Francium

Uranium

&

Hydrogen

Baked into

One

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ISAC 20 Symposium, August 2019

https://uwaterloo.ca/chemistry/international-year-chemistry/periodic-table-project/francium

How do you end up with francium ?

- no stable isotope — shortest lifetime of first 103 elements
- only a few grams naturally on Earth
- why would we want to deal with this?

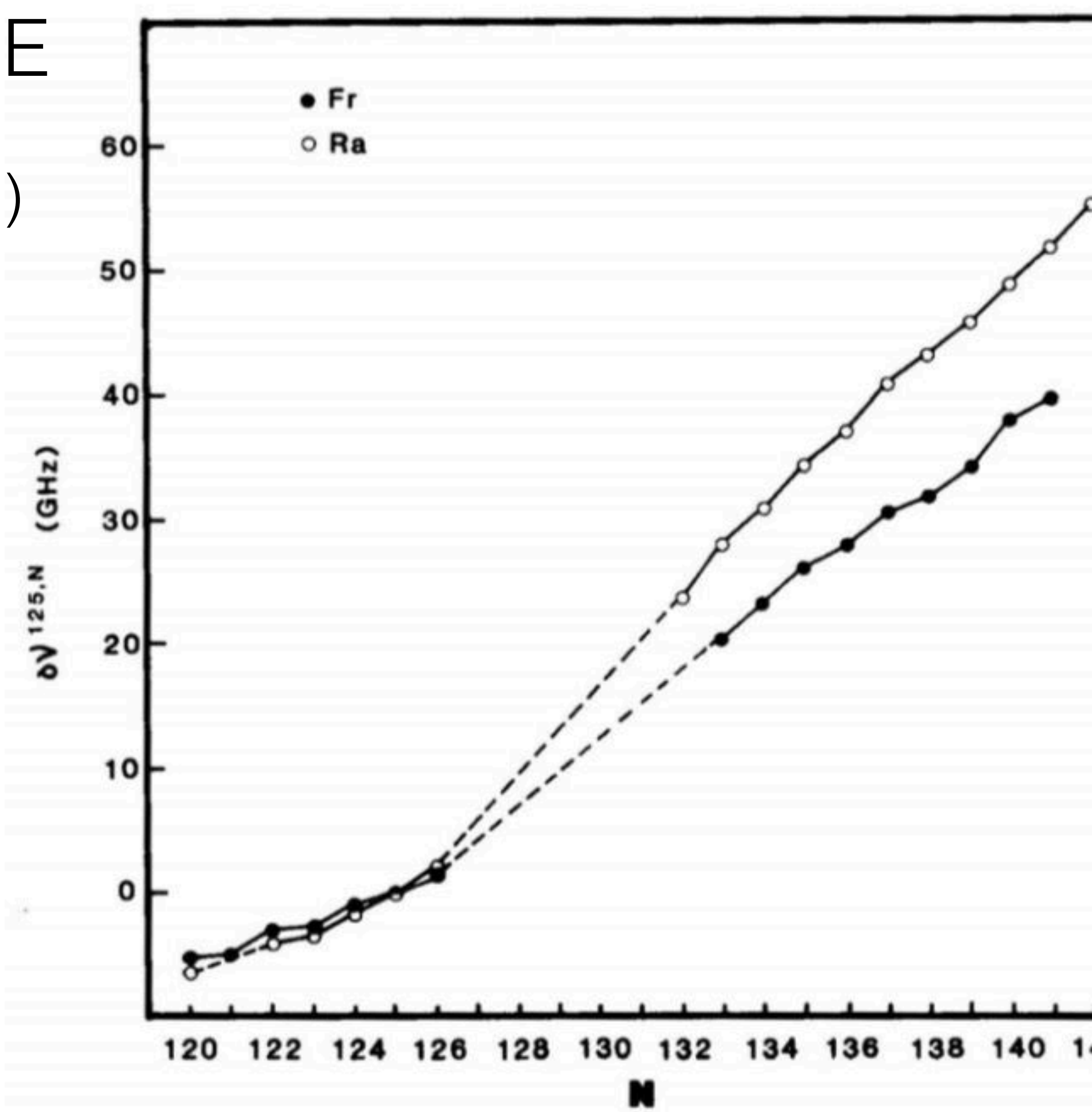
> *What plays the role of hydrogen in this problem?*
>
> E. Fermi
>
> (according to I.B. Khriplovich)

- many atomic tests of fundamental symmetries, need:
  - heavy nucleus (massive enhancement of effects such as parity violation or permanent EDMs)
  - simple atomic structure (aka alkali)
  - neutral atom or singly charged ion (precision spectr.)

- → Cs (historically) or Fr / Ra^+ II (if you can afford it)

Brief history of pre-ISAC atomic Fr spectroscopy

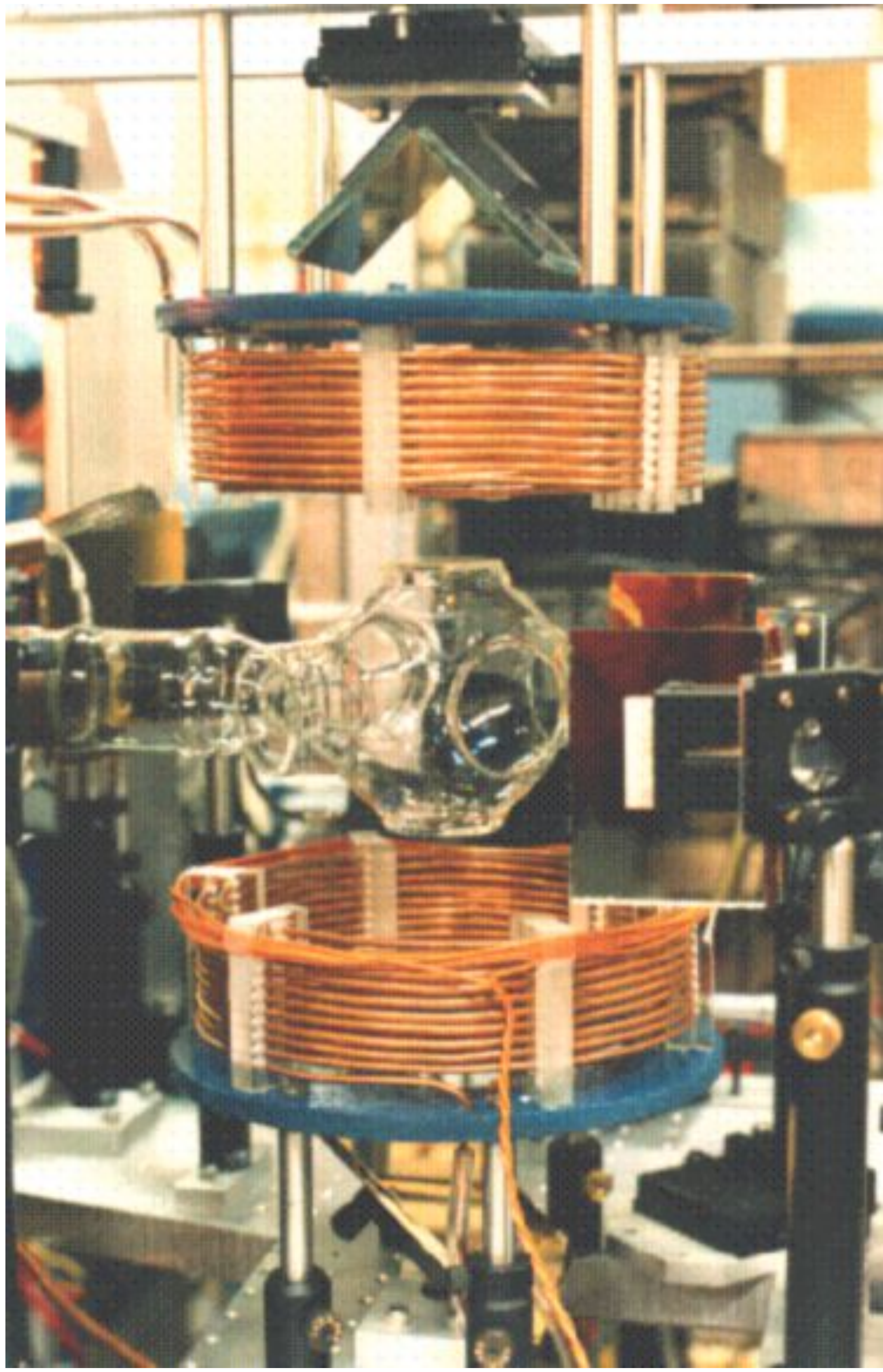
- element discovered by Marguerite Perey (1939)
- atomic beam spectroscopy at ISOLDE
  - first observation, 1978 (Liberman et al.)
  - phase 1: 1978 - 1990
  - renewed interest: 2010's
  - mostly $7s_{1/2}$ - $7p_{3/2}$ isotope shifts → change in nucl. charge radius



- photo-ionization spectroscopy (Letokhov group, late 80s)
  - 1000 ^{221}Fr/s from ^{229}Th source
  - spectr. of high Rydberg states → ionization potential of Fr is 4.07 eV (Cs: 3.89 eV, Rb: 4.17 eV) → relativity!
- Even at ISOLDE, not enough atom flux for forbidden transitions

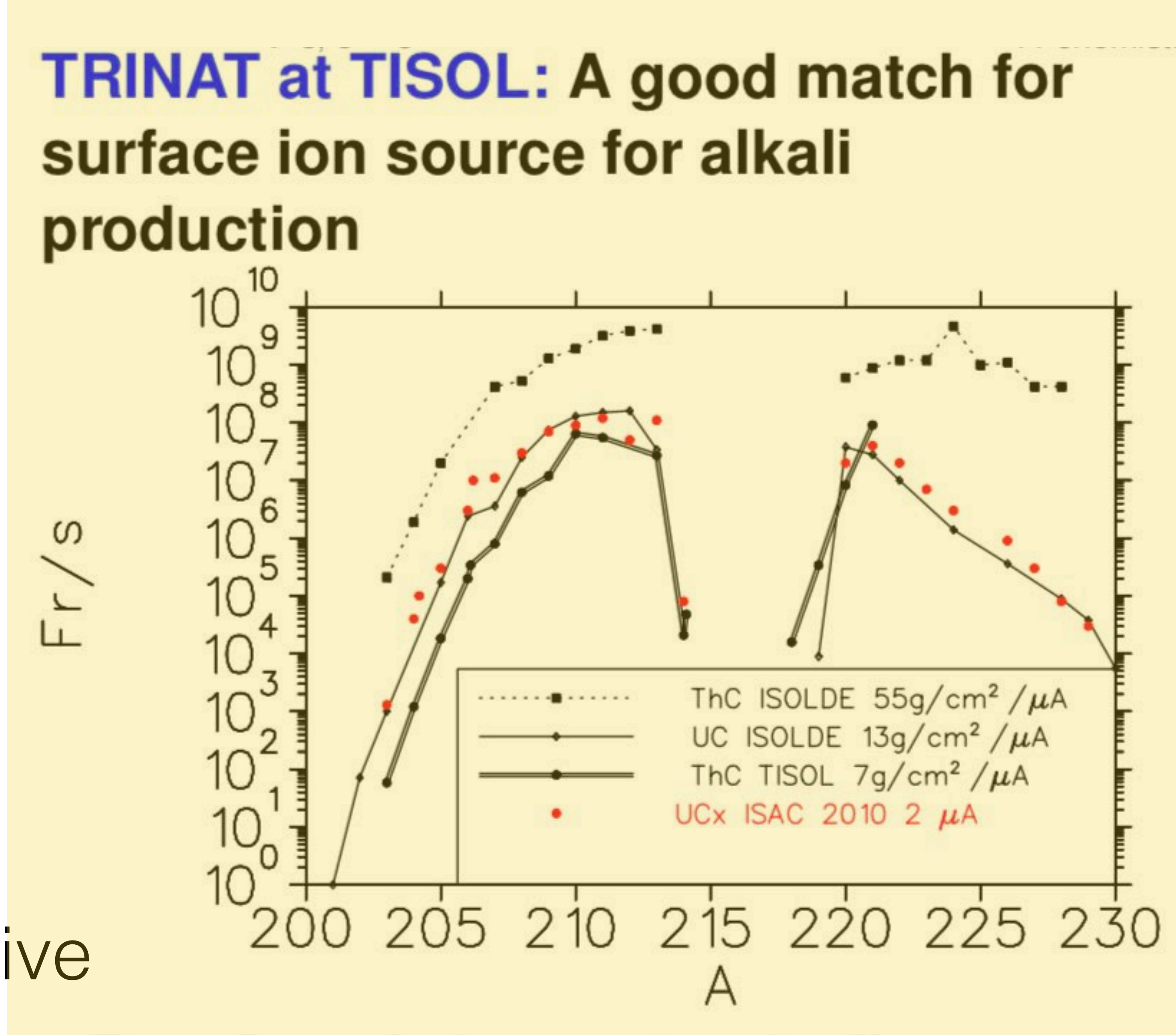
Brief history of pre-ISAC atomic Fr spectroscopy

