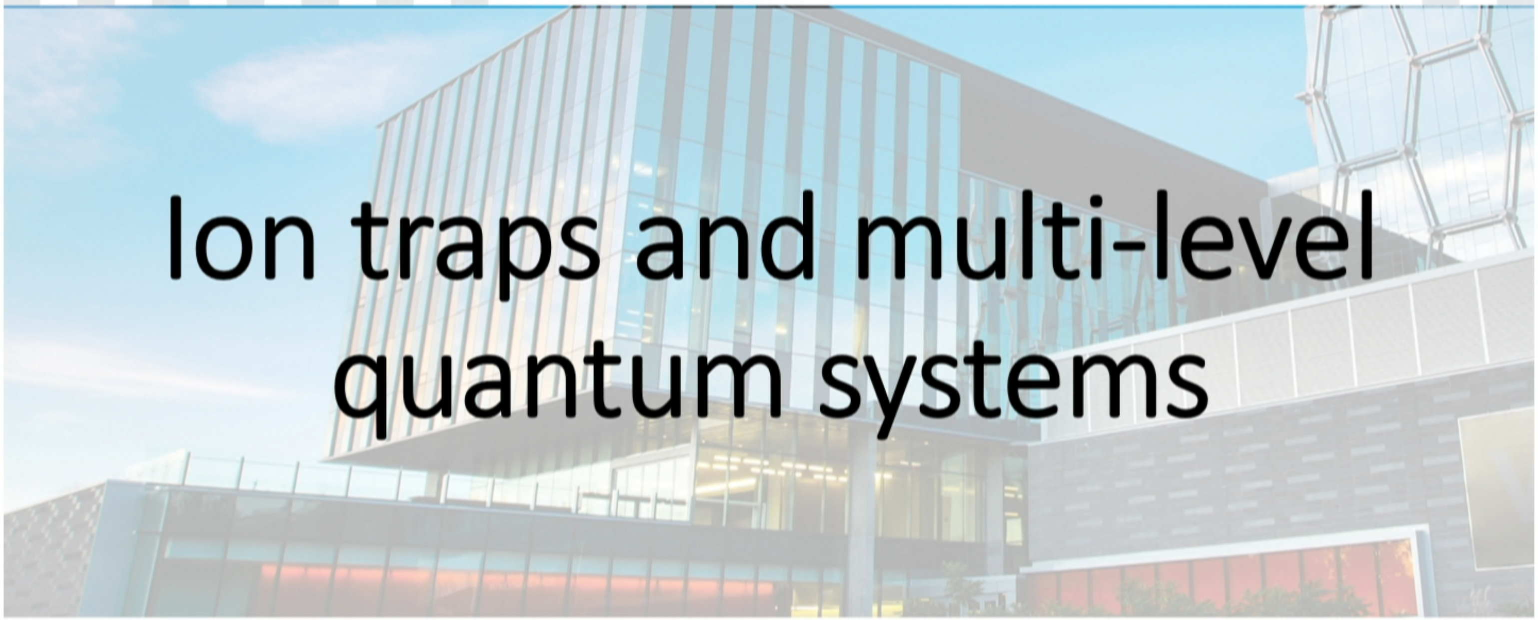
Title: Trapped ions for multi-valued quantum information

Date: Nov 07, 2018 02:00 PM

URL: http://pirsa.org/18110059

Abstract: <p>I give an overview of trapped ion quantum information experiments and discuss prospects for implementing multi-valued quantum logic using trapped ions. Qudits (the multi-state generalization of qubits) are attractive for quantum computing because they enable a much larger Hilbert space for the same number of trapped ions, which may allow us to improve the information capacity of a quantum processor. I describe possible advantages and disadvantages of using qudits in place of qubits, and lay out some of the protocols that my lab will test for implementing measurements, single-qudit operations, and two-qudit operations in a trapped ion system.</p>

Institute for Quantum Computing

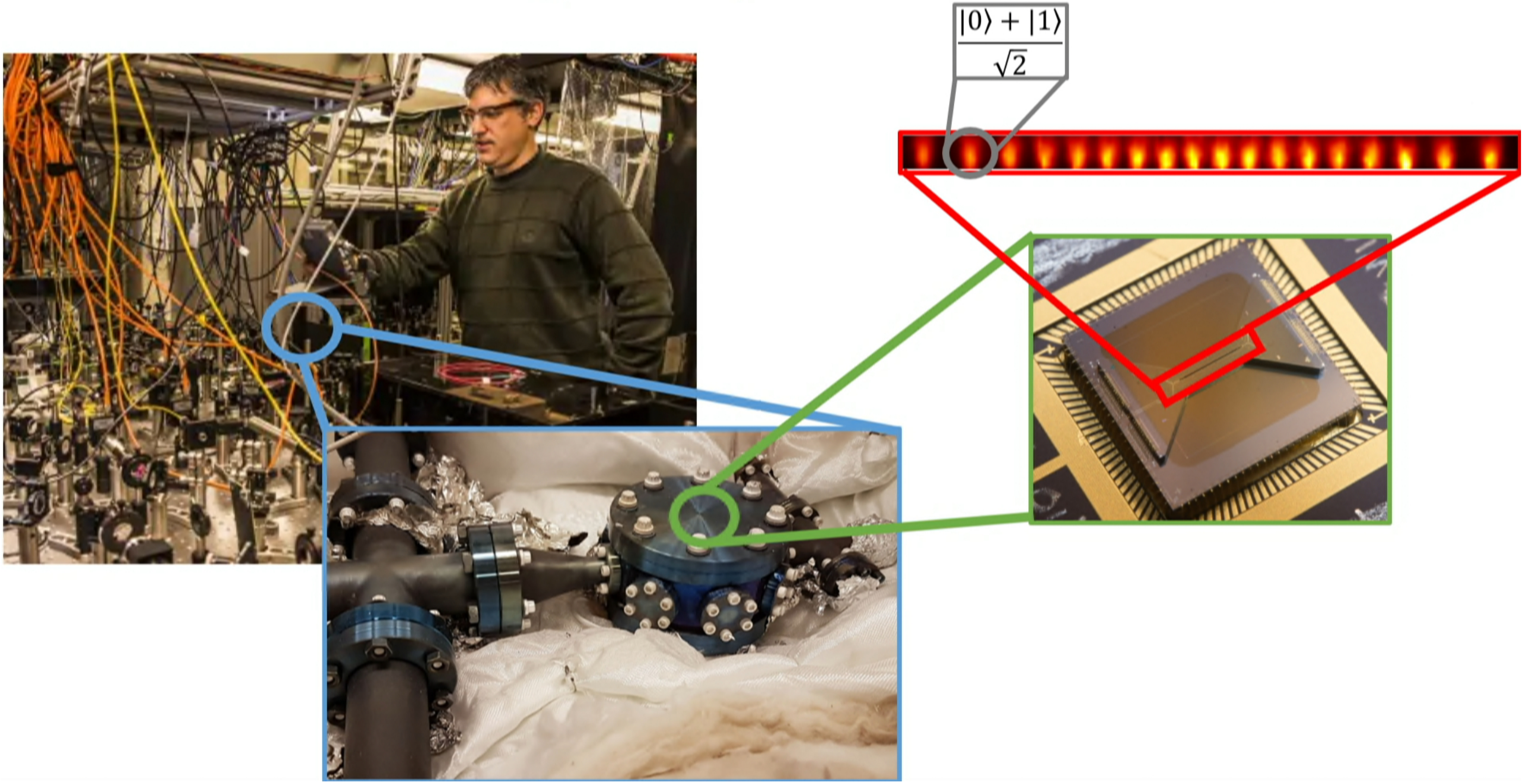


Ion traps and multi-level quantum systems

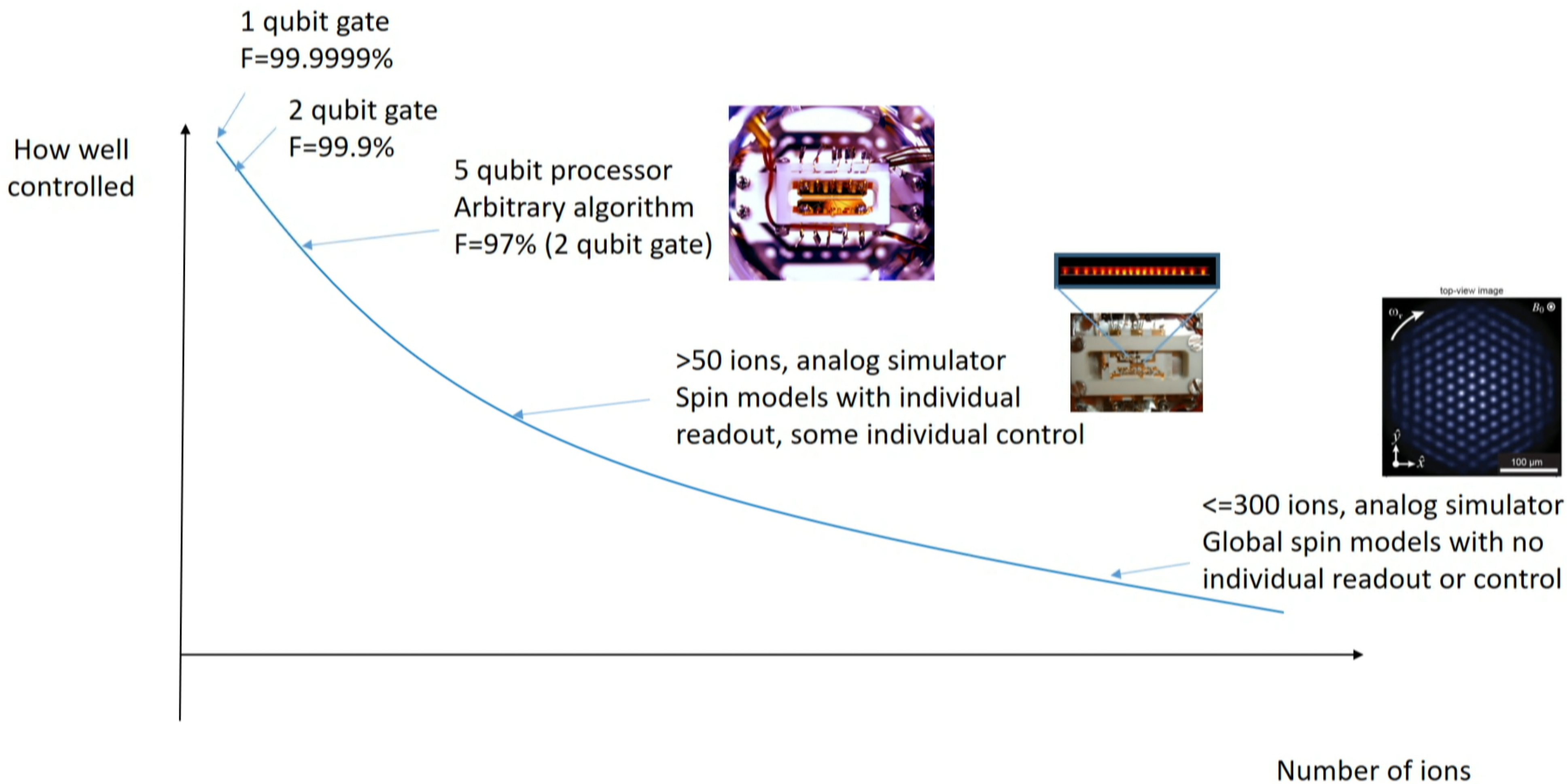
Crystal Senko
Perimeter Institute colloquium, Nov. 7, 2018

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

What does a trapped ion quantum computer look like?

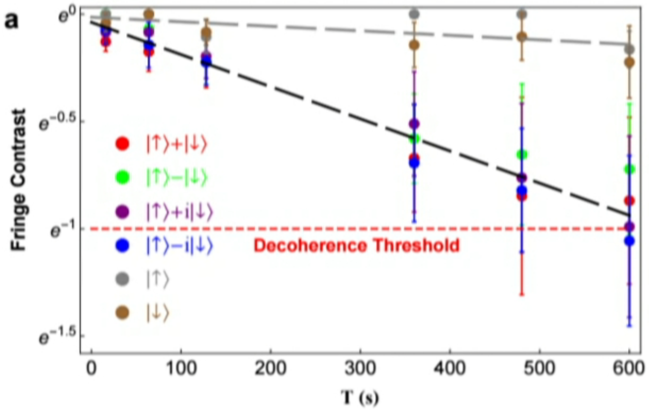


What can we do with ions?



For computation: care about precision, information capacity

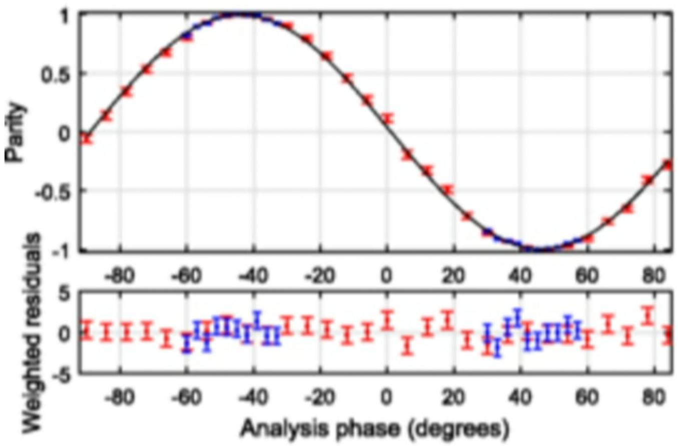
10 minute coherence time



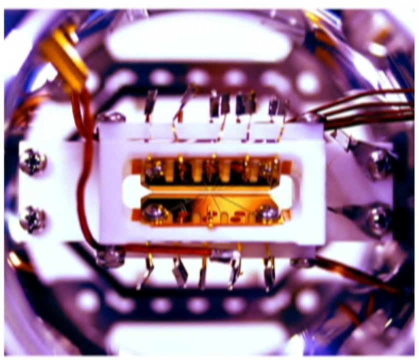
Nature Photonics 11, 646-650 (2017) - Kim group

High fidelity quantum gates

Two-qubit: **99.9%**
PRL 117, 060504 (2016)
Single qubit: **99.9999%**
PRL 113, 220501 (2014)
Lucas group

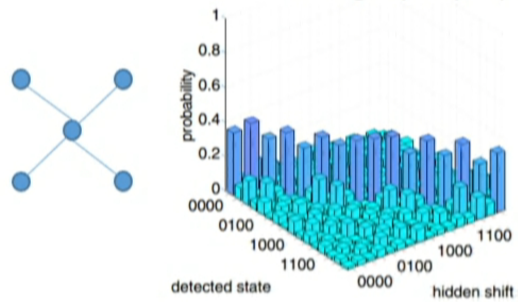


Fully connected programmable quantum processor

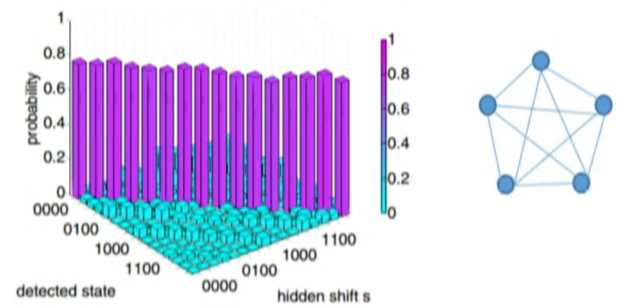


Nature 563, 63 (2016) - Monroe group

Star graph (SC)

