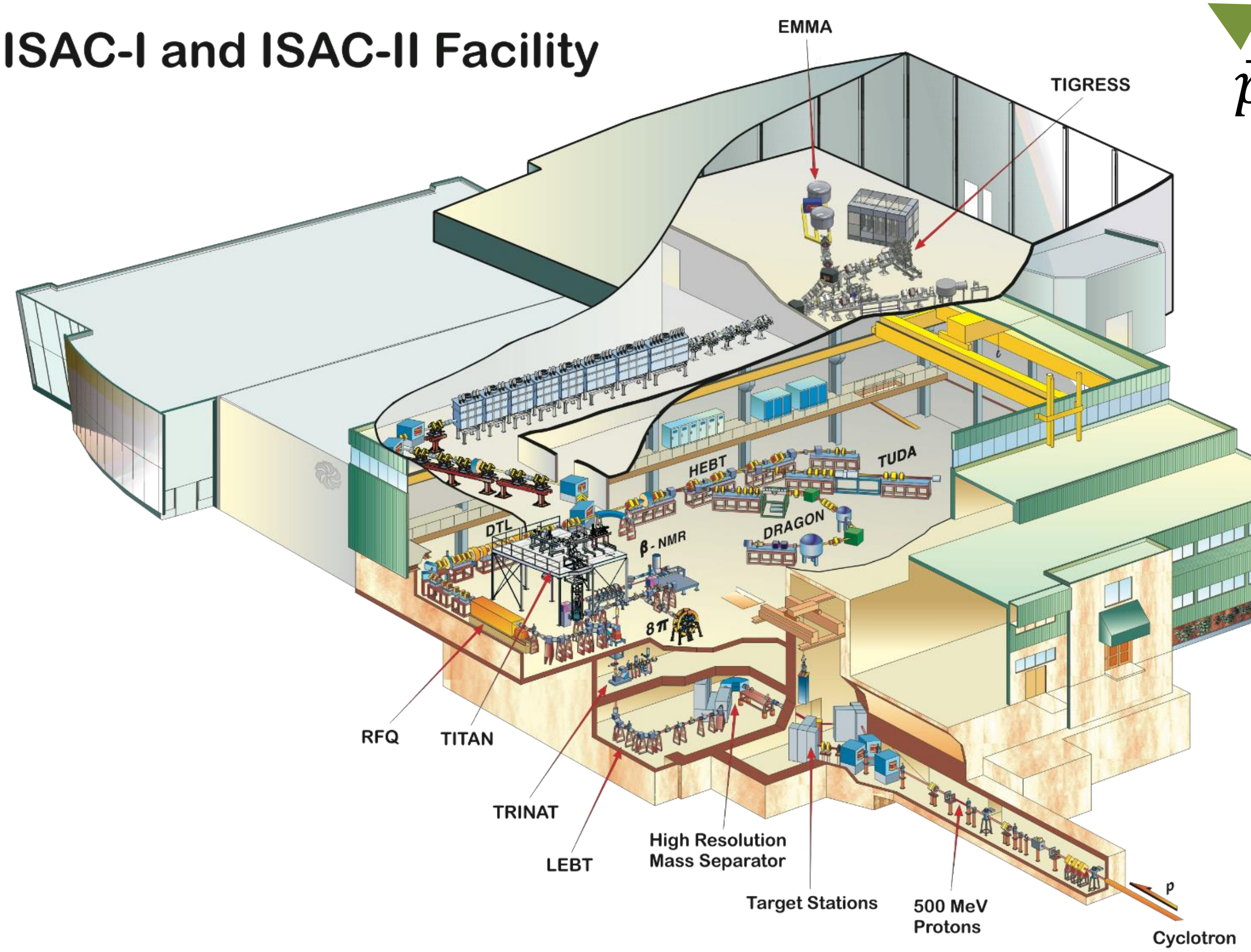
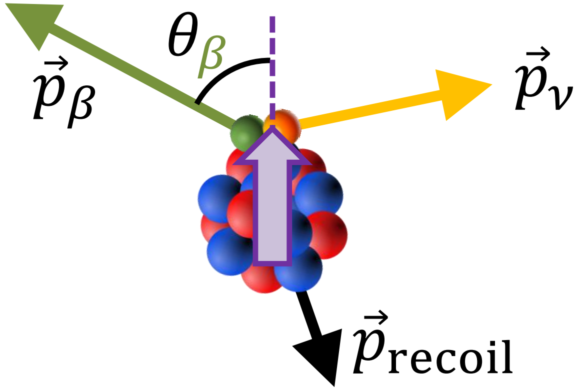
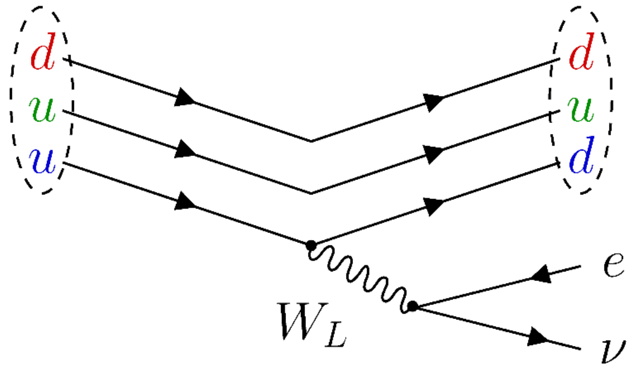
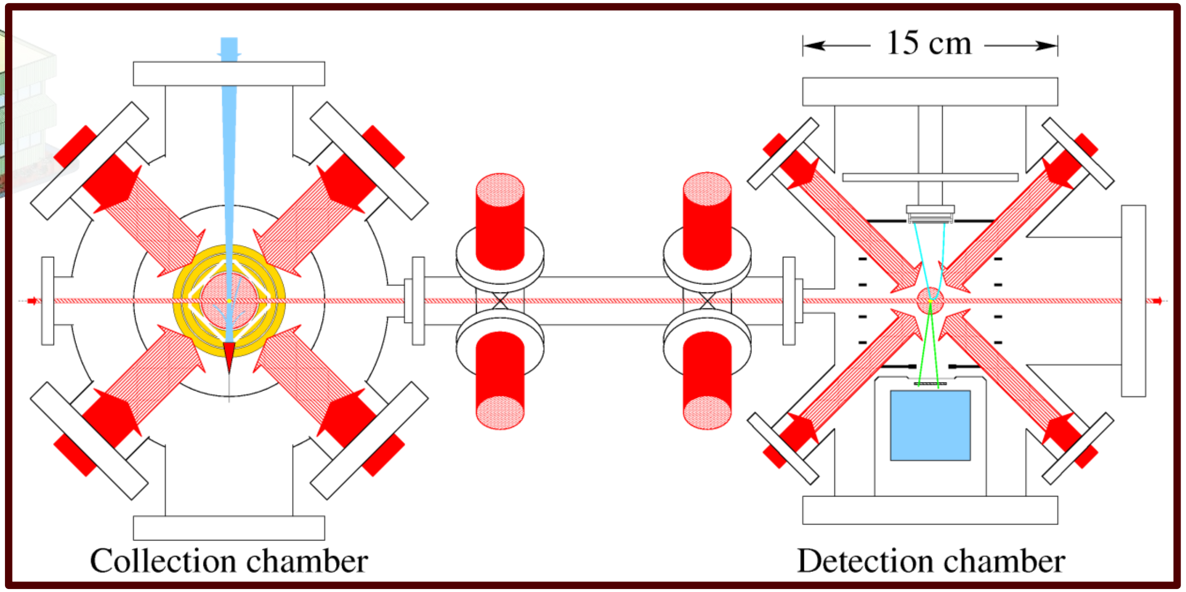
A precision measurement of the β asymmetry parameter using laser-cooled ^{37}K





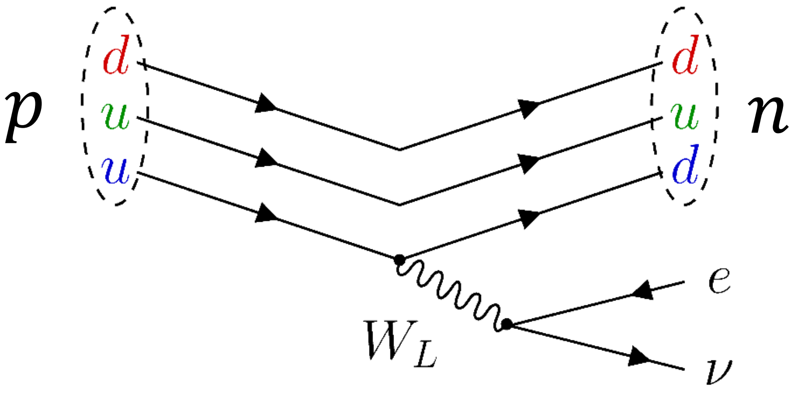




Dan Melconian – SSP 2018

The standard model and beyond

- This is the standard model:



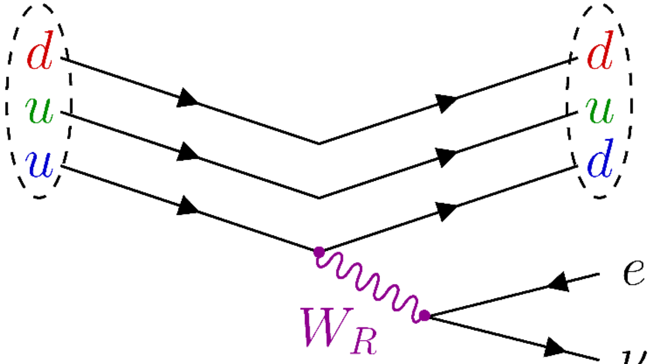
pure $V - A$ interaction

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

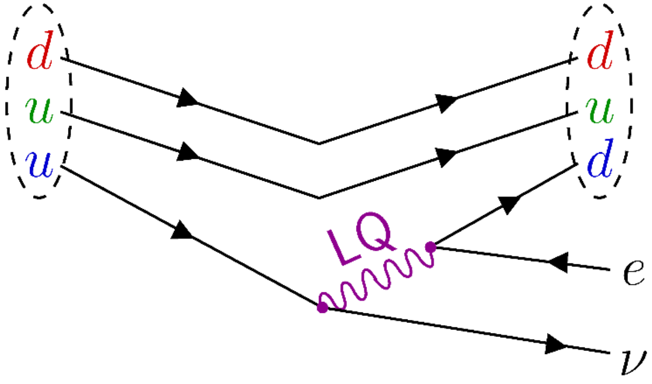
$$C_V = C_V' = 1$$
$$C_A = C_A' \approx 1.27$$

- These are not:

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



$C_i \neq C_i'$

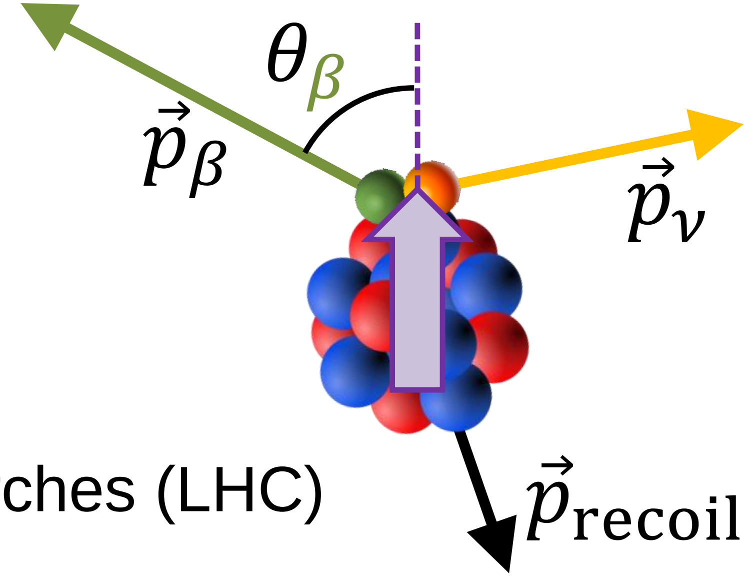


$C_S, C_T \neq 0$

- 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

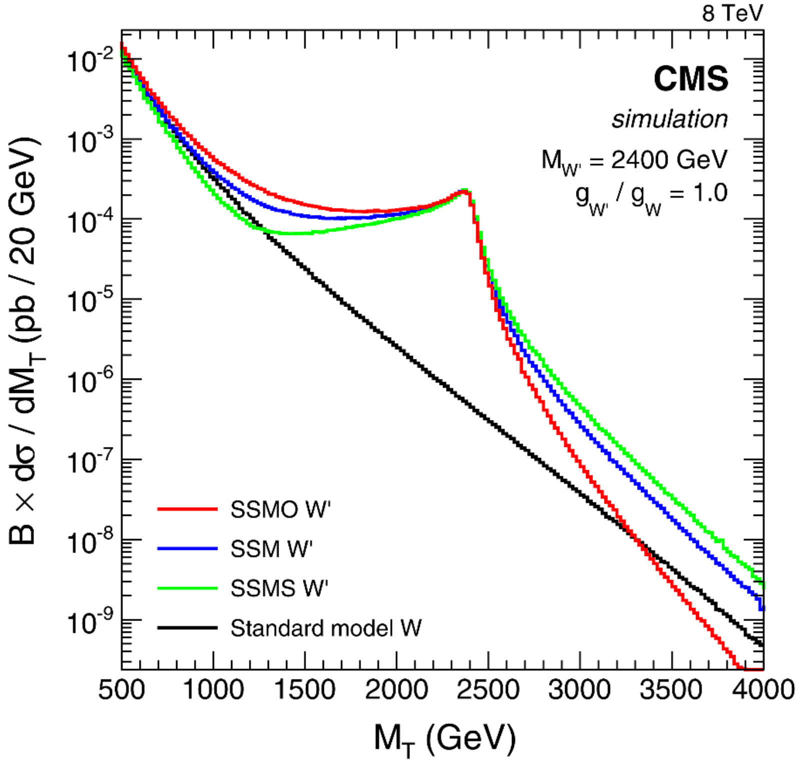


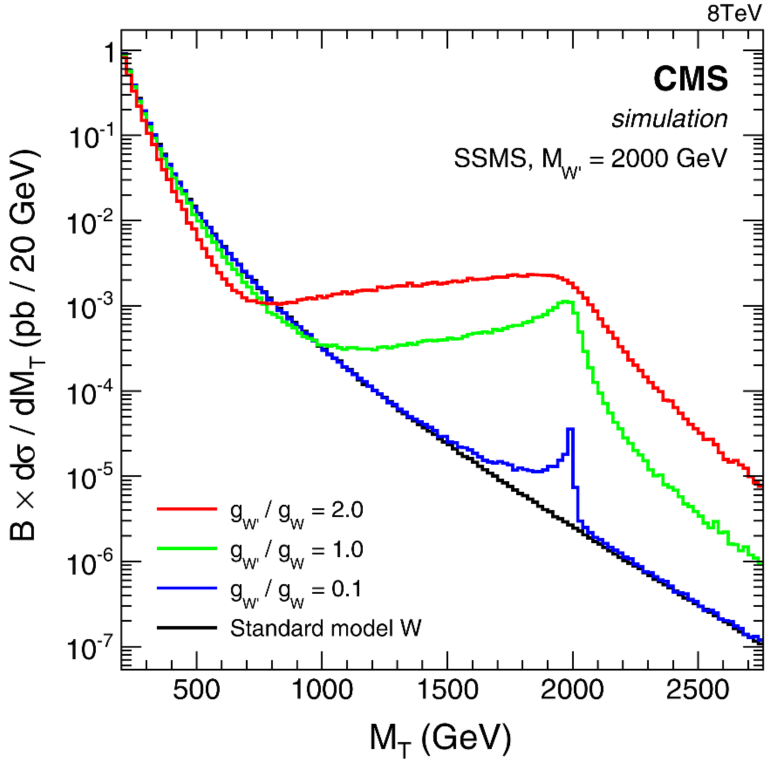
- Global gameplan:
  - Measure the β-decay parameters
  - Compare to SM predictions
  - Look for deviations ⇔ new physics
  - Precision of $\leq \mathbf{0.1\%}$ needed to complement other searches (LHC)

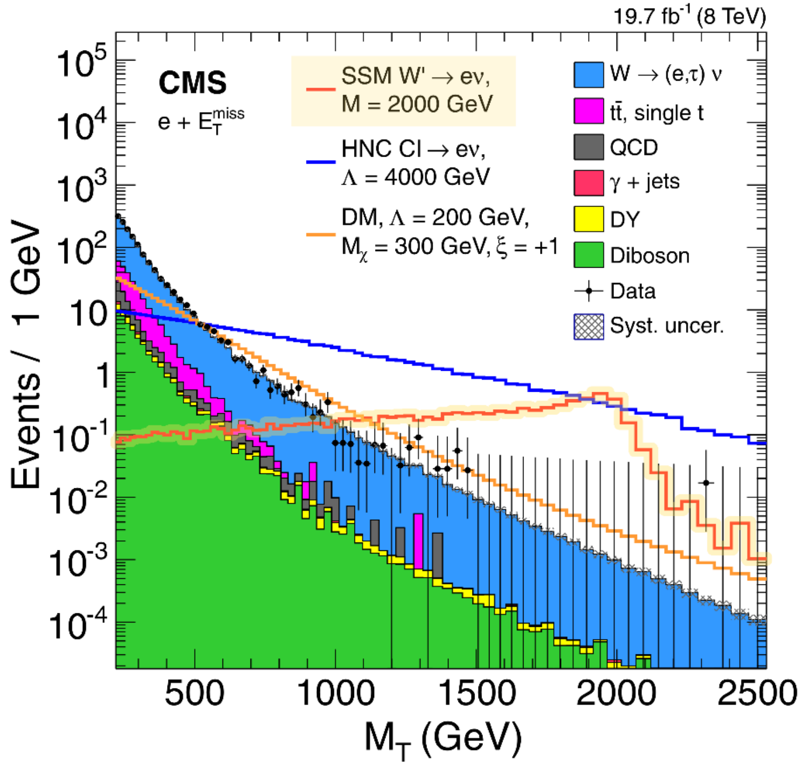
Naviliat-Cuncic and Gonzalez-Alonso, Ann Phys **525**, 600 (2013)
Cirigliano, Gonzalez-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)
González-Alonso, Naviliat-Čunčić and Severijns, arXiv:1803.08732

