quantum technologies for fundamental science (@ TRIUMF)

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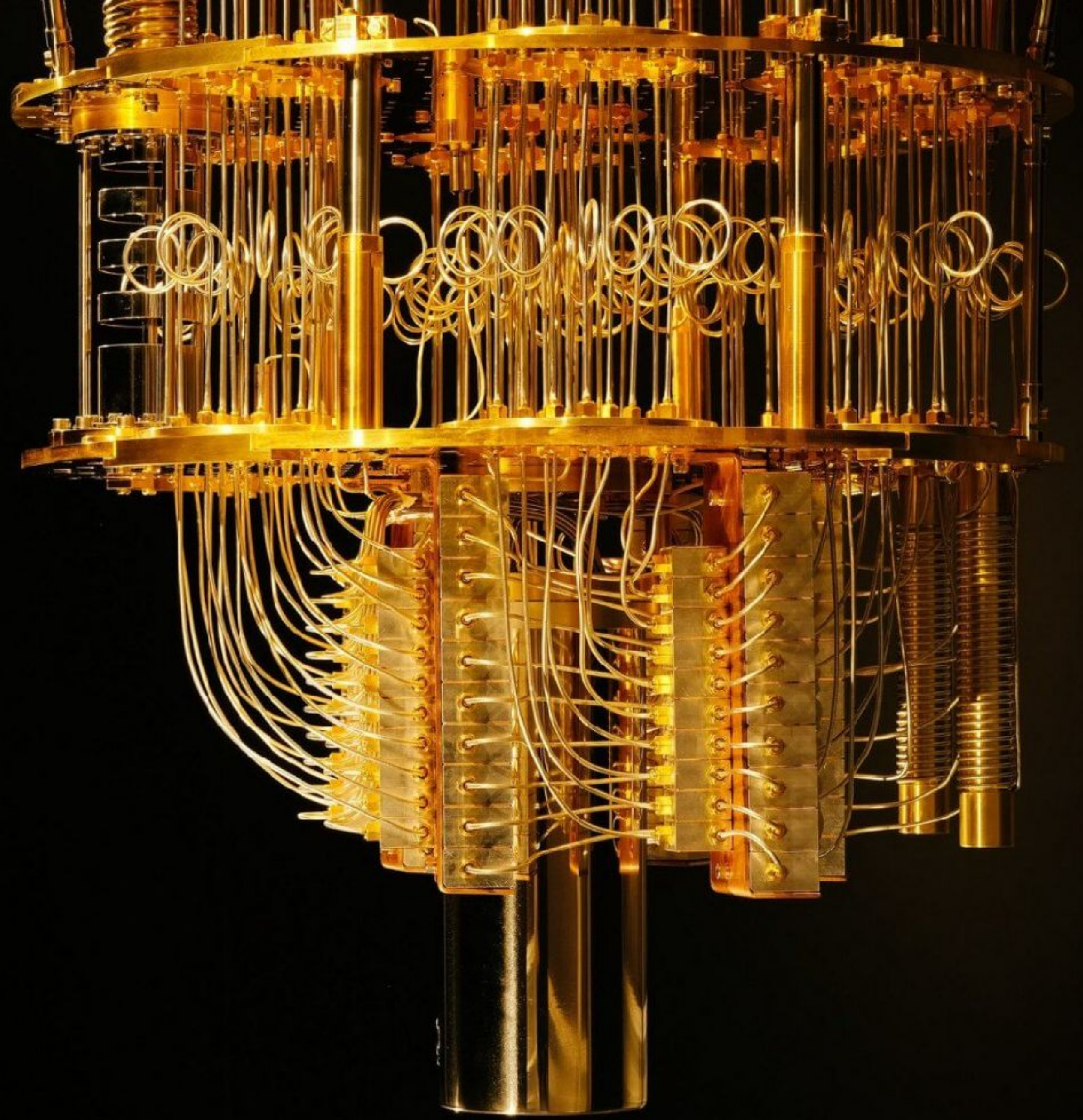
University of Manitoba

28 Nov 2019



What are we talking about?

- Original plan: take part in the retreat, enjoy the free snacks, relax, and learn what q-technology really is.
- After 30 years in the atomic spectroscopy business using lasers and microwaves, I find that this is apparently not necessarily considered "quantum" in the age of the *2nd quantum revolution*.

- Change of plan: JD asks me to talk about q-tech as related to (AMO) activities at TRIUMF. Bummer! So I have to figure this out up front.
    - GG: A talk was not part of the plan!
    - JD: I am altering the deal, pray I don't alter it any further.

What is quantum technology exactly?

- Wikipedia: *relies on principles of quantum physics*

- q-computers
- q-sensing
- q-cryptography
- q-simulation
- q-metrology
- q-imaging

at first sight, (could) play a role at TRIUMF

- in particular
  - q-entanglement
  - q-superposition
  - q-tunnelling

If I use a SQUID device in my lab, am I a q-technologist?

- coherence
- phase
- no spontaneous processes

great scientists measure frequency
geniuses measure phase
amplitudes are for losers

GG ca. 1992

q-experiments at TRIUMF

- surprising number of sophisticated AMO(ish) efforts for a *nuclear and particle physics national lab*
  - EDM with ultracold neutrons (TUCAN)
  - beta-neutrino correlations in a laser trap (TRINAT)
  - APV with laser trapped francium (FrPNC)
  - EDM with a francium atom fountain (FrEDM)
  - (anti)-hydrogen metrology (ALPHA)

not on the floor yet

  - precision nuclear mass measurements (TITAN)

