Precision atomic measurements and tests of CKM unitarity

EPIC 2024: Electroweak Physics InterseCtions

Peter Plattner

Outline

- Motivation from Standard Model
- Determination of Vud
- Introduction to laser spectroscopy and isotope production
- Results of measurements
- Outlook and conclusion

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CKM Unitarity (1)

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Cabibbo-Kobayashi-Maskawa (CKM) matrix describes mixing of quarks via weak interaction
- Absolute square (i.e. $|V_{ij}|^2$) of each CKM-entry is probability of weak decay of j-type quark into i-type quark
- Standard Model of particle physics predicts unitarity of CKM matrix
- Deviation from unitarity would imply incomplete picture of Standard model

- Unitarity: $V_{CKM} \cdot {V_{CKM}}^T = I_3$
- In particular: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta_{CKM}$

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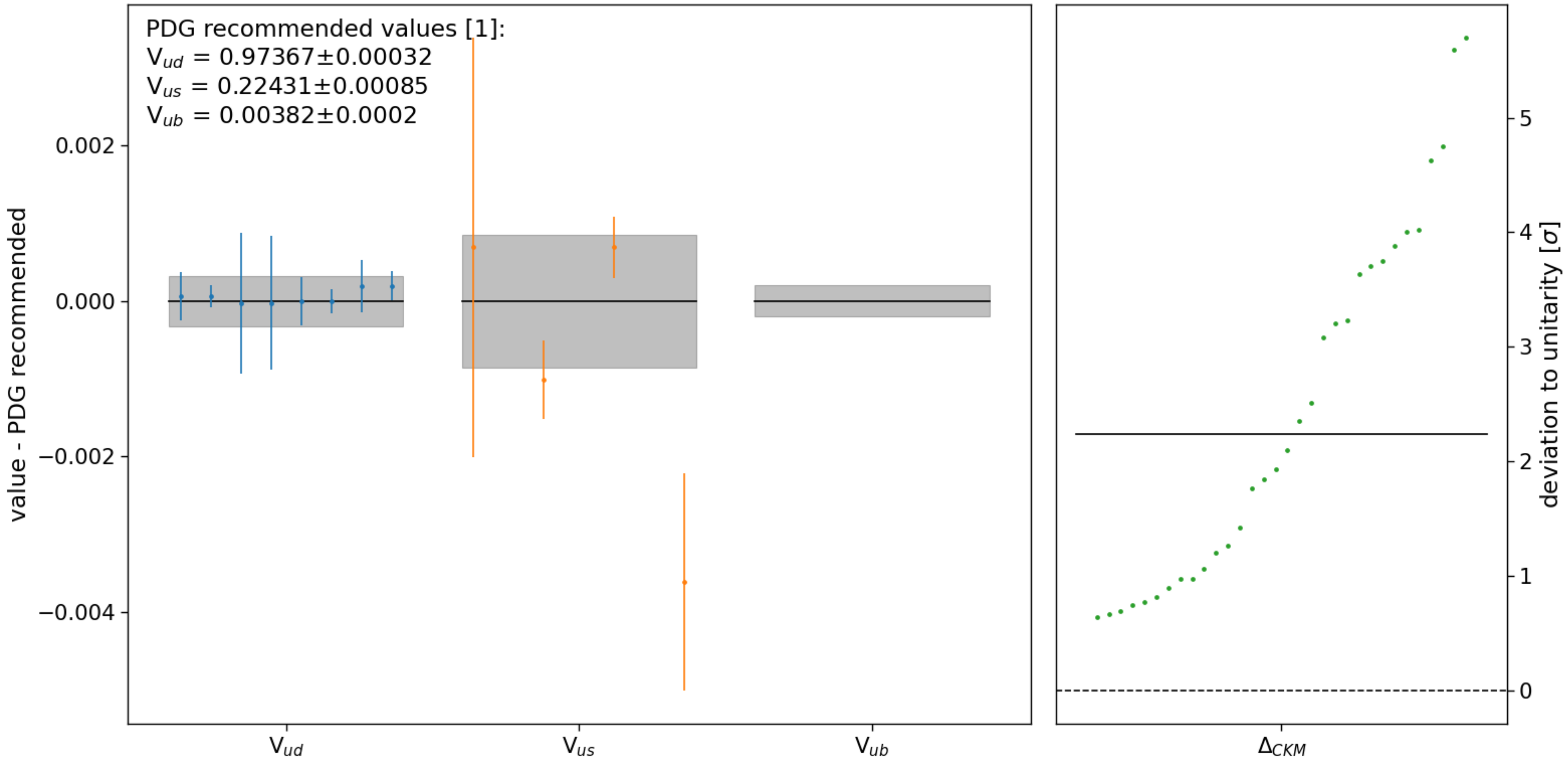
Tension to Unitarity

- Currently recommended values by PDG:



[1] S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024)
[2] J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

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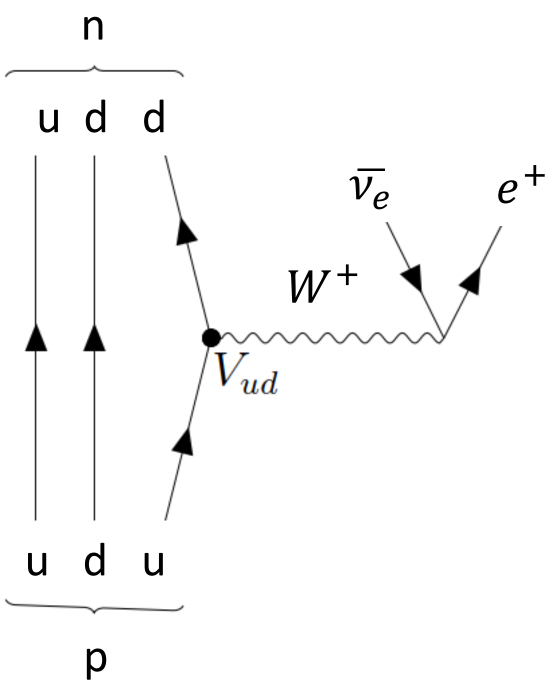
CKM Unitarity (2)

- Determination of couplings for:
- V_{us}
  - Kaon decays
  - Hyperon decays
  - Tau decays
- V_{ud}
  - Neutron decay
  - Pion decay
  - Mirror decays (e.g. $^{21}Na \rightarrow {}^{21}Ne$)
  - **Superallowed $0^{+} \rightarrow 0^{+}$ β decays**



Determination of V_{ud}

- V_{ud} can be determined via $\mathcal{F}t$ value of superallowed $0^+ \rightarrow 0^+$ β decays

$$|V_{ud}|^2 = \frac{K}{2G_F^2(1+\Delta_R^V)\overline{\mathcal{F}t}}$$

Partial half life

Energy difference

Small theoretical corrections (leading uncertainty!)

$$\mathcal{F}t = ft \cdot (1+\delta'_R)(1+\delta_{NS}-\delta_C)$$

- Nuclear charge radius r_c important experimental input into theoretical calculation of isospin-symmetry-breaking corrections

$$\delta_c \coloneqq f(r_c, \dots)$$

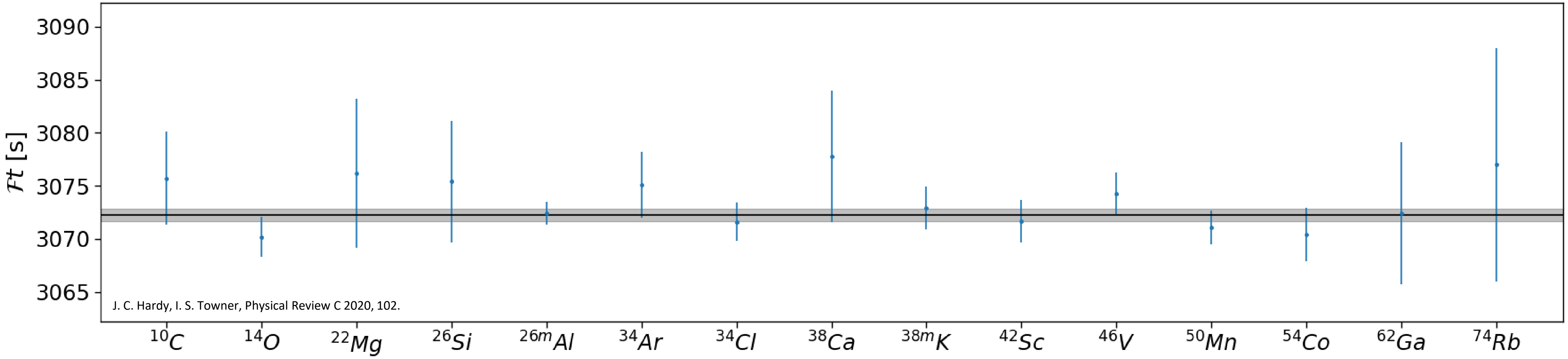
J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

Importance of charge radius of ^{26m}Al

- Weighted mean $\overline{\mathcal{F}t}$ of 15 precision cases used to calculate V_{ud}

$$|V_{ud}|^2 = \frac{K}{2G_F^2(1+\Delta_R^V)\overline{\mathcal{F}t}}$$

- $\mathcal{F}t$ value of ^{26m}Al
  - Most accurately known of 15 isotopes used to calculate $\overline{\mathcal{F}t}$



