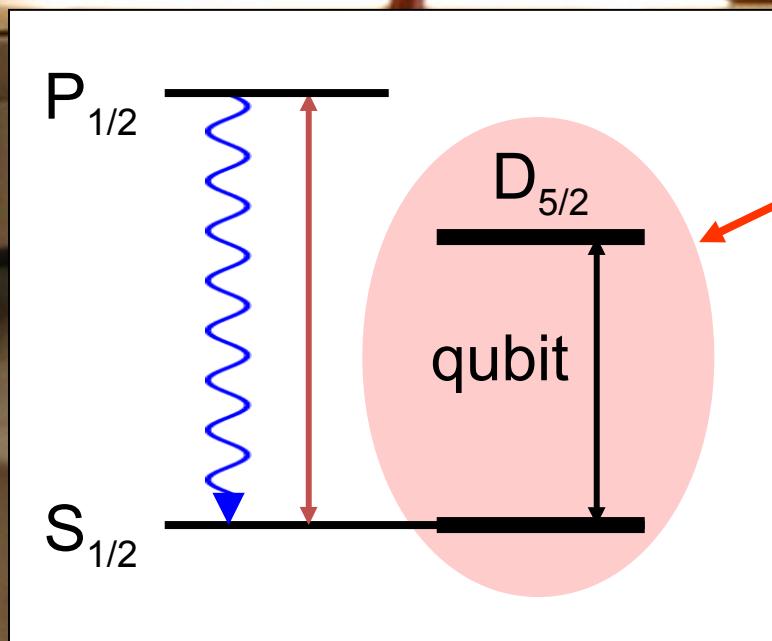
Physics motivations:

- quantum mechanics.
- impact on condensed matter physics, Chemistry, Biology.
- impact on cosmology.
- unforeseen applications ...

# Ion trap quantum computing



# The hardware



# Quantum computing

## Classical computer

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

Computational space:

00

01

10

11

- Read out  
→ result

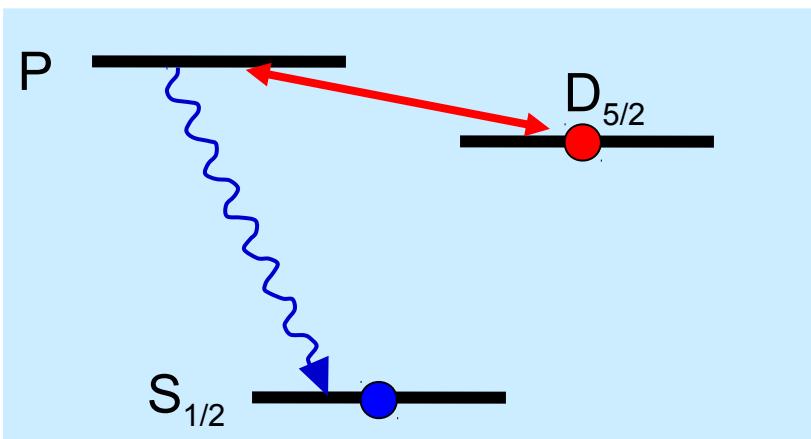
## Quantum computer

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

Computational space: Hilbert space  
 $2^n$  dimensional

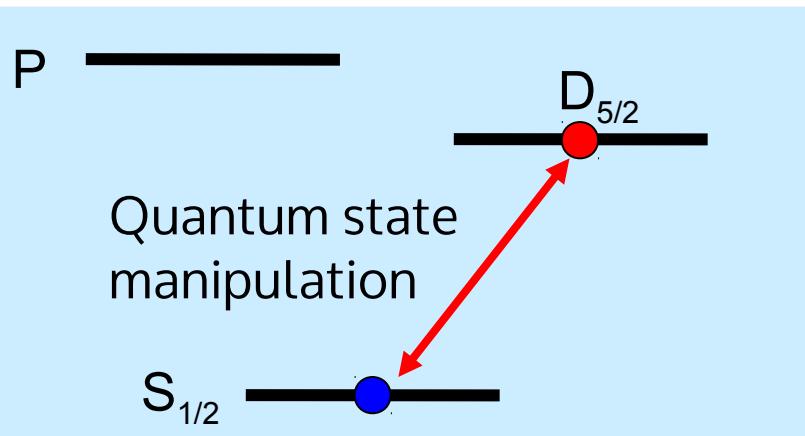
- Read out of qubits  
→ gain of classical information

# Experimental procedure



1. Initialization in a pure quantum state

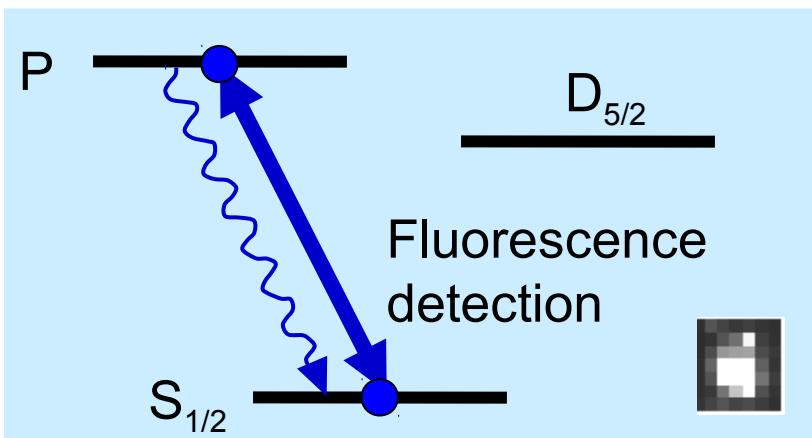
# Experimental procedure



1. Initialization in a pure quantum state

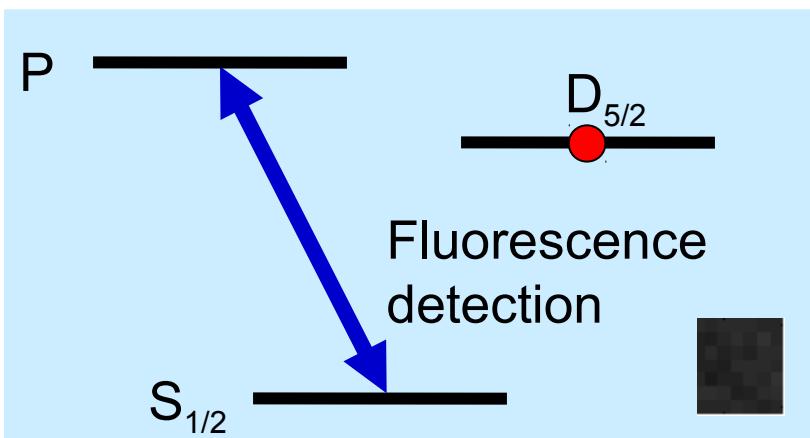
2. Quantum state manipulation on  
 $S_{1/2} - D_{5/2}$  transition

# 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

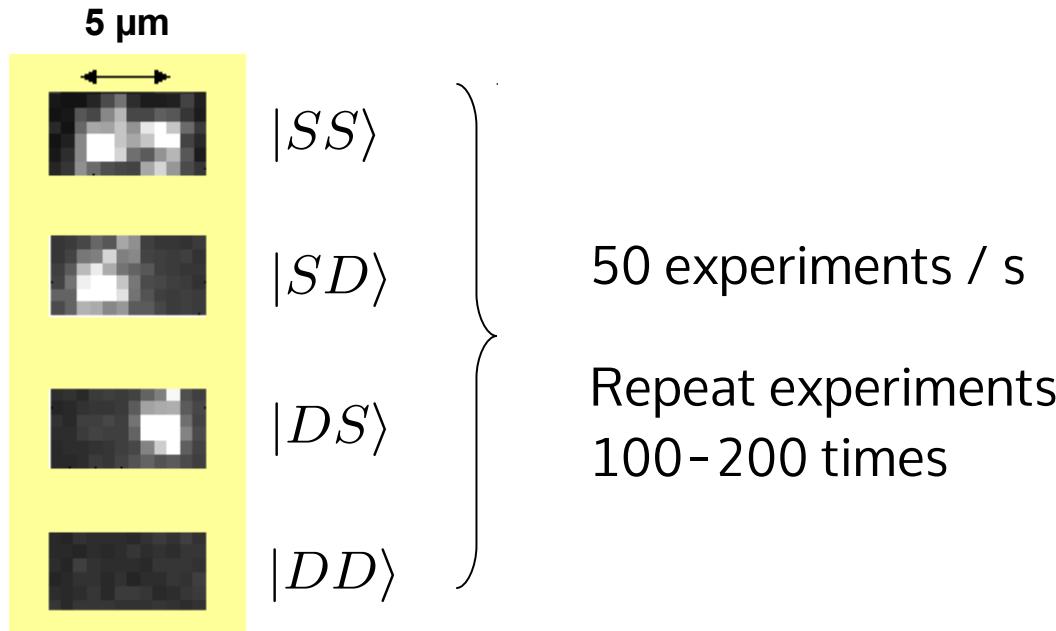
# Experimental procedure



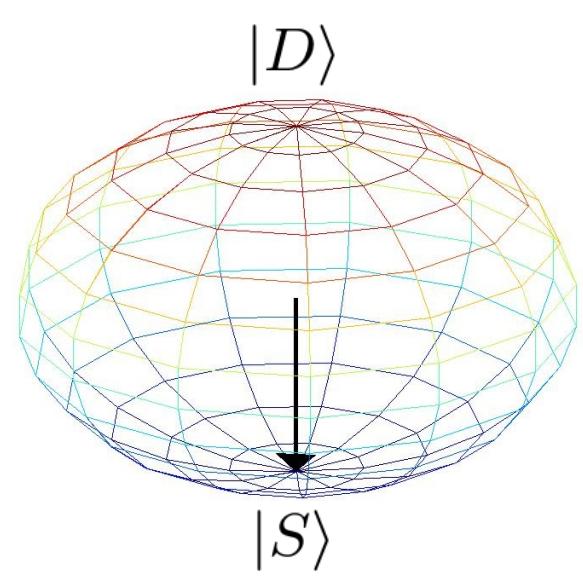
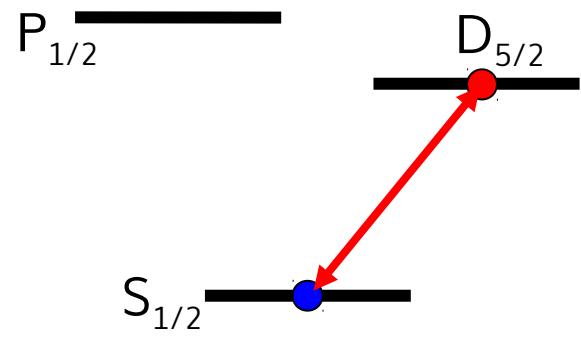
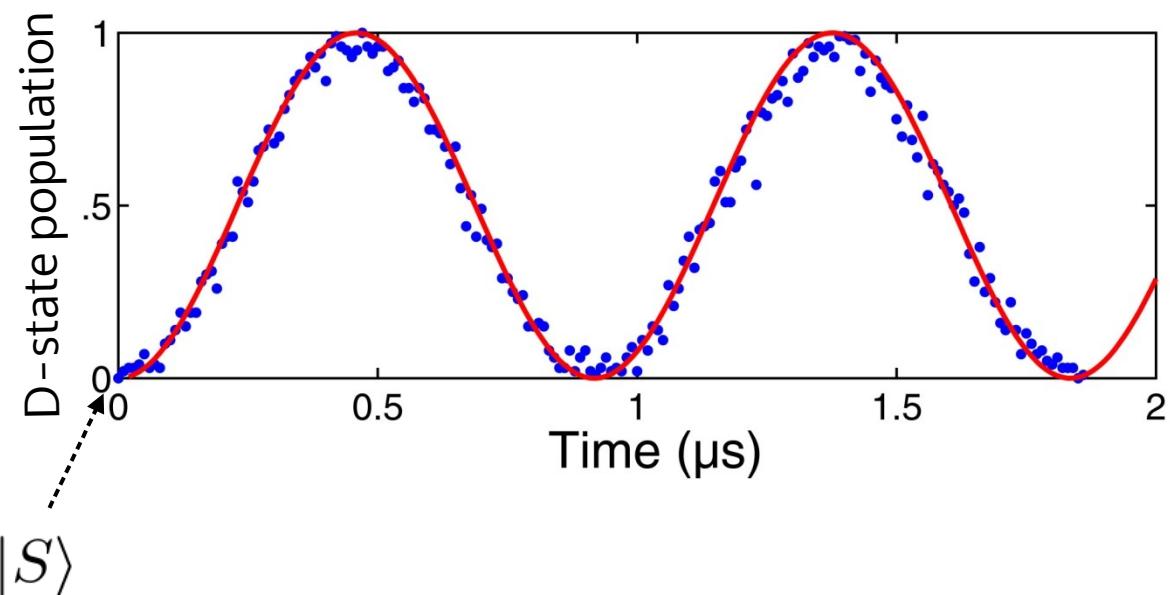
1. Initialization in a pure quantum state
2. Quantum state manipulation on  $S_{1/2} - D_{5/2}$  transition
3. Quantum state measurement by fluorescence detection

Two ions:

Spatially resolved  
detection with  
CCD camera

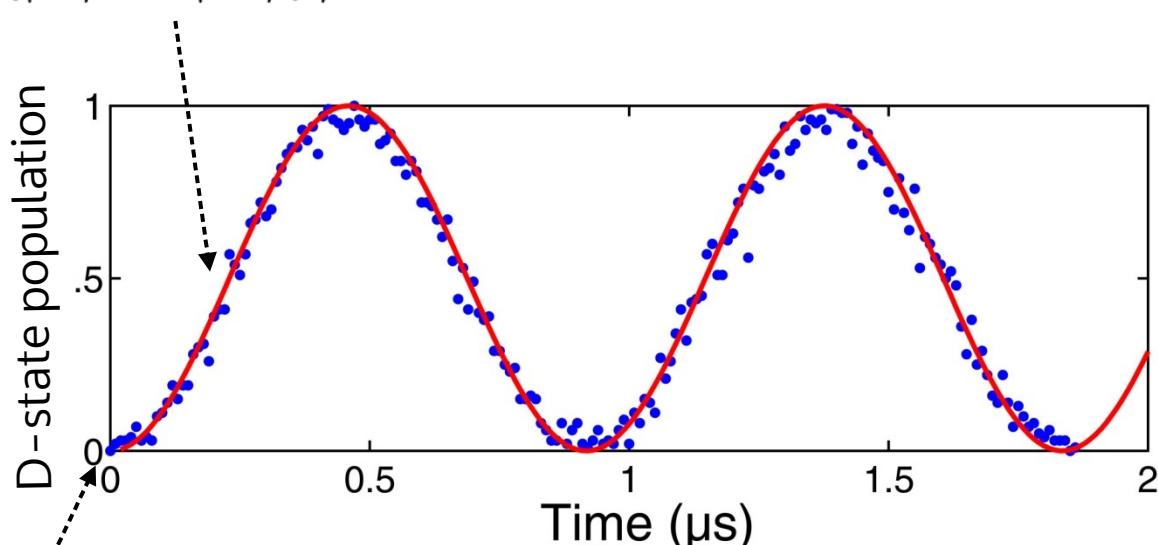


# Single qubit gates



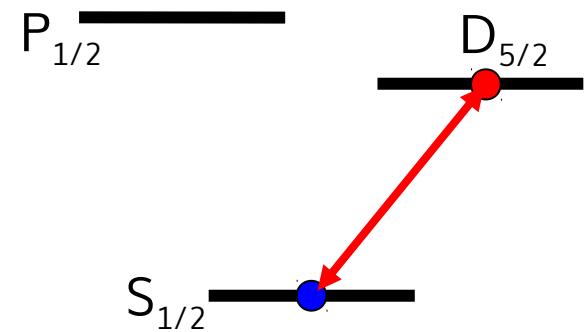
# Single qubit gates

$$(|S\rangle + |D\rangle)/\sqrt{2}$$

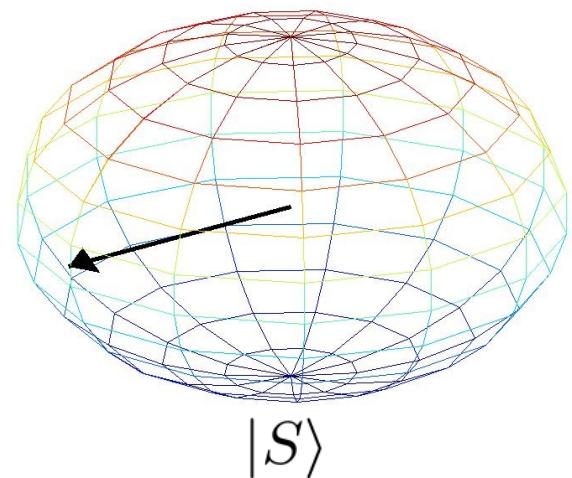


$$|S\rangle$$

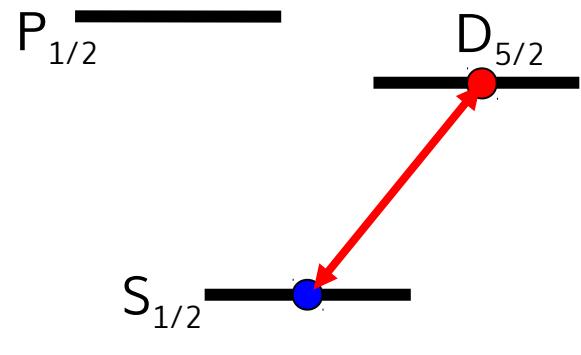
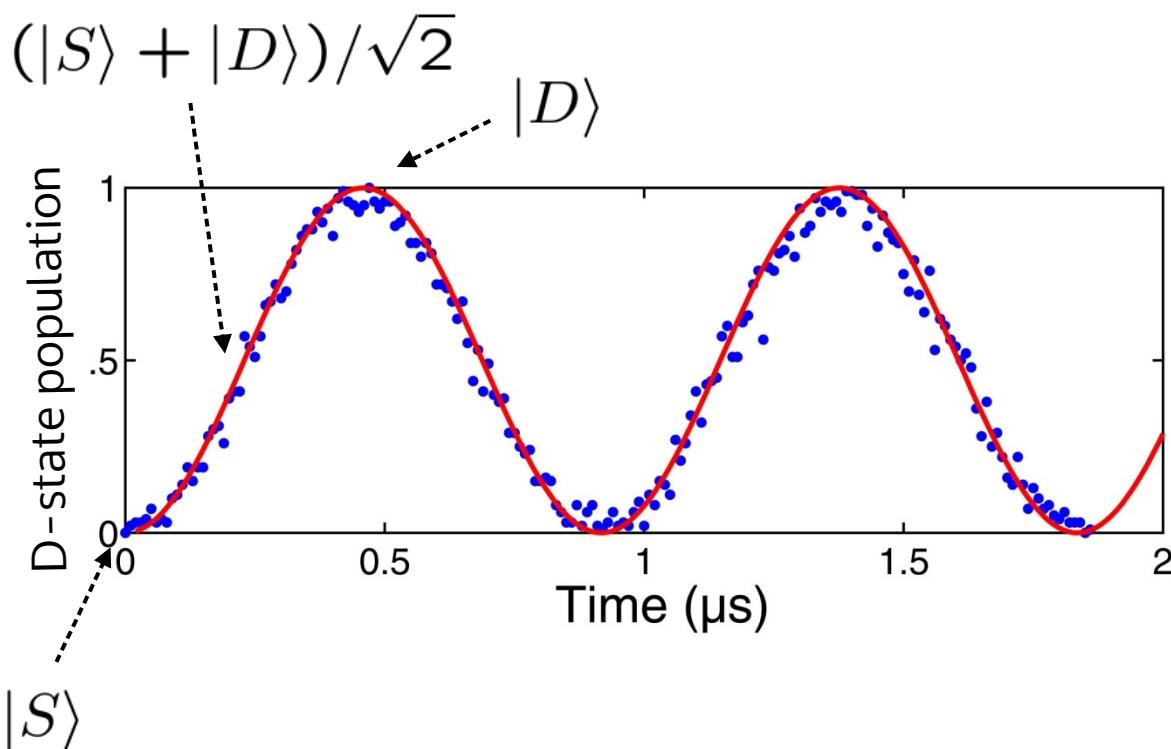
$$(|S\rangle + |D\rangle)/\sqrt{2}$$



