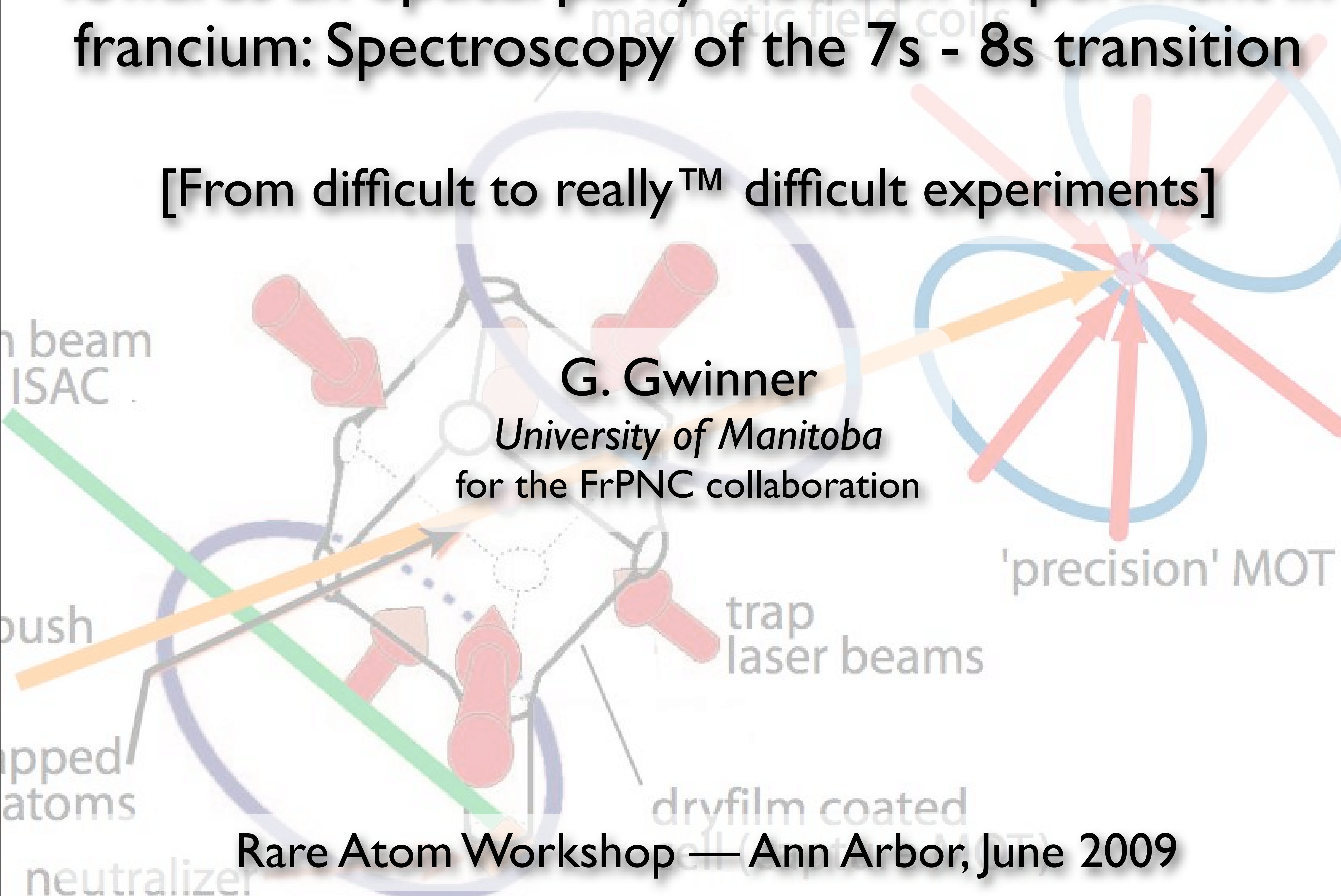
Towards an optical parity violation experiment in francium: Spectroscopy of the 7s - 8s transition

[From difficult to really™ difficult experiments]



G. Gwinner
University of Manitoba
for the FrPNC collaboration

Rare Atom Workshop — Ann Arbor, June 2009

ISAC + actinide target: great place to study fundamental symmetries in heavy atoms

Atoms/nuclei provide access to fun. sym., should be viewed as complementary to high energy approaches

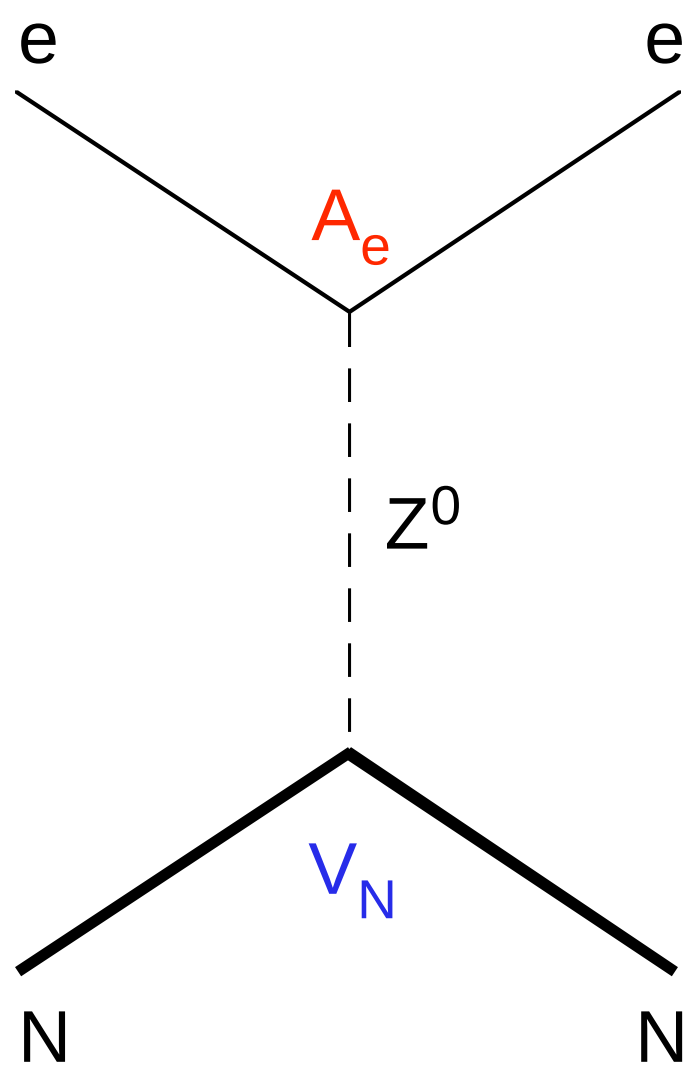
	Atom	Nucleus
Charged current weak interactions, β-decay	new powerful techniques (atom traps)	rich selection of spin, isospin, half-life
Neutral current weak interactions APNC anapoles	tremendous accuracy of atomic methods (lasers, microwaves) neutral (strong external fields) traps, cooling	huge enhancement 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