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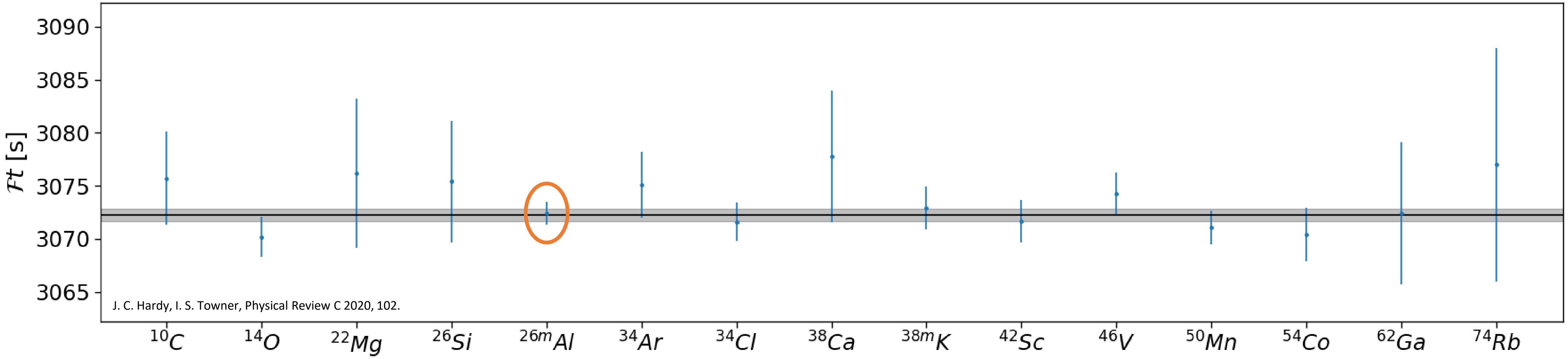
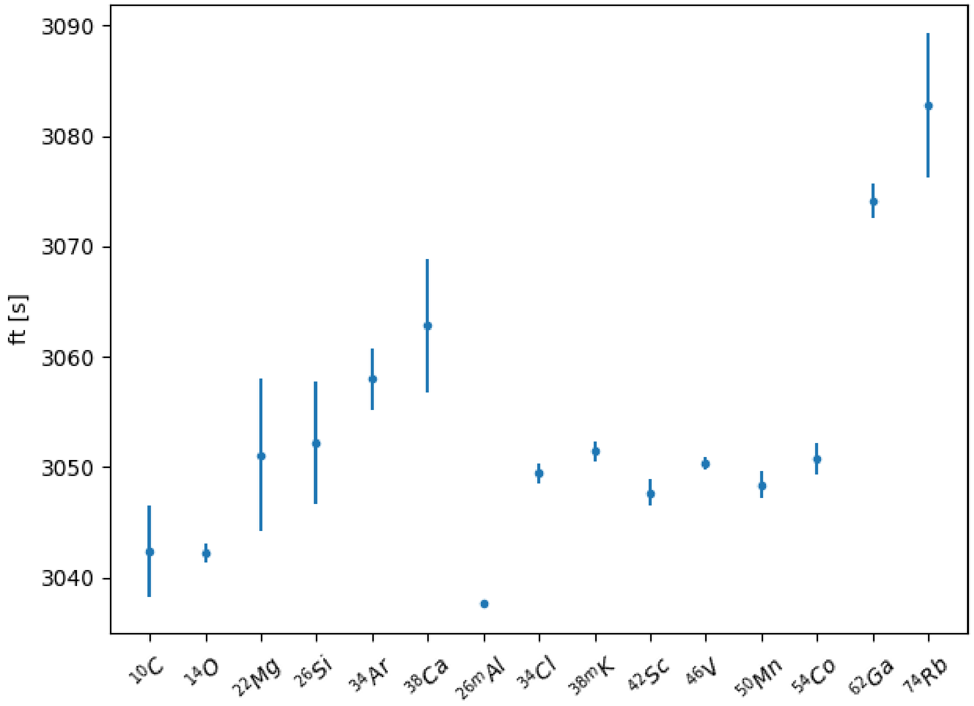
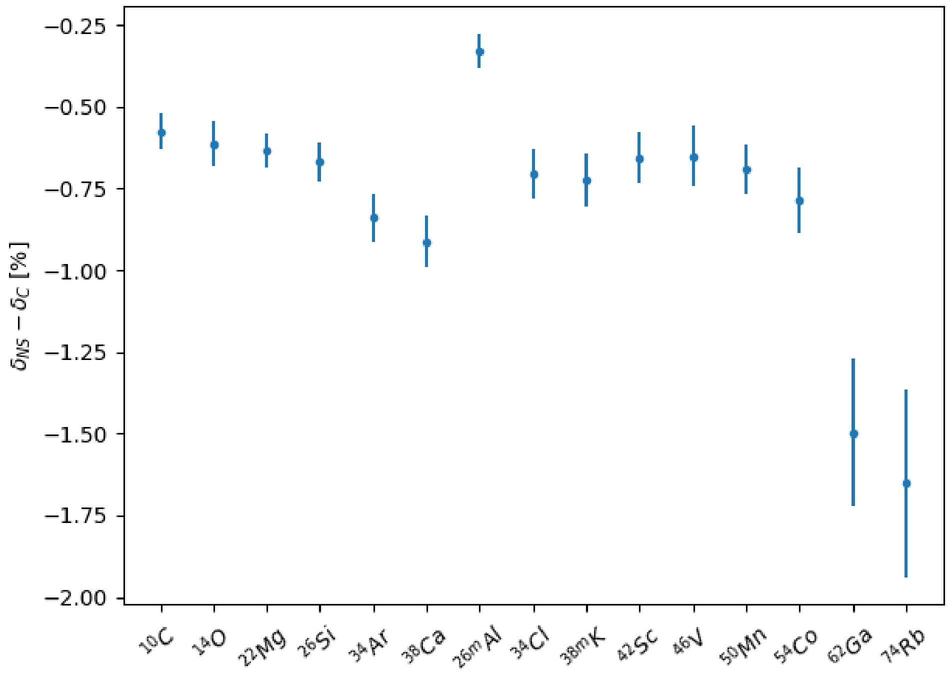


Importance of charge radius of ^{26m}Al

- Accuracy of $\mathcal{F}t$ value of ^{26m}Al coming from
  - Small uncertainty on ft
  - Small uncertainty on nuclear structure and isospin-symmetry breaking corrections
  - Lowest numerical correction on combined $\delta_{NS} - \delta_c$





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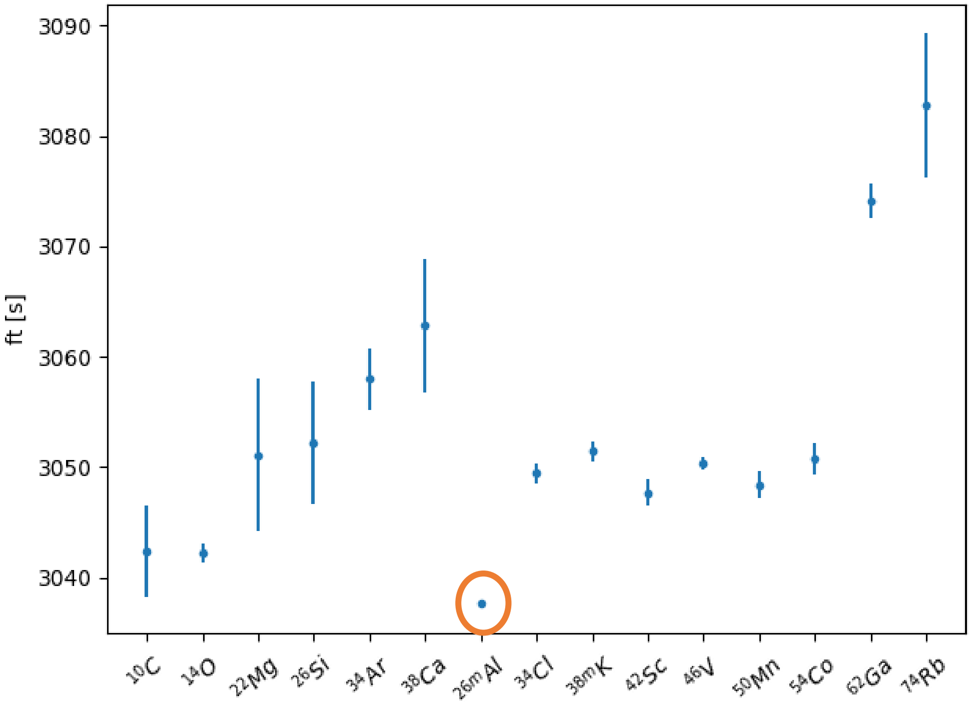

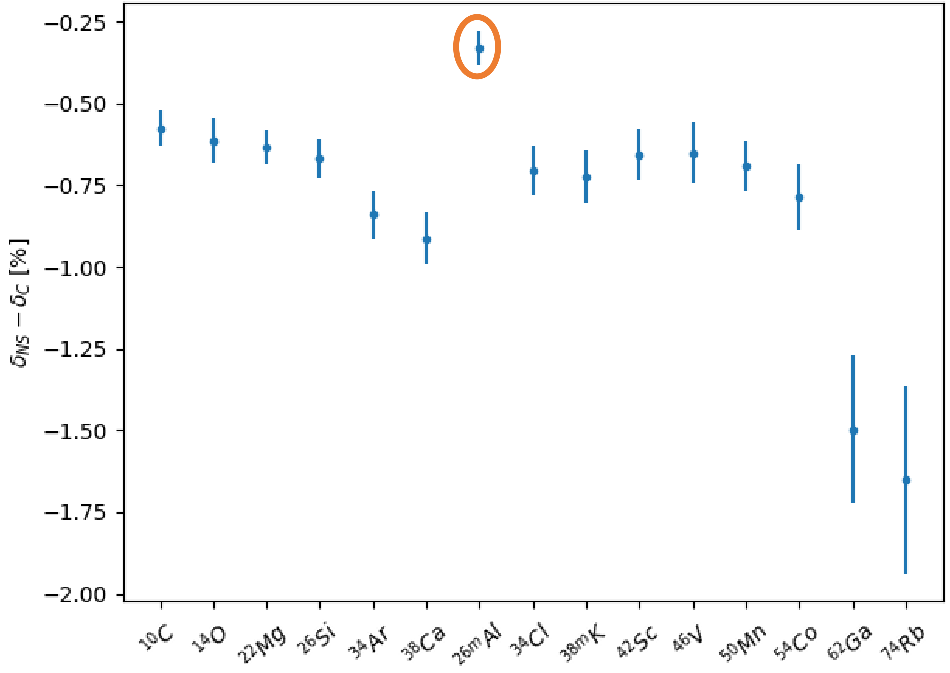

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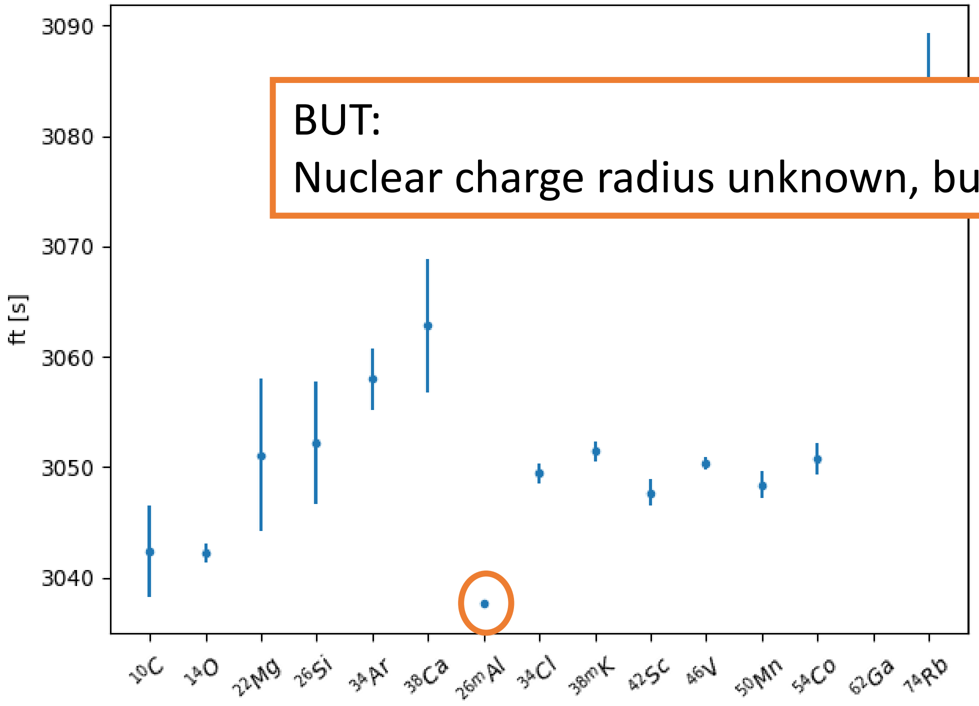
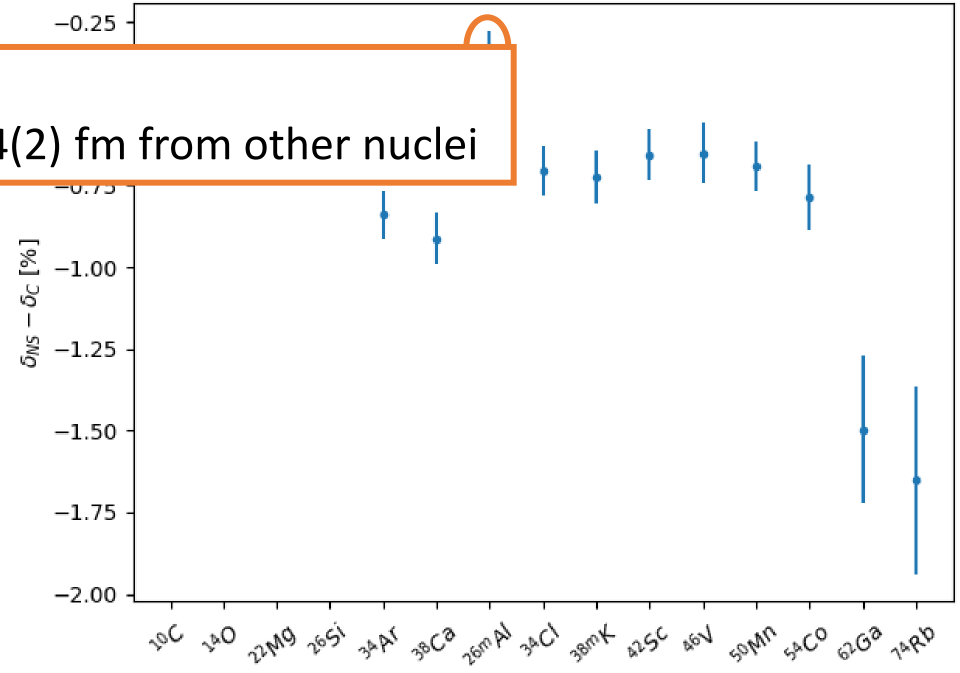
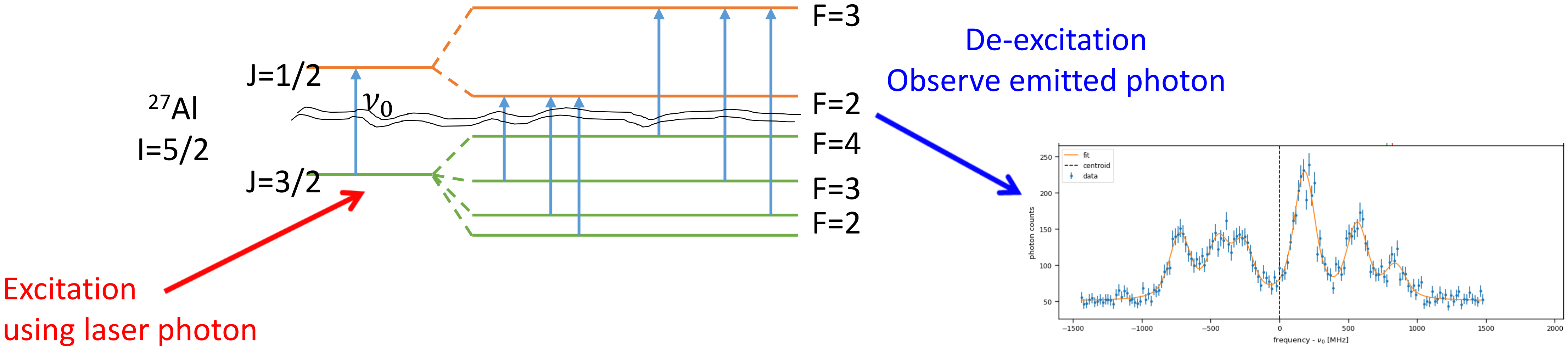