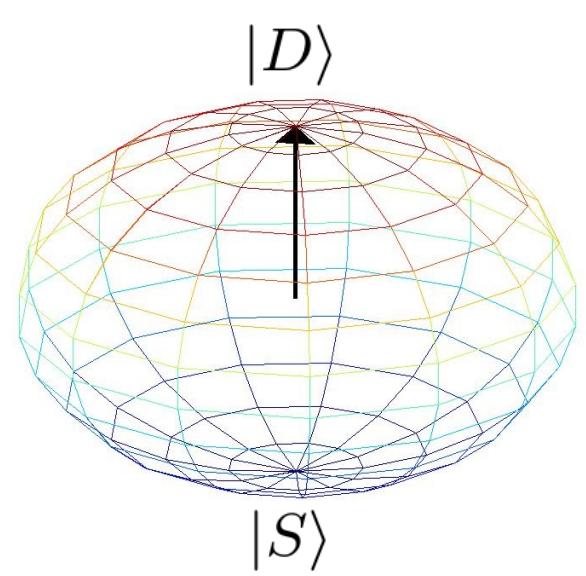
$$|D\rangle$$



# Single qubit gates

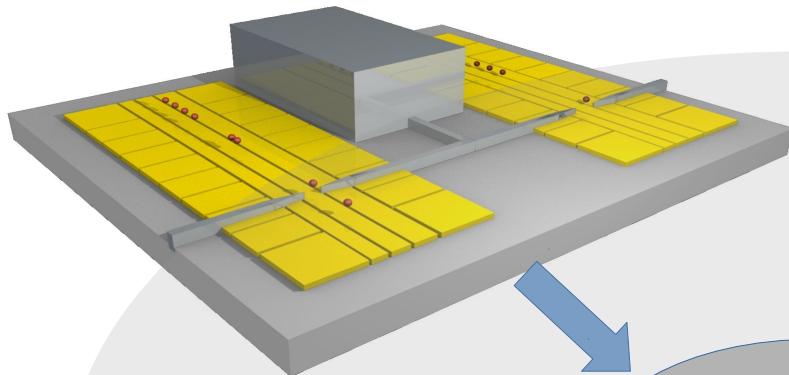


$$(|S\rangle + |D\rangle)/\sqrt{2}$$

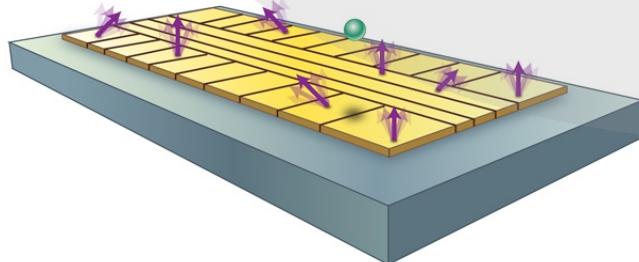


# Research overview

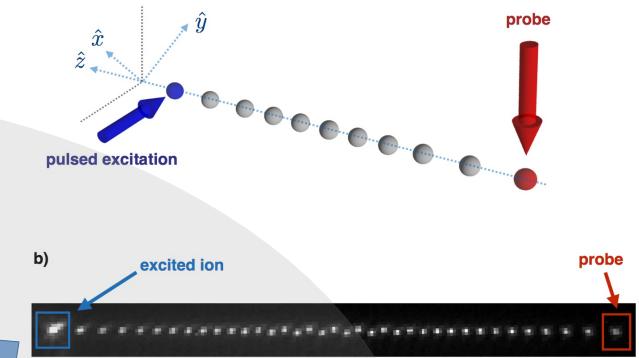
Novel QIP-architectures,  
hybrid quantum systems



Improving ion traps,  
reducing surface noise



Quantum many-body physics,  
quantum correlations

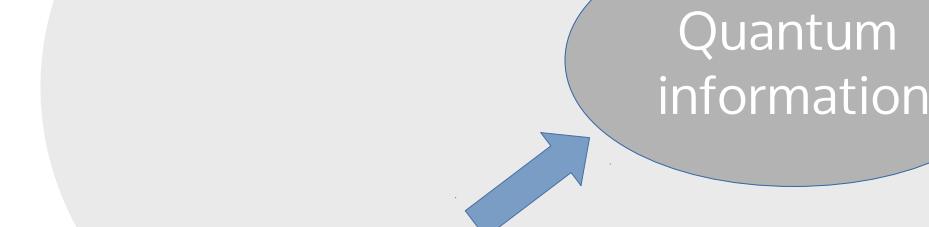
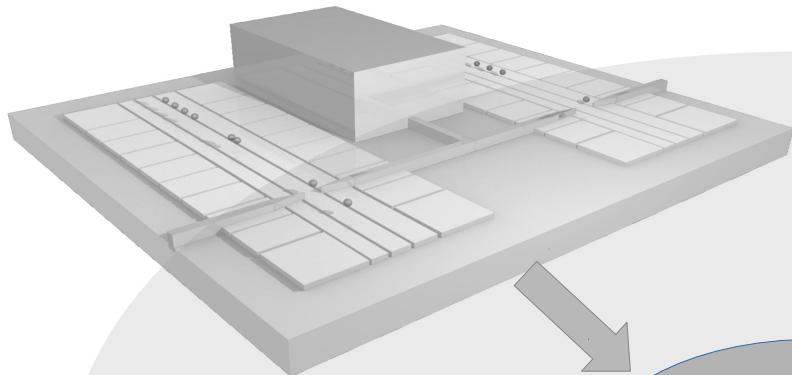


Application to Physics,  
fundamental symmetries

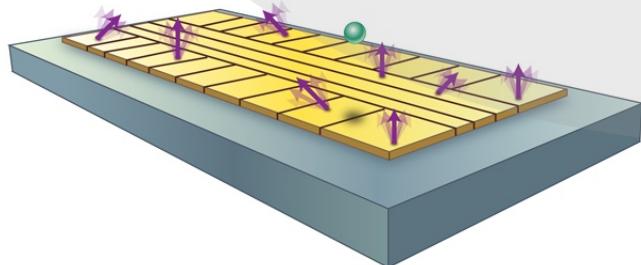
$$|\Psi\rangle = |\text{two lobes}\rangle + e^{i2\omega t} |\text{one lobe}\rangle$$

# Research overview

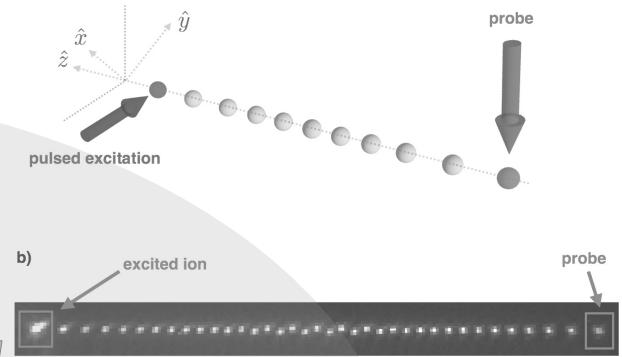
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Improving ion traps,  
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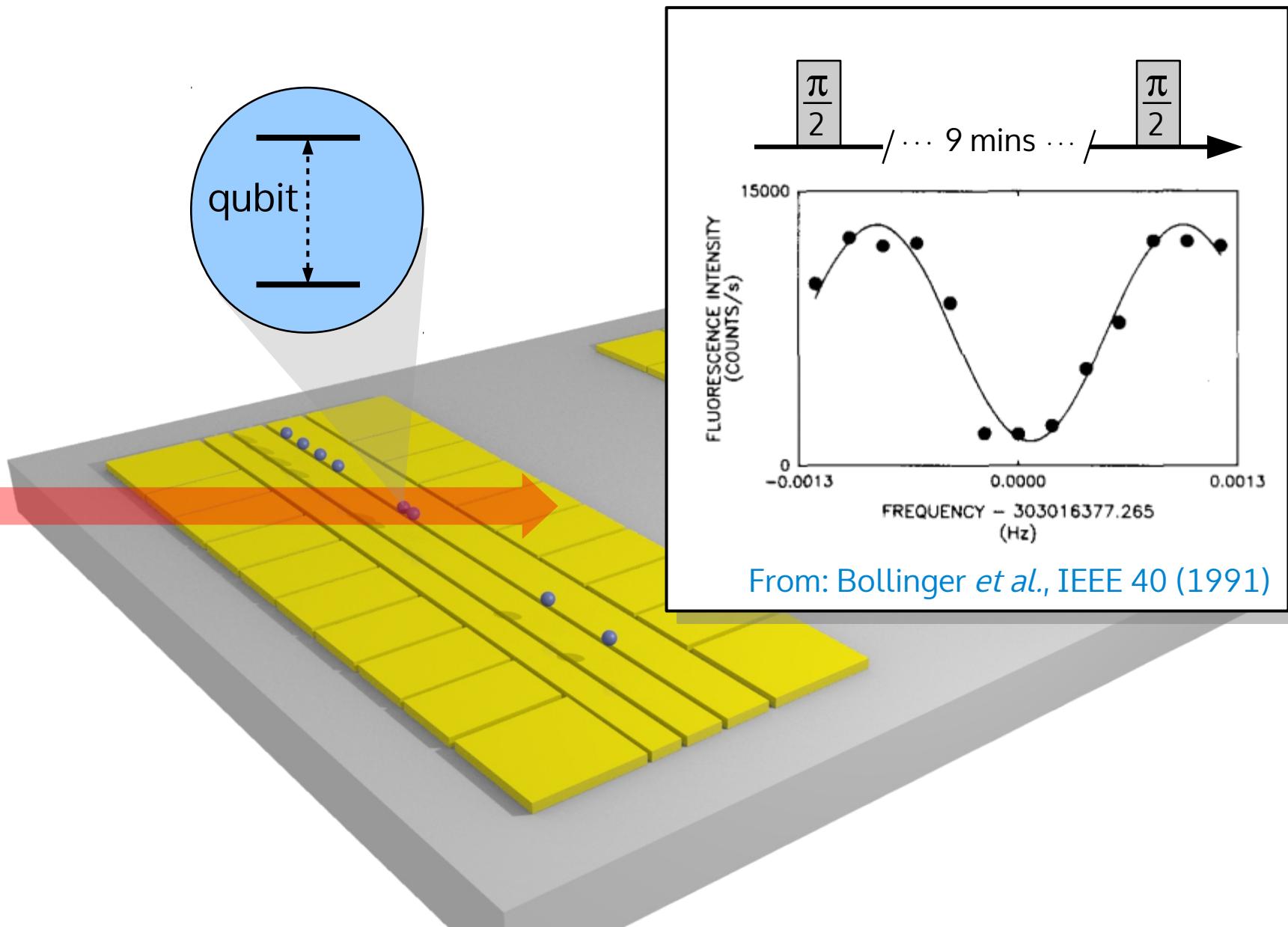


Application to Physics,  
fundamental symmetries

$$|\Psi\rangle = |\text{two lobes}\rangle + e^{i2\omega t} |\text{two lobes rotated}\rangle$$

- Introduction
- Improved ion traps for quantum computing
- A Michelson-Morley test with electrons
- Conclusions

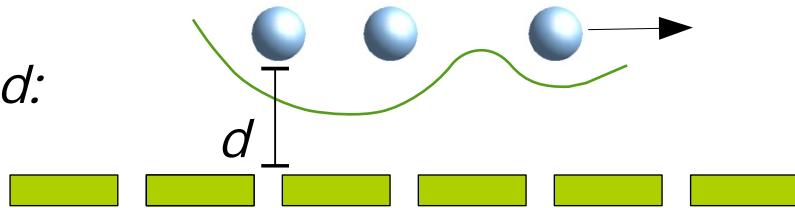
# Ion trap quantum computing



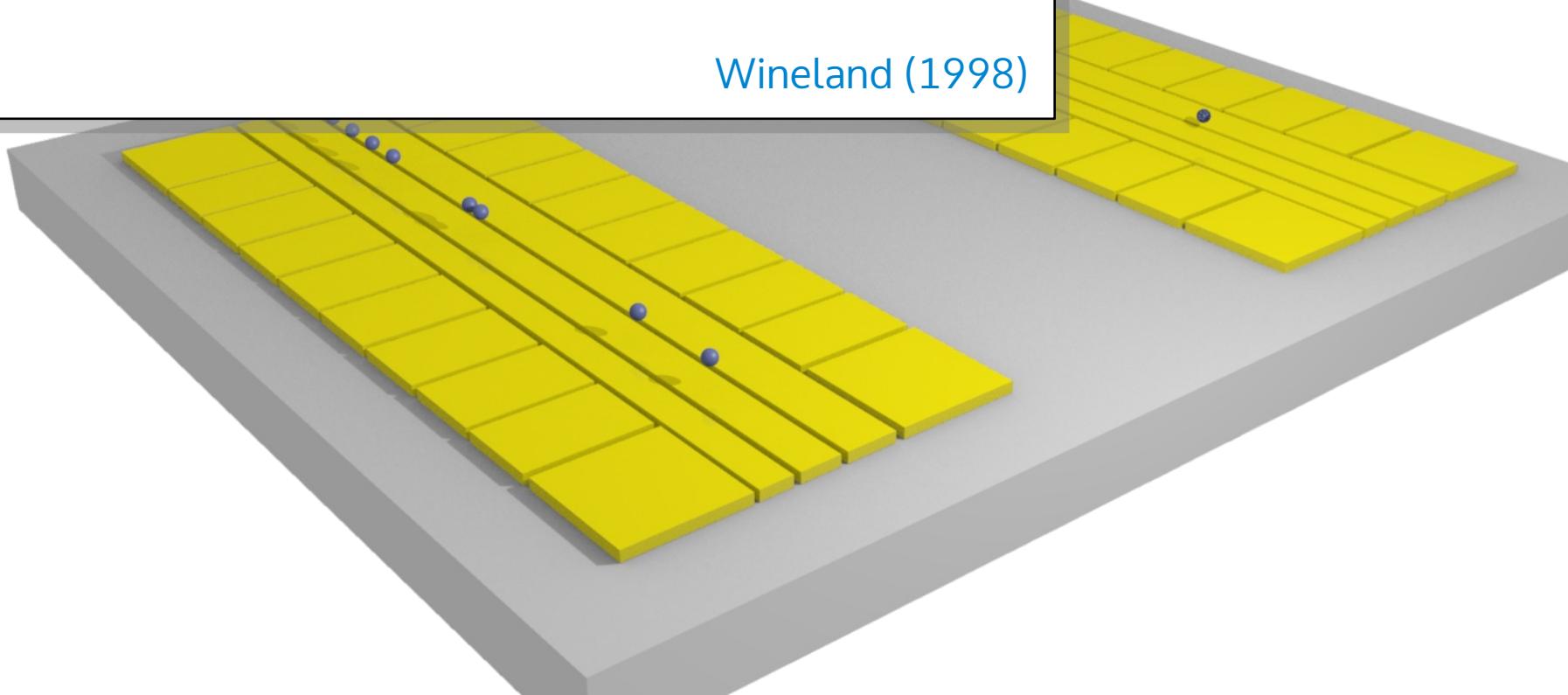
# Ion trap quantum computing

Need to split and merge ion strings fast for multi-qubit gates.

