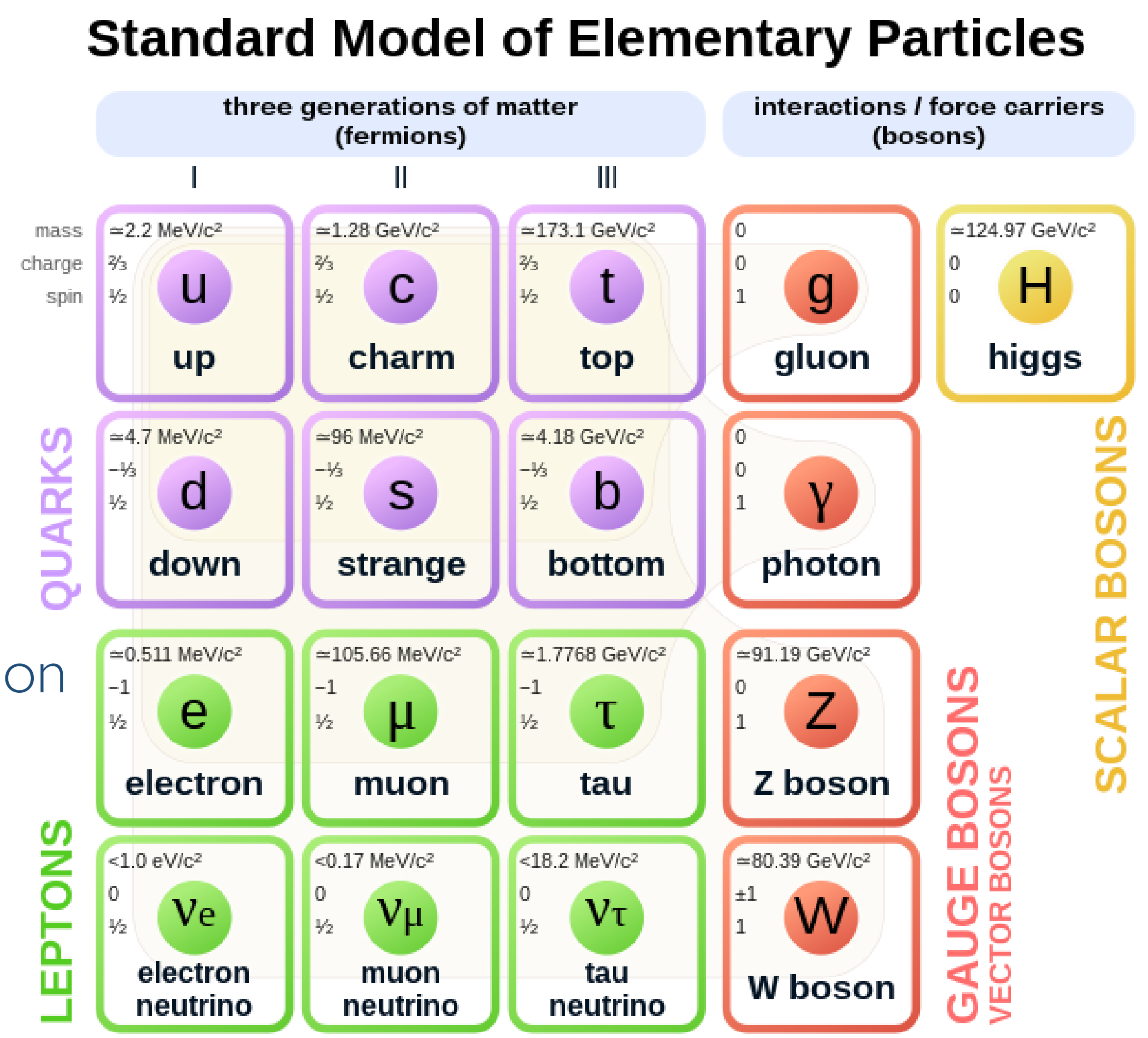
Towards an atomic parity-violation experiment in francium

Tim Hucko

CAP 2023

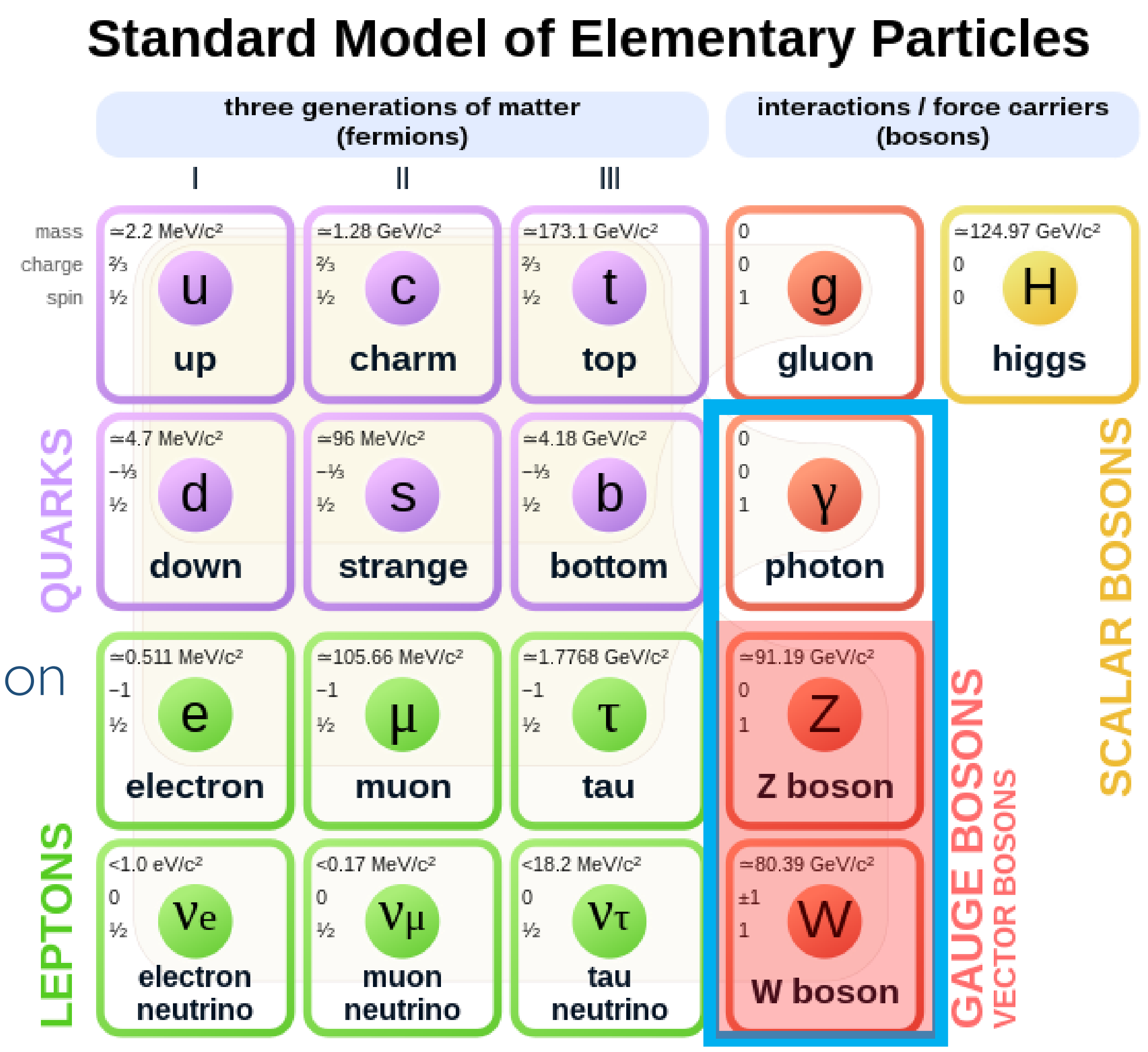
Standard Model

- Classifies all known elementary particles
- Describes 3 of the 4 fundamental forces; mediated by bosons
- Very successful theory, but still missing
  1. Baryon asymmetry
  2. Gravity
  3. Dark energy
  4. Dark matter
- Search for new physics using (electro)weak interaction
  - Leptoquarks[1]
    - Change: quarks ↔ leptons
    - Unification of matter
    - Lower mass limit ~ 1TeV
  - Z' boson[1-4]
    - Neutral current that mixes with Z boson
    - Z' possible dark matter candidate



Standard Model

- Classifies all known elementary particles
- Describes 3 of the 4 fundamental forces; mediated by bosons
- Very successful theory, but still missing
  1. Baryon asymmetry
  2. Gravity
  3. Dark energy
  4. Dark matter
- Search for new physics using (electro)weak interaction
  - Leptoquarks[1]
    - Change: quarks ↔ leptons
    - Unification of matter
    - Lower mass limit ~ 1TeV
  - Z' boson[1-4]
    - Neutral current that mixes with Z boson
    - Z' possible dark matter candidate

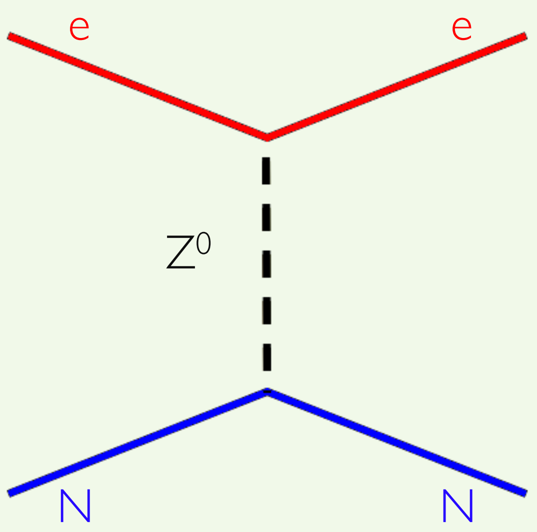


Atomic parity-violation (APV)

Z-boson exchange between electrons an nucleons (quarks)

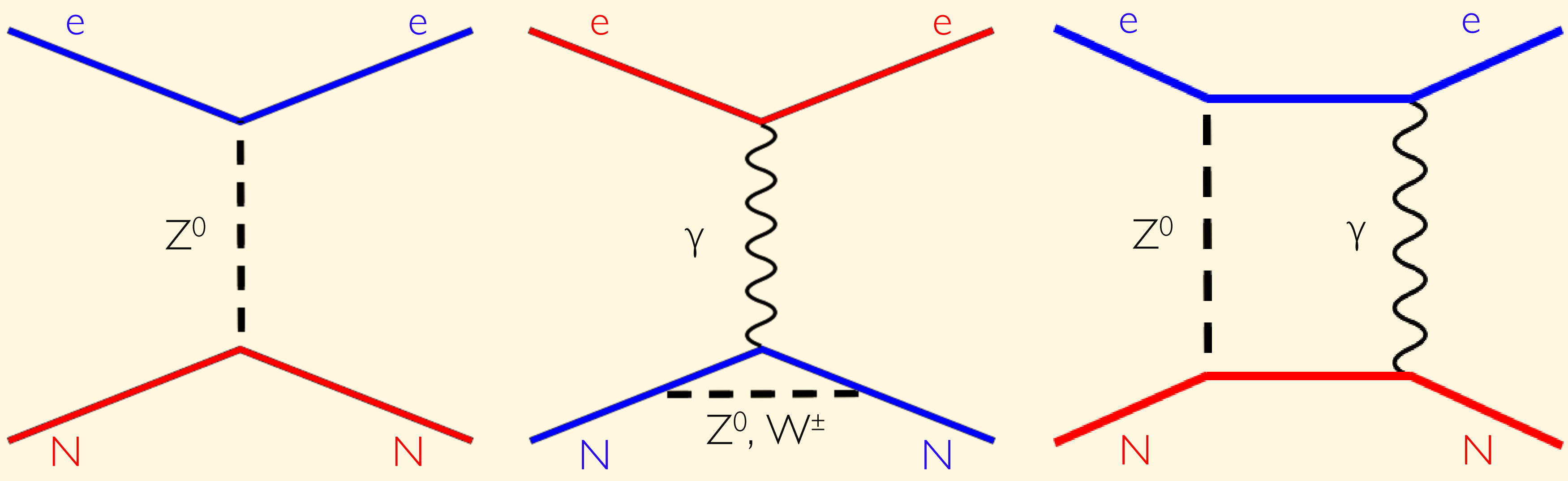
H_{PV} mixes s and p states $\rightarrow \langle ns|H_{PV}^{NSI}|n'p\rangle \propto Z^2 N$[5,6]

Nuclear Spin Independent



- Dominates in heavy atoms
- Coherent over all nucleons
- Vector nucleon axial-vector electron interaction
- Connection to the Q_W

Nuclear Spin Dependent



- NSD Z-exchange; Vector electron axial-vector nucleon
- Inter-nucleus interaction; anapole moment
  - Dominates in heavy atoms
- Hyperfine correction to the weak interaction

NSI Hamiltonian

$$H_{PV}^{NSI} = \frac{G_F}{2\sqrt{2}} \gamma_5 \delta(r) Q_W$$

NSI Hamiltonian

$$H_{PV}^{NSI} = \frac{G_F}{2\sqrt{2}} \gamma_5 \delta(r) Q_W$$

- Fermi constant

NSI Hamiltonian

$$H_{PV}^{NSI} = \frac{G_F}{2\sqrt{2}} \gamma_5 \delta(r) Q_W$$

- Fermi constant
- Weak interaction "zero" range → electron at the nucleus

NSI Hamiltonian

$$H_{PV}^{NSI} = \frac{G_F}{2\sqrt{2}} \gamma_5 \delta(r) Q_W$$

- Fermi constant
- Weak interaction "zero" range → electron at the nucleus
- $\langle ns|\gamma_5|n'p\rangle$ matrix element depends on electronic wave function at the nucleus
  - Scales as Z^2

NSI Hamiltonian

$$H_{PV}^{NSI} = \frac{G_F}{2\sqrt{2}} \gamma_5 \delta(r) Q_W$$

- Fermi constant
- Weak interaction “zero” range ⟶ electron at the nucleus
- $\langle ns|\gamma_5|n'p\rangle$ matrix element depends on electronic wave function at the nucleus
  - Scales as Z^2
- Weak charge of the nucleus
  - $Q_W = 2(\kappa_{1p} Z + \kappa_{1n} N)$
    - $\kappa_{1p} = \frac{1}{2}(1 - 4\sin^2\theta_W) \approx 0.024$
    - $\kappa_{1n} = -\frac{1}{2}$

$$\Rightarrow Q_W^{APV} \approx N$$

NSI Hamiltonian

$$H_{PV}^{NSI} = \frac{G_F}{2\sqrt{2}} \gamma_5 \delta(r) Q_W$$

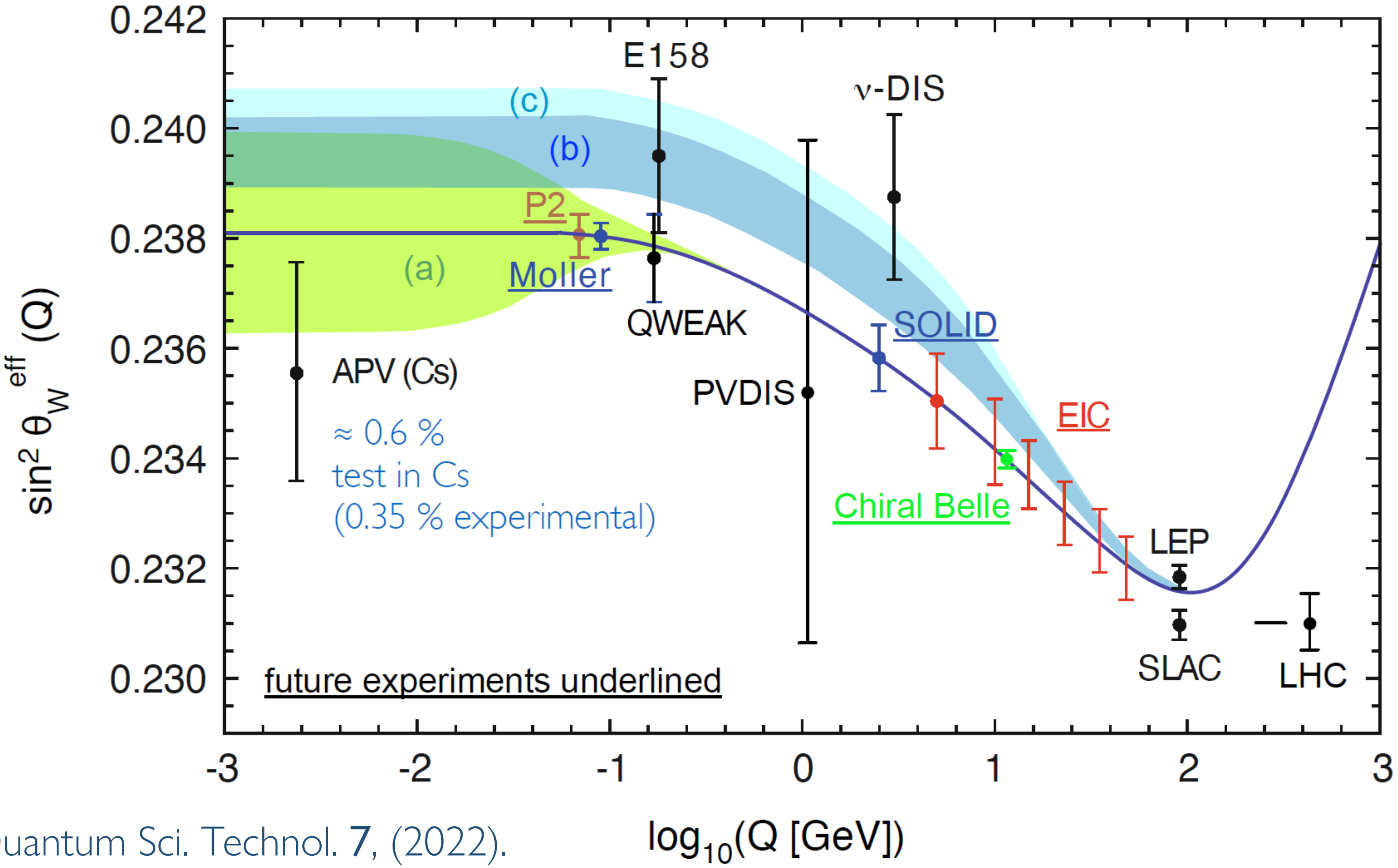
- APV → Z^2N
- Highly non-trivial to calculate matrix element
- Alkalis provide suitable systems for calculations
- Measured in Cs(Z=55)[7]
- In Fr(Z=87), APV effect is x18 larger compared to Cs(Z=55)

- Fermi constant
- Weak interaction "zero" range → electron at the nucleus
- $\langle ns|\gamma_5|n'p\rangle$ matrix element depends on electronic wave function at the nucleus
  - Scales as Z^2
- Weak charge of the nucleus
  - $Q_W = 2(\kappa_{1p}Z + \kappa_{1n}N)$
    - $\kappa_{1p} = \frac{1}{2}(1 - 4\sin^2\theta_W) \approx 0.024$
    - $\kappa_{1n} = -\frac{1}{2}$

$Q_W^{APV} \approx N$

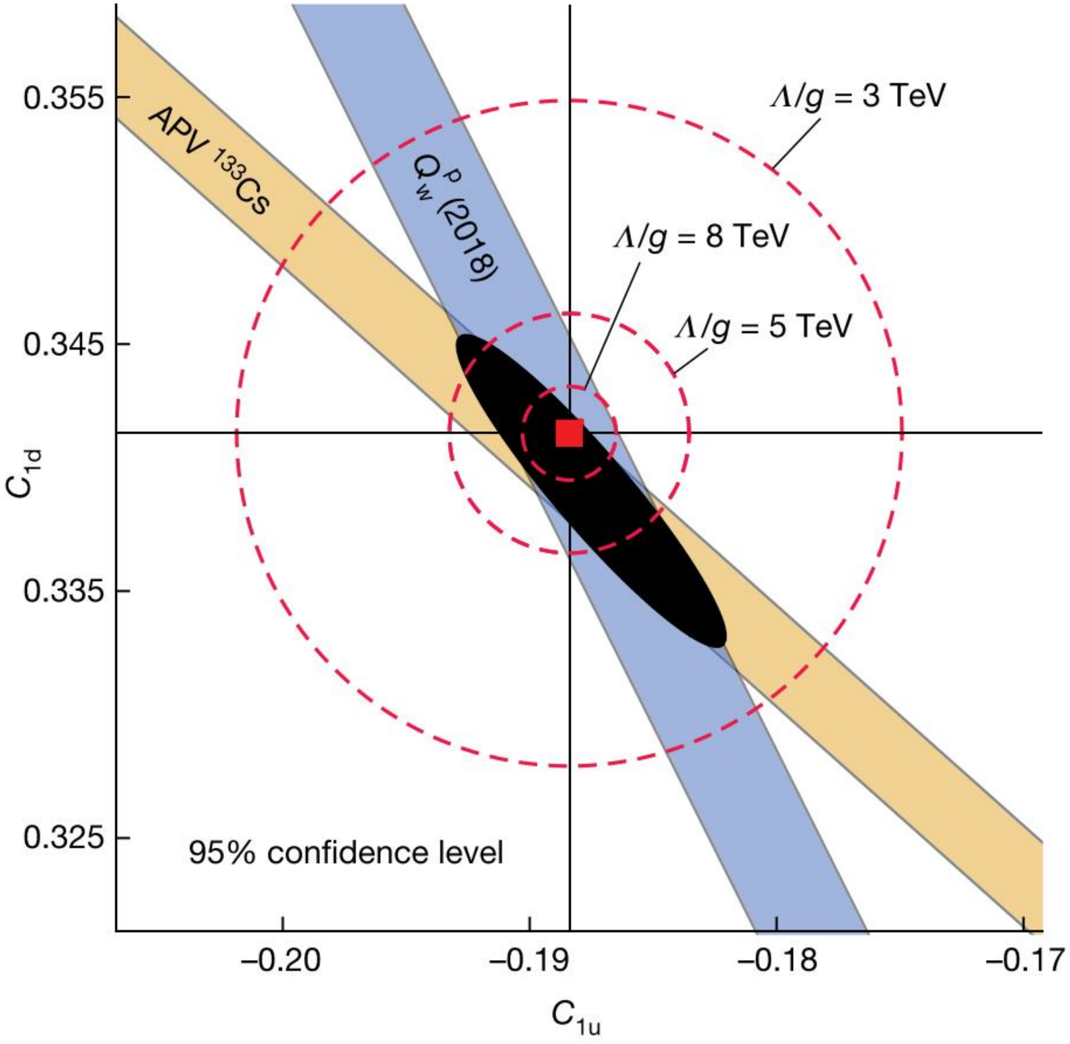
Electroweak interaction

- Running of the Weinberg angle: $Q_W \rightarrow \sin^2\theta_W$
- APV tests at low momentum transfer
- Colored bands represents scenarios with dark Z' bosons



Gwinner & Orozco, Quantum Sci. Technol. 7, (2022).