BUT:
Nuclear charge radius unknown, but extrapolated as 3.04(2) fm from other nuclei



Laser Spectroscopy

$$\vec{F} = \vec{I} + \vec{J}$$



- Hyperfine transitions in atoms or ions yield information about
  - Nuclear spin
  - Magnetic dipole and electric quadrupole moments of nuclei
  - **Isotope shifts and nuclear charge radii**

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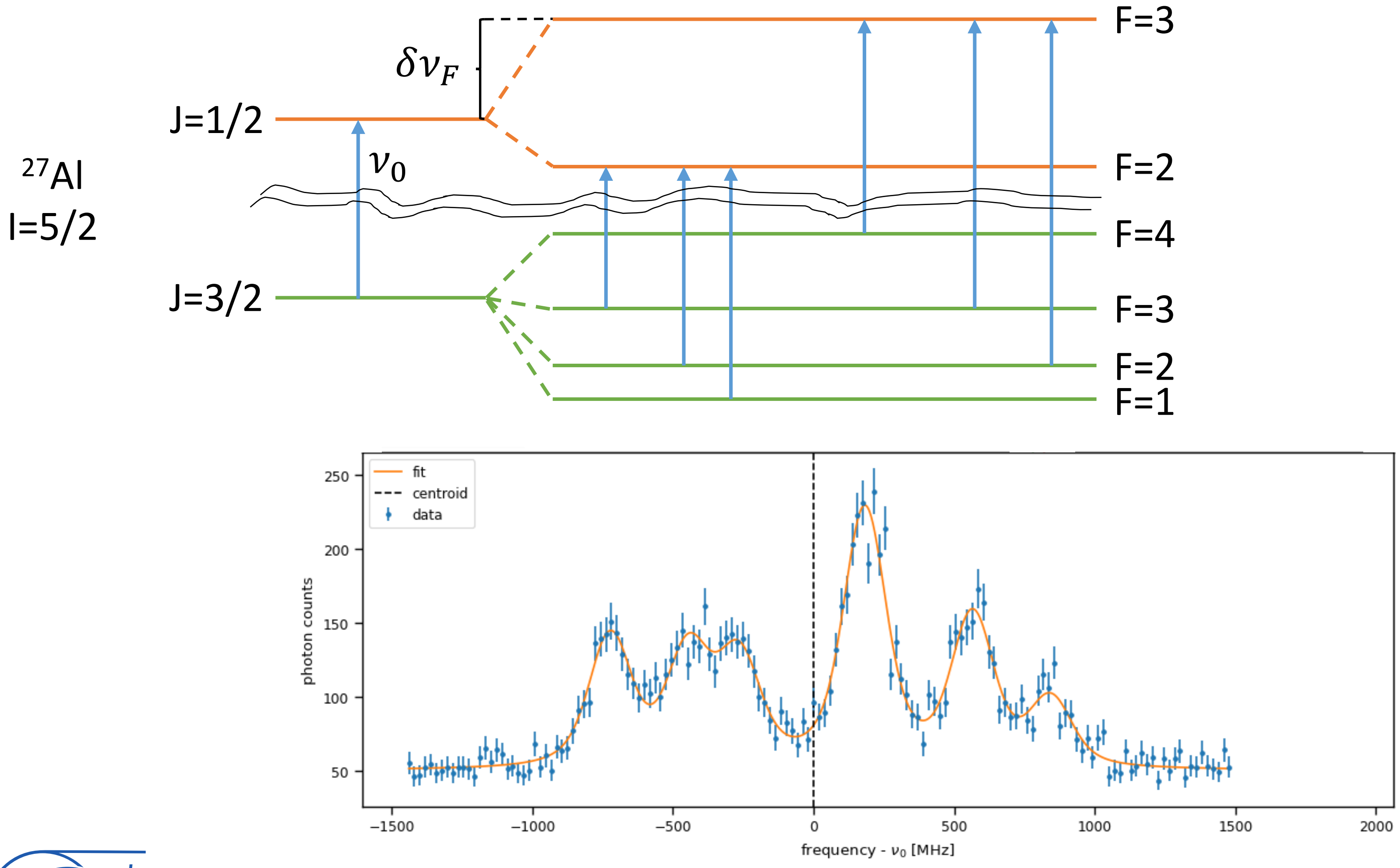
Hyperfine Spectrum



$$\delta\nu_F = A_J\frac{C}{2} + B_J\frac{3C(C+1) - 4I(I+1)J(J+1)}{8I(2I-1)J(2J-1)}$$

$$C = F(F+1) - I(I+1) - J(J+1)$$

electric quadrupole moment $Q = \frac{B_J}{eV_{JJ}}$

magnetic dipole moment $\mu = \frac{A_J \cdot I\ J}{B_0}$

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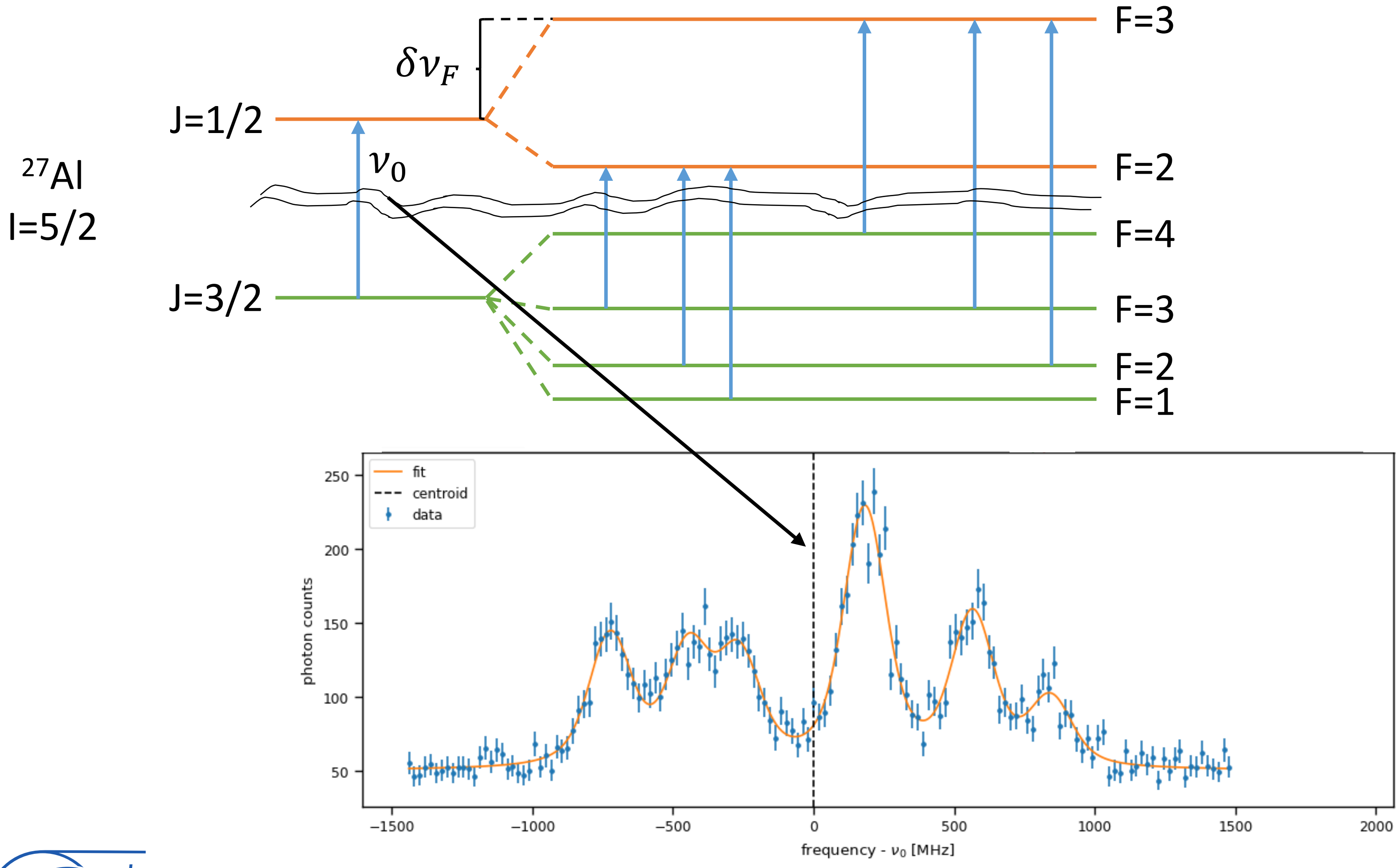
Hyperfine Spectrum



