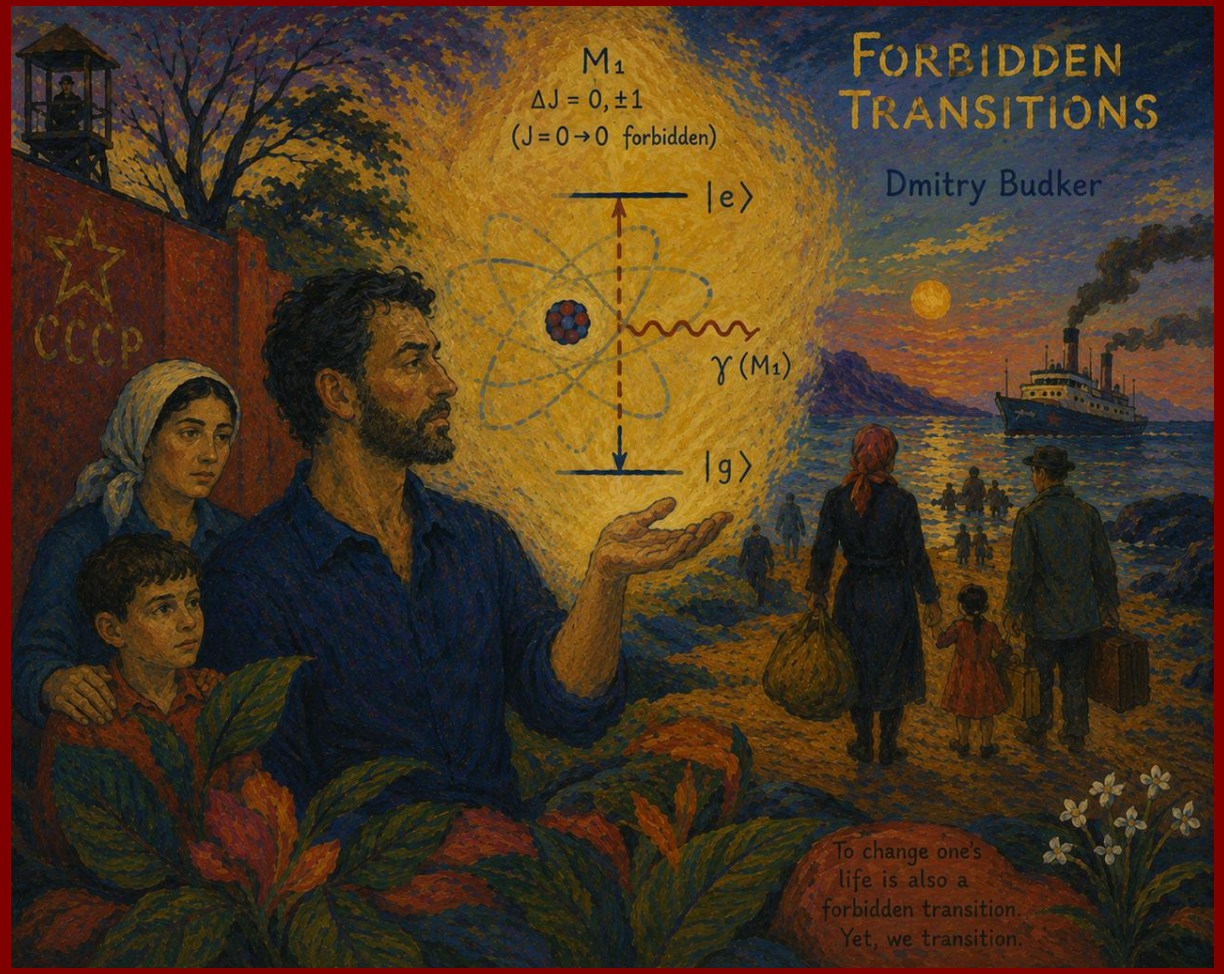
FORBIDDEN TRANSITIONS
FOR
TESTS OF FUNDAMENTAL PHYSICS

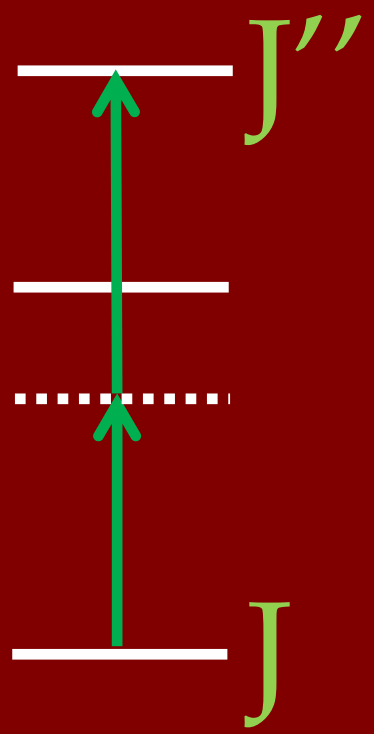
ICAP, WUHAN
JUNE 2026



Dmitry Budker
Helmholtz Institute, JGU Mainz, Germany
University of California, Berkeley, USA

Forbidden Transitions: Challenge and Opportunity

Example: Two-photon selection rules (E1-E1)



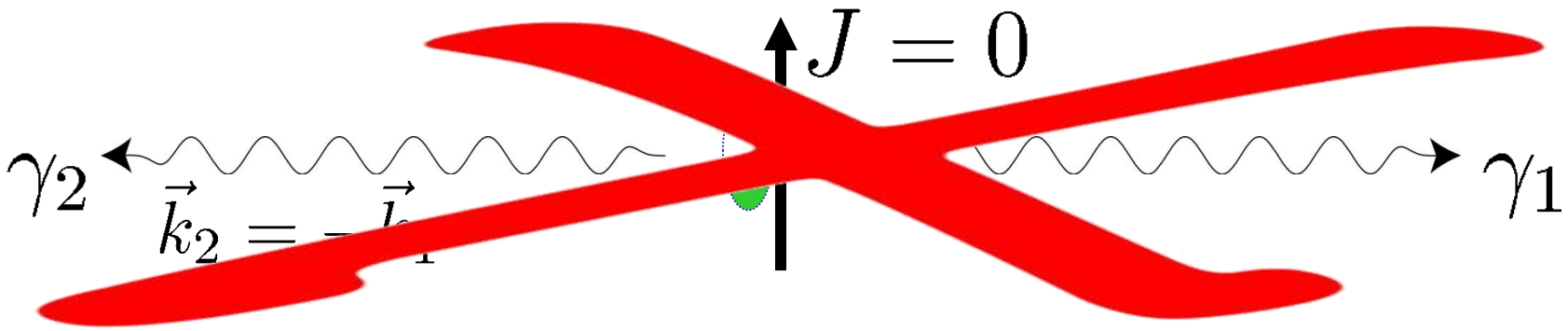
- Parity must **not** change
- $\Delta J = 0, \pm 1$, or ± 2
- **Everybody knows these rules !**
- $J=0 \rightarrow J''=1$ generally allowed
- but forbidden for degenerate photons
- Not only E1-E1 !
- **Almost nobody knows this rule**

Landau, L. D., Dokl. Akad. Nauk., USSR **60**, 207-209 (1948)

PHYSICAL REVIEW VOLUME 77, NUMBER 2 JANUARY 15, 1950

Selection Rules for the Dematerialization of a Particle into Two Photons

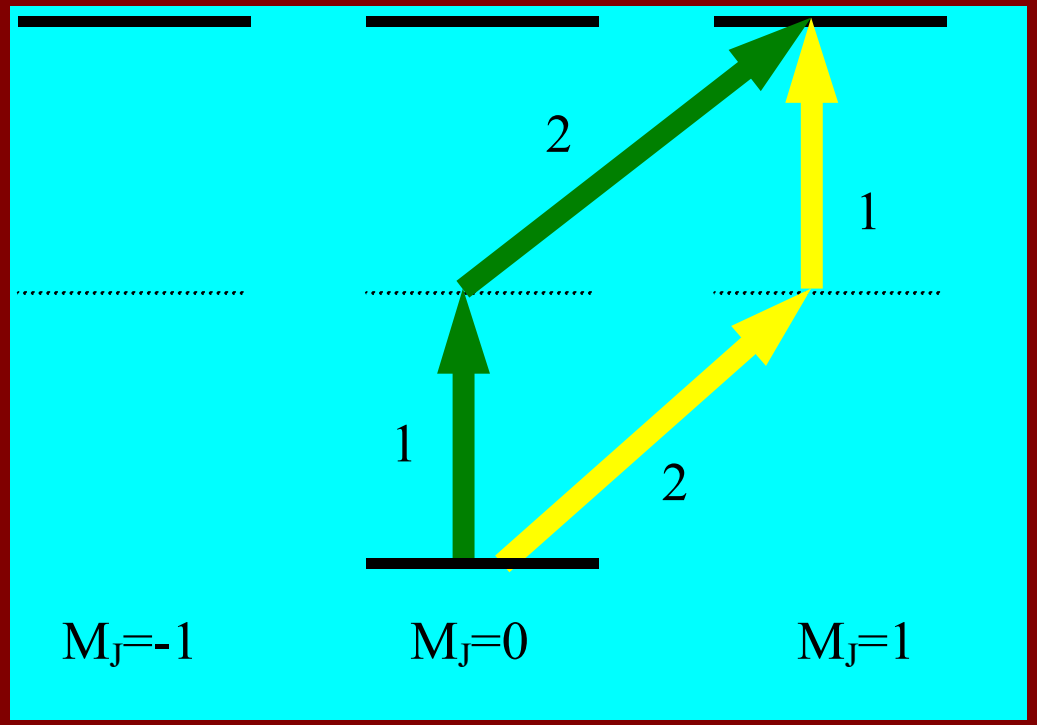
C. N. YANG*
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 22, 1949)



Doesn't go because no symmetric state
for two photons with J=1

Landau-Yang theorem and the degenerate two-photon transition selection rule

- **L-Y:** V(J=1) $\not\Rightarrow$ γγ
- **Inverse L-Y:** Nothing(J=0) + γγ $\not\Rightarrow$ V(J=1)



➢ **Destructive interference of two quantum paths**


Amsterdam, Summer
96

Testing Photon Quantum Statistics

VOLUME 83, NUMBER 20 PHYSICAL REVIEW LETTERS 15 NOVEMBER 1999

Search for Exchange-Antisymmetric Two-Photon States

D. DeMille,[1] D. Budker,[2] N. Derr,[3,*] and E. Deveney[3,†]
[1]*Department of Physics, Yale University, New Haven, Connecticut 06520*
[2]*Department of Physics, University of California, Berkeley, California 94720-7300 and Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[3]*Department of Physics, Amherst College, Amherst, Massachusetts 01002*

Towards an improved test of Bose-Einstein statistics for photons

Cite as: AIP Conference Proceedings **545**, 281 (2000); https://doi.org/10.1063/1.1337737
Published Online: 19 March 2001

Damon Brown, Dmitry Budker, and David P. DeMille

PHYSICAL REVIEW A **80**, 042504 (2009)

Symmetry-suppressed two-photon transitions induced by hyperfine interactions and magnetic fields

M. G. Kozlov,[1] D. English,[2] and D. Budker[2,3,*]
[1]*Petersburg Nuclear Physics Institute, Gatchina 188300, Russia*
[2]*Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300, USA*
[3]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

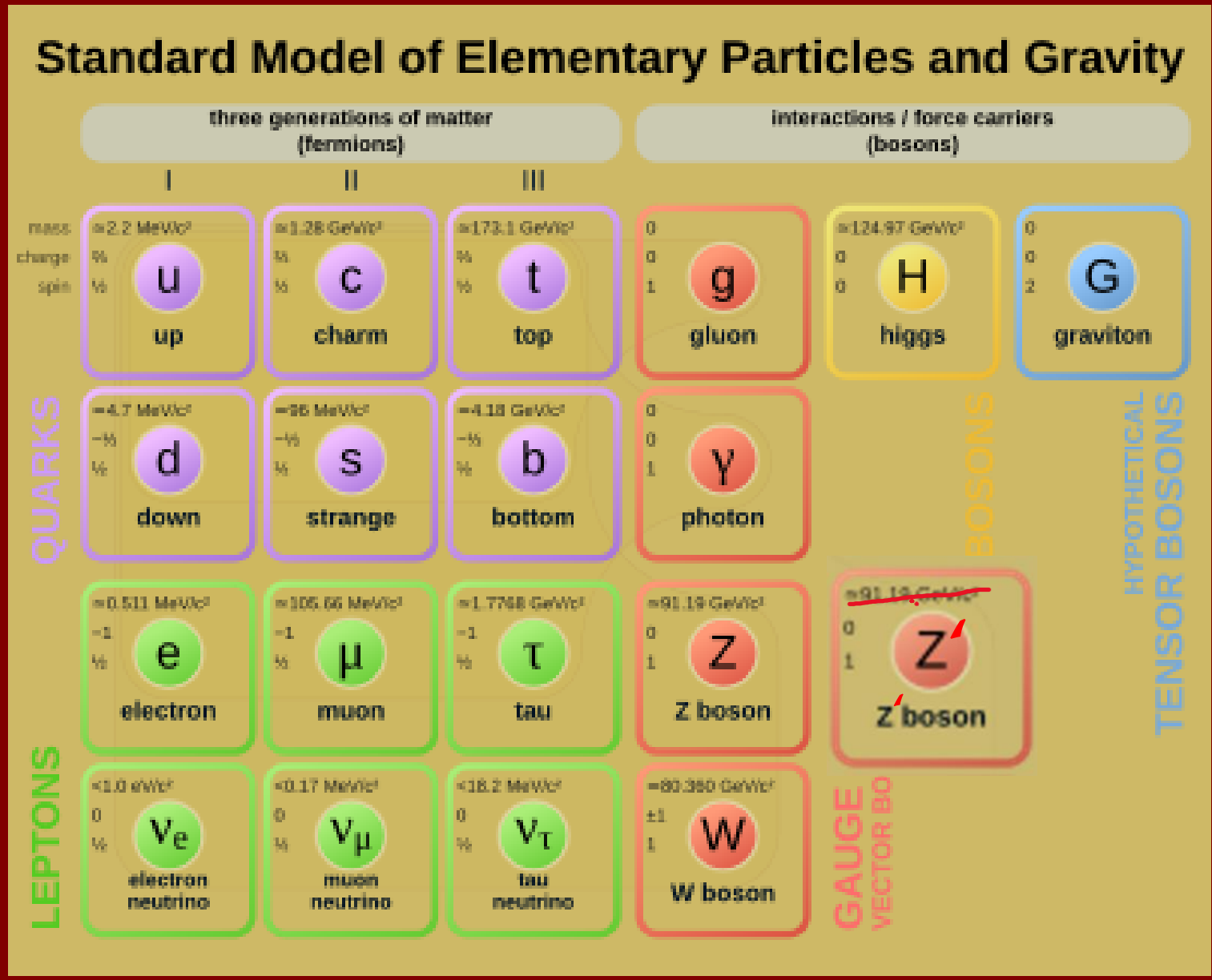
PRL **104,** 253604 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Spectroscopic Test of Bose-Einstein Statistics for Photons

D. English,[1,*] V. V. Yashchuk,[2] and D. Budker[1,3]
[1]*Department of Physics, University of California, Berkeley, California 94720-7300, USA*
[2]*Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[3]*Nuclear Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

Beyond

BSM
BBSM
Frontiers



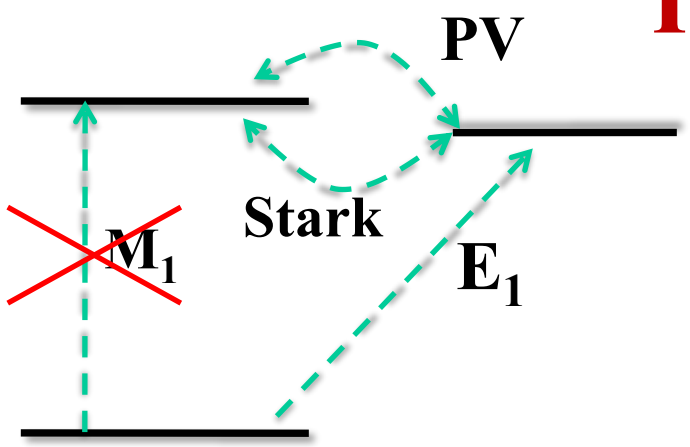
https://en.wikipedia.org/wiki/Physics_beyond_the_Standard_Model

D. Budker

Low-energy Tests of Fundamental Physics

European Review, 1-8 (2018)

How to measure parity violation on **forbidden transitions**?



- **Stark-interference technique**
  Bouchiat & Bouchiat

$$W_{\pm} = |\pm A_{Stark} + A_{PV}|^2$$

$$\approx \underbrace{A_{Stark}^2}_{P-conserving} \quad \underbrace{\pm 2A_{Stark} \cdot A_{PV}}_{P-violating}$$

$$Asymmetry = \frac{W_+ - W_-}{W_+ + W_-} \sim \frac{E1_{PV}}{E1_{Stark}}$$

Also need magnetic field B !

Many reversals to control systematics

S/N nominally independent of el. field

PV in ytterbium

Yb

Z=70

$(Xe)4f^{14}6s^2$

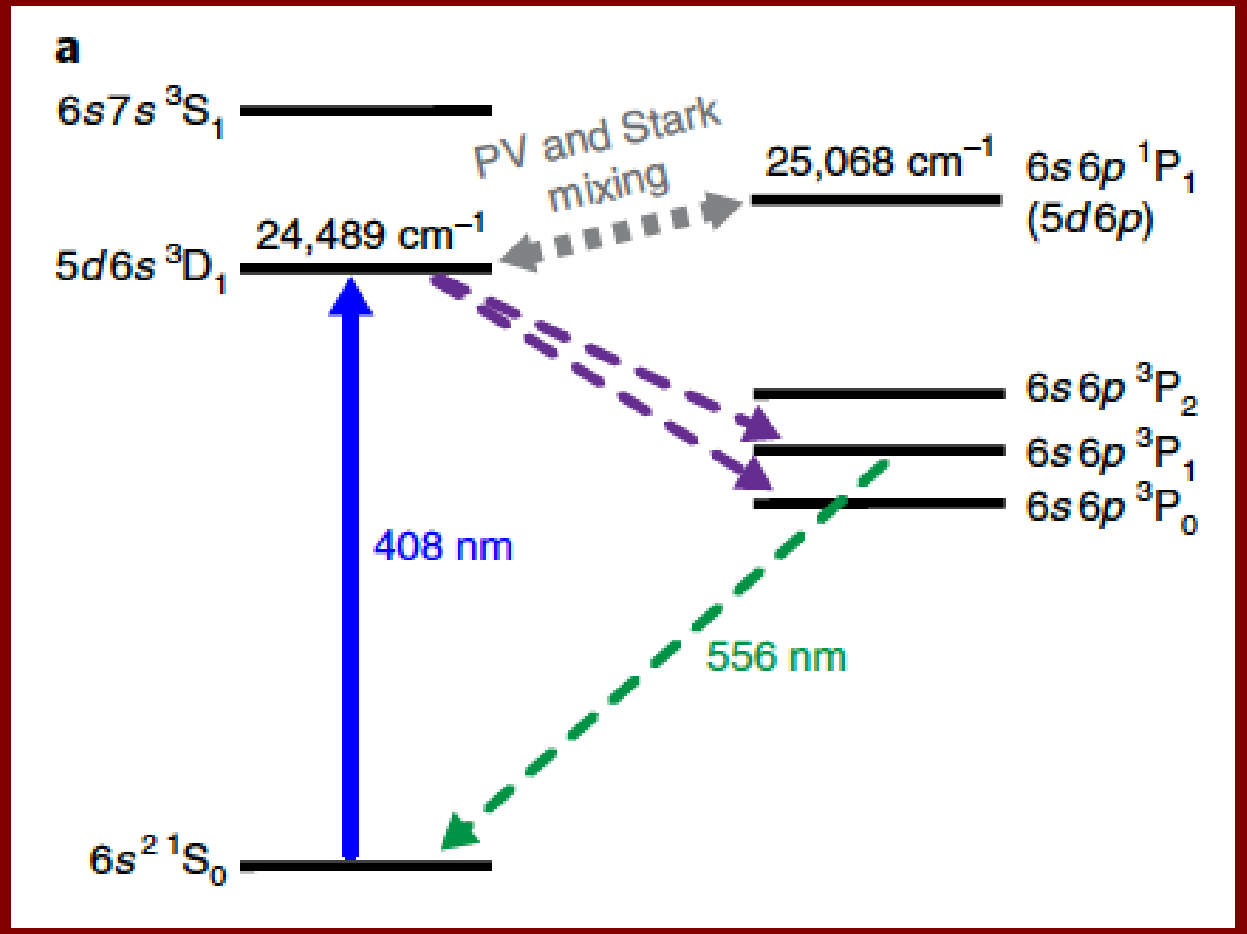
- **Large** APV effect (DeMille, 1995 - Tsigutkin *et al*, 2009)
- 7 stable isotopes (A=168, 170-174,176)

