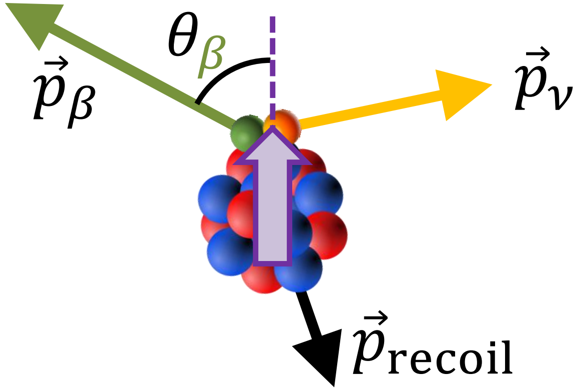
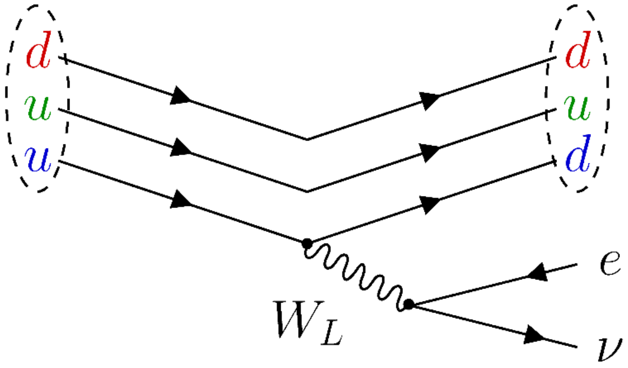
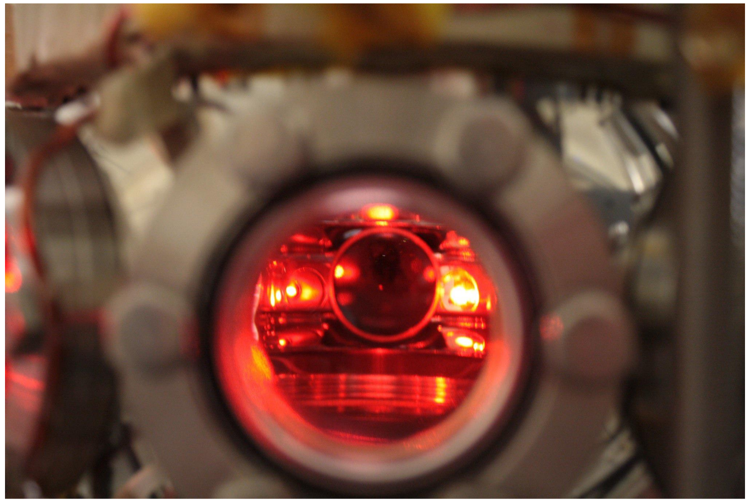
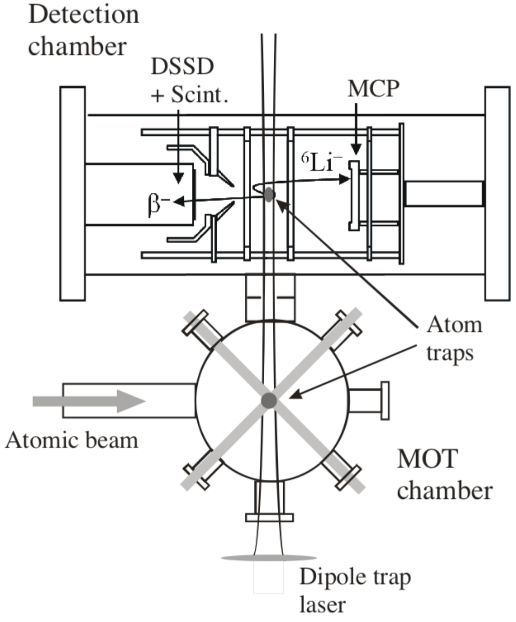
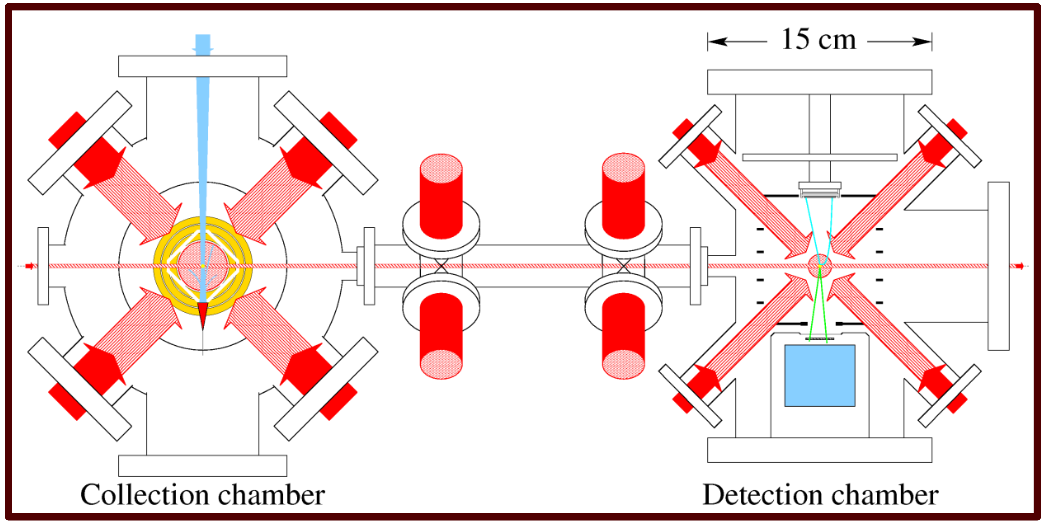
β decay asymmetry measurements with trapped atoms











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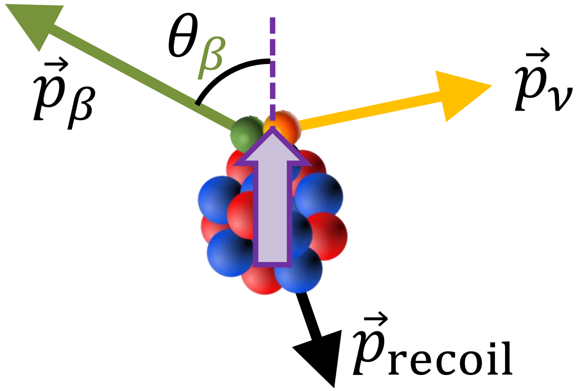
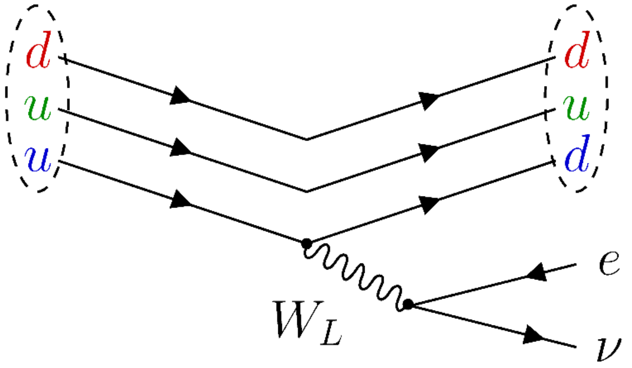
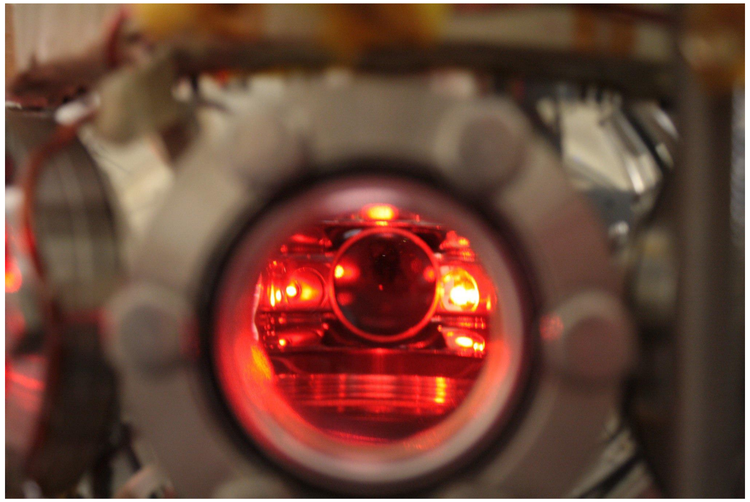
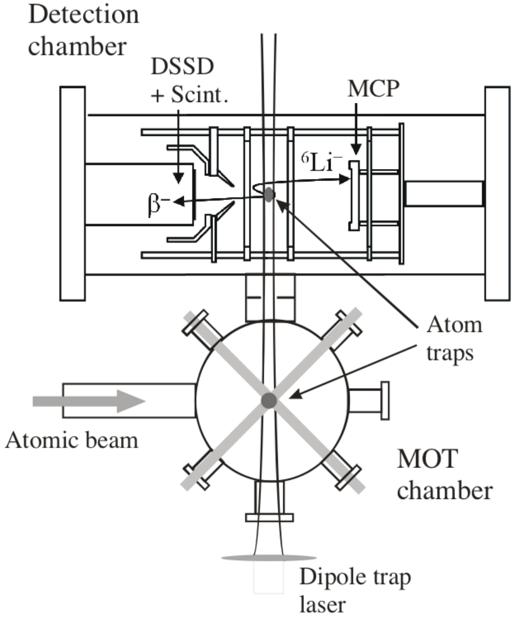
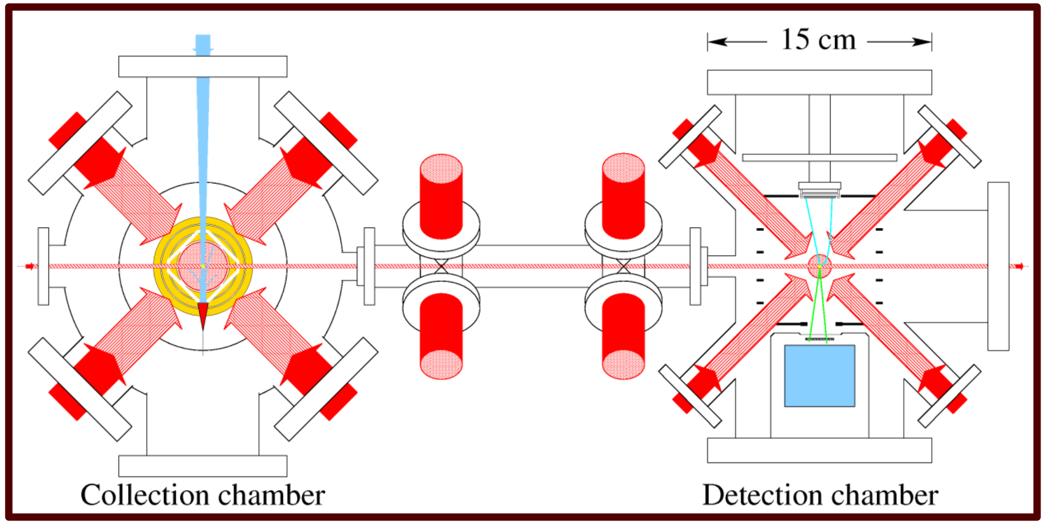
β decay ~~asymmetry~~ correlation measurements with trapped atoms











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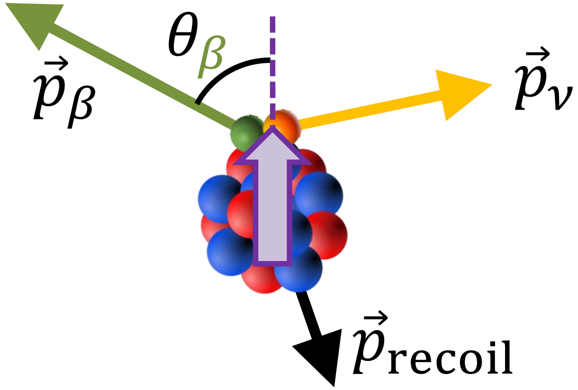
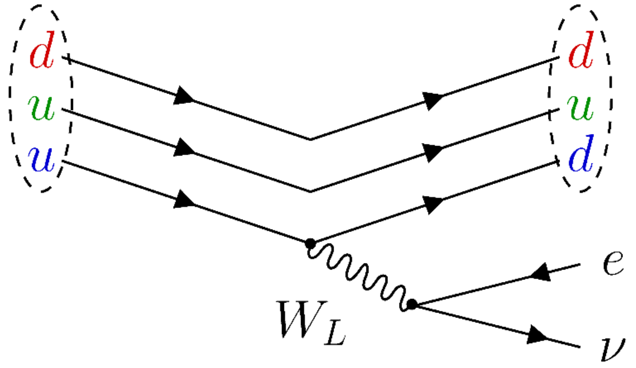
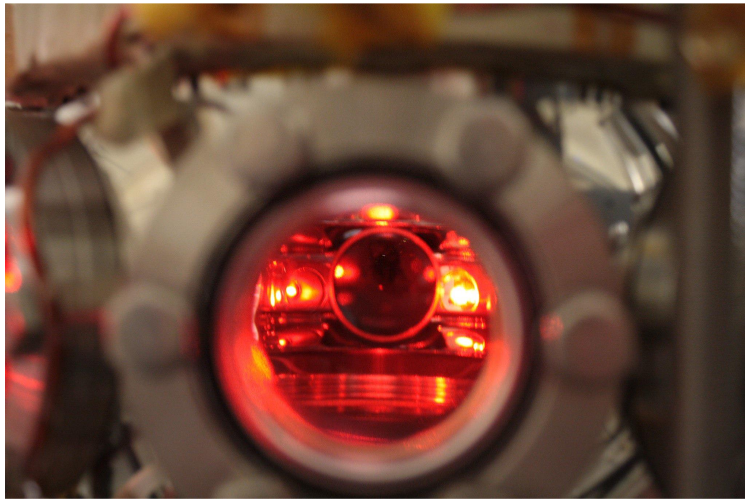
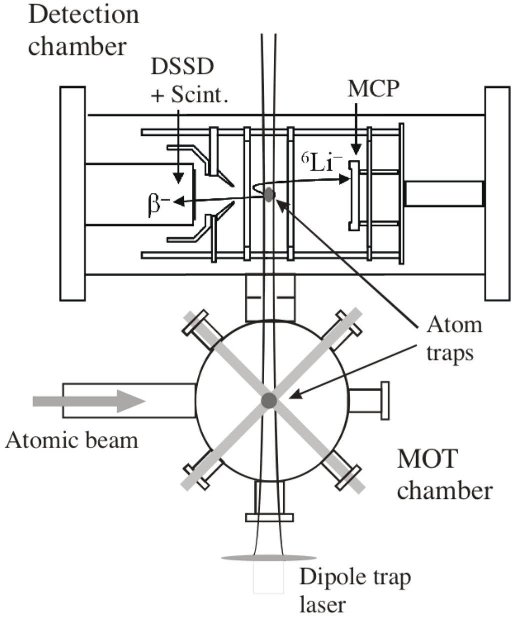
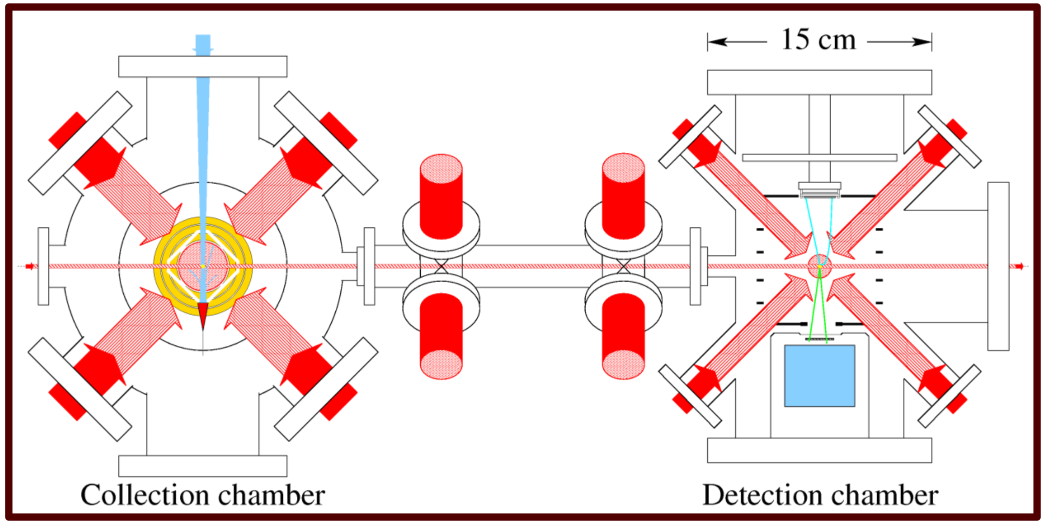
Precision β decay ~~correlation~~ ~~asymmetry~~ measurements with trapped atoms





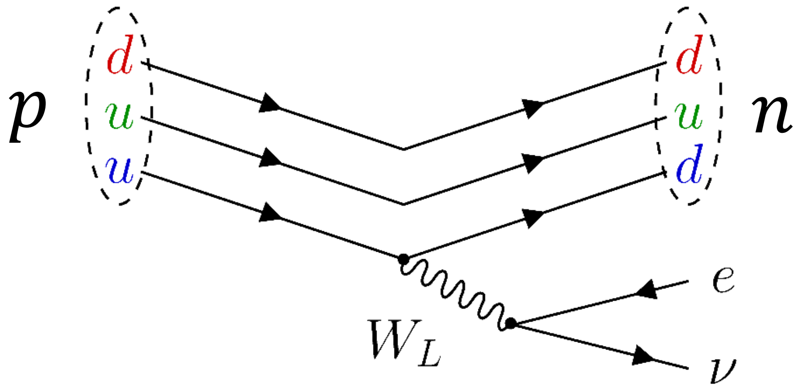






The standard model and beyond

- This is the standard model:



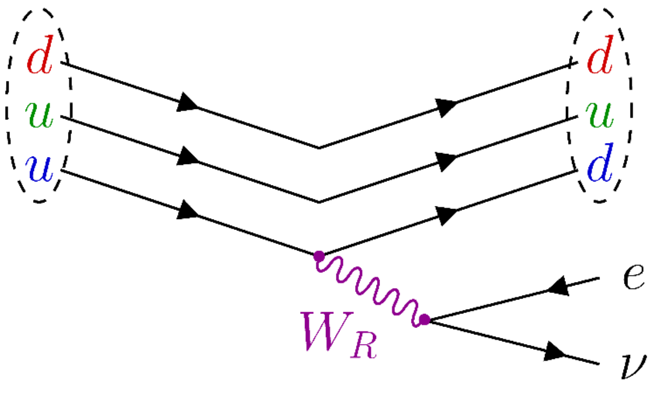
pure $V - A$ interaction

$$H_\beta = \quad \bar{p}\gamma_\mu n(C_V \bar{e}\gamma^\mu \nu \; + \; C_V' \bar{e}\gamma^\mu \gamma_5 \nu)$$
$$- \bar{p}\gamma_\mu \gamma_5 n(C_A \bar{e}\gamma^\mu \gamma_5 \nu \; + \; C_A' \bar{e}\gamma^\mu \nu)$$

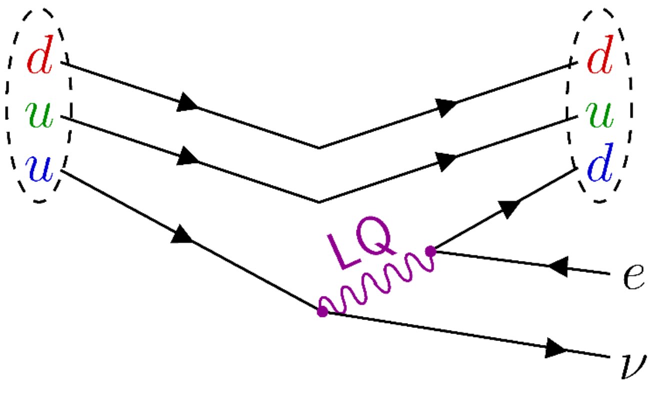
$$C_V = C_V' = 1$$
$$C_A = C_A' \approx 1.27$$

- These are not:

Right-handed bosons, or scalar/tensor leptoquarks, or SUSY, or…



$C_i \neq C_i'$



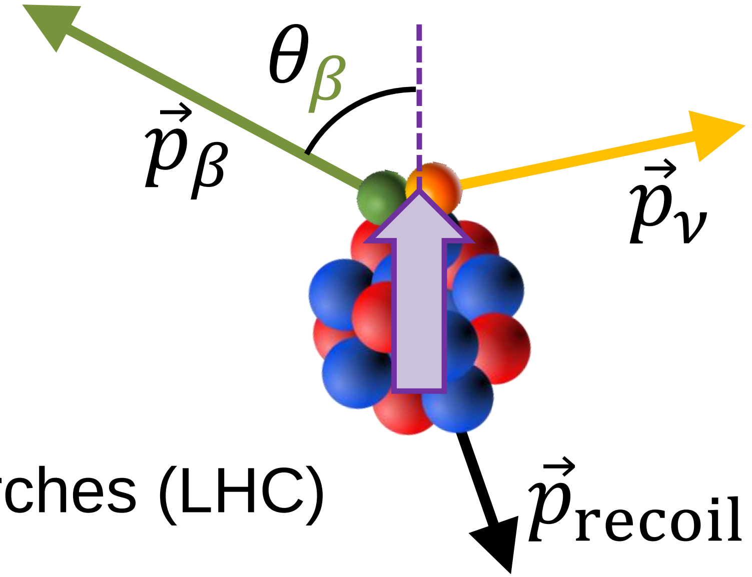
$C_S, C_T \neq 0$

- Profumo, Ramsey-Musolf, Tulin, Phys. Rev. D **75**, 075017 (2007)
- Vos, Wilschut, Timmermans, Rev. Mod. Phys. **87**, 1483 (2015)
- Bhattacharya *et al.*, Phys. Rev. D **94**, 054508 (2016)

The precision frontier

- Goal:
  - To complement high-energy experiments by pushing the precision frontier
  - Angular correlations in β decay: values sensitive to new physics