- Stony Brook/Maryland group (1995-2005)
  - Gene Sprouse and Luis Orozco 1991
    - “Let’s use an atom trap”
      - atomic beam: few μs of availability
      - magneto-optical trap: 10s of secs
  - 1995: first laser trapping of Fr
  - 8s, 9s states, lifetimes of excited states
  - ≈ 10^6 Fr/s prod., ≈ 60,000 trapped
- Boulder (Wieman, Lu et al.) 1997
  - laser trapped ≈ 900 ^{221}Fr from source
- Legnaro (early 2000s to present)
  - laser trap a few 1000 Fr, misc. spectr. of allowed transitions
- Tohoku, EDM; since 2010, getting ready to trap Fr



The ISAC Era

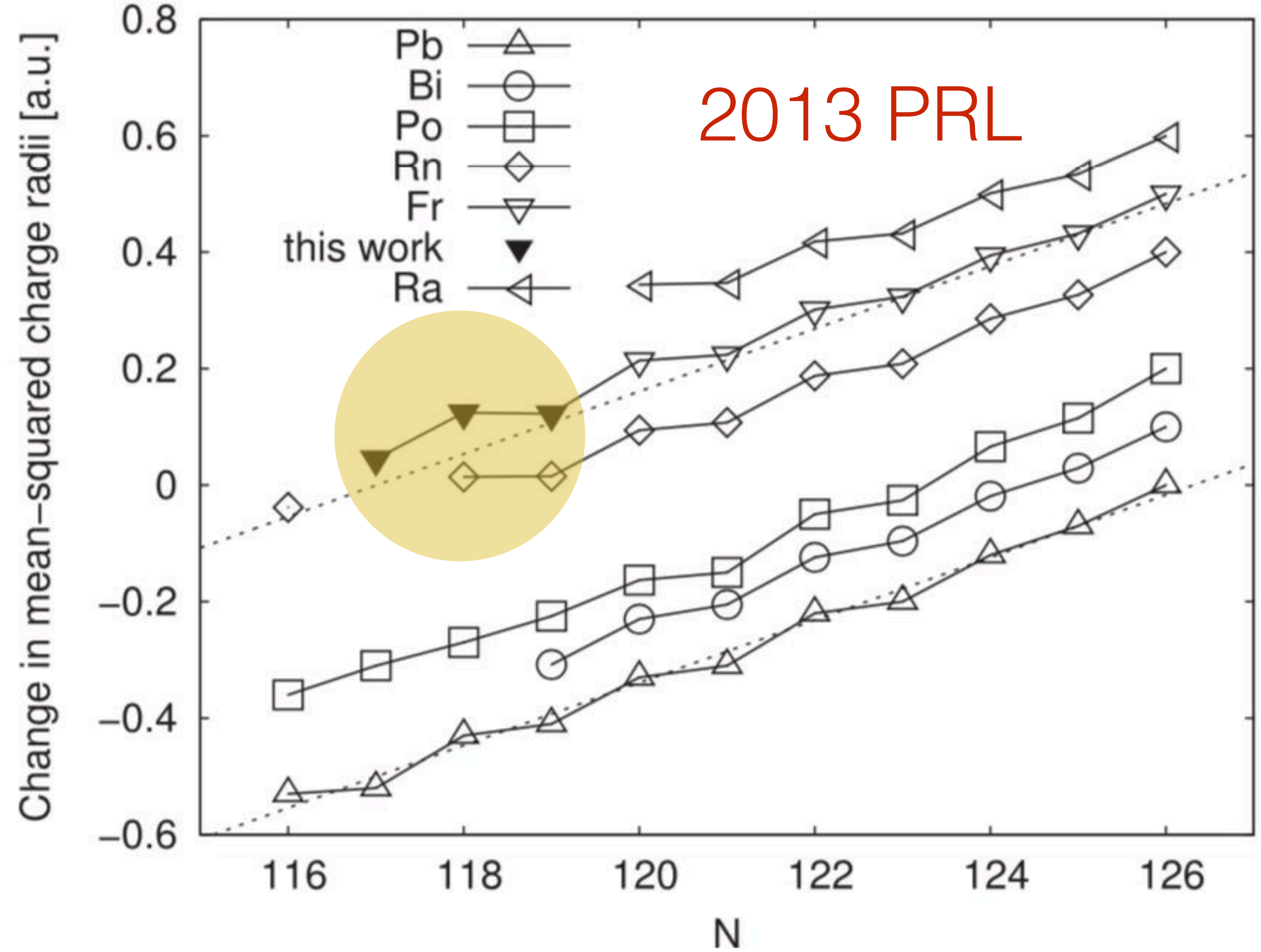
- Behr, d'Auria, Häusser, Jackson 1996
  - good Fr production at TISOL, think about ^{226}Fr trapping
  - puts TRIUMF on the Fr map!



- ISAC 2010: UC_x target at last!
- Pearson group first out of the gate with collinear spectr.
- 2011 FrPNC beamline
  (thanks, Gordon!)
- 2012: FrPNC Fr laser trap goes live
  - order of 10^6 trappable, in particular isotopes 207-213, which are 'nice' in terms of nuclear structure

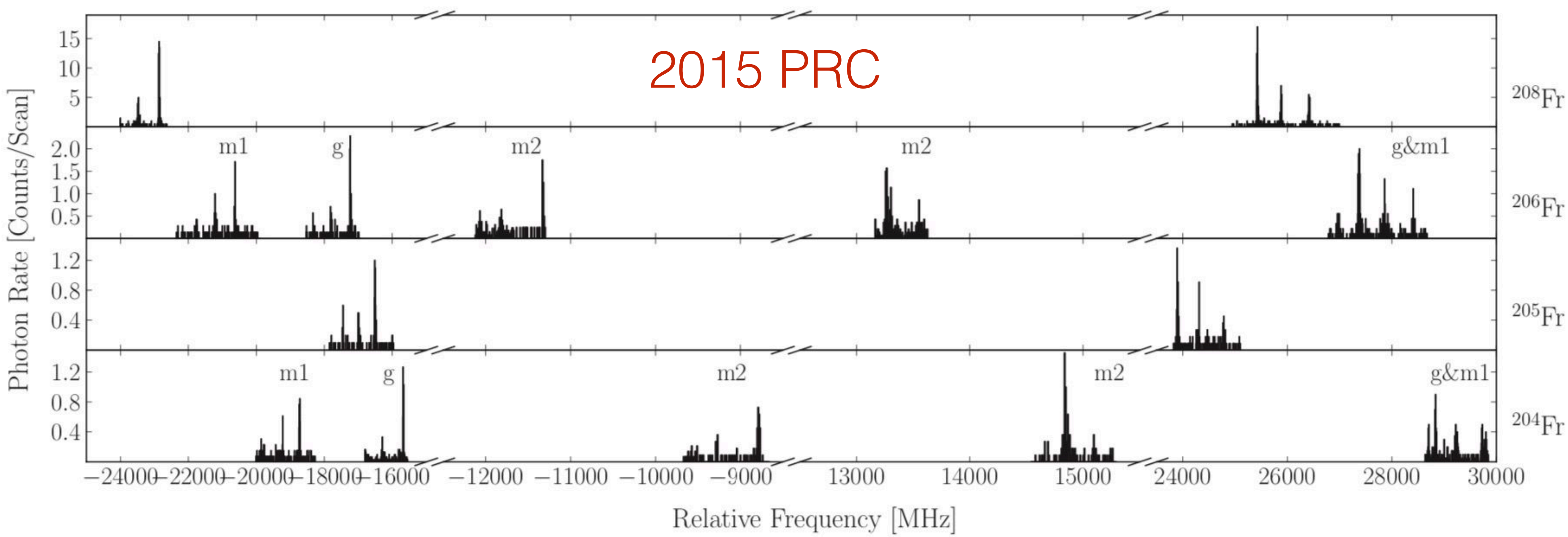
Collinear Fr spectroscopy at ISAC

- M. Pearson, A. Voss et al.
    - high-frequency intensity mod. → improved sensitivity



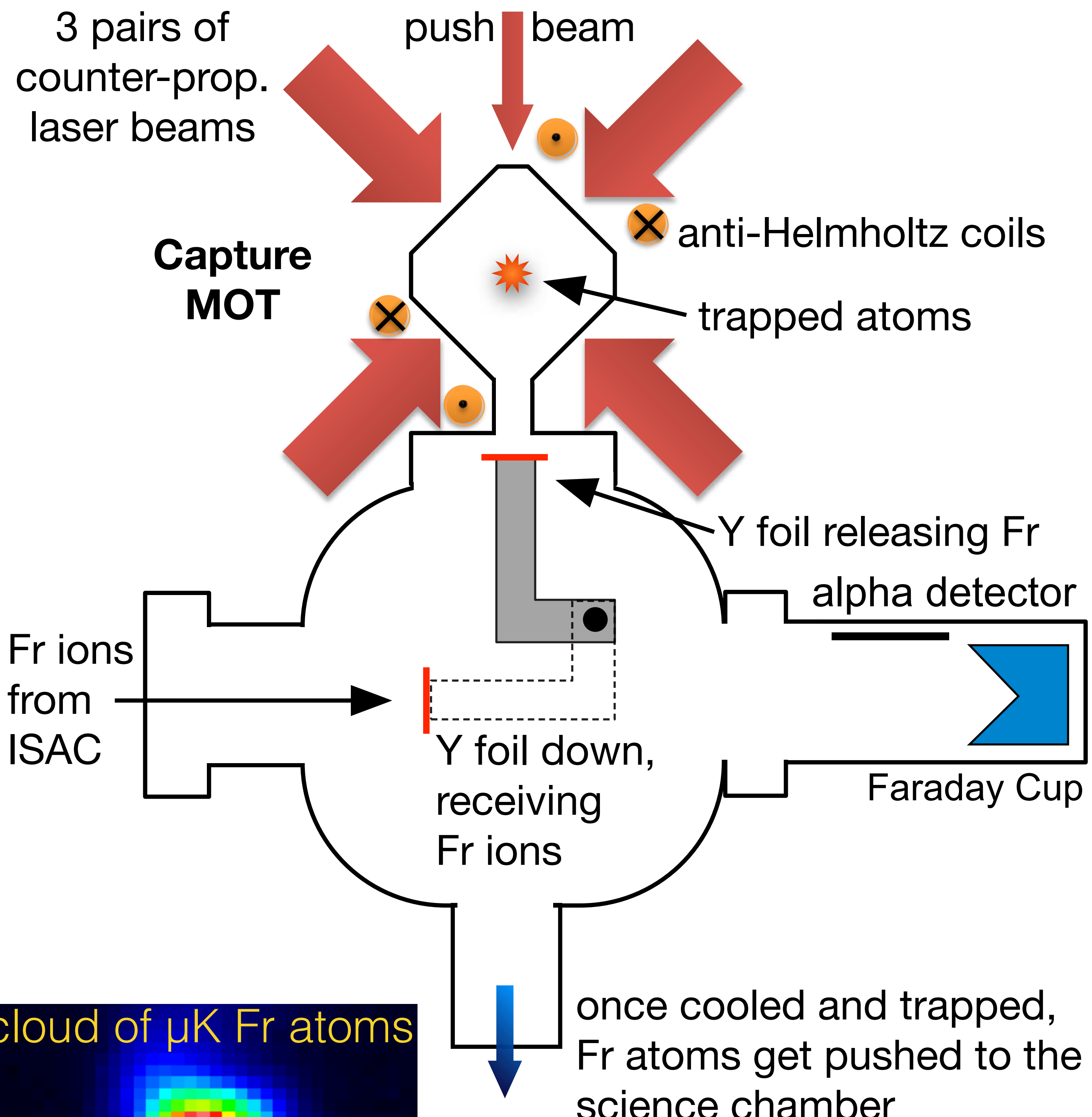
Voss et al. PRL 111, 122501 (2013)

