BSM Searches with Thorium-229

Joachim Kopp (CERN & JGU Mainz)
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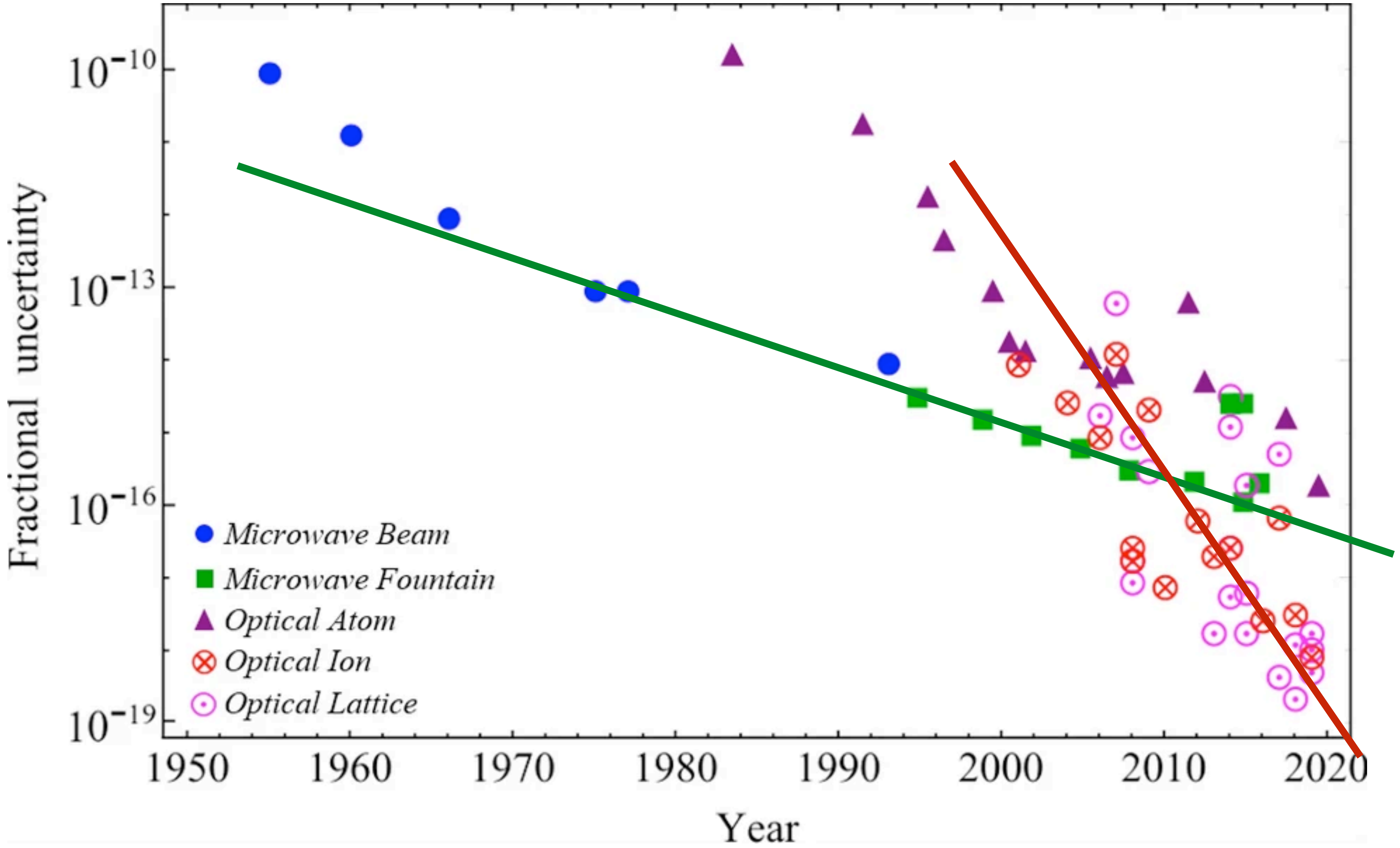
Progress in Atomic Clocks

