Tests of Time Reversal Violation in *atomic* and *nuclear* physics

(The TRImP facility nearing its completion)

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Contents

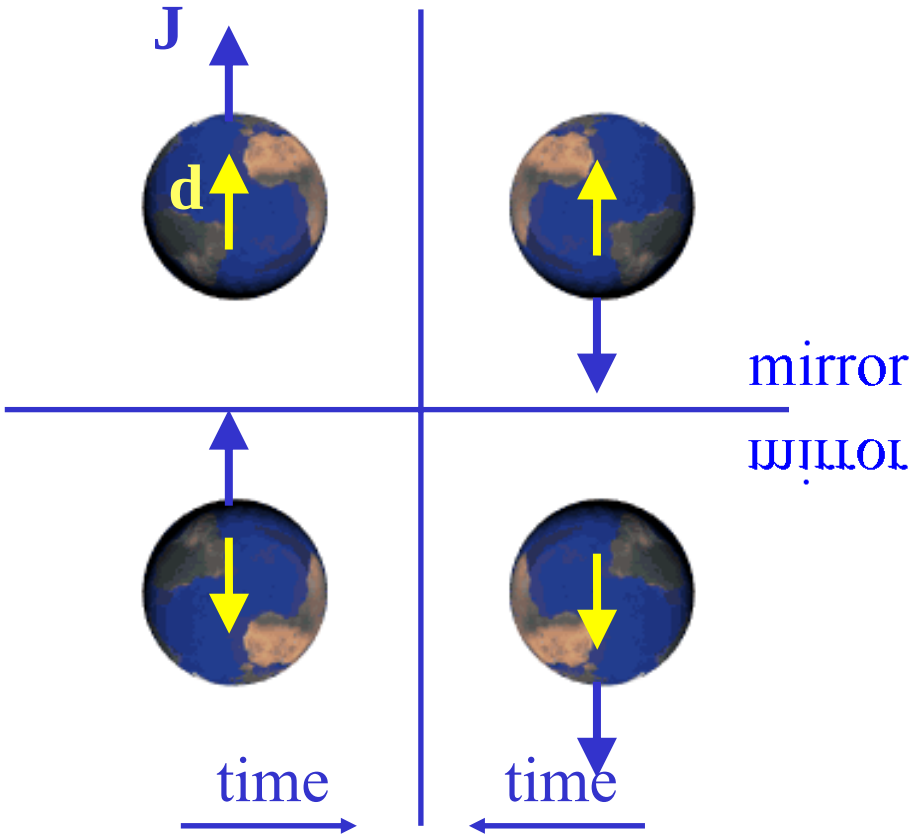
- What can nuclear and atomic physics contribute to TRV search
- EDM $\leftrightarrow$ other (nuclear/atomic) searches
- Role of (degenerate) opposite parity states
- Role of atomic trapping
- TRImP
- Outlook

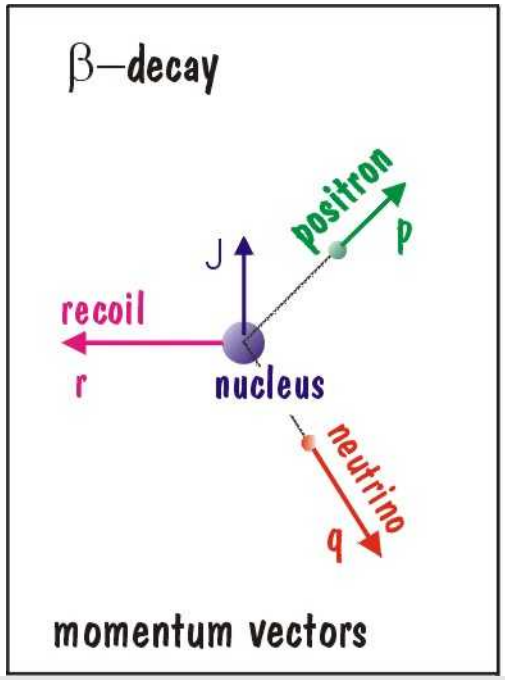
Role of Nuclear Physics

other searches

in nuclear and atomic physics

TRV beyond the standard model





$$\langle \vec{J} \cdot \vec{p} \times \vec{q} \rangle \neq 0 \ ?$$

Electric dipole moment (EDM)
violates parity and time reversal

if ≠ 0 then TRV

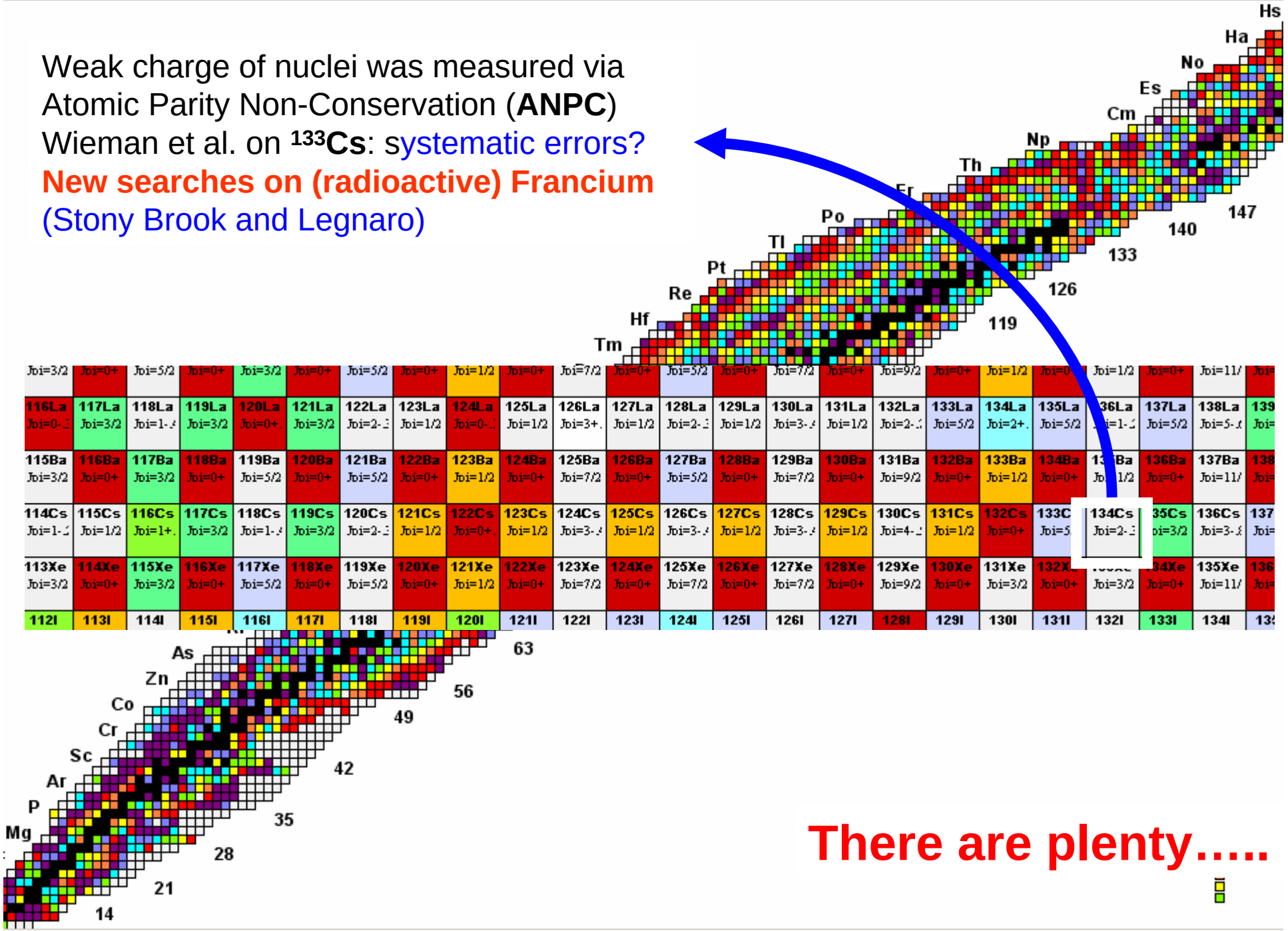
any particle will do: including **radioactive nuclei**