  (Hopefully you saw the nice talk by González-Alonso this morning)

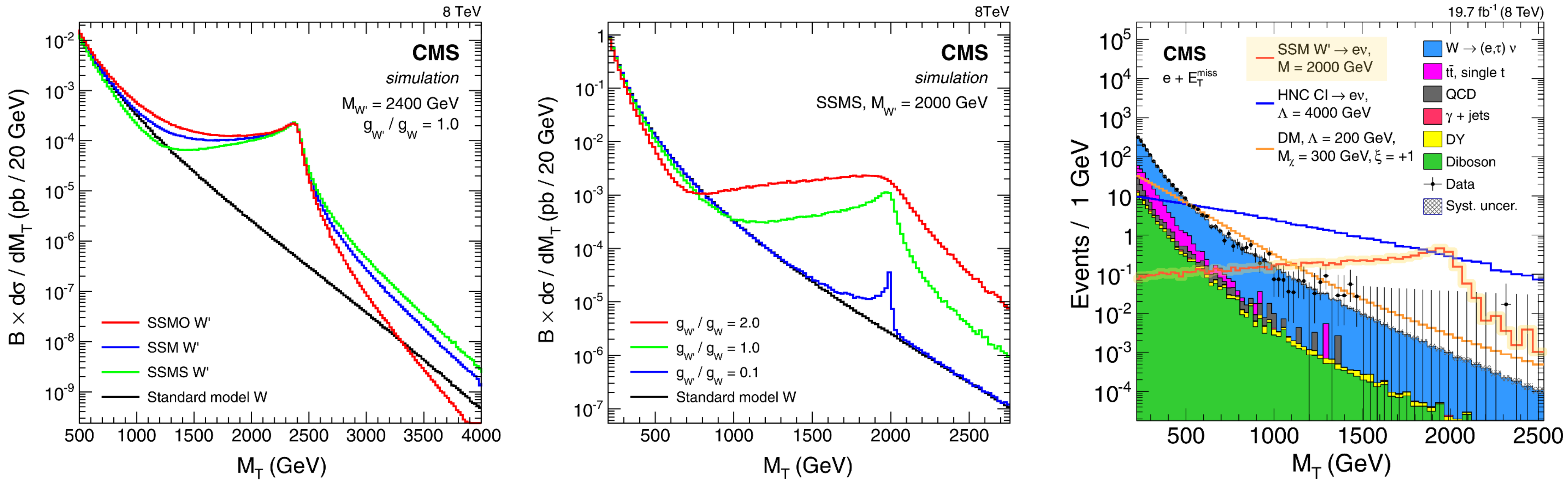


- Global gameplan:
  - Measure the β-decay parameters
  - Compare to SM predictions
  - Look for deviations ⇔ new physics
  - Precision of $\leq \mathbf{0.1\%}$ needed to complement other searches (LHC)

Naviliat-Cuncic and Gonzalez-Alonso, Ann Phys **525**, 600 (2013)
Cirigliano, Gonzalez-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)
González-Alonso, Naviliat-Čunčić and Severijns, arXiv:1803.08732

The energy frontier

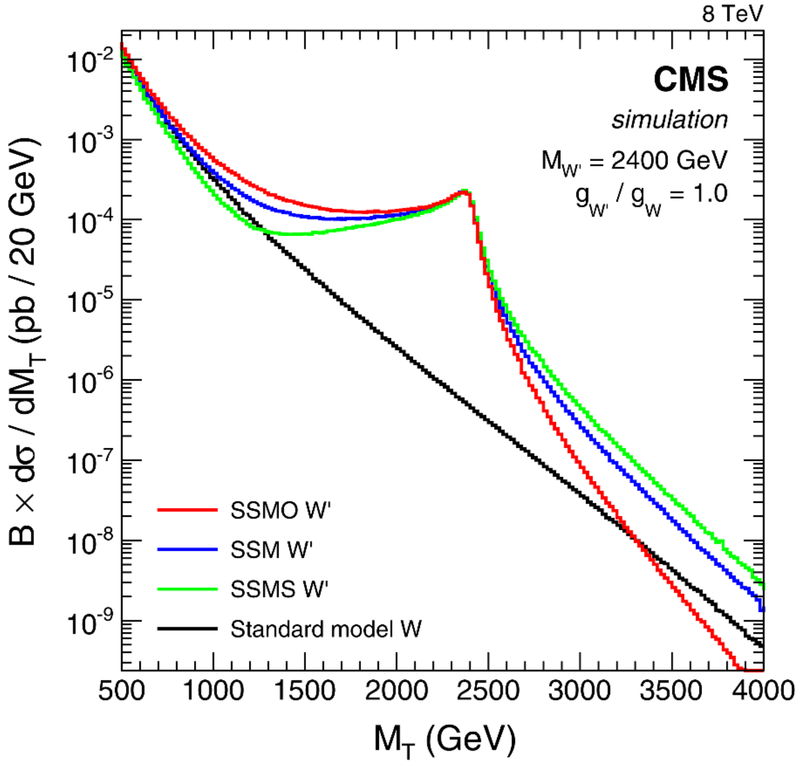
- CMS collaboration, Phys. Rev. D **91**, 092005 (2015)
  - Look for direct production ⇒ excess of events in the missing transverse energy
  - $\sigma(pp \to e + \mathrm{MET} + X)$ channel with $\int L = 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8\ \mathrm{TeV}$

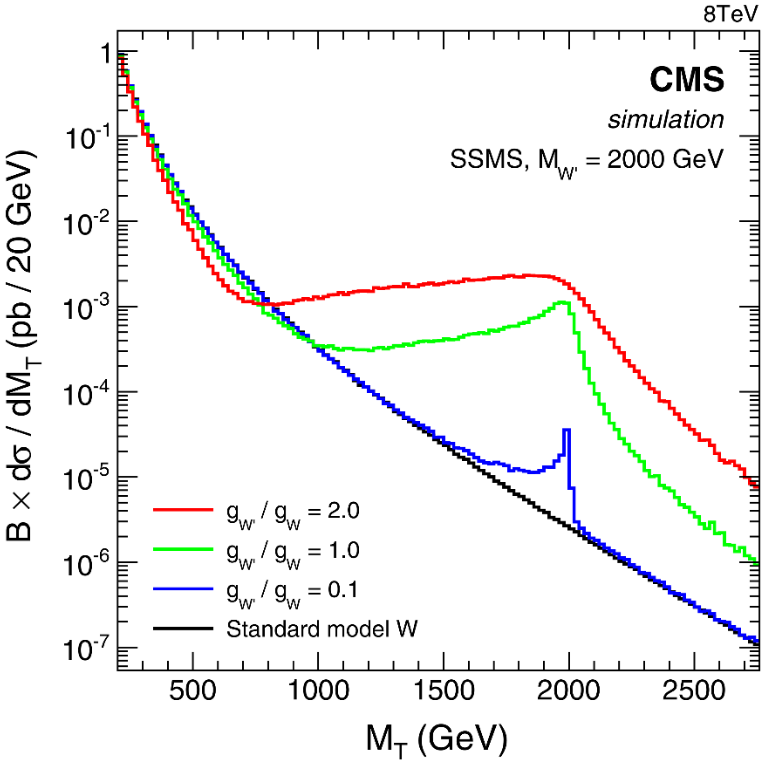


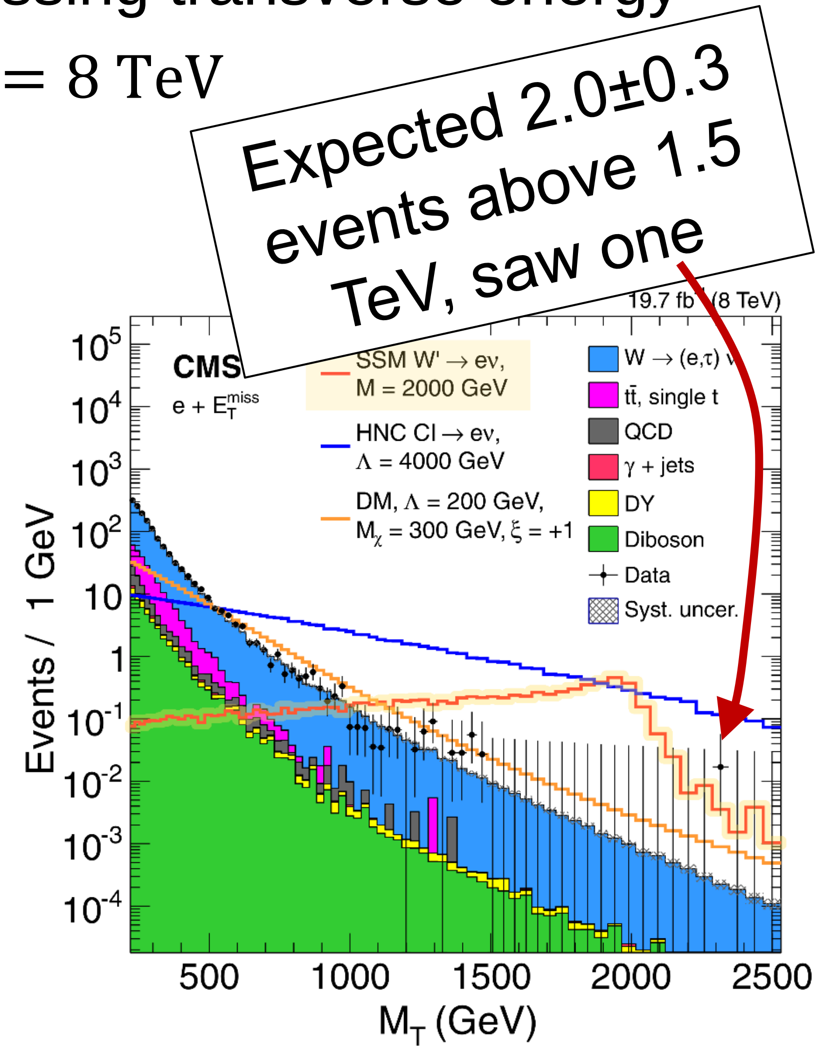
The energy frontier

- CMS collaboration, Phys. Rev. D **91**, 092005 (2015)
  - Look for direct production ⇒ excess of events in the missing transverse energy
  - $\sigma(pp \to e + \mathrm{MET} + X)$ channel with $\int L = 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8\ \mathrm{TeV}$
  - No excess observed ⇝ place limits
    (see Gonzalez-Alonzo, arXiv:1803.08732 for EFT interpretation)

Expected 2.0±0.3 events above 1.5 TeV, saw one

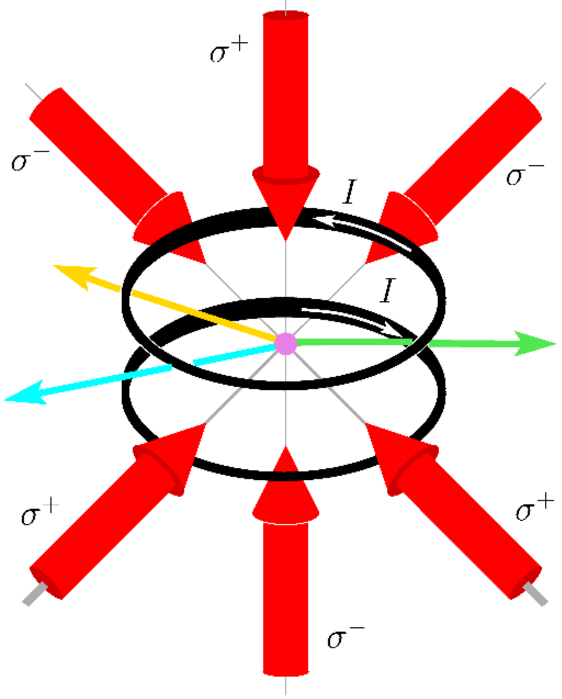




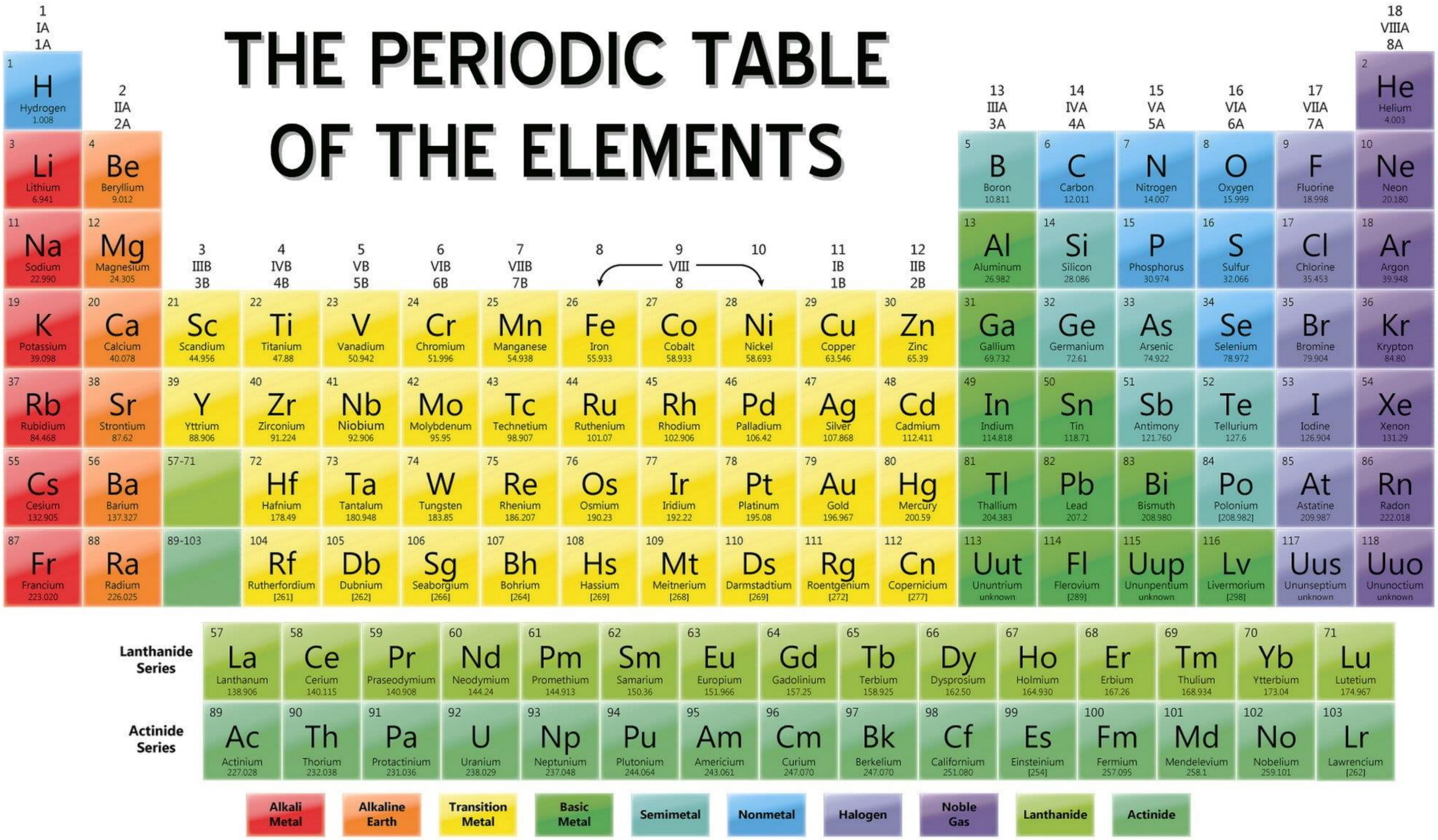


0.1% is a tall order…how to reach that precision?

- Ion traps
  - Can trap any ion
  - Well-known for mass measurements (ISOLTRAP, JYFLTRAP, LEBIT, TITAN,…)
  - Beta-Decay Paul Trap @ ANL
    - β-ν correlation of ^{8}Li to 1%; poised to reach 0.1% precision
  - No other correlation experiments completed yet, but a number are planned:
    - TAMUTRAP @ Texas A&M (^{32}Ar; ^{20}Mg, ^{24}Si, ^{28}S, ^{36}Ca, ^{40}Ti)
    - LPCTrap @ GANIL (^{6}He)
    - EIBT @ Weizmann Institute → SARAF (^{6}He to start)
    - NSLTrap @ Notre Dame (^{11}C, ^{13}N, ^{15}O, ^{17}F)
- Magneto-optical traps
  - Atoms are cold and confined to a small volume
  - Isomerically selective; low backgrounds
  - Very shallow trap, minimal volumes to scatter off



Difficulty with MOTs: not all atoms can be trapped



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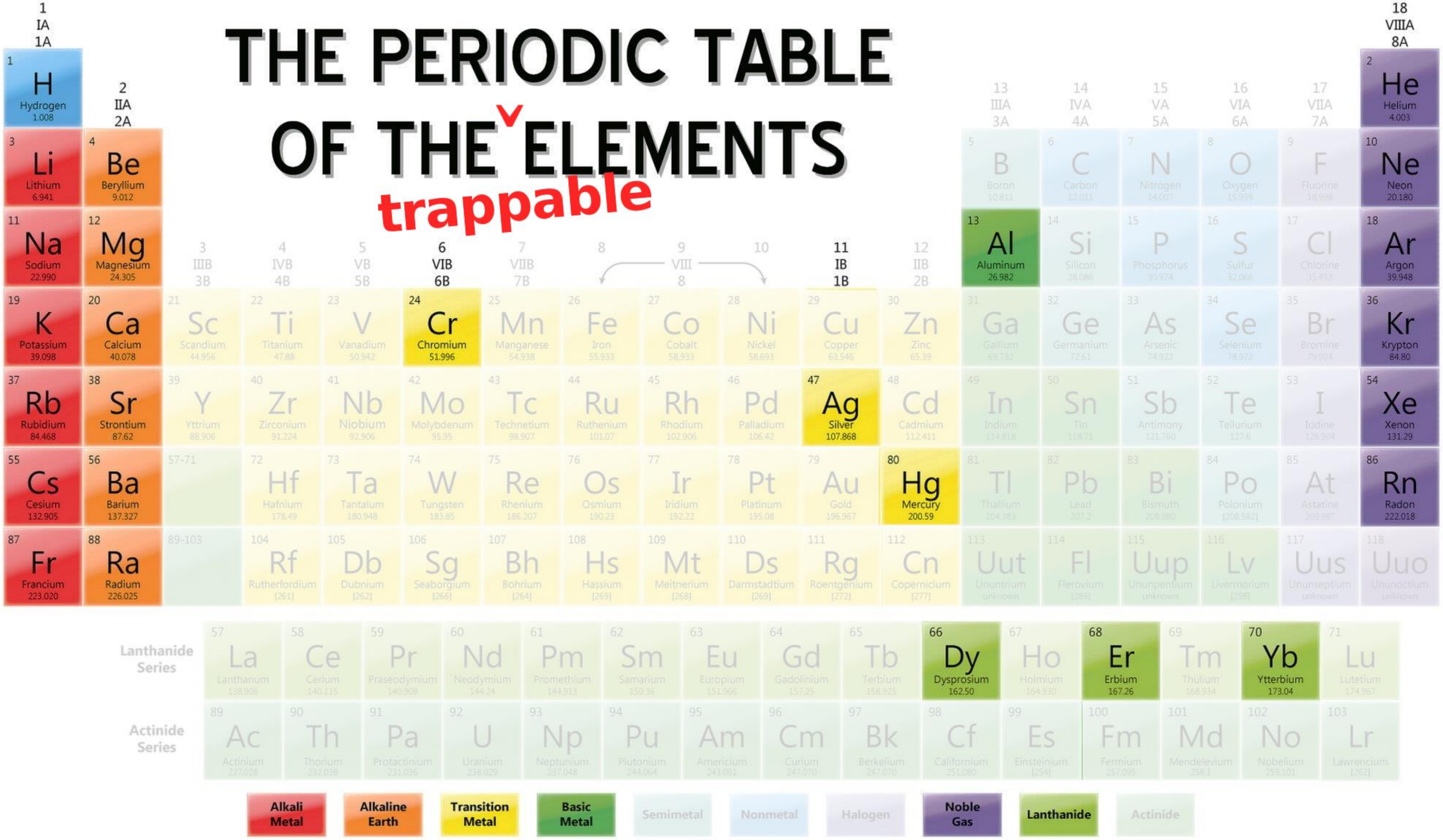

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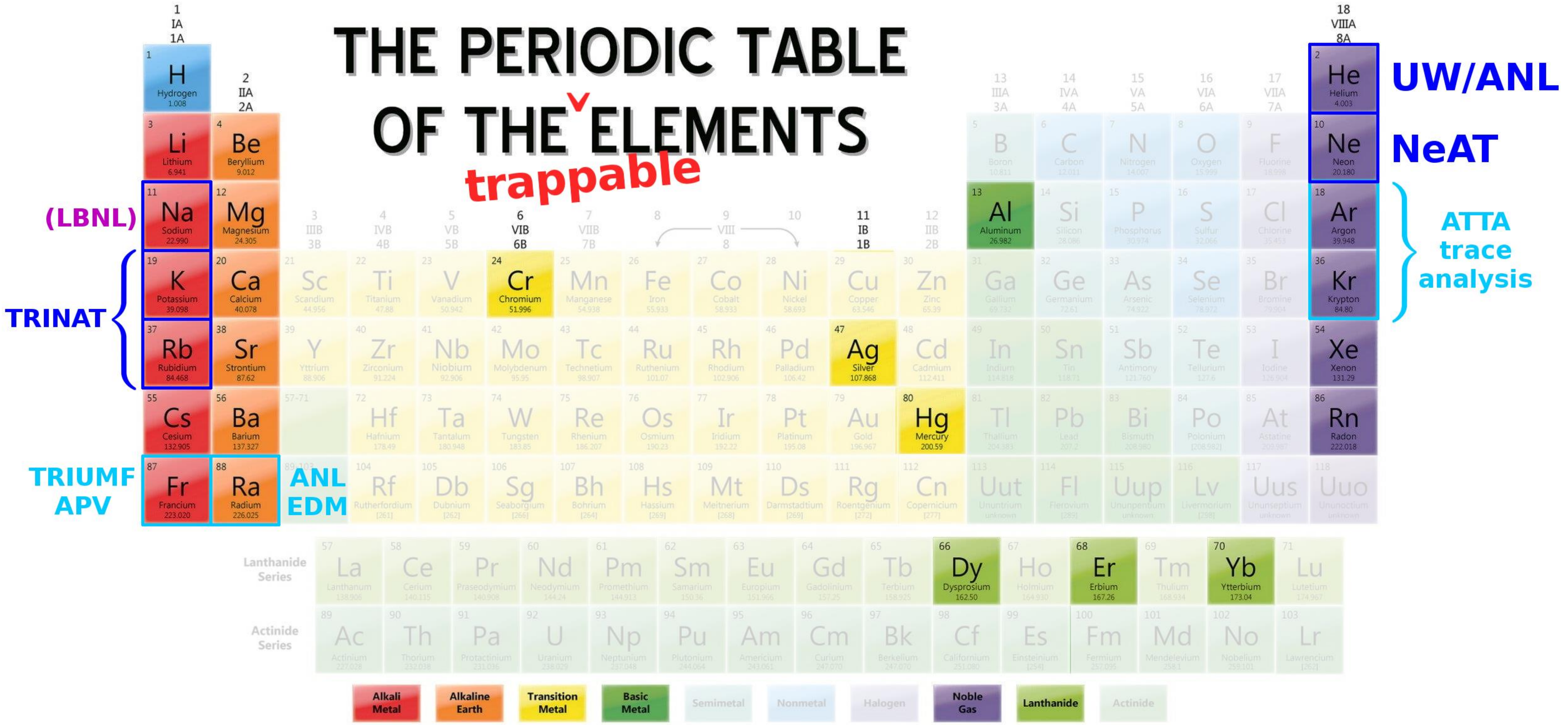