Sharma *et al.* 2023



Optical Lattice Clocks

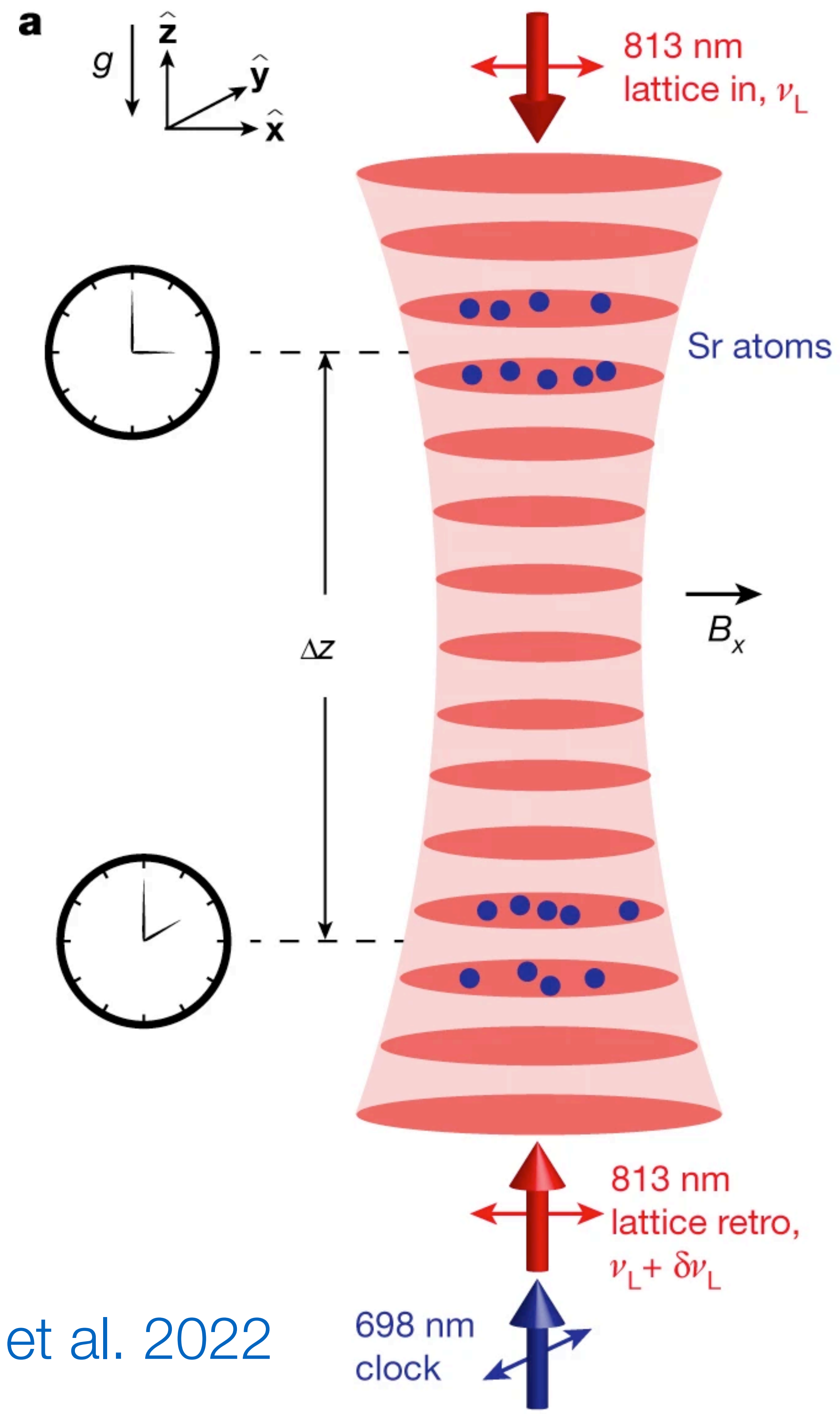


Image:
Zheng et al. 2022

Sr-87

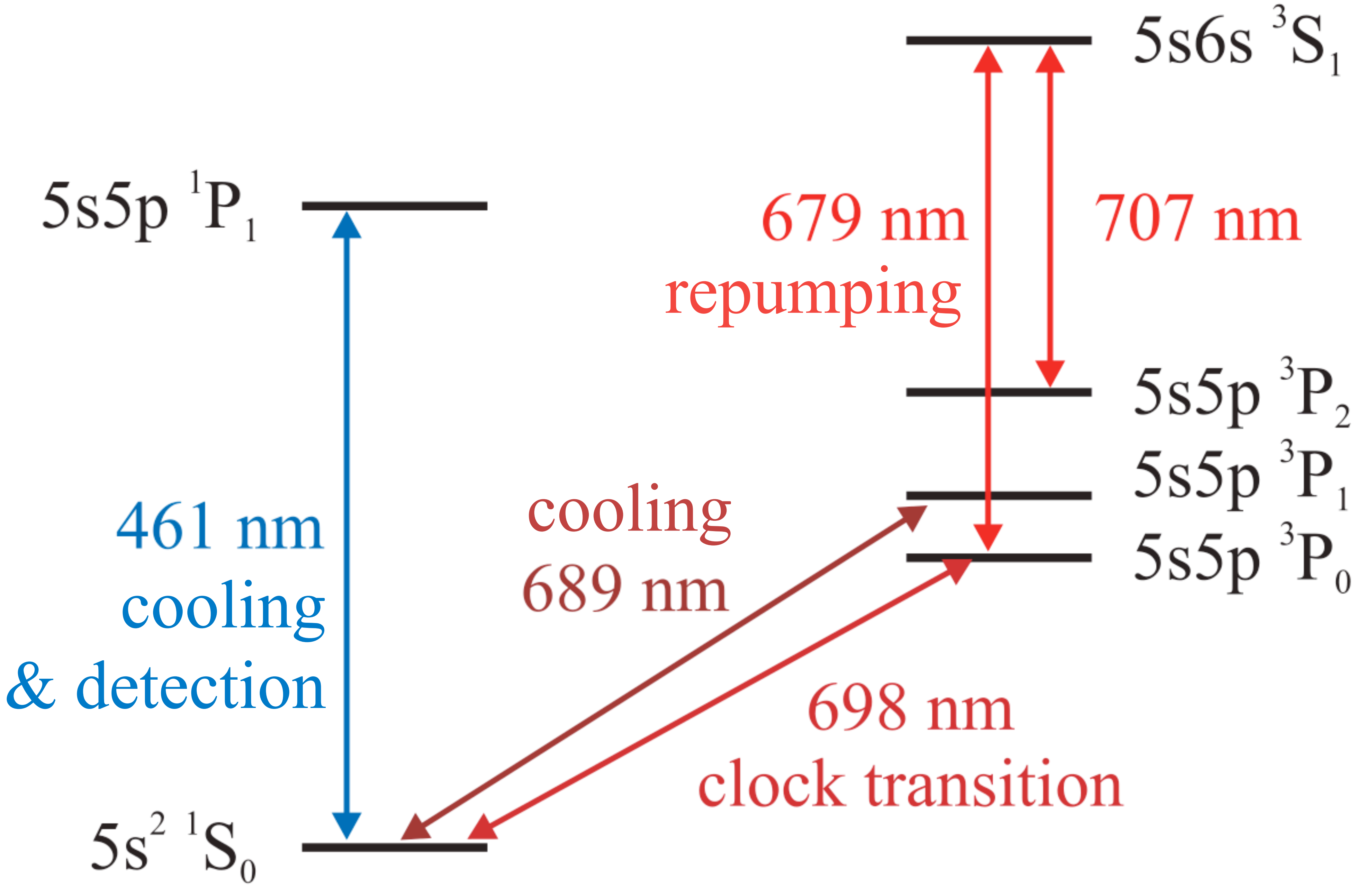
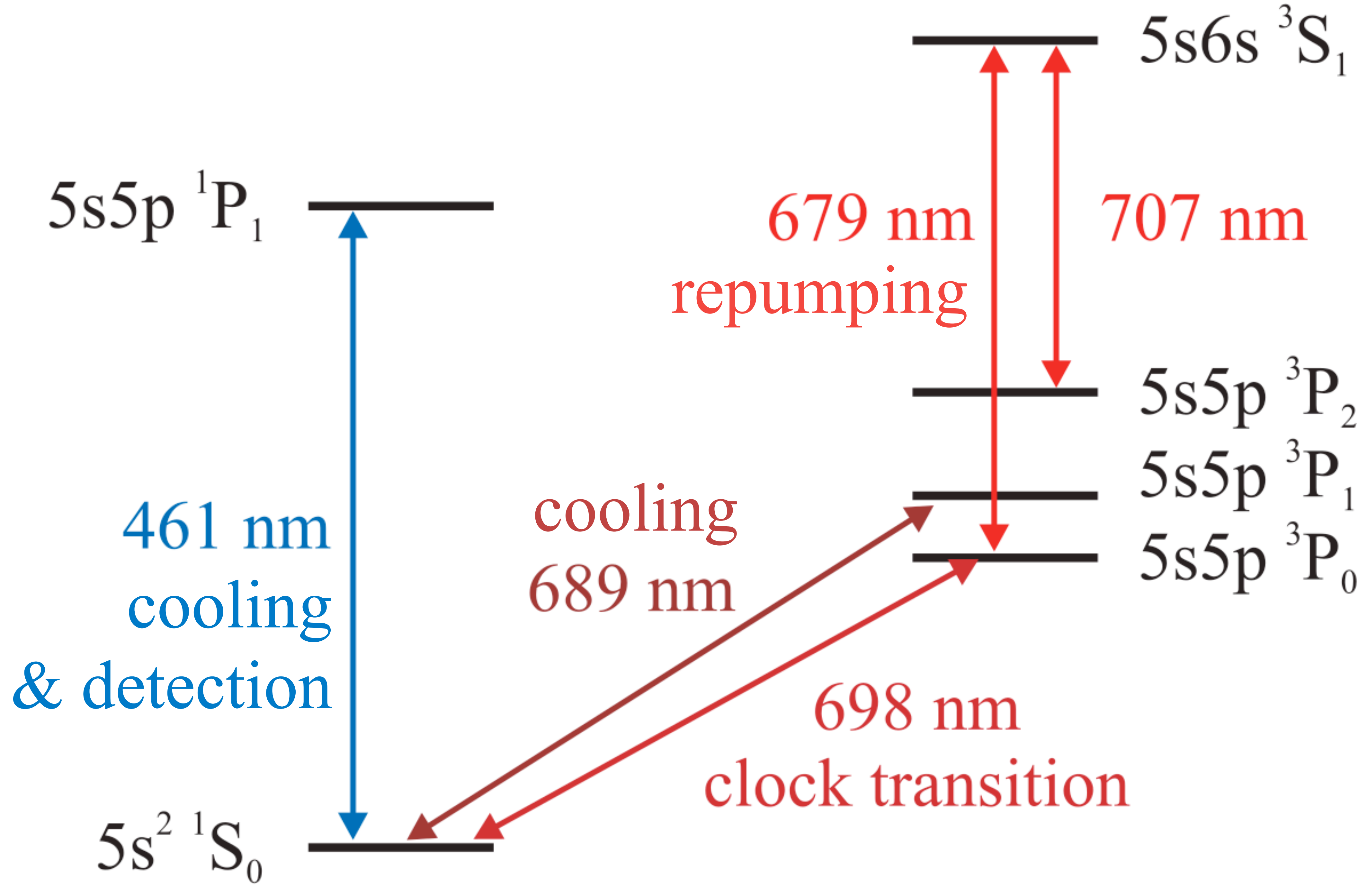


Image: Wikimedia Commons

Optical Lattice Clocks

- ☐ ultra-narrow atomic transition ("clock transition")
- ☐ clock laser pulses start/stop Raman oscillations
- ☐ detection pulse excites atoms remaining in $^1S_0$
- ☐ observe fluorescence intensity (= phase of Raman oscillations)
- ☐ repeat.