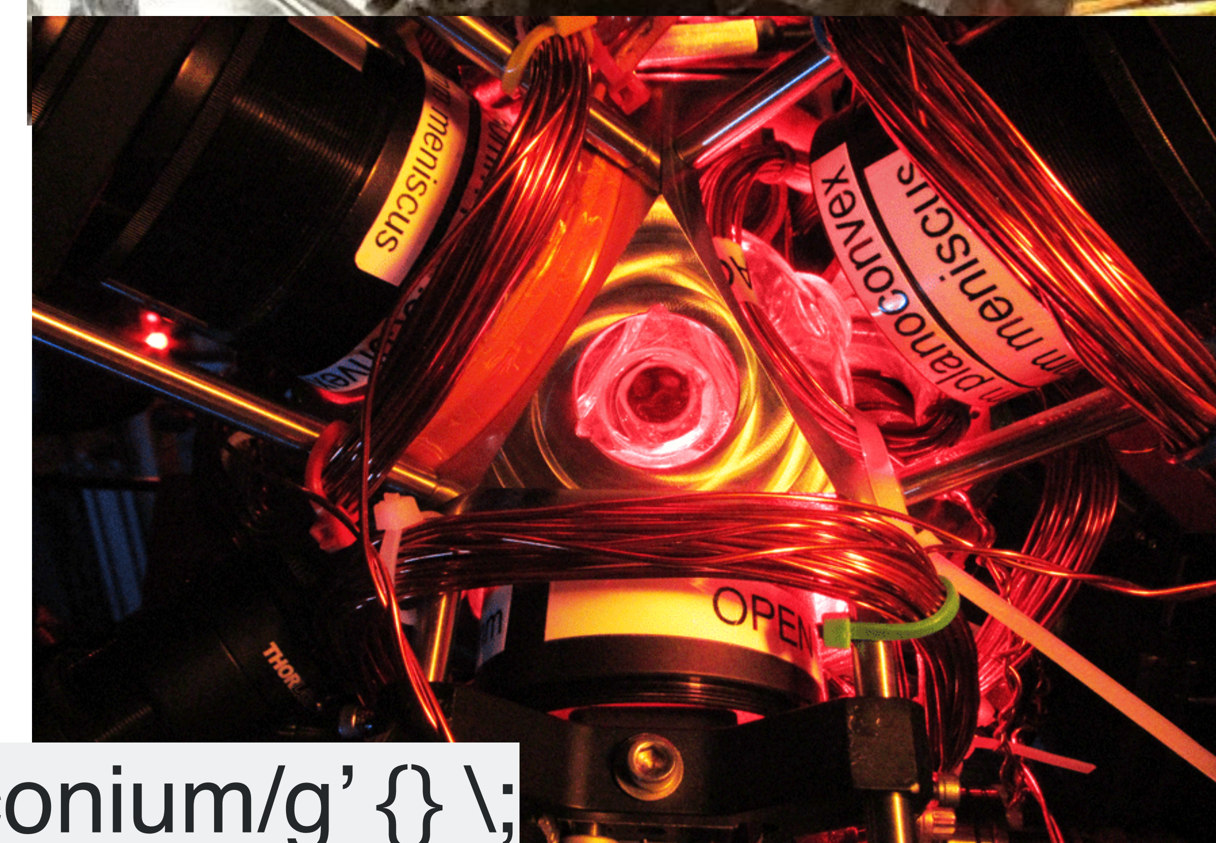
Voss et al. PRC 91, 044307 (2015)

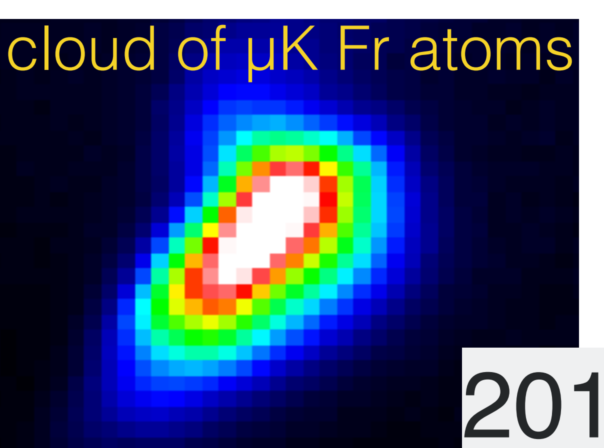


The Francium Trapping Facility at TRIUMF/ISAC

part 1: online capture trap

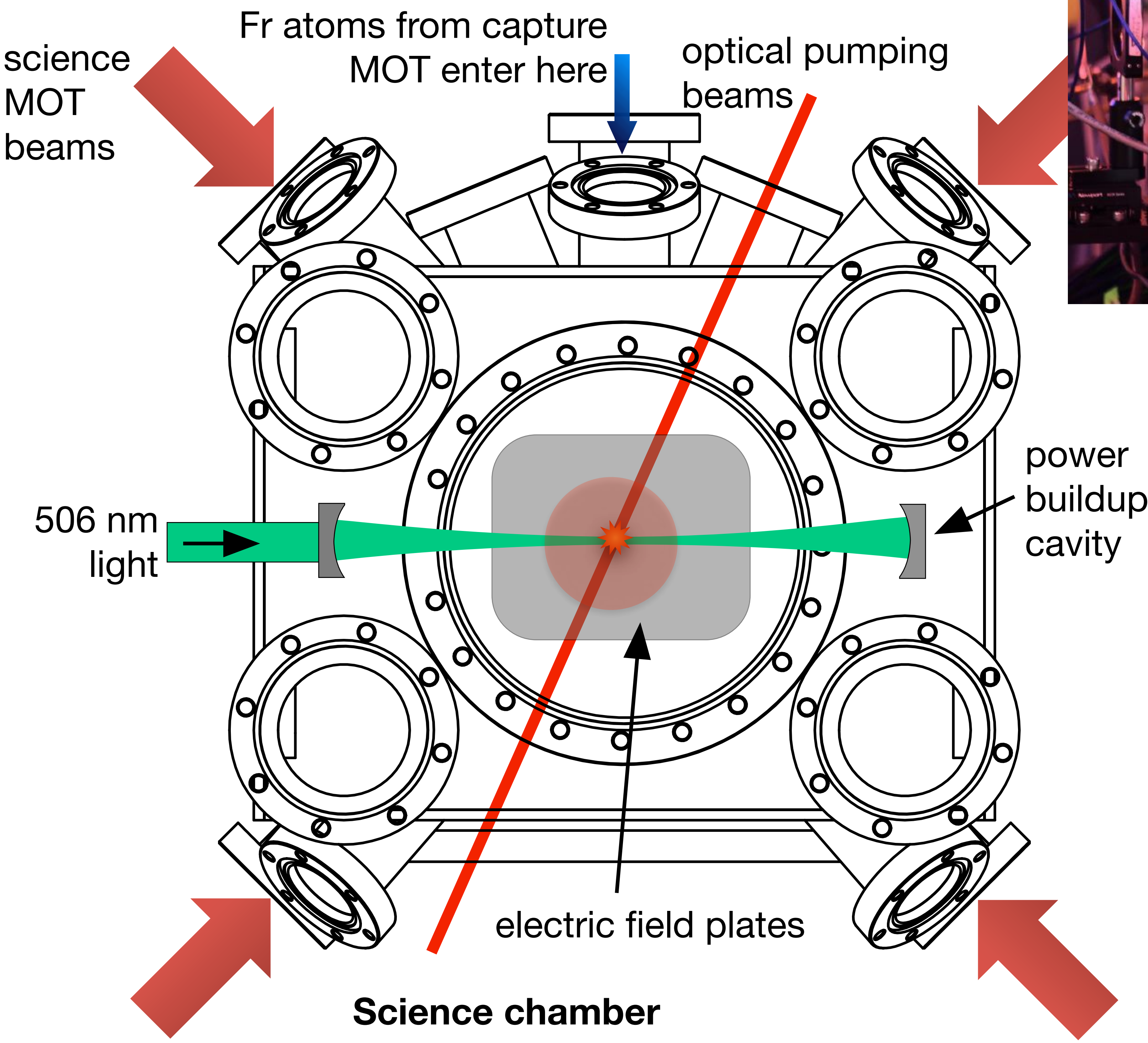


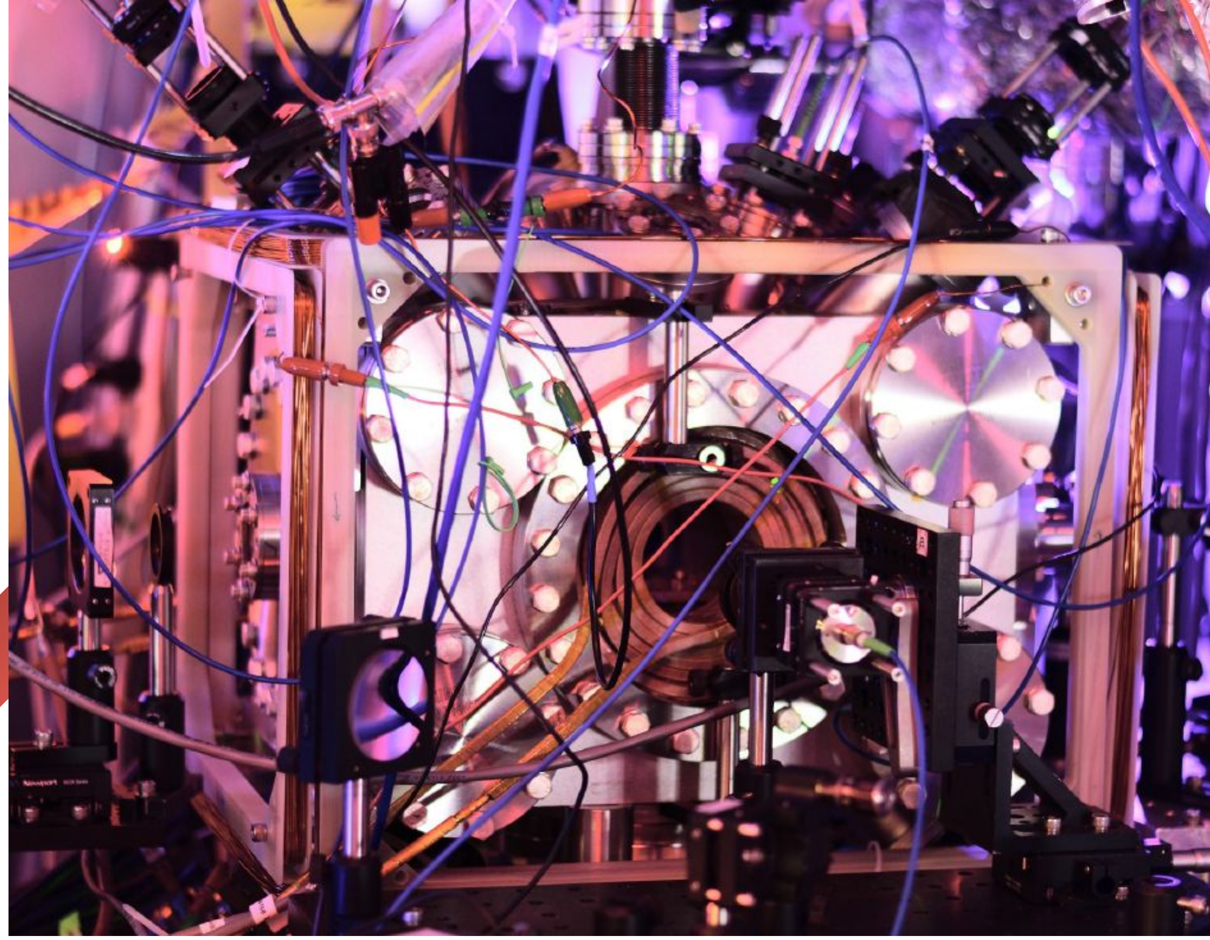




2017: sed -i 's/yttrium/zirconium/g' {} \;