Weak charge of nuclei was measured via Atomic Parity Non-Conservation (**ANPC**)

Wieman et al. on ^{133}**Cs**: systematic errors?

New searches on (radioactive) Francium

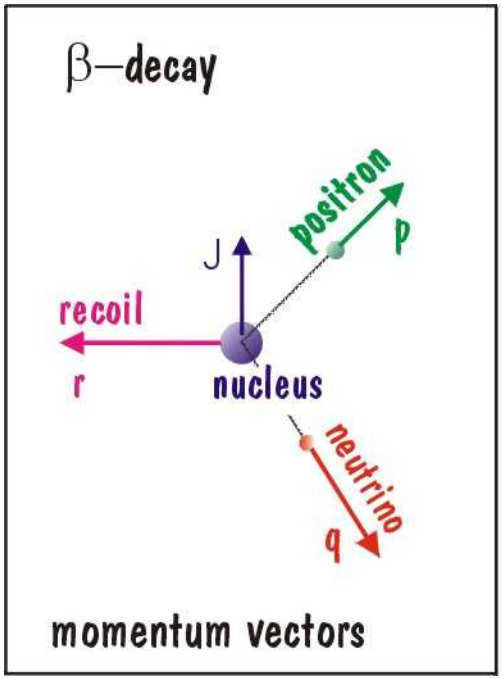
(Stony Brook and Legnaro)



There are plenty…..

β-decay and new physics

$$\frac{\mathrm{d}^2W}{\mathrm{d}\Omega_e \mathrm{d}\Omega_\nu} \sim 1 + a\frac{\boldsymbol{p}\cdot\hat{\boldsymbol{q}}}{E} + b\Gamma\frac{m_e}{E} + \langle \boldsymbol{J}\rangle \cdot \left[A\frac{\boldsymbol{p}}{E} + B\,\hat{\boldsymbol{q}} + D\frac{\boldsymbol{p}\times\hat{\boldsymbol{q}}}{E}\right] + \langle \boldsymbol{\sigma}\rangle \cdot \left[G\frac{\boldsymbol{p}}{E} + Q\langle \boldsymbol{J}\rangle + R\langle \boldsymbol{J}\rangle \times \frac{\boldsymbol{p}}{E}\right]$$