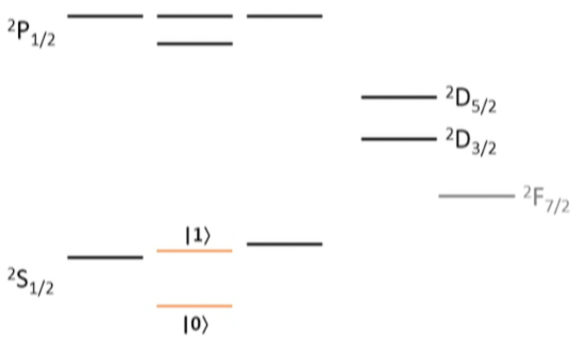


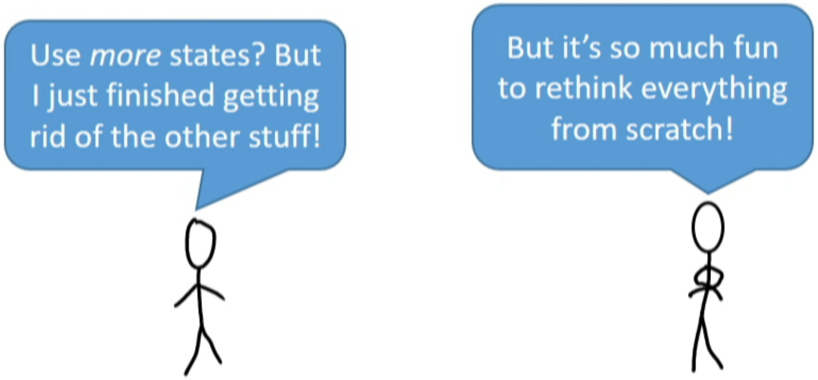
Fully connected (ions)



PNAS 114, 13 (2017) - Monroe group

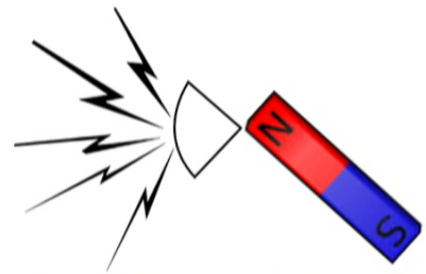
We want to use qu**d**its: like qu**b**its, with more states

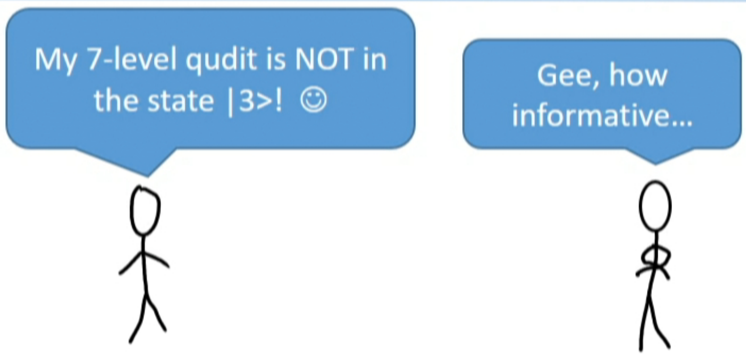




Why the experiments haven't been done?

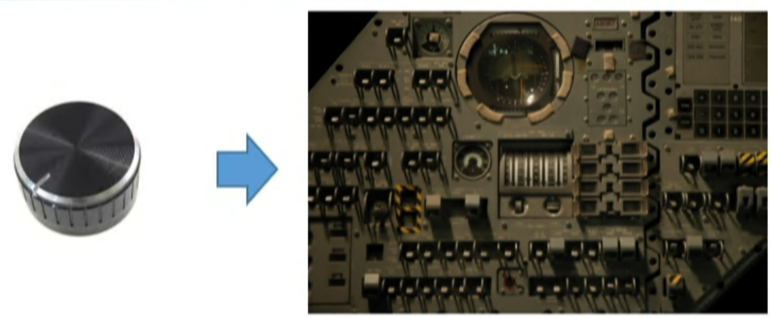
- Coherence more limited by magnetic field noise



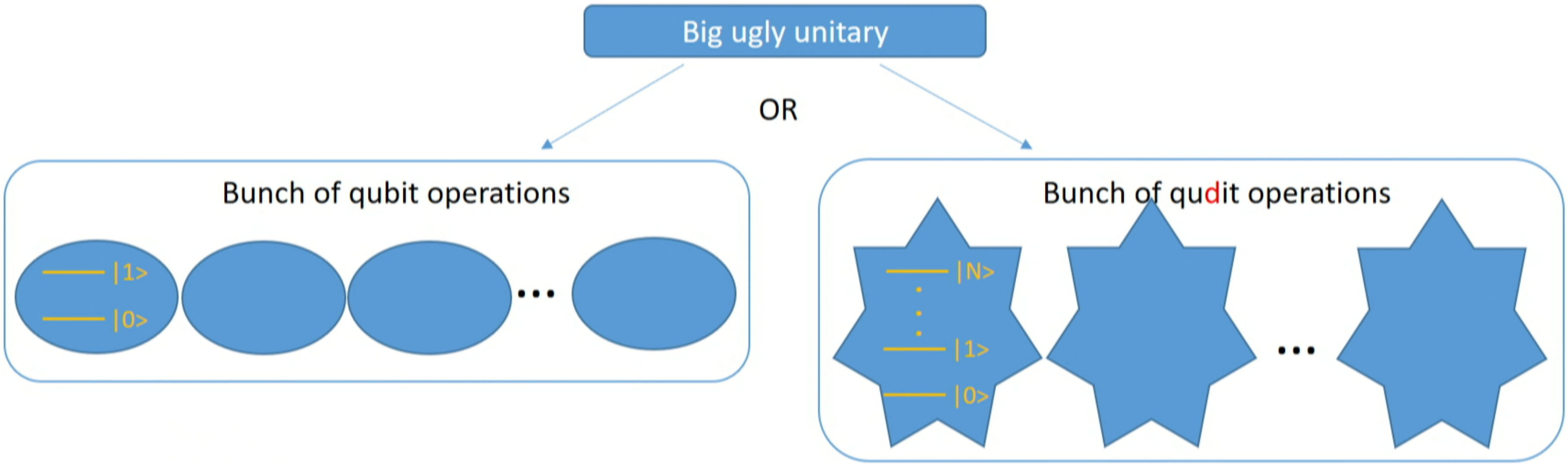


- Experiments hard to interpret without full readout

- More control knobs required



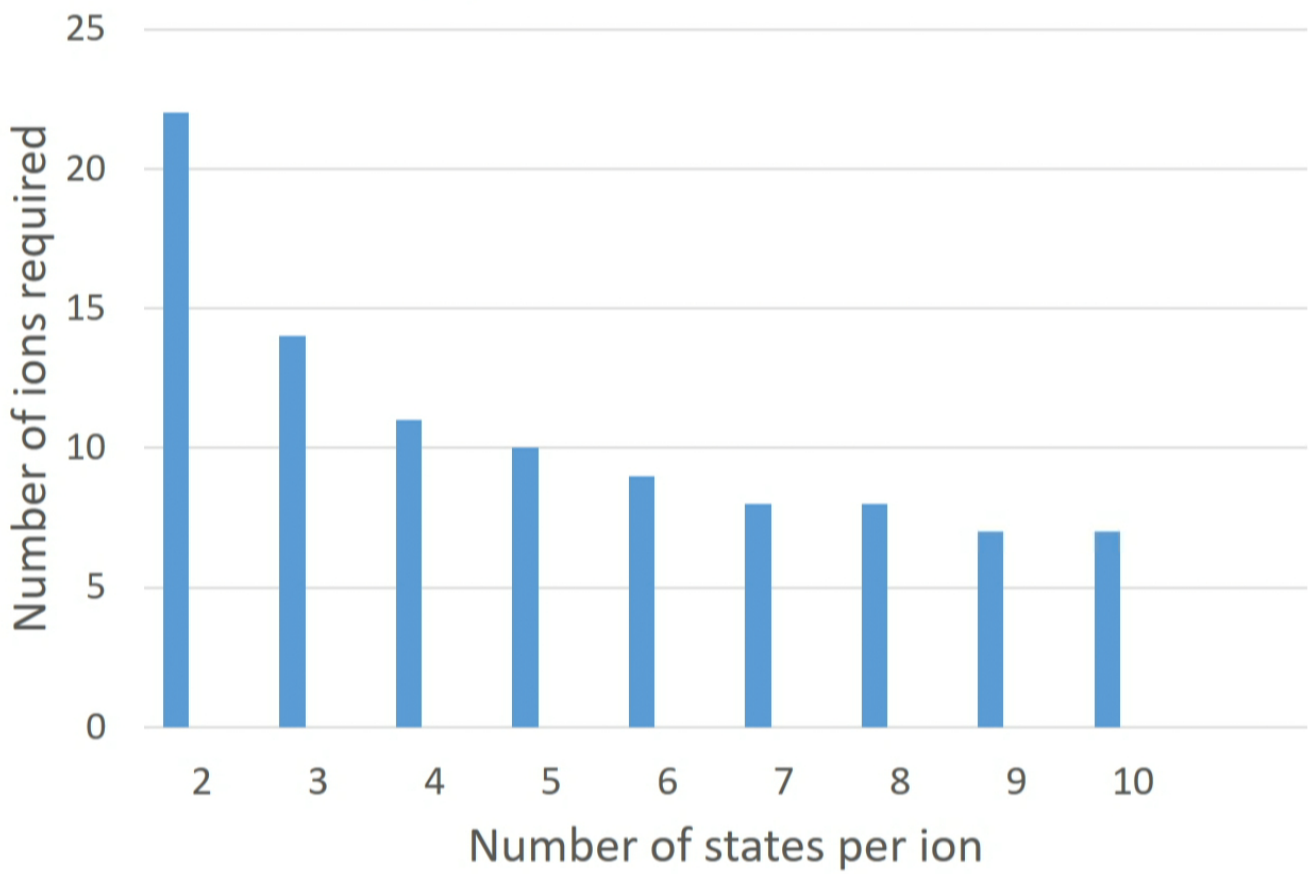
Why qudits?



- Simple components
- Complexity is entirely in the number of qubits and how they're wired

- Components are more difficult
- Could simplify other aspects… maybe

Computational gains from a larger Hilbert space?

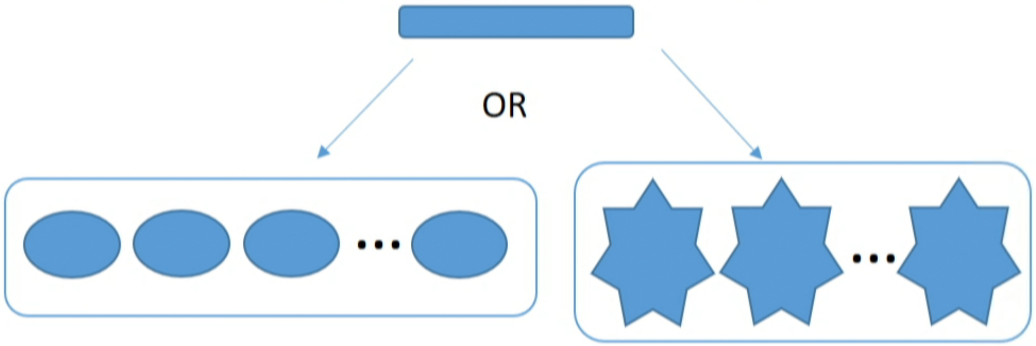


How many qudits are required to obtain a given precision in a quantum phase estimation algorithm

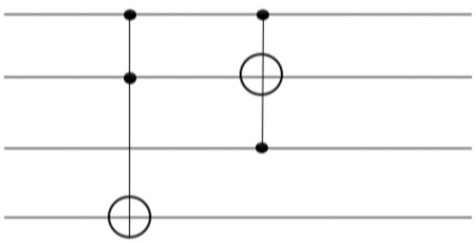
Parasa and Perkowski, 2011 IEEE International Symposium on Multivalued Logic

Why qudits?

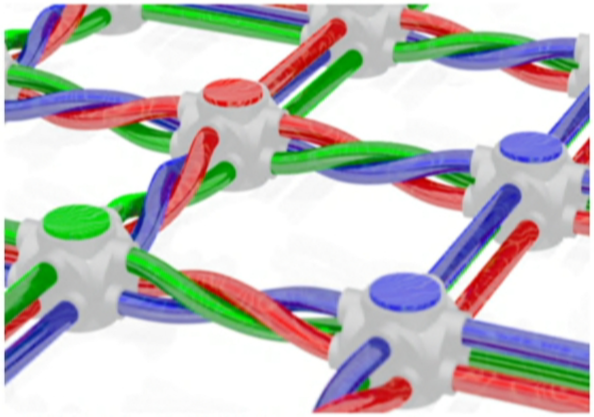
Higher dimensionality another tradeoff for complexity



Specific improvements e.g. simplifying algorithms



Specific improvements e.g. error correcting code thresholds



PRA 91, 042331

Central question: Can qu**d**its offer computational advantages?