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

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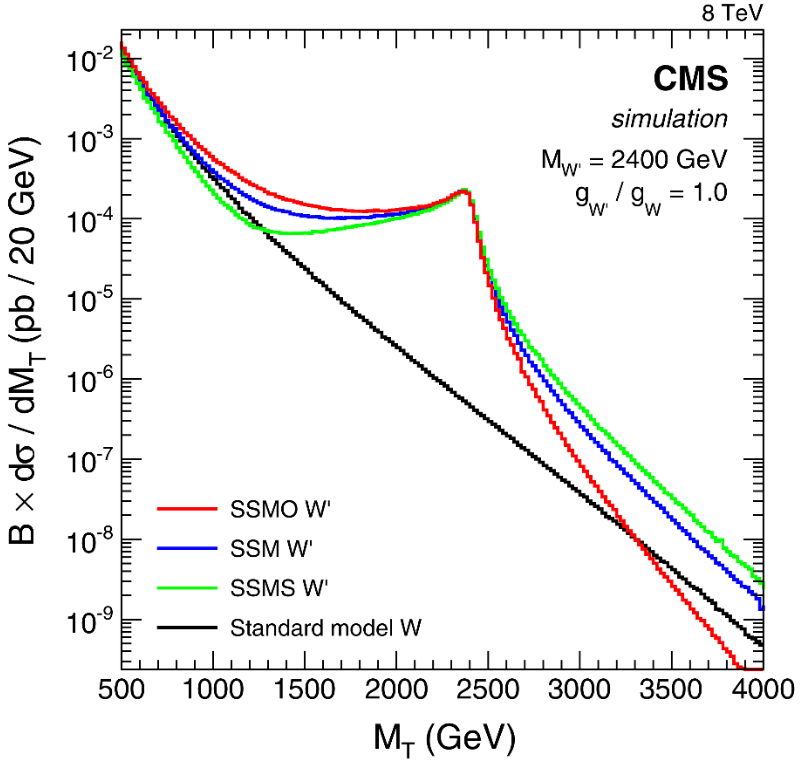
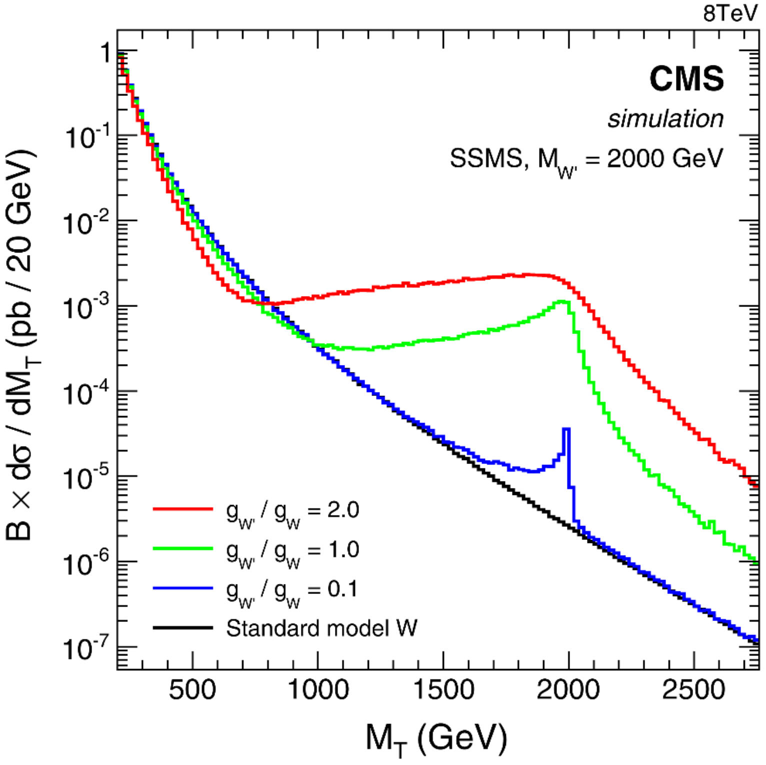
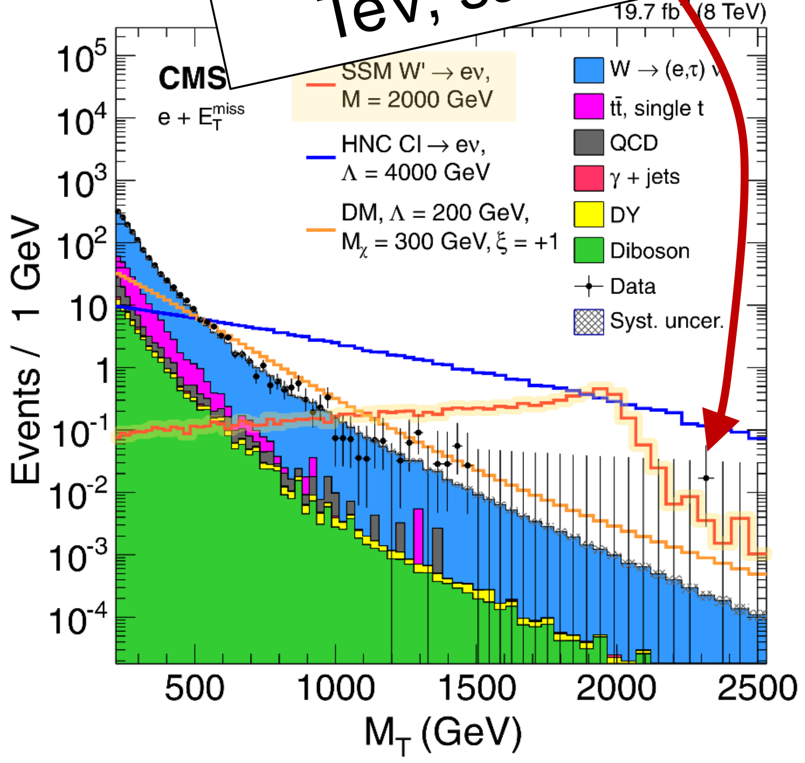
  - $\sigma(pp \to e + \mathrm{MET} + X)$ channel with $\int L = 20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8\ \mathrm{TeV}$
  - No excess observed ⇝ place limits
    (see Gonzalez-Alonzo, arXiv:1803.08732 for EFT interpretation)



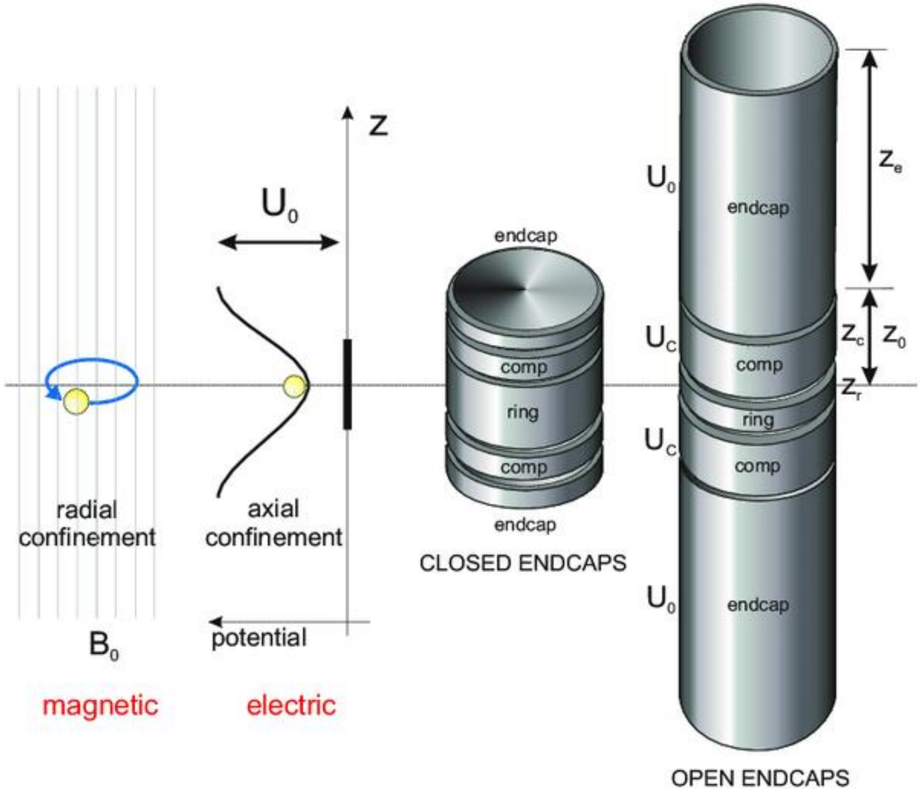




Expected 2.0±0.3 events above 1.5 TeV, saw one

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

- Ion traps (no time to discuss)
  - 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)



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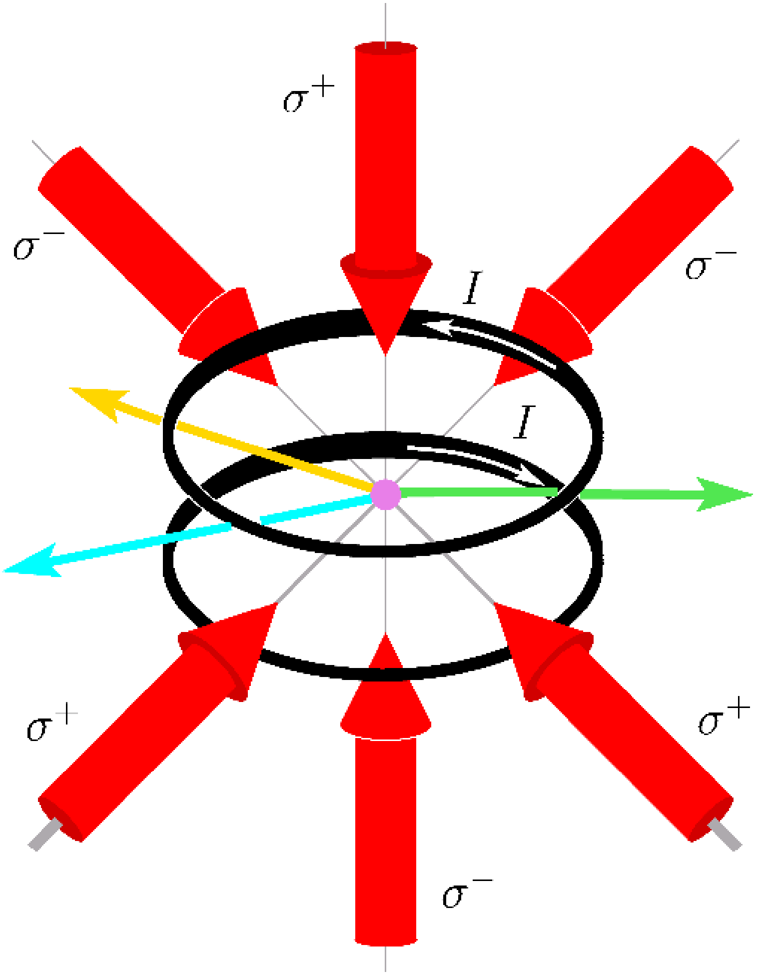
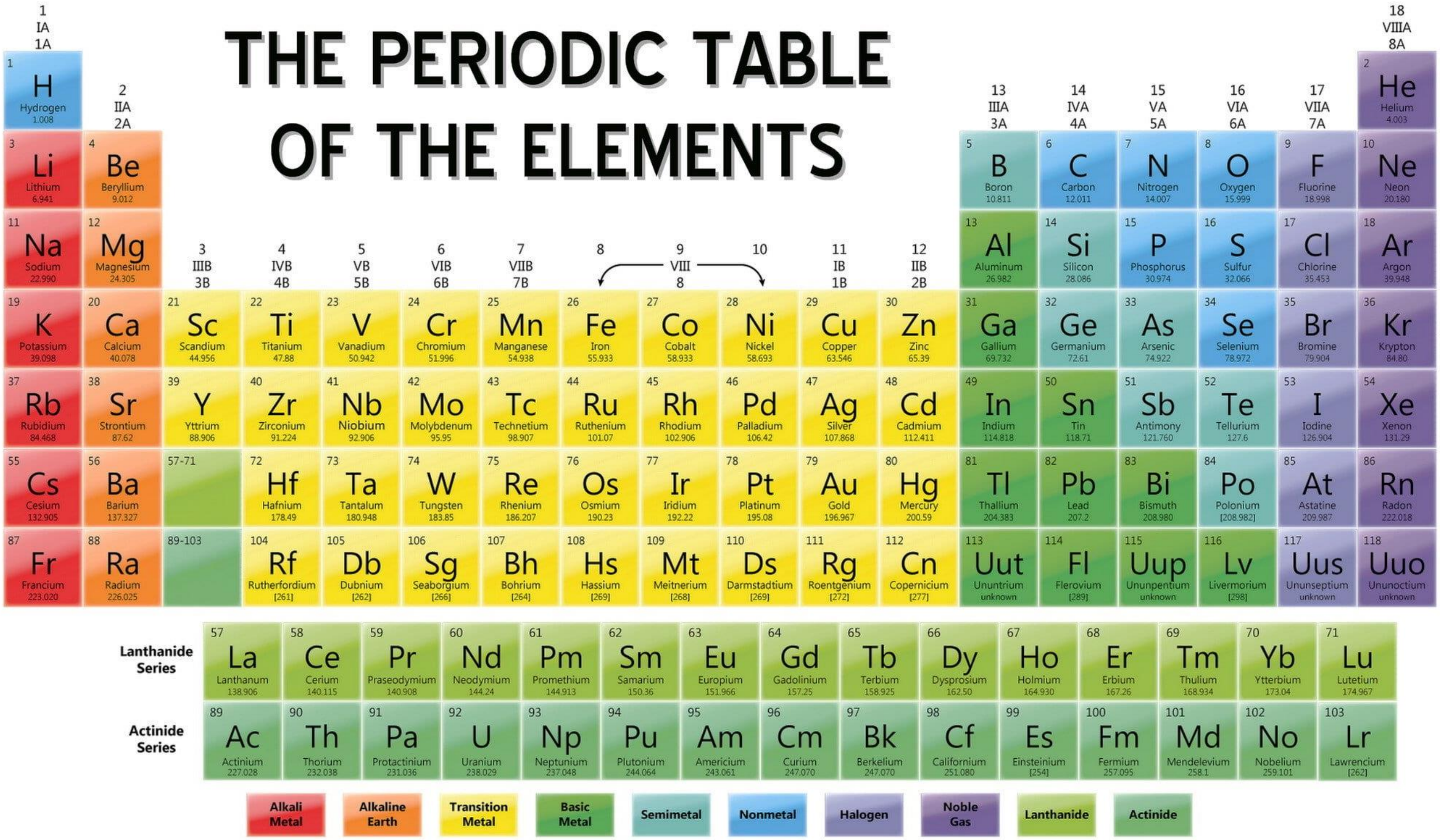
    - NSLTrap @ Notre Dame (^{11}C, ^{13}N, ^{15}O, ^{17}F)
- Magneto-optical traps
  - Atoms are cold and confined to a small volume
  - Isomerically selective; low backgrounds
  - Very shallow trap, minimal volumes to scatter off



Difficulty with MOTs: not all atoms can be trapped



THE PERIODIC TABLE OF THE ELEMENTS

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

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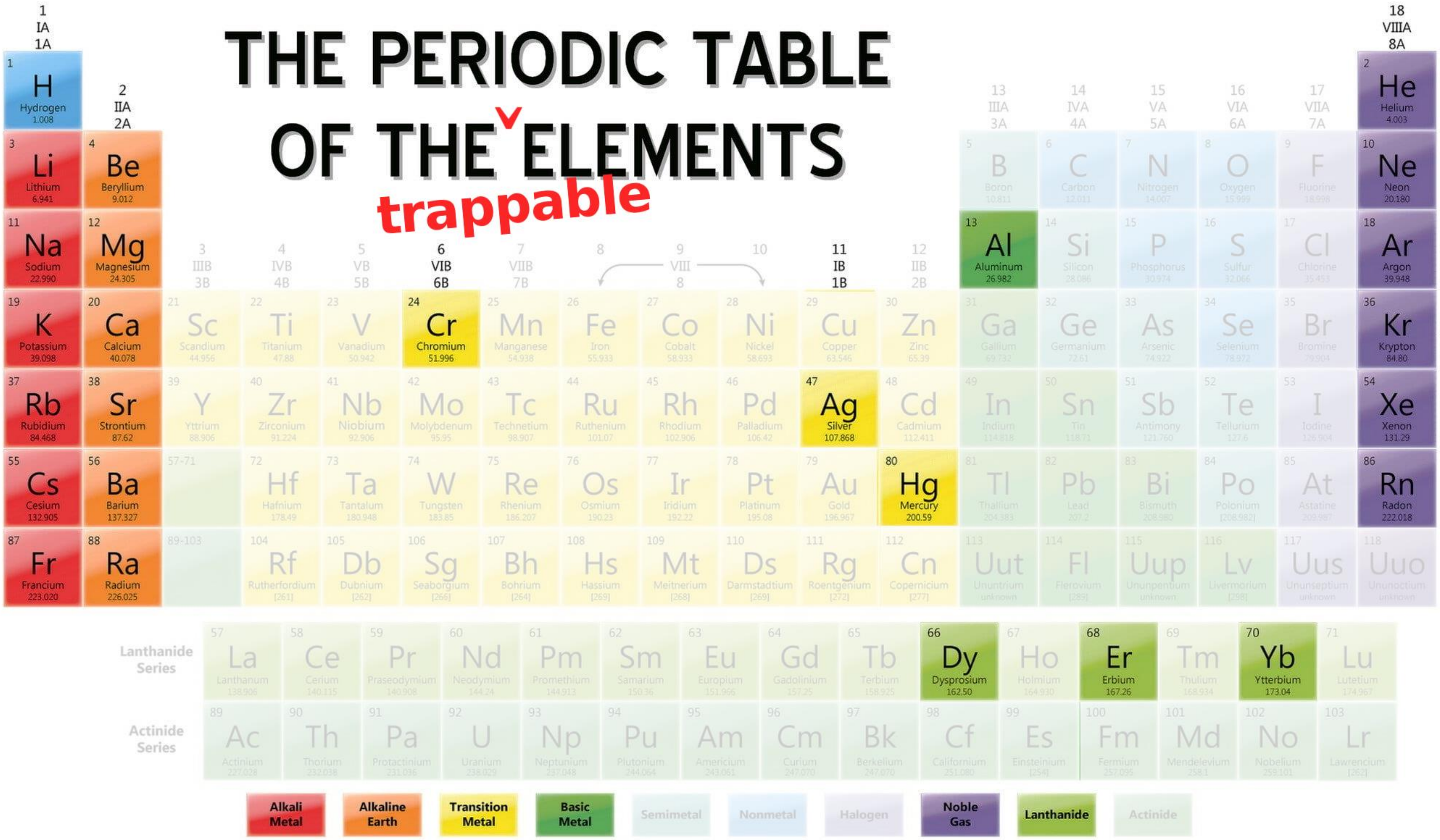

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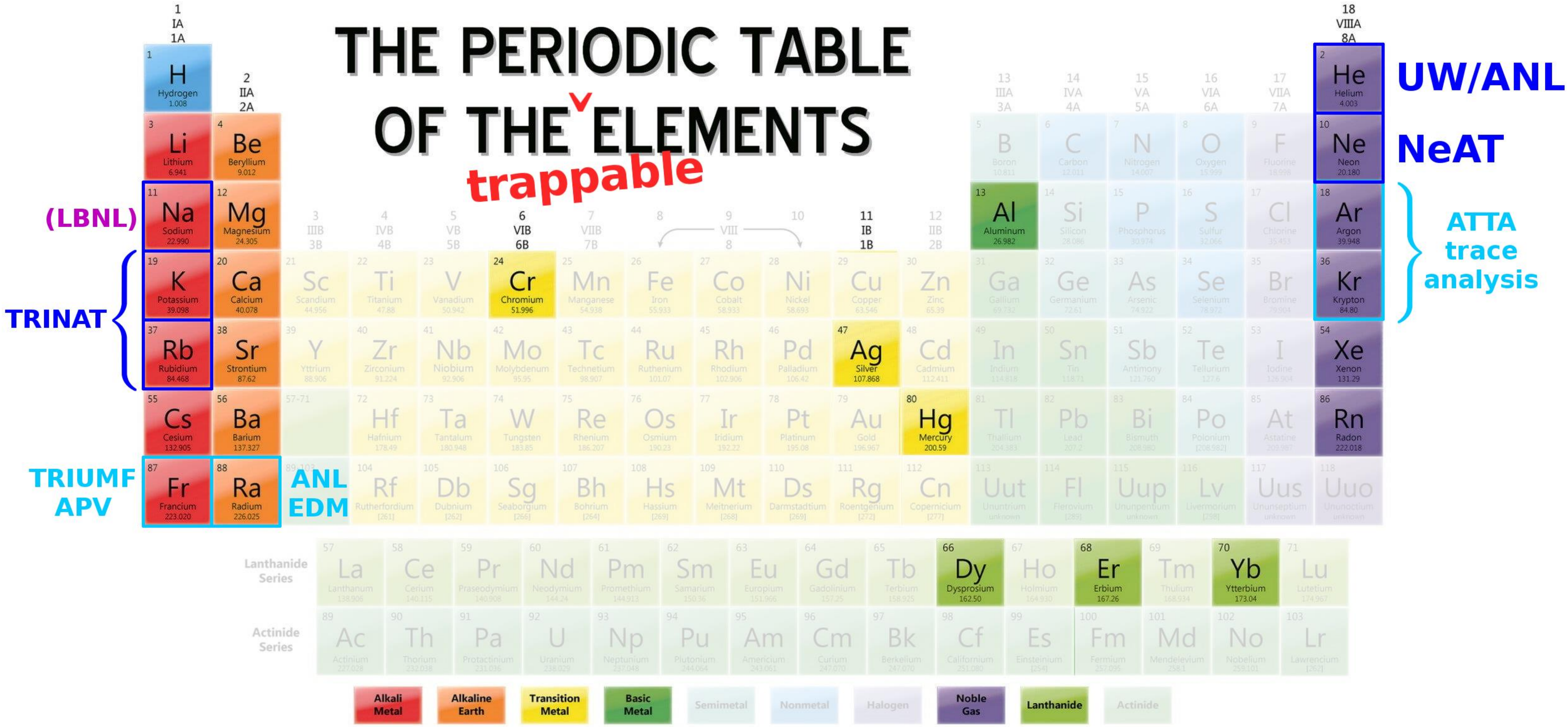
Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetal | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