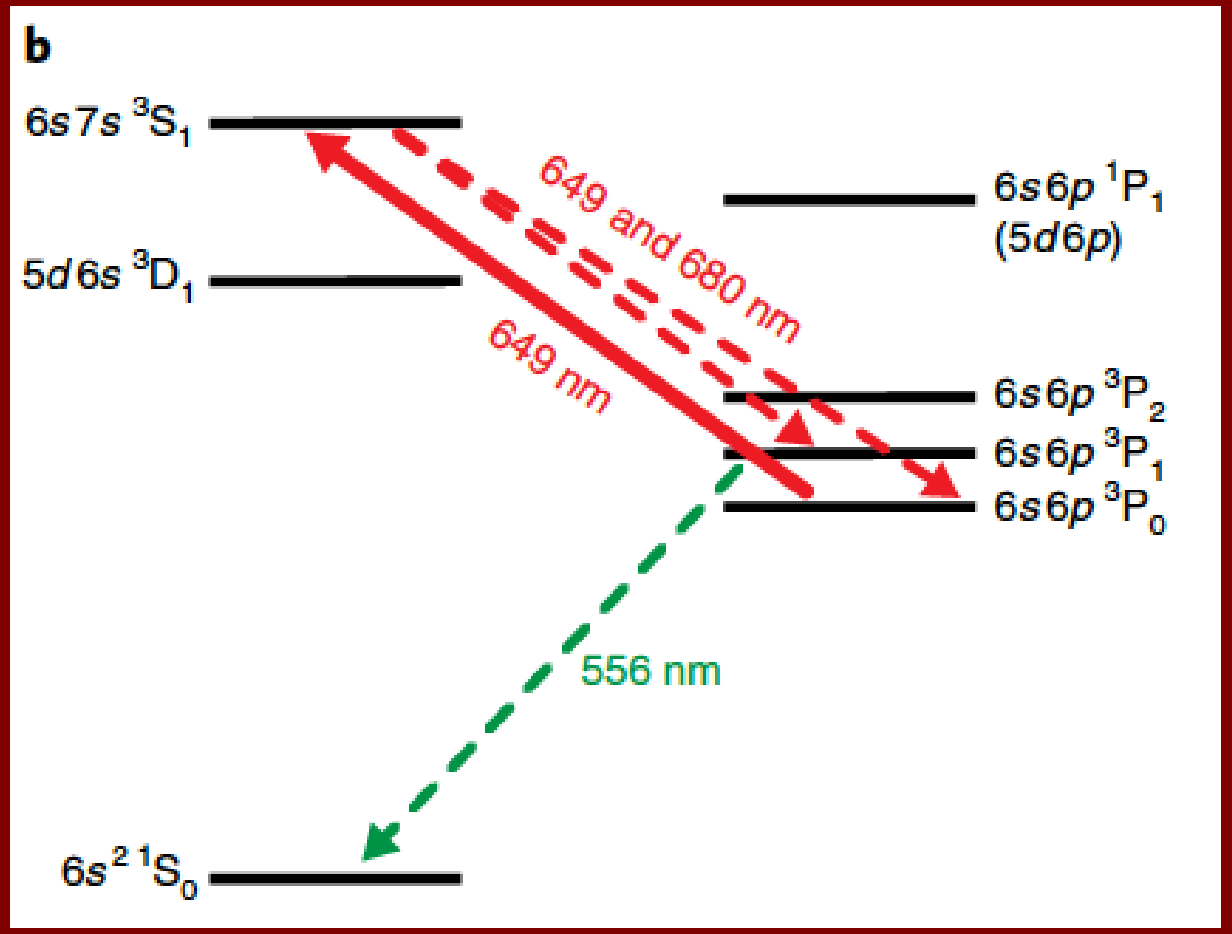
Isotope	NA (%)	I
^{174}Yb	31.8	0
^{172}Yb	21.8	0
^{176}Yb	12.8	0
^{173}Yb	16.1	5/2
^{171}Yb	14.3	1/2
^{170}Yb	3.04	0
^{168}Yb	0.13	0

- PNC on chain of isotopes → neutron distributions

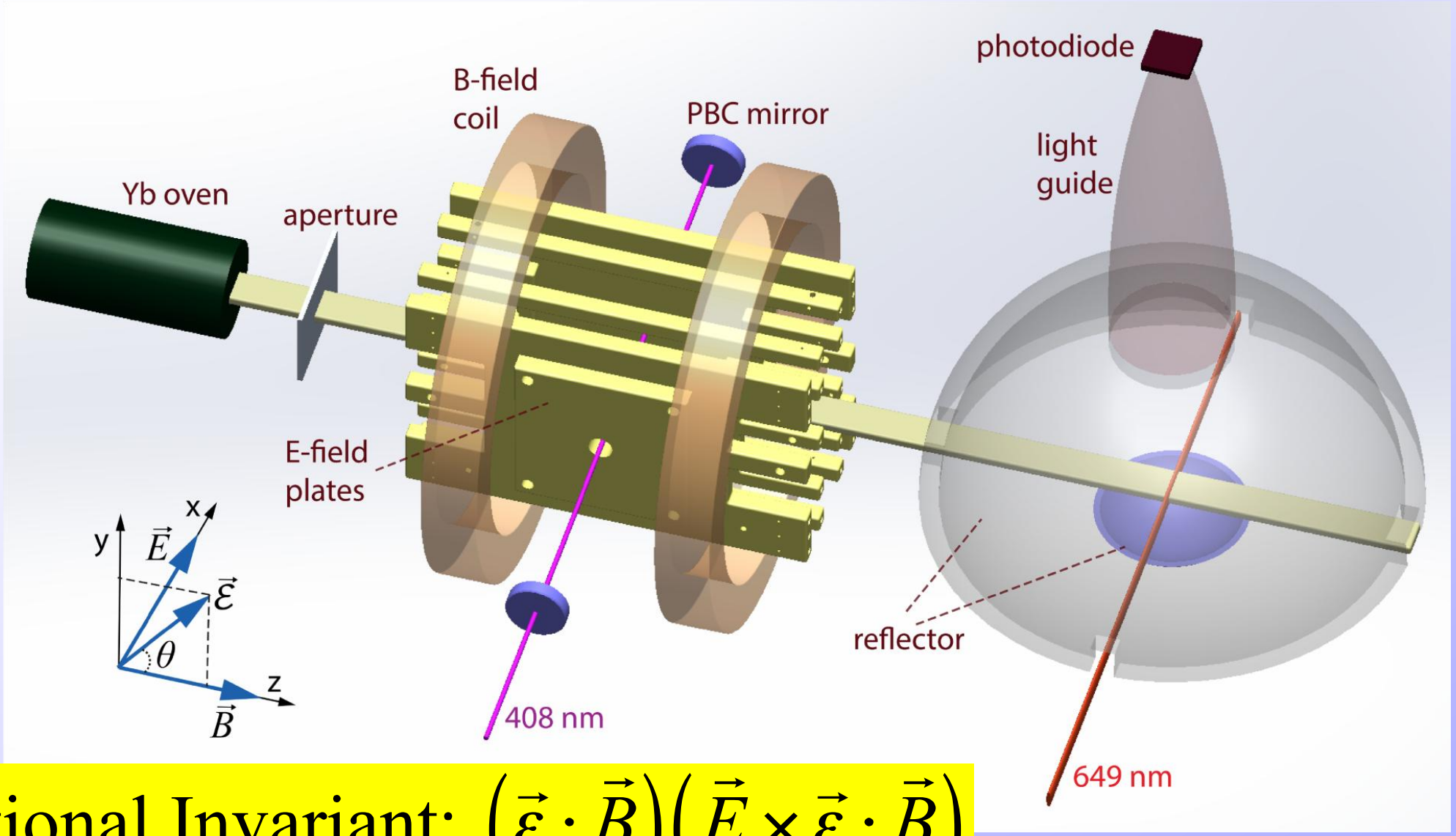
  → Physics beyond Standard Model

- Two isotopes with nuclear spin → hadronic weak interaction


a
6s7s ³S₁
PV and Stark mixing
25,068 cm⁻¹
6s6p ¹P₁ (5d6p)
24,489 cm⁻¹
5d6s ³D₁
6s6p ³P₂
6s6p ³P₁
6s6p ³P₀
408 nm
556 nm
6s² ¹S₀

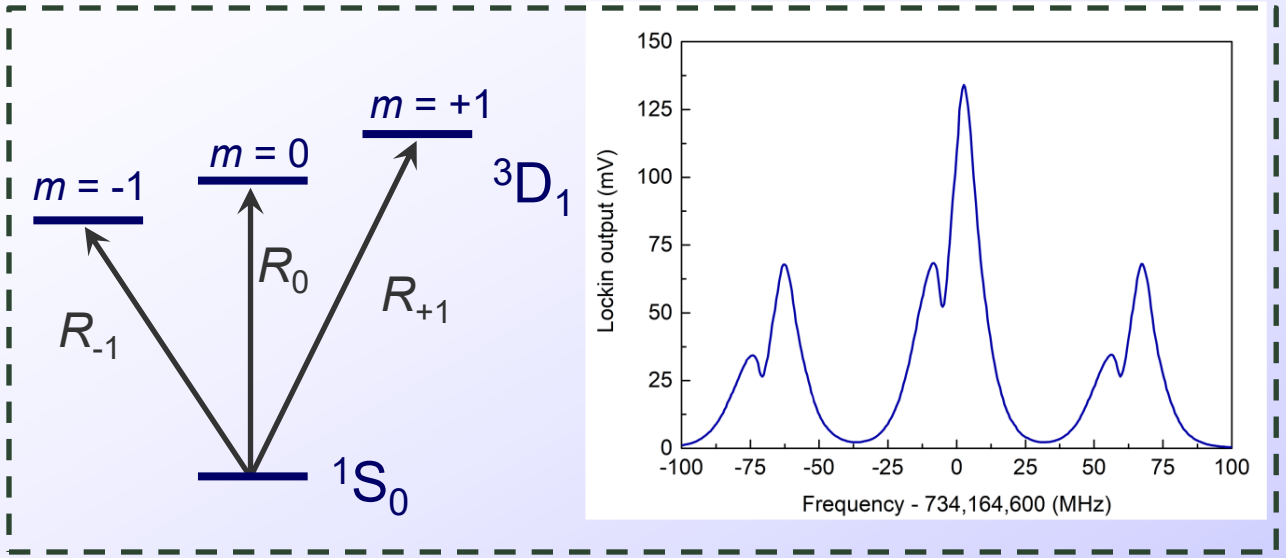

b
6s7s ³S₁
649 and 680 nm
649 nm
6s6p ¹P₁ (5d6p)
5d6s ³D₁
6s6p ³P₂
6s6p ³P₁
6s6p ³P₀
556 nm
6s² ¹S₀

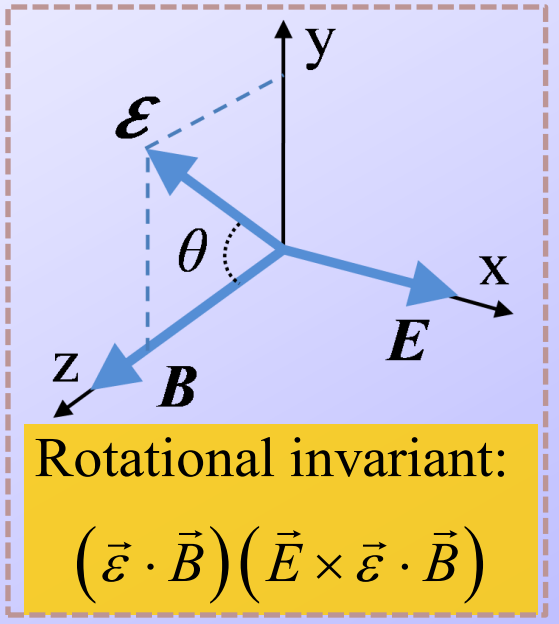
Yb atomic beam apparatus



Rotational Invariant: $\left(\vec{\varepsilon}\cdot\vec{B}\right)\left(\vec{E}\times\vec{\varepsilon}\cdot\vec{B}\right)$

Yb PV experiment





Rotational invariant:

$$\left(\vec{\varepsilon}\cdot\vec{B}\right)\left(\vec{E}\times\vec{\varepsilon}\cdot\vec{B}\right)$$

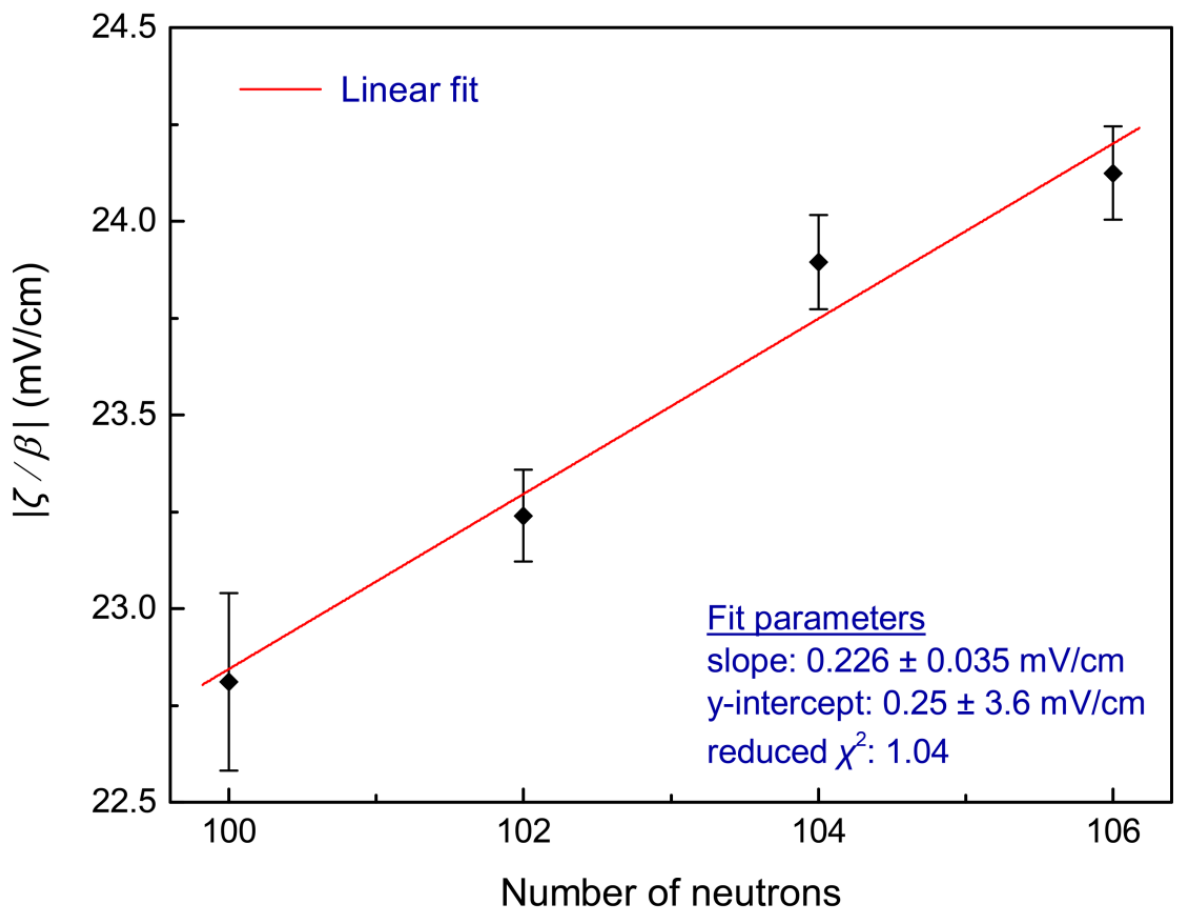
$$R_0 \propto \left|A_{Stark} + A_{PNC}\right|^2 \approx \beta^2 E^2 \sin^2\theta + 2E\beta\zeta\cos\theta\sin\theta$$

Stark-PV interference

PV asymmetry: $2\zeta/\beta E_0 \approx 5\cdot10^{-5}$

Parity reversals: E (20 Hz) and θ (0.2 Hz)

First observation of isotopic variation of atomic PV



0.5% single isotope accuracy

SM: $Q_W \approx -N+Z(1-4\sin^2\theta_W)$ → 1% change per neutron around N=103

Observation: 0.96(15) % change per neutron

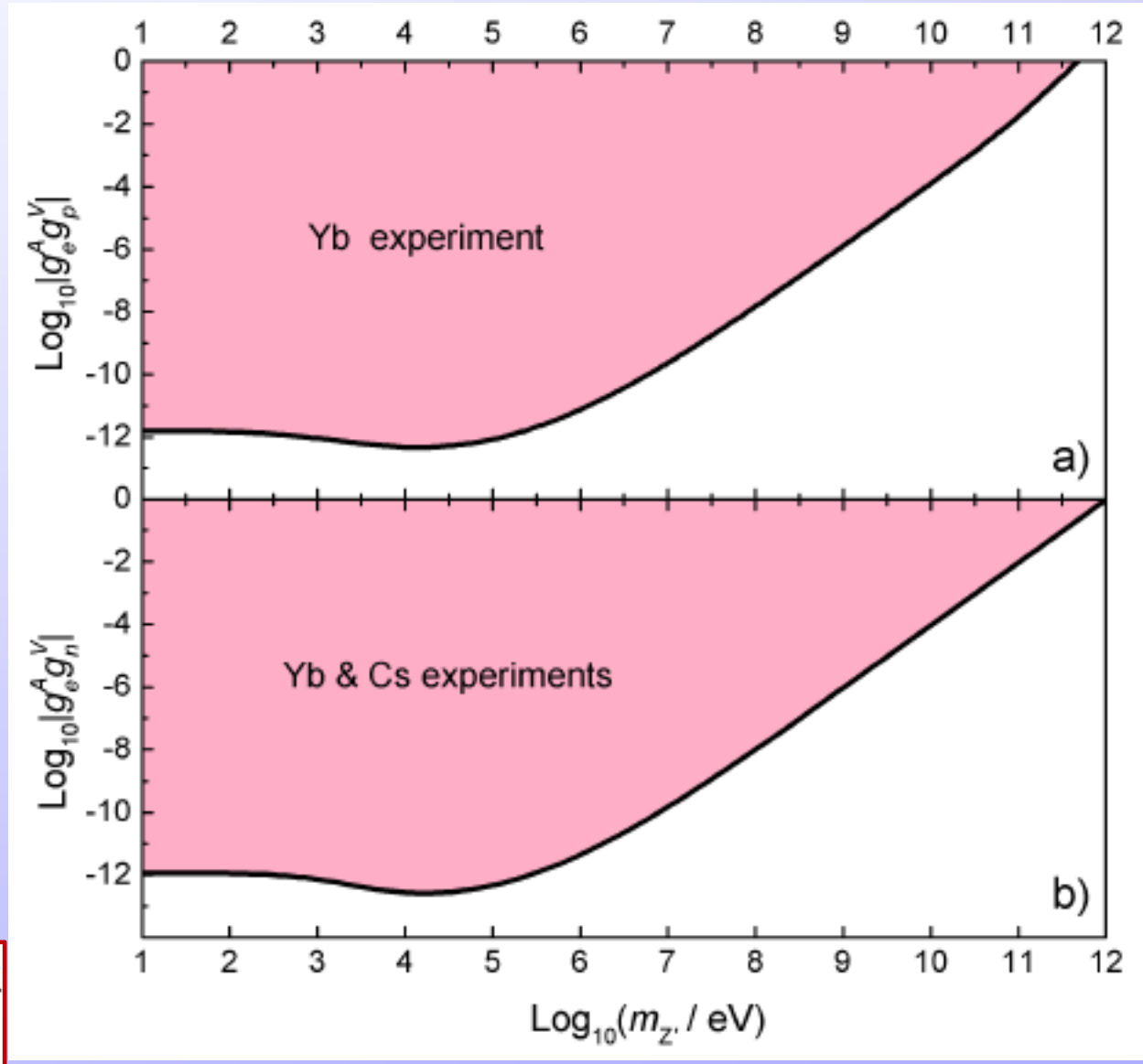
Implication for light mediators (V.V. Flambaum)

$$\mathcal{L} = Z'_\mu \sum_{f=e,p,n} \overline{f}\gamma^\mu (g_f^V + \gamma_5 g_f^A) f$$

PRL 119, 223201 (2017) PHYSICAL REVIEW LETTERS week ending 1 DECEMBER 2017

Probing Low-Mass Vector Bosons with Parity Nonconservation and Nuclear Anapole Moment Measurements in Atoms and Molecules