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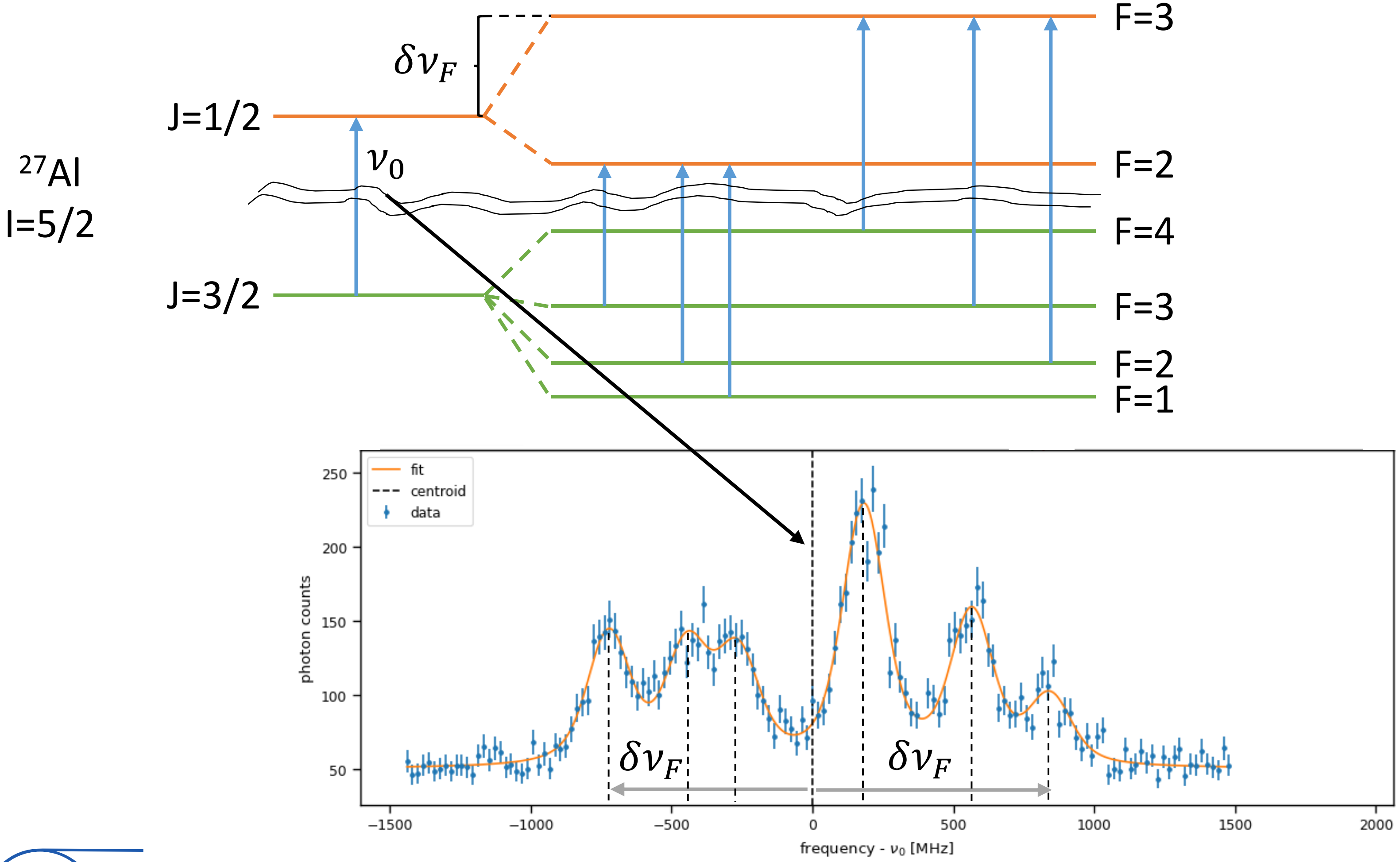

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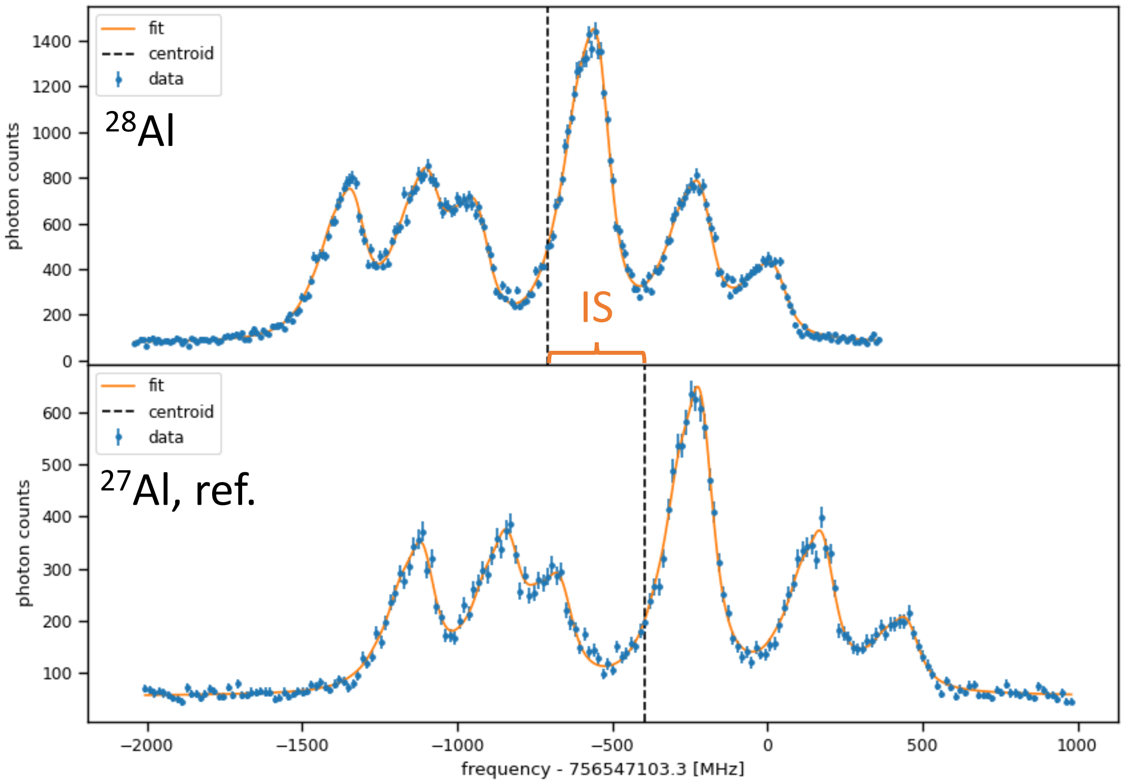
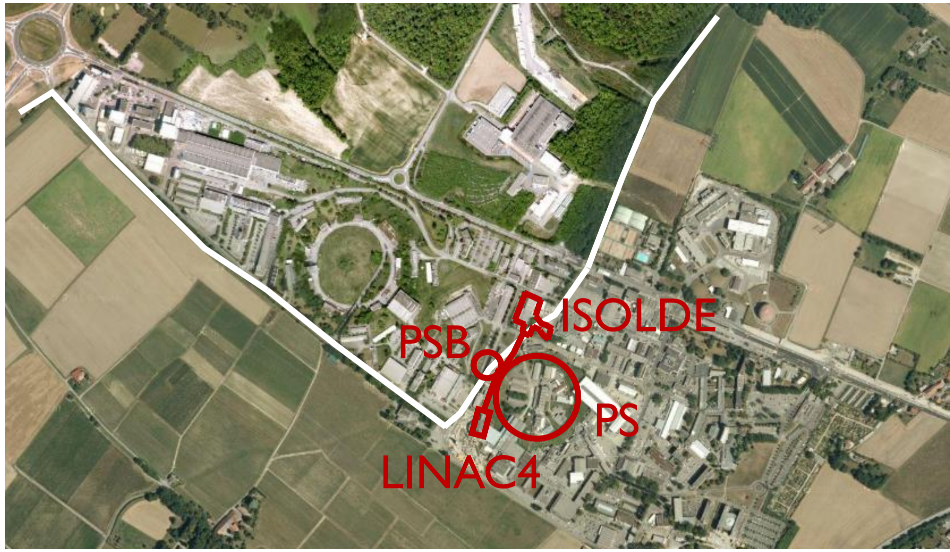
Isotope Shift



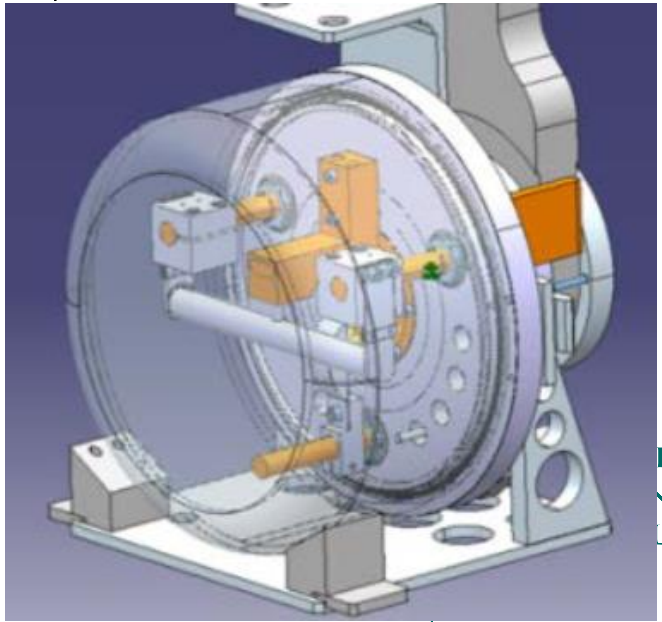
- Isotope shift IS = difference of centroid frequencies for different isotopes
- Used to calculate difference in mean square charge radii between isotopes

ISOLDE

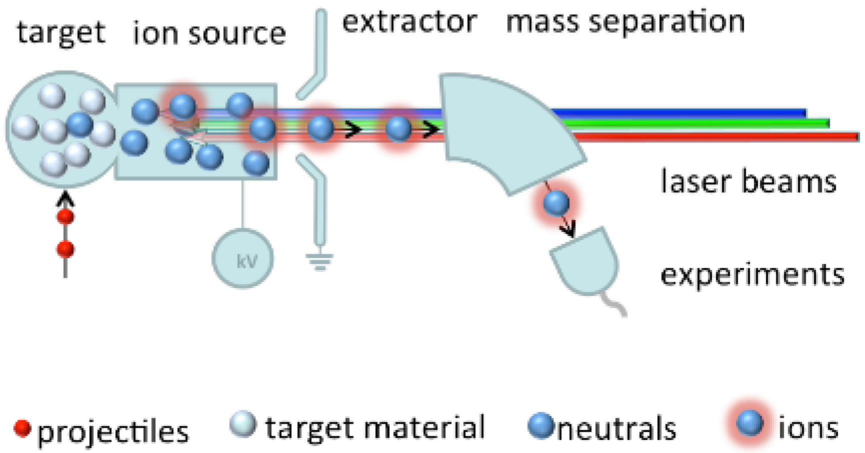
- Located at CERN
- Two target stations can be irradiated with up to 2 uA of 1.4 GeV protons from proton synchrotron booster (PSB)
- Isotopes produced via nuclear reactions in target material
- Then ionised and transported to experimental setup

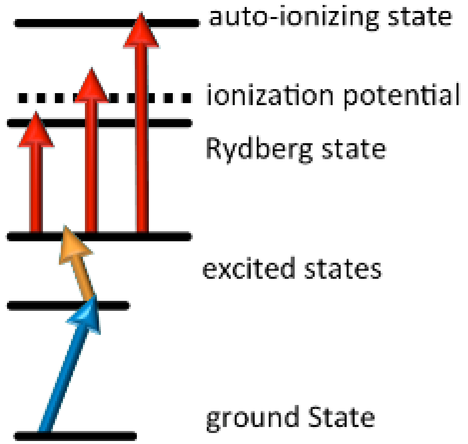


Source: http://cds.cern.ch/record/1693046/files/arXiv:1404.0515.pdf



Ionisation





- Resonance ionisation laser ion source (RILIS)
- Electron exited through several resonant transition steps until ionization
- Very element specific
- Ionisation efficiency enhancement of factor ~10-100 (varies for different schemes for different elements)

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Isotope Selection and Bunching

- Mass selection via High Resolution Separator (HRS) by two dipole magnets
- Offers mass resolving power of ~5000
- Injected into helium buffer gas filled Paul trap (ISCOOL)
- Used as cooler-buncher to accumulate isotopes before transporting bunches to experiment