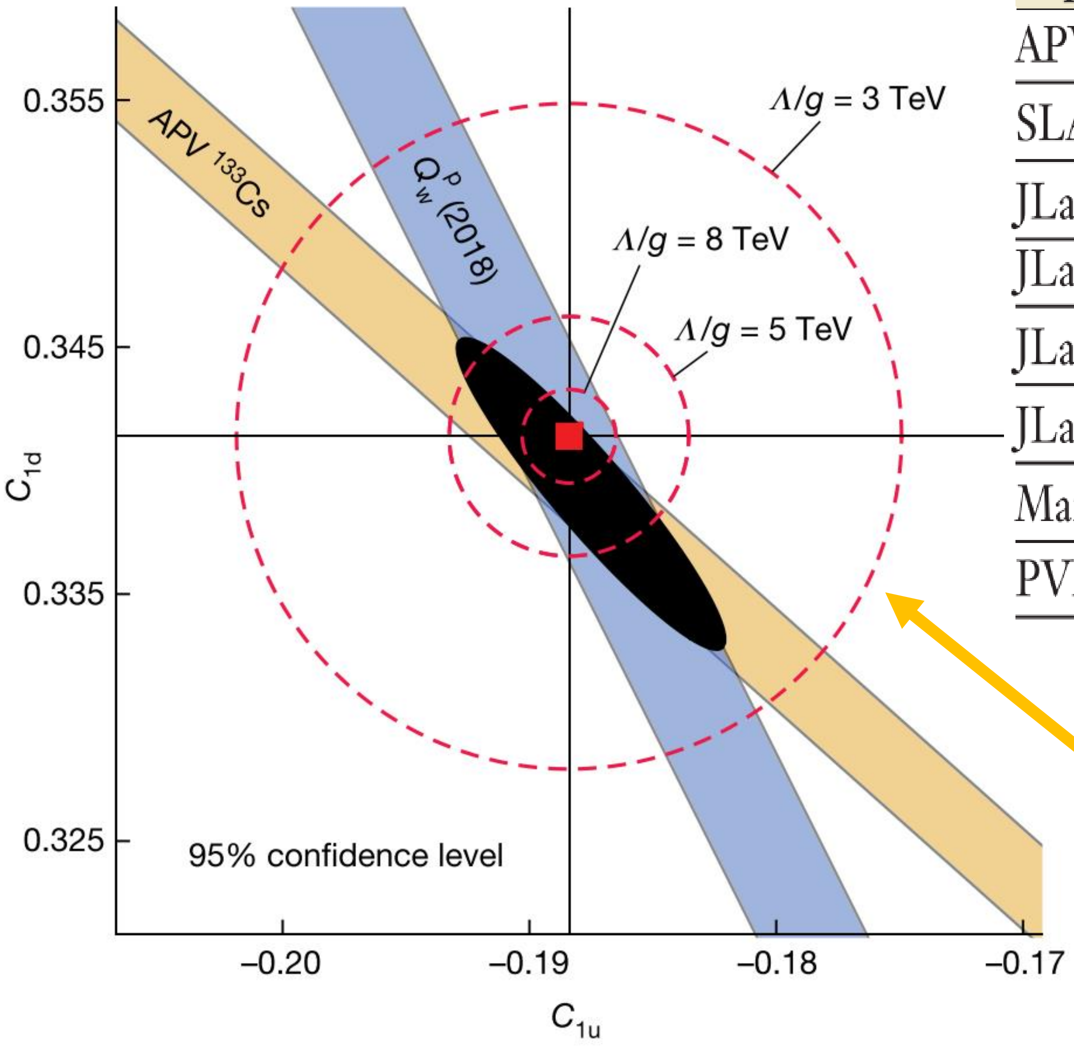
- Electron-quark coupling constants
- Combination of results from PVES and APV (black ellipse) @ 95% CL
- Red dot is SM prediction



D. Androi´c et al., Nature 557, 207 (2018).

- Electron-quark coupling constants
- Combination of results from PVES and APV (black ellipse) @ 95% CL
- Red dot is SM prediction

J. Erler *et al.*, Annu. Rev. Nucl. Part. Sci. **64**, 269 (2014).



Experiment	Precision (%)	$\Delta \sin^2 \hat{\theta}_W(0)$	Λ_{new} (TeV)
APV (^{133}Cs)	0.58	0.0019	32.3
SLAC–E158	14	0.0013	17.0
JLab–Qweak (run I)	19	0.0030	17.0
JLab–Qweak (final)	4.5	0.0008	33
JLab–SoLID	0.6	0.00057	22
JLab–MOLLER	2.3	0.00026	39
Mainz–P2	2.0	0.00036	49
PVES (^{12}C)	0.3	0.0007	49

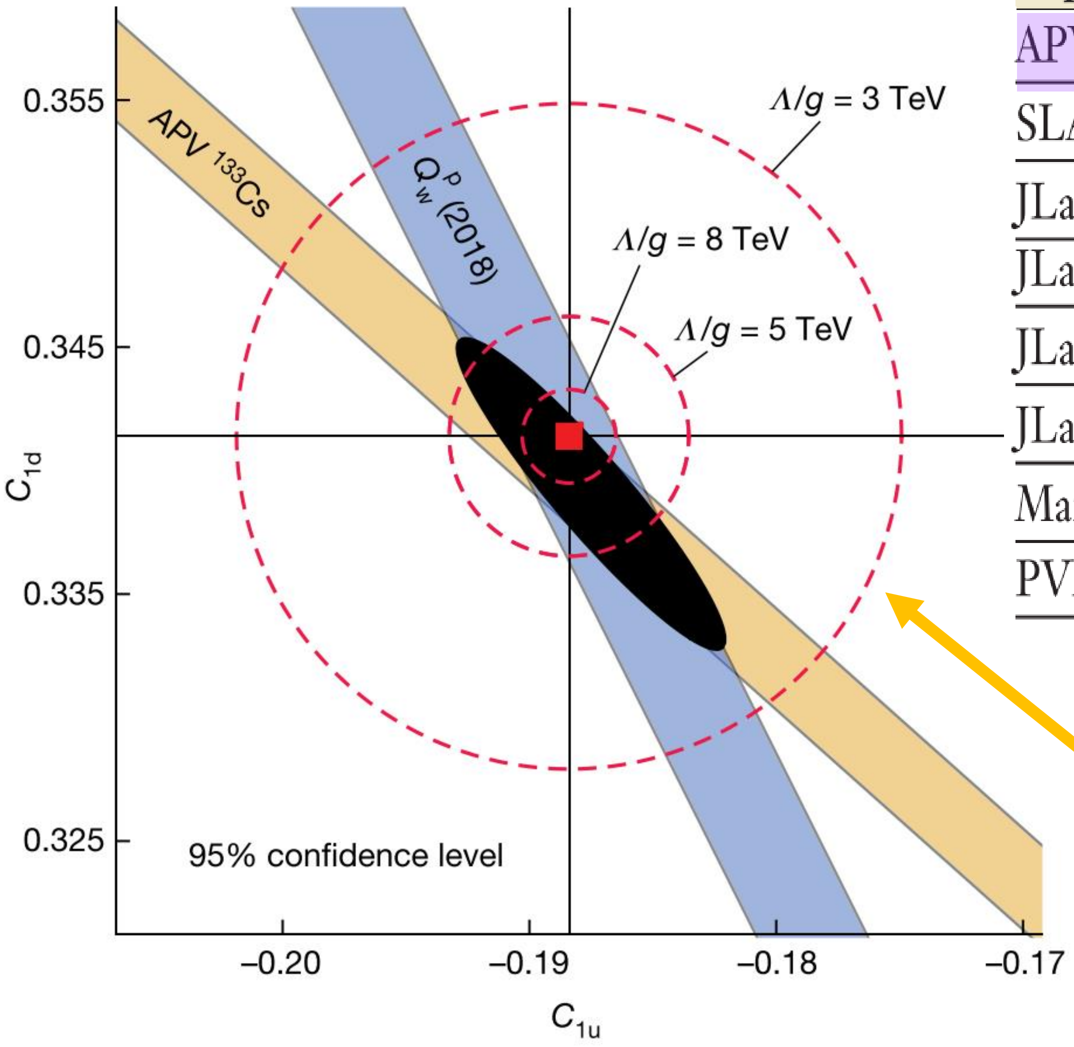
Dashed circles represents mass reaches for new physics ($g^2=4\pi$)

D. Androi´c et al., Nature 557, 207 (2018).

- Electron-quark coupling constants
- Combination of results from PVES and APV (black ellipse) @ 95% CL
- Red dot is SM prediction

J. Erler *et al.*, Annu. Rev. Nucl. Part. Sci. **64**, 269 (2014).

Experiment	Precision (%)	$\Delta \sin^2 \hat{\theta}_W(0)$	Λ_{new} (TeV)
APV (^{133}Cs)	0.58	0.0019	32.3
SLAC–E158	14	0.0013	17.0
JLab–Qweak (run I)	19	0.0030	17.0
JLab–Qweak (final)	4.5	0.0008	33
JLab–SoLID	0.6	0.00057	22
JLab–MOLLER	2.3	0.00026	39
Mainz–P2	2.0	0.00036	49
PVES (^{12}C)	0.3	0.0007	49

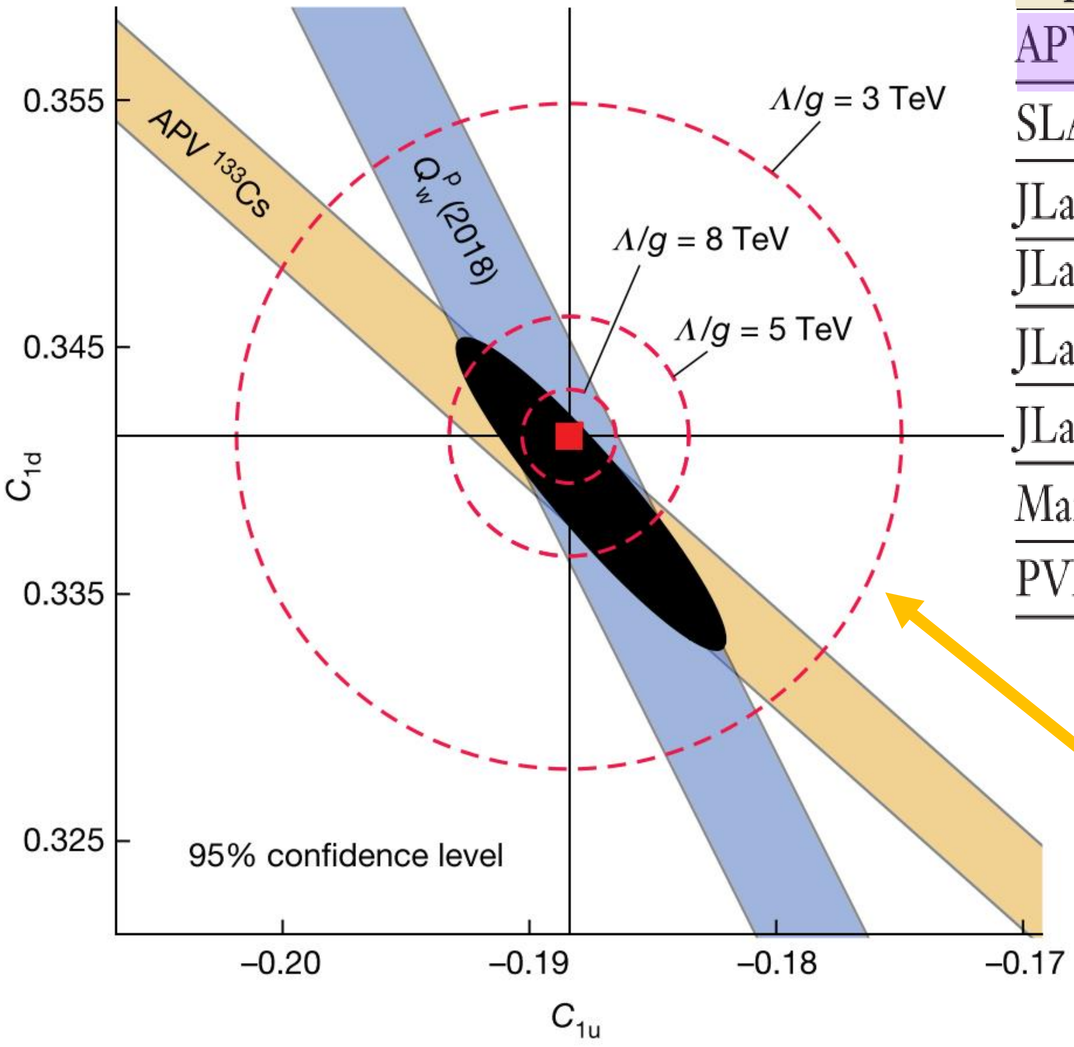


D. Androi´c et al., Nature 557, 207 (2018).

Dashed circles represents mass reaches for new physics (g^2=4π)

- Electron-quark coupling constants
- Combination of results from PVES and APV (black ellipse) @ 95% CL
- Red dot is SM prediction

J. Erler *et al.*, Annu. Rev. Nucl. Part. Sci. **64**, 269 (2014).



D. Androi´c et al., Nature 557, 207 (2018).

Experiment	Precision (%)	$\Delta \sin^2 \hat{\theta}_W(0)$	Λ_{new} (TeV)
APV (^{133}Cs)	0.58	0.0019	32.3
SLAC–E158			17.0
JLab–Qweak (run I)			17.0
JLab–Qweak (final)			33
JLab–SoLID			22
JLab–MOLLER			39
Mainz–P2			49
PVES (^{12}C)	0.3	0.0007	49

Impressive sensitivity provides strong motivation for APV as searches of new physics beyond SM!

Dashed circles represents mass reaches for new physics (g^2=4π)

Current APV results

- Current best result is for Cs
  - 1997 by Boulder group
  - Performed interference experiment (more on this later)
  - Experimental accuracy → 0.35%
    - Other Cs measurements reach 12%[8] and 2.6%[9]

$$\frac{-\operatorname{Im}(\mathcal{E}1_{PV})}{\beta} = \begin{cases} 1.6349(80)\ \mathrm{mV/cm} \rightarrow \textit{6s(F=4)-7s(F=3)} \\ 1.5576(77)\ \mathrm{mV/cm} \rightarrow \textit{6s(F=3)-7s(F=4)} \end{cases}$$

Current APV results

- Current best result is for Cs
  - 1997 by Boulder group
  - Performed interference experiment (more on this later)
  - Experimental accuracy $\longrightarrow$ 0.35%
    - Other Cs measurements reach 12%[8] and 2.6%[9]

$$\frac{-\,\mathrm{Im}(\mathcal{E}1_{PV})}{\beta} = \begin{cases} 1.6349(80)\ \mathrm{mV/cm} \longrightarrow 6s(F{=}4)\text{-}7s(F{=}3) \\ 1.5576(77)\ \mathrm{mV/cm} \longrightarrow 6s(F{=}3)\text{-}7s(F{=}4) \end{cases}$$

Average gives NSI contribution

$$-\frac{\mathrm{Im}(\varepsilon_{PV}^{NSI})}{\beta} = 1.5935(56)\ \mathrm{mV/cm}$$

Current APV results

- Current best result is for Cs
  - 1997 by Boulder group
  - Performed interference experiment (more on this later)
  - Experimental accuracy → 0.35%
    - Other Cs measurements reach 12%[8] and 2.6%[9]

$$\frac{-\operatorname{Im}(\mathcal{E}1_{PV})}{\beta} = \begin{cases} 1.6349(80)\ \text{mV/cm} \rightarrow 6s(F{=}4)\text{-}7s(F{=}3) \\ 1.5576(77)\ \text{mV/cm} \rightarrow 6s(F{=}3)\text{-}7s(F{=}4) \end{cases}$$

Average gives NSI contribution

$$-\frac{\operatorname{Im}(\varepsilon_{PV}^{NSI})}{\beta} = 1.5935(56)\ \text{mV/cm}$$

Difference gives NSD contribution

$$\frac{\operatorname{Im}(\varepsilon 1_{PV}^{NSD})}{\beta} = 0.077(11)\ \text{mV/cm}$$

Current APV results

- Current best result is for Cs
  - 1997 by Boulder group
  - Performed interference experiment (more on this later)
  - Experimental accuracy → 0.35%
    - Other Cs measurements reach 12%[8] and 2.6%[9]

$$\frac{-\operatorname{Im}(\mathcal{E}1_{PV})}{\beta} = \begin{cases} 1.6349(80)\ \mathrm{mV/cm} \rightarrow \mathit{6s(F{=}4)\text{-}7s(F{=}3)} \\ 1.5576(77)\ \mathrm{mV/cm} \rightarrow \mathit{6s(F{=}3)\text{-}7s(F{=}4)} \end{cases}$$

Average gives NSI contribution

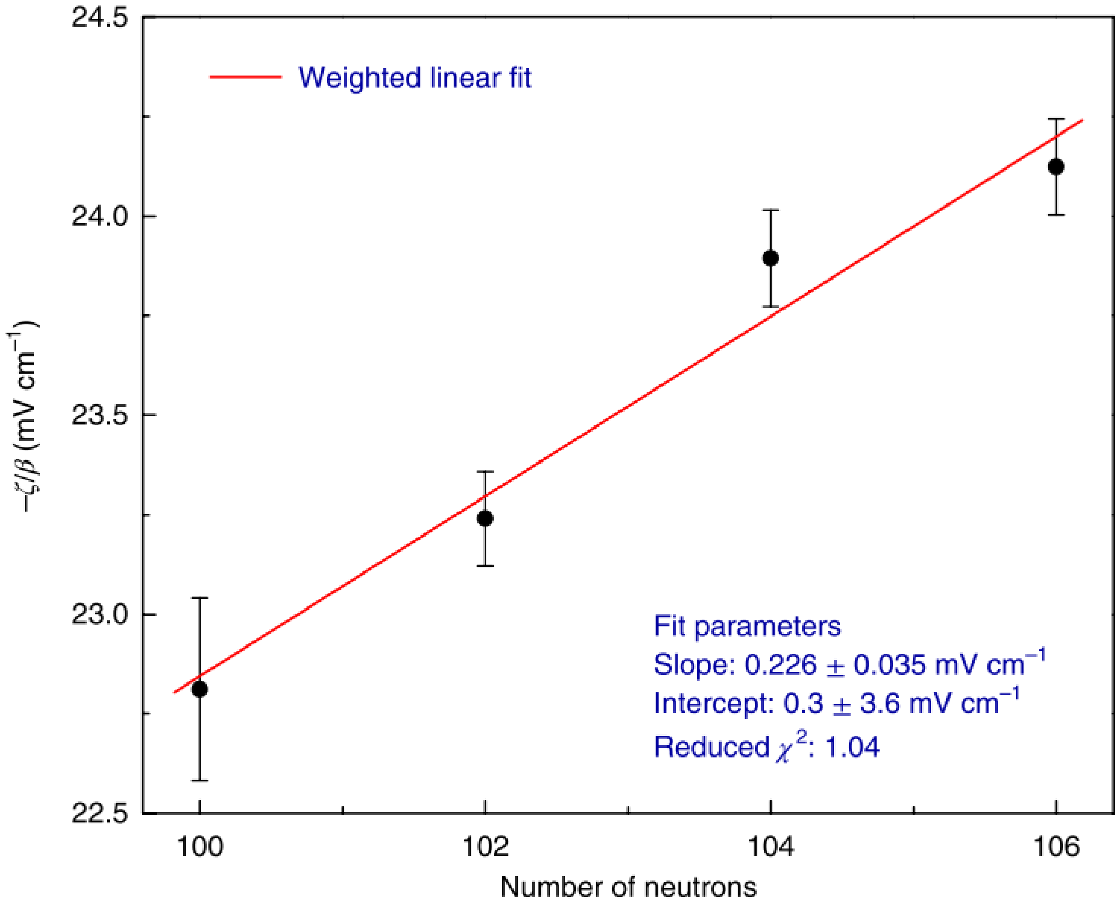
$$-\frac{\mathbf{Im}(\boldsymbol{\varepsilon}_{PV}^{NSI})}{\beta} = \mathbf{1.5935(56)}\ \mathrm{mV/cm}$$

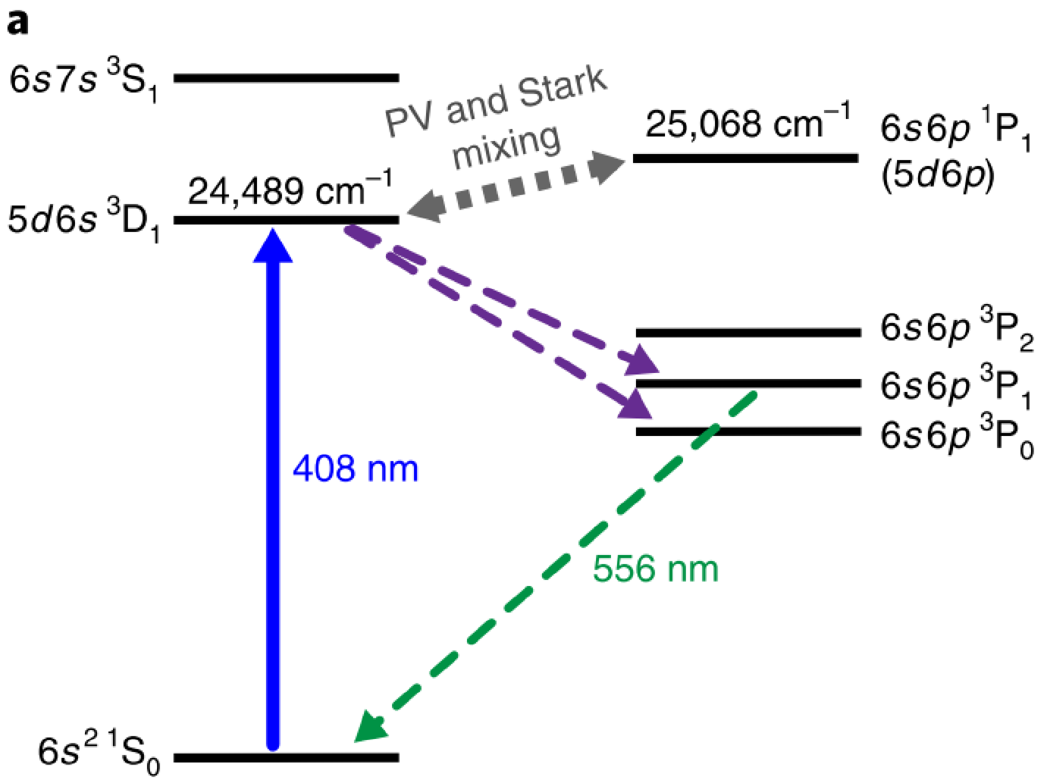
Difference gives NSD contribution

$$\frac{\mathbf{Im}(\boldsymbol{\varepsilon}1_{PV}^{NSD})}{\beta} = \mathbf{0.077(11)}\ \mathrm{mV/cm}$$

1999 improved Q_W = -72.06(28), by measuring β using the 6s-7s M1 transition[10] → Progress made in measuring M1 in Fr!