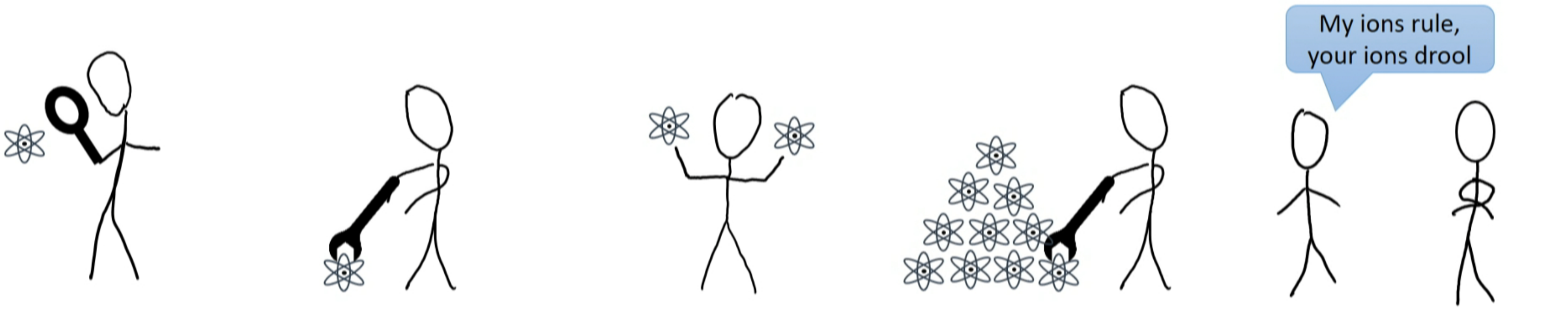
Can we measure whether a qudit is in state $|0\rangle$ vs $|1\rangle$ vs $|2\rangle$ vs …

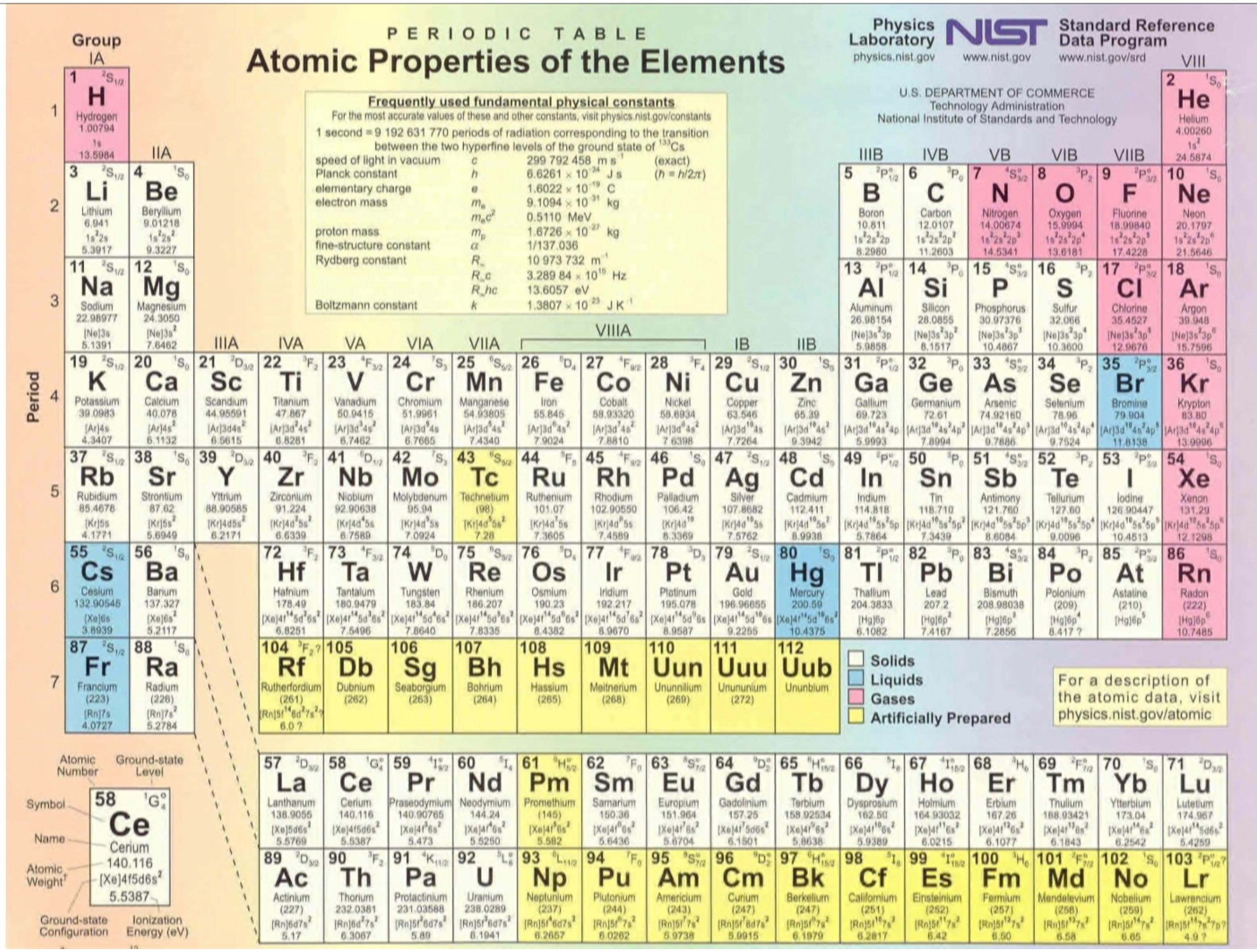
→ Can we implement logic operations on a single qudit

→ Can we implement two-qudit logic operations (i.e. entangling interactions)

→ Can we do all that with multiple qudits

→ Can we directly show that N qu**d**its do something better than N qu**b**its





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Atomic Properties of the Elements
Physics Laboratory
physics.nist.gov
www.nist.gov
Standard Reference Data Program
www.nist.gov/srd
U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Frequently used fundamental physical constants
For the most accurate values of these and other constants, visit physics.nist.gov/constants
1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of 133Cs
speed of light in vacuum c 299 792 458 m s-1 (exact)
Planck constant h 6.6261 × 10-34 J s (ħ = h/2π)
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electron mass me 9.1094 × 10-31 kg
mec2 0.5110 MeV
proton mass mp 1.6726 × 10-27 kg
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R∞hc 13.6057 eV
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Group
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Liquids
Gases
Artificially Prepared
For a description of the atomic data, visit physics.nist.gov/atomic
Atomic Number
Ground-state Level
Symbol
Name
Atomic Weight
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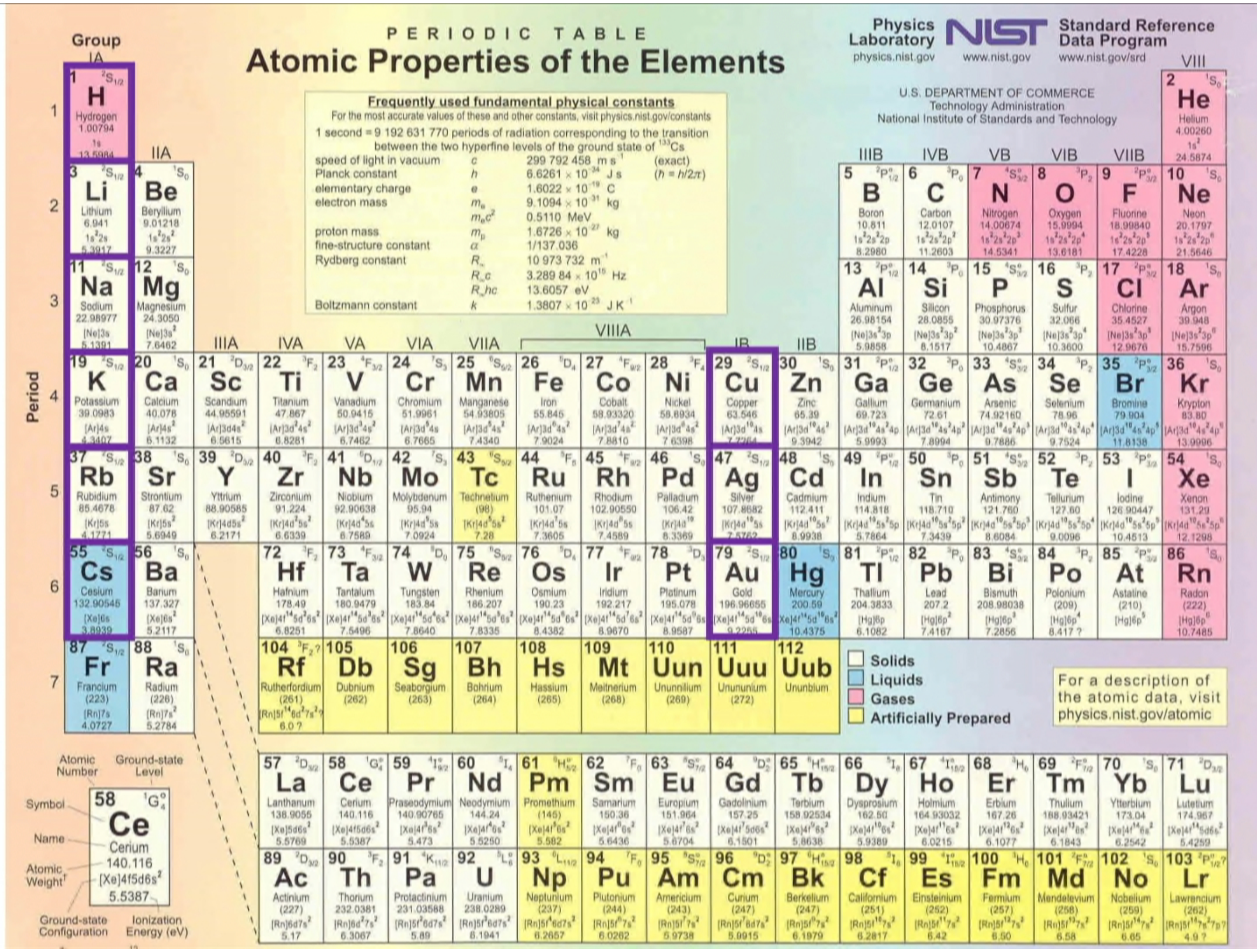
Ionization Energy (eV)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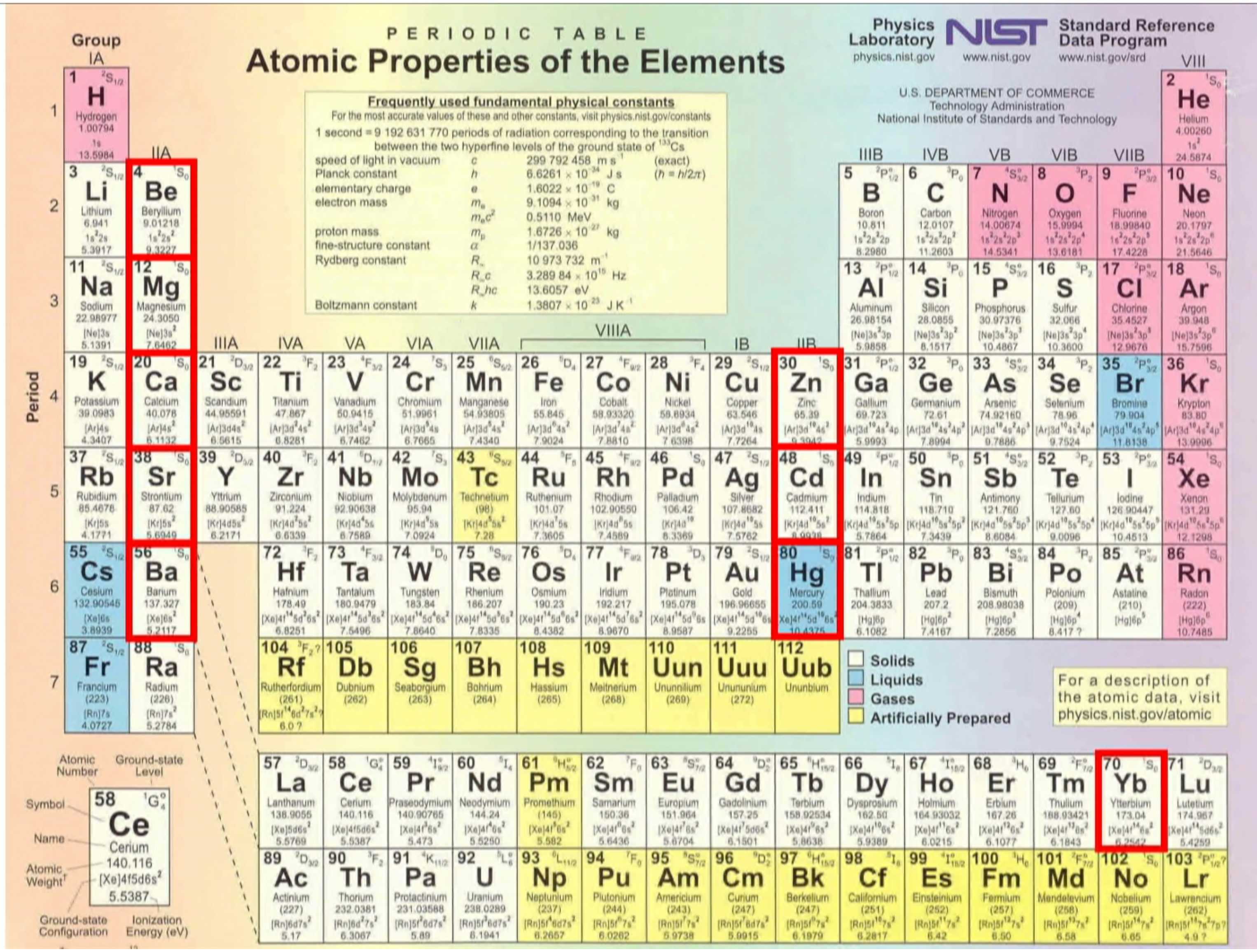
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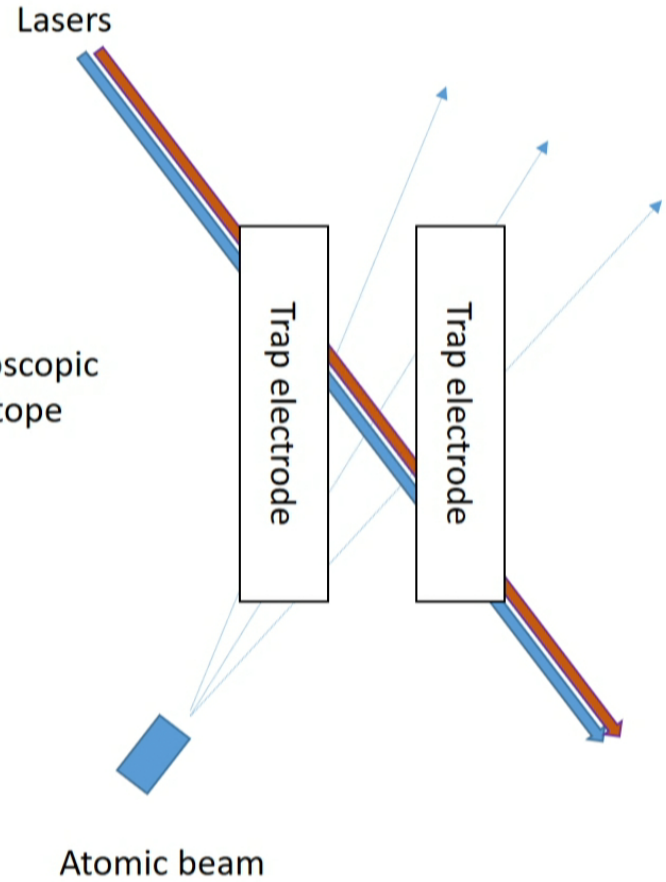
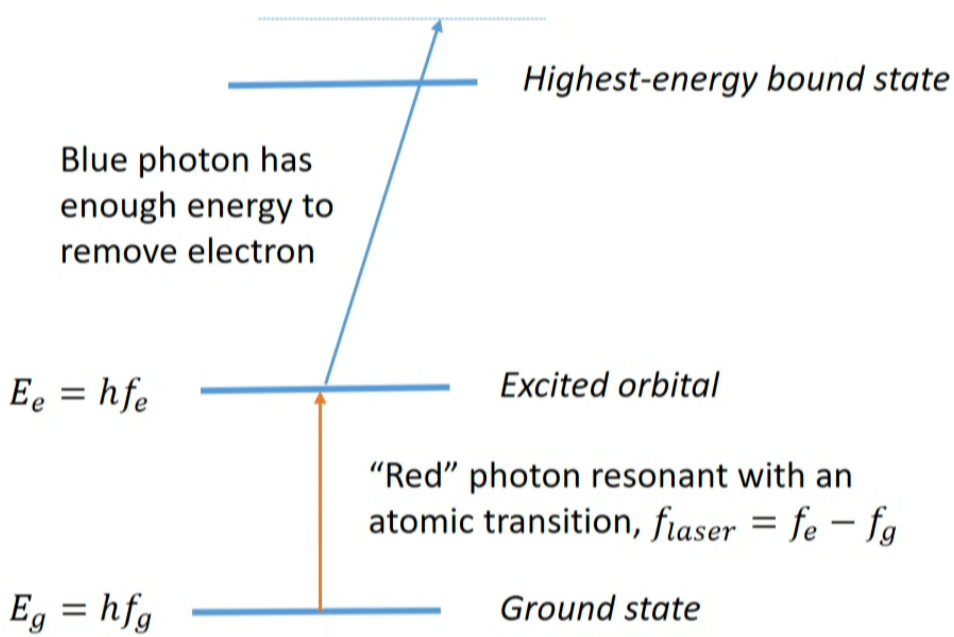
Symbol
Name
Atomic Weight
Ground-state Configuration
Ionization Energy (eV)