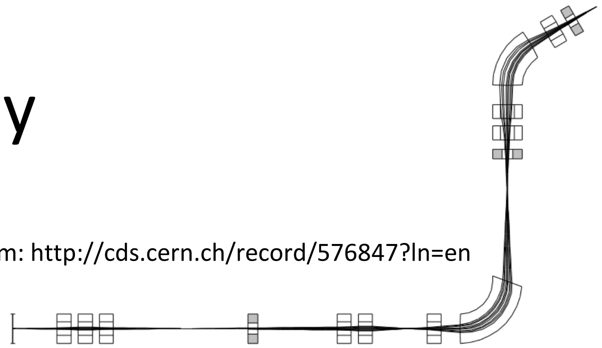
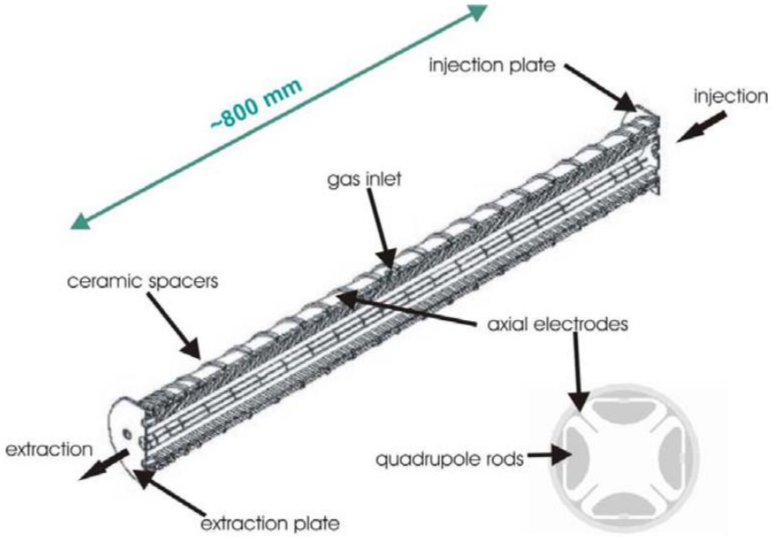
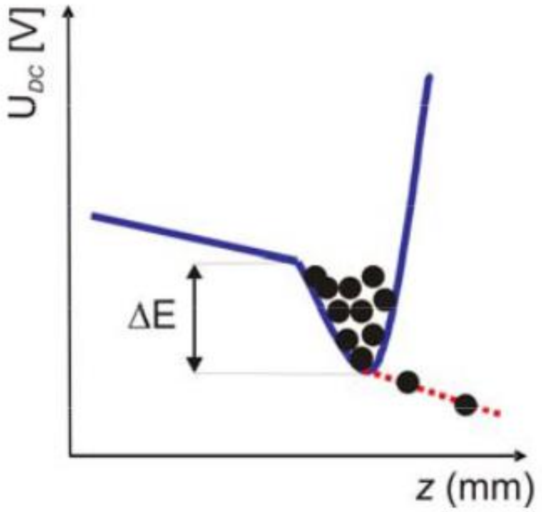


Image from: http://cds.cern.ch/record/576847?ln=en

Images from: http://cds.cern.ch/record/1058103/files/p57.pdf





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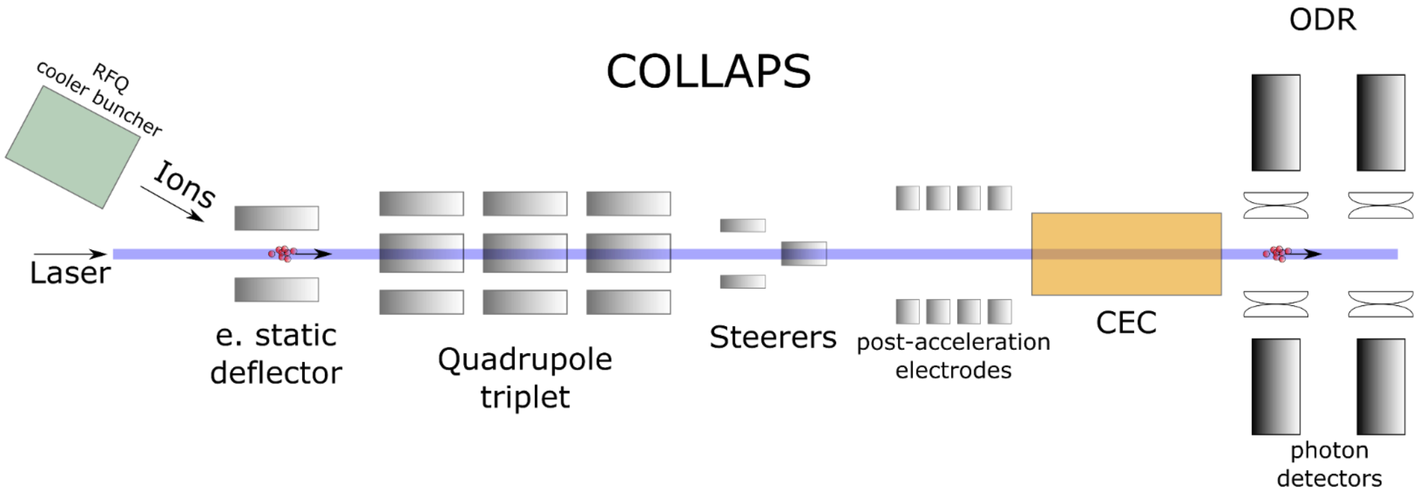
Collinear Laser Spectroscopy

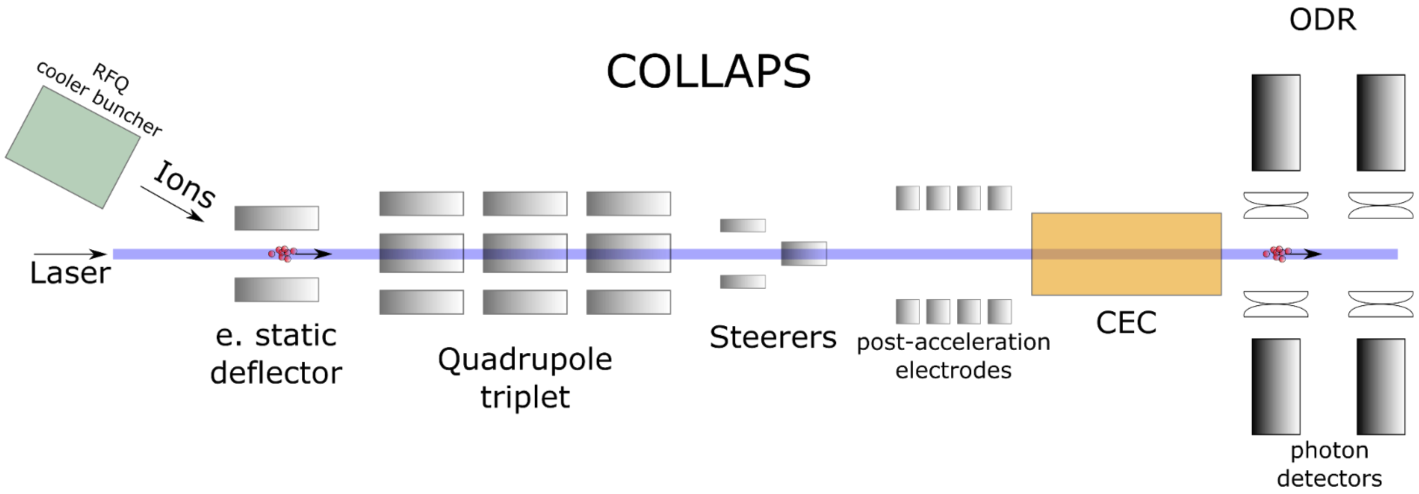


- Ions and laser collinearly overlapped via electrostatic bender
- Reduced doppler spread (<100MHz) due to “high” kinetic energy of 30keV

$$\delta f \propto \frac{\delta E_{kin}}{\sqrt{E_{kin}}}$$

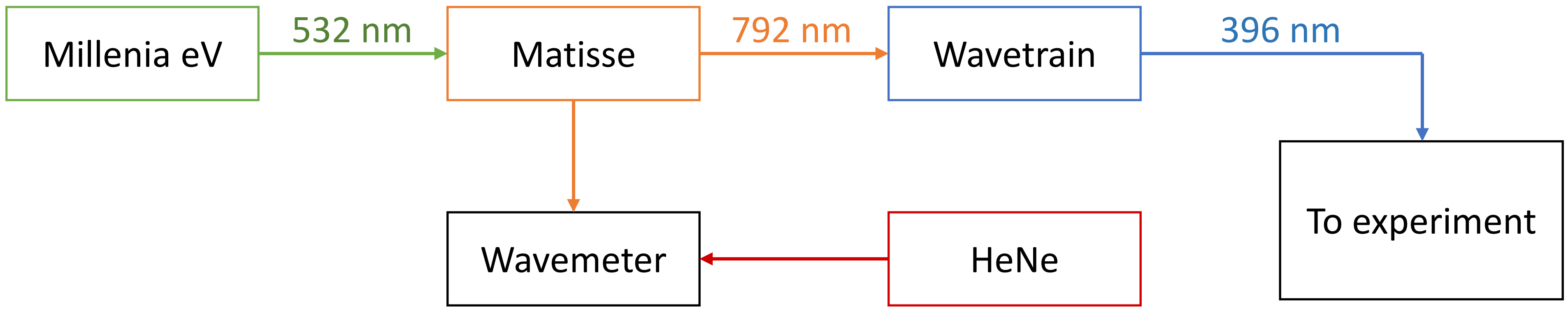
- Bunched beam enables gating to increase signal-to-background by factor of ~10 000

Collinear Laser Spectroscopy

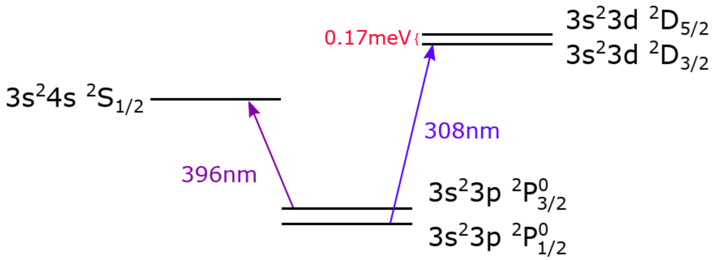


- Post-acceleration leads to frequency shift in ion rest frame
- Charge exchange with sodium to neutralize ions
- Measure fluorescence photons of resonant transitions