see next talk by Ania

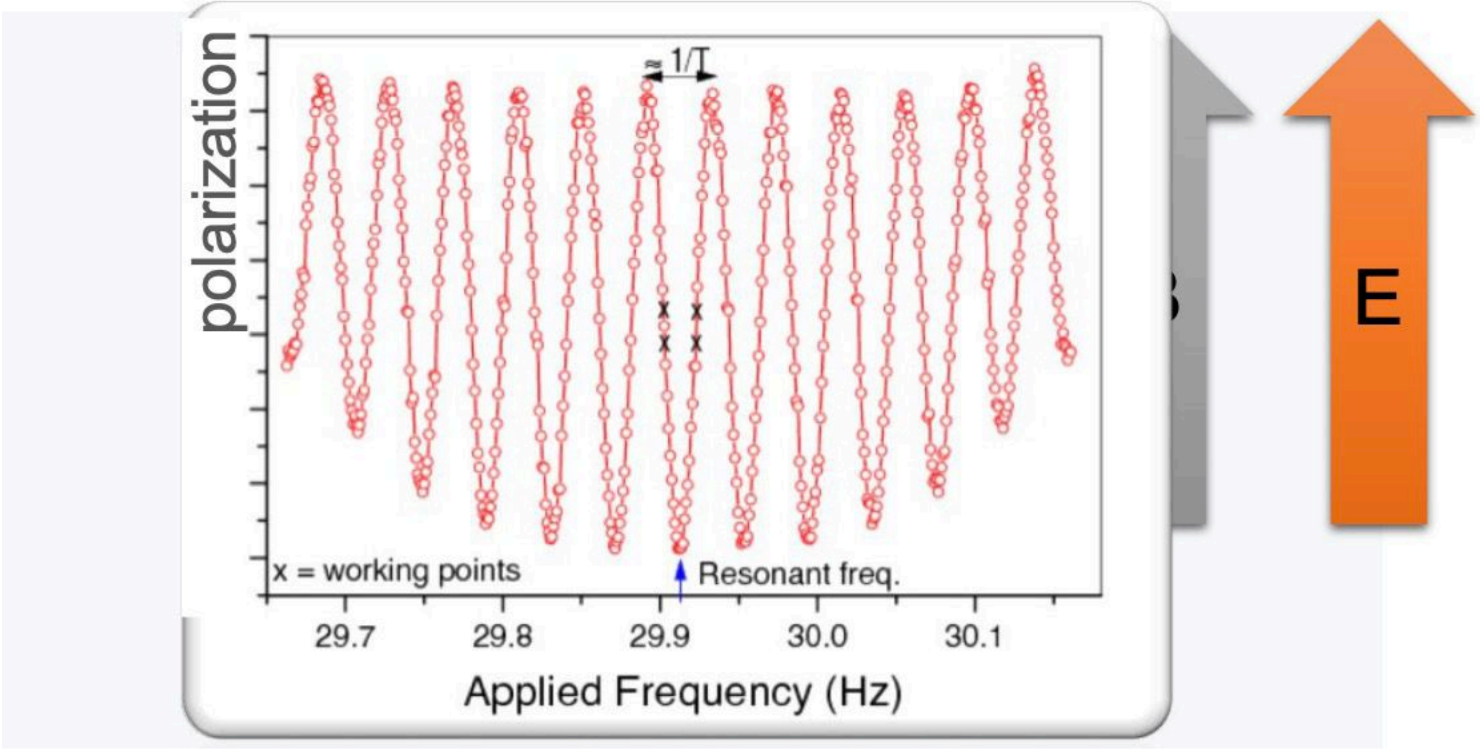
  - …

Neutron EDM searches

- q-entanglement
- q-superposition
- q-tunnelling
- coherence
- phase sensitive det.
- no spont. decay

TRIUMF **Ramsey method**

N. F. Ramsey, Phys.Rev.**76** 996 (1949) ⇒ **Nobel Prize 1989**



1. prepare a sample of **polarized neutrons**
2. make a 90°spin flip(“**start clock**”)
3. allow **free spin precession** in (anti-)parallel ***B*** and ***E*** static fields
4. make another 90°spin flip (“**stop clock**”)
5. **analyze direction** of neutron spin
6. **Flip E field and repeat**

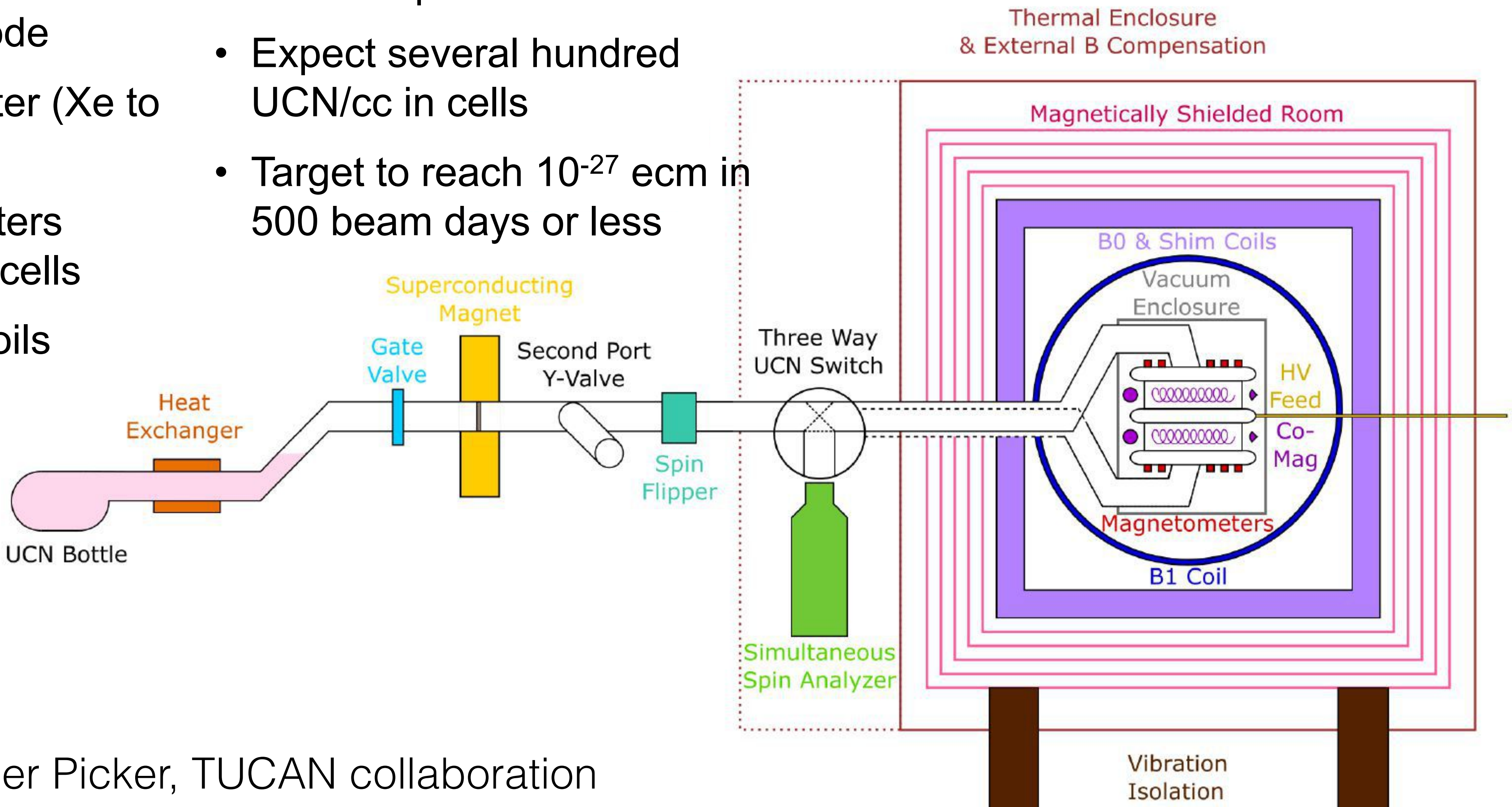
slide courtesy Rüdiger Picker, TUCAN collaboration