Difficulty with MOTs: not all atoms can be trapped



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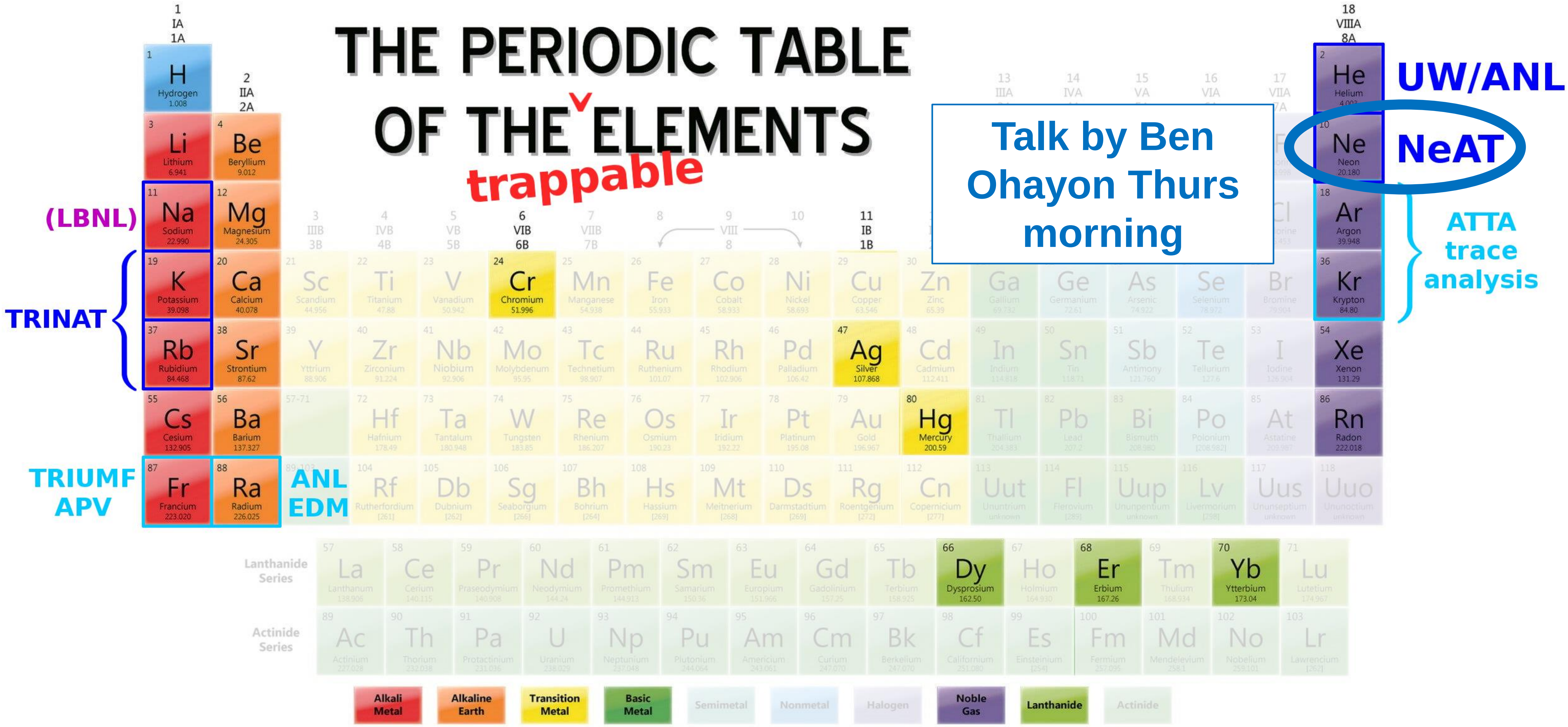

Talk by Ben Ohayon Thurs morning

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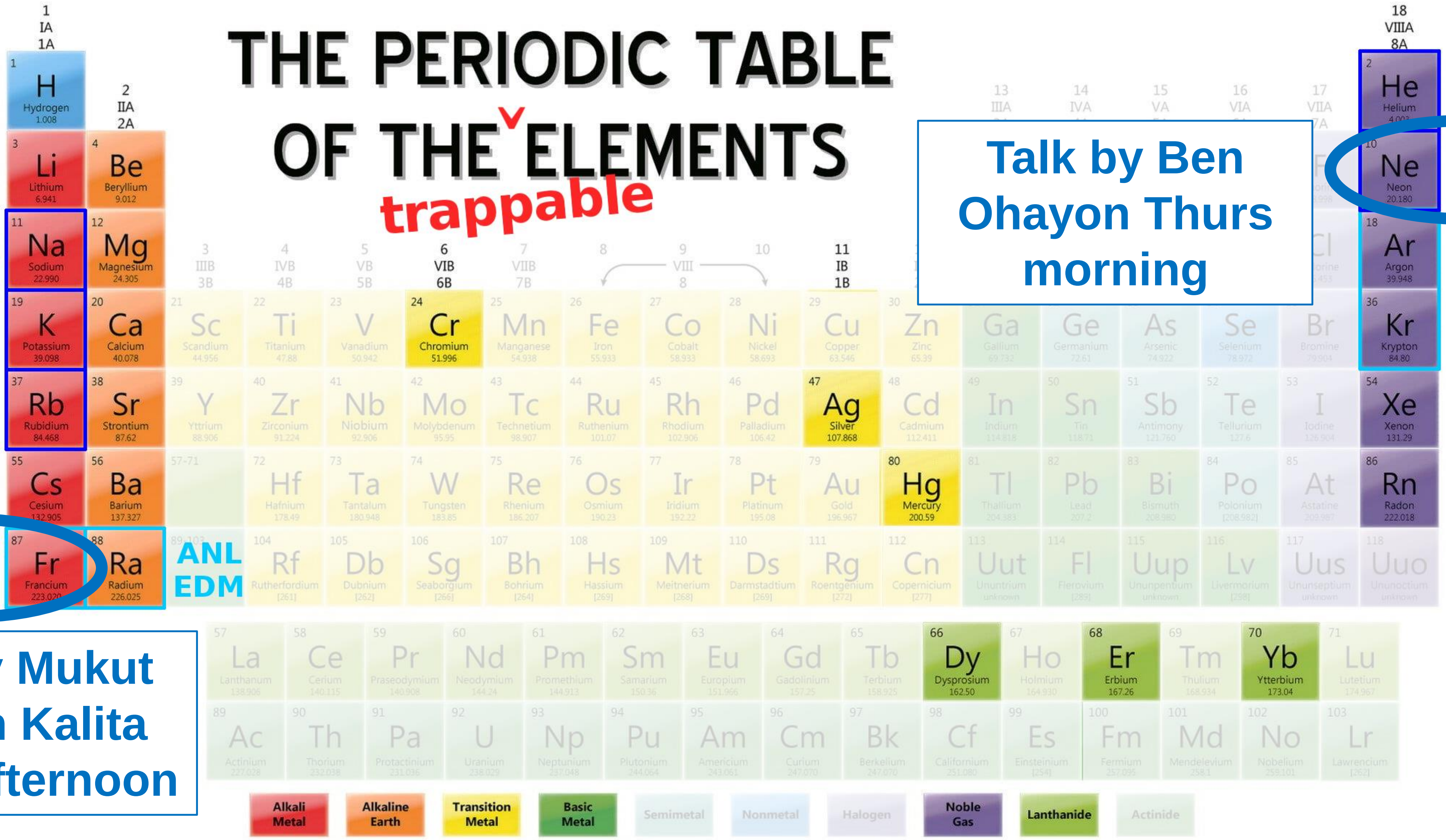


Talk by Ben Ohayon Thurs morning

UW/ANL

NeAT

ATTA trace analysis

(LBNL)

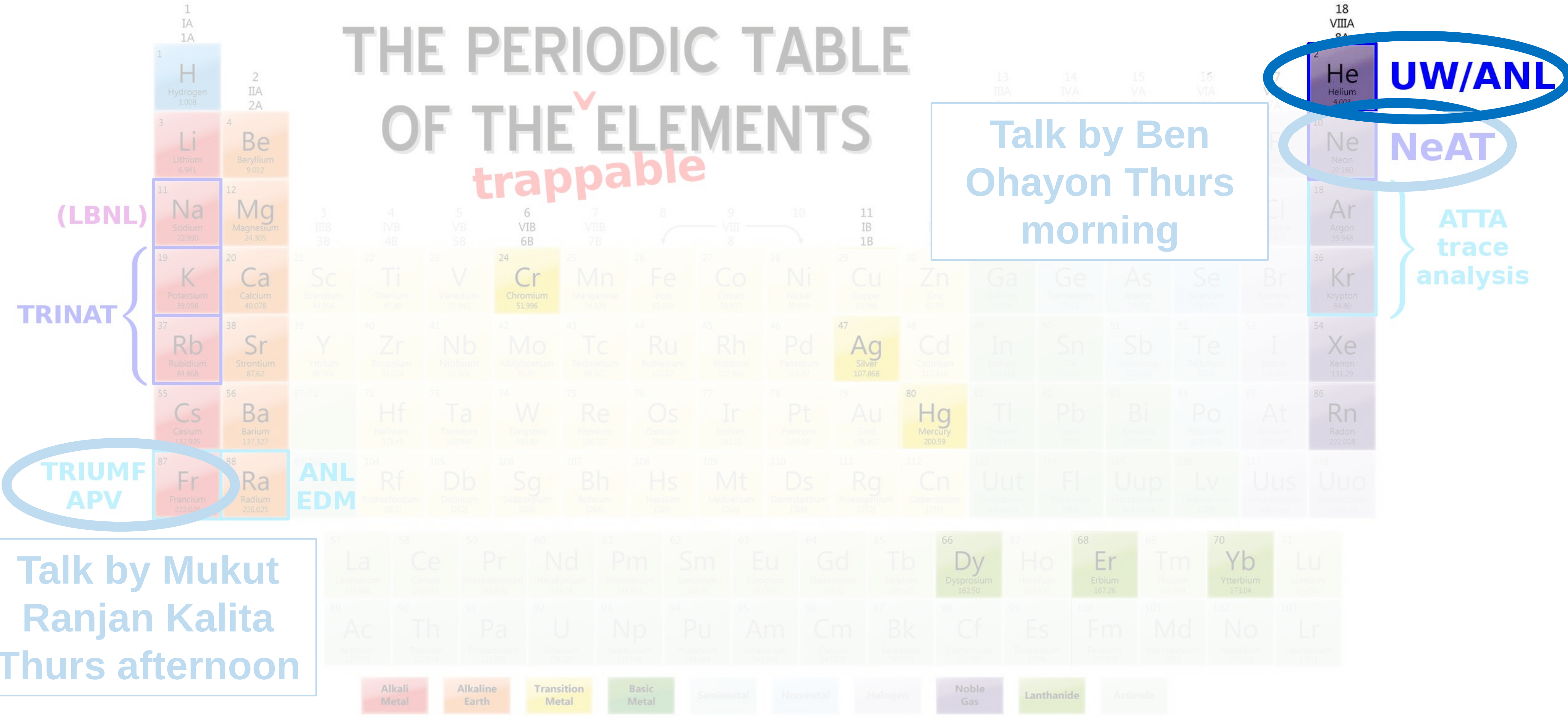
TRINAT

TRIUMF APV

ANL EDM

Talk by Mukut Ranjan Kalita Thurs afternoon

Difficulty with MOTs: not all atoms can be trapped



Talk by Ben Ohayon Thurs morning

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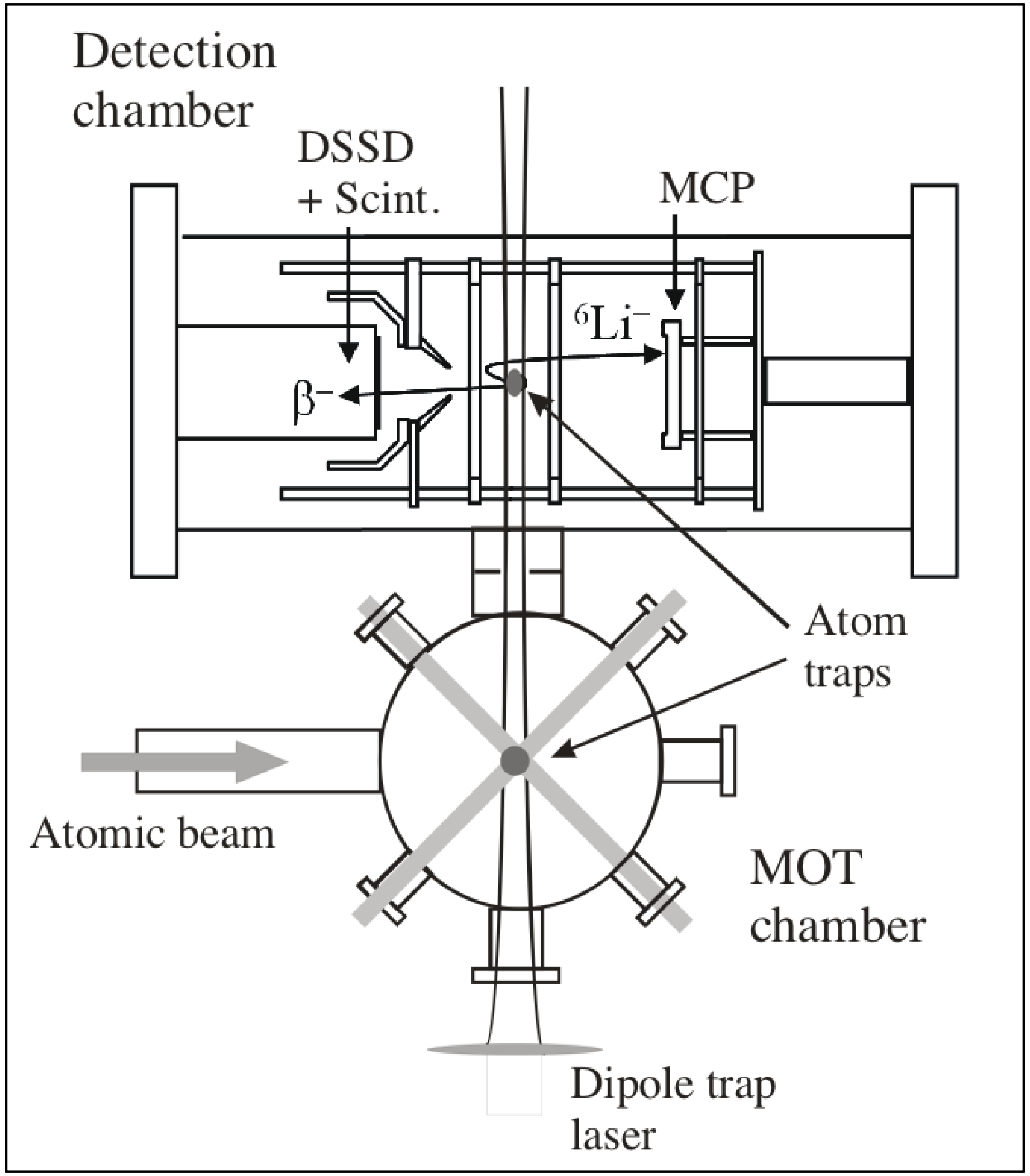
^{6}He at UW

Slides from Alejandro García

- ^{6}He is a great case!
  - Large endpoint (3.5 MeV)
  - Nuclear structure under control
  - Simple decay
  - Sensitive to tensor interactions

See poster by Xueying Huyan



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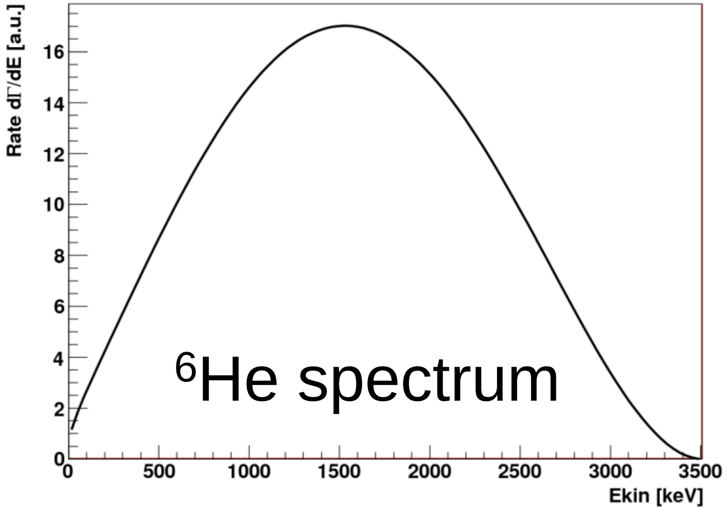

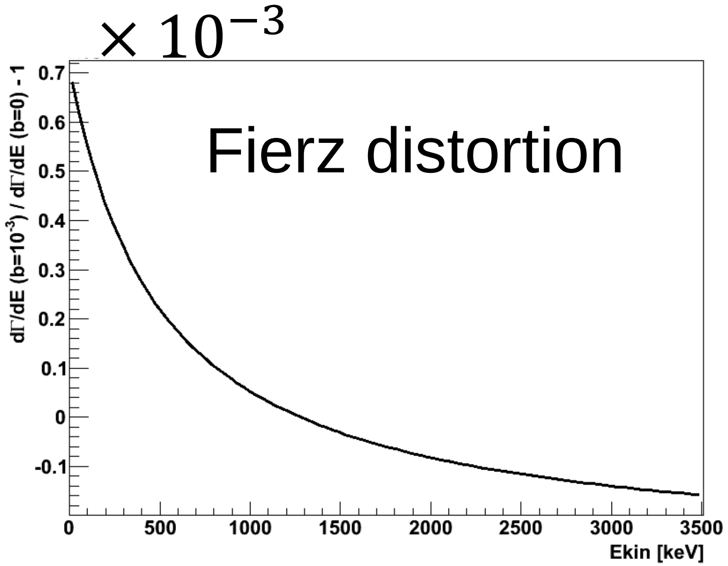

- Most sensitive probe is the Fierz interference:
  - Decay rate is: $dw = dw_0\left[1 + a_{\beta\nu}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\,\frac{\Gamma m_e}{E_e}\right]$

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

$\beta - \nu$ correlation

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

Fierz interference

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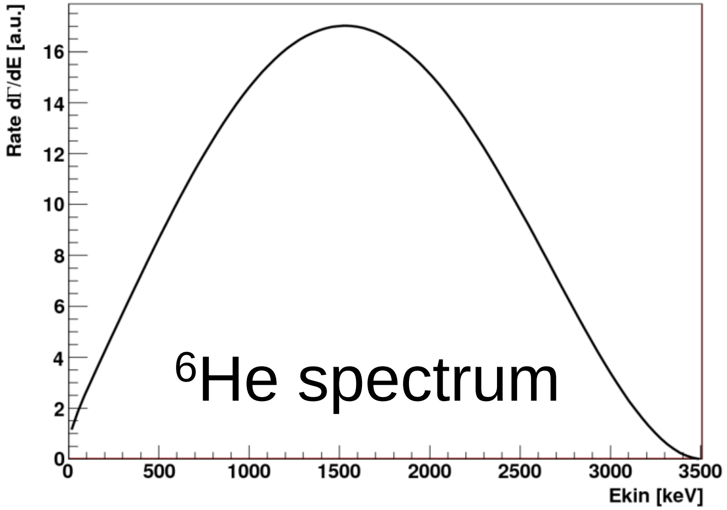

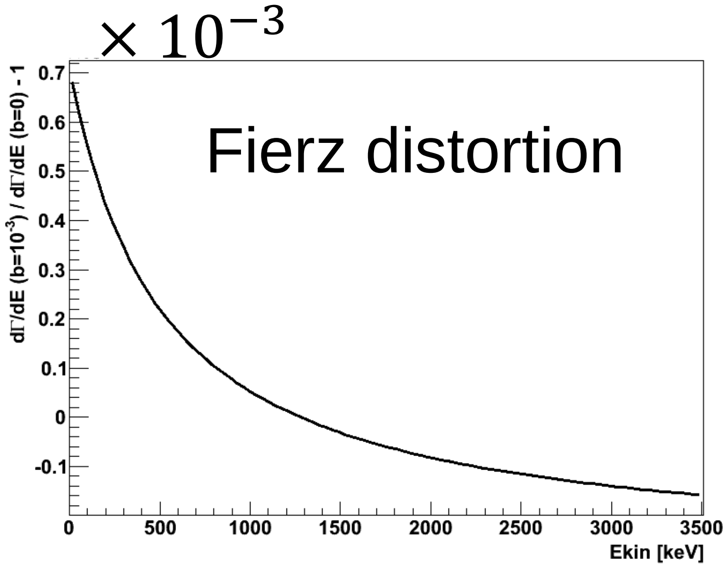

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- Status:
  - Lifetime (PRC **86**, 035506)
  - Charge state fractions
  - $a_{\beta\nu}$: stats for 0.2%; systematics?