Part2: Science chamber



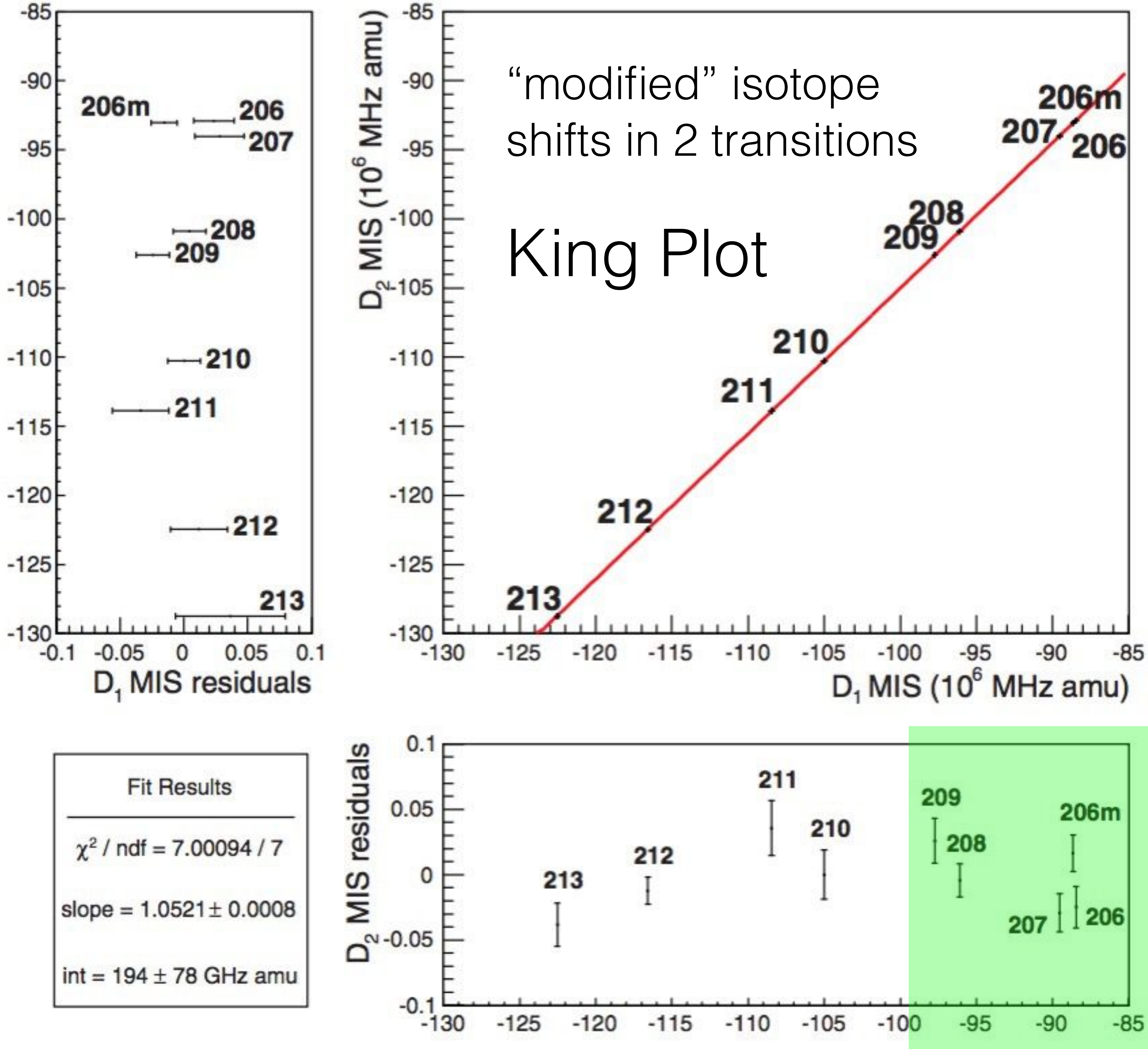


transparent field plates

operate APV experiment inside MOT
temporal APV sequence

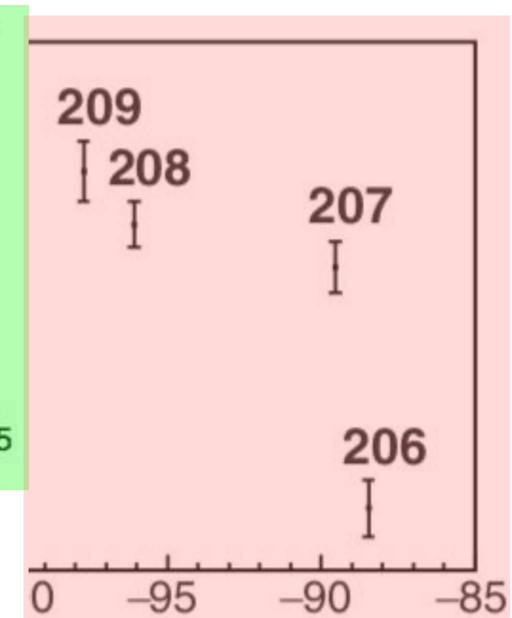
UHV-compatible power buildup cavity (1000x)

ISAC Fr trap: tune up with allowed transitions



D1 isotope shifts in a string of light francium isotopes

Benchmarks state-of-the-art atomic theory in Fr by Safranova and others.

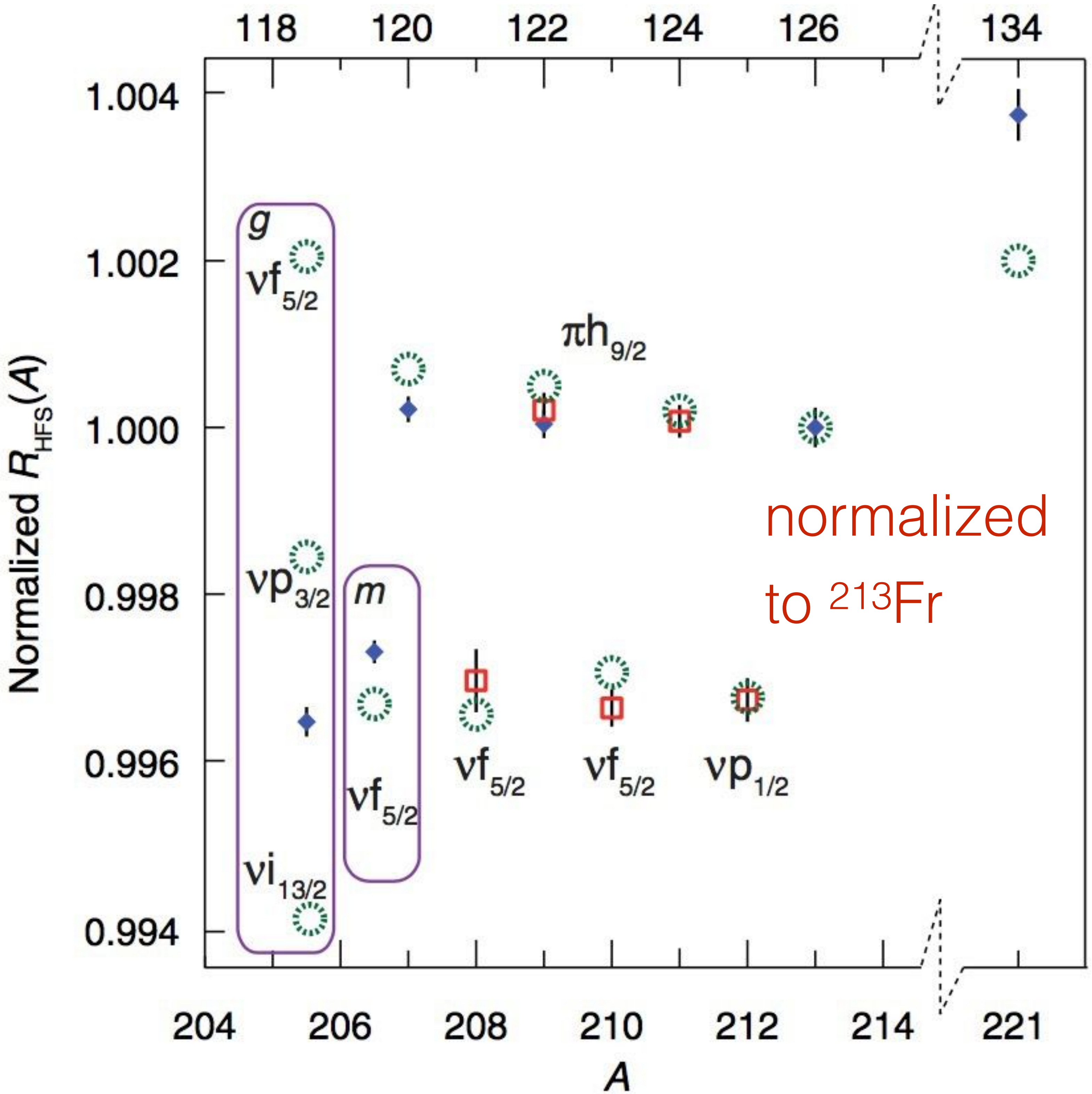


Fresh D2 data for 206 by Voss et al.

Collister et al., Phys Rev A 90, 052502 (2014) and A 92, 019902(E) (2015)

Hyperfine anomaly (Bohr-Weisskopf effect)

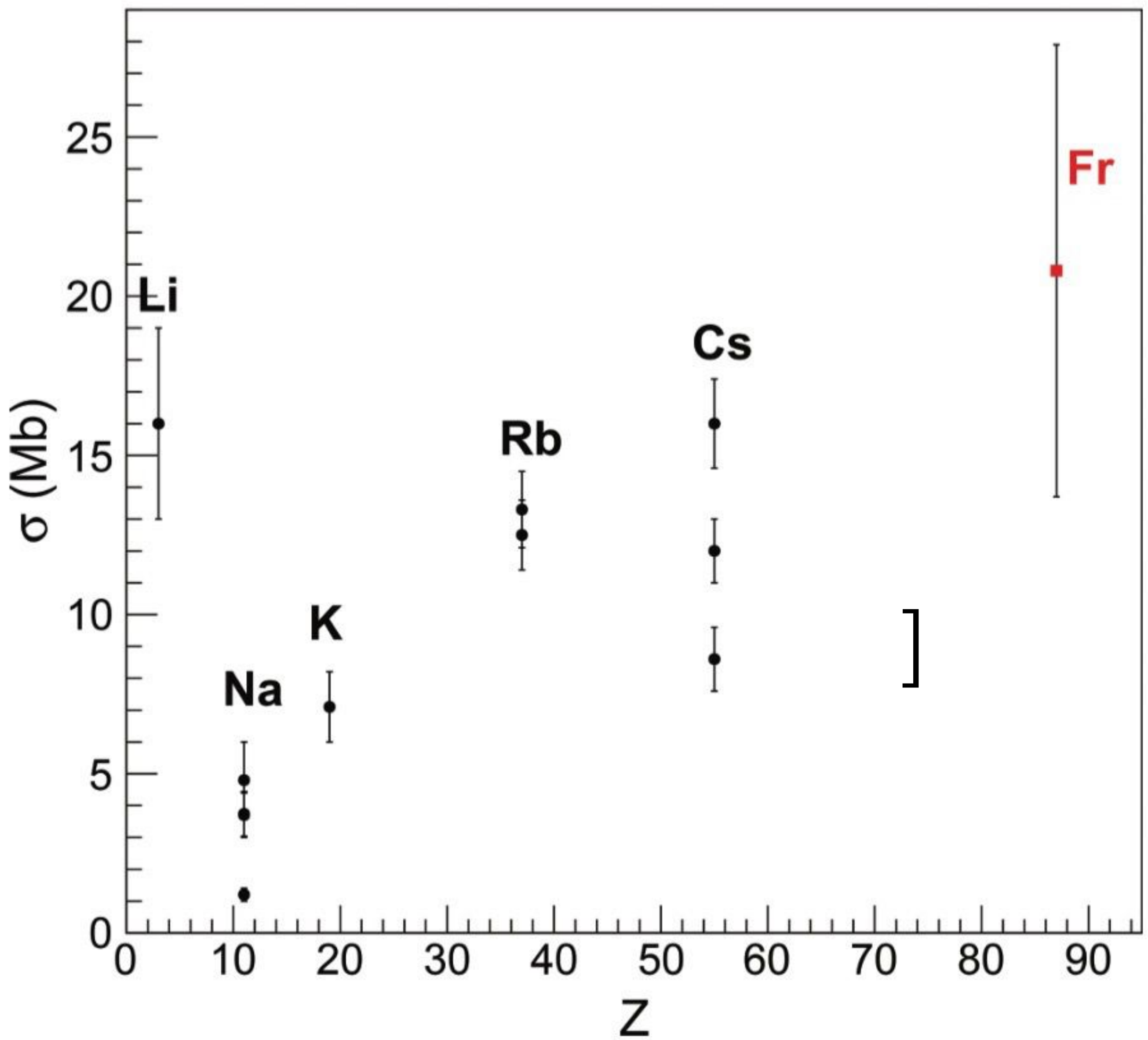
Zhang et al., Phys Rev Lett 115, 042501 (2015)