$$\Delta\varepsilon = h\,|\Delta\nu| = 4Ed_n$$

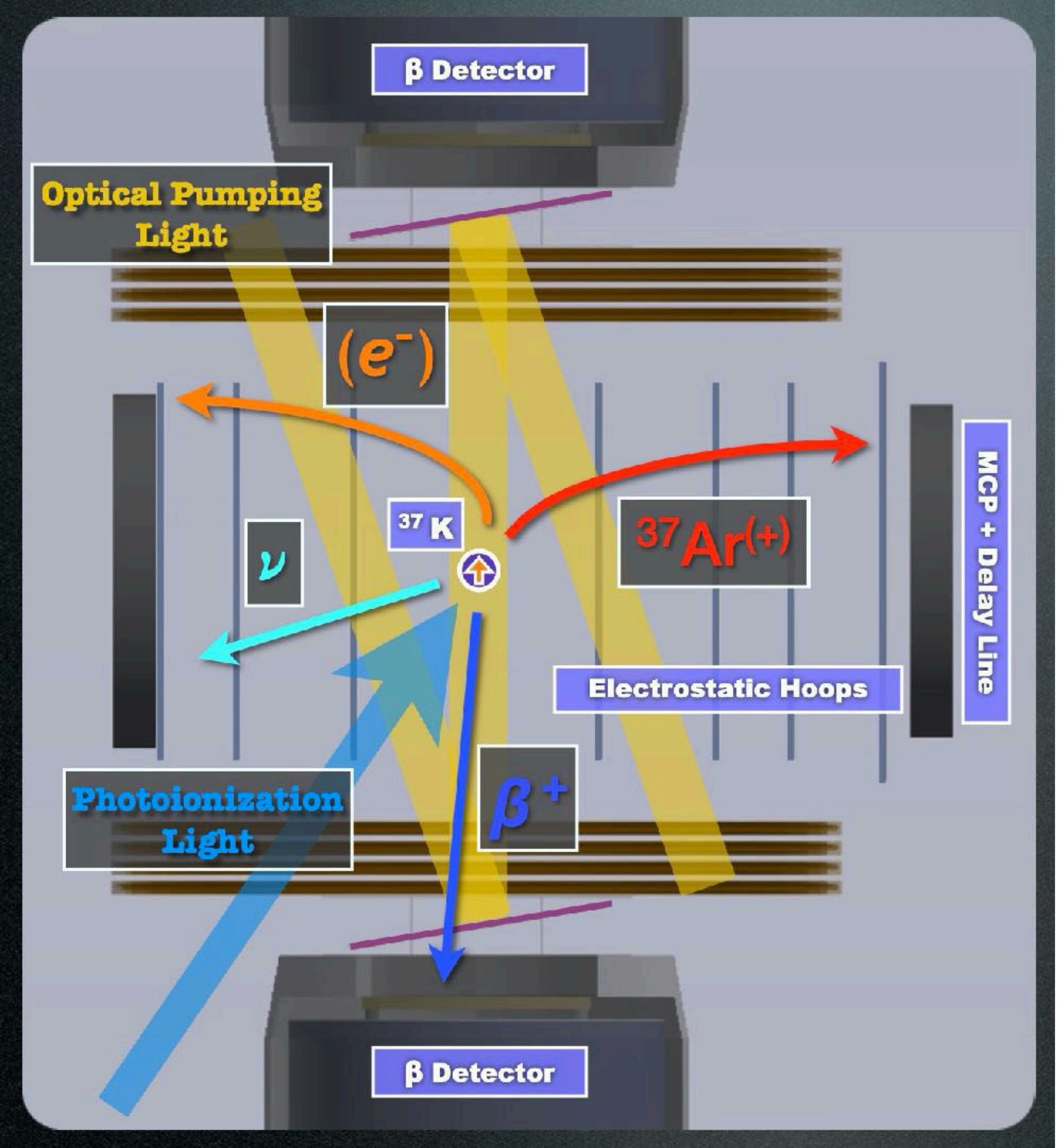
TUCAN EDM experiment layout

- Double cell EDM spectrometer at room temperature
- Central HV electrode
- Hg comagnetometer (Xe to follow later)
- Alkali magnetometers surrounding EDM cells
- Self shielded B_0 coils

- Magnetically shielded room
- Thermal enclosure and mag field compensation
- Expect several hundred UCN/cc in cells
- Target to reach 10^{-27} ecm in 500 beam days or less



slide courtesy Rüdiger Picker, TUCAN collaboration



Beta-neutrino correlations

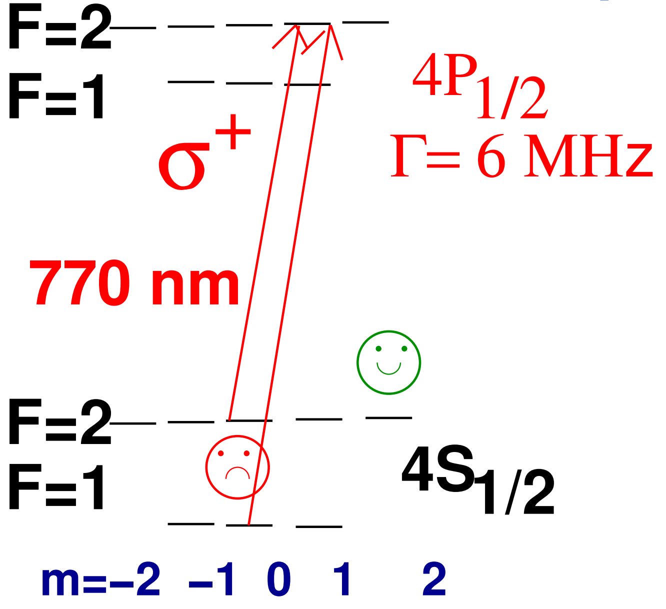
- TRINAT, J. Behr et al.
- beta decay in MOT
- many AMO techniques
  - optical pumping for spin polarizing the nucleus (AC MOT)
  - photoionization for trap imaging
  - mostly "old-style quantum" techniques

