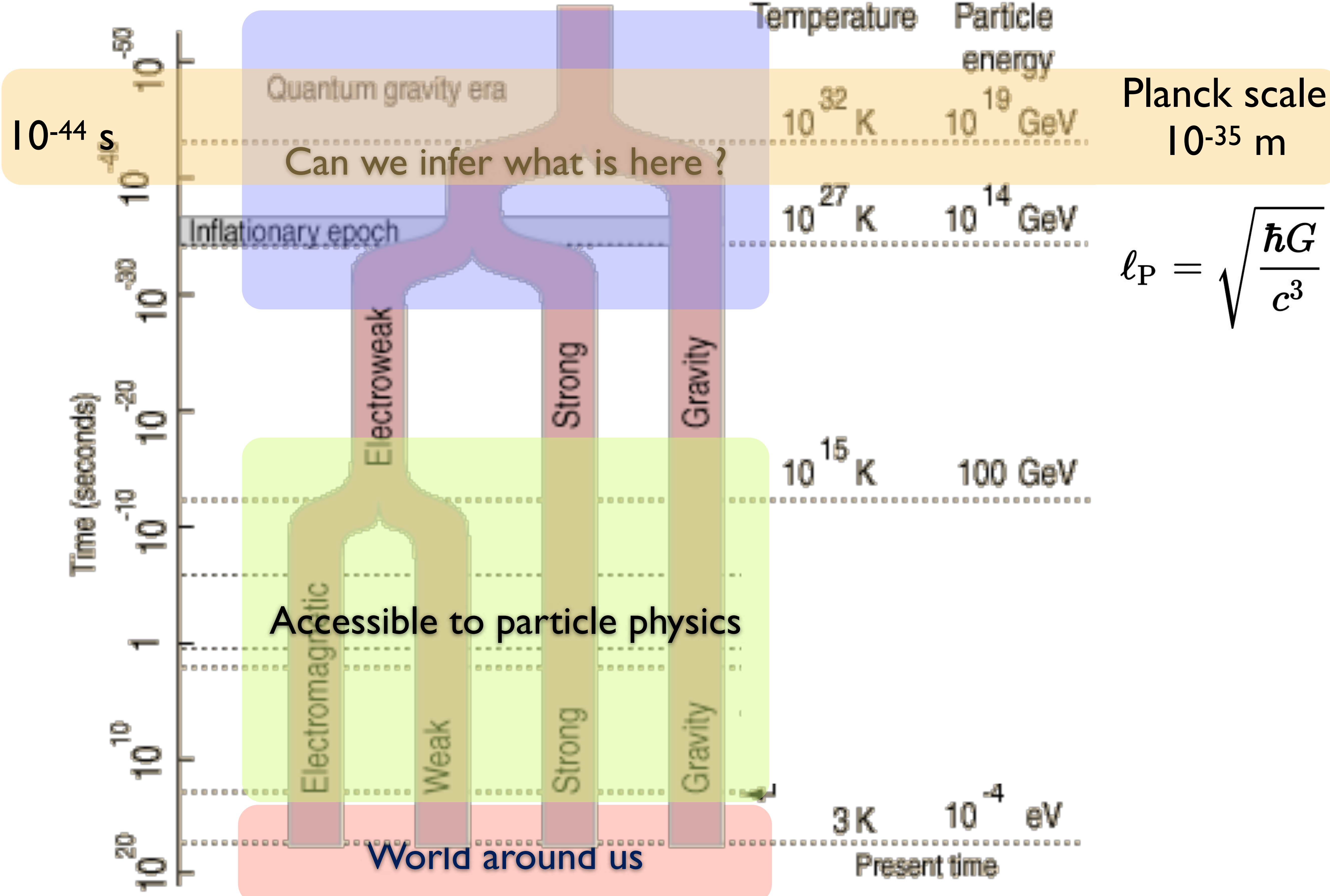
Fundamental Symmetries

What are they good for?

@ ARIEL

Gerald Gwinner — University of Manitoba

Image source


Temperature
Particle energy
Quantum gravity era
Planck scale
10-35 m
10-44 s
10 32 K
10 19 GeV
Can we infer what is here ?
10 27 K
10 14 GeV
Inflationary epoch
ℓP = √(ħG/c3)
Electroweak
Strong
Gravity
10 15 K
100 GeV
Time (seconds)
10 -50
10 -40
10 -30
10 -20
10 -10
1
10 10
10 20
Accessible to particle physics
Electromagnetic
Weak
Strong
Gravity
3 K
10 -4 eV
World around us
Present time

FunSym — What is it good for?

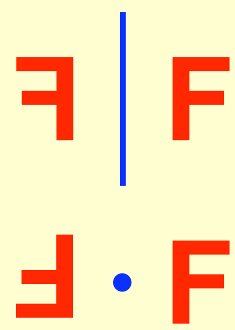
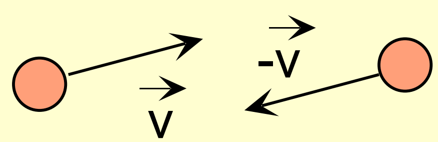
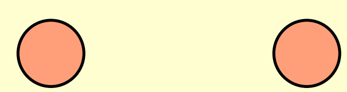
- Goal: Finding "new physics" beyond the Standard Model (BtSM)
- Obvious: push at the energy frontier → colliders → $ frontier
- Other paths
  - Intensity frontier (B-physics)
  - Precision frontier → fundamental symmetries

- Low-energy tests try (mostly) to "catch the tail" of high-energy physics
  - tiny signatures often swamped by conventional signals
  - (discrete) symmetry-violations allow to find the needle in the haystack

- Generally, low-energy BtSM work is labelled "fundamental symmetries"
- For some FunSym tests, RIB are foundational (decay experiments)
- For others, RIB is accidental
  - specific atomic structure at high Z
  - nuclear deformation

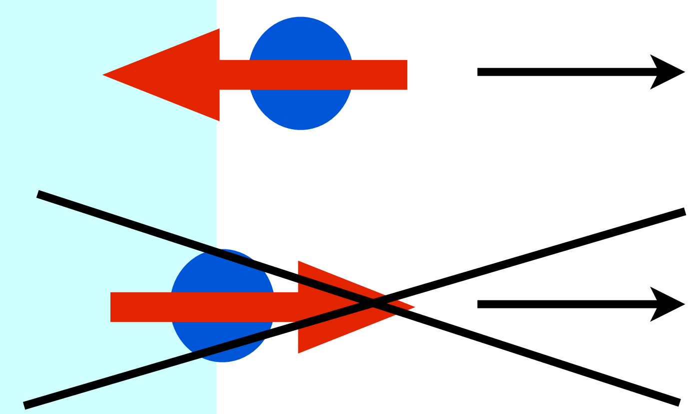
TRIUMF has attracted an above average number of RIB FunSym efforts, in particular trap-based

Antoine Weis, Université de Fribourg

		symmetry operation	
mirror symmetry		reflection at plane / point	**P**
time reversal symmetry		reversal of arrow of time	**T**
charge exchange symmetry	 Proton Antiproton	exchange of matter and anti-matter	**C**

Laws of nature are invariant under the combined symmetry operation CPT

neutrino



also

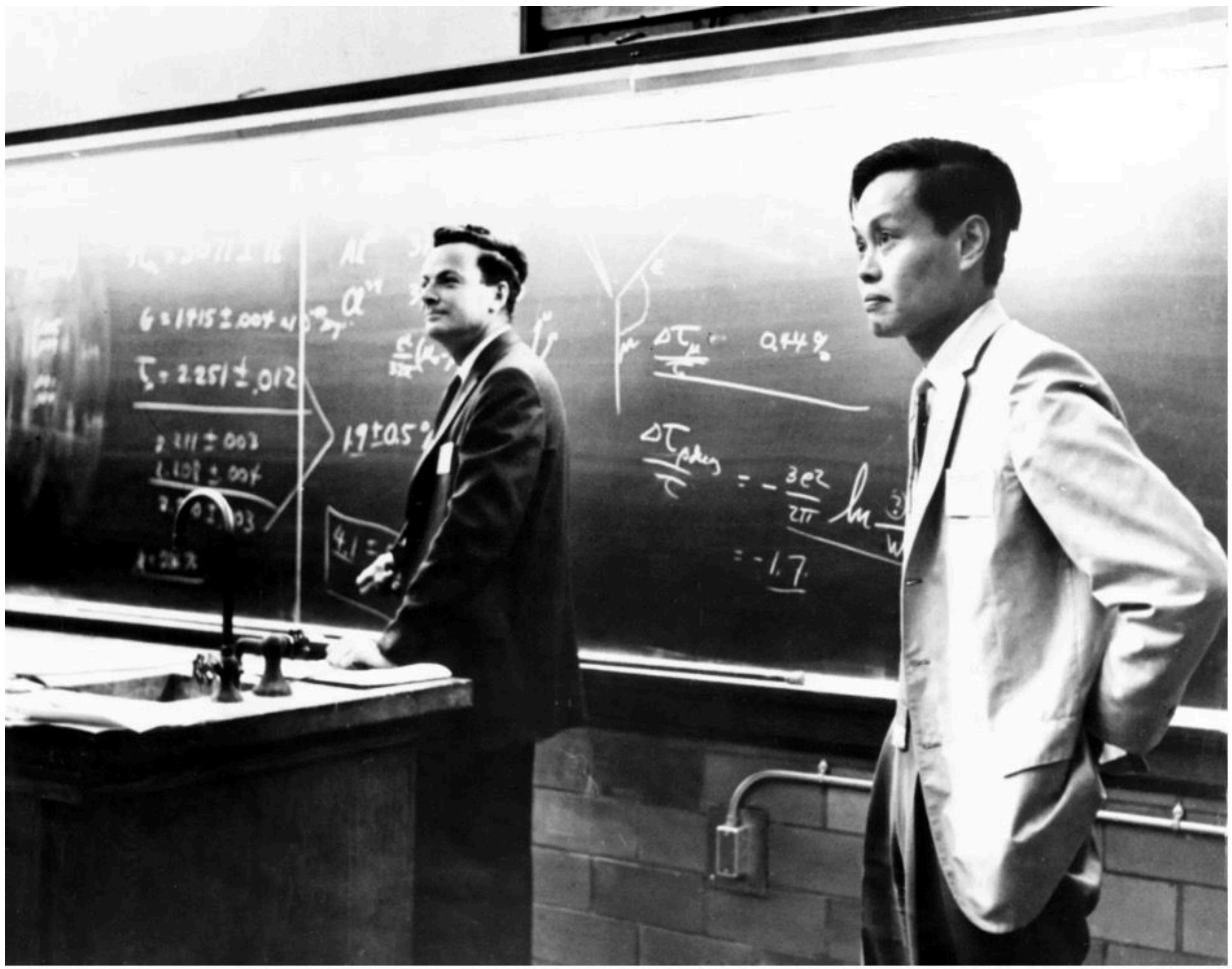
- Lorentz invariance
- Lorentz structure of currents (V-A vs S-T)

A process violates (C,P,T) if the process and the (C,P,T)-transformed process do not occur in nature with equal probability

C.N. Yang, 1922 - 18.Oct.2025

Chen Ning Yang, Nobel-Winning Physicist, Is Dead at 103

He and a colleague, Tsung-Dao Lee, created a sensation in 1956 by proposing that one of the four forces of nature might violate a law of physics.



Dr. Yang with his fellow physicist Richard Feynman in the 1950s. SSPL/Getty Images

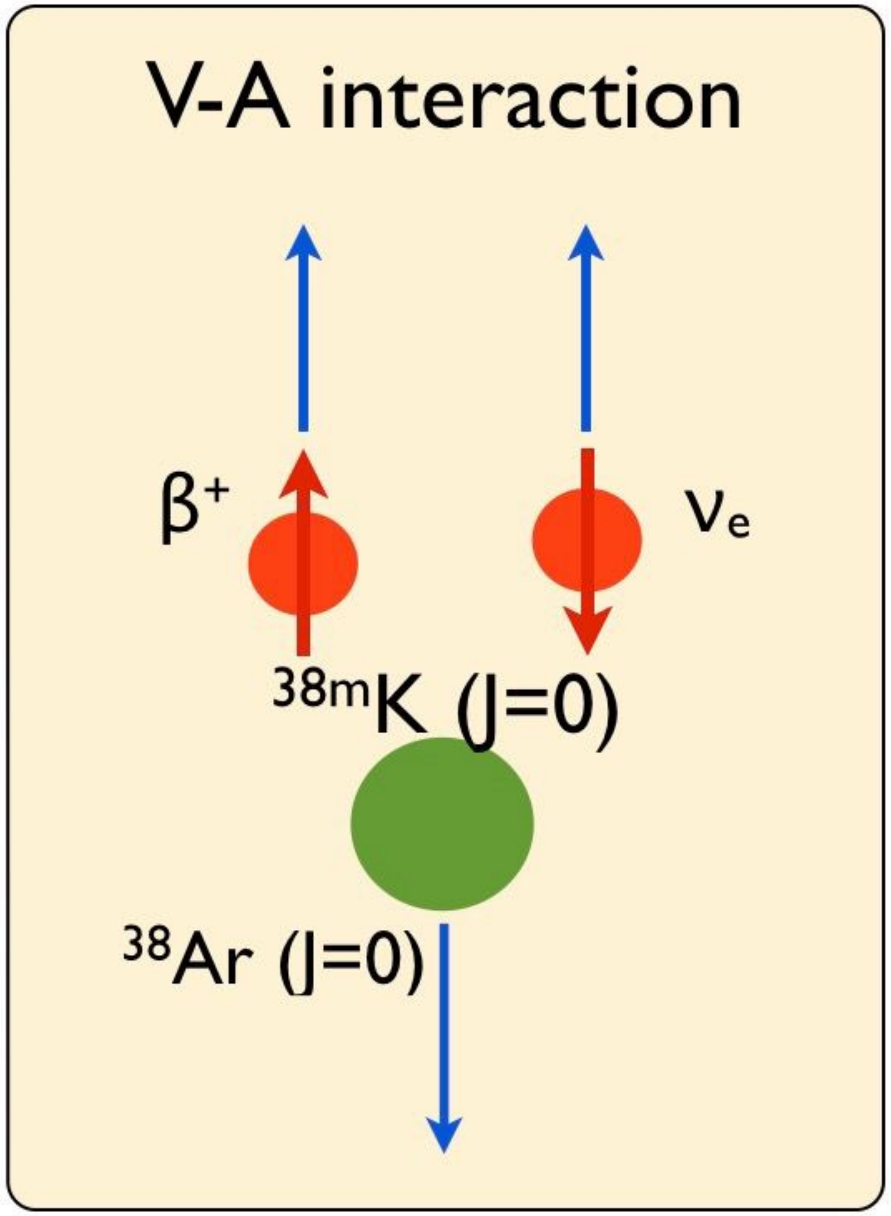
Type of FunSym tests and techniques

- Why not test fundamental symmetries in fundamental particles?
- Complementary to high energy approaches.
- Relatively cost-effective, great training ground.

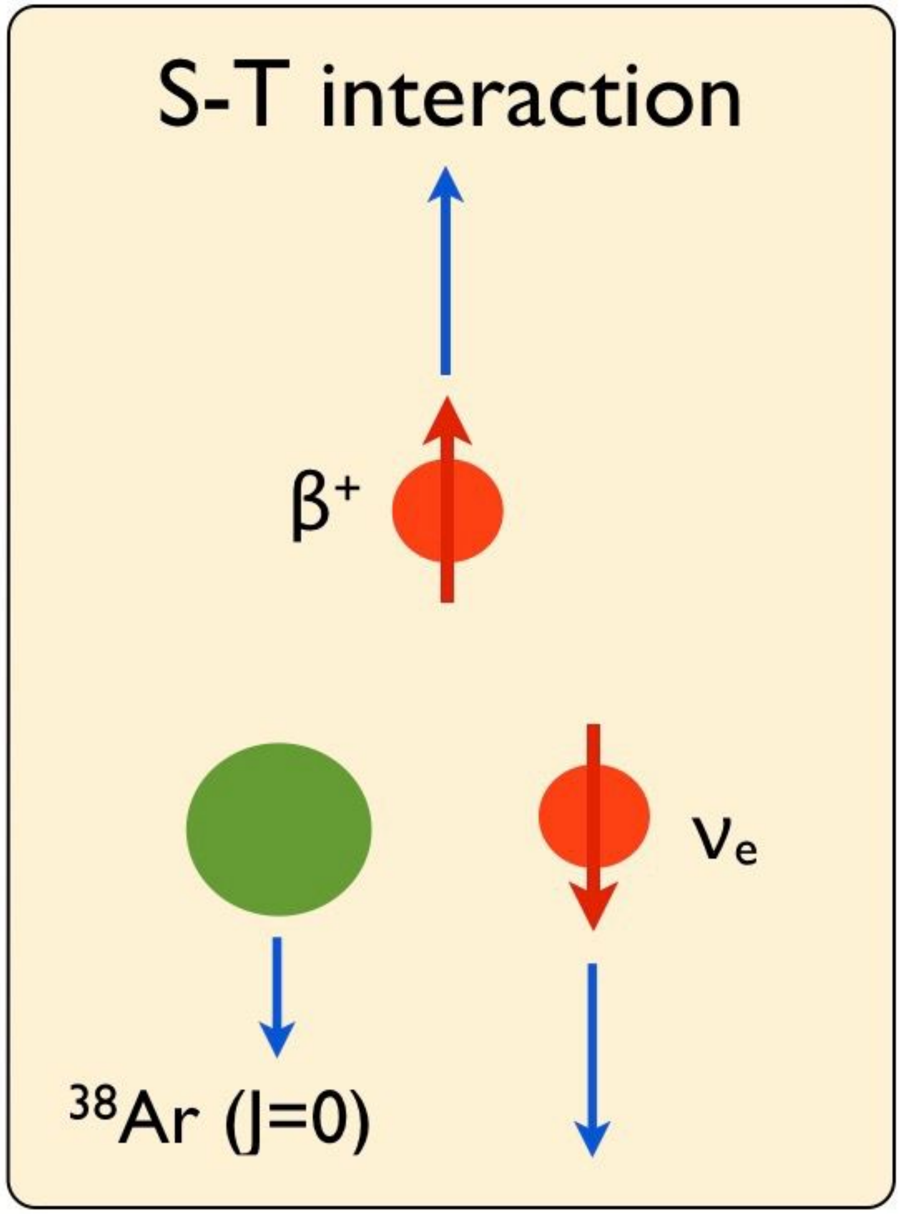
	Atom	**Nucleus**
Charged current weak interactions, β-decay	new powerful techniques (atom traps)	rich selection of spin, isospin, half-life
Neutral current weak interactions APNC anapoles	tremendous accuracy of atomic methods (lasers, microwaves) neutral (strong external fields) traps, cooling	huge enhancement of effects (high Z, deformation) over elementary particles rich selection of spin, isospin, Z, N, deformation
Permanent electric dipole moments		
Lorentz-symmetry & CPT violation	accuracy	selection of spin, Z, N