- nuclear magnetization distrib. differs from isotope to isotope
- → ratio of $7p_{1/2}$ and $7s_{1/2}$ hyperfine splittings isotope dependent

Reconfirms that in terms of nuclear structure, 208-213 are “good” nuclei for APNC/anapoles

Francium $7p_{3/2}$ photo-ionization — Collister et al. 2017, Can J Phys



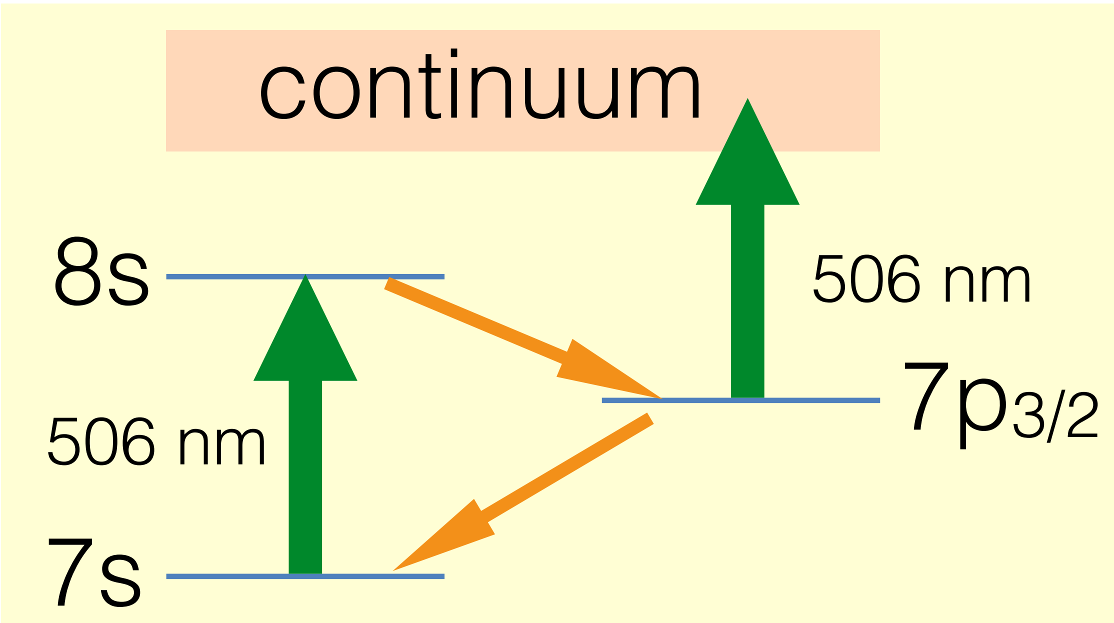
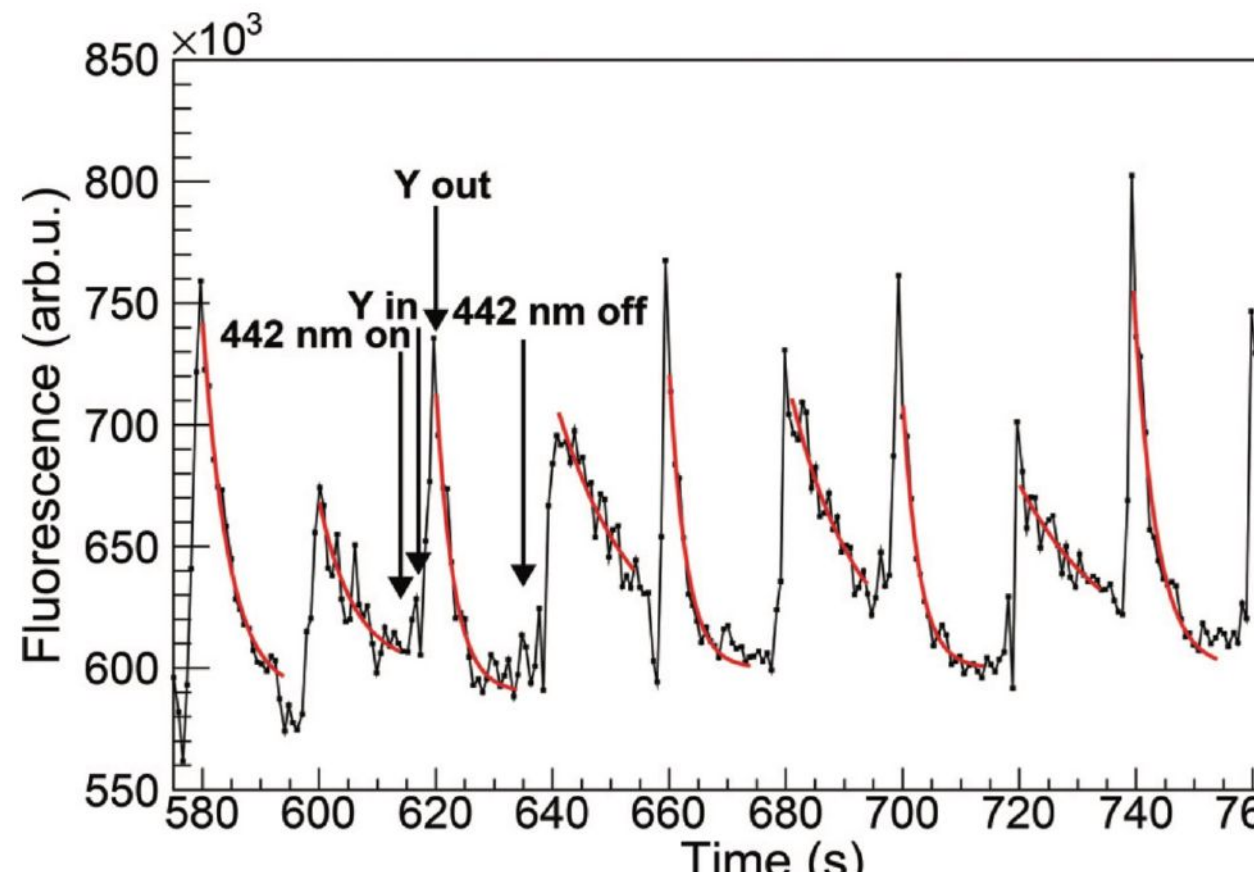
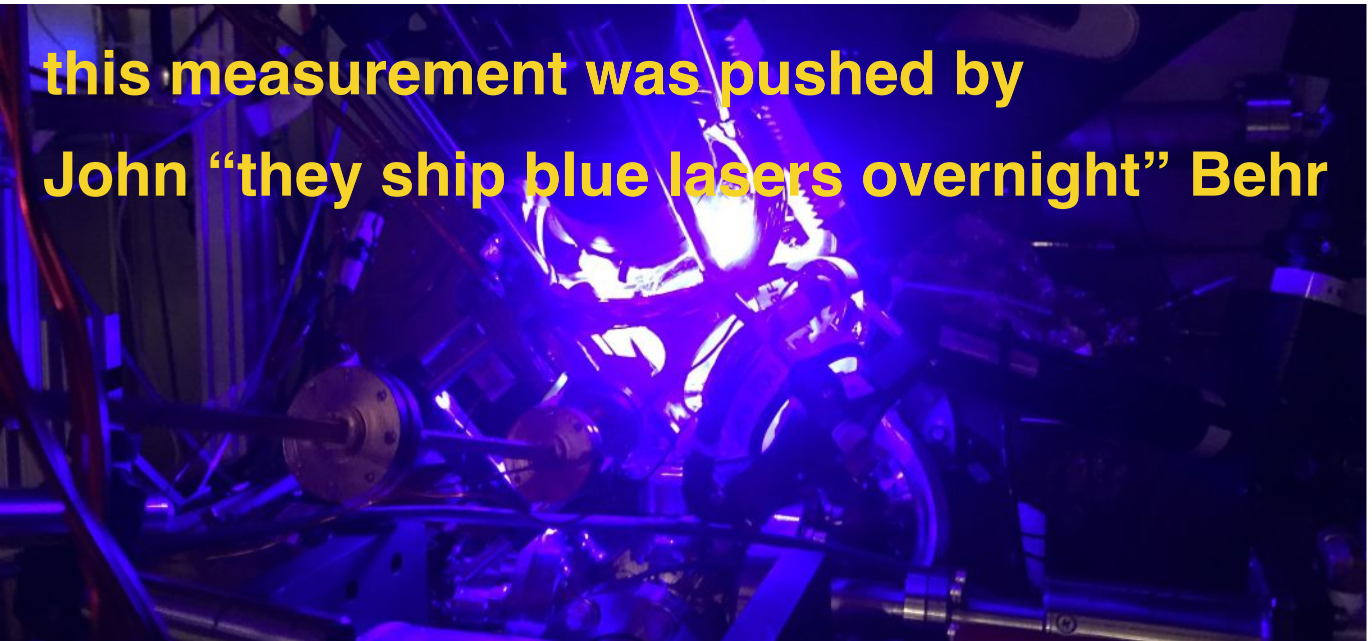


photo-ionization kills trap

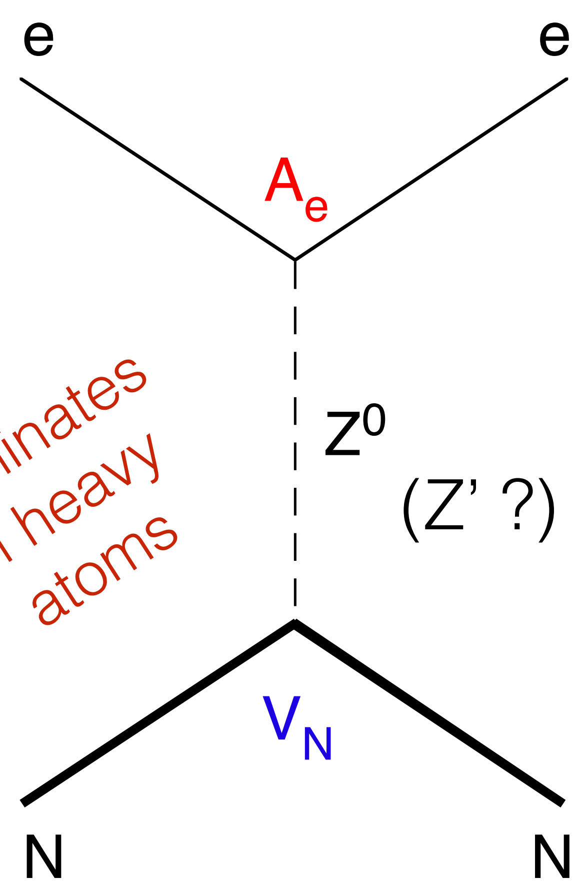
how bad is this effect?