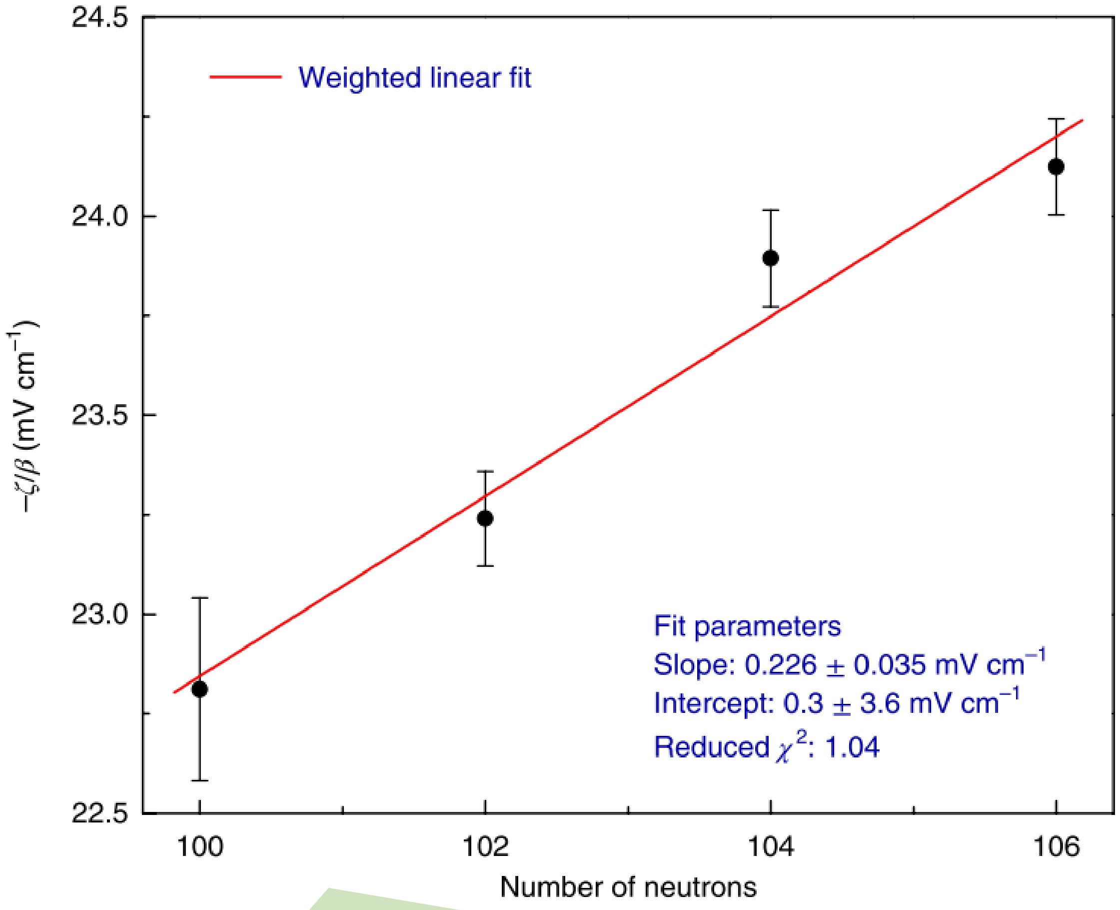
- New result for APV in 2019, Antypas, *et al.*, Nat. Phys. 15, 120 (2019).
- Used Ytterbium; N = 170, 172, 174, and 176

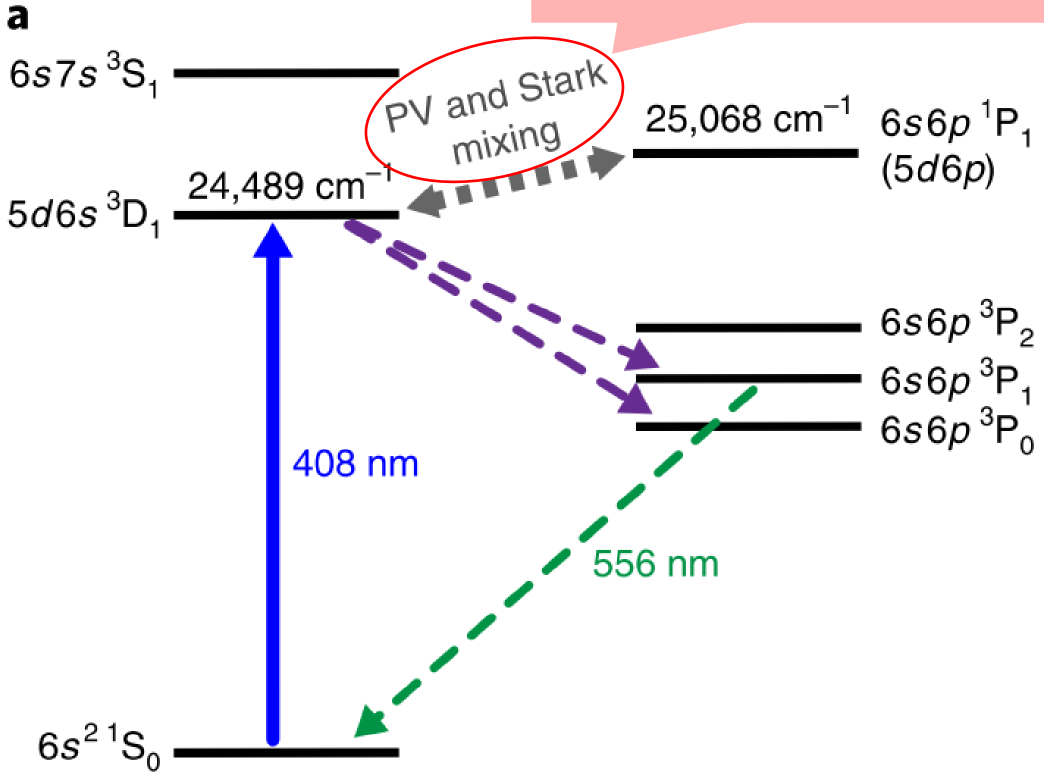




- New result for APV in 2019, Antypas, *et al.*, Nat. Phys. 15, 120 (2019).
- Used Ytterbium; N = 170, 172, 174, and 176

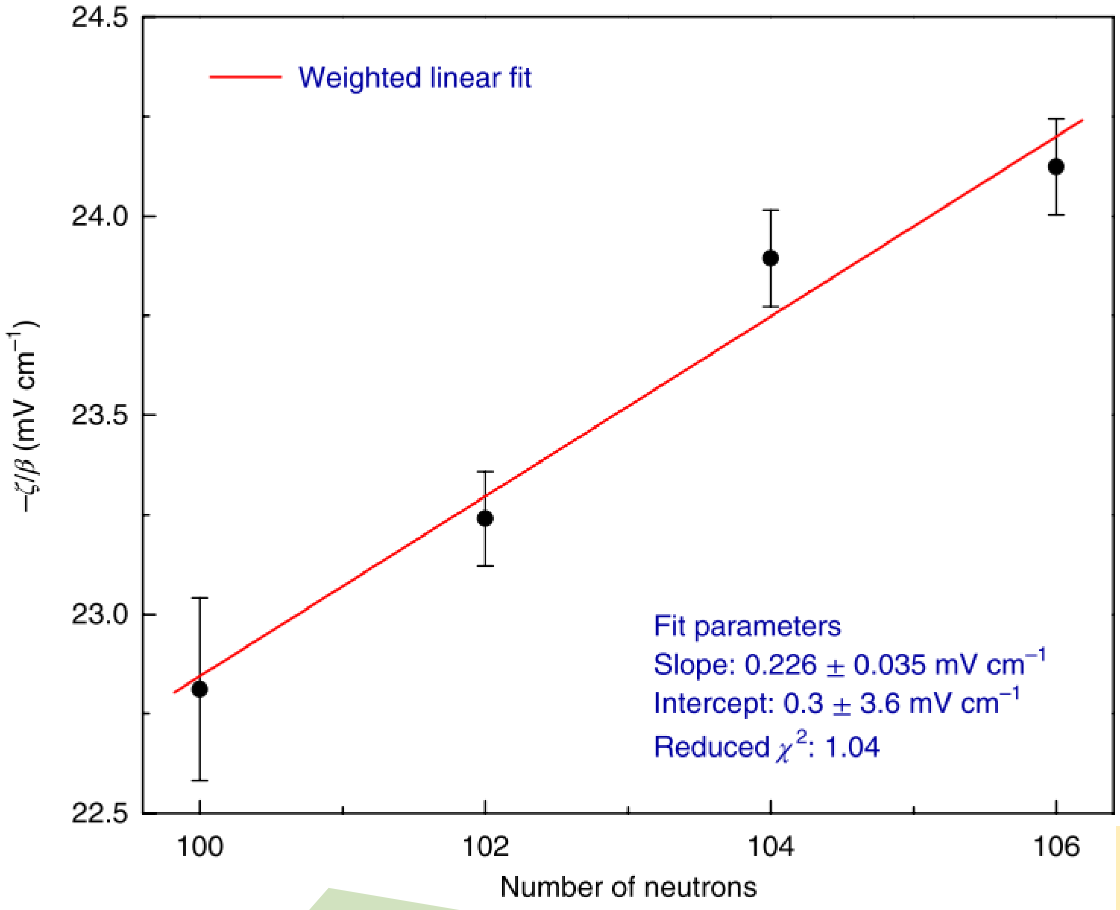
Same interference experiment as Cs.



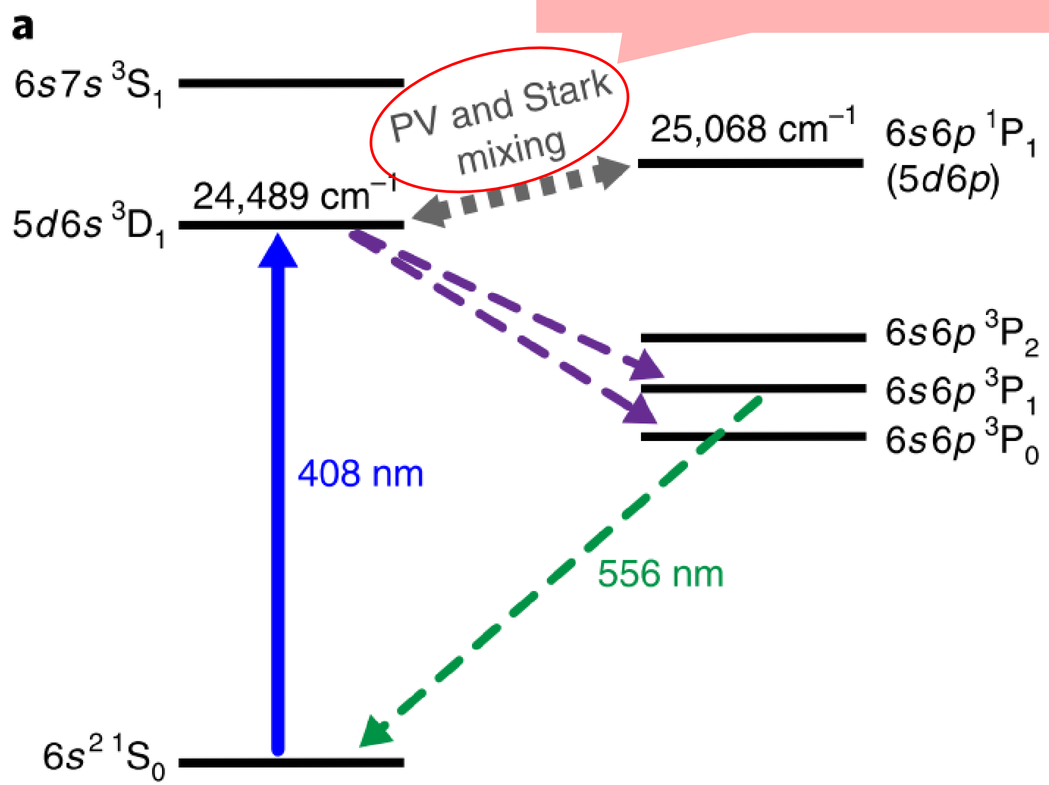


First demonstration of Weak charge dependence on neutron # in atomic system

- New result for APV in 2019, Antypas, *et al.*, Nat. Phys. 15, 120 (2019).
- Used Ytterbium; N = 170, 172, 174, and 176



Same interference experiment as Cs.



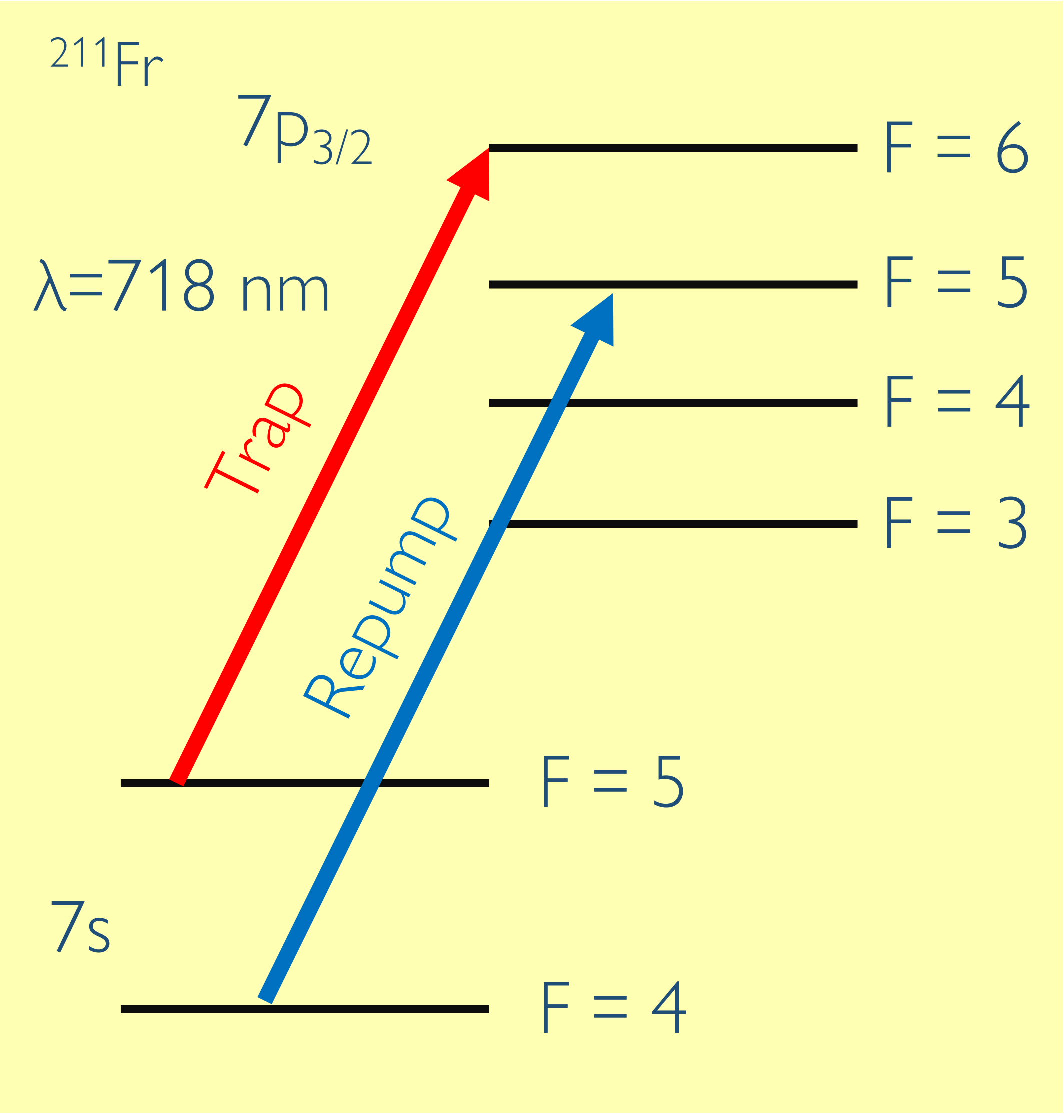
First demonstration of Weak charge dependence on neutron # in atomic system

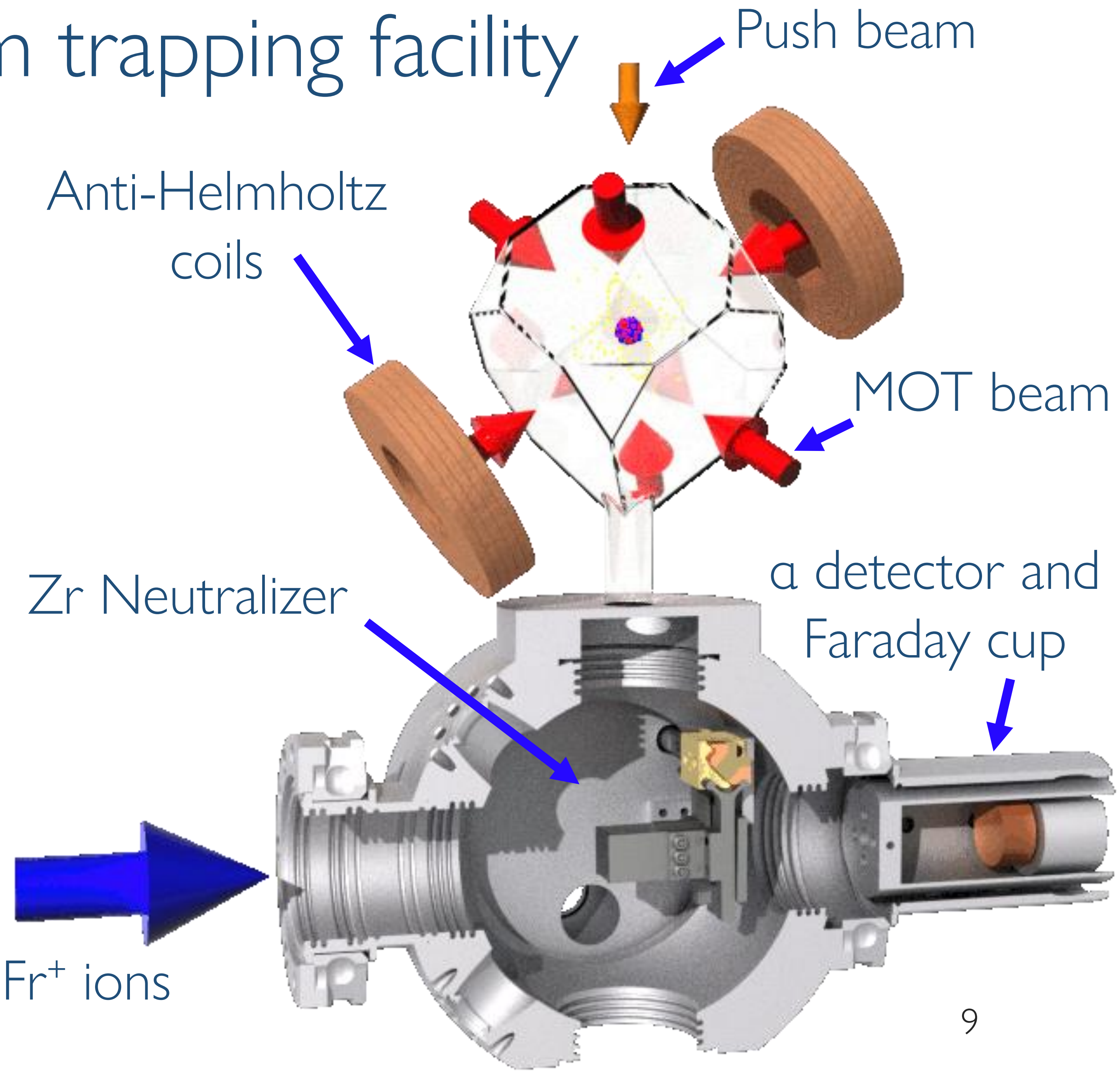
Single-isotope measurement accuracy 0.5%! But theory not at the same level of accuracy → Alkalis still have the upper hand

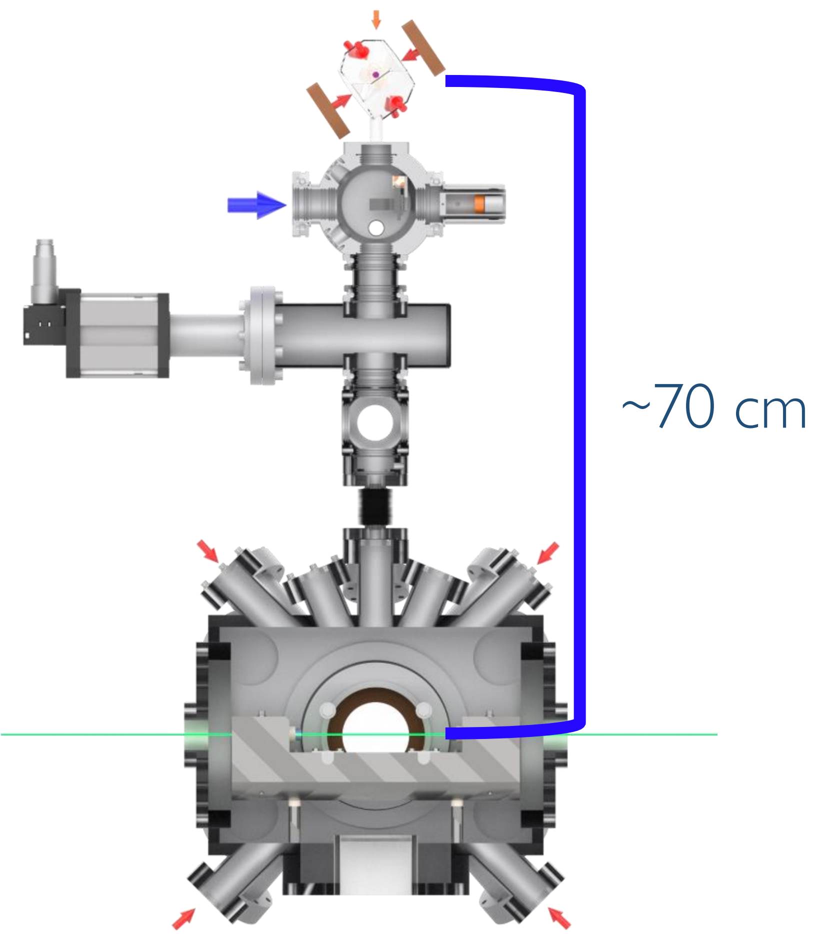
Future APV with francium

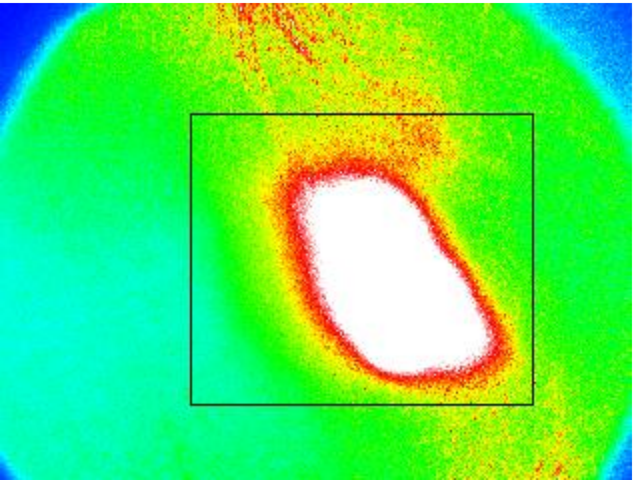
- Heaviest of the alkalis (Z=87)
  - APV ~18x larger than Cs
- Simple atomic structure → single valence electron
- Main drawback: highly radioactive
  - No abundant source on earth
- Need radioactive facility → ISAC I at TRIUMF
- Boulder group had thermal beam of 10^{13} Cs atoms/s → not feasible with Fr
- Solution: Use magneto-optical trap (MOT)
  - Need 10^6-10^7 trapped atoms to achieve comparable signal to Cs