Sr-87



The Nuclear Clock

Sr-87 atomic clock

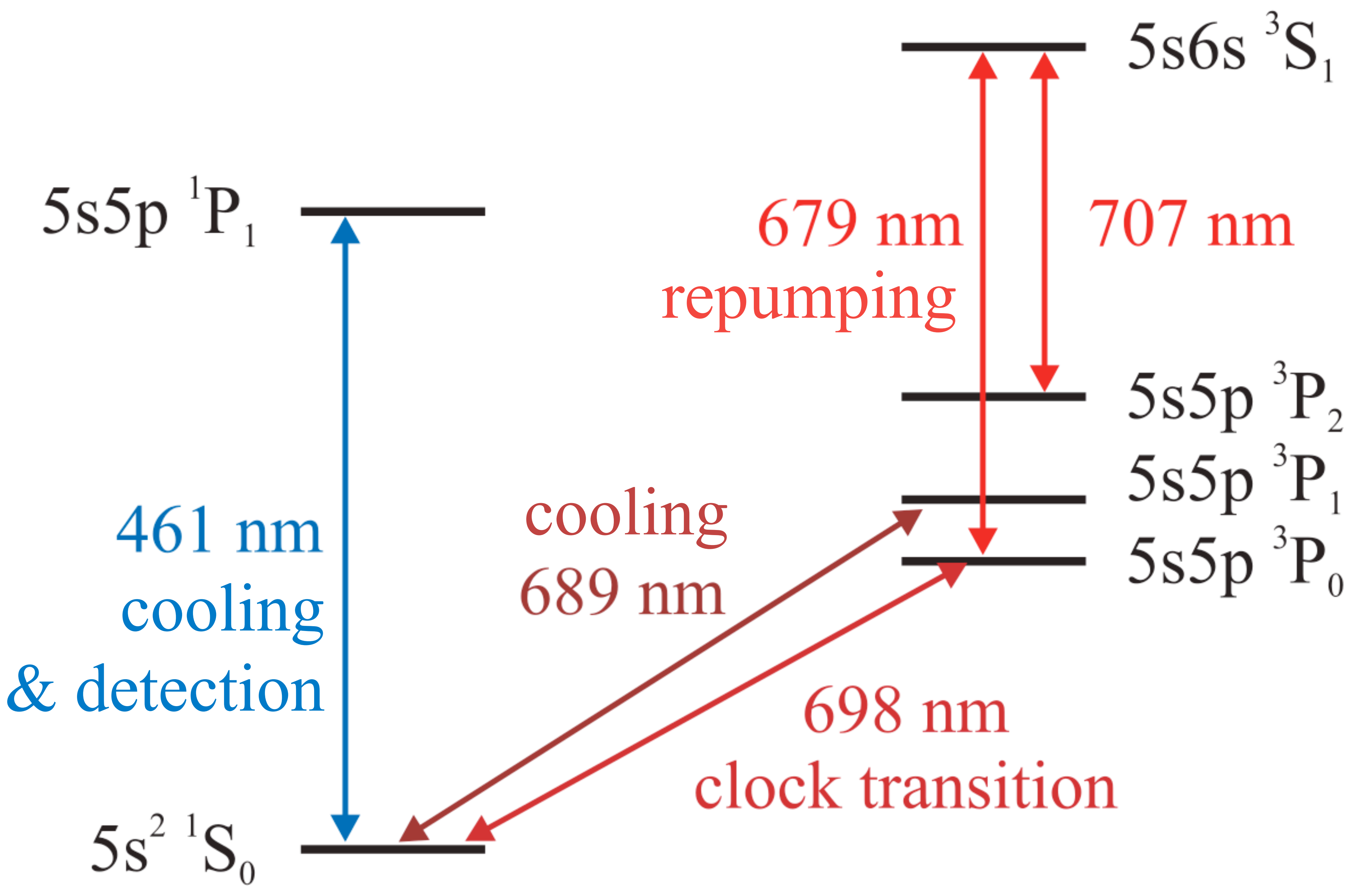


Image: Wikimedia Commons

The Nuclear Clock

Sr-87 atomic clock

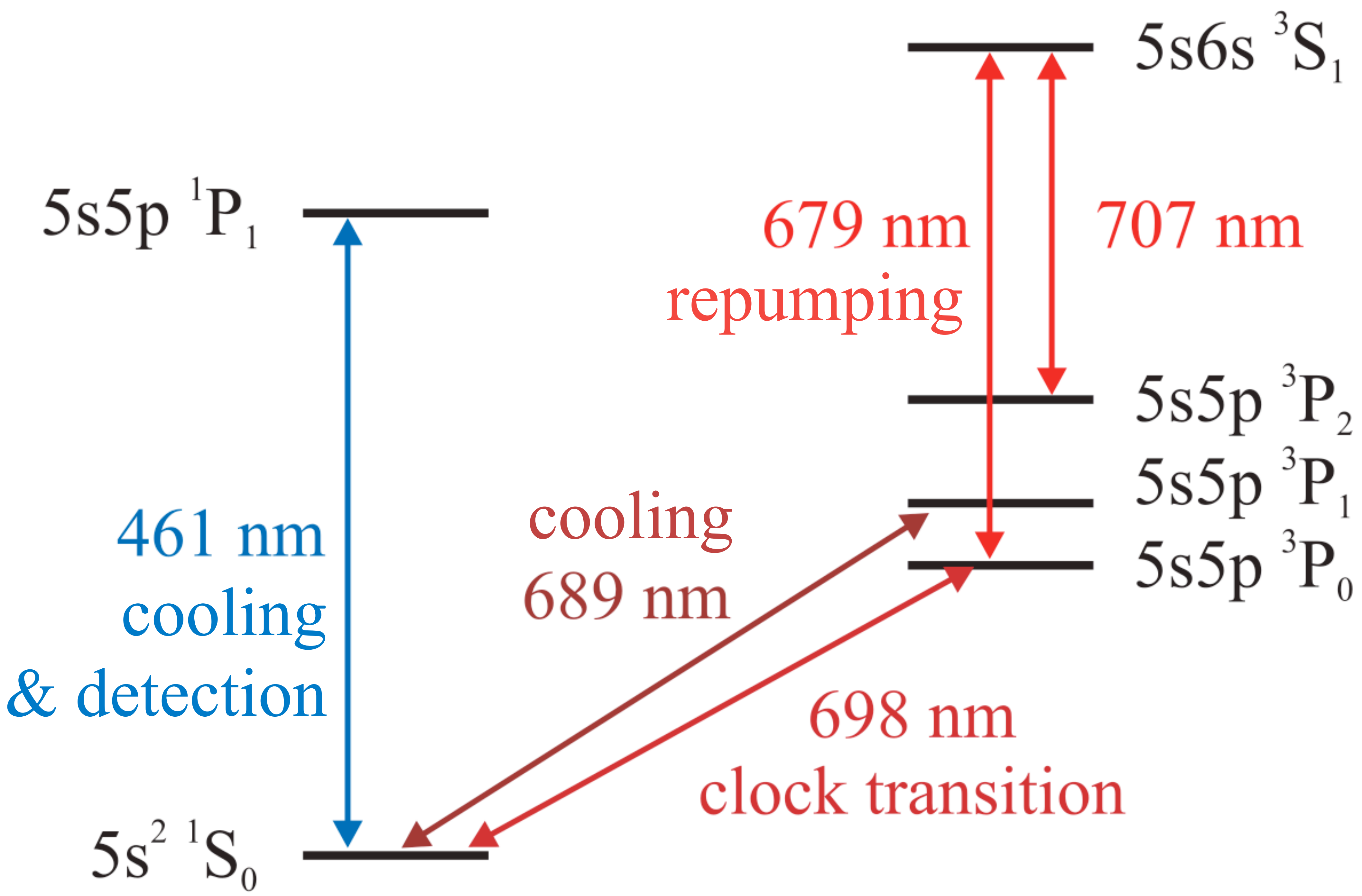


Image: Wikimedia Commons

Th-229 nuclear clock

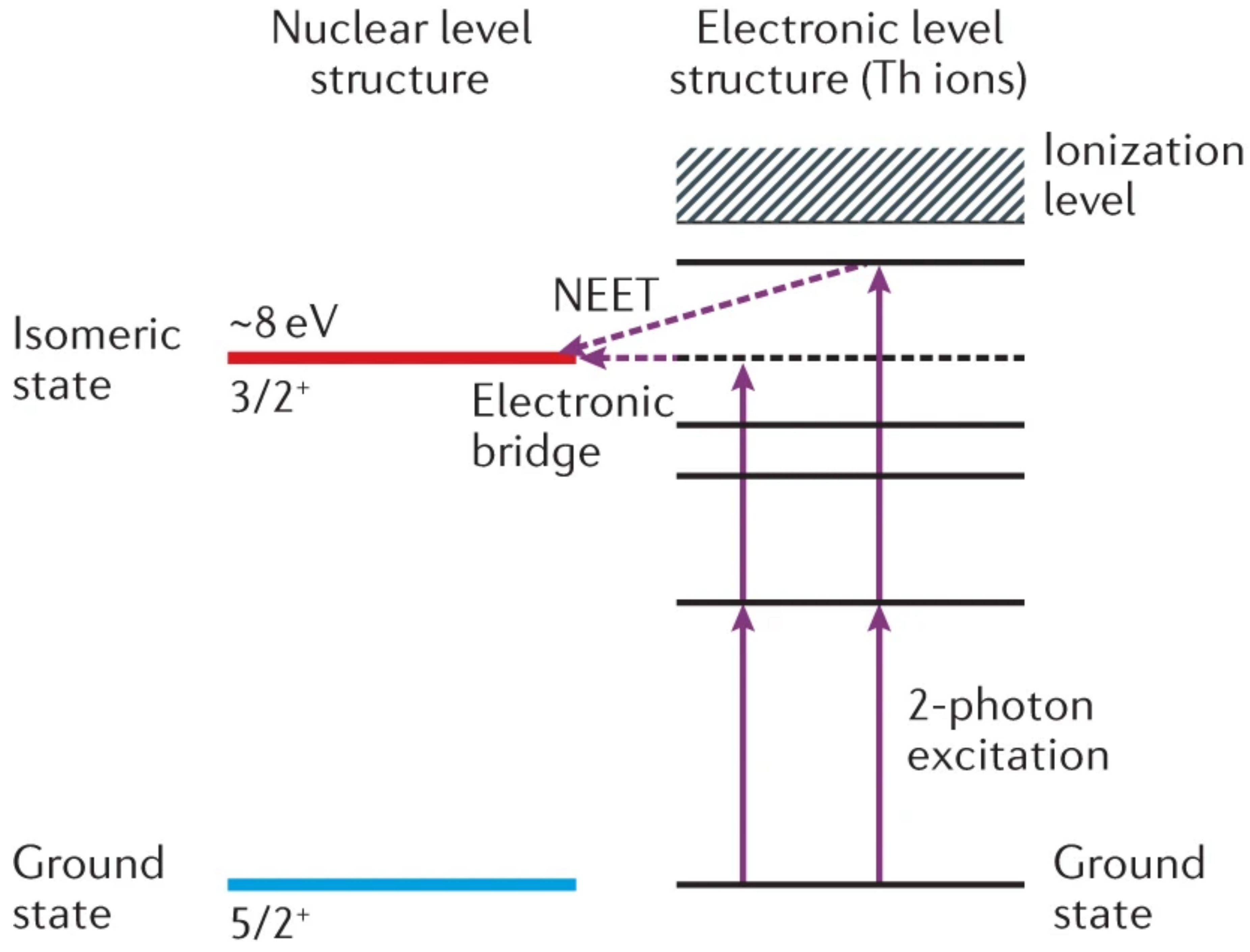


Image: Beeks *et al.* 2021

The Nuclear Clock

Beeks et al. 2021
Thirolf et al. 2024

- The isomeric transition in Th-229 is the only known nuclear transition with ΔE low enough for laser excitation (~8 eV)
- Advantages
  - radiative decay ultra-narrow ($\Gamma \sim 10^{-27}$ eV)
  - nucleus offers excellent shielding from environmental noise
- Challenges
  - Th-229m dominantly decays too quickly via IC
    ➠ work with Th-229 ions
    ➠ embed thorium in materials with band gap > 8 eV
  - Th-229 production either from U-233 stocks (~750 g exist in the world) or at accelerators (trace amounts)

The Nuclear Clock

- ☐ 2016: proof of existence of Th-299m (via IC decay) — von der Wense et al. 2016
- ☐ 2022: first observation of *radiative* Th-229m decay at ISOLDE — Kraemer et al. 2022
- ☐ 2024: first laser excitation — Tideau et al. 2024, Elwell et al. 2024, Zhang et al. 2024

New Physics Searches with Atomic Clocks

- atomic clocks measure transition frequencies with extreme precision (via Raman oscillations)
- extremely sensitive to tiny variations, especially time-dependent variations
- example: ultra-light dark matter field ϕ

$$\mathscr{L}_{\mathrm{Pl}} \in d_g \frac{\phi}{M_{\mathrm{Pl}}} \frac{\alpha_s}{\pi} G G \implies d_g \frac{m_n}{M_{\mathrm{Pl}}} \phi \, \bar{n} n$$

$$\mathscr{L}_{\mathrm{axion}} \in \frac{a}{32\pi^2 f} G \tilde{G} \implies \frac{m_n}{f} a \, \bar{n} \gamma_5 n$$