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

$\beta - \nu$ correlation

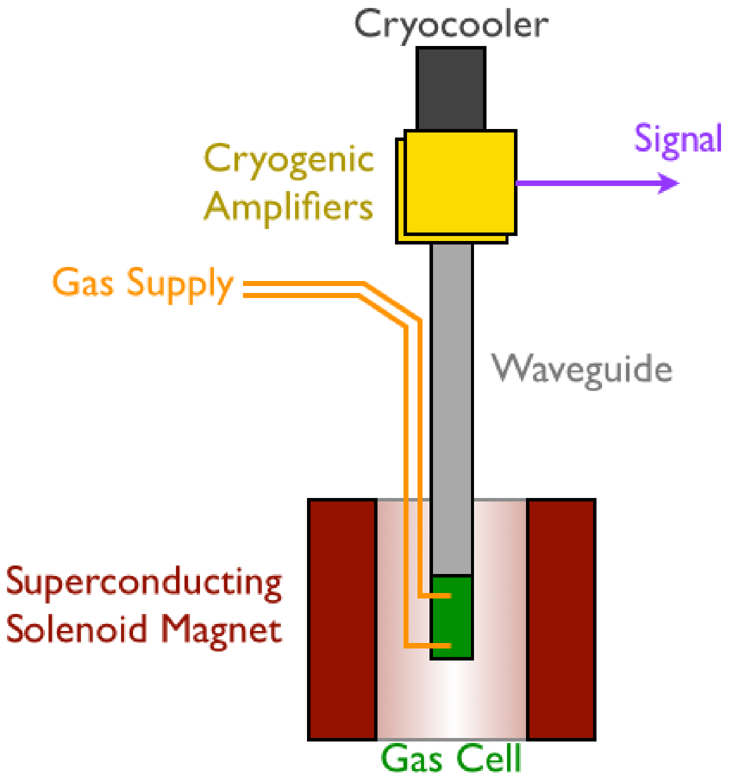
$$\boxed{b \approx \pm\frac{(C_T + C_T')}{C_A}}$$

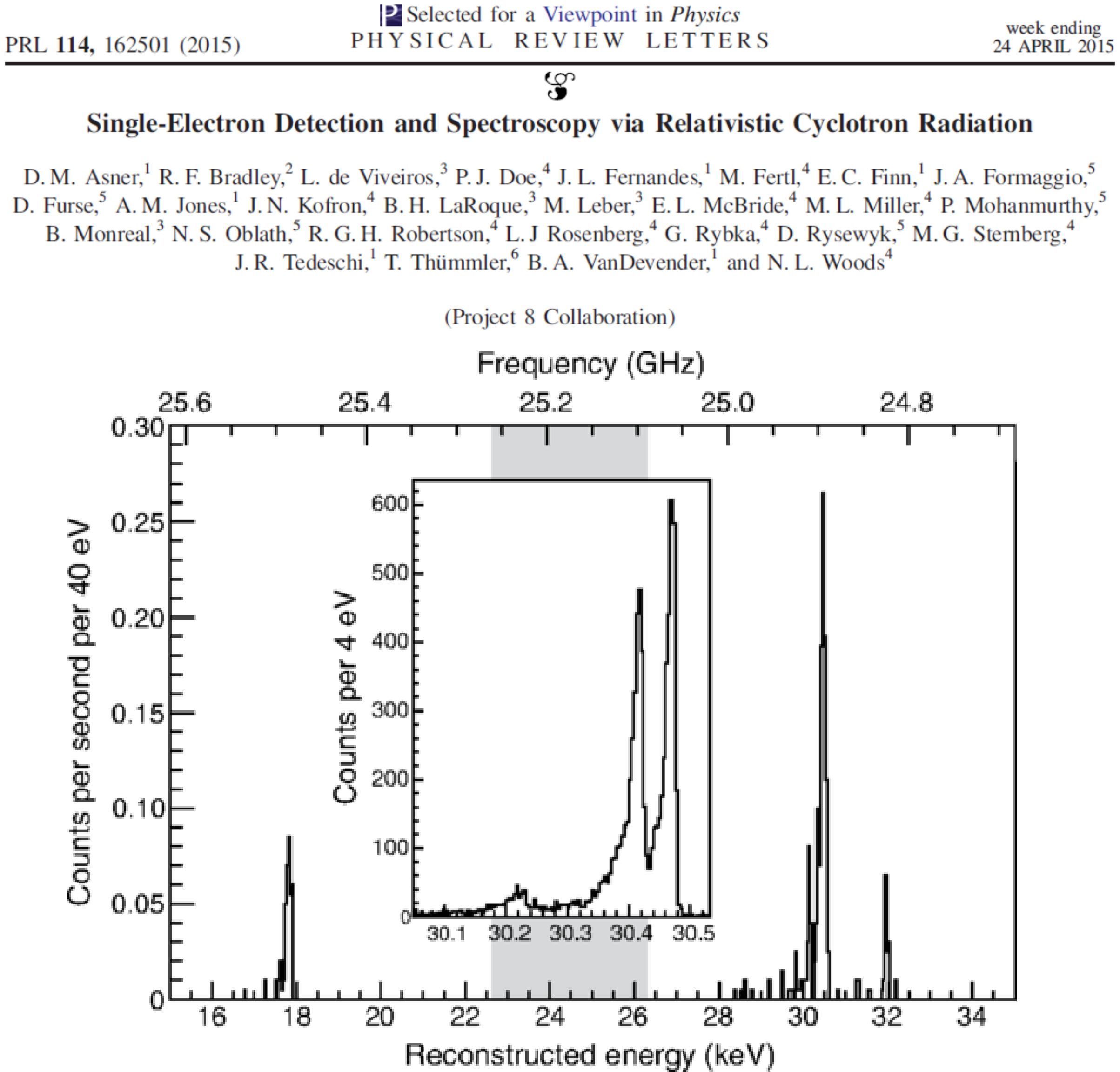
Fierz interference

^{6}He at UW – CRES technique

Martin Fertl's talk on Monday

- 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

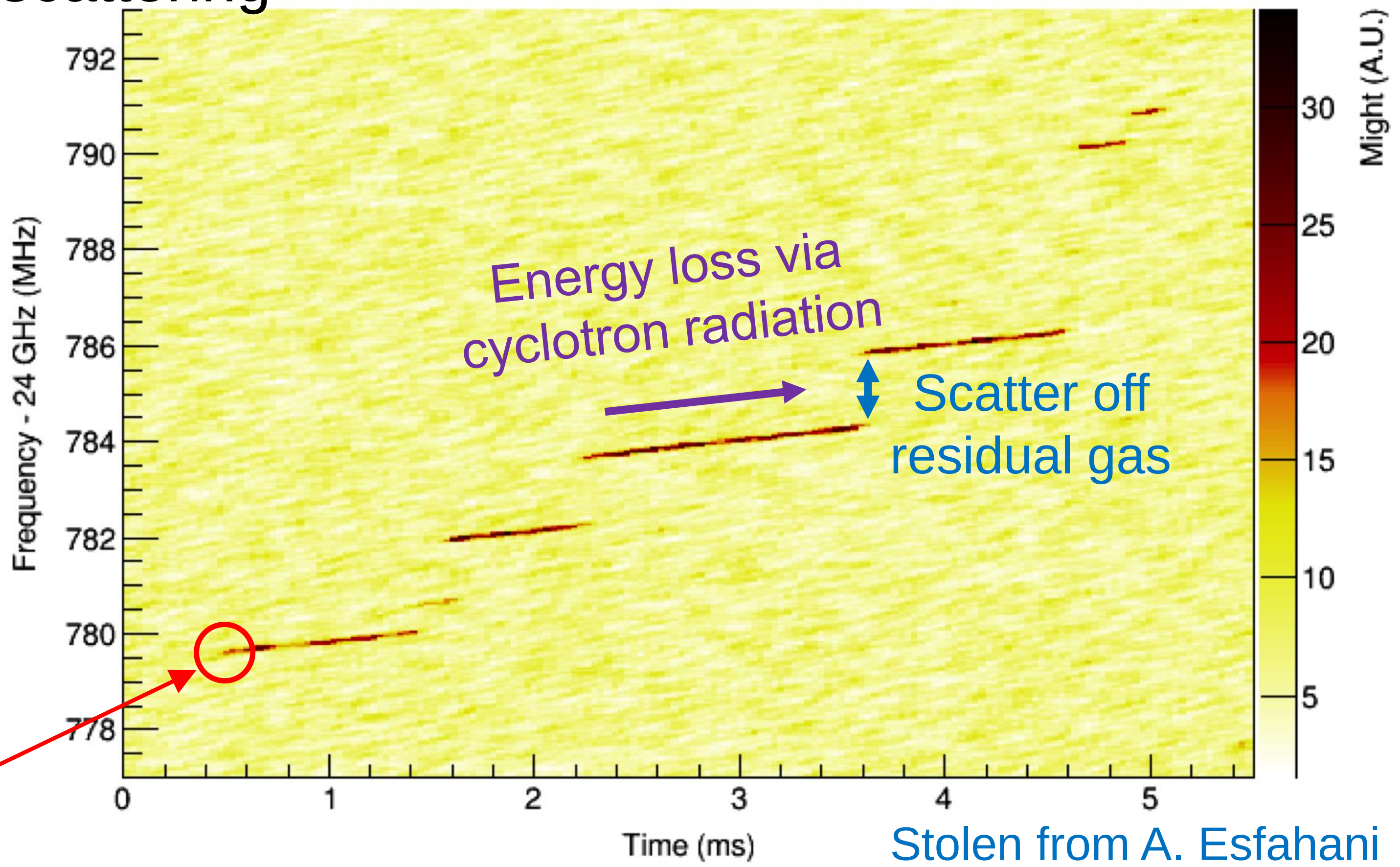
Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

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



Energy loss via cyclotron radiation

Scatter off residual gas

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

Initial frequency → E

Stolen from A. Esfahani

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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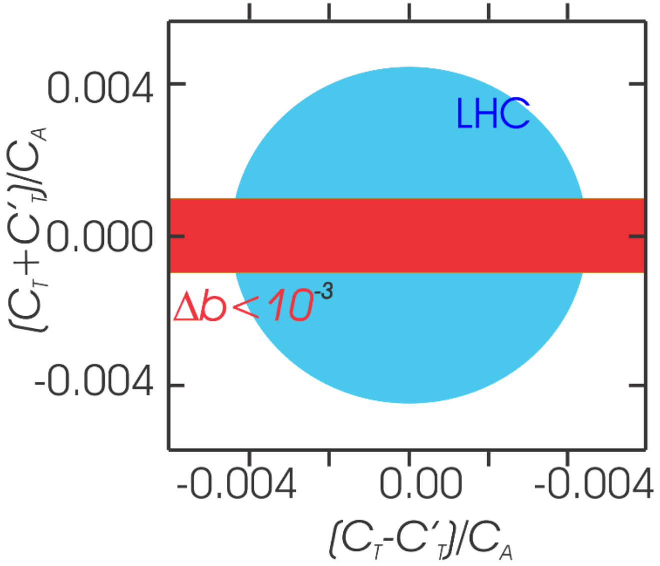
  - 6 GHz bandwidth
  - ^{6}He and ^{19}Ne measurements

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}



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- Phase III: ultimate measurement ($b < 10^{-4}$)
  - Ion trap for no limitation from geometric effect

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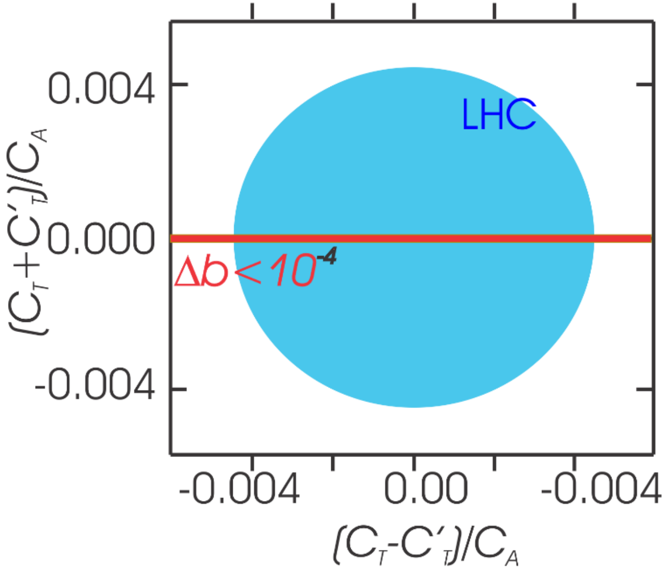
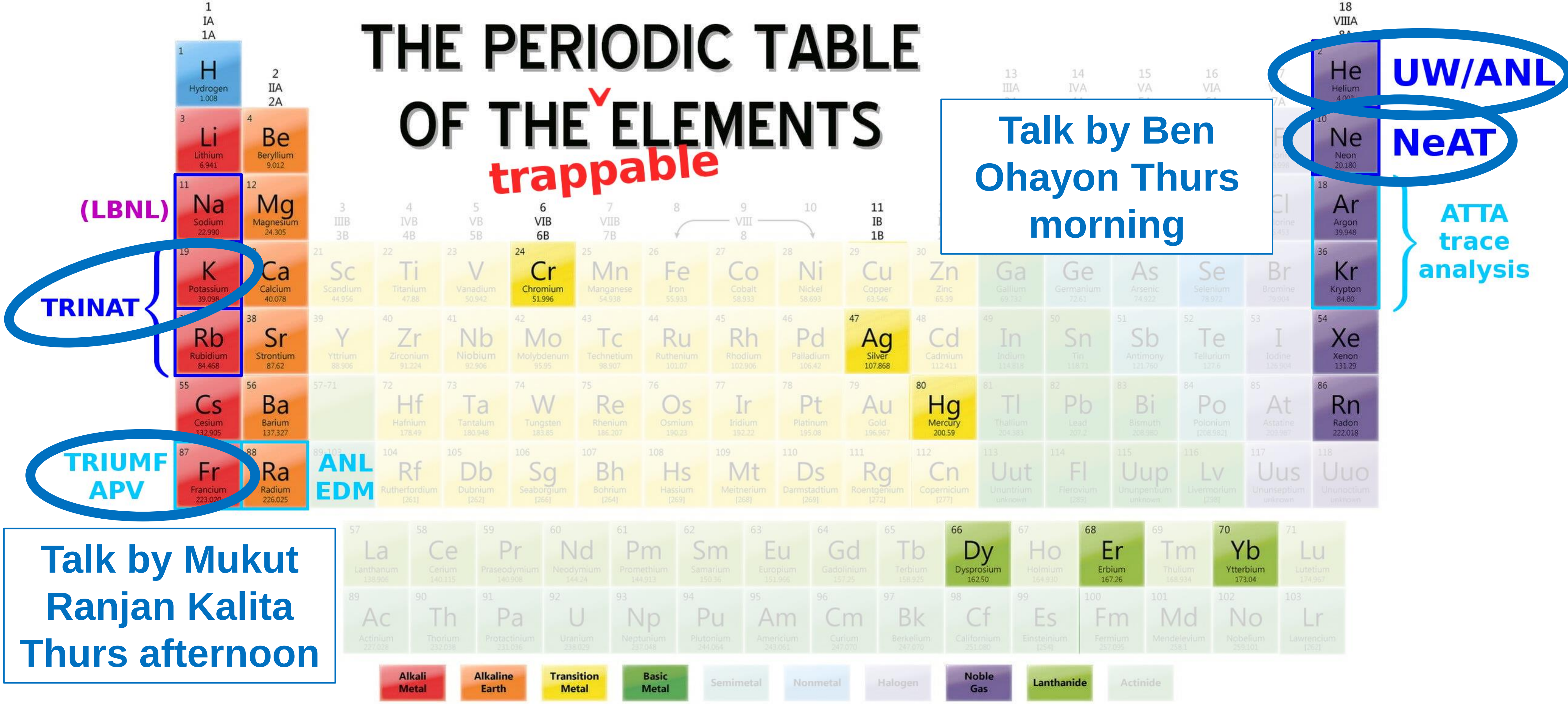


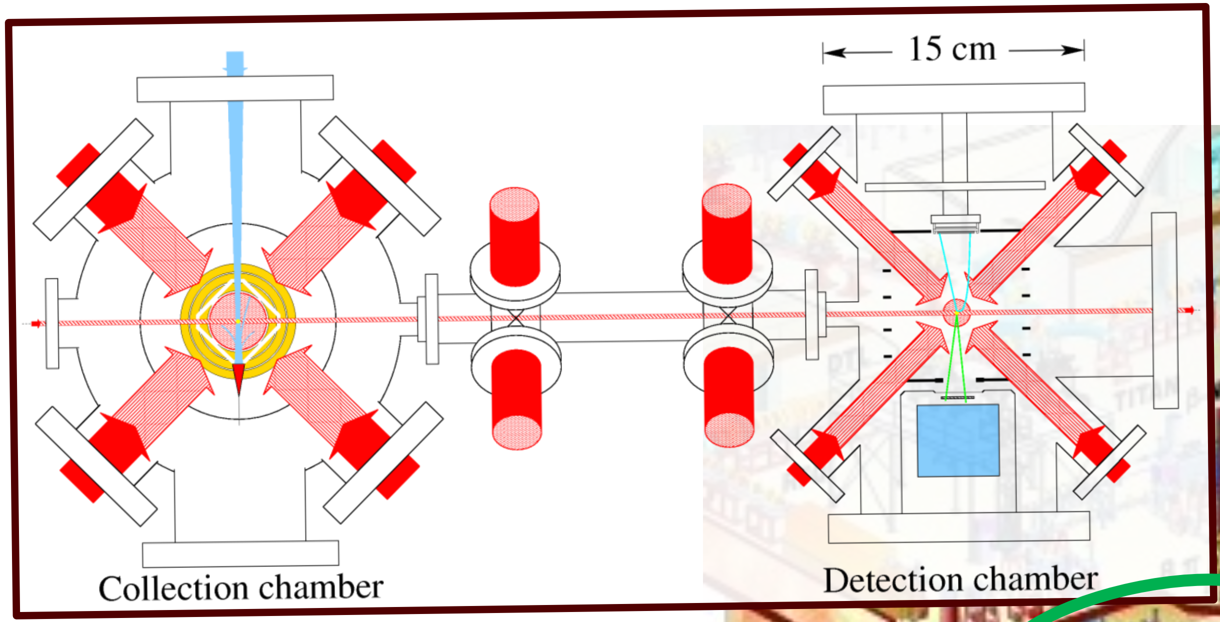
Difficulty with MOTs: not all atoms can be trapped