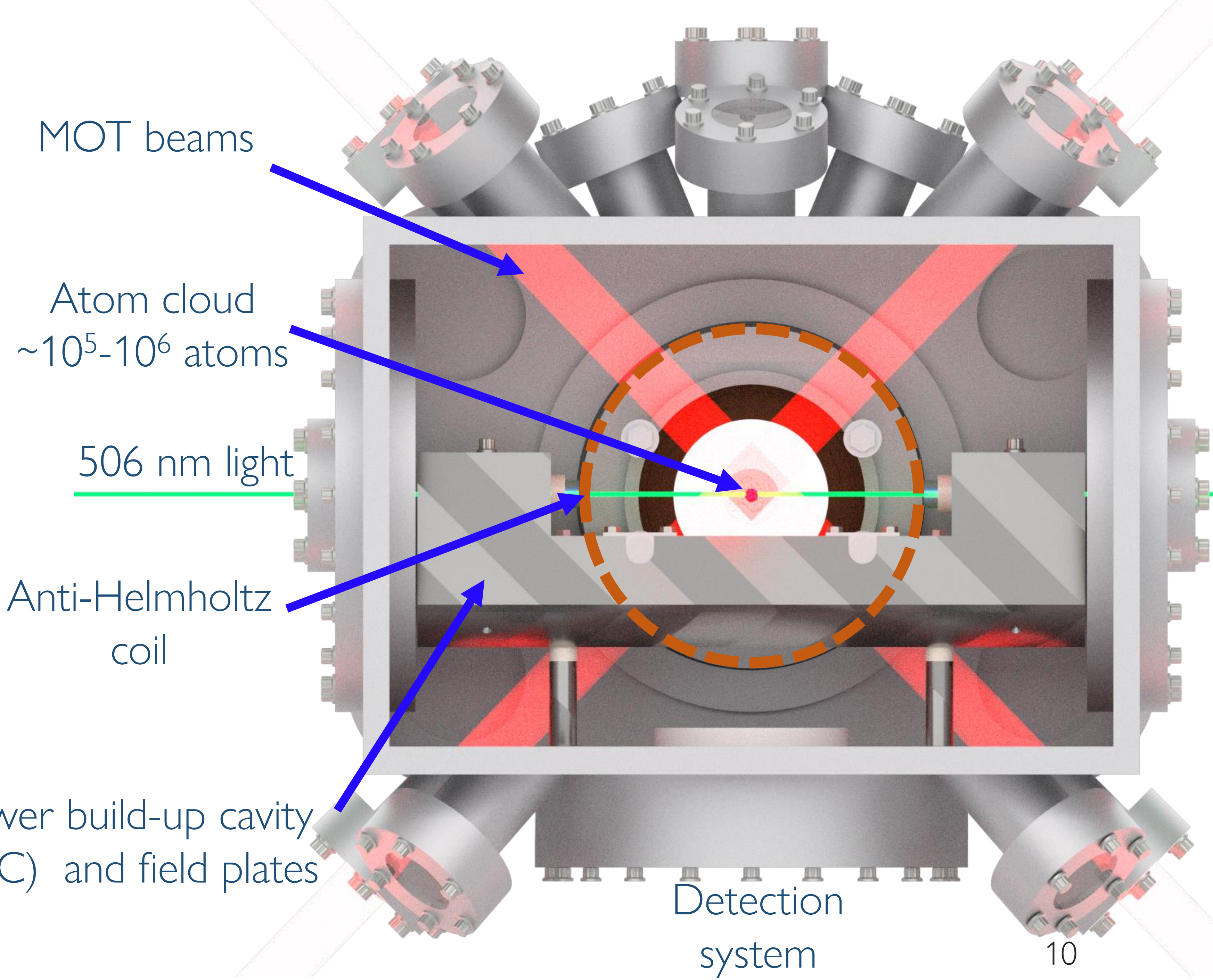
Francium trapping facility





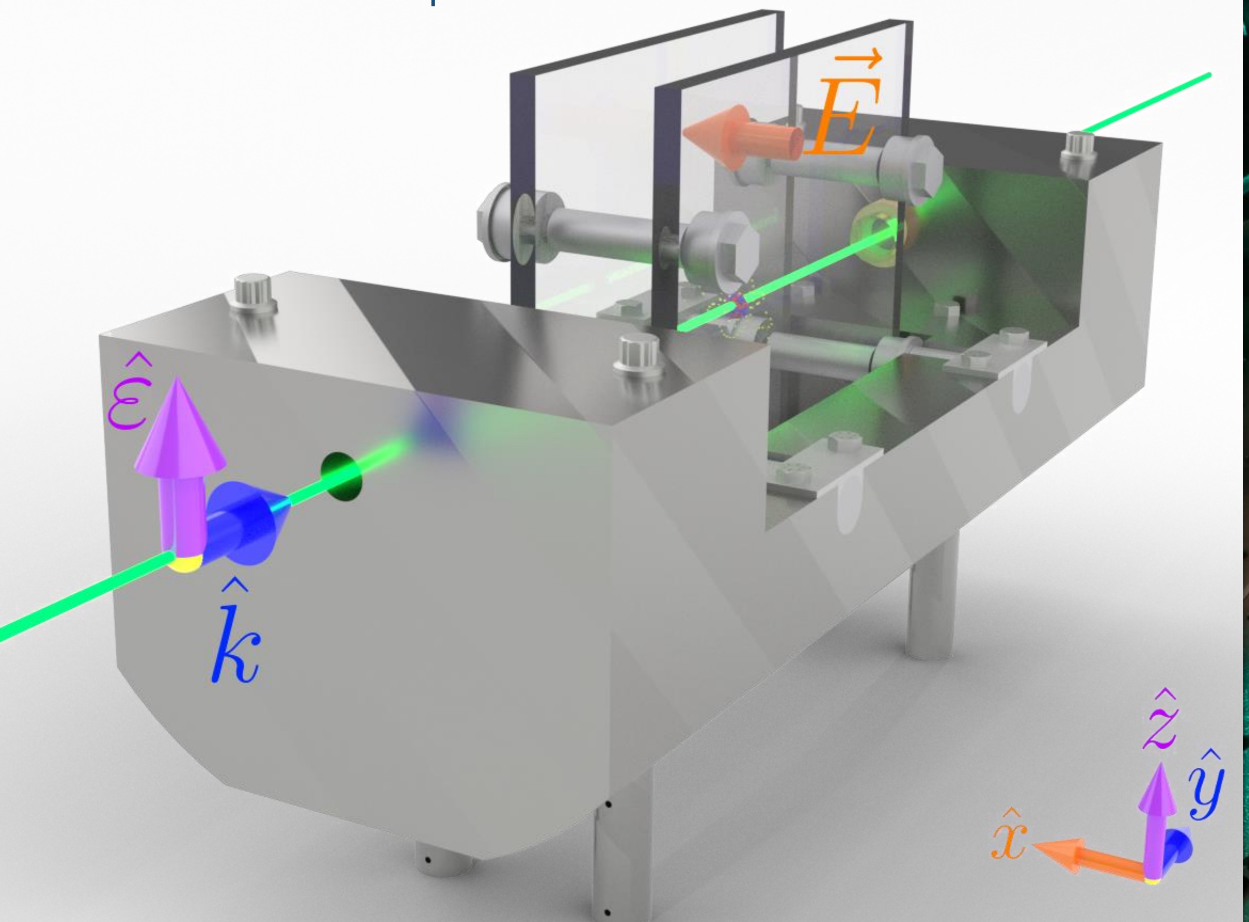

~70 cm

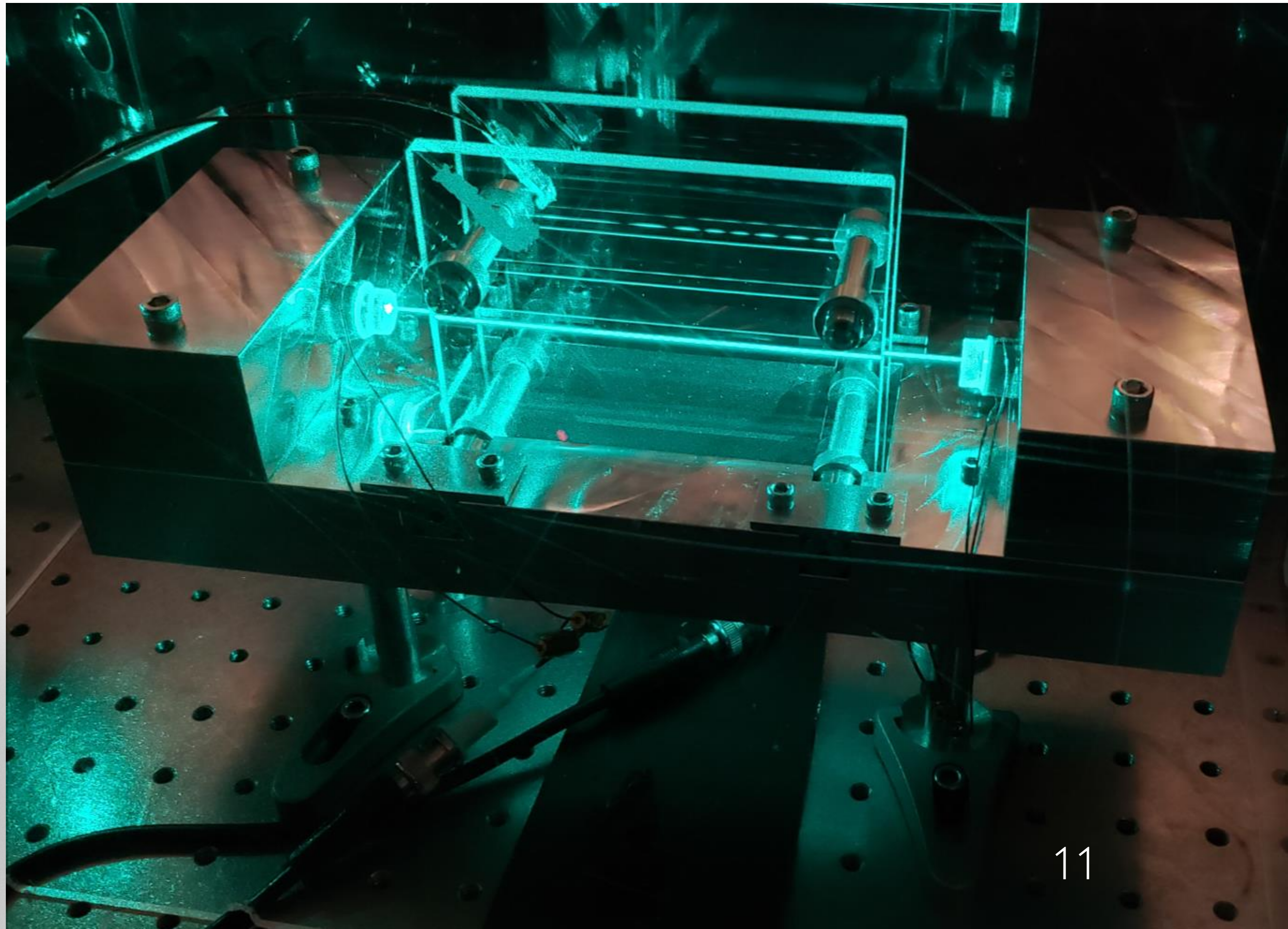



MOT beams
Atom cloud
~10^5-10^6 atoms
506 nm light
Anti-Helmholtz
coil
Power build-up cavity
(PBC) and field plates
Detection
system

Electric field plates and PBC

- Indium tin oxide (ITO) transparent field plates
  - Separation is 2.858 ± 0.003 cm
- PBC developed during the pandemic
- Build-up factor of ~4000





Previous Measurements

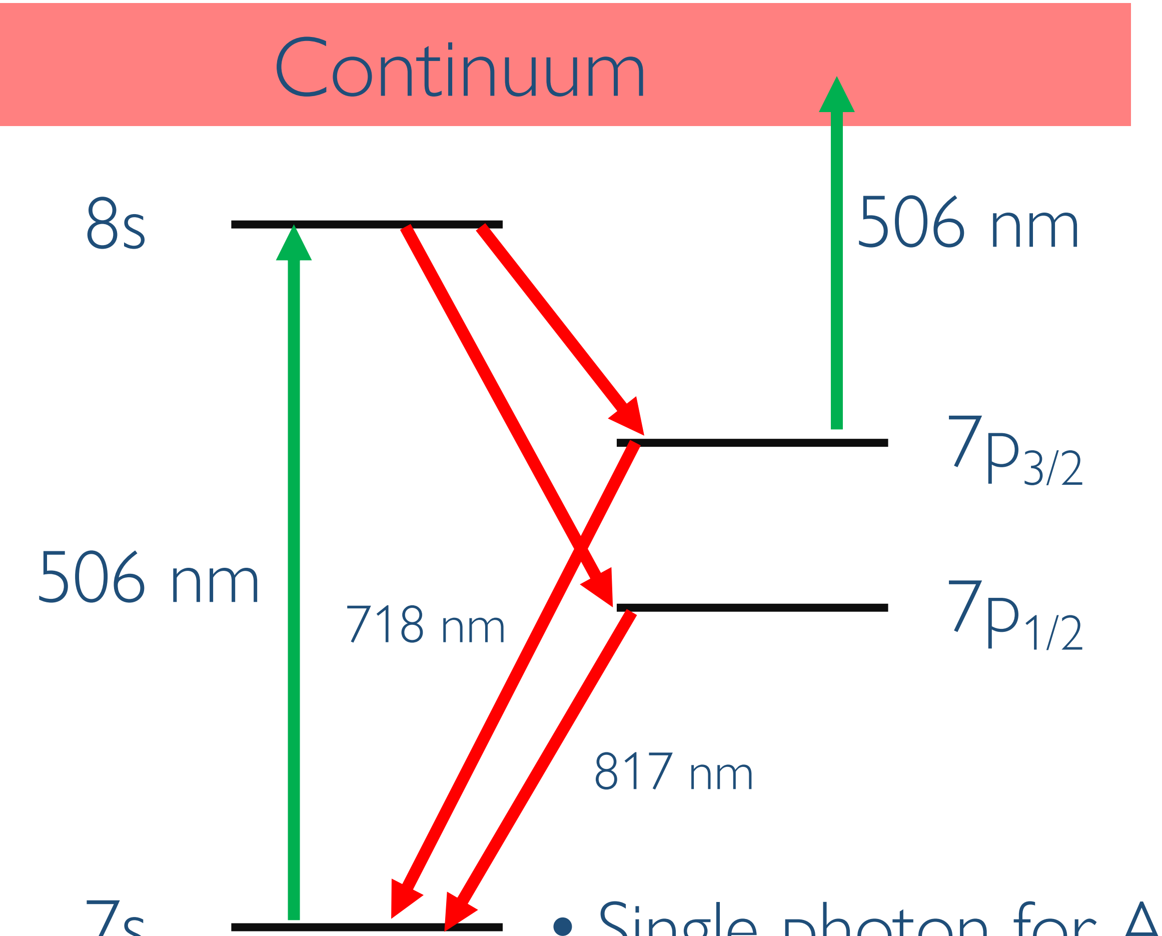
- Test atomic theory using allowed transitions
- 7s-7$p_{1/2}$ isotope shift in Fr → Collister, R., *et al.*, *PRA 90*, 052502 (2014)
- Hyperfine Anomaly in light Fr isotopes → Zhang, J. *et al.*, *PRL*, 115, 042501 (2015)
- Fr 7$p_{3/2}$ photoionization → Collister, R. *et al.*, *Can J Phys 95*(3), 234–237.
- 7s-8s isotope shift in Fr (2 photon) → Kalita, M. R. *et al.*, *PRA*, 97, 042507 (2018)

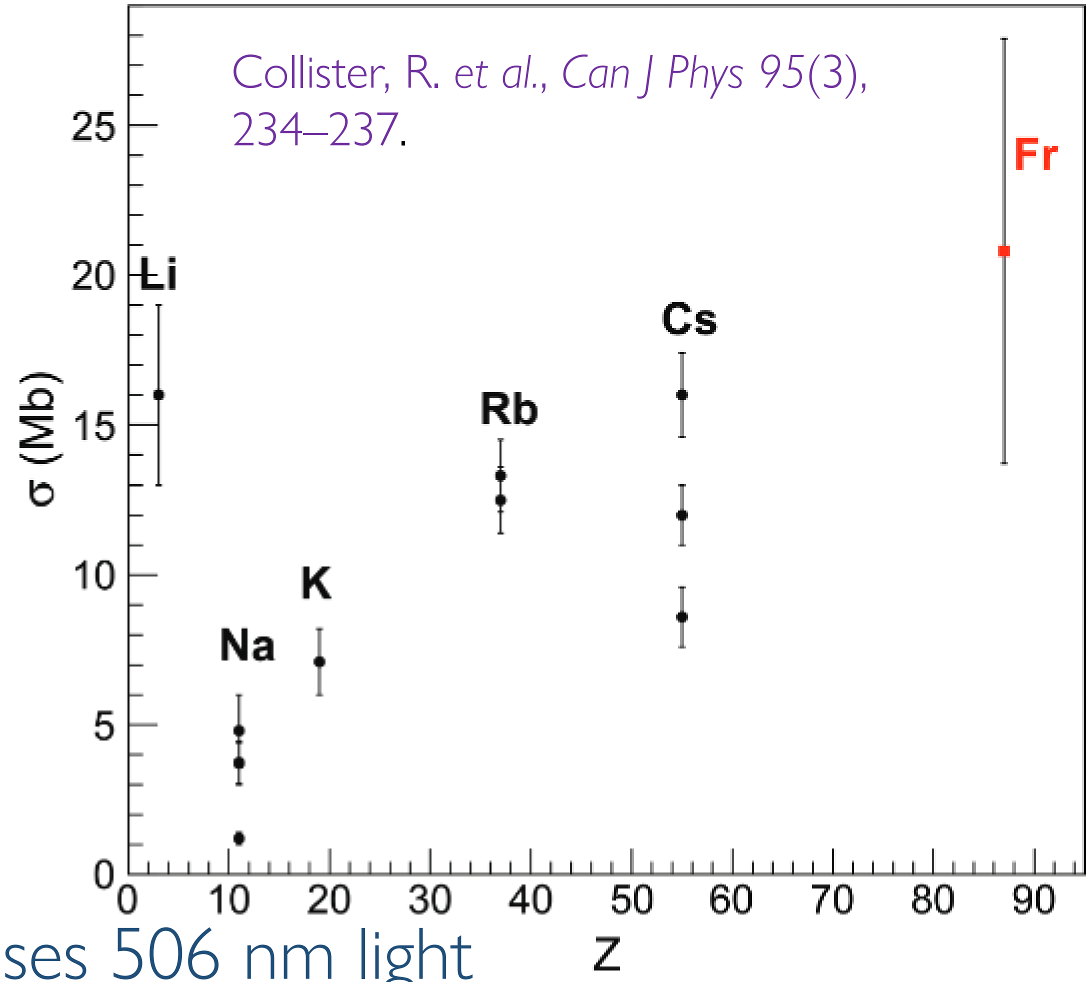
Previous Measurements

- Test atomic theory using allowed transitions
- 7s-7$p_{1/2}$ isotope shift in Fr → Collister, R., *et al.*, *PRA 90*, 052502 (2014)
- Hyperfine Anomaly in light Fr isotopes → Zhang, J. *et al.*, *PRL*, 115, 042501 (2015)
- Fr 7$p_{3/2}$ photoionization → Collister, R. *et al.*, *Can J Phys 95*(3), 234–237.
- 7s-8s isotope shift in Fr (2 photon) → Kalita, M. R. *et al.*, *PRA*, 97, 042507 (2018)

This is very important for any 7s-8s transition!