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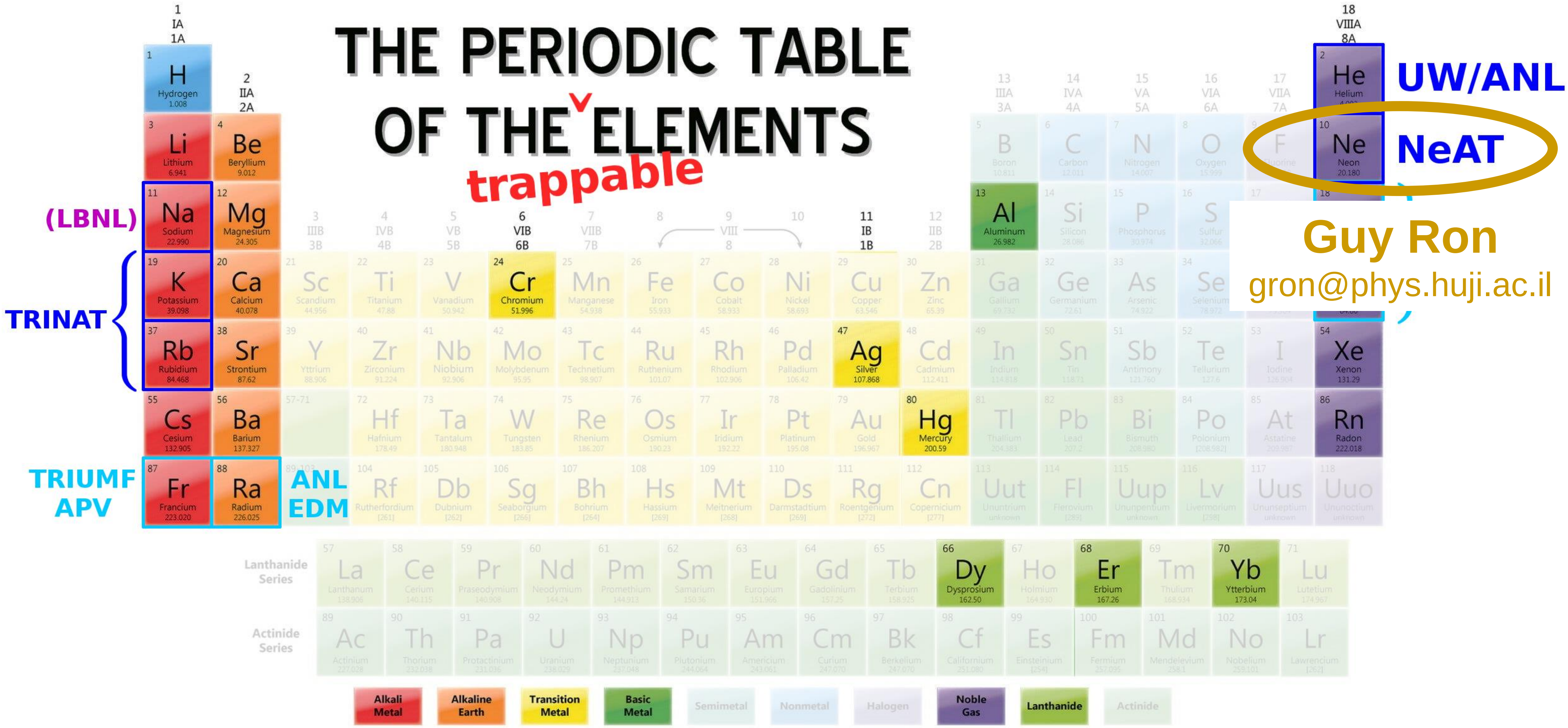
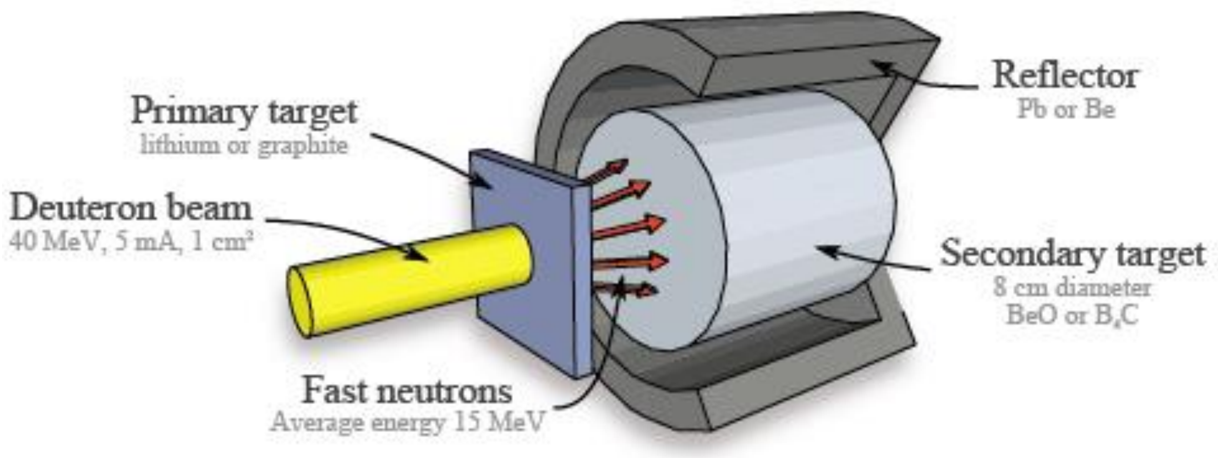


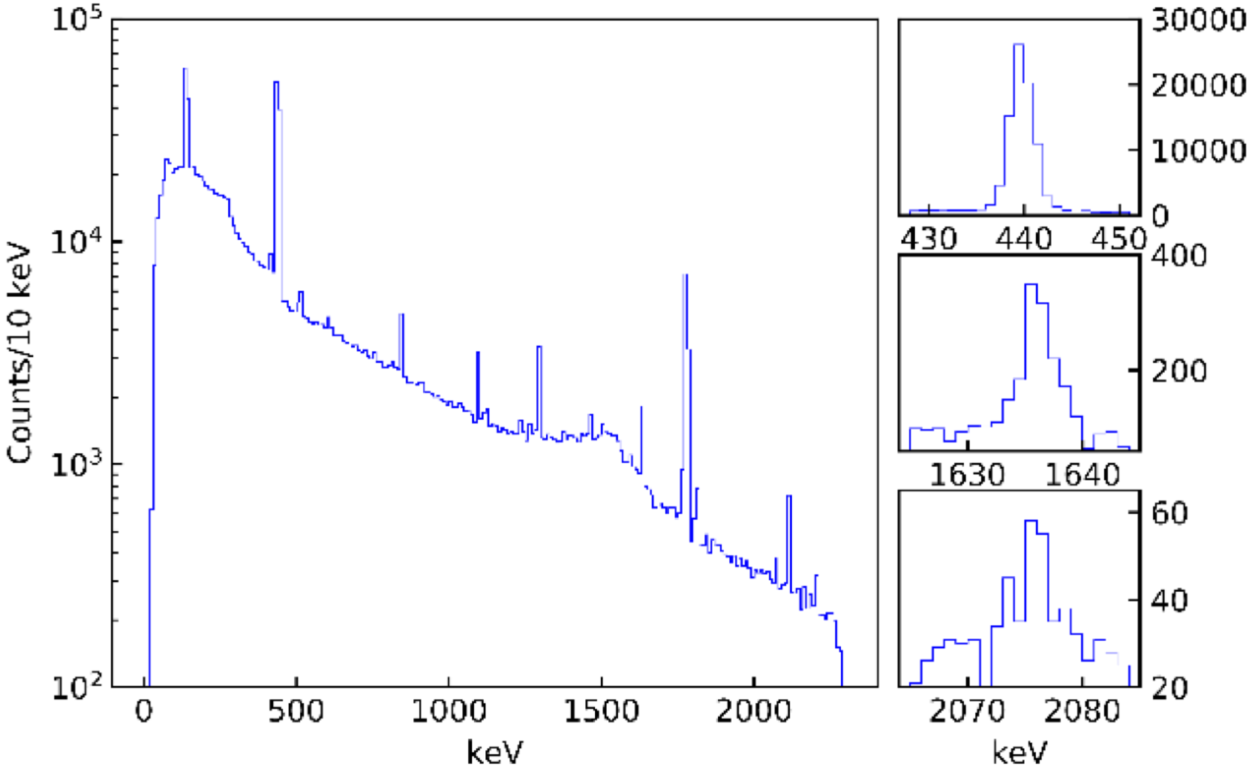
Neon isotopes to be studied, and why

- **^{18}Ne**
  - Pure GT to ground state (tensor interaction)
  - Pure F to 1st excited state (V_{ud})
  - PNC via mixing of 0^- with 0^+
- **^{19}Ne**
  - Mirror transition to ground state (V_{ud}, and if polarized esp. sensitive to RHC)
- **^{23}Ne**
  - Easiest to produce (reaction threshold only 3.8 MeV)
  - Pure GT to ground state; almost pure GT to 1st excited (tensor interaction)
- **^{17}Ne**
  - Large Q-value $\Rightarrow$ Fierz?
  - Interesting spectroscopy (Borromean halo $\rightarrow$ halo ^{17}F)

Production of Ne isotopes @ SARAF

- Initial test @ WI successful ⇒ able to produce and move ^{23}Ne
- SARAF: New, (very) high current *p*/*d* accelerator (5 mA/up to 40 MeV) under construction at SOREQ
  - Currently running *d* beams on LiF target for neutron beam production with SARAF-I





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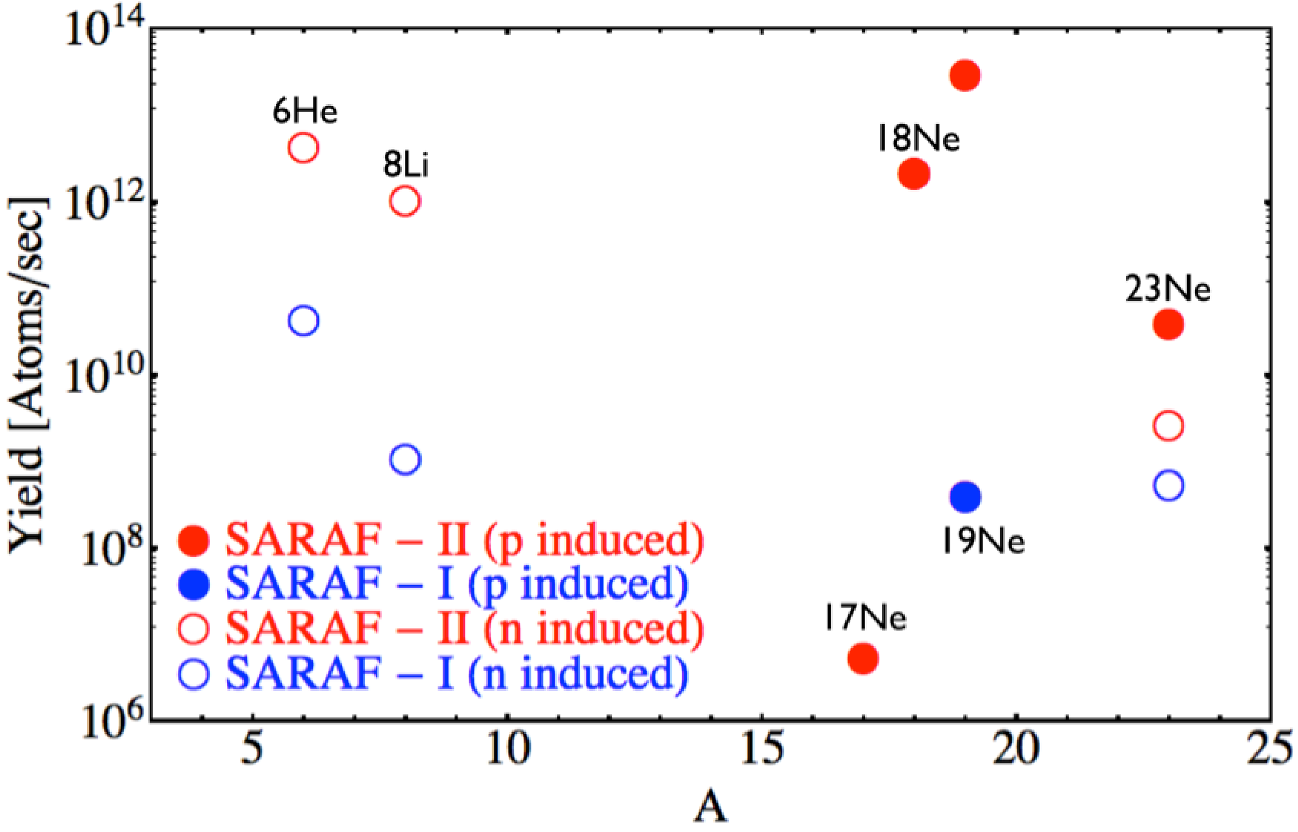
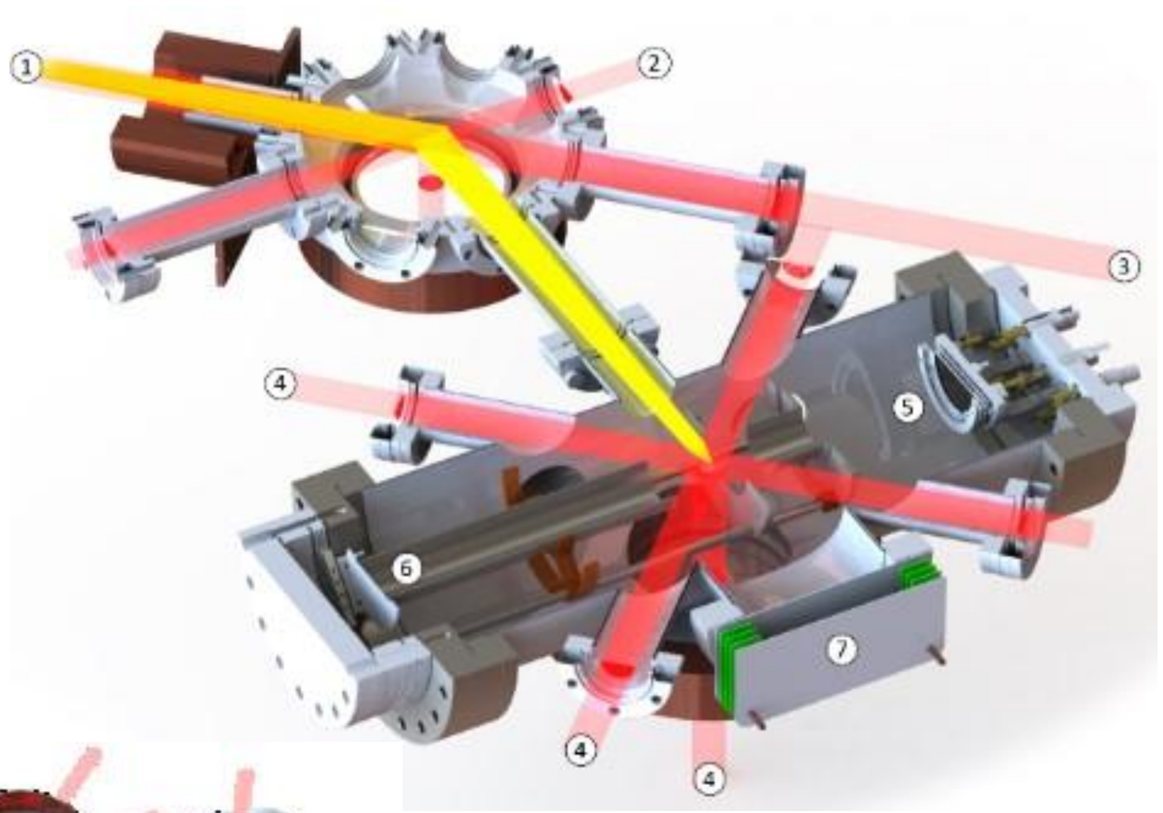
  - Currently running *d* beams on LiF target for neutron beam production with SARAF-I
  - Neutron production also possible with liquid-Li (under construction)

High yields expected!



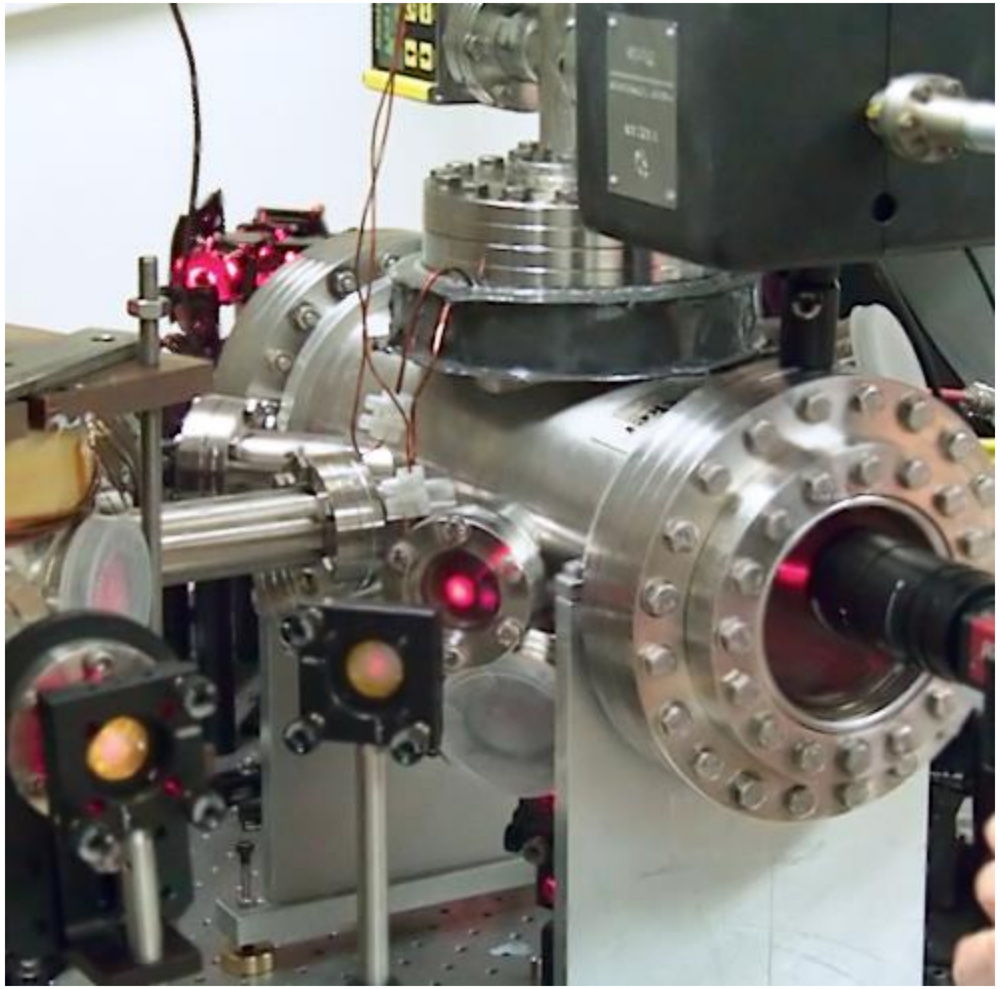
Trapping Ne isotopes with NeAT

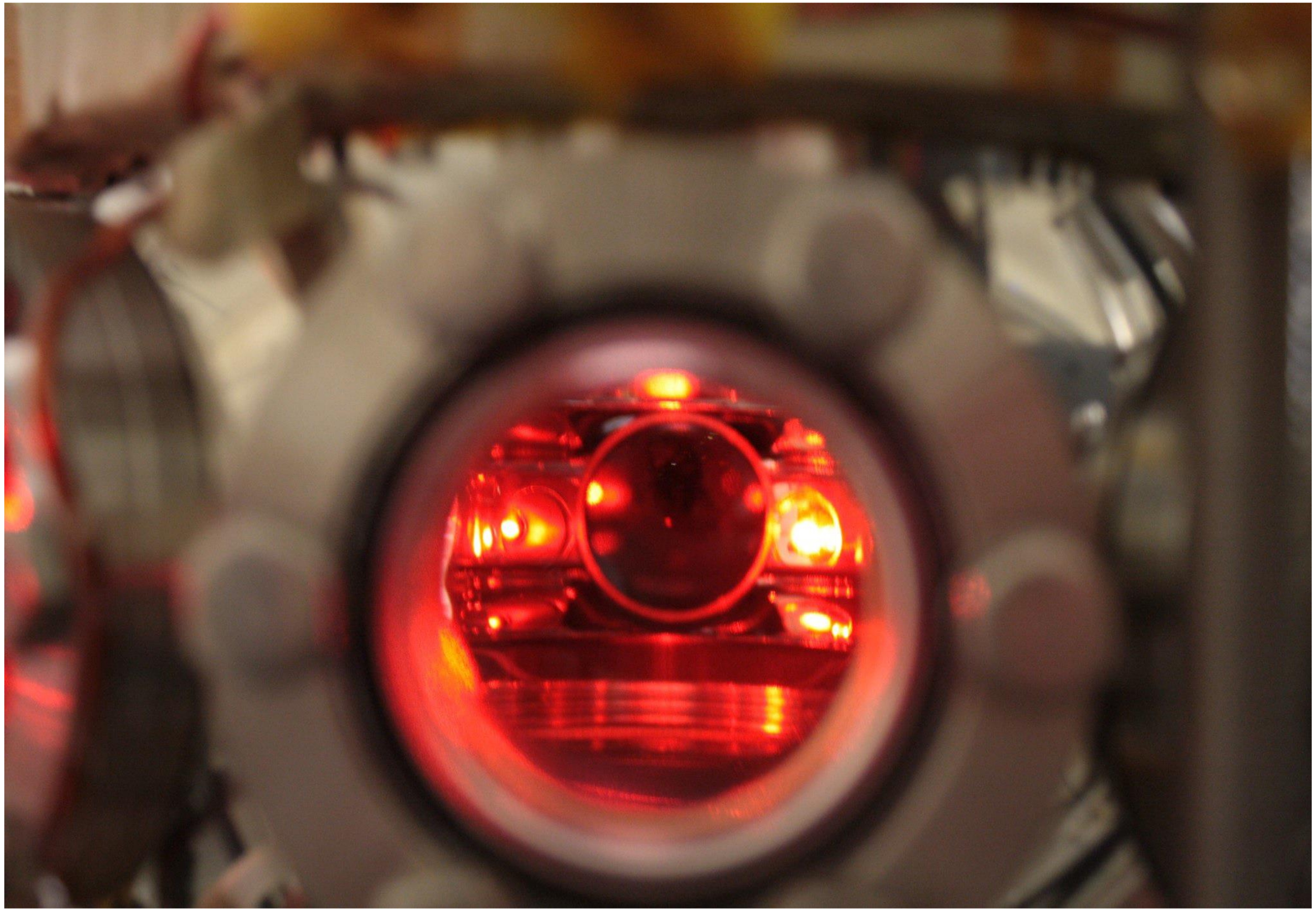
- Produce and transport to NeAT
- Excite to metastable state ($\varepsilon \sim 10^{-5}$)
- Zeeman slower and deflector to reduce backgrounds
- Trap in science chamber, observe β and recoil