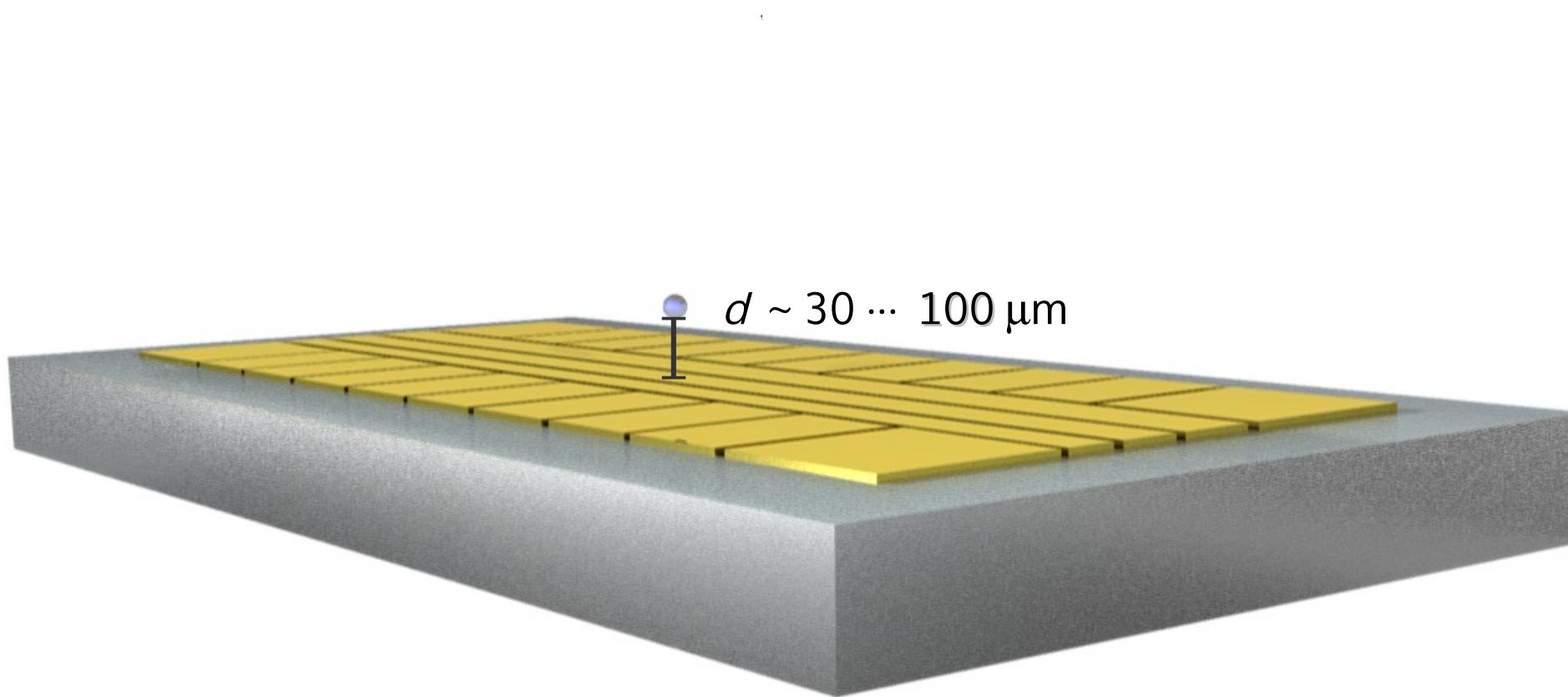
Speed  $\sim 1/d$ :



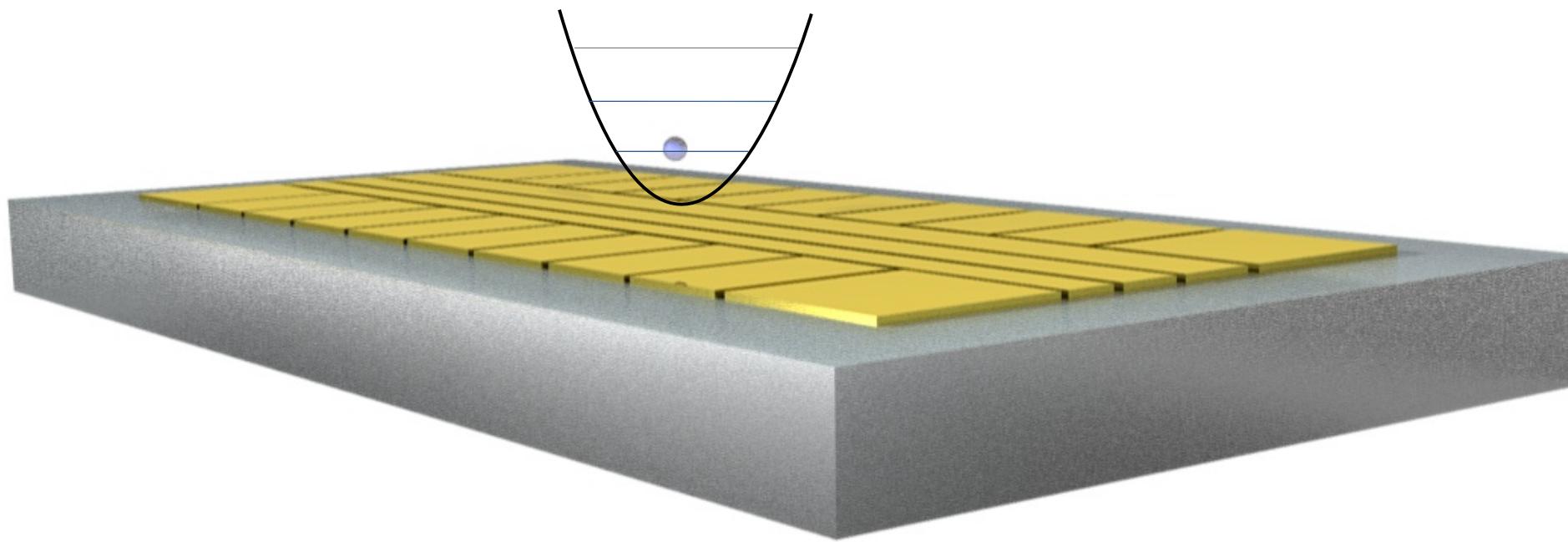
Wineland (1998)



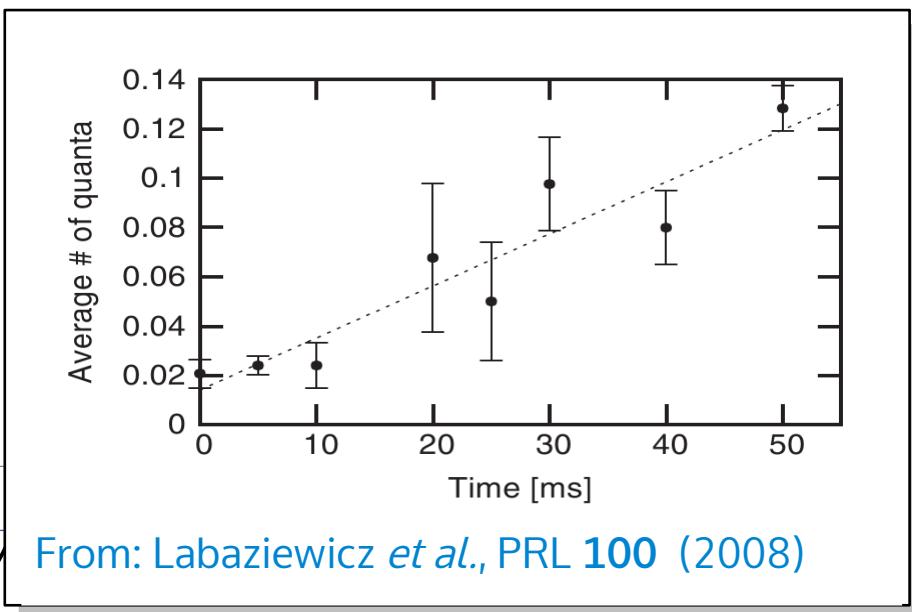
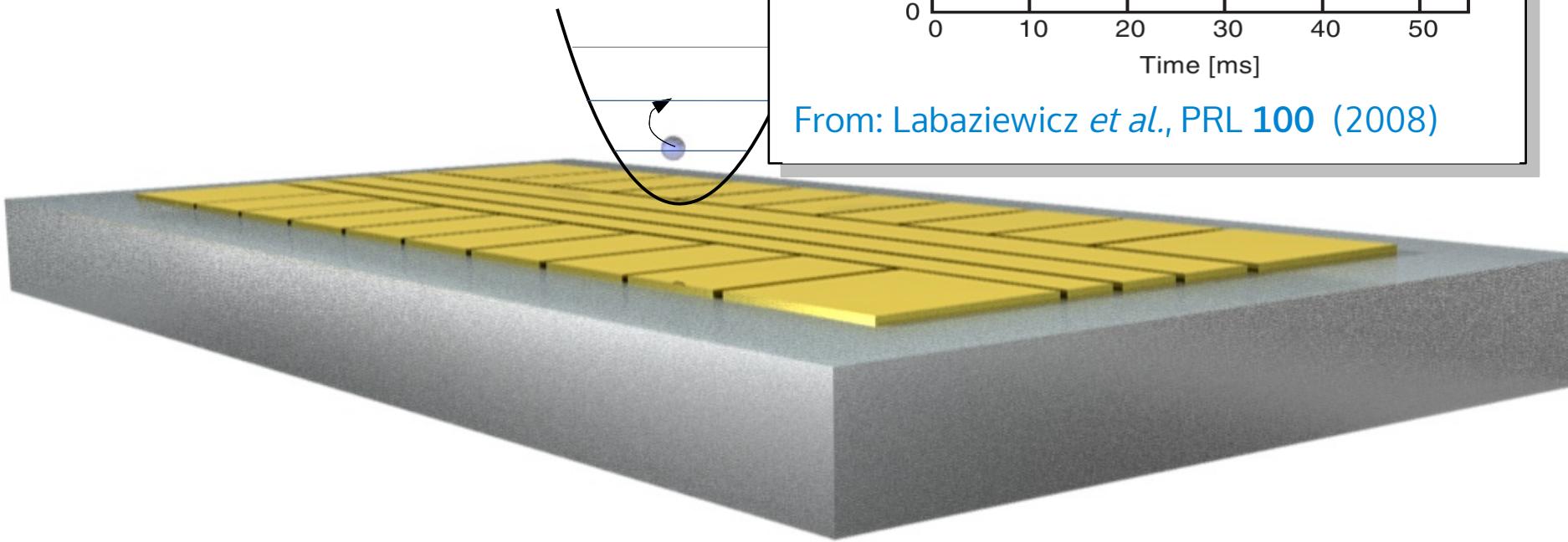
# Motional decoherence



# Motional decoherence



# Motional decoherence

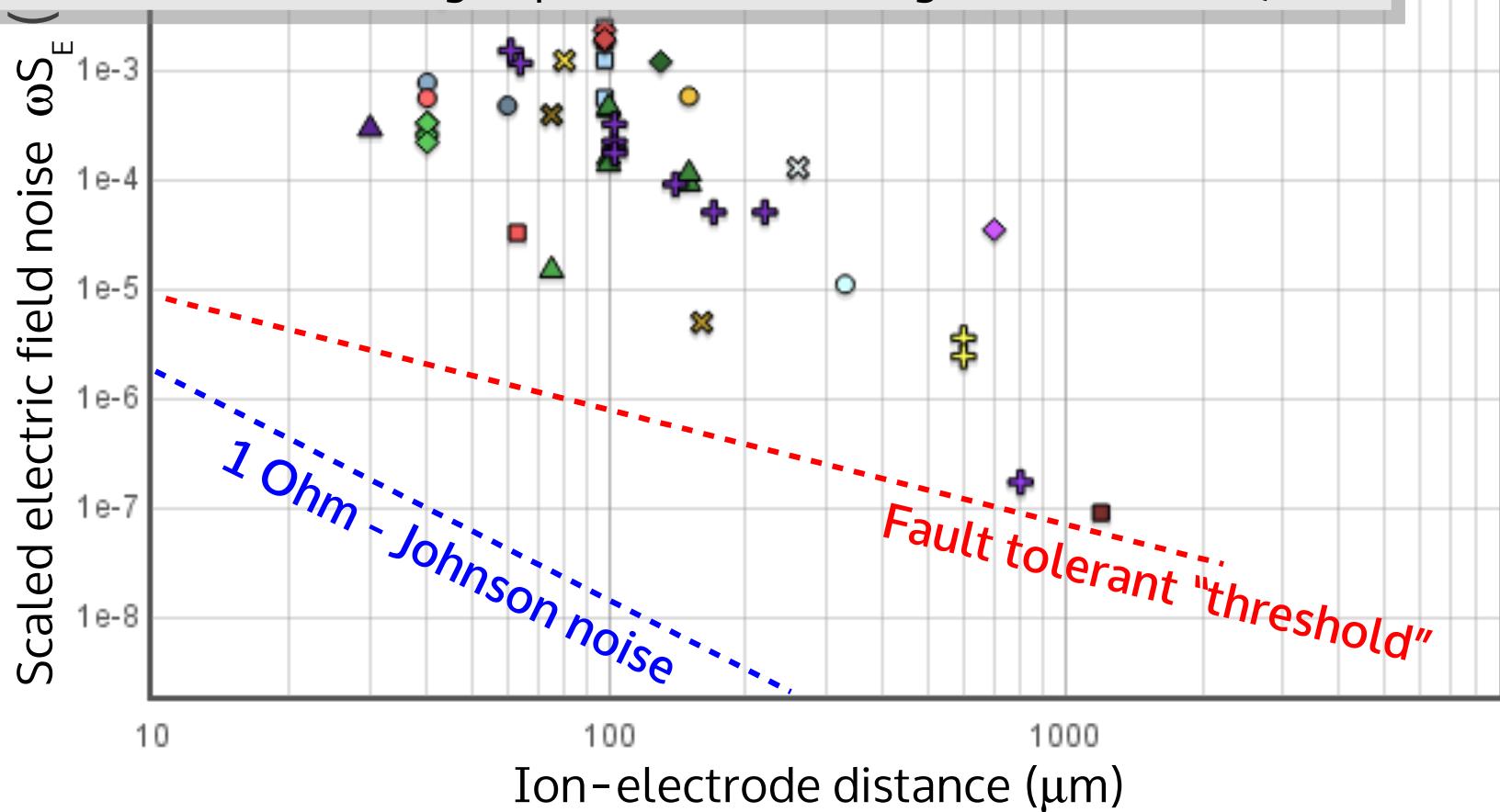


# Excessive heating in ion traps

- Need to know what is causing it to deal with it

[ht.shtml](#)

- Other technologies have similar problems:  
scanning probe microscopy, Casimir force measurements,  
free fall of charged particles, tests of general relativity

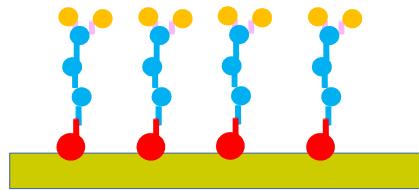


# What is causing “the” anomalous heating ?

- fluctuating patch potentials, ad-atom diffusion (Wineland 1998)



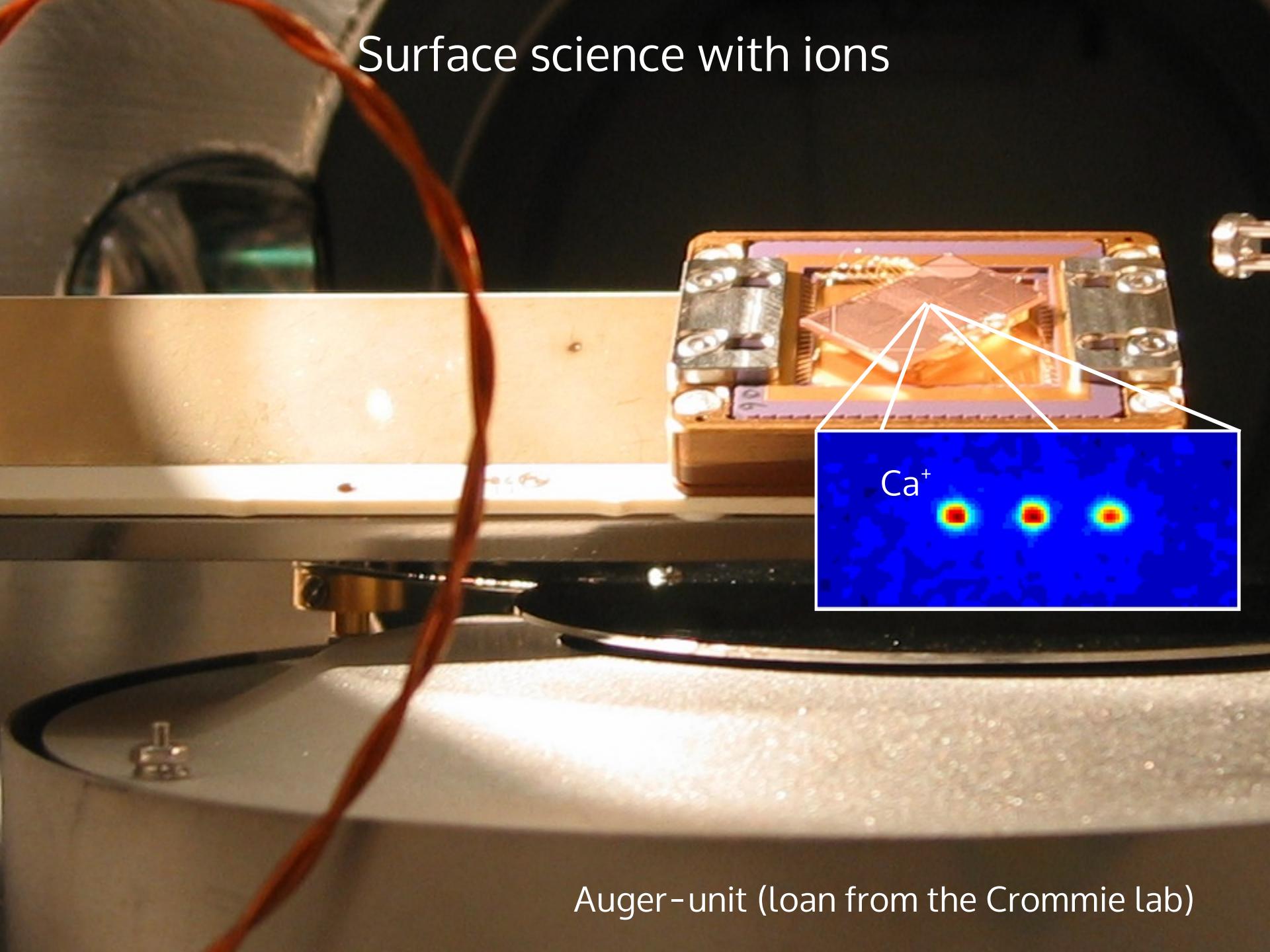
- independently fluctuating dipoles (Daniilidis 2010)