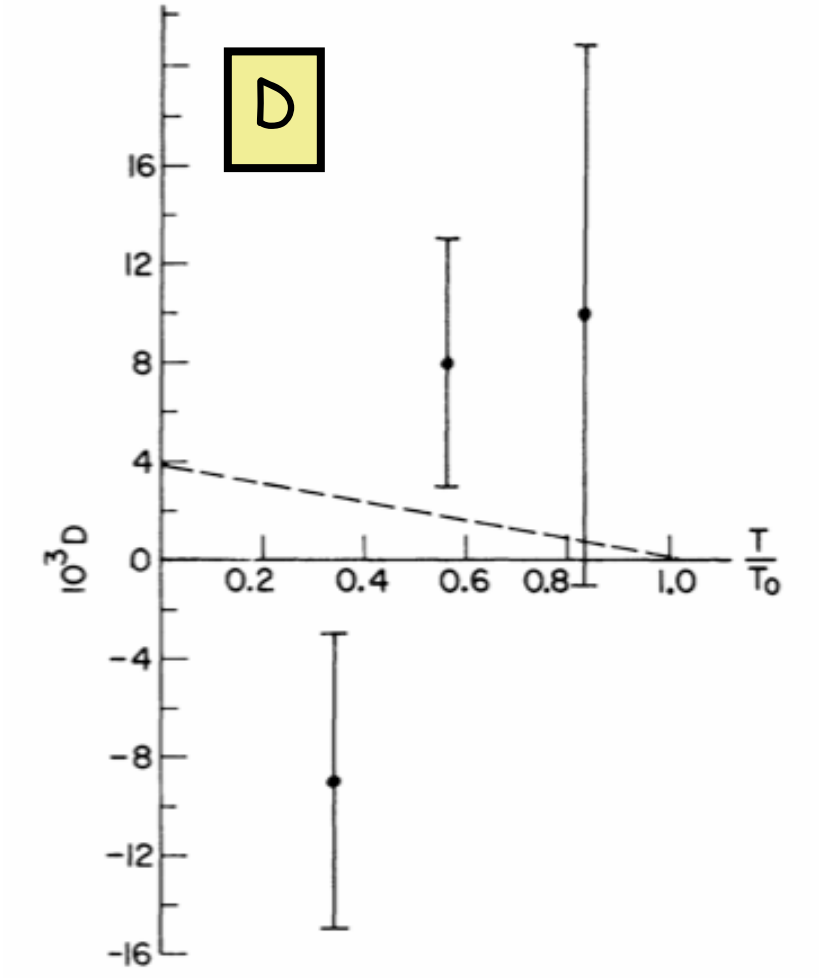


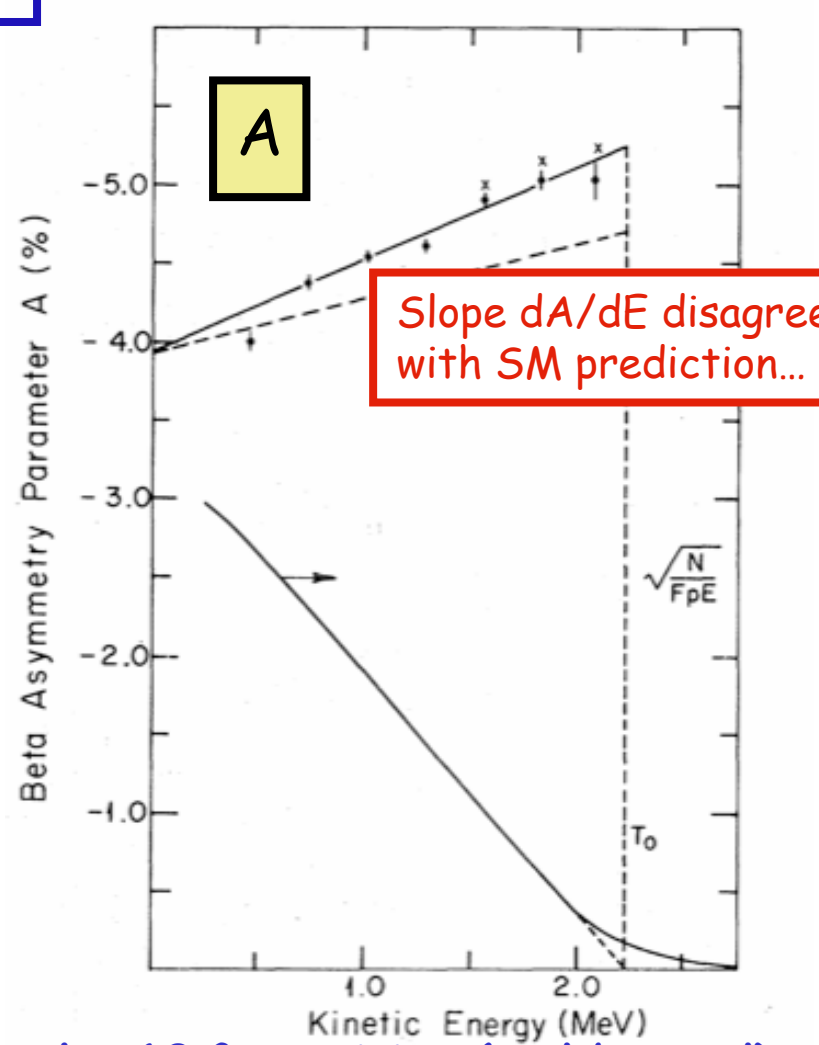
- β-decay rate $V_{ud} \rightarrow V_{us}$ (see NuPAC W. Marciano)
- Correlation *a…R* search for BSM in nuclear β-decay

  (e.g. P. Herczeg Prog. Part. Nucl. Phys. 46(2001)413)
- *D* (TRV) has most potential, complementary to EDM search

  (probes lepto quark exchange)
- same aims in neutron decay

Princeton expt's on $^{19}Ne \rightarrow {}^{19}F + e^{+} + \nu_e$





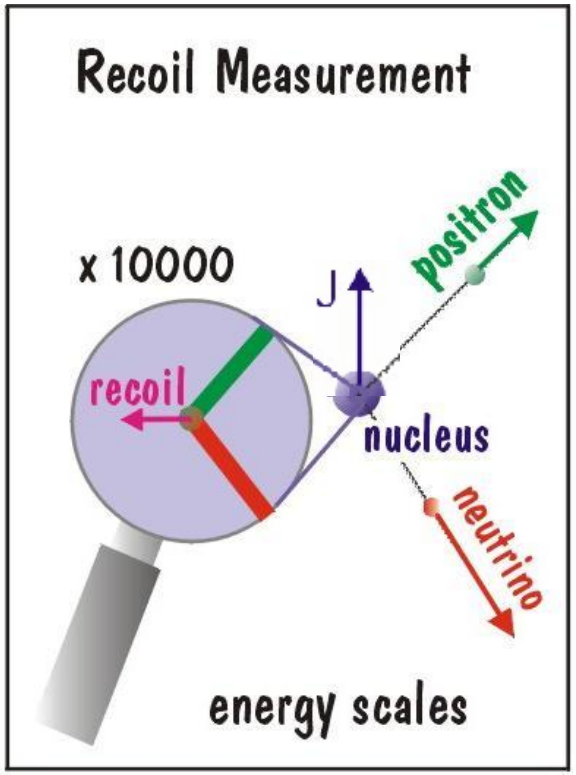
Slope dA/dE disagrees with SM prediction…

"To move correlation measurements into the 10^{-3} precision (and beyond), it is essential to obtain correlations differentiated in angle and momentum"