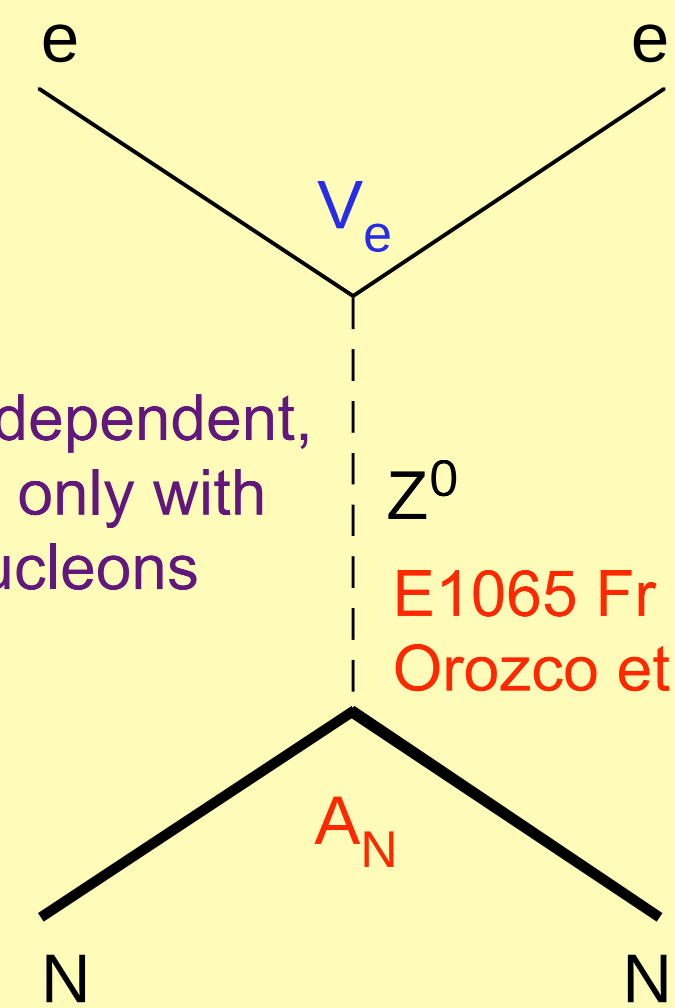
Some of most promising new candidates are heavy, radioactive systems (Rn, Fr)
Radioactive beam facilities are crucial

Demanding, long experiments → strong motivation for dedicated beam delivery

Atomic Parity Violation

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





nucl. spin dependent, interaction only with valence nucleons

E1065 Fr anapole Orozco et al.

nucl. spin *independent* interaction: coherent over all nucleons

H_{PNC} mixes electronic *s* & *p* states

$< n's' | H_{PNC} | np > \propto Z^3$

Drive s → s E1 transition!

Cs: 6s → 7s osc. strength f ≈ 10^{-22}

use interference:

$f \propto | A_{PC} + A_{PNC} |^2$

$\approx A_{PC}^2 + A_{PC} A_{PNC} \cos \varphi$

The nuclear-spin independent APNC Hamiltonian for a pointlike nucleus:

$$H^{nsi}_{\rm PNC} = \frac{G}{\sqrt{2}}\frac{Q_W}{2}\gamma_5\,\delta(\mathbf{r}).$$

$$Q_W = 2(\kappa_{1p}Z + \kappa_{1n}N)$$

$$\kappa_{1p} = \frac{1}{2}(1 - 4\sin^2\theta_W),\kappa_{1n} = -\frac{1}{2}$$

The "nuclear weak charge"
contains the weak interaction physics

$$< n'L'|H^{\rm nsi}_{\rm PNC}|nL > \quad = \frac{G}{\sqrt{2}}\frac{Q_w}{2} < n'L'|\delta(r)\vec{\sigma}\cdot\vec{p}|nL >$$

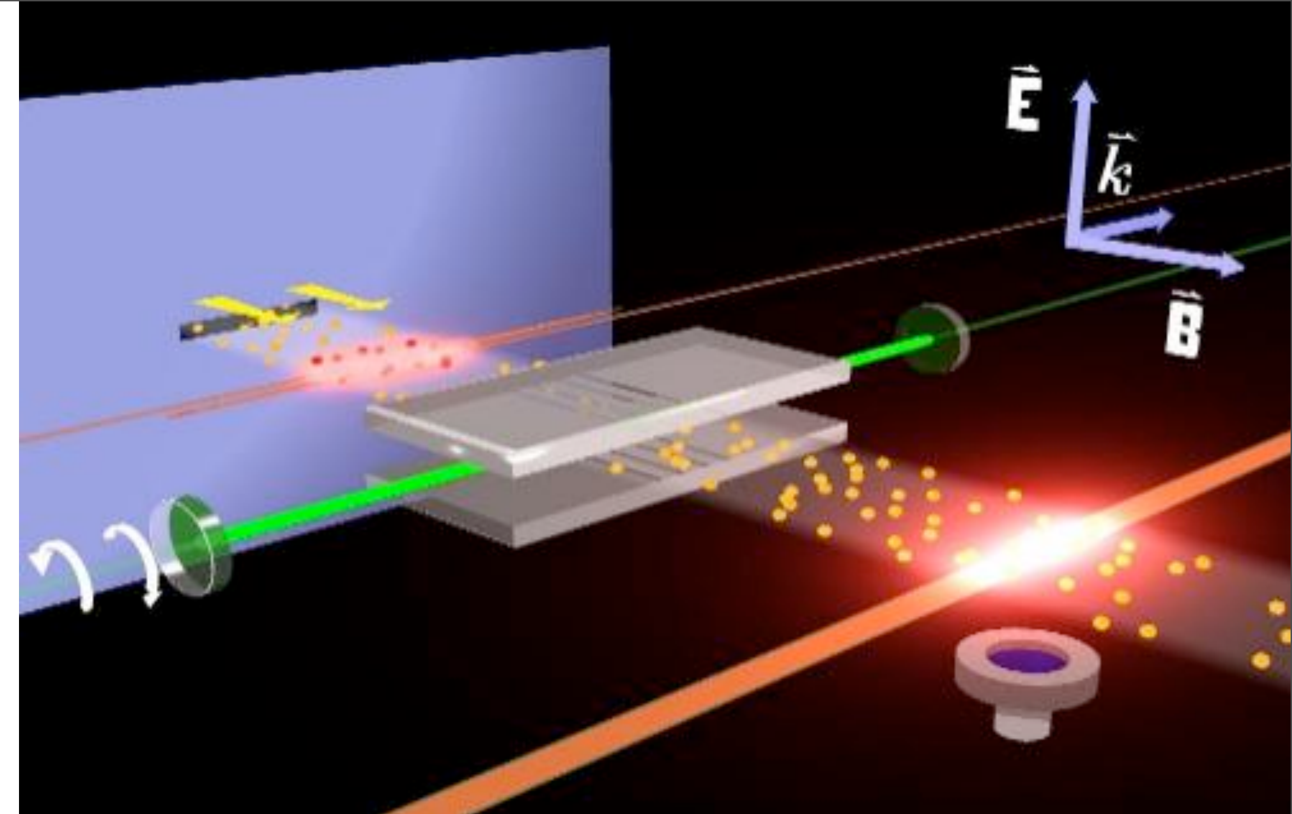
$$\propto < n'L'|\frac{d}{dr}|nL > |_{r=0} \qquad R_{nL} \approx r^L Z^{L+1/2}$$