V. A. Dzuba,[1] V. V. Flambaum,[1,2] and Y. V. Stadnik[2]



Reference

nature physics

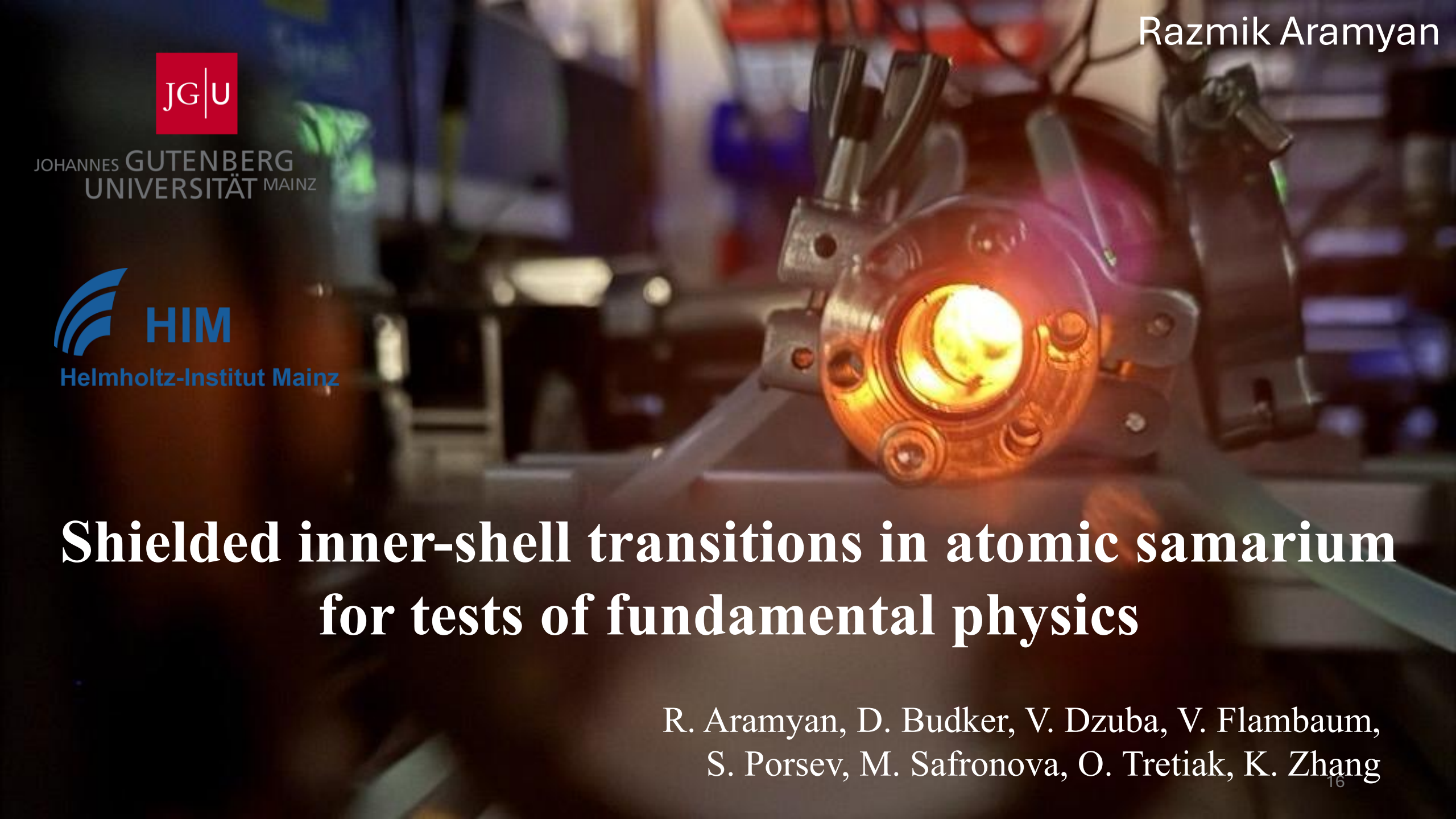
LETTERS

https://doi.org/10.1038/s41567-018-0312-8

Isotopic variation of parity violation in atomic ytterbium

D. Antypas[1*], A. Fabricant[2], J. E. Stalnaker[3], K. Tsigutkin[4], V. V. Flambaum[2,5] and D. Budker[1,2,6]

arXiv:1804.05747 (2018)



Razmik Aramyan

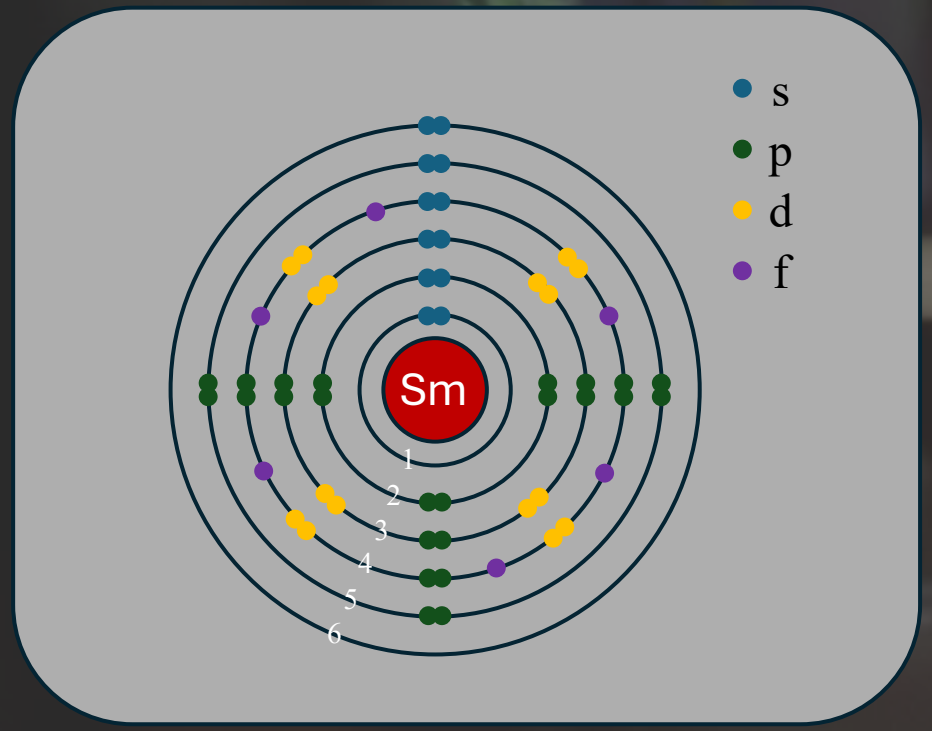
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

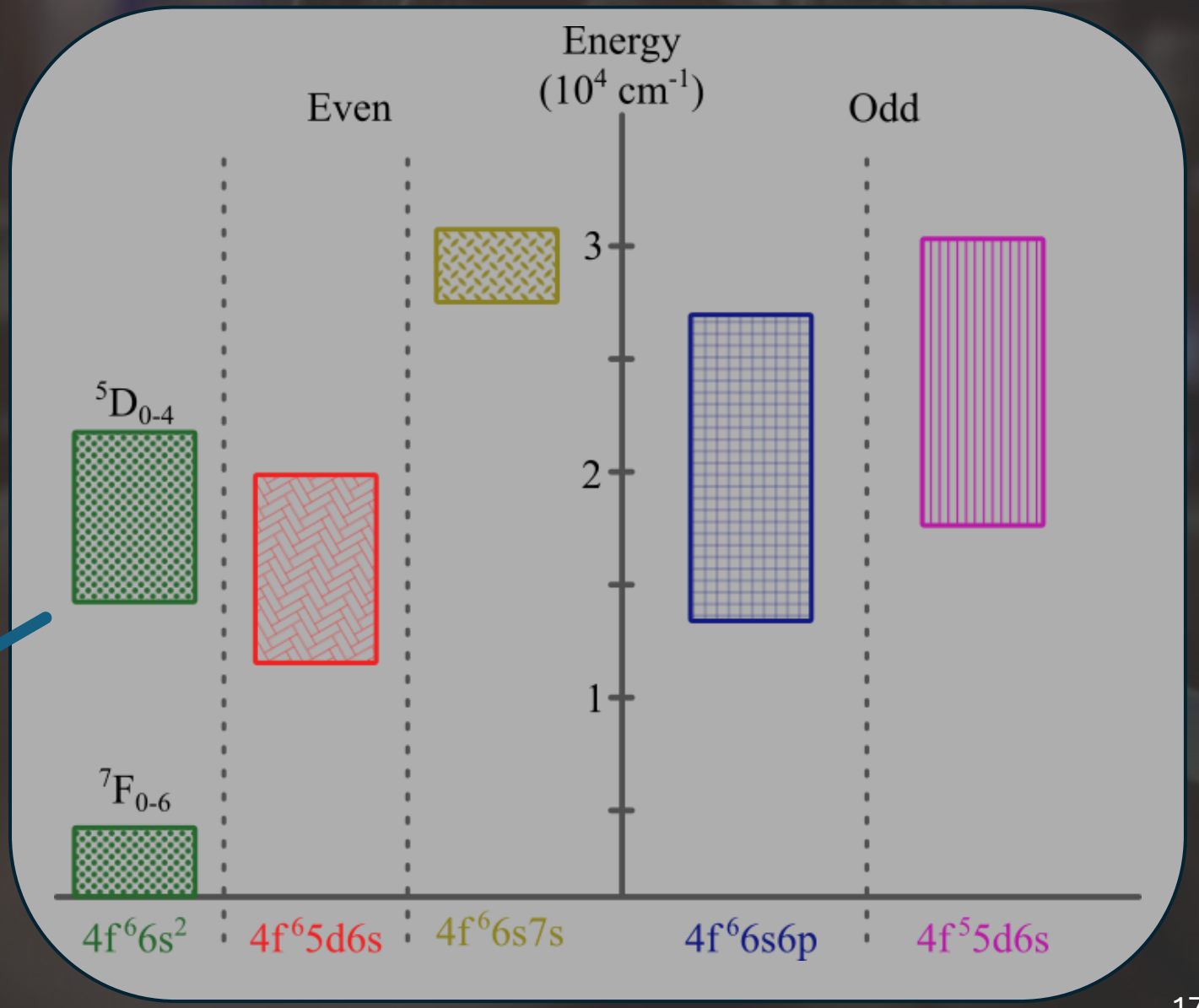
HIM
Helmholtz-Institut Mainz

Shielded inner-shell transitions in atomic samarium for tests of fundamental physics

R. Aramyan, D. Budker, V. Dzuba, V. Flambaum,
S. Porsev, M. Safronova, O. Tretiak, K. Zhang

Samarium (Sm, Z = 62)

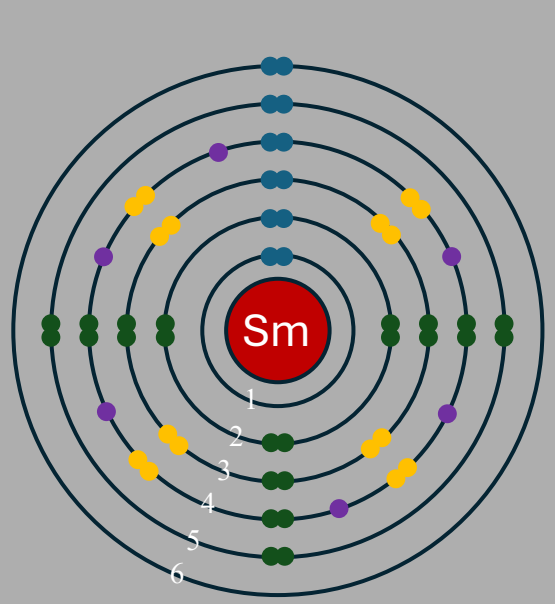




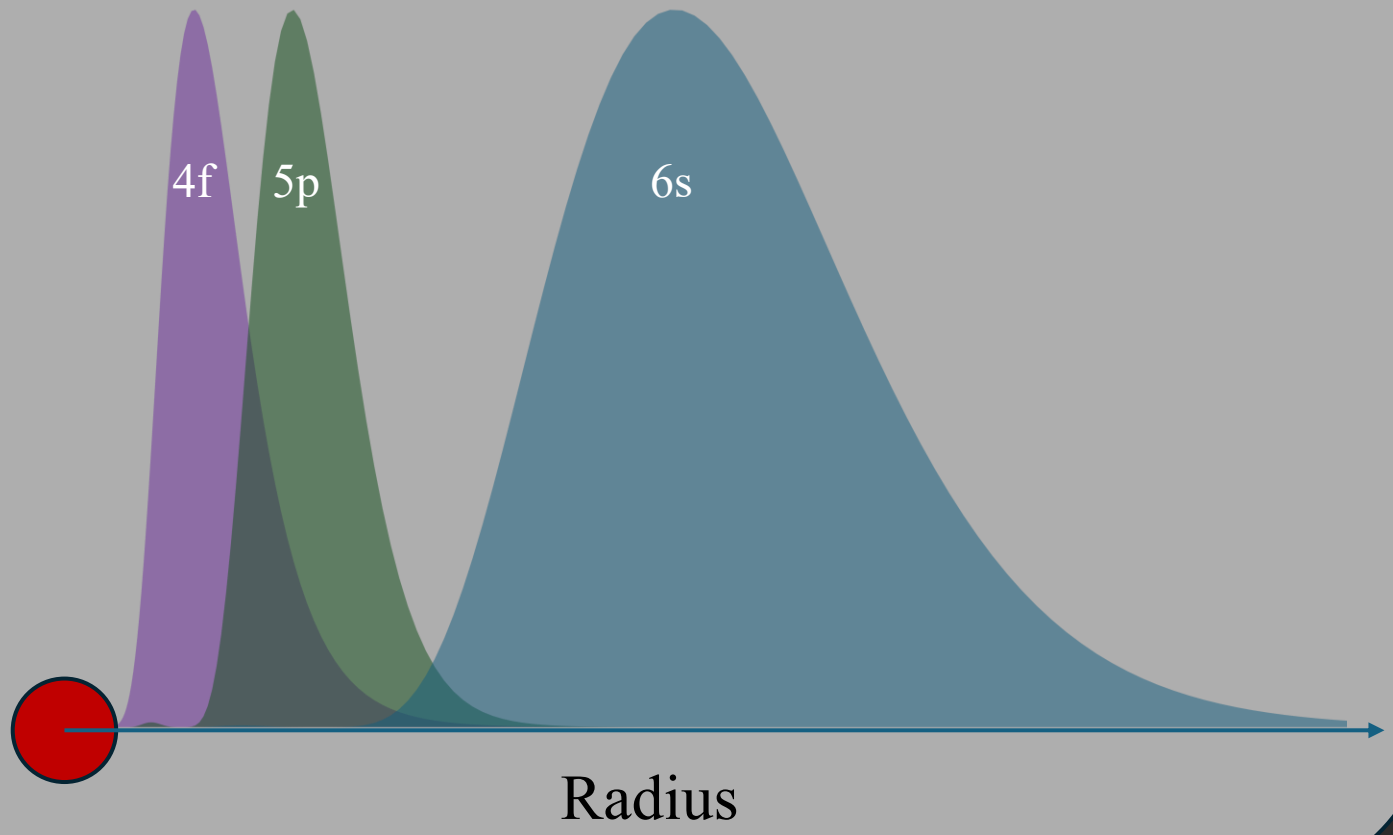
$^5D_0$ and $^5D_4$
where unknown

Shielded inner-shell transitions

Razmik Aramyan

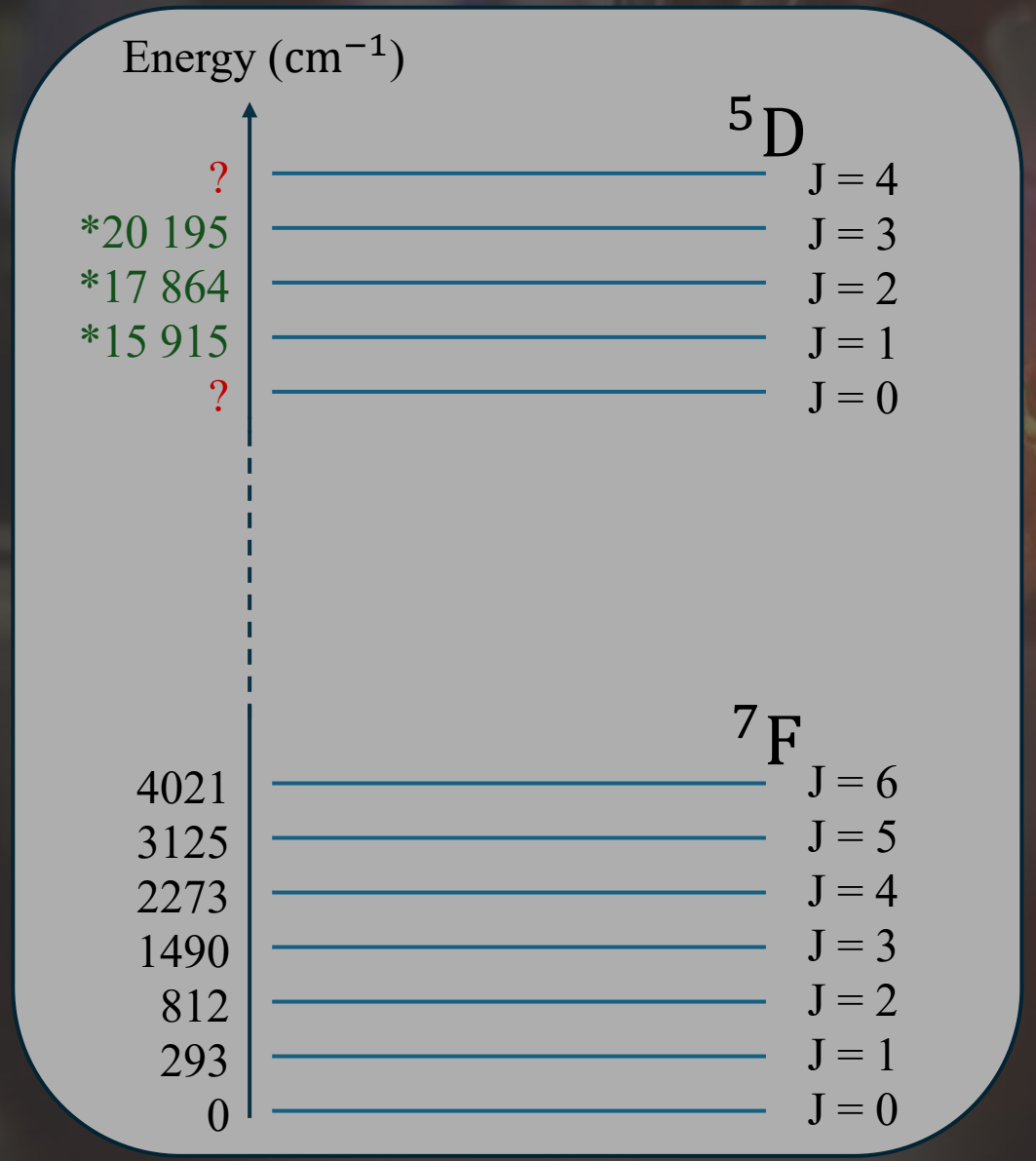


s
p
d
f



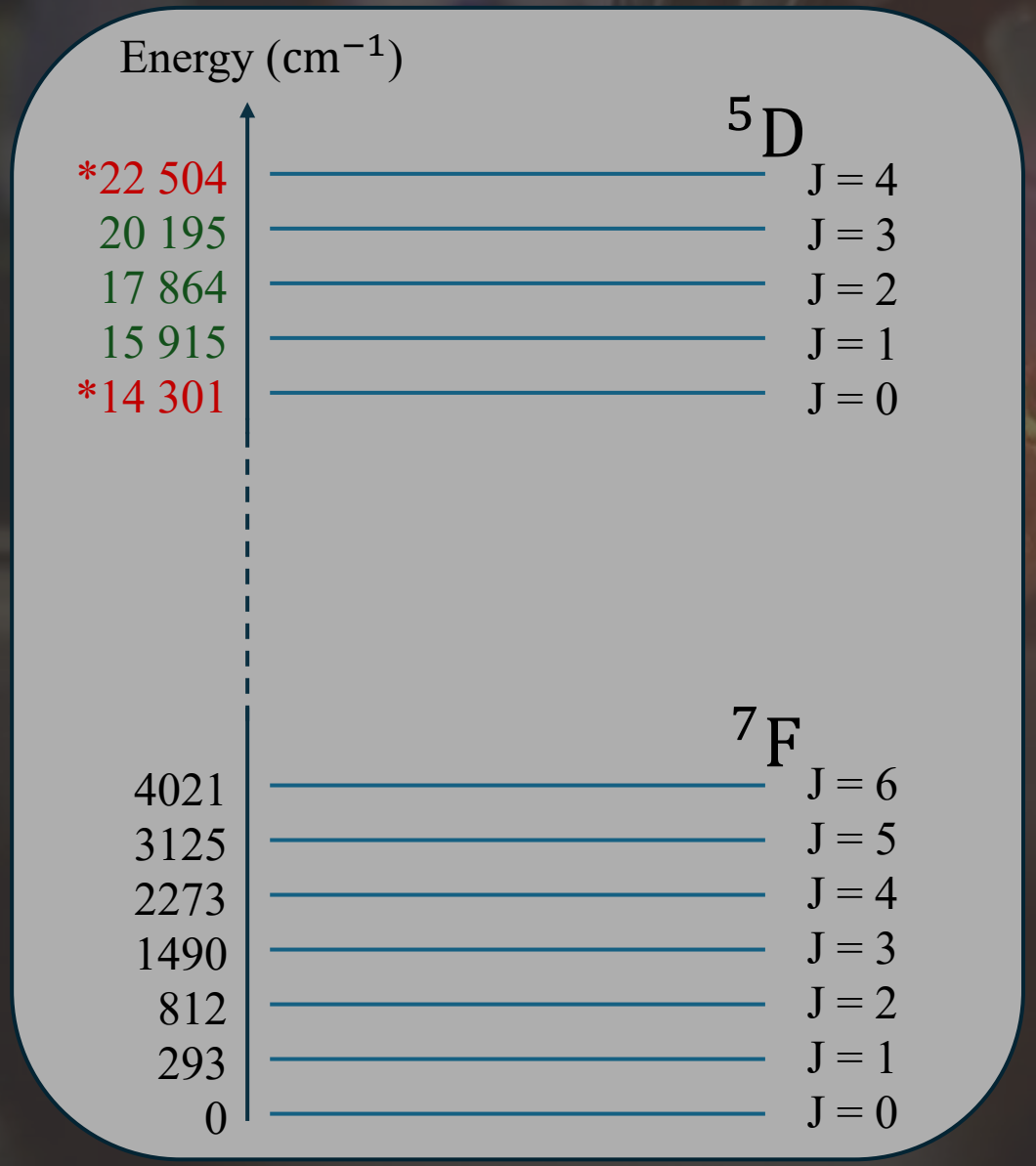
$4f^6 6s^2\ {}^7F \rightarrow 4f^6 6s^2\ {}^5D$