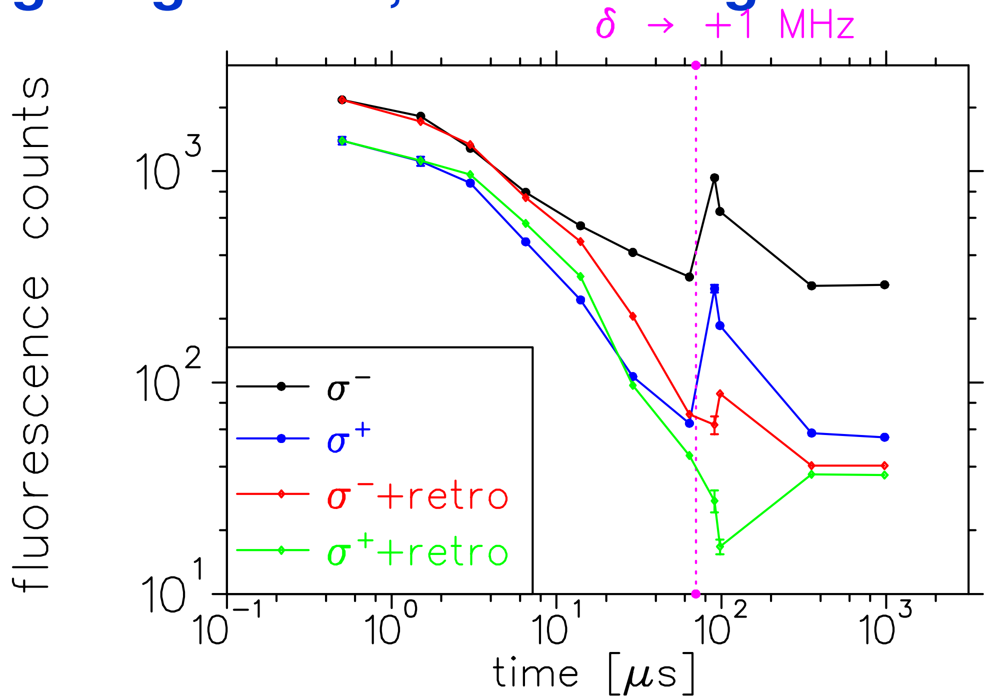
Melissa Anholm, TRINAT collaboration

TRINAT: Coherent Population Trapping

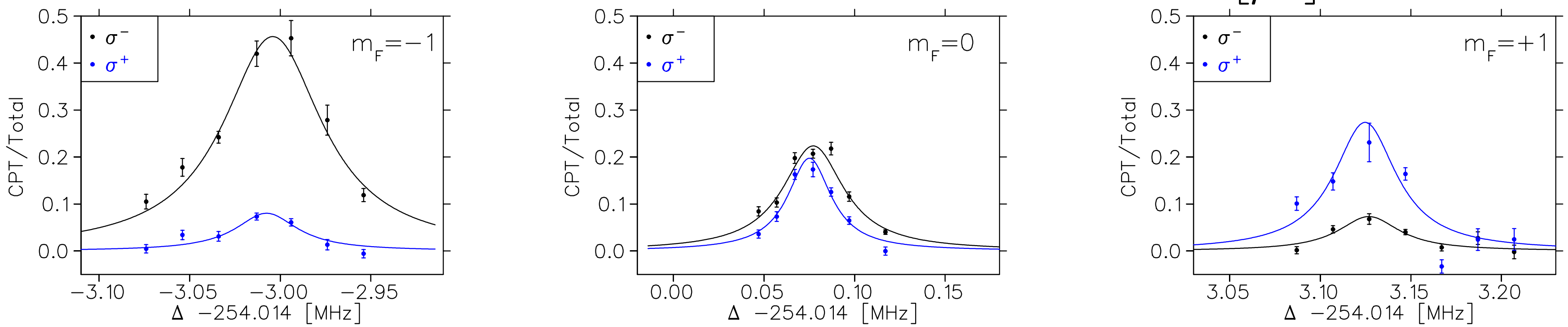
Beams @ hyperfine splitting → superposition 'dark state' ☹

Easy to kill ☺: counter-propagating beams, RF detuning





- CPT as a diagnostic (B-field)



In situ sensor for TRINAT ⇒ B_z = 2.339(10) G

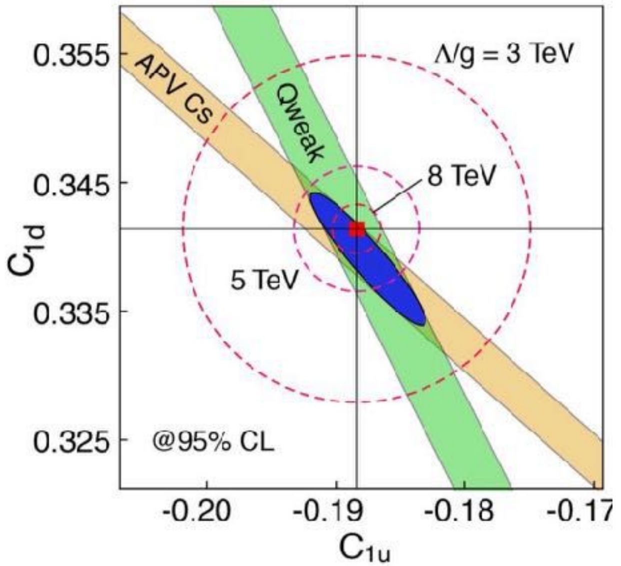
Atomic parity violation in laser trapped francium