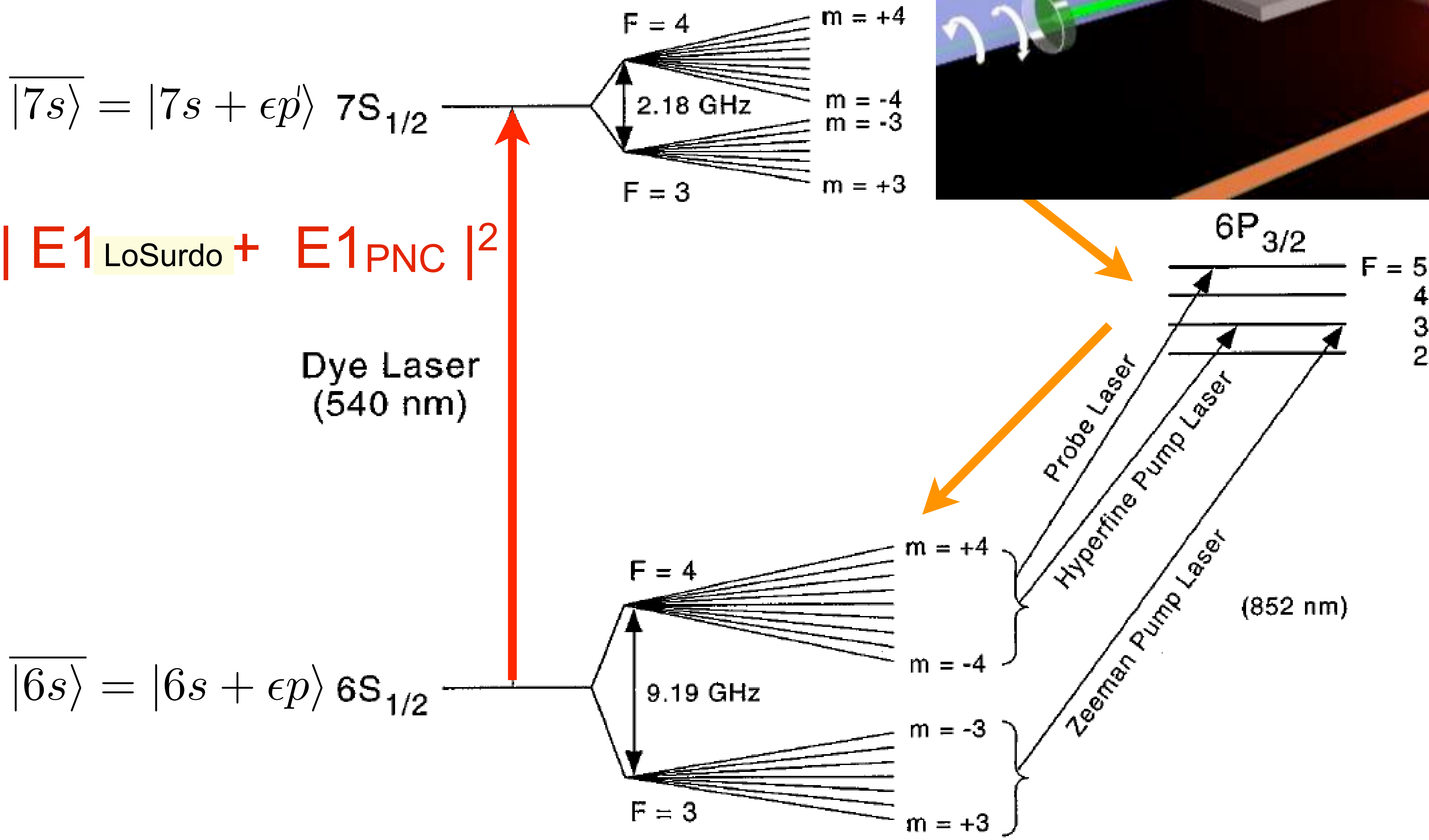
$\Rightarrow$ at $r = 0$ only R_{ns}, $\frac{d}{dr}R_{np}$ are finite

$H_{\rm PNC}$ mixes s and p states $\qquad < ns|H^{\rm nsi}_{\rm PNC}|n'p > \propto Z^3$

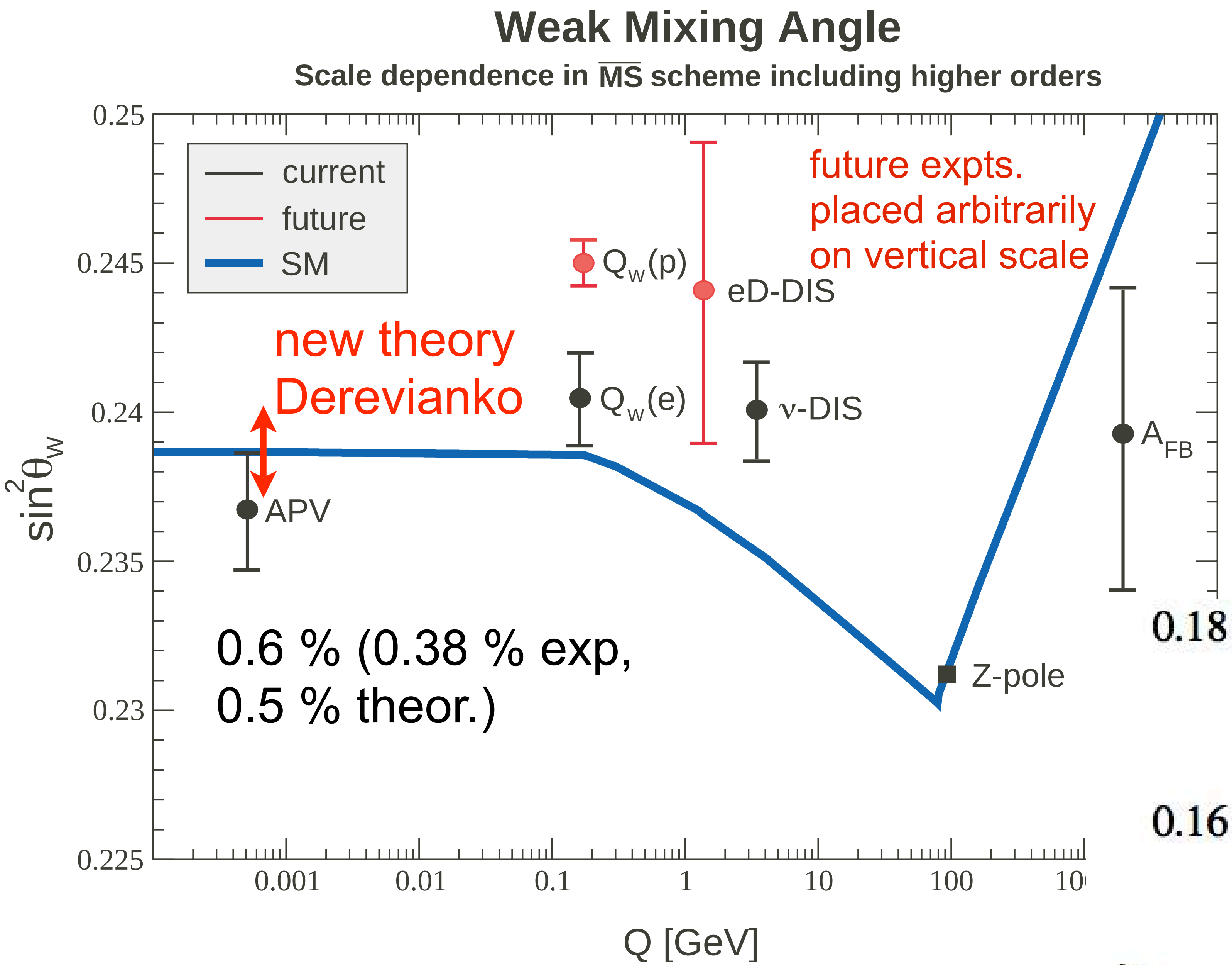
Bouchiat, 1974

The Boulder Cs Experiment (Wood, 1996)