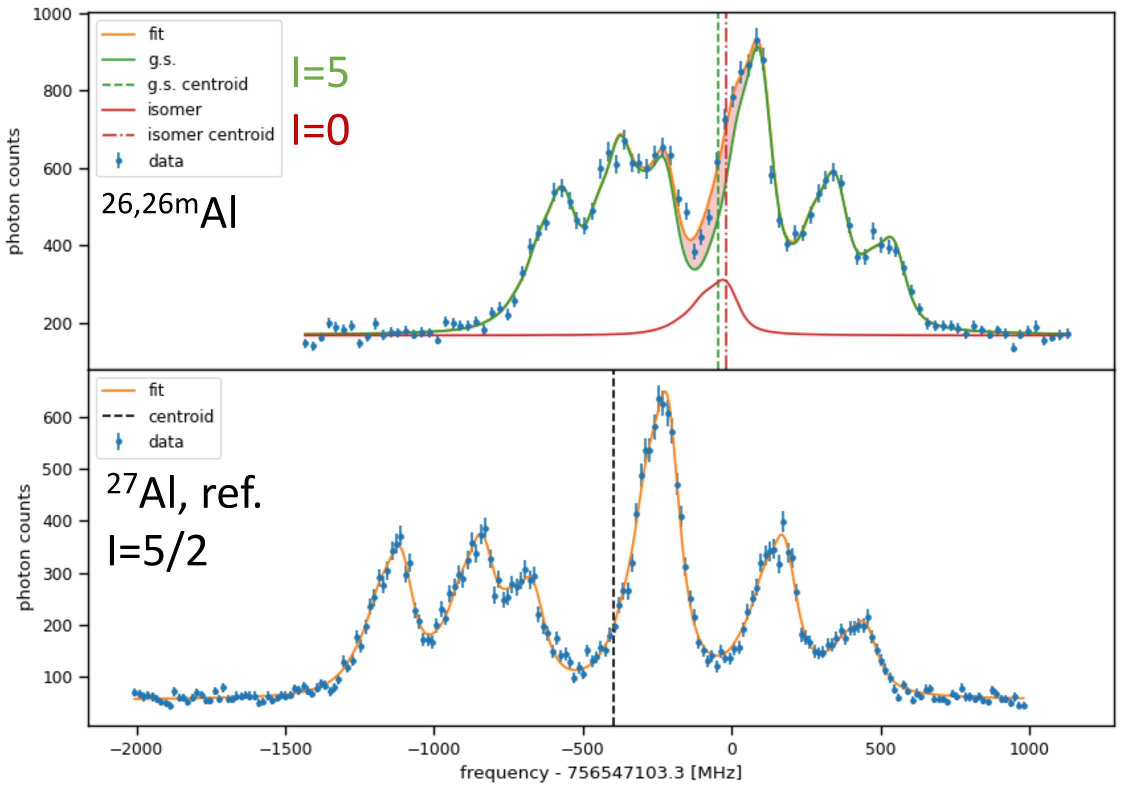
Laser System

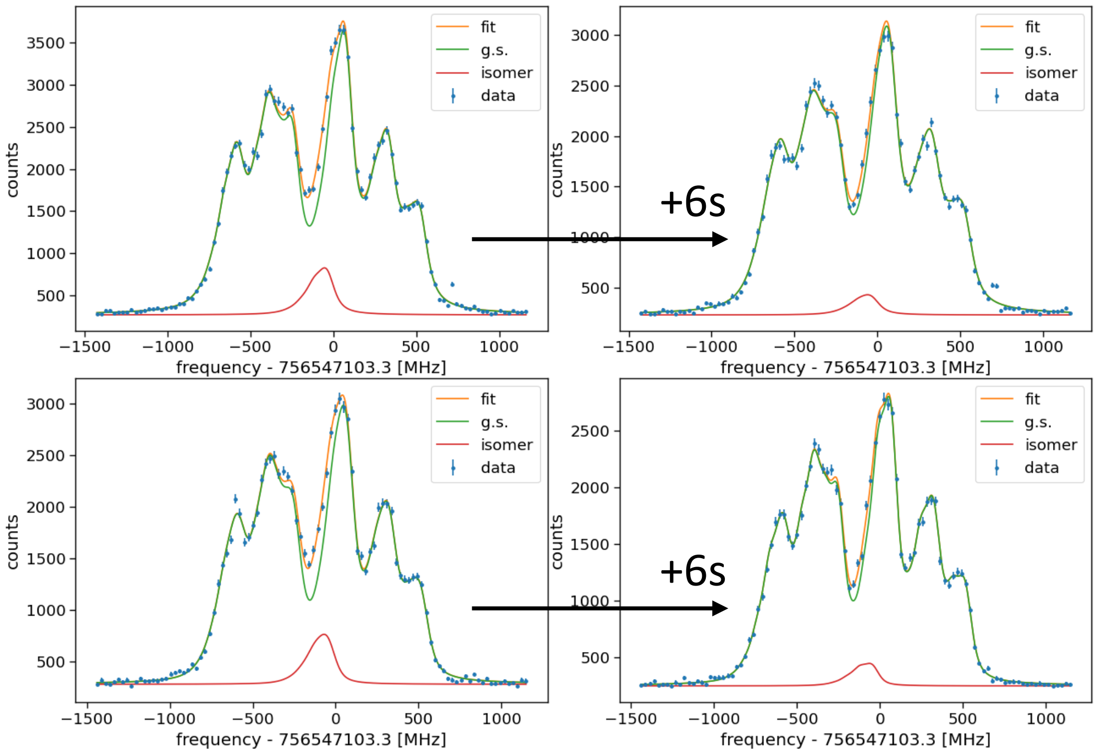


- Used transition: $3s^2 3p\ ^2P^{\circ}_{3/2} \rightarrow 3s^2 4s\ ^2S_{1/2}$ provided by frequency doubled Matisse Ti:Sa ring cavity laser
- Frequency stabilised by WSU-10 wavemeter
- Regularly calibrated by HeNe laser



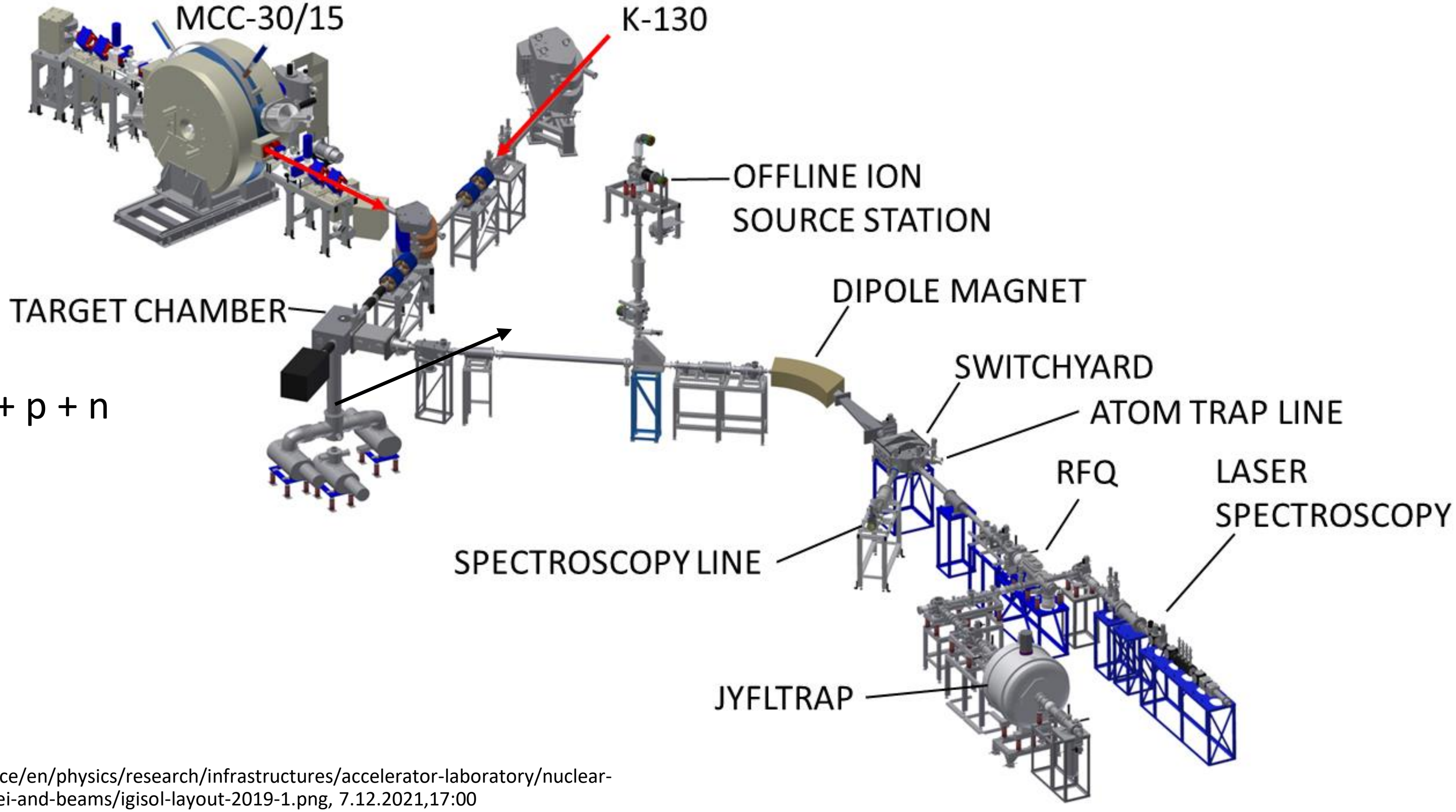
Hyperfine Spectra





- Ion extraction 0 and 6s after proton trigger
- Decrease in isomer intensity in fit consistent with half-life
  - $N_2 = N_1 \cdot \left(\frac{1}{2}\right)^{\frac{6s}{t_{1/2}}}$

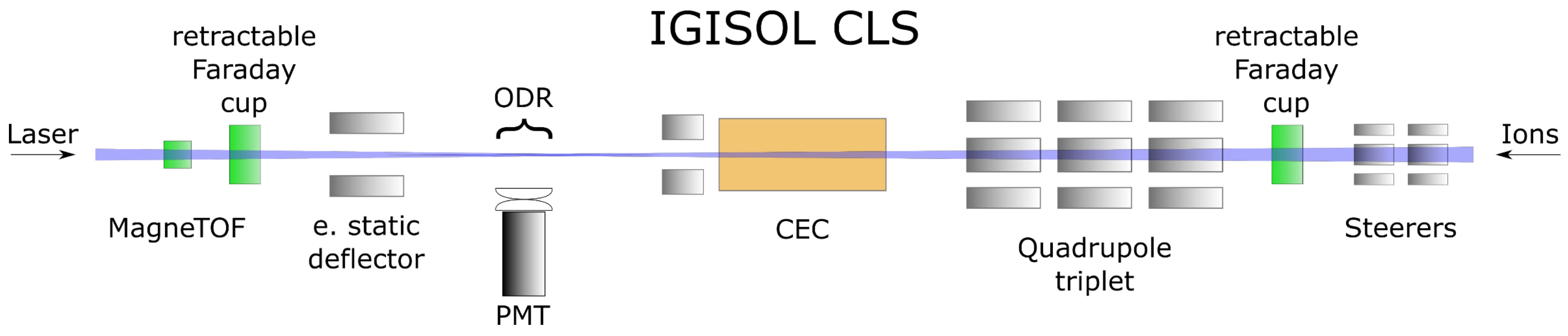
IGISOL



$^{27}Al + p \rightarrow ^{26}Al + p + n$
at 25 MeV

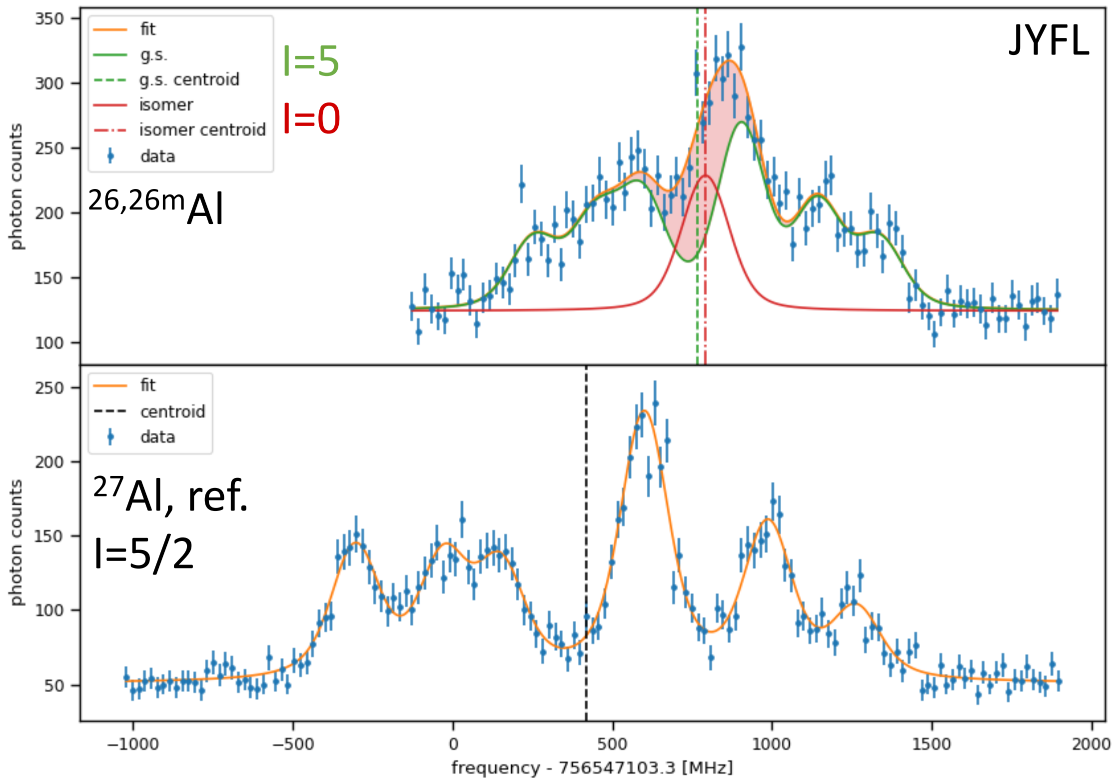
Source: https://www.jyu.fi/science/en/physics/research/infrastructures/accelerator-laboratory/nuclear-physics-facilities/the-exotic-nuclei-and-beams/igisol-layout-2019-1.png, 7.12.2021,17:00