- fluctuating strength of dipoles (Safavi-Naini 2011, 2013)

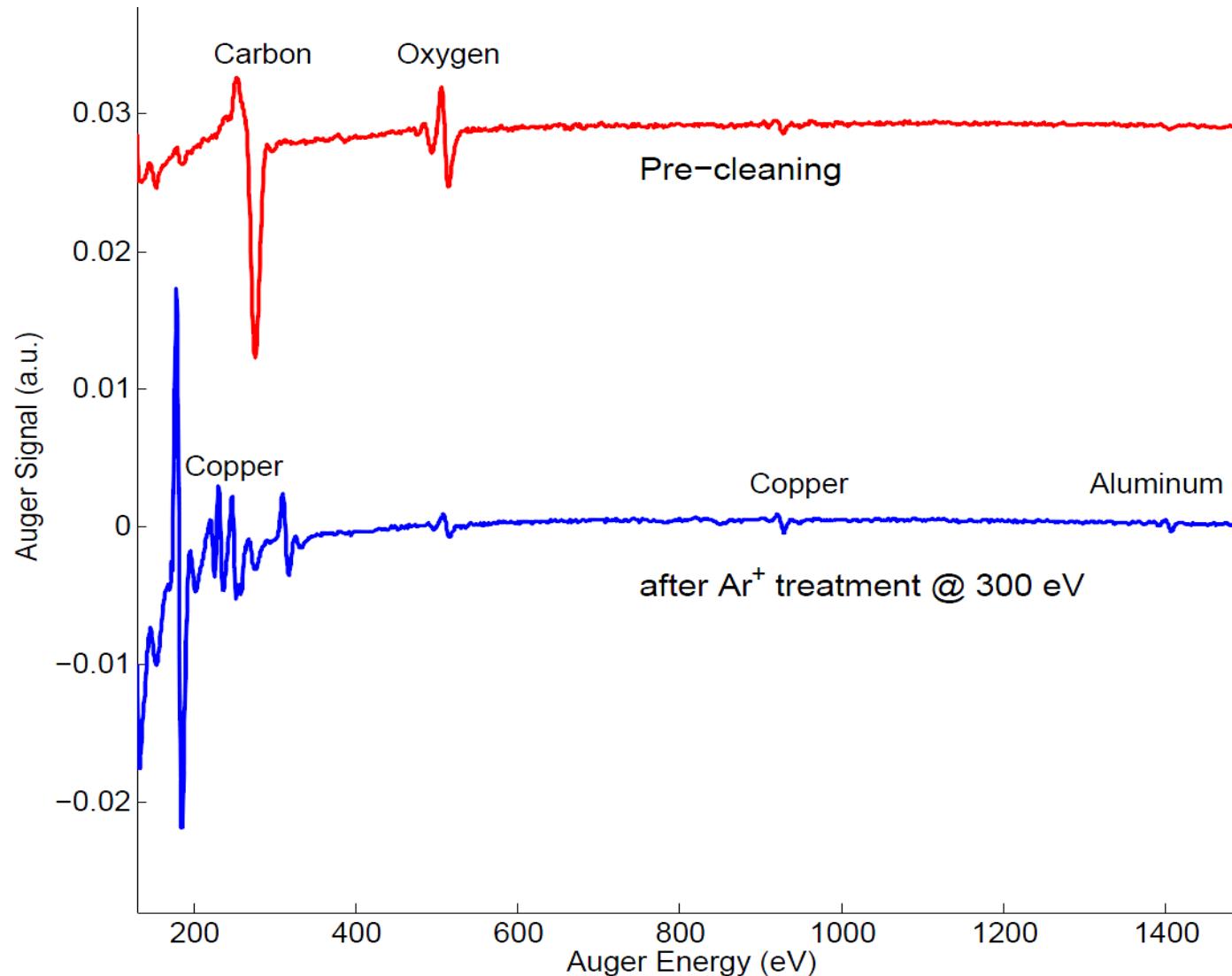


# Surface science with ions

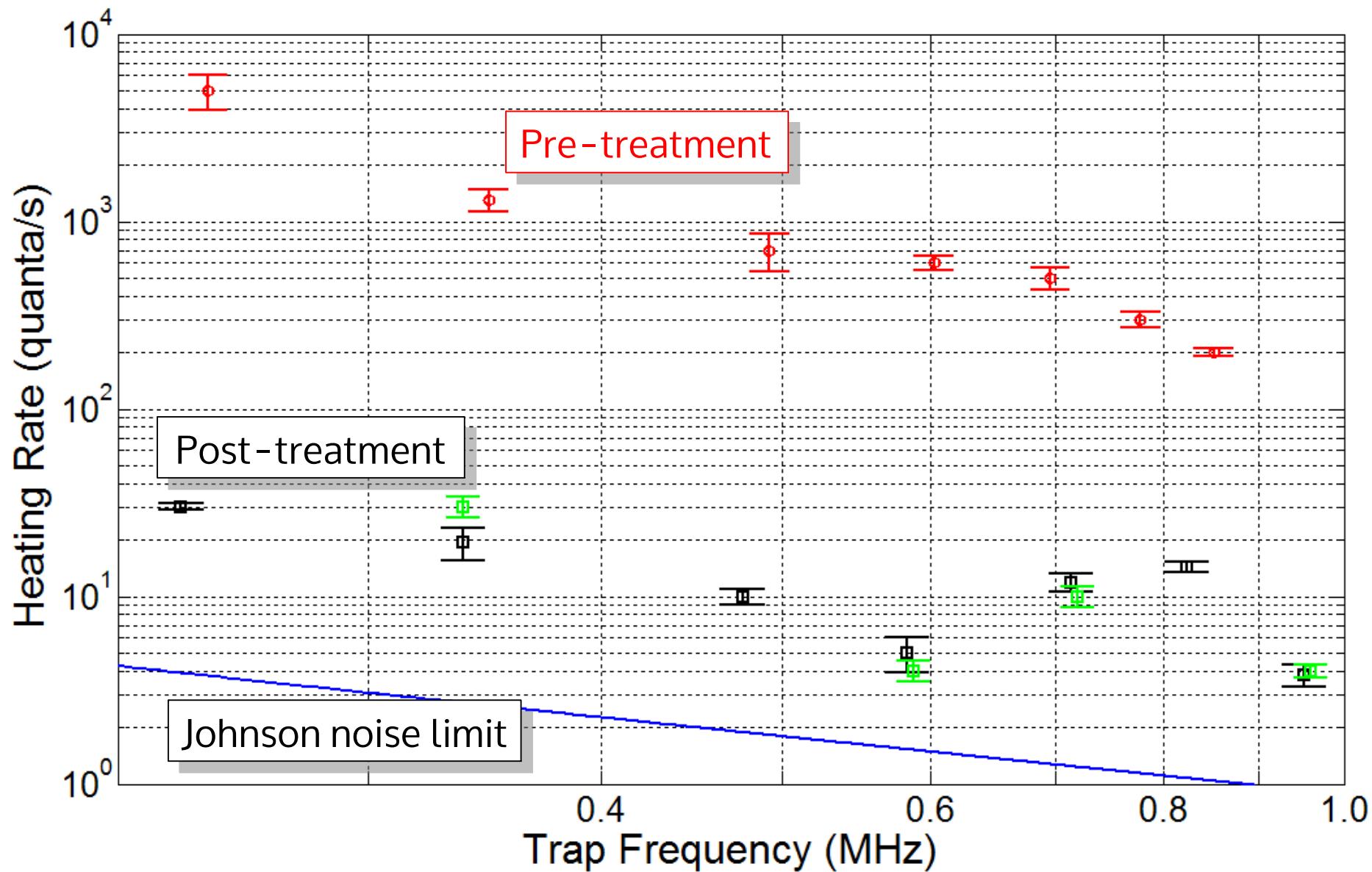


Auger-unit (loan from the Crommie lab)

# Auger spectra of a Cu-Al surface

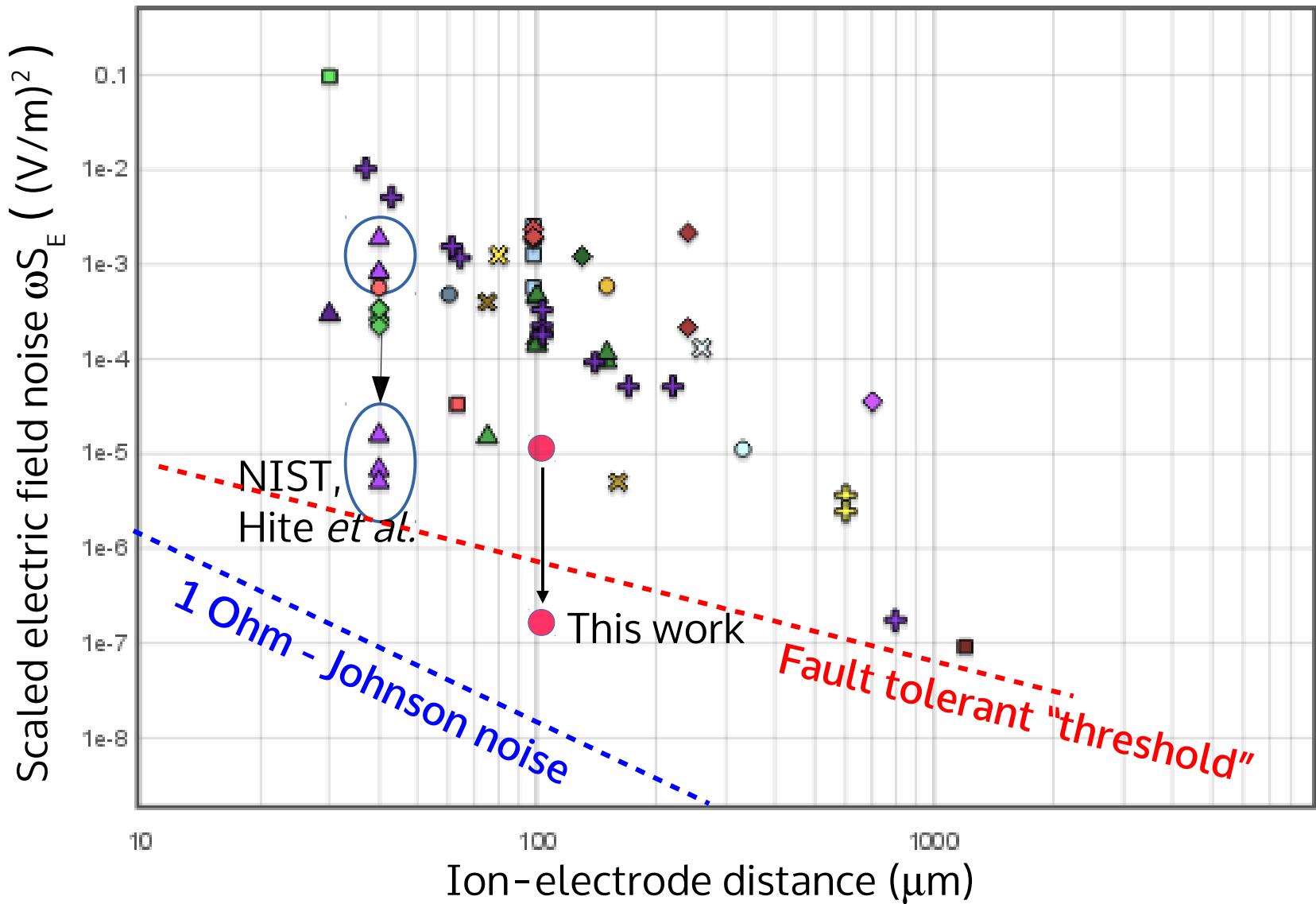


# Heating rates



# Excessive heating in ion traps

From: [http://www.quantum.gatech.edu/heating\\_rate\\_plot.shtml](http://www.quantum.gatech.edu/heating_rate_plot.shtml)



# Taking advantage of quantum information ?

Schrödinger equation for 300 interacting spins.

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

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

Physics motivations:

- quantum mechanics.
- aspects of condensed matter systems.
- aspects of cosmology.
- unforeseen applications ...

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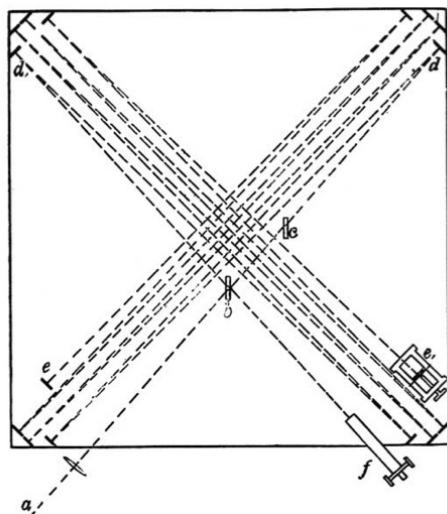
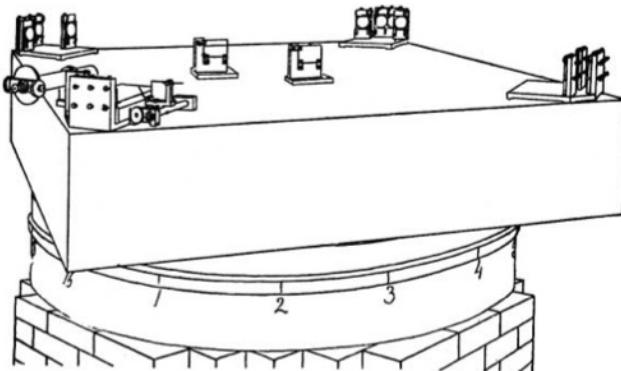
Physics motivations:

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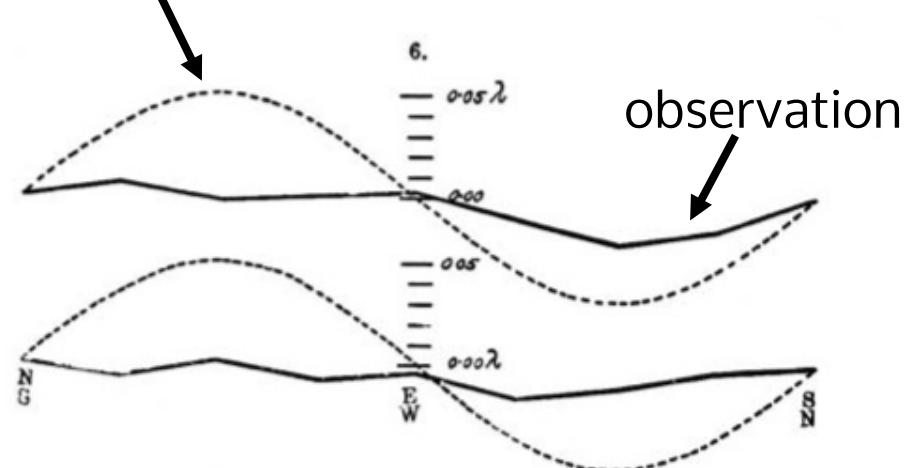
- Introduction
- Improved ion traps for quantum computing
- A Michelson-Morley test with electrons**
- Conclusions

# A most famous null experiment

Test for “aether”.



expected fringe shift due to aether



Michelson-Morley experiment  
confirms Lorentz symmetry to  $10^{-9}$

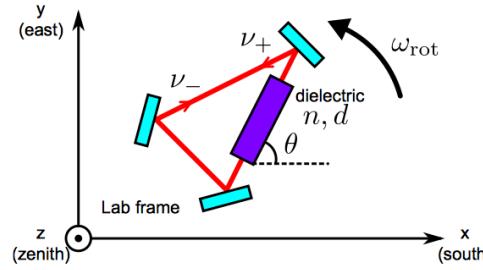
Michelson & Morley, Am. J. Science 34, 427 (1887).