Beta-neutrino correlations

- V-A now established, scalar admixture ?
- infer neutrino momentum from recoiling daughter
- daughter $\lesssim$ 100 eV
- traps ideal



$$\hat{p}_e \cdot \hat{p}_\nu = +1$$

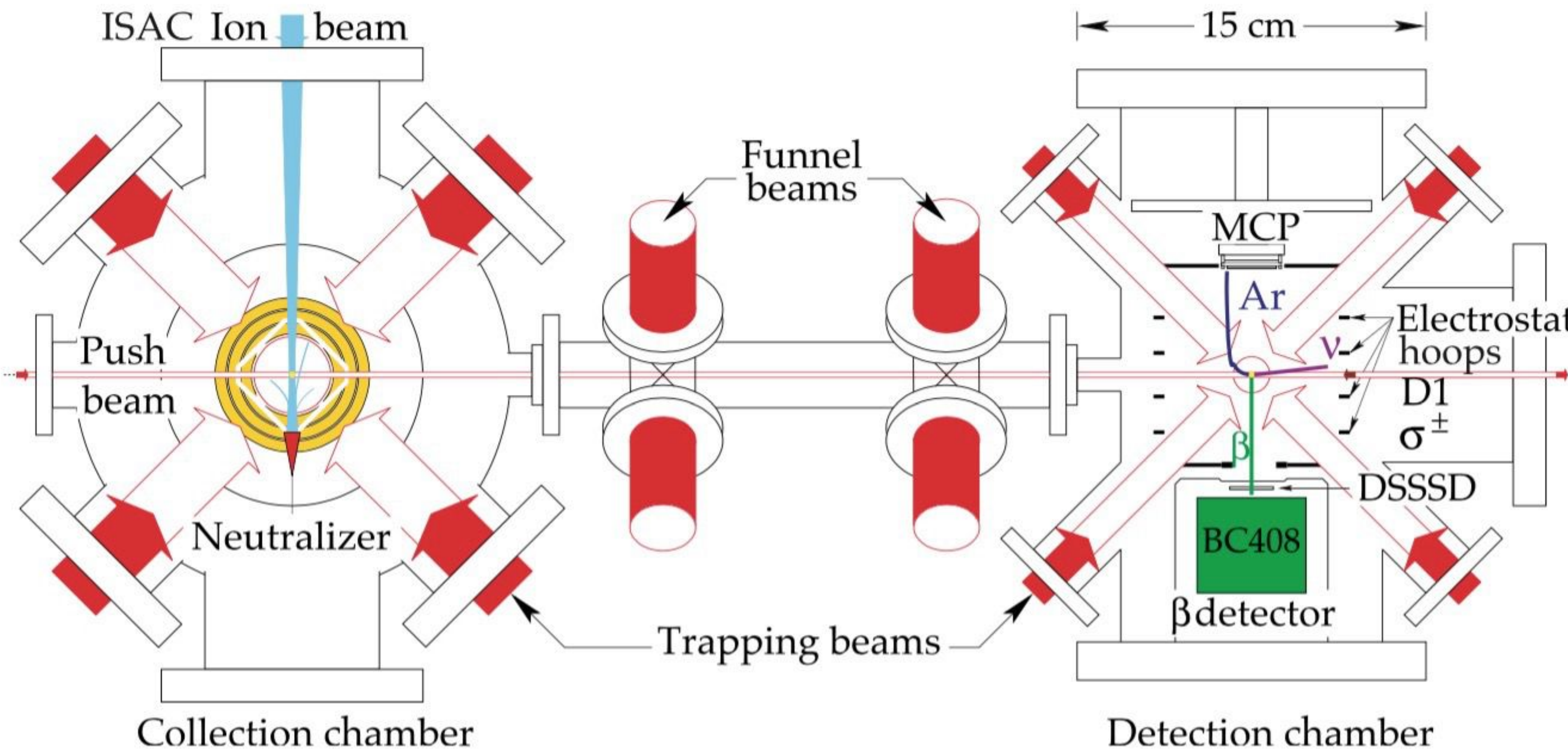


$$\hat{p}_e \cdot \hat{p}_\nu = -1$$

need for RIB: obvious

Beta-neutrino correlations

- TRINAT apparatus (1994 - present)
- Behr, Häusser, Gorelov, Melconian and many others
- TRIUMF/SFU/TAMU/Tel Aviv/Manitoba



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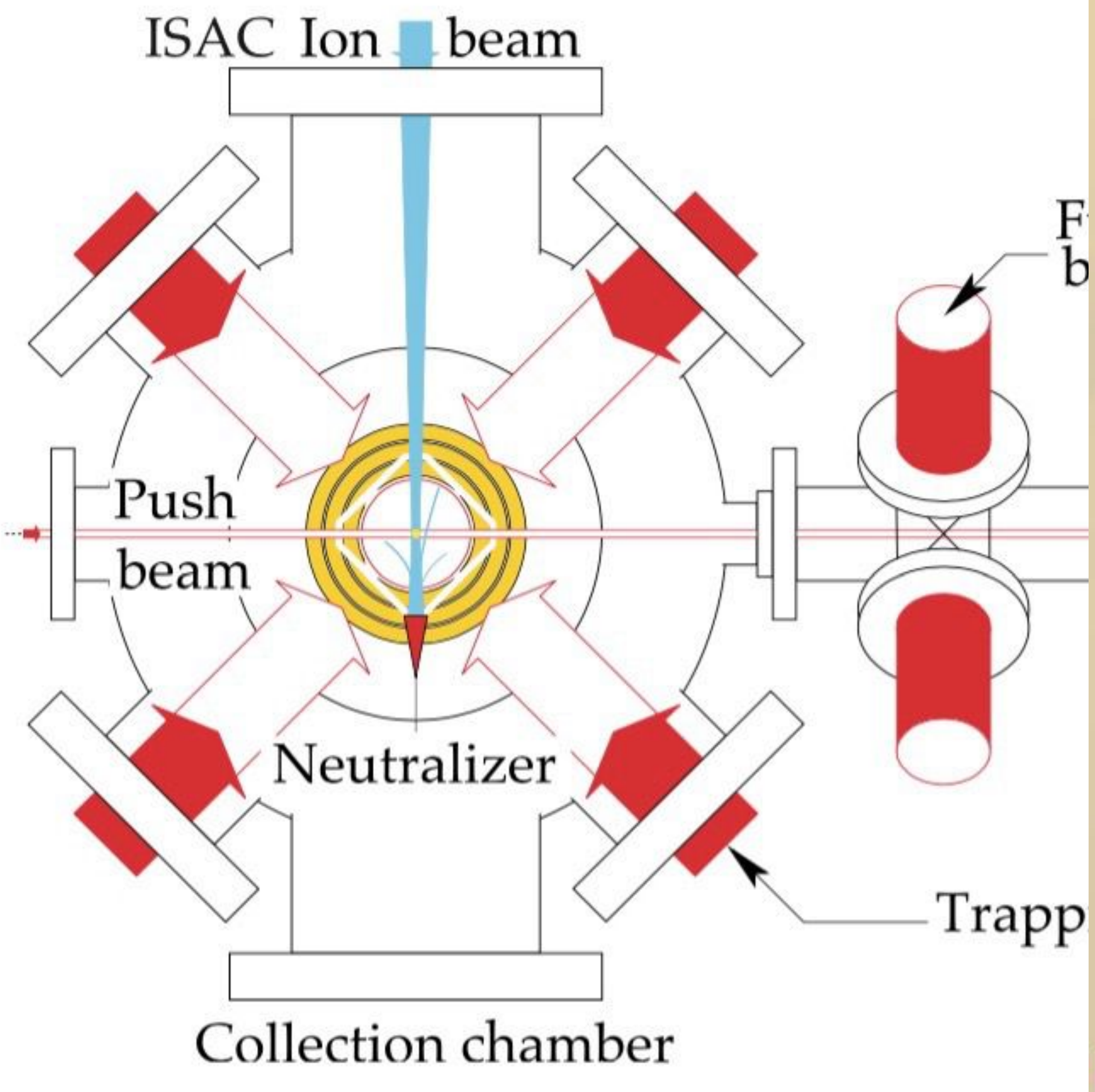
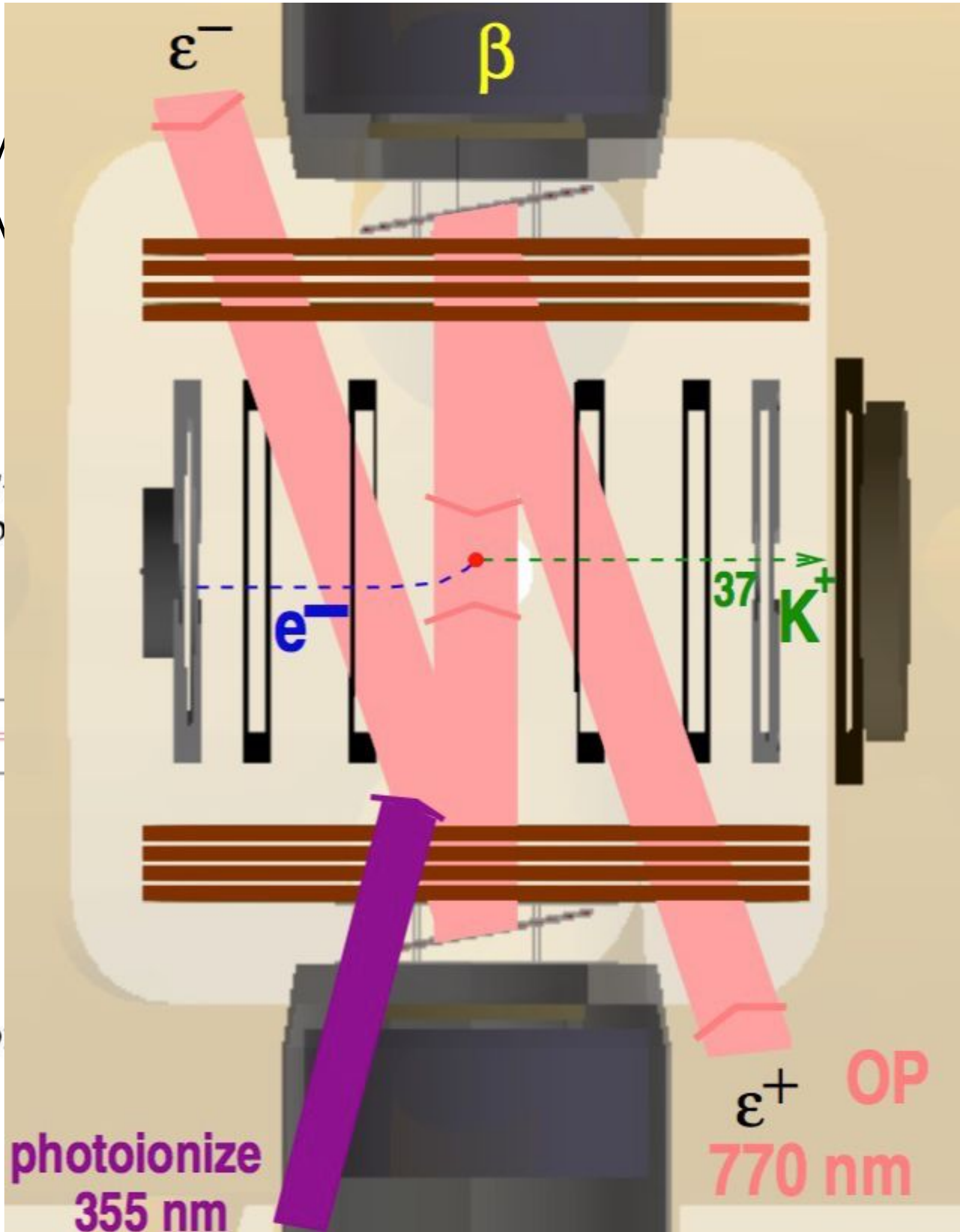
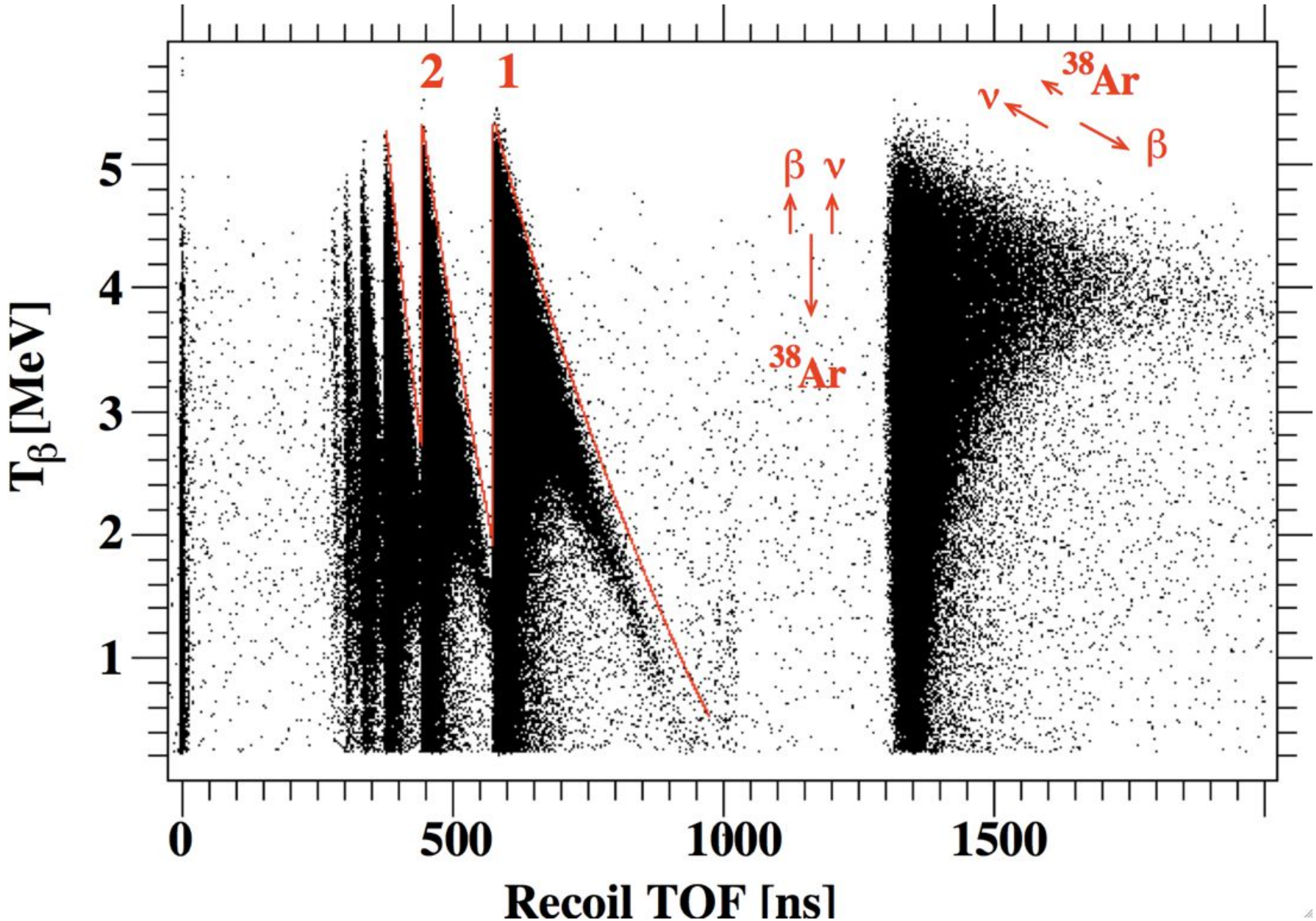
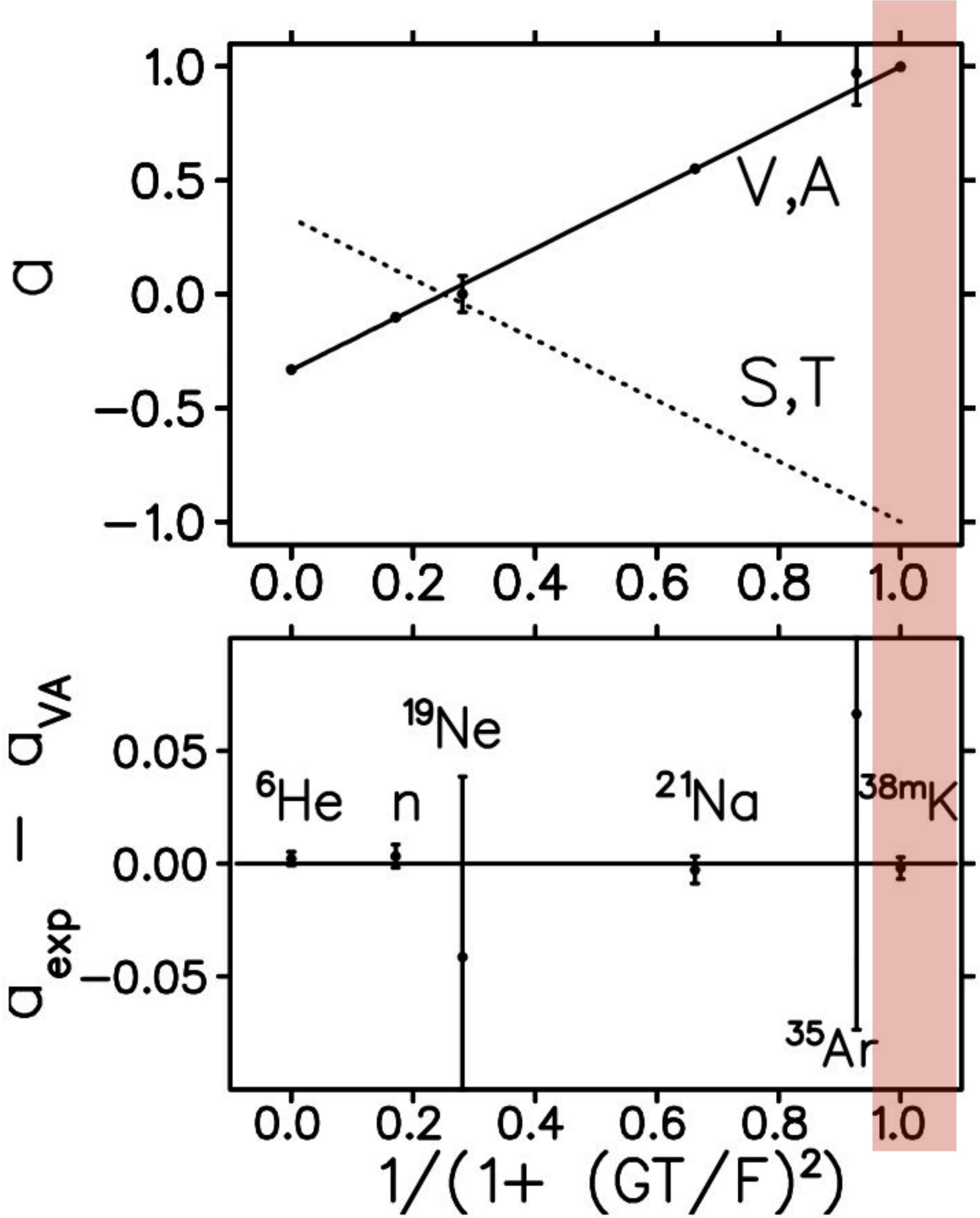




Beta-neutrino correlations

- ^{38m}K $0^+ \to 0^+$ decay   alkali, half-life ≈ 1s   → MOT

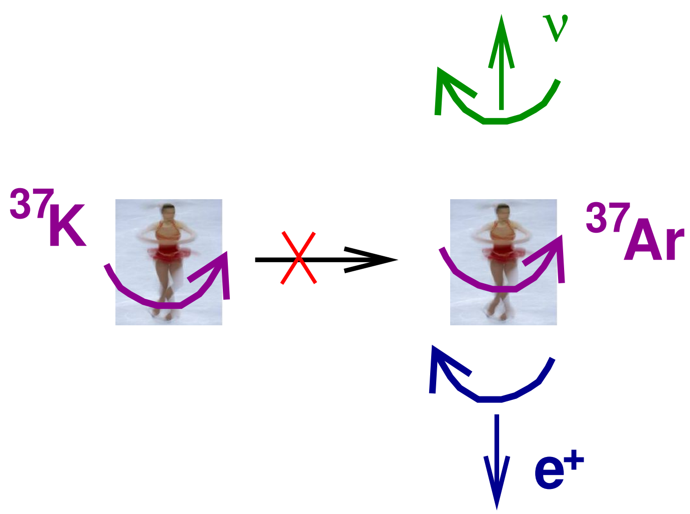




J=0 → J=0
pure Fermi decays

$$W\,\mathrm{d}E_e\,\mathrm{d}\Omega_e\,\mathrm{d}\Omega_\nu \quad \propto \quad 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \ \ldots$$

A spin-polarized angular distribution sensitive to ν helicity



If I_z = I_{initial} and I_{initial} = I_{final}, the leptons can't increase $I_{z\ \text{final}}$

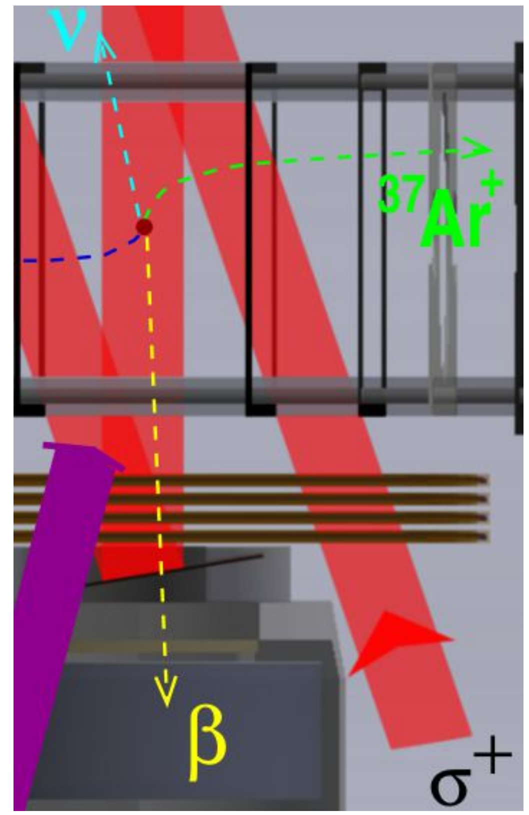
If β^+ down, the ν can't go up, unless either β or ν have wrong helicity