Making ions to trap

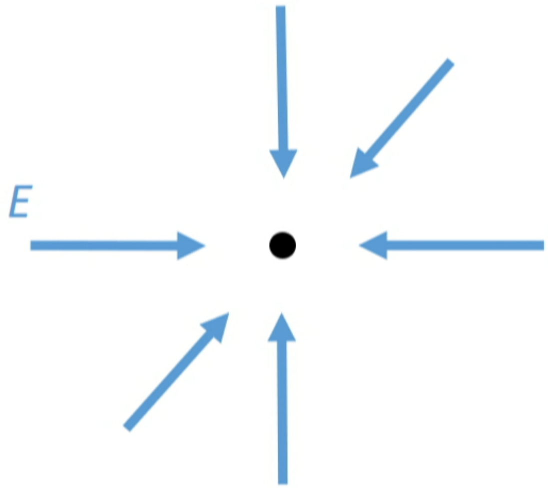


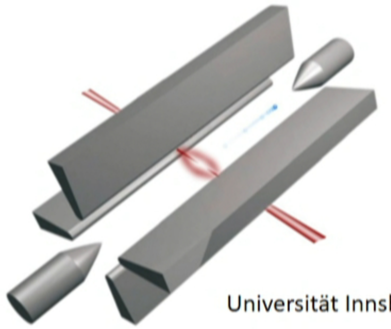
Enables spectroscopic selection of isotope

Atom structure:



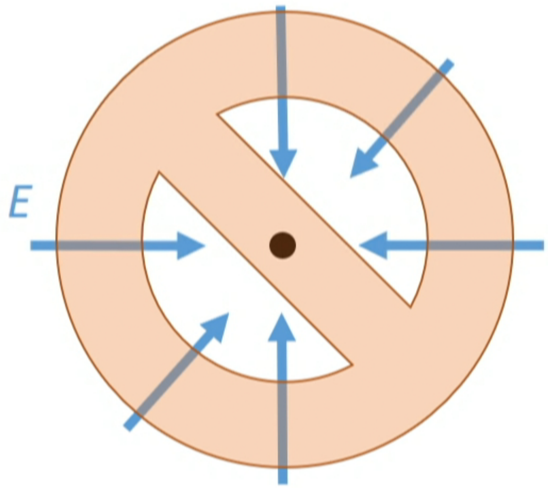
Trapping ions with a Paul trap



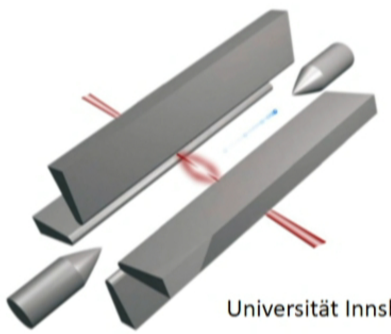


- Electric fields exert a force on a charged particle

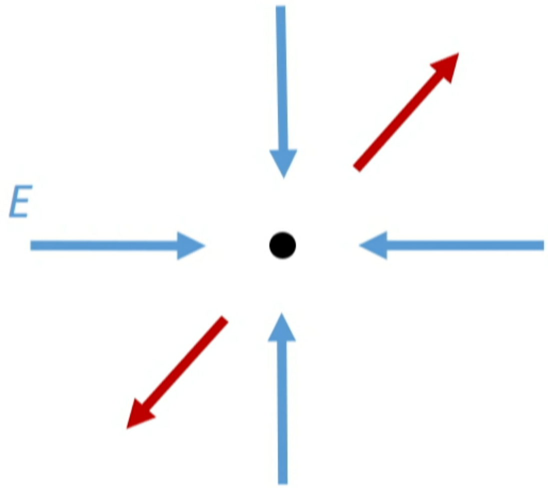
Trapping ions with a Paul trap



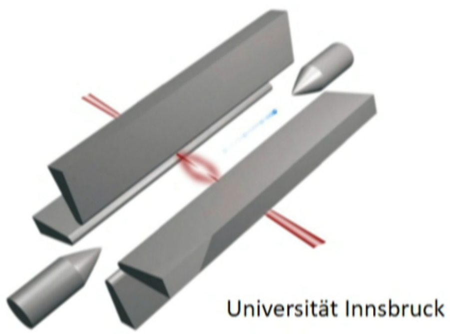
- Electric fields exert a force on a charged particle
- Maxwell's equations, Earnshaw theorem: $\vec{\nabla} \cdot \vec{E} = 0$
- Static electric fields cannot trap a charged particle

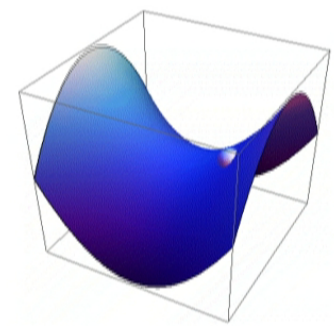

Universität Innsbruck

Trapping ions with a Paul trap



- Electric fields exert a force on a charged particle
- Maxwell's equations, Earnshaw theorem: $\vec{\nabla} \cdot \vec{E} = 0$
- Static electric fields cannot trap a charged particle
- Time-varying electric fields can!

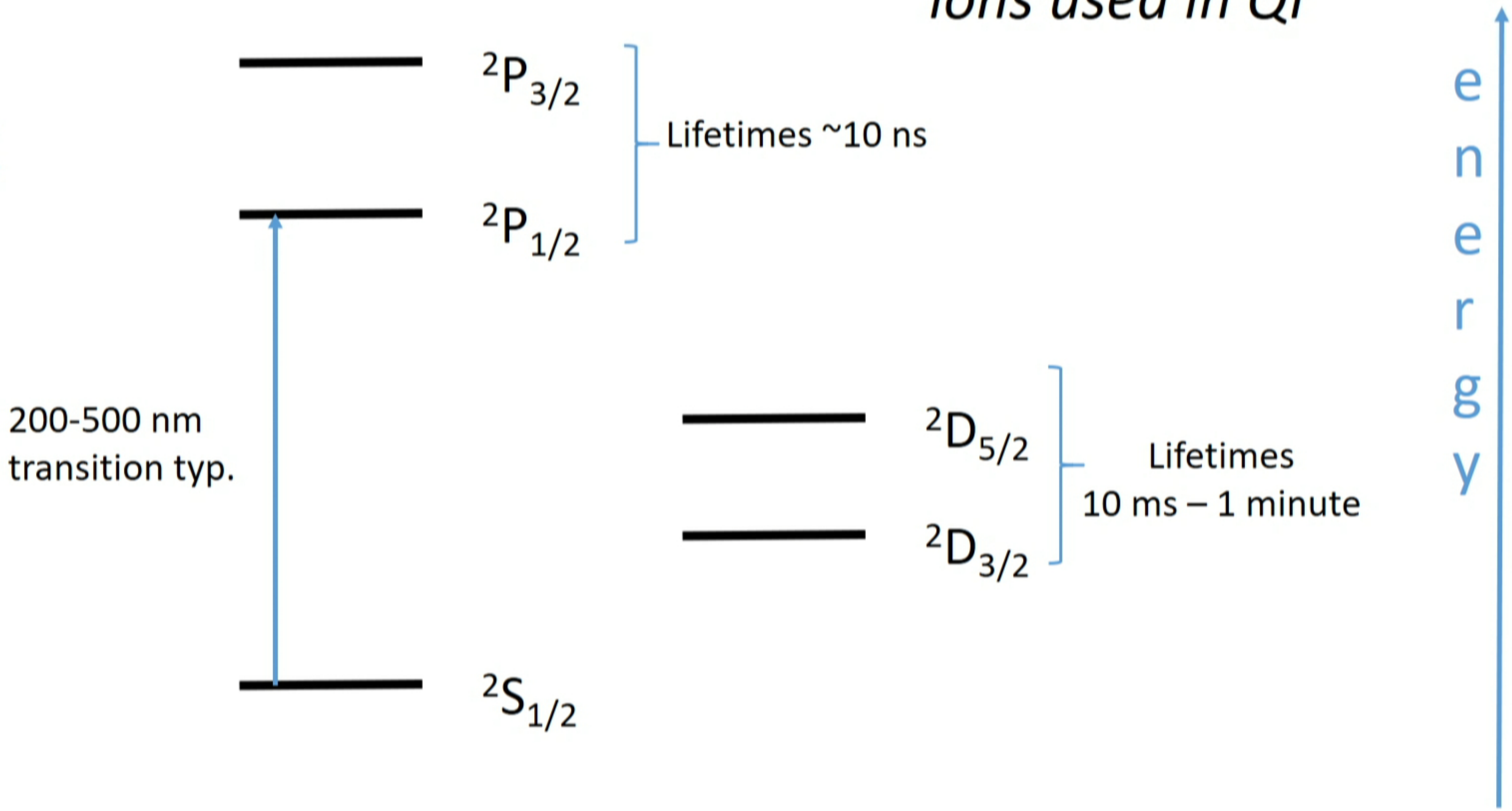




Typical atomic structure for ions used in QI

Which ion?

Be^+, Mg^+,
Ca^+, Sr^+, Ba^+,
Hg^+, Cd^+, Yb^+



From 2 to more: qudit development

Tools we need, a la DiVincenzo
Qudit encoding (multi-level system) with acceptable coherence
State preparation (includes trapping and cooling ions)
Measurement
Single-qudit gates
Two-qudit gates

Disclaimer:
Fidelity limitations are preliminary estimates
Initial experiments will probably not reach these numbers
Always assumes state-of-the-art technology

Tools we need
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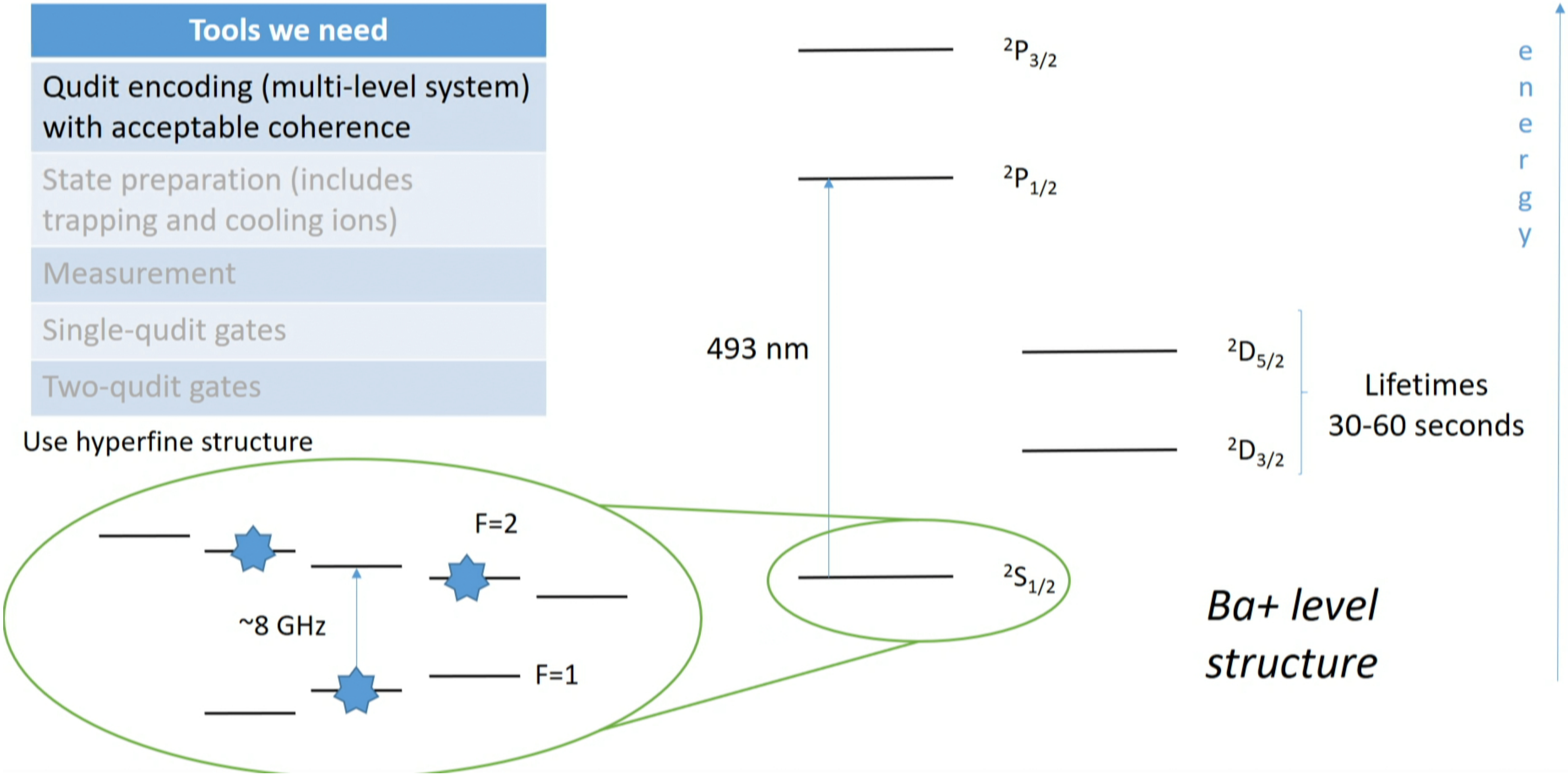
Use hyperfine structure