# Modern tests of Lorentz symmetry

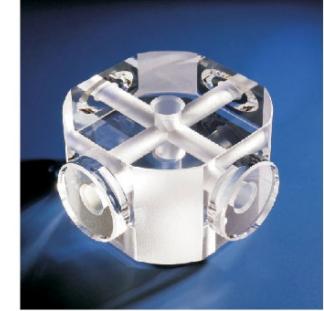
## Accelerator



## Optical cavities

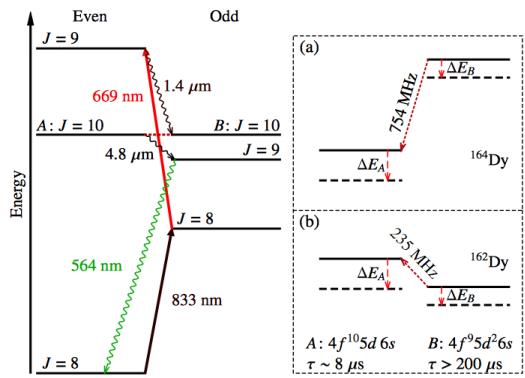


Michimura (2013)



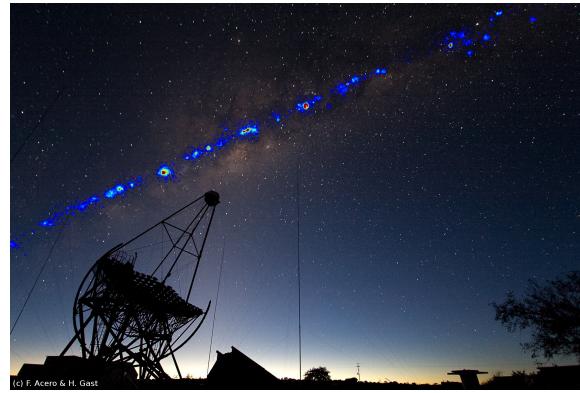
Herrmann (2009)

## Spectroscopy



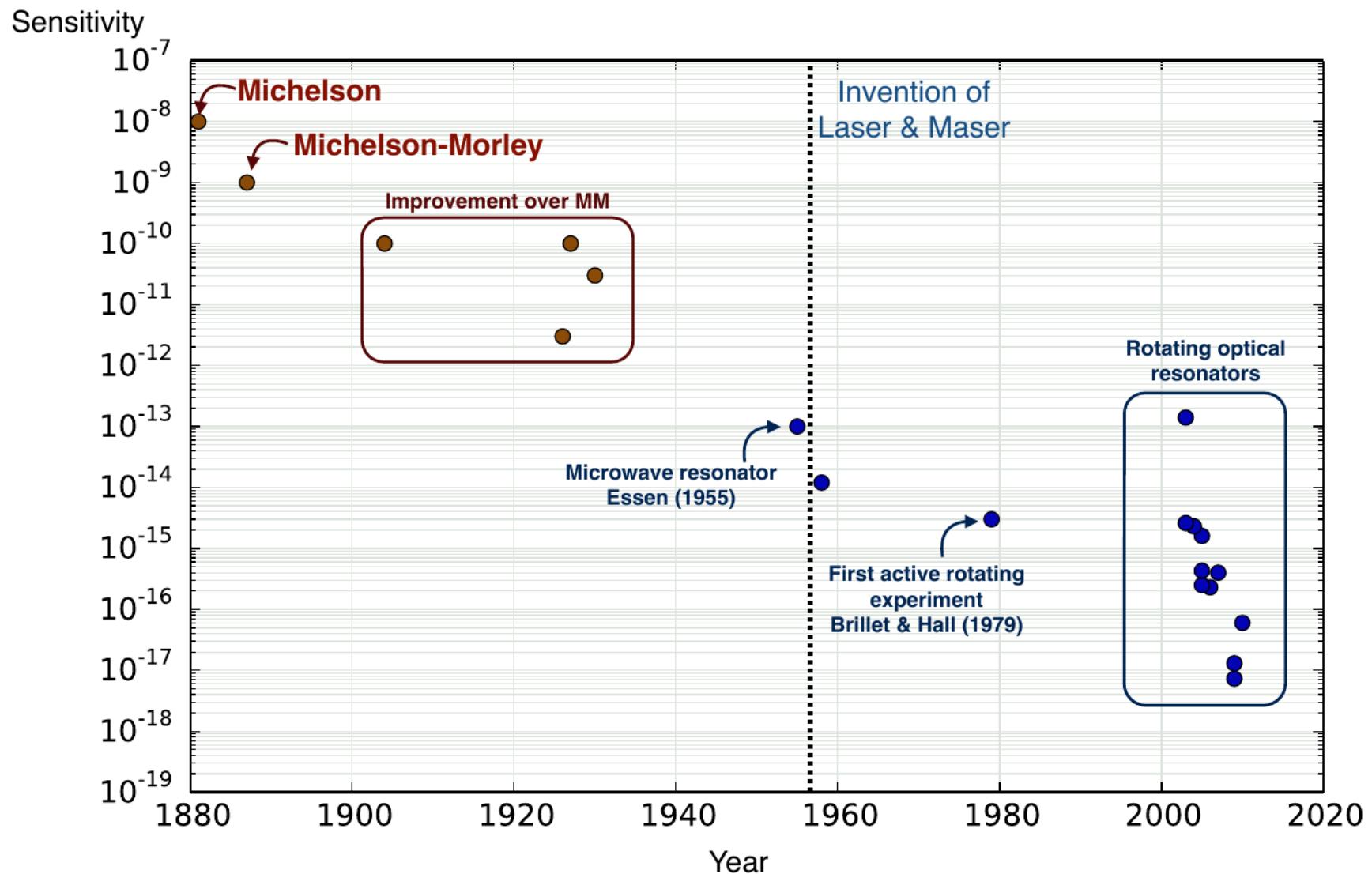
Hughes-Drever (1960/1961)  
Hohensee (2013)

## Astrophysics



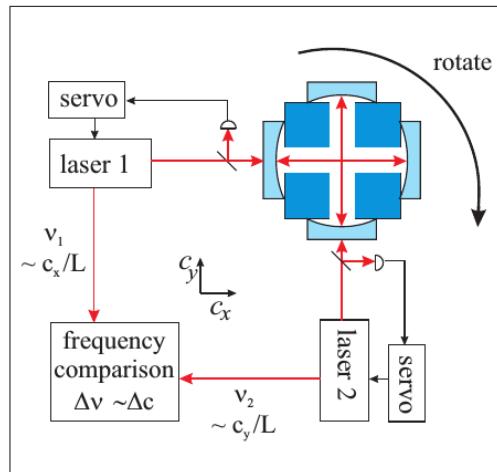
HESS telescope, Altschul (2006)

# A most famous null experiment



# Lorentz-violating effects?

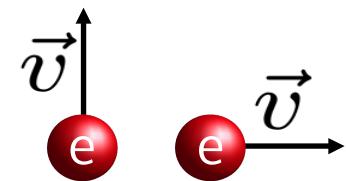
Modern Michelson-Morley experiments



Herrmann (2009)

Electrons

- maximum attainable speed is (not) "c"
- dependence of energy on direction of velocity



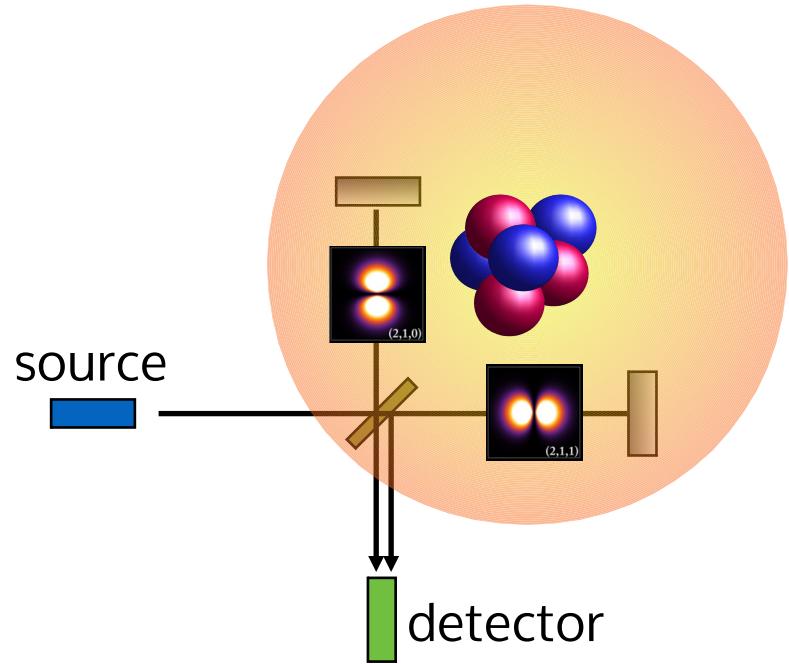
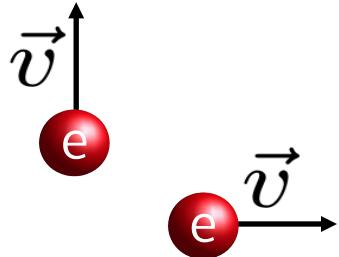
electron

Others ....

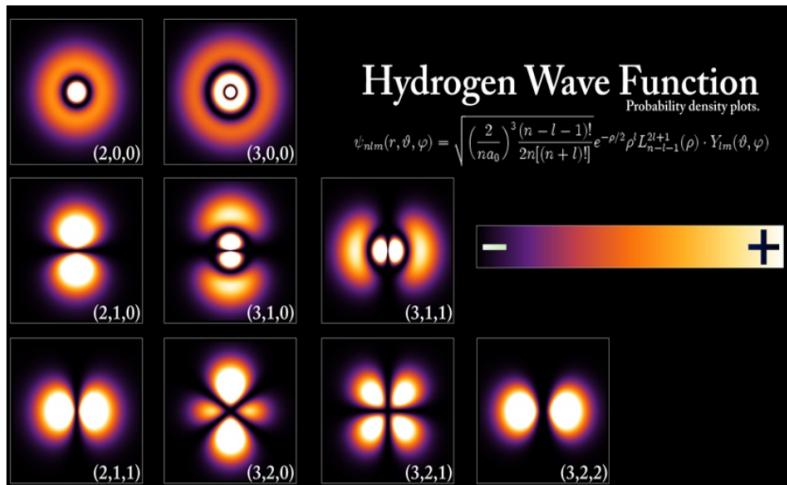
- neutron, proton, ....
- ➡ Hughes-Drever experiments

same energy?

# Interferometer with electrons?



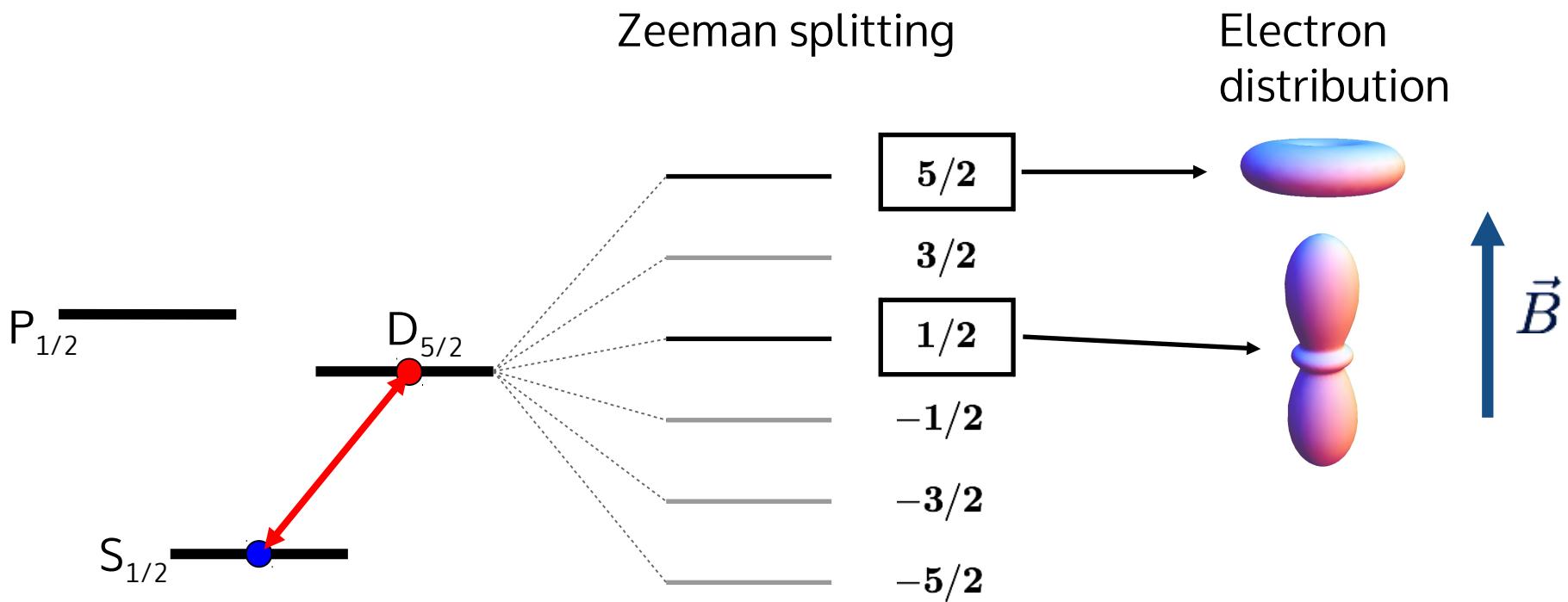
Standing waves for electrons:



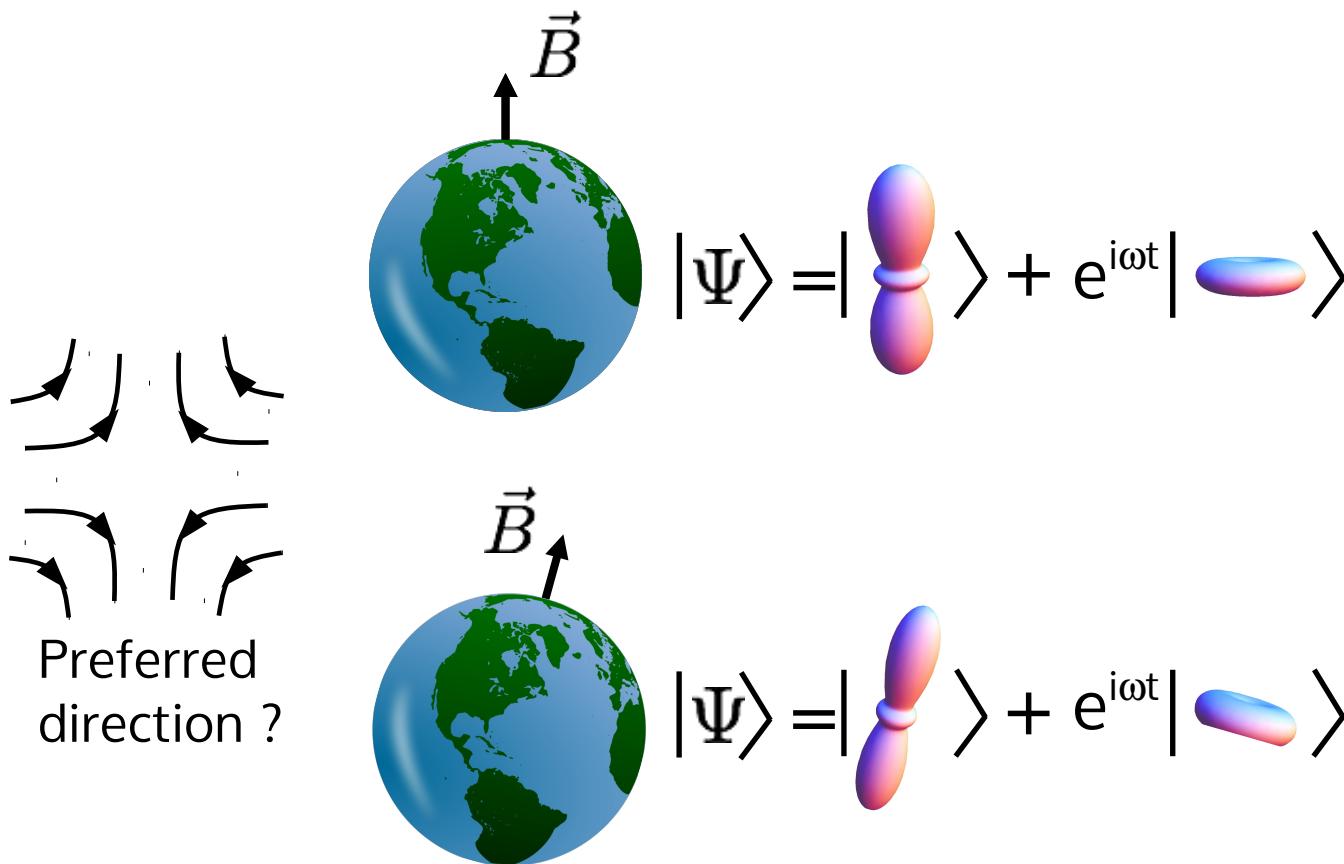
Michelson interferometer

# Interferometer with electrons?

Use the  $D_{5/2}$ -manifold of  $^{40}\text{Ca}^+$



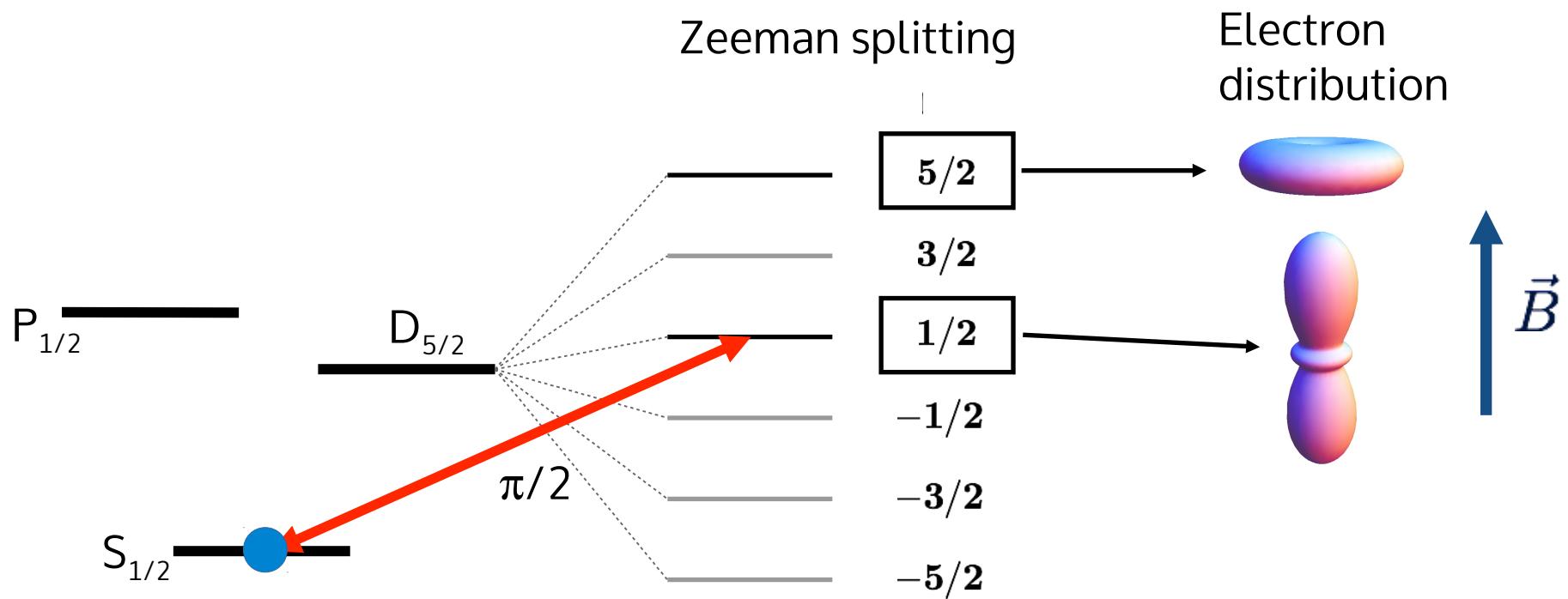
# Measurement scheme



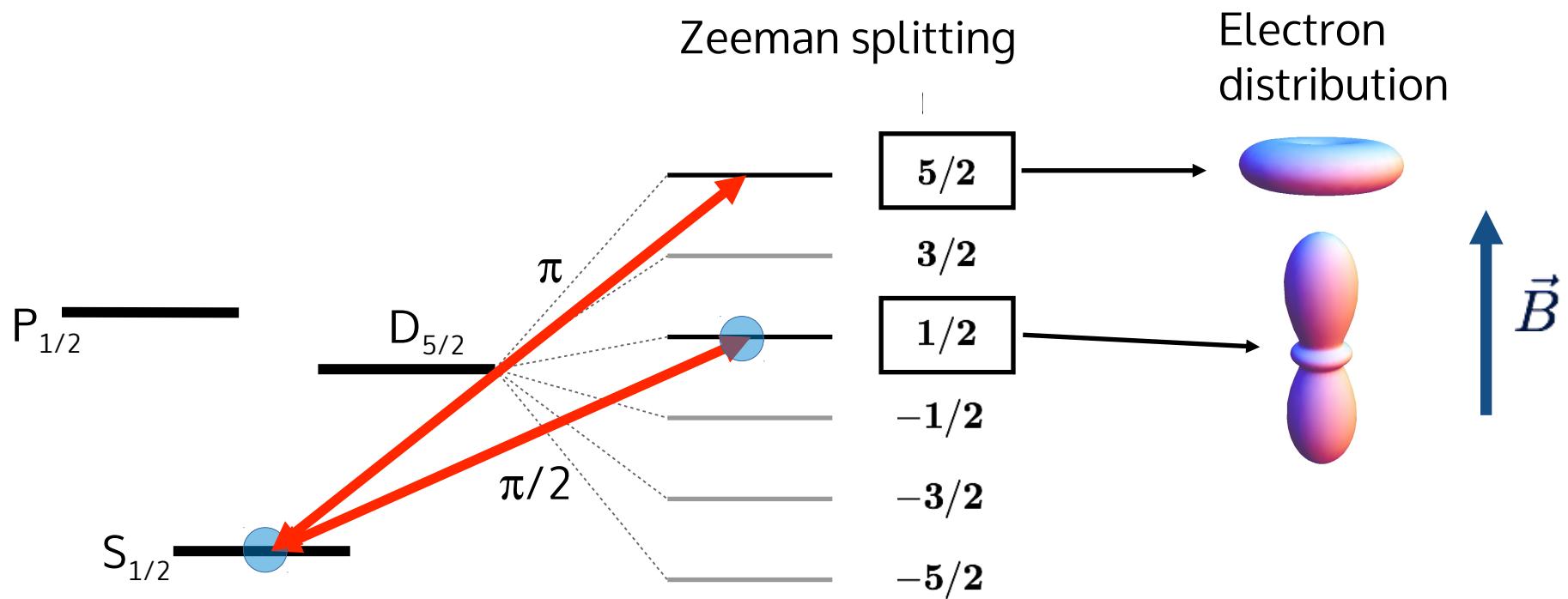
Preferred direction due to Lorentz violation ?

→ energy modulated with the Earth's rotation

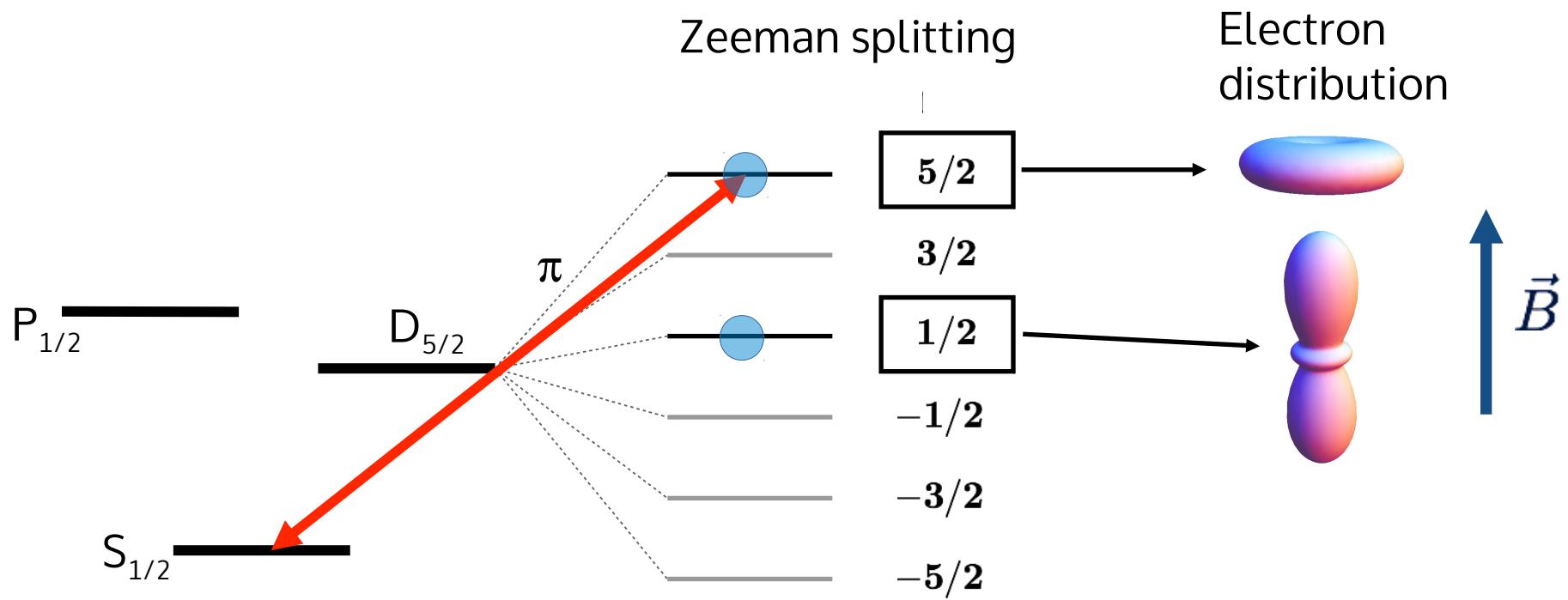
# State preparation



# State preparation



# State preparation



# Decoherence-free subspace

$$|\Psi\rangle = |\text{atom}\rangle + e^{i\omega t} |\text{molecule}\rangle$$

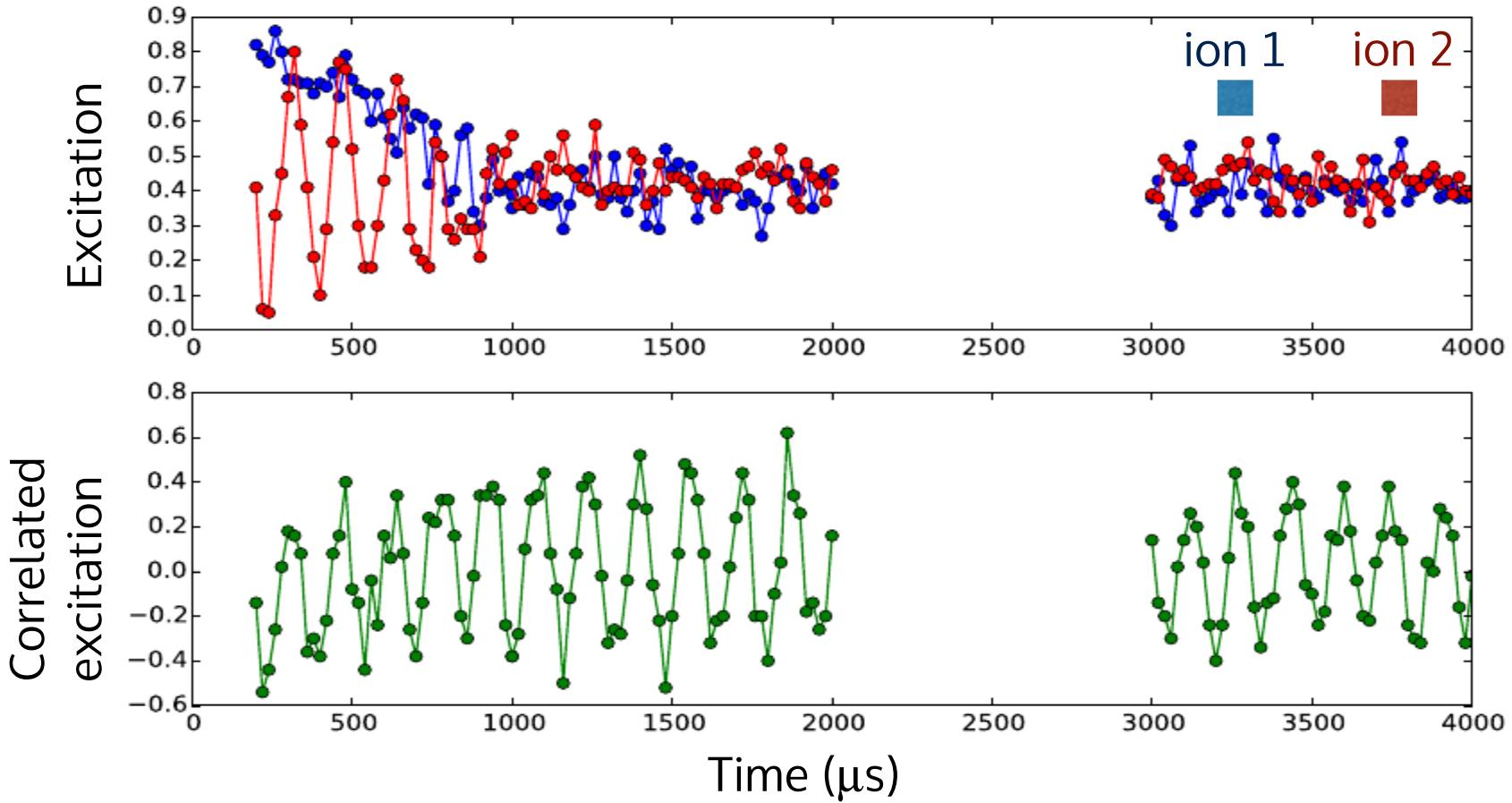
## Problem: Zeeman effect swamps phase evolution

## Use two ions:

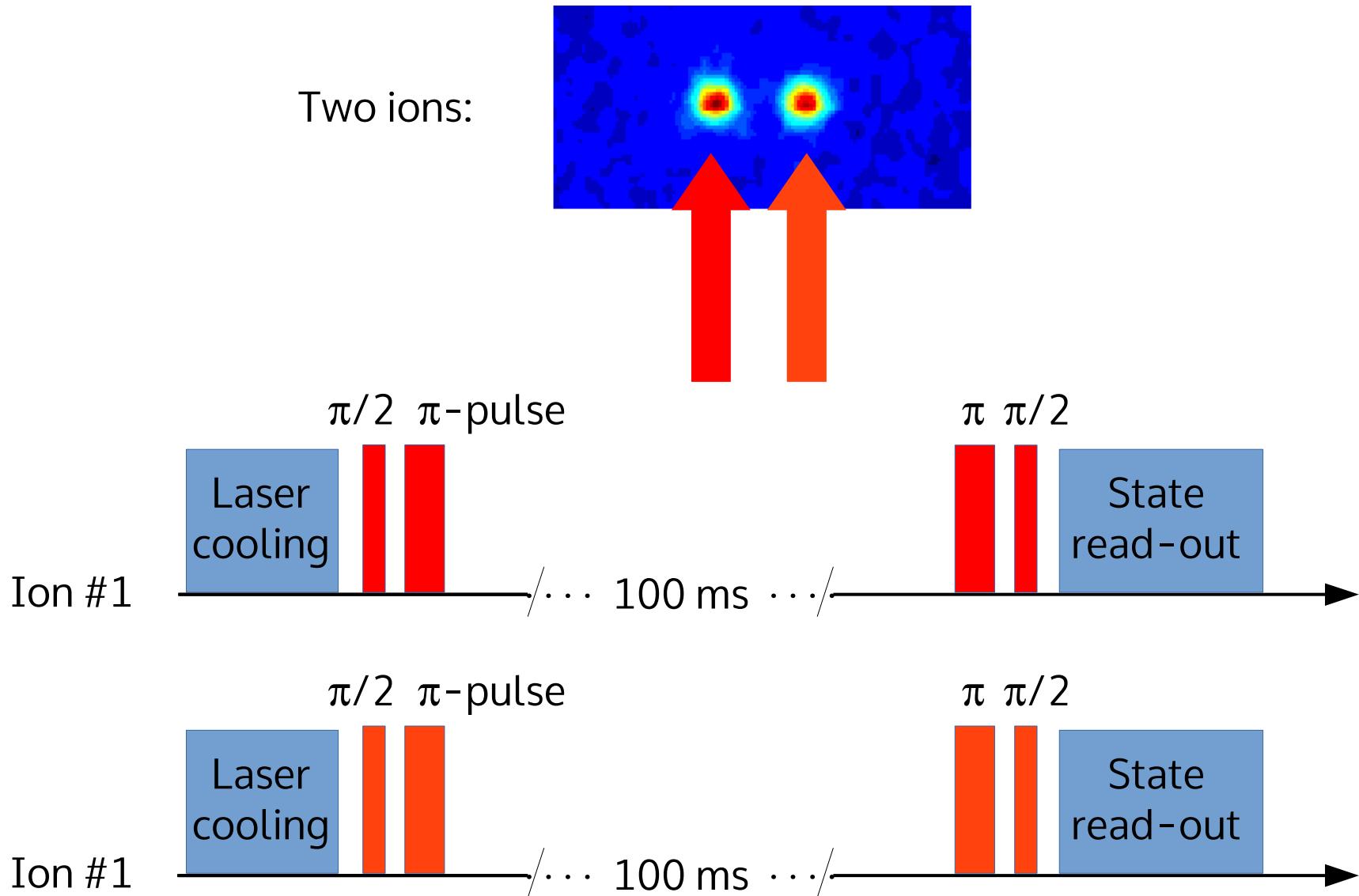
$$|\Psi\rangle = \overbrace{| -1/2, 1/2 \rangle + | -5/2, 5/2 \rangle}^{\mu_{\text{eff}}=0} = \left| \begin{array}{c} \text{two vertical dumbbells} \\ \text{aligned horizontally} \end{array} \right\rangle + e^{i2\omega t} \left| \begin{array}{c} \text{two horizontal dumbbells} \\ \text{aligned vertically} \end{array} \right\rangle$$