Any imperfect I_z/I mimics a wrong-handed ν

^{38}K G.T. $3^+ \rightarrow 2^+$ needs both ν and β^+ helicities wrong:

would be most direct ν helicity measurement since Goldhaber 1957

Helicity-driven null

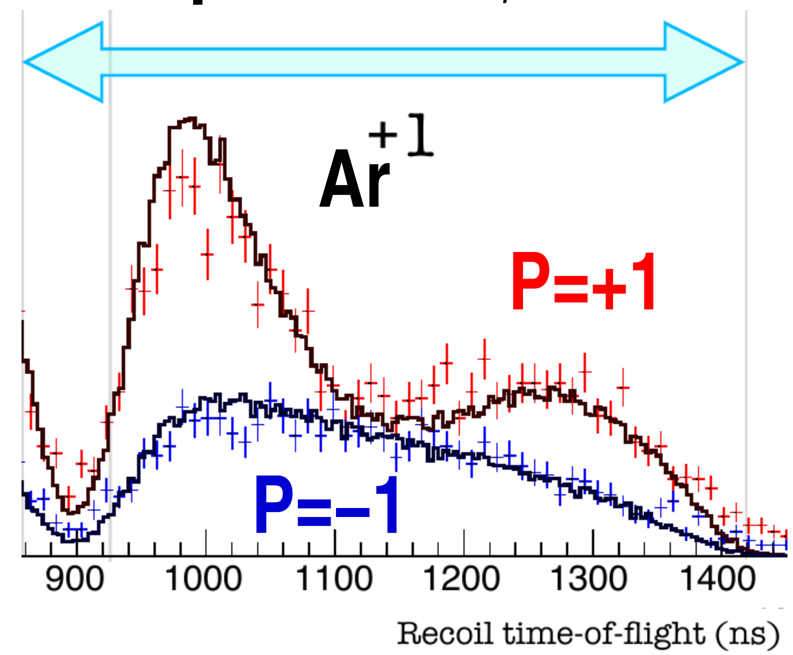


Fenker et al. PRL 2018

A_β= -0.5707$\pm$ 0.001913 in agreement with SM

achieved I_z/I = 0.991 $\pm$ 0.001

2014 polarized β-recoil



$v_{\text{TOFaxis}} = 0$ suppressed. Dip would be deeper with ion MCP position cut or $\cos(\theta_{\beta-\nu})$ determination

$$W(\theta,P) \approx 1 + a_{\text{pol}} \cos(\theta_{\beta\nu})$$

$$a_{\text{pol}} = \frac{a_{\beta\nu} - 2c/3T + PB_\nu}{1 + PA_\beta + bm/E}$$

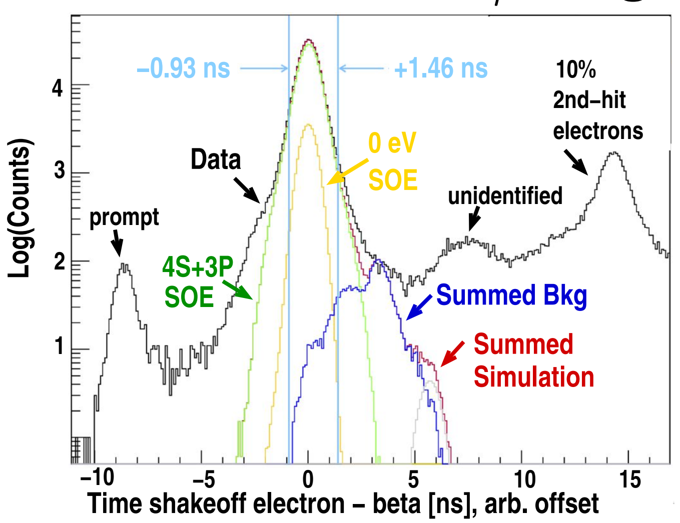
= 1 or 0, independent of $\frac{M_{GT}}{M_F}$

$A_\beta E_\beta$ in ^{37}K decay: new physics with opposite β helicity

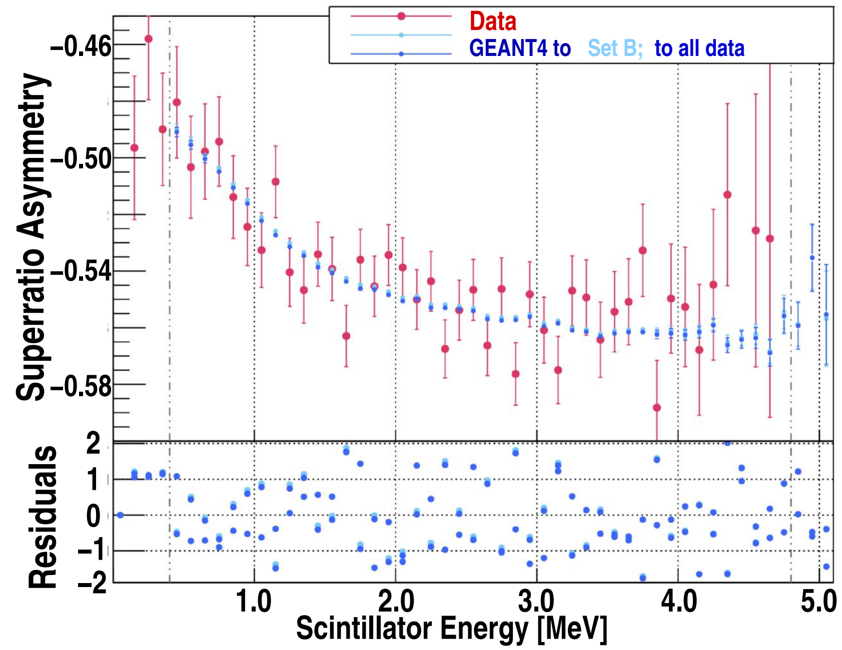
Fierz term $\propto m_\beta / E_\beta$, a helicity factor to generate existing wrong-handed β

M. Anholm et al. arXiv:2509.11502

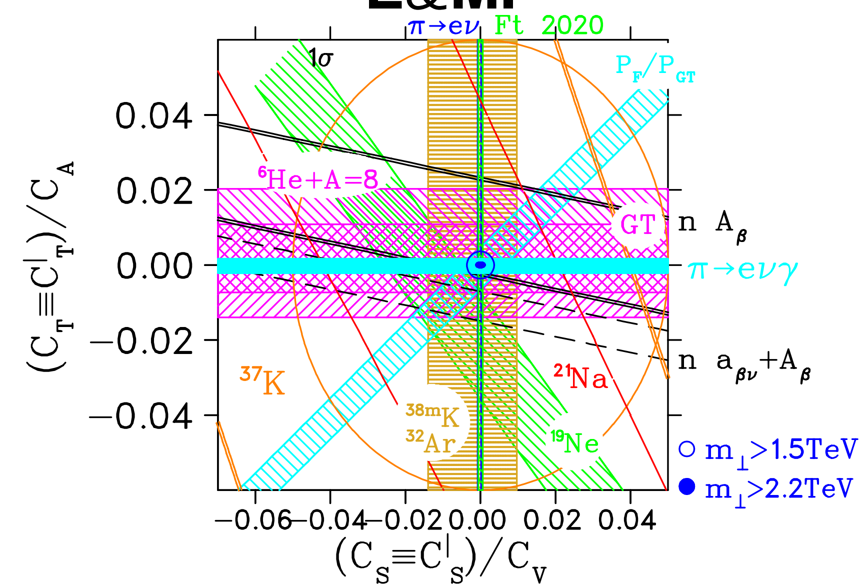
Cut on corrected timing walk of Fenker et al. 2018 data minimizes low-E_β bkg



Fit constrains Fierz term



It's amazing physics at many different scales has comparable sensitivity to general Lorentz scalar and Lorentz tensor-transforming 'currents' (extensions of SM vector and axial vector after E&M.



This sets a goal of 5x better to be helpful, which we will try to do this week with lower-Z materials and mirrors and ΔE detector

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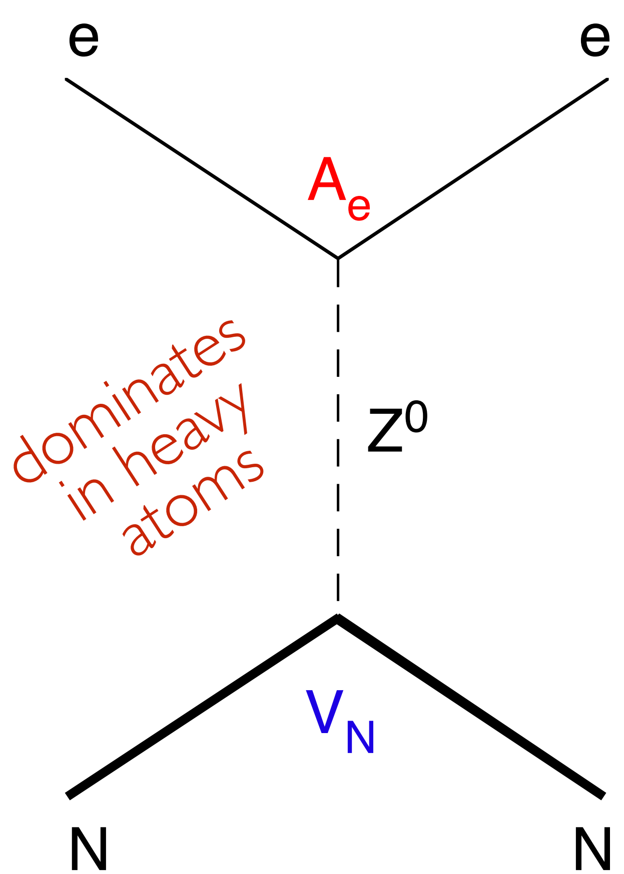
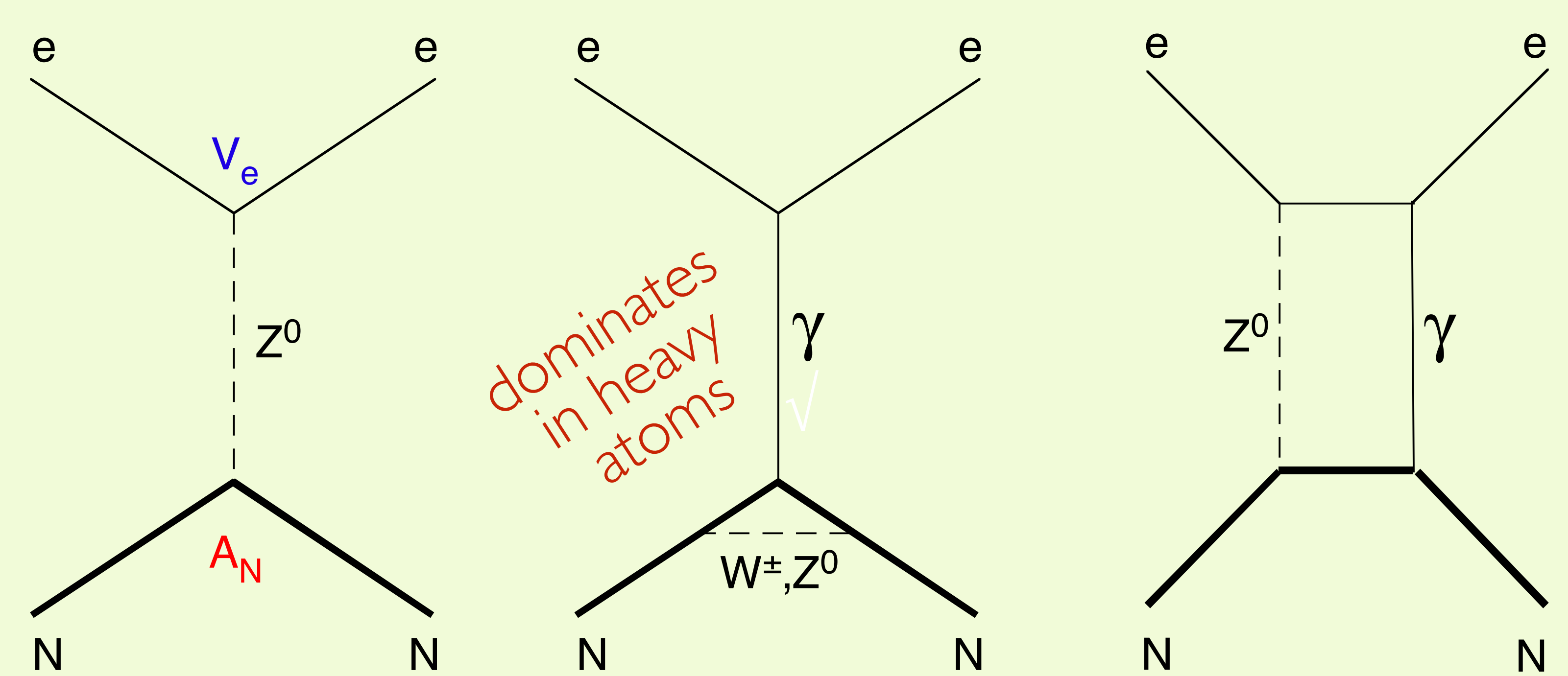
Atomic Parity Violation

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

Nuclear spin independent



Nuclear spin dependent



NSD Z-exchange

PV hadronic interactions → anapole moment

hyperfine corr. to weak neutral current

NSI: coherent over all nucleons (quarks):

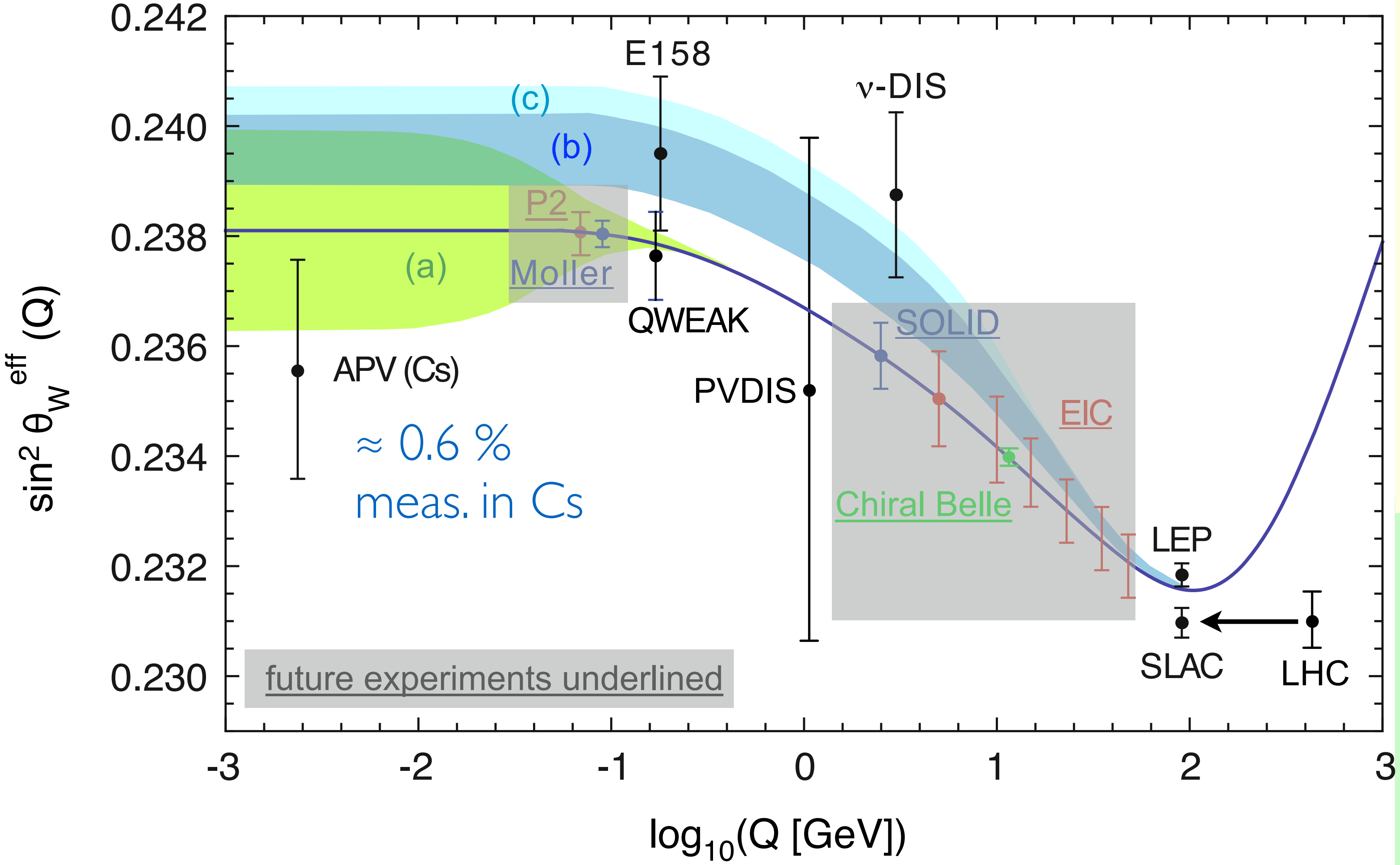
H_{pv} mixes electronic s & p states: $\langle n's|H_{\text{pv}}|np\rangle \propto Z^3$

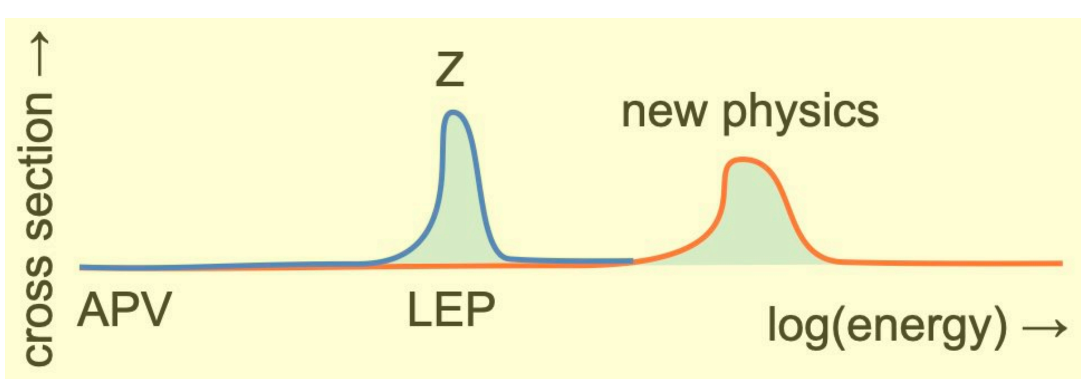
Signature: drive $s \rightarrow s$ electric dipole ($E1$) transition