$7p_{3/2}$ photoionization

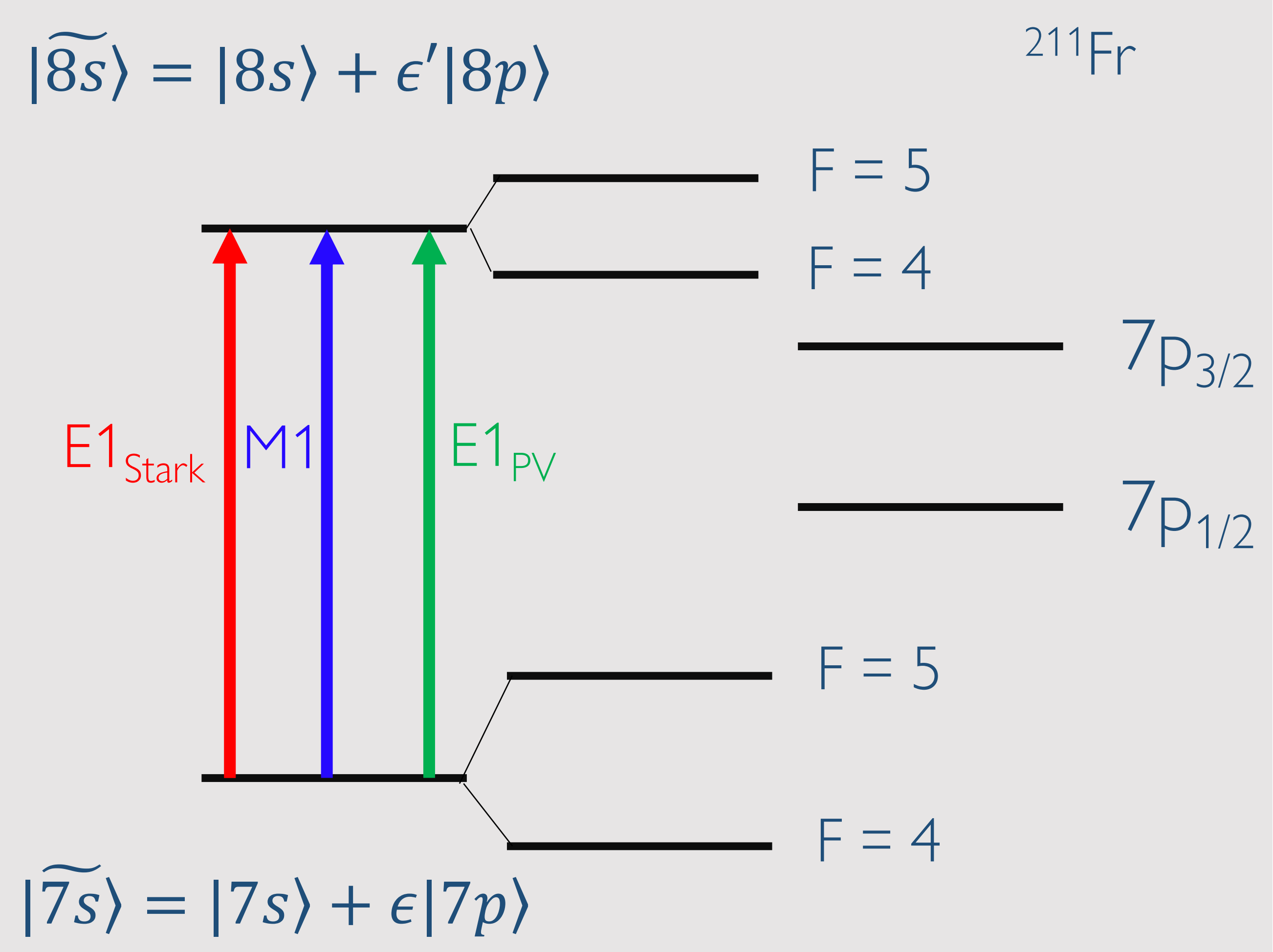




- Single photon for APV uses 506 nm light
- $7p_{3/2}$ populate via decay or trap
- Provides additional loss mechanism to the MOT
  - Enhanced with PBC

7s-8s transition

- s-s typically E1 and M1 forbidden
- Oscillator strengths:
- $f_{Stark} \sim 10^{-10}$ → for a few kV/cm
- $f_{M1} \sim 10^{-13}$
- $f_{PV} \sim 10^{-21}$
- APV to small to observe alone
- Observe interference between $E1_{Stark}$ and $E1_{PV}$



- Reversal of coordinate system → change in sign of interference term
  - Example: electric field reversal
- $R_{7s-8s} \propto |E1_{Stark} + M1 + E1_{PV}|^2$

7s-8s transition rate

$$R_{7s-8s} \propto |\alpha\left(\hat{\varepsilon} \cdot \vec{E}\right)\delta_{mm'} + (\beta\left(\hat{\varepsilon} \times \vec{E}\right) + M + \mathrm{Im}(\mathcal{E}1_{PV}))\langle F'm'|\vec{\sigma}|Fm\rangle|^2$$

7s-8s transition rate

$$R_{7s-8s} \propto |\alpha(\hat{\varepsilon} \cdot \vec{E})\delta_{mm'} + (\beta(\hat{\varepsilon} \times \vec{E}) + M + \mathrm{Im}(\mathcal{E}1_{PV}))\langle F'm'|\vec{\sigma}|Fm\rangle|^2$$

- Stark-induced components
- α and $\beta \longrightarrow$ scalar and tensor polarizabilities, respectively
- $\alpha \longrightarrow$ ΔF=0
- $\beta \longrightarrow$ ΔF=0, ±1
- α/β ~ 5.05

7s-8s transition rate

$$R_{7s-8s} \propto |\alpha(\hat{\varepsilon} \cdot \vec{E})\delta_{mm'} + (\beta(\hat{\varepsilon} \times \vec{E}) + M + \mathrm{Im}(\mathcal{E}1_{PV}))\langle F'm'|\vec{\sigma}|Fm\rangle|^2$$

- Stark-induced components
- α and $\beta \longrightarrow$ scalar and tensor polarizabilities, respectively
- $\alpha \longrightarrow \Delta F=0$
- $\beta \longrightarrow \Delta F=0, \pm 1$
- $\alpha/\beta \sim 5.05$

- M1 component
- $M = M_{rel} \pm M_{hf}\delta_{FF'\pm 1}$
- For Fr, M_{hf} ~12% contribution to M

7s-8s transition rate

PV contribution

$$R_{7s-8s} \propto \left|\alpha\left(\hat{\varepsilon}\cdot\vec{E}\right)\delta_{mm'} + \left(\beta\left(\hat{\varepsilon}\times\vec{E}\right) + M + \mathrm{Im}(\mathcal{E}1_{PV})\right)\langle F'm'|\vec{\sigma}|Fm\rangle\right|^2$$

- Stark-induced components
- α and $\beta \longrightarrow$ scalar and tensor polarizabilities, respectively
- $\alpha \longrightarrow \Delta F=0$
- $\beta \longrightarrow \Delta F=0, \pm 1$
- $\alpha/\beta \sim 5.05$

- M1 component
- $M = M_{rel} \pm M_{hf}\delta_{FF'\pm 1}$
- For Fr, M_{hf} ~12% contribution to M

7s-8s transition rate

PV contribution

$$R_{7s-8s} \propto |\alpha(\hat{\varepsilon}\cdot\vec{E})\delta_{mm'} + (\beta(\hat{\varepsilon}\times\vec{E}) + M + \mathrm{Im}(\mathcal{E}1_{PV}))\langle F'm'|\vec{\sigma}|Fm\rangle|^2$$

- Stark-induced components
- α and $\beta \longrightarrow$ scalar and tensor polarizabilities, respectively
- $\alpha \longrightarrow \Delta F=0$
- $\beta \longrightarrow \Delta F=0, \pm 1$
- $\alpha/\beta \sim 5.05$

- M1 component
- $M = M_{rel} \pm M_{hf}\delta_{FF'\pm 1}$
- For Fr, M_{hf} ~12% contribution to M

- We use $\Delta F=\pm 1$ to avoid α
- To get $\mathcal{E}1_{PV}$ we need $\beta, M_{rel},$ and M_{hf} to sub-%

Importance of M1

- β cannot be measured alone → measure against M1

$$\frac{M_{rel} \pm M_{hf}\delta_{FF'\pm 1}}{\beta}$$

Importance of M1

- β cannot be measured alone → measure against M1

$$\frac{M_{rel} \pm M_{hf}\delta_{FF'\pm 1}}{\beta}$$

Needed for $E1_{Stark}$–$E1_{PV}$ interference experiment. Can be calculated reasonably well.

Importance of M1

- β cannot be measured alone → measure against M1

Extremely difficult to calculate. Has only been measured in Cs.

$$\frac{M_{rel} \pm M_{hf}\,\delta_{FF'\pm1}}{\beta}$$

Needed for $E1_{Stark}$–$E1_{PV}$ interference experiment. Can be calculated reasonably well.

Importance of M1

- β cannot be measured alone → measure against M1

Extremely difficult to calculate. Has only been measured in Cs.

$$\frac{M_{rel} \pm M_{hf}\delta_{FF'\pm 1}}{\beta}$$

Calculate semi-empirically.

$$M_{hf} = \frac{-\sqrt{\Delta E_{7s}^{hf}\,\Delta E_{8s}^{hf}}}{E_{8s} - E_{7s}}$$

Needed for $E1_{Stark}$–$E1_{PV}$ interference experiment. Can be calculated reasonably well.

Importance of M1

- β cannot be measured alone → measure against M1

Extremely difficult to calculate. Has only been measured in Cs.

$$\frac{M_{rel} \pm M_{hf}\,\delta_{FF'\pm1}}{\beta}$$

Calculate semi-empirically.

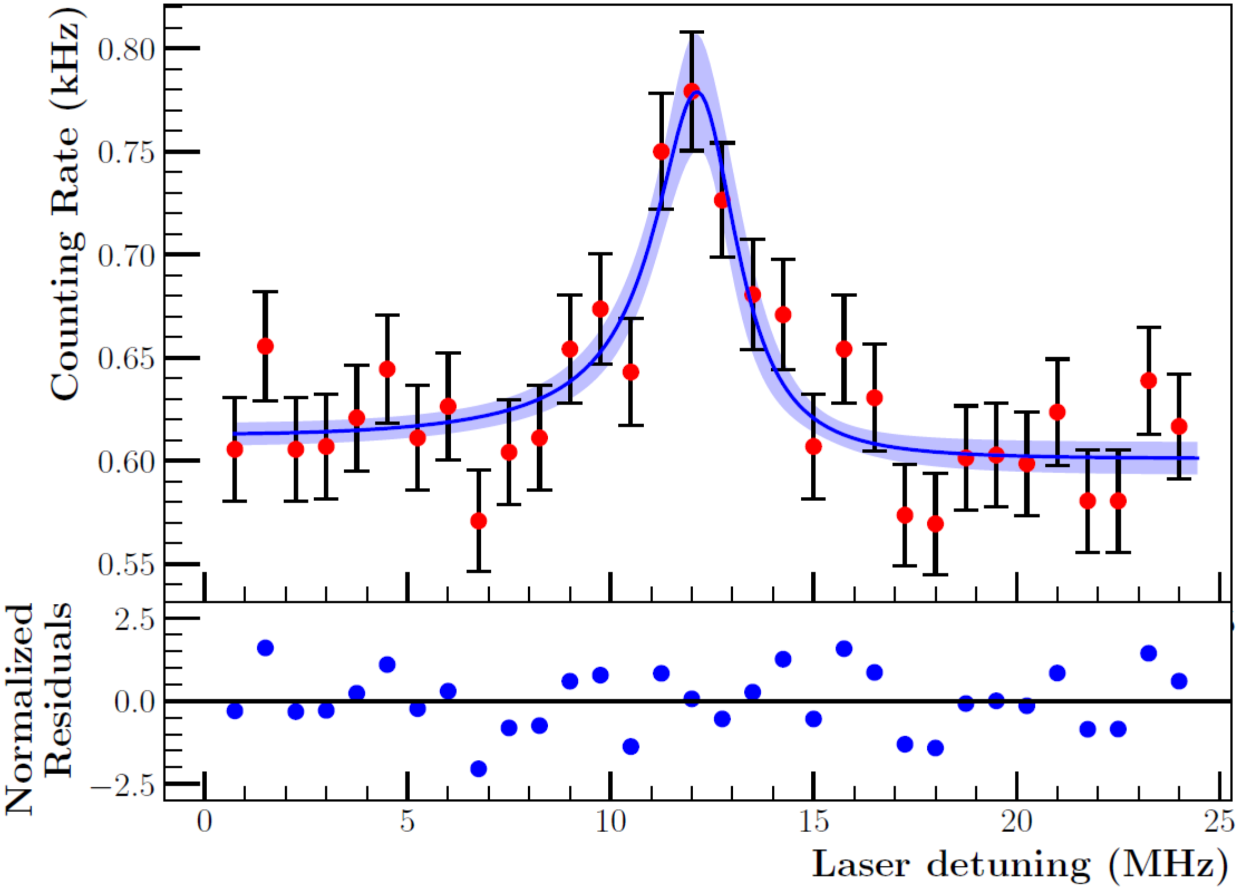
$$M_{hf} = \frac{-\sqrt{\Delta E^{hf}_{7s}\,\Delta E^{hf}_{8s}}}{E_{8s} - E_{7s}}$$

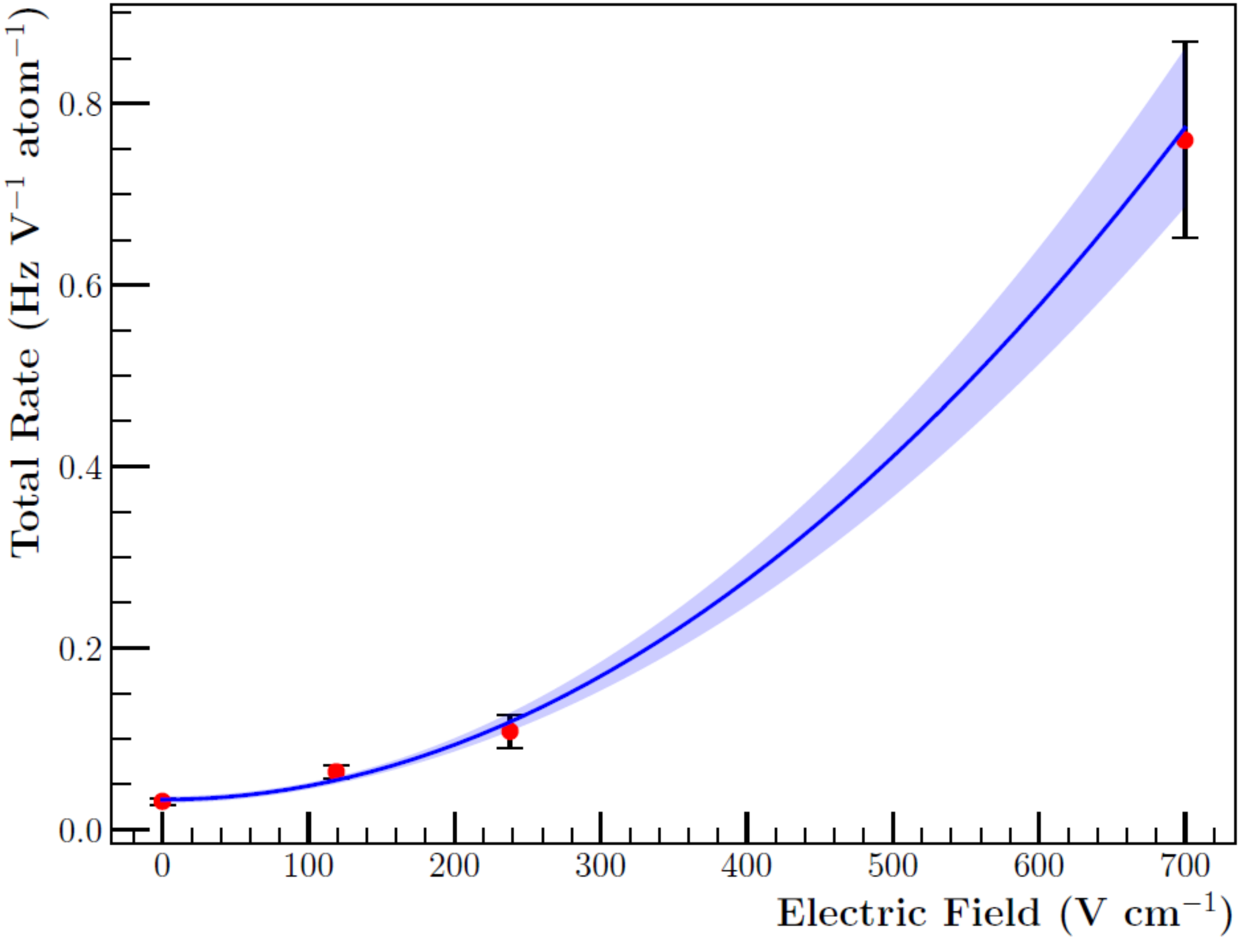
Needed for $E1_{Stark}$–$E1_{PV}$ interference experiment. Can be calculated reasonably well.

- We can use M_{hf} to determine β and then M_{rel} in a series of measurements
- Need to measure the ratio for ΔF=±1

Recent Measurement

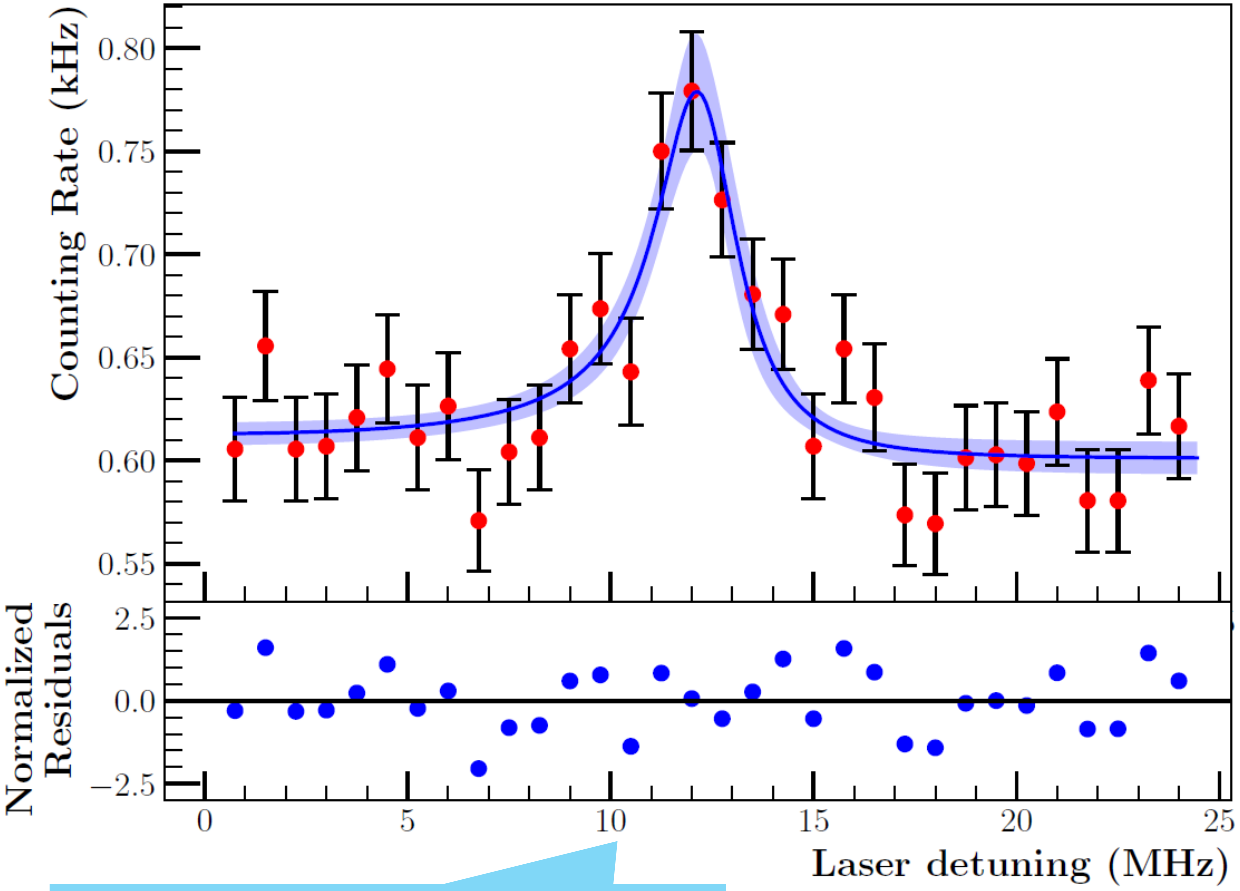
- September 2021: Observed M1 using PBC
- First measurement of M_{rel} in francium



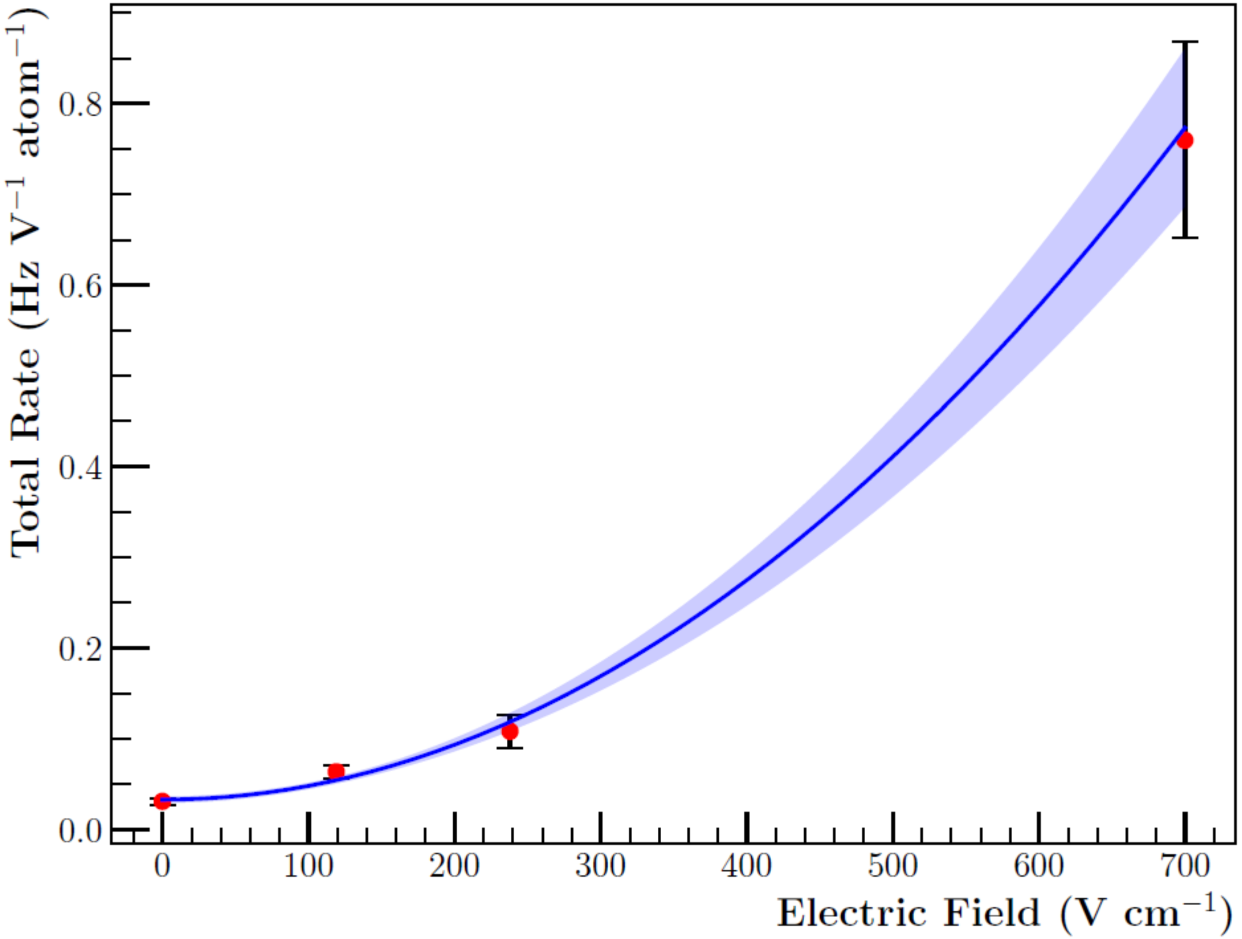


Recent Measurement

- September 2021: Observed M1 using PBC
- First measurement of M_{rel} in francium