^{5}D levels



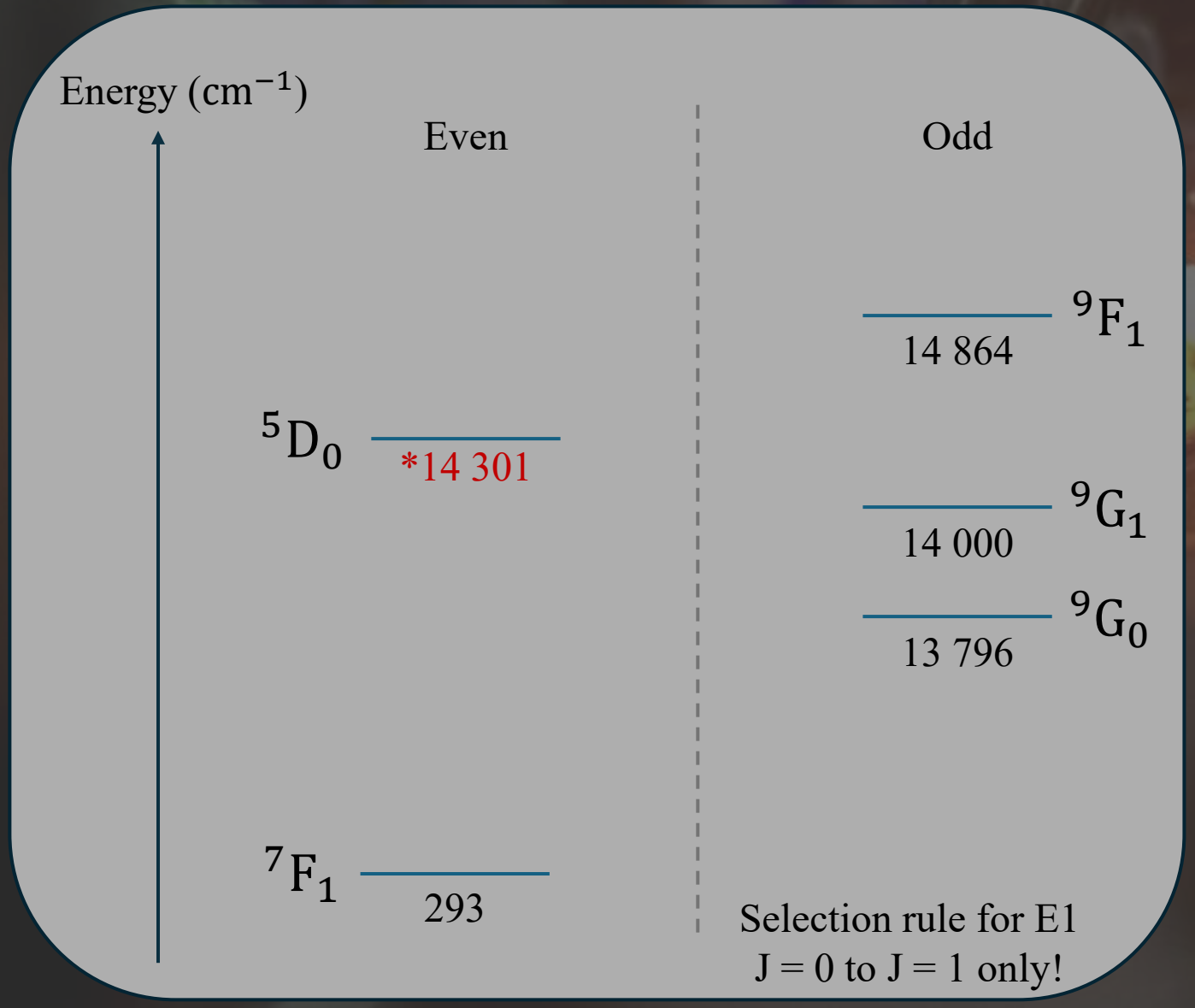
*L. M. Barkov, et al. *Tech. Rep.* **IYaF-88-142** (1988)

^{5}D levels



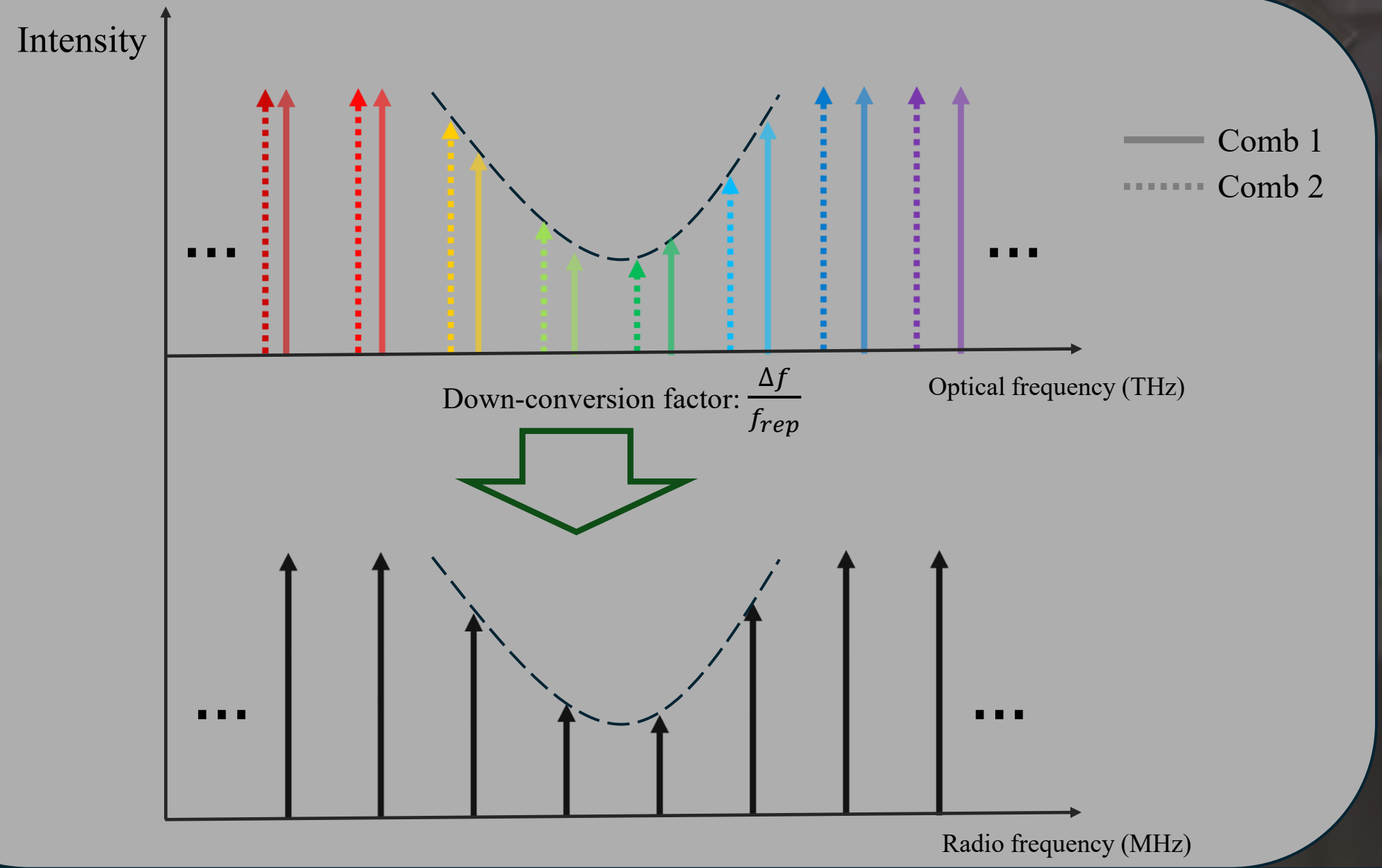
*Donald R Beck and Steven M O'Malley, *J. Phys. B: At. Mol. Opt. Phys.* **43** 215003 (2010)

$^5D_0$ level



- Optical lattice clock
- Isotope shift
- Atomic parity violation

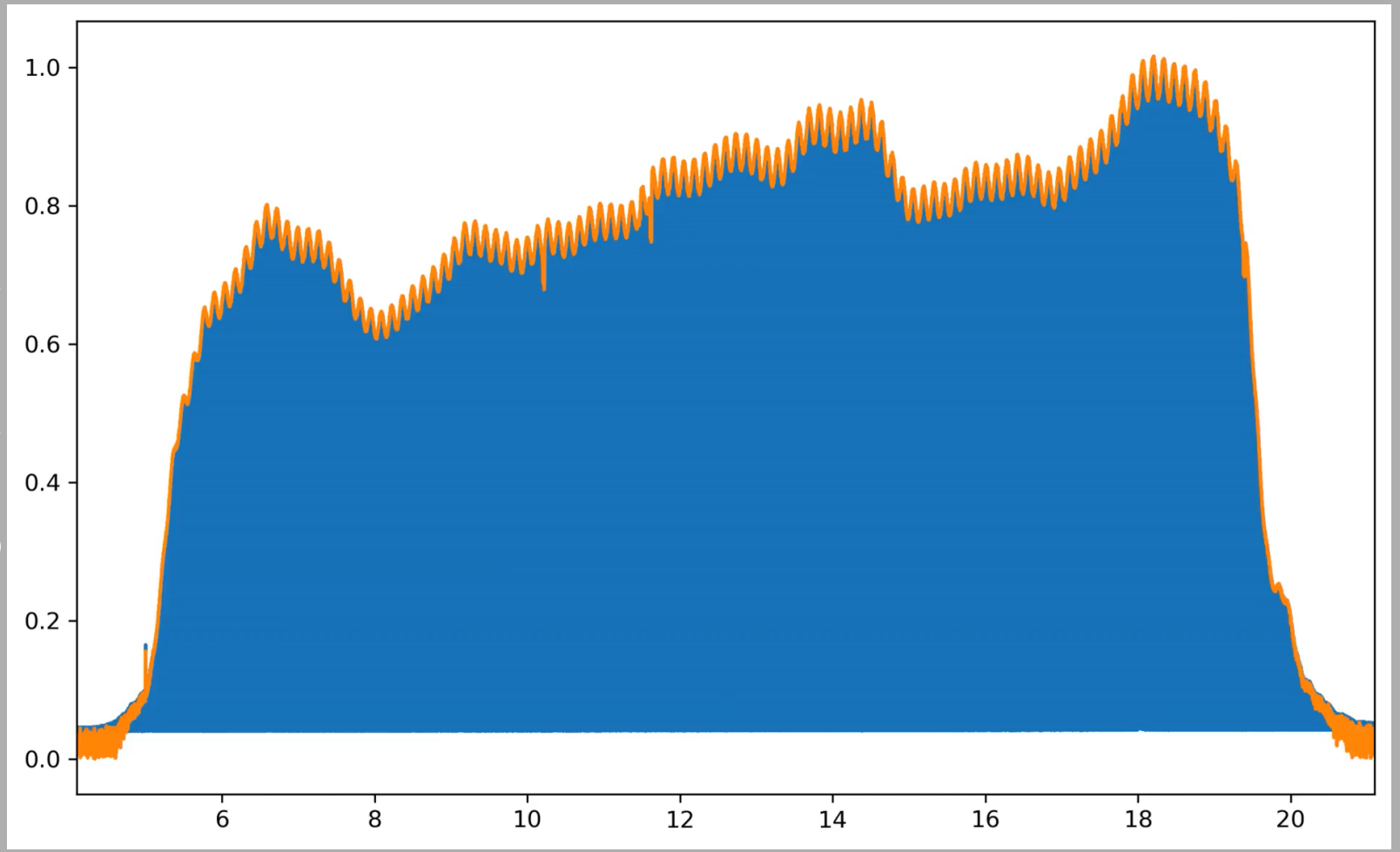
Dual-Comb Spectroscopy (DCS)



DCS of the Samarium

Razmik Aramyan

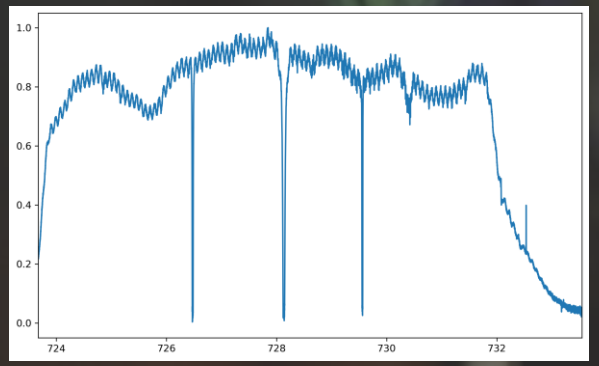
Sm ~500˚C

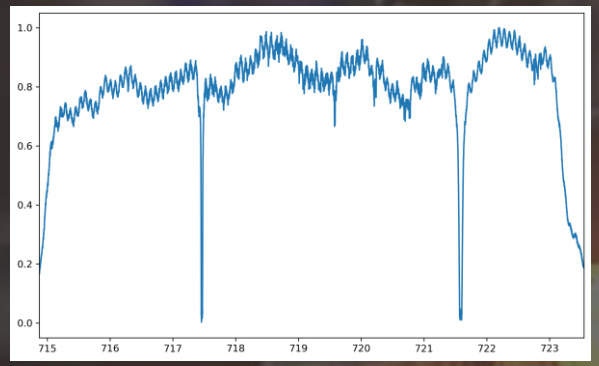


DCS Results

Range – 680 nm to 730 nm
Average SNR - 900

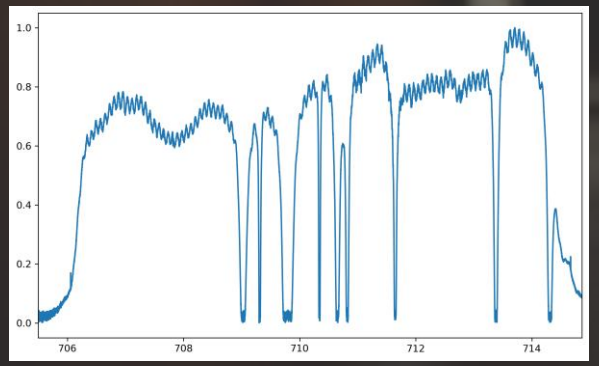
Ch1

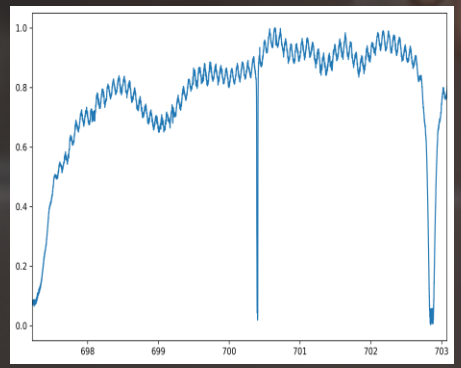




Ch2

Ch3





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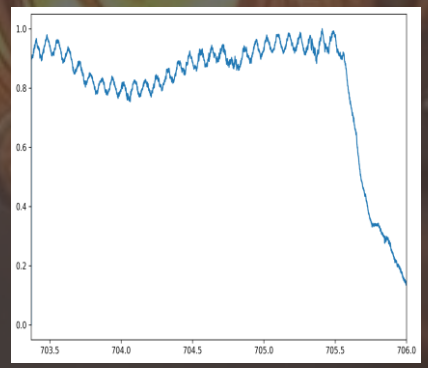
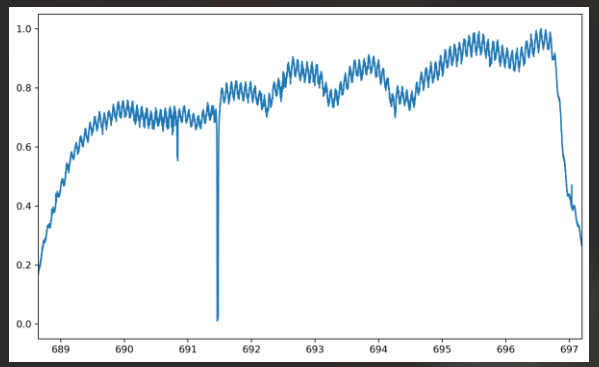
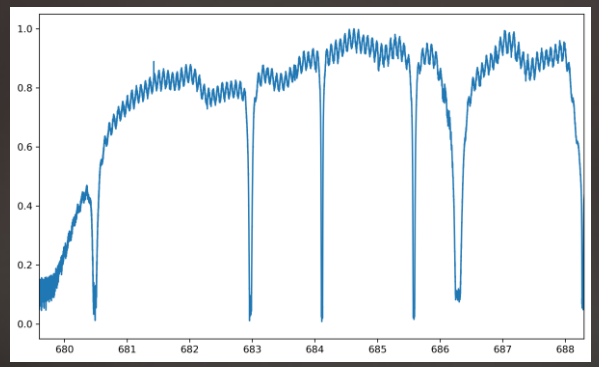


Ch4

Ch5

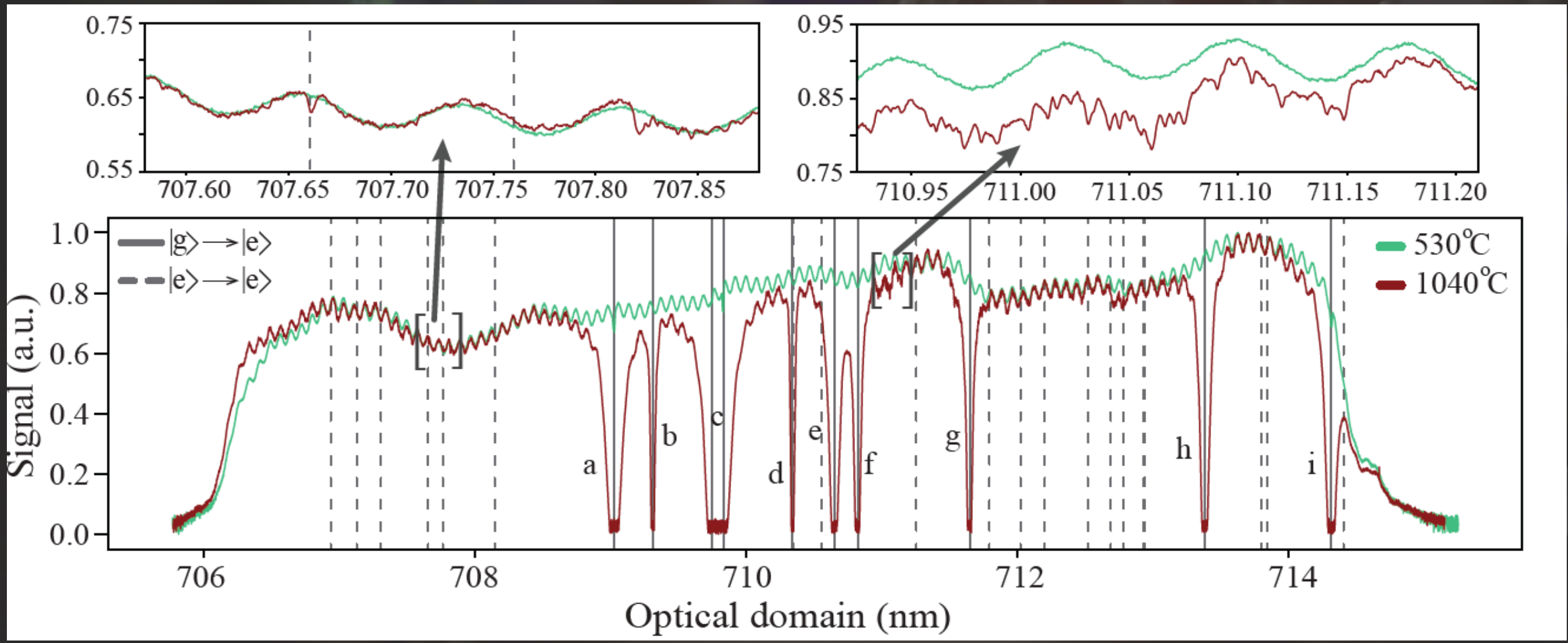




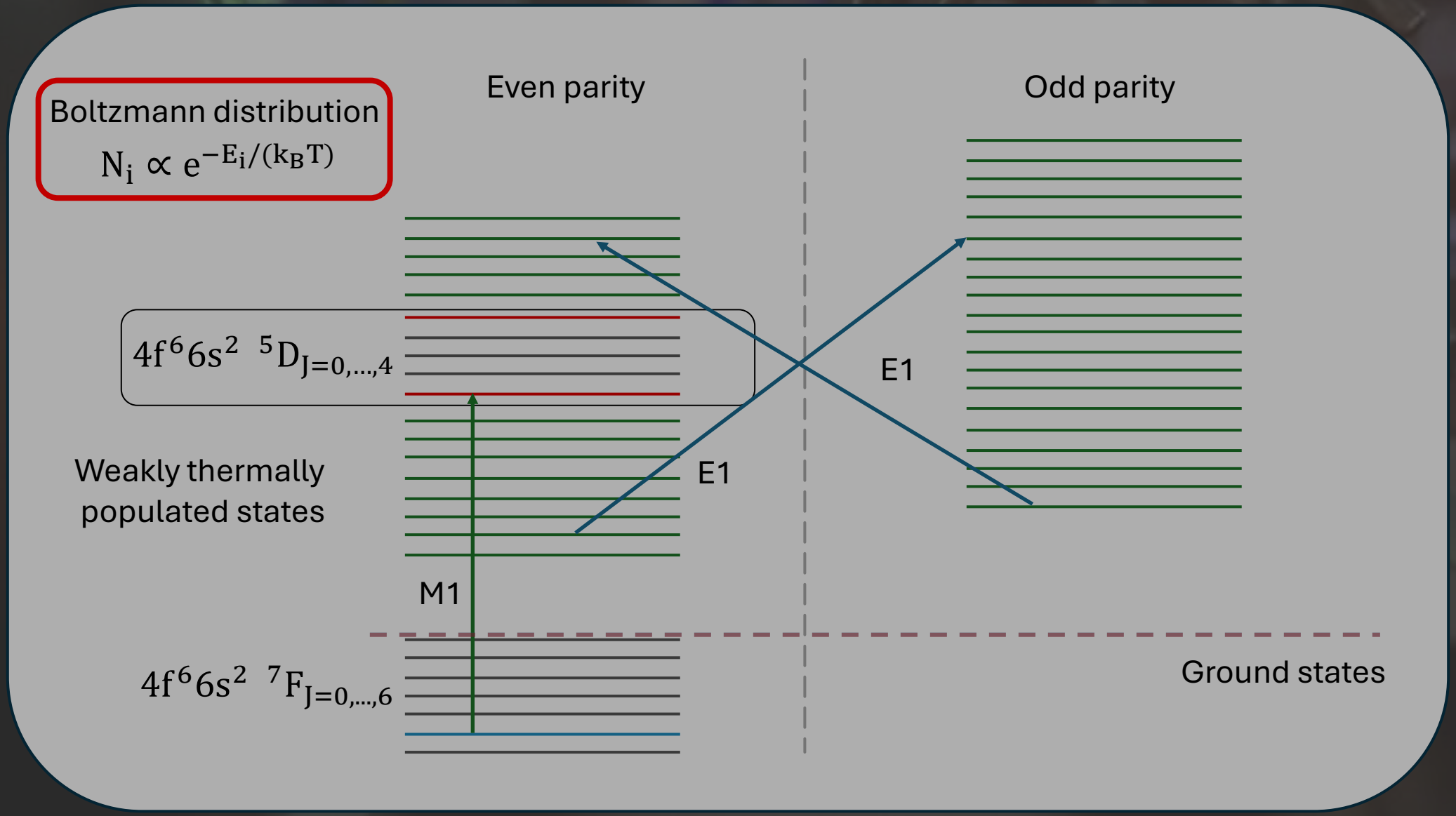
Ch6

Aramyan R., et al., *Phys. Rev. Applied* **24**, L021002 (2025)