Role of Atomic Physics

Degenerate opposite parity states
in nuclear and atomic physics

The role of atomic trapping

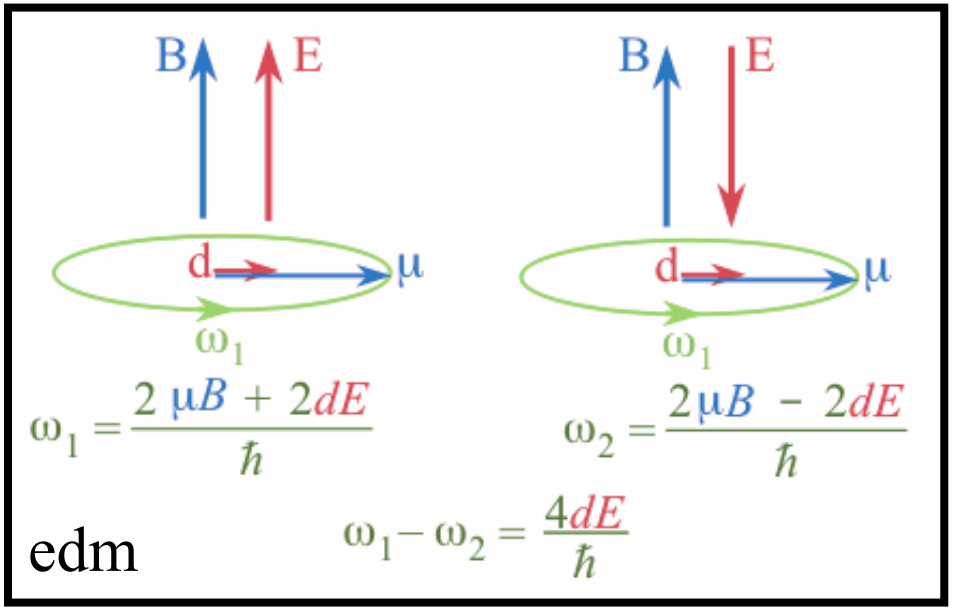


$$E_{recoil} = \frac{(\vec{p} + \vec{q})^2}{2M_{recoil}} < 100\,\text{eV}$$

β-decay

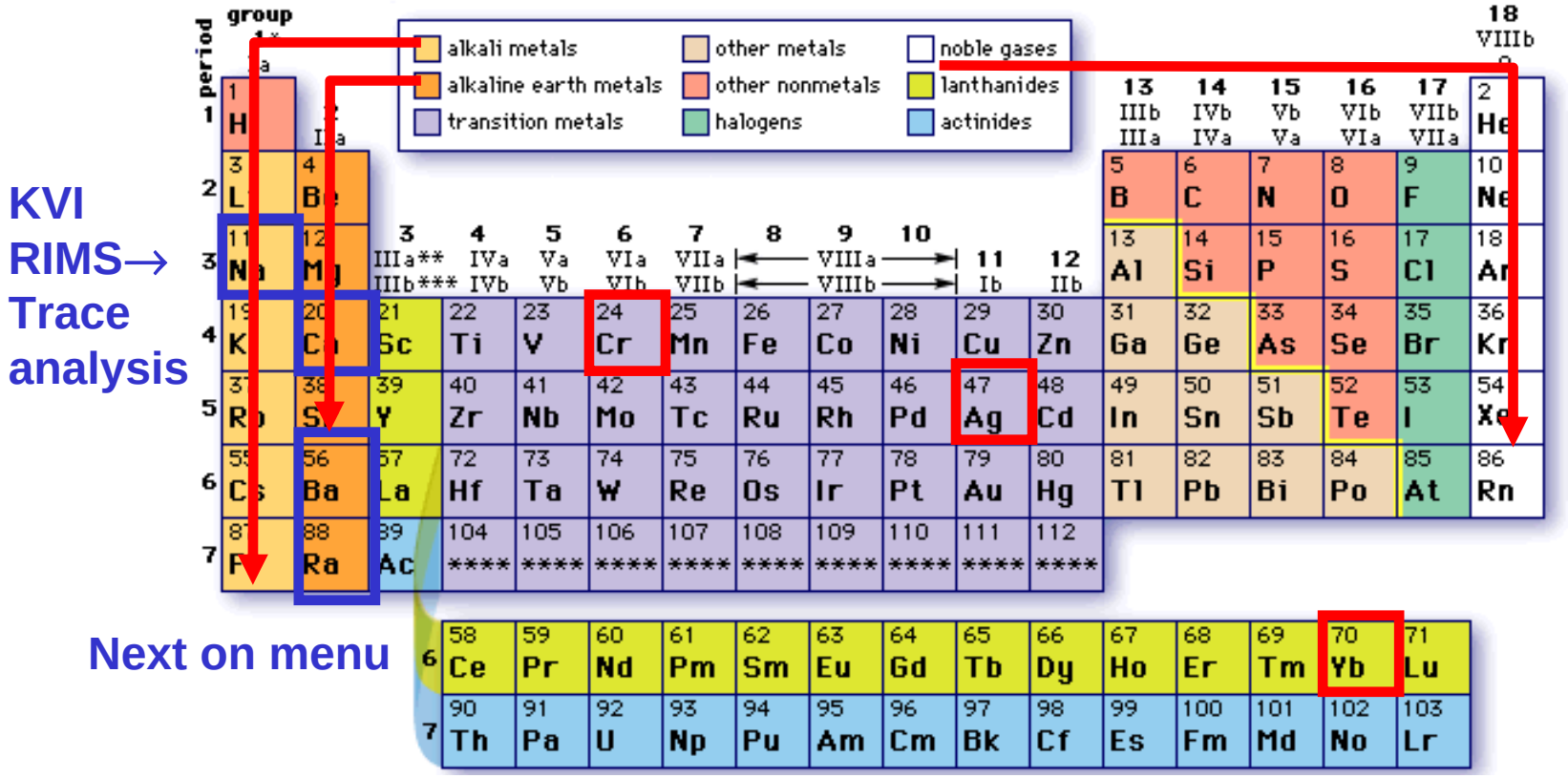
The trap sample:

- isotope (isomer) selective
- spin manipulation (edm)
- point source, no substrate
- recoil ion momentum spectrometry



- Ideal environment
  for precision experiments

Which atoms were trapped in a MOT



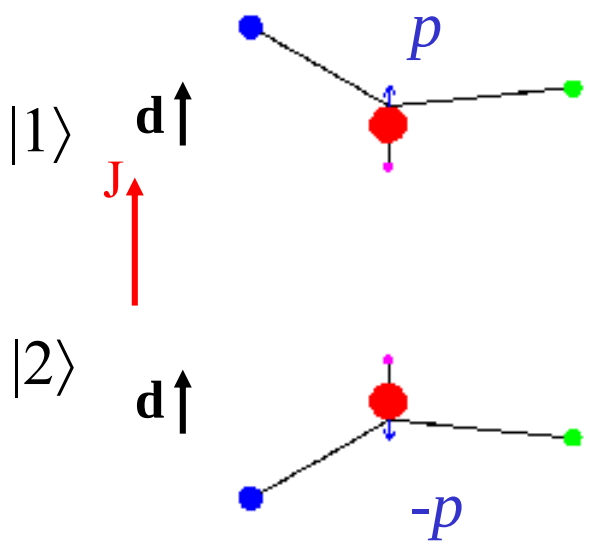
KVI – atomic physics is working with ^{23}Na and $^{(41)}$Ca

KVI – TRIμP Ba trapping as intermediate step for Ra (edm).