Status of NeAT

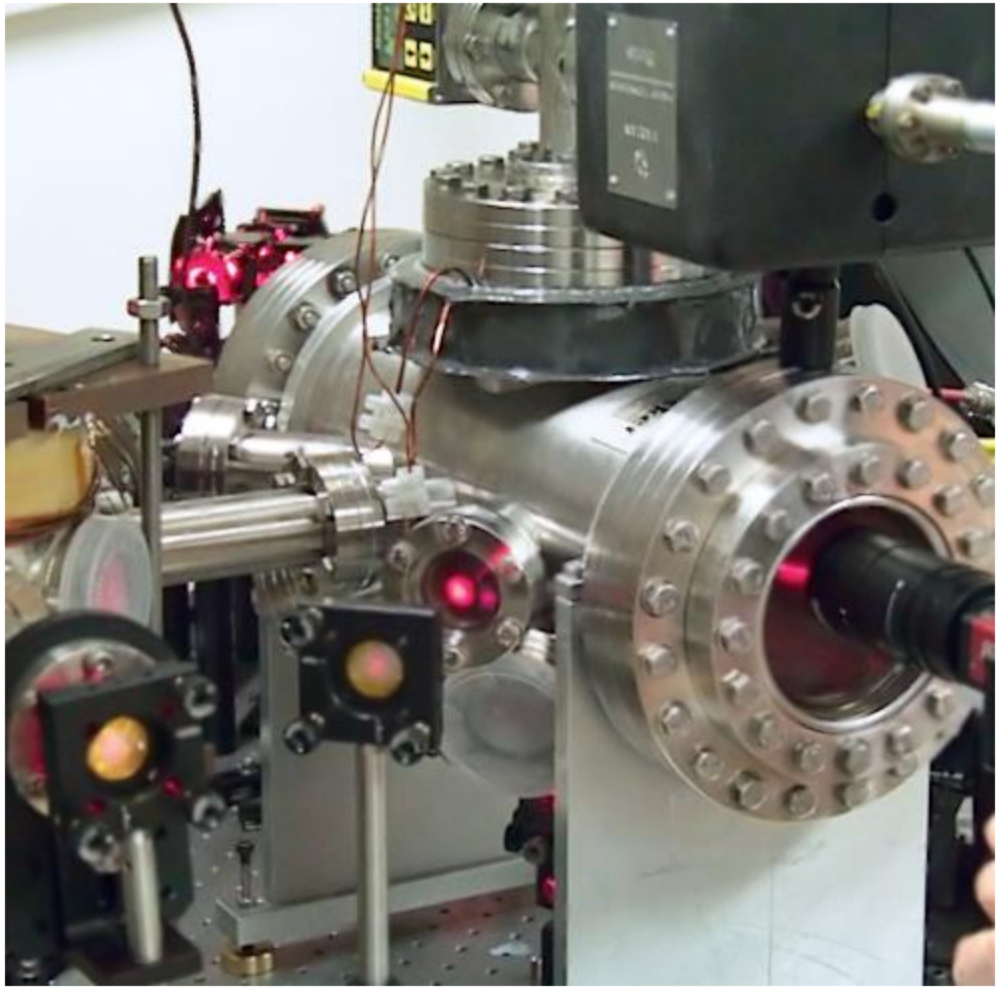
- Demonstrated ability to trap ~10,000 Ne atoms





Status of NeAT

- Demonstrated ability to trap ~10,000 Ne atoms
- Recently moved to SARAF



^{6}He at UW

- Most sensitive probe is the Fierz interference:
  - Decay rate is: $dw = dw_0 \left[1 + a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{\Gamma m_e}{E_e}\right]$
- ^{6}He is a great case!
  - Large endpoint (3.5 MeV)
  - Nuclear structure under control
  - Simple decay
  - Sensitive to tensor interactions

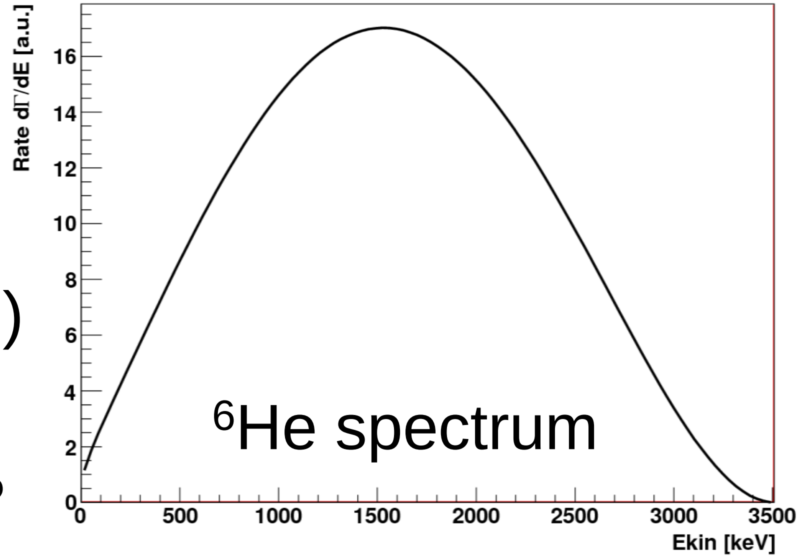
$$\boxed{a_{\beta\nu} \approx -\frac{1}{3}\left(1 - \frac{C_T^2 + C'^2_T}{2C_A^2}\right)}$$

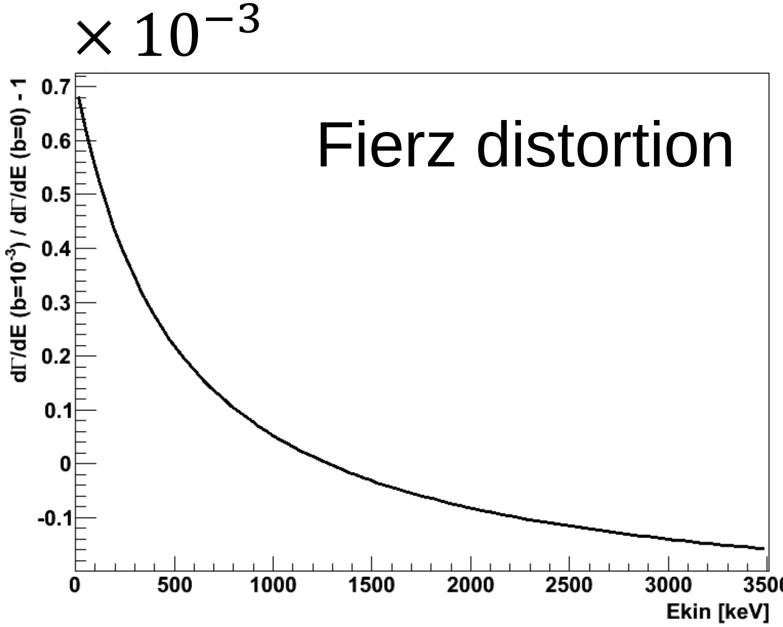
$\beta - \nu$ correlation

$$\boxed{b \approx \pm \frac{(C_T + C_T{}')}{C_A}}$$

Fierz interference

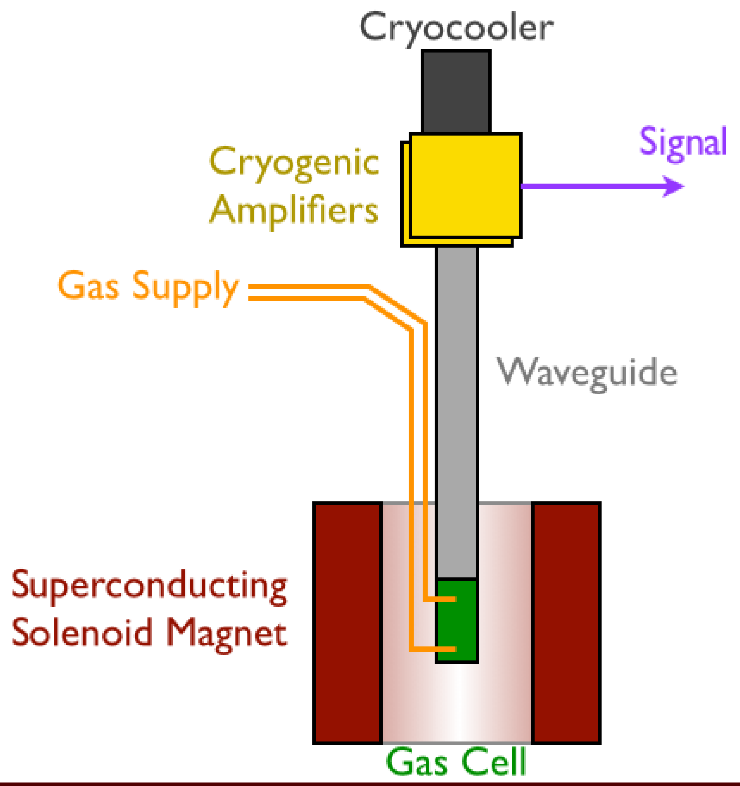
- Status:
  - Lifetime (PRC **86**, 035506)
  - Charge state fractions
  - $a_{\beta\nu}$: stats for 0.2%; systs?

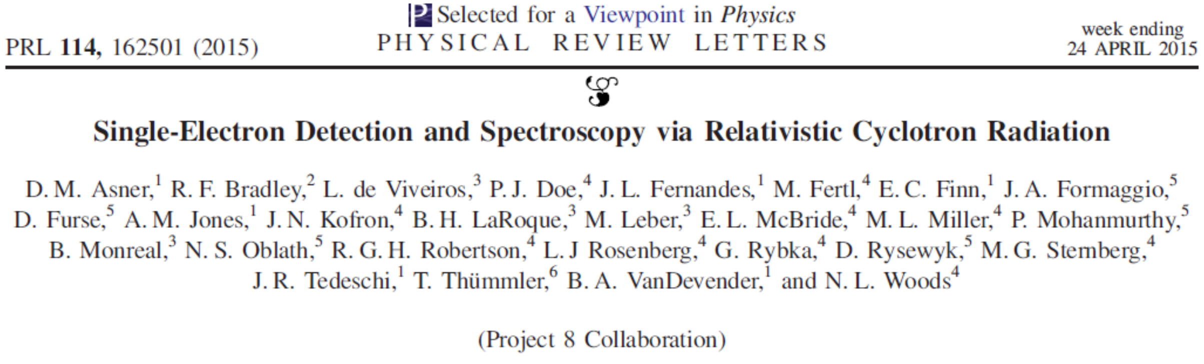




^{6}He at UW – CRES technique

- New idea: use the Cyclotron Radiation Emission Spectroscopy (CRES) technique
  - Project 8 collaboration gets $\frac{FWHM}{E} \approx 10^{-3}$ resolution for conversion electrons of 18 – 32 keV



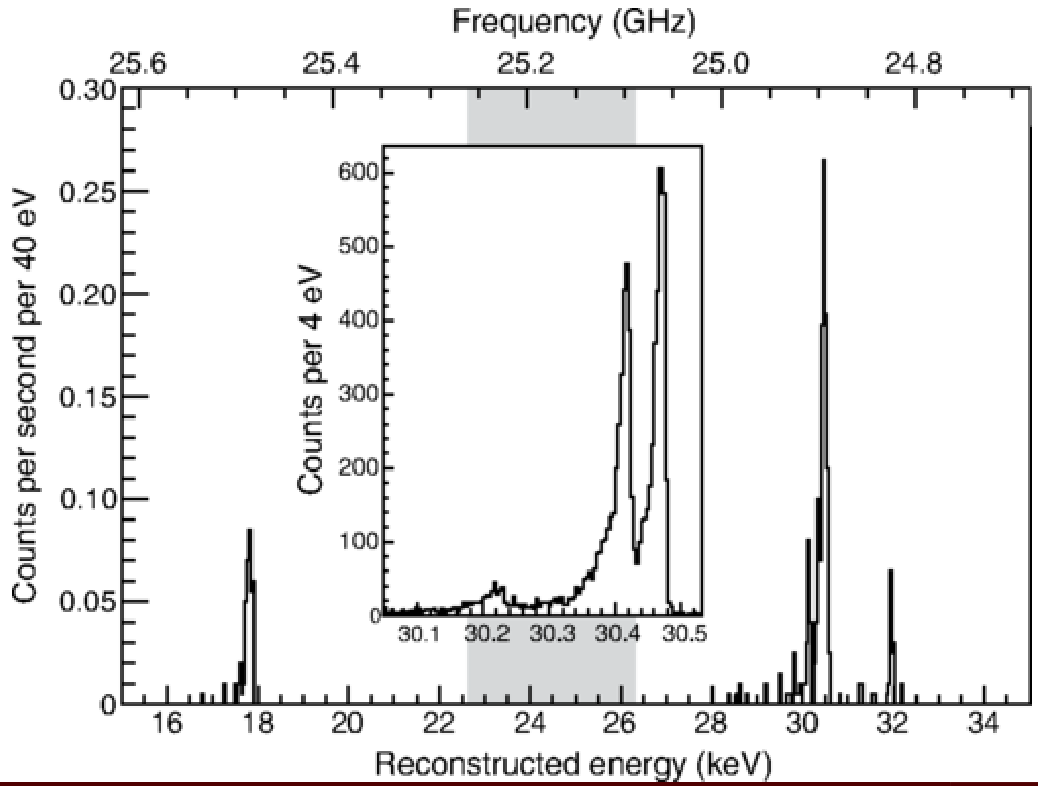


Selected for a Viewpoint in *Physics*
PRL **114,** 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. G. H. Robertson,[4] L. J Rosenberg,[4] G. Rybka,[4] D. Rysewyk,[5] M. G. Sternberg,[4] J. R. Tedeschi,[1] T. Thümmler,[6] B. A. VanDevender,[1] and N. L. Woods[4]

(Project 8 Collaboration)

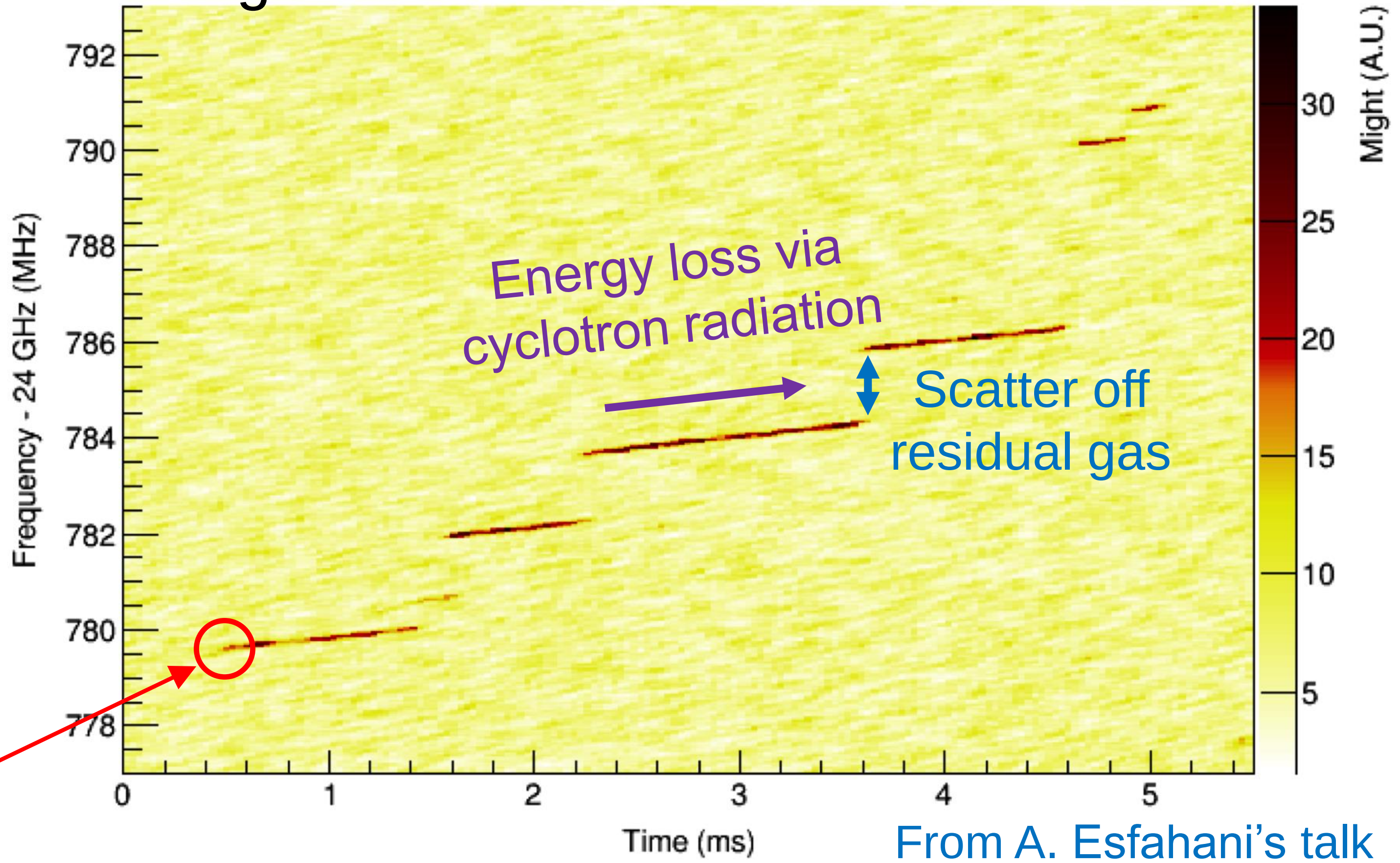


^{6}He at UW – CRES technique

- Why CRES for ^{6}He?
  - Measures β energy at creation, before complicated energy-loss mechanisms
  - High resolution allows debugging of systematic uncertainties
  - No background from photon or e scattering
  - ^{6}He in gaseous form works well with the technique
  - ^{6}He ion trap allows sensitivity higher than any other proposed
  - Counts needed not a big demand on running time

$$2\pi f = \frac{qB}{m + E_{\text{kin}}}$$

Initial frequency → E



From A. Esfahani's talk

Emerging ^{6}He little-*b* collaboration

W. Byron[1], M. Fertl[1] , A. Garcia[1], B. Graner[1], G. Garvey[1], M. Guigue[4], K.S. Khaw[1], A. Leredde[2], D. Melconian[3], P. Mueller[2], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[5], H.E. Swanson[1], B.A. Vandeevender[4], F. Wietfeldt[6], A. Young[5]

[1]*University of Washington*, [2]*Argonne National Lab*, [3]*Texas A&M*, [4]*North Carolina State University*, [5]*Pacific Northwest National Laboratory*, [6]*Tulane University*

- Phase I: proof of principle (next 3 yrs)
  - 2 GHz bandwidth
  - Show detection of cyclotron radiation from ^{6}He
  - Study power distribution