# Decoherence-free subspace

Coherence time improved by  $10^4$   
→ decoherence-free subspace

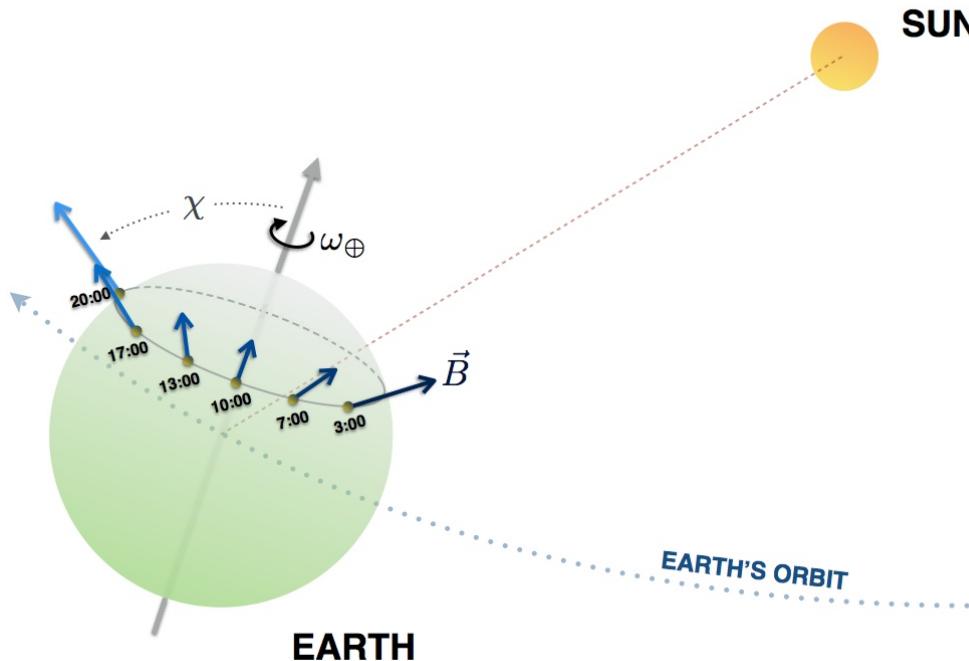


# Measurement scheme



# Measurement scheme

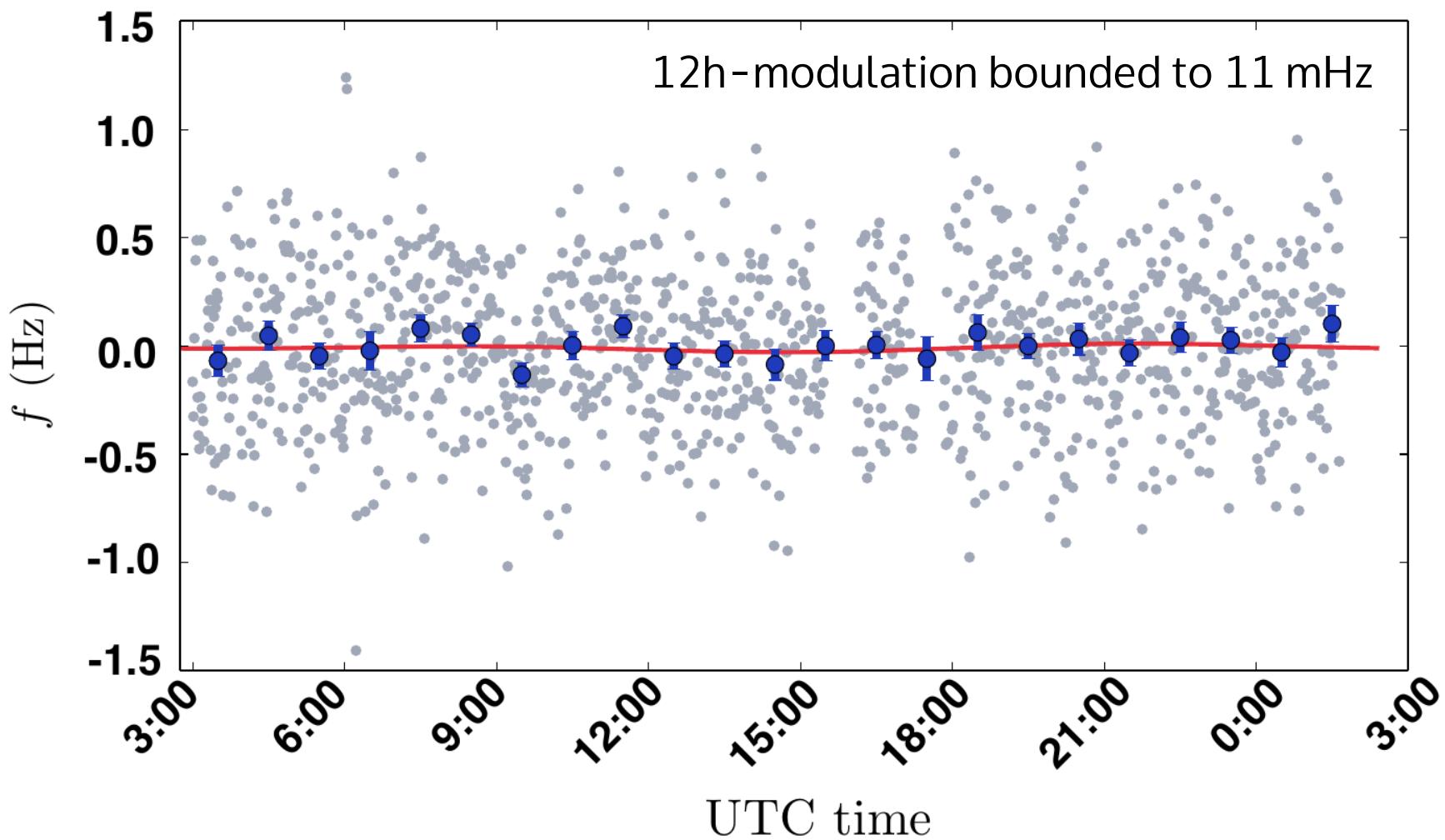
Magnetic field and wavefunction  
change direction.



Lorentz-violation will modulate the energy shift  
correlated with the Earth's motion.

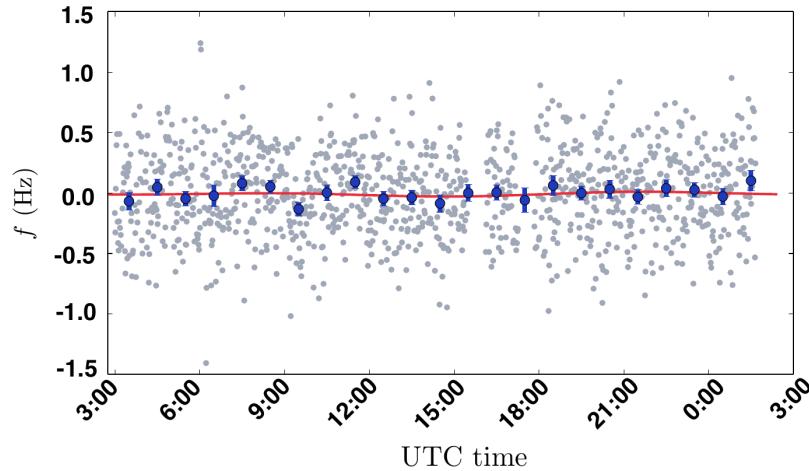
# Data

Energy variations of a pair of  $^{40}\text{Ca}^+$  ions on April 19<sup>th</sup> 2014



# Results

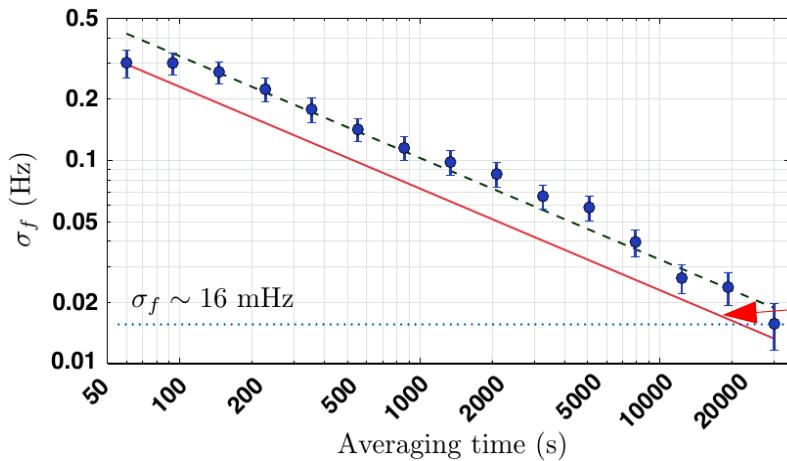
Energy variations of a pair of  $^{40}\text{Ca}^+$  ions on April 19<sup>th</sup> 2014



12h-modulation bounded to 11 mHz

$$\frac{\Delta E}{\langle E_{\text{kin}} \rangle} \approx \frac{5 \times 10^{-17} \text{ eV}}{50 \text{ eV}} = 10^{-18}.$$

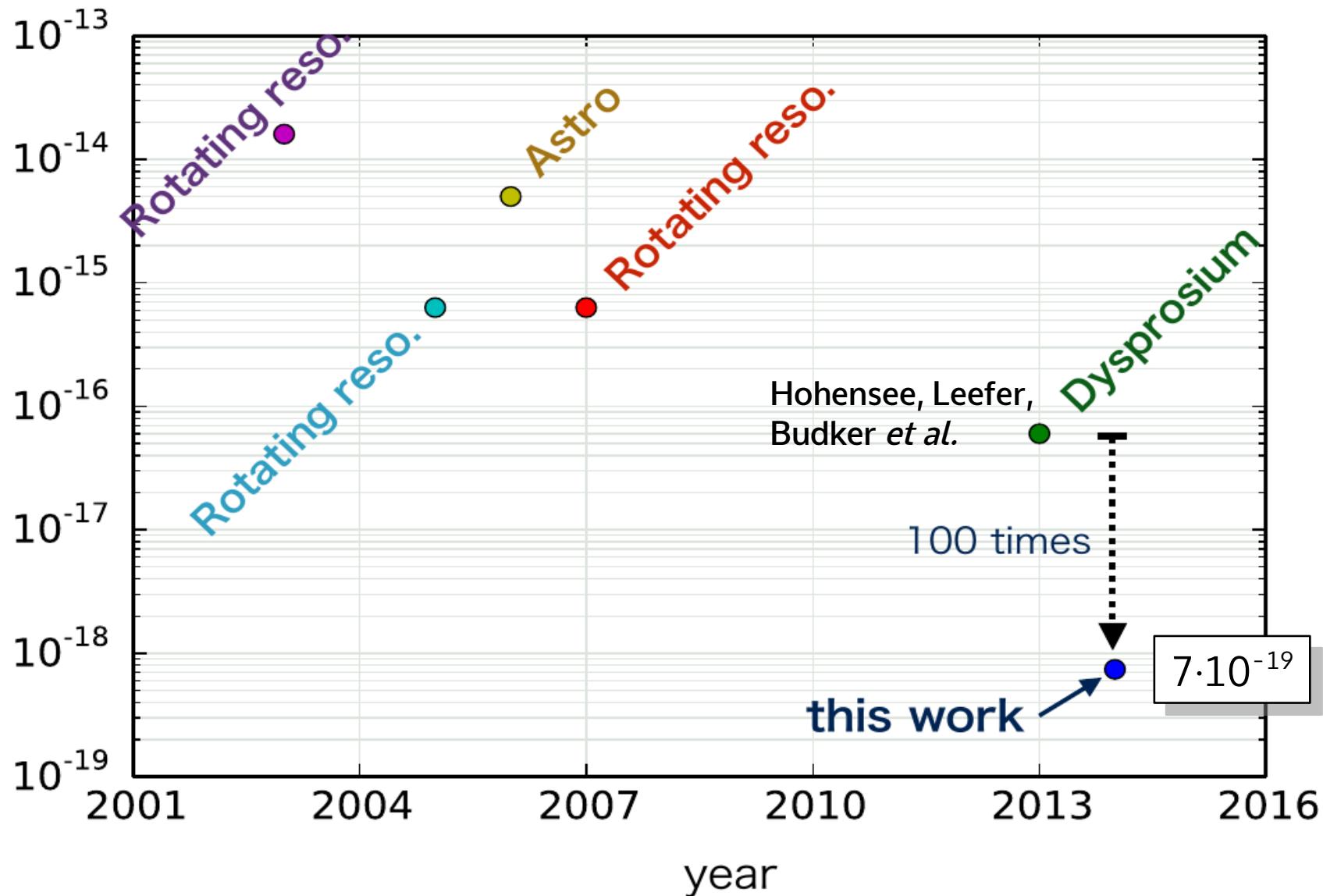
Bound as a function of averaging time



Still averaging down with  $\sqrt{\tau}$ , no signs of systematic drifts.

Expected quantum projection noise.

# Lorentz tests for the electron



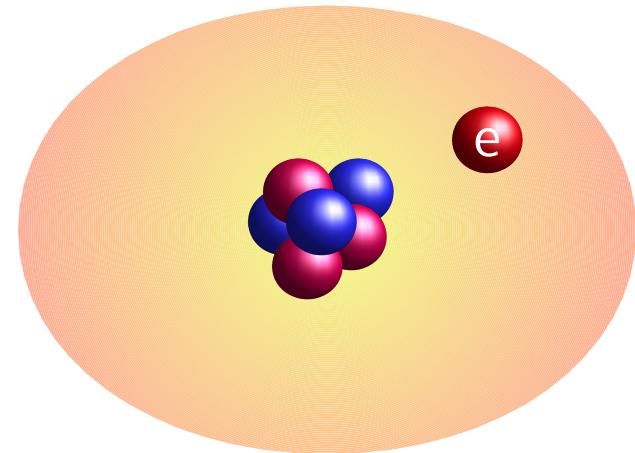
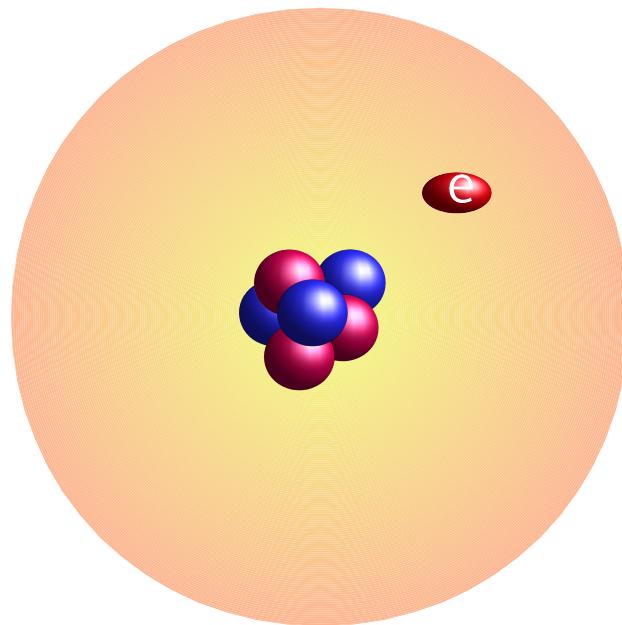
# Interpretation

To analyze the experiment, we need to pick a reference.

Assumption: Coulomb force is symmetric.

→ any LV - signal is attributed to the electron

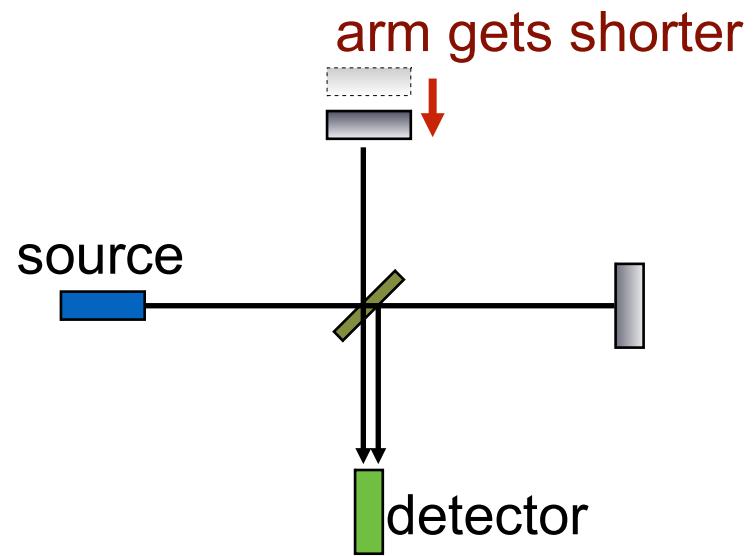
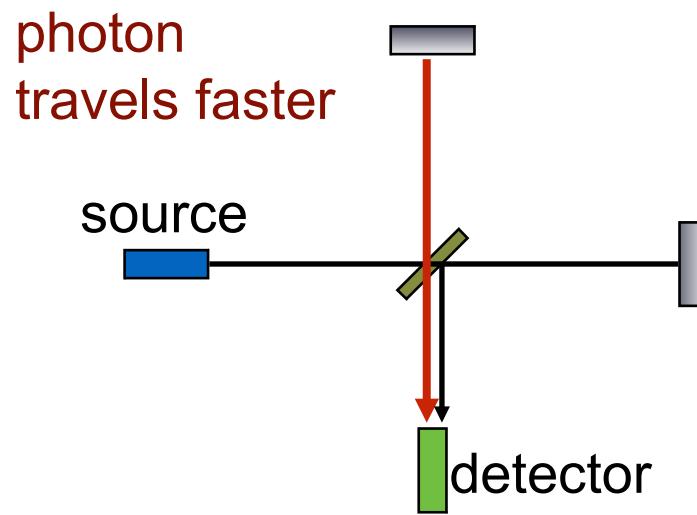
or: electron obeys Lorentz symmetry  
→ photon violates Lorentz symmetry



→ We probe the difference between the electron and photon dispersion !

# Interpretation of the Michelson Morley experiment

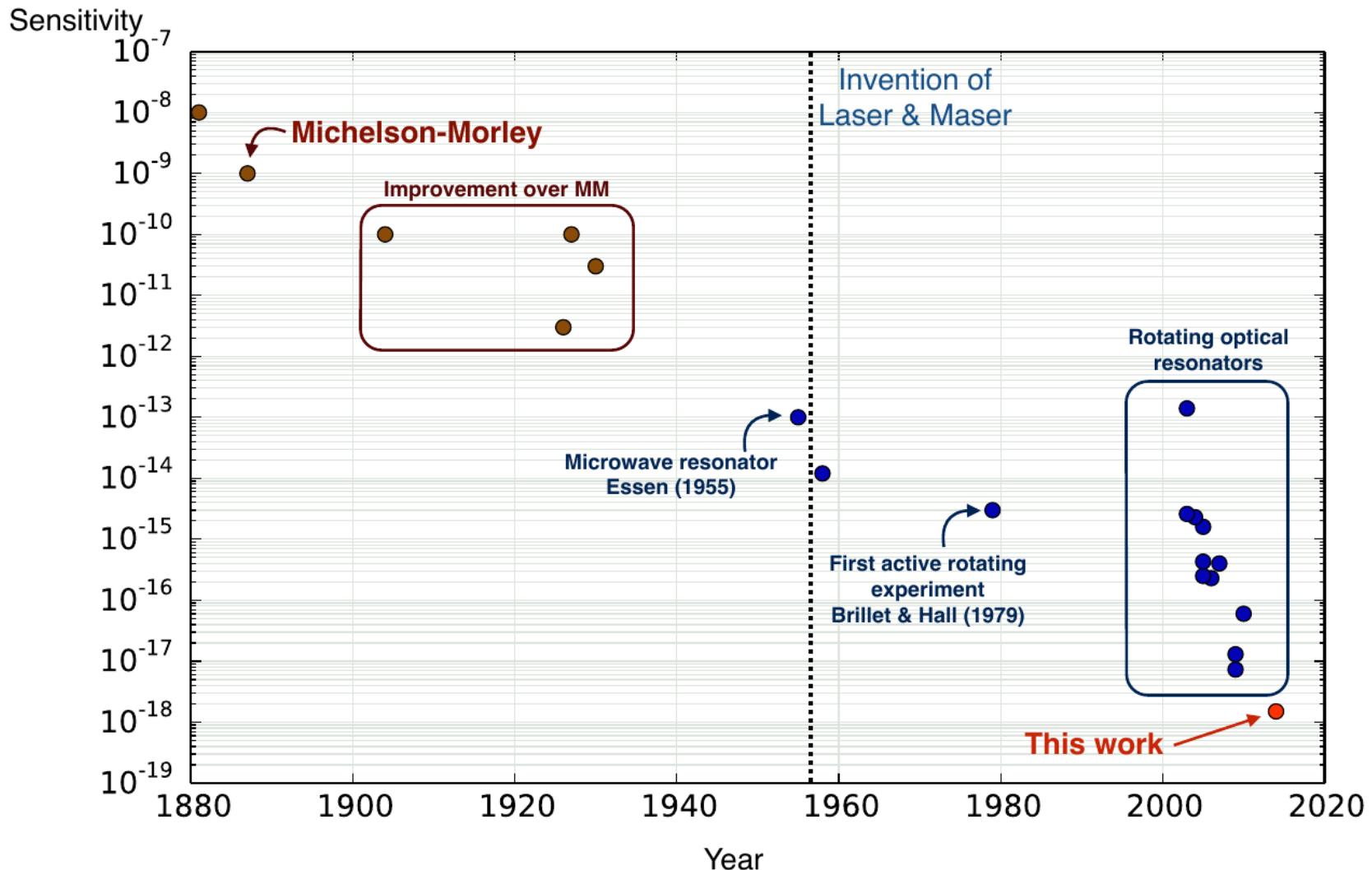
To analyze the experiment, we need to pick a reference.