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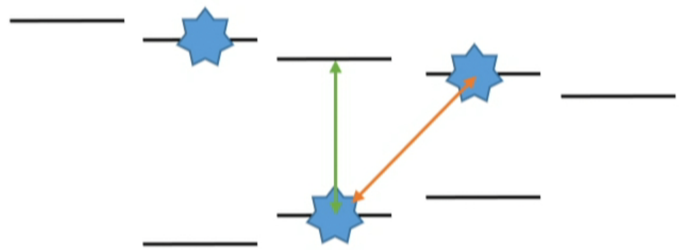

$$\Delta E = g_F m_F \mu_{\mathrm{B}} \Delta B \approx h * 0.7 \;\; MHz/G$$

Coherence times:

10 minutes, m=0 to m=0

5 seconds (projected), m=0 to m=1

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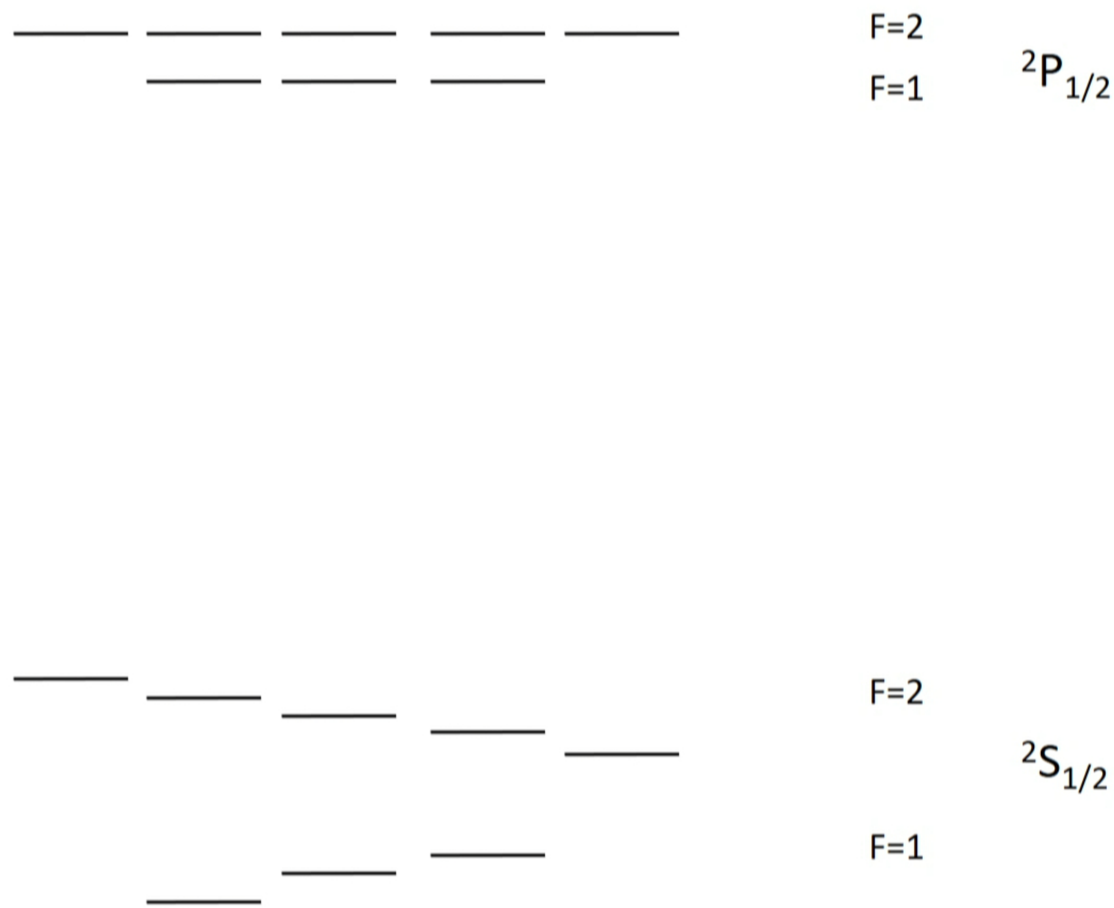
Optical pumping similar to qubit case



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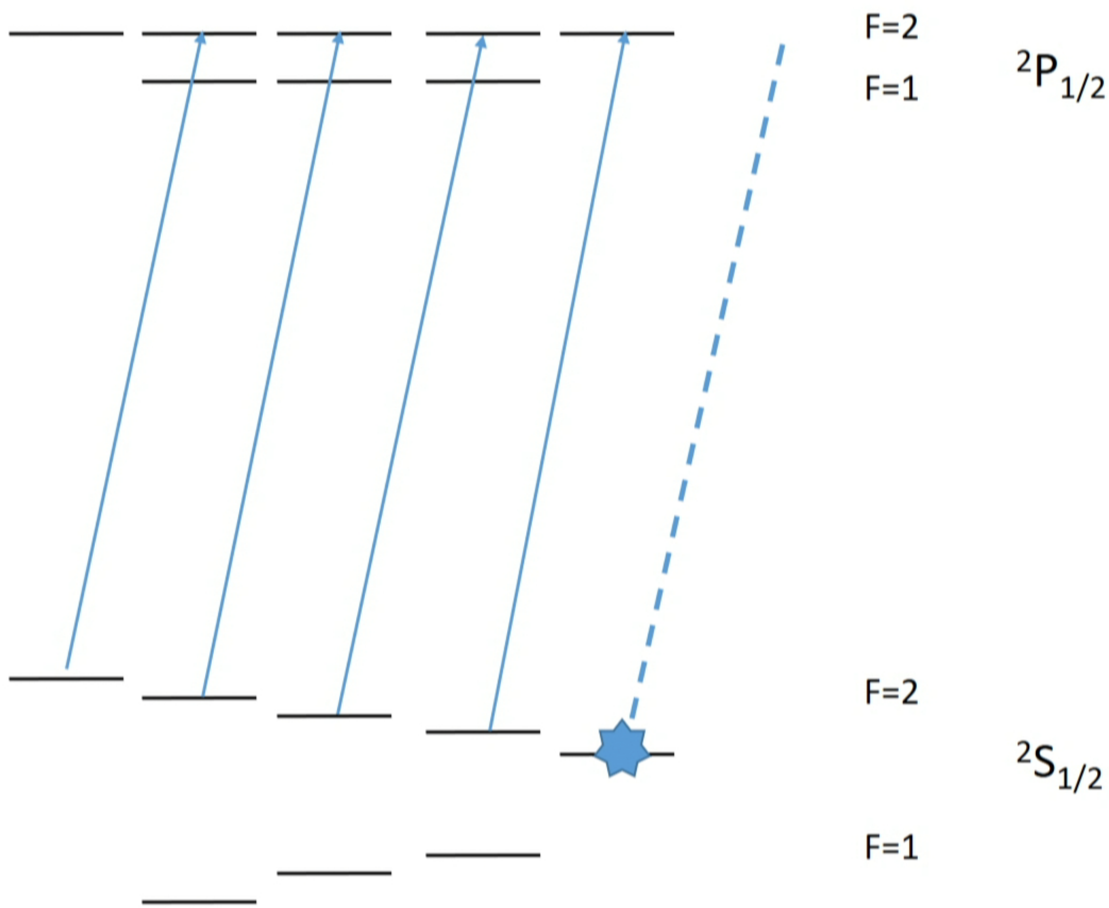

Tools we need
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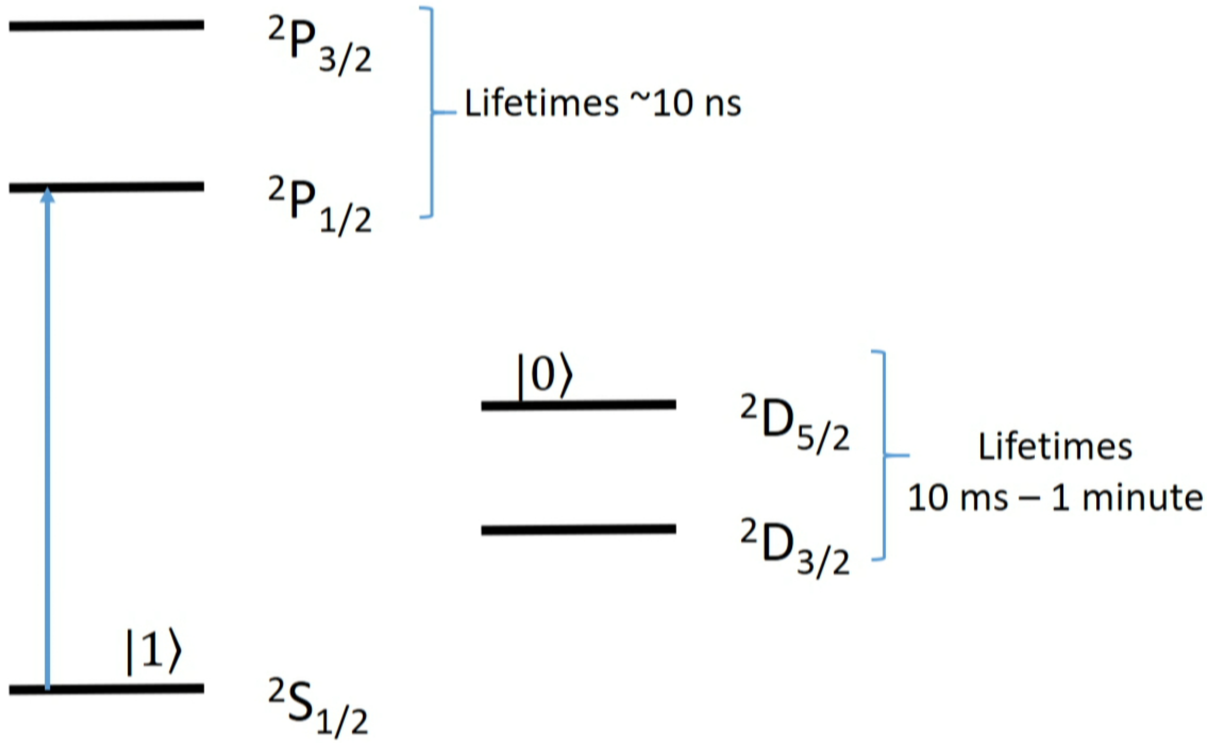
Apply blue laser:
$|1\rangle$ fluoresces
$|0\rangle$ does not



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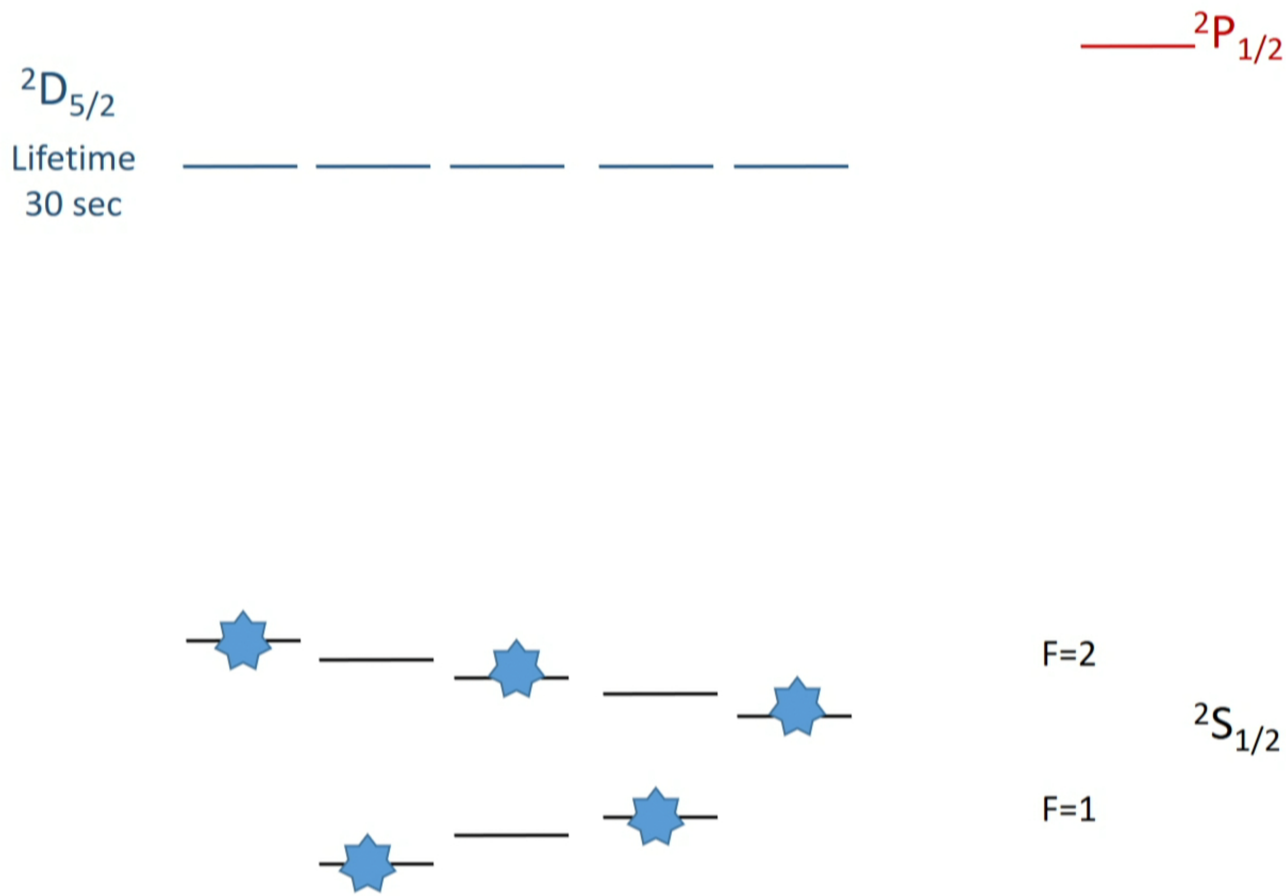