DCS Results

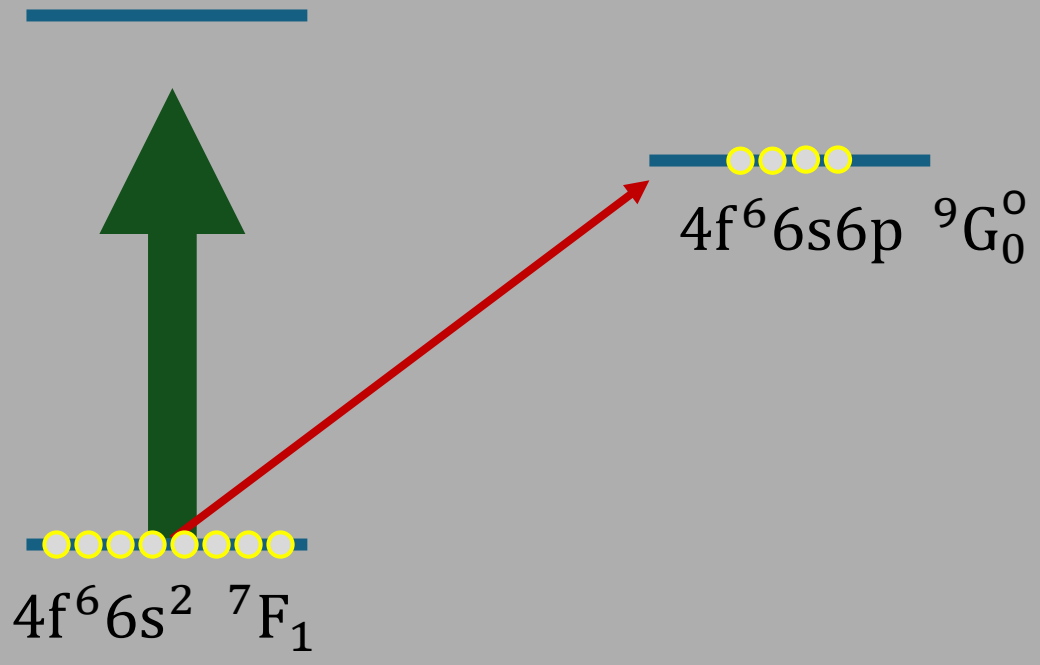

0.75
0.65
0.55
707.60
707.65
707.70
707.75
707.80
707.85
0.95
0.85
0.75
710.95
711.00
711.05
711.10
711.15
711.20
1.0
0.8
0.6
0.4
0.2
0.0
Signal (a.u.)
|g⟩ → |e⟩
|e⟩ → |e⟩
530℃
1040℃
a
b
c
d
e
f
g
h
i
706
708
710
712
714
Optical domain (nm)

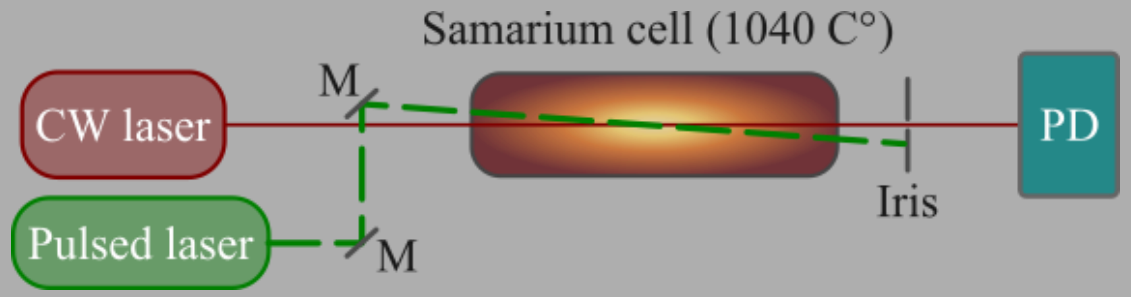
Problem


Boltzmann distribution
$N_i \propto e^{-E_i/(k_B T)}$
Even parity
Odd parity
$4f^6 6s^2\ {}^5D_{J=0,\ldots,4}$
E1
E1
Weakly thermally
populated states
M1
$4f^6 6s^2\ {}^7F_{J=0,\ldots,6}$
Ground states