Atomic parity violation

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



dominates in heavy atoms

Z³ law easy enough to motivate

The NSI APV Hamiltonian for a point-like nucleus

$$H^{nsi}_{\rm PNC} = \frac{G}{\sqrt{2}}\frac{Q_W}{2}\gamma_5\,\delta(\mathbf{r}) \qquad Q_W = 2(\kappa_{1p}Z + \kappa_{1n}N)$$

$$\kappa_{1p} = \frac{1}{2}(1 - 4\sin^2\theta_W),\ \kappa_{1n} = -\frac{1}{2}$$

The "nuclear weak charge" Q_w contains the weak interaction physics

≈ 0.02

$\rightarrow$ APV $\approx Q_w(n)$

$$< n'L'|H^{\rm nsi}_{\rm PNC}|nL > \;= \frac{G}{\sqrt{2}}\frac{Q_w}{2} < n'L'|\delta(r)\vec{\sigma}\cdot\vec{p}|nL >$$

$$\propto < n'L'|\tfrac{d}{dr}|nL > |_{r=0} \qquad R_{nL} \approx r^L Z^{L+1/2}$$

$\Rightarrow$ at $r = 0$ only R_{ns}, $\frac{d}{dr}R_{np}$ are finite

$H_{\rm PNC}$ mixes s and p states $\qquad < ns|H^{\rm nsi}_{\rm PNC}|n'p > \propto Z^3$

Bouchiat, 1974

nuclear spin indep. interaction: coherent over all nucleons

H_{PNC} mixes atomic s & p states

< n's' | H_{PNC} | np > ∝ Z^3 times a relativistic factor

Drive s → s E1 transition!

but let's try some intuition

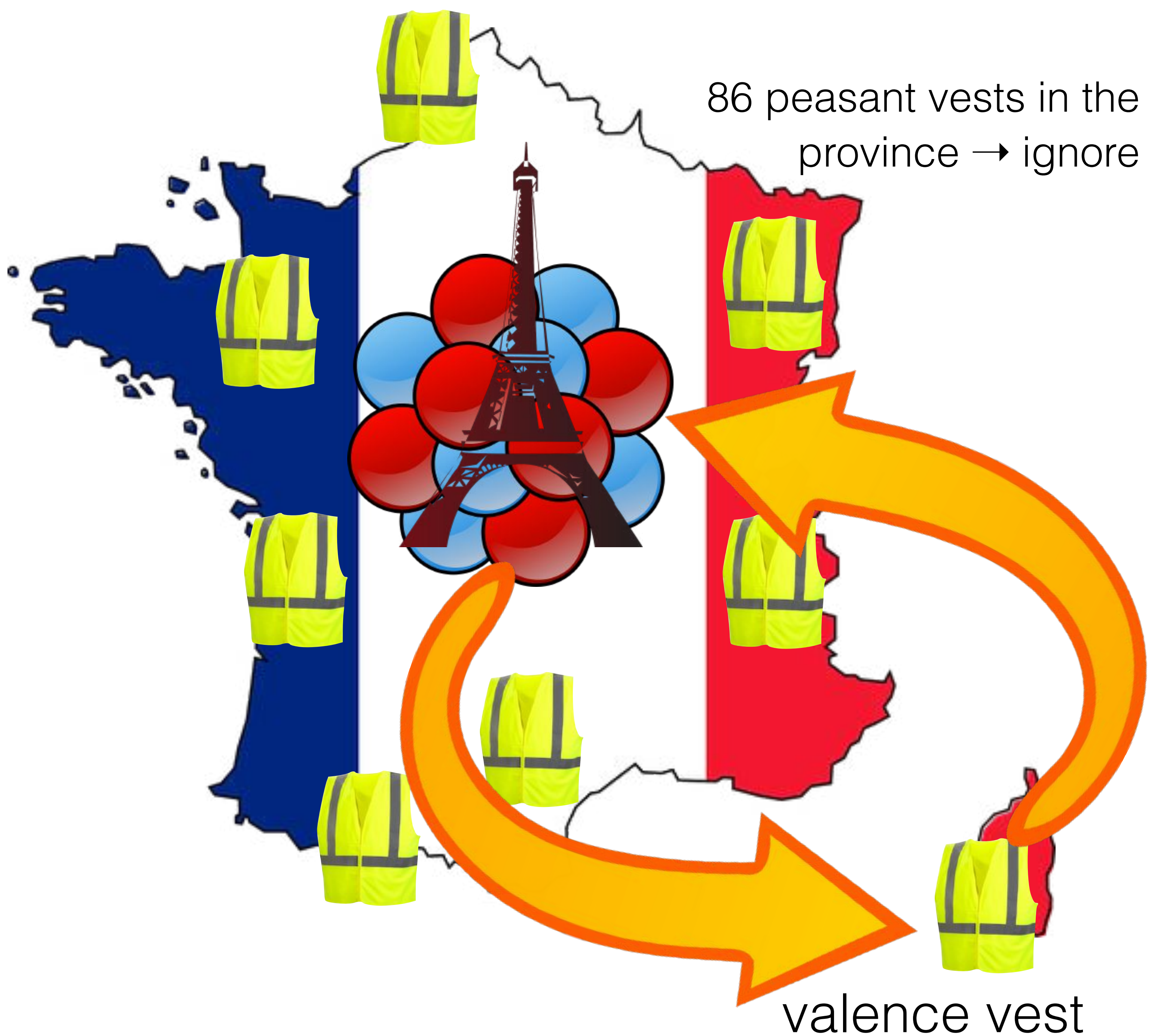
Bouchiat & Bouchiat 1974

Atomic parity violation in Fr

France and the Rutherford atom are very similar:

Gigantic thing in the middle and nothing worth mentioning around it

(according to the inhabitants of the gigantic thing — don't shoot the messenger)

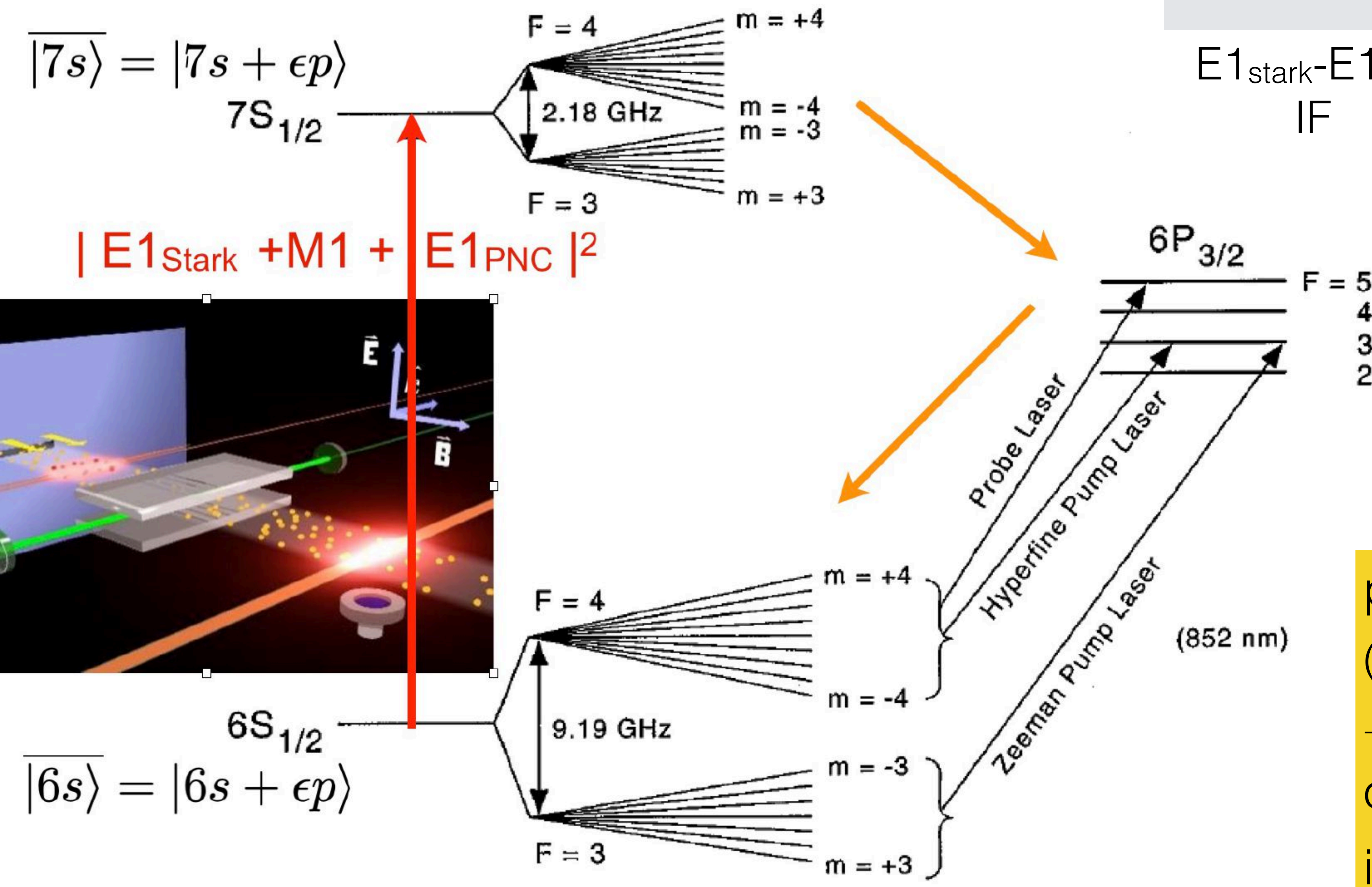


How is this measured ?

Plan to follow Wieman's Boulder Cs experiment

Q_w (Cs 133) to ≈ 0.5%

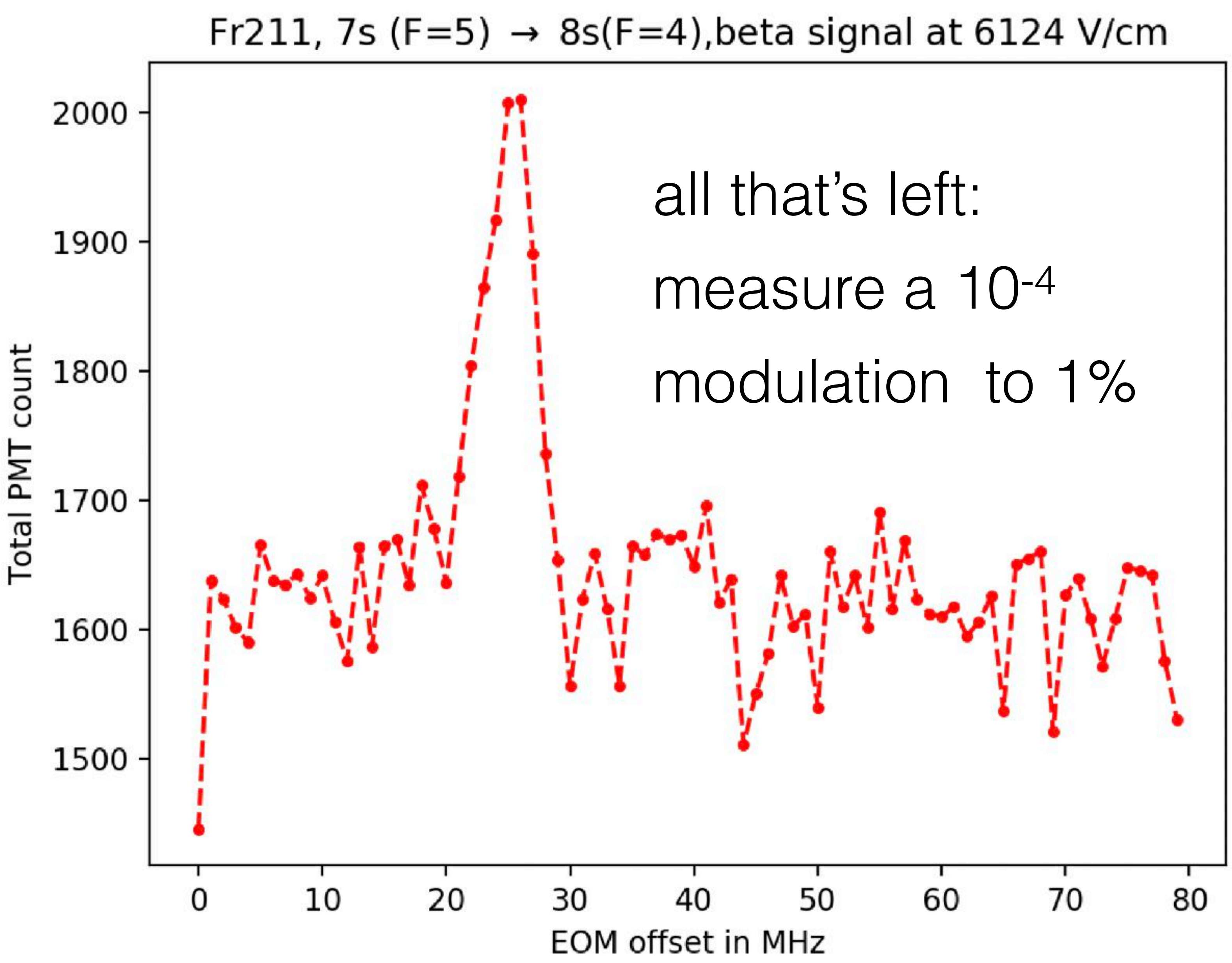
Oscillator strength	Cs	Fr
$E1_{Stark}$ @ 500 V/cm	10^{-11}	10^{-10}
M1	10^{-13}	10^{-11}
$E1_{pnc}$	10^{-22}	10^{-21}
$E1_{stark}$-$E1_{pnc}$ IF	10^{-16}	10^{-15}