- coherent ϕ background behaves as classical field: $\phi \sim \phi_0 \cos(m_\phi t)$
- effective variation of fundamental constants

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- ○ oscillating pion mass Kim Perez 2022

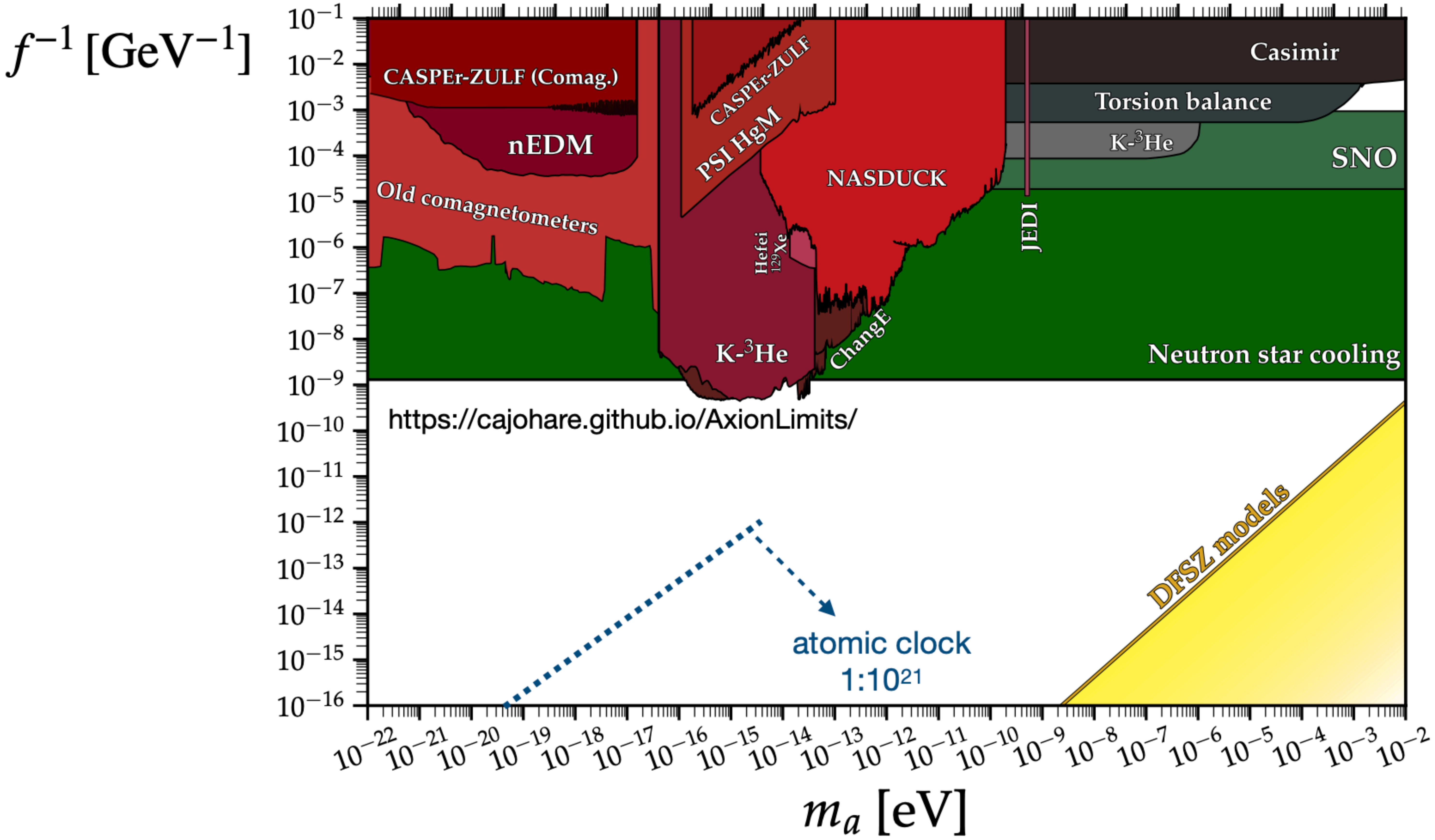
$$\frac{\delta m_\pi^2}{m_\pi^2} = -\frac{m_u m_d}{2(m_u + m_d)^2} \theta^2$$

- ○ leads to oscillating proton mass and *g*-factor
- ○ results in oscillating atomic transition frequencies

- ☐ coherent ϕ background behaves as classical field: $\phi \sim \phi_0 \cos(m_\phi t)$
- ☐ effective variation of fundamental constants

New Physics Searches with Atomic Clocks

$$\mathscr{L}^{\text{eff}}_{\text{axion}} \in 10^{-3}\,\theta^2(t)\,m_N\,\bar{n}n$$



Slide by Gilad Perez

New Physics Searches with Nuclear Clocks

- Low transition energy presumably due to **fine-tuned cancellation** between strong and electromagnetic contribution
- new physics that affects one but not the other breaks this tuning
  ➠ hugely enhanced sensitivity (by factor ~ MeV / 8 eV)
- to meaningfully interpret nuclear clock data in the context of BSM physics, this enhancement factor needs to be known

Fuchs et al. 2024
Caputo et al. 2024

Modeling the Th-229 Nucleus

Fadeev et al. 2020
Caputo et al. 2024

- Estimating nuclear contribution to ΔE hopeless ➠ focus on e.m. contribution
- simplest approach: a geometric model
  - model Th-229 as ellipsoid with varying charge density

$$\rho(r,\theta) = \frac{\rho_0}{1 + \exp\left(\frac{r - R(\theta)}{z}\right)} \qquad R(\theta) = R_0 \left[1 + \beta_2 Y_{20}(\theta) + \beta_3 Y_{30}(\theta) + \beta_4 Y_{40}(\theta) + \dots\right]$$