Population-Depletion Spectroscopy

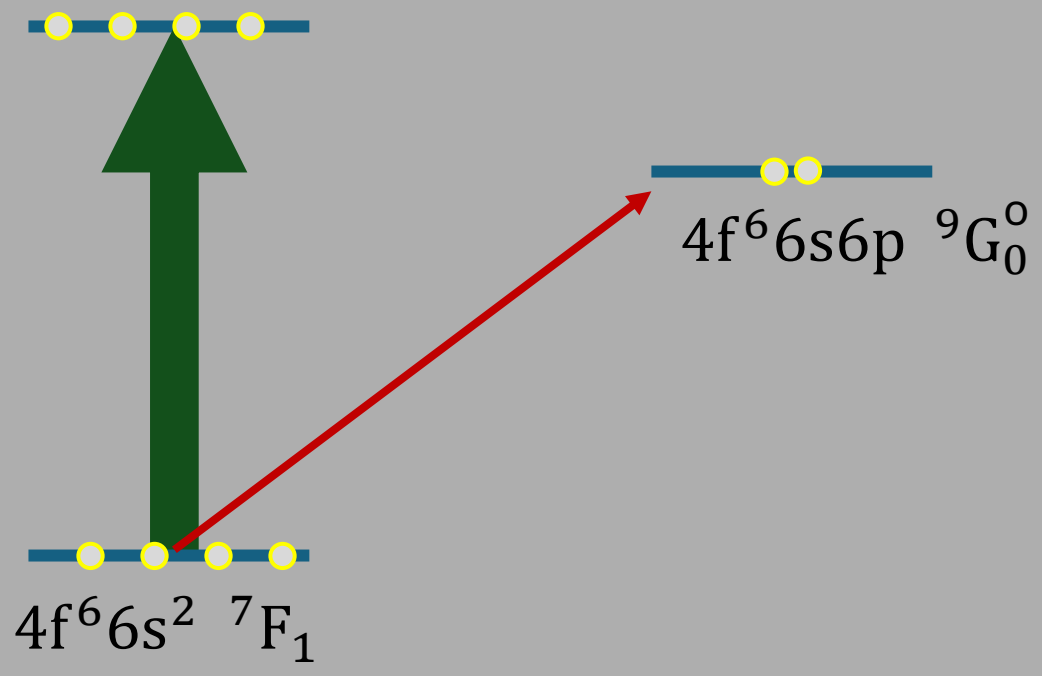
Razmik Aramyan

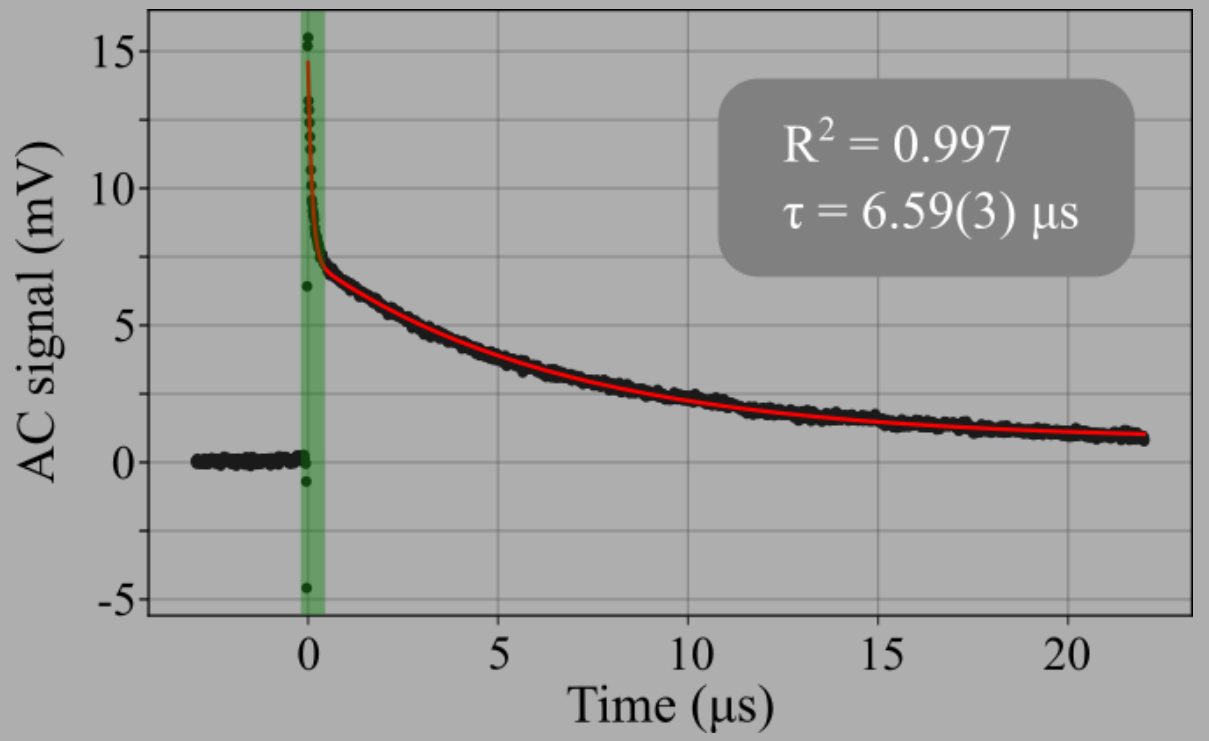




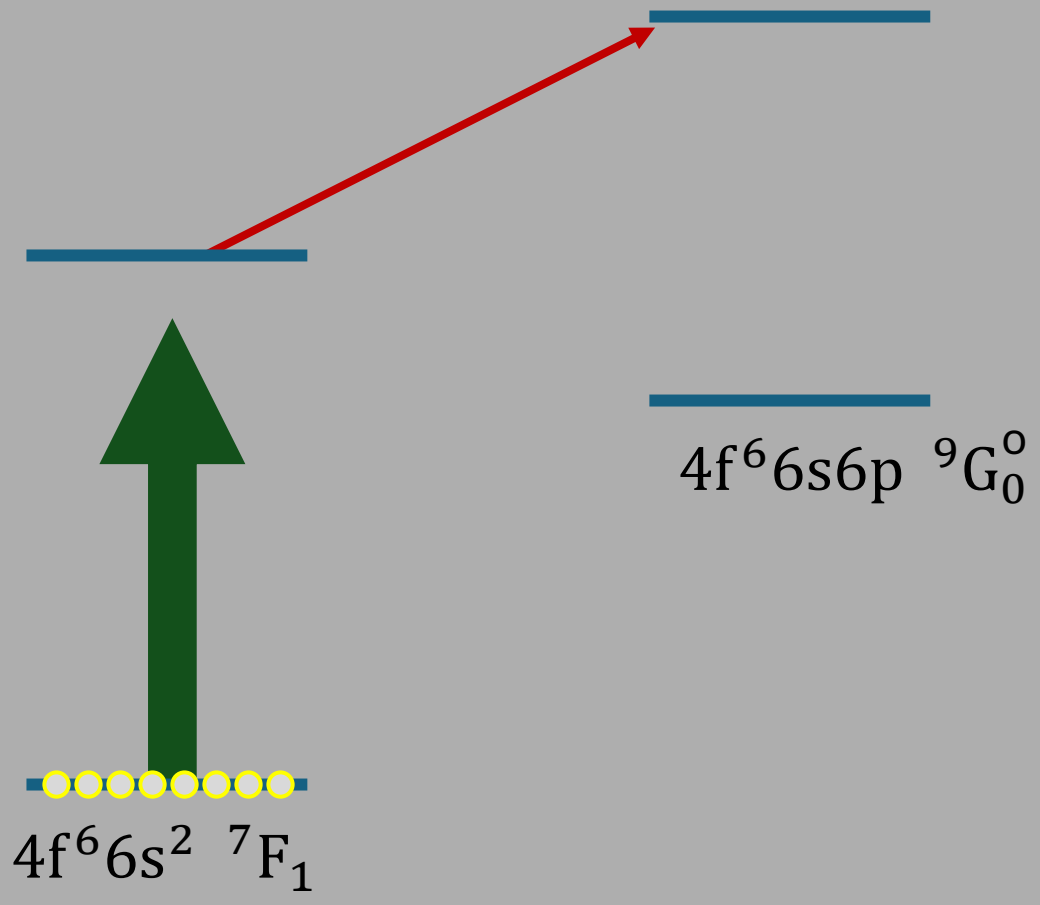
Population-Depletion Spectroscopy

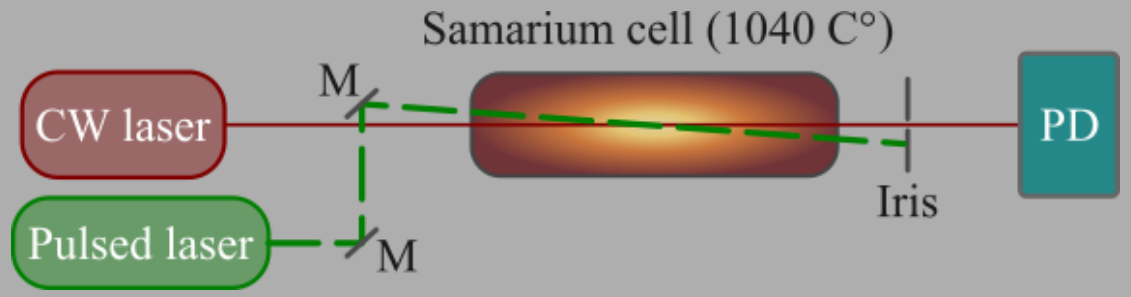
Razmik Aramyan





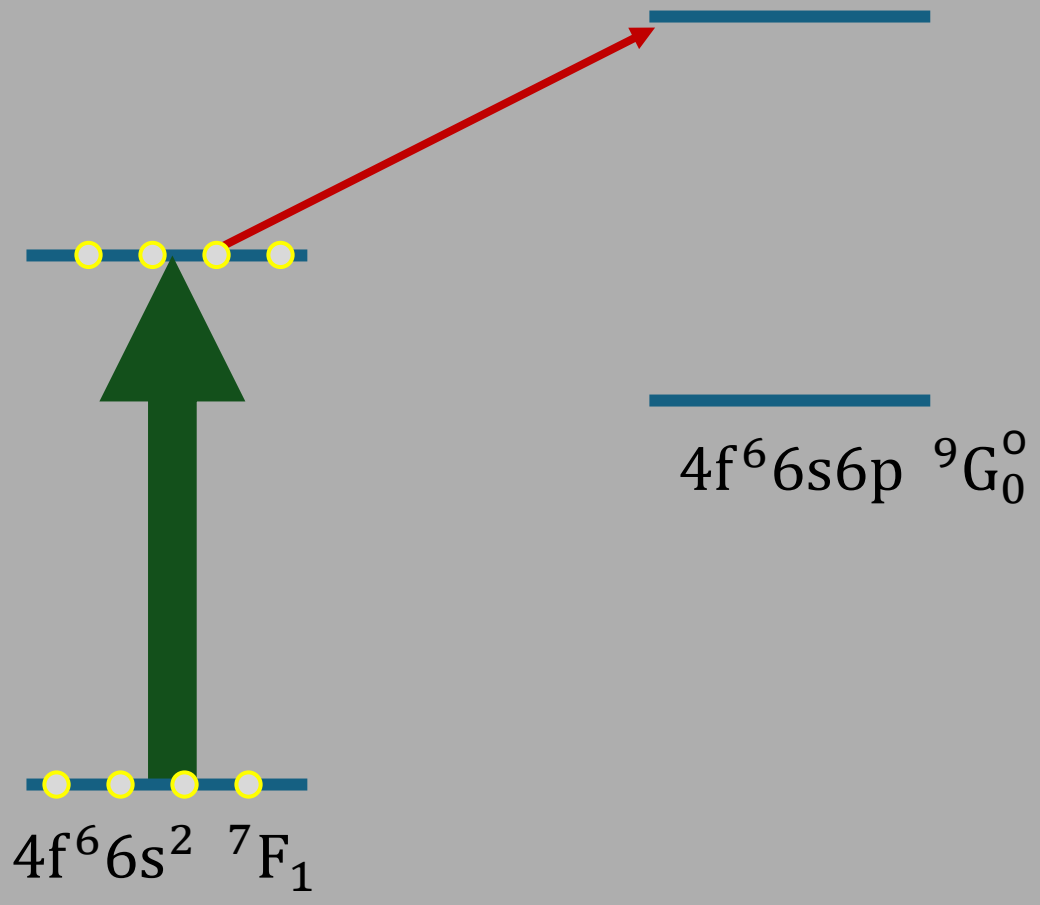
Sequential Excitation Spectroscopy

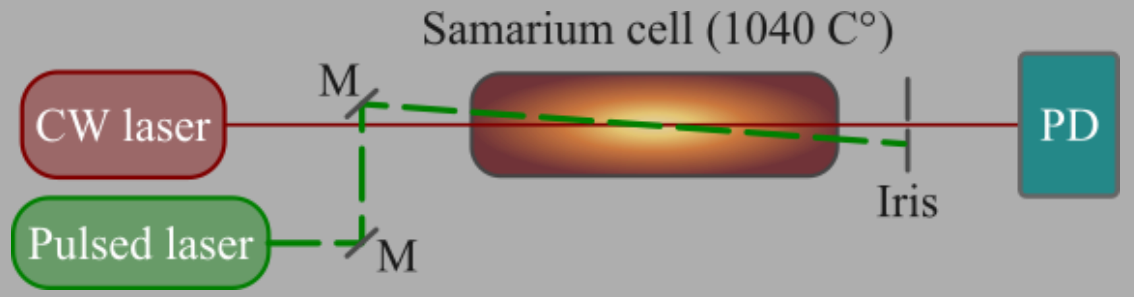




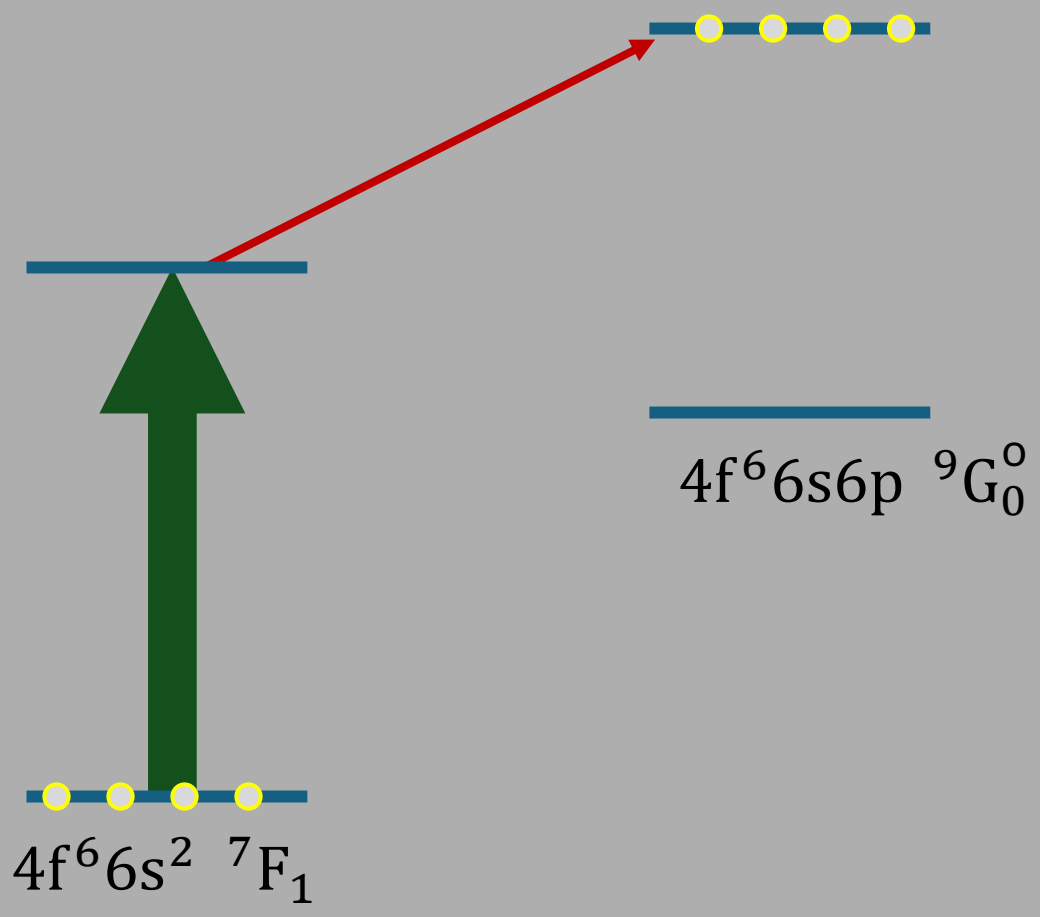
Sequential Excitation Spectroscopy

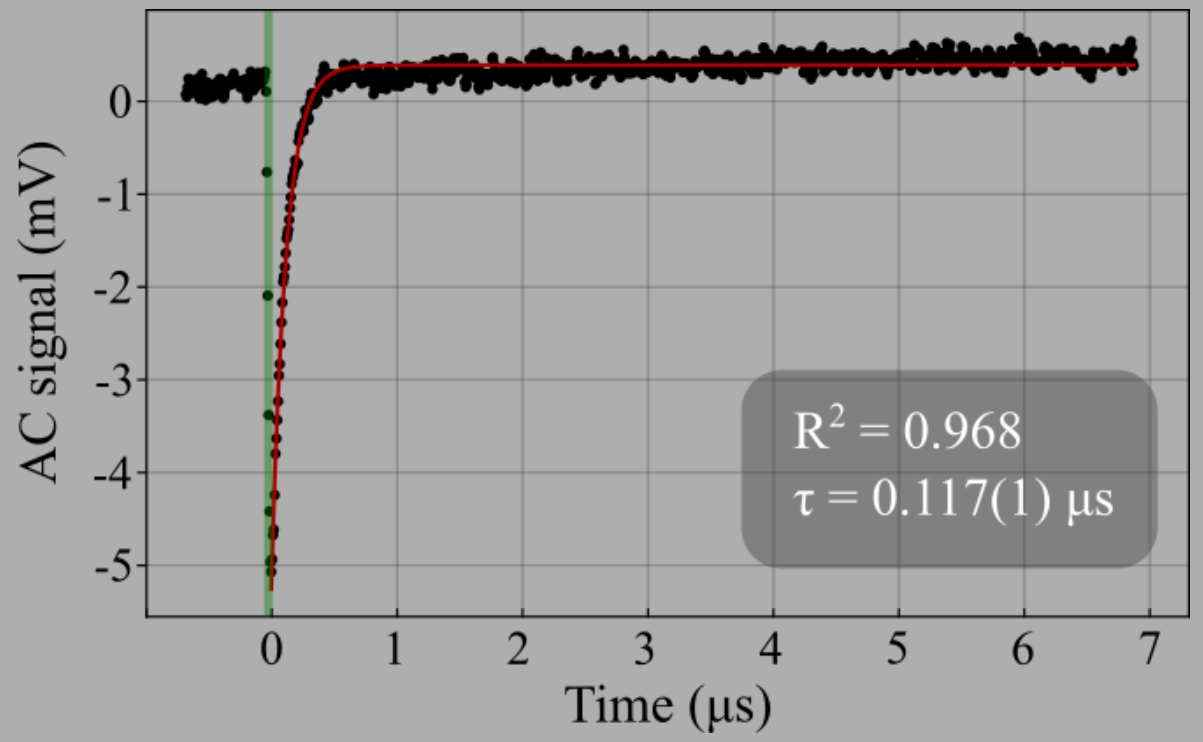
Razmik Aramyan



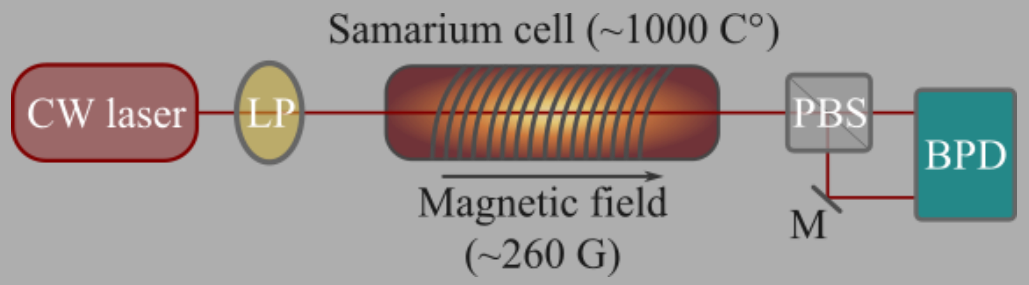


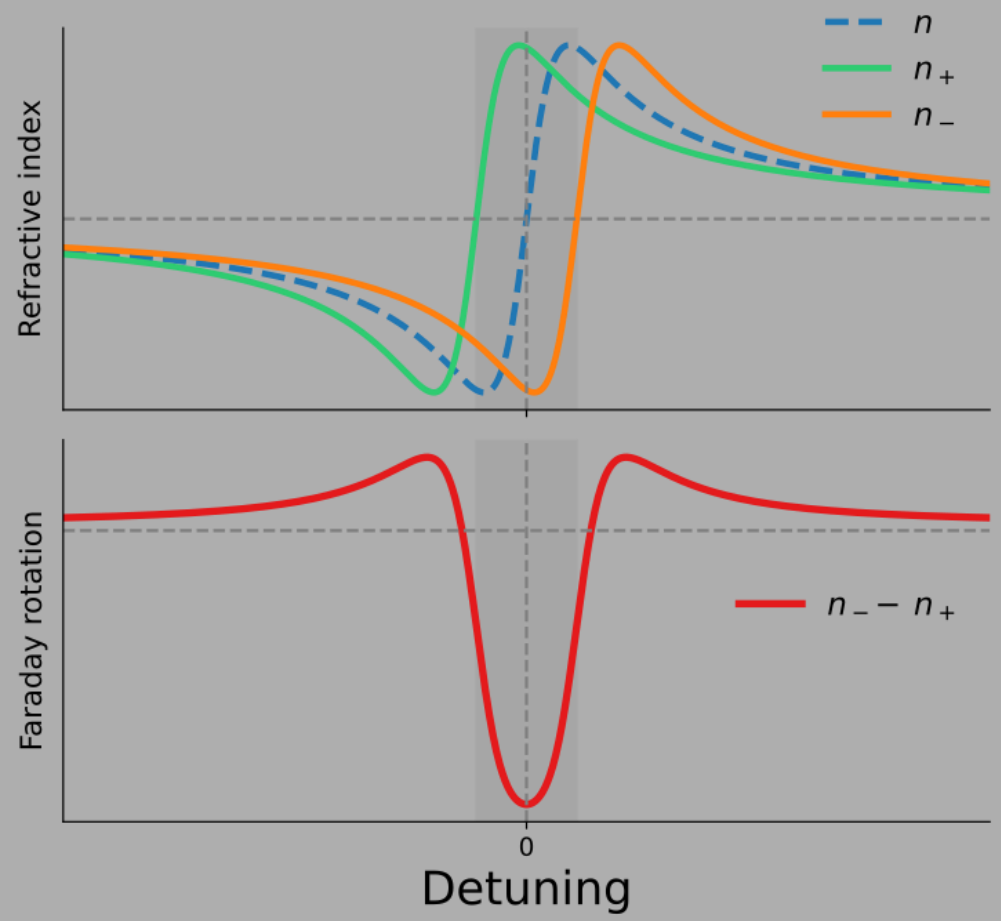
Sequential Excitation Spectroscopy



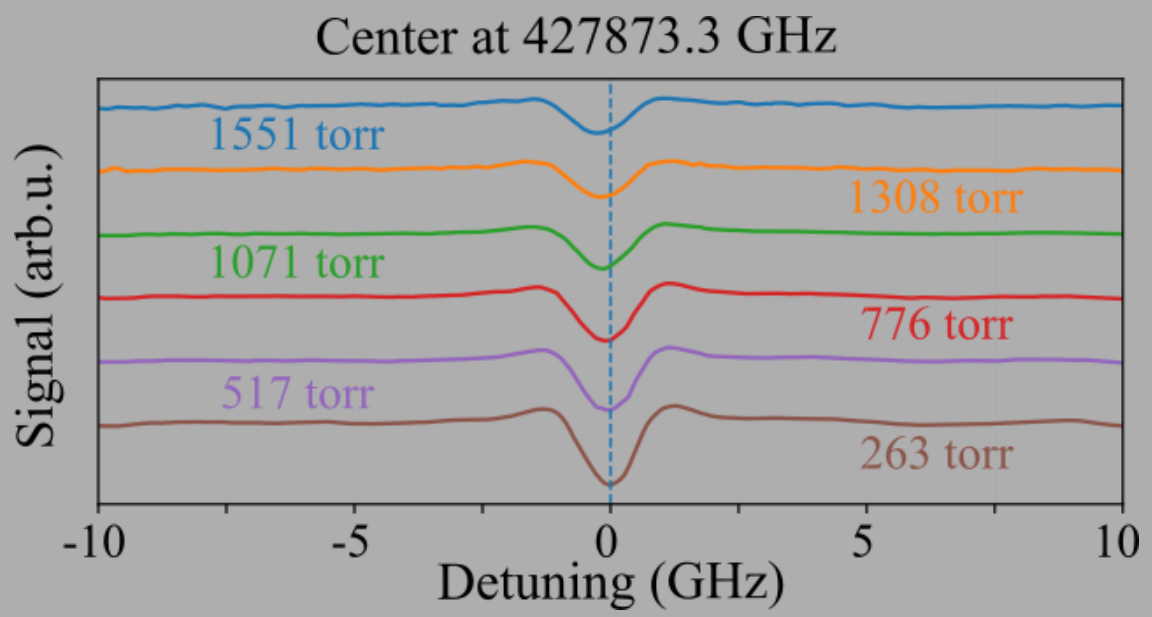


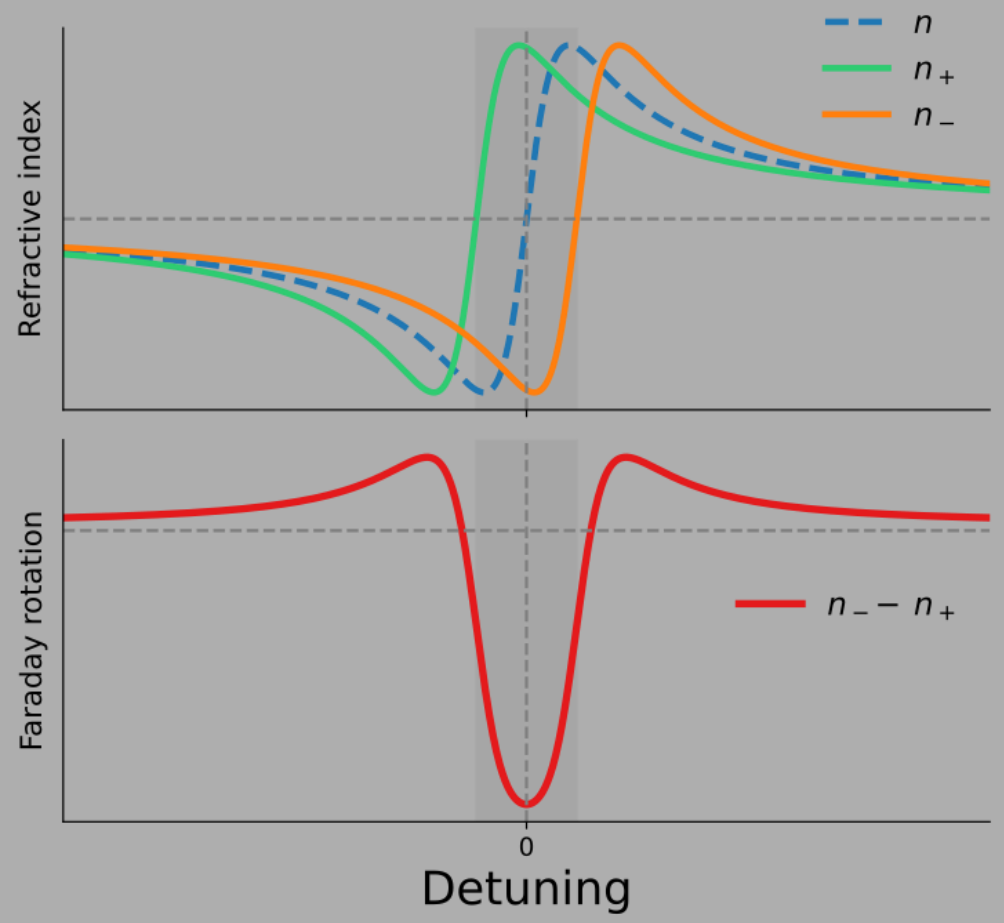
Faraday Rotation



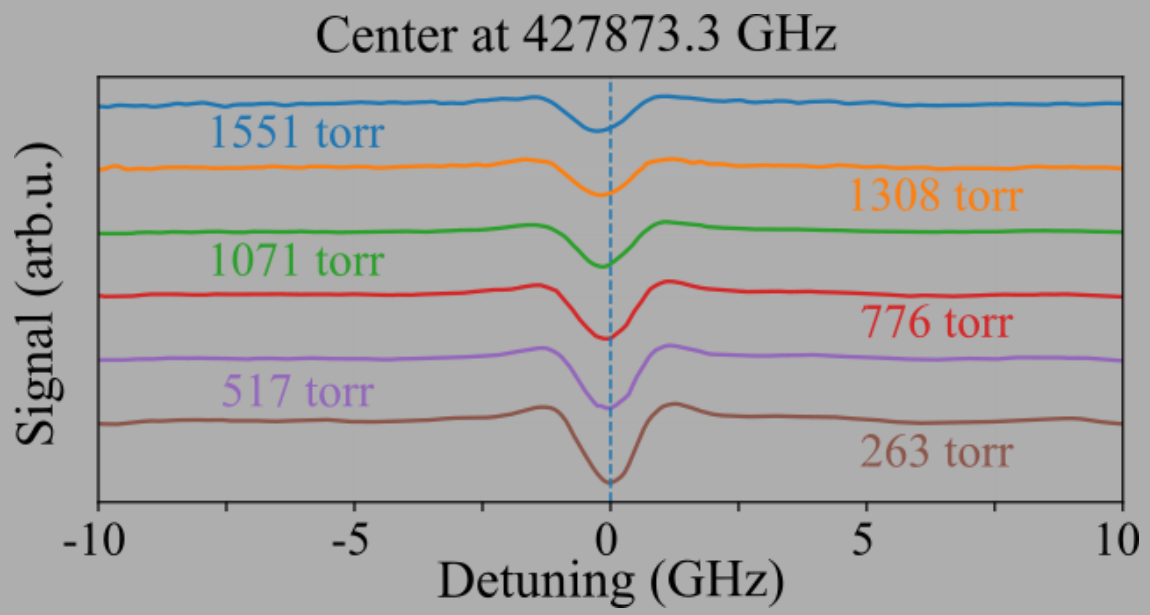


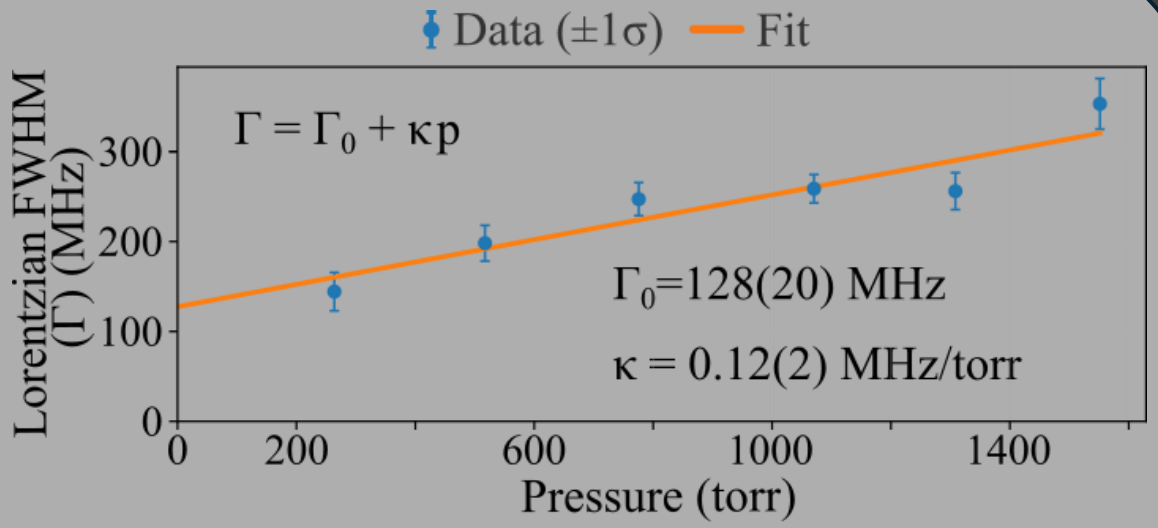
Faraday Rotation

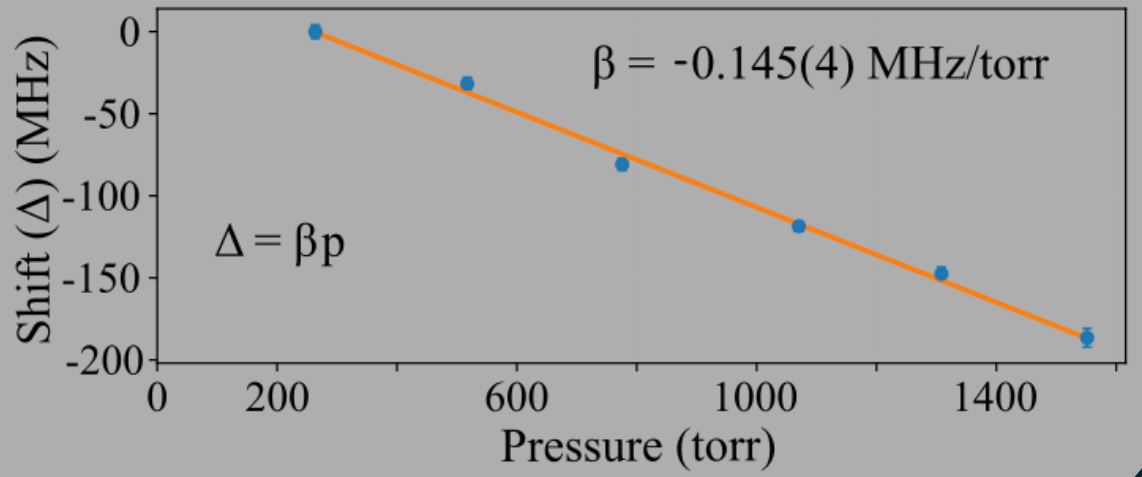




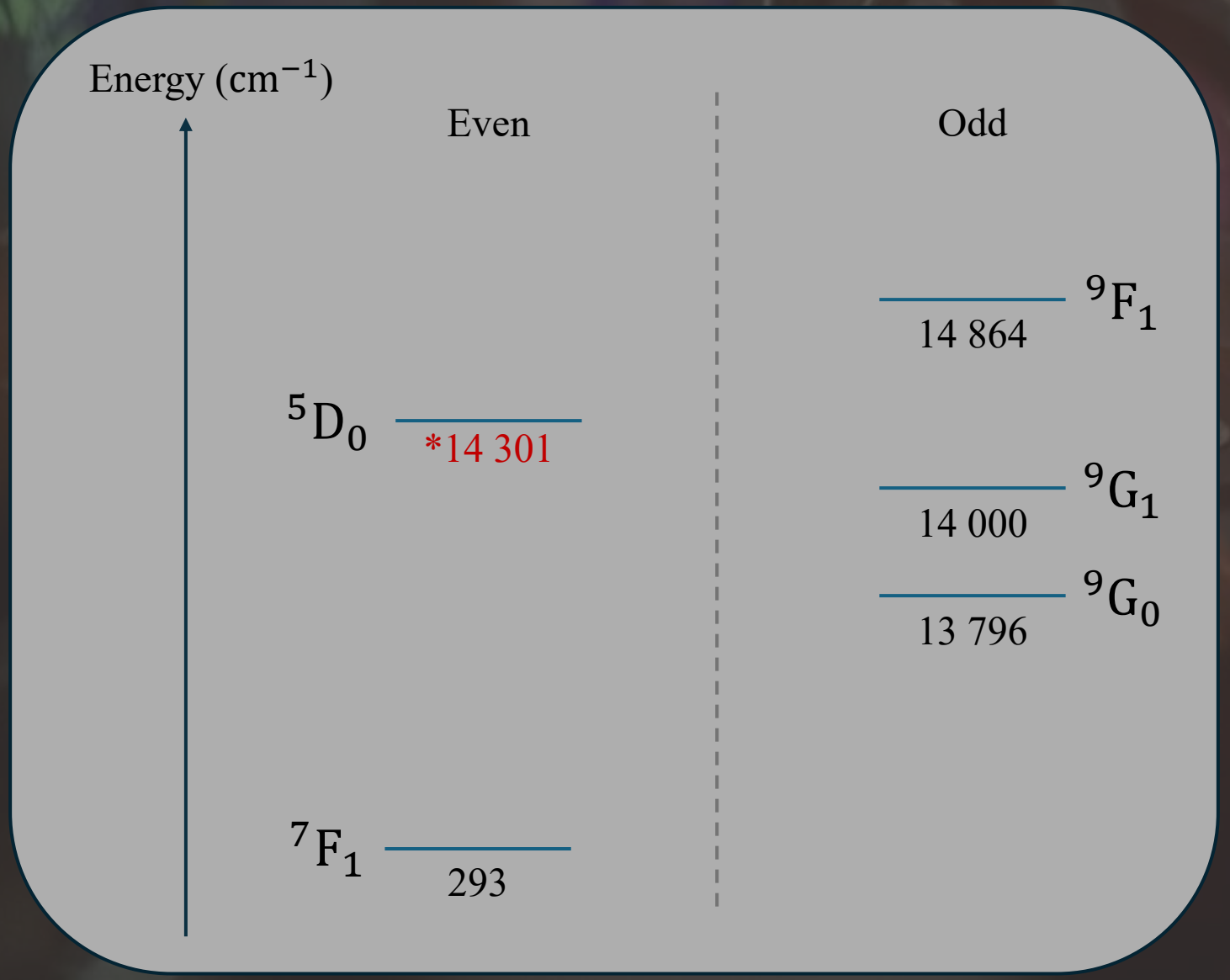
Faraday Rotation



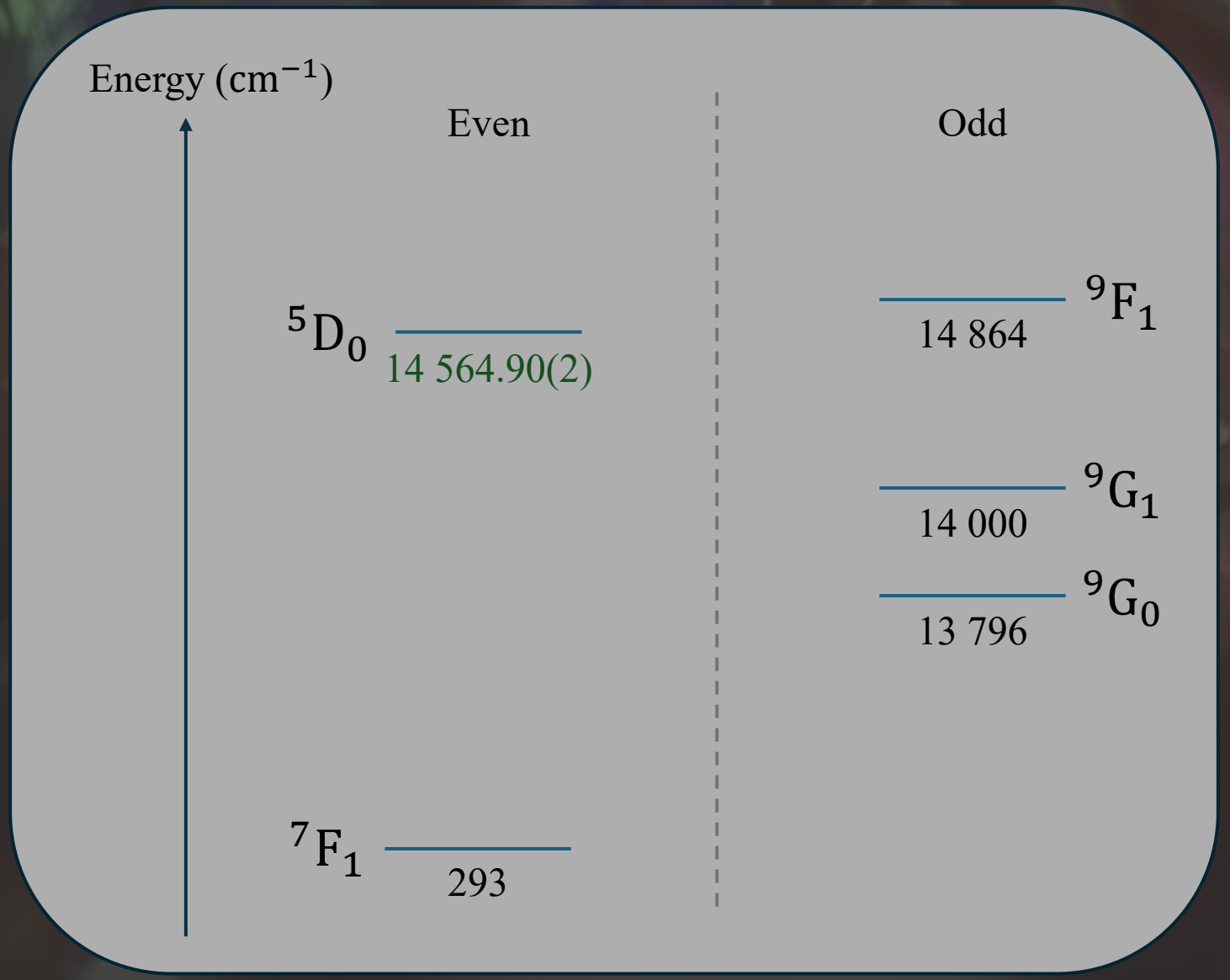




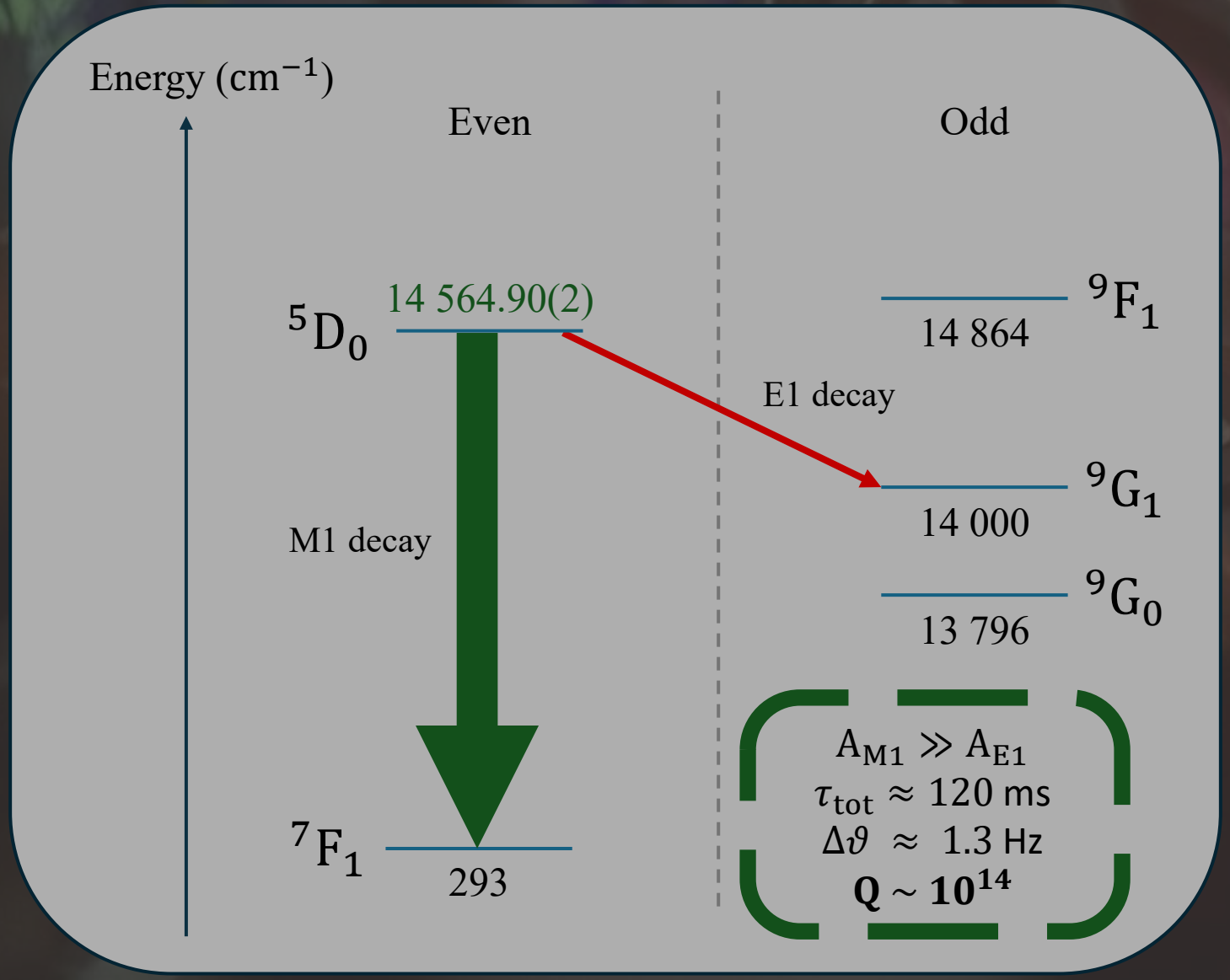
Result


Energy (cm^{-1})
Even
Odd