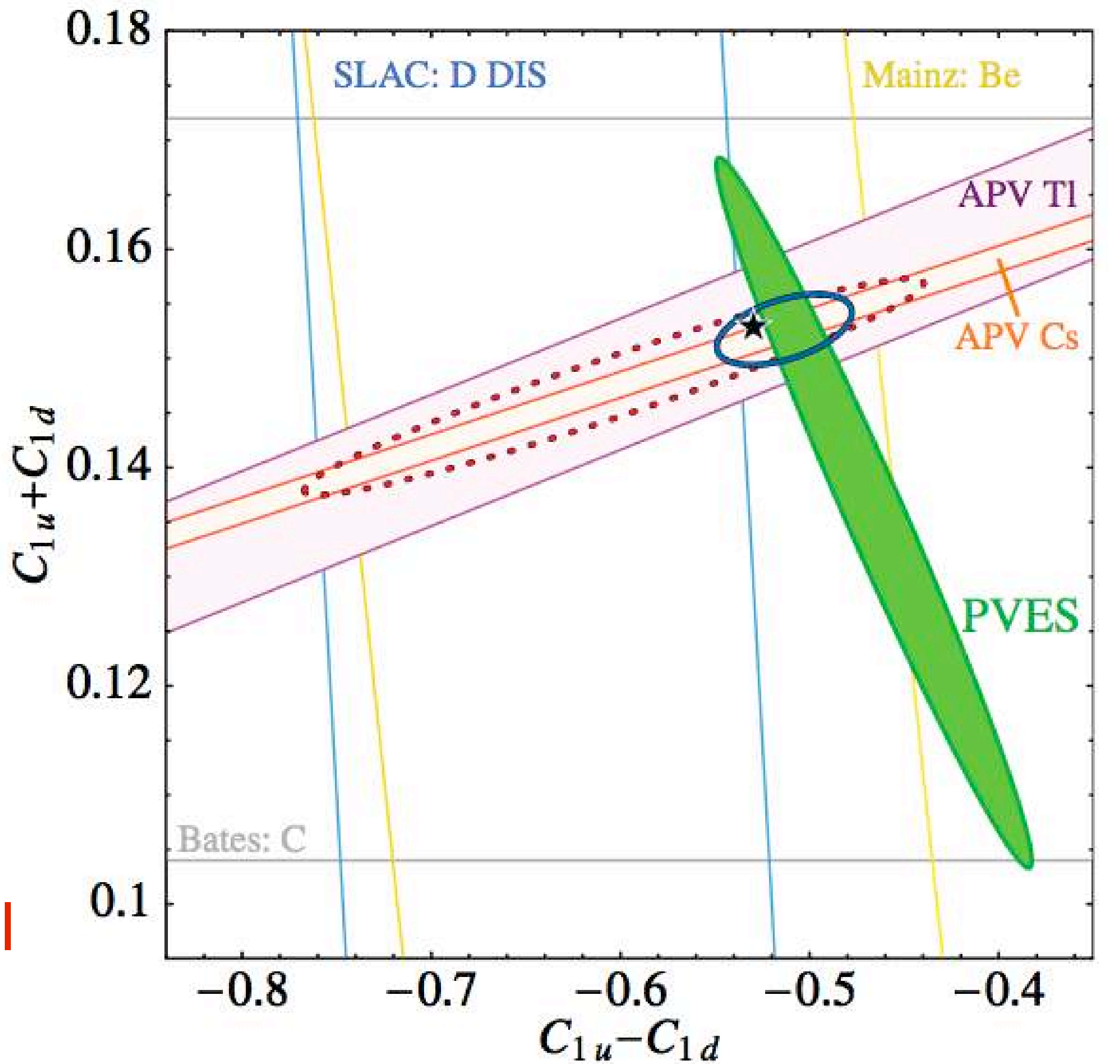




$$\frac{\mathrm{Im}(E1_{\mathrm{PNC}})}{\beta} = \begin{array}{lll} -1.5576(77) & \mathrm{mV/cm} & 6S\ F=3 \rightarrow 7S\ F'=4 \\ -1.6349(80) & \mathrm{mV/cm} & 6S\ F=4 \rightarrow 7S\ F'=3 \end{array}$$



S. G. Porsev, K. Beloy, and A. Derevianko. PRL, 102,:181601, 2009.



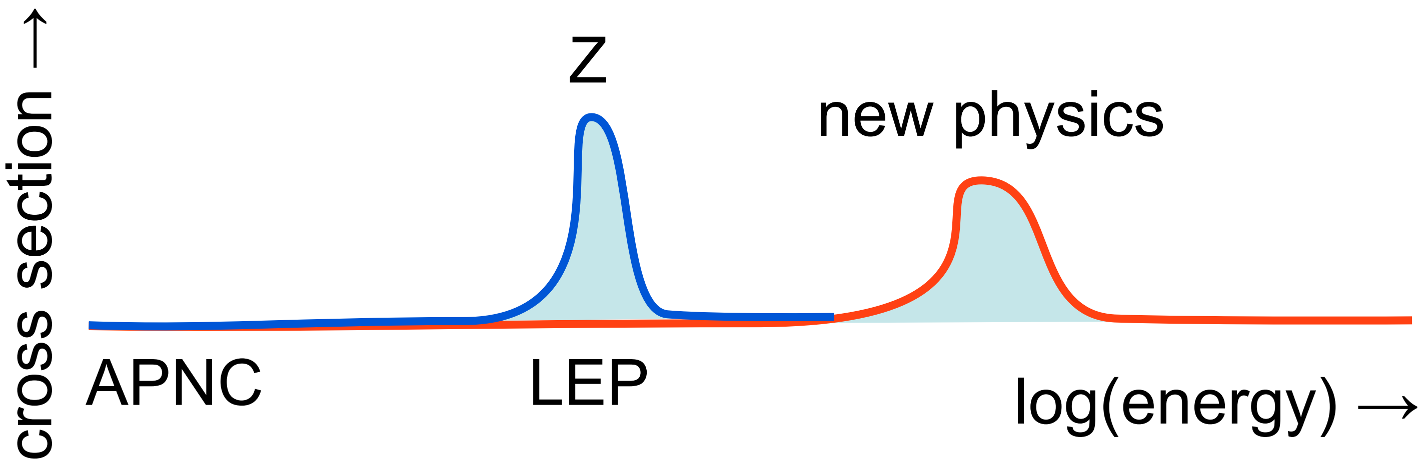
Young et al., PRL 2007: Dramatic recent progress from PV electron scattering for (C_{1u} - C_{1d})

APNC uniquely provides the orthogonal constraint (C_{1u} + C_{1d})

Implications on 'new physics' from the Boulder Cs experiment
(adapted from D. Budker, WEIN 98)

New Physics	Parameter	Constraint from atomic PNC	Direct constraints from HEP
Oblique radiative corrections	$S+0.006T$	S = -0.56(60)	S=−0.13 ± 0.1 (−0.08) T=−0.13 ± 0.11 (+0.09)
Z_x-boson in SO(10) model	$M(Z_x)$	> 1.4 TeV	> 820 GeV LHC, ILC: > 5 TeV (?)
Leptoquarks	M_S	>0.7 TeV	> 256 GeV, >1200 GeV indir.
Composite Fermions	L	>14 TeV	>6 TeV

Why is APNC so sensitive?



APNC can also constrain other scenarios, e.g. couplings to new light particles
(e.g. Bouchiat & Fayet 05)

Why Cs ? Not particularly heavy...

It's the heaviest, stable 'simple atom'

atomic structure factor

nuclear structure factors

$$\langle i|H_{\mathrm{PNC},1}|j\rangle = \frac{G_F}{2\sqrt{2}} C_{ij}(Z)\,\mathcal{N} \times \left[-N q_n + Z(1-4\sin^2\theta_W)q_p\right]$$

$$q_n = \int \rho_n(r)\,f(r)\,d^3r\,,$$

$$q_p = \int \rho_p(r)\,f(r)\,d^3r\,.$$

from Pollock et al. 1992

Precise experiments in Tl (and Bi, Pb) have been limited by their more complicated atomic structure!

Use francium (Z=87)

atomic structure (theory) understood at the same level as in Cs

APNC effect 18 x larger!