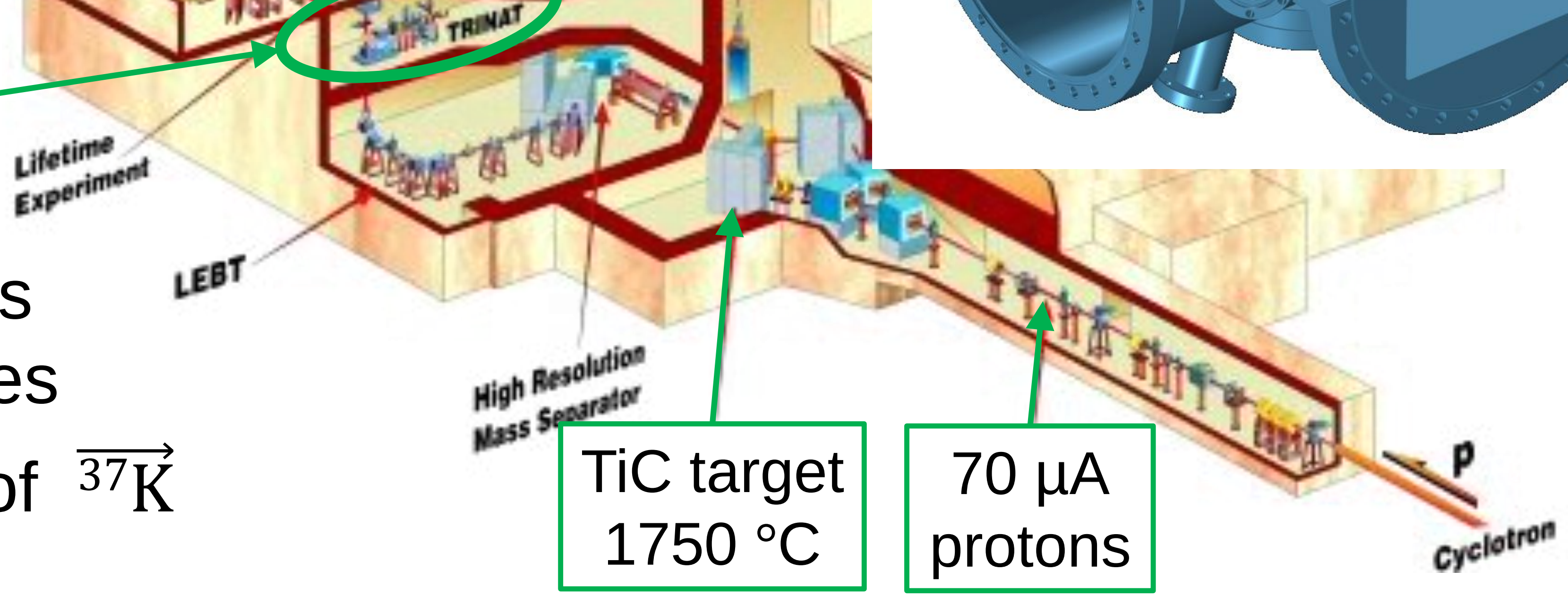


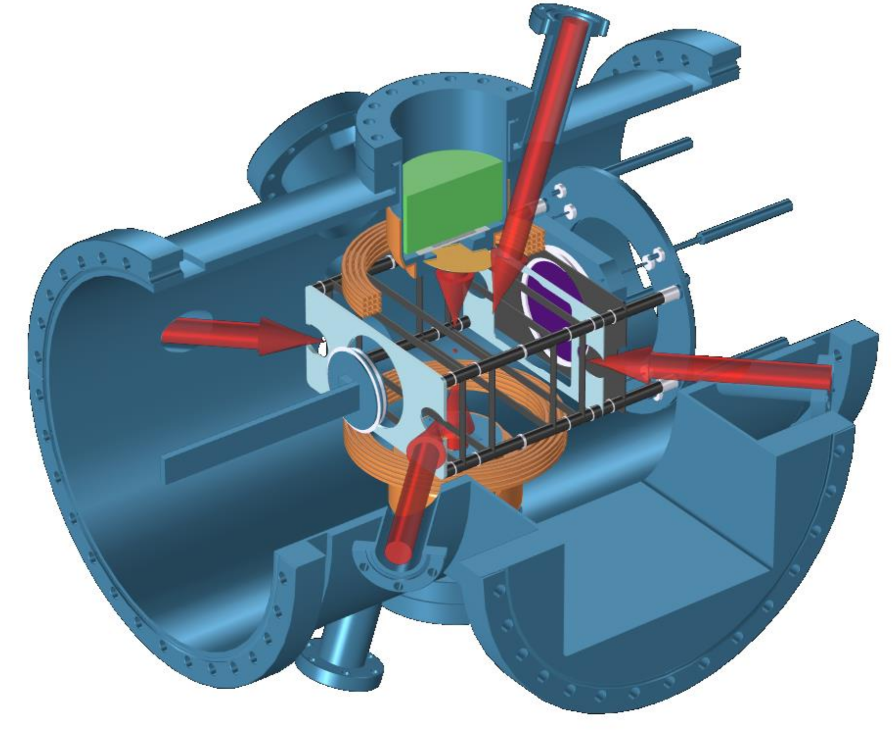
Talk by Ben Ohayon Thurs morning

Talk by Mukut Ranjan Kalita Thurs afternoon

The TRIUMF Neutral Atom Trap







up to 8×10^{7} ^{37}K/s

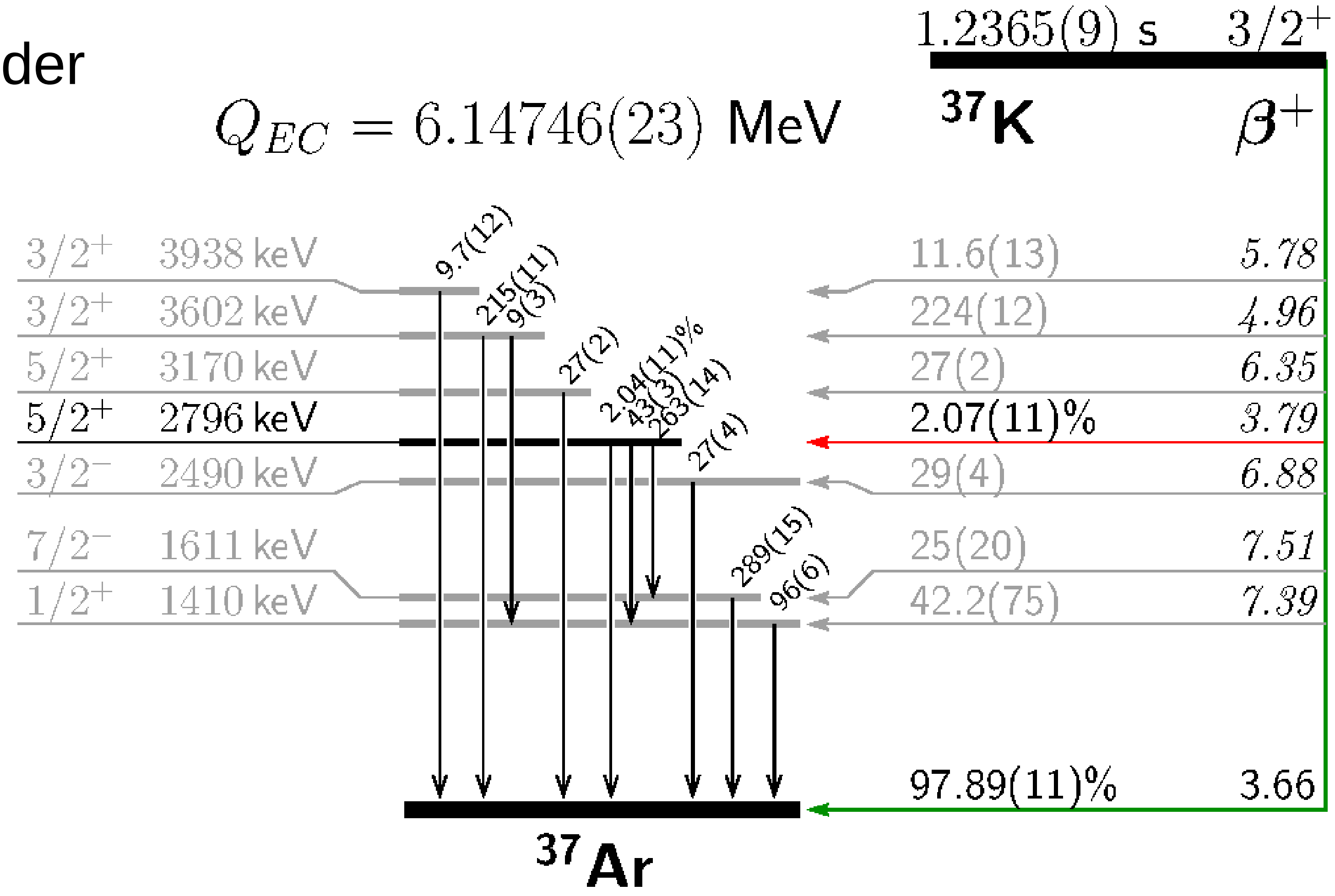
TiC target
1750 °C

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

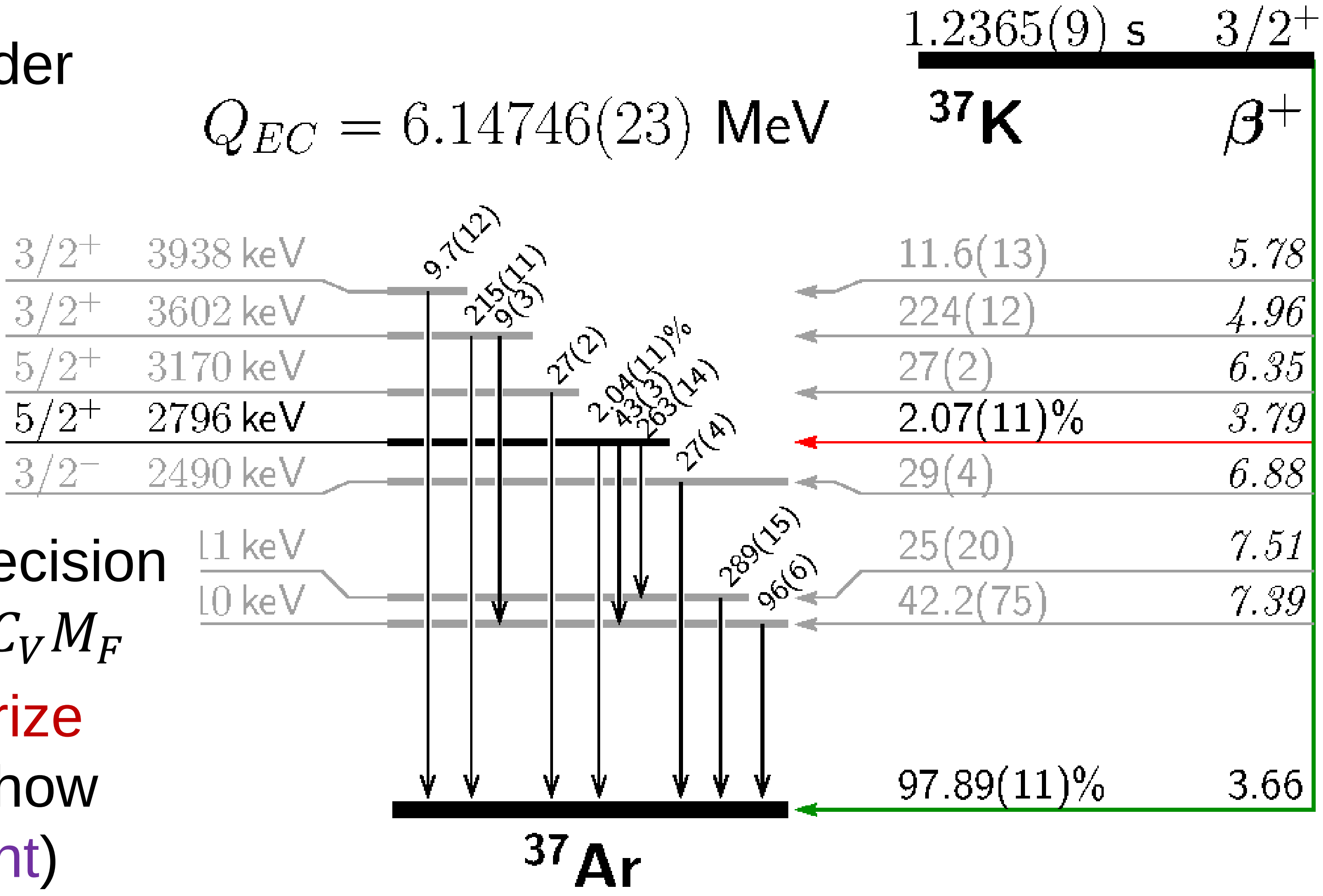
- Beautiful nucleus to test the standard model:
  - Alkali atom ⇒ “easy” to trap with a MOT and polarize with optical pumping
  - Isobaric analogue decay
    ⇒ theoretically clean; recoil-order corrections under control
  - Lifetime, Q-value and branches (*i.e.* the $\mathcal{F}t$ value) well known
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



$$Q_{EC} = 6.14746(23)\ \mathrm{MeV}$$

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.
- But there are challenges…
  - Can’t calculate $C_A M_{GT}$ to high precision
    ⇒ need to measure $\rho \equiv C_A M_{GT} / C_V M_F$
  - Nuclear spin 3/2 ⇒ need to polarize the atoms, and especially know how polarized they are (also alignment)



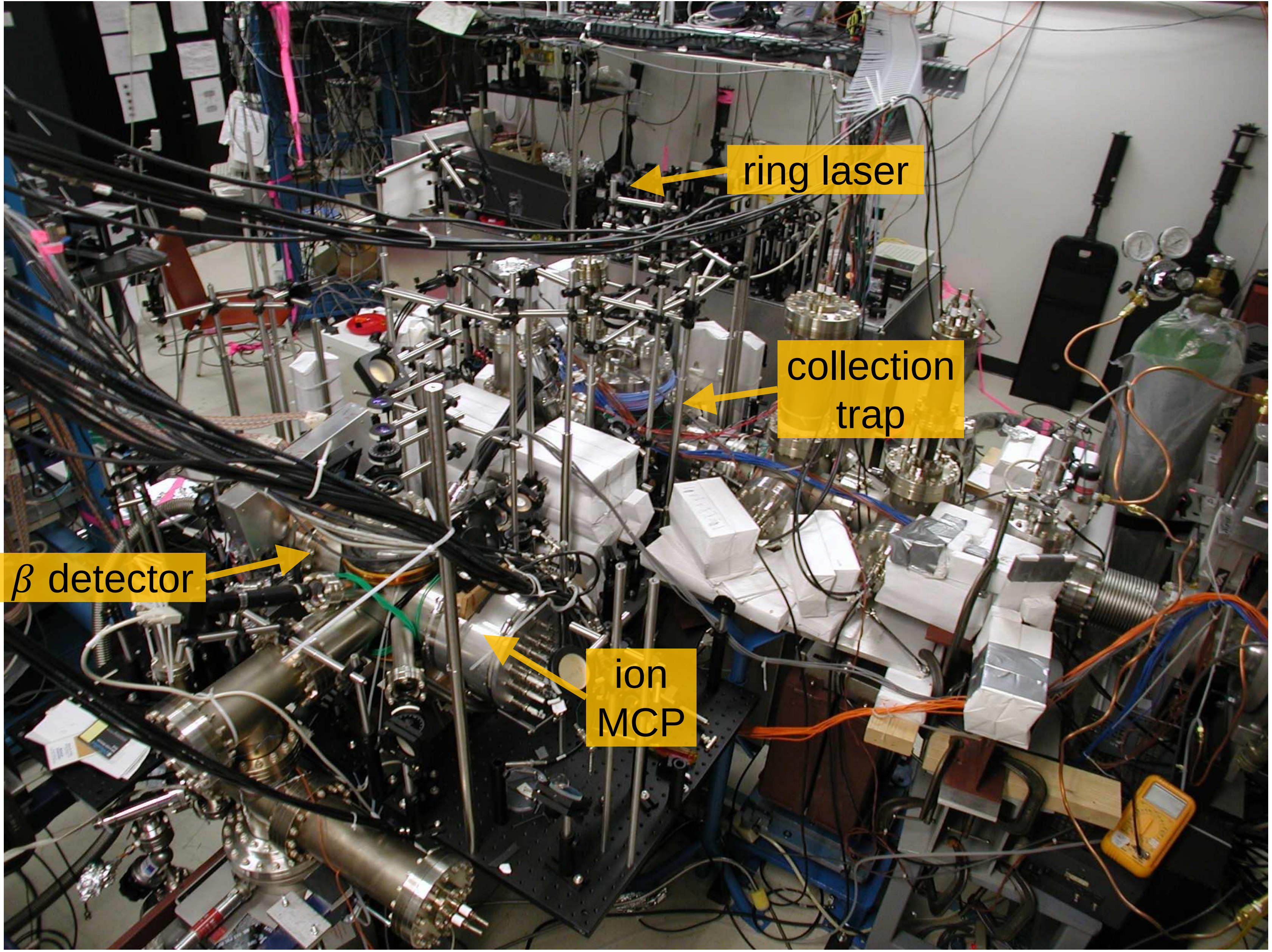
The Ft is measured well enough (for now)

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

Correlation	SM expectation
$\beta - \nu$ correlation	$a_{\beta\nu} = 0.6648(18)$
Fierz interference	$b = 0$ (sensitive to scalars & tensors)
β asymmetry	$A_\beta = -0.5706(7)$
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)

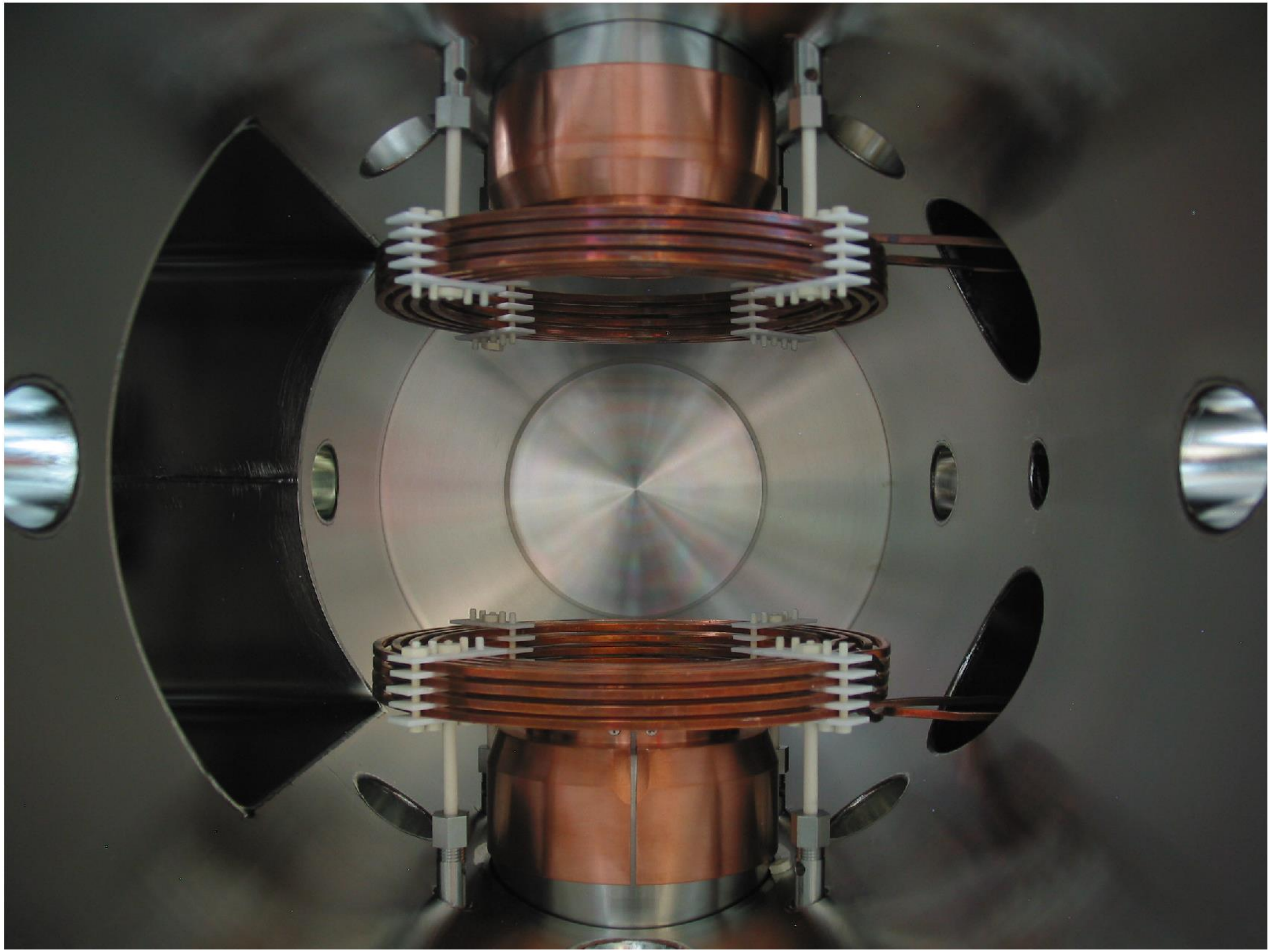
The TRINAT lab (an older picture)



RIB from ISAC

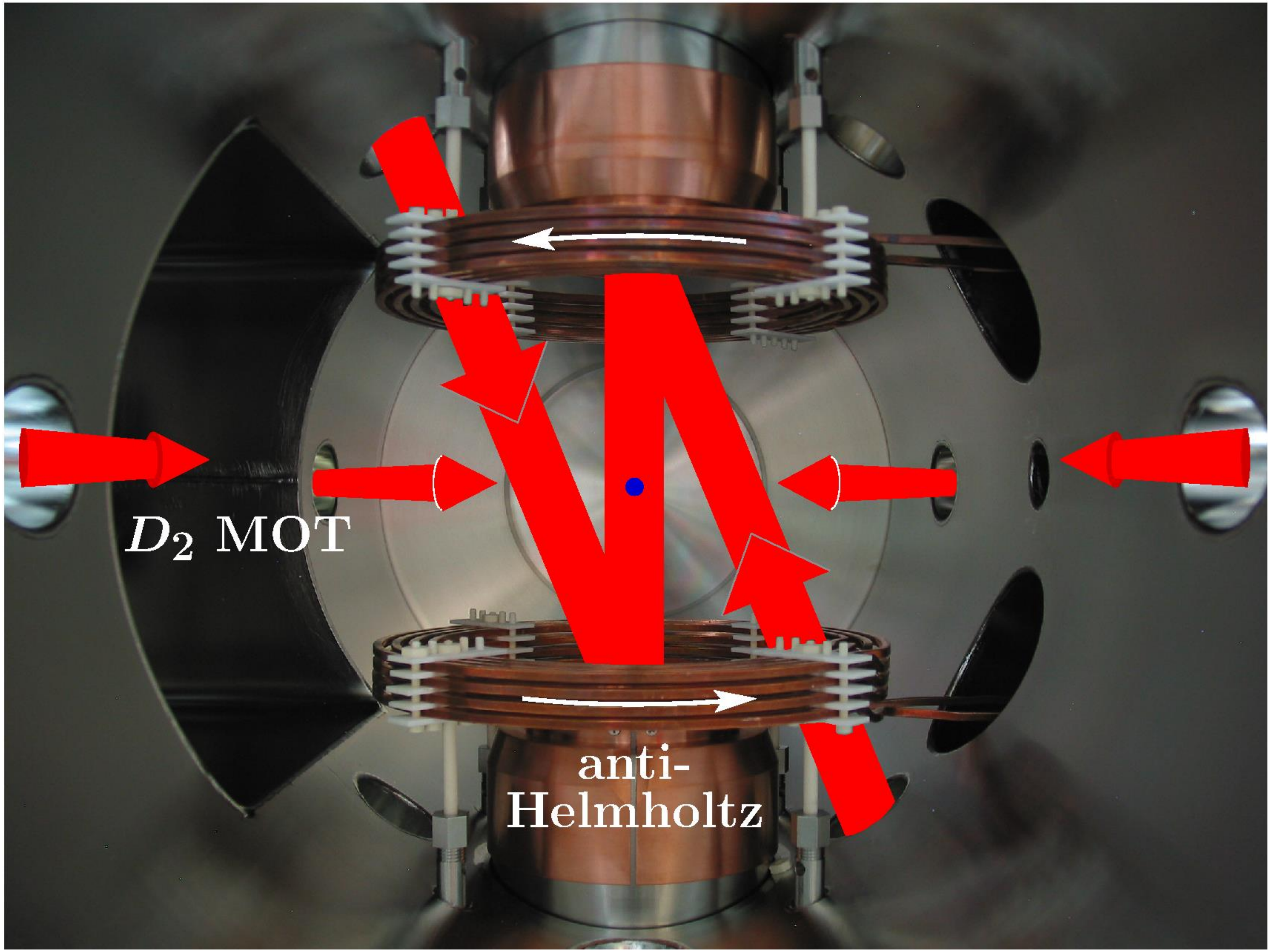
Outline of β asym & polarization measurements