parity flip
(e.g. E-field reversal)
→ 10^{-4} modulation of decay fluoresc. in Fr

The latest results: 7s-8s at last

- September 2018: Observed the ß-type Stark-induced 7s-8s transition (basis of the planned APV measurement)

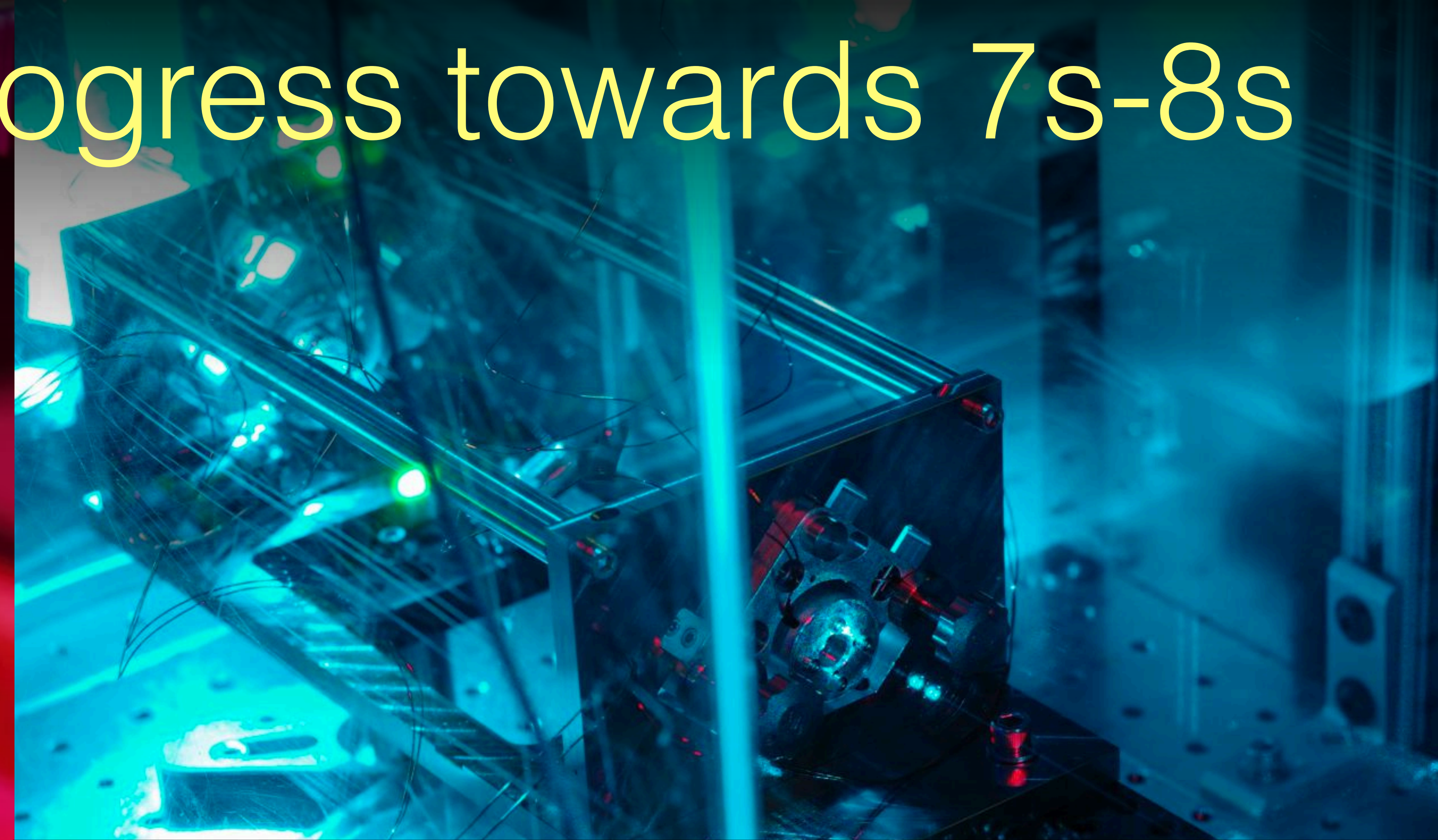


- 10^8 - 10^9 x weaker than typ. E1 trans.
- in least stable of first 103 elements
- true milestone
- the bad:
  - for APNC need to use 10x less E-field → 100x less signal
- the good:
  - some aces up our sleeves

Technical progress towards 7s-8s

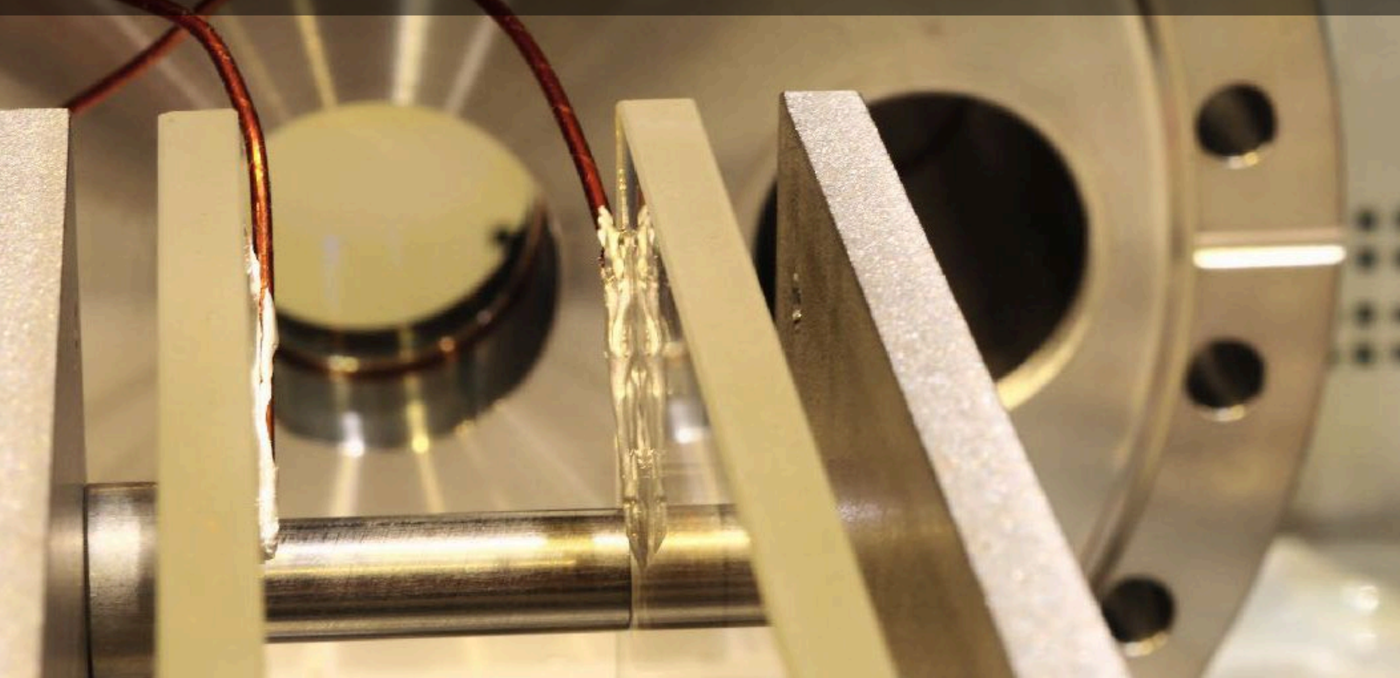
Photos: M. Kossin

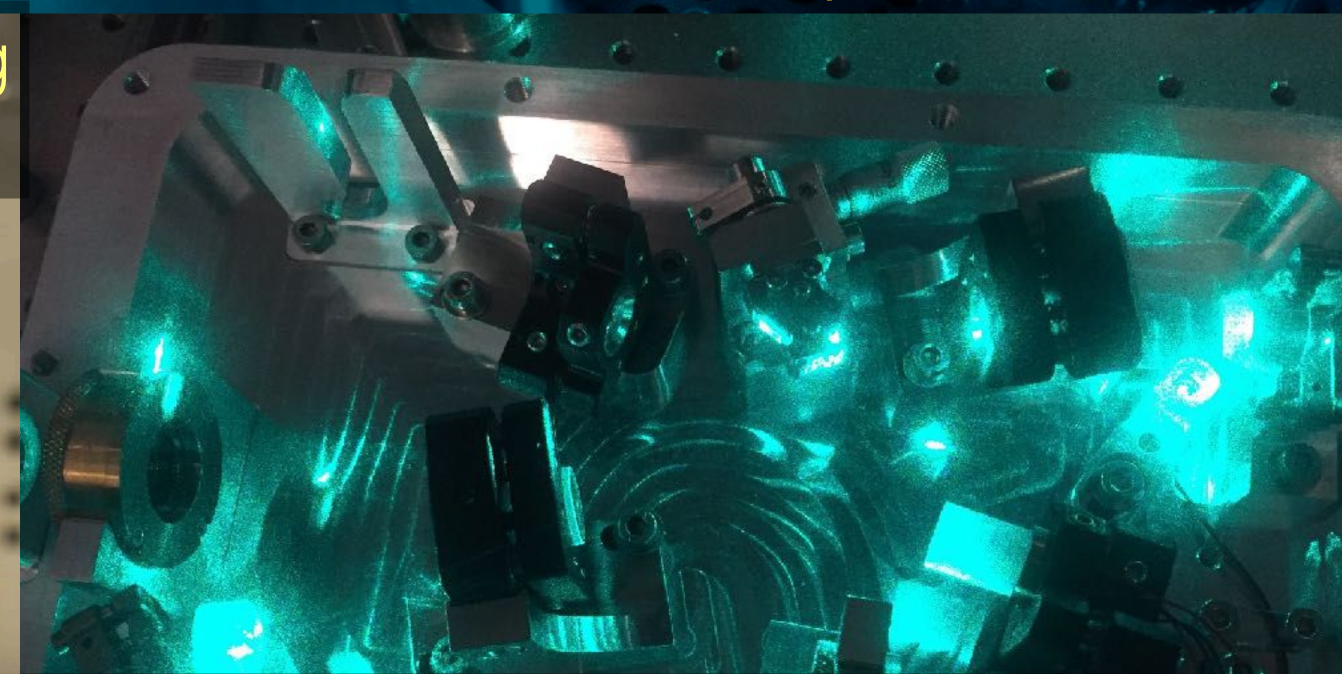
done: ultra-stable (10^{-10} level) ref. cavity for 7s-8s spectr.