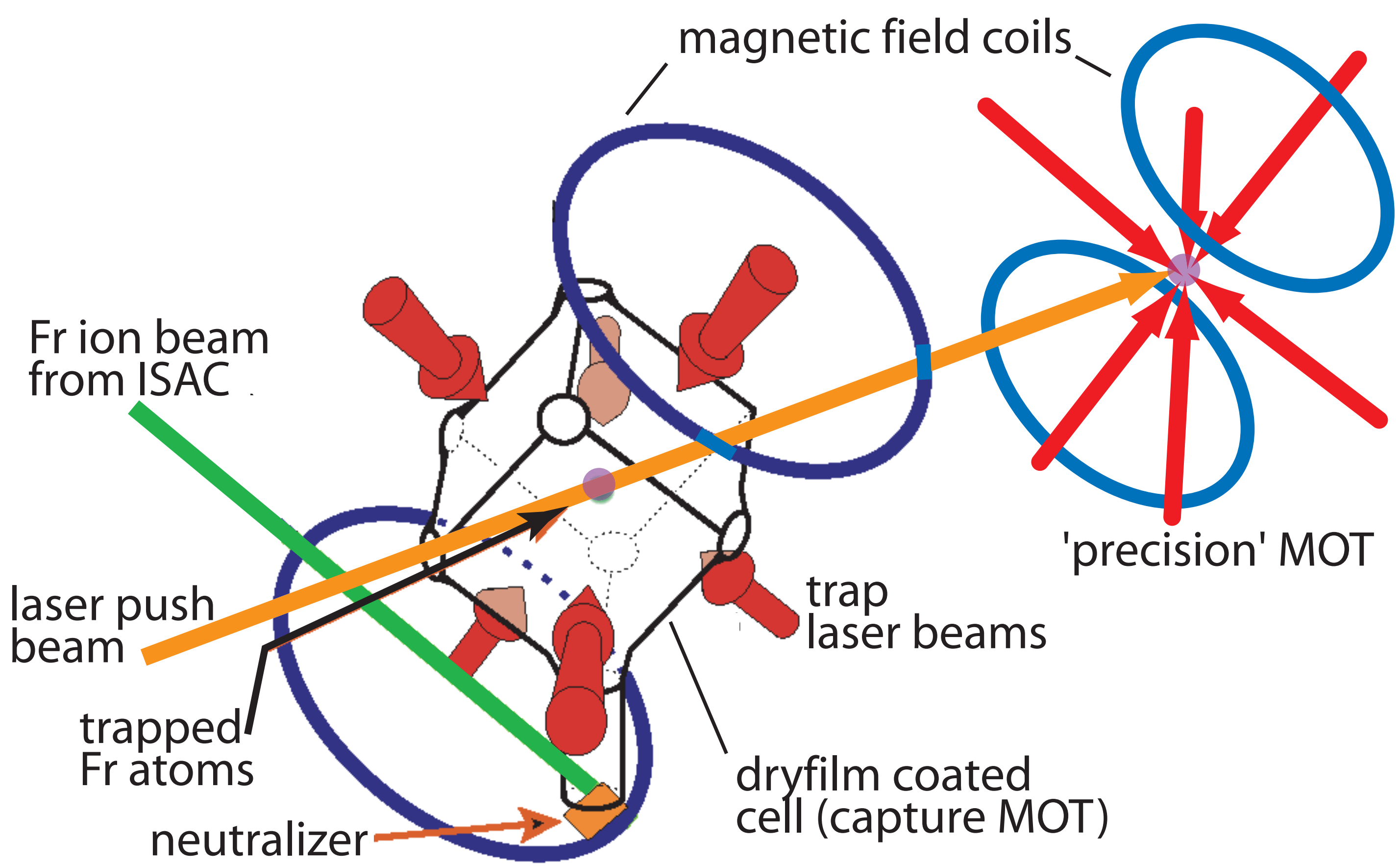
Problems: (i) no stable isotope
(ii) need to know neutron radius better than for Cs expt.

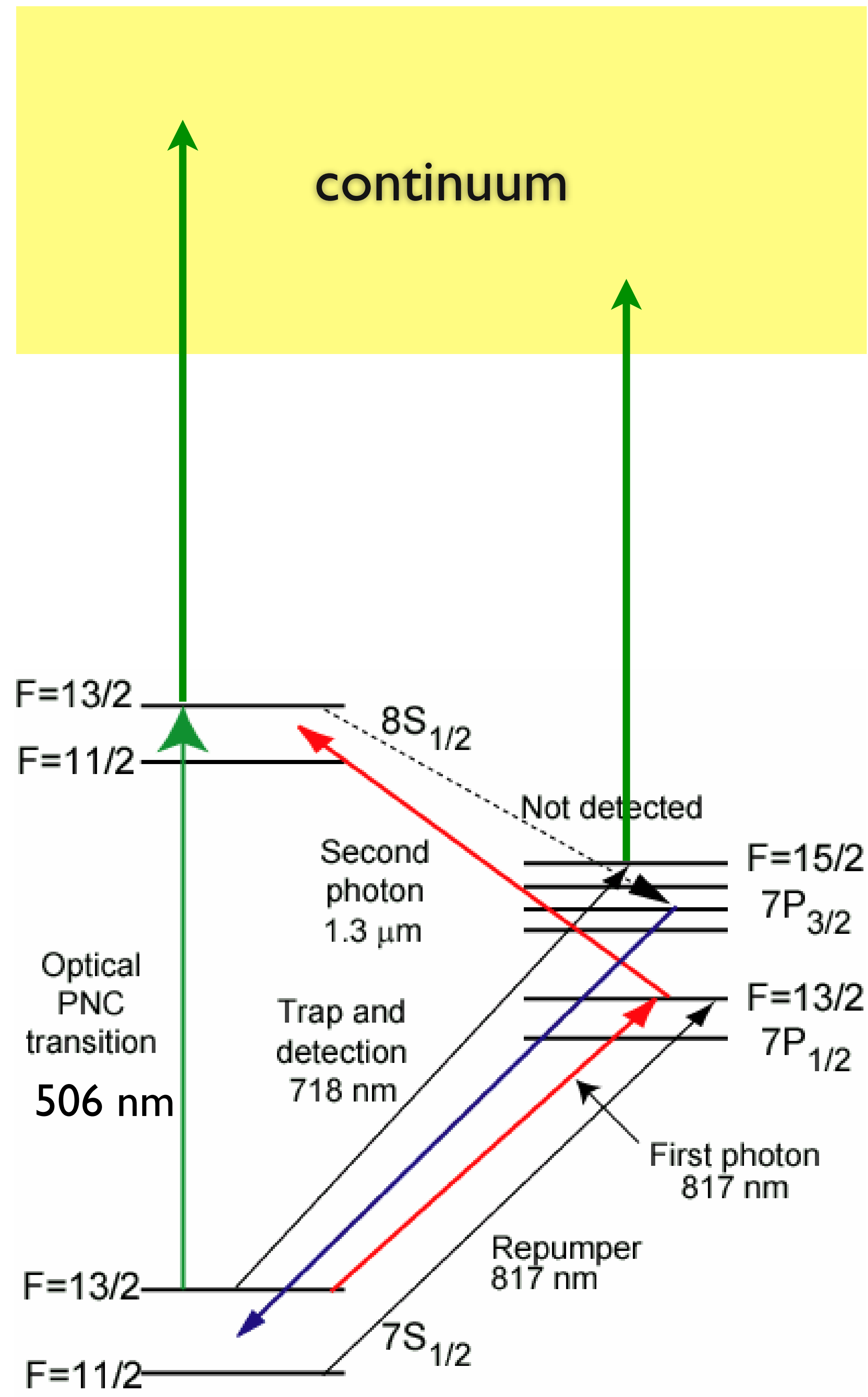
Answers: (i) go to TRIUMF’s actinide target to get loads of Fr
(ii) the upcoming PREX experiment at Jefferson Lab will measure the neutron radius of ^{208}Pb

A Francium APNC Experiment at TRIUMF

Boulder Cs: massive atomic beam (10^{13} s^{-1} cm^{-2})
key figure: 10^{10} 6s-7s excitations /sec

Fr trap:
excitation rate per atom: 30 s^{-1}
but asymmetry 18x larger
APNC possible with 10^6 - 10^7 atoms!