  - measured charge radius and quadrupole moment fix two parameters (e.g. R_0 and β_2) independently for ground state and isomer

$$\langle r^2 \rangle \equiv \frac{1}{e\,Z} \int d^3\mathbf{r}\, r^2 \rho(r,\theta) \qquad Q_0 \equiv \int d^3\mathbf{r}\, r^2 \rho(r,\theta) \left[3\cos^2(\theta) - 1\right]$$

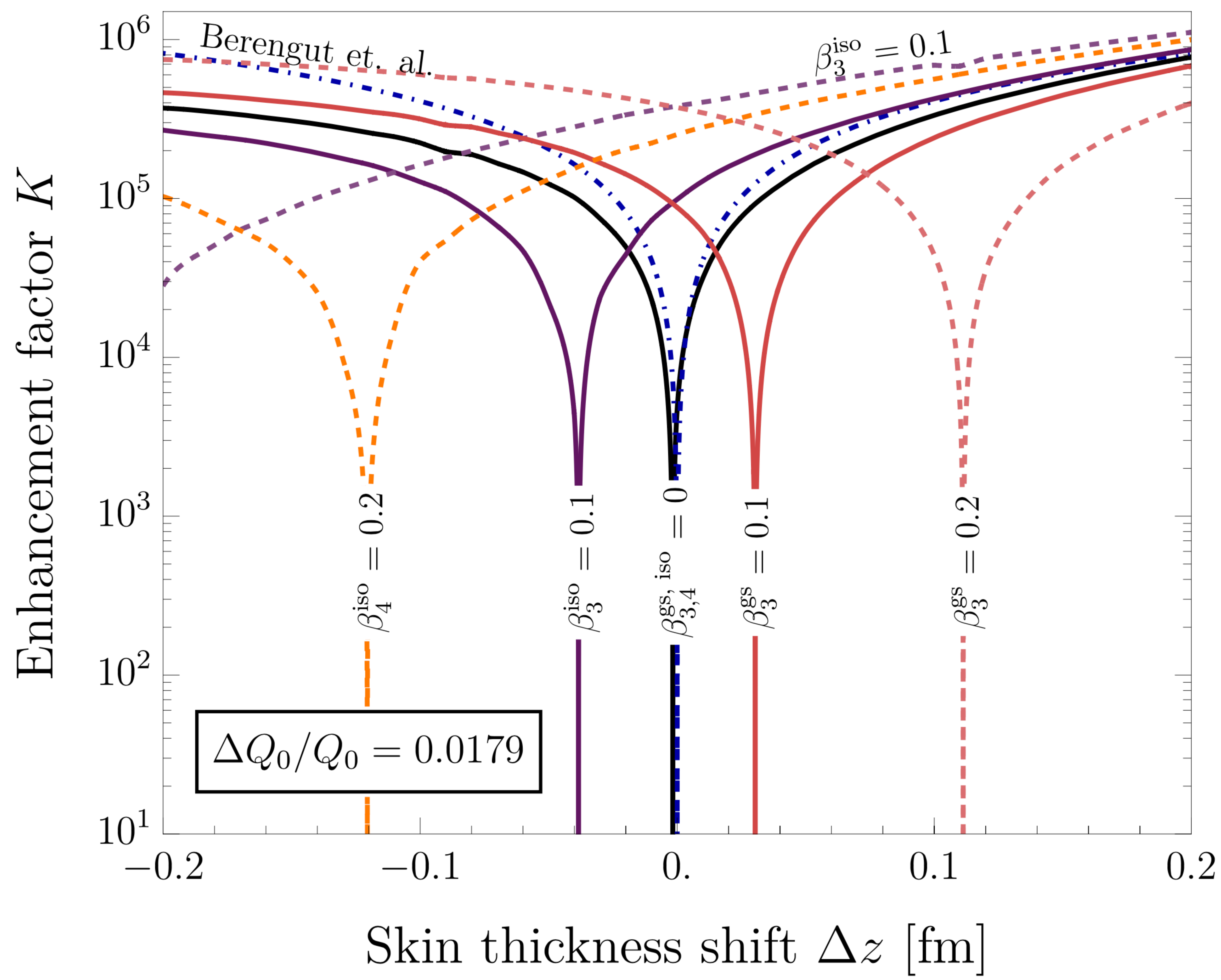
  - compute Coulomb energy difference between the two states

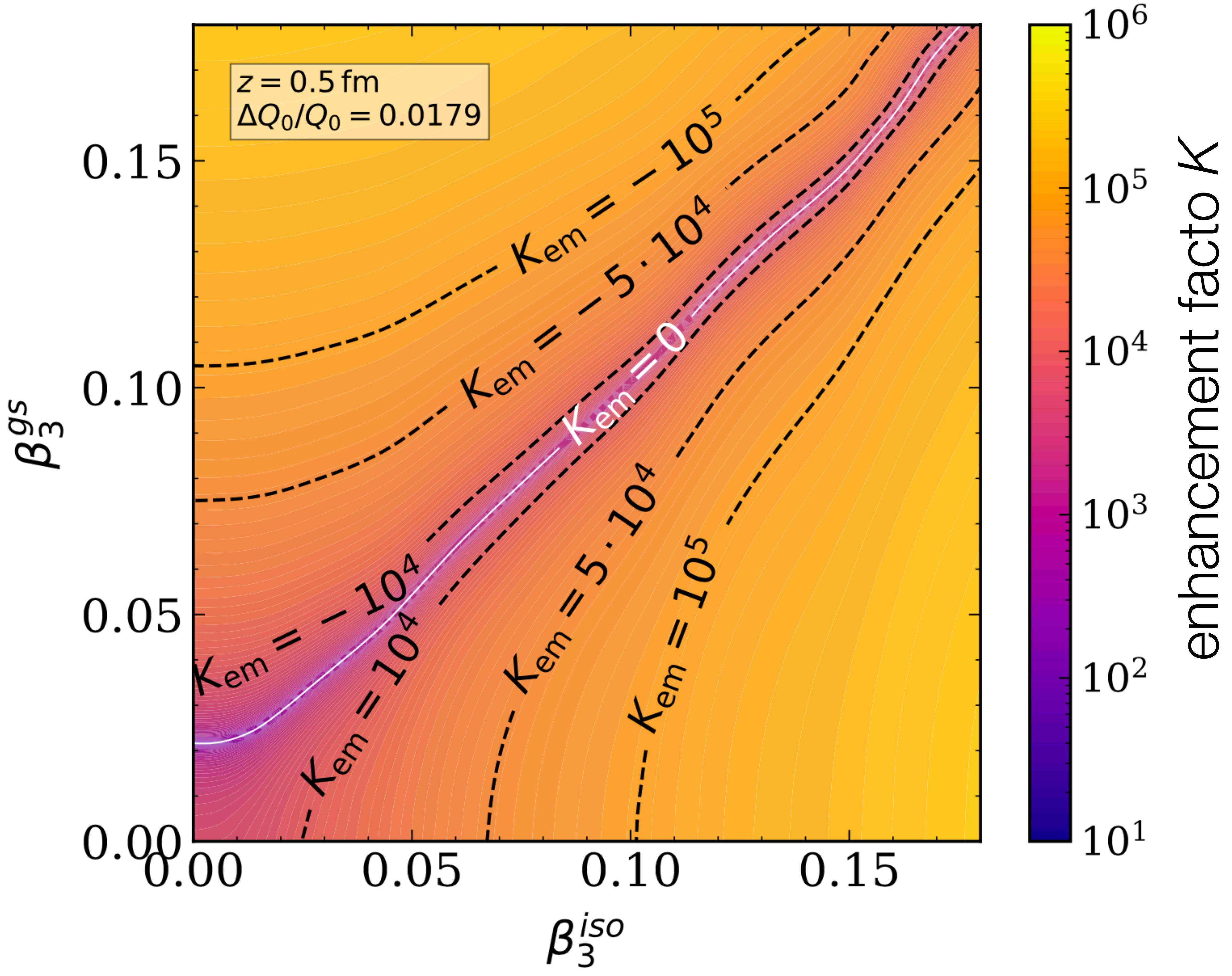
$$E_{\text{em}} \simeq E_{\text{C}}[\langle r^2 \rangle, Q_0, z, \beta_3, \beta_4] = \frac{1}{2} \int d^3\mathbf{r}\, d^3\mathbf{r}' \, \frac{\rho(r,\theta)\,\rho(r',\theta')}{|\mathbf{r} - \mathbf{r}'|}$$

Modeling the Th-229 Nucleus

Caputo et al. 2024

☐ Additional nuclear shape information needed to refine the model





Halo Model for Th-229

Caputo et al. 2024

- ☐ treat Th-229 as inert Th-228 core, orbited by halo neutron
  - ○ spins of g.s. (5/2) and isomer (3/2) suggest spin flip of halo neutron
  - ○ neutron separation energies (Th-229: 5.2 MeV; Th-228: 7.1 MeV) lend further support
- ☐ charge distribution of g.s. and isomer identical in this model except for the spin–orbit coupling

$$\rho_{\mathrm{SO}} = \frac{\mu_n}{2m_n^2} i\sigma_{\alpha\beta} \cdot \Big[(\nabla\Phi_\alpha^\dagger) \times (\nabla\Phi_\beta)\Big]$$

Ong Berengut Flambaum 2010

- ☐ $\langle r^2 \rangle$ and Q_0 are *independent* of the neutron wave function (the same is *not* true for higher moments)

Halo Model for Th-229

Caputo et al. 2024

☐ treat Th-229 as inert Th-228 core, orbited by halo neutron

☐ Verification

$\langle r^2\rangle^{\mathrm{iso}} - \langle r^2\rangle^{\mathrm{g.s.}} = 0.0047\ \mathrm{fm}^2$ ↔ experimentally: $0.012(2)\ \mathrm{fm}^2$

$Q_0^{\mathrm{iso}} - Q_0^{\mathrm{g.s.}} = 0.185\ \mathrm{fm}^2$ ↔ experimentally: $0.175\,525(6)\ \mathrm{fm}^2$

☐ Spin–orbit contribution to the transition energy

$$E_{\mathrm{SO}} = \frac{e\,\mu_n}{2m_n^2}\frac{1}{2}\left[j(j+1) - l(l+1) - \frac{3}{4}\right]\int_0^\infty \left[\frac{[u(r)]^2}{r}\frac{dV_{\mathrm{C}}}{dr}\right] dr$$

$$\boxed{\Delta E_{\mathrm{SO}} = E_{\mathrm{SO}}\big|_{j=5/2} - E_{\mathrm{SO}}\big|_{j=3/2} \approx 144\,p\,\mathrm{keV}}$$

➠ $K \sim 10^4$

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$Q_0^{\text{iso}} - Q_0^{\text{g.s.}} = 0.185\ \text{fm}^2$ ↔ experimentally: 0.17

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neutron radial **wave function** (use hydrogen orbitals)

Coulomb potential

$$\boxed{\Delta E_{\text{SO}} = E_{\text{SO}}\big|_{j=5/2} - E_{\text{SO}}\big|_{j=3/2} \approx 144\,p\,\text{keV}}$$

➠ $K \sim 10^4$

O(1) factor from regularization at r=0 (from more complete nuclear model)

Conclusions

☐ we’re witnessing a revolution in AMO physics

☐ New Physics could break fine-tuned cancellations between strong and e.m. contributions to the energy of Th-229m
➠ hugely enhanced sensitivity

☐ two models
  ○ geometric model – depends crucially on nuclear shape
  ○ halo model

☐ both predict enhancement factors ~10^4
(with large uncertainties still ➠ more detailed nuclear modelling desirable)

Thank You!