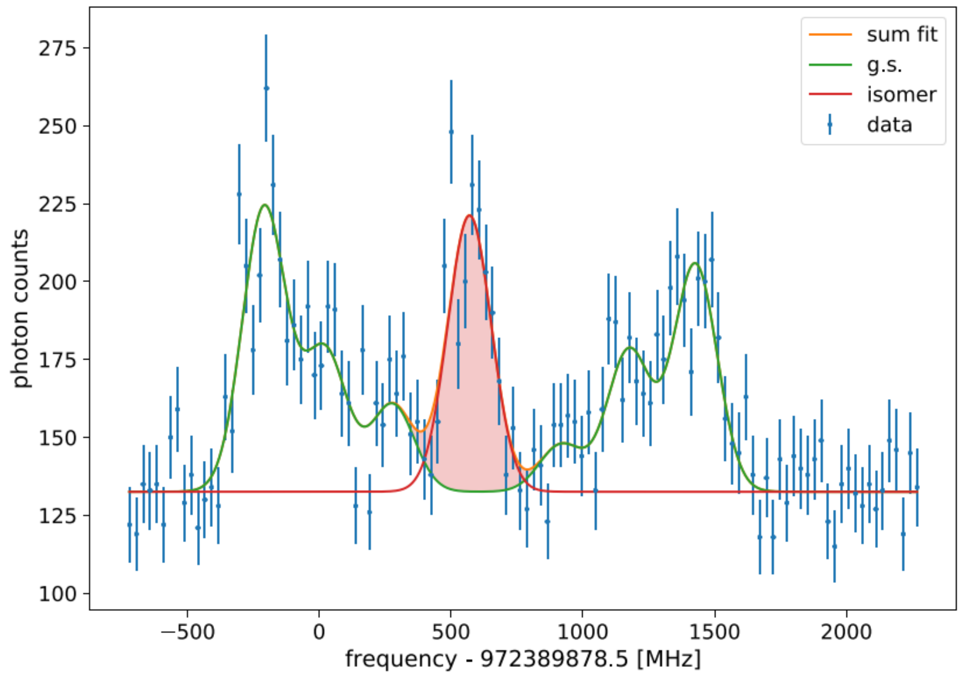
Collinear Laser Spectroscopy at IGISOL



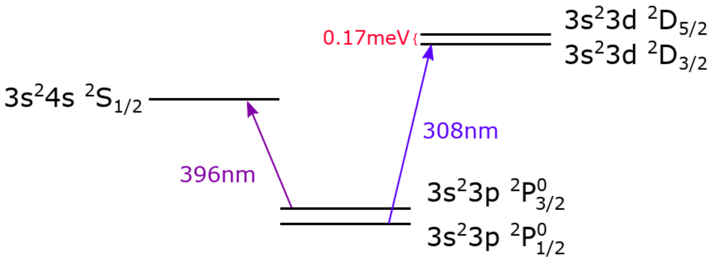
- Collaboration with IGISOL
- Second set of measurements performed at IGISOL, Jyväskylä
- Known to have more favorable isomer : ground state ratio for $^{26,26m}Al$

Hyperfine Spectra





- Clear presence of isomer in Al I $P_{1/2} \rightarrow D_{3/2}$ transition



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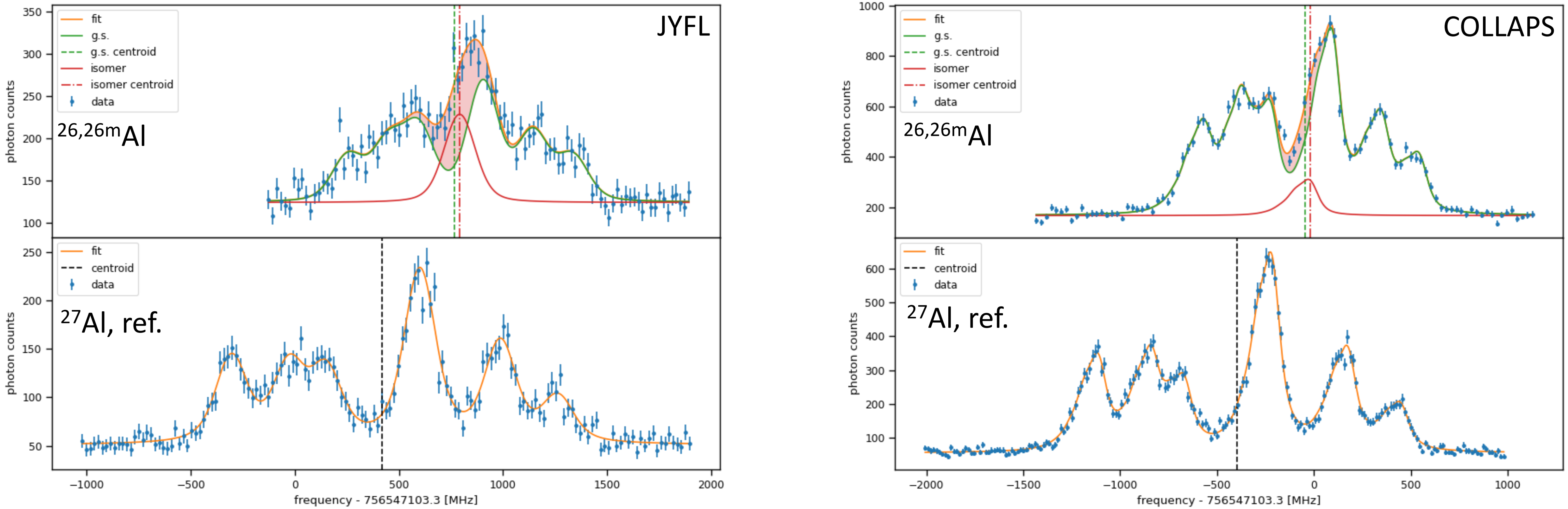
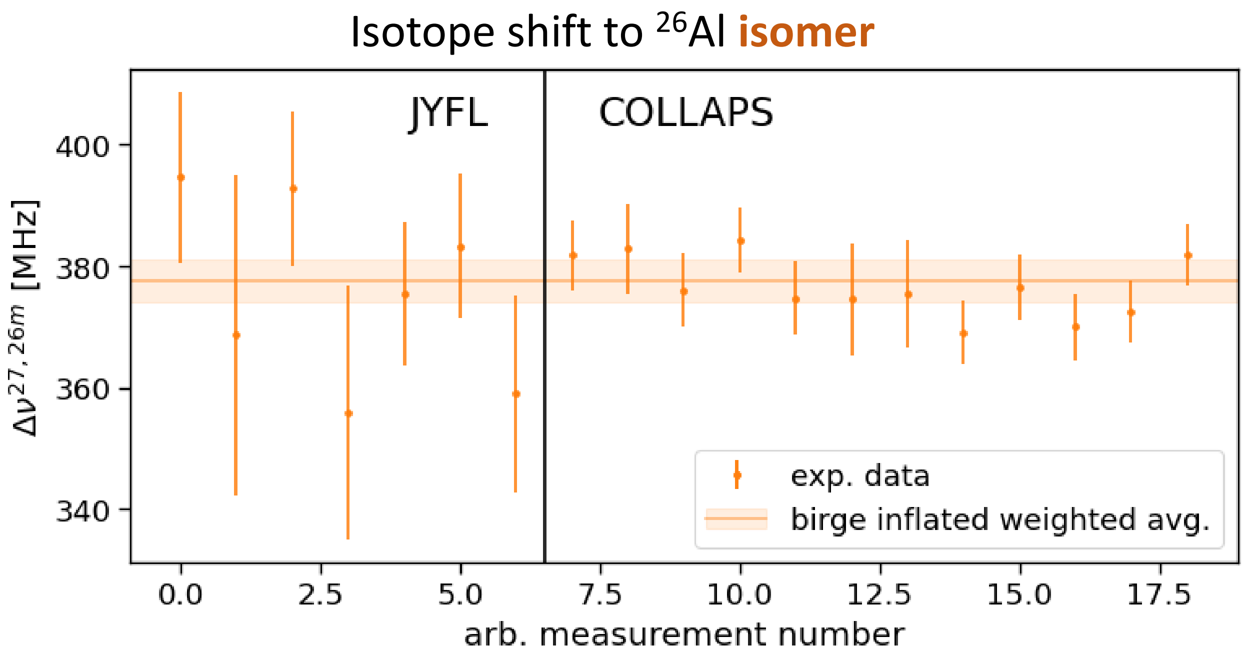


Isotope Shift



Isotope Shift [MHz]	
IGISOL	379.7{5.5}[2.2]
COLLAPS	376.5{1.7}[3.7]
weighted avg.	377.5(3.4)

- Statistical and systematic uncertainties combined in quadrature for each experiment
- Combination of both datasets as weighted average

[1] Heylen et al., Physical Review C 2021, 103.

Mean Square Charge Radius

- Isotope shifts $\delta\nu^{27,26}$, $\delta\nu^{27,26m}$ used to calculate difference in mean square nuclear charge radii $\delta\langle r^2\rangle^{27,A}$ between ^{26,26m}Al and ^{27}Al

$$\delta\langle r^2\rangle^{27,A} = \frac{\delta\nu^{27,A}}{F} - \frac{M}{F}\frac{m_A - m_{27}}{m_{27}\cdot(m_A + m_e)}$$

- Depends on
  - Respective nuclear masses m_A, electron mass m_e
  - Atomic mass shift factor M
  - Field shift factor F
  - Known nuclear charge radius of a reference isotope

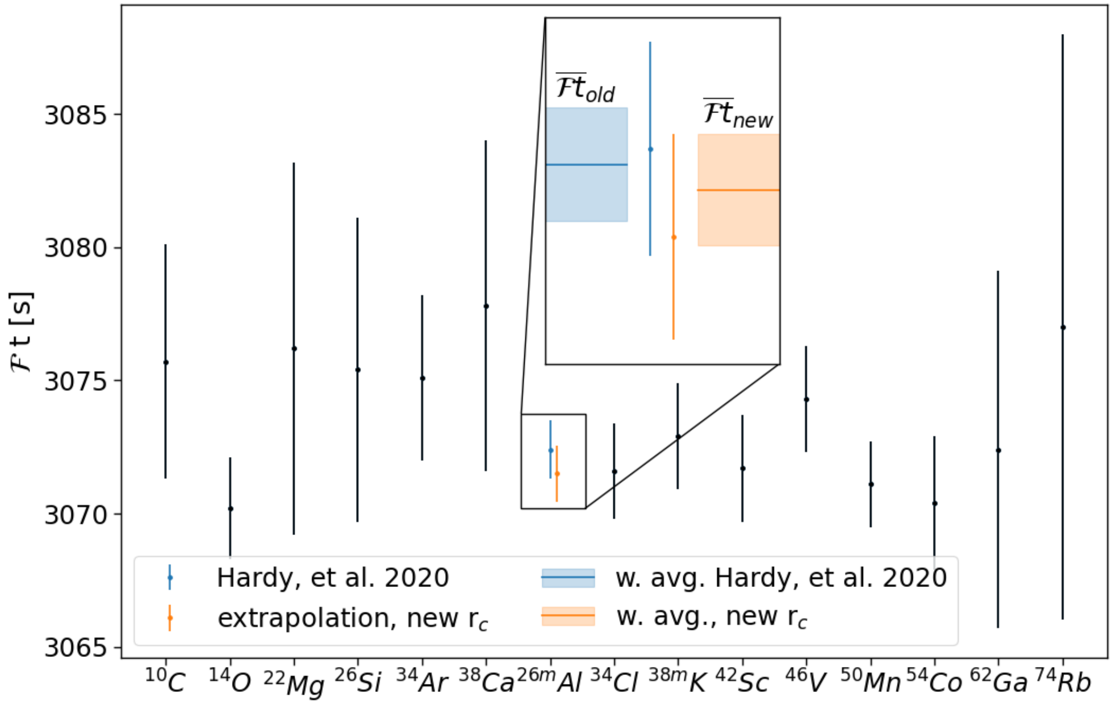
- Nuclear charge radius of ^{27}Al, F, M from [1]

[1] Heylen et al., Physical Review C 2021, 103.