UHV-compatible 506 nm power buildup cavity (1000-2000 x) in development

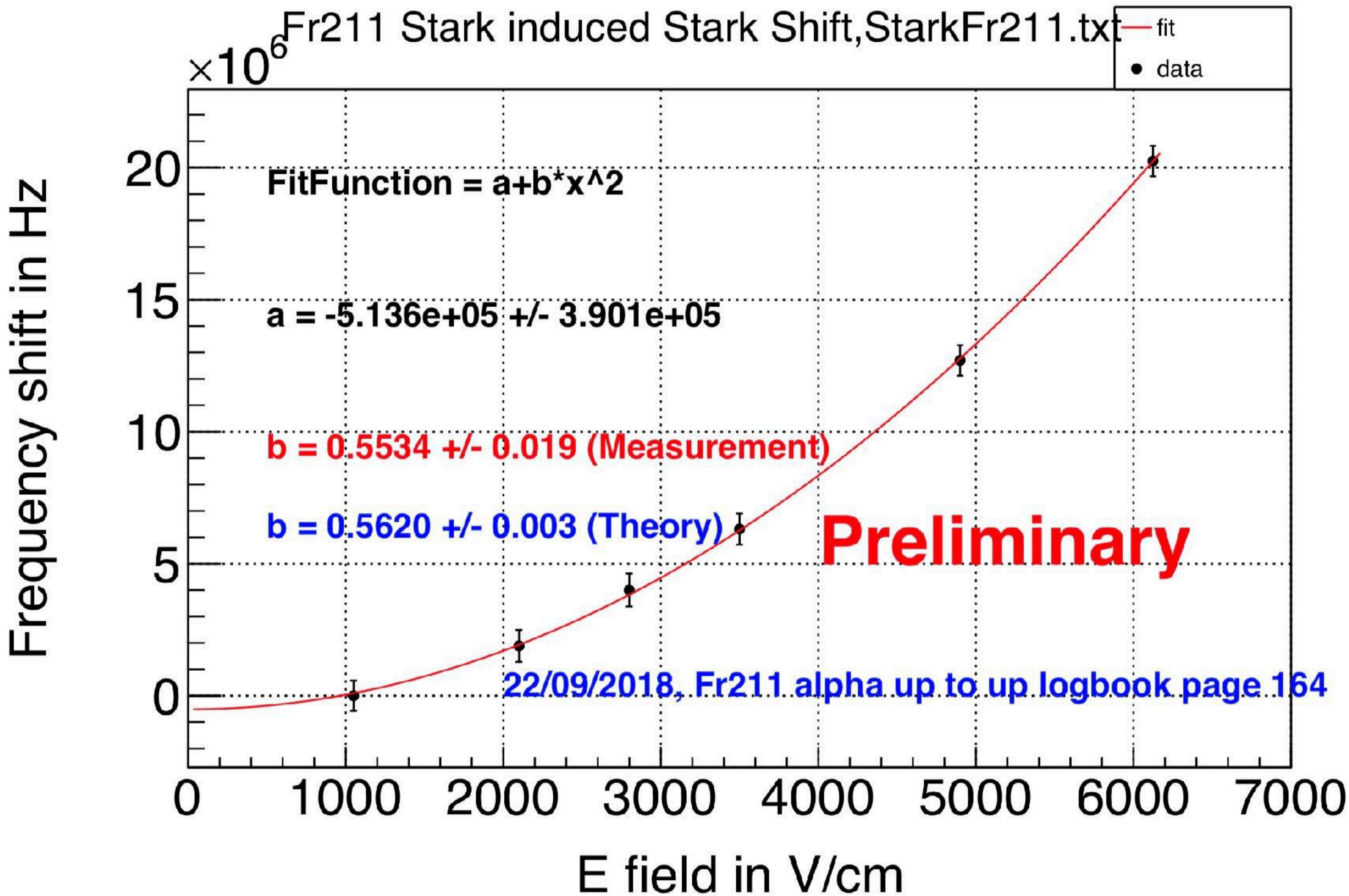
done: transparent field plates for operating laser trap internally





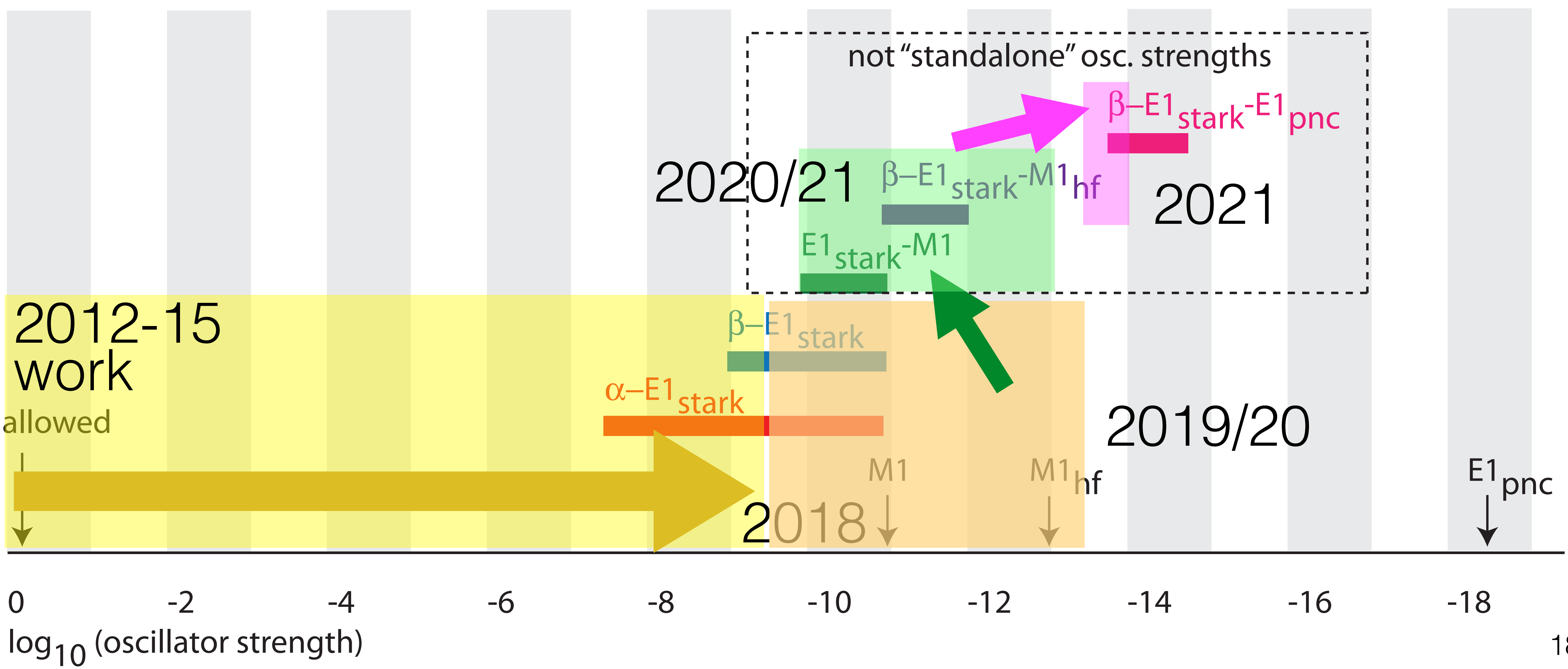
506 nm 7s-8s light (… until the great power outage of 2018)

Fr 7s - 8s DC Stark effect

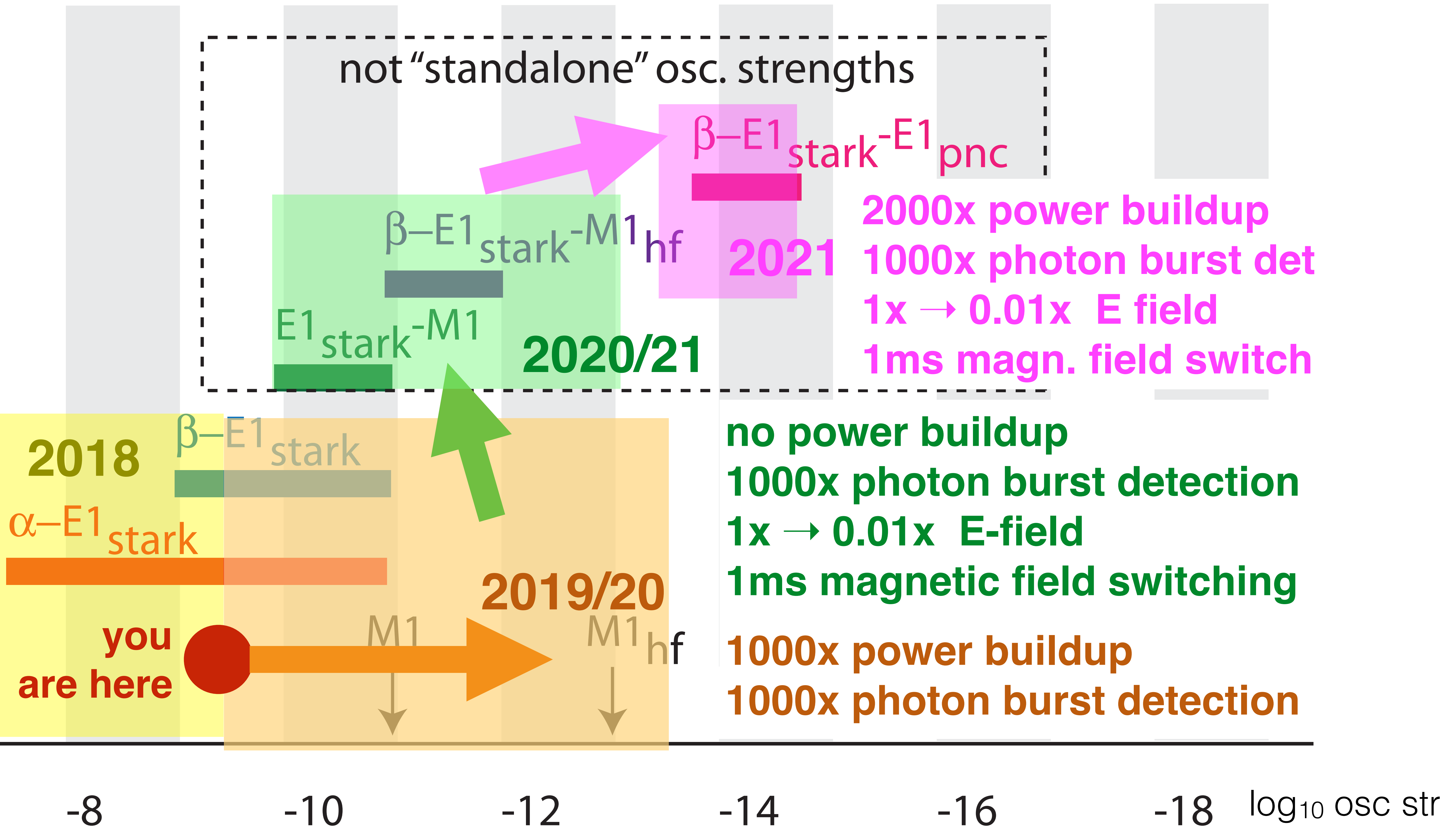


The road ahead

- Now in a position to move forward with the 7s - 8s spectroscopic program towards APV
- Over ≈ 3 years, expect to work our way down towards detecting the APV amplitude



The road ahead



The FrPNC team

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L. Orozco — U Maryland

E. Gomez — San Luis Potosi

S. Aubin — William & Mary

Sept 2018 beamtime

Alumni:

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J. Zhang (PhD 2015, U Maryland)
R. Collister (Phd 2015, U Manitoba)
A. DeHart (MSc 2018, U Manitoba)
A. Senchuk (PhD 2018, U Manitoba)

grad student
postdoc / res. assoc.

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NSERC, NRC/TRIUMF, U Maryland, U Manitoba
DOE: Fr trapping facility infrastructure
NSF: previously