Z-boson exchange between atomic electrons and the quarks in the nucleus

H_{PNC} mixes electronic *s* & *p* states

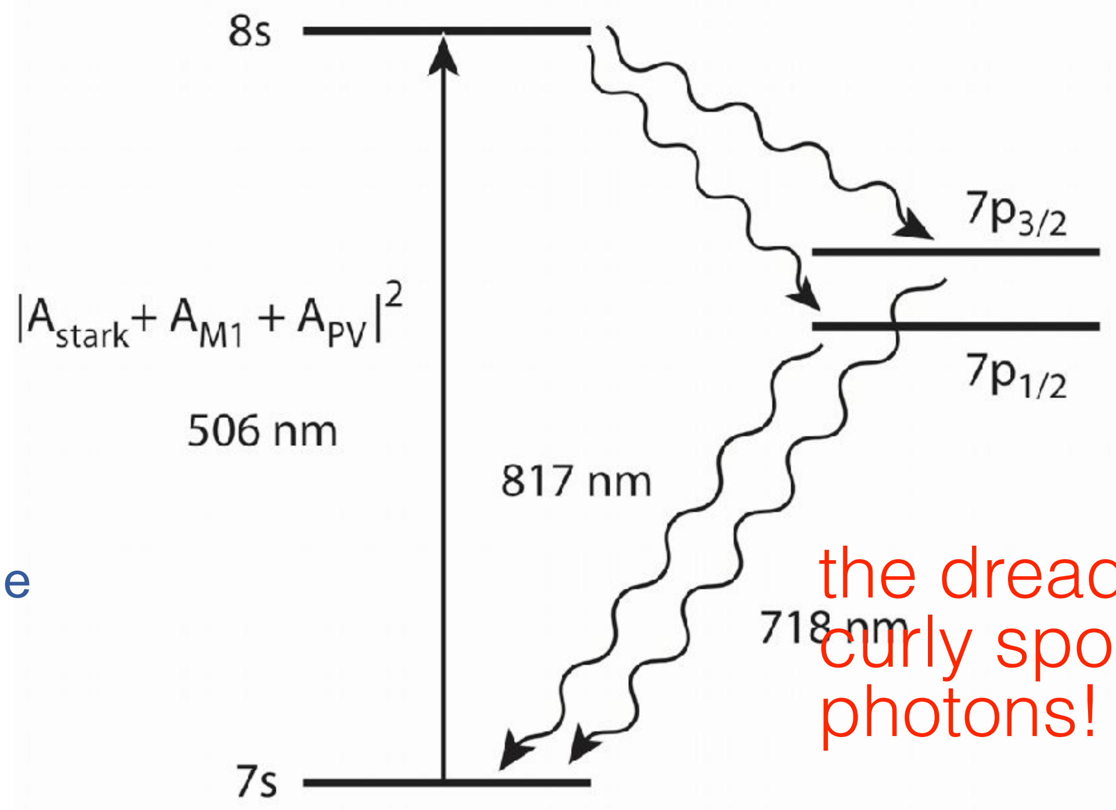
$< n's' \,|\, H_{PNC} \,|\, np > \propto Z^3$ (Bouchiat, 74)

- signature: drive strictly parity-forbidden *s* → *s E1* transition
- effect in Fr ***18x*** larger than in Cs



APV **uniquely** provides the 'orthogonal' constraint on parity violating electron-quark couplings (C_{1u}, C_{1d})

Additional, independent test in Fr, Yb etc important (experiment and theory (e.g. rad. corr.) differ significantly

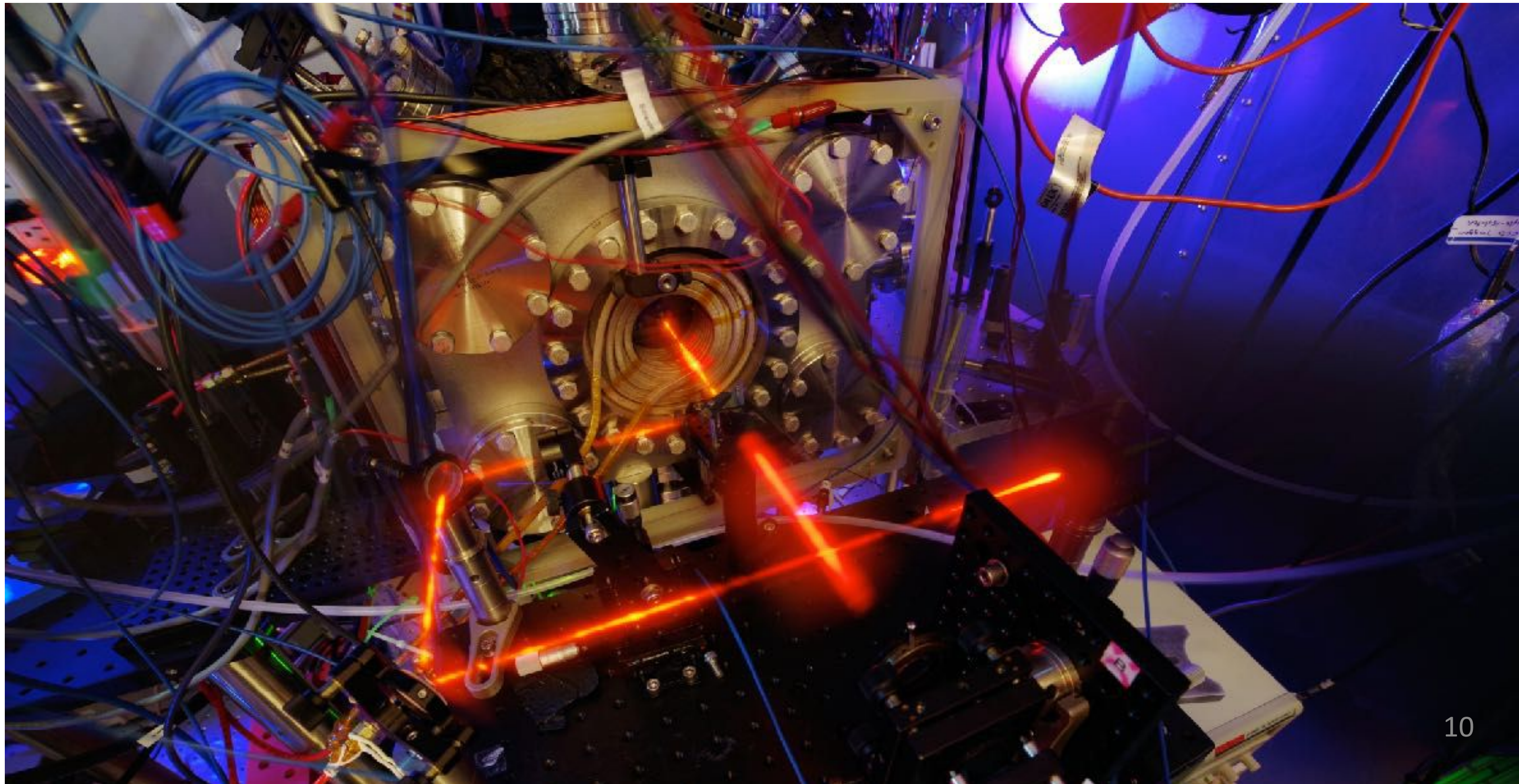


the dreaded curly spont. photons!