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  - Show detection of cyclotron radiation from ^{6}He
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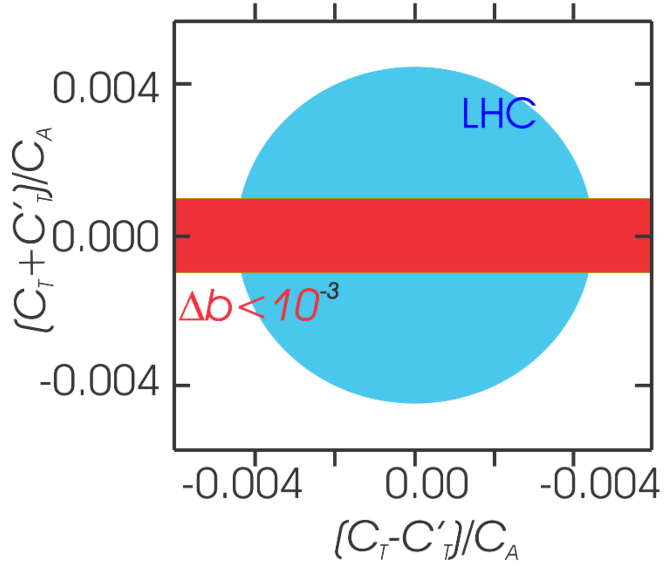
- Phase II: first measurement ($b < 10^{-3}$)
  - 6 GHz bandwidth
  - ^{6}He and ^{19}Ne measurements

Effect	Δb No trap	Δb Ion trap
Magnetic field uncertainties	10^{-4}	$< 10^{-4}$
Wall effect uncertainties	10^{-3}	
RF pickup uncertainties	10^{-4}	10^{-5}
Misidentification of events	10^{-4}	5×10^{-5}



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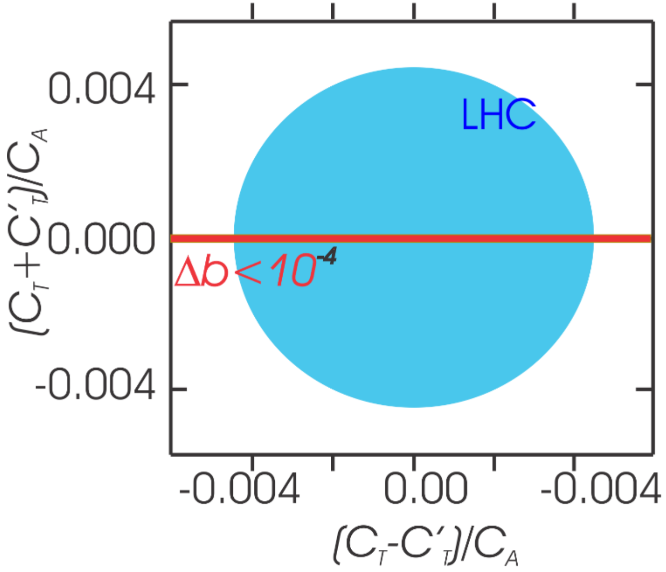
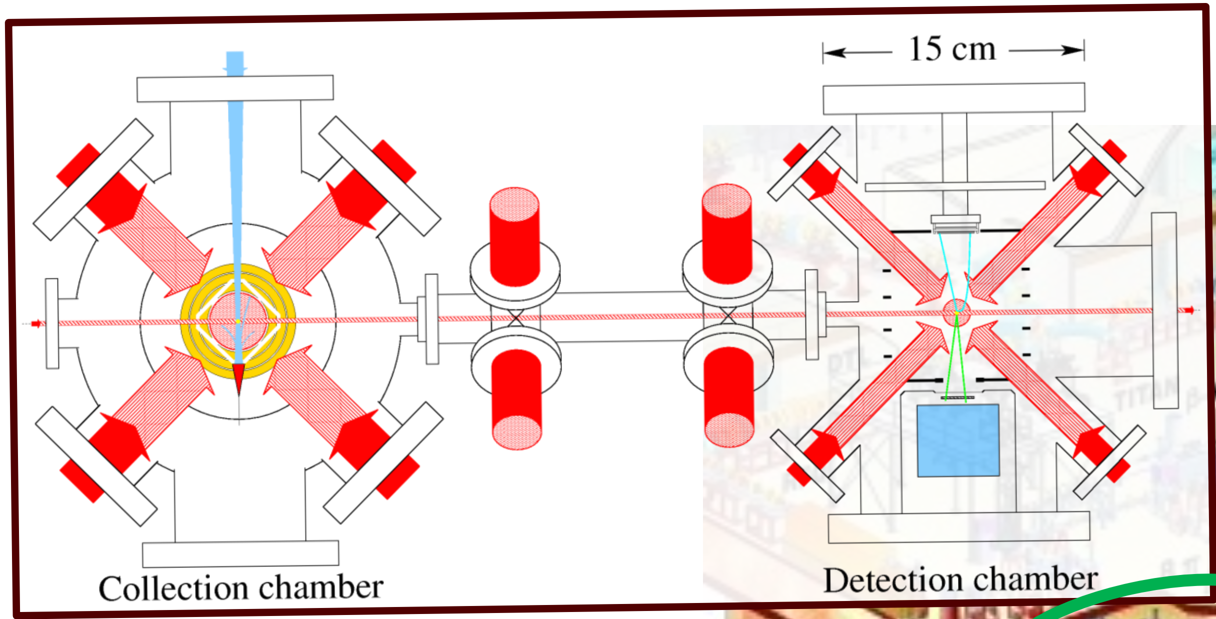
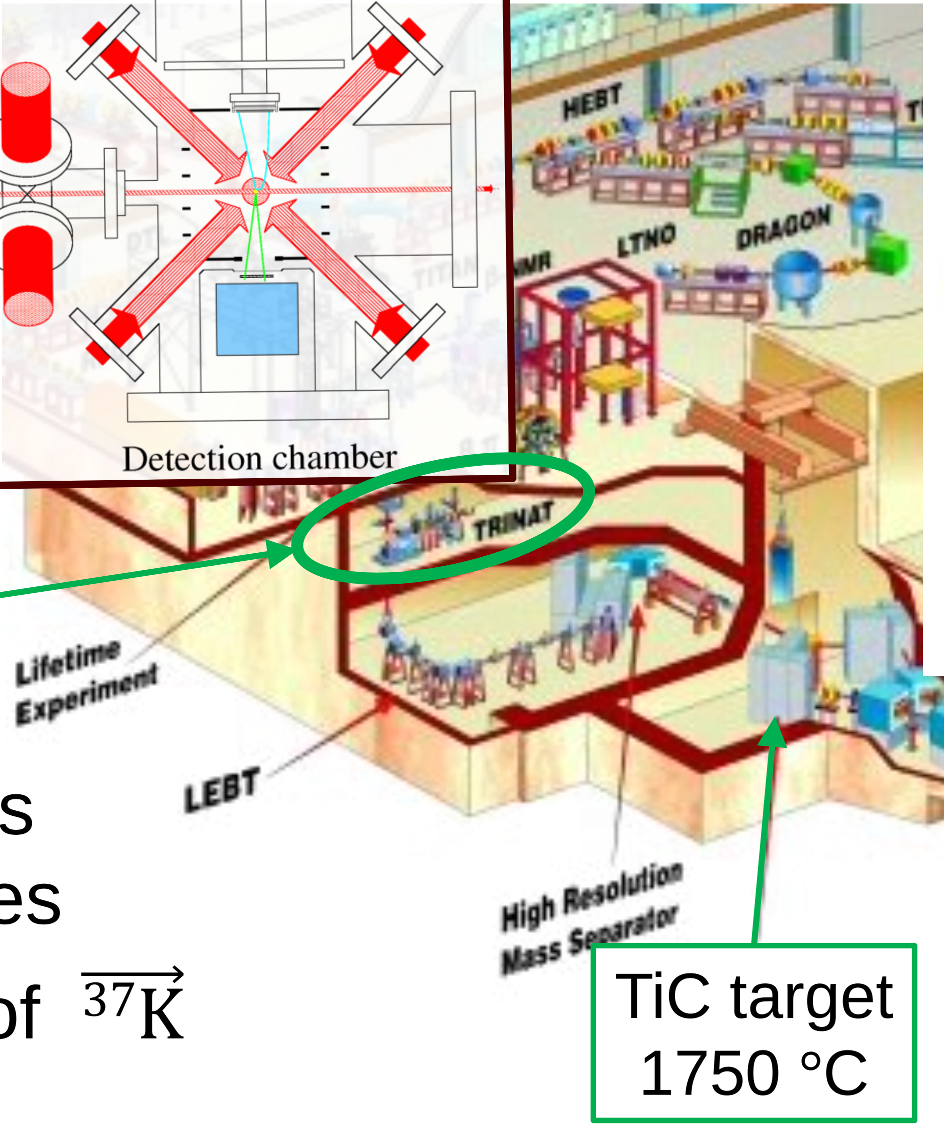
- Phase II: first measurement ($b < 10^{-3}$)
  - 6 GHz bandwidth
  - ^{6}He and ^{19}Ne measurements
- Phase III: ultimate measurement ($b < 10^{-4}$)
  - Ion trap for no limitation from geometric effect

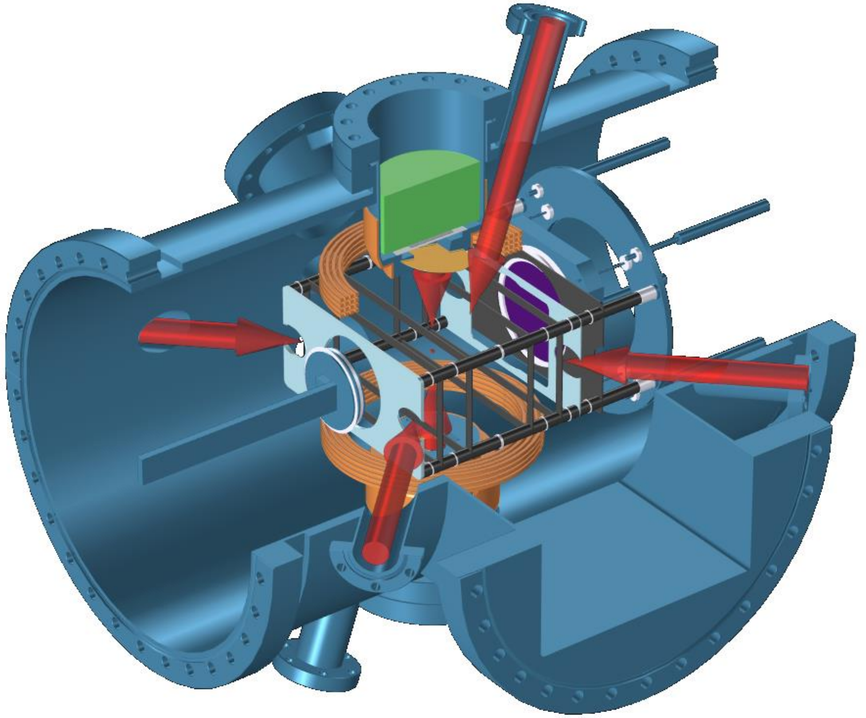
Effect	Δb	
	No trap	Ion trap
Magnetic field uncertainties	10^{-4}	$< 10^{-4}$
Wall effect uncertainties	10^{-3}	
RF pickup uncertainties	10^{-4}	10^{-5}
Misidentification of events	10^{-4}	5×10^{-5}



The TRIUMF Neutral Atom Trap







up to 8×10^7 ^{37}K/s

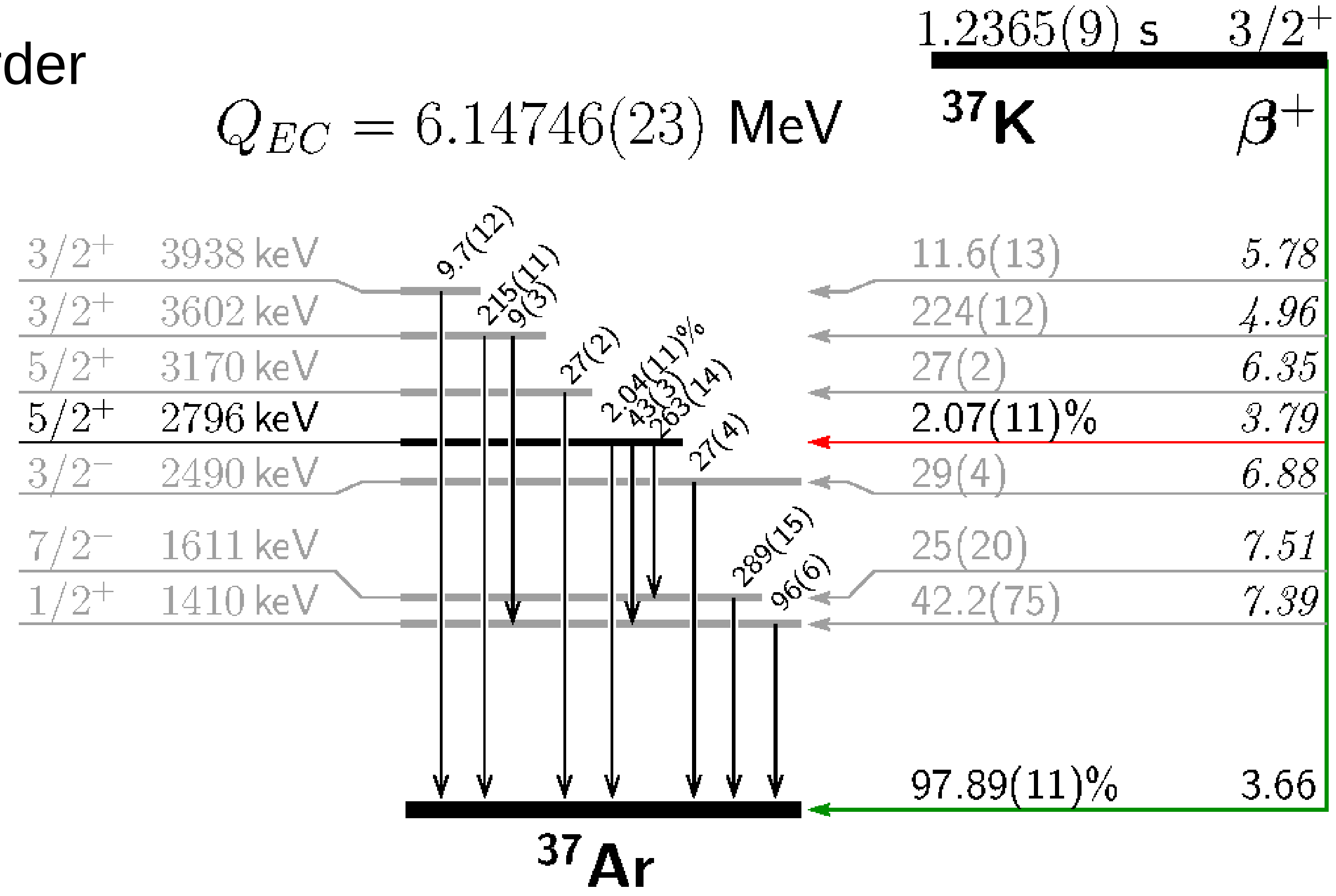
TiC target 1750 °C

70 µA protons

- Angular correlations of K and Rb isotopes
- Recent result: A_β of $\overrightarrow{^{37}\mathrm{K}}$

Isobaric analogue decay of ^{37}K

- Beautiful nucleus to test the standard model:
  - Alkali atom ⇒ “easy” to trap with a MOT and polarize with optical pumping
  - Isobaric analogue decay
    ⇒ theoretically clean; recoil-order corrections under control
  - Lifetime, Q-value and branches (*i.e.* the $\mathcal{F}t$ value) well known
  - Strong branch to the g.s.



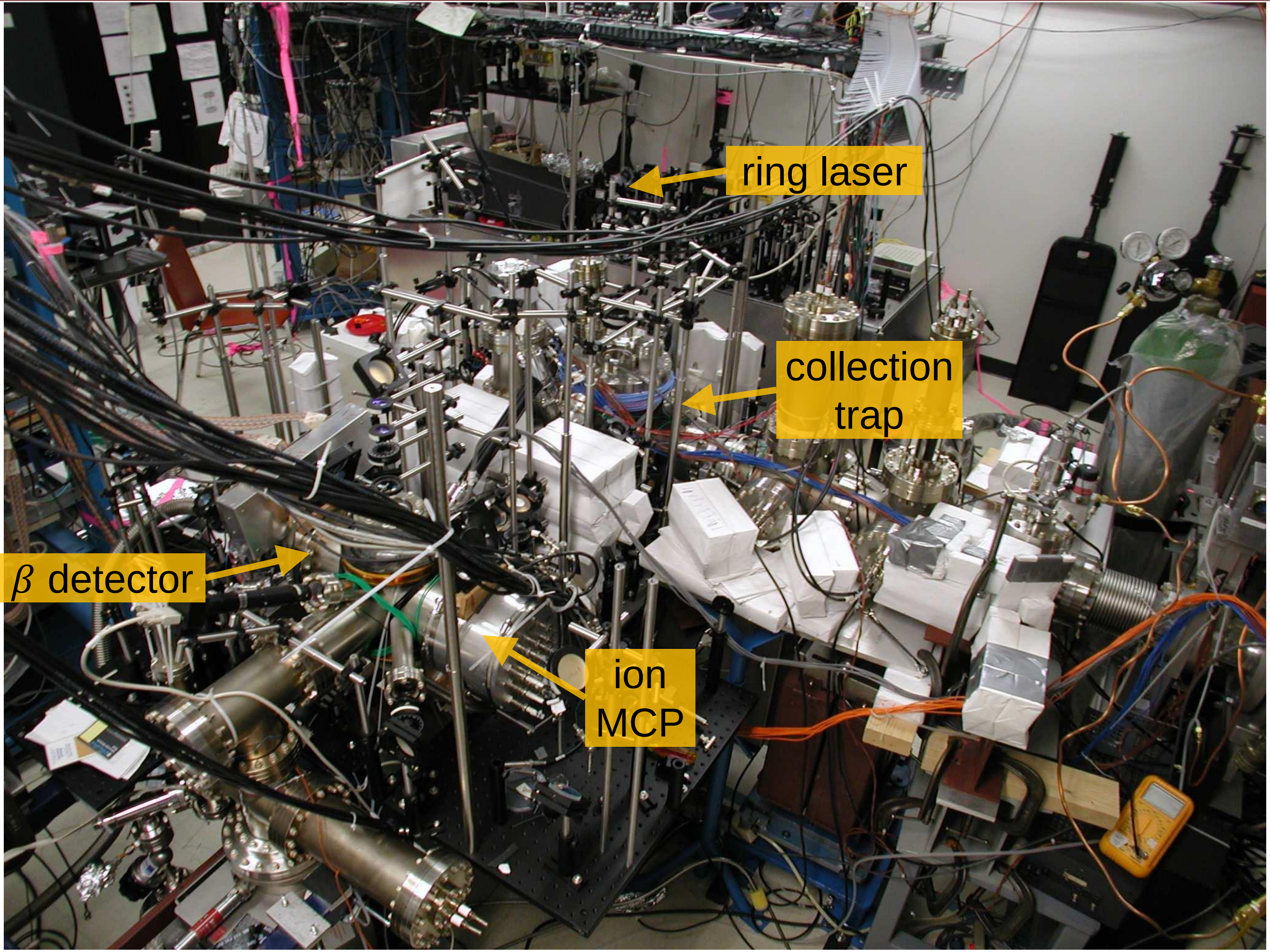
The Ft is measured well enough (for now)

$$dW = dW_0 \left[1 + a\frac{\vec{p}_\beta \cdot \vec{p}_\nu}{E_\beta E_\nu} + b\frac{\Gamma m_e}{E_\beta} + \frac{\langle \vec{I} \rangle}{I} \cdot \left(A_\beta \frac{\vec{p}_\beta}{E_\beta} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\beta \times \vec{p}_\nu}{E_\beta E_\nu} \right) + \begin{array}{c}\text{alignment}\\ \text{term}\end{array} \right]$$

Correlation	SM expectation	
$\beta - \nu$ correlation	$a_{\beta\nu} = 0.6648(18)$	
Fierz interference	$b = 0$	(sensitive to scalars & tensors)
$\boldsymbol{\beta}$ asymmetry	$\boldsymbol{A_\beta = -0.5706(7)}$	
ν asymmetry	$B_\nu = -0.7702(18)$	
Time-violating correlation	$D = 0$	(sensitive to imaginary couplings)

⇝ Data is in hand for improved branching ratio (currently limits predictions)

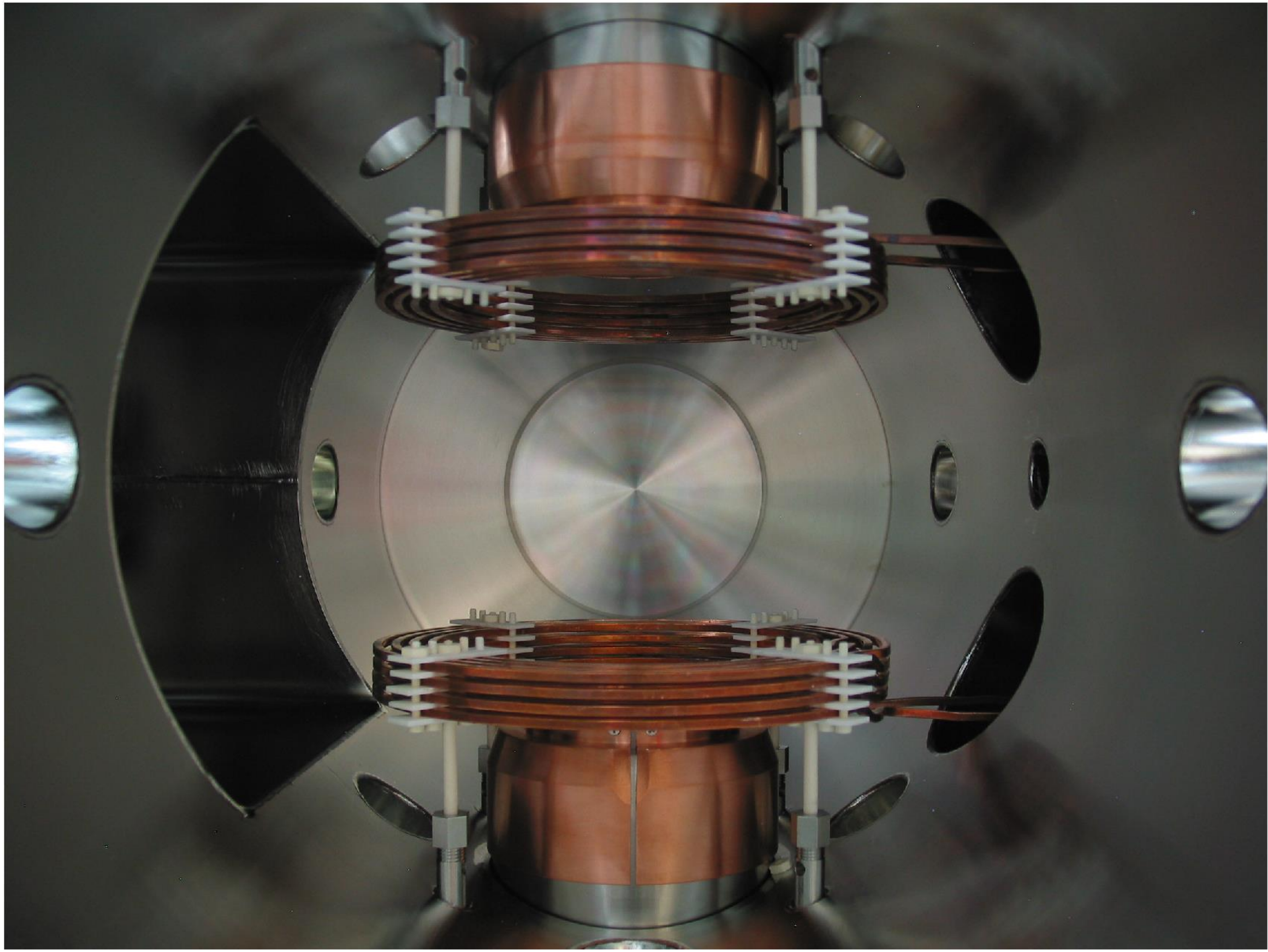
The TRINAT lab (an older picture)