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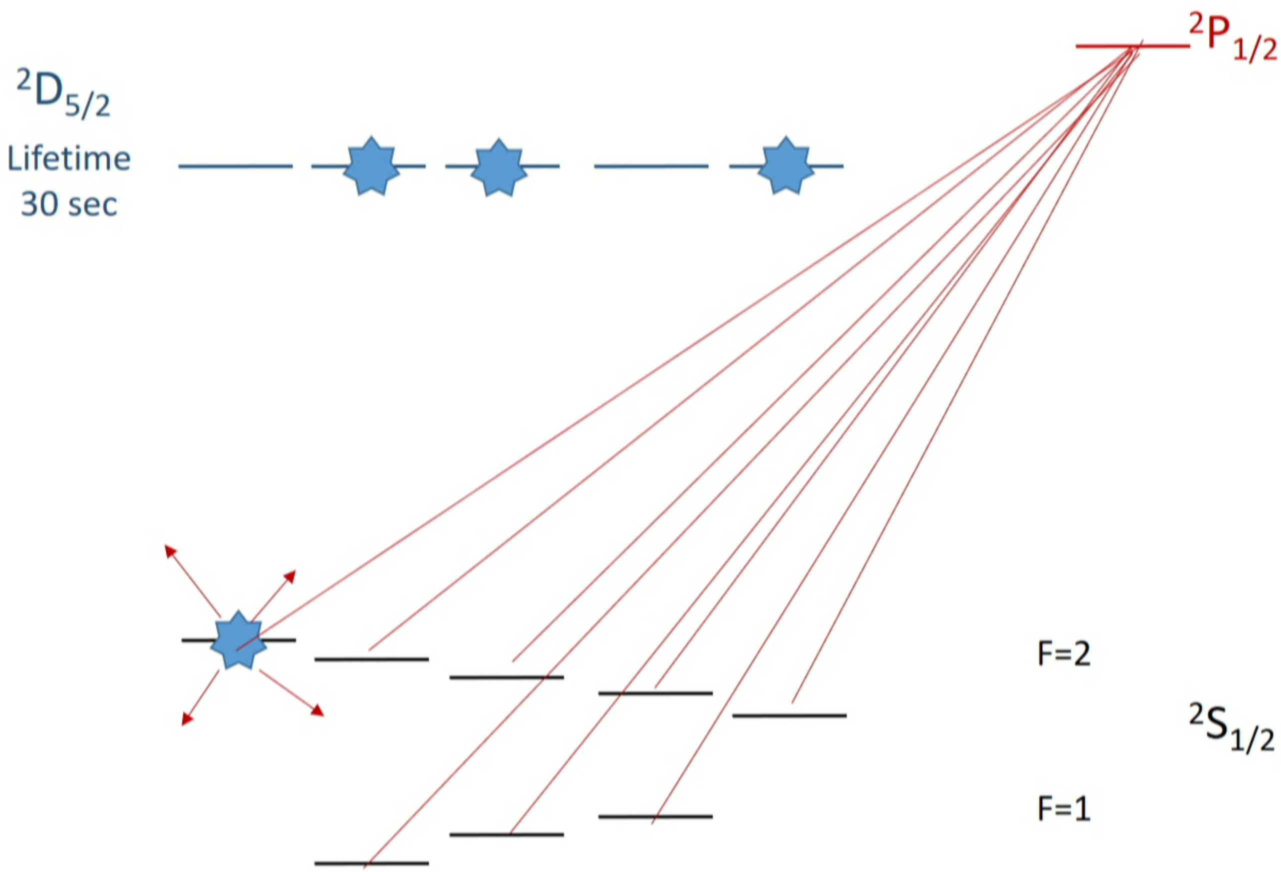

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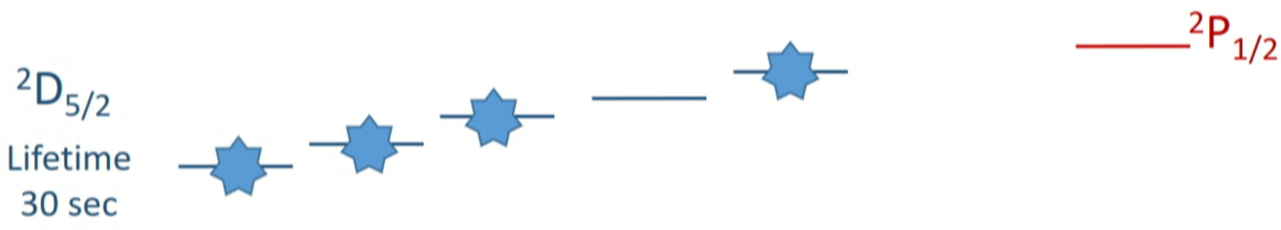
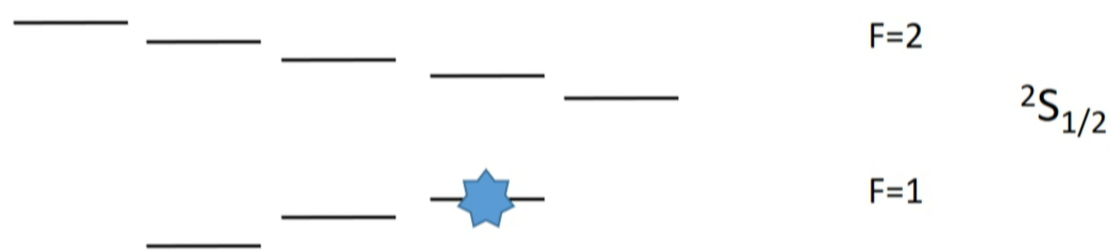
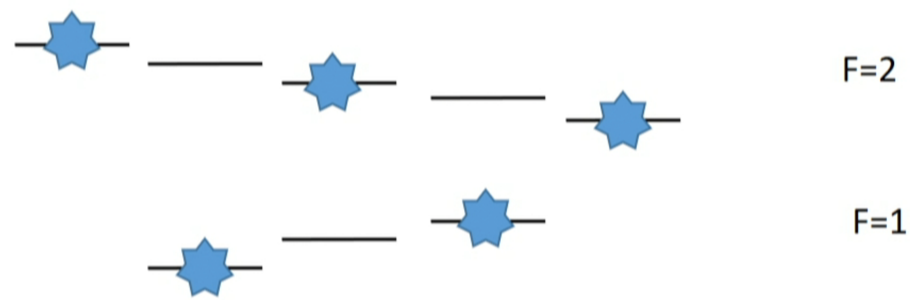


Limiting factor = fidelity of transfer between S and D states
Simple RAP protocol: limit ~0.998 for single transfer

Qudit dimension, *d*	Fidelity of measurement
3	0.996
5	0.984
7	0.976



Tools we need
Qutrit encoding (three-level system) with acceptable coherence
State preparation
Measurement
Single-qudit gates
Two-qudit gates



Synthesize unitaries from Givens rotations:

$$H_{jk} = e^{i\phi}|j\rangle\langle k| + e^{-i\phi}|k\rangle\langle j|$$

We would like: Connected graph; frequency addressing

Tools we need
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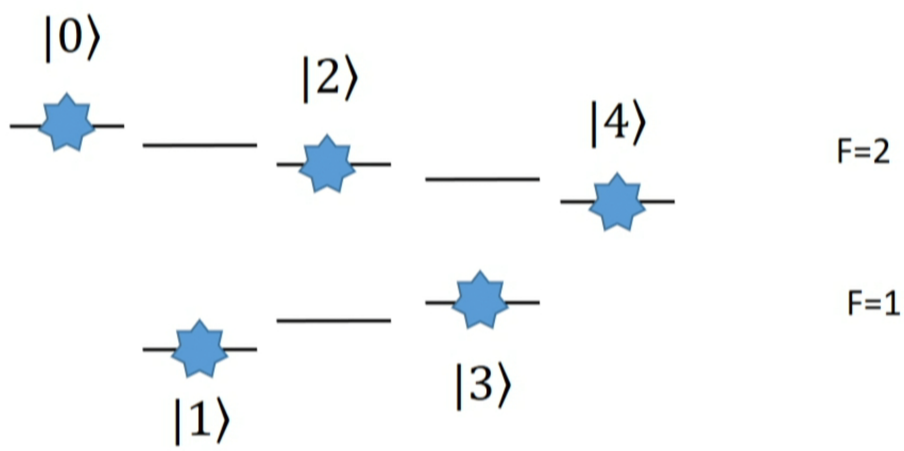

Error rate for single Givens rotation (from decoherence): 10^-6
Error rate for single-qudit gate: 10^-4 achievable

Example: X gate

$$X|i\rangle = |i + 1 \; mod \; d\rangle$$

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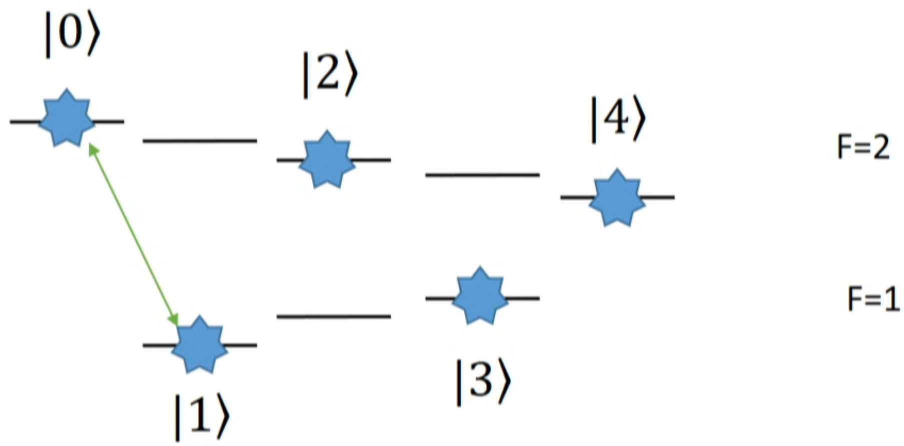

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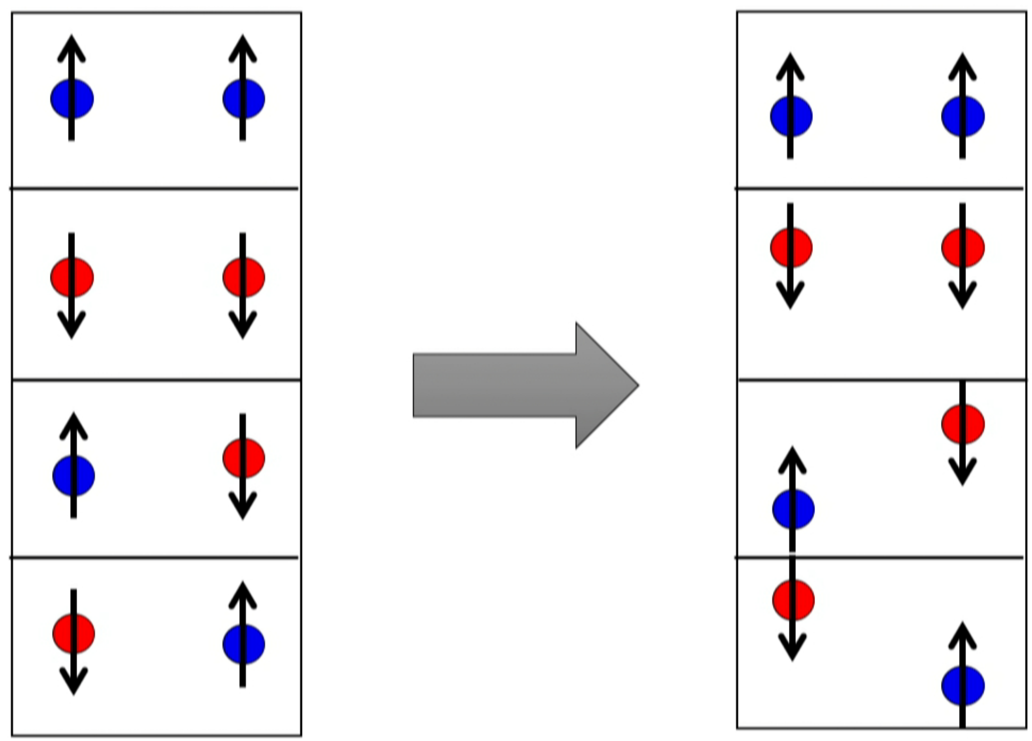
Spin dependent force + Coulomb interaction = spin-spin interaction

$$H = F \cdot x \propto \sigma_x [x_0 (a^\dagger + a)]$$



Spin-dependent potential from laser standing wave

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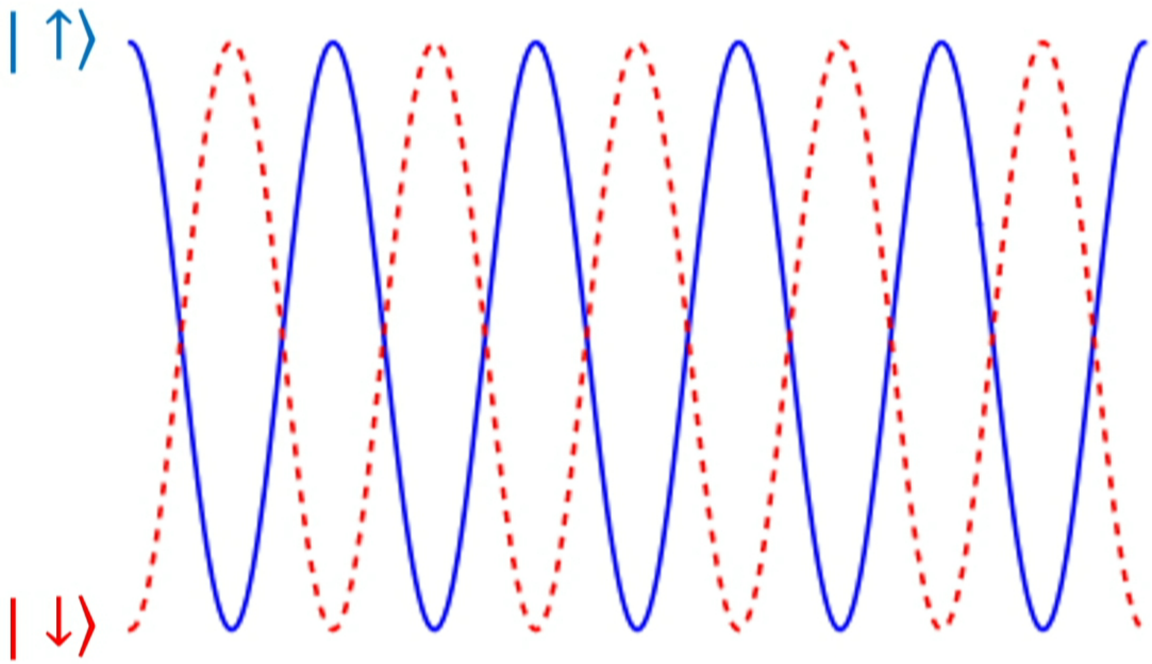

Two lasers interfere to create potential
Detuning one laser → potential oscillates in time

Drive a harmonic oscillator off resonance → excite and de-excite the motion

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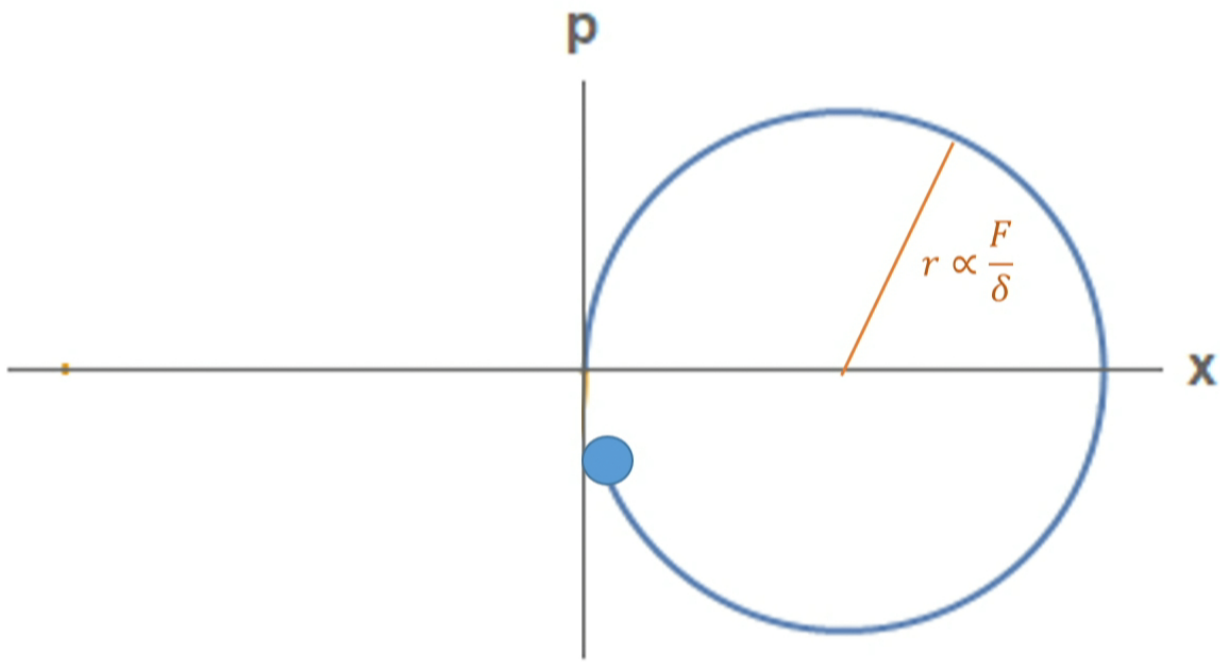

Ions in a harmonic trap = harmonic oscillators!