KVI – TRIμP pursues ^{21}Na trapping for β-decay correlations

Importance of parity degenerate states

Feynman III, ch. 9



$\langle 1|H_{11}|1\rangle = E_0 = \langle 2|H_{22}|2\rangle$

$\langle 1|H_{12}|2\rangle = -A = \langle 2|H_{12}|1\rangle$

$p = \langle 1|ez|1\rangle = -\langle 2|ez|2\rangle$

$p_I = \langle I|ez|I\rangle = 0$

Diagonalizing

$$H_{ij} = \begin{pmatrix} E_0 & -A \\ -A & E_0 \end{pmatrix}$$

New states **I** and **II**

$E_{I,II} = E_0 \pm A$

$$\begin{pmatrix} I \\ II \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \end{pmatrix}$$

$$H_{ij} = \begin{pmatrix} E_0 + \Delta & -A \\ -A & E_0 - \Delta \end{pmatrix}$$

New states **L** and **S**

$E_{S,L} = E_0 \pm \sqrt{(A^2 + \Delta^2)}$

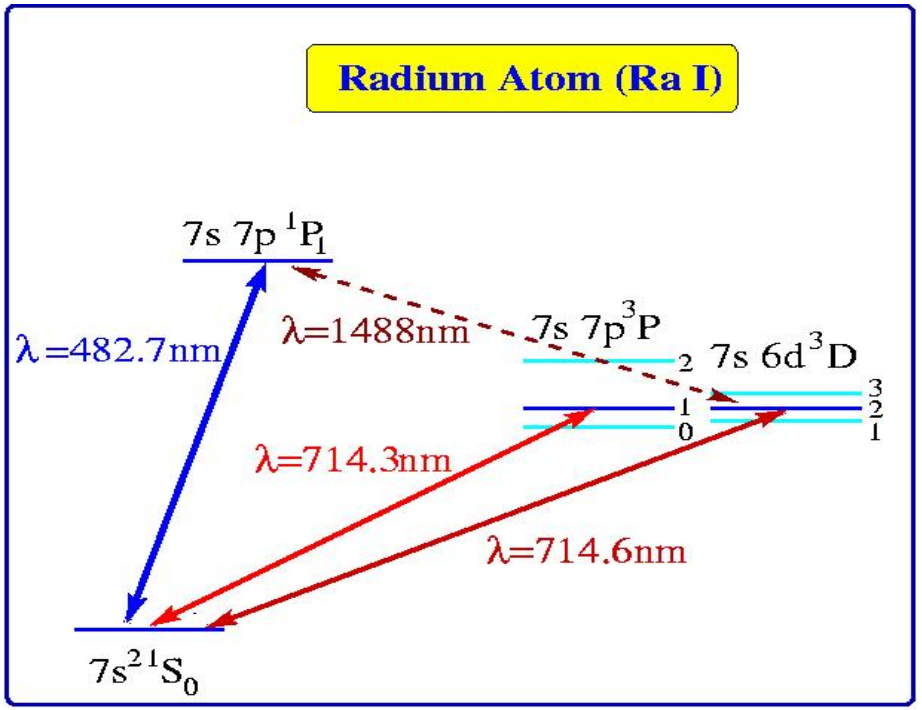
$$\begin{pmatrix} S \\ L \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} I \\ II \end{pmatrix}$$

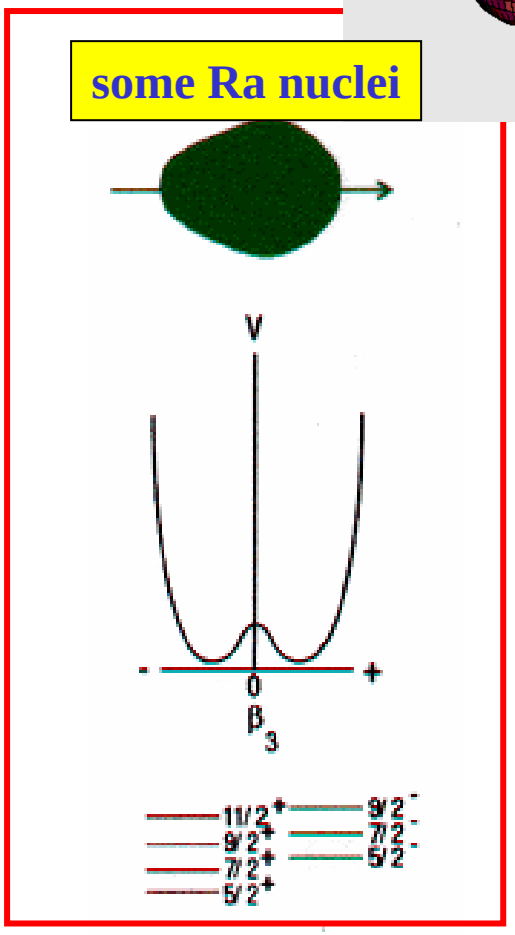
$p_S = \langle S|ez|S\rangle = p \sin 2\alpha = p\, \Delta/A$

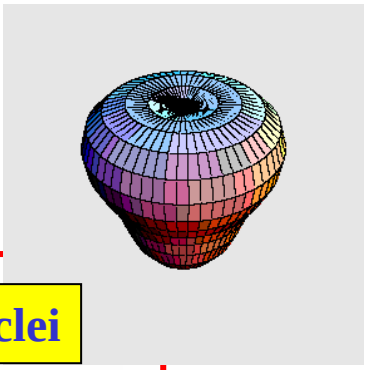
Enhancement factor $p_S/d \approx \frac{p^2}{Aa^3} \approx 10^5$