RIB from ISAC

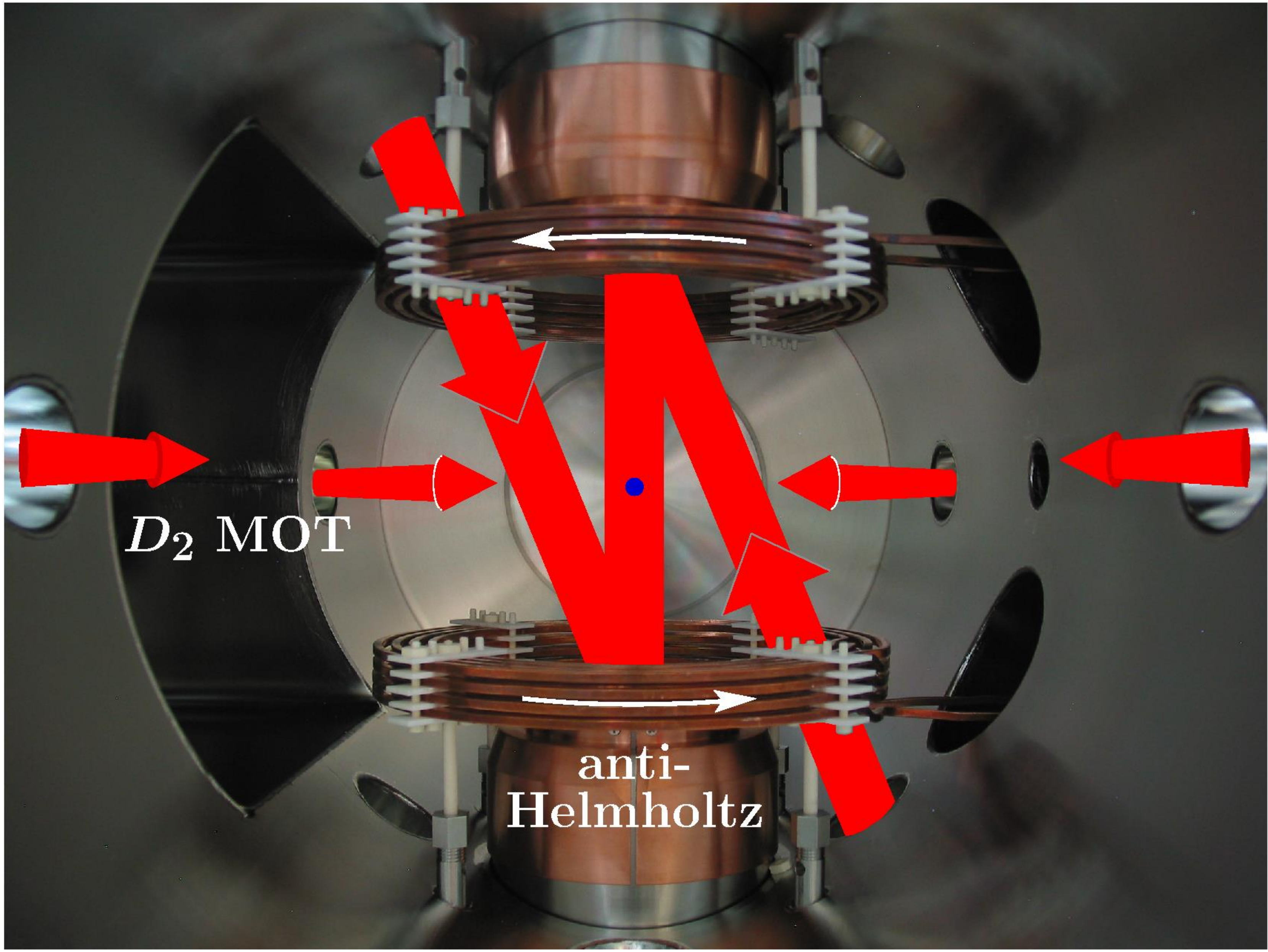
Outline of β asym & polarization measurements

- Not shown:
  - Recoil MCP detector into page
  - Shake-off e^- MCP out of page
  - Hoops for electric field to collect recoil and shake-off e^-
  - The β telescopes within the re-entrant flanges (top *and* bottom)



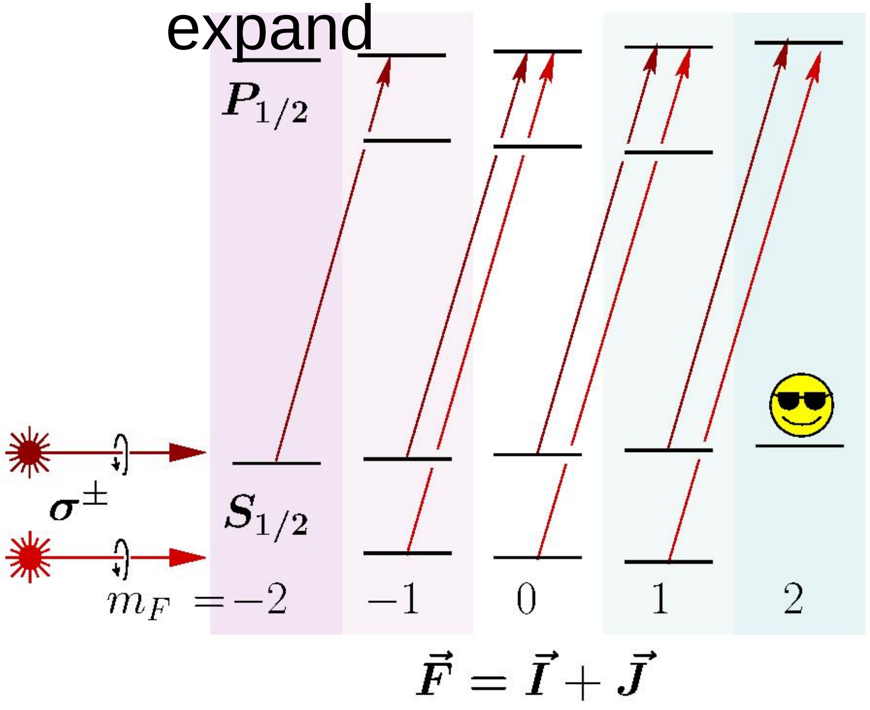
Outline of β asym & polarization measurements

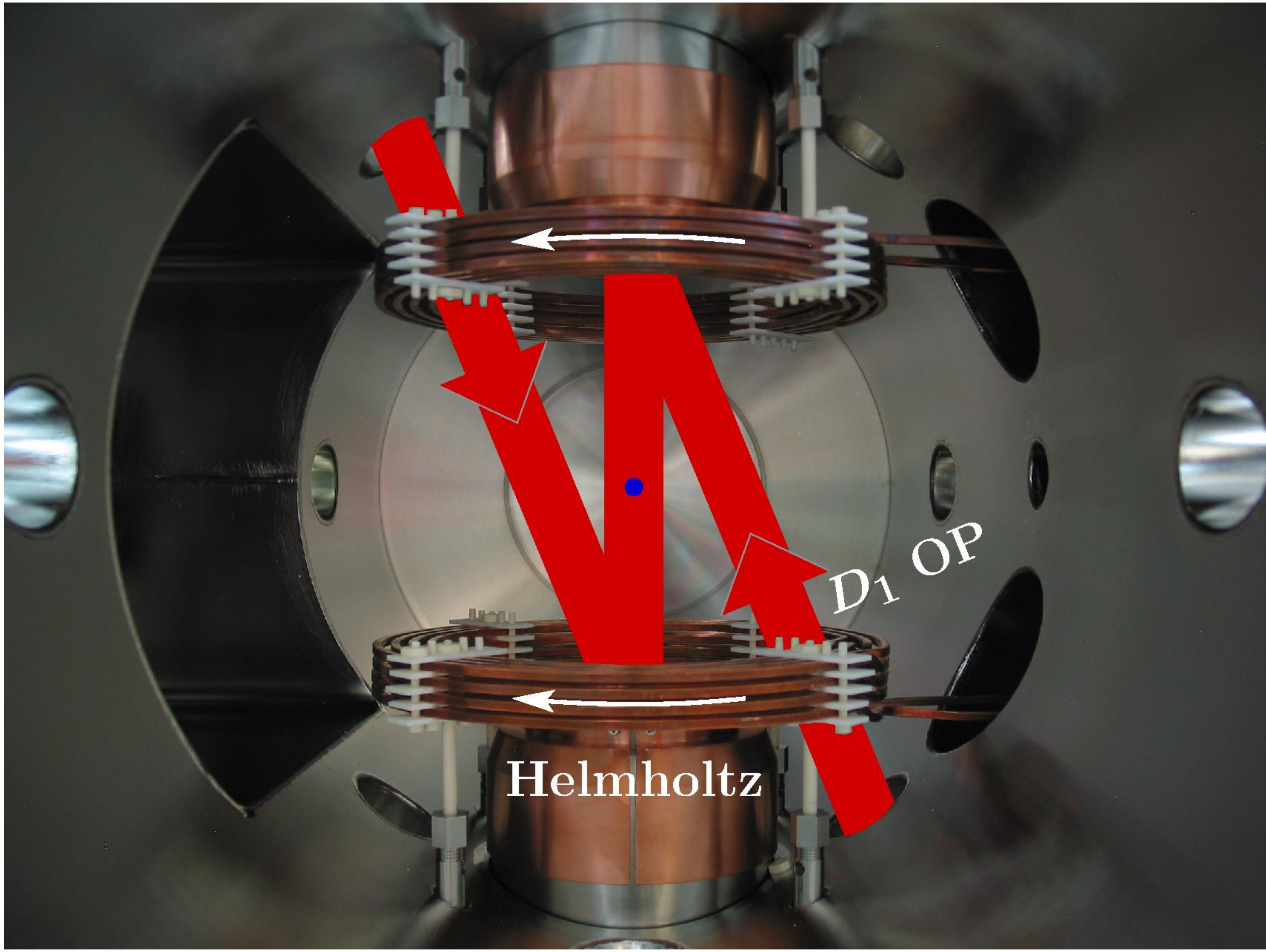
- MOTs provide a source that is:
  - Cold ($\sim 1\ \mathrm{mK}$)
  - Localized ($\sim 1\ \mathrm{mm}^3$)
  - In an open, backing-free geometry
- Allows us to detect $\vec{p}_\beta$ and $\vec{p}_{\mathrm{rec}}$ $\Rightarrow$ deduce $\vec{p}_\nu$ event-by-event



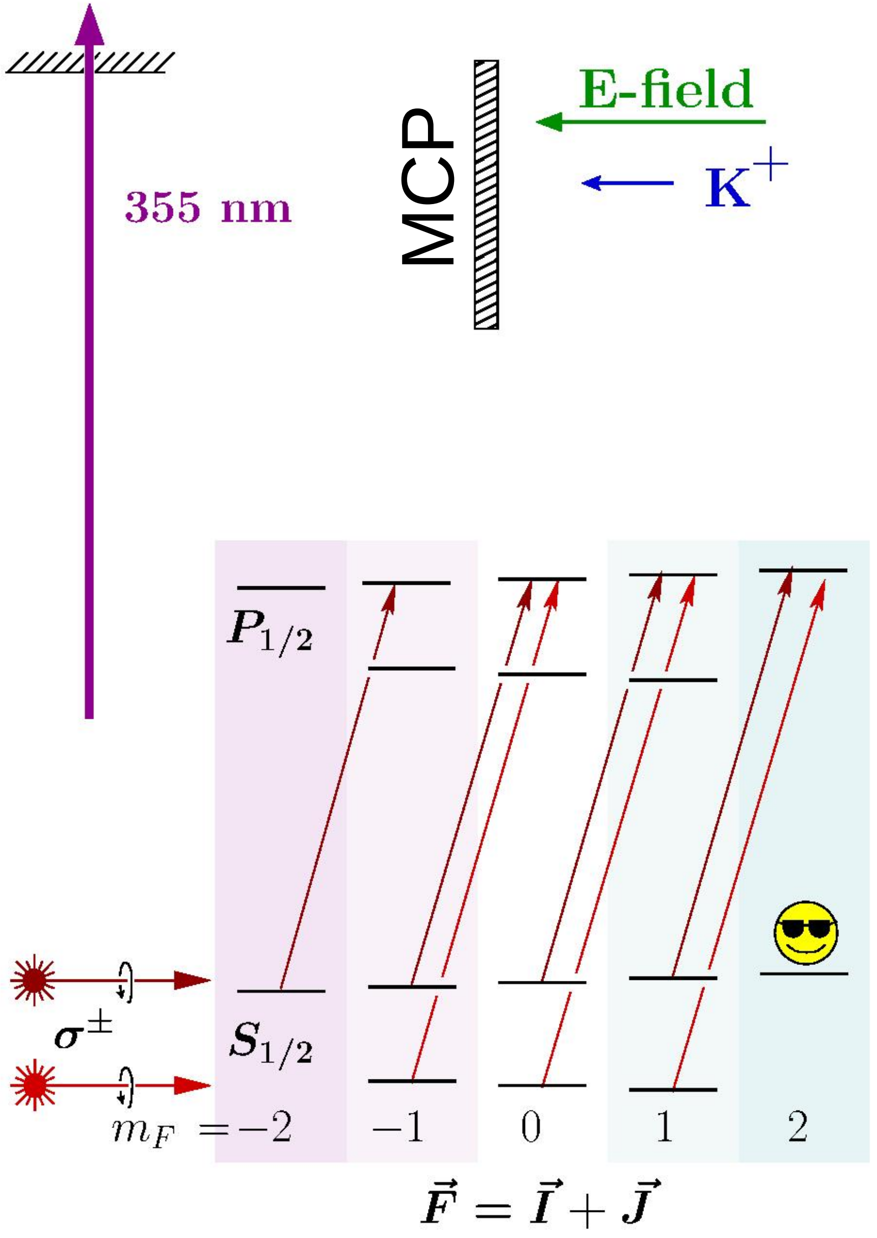
Outline of β asym & polarization measurements

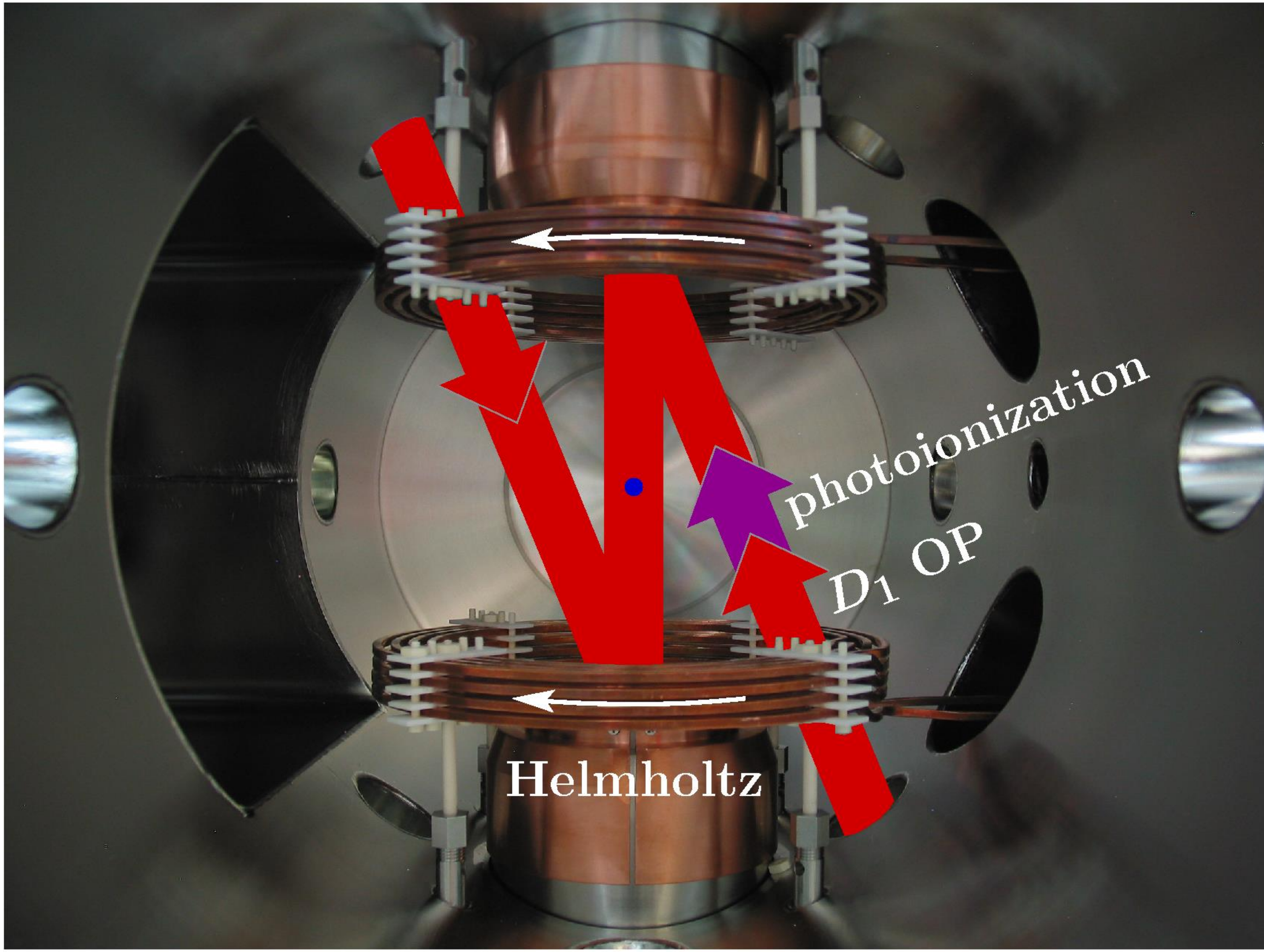
- Optical pumping:
  - Polarized light transfers ang momentum to atom
  - Nuclear and atomic spins are coupled
  - Polarize as (cold) atoms expand





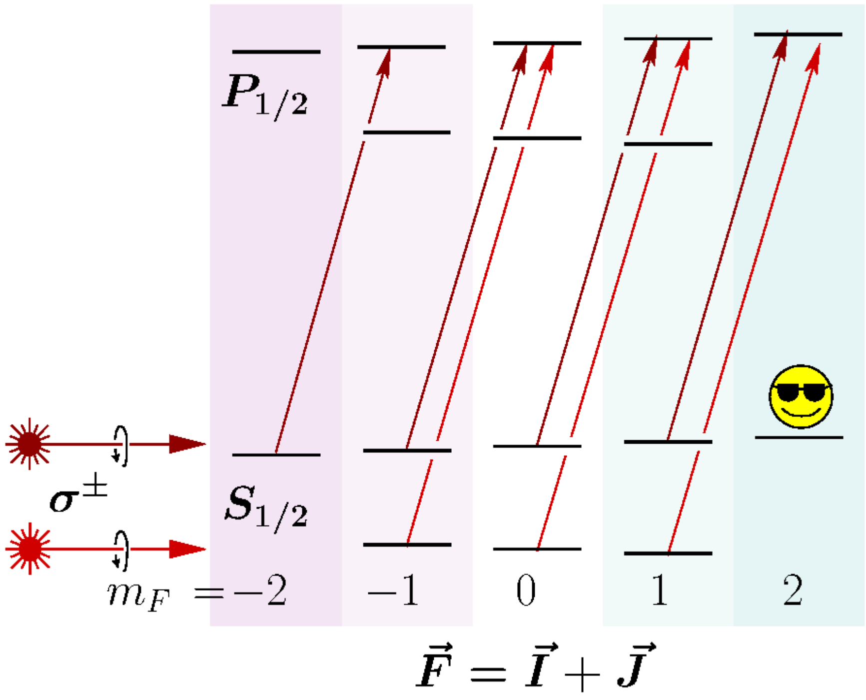
Outline of β asym & polarization measurements

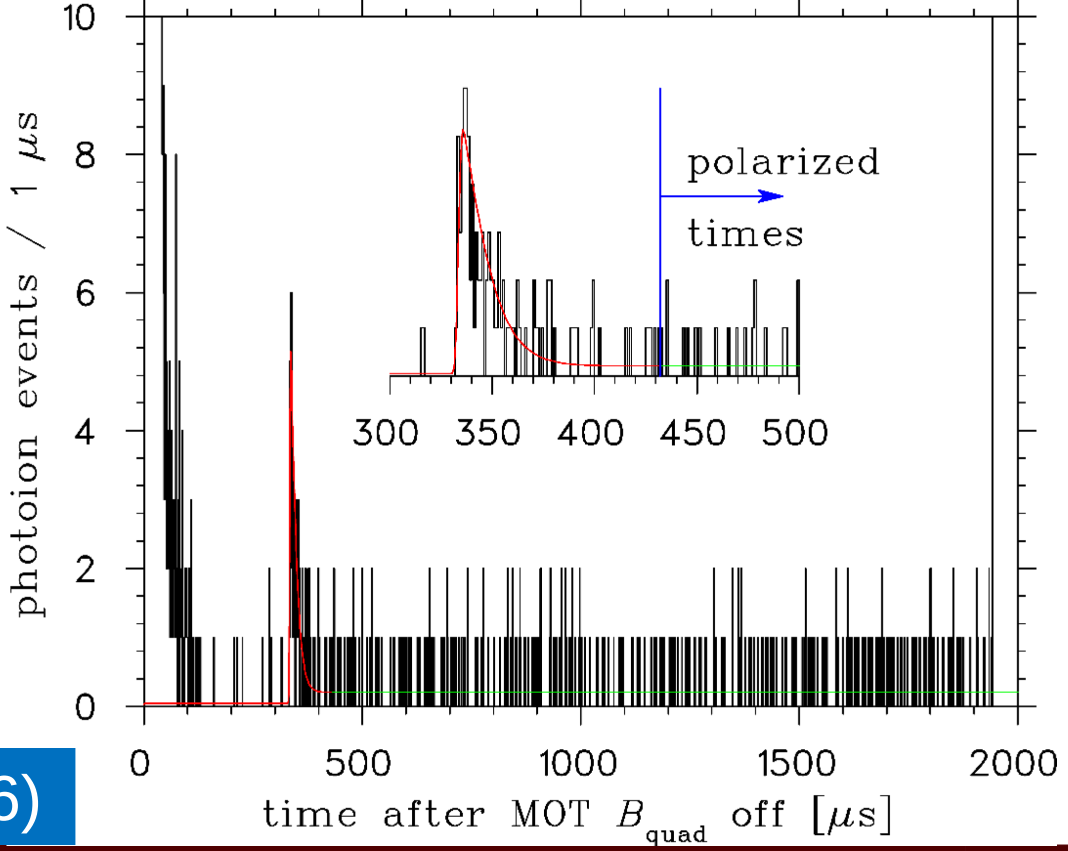




Optical pumping is fast and *efficient*!