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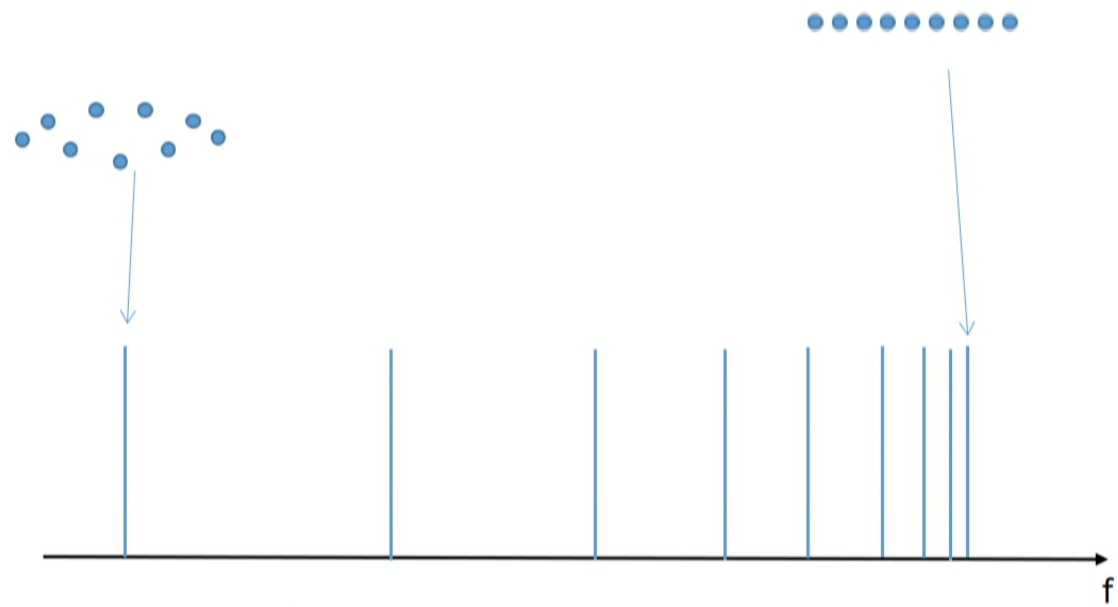

Normal mode spectrum

Two ions: Excite center of mass mode

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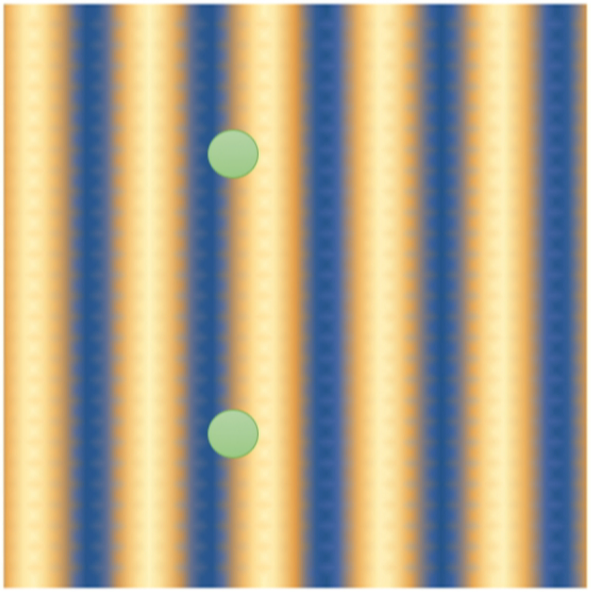
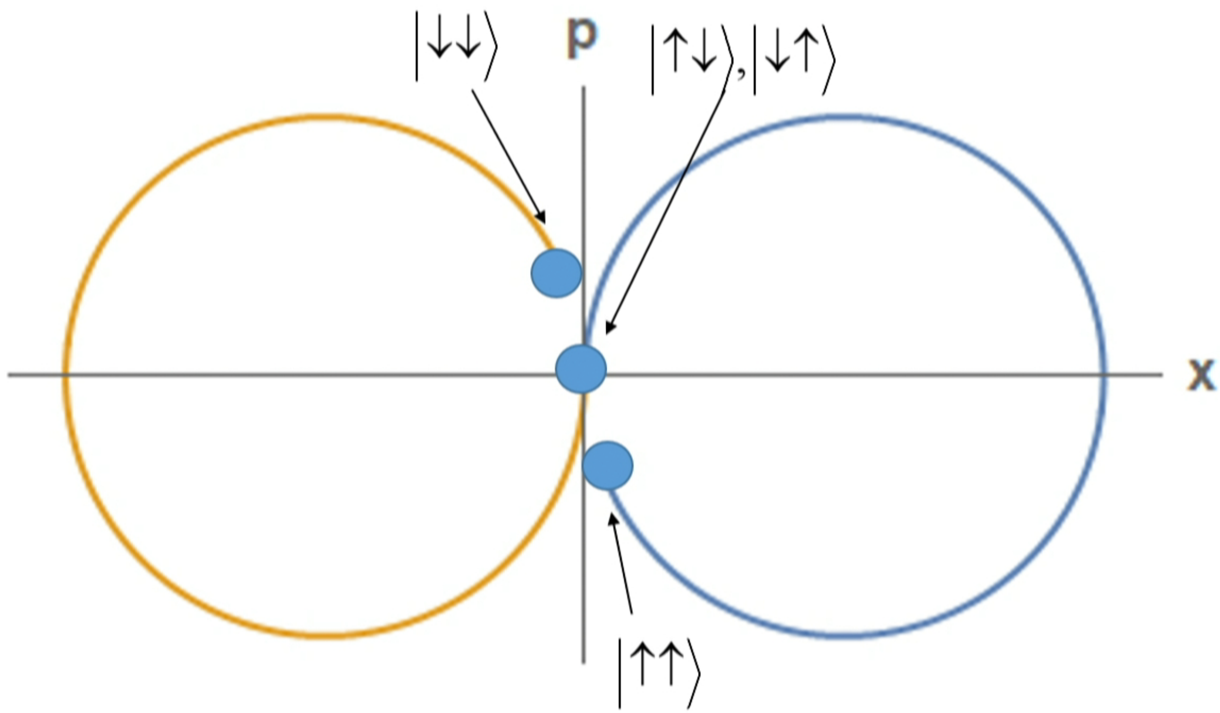
Single-qudit gates
Two-qudit gates



Ions in same spin state: mode is excited
Ions in different states: mode is not excited

Tools we need
Qudit encoding (multi-level system) with acceptable coherence
State preparation
Measurement
Single-qudit gates
Two-qudit gates

Geometric phase gates: obtained by driving harmonic oscillator off resonance



Geometric phase gates: work for larger spins too!

Tools we need
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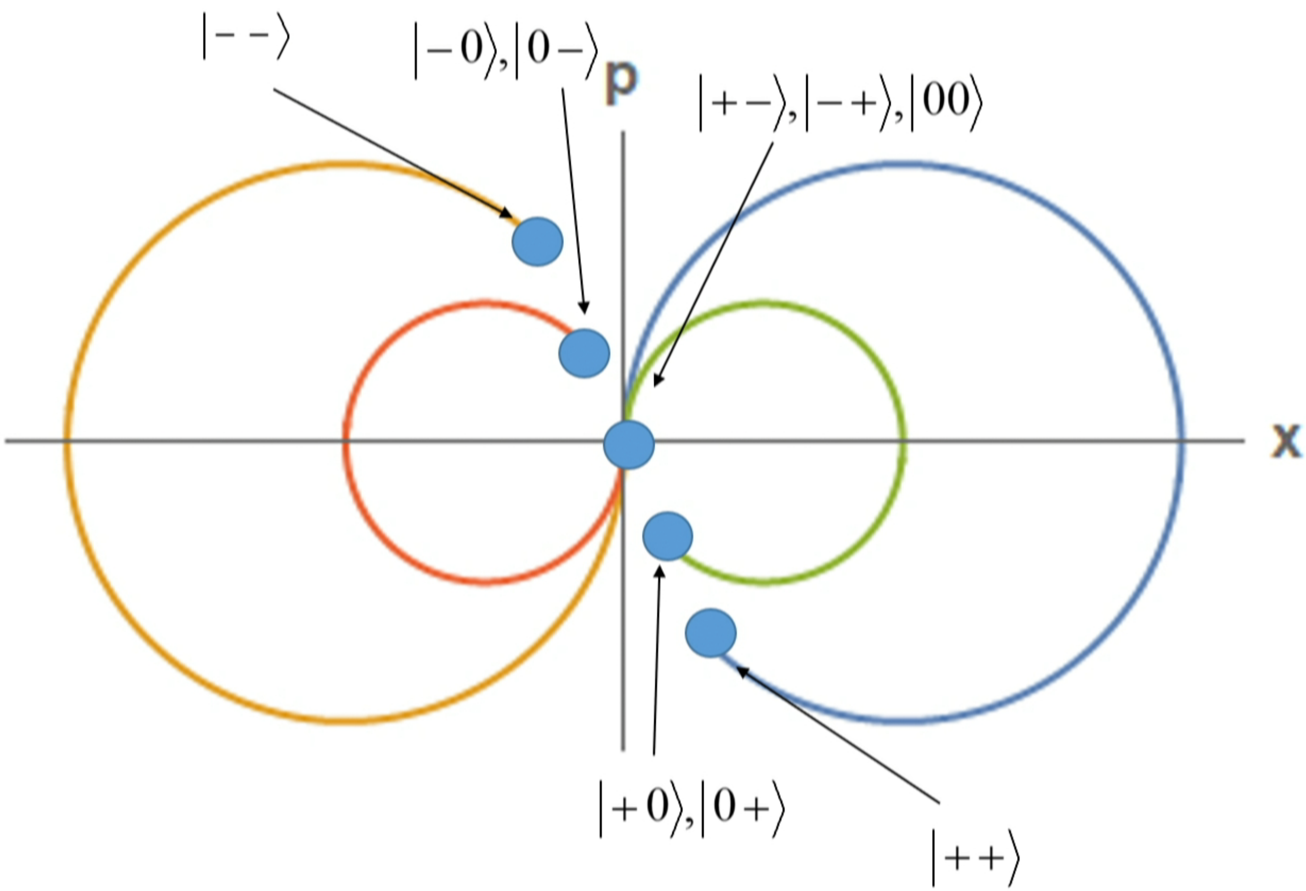
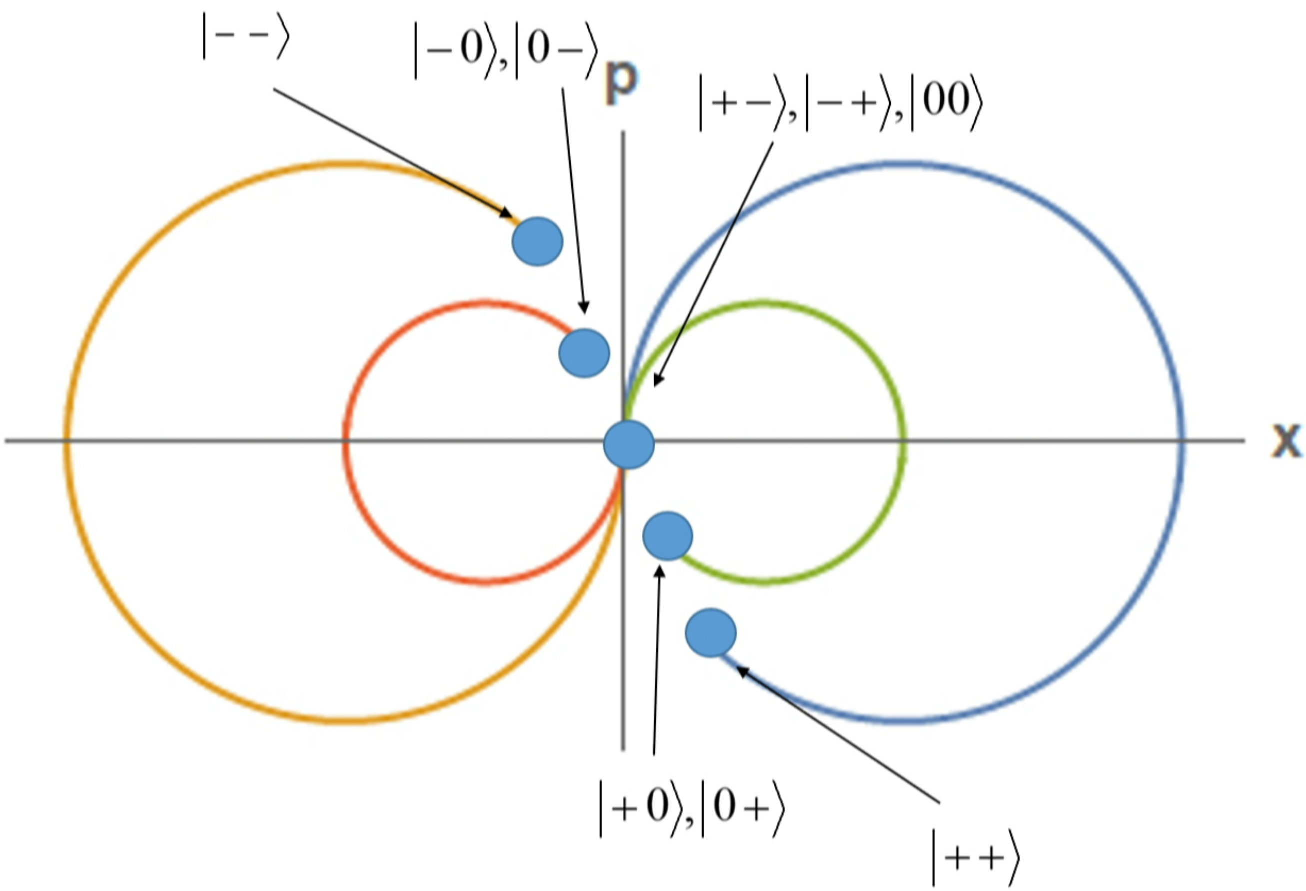