Boulder-style APV measurement measures amplitude

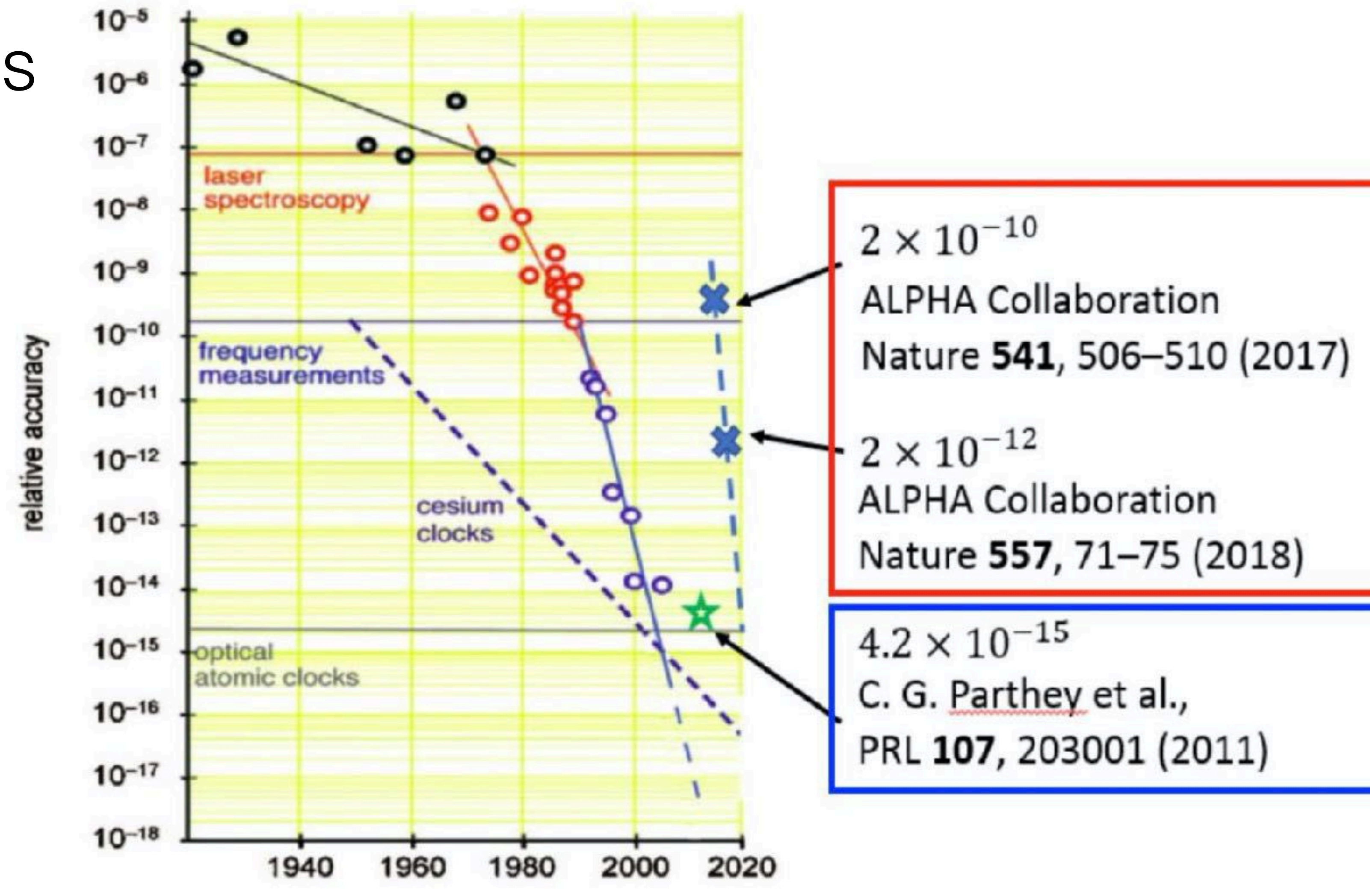
Atomic parity violation in laser trapped francium

- extensive use of optical pumping for state selection
- UHV power buildup cavity
- probing by photon burst from cycling transition
  - **avoid** coherent population trapping (→ anti-q-technology?)
- interference between Stark-induced ($f \approx 10^{-11}$), M1 ($f \approx 10^{-13}$), PV-induced E1 ($f \approx 10^{-22}$) amplitudes



Anti-hydrogen spectroscopy (ALPHA)