- 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)



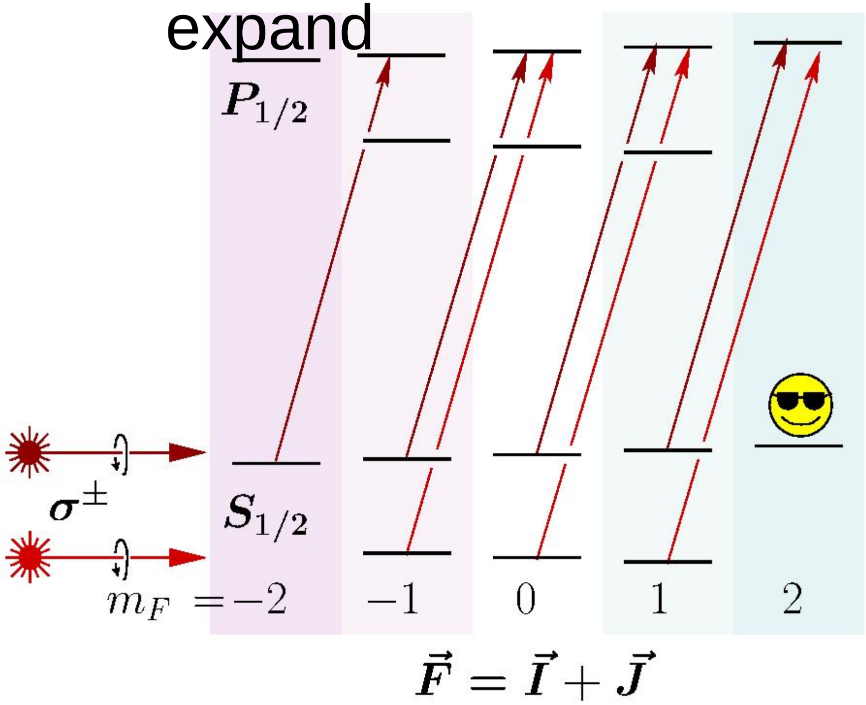
Outline of β asym & polarization measurements

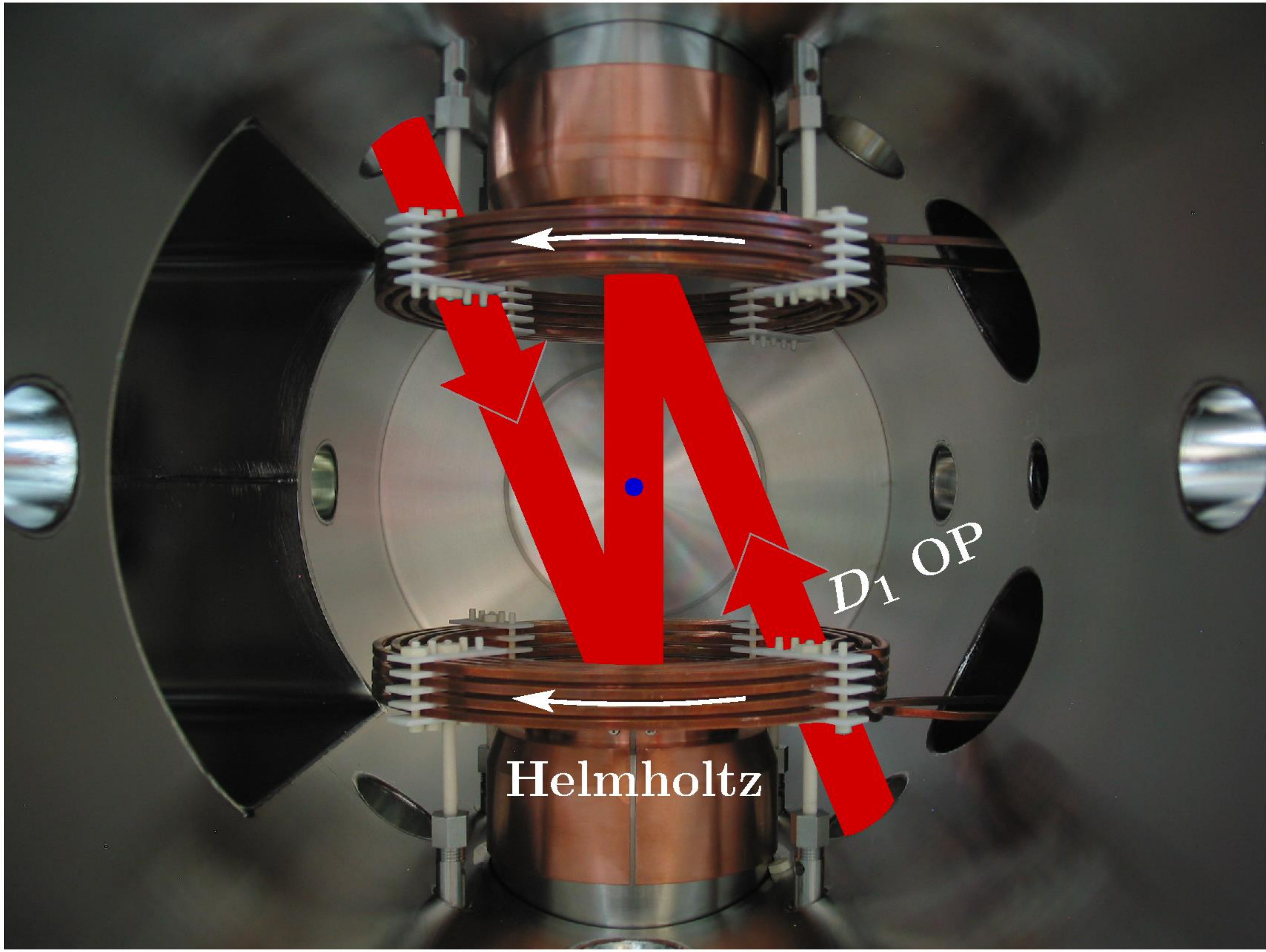
- MOTs provide a source that is:
  - Cold ($\sim 1\ \mathrm{mK}$)
  - Localized ($\sim 1\ \mathrm{mm}^3$)
  - In an open, backing-free geometry
- Allows us to detect $\vec{p}_\beta$ and $\vec{p}_{\mathrm{rec}}$ $\Rightarrow$ deduce $\vec{p}_\nu$ event-by-event



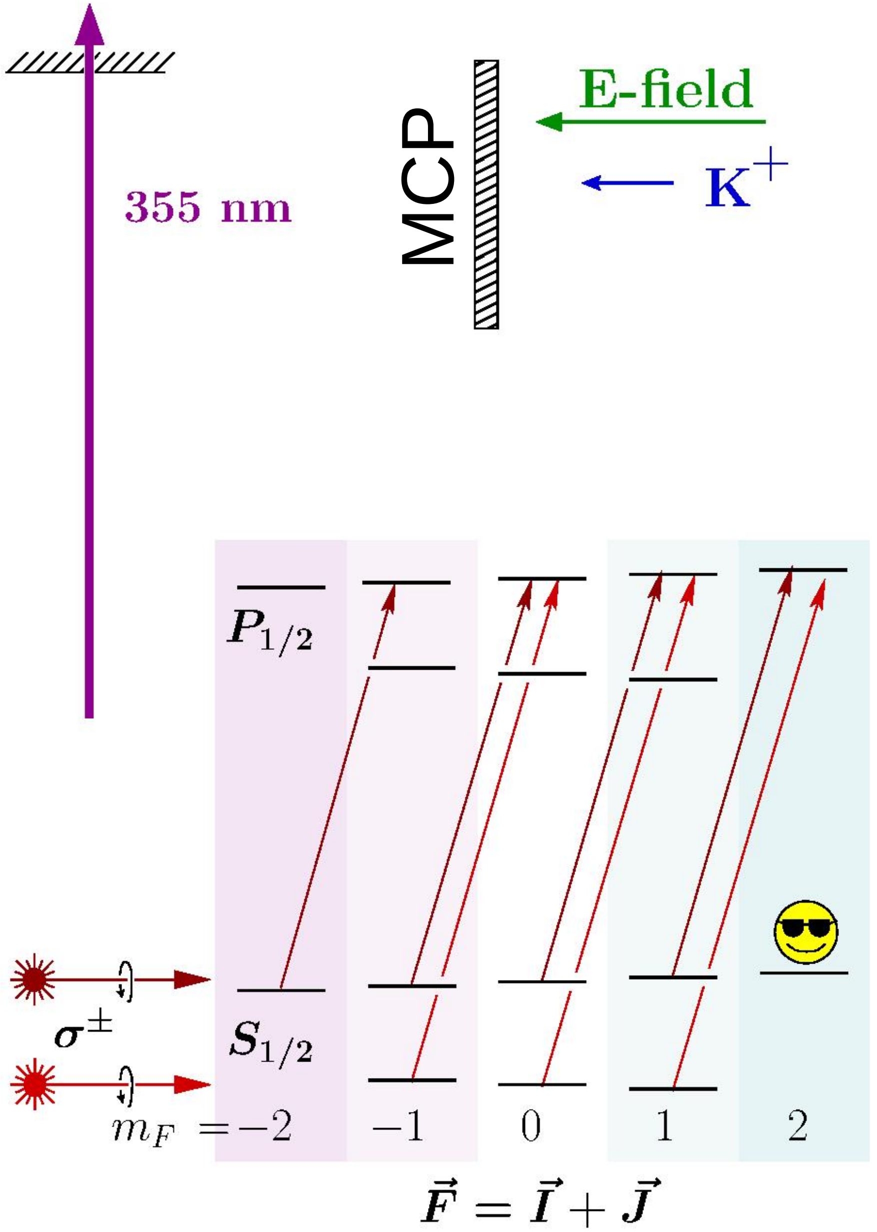
Outline of β asym & polarization measurements

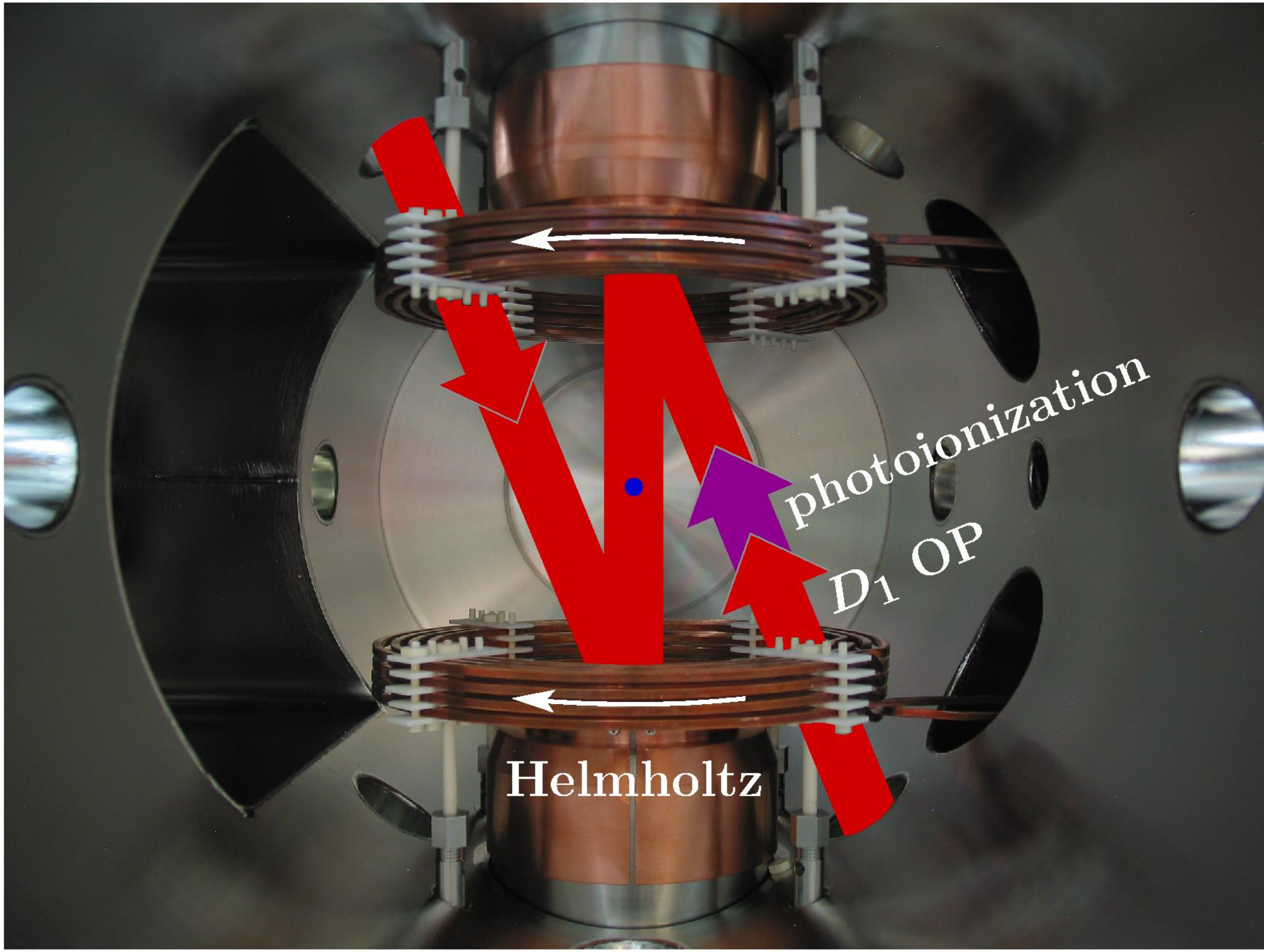
- Optical pumping:
  - Polarized light transfers ang momentum to atom
  - Nuclear and atomic spins are coupled
  - Polarize as (cold) atoms expand





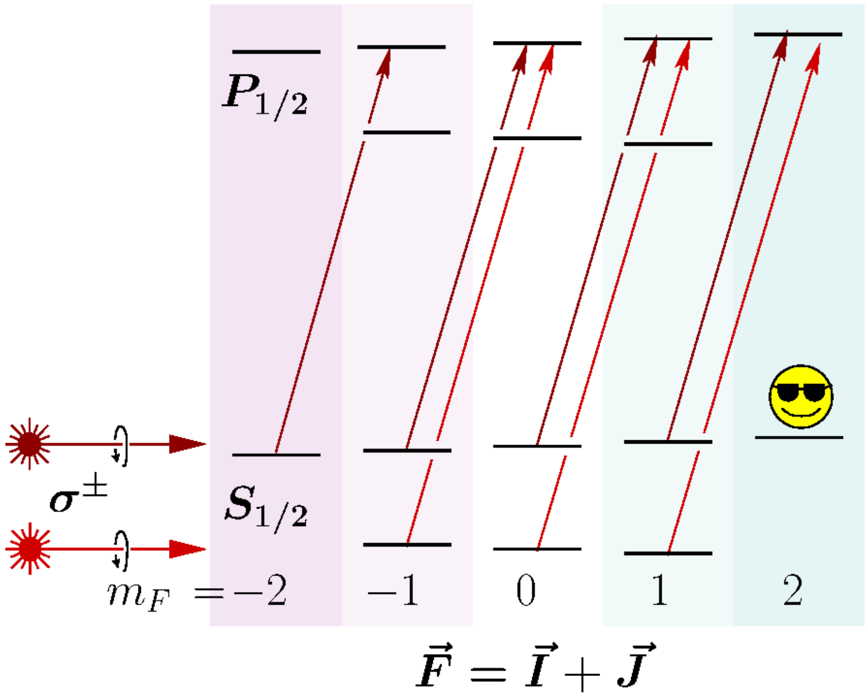
Outline of β asym & polarization measurements

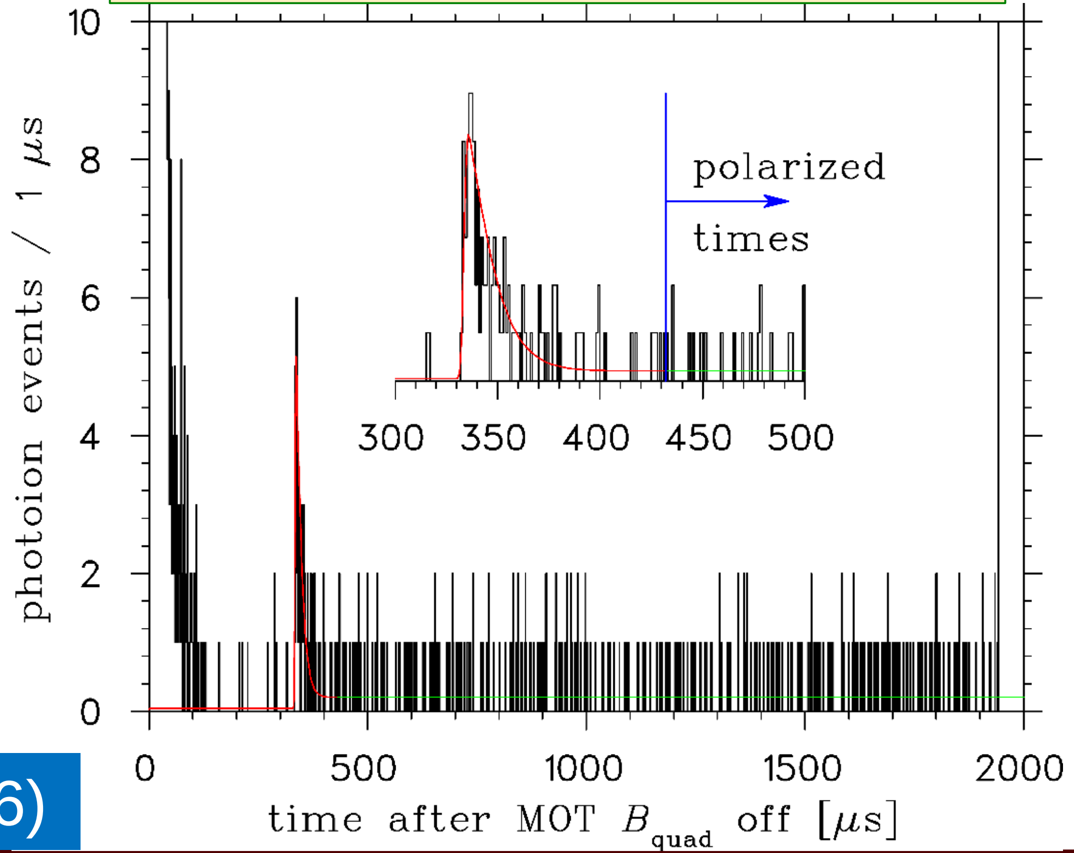




Optical pumping is fast and *efficient*!