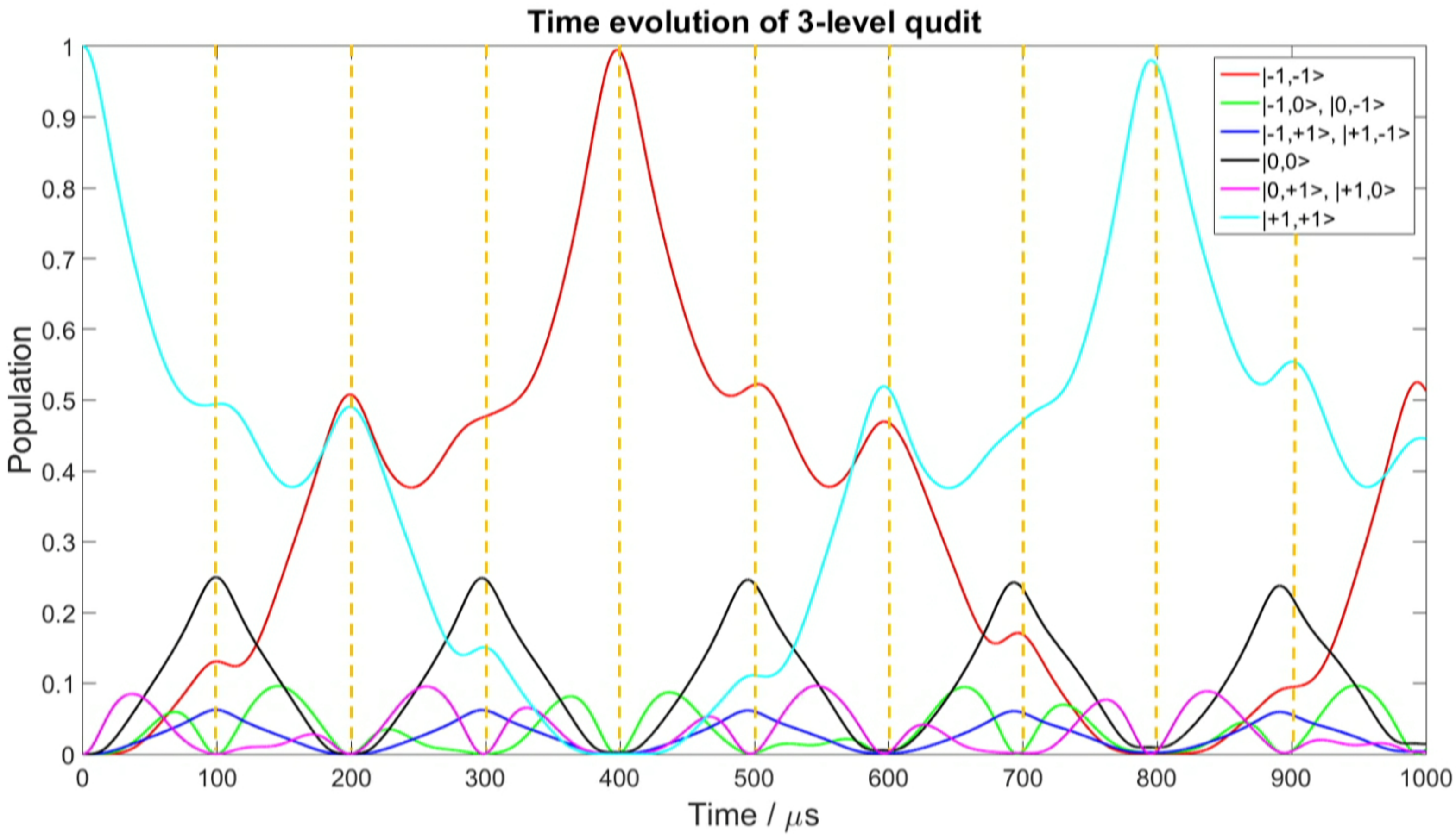
Geometric phase gates: work for larger spins too!

Tools we need
Qudit encoding (multi-level system) with acceptable coherence
State preparation
Measurement
Single-qudit gates
Two-qudit gates

|m1,m2> acquires phase proportional to $(m1+m2)^2$

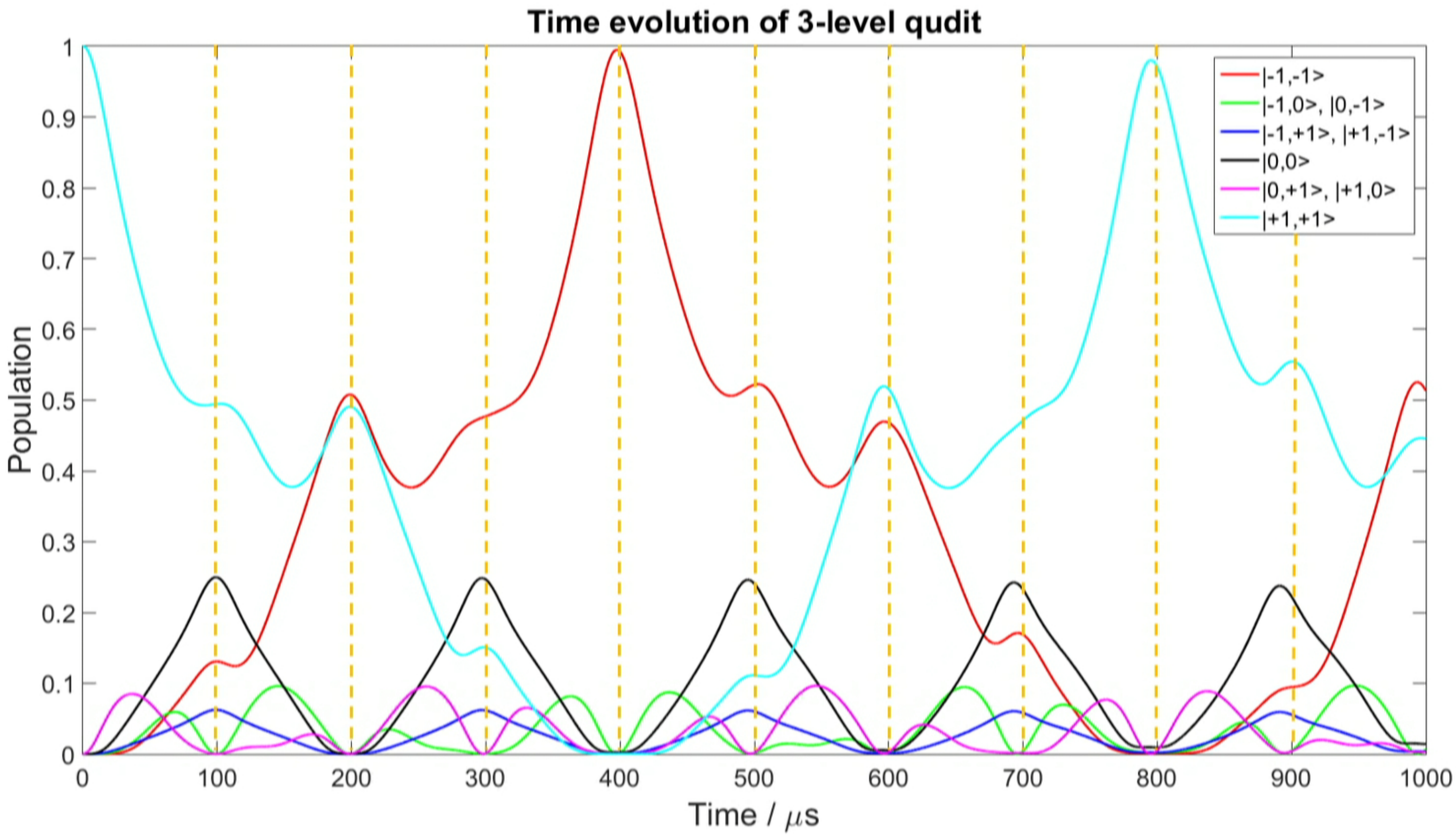


Visualizing errors in entangling gates?

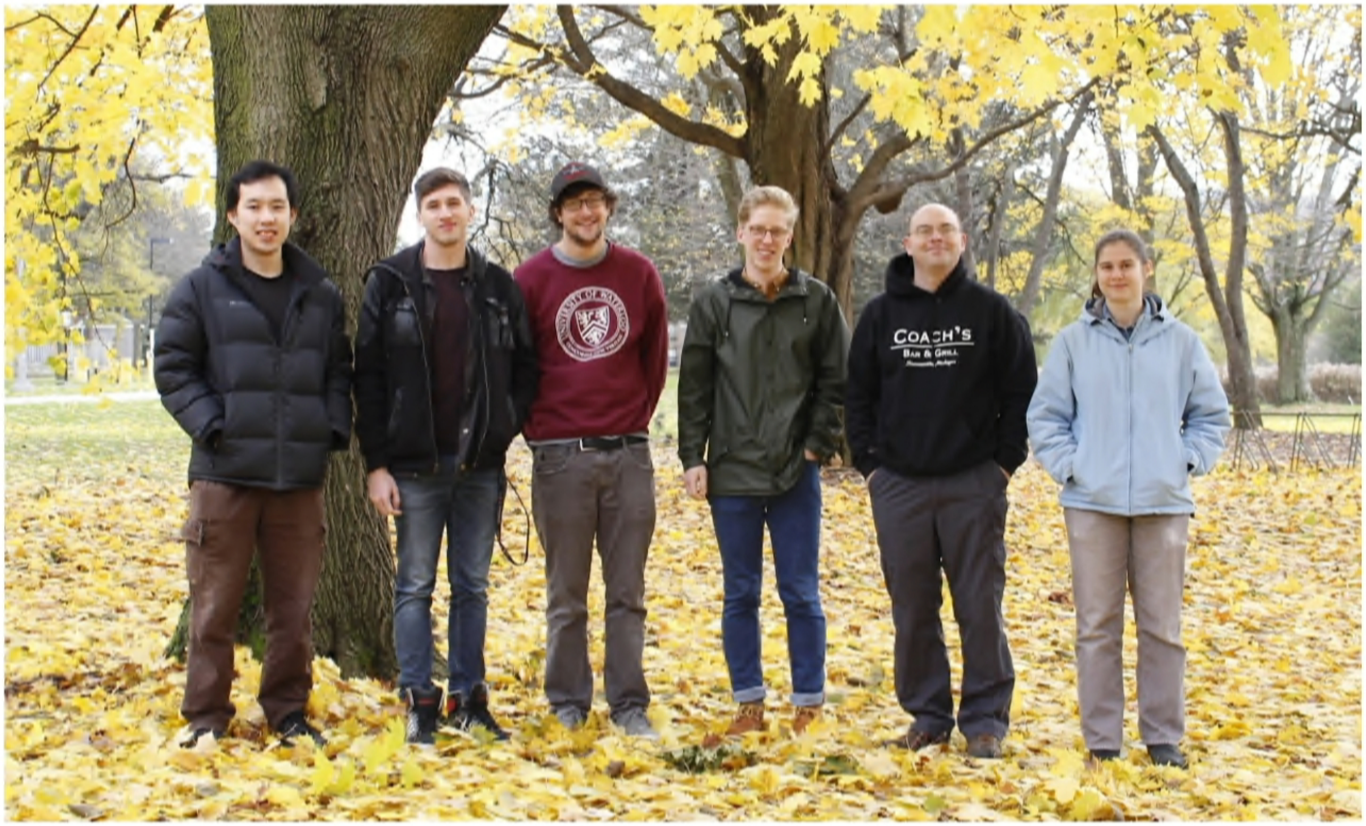


Yellow lines = entangling gates = integer number of complete circles

Visualizing errors in entangling gates?



Yellow lines = entangling gates = integer number of complete circles



- Protocols for all needed qudit operations
- Fidelity limitations seem promising
- Experiments coming soon!

NSERC CRSNG

TQT Transformative Quantum Technologies

CANADA FIRST RESEARCH EXCELLENCE FUND

From left: Pei Jiang Low, Brendan Bramman, Noah Greenberg, Dr. Matt Day, Richard Rademacher

UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

Contact Crystal Senko or Rajibul Islam to learn more about the IQC Ions crew.

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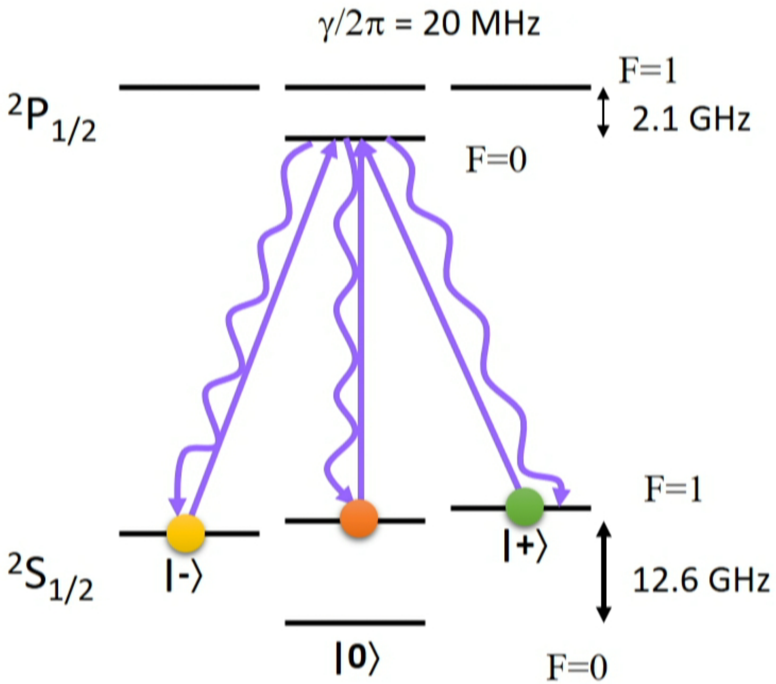
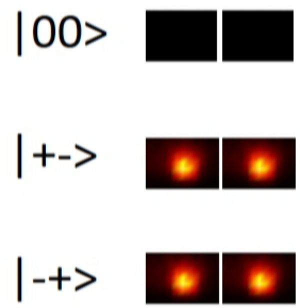
Thank you

Detection of spin states: Only binary readout

Dark = |0>
Bright = not |0>



Should only populate:



C. Senko et al, Phys. Rev. X **5**, 021026 (2015)