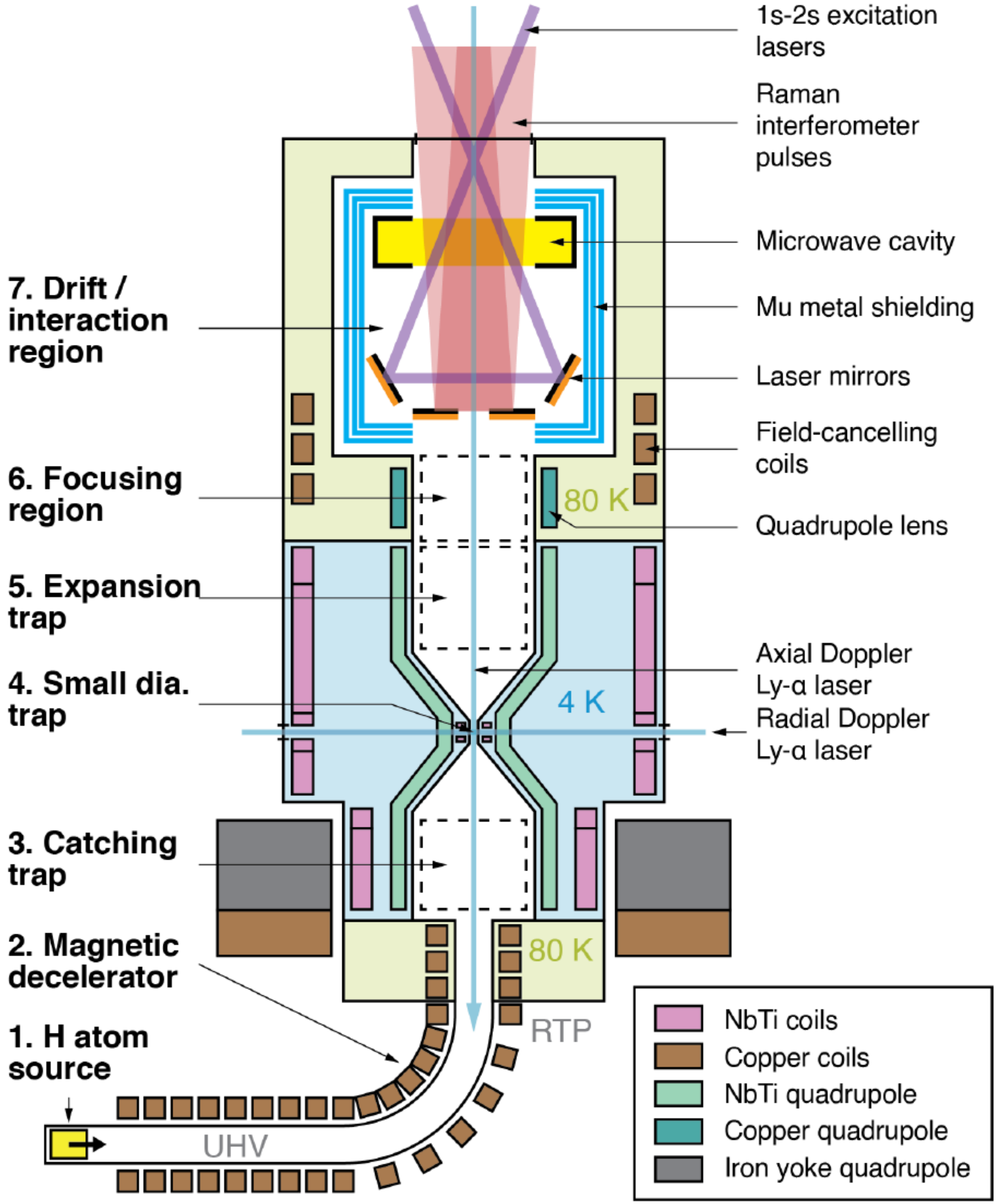
- spectacular successes in the past decade
- in context of q-tech, focus on upcoming plans
    - metrology in (anti) hydrogen
    - cooling, mK→ μK
    - H/Hbar fountain



T. W. Hänsch, Rev. Mod. Phys. **78** 1297 (2005)

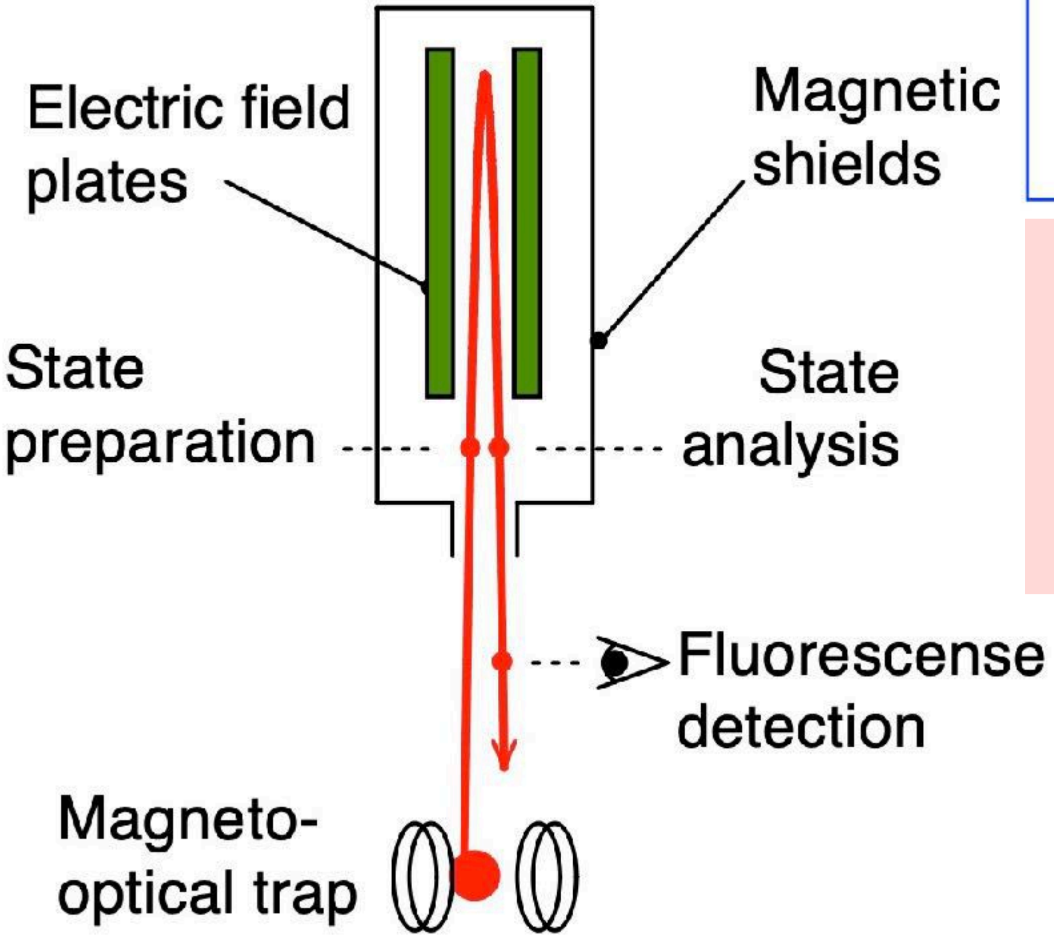
- cryogenic fountain apparatus
- gravity test via atom interferometry
- hyperfine splitting, Ramsey technique → UCN