- No time to go into details, but basically
  - Measure the rate of photons (⇔ fluorescence) as a function of time
  - Model sublevel populations using the optical Bloch equations
  - Determine the average nuclear polarization: $\langle|P_{\mathrm{nucl}}|\rangle = 0.9913(9)$





B.Fenker *et al*, New J. Phys. **18**, 073028 (2016)

The β asymmetry measurement

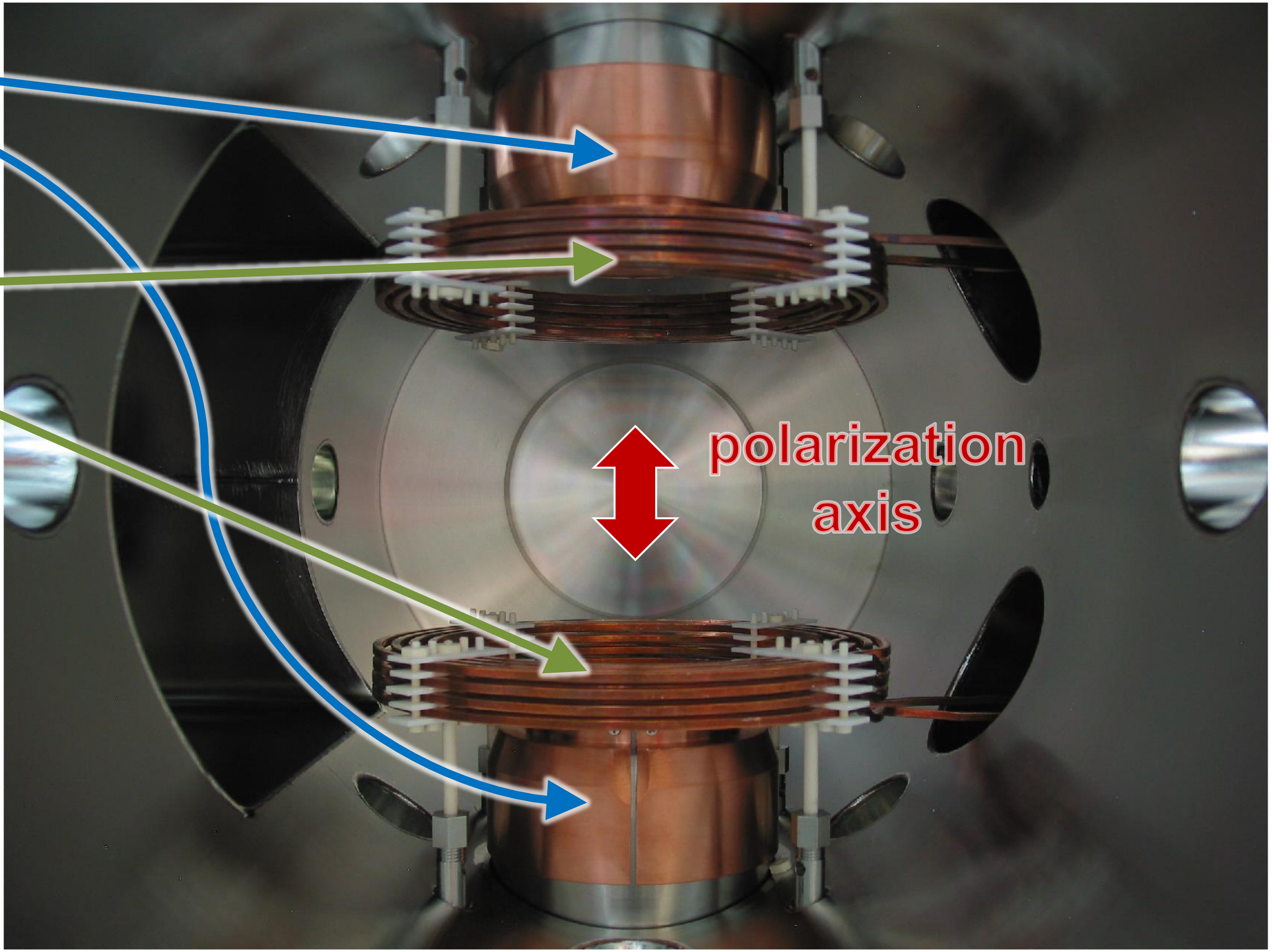
E_β detectors:
Plastic scintillator

ΔE_β detectors:
Double-sided Si-strip

Use **all** information via the super-ratio:

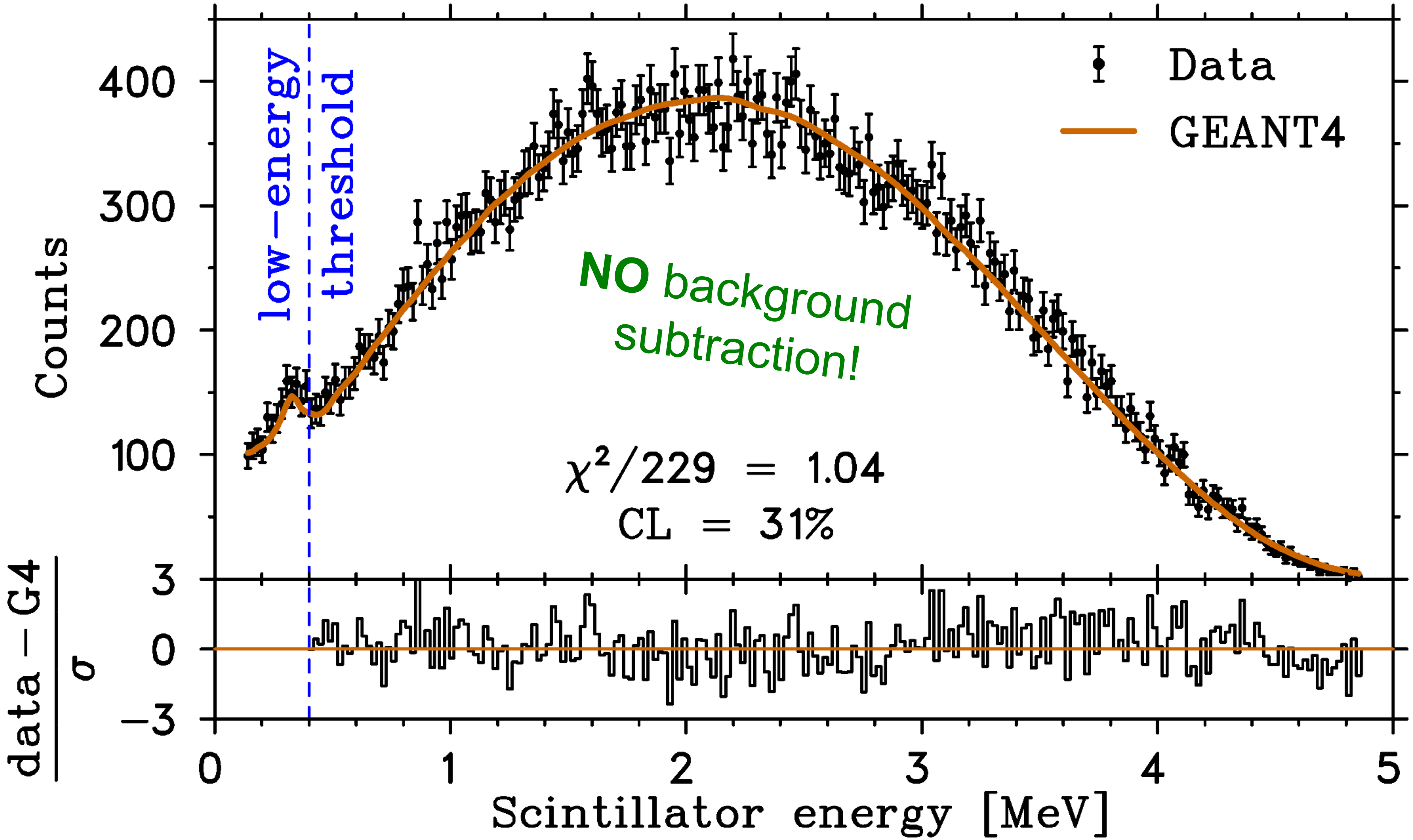
$$A_{\text{obs}}(E_e) = \frac{1-S(E_e)}{1+S(E_e)}$$

with $S(E_e) = \sqrt{\frac{r_1^{\uparrow}(E_e)\, r_2^{\downarrow}(E_e)}{r_1^{\downarrow}(E_e)\, r_2^{\uparrow}(E_e)}}$



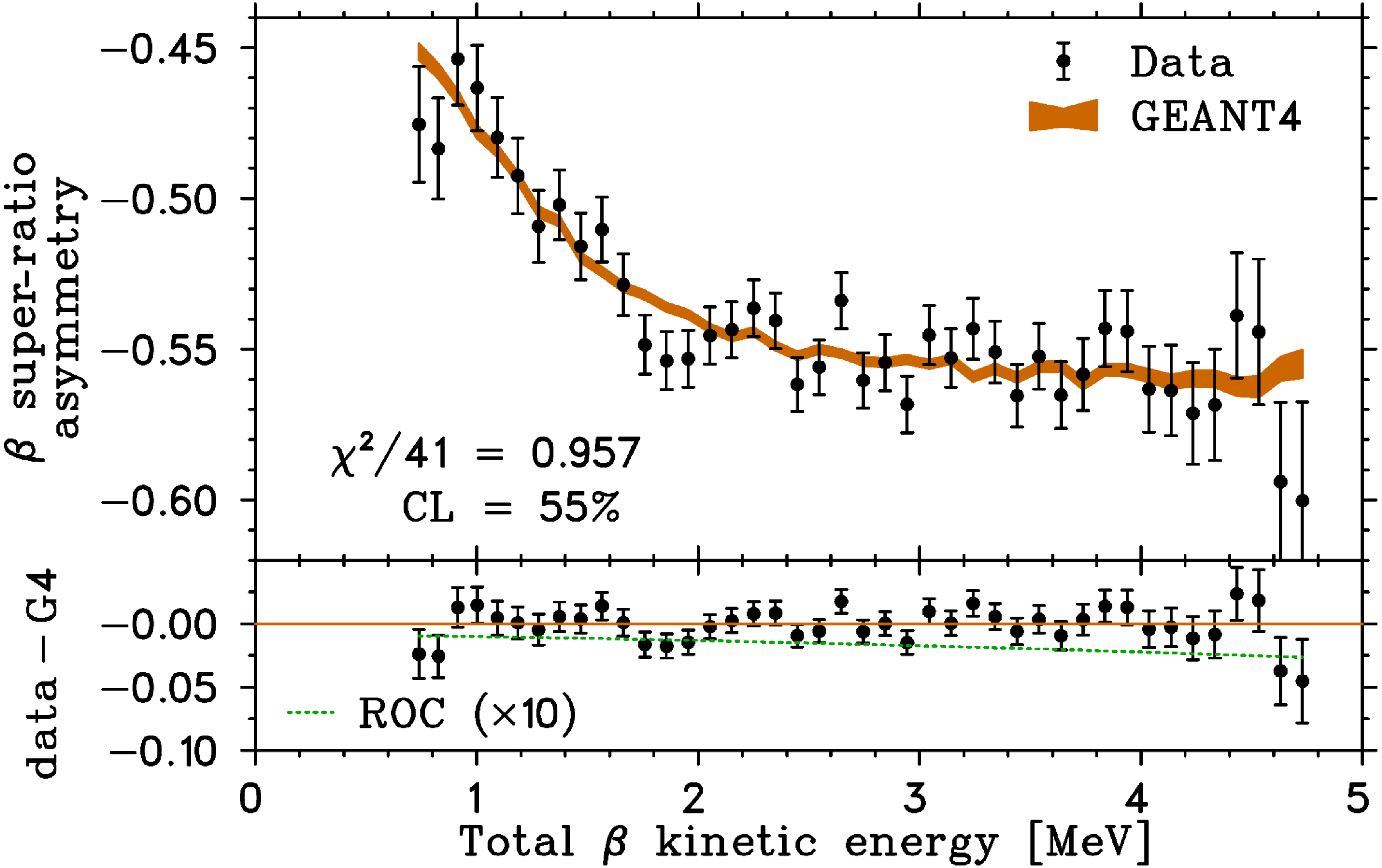
^{37}K β asymmetry measurement

- Energy spectrum – ***great agreement*** with GEANT4 simulations:



^{37}K β asymmetry measurement

- Asymmetry as a function of β energy after unblinding (again, **no** background subtraction!):

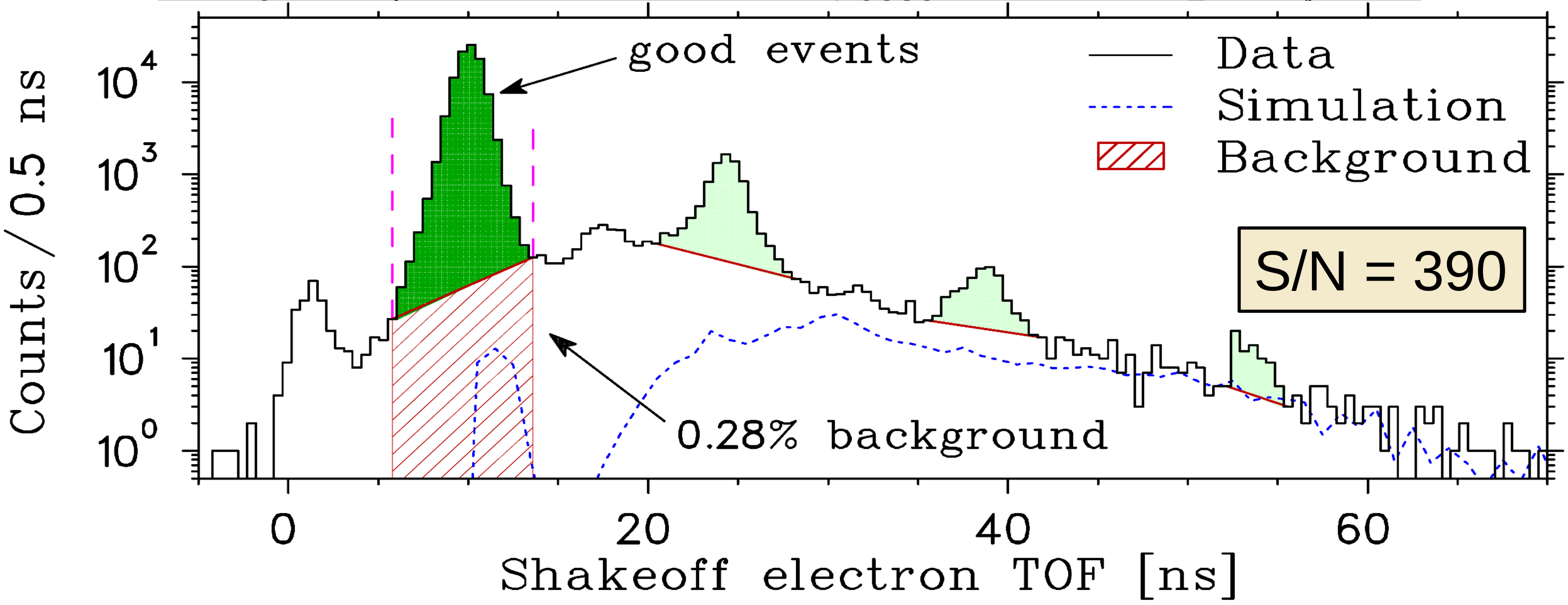


(Dominant) Error budget

Source	Correction	Uncertainty, ΔA_β
Systematics		
Background	1.0014	8×10^{-4}
β scattering	1.0230	7×10^{-4}
Trap position		4×10^{-4}
Trap movement		5×10^{-4}
ΔE position cut		4×10^{-4}
Shake-off e^- TOF region		3×10^{-4}
TOTAL SYSTEMATICS		13×10^{-4}
STATISTICS		13×10^{-4}
POLARIZATION		5×10^{-4}
TOTAL UNCERTAINTY		19×10^{-4}

(Dominant) Error budget and A_β result

Source	Correction	Uncertainty, ΔA_β
Systematics		
Background	**1.0014**	8×10^{-4}



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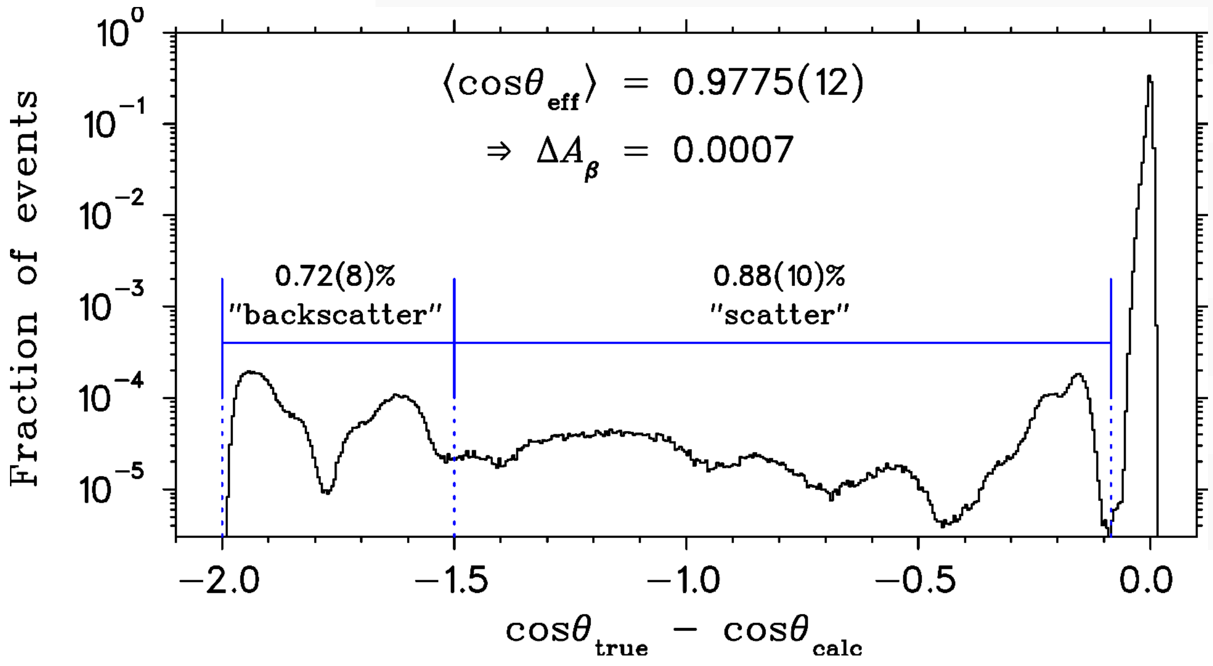