$^5D_0$
*14 301
$^7F_1$
293
$^9F_1$
14 864
$^9G_1$
14 000
$^9G_0$
13 796

Result


Energy (cm^{-1})
Even
Odd
$^5D_0$
14 564.90(2)
$^7F_1$
293
$^9F_1$
14 864
$^9G_1$
14 000
$^9G_0$
13 796

Lifetime


Energy (cm^{-1})
Even
Odd
$^5D_0$
14 564.90(2)
M1 decay
$^7F_1$
293
E1 decay
$^9F_1$
14 864
$^9G_1$
14 000
$^9G_0$
13 796
$A_{M1} \gg A_{E1}$
$\tau_{tot} \approx 120$ ms
$\Delta\vartheta \approx 1.3$ Hz
$\mathbf{Q \sim 10^{14}}$

Atomic clock

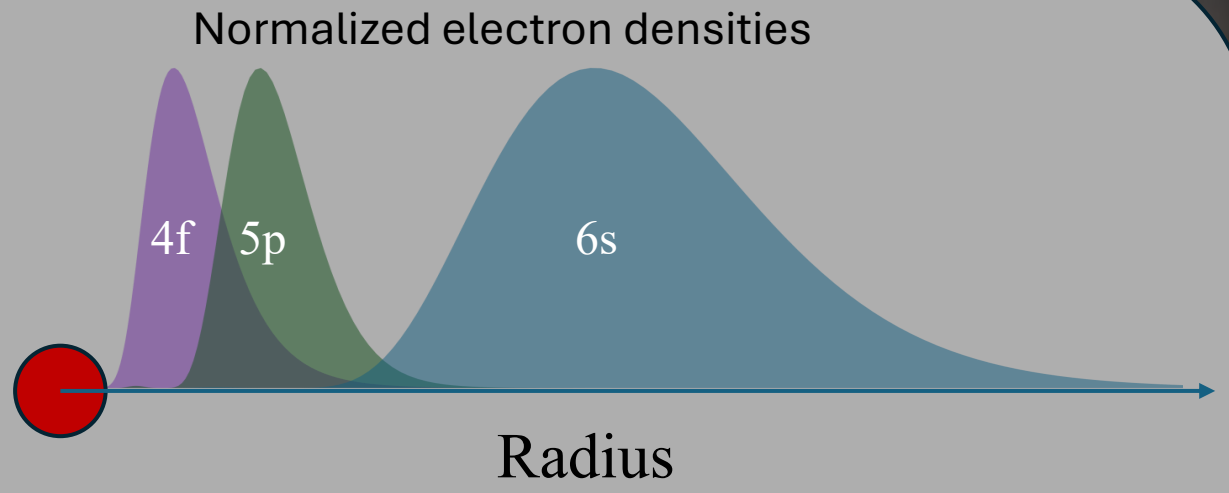
Best lattice clocks (Yb, Sr) vs Samarium

- Quality factor - Q:

Same order of magnitude

- Transition:

Sr $5s^2 \rightarrow 5s5p$
Yb $6s^2 \rightarrow 6s6p$
Sm 4f →4f



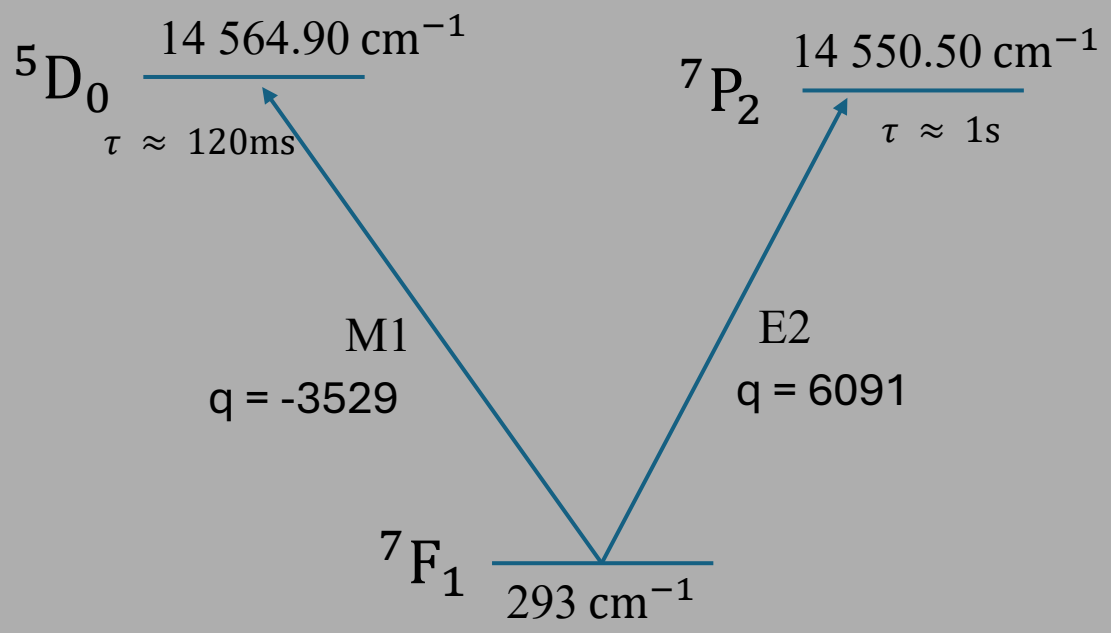
Limited by external perturbations: Inhomogeneous external fields
Collisions
BBR (AC&DC Stark shifts)
…

α – Variation

Sm

$\Delta q = 9620\ cm^{-1}$

$$K = \frac{2\Delta q}{\Delta E} = -1336$$

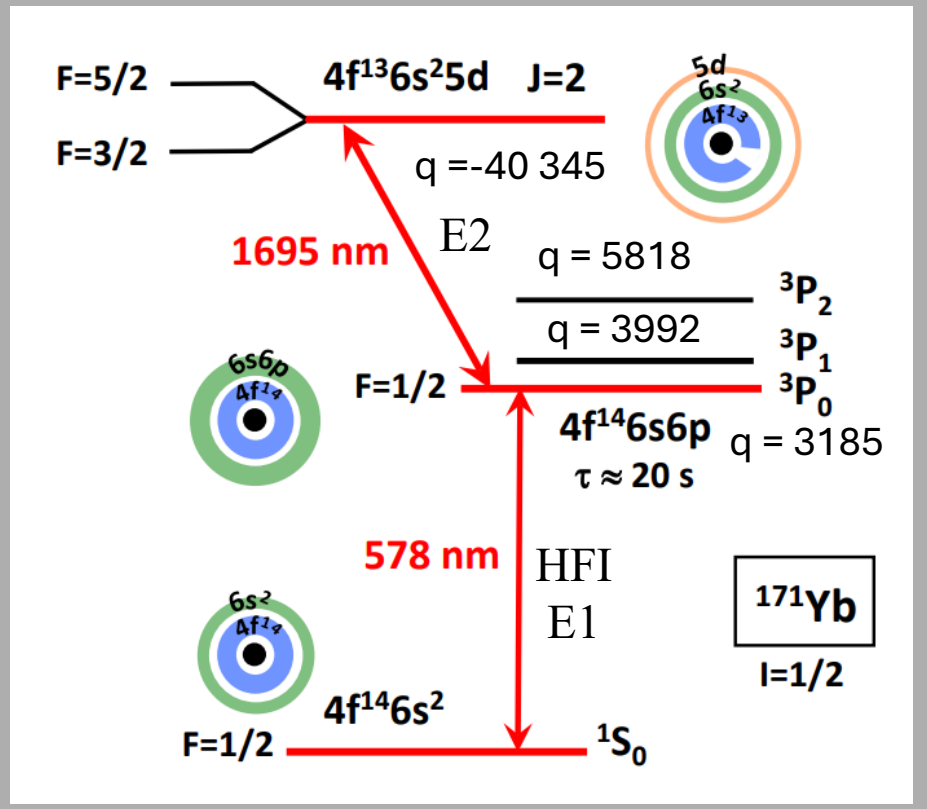


Yb

$\Delta q = -43\,530\ cm^{-1}$

$$K = \frac{2\Delta q}{\Delta E} = -15$$

*



* M. Safronova, et al., *Phys. Rev. Lett.* **120**, 173001(2018)