- (anti)H_2^- clock → CPT test



eEDM francium atom fountain

- Gould et al., LBNL

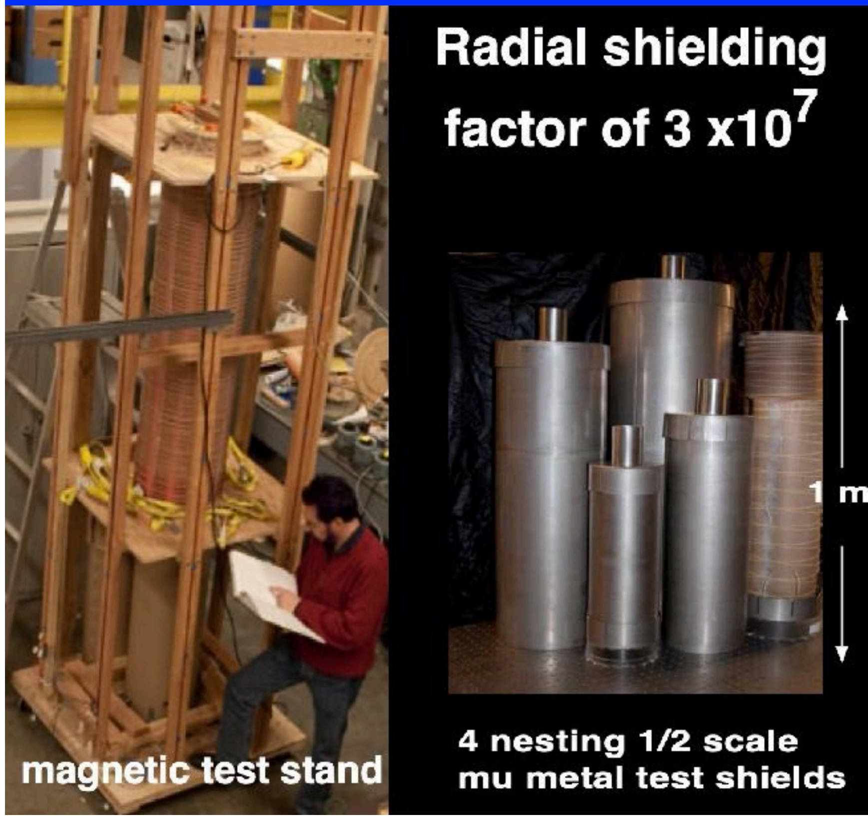


Enhancement Factors

Element	R
Fr	**900**
Cs	115
Rb	25
K	2.4
Na	0.3

Current frontier dominated by molecules. Atoms valuable for their simplicity.

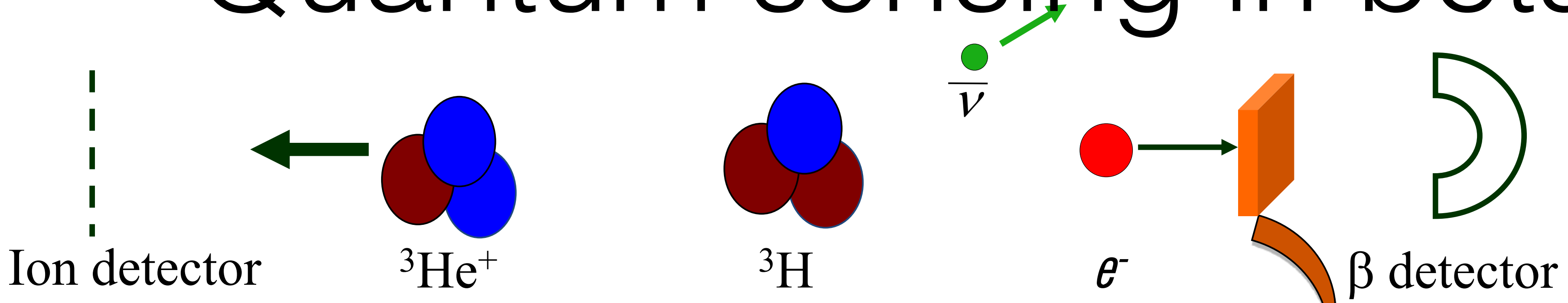
Magnetic Field Noise ≤ 10^{-15} T



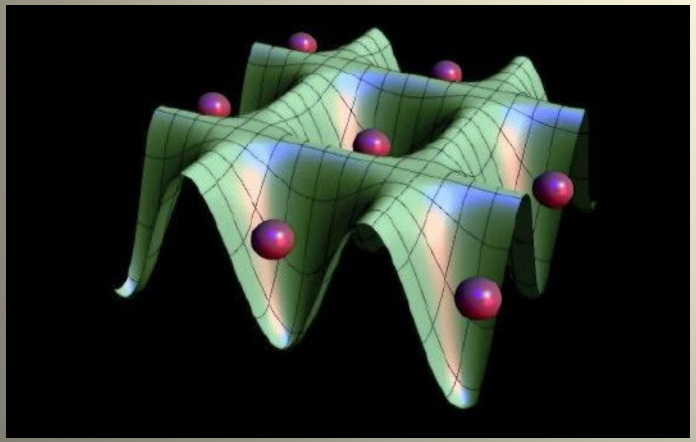
$$\Delta f = \frac{2RMEd_e}{hF}$$

$= 3 \times 10^{-7}$ Hz for $R = 900$,
$E = \pm 10^5$ V/cm, $M=F$,
$d_e = 10^{-50}$ C•m,

Quantum sensing in beta decay



Create an optical lattice of n=53 Rydberg Rubidium atoms



How do we measure the β's momentum?

1) Slow β down to < 900 eV after leaving source
2) Cross section for passing β to excite atom from 53s to 53p is: 0.36×10^{-9} cm^2
3) When spectrometer detects the β, the 53s atoms are optically de-excited using STIRAP
4) 100 V/cm is ramped to ionize the 53p atoms
5) MCP detects the ionized Rydberg atoms, giving us a 1D track projection of the β's path

Lattice Specifications:

- Density of Rydberg atoms ~10^{11} atoms/cm^3
- Optical lattice size: 10 cm x 10 cm x 1 cm
- β excites an atom within ~5 microns as it transverses lattice

- ≲ few MeV e- notorious to detect, scatter off everything
- Raizen group proposed dilute Rydberg lattice (2009) → non-destructive momentum tracking
- ultimately not pursued (I wonder why :-)

PHYSICAL REVIEW LETTERS 120, 210501 (2018)

Editors' Suggestion   Featured in Physics

nuclear q-simulation (Oak Ridge)

Cloud Quantum Computing of an Atomic Nucleus

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We report a quantum simulation of the deuteron binding energy on quantum processors accessed via cloud servers. We use a Hamiltonian from pionless effective field theory at leading order. We design a low-depth version of the unitary coupled-cluster ansatz, use the variational quantum eigensolver algorithm, and compute the binding energy to within a few percent. Our work is the first step towards scalable nuclear structure computations on a quantum processor via the cloud, and it sheds light on how to map scientific computing applications onto nascent quantum devices.

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