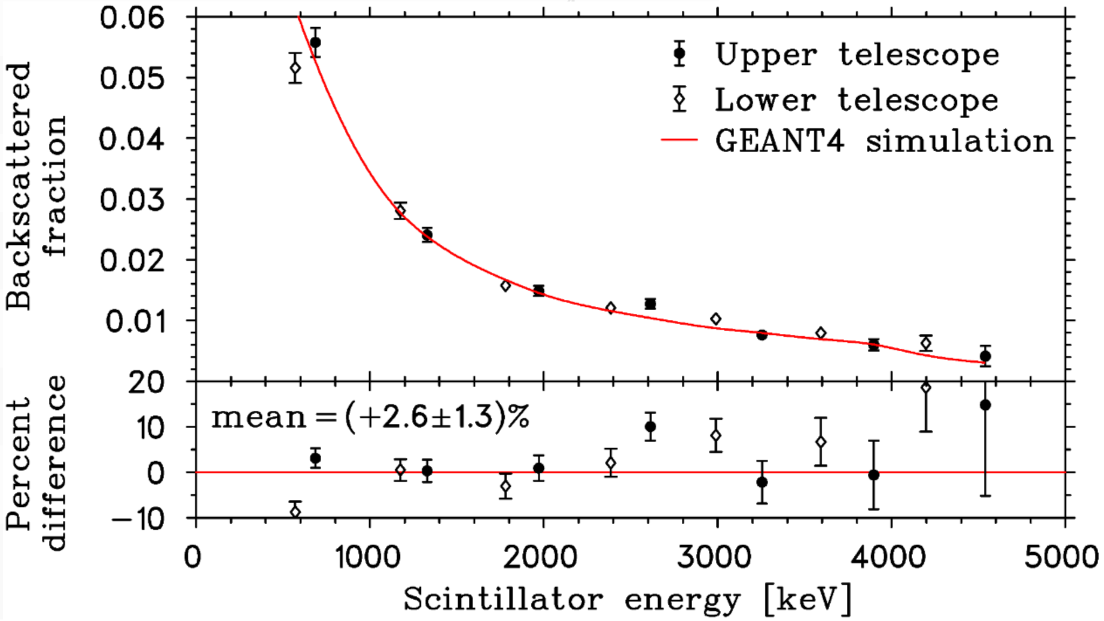

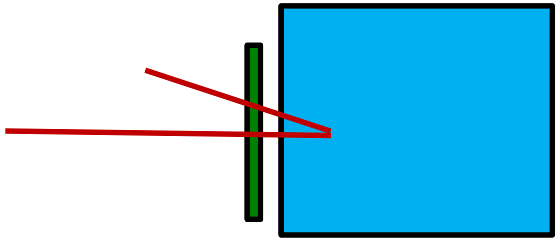

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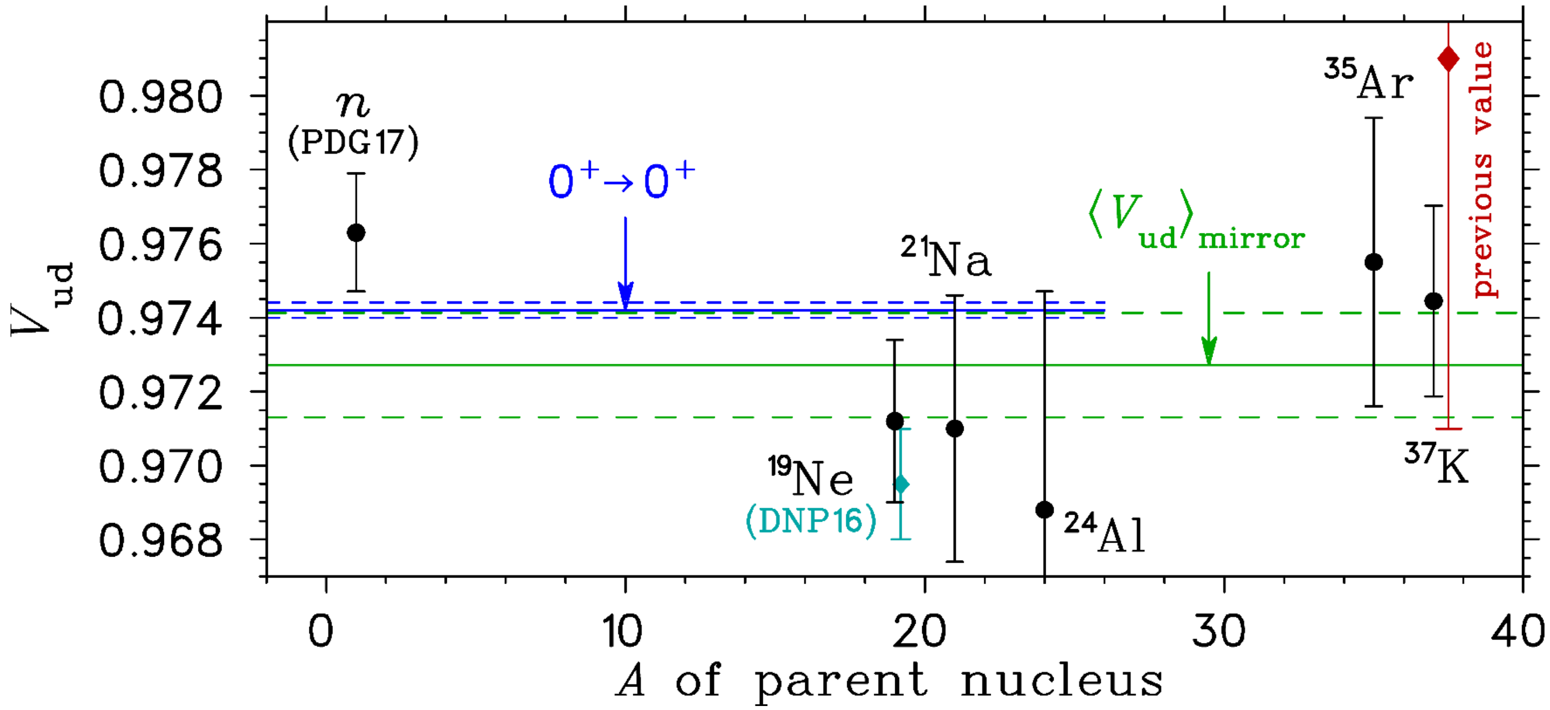
$$A_\beta^{\mathbf{meas}} = -0.5707(19) \quad \textit{cf} \quad A_\beta^{\mathrm{SM}} = -0.5706(7)$$

(includes recoil-order corrections, $\Delta A_\beta \approx -0.0028\frac{E_\beta}{E_0}$)

B.Fenker *et al*, PRL **120**, 062502 (2018)

Interpretation and future prospects

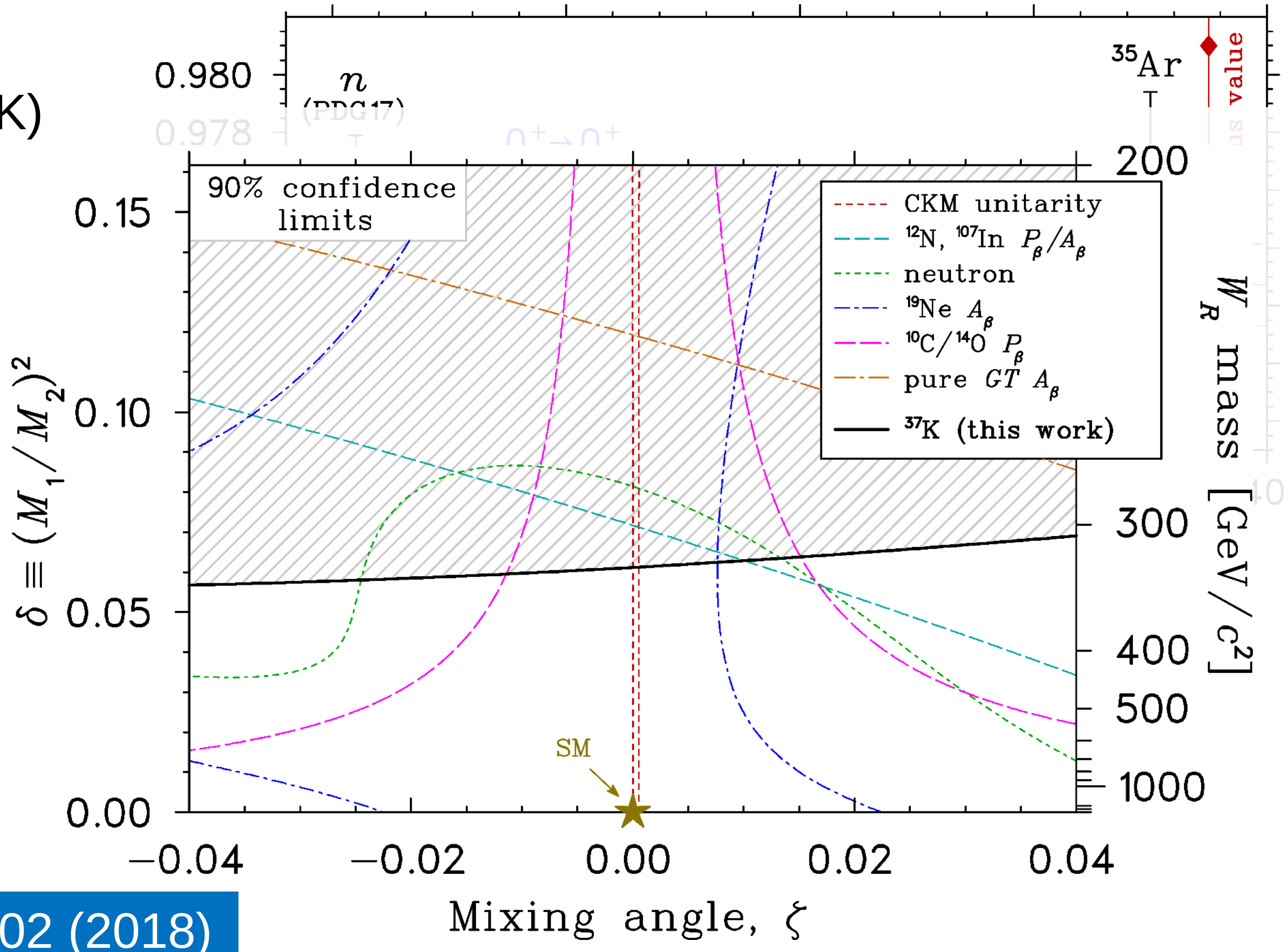
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays



B.Fenker *et al*, PRL **120**, 062502 (2018)

Interpretation and future prospects

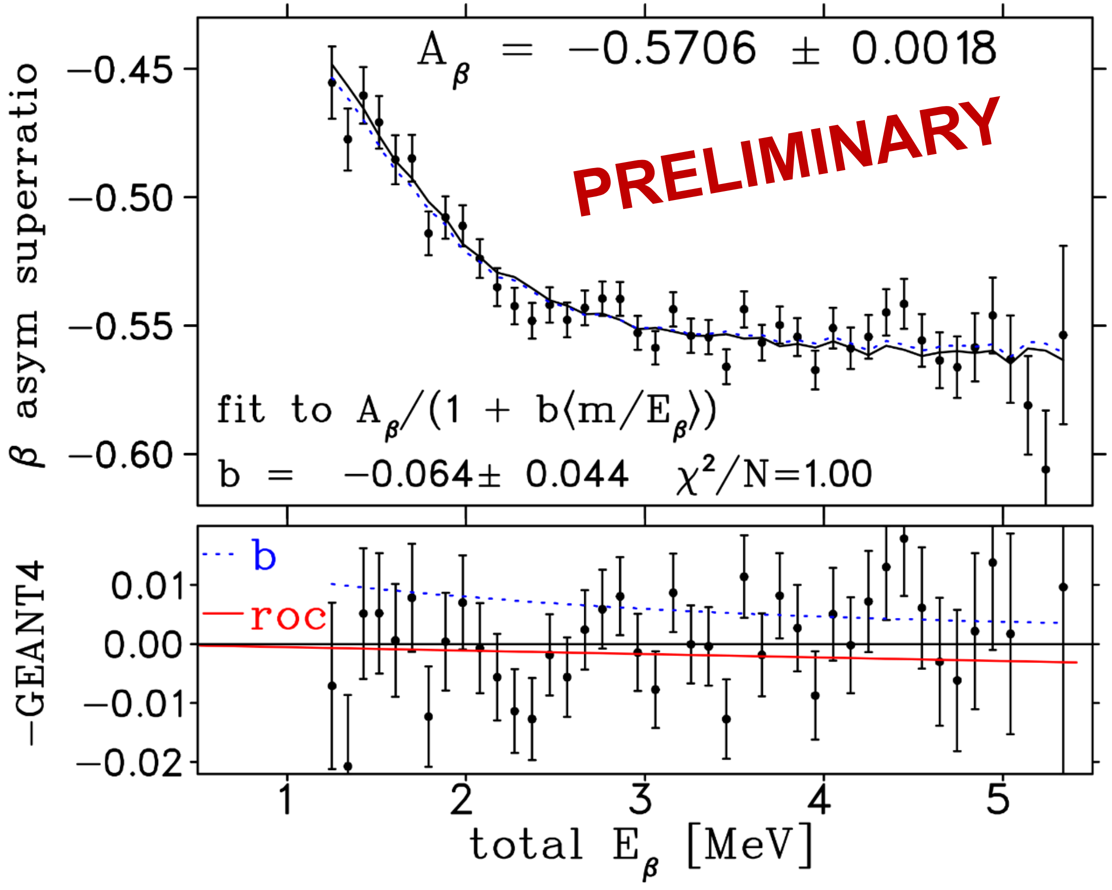
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays
- Also other physics to probe:
  - Right-handed currents
  - 2nd class currents
  - Scalar & tensor currents

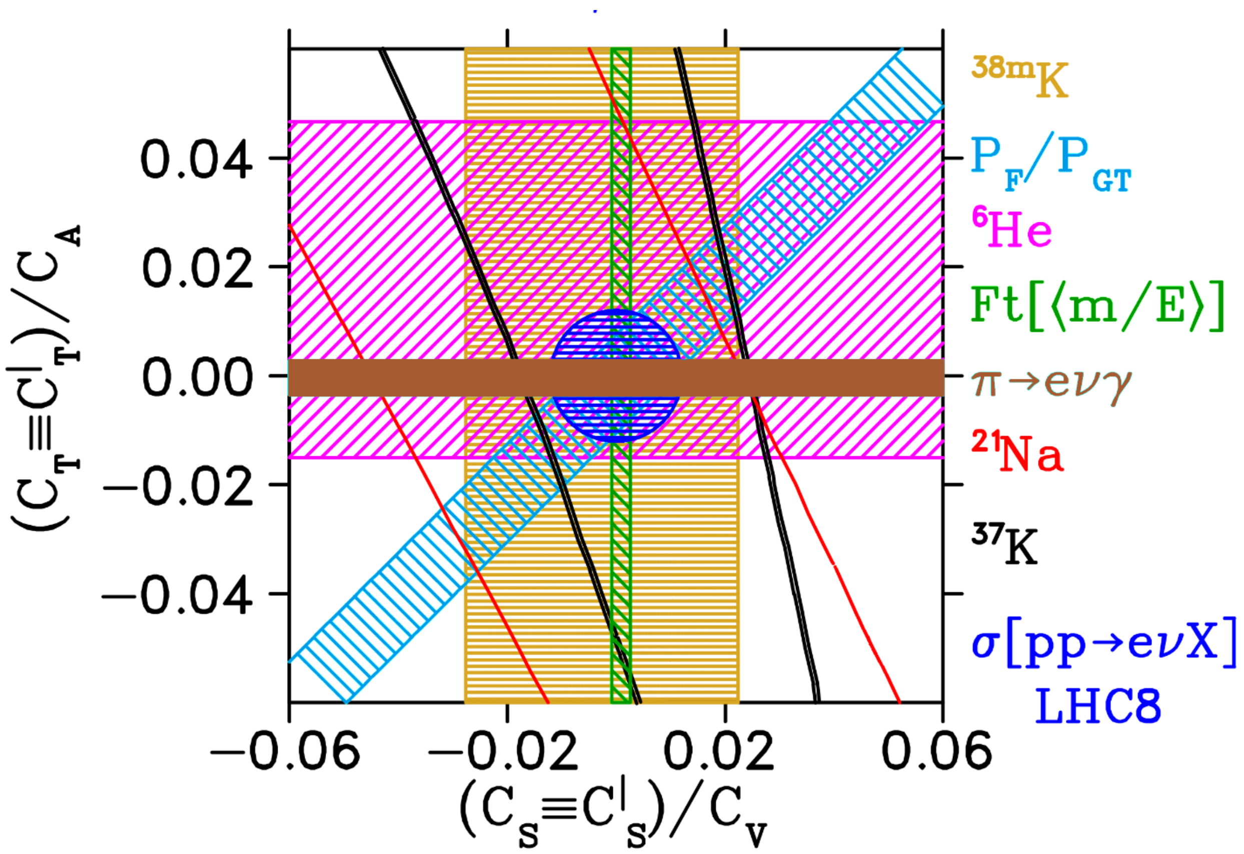


B.Fenker *et al*, PRL **120**, 062502 (2018)

Future plans

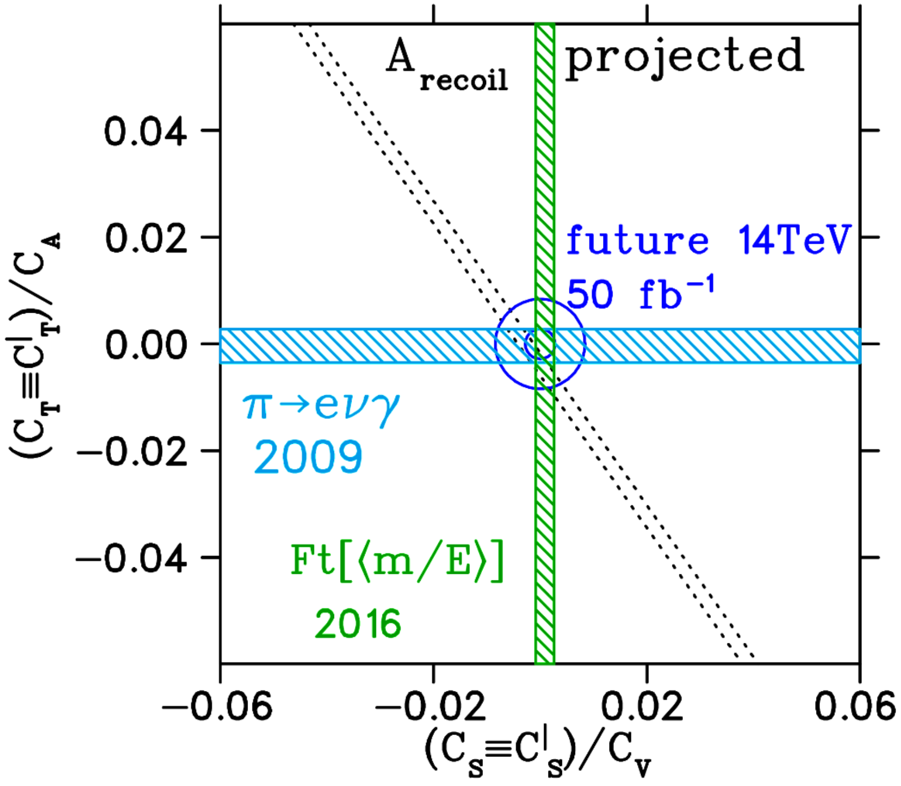
- Complete analysis as a function of $E_\beta \Rightarrow$ Fierz, 2nd class currents
- Improve A_β measurement by $3-5\times$





Future plans

- Complete analysis as a function of $E_\beta \Rightarrow$ Fierz, 2nd class currents
- Improve A_β measurement by $3-5\times$
- Measure $A_{\text{recoil}} \propto A_\beta + B_\nu$
  - Technique demonstrated in ^{80}Rb (Pitcairn *et al*., PRC **79**, 015501 (2009))
  - High statistics measurement



(assumes the LHC sees a 2σ signal)

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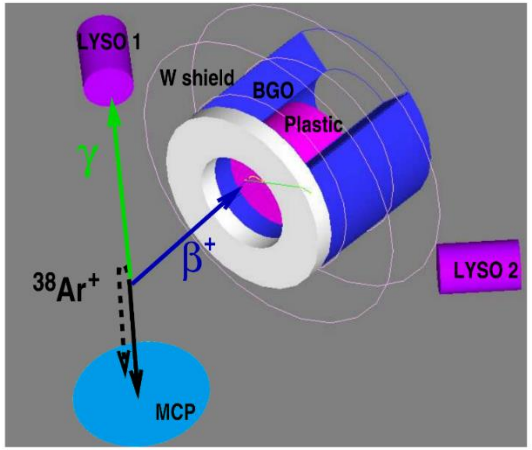
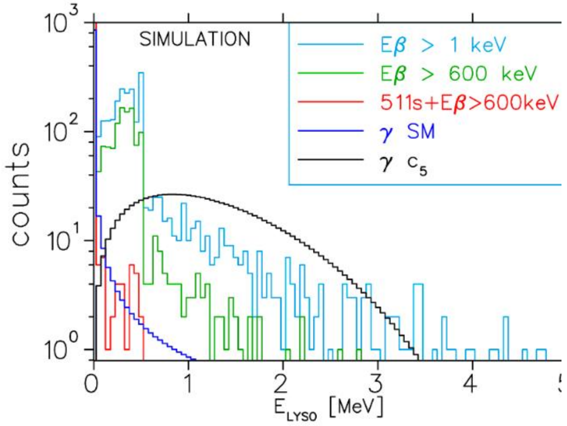
  - Motivated by Gardner and He, PRD **87**, 116012 (2013)





- Effect 250x larger than for the neutron
- Fake final state effect small: 8×10^{-4}
- unique measurement in 1st generation
- $\sigma \sim 0.02$ in 1 week

Future plans

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  - Motivated by Gardner and He, PRD **87**, 116012 (2013)
- E_ν spectrum in $0^- \rightarrow 0^+$ decay of ^{92}Rb
  - Important for modeling nuclear reactors (sterile ν?) and non-proliferation

⋮

Final thought and thanks

- MOTs helping pave the way for the precision frontier
- NeAT about to get going, ^{6}He with CRES super-exciting, and more good things to come from TRINAT

Final thought and thanks

- MOTs helping pave the way for the precision frontier
- NeAT about to get going, ^{6}He with CRES super-exciting, and more good things to come from TRINAT

TEXAS A&M UNIVERSITY

B. Fenker
S. Behling
M. Mehlman
D. Melconian
P.D. Shidling

TRIUMF

J.A. Behr
I. Craiciu
A. Gorelov
S. Smale
C.L. Warner

University of Manitoba

M. Anholm
G. Gwinner

Tel Aviv University

D. Ashery
I. Cohen

University of British Columbia

J. McNeil

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