A Fr APNC experiment at TRIUMF

- Actinide target will make ISAC the best place to pursue Fr physics such as NSI APNC
- data collection time (purely statistical, no duty factor)
  - 10^6 trapped atoms, 1.0% APNC: 2.3 hours
  - 10^7 trapped atoms, 0.1% APNC: 23 hours

➡ APNC work can start even with low current on ISAC target!

➡ But: most of the time needs to be spent on systematics. So realistically we are talking 100 days or more of beam, spread of more than a year!

- 1% neutron radius measurement in ^{208}Pb with PREX would put a 0.2 % uncertainty on Q_W in ^{212}Fr (Sil 2005)
- atomic theory similar to Cs ~~(0.4 - 0.5 % uncertainty)~~, so progress in this direction required to go beyond Wood et al.
- can expect that all aspects improve over time (already happening: new Cs (alkali) APNC calculation by Derevianko et al.)

Working our way down: Spectroscopy of the highly forbidden 7s → 8s transition (indispensable for APNC, but very interesting by itself)

$$A_{7s\to 8s} = E1_{\text{stark}} + M1 + E1_{\text{pnc}}$$

$$E1_{\text{stark}}(F,m \to F',m') = \alpha \vec{E}\cdot\vec{\epsilon}\,\delta_{F,F'}\delta_{m,m'} + i\beta(\vec{E}\times\vec{\epsilon})\cdot\langle F'm'|\vec{\sigma}|Fm\rangle$$

- One of the faintest transitions observed in atoms (osc. strength in Cs about 10^{-13} in vacuum)
- M1 amplitude due to relativistic effect and hyperfine interaction, mech. for $M1_{rel}$ has been unclear for a long time
- "Most sensitive electromagnetic transition to the accuracy of the relativistic description of an atomic system" (Savukov et al, PRL 1999)
- So far, only measured in Cs (Gilbert 1983), in context of APNC measurements
- Wavelengths in Rb (497 nm) and Fr (506 nm) very similar ⇒can use same equipment

Relativistic atomic structure

- Savukov et al: precise calculation of $M1_{rel}$ for all alkalis
  - importance of negative-energy states, found large effect

	Li	Na	K	Rb	Cs	Fr
Z	3	11	19	37	55	87
I	0.91	1.16	1.15	1.38	1.51	2.09
II, no-pair	0.12	0.03	-0.08	-1.86	-10.69	-116
II, NES	0.02	0.13	0.20	0.31	0.40	0.64
Total	1.05	1.06	1.27	-0.17	-8.78	-113
Experiment					-10.40 (0.03)	

- Rb: cancellation of terms leads to very small $M1_{rel}$
- Cs: 16% discrepancy between theory and experiment
- Fr: one term dominates
- data in all 3 elements could constrain different terms

I. M. Savukov, A. Derevianko, H. G. Berry, and W. R. Johnson, Phys. Rev. Lett. 83, 2914 (1999)

Importance of M1 in context of APNC

- $M1_{rel}$ is extremely valuable benchmark for calculations of relativistic effects and radiative corrections in Fr
- $M1_{hf}$ is best way to determine tensor transition polarizability β
  - β hard to measure, but essential for APNC, which observes the quantity

$$\frac{E1_{\mathrm{PNC}}}{\beta E}$$

  - Measure $E1_{stark}$-M1 interference

$$\frac{M1}{\beta E}$$

    - $M1_{hf}$ part can be reliably calculated from the hyperfine structure, and hence used to get β
  - $E1_{stark}$-M1 interference has been biggest systematic error in Cs APNC measurements, need to understand it

Pre-APNC Measurements with 7s → 8s

- Can (need to) measure α, β, $M1_{rel}$, $M1_{hf}$
- Follow largely procedure developed over the years by the Boulder group
- Big difference: atom source
  - Cs beam: up to 10^{15} s^{-1} cm^{-2}
  - relevant # for comparison with trap

2.2×10^6 atoms in interaction region

(about 10 × less in 1980s work)

- 10^6 to 10^7 atoms in the precision trap should be sufficient to do similar work (even 10^5 for α)

All of these measurements are difficult, but let's start with something 'relatively easy'

- Can we do something in a 'standard issue' MOT, e.g. developed and debugged with hyperfine anomalies/isotope shifts ?
- I think so
  - Scalar transition polarizability

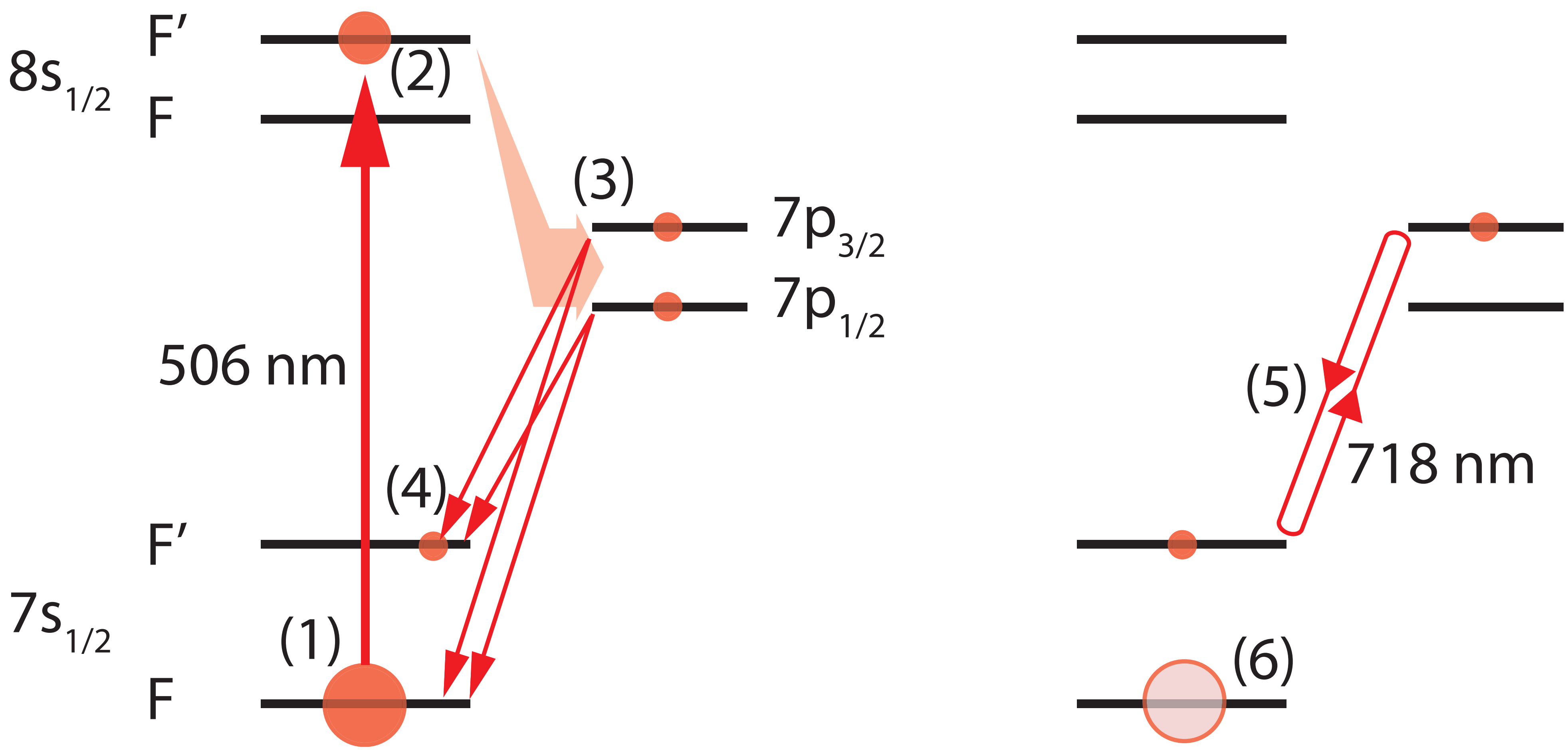
$$E1_{\rm stark}(F,m \rightarrow F',m') = \alpha \vec{E}\cdot\vec{\epsilon}\,\delta_{F,F'}\delta_{m,m'} + i\beta(\vec{E}\times\vec{\epsilon})\cdot\langle F'm'|\vec{\sigma}|Fm\rangle$$