Nearly degenerate states with opposite parity allow to observe TRV and PNC

Enhancements in Radium







Nuclei with J=1/2 available

225Ra (1/2 +) (source, from 229Th),

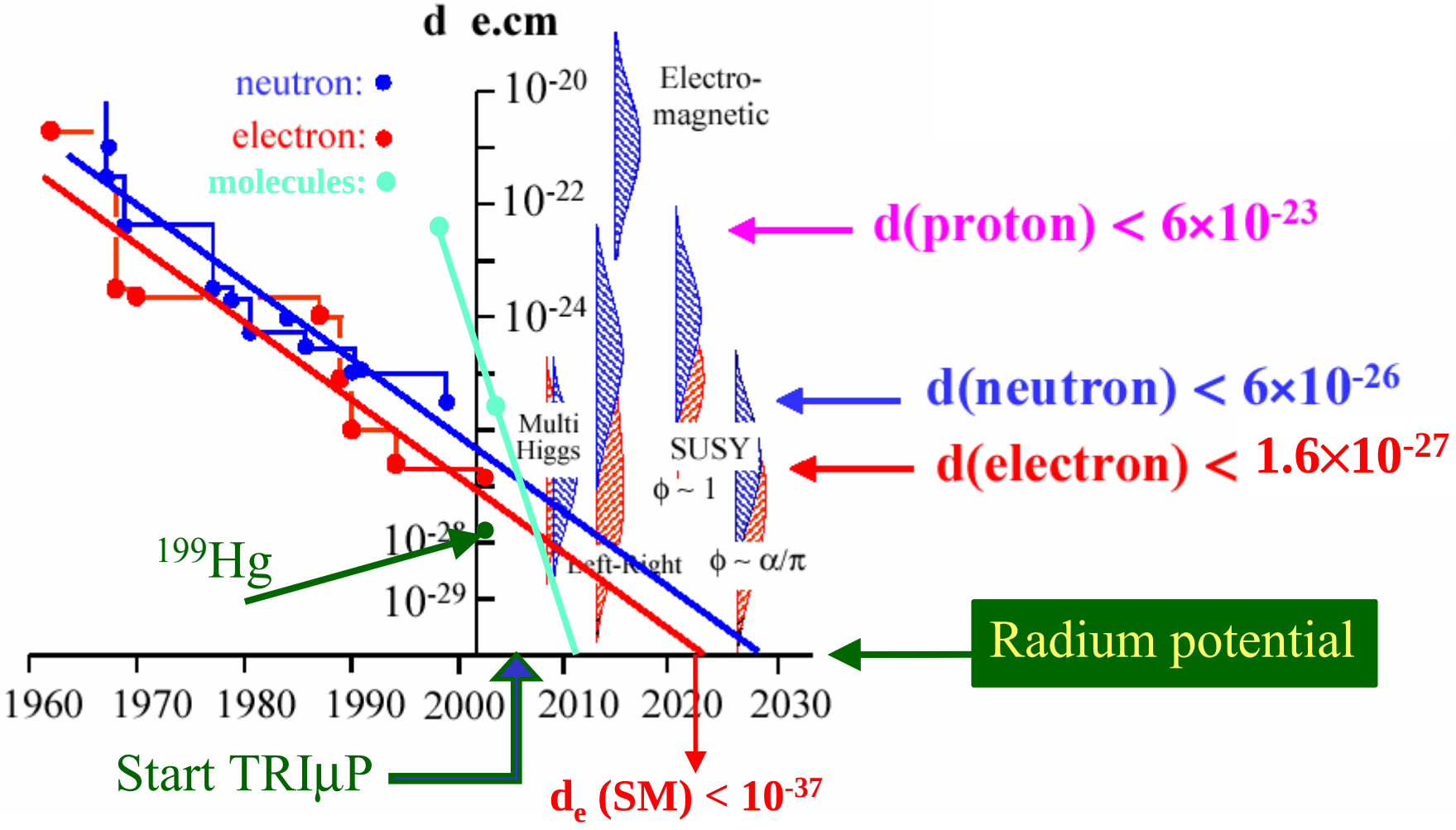
213Ra (1/2 -) (e.g. fusion 12C + Pb)

Atomic enhancement more important

….attracting attention …

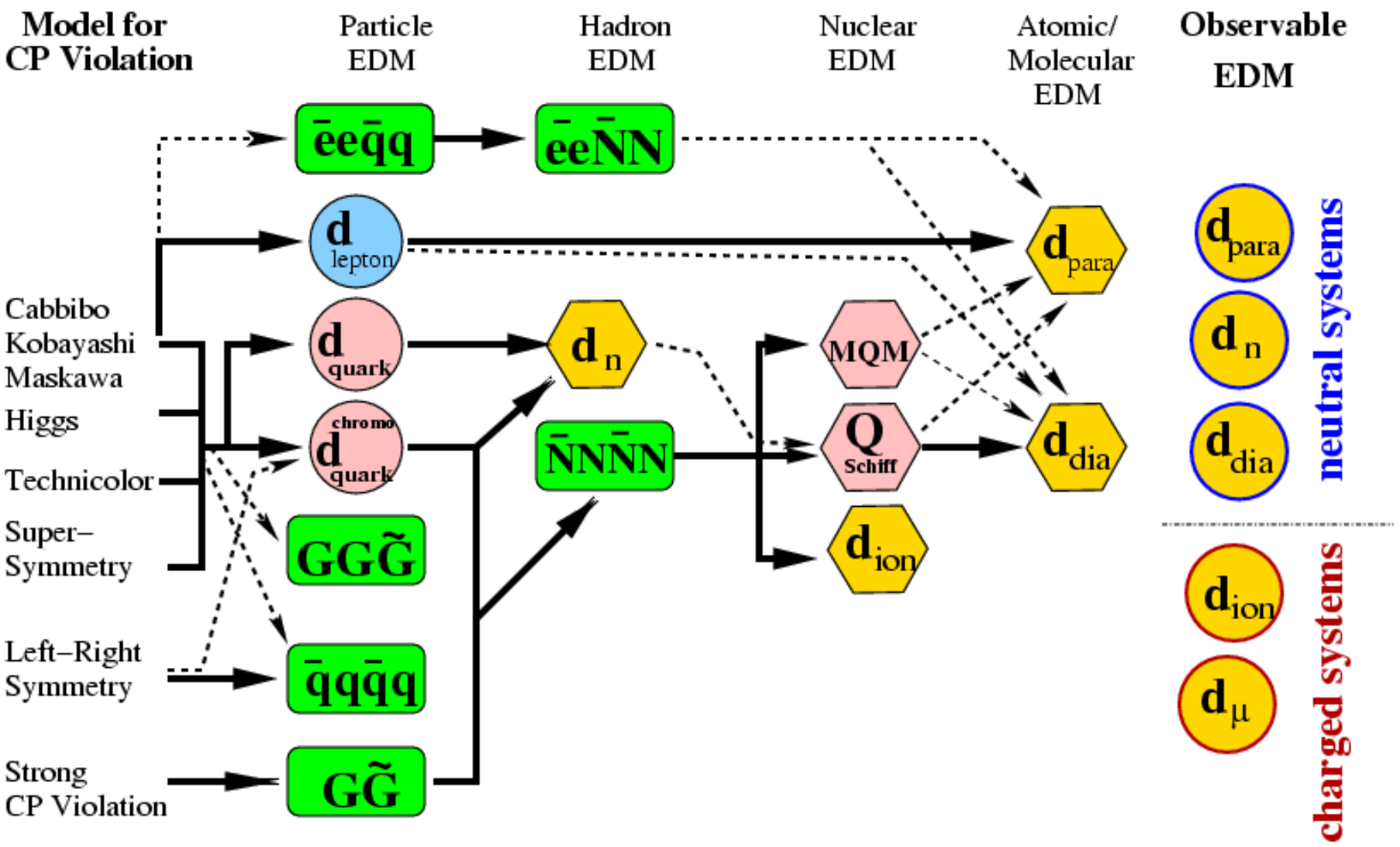
Schiff moments by
Flambaum and Zelevinsky
PRC 68(2003)033502