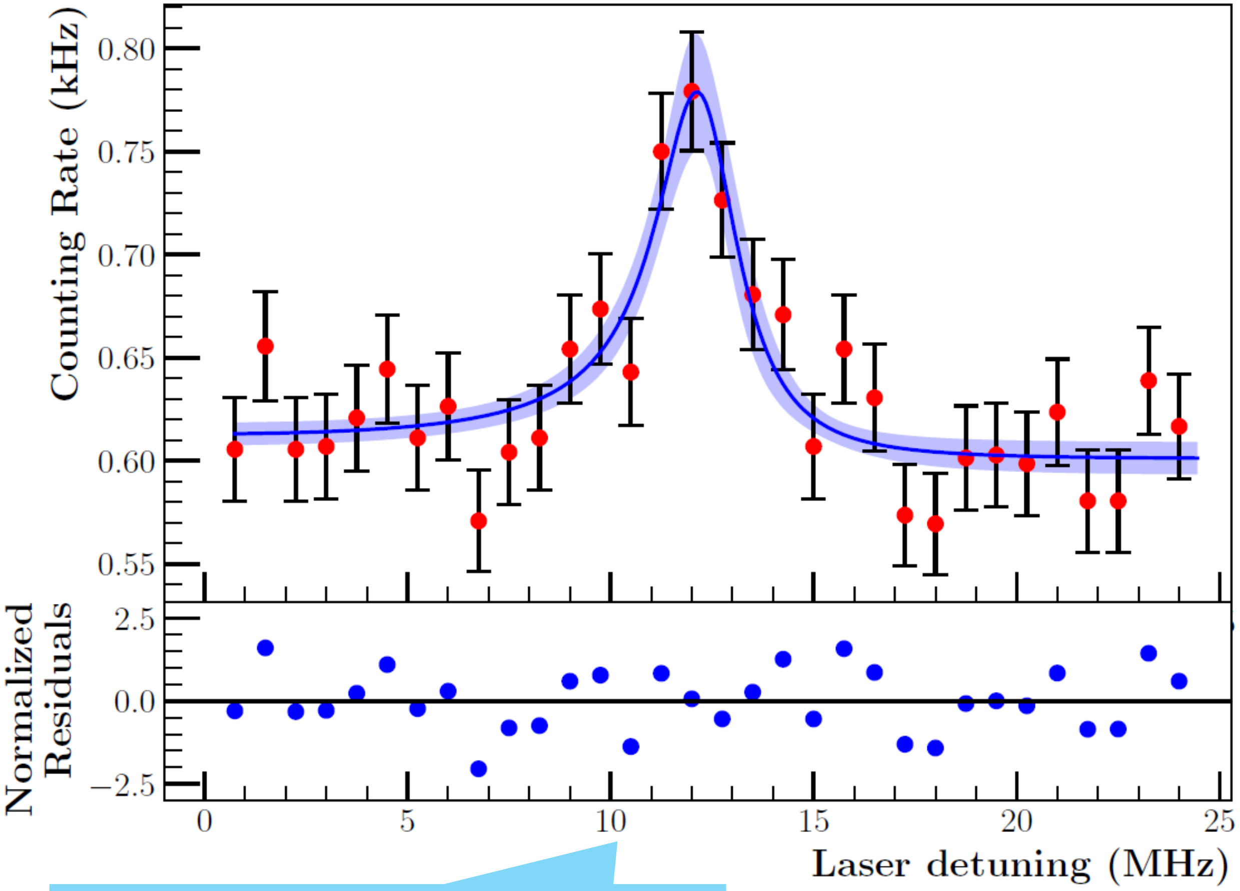
M1 transition @ 0 V/cm

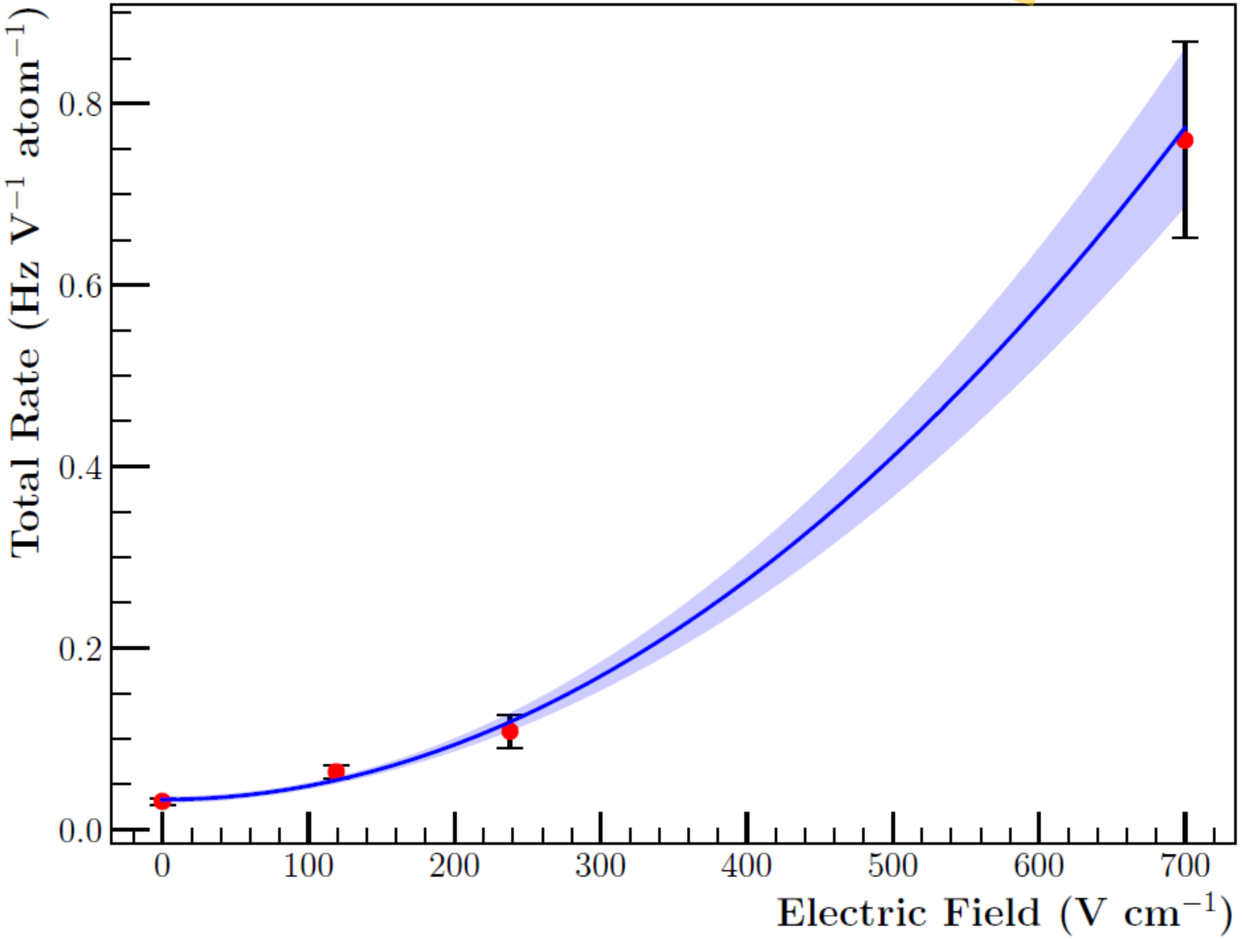


Recent Measurement

- September 2021: Observed M1 using PBC
- First measurement of M_{rel} in francium

Measured transition rate for ΔF = -1 transition



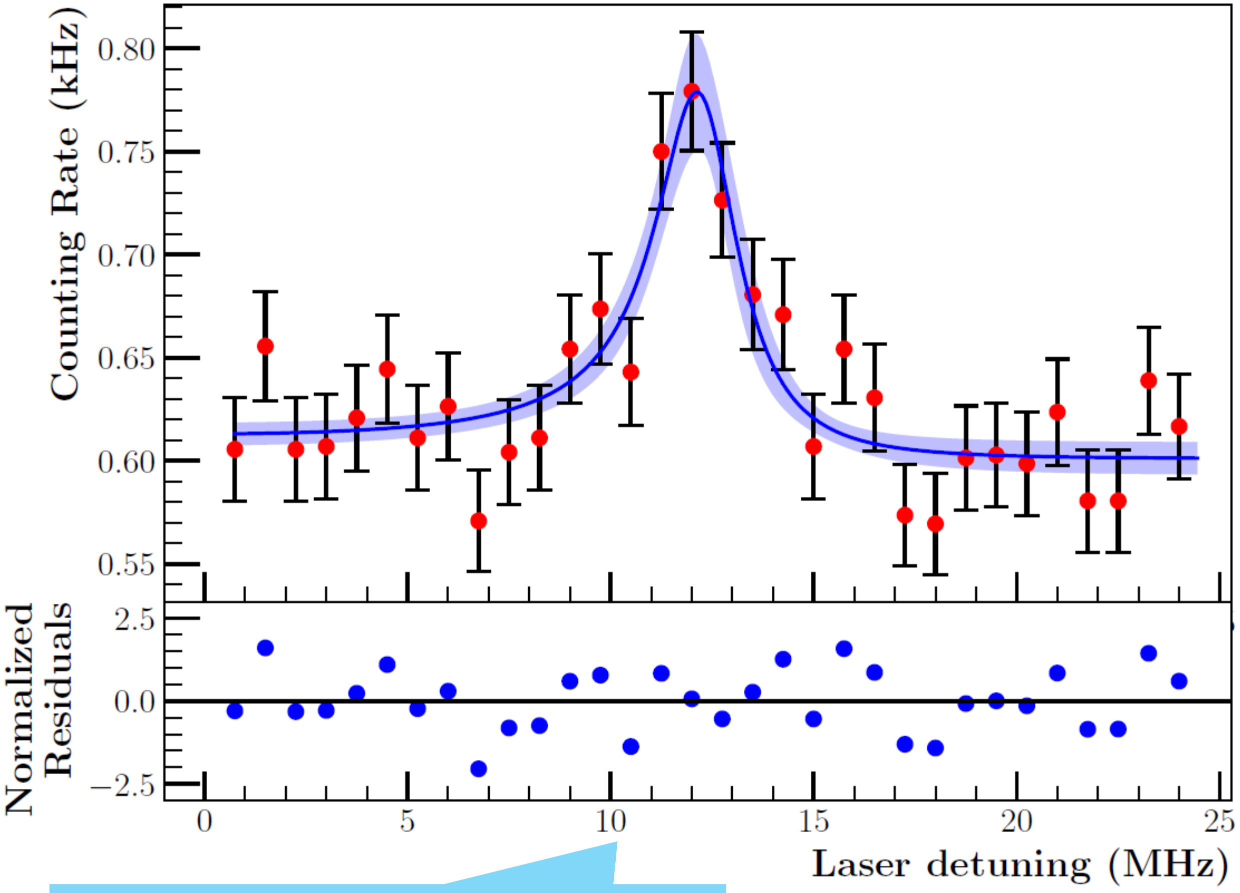


M1 transition @ 0 V/cm

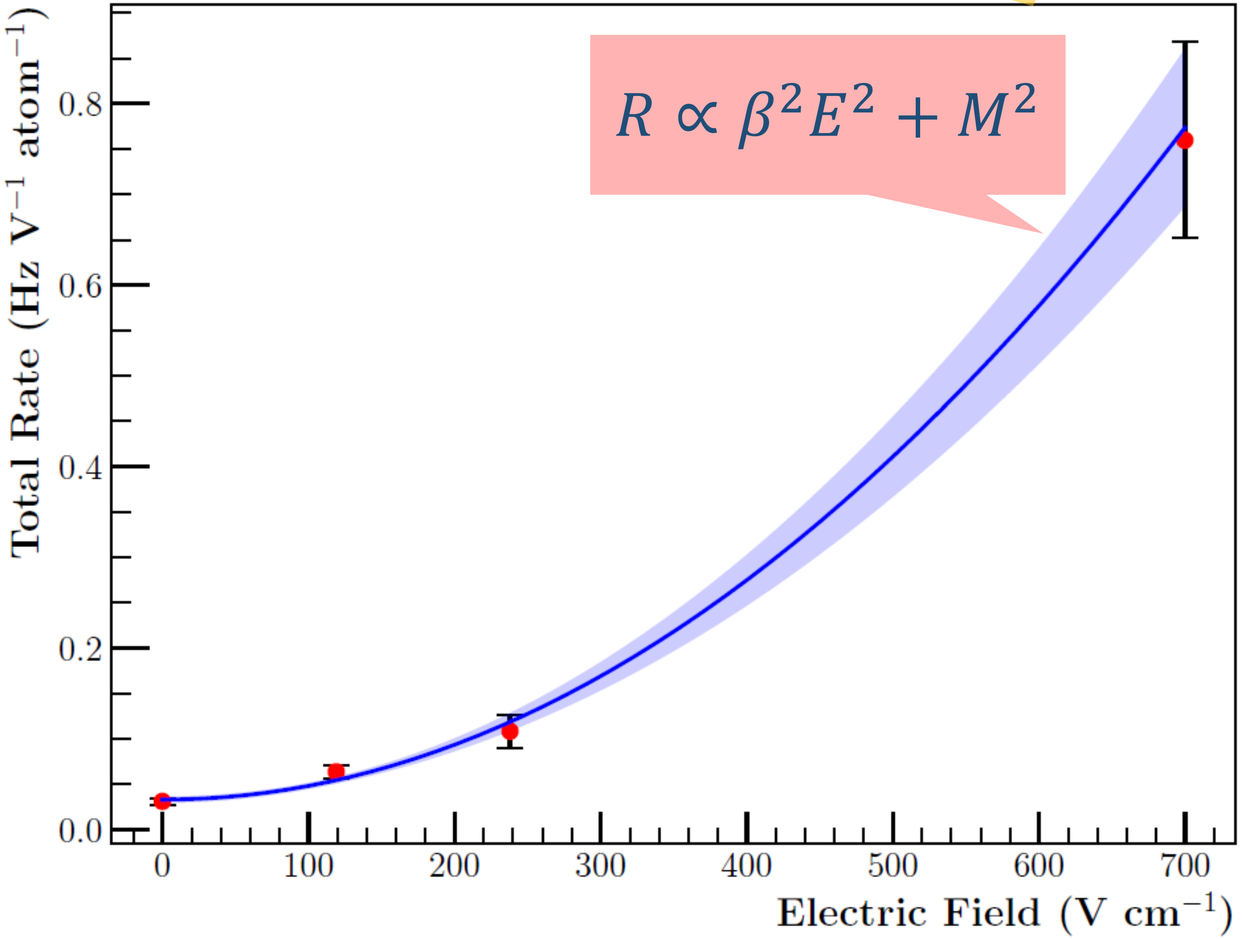
Recent Measurement

- September 2021: Observed M1 using PBC
- First measurement of M_{rel} in francium

Measured transition rate for ΔF = -1 transition



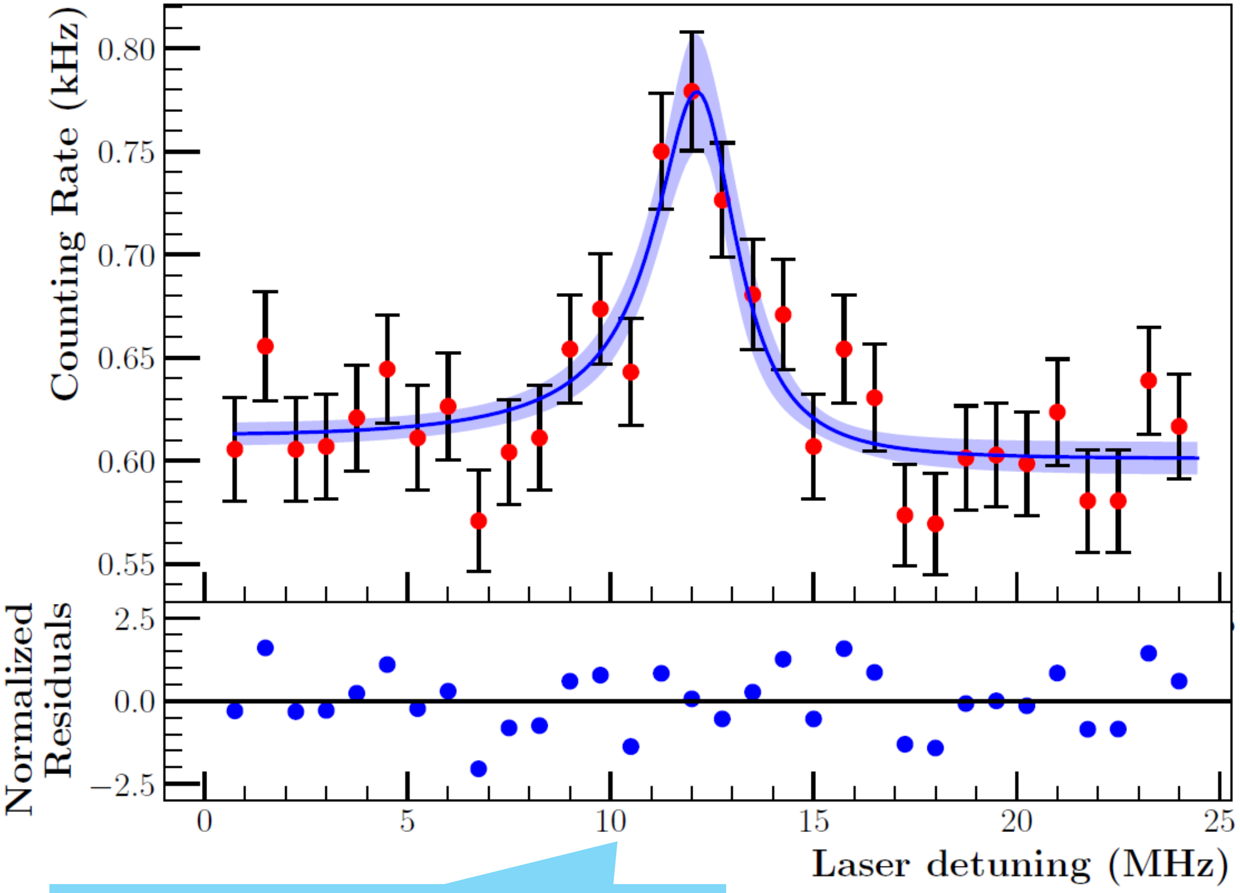
M1 transition @ 0 V/cm



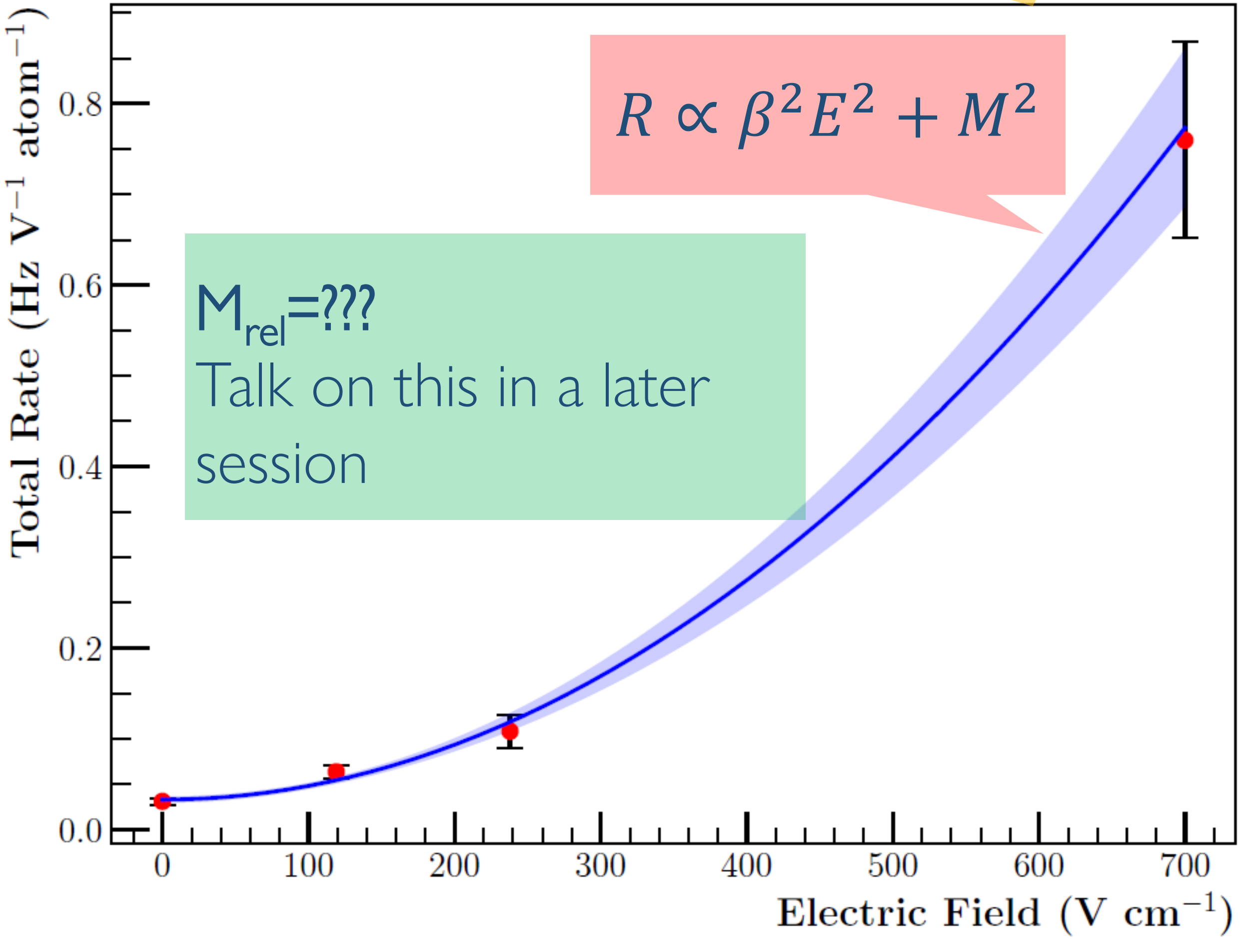
Recent Measurement

- September 2021: Observed M1 using PBC
- First measurement of M_{rel} in francium