- In Fr, for E > 20 V/cm, "α-type" Stark amplitude dominates
  - at kV/cm by far easiest to detect
  - need electric field, but no need to flip it
  - no need to lift m-degeneracy

  - start with regular MOT, B and E fields permanent

“α-type” Stark Amplitude Measurement

- ΔF, Δm = 0 $$E1_{\text{stark}}(F,m \rightarrow F',m') = \alpha\vec{E}\cdot\vec{\epsilon}\,\delta_{F,F'}\delta_{m,m'} + i\beta(\vec{E}\times\vec{\epsilon})\cdot\langle F'm'|\vec{\sigma}|Fm\rangle$$
- $R_\alpha = 0.00034 \times E^2$ per second and atom
- 3 kV/cm, 10^6 atoms, 200 mW laser focused to 1 mm ∅
  ⇒ 3×10^9 excitations per second
- cycling scheme, can get near 100% 7s → 8s photon det. eff.



β-type: same principle, but 30x smaller

E1$_{stark}$ - M1 IF Measurement

- m - degeneracy needs to be lifted
  - turn off MOT fields and turn on homogenous B field for a few msec (10- few 10 Gauss) → new exciting development: AC MOT
  - or: transfer into dipole trap

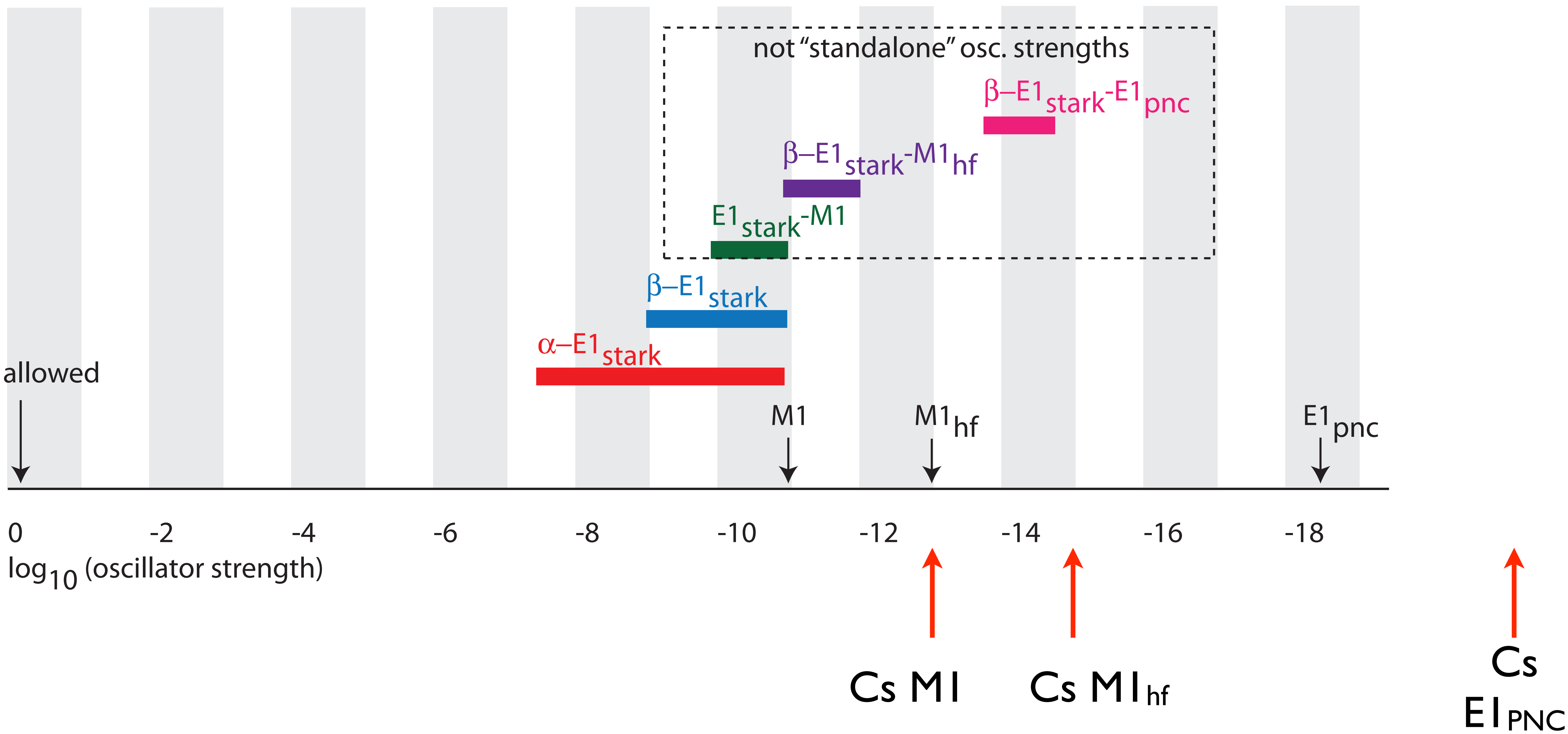
- choose e.g. F = 11/2, m = 11/2 → F = 13/2, m = 13/2 transition
- E = 2 kV/cm ⇒ M1 excitation rate 400 × weaker than E1, but IF term is only 20 × down
- asymmetry under reversals is then 20% !