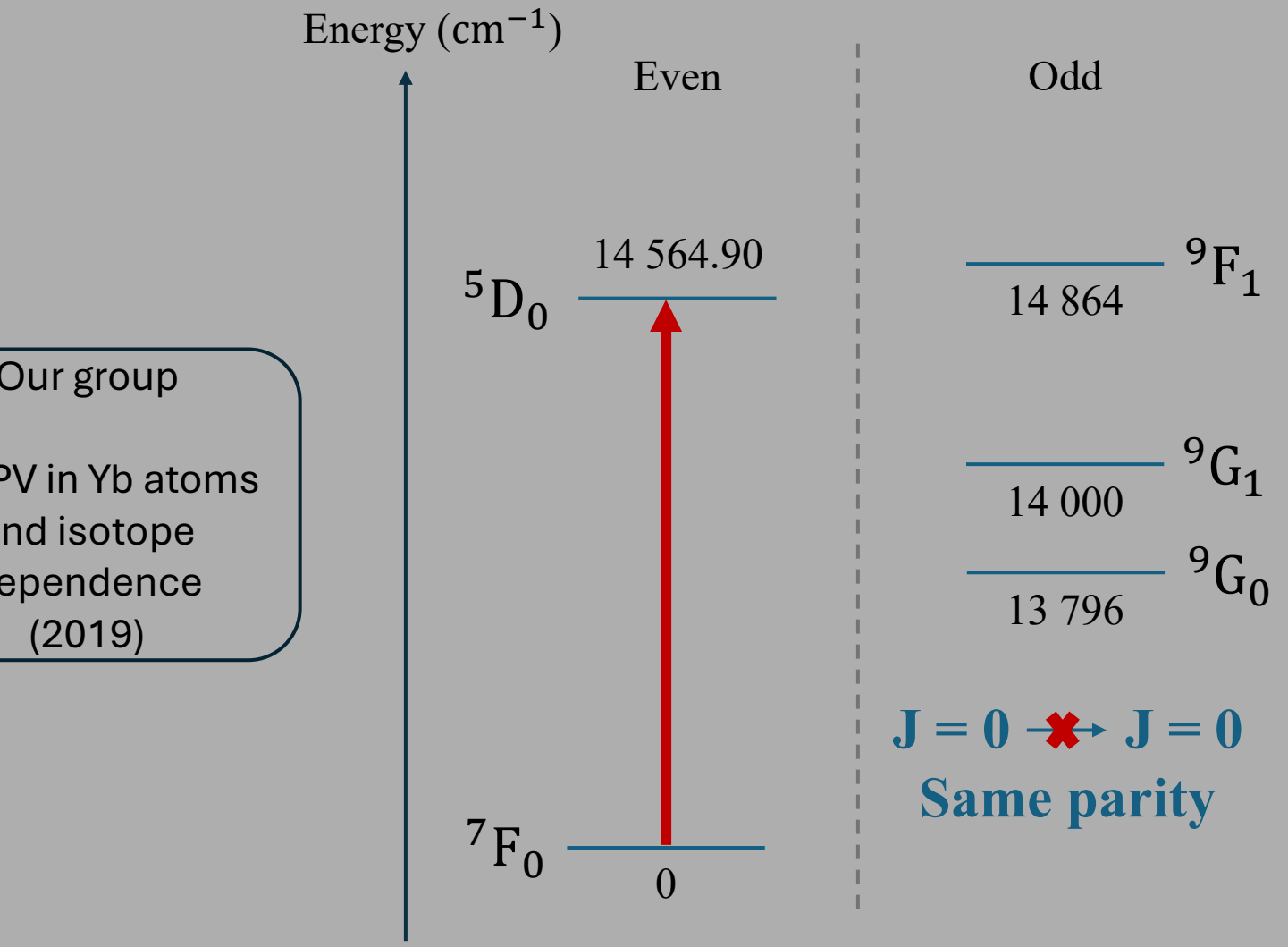
APV

C. Weiman group

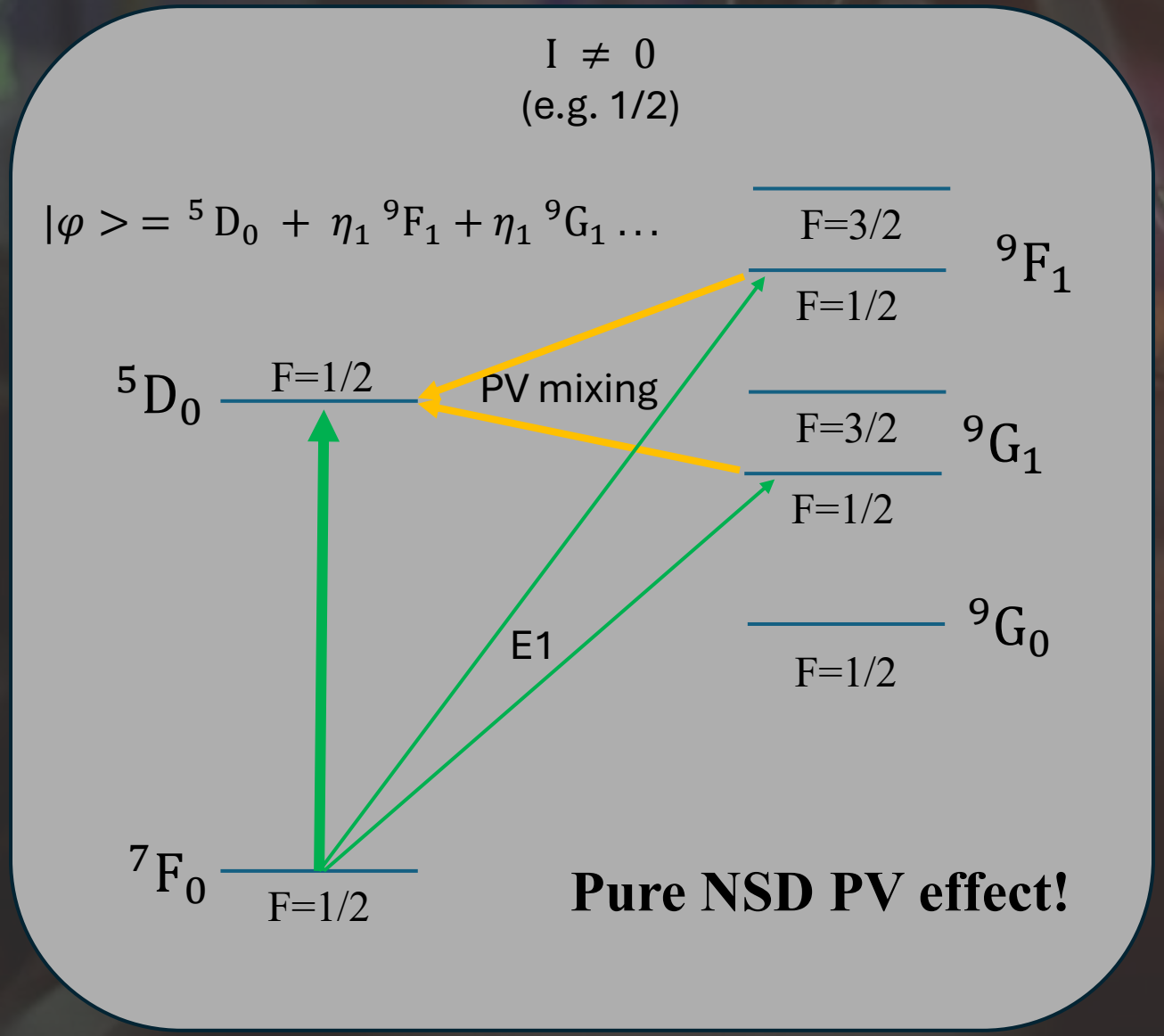
NSI and NSD PV in Cs atoms (1997)

Our group

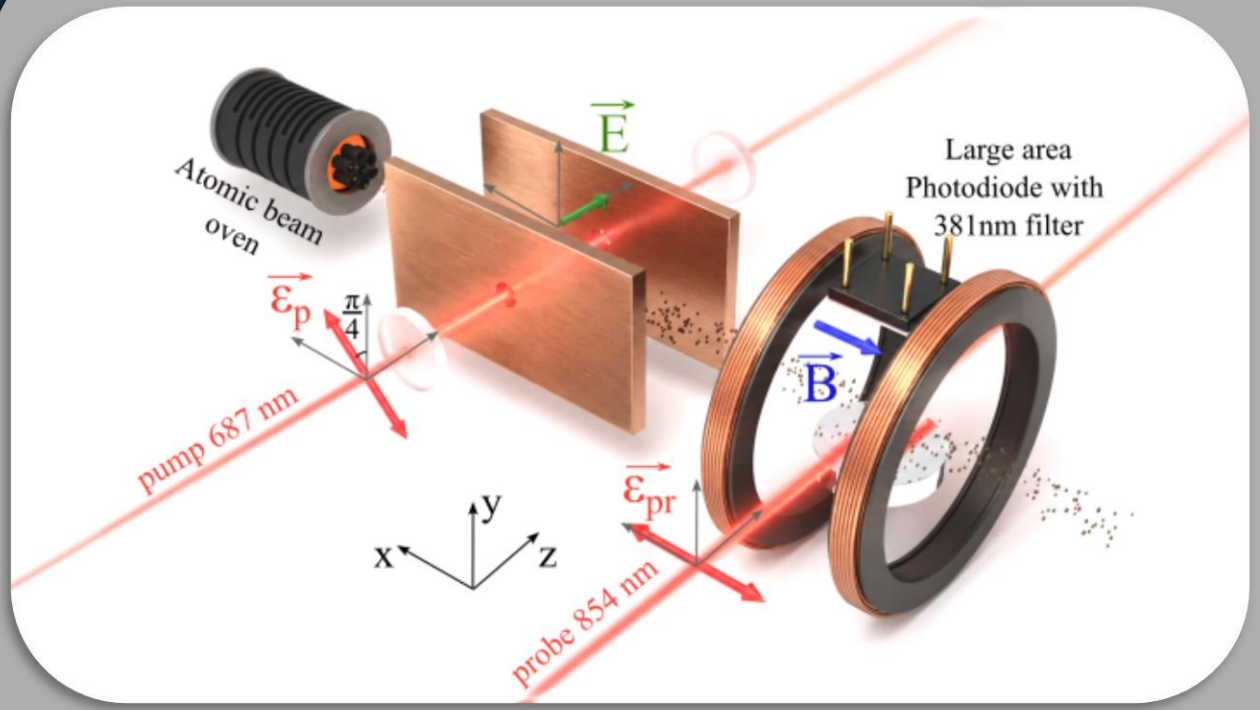
NSI PV in Yb atoms and isotope dependence (2019)



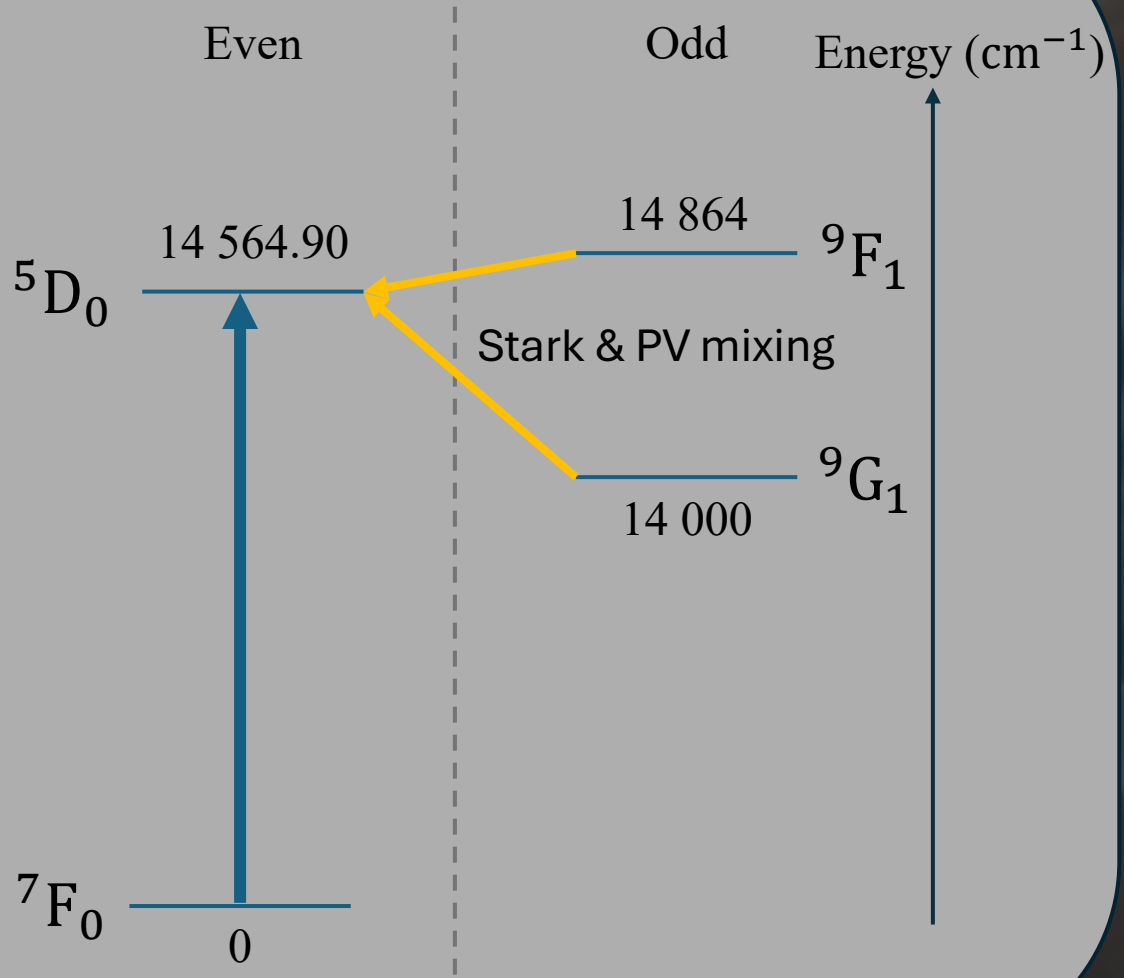
NSD APV in Samarium



APV NSD



$$(\epsilon_p \cdot \epsilon_{pr})(\epsilon_p \cdot \boldsymbol{E} \times \epsilon_{pr})$$



APV systematics

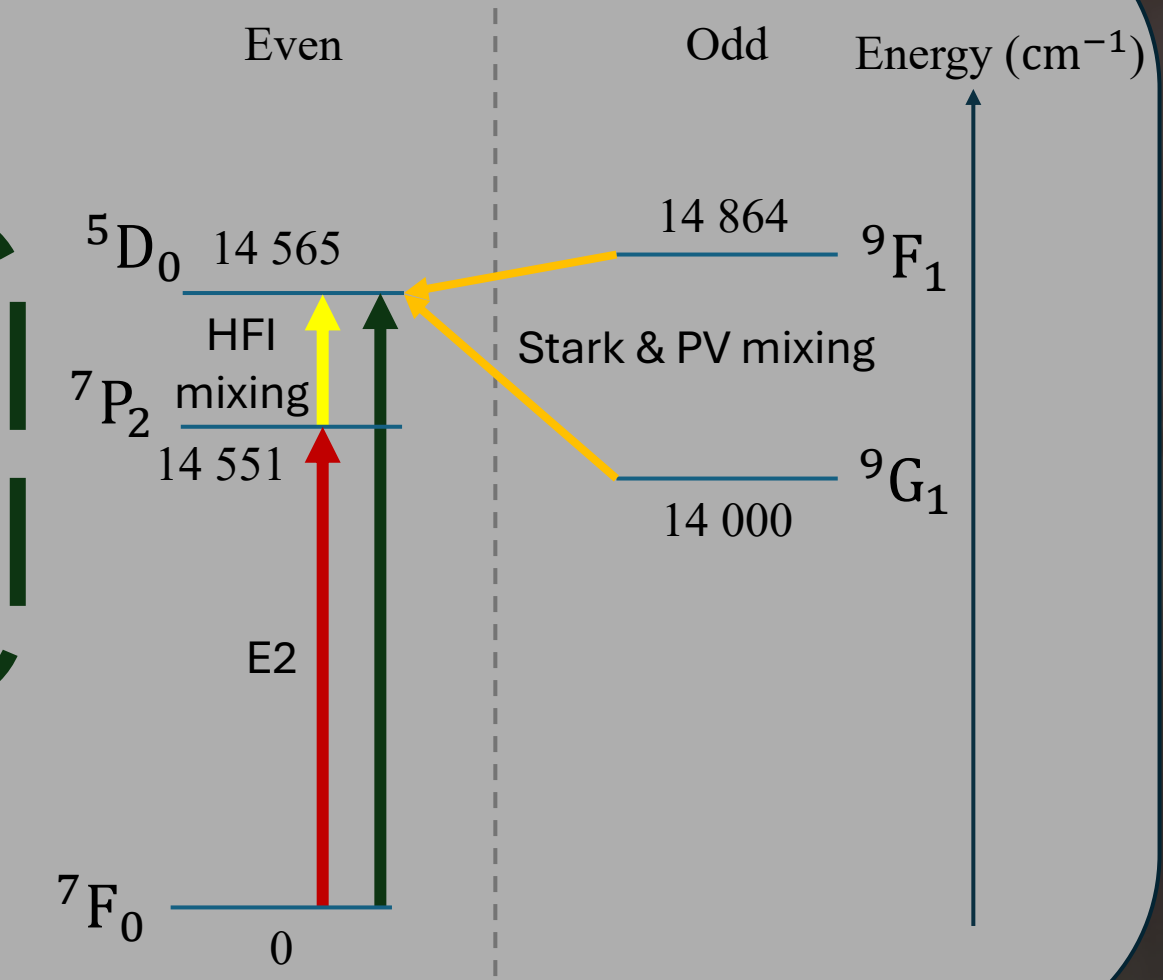
$A_{NSI} = 0$

NSD signal

$A_{Sm} \approx A_{Cs}$

Systematics

$A_{Sm} \approx 10^{-2} \cdot A_{Cs}$



Summary

Sm $^5D_0$

- Clock transition with low sensitivity to external perturbations
- Self referenced system with high sensitivity to the α variations
- Pure **NSD-APV**, comparable to Cs but with far lower systematics
- Isotope shift dominated by anomalous mass shift
- Exactly the same system as in Eu^{3+} in crystals

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- Single-photon microwave detectors
- High Frequency Gravitational Waves
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3. GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
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Special Issues, Collections and Topics in MDPI journals

Ultralight Bosonic Dark Matter: Theoretical Developments and Experimental Searches

Derek F. Jackson-Kimball

Jason E. Stalnaker

Spin-dependent exotic interactions

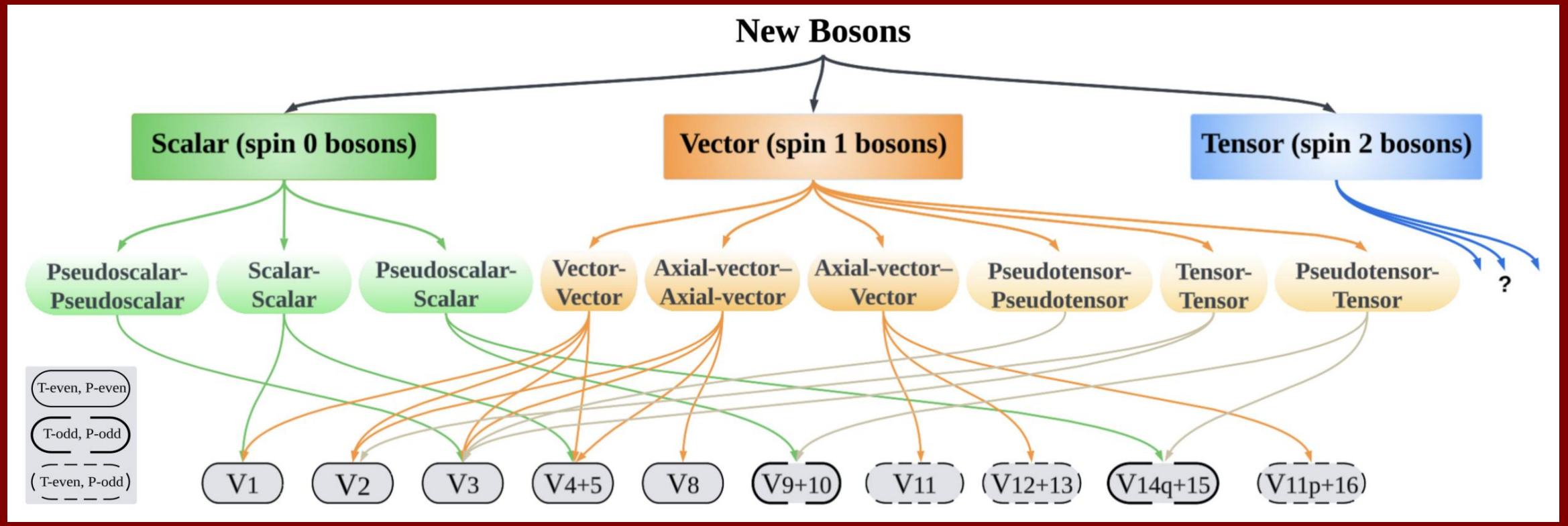
Rev. Mod. Phys. **97**, 025005 (2025); arXiv:2408.15691

Lei Cong, Wei Ji, Pavel Fadeev, Filip Ficek, Min Jiang, Victor V. Flambaum, Haosen Guan, Derek F. Jackson Kimball, Mikhail G. Kozlov, Yevgeny V. Stadnik, Dmitry Budker

Lei Cong

Wei Ji

Yevgeny Stadnik



A website[23] collects the results:

Spin-Dependent-5th-Force-Limits

This dataset compiles results from existing exotic boson searches, with a specific focus on the fifth force—particularly the spin-dependent fifth force (SDFF). It is intended as a live platform to provide researchers in the field with convenient access to relevant data.

View the Project on GitHub
Lei-Cong/Spin-Dependent-5th-Force-Limits

Datasets

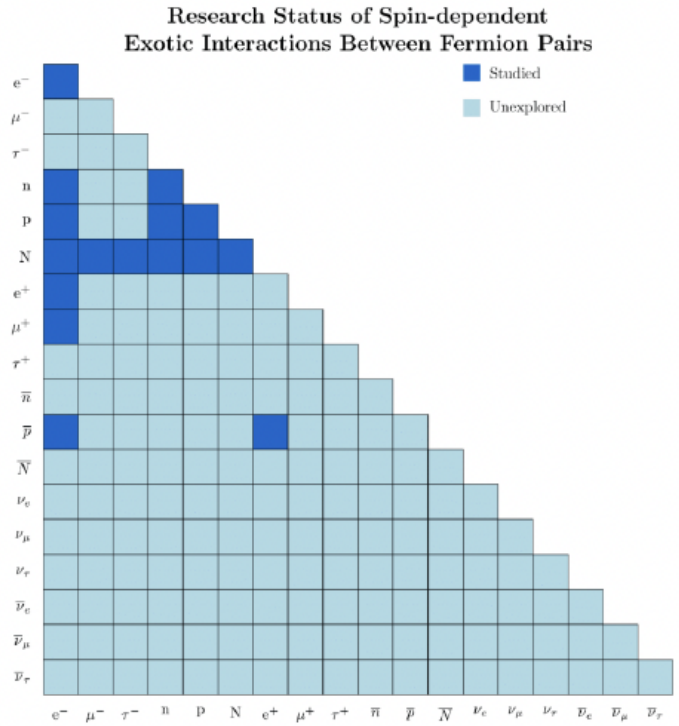


Figure 2: Studied and unexplored fermion pairs.

Spin-Dependent Fifth Force

[23] https://lei-cong.github.io/Spin-Dependent-5th-Force-Limits/

APPROVED

P…d ECT* Workshop (Mid-2027, Trento, Italy)

Spin-Dependent Exotic Interactions: From Nuclear Structure to Fundamental Symmetry Tests

- Spin-dependent exotic interactions and fifth forces
- Nuclear theory and symmetry-violating interactions (EDMs, parity violation, etc.)
- Precision symmetry experiments (comagnetometers, atomic clocks, etc.)
- BSM / particle-theory interface (axions, ultralight bosons, dark sectors, etc.)
- Atomic and molecular precision theory (precision spectroscopy, APV, HCI systems, etc.)
- Advanced precision measurement platforms (NV centers, levitated sensors, etc.)

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D. Budker · Y. Stadnik · C. Frugiuele · L. Cong