The race for a nonzero EDM…



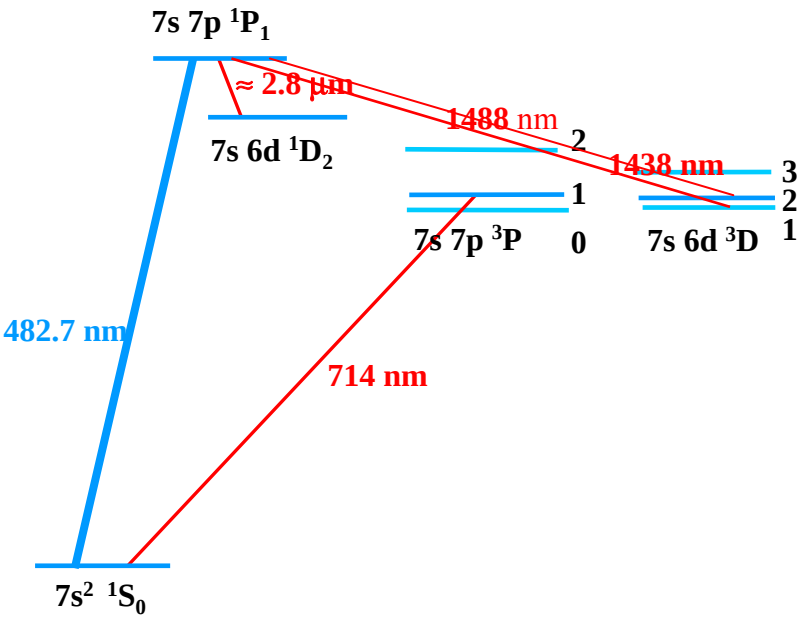
Multiple searches: eventually essential

Isn't there already an adequate Sufficiency of TRV Searches?

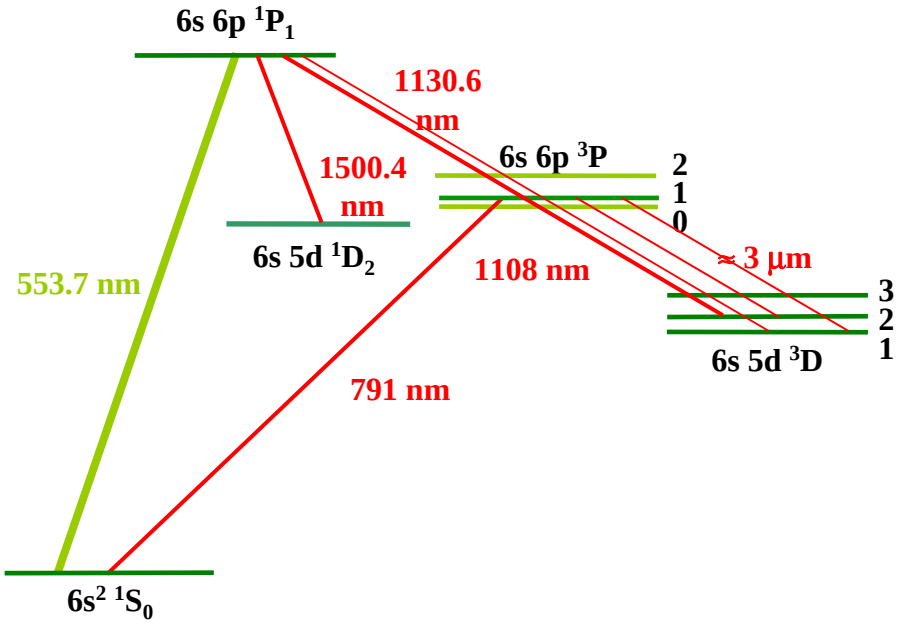


We need many experiments to sort out a possible physical origin !

Progress in Radium trapping



Radium



Barium

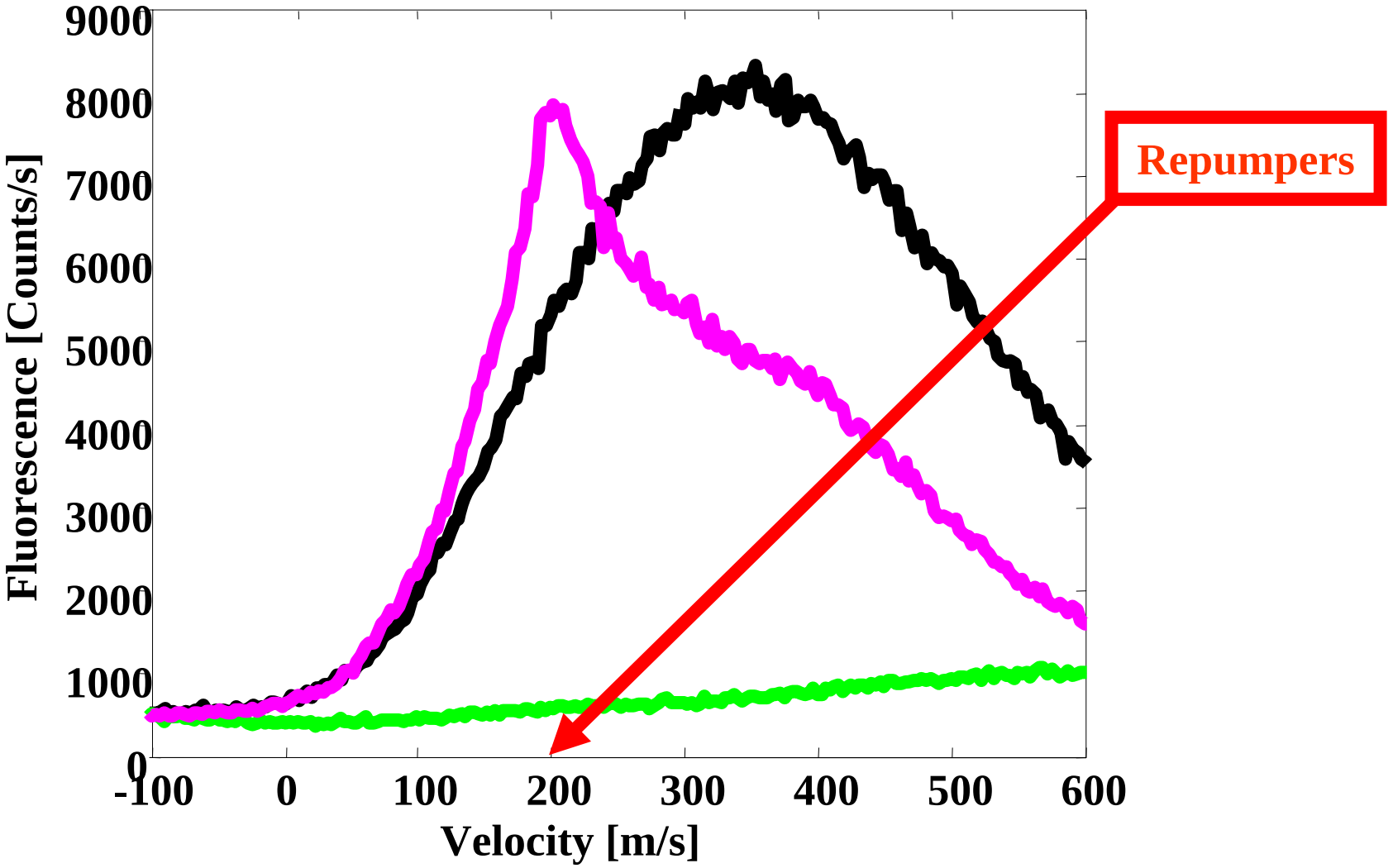
Stable Ba isotopes: KVI cooling demonstrated