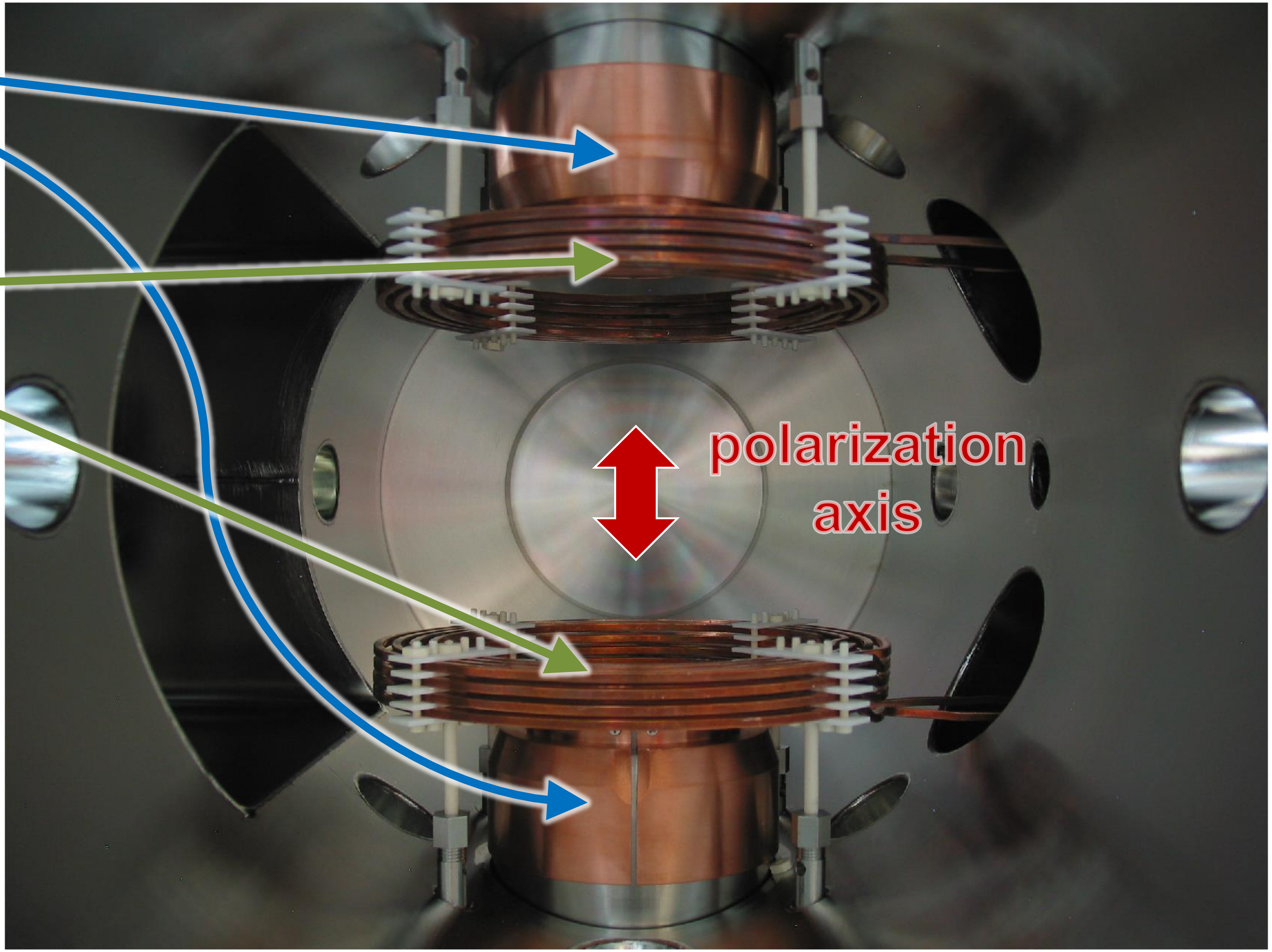
- No time to go into details, but basically
  - Measure the rate of photons (⇔ fluorescence) as a function of time
  - Model sublevel populations using the optical Bloch equations
  - Determine the average nuclear polarization: $\langle|P_{\mathbf{nucl}}|\rangle = \mathbf{0.9913(9)}$





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

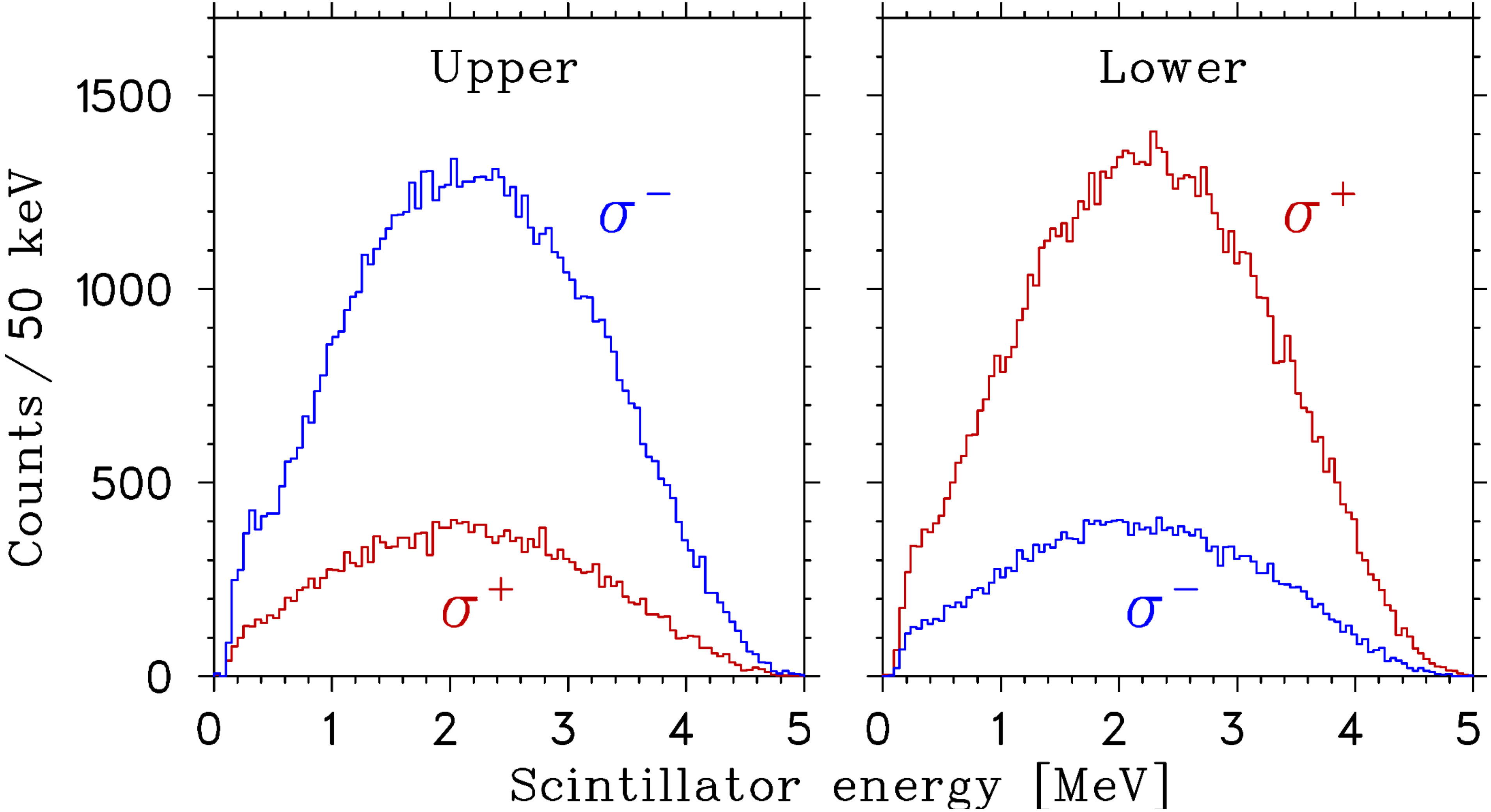
Use **all** information via the super-ratio:

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

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

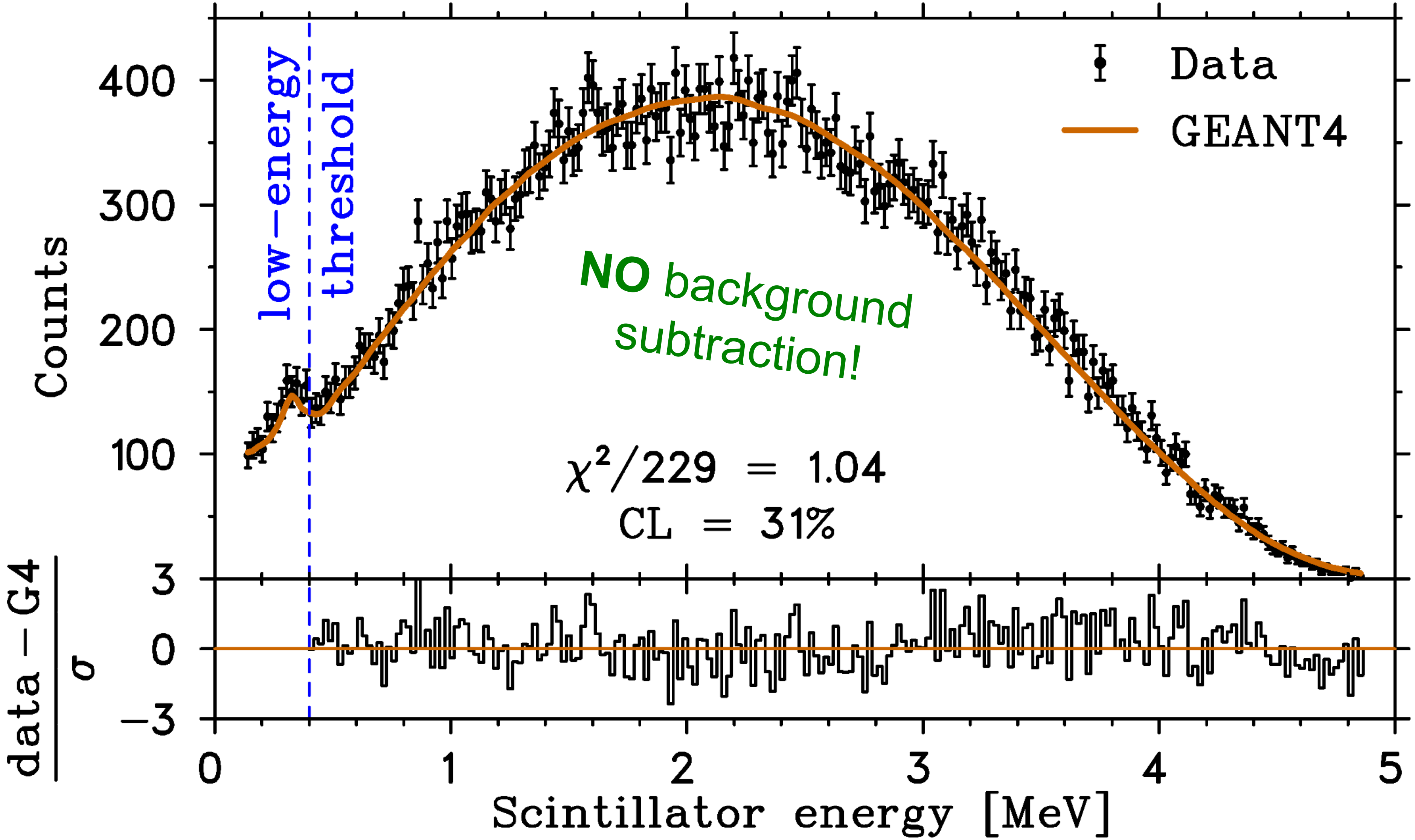
^{37}K β asymmetry measurement

- **Two detectors** and **polarization states**: reduce systematics
- **Blind analysis**: remove small subset of one data set until all cuts defined



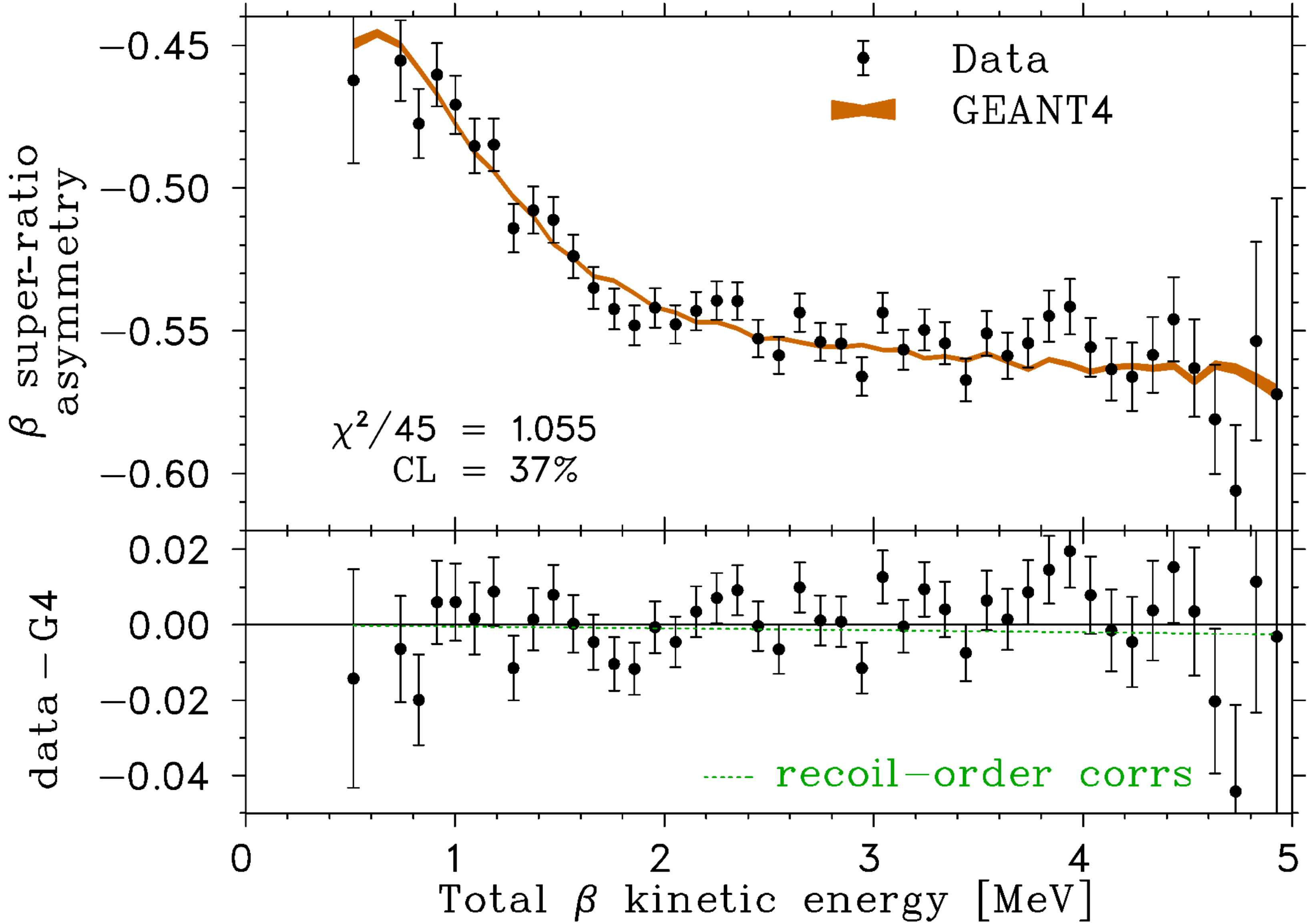
^{37}K β asymmetry measurement

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



^{37}K β asymmetry measurement

- Asymmetry as a function of β energy after unblinding:



(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
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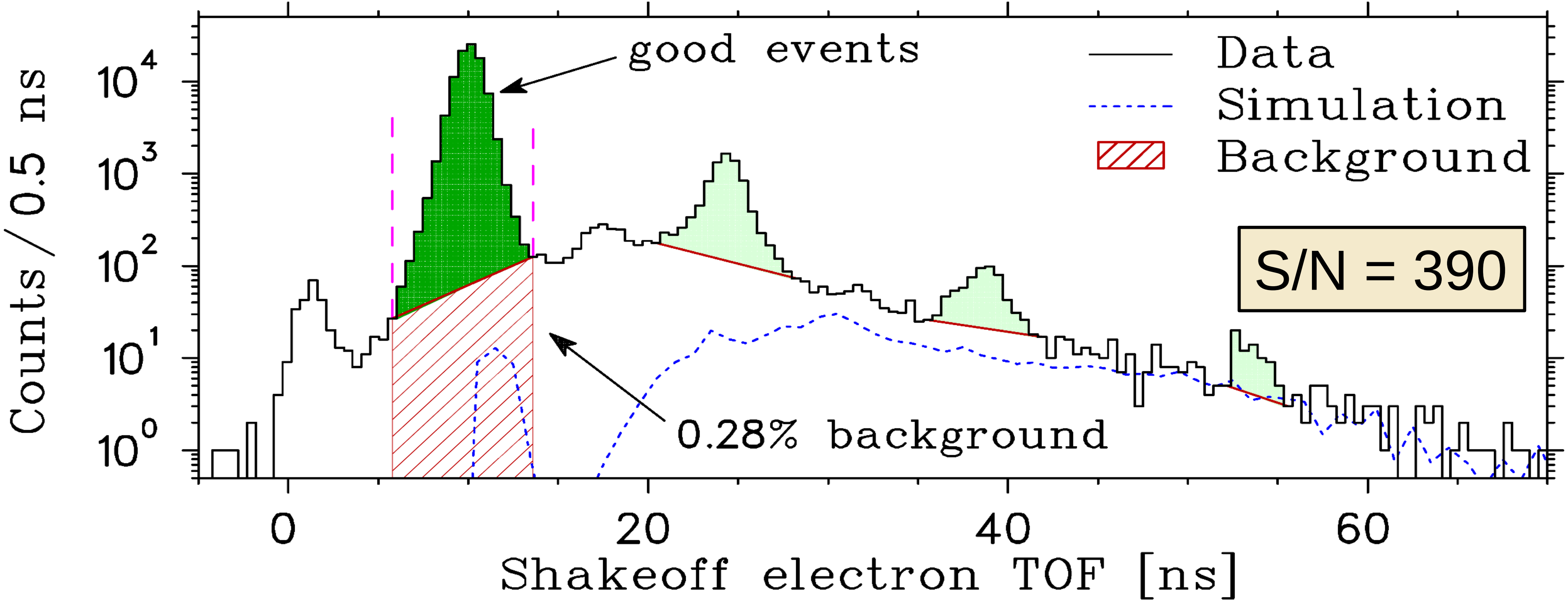

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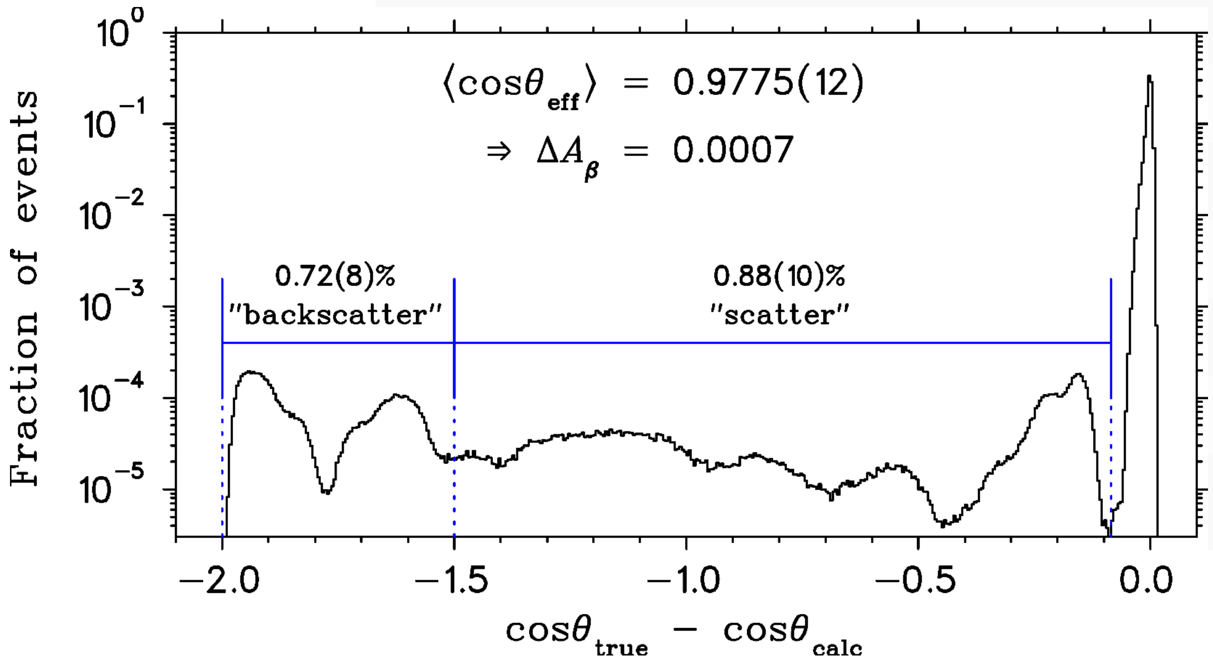