Measured transition rate for ΔF = -1 transition



M1 transition @ 0 V/cm



$R \propto \beta^2 E^2 + M^2$

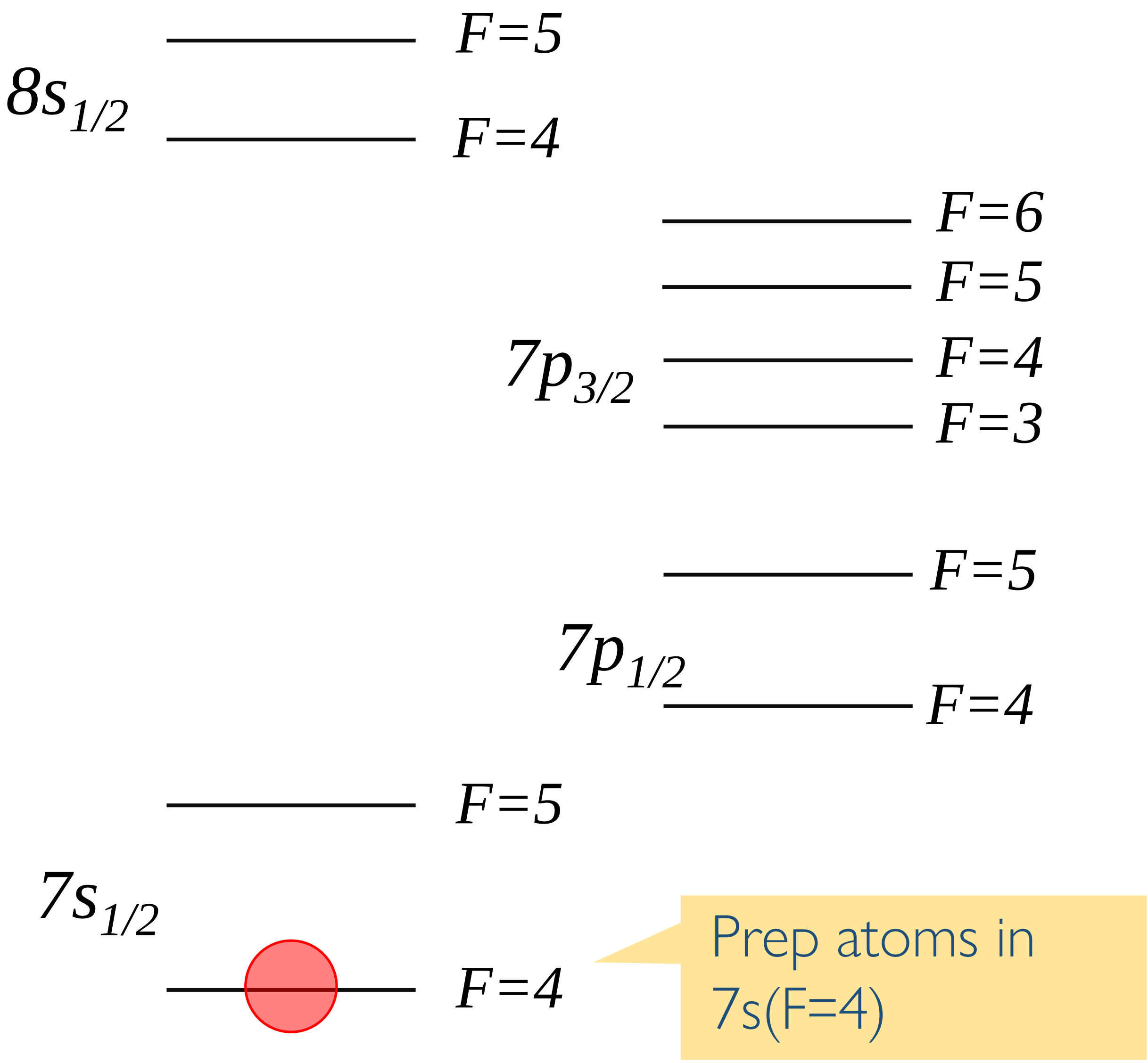
M_{rel}=???
Talk on this in a later session

Recent development: Burst technique

- Further amplification of signal is needed for APV
- Detection efficiency is ~1/4500
- Cycle atoms that have been excited via 7s-8s
- Estimate 10^4 to 10^5 cycles for Fr

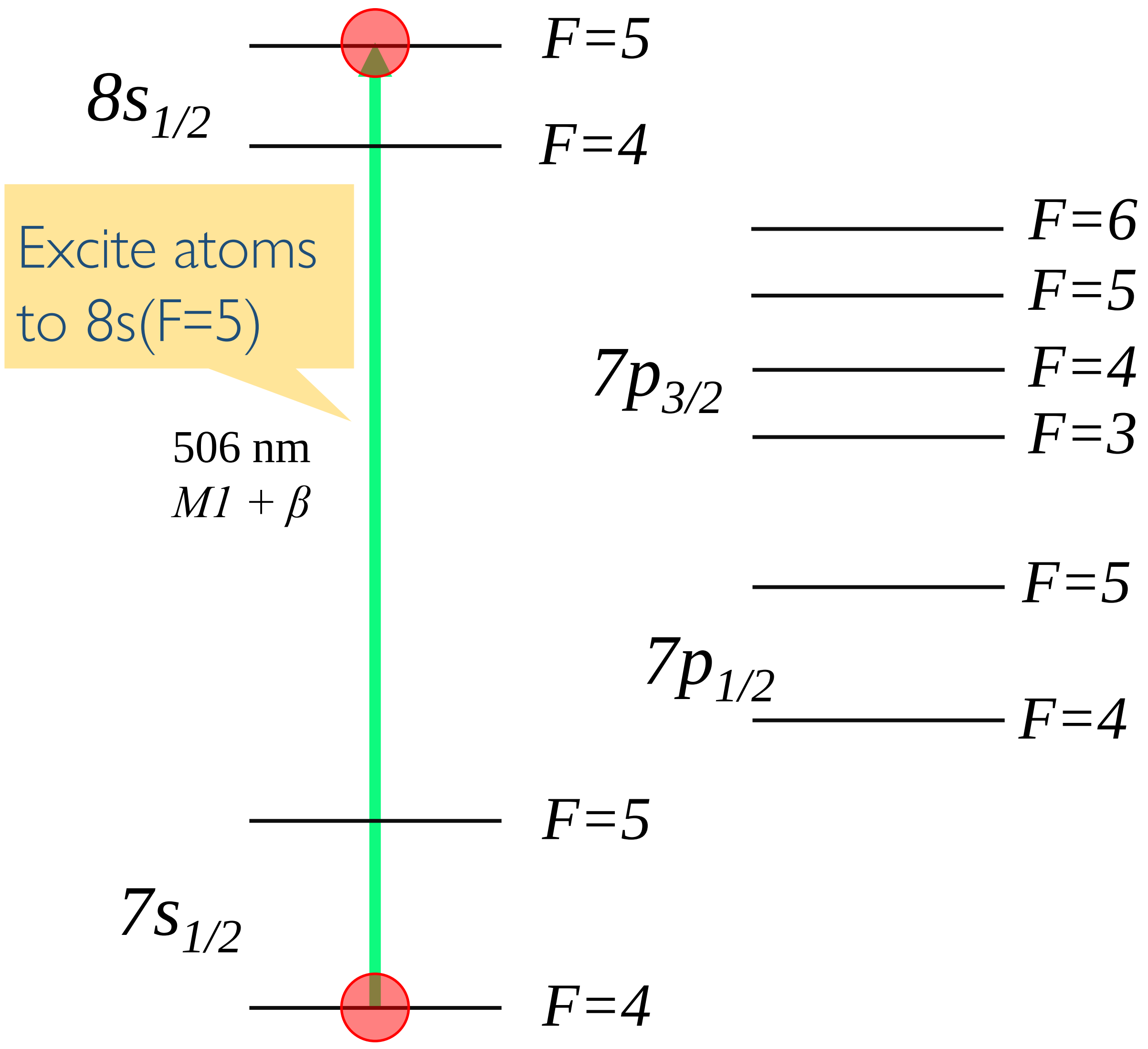
Recent development: Burst technique

- Further amplification of signal is needed for APV
- Detection efficiency is ~1/4500
- Cycle atoms that have been excited via 7s-8s
- Estimate 10^4 to 10^5 cycles for Fr



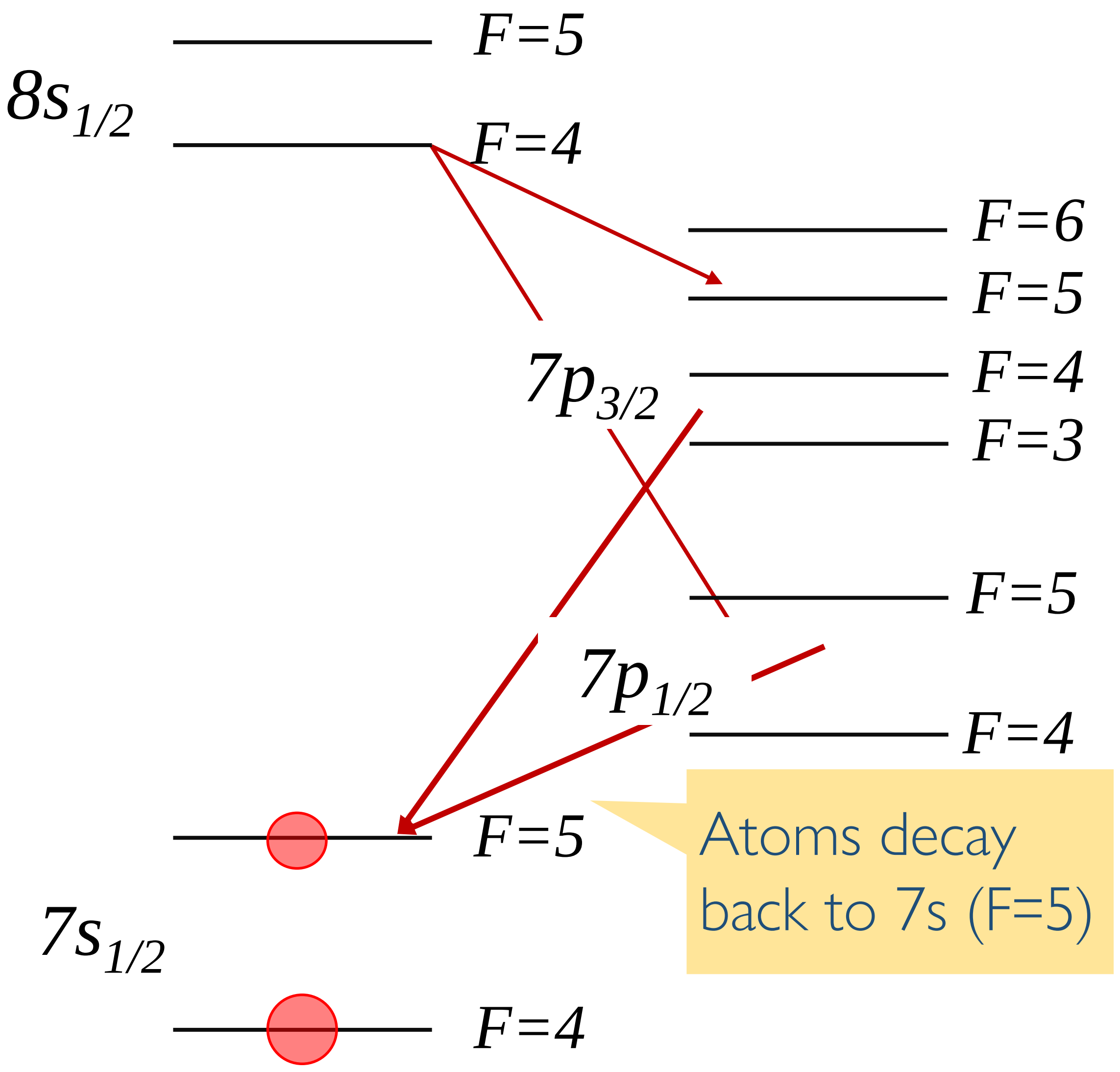
Recent development: Burst technique

- Further amplification of signal is needed for APV
- Detection efficiency is ~1/4500
- Cycle atoms that have been excited via 7s-8s
- Estimate 10^4 to 10^5 cycles for Fr



Recent development: Burst technique

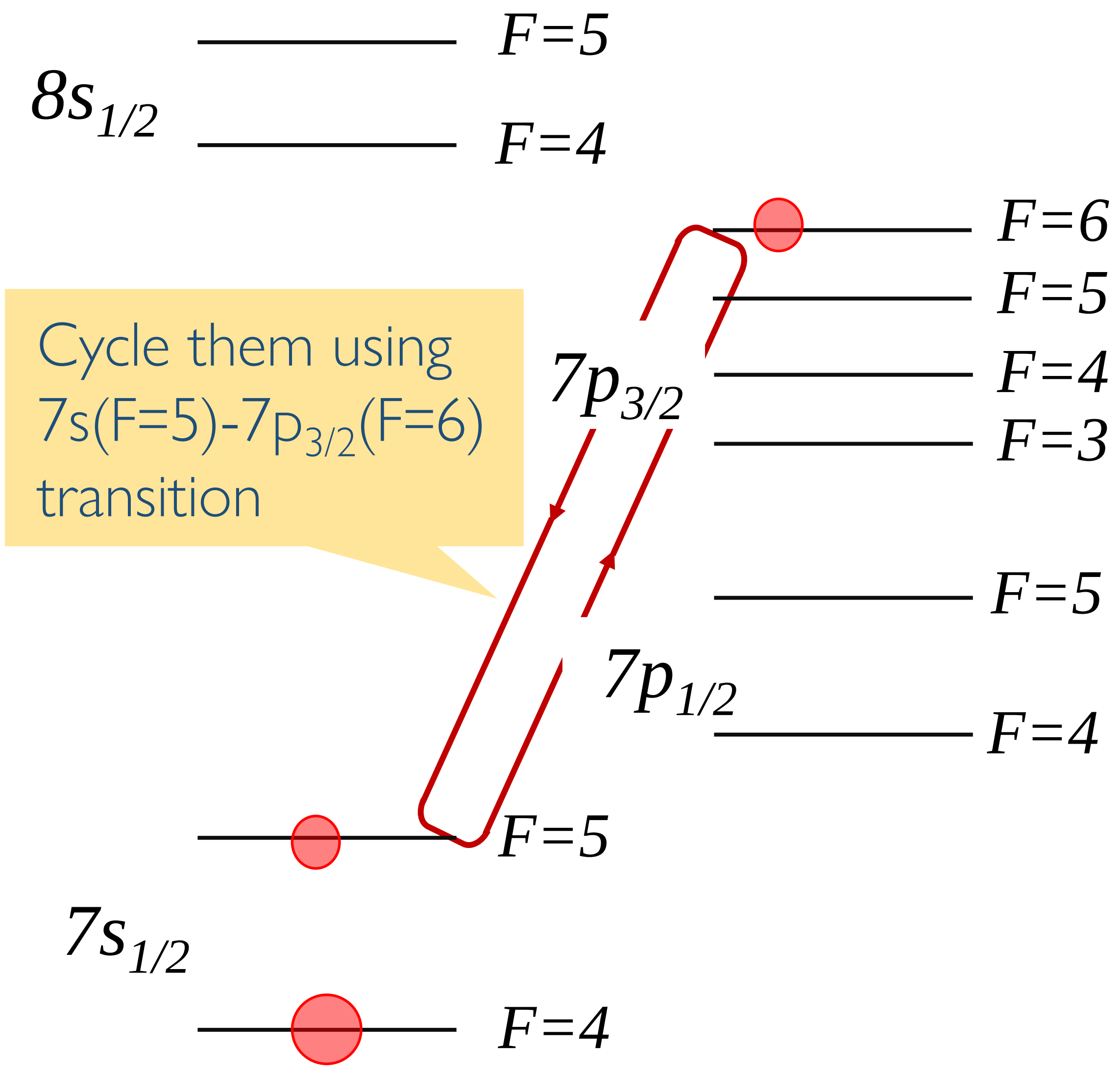
- Further amplification of signal is needed for APV
- Detection efficiency is ~1/4500
- Cycle atoms that have been excited via 7s-8s
- Estimate 10^4 to 10^5 cycles for Fr



Recent development: Burst technique

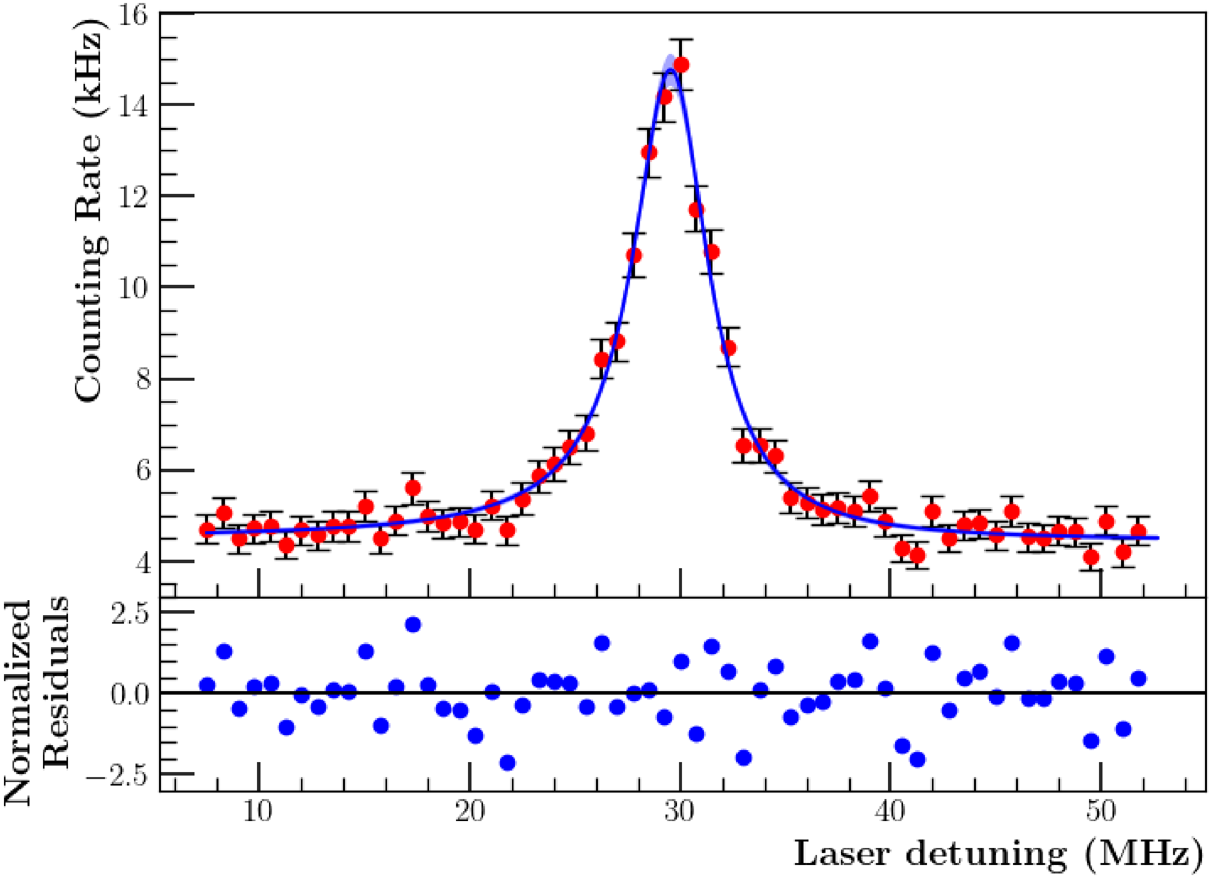
- Further amplification of signal is needed for APV
- Detection efficiency is ~1/4500
- Cycle atoms that have been excited via 7s-8s
- Estimate 10^4 to 10^5 cycles for Fr

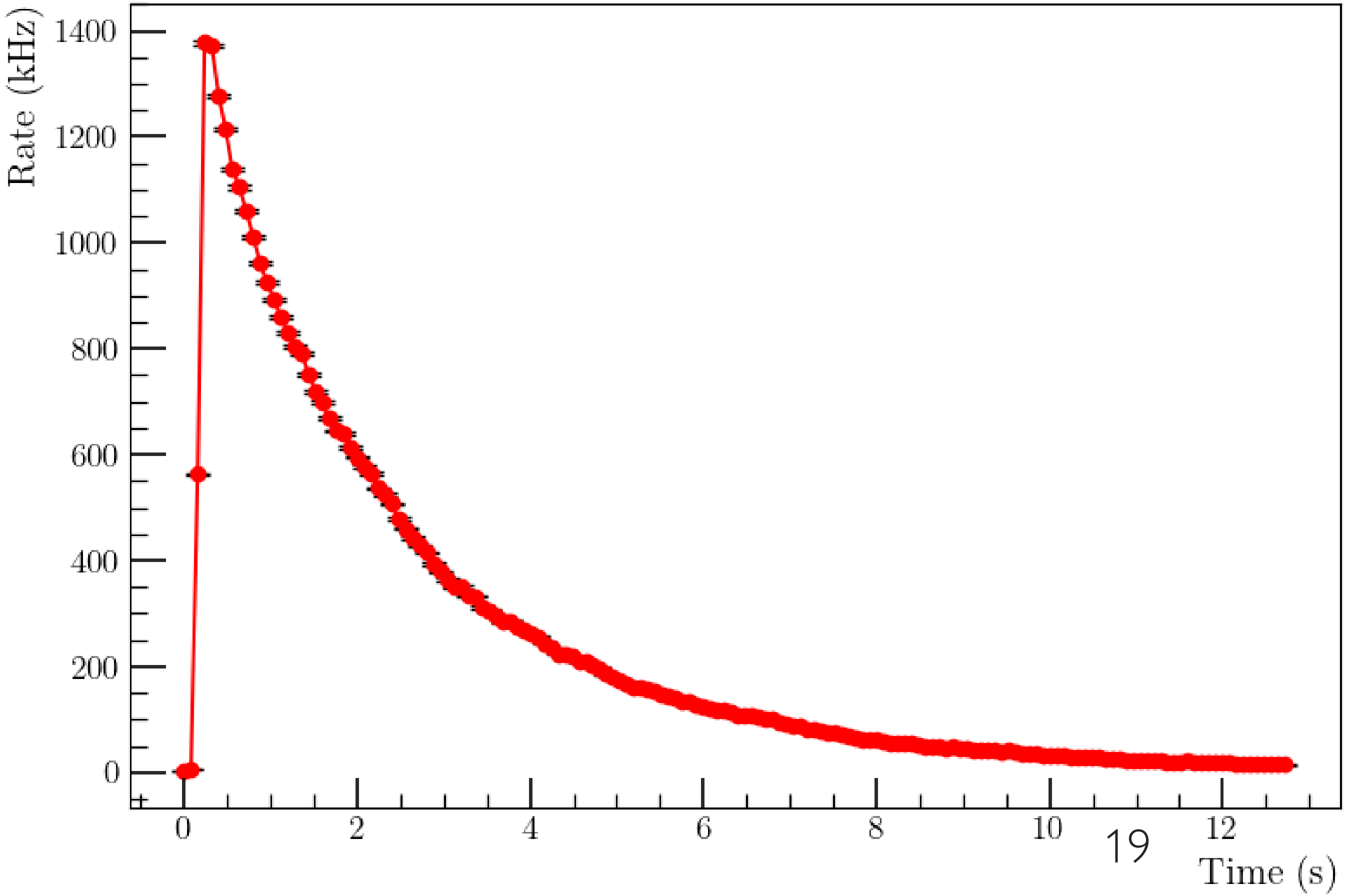
We can also use 7s(F=4)-$7p_{3/2}$(F=3) to cycle atoms that have been exited to 8s(F=4) from 7s(F=5).