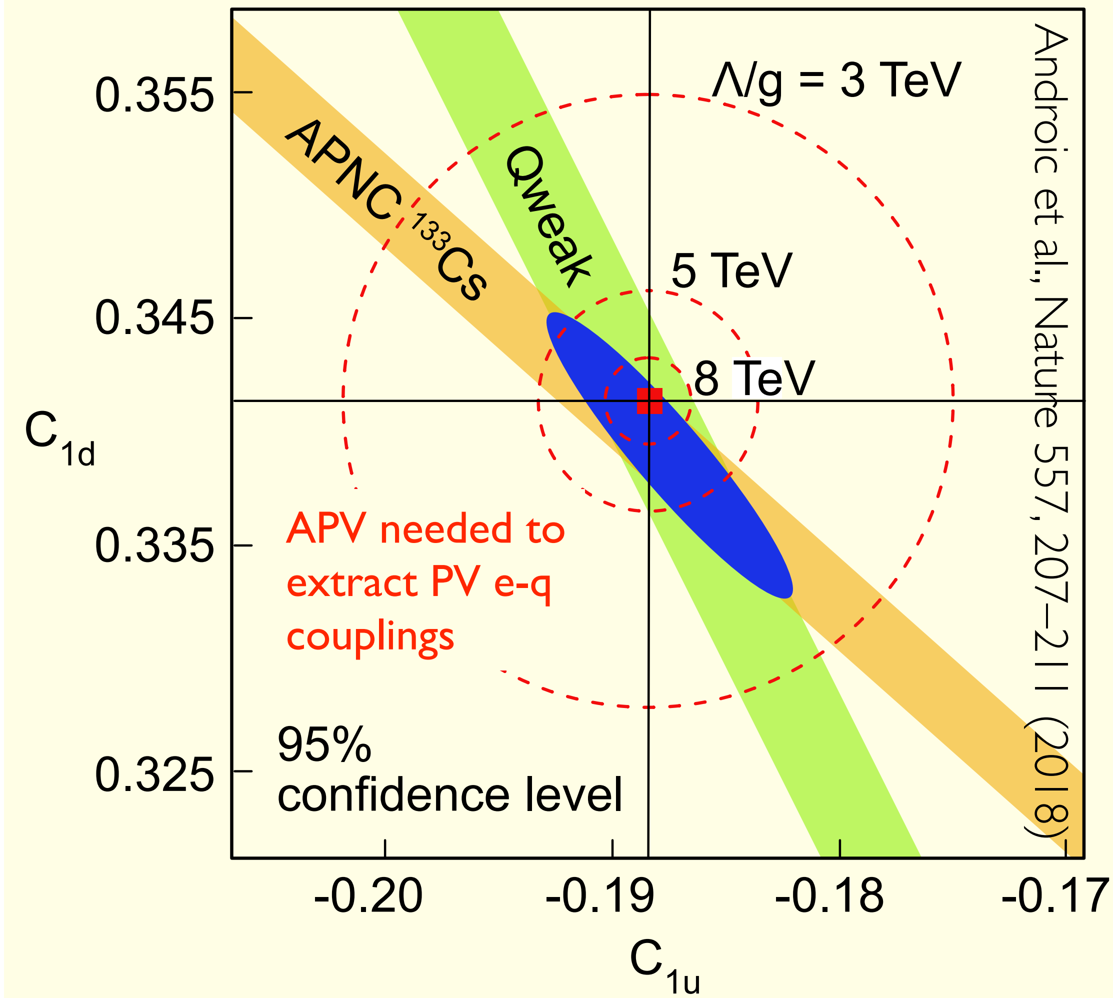
need for RIB: not essential, heaviest alkali systems (Fr, Ra+) have not stable isotopes

Atomic Parity Violation

- APV is a uniquely low-energy probe
  - sensitive to light dark boson scenarios



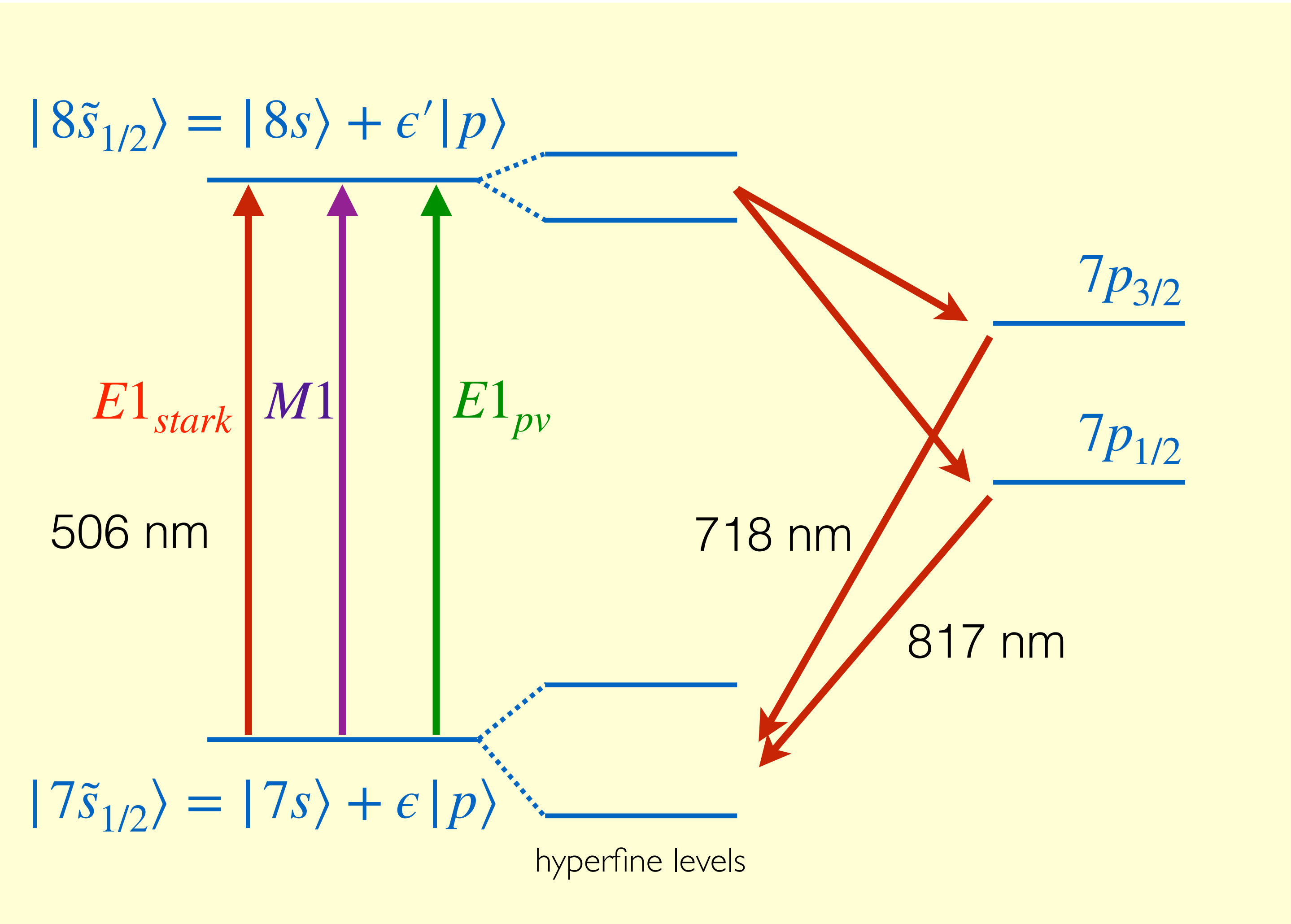




	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

Physics sensitivity from contact interaction
(LEP2 convention $g^2 = 4\pi$)
Frank Maas, CIPANP 2018 talk

APV measurement



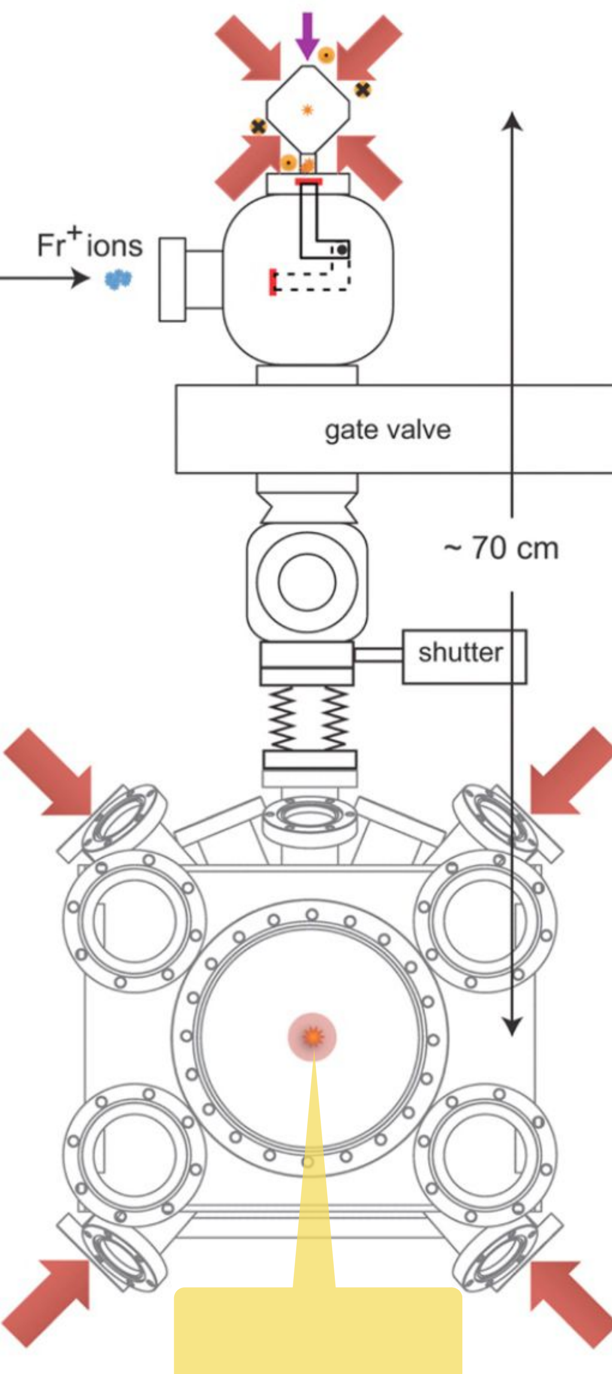
- faint transitions
- oscillator strengths
  - $f_{stark} \approx 10^{-10}$
  - $f_{M1} \approx 10^{-13}$
  - $f_{pv} \approx 10^{-21}$

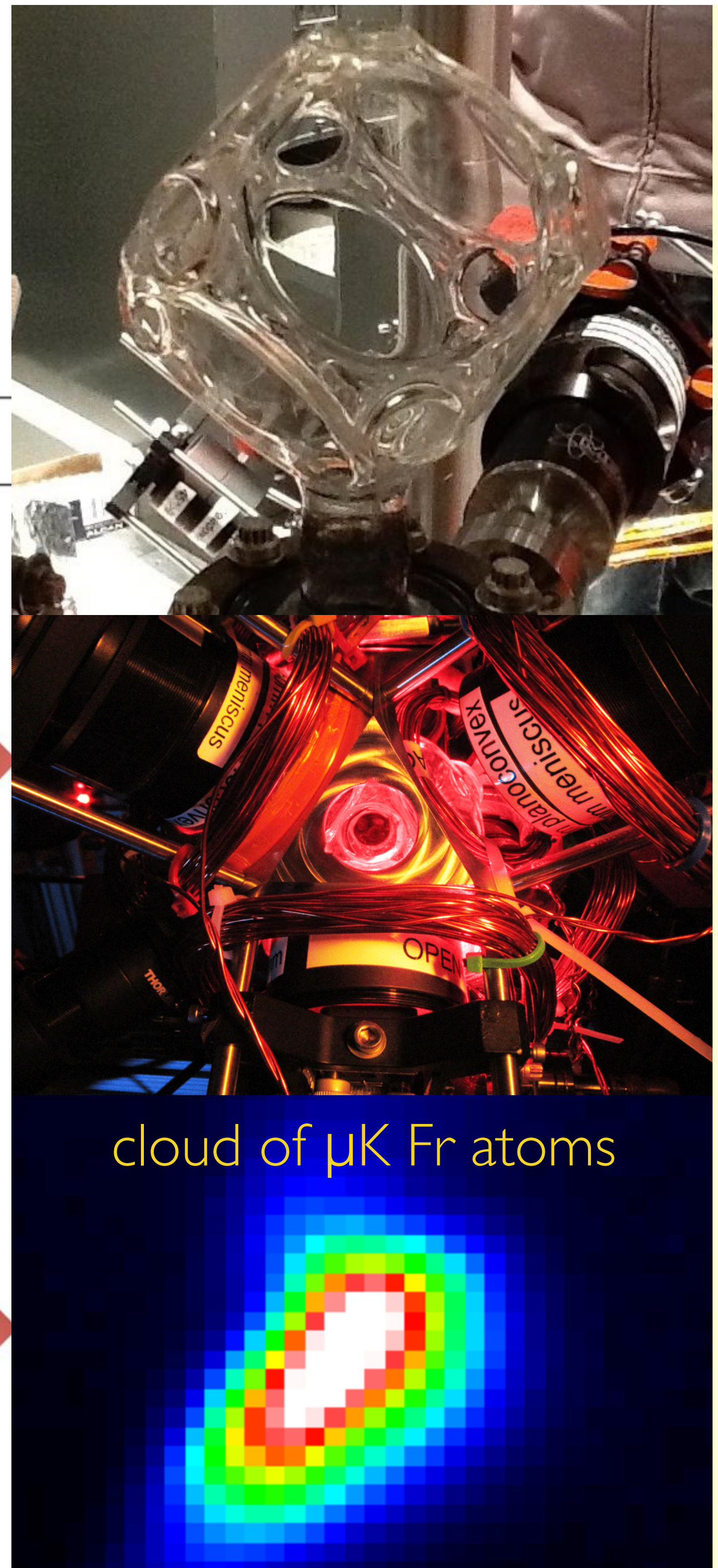
$$R_{7s\to 8s} \propto |E1_{stark} + M1 + E1_{pv}|^2$$

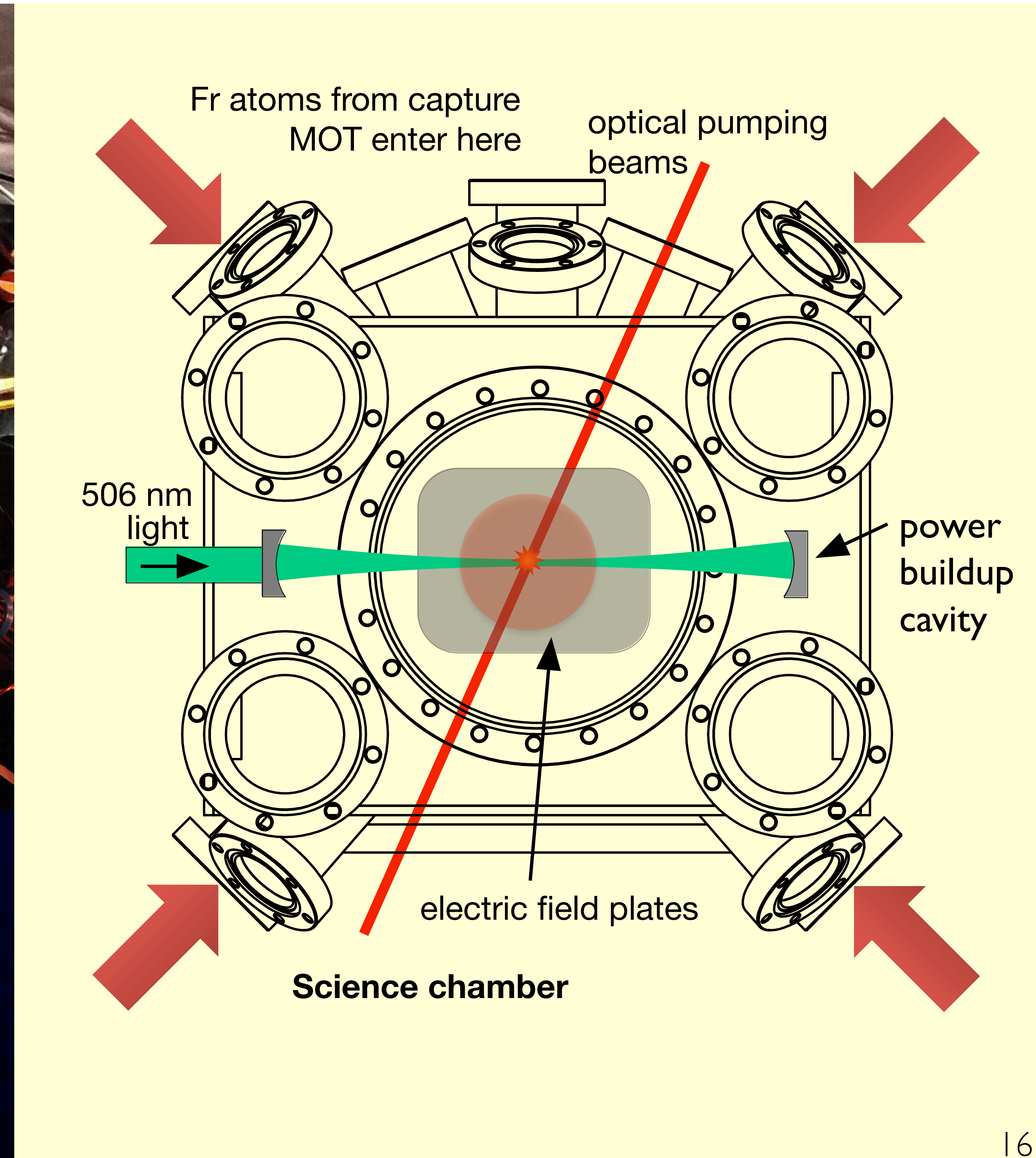
- Observe **interference** (IF) between the Stark-induced & PV amplitudes ($f_{eff} \approx 10^{-16.5}$)
- IF term changes sign under parity transformations (e.g. electric field reversals)
  - modulation of decay fluorescence (in Fr $\approx 10^{-4}$) ➞ extract weak charge of Fr
- $M1$ always present ➞ study and understand $M1$ and $E1_{stark}$ in detail

The Francium Trapping Facility at TRIUMF/ISAC

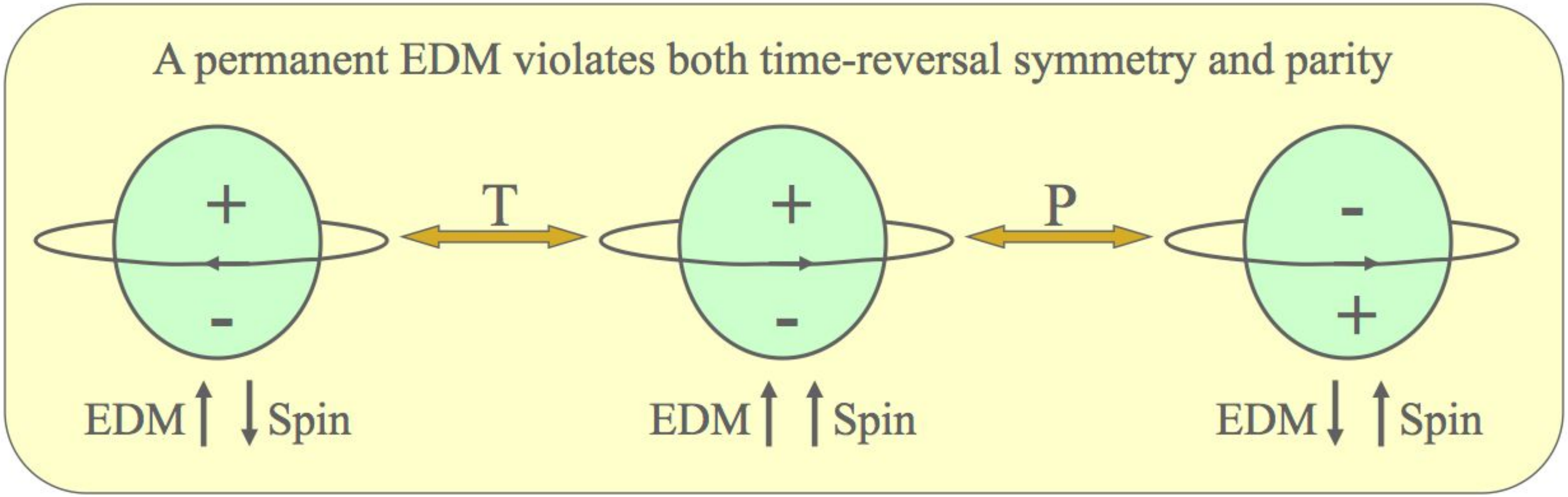
- No stable Fr isotope → need to laser-trap Fr atoms for efficiency ($10^6 - 10^7$ for APV)