$$\eta = 2\frac{|E1 + M1|^2 - |E1 - M1|^2}{|E1 + M1|^2 + |E1 - M1|^2}$$

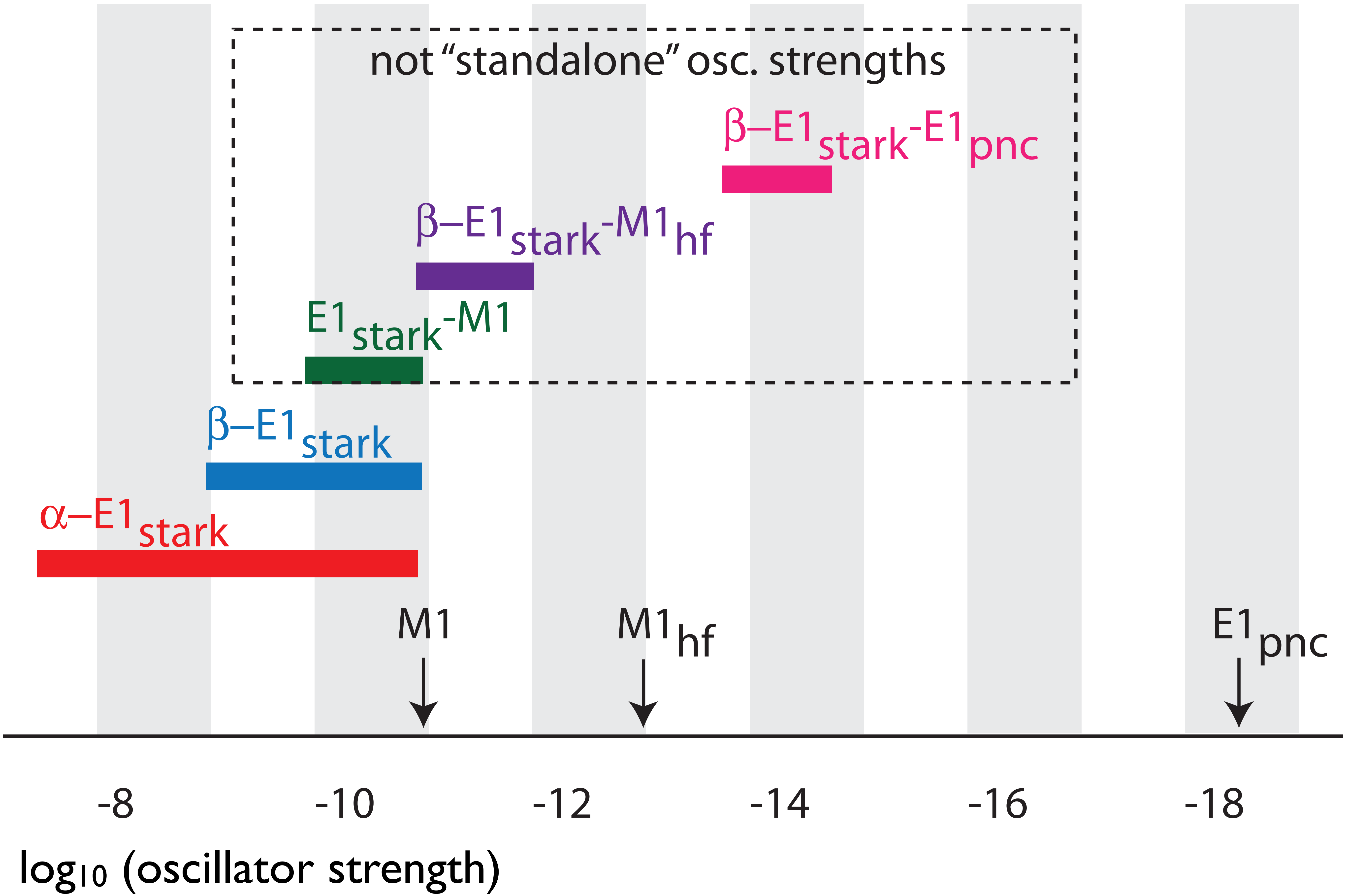
$E1_{stark}$ - M1 IF Measurement

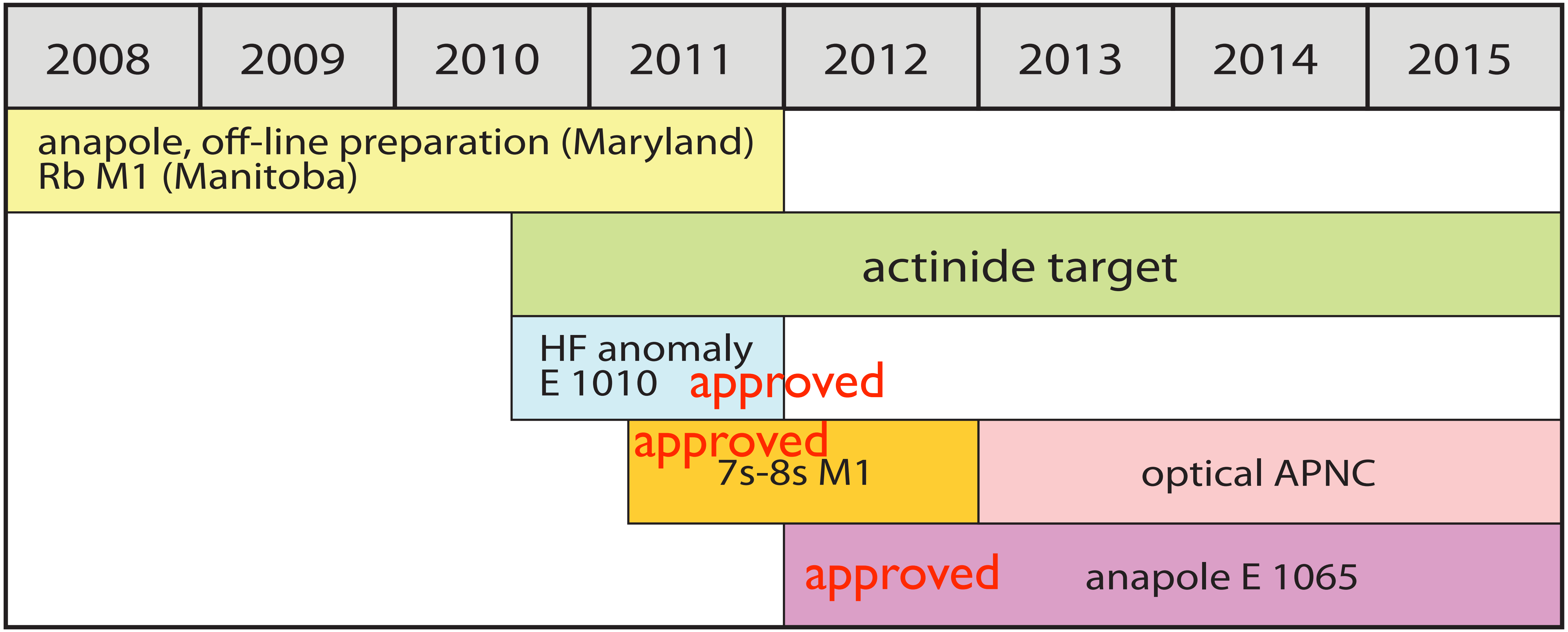
- 1 % measurement of asymmetry required 0.2 % on the overall transition
- in the shot noise limit: need to detect 250 000 excitations
- 10^6 atoms, 10% duty factor in the trap: can be done in a fraction of a second

- By performing this measurement on the $\Delta F = \pm 1$ transitions and looking at the difference, can get $M1_{hf}$
- In Fr, roughly 10 × smaller than $M1_{rel}$, so statistics on overall transition need to be at 0.02% level, takes 100 × longer (about 10 seconds)


not “standalone” osc. strengths
β–E1stark-E1pnc
β–E1stark-M1hf
E1stark-M1
β–E1stark
α–E1stark
allowed
M1
M1hf
E1pnc
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
log10 (oscillator strength)
Cs M1
Cs M1hf
Cs
E1PNC

The power of Stark-tunability





- Canadian SAP plan: high priority for francium
- Hyperfine anomalies: study of nuclear properties, tune up Fr apparatus (E 1010 approved)
- Anapole measurement (E 1065 approved)
- 7s-8s Stark/M1: precursor to optical APNC (in preparation)
- Optical APNC (future EEC proposal)

- e-EDM: letter of intent by H. Gould (LBNL)

The FrPNC members participating in S1218

(in fairly arbitrary order):

G. Gwinner, C. de Oliveira* (*Manitoba*)
E. Gomez (*San Luis Potosi, Mexico*)
J.A. Behr, M.R. Pearson *(TRIUMF)*
L.A. Orozco, A. Perez Galvan*, D. Sheng* *(Maryland)*
D.G. Melconian (*Texas A&M*)
S. Aubin *(William and Mary)*

* *Students*