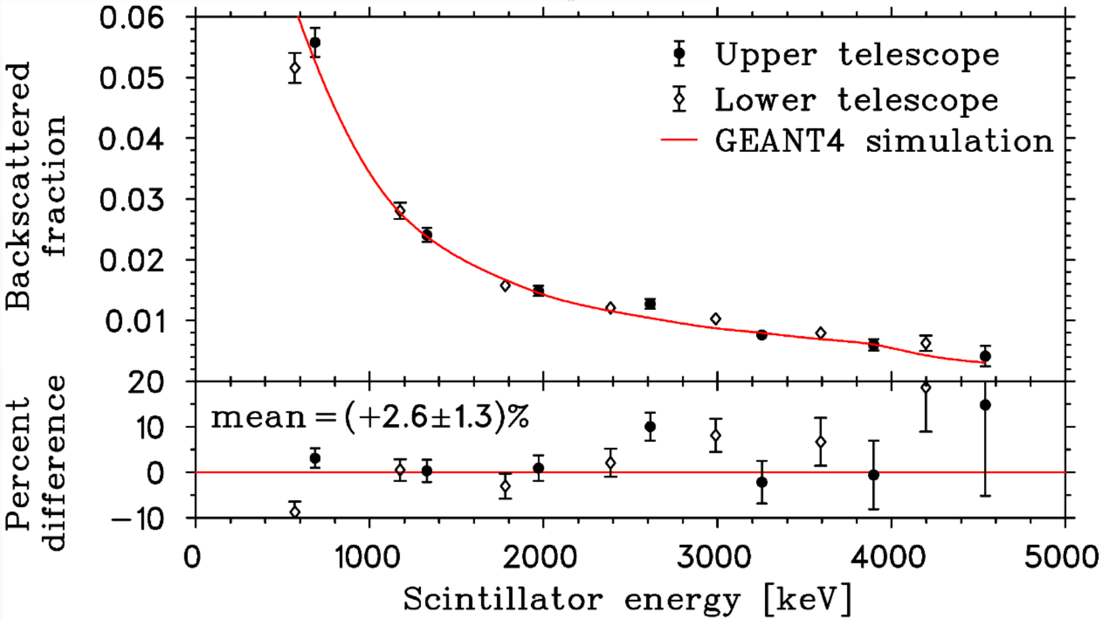

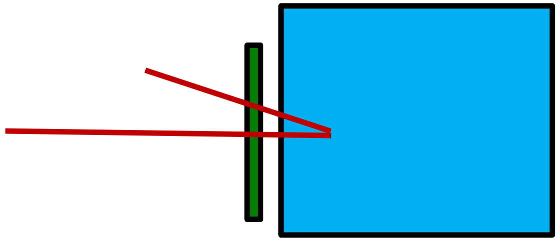

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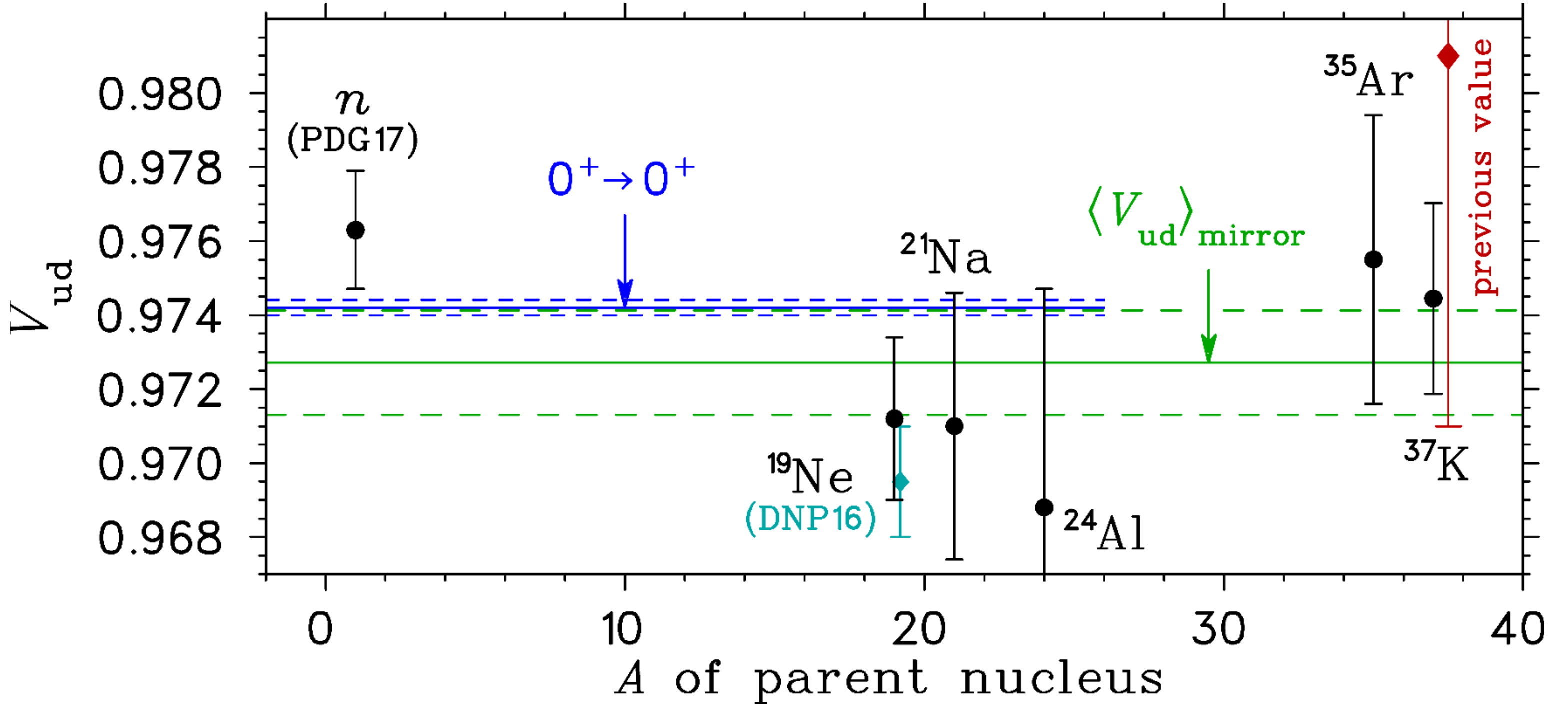
$\boldsymbol{A_\beta^{\mathrm{meas}} = -0.5707(19)}$ *cf* $A_\beta^{\mathrm{SM}} = -0.5706(7)$ (includes recoil-order corrections, $\Delta A_\beta \approx -0.0028\frac{E_\beta}{E_0}$)

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

Interpretation and future prospects

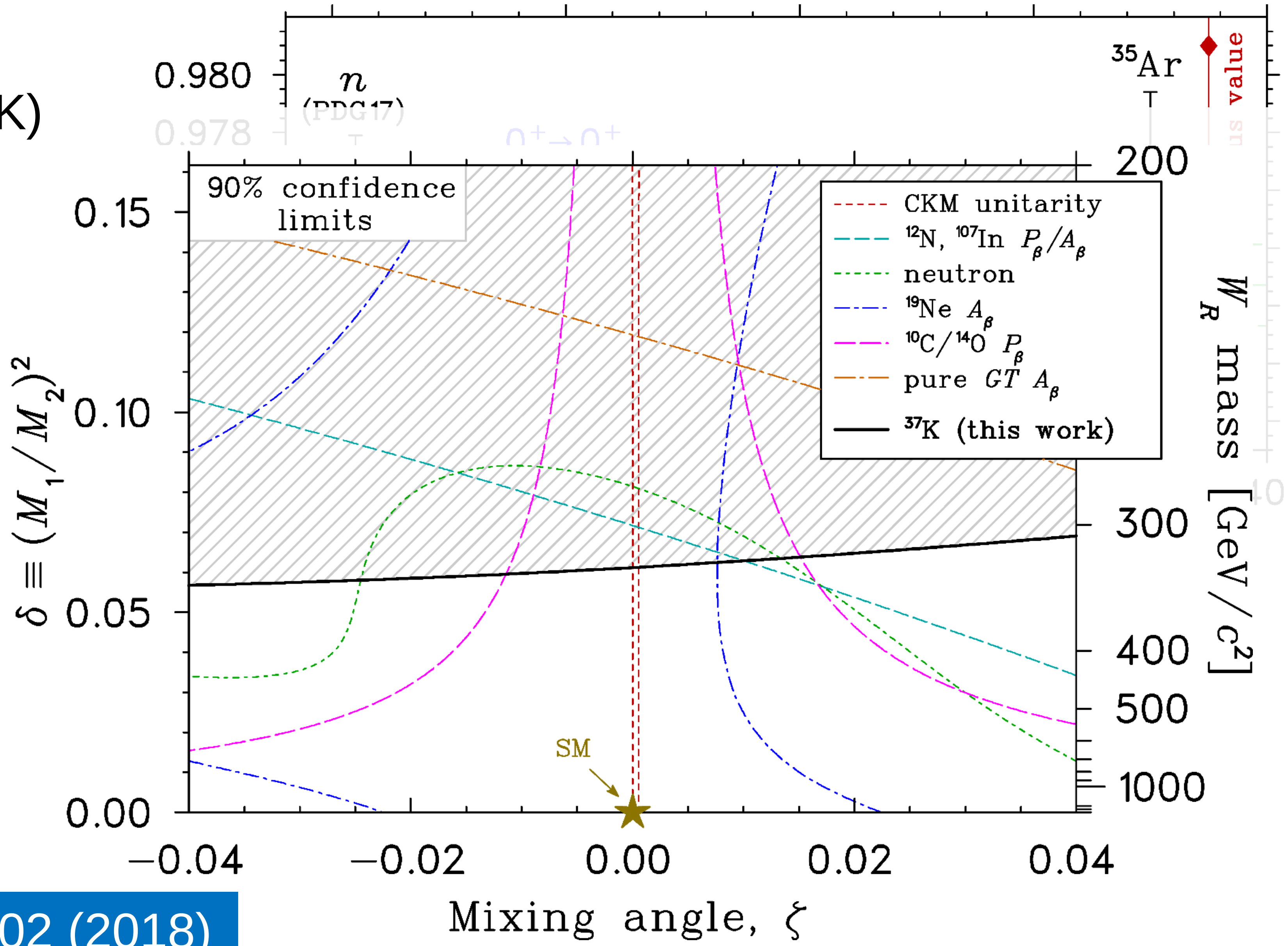
- Comparison of $V_{\rm ud}$ from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays



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

Interpretation and future prospects

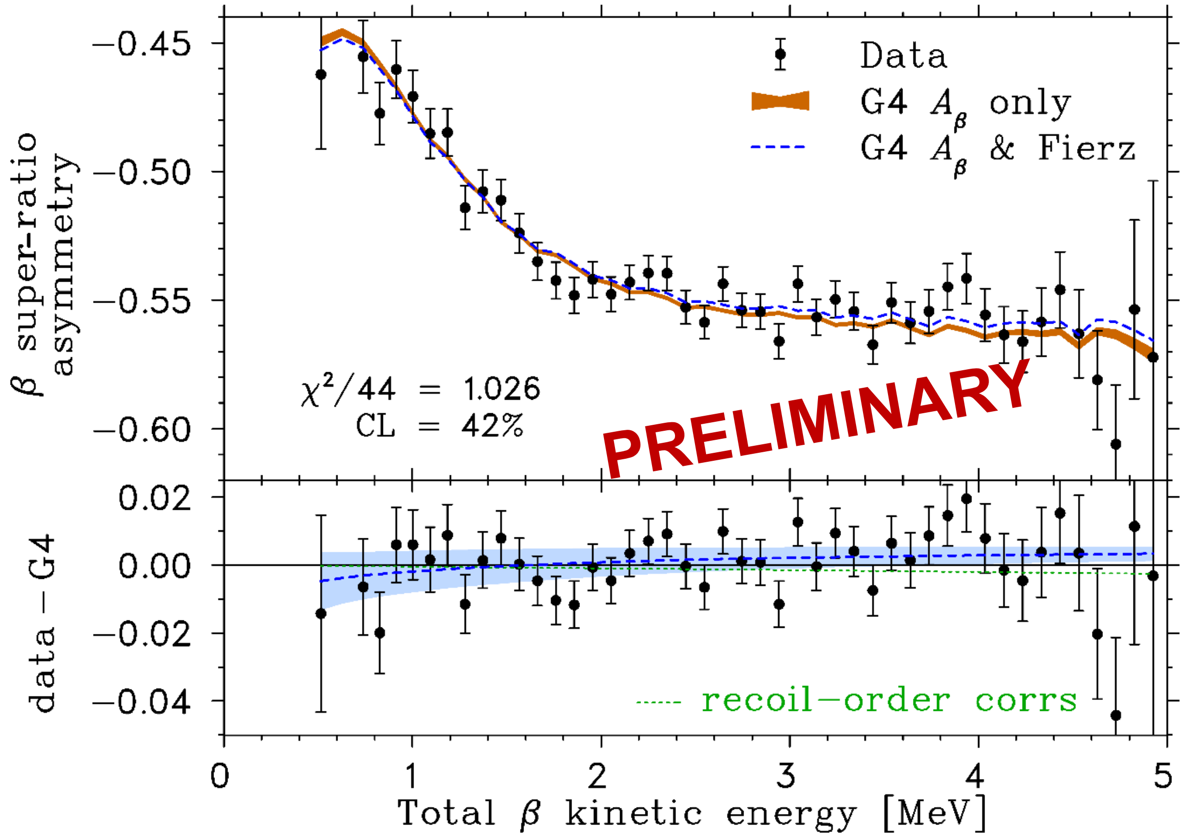
- Comparison of V_{ud} from:
  - Mirror nuclei (including ^{37}K)
  - The neutron
  - Pure Fermi decays
- Also other physics to probe:
  - Right-handed currents
  - 2nd class currents
  - Scalar & tensor currents

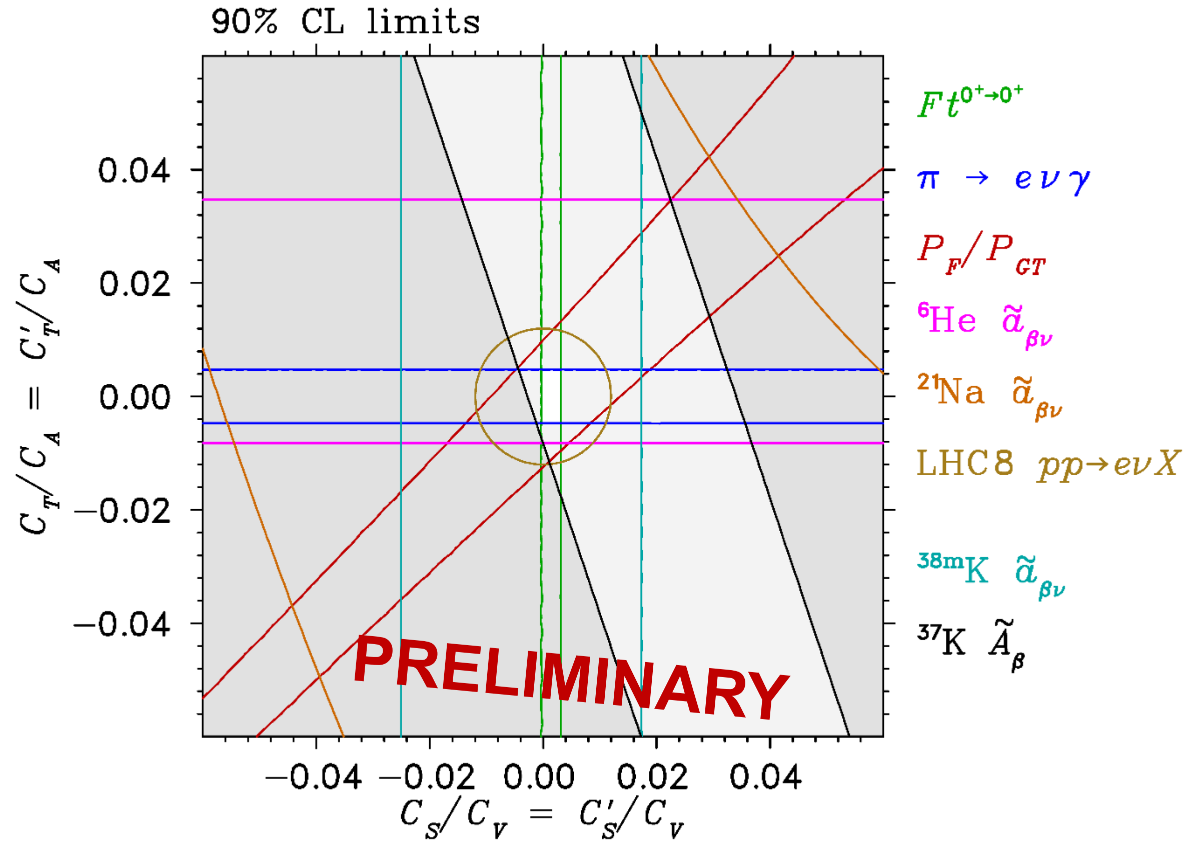


B.Fenker *et al*, PRL **120**, 062502 (2018)

Future plans

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





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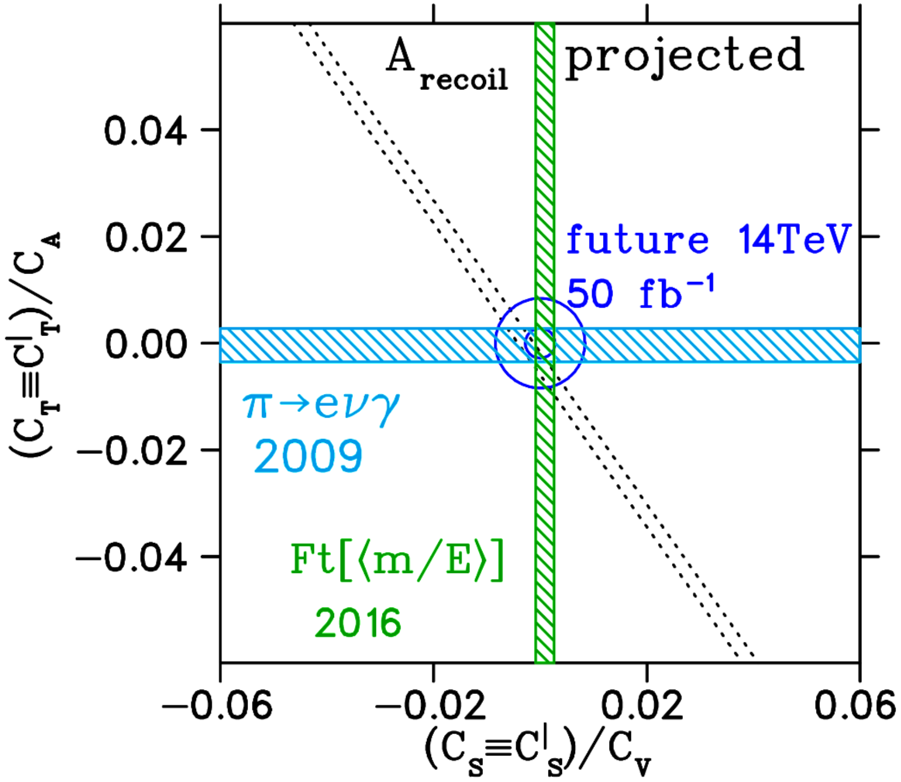
- Measure $A_{\text{recoil}} \propto A_\beta + B_\nu$
  - Technique demonstrated in ^{80}Rb (Pitcairn *et al*., PRC **79**, 015501 (2009))
  - High statistics measurement



(assumes the LHC sees a 2σ signal)

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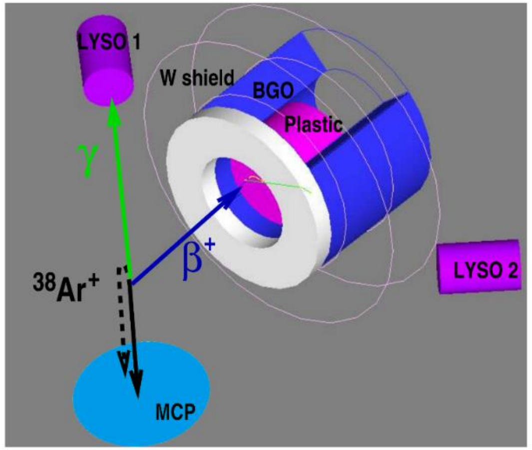
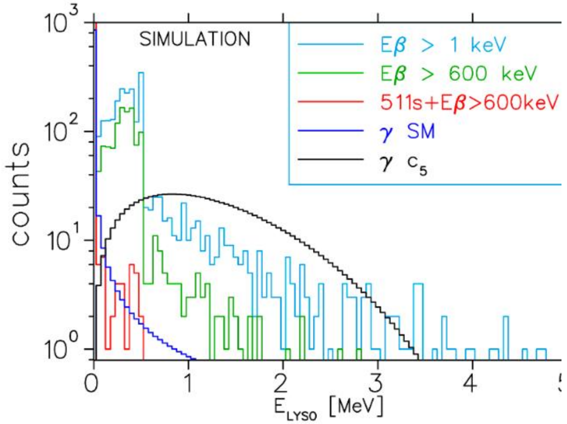
- Measure triple-vector $\left(\vec{p}_e \times \vec{k}_\gamma\right)\cdot\vec{p}_\nu$ (T-violating) correlation in ^{38m}K
  - Motivated by Gardner and He, PRD **87**, 116012 (2013)





- ○ 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

⋮

Mentioned by Leendert Hayen Monday morning

Final thought and thanks

- Atom traps [and optical pumping] helping pave the way for the precision frontier to complement the energy frontier
- 0.3% measurement of $\tilde{A}_\beta$ getting interesting, <0.1% in sight!
- Other promising measurement planned with TRINAT and other groups

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If I wasn't clear, I apologize…I've been distracted and watching too much CNN the last few days!

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