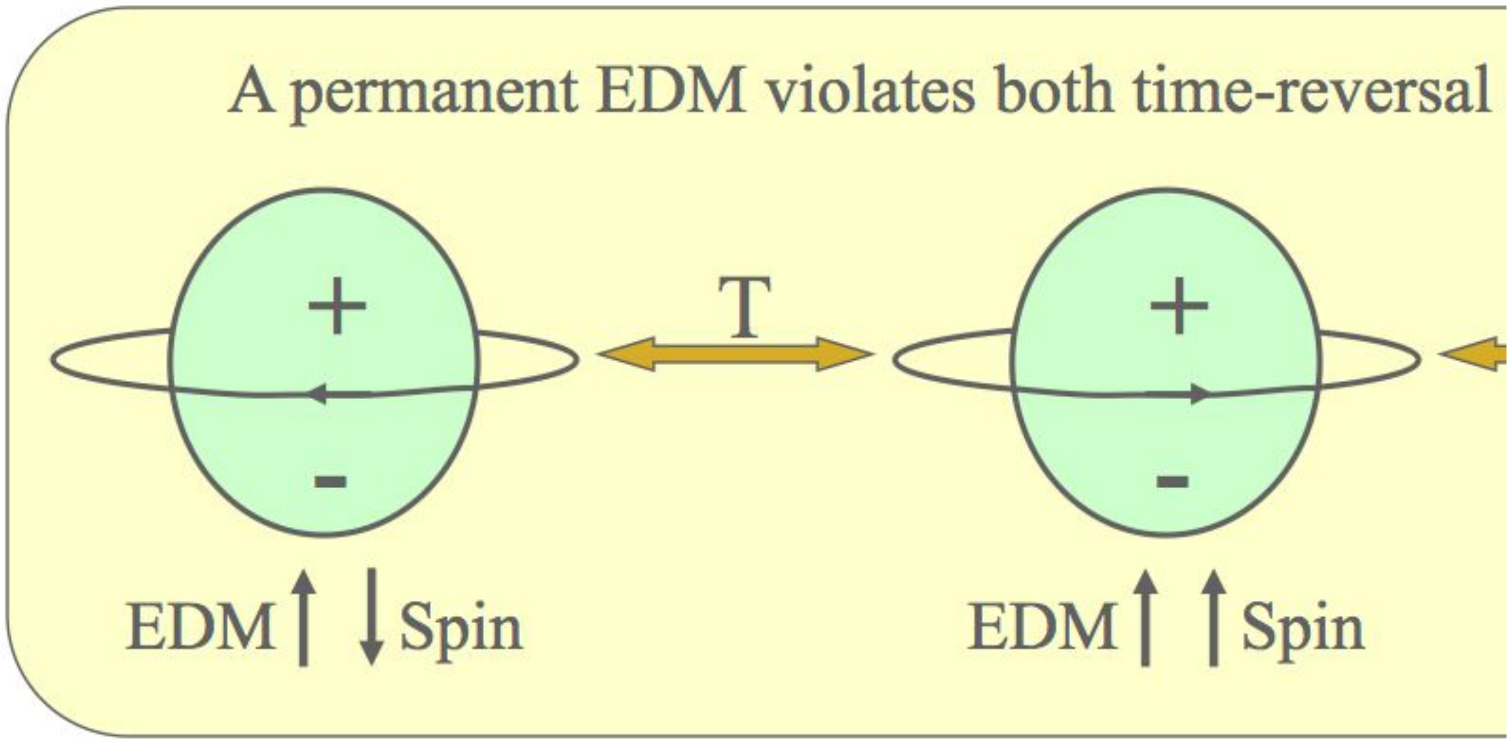


Electric Dipole Moment (EDM) Violates Both P and T



Sector	Exp Limit (e-cm)	Location	Method	Standard Model
Electron	9×10^{-29}	Harvard (ACME)	ThO molecules in a beam	10^{-38}
Neutron	3×10^{-26}	ILL	UCN in a bottle	10^{-31}
Nuclear	7×10^{-30}	U. Washington	^{199}Hg atoms in a cell	10^{-33}

Electric Dipole Moment (EDM) Violates Both P and T



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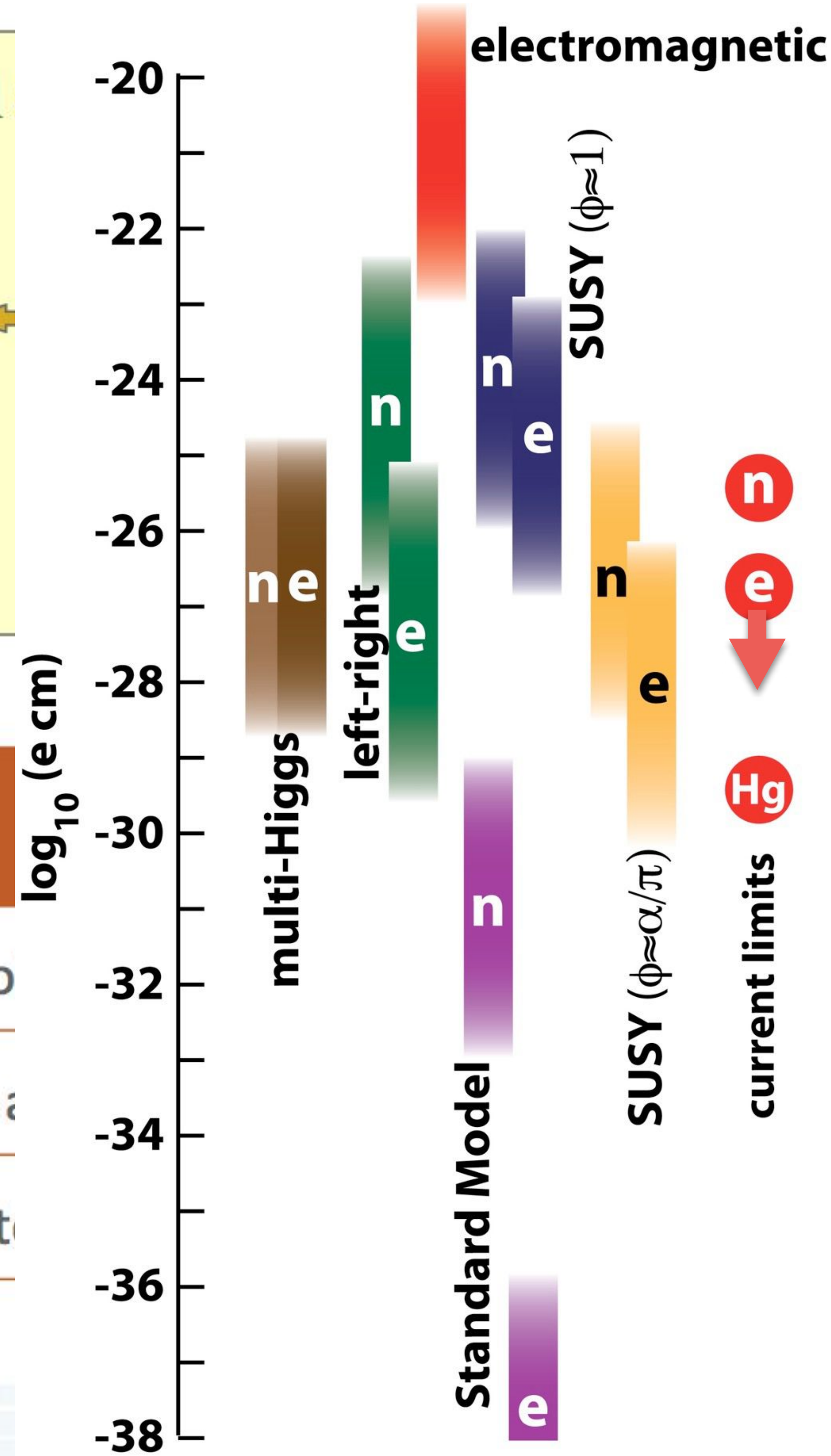
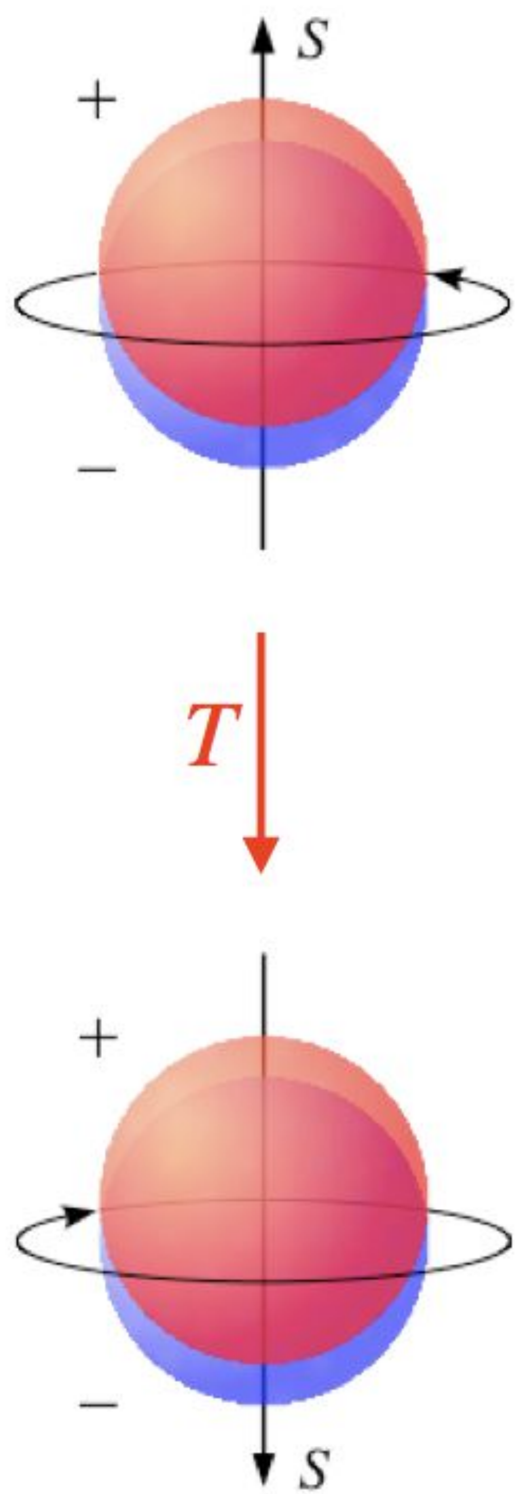
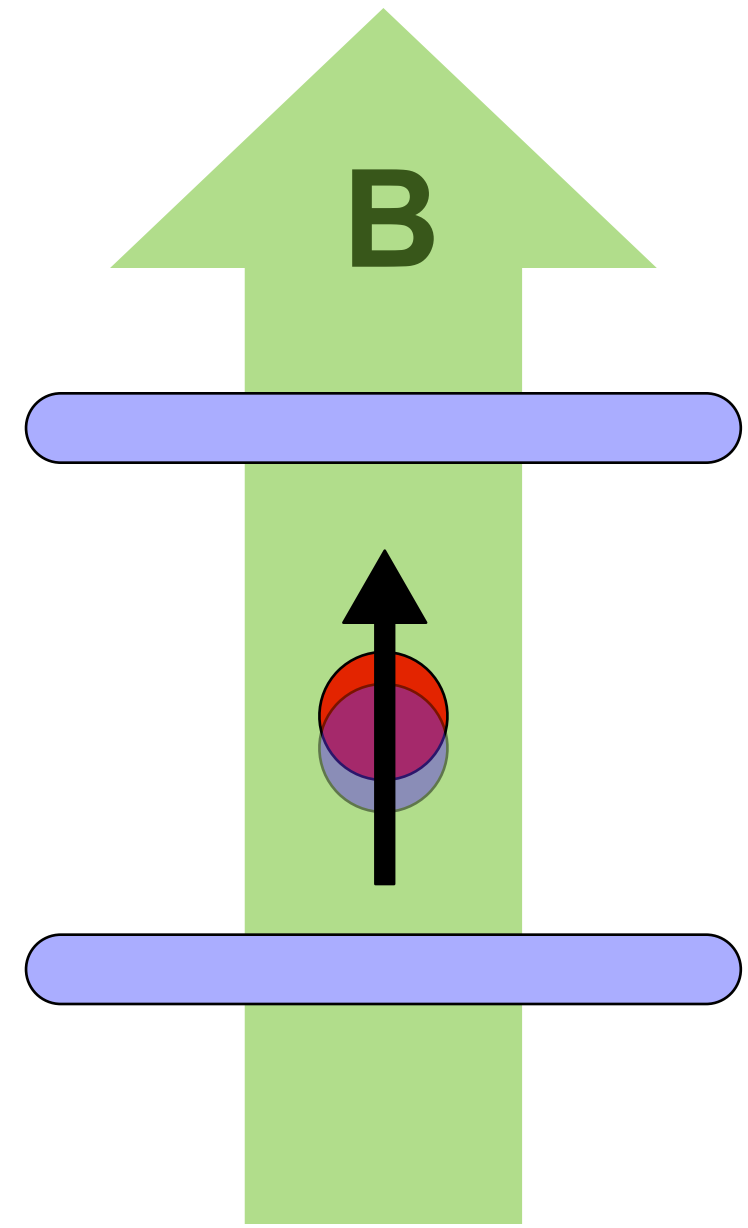


Searches for permanent electric dipole moments



$$W = -\vec{\mu} \cdot \vec{B} \pm \vec{d} \cdot \vec{E}$$



- already know EDMs are tiny
- need largest electric fields → molecules
- nuclear/atomic amplification of EDM effect

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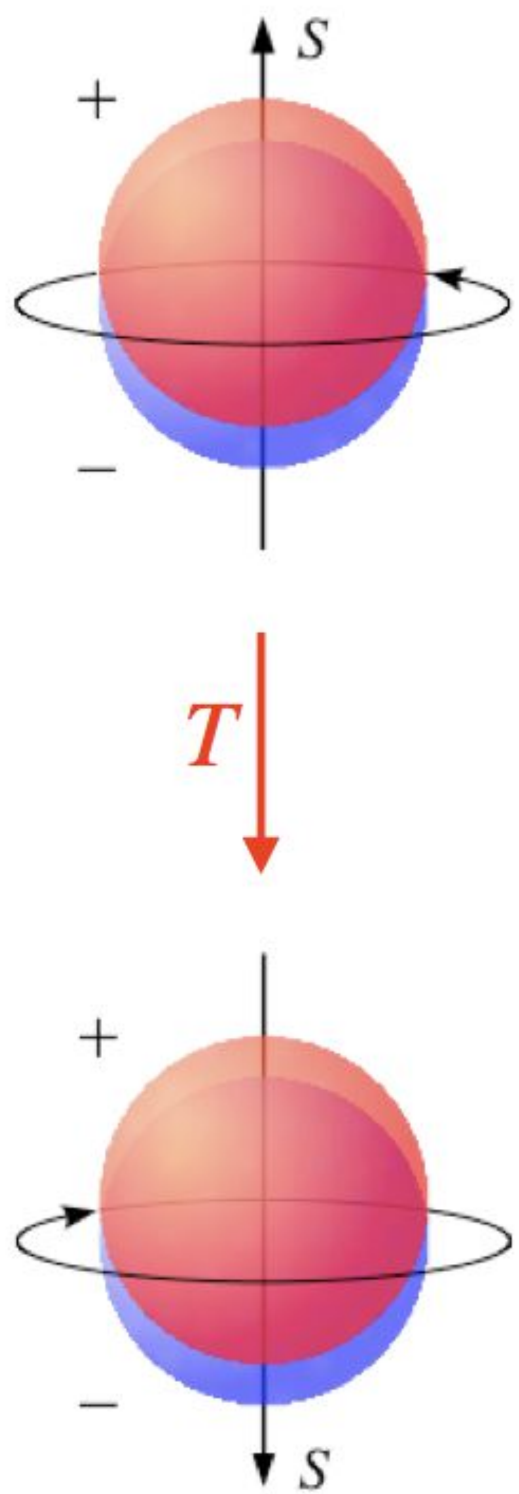

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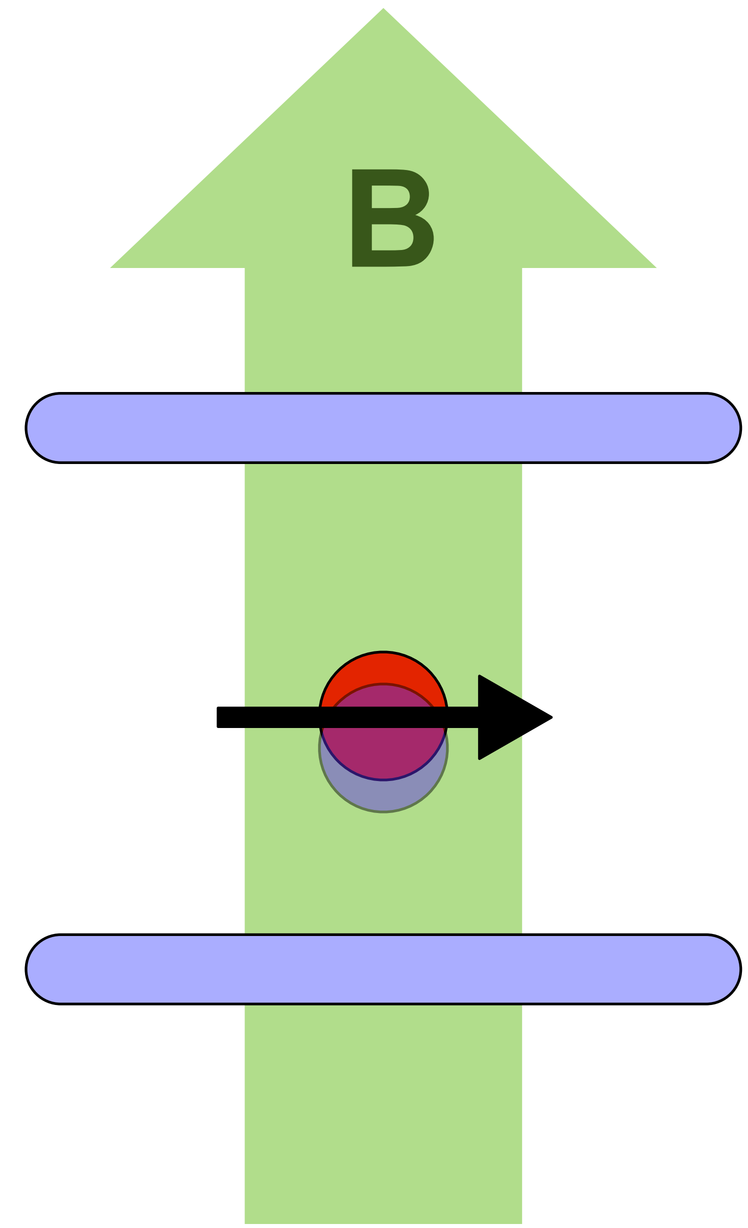

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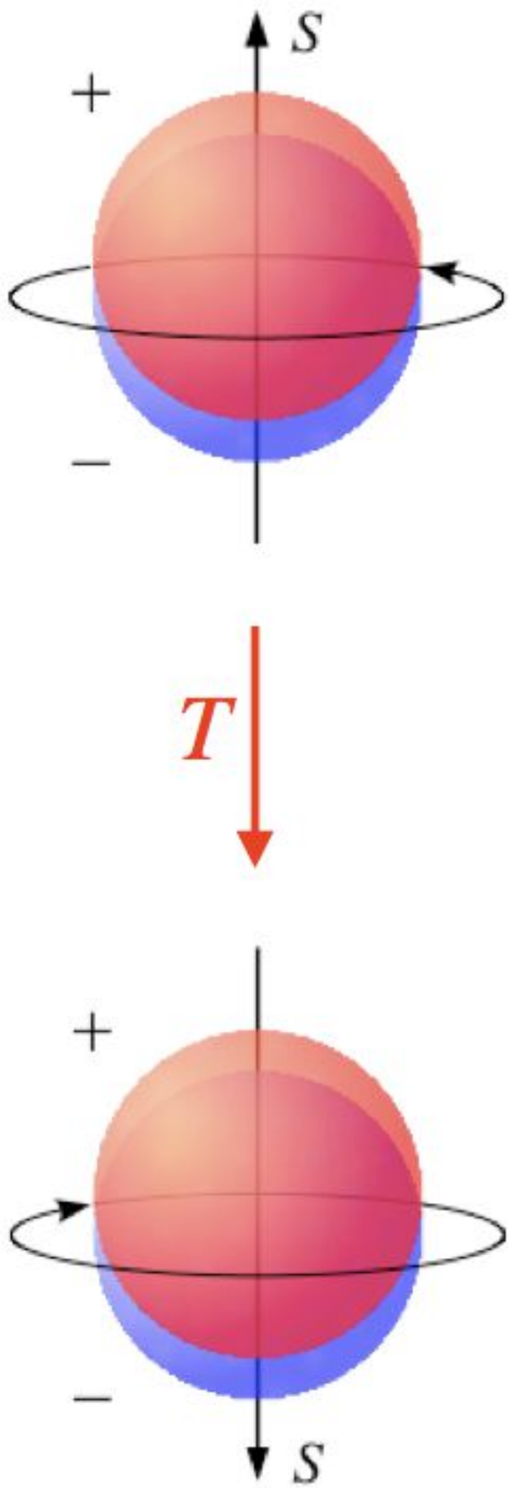