Burst observation in Fr

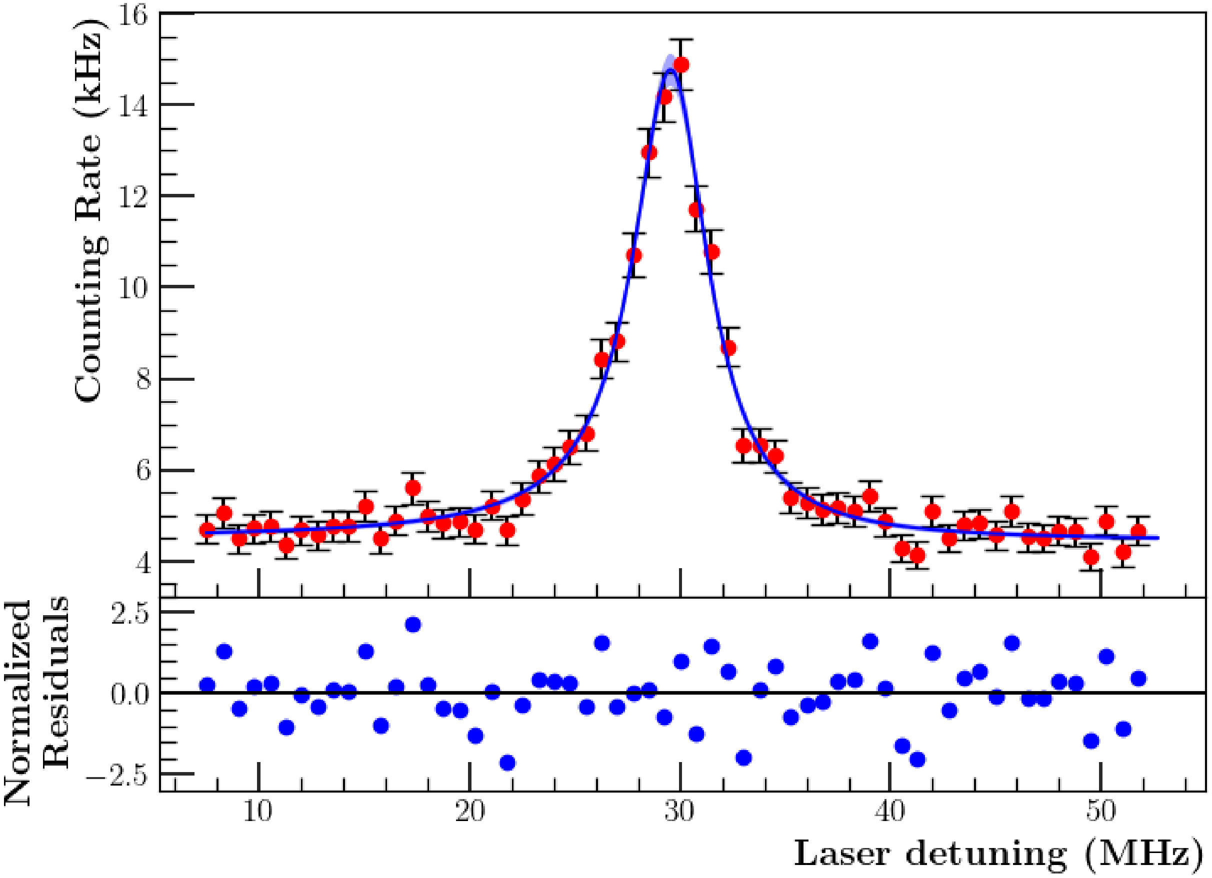
- Dec 2022: ^{211}Fr burst using $7s(F=5)$-$7p_{3/2}(F=6)$
- PMT with 100-fold attenuation in front ⟶ not present in Sept 2021
- 10x less atoms, excitation 4x shorter, and 2x less 506 nm light than Sept 2021

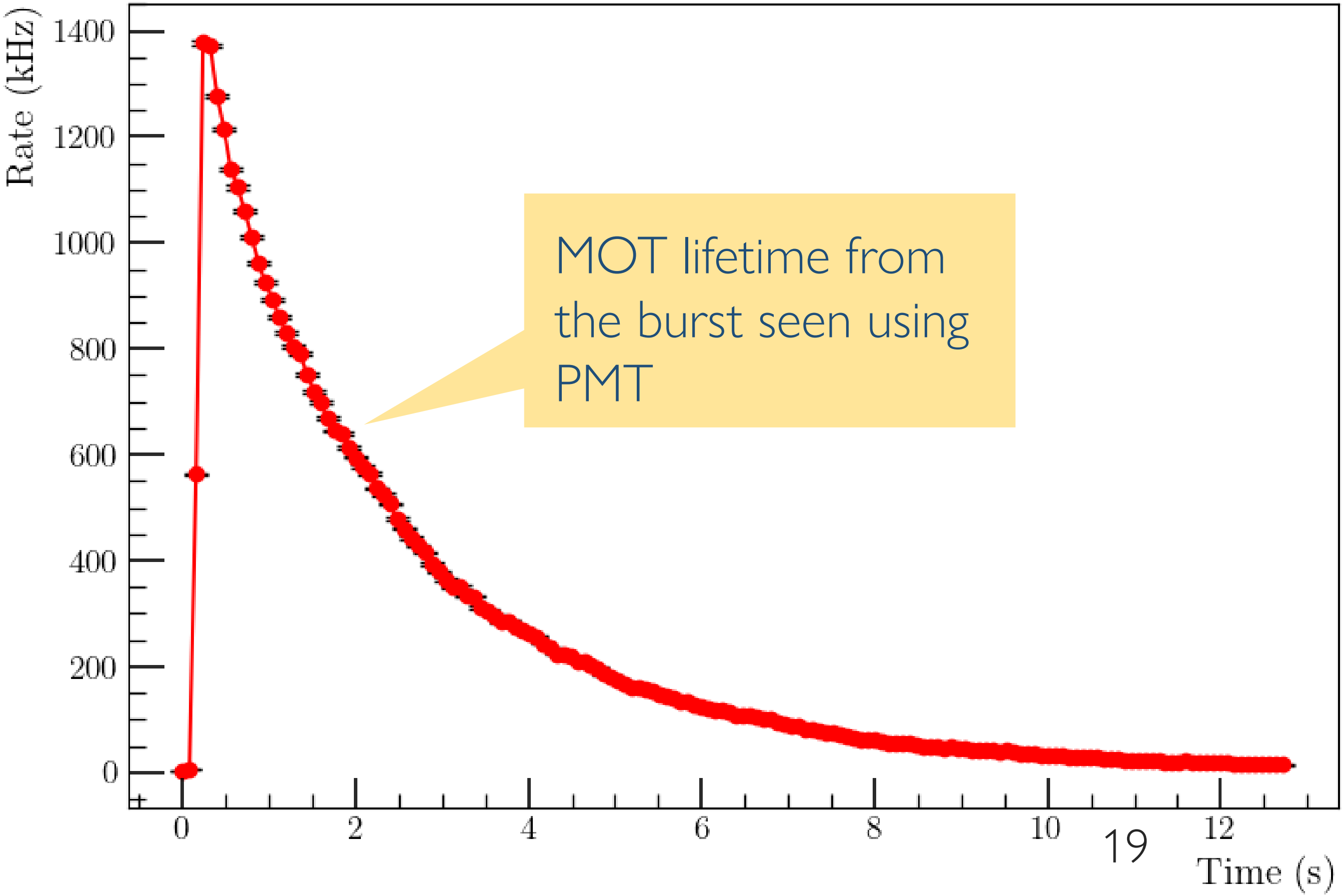




Burst observation in Fr

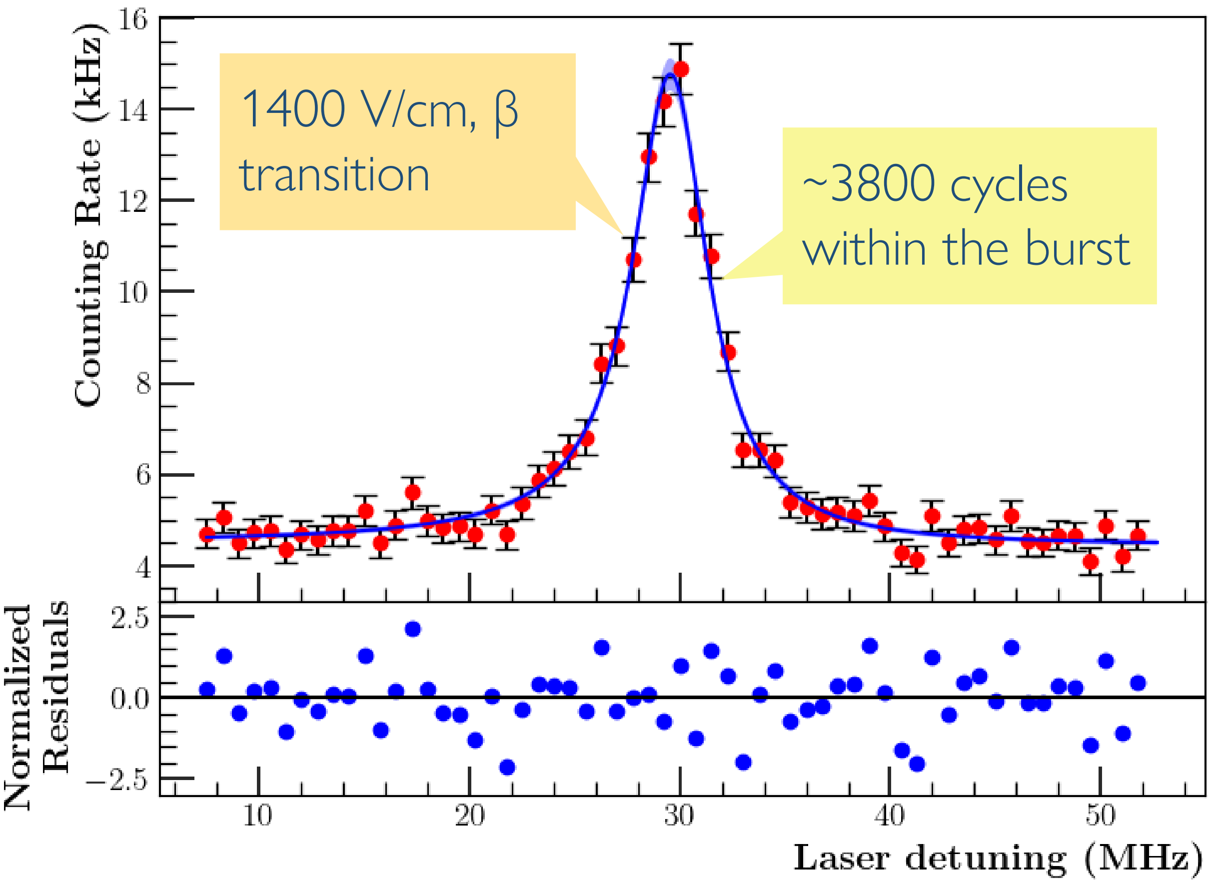
- Dec 2022: ^{211}Fr burst using $7s(F=5)$-$7p_{3/2}(F=6)$
- PMT with 100-fold attenuation in front → not present in Sept 2021
- 10x less atoms, excitation 4x shorter, and 2x less 506 nm light than Sept 2021

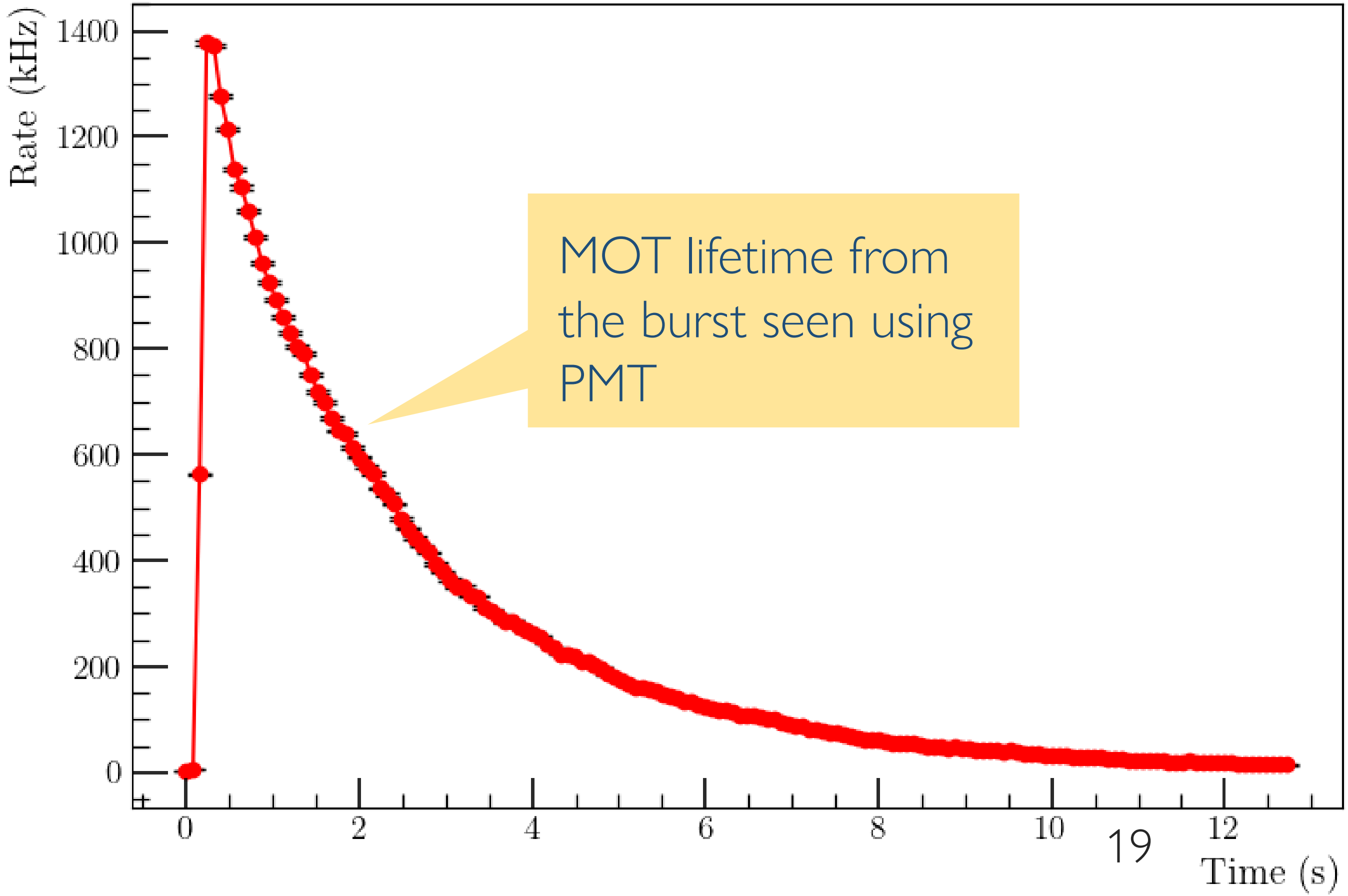




Burst observation in Fr

- Dec 2022: ^{211}Fr burst using 7s(F=5)-7$p_{3/2}$(F=6)
- PMT with 100-fold attenuation in front ⟶ not present in Sept 2021
- 10x less atoms, excitation 4x shorter, and 2x less 506 nm light than Sept 2021





Challenges with the burst technique

- Burst are on cycling transitions → could destroy the atom cloud
- Burst signal is same as MOT light → possible large background
- Utilize the $7p_{3/2}$ state → risk of photoionization if overlapped with 506 nm
- Could produce a large signal → complications with detector
  - i.e. linearity and protection of detector

Challenges with the burst technique

Retroreflect the laser beam

- Burst are on cycling transitions → could destroy the atom cloud
- Burst signal is same as MOT light → possible large background
- Utilize the $7p_{3/2}$ state → risk of photoionization if overlapped with 506 nm
- Could produce a large signal → complications with detector
  - i.e. linearity and protection of detector

Challenges with the burst technique

- Burst are on cycling transitions → could destroy the atom cloud
- Burst signal is same as MOT light → possible large background
- Utilize the $7p_{3/2}$ state → risk of photoionization if overlapped with 506 nm
- Could produce a large signal → complications with detector
  - i.e. linearity and protection of detector

Retroreflect the laser beam

Shutter light using AOM and timing schemes

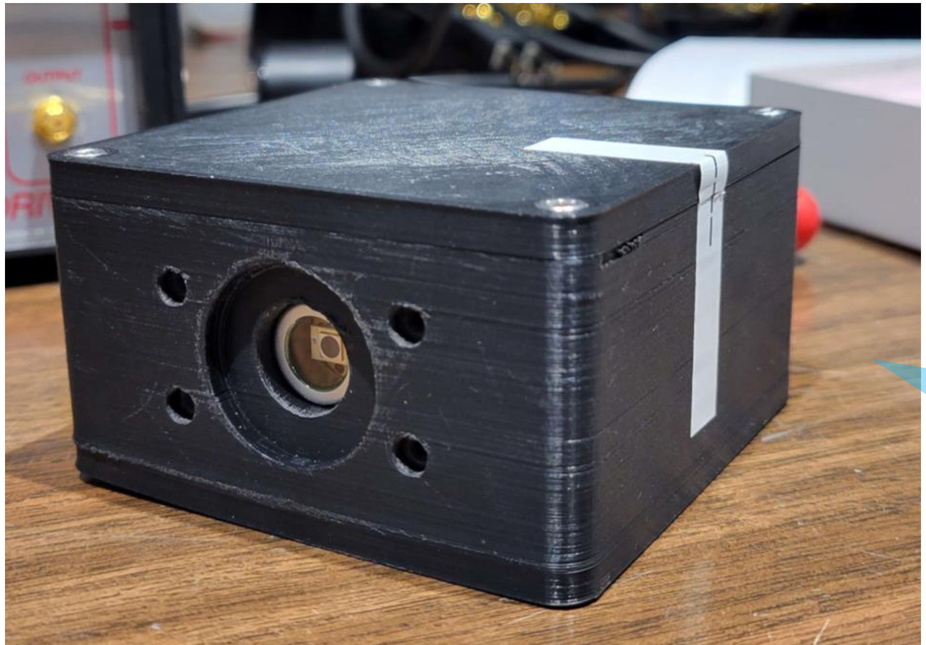
Challenges with the burst technique

Retroreflect the laser beam

- Burst are on cycling transitions ⟶ could destroy the atom cloud
- Burst signal is same as MOT light ⟶ possible large background
- Utilize the $7p_{3/2}$ state ⟶ risk of photoionization if overlapped with 506 nm
- Could produce a large signal ⟶ complications with detector
  - i.e. linearity and protection of detector

Shutter light using AOM and timing schemes

Switching to SiPM with increased linearity and is more robust



Hamamatsu SiPM, linearity upwards of 11 MHz

What's next?

- Still need to measure $\Delta F=+1$ to extract β
- Sub-% measurement of M_{rel}
- Next phase will be interference experiments
- Atoms in a MOT are generally (but not completely) unpolarized
- Need to optically pump atoms into $m_F = \pm F$ states
- Need to control magnetic fields used in the MOT
  - Center of science chamber → magnetic field to zero in < 1ms
- Use 200 kHz bipolar power supplies from Matsusada

What's next?

- Still need to measure $\Delta F=+1$ to extract β
- Sub-% measurement of M_{rel}
- Next phase will be interference experiments
- Atoms in a MOT are generally (but not completely) unpolarized
- Need to optically pump atoms into $m_F = \pm F$ states
- Need to control magnetic fields used in the MOT
  - Center of science chamber → magnetic field to zero in < 1ms
- Use 200 kHz bipolar power supplies from Matsusada

Attempt for August 2023

What's next?

- Still need to measure $\Delta F=+1$ to extract β
- Sub-% measurement of M_{rel}

Attempt for August 2023

- Next phase will be interference experiments
- Atoms in a MOT are generally (but not completely) unpolarized
- Need to optically pump atoms into $m_F = \pm F$ states
- Need to control magnetic fields used in the MOT
  - Center of science chamber → magnetic field to zero in < 1ms
- Use 200 kHz bipolar power supplies from Matsusada
- Using optically pumped atoms (late 2023 or 2024):
  - Measure the ratio between the scalar and tensor polarizabilities α/β
  - Interference experiment between $E1_{Stark}$-M1 (without PBC)
- Nearing first attempt of interference $E1_{Stark}$-$E1_{PV}$ (2024-2025)

References

[1] K. Cheung, Phys. Lett. B 517, 167 (2001).

[2] J. Erler, A. Kurylov, and M. J. Ramsey-Musolf, Phys. Rev. D 68,1 (2003).

[3] R. Diener, S. Godfrey, and I. Turan, Phys. Rev. D 86, 1 (2012).

[4] C. Bouchiat and P. Fayet, Phys. Lett. B 608, 87 (2005).

[5] M. A. Bouchiat and C. Bouchiat, J. Phys. 35, 899 (1974).

[6] M. A. Bouchiat and C. Bouchiat, J. Phys. 36, 493 (1975).

[7] C. S. Wood, *et al.*, Science 275, 1759 (1997).

[8] M. A. Bouchiat, *et al.*, Atomic, J. Phys. 47, 1709 (1986).

[9] J. Gu´ena, M. Lintz, and M. A. Bouchiat, Phys. Rev. A At. Mol. Opt. Phys. 71, 1 (2005).

[10] S. C. Bennett and C. E. Wieman, Phys. Rev. Lett. 82, 205 (1999).

Thank you.

Collaboration:

University of Manitoba:

Tim Hucko, Iris Halilovic, Tasanul Morshed, Anima Sharma, Gerald Gwinner (PI)

TRIUMF:

Mukut Kalita, Alexandre Gorelov, Matt Pearson, Andrea Teigelhoefer, John Behr, Liang Xie

University of Maryland:

Luis Orozco

College of William and Mary:

Seth Aubin

Universidad Autónoma de San Luis Potosí:

Eduardo Gomez

Funding by:

NSERC CRSNG · University of Manitoba · University of Maryland · NRC·CNRC · TRIUMF