Argonne: lifetime of $^3P_1$ (Scielzo et al. PRA 73(2006)010501)

Theory: level scheme (Dzuba and Ginges PRA 73(2006)032503)

progress on many fronts

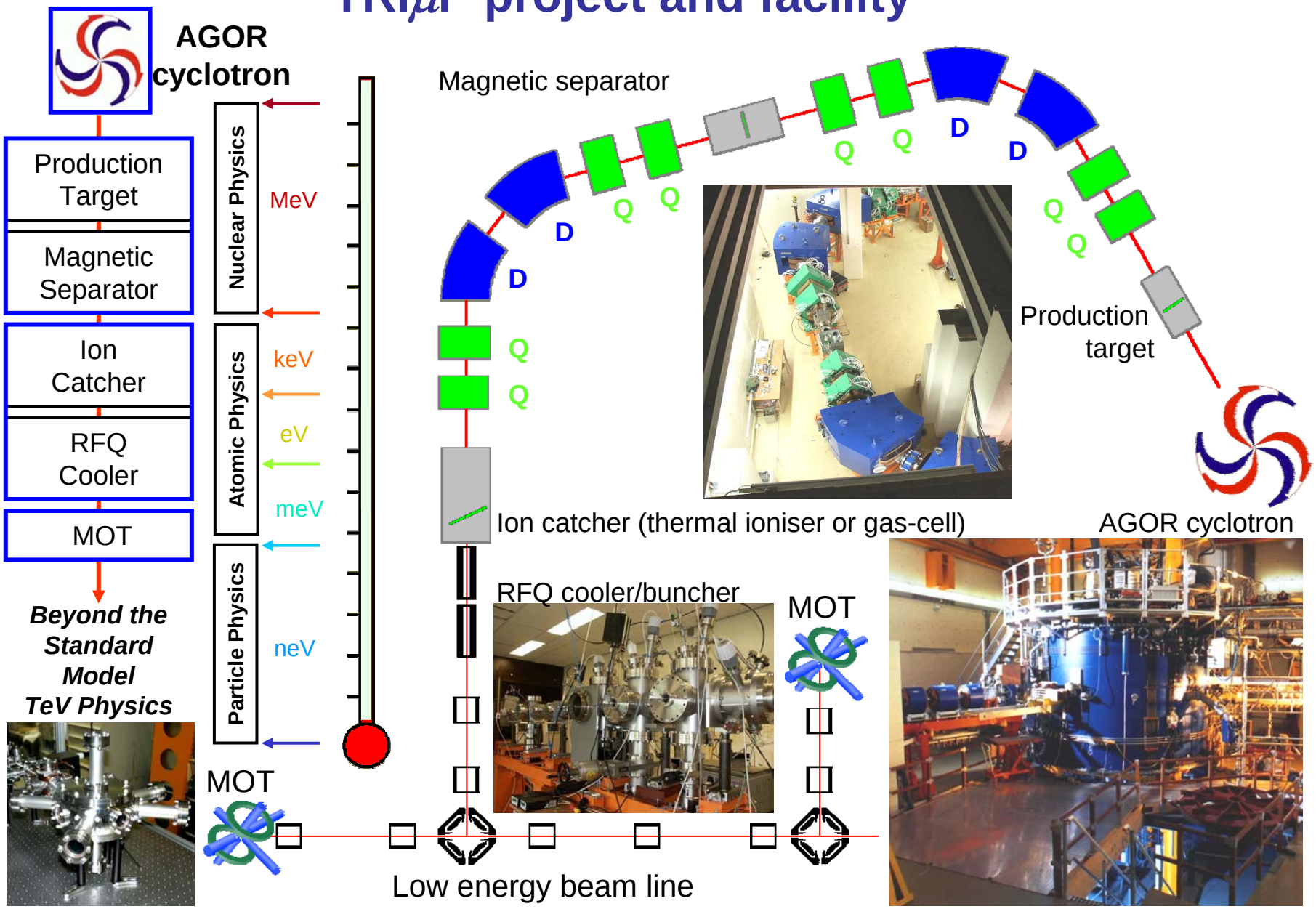
Experimental result



Slow down (velocity change) at least 20 m/s

No further slowing because Doppler shift changes

TRIμP project and facility



KVI Trapped Radioactive Isotopes: μicro-laboratories for Fundamental Physics

Conclusions and Outlook

Atomic and nuclear physics →TRV searches

- atomic:
  - Precision techniques (not only trapping …)
  - Enhancement TRV (APNC) signal
- nuclear:
  - Exploiting weak decay (D)
  - Enhancement TRV signal (edm)
- relatively cheap (Isolde) / flexible