➡ Arm length determined by the Coulomb force and electron dispersion

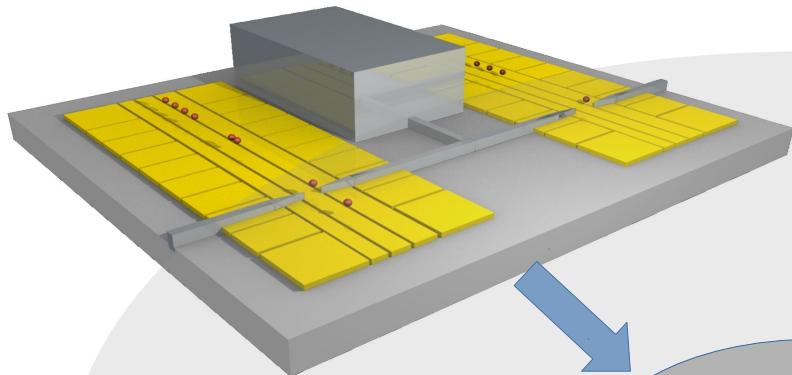
# Lorentz invariance tests for light

Both experiments compare  
the photon and the electron dispersion relation.

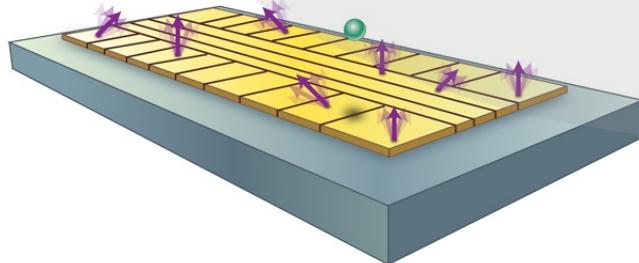


# Summary

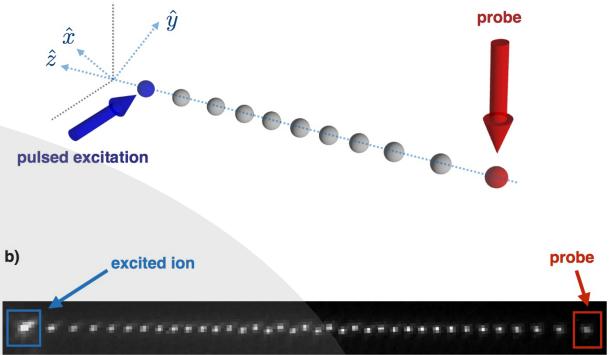
Novel QIP-architectures,  
hybrid quantum systems



Improving ion traps,  
reducing surface noise



Quantum many-body physics,  
quantum correlations

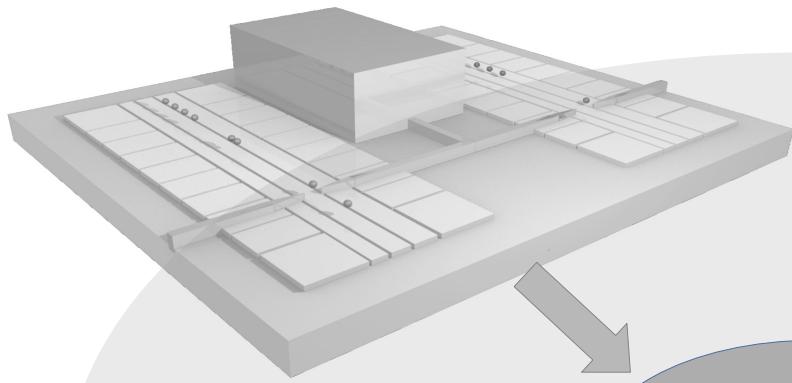


Application to Physics,  
fundamental symmetries

$$|\Psi\rangle = |\text{two lobes}\rangle + e^{i2\omega t} |\text{one lobe}\rangle$$

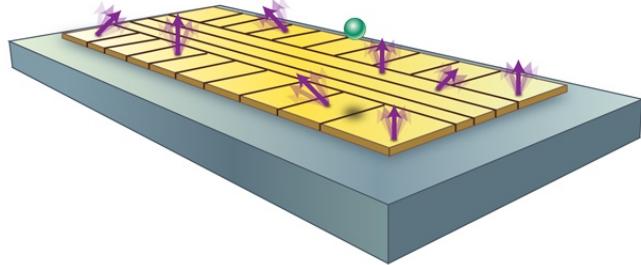
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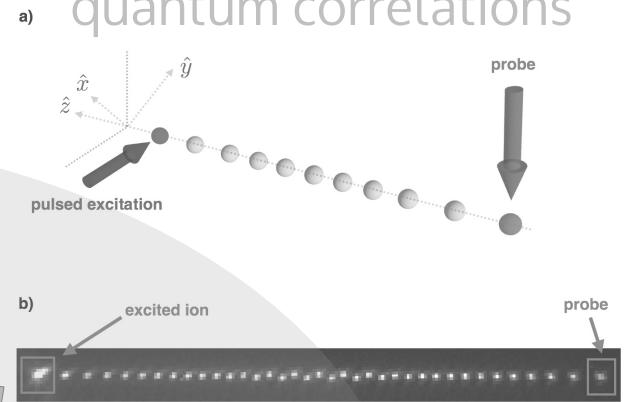


Scalable ion traps compatible with  
fault tolerant quantum computing

Improving ion traps,  
reducing surface noise



Quantum many-body physics,  
quantum correlations

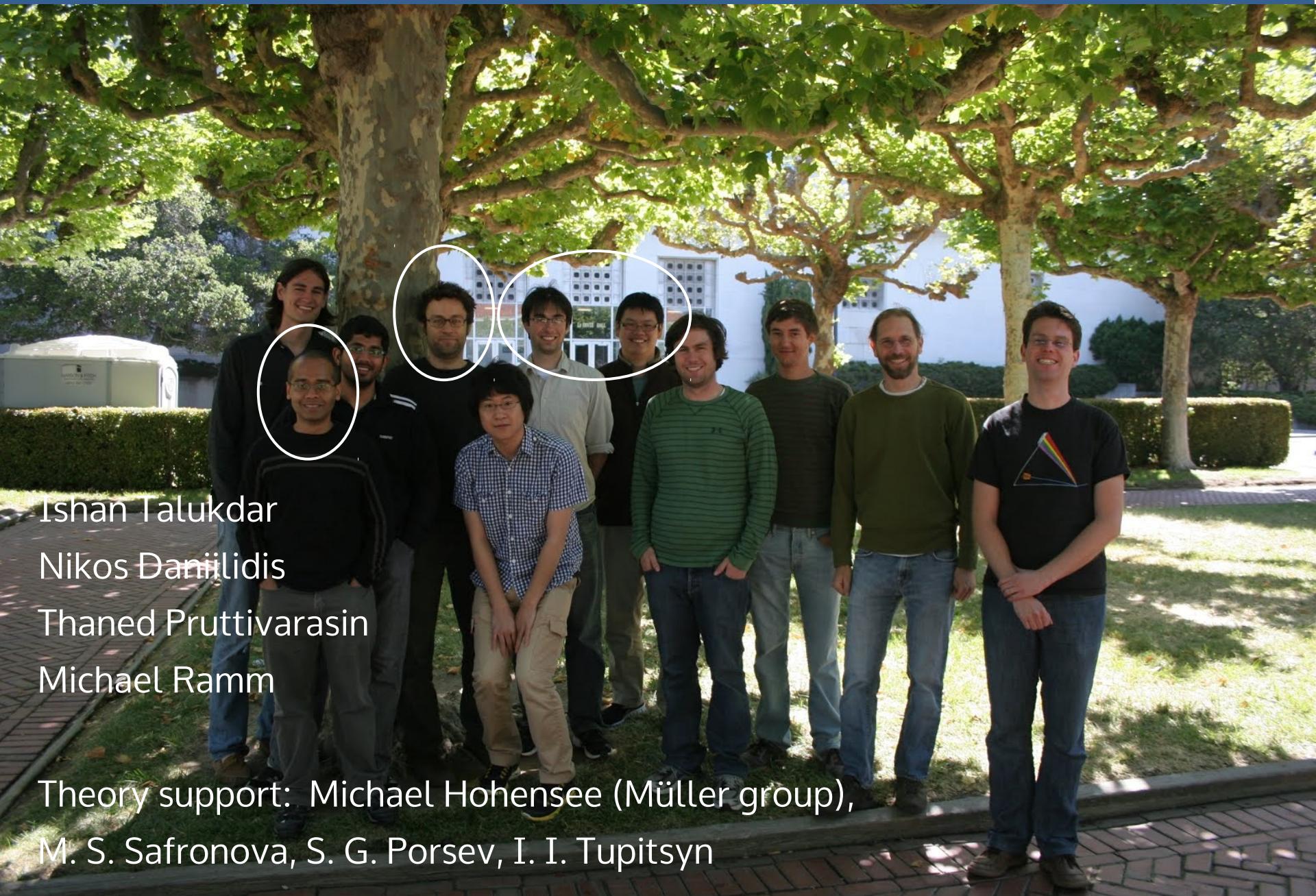


Lorentz symmetry  
holds at a level of  $10^{-18}$

Application to Physics,  
fundamental symmetries

$$|\Psi\rangle = |\text{two lobes}\rangle + e^{i2\omega t} |\text{two ellipses}\rangle$$

# The group



Ishan Talukdar

Nikos Daniilidis

Thaned Pruttivarasin

Michael Ramm

Theory support: Michael Hohensee (Müller group),  
M. S. Safronova, S. G. Porsev, I. I. Tupitsyn

# The group

Current team:

Ahmed Abdelrahman  
Christian Zimmer  
Crystal Noel  
Dylan Gorman  
Henning Kaufmann  
Ishan Talukdar  
Maya Lewin-Berlin  
Omid Khosravani  
Philipp Schindler  
Sönke Möller

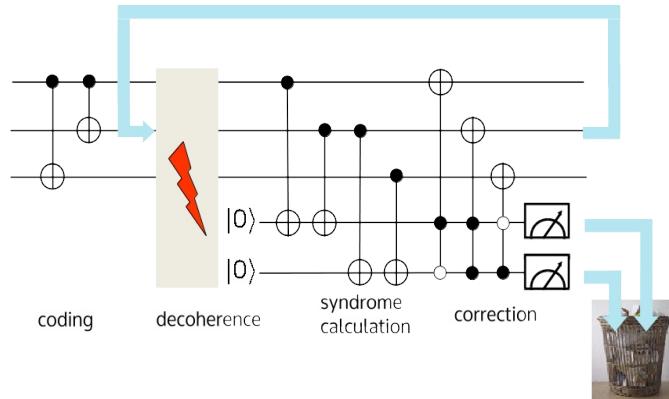
Undergraduate students:

Alex Chuang  
Chen Chen  
Hong Wong  
Po-Jen Wang  
Ryoh Masuda  
William Tokumaru

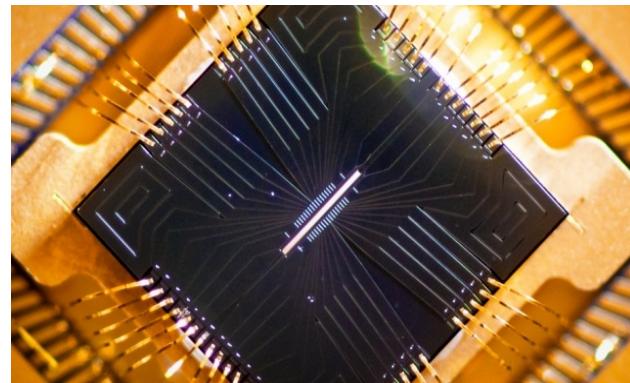


# Conclusions

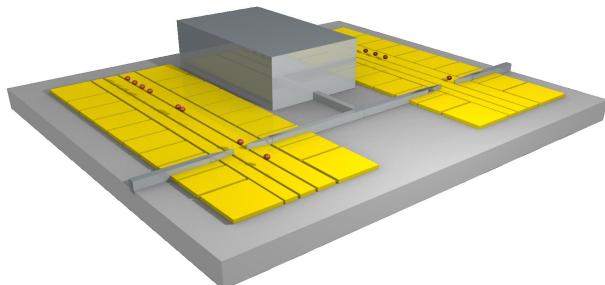
Advanced algorithms have been performed with trapped ions



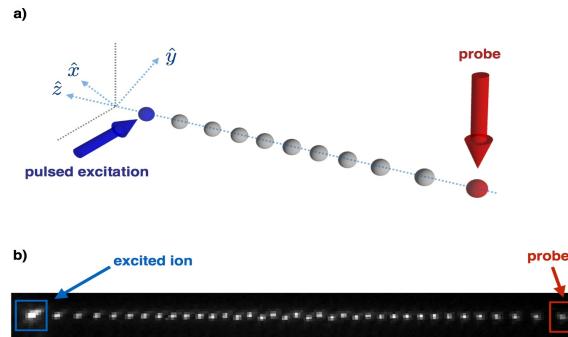
Microfabricated traps for scaling to thousands of qubits



Microwaves can ease the technology

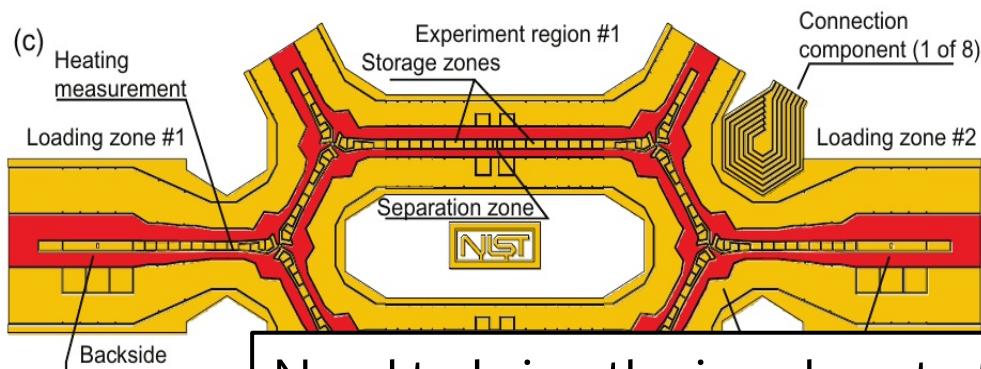
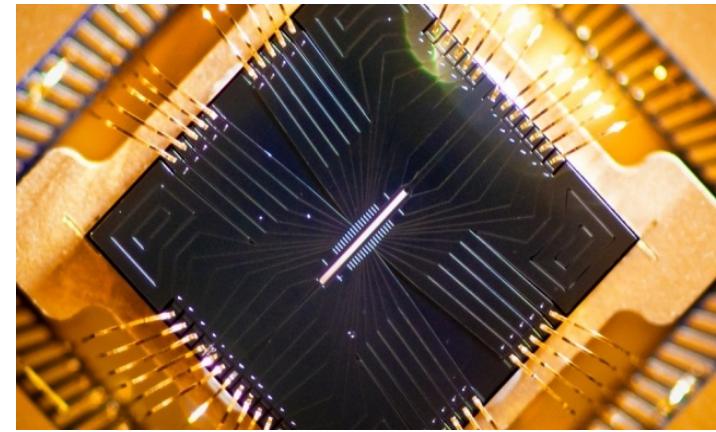
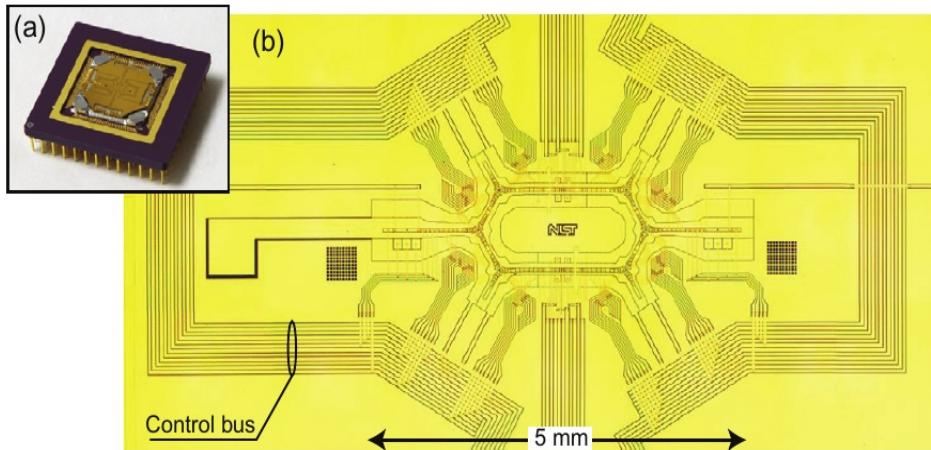


Quantum simulation  
is a promising field



# Microfabricated ion traps

Advanced microfabrication predominantly at national labs!



Sandia National Labs



Need to bring the ion close to the surface to speed up operations.

Speed  $\sim 1/d^2$

NIST, Amini *et al.*, NJP 2010