Nuclear Charge Radii

- Nuclear charge radius of ^{26m}Al: 3.130(15) fm
- 4.5 statistical standard deviations from extrapolated value
- First extrapolation by same number of standard deviations for radial overlap correction of ISB correction

	Old values from [1]	New Values
^{26m}Al nuclear charge radius	3.04(2) fm	3.130(15) fm
$\mathcal{F}t$ of ^{26m}Al	3072.4(1.1) s	3071.4(1.0) s
$\overline{\mathcal{F}t}$	3072.24(1.85) s	3071.96(1.85) s



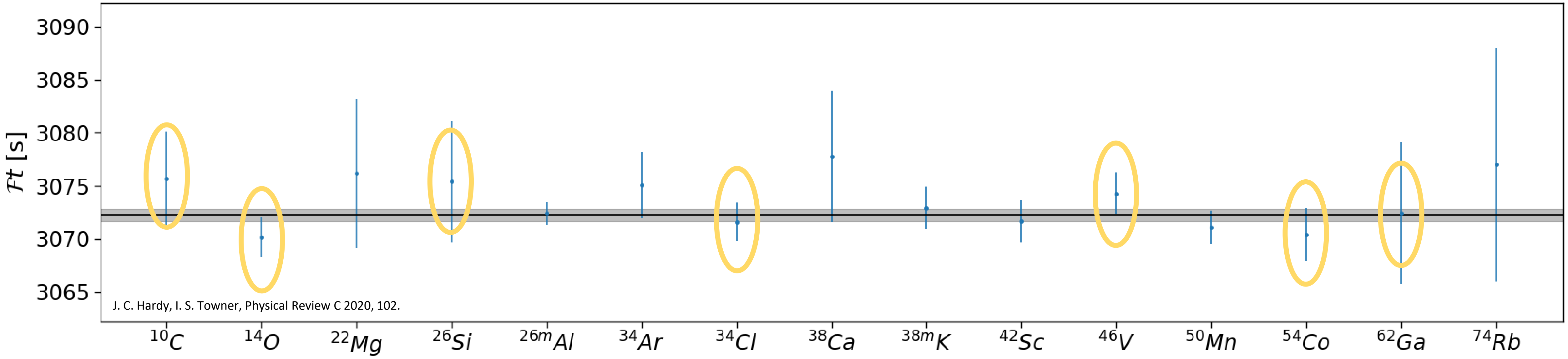
[1] J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

Implications for CKM unitarity

- Shifts the result of unitarity test closer towards unitarity by ~1/10 standard deviations

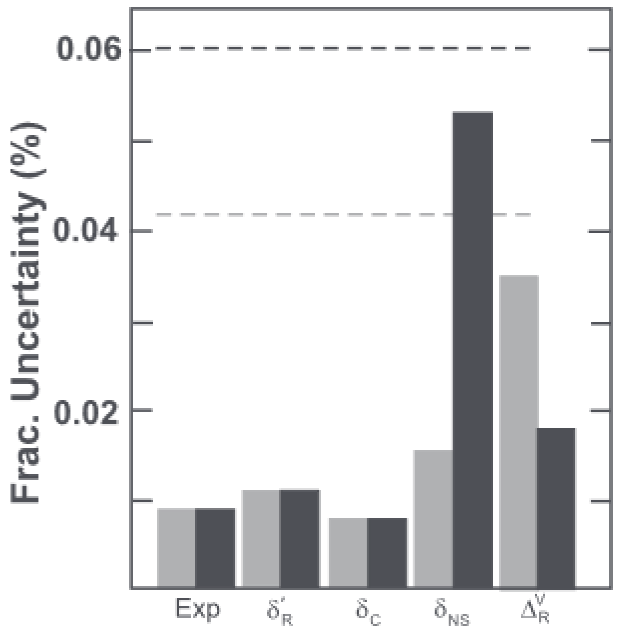
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = \sout{0.99848(70)} \rightarrow 0.99856(70)$$

- Motivates further studies of nuclear charge radii in other superallowed β emitters with so-far unknown charge radii:



Outlook

- Current status: charge radii of 7/15 superallowed beta emitters still unknown
- Ongoing efforts to measure ^{54}Co at IGISOL
- Uncertainty of $|V_{ud}|^2$ currently dominated by theoretical uncertainties on δ_{NS}
- Further effect of charge radius of ^{26m}Al on Fermi function → might result in nother shift



Grey: 2015
Black: 2020

Source: J. C. Hardy, I. S. Towner, Physical Review C 2020, 102.

Summary and Conclusion

- The charge radius of ^{26m}Al has been determined by Collinear Laser spectroscopy
- 4.5 standard deviations difference to extrapolated value used in isospin-symmetry-breaking corrections for V_{ud} of CKM matrix
- Extrapolation points towards slight shift towards CKM unitarity
- For more information:
  PRL 131, 222502 (2023) (DOI:10.1103/PhysRevLett.131.222502)

Questions

- Most promising cases to measure charge radii of superallowed beta emitters (or others) from theory side?
- Charge radius does not only enter for ISB corrections but also in the Fermi function → estimate of effect of this on V_{ud}?
- Nuclear structure correction currently dominating Vud uncertainty. Observables from experiment to help reduce this?

Thank you for your attention!

P. Plattner[1], E. Wood[2], L. Al Ayoubi[3], O. Beliuskina[3], M. L. Bissell[4,5], K. Blaum[1], P. Campbell[4], B. Cheal[2], R. de Groote[6], C. Devlin[2], T. Eronen[3], L. Filippin[7], R. F. García Ruíz[8], Z. Ge[3], S. Geldhof[6], W. Gins[3], M. Godefroid[7], H. Heylen[5], M. Hukkanen[3], J. D. Holt[9,10], P. Imgram[11], A. Jaries[3], A. Jokinen[3], A. Kanellakopoulos[6], A. Kankainen[3], S. Kaufmann[11], K. König[11], Á. Koszorús[5], S. Kujanpää[3], S. Lechner[5], S. Malbrunot-Ettenauer[5], R. Mathieson[2], T. Miyagi[11], I. Moore[3], P. Müller[11], D. Nesterenko[3], R. Neugart[1,12], G. Neyens[6], W. Nörtershäuser[11], A. Ortiz-Cortes[3], H. Penttilä[3], I. Pohjalainen[3], A. Raggio[3], M. Reponen[3], S. Rinta-Antila[3], L. V. Rodríguez[5,1], J. Romero[3], R. Sánchez[13], F. Sommer[11], M. Stryjczyk[3], V. Virtanen[3], L. Xie[4], Z. Y. Xu[6], X. F. Yang[6,14], and D. T. Yordanov[15]

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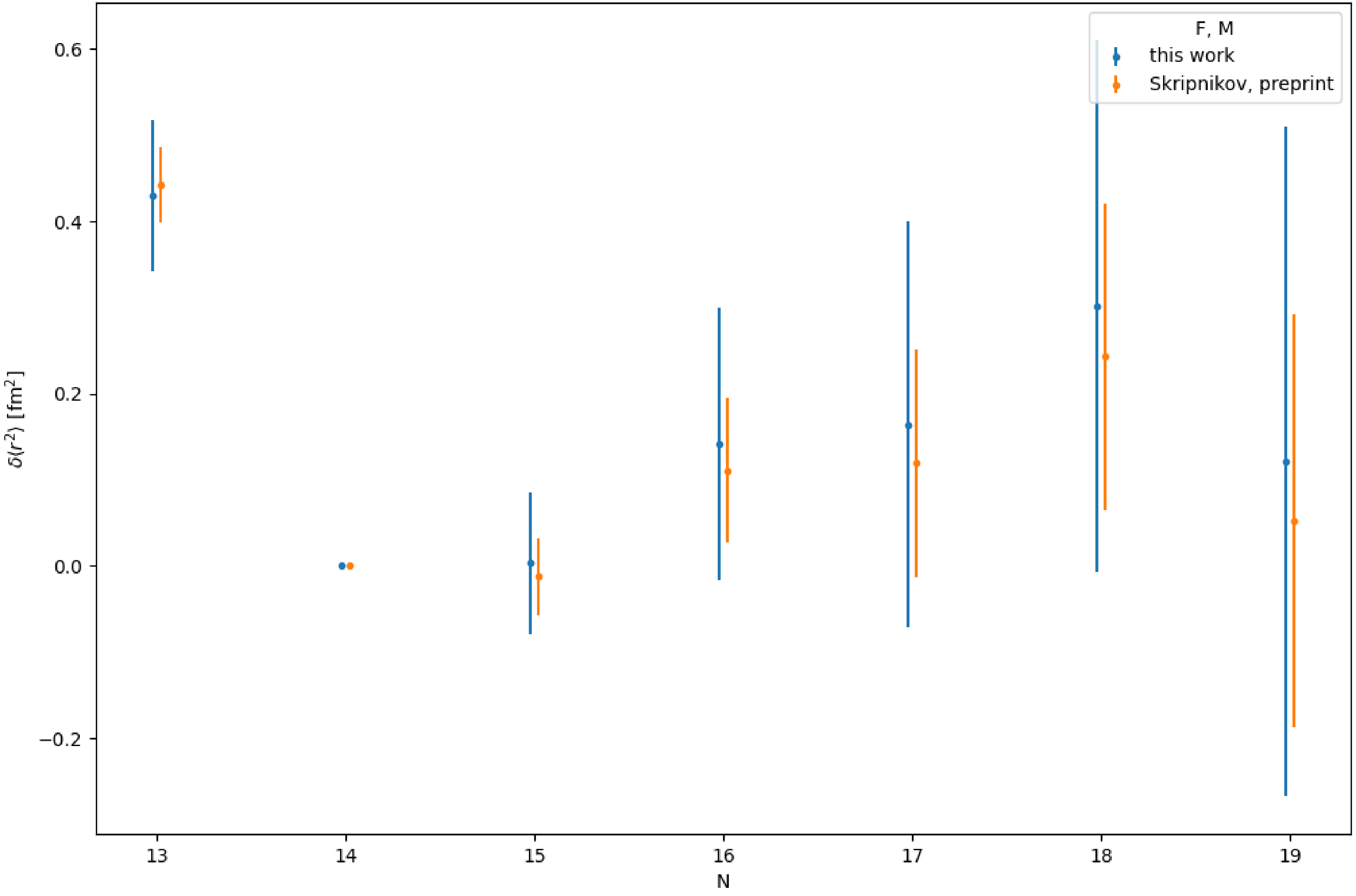
Backup (1)



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