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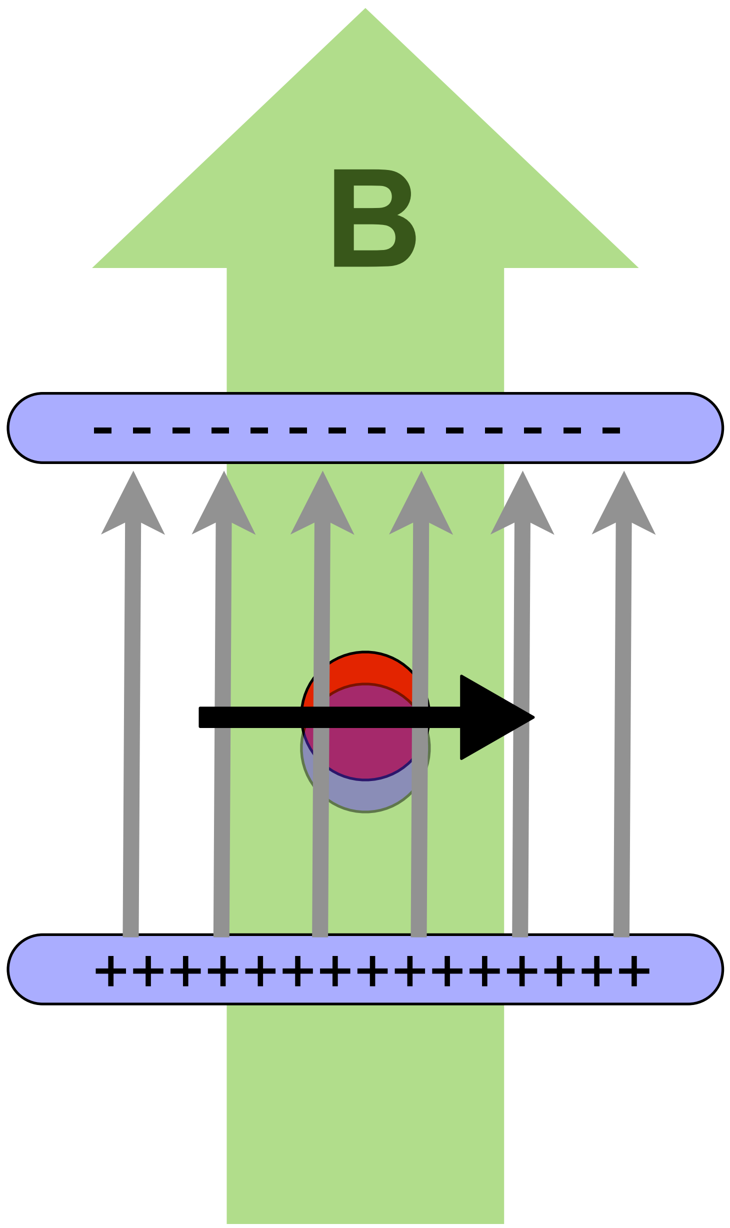

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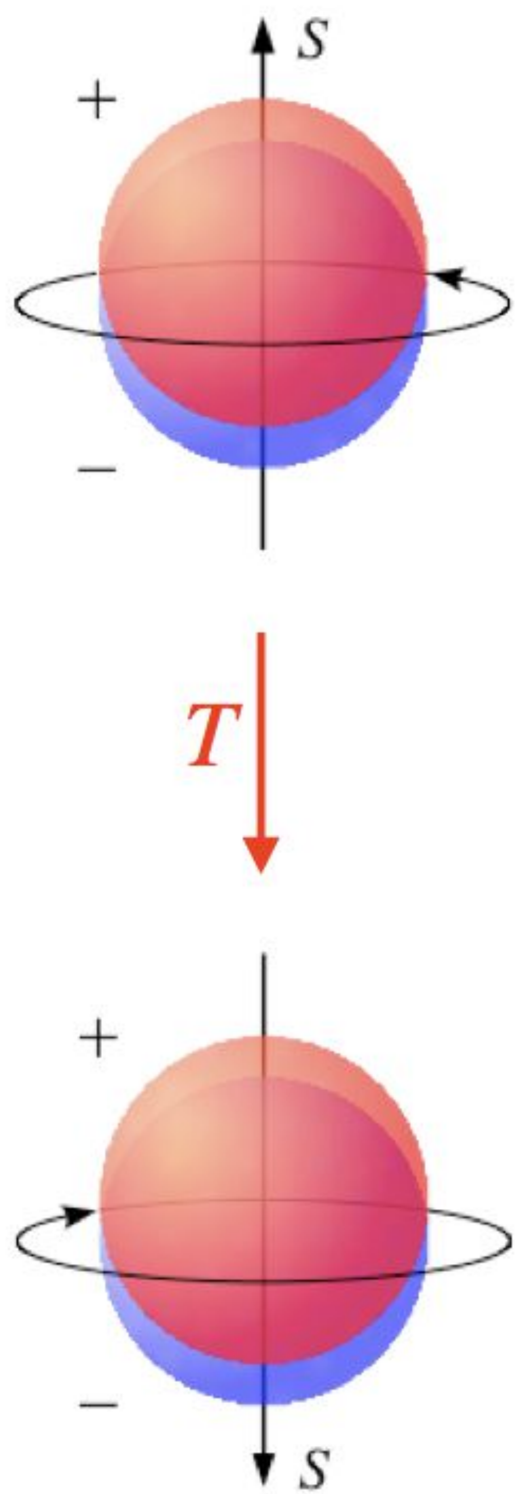

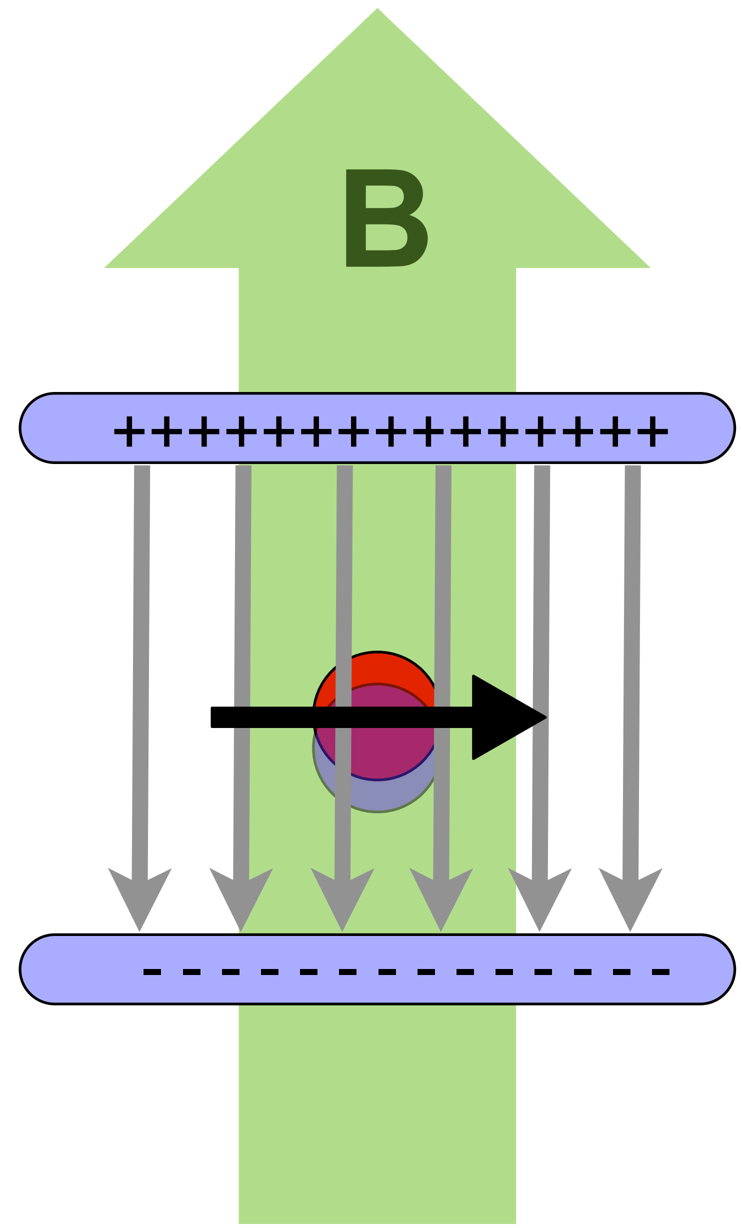

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‘Designer Molecules’

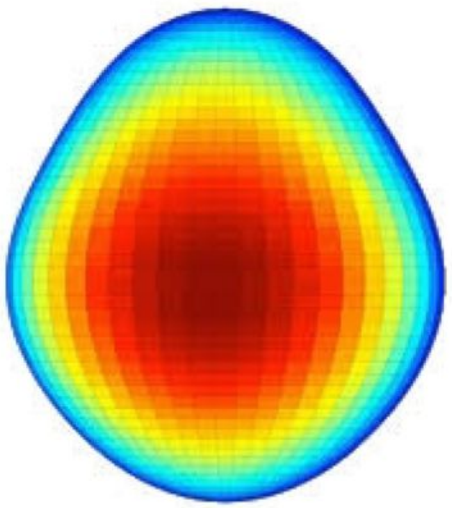
… for searches for time-reversal violation (TV) in atomic nuclei

^{199}Hg present ‘gold standard’ for limit on nuclear Schiff moment

$|d_{Hg}| < 7.4 \cdot 10^{-30}$ e cm (95% confidence limit)

$|S_{Hg}| < 3.1 \cdot 10^{-13}$ e fm^3

B. Graner et al., Phys. Rev. Lett. 116, 161601 (2016)



Enhancement factors in our approach:

- **octupole** deformed nuclide x 100-1,000
- in polar molecule x 1,000-10,000

} compared to ^{199}Hg

- in atom or ion trap x 1,000 compared to beam experiments

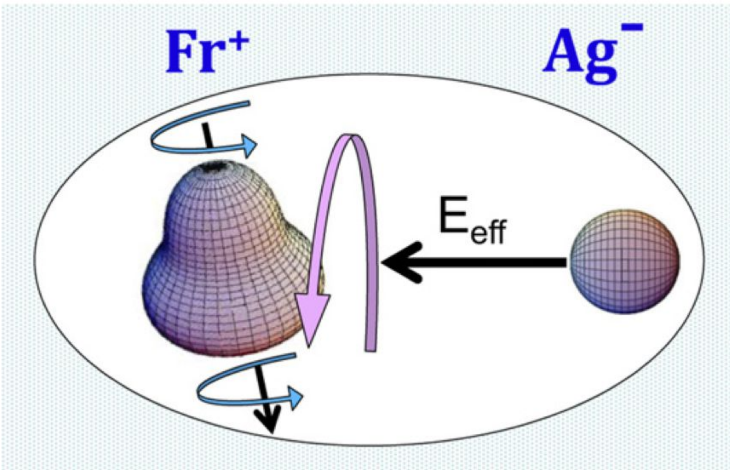
all known cases in radionuclides

Example: ^{223}FrAg

- **intrinsic enhancement of 10^7 compared to ^{199}Hg**

V. V. Flambaum and V. A. Dzuba. Phys. Rev. A 101, 042504 (2020)
T. Fleig. private communications with D. DeMille (2022)

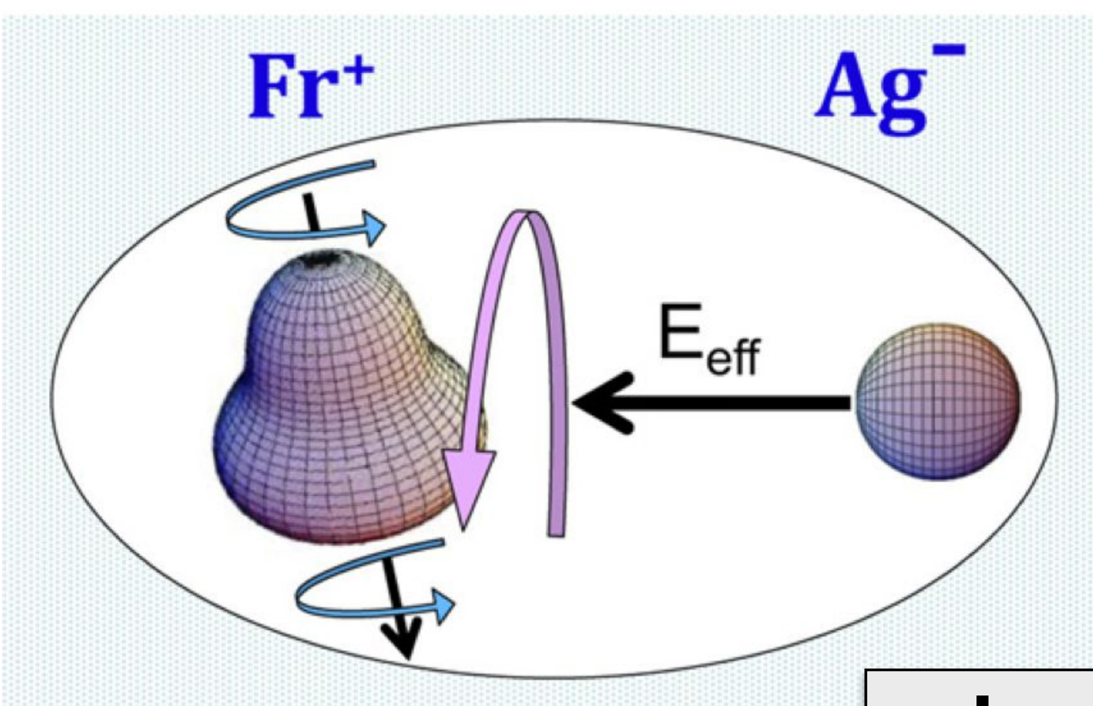
- need to be produced at RIB facility
  ➡ challenge: reduced availability
- **anticipated gain: x 1,000 for certain TV-parameters (comp to ^{199}Hg)**



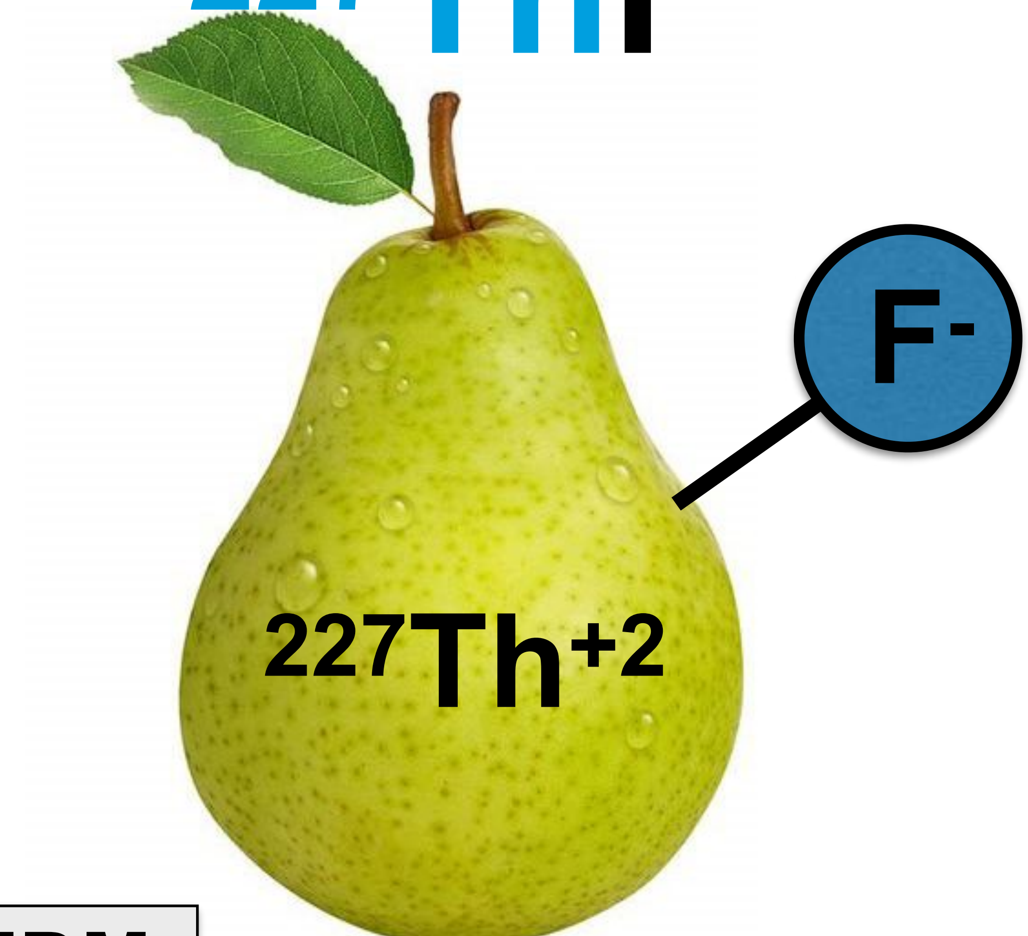
Initial focus:

Precision Experiments on

^{223}FrAg



^{227}ThF^{+}



molecular EDM

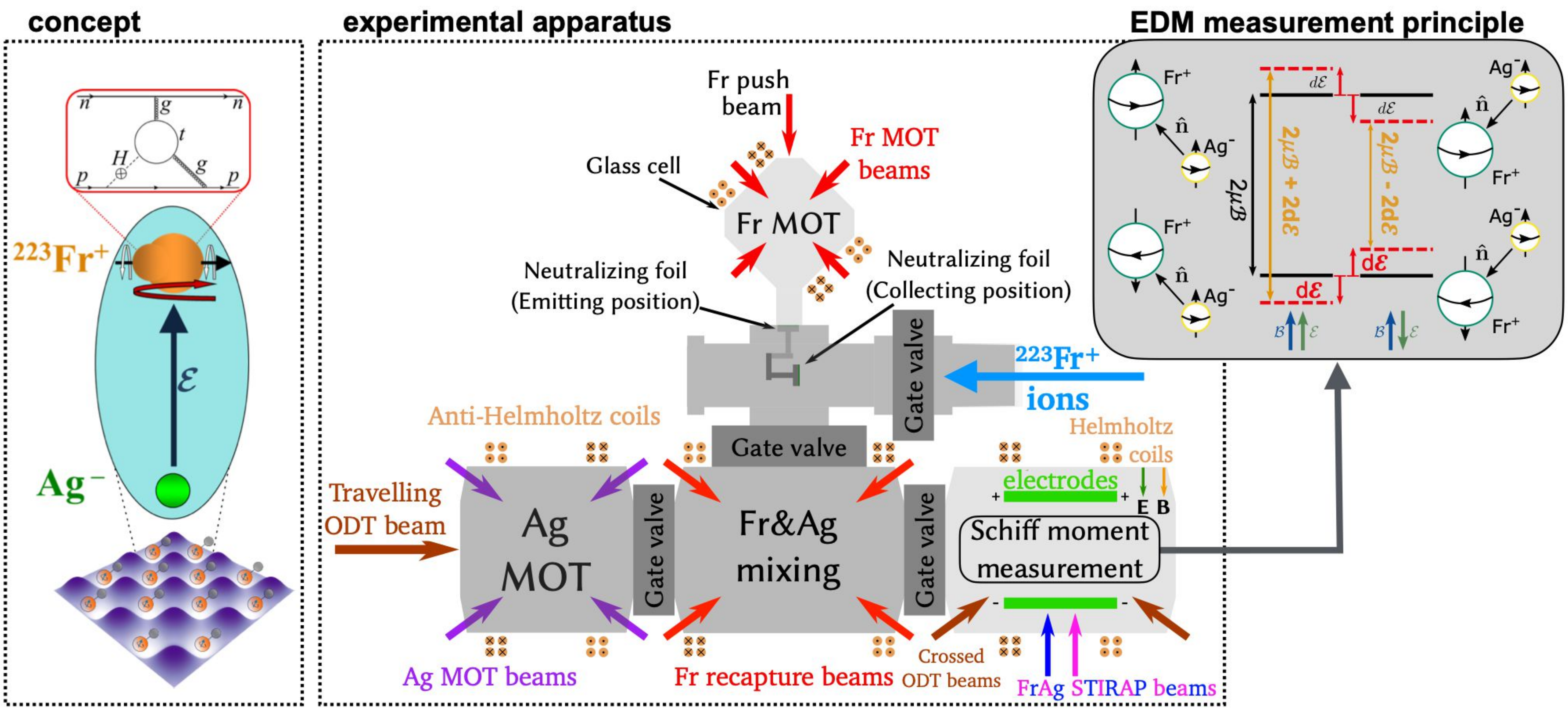
↓

nuclear Schiff moment

↓

new physics

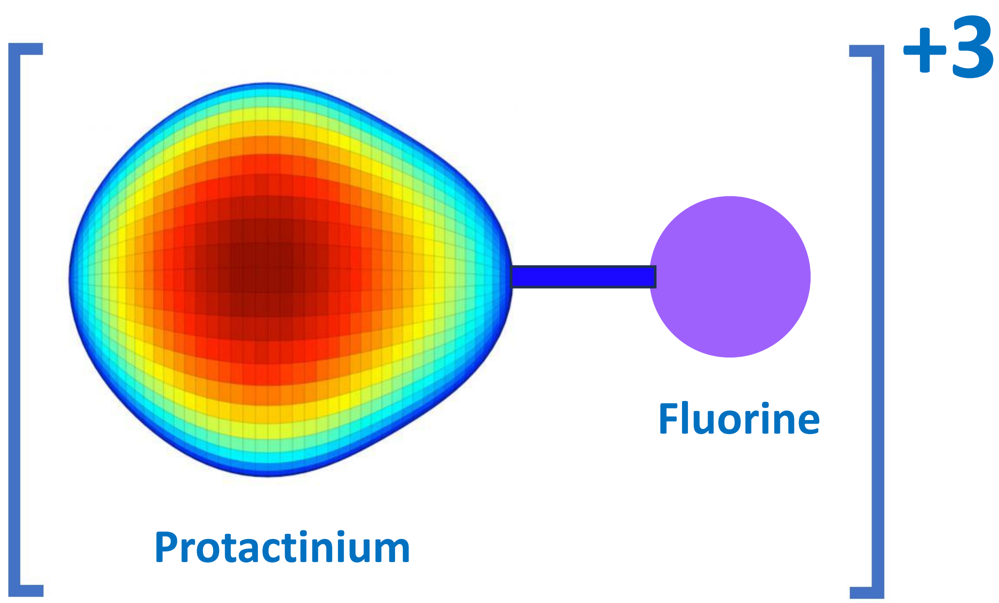
^{223}FrAg experiment

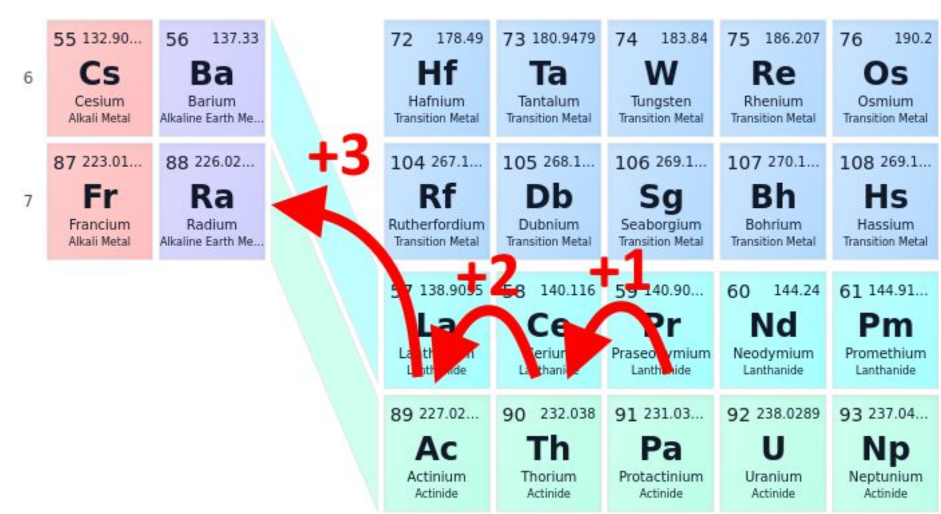


- led by D. DeMille
- benefits from Fr trapping knowhow at TRIUMF/Manitoba
- ^{223}Fr's half-life 23 min
- Vision: ^{227}Ac offline-source based experiment @ JHU
  high-intensity online access + low-intensity offline source @ TRIUMF

‘Highly’ charged radioactive molecules

$^{229}PaF^{3+}$





C. Zülch et al., arXiv 2203.10333 (2022)

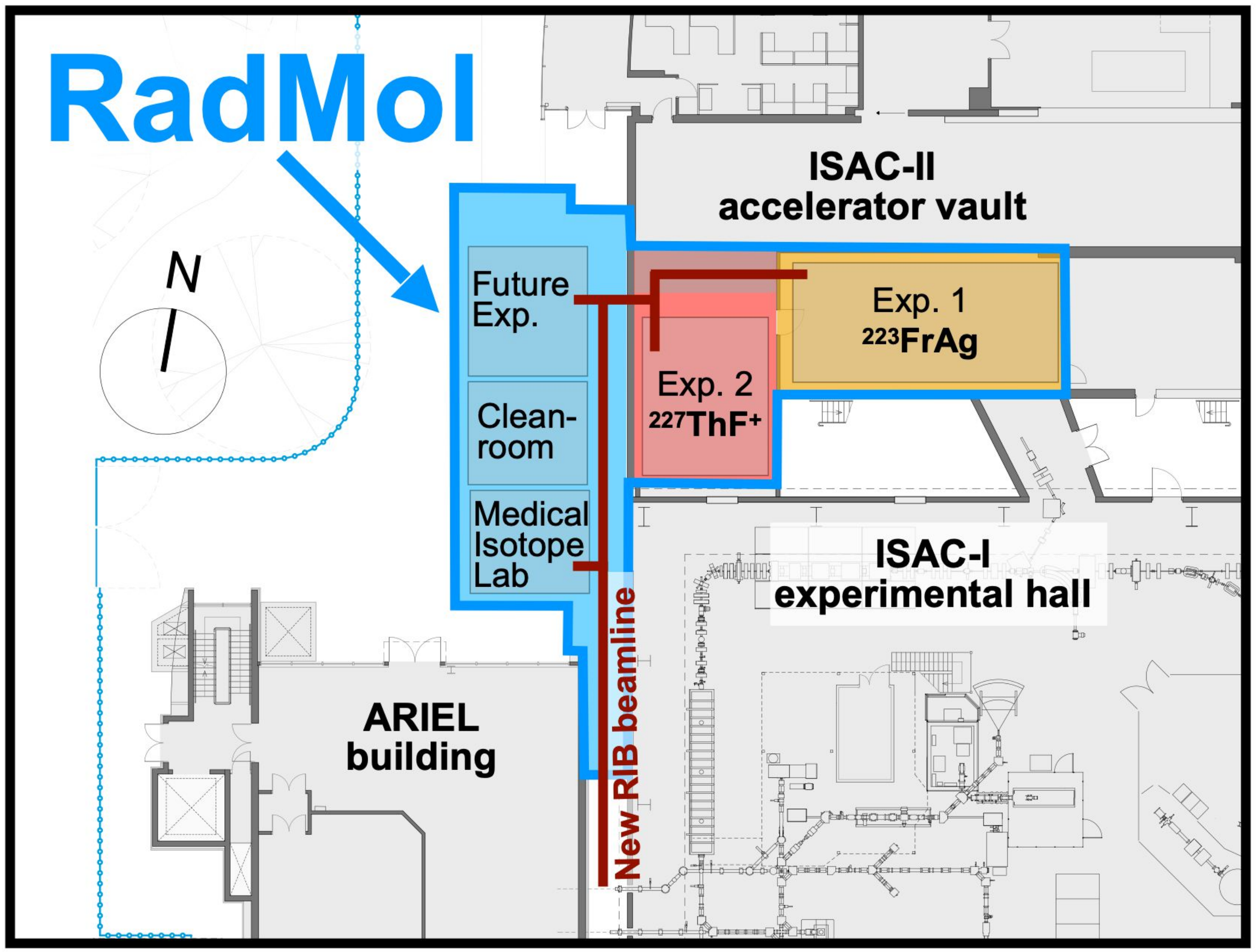
- iso-electronic to (neutral) RaF
- notable sensitivity increase for new physics
- easily trap-able
- potential for direct laser cooling?

Species	Schiff Scaling Factor (relative to ^{225}Ra)
^{225}Ra	:= 1 (~200x larger than 199Hg)
^{229}Th	2
^{227}Ac	6
^{229}Pa	40

other iso-electronic molecules: AcF^{+}, ThF^{+2}

RadMol

a radioactive molecule lab for fundamental physics



Goal:

- dedicated laboratory to study radioactive molecules
- to host multiple experimental stations
- precision studies for searches for new physics
- Molecular EDM with unprecedented sensitivity to nuclear T-breaking Schiff moments using <u>**octupole deformed nuclei**</u>
- provision for expansions into other fields

TRIUMF advantages:

- large variety in radioactive ion beams (RIB)
- high beamtime availability (3 independent RIBs)
- existing laboratory space for large, multi-station program

RadMol Collaboration:

UBC, University of Manitoba, TRIUMF, McGill, The University of Chicago, University of Colorado Boulder, Massachusetts Institute of Technology, Laurier Wilfrid Laurier University, University of Toronto, uOttawa, University of Waterloo, Johns Hopkins University, University of Maryland, Philipps Universität Marburg, Temple University, university of groningen, The University of Edinburgh, University of Guelph, University of Regina

Superallowed beta decay

need for RIB: obvious

From equation IV.25

$$\frac{1}{\tau} = (\text{universal constant}) |\mathcal{M}|^2 F(Z, \eta_0)$$

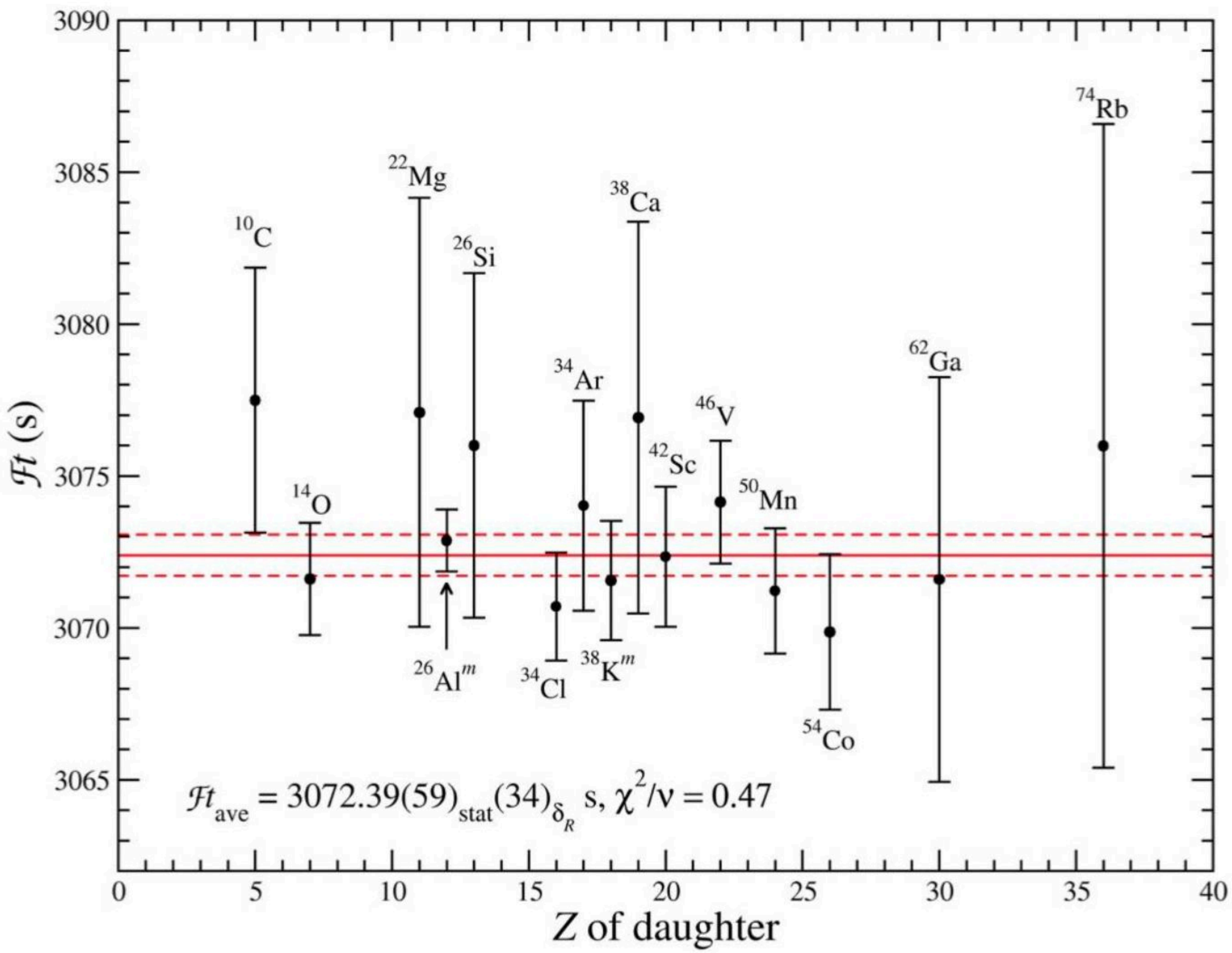
Therefore

$$F\tau = \frac{\text{constant}}{|\mathcal{M}|^2}$$

straight from the source

Fermi, *Nuclear Physics*

"**1**" for superallowed ($0^+ \to 0^+$) decays



- $0^+ \to 0^+$: strength of charged weak interaction in nuclei
- compare to leptonic (e.g. muon decay)
  - conserved vector current hypothesis (CVC)
- test weak interaction universality
  - unitarity of the Cabibbo–Kobayashi–Maskawa matrix

CVC and CKM

- if it were only that easy

$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{\mathrm{NS}}-\delta_C) = \frac{K}{2G_V^2\left(1+\Delta_R^V\right)}$$

Q-value

measure lifetime and branching ratio

we want to test this

- lifetimes
- branching ratios
- Q-values

- for as many decays over widest range of Z

- ISAC/ARIEL: record number of superallowed β emitters
- lifetimes and branching ratios:
    - 4π gas proportional counter GPS
    - gamma detector array GRIFFIN
- Q values
    - TITAN ion trap facility (parent, daughter mass measurements)
- nuclear charge radius
    - collinear spectroscopy (e.g. ^{74}Rb)
    - laser trapping (^{38m}K)

Cabibbo–Kobayashi–Maskawa matrix

weak eigenstates

should be **unitary** for 3 generation

mass eigenstates

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

$$|V_{\mathrm{ud}}|^2 + |V_{\mathrm{us}}|^2 + |V_{\mathrm{ub}}|^2 = .999997 \pm .0007$$

2023 update

Rev. of Particle Physics

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97435 \pm 0.00016 & 0.22500 \pm 0.00067 & 0.00369 \pm 0.00011 \\ 0.22486 \pm 0.00067 & 0.97349 \pm 0.00016 & 0.04182^{+0.00085}_{-0.00074} \\ 0.00857^{+0.00020}_{-0.00018} & 0.04110^{+0.00083}_{-0.00072} & 0.999118^{+0.000031}_{-0.000036} \end{bmatrix}$$

Improved measurement of ^{38m}K $\langle r^2_{ch} \rangle$ for V_{ud} corrections

J.A. Behr, L. Haddad, F. Klose, B. Ohayon, B.K. Sahoo

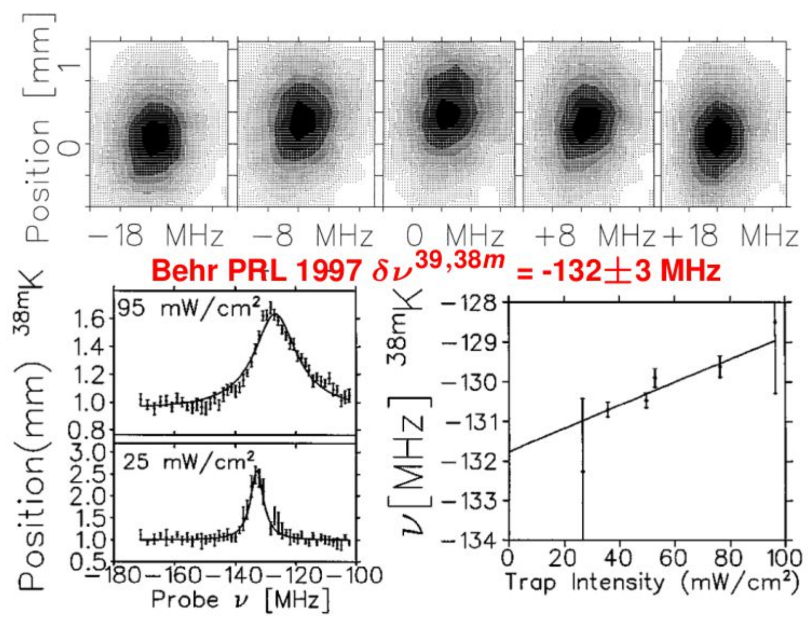
Isospin breaking of β decay ψ_i and ψ_f can be related to triplets of isobaric charge radii Seng, Gorchtein Phys Lett B 2023

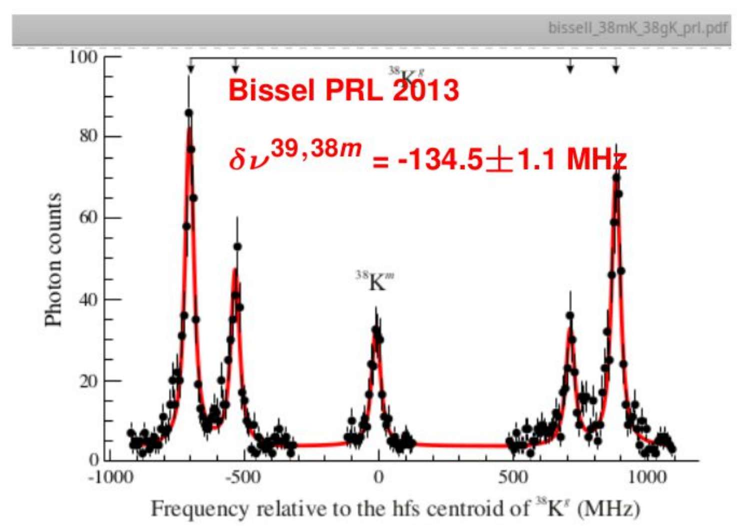
Only triplet with $\langle r^2_{charge} \rangle^{\frac{1}{2}}$ known is A=38:
^{38}Ca 3.467(1) fm,
^{38m}K 3.437(4) fm,
^{38}Ar 3.4028(19) fm

$\Rightarrow \Delta M_B^{(1)}$ = -0.03(54) fm^2;
models span 0.42 to 0.04 fm^2

Needs order of magnitude better $\langle r^2_{charge} \rangle^{\frac{1}{2}}$!

4S→4P$_{1/2}$ Γ=6 MHz



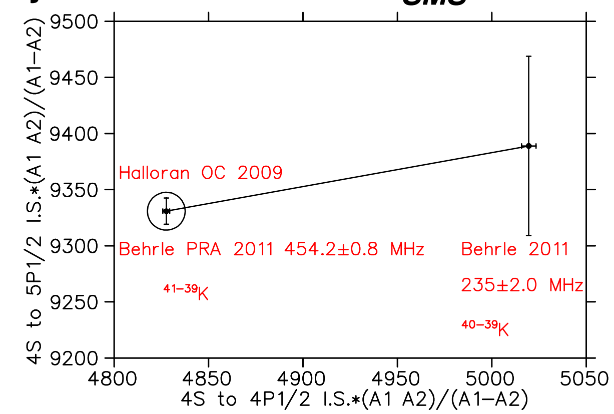


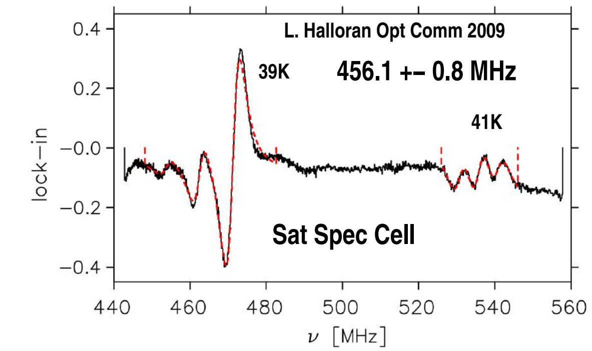
ISOLDE did much better

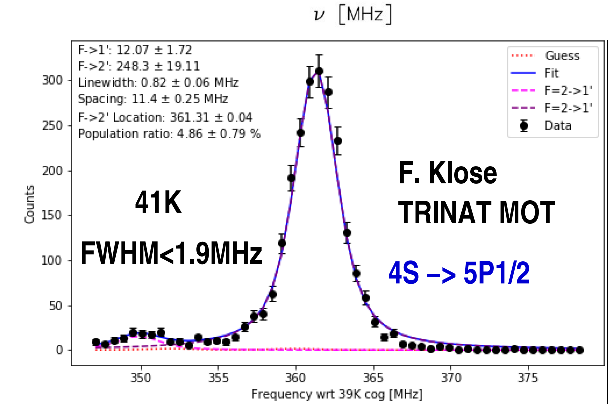
4S$_{1/2}$ → 5P$_{1/2}$: Γ = 1.1 MHz

for 0.1 MHz accuracy?

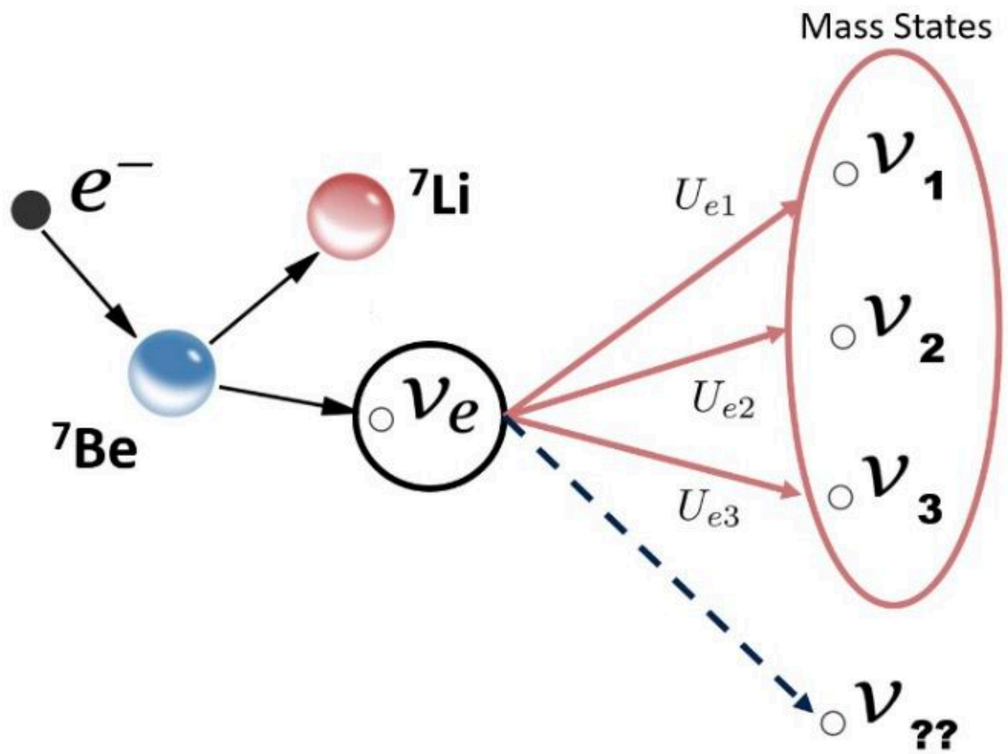
Katyal 2412.05921 RCC K_{SMS}=-30.6±5.2

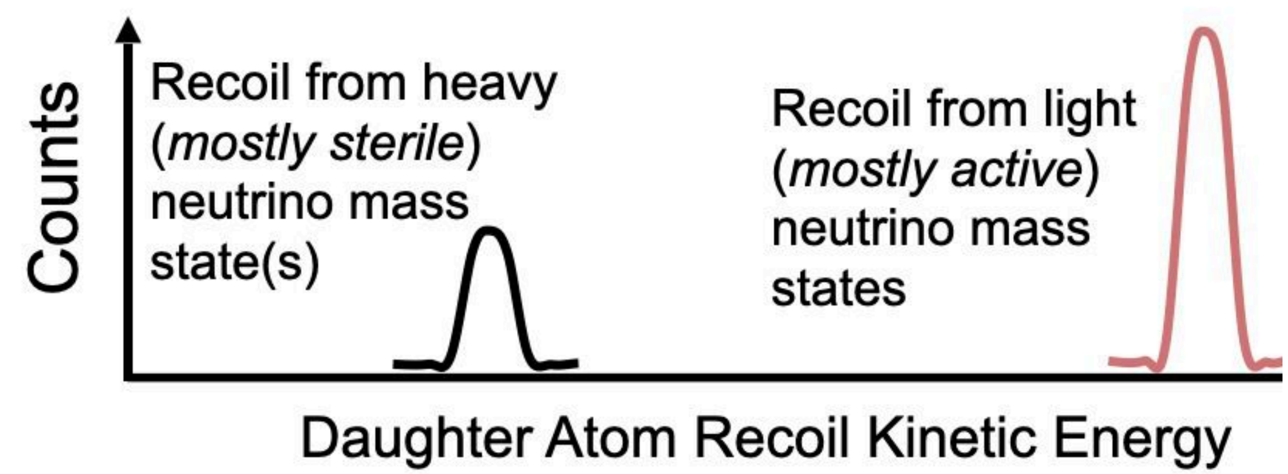






BeEST: The search for sterile neutrinos





Pontecorvo–Maki–Nakagawa–Sakata matrix

neutrino cousin of CKM

$$\begin{pmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}|e^{i\delta_{\mu 1}} & |U_{\mu 2}|e^{i\delta_{\mu 2}} & |U_{\mu 3}| \\ |U_{\tau 1}|e^{i\delta_{\tau 1}} & |U_{\tau 2}|e^{i\delta_{\tau 2}} & |U_{\tau 3}| \end{pmatrix}$$

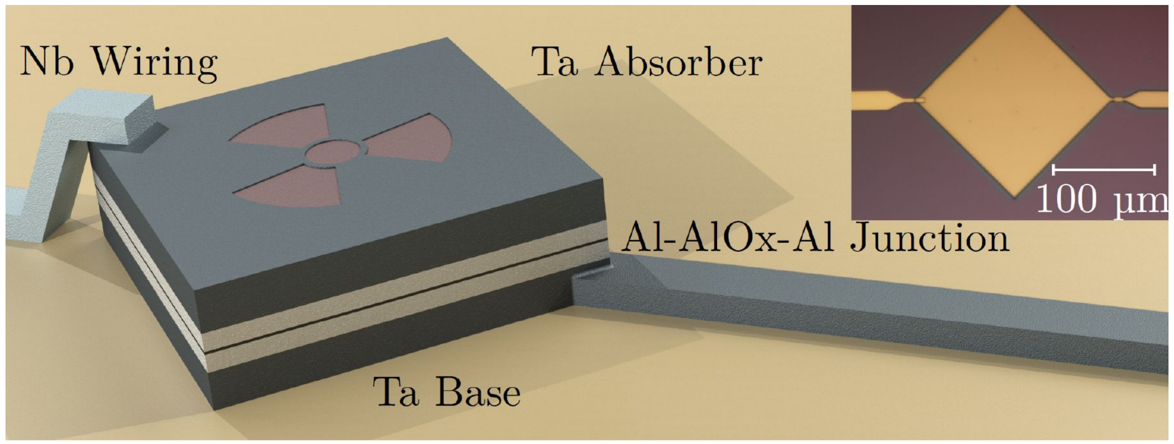
transforms between neutrino mass and weak eigenstates

expand to (almost) sterile neutrino → 4x4

need for RIB: obvious

Superconducting Tunnel Junctions (STJs) – Working Principle

High-precision energy-resolving sensor → Direct Cooper pair breaking and QP generation

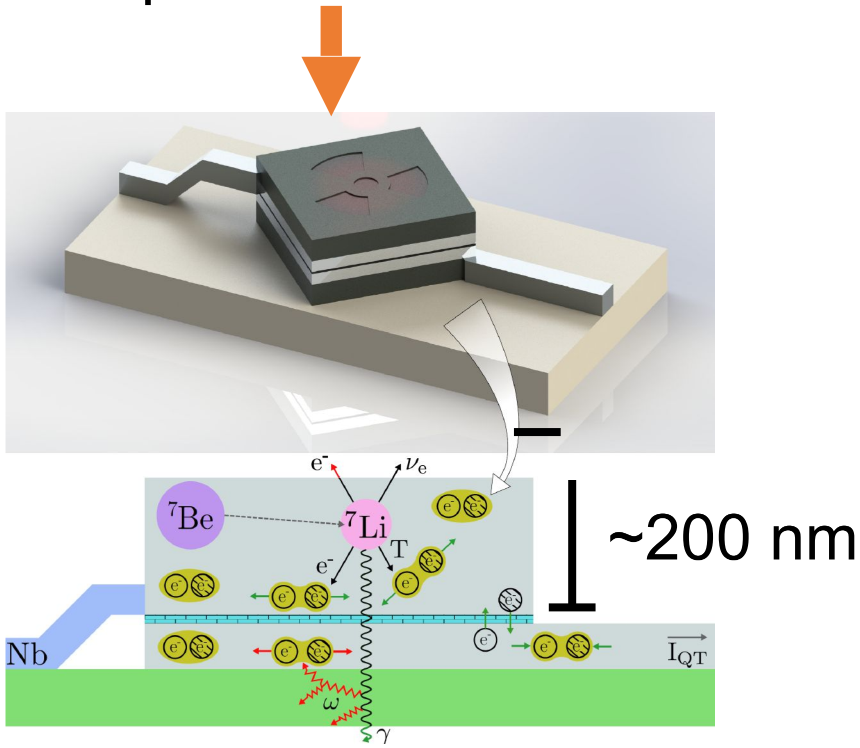


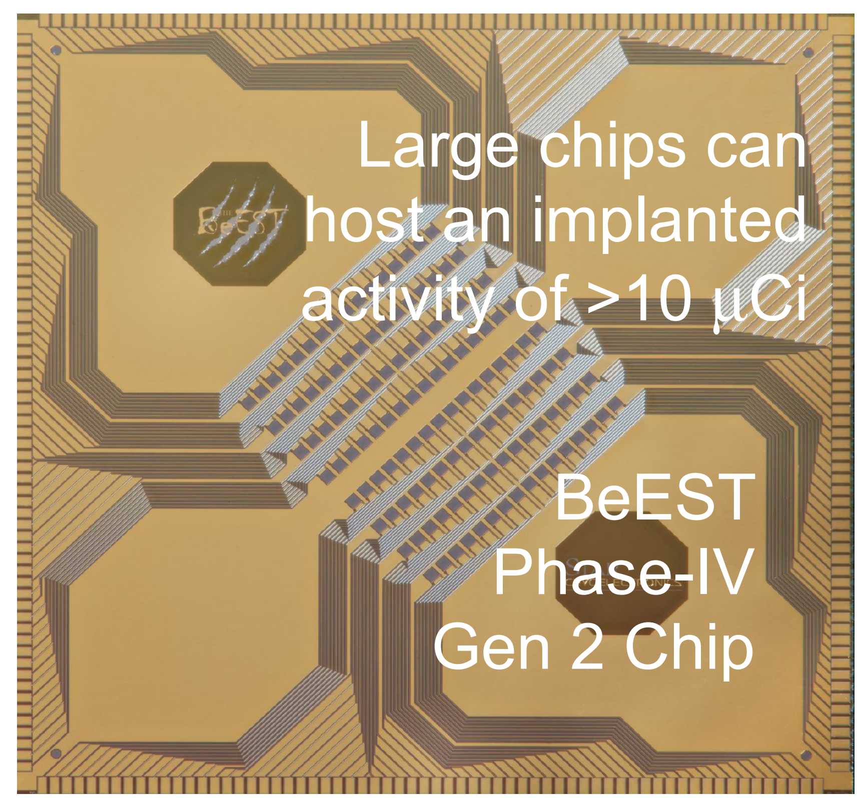
S. Fretwell et al., Phys. Rev. Lett. **125**, 032701 (2020)

- Superconductor-Insulator-Superconductor

  "Josephson junction"
- "Cryogenic-charge" sensors
- Operation at temperatures <0.1 K
- Ta, Nb, and Al STJs

Rare Isotope Beam Implantation



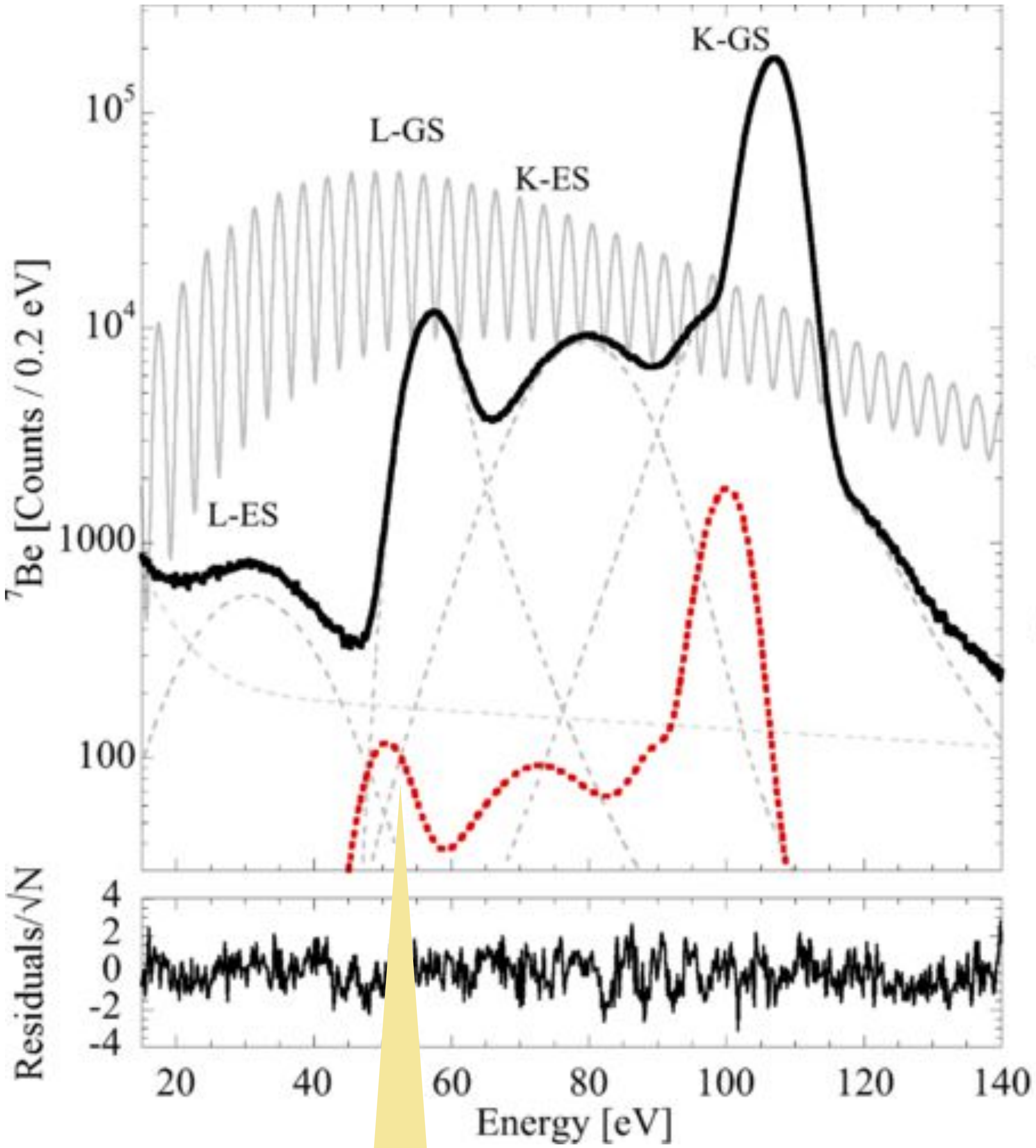


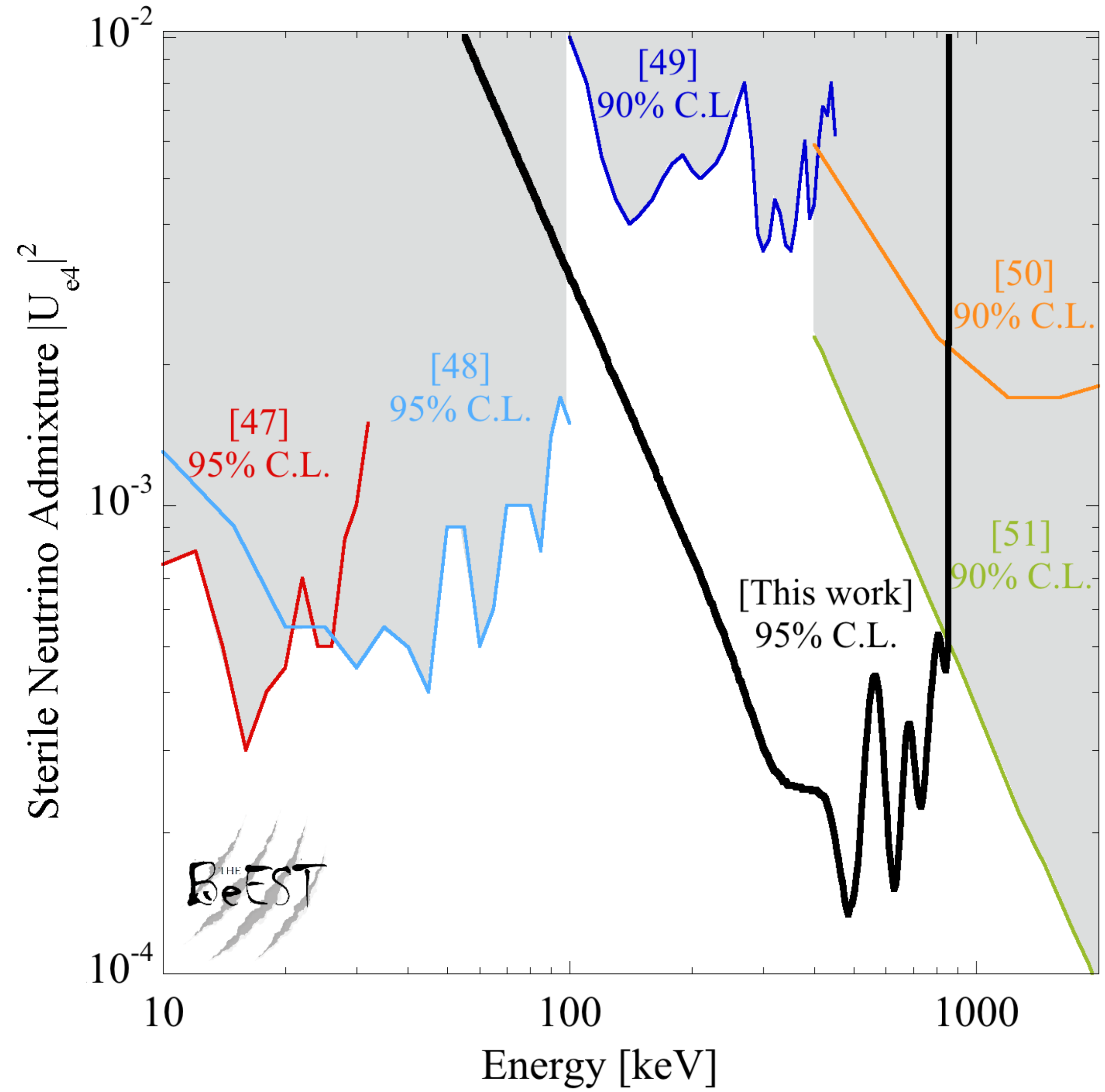
Slide from K. Leach

Searching for Heavy Neutrinos in the BeEST Data

new limits ***on the existence of sterile neutrinos in the*** ***mass range of 100-800 keV***

BeEST Collaboration, PRL **126**, 021803 (2021)





- heavy sterile neutrino admixture shifts recoil spectrum left
- example: 300 keV neutrino @ 1% admixture

FunSymmers get very attached to their cause

"He’s all right. Just don’t mention proton decay."

— Thomas Harris, The Silence of